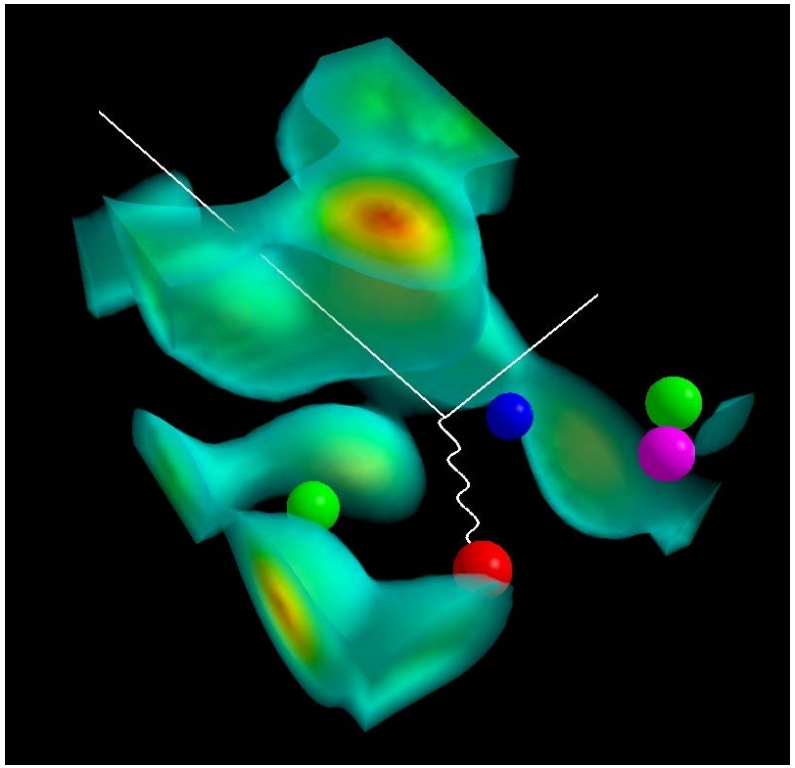
Science Opportunities Enabled by the 12 GeV Upgrade



Anthony W. Thomas

Science Review for the 12 GeV Upgrade
April 6th, 2005

NSAC Long Range Plan, April 2002 "Opportunities in Nuclear Science"

- **Recommendation 4:**

We strongly recommend the upgrade of CEBAF at Jefferson Laboratory to 12 GeV as soon as possible.

The 12 GeV upgrade of the unique CEBAF facility is critical for our continued leadership in the experimental study of hadronic matter. This upgrade will provide new insights into the structure of the nucleon, the transition between the hadronic and quark/gluon descriptions of matter, and the nature of quark confinement.

Statement by Dr. Raymond Orbach before the House Committee on Appropriations Subcommittee on Energy and Water March 15, 2005

In FY 2006 funds are provided to continue R&D activities for a potential 12 GeV Upgrade of the Continuous Electron Beam Accelerator Facility (CEBAF). These investments will poise the facility for a cost-effective upgrade that would allow insight on the mechanism of "quark confinement" – one of the compelling unanswered puzzles of physics.

NSAC 2003 Facilities Review

"The accelerator portion of the Upgrade is straightforward"

"The key issues…..have been addressed successfully."

"The scientific goals and proposed design of the Upgrade have been positively evaluated by internal and peer review committees,…."

"All remaining R&D is focused on cost reduction and/or improved technical contingency; no R&D is needed to demonstrate feasibility. *The project is fully ready to initiate construction."*

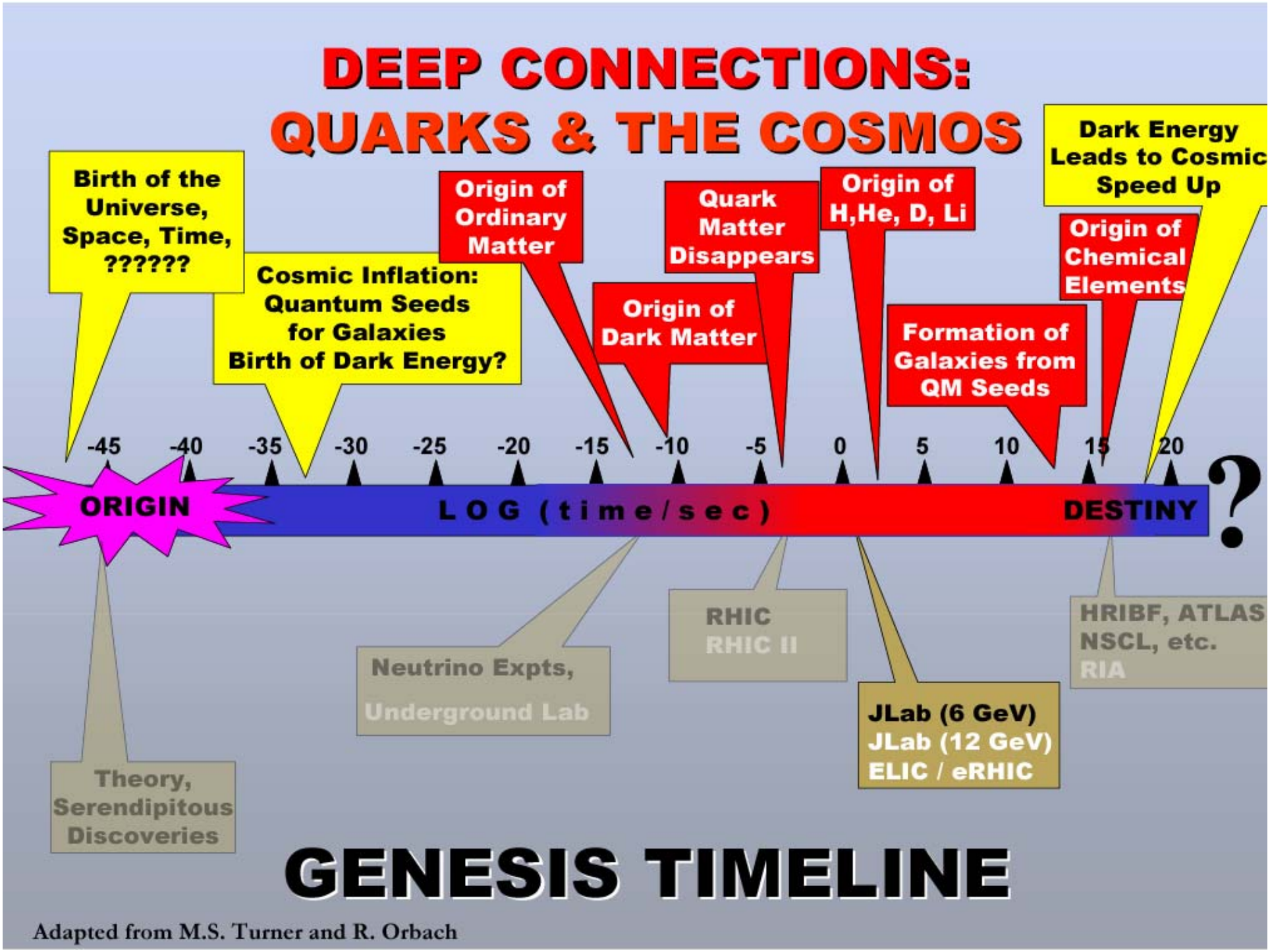
JLab is the Current and Future International Flagship for Hadron Physics

- **Important competition in limited areas from Bates, ELSA, GRAAL, HERMES, MAMI, SPring8….**

- **Complementary work at: COMPASS, COSY, Fermilab, RHIC…**

NONE of these facilities has the combination of luminosity, duty factor and kinematic reach to compete with JLab in any area of science outlined here

NO other facility is planned ANYWHERE which can do this science: science essential to discovering how the strong interaction works



Adapted from M.S. Turner and R. Orbach

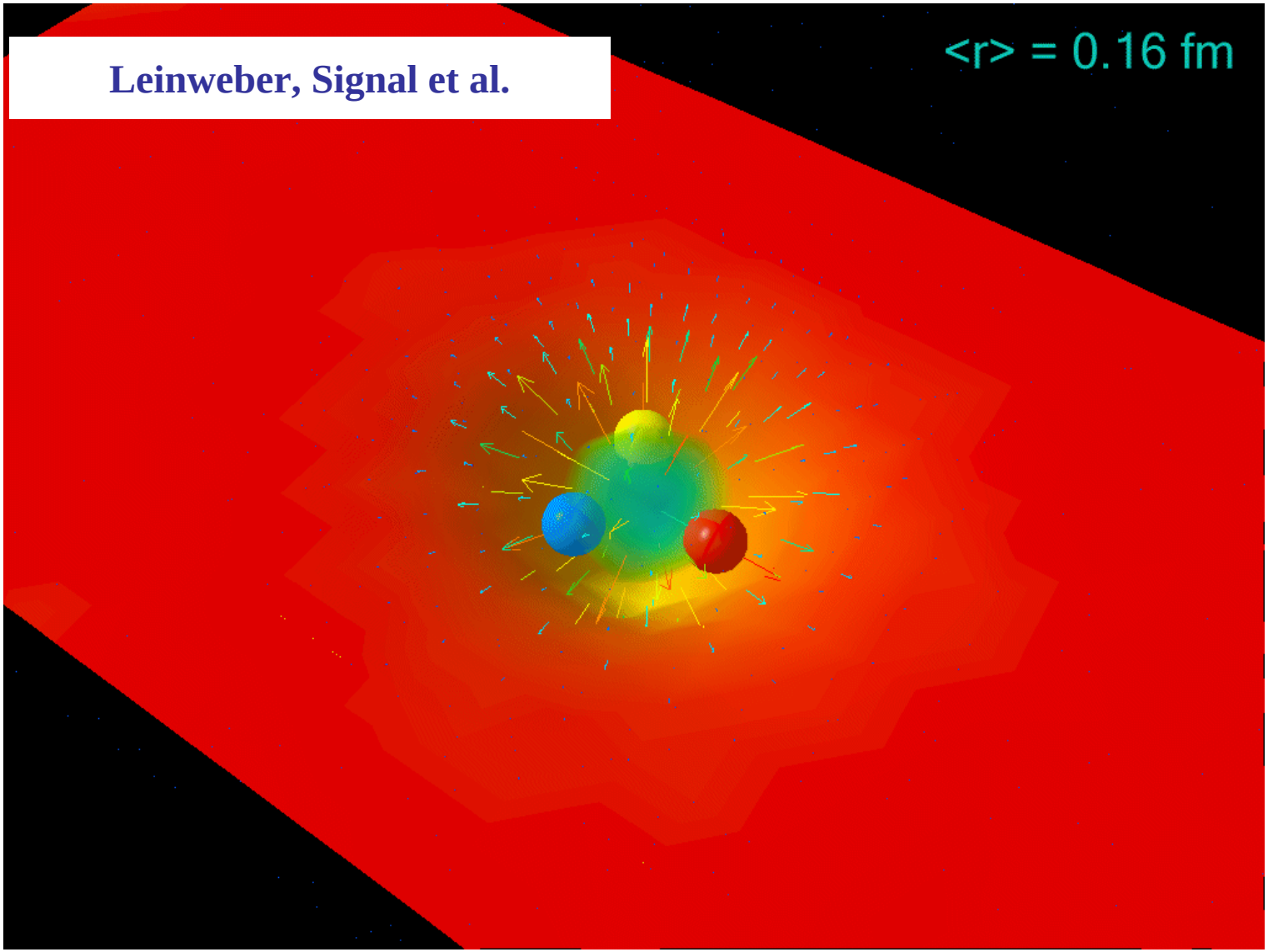
QCD and the Origin of Mass

$$u + u + d = \text{proton}$$

$$\text{mass: } 0.003 + 0.003 + 0.006 \neq 0.938$$

HOW does the rest of the proton mass arise?

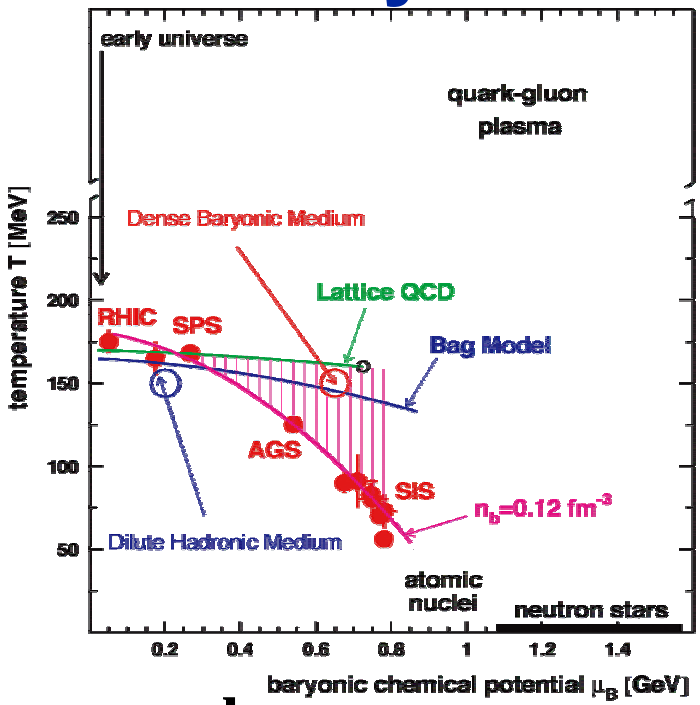
Lattice QCD Simulation of Vacuum Structure



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….**

- **Approaches rooted in 1930s: NN forces, NNN forces**
  more recently: EFT / Effective (Skyrme) Forces

- **But Λ N, Σ N, Ξ N interactions, origin of M* ???**

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**

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!**

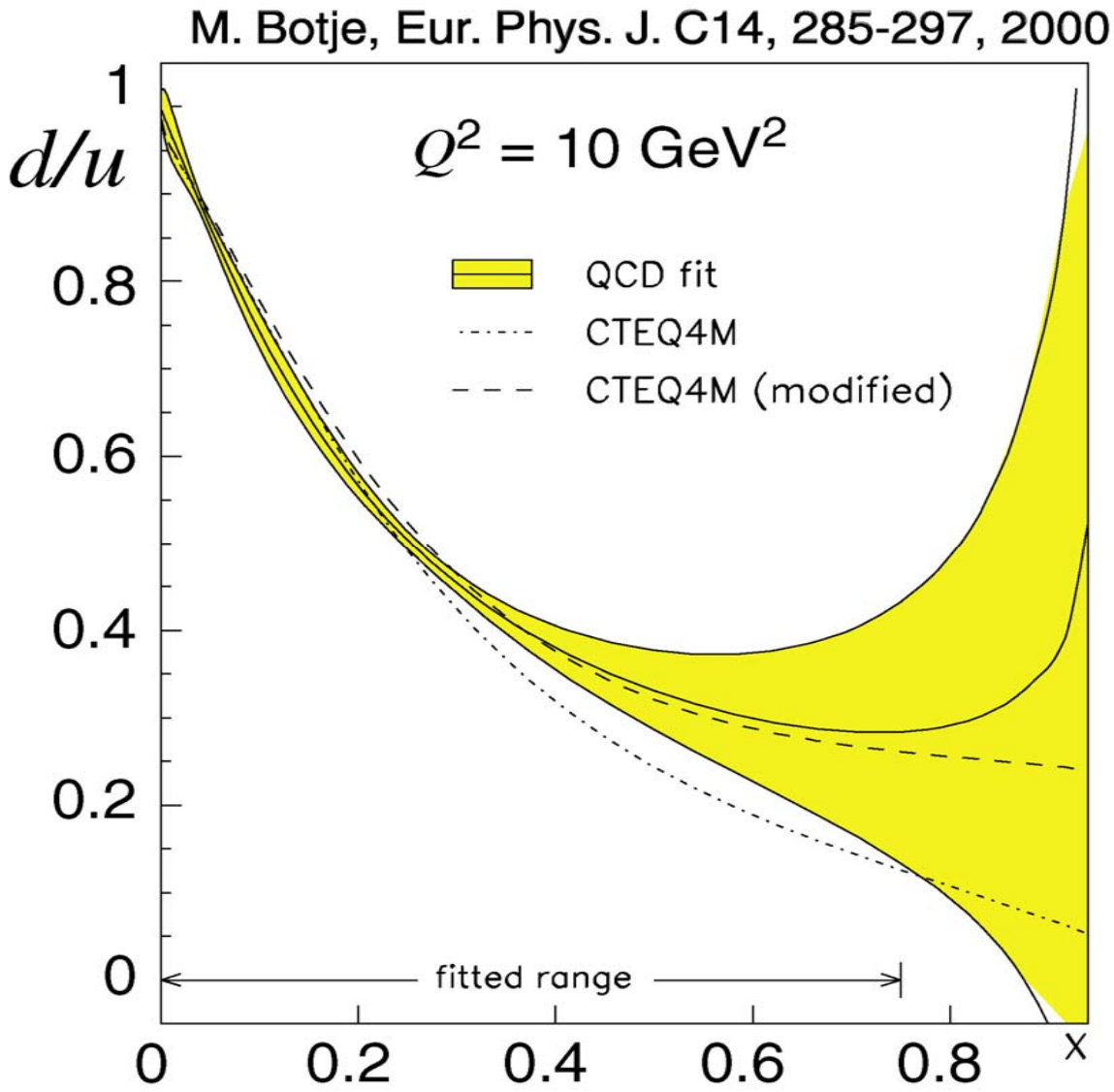
  Role of di-quark correlations?

  Role of hard scattering: pQCD / LCQCD guidance?

  Breaking of SU(6) symmetry?

