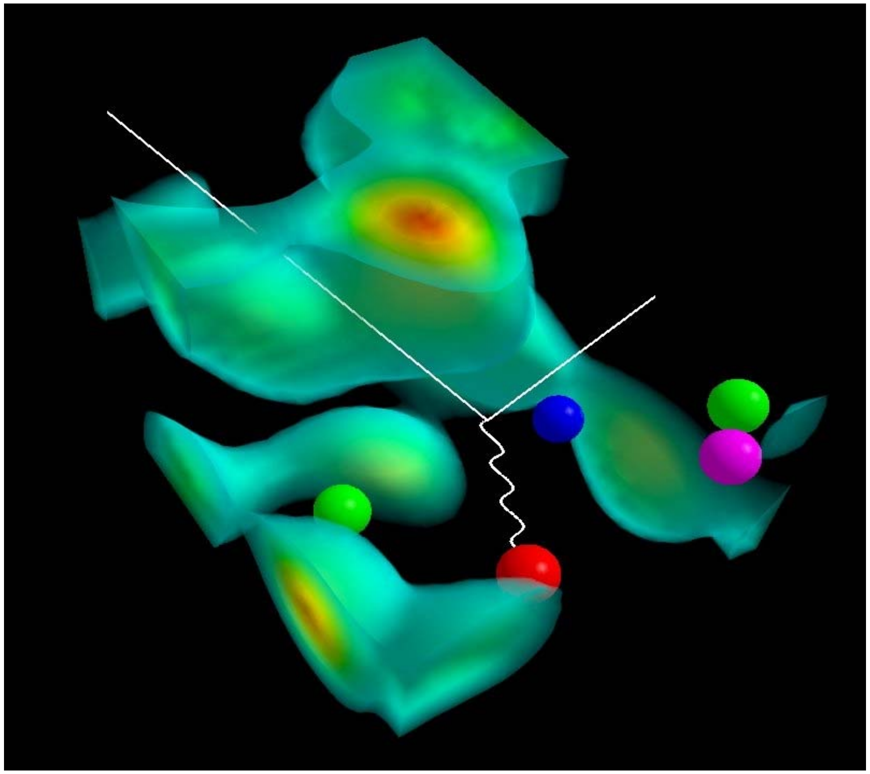
Report from Jefferson Laboratory



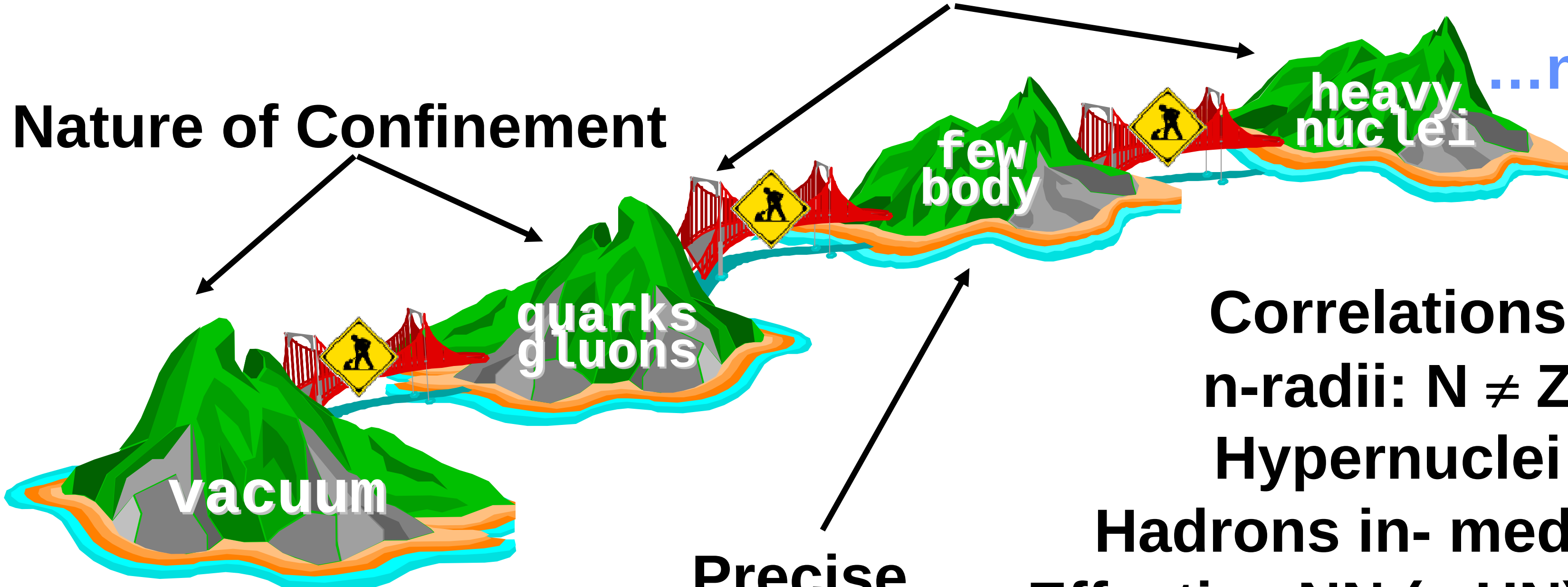
Anthony W Thomas

NSAC Meeting: March 3rd 2006

JLab is Central to Nuclear Science

Quark-Gluon Structure
Of Nucleons and Nuclei

Nature of Confinement



...n-stars

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

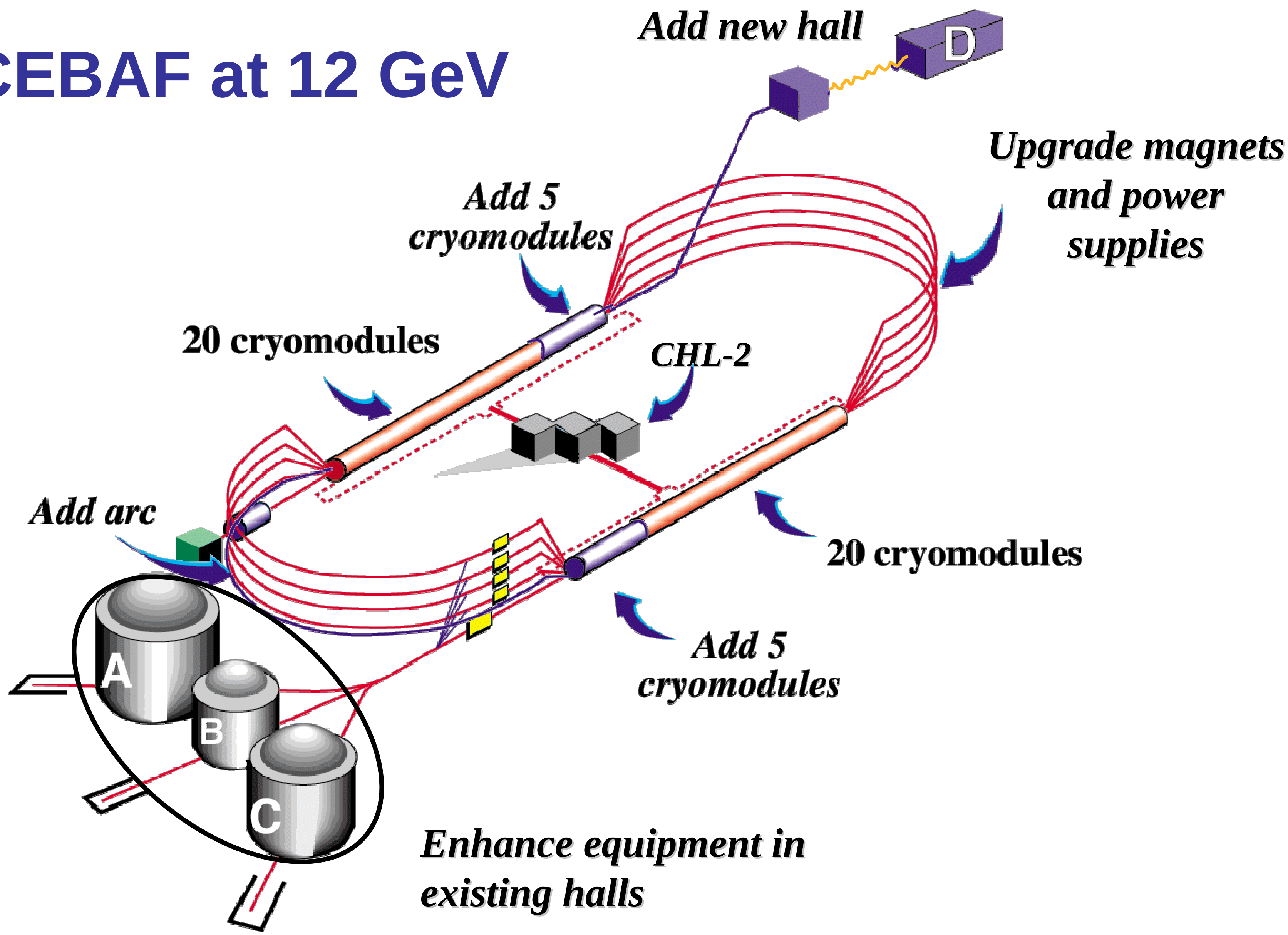
Precise
few-nucleon
calculations

Exotic mesons
and baryons

12 GeV Upgrade Project

- Status
  - CD-1 approved!!!
  - R&D providing valuable information
  - ACD effort on track for CD-2A mid-year
- Planning
  - Project is supported in all funding scenarios
  - CD-1 approval opens the door for getting firm commitments of resources from non-DOE funding sources
  - February '06 project funding guidance:
    - Reduced construction funds in FY08 and FY09, increased in FY10 and FY11
    - Best current guess: 6 GeV program to end CY10

CEBAF at 12 GeV



Highlights of the 12 GeV Program

- **Revolutionize Our Knowledge of Spin and Flavor Dependence of Valence PDFs**

- **Revolutionize Our Knowledge of Distribution of Charge and Current in the Nucleon**

- **Totally New View of Hadron (and Nuclear) Structure: GPDs**
  - **Determination of the quark angular momentum**

Highlights of the 12 GeV Program….2

- **Exploration of QCD in the Nonperturbative Regime:**
  - **Existence and properties of exotic mesons**
- **New Paradigm for Nuclear Physics:**
  Nuclear Structure in Terms of QCD
  - **Spin and flavor dependent EMC Effect**
  - **Study quark propagation through nuclear matter**
- **Precision Tests of the Standard Model**
  - **Factor 20 improvement in ($2C_{2u}$-C_{2d})**

Nuclear Physics Research Goals

Year	OMB Milestones in Hadronic Physics — TJNAF Responsible for 8 of 10
2008	**Make measurements of spin carried by the glue in the proton with polarized proton-proton collisions at center of mass energy, $\sqrt{s_{NN}}$ = 200 GeV.**
2008	Extract accurate information on generalized parton distributions for parton momentum fractions, x, of 0.1 - 0.4 , and squared momentum change, –t, less than 0.5 GeV^2 in measurements of deeply virtual Compton scattering.
2009	Complete the combined analysis of available data on single π, η, and K photo-production of nucleon resonances and incorporate the analysis of two-pion final states into the coupled-channel analysis of resonances.
2010	Determine the four electromagnetic form factors of the nucleons to a momentum-transfer squared, Q^2, of 3.5 GeV^2 and separate the electroweak form factors into contributions from the u, d and s-quarks for $Q^2 < 1$ GeV^2 .
2010	Characterize high-momentum components induced by correlations in the few-body nuclear wave functions via (e,e'N) and (e,e'NN) knock-out processes in nuclei and compare free proton and bound proton properties via measurement of polarization transfer in the reaction.
2011	Measure the lowest moments of the unpolarized nucleon structure functions (both longitudinal and transverse) to 4 GeV^2 for the proton, and the neutron, and the deep inelastic scattering polarized structure functions $g_1(x, Q^2)$ and $g_2(x,Q^2)$ for x=0.2-0.6, and $1 < Q^2 < 5$ GeV^2 for both protons and neutrons.
2012	Measure the electromagnetic excitations of low-lying baryon states (<2 GeV) and their transition form factors over the range Q^2 = 0.1 – 7 GeV^2 and measure the electro- and photo-production of final states with one and two pseudoscalar mesons.
2013	**Measure flavor-identified q and $\bar{q}$ contributions to the spin of the proton via the longitudinal-spin asymmetry of W production.**
2014	Perform lattice calculations in full QCD of nucleon form factors, low moments of nucleon structure functions and low moments of generalized parton distributions including flavor and spin dependence.
2014	Carry out ab initio microscopic studies of the structure and dynamics of light nuclei based on two-nucleon and many-nucleon forces and lattice QCD calculations of hadron interaction mechanisms relevant to the origin of the nucleon-nucleon interaction.

