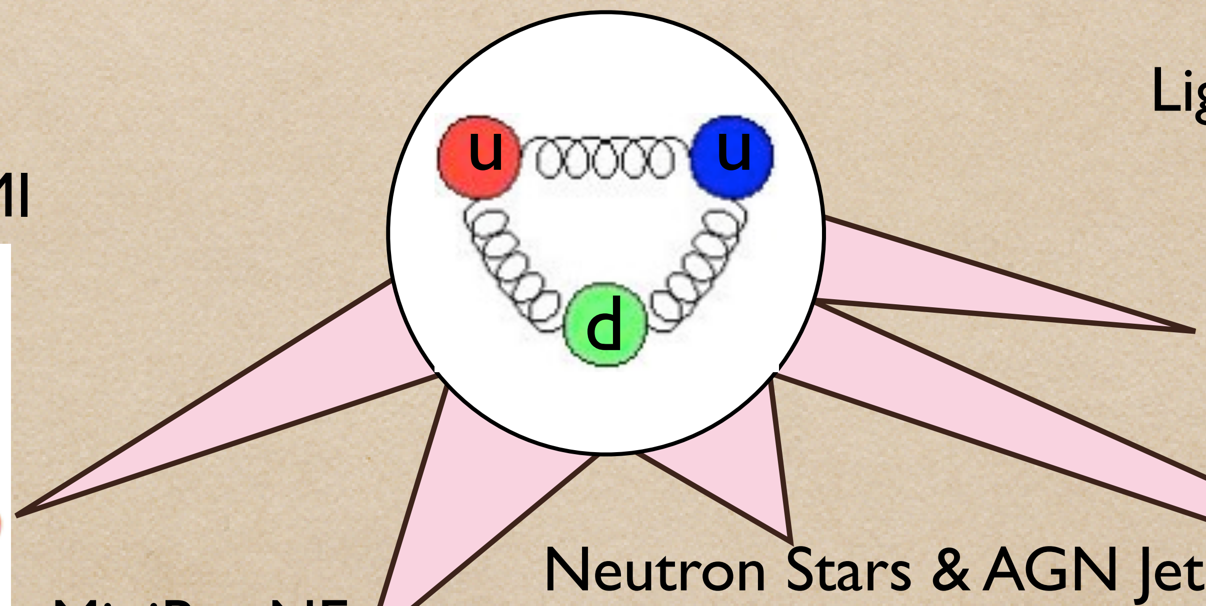
Mikhail Gorshteyn

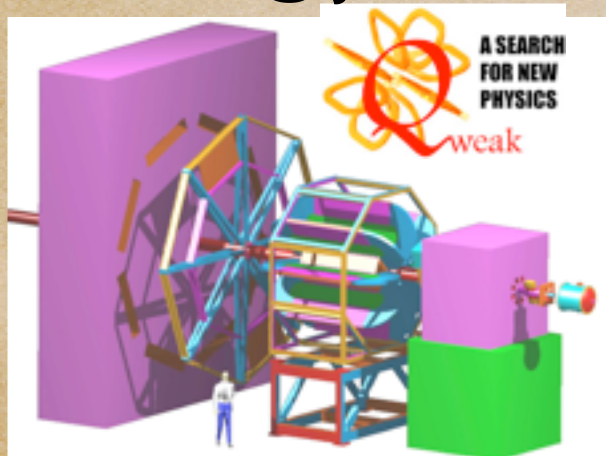
March 2013

Resolving New Physics with Theoretical Study of QCD and Hadron Structure



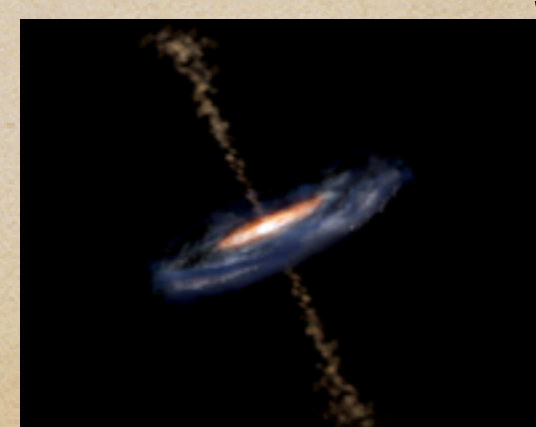
Light muonic atoms @ PSI

QWEAK @ JLab, MAMI



MiniBooNE

Neutron Stars & AGN Jets



PREX @ JLab

STANDARD MODEL

OF ELEMENTARY PARTICLES AND FUNDAMENTAL INTERACTIONS

FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin =1/2

Flavor	Mass GeV/c^2	Electric charge
ν_L lightest neutrino*	$(0-0.13)\times10^{-9}$	0
e electron	0.000511	–1
ν_M middle neutrino*	$(0.009-0.13)\times10^{-9}$	0
μ muon	0.106	–1
ν_H heaviest neutrino*	$(0.04-0.14)\times10^{-9}$	0
τ tau	1.777	–1

Quarks spin =1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.002	2/3
d down	0.005	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	173	2/3
b bottom	4.2	–1/3

BOSONS

force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.39	–1
W^+ W bosons	80.39	+1
Z^0 Z boson	91.188	0

Strong (color) spin =1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Properties of the Interactions

The strengths of the interactions (forces) are shown relative to the strength of the electromagnetic force for two u quarks separated by the specified distances.

Property	Gravitational Interaction	Weak Interaction (Electroweak)	Electromagnetic Interaction	Strong Interaction
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge
Particles experiencing:	All	Quarks, Leptons	Electrically Charged	Quarks, Gluons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons
Strength at 10^{-18} m	10^{-41}	0.8	1	25
Strength at 3×10^{-17} m	10^{-41}	10^{-4}	1	60

STANDARD MODEL

Unified framework for 3 of 4 forces - renormalizable non-abelian gauge field theory

Simple symmetry principle to organize all known phenomena;

$$SU(3)_c \times SU(2)_L \times U(1)_Y$$

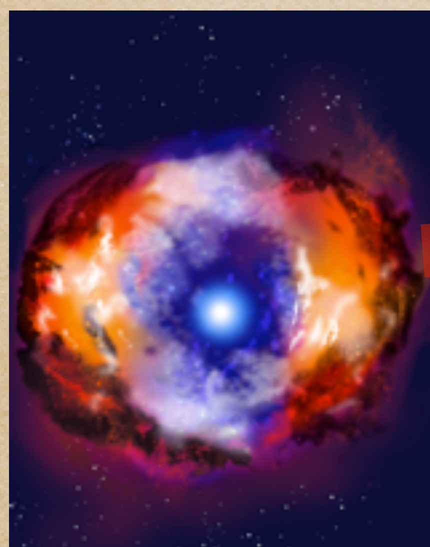
Predictive power - experimentally observed predictions (Z,W, Higgs bosons, 3 fermion generations, asymptotic freedom, anomaly, CVC, t-quark mass, running coupling etc.);

Offers an explanation to the origin of mass - Higgs boson;

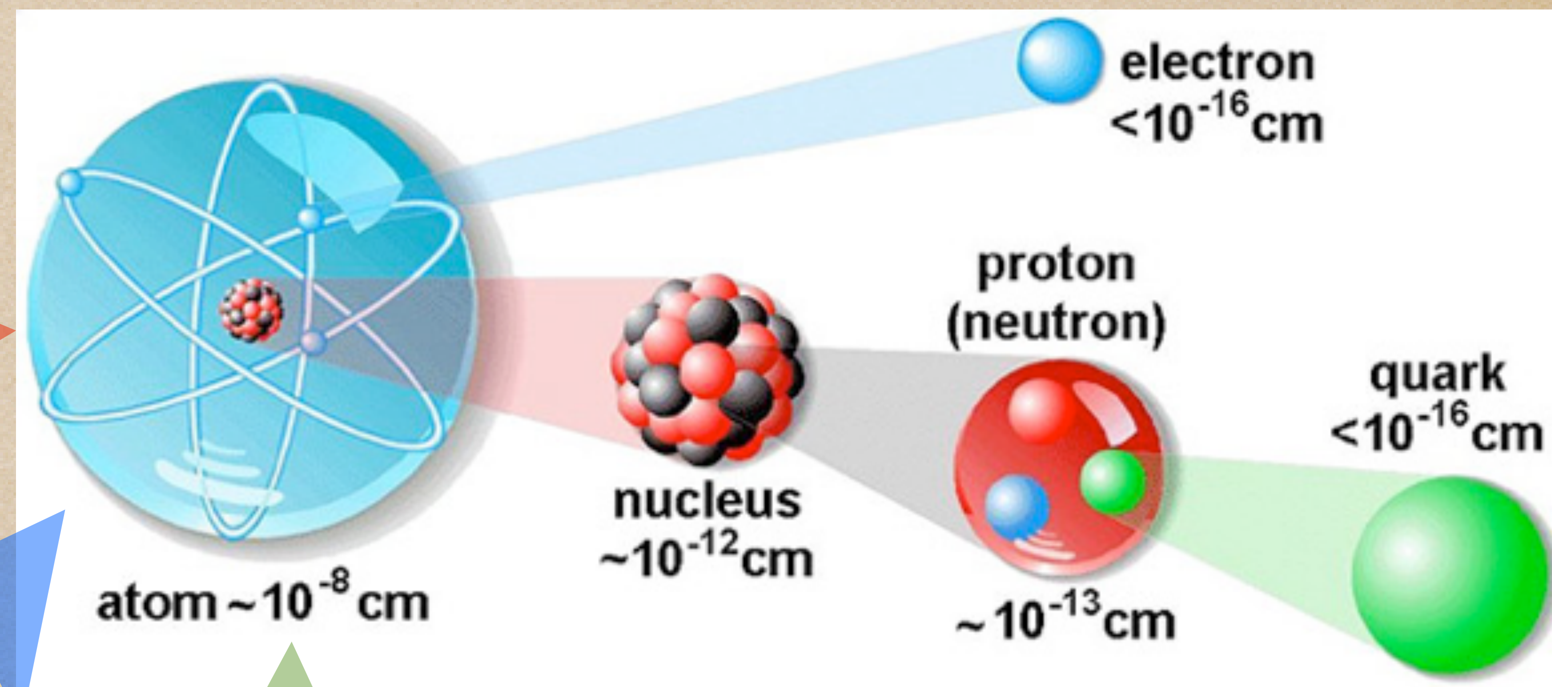
Can accommodate further properties (neutrino oscillations, CP-violation in K, B-decays etc.)

Everything we know is made of the same building blocks and is bound together by the same interactions

Stars & Galaxies



$\mathbf{R_{Galaxy}} \sim 10^{22}\mathbf{cm}$



Earth & planets

$\mathbf{R_{Earth}} \sim 6.4 \cdot 10^{8}\mathbf{cm}$

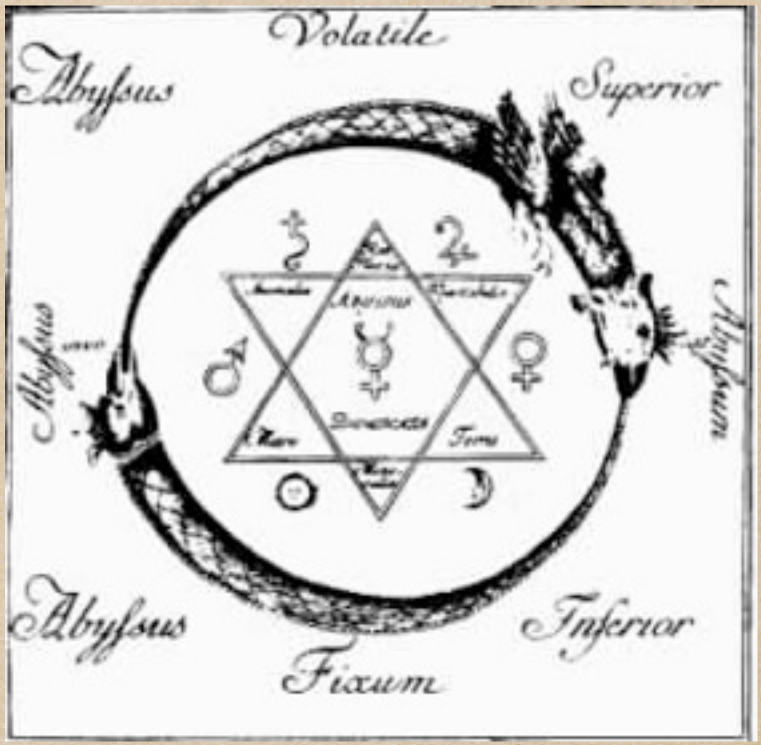
Life

$\mathbf{DNA} \sim 10^{-5}\mathbf{cm}$

WE LIVE AN ALCHEMIST'S DREAM

Hermetics: the whole Universe is driven by one and only principle

Study the microcosm (small) to learn about the macrocosm (big)



Standard Model is our philosophical stone

same principles describe phenomena in atoms and in stars.

If our understanding of the hydrogen atom changes, it propagates in all Universe

WE LIVE AN ALCHEMIST'S DREAM

An alchemist kneels to a Royalty/Duke/Count promising to make gold out of lead;

After N years no gold found - alchemist imprisoned/decapitated

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A physicist submits a grant proposal to DOE/NSF promising to find New Physics;

After 3 years no New Physics found - grant renewed/terminated, the life of the physicist spared

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Great improvement in safety at work

IT'S NOT THE END OF THE STORY...

We may know WHAT everything is made of,
but we still don't know HOW exactly...

The Higgs mechanism only accounts for ~5% of the nucleon mass - where does the rest come from?

Quarks are confined inside hadrons - what exactly is the mechanism of confinement?

Do other QCD bound states (exotics) exist? - Hall D @ JLab

Are neutrinos Dirac or Majorana?

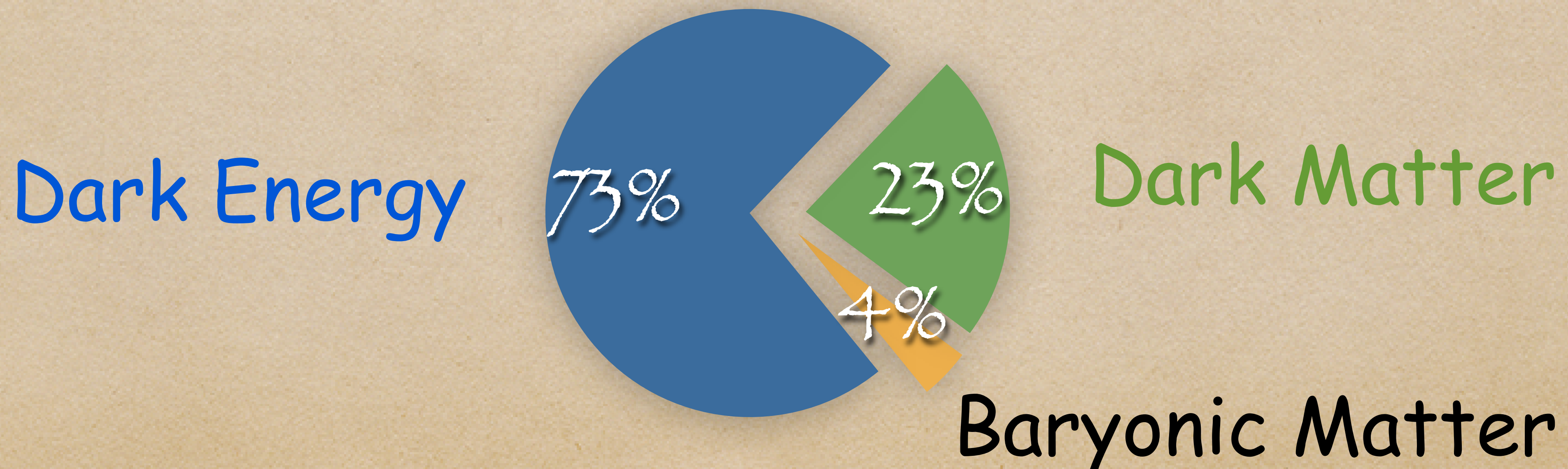
IT'S NOT THE END OF THE STORY...

Standard Model is incomplete:

- SM turns out to be extremely fine-tuned (hierarchy problem)

- CP violation and matter-antimatter asymmetry (SM is symmetric w.r.t. matter-antimatter but the Universe is not)

- Cosmology: known matter is only small part of the Universe!

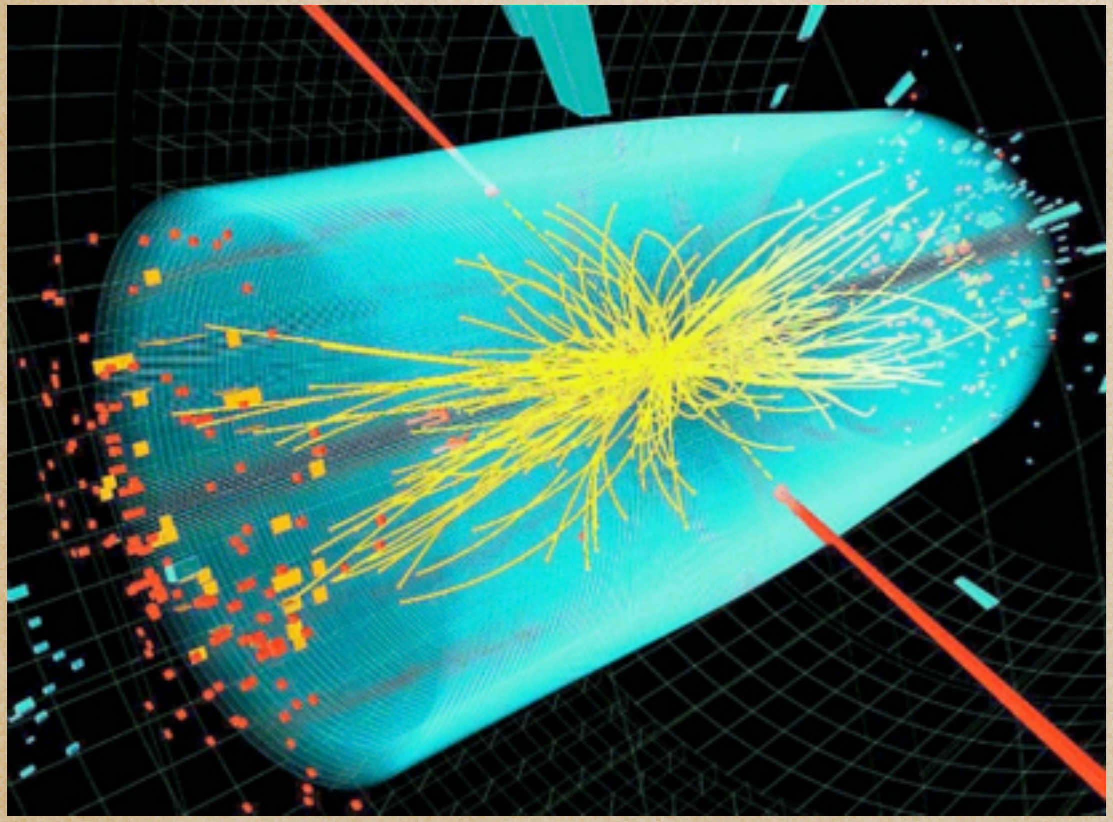


SEARCHES FOR NEW PHYSICS

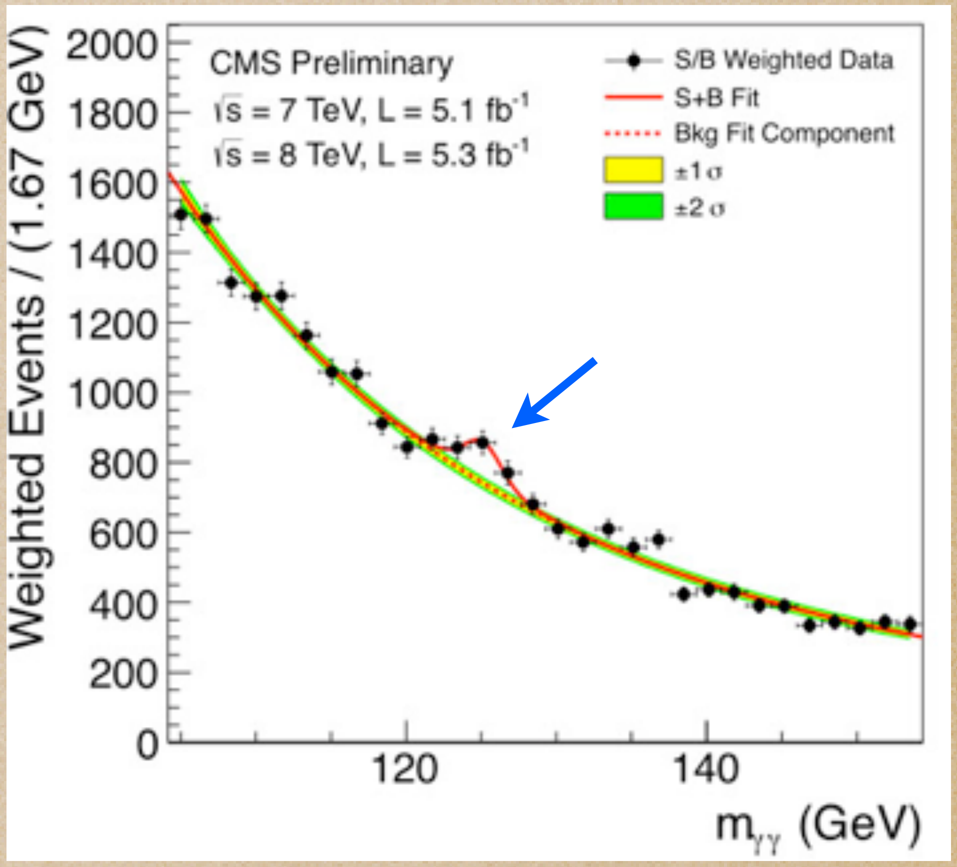
- Collider searches:

  accelerate known particles to produce heavy new particles

A typical p-p event in the CMS detector @ LHC



A peak at 126 GeV in $\gamma\gamma$ decay channel - probably Higgs boson

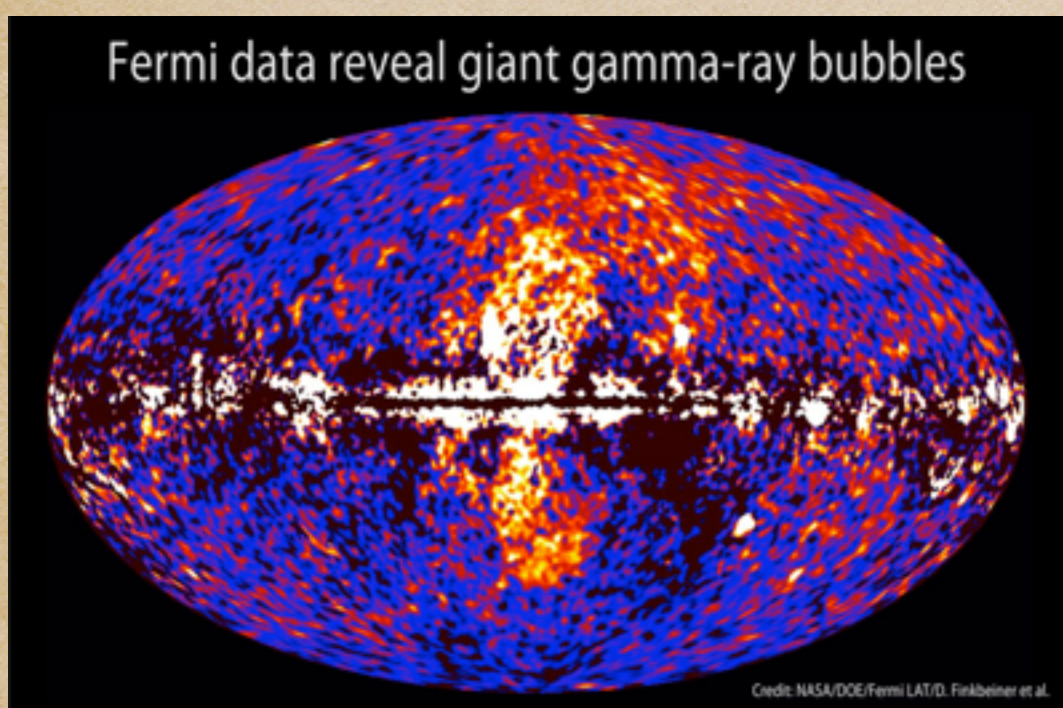


No new particles (few 100's GeV) observed yet - quest continues

SEARCHES FOR NEW PHYSICS

- Astrophysics searches:

  observe signals of new particles coming from the space



No new particles observed yet

< 300 GeV

- quest continues

SEARCHES FOR NEW PHYSICS

Low energy tests:

deviations from SM predictions

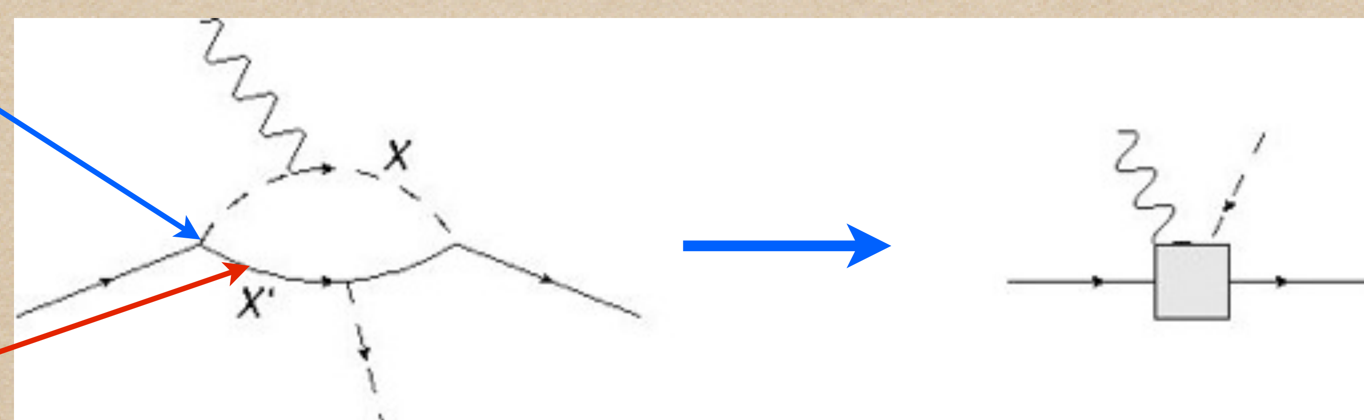
set constraint onto quantum fluctuations due to unknown heavy particles

?

