Flavor Structure of the Proton and Electroweak Interactions

Paul E. Reimer

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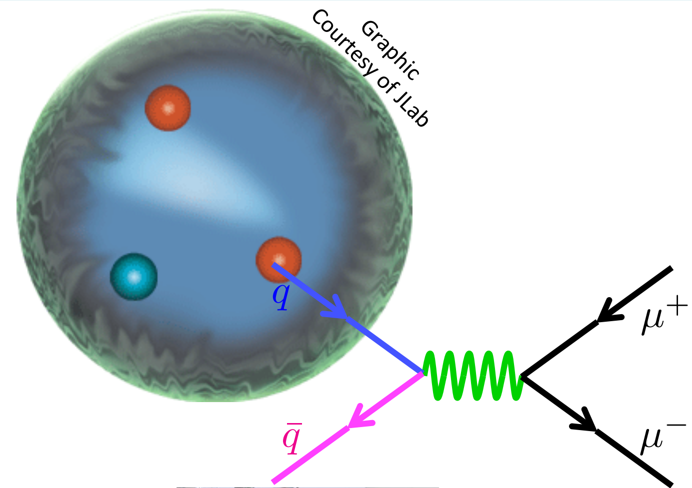
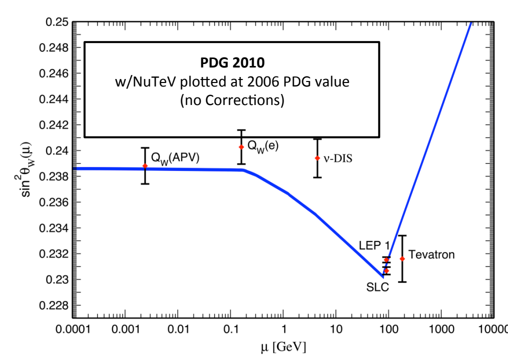
HUGS, 4-22 June 2012



Really—two separate topics unified by my interests

I. Flavor Structure of the Proton
   - A. Proton structure—historical view
   - B. Sea quarks in the proton & the Drell-Yan reaction
   - C. Proton structure in nuclei

II. Measurements of Parity Violation in Electron Scattering
   - A. The Standard Model, electroweak interactions and parity
   - B. Tests of the Standard Model with parity violation
   - C. Nuclear Structure with Parity Violation



I have borrowed heavily from slides made by John Arrington, Krishna Kumar and graphics from particleadventure.org and of course many, many collaborators.

Safety First

Please feel free to speak up at any time.

- This could get really boring if I'm doing all the talking
- This will get really boring if you don't understand something and I'm doing all the talking

Either of the above could cause the canary to die and I don't want that

You can e-mail me comments or questions to **reimer@anl.gov**

Proton structure—historical view

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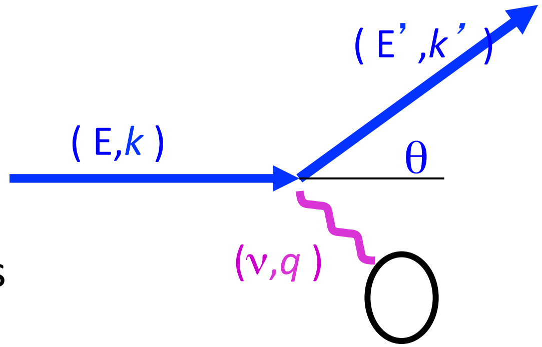
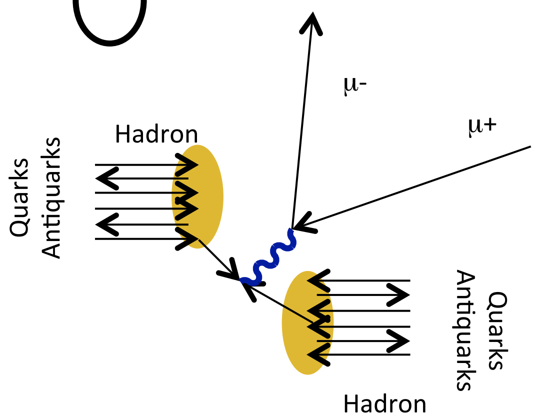
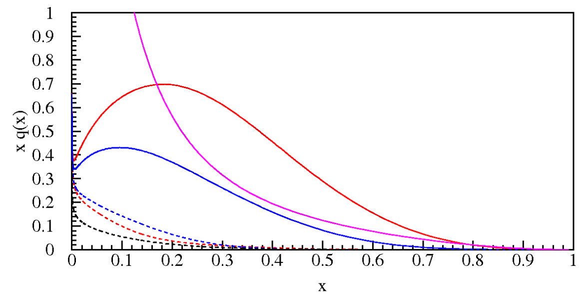


Really—two separate topics unified by my interests

I. Flavor Structure of the Proton
   A. Proton structure—historical view
      1. Historical overview: Nuclei to nucleons to quarks
      2. "Traditional" picture of nuclear physics (hadrons)
      3. QCD picture of nuclear physics (quarks & gluons)
      4. How is the flavor structure determined?
   B. Sea quarks in the proton & the Drell-Yan reaction
   C. Proton structure in nuclei



II. Measurements of Parity Violation in Electron Scattering
   A. The Standard Model, electroweak interactions and parity
   B. Tests of the Standard Model with parity violation
   C. Nuclear Structure with Parity Violation



Pre-history of Nuclear Physics

Ancient Tradition: Basic Elements (see, *e.g.* ParticleAdventure.org):

- ca. 450 BC, Greece (**Empedocles**) Earth, Air, Fire and Water
- ca. 200-300 AD, India (**Samkhya-karikas** by Ishvarakrsna) Space, Air, Fire, Water, and Earth.
- Chinese (in Pinyin, *Wu Xing*) Earth, Wood, Metal, Fire, and Water

Indivisible Unit: The Atom

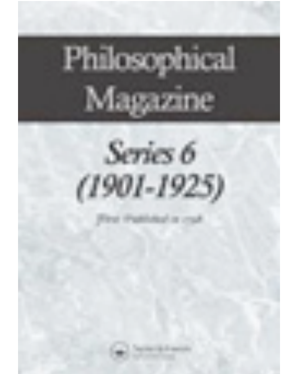
- BC 600's in India the concept of smallest piece of mater developed
- BC 450 Democritus used the term ατομοσ or atom for this

Empty Space: Rutherford scattering

- 1909: Small hard core surrounded by empty space
- Expected small scattering through diffuse material but saw occasional large angle scattering

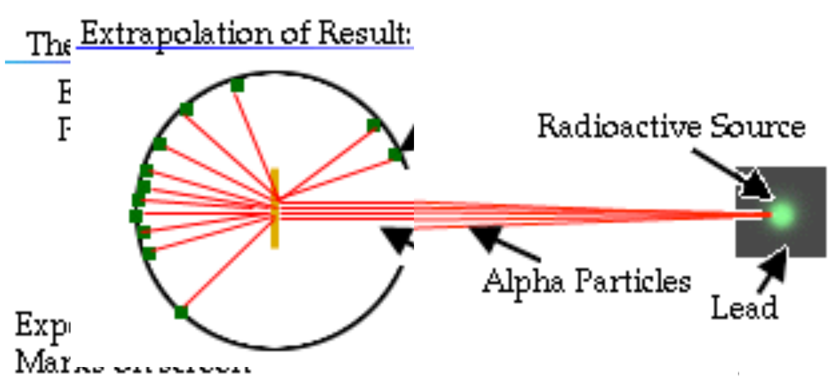
- Actual measurements may by **Hans Geiger** and **Ernest Marsden**—under Rutherford's supervision

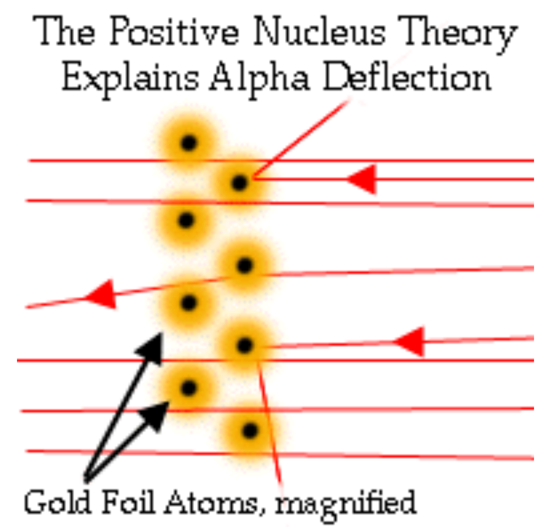
Rutherford's Atom



LXXIX. *The Scattering of α and β Particles by Matter and the Structure of the Atom.* *By* Professor E. RUTHERFORD, *F.R.S., University of Manchester* *.

§ 1. IT is well known that the α and β particles suffer deflexions from their rectilinear paths by encounters with atoms of matter. This scattering is far more marked for the β than for the α particle on account of the much smaller momentum and energy of the former particle.

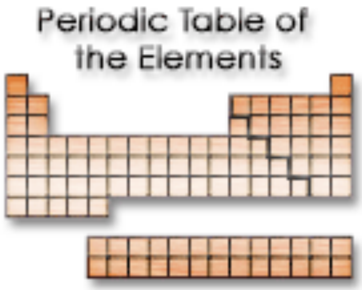




Graphics: ParticleAdventure.org

Interpreted data as a positively charged core with negatively charged electron cloud, partially based on the low mass of the electron

Other Particles



Neutron

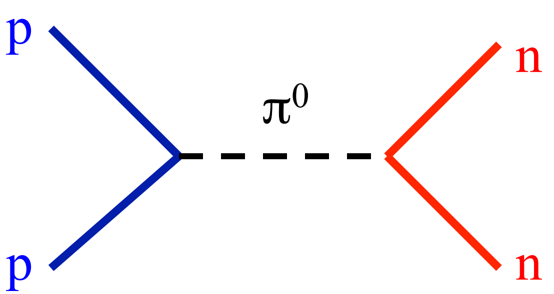
- 1920 existence speculated on by Rutherford
- 1932 discovered by Chadwick

Now we could explain the periodic table

except that something had to hold the positively charged core together

First attempt:

- Yukawa's original idea—nucleons interact by exchanging massive particles (mesons)

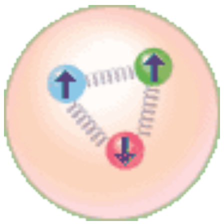


- Range ≅ cΔt ≅ h/2mc ≅ 1fm or m ≅100 MeV for the lightest meson (the pion)

- The pion was discovered in 1947 by Cecil Powell, confirming Yukawa's prediction

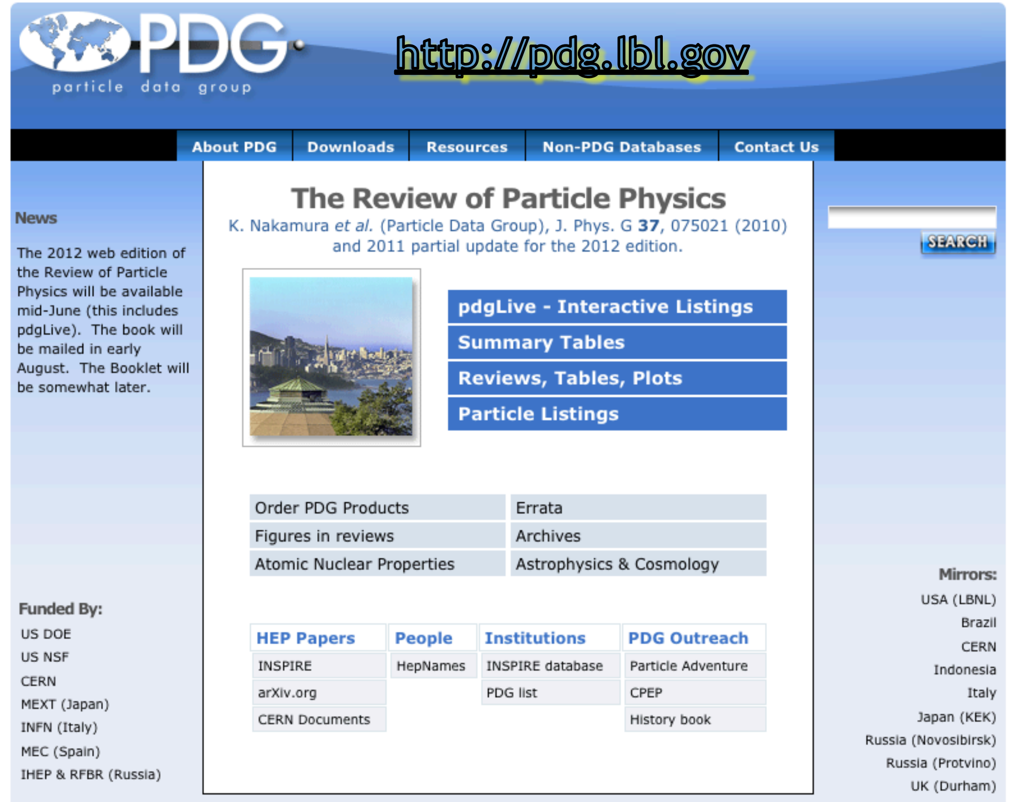
The discovery of the pion was followed by an explosion of particle discoveries (1947-1960s)

This Led Gell-Mann and Zweig introduce quarks to organize the spectrum (particle zoo).



Δ^{++} (u,u,u) ⇨ additional quantum number (color)

Provides classification scheme for observed particles, properties and decays. (See for example, Halzen and Martin.)

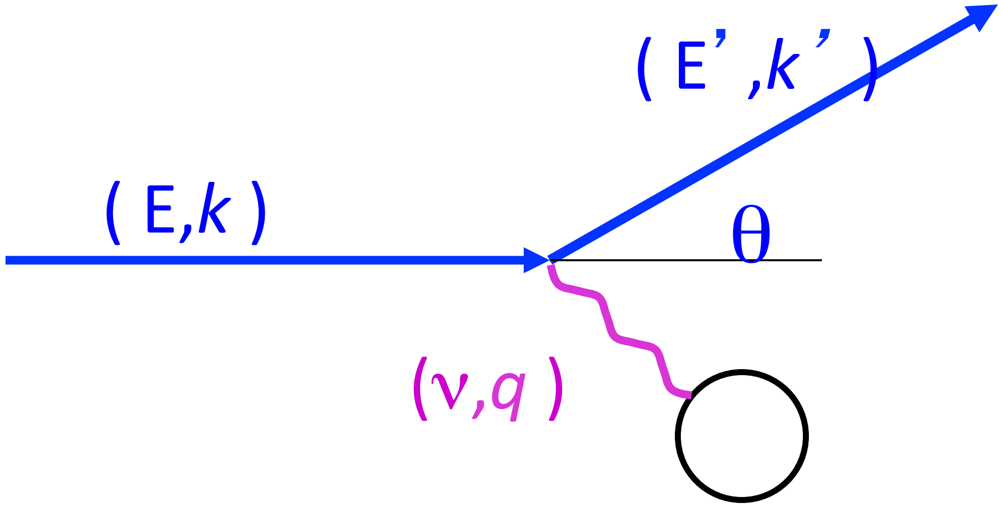


But, how do we know* that there is substructure to the proton?

*As an experimentalist, I claim we don't "know" something until we measure** it

**Measurements are subject to mistakes and data is subject to interpretation.

Inclusive Scattering: Kinematics



Measure:

E, E’ , θ

Reconstruct virtual photon:

$\nu = E - E'$ (energy transfer)

$q = k - k'$ (momentum transfer)

$Q^2 = q^2 - \nu^2 = 4EE' \sin^2(\theta/2)$

$x = Q^2 / 2M\nu$

$$\left(\frac{d\sigma}{d\Omega}\right)_{\rm point} = \left(\frac{d\sigma}{d\Omega}\right)_{\rm Mott} = \frac{(Z\alpha)^2 E^2}{2k^4 \sin^4\frac{\theta}{2}}\left(1 - \frac{k}{E}\sin^2\frac{\theta}{2}\right)$$

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{\rm point} |F(q)|^2$$

Non-pointlike behavior kept in structure function

See Perkins and/or Halzen & Martin

The Standard Model

BOSONS force carriers spin = 0, 1, 2, …

Unified Electroweak spin = 1		
Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	–1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1		
Name	Mass GeV/c^2	Electric charge
g gluon	0	0

FERMIONS matter constituents spin = 1/2, 3/2, 5/2, …

Leptons spin = 1/2		
Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	–1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	–1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	–1

Quarks spin = 1/2		
Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	175	2/3
b bottom	4.3	–1/3

Graphics: ParticleAdventure.org

Problem:

- Quarks and gluons make up the bulk of the matter, but do not appear as relevant can never be "seen"!

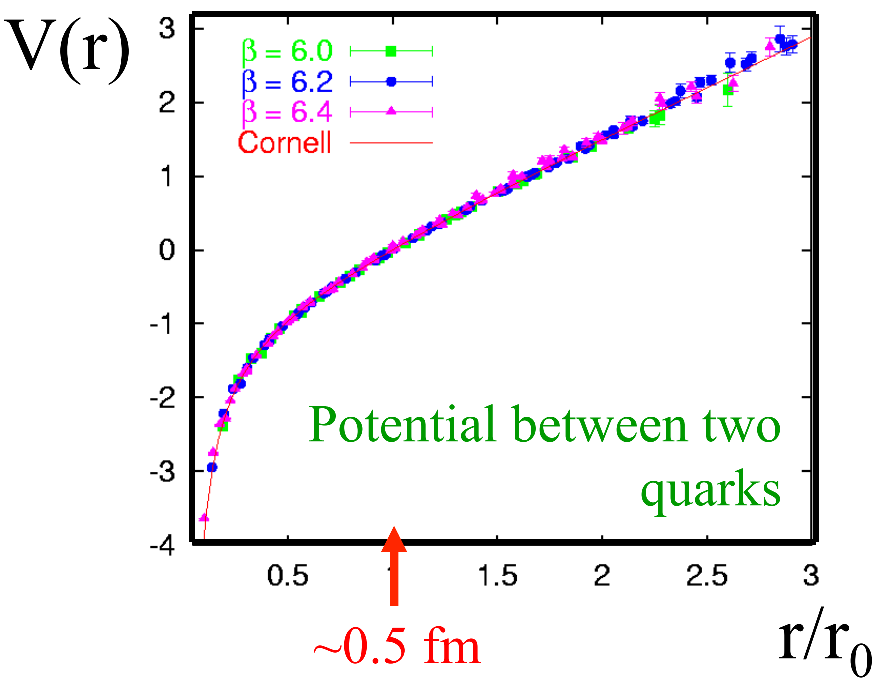
Aside: Do Quarks really exist?
Two "Realms" of Nuclear Physics

Quantum Chromo Dynamics (QCD): The fundamental theory describing the strong force in terms of quarks and gluons carrying color charges.

Strongly attractive at all distances.

1 GeV/cm → *18 tons*

$>10^{12}$ times the Coulomb attraction in hydrogen



Slide from John Arrinton

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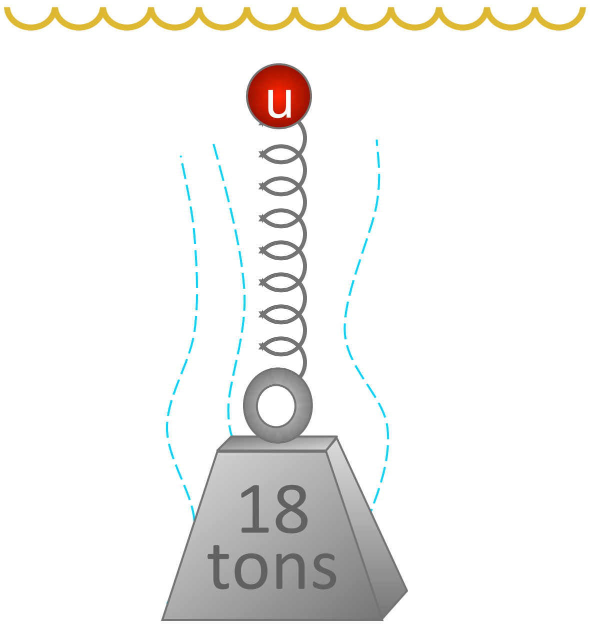
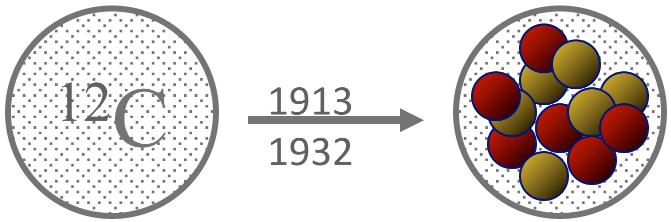
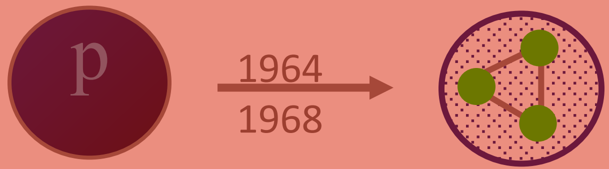


Slide from John Arrinton

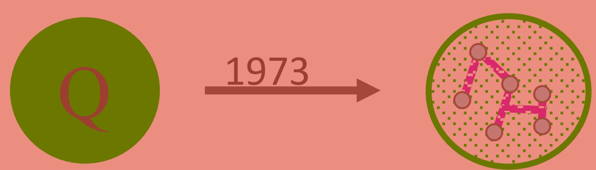
Summary (last 100 years)



Nucleus = protons + neutrons +
strong interaction of hadrons



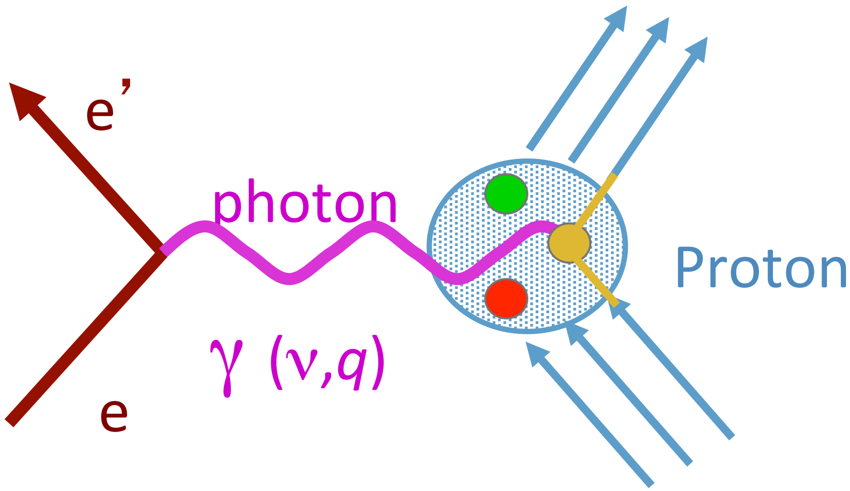
proton = Constituent Quarks + strong
interaction of Quarks



Constituent Quark = quarks
+ gluons + strong
interaction of QCD

Nearly a century of nuclear physics has shown that a ***NUCLEUS*** can be well described in terms of protons, neutrons, the strong force, *and nothing else*

X and Q^2



$$Q^2 = q^2 - \nu^2 = 4EE' \sin^2(\theta/2)$$

$$x = Q^2 / 2M\nu$$

Q^2 : Square of four momentum of the virtual photon, or momentum transfer square (higher Q^2 probes shorter distances)

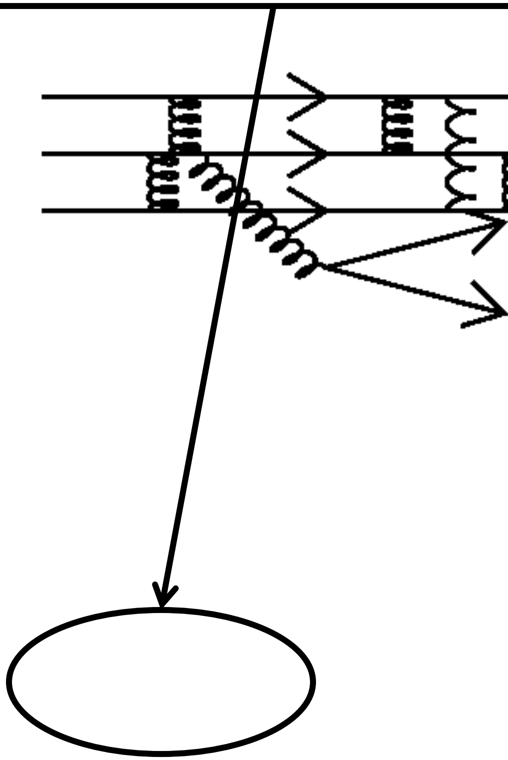
x_{Bj} : Fraction of nucleon momentum carried by the struck quark in the infinite momentum frame

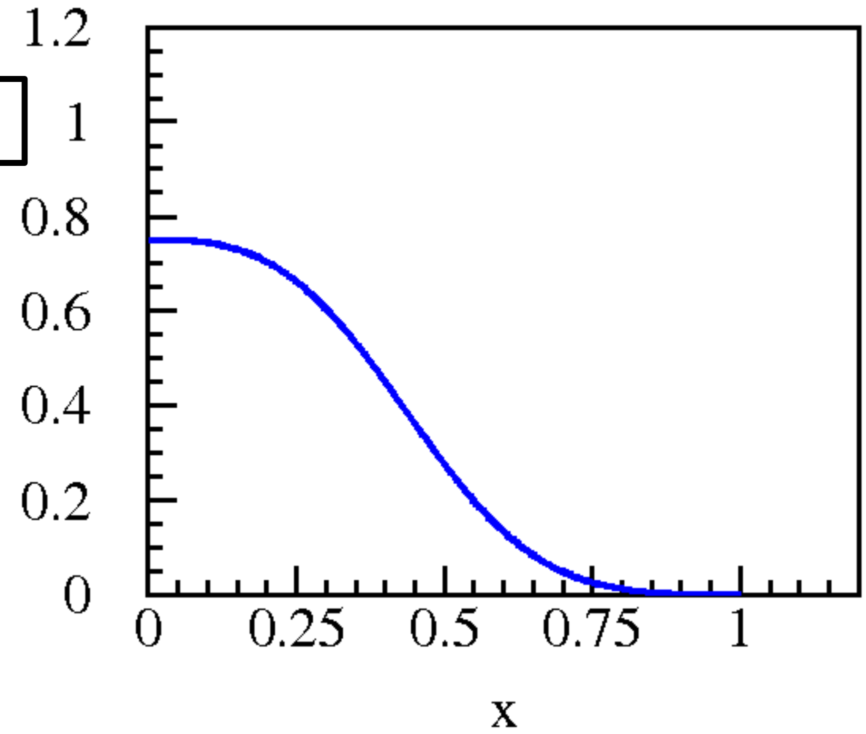
Proton target: $0 < x < 1$
Nuclear target: $0 < x < A$

Parton Distributions and $x_{Bjorken}$

Consider the proton as a

Gluon splitting responsible for quark sea?





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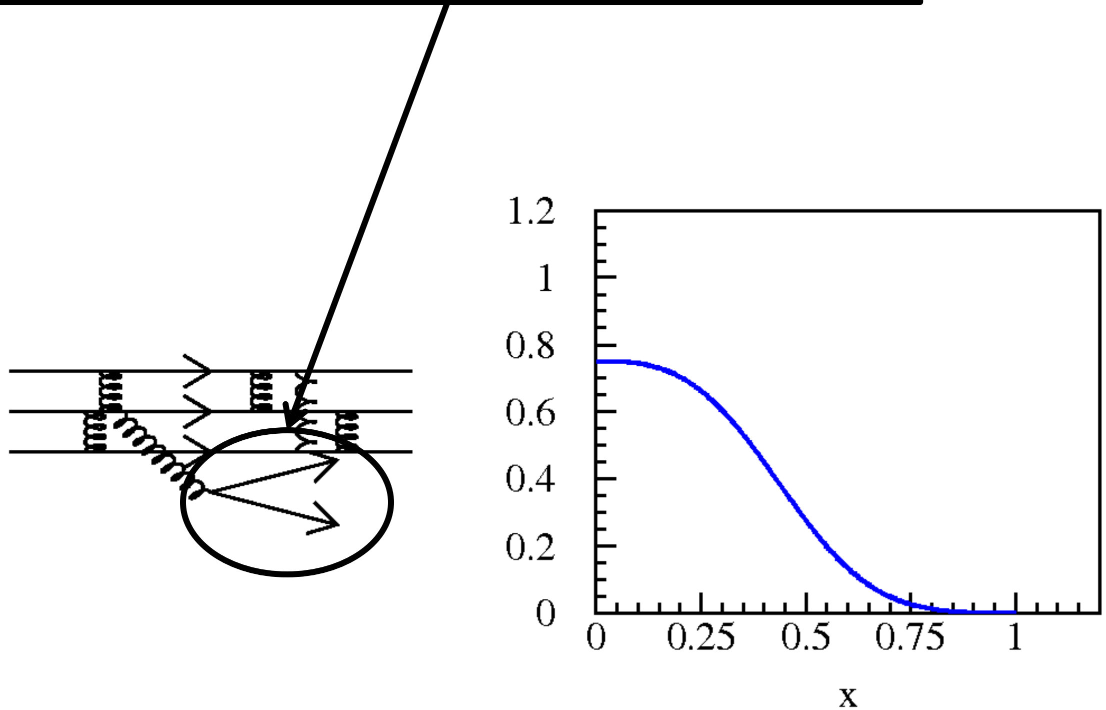
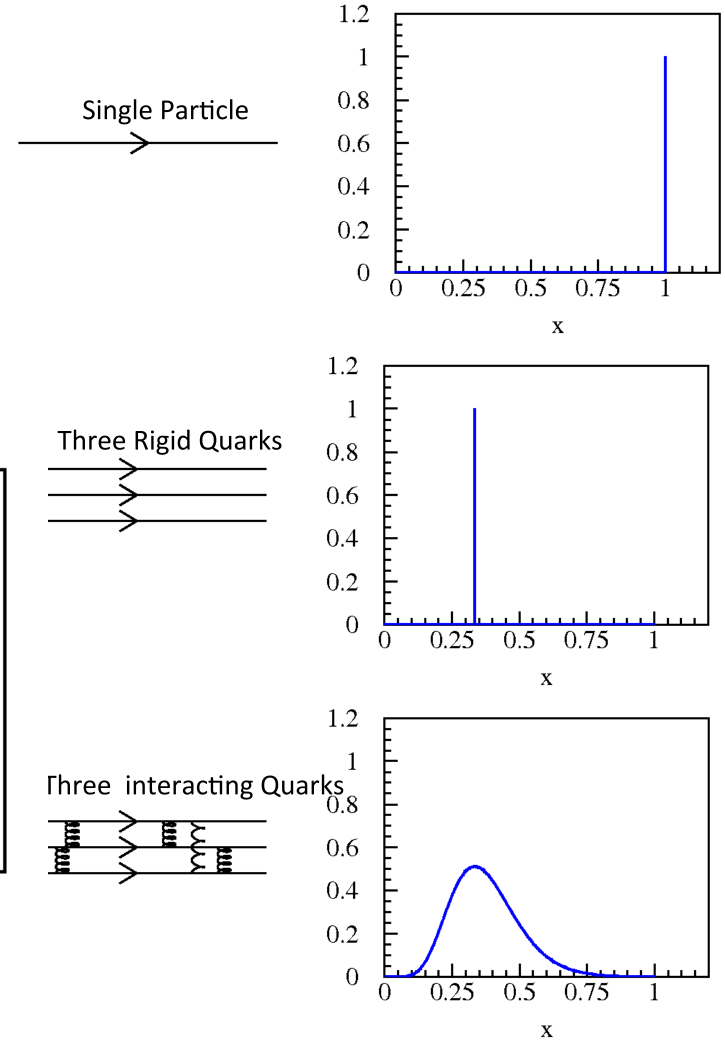




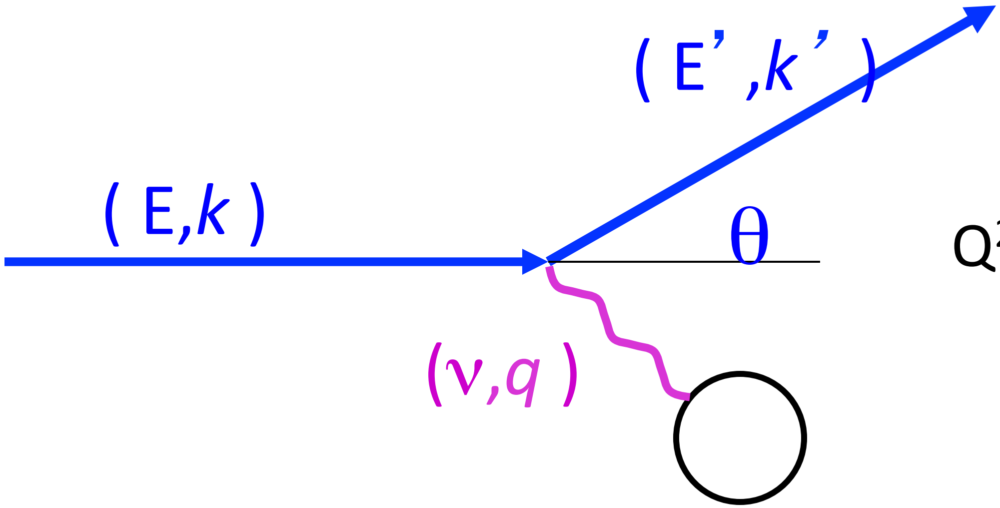
Notation & Definitions

Fractional momentum carried by interacting quark

$$x \equiv x_{\mathrm{B}j} \in [0, 1]$$

Not to be confused with Feynman-x, x_F

Energy Transfer—Negative squared 4-momentum of intermediate vector boson that is interacting with the probed quark.



$Q^2 = q^2 - \nu^2 = 4EE' \sin^2(\theta/2)$

$x = Q^2 / 2M\nu$

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Notation & Definitions

Parton Distribution Function (PDF) {sometimes Parton *Density* Function}

Probability of finding a quark of flavor *q* with momentum fraction in {x, x+dx}

$$q\left(x, Q^2\right)$$

Note that PDF's are functions not only of x_{Bj} but also of the energy scale (Q^2) at which the experiment probes the PDF, but frequently Q^2 is dropped in notation

But for confusion, sometimes also denoted $f(x,Q^2)$.

For additional confusion, for now, I'm only discussing "longitudinal" distributions and ignoring movement transverse to the proton's motion

Specific flavors of parton distributions can be denoted by:

$$u\left(x, Q^2\right) d\left(x, Q^2\right) s\left(x, Q^2\right) \ldots$$

$$\bar{u}\left(x, Q^2\right) \bar{d}\left(x, Q^2\right) \bar{s}\left(x, Q^2\right) \ldots$$

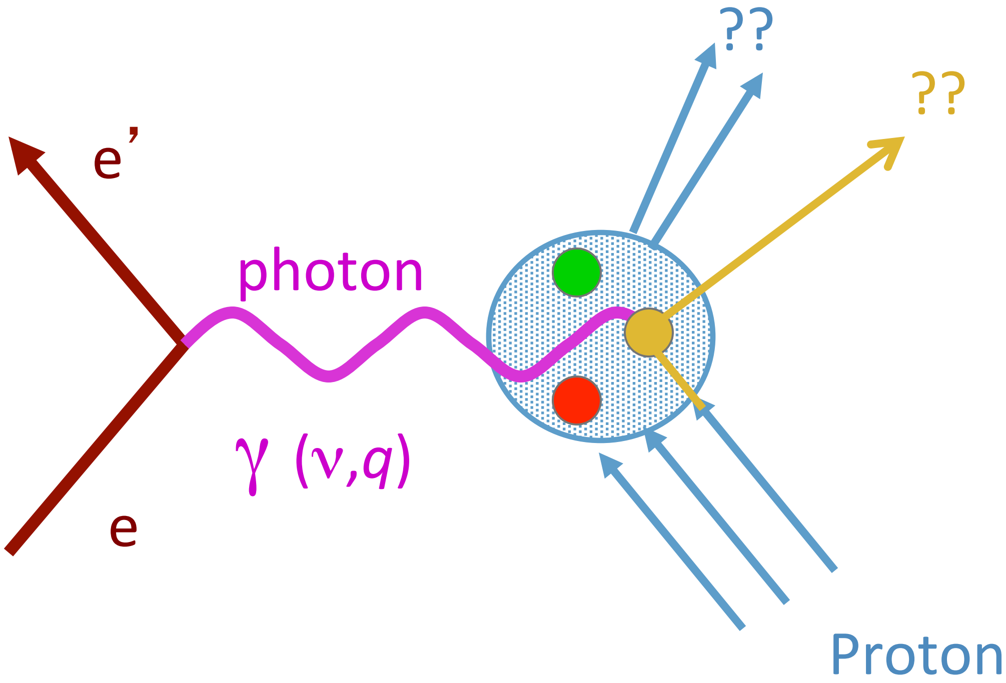
$$g\left(x, Q^2\right)$$

Frequently sum over all flavors of quarks

$$\sum_{q \in \{u, d, \ldots\}}$$

Parton distributions generally refer to the proton, unless they don't (in which case I will use a superscript, *e.g.* $u^n(x)$ $\bar{d}^\pi(x)$

Deep Inelastic Scattering



For e p → e' X the cross-section can be written as

$$\frac{d\sigma}{dE'\,d\Omega} = (K)[2W_1(\nu,Q^2)\sin^2(\theta/2) + W_2(\nu,Q^2)\cos^2(\theta/2)]$$

Structure Functions

$$\frac{d\sigma}{dE'd\Omega} = (K)[2W_1(\nu,Q^2)\sin^2(\theta/2) + W_2(\nu,Q^2)\cos^2(\theta/2)]$$

$W_1(\nu,Q^2), W_2(\nu,Q^2)$ are the two structure functions which describes what's inside the proton.

As Q^2 increases the structure functions simplify and depend only on the fraction of momentum carried by the partons.

$Q^2 = q^2 - \nu^2 = 4EE' \sin^2(\theta/2)$

$x = Q^2 / 2M\nu$

at large Q^2

$$mW_1(\nu,Q^2) \rightarrow F_1(x)$$

$$\nu W_2(\nu,Q^2) \rightarrow F_2(x)$$

$$2xF_1 = F_2$$

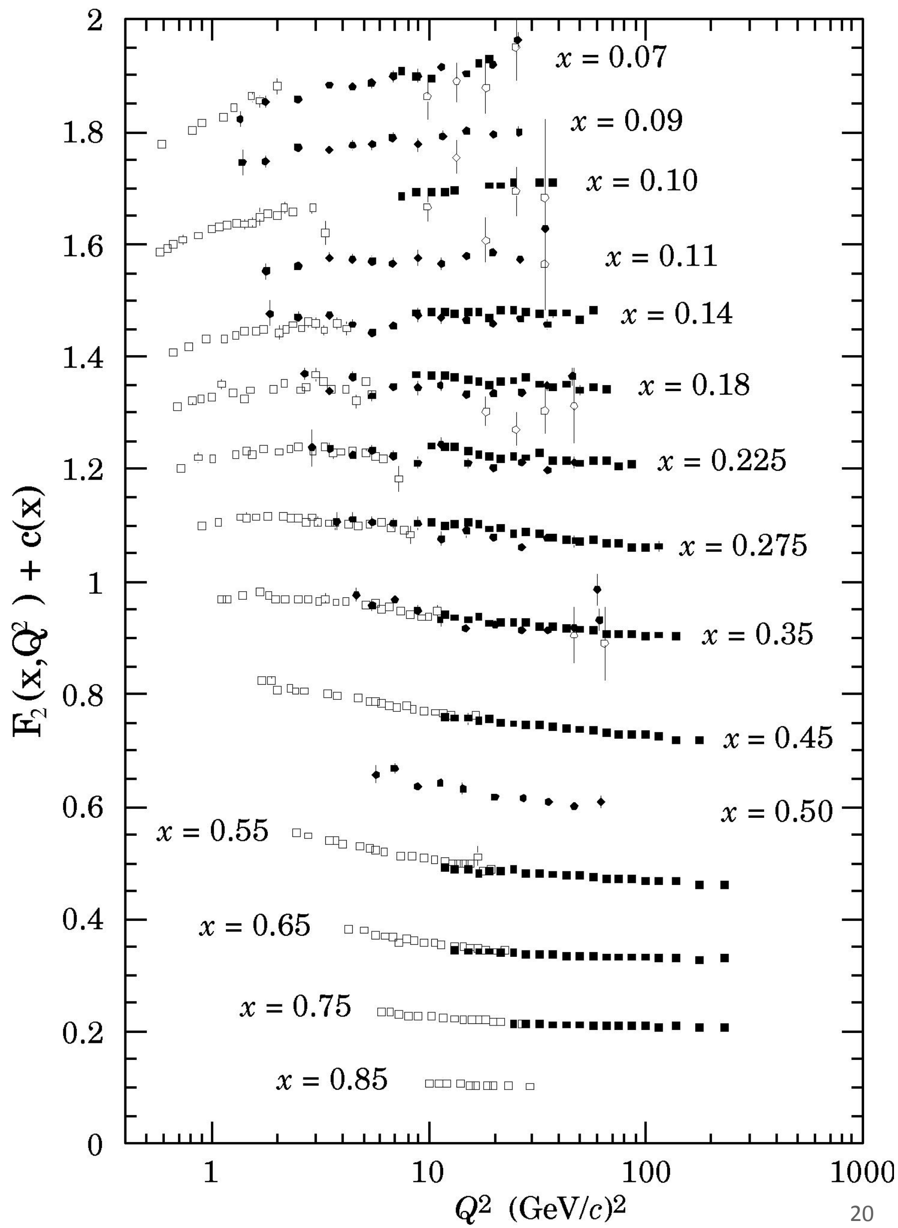
Quarks matter at high energy

Hard scattering processes such as DIS allow us to probe the quark structure of hadrons

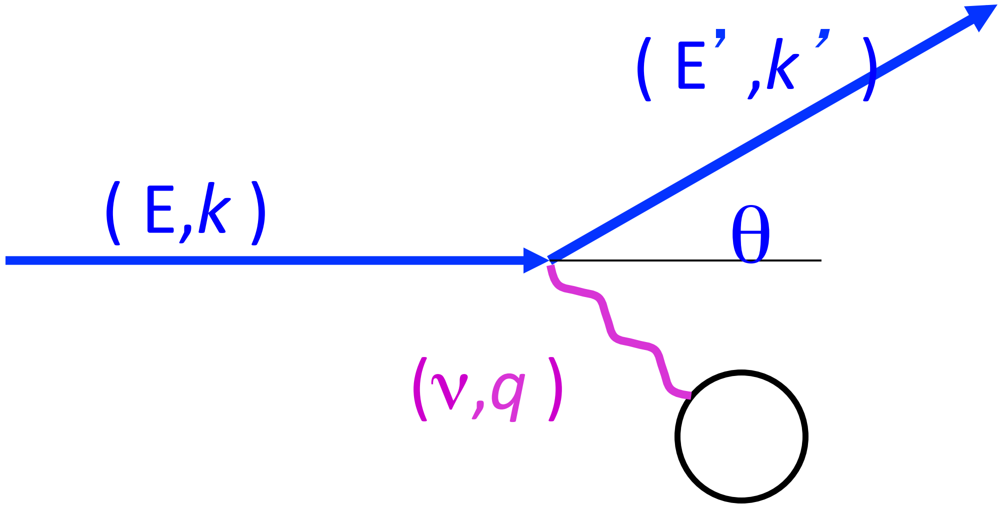
- ➢ Extract quark distributions
- ➢ See the *end result* of confinement
- ➢ Test QCD (e.g. scaling, evolution)

If 1 GeV is enough to look for quarks hiding under the "rock" (18 tons)

- SLAC (50 GeV) can peek under a 747
- HERA can look under the Titanic
- LHC can shift The Iceberg



How do we determine Quark (Parton) distributions?



$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{point}} |F(q)|^2$$

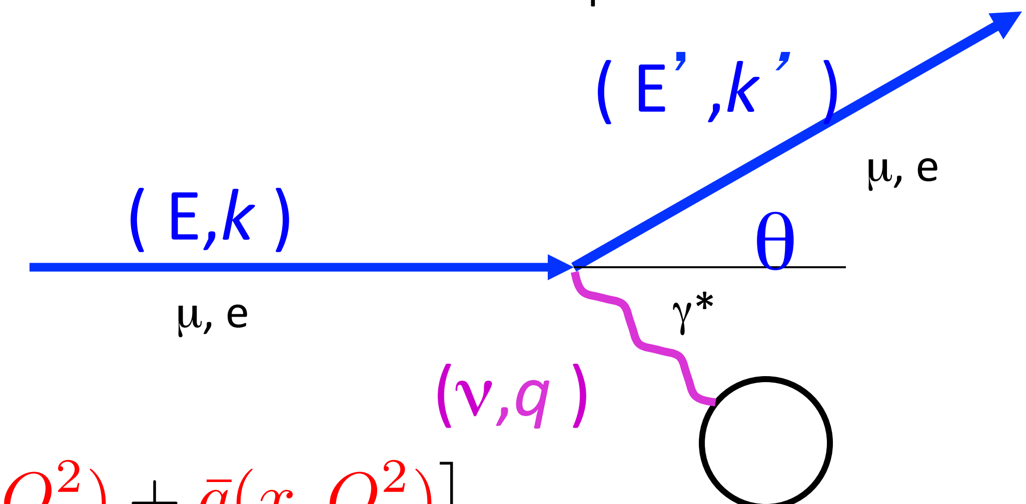
Hit the atom hard enough that

- Nuclear binding energies are small
- We begin to see point-like behavior again.

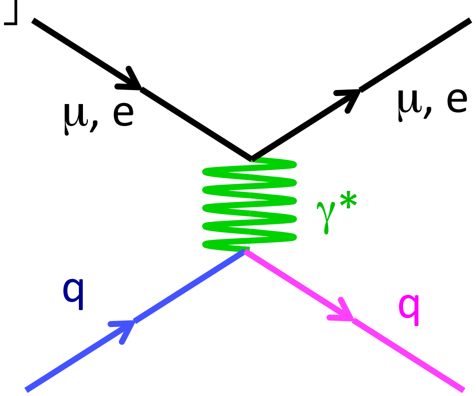
How are parton distributions determined?

1. Make measurements—Look data from "hard" processes
   - Where "hard" means that there was sufficient energy to believe that the primary interaction was between the probe and a quark
   - Different processes are sensitive to different combinations of quark distributions

Charged Lepton DIS



$$F_2^p(x) \propto \sum_{q\in\{u,d,\dots\}} e_q^2 x \left[q(x,Q^2) + \bar{q}(x,Q^2)\right]$$

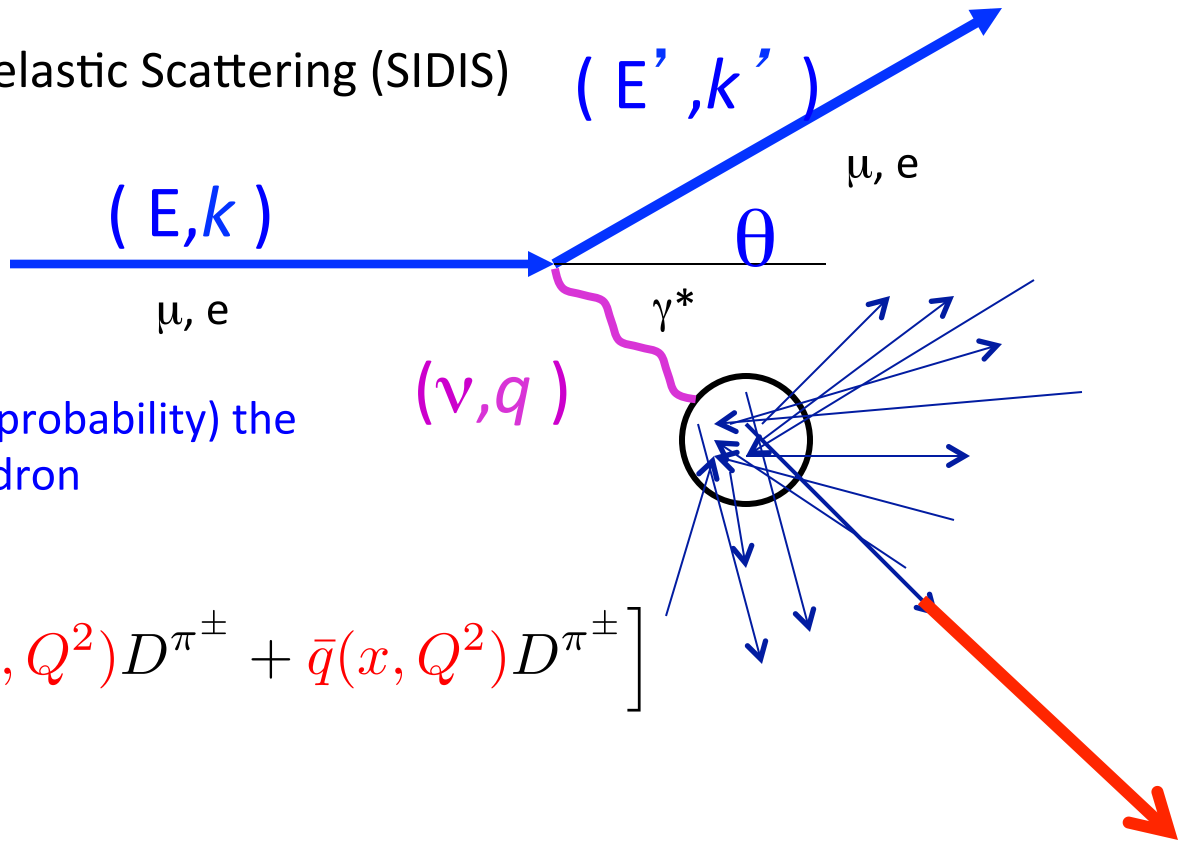


Signal: Scattered charged lepton

(and other stuff from the hadron you just blew apart, but you ignore that stuff)

How are parton distributions determined? SIDIS

1. Semi-Inclusive Deep Inelastic Scattering (SIDIS)



Struck quark is (with some probability) the contained in the fastest hadron

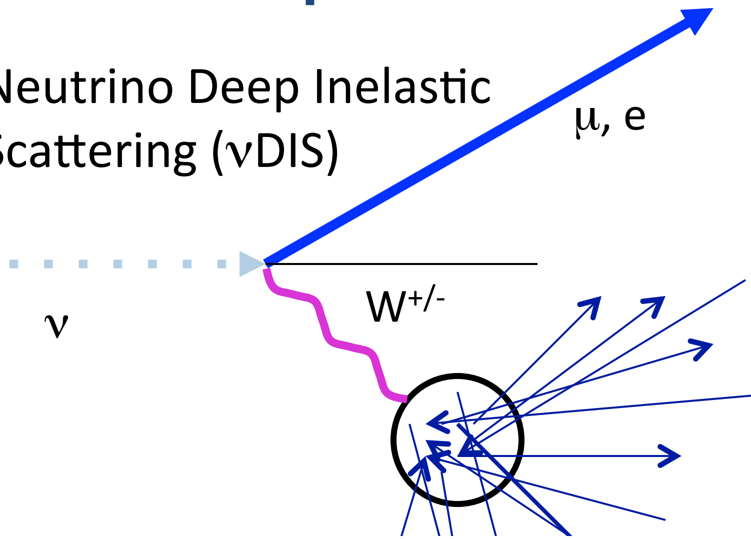
$$N^{\pi^\pm} \propto \sum_{q\in\{u,d,\dots\}} \left[q(x,Q^2) D^{\pi^\pm} + \bar{q}(x,Q^2) D^{\pi^\pm} \right]$$

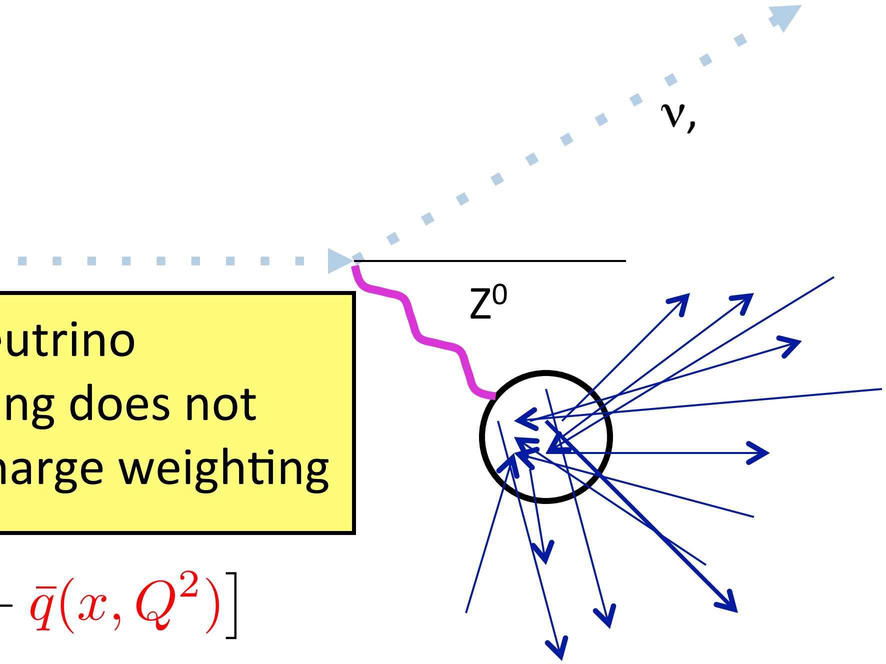
Signal:

- Scattered charged lepton and a fast meson (pion, kaon, etc) and other stuff
- Count number of (DIS+pion) events relative to number of DIS events

How are parton distributions determined? νDIS

Neutrino Deep Inelastic Scattering (νDIS)

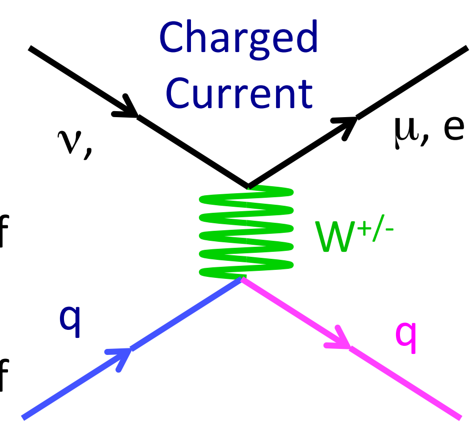




Note: Neutrino scattering does not have charge weighting

$$F_2^{\nu p}(x) + F_2^{\nu n} \propto \sum_{q\in\{u,d,\ldots\}} x\left[q(x,Q^2) + \bar{q}(x,Q^2)\right]$$

$$xF_3^{\nu N}(x) \propto \sum_{q\in\{u,d,\ldots\}} x\left[q(x,Q^2) - \bar{q}(x,Q^2)\right]$$



Signal—Charged Current (W boson exchange):

- No track in (neutrino) lepton track out and scattered other stuff

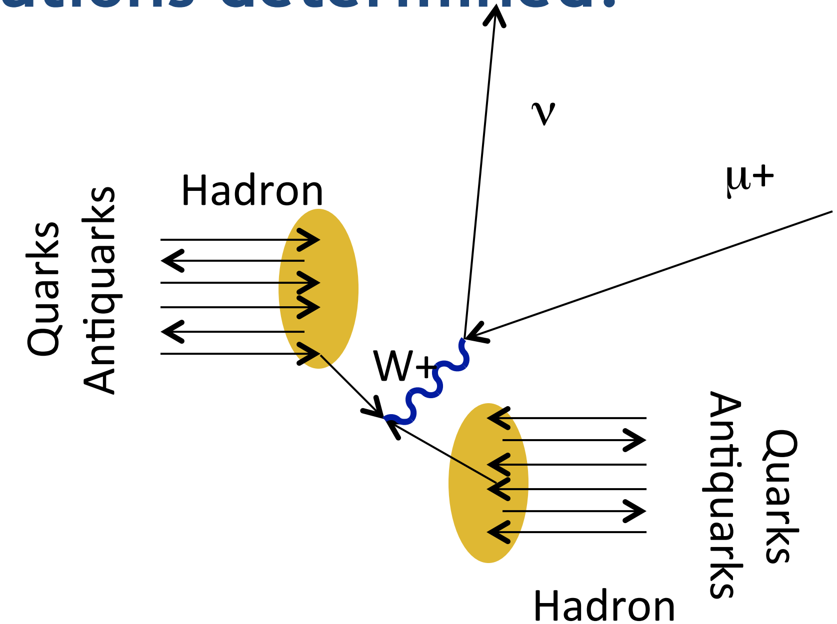
Signal—Neutral Current (Z boson exchange):

- No track in (neutrino) lepton track out and scattered other stuff

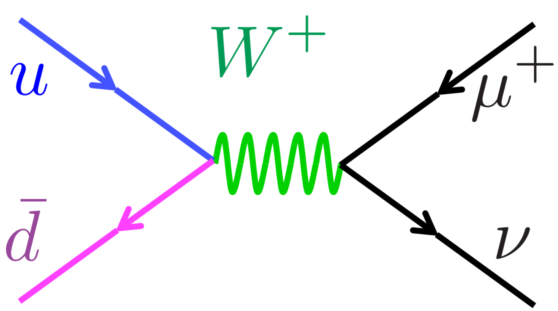
How are parton distributions determined?

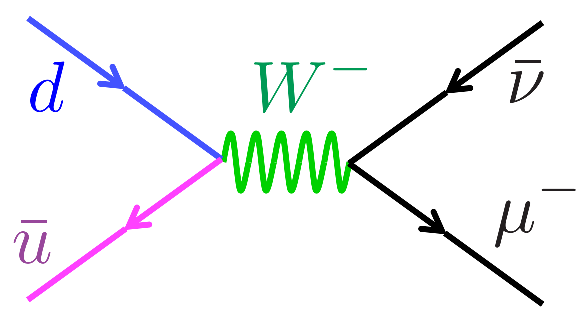
W Production Asymmetry

- In a collider such as Fermilab or LHC W's are produced through annihilation of quark-antiquark pairs of "opposite" flavor



$$A_W(y) \propto \frac{u(x_1)\bar{d}(x_2) - d(x_1)\bar{u}(x_2)}{u(x_1)\bar{d}(x_2) + d(x_1)\bar{u}(x_2)}$$

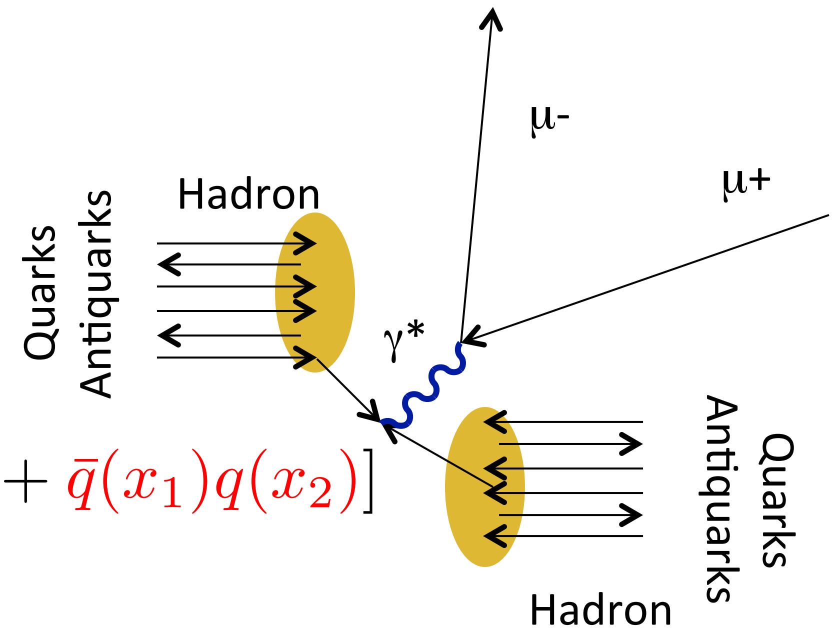




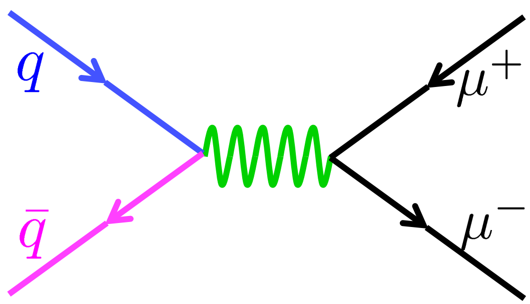
How are parton distributions determined? Drell-Yan

Drell-Yan

- Like flavor quark-antiquark annihilation
- Much more on this process later



$$\frac{d\sigma}{dx_1 dx_2} \propto \sum_{q\in\{u,d,\dots\}} e_q^2 \left[q(x_1)\bar{q}(x_2) + \bar{q}(x_1)q(x_2)\right]$$



Other data also contributes. See, for example, the CTEQ *Handbook of Perturbative QCD* http://www.phys.psu.edu/~cteq/#Handbook

How are parton distributions determined?

2. Make assumptions
   a. Two up quark and one down quark in the proton

$$\int_0^1 \left[u^p(x) - \bar{u}^p(x)\right] dx = 2 \qquad \int_0^1 \left[d^p(x) - \bar{d}^p(x)\right] dx = 1$$

   That is, there is an excess of two up quarks over the antiup quarks and one more down quark than antidown quark.

   b. All the proton's momentum is accounted for (this is really a definition)

$$\int_0^1 \left\{ \sum_{q\in\{u,d,\dots\}} x\left[q^p(x) - \bar{q}^p(x)\right] + xg(x) \right\} dx = 1$$

   c. Neutrons are like protons, except that

$$u^p(x) \equiv d^n(x) \qquad d^p(x) \equiv u^n(x)$$
$$\bar{u}^p(x) \equiv \bar{d}^n(x) \qquad \bar{d}^p(x) \equiv \bar{u}^n(x)$$

(This is a relative good but not exact assumption that I will come back to several times.)

How are parton distributions determined?

3. Make even more assumptions
   - What is the mathematical functional form?

$$xq(x) = A_q x^{\alpha} (1-x)^{\beta}$$

Can even make theoretical arguments about the values of α and β based on, for example Dyson-Schwinger equations, pQCD, *etc*, but not all arguments give the same values. (There is an interesting story about the pion here.)

   - Typically not enough flexibility

$$xq(x) = A_q x^{\alpha} (1-x)^{\beta} (1 + \gamma x + \delta\sqrt{x} + \ldots)$$

A_q is essentially determined by the normalization integrals on the previous slide

NNPDF Neural Network PDF collaboration avoids this problem, using a neural network, at the expense of much greater uncertainty (or is is much greater?) http://nnpdf.hepforge.org/

How are parton distributions determined?

