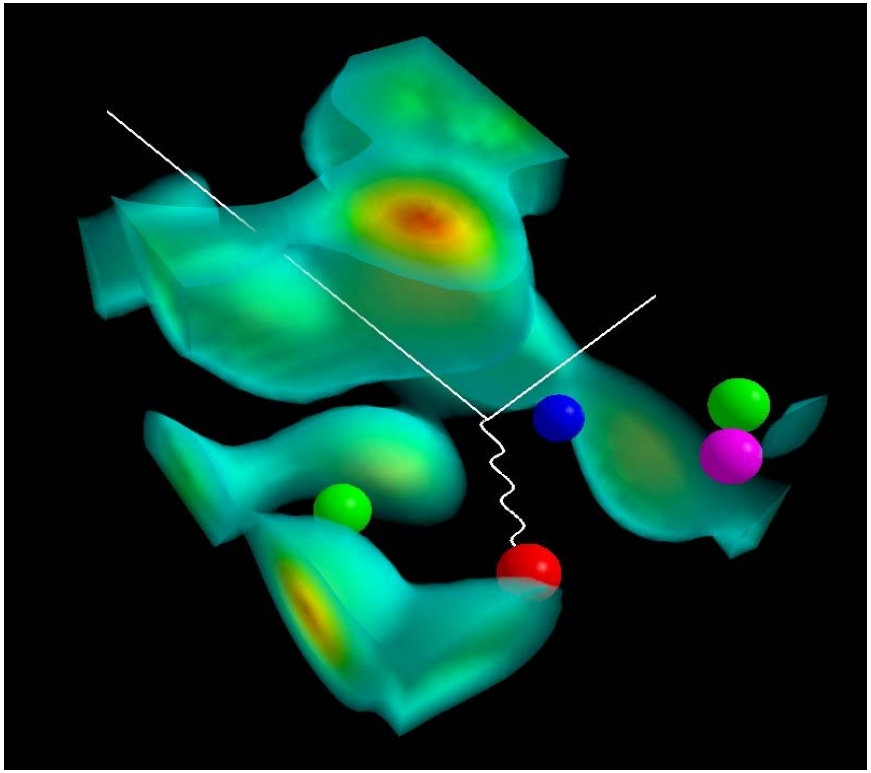
Precise Electro-Weak Studies: An Essential Component of the World-Wide Nuclear Physics Program



Anthony W. Thomas

D. Allan Bromley Memorial Symposium: Yale December 8-9, 2005

Building Blocks of the Universe

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

- **Each quark comes in 3 "colours": red, green and blue.**
- **Leptons do not carry color charge.**

These are the building blocks of matter!

Force Carriers of the Universe

BOSONS

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

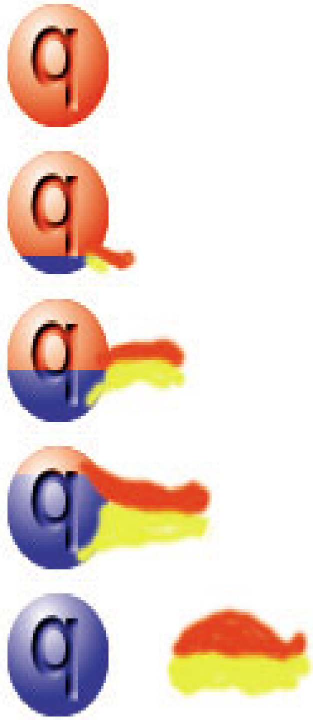
Unified Electroweak spin = 1		
Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	–1
W^+	80.4	+1
Z^0	91.187	0

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

- The massless photon mediates the long-range e.m. interactions.
- Gluons carry color and mediate the strong interaction.
- The very massive W^-, W^+, and Z^0 bosons mediate the weak interaction

Quantum Chromodynamics (QCD)

- Photons do not carry electric charge.
- Gluons *do* carry colour charge!
- Gluons can directly interact with other gluons!
- This is new!



A red quark emitting a red anti-blue gluon to leave a blue quark.

Quark-quark force grows WEAKER as quarks come close

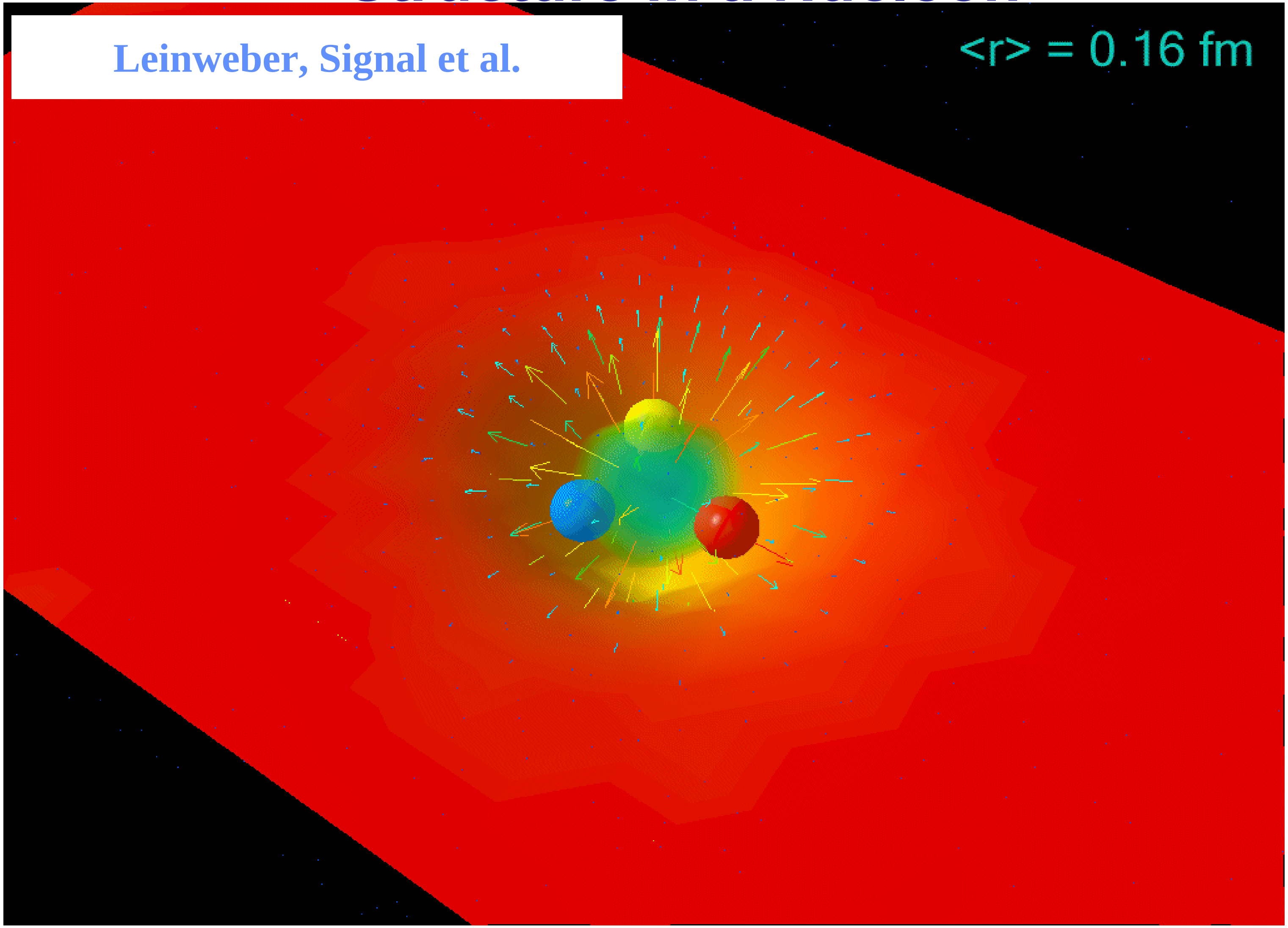
≡ "Asymptotic Freedom"

QCD and the Origin of Mass

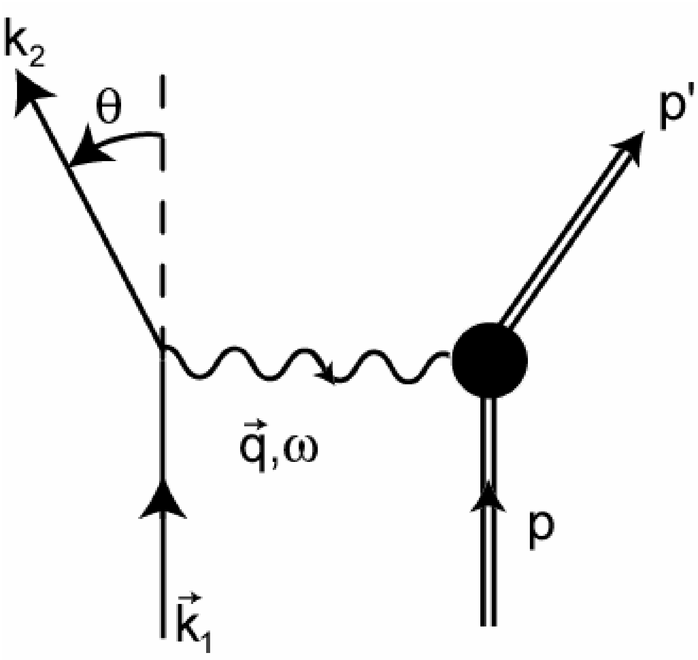
	u	+	u	+	d	=	proton
mass:	0.003	+	0.003	+	0.006	$\neq$	0.938

HOW does the rest of the proton mass arise?

Lattice QCD Simulation of Change of Vacuum Structure in a Nucleon



Electron Scattering Provides an Ideal Microscope for Nuclear Physics



- Electrons are point-like
- The interaction (QED) is well-known
- The interaction is weak
- Vary *q* to map out Fourier Transforms of charge and current densities:

$\lambda \cong 2\pi/q$ **(1 fm ⇔ 1 GeV/c)**

$$S_{fi} = \frac{-e^2}{\Omega} \bar{u}(k_2)\, \gamma^{\mu}\, u(k_1) \frac{1}{q^2} \int e^{iq\cdot x} \langle f | \hat{J}_{\mu}(x) | i \rangle d^4 x$$

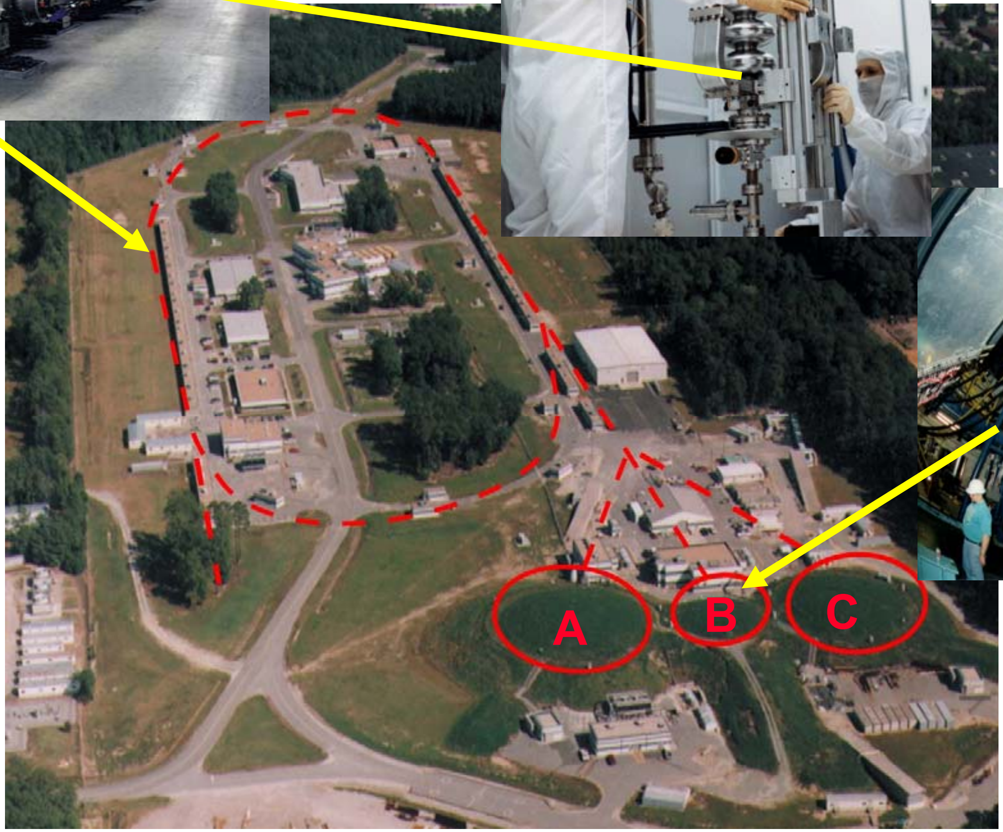
$Q^2 = -q^2 =$ 4-Momentum Transfer

CEBAF's $\vec{e}$ and CW beams dramatically enhance the power of electron scattering

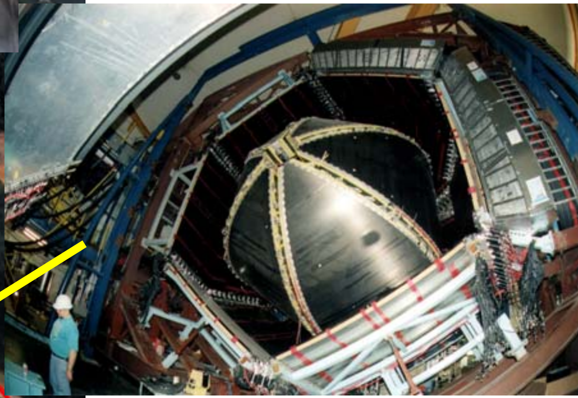
JLab: Unique Forefront Capabilities for Science

Cryomodules in the accelerator tunnel

Superconducting radiofrequency (SRF) cavities undergo vertical testing.

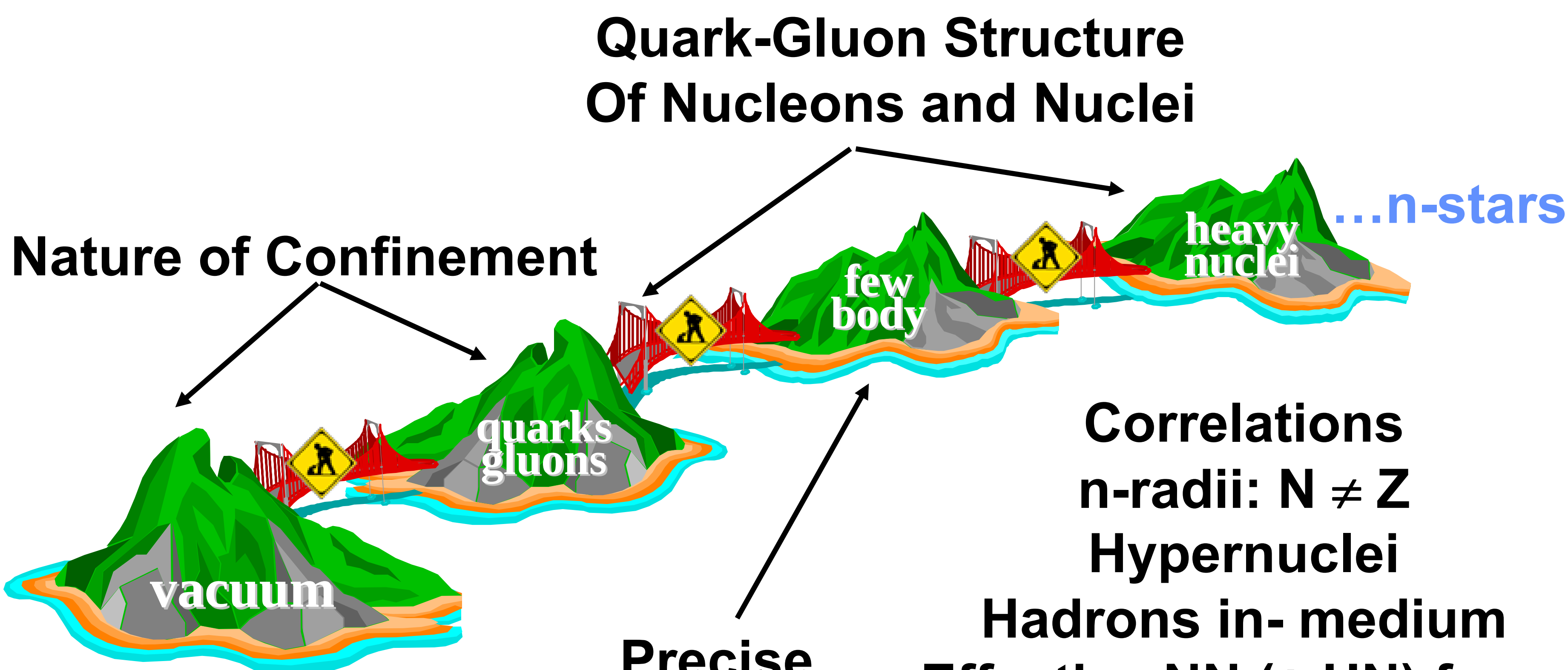


An aerial view of the recirculating linear accelerator and 3 experimental halls.