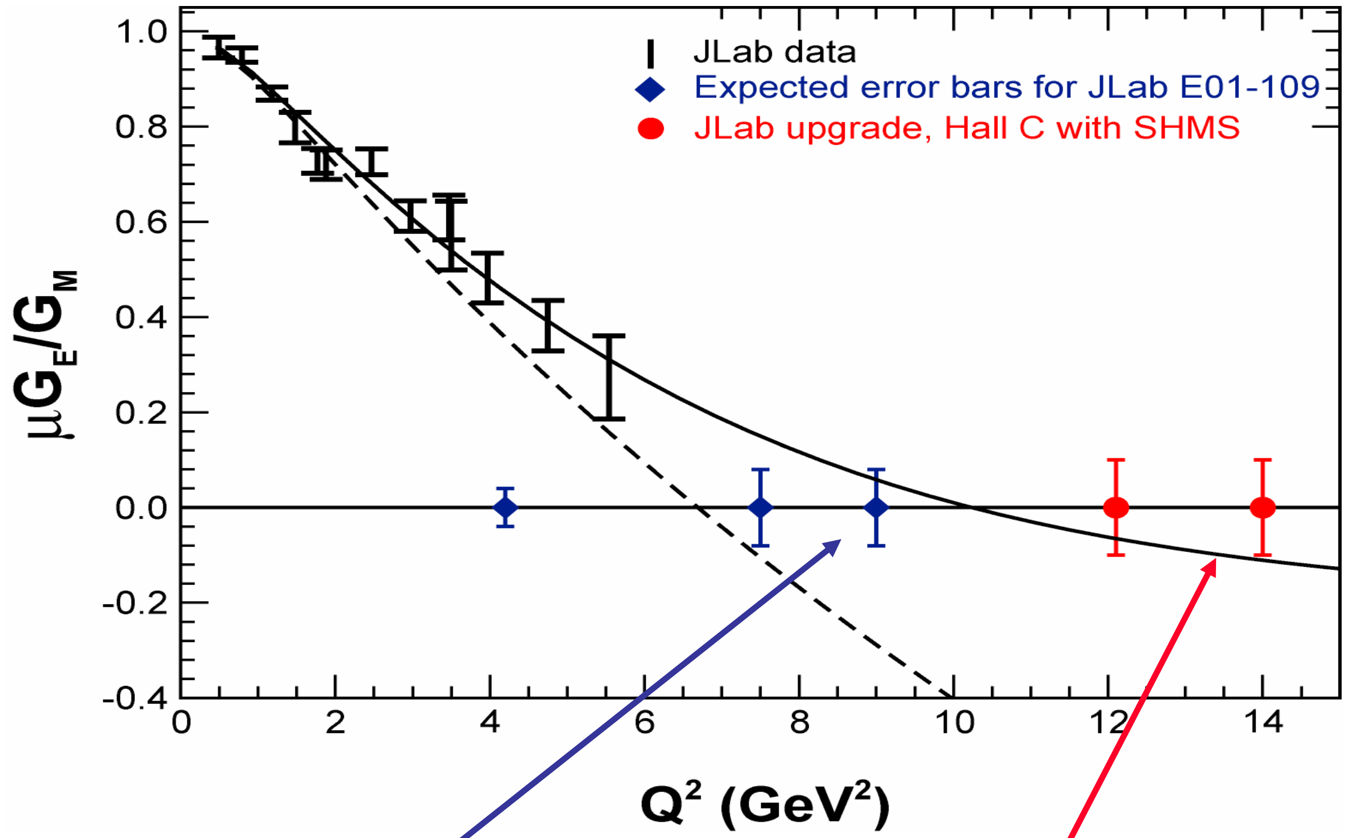
Summary of Approved Experiments CY 2007+

- **HALL A: 20 experiments, 12 rated A or A$^-$**
  - **3.9 years normal operation**

- **HALL B: 12 experiments, 10 rated A or A$^-$**
  - **2.34 years normal operation**

- **HALL C: 14 experiments, 12 rated A or A$^-$**
  - **5 years with Q_{weak} II**

Distribution of Charge and Current in the Nucleon



HP 2010

Apparatus almost complete: new scattering Chamber, 1700 block calorimeter, new focal plane polarimeter

- 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

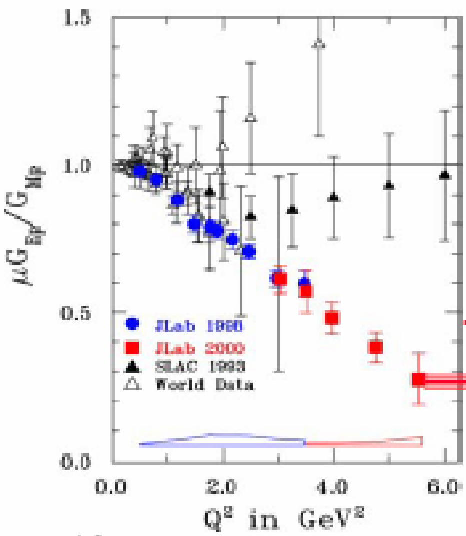
JLab data on the EM form factors provide a testing ground for theories constructing nucleons from quarks and glue

Planned Extensions w/ 6 GeV beams

Proton

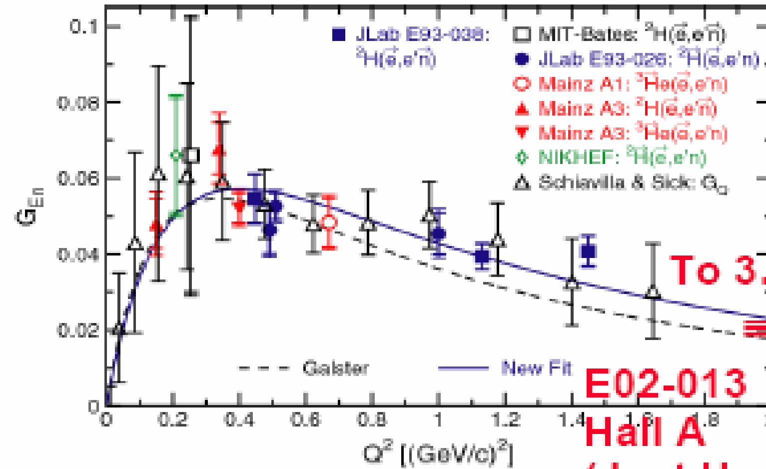
Neutron

Electric



To 9 GeV^2

E04-108
Hall C (2008)

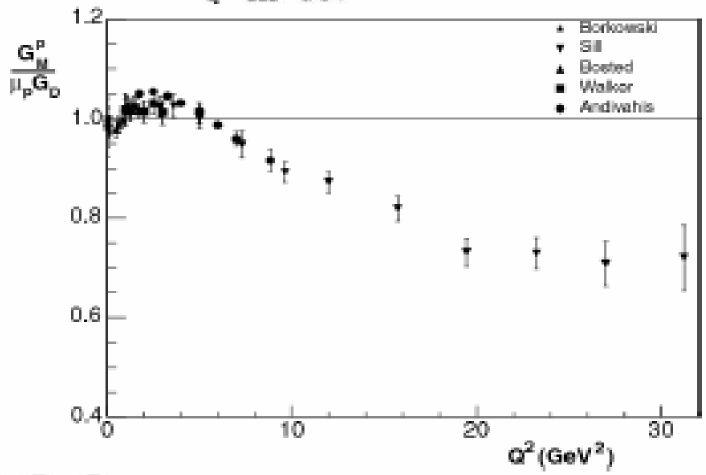


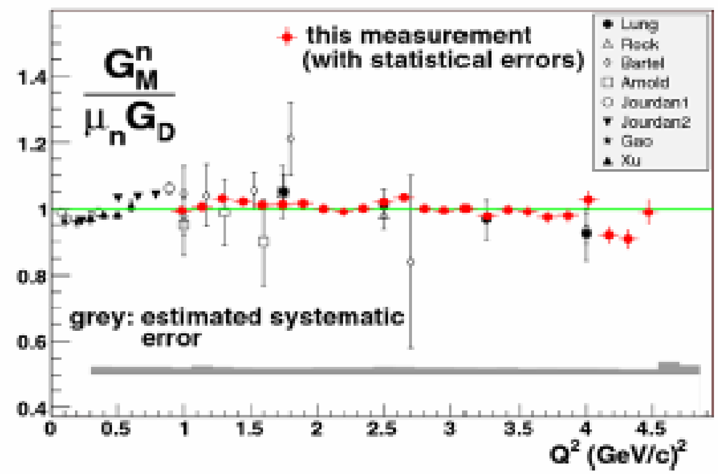
To 3.5 GeV^2

E02-013
Hall A
(Just Underway)

Selected World Data

Magnetic

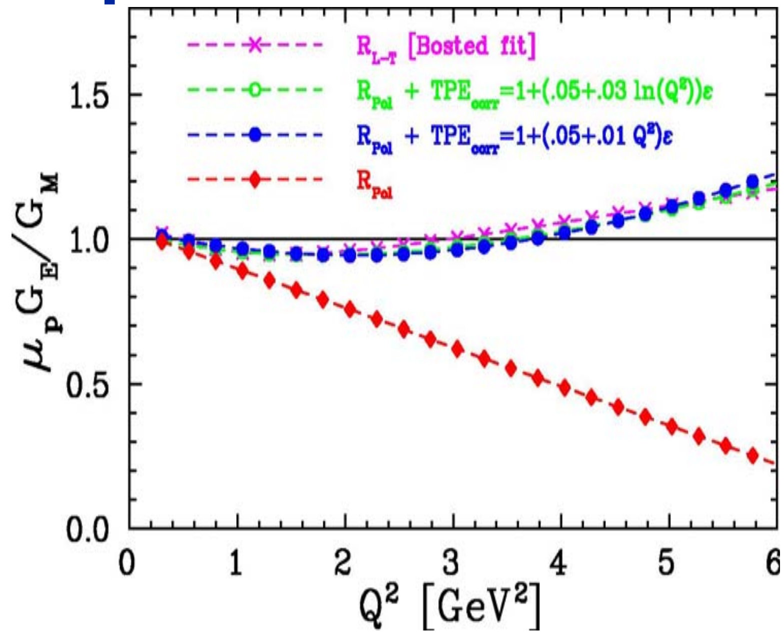


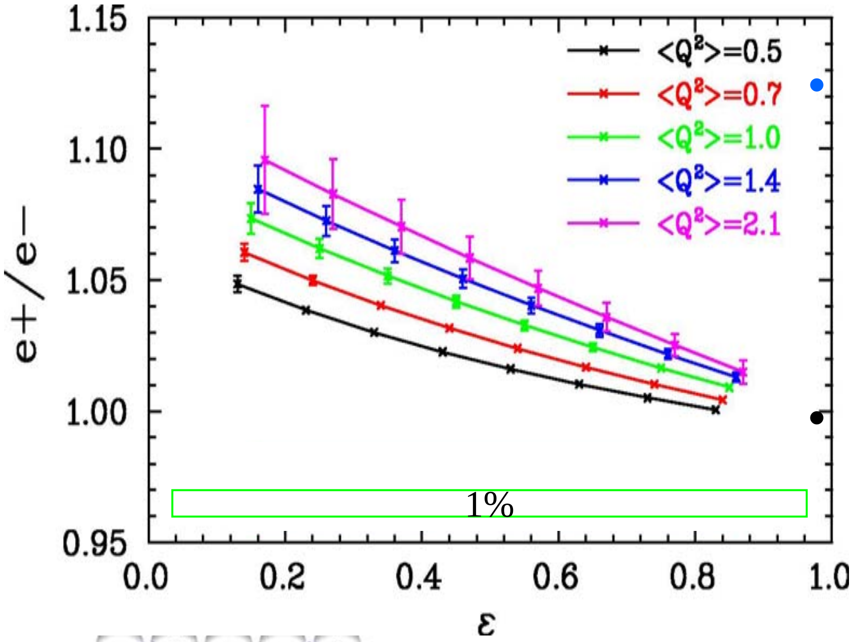


Two-Photon Exchange Experiment

- **Measurement of proton *electric* form factor differs by factor of 4 in two different measurements**

- **Two-photon exchange is only known explanation**





- **Unambiguous determination of this process can be made by comparing positron-proton to electron-proton elastic scattering**

