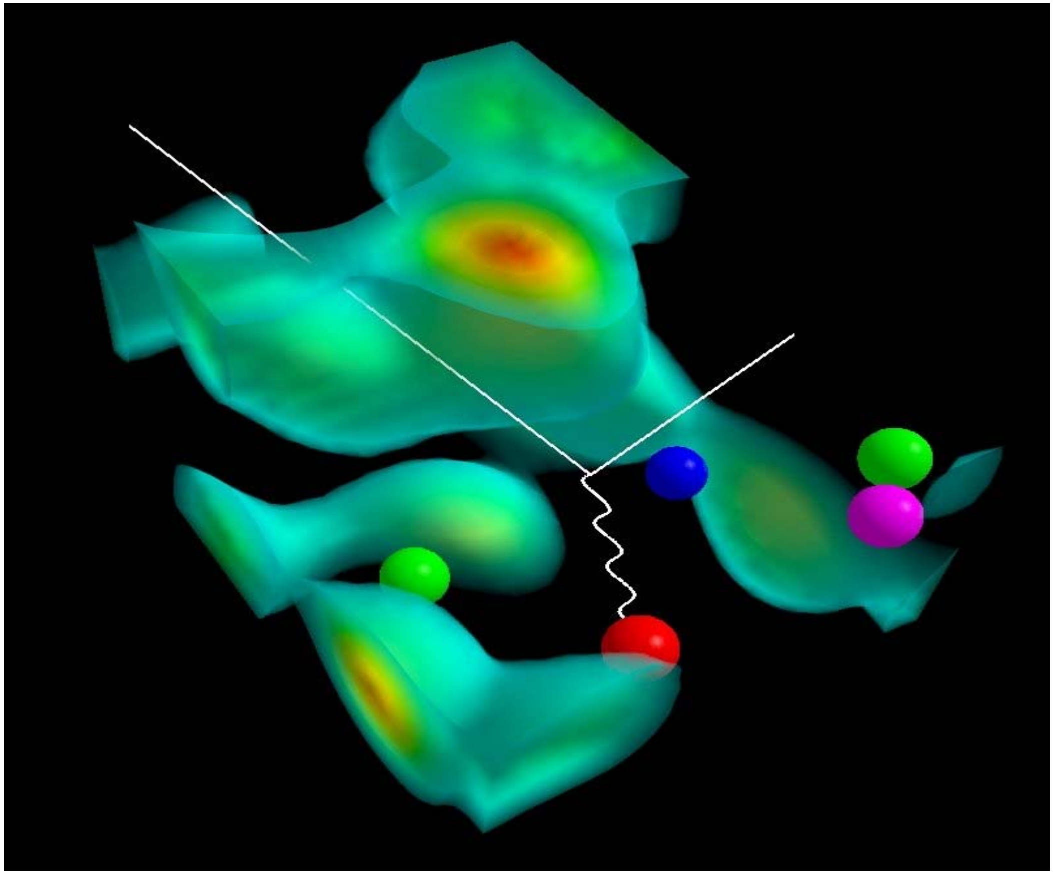
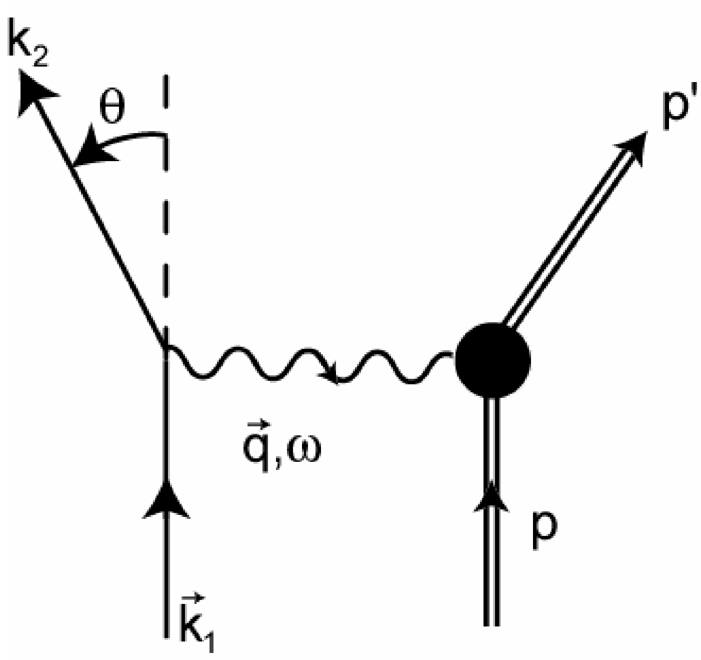
Precise Electro-Weak Studies: An Essential Element of the World-Wide Nuclear Physics Program



Anthony W. Thomas

LRP Resolution Meeting : May 1st 2007

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:

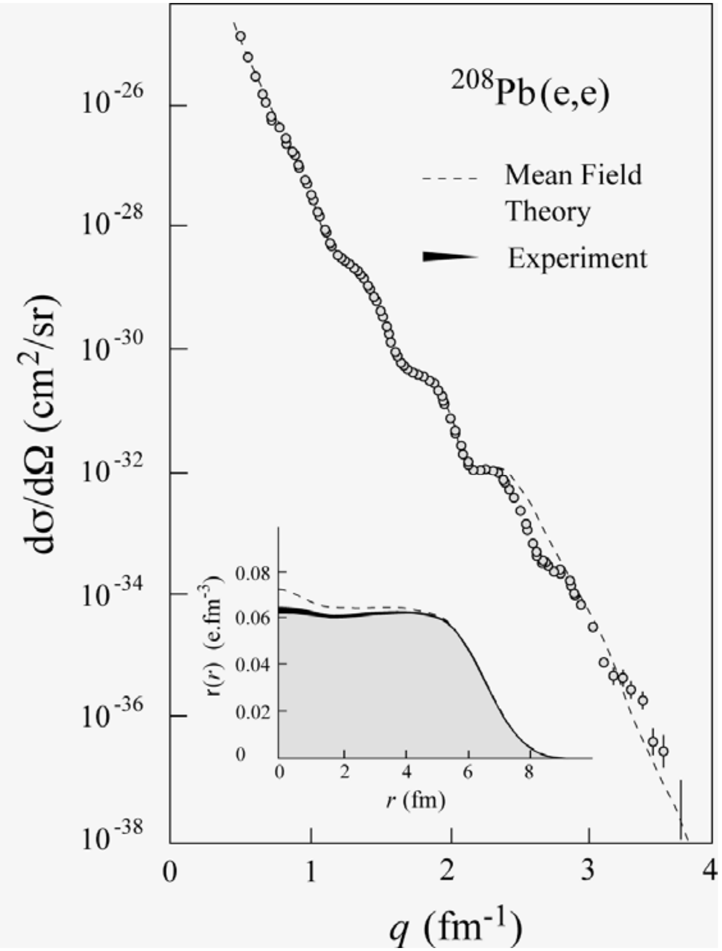
  $\lambda \cong 2\pi/q$ **(1 fm ⇔ 1 GeV/c)**

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

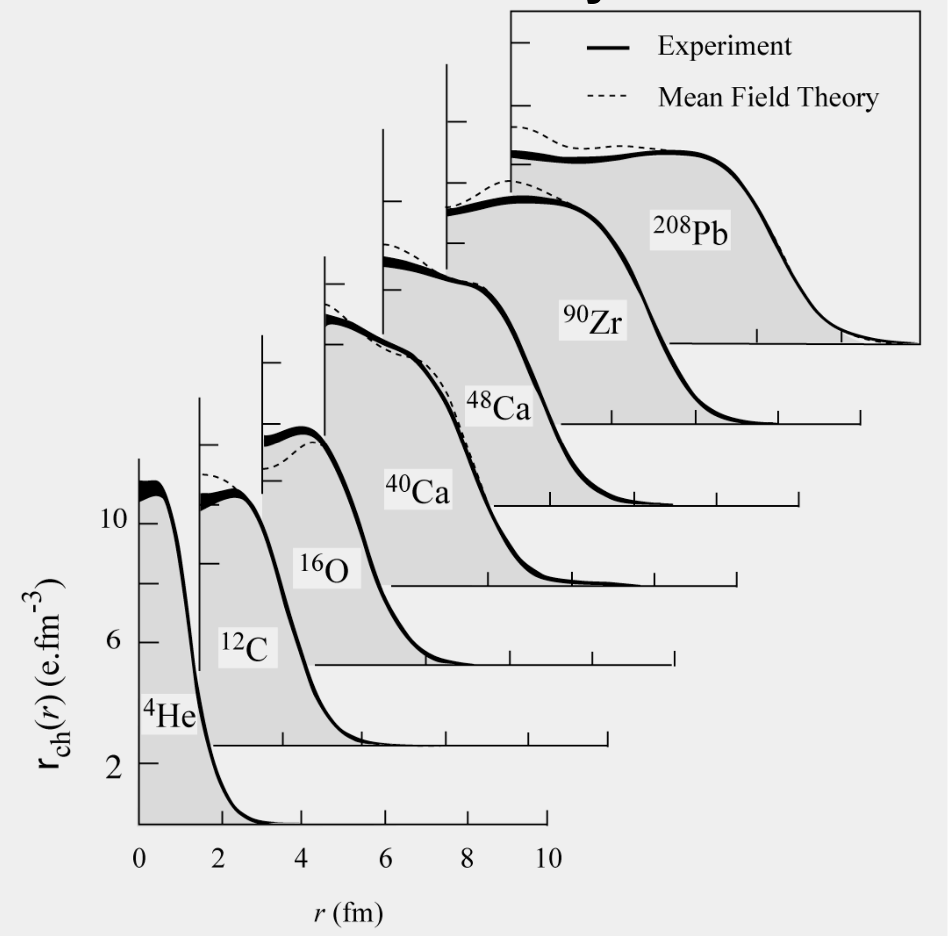
$Q^2 = -q^2 = $ 4-Momentum Transfer

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

(e,e) ⇒ Nuclear Charge Distributions



From Stanford to Saclay and Nikhef

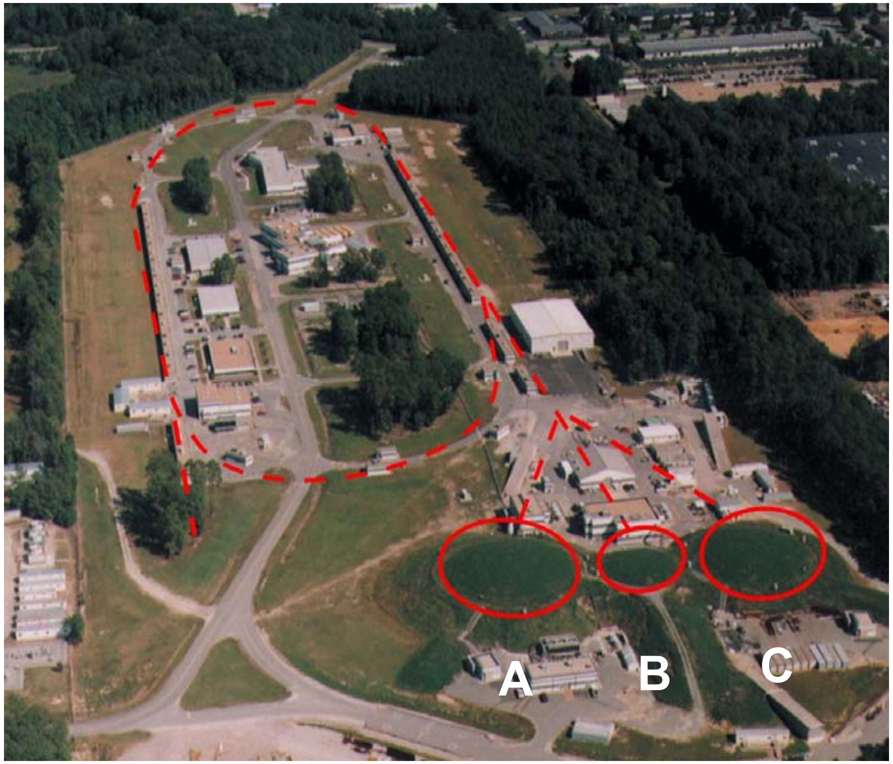


Model-independent analysis ⇒ accurate nuclear charge distributions

Jefferson Lab Today

2000 member international user community engaged in exploring quark-gluon structure of matter

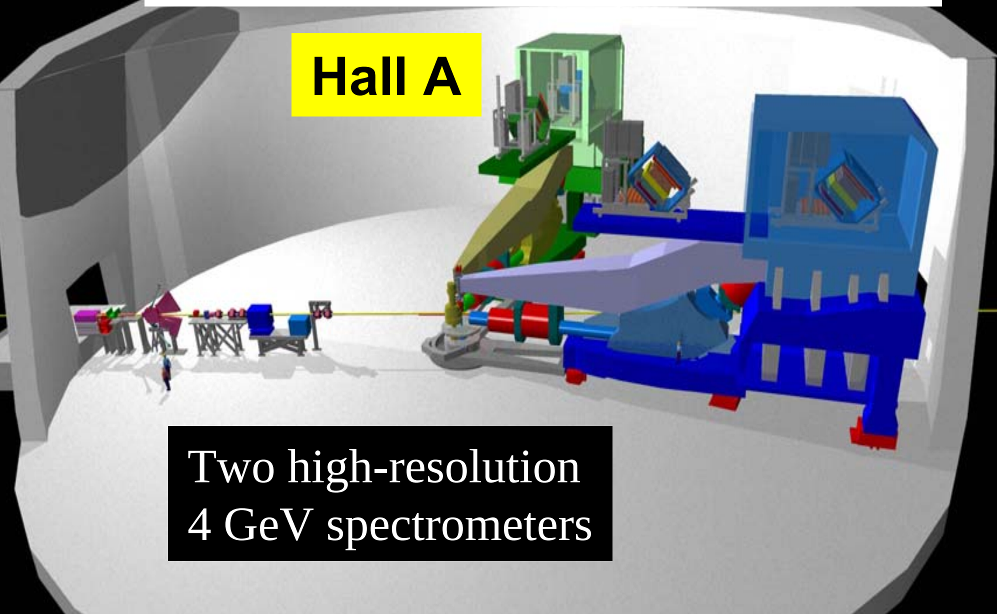
Superconducting accelerator provides 100% duty factor beams of unprecedented quality, with energies to 6 GeV

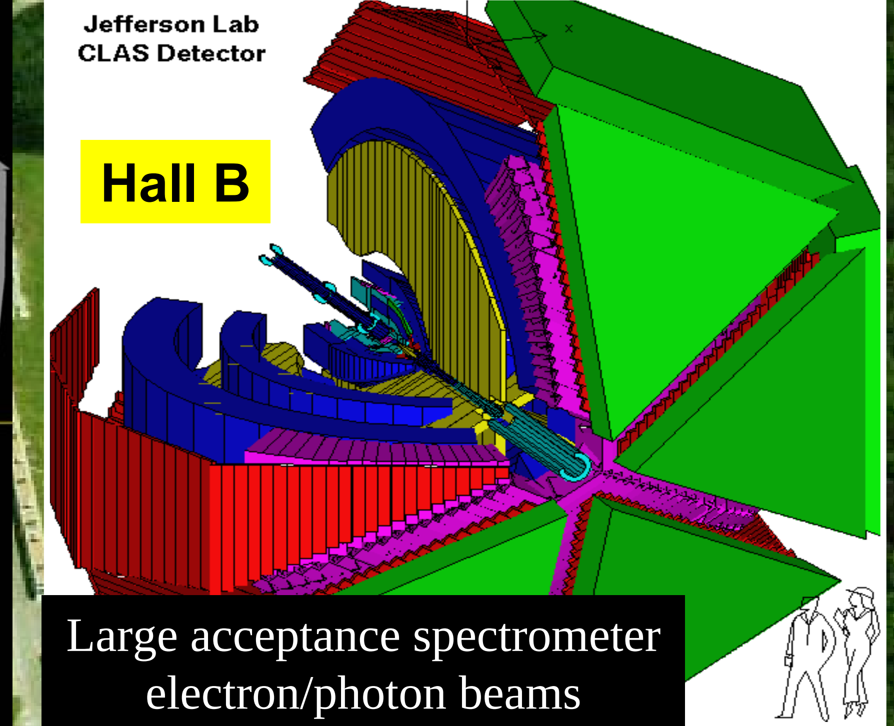


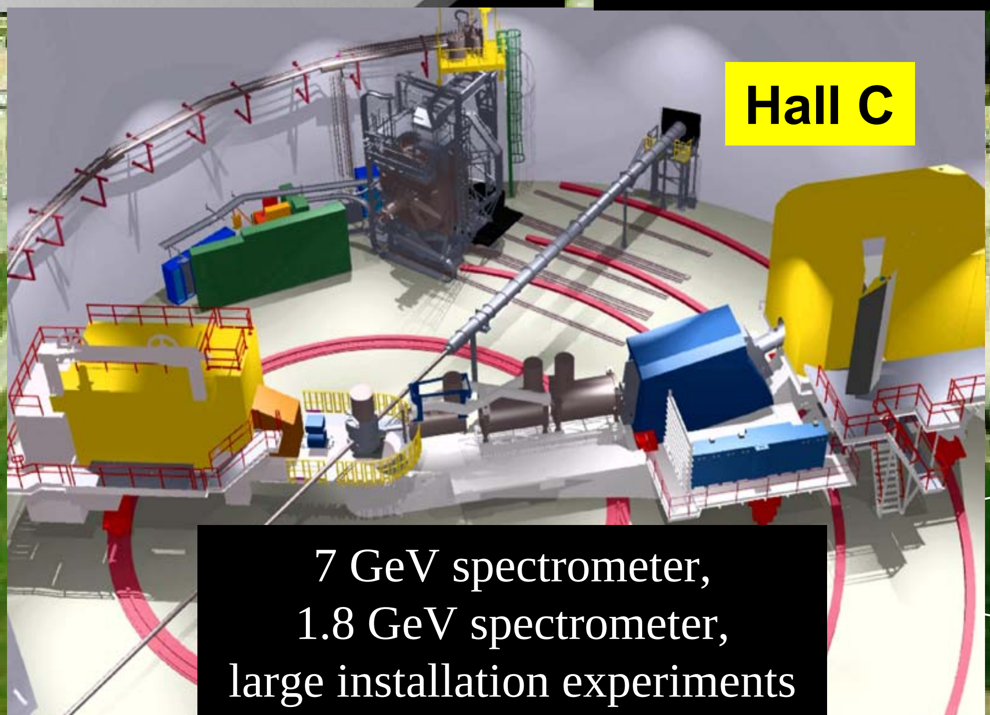
CEBAF's innovative design allows delivery of beam with unique properties to three experimental halls simultaneously