Theory (SM)

Coupling g

Mass Λ



$$\sim \frac{g^2}{\Lambda^2}$$

Precision = scale of New Physics

Precision in BOTH experiment and SM theory becomes crucial

LOW ENERGY PRECISION TESTS

Parity-Violating Electron Scattering

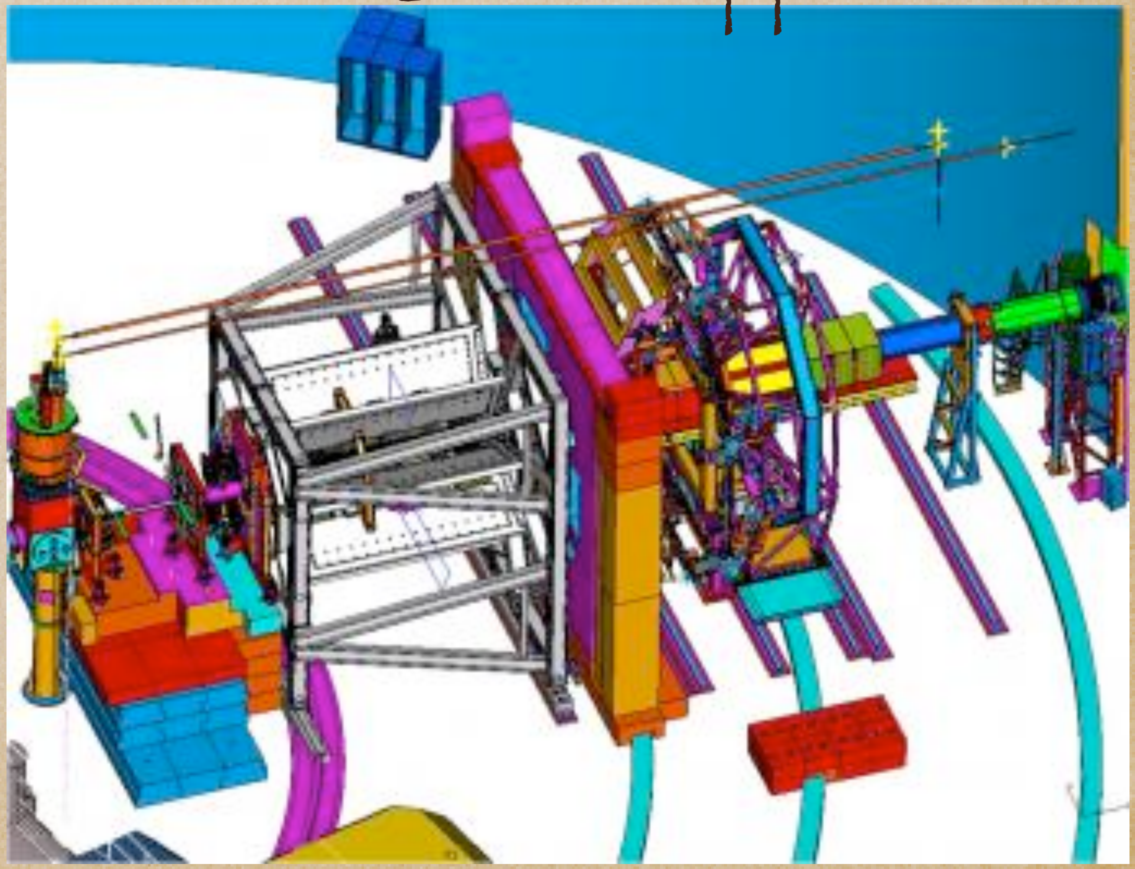
QWEAK, PVDIS, HAPPEX, PREX, G0 @ JLab; A4 @ Mainz; SAMPLE @ MIT-Bates; E158 @ SLAC;

Future: QWEAK @ Mainz, PVDIS (Hall C), Møller @ JLab

Measurements of the PV asymmetry in elastic electron scattering to extract:
- weak mixing angle;
- nucleon's strange FFs;

Probe the scale of New Physics
- few TeV

QWEAK apparatus



LOW ENERGY PRECISION TESTS

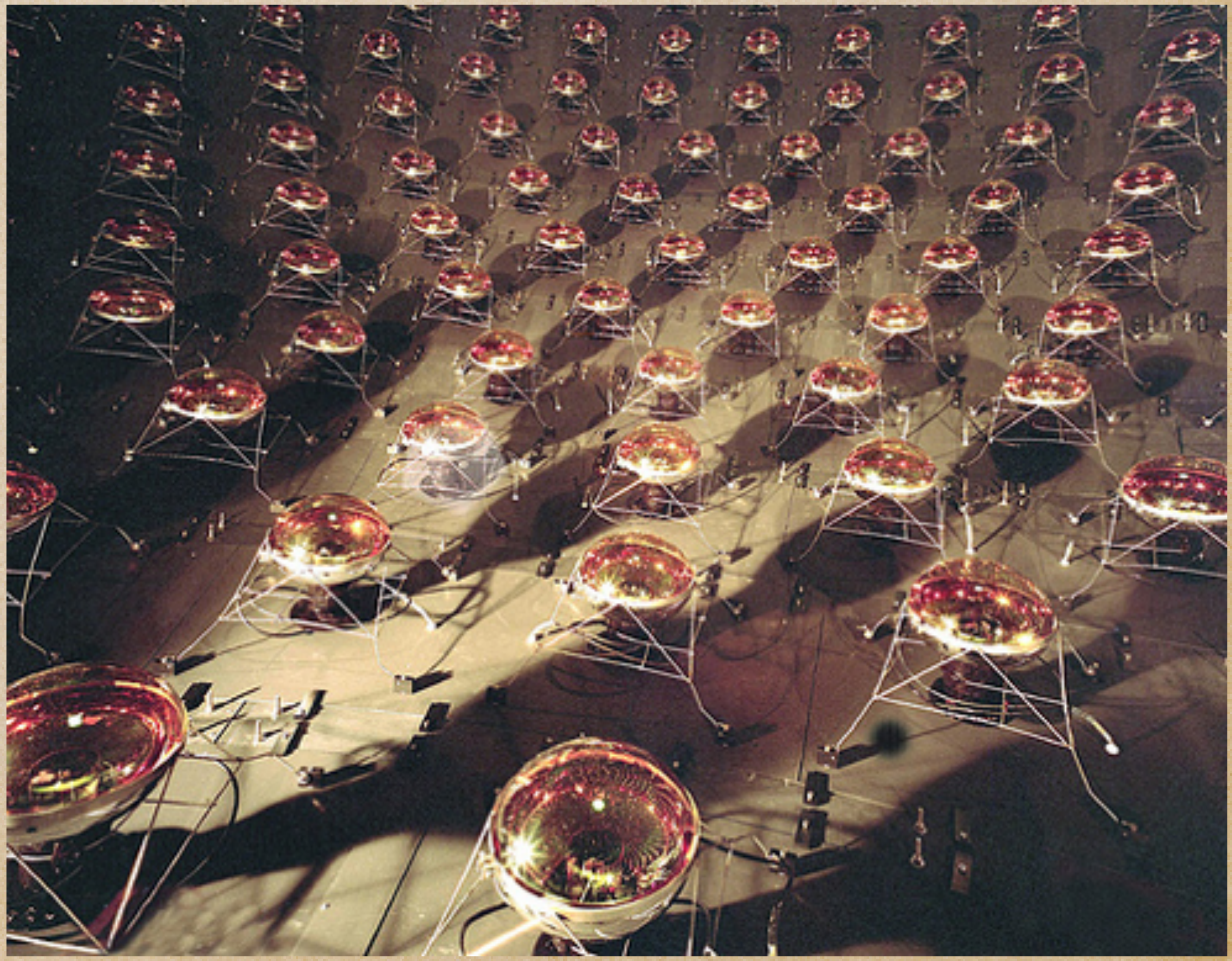
Neutrino Oscillation Experiments

NuTeV, LSND, Daya Bay, MiniBooNE, SciBooNE, NOvA, SNO, Super-K, OPERA, NEMO, MINOS, Ice Cube, Borexino, ANTARES, Double Chooz

Measurements of neutrino oscillation parameters:

- masses;
- neutrino mixing angles;
- Dirac vs. Majorana neutrino

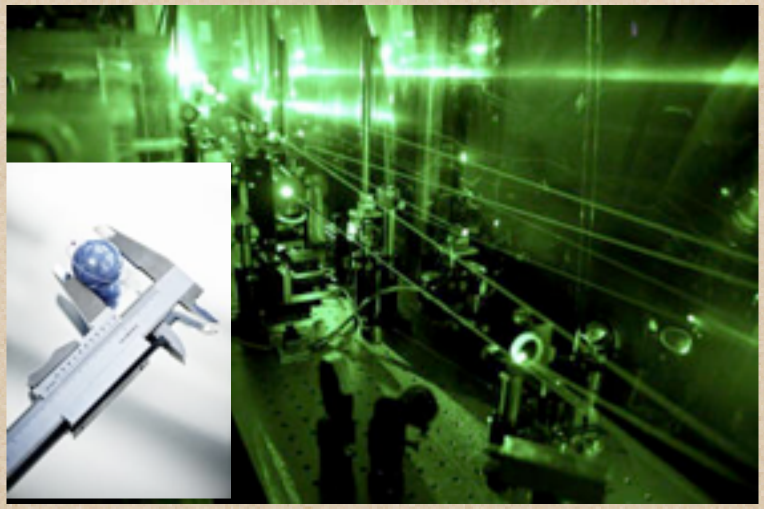
MiniBooNE detector



LOW ENERGY PRECISION TESTS

Precision tests of QED

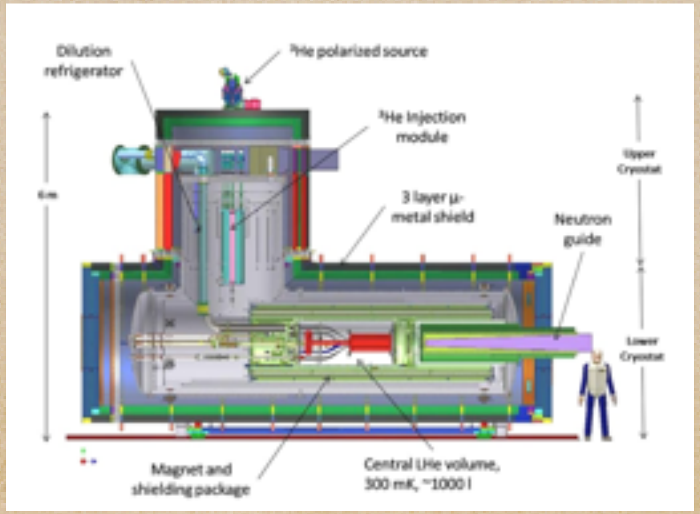
Lamb shift in muonic atoms @ PSI



Muonic g-2 @ BNL, Fermilab

New Physics at Low Energies

nEDM, eEDM - @ PSI, ORNL, ILL,...



Dark Photon Search @ JLab, Mainz, ...

THEORY SUPPORT TO LOW ENERGY TESTS

Leave to the experimentalists gauging the scale

Theorists: gauge the weights!

- Precision calculations of observables in the kinematics of atomic, nuclear and hadronic experiments are needed!

- Appropriate model-independent methods for strong interacting systems with reliable error estimation

- Requires understanding QCD in the non-perturbative regime

THEORY SUPPORT: QCD

QCD Lagrangian

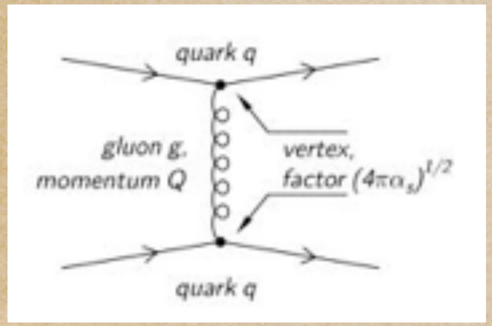
Gluon fields

$$\mathcal{L} = \sum_q \bar{\psi}_{q,a}(i\gamma^\mu \partial_\mu \delta_{ab} - g_s \gamma^\mu t^C_{ab} \mathcal{A}^C_\mu - m_q \delta_{ab})\psi_{q,b} - \frac{1}{4} F^A_{\mu\nu} F^{A\,\mu\nu}$$

Quark fields

$$F^A_{\mu\nu} = \partial_\mu \mathcal{A}^A_\nu - \partial_\nu \mathcal{A}^A_\mu - g_s\, f_{ABC} \mathcal{A}^B_\mu \mathcal{A}^C_\nu \qquad [t^A, t^B] = i f_{ABC} t^C$$

Strong (running) coupling constant



$$\alpha_s(\mu^2) = \frac{1}{\frac{11N_c - 2n_f}{12\pi} \ln(\mu^2/\Lambda^2)}$$

$$\alpha_s = \frac{g_s^2}{4\pi}$$

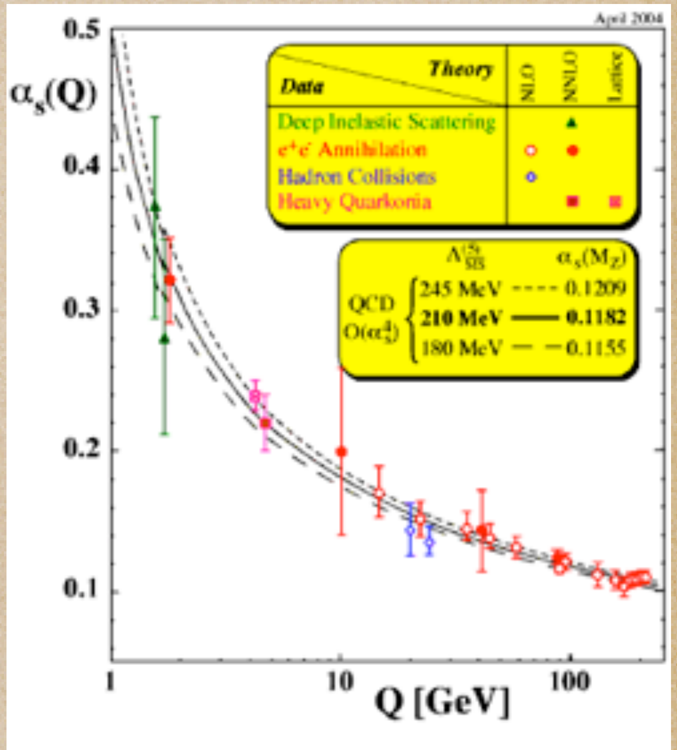


FIG. 1: QCD running coupling constant

Asymptotic freedom and Confinement

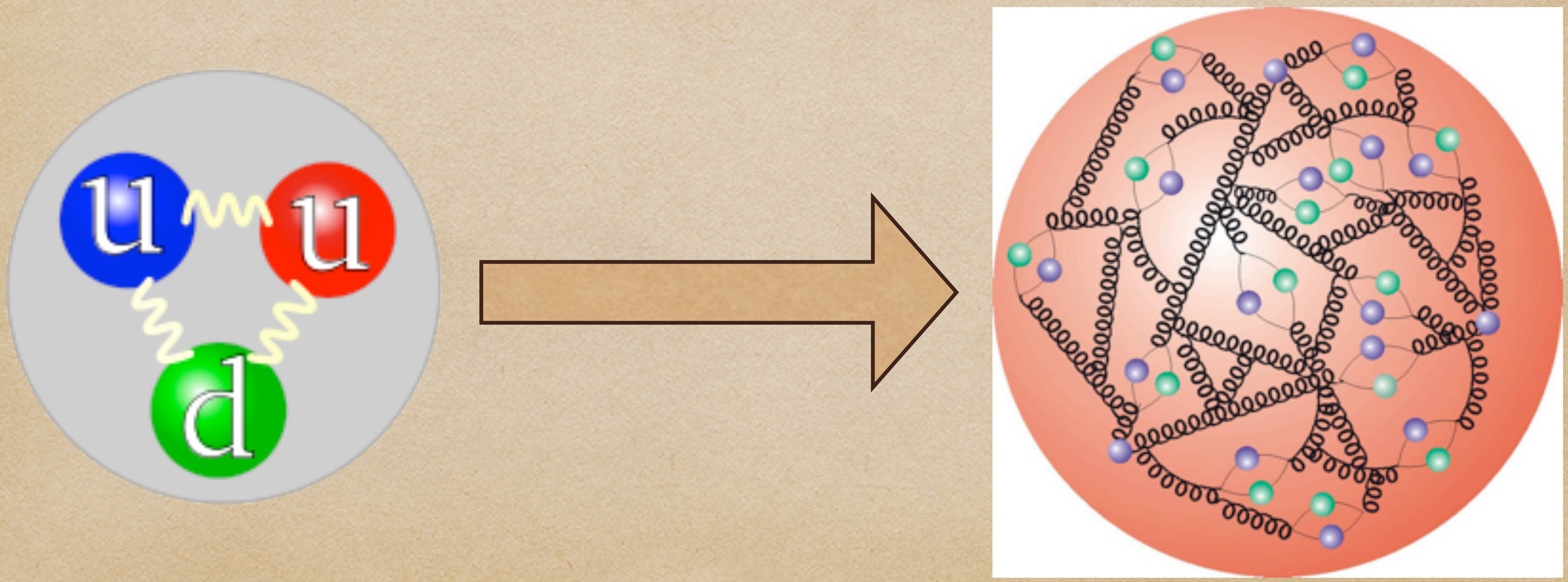
No free quarks or gluons observed - remain bound inside hadrons

THEORY SUPPORT: QCD

QCD Lagrangian is written in terms of quark and gluon fields

BUT: asymptotic (in and out) states are hadrons

Hadrons are composed from quarks and gluons, but we do not know how exactly



THEORY SUPPORT: QCD

• Numerical solution of QCD in a discretized Euclidean space-time - Lattice QCD: much progress recently but not all observables can be calculated; unclear estimation of systematic uncertainties

A few special cases exist where one can use perturbation theory

- Hard kinematics (DIS and hard processes): minimal Fock states dominate, others give kinematical corrections;

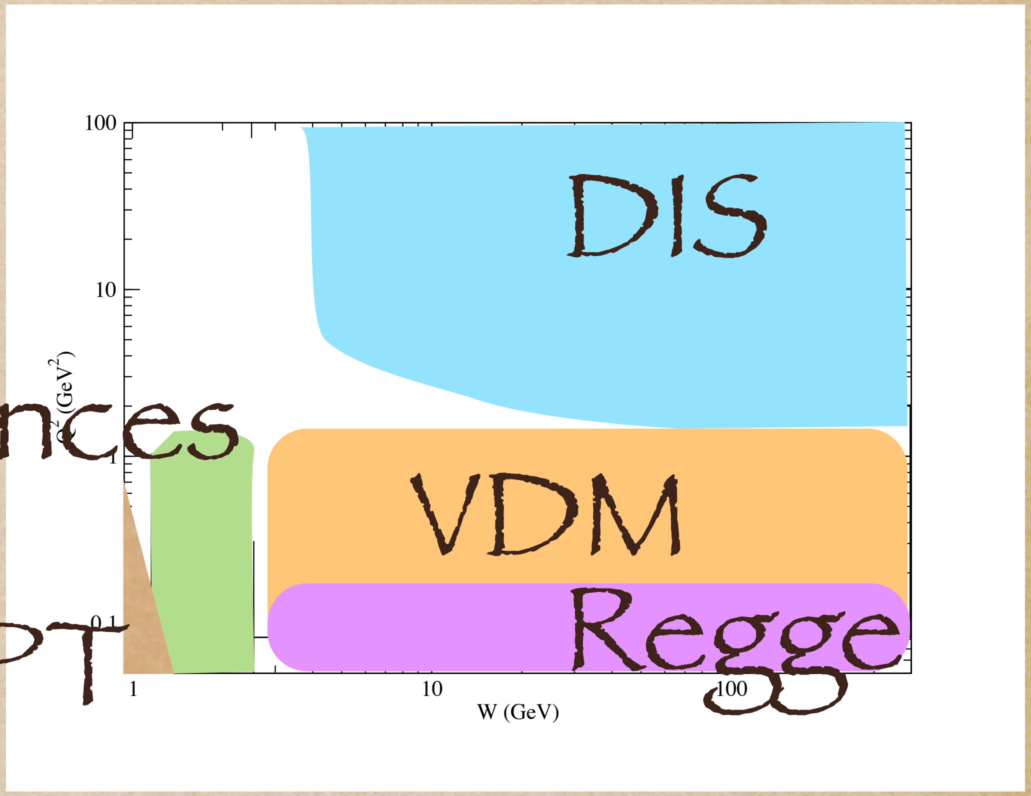
- Low energies: the relevant degrees of freedom are pions and nucleons, ChPT grasps some features of the QCD

Perturbative methods have limited range of applicability

THEORY SUPPORT: DISPERSION RELATIONS

Various models/frameworks

live in different regions on W-Q^2 plot



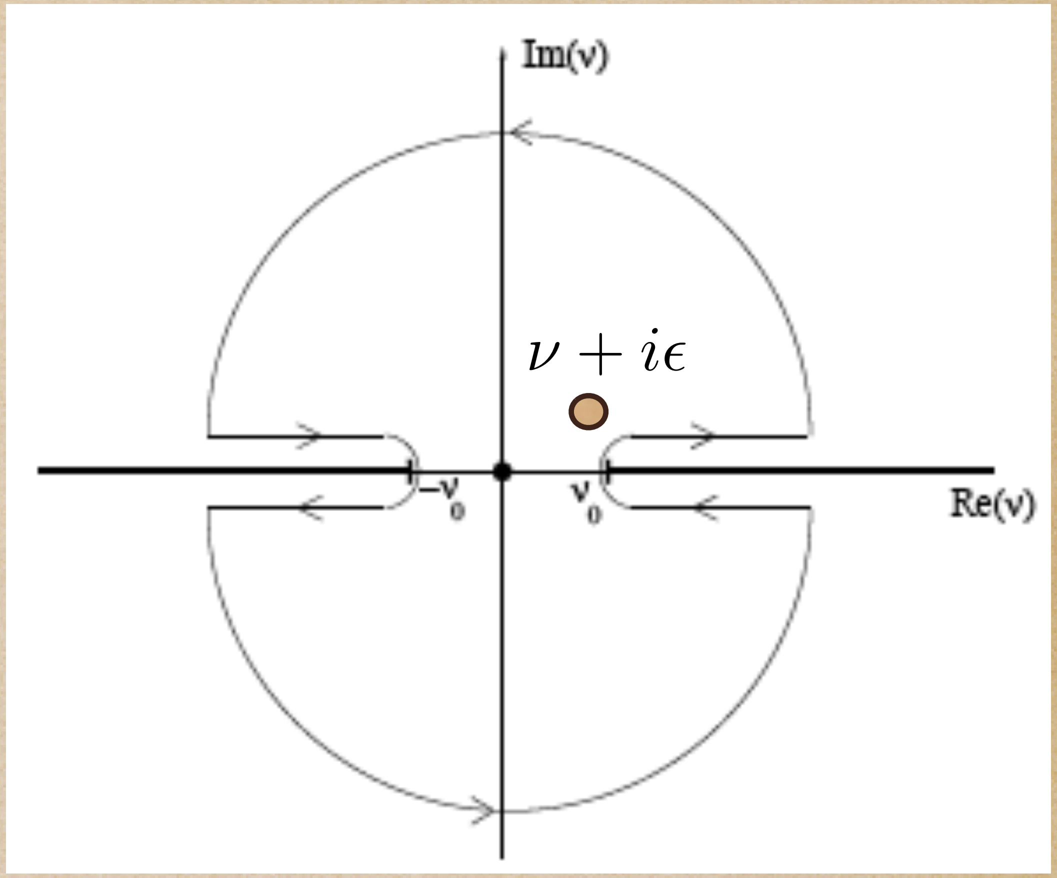
Dispersion relations:

+ different regimes are naturally connected
+ works with hadronic states - straightforward to relate to observables
+ respect all symmetries of QCD, analyticity, unitarity
+ possible error estimation directly from data
+ minimal model dependence
- are largely ignorant of the underlying theory, QCD

DISPERSION RELATIONS

Cauchy's Theorem

$$f(\nu + i\epsilon) = \frac{1}{2\pi i} \oint_C \frac{f(\nu')}{\nu' - \nu - i\epsilon} d\nu'$$



Reconstruct the scattering amplitude using several principles:

- Singularities = Physical Processes
- Analyticity = Causality
- Unitarity = Conservation of Probability
- Operate with physical (hadronic) states - directly related to observables measured in experiment

Establish model-independent relations between various processes without having to understand in detail the underlying theory!