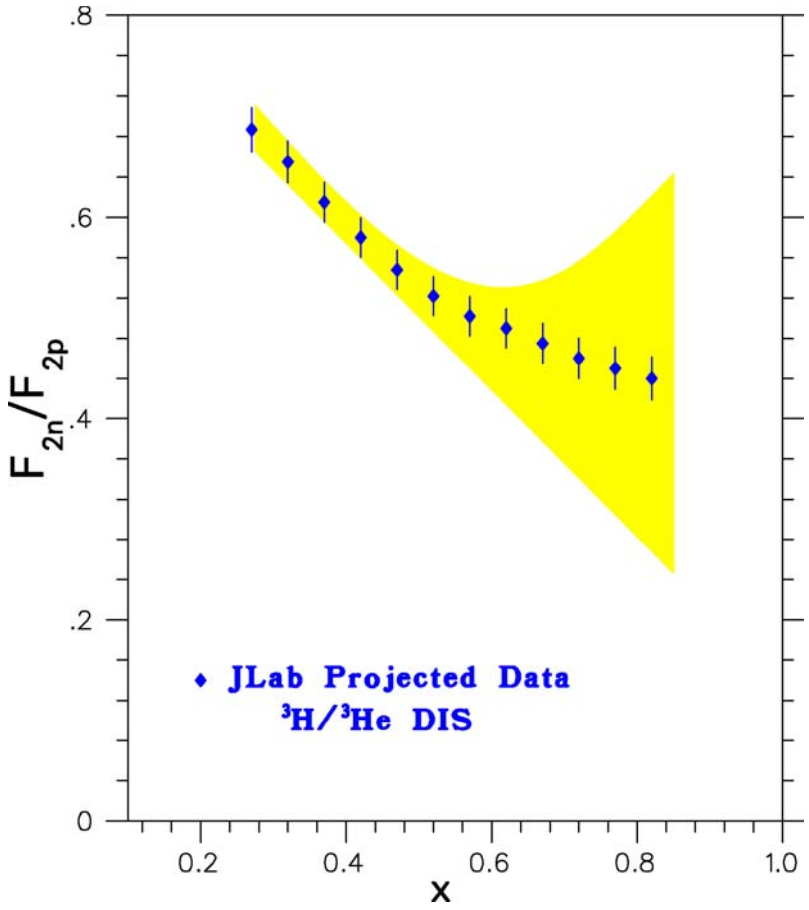
  Moments of PDFs (and GPDs) from Lattice QCD….

Miserable Lack of Knowledge of Valence d-Quarks

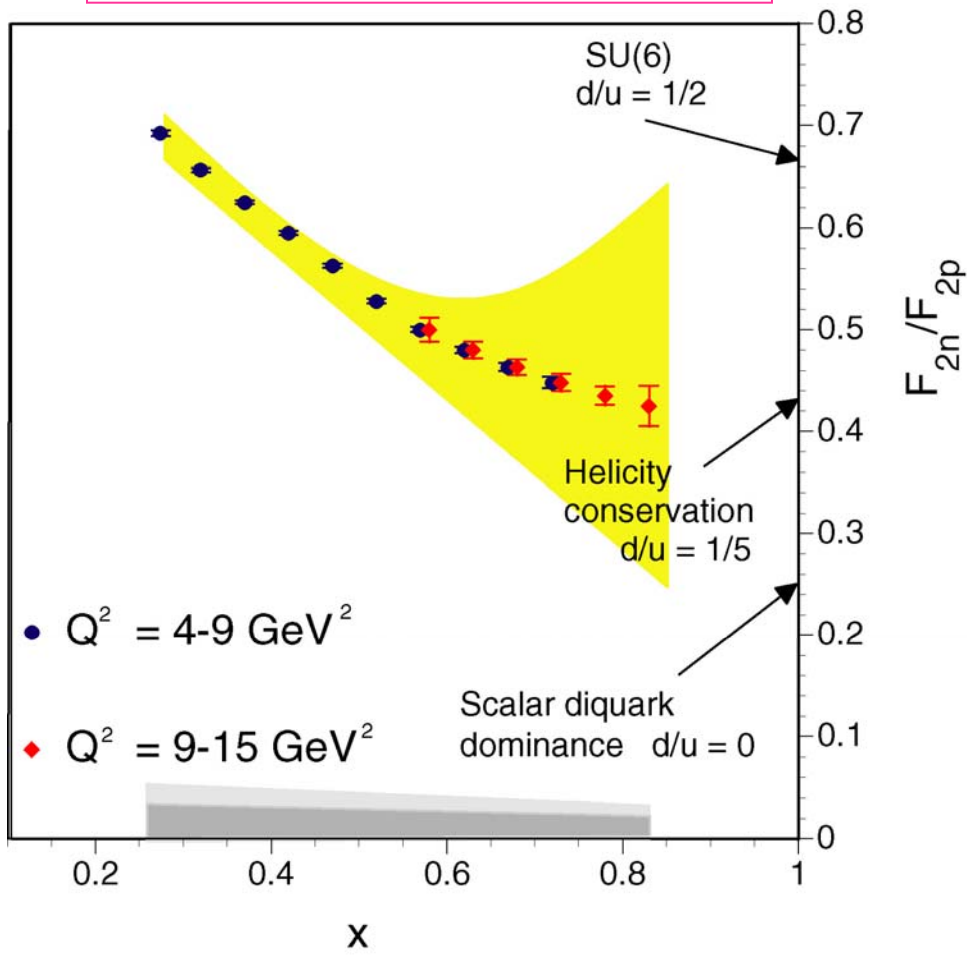


12 GeV : Unambiguous Resolution

Hall C 11 GeV with HMS

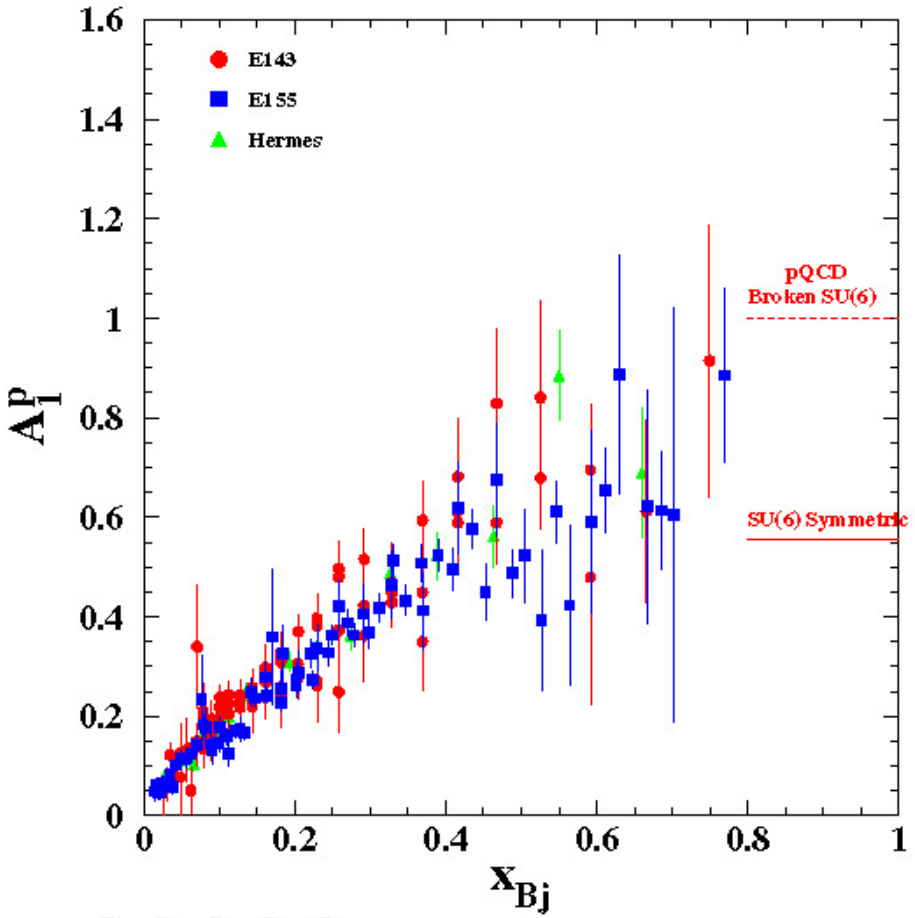


HallB 11 GeV with CLAS12

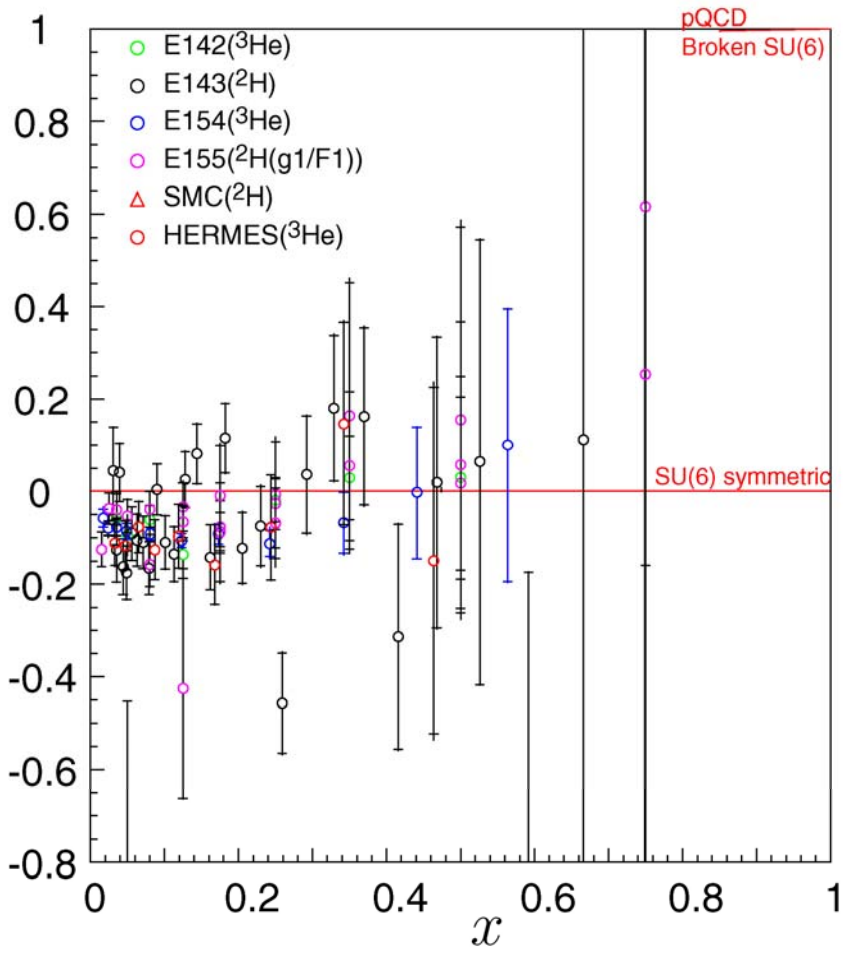


Spin Dependence at Larger x Unknown

Proton

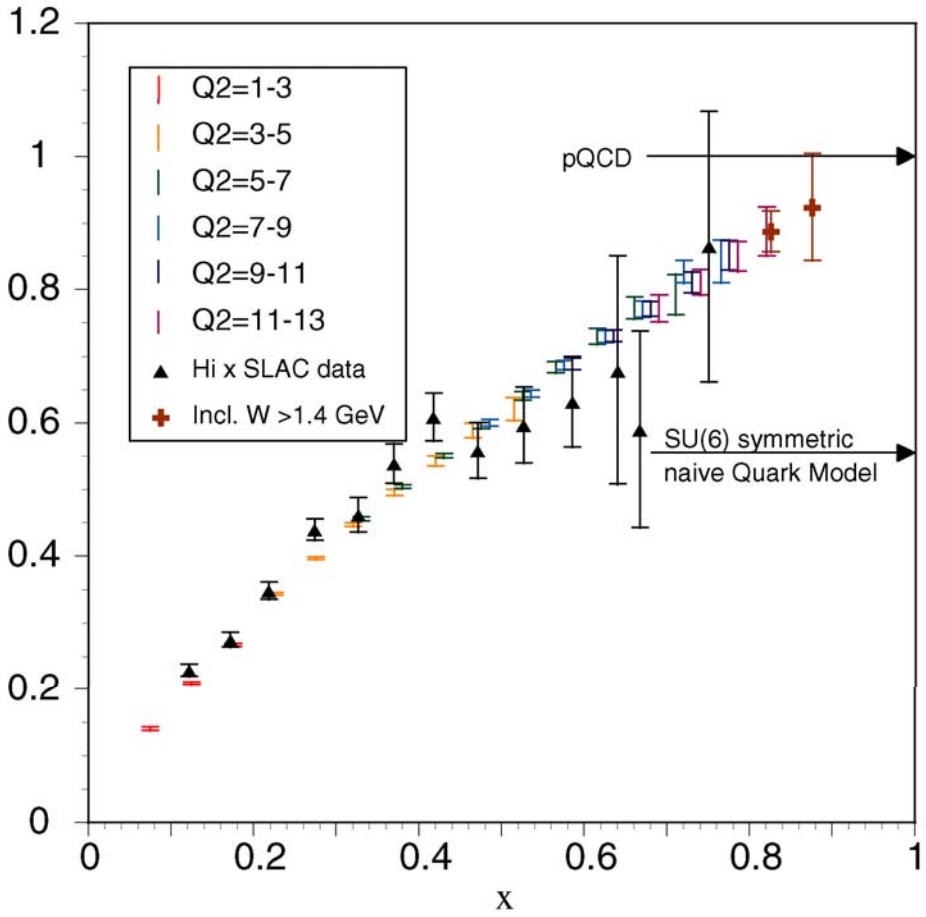


Neutron

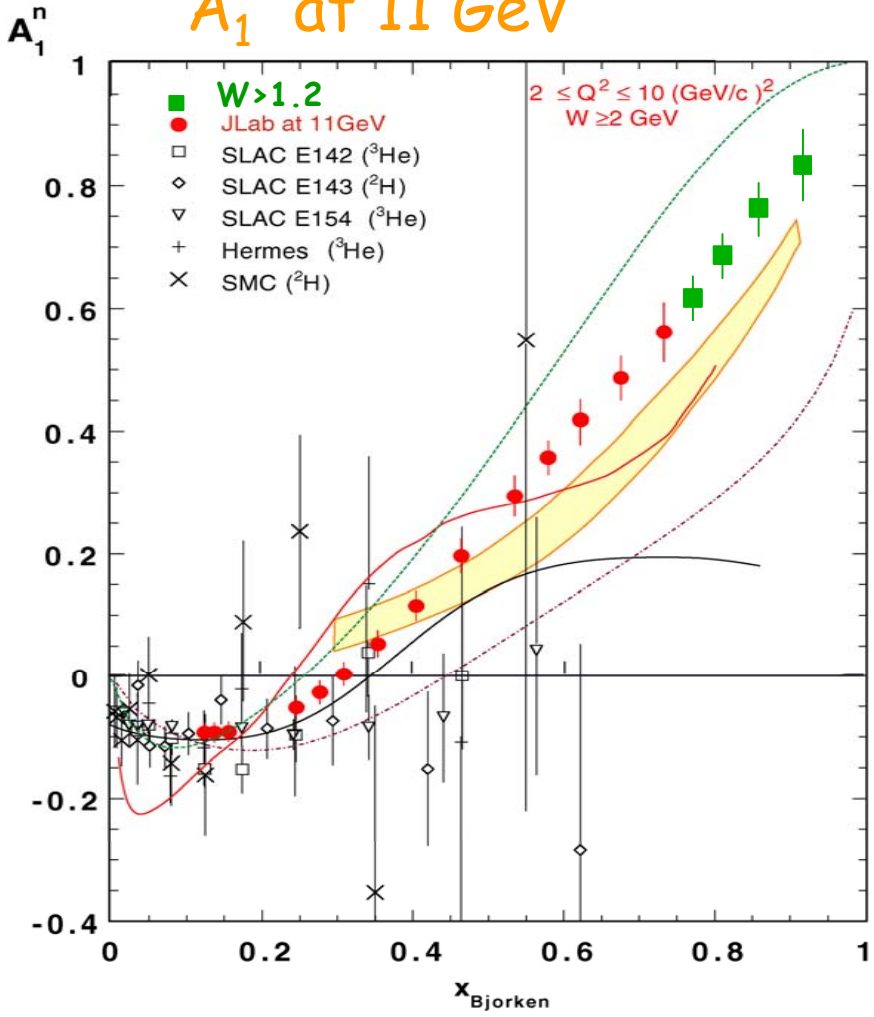


12 GeV : Unambiguous Resolution

A_1^p at 11 GeV



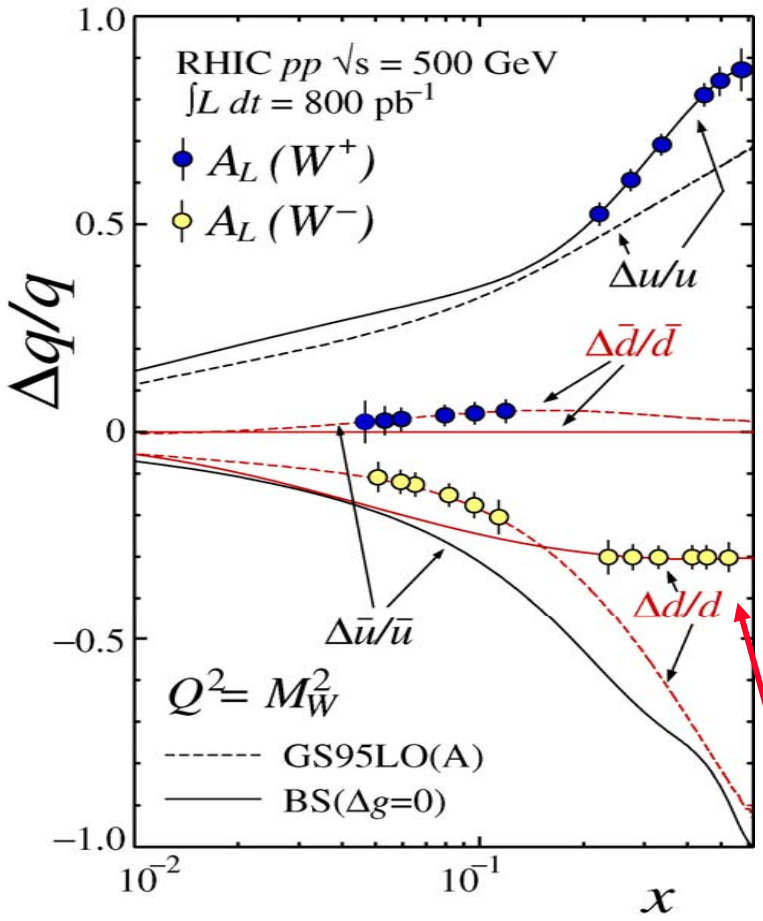
A_1^n at 11 GeV



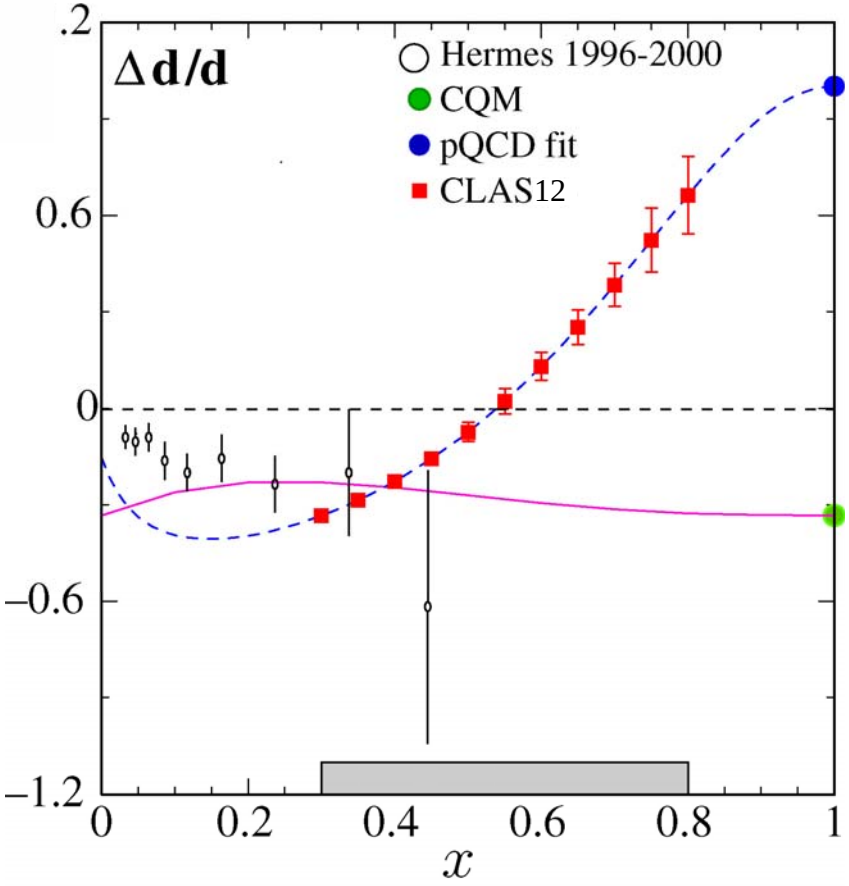
Unique Reach and No Ambiguity

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)

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Color Polarizabilities

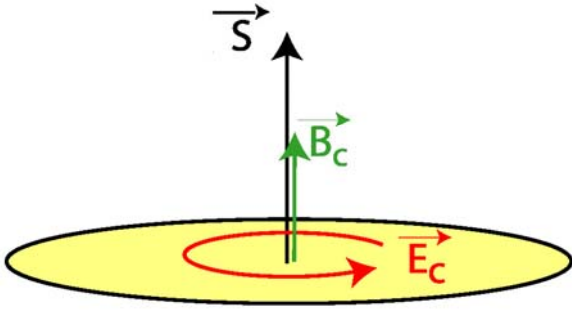
How does the gluon field respond when a nucleon is polarized ?