Each of the three halls offers complementary experimental capabilities

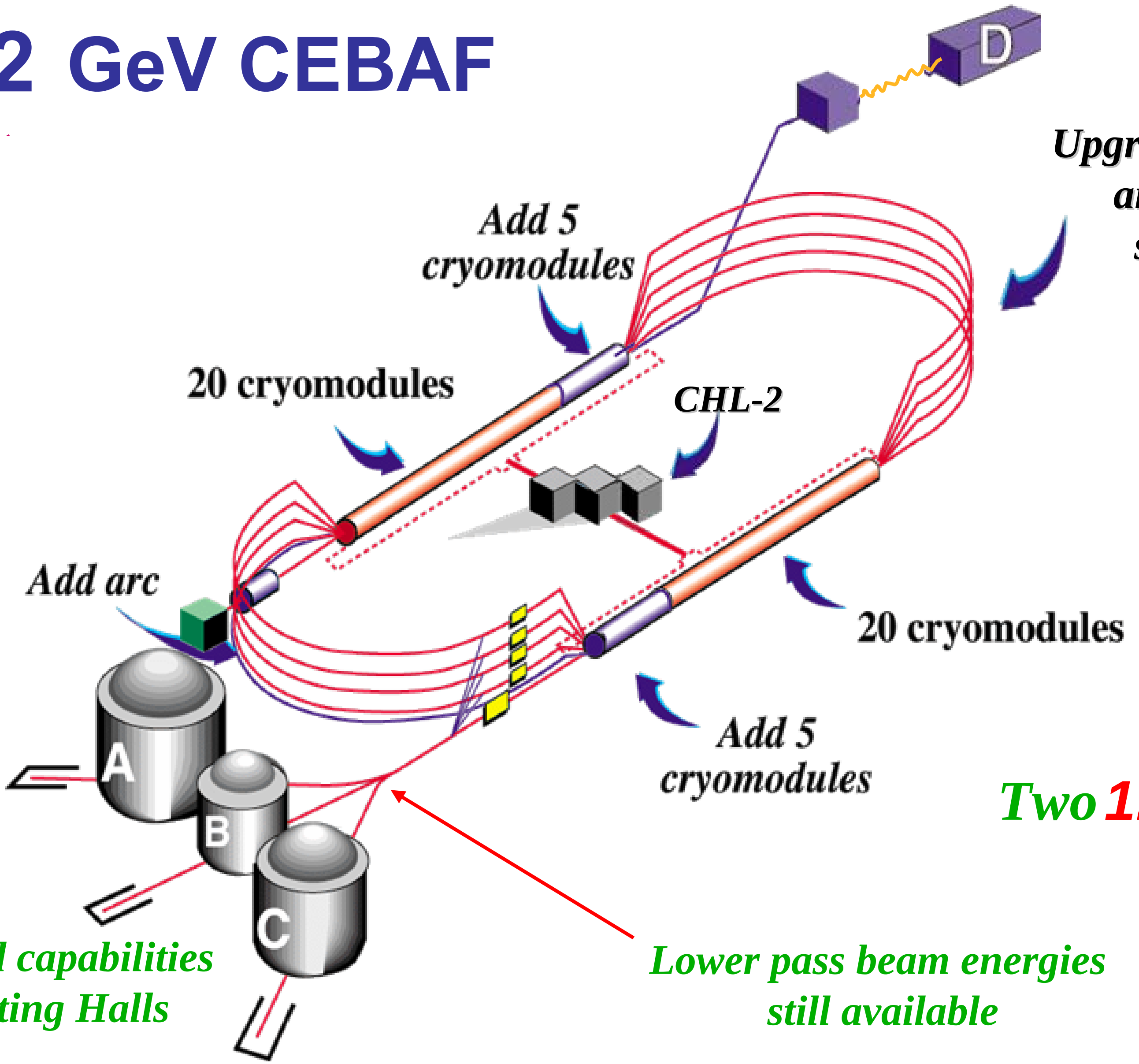
Jefferson Lab Today







12 GeV CEBAF

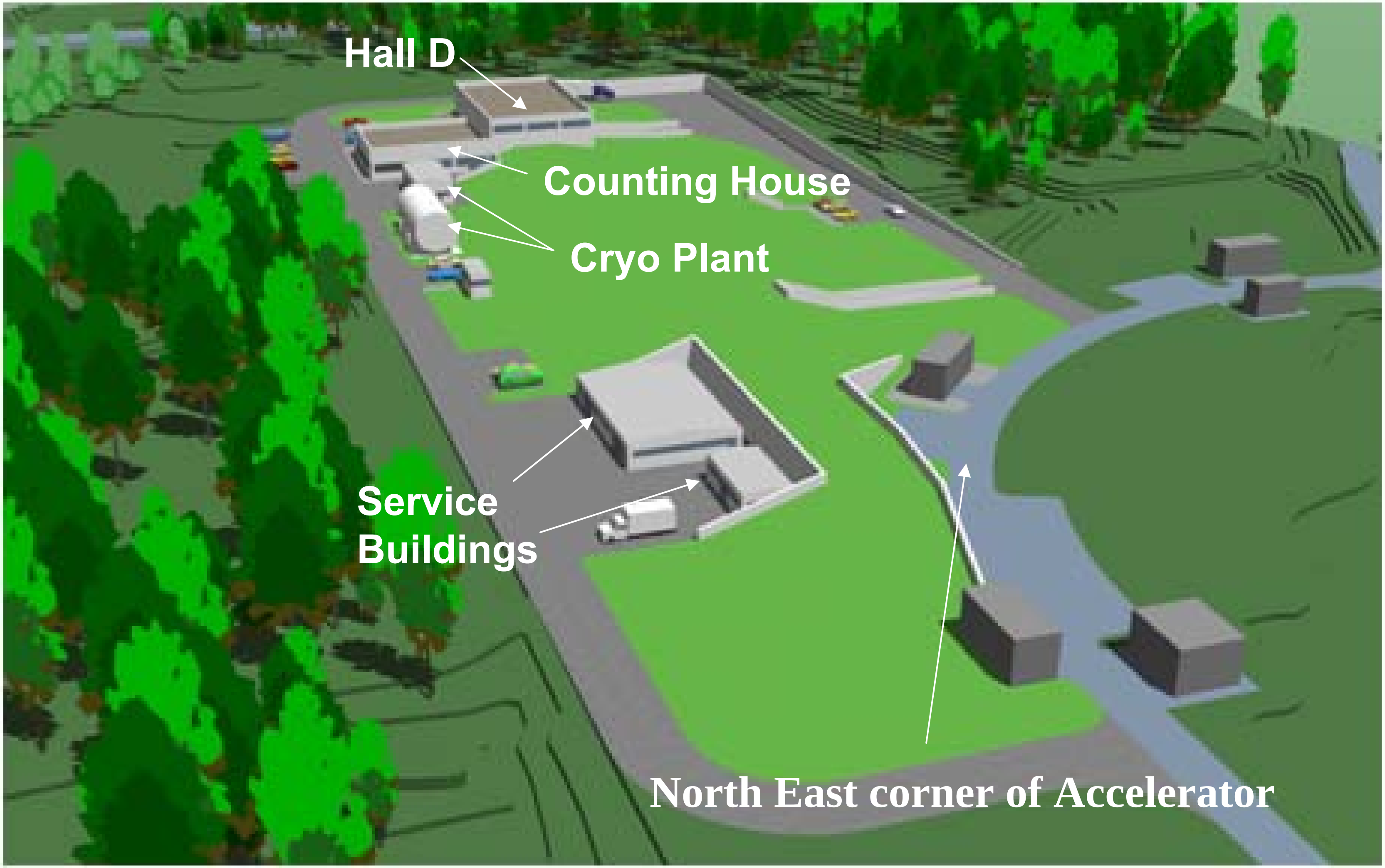


*Two **1.1** GV linacs*

Enhanced capabilities in existing Halls

Lower pass beam energies still available

Architect's Rendering of Hall D Complex



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

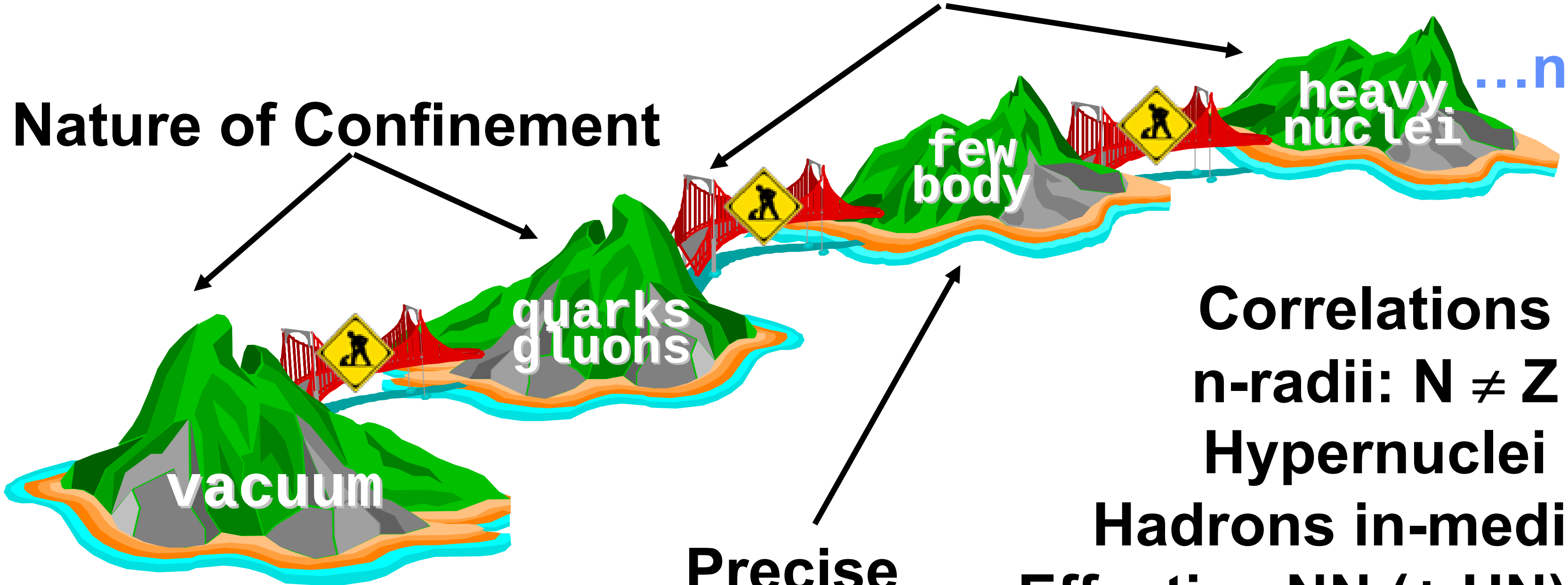
Highlights of the 12 GeV Program….2

- 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
  - Parity Violating DIS & Möller

The Program is Central to Nuclear Science

Quark-Gluon Structure
Of Nucleons and Nuclei

Nature of Confinement



…n-stars

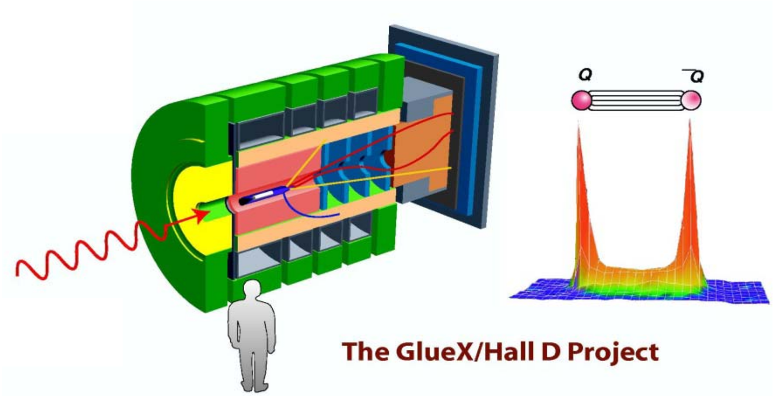
Correlations
n-radii: N ≠ Z
Hypernuclei
Hadrons in-medium
Effective NN (+ HN) force

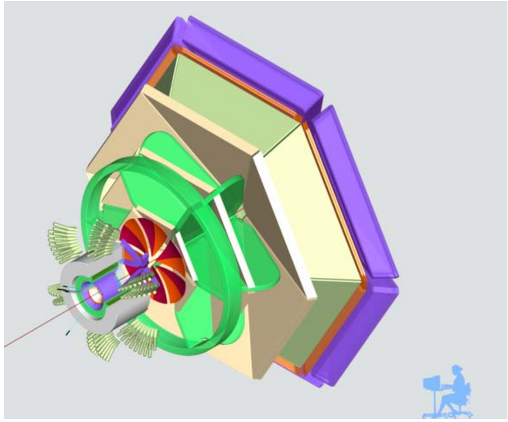
Precise
few-nucleon
calculations

Exotic mesons
and baryons

12 GeV Capabilities

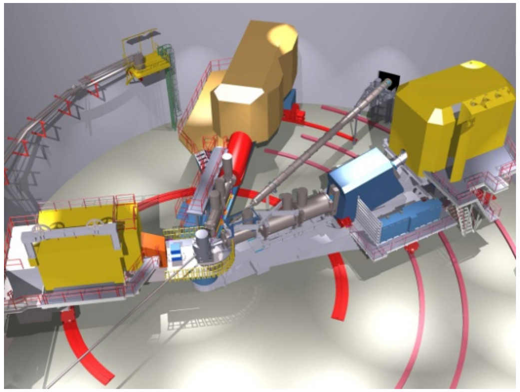
Hall D – exploring origin of confinement by studying exotic mesons

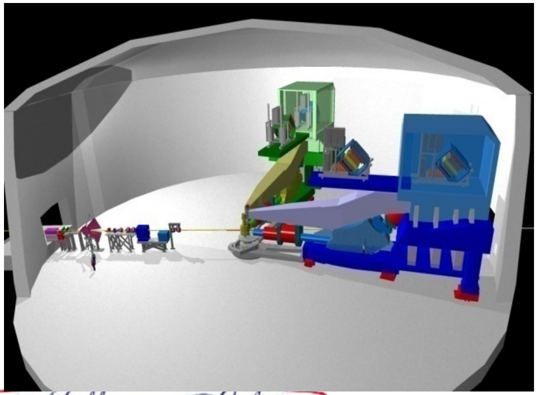




Hall B – understanding nucleon structure via generalized parton distributions

Hall C – precision determination of valence quark properties in nucleons and nuclei





Hall A – major installation experiments: symmetry tests, short range correlations, form factors, hyper-nuclear physics….

12 GeV Cost Summary

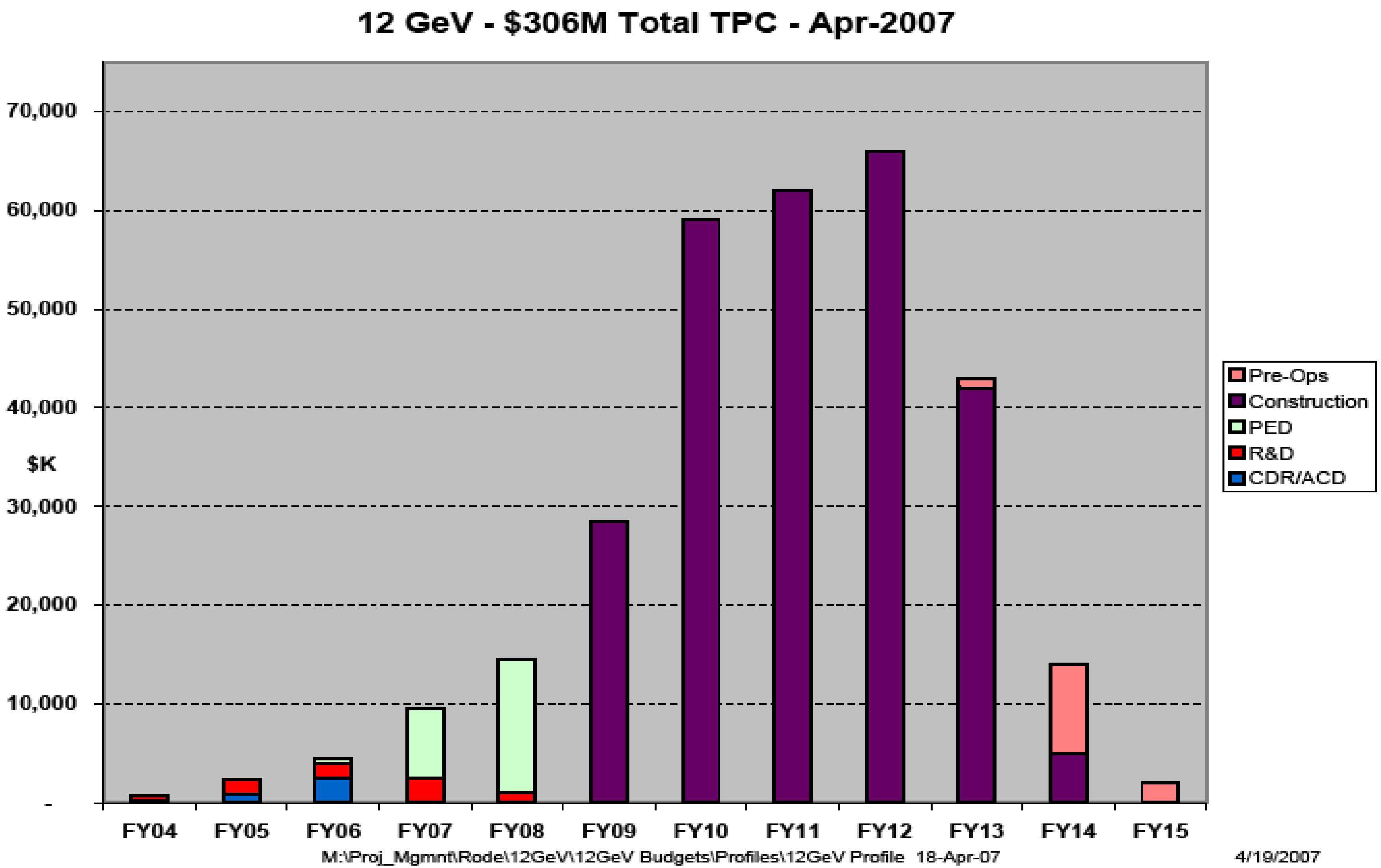
WBS	SCOPE	01-Oct-06 FY07$M
1.2.	PED	18.0
1.3.	Accelerator systems	74.7
1.4	Upgrade Hall A, B & C	46.5
1.5	Hall D	29.5
1.6	Civil	21.7
1.7	Project Management	7.2
TEC SUBTOTAL		**197.6**
	Obligated	0.1
TEC ETC		**197.5**
	Contingency	**56.6**
	Contingency %	**28.6%**
	Escalation	**23.3**
TEC TOTAL		**277.5**
1.0.	CDR	3.5
1.1.	R&D	5.9
1.8	Pre-Ops	6.2
OPC SUBTOTAL		**15.6**
	Obligated	6.7
OPC ETC		**8.9**
	Contingency	**5.2**
	Contingency %	**58.5%**
	Escalation	**1.7**
OPC TOTAL		**22.5**
TPC TOTAL		**300.0**

- **Accelerator and Hall equipment are roughly equal**
- **Hall B/C/D equipment cost averages ~$24M**
- **Civil split ~equally between Accelerator systems & Hall D**

October 2006;
Being updated for CD-2

CD-1 Announced at JLab on Valentines Day 2006
By Secretary Bodman

12 GeV Funding Profile

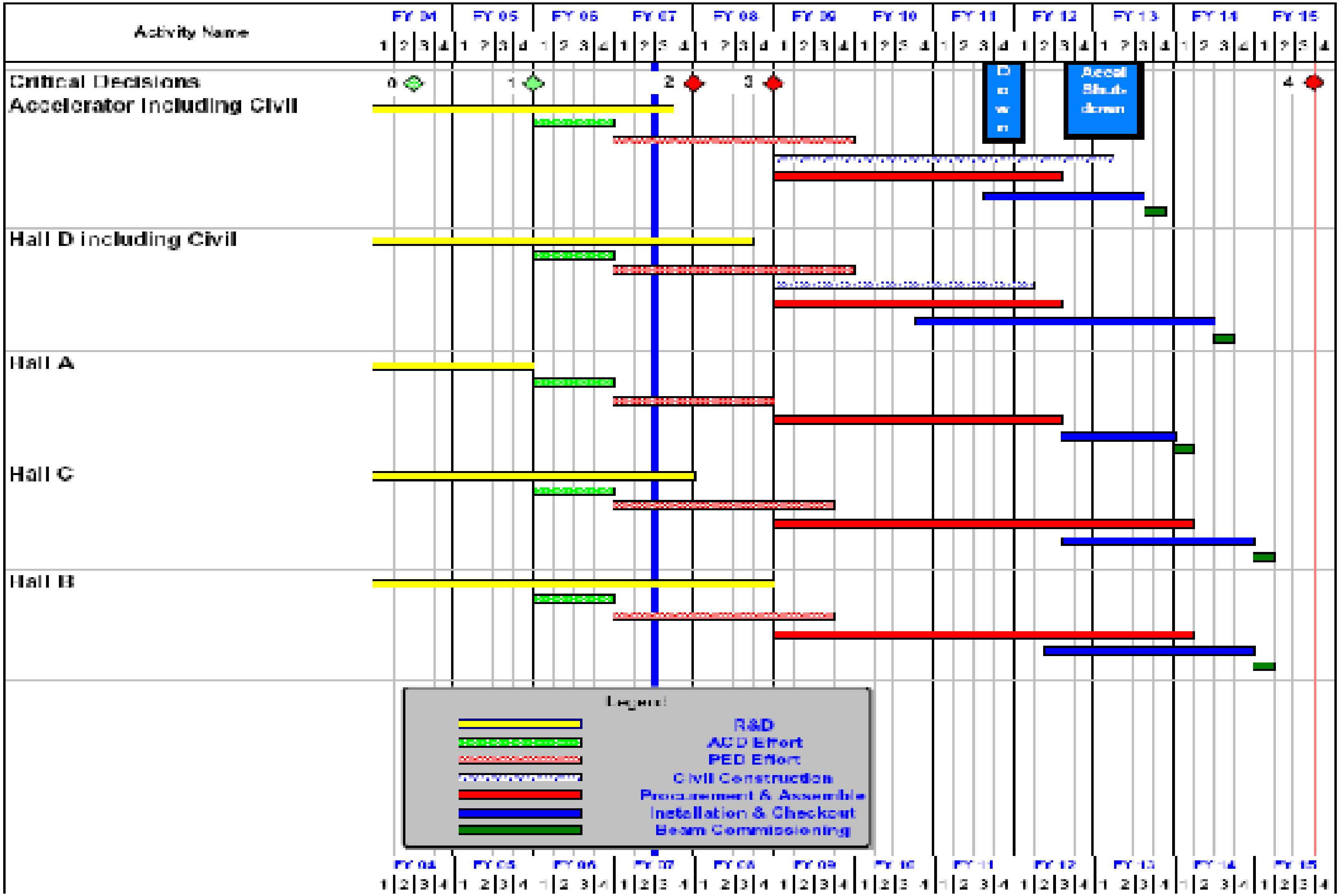


12 GeV Upgrade: Phases and Schedule

(based on funding guidance provided by DOE-NP in April 2007)