CEBAF Large Acceptance Spectrometer (CLAS) in Hall B

Program Central to *all* of Nuclear Science

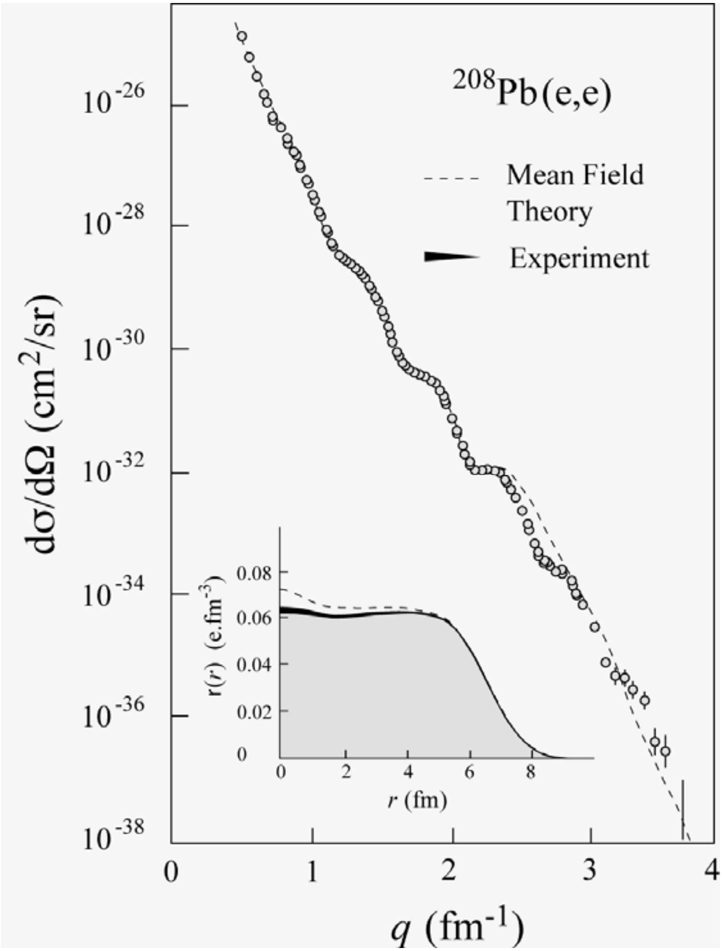


Precise
few-nucleon
calculations

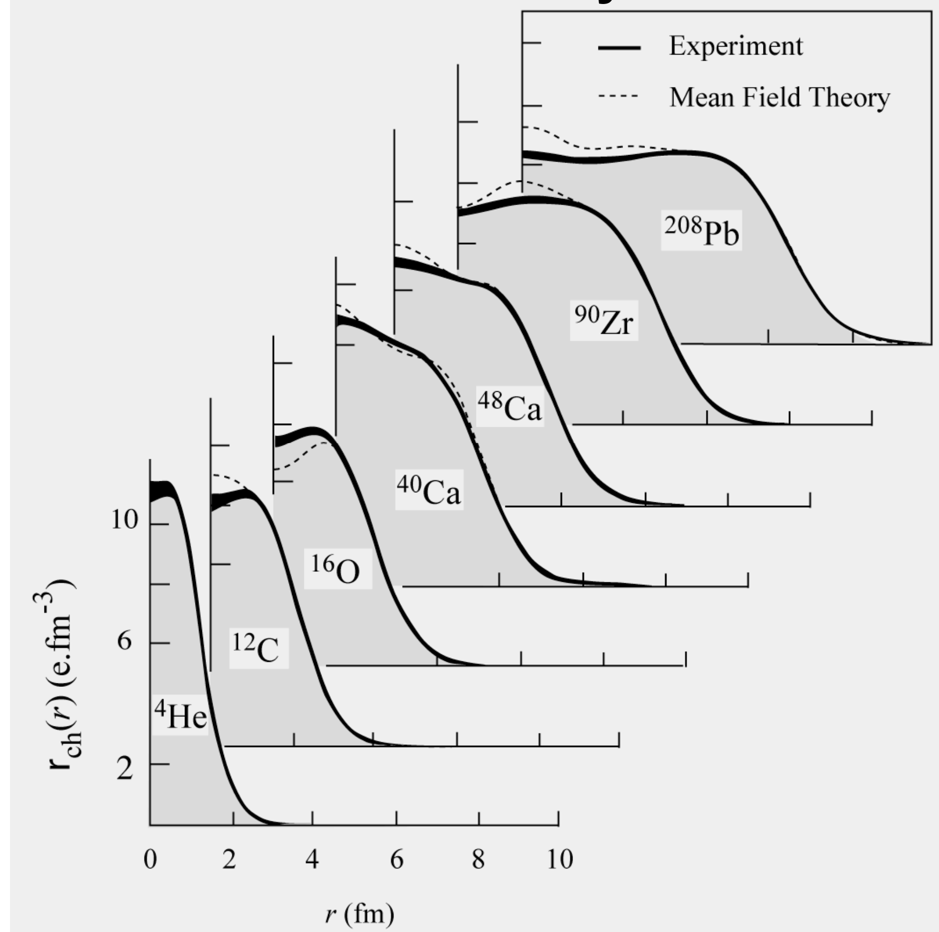
Correlations
n-radii: $N \neq Z$
Hypernuclei
Hadrons in- medium
Effective NN (+ HN) force

Exotic mesons
and baryons

(e,e) ⇒ Nuclear Charge Distributions



From Stanford to Saclay and Nikhef

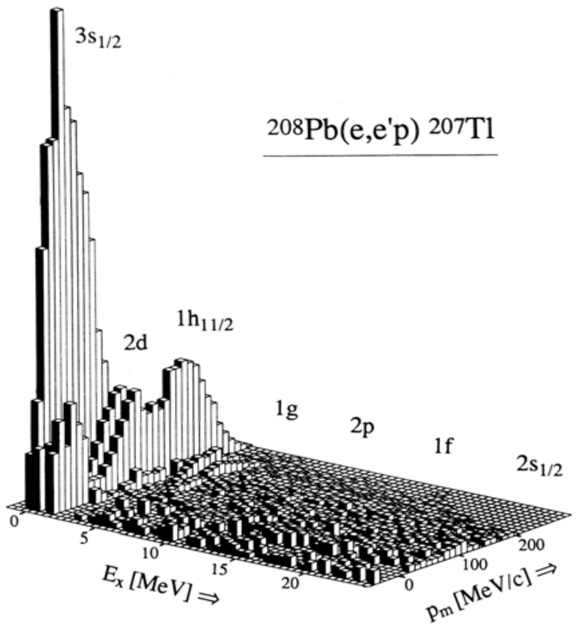


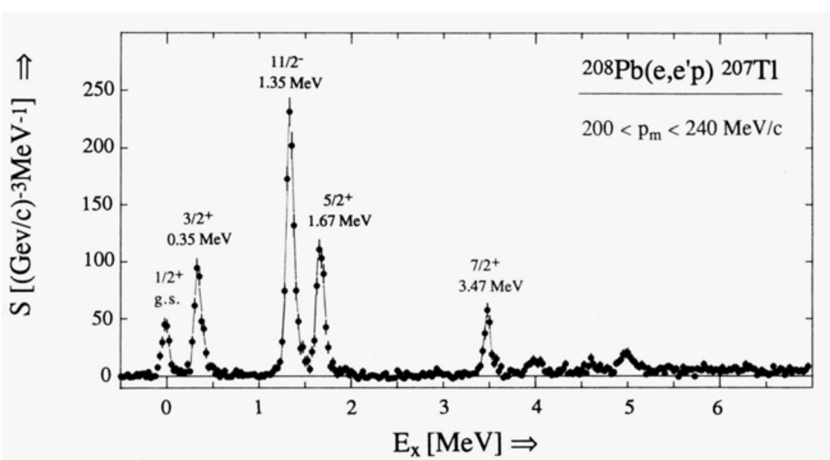
Model-independent analysis ⇒ accurate results on charge distributions

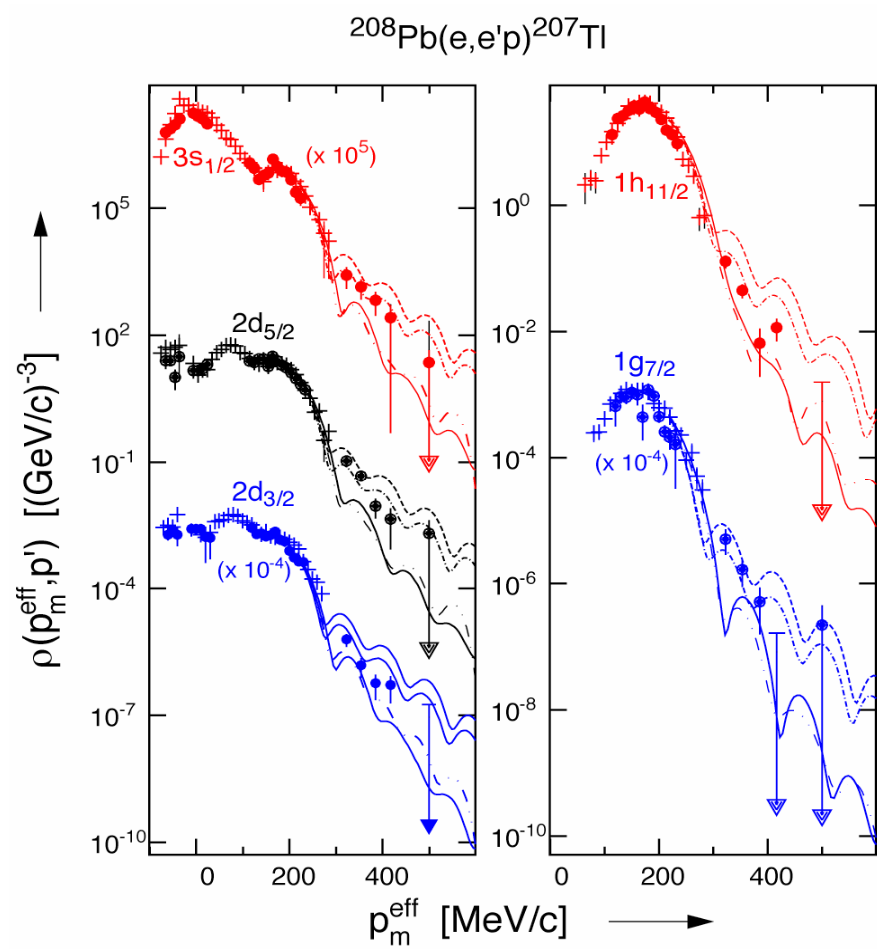
(e,e'p) ⇒ Nucleon Momentum Distributions, Shell-by-Shell

$$p_m = E_e - E_{e'} - p = q - p$$

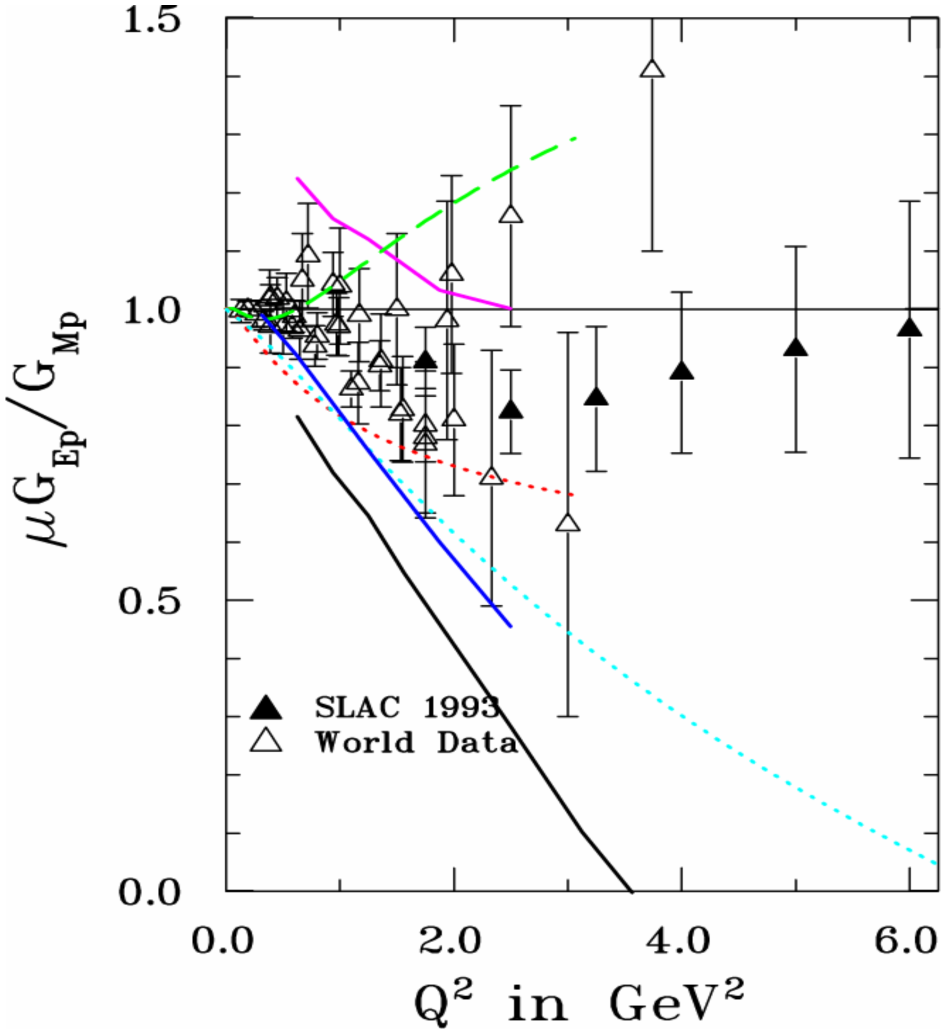
$$E_m = \omega - T_p - T_{A-1} = E_{sep} + E_{exc}$$







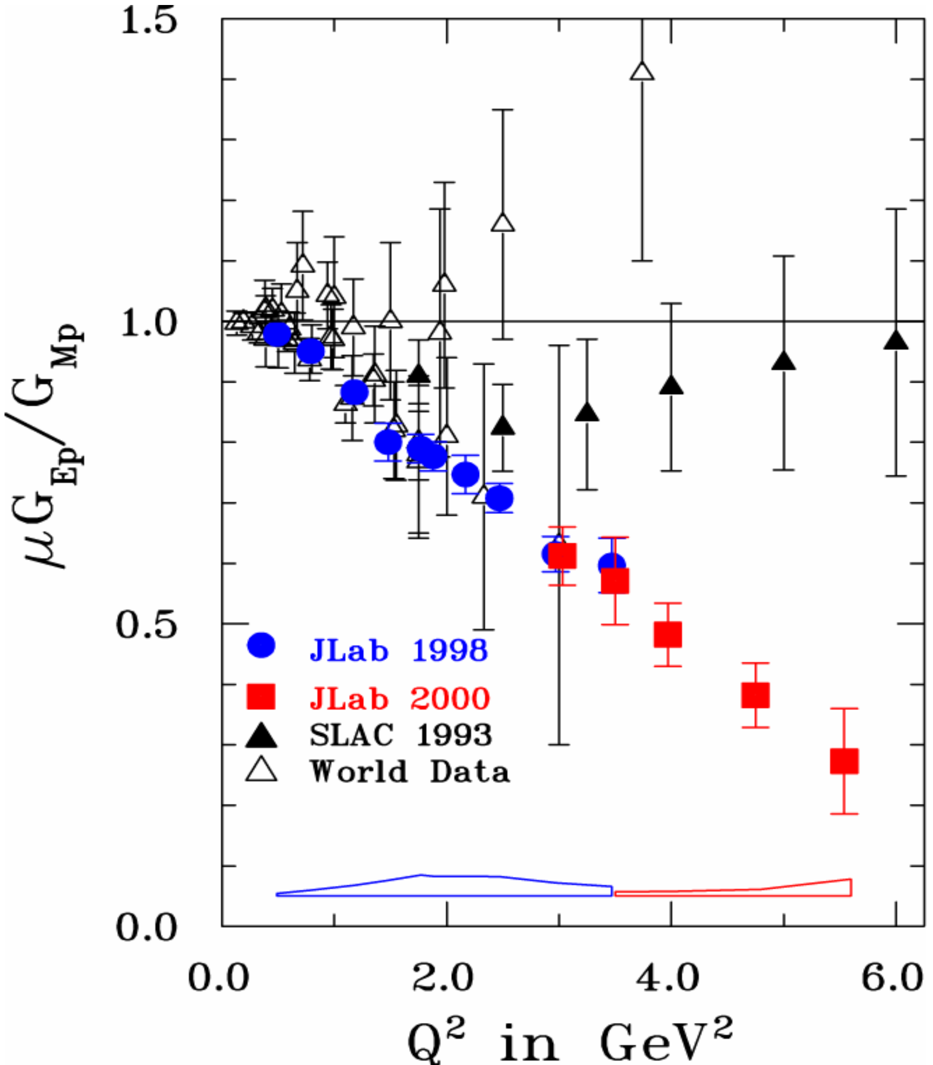
Initial Investigation of Charge vs Current in the Proton at SLAC



- Distribution of charge and magnetization in the proton seemed identical

- The experiments were limited by the precision of absolute cross section measurements