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

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



$$\chi_E^n = (4d_2^n + 2f_2^n)/3$$
$$\chi_B^n = (4d_2^n - f_2^n)/3$$

χ_E and χ_B represent the response of the color $\vec{B}$ & $\vec{E}$ fields to the nucleon polarization

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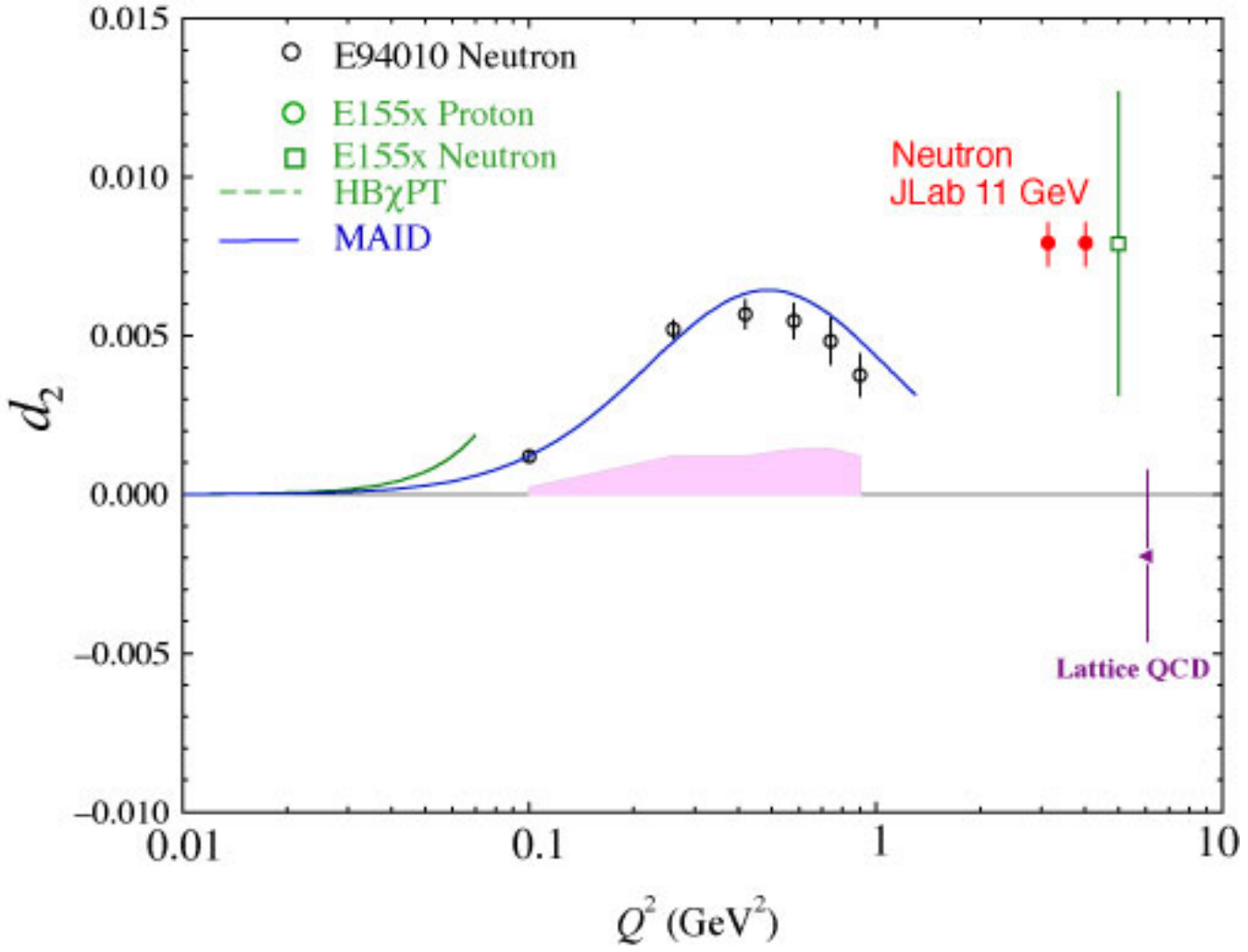
Precision Determination of d_2



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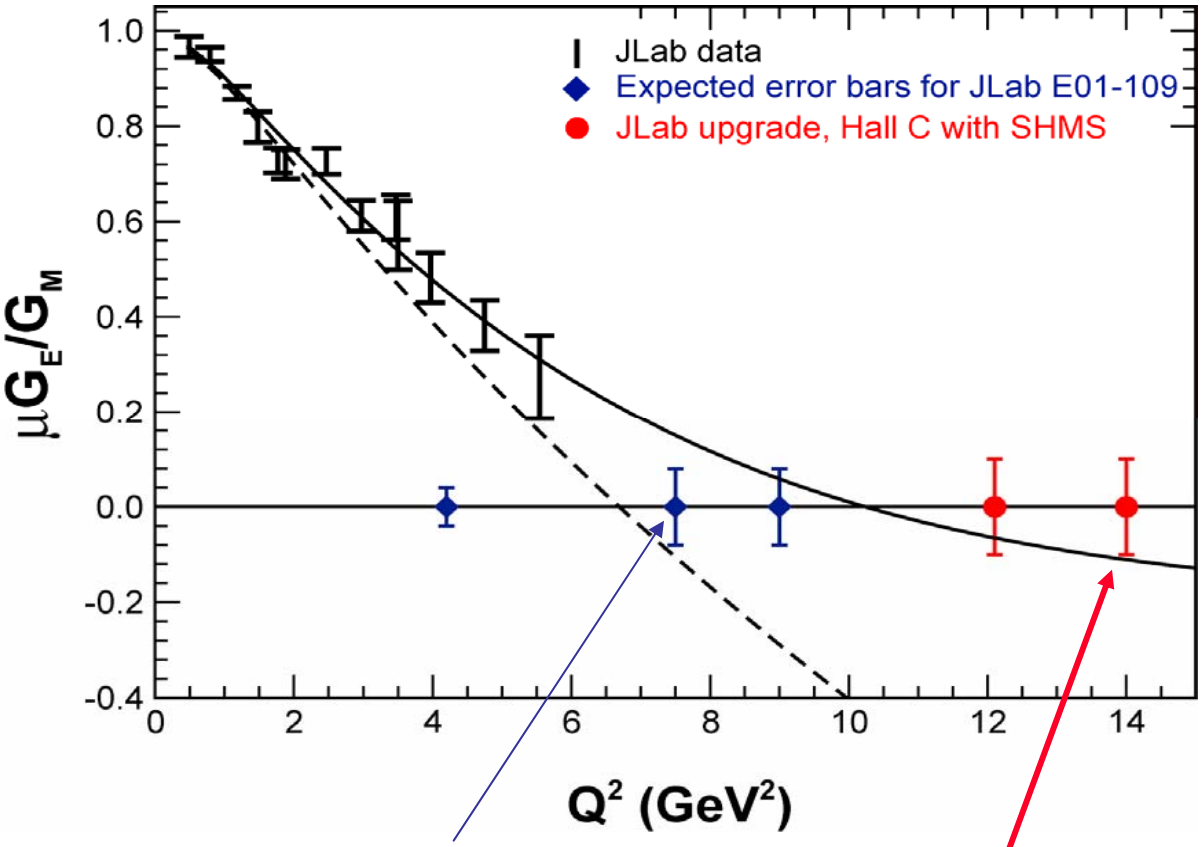
Revolutionize Our Knowledge of Distribution of Charge and Current in the Nucleon

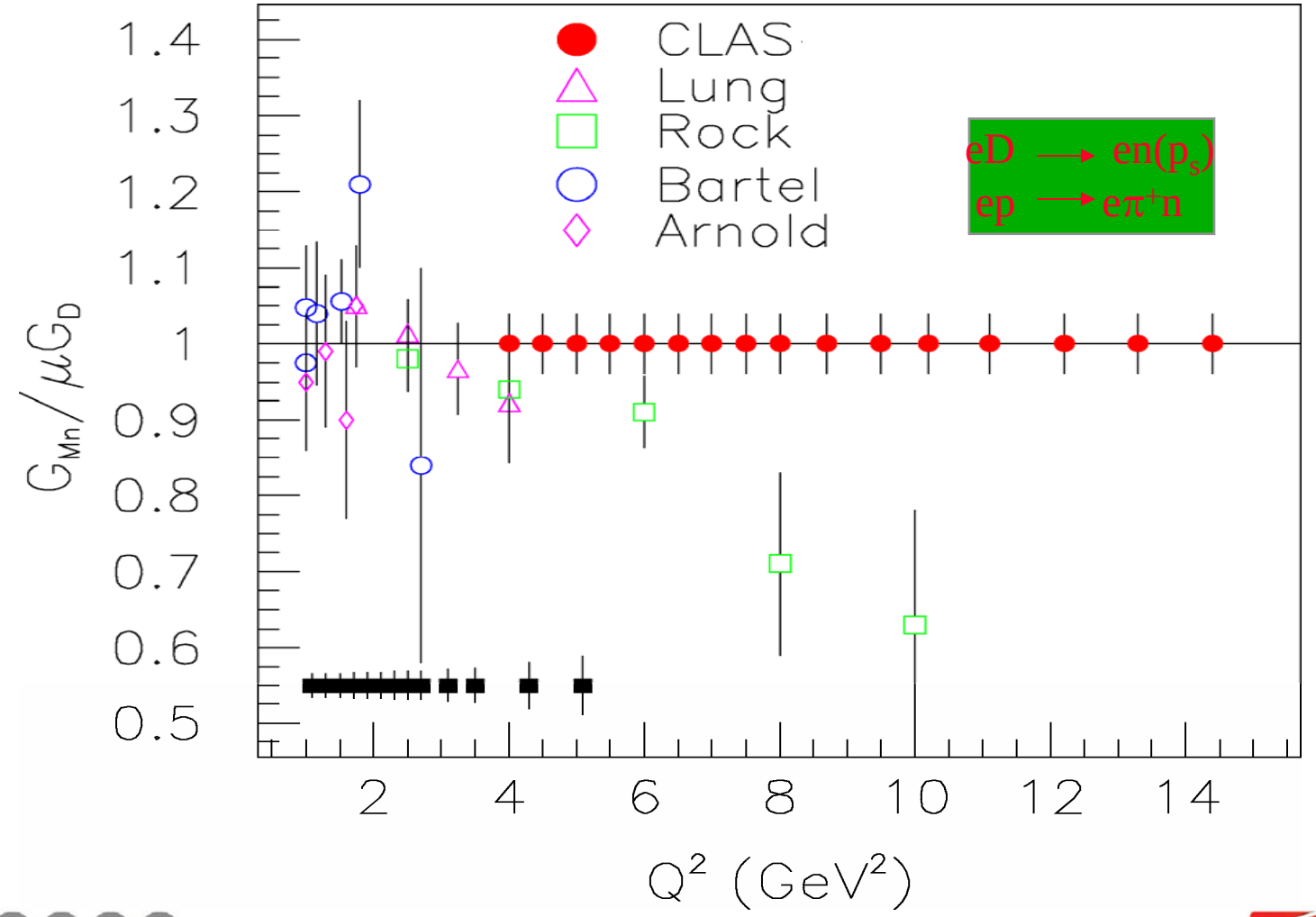


full: Lomon
dashed: Miller

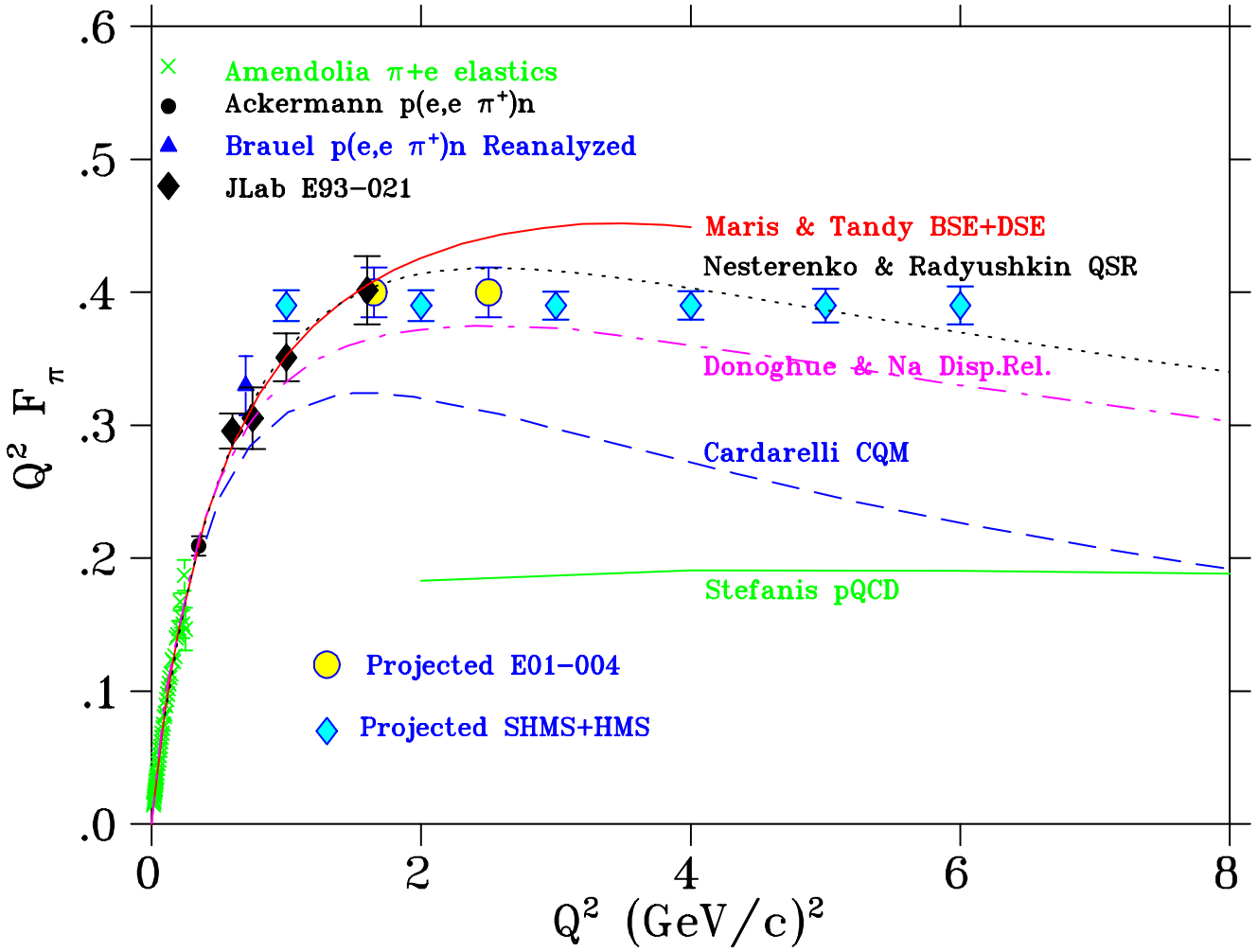
- Perdrisat *et al*. E01-109
- SHMS in Hall C at 11 GeV