- **CLAS experiment can determine this with 1% systematic error**

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

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

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

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

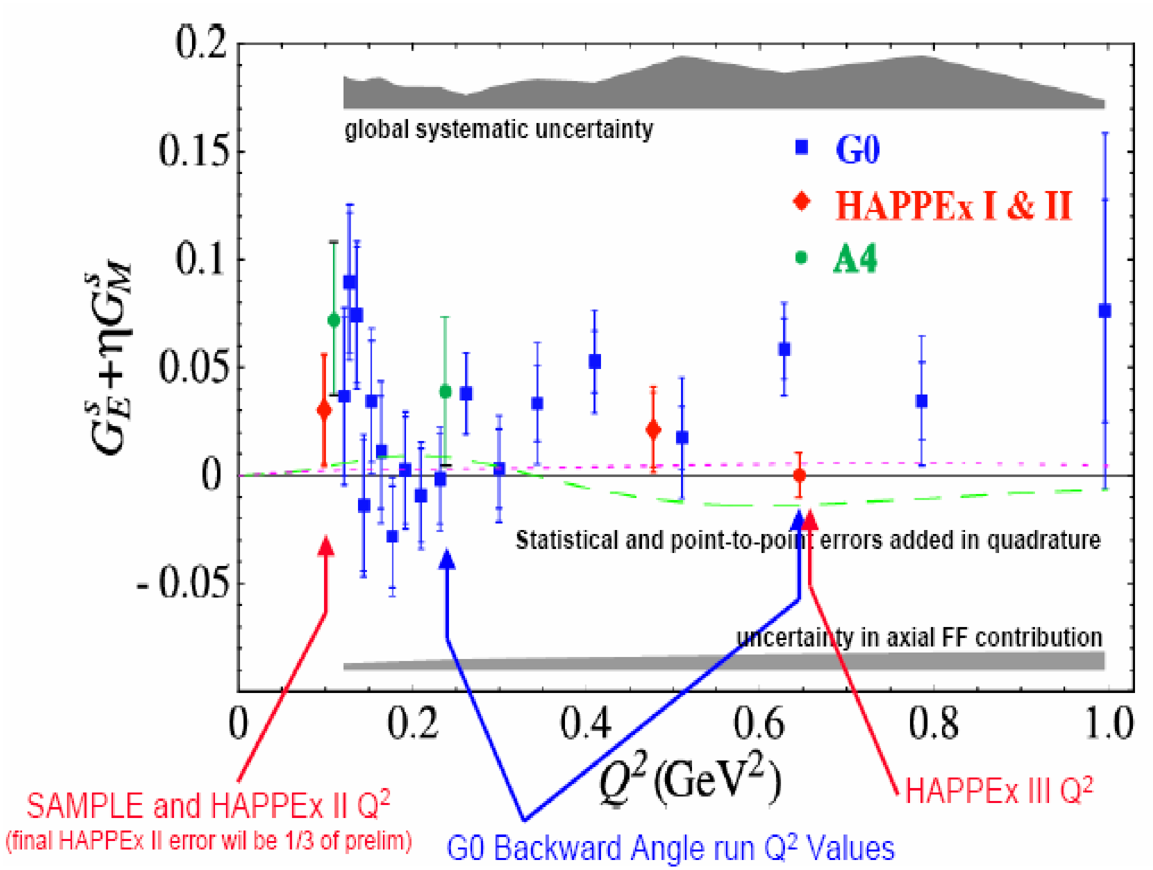
- Through proton spin crisis: as much as 10% of the spin of the proton

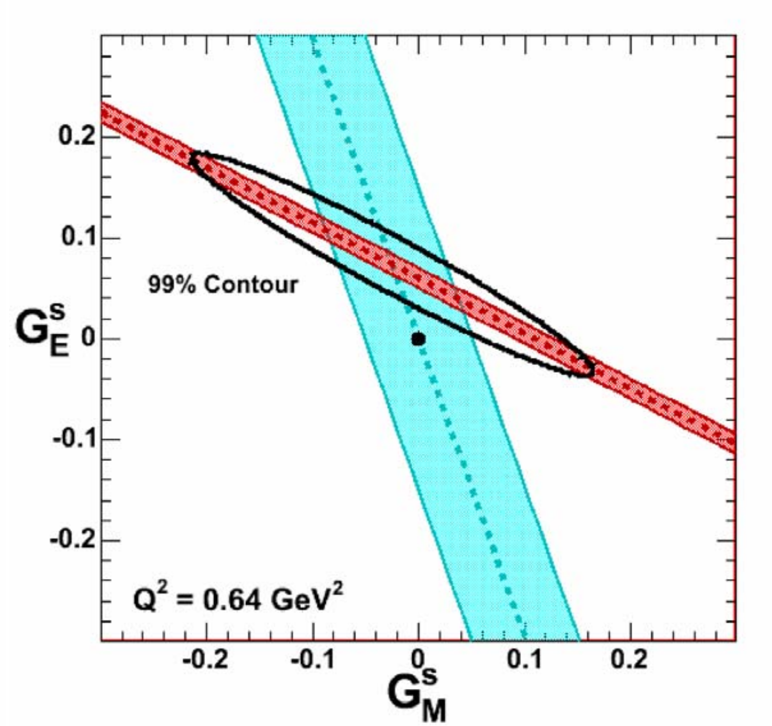
HOW MUCH OF THE ELECTRIC & MAGNETIC FORM FACTORS ?

HAPPEx-III and G0 Backward Angle

E05-109, HAPPEx-III, together with Backward angle G0, will provide an unprecedented precision on a measurement of all three strange form factors at $Q^2 = 0.64$ GeV^2

HP 2010





Nuclear Physics: The Core of Matter, The Fuel of Stars
(NAS/NRC Report, 1999)

Science Chapter Headings:

The Structure of the Nuclear Building Blocks

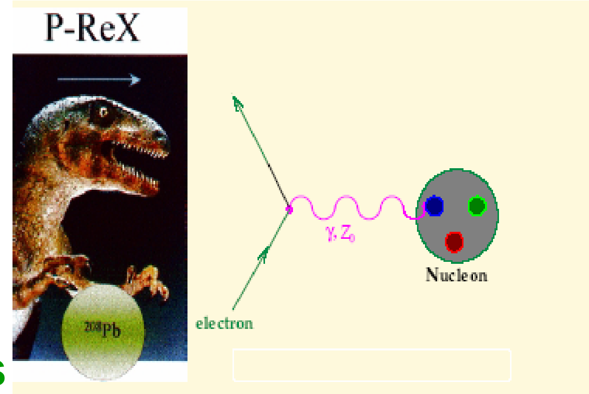
The Structure of Nuclei

Matter at Extreme Densities

The Nuclear Physics of the Universe

Symmetry Tests in Nuclear Physics

PREX : ^{208}Pb Radius Experiment



Low Q^2 elastic e-nucleus scattering

(E = 850 MeV, $\Theta = 6^{\circ}$)

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

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

Measure a Parity Violating Asymmetry

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

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!

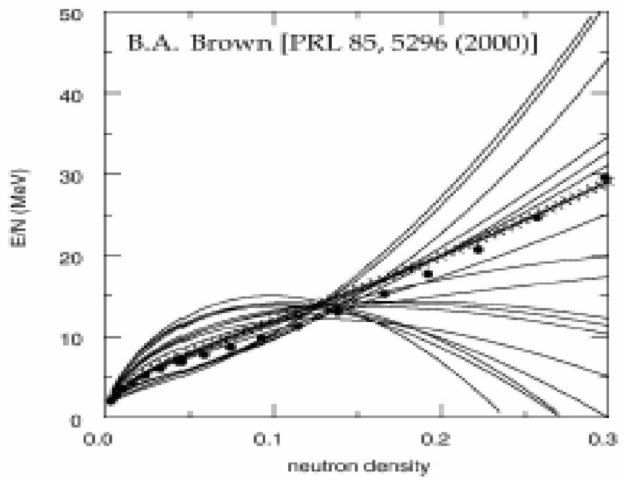


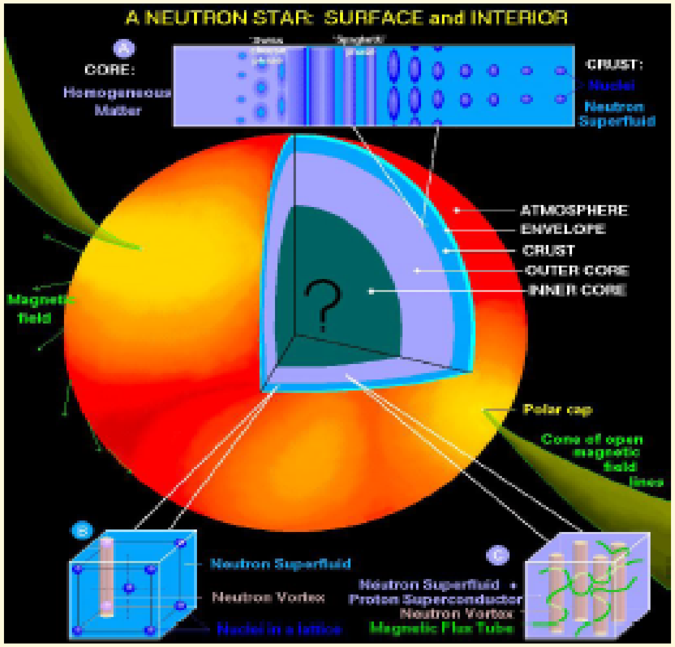
FIG. 2. The neutron EOS for 18 Skyrme parameter sets. The filled circles are the Friedman-Pandharipande (FP) variational calculations and the crosses are SkX. The neutron density is in units of neutron/fm^3.

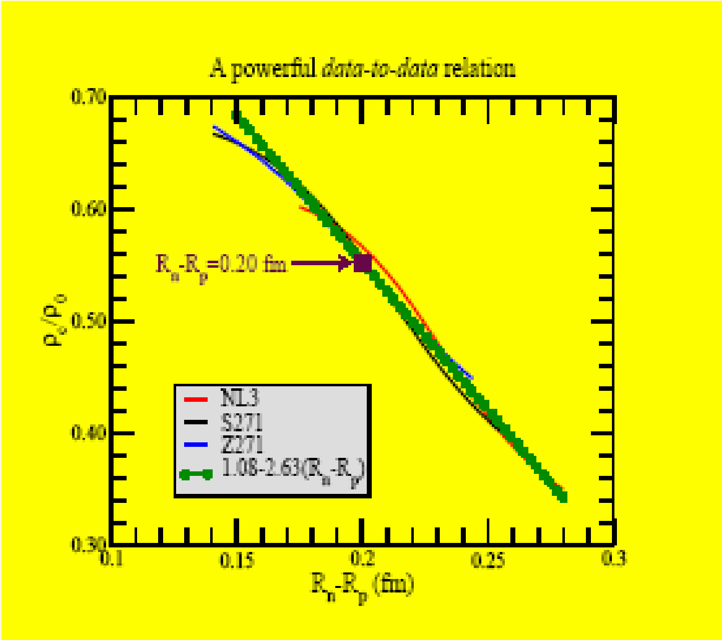
Adding the neutron radius of a single heavy nucleus to the database will eliminate the large dispersion in the plot!

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

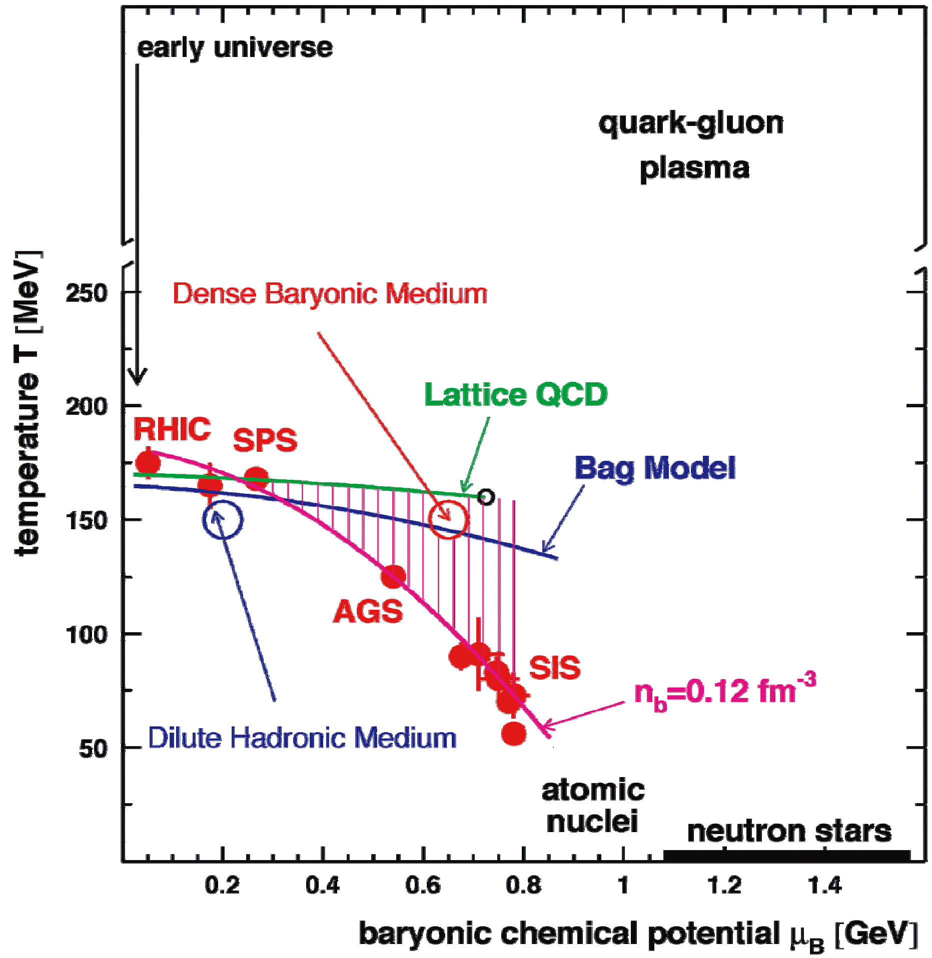
- Neutron stars contain a solid crust above a uniform liquid mantle
- The stiffer the EOS the lower the transition to non-uniform matter
  - ⋆ Energetically unfavorable to separate into low- and high-density regions
- The stiffer the EOS the larger the neutron skin of a heavy nucleus





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 ...

