Building Nucleons and Nuclei from Quarks and Glue: Nuclear Physics Research at Jefferson Lab, Now and in the 12 GeV Era

L. Cardman

Thomas Jefferson National Accelerator Facility and

University of Virginia

CEBAF @ Jefferson Lab

- A 4 GeV (now 6 GeV), high intensity, cw electron accelerator built to investigate the structure of mesons, nucleons, and nuclei
- The approved research program:
  - 185 approved “6 GeV” experiments on a broad variety of topics
  - An International User Community:
    1351 scientists from 233 institutions in 28 countries
- Research operations began 10/95
  - In full operation for ~14 years (since 11/97)
  - Data for 174 experiments is complete, 11 more partially complete
  - Results of many have been published; while many others are under detailed analysis. The results are emerging regularly in the published literature (e.g. 333 PRL and PL to date: ½ expt, ½ theory)
  - 371 PhDs to date and 189 in progress (~1/3 of US PhDs in Nuclear Physics)
- The Upgrade of CEBAF to 12 GeV (the highest priority of the 2007 NSAC Long Range Plan) is well underway
  - The enhanced reach of the facility and the associated suite of experimental equipment will support continued, cutting edge research well into the 2020s

JLab's Scientific Mission

- Understand how hadrons are constructed from the quarks and gluons of QCD
- Understand the QCD basis for the nucleon-nucleon force
- Explore the limits of our understanding of nuclear structure
  - high precision
  - short distances
  - the transition from the nucleon-meson to the QCD description

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To make progress in these areas we must address critical issues in "strong QCD":

- What is the mechanism of confinement?
- Where does the dynamics of the q-q interaction make a transition from the strong (confinement) to the perturbative (QED-like) QCD regime?
- How does Chiral symmetry breaking occur?

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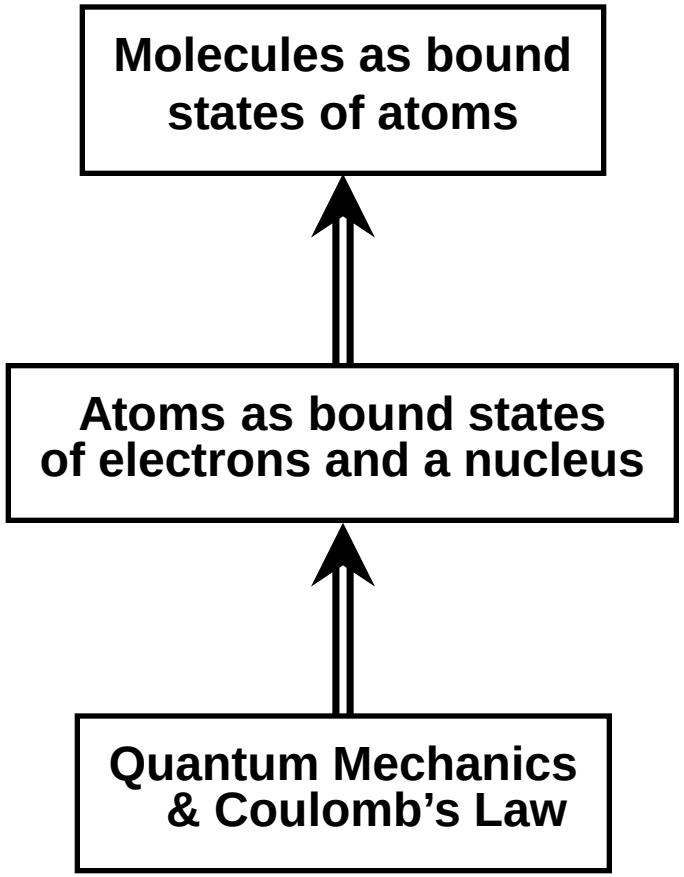
- And an emerging new area of research has been added:
  Tests of the Standard Model using high precision at low energies

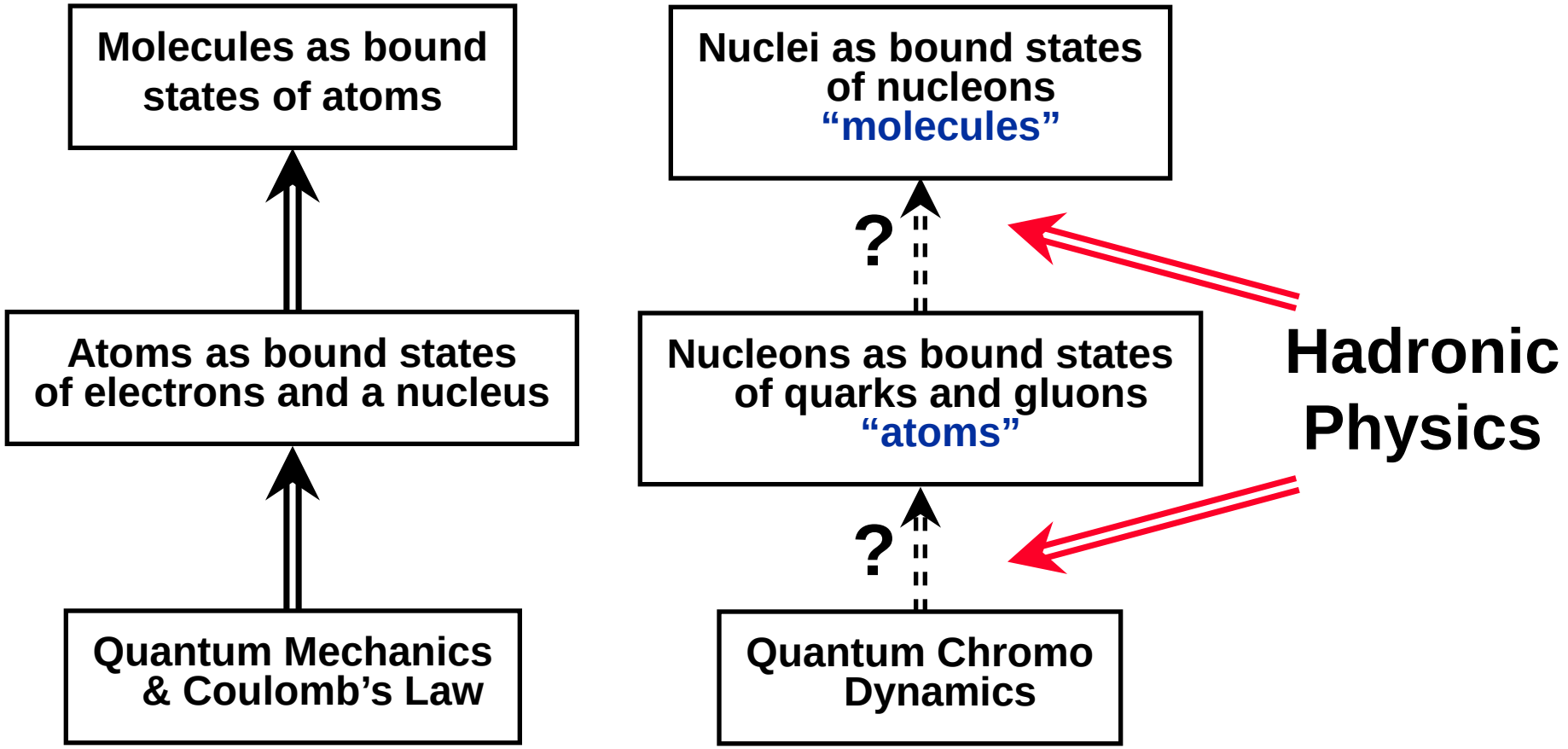
Atomic Physics



Atomic Physics

1930's

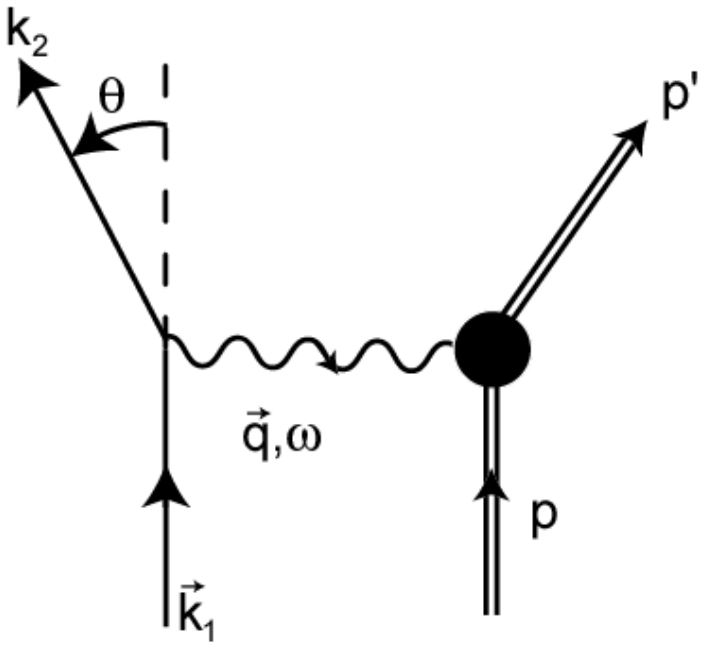
Atomic Physics versus Quark Physics



Atomic Physics
1930's

Nuclear and Particle Physics
Today

Electron Scattering Provides an Ideal Microscope for Nuclear Physics



- Electrons are point-like
- The interaction (QED) is well-known
- The interaction is weak

$$\vec{q} = \vec{k}_1 - \vec{k}_2 = \text{Momentum Transfer}$$

$$\omega = E_p - E_{p'} = \text{Energy Transfer}$$

$$Q^2 = -q^2 = \text{4-Momentum Transfer}$$

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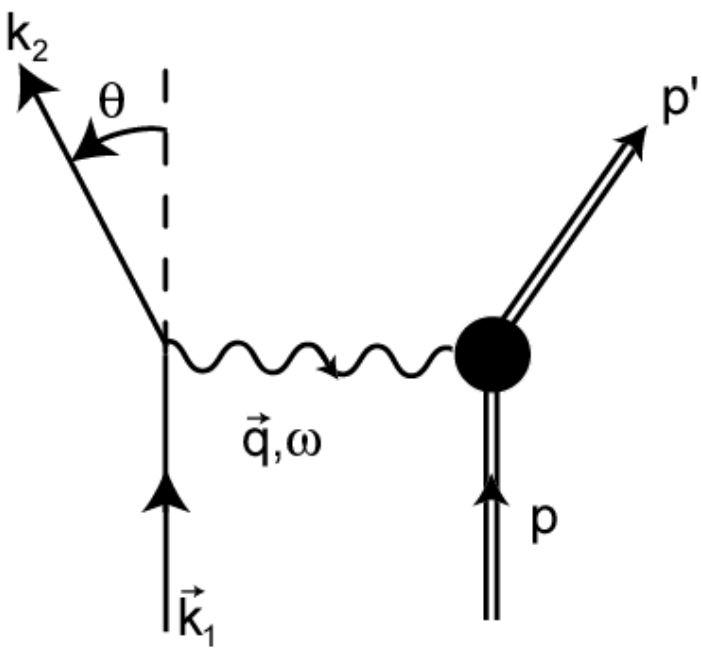

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- Vary *q* to map out Fourier Transforms of charge and current densities:

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

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

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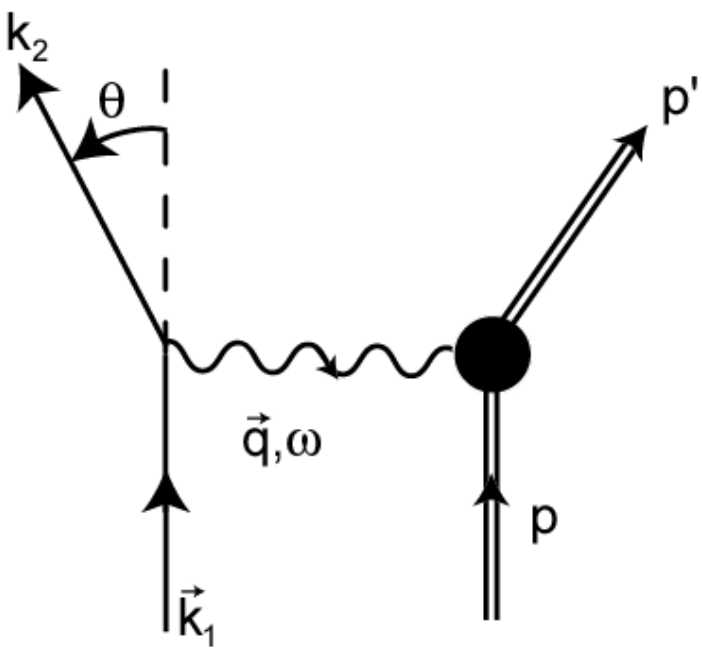

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CEBAF's $\vec{e}$ and CW beams dramatically enhance the power of electron scattering

Electron Scattering

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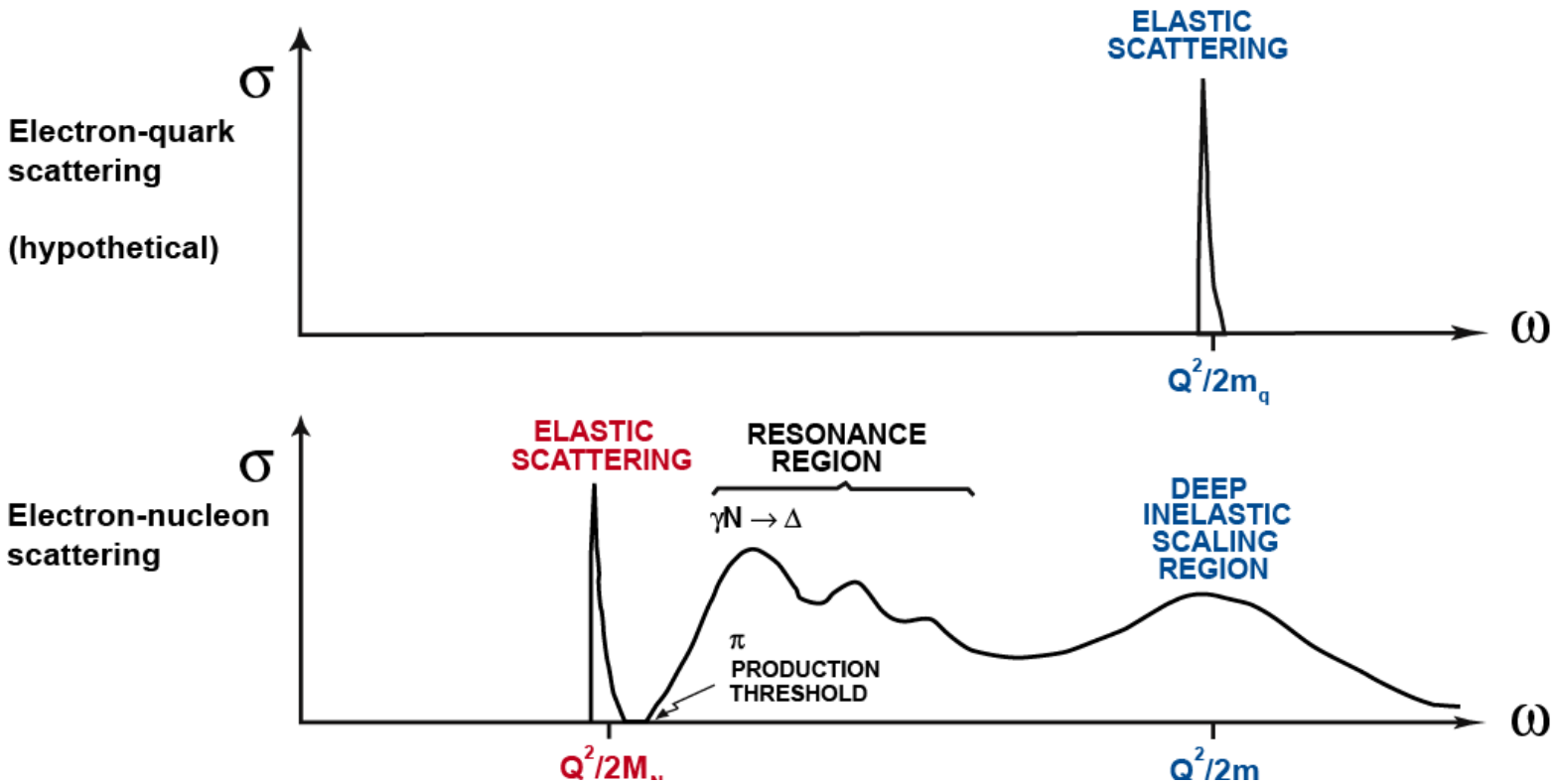

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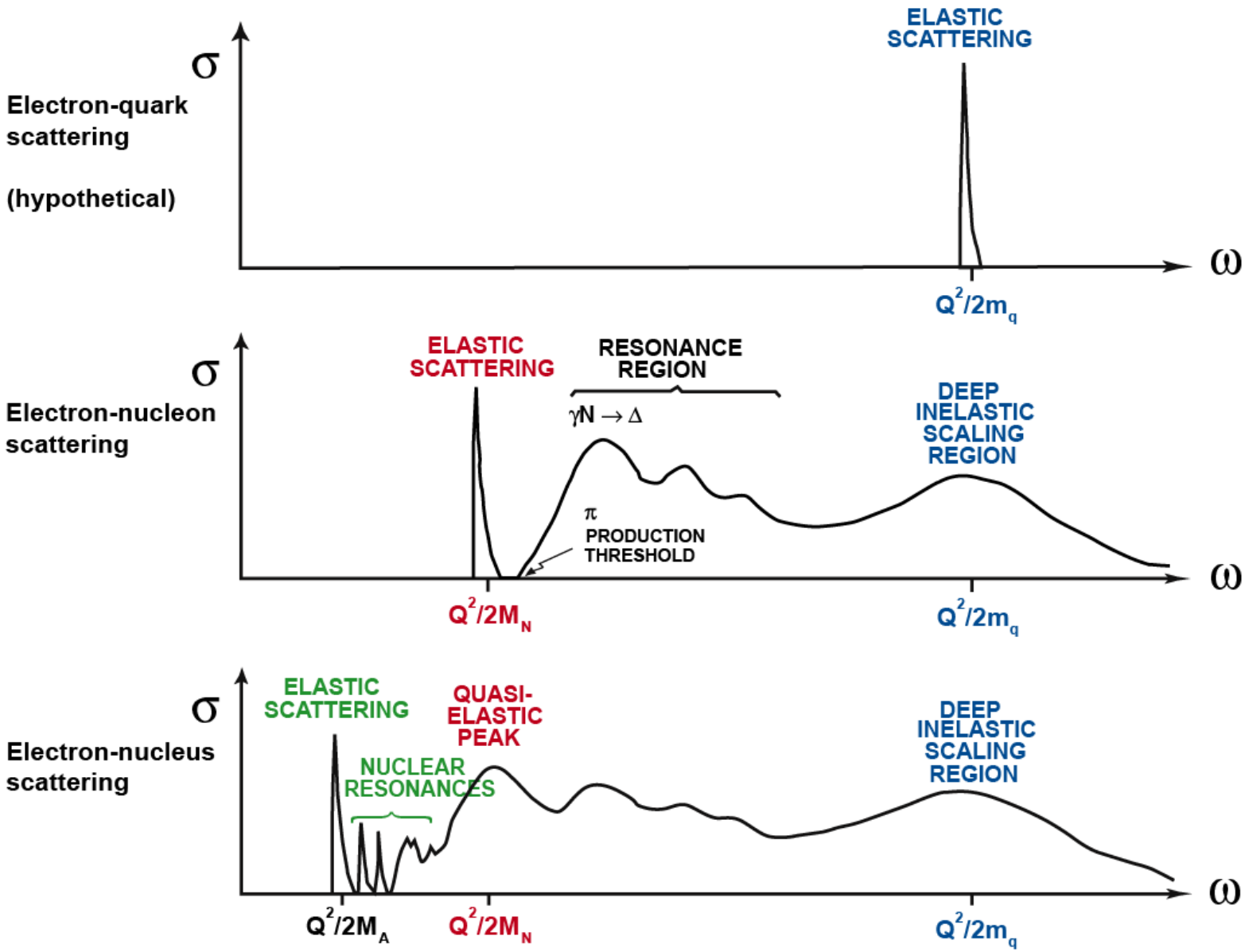