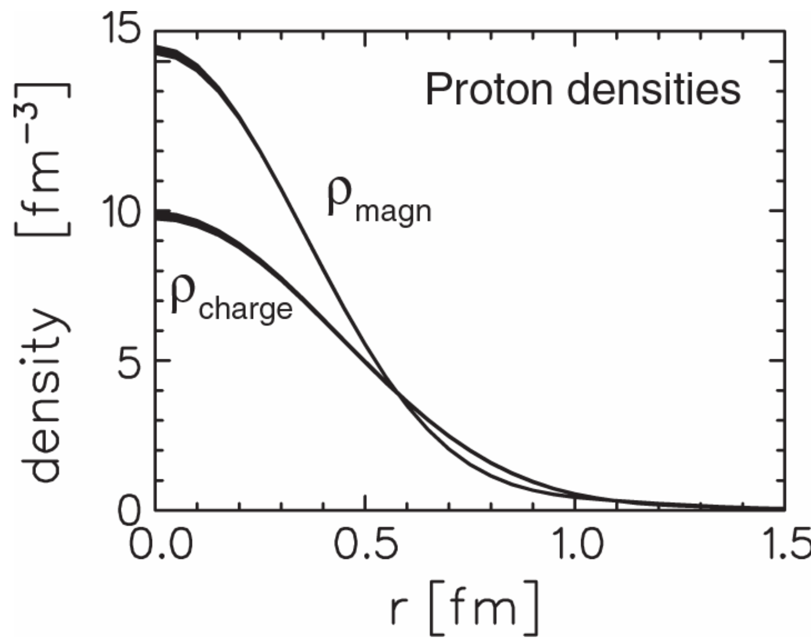
JLab Data Rewrote the Text Book



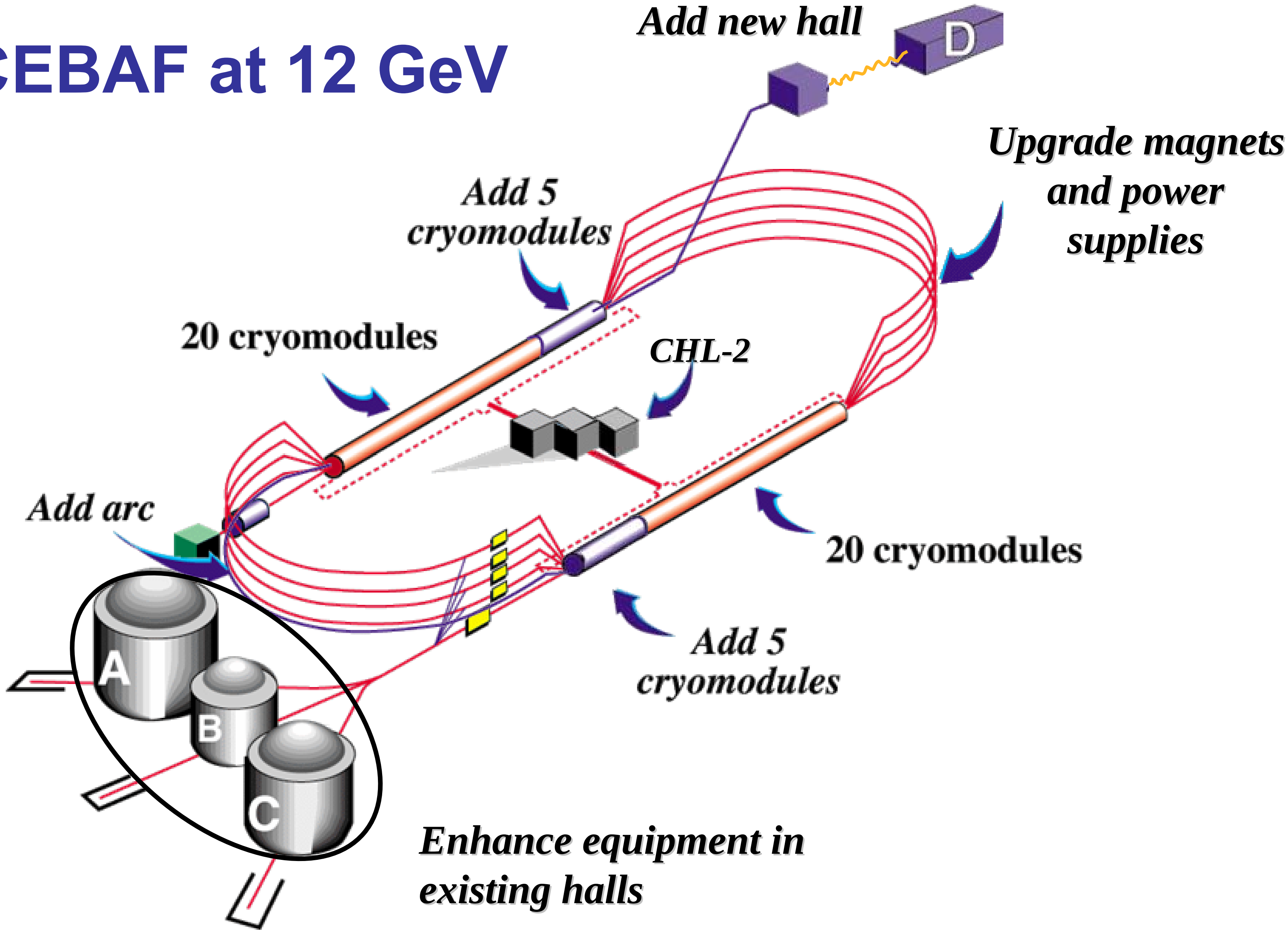
- High Intensity
- High Duty Factor
- High Polarization

⇒ Revolutionized our knowledge

⇒



CEBAF at 12 GeV



6 GeV Highlights Leading to the 12 GeV Upgrade

- Parton Distribution Functions
- Form Factors
- Generalized Parton Distributions
- Exotic Meson Spectroscopy:
  Confinement and the QCD vacuum
- Nuclei at the level of quarks and gluons
- Tests of Physics Beyond the Standard Model

Revolutionize Our Knowledge of Spin and Flavor Dependence of Valence PDFs

- **In over 35 years of study of DIS no-one has had the facilities to map out the crucial valence region**

- **Region is fundamental to our understanding of hadron structure: i.e. how nonperturbative QCD works!**

Role of di-quark correlations?

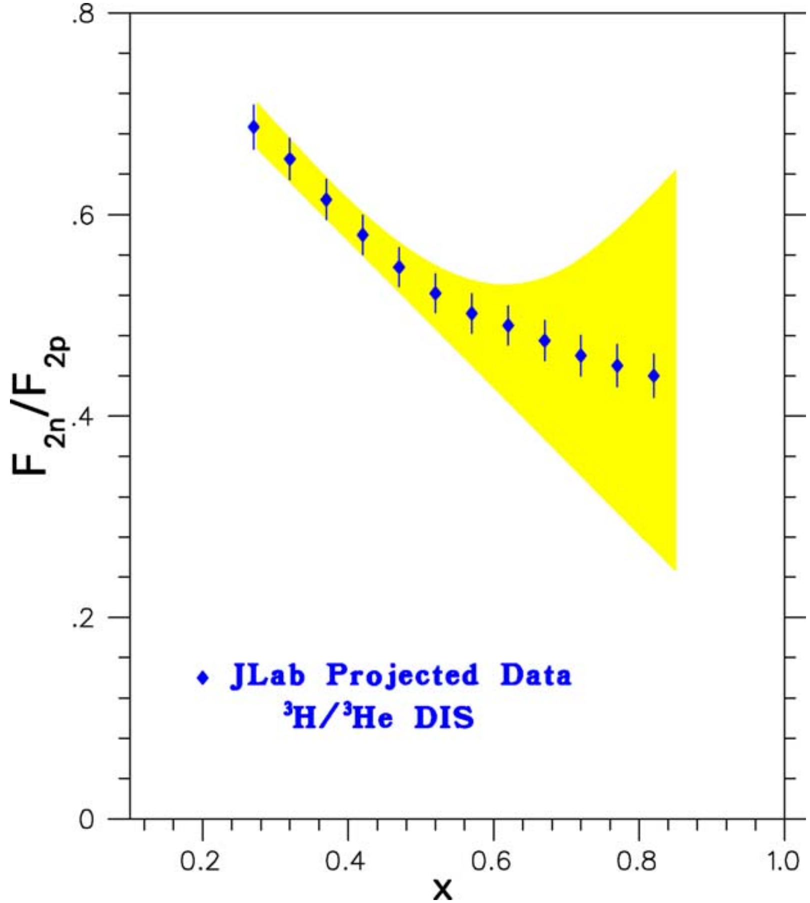
Role of hard scattering: pQCD / LCQCD guidance?

Breaking of SU(6) symmetry?

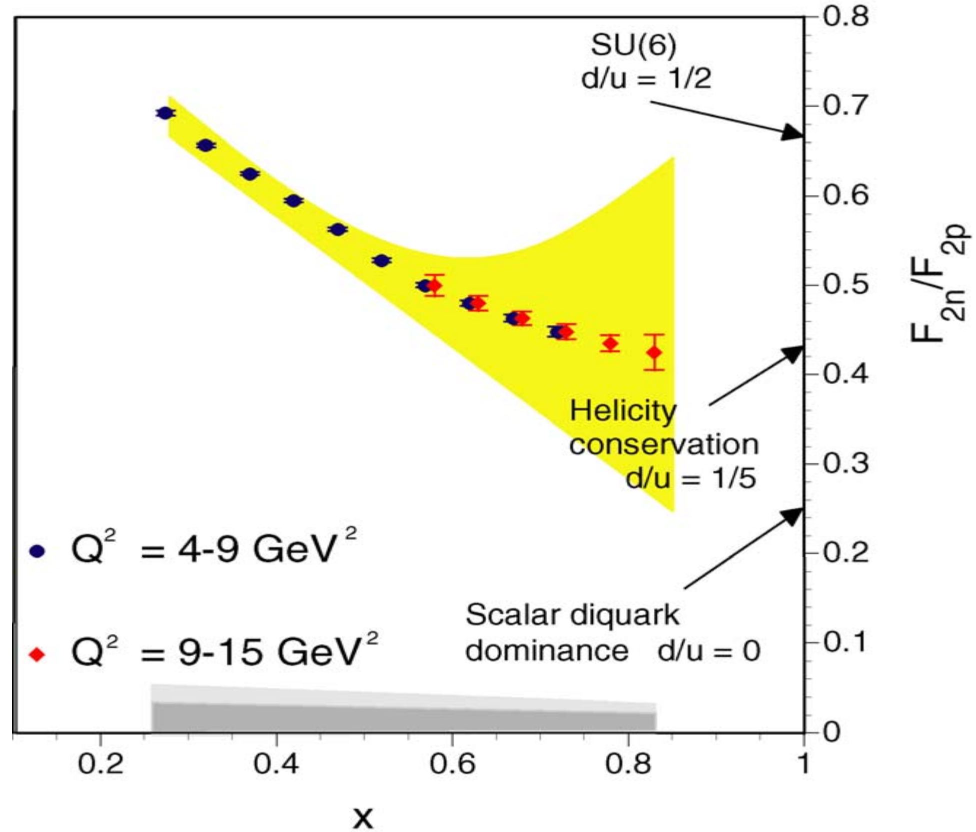
Moments of PDFs (and GPDs) from Lattice QCD….

12 GeV : Unambiguous Flavor Structure x→ 1

Hall C 11 GeV with HMS



HallB 11 GeV with CLAS12



Initial investigation with BONUS early 06

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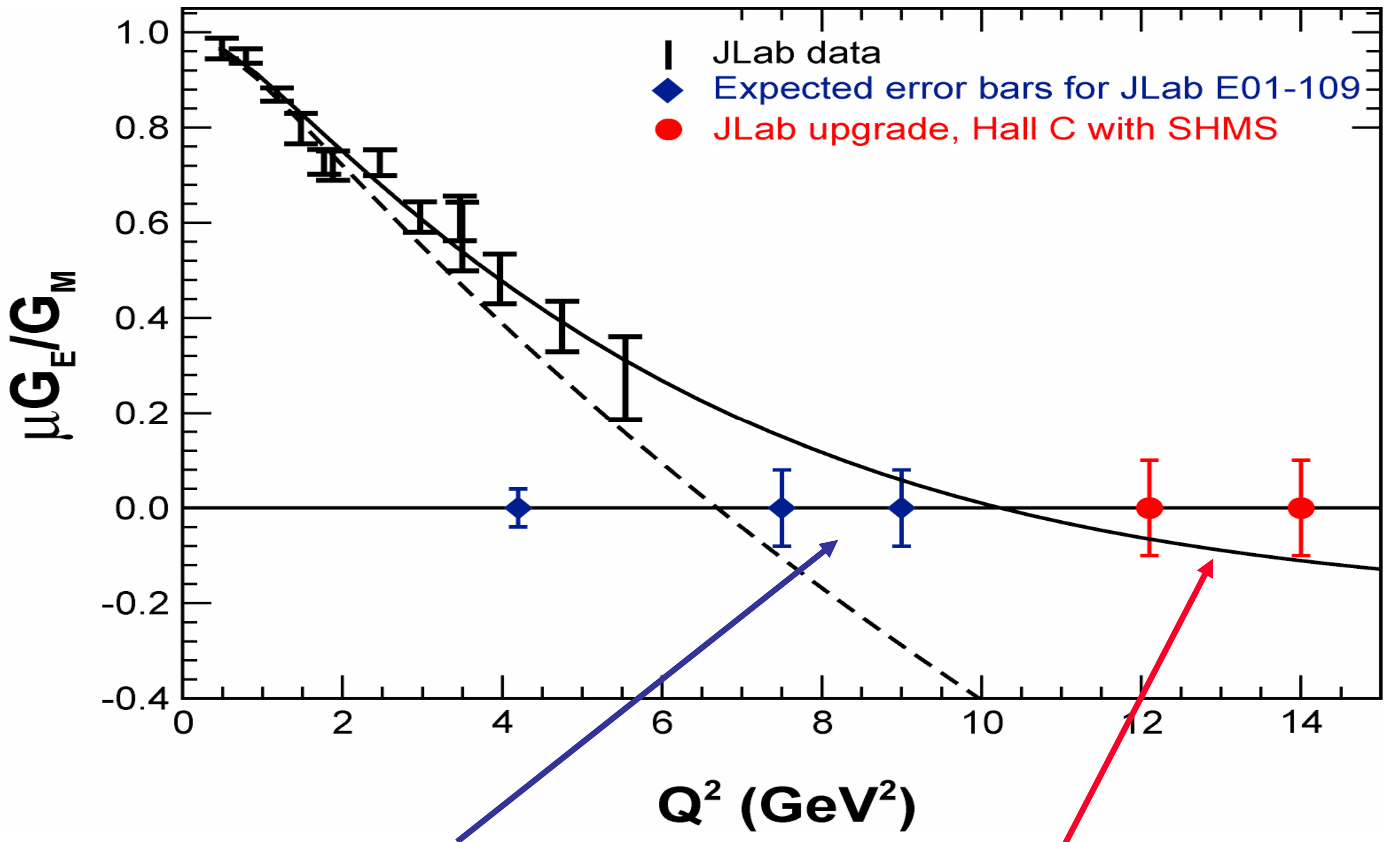


HP 2010

- Perdrisat *et al*. E01-109 — will increase range of Q^2 by 50% in 2007 (range of Q^2 for n will double over next 3-4 years)
- With 12 GeV and SHMS in Hall C

Strangeness Widely Believed to Play a Major Role – Does It?

- **As much as 100 to 300 MeV of proton mass:**

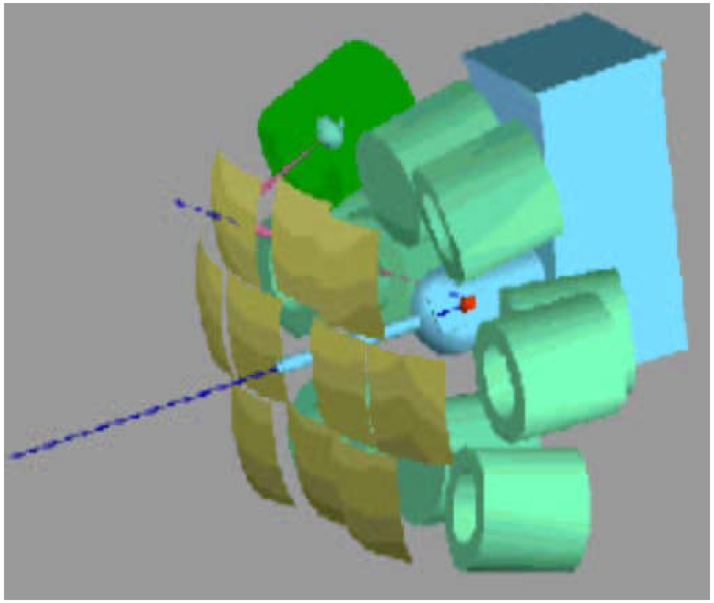
$$M_N = \langle N(P)| -\frac{9\,\alpha_s}{4\,\pi}\,\mathrm{Tr}(G_{\mu\nu}G^{\mu\nu}) + m_u\bar{\psi}_u\psi_u + m_d\bar{\psi}_d\psi_d + m_s\bar{\psi}_s\psi_s |N(P)\rangle$$

$$\Delta M_N^{s-\mathrm{quarks}} = \frac{y m_s}{m_u + m_d}\,\sigma_N$$

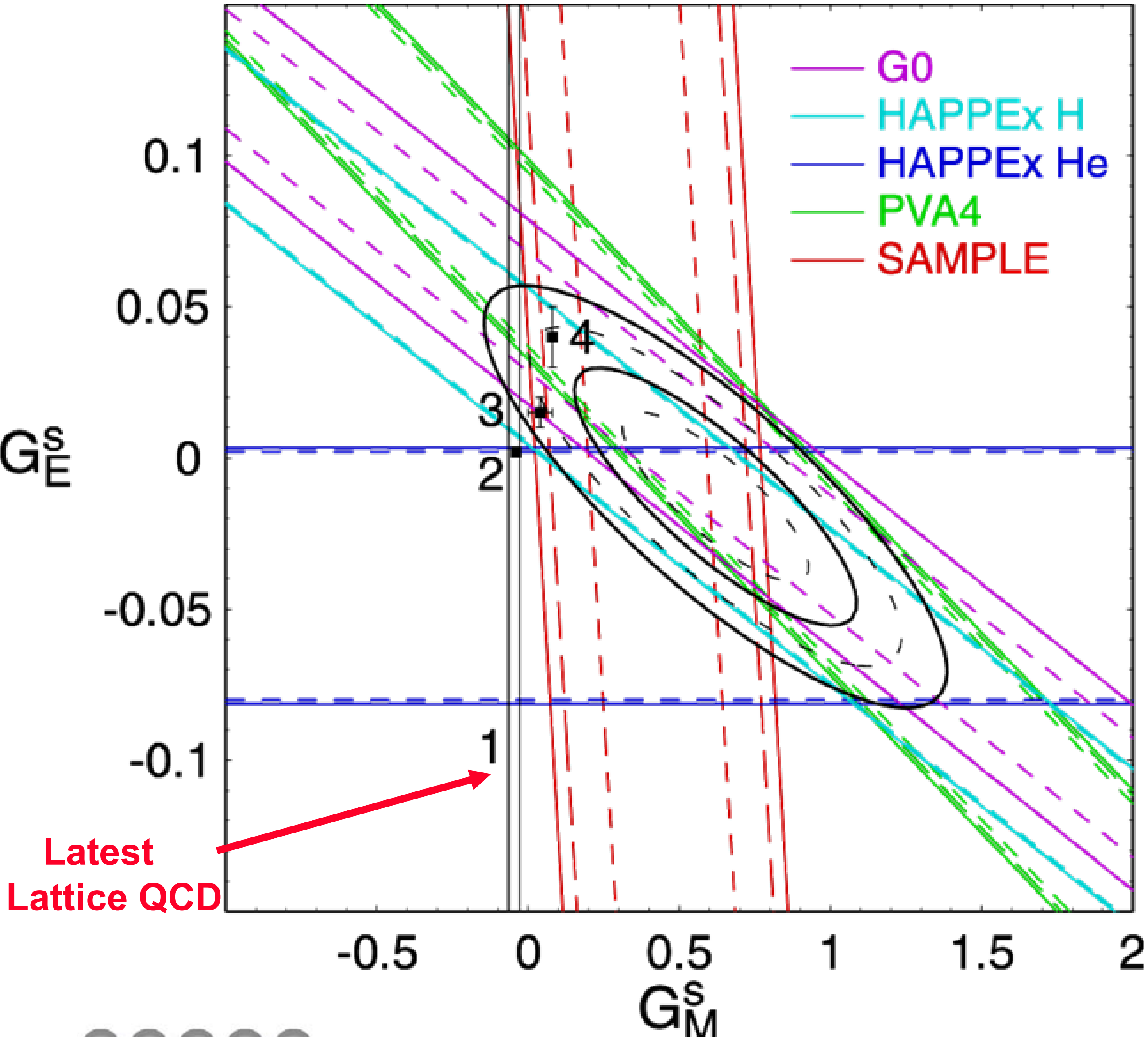
- **Through proton spin crisis: as much as 10% of the spin of the proton**

HOW MUCH OF THE ELECTRIC & MAGNETIC FORM FACTORS ?