CLAS 12 : Neutron G_M^n

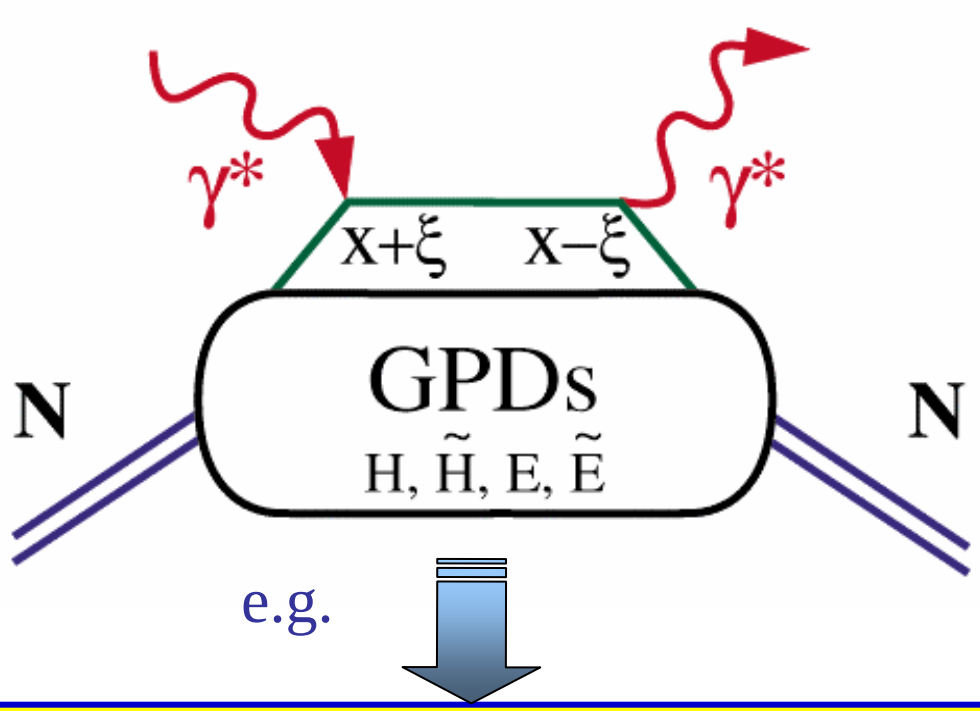
With 12 GeV Upgrade



Unique Probe of the Deep Structure of the Pion: The Goldstone Boson of QCD



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

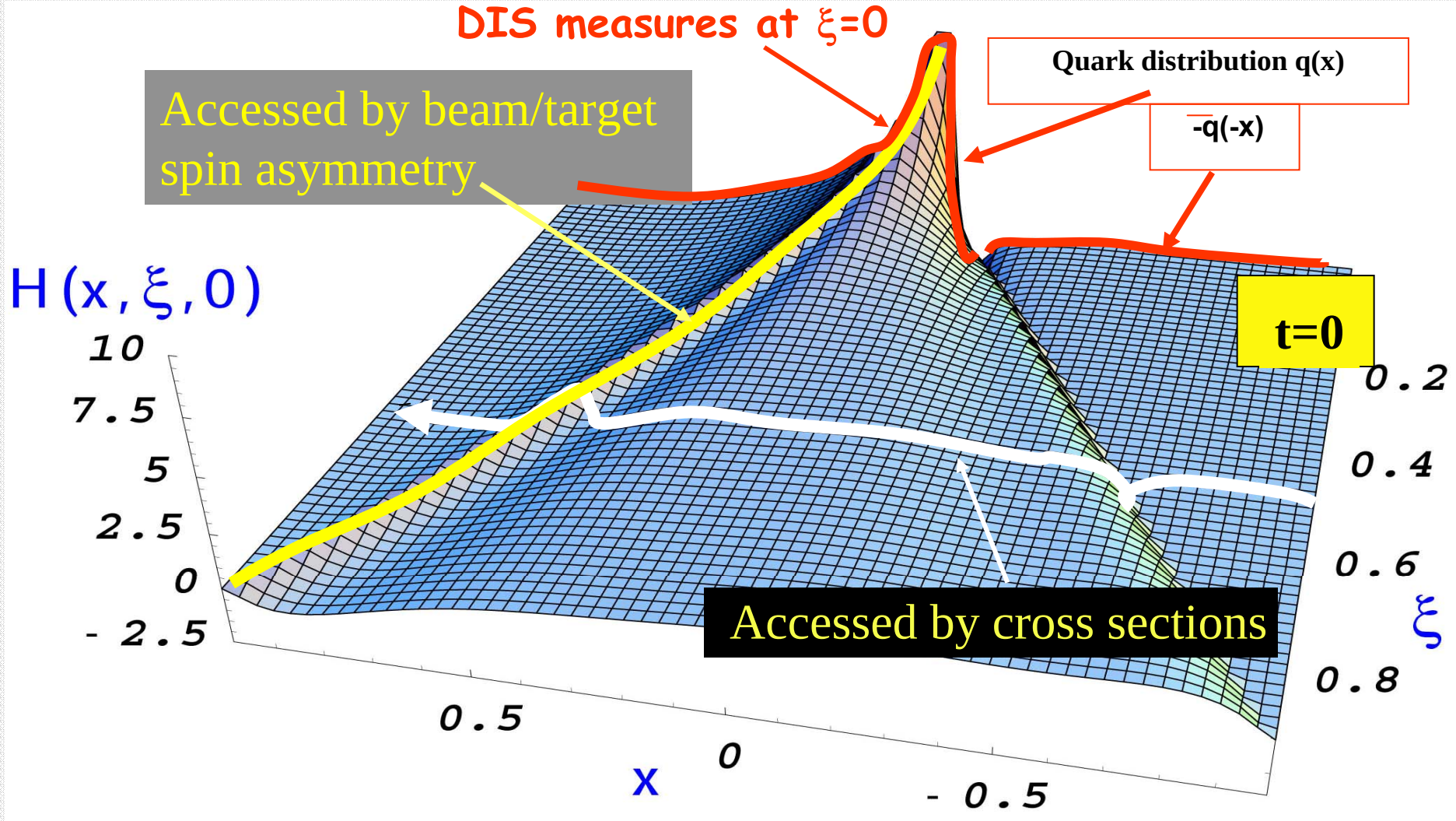


Quark angular momentum (Ji's sum rule)

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

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

Access GPDs through x-section & asymmetries



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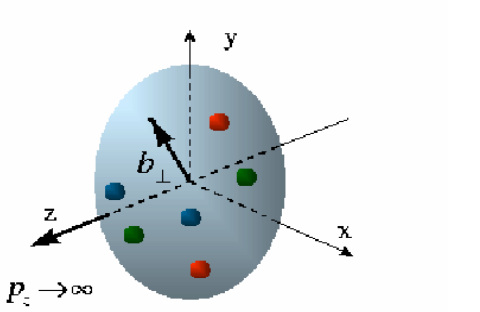
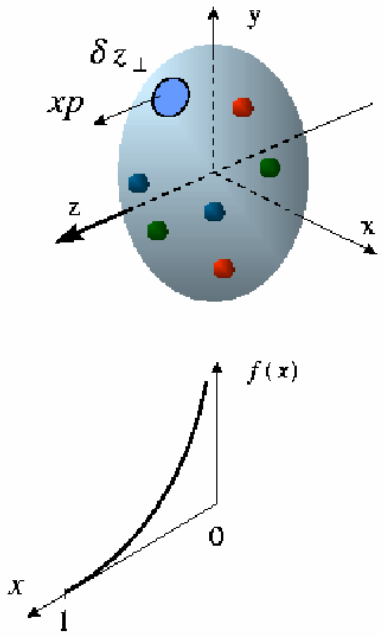
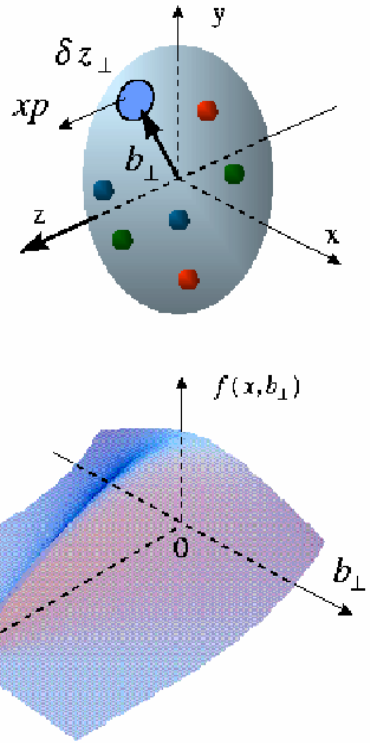
GPDs Yield 3-Dimensional Quark Structure







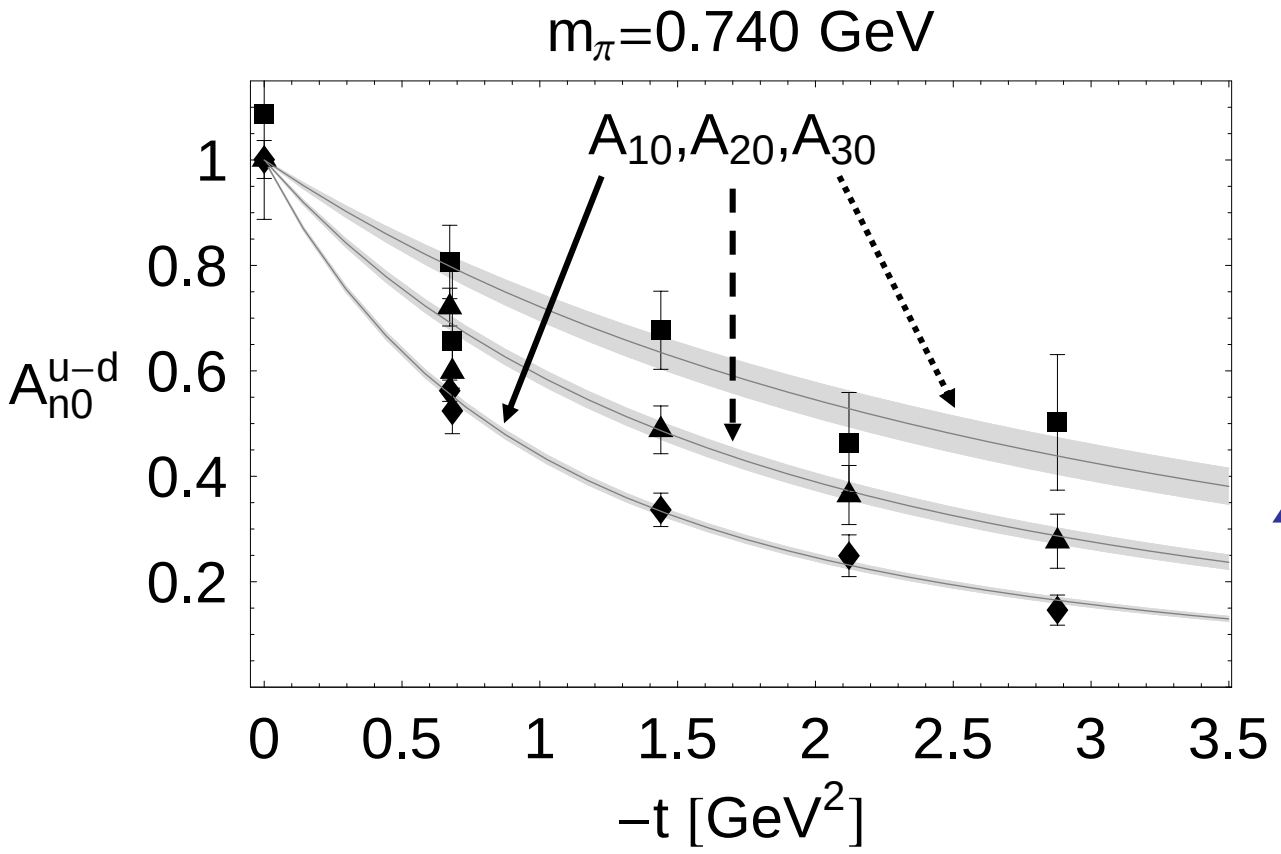
Elastic Scattering
transverse quark distribution in Coordinate space

$b_\perp$

DIS
$_\perp$ longitudinal quark distribution in momentum space

DES (GPDs)
Fully-correlated quark distribution in both coordinate and momentum space

Generalized form factors…



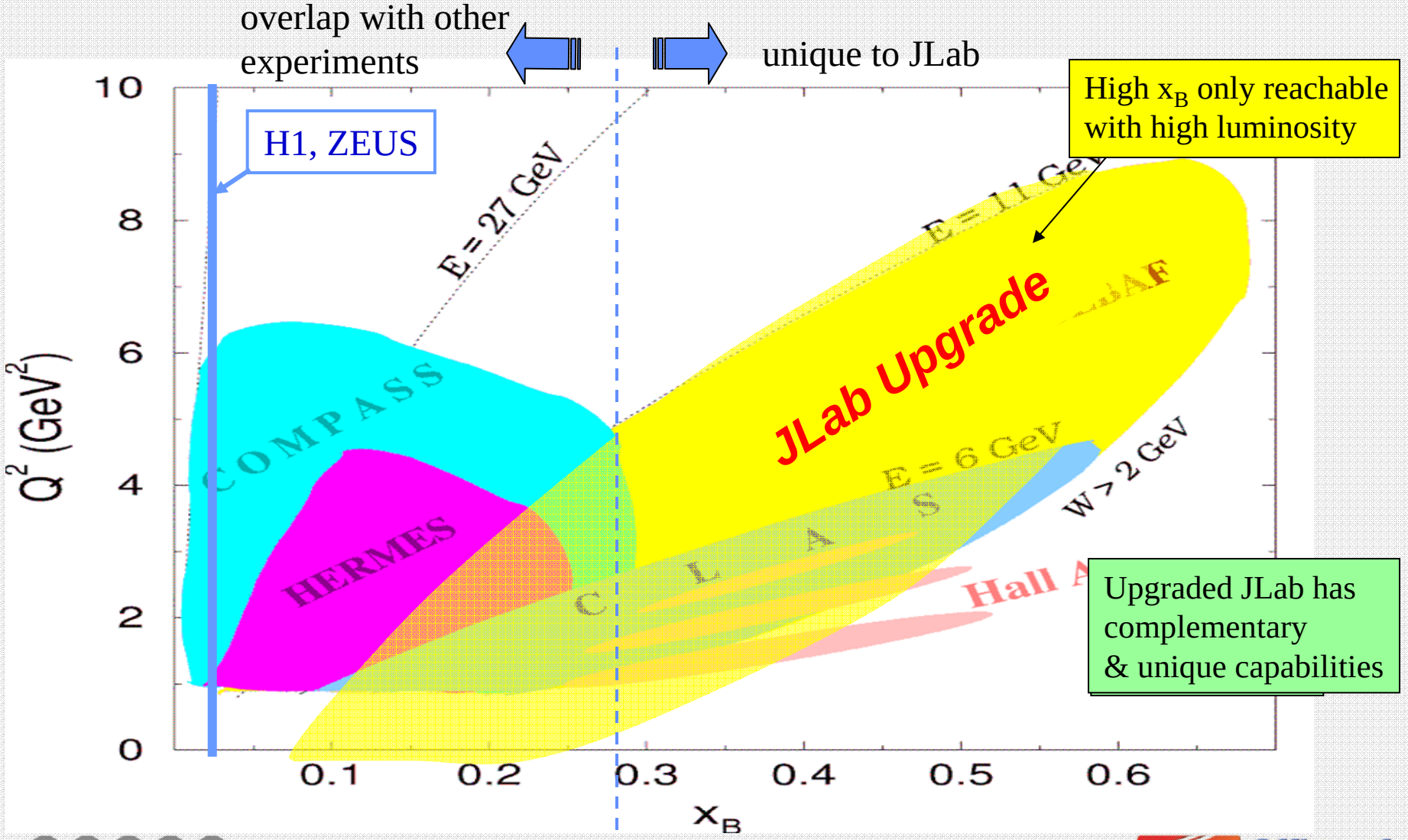
LHPC (Edwards, Richards et al..)

Weighting larger x

Decrease slope : decreasing transverse size as $x \to 1$

Burkardt

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



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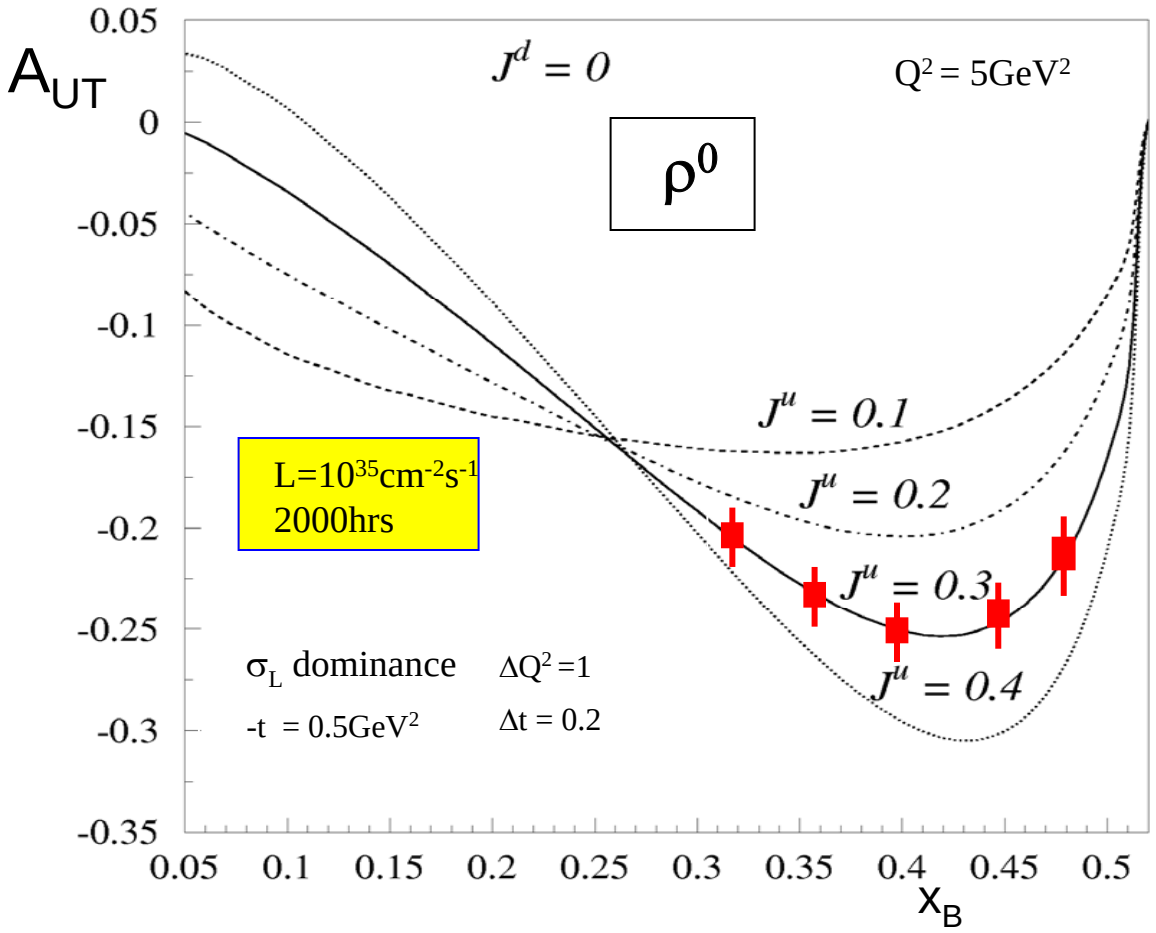
Exclusive ρ^0 with transverse target

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

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.