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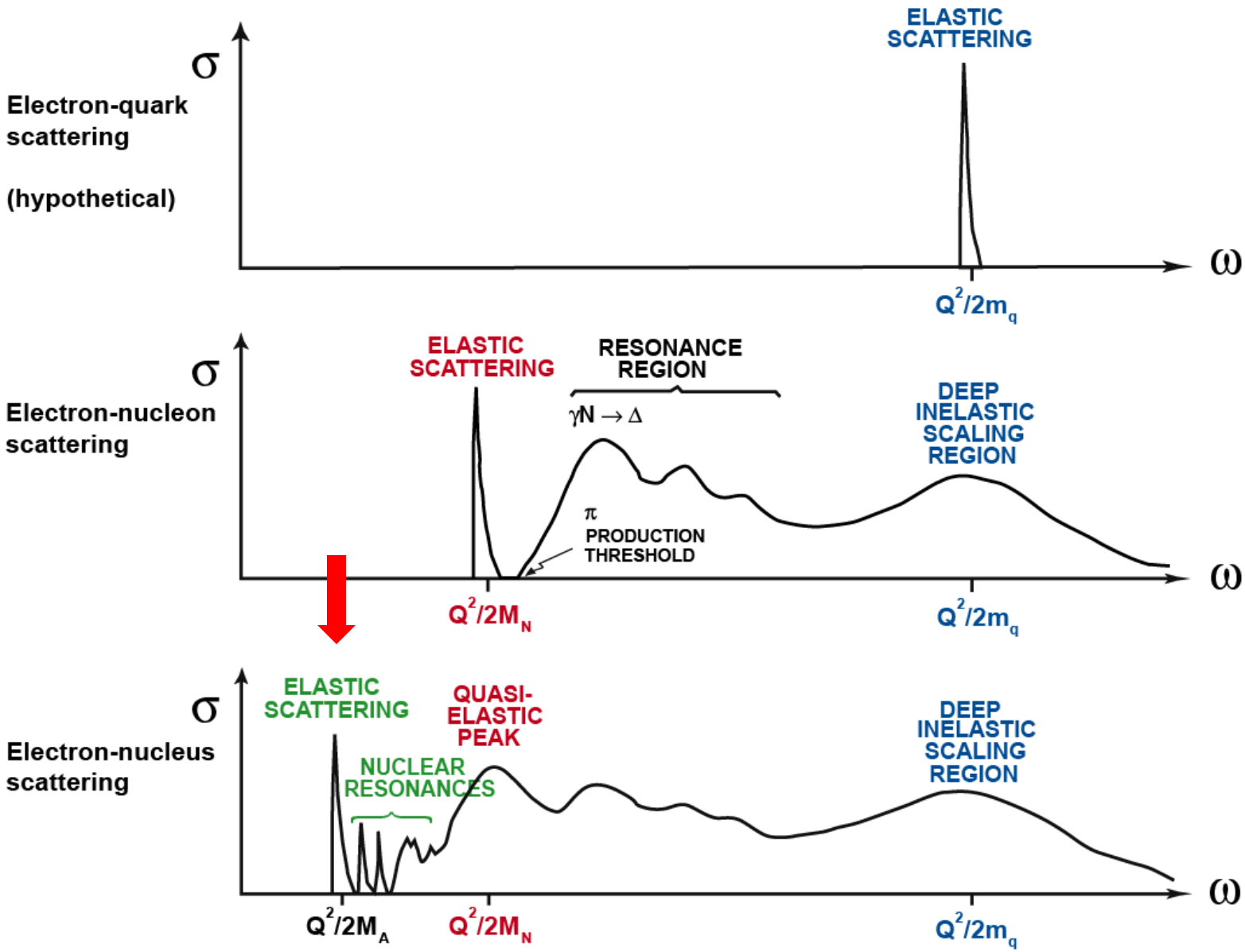
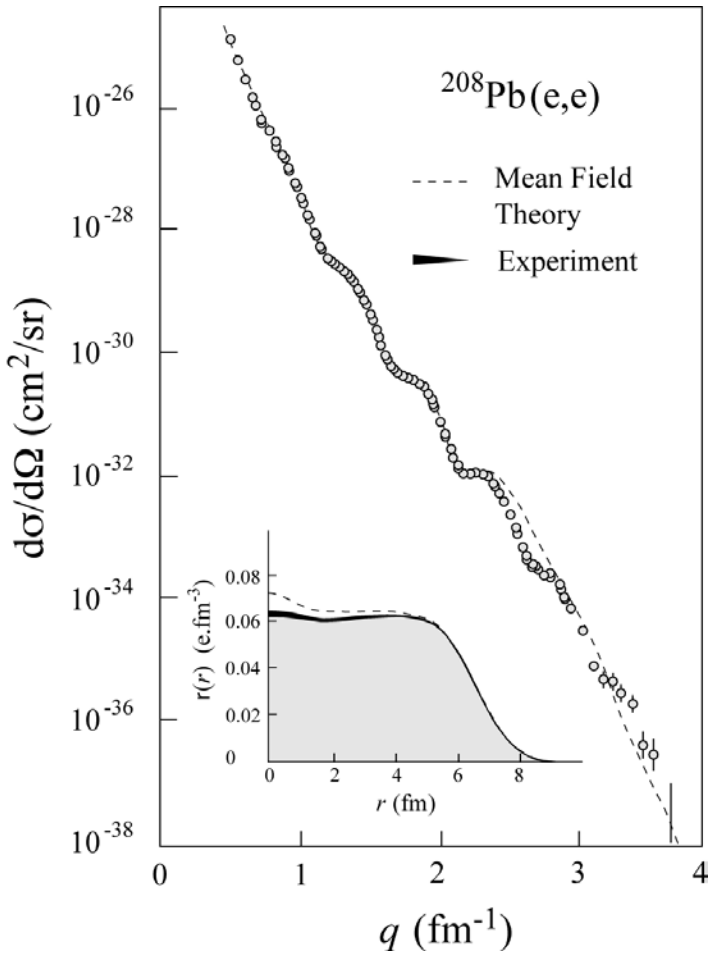
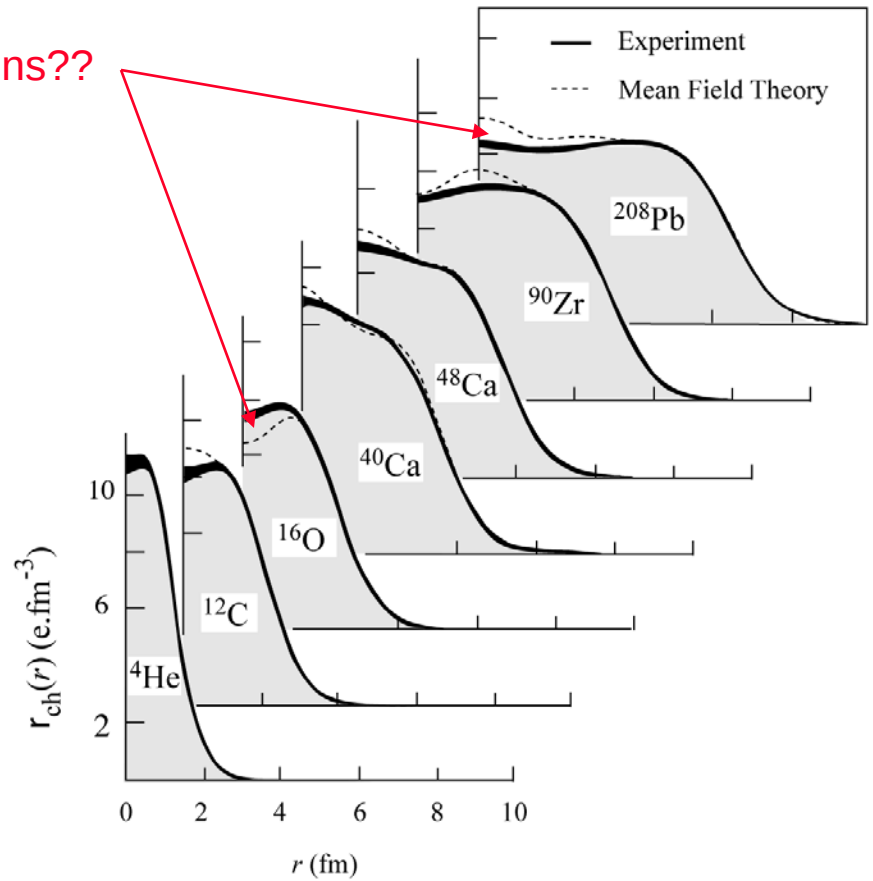


(e,e) ⇒ Nuclear Charge Distributions



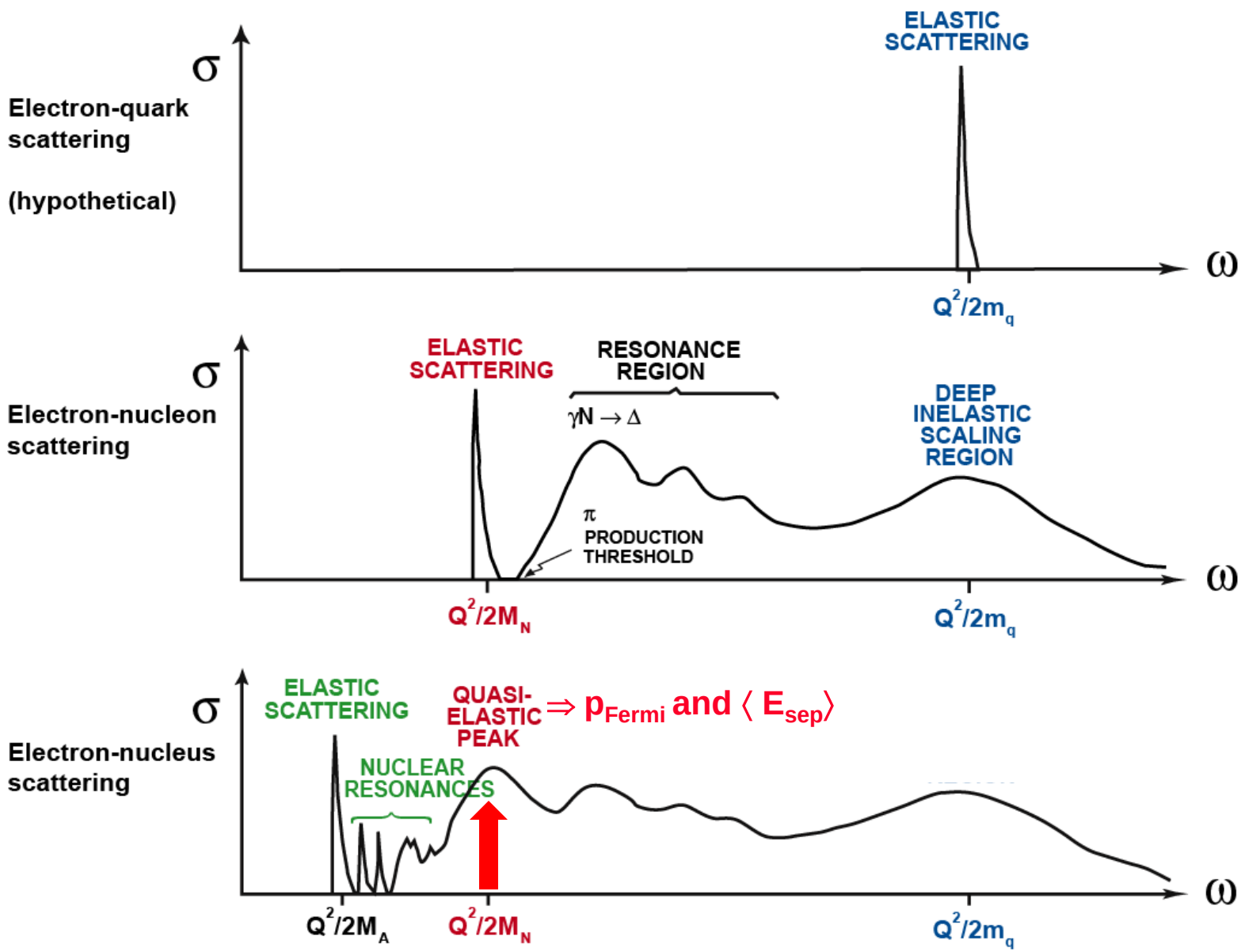
Correlations??



In '70s a large data set was acquired on elastic electron scattering (mainly at Saclay) over large Q^2-range and for variety of nuclei

"Model-independent" analysis of these data provided accurate results on charge distribution for comparison with the best available theory: Mean-Field Density-Dependent Hartree-Fock

Electron Scattering



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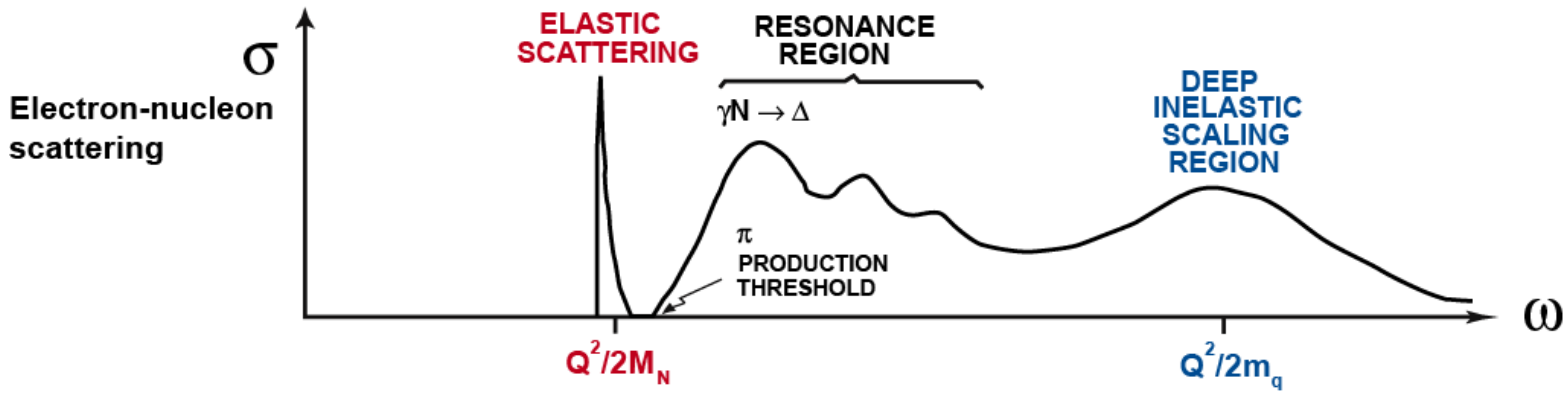
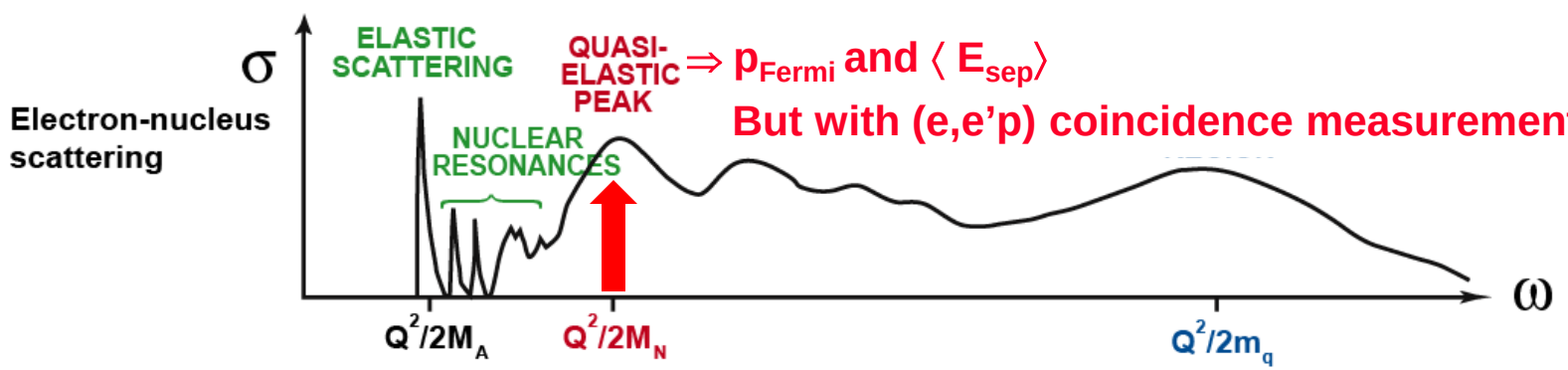


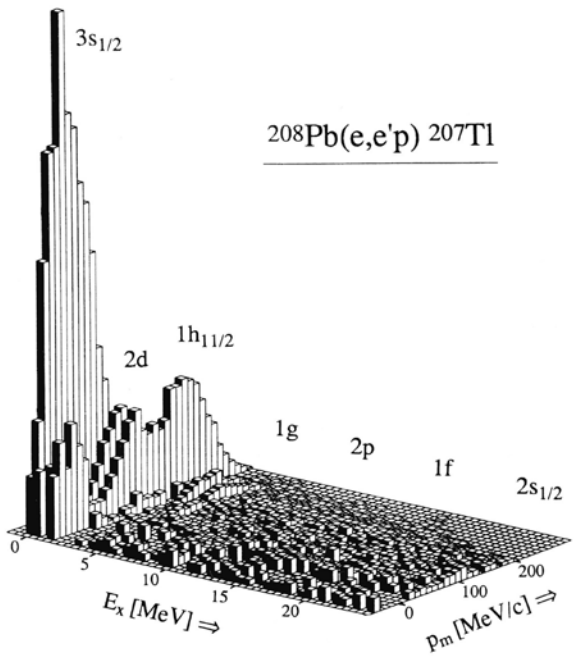


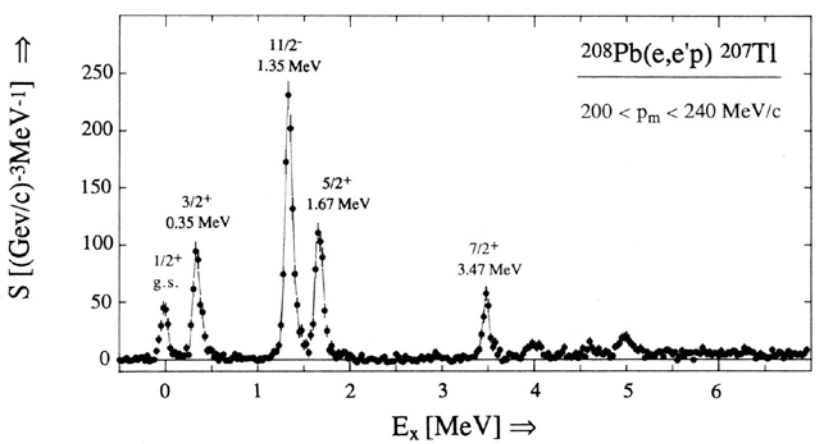
⇒ p_{Fermi} and $\langle E_{sep} \rangle$