- **2004-2005** **Conceptual Design (CDR) -** *finished*
- **2004-2008** **Research and Development (R&D) -** *ongoing*
- **2006** **Advanced Conceptual Design (ACD) -** *finished*
- **2006-2008** **Project Engineering & Design (PED) -** *ongoing*
- **2009-2013** **Construction –** ***starts in ~18 months!***
  - **Accelerator shutdown start mid 2012**
  - **Accelerator commissioning mid 2013**
- **2013-2015** **Pre-Ops (beam commissioning)**
  - **Hall commissioning starts late 2013**

12 GeV Schedule



M:\Proj_Mgmnt\12GeV Upgrade\Fast Track Schedules\12 GeV Schedule Archive\12 GeV Upgrade Schedule_30Mar07.fts

Current Schedule

CD-2 → September '07

- **December & January: DOE Project Status Review**
  - "The 12 GeV Upgrade Project is on track in their preparations and readiness for the SC IPR, OECM EIR and September 2007 CD-2 approval."
- **June 26-28: Critical Decision 2 Review, stage I**
  - SC Independent Project Review (IPR): conducted by Dan Lehman (DOE SC Office of Project Assessment)
- **Aug 6-10 (tentative): Critical Decision 2 Review, stage II**
  - External Independent Review (EIR): conducted by DOE Office of Engineering Construction Management (OECM)

Aug 6-10: JLab PAC32

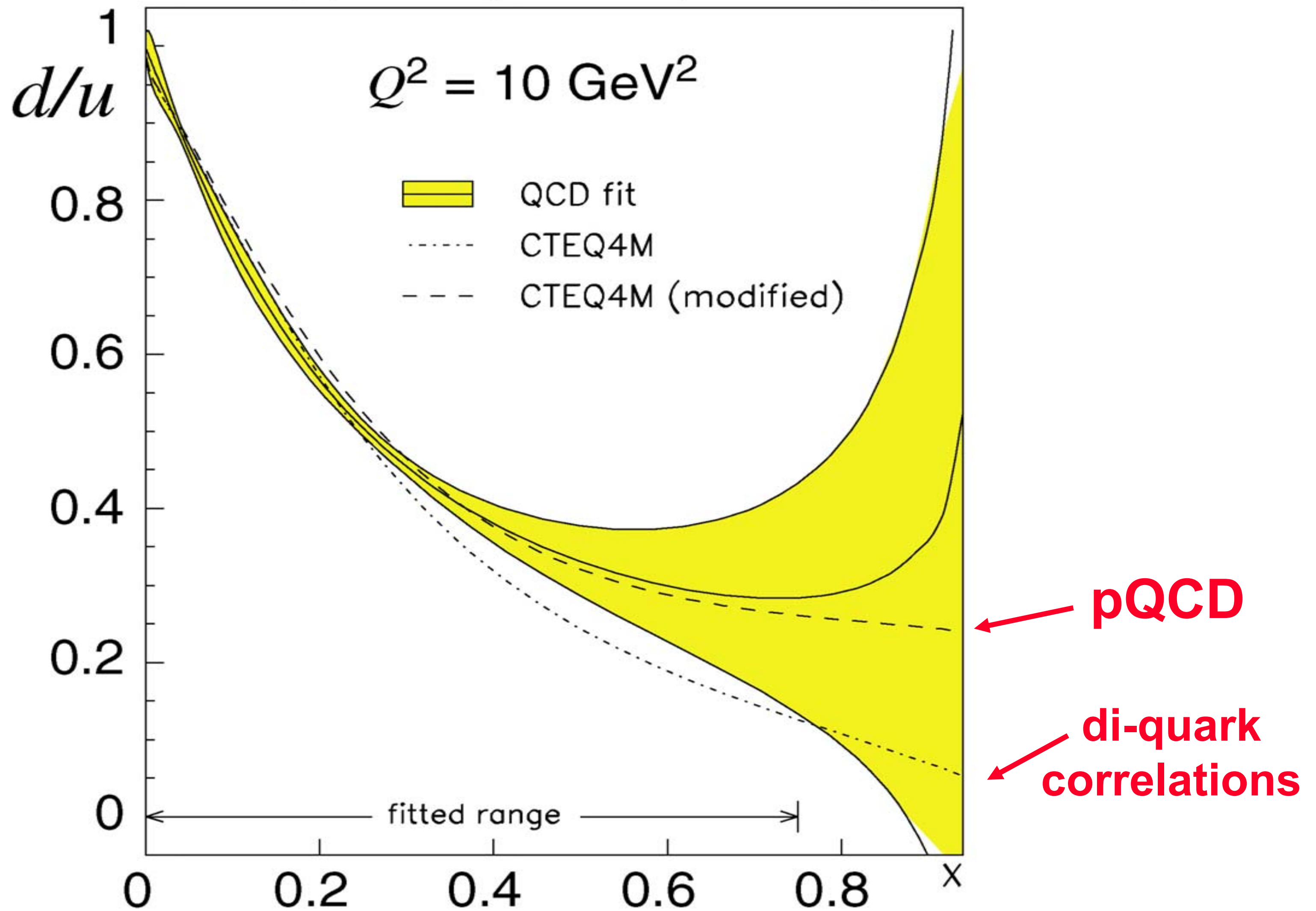
- Second review of 12 GeV proposals – "commissioning experiments"
- Key step in identifying the research interests and contributions of international collaborators

Anticipated Highlights of the 1st 5 Years

- **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**

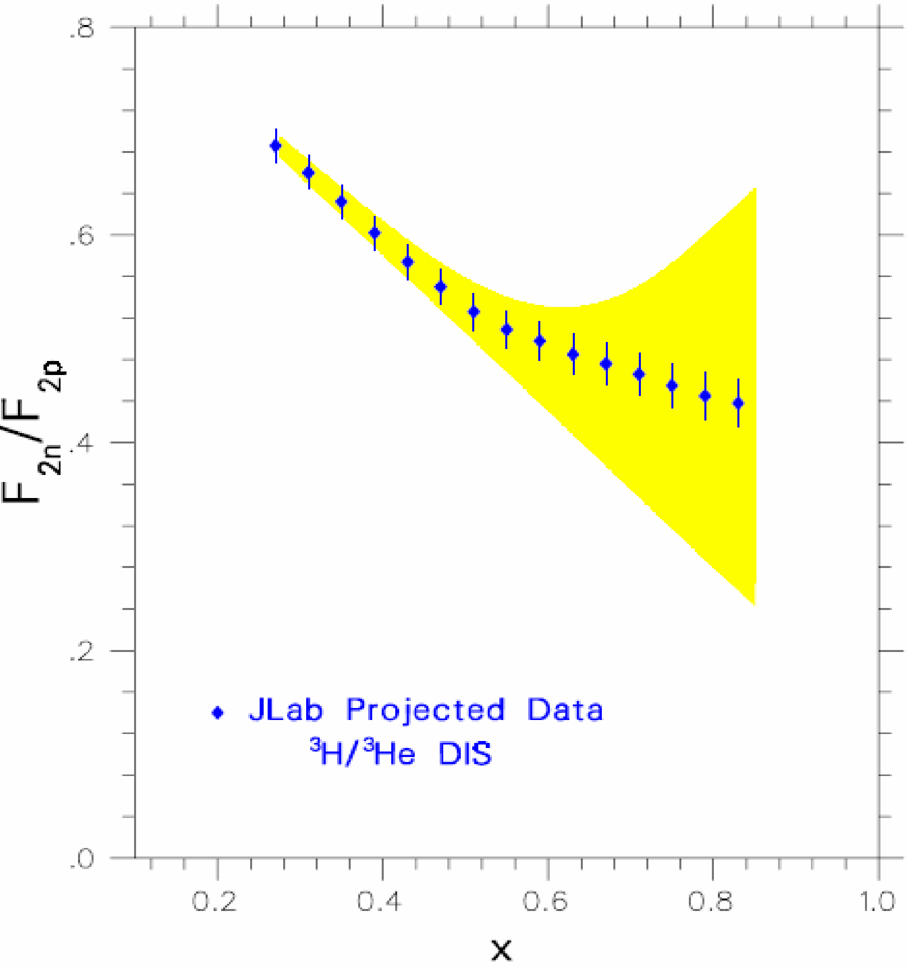
After 35 years: Miserable Lack of Knowledge of Valence d-Quarks

M. Botje, Eur. Phys. J. C14, 285-297, 2000

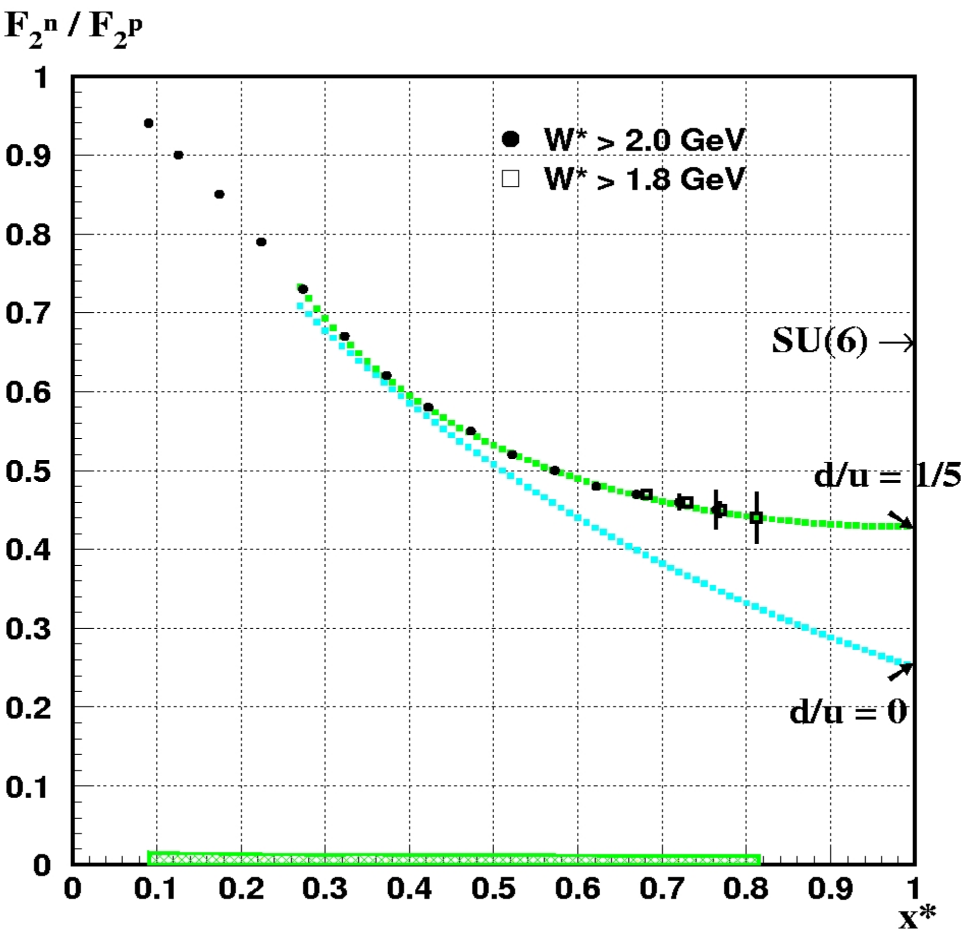


12 GeV : Unambiguous Flavor Structure $x \rightarrow 1$

Hall A 11 GeV with HMS

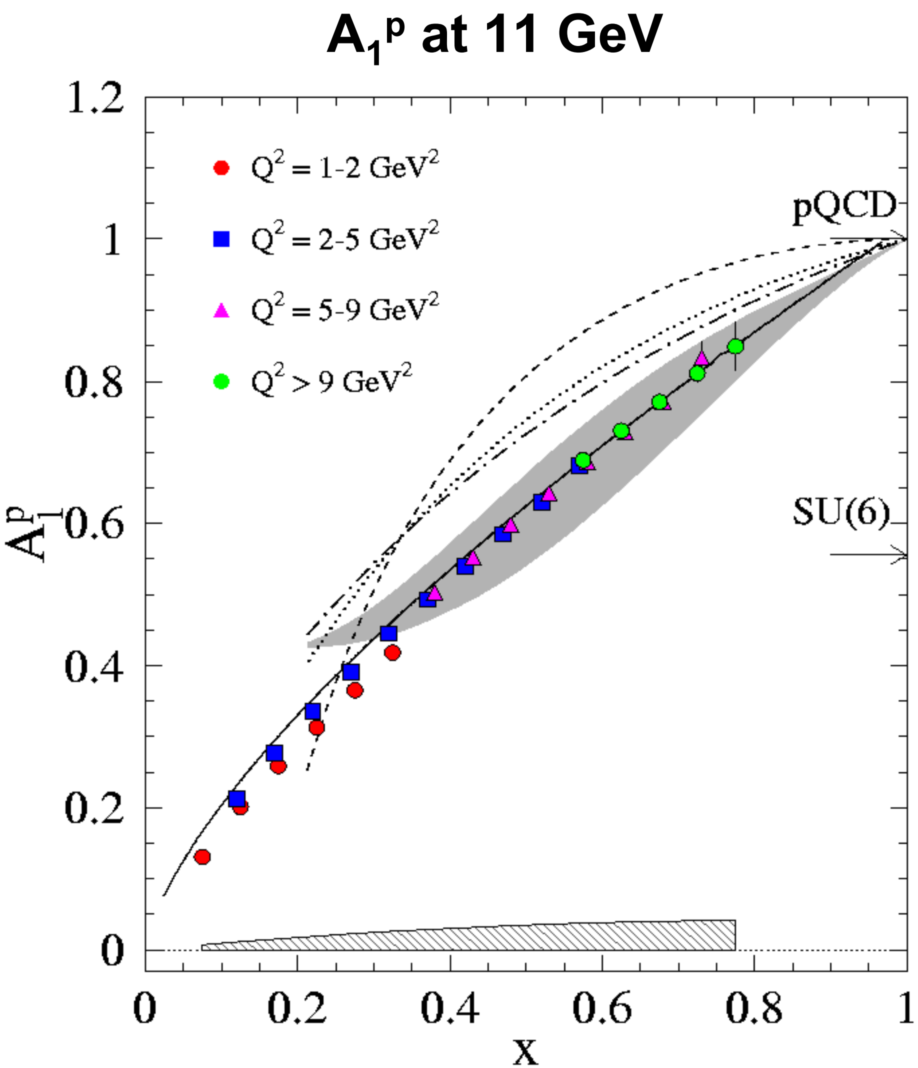


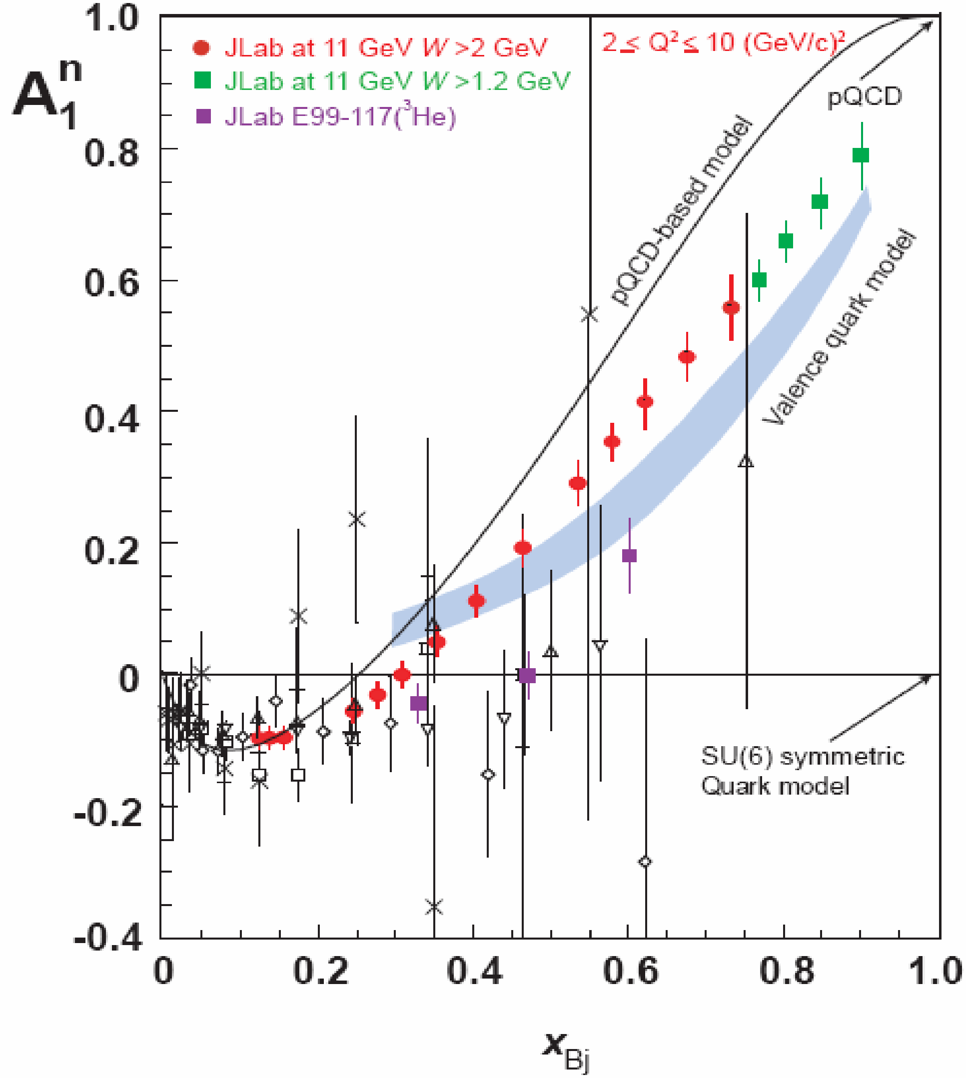
Hall B 11 GeV with CLAS12



Initial investigation with BONUS early 06 successful

12 GeV : Unambiguous Resolution of Valence Spin

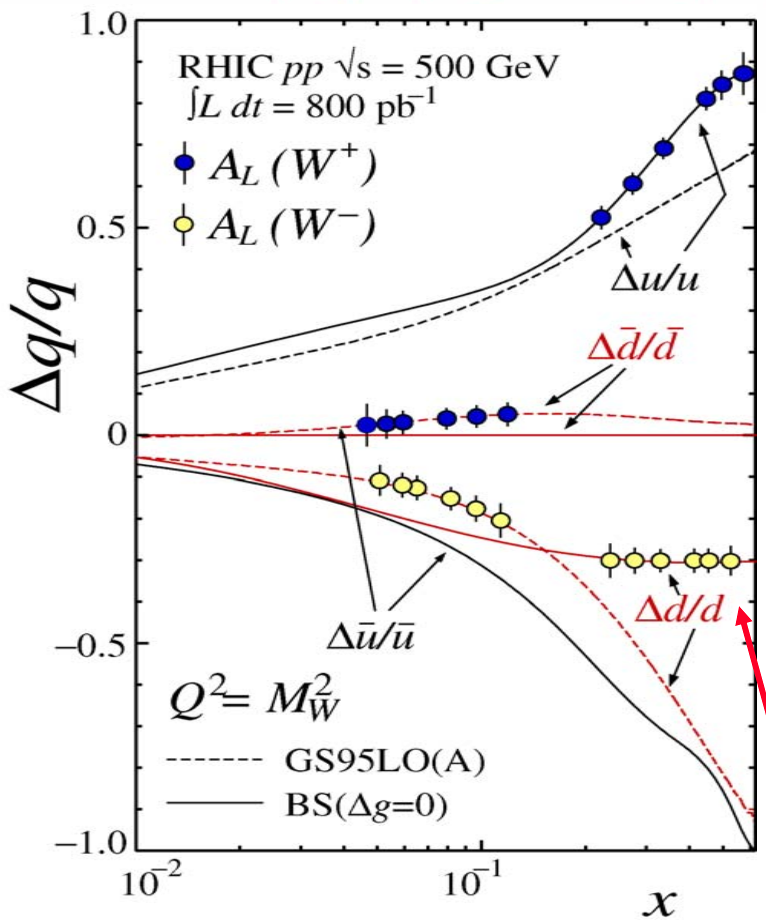




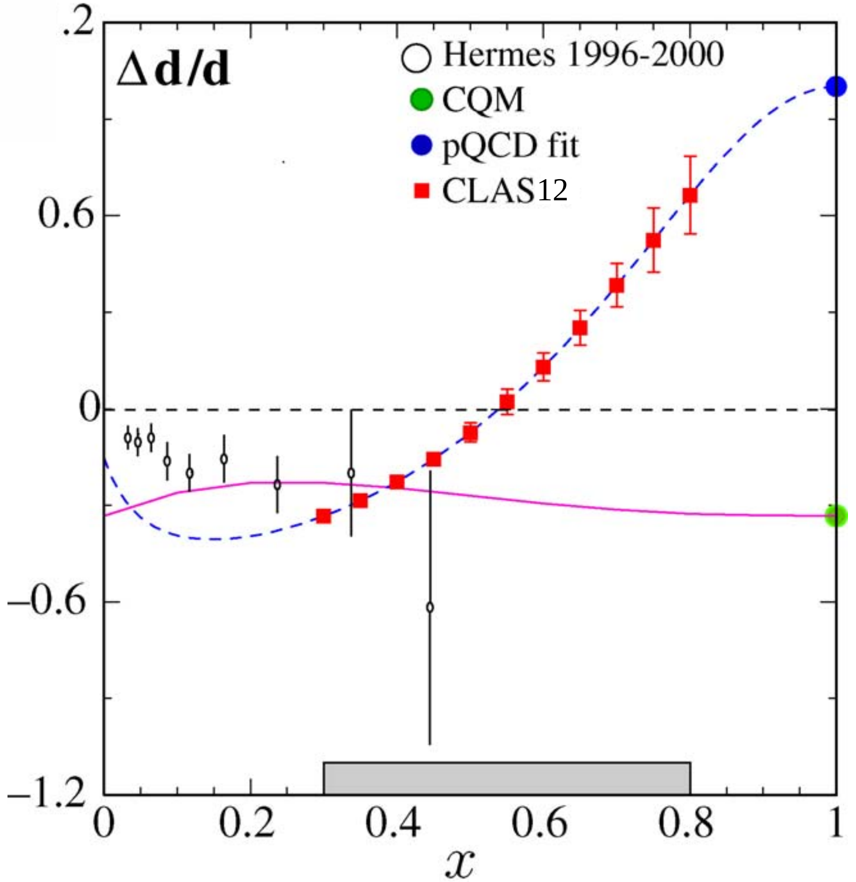
Complements Spin-Flavor Dependence at RHIC