DISPERSION RELATIONS

Example: Gerasimov-Drell-Hearn Sum Rule - 1960's

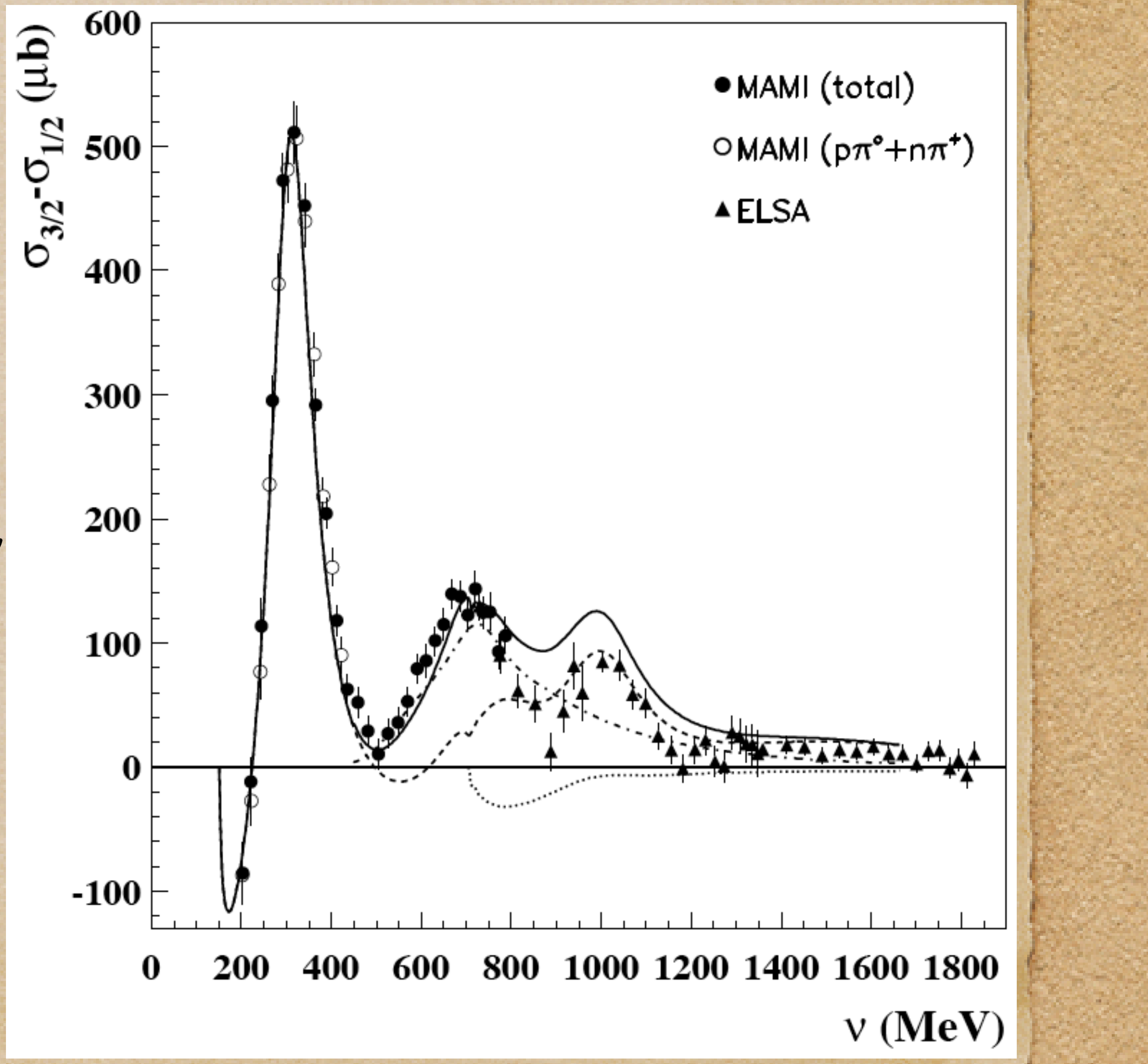
Anomalous magnetic moments = weighted integral over photo-absorption cross section

Measured with static magnetic field

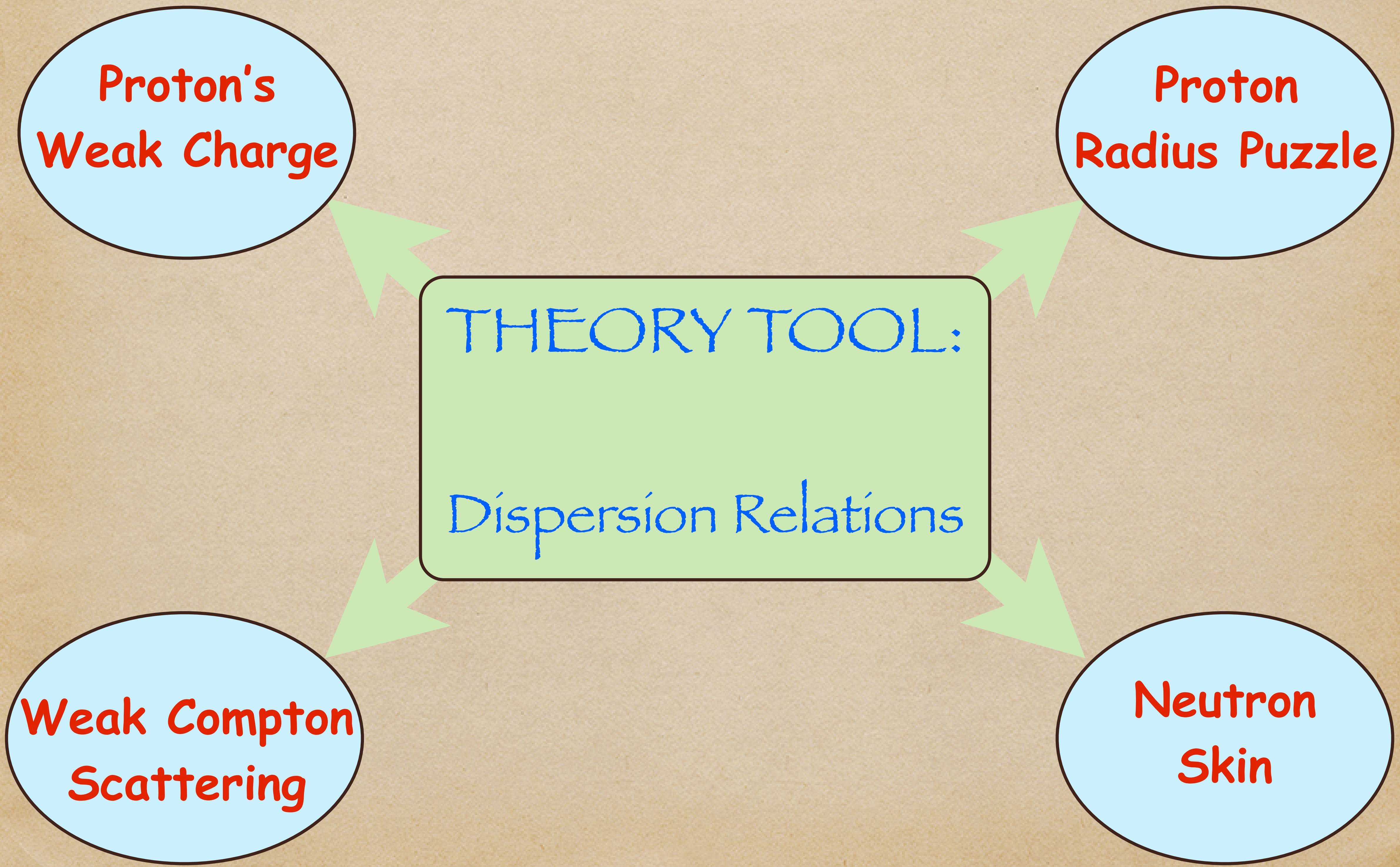
Measured with MeV to GeV photons

$$\frac{\pi e^2}{2M^2}\kappa_N^2 \quad = \quad \int_{\nu_0}^{\infty} \frac{\sigma_{3/2}(\nu) - \sigma_{1/2/}(\nu)}{\nu} d\nu$$

$$204\,\mu b \quad \leftrightarrow \quad (212 \pm 6_{stat} \pm 16_{syst})\mu b$$



THEORY SUPPORT: DISPERSION RELATIONS



THEORY SUPPORT: DISPERSION RELATIONS

Proton's Weak Charge

Proton Radius Puzzle

THEORY TOOL:

Dispersion Relations

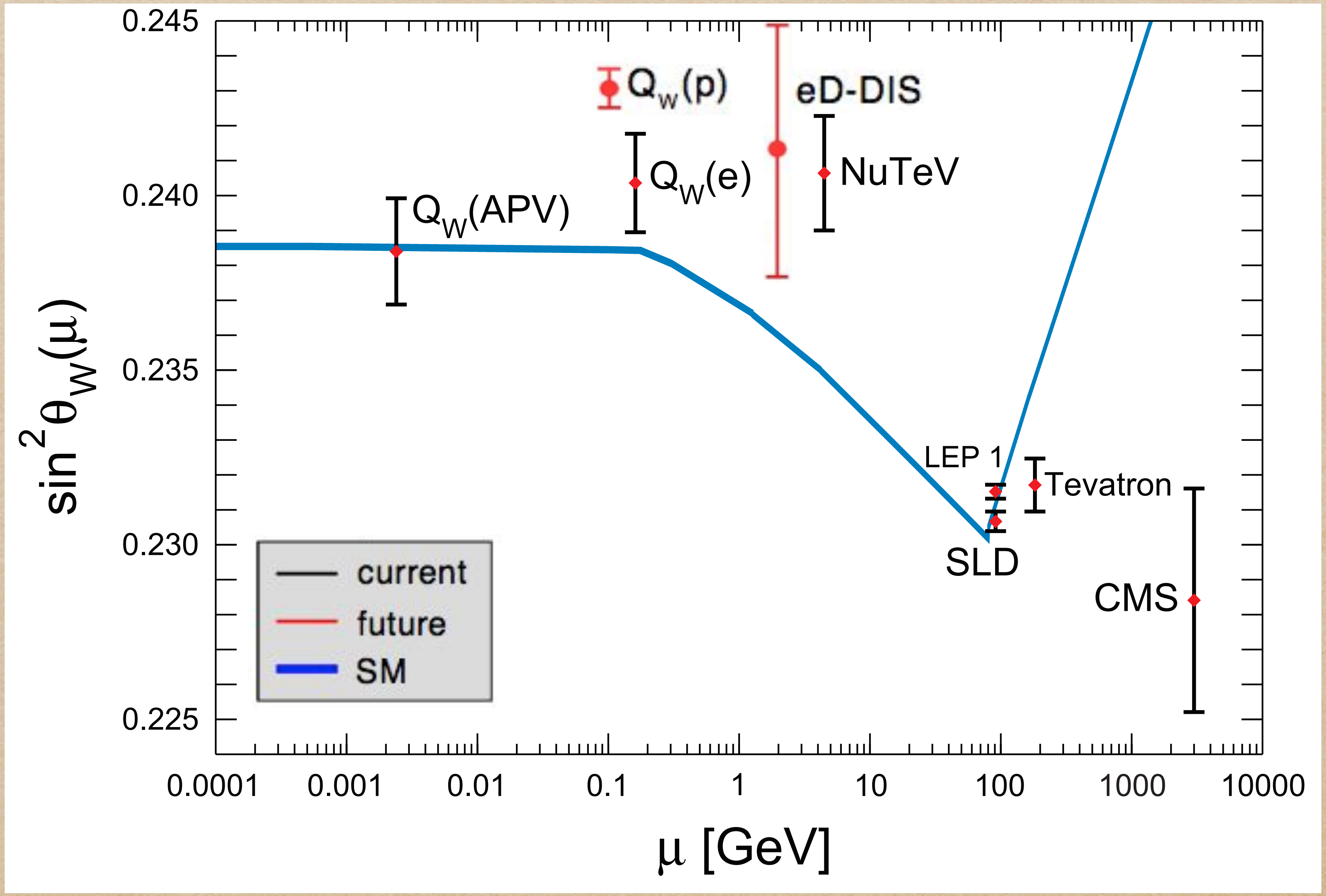
Weak Compton Scattering

Neutron Skin

Weak mixing angle: central role in SM

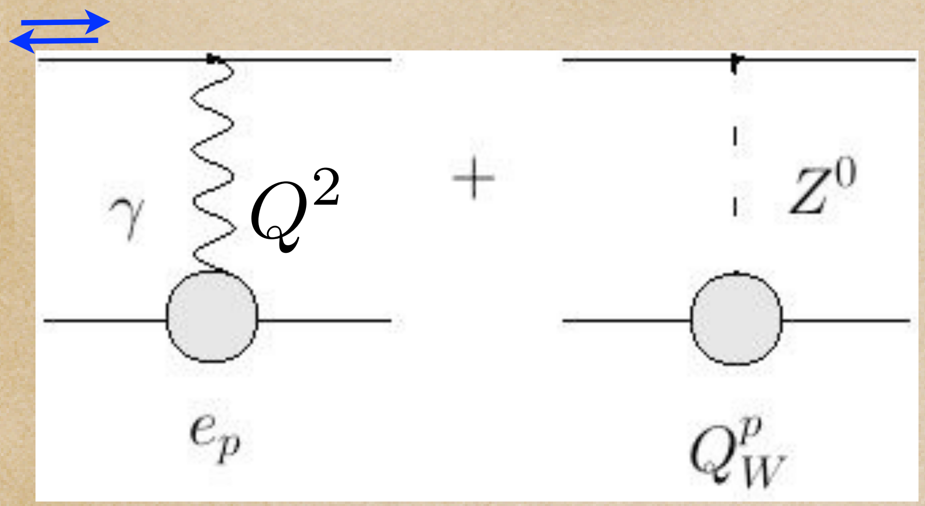
Running of the w.m.a. - an authentic prediction of Standard Model;

Substantial deviation ANYWHERE = signal of New Physics



The theory uncertainty corresponds to the thickness of the line!

Weak Charge of the Proton



Elastic e-p scattering with polarized e⁻ beam

$$A^{PV} = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow} = -\frac{G_F Q^2}{4\sqrt{2}\pi\alpha_{em}} Q_W^p + \mathcal{O}(Q^4)$$

Effective e-q interaction

$$-\mathscr{L}^{eh} = -\frac{G_F}{\sqrt{2}} \sum_i \left[C_{1i}\, \bar{e}\, \gamma_\mu \gamma^5 e\, \bar{q}_i\, \gamma^\mu q_i + C_{2i}\, \bar{e}\, \gamma_\mu e\, \bar{q}_i\, \gamma^\mu \gamma^5 q_i \right]$$

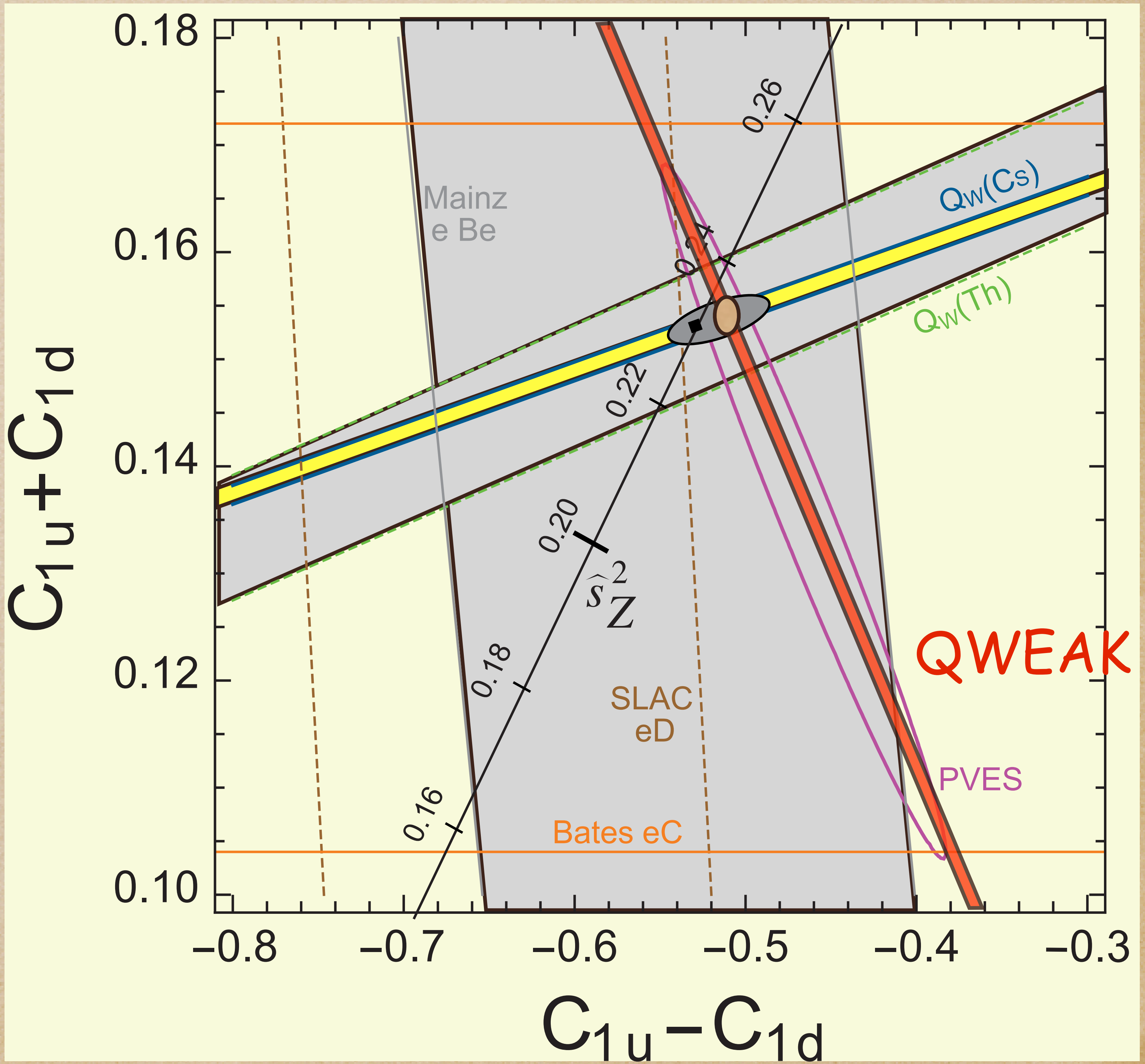
Standard Model (tree-level)

$$Q_W^{p,\,tree} = -2(2C_{1u} + C_{1d}) = 1 - 4\sin^2\theta_W \approx 0.05$$

QWEAK measurement

QWeak @ JLab:

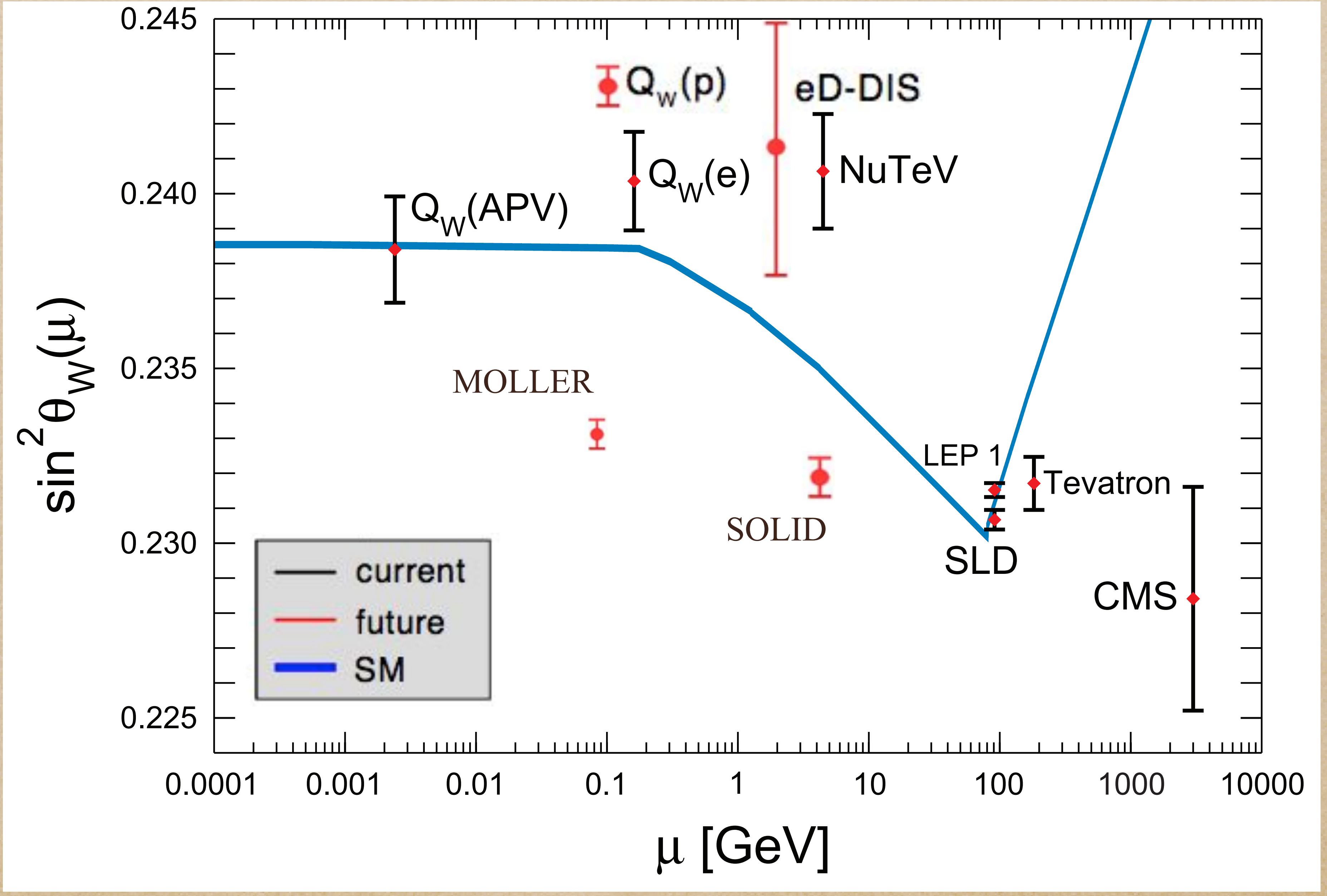
Determination of the weak mixing angle to ~ 0.3% precision