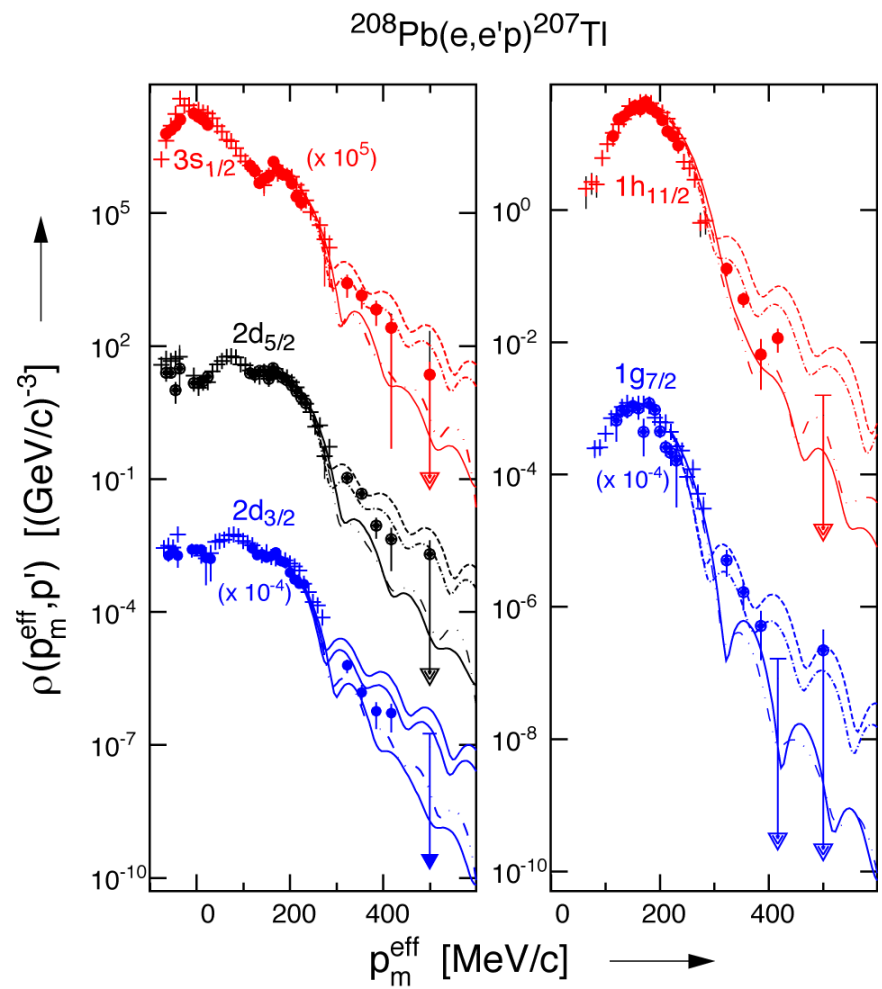
But with (e,e'p) coincidence measurements……

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

$$p_m = E_e - E_{e'} - p = q - p$$
$$E_m = \omega - T_p - T_{A-1} = E_{sep} + E_{exc}$$







CEBAF Design Parameters

- Primary Beam: Electrons
- Beam Energy: 4 GeV (with upgrade path)

  $10 > \lambda > 0.1$ fm
  nucleon $\rightarrow$ quark transition
  baryon and meson excited states
- 100% Duty Factor (cw) Beam

  coincidence experiments
- Three Simultaneous Beams with Independently Variable Energy and Intensity

  complementary, long experiments
- Polarization (beam and reaction products)

  spin degrees of freedom
  weak neutral currents

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  coincidence experiments $\Rightarrow$ **excite system with a known ($\vec{q}$, ω) and observe its evoluton**
- Three Simultaneous Beams with Independently Variable Energy and Intensity

  complementary, long experiments
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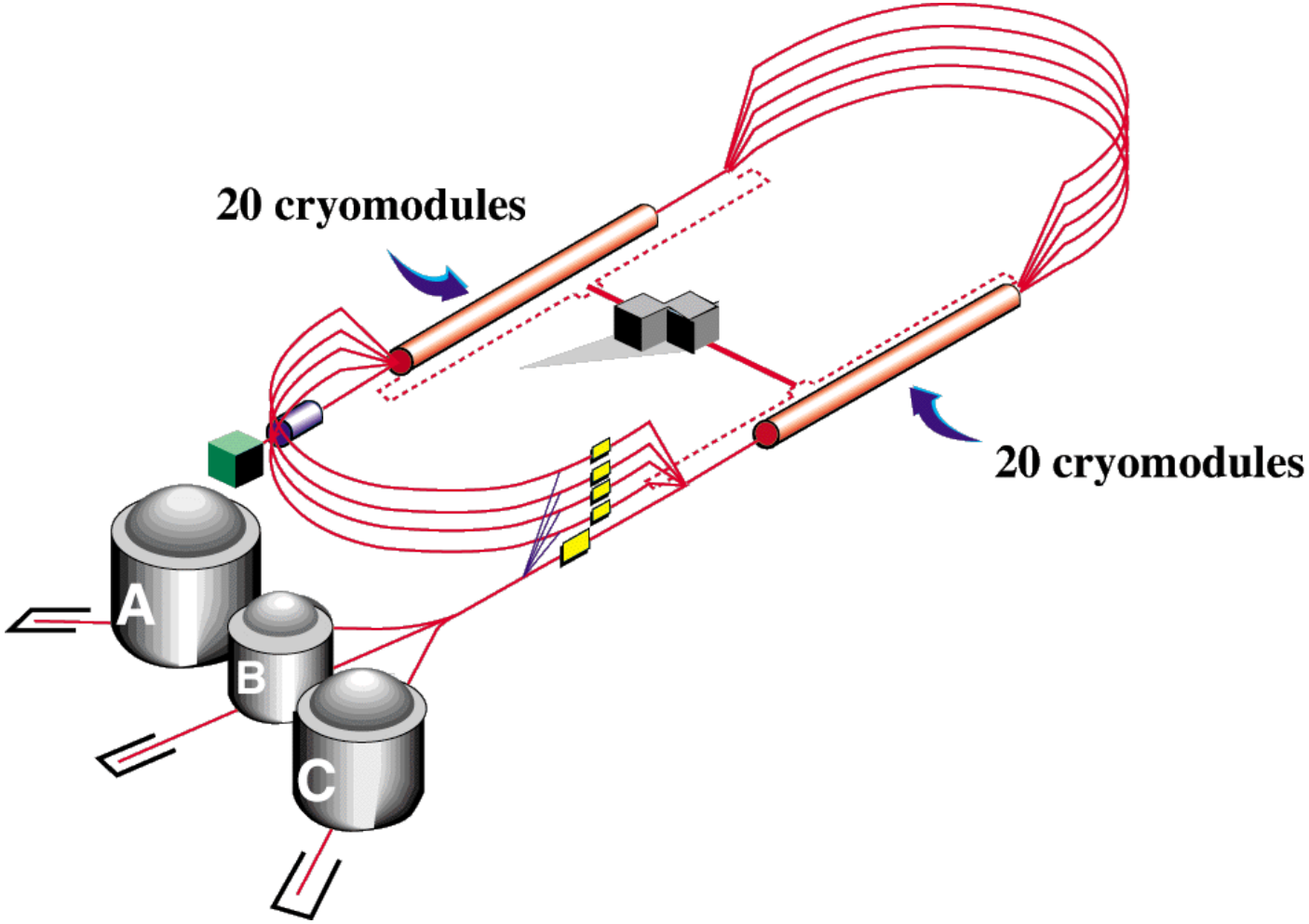
$\mathcal{L} > 10^6$ X SLAC at the time of the original DIS experiments

The Facility Today

6 GeV CEBAF



World's first large-scale use of SRF

Resulted in an Accelerator with REMARKABLE characteristics

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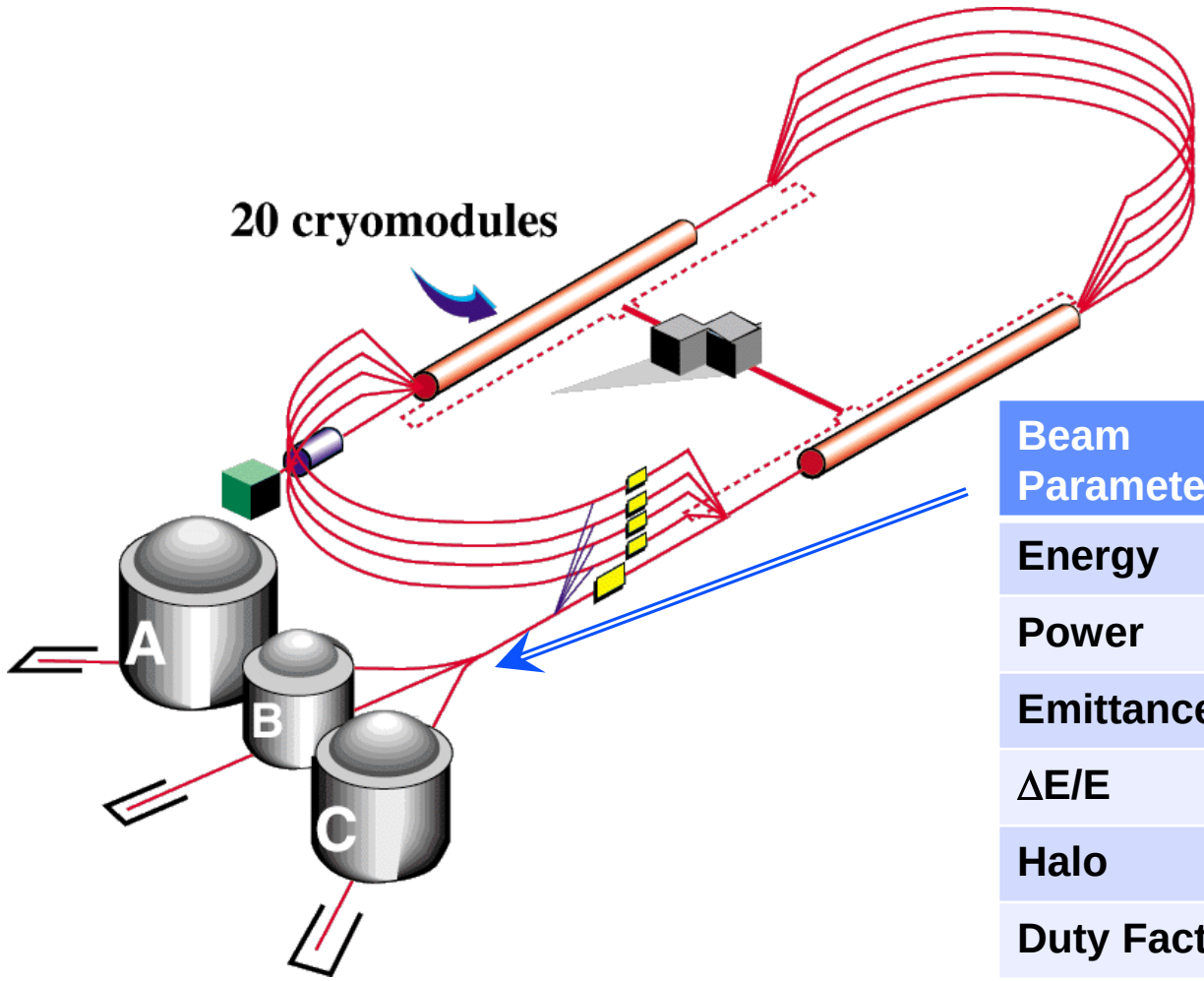

Beam Parameters	Energy
Energy	0.5 – 6.0 GeV
Power	1 MW
Emittance	1 nm•rad
$\Delta E/E$	10^{-4}
Halo	$<<10^{-4}$
Duty Factor	100%

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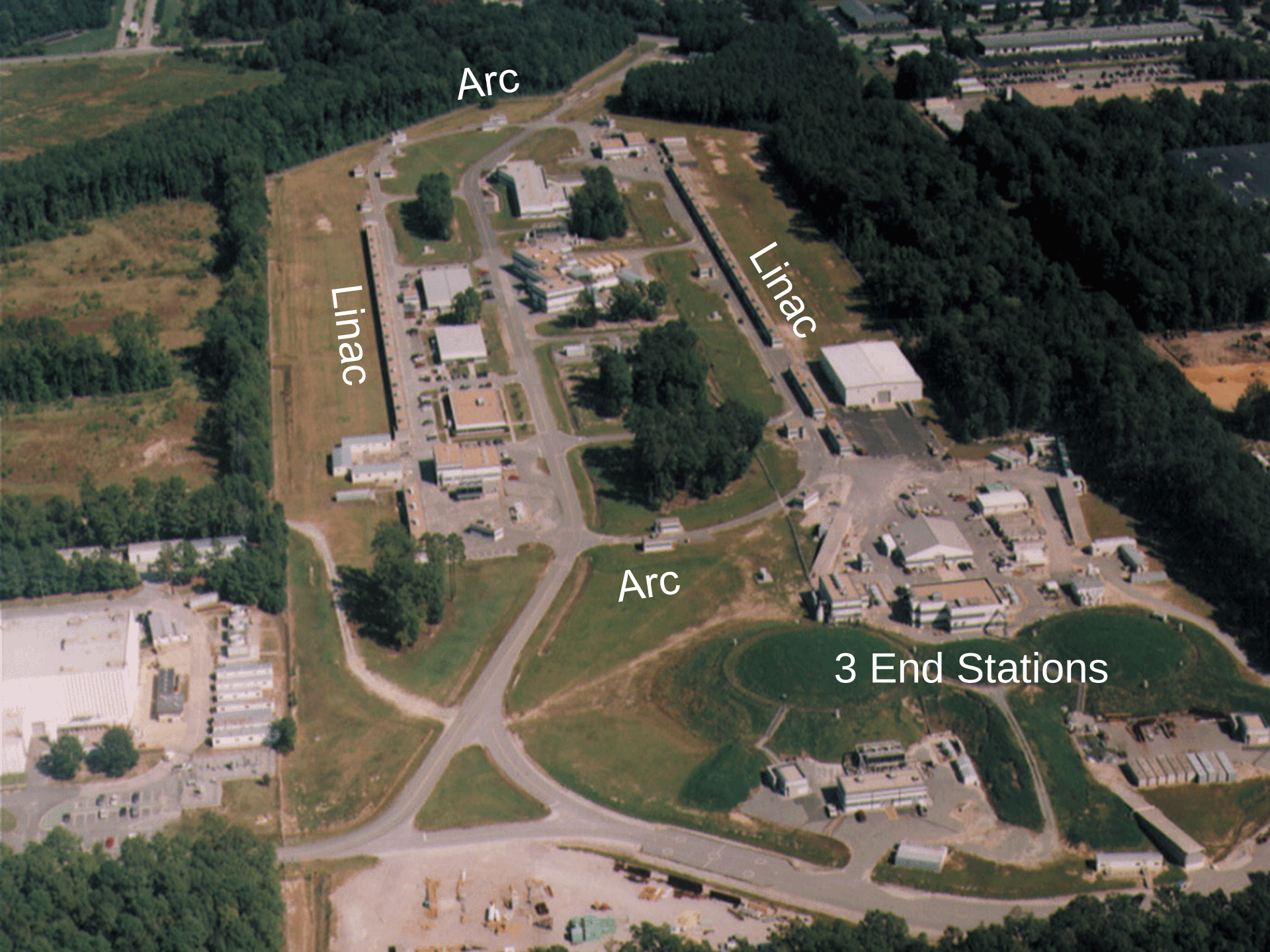
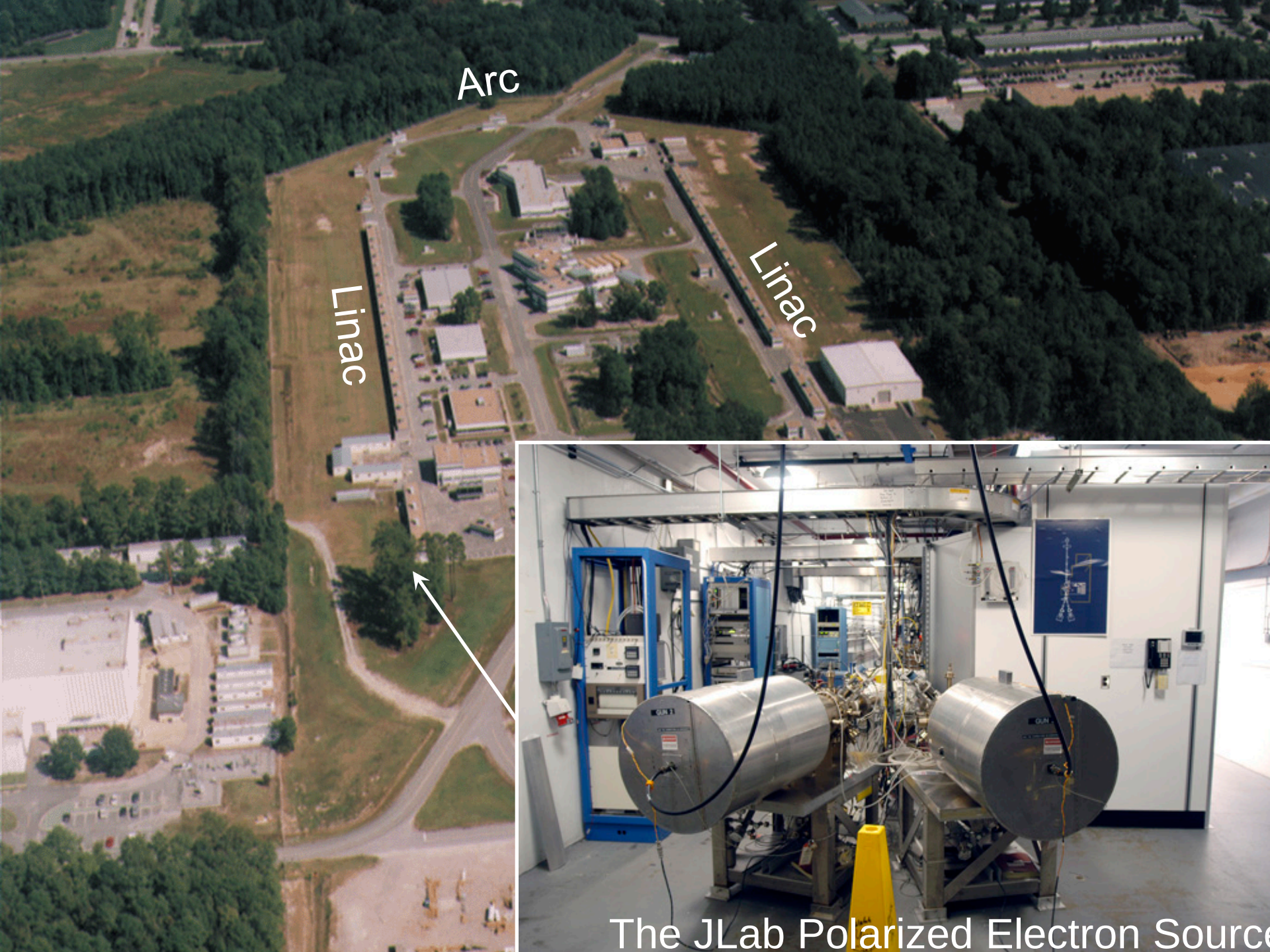
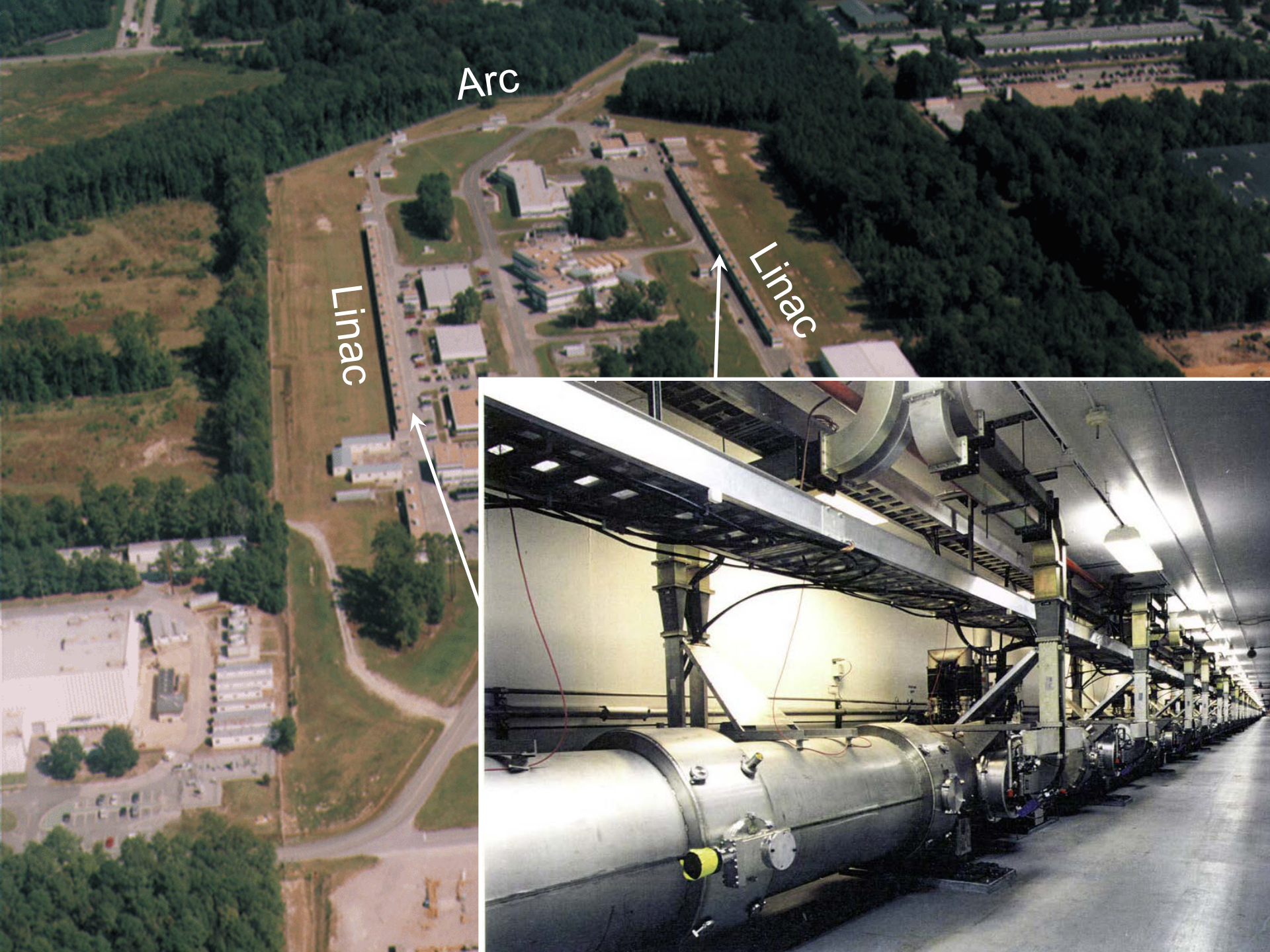