3. Make even more assumptions
   - What is the mathematical functional form?

$$xq(x) = A_q x^{\alpha} (1-x)^{\beta} (1 + \gamma x + \delta\sqrt{x} + \ldots)$$

Aside:

Example where parameterization matters: What is d/u as x->1

$$\lim_{x \to 1} = \frac{A_d x^{\alpha_d} (1-x)^{\beta_d} (\ldots)}{A_u x^{\alpha_u} (1-x)^{\beta_u} (\ldots)}$$

$$\text{if } \beta_d = \beta_u \text{ then} \qquad\qquad \text{if } \beta_d > \beta_u \text{ then}$$

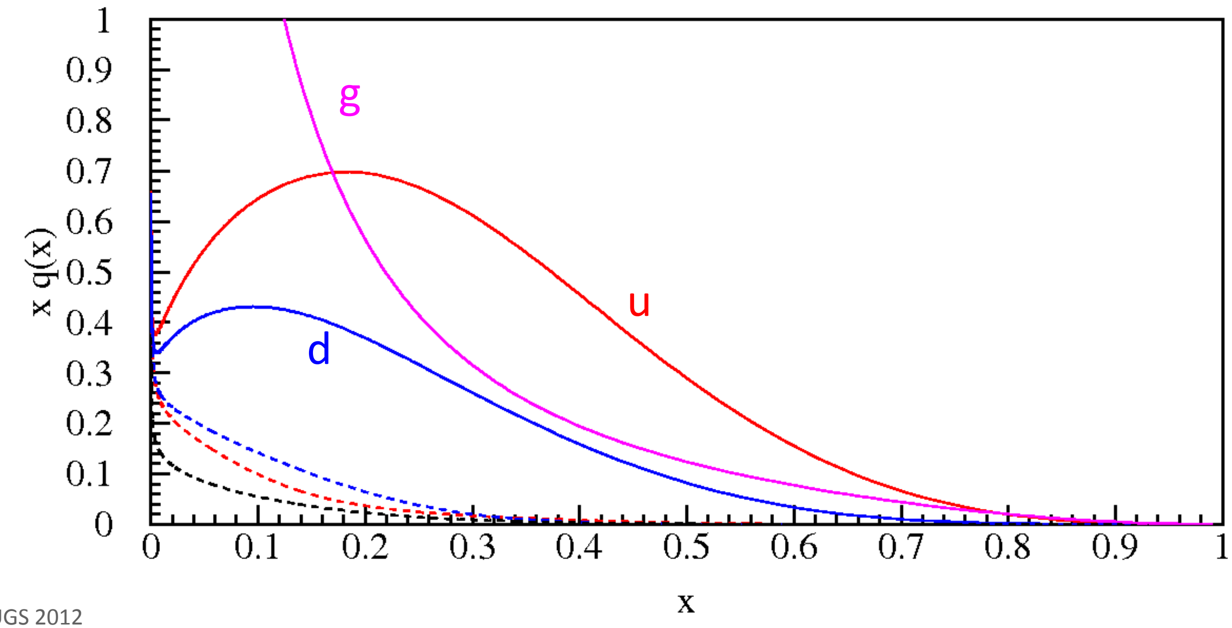
$$= \frac{A_d}{A_u} \qquad\qquad = 0$$

That is, you could be building in a result that is not there; especially if there is no data in that region

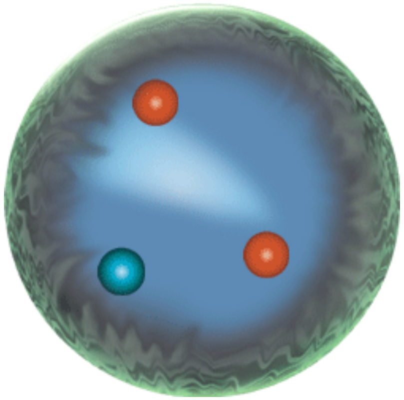
How are parton distributions determined?

4. **Now become arrogant** (we're physicists, so were good at this step)—Assume that you actually know the physics in all processes that are being included in the fit.
   – Is leading order enough; Is next-to-leading order enough? (There is an interesting story about the pion here.)
5. Write a large least squares fitting program to calculate all known cross sections for which you have data and minimize parameters.

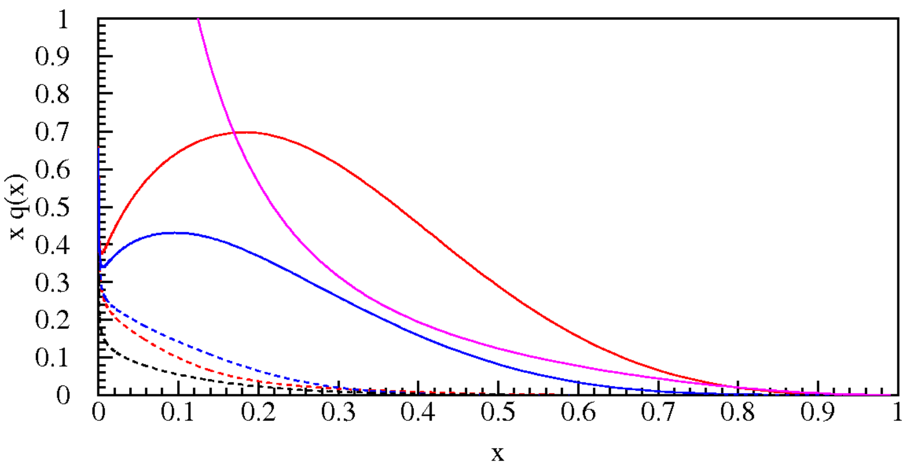
For a comprehensive list of the data, see http://durpdg.dur.ac.uk/HEPDATA/HEPDATA.html

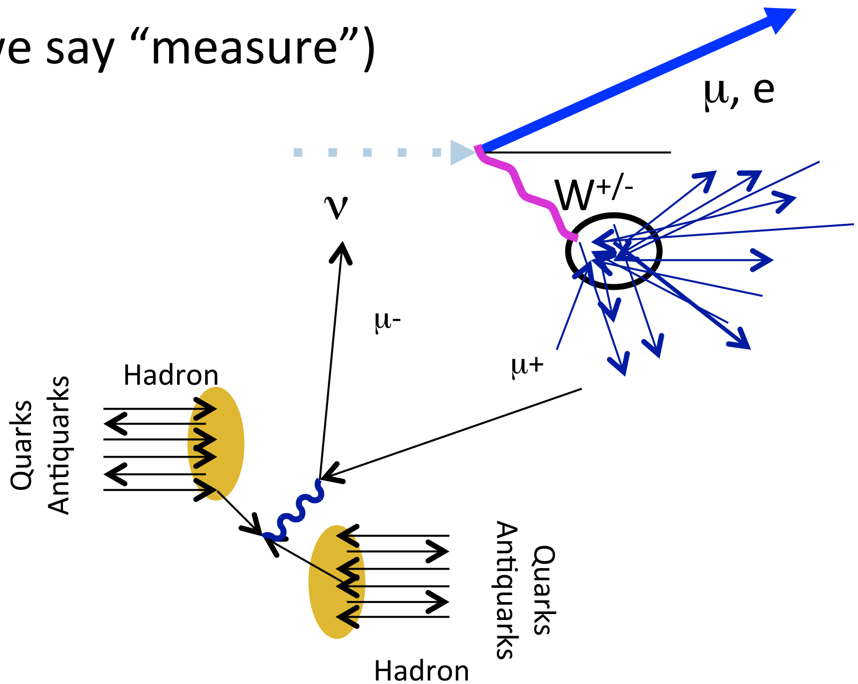


Review



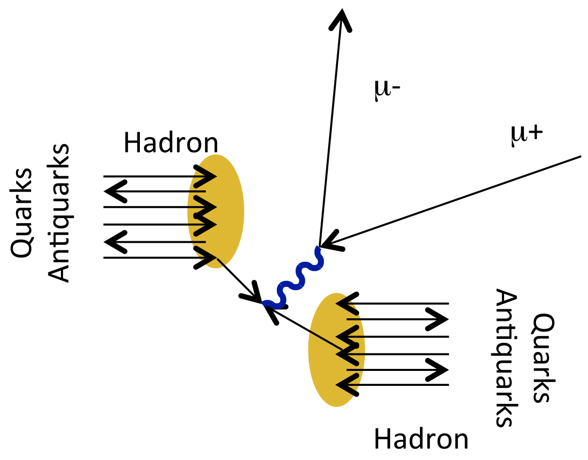
- Protons, neutrons, pions, *etc* are composed of quarks bound together by gluons.
  - Hadrons are categorized by their quark content. For example the proton is uud, neutron is udd, π^+ is u anti-d
- Quark distributions are discussed in terms of x_{Bj}—representing the fraction of the hadron's momentum carried by that particular quark.
- It is possible to study (if we are arrogant, we say "measure") the quark probability distributions.





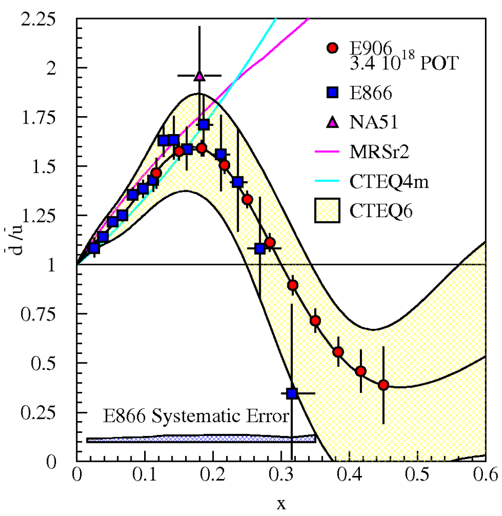
Sea quarks in the proton & the Drell-Yan reaction

Paul E. Reimer
Physics Division, Argonne National Laboratory
HUGS, 4-22 June 2012



Really—two separate topics unified by my interests

I. Flavor Structure of the Proton
    A. Proton structure—historical view
    B. Sea quarks in the proton & the Drell-Yan reaction
        1. Drell-Yan history
        2. SeaQuarks
        3. Fermilab and CERN Drell-Yan experiment
    C. Proton structure in nuclei
II. Measurements of Parity Violation in Electron Scattering
    A. The Standard Model, electroweak interactions and parity
    B. Tests of the Standard Model with parity violation
    C. Nuclear Structure with Parity Violation



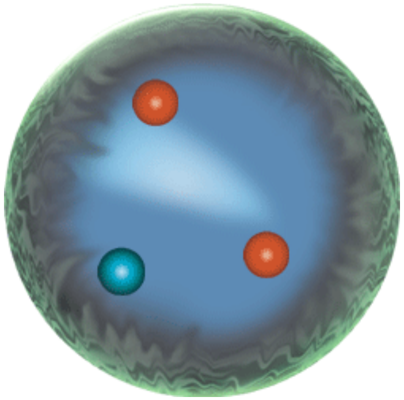
Please feel free to speak up at any time.

- This could get really boring if I'm doing all the talking
- This will get really boring if you don't understand something and I'm doing all the talking

Hopefully I will rise above the level of a small annoying insect

You can e-mail me comments or questions to **reimer@anl.gov**

Review from last lecture



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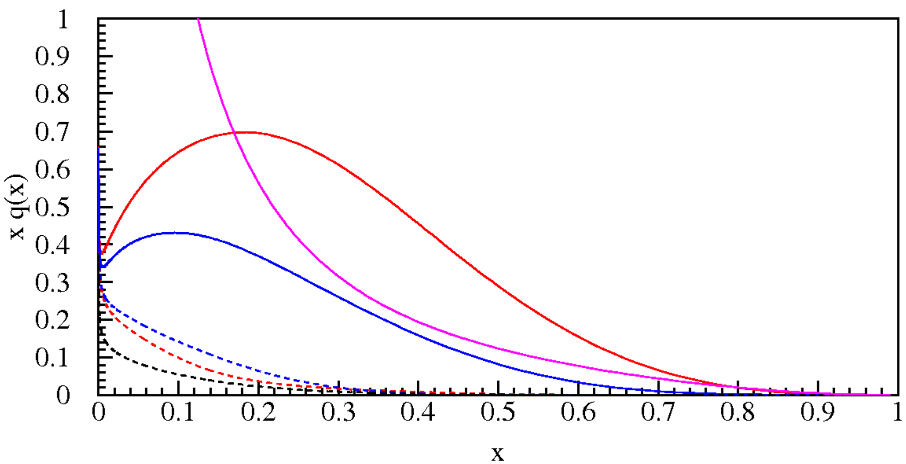
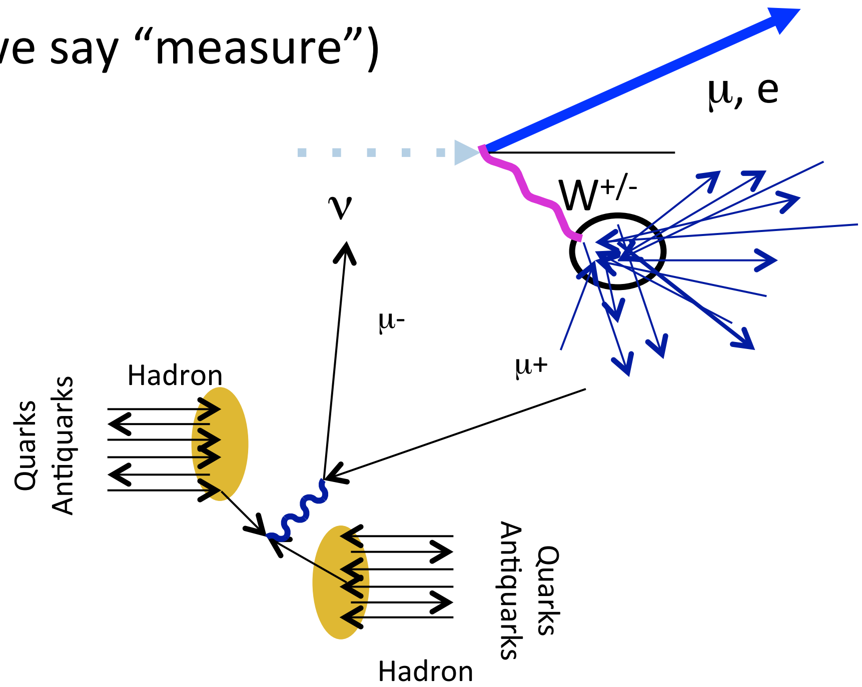
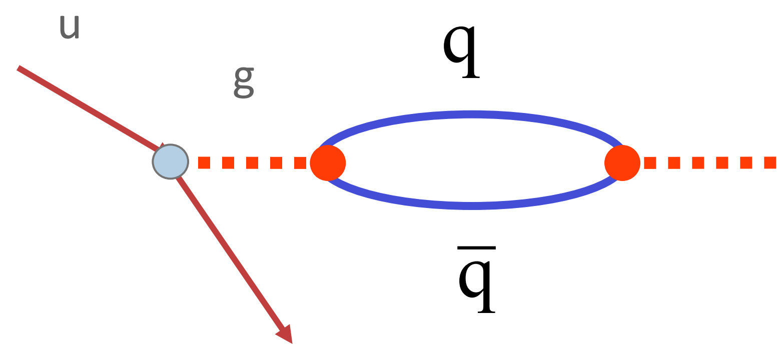
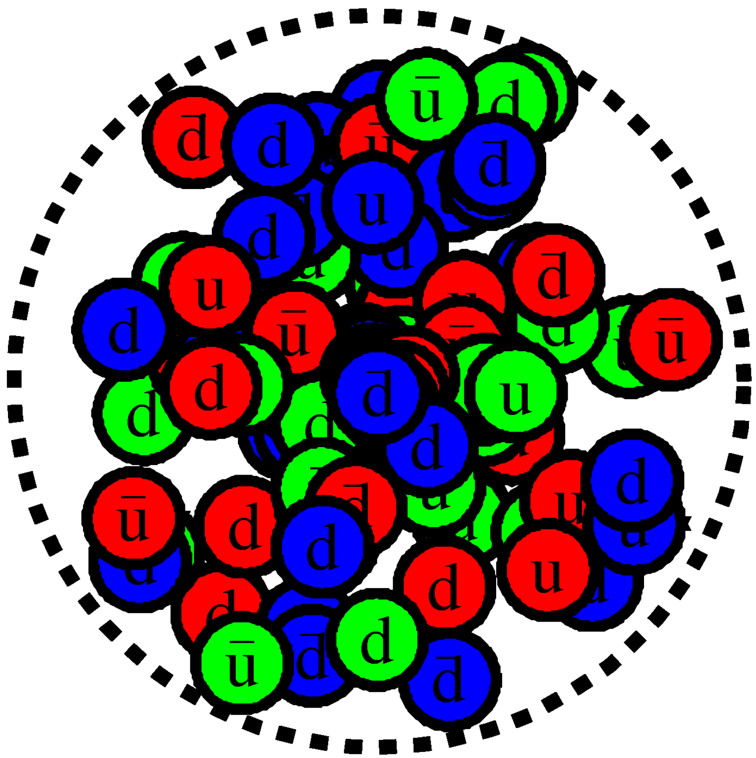




What are the origins of the Sea?



- Constituent Quark/Bag Model motivated valence approach
  - Use valence-like (primordial) quark distributions at some very low scale, Q^2, perhaps a few hundred MeV
  - Radiatively generate sea and glue. Gluck, Godbole, Reya, ZPC **41** 667 (1989)



Great idea but it didn't agree with the data

Sea is a fundamental part of the proton

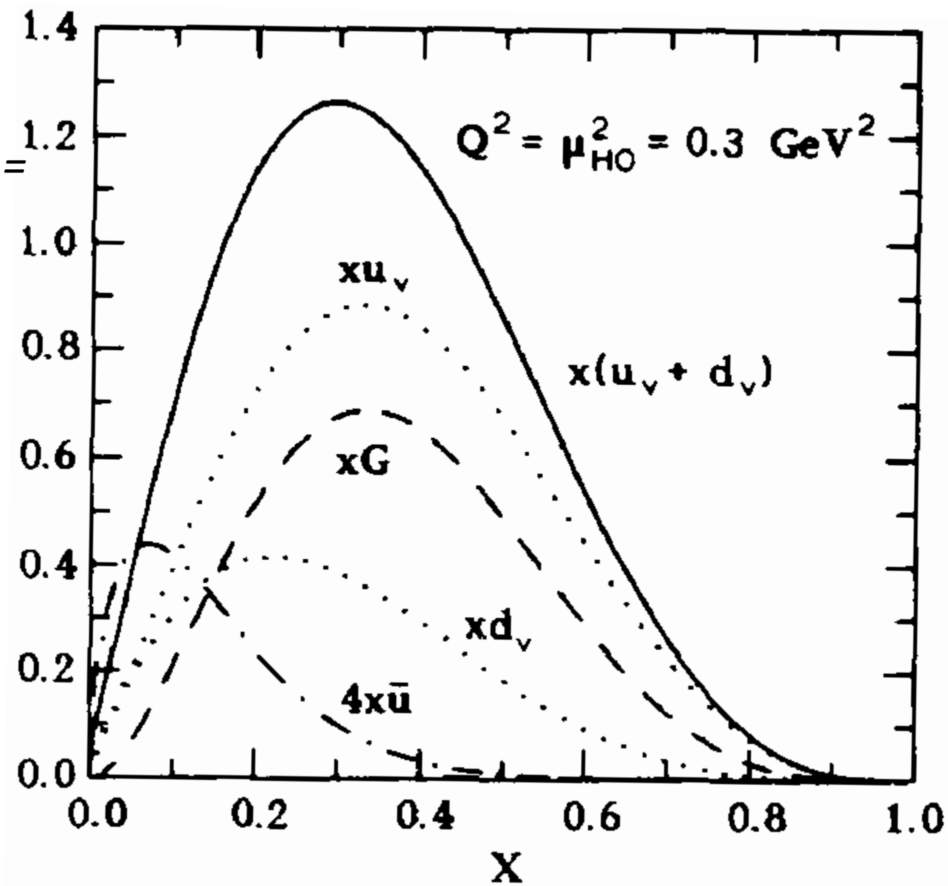
Parton distributions for high energy collisions

Gluck, Reya, Vogt, ZPC 53, 127 (1992)

M. Glück, E. Reya, A. Vogt
Institut für Physik, Universität Dortmund, Postfach 500500, W-4600 Dortmund 50, Federal Republic of Germany

Received 10 June 1991

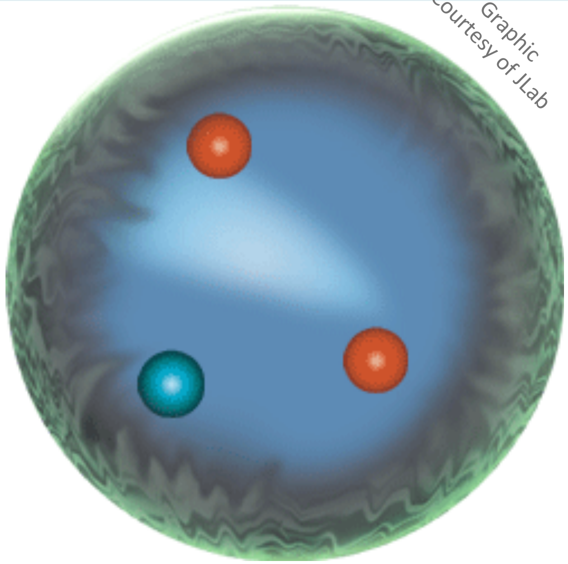
Abstract. Recent data from deep inelastic scattering experiments at $x > 10^{-2}$ are used to fix the parton distributions down to $x = 10^{-4}$ and $Q^2 = 0.3\ GeV^2$. **The predicted extrapolations are uniquely determined by the requirement of a *valence*-like structure of *all* parton distributions at some low resolution scale** . . . .



Note: Even Wikipedia gets it wrong

Paul E.

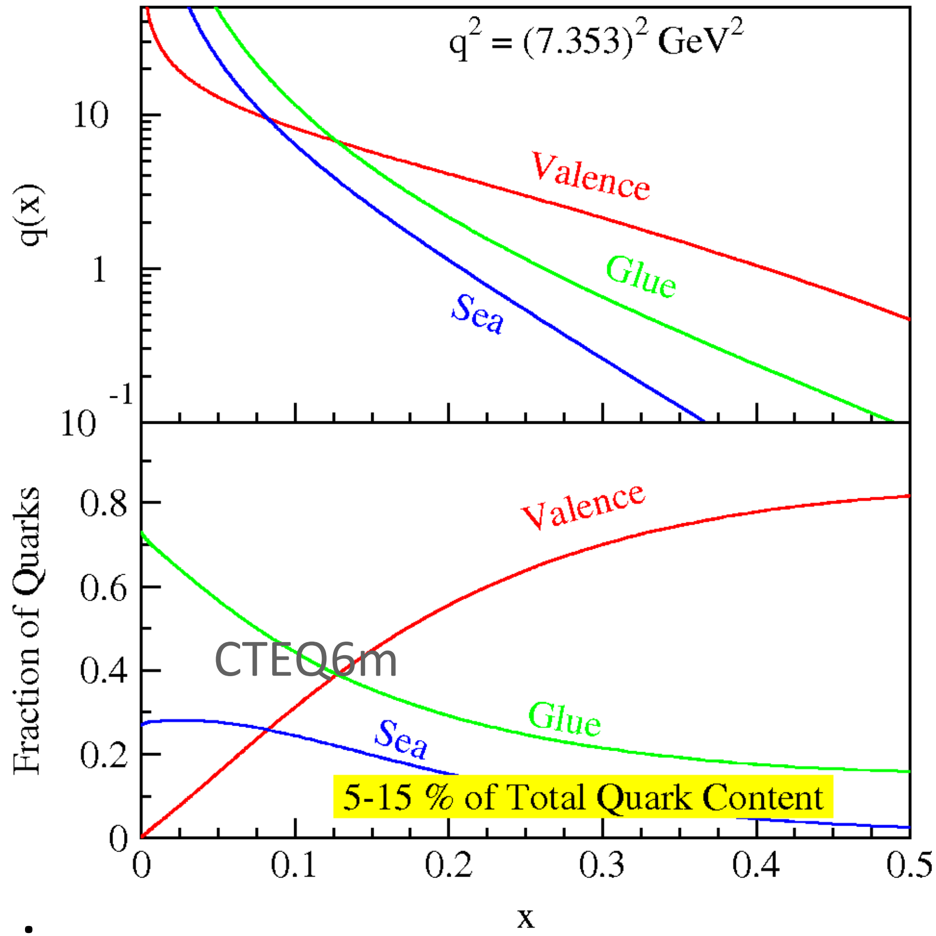
What's in the proton?



- Just three valence quarks?
- NO!
- Solution was to add in sea, but still kept idea that sea was flavor symmetric
- But, sysmetric sea was artifact of gluon splitting—so why keep it?

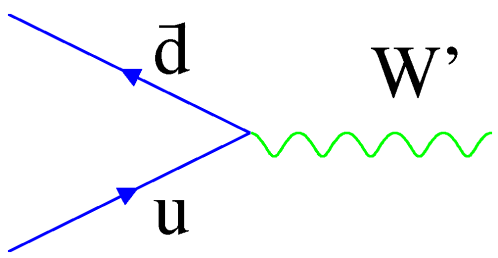
http://www.sciencecartoonsplus.com/index.htm

Why care about the distributions of the sea quarks?



In the nucleon:

- Sea and gluons are important:
  - 98% of mass; 60% of momentum at Q^2 = 2 GeV^2
- Not just three valence quarks and QCD. Shown by E866/NuSea d-bar/u-bar data
- What are the origins of the sea?
- Significant part of LHC beam.



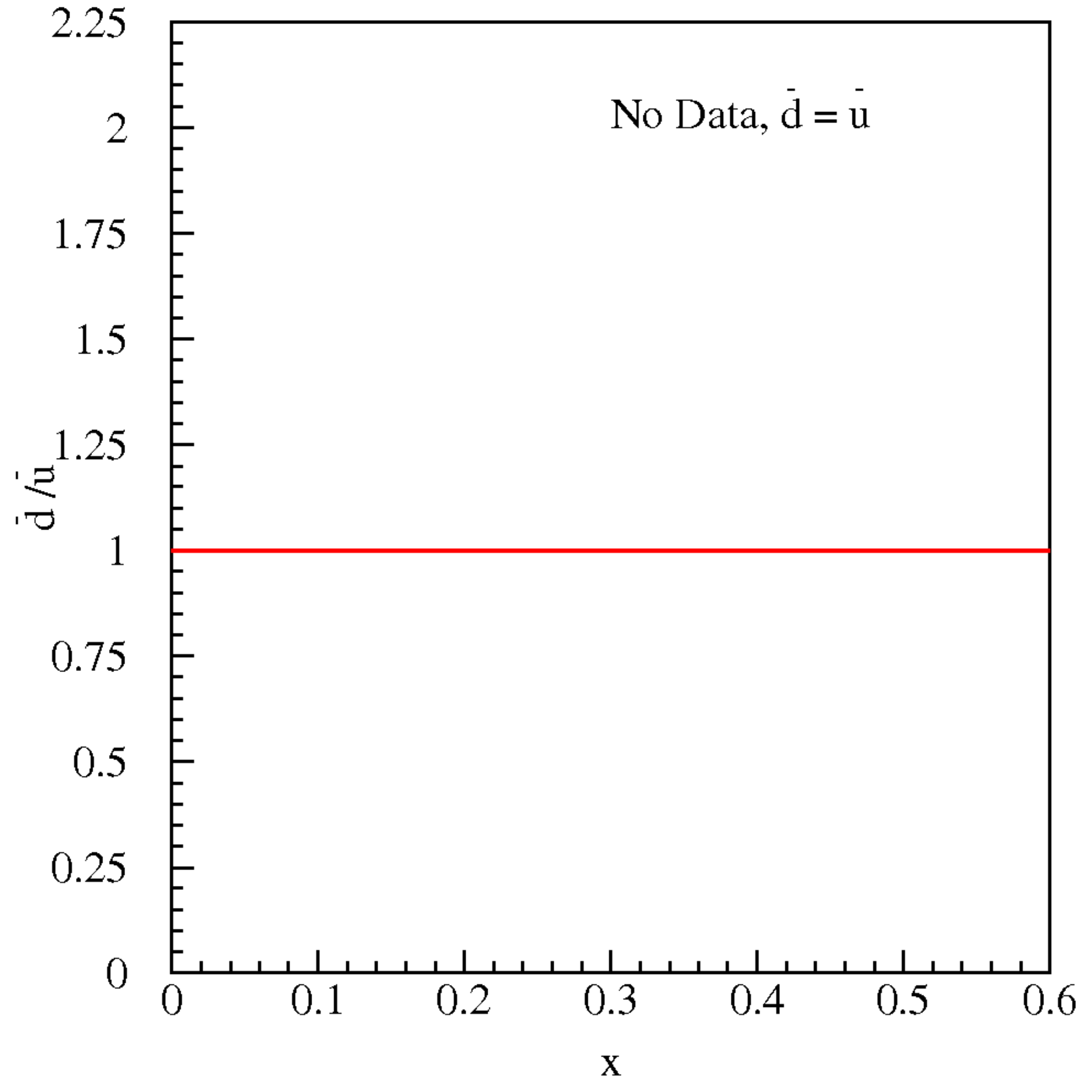
In nuclei:

- The nucleus is not just protons and neutrons
- What is the difference?
  - Bound system
  - Virtual mesons affects antiquarks distributions

Light Antiquark Flavor Asymmetry: Brief History

- Naïve Assumption:

$$\bar{d}(x) = \bar{u}(x)$$



Light Antiquark Flavor Asymmetry: Brief History

- Gottfried Sum Rule

$$I_{\rm GS} = \int_0^q \left[F_2^{\mu p}(x) - F_2^{\mu n}\right] \frac{dx}{x}$$

$$F_2^{\mu N}(X) = \sum_{q\in\{u,d,\dots\}} e_q^2 x \left[q^N(x) + \bar{q}^N(x)\right]$$

$$\begin{aligned}
I_{\rm GS} &= \int_0^1 \left\{ \sum_{q\in\{u,d,\dots\}} e_q^2 \left[q^p(x) + \bar{q}^p(x) - q^n(x) - \bar{q}^n(x)\right] \right\} dx \\
&= \int_0^1 \frac{1}{9}\left[4u^p(x) + 4\bar{u}^p(x) + d^p(x) + \bar{d}^p(x) - 4u^n(x) - 4\bar{u}^n(x) - d^n(x) - \bar{d}^n(x)\right] dx \\
&= \int_0^1 \frac{1}{3}\left[u^p(x) + \bar{u}^p(x) - d^p(x) - \bar{d}^p(x)\right] dx \\
&= \frac{1}{3} - \frac{2}{3}\int_0^1 \left[\bar{d}^p(x) - \bar{u}^p(x)\right] dx
\end{aligned}$$

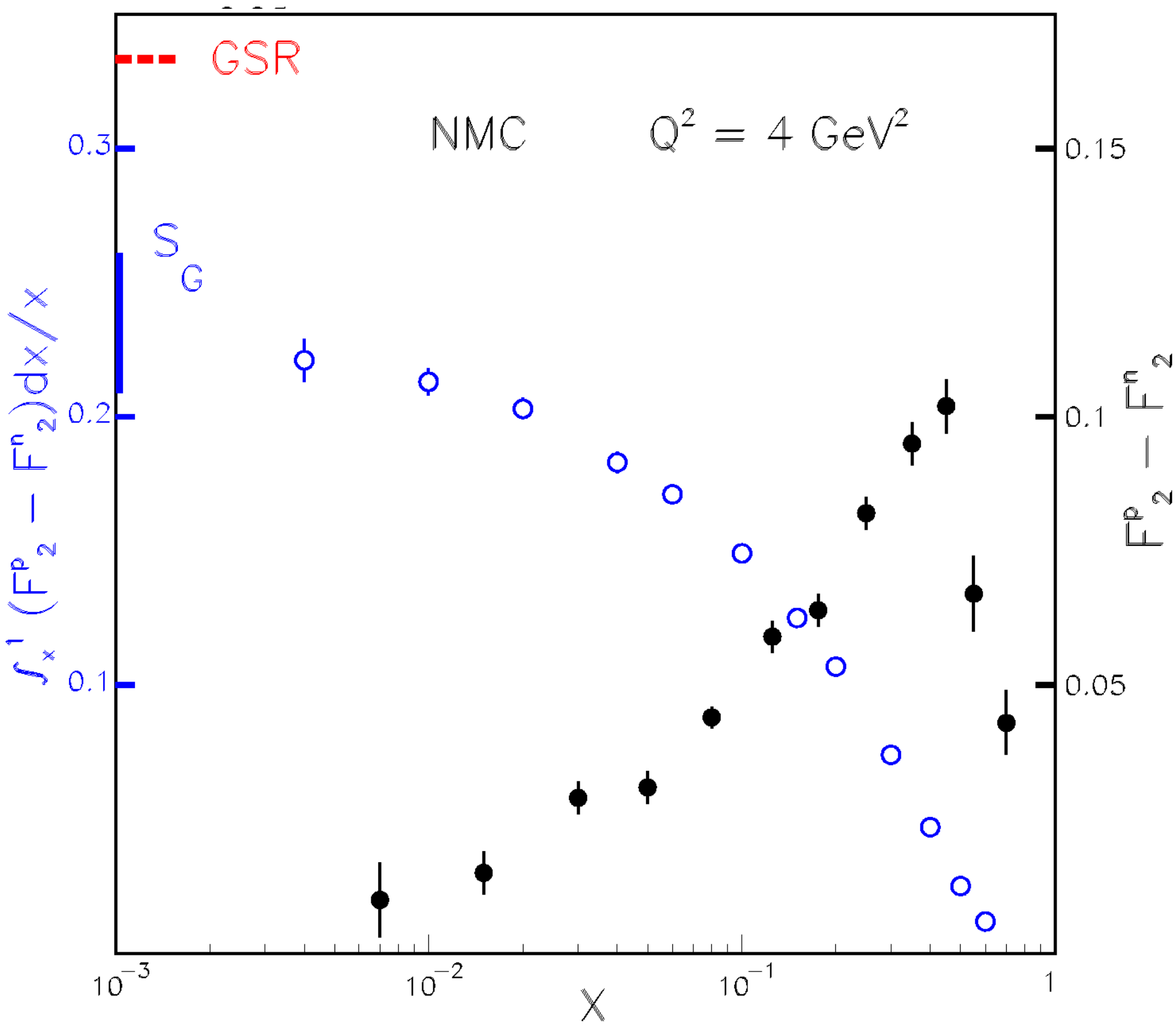
Light Antiquark Flavor Asymmetry: Brief History

- Naïve Assumption:

$$\bar{d}(x) = \bar{u}(x)$$

- NMC (Gottfried Sum Rule)

$$\int_0^1 \left[\bar{d}(x) - \bar{u}(x)\right] dx \neq 0$$



How can we measure the sea distributions?

Need a process that can isolate sea contributions:

- SIDIS
  - Low statistics
  - K/π identification
  - Knowledge of fragmentation functions (D^π)
  - HERMES, COMPASS, JLab 12 GeV
- Collider W production
  - Fermilab Tevatron, CERN LHC
- Drell-Yan
  - Rest of lecture

$$F_2^{\mu p}(x) \propto \sum_{q\in\{u,d,\dots\}} e_q^2 x \left[q(x,Q^2) + \bar{q}(x,Q^2)\right]$$

$$F_2^{\nu p}(x) + F_2^{\nu n} \propto \sum_{q\in\{u,d,\dots\}} x \left[q(x,Q^2) + \bar{q}(x,Q^2)\right]$$

$$xF_3^{\nu N}(x) \propto \sum_{q\in\{u,d,\dots\}} x \left[q(x,Q^2) - \bar{q}(x,Q^2)\right]$$

$$N^{\pi^\pm} \propto \sum_{q\in\{u,d,\dots\}} \left[q(x,Q^2) D^{\pi^\pm} + \bar{q}(x,Q^2) D^{\pi^\pm}\right]$$

$$A_W(y) \propto \frac{u(x_1)\bar{d}(x_2) - d(x_1)\bar{u}(x_2)}{u(x_1)\bar{d}(x_2) + d(x_1)\bar{u}(x_2)}$$

$$\frac{d\sigma}{dx_1 dx_2} \propto \sum_{q\in\{u,d,\dots\}} e_q^2 \left[q(x_1)\bar{q}(x_2) + \bar{q}(x_1)q(x_2)\right]$$

Early Muon Pair Data

VOLUME 25, NUMBER 21 PHYSICAL REVIEW LETTERS 23 NOVEMBER 1970

Observation of Massive Muon Pairs in Hadron Collisions*

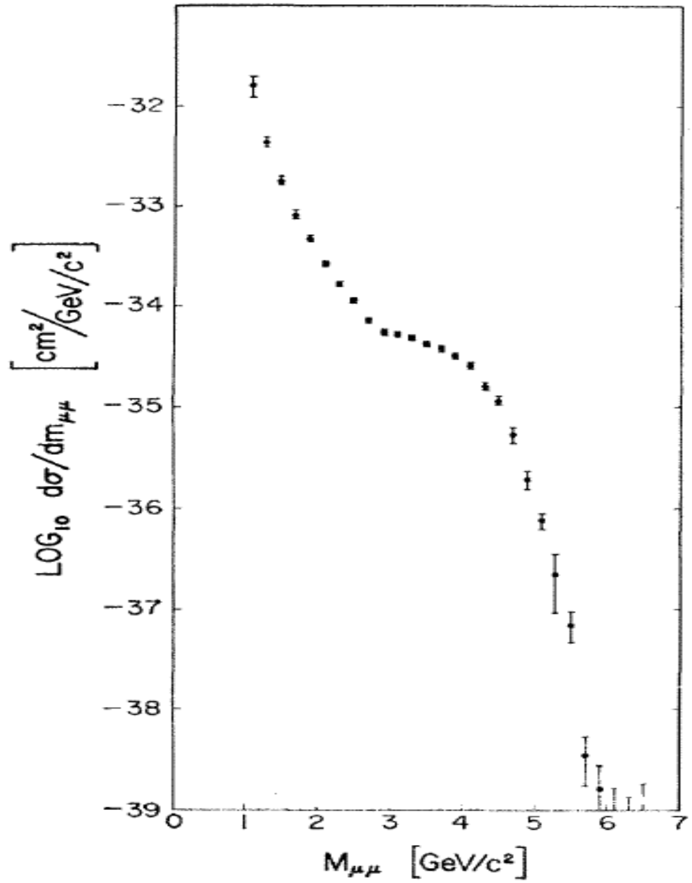
J. H. Christenson, G. S. Hicks, L. M. Lederman, P. J. Limon, and B. G. Pope
Columbia University, New York, New York 10027, and Brookhaven National Laboratory, Upton, New York 11973

and

E. Zavattini
CERN Laboratory, Geneva, Switzerland

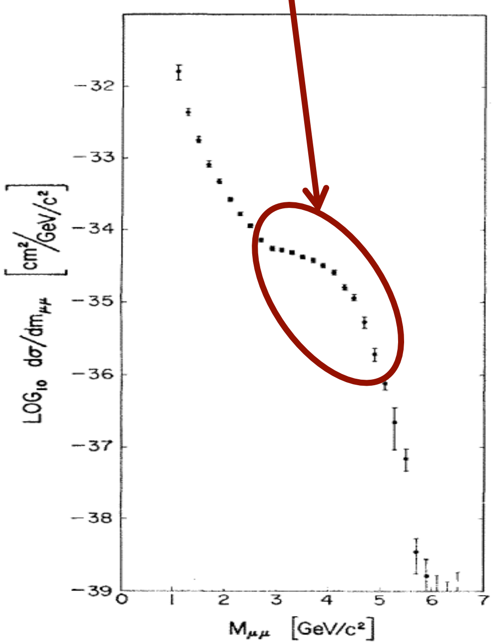
(Received 8 September 1970)

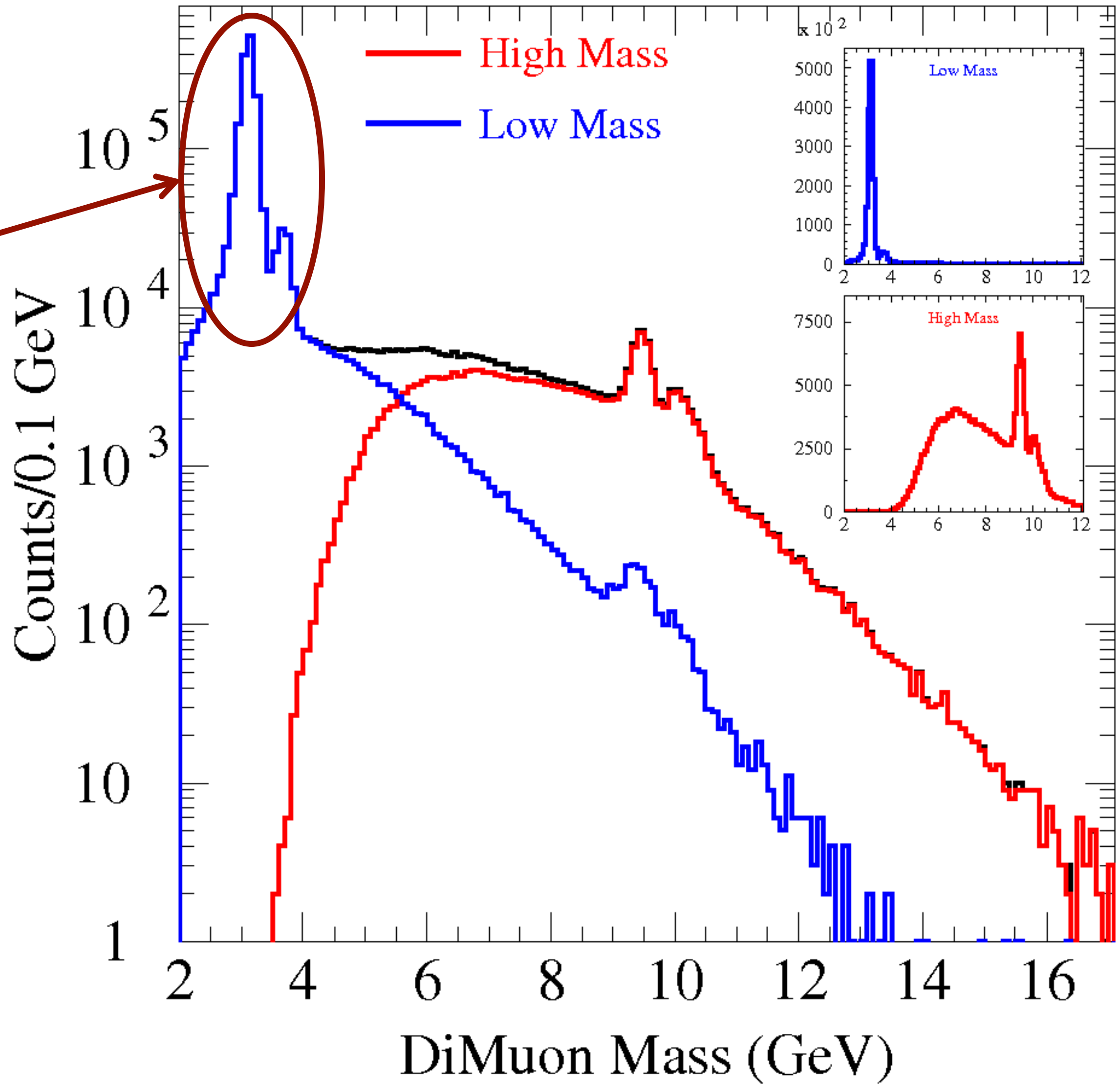
Muon Pairs in the mass range $1 < m_{\mu\mu} < 6.7$ GeV/c^2 have been observed in collisions of high-energy protons with uranium nuclei. At an incident energy of 29 GeV, **the cross section varies smoothly as $d\sigma/dm_{\mu\mu} \approx 10^{-32} / m_{\mu\mu}^5$ cm^2 (GeV/c)$^{-2}$ and exhibits no resonant structure.** The total cross section increases by a factor of 5 as the proton energy rises from 22 to 29.5 GeV.



Drell-Yan Mass Spectra

- What they could have seen if they had sufficient resolution
- Could have been a Nobel Prize!





Data from Fermilab E-866/NuSea

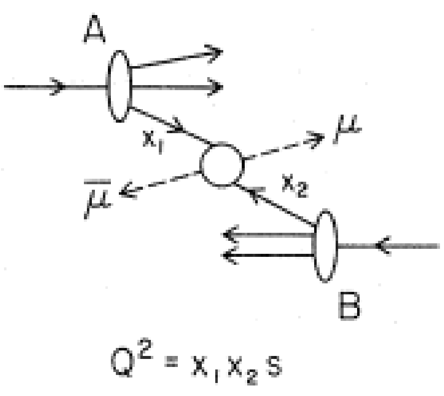
Drell and Yan's explanation

VOLUME 25, NUMBER 5 PHYSICAL REVIEW LETTERS 3 AUGUST 1970

MASSIVE LEPTON-PAIR PRODUCTION IN HADRON-HADRON COLLISIONS AT HIGH ENERGIES*

Sidney D. Drell and Tung-Mow Yan
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305
(Received 25 May 1970)

On the basis of a parton model studied earlier we consider the production process of large-mass lepton pairs from hadron-hadron inelastic collisions in the limiting region, $s \to \infty$, Q^2/s finite, Q^2 and s being the squared invariant masses of the lepton pair and the two initial hadrons, respectively. General scaling properties and connections with deep inelastic electron scattering are discussed. In particular, a rapidly decreasing cross section as $Q^2/s \to 1$ is predicted as a consequence of the observed rapid falloff of the inelastic scattering structure function νW_2 near threshold.



(b)

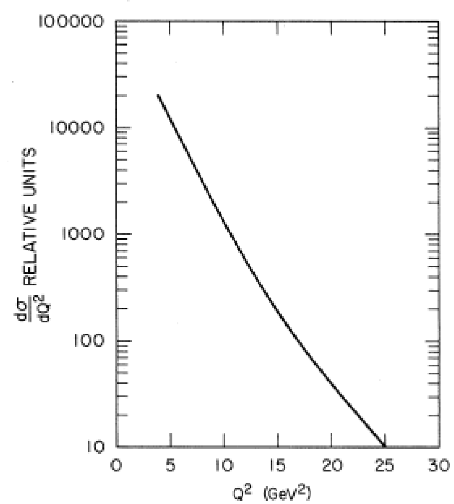
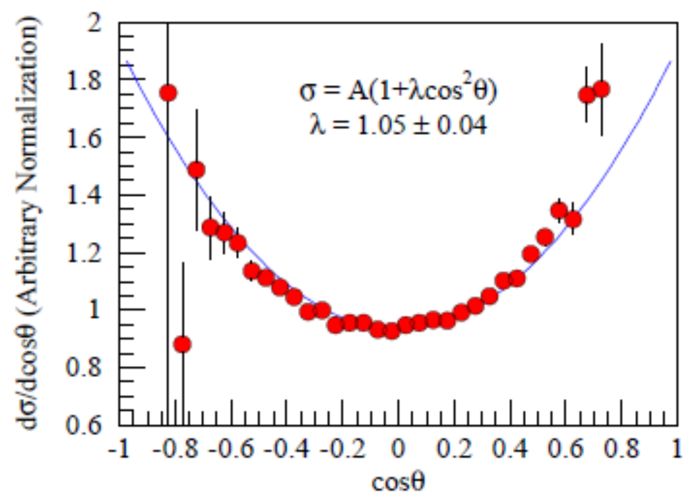


FIG. 2. $d\sigma/dQ^2$ computed from Eq. (10) assuming identical parton and antiparton momentum distributions and with relative normalization.

- Also predicted $\lambda(1+\cos^2\theta)$ angular distributions



Naive Drell-Yan and Its Successor*

T-M. Yan
Floyd R. Newman Laboratory of Nuclear Studies
Cornell University
Ithaca, NY 14853

February 1, 2008

Abstract

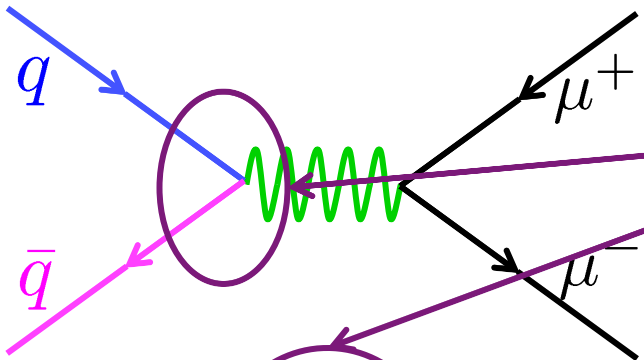
We review the development in the field of lepton pair production since proposing parton-antiparton annihilation as the mechanism of massive lepton pair production. The basic physical picture of the Drell-Yan model has survived the test of QCD, and the predictions from the QCD improved version have been confirmed by the numerous experiments performed in the last three decades. The model has provided an active theoretical arena for studying infrared and collinear divergences in QCD. It is now so well understood theoretically that it has become a powerful tool for new phyiscs information such as precision measurements of the W mass and lepton and quark sizes.

*Talk given at the Drell Fest, July 31, 1998, SLAC on the occasion of Prof. Sid Drell's retirement.

- "… our original crude fit did not even remotely resemble the data. Sid and I went ahead to publish our paper because of the model's simplicity…"
- "… the successor of the naïve model, the QCD improved version, has been confirmed by the experiments…"
- "The process has been so well understood theoretically that it has become a powerful tool for precision measurements and new physics."

Slide from Jen-Chieh Peng, Illinois presented at ECT*

The Drell-Yan reaction:



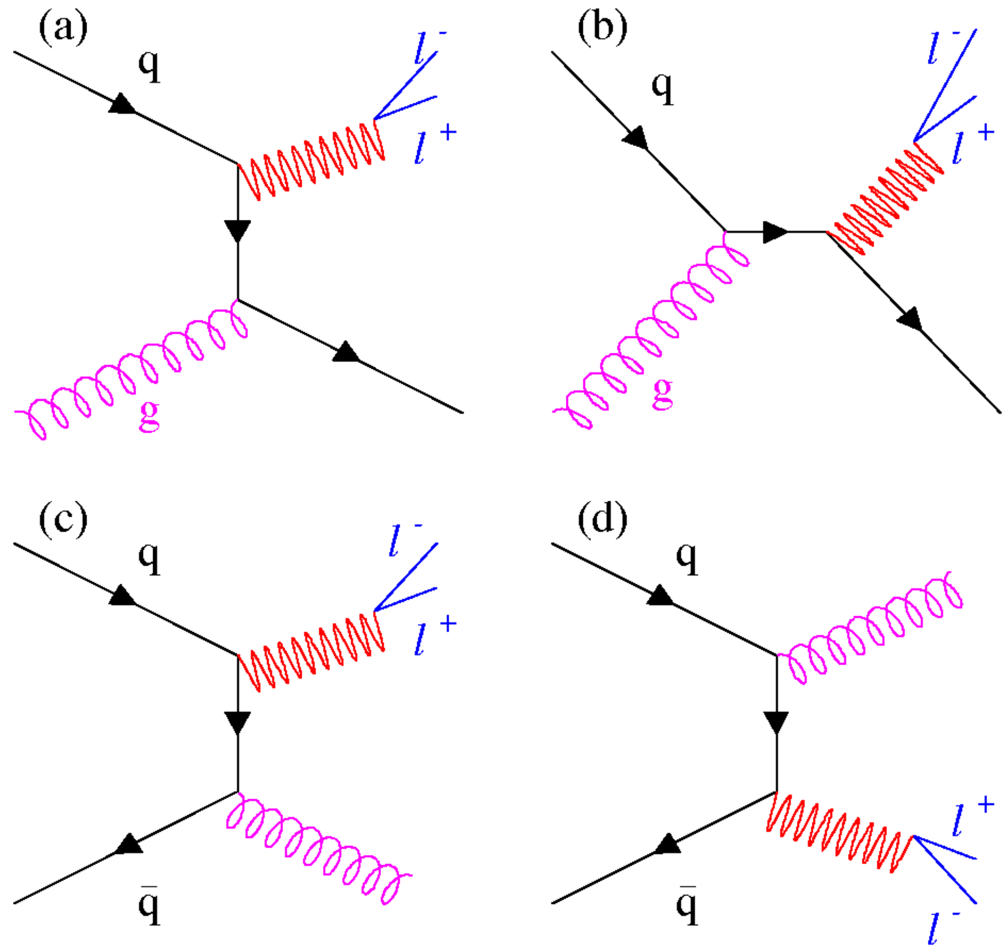
Start with point cross section for two annihilating Fermions (See Halzen and Martin or Perkins)

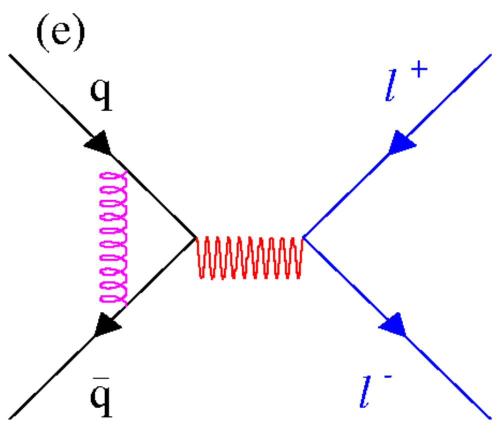
$$\frac{d^2\sigma}{dx_{\mathrm{b}}dx_{\mathrm{t}}} = \frac{4\pi\alpha^2}{x_{\mathrm{b}}x_{\mathrm{t}}s} \sum_{q\in\{u,d,s,\ldots\}} e_q^2 \left[\bar{q}_{\mathrm{t}}(x_{\mathrm{t}})q_{\mathrm{b}}(x_{\mathrm{b}}) + \bar{q}_{\mathrm{b}}(x_{\mathrm{b}})q_{\mathrm{t}}(x_{\mathrm{t}})\right]$$

Calculate the probability of finding two quarks with momentum in the range [x_t, x_t+dx_t] and [x_b, x_b+dx_b]

Next-to-Leading Order Drell-Yan

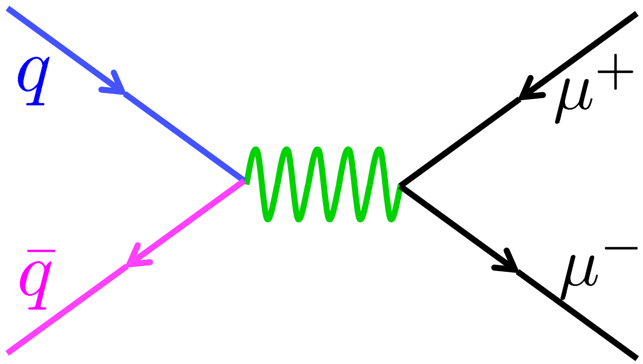
- Next-to-leading order diagrams complicate the picture
- These diagrams are responsible for **50% of the measured cross section**
- Intrinsic transverse momentum of quarks (although a small effect, λ > 0.8)
- Actual data analysis used full Next-to-Leading Order (NLO) calculation

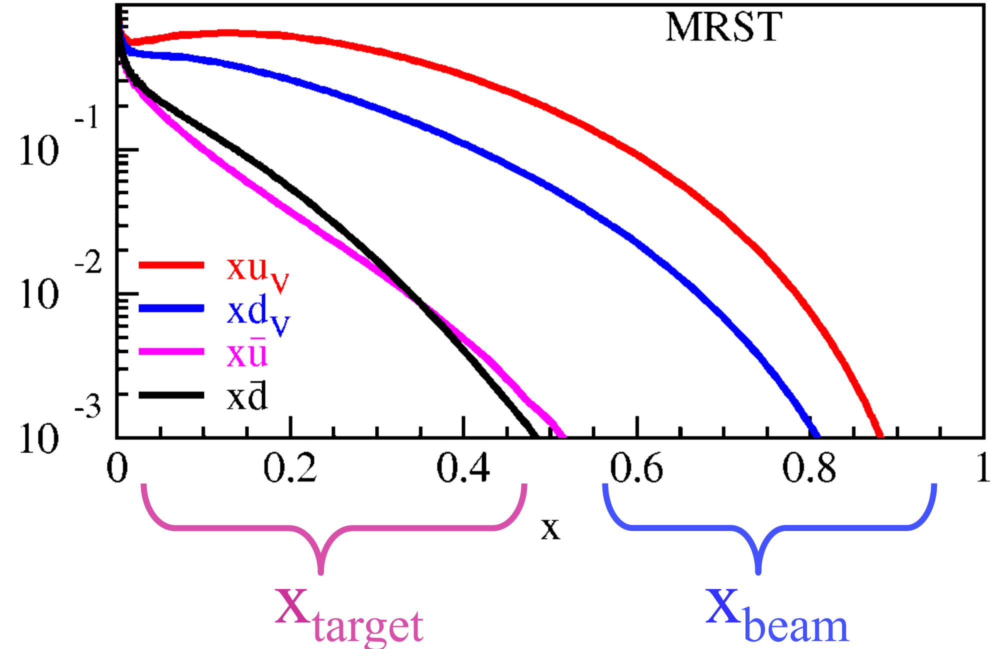




- NLO calculations require integration over intermediate momentums

The Drell-Yan reaction:
A laboratory for sea qua



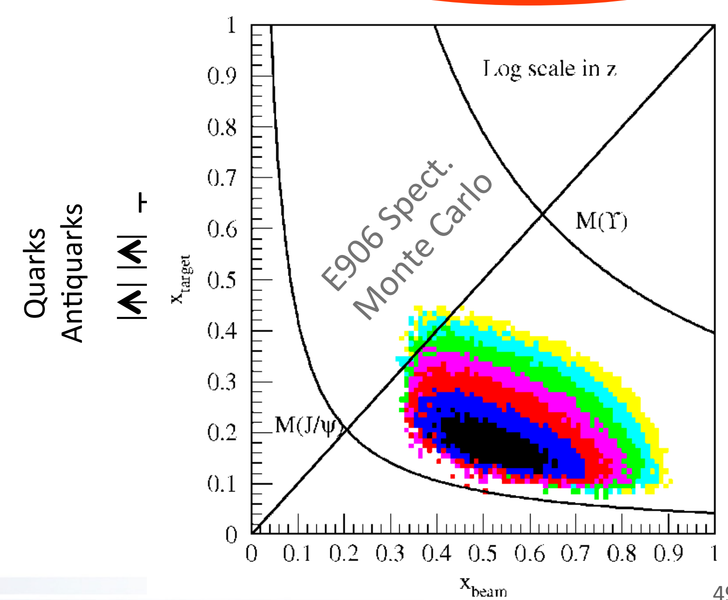


$$\frac{d^2\sigma}{dx_b dx_t} = \frac{4\pi\alpha^2}{x_b x_t s} \sum_{q\in\{u,d,s,\ldots\}} e_q^2 \left[\bar{q}_t(x_t) q_b(x_b) + q_b(x_b) q_t(x_t)\right]$$

Would like to look at only one term

- Quarks in beam, antiquarks in target
- Is it possible to select kinematics so that one term is dominant?

$$\left.\frac{\sigma^{pd}}{2\sigma^{pp}}\right|_{x_b \gg x_t} \approx \frac{1}{2}\left[1 + \frac{\bar{d}(x_t)}{\bar{u}(x_t)}\right]$$



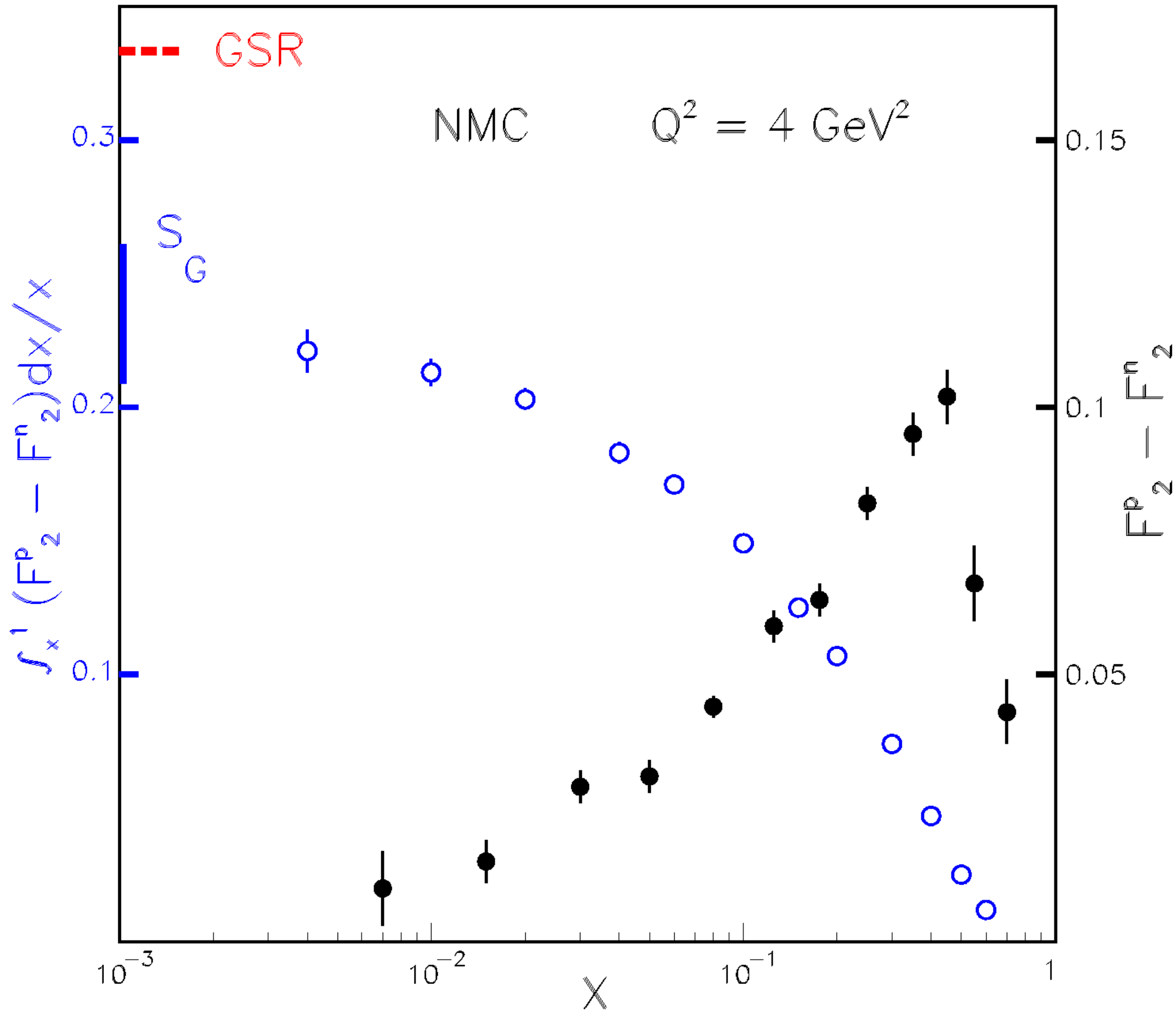
Light Antiquark Flavor Asymmetry: Brief History

- Naïve Assumption:

$$\bar{d}(x) = \bar{u}(x)$$

- Gottfried Sum Rule:

$$\int_0^1 \left[\bar{d}(x) - \bar{u}(x)\right] dx \neq 0$$



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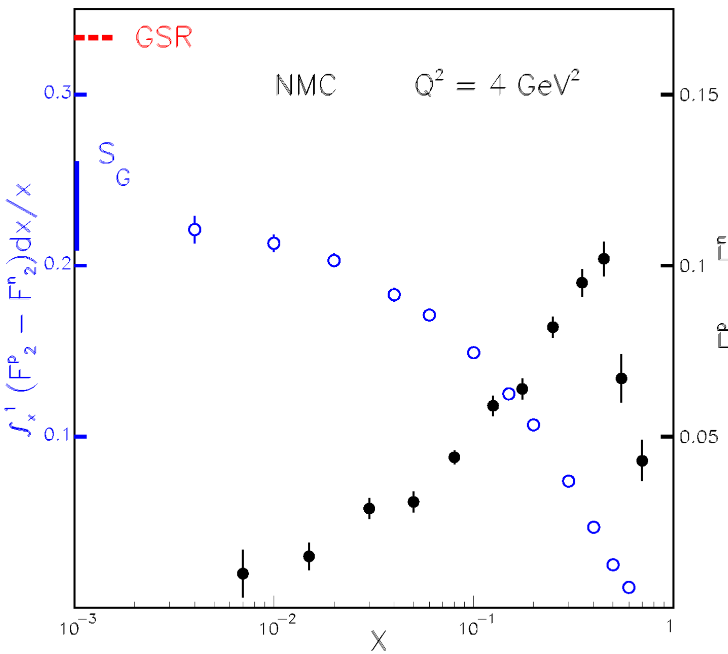