QWEAK measurement

Important and independent test of Standard Model at low energies

Complimentary to measurements at the Z-pole



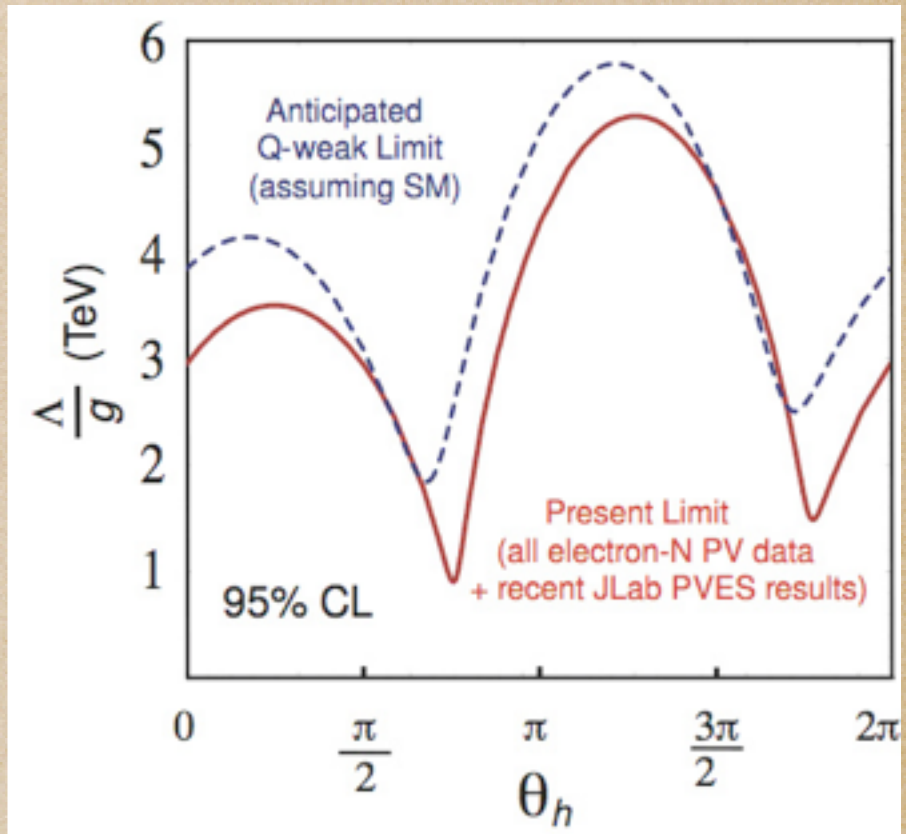
QWEAK & New Physics

Generic New Physics parametrization

$$\mathcal{L}_{NP}^{PV} = -\frac{g^2}{4\Lambda^2}\bar{e}\gamma_\mu\gamma_5 e \sum_q h_V^q \bar{q}\gamma^\mu q$$

Generic flavor dependence

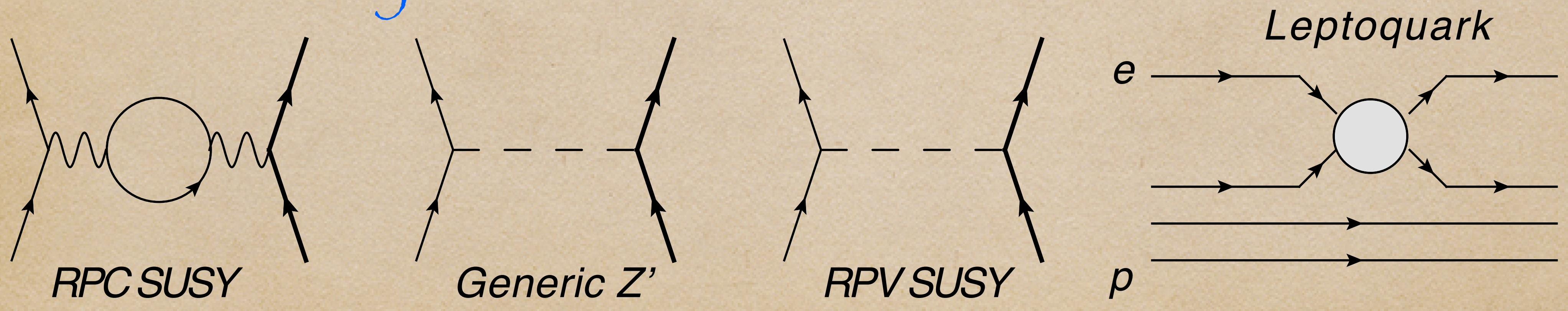
$$h_V^u = \cos\theta_h \quad h_V^d = \sin\theta_h$$



Sensitive to New Physics
above 2 TeV- comparable to the LHC!

Young et al., PRL 99 (2007) 122003

Possible New Physics scenarios

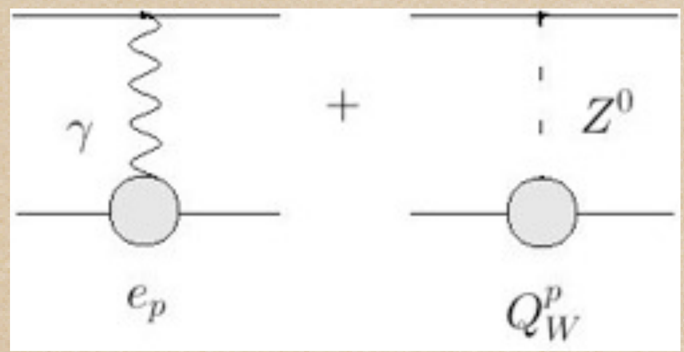


Ramsey-Musolf, PRC 60 (1999) 015501; Erler et al., PRD 68 (2003) 016006.

Weak Charge of the Proton: EW corrections

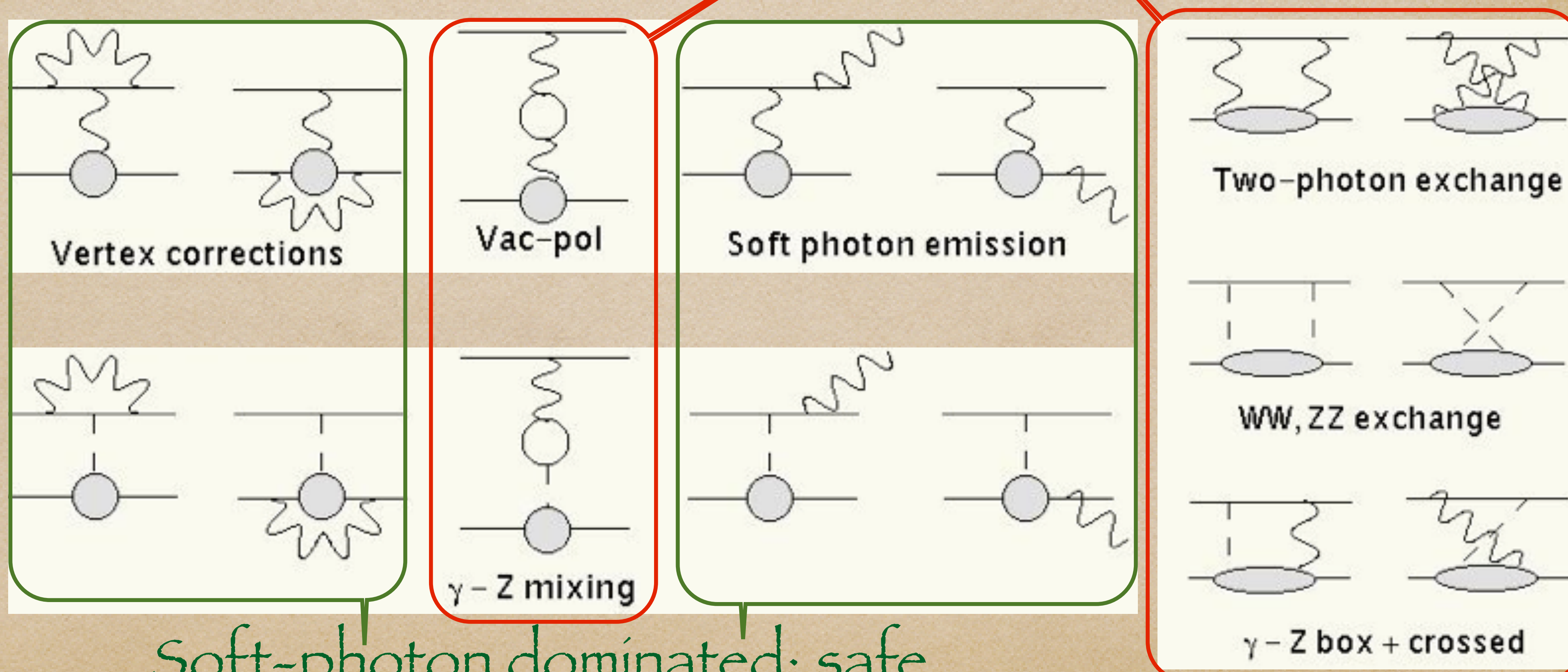
To match the experimental precision - include radiative corrections

$\mathcal{O}(1)$



Hadronic structure-dependent

$\mathcal{O}(\alpha_{em})$ $\qquad \alpha_{em} \approx 1/137$



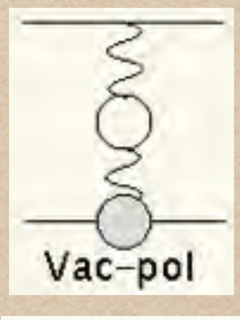
Soft-photon dominated: safe

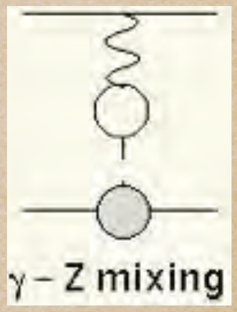
Weak Charge of the Proton: EW corrections

Hadronic structure effects are under control

$$Q_W^p = \boxed{(1+\Delta_\rho+\Delta_e)(1-4\sin^2\hat{\theta}_W+\Delta_e') + \Box_{WW} + \Box_{ZZ}} + \boxed{\Box_{\gamma Z}}$$

W. J. Marciano and A. Sirlin, PRD **27**, 552 (1983); **29**,75 (1984); **31**, 213 (1985).
M.J. Ramsey-Musolf, PRC 60, 015501 (1999).





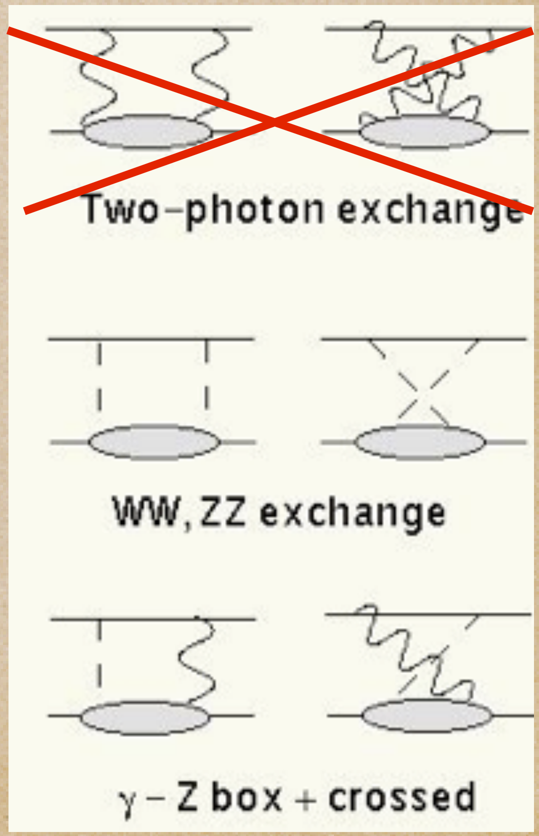
Vacuum polarization: reconstructed from $e^+e^- \rightarrow$ hadrons with dispersion relations

2γ-Box: kinematically suppressed

WW,ZZ-Box: perturbative- calculable reliably

γZ: for low energies (atomic PV experiments) cancellation between box and crossed

- is it still true for ~1 GeV energy experiment?



Energy dependence of the γZ-Correction

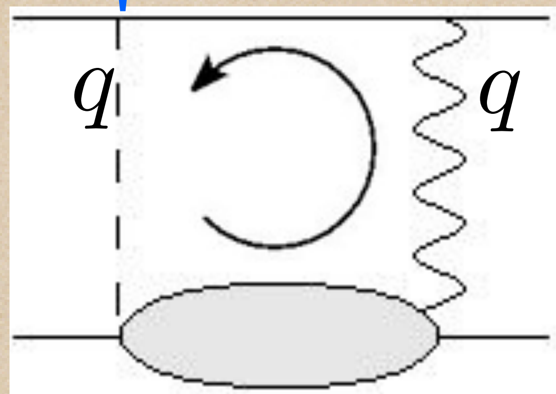
MG & C.J. Horowitz, PRL102, 091806 (2009)

$g_V^e, \; g_A^e$

$k^\mu = (E, \vec{k})$

$Q^2 = -q_\mu q^\mu \geq 0$

$p^\mu = (M, \vec{0})$



$W^2 = (p+q)^2$

Forward dispersion relation for

$$\Box_{\gamma Z} = g_V^e \Box_{\gamma Z_A} + g_A^e \Box_{\gamma Z_V}$$

Possess different symmetry between box and crossed terms:

$$\mathrm{Re}\Box_{\gamma Z_A}(E) = \frac{2}{\pi}\int_{\nu_0}^{\infty} \frac{E' dE'}{E'^2 - E^2} \mathrm{Im}\Box_{\gamma Z_A}(E')$$

$$\mathrm{Re}\Box_{\gamma Z_V}(E) = \frac{2E}{\pi}\int_{\nu_0}^{\infty} \frac{dE'}{E'^2 - E^2} \mathrm{Im}\Box_{\gamma Z_V}(E')$$

$$\mathrm{Re}\Box_{\gamma Z_A}(0) \neq 0$$

$$\mathrm{Re}\Box_{\gamma Z_V}(0) = 0$$

APV result

Can quantify the energy dependence

Energy dependence of the γZ-Correction

$$\mathrm{Re}\Box_{\gamma Z_V}(E) = \frac{2E}{\pi}\int_0^\infty dQ^2 \int_{W_\pi^2}^\infty dW^2 \left[A F_1^{\gamma Z}(W^2,Q^2) + B F_2^{\gamma Z}(W^2,Q^2)\right]$$

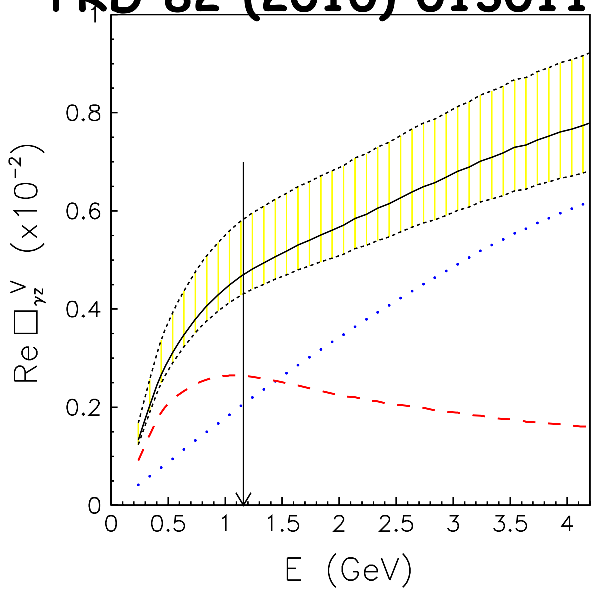
PV DIS data

- not (YET!) available

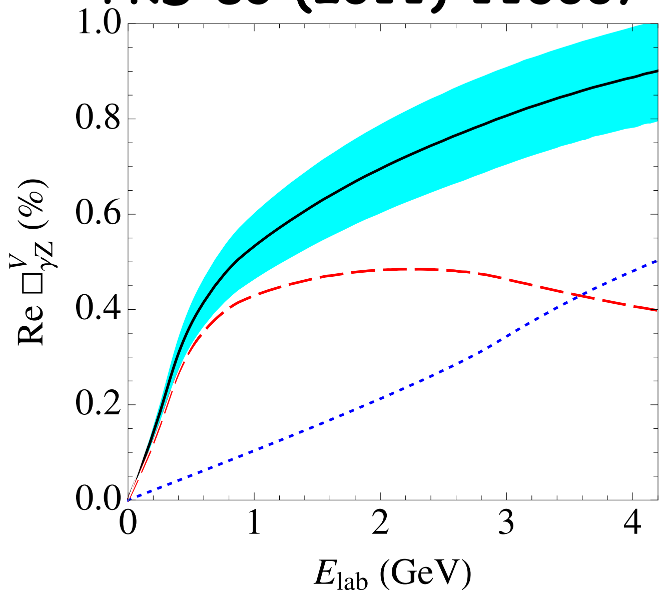
Isospin-rotate the e.-m. data

Evaluate at E ≈ 1.165 GeV (QWEAK)

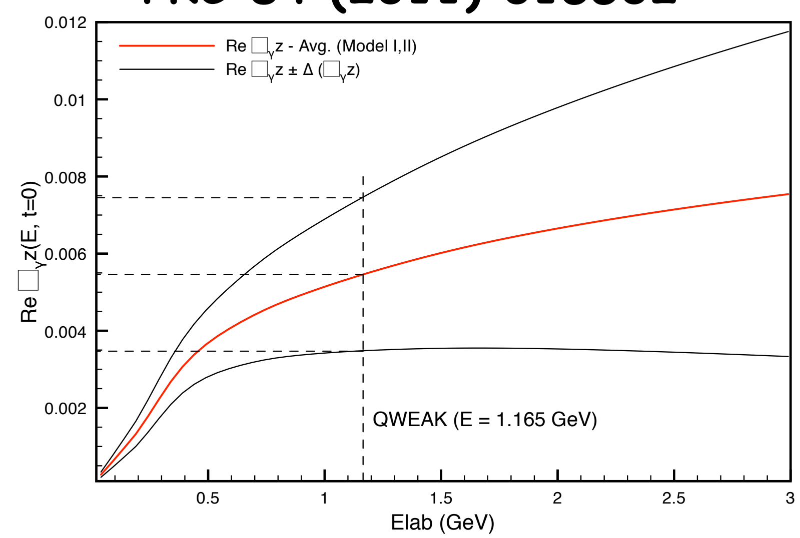
Sibirtsev et al.
PRD 82 (2010) 013011



Rislow & Carlson
PRD 83 (2011) 113007



Gorchtein et al.
PRC 84 (2011) 015502



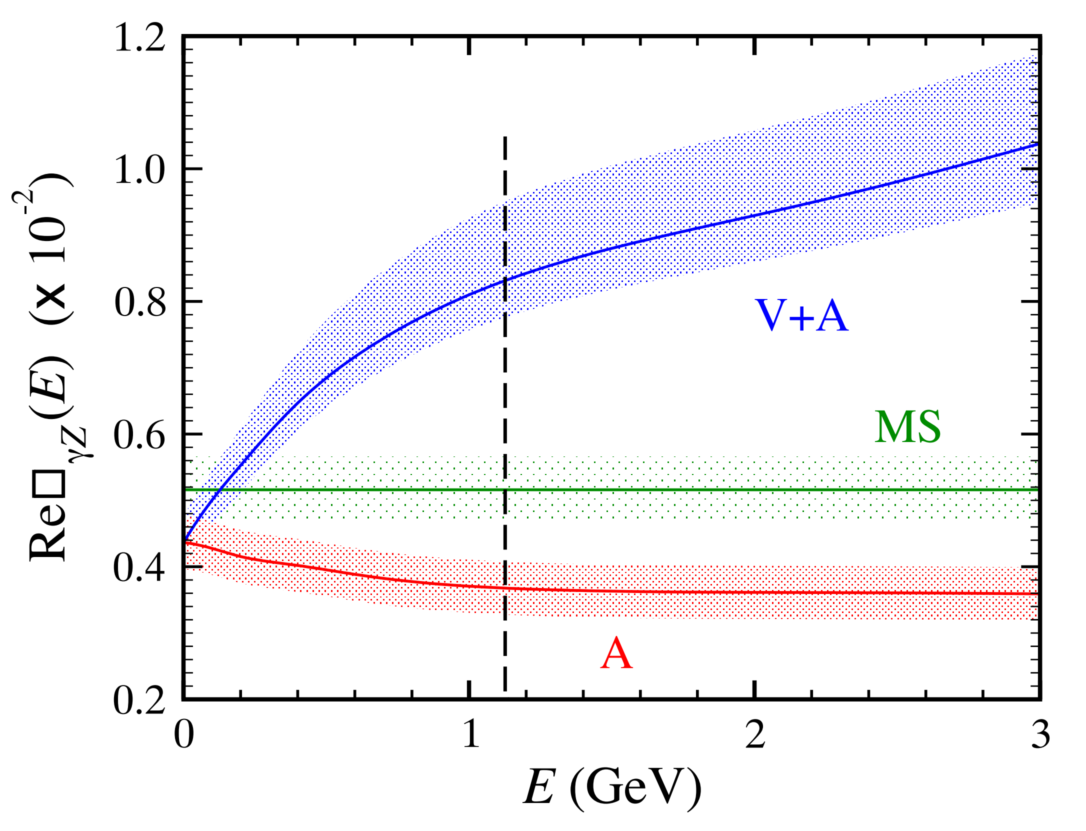
$$\mathrm{Re}\,\Box_{\gamma Z}(E = 1.165\ \mathrm{GeV})$$

$\left(4.7\,^{+1.1}_{-0.4}\right)\times 10^{-3}$ $(5.7 \pm 0.9)\times 10^{-3}$ $(5.4 \pm 2.0)\times 10^{-3}$

Energy dependence of the γZ-Correction

Also the axial part can be evaluated through a DR - check the old Marciano & Sirlin's calculation

Blunden et al., PRL 107 (2011) 081801



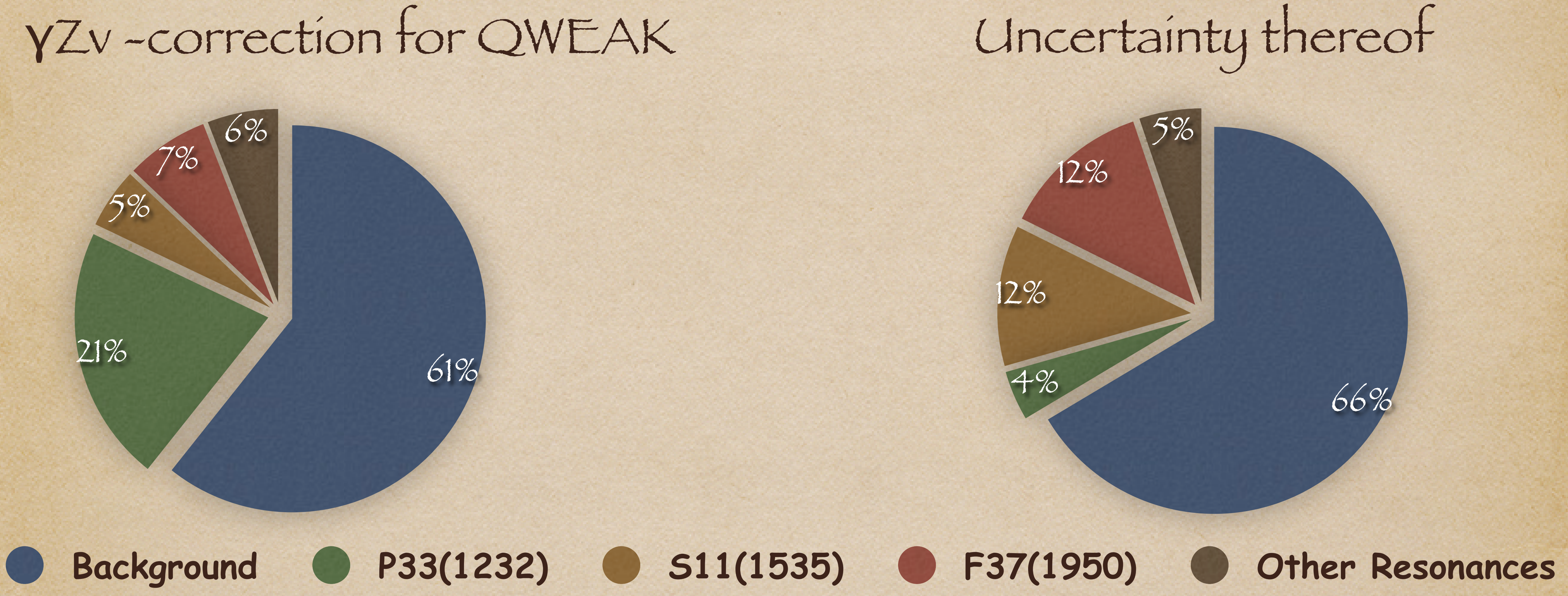
New SM prediction for the proton's weak charge

$$Q_W^p + \mathrm{Re}\Box_{\gamma Z}(E = 1.165\,\mathrm{GeV}) = 0.0767 \pm 0.0008 \pm 0.0020_{\gamma Z}$$