Arc
Linac
Linac
Arc
3 End Stations



The JLab Polarized Electron Source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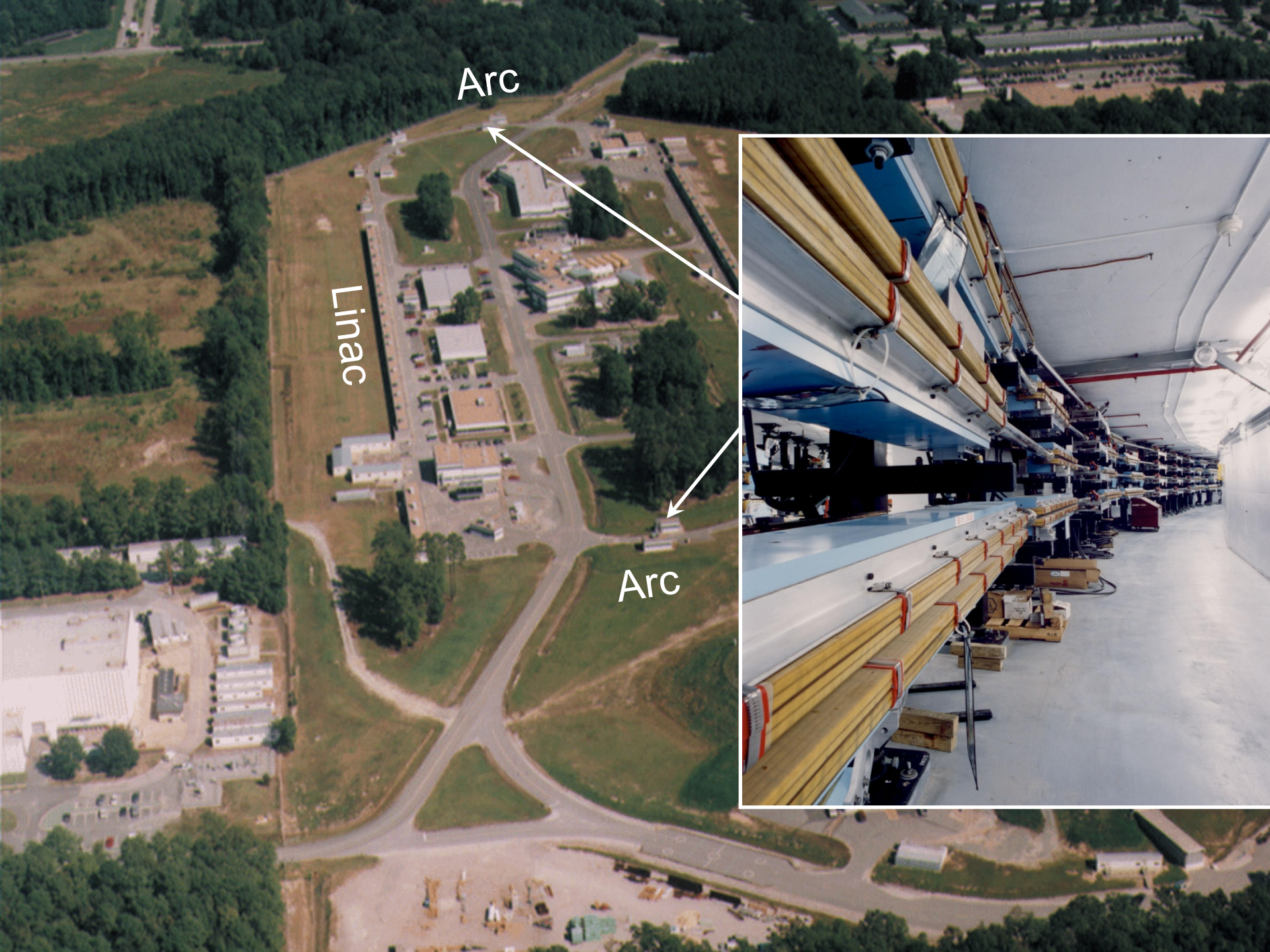
Arc
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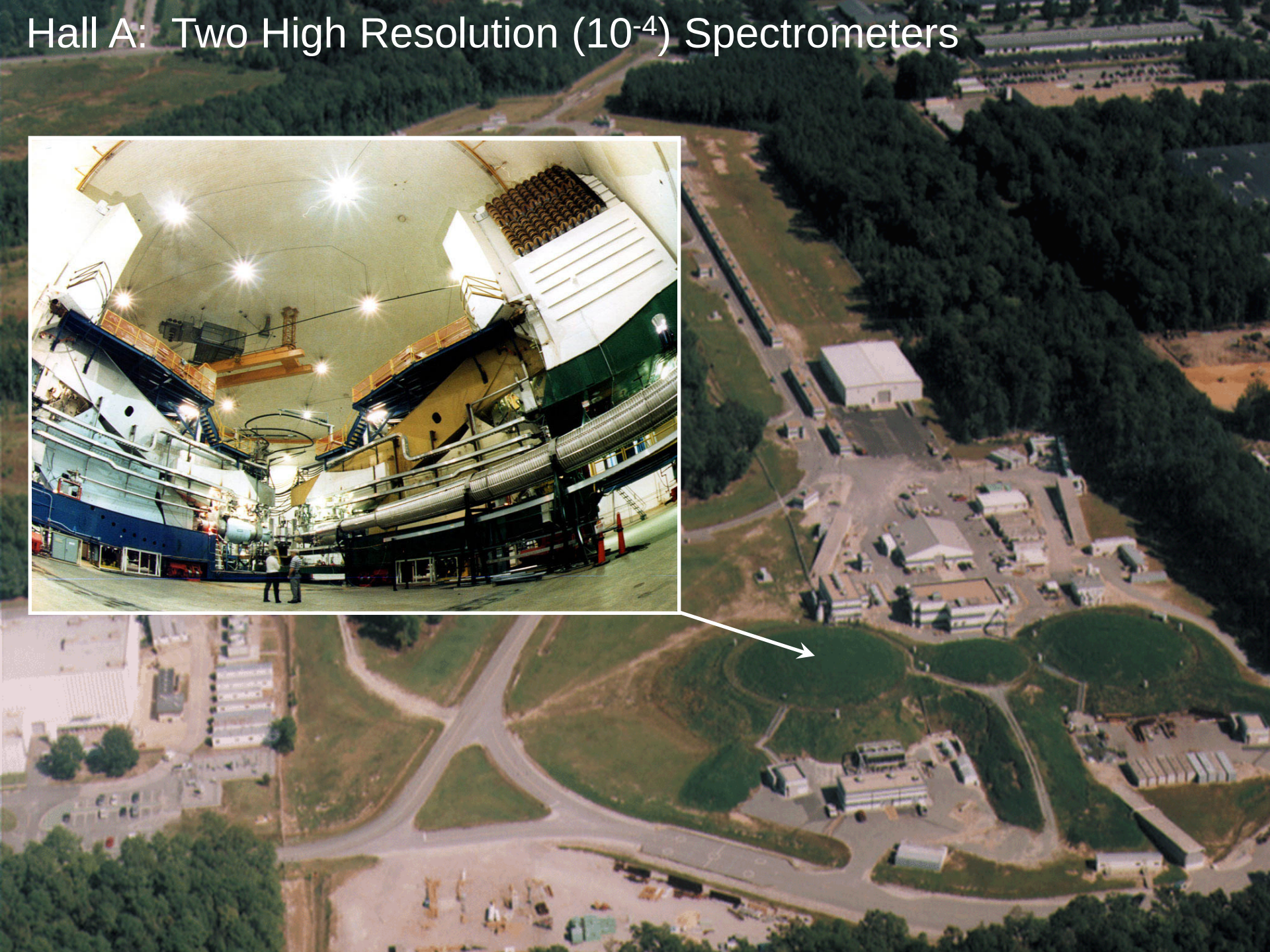
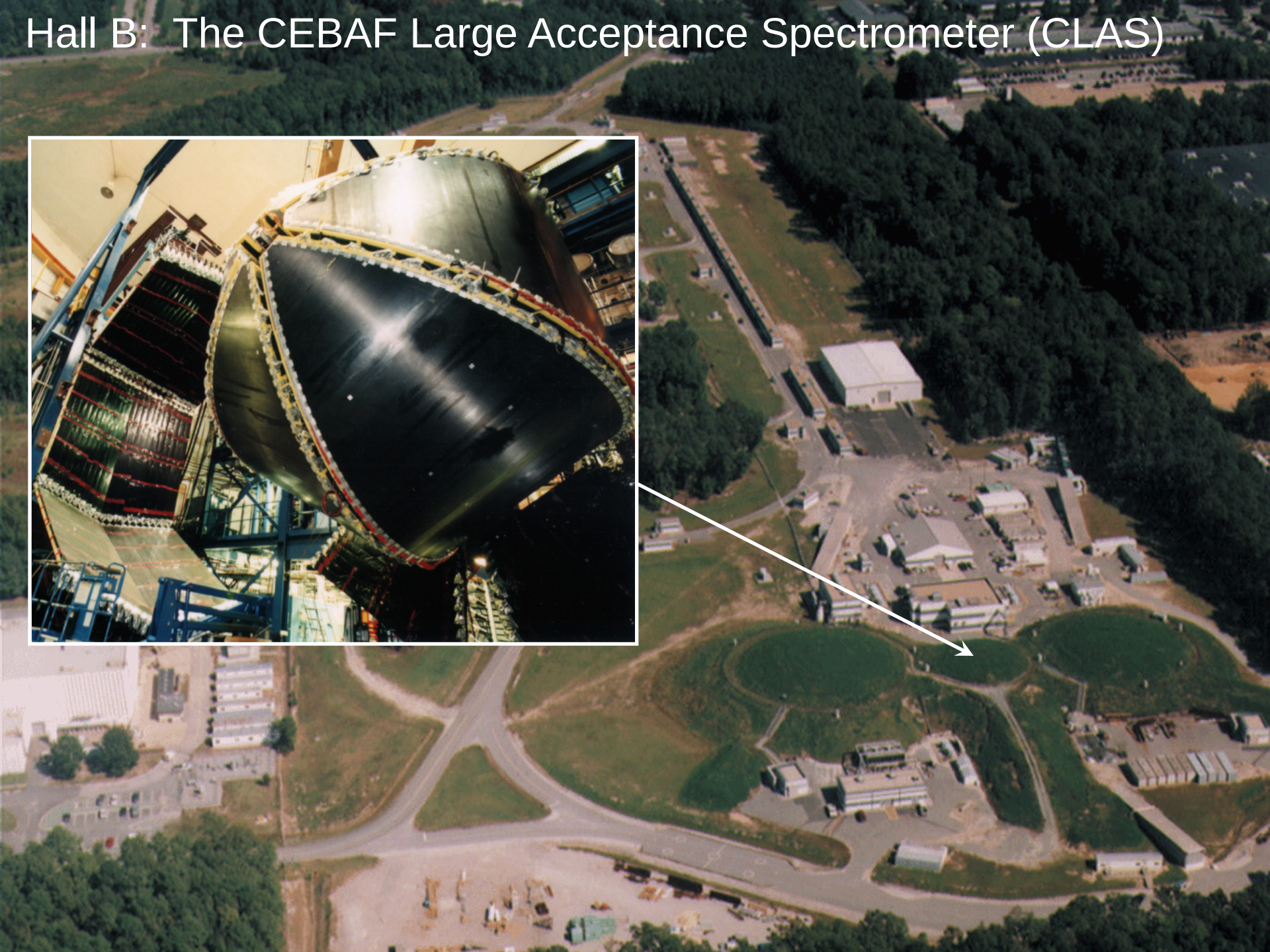
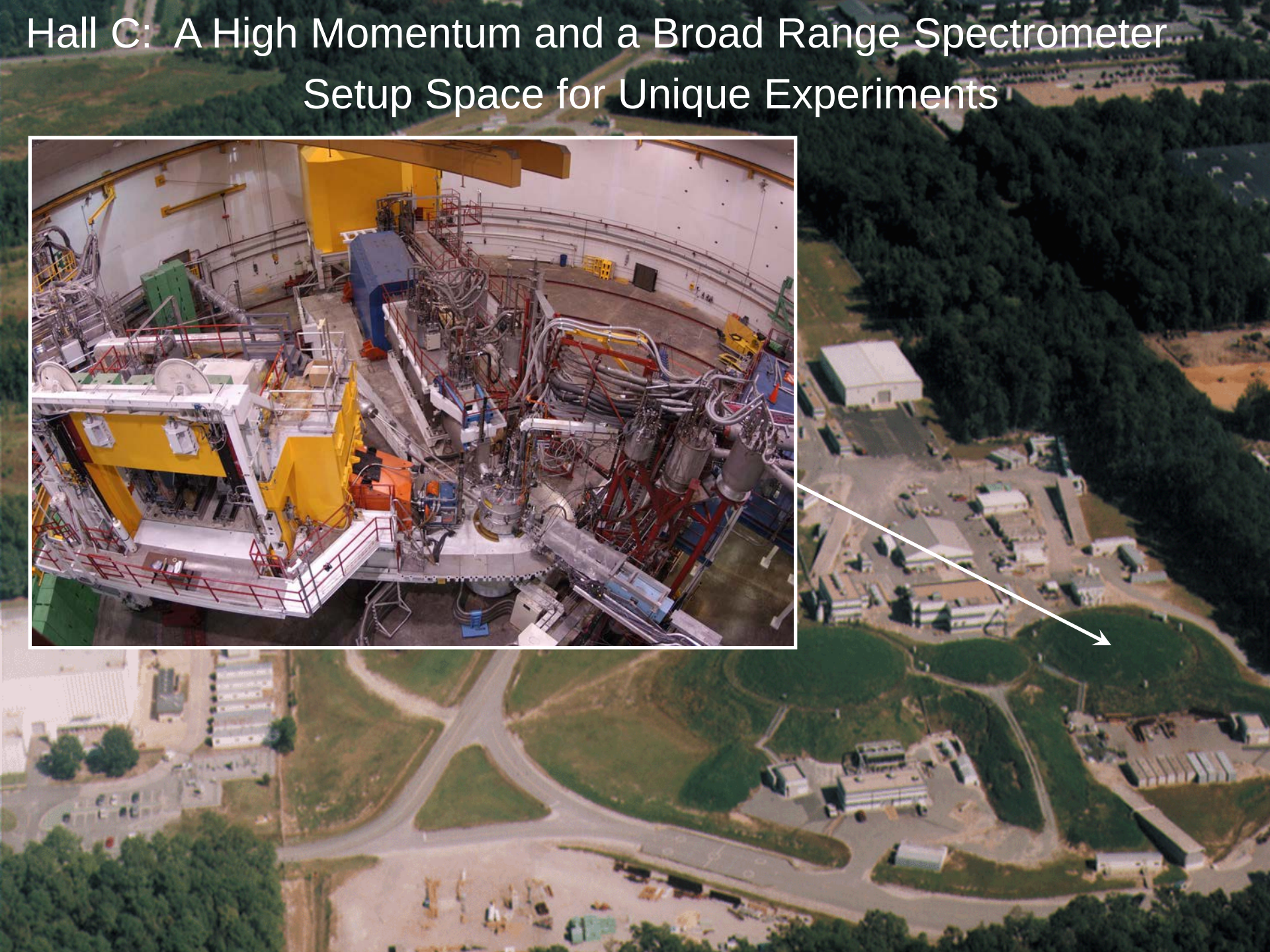
Hall A: Two High Resolution (10^{-4}) Spectrometers



Hall B: The CEBAF Large Acceptance Spectrometer (CLAS)



Hall C: A High Momentum and a Broad Range Spectrometer Setup Space for Unique Experiments



NSAC Long Range Plan 2007

Science Chapter Headings:

- **Quantum Chromodynamics: From the Structure of Hadrons to the Phases of Nuclear Matter**
  - **QCD and the Structure of Hadrons**
  - **The Phases of Nuclear Matter**
  - **The Emerging QCD Frontier: The Electron-Ion Collider**
- **Nuclei: From Structure to Exploding Stars**
- **In Search of the New Standard Model**

Will provide examples from each area

Highlights from the first 10 Years

- **Quantum Chromodynamics and the Structure of Hadrons**
  - Discovery of unexpected behavior of G_e^p
  - Strangeness content of the proton
  - The deformation of Δ and N* transition form factors
  - Spin dependent structure functions:
    Bjorken & GDH sum rule; g_1^n; $|\Delta G|$
  - Measurement of the pion form factor
  - Exploration of duality, pQCD counting rules, color transparency
  - Initial exploration of Generalized Parton Distributions (GPDs) towards mapping of angular momentum in the proton
- **Nuclei: From Structure to Exploding Stars**
  - New information on correlations in nuclei and the role of the tensor force
  - Studies of hypernuclei – better than 400keV resolution
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  - Factor 5 increase in precision of Standard Model couplings

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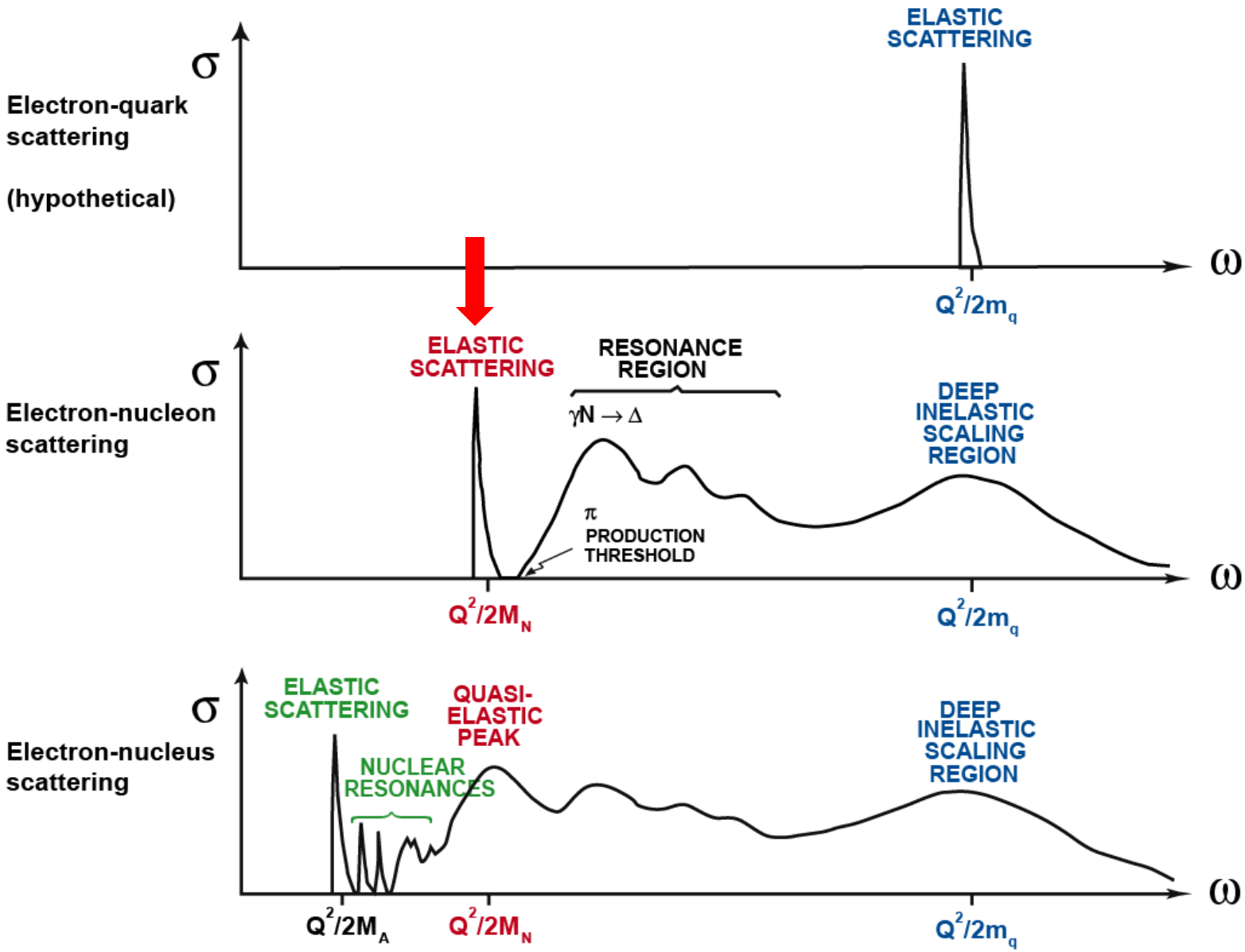