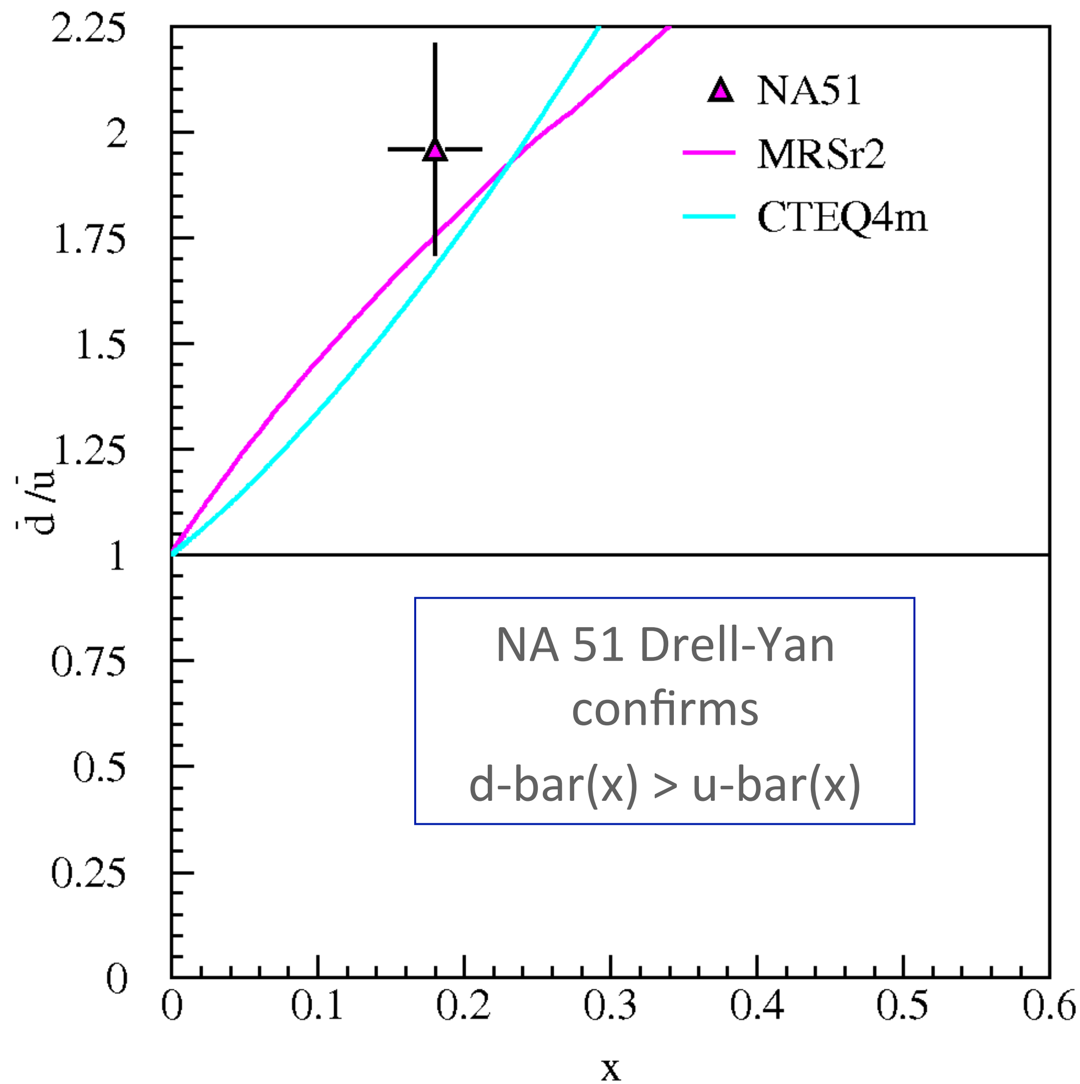

Light Antiquark Flavor Asymmetry: Brief History

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- NMC (Gottfried Sum Rule)

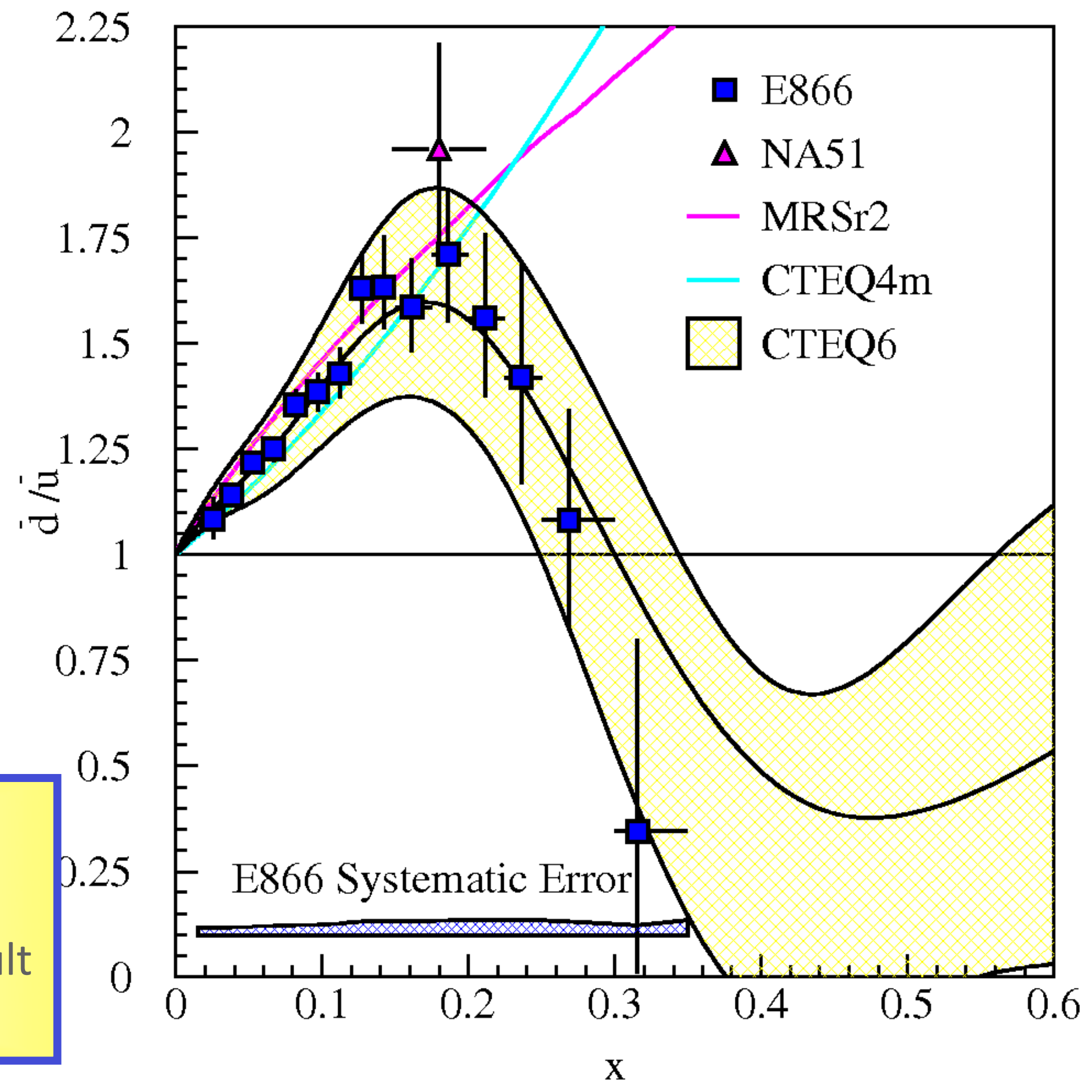
  $$\int_0^1 \left[\bar{d}(x) - \bar{u}(x)\right] dx \neq 0$$

- NA51 (Drell-Yan)

  $\bar{d} > \bar{u}$ at $x = 0.18$

- E866/NuSea (Drell-Yan)

  $\bar{d}(x)/\bar{u}(x)$ for $0.015 \leq x \leq 0.35$



- Knowledge of distributions is data driven
  - Sea quark distributions are difficult for Lattice QCD

FNAL E866/NuSea Collaboration

Abilene Christian University
Donald Isenhower, Mike Sadler, Rusty Towell,
Josh Bush, Josh Willis, Derek Wise

Argonne National Laboratory
Don Geesaman, Sheldon Kaufman,
Naomi Makins, Bryon Mueller, Paul E. Reimer

Fermi National Accelerator Laboratory
Chuck Brown, Bill Cooper

Georgia State University
Gus Petitt, Xiao-chun He, **Bill Lee**

Illinois Institute of Technology
Dan Kaplan

Los Alamos National Laboratory
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Terry Awes, Paul Stankus, Glenn Young

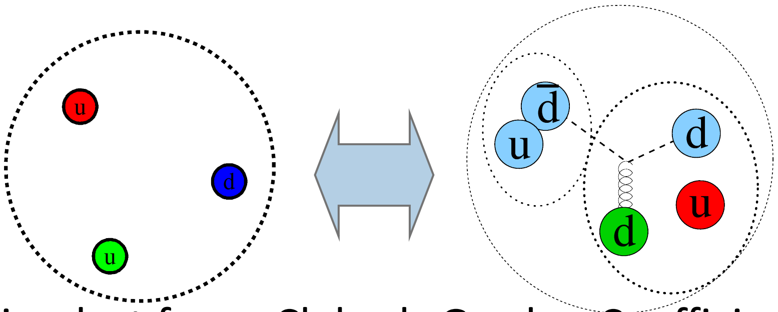
Texas A & M University
Carl Gagliardi, Bob Tribble, **Eric Hawker**, Maxim Vasiliev

Valparaiso University
Don Koetke, Paul Nord

Non-perturbative Models: Pion Cloud

- Meson Cloud in the nucleon Sullivan process in DIS

$$|p\rangle = |p_0\rangle + \alpha|N\pi\rangle + \beta|\Delta\pi\rangle + \gamma|\Lambda K\rangle + \ldots$$



- In its simplest form, Clebsch-Gordon Coefficients and πN, πΛ couplings

$$\bullet\ \alpha : \quad |N\pi\rangle = \begin{cases} |p,\pi^0\rangle & \frac{u\bar{u}+d\bar{d}}{2} & -\sqrt{\frac{1}{3}} \\ |n,\pi^+\rangle & u\bar{d} & \sqrt{\frac{2}{3}} \end{cases}$$

$$\bullet\ \beta : \quad |\Delta\pi\rangle = \begin{cases} |\Delta^{++},\pi^-\rangle & d\bar{u} & \sqrt{\frac{1}{2}} \\ |\Delta^+,\pi^0\rangle & \frac{u\bar{u}+d\bar{d}}{2} & -\sqrt{\frac{1}{3}} \\ |\Delta^0,\pi^+\rangle & u\bar{d} & \sqrt{\frac{1}{6}} \end{cases}$$

- Predicts

$$\bar{d} \geq \bar{u}$$

- Cannot have

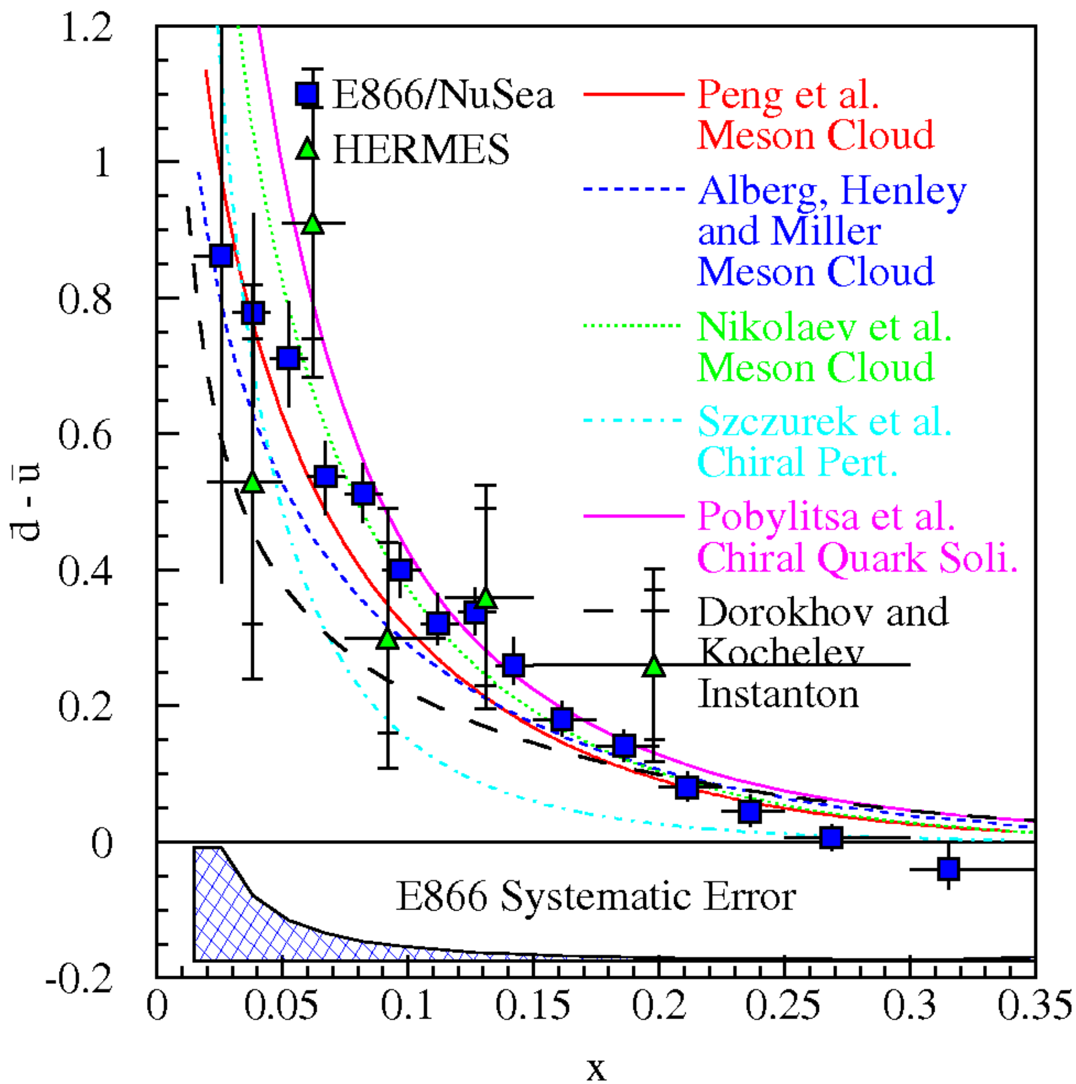
$$\bar{d} \leq \bar{u}$$

Proton Structure: By What Process Is the Sea Created?

- There is a gluon splitting component which is symmetric

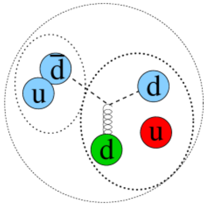
$$\bar{d}_{\text{split}}(x) = \bar{u}_{\text{split}}(x) = \bar{q}_{\text{split}}(x)$$

- $\bar{d}(x) - \bar{u}(x)$
  - Symmetric sea via pair production from gluons subtracts away
  - No Gluon contribution at 1st order in α_s
  - Nonperturbative models are motivated by the observed difference
- A proton with 3 valence quarks plus glue cannot be right at any scale!!



Models Relate Antiquark Flavor Asymmetry and Spin

- Meson Cloud in the nucleon—Sullivan process in DIS



$$|p\rangle = (1 - a - b)\,|p_0\rangle + a|N\pi\rangle + b|\Delta\pi\rangle$$

Antiquarks in spin 0 object $\longrightarrow$ No net spin

- Chiral Quark models—effective Lagrangians

$$\langle q|\bar{q}\rangle = \left[1 - \frac{3a}{2}\right]\langle q|\bar{q}\rangle + \frac{3a}{2}\langle q\pi|\bar{q}\pi\rangle$$

$$\int_0^1 \left[\bar{d}(x) - \bar{u}(x)\right] dx = \frac{2a}{3} \qquad g_A = \int_0^1 \left[\Delta u(x) - \Delta d(x)\right] dx = \frac{5}{3}3a$$

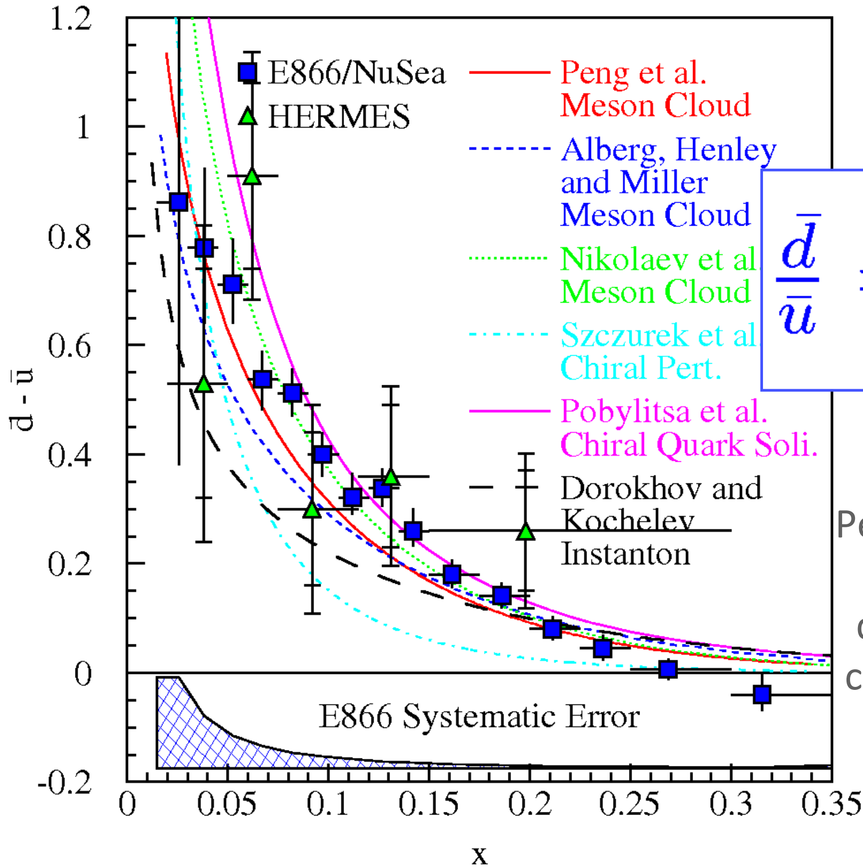
- Instantons

$$\mathcal{L} \propto \bar{u}_R u_L \bar{d}_R d_L + \bar{u}_L u_R \bar{d}_L d_R \qquad \bar{d}_I(x) - \bar{u}_I(x) = \frac{5}{3}\left[\Delta u_I(x) - \Delta d_I(x)\right]$$

- Statistical Parton Distributions

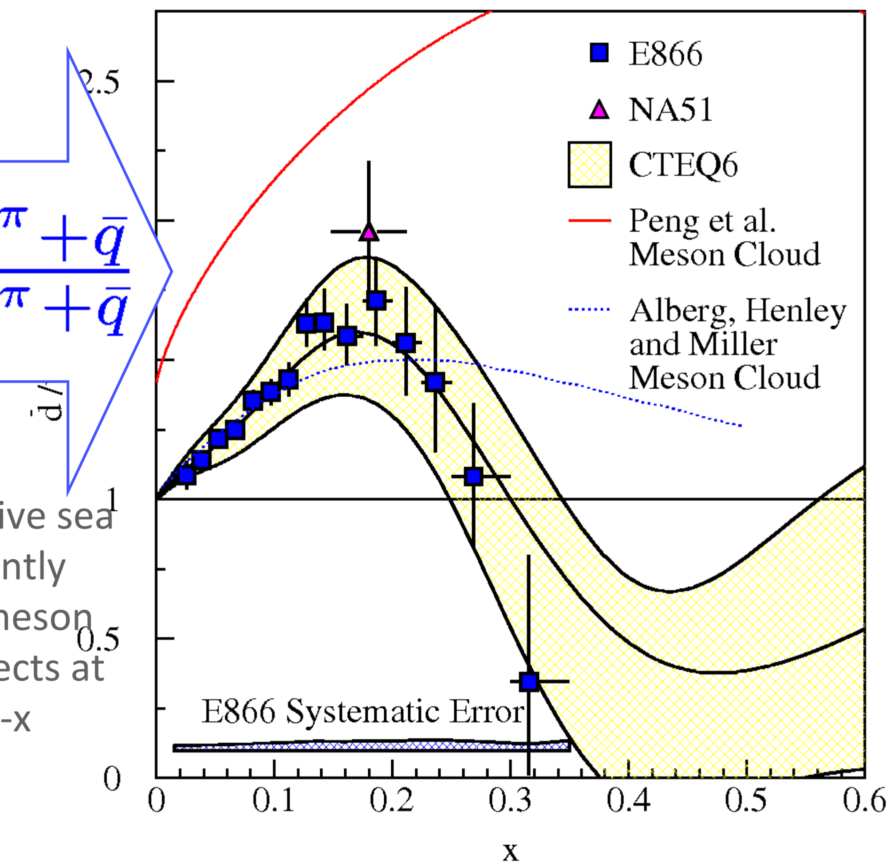
$$\bar{d}(x) - \bar{u}(x) = \Delta\bar{u}(x) - \Delta\bar{d}(x)$$

Proton Structure: By What Process Is the Sea Created?



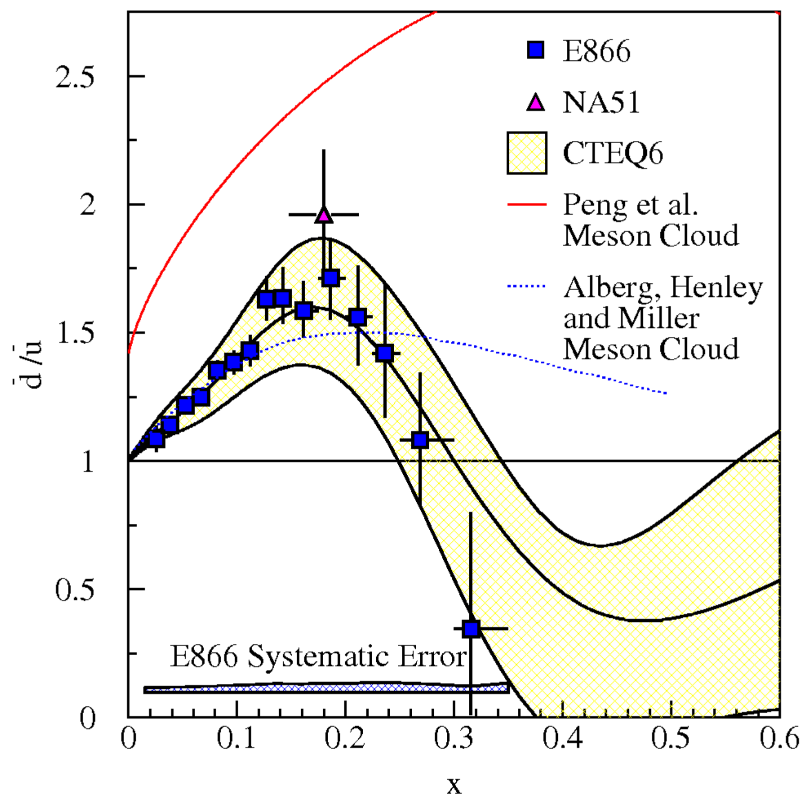
$$\frac{\bar d}{\bar u} = \frac{\bar d^{\pi} + \bar q}{\bar u^{\pi} + \bar q}$$

Perturbative sea apparently dilutes meson cloud effects at large-x



Something is missing

- All non-perturbative models predict large asymmetries at high x.
- Are there more gluons and therefore symmetric anti-quarks at higher x?
- Does some mechanism like instantons have an unexpected x dependence? (What is the expected x dependence for instantons in the first place?)



Advantages of 120 GeV Main Injector

The (very successful) past:

Fermilab E866/NuSea

- Data in 1996-1997
- ^{1}H, ^{2}H, and nuclear targets
- 800 GeV proton beam

The future:

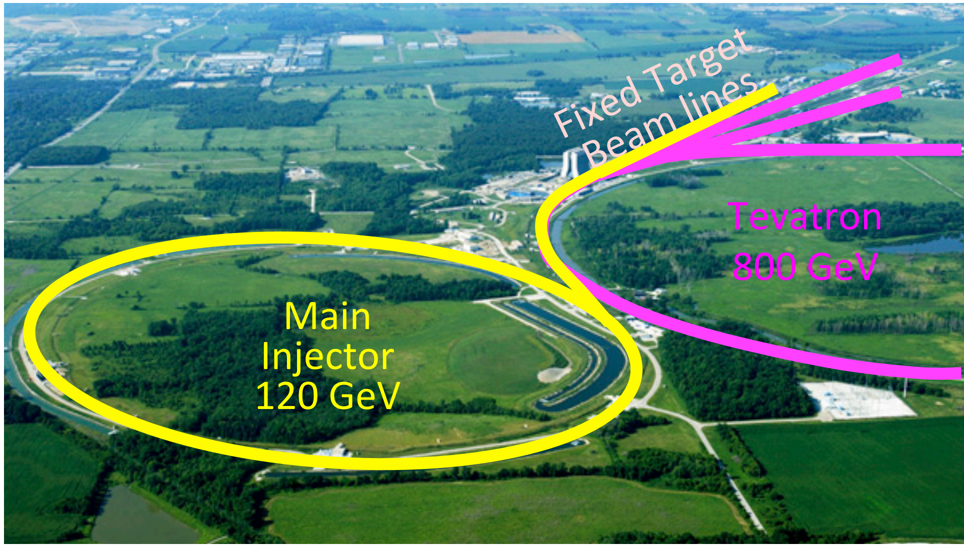
Fermilab E906

- Data in 2009
- ^{1}H, ^{2}H, and nuclear targets
- 120 GeV proton Beam

$$\frac{d^2\sigma}{dx_t dx_b} = \frac{4\pi\alpha^2}{9x_t x_b}\frac{1}{s}\sum e^2\left[\bar{q}_t(x_t)q_b(x_b) + q_t(x_t)\bar{q}_b(x_b)\right]$$

- Cross section scales as 1/s
  - *7£ that of 800 GeV beam*
- Backgrounds, primarily from J/ψ decays scale as s
  - *7£ Luminosity for same detector rate as 800 GeV beam*

50£ statistics!!

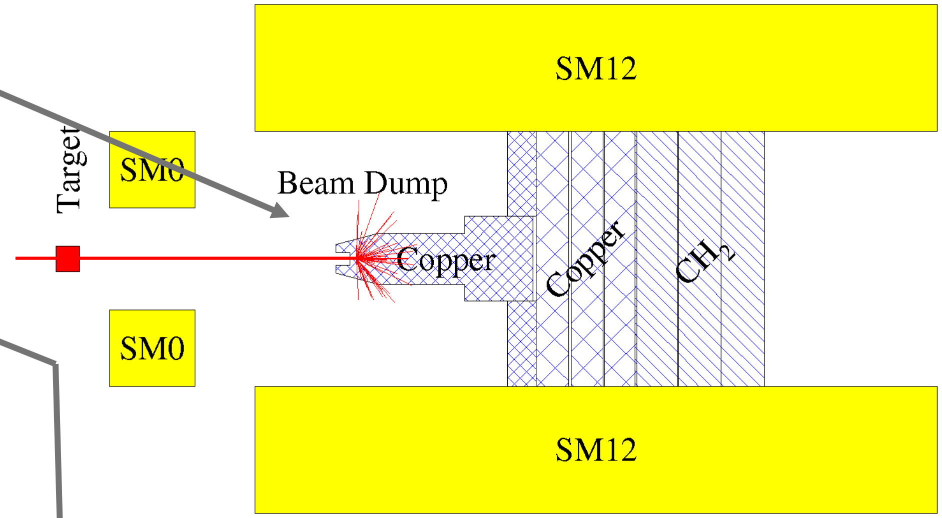


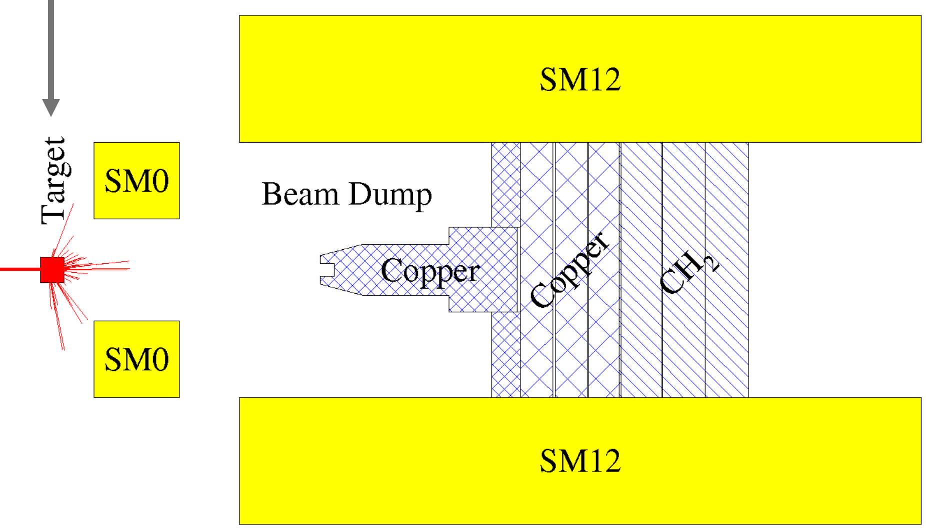
Splat, splat and more splat

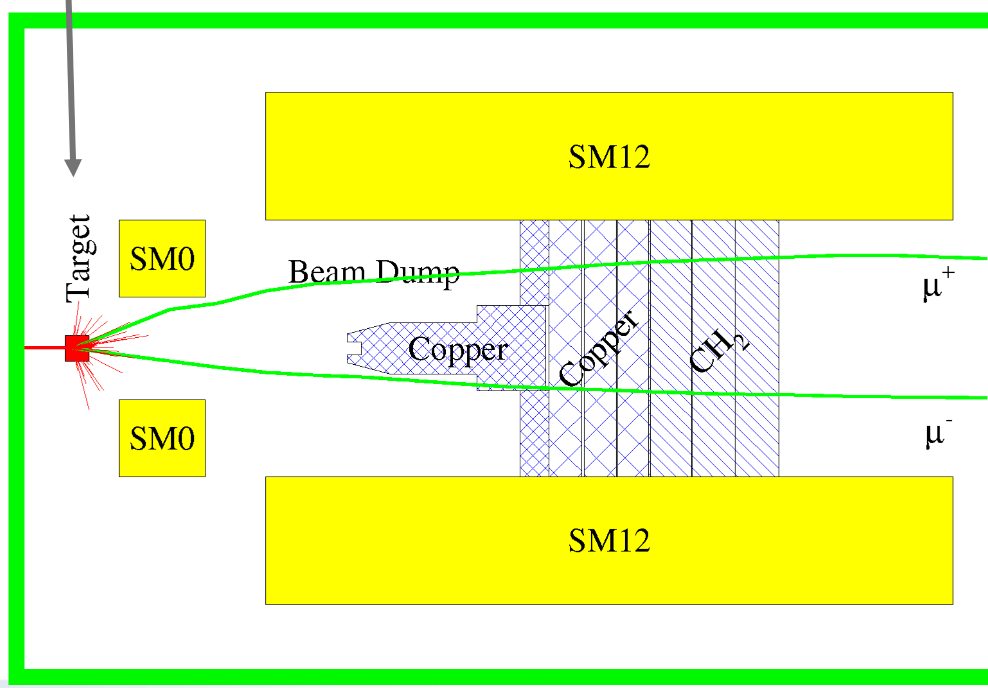
Proton interactions:

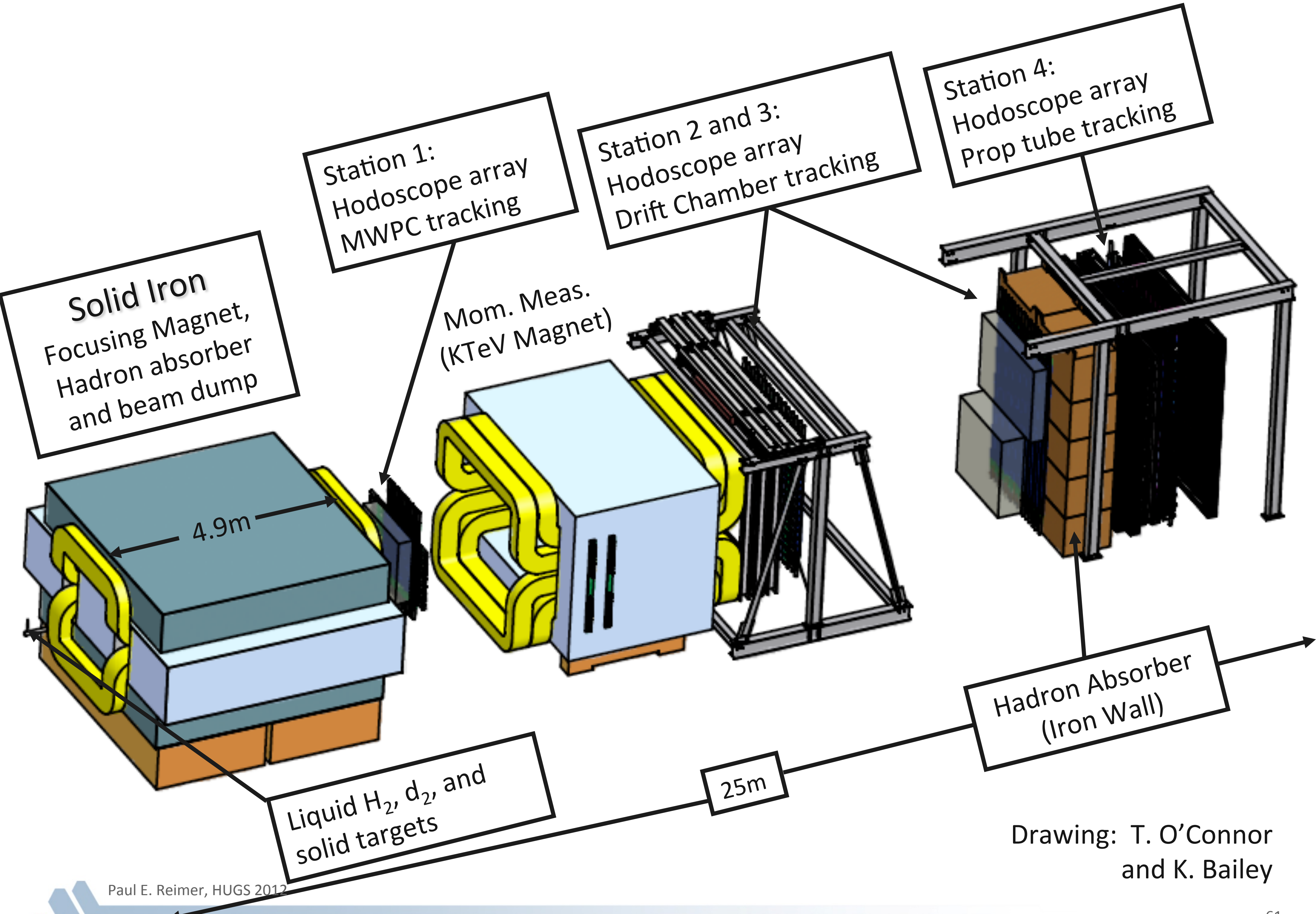
1. Go "splat" in the beam dump.
2. Go "splat" in the target.
3. Drell-Yan $\mu^+\mu^-$ interaction with accompanying "splat".

Get rid of particles from "splat" with "splat absorber" and magnetic field.









Drawing: T. O'Connor
and K. Bailey

Fermilab E906/Drell-Yan Collaboration

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Ling-Tung University
Ting-Hua Chang

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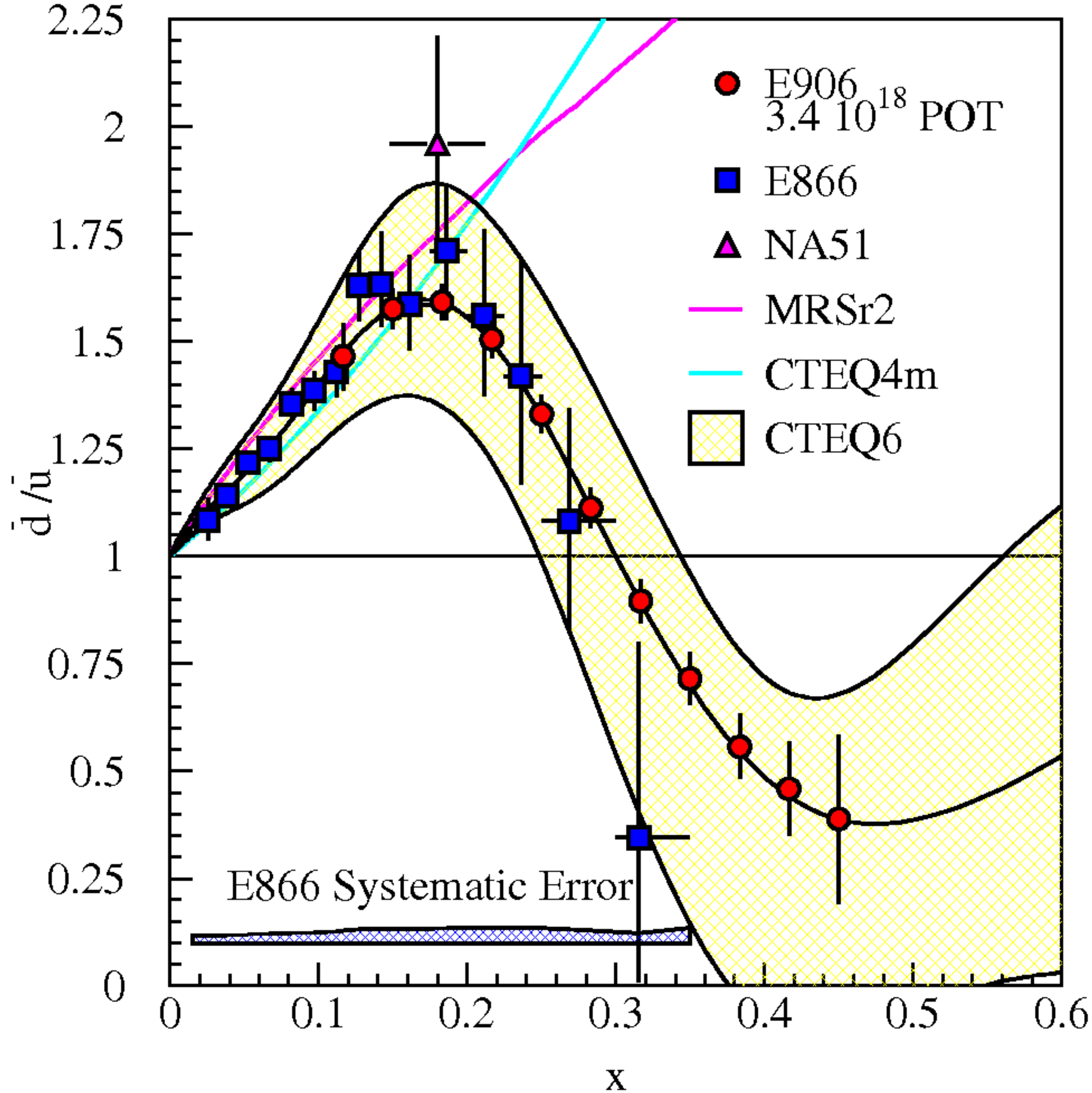
Tokyo Tech
Ken-ichi Nakano, Toshi-Aki Shibata

Yamagata University
Yoshiyuki Miyachi

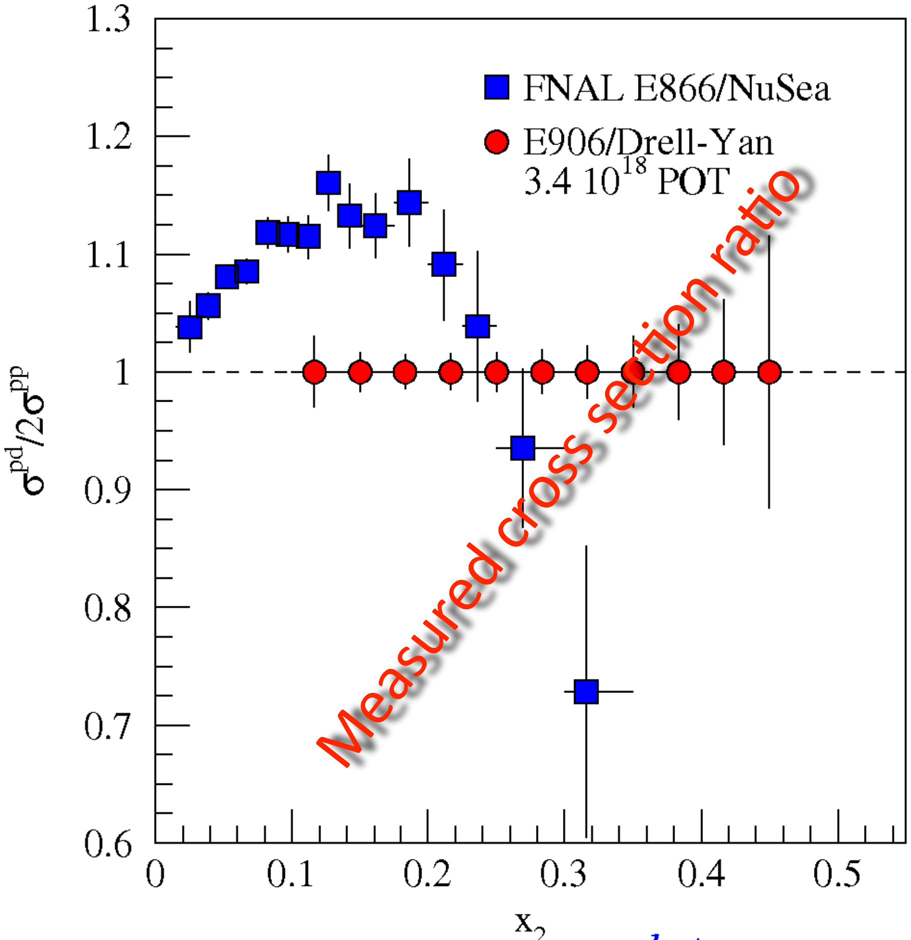
*Co-Spokespersons

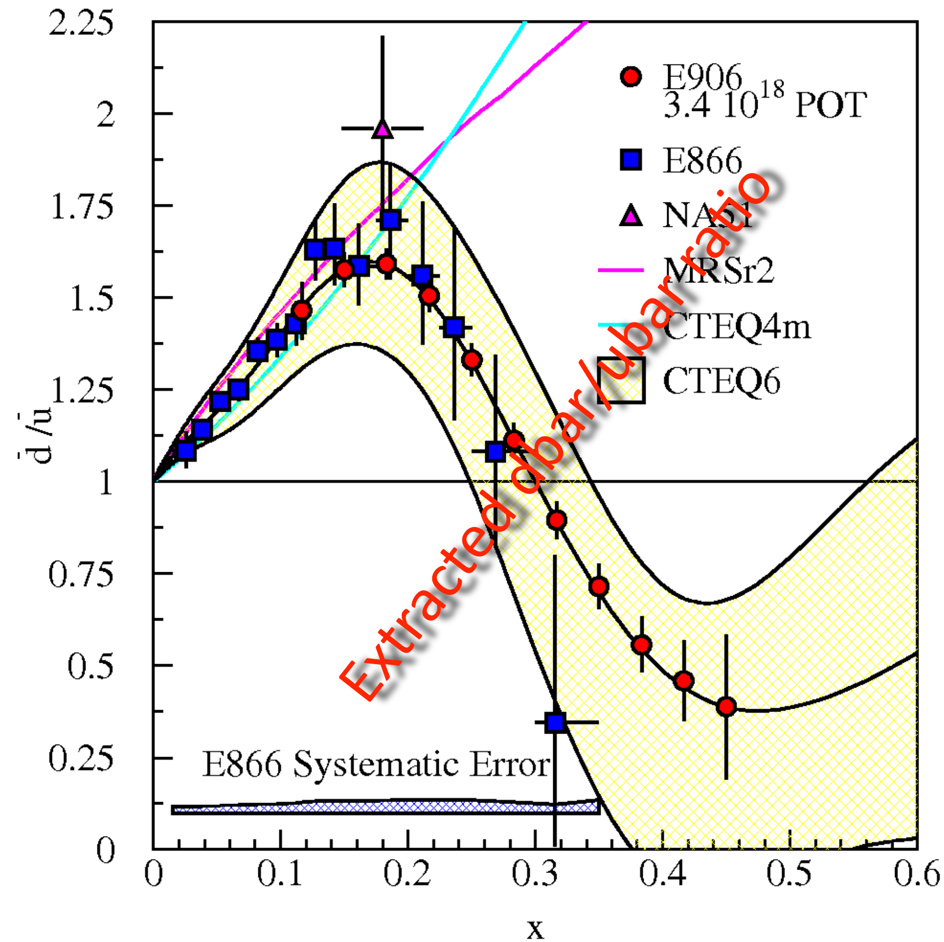
Extracting d-bar/-ubar from the Drell-Yan reaction

- E906/Drell-Yan will extend these measurements and reduce statistical uncertainty.
- E906 expects systematic uncertainty to remain at approx. 1% in cross section ratio.



Drell-Yan Cross Section Ratio and d-bar/u-bar

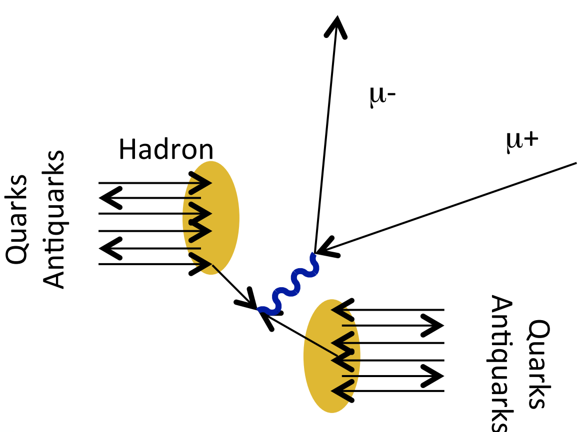


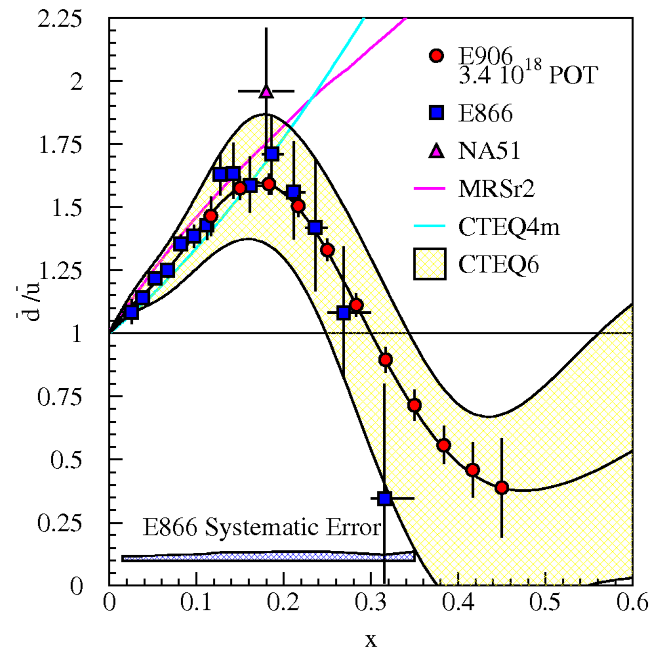


$$\left.\frac{\sigma^{pd}}{2\sigma^{pp}}\right|_{x_b \gg x_t} \approx \frac{1}{2}\left[1 + \frac{\bar{d}(x_t)}{\bar{u}(x_t)}\right]$$

Review

- Proton is almost equal parts **matter and antimatter with a lot of glue**.
- There is an **intrinsic sea of quarks** in the proton—just as fundamental as the intrinsic “valence” quarks
- The sea has a large and x-dependent **asymmetry between ubar and dbar**
- The Drell-Yan process is a great tool for studying the distributions of SeaQuarks

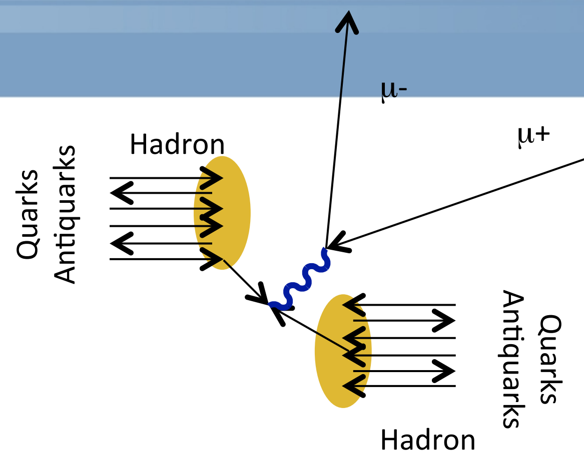




Proton structure in nuclei

Argonne NATIONAL LABORATORY

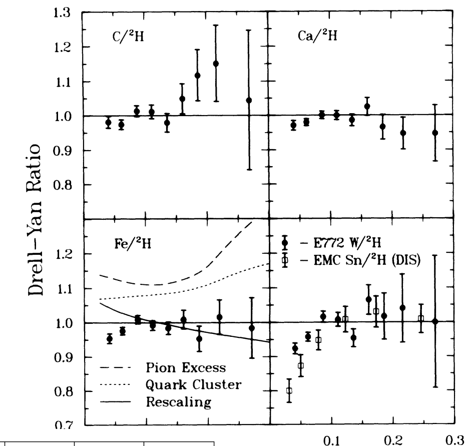
Paul E. Reimer
Physics Division, Argonne National Laboratory
HUGS, 4-22 June 2012

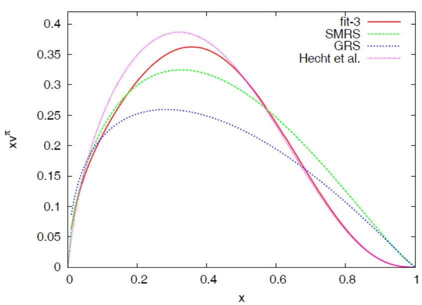


Really—two separate topics unified by my interests

I. Flavor Structure of the Proton
   A. Proton structure—historical view
   B. Sea quarks in the proton & the Drell-Yan reaction
   C. Proton structure in nuclei
      1. EMC Effect
      2. Pions

II. Measurements of Parity Violation in Electron Scattering
   A. The Standard Model, electroweak interactions and par
   B. Tests of the Standard Model with parity violation
   C. Nuclear Structure with Parity Violation





β = 2.03 ±0.06

$$xq_V^\pi(x) = A_V^\pi x^\alpha (1-x)^\beta (1+\gamma x^\delta)$$

Office of Nuclear Physics — Exploring Nuclear Matter - Quarks to Stars

U.S. DEPARTMENT OF ENERGY

Review

- Proton is almost equal parts **matter and antimatter with a lot of glue**.
- There is an **intrinsic sea of quarks** in the proton—just as fundamental as the intrinsic "valence" quarks
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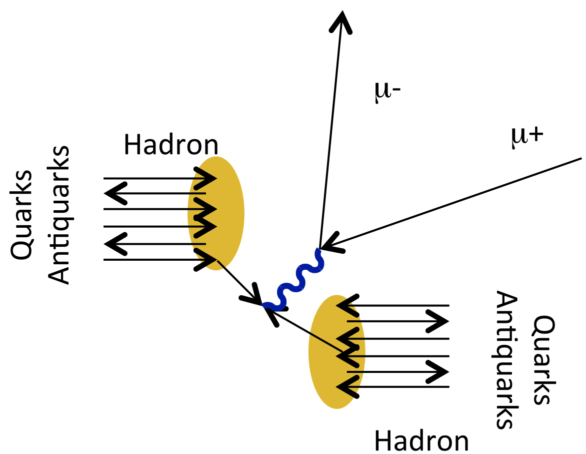
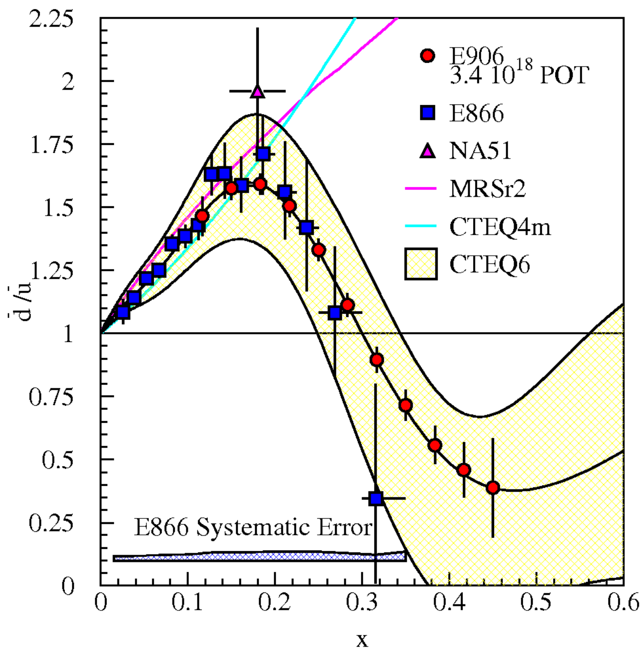




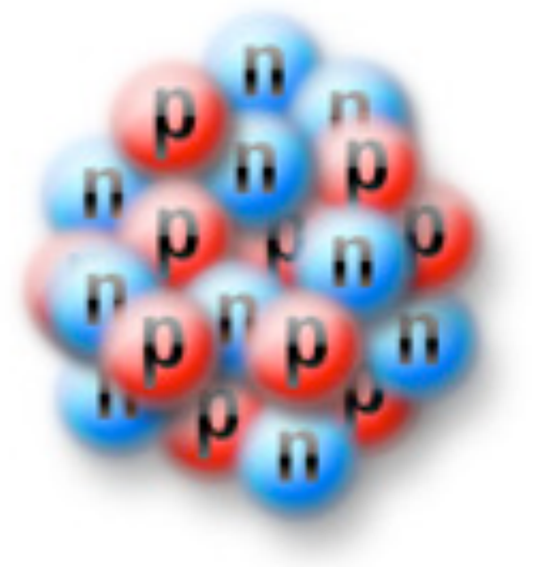
Please feel free to speak up at any time.

- This could get really boring if I'm doing all the talking
- This will get really boring if you don't understand something and I'm doing all the talking

Either of the above could cause you to have the same energy level as my puppy-dog

You can e-mail me comments or questions to reimer@anl.gov

The European Muon Collaboration (EMC) Effect



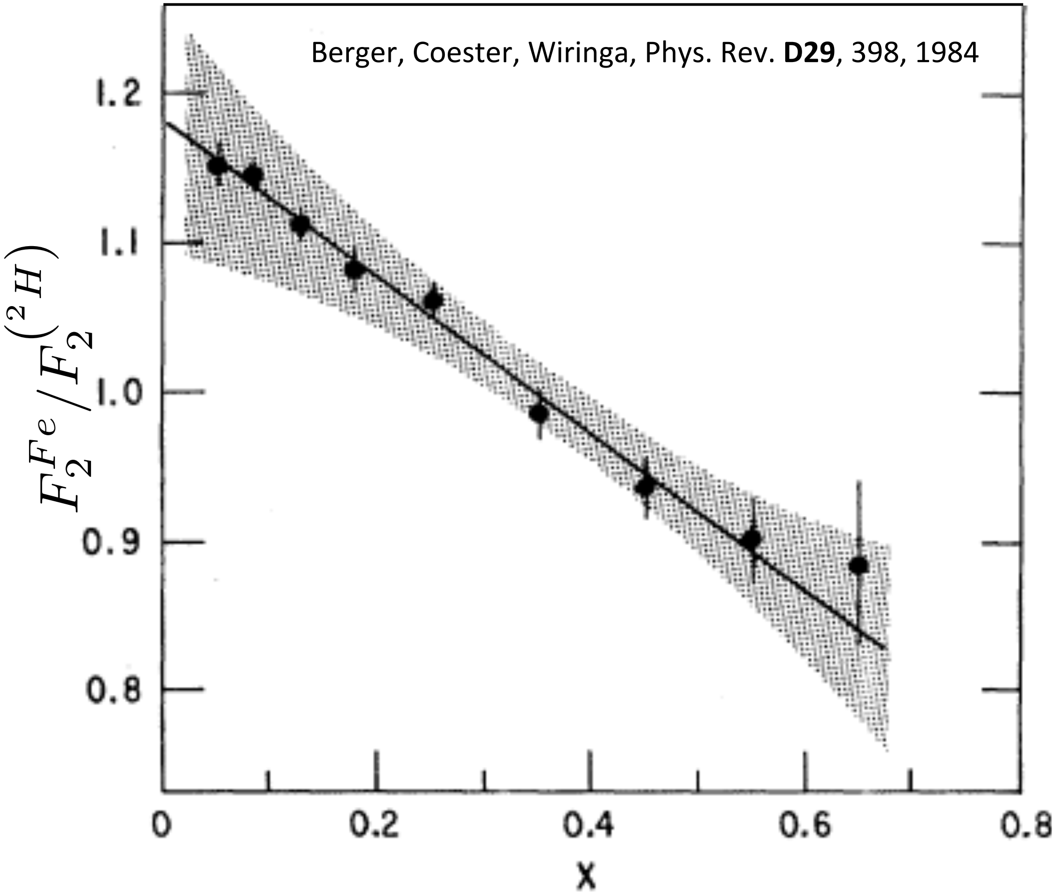
Are the parton distributions in nucleons within a nucleus the same as free nucleons?

- Is there a difference between hitting a proton in a nucleus and a free proton?
- Hard scattering makes an implicit assumption that the interaction is energetic enough so that the binding of quarks in a proton is small so surely, the binding of protons in the nucleus is also small?
- Do the quarks change configuration?

The European Muon Collaboration (EMC) Effect

Are the parton distributions in nucleons within a nucleus the same as free nucleons?

- Experimentally—No
- EMC measured the DIS F_2 ratio for Iron to Deuterium



Why?

- Shadowing
- Nuclear binding effects

$$F_2(x) = \sum_{q \in \{u,d\ldots\}} e_q^2 \left[q(x) + \bar{q}(x) \right]$$

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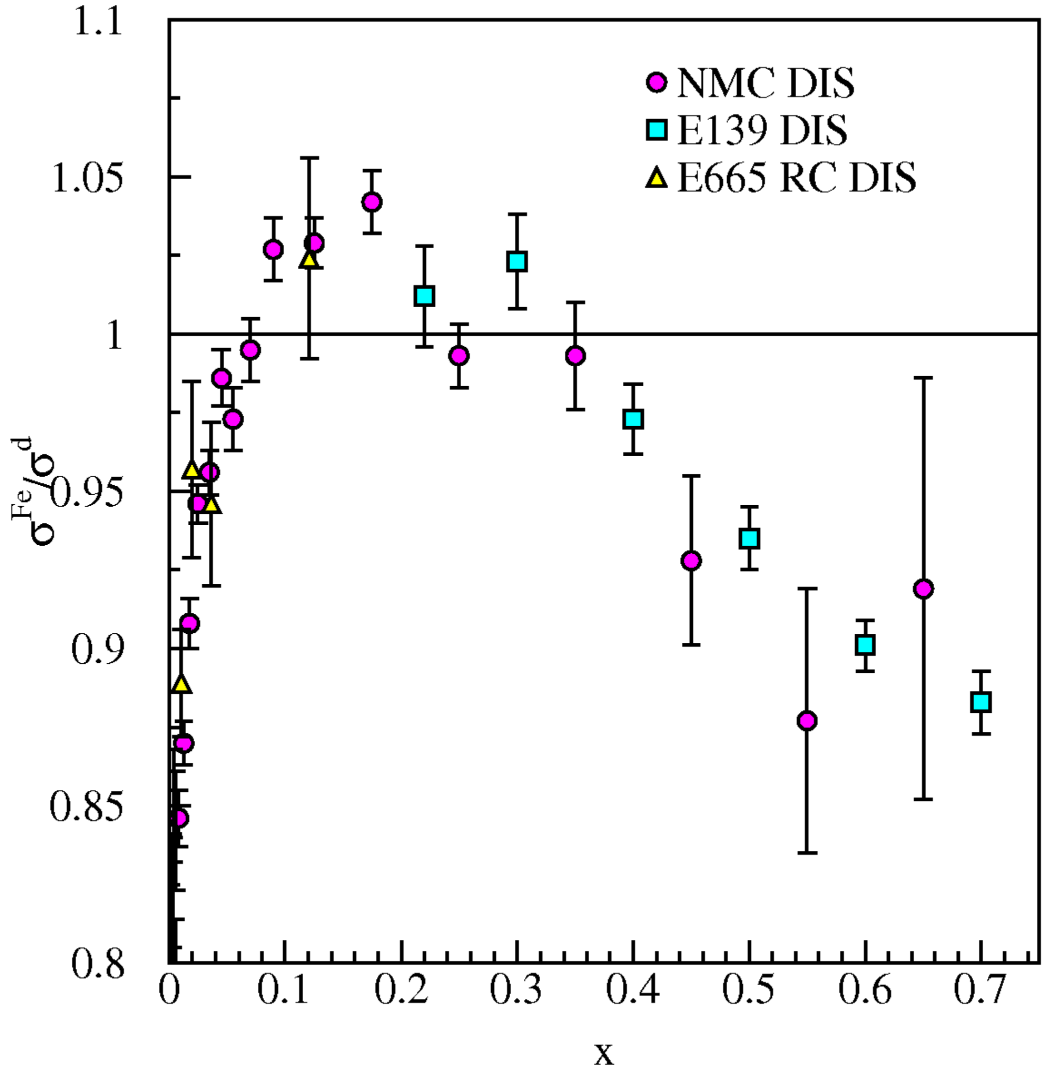


$$F_2(x) = \sum_{q\in\{u,d\ldots\}} e_q^2 \left[q(x) + \bar{q}(x)\right]$$

Do quarks and antiquarks experience the same modifications?