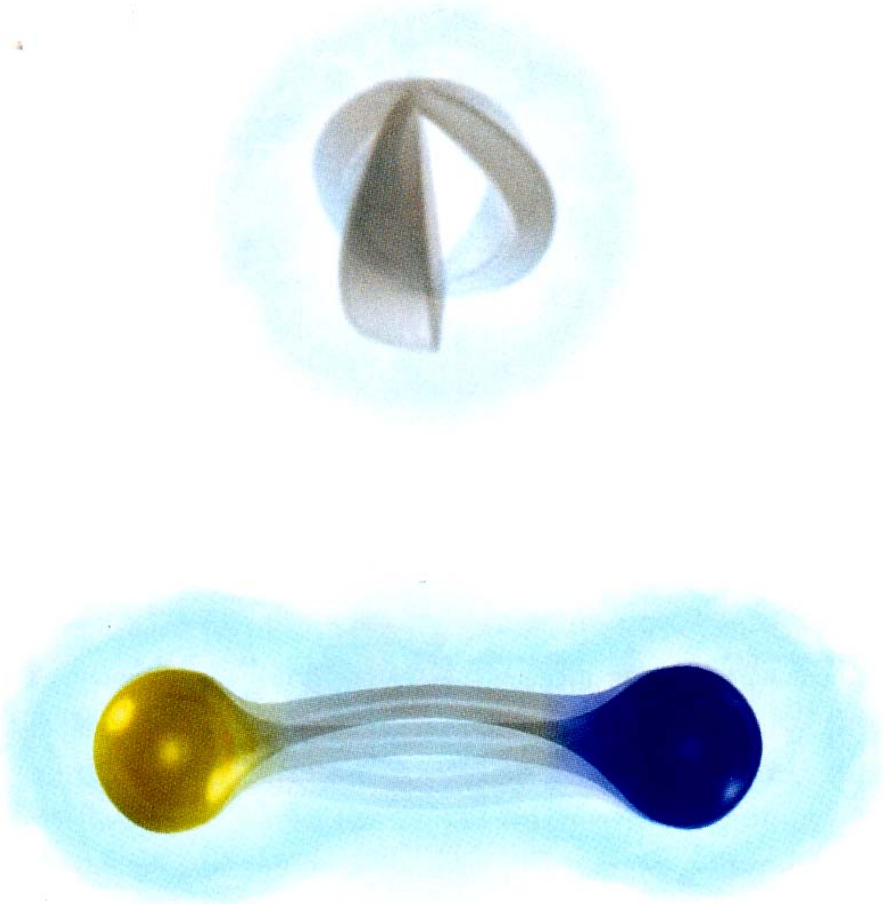
K. Goeke, M.V. Polyakov, M. Vanderhaeghen, 2001

QCD: Unsolved in Nonperturbative Regime

- **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?**
- **Do glueballs, exotics and other apparent predictions of QCD in this regime agree with experiment?**

JLab at 12 GeV is uniquely positioned to answer!

QCD: Exotics



QCD predicts the existence of exotic mesons

Glueballs are mesons without valence quarks

Other exotics involve excitation or vibration of gluons

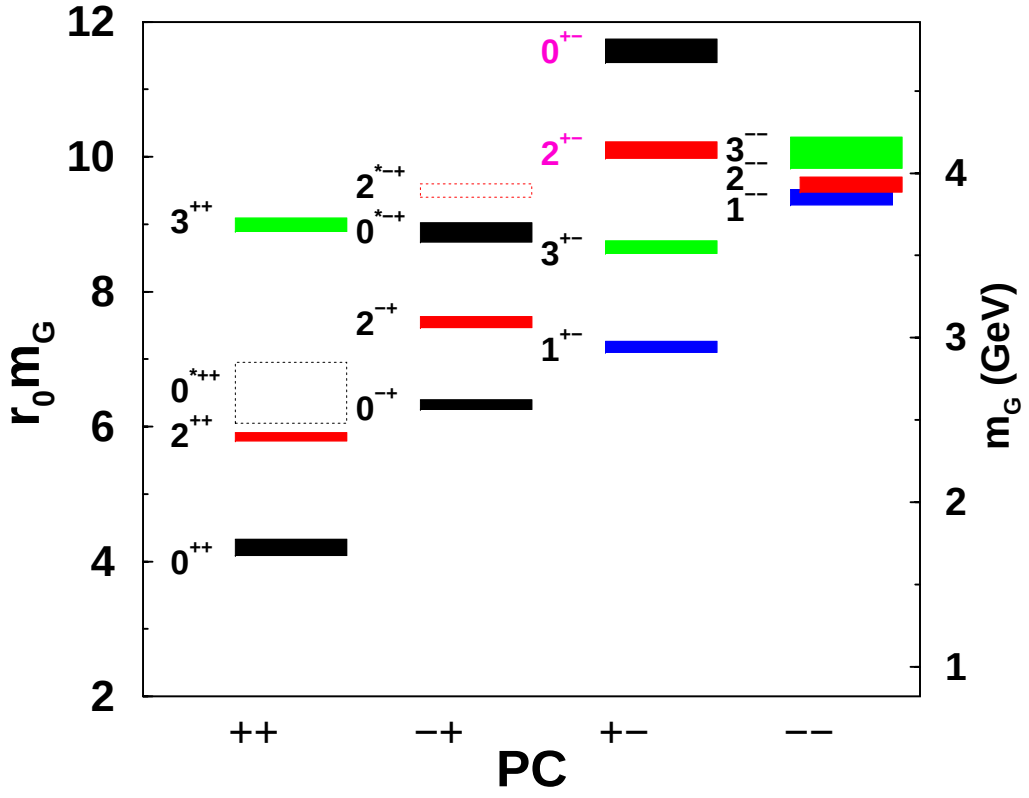
Glueballs

- Glueballs are “pure gluon” states emblematic of non-Abelian nature of QCD
- Aim to compute masses of lowest few states of given quantum number

Morningstar and Peardon
PRD60, 034509

Quenched glueball calculations provide road-map

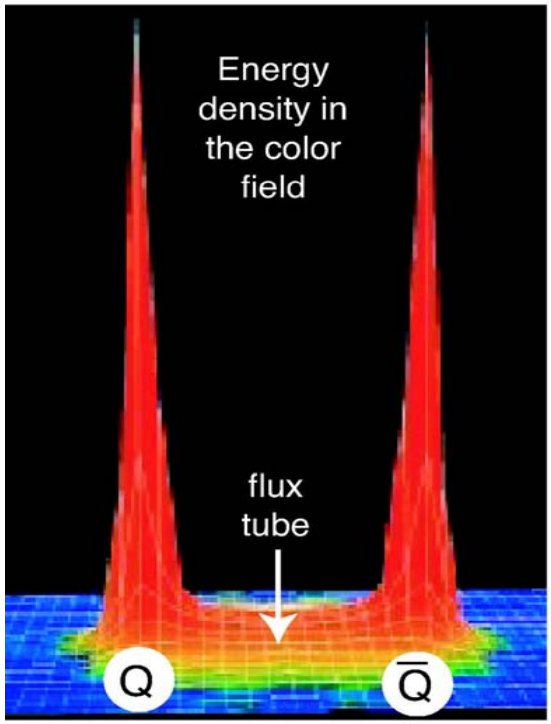
• Method more demanding for particles containing quarks

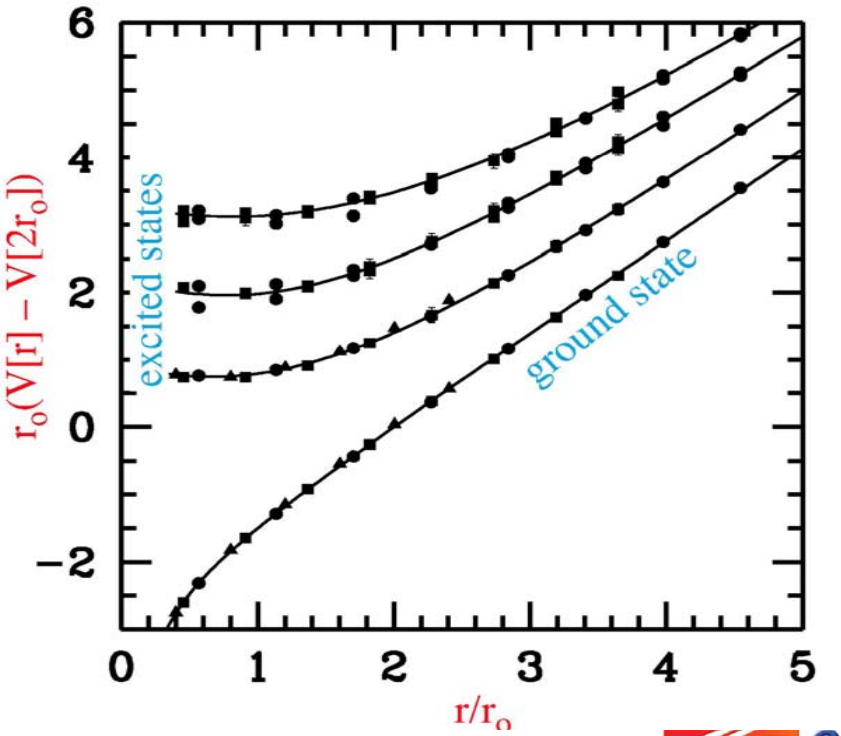


(N.B. $r_0^{-1} \sim 0.4$ GeV)

Exotics – BNL/ JLab/ GSI

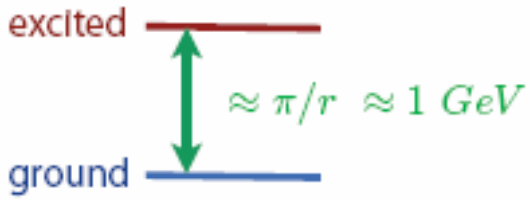
- Computations in heavy-quark sector- insight into excitations of the string
- For heavy quarks, **energy associated with "excited string" of around 1 GeV**
- Lowest 1^{-+} state around 1.8-2.0 GeV:
  plus χ'al correction ~ -0.1 to -0.2 GeV





Masses and Widths of Hybrid Mesons

Masses and Widths



widths are expected to be of order 150-200 MeV

LQCD Mass Predictions for: $J^{PC} = 1^{-+}$

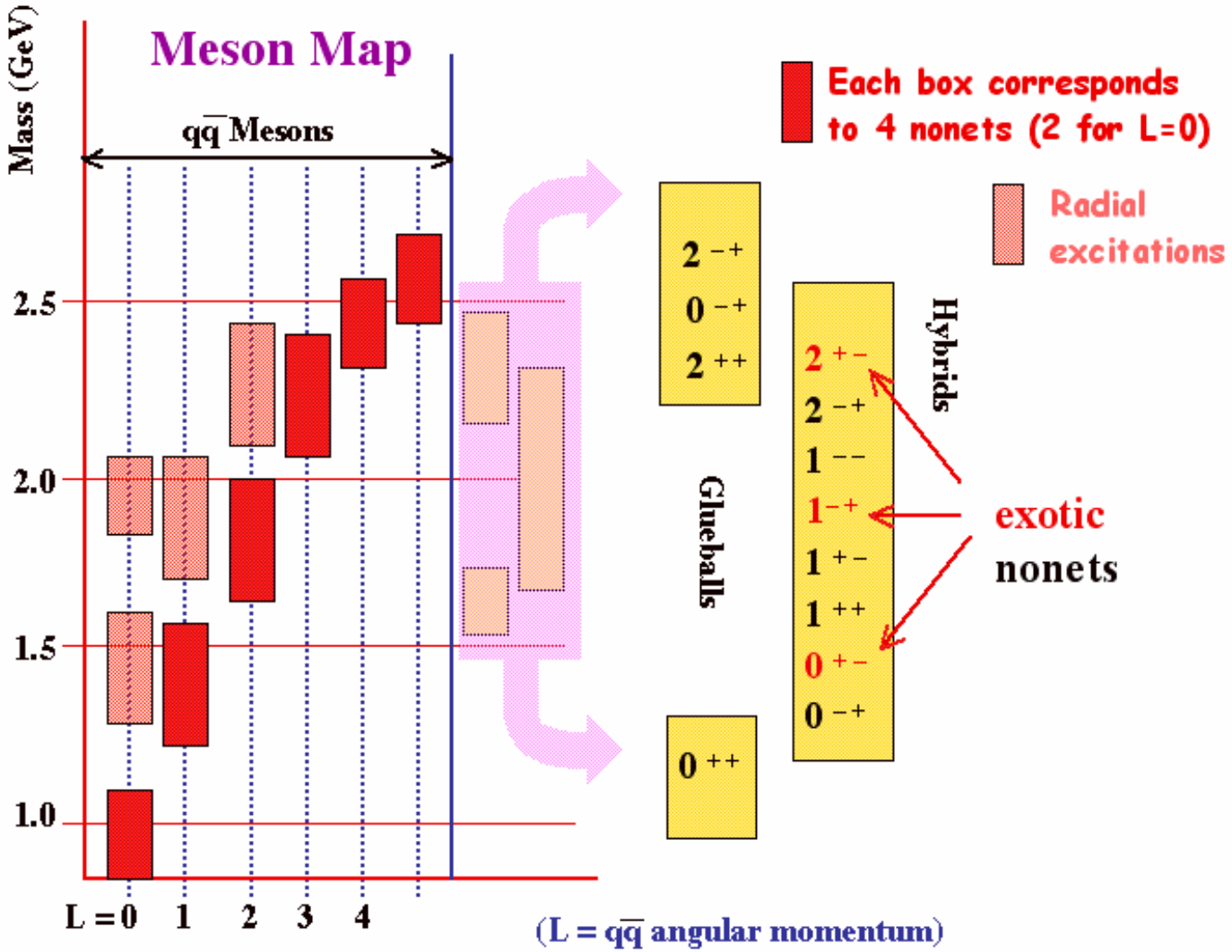
Author		1^{-+} Mass (GeV/c^2)	
Collab.	Year	$u\bar{u}/d\bar{d}$	$s\bar{s}$
UKQCD	(1997)	1.87 ± 0.20	2.0 ± 0.2
MILC	(1997)	$1.97 \pm 0.09 \pm 0.30$	$2.170 \pm 0.080 \pm 0.30$
MILC	(1999)	$2.11 \pm 0.10 \pm (sys)$	
SESAM	(1998)	1.9 ± 0.20	
Mei& Luo	(2003)	$2.013 \pm 0.026 \pm 0.071$	
Bernard *et al.*	(2004)	1.792 ± 0.139	2.100 ± 0.120

LQCD Mass Predictions for other exotic J^{PC}

Multiplet	J^{PC}	Mass (GeV/c^2)
π_1	1^{-+}	1.9 ± 0.2
b_2	2^{+-}	2.0 ± 0.11
b_0	0^{+-}	2.3 ± 0.6

above for $u\bar{u}/d\bar{d}$ for $s\bar{s}$ add ≈ 0.3 GeV

Glueballs and hybrid mesons



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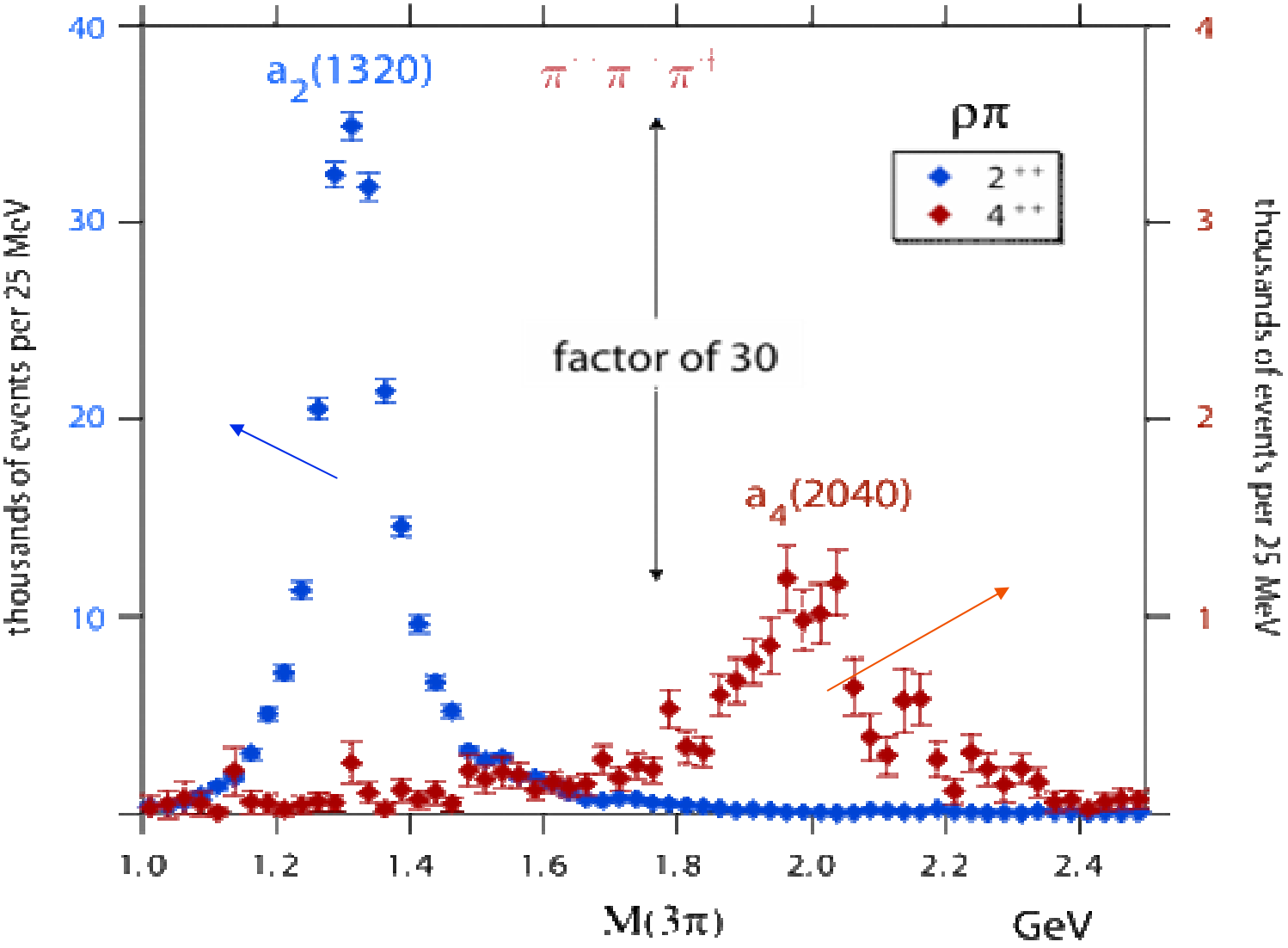
PWA Has A Large Dynamic Range