The Proton and Neutron are the “Hydrogen Atoms” of QCD

<u>What we “see” changes with spatial resolution</u>

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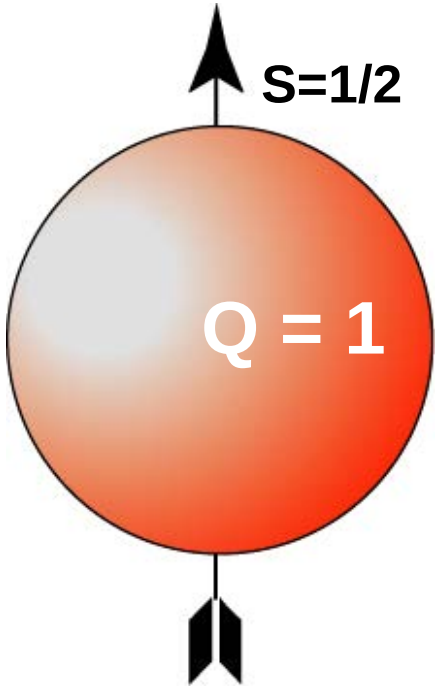
What we "see" changes with spatial resolution

>1 fm

Nucleons



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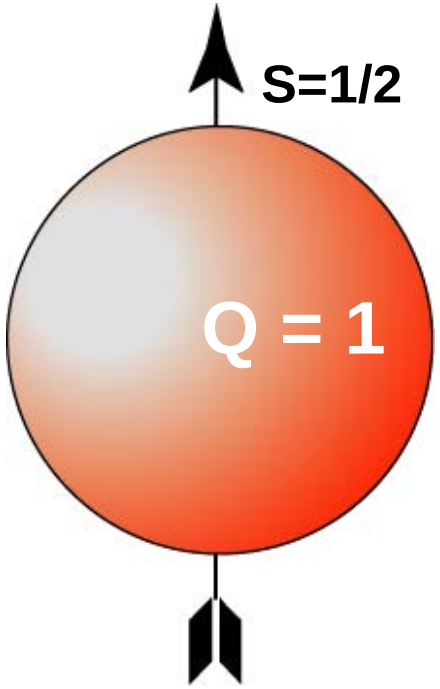
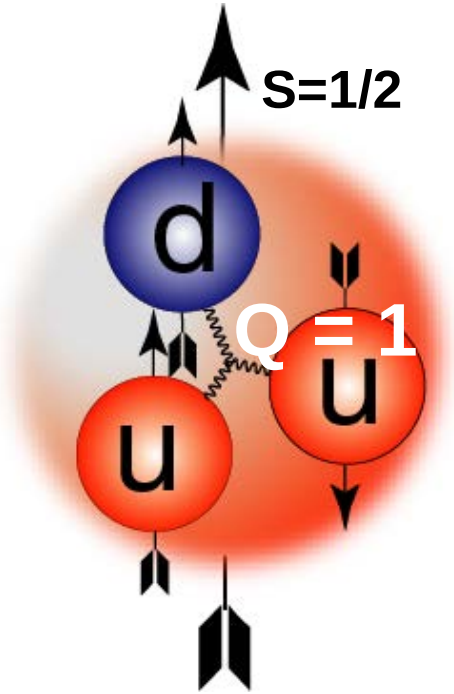


0.1 — 1 fm

Constituent quarks and glue



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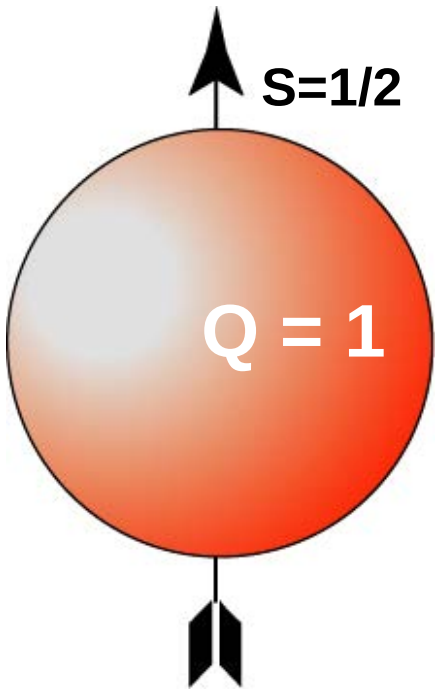

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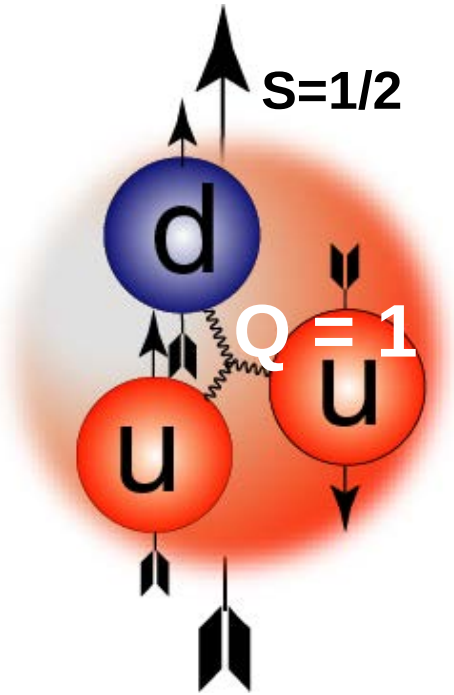
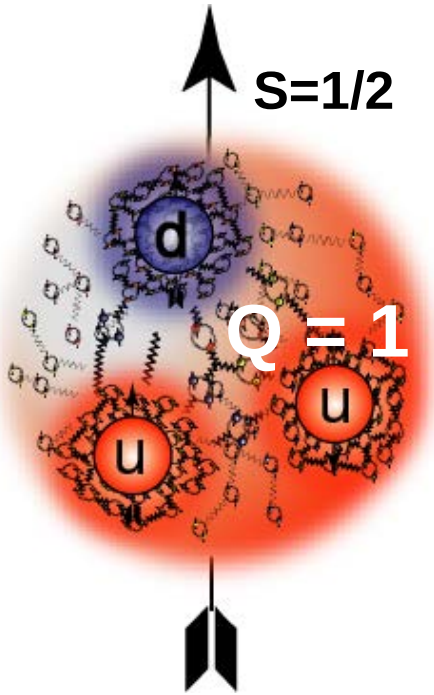
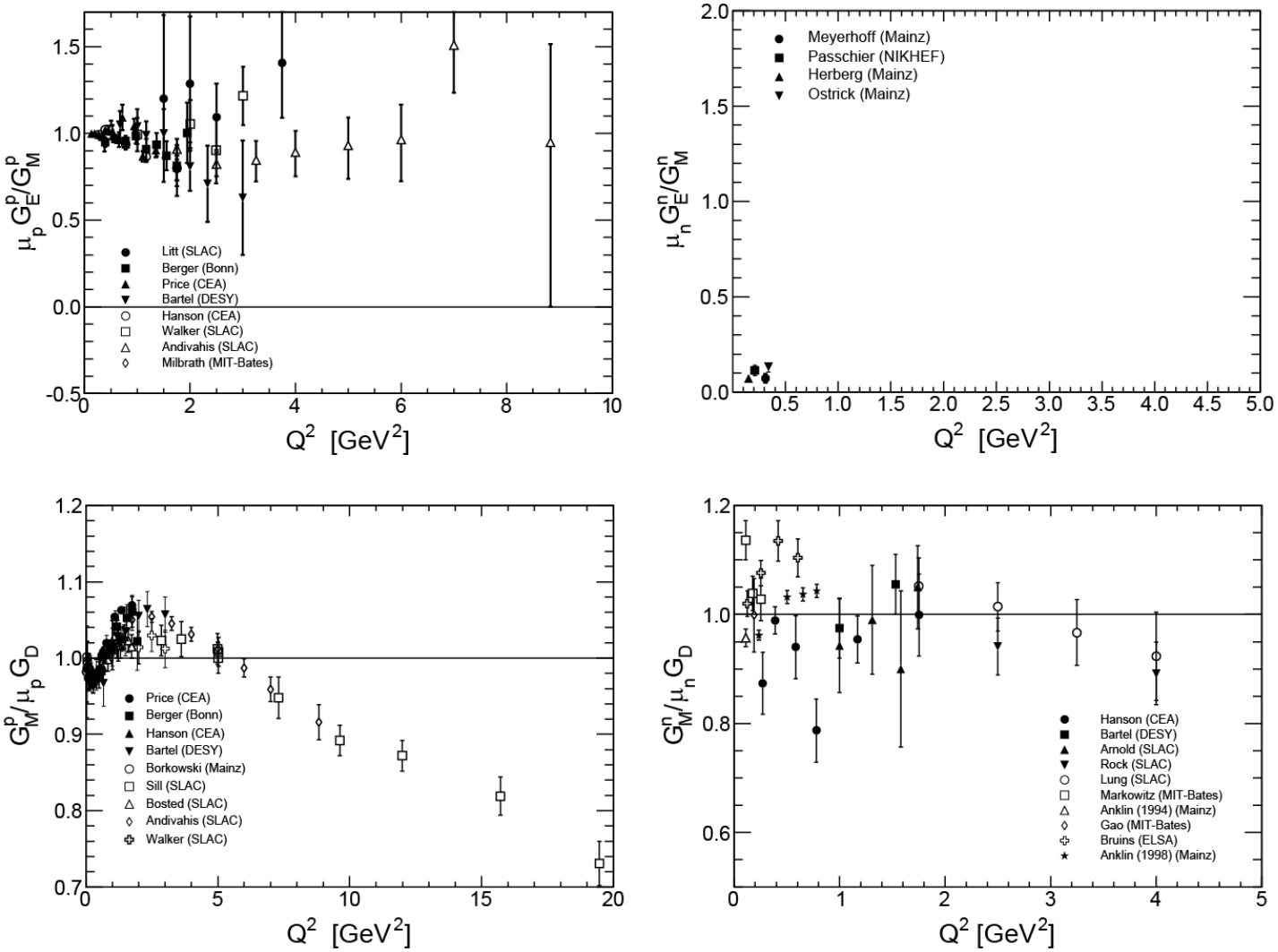


< 0.1 fm
"bare" quarks and glue



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

Before JLab and Recent non-JLab Data



S. Riordan

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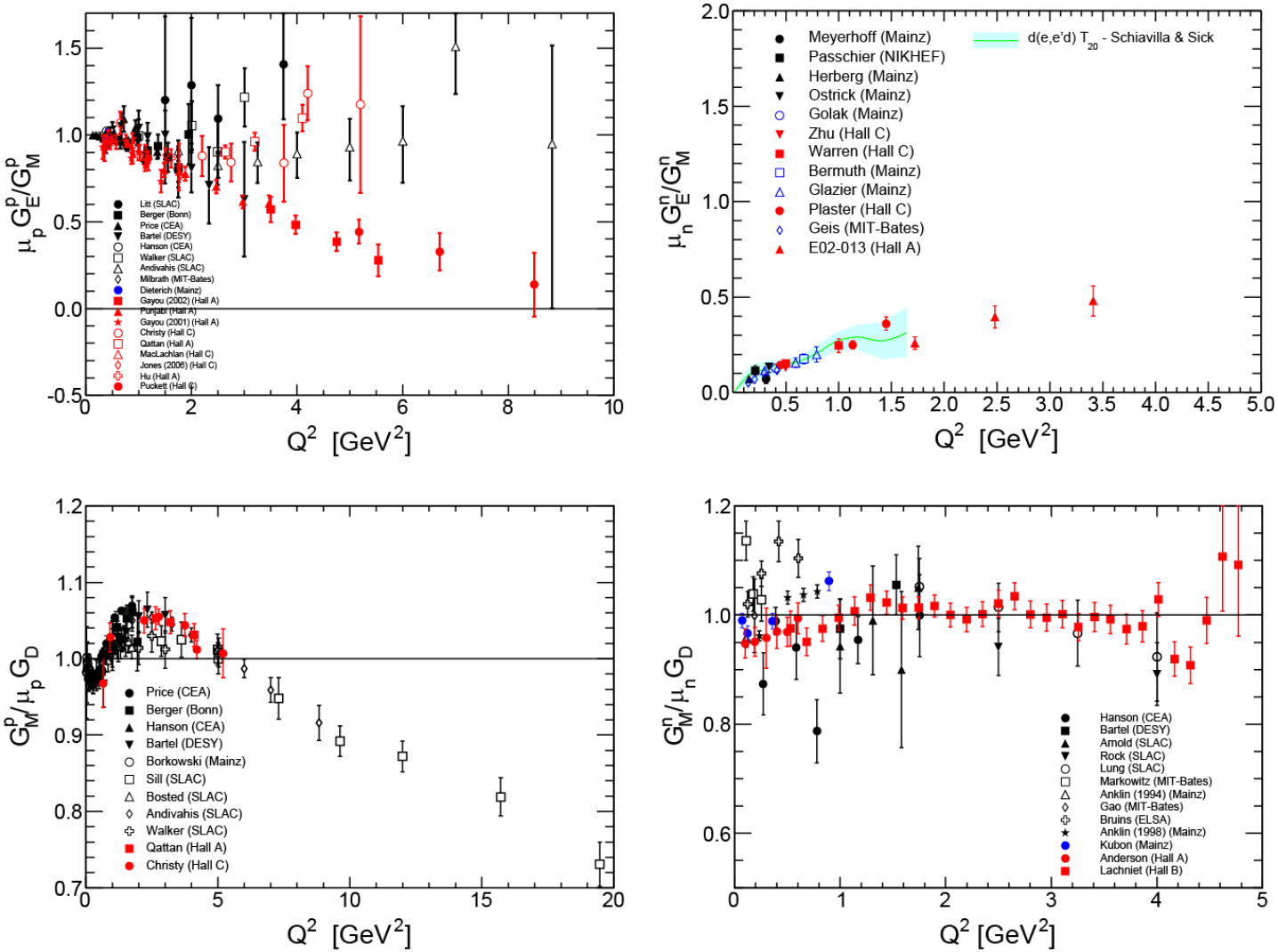
Today, with Available JLab Data



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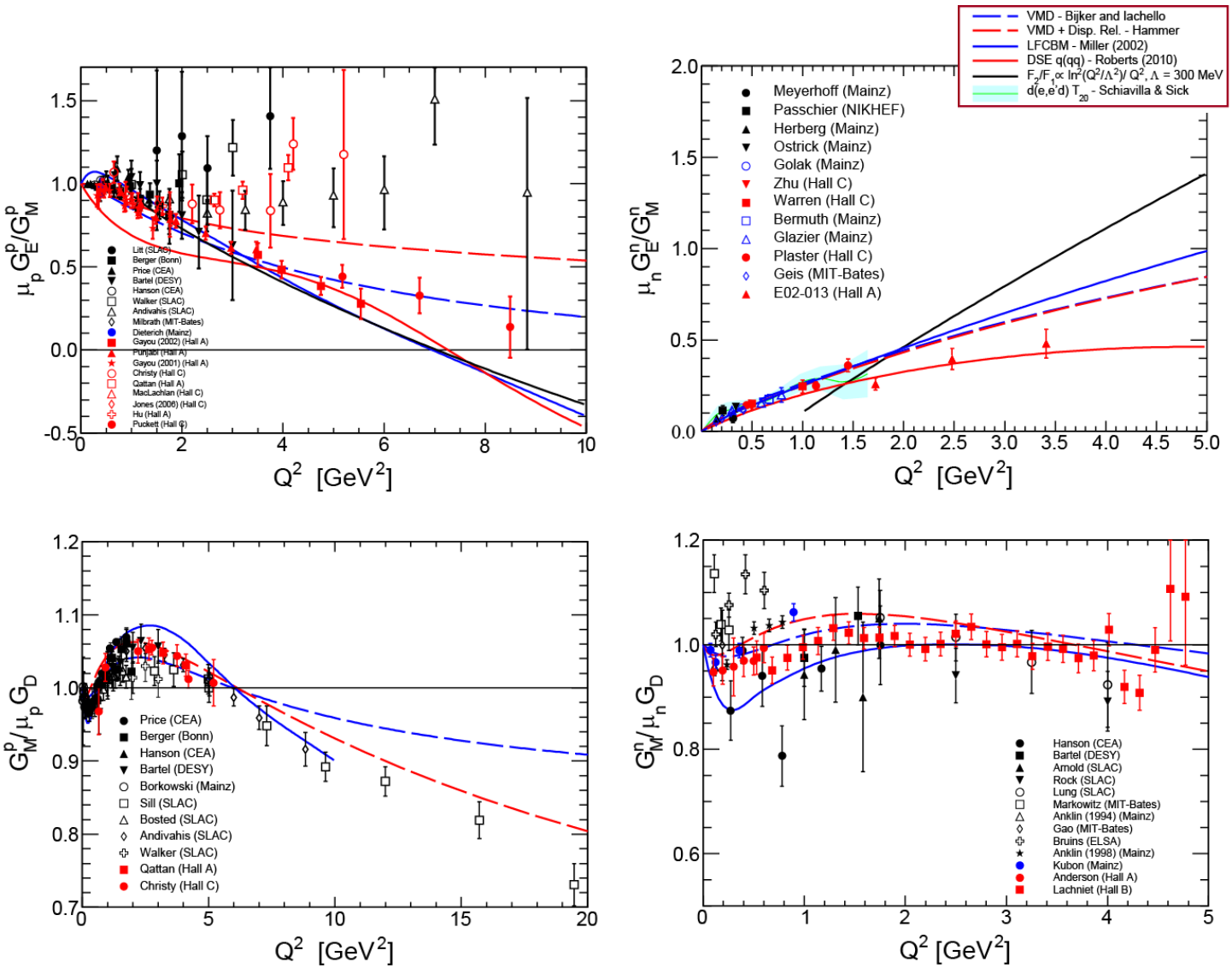
Today, with Available JLab Data, Compared w/ Theory