Aside: Problem for PDF fits

- Many experiments used nuclear targets

- Does this data need to be thrown out now?
  - Information of d-quark distributions comes from Deuterium and isospin symmetry

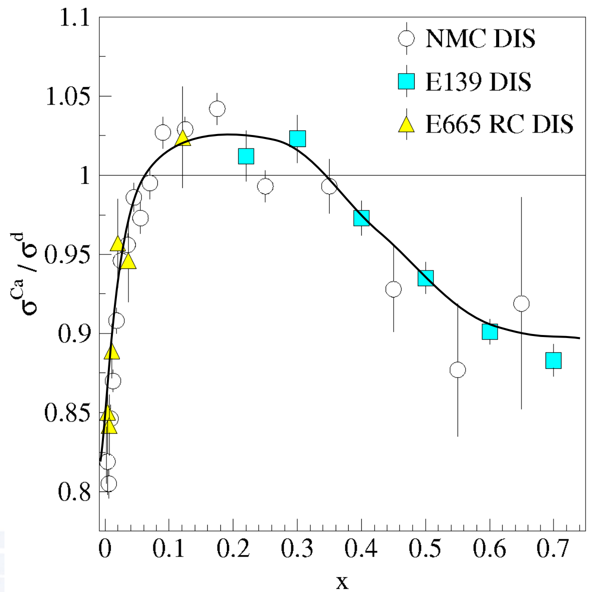
$$F_2^{\nu p}(x) + F_2^{\nu n} \propto \sum_{q\in\{u,d,\dots\}} x\left[q(x,Q^2) + \bar{q}(x,Q^2)\right]$$

  - Neutrino DIS data?
    - Old H_2 bubble chamber data OK
    - Modern experiments use iron target
    - Magnitude of Sea Quark distributions dominated by neutrino data

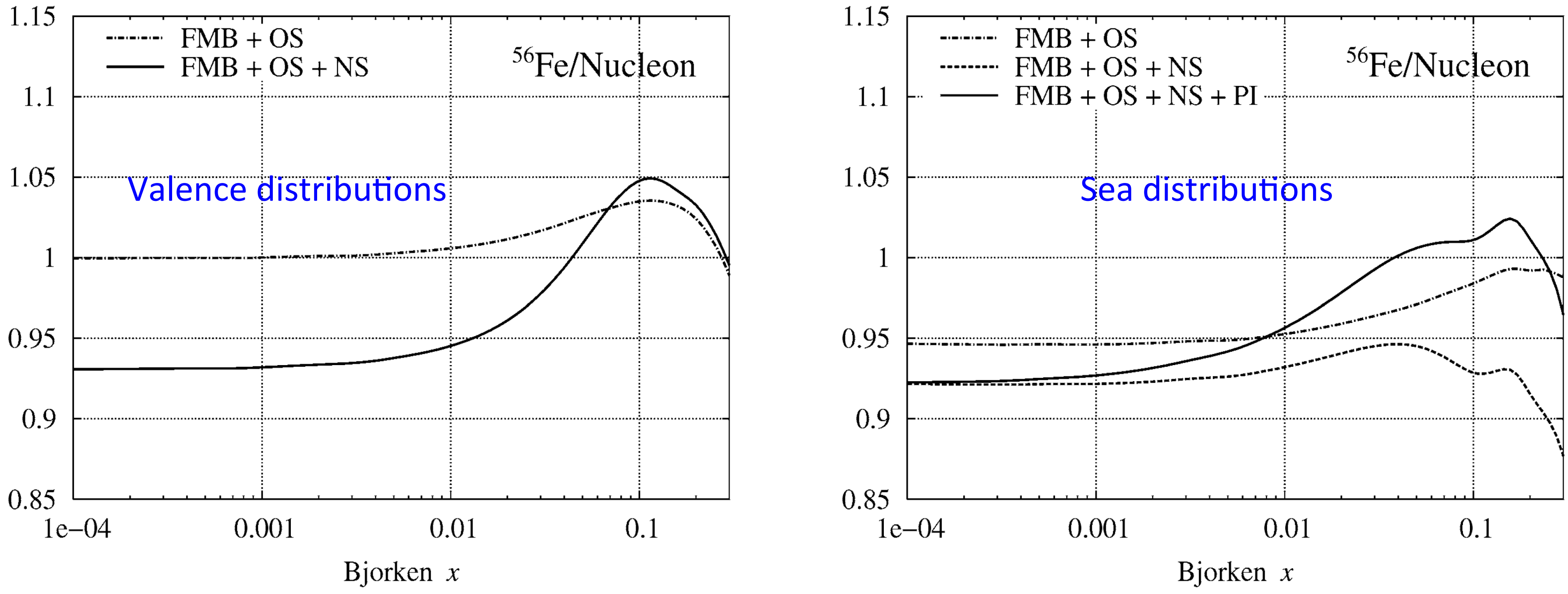
$$xF_3^{\nu N}(x) \propto \sum_{q\in\{u,d,\dots\}} x\left[q(x,Q^2) - \bar{q}(x,Q^2)\right]$$

- Parameterize measurements?

  K. J. Eskola, V. J. Kolhinen, and P. V. Ruuskanen, Nucl. Phys. B535, 351 (1998);



Kulagin and Petti sea vs. valence nuclear effects



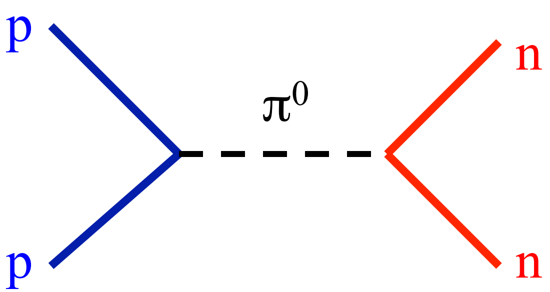
Nuclear Physics A 765 (2006) 126–187

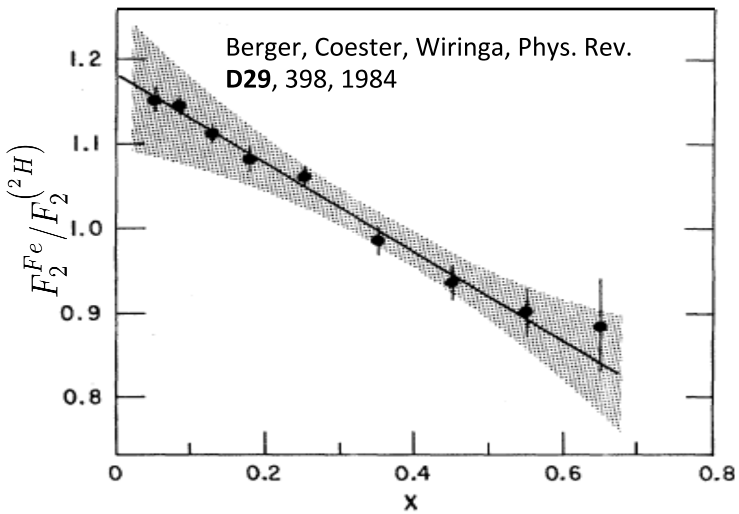
FMB—Fermi Motion and Nuclear Binding
OS—Off shell effects
NS—nuclear shadowing
PI—nuclear pions

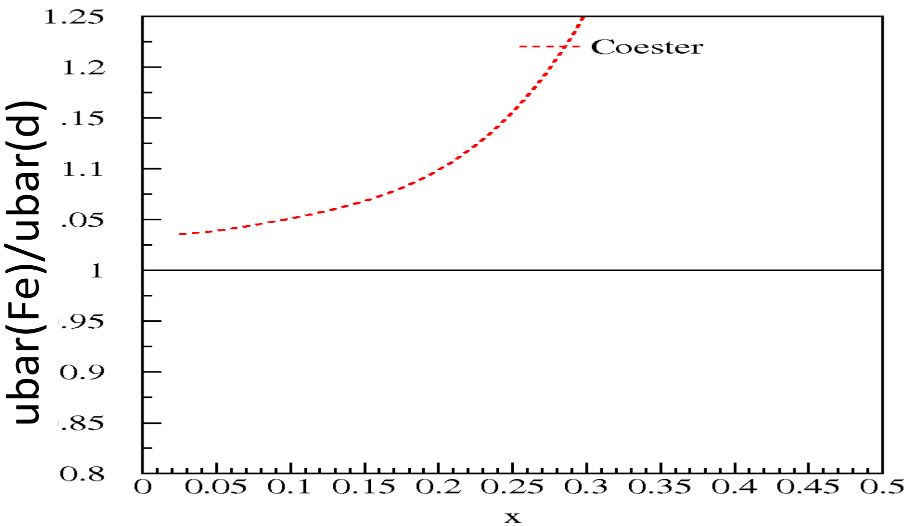
How are nucleons bound together?

Residual strong force binds nucleons together in nucleus

- Originally modeled as via the exchange of intermediate mesons (π's)
- Mesons contain antiquarks, so this should lead to an enhancement of the antiquark distributions in the nucleus

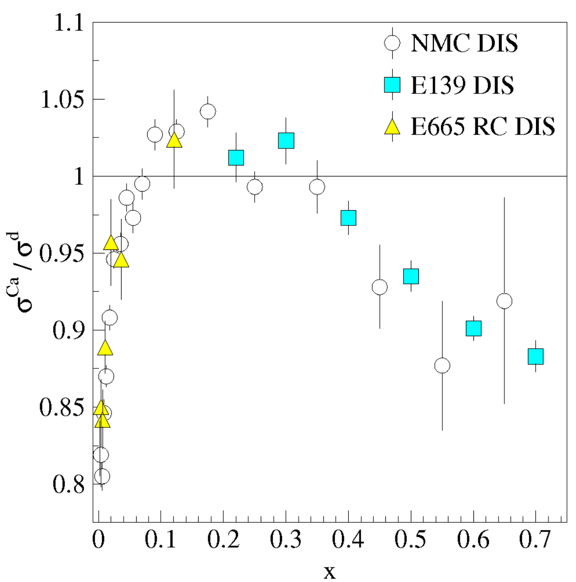


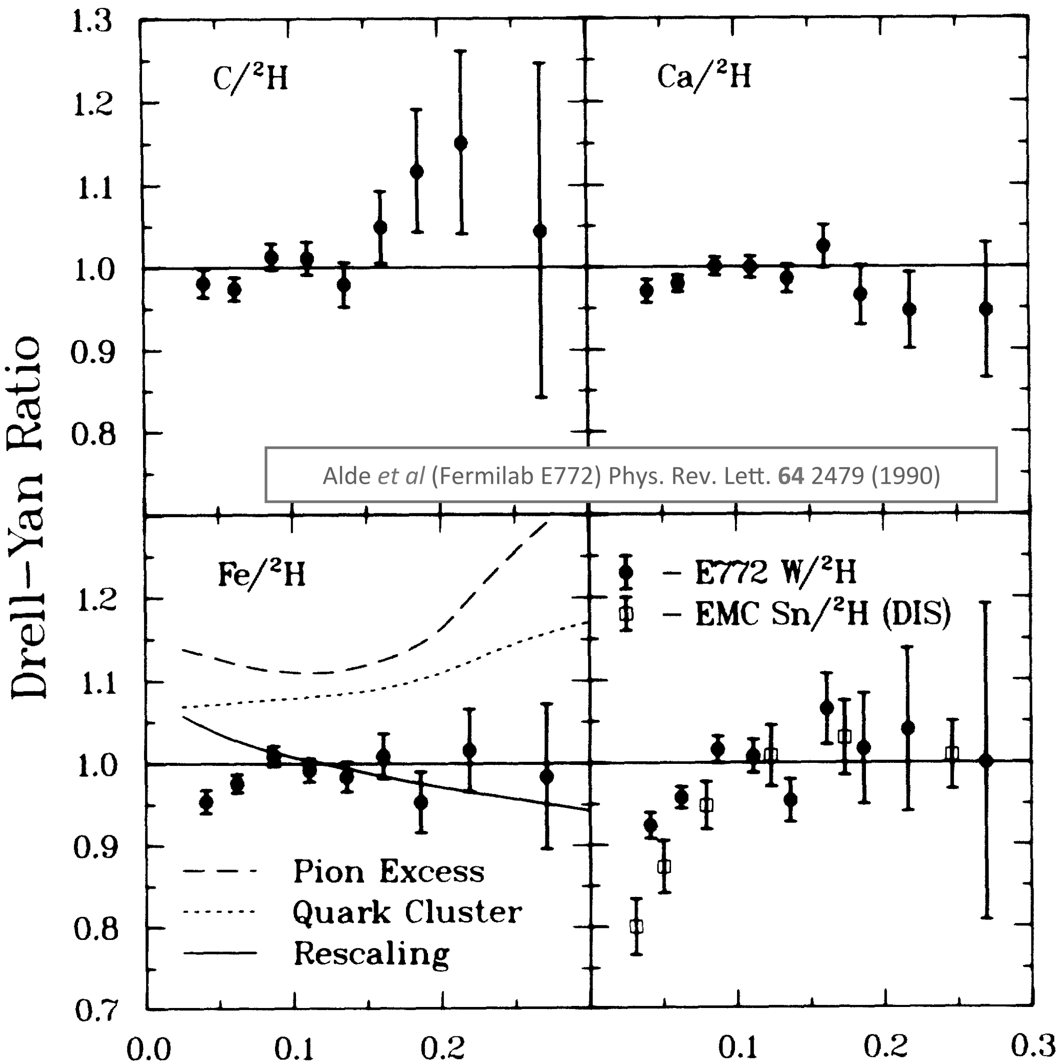




Nuclear effects in Sea Quarks

- No noticeable effects at large x
- evidence for shadowing at low x

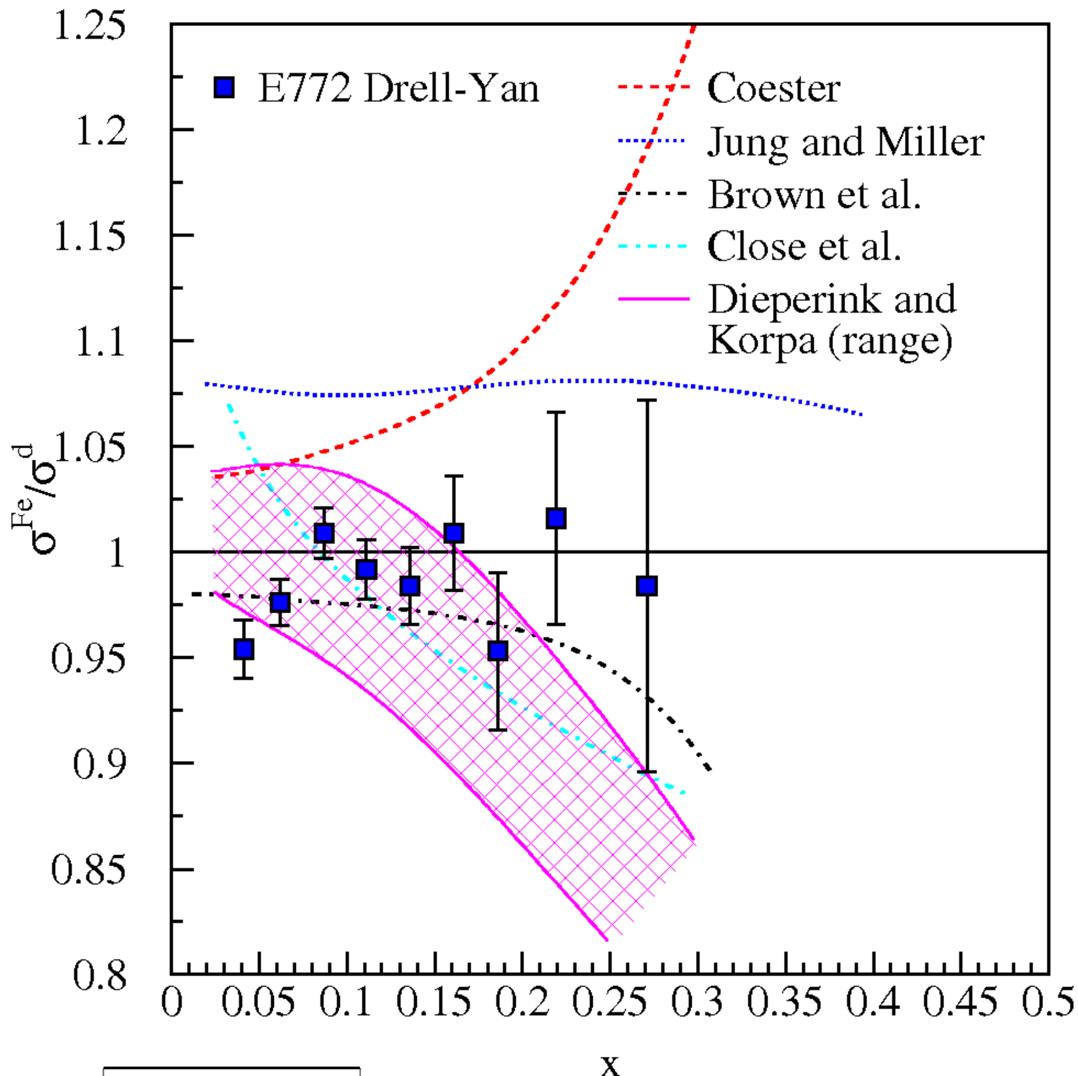


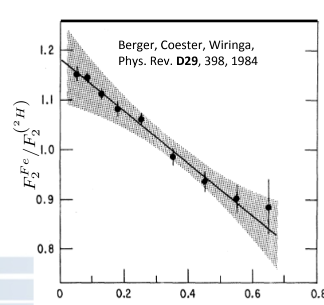


Alde *et al* (Fermilab E772) Phys. Rev. Lett. **64** 2479 (1990)

Structure of nucleonic matter: Where are the nuclear pions?

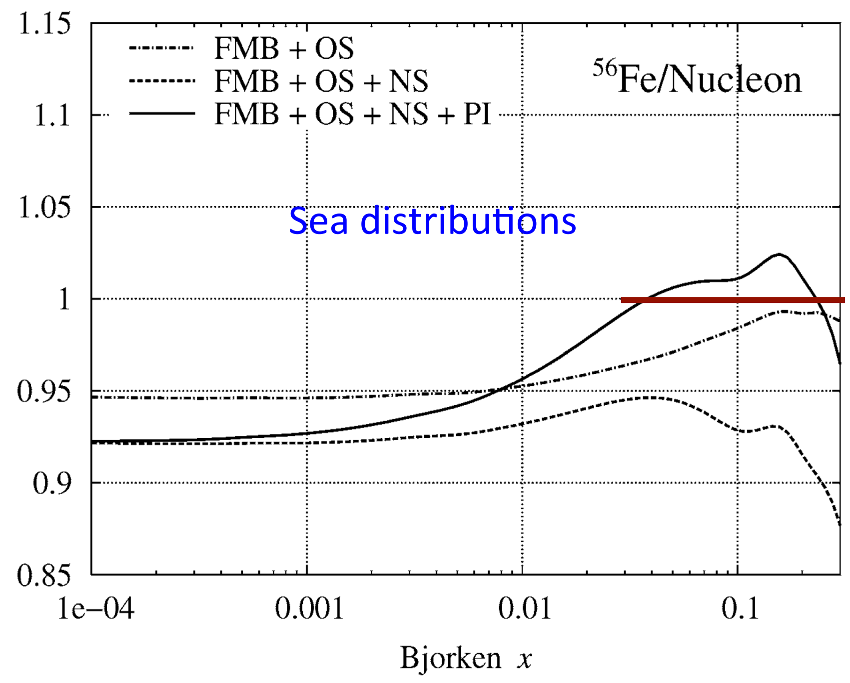
- The binding of nucleons in a nucleus is expected to be governed by the exchange of virtual "Nuclear" mesons.
- No antiquark enhancement seen in Drell-Yan (Fermilab E772) data.
- Contemporary models predict large effects to antiquark distributions as x increases.
- Models must explain both DIS-EMC effect and Drell-Yan





Kulagin and Petti sea vs. valence nuclear effects

Some general EMC effect in antiquark should be present



Nuclear Physics A 765 (2006) 126–187

FMB—Fermi Motion and Nuclear Binding

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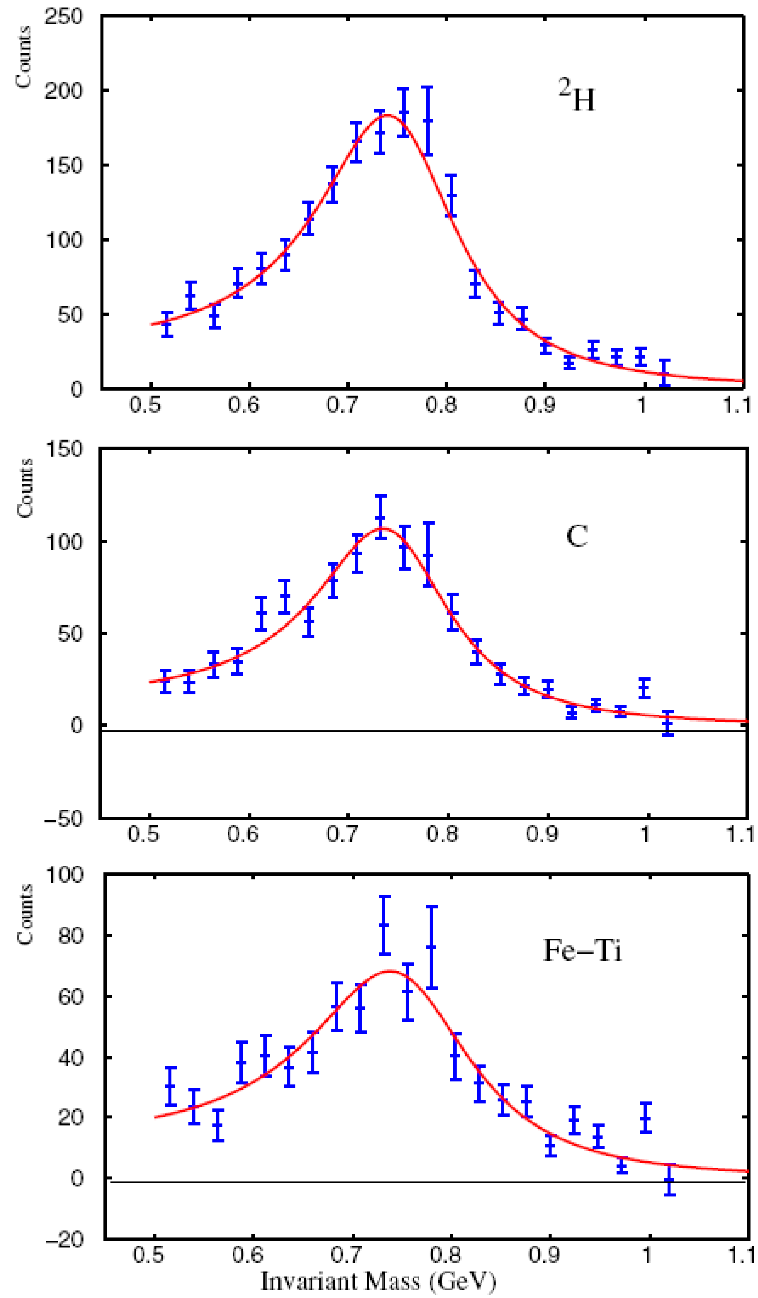
Aside: Rescaling Models in Trouble?

- Prediction of ρ mass/width modification not seen in JLab/CLAS data Nasseripour *et al.* (CLAS) PRL 99, 262302 (2007)



Structure of nucleonic matter: Where are the nuclear pions?

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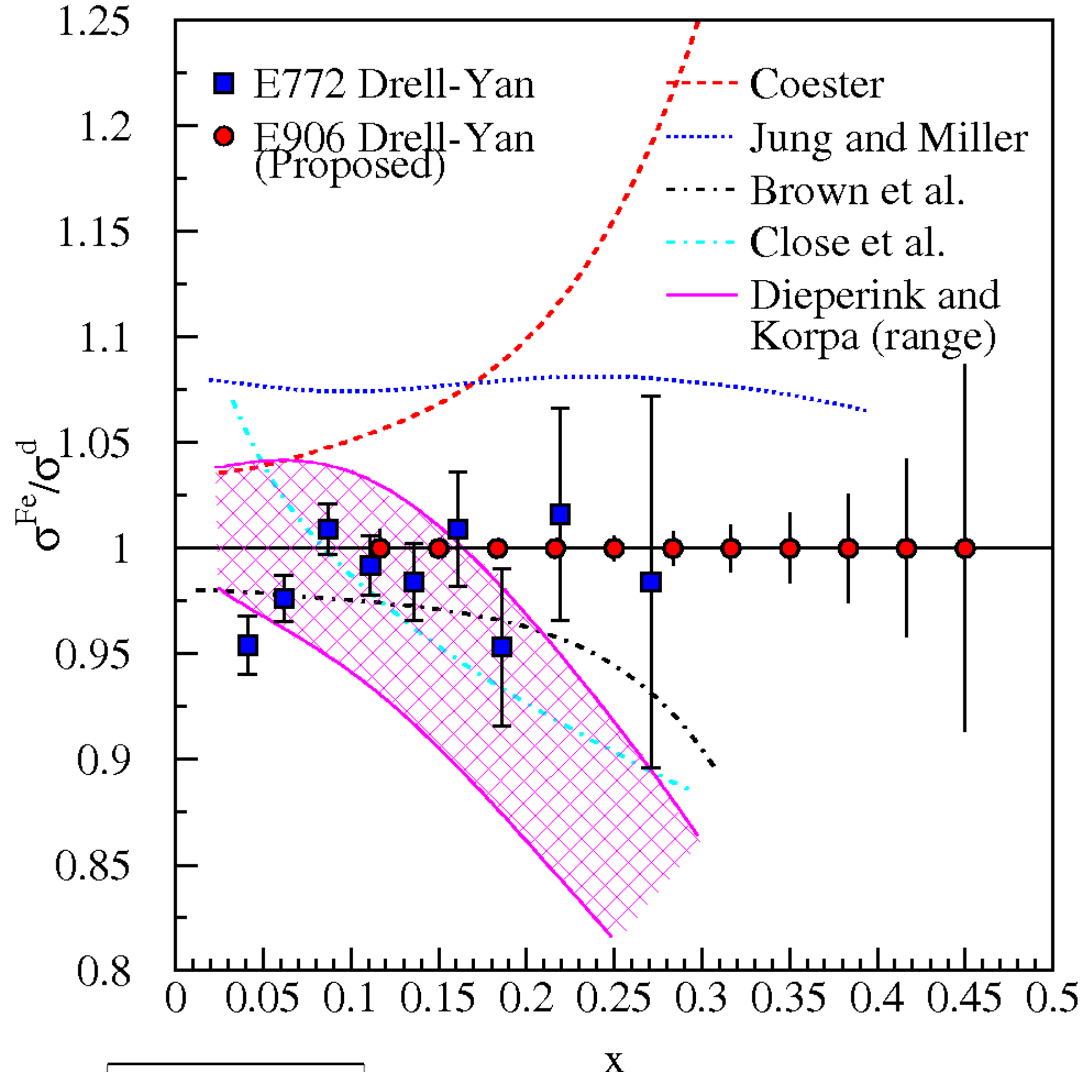
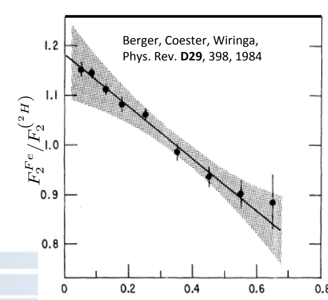


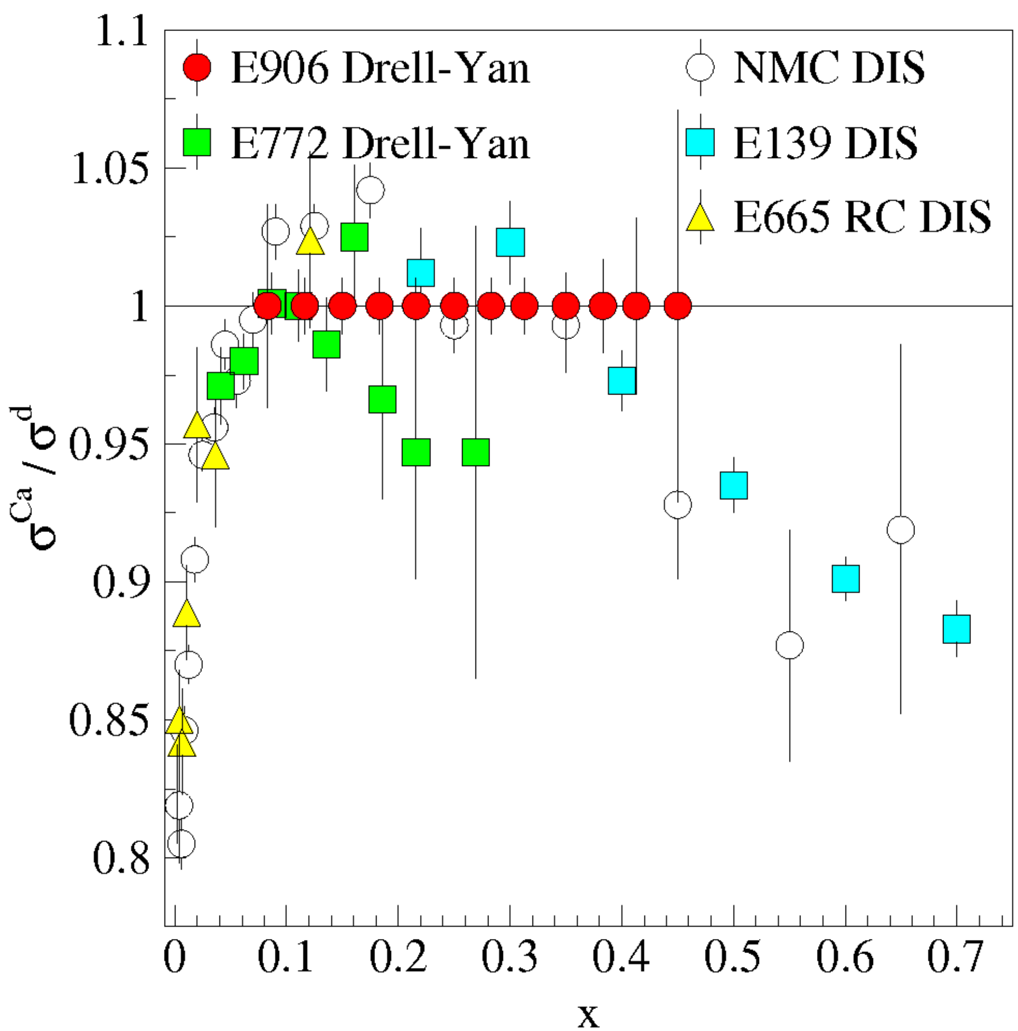


Fermilab E-906/SeaQuest expected statistical sensitivity

Test for neutrino DIS sea quark measurements

Intermediate-*x* *sea* PDF's

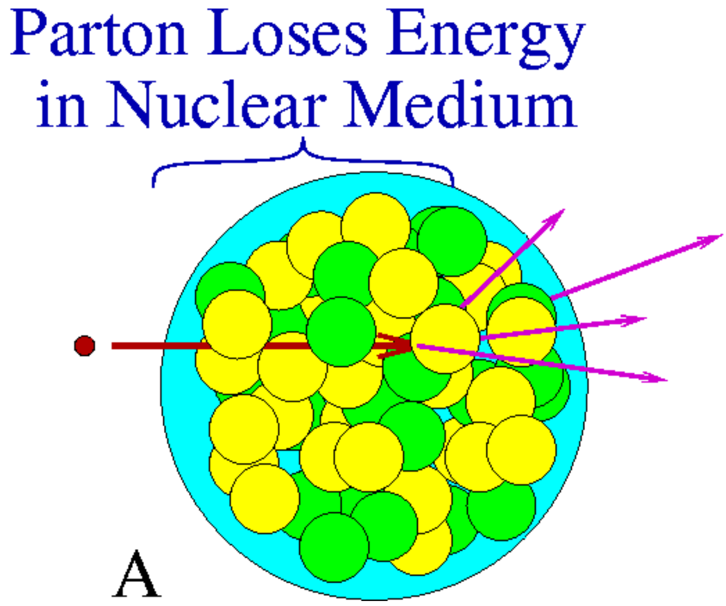
- ν-DIS on iron—Are nuclear effects with the weak interaction the same as electromagnetic?
- Are nuclear effects the same for sea and valence distributions
- What can the sea parton distributions tell us about the effects of nuclear binding?

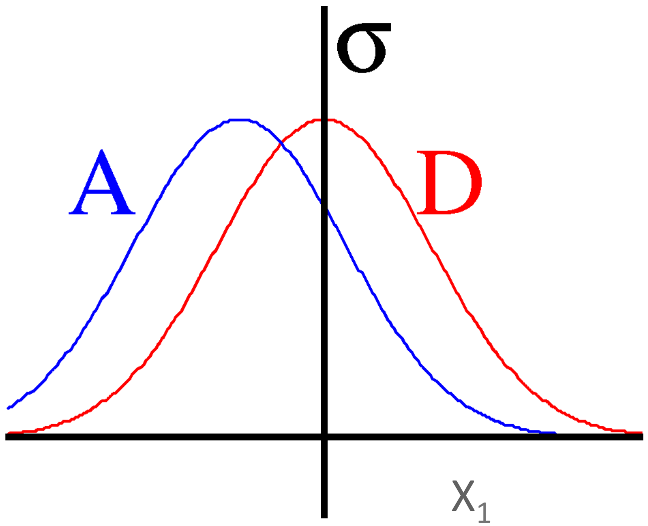


The Big Picture:
Other uses for the Drell-Yan reaction

Partonic Energy Loss

- An understanding of partonic energy loss in both cold and hot nuclear matter is paramount to elucidating RHIC data.
- Pre-interaction parton moves through cold nuclear matter and looses energy.
- Apparent (reconstructed) kinematic values (x_1 or x_F) is shifted
- Fit shift in x_1 relative to deuterium



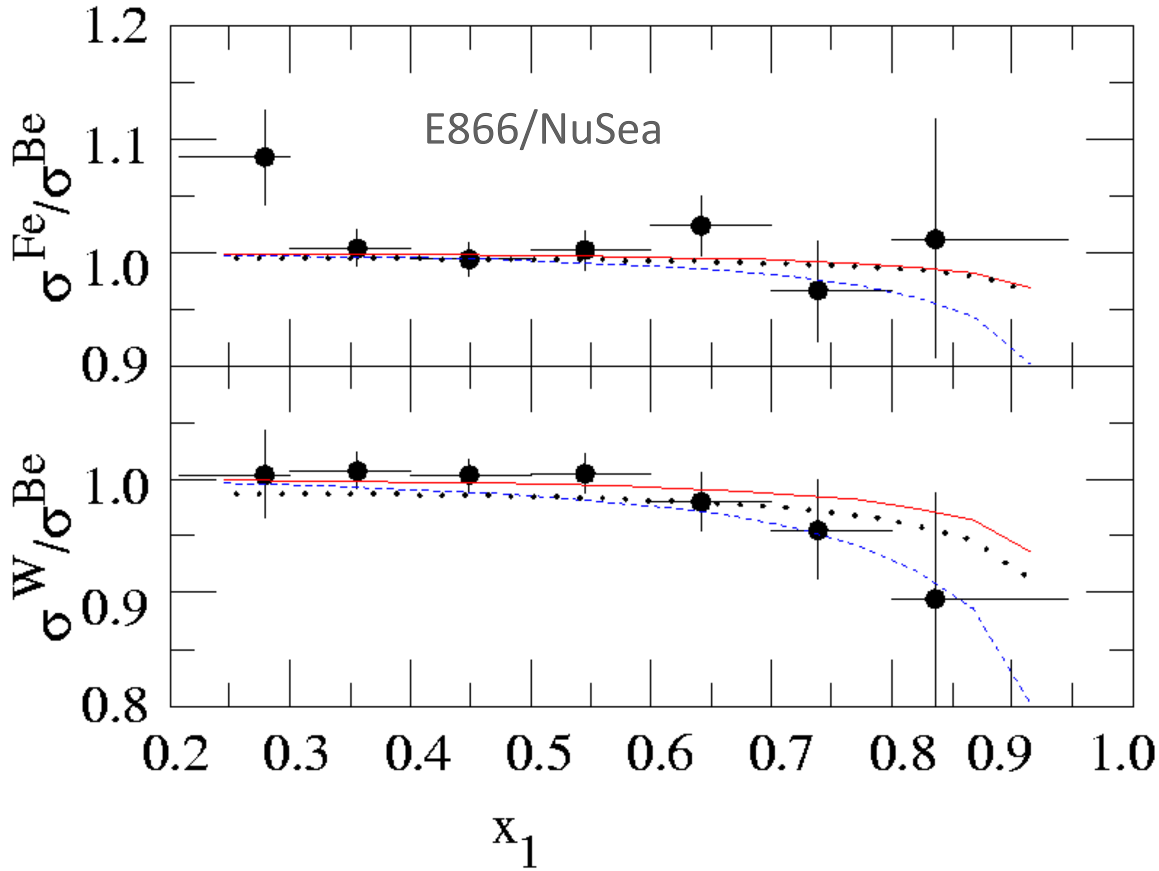


Models:

- Galvin and Milana $\Delta x_1 = -\kappa_1 x_1 A^{\frac{1}{3}}$
- Brodsky and Hoyer $\Delta x_1 = -\frac{\kappa_2}{s} A^{\frac{1}{3}}$
- Baier *et al.* $\Delta x_1 = -\frac{\kappa_3}{s} A^{\frac{2}{3}}$

Partonic Energy Loss

- E866 data are consistent with NO partonic energy loss for all three models
- Caveat: A correction must be made for shadowing because of x_1—x_2 correlations
  - E866 used an empirical correction based on EKS fit do DIS and *Drell-Yan*.

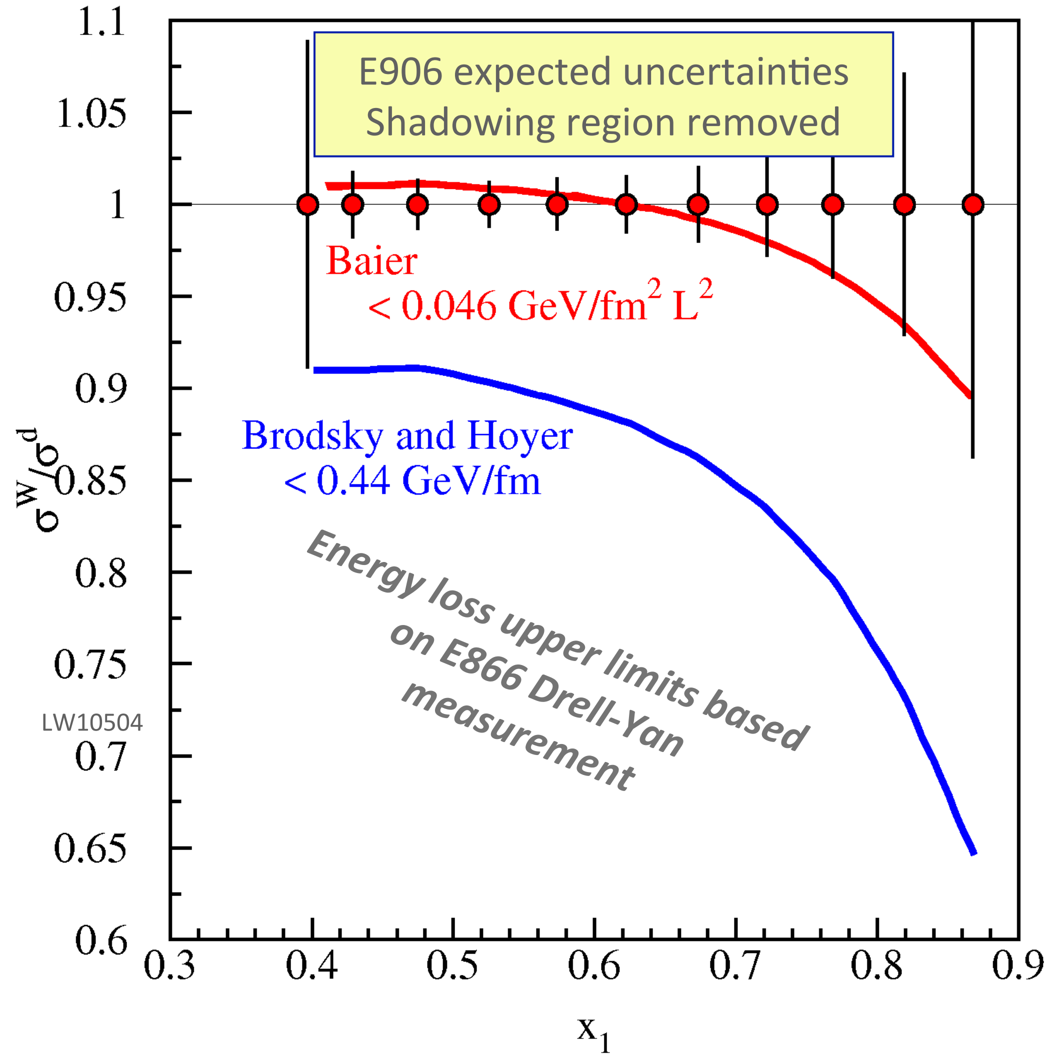


- Treatment of parton propagation length and shadowing are critical
  - Johnson *et al.* find 2.7 GeV/fm (≈1.7 GeV/fm after QCD vacuum effects)
  - Same data with different shadowing correction and propagation length
  - Better data outside of shadowing region are necessary.

- **Drell-Yan p_T broadening also will yield information**

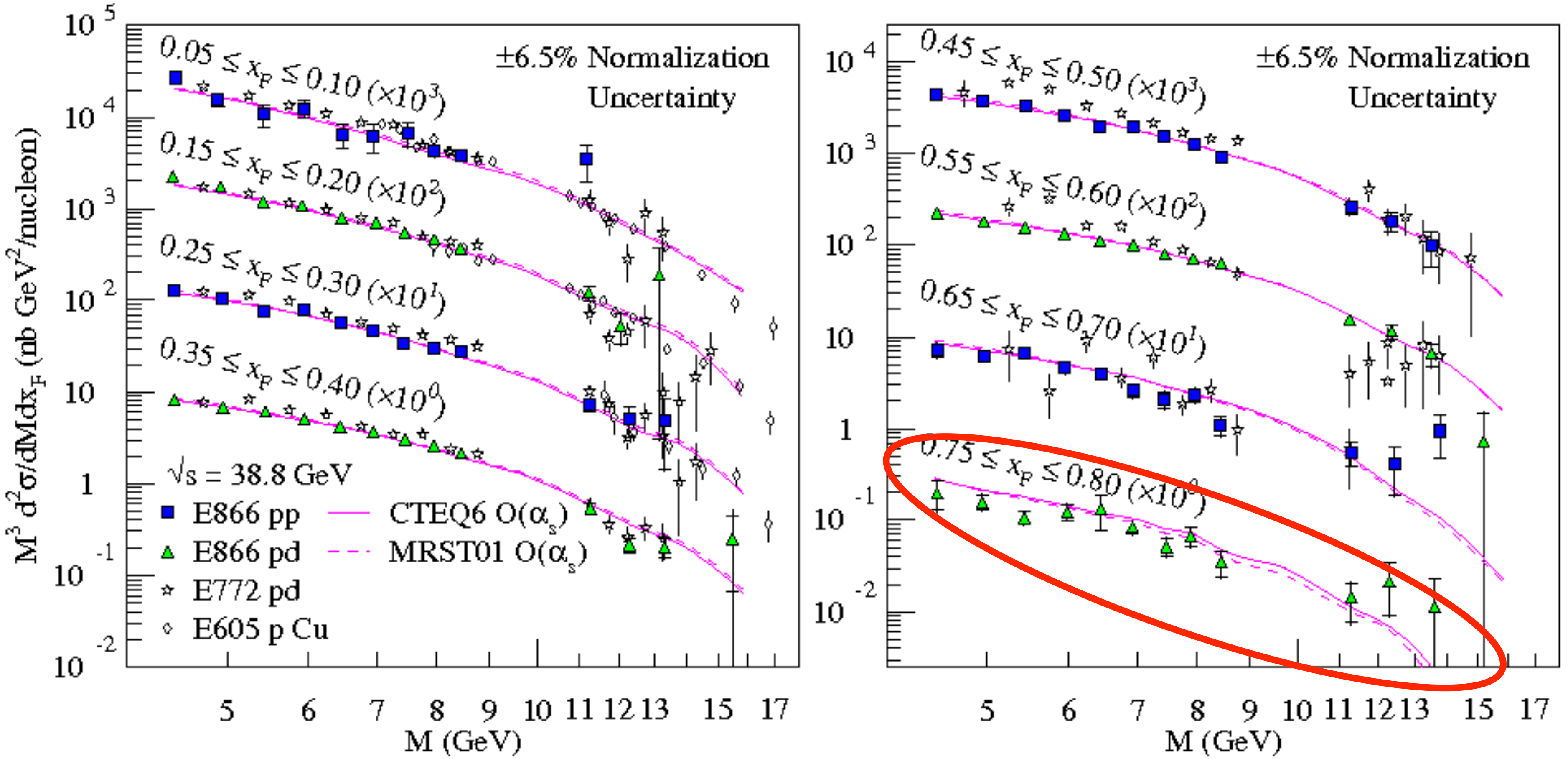
Parton Energy Loss

- Shift in Δx / 1/s
  - larger at 120 GeV
- Ability to distinguish between models
- Measurements rather than upper limits
- E906 will have sufficient statistical precision to allow events within the shadowing region, $x_2 < 0.1$, to be removed from the data sample
- Reasonable statistical precision at large p_T to study p_T broading



Other interesting tricks with the Drell-Yan reaction: Absolute cross sections, not just ratios

Drell-Yan Absolute Cross Sections



- ¼ of data represented in plot (alternate decades, alternate targets)
- Last few x_F bins show PDF's "over predict" NLO cross section

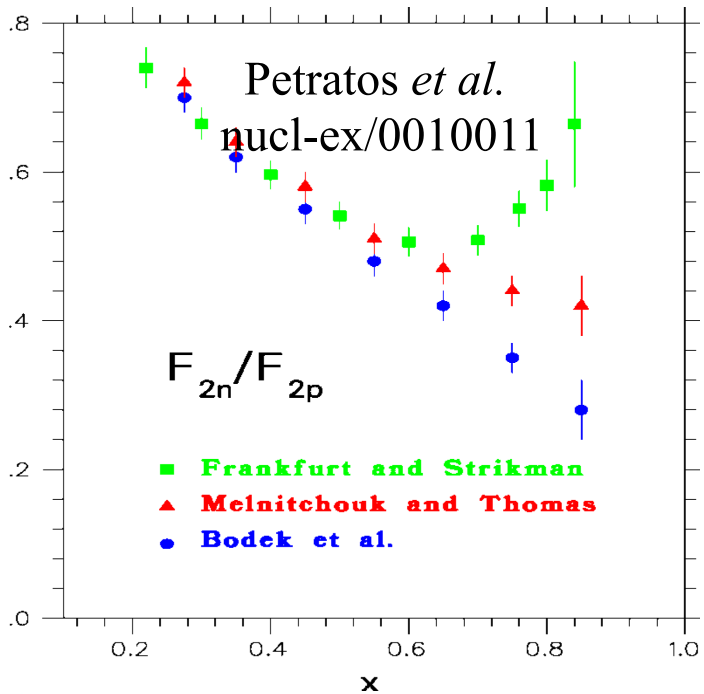
Proton Valence Structure: Unknown as x! 1

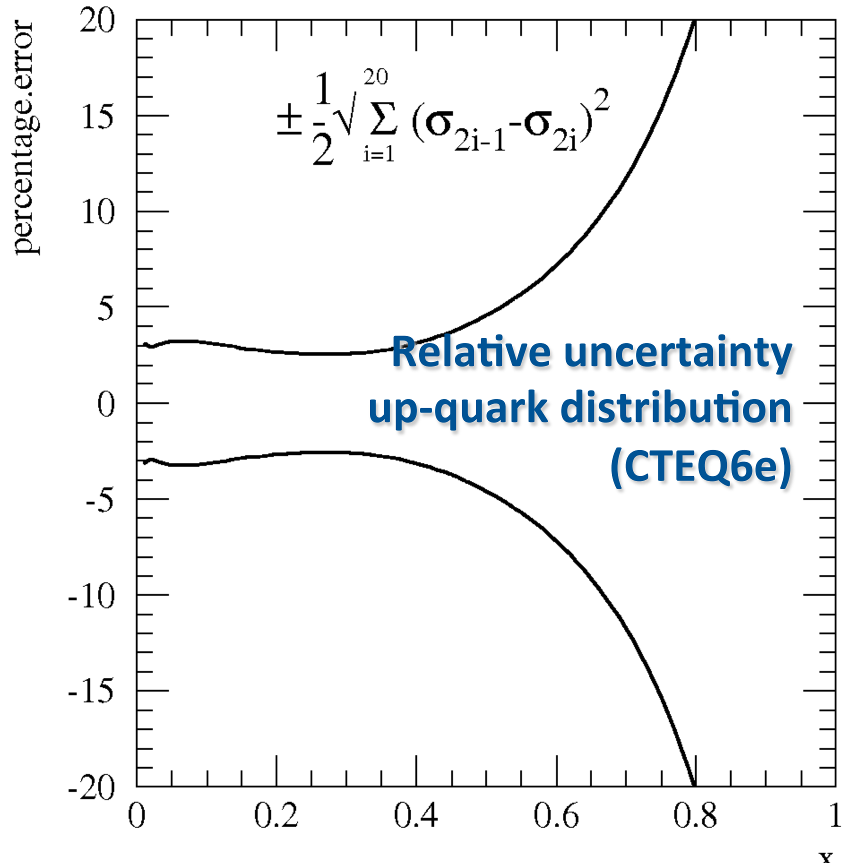
Theory

- Exact SU(6): d/u -> 1/2
- Diquark S=0 dom.: d/u -> 0
- pQCD: d/u -> 3/7

Data

- Binding/Fermi Motion effects in deuterium—choice of treatments.
- ***Proton data is needed.***

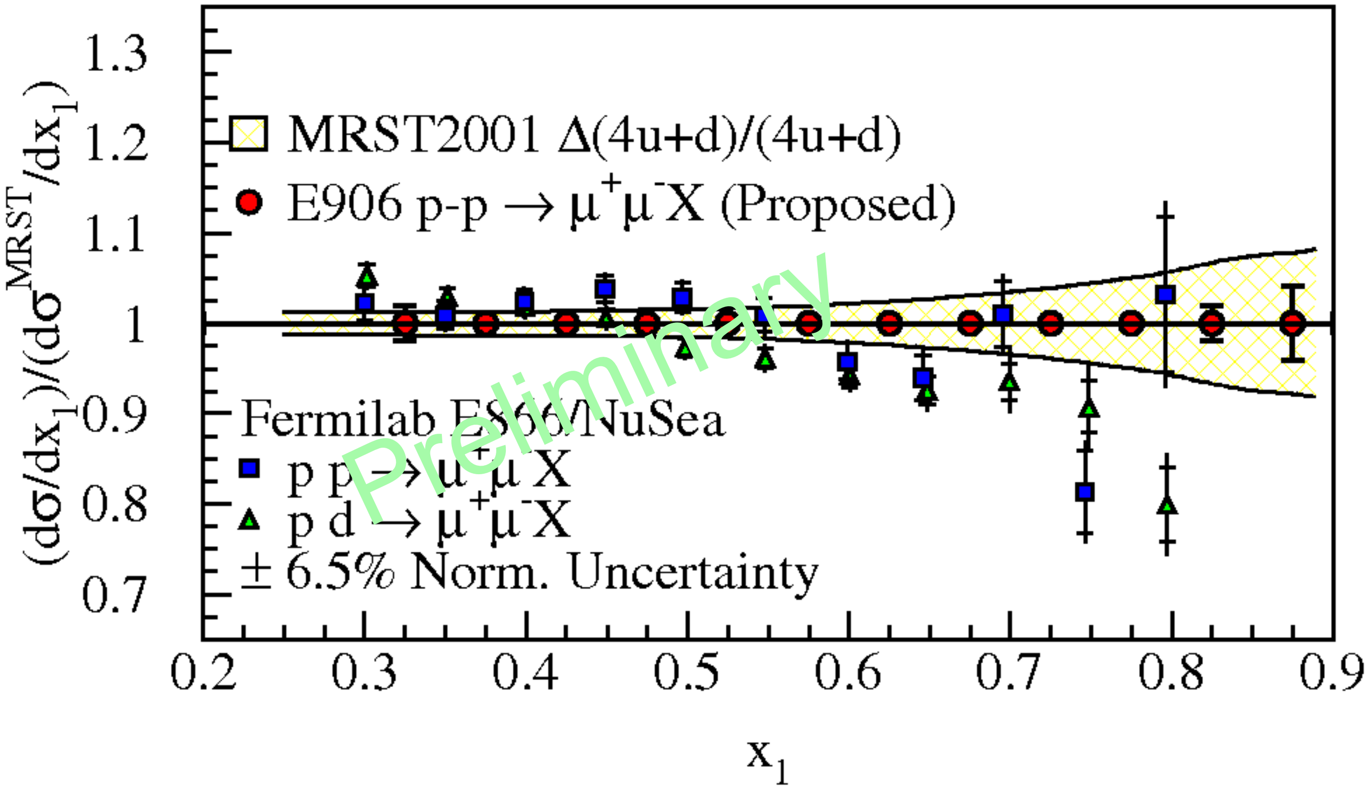




Reality:
We don't even know the u or d quark distributions—there really is very little high-x proton data

Drell-Yan Absolute Cross Sections: x_{target}

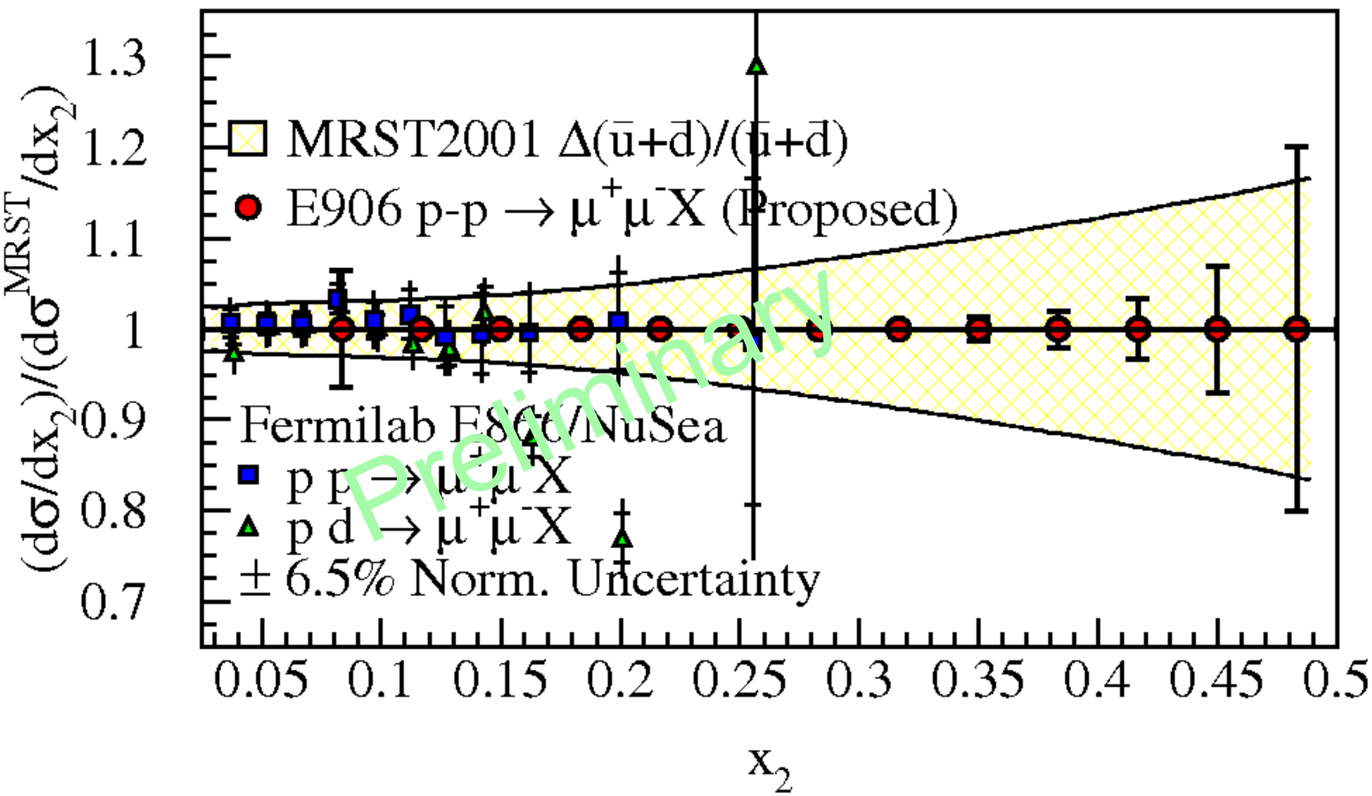
- Reach high-x through *beam proton*—Large x_F) large x_{beam}.
- High-x distributions poorly understood
  - Nuclear corrections are large, even for deuterium
  - Lack of proton data
- Proton-Proton—no nuclear corrections—*4u(x) + d(x)*



Drell-Yan Absolute Cross Sections: x_{target}

Measures a convolution of beam and target PDF

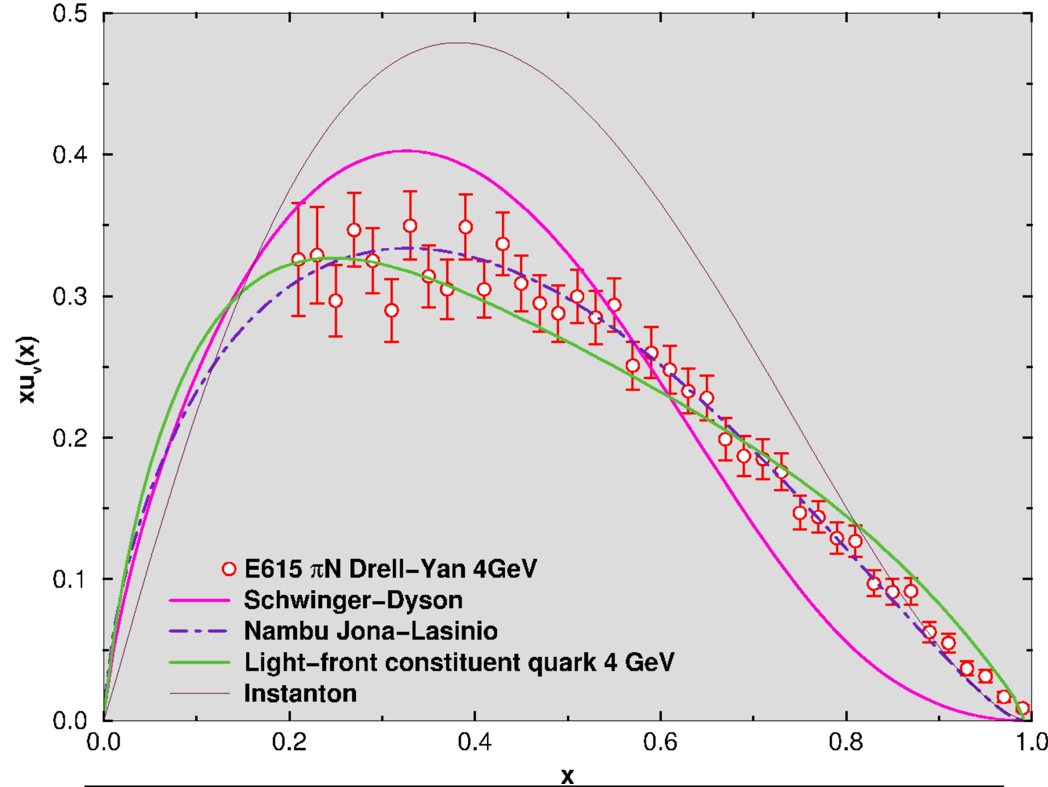
- absolute magnitude of high-x valence beam distributions
- absolute magnitude of the sea in the target
  - *Currently determined by ν–Fe DIS*



What's in the pion—a direct challenge from a theorist

Models of the Pion

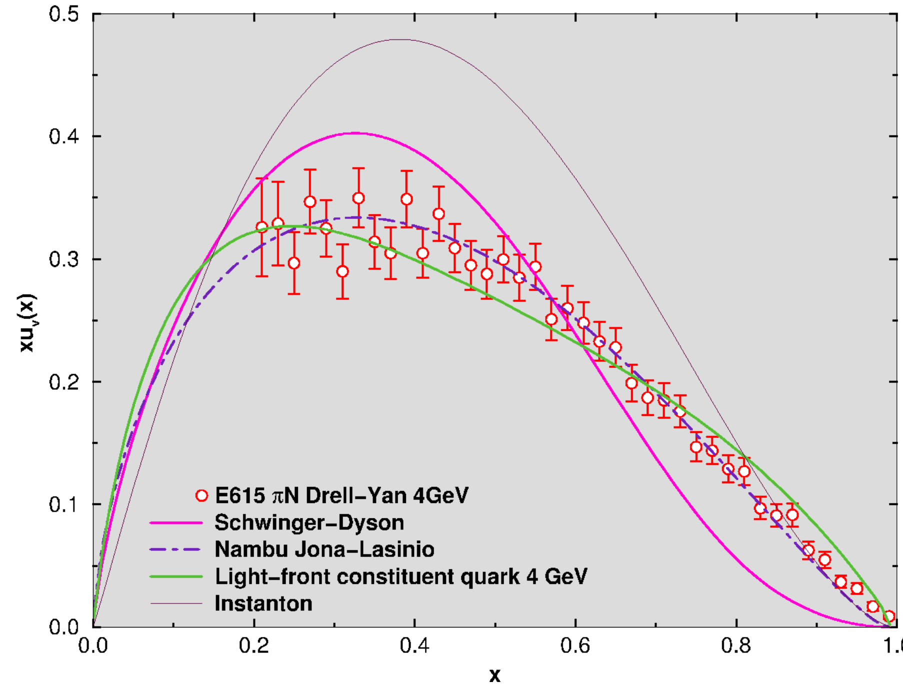
- Nambu and Jona-Lasinio Model:
  - R. Davidson, E. Arriola, PLB (1995)
  - J.T. Londergan *et al.* PLB (1994).
  - T. Shigetani *et al.* PLB (1993).
- Dyson Schwinger Equation:
  - M. Hecht *et al.* PRD (2001).
- Chiral Quark Model:
  - K. Suzuki, W. Weise, NPA (1998).
  - D. Arndt, M. Savage, nucl-th (2001)
- Light-front constituent quark models:
  - Gerry Miller, *et al.* (too many to list).
- Instanton Model:
  - A. Dorokhov, L. Tomio, PRD (2000)
- QCD Sum Rule Calculations
  - A. Bakulev *et al.* PLB (2001).
- Lattice Gauge
  - C. Best *et al.* PRD (1997).



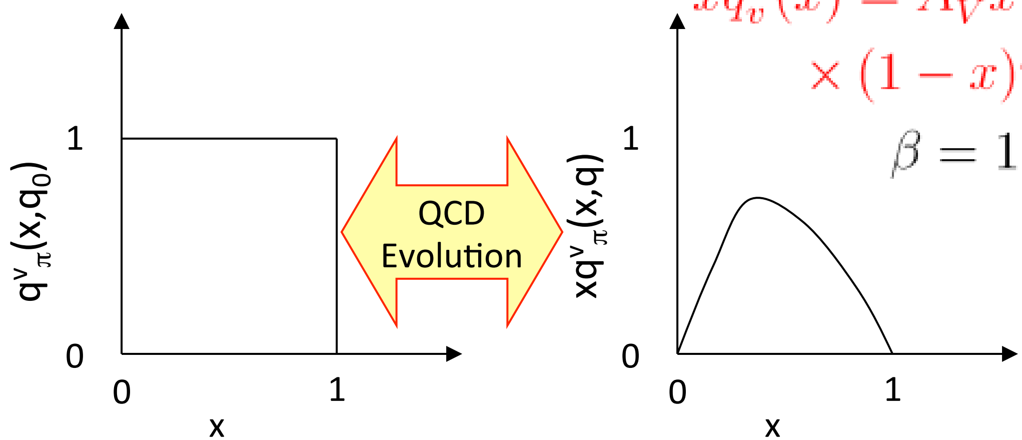
At some base q_0
NJL: $xq(x)/(1-x)^\beta$ $\beta = 1$
pQCD: $xq(x)/(1-x)^\beta$ $\beta = 2$
DSE: $xq(x)/(1-x)^\beta$ $\beta \cong 1.9$
Evolution to experimental Q increases β.

Models of the Pion

At some base Q_0
pQCD: $xq(x)/ (1-x)^{\beta}$ β = 2
NJL: $xq(x)/ (1-x)^{\beta}$ β = 1
DSE: $xq(x)/ (1-x)^{\beta}$ β ¼ 1.9
Evolution to experimental
Q increases β.