Major Challenges for Nuclear Physics



- **Origin of Nuclear Saturation**

- **EOS … as ρ " ; as T "**
  as S " ; as N-Z "

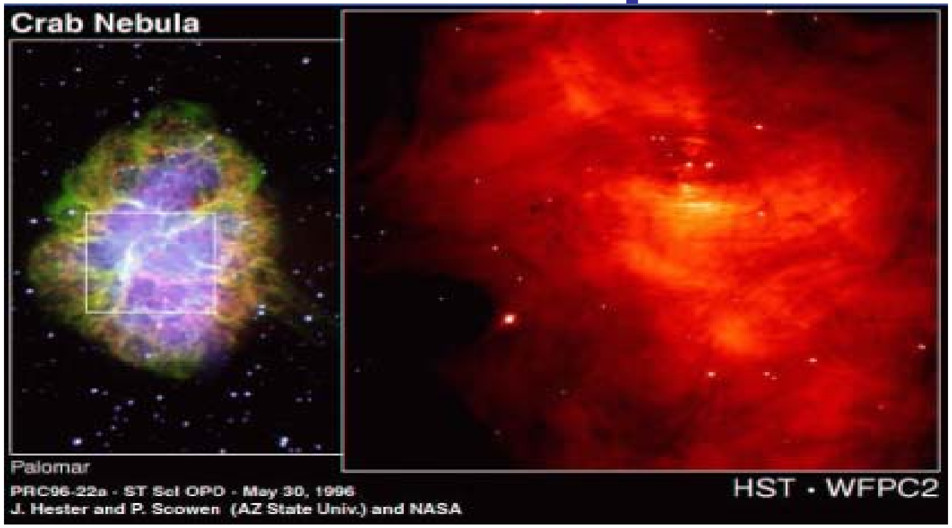
- **Phase Transition to:**
  - **quark matter (QM)**
    superconducting QM, strange condensate
  - **related to nuclear astrophysics; n-stars….**

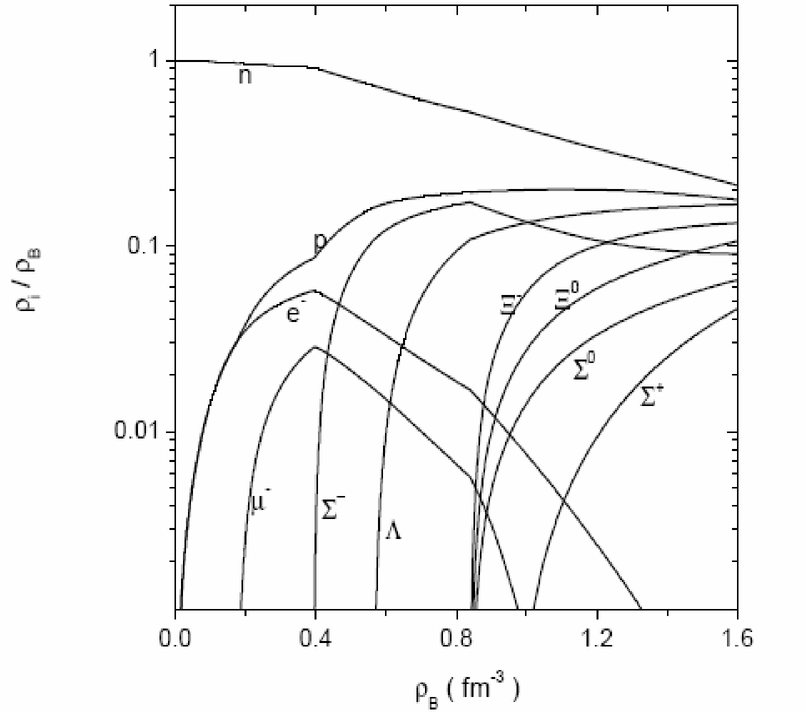
Neutron Star Composition

Hyperons enter at just 2-3 ρ_0

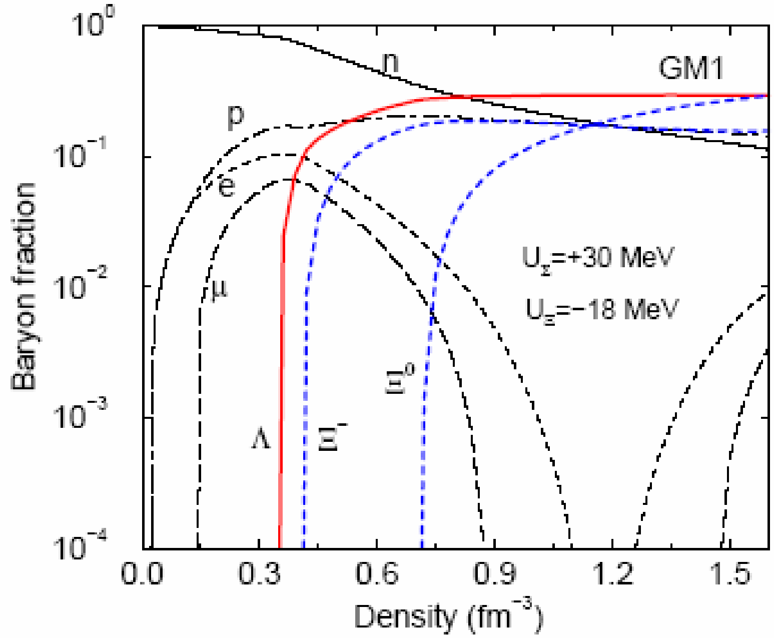
Hence need effective Σ-N and Λ-N forces in this density region!

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





?



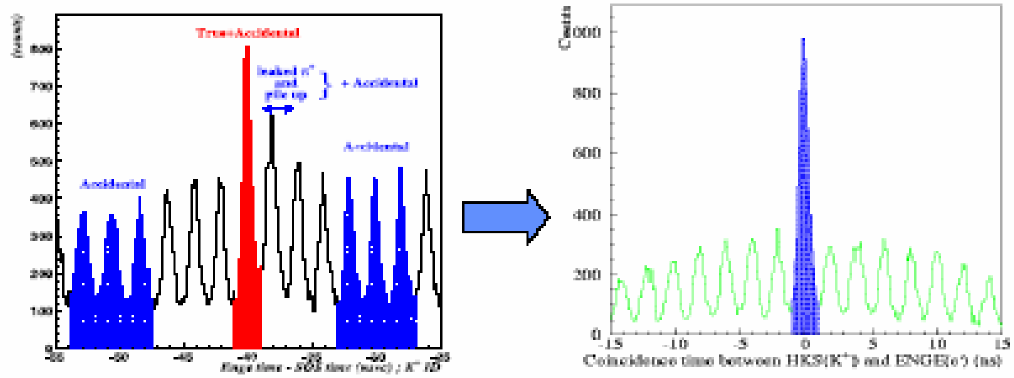
E01-011 (HKS) in Hall C: the Next Generation

HKS has demonstrated improved performance in its first run (completed 9/05)

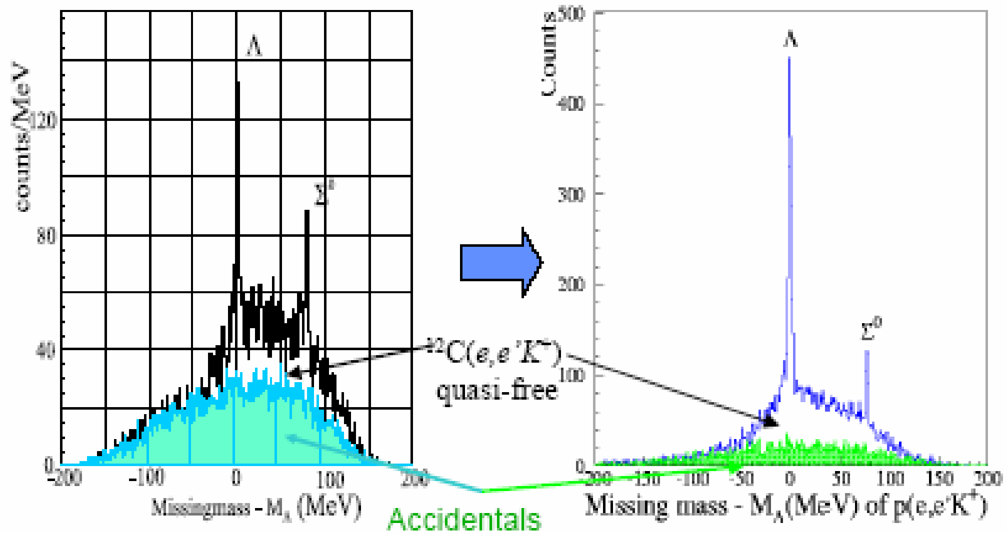
Net factor of 50 in Figure of Merit, and resolution < 500 keV

New electron spectrometer under construction in Japan for final configuration

Improved Trues to Accidentals Ratio



Reduced Backgrounds



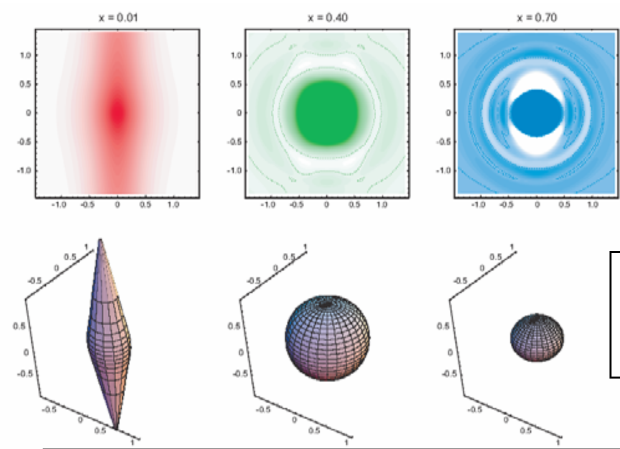
Enhanced Luminosity

210 Lambdas → 1390 Lambdas

Generalized Parton Distribution (GPDs) & Nucleon Tomography (06-003)

Begin the exploration of a major New Direction in Hadron Physics at 6 GeV, and prepare for the full exploration at 12 GeV.

3D mapping of the quark structure of the nucleon via Deeply Virtual Compton Scattering (DVCS)

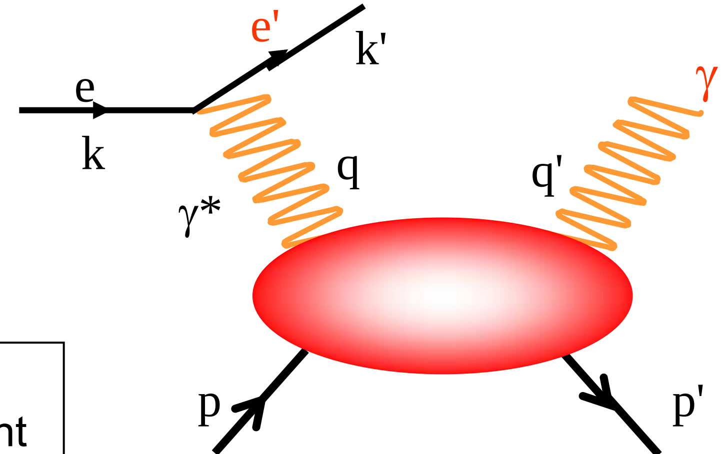


Quark distributions in protons at different momentum fractions.

The shape of the proton varies with momentum.