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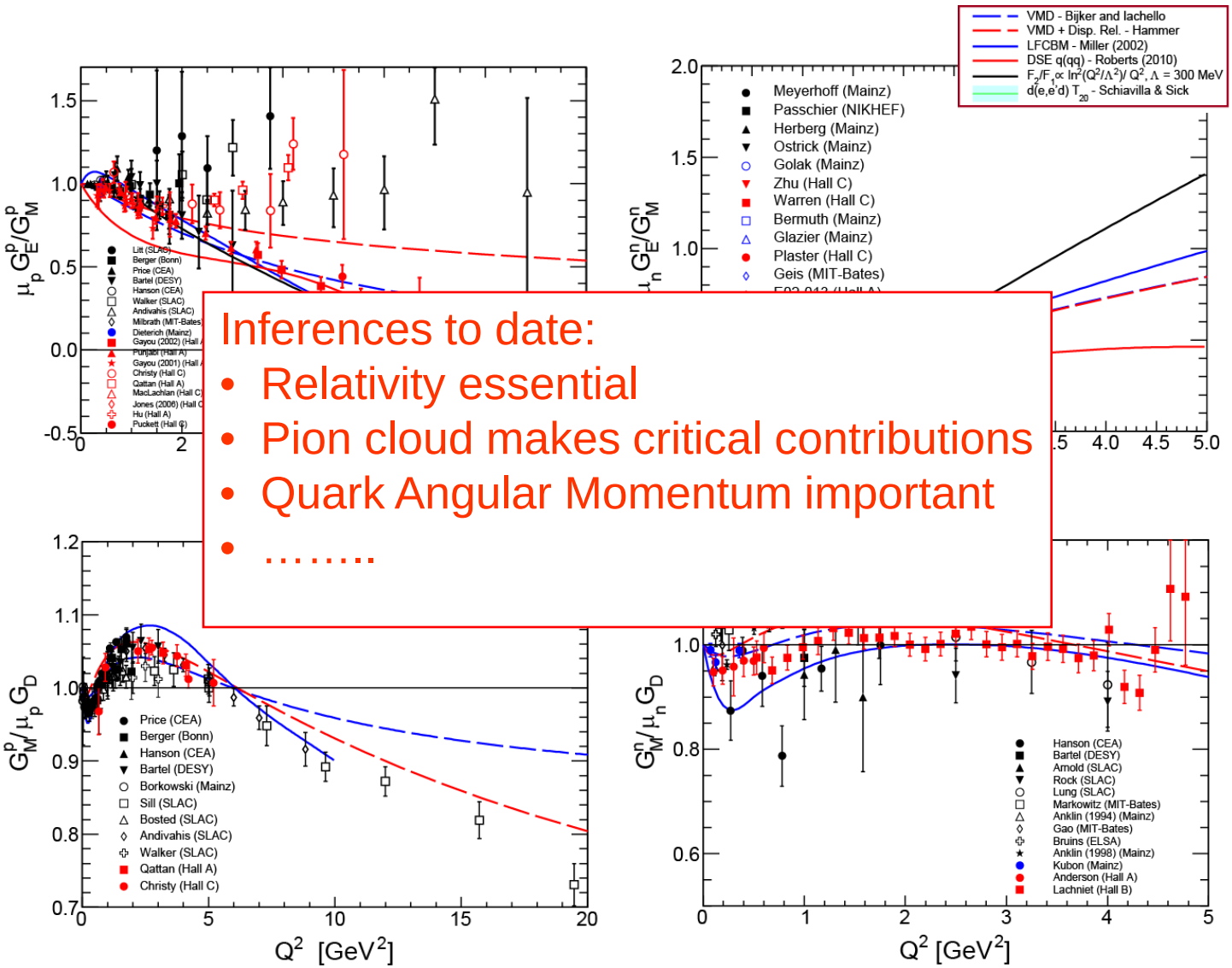


Inferences to date:

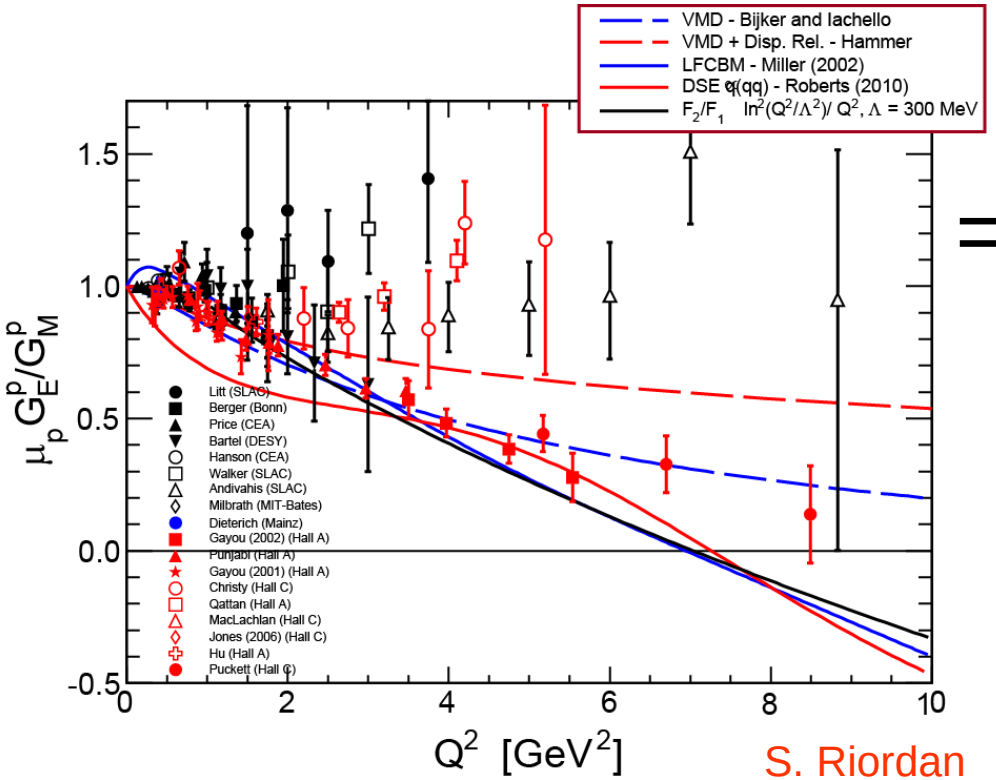
- Relativity essential
- Pion cloud makes critical contributions
- Quark Angular Momentum important
- ……..

S. Riordan

These Data Are Elucidating the Nucleon's Structure

The inequality of G_E^p and μG_M^p was a surprise. It:

- Established the role of quark Orbital Angular Momentum (OAM) in the nucleon (and in the "spin crisis", ΔG, …)
- Demonstrated that a proper treatment of relativity is essential in describing nucleon structure



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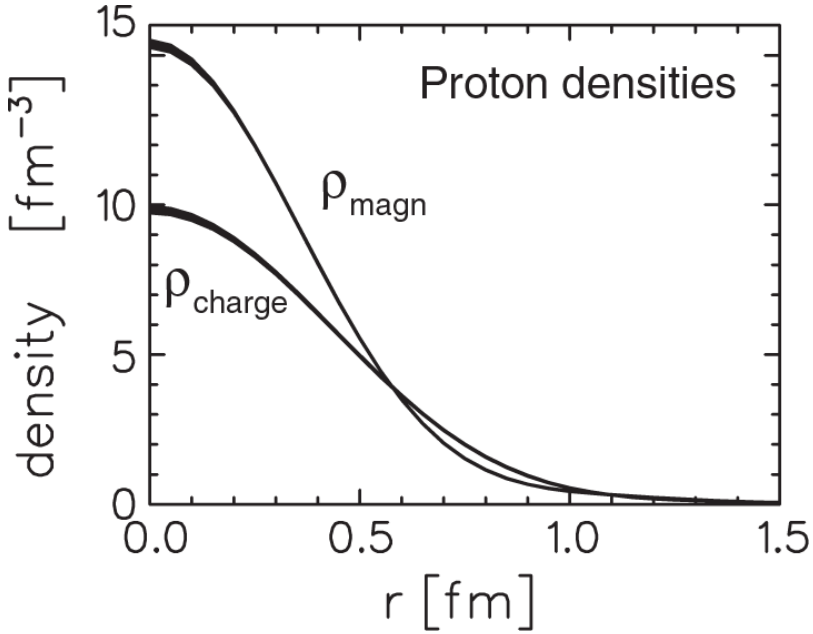
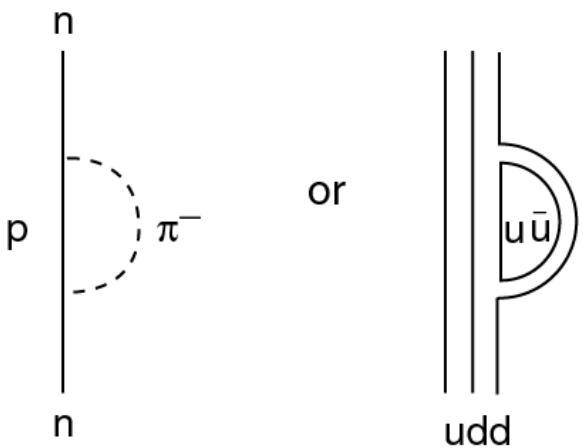


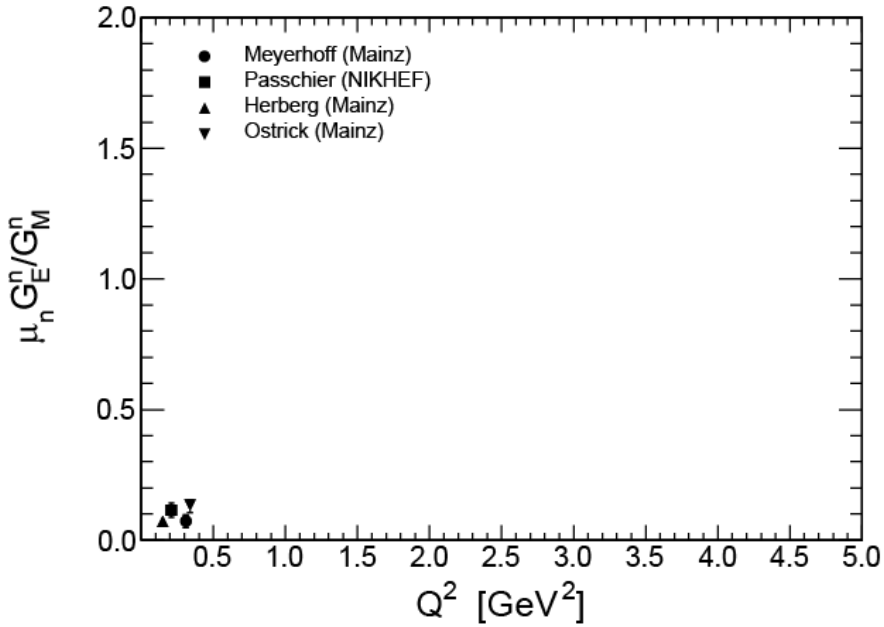
S. Riordan

These Data Are Elucidating the Nucleon's Structure

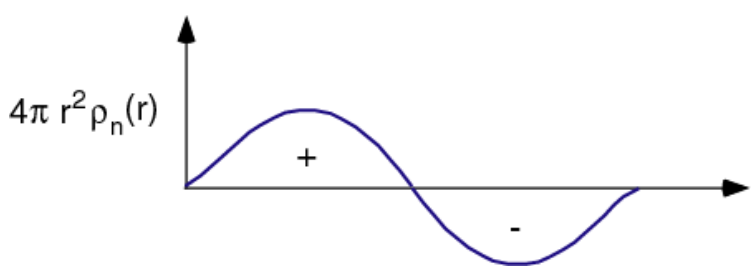
The charge form factor of the neutron is particularly interesting

$Q_n = 0$ But $\rho_n(r) \neq 0$





n - Scattering => $G_E^n(q=0)$



Previously available data limited to modest Q^2, just barely sensitive to details beyond the RMS radius

These Data Are Elucidating the Nucleon's Structure

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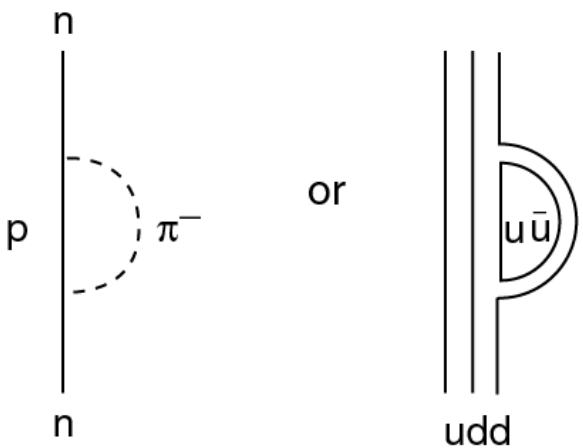
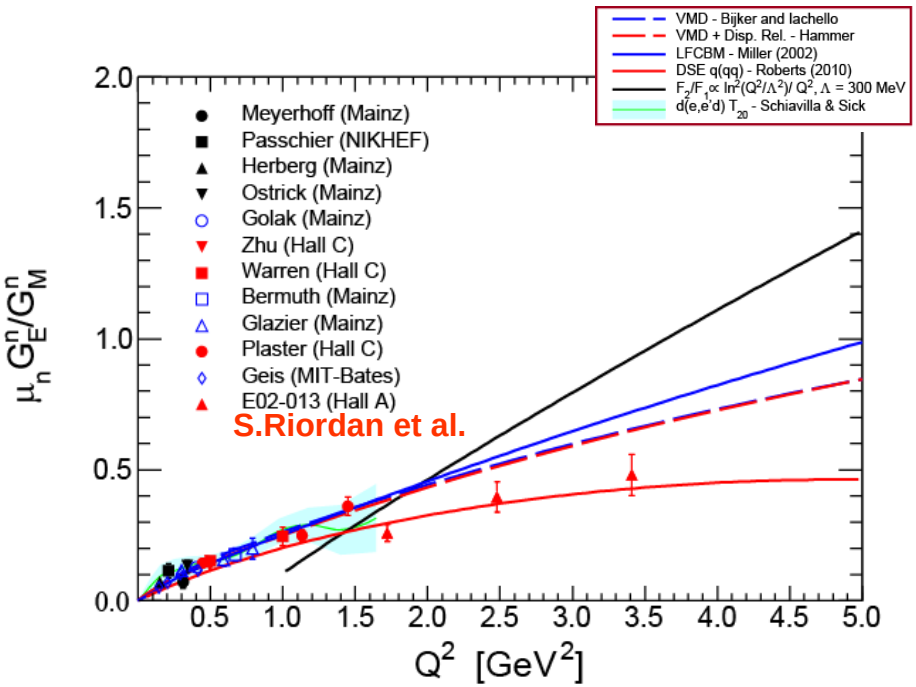
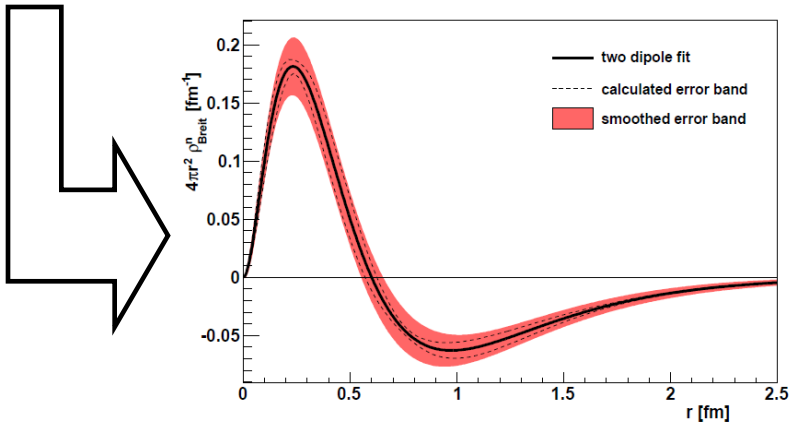




- Neutron electric form factor data reveal the shape of the charge distribution,
- Show the pion cloud clearly, and
- Confirm the importance of relativistic effects in nucleon structure



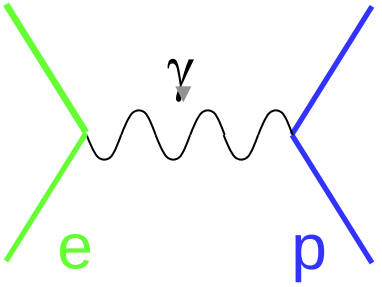
C. Crawford, et al.

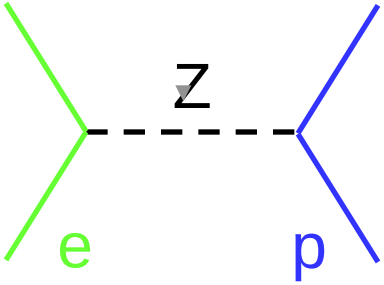
Use Parity-Violating Electron Scattering to Measure the Weak Neutral Current Form Factors of the Nucleon

- $G^{Z,p}$ contributes to electron scattering

$$\sigma \propto \left| M^{\gamma} + M^{Z} \right|^{2}$$

but $M^{\gamma} >> M^{Z}$, so it is not measurable





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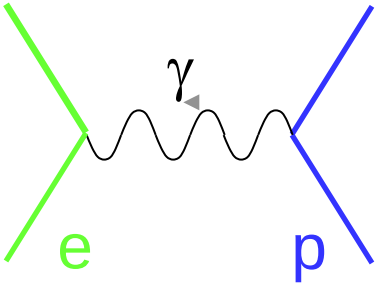

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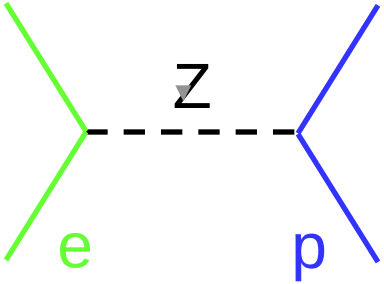
However, the *interference* term multiplies

(**large** M^{γ}**)** x (small M^{Z})



- Interference term violates parity: use $(\vec{e},e')$

$$A^{PV} \equiv \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$$

$$= -\frac{G_F Q^2}{4\sqrt{2}\pi\alpha} \frac{A_E + A_M + A_A}{\varepsilon\left(G_E^{\gamma}\right)^2 + \tau\left(G_M^{\gamma}\right)^2}$$

where $A_E = \varepsilon(\theta) G_E^{\gamma} G_E^{Z}, \quad A_M = \tau G_M^{\gamma} G_M^{Z}$

$$A_A = -\left(1 - 4\sin^2\theta_W\right)\varepsilon'(\theta)\, G_M^{\gamma} G_A^{e}$$

$$\varepsilon(\theta) = \left[1 + 2(1+\tau)\tan^2(\theta/2)\right]^{-1},$$

$$\tau = \frac{Q^2}{4M_p^2},$$

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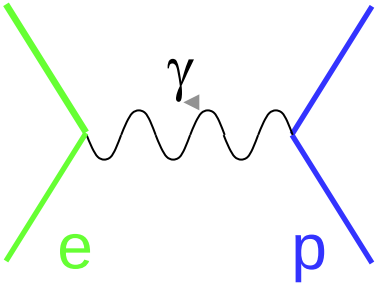

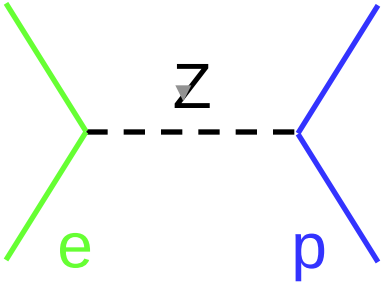

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ε and τ dependence allow separation of terms ("Rosenbluth Separation")

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Measurements of the Strange Quark Distribution (G0 and HAPPEx) Are Providing a Unique New Window into Hadron Structure

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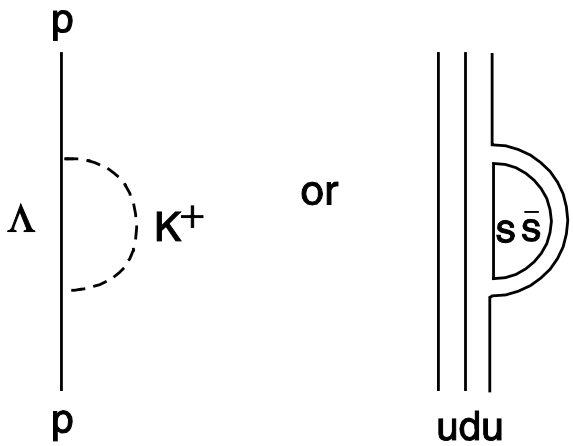