Structureless pion
described by old
parameterization with
α =0.67, β =1.13
(NJL Model)



$$xq_v^{\pi}(x) = A_V^{\pi} x^{\alpha} \times (1-x)^{\beta}$$

$\beta = 1?$

Pion Drell-Yan Data: Fermilab E615

PHYSICAL REVIEW D VOLUME 39, NUMBER 1 1 JANUARY 1989

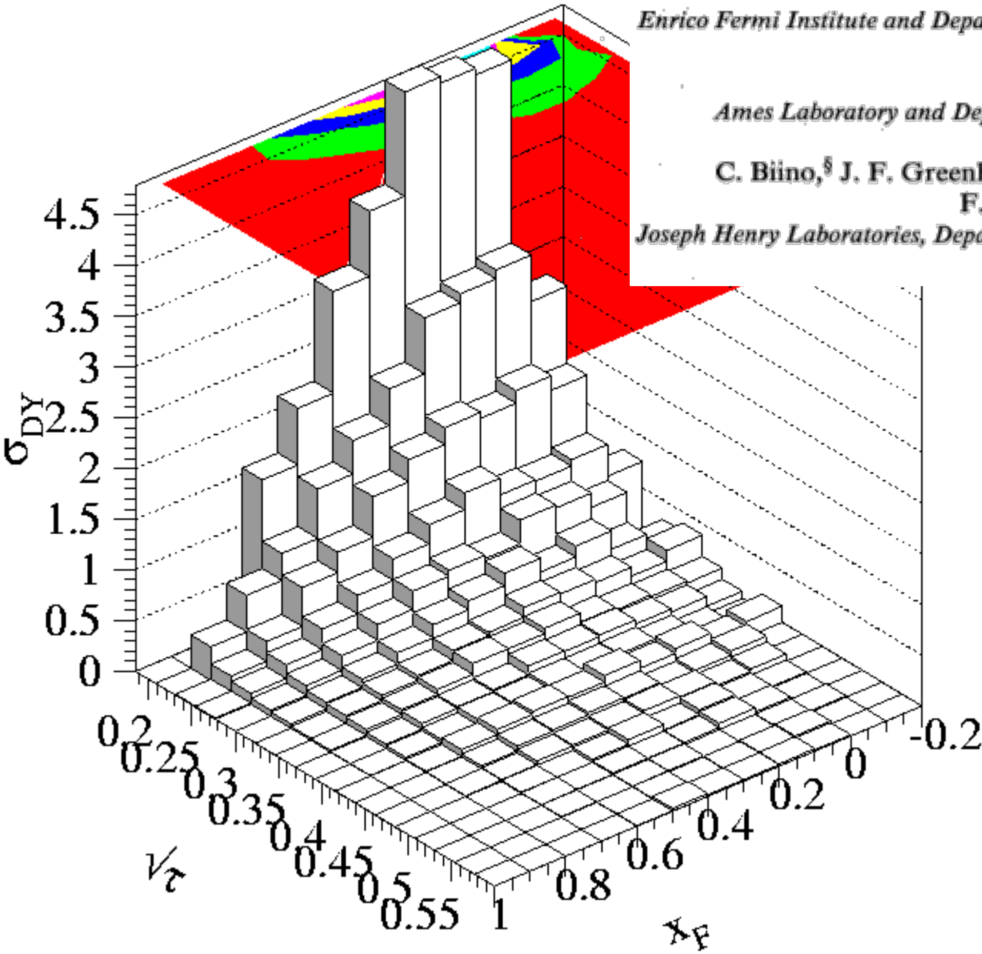
Experimental study of muon pairs produced by 252-GeV pions on tungsten

J. S. Conway,* C. E. Adolphsen,† J. P. Alexander,‡ K. J. Anderson, J. G. Heinrich, J. E. Pilcher, and A. Possoz
Enrico Fermi Institute and Department of Physics, The University of Chicago, Chicago, Illinois 60637

E. I. Rosenberg
Ames Laboratory and Department of Physics, Iowa State University, Ames, Iowa 50011

C. Biino,§ J. F. Greenhalgh,** W. C. Louis,†† K. T. McDonald, S. Palestini,§ F. C. Shoemaker, and A. J. S. Smith
Joseph Henry Laboratories, Department of Physics, Princeton University, Princeton, New Jersey 08544

(Received 8 July 1988)



Fermilab E615

- 252 GeV π^-W Drell-Yan
- Projected each data point onto x_π axis (diagonal)
- Valence quark distributions extracted assuming

  $xq(x) = A\, x^{\alpha}(1-x)^{\beta}$

Experimental Tools for π structure

- Deeply Inelastic Scattering:

  “pion targets are not abundant” Hecht

  – DIS on virtual pions:

    ep→eNx HERA data [ZEUS, NPB637 3 (2002)]

    Possible JLab and EIC.

  – Low-x data (Different Workshop?)

- Direct photos in πp interactions

  – Sensitive to gluon distributions.

    [CERN WA 70, Z. Phys. **C37** 535 (1988)]

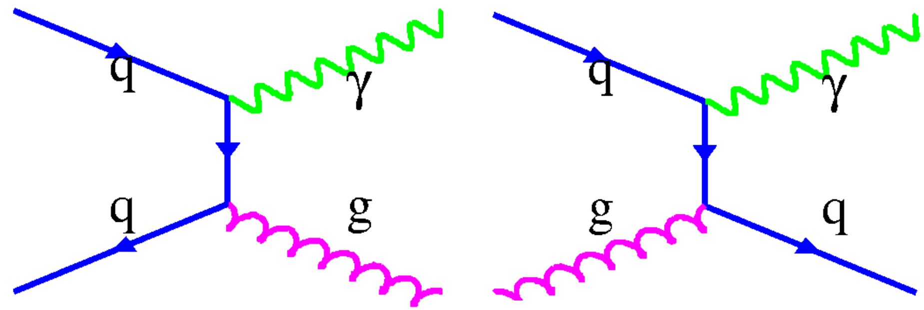
  – Assume parameterization

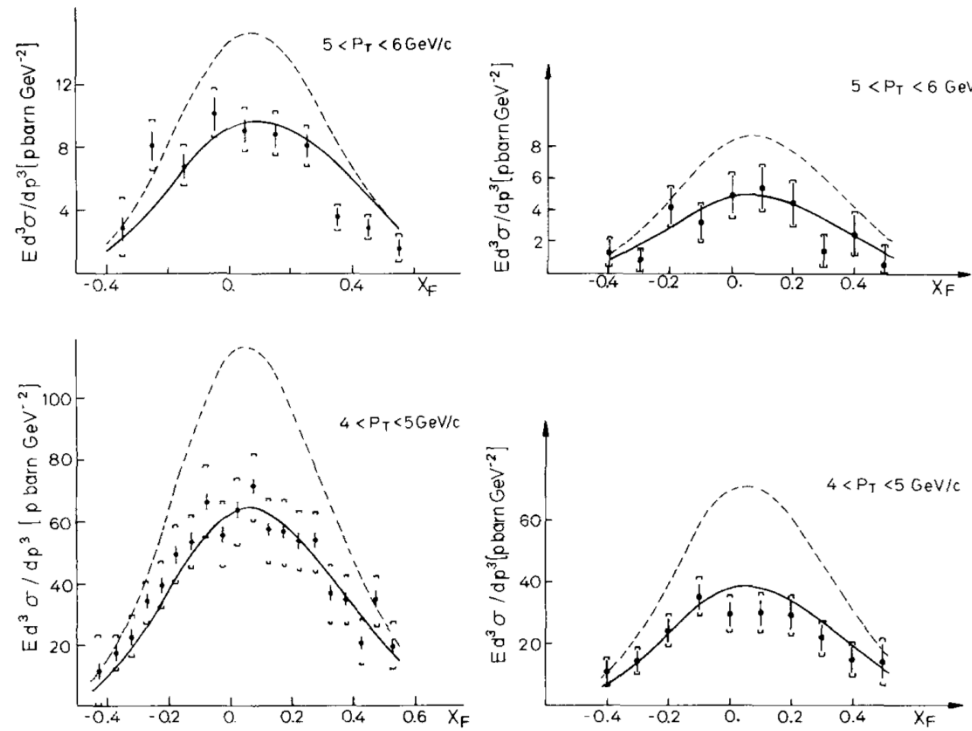
$$xg^{\pi}(x) = A_g^{\pi}(1-x)^{\eta}$$

$$\eta \approx 2.1$$

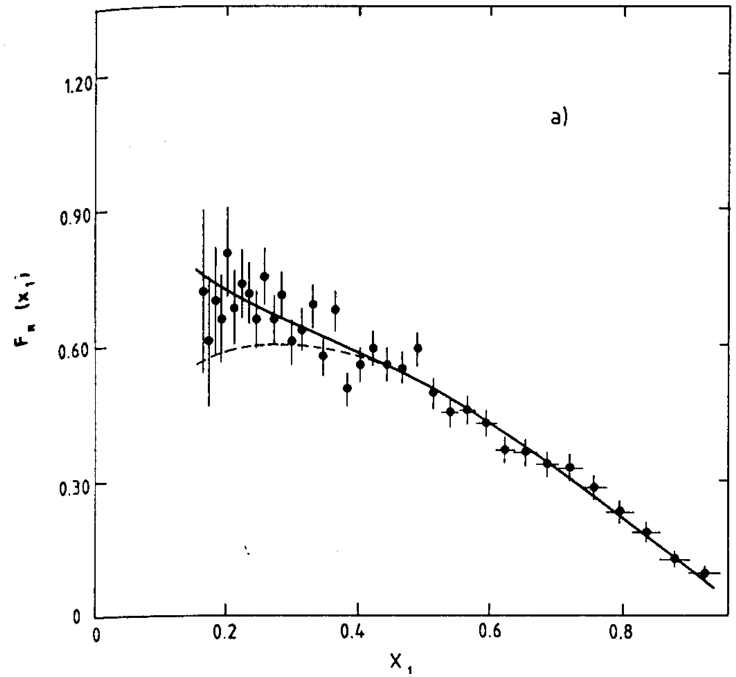
$$G_\pi \equiv \int_0^1 xg_\pi(x)dx = 0.47$$

SMRS, PR**D45** 2349 (1992)





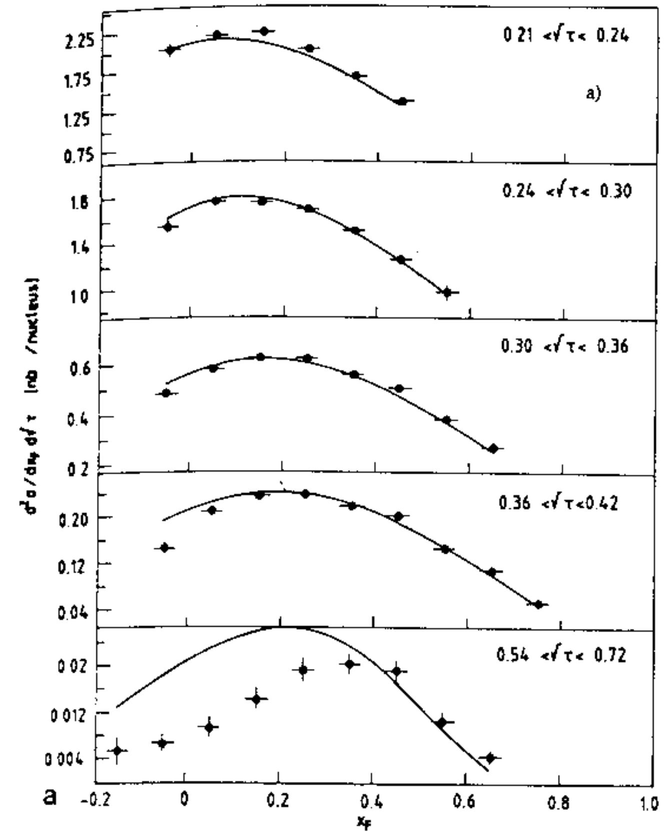
Pion Drell-Yan Data: CERN NA3 ($\pi^{\S}$) NA10 (π^-)



NA3 200 GeV π^- data (also have 150 and 180 GeV π^- and 200 GeV π^+ data).

Can determine pion sea!

$$Q_\pi^{\rm sea} \equiv \int_0^1 x q_\pi^{\rm sea}(x) dx = 0.01$$



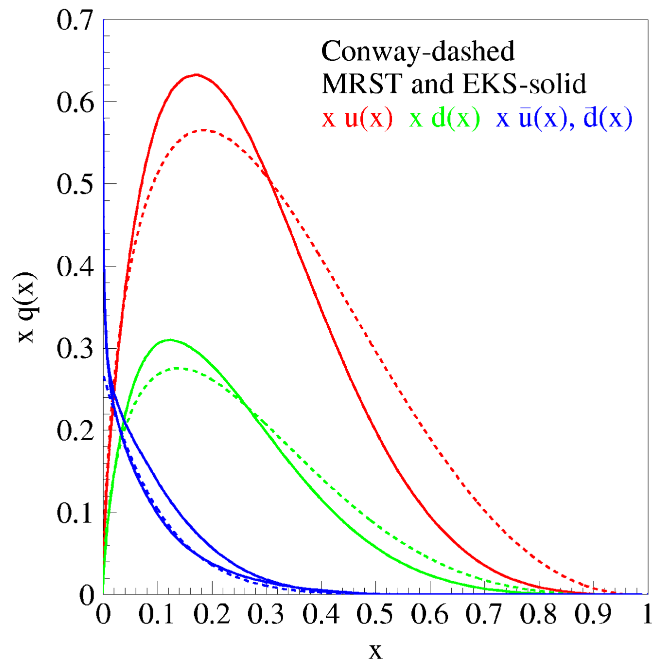
NA10 194 GeV π^- data

Could it be a problem with the treatment of the raw data?

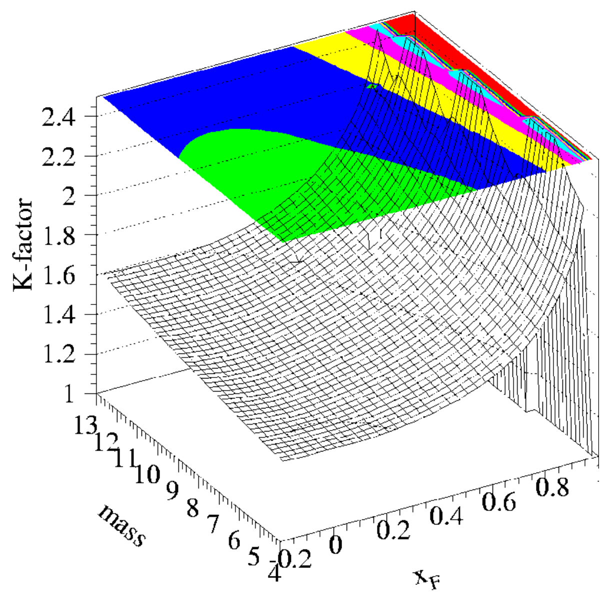
- More flexible parameterization (Hecht *et al.)*
- Modern **Proton** PDF w/nuclear corrections
- Inclusion of NLO terms rather than K-Factor
  - Look at 800 GeV *proton-proton* Drell-Yan:

$$xu_v(x) = A_0 x^\alpha (1-x)^\beta$$

$$xu_v(x) = A_0 x^\alpha (1-x)^\beta \times \left(1 - \epsilon\sqrt{x} + \gamma x\right)$$



Proton-proton K-factor is not constant at high x_F (high x_π)!



- Higher twist terms?

Fit of Drell-Yan Data in NLO

- Number of valence quarks [defines normalization on $q_\pi^{v}(x)$]:

$$\int_0^1 q_\pi^{v}(x)dx = 1$$

- Total momentum conservation:

$$2\int_0^1 xq_\pi^{v}(x)dx + 6\int_0^1 xq_\pi^{sea}(x)dx + G_\pi = 1$$

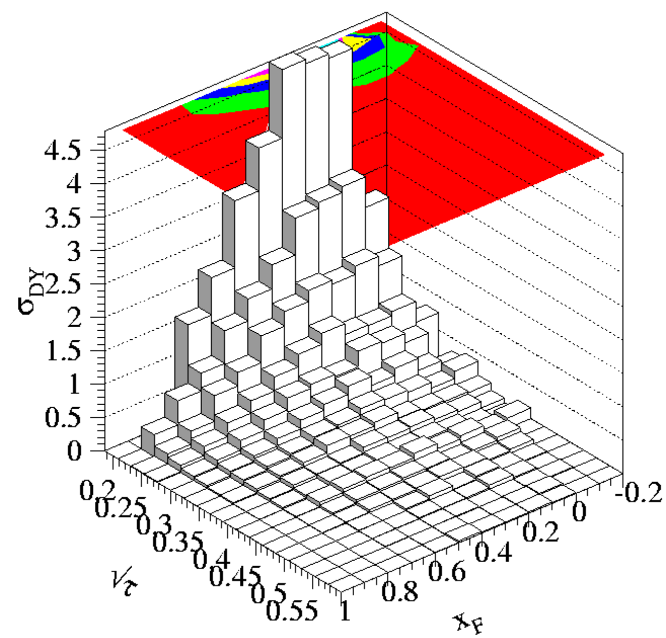
- Gluon content determined from other data (NA3/10 and WA80 direct photon)

$$G_\pi = \int_0^1 xg_\pi(x)dx = 0.47$$

- Sea quark parameterization from fits to π^+/π^- Drell-Yan data

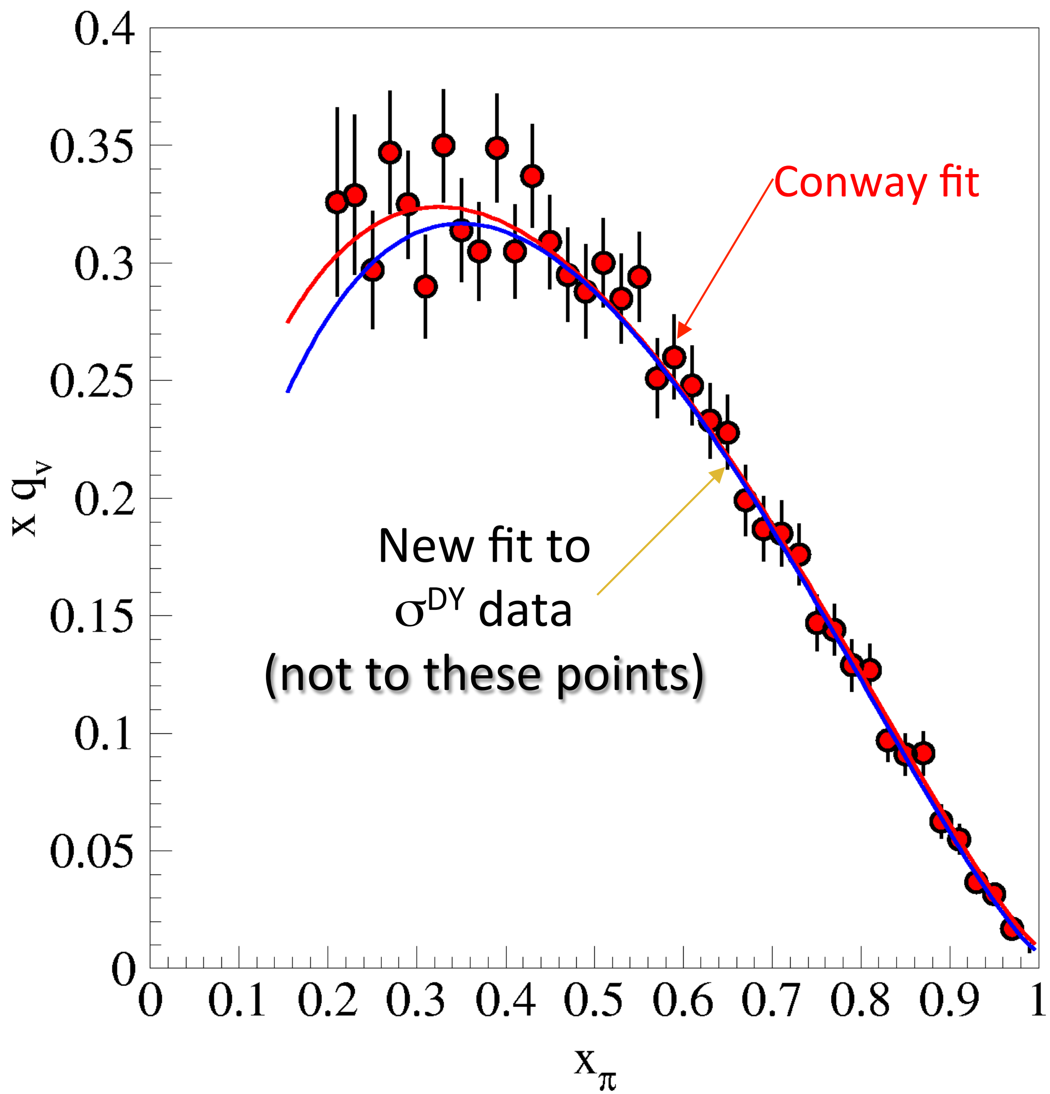
$$xq_\pi^{sea}(x) = A_\pi^{sea}(1-x)^\delta$$

$$\delta = 8.4$$

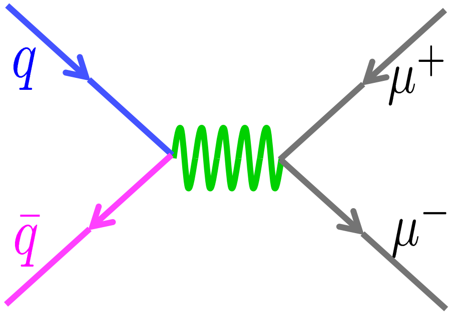


What did we learn?

- Even with new freedom from parameterization, curve does not change.
- Weak higher twist effects.
- Data do NOT prefer convex-up shape at high-x_π as required by DSE analysis!
- But this is not the end of the story!



Soft Gluon Resummation



$$\frac{d\sigma}{dQ^2 d\eta} = \sigma_0 \sum_{a,b} \int_{x_1^0}^{1} \frac{dx_1}{x_1} \int_{x_2^0}^{1} \frac{dx_2}{x_2} \left[q_a^{\pi}(x_1) q_b^{p}(x_2) \times \omega_{ab}\left(x_1, x_1^0, x_2, x_2^0, Q/\mu\right) \right]$$

- ω_{ab} is hard scattering function
- Resum large logarithmic "soft" gluon contributions which arise as

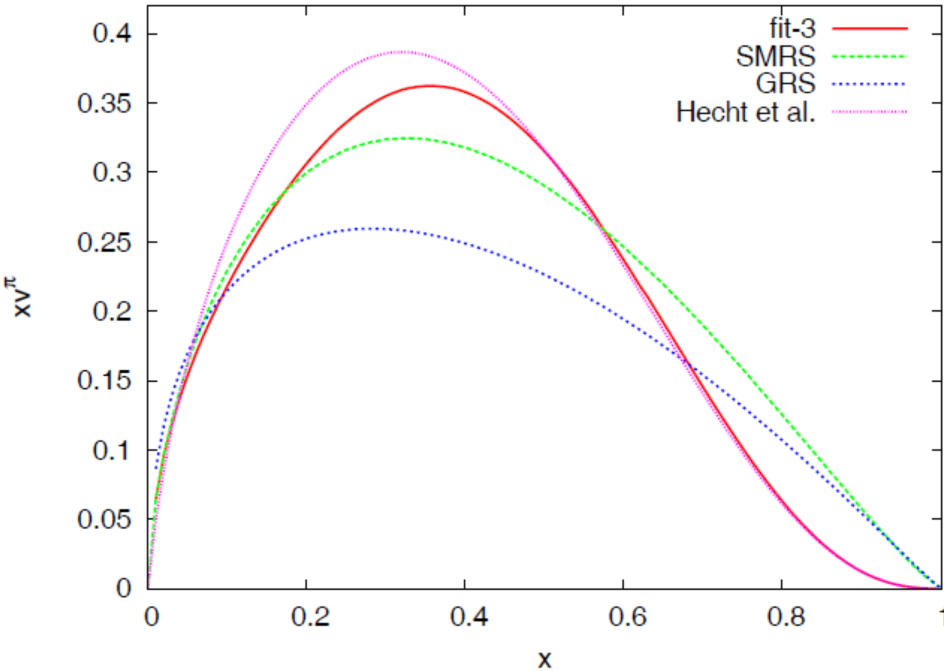
$$z = \frac{Q^2}{\hat{s}} = \frac{\tau}{x_1 x_2} \to 1$$

- Accc ellin and Fourier transform of the cross section

  Aicher, Schäfer and Vogelsang, arXiv:1009.2481

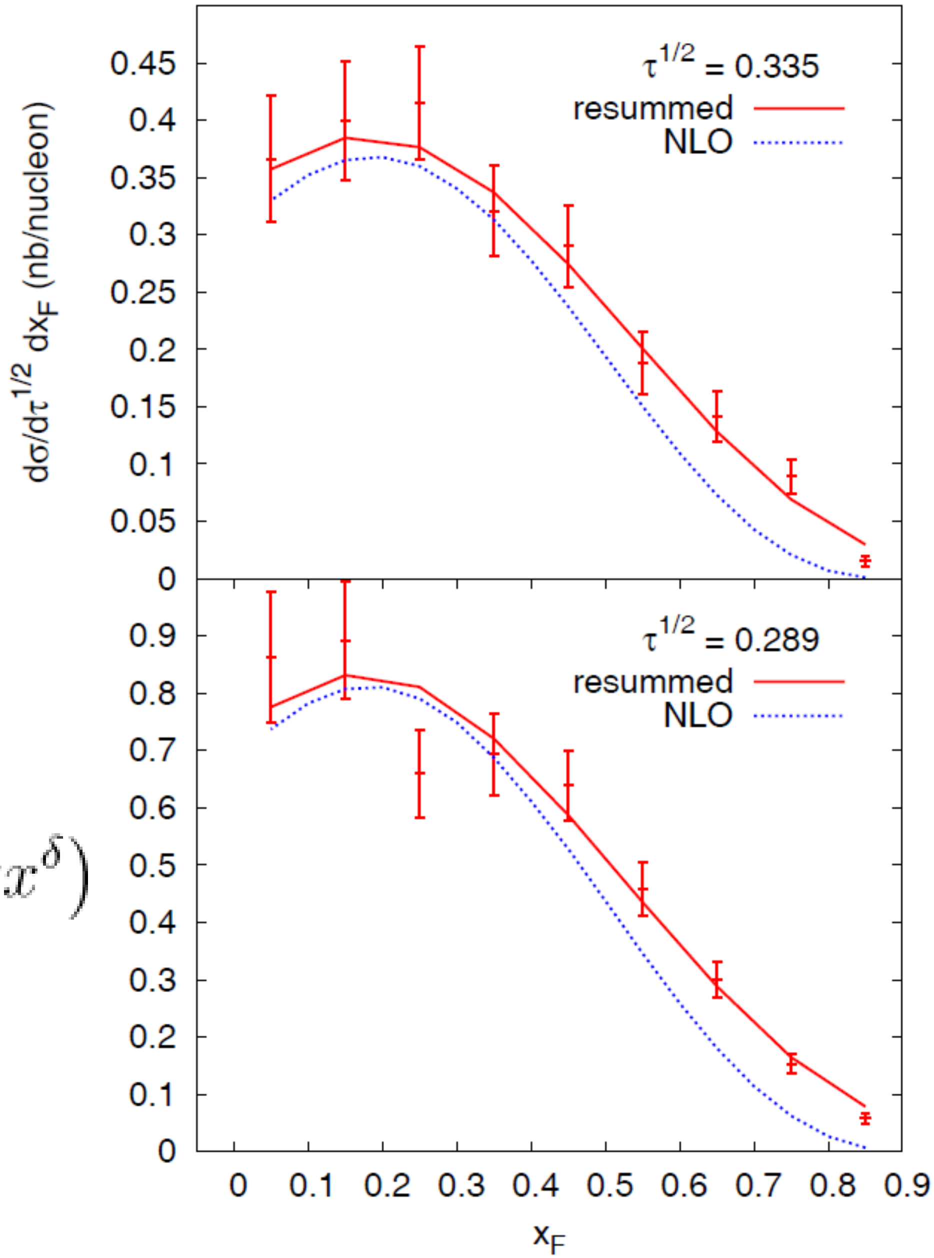
- Refit of pion Drell-Yan data

Soft Gluon Resummation



$$xq_V^{\pi}(x) = A_V^{\pi} x^{\alpha} (1-x)^{\beta} \left(1+\gamma x^{\delta}\right)$$

β = 2.03 ±0.06



QCD and Dyson-Schwinger survive!

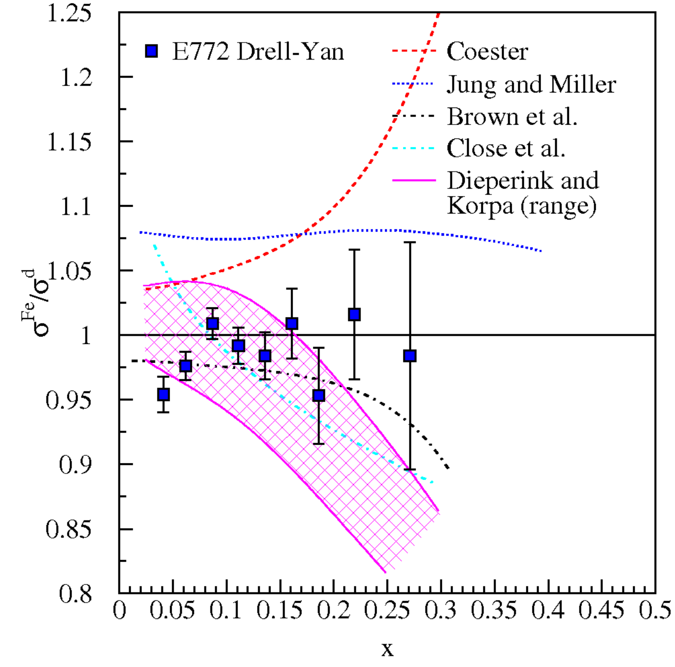
pQCD: $xq(x)/(1-x)^{\beta}$ β = 2

DSE: $xq(x)/(1-x)^{\beta}$ β ¼ 1.9

Review

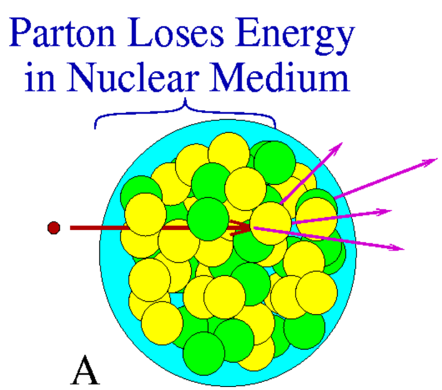
Nuclear parton distributions are different from nucleon parton distributions

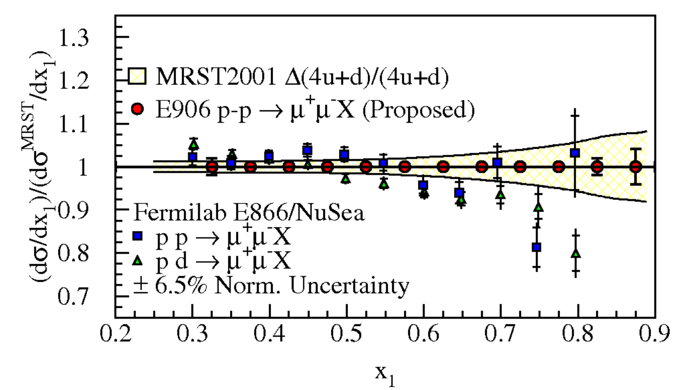
- The change depends on shadowing, nuclear binding and Fermi motion,
- It is different for "valence" and "sea" distributions
- We don't understand it, we can only measure it.



Drell-Yan is a useful probe for other things:

- Partonic energy loss
- Valence quark distributions
- Meson quark distributions





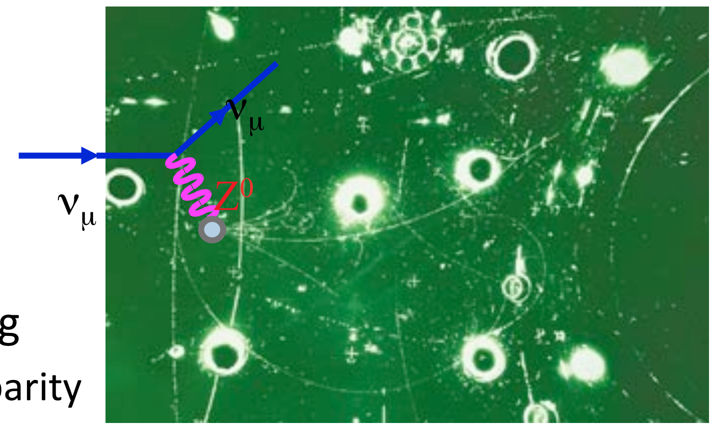
The Standard Model, electroweak interactions and parity

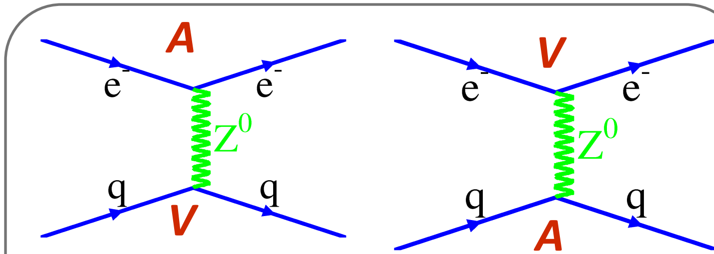
Paul E. Reimer
Physics Division, Argonne National Laboratory
HUGS, 4-22 June 2012

$$A_{\rm PV} = \frac{\sigma^r - \sigma^l}{\sigma^r + \sigma^l} = -A_{\rm LR}$$
$$= \frac{\mathcal{M}^r_{\rm weak} - \mathcal{M}^l_{\rm weak}}{\mathcal{M}_{\rm em}} \approx 10^{-4} Q^2 ({\rm GeV})^2$$

Really—two separate topics unified by my interests

I. Flavor Structure of the Proton
   A. Proton structure—historical view
   B. Sea quarks in the proton & the Drell-Yan reaction
   C. Proton structure in nuclei
II. Measurements of Parity Violation in Electron Scattering
   A. The Standard Model, electroweak interactions and parity
      1. Parity conservation and violation
      2. The Standard Model
      3. PV in electron scattering
   B. Tests of the Standard Model with parity violation
   C. Nuclear Structure with Parity Violation





$$C_{1i} \equiv 2 g_A^e g_V^i \qquad C_{2i} \equiv 2 g_V^e g_A^i$$

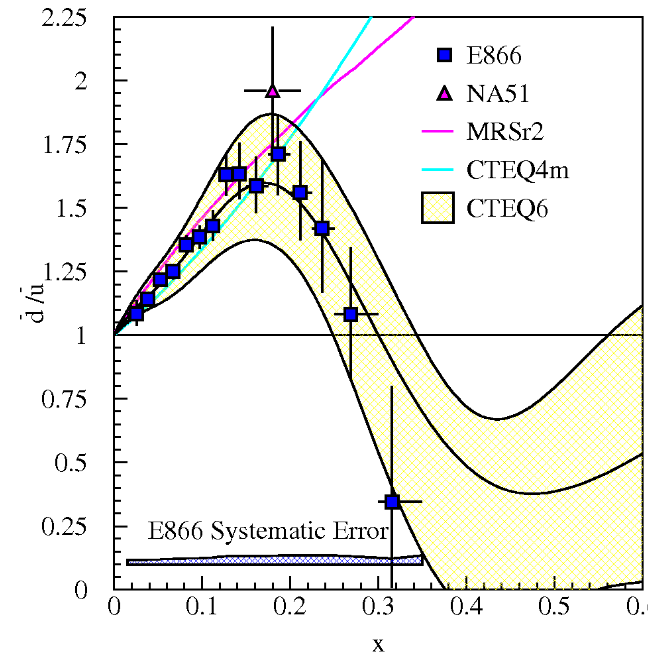
Review

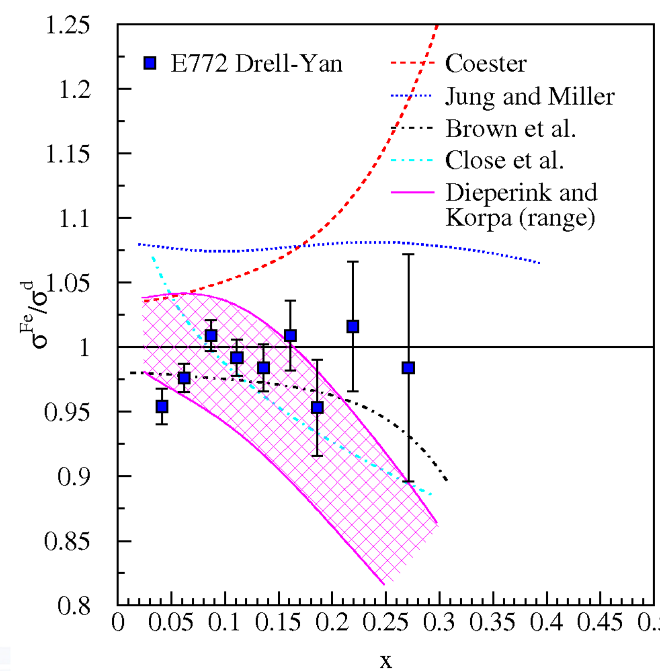
The last two days, I've discussed

- Parton distribution and how to measure them using electromagnetic probes (DIS and Drell-Yan) and how these distributions are measured (and not calculated)

- Models of how the sea quarks are created and how we really don't know if any are correct based on the flavor asymmetry in the sea (dbar/ubar)

- How the parton distributions are observed to change when the nucleon is put into a nucleus (and how we really don't know why).





Remember—I' m not the expert here.

P, C, and T symmetries

$$\vec{x} \to -\vec{x}, \quad \vec{p} \to -\vec{p},$$
$$\vec{L} \to \vec{L}, \quad \vec{s} \to \vec{s},$$

Parity Operator P

$$P|\psi(\vec{r},t)\rangle = |\psi(-\vec{r},t)\rangle$$

The parity group has only two elements {P, I}

$$P^2\psi(\vec{r},t) = P\psi(-\vec{r},t) = \psi(\vec{r},t)$$

If the Hamiltonian is invariant under party, the π is conserved and observable

$$[H,P] = 0 \Longrightarrow P\psi(\vec{r},t) \equiv \psi(-\vec{r},t) = \pi\psi(\vec{r},t) \qquad \pi = \pm 1$$

Charge Conjugation Operator

All quantum numbers flip sign except mass and spin

$$C|\psi(\vec{r},t)\rangle = |\bar{\psi}(\vec{r},t)\rangle$$

Only particles that are its own anti-particles are eigenstates of C

The charge conjugation group also only has two elements {C, I}

Time Reversal

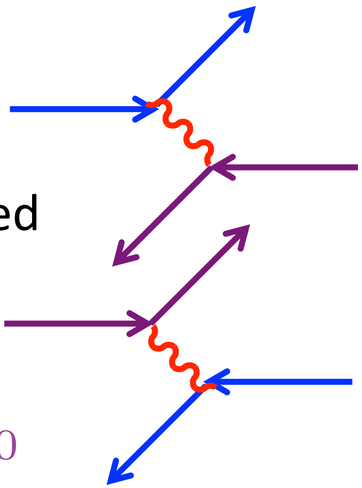
$$T|\psi(\vec{r},t)\rangle = |\psi(\vec{r},-t)\rangle$$

Time Reversal reactions are reversible in principle if T is conserved

P, C, and T conservation

- Particles have intrinsic parity, classified by J^{π}

Particle	π	ρ	f_2	K	J/ψ	. . .
J^{π}	0^-	1^-	2^+	0^-	1^-	$-(-1)^L$



- Historically, P, C and T were believed to be individually conserved

  Why not? Shouldn't these two interactions be the same?

- $\tau - \theta$ puzzle—Two particles with same mass, but opposite parity

$$\theta^+ \to \pi^+\pi^0 \qquad \tau^+ \to \pi^+\pi^0\pi^0$$

$$P = (-1)(-1) = +1 \qquad P = (-1)(-1)(-1) = -1$$

T.D. Lee and C. N. Yang Phys. Rev. **104**, 254–258 (1956) ***propose*** that this is the same particle, formed in STRONG interactions where parity is conserved and decaying via a WEAK interaction where parity is not conserved.

Question of Parity Conservation in Weak Interactions*

T. D. Lee, *Columbia University, New York, New York*

AND

C. N. Yang,† *Brookhaven National Laboratory, Upton, New York*
(Received June 22, 1956)

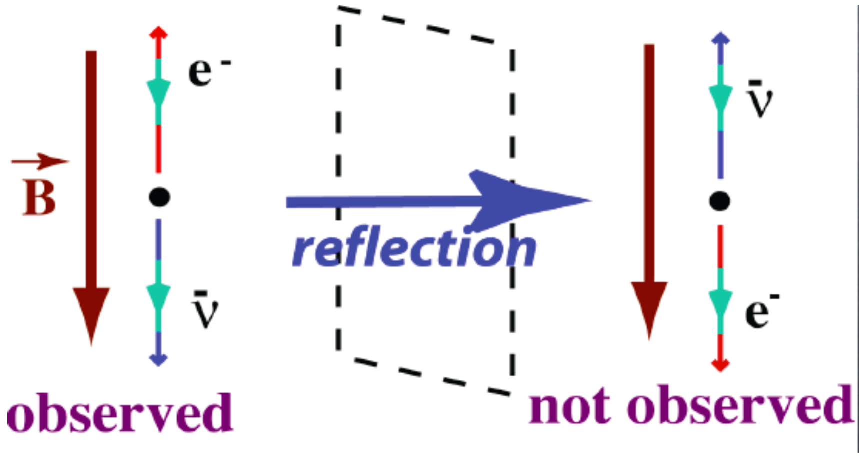
To be more specific, let us consider the allowed β transition of any oriented nucleus, say Co^{60}. The angular distribution of the β radiation is of the form (see Appendix):

$$I(\theta)d\theta = (\text{constant})(1+\alpha\cos\theta)\sin\theta d\theta, \qquad (2)$$

where α is proportional to the interference term CC'. If $\alpha \neq 0$, one would then have a positive proof of parity nonconservation in β decay. The quantity α can be obtained by measuring the fractional asymmetry between $\theta < 90°$ and $\theta > 90°$; i.e.,

$$\alpha = 2\left[\int_0^{\pi/2} I(\theta)d\theta - \int_{\pi/2}^{\pi} I(\theta)d\theta\right] \Big/ \int_0^{\pi} I(\theta)d\theta.$$

It is noteworthy that in this case the presence of the magnetic field used for orienting the nuclei would automatically cause a spatial separation between the electrons emitted with $\theta < 90°$ and those with $\theta > 90°$.



Discovery (1st Observation) of parity violation

C.S. Wu *et al.* Phys. Rev. **105**, 1413–1415 (1957)

- Observation of β decay of ^{60}Co nuclei aligned in a magnetic field show anisotrophy

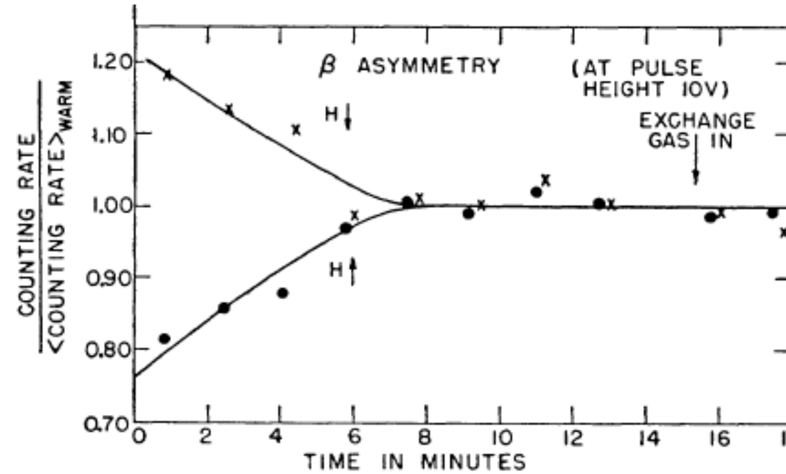
Experimental Test of Parity Conservation in Beta Decay*

C. S. Wu, *Columbia University, New York, New York*

AND

E. Ambler, R. W. Hayward, D. D. Hoppes, and R. P. Hudson, *National Bureau of Standards, Washington, D. C.*

(Received January 15, 1957)



- Polarized ^{60}Co cooled to 0.01K and looked for asymmetry in angular distribution between θ and 180°-θ relative to spin direction

- Lee and Yang also pointed out this was evidence for C violation

- Aside, the τ^+ and θ^+ are now both accepted to be the K^+

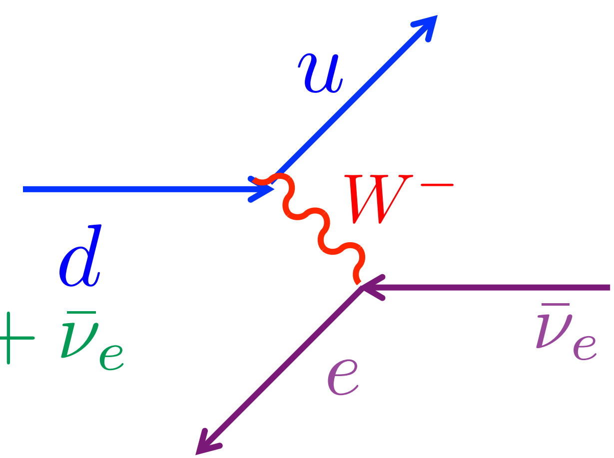
The Standard Model

Graphics: ParticleAdventure.org

Force	Gravity	Weak	Electromagnetic	Strong
		(Electroweak)		
Carried By	Graviton (not yet observed)	W^+, W^-, Z^0	Photon	Gluon
Acts on	All	Quarks and Leptons	Quarks, Charged Leptons, W^+, W^-	Quarks and Gluons
Couples to	Mass	Weak Charge	Electric Charge	Color

β decay is mediated by the W

$$n \to p + e + \bar{\nu}_e \text{ or } d \to u + e + \bar{\nu}_e$$



The Standard Model

BOSONS force carriers
spin = 0, 1, 2, …

Unified Electroweak spin = 1		
Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	−1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1		
Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Both Gluons and Quarks also carry color charge, but color charge is not tied to the flavor quantum number

FERMIONS matter constituents
spin = 1/2, 3/2, 5/2, …

Leptons spin = 1/2		
Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	−1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	−1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	−1

Quarks spin = 1/2		
Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	−1/3
c charm	1.3	2/3
s strange	0.1	−1/3
t top	175	2/3
b bottom	4.3	−1/3

Neutrinos have neither electric charge nor color charge and so can only interact through the weak force.

Graphics: ParticleAdventure.org

V-A interaction

- Electromagnetic interaction between two charged particles is a Vector-Vector interaction:

$$\mathcal{M}_{\rm em} = (e\bar{u}_p\gamma^\mu u_p)\,\frac{-1}{q}\,(-e\bar{u}_e\gamma_\mu u_e)$$

- Empirically Parity Violation was observed in beta decay—Weak Interaction.
  - A V-V interaction will not violate parity
  - V-A will violate parity, making the matrix

$$J^{\mu\dagger} = \bar{u}_e\gamma^\mu\frac{1}{2}\left(1-\gamma^5\right)u_\nu$$

- C.S. Wu *et al.*'s measurement of parity violation can only be explained with a right-handed antineutrino and an left handed electron!
- No right handed neutrinos have been observed

V-A interaction

- Only left handed particles (right handed antiparticles participate in weak interactions
  - neutrinos only interact weakly so that only ν_l will appear,
  - assuming they are massless (which they are not)

$$\begin{pmatrix} e_l^- \\ \nu_l \end{pmatrix} \quad \begin{pmatrix} e_r^+ \\ \bar{\nu}_r \end{pmatrix}$$

  - For massive particles, you can always “run” faster than the particle and hence observe it with a reversed spin (OK, boost to a frame in which . . .)

Weinberg-Salam model (AKA the Standard Model) and $\sin^2(\theta_W)$

Unification of Weak and E&M Force
- SU(2)—weak isospin—Triplet of gauge bosons
- U(1)—weak hypercharge—Single gauge boson

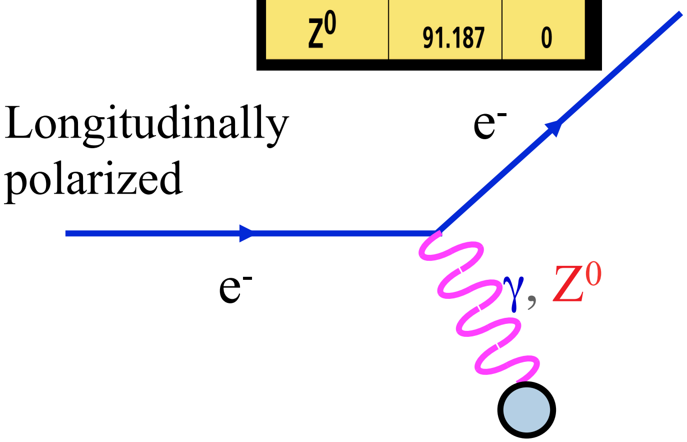
BOSONS		
Unified Electroweak spin = 1		
Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	–1
W^+	80.4	+1
Z^0	91.187	0

Electroweak Lagrangian:

$$\mathcal{L} = g\vec{J}_\mu \cdot \vec{W}_\mu + g' J^Y_\mu B_\mu$$

$$J^Y_\mu = J^{\rm EM}_\mu - J^{(3)}_\mu$$

J_μ, J^Y_μ isospin and hypercharge currents
g, g' couplings between currents and fields



$$\begin{aligned} W^\pm_\mu &= \tfrac{1}{\sqrt{2}}\left(W^{(1)}_\mu \pm iW^{(2)}_\mu\right) && \text{Weak CC} \\ A_\mu &= \frac{1}{\sqrt{g^2+g'^2}}\left(g'W^{(3)}_\mu + gB_\mu\right) && \text{EM NC} \\ Z^0_\mu &= \frac{1}{\sqrt{g^2+g'^2}}\left(g'W^{(3)}_\mu - gB_\mu\right) && \text{Weak NC} \end{aligned}$$

$$\sin^2\theta_W \equiv \frac{g'^2}{g'^2+g^2}$$

Weinberg-Salam model and $\sin^2(\theta_W)$

Standard Model parameters:

- Charge, e , α_{em}
- g , G_F μ lifetime
- M_Z
- $\sin^2(\theta_W)$

- Note that if θ = 0, then Z^0 will not couple to anything

Vector: $g^i_V = t_{3L}(i) - 2q_i \sin^2(\theta_W)$ — Charge

Axial: $g^i_A = t_{3L}(i)$ — Weak isospin

	Left	Right
γ **Charge**	$q = 0, \pm 1, \pm\frac{1}{3}, \pm\frac{2}{3}$	$0, \pm 1, \pm\frac{1}{3}, \pm\frac{2}{3}$
W Charge	$T = \pm\frac{1}{2}$	
Z Charge	$T - q\sin^2\theta_W$	$-q\sin^2\theta_W$

Parity Violation in Electron Scattering

Parity Conservation Violation and Electron Scattering

LETTERS TO THE EDITOR

PARITY NONCONSERVATION IN THE FIRST ORDER IN THE WEAK-INTERACTION CONSTANT IN ELECTRON SCATTERING AND OTHER EFFECTS

Ya. B. ZEL'DOVICH

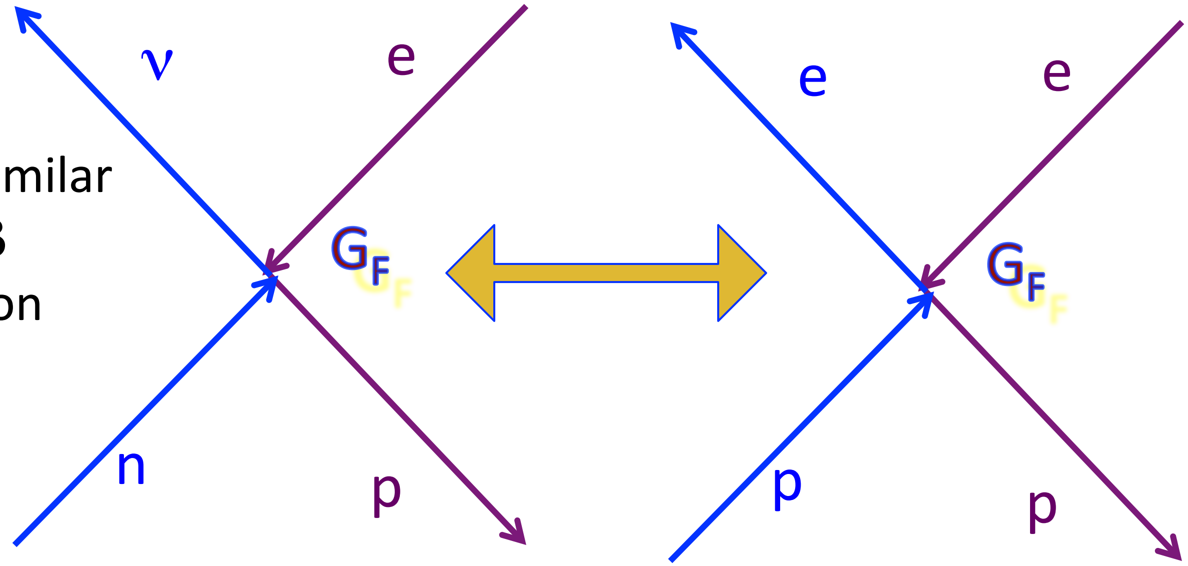
Submitted to JETP editor December 25, 1958

J. Exptl. Theoret. Phys. (U.S.S.R.) **36**, 964–966 (March, 1959)

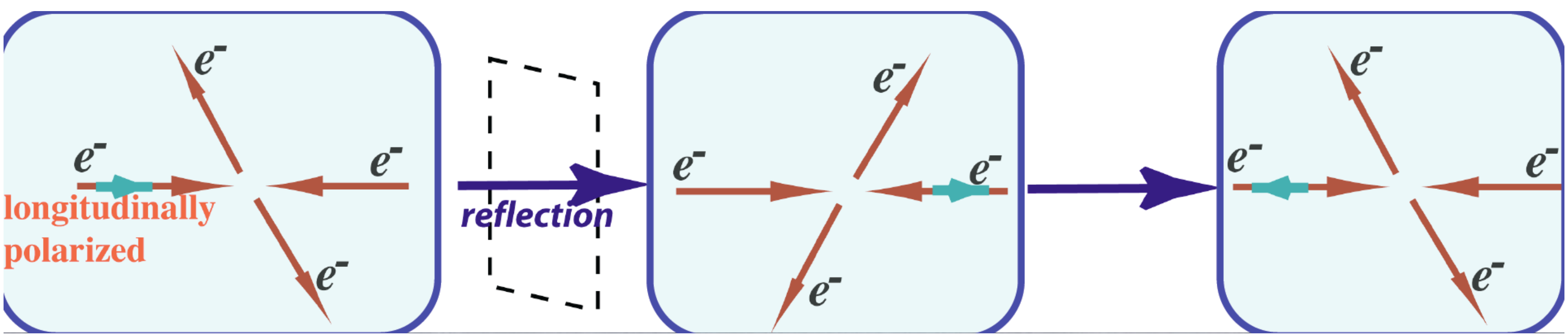
Proposes that electron scattering should have measureable parity violating asymmetry

Zel'dovich

- Postulates interaction similar to that responsible for β decay to occur in electron scattering
- What would this imply?



- Argues cross sections for scattering left and right handed electrons could differ



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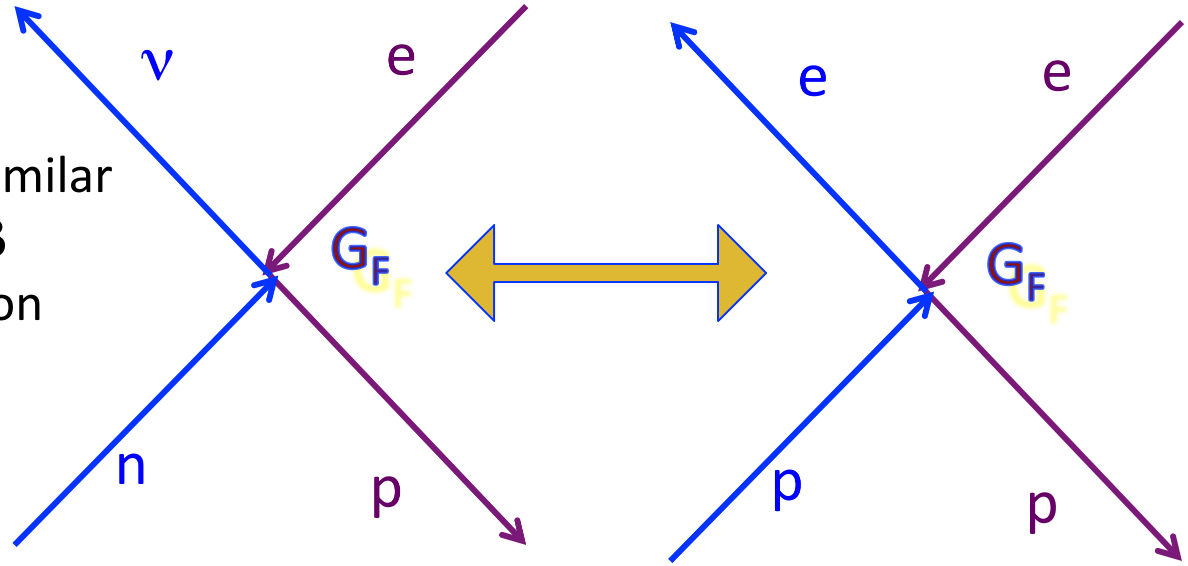


- What would this imply?
- Argues cross sections for scattering left and right handed electrons could differ

$$\sigma^l \propto |\mathcal{M}_{\rm em} + \mathcal{M}^l_{\rm weak}|^2 \qquad \sigma^r \propto |\mathcal{M}_{\rm em} + \mathcal{M}^r_{\rm weak}|^2$$

$$\approx |\mathcal{M}_{\rm em}|^2 + 2\mathcal{M}_{\rm em}\mathcal{M}^l_{\rm weak} + |\mathcal{M}^l_{\rm weak}|^2$$

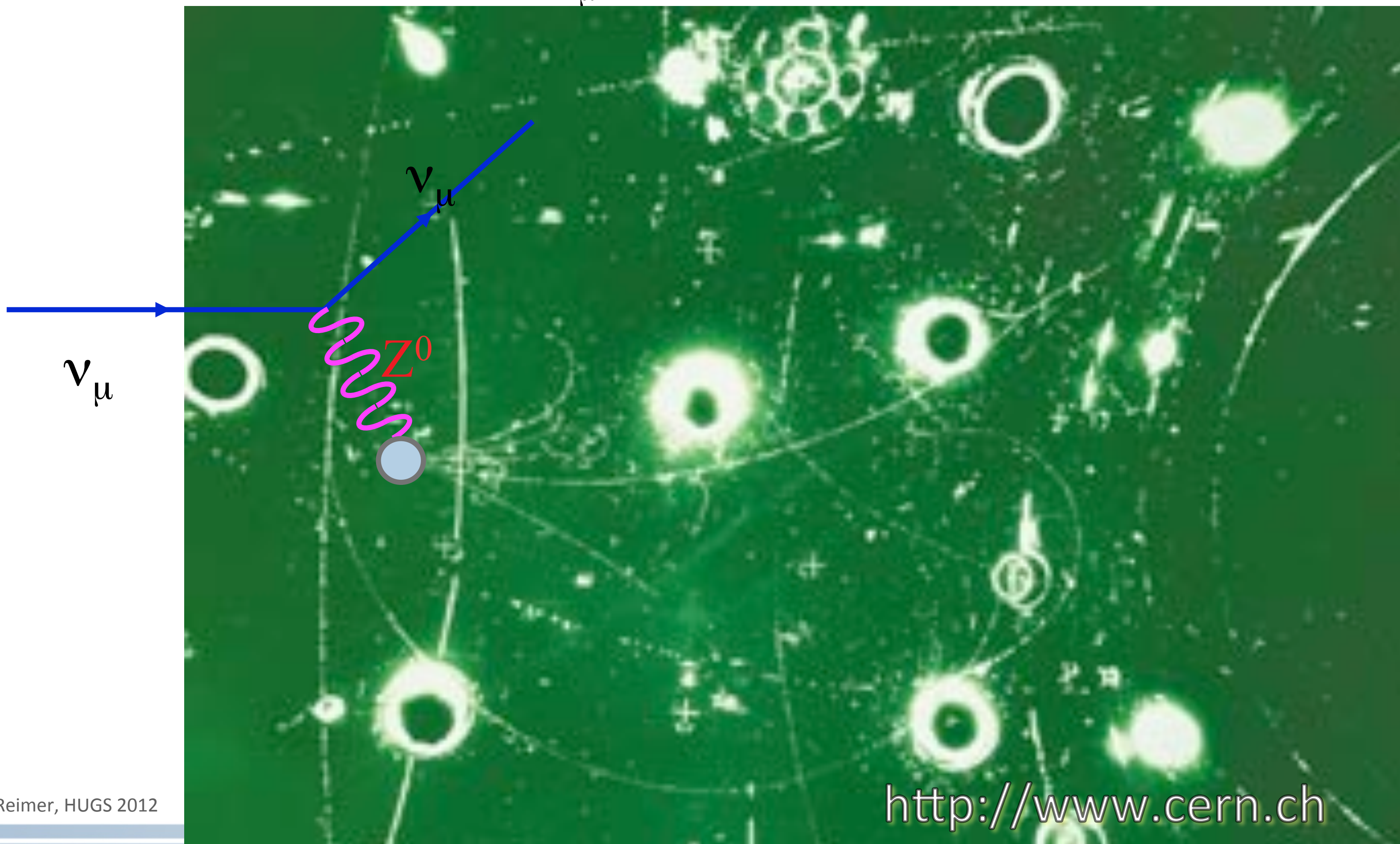
Large ($\mathcal{M}_{\rm em}$) Tiny ($\mathcal{M}_{\rm weak}$)

$$A_{\rm PV} = \frac{\sigma^r - \sigma^l}{\sigma^r + \sigma^l} = -A_{\rm LR}$$

$$= \frac{\mathcal{M}^r_{\rm weak} - \mathcal{M}^l_{\rm weak}}{\mathcal{M}_{\rm em}} \approx 10^{-4} Q^2 ({\rm GeV})^2$$

Discovery of the weak neutral current Z^0

- Observation of the neutral weak current by Gargamelle bubble chamber at CERN
- ν_μ (not seen but in the beam) and ν_μ (unseen) out and a n*



Parity Violation in Electron Scattering Realized

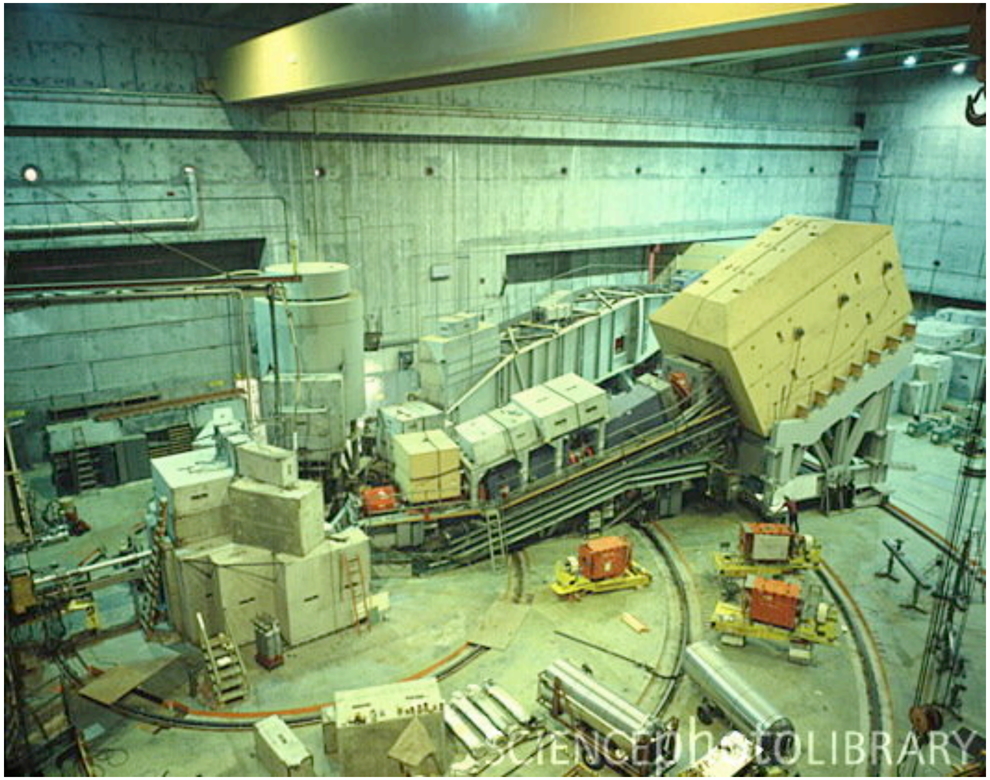
Basic question: Was the Weinberg Salam model correct?