MIT-Bates & A4 at Mainz



Strange Quark Form Factors at $Q^2 = 0.1$ GeV^2



Latest Lattice QCD

$G_E^s = -0.013 \pm 0.028$

$G_M^s = +0.62 \pm 0.31\ \mu_N$

Theories

1. Leinweber, et al. PRL **94** (05) 212001
2. Lyubovitskij, et al. PRC **66** (02) 055204
3. Lewis, et al. PRD **67** (03) 013003
4. Silva, et al. PRD **65** (01) 014016

Significance & Comparison with Lattice QCD

Size and sign of the strange magnetic moment
is astonishing!

- Experimental isoscalar nucleon moment is 0.88 μ_N

c.f. this result which is (G0) - 0.54 μ_N : i.e. - 60% !!

- Also remarkable versus lattice QCD which gives
+0.03 $\pm$ 0.01 μ_N (Leinweber et al., PRL 94 (2005) 212001)

- Sign would require violation of universality of
valence quark moments by $\sim$ 70% !

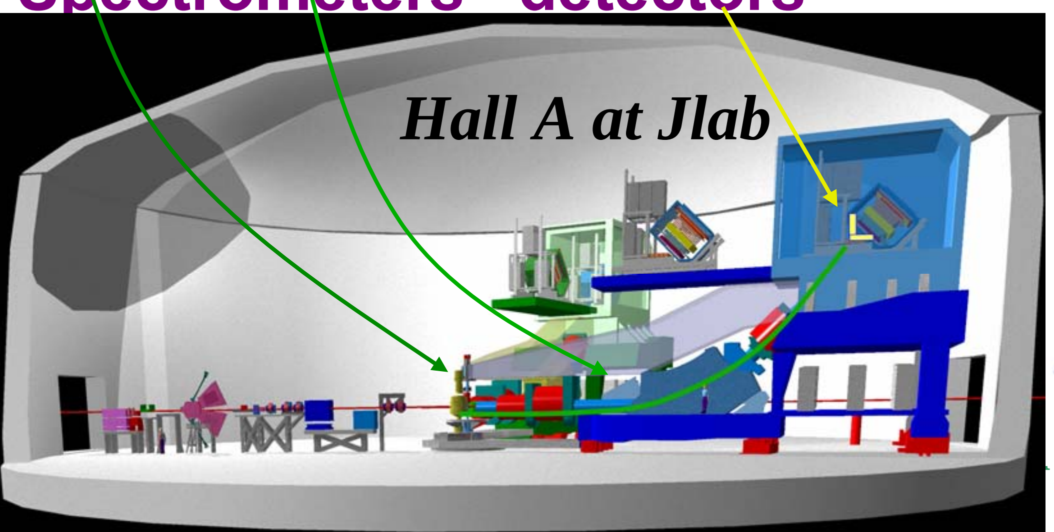
Parity Violating Studies on ^{1}H and ^{4}He

3 GeV beam in Hall A $\theta_{lab} \sim 6°$ $Q^2 \sim 0.1\ (GeV/c)^2$

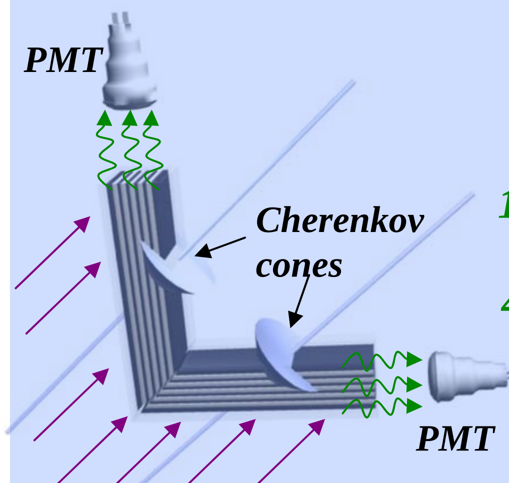
target	A_{PV} $G^s = 0$ (ppm)	Stat. Error (ppm)	Syst. Error (ppm)	sensitivity
^{1}H	-1.6	0.08	0.04	$\delta(G^s_E + 0.08 G^s_M) = 0.010$
^{4}He	+7.8	0.18	0.18	$\delta(G^s_E) = 0.015$

Septum magnets (not shown)

High Resolution Spectrometers detectors



Brass-Quartz integrating detector



Elastic Rate:

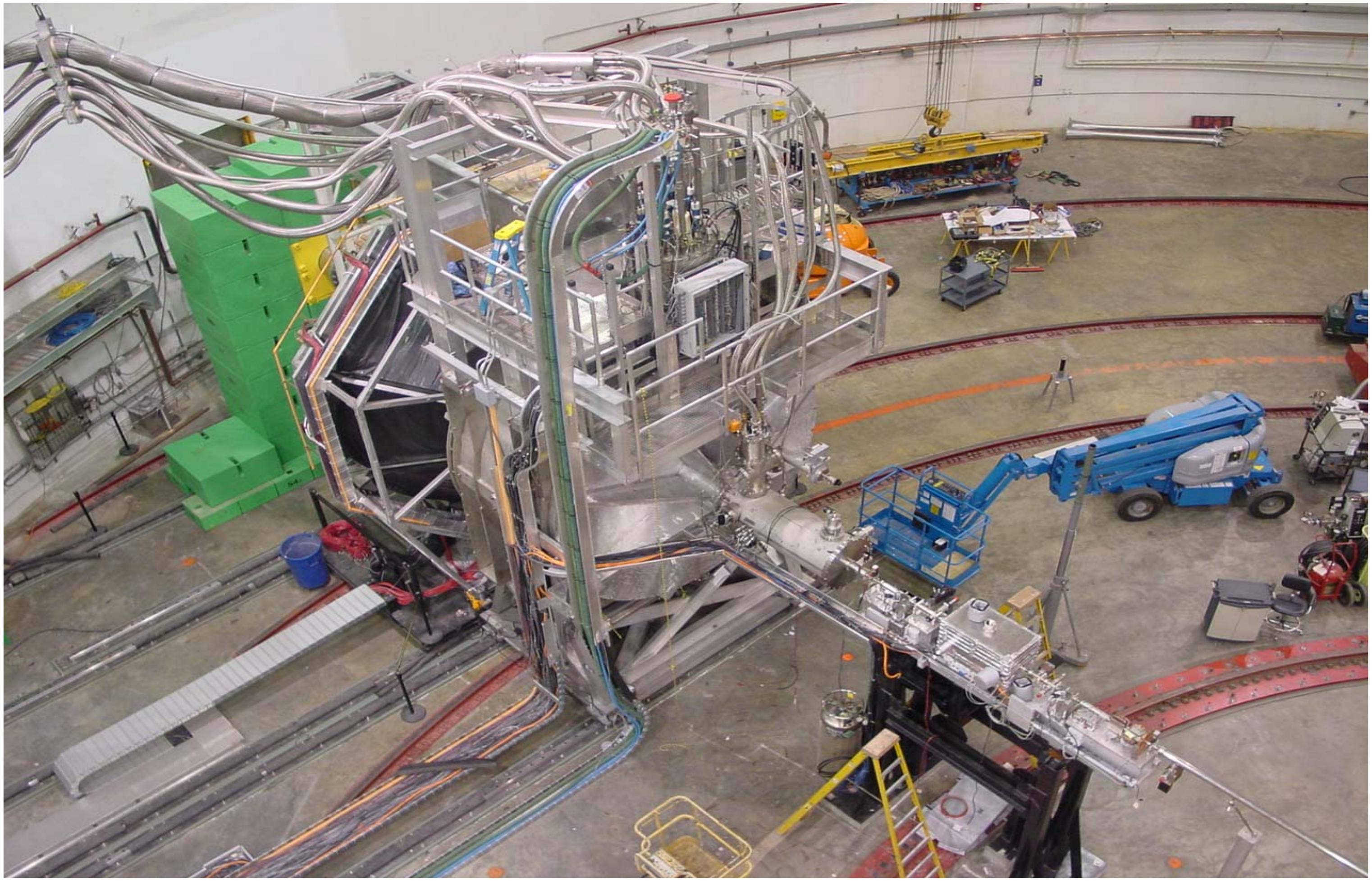
^{1}H: 120 MHz

^{4}He: 12 MHz

Background ≤ 3%

Office of Science
U.S. DEPARTMENT OF ENERGY

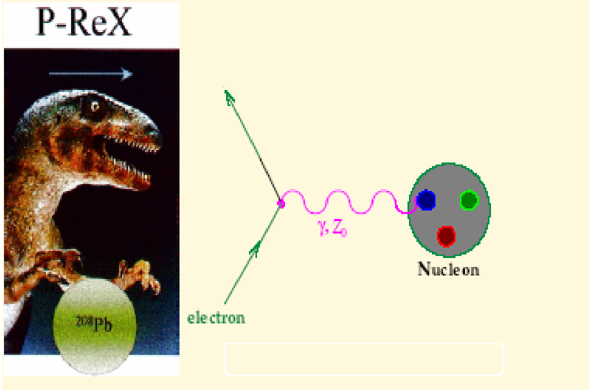
G0 Experiment in Hall C



G0 and HAPPEx will define these form factors up to 1 GeV^2 over the next 2 years

2010

PREX : ^{208}Pb Radius Experiment



Low Q^2 elastic e-nucleus scattering

(E = 850 MeV, $\Theta=6^o$)

Z^0 **(Weak Interaction)** : **couples mainly to neutrons**

$$\frac{dA}{A} = 3\% \rightarrow \frac{dR_n}{R_n} = 1\%$$

Measure a Parity Violating Asymmetry

$$A = \frac{G_F Q^2}{2\pi\alpha\sqrt{2}} \left[1 - 4\sin^2\theta_W - \frac{F_n(Q^2)}{F_P(Q^2)} \right]$$

Applications:

- **Fundamental check of Nuclear Theory**
- **Input to Atomic PV Expts**
- **Neutron Star Structure**

Nuclear Structure

After more than 70 years, the neutron density of a heavy nucleus is a fundamental nuclear-structure observable that remains elusive!

- As fundamental as the charge density of a heavy nucleus
  - ⋆ *cf.* proton and neutron electromagnetic structure
- Reflects a poor understanding of the symmetry energy of NM
  - ⋆ Symmetry energy penalty imposed for breaking $N=Z$ balance
- Pure neutron matter well constrained at $\rho\approx(2/3)\rho_0$
- Slope is completely unconstrained by available nuclear data!

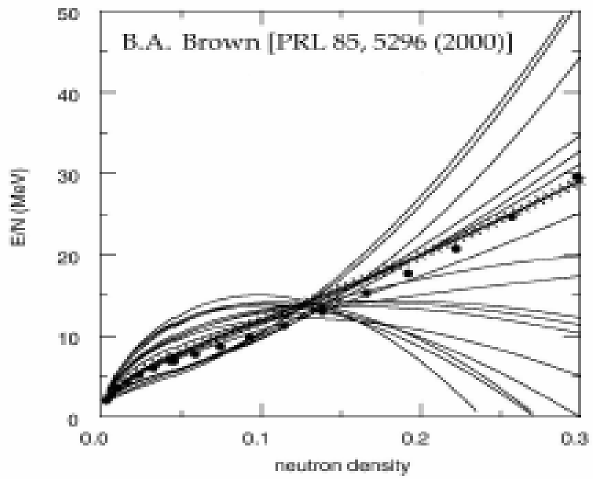


FIG. 2. The neutron EOS for 18 Skyrme parameter sets. The filled circles are the Friedman-Pandharipande (FP) variational calculations and the crosses are SkX. The neutron density is in units of neutron/fm^3.

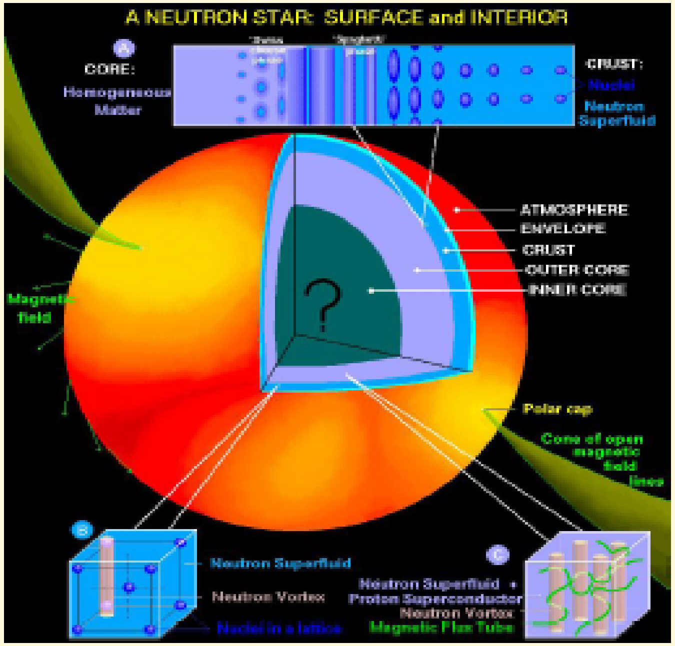
Adding the neutron radius of a single heavy nucleus to the database will eliminate the large dispersion in the plot!

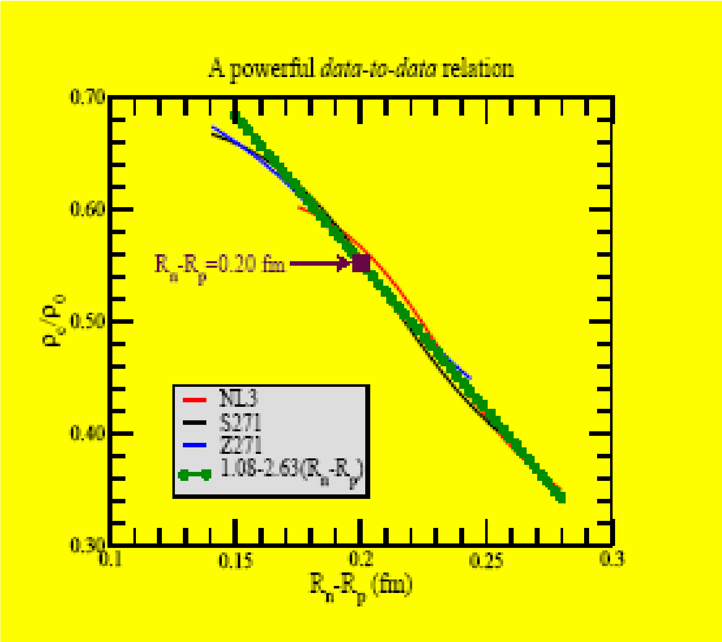
Neutron Skin and Neutron Stars

(Nuclear Astrophysics at Jefferson Lab)

The neutron skin of ^{208}Pb and the crust of a neutron star are made up of similar material: neutron-rich matter at (slightly) subnuclear densities

- Neutron stars contain a solid crust above a uniform liquid mantle
- The stiffer the EOS the lower the transition to non-uniform matter
  - ⋆ Energetically unfavorable to separate into low- and high-density regions
- The stiffer the EOS the larger the neutron skin of a heavy nucleus





A powerful data-to-data relation: The thicker the neutron skin of a heavy nucleus, the lower the transition density from uniform to non-uniform neutron-rich matter ...