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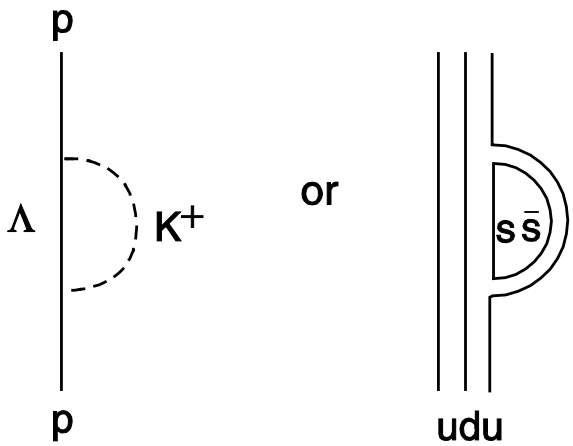
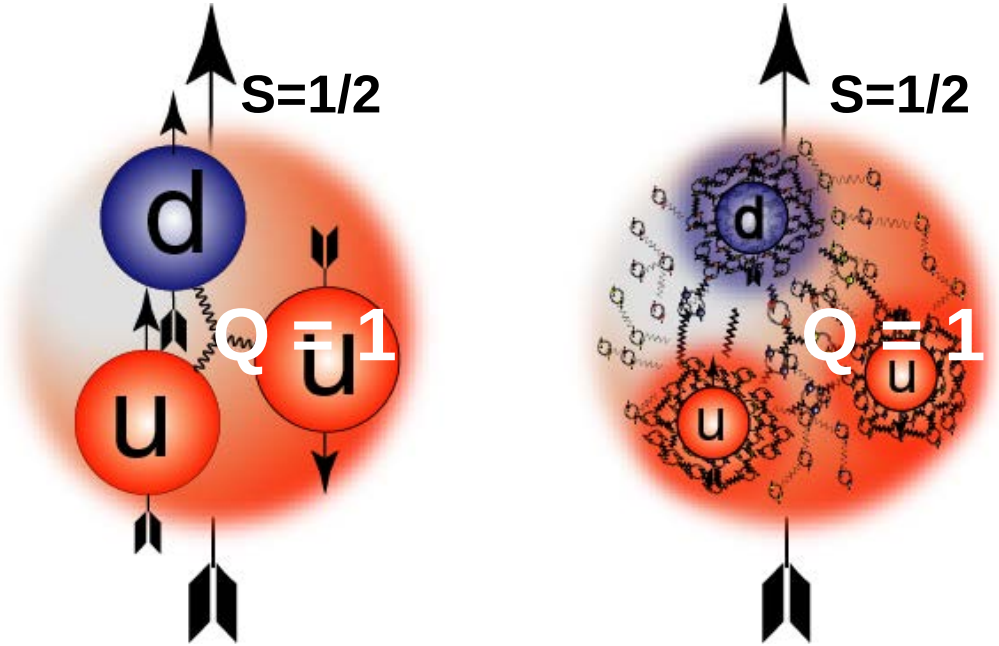


Unlike G_E^n, the $s\bar{s}$ pairs come uniquely from the sea; there is no "contamination" from pre-existing u or d quarks



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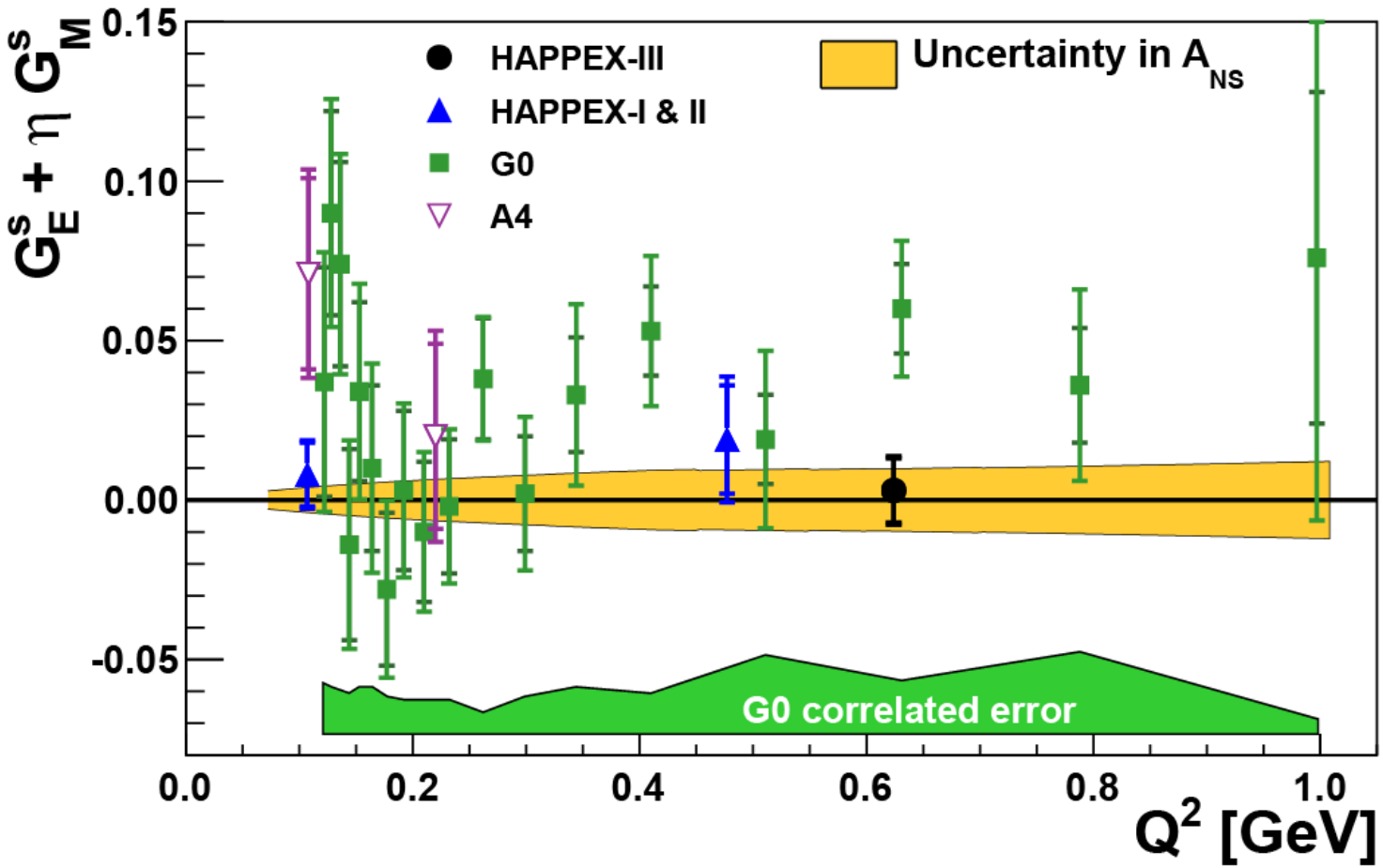
The Strange Quark Form Factors of the Nucleon



Z. Ahmet, *et al.*
arXiv:1107.0913

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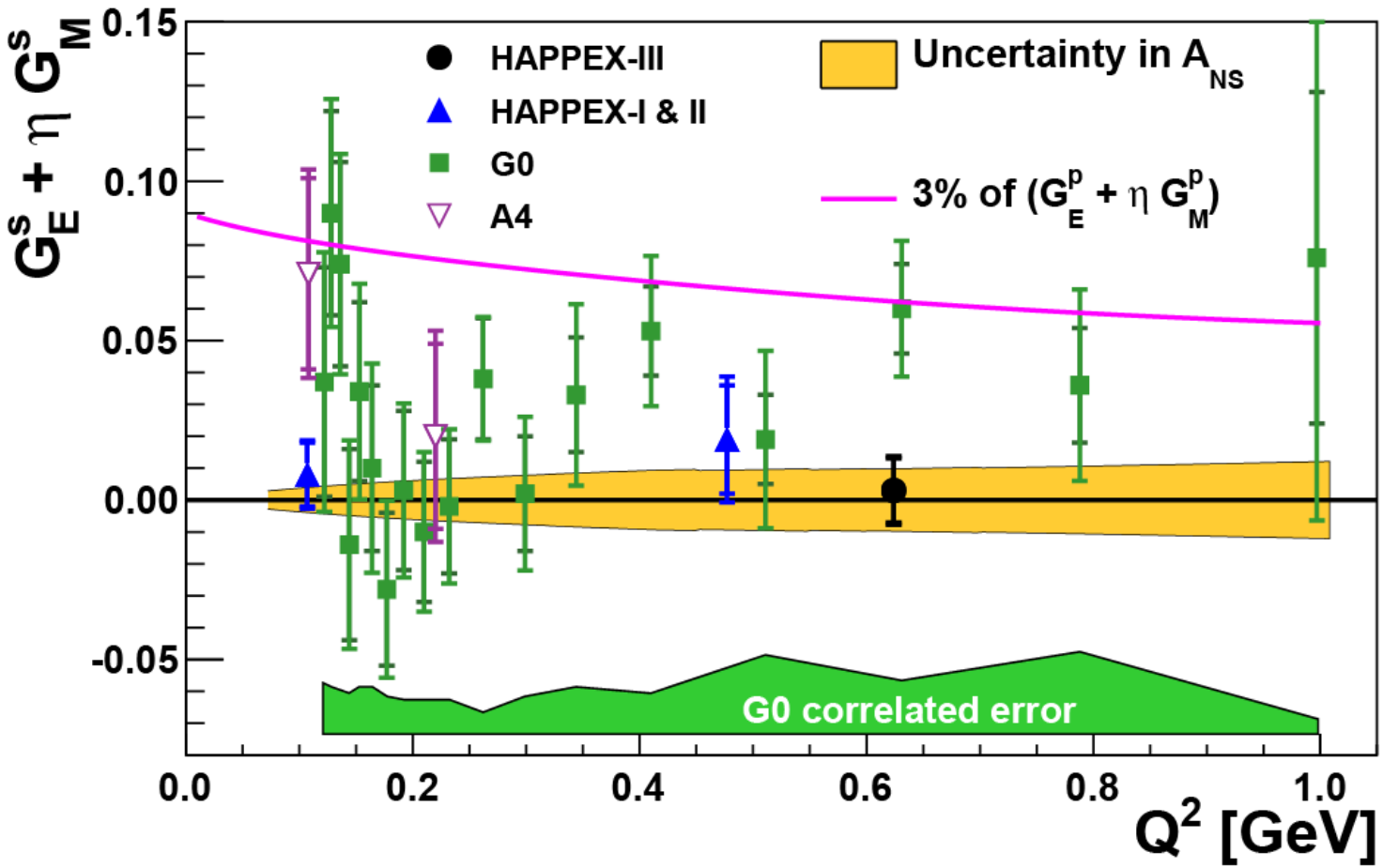

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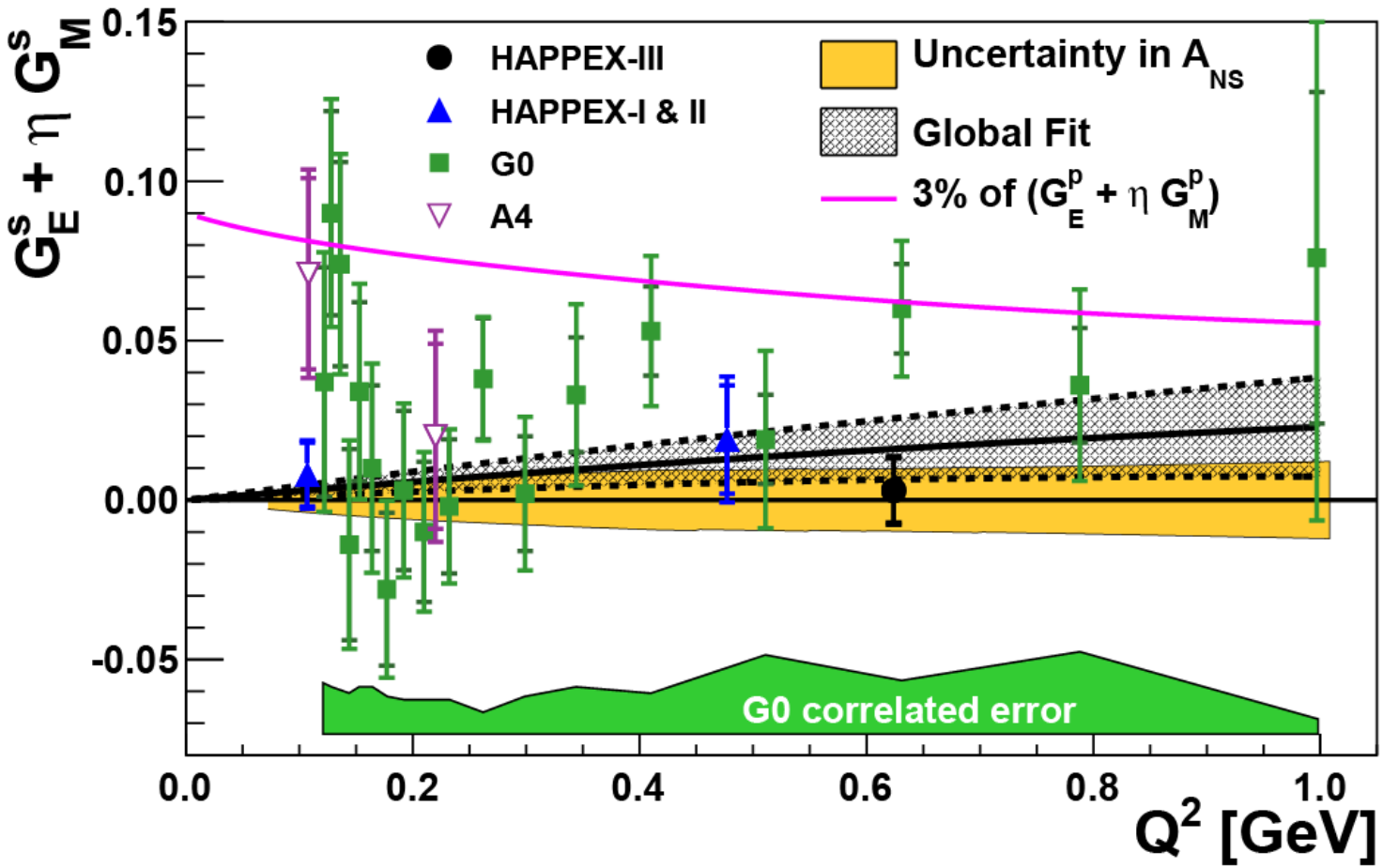

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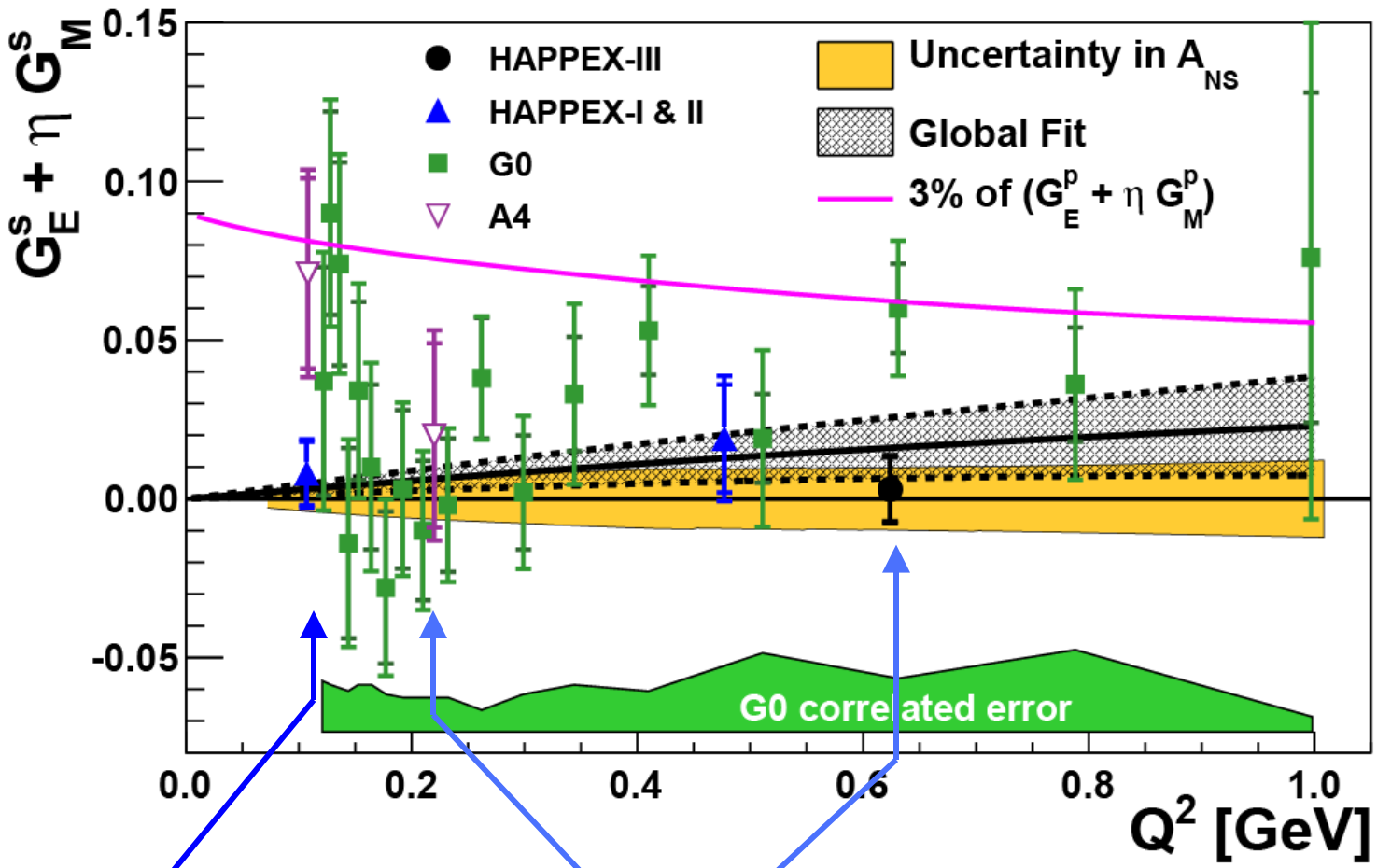
The Strange Quark Form Factors of the Nucleon

Backward Angle and Helium Data Permit Electric/Magnetic Separations



Backward Angle Data Available from SAMPLE and HAPPEx II

Backward Angle Data Available from G0 Backward Angle runs

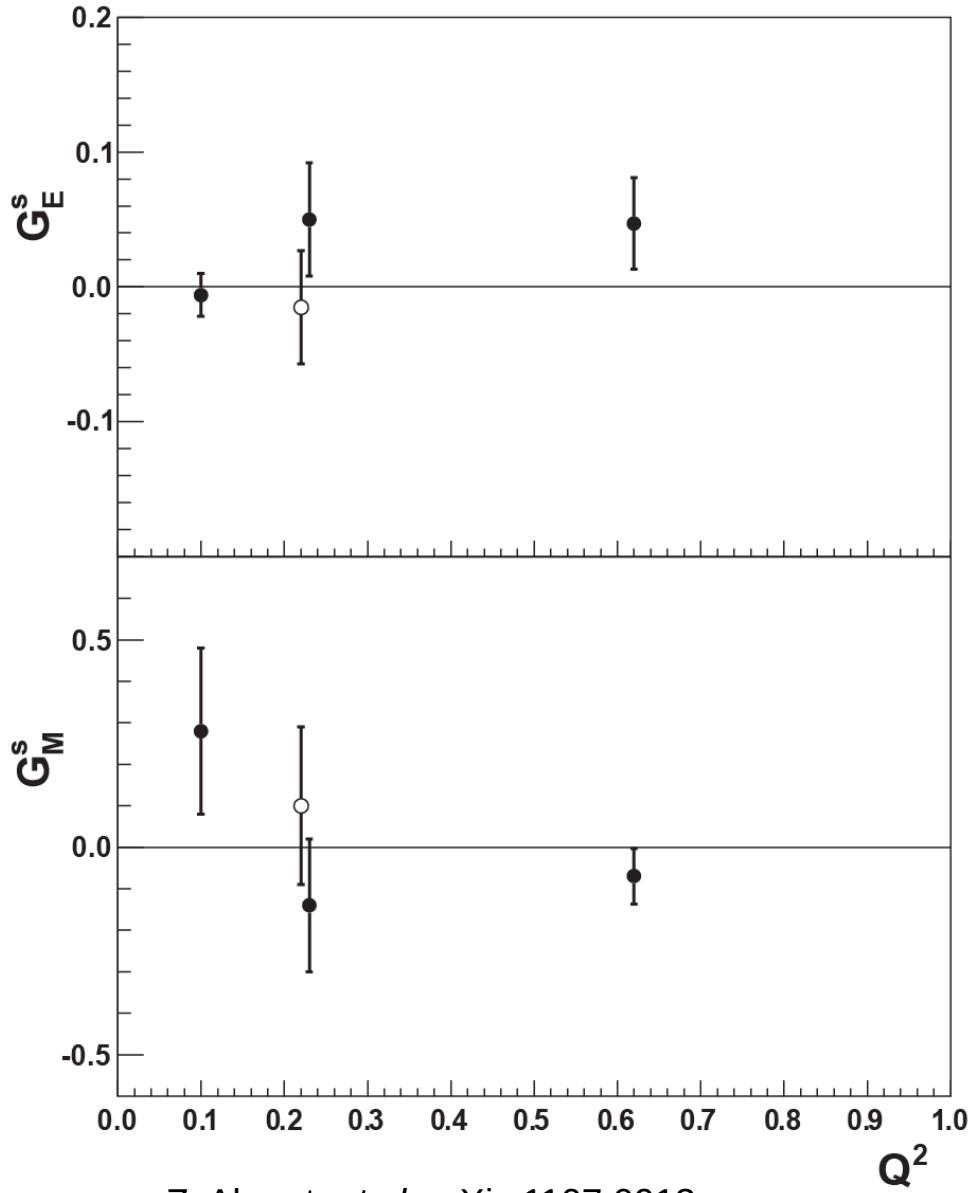
Z. Ahmet, *et al.*
arXiv:1107.0913

Strange Quark Form Factor Extraction

Analysis of G0 Backward Data now Complete

HAPPEx-III (analysis just completed) increased precision at Q^2=0.6 GeV^2

Bottom Line: Strange quarks contribute ≤ 10% to the nucleon G_E and G_M and can be neglected in the flavor decomposition of the form factors