- "High quality" polarized electron beam
- SLAC E122

$$\begin{pmatrix} \nu \\ e \end{pmatrix}_l \quad (e)_r$$

or

$$\begin{pmatrix} \nu \\ e \end{pmatrix}_l \quad \begin{pmatrix} E^0 \\ e \end{pmatrix}_r$$

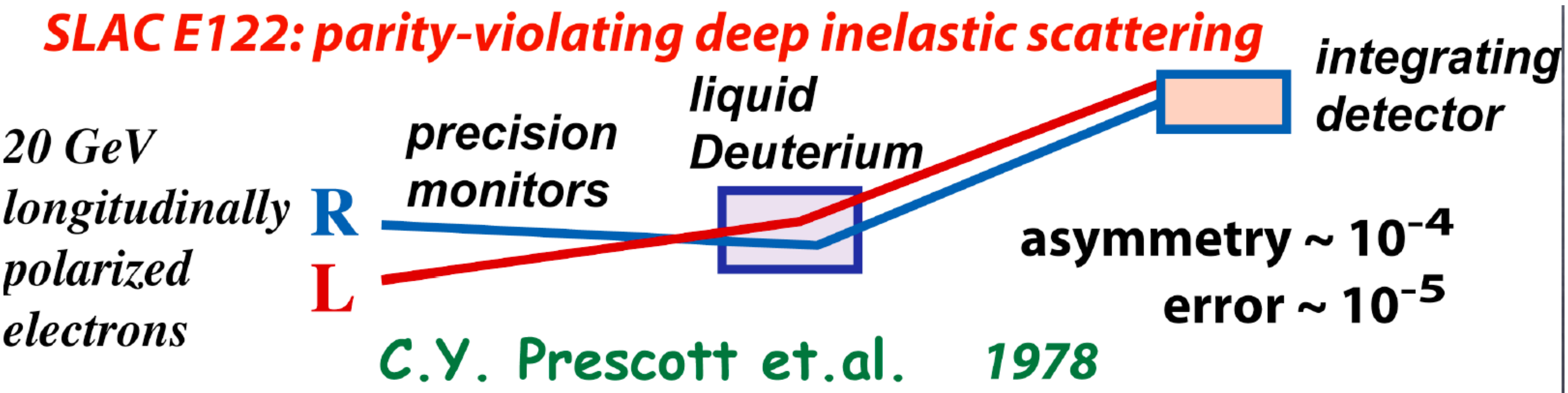


Aside: Same spectrometer that discovered proton substructure

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{point}} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}}$$

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{point}} |F(q)|^2 \qquad = \frac{(Z\alpha)^2 E^2}{2k^4 \sin^4 \frac{\theta}{2}} \left(1 - \frac{k}{E} \sin^2 \frac{\theta}{2}\right)$$

Basic concept of all electron parity violation measurements



- Scatter left and right polarized electrons from target
- Count/measure (frequently integrating) number scattered into specific solid angle
- **Keep systematic effects in control**
- Form asymmetry and publish

PVDIS variables

Weak PV

Electromagnetic

Kinematic factor

$$A_{\text{iso}} = \frac{\sigma^l - \sigma^r}{\sigma^l + \sigma^r} \approx \frac{\mathcal{M}^l_{Z^0} - \mathcal{M}^r_{Z^0}}{\mathcal{M}_\gamma}$$

$$\propto -\left(\frac{G_F Q^2}{4\pi\alpha}\right)\left(g^e_A g^T_V + \beta g^e_V g^T_A\right)$$

- The couplings g depend on electroweak physics as well as on the weak vector and axial-vector hadronic current.
- Both new physics at high energy scales as well as interesting features of hadronic structure come into play.

PVDIS variables

Cahn and Gilman, PRD **17** 1313 (1978) polarized electrons on deuterium

$$Y = \frac{1-(1-y)^2}{1+(1-y)^2 - y^2\frac{R}{R+1}}$$

$$R(x,Q^2) = \sigma^l/\sigma^r \approx 0.2$$

$$\begin{aligned} A_{\rm iso} &= \frac{\sigma^l - \sigma^r}{\sigma^l + \sigma^r} \\ &= -\left(\frac{3G_F Q^2}{\pi\alpha 2\sqrt{2}}\right)\frac{2C_{1u} - C_{1d}(1+R_s) + Y(2C_{2u} - C_{2d})R_v}{5+R_s} \\ &\approx 10^{-4}Q^2\ (\mathrm{GeV})^2 \end{aligned}$$

At $Q^2 = 1.9\ \mathrm{GeV}^2$, and asymmetry of 1.6×10^{-4}
Or 800 pixels in a 5 M pixel image

- easily measureable (at least when compared with PREx—*Measurement of the Neutron Skin of* ^{208}*Pb* —which proposed measuring 0.5×10^{-6} or 2.5 pixels)

PVDIS variables

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$$R_s(x) = \frac{2S(x)}{U(x)+D(x)} \xrightarrow{\text{Large } x} 0$$

$$R_v(x) = \frac{u_v(x)+d_v(x)}{U(x)+D(x)} \xrightarrow{\text{Large } x} 1$$

QCD

- Parton distributions (u, d, s, c)
- Charge Symmetry (CSV)
- Higher Twist (HT)
- Nuclear Effects (EMC)

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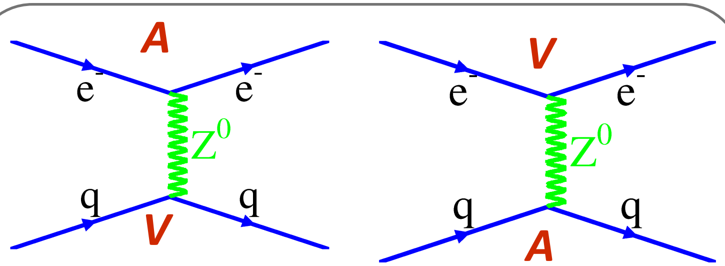

$$C_{1i} \equiv 2g_A^e g_V^i \qquad C_{2i} \equiv 2g_V^e g_A^i$$

$$R_s(x) = \frac{2S(x)}{U(x)+D(x)} \xrightarrow{\text{Large } x} 0$$

$$R_v(x) = \frac{u_v(x)+d_v(x)}{U(x)+D(x)} \xrightarrow{\text{Large } x} 1$$

$$\begin{aligned}
C_{1u} &= -\tfrac{1}{2}+\tfrac{4}{3}\sin^2\theta_W &\approx& -0.19\\
C_{1d} &= \tfrac{1}{2}-\tfrac{2}{3}\sin^2\theta_W &\approx& 0.35\\
C_{2u} &= -\tfrac{1}{2}+2\sin^2\theta_W &\approx& -0.04\\
C_{2d} &= \tfrac{1}{2}-2\sin^2\theta_W &\approx& 0.04
\end{aligned}$$

QCD

- Parton distributions (u, d, s, c)
- Charge Symmetry (CSV)
- Higher Twist (HT)
- Nuclear Effects (EMC)

1st Generation PV experiment in 1977

PARITY NON-CONSERVATION IN INELASTIC ELECTRON SCATTERING ☆

C.Y. PRESCOTT, W.B. ATWOOD, R.L.A. COTTRELL, H. DeSTAEBLER, Edward L. GARWIN, A. GONIDEC [1], R.H. MILLER, L.S. ROCHESTER, T. SATO [2], D.J. SHERDEN, C.K. SINCLAIR, S. STEIN and R.E. TAYLOR
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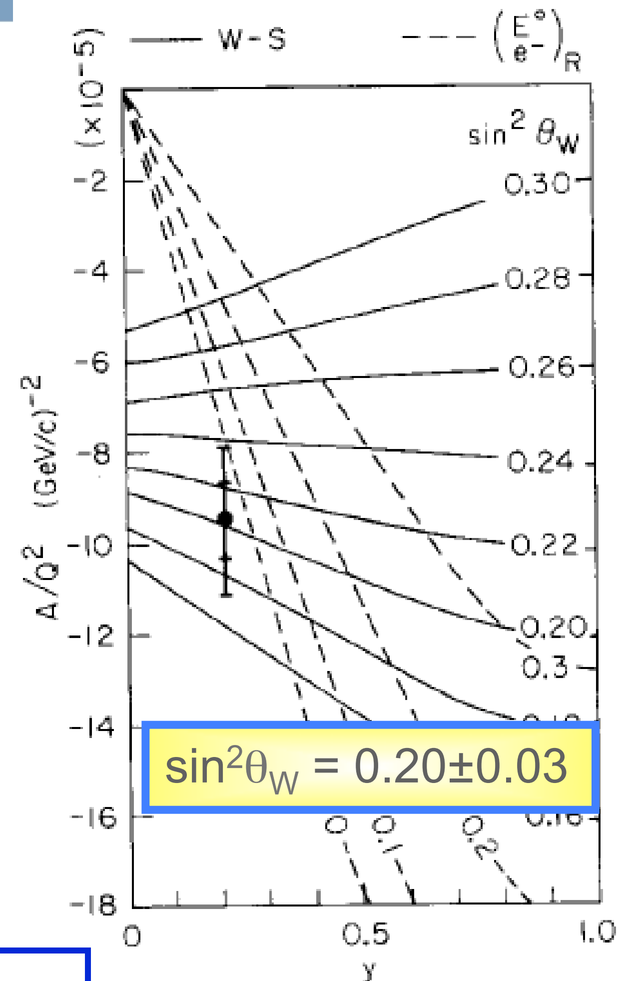
Phys. Lett. 77B, 347 (1979)

Received 14 July 1978



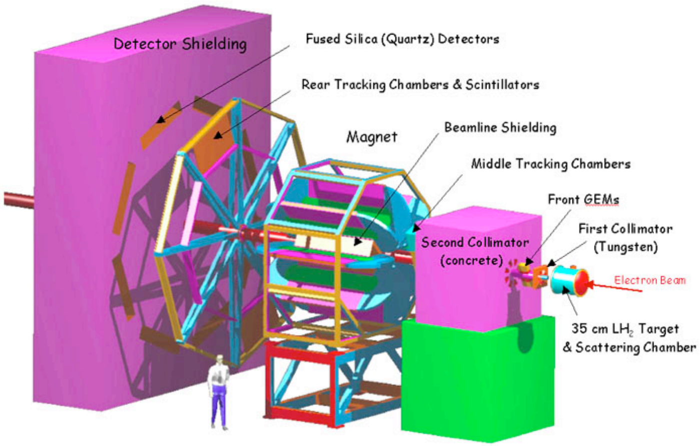
Abstract
We have measured parity violating asymmetries in the inelastic scattering of longitudinally polarized electrons from deuterium and hydrogen. For deuterium near $Q^2 = 1.6\ (GeV/c)^2$ the asymmetry is $(-9.5\times10^{-5})Q^2$ with statistical and systematic **uncertainties each about 10%**

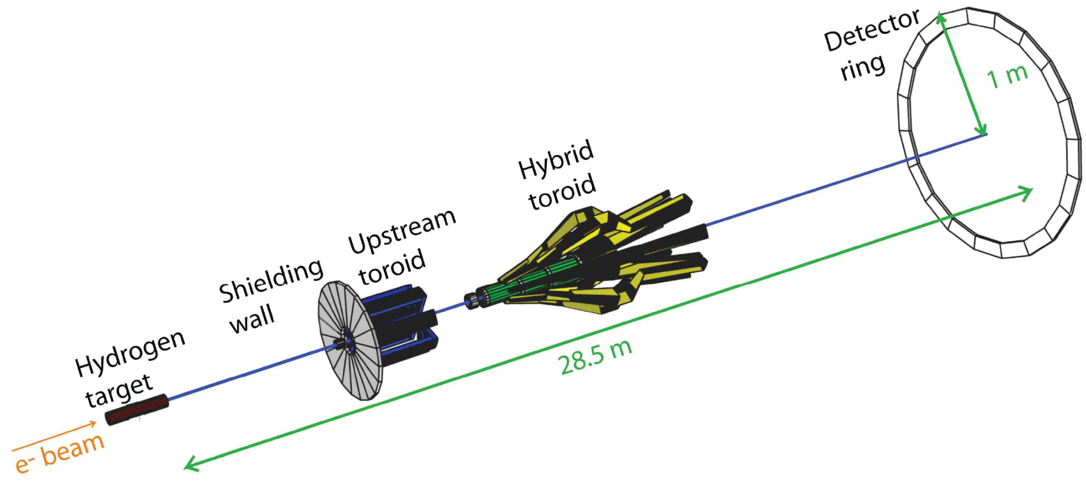
This experiment convinced the world that the Z-boson violated parity.

SLAC E122

- Proved that neutral weak current violated parity
- Won Nobel prize for Glashow, Weinberg and Salam—1979

- Pioneered techniques now commonly used here at JLab and elsewhere





Review

$$\vec{x} \to -\vec{x}, \quad \vec{p} \to -\vec{p},$$
$$\vec{L} \to \vec{L}, \quad \vec{s} \to \vec{s},$$

Parity Operator P

$$P|\psi(\vec{r},t)\rangle = |\psi(-\vec{r},t)\rangle$$

The parity group has only two elements {P, I}

$$P^2\psi(\vec{r},t) = P\psi(-\vec{r},t) = \psi(\vec{r},t)$$

If the Hamiltonian is invariant under party, the π is conserved and observable

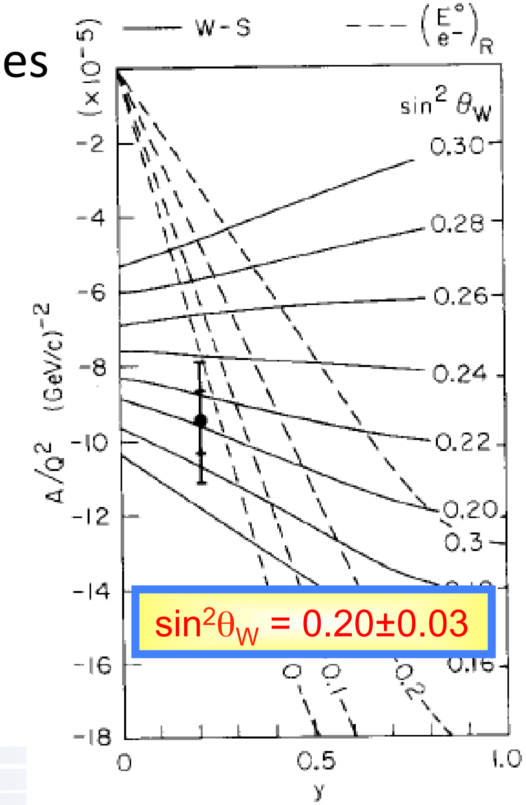
$$[H,P] = 0 \Longrightarrow P\psi(\vec{r},t) \equiv \psi(-\vec{r},t) = \pi\psi(\vec{r},t) \qquad \pi = \pm 1$$

- Gravitational, Strong and Electromagnetic forces conserve parity
- Weak Force does not conserve parity

Parity Violation in electron scattering:

- proposed by Zel'dovich
- requires neutral weak boson Z^0
- Realized at SLAC E122 (Prescott *et al.*)

$$\begin{pmatrix} \nu \\ e \end{pmatrix}_l \quad \left(e \right)_r$$

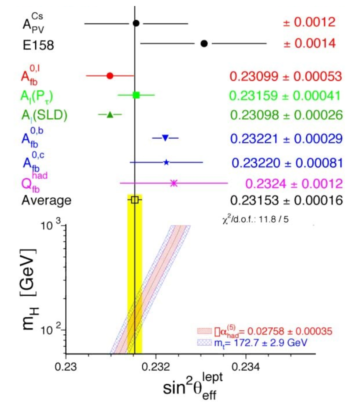


Tests of the Standard Model with Parity Violating Electron Scattering

Paul E. Reimer

Physics Division, Argonne National Laboratory

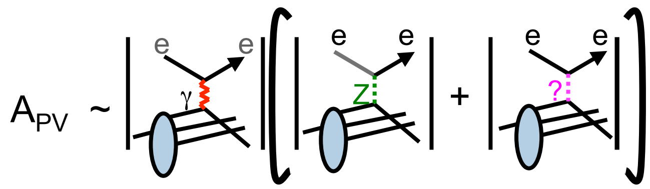
HUGS, 4-22 June 2012

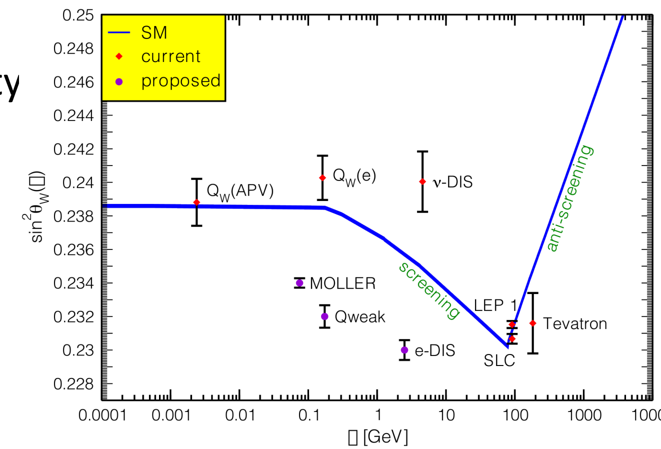


Really—two separate topics unified by my interests

I. Flavor Structure of the Proton
   - A. Proton structure—historical view
   - B. Sea quarks in the proton & the Drell-Yan reaction
   - C. Proton structure in nuclei

II. Measurements of Parity Violation in Electron Scattering
   - A. The Standard Model, electroweak interactions and parity
   - B. Tests of the Standard Model with parity violation
     1. Standard Model and running of $\sin^2\theta_W$
     2. Parity Violating Deep Inelastic Scattering revisited
     3. Moller Scattering
   - C. Nuclear Structure with Parity Violation





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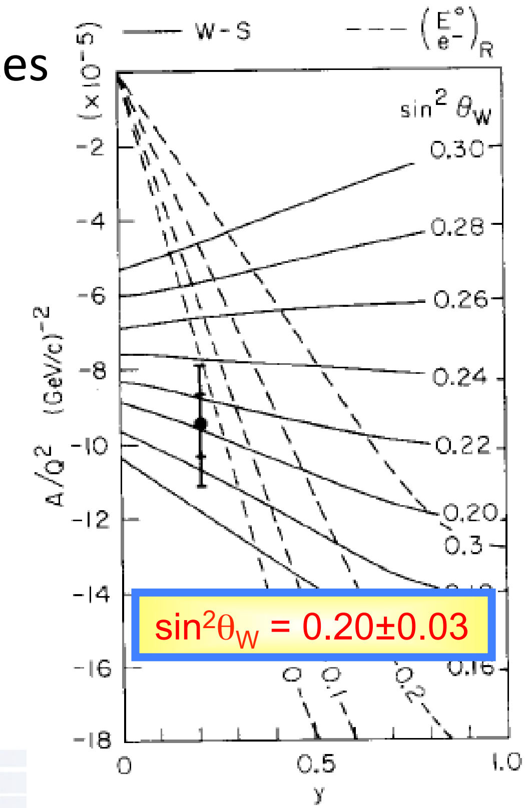
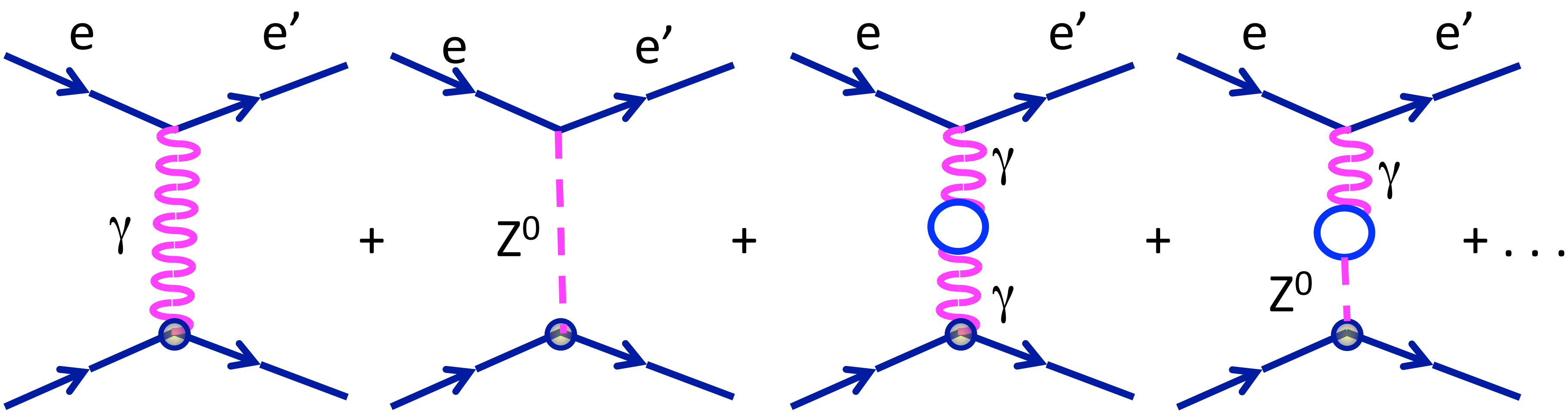


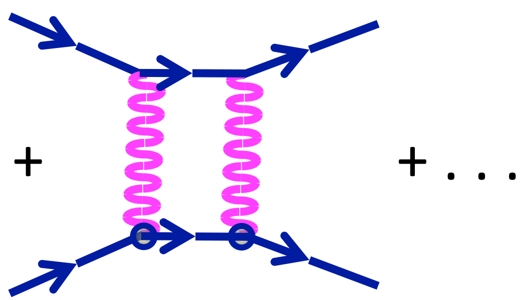
Electron Scattering



Dominate term at
“low” energy

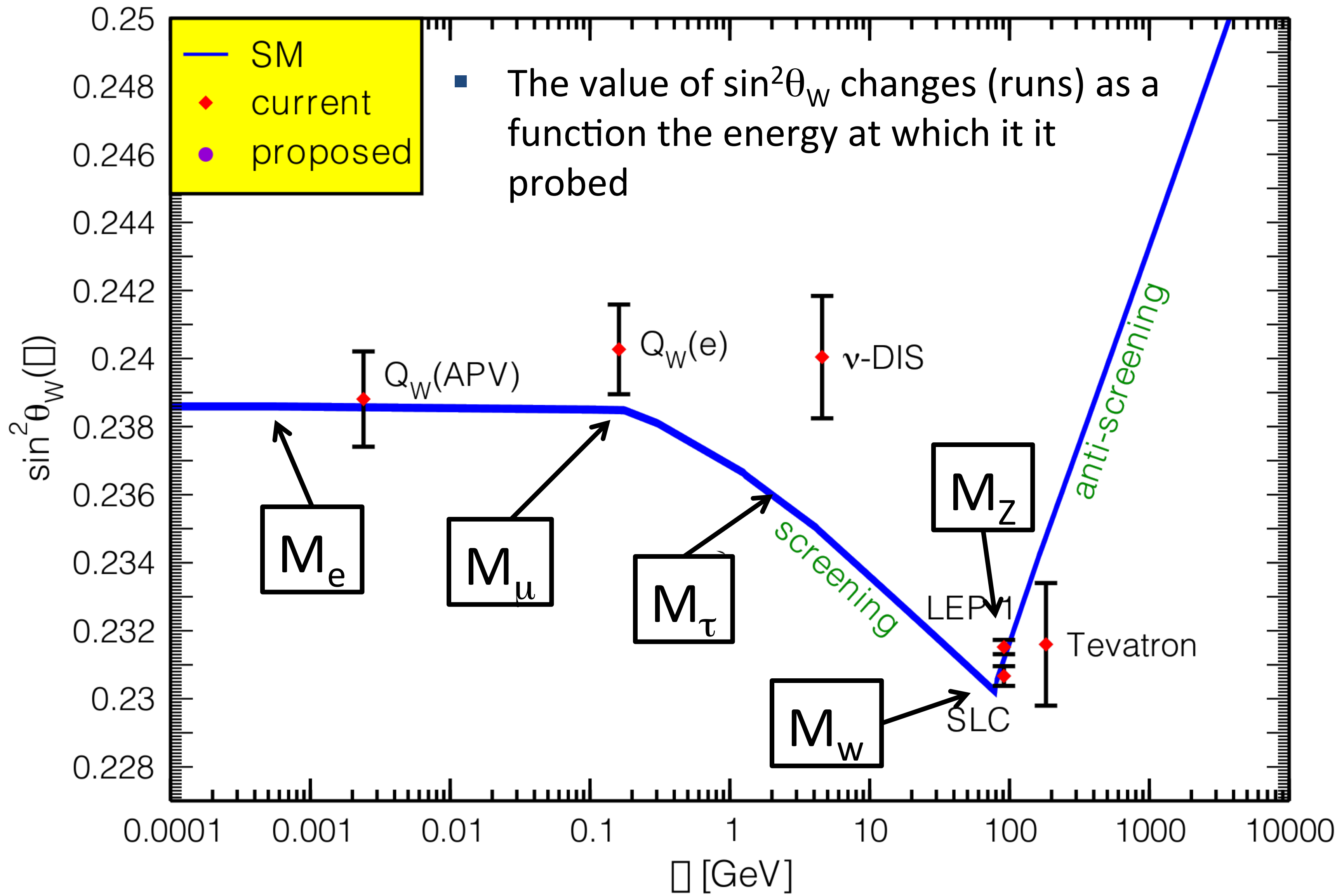
Running of α_{EM}

Running of
$\sin^2\theta_W(\mu)$



$\sin^2\theta_W$ and the Standard Model

- The value of $\sin^2\theta_W$ changes (runs) as a function the energy at which it it probed



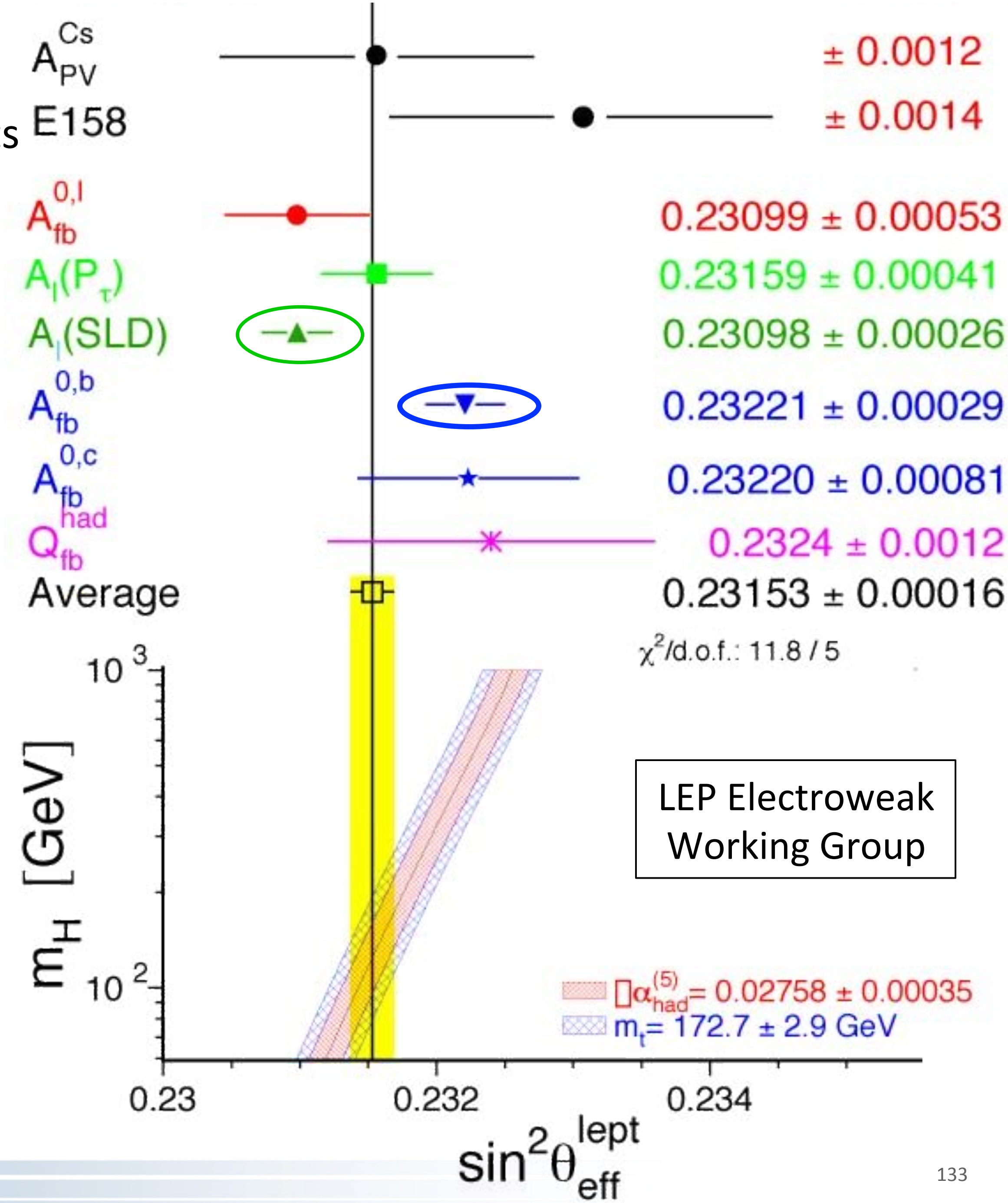
$\sin^2\theta_W$ and Higgs Mass

- World average of $\sin^2\theta_W$ predicts Higgs mass in range for LHC discovery.
- Two best measurements of $\sin^2\theta_W$ disagree
- Consequences for Higgs
  - **Already excluded (<115 GeV)**
  - **High mass 200-300 GeV**

Won't the LHC solve everything?

. . . Or Won't the LHC confuse us?

- LHC is a very good device for finding particles, but more is needed to put these discoveries into a wider context of a **New Standard Model**



LEP Electroweak Working Group

Aside: Renormalizations Schemes

Definition of $\sin^2(\theta_W)$ depends on renormalization scheme that is used.

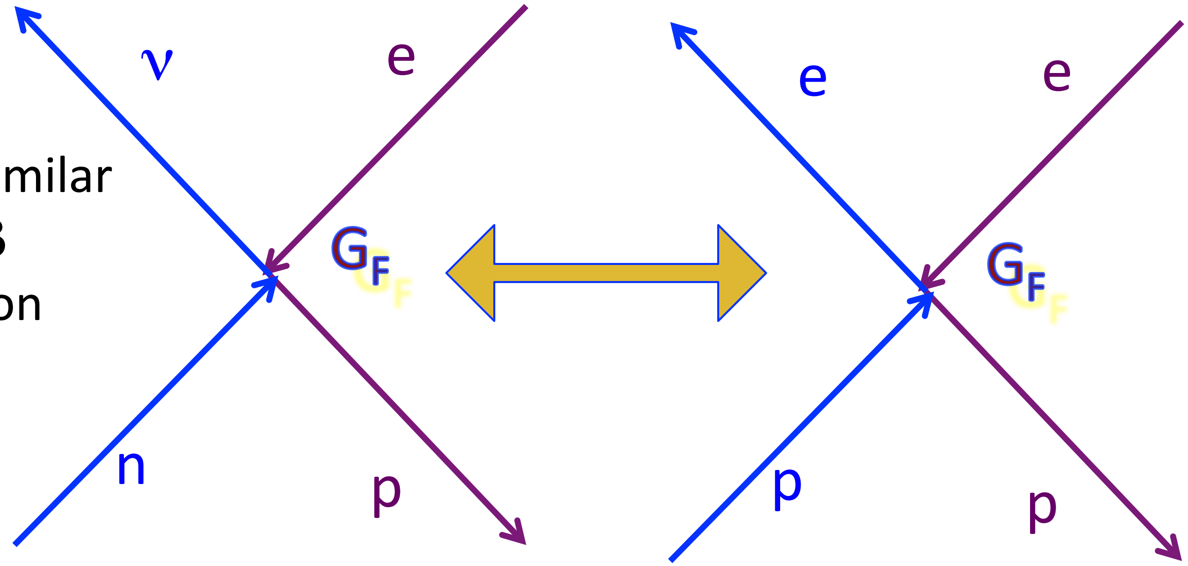
- Well defined relationships for converting between schemes depending on m_t and m_H.

On Shell	Z Mass	$\overline{\mathrm{MS}}$	Effective (Z-Pole)
$s_W^2 \equiv \left(1 - \frac{M_W^2}{M_Z^2}\right)$	$s_{M_Z}^2\left(1 - s_{M_Z}^2\right) \equiv \frac{\pi\alpha(M_Z)}{\sqrt{2}G_F M_Z^2}$	$\hat{s}_Z^2 \equiv \frac{\hat{g}'^2(M_Z)}{\hat{g}'^2(M_Z)+\hat{g}^2(M_Z)}$	$\bar{s}_f^2 \equiv \frac{1}{4}\left(1 - \frac{\bar{g}_{Vf}}{\bar{g}_{Af}}\right)$
$s_W^2 = 0.22272(38)$	$s_{M_Z}^2 = 0.23105(8)$	$\hat{s}_Z^2 = 0.23107(16)$	$\bar{s}_l^2 = 00.23136(15)$
Familiar, simple Large m_t, M_H dependence	Most precise—No m_t, M_H dependence m_t, M_H reenter w/other observables	Based on coupling constants—theorist's definition Not conceptually simple Determined through global fits	Simple Phenomenological definition

See PDB "Electroweak Model" (J. Erler and P. Langacker) for a better discussion.

Zel'dovich

- Postulates interaction similar to that responsible for β decay to occur in electron scattering



- What would this imply?
- Argues cross sections for scattering left and right handed electrons could differ

$$\sigma^l \propto \left|\mathcal{M}_{\rm em} + \mathcal{M}^l_{\rm weak}\right|^2 \qquad \sigma^r \propto \left|\mathcal{M}_{\rm em} + \mathcal{M}^r_{\rm weak}\right|^2$$

$$\approx \left|\mathcal{M}_{\rm em}\right|^2 + 2\mathcal{M}_{\rm em}\mathcal{M}^l_{\rm weak} + \left|\mathcal{M}^l_{\rm weak}\right|^2$$

Large ($\mathcal{M}_{\rm em}$) Tiny ($\mathcal{M}_{\rm weak}$)

$$A_{\rm PV} = \frac{\sigma^r - \sigma^l}{\sigma^r + \sigma^l} = -A_{\rm LR}$$

$$= \frac{\mathcal{M}^r_{\rm weak} - \mathcal{M}^l_{\rm weak}}{\mathcal{M}_{\rm em}} \approx 10^{-4} Q^2 ({\rm GeV})^2$$

Zel'dovich revisited

- Argues cross sections for scattering left and right handed electrons could differ

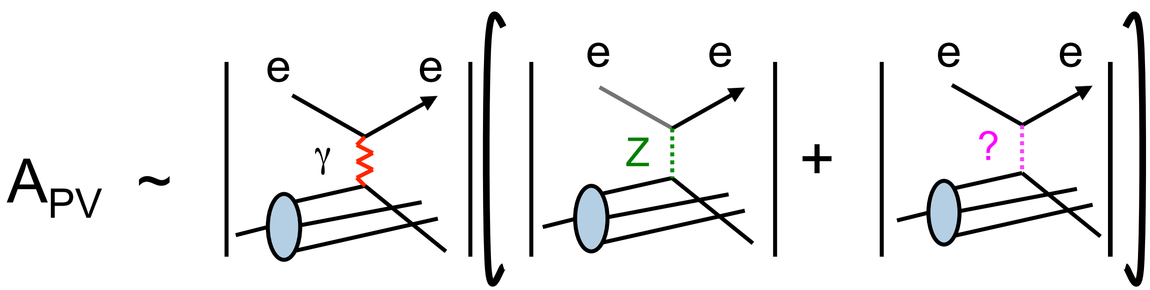
$$\sigma^l \propto \left|\mathcal{M}_{\rm em} + \mathcal{M}^l_{\rm weak} + \mathcal{M}^l_{\rm other}\right|^2 \qquad \sigma^r \propto \left|\mathcal{M}_{\rm em} + \mathcal{M}^r_{\rm weak} + \mathcal{M}^r_{\rm other}\right|^2$$

$$\approx \left|\mathcal{M}_{\rm em}\right|^2 + 2\mathcal{M}_{\rm em}\mathcal{M}^l_{\rm weak} + 2\mathcal{M}_{\rm em}\mathcal{M}^l_{\rm other} + \ldots$$

$$A_{\rm PV} = \frac{\sigma^r - \sigma^l}{\sigma^r + \sigma^l} = -A_{\rm LR}$$

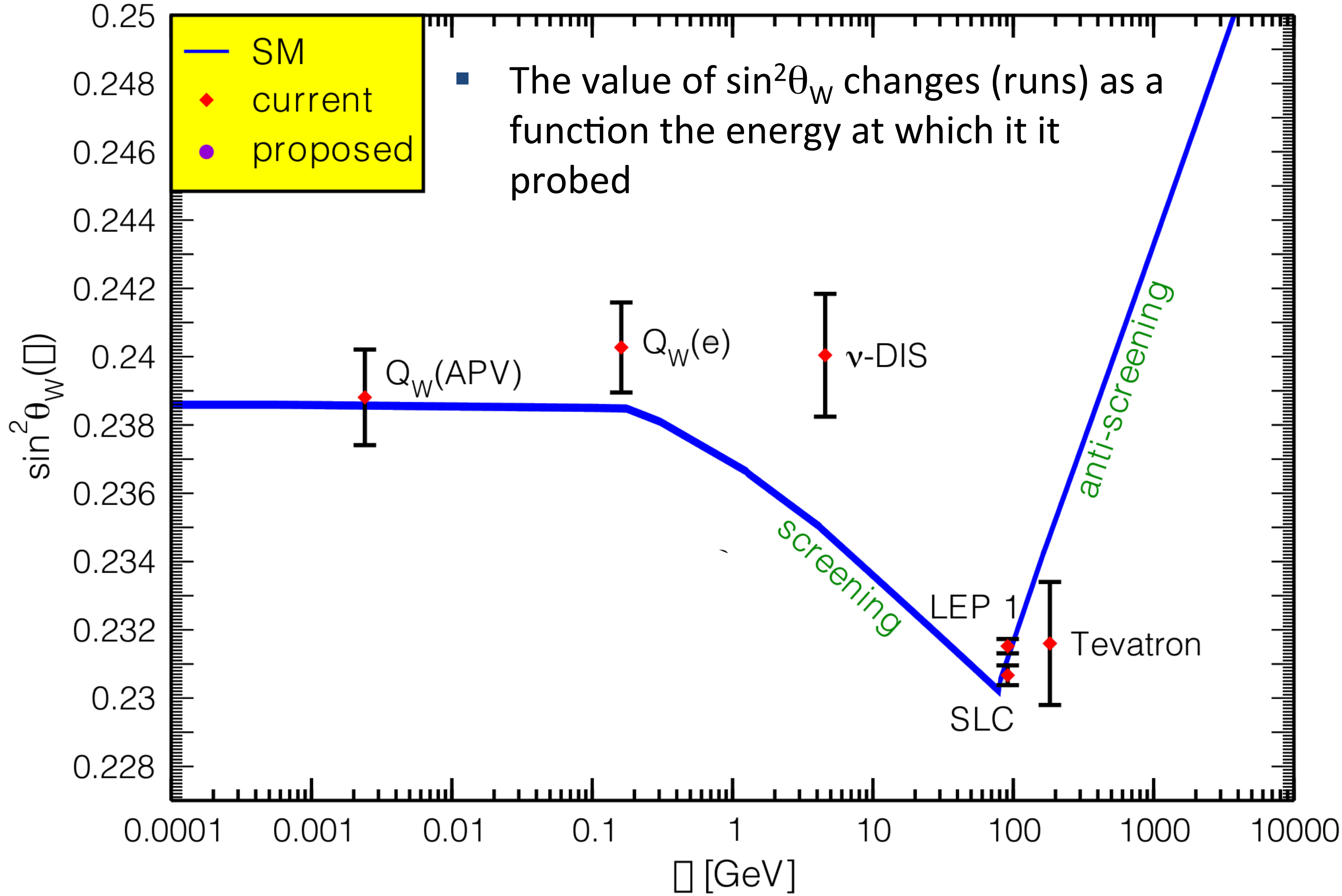
$$= \frac{\mathcal{M}^r_{\rm weak} + \mathcal{M}^r_{\rm other} - \mathcal{M}^l_{\rm weak} - \mathcal{M}^l_{\rm other}}{\mathcal{M}_{\rm em}} \approx 10^{-4} Q^2 ({\rm GeV})^2$$

- Life is hard—now we are looking for a small contribution to a small contribution



- But we can now accurately calculate what A_{PV} should be is the SM is correct

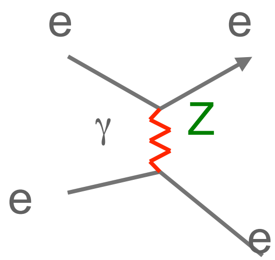
$Sin^2\theta_W$ and the Standard Model



- The value of $\sin^2\theta_W$ changes (runs) as a function the energy at which it it probed

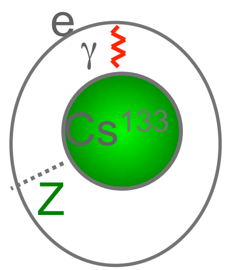
How does DIS-Parity fit in?

SLAC E158/Møller



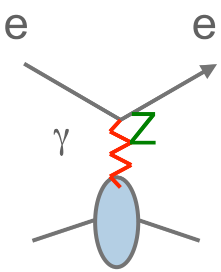
- Purely Leptonic—no quark interactions
- Complete in 2003

Atomic Parity Violation



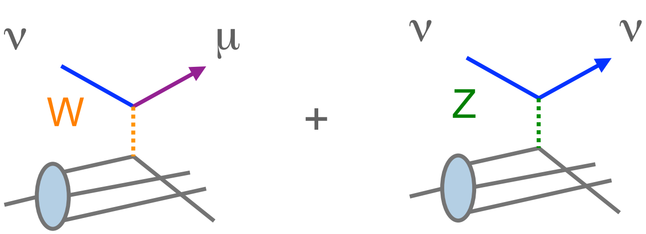
- Coherent quarks in entire nucleus
- Nuclear structure uncertainties
- $-376\ C_{1u} - 422\ C_{1d}$

Q-Weak (JLab)



- Coherent quarks in Proton
- Results in 2012/13
- $2(2C_{1u}+C_{1d})$

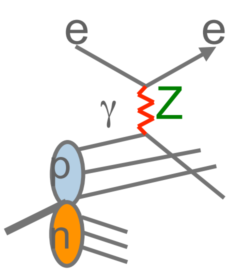
NuTeV (Fermilab)



- Quark scattering (from nucleus)
- Weak charged and neutral current difference

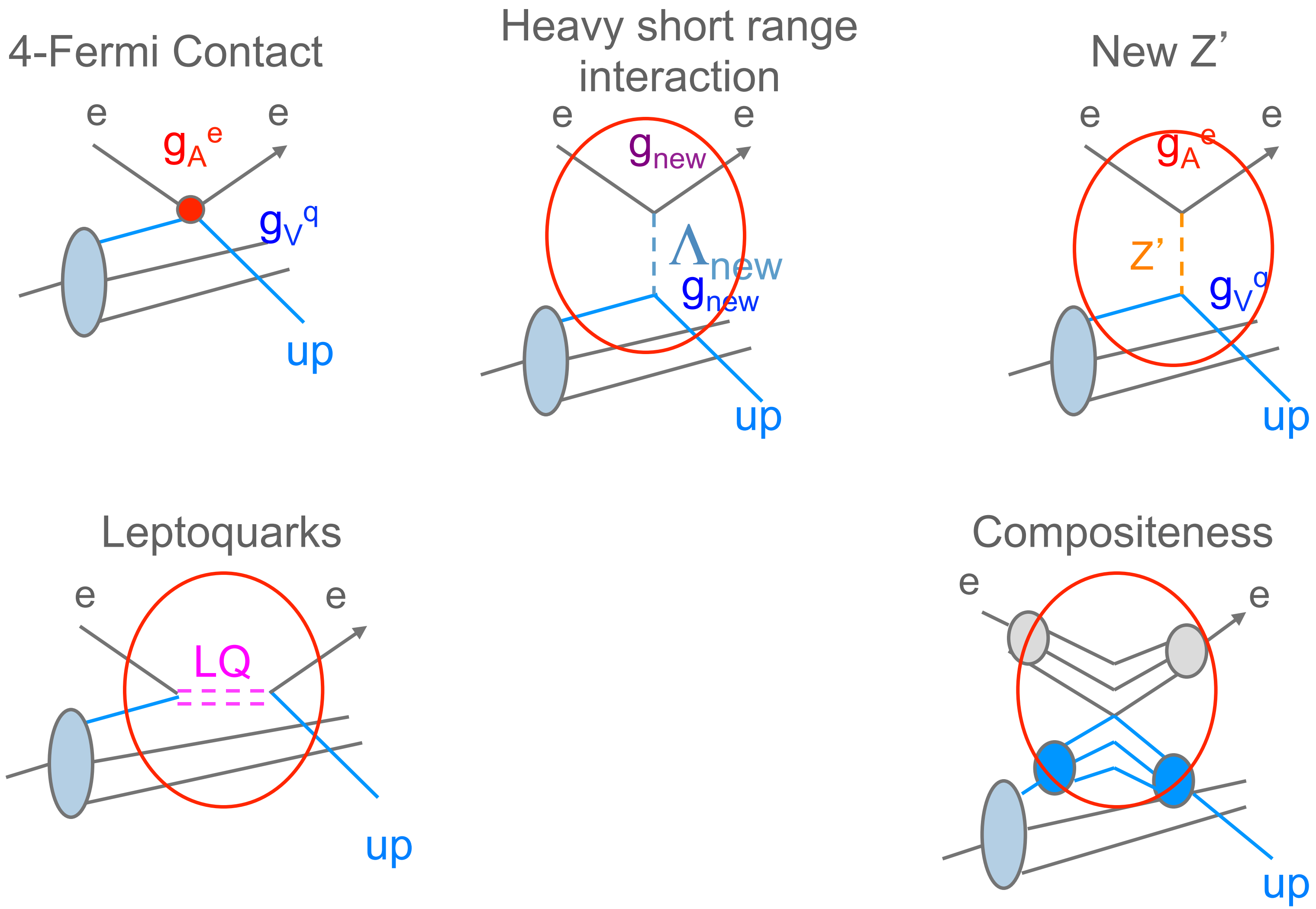
Expt. Probe different parts of Lagrangian

DIS-Parity



- Isoscaler quark scattering
- $(2C_{1u}-C_{1d})+Y(2C_{2u}-C_{2d})$

Standard Model Extensions



Z^0 mass limit of 1.5TeV

New Physics Examples

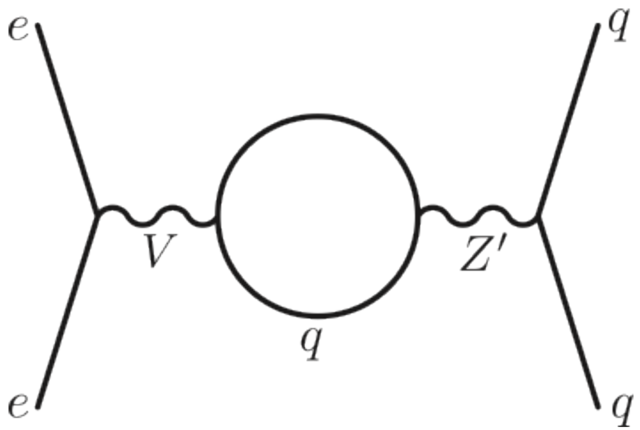
Leptophobic Z'

- ***Virtually all GUT models predict new Z's***
- ***LHC reach ~ 5 TeV, but....***
- ***Little sensitivity if Z' doesnt couple to leptons***
- ***Leptophobic Z' as light as 120 GeV could have escaped detection***

*Since electron vertex must be vector, the Z' cannot couple to the C_{1q}'s if there is no electron coupling: can only affect **C_{2q}'s***

SOLID can improve sensitivity:
100-200 GeV range

arXiv:1203.1102v1
Buckley and Ramsey-Musolf



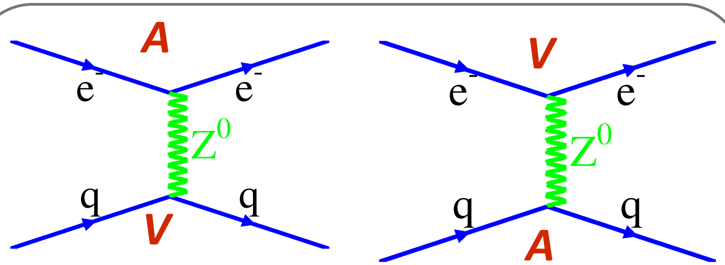
PV deep inelastic scattering

$$Y = \frac{1-(1-y)^2}{1+(1-y)^2 - y^2\frac{R}{R+1}}$$

Cahn and Gilman,
PRD **17** 1313 (1978)

$$R(x,Q^2) = \sigma^l/\sigma^r \approx 0.2$$

$$A_{\rm iso} = \frac{\sigma^l - \sigma^r}{\sigma^l + \sigma^r} = -\left(\frac{3G_F Q^2}{\pi\alpha 2\sqrt{2}}\right)\frac{2C_{1u} - C_{1d}(1+R_s) + Y(2C_{2u} - C_{2d})R_v}{5+R_s}$$



$$C_{1i} \equiv 2g_A^e g_V^i \qquad C_{2i} \equiv 2g_V^e g_A^i$$

$$R_s(x) = \frac{2S(x)}{U(x)+D(x)} \xrightarrow{\text{Large } x} 0$$

$$R_v(x) = \frac{u_v(x)+d_v(x)}{U(x)+D(x)} \xrightarrow{\text{Large } x} 1$$

$$C_{1u} \stackrel{\text{SM}}{=} -\tfrac{1}{2} + \tfrac{4}{3}\sin^2\theta_W \approx -0.192$$

$$C_{1d} \stackrel{\text{SM}}{=} \tfrac{1}{2} - \tfrac{2}{3}\sin^2\theta_W \approx 0.346$$

$$C_{2u} \stackrel{\text{SM}}{=} -\tfrac{1}{2} + 2\sin^2\theta_W \approx -0.038$$

$$C_{2d} \stackrel{\text{SM}}{=} \tfrac{1}{2} - 2\sin^2\theta_W \approx 0.038$$

QCD
- Parton distributions (u, d, s, c)
- Charge Symmetry (CSV)
- Higher Twist (HT)
- Nuclear Effects (EMC)

Doesn't matter at 10% level, but does for a more precise measurement, but . . .

QCD: Charge Symmetry Violation

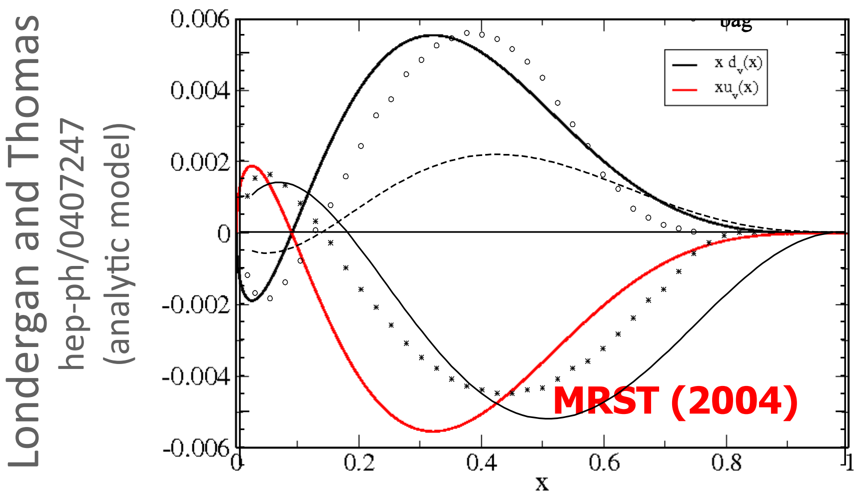
$$u^p(x) \stackrel{?}{=} d^n(x) \quad \Rightarrow \quad \delta u(x) \equiv u^p(x) - d^n(x)$$
$$d^p(x) \stackrel{?}{=} u^n(x) \quad \Rightarrow \quad \delta d(x) \equiv d^p(x) - u^n(x)$$

$$\frac{\delta A_{PV}}{A_{PV}} \approx 0.28 \frac{\delta u(x) - \delta d(x)}{u(x) + d(x)}$$

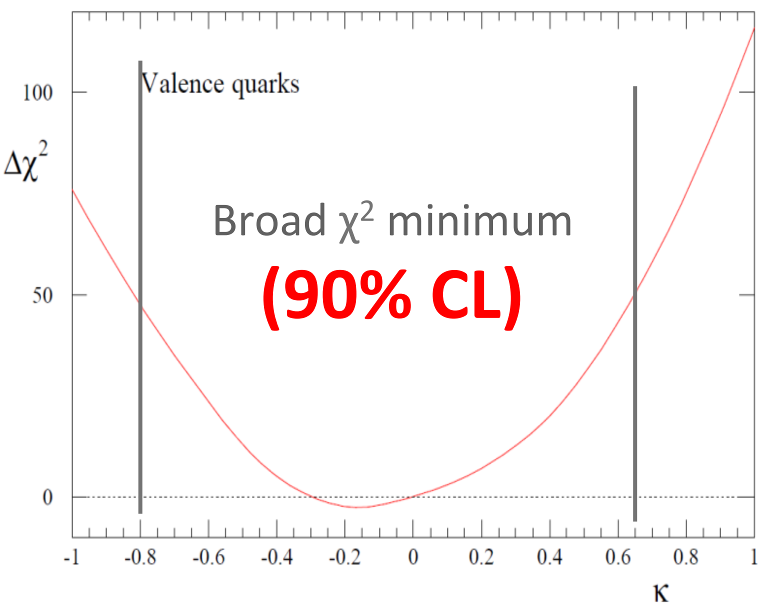
For A_{PV} in electron-^{2}H DIS:

We already know CSV exists:

- u-d mass difference $\delta m = m_d - m_u \approx 4$ MeV
  $\delta M = M_n - M_p \approx 1.3$ MeV
- electromagnetic effects
- Direct observation of CSV—very exciting!
- Important implications for PDF's
- *Could be a* partial explanation of the NuTeV anomaly



MRST PDF global with fit of CSV
Martin, Roberts, Stirling, Thorne Eur Phys J C**35**, 325 (04)



A Special HT Effect

The observation of Higher Twist in PV-DIS would be exciting direct evidence for diquarks following the approach of

Bjorken, PRD 18, 3239 (78),
Wolfenstein, NPB146, 477 (78)

$$V_\mu = (\bar{u}\gamma_\mu u - \bar{d}\gamma_\mu d) \Leftrightarrow S_\mu = (\bar{u}\gamma_\mu u + \bar{d}\gamma_\mu d)$$

$$\langle VV \rangle = l_{\mu\nu} \int \langle D | V^\mu(x) V^\nu(0) | D \rangle e^{iq\cdot x} d^4x$$

Isospin decomposition before using PDF's

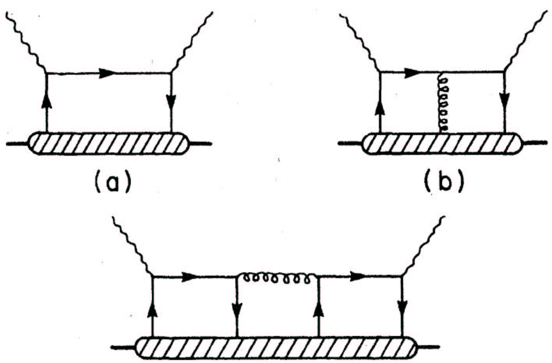
$$A_{PV} = \frac{G_F Q^2}{\sqrt{2}\pi\alpha}\left[a(x) + f(y)b(x)\right]$$

$$\delta = \frac{\langle VV \rangle - \langle SS \rangle}{\langle VV \rangle + \langle SS \rangle} \qquad a(x) \propto \frac{F_1^{\gamma Z}}{F_1^{\gamma}} \propto 1 - 0.3\delta$$

Higher-Twist valence quark-quark correlation

Zero in quark-parton model

$$\langle VV \rangle - \langle SS \rangle = \langle (V-S)(V+S) \rangle \propto l_{\mu\nu} \int \langle D | \bar{u}(x)\gamma^\mu u(x)\bar{d}(0)\gamma^\nu d(0) \rangle e^{iq\cdot x} d^4x$$



(c) *Castorina & Mulders, '84*

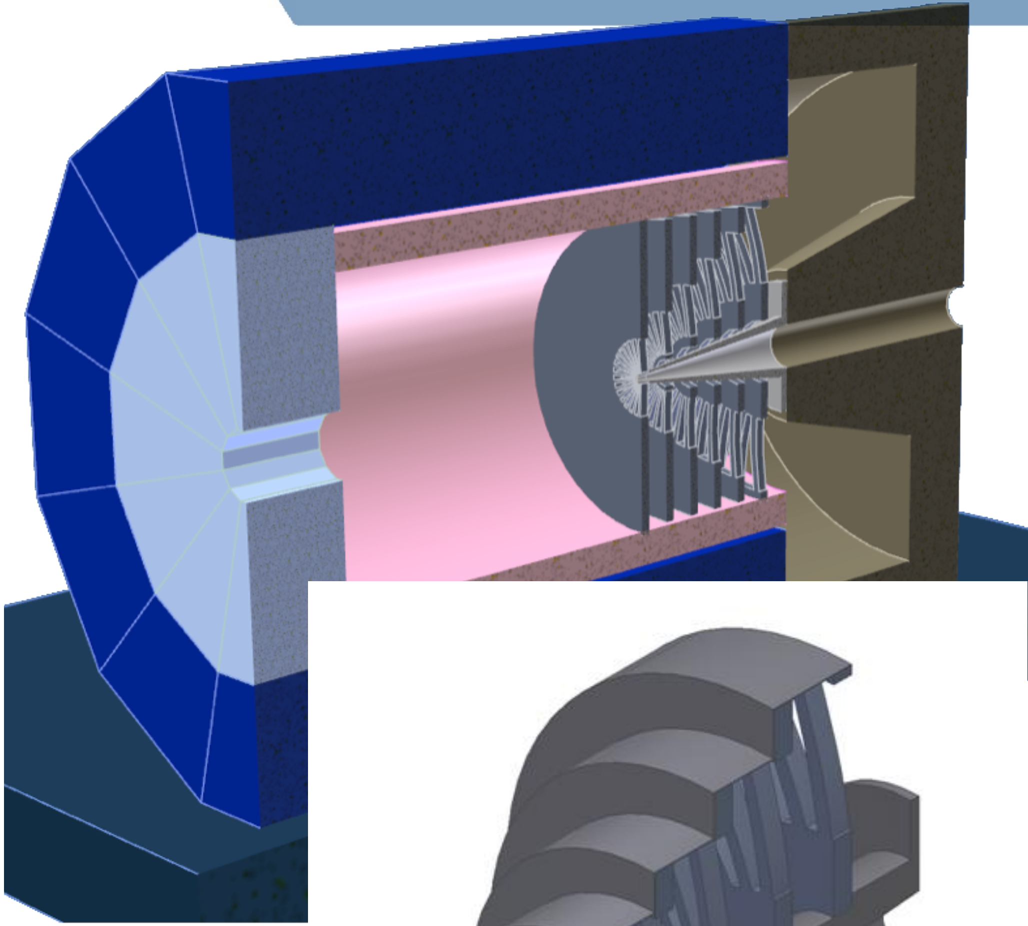
(c) type diagram is the only operator that can contribute to a(x) higher twist: theoretically very interesting!

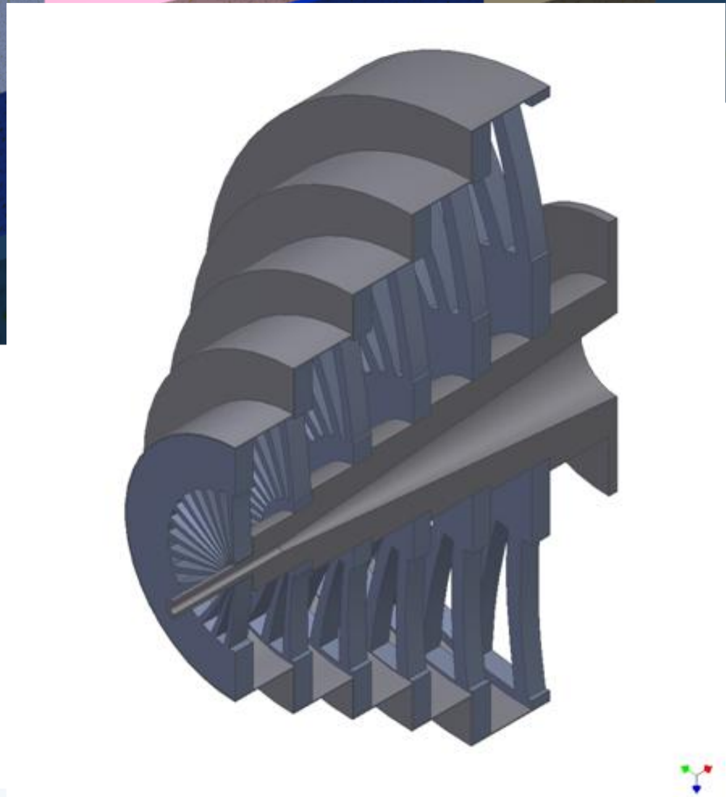
σ_L contributions cancel

Use ν data for small b(x) term.