To be compared to the previous prediction $Q_W^p = 0.0713 \pm 0.0008$

4σ (theory) effect was missed in the original QWEAK analysis;
Theory uncertainty needs to be further reduced

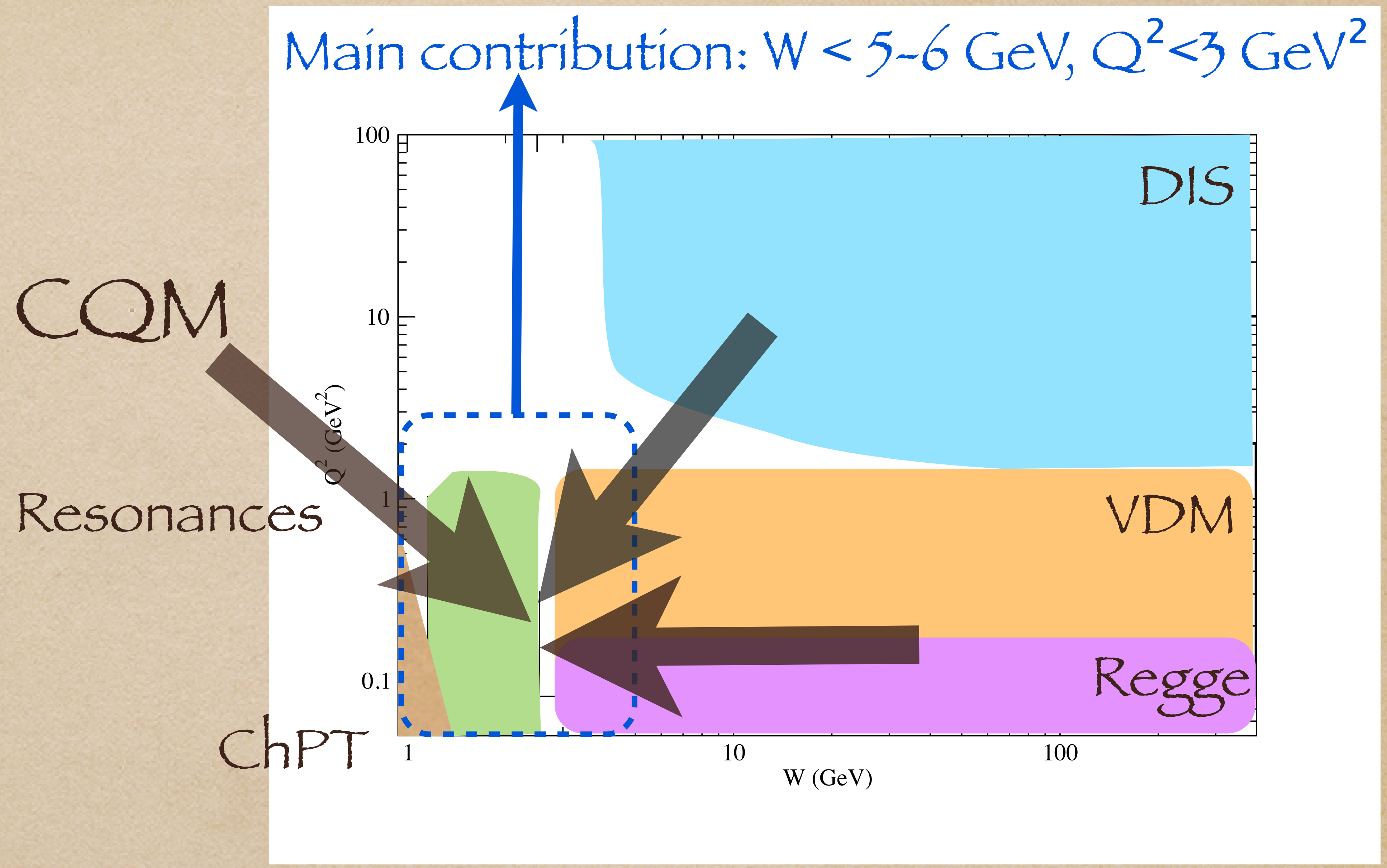
γZ-Correction to the QWEAK Measurement



Reduce uncertainty on S11 resonances - joint effort with Data Analysis Center @ GWU and PAC @ JLab

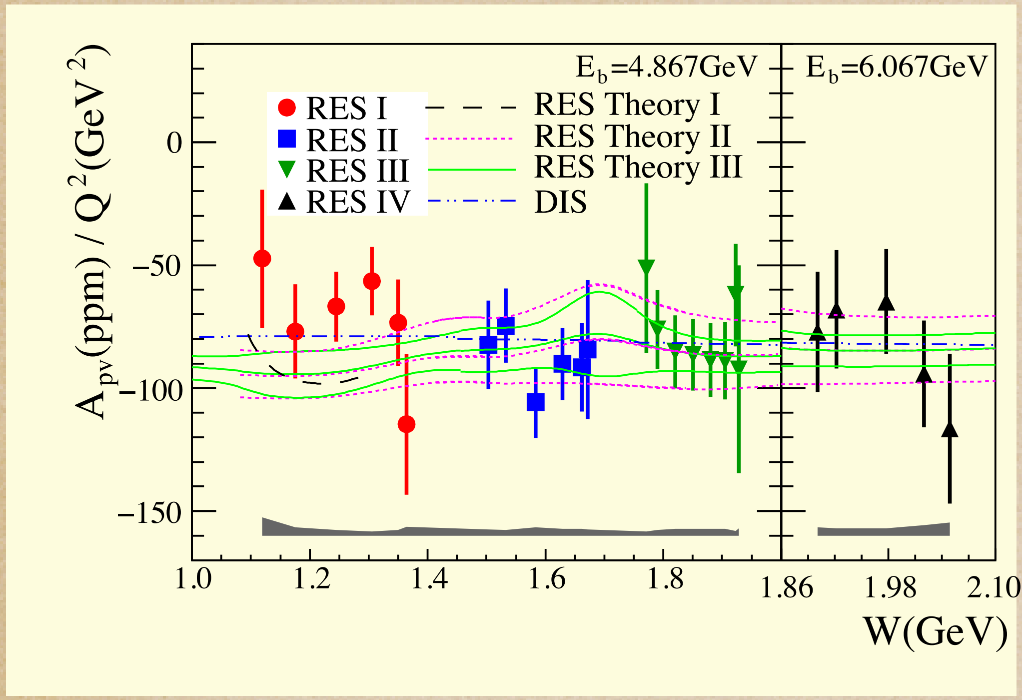
Reduce uncertainty on the background: evaluate the VDM sum rule at JLab energies (possible new measurements?)

Uncertainty of the γZ-Correction to the QWEAK



Main source of the uncertainty:
background in the resonance region and above
- how a gamma/Z polarizes vacuum in the target's proximity?

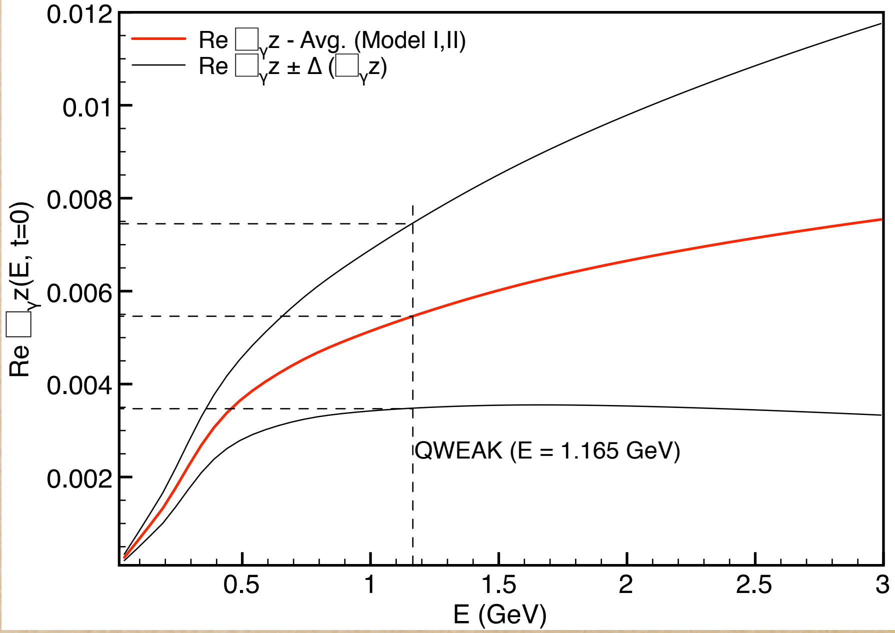
Reducing Theory Uncertainty



New data on PV DIS structure functions coming - PV DIS, SOLID - will help constraining the theory uncertainty

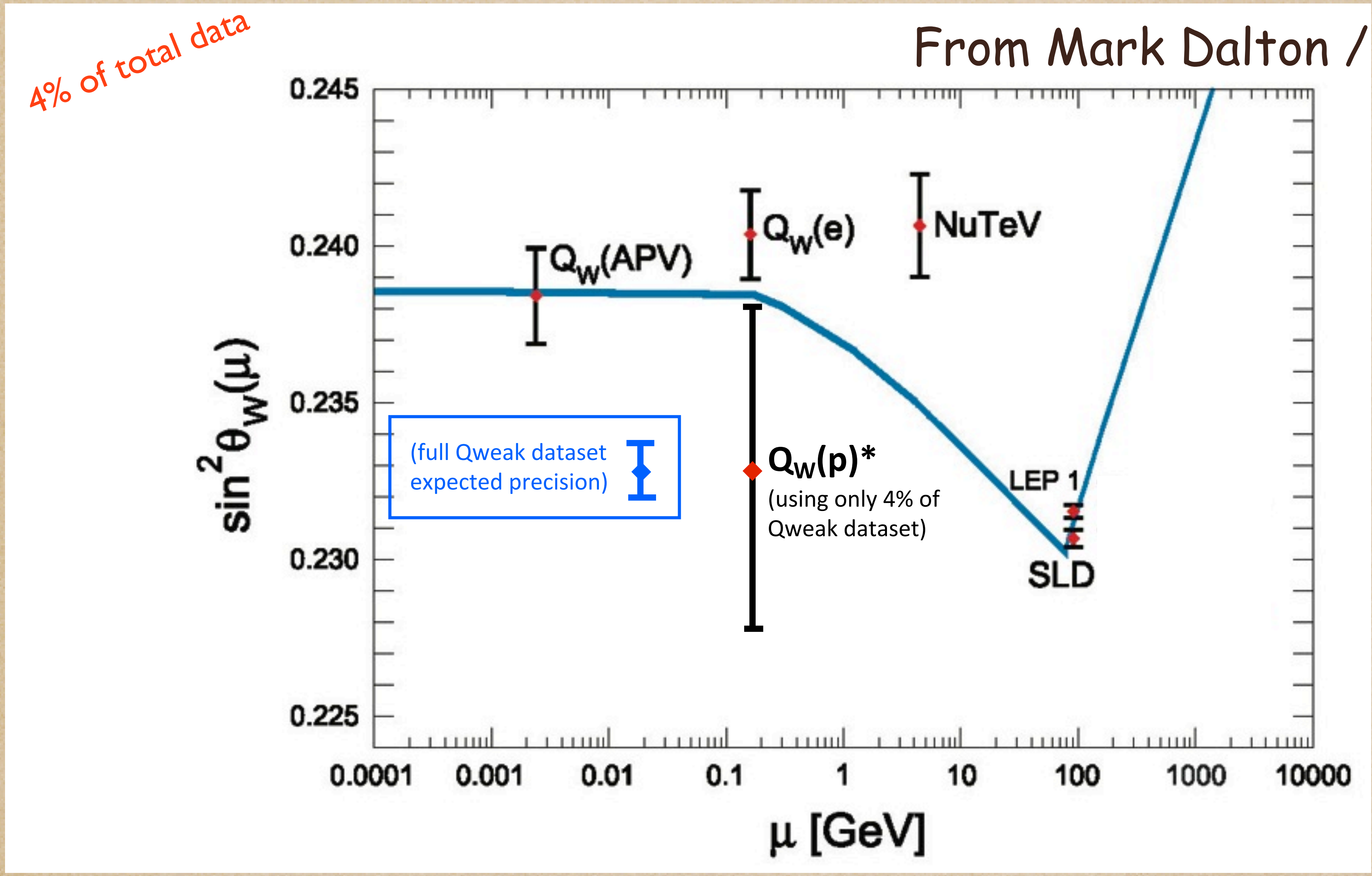
Steep energy dependence of the dispersion correction

A measurement at Mainz with 180MeV beam is planned - SFB 1044 Project P2



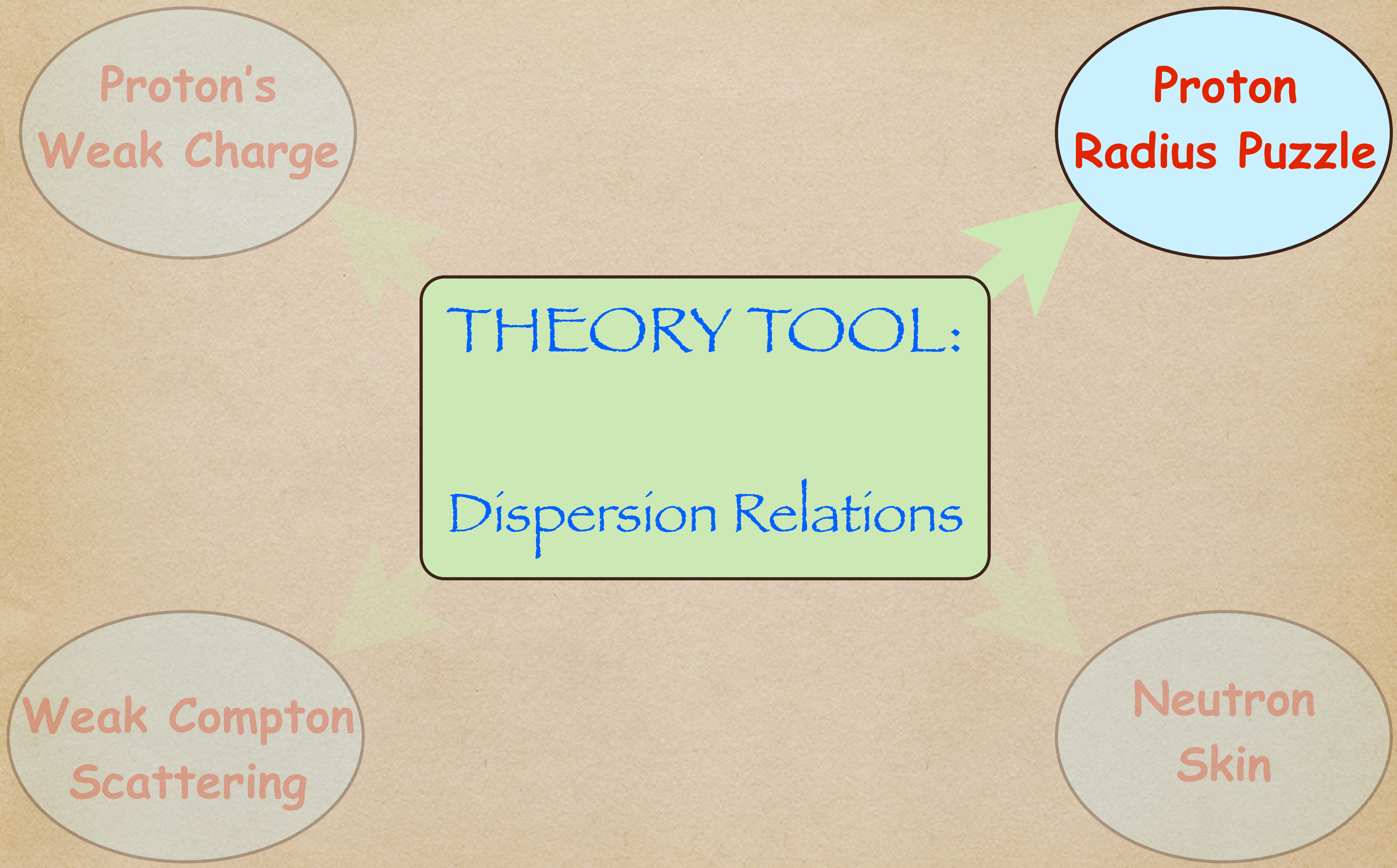
$$Q_W^p + \mathrm{Re}\square_{\gamma Z}(E = 0.180\,\mathrm{GeV}) = 0.0726 \pm 0.0008 \pm 0.0003_{\gamma Z}$$

QWEAK HAS ANALYZED 4% OF THEIR DATA



Weak mixing angle a little low;
Stay tuned!

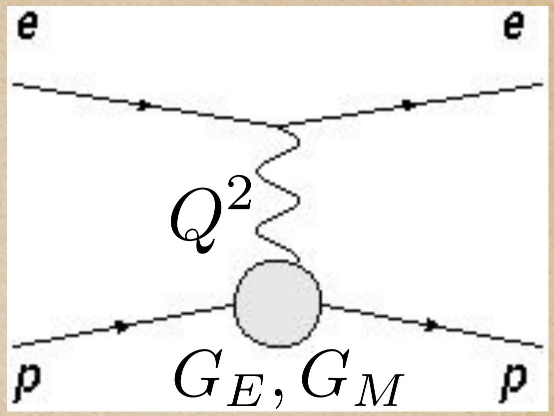
New Physics smoking gun?


Proton's
Weak Charge
Proton
Radius Puzzle
THEORY TOOL:
Dispersion Relations
Weak Compton
Scattering
Neutron
Skin

Proton Charge Radius from Electron Scattering

Elastic e-p scattering

$$\left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right) = \left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right)_{\mathrm{Mott}} \frac{\varepsilon G_E^2 + \tau G_M^2}{\varepsilon\,(1+\tau)}$$



Charge/magnetic radii

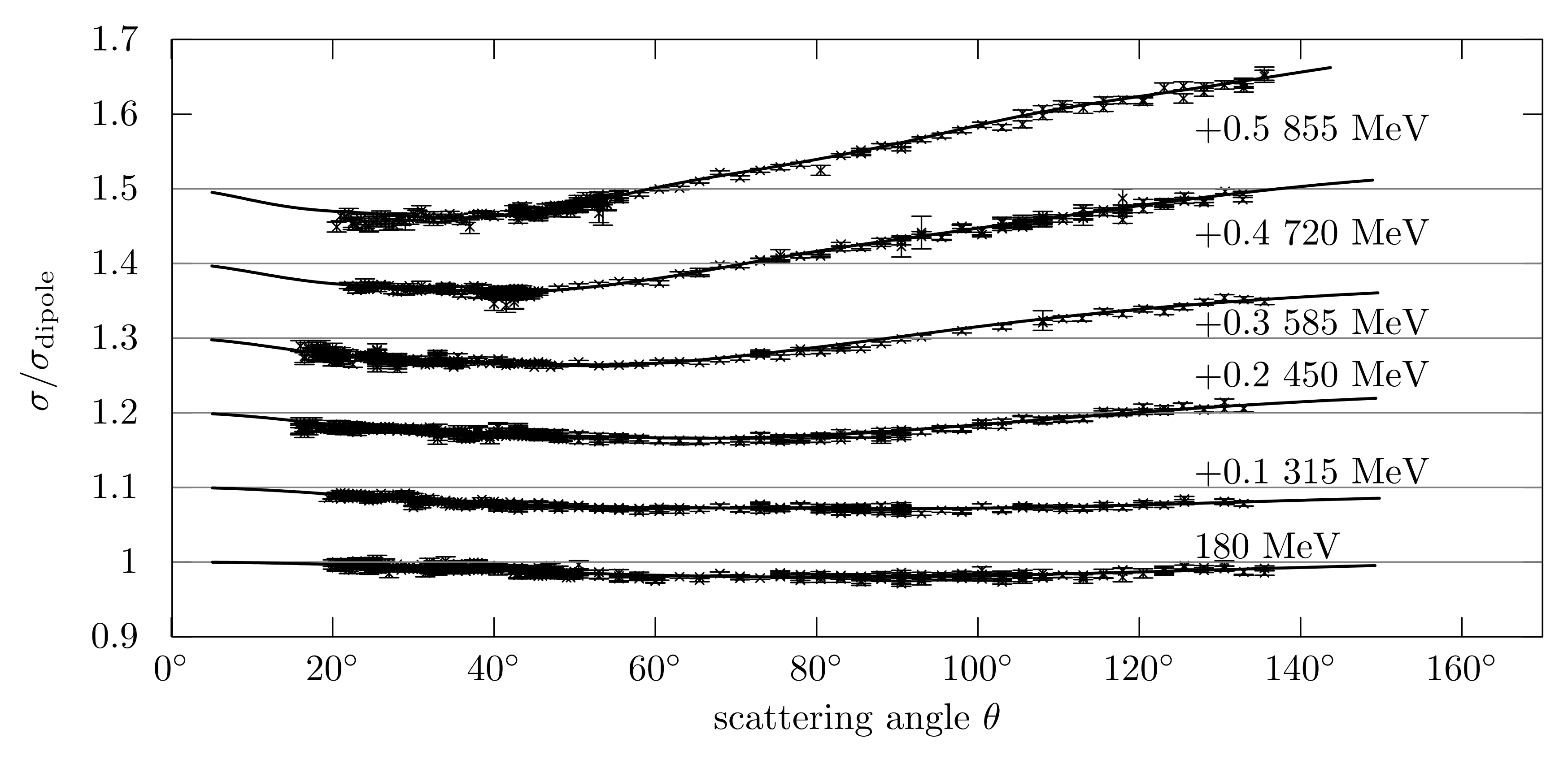
$$\left\langle r_{E/M}^2 \right\rangle = -\frac{6\hbar^2}{G_{E/M}(0)} \left.\frac{\mathrm{d}G_{E/M}(Q^2)}{\mathrm{d}Q^2}\right|_{Q^2=0}$$

Precise

measurement

at Mainz

$$r_E^p = 0.8791(79)\ \mathrm{fm}$$

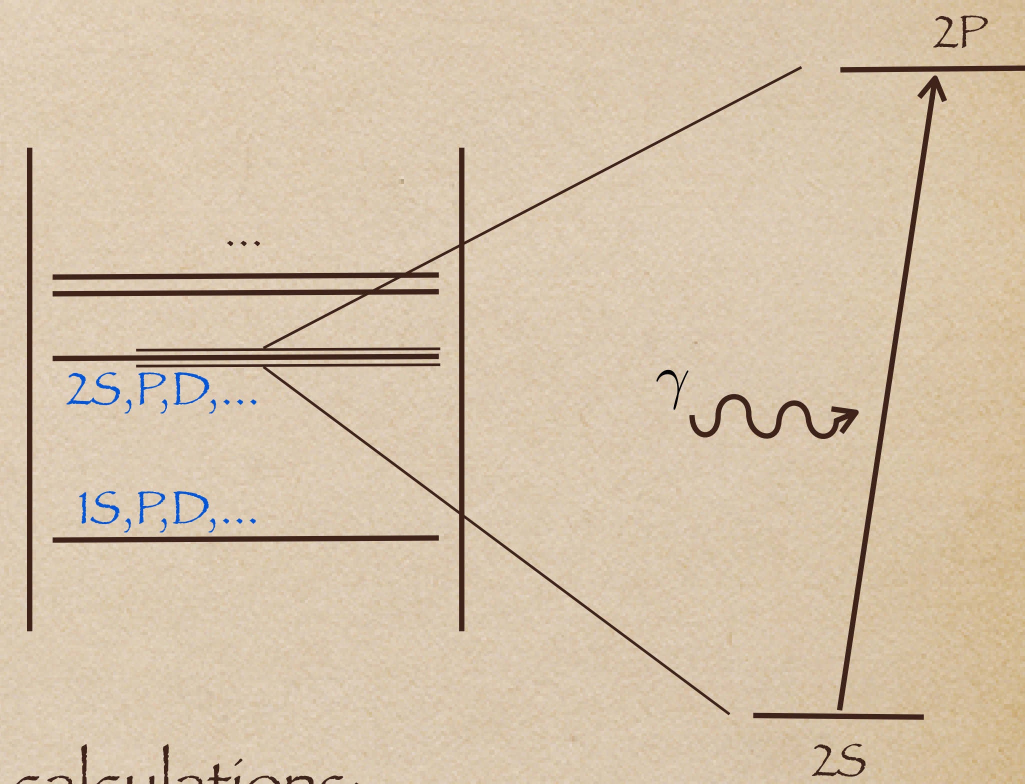


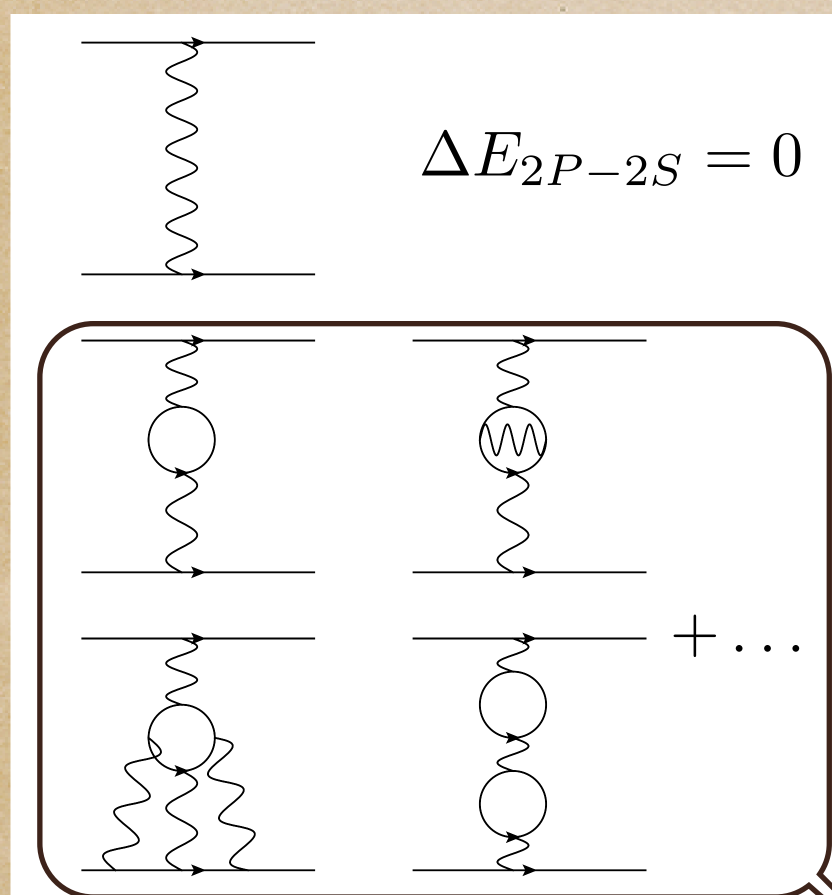
Bernauer et al [A1 Coll.], PRL 105 (2010) 242001