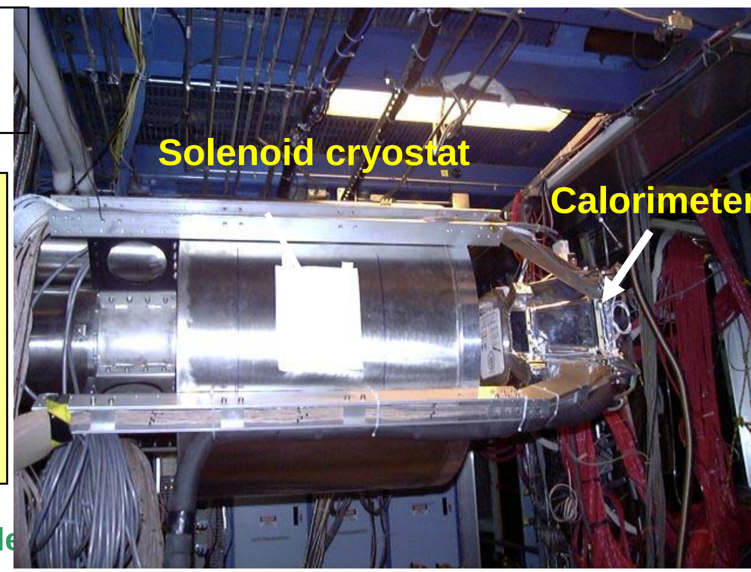
Study of the nucleon orbital angular momentum.

$$J_q = \frac{1}{2} A_q\left(0,\mu^2\right) + \frac{1}{2} B_q\left(0,\mu^2\right) =$$
$$= \frac{1}{2}\int dx x[H(x,\xi,0,\mu^2) + E(x,\xi,0,\mu^2)]$$



Deeply Virtual Compton Scattering

HP 2008 +
Extract accurate information on generalized parton distributions ……. in measurements of deeply virtual Compton scattering.

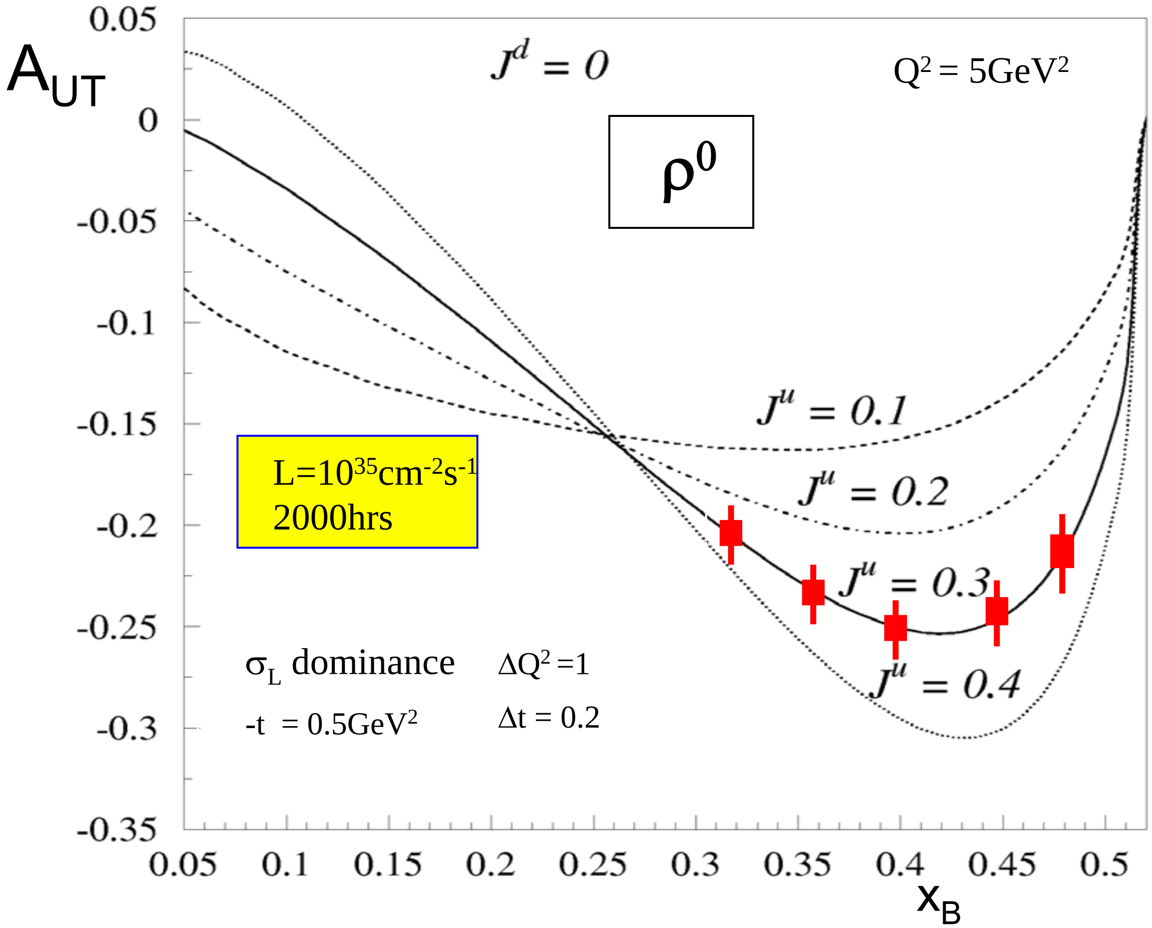


At 12 GeV: Exclusive ρ^0 with transverse target

$$A_{UT} = -\frac{2\Delta\,(\mathrm{Im}(AB^*))/\pi}{|A|^2(1-\xi^2) - |B|^2(\xi^2+t/4m^2) - \mathrm{Re}(AB^*)2\xi^2}$$

ρ^0

$A \sim (2H^u + H^d)$
$B \sim (2E^u + E^d)$



Asymmetry depends linearly on the GPD E, which enters Ji's sum rule.

K. Goeke, M.V. Polyakov, M. Vanderhaeghen, 2001

Spin Asymmetries on the Nucleon Experiment

HP 2011

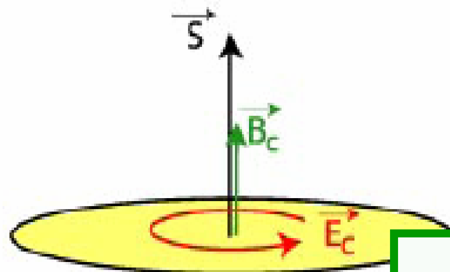
How does the gluon field respond when a nucleon is polarized ?

Define color magnetic and electric polarizabilities (in nucleon rest frame):

$$\chi_{B,E} 2M^2 \vec{S} = \langle PS | \vec{O}_{B,E} | PS \rangle$$

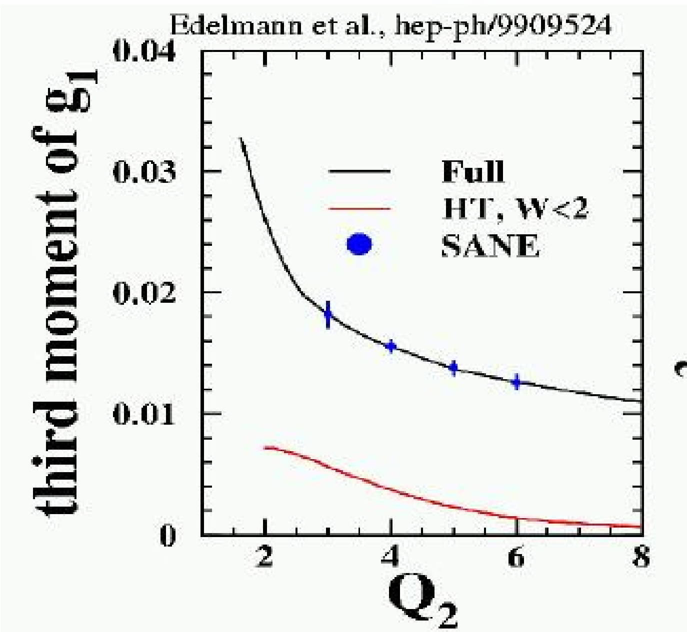
where $\vec{O}_B = \psi^\dagger g \vec{B} \psi$

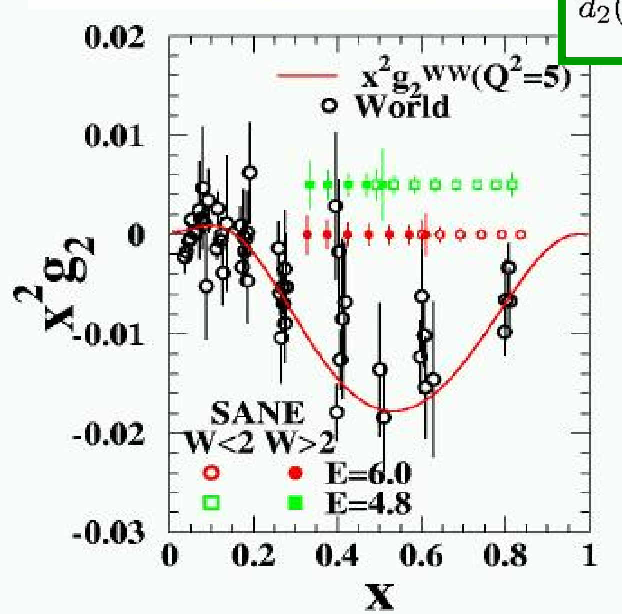
$$\vec{O}_E = \psi^\dagger \vec{\alpha} \times g \vec{E} \psi$$



SANE: A Precise measurement of g_1 & g_2 in the high-x region, allowing an extraction of their third moments at $Q^2 \sim 4$ GeV^2, related to the quark's induced color electric and magnetic polarizabilities.

$$d_2(Q^2) = \int_0^1 dx x^2 \left[2g_1(x,Q^2) + 3g_2(x,Q^2) \right]$$





Twist-3 matrix element d_2 is calculable in Lattice QCD (presently aimed at $Q^2 = 4$).

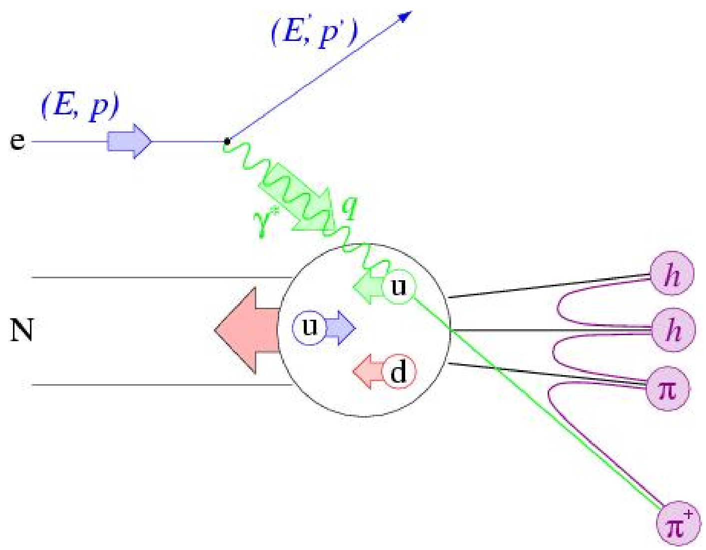
$d_2 = (2\chi_B + \chi_E)/8$

Anticipated error on d_2: 0.0009 (1/2 world error)

Flavor Decomposition: semi-inclusive DIS

"semi-SANE" : HP 2011

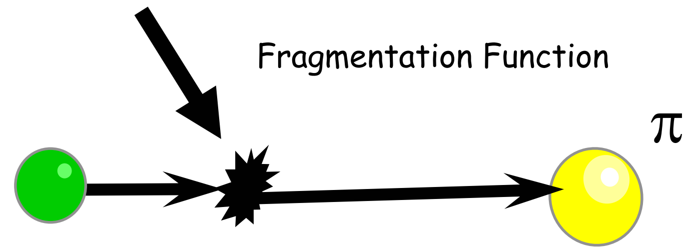
DIS probes only the sum of quarks and anti-quarks → requires assumptions on the role of sea quarks $\sum e_q^2 (q + \bar{q})$



Solution: Detect a final state hadron in addition to scattered electron

→ Can 'tag' the flavor of the struck quark by measuring the hadrons produced: 'flavor tagging'

$$\sum e_q^2 \, q(x) \, D_{q \to M}(z)$$



(e,e') $W^2 = M^2 + Q^2 (1/x - 1)$

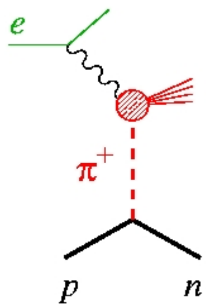
For M_m small, $\vec{p}_m$ collinear with $\vec{\gamma}$, and $Q^2/\nu^2 \ll 1$

(e,e'm) $W'^2 = M^2 + Q^2 (1/x - 1)(1 - z)$ $z = E_m/\nu$

Flavor asymmetry of proton sea: Vacuum structure inside proton?

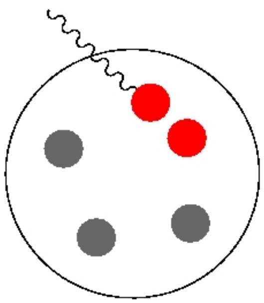
HP 2013

...New: Polarization!