At RHIC with W production

$$A_L^{W^+} \approx \frac{\Delta u(x_1)\,\bar{d}(x_2) - \Delta\bar{d}(x_1)\,u(x_2)}{u(x_1)\,\bar{d}(x_2) + \bar{d}(x_1)\,u(x_2)}$$



At JLab with 12 GeV upgrade



Stops below x=0.5 AND needs valence d(x)

Anticipated Highlights of the 1st 5 Years

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- **Form Factors**
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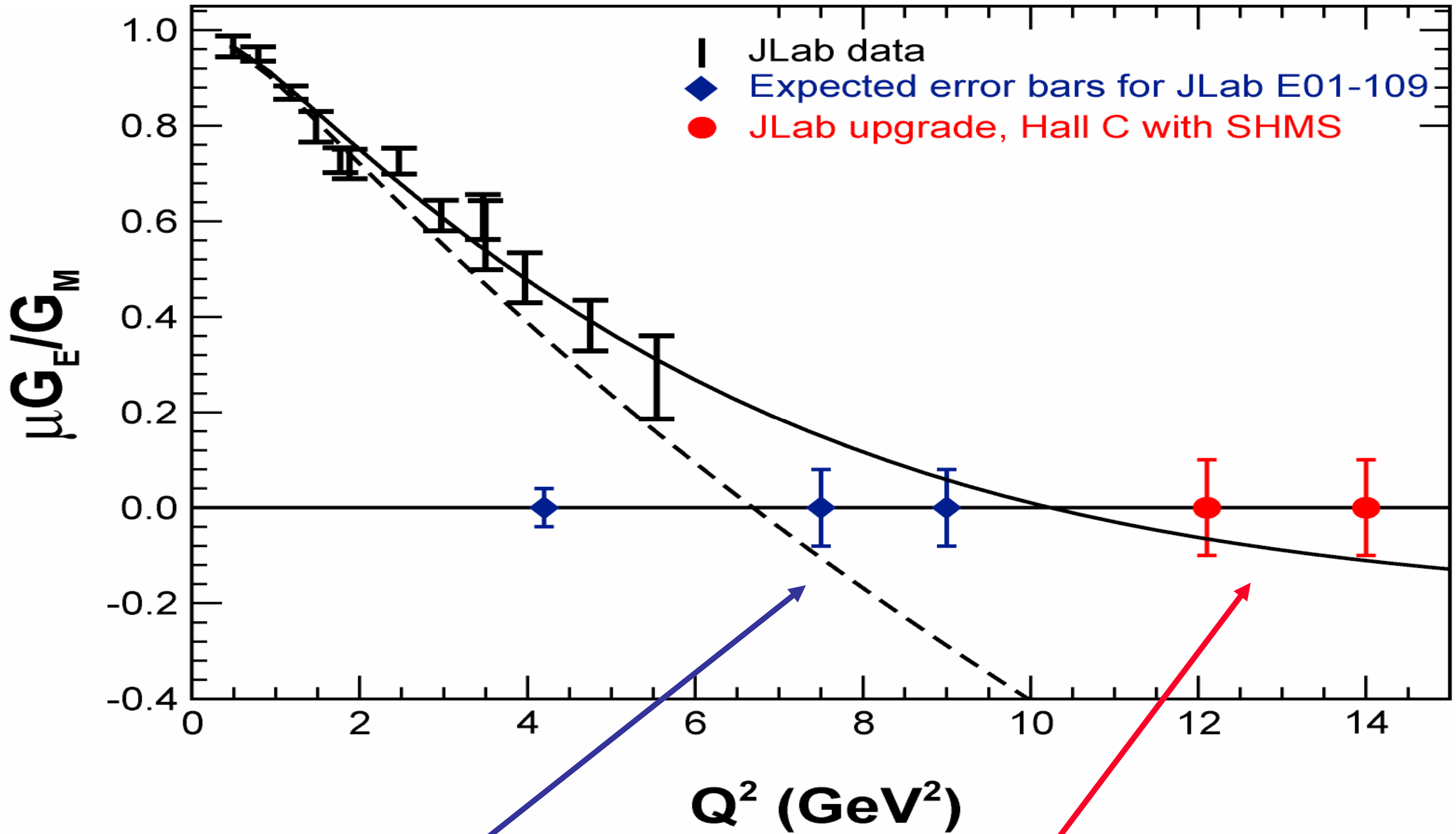
Future Measurements on G_E^p



- Perdrisat *et al*. E01-109 — will increase range of Q^2 by 50% in FY08 (range of Q^2 for neutron will double over next 3-4 years)
- **With 12 GeV and SHMS in Hall C : similarly for G_M^n (and G_E^n)**

Anticipated Highlights of the 1st 5 Years

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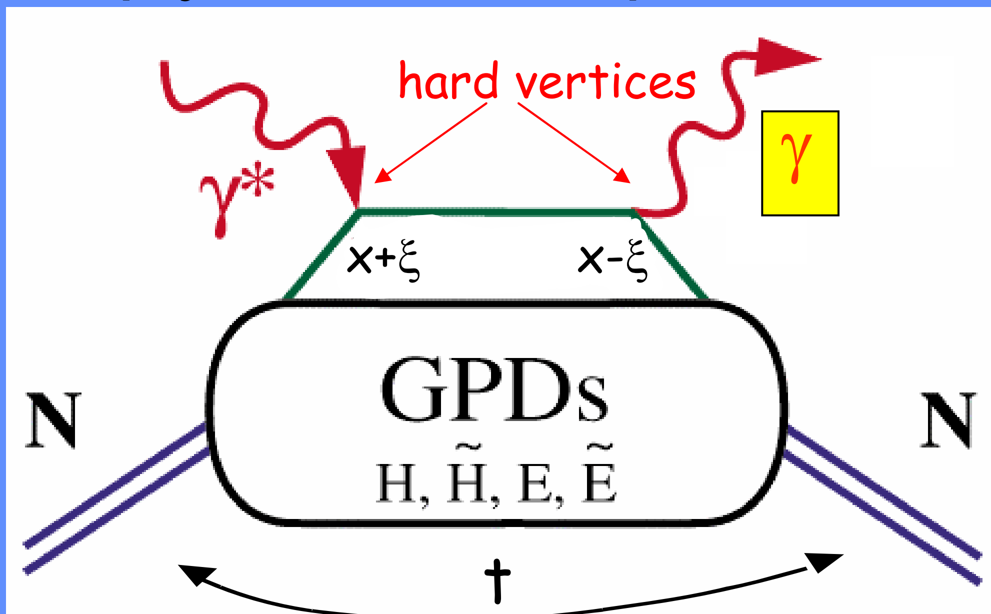
GPDs & Deeply Virtual Exclusive Processes
- New Insight into Nucleon Structure

Deeply Virtual Compton Scattering (DVCS)



x – quark momentum fraction

ξ– longitudinal momentum transfer

$\sqrt{-t}$ – Fourier conjugate to transverse impact parameter

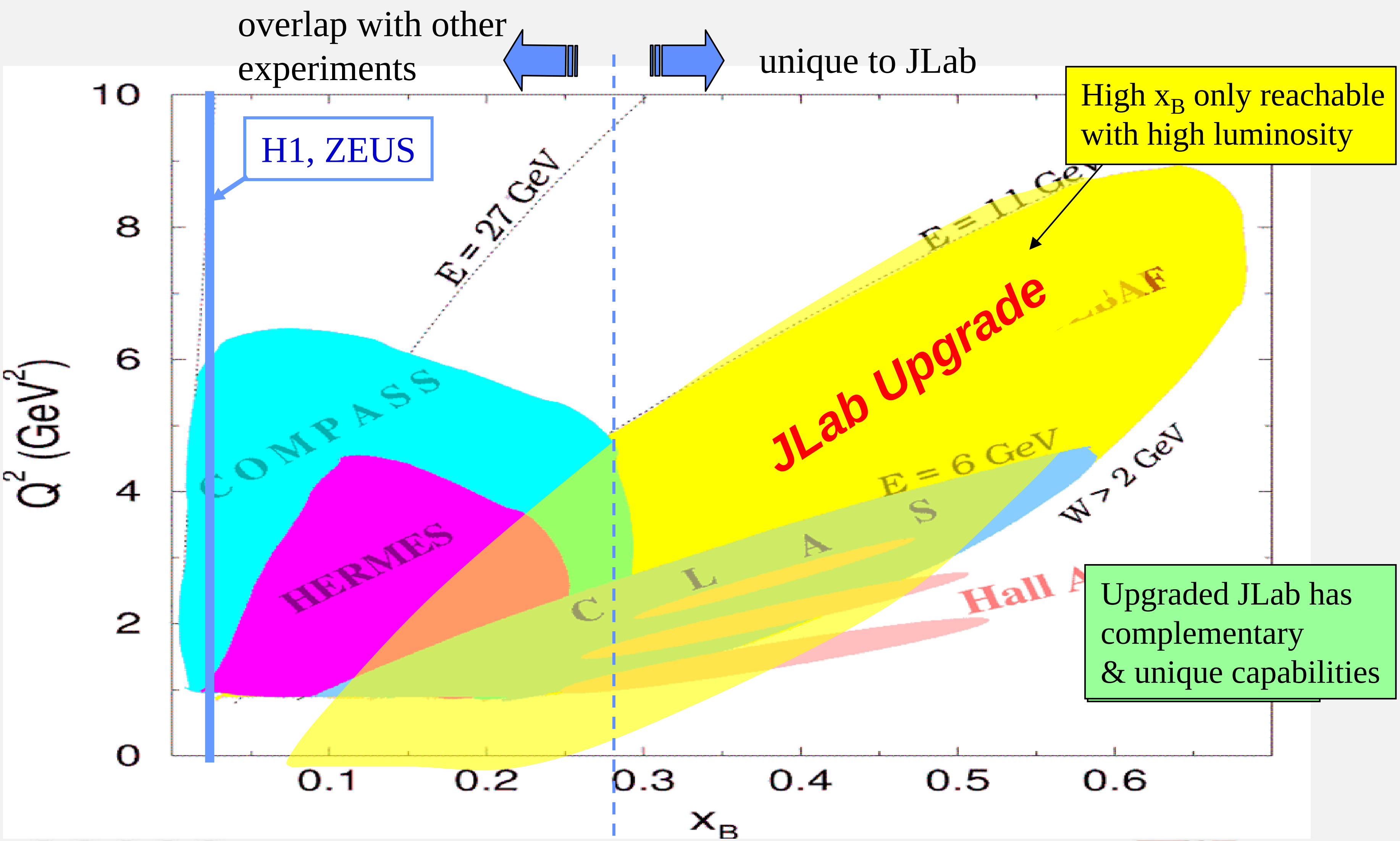
$H(x,\xi,t), E(x,\xi,t), \ldots$ "Generalized Parton Distributions"

Quark angular momentum (Ji sum rule)

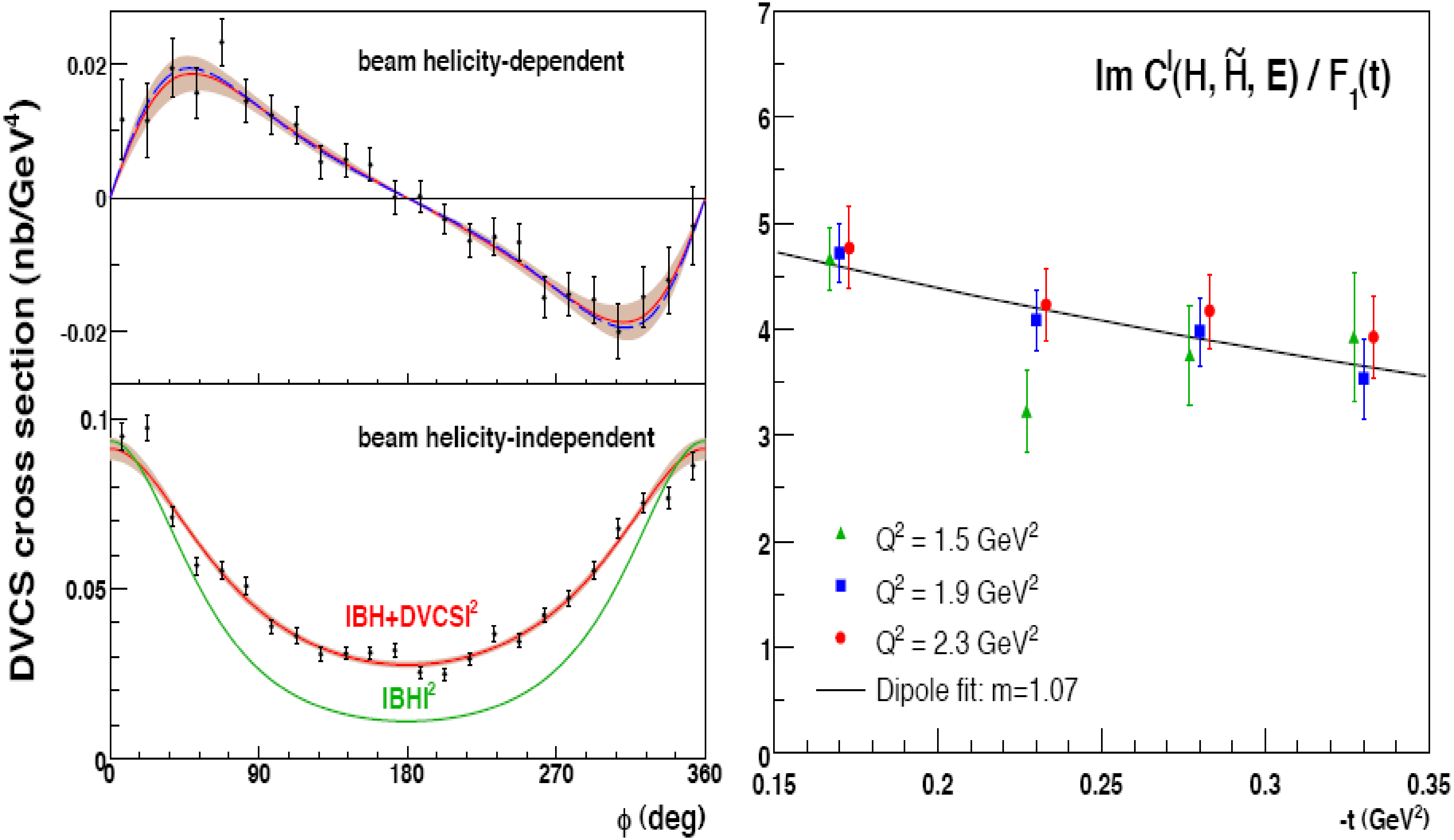
$$J^q = \frac{1}{2} - J^G = \frac{1}{2}\int_{-1}^{1} x\,dx\left[H^q(x,\xi,0) + E^q(x,\xi,0)\right]$$

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

Deeply Virtual Exclusive Processes - Kinematics Coverage of the 12 GeV Upgrade



Recent Hall A Data: Suggests in Scaling Regime Even at Relatively Low Q^2

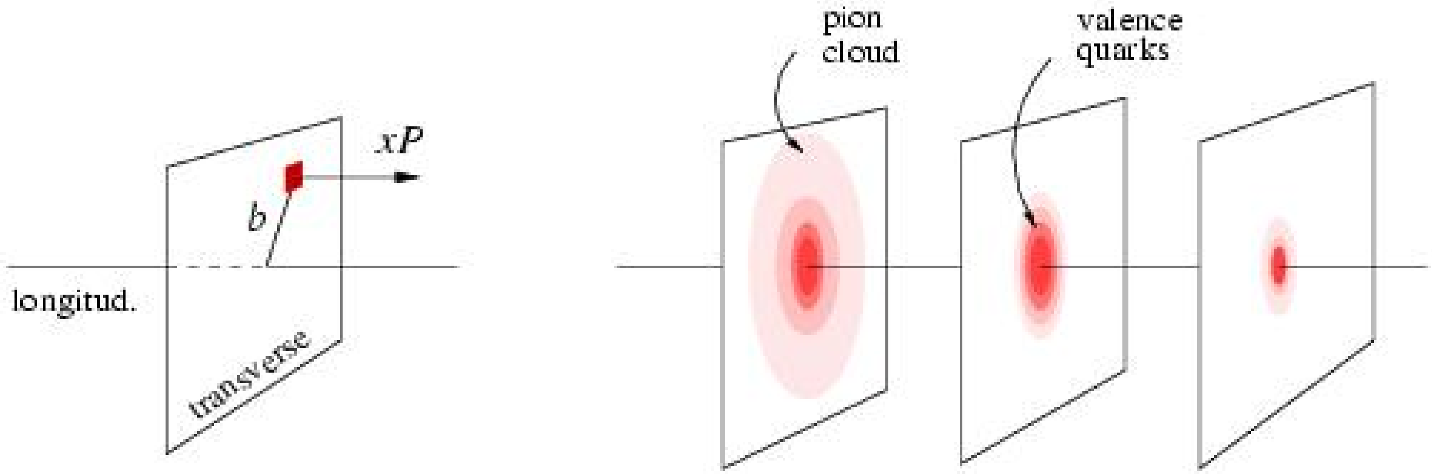


What's the use of GPDs?