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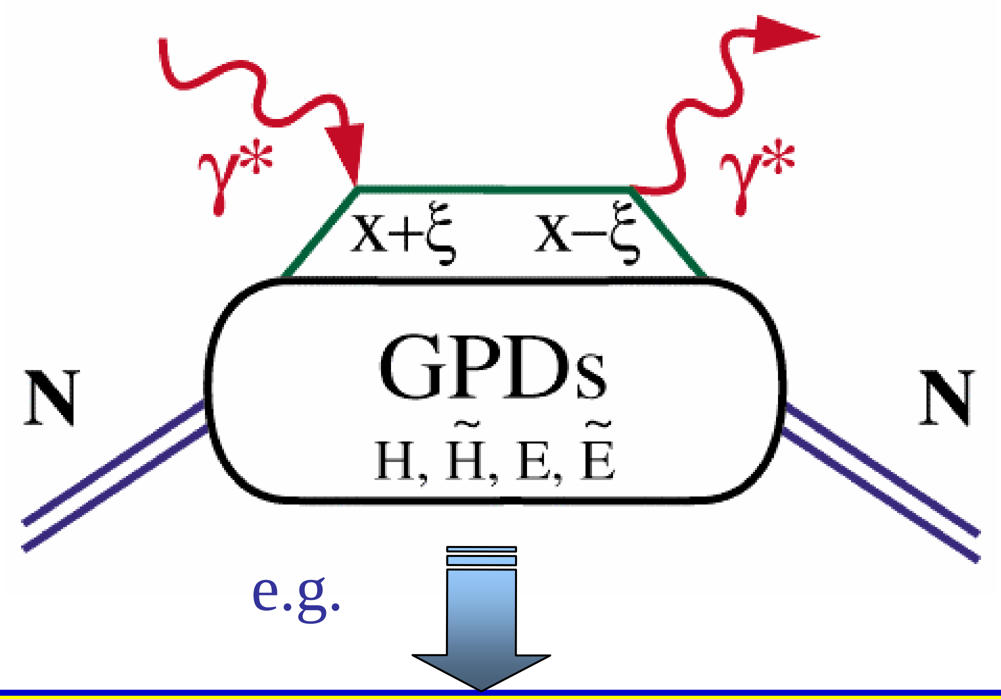
Studies of the Generalized Parton Distributions (GPDs): New Insight into Hadron Structure

HP 2008



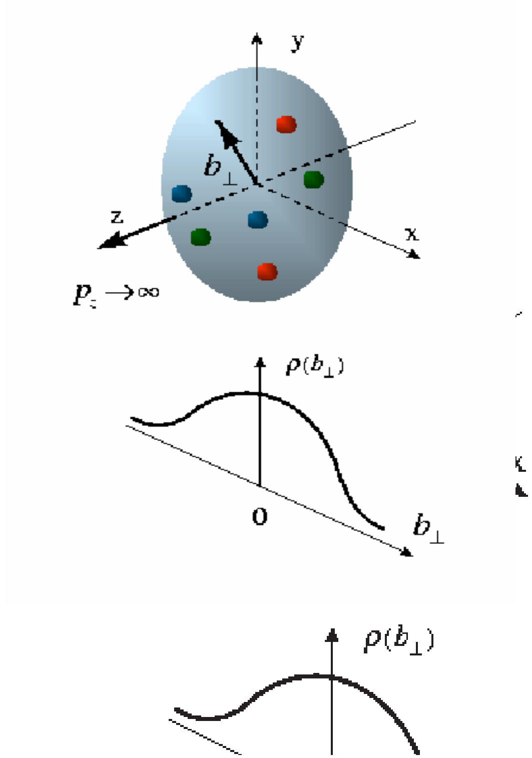
X. Ji &
A. Radyushkin
(1996)

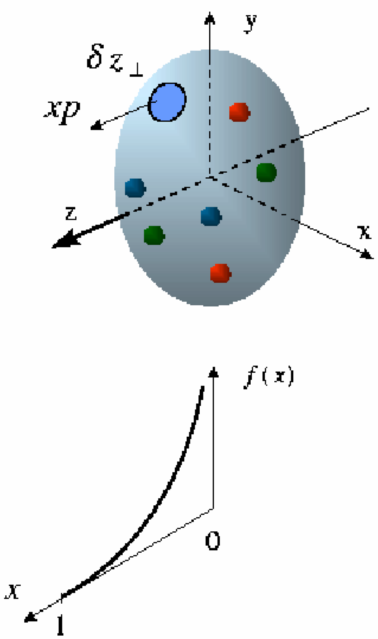
Quark angular momentum (Ji's sum rule)

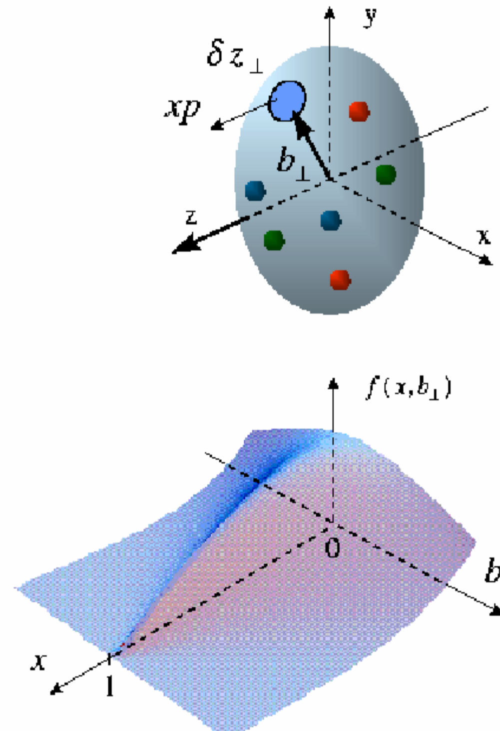
$$J^q = \frac{1}{2} - J^G = \frac{1}{2}\int_{-1}^{1} x dx \left[H^q(x,\xi,0) + E^q(x,\xi,0) \right]$$

X. Ji, Phy.Rev.Lett.78,610(1997)

The Next Generation of Proton Structure Experiments







Elastic Scattering

transverse quark distribution in Coordinate space

DIS

longitudinal quark distribution in momentum space

GPDs

The fully-correlated Quark distribution in both coordinate and momentum space

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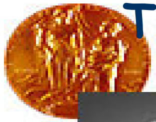
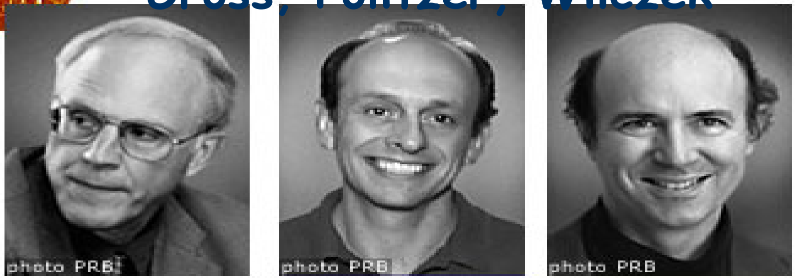
QCD: Unsolved in Nonperturbative Regime



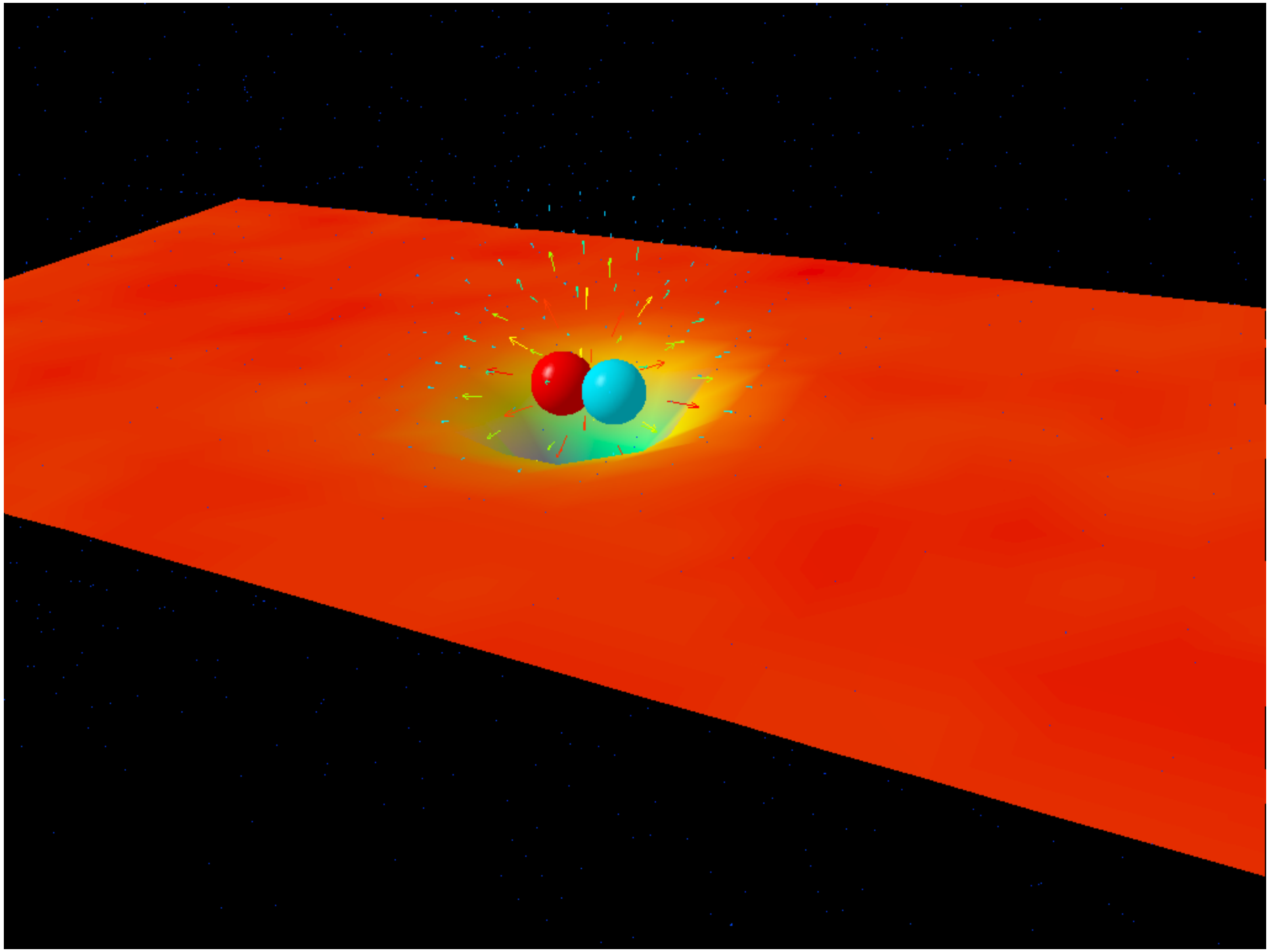
The Nobel Prize in Physics 2004
Gross, Politzer, Wilczek



- **2004 Nobel Prize awarded for “asymptotic freedom”**
- **BUT in nonperturbative regime QCD is still unsolved**
- **One of the top 10 challenges for physics!**
- **Is it right/complete?**
- **Do glueballs, exotics and other apparent predictions of QCD in this regime agree with experiment?**

JLab at 12 GeV is uniquely positioned to answer!

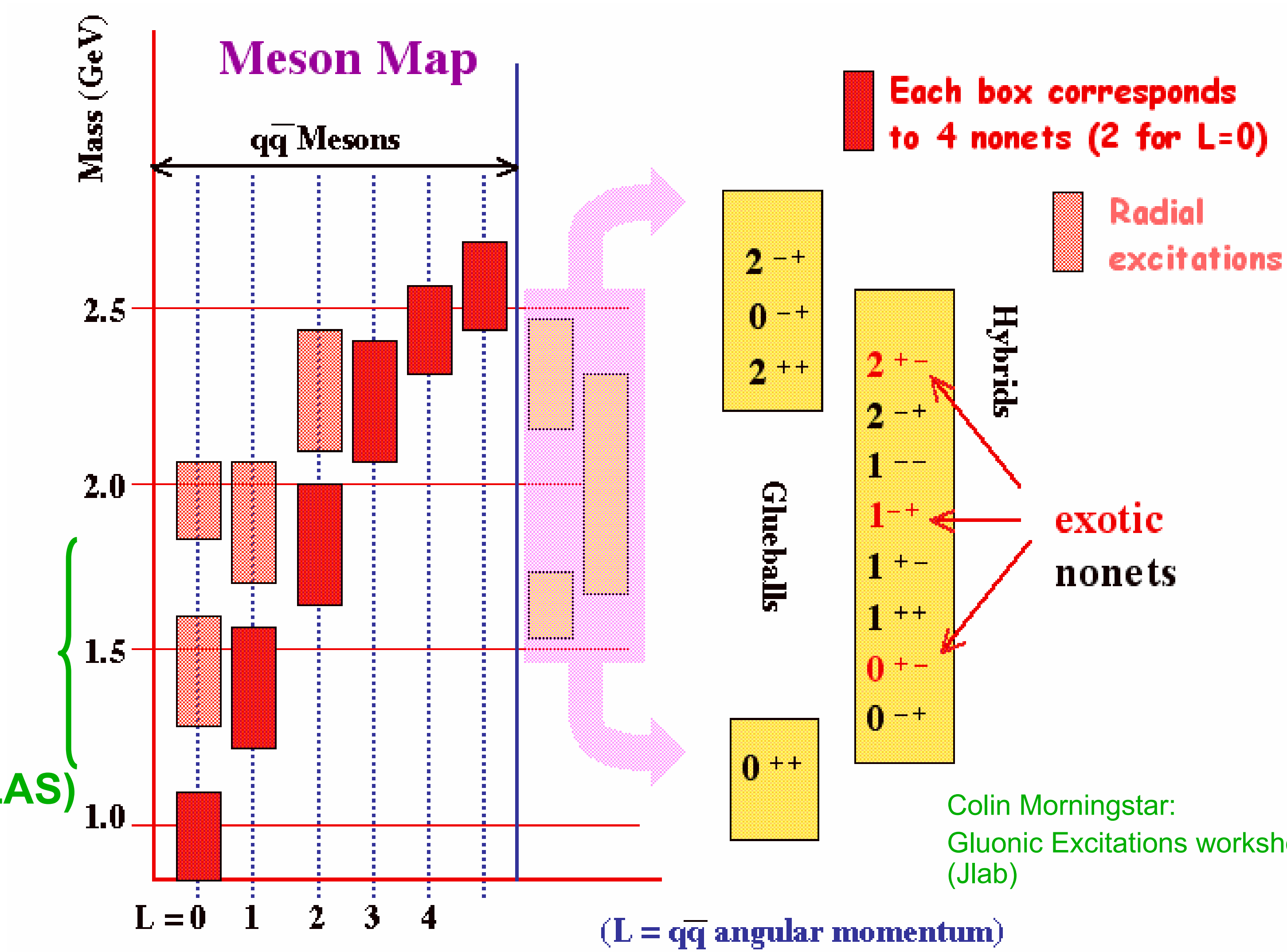
Quark-Anti-Quark Flux Tube: "String"



Lasscock, Leinweber, Thomas & Williams

Glueballs and hybrid mesons

Initial search FY07 – G12 (CLAS)



Colin Morningstar:
Gluonic Excitations workshop, 2003 (Jlab)

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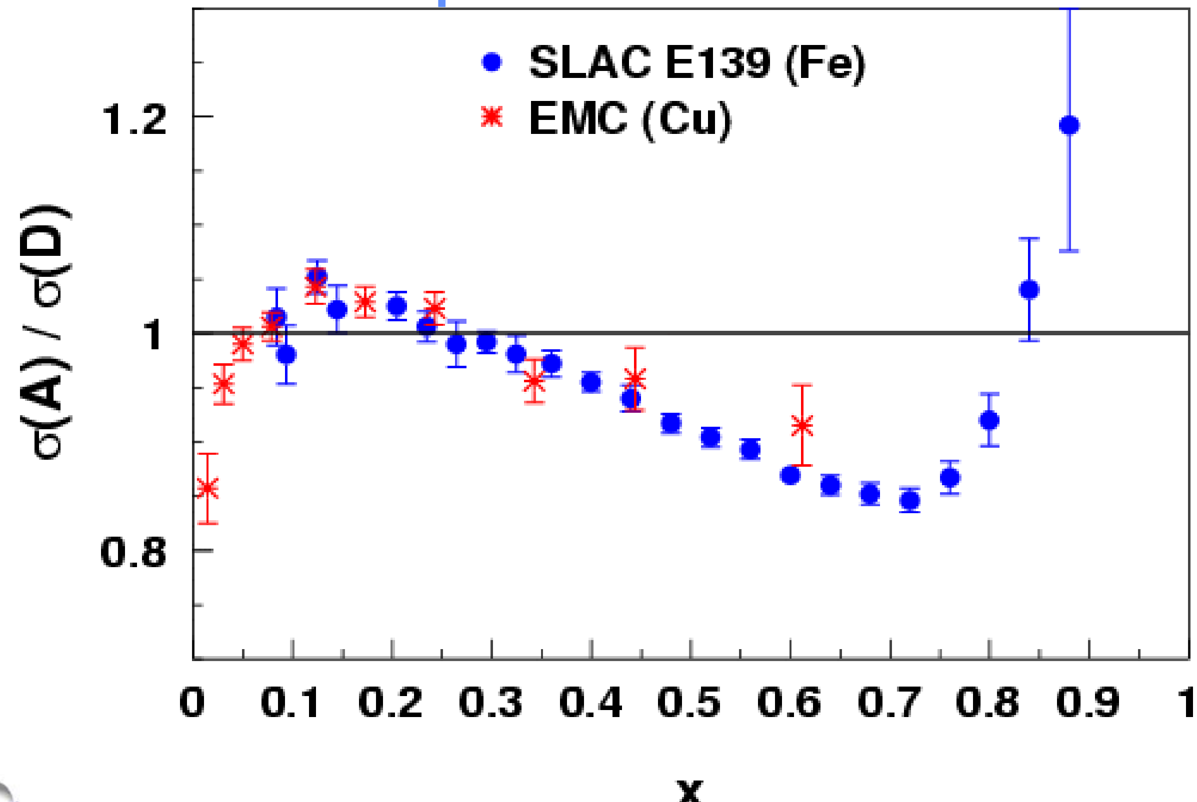
The EMC Effect: Nuclear PDFs

- Observation **stunned and electrified** the HEP and Nuclear communities 20 years ago

- Nearly 1,000 papers have been generated…..