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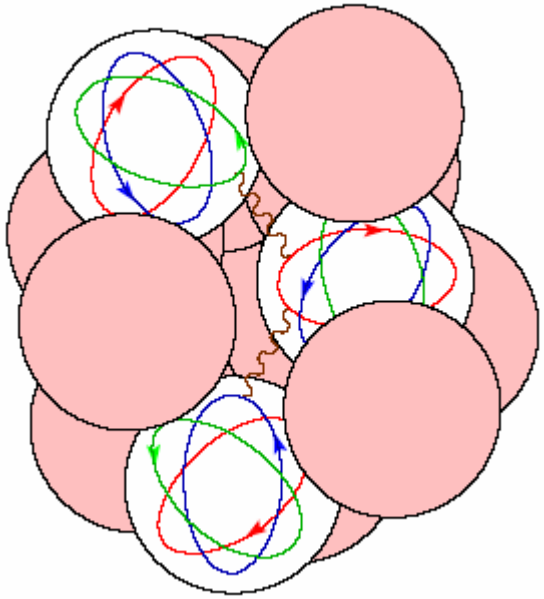
Nuclear Structure in Terms of QCD

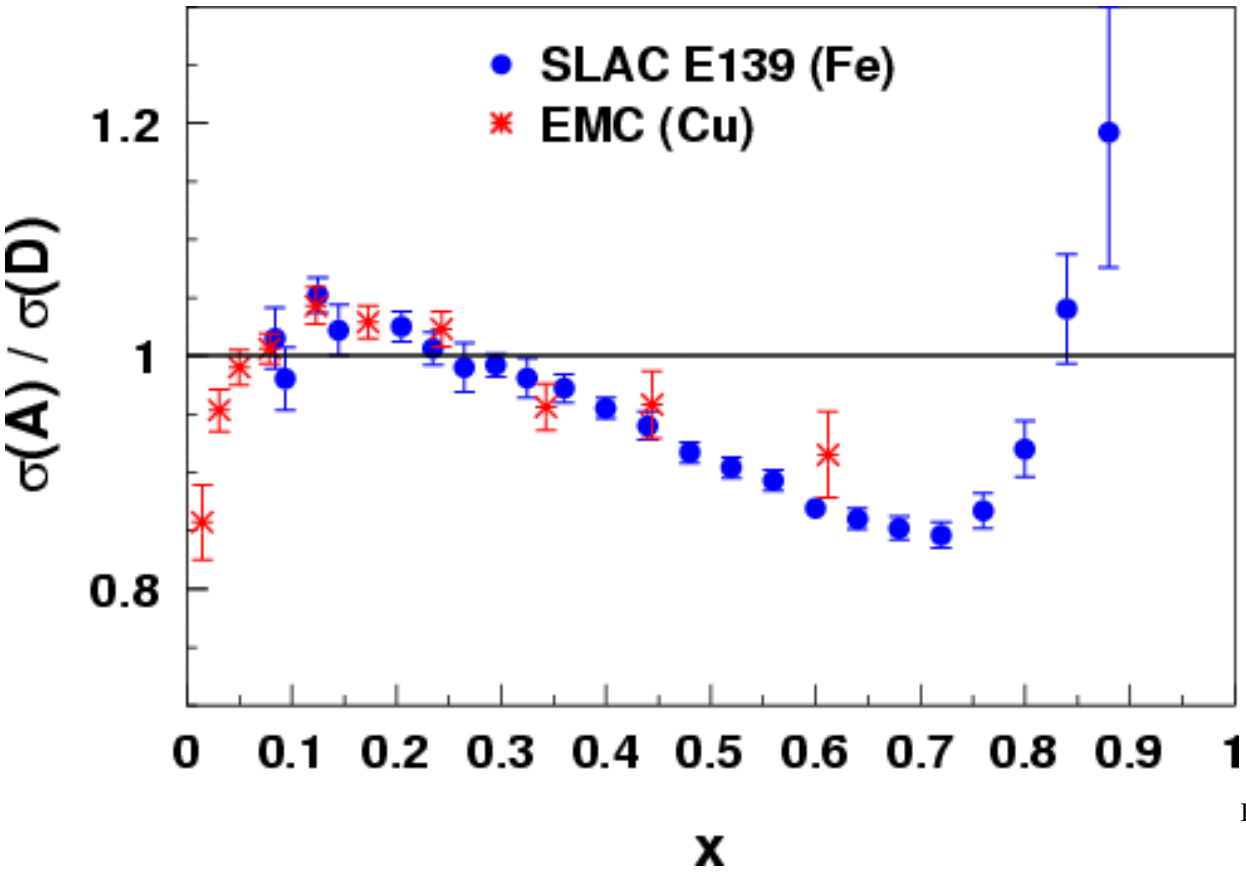
Aim for :



- New physical insight into nuclear structure
- e.g. new mechanism for nuclear saturation!
- Precursors of the deconfinement transition?
- Guidance as to signals of deconfinement transition
- Signals of chiral restoration as density rises….
- **Changes in hadron properties in-medium !**

Properties of quark systems in-medium: Origin of the EMC effect

- **Observation that structure functions are altered in nuclei stunned and electrified much of the HEP community 30 years ago**
- **Nearly one thousand papers have been generated, many models can fit the curve, but data are insufficient to uniquely identify the origin**
- **What is it that alters the quark momentum in the nucleus?**

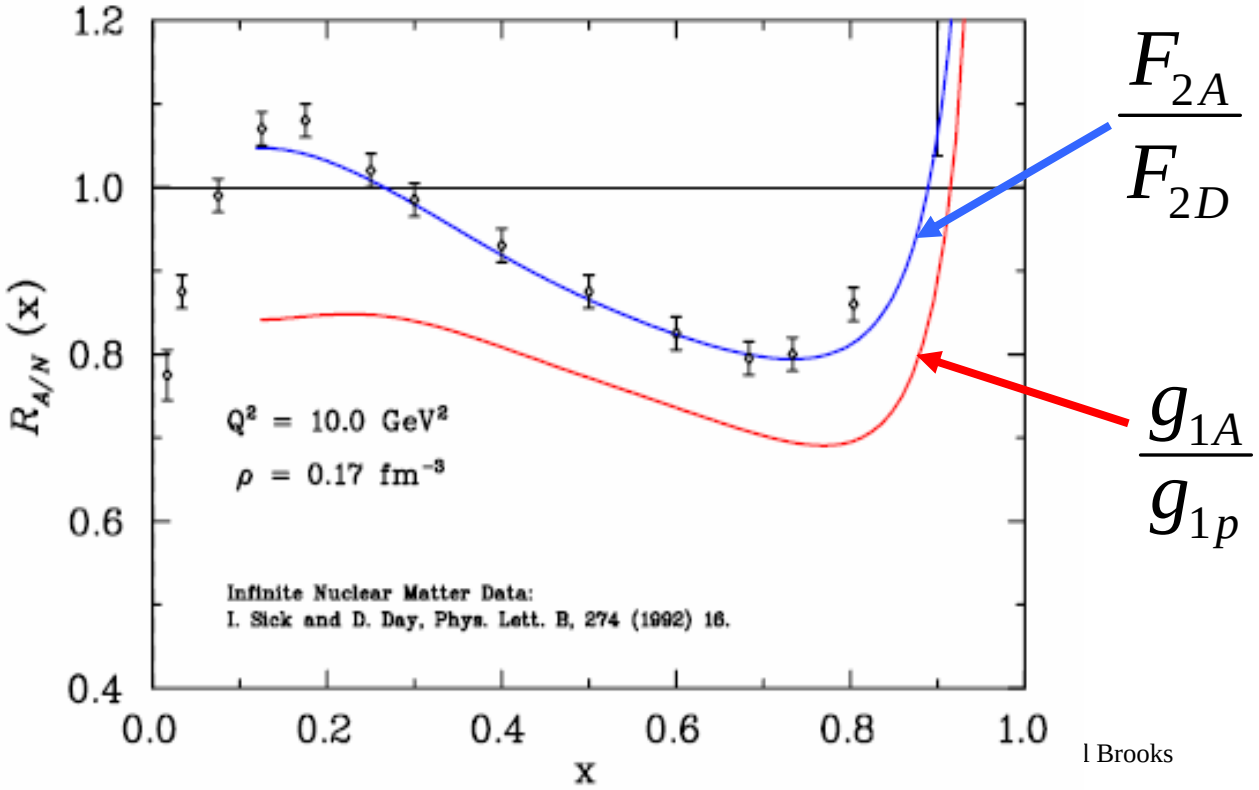


J. Ashman *et al.*, Z. Phys. C57, 211 (1993)

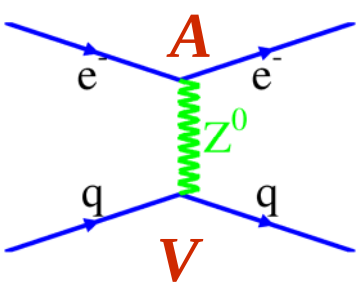
J. Gomez *et al.*, Phys. Rev. D49, 4348 (1994)

$g_1(A)$ – "Polarized EMC Effect"

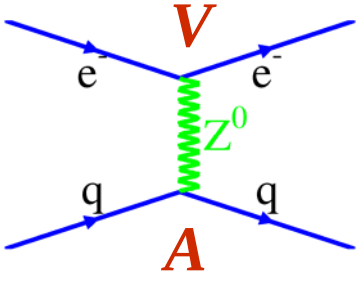
- **New calculations indicate larger effect for polarized structure function than for unpolarized: scalar field modifies lower components of Dirac wave function**
- **Spin-dependent parton distribution functions for nuclei nearly unknown**
- **Can take advantage of modern technology for polarized solid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



Electron-Quark Phenomenology



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



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

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

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

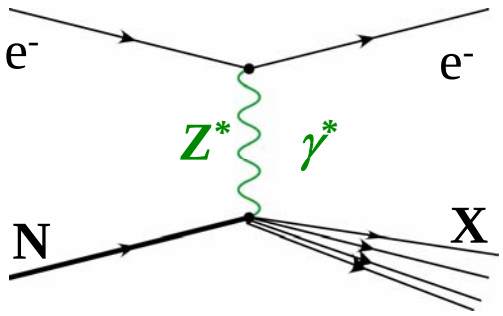
C_{2u} and C_{2d} are small and poorly known: can be accessed in PV DIS

New physics such as compositeness, new gauge bosons:

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

Proposed JLab upgrade experiment will improve knowledge of $2C_{2u}$-C_{2d} by more than a factor of 20

Parity Violating Electron DIS



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

$$a(x) = \frac{C_{1i} Q_i f_i(x)}{Q_i^2 f_i(x)} \qquad b(x) = \frac{C_{2i} Q_i f_i(x)}{Q_i^2 f_i(x)}$$

$f_i(x)$ are quark distribution functions

For an isoscalar target like ^{2}H, structure functions largely cancels in the ratio:

Provided Q^2 and W^2 are high enough and x ~ 0.3

$$a(x) = \frac{3}{10}\left[(2C_{1u} - C_{1d})\right] \qquad b(x) = \frac{3}{10}\left[(2C_{2u} - C_{2d})\frac{u_v(x) + d_v(x)}{u(x) + d(x)}\right]$$

Must measure APV to fractional accuracy better than 1%

- **11 GeV at high luminosity makes very high precision feasible**
- **JLab is uniquely capable of providing beam of extraordinary stability**
- **Control of systematics being developed at 6 GeV**