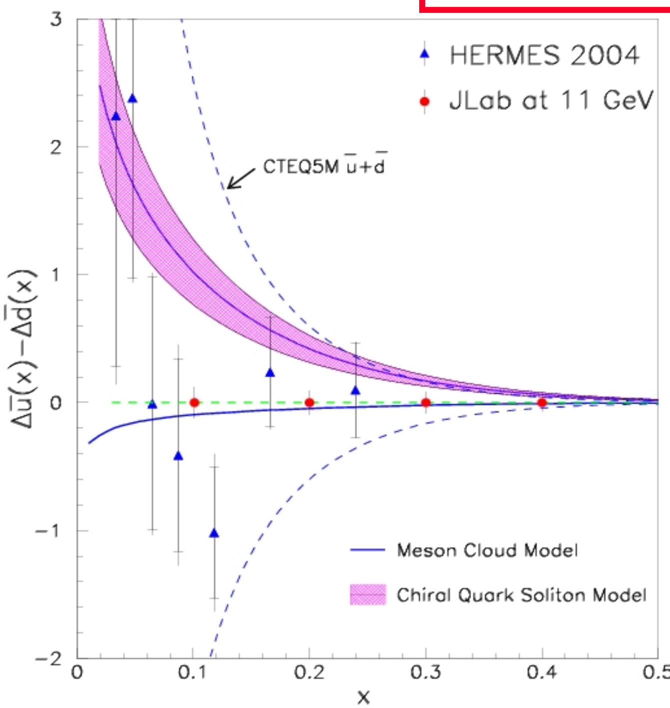
pion cloud

$$\Delta\bar{u} - \Delta\bar{d} = 0$$



$q\bar{q}$ pair
(Pauli blocking)

$$\Delta\bar{u} - \Delta\bar{d} > 0$$

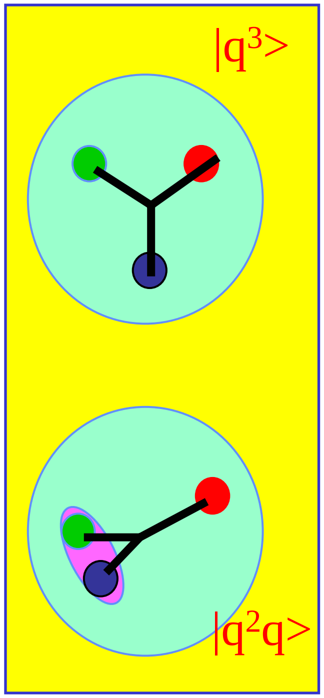


...Can be answered by initial SIDIS measurements in 2009 and fully with 12 GeV

[Thomas 83; Schreiber *et al.*, 90; Diakonov *et al.* 96; Fries, Schaefer, Weiss 03]

FROST: Frozen-Spin Target Experiments at CLAS (E02-112: 2007)

HP 2009



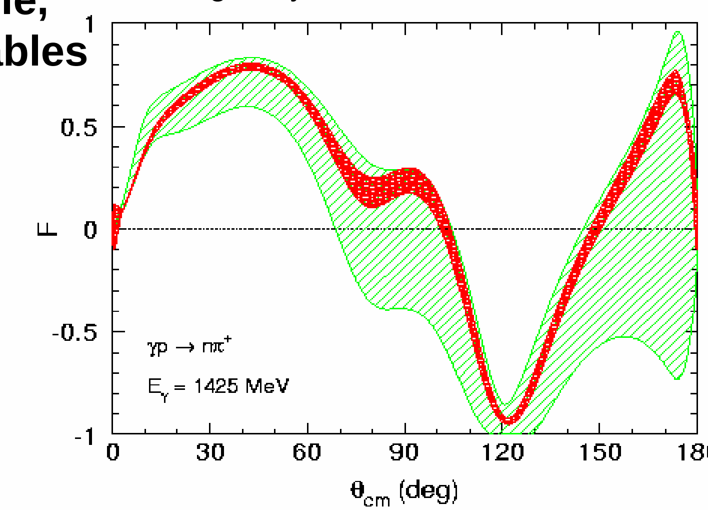
Determine basic symmetry properties of baryon matter at the core of the visible universe.

- ➢Discover excited baryon states if produced in photoproduction of pseudo-scalar mesons.
- ➢ Use high-energy photons with circular and linear polarization on FROST with longitudinal and transverse spin polarization.
- ➢ **Measure nearly complete set of single, double, and triple polarization observables including hyperon recoil polarization.**

One of the top 10 milestones in hadron physics:

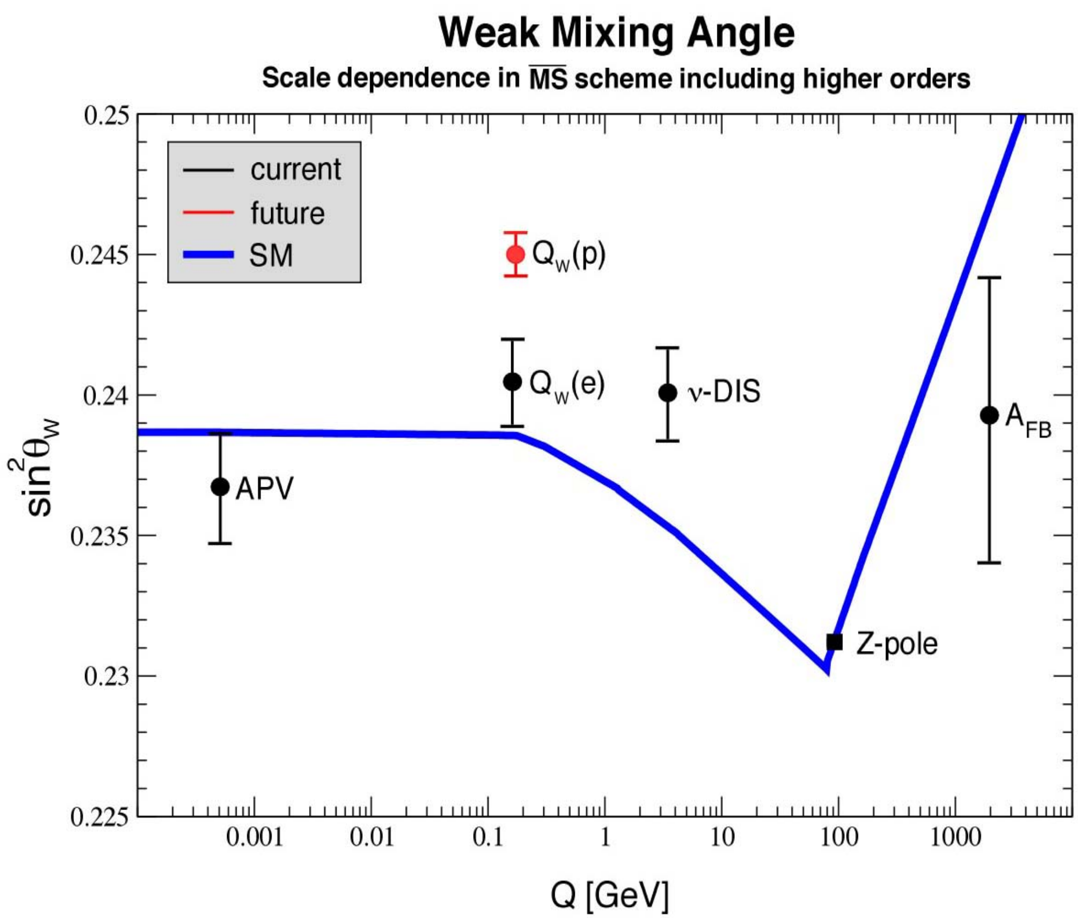
❖ Complete the combined analysis of available data on single π, η and K photoproduction of resonances and incorporate the analysis of 2π final states into the coupled channel analysis of resonances.

Example (sample PWA using MC data)
► greatly reduced uncertainties!

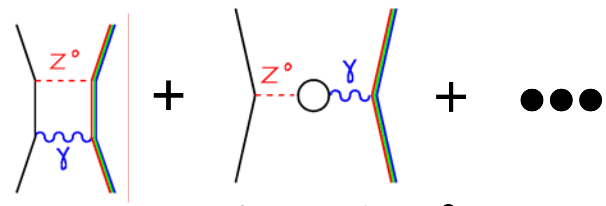


The Q^p_{weak} Experiment

The first measurement of the weak charge of the proton; a precision test of the Standard Model and a search for New Physics Beyond the Standard Model – at the TeV scale



- Electroweak radiative corrections
  → $\sin^2\theta_W$ varies with Q



- Extracted values of $\sin^2\theta_W$ must agree with Standard Model or new physics is indicated.

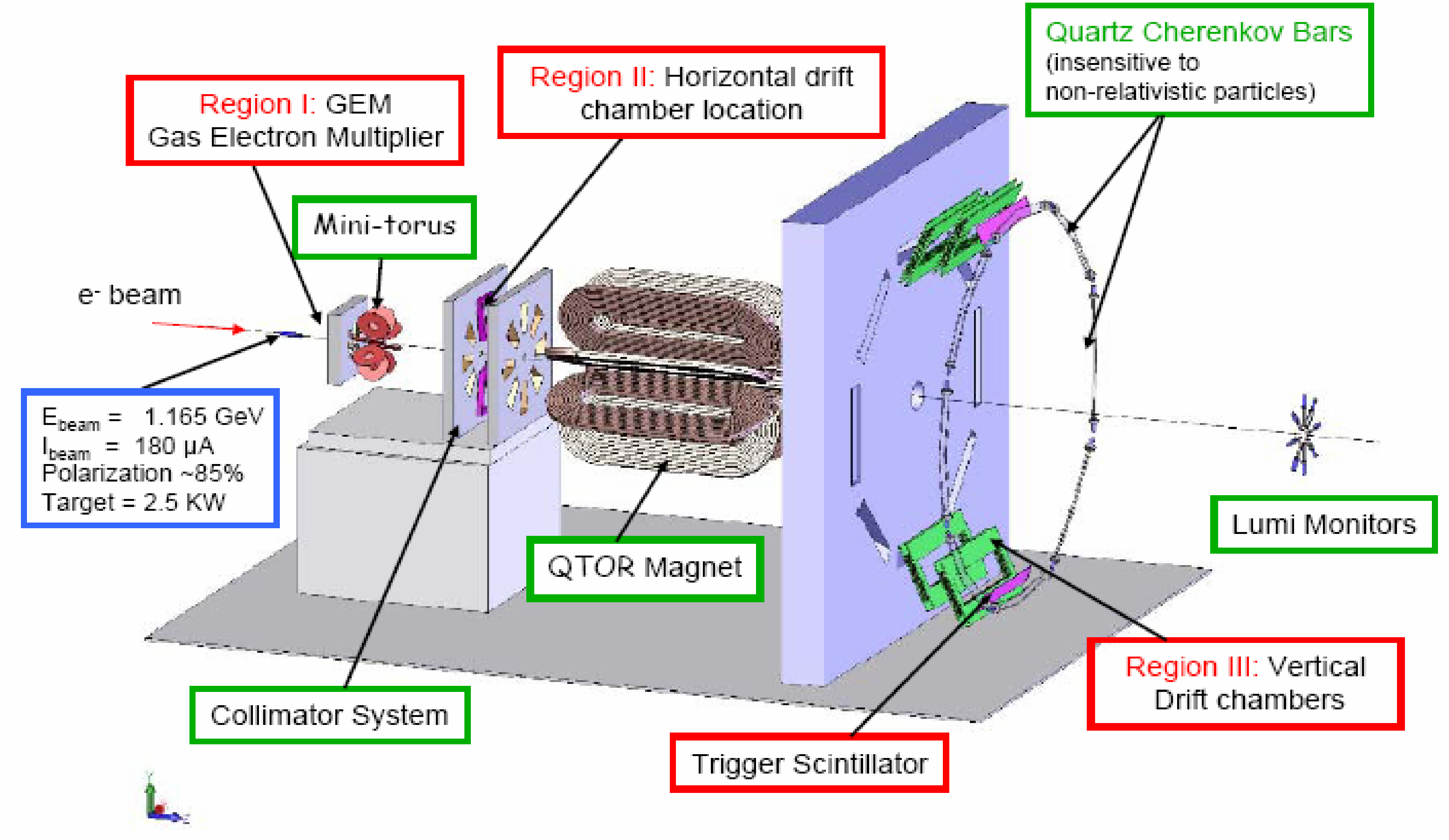
$$Q^p_{weak} = 1 - 4\sin^2\theta_W \sim 0.072$$

- A 4% Q^p_{Weak} measurement probes for new physics at energy scales to:

$$\frac{\Lambda}{g} \sim \frac{1}{\sqrt{\sqrt{2}G_F|\Delta Q^p_W|}} \approx 4.6 \text{ TeV}$$

- **Q^p_{weak} (semi-leptonic) and E158 (pure leptonic) make a powerful program to search for and identify new physics.**