- What is it that alters the quark momentum in the nucleus?



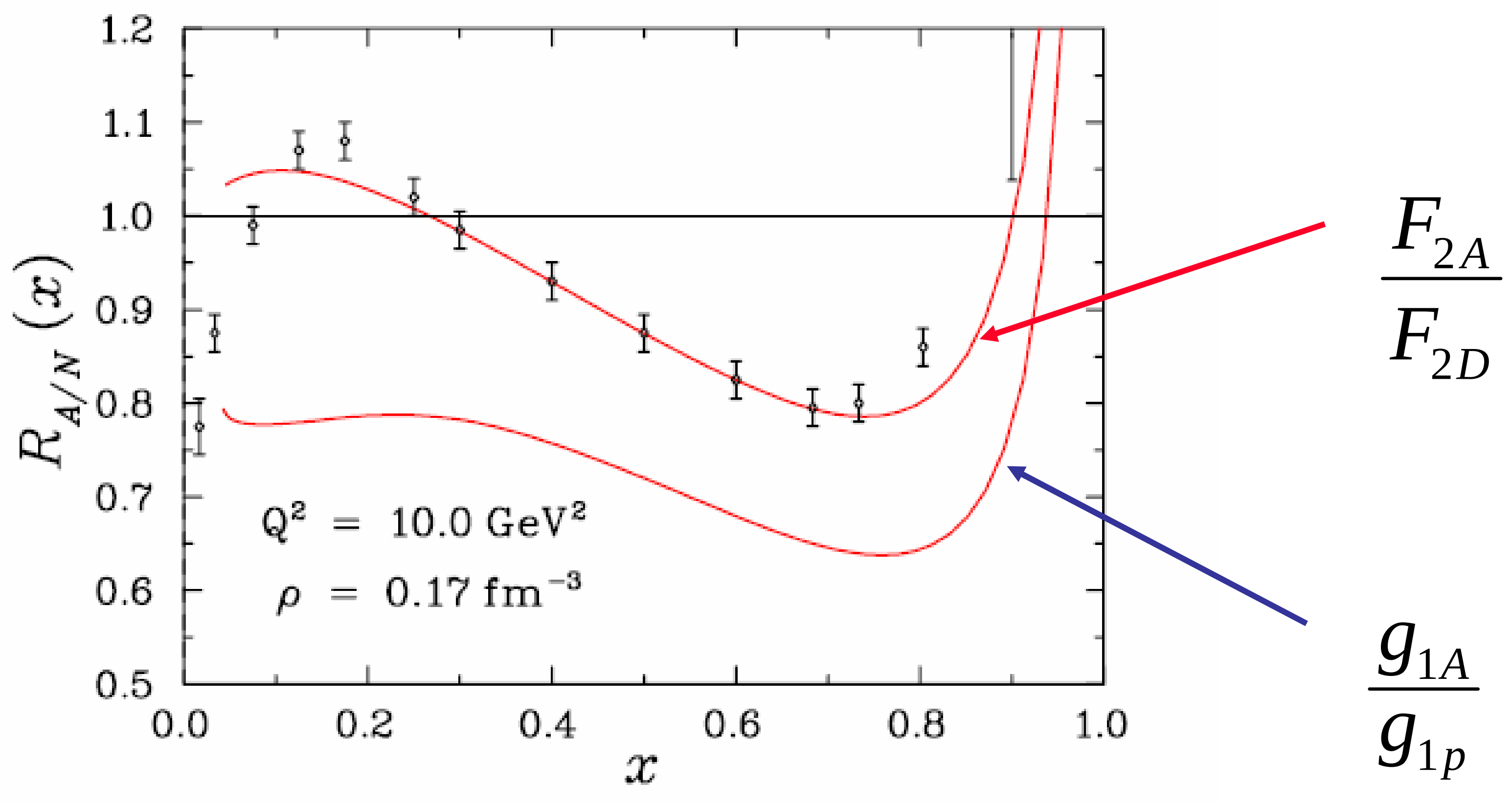
J. Ashman *et al*., Z. Phys. C57, 211 (1993)

J. Gomez *et al*., Phys. Rev. D49, 4348 (1994)

$g_1(A)$ – "Polarized EMC Effect"

- New calculations indicate larger effect for polarized structure than unpolarized: scalar field modifies lower cpts of Dirac wave function

  (Cloet, Bentz, AWT, Phys Rev Lett 95 (2005) 0502302)
- Spin-dependent parton distribution functions for nuclei unknown



Microscopic Origin of Skyrme Force

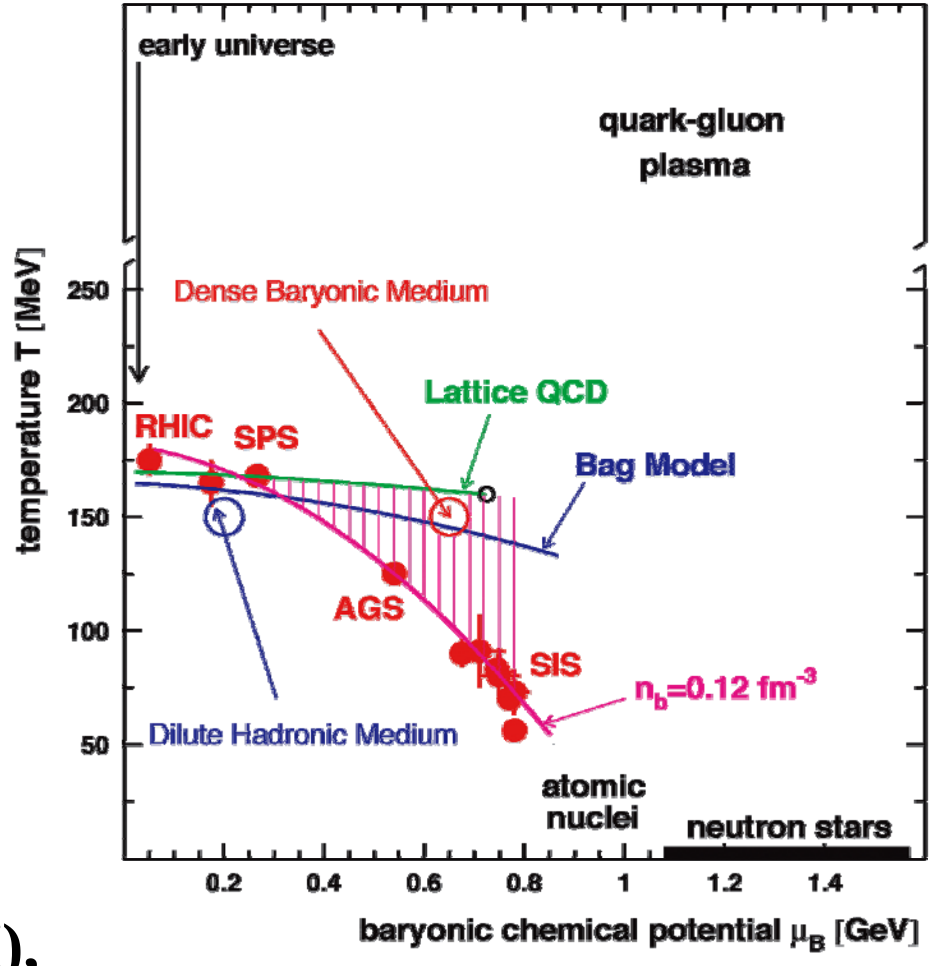
	QMC	Skyrme III	QMC(N=3)
$m_\sigma (MeV)$	600		600
$t_0 (MeV\ fm^3)$	-1082	-1129	-1047
x_0	0.59	0.45	0.61
$t_3 (MeV\ fm^6)$	14926	14000	12996
M_{eff} / M	0.814	0.763	0.821
$5t_2 - 9t_1 (MeV\ fm^5)$	-4330	-4030	-4036
$W_0 (MeV\ fm^5)$	97	120	91

$$\frac{M_{eff}}{M} = \left(1 + \frac{(3t_1 + 5t_2) M \rho_0}{8}\right)^{-1}$$

Guichon & Thomas, PRL 93 (2004) 132502

Major Challenges for Nuclear Physics

- Origin of Nuclear Saturation



- EOS … as $\rho\uparrow$; as $T\uparrow$
  as $S\uparrow$; as $N\text{-}Z\uparrow$

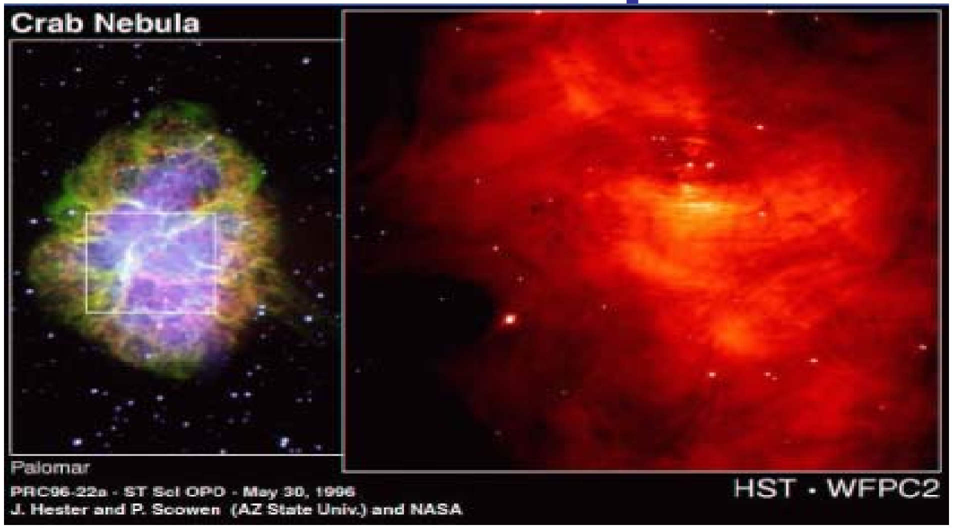
- Phase Transition to:
  - quark matter (QM), superconducting QM, strange condensate
  - related to nuclear astrophysics; n-stars….

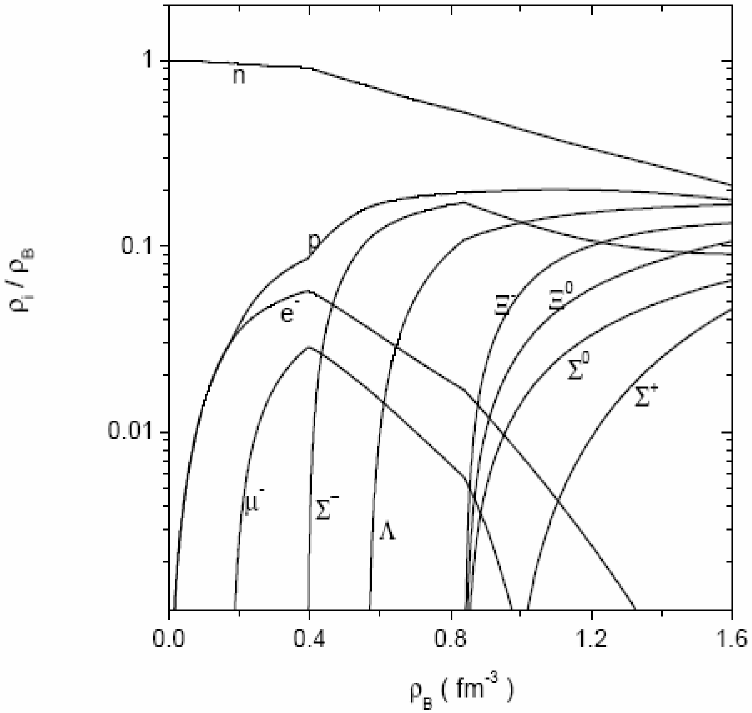
Neutron Star Composition

Hyperons enter at just 2-3 ρ_0

Hence need effective Σ-N and Λ-N forces in this density region!

Ξ - Hypernuclear data is important input: we have none!





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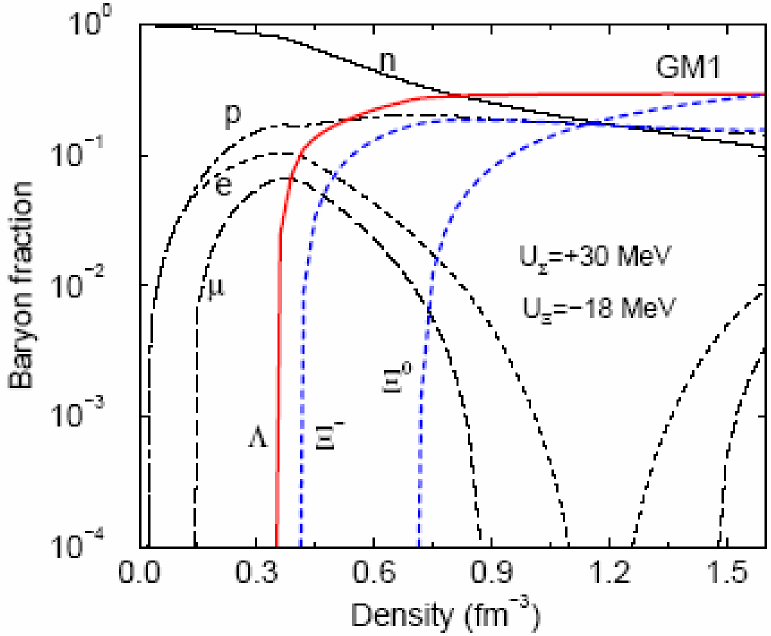
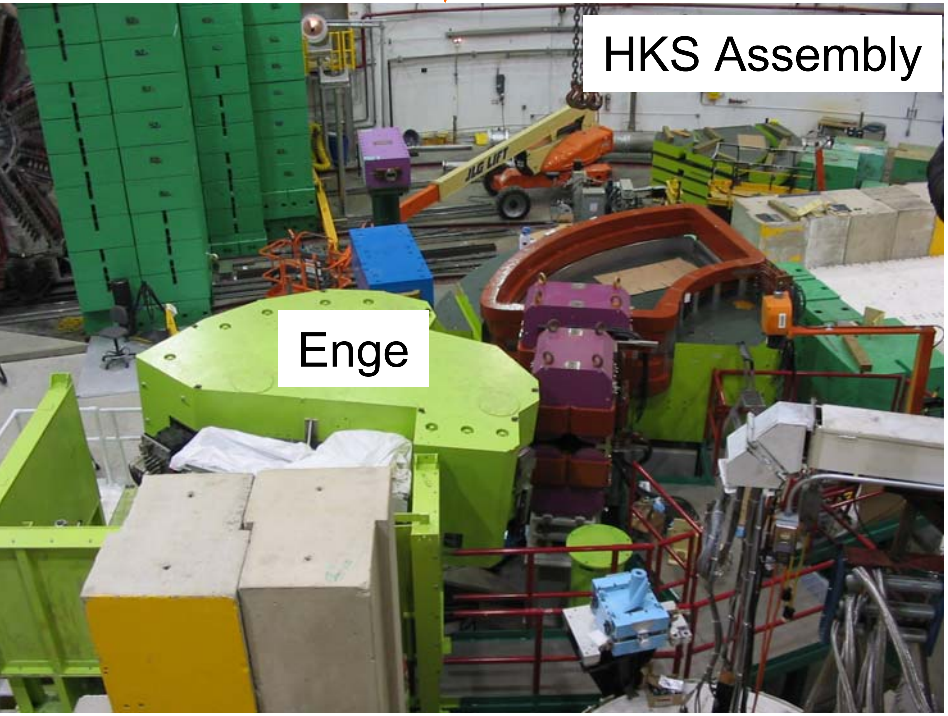


Present Installation: HKS

Present Hypernuclear Spectroscopy equipment combination is beam splitter, Enge (e^-), HKS (K^+)

Installation ongoing in Hall C (April 13)

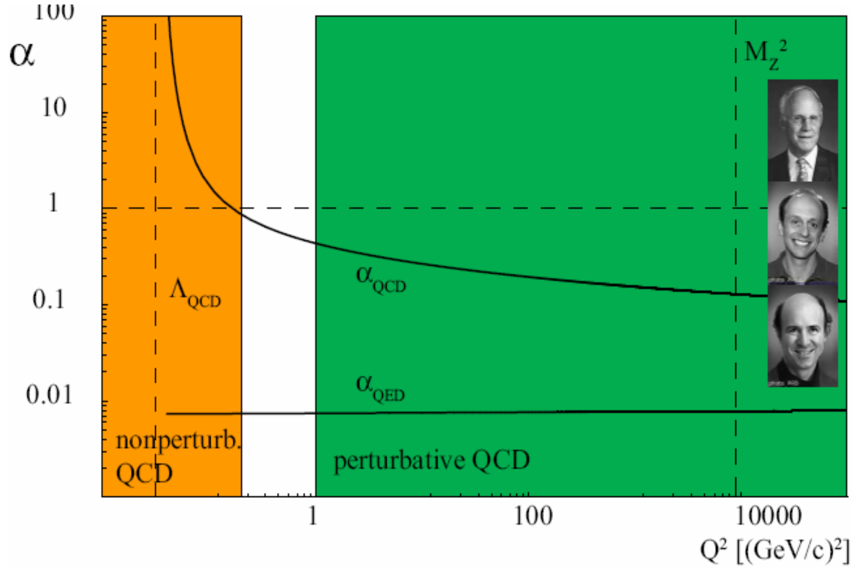


Installation completed (early June)