1. Allow for a unified description of form factors and parton distributions

2. Allows for Transverse Imaging

Fourier transform in momentum transfer



x < 0.1 x ~ 0.3 x ~ 0.8

gives transverse size of quark (parton) with longitudinal momentum fraction x

3. Allows access to quark angular momentum (in model-dependent way)

The path towards the extraction of GPDs

Use polarization!

$$A = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} = \frac{\Delta\sigma}{2\sigma}$$

$$\vec{e}\,p \longrightarrow ep\gamma$$

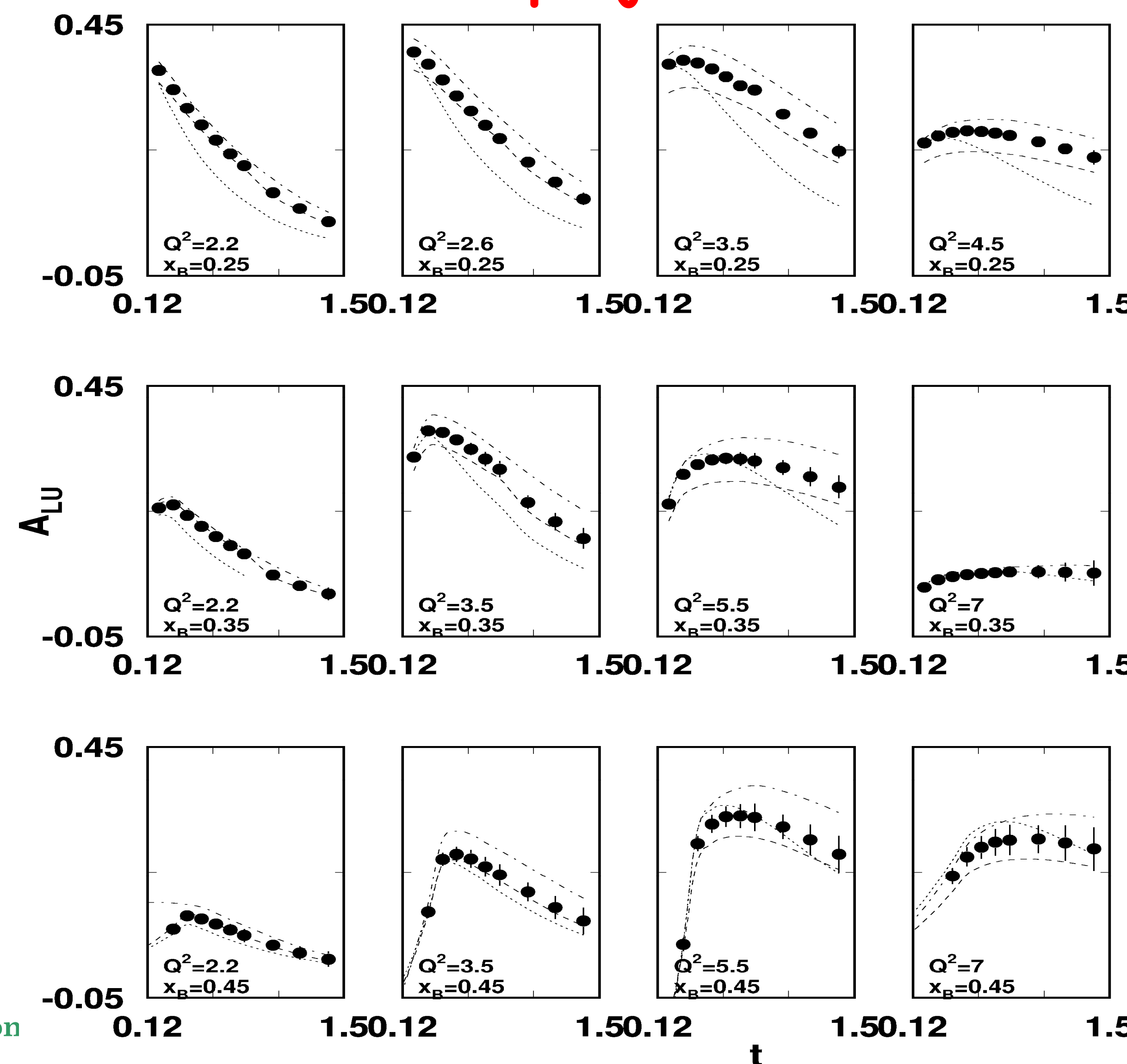
$$\Delta\sigma_{LU} \sim \sin\phi \, \mathrm{Im}\{F_1 H + \ldots\} d\phi$$

Kinematically suppressed

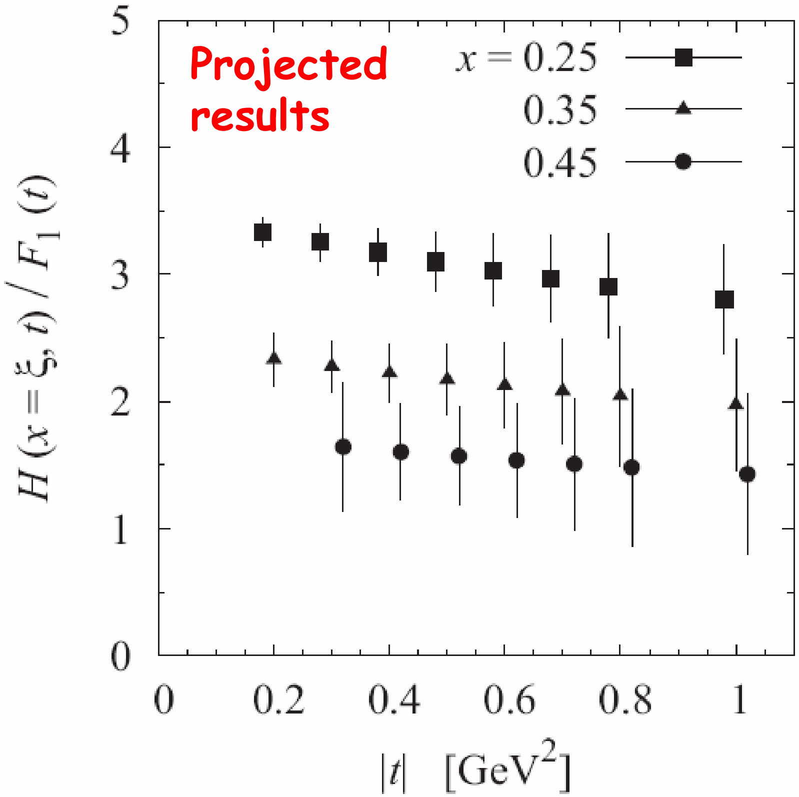
$\Rightarrow$ $H(\xi, t)$

$$\xi = x_B/(2-x_B)$$
$$k = t/4M^2$$

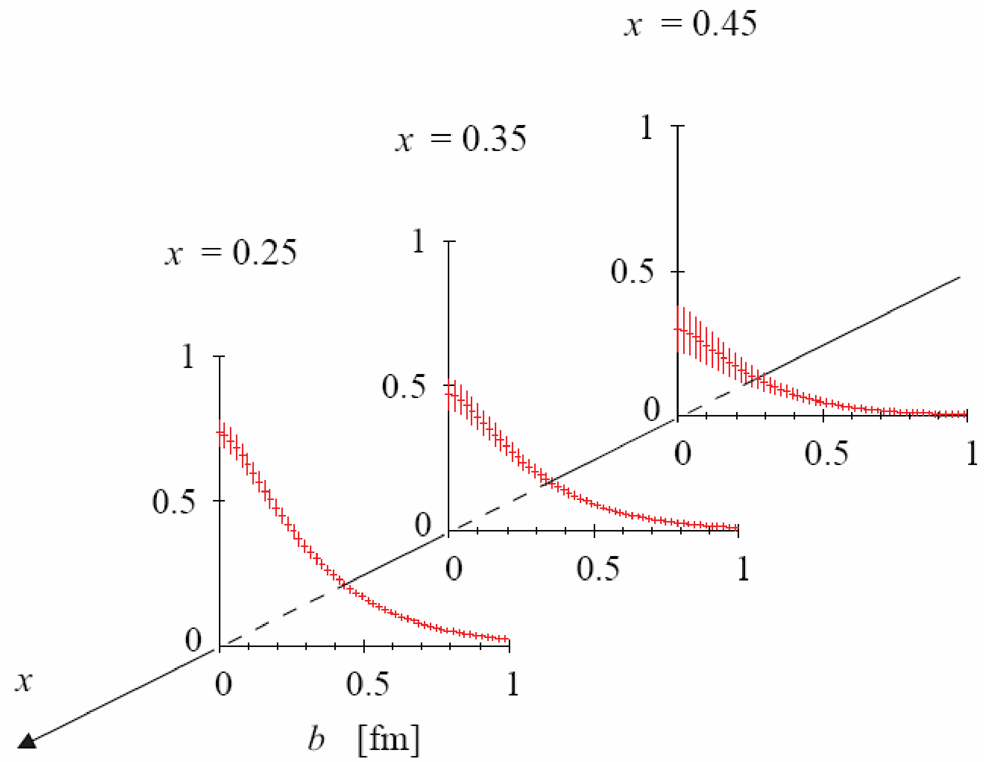
Subset of projected results



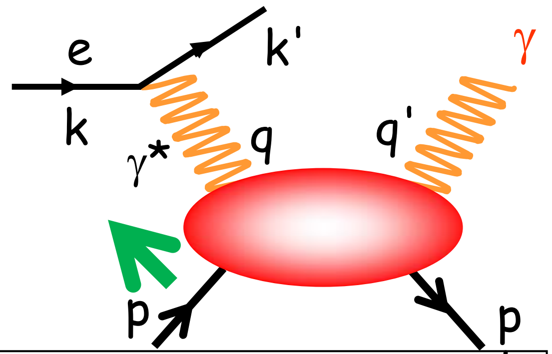
Projected precision in extraction of GPD H at x = ξ



→ Spatial Image



Orbital Angular Momentum carried by quarks : solving the spin puzzle



At one value of x only

Ingredients:

1) GPD Modeling

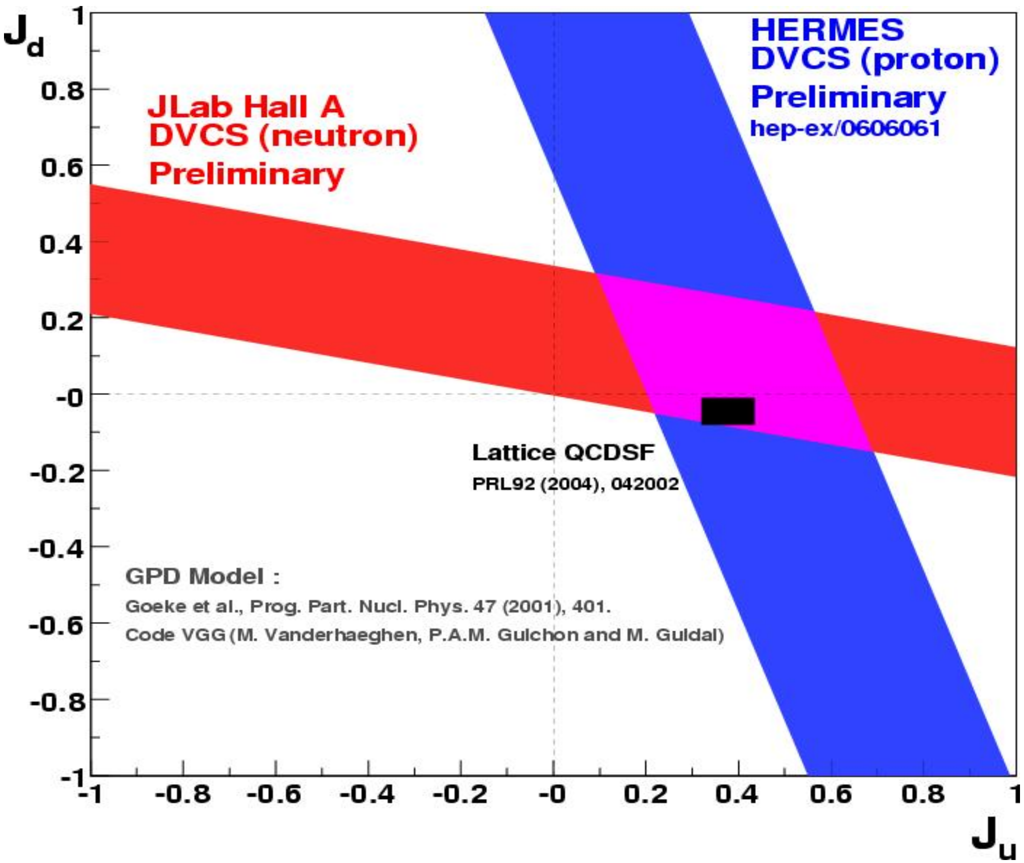
2) HERMES $^1H(e,e'\gamma)p$

(transverse target spin asymmetry)

3) Hall A $^2H(e,e'\gamma p)n$

Or independent:

Lattice QCD!



→ **Tremendous progress to constrain quark angular momenta**

→ **12 GeV will give final answers for quarks**

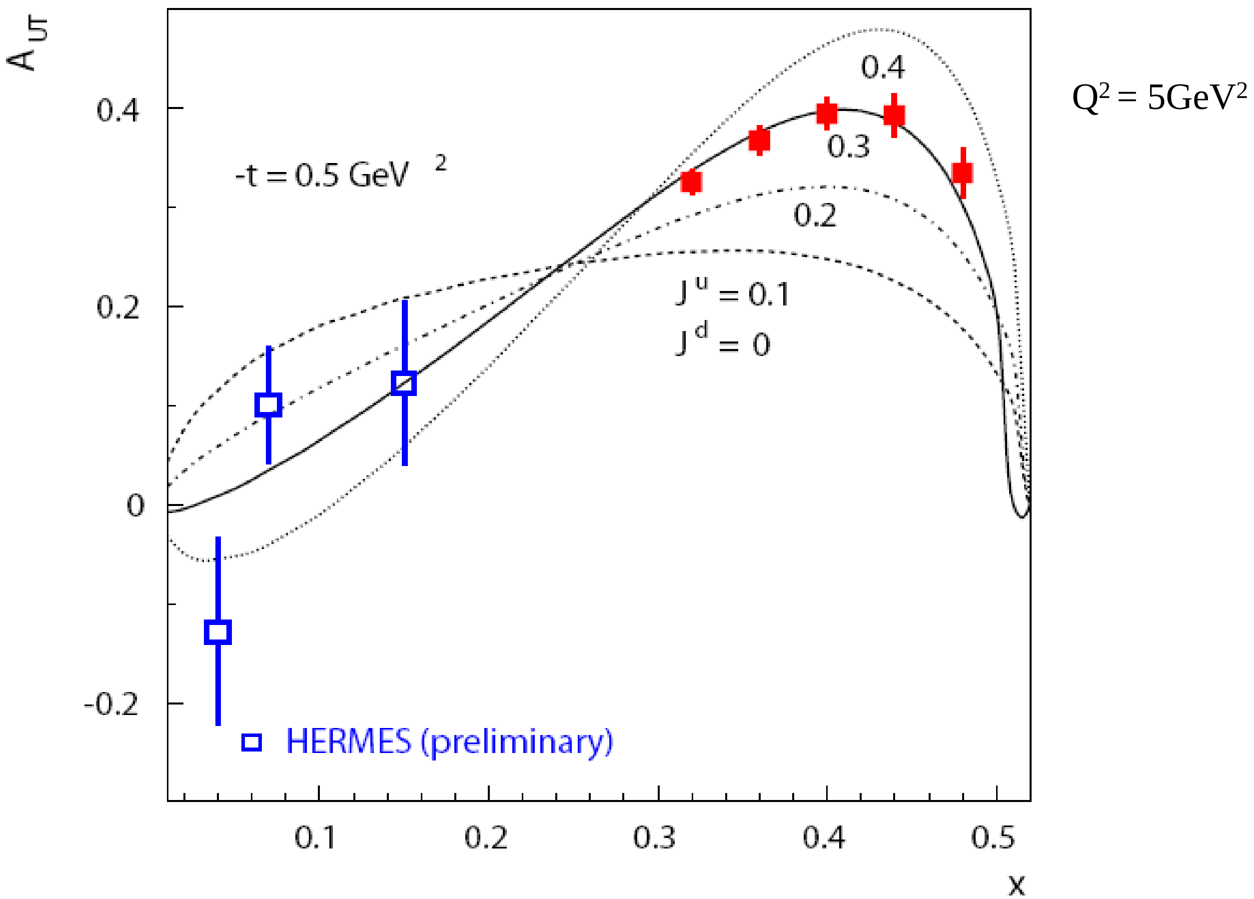
At 12 GeV: Exclusive ρ^0 with transverse target

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

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

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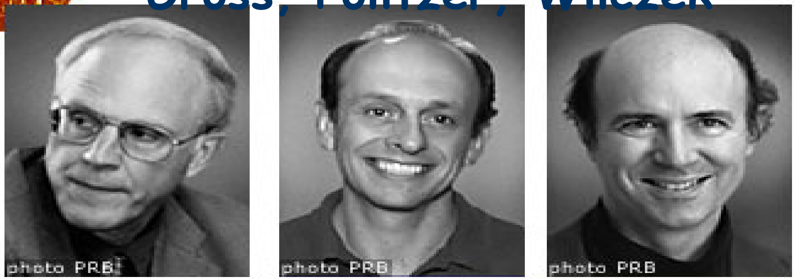
QCD: Unsolved in Nonperturbative Regime

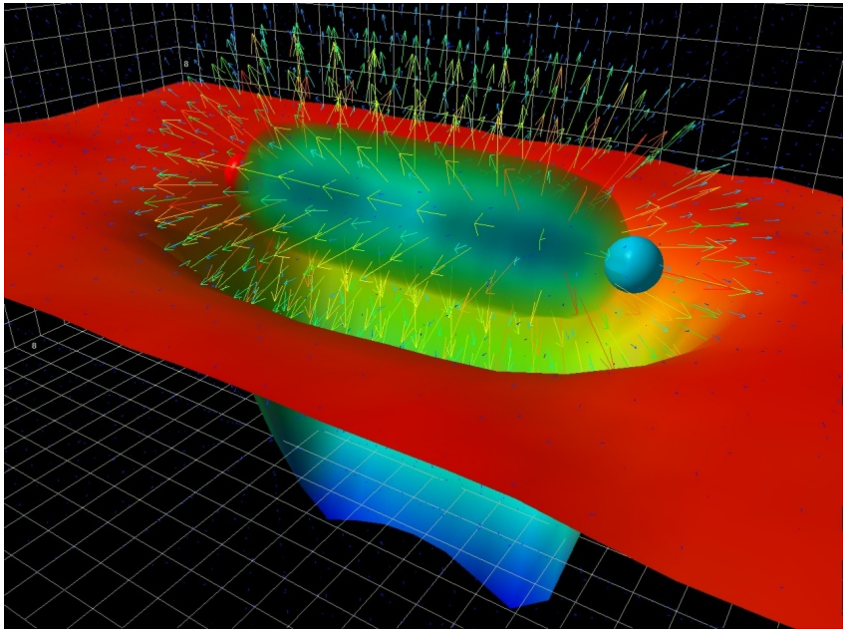
The Nobel Prize in Physics 2004
Gross, Politzer, Wilczek



- **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!

Gluonic Excitations and the Origin of Confinement

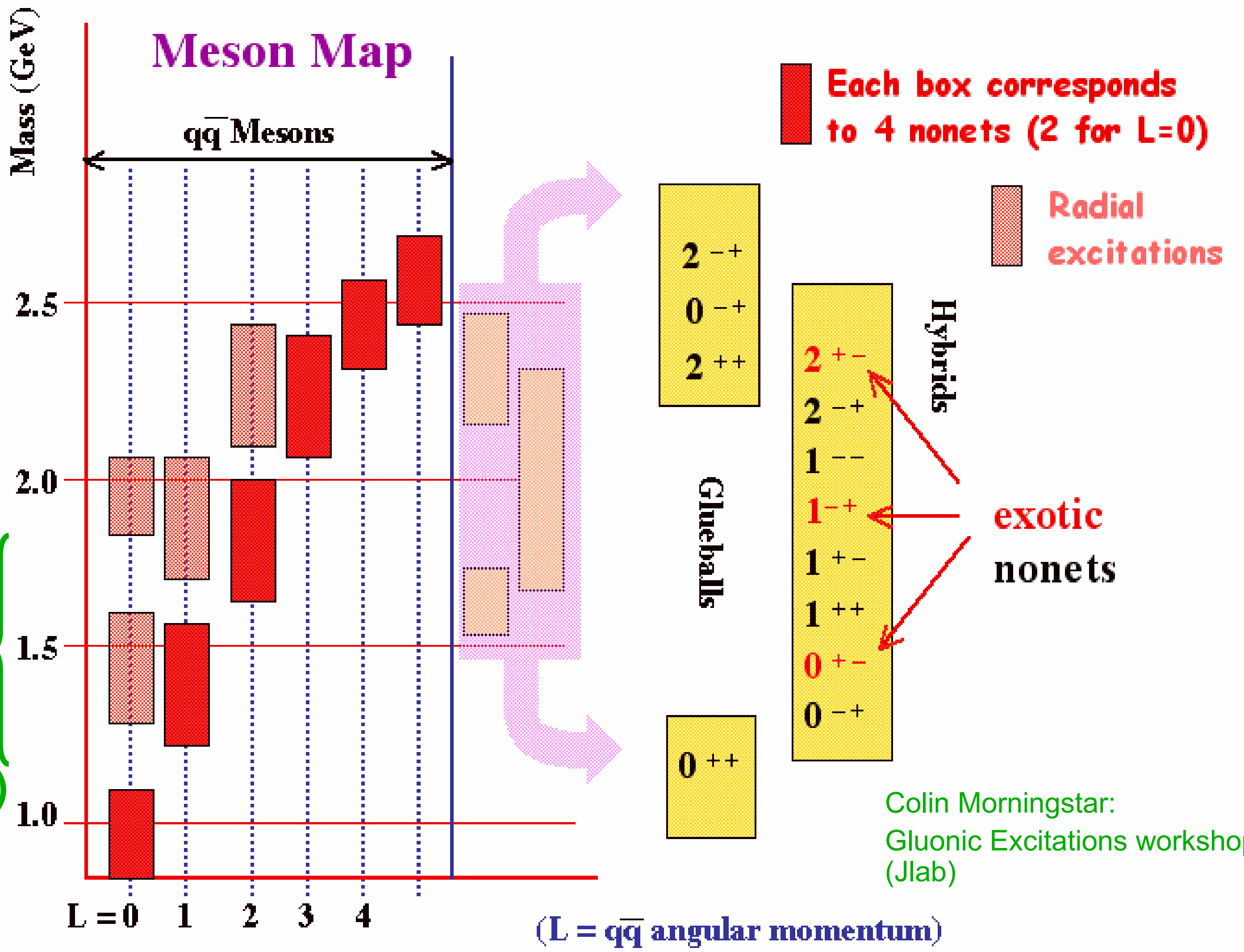


QCD predicts a rich spectrum of as yet to be discovered gluonic excitations - whose experimental verification is crucial for our understanding of QCD in the confinement regime.