Proton Radius from Lamb Shift in Hydrogen Atom

Leading order: degenerate spectrum

Radiative corrections: fine structure





Modern QED calculations:

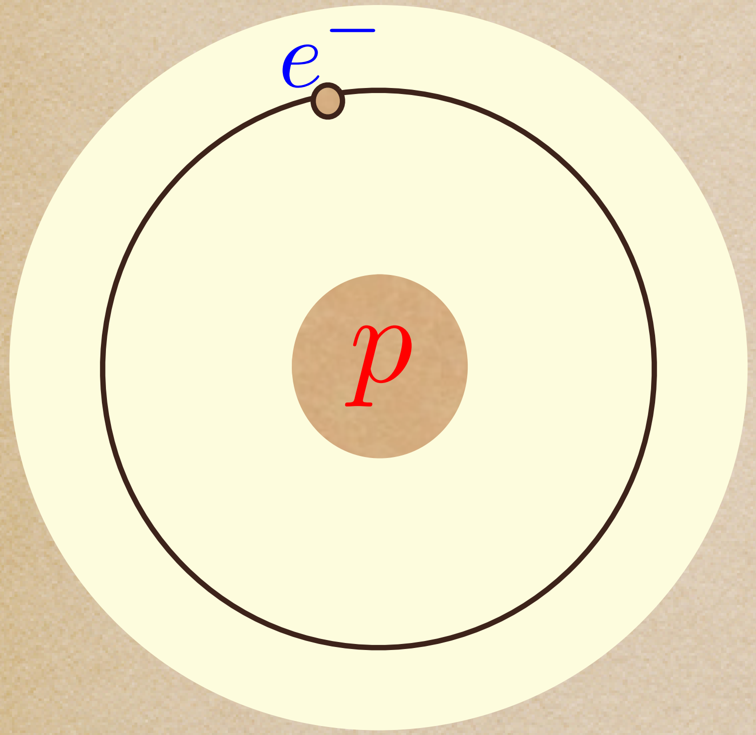
Borie, Annals Phys. 327 (2012) 733;
Eides et al., Phys.Rept. 342 (2001) 63;
Indelicato, arXiv:1210.5828, ...

Finite size correction

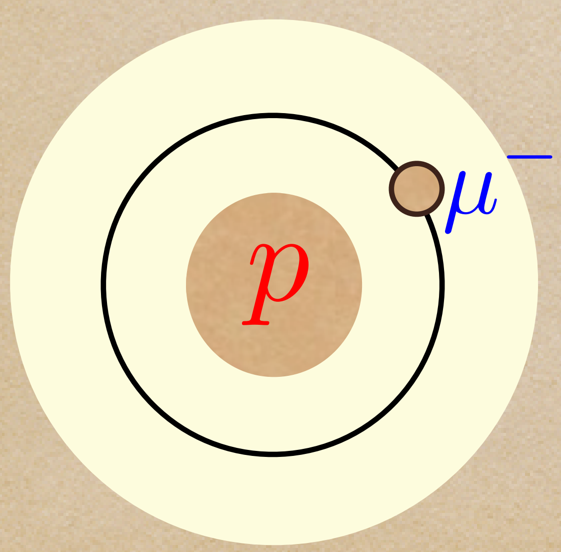
$$\Delta E_{nP-nS} = \Delta E^{QED}_{nP-nS} - \boxed{\frac{2(Z\alpha)^4}{3n^3} m_r^3\, r_E^2} + \mathcal{O}(\alpha_{em}^5)$$

Muonic vs Electronic Hydrogen

Hydrogen atom



muonic Hydrogen atom



SM: the only difference is the mass

Bohr radius $$\frac{R_{\mu-H}}{R_{e-H}} = \frac{m_e}{m_\mu} \approx \frac{1}{200}$$

$$\Delta E^{FS,\, e-H}_{2P_{3/2}-2S_{1/2}} = -8.1 \times 10^{-7}\, r_E^2\, (\mathrm{meV})$$

$$\Delta E^{FS,\, \mu-H}_{2P_{3/2}-2S_{1/2}} = -5.2275(10)\, r_E^2\, (\mathrm{meV})$$

Extractions of Proton Charge Radius

Recent measurement of Lamb shift in muonic Hydrogen

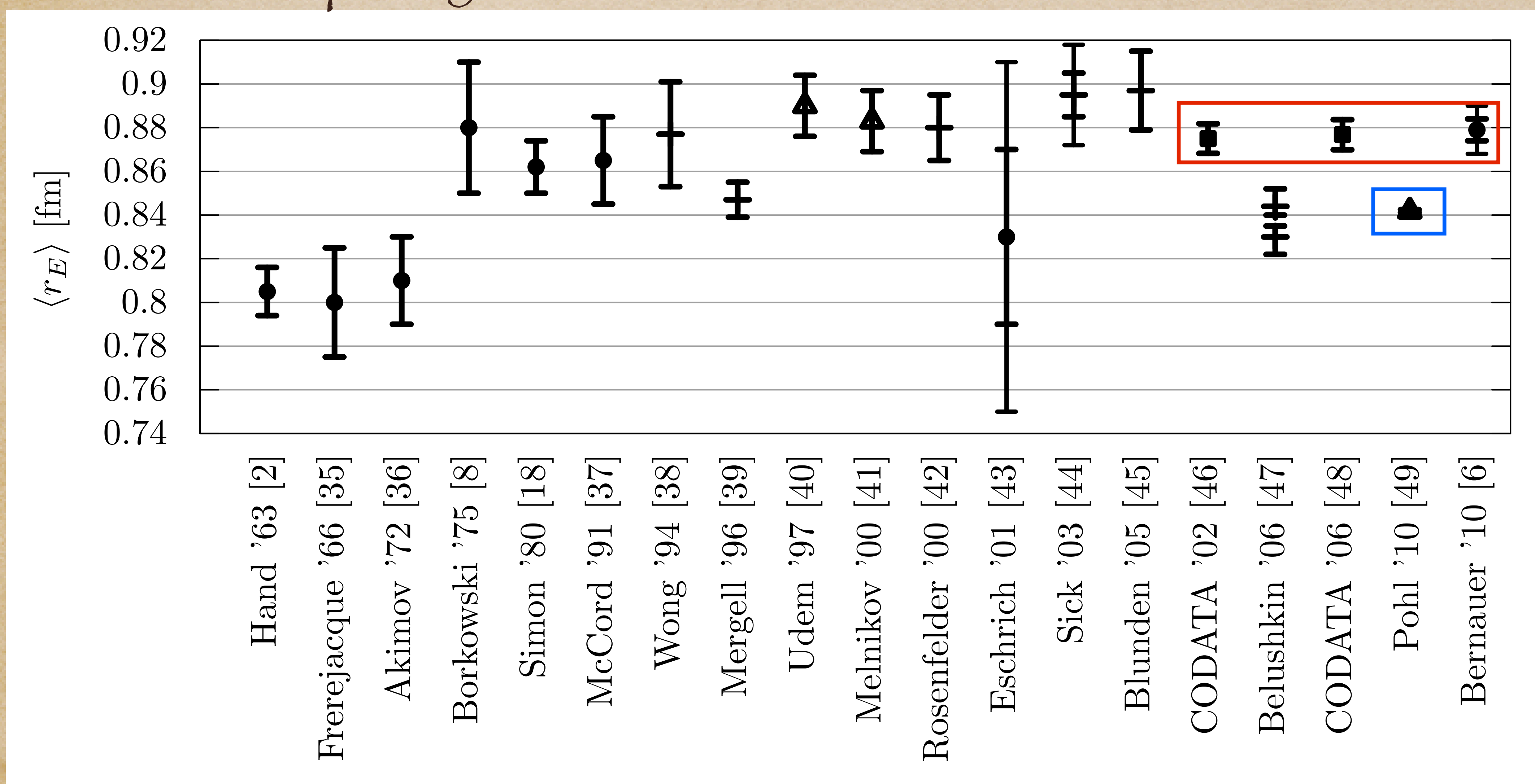
CREMA Collaboration

$r_E^p = 0.84087(39)\ \mathrm{fm}$

Pohl et al., Nature 466 (2010) 213

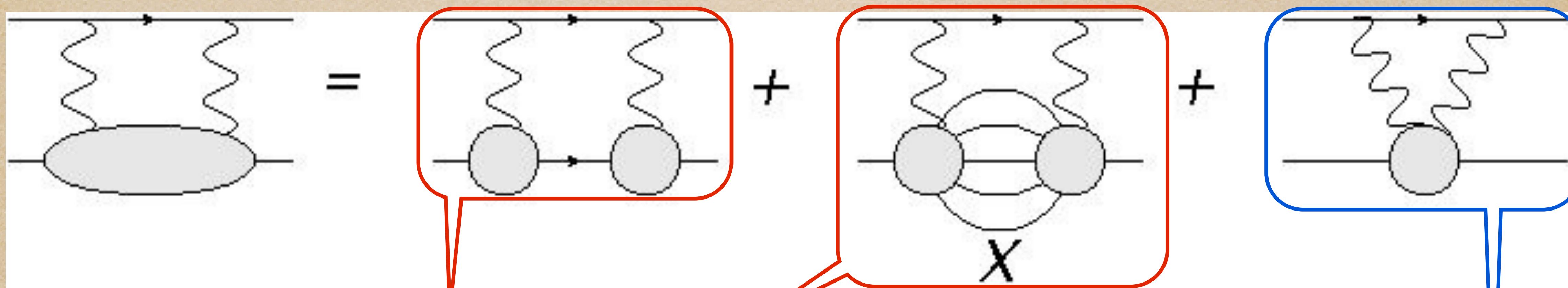
Antognini et al., Science 339 (2013) 417

7σ-discrepancy!



"Polarizability" Correction to Lamb Shift

Order $\mathcal{O}(\alpha^5)$ correction



Dispersion Relation + Data

Cannot be obtained directly from data;
Need for an input from theory

Subtraction Constant

DR: Pachucki, PR A 53 (1996) 2092;
DR: Vanderhaeghen & Carlson, PR A 84 (2011) 020102;
ChPT: Birse & McGovern, EPJ A48 (2012) 120;
DR+FESR: **MG**, Llanes-Estrada, Szczepaniak, arXiv:1302.2807

$$\Delta E_{2P-2S} = -40 \pm 5\,\mu\text{eV}$$
$$\updownarrow$$
$$\Delta E_{\text{Missing}} \approx -300\,\mu\text{eV}$$

"Polarizability" Correction to Lamb Shift

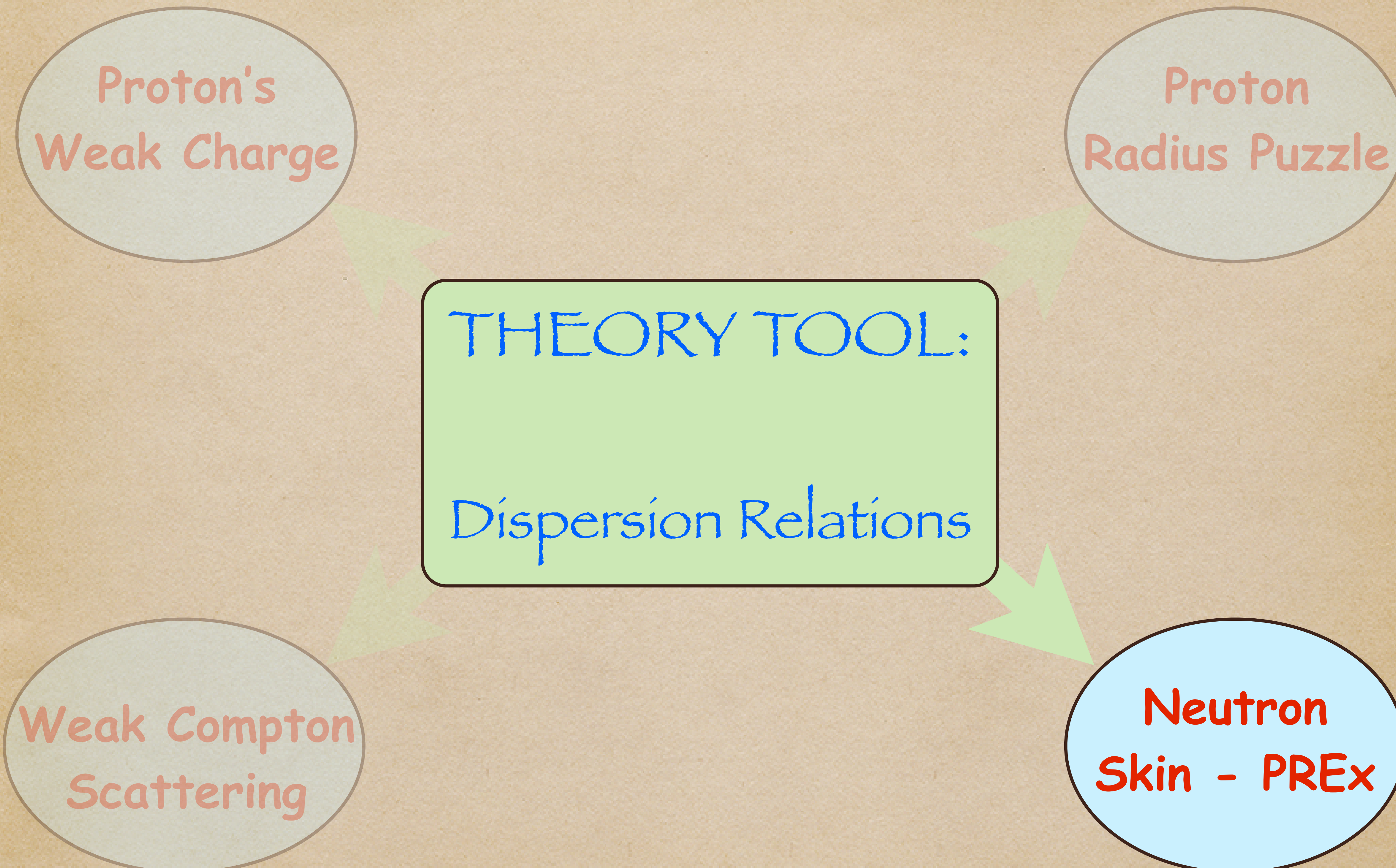
Uncertainty in the dispersive part = uncertainty in the data on elastic form factors and total photoabsorption cross section at low energy and Q^2;

Subtraction constant: constrained by the magnetic polarizability, by resonances (in FESR approach) at low Q^2 and by J=0 pole at high Q^2

Proton size is a true puzzle!

Hard to understand even within New Physics scenario: lepton non-universality constrained by the $(g-2)\mu$!

New Physics smoking gun?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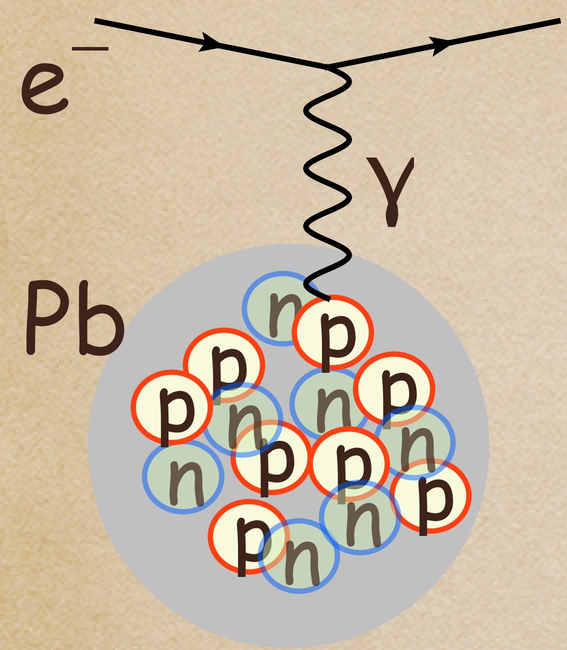
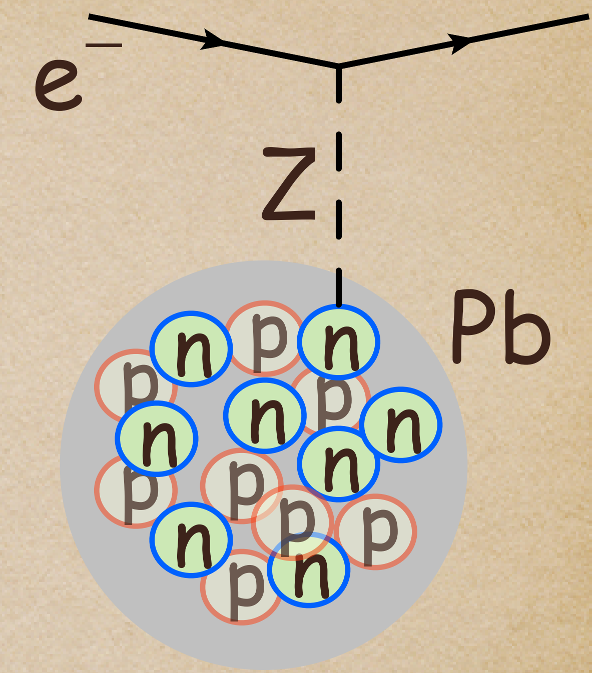
Scattering
Neutron
Skin - PREx

Neutron Skin Measurement @ PREx



PV asymmetry on nuclei

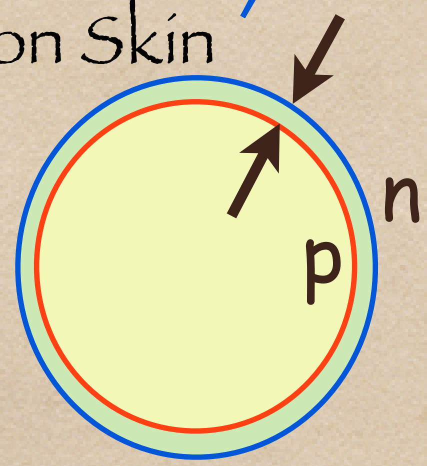
$$A_{PV}^{Z,N} \approx \frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \frac{N}{Z} \boxed{\frac{F_W(Q^2)}{F_C(Q^2)}}$$



Charge: Z protons

Weak charge: N neutrons

Neutron Skin



PREx:

PV asymmetry to **parts per billion** accuracy

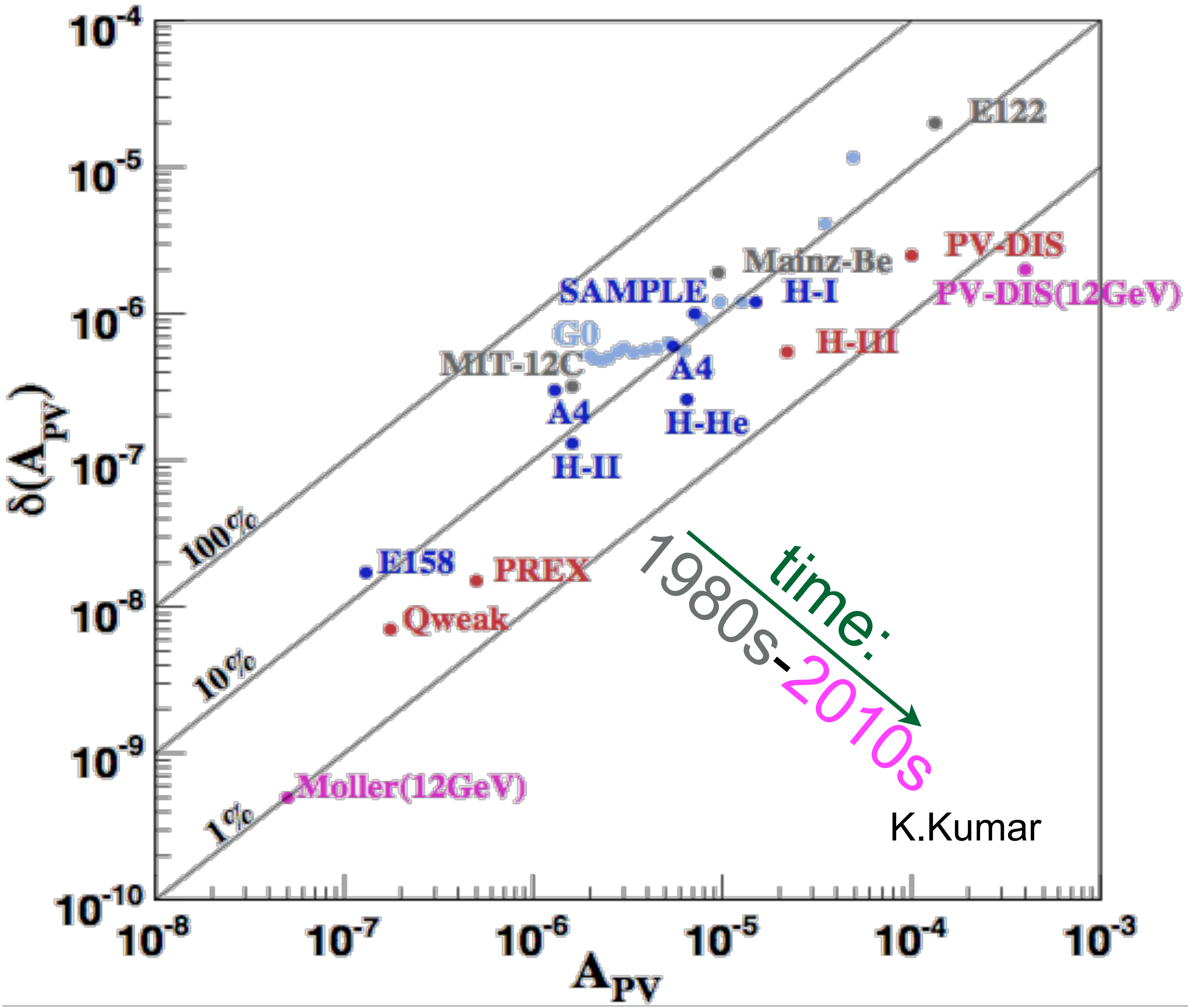
$$A_{\rm PV}^{\rm Pb} = 656 \pm 60({\rm stat}) \pm 14({\rm syst})\ {\rm ppb}$$

$$R_n - R_p = 0.33^{+0.16}_{-0.18}\ {\rm fm}$$

Important input to nuclear astrophysics (properties of neutron-rich matter)

Neutron Skin Measurement @ PREx

At the frontier of precision PV program



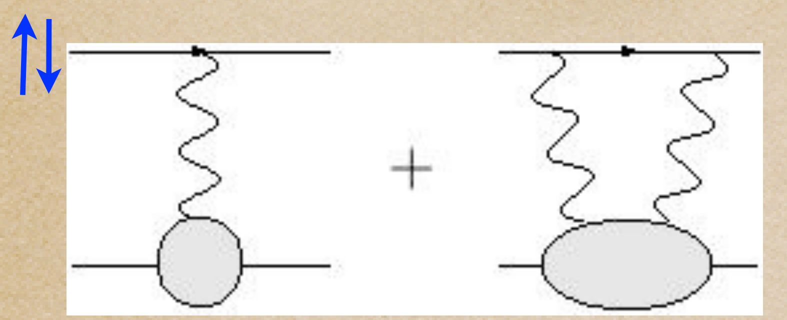
- Foundation of Standard Model
  - E122 @ SLAC
- Perturbative and non-perturbative QCD structure of the nucleon
  - Bates-[12]C, SAMPLE (MIT-Bates), Mainz-Be, A4 @ Mainz, G0, HAPPEX, PV-DIS @ JLab
- Neutron skin of a heavy nucleus
  - PREX @ JLab
- Beyond Standard Model Searches
  - E158 @ SLAC, QWeak, MOLLER, SOLID @ JLab

Parity-violating electron scattering has become a precision tool

$\rightarrow$ Sub-ppb statistical and systematic uncertainties, sub-1% normalization

Are radiative corrections, most notably Coulomb distortion effects under control?