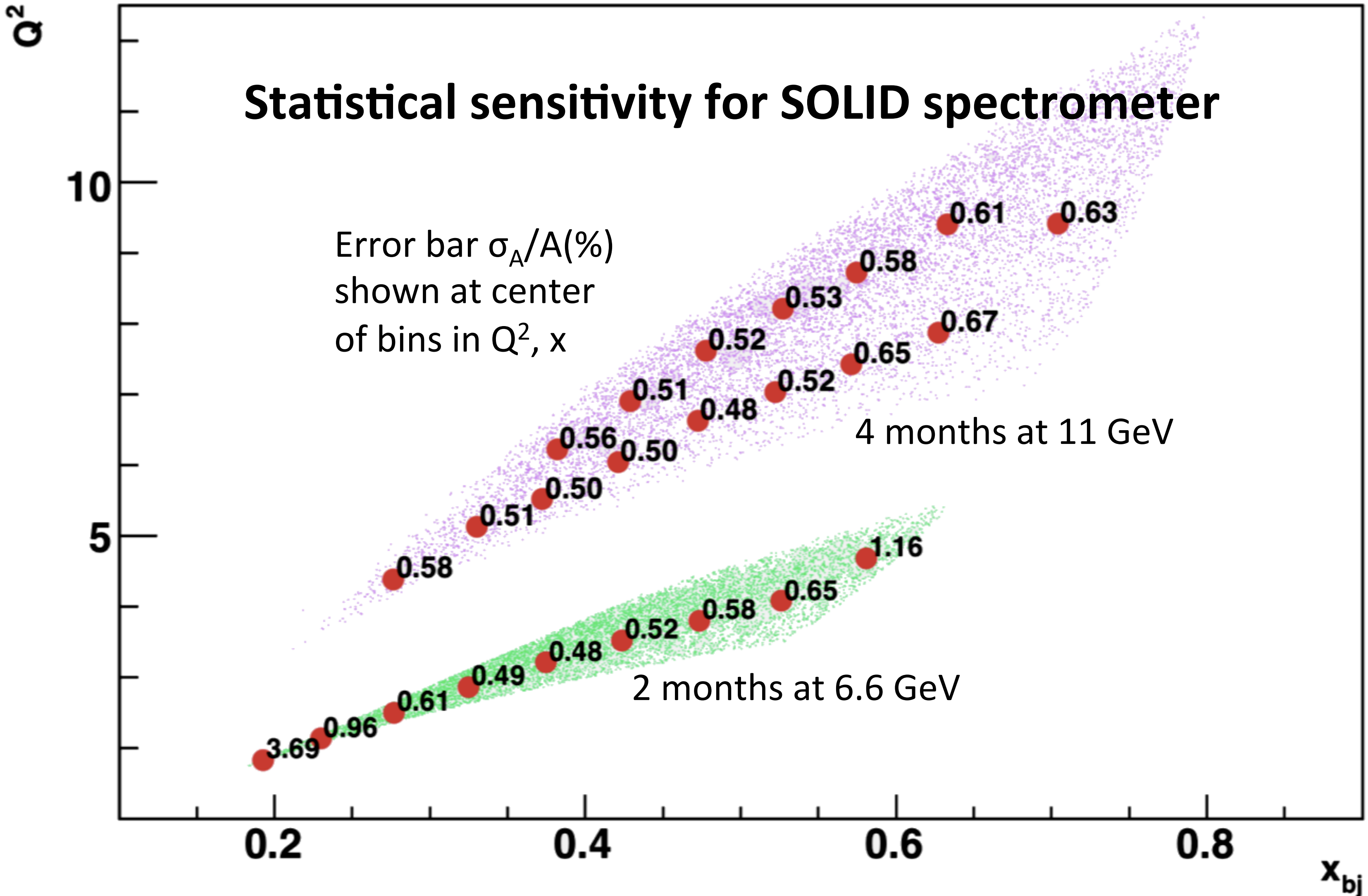
SoLID: A large acceptance apparatus for JLab Hall A

- **Moderate running times**
  - **Large Acceptance**
  - High Luminosity on LH_2 & LD_2
  - Measure everything at once, so that relative comparisons can neglect beam polarization uncertainty
- Better than 1% errors for small bins
- Kinematics:
  - Large Q^2 coverage
  - x-range 0.25-0.75
  - $W^2 > 4$ GeV^2
- Spectrometer requirements:
  - Solenoid contains low energy backgrounds (Møller, pions, etc)





Statistical Errors (%) vs. Kinematics



Coherent Program of PVDIS Study

Strategy: requires precise kinematics and broad range

	x	Y	Q^2
New Physics	no	yes	no
CSV	yes	no	no
Higher Twist	yes	no	yes

$$A_{\mathrm{iso}} = \frac{\sigma^l - \sigma^r}{\sigma^l + \sigma^r} = -\left(\frac{3G_F Q^2}{\pi\alpha 2\sqrt{2}}\right) \frac{2C_{1u} - C_{1d}(1+R_s) + Y(2C_{2u} - C_{2d})R_v}{5+R_s}$$

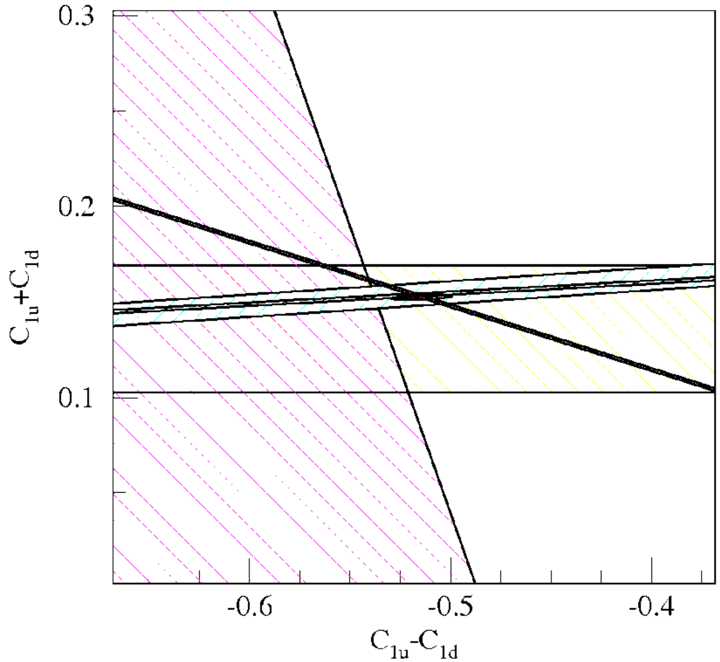
- Measure A_d in **narrow** bins of *x*, Q^2 with *0.5%* precision
- Cover broad Q^2 range for *x* in *[0.3,0.6]* to constrain HT
- Search for CSV with *x* dependence of A_d at high *x*
- Use $x > 0.4$, high Q^2 to measure a combination of the C_{iq}'s

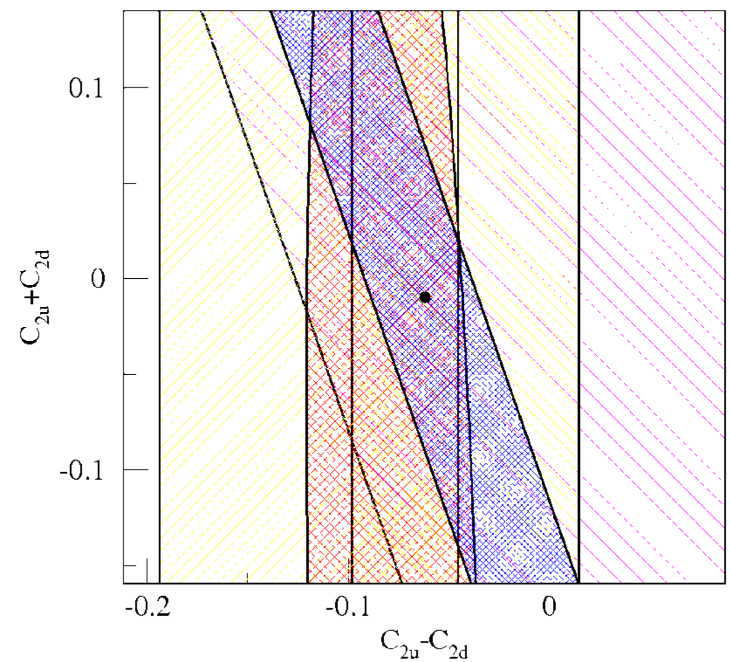
Fit data to:

$$A_{\mathrm{Meas.}} = A_{\mathrm{SM}} \left[1 + \frac{\beta_{\mathrm{HT}}}{(1-x)^3 Q^2} + \beta_{\mathrm{CSV}} x^2\right]$$

Sensitivity: C_1 and C_2 Plots

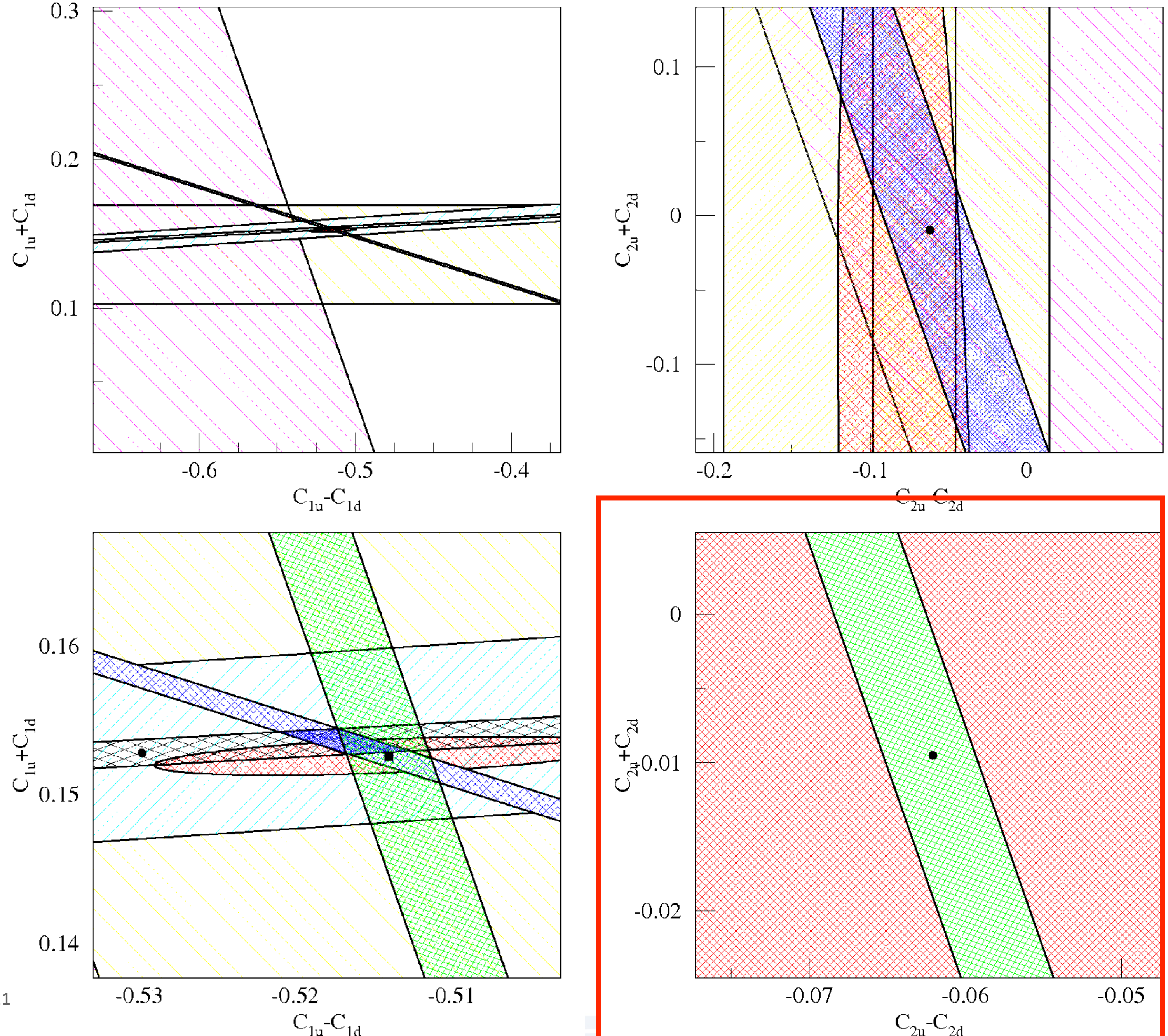
World's data



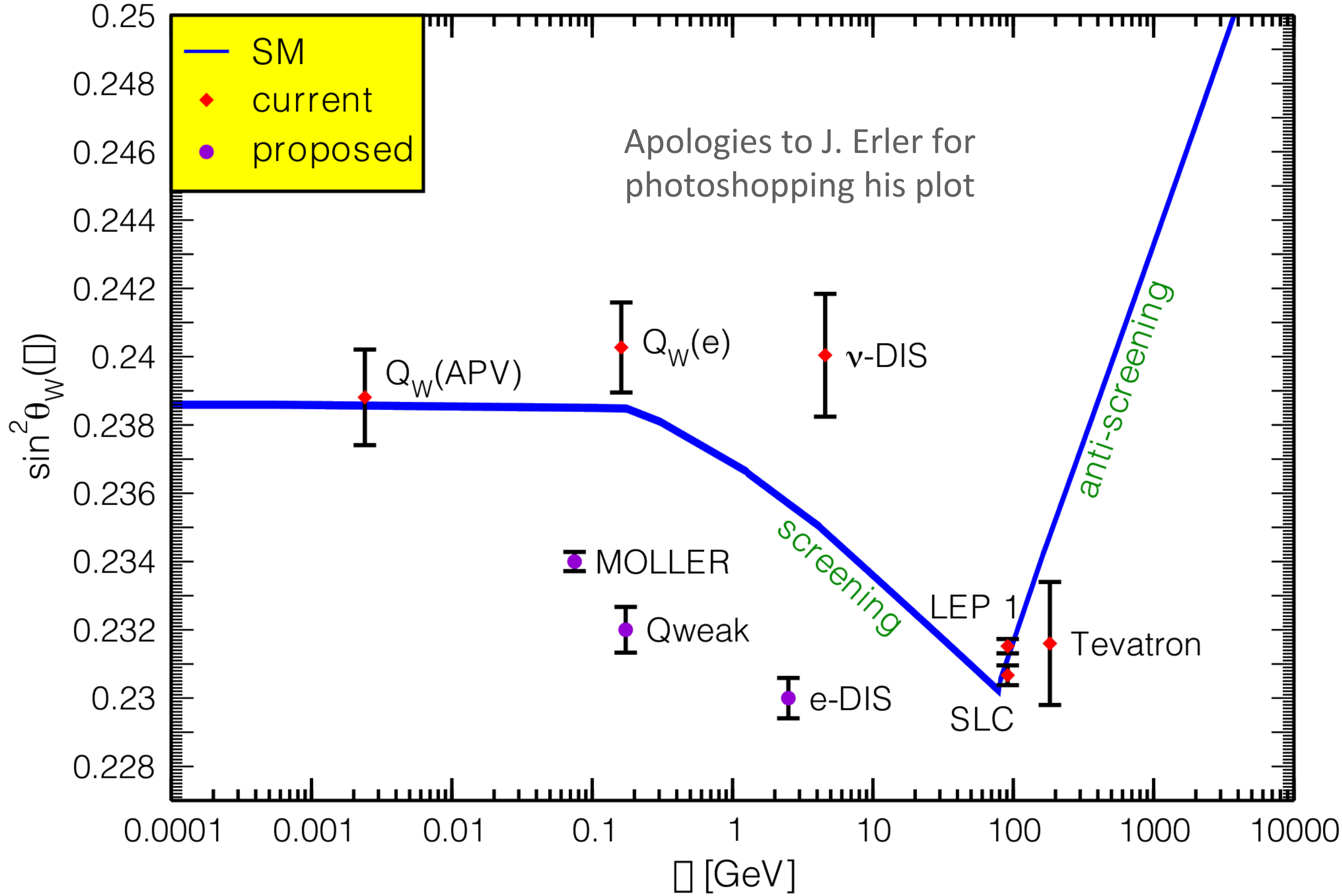


Sensitivity: C_1 and C_2 Plots

World's data



What about NuTeV?



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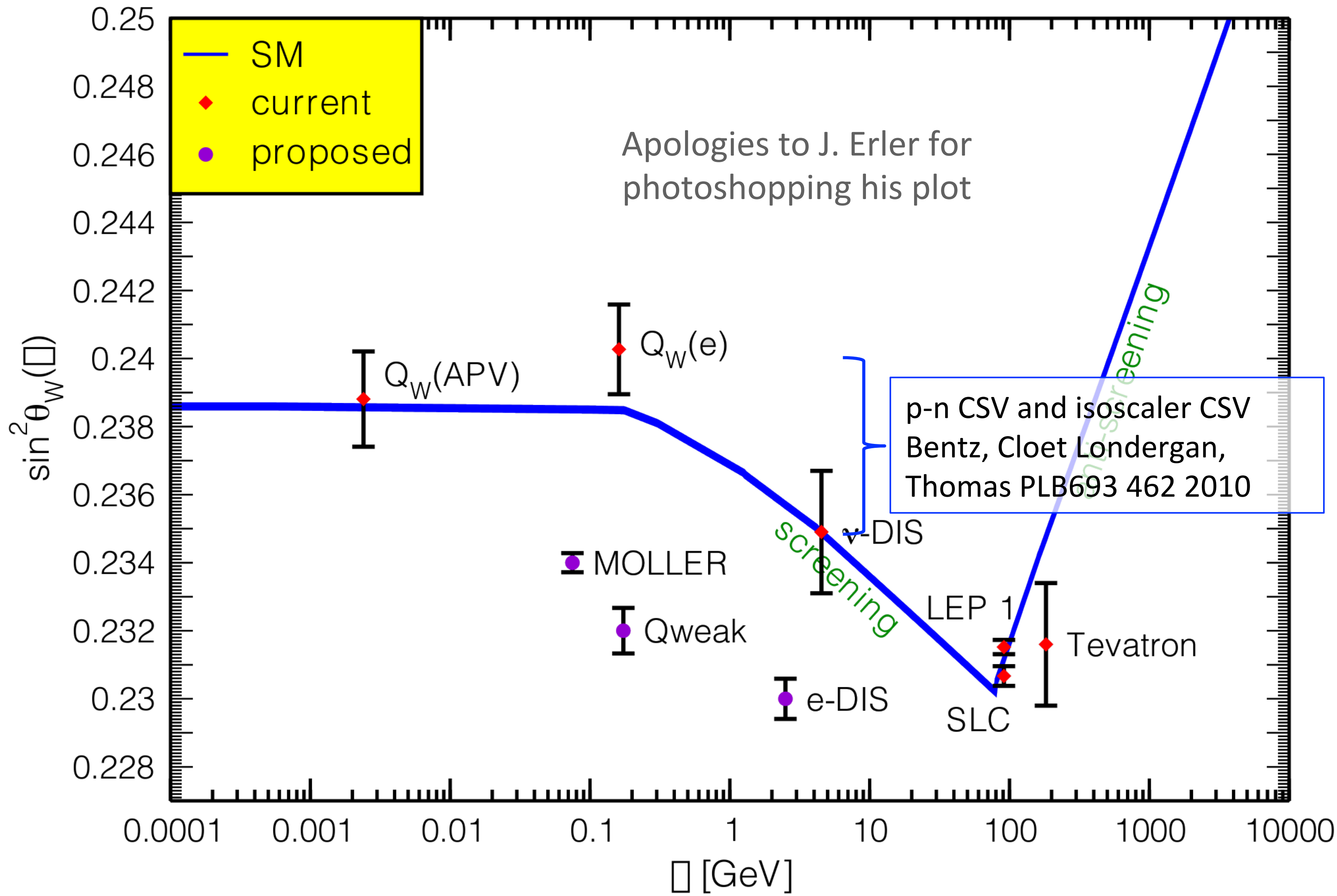
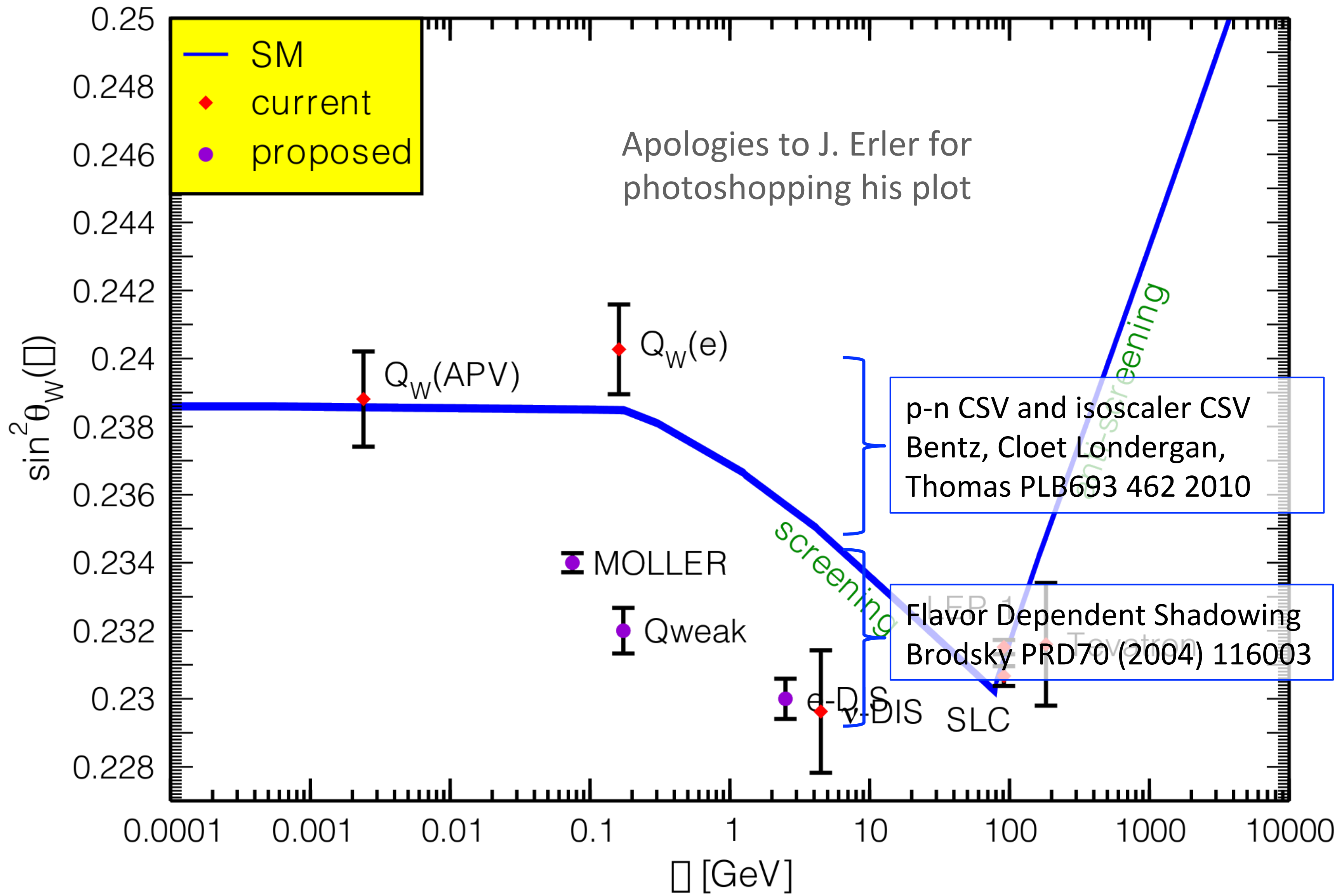
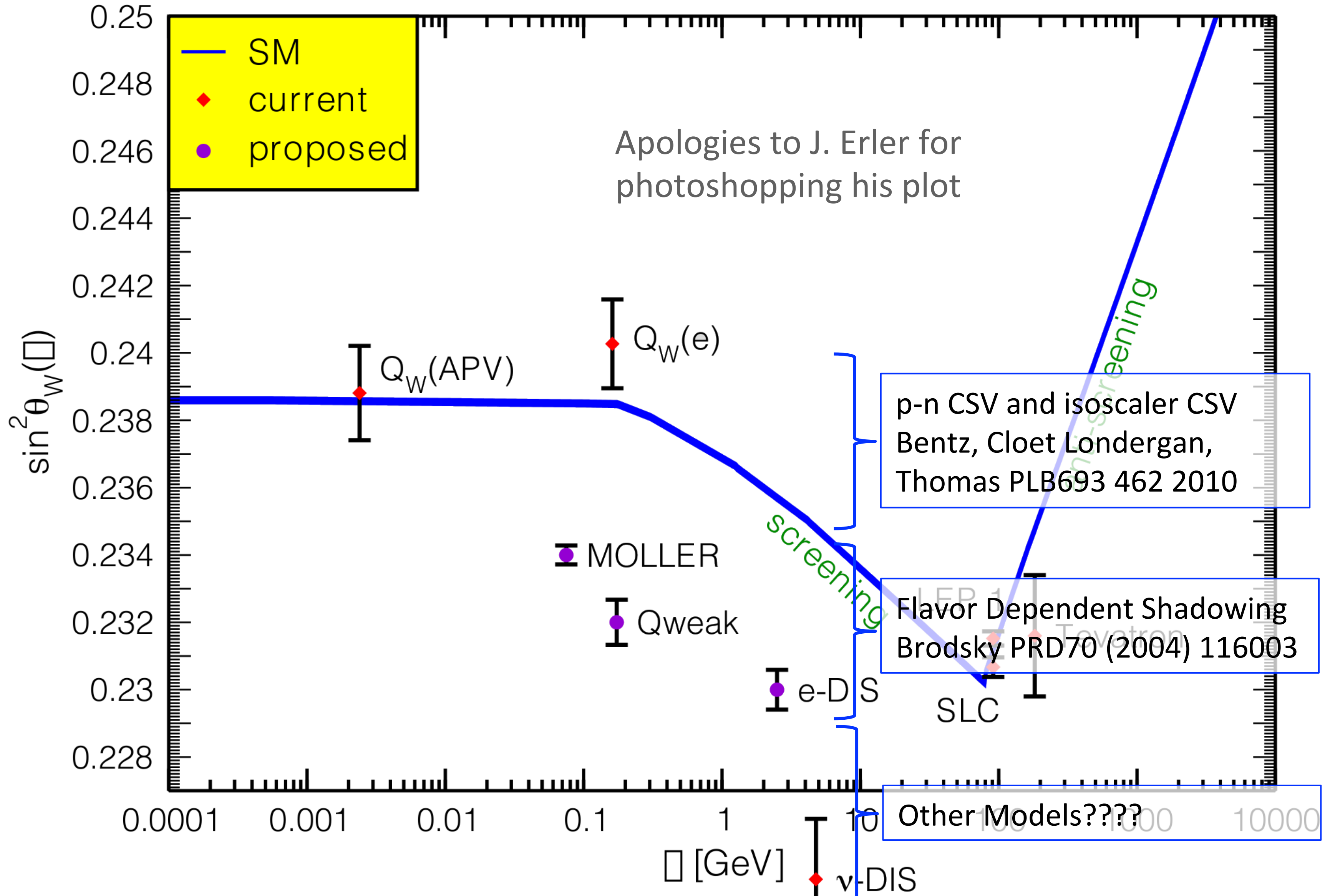


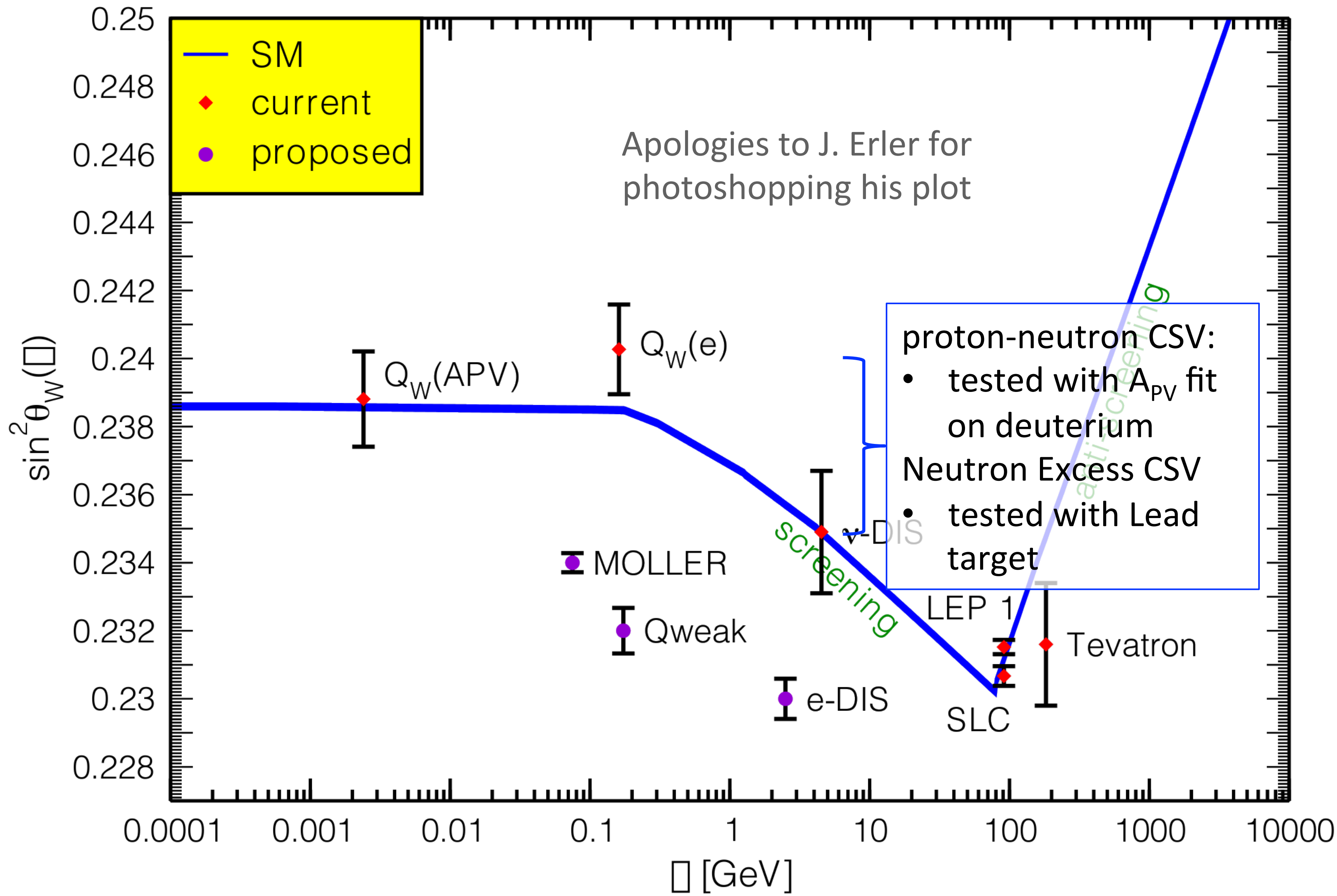
What about NuTeV?



What about NuTeV?

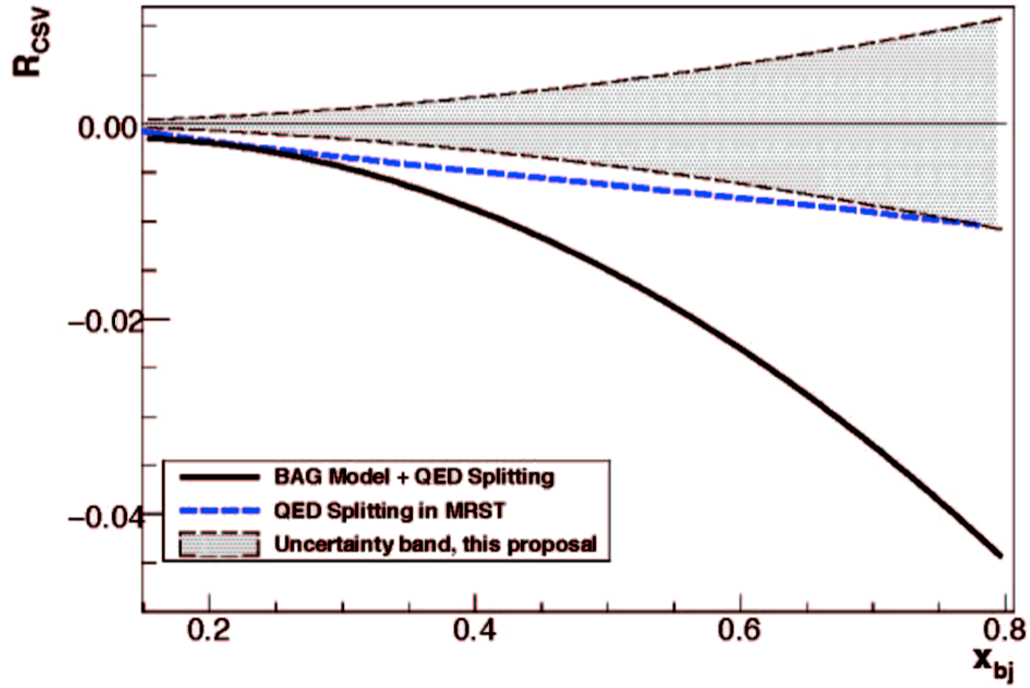


What about NuTeV?



Charge Symmetry Violation

$$\frac{\delta A_{PV}}{A_{PV}} \approx 0.28 \frac{\delta u(x) - \delta d(x)}{u(x) + d(x)}$$



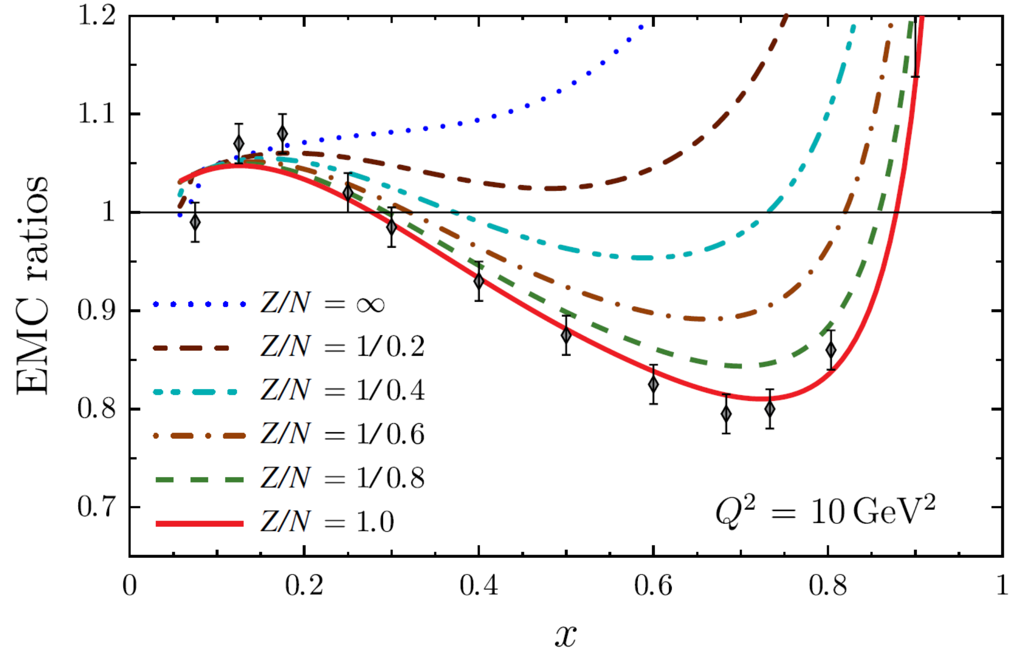
CSV in Heavy Nuclei: EMC Effect

Isovector EMC Effect and the NuTeV Anomaly

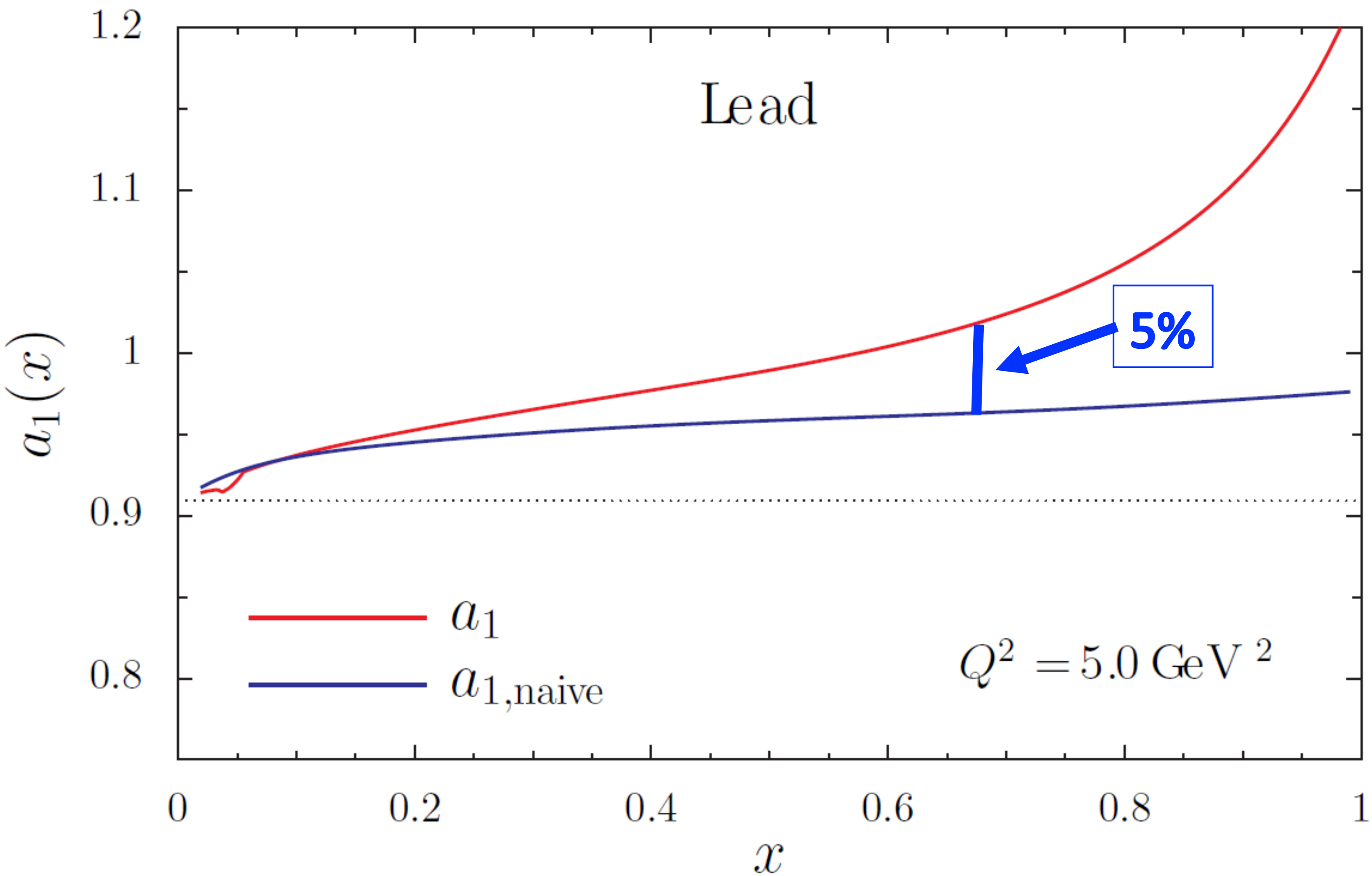
I. C. Cloët,[1] W. Bentz,[2] and A. W. Thomas[3]

PRL **102,** 252301 (2009)

- Mean Field approach to estimate an EMC-like effect for N ≠ Z nuclei
- Possible explanation for NuTeV anomaly which used iron target.



CSV in Heavy Nuclei: EMC Effect

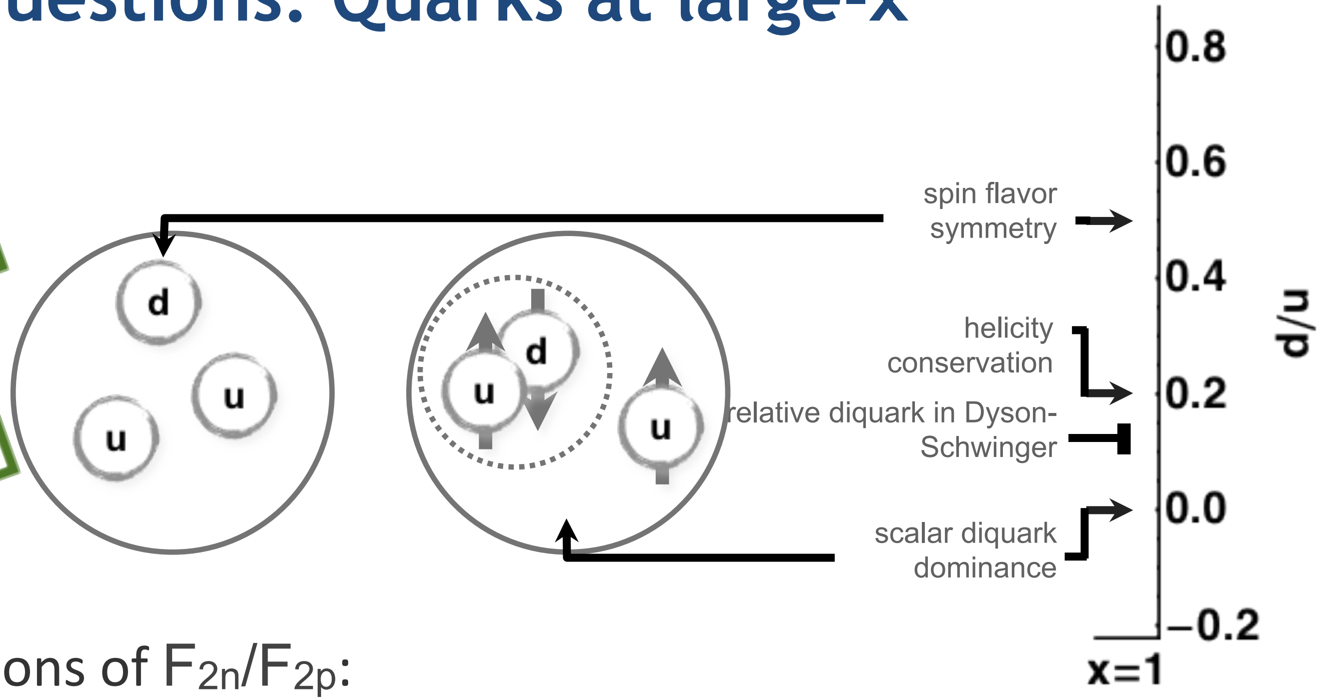


Motivating questions: Quarks at large-x

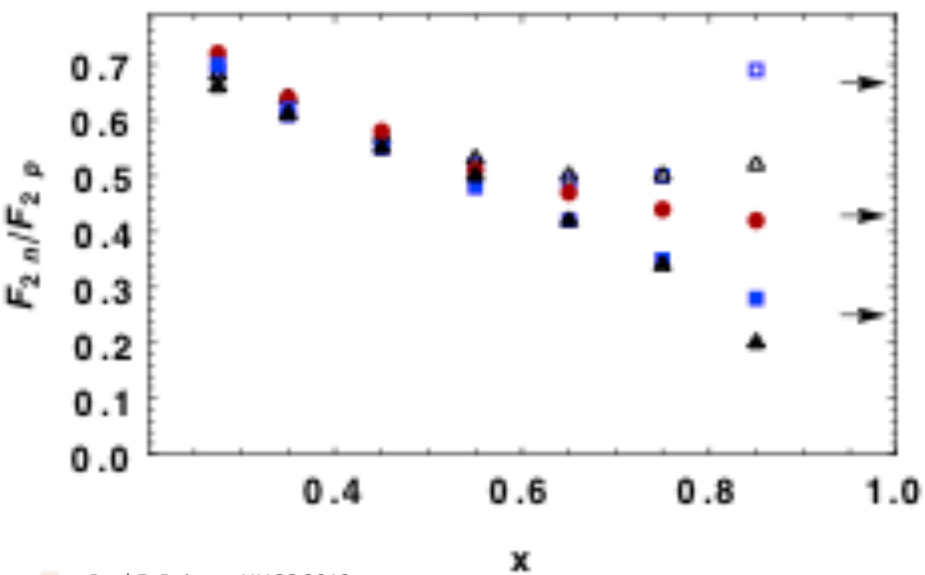
Slide borrowed from Josh Rubin

spin-flavor dynamics

Q^2 evolution



Previous calculations of F_{2n}/F_{2p}:



Closed symbols: microscopic deuteron models
Open symbols: extrapolations of nuclear effects from heavier nuclei

Basic point—we don't understand the 2nd simplest atom and we need to

Physics with Hydrogen

d(x)/u(x) as x→1

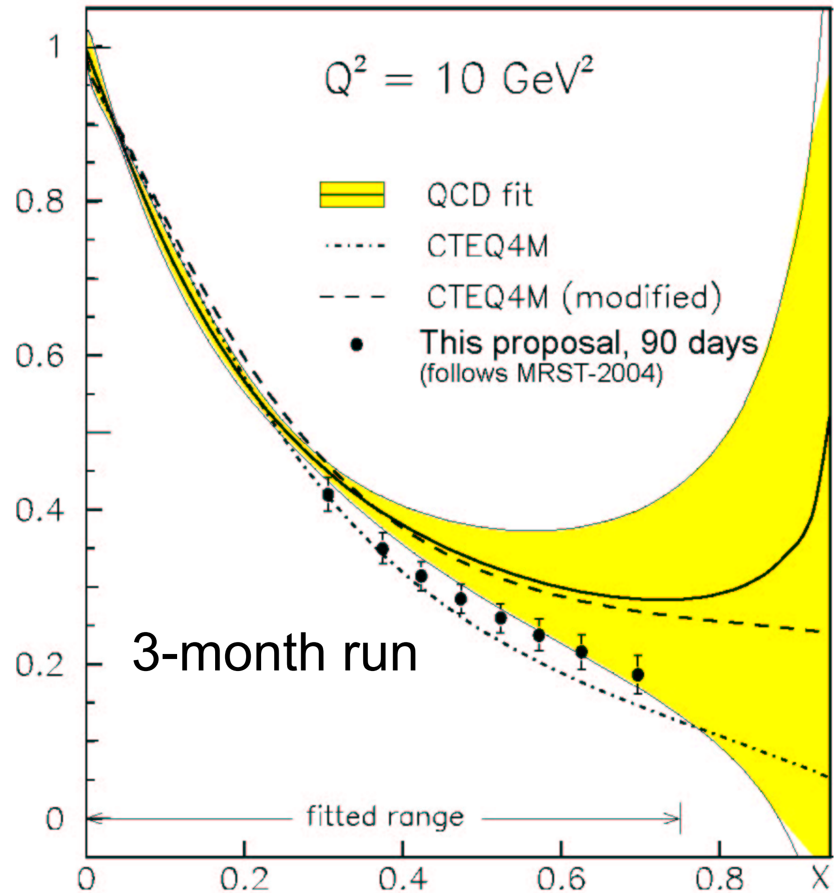
SU(6): d/u~1/2
Valence Quark: d/u~0
Perturbative QCD: d/u~1/5

Longstanding issue in proton structure

PV-DIS off the proton (hydrogen target)

$$A_{PV} = \frac{G_F Q^2}{\sqrt{2}\pi\alpha}\left[a(x) + f(y)b(x)\right]$$

$$a^P(x) \approx \frac{u(x) + 0.91d(x)}{u(x) + 0.25d(x)}$$

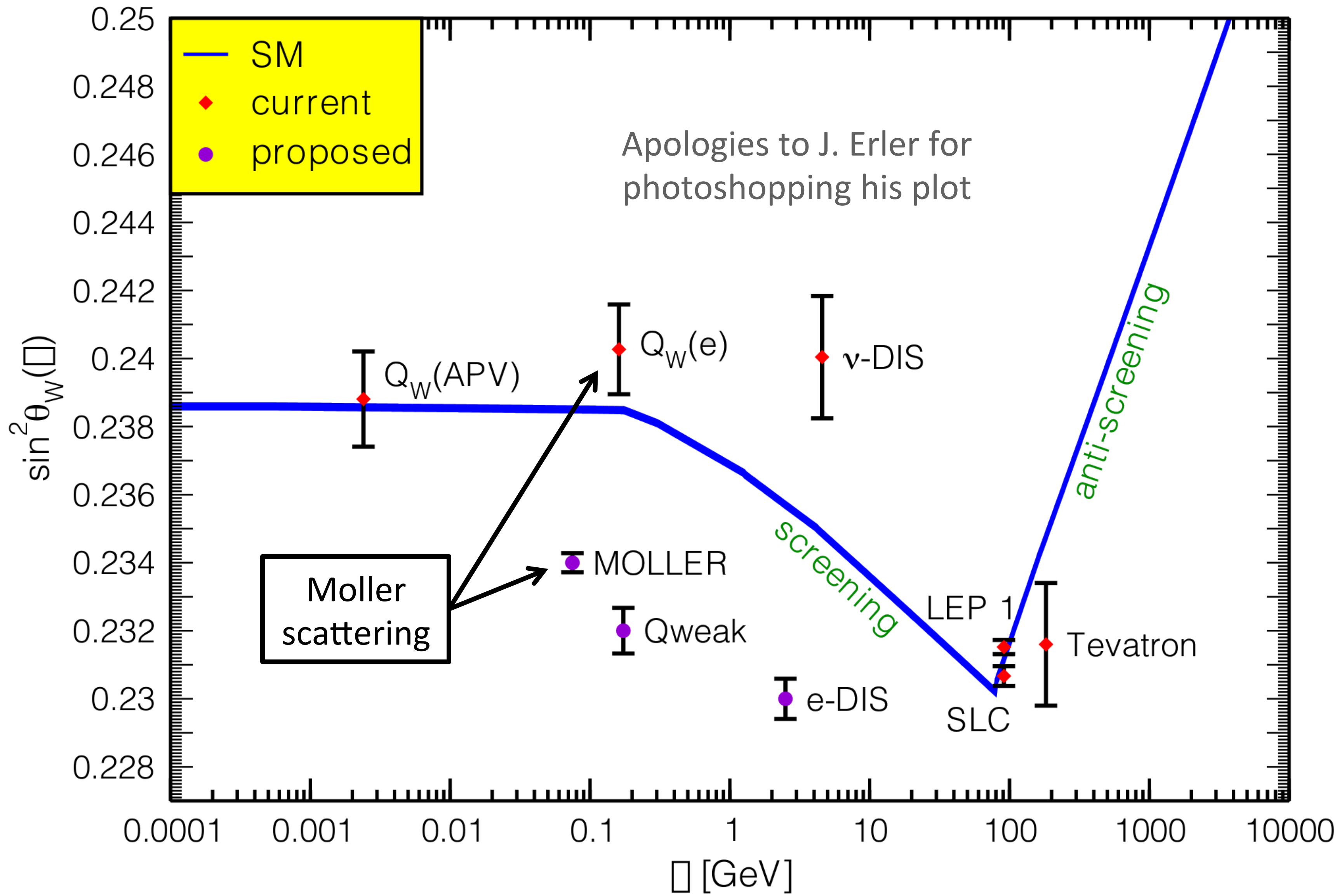


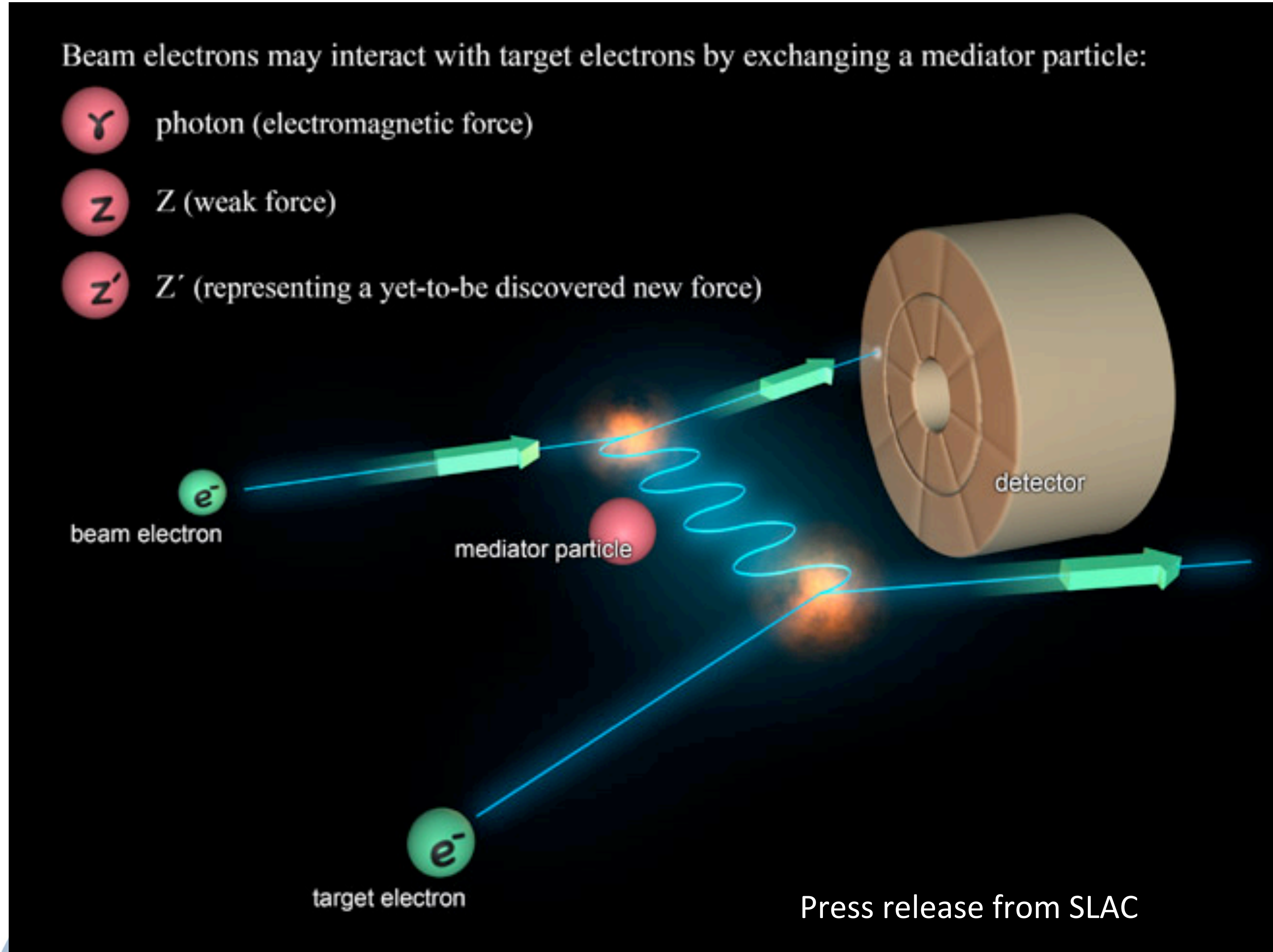
Deuteron analysis has large nuclear corrections (Yellow)

A_{PV} for the proton has no such corrections

The challenge is to get statistical and systematic errors ~ 2%

What about NuTeV?



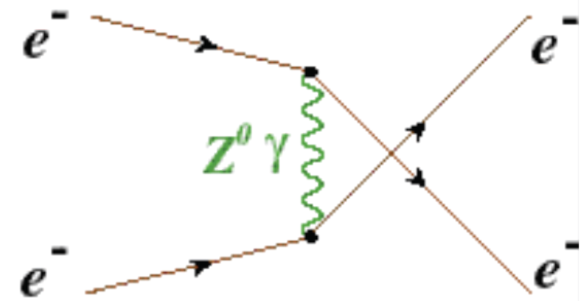


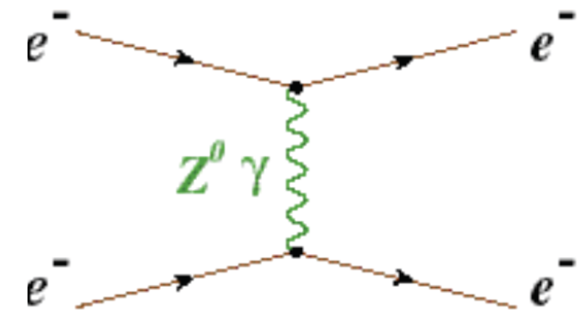
Press release from SLAC

PV in Electron Elastic (Møller) Scattering: Q^e_{Weak}

$$A^{PV}_{\text{Møller}} = -mE \frac{G_F}{\sqrt{2}\pi\alpha} \frac{4\sin^2\theta}{(3+\cos^2\theta)^2} Q^e_W$$

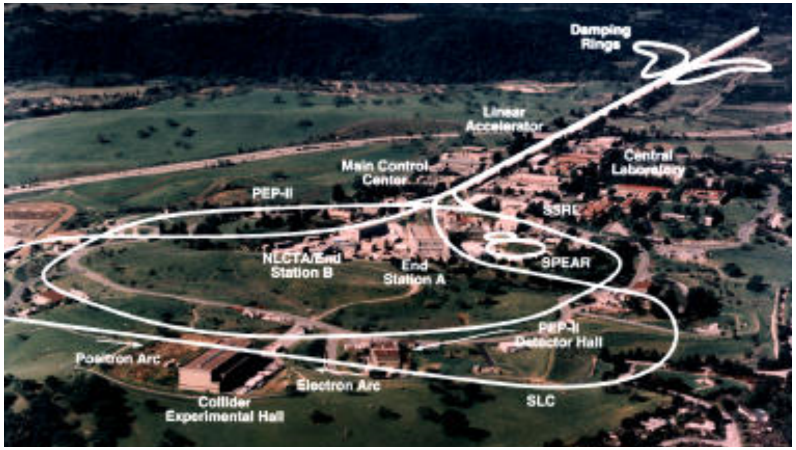
$$Q^e_W \equiv 4 g^e_V g^e_A = 1 - 4\sin^2\theta_W$$





Measured by SLAC E-158

- δA_{LR} = 17 x 10^{-9}
- $\sin2\theta^{eff}_W$ = 0.2397 ± 0.0010 (stat.)
  ± 0.0008 (syst.)



PV in Electron Elastic (Møller) Scattering: Q^e_{Weak}

Measured by SLAC E-158

- $\delta A_{LR} = 17 \times 10^{-9}$
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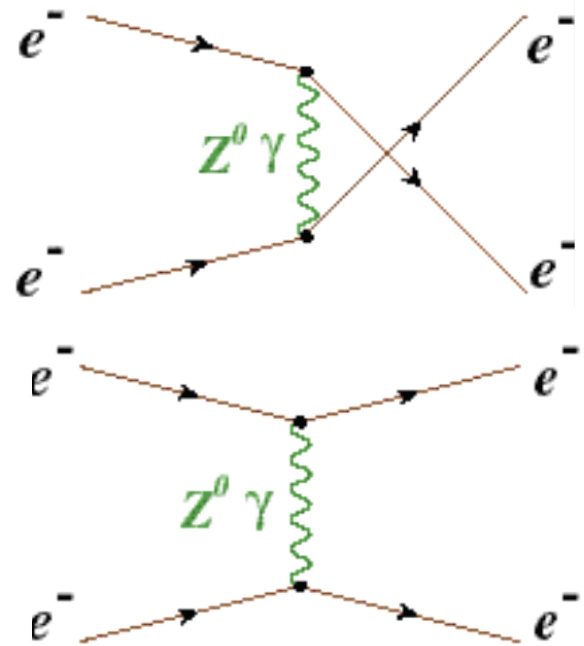
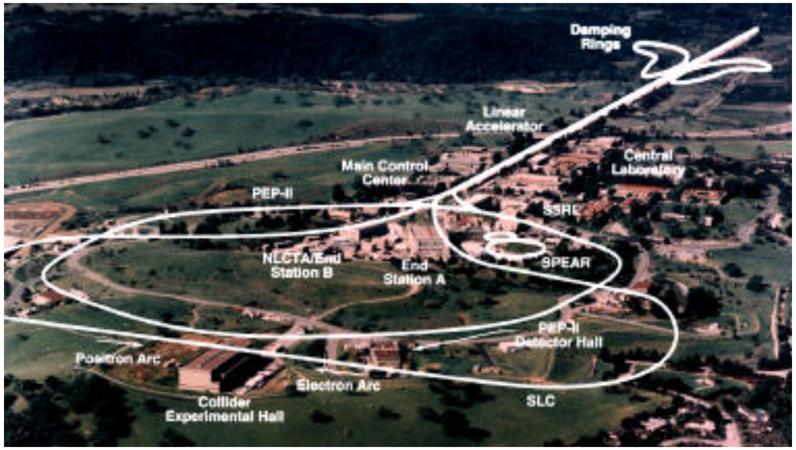


$$\sigma \propto \frac{1}{E_{\text{Lab}}} \qquad A_{\text{Møller}} \propto E_{\text{Lab}} Q^e_W \propto E_{\text{Lab}} \left(1 - 4\sin^2\theta_W\right)$$

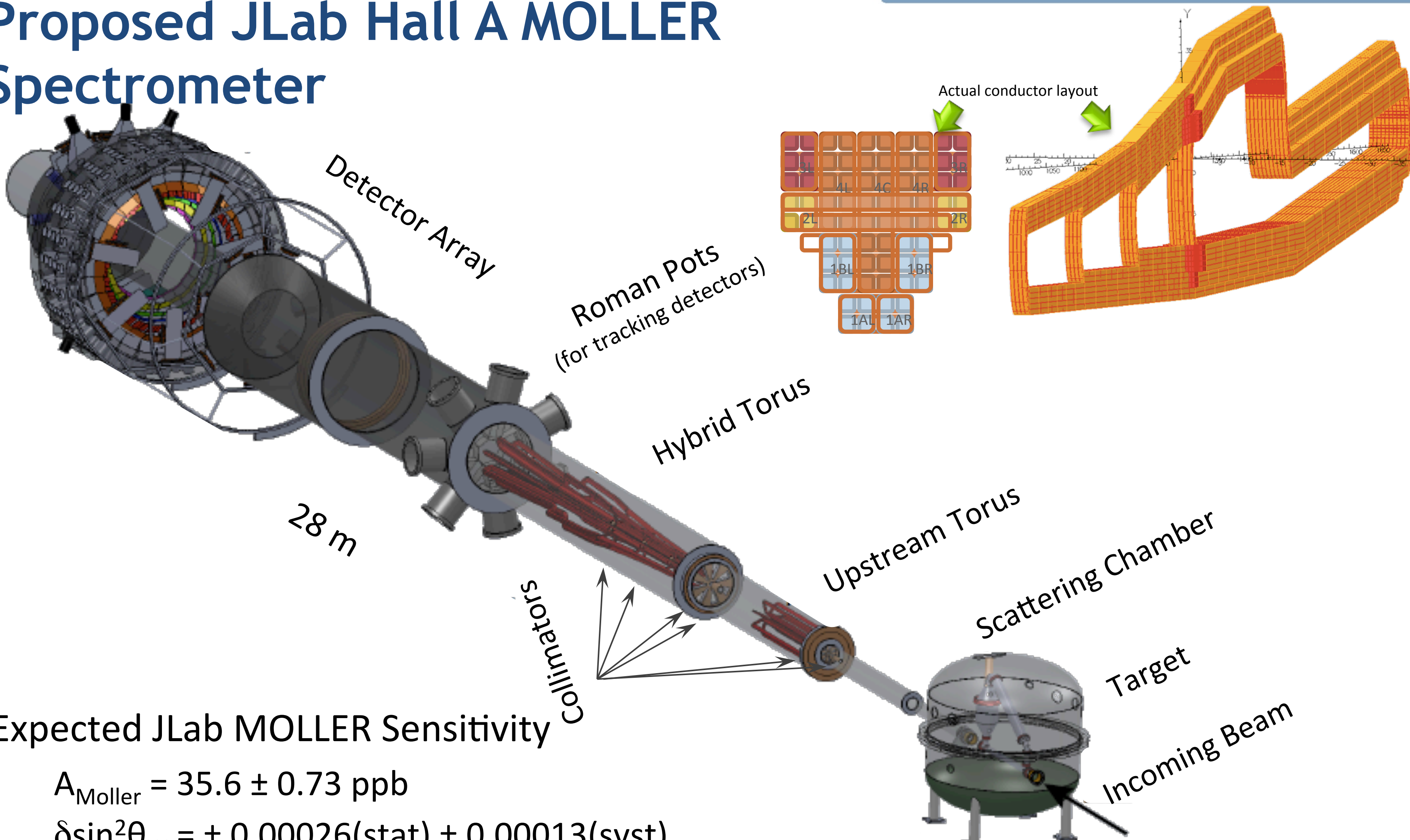
$$\text{Uncertainty} \propto \frac{1}{A_{\text{Møller}}\sqrt{\sigma}} \propto \frac{1}{\sqrt{E_{\text{Lab}}}}$$

Why can we do better @ JLab?