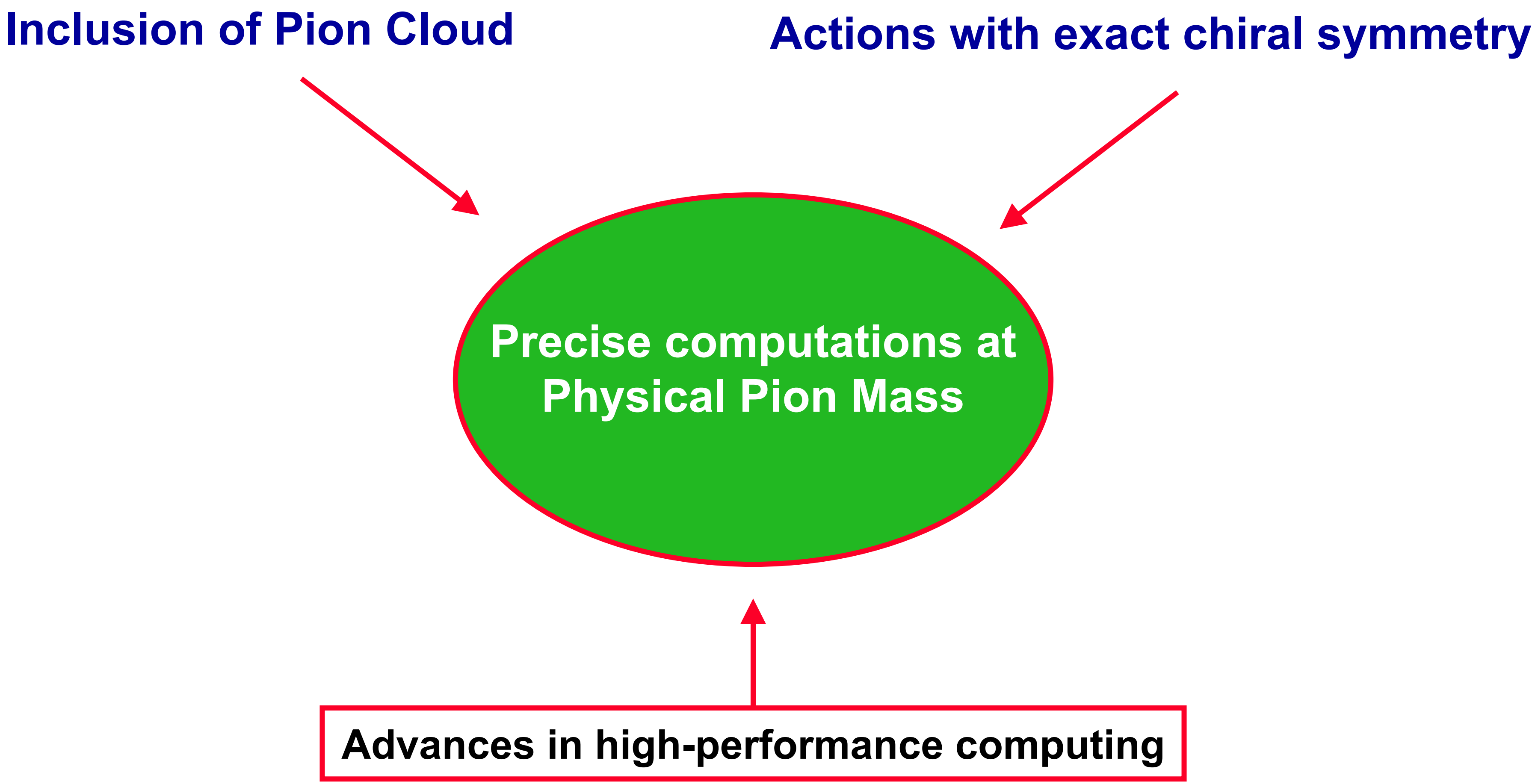
Time Frame for 12 GeV & Advances in Lattice QCD $\Rightarrow$ Wonderful synergy!

That is: Our growing ability to use lattice QCD to calculate the unambiguous consequences of nonperturbative QCD is beautifully matched to the capacity of Jlab at 12 GeV to measure the corresponding observables with precision!

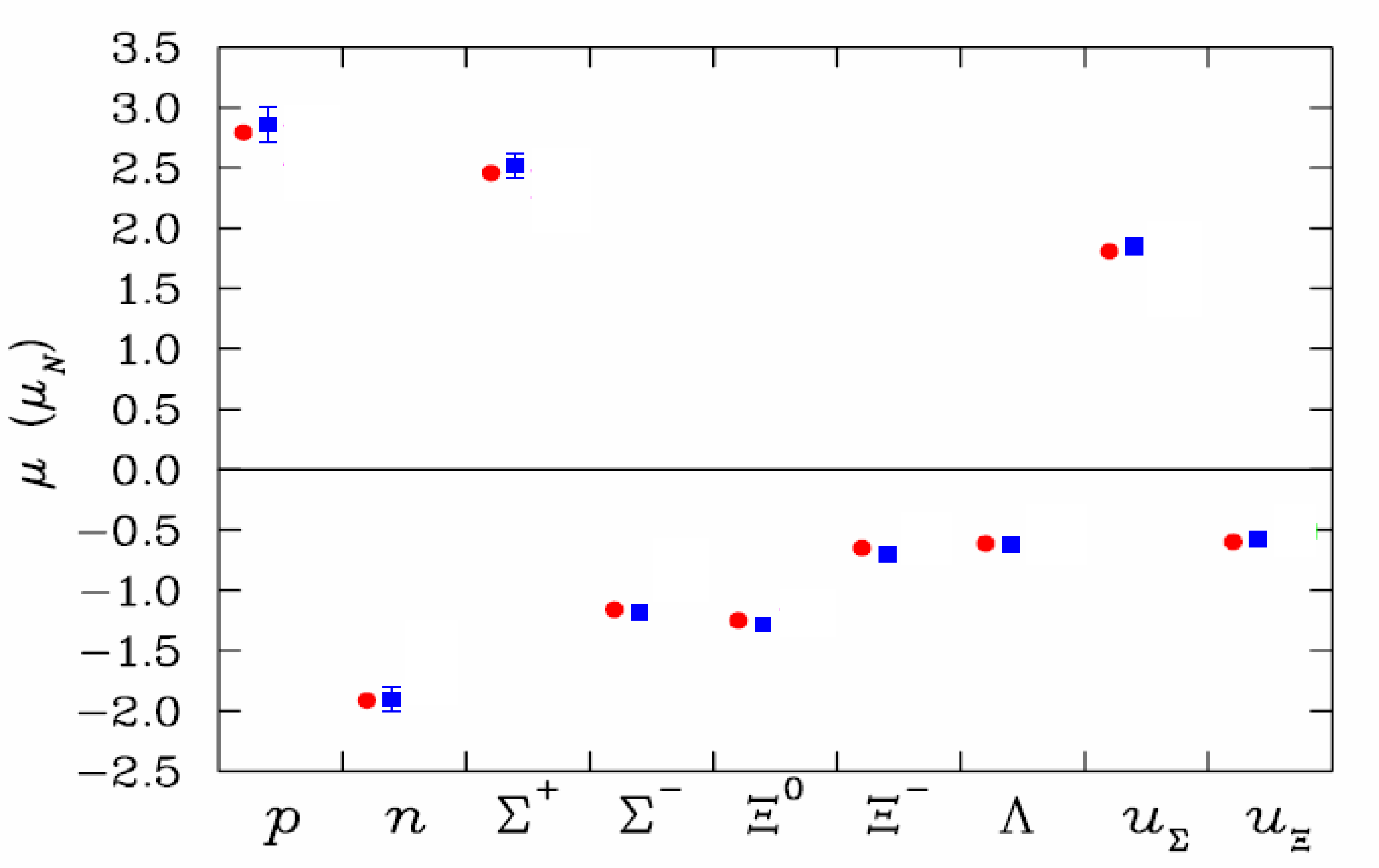
….and hence really test if QCD is the complete theory of the strong interaction



Advances in Lattice QCD



Octet Magnetic Moments

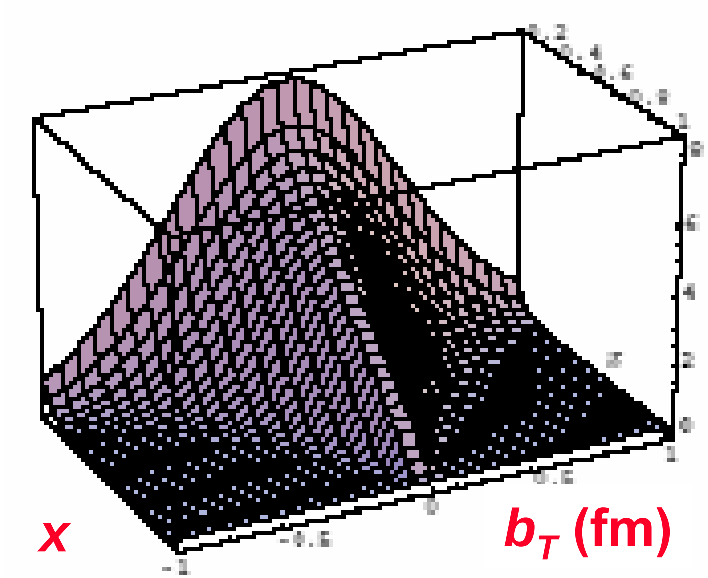


Leinweber ..Young et al., PRL 94 (2005) 212001

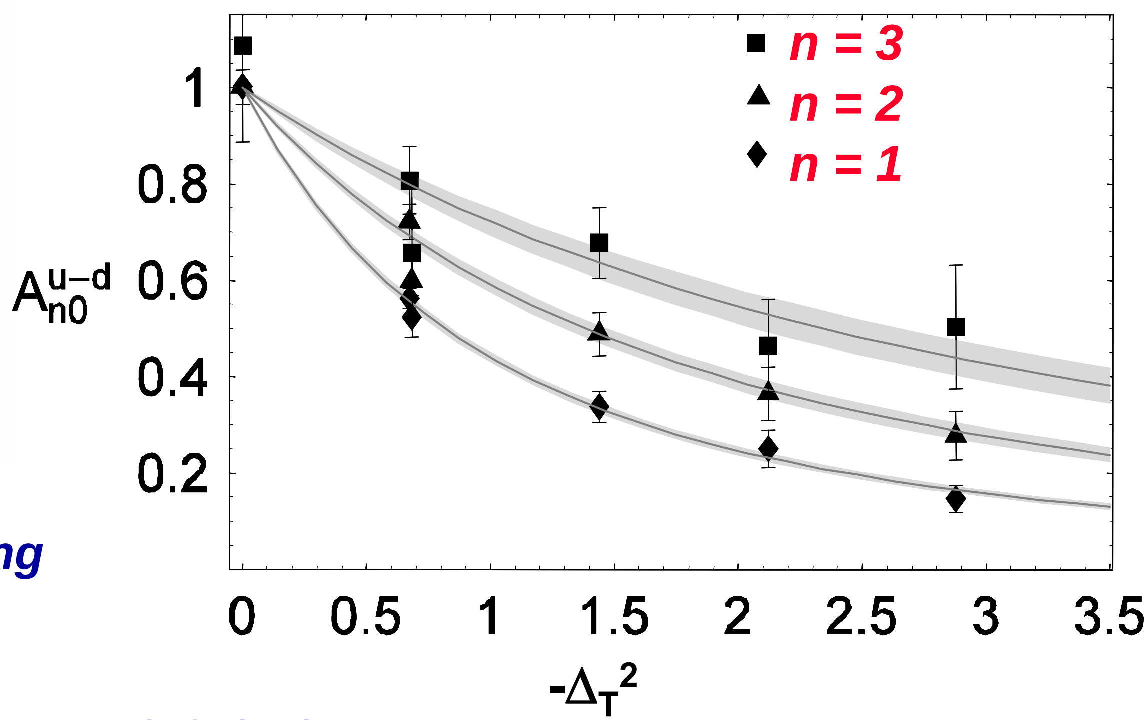
Moments of Flavor-NS PDFs and GPDs - I

- **Lattice QCD can compute both moments of GPD's with respect to *x*, and *t*-dependence**

$$A^q_{n0}(-\vec{\Delta}^2_\perp) = \int d^2 b_\perp \, e^{i\vec{\Delta}_\perp \cdot \vec{b}_\perp} \int_{-1}^{1} dx \, x^{n-1} q(x, \vec{b}_\perp)$$



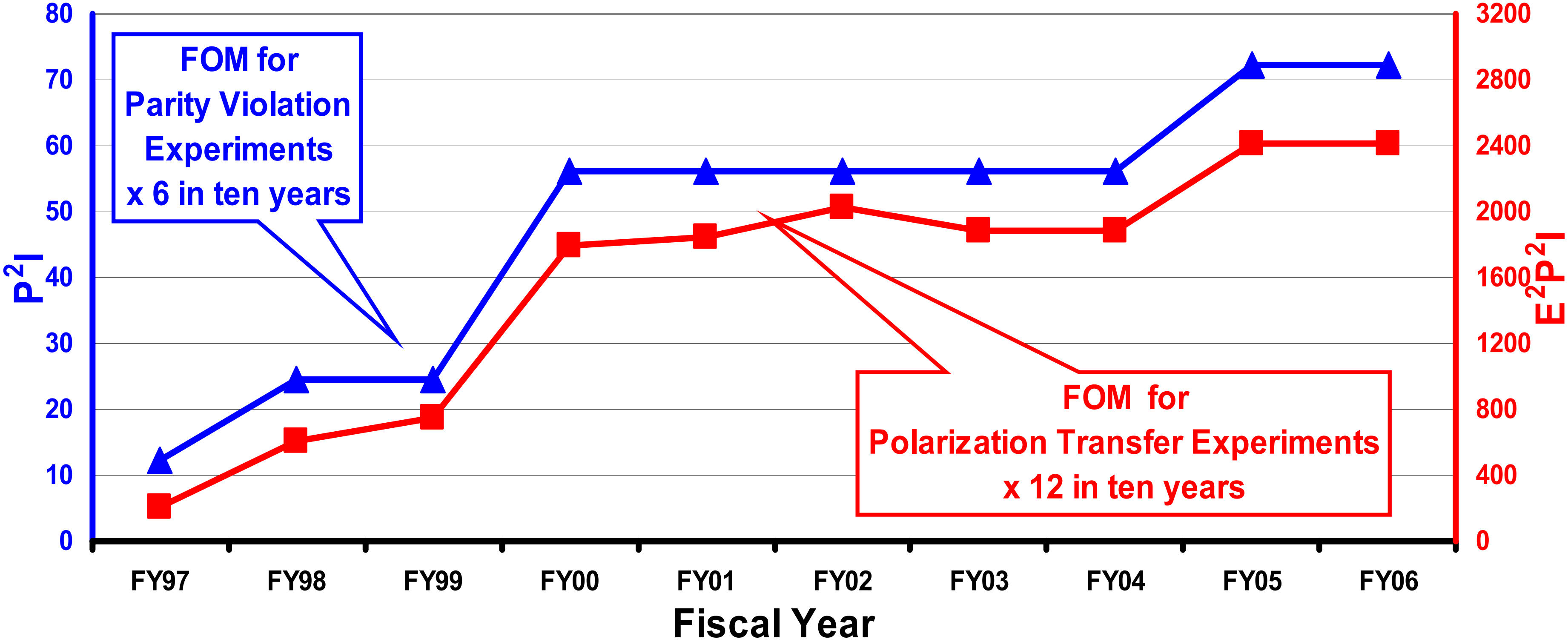
Lattice data: m_π = 740 MeV



Decrease slope : decreasing transverse size as x → 1 - **Burkardt**

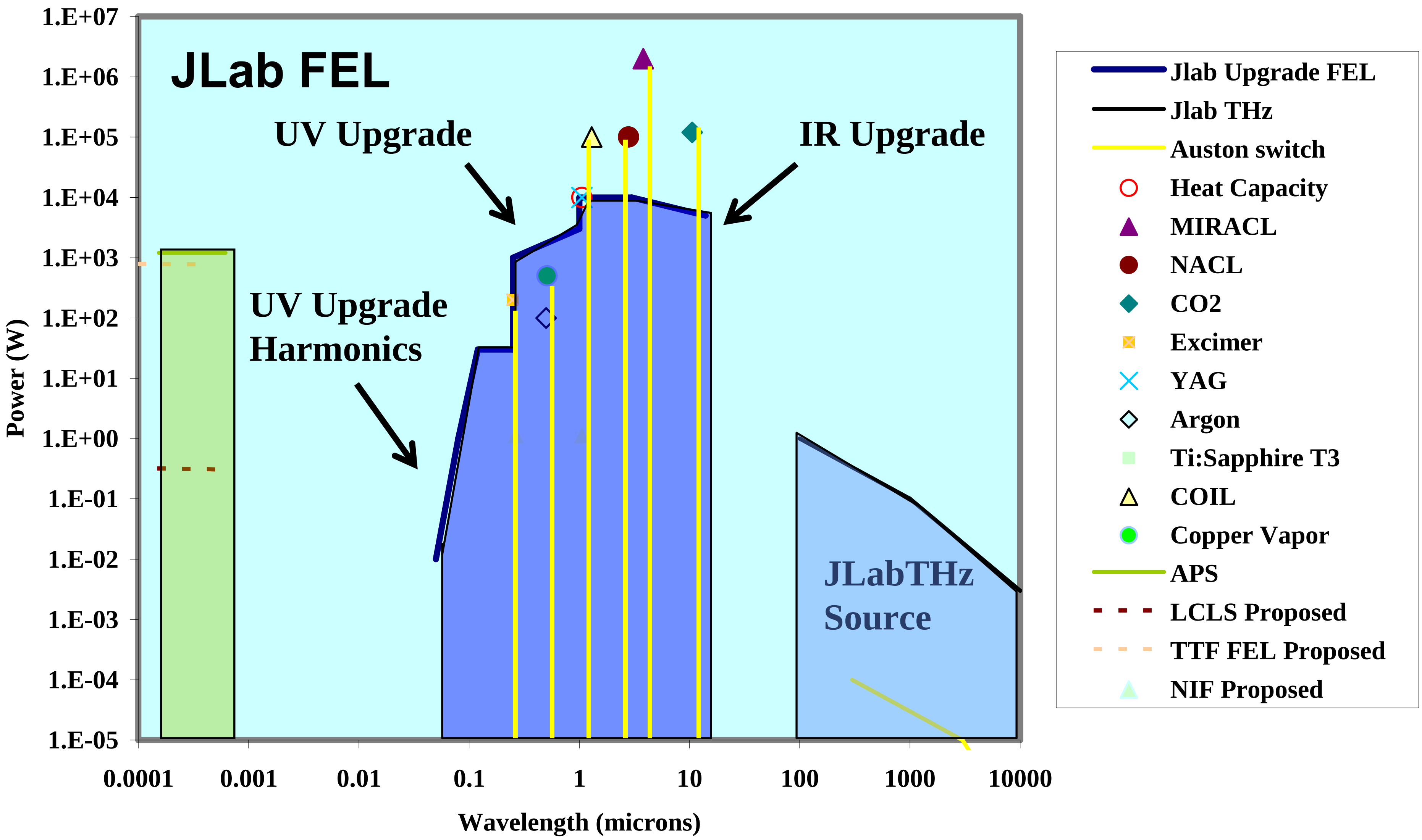
From: LHPC & SESAM

Science Drives Technology Drives Science.....