With the upgraded CEBAF, a linearly polarized photon beam, and the GlueX detector, Jefferson Lab will be uniquely poised to:

- **discover these states,**
- **map out their spectrum, and**
- **measure their properties**

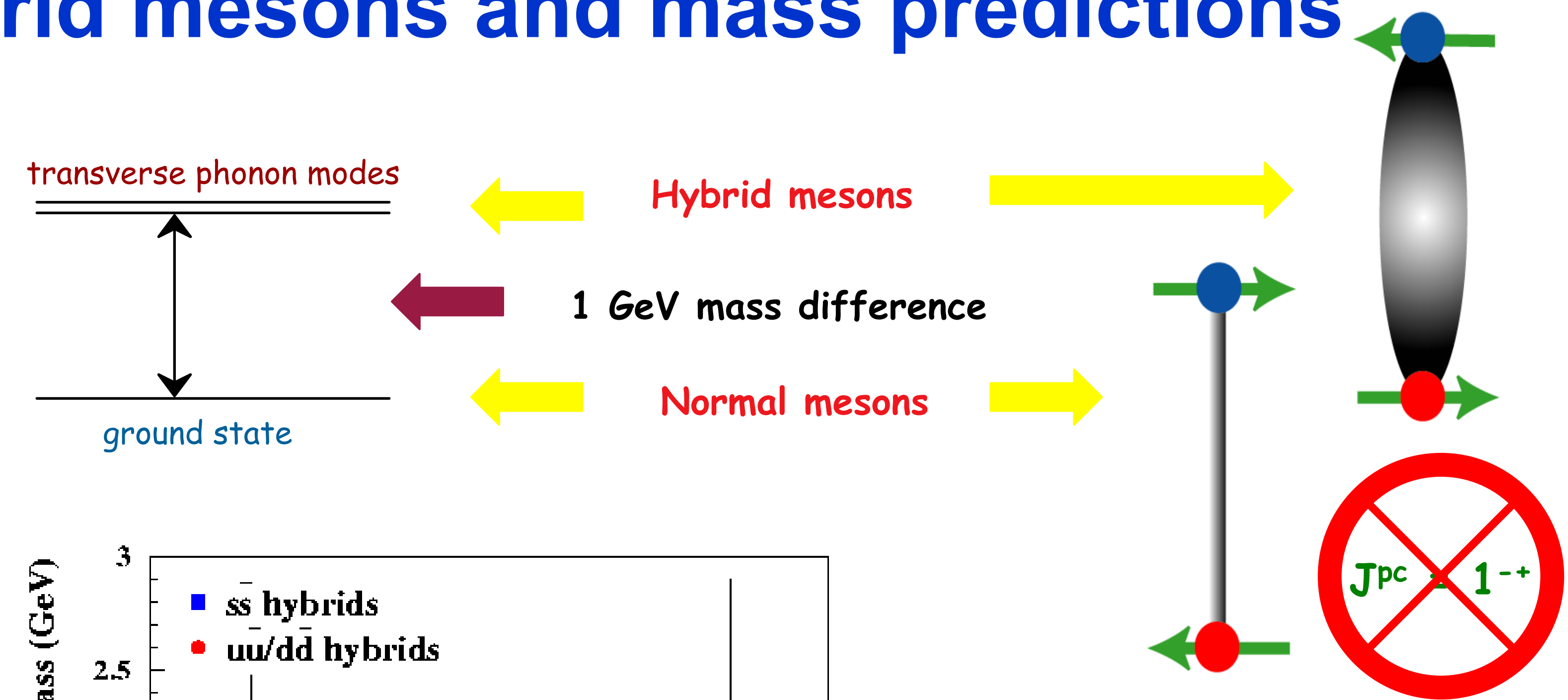
Glueballs and hybrid mesons

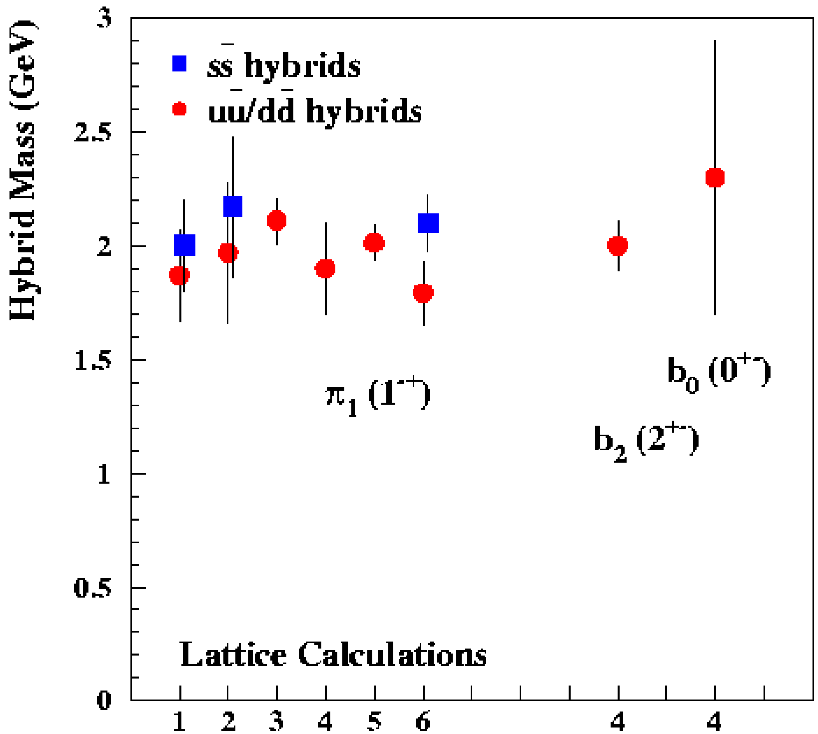


Initial search FY07 – G12 (CLAS)

Colin Morningstar:
Gluonic Excitations workshop, 2003 (Jlab)

Hybrid mesons and mass predictions





Lattice

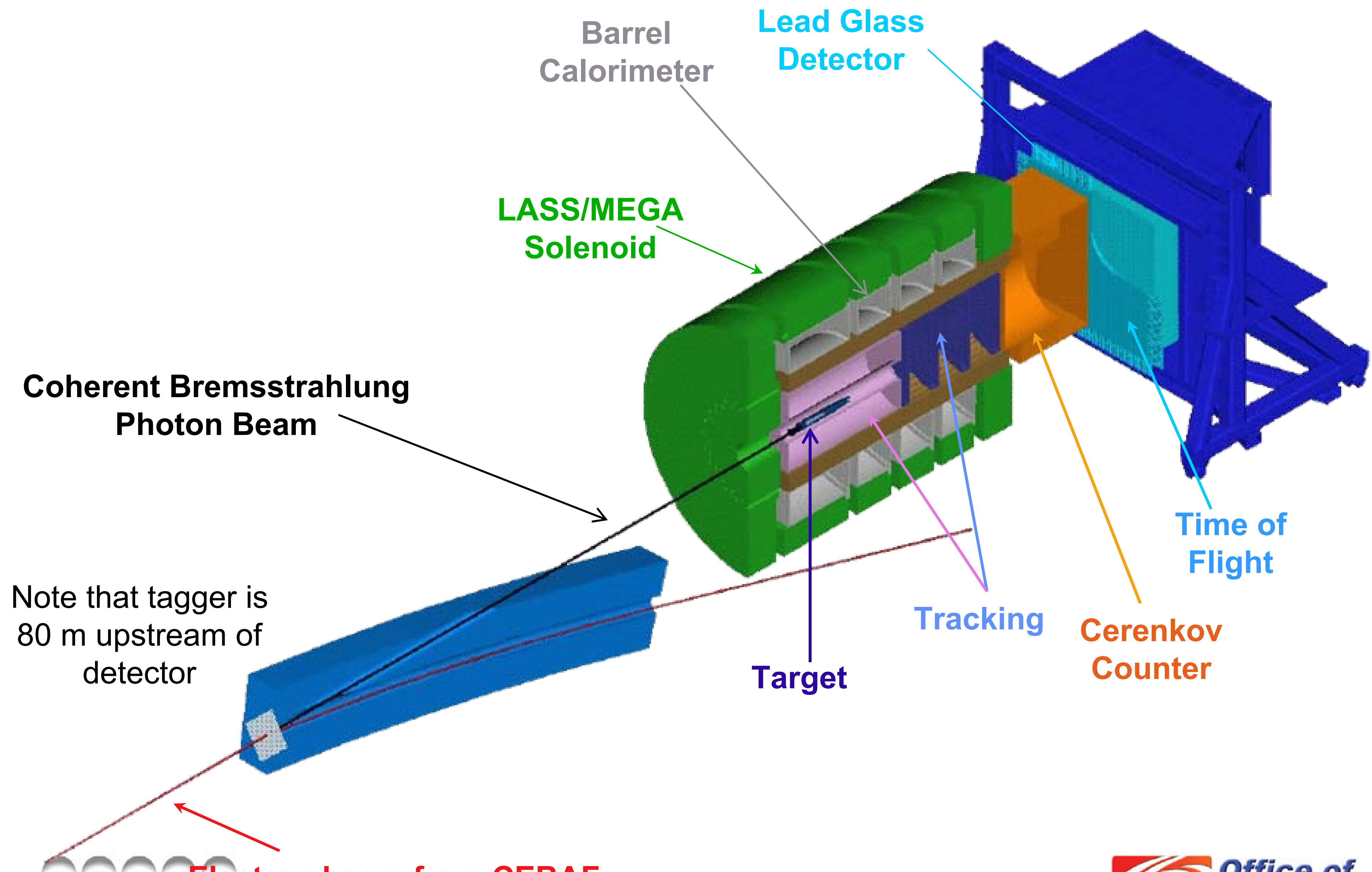
1^{-+} 1.9 GeV

2^{+-} 2.1 GeV

0^{+-} 2.3 GeV

Lowest mass expected to be $\pi_1(1^{-+})$ at 1.9±0.2 GeV

Hall D GlueX Detector



Finding the Exotic Wave

(Double-blind M. C. exercise)

$\gamma \rightarrow$ V(ector Meson) S = 1

An exotic wave ($J^{PC} = 1^{-+}$) was generated at level of 2.5 % with 7 other waves. Events were smeared, accepted, passed to PWA fitter.

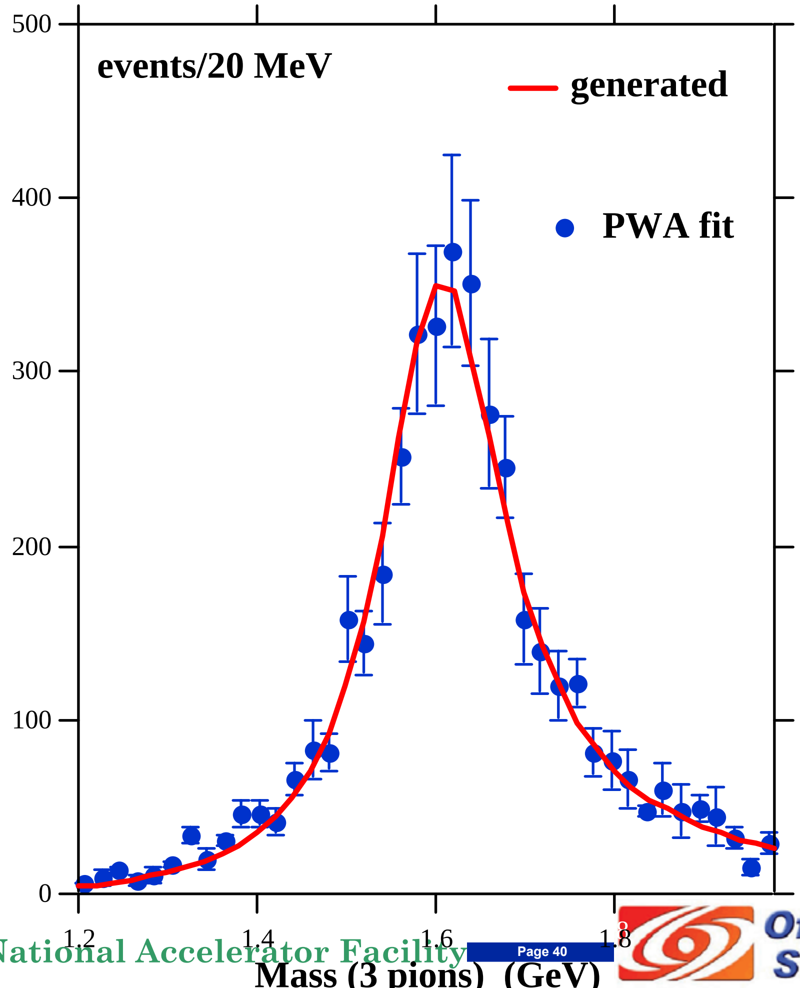
$$X(\text{exotic}) \rightarrow \rho\pi \rightarrow 3\pi$$

Mass

Input: 1600 MeV
Output: 1598 +/- 3 MeV

Width

Input: 170 MeV
Output: 173 +/- 11 MeV

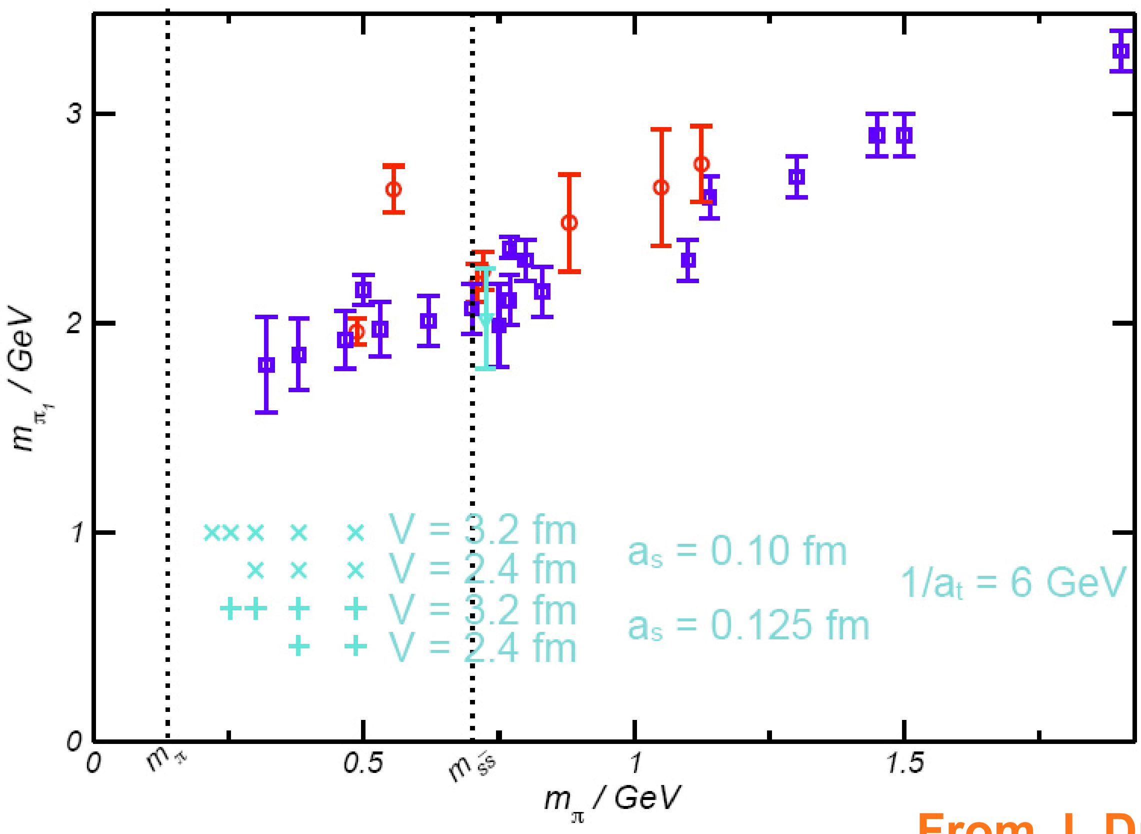


Statistics shown here correspond to a few days of running.

JLab plans in ‘06-’07

- Dynamical anisotropic Clover
- NF = 2+1 gauge fields in ‘06, ’07

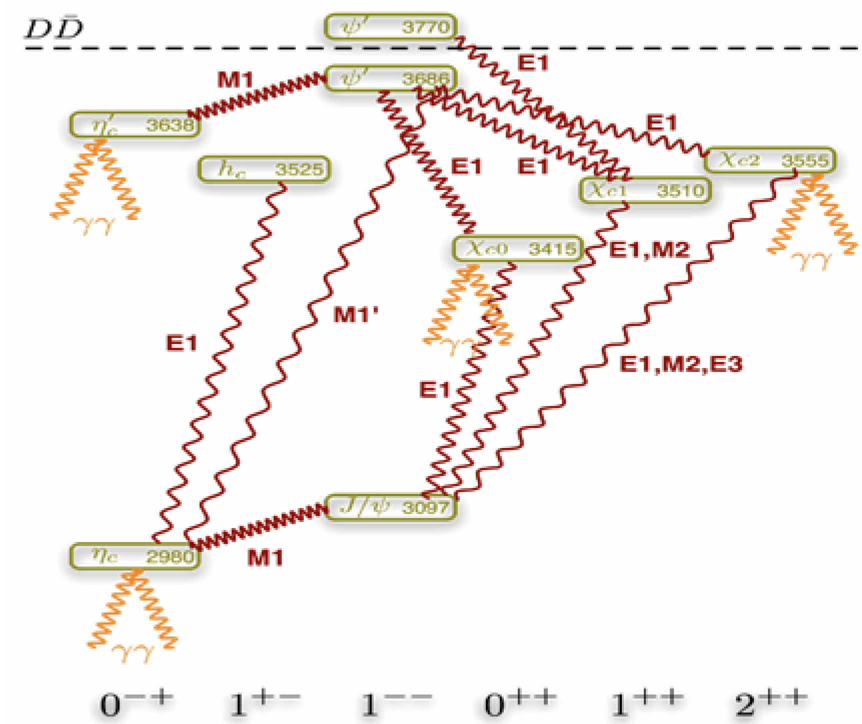
— ideal for spectroscopy

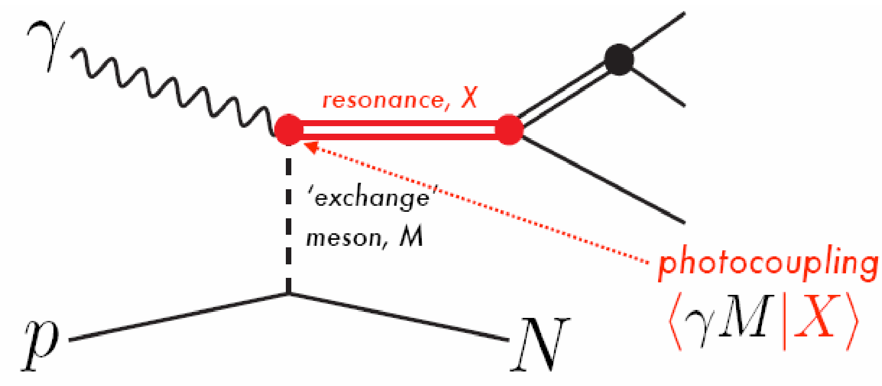


From J. Dudek

Lattice Estimates of Photo-production Rates for GlueX

- An important realization of JLab Theorists was that lattice QCD enabled calculation of photocouplings
- Guide experimental program as to expected photoproduction rates.