Related observable: vector analyzing power A_n



Mott asymmetry: beam polarized normal to the scattering plane

$$A_n = \frac{\sigma_{\perp +} - \sigma_{\perp -}}{\sigma_{\perp +} + \sigma_{\perp -}} \sim \frac{2\mathrm{Im} T_{\gamma\gamma} T_\gamma^*}{|T_\gamma|^2}$$

About 10 times larger than PV asymmetry in the same kinematics

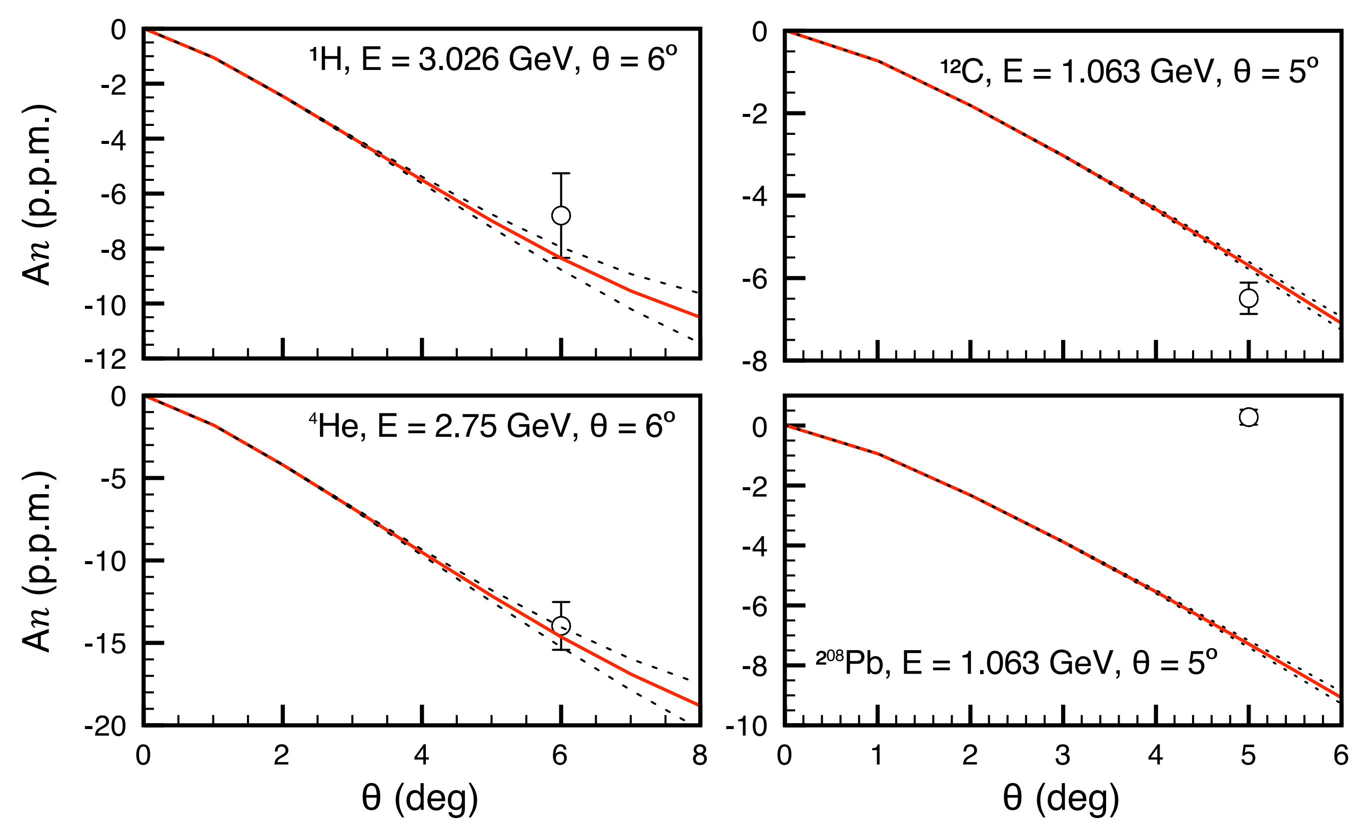
- important systematic effect for PVES experiments

Test our understanding of the theory entering γZ calculation

$$\mathrm{Im}\, T_{\gamma\gamma} = \alpha_{em}^2 \int_0^{Q^2_{max}} dQ^2 \int_{\omega_0}^{E} d\omega \, \{\mathrm{KIN.\,FACTOR} \times \mathrm{DATA}\}$$

In the two-photon exchange approximation: no theory uncertainty

Vector analyzing power An



S. Abrahamyan et al. [HAPPEX and PREX Coll.] PRL 109 (2012) 192501

The theory does well for H-1, He-4 and C-12 but not for Pb-208

Coulomb distortions? Go the opposite direction for elastic states...

Check intermediate nuclei - CREX @ JLab

Proton's
Weak Charge

Proton
Radius Puzzle

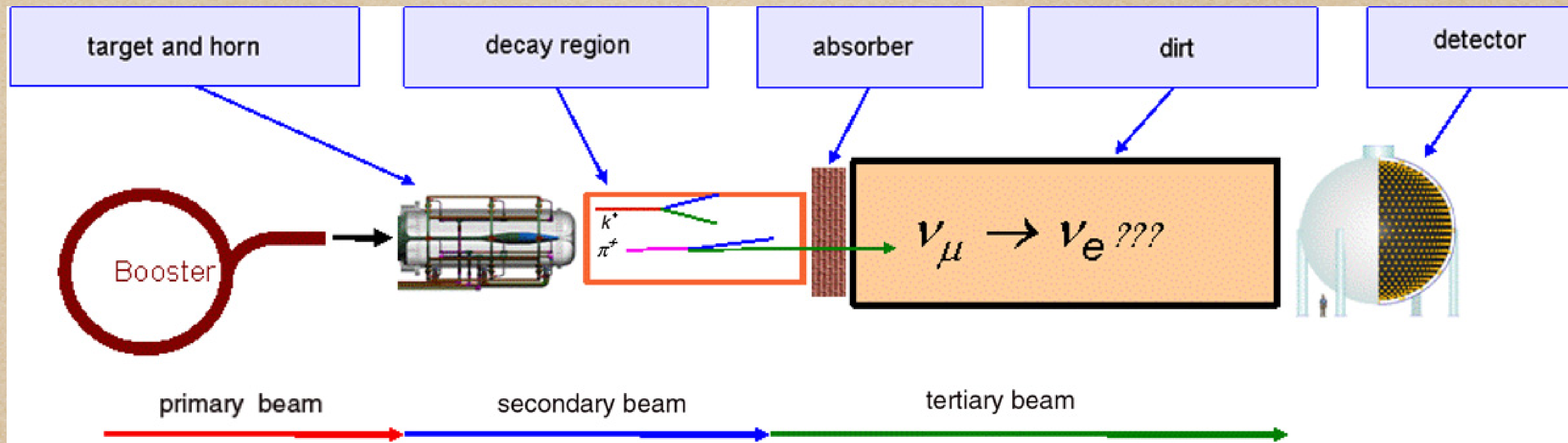
THEORY TOOL:

Dispersion Relations

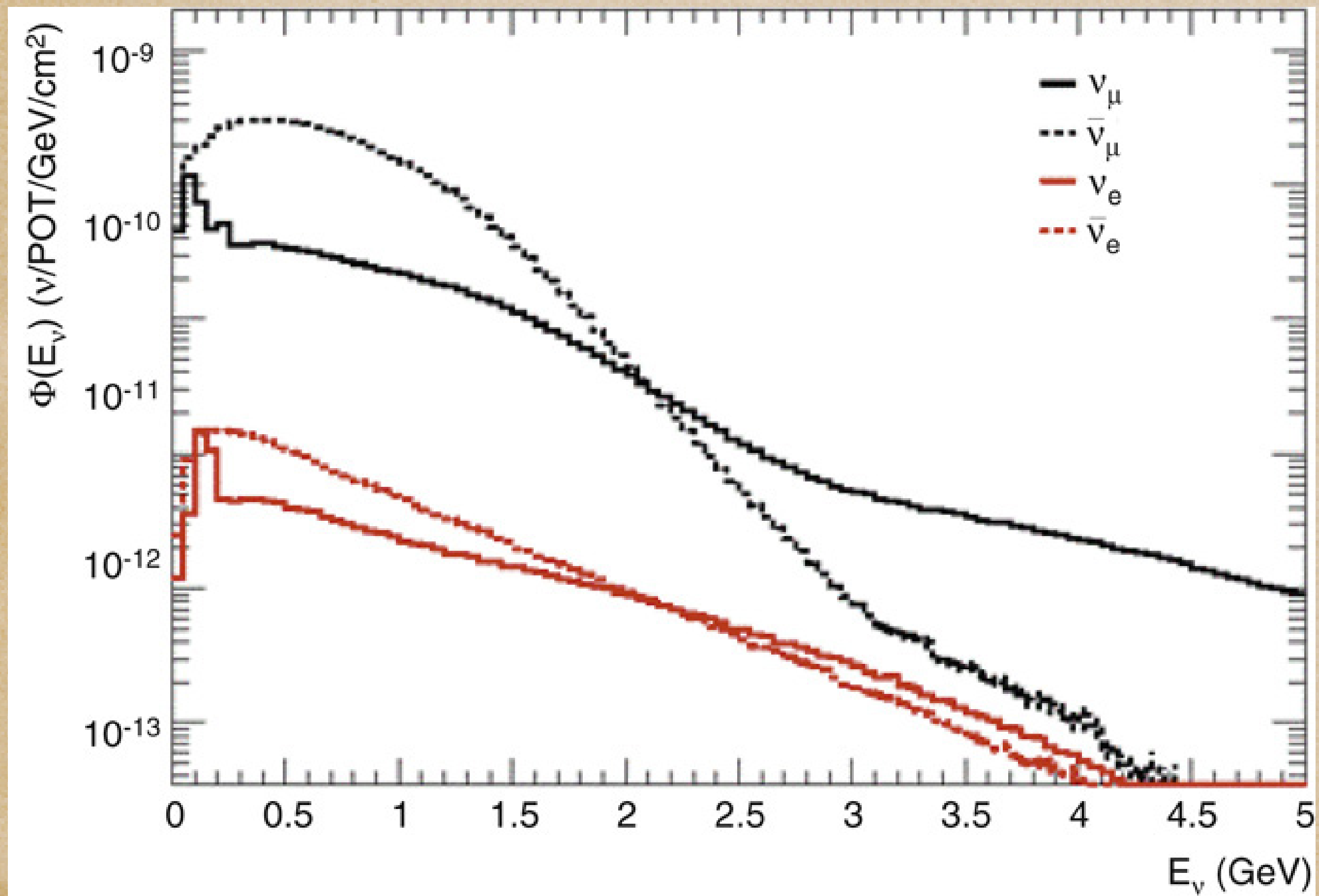
Weak Compton
Scattering

Neutron
Skin

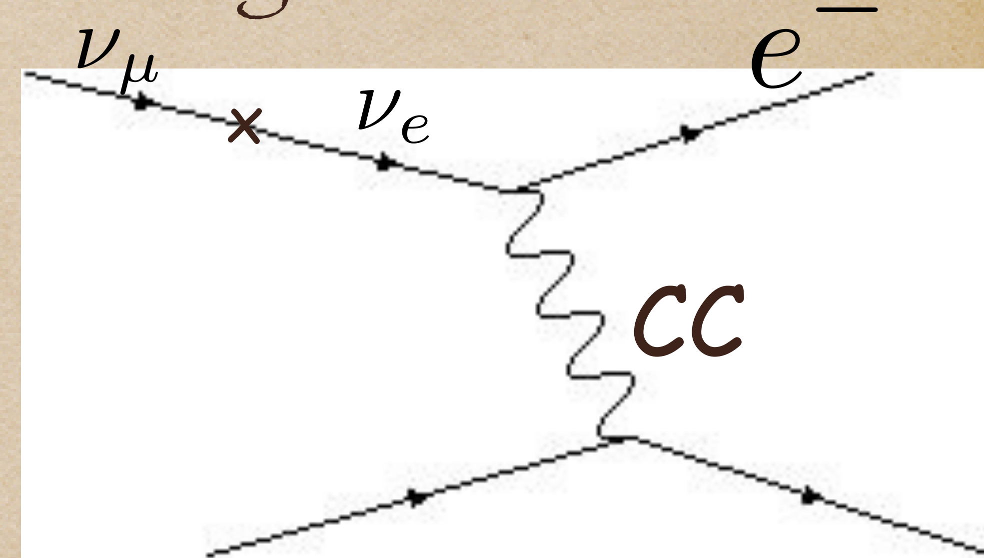
Motivation: MiniBooNE Excess



Incident neutrino flux



Charged current events



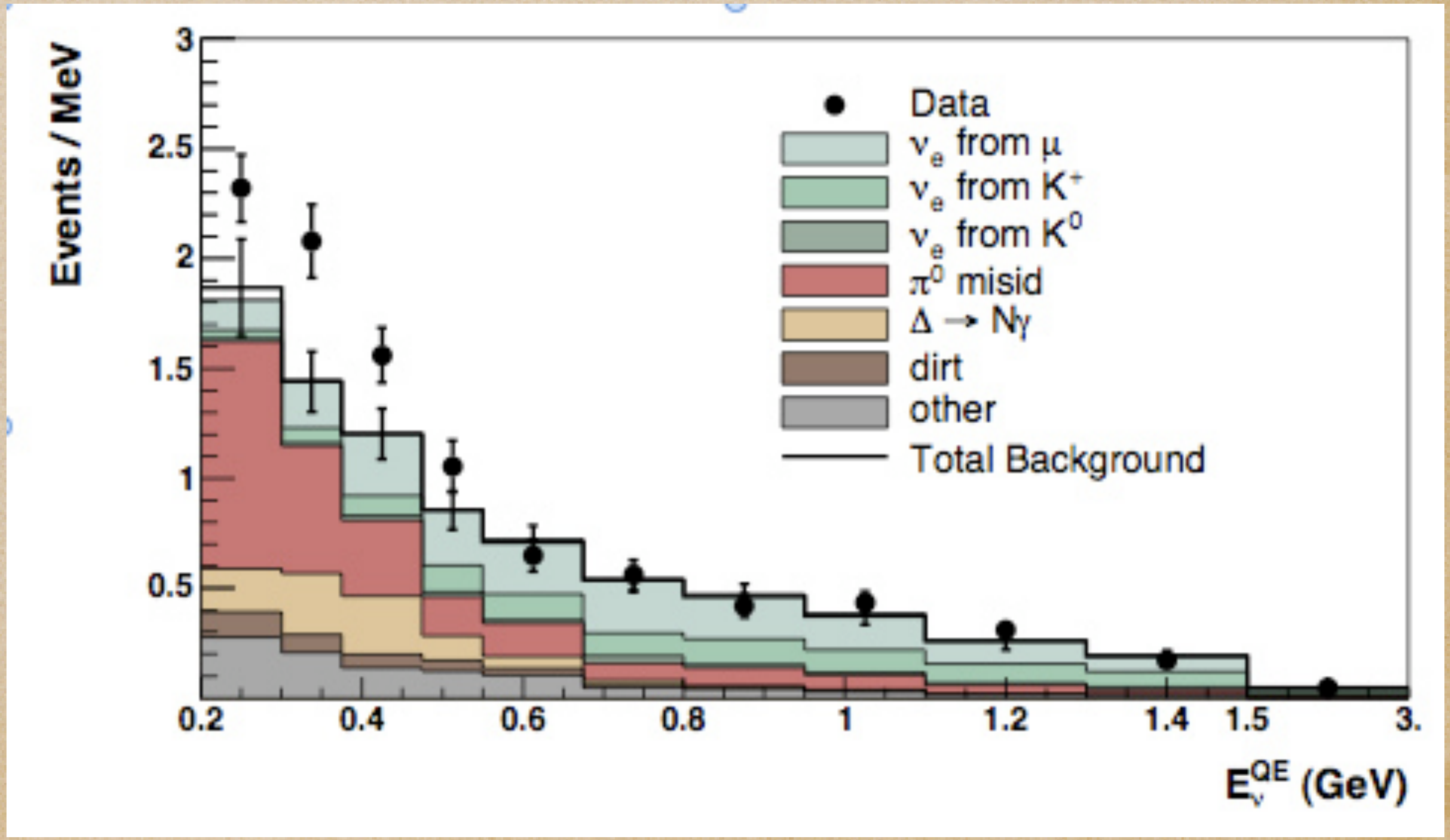
MiniBooNE Excess of Events

The more electrons are seen in the detector
- the more muon-ν converted into electron-ν
- larger neutrino mass differences

MiniBooNE motivation:

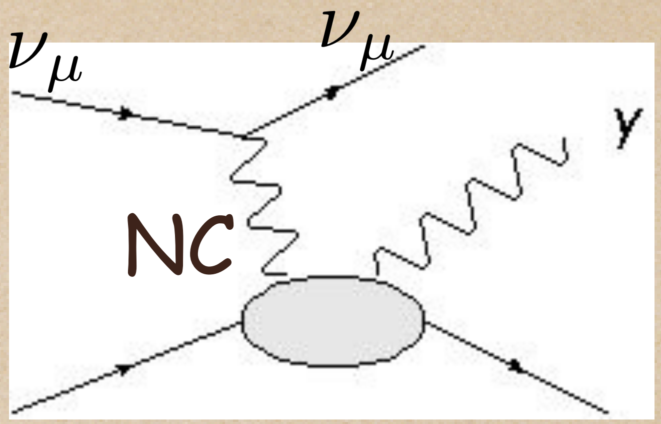
Solar, reactor ν's	$\Delta m^2 \sim 8 \times 10^{-5}\ \mathrm{eV}^2$,
Atmospheric, long-base ν's	$\Delta m^2 \sim 3 \times 10^{-3}\ \mathrm{eV}^2$.
LSND puzzle	$\Delta m^2 \sim 1\ \mathrm{eV}^2$

MiniBooNE results:
- exclude LSND for $E > 0.5$ GeV
- observe excess at $0.2 < E < 0.5$ GeV



MiniBooNE Excess of Events

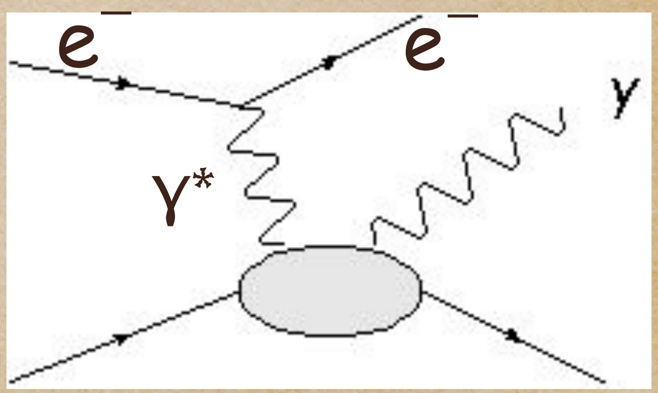
Hypothesis: NC-induced photons
mis-ID for electrons in the detector



Currently: only a model with Delta excitation in the analysis

A generalization of virtual Compton scattering to a weak probe

VCS measurements @ Mainz, JLab, MIT-Bates



Dispersion relations for VCS:

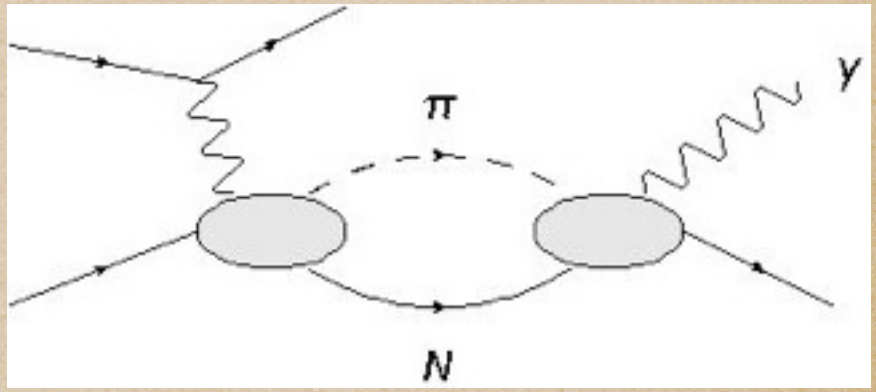
Pasquini, MG, Drechsel, Metz, Vanderhaeghen, EPJA (2001)

Weak Compton Scattering

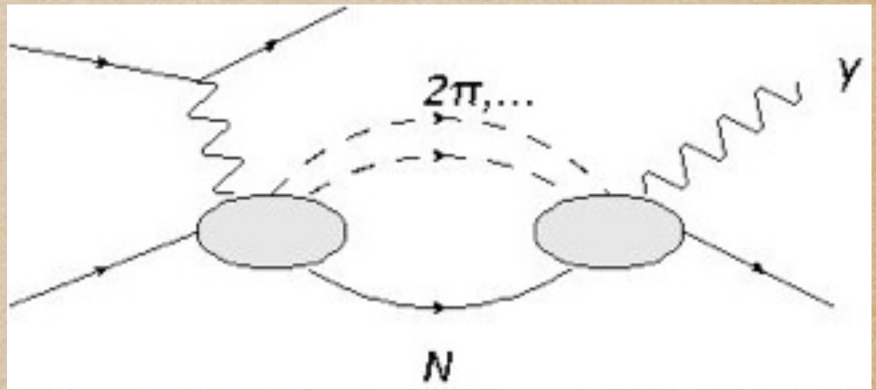
Dispersion relations for weak Compton scattering:

MG, X. Zhang, in preparation

Pion-nucleon intermediate state:
use the know-how of pion photo-
and electro-production:
SAID@GWU, MAID@Mainz
- extend to weak probes!