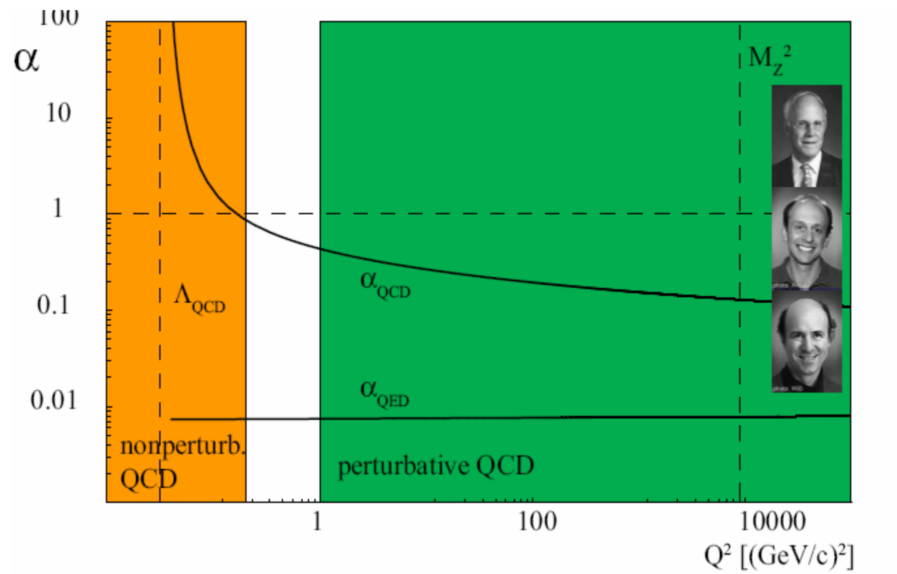
Q_{weak} Apparatus



Time Frame for 12 GeV & Advances in Lattice QCD) 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

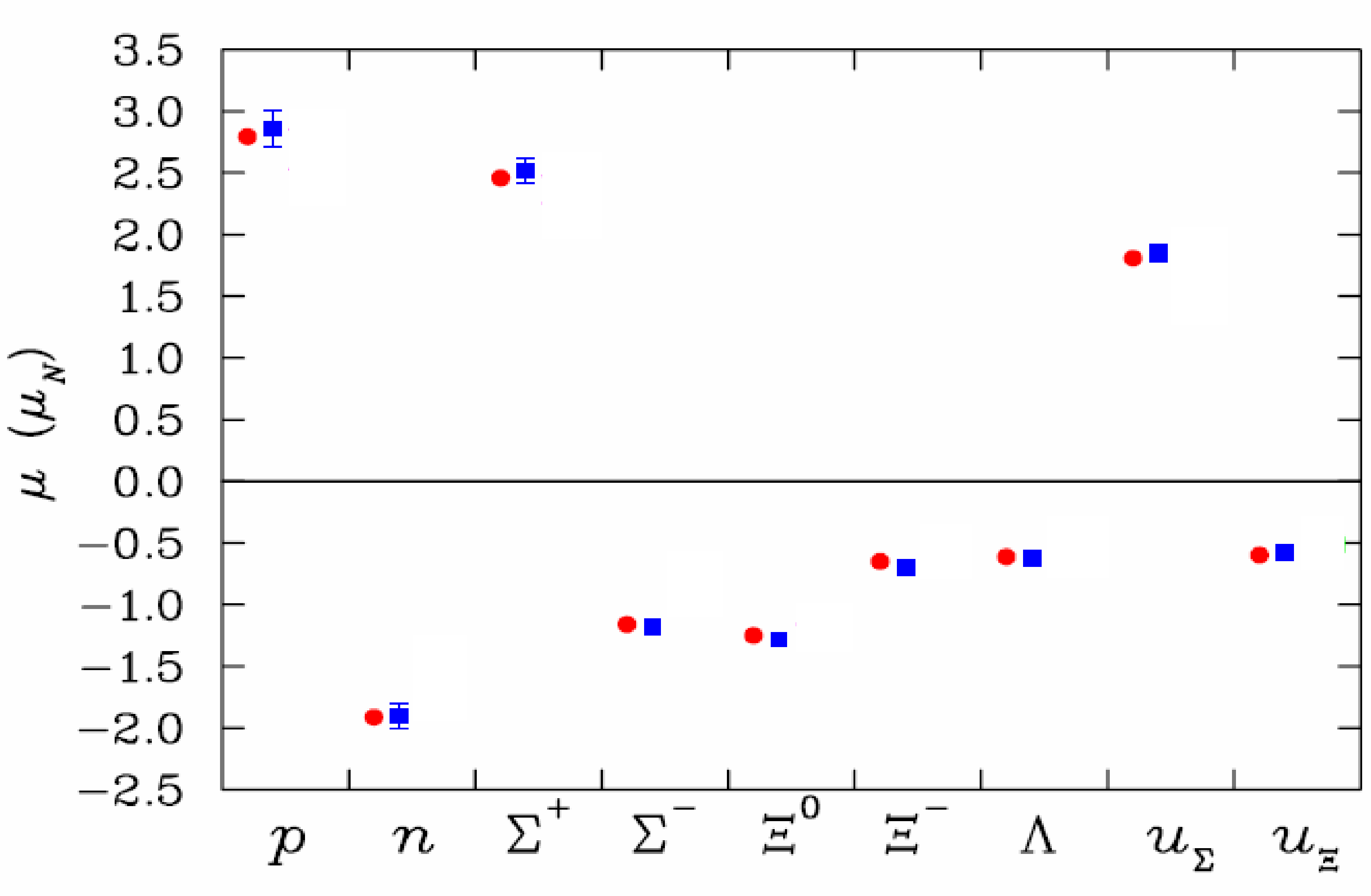
Inclusion of Pion Cloud

Actions with exact chiral symmetry

Precise computations at Physical Pion Mass

Advances in high-performance computing

Octet Magnetic Moments

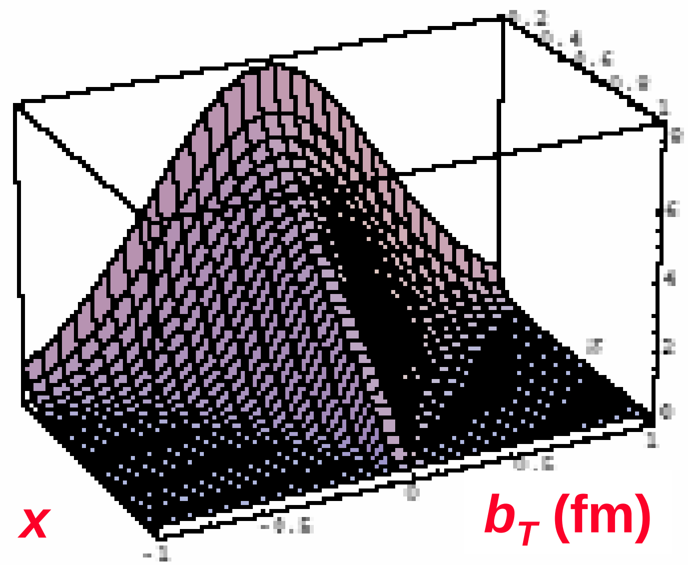


Leinweber et al., PRL 94 (2005) 212001

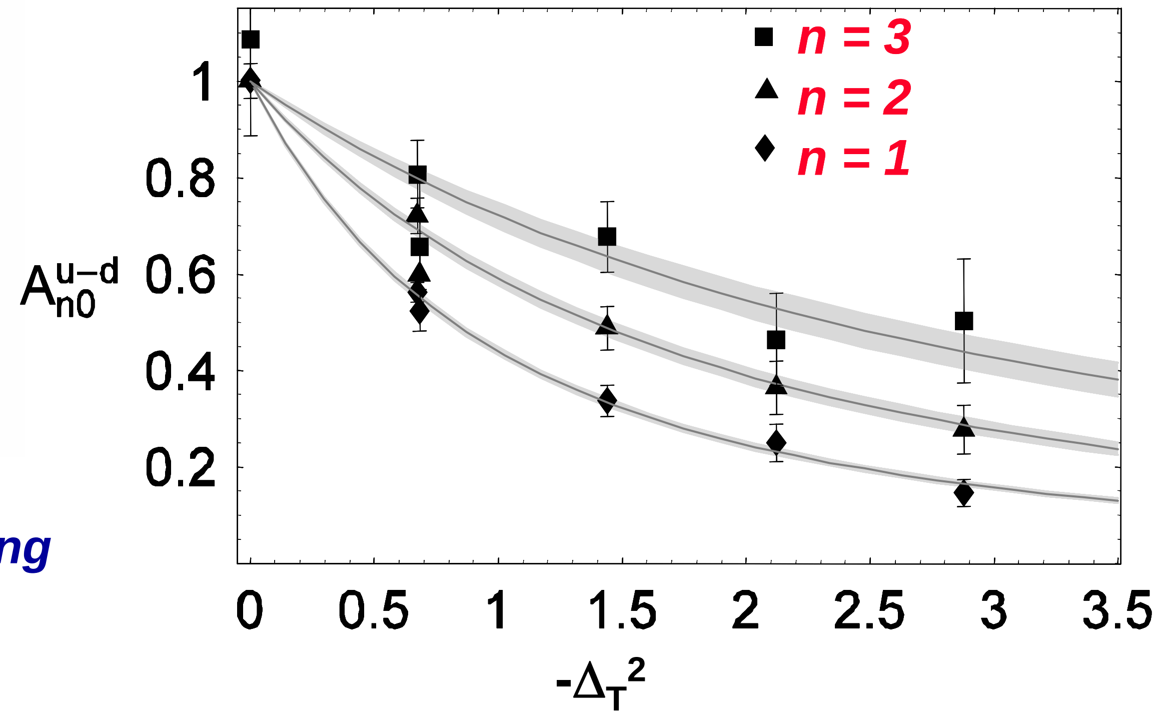
Moments of Flavor-NS PDFs and GPDs - I

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

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



Lattice data: m_π = 740 MeV



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

From: LHPC & SESAM

Axion Search : Recent Observation by PVALS

Polarization experiments

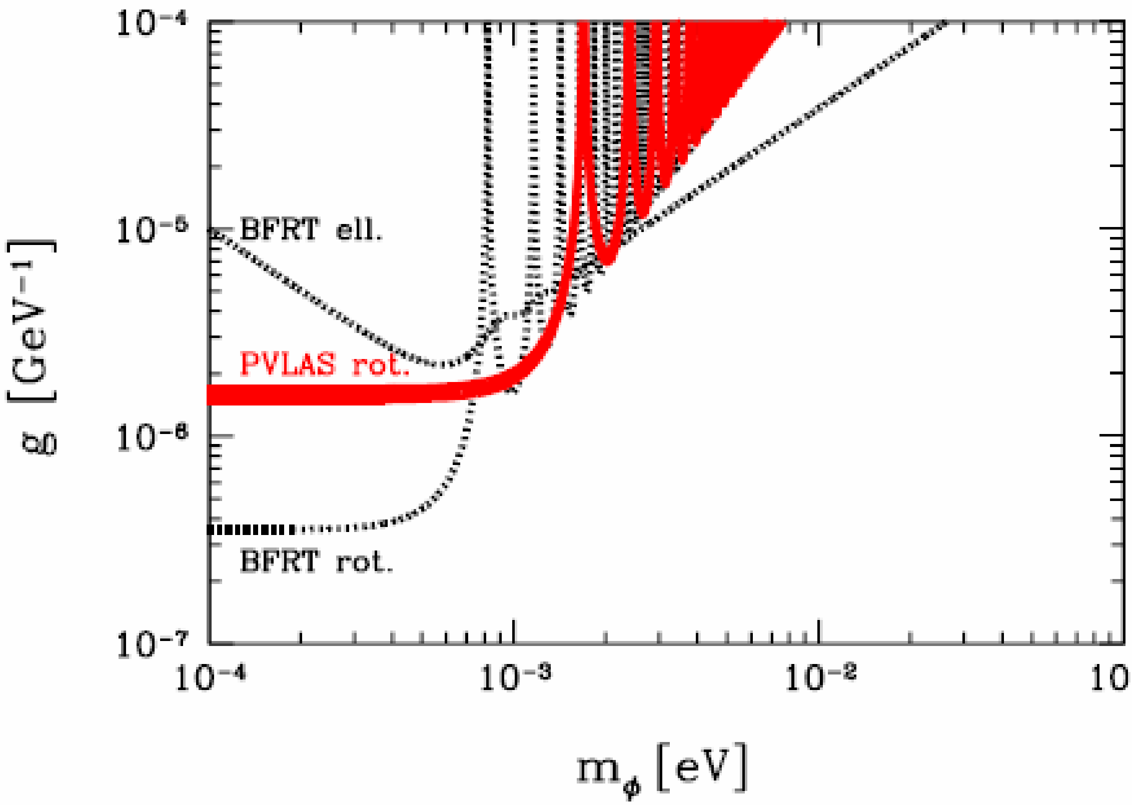
- Send linearly polarized laser beam through transverse magnetic field $\Rightarrow$ measure changes in polarization state
- Real and virtual production induce
  - **rotation:** photons polarized $\|$ $\boldsymbol{B}$ will disappear leading to apparent rotation of polarization plane by

$$\varepsilon_\phi = -N_r \left(\frac{gB\ell}{4}\right)^2 F(q\ell)\,\sin 2\theta$$

  - **ellipticity:** virtual production causes retardation between $\boldsymbol{E}_{||}$ and $\boldsymbol{E}_{\perp}$ $\Rightarrow$ elliptic polarization

$$\psi_\phi \approx \frac{N_r}{6}\left(\frac{g\,B\,\ell}{4}\right)^2 \frac{m_\phi^2\,\ell}{\omega}\,\sin 2\,\theta$$

for small masses, $m_\phi^2 \ell/4\omega \ll 1$.