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^{2}H Experiment at 11 GeV

E': 6.8 GeV ± 10%

$I_{beam} = 90\ \mu A$

$\theta_{lab} = 12.5^o$

60 cm LD_2 target

A_{PV} = 290 ppm

800 hours

$\delta(A_{PV})$=1.0 ppm

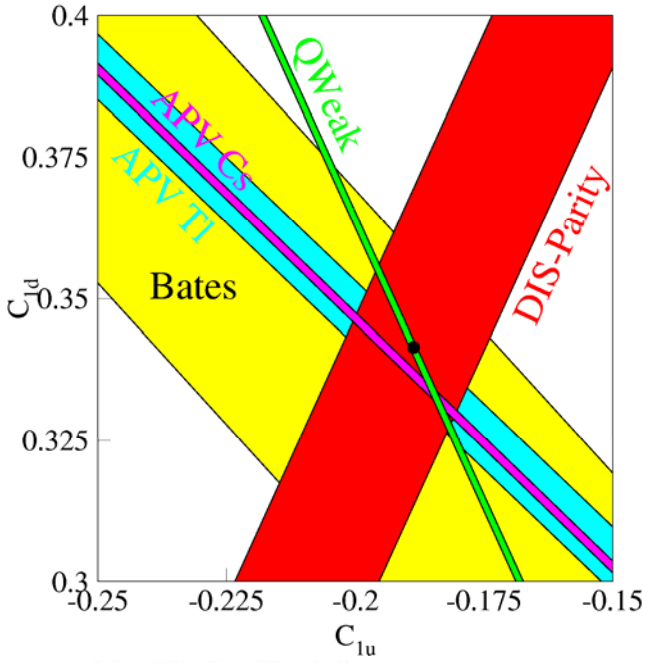
1 MHz DIS rate, π/e ~ 1

→ HMS+SHMS or MAD

$x_{Bj} \sim 0.45$

$Q^2 \sim 3.5\ GeV^2$

$W^2 \sim 5.23\ GeV^2$

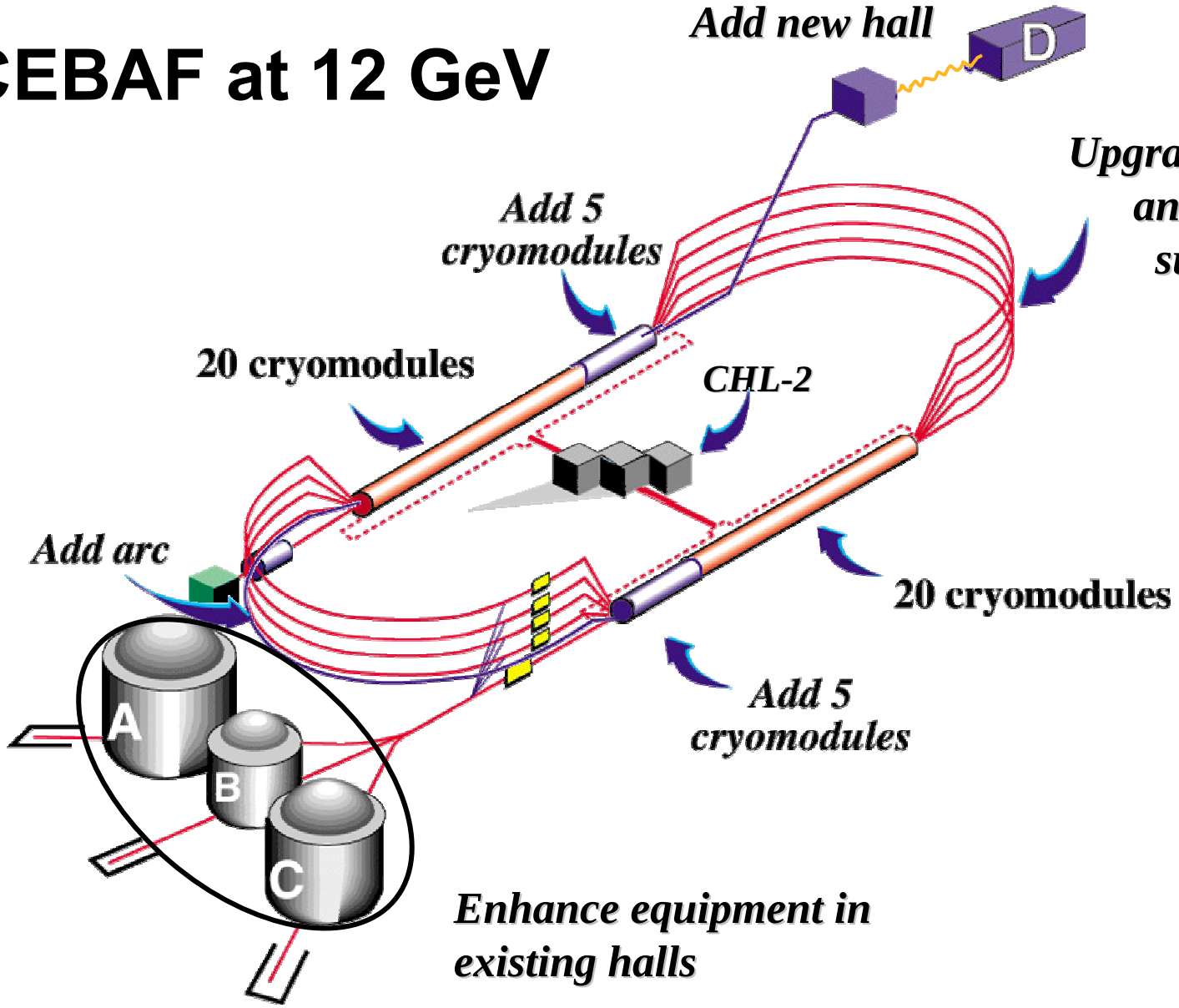


$\delta(2C_{2u}-C_{2d})$=0.01

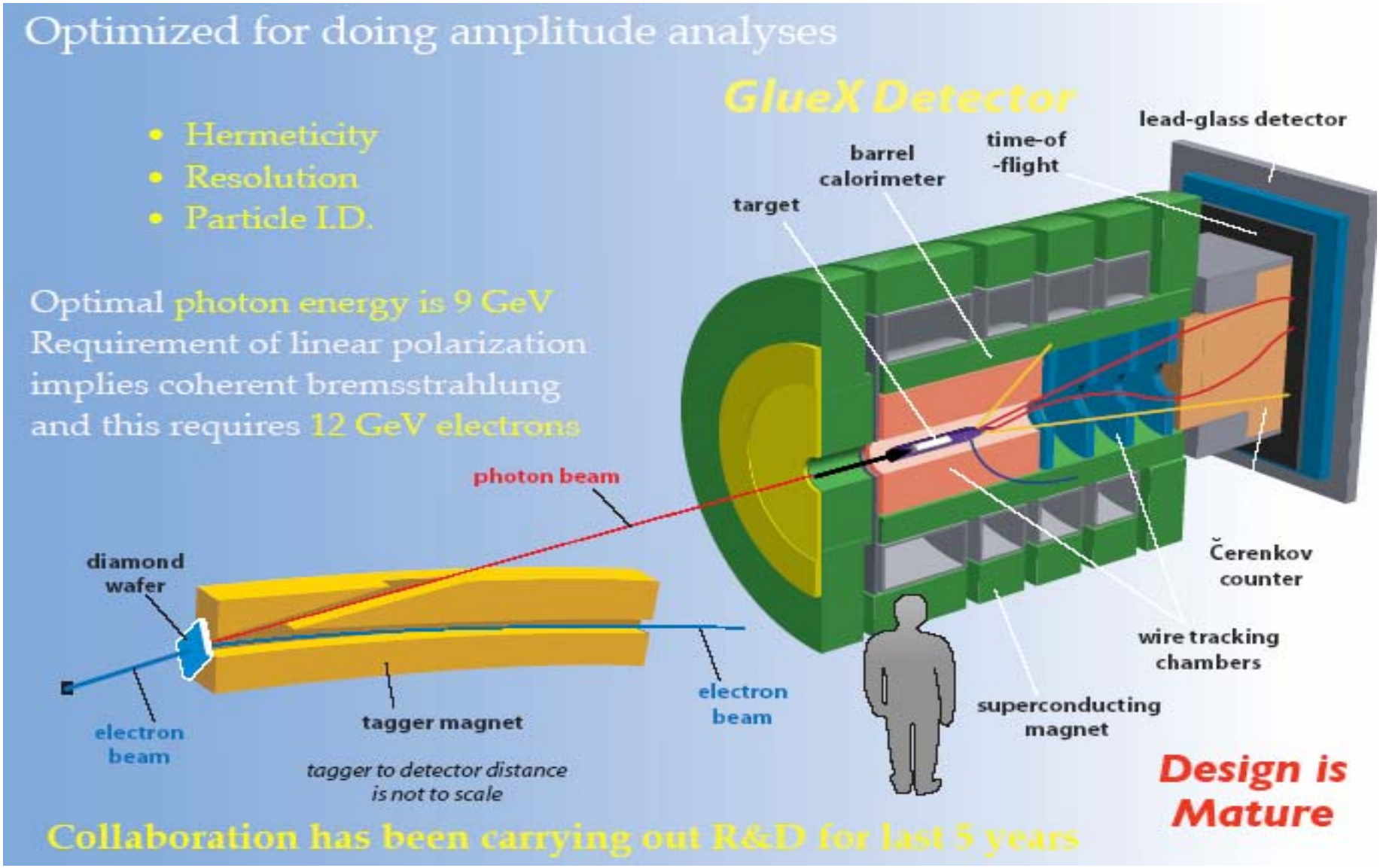
PDG: -0.08 ± 0.24

Theory: +0.0986

CEBAF at 12 GeV

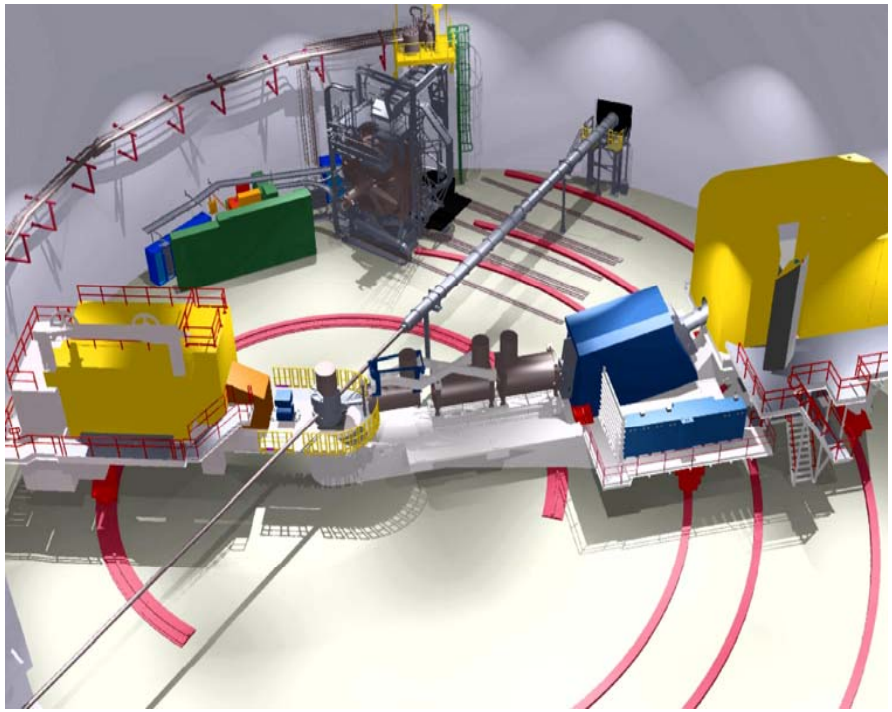


Gluex: Hall D

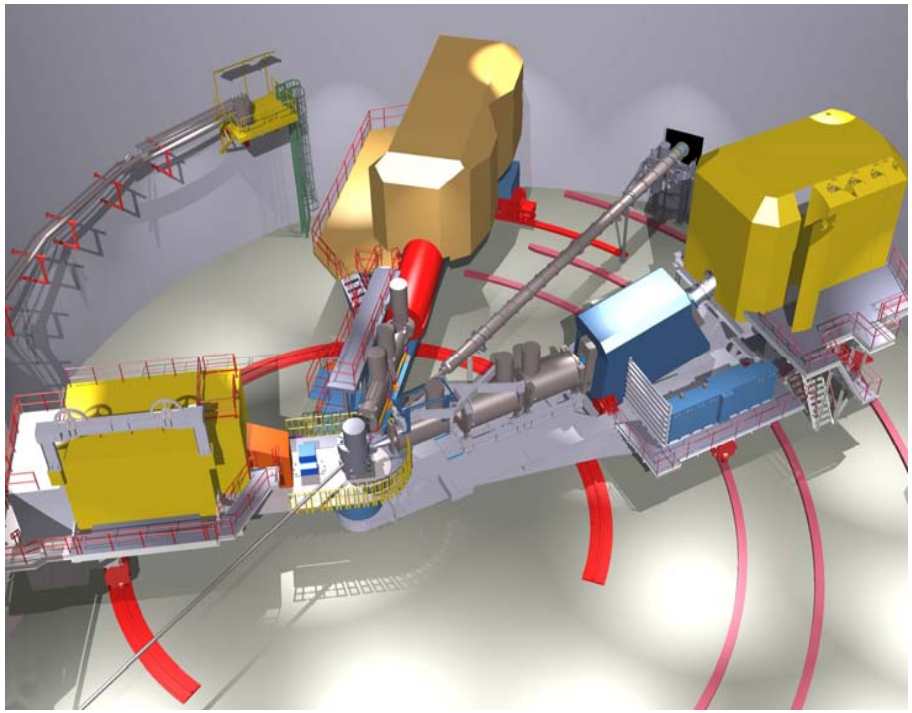

Optimized for doing amplitude analyses
• Hermeticity
• Resolution
• Particle I.D.
Optimal photon energy is 9 GeV
Requirement of linear polarization
implies coherent bremsstrahlung
and this requires 12 GeV electrons
GlueX Detector
lead-glass detector
time-of
-flight
barrel
calorimeter
target
photon beam
diamond
wafer
Čerenkov
counter
wire tracking
chambers
electron
beam
tagger magnet
electron
beam
superconducting
magnet
tagger to detector distance
is not to scale
Design is
Mature
Collaboration has been carrying out R&D for last 5 years

Experimental Hall C

At the present 6 GeV Beam Energy



After the 12 GeV Upgrade



Hall C's High Momentum Spectrometer, Short Orbit Spectrometer and specialized equipment for studying:

- The strange quark content of the proton
- Form factors of simple quark systems
- The transition from hadrons to quarks
- Nuclei with a strange quark embedded

Add a Super- High Momentum (11 GeV) Spectrometer for studying:

- Super-fast quarks
- Form factors of simple quark systems
- The transformation of quarks into hadrons
- Quark-quark correlations

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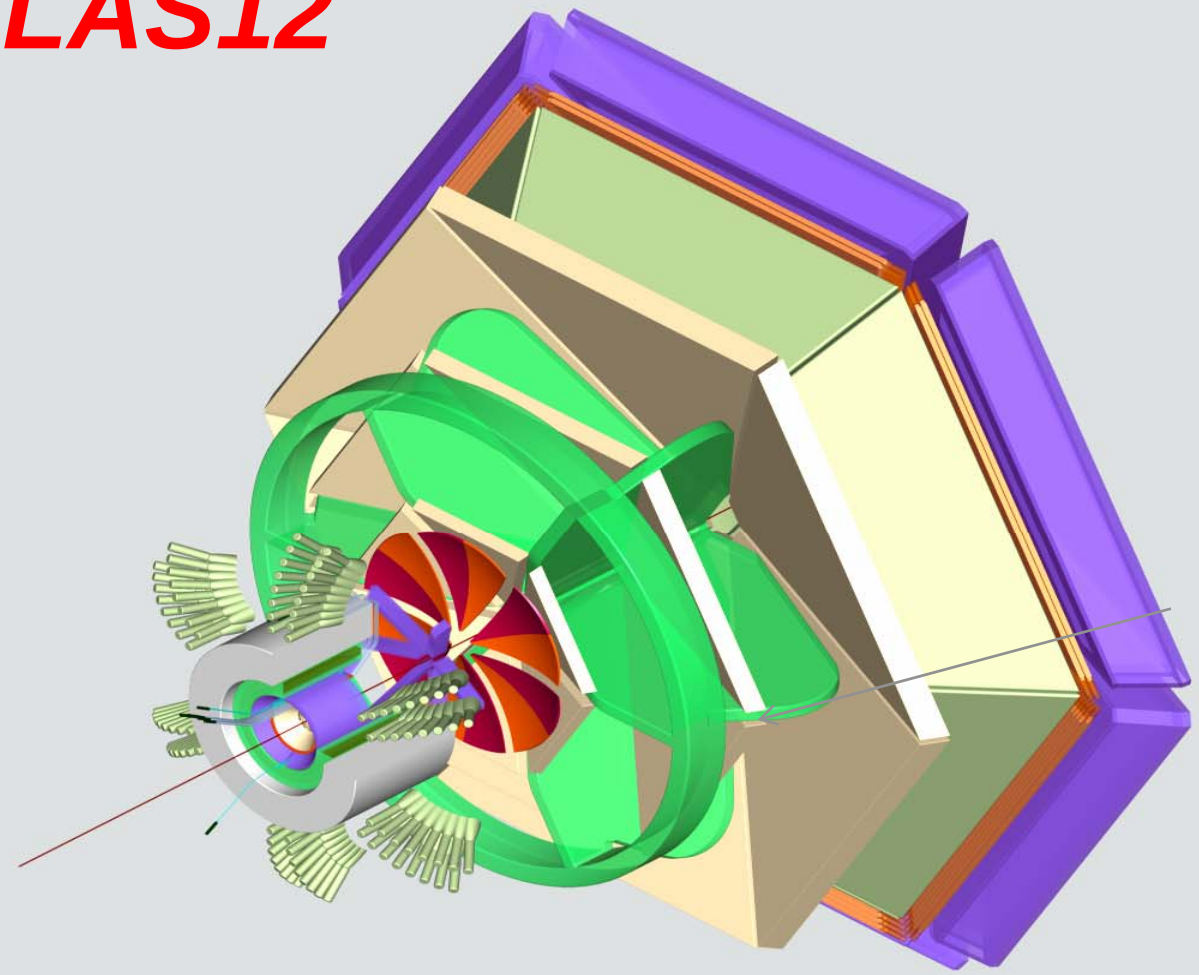
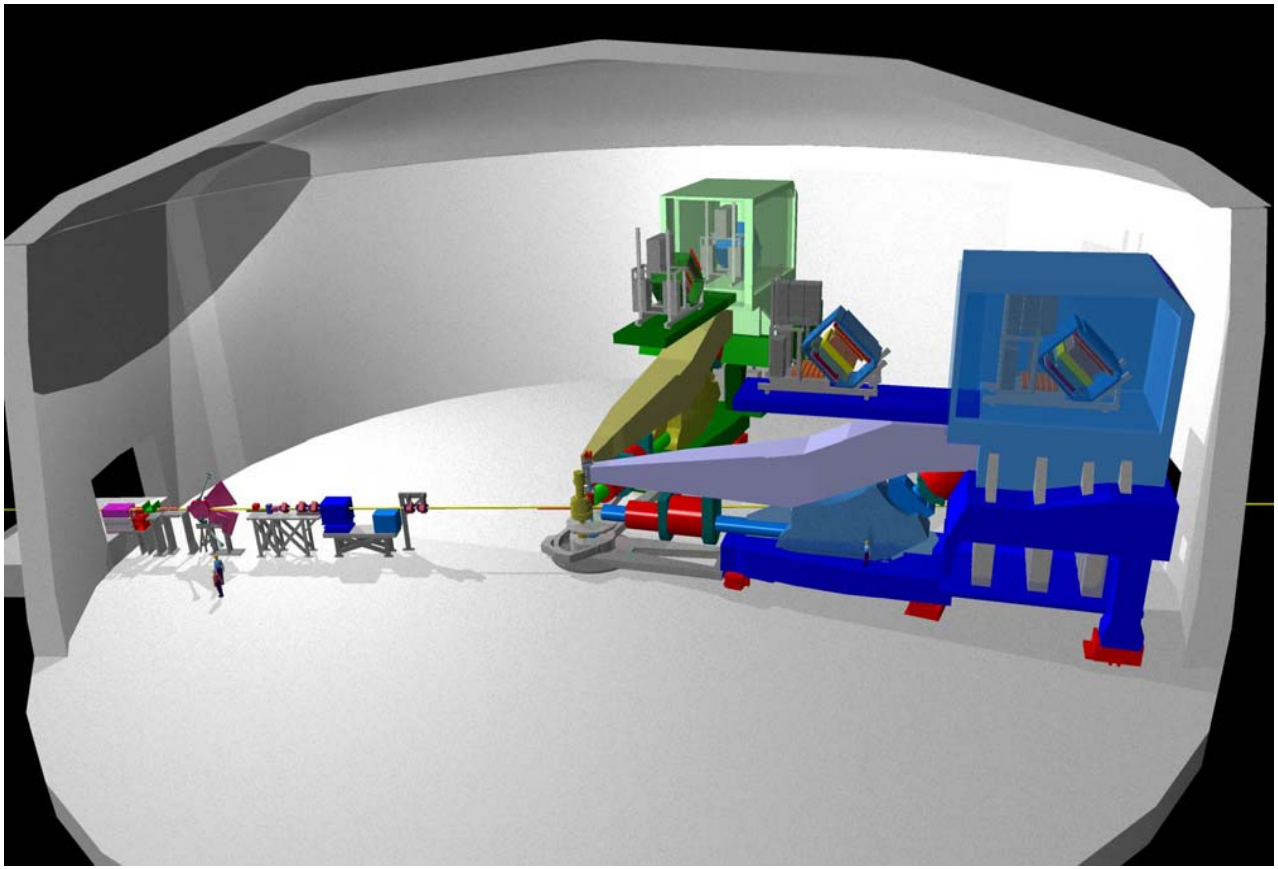
CLAS12



Hall A w/ 11 GeV Beam



Retain High Resolution Spectrometer (HRS) pair for continuation of research in which energy resolution comparable to nuclear level spacing is essential, and for specialized large installation experiments

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 $(2C_{2u}-C_{2d})$**

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

End of Presentation

12 GeV Project

Project Item	Escalated Mission Need Statement TPC=$234M (AY$)	Optimal Scientific Capability TPC=$270M (AY$)
Accelerator incl. Civil	129	130
GlueX in Hall D incl. Civil	65	65
Hall upgrades	40	75

$234M = Accel, GlueX in Hall D, and significant upgrade to one existing Hall
$270M = Accel, GlueX in Hall D, and significant upgrade to two existing Halls, plus delivery of maximum energy 5-pass beam to third Hall

Project Goal: maximize scientific capability within funding envelope

12 GeV Upgrade is Essential Even with Tough Budget

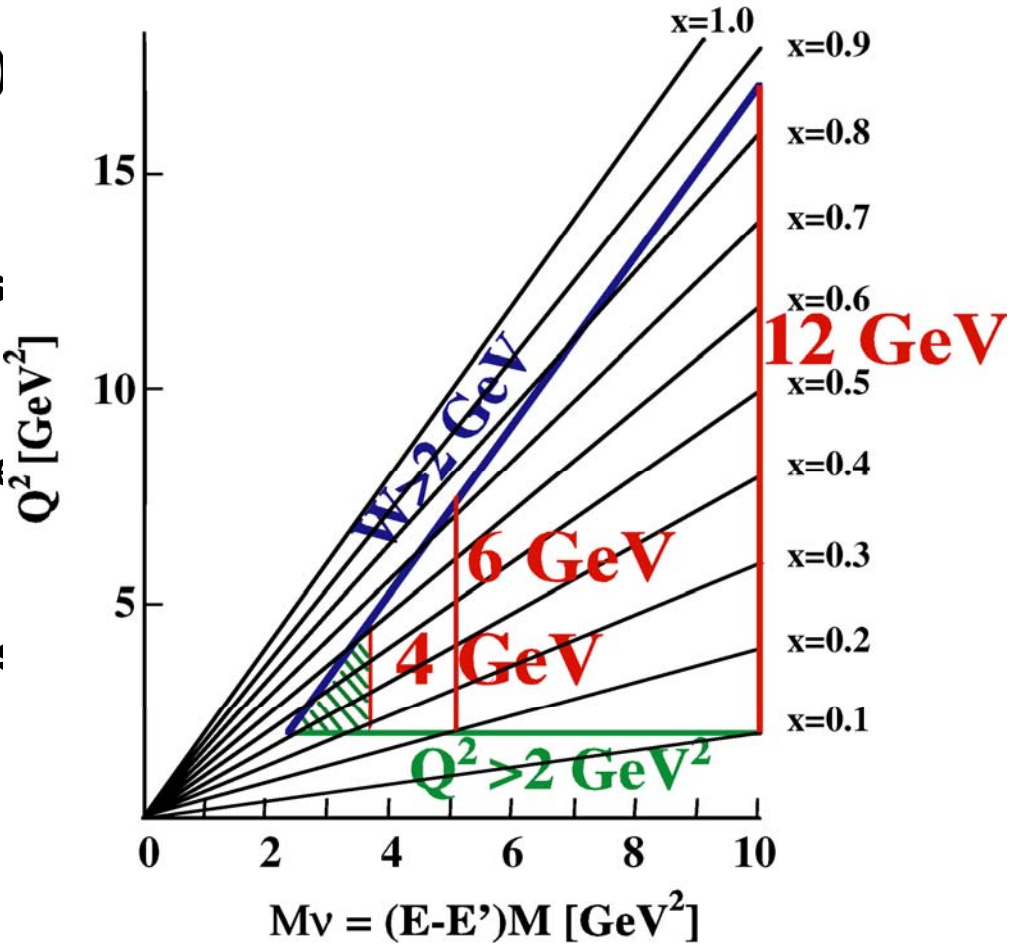
This is the only major construction initiative that is feasible within a constant effort budget:

"We should emphasize that smaller initiatives – even medium size initiatives such as the Jefferson Lab Upgrade – should be accommodated within a constant effort budget"

Source: 2002 NSAC Long Range Plan

12 GeV Upgrade: Kinematic Reach

- Access to very large x (x > 0.4)
  - Clean region
    - No strong sea effects
    - No explicit hard gluons to be included
- Quark models can be a powerful tool to investigate the structure of the nucleon
- Comparison with lattice QCD is possible for higher moments of structure functions (dominated by the large x region).