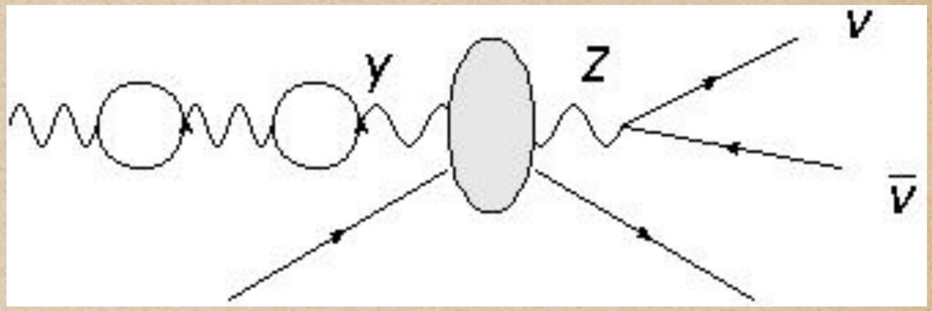
Two pion-nucleon and higher states:



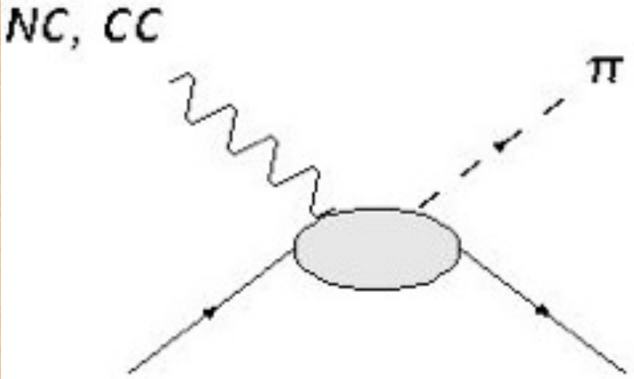
At low energies: constraints from ChPT

Weak Compton Scattering

Inverse process:
gamma-Z conversion in dense matter
- energy budget of neutron stars
- induced e.-m. properties of neutrinos



Weak pion production:
- an amendment to existing analyses;
- useful tool for neutrino experimentalists



Dispersion approach to weak Compton scattering:
brings together baryon spectroscopy (JLab & GWU), ChPT, neutrino experiments (MiniBooNE) and astrophysics

SUMMARY

- Standard Model: great success but not the end of the story
- Low energies tests: probe new physics in the TeV range
- Need for precision calculations that account for strongly-interacting matter
- Dispersion relations and sum rules: model-independent formalism, use experimental data, reliable error estimation
- Overlap of atomic, nuclear, neutrino and astrophysics!
- Theorists are urged to estimate systematical uncertainties of their calculations - need to understand QCD better - DR offer a unique model-independent tool for this task

THANK YOU!

Back-Up Slides

Isospin rotation of e.-m. data: resonances

Isospin 1/2, 3/2 resonances

$$\langle X|J^{\mu}_{NC,V}|p\rangle = (1-4s^2\theta_W)\langle X|J^{\mu}_{em}|p\rangle - \langle X|J^{\mu}_{em}|n\rangle$$

$$\langle p|J^{\mu}_{em}|R\rangle\langle R|J^{\mu}_{NC,V}|p\rangle = (1-4s^2\theta_W)|\langle R|J^{\mu}_{em}|p\rangle|^2 - \langle p|J^{\mu}_{em}|R\rangle\langle R|J^{\mu}_{em}|n\rangle$$

Rescale each I=1/2 resonance from e.-m. to γZ cross section as

$$\boxed{\xi^{R}_{Z/\gamma} \equiv \frac{\sigma^{\gamma Z,p}_{T,R}}{\sigma^{\gamma\gamma p}_{T,R}} = (1-4s^2\theta_W) - \underbrace{\frac{A^{p}_{R,1/2}A^{n*}_{R,1/2} + A^{p}_{R,3/2}A^{n*}_{R,3/2}}{|A^{p}_{R,1/2}|^2 + |A^{p}_{R,3/2}|^2}}_{y_R}}$$

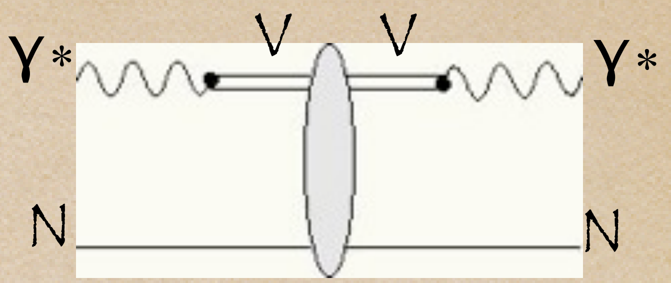
	$P_{33}(1232)$	$S_{11}(1535)$	$D_{13}(1520)$	$S_{11}(1665)$	$F_{15}(1680)$	$P_{11}(1440)$	$F_{37}(1950)$
y_R	$-1.0^{-0.1}_{+0.1}$	$-0.51^{-0.71}_{+0.35}$	$-0.77^{-0.125}_{+0.125}$	$-0.28^{-0.86}_{+0.45}$	$-0.27^{-0.12}_{+0.1}$	$-0.62^{-0.2}_{+0.19}$	-1^{-1}_{+1}

Uncertainties - from PDG helicity amplitudes values

Isospin rotation of e.-m. data: background

Vector Dominance Model (VDM)

$$|\gamma^*\rangle = \sum_V C_{\gamma^* V} |V\rangle \qquad V = \rho\,,\ \omega\,,\ \phi$$



$$\sigma_{tot}^{\gamma p} = \sum_{V=\rho,\omega,\phi} \frac{4\pi\alpha}{f_V^2}\sigma_{Vp}$$

Elastic Vp cross section - independent of V

VM decay constants $\frac{4\pi}{f_V^2} = 0.4545, 0.04237, 0.05435 \quad (\rho,\omega,\phi)$

VDM sum rule: $\sigma_{tot}(\gamma p) = \sum_{V=\rho,\omega,\phi} \sqrt{16\pi \frac{4\pi\alpha}{f_V^2} \frac{d\sigma^{\gamma p\to Vp}}{dt}(t=0)}$

Measured experimentally

HERA: NPB' 02 ZEUS: Z.Phys.'95,'96, PLB'96

$139 \pm 4\ (\mu b) \quad \leftrightarrow \quad 111 \pm 13\ (\mu b) \quad \text{at } W = 70 \text{ GeV}$

Generalized VDM - continuum contribution $\sigma_{tot}^{\gamma p} = \sum_{V=\rho,\omega,\phi} \frac{4\pi\alpha}{f_V^2}\sigma_{Vp} + \sigma_{Cp}$

Isospin rotation of e.-m. data: background

Rescale the background according to

$$\boxed{\frac{\sigma^{\gamma^* p\to Zp}}{\sigma^{\gamma^* p\to \gamma^* p}} = \frac{\frac{g_V^{I=1}}{e_{I=1}} + \frac{g_V^{I=0}}{e_{I=0}}\frac{\sigma^{\gamma^* p\to\omega p}}{\sigma^{\gamma^* p\to\rho p}} + \frac{g_V^{s}}{e_{s}}\frac{\sigma^{\gamma^* p\to\phi p}}{\sigma^{\gamma^* p\to\rho p}} + \frac{X'}{\sigma^{\gamma^* p\to\rho p}}}{1 + \frac{\sigma^{\gamma^* p\to\omega p}}{\sigma^{\gamma^* p\to\rho p}} + \frac{\sigma^{\gamma^* p\to\phi p}}{\sigma^{\gamma^* p\to\rho p}} + \frac{X}{\sigma^{\gamma^* p\to\rho p}}}}$$

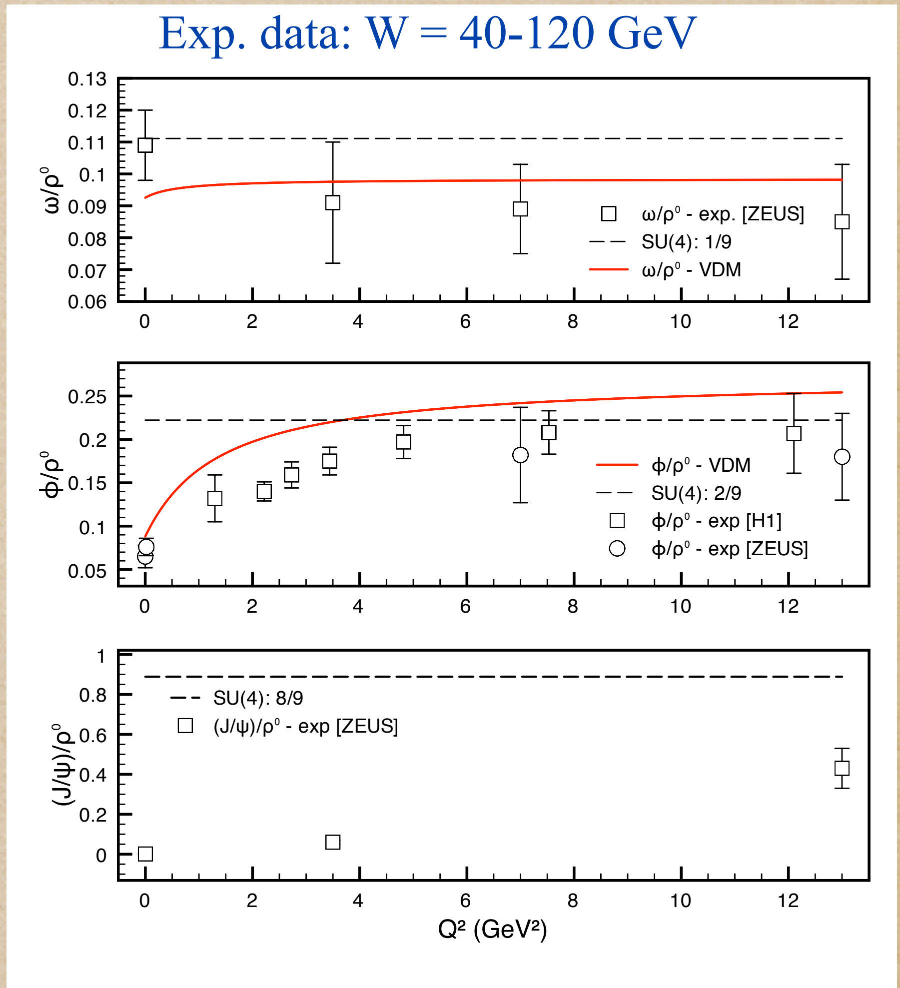
VDM: identify X(X') with continuum

$$\frac{\sigma^{\gamma^* p\to Vp}}{\sigma^{\gamma^* p\to\rho p}} = \frac{r_V}{r_\rho}\frac{m_V^4}{m_\rho^4}\frac{(m_\rho^2+Q^2)^2}{(m_V^2+Q^2)^2}$$

Uncertainty estimate - from data!

$$\Delta\xi_{Z/\gamma}^{V,Model\ A} = \left[\left(\frac{\sigma^{\gamma^*\to V}}{\sigma^{\gamma^*\to\rho}}\right)^{exp} - \left(\frac{\sigma^{\gamma^*\to V}}{\sigma^{\gamma^*\to\rho}}\right)^{Model\ A}\right]\sigma^{\gamma^*\to V\to Z}$$

Continuum - 100% uncertainty



Uncertainty Estimates

Our approach: modeling, isospin decomposition AND systematic uncertainty estimate are driven by INDEPENDENT SETS OF DATA; The main region of validity of VDM corresponds to the region that gives the dominant contribution to the γZ-box correction

Rislow & Carlson: use resonance + background to model the data and CQM to model the isospin structure and estimate uncertainty - what is the intrinsic uncertainty of the CQM?

Sibirtsev et al: use resonance + background to model the data and DIS to isospin-rotate the background and estimate the uncertainty; The main contribution to the γZ-box - from low Q^2, intermediate W^2 - is DIS picture reliable at $0 < Q^2 < 1$ GeV^2?

How Everything is Made?

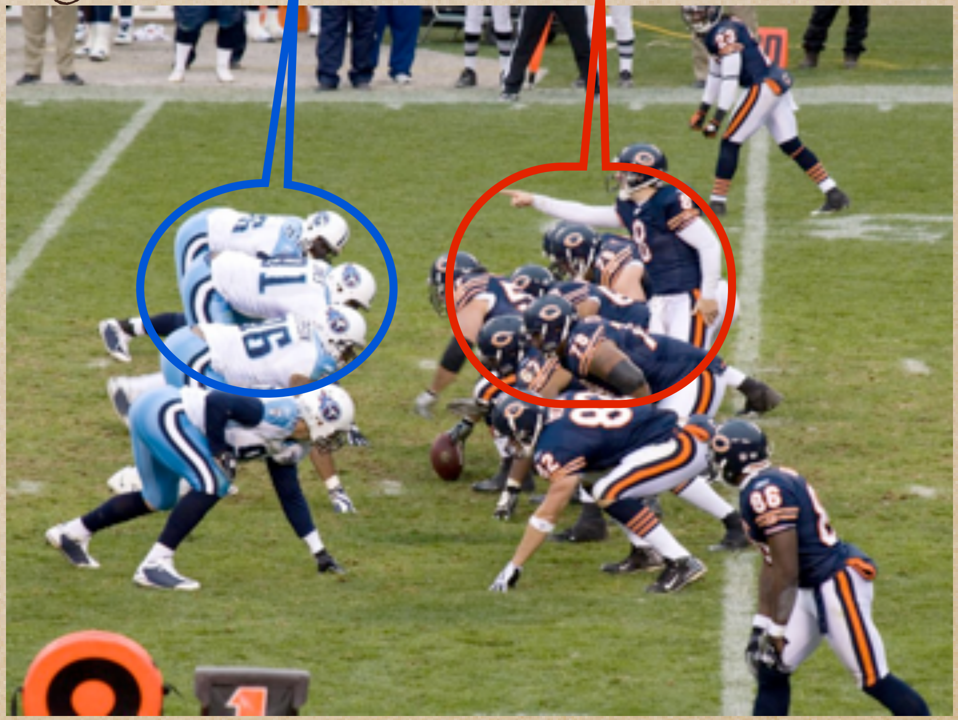
Strong interaction acts on **color charge**

(carried by quarks and gluons)

Quarks form mesons and baryons (proton, neutron etc.)

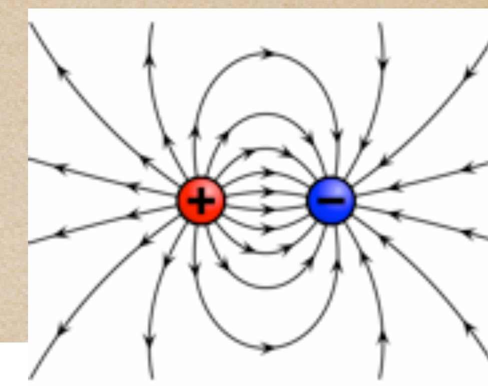
$Q \quad \bar{Q}$ "Meson"

"Baryon" $Q\,Q\,Q$ $\quad \bar{Q}\,\bar{Q}\,\bar{Q}$ "Anti-baryon"



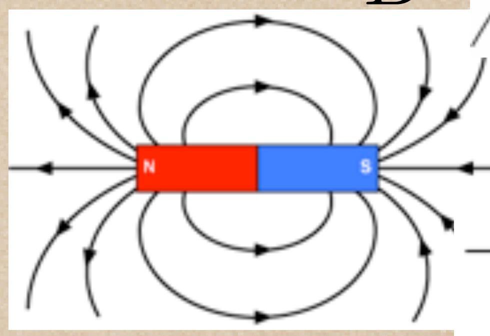
ELECTROMAGNETIC INTERACTION

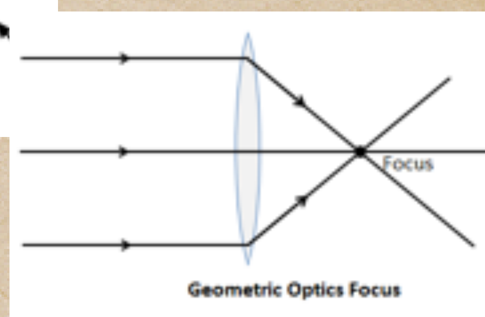
Faraday's experiments in mid 1800's, Maxwell 1873:
electricity, magnetism and optics
are encoded in these simple equations



$\vec{E}$

$\vec{B}$





$$\boxed{\begin{aligned} \partial_\mu F^{\mu\nu} &= J^\nu \\ \partial_\mu \tilde{F}^{\mu\nu} &= 0 \end{aligned}}$$

Field strength tensor $\quad F^{\mu\nu} = \partial^\mu A^\nu - \partial^\nu A^\mu$

Its Dual $\quad \tilde{F}^{\mu\nu} = \frac{1}{2}\epsilon^{\mu\nu\alpha\beta} F_{\alpha\beta}$

4-vector potential $\quad A^\mu = (\phi, \vec{A})$

Fields $\quad \vec{E} = \vec{\nabla}\phi, \qquad \vec{B} = \vec{\nabla} \times \vec{A}$

Current (sources) $\quad J^\mu = (\rho, \vec{J})$

ELECTROMAGNETIC INTERACTION

1920-1940's: Quantum electrodynamics (Dirac, Pauli, Feynman, ...)

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \bar{\psi}(i\,\partial\!\!\!/ - m)\psi + eA_\mu\bar{\psi}\gamma^\mu\psi$$

Invariant under U(1) group of transformations
- Abelian gauge field theory

The interaction mediator - the photon - is massless:
the range of the interaction is infinite

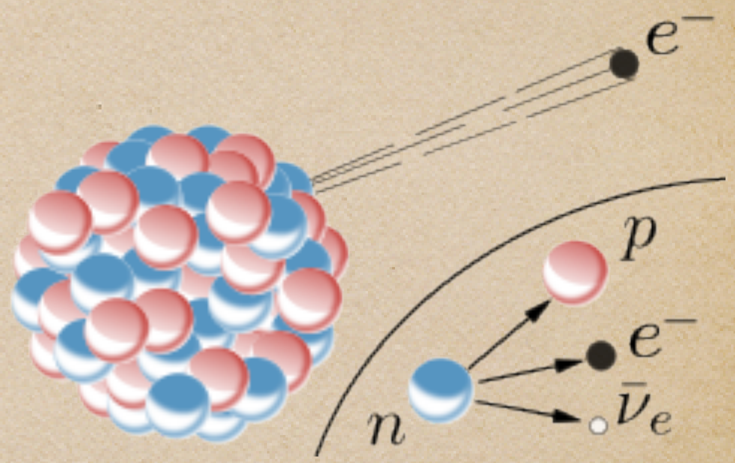
Renormalization - meaningful perturbation theory
- extremely precise theoretical calculations possible
- precision tests of QED

WEAK INTERACTION

Continuous spectrum

➟ existence of neutrino (Pauli)

$$(Z, A) \to (Z+1, A) + e^- + \bar{\nu}_e$$

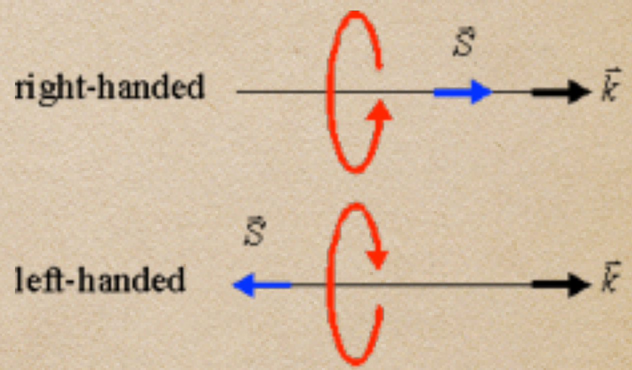


parity non-conservation

➟ contact Fermi interaction

$$\mathcal{L}^{\text{Fermi}} = G_F \bar{e}\gamma^\mu(1-\gamma_5)\nu\,\bar{p}\gamma_\mu(1-\gamma_5)n$$

The rates for left and right-handed electrons in beta decay are different



Weak interaction changes the kind of particle - “flavor”

Nuclear transmutations

Flavor change = rotation in flavor space - $SU(2)_L$ symmetry

ELECTROWEAK INTERACTION

Postulate the existence of further spin-1 gauge bosons - connected by a rotation in the "weak isospin"

New boson fields

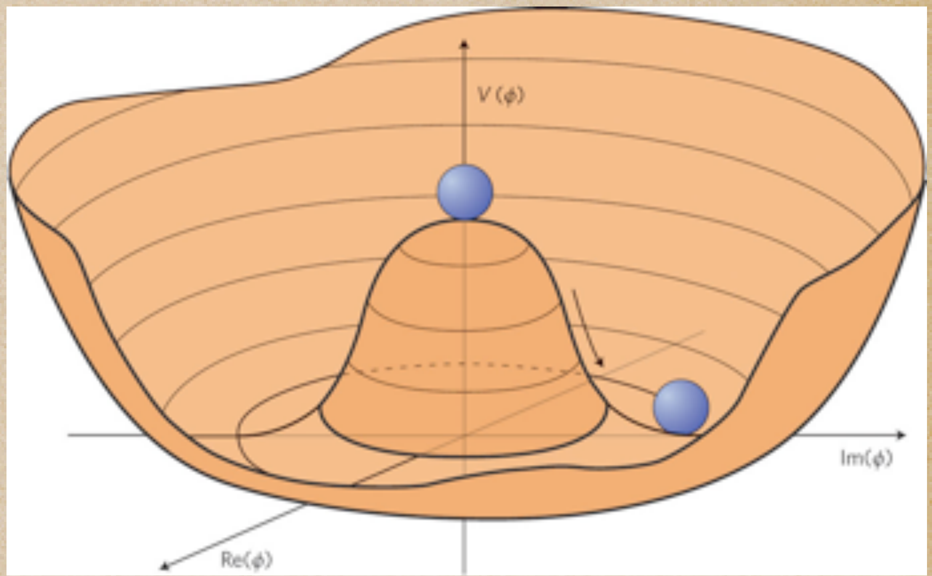
$$\boxed{\begin{aligned} W^\mu_\pm &= \frac{1}{\sqrt{2}}\left(A^\mu_1 \pm i A^\mu_2\right) \\ Z^\mu &= \cos\theta_W A^\mu_3 + \sin\theta_W B^\mu \end{aligned}}$$

$$\boxed{A^\mu = -\sin\theta_W A^\mu_3 + \cos\theta_W B^\mu}$$

Photon field

New bosons have to be massive (weak interaction is short-range)
- leave the photon massless

SU(2)L symmetry is broken by masses
- spontaneous symmetry breaking
- new spin-0 Higgs doublet
- mass ≈ coupling to Higgs field



$$\begin{pmatrix} H^+ \\ H^0 \end{pmatrix} \rightarrow \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v \end{pmatrix} \qquad v = 245\, GeV \qquad \sin\theta_W = 0.23118$$

ELECTROWEAK INTERACTION

Electroweak Lagrangian

$$\mathcal{L}_{G,H} = -\frac{1}{4}A^a_{\mu\nu}A^{a\,\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + \frac{g^2v^2}{4}W^+_\mu W^{-\mu} + \frac{v^2}{8}\left(gW^3_\mu - g'B_\mu\right)^2 + \frac{1}{2}(\partial_\mu H)^2 - \frac{1}{2}m^2_H H^2$$

$$\mathscr{L}_F = \boxed{\sum_i \overline{\psi}_i \left(i\,\partial\!\!\!/ - m_i - \frac{g m_i H}{2M_W}\right)\psi_i}$$ Kinetic term + Higgs

$$\boxed{-\frac{g}{2\sqrt{2}}\sum_i \overline{\psi}_i\,\gamma^\mu\,(1-\gamma^5)(T^+\,W^+_\mu + T^-\,W^-_\mu)\,\psi_i}$$ Charged current

$$\boxed{-\,e\sum_i q_i\,\overline{\psi}_i\,\gamma^\mu\,\psi_i\,A_\mu}$$ Electromagnetic piece

$$\boxed{-\frac{g}{2\cos\theta_W}\sum_i \overline{\psi}_i\,\gamma^\mu(g^i_V - g^i_A\gamma^5)\,\psi_i\,Z_\mu}$$ Neutral current

Predicted new particles: W^{+-}, Z^0, H^+, H^0

W^{+-}, Z^0, H^0 (?) observed experimentally!

Related observable: vector analyzing power A_n

$$A_n \sim \epsilon_{\mu\nu\alpha\beta} p^\mu k^\nu \Delta^\alpha S^\beta$$

Requires momentum transfer

"Correct" the input (optical theorem) for non-forward kinematics

Compton diff. cross section shows an exponential fall-off

$$\frac{d\sigma}{d\Omega}(t) = \frac{d\sigma}{d\Omega}(0) e^{-B|t|}$$

At high energies $\quad \mathrm{Im}F \gg \mathrm{Re}F \qquad \frac{d\sigma}{d\Omega}(t) \sim |\mathrm{Im}F|^2$

$$\sigma_{tot}(t) \sim \mathrm{Im}F \approx \sigma_{tot}(0) e^{-B|t|/2}$$

A.Afanasev, PRD 70, 073002 (2004); PLB 599, 48 (2004).

MG PRC 73, 035213 (2006); PLB 644, 322 (2007) - for the proton

MG, C.J. Horowitz, PRC 77, 044606 (2008) - for spin-0 nuclei

$$A_n^{inelast} \approx -\frac{1}{4\pi^2} \frac{m_e}{E_{lab}} \frac{M}{\sqrt{s}} \frac{A}{Z} \frac{e^{-(B/2)Q^2}}{F_C(Q^2)} \tan(\theta_{cm}/2) \int_0^{E_{lab}} d\omega \omega \frac{1}{A} \sigma_{\gamma A}(\omega) \ln\left[\frac{Q^2}{m_e^2}\left(\frac{E_{lab}}{\omega} - 1\right)^2\right]$$