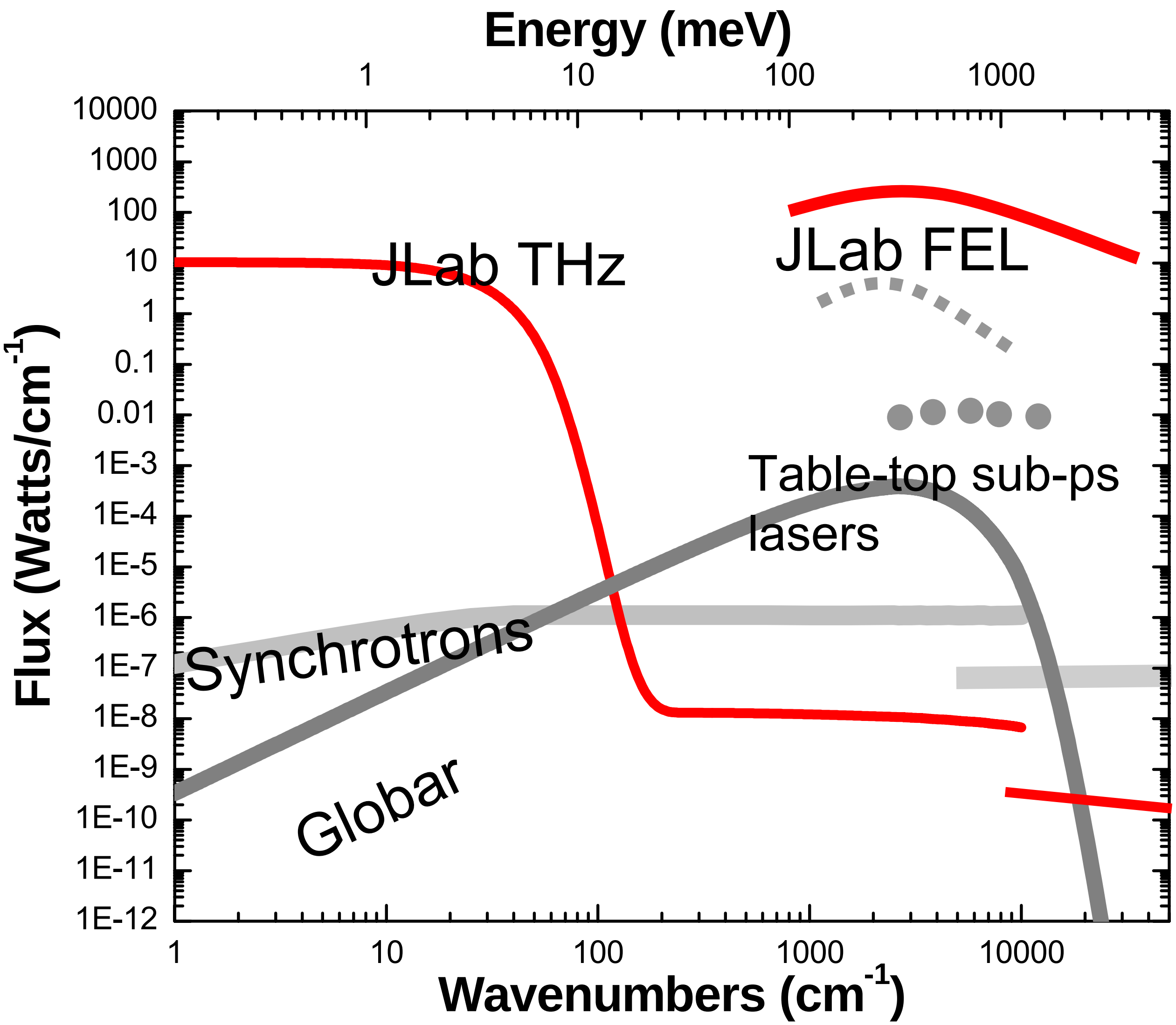


Publication: [Zavattini *et al.* '05]

$$1.7 \times 10^{-6}\ \mathrm{GeV}^{-1} \lesssim \quad g \quad \lesssim 1.0 \times 10^{-5}\ \mathrm{GeV}^{-1}$$

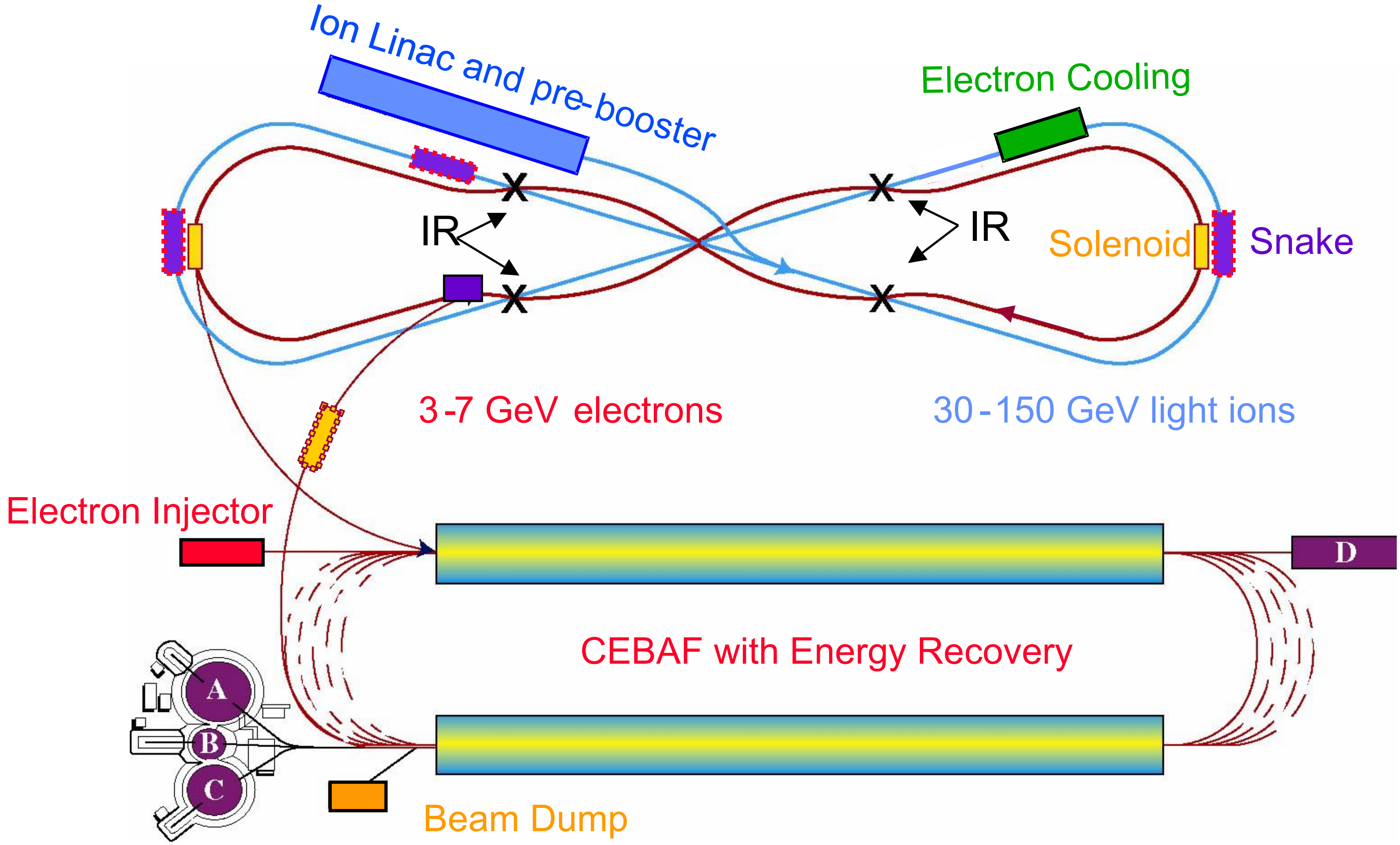
$$0.7\ \mathrm{meV} \lesssim \quad m_\phi \quad \lesssim 2.0\ \mathrm{meV}$$

JLab FEL Power from THz to UV

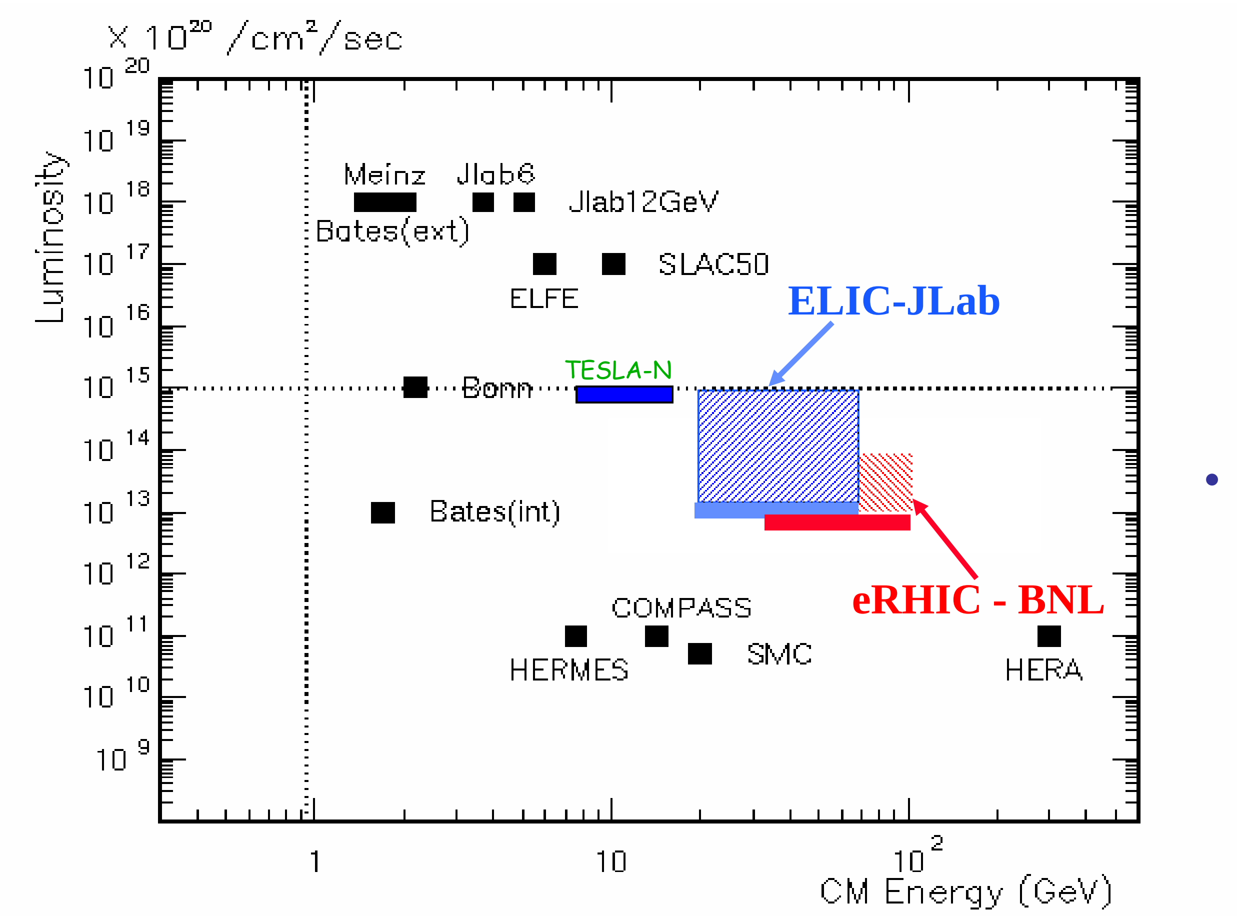


For information: www.jlab.org/FEL

Long-term Landscape : ELIC/eRHIC



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}

AIM: Establish a New Paradigm for Nuclear Physics

In the 21st Century we have the challenge to unify our understanding of nuclear systems over otherwise impossible ranges of density and strangeness in terms of THE best candidate for a fundamental theory of the strong force: QCD

- **Precision electron scattering is essential to guide this unification**

- **On world scene JLab will beautifully complement the work in this area by J-PARC and GSI as well as RIA**

- **12 GeV will play a crucial role in solving one of the 10 outstanding problems in modern physics: origin of confinement**