- Well developed Parity-Violation program
  - Large Polarized Luminosity
  - Precise control of beam position and other systematic effects.
- Nearly 100% Azimuthal Acceptance Spectrometer—toroidal design



Proposed JLab Hall A MOLLER Spectrometer



Expected JLab MOLLER Sensitivity

$A_{Moller} = 35.6 \pm 0.73$ ppb

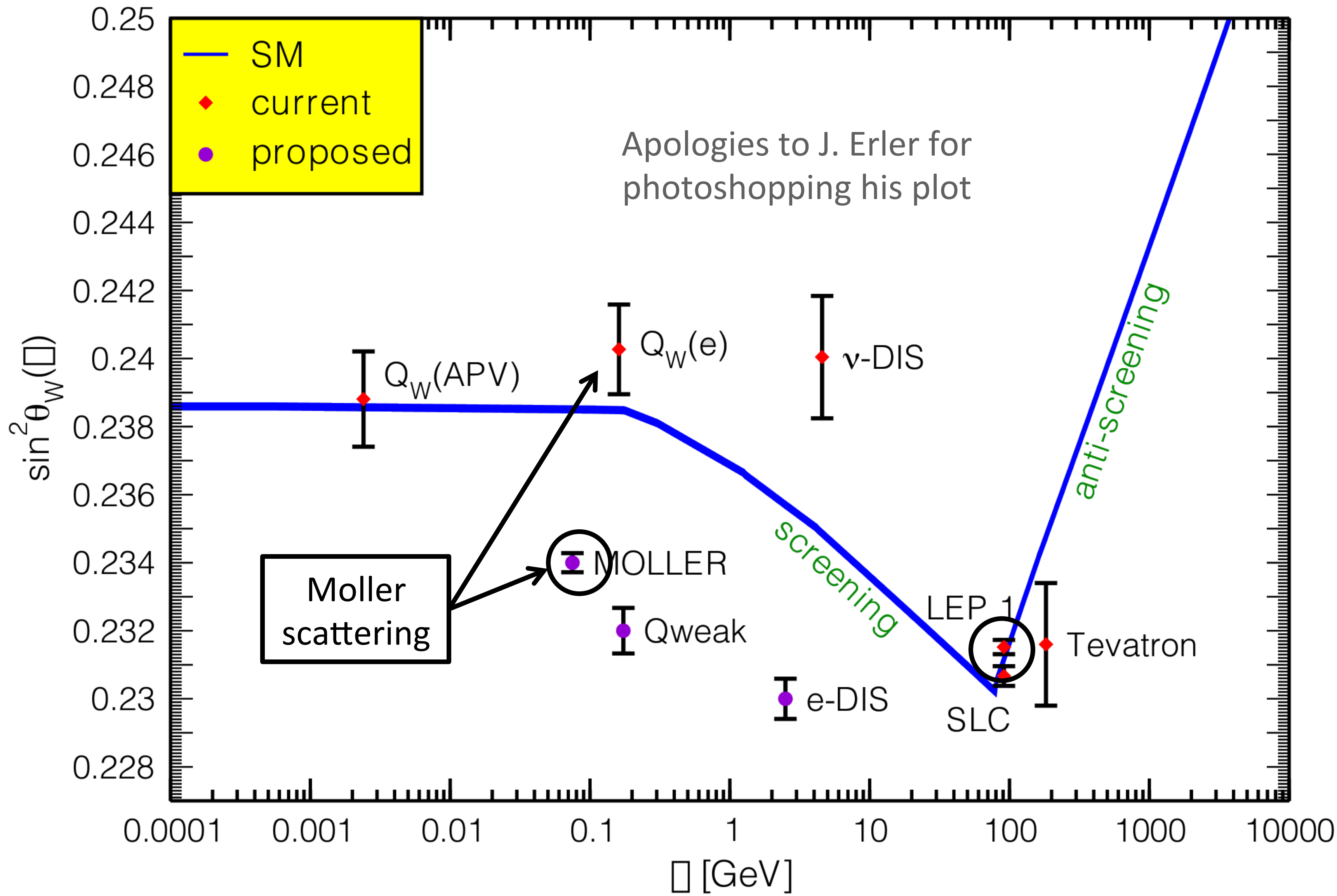
$\delta\sin^2\theta_W = \pm 0.00026(\text{stat}) \pm 0.00013(\text{syst})$

Measured by SLAC E-158

$\sin2\theta^{eff}_W = 0.2397 \pm 0.0010\ (\text{stat.}) \pm 0.0008\ (\text{syst.})$

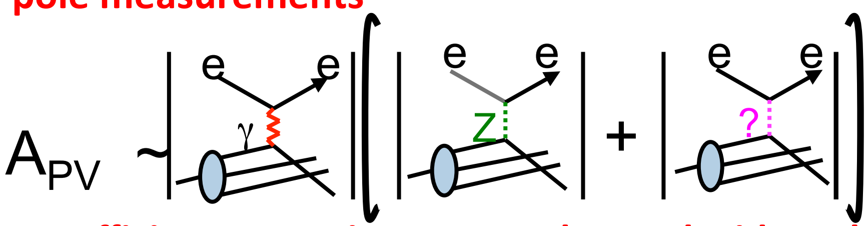
Paul E. Reimer EINN 2011

What about NuTeV?

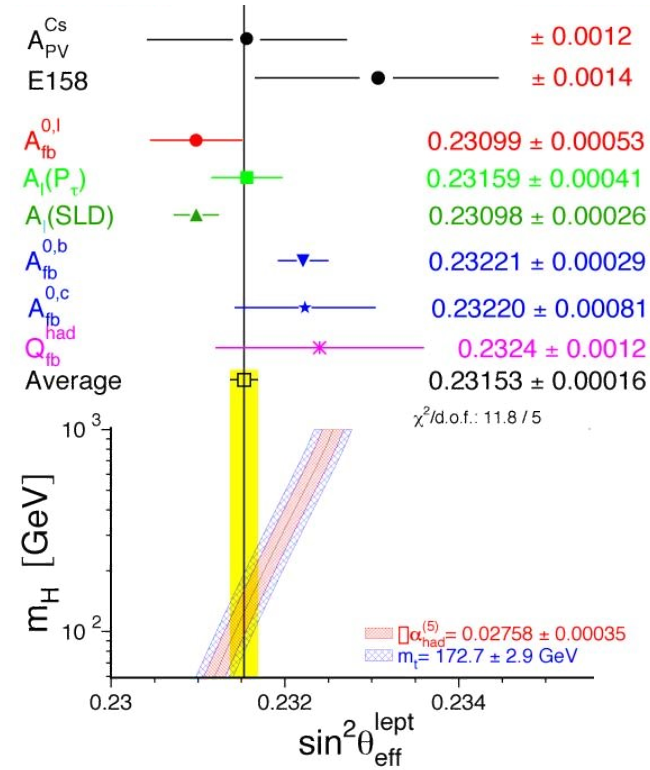


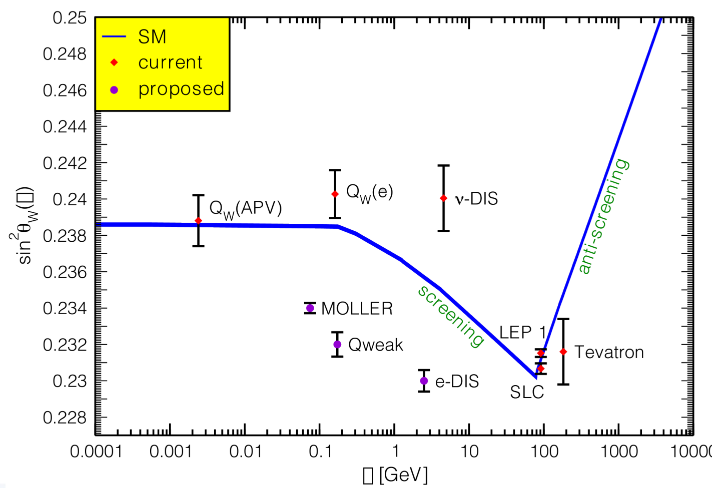
Review

- Measurements of $\sin^2\theta_W$ provide a method to look for processes not included in the Standard Model
- There is "tension" between the best two measurements of (both at the Z-pole)
- Interference terms provide a good way to look for processes/particles not included in the Standard Model
  - **Provides sensitivity to physics which CANNOT be seen in Z-pole measurements**



  - **Not sufficient to use just one probe to elucidate the SM**
- PV-DIS is able to probe both hadron structure and the electroweak Standard Model
  - Blessing and Curse—Wide sensitivity, but need to disentangle
- Moller scattering probes electron vertices
  - Very precise measurement at JLab is possible





Measurements of Nuclear Structure with Parity Violation

Paul E. Reimer

Physics Division, Argonne National Laboratory

HUGS, 4-22 June 2012

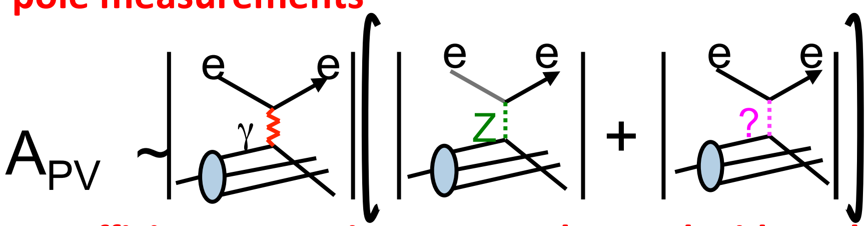
Really—two separate topics unified by my interests

I. Flavor Structure of the Proton
   A. Proton structure—historical view
   B. Sea quarks in the proton & the Drell-Yan reaction
   C. Proton structure in nuclei

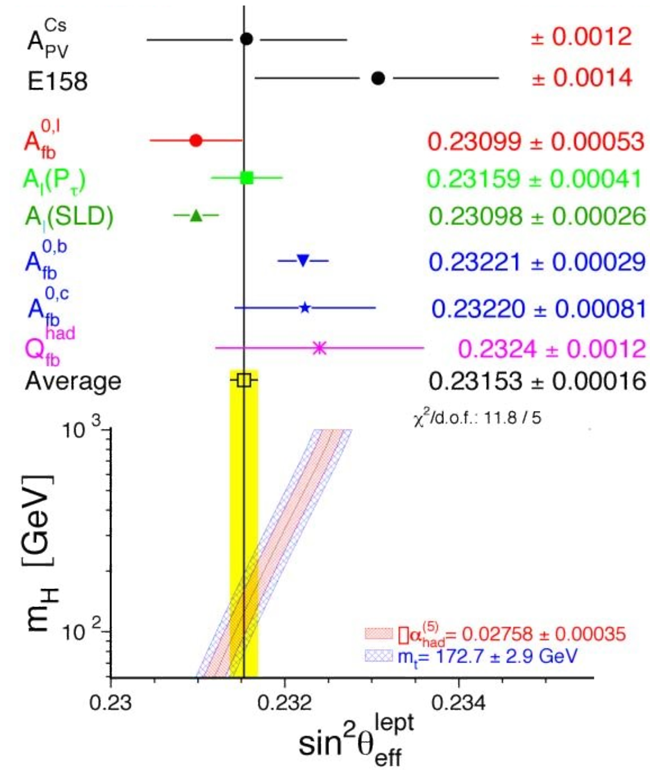
II. Measurements of Parity Violation in Electron Scattering
   A. The Standard Model, electroweak interactions and parity
   B. Tests of the Standard Model with parity violation
      4. Proton Elastic scattering Q_W(proton)
   C. Nuclear Structure with Parity Violation
      1. Strange Form Factors
      2. Neutron skin radius in lead

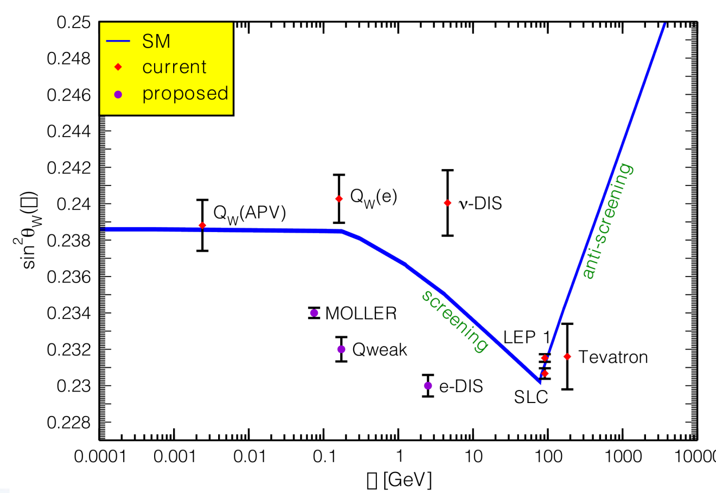
Review

- Measurements of $\sin^2\theta_W$ provide a method to look for processes not included in the Standard Model
- There is "tension" between the best two measurements of (both at the Z-pole)
- Interference terms provide a good way to look for processes/particles not included in the Standard Model
  - **Provides sensitivity to physics which CANNOT be seen in Z-pole measurements**



  - **Not sufficient to use just one probe to elucidate the SM**
- PV-DIS is able to probe both hadron structure and the electroweak Standard Model
  - Blessing and Curse—Wide sensitivity, but need to disentangle
- Moller scattering probes electron vertices
  - Very precise measurement at JLab is possible





Parity Violation in Proton Elastic Scattering: The Weak Charge of the Proton

Parity Violation in Proton Elastic Scattering

- In proton elastic scattering, only C_{1q} terms contribute

  C_{2q} terms are missing because they only occur for non-zero **y = 1 – E'/E**

  Similar derivation to that of PD-DIS—also done in Cahn and Gilman

$$A_{\rm PV} = \frac{\sigma^l - \sigma^r}{\sigma^l + \sigma^r} \propto \frac{\mathcal{M}^l - \mathcal{M}^r}{\mathcal{M}_\gamma} \propto \left(g_A^e g_V^T + \beta g_V^e g_A^T\right)$$

Weak PV

Electromagnetic

Kinematic factor

$$C_{1u} \stackrel{\rm SM}{=} -\tfrac{1}{2} + \tfrac{4}{3}\sin^2\theta_W \approx -0.192$$

$$C_{1d} \stackrel{\rm SM}{=} \tfrac{1}{2} - \tfrac{2}{3}\sin^2\theta_W \approx 0.346$$

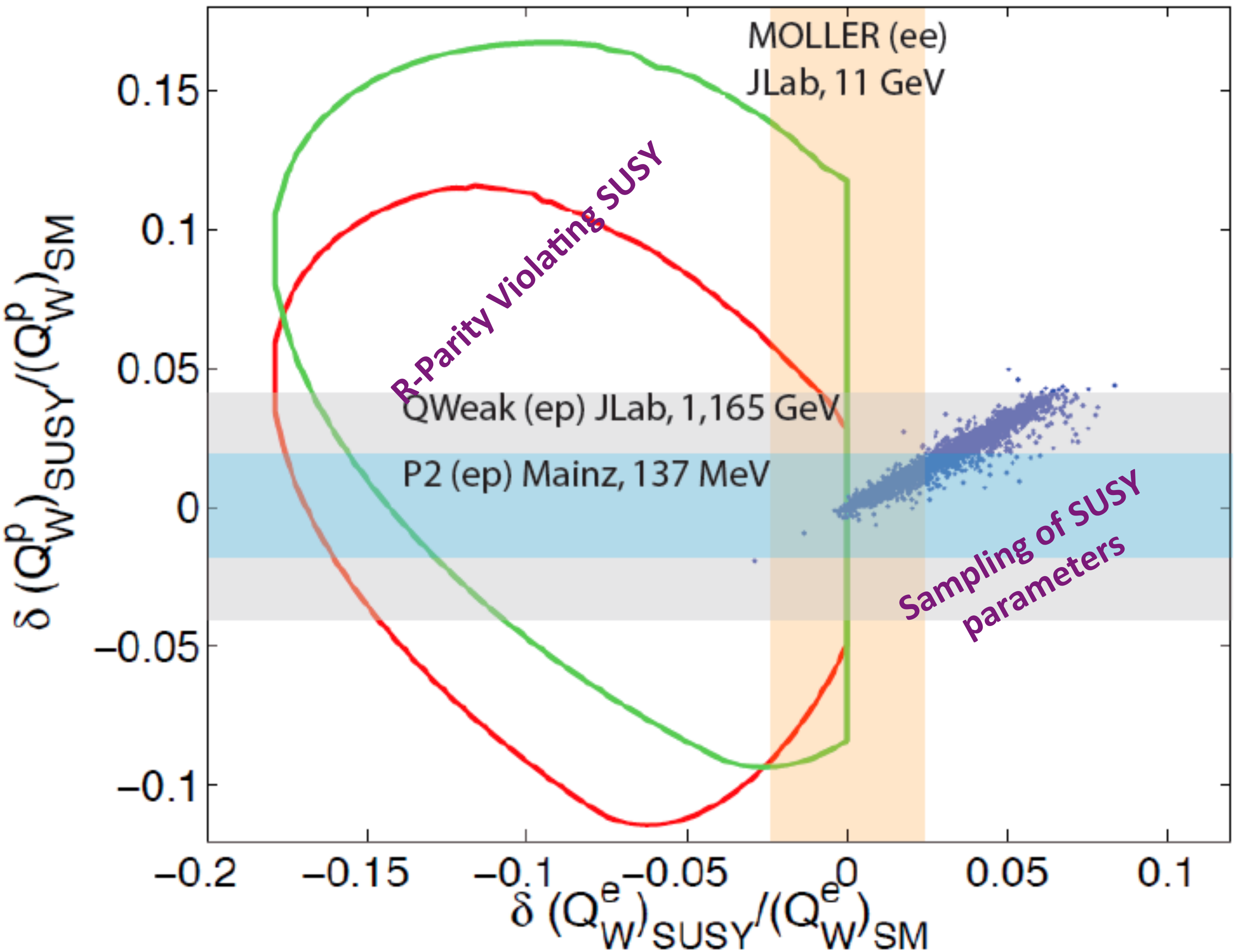
$$C_{2u} \stackrel{\rm SM}{=} -\tfrac{1}{2} + 2\sin^2\theta_W \approx -0.038$$

$$C_{2d} \stackrel{\rm SM}{=} \tfrac{1}{2} - 2\sin^2\theta_W \approx 0.038$$

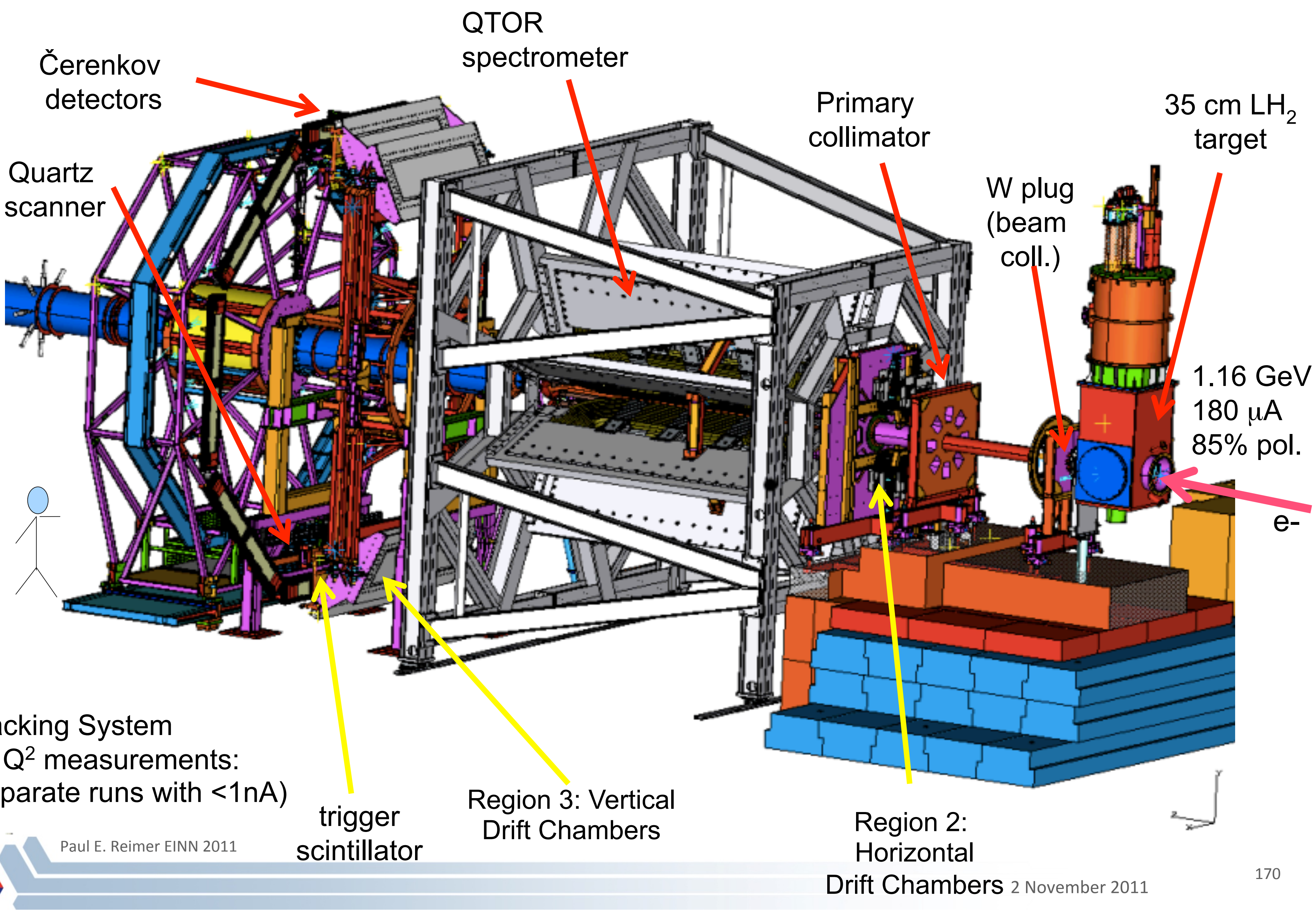
$$A_{\rm elastic} \approx \frac{-G_F}{4\pi\alpha\sqrt{2}} Q^2 Q_W^p + B(\text{nucl. str.})$$

$$Q_{\rm W}^p \equiv -2\left(2C_{1u} + C_{1d}\right) \stackrel{\rm SM}{=} 1 - 4\sin^2\theta_W$$

Example: supersymmetric Standard Model extensions

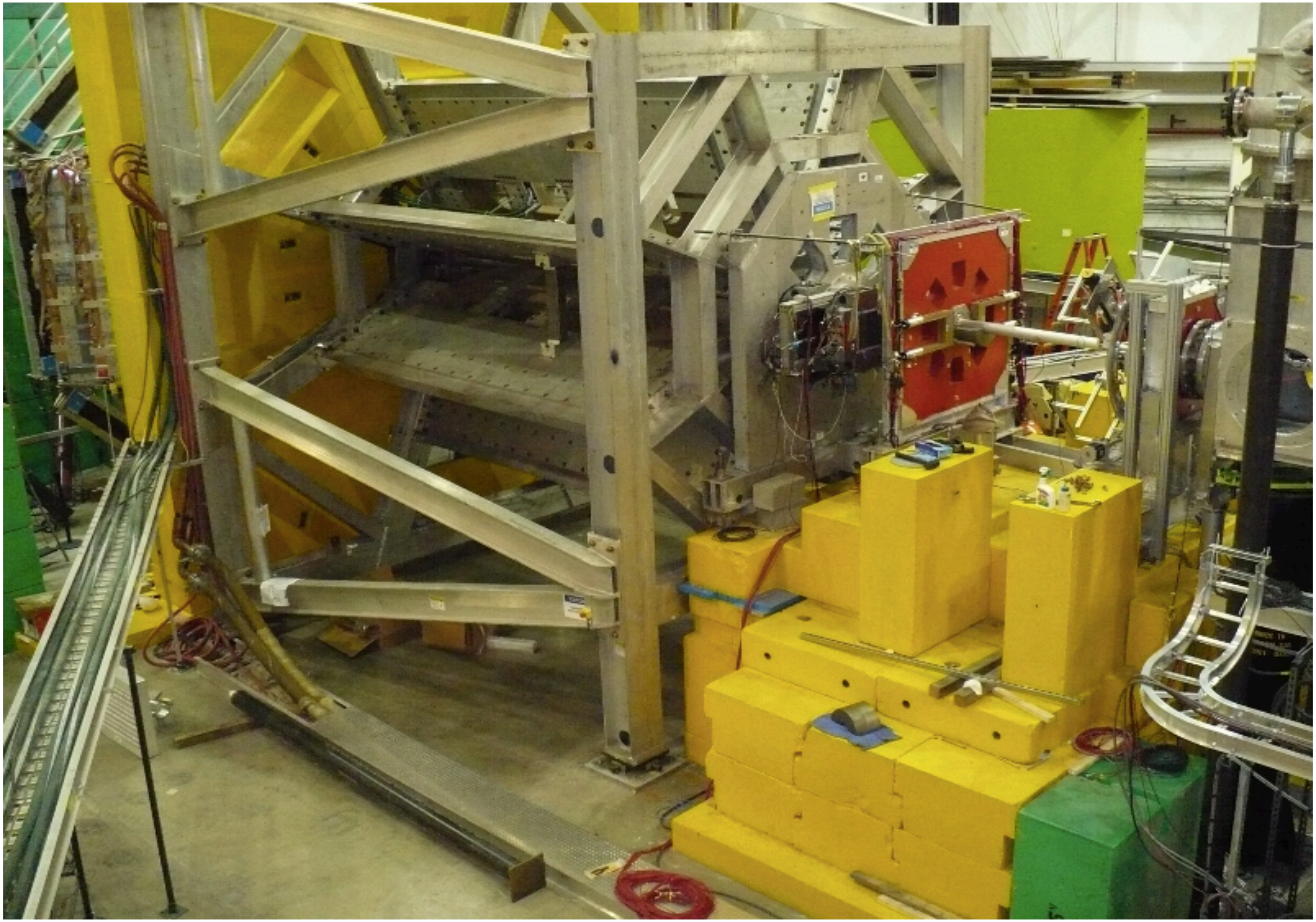


QWeak@JLab Overview

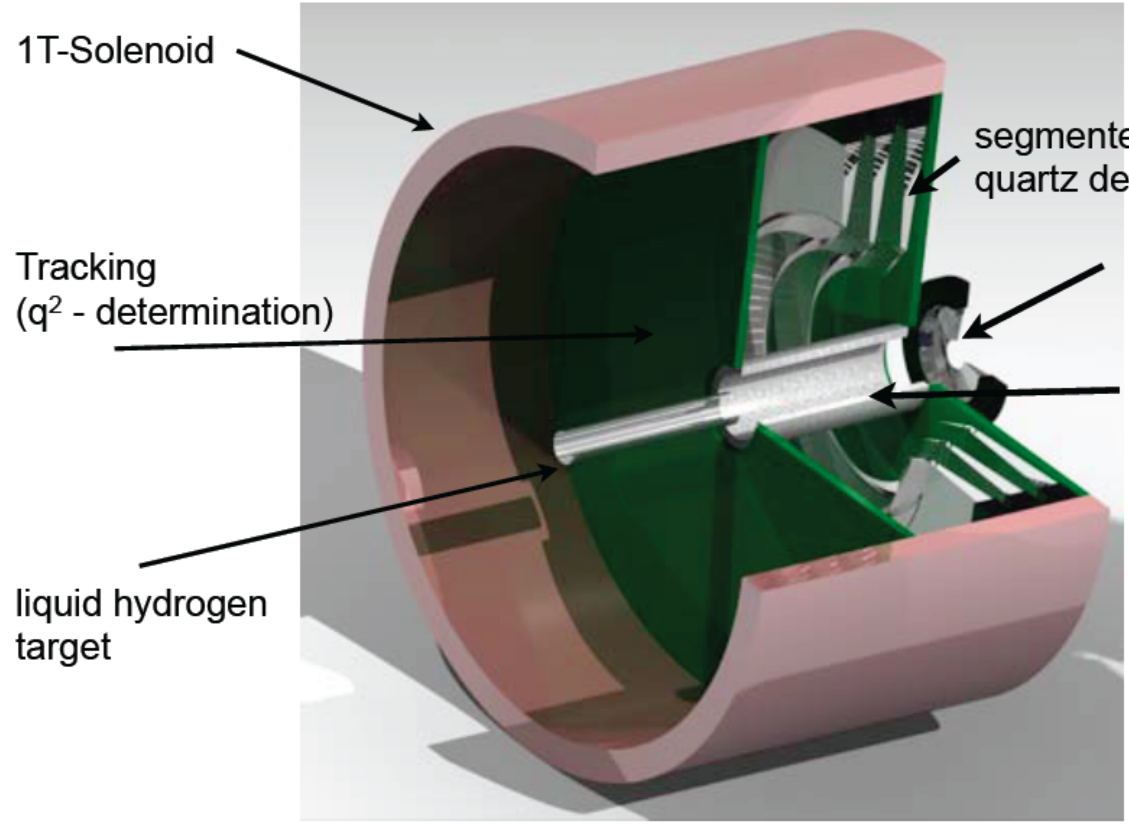


Tracking System
for Q^2 measurements:
(separate runs with <1nA)

Qweak Installation – Spring 2010



P2@MESA



investigate
usability of existing
solenoid (ZEUS)

Central angle 20°

acceptance $\Delta\theta = 20^{o}$

Qweak Proton Status

JLab Qweak

- Just finished data collection
- Run was a fabulous success!!
- Proposal—*expect* $\delta A/A = 2\%$,

  $\delta Q_W/Q_W = 2.8\%$ (stat) 4.0% (total)

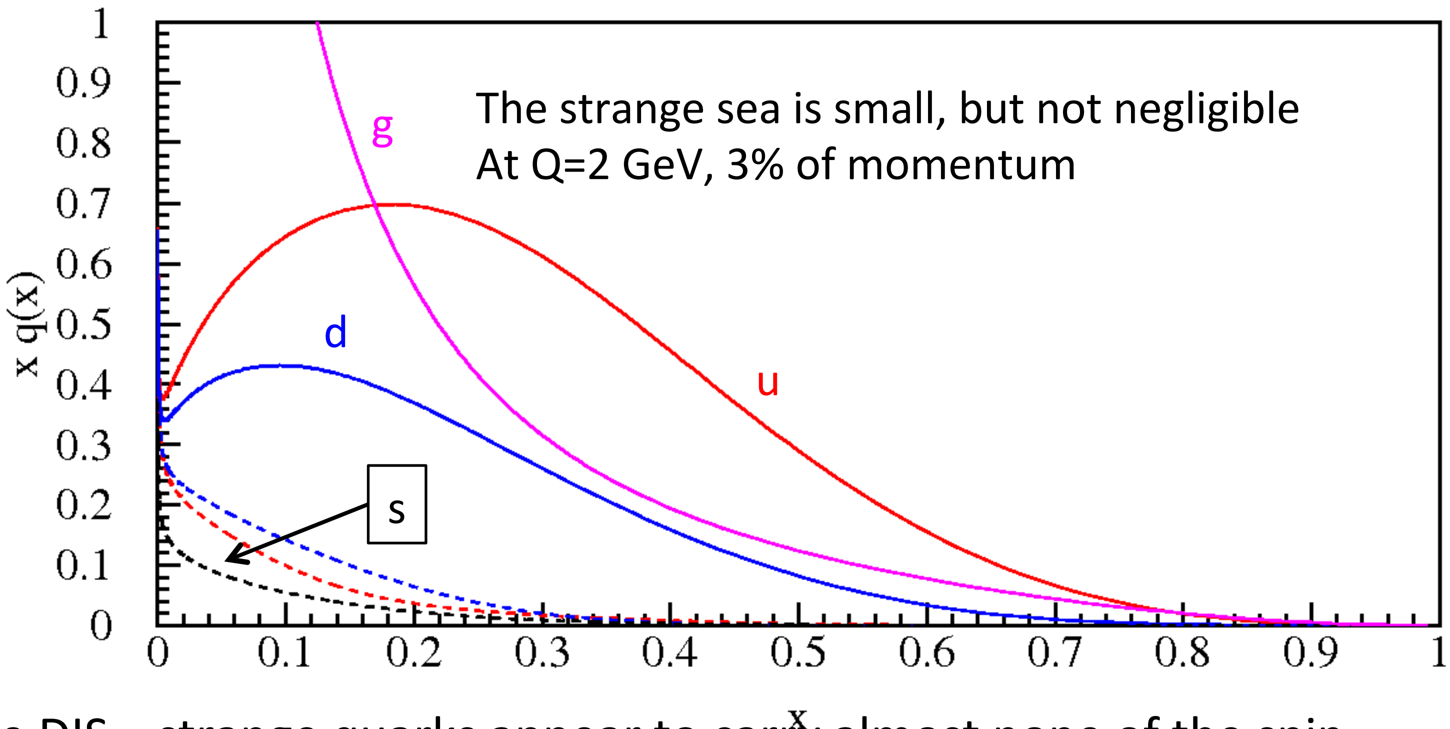
Mainz P2@MESA

- In proposal stage
  - Investigating magnets, funding, . . .
  - Proposal, *expect* $\delta A/A = \pm 1.2\%$ (stat) $\pm 0.9\%$ (syst)

    $\delta \sin^2\theta_W/\sin^2\theta_W = \pm 0.15\%$

Strange Quark Contributions to the Proton's Structure

How Does the Strange Quark Contribute to the Proton?



- Semi-Inclusive DIS—strange quarks appear to carry almost none of the spin

$$S_p = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + \Delta L$$

quark glue orbital

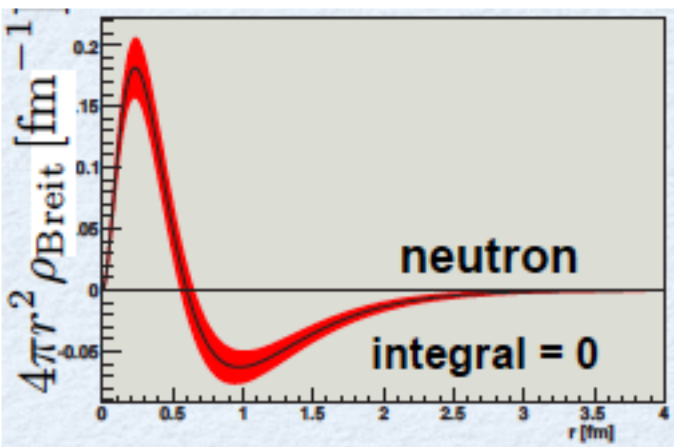
$\Delta\Sigma \sim 0.25$

$$\Delta s = 0.028 \pm 00.033 \pm 0.009$$

Strange Quark Contribution to E & M Form Factors?

- Recall Pion cloud partially accounted for dbar/ubar asymmetry.

$$|p\rangle = |p_0\rangle + \alpha|N\pi\rangle + \beta|\Delta\pi\rangle + \gamma|\Lambda K\rangle + \dots$$



- Same model could account for Neutron's charge distribution
- Why not have a Kaon cloud?
- This would lead to a significantly non-zero strange form factor

Sachs Form Factors

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{Mott}} \left[\frac{G_E^2 + \tau G_M^2}{1+\tau} + \tau G_M^2 \tan^2\frac{\theta}{2}\right] \qquad \tau = \frac{Q^2}{4M^2}$$

1. Express form factors in terms of quark contributions for proton and neutron

$$G_E^p = \frac{2}{3} G_E^{u,p} - \frac{1}{3} G_E^{d,p} - \frac{1}{3} G_E^s$$

$$G_E^n = \frac{2}{3} G_E^{d,n} - \frac{1}{3} G_E^{u,n} - \frac{1}{3} G_E^s$$

2. Invoke isospin symmetry (flavor/strong isospin)
3. Two measurements—H and n (or Deuterium) → two equations and three unknowns
   - Need third equation
   - No Parity Violation so far

Enter Parity Violation

For a proton:

$$A = \left[\frac{-G_F Q^2}{4\pi\alpha\sqrt{2}}\right]\frac{A_E + A_M + A_A}{\sigma_p}$$ ~ few parts per million

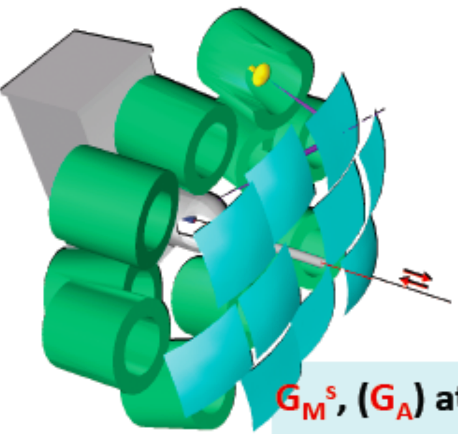
$$A_E = \epsilon G_E^p G_E^Z \qquad A_M = \tau G_M^p G_M^Z \qquad A_A = (1 - 4\sin^2\theta_W)\epsilon' G_M^p \tilde{G}_A$$

Forward angle — Backward angle

$$G_E^{p,Z} = \left(1 - \frac{8}{3}\sin^2\theta_W\right) G_E^u - \left(1 - \frac{4}{3}\sin^2\theta_W\right) G_E^d - \left(1 - \frac{4}{3}\sin^2\theta_W\right) G_E^s$$

- For a proton target—measure at forward angles to pick out G_E^Z term
- HAPPEX He (II) alternative
  - Use ^{4}He target then for S=0, T=0 only G_E^s contributes

Experimental Overview



SAMPLE

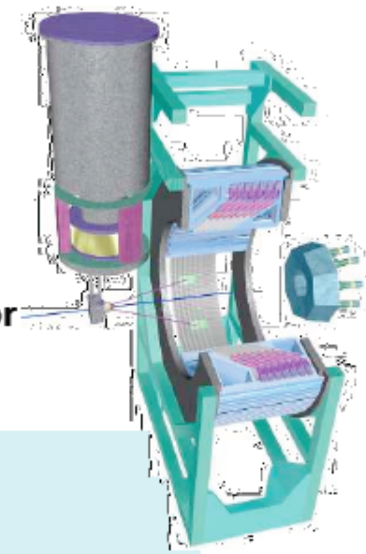
open geometry, integrating

G_M^s, (G_A) at $Q^2 = 0.1$ GeV^2

A4

Open geometry

Fast counting calorimeter for background rejection



$G_E^s + 0.23\, G_M^s$ at $Q^2 = 0.23$ GeV^2

$G_E^s + 0.10\, G_M^s$ at $Q^2 = 0.1$ GeV^2

G_M^s, G_A^e at $Q^2 = 0.23$ GeV^2

HAPPEX

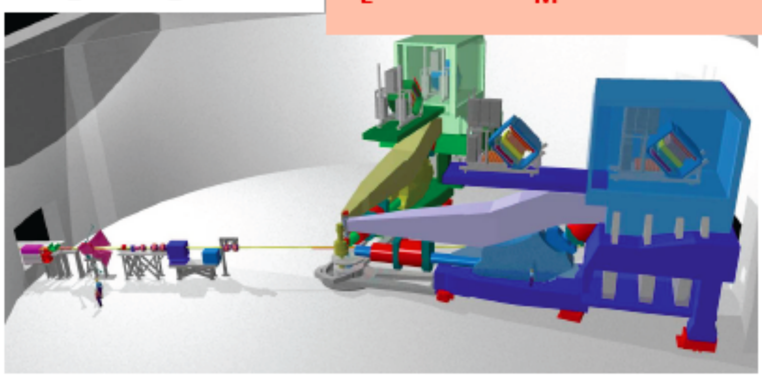
Precision spectrometer, integrating

$G_E^s + 0.39\, G_M^s$ at $Q^2 = 0.48$ GeV^2

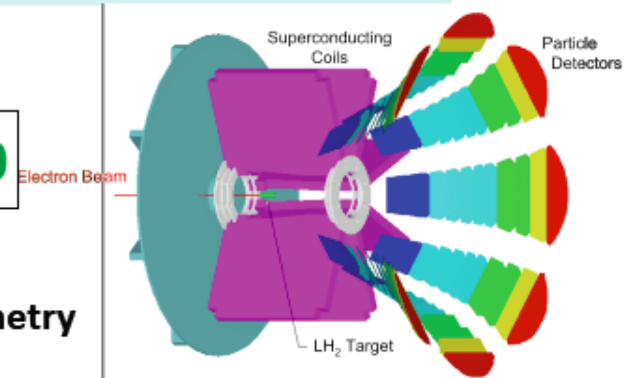
$G_E^s + 0.08\, G_M^s$ at $Q^2 = 0.1$ GeV^2

G_E^s at $Q^2 = 0.1$ GeV^2 (^{4}He)

$G_E^s + 0.48\, G_M^s$ at $Q^2 = 0.62$ GeV^2



G0



Open geometry

Fast counting with magnetic spectrometer + TOF for background rejection

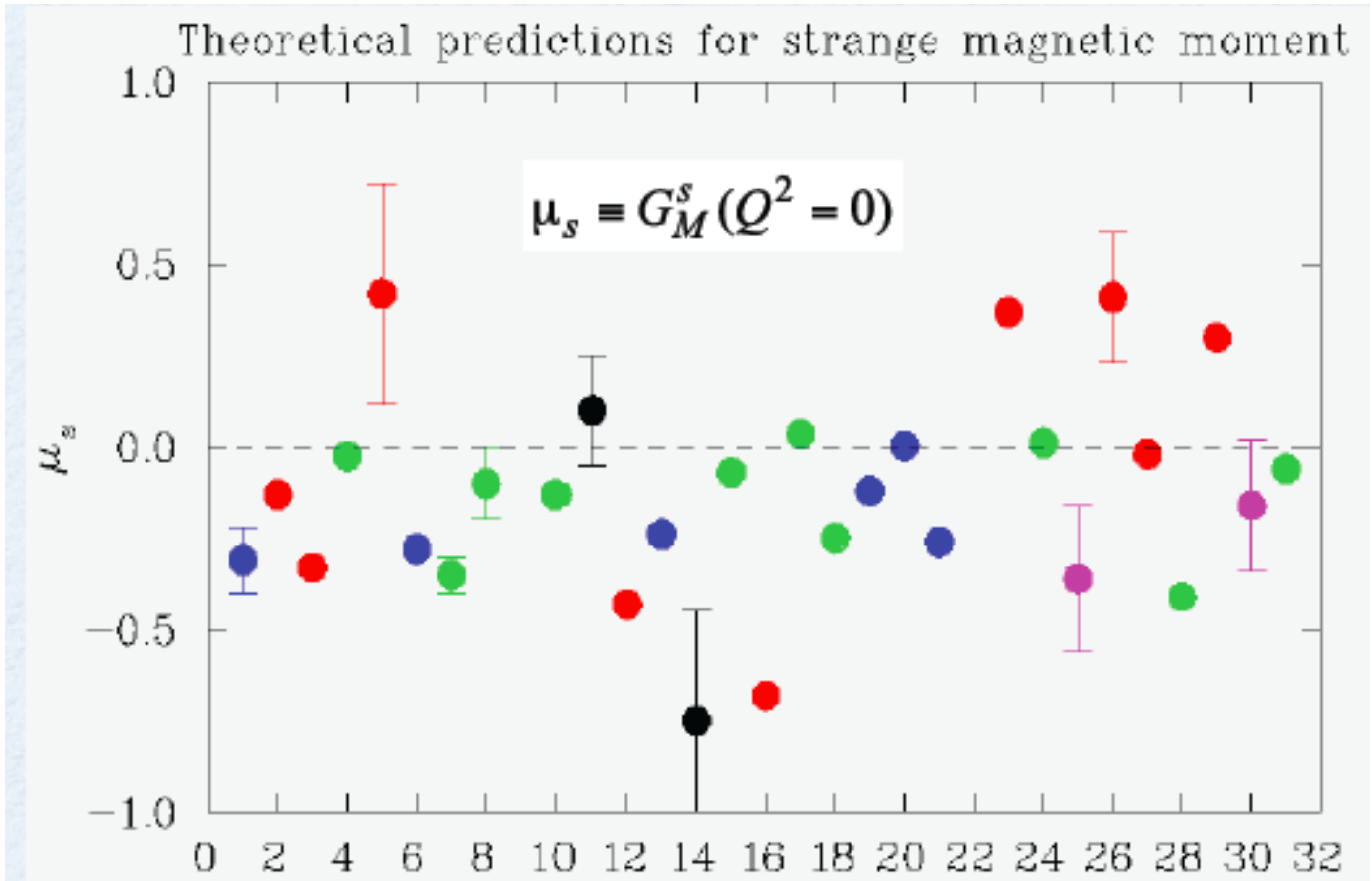
$G_E^s + \eta\, G_M^s$ over $Q^2 = [0.12, 1.0]$ GeV^2

G_M^s, G_A^e at $Q^2 = 0.23, 0.62$ GeV^2

Slide from Kent Paschke, PAVI 09 and Krishna Kumar

Theoretical Estimates for G^s

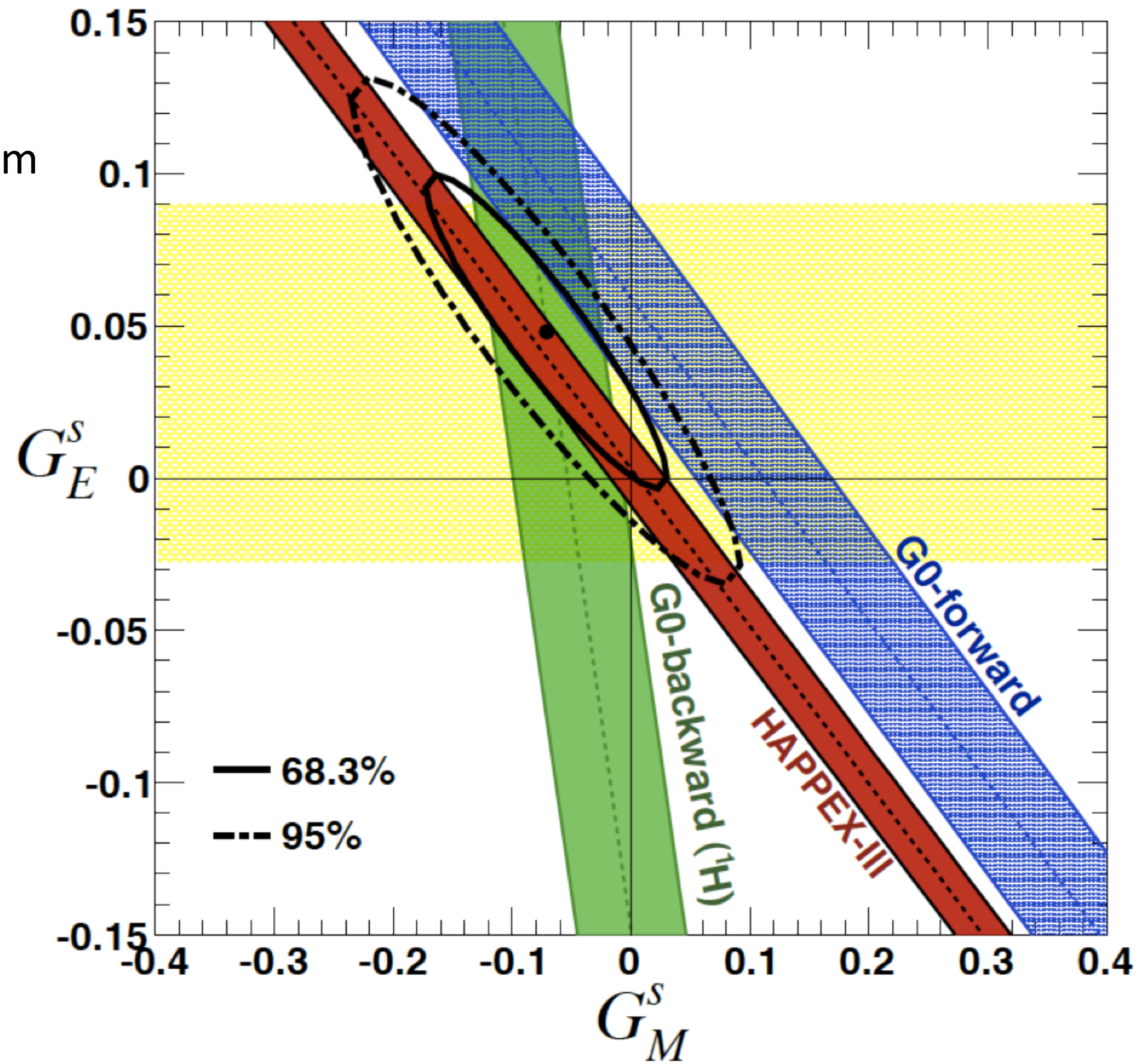
- Expectation that it was likely there was a significant strange contribution to the magnetic moment of the proton
- Theory couldn't agree on size or even sign, however



HAPPEX III Results

- Very little contribution from strange quarks to the observed Electric and Magnetic form factors of the proton
- HAPPEX He results:

  G_E^s = -0.038 +/-0.042 (stat) +/-0.010 (syst)

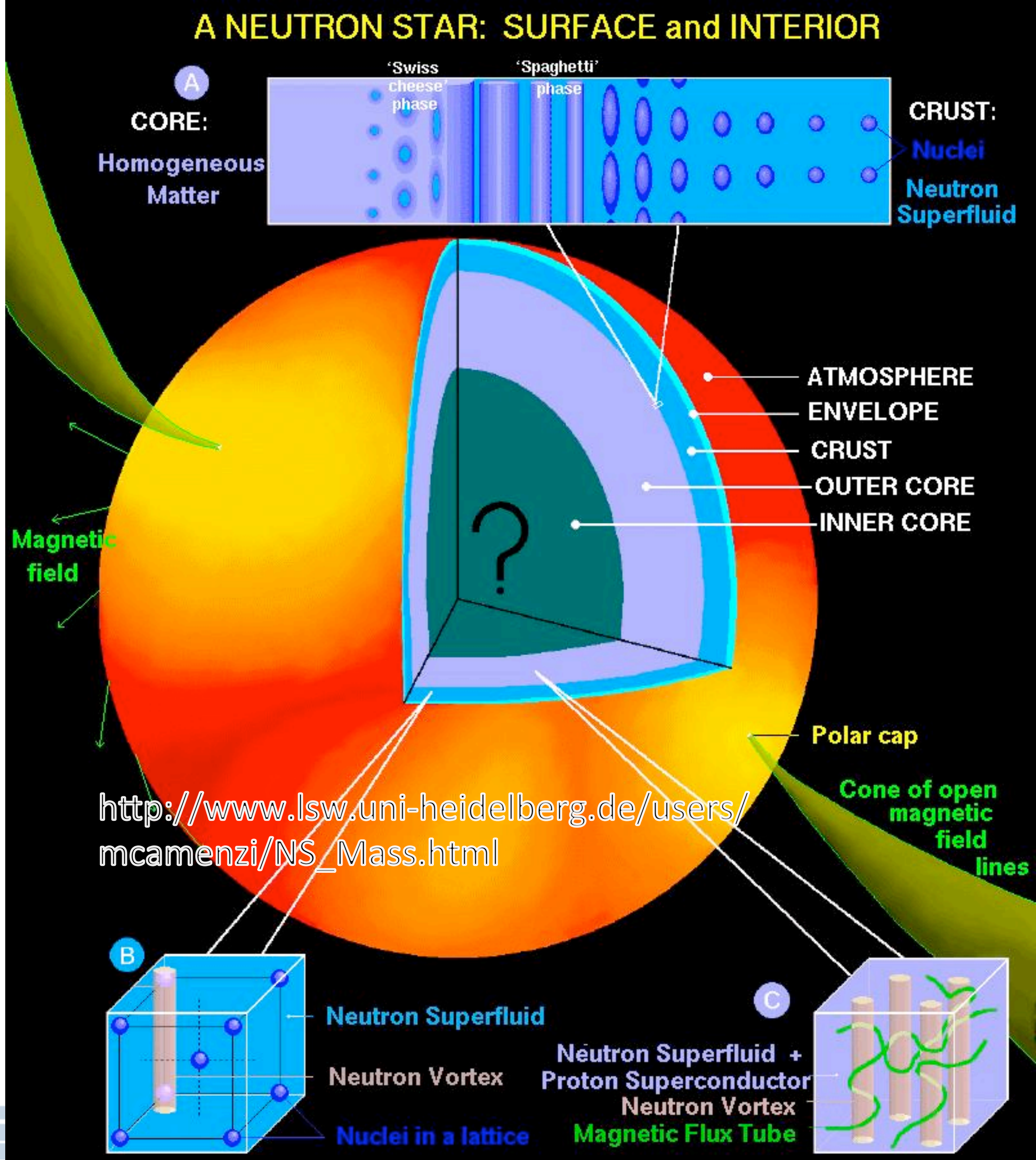


Neutron Stars

Neutron Star

- Outer crust of dense neutrons
- Unknown equation of state

- Would like to know about the neutron solid<-> liquid transition in neutron star



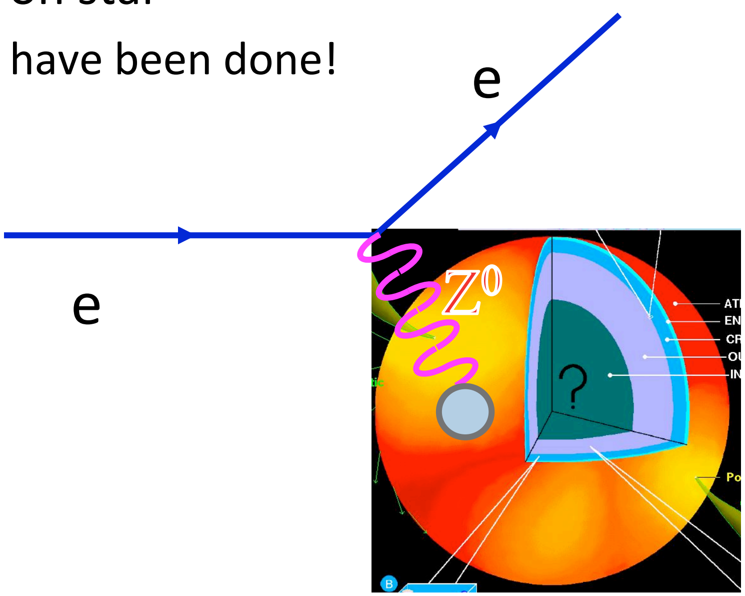
http://www.lsw.uni-heidelberg.de/users/mcamenzi/NS_Mass.html

Measuring Neutrons densities

- Electron scattering, in general, does not “see” neutrons
  - Electrons scatter via photons, which couple to electric charge
  - Neutron has not nuclear charge, hence no scattering

	EM	Weak
Proton	+1	$1\text{-}4\sin^2\theta_W$ (small)
Neutron	0	+1

- Weak scattering couples to weak charge
  - Weak charge of Neutron is large
- Just need to to PV measurement on neutron star
  - Difficult experiment, but all the easy ones have been done!
- Use 208Pb as a surrogate for Neutron star
  - Both have approximately the same neutron density in their skin
  - Both should share similar equation of state



PREX and the neutron skin in lead

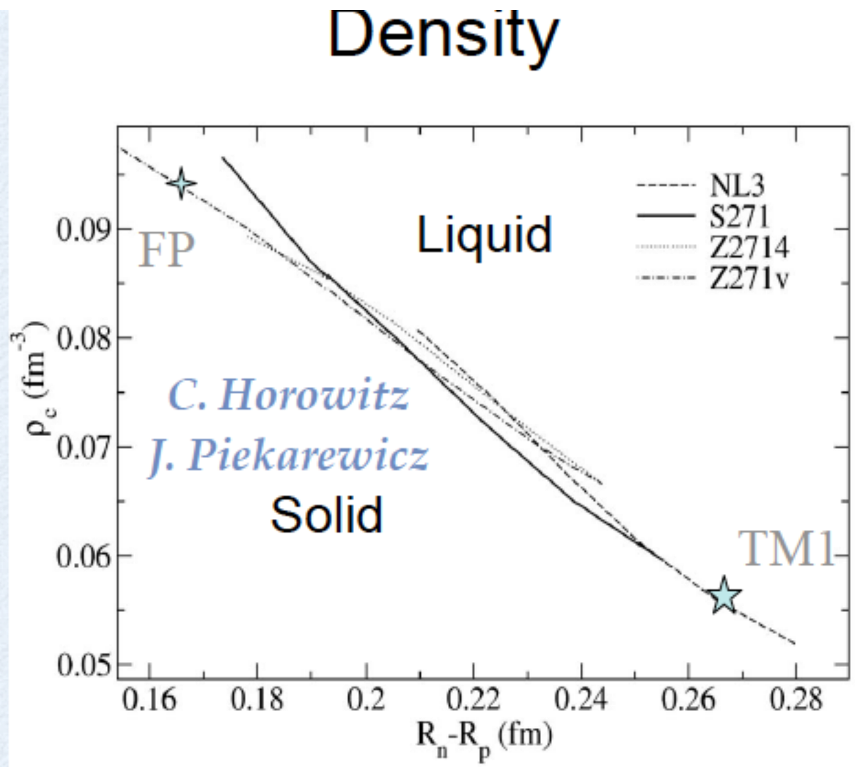
PREX Experiment

- First run in 2009

A_{PV} =0.656 +/-0.060 (stat) +/-0.014 (syst)

$\delta(R_p\text{-}R_n)$ = 0.33+0.16-0.18

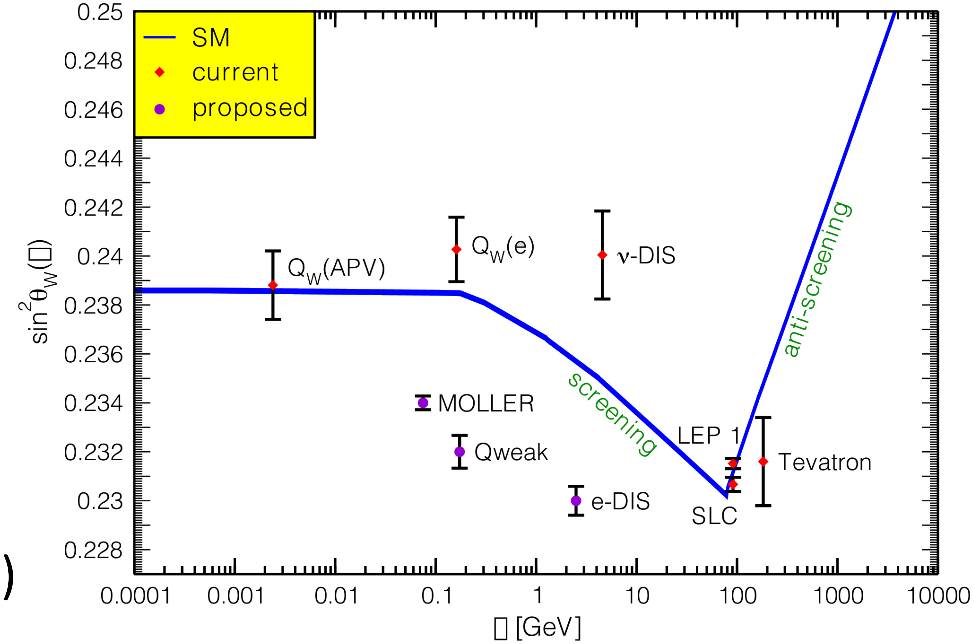
- hope to run again after upgrade

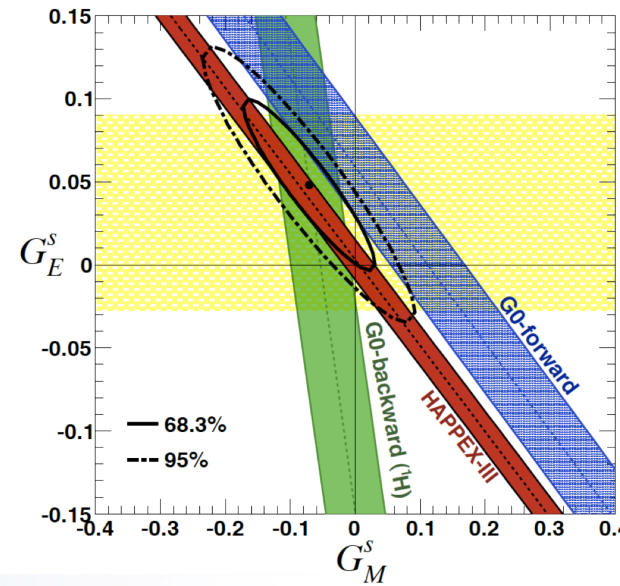


- Thicker neutron skin in Pb means energy rises rapidly with density→Quickly favors uniform phase.
- Thick skin in Pb→low transition density in star.

Summary of Electroweak Interactions

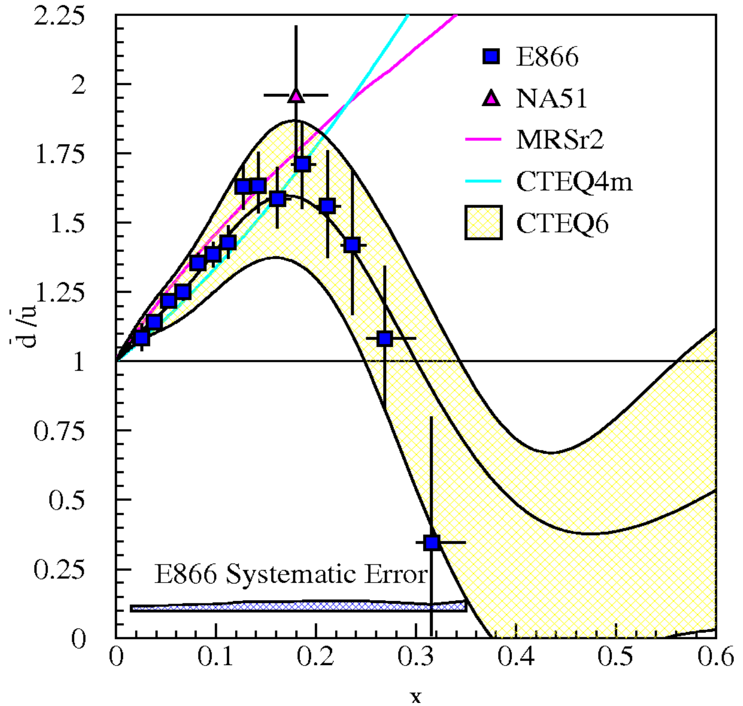
- Measurements of Standard Model parameters at low and intermediate energies is important
  - Sensitivity to interactions that may not be apparent at the Z-pole or higher energies
  - Extremely precise measurements are possible
- Weak physics can probe parton (strong) configurations
  - PVDIS measurements of Charge Symmetry Violation and Higher twist expansion
  - Strange quark form factors
- Parity Violating Electron Scattering is a great tool

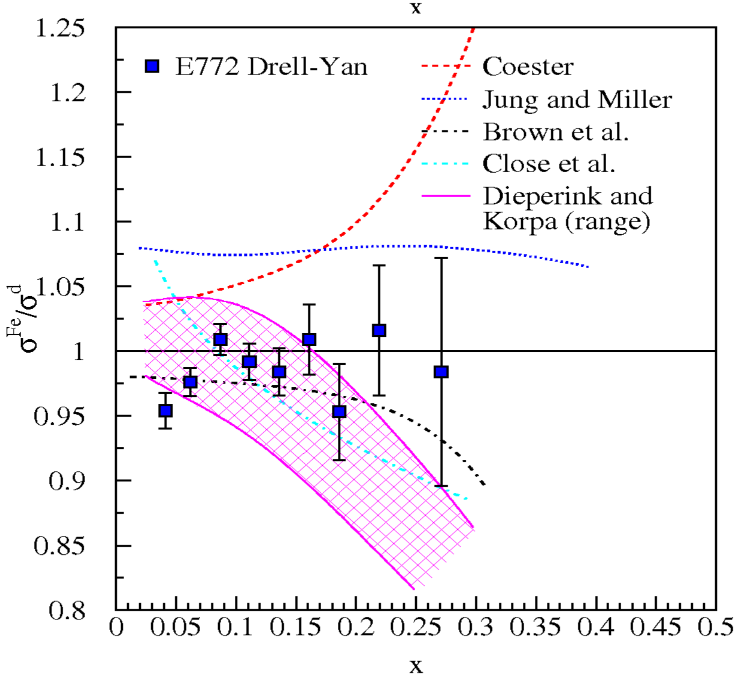




Summary of Flavor Structure

- **The proton is fundamentally more than three valence quarks and glue**
  - At any energy scale, there must be sea quarks
  - There is a large flavor asymmetry in within the sea and at present we have little understanding of its origins
  - Nevertheless, categorizing hadrons by their valence structure is amazingly effective
- **The nucleus is not just a "bag" of protons and neutrons**
  - The internal quark-level structure of the nucleons appears to be modified by the nuclear environment
  - It appears to affect valance and sea distributions differently
  - At present, we have little understanding of the origin of this effect
- **Drell-Yan is a wonderful tool**






Physics is
Exciting!