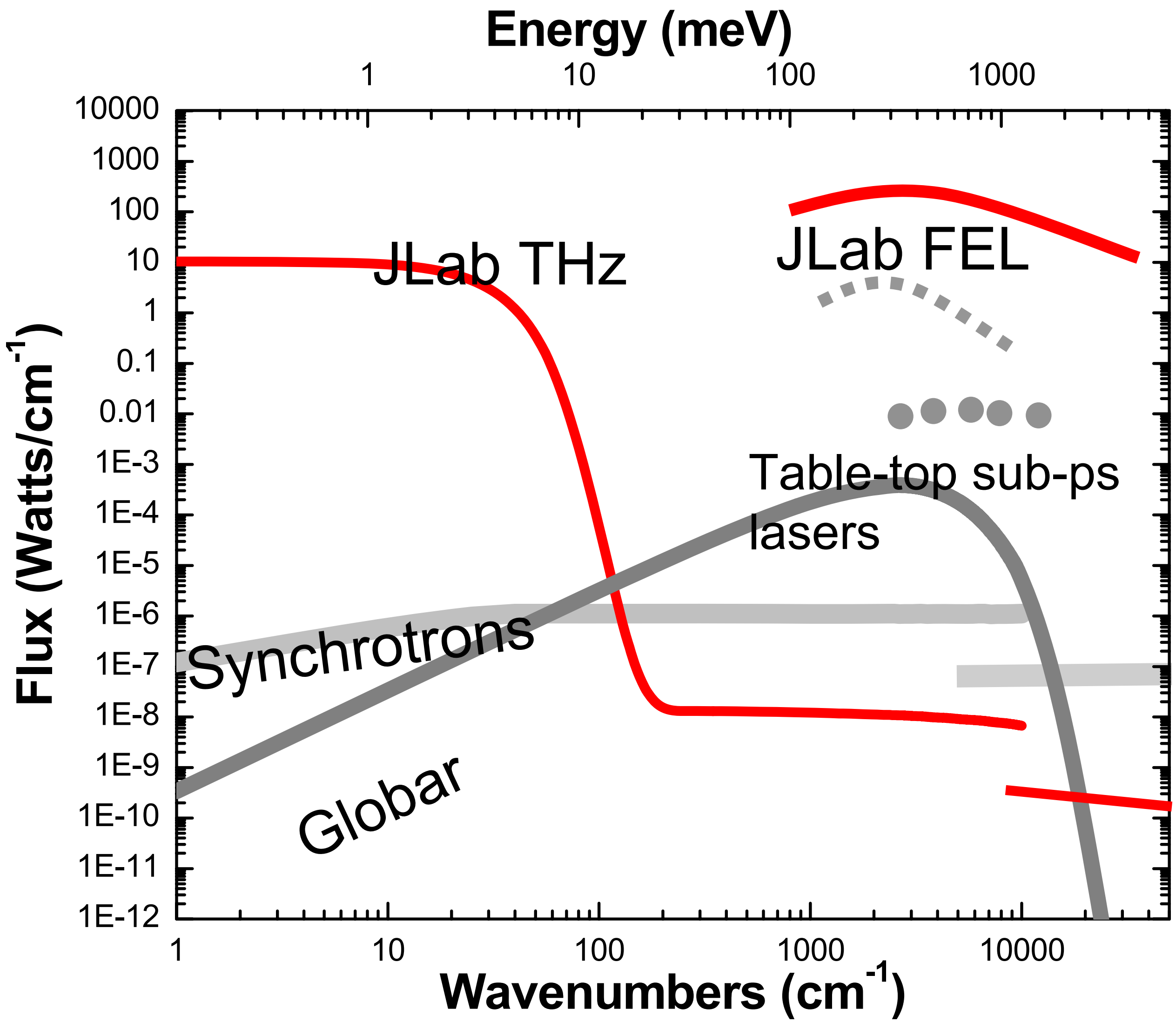


PLUS: In 2005 JLab SRF Institute demonstrated near theoretical maximum field in single grain cavities ⇒ may be crucial for ILC

World's Highest Average Power Light Sources



JLab FEL Power from THz to UV

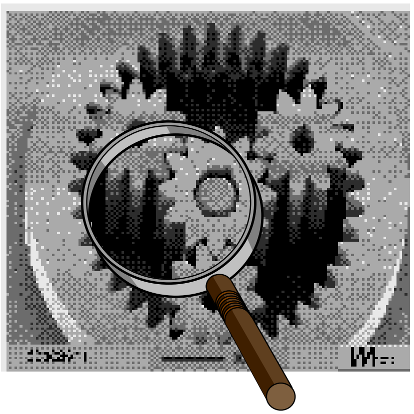


For information: www.jlab.org/FEL

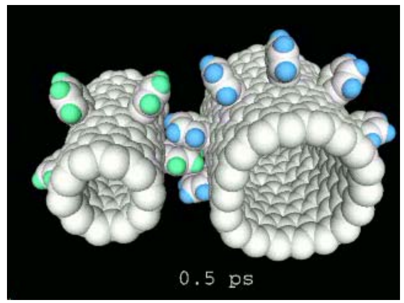
Forefront Condensed Matter and Life Sciences

Nano-Fluids

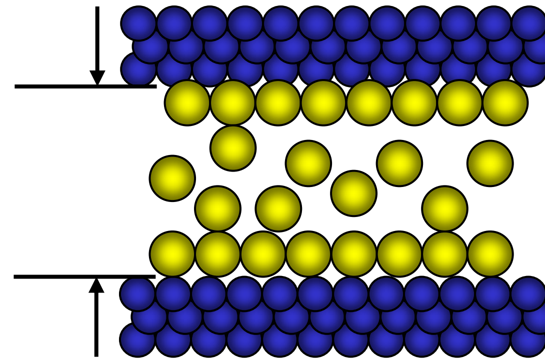
in New Technologies, in Chemistry, Bio Medicine, Geology



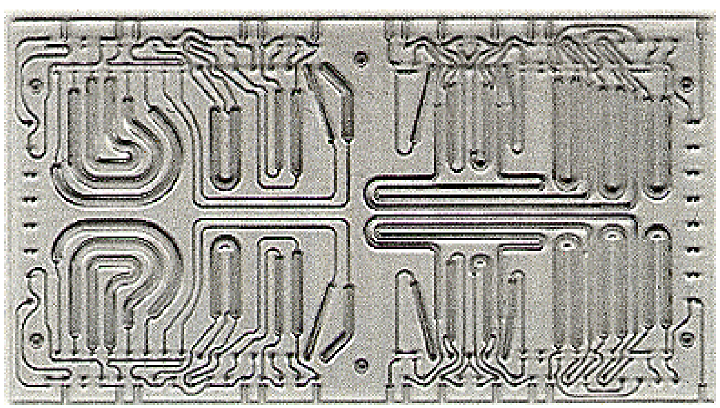
From Micro- to Nano-Gears



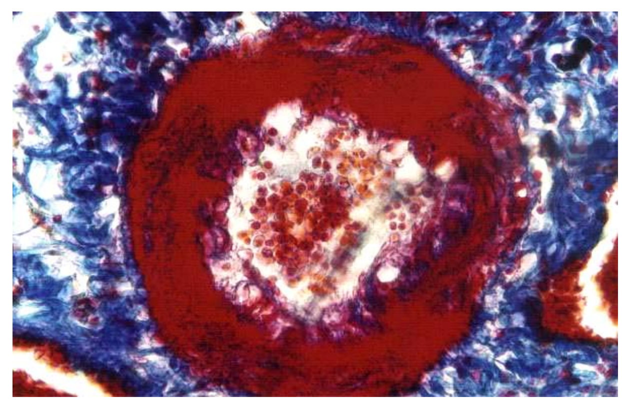
Nano Tubes



Lubrication in Nano Slits



Chemistry Lab of Tomorrow: On a Chip



Blood/Fat Flow in Capillaries

World Community in 2012 and Beyond

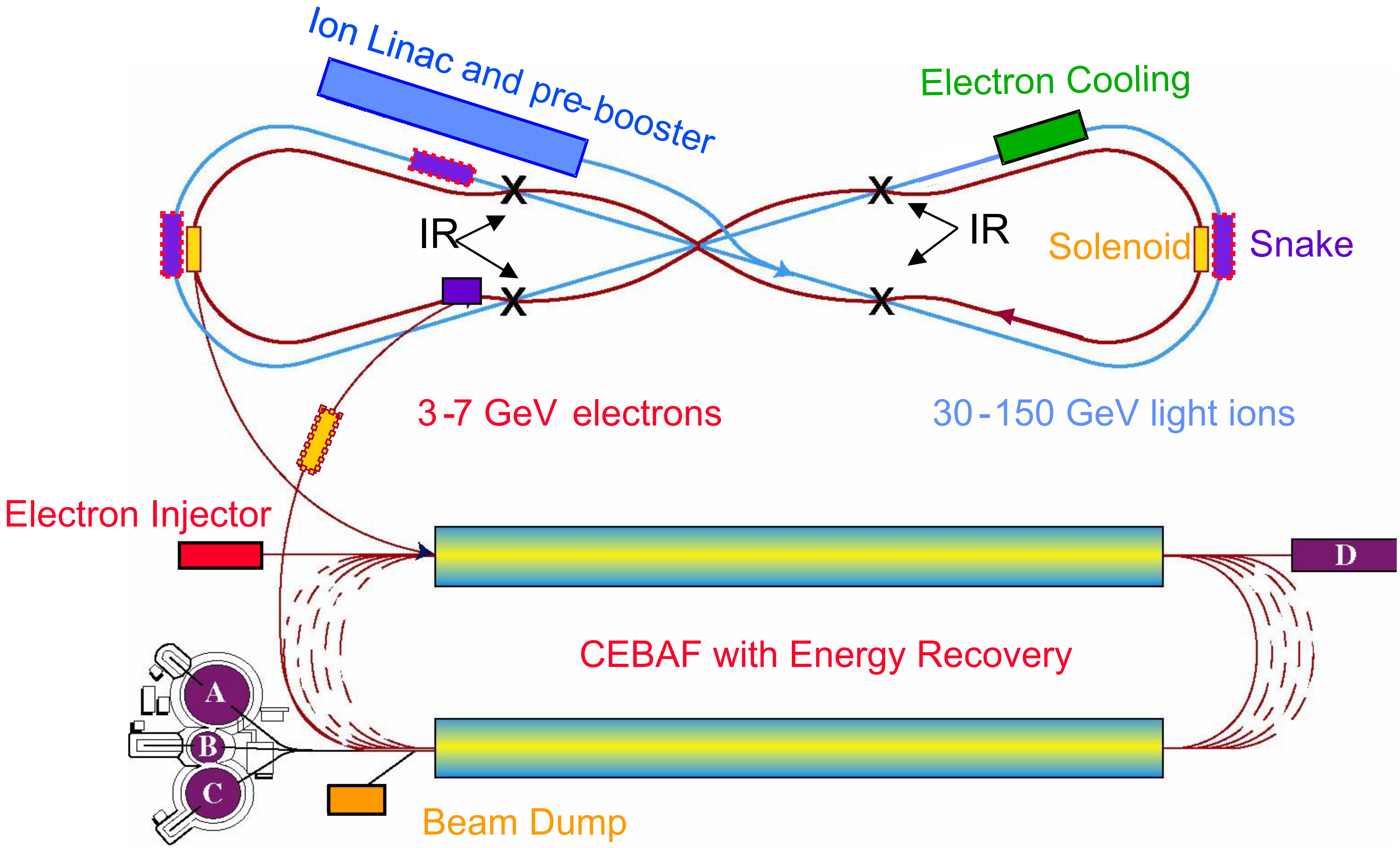
- With Upgrade will have three major new facilities investigating nuclear physics at hadronic level (QCD) : GSI (Germany), J-PARC (Japan) and JLab*

- Complementary programs (e.g. charmed vs light-quark exotics, hadrons in-medium….)

- Wonderful opportunities to build international community and take our field to a new level

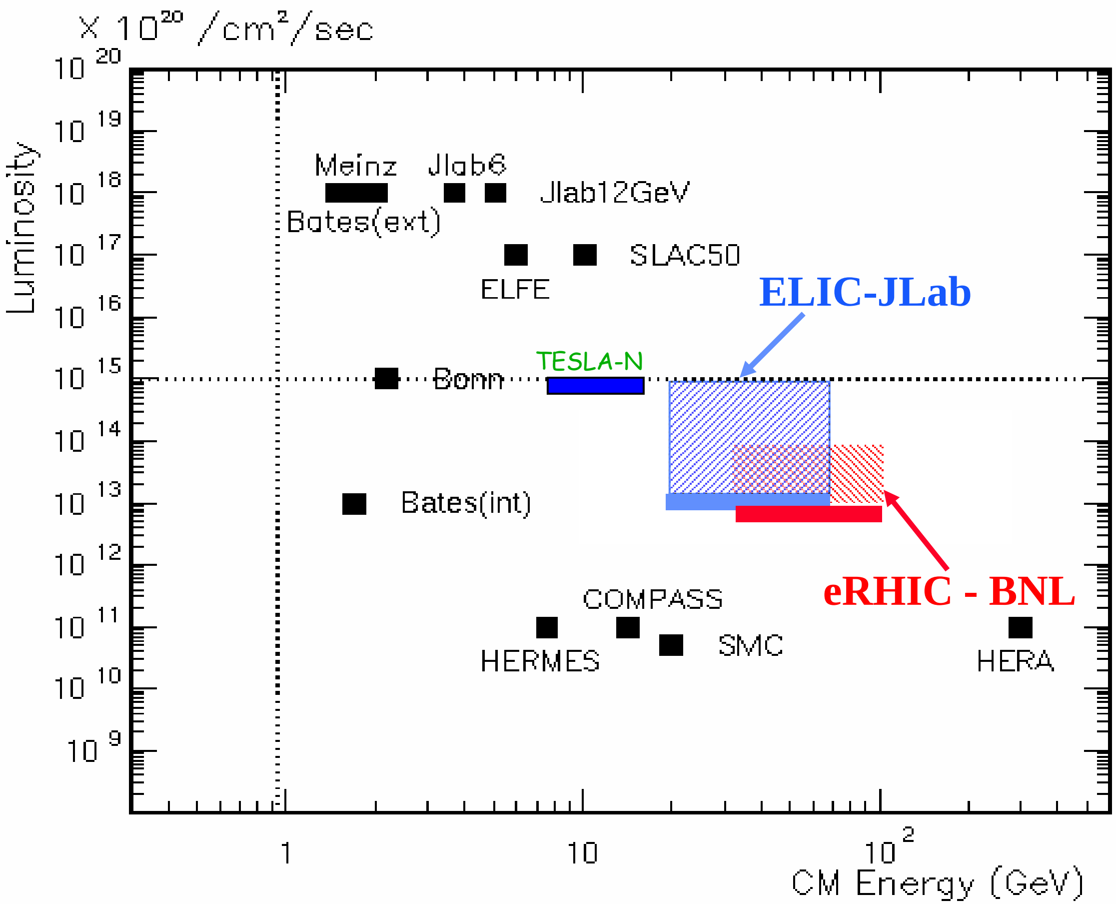
* Unique: only electromagnetic machine

Long-term Landscape : ELIC/eRHIC

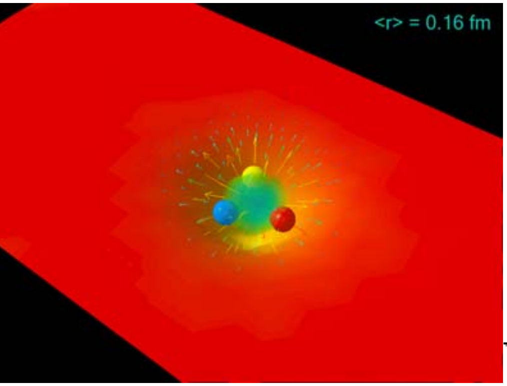


More in talk of Sam Aronson tomorrow

Luminosity vs CM Energy



- **ELIC at Jlab**
  - 3-7 GeV e^- on 30-150 GeV p (both polarized)
  - 20-65 GeV CM Energy
  - Polarized light ions
  - Luminosity as high as 0.8×10^{35} cm^{-2} sec^{-1}
- **eRHIC at BNL**
  - 5-10 GeV e^- on 50-150 GeV p (both polarized)
  - 30-100 GeV CM Energy
  - Polarized light ions
  - Heavy ion beams available
  - Luminosity from 10^{33} to perhaps as high as 10^{34}



"QUARKS. NEUTRINOS. MESONS. ALL THOSE DAMN PARTICLES YOU CAN'T SEE. THAT'S WHAT DROVE ME TO DRINK. BUT NOW I CAN SEE THEM."