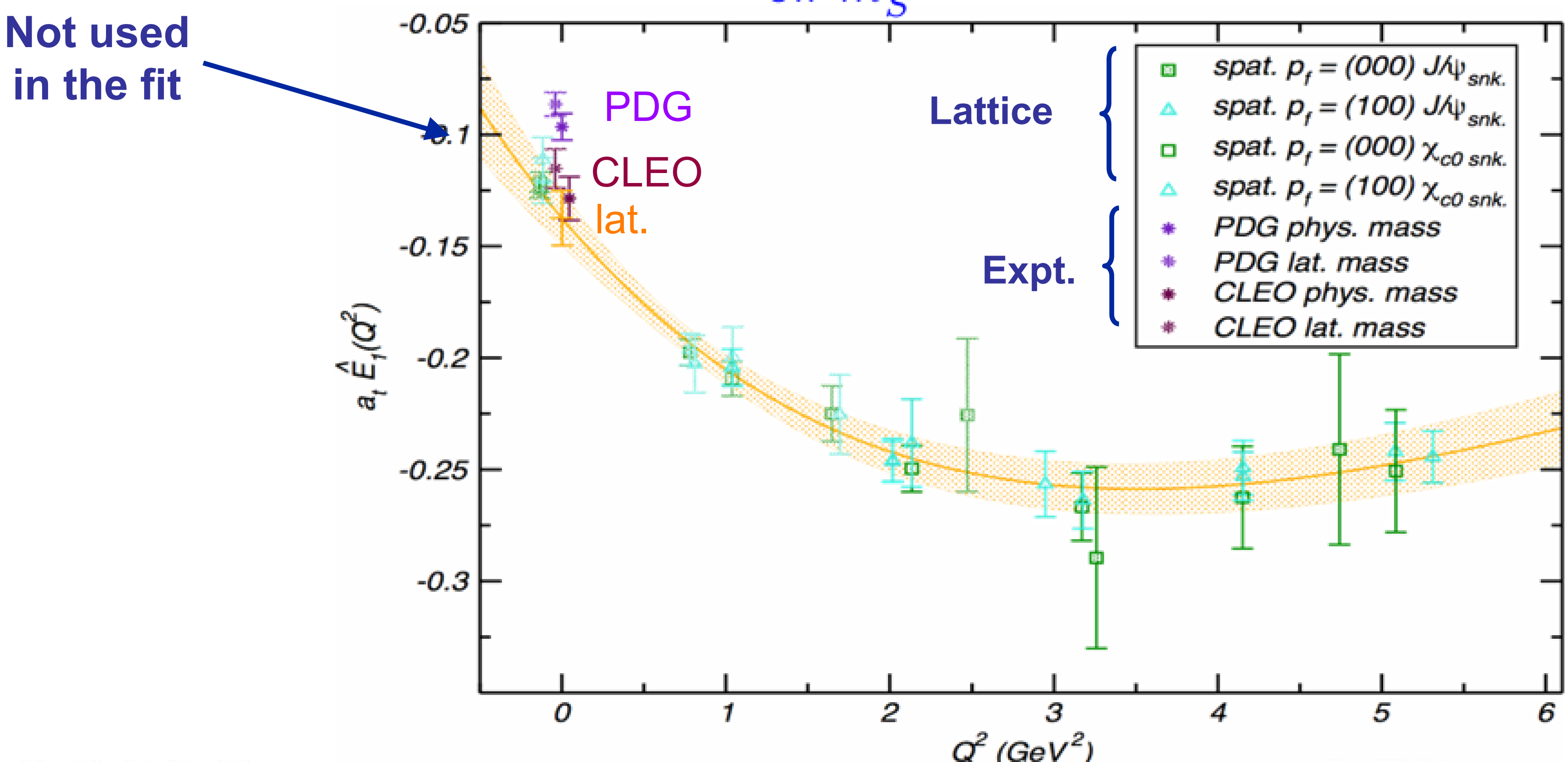
Initial exploration in Charmonium
- Good experimental data
- Allow comparison with QCD-inspired models
- Lattice computations pioneered at JLab

Photo-couplings

Dudek, Edwards, Richards, PRD73, 074507

- Recent study of transitions between conventional mesons, e.g. **S** $\rightarrow \gamma$ **V**

$$\Gamma(\chi_{c0} \to J/\psi\,\gamma) = \frac{1}{8\pi}\frac{|\vec{q}\,|}{m_S^2}\,2\,(2e_c)^2\,|\,E_1(0)\,|^2$$

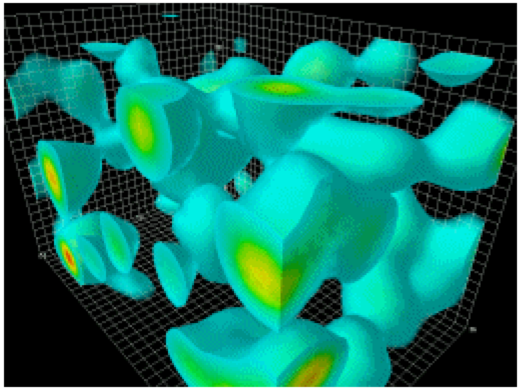


Anticipated Highlights of the 1st 5 Years

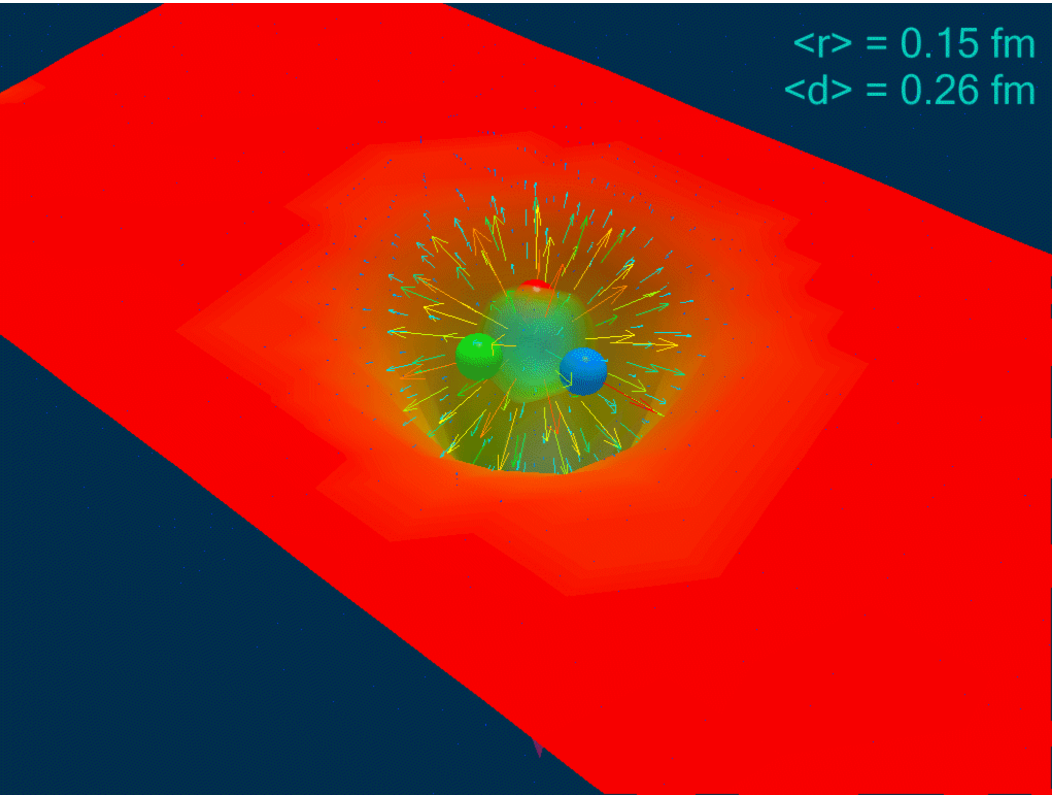
- Parton Distribution Functions
- Form Factors
- Generalized Parton Distributions
- Exotic Meson Spectroscopy:
  Confinement and the QCD vacuum
- **Nuclei at the level of quarks and gluons**
- Tests of Physics Beyond the Standard Model

The QCD Lagrangian and Nuclear "Medium Modifications"

The QCD vacuum



Long-distance gluonic fluctuations



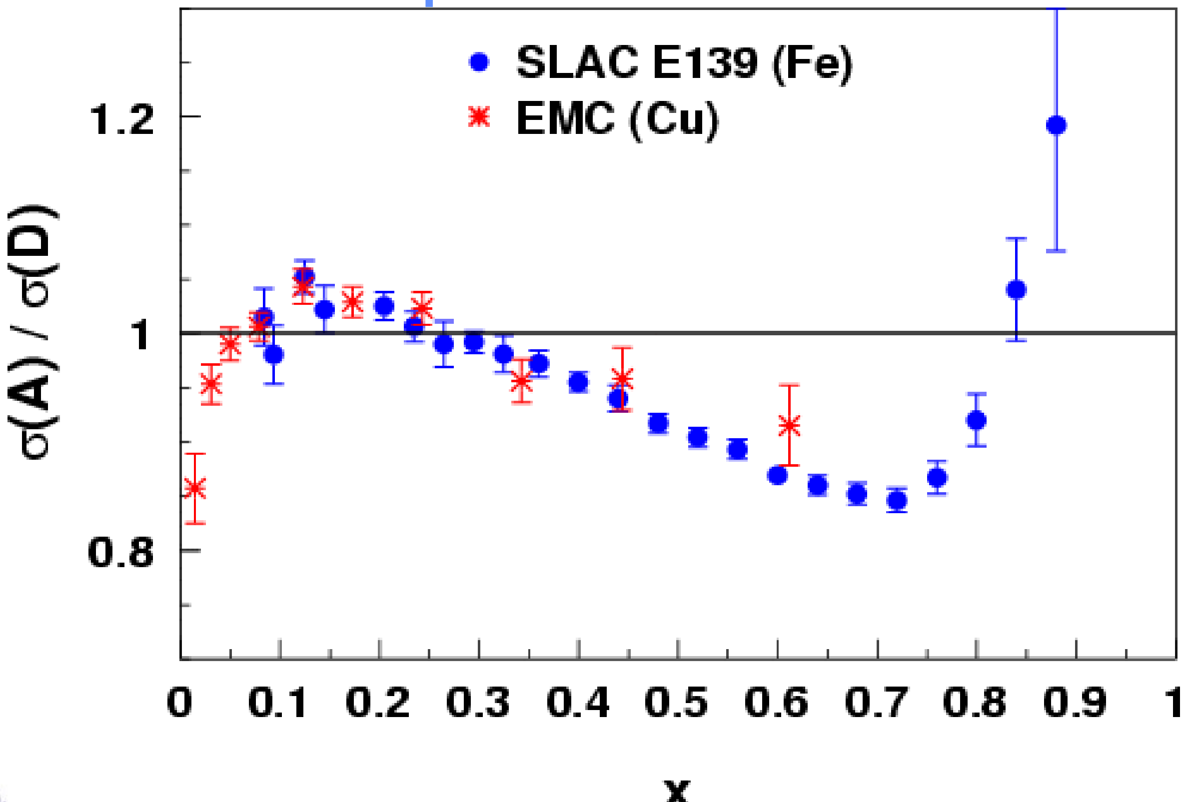
Lattice calculation demonstrates *reduction of chiral condensate* $\langle q\bar{q} \rangle$ of QCD vacuum in presence of hadronic matter

Does the quark structure of a nucleon get modified by the suppressed QCD vacuum fluctuations in a nucleus?

Leinweber, Signal et al

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?



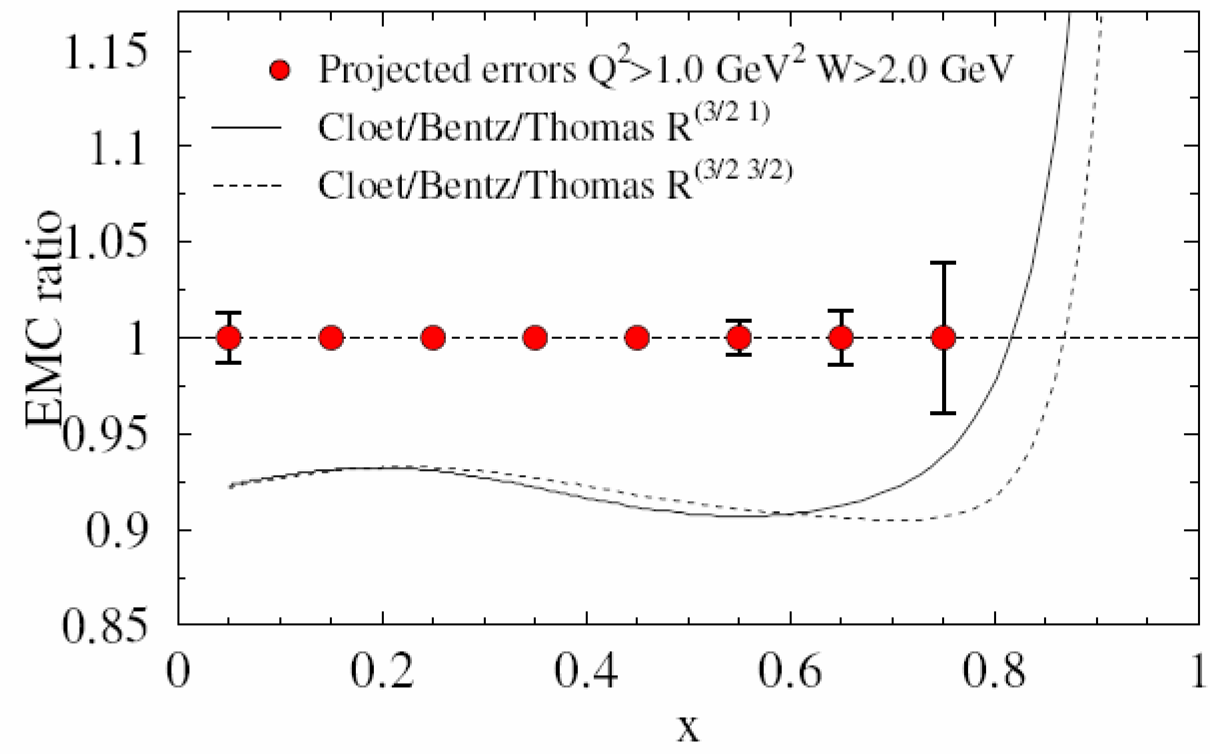
J. Ashman *et al.*, Z. Phys. C57, 211 (1993)

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

$g_1(A)$ – "Polarized EMC Effect"

- New calculations indicate larger effect for polarized structure function than for unpolarized: scalar field modifies lower components of Dirac wave function
- Spin-dependent parton distribution functions for nuclei nearly unknown
- Can take advantage of modern technology for polarized solid targets to perform systematic studies – Dynamic Nuclear Polarization

- $\frac{g_{1A}(^7Li)}{g_{1p}}$ (polarized EMC effect)

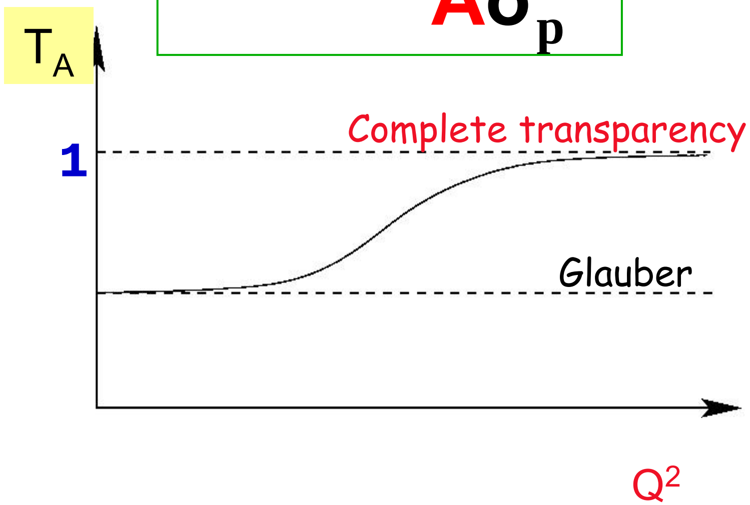


Curve follows calculation by W. Bentz, I. Cloet, A. W. Thomas.

CLAS

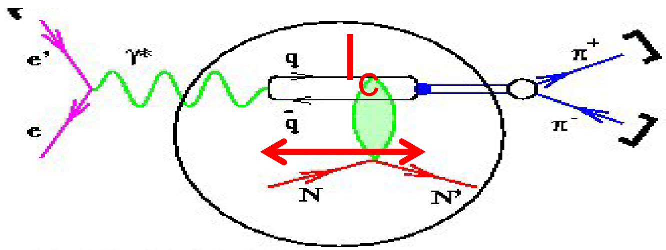
Color Transparency

$$T_A = \frac{\sigma(A)}{A\sigma_p}$$



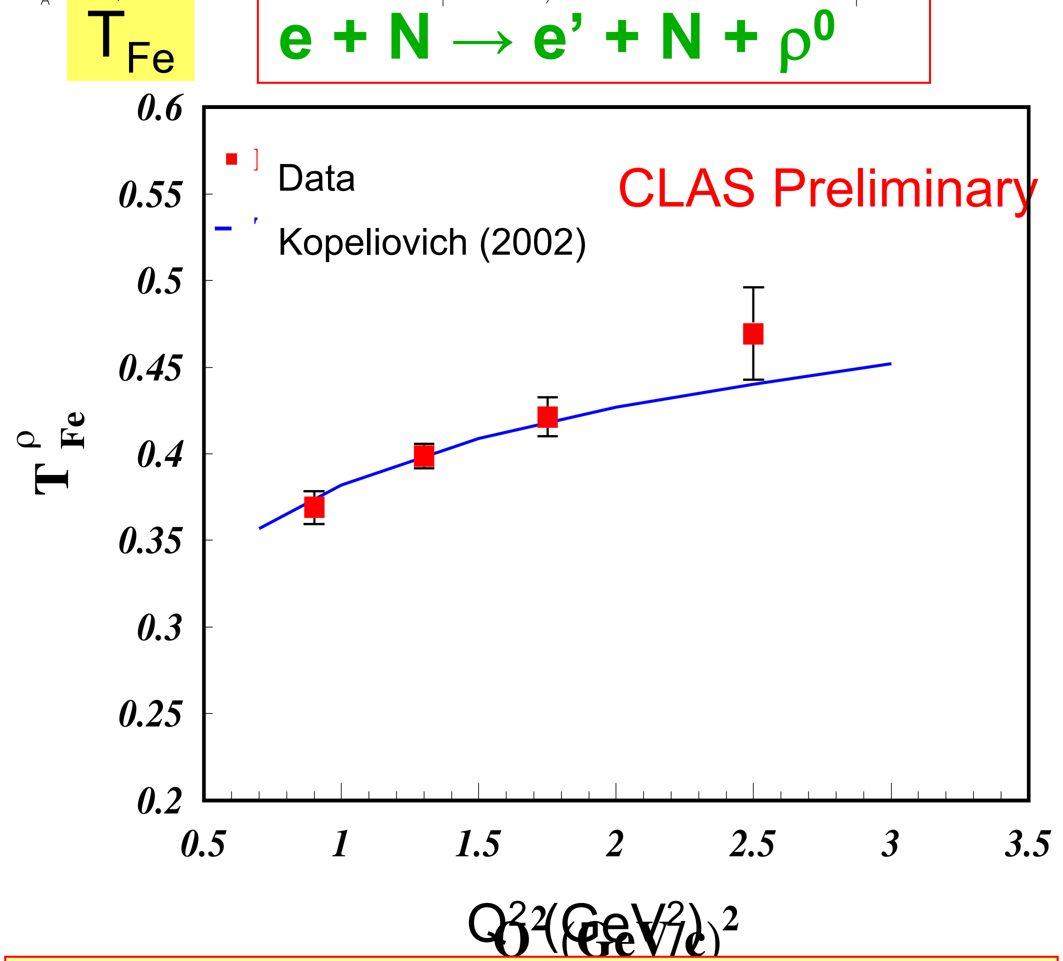
Measure at small coherence length

$\ell_c = 2\nu/(M^2 + Q^2)$, i.e. high Q^2, small ν



T_A vs. Q^2 corrected with acceptance, radiative and absorption effects

$e + N \rightarrow e' + N + \rho^0$

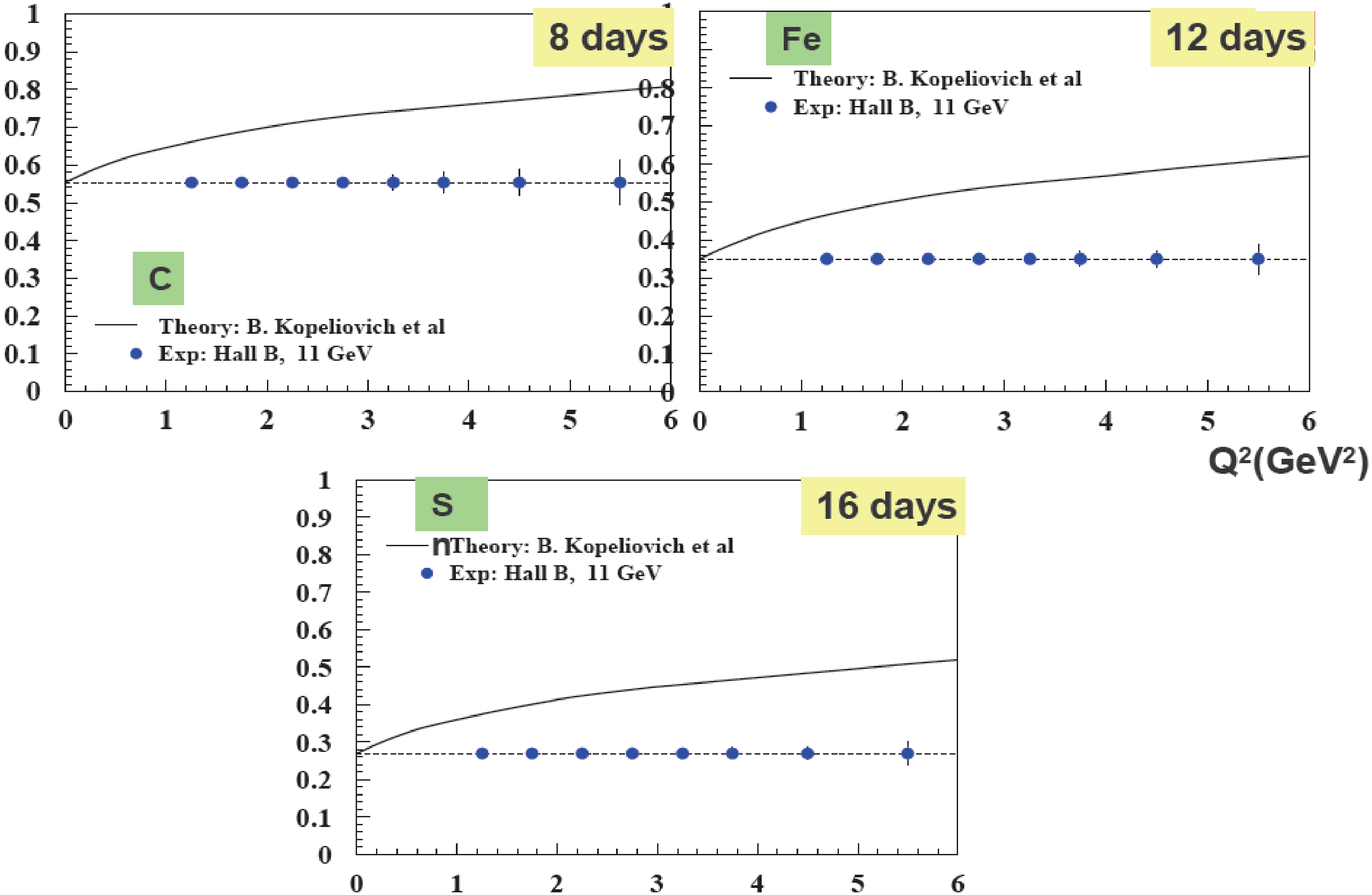


First hint of color transparency for ρ meson

K. Hafidi

CLAS12 - Projected data for 12 GeV Upgrade

Color Transparency for: $e + N \rightarrow e' + N + \rho^0$



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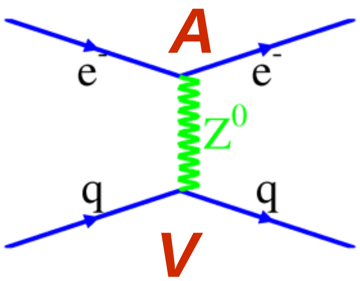
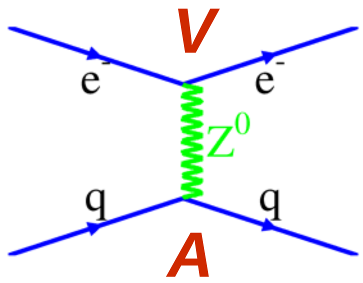
Electron-Quark Phenomenology