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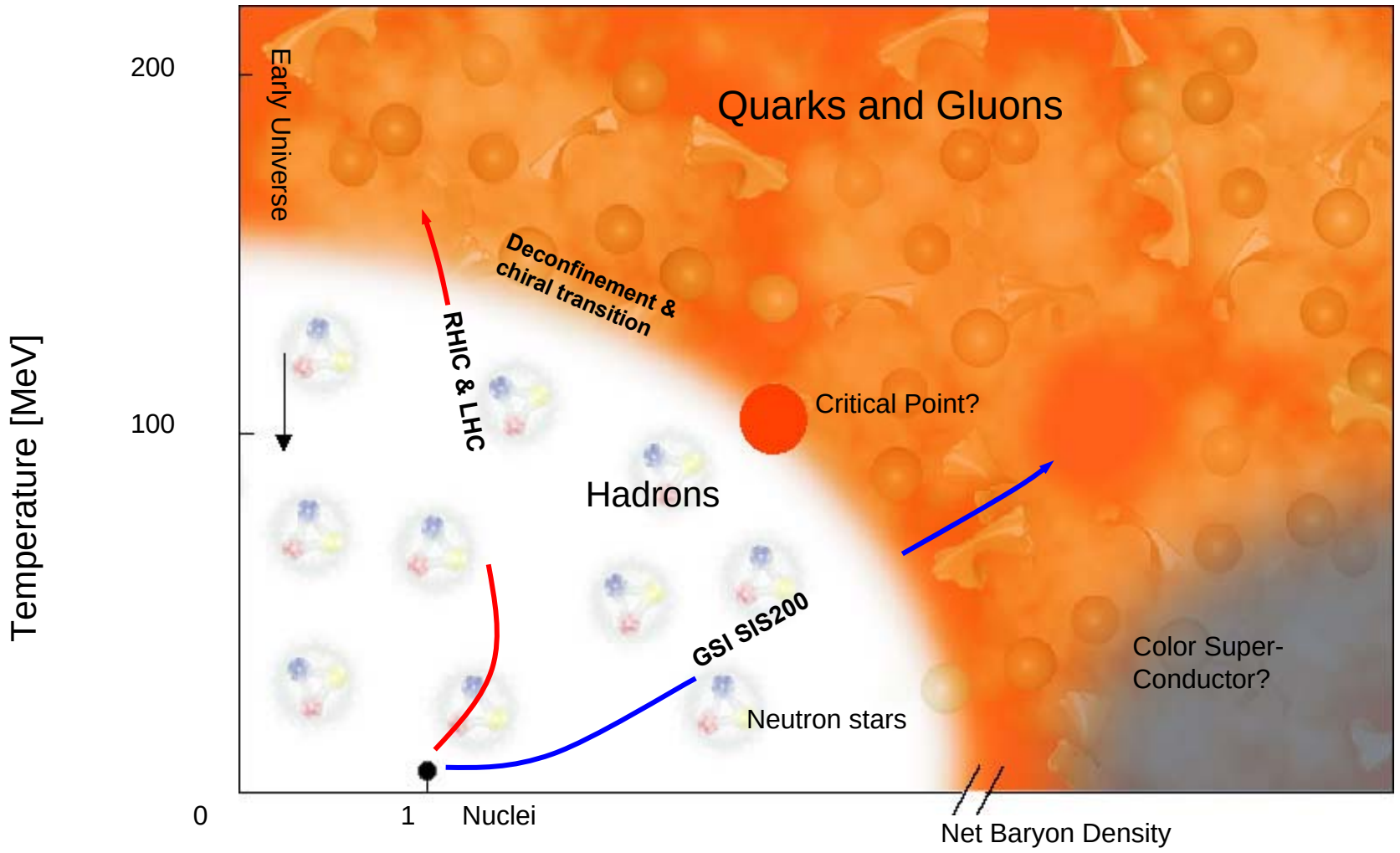
Microscopic Origin of Skyrme Force

	QMC	QMC	SkIII	QMC(N=3)
$m_\sigma(MeV)$	500	600		600
$t_0(MeV\ fm^3)$	-1071	-1082	-1129	-1047
x_0	0.89	0.59	0.45	0.61
$t_3(MeV\ fm^6)$	16620	14926	14000	12996
M_{eff}/M	.915	.814	.763	.821
$5t_2 - 9t_1(MeV\ fm^5)$	-7622	-4330	-4030	-4036
$W_0(MeV\ fm^5)$	118	97	120	91

Guichon & Thomas, PRL 93 (2004) 132502

T - μ Phase Diagram



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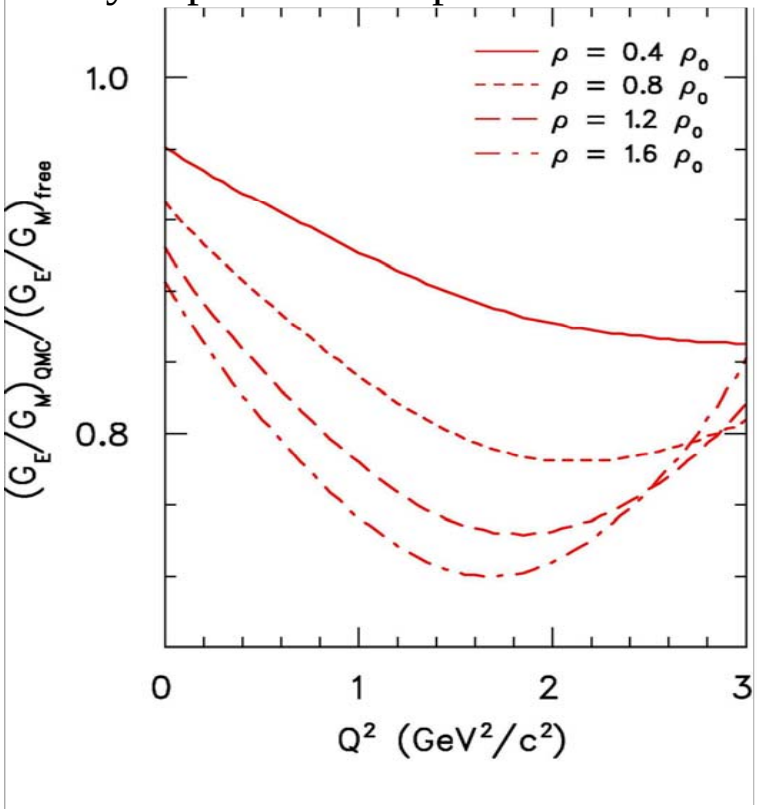
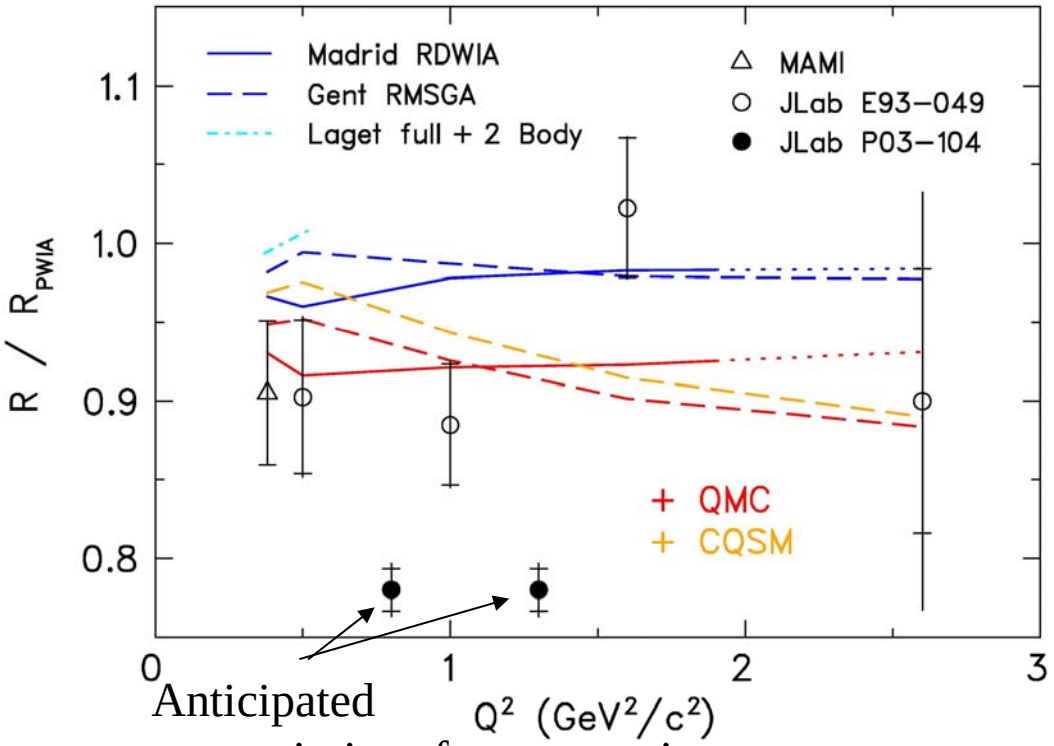
The QCD Lagrangian and Nuclear Medium Modifications

Density dependence of proton form factor ratio



Polarization transfer ratio on ^{4}He



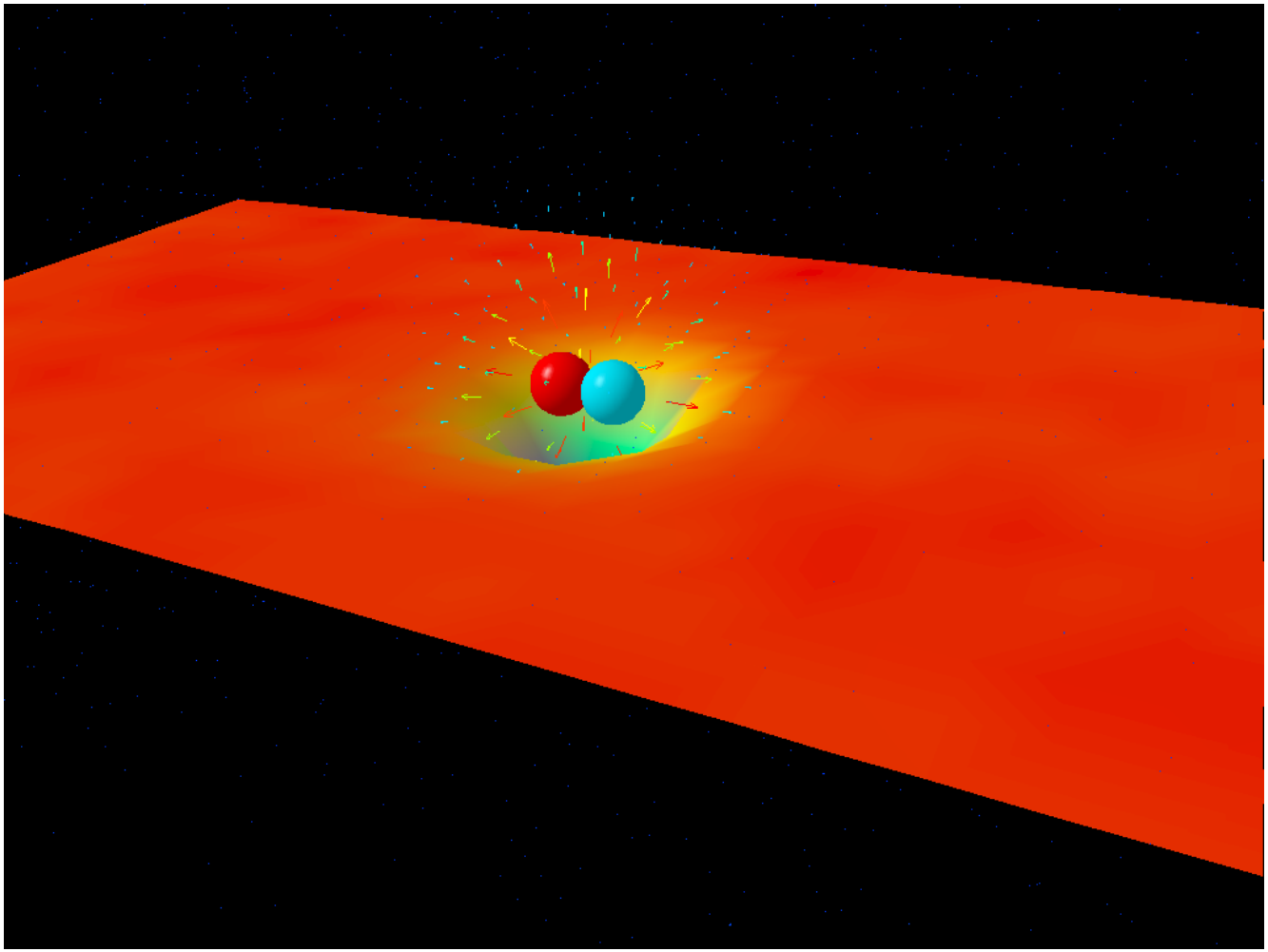
Anticipated uncertainties of new experiment

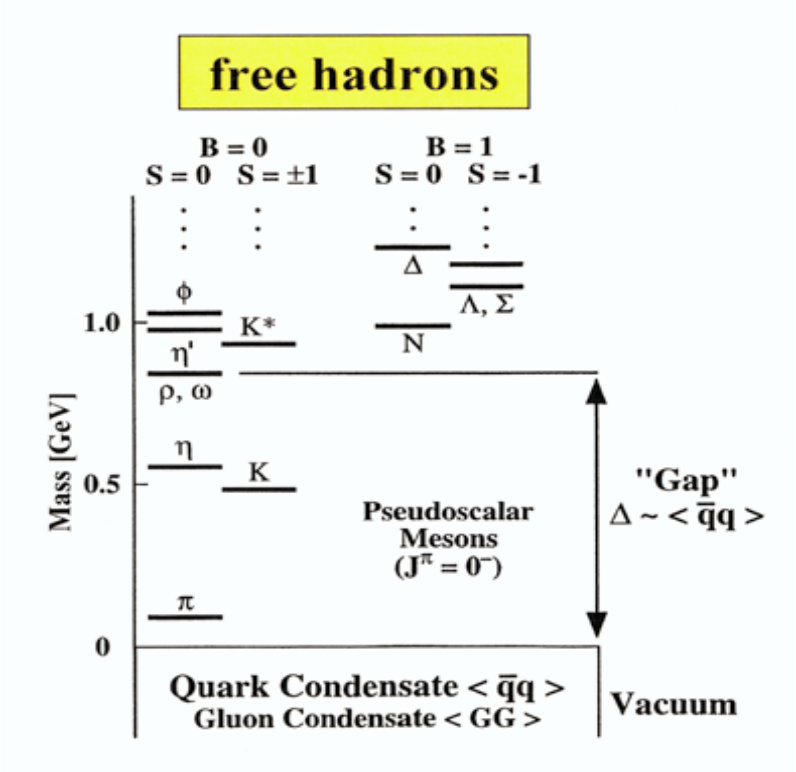
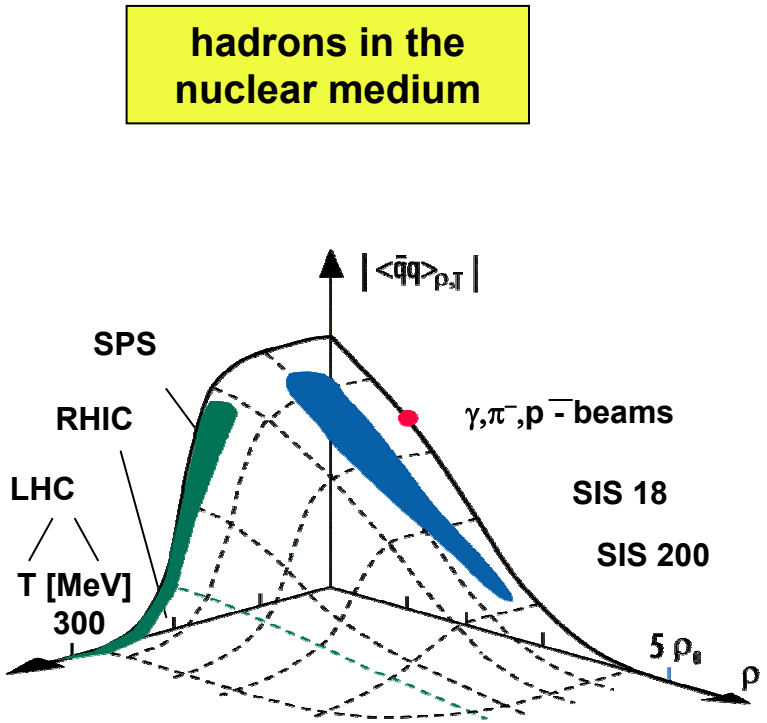
QMC: D.H. Lu *et al.*, Phys. Rev. C **60**, 068201 (1999)

Soliton: Jason R. Smith and Gerald A. Miller, Phys. Rev. Lett. **91**, 212301 (2003)

Skyrme: U. Yakhshiev, U. Meißner, A. Wirzba, Eur. Phys. J. A **16**, 569 (2003)

Quark-Anti-Quark Flux Tube: “String”



Lasscock, Leinweber, Thomas & Williams

Condensate versus T and ρ