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



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

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

C_{1u} and C_{1d} will be determined to high precision by APV and Qweak

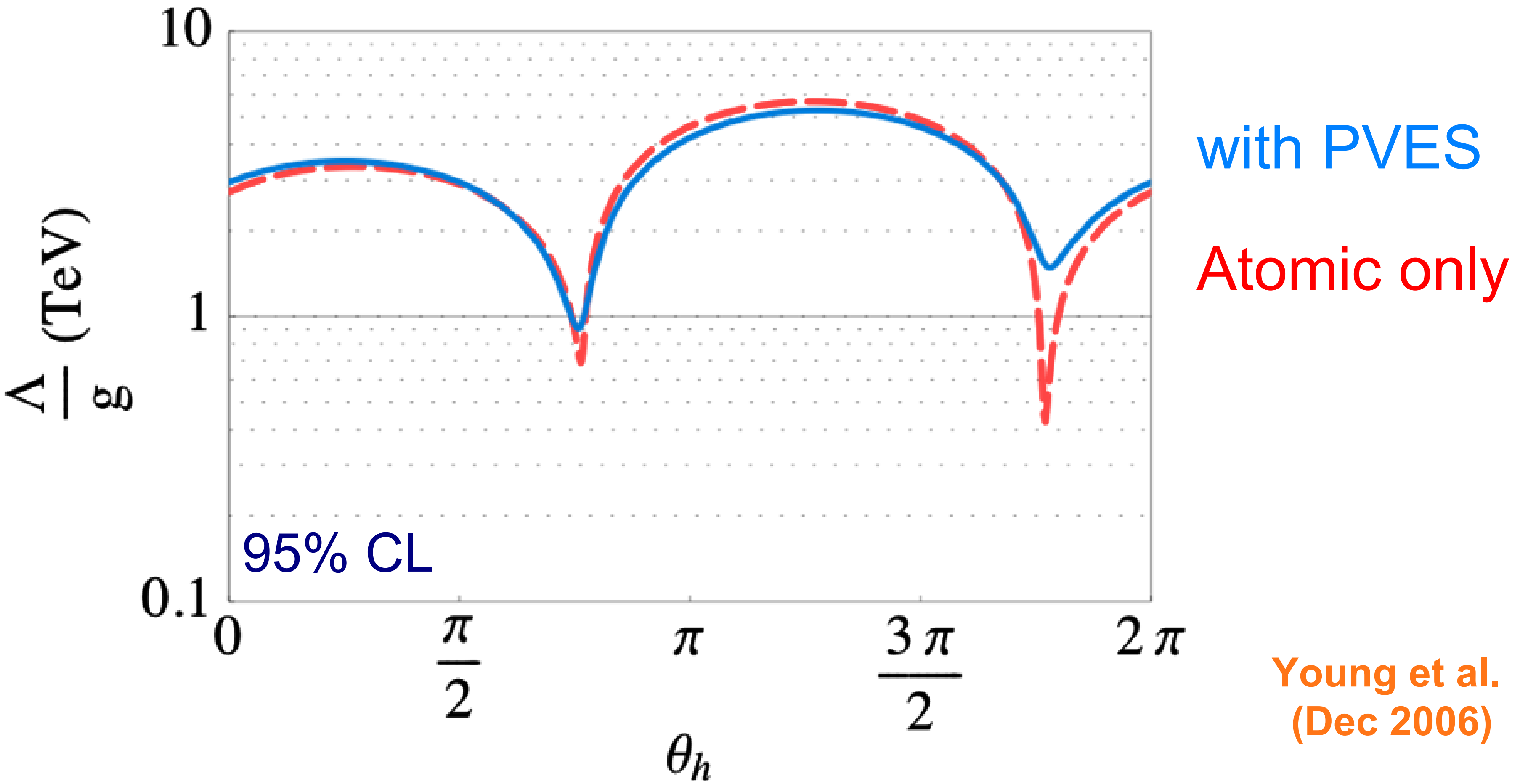
C_{2u} and C_{2d} are small and poorly known: can be accessed in PV DIS

New physics such as compositeness, new gauge bosons:

Deviations in C_{2u} and C_{2d} might be fractionally large

Proposed JLab upgrade experiment will permit increase in precision of measurement of $2C_{2u}$-C_{2d} by more than a factor of 20

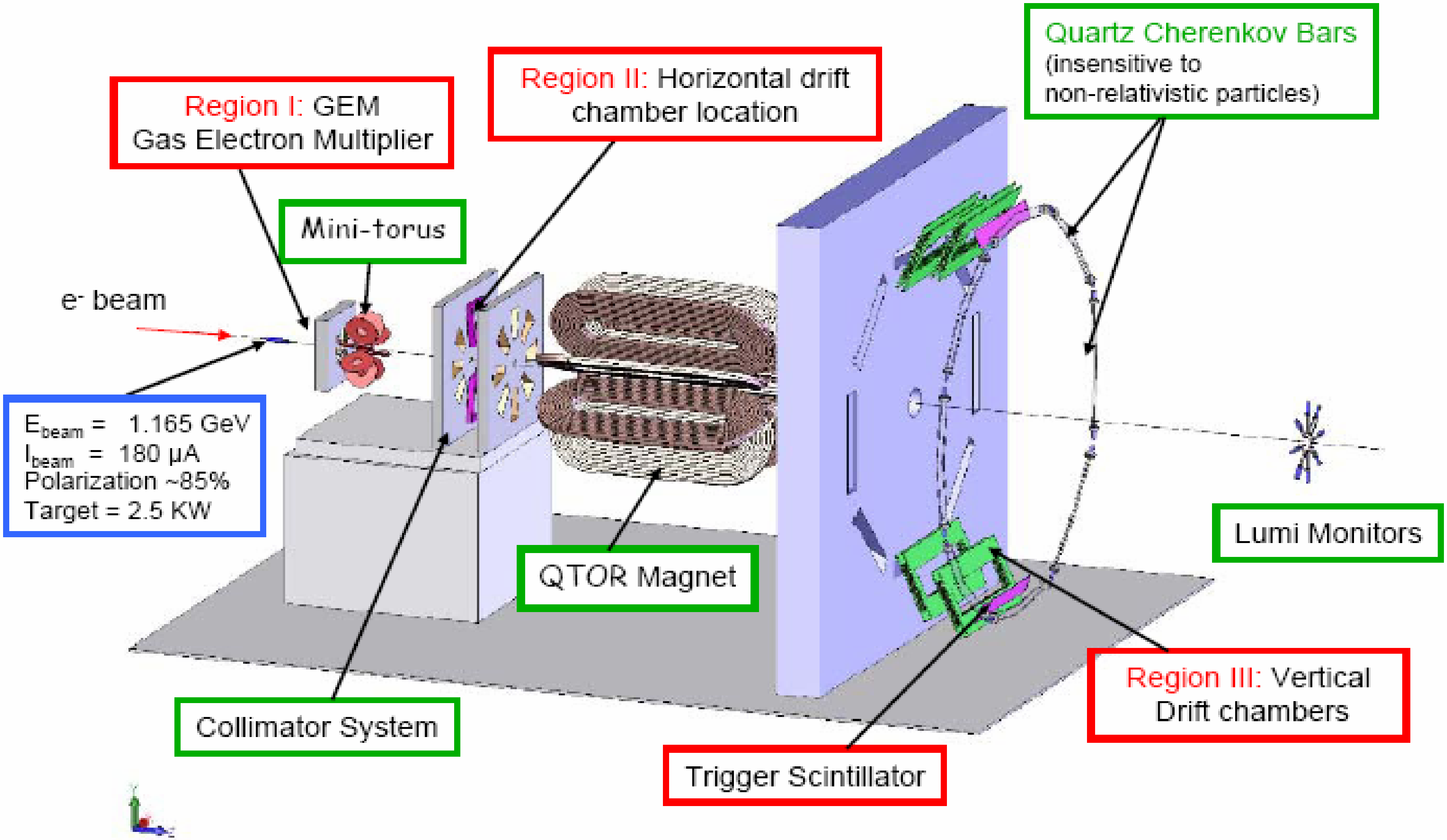
Lower bound on New Physics scale: Current



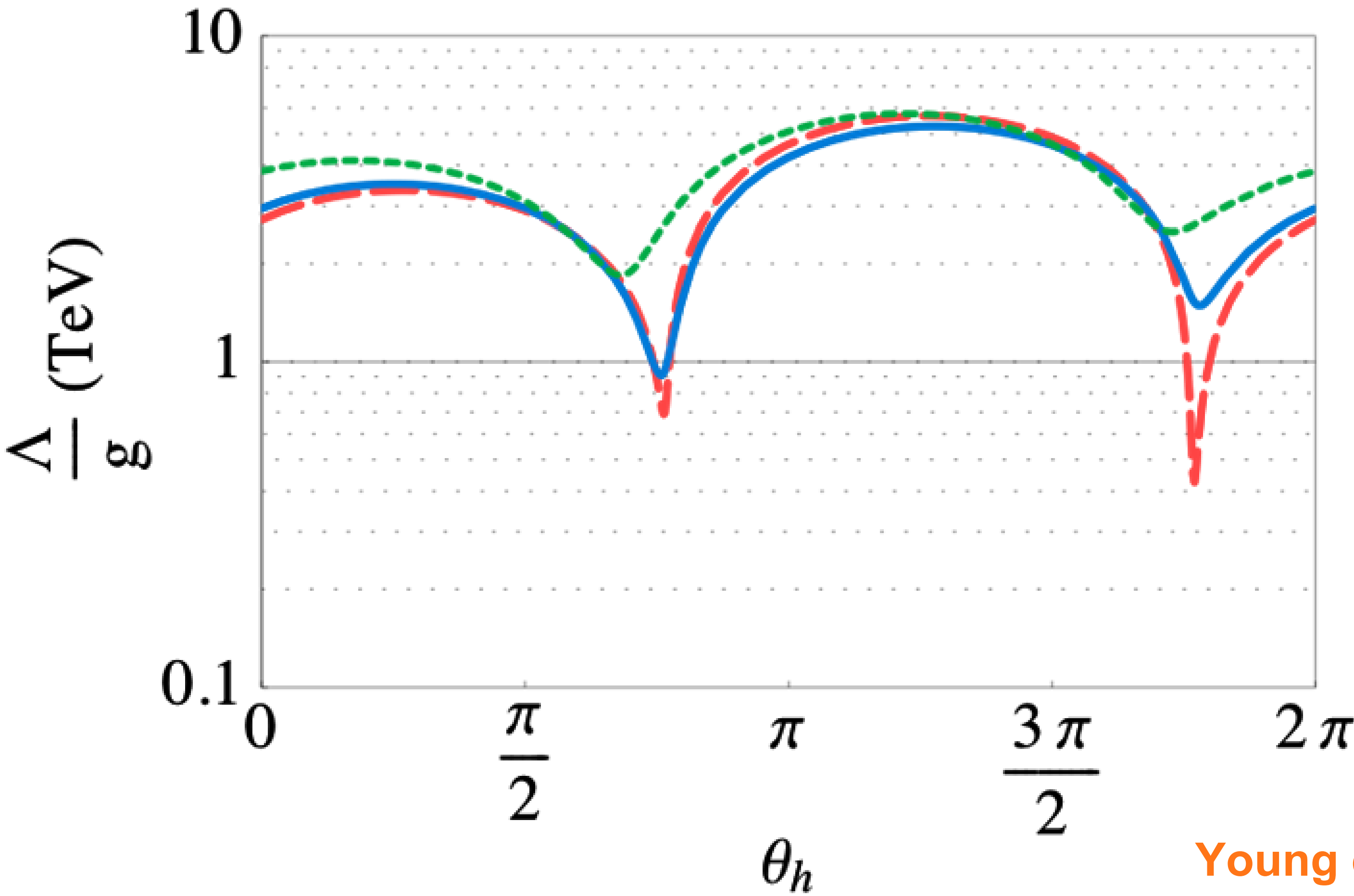
Young et al. (Dec 2006)

New physics scale >0.9 TeV! (up from 0.4 TeV)

Q_{weak} Apparatus



New Physics Limits
(if result consistent with Standard Model)



future Qweak

with PVES

Atomic only

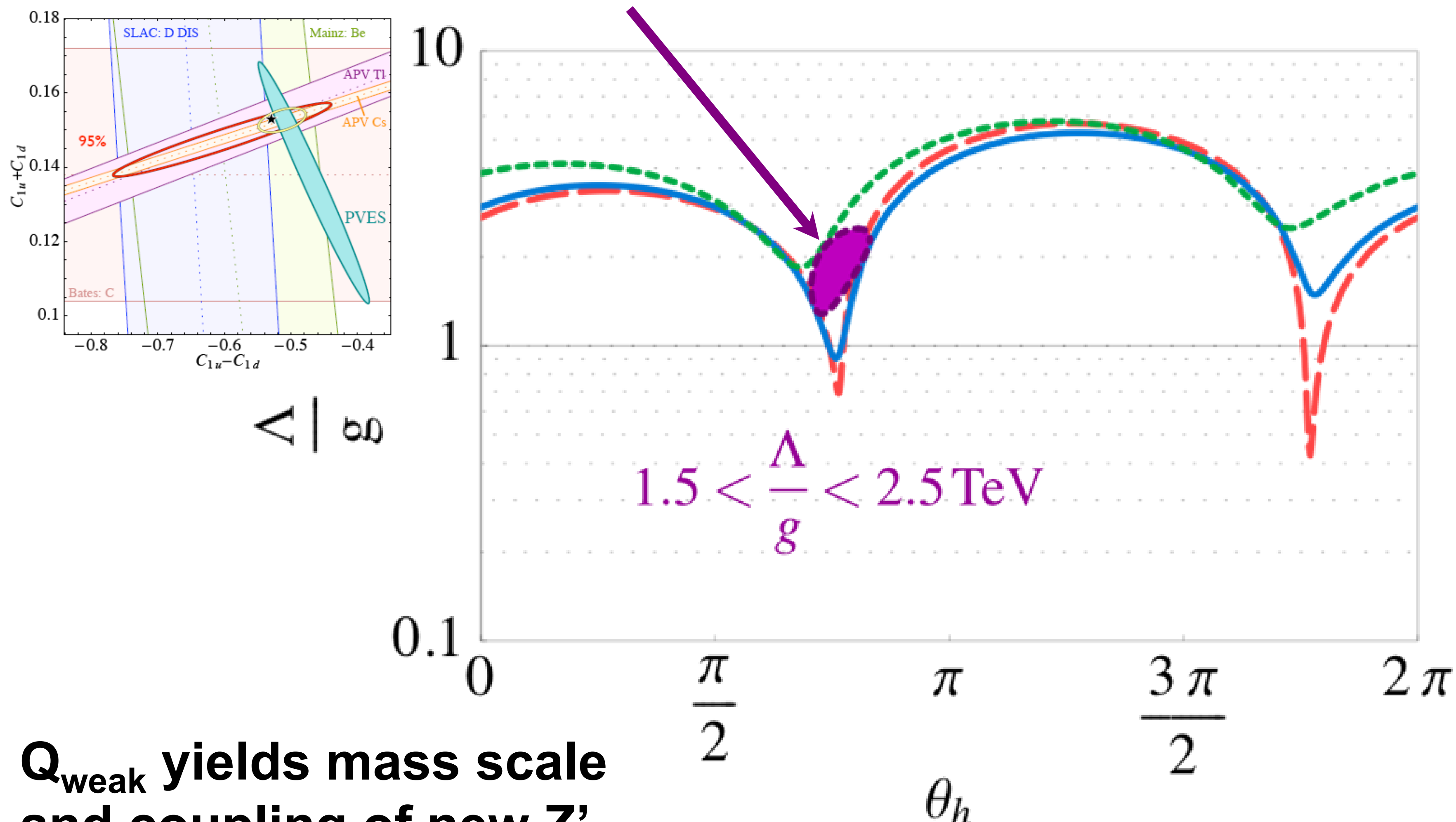
95% CL

Young et al. (Dec 2006)

Qweak constrains new physics to beyond 2 TeV

But: Q_{weak} has real discovery potential!

IF: Q_{weak} takes central value of current PVES measurement



Q_{weak} yields mass scale and coupling of new Z'

Young et al. (Dec 2006)

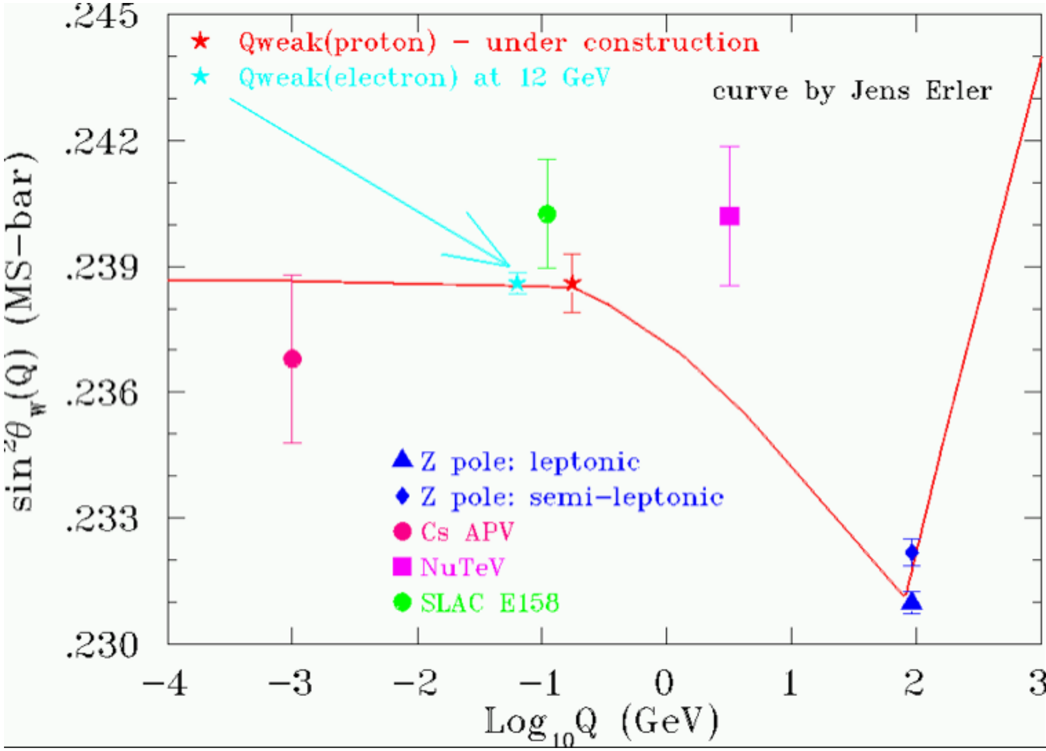
Future Möller Experiment at 12 GeV

Appears feasible to measure $\sin^2 \theta_W$ to $\pm$ 0.0002

Consensus Statement from December 2006 Workshop:

"There was overwhelming enthusiasm to aggressively proceed with the design of such an experiment"

"unique sensitivity to properties of new physics phenomena such as R-parity violating SUSY"

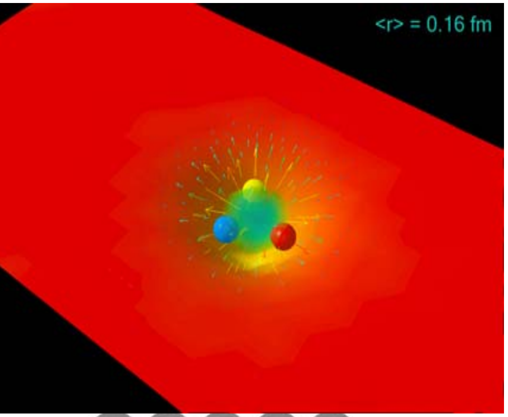


World Community in 2013 and Beyond

- With 12 GeV Upgrade will have three major new facilities investigating nuclear physics at quark level (QCD) : FAIR (GSI, Germany), J-PARC (Japan) and JLab*

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

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



* Unique: only electromagnetic machine