Z. Ahmet, *et al.* arXiv:1107.0913

Androic et al., Phys. Rev. Lett. 104, 012001 (2010)

$F_{1,2}$ Form Factor Flavor Decomposition

Now Carry Out a Form Factor Flavor Decomposition:

- **Start w/ complete set of EM FFs: (G_E^p, G_M^p, G_E^n, G_M^n, and parity violation FFs measured to extract G_E^s and G_M^s)**
- **Infer strange quark form factors from the parity violation data**
- **Since $G_{E,M}^s \approx 0$; set it to 0 and then use isospin symmetry to simplify the relationship between the quark flavors and the form factors:**

$$F_{1,2}{}^{p} = \frac{2}{3}F_{1,2}^{u} - \frac{1}{3}F_{1,2}^{d}; \qquad F_{1,2}{}^{n} = \frac{2}{3}F_{1,2}^{d} - \frac{1}{3}F_{1,2}^{u}$$

Assuming isospin symmetry:

$$F_{1,2}^{u,p} = F_{1,2}^{d,n} \quad \text{and} \quad F_{1,2}^{d,p} = F_{1,2}^{u,n}$$

- **Use these formulae and the more complete set of EM FFs to extract Pauli and Dirac FFs for u and d quarks over a broad range of Q^2**

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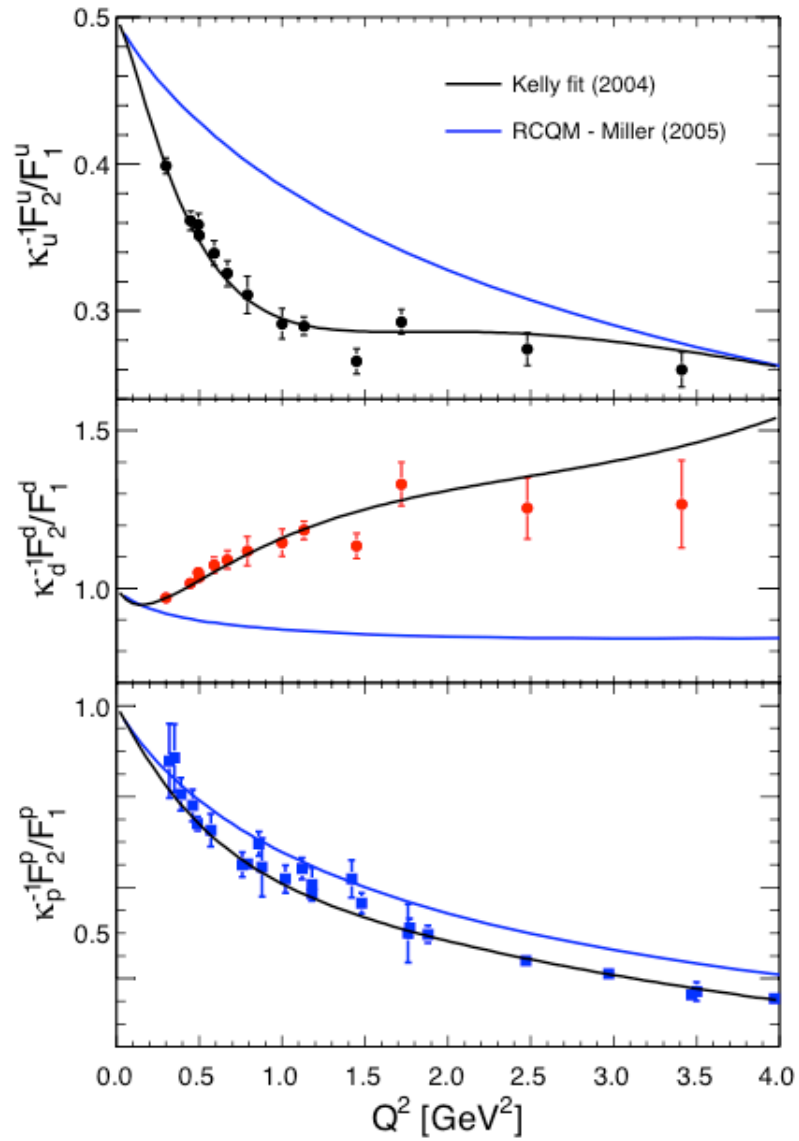
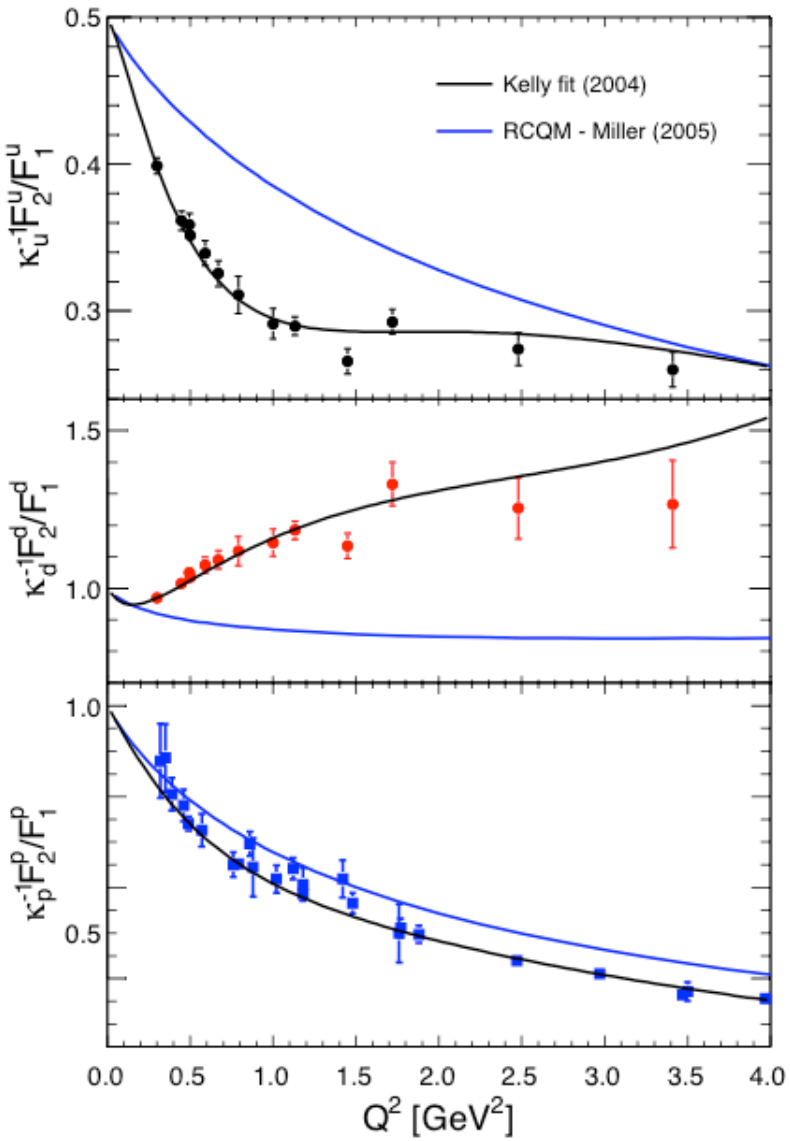


G. Cates *et al.*, PRL 106, 252003 (2011)

$F_{1,2}$ Form Factor Flavor Decomposition

Result is quite sensitive to theories of the nucleon

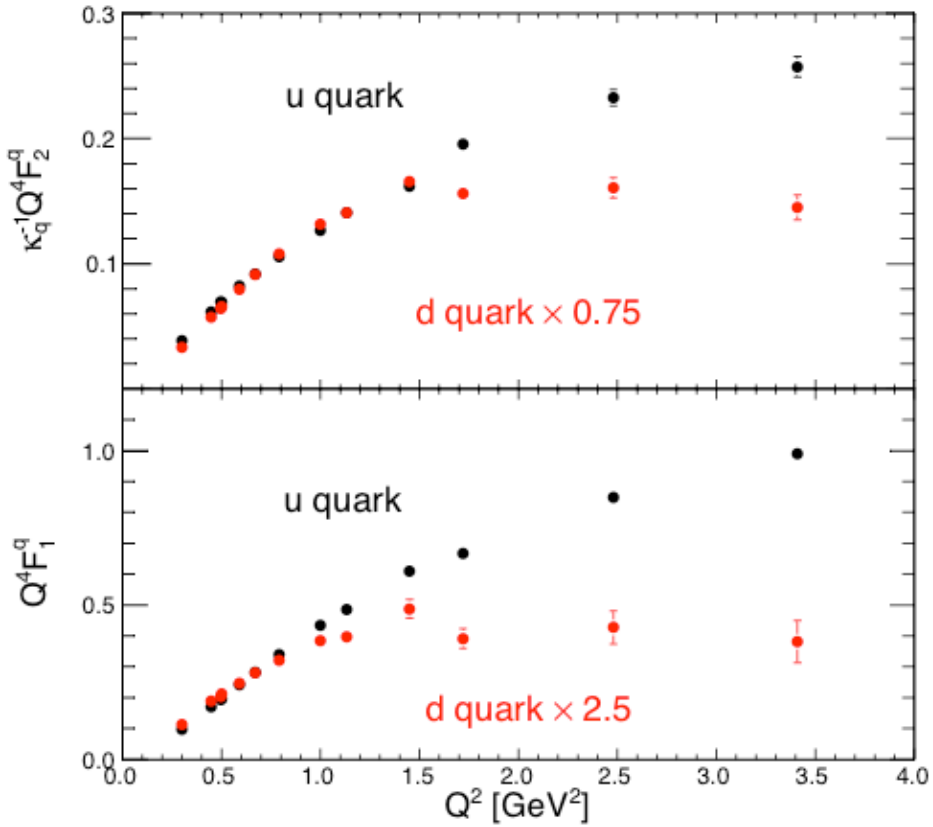
- **Form factors shown are for (u,d) in the proton**
- **The ratio F_2/F_1 appears to become constant for both constituents from ~ 1.5 GeV^2, in contrast even to the expectation for that ratio for each nucleon to scale with $1/Q^2$, at least in the pQCD limit (this scaling has not – yet – been observed)**
- **Constituent Quark Model is unable to describe this behavior**



G. Cates *et al.*, PRL 106, 252003 (2011)

Mapping of nucleon constituents (in the proton)

The flavor-separated F_1 and F_2 ratios were then used to extract the transverse densities for the u- and d-quark (in the proton)



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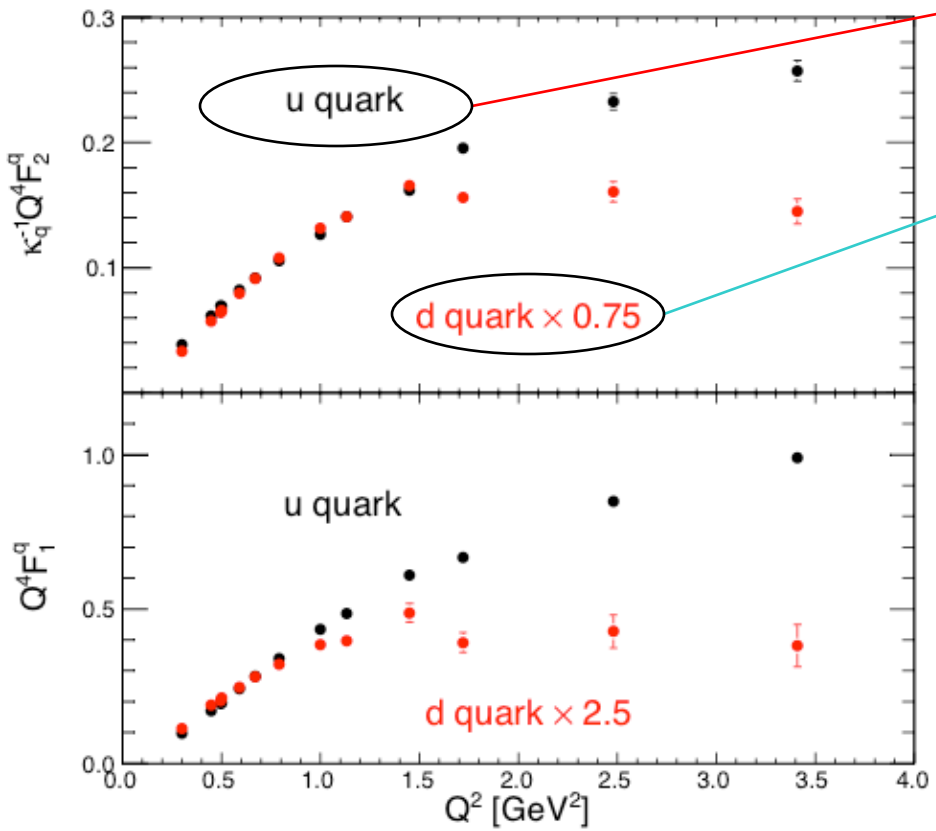
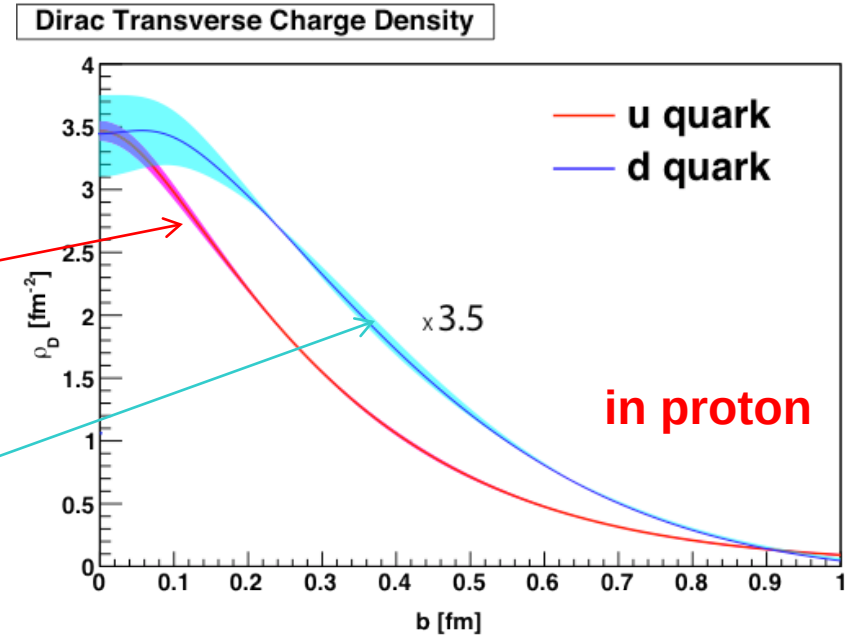




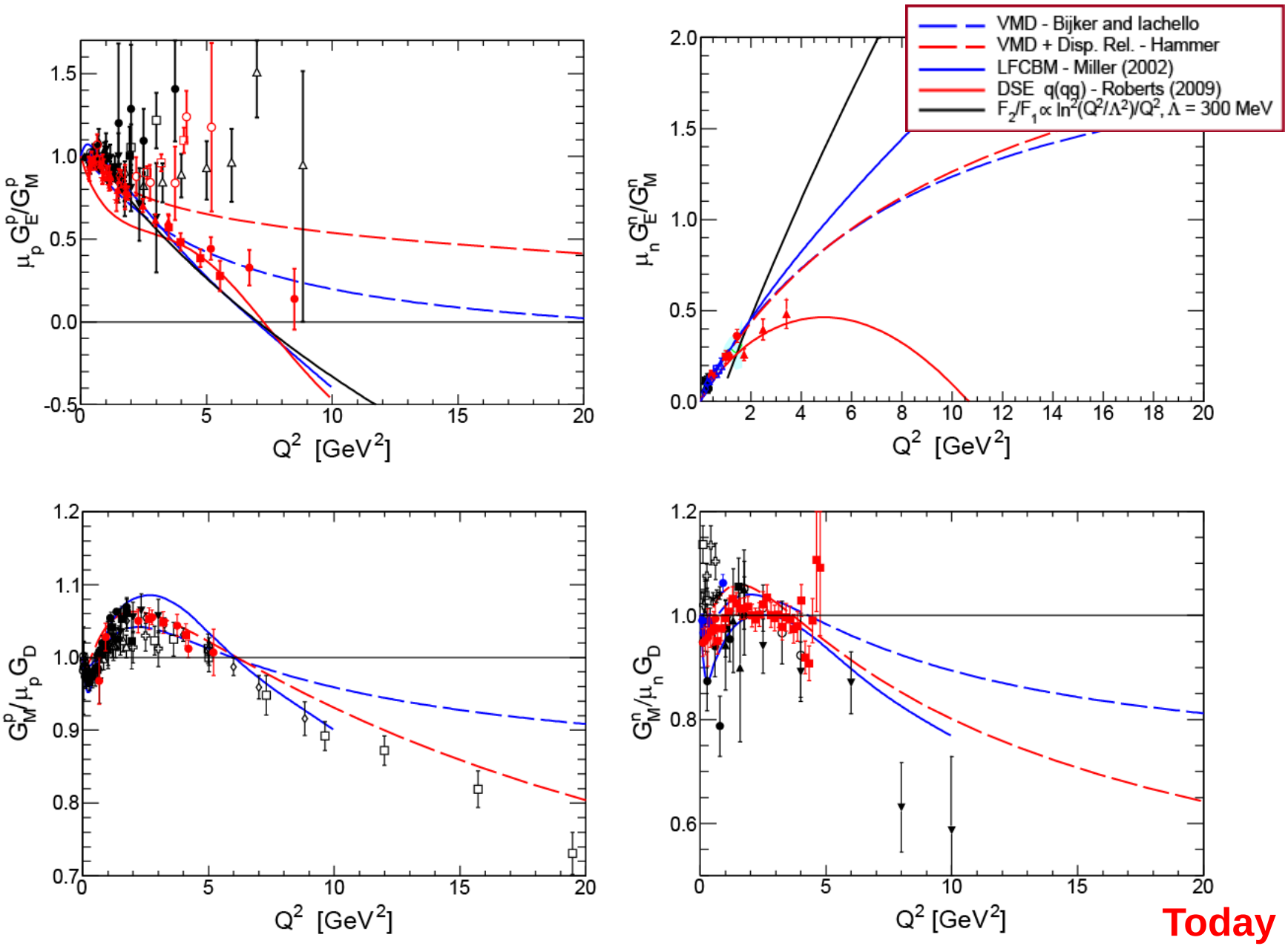
→Why is the d-quark so much wider?

Impact parameter *b* is defined relative to the transverse center of the quark's longitudinal momentum fractions

$$R = \sum x_i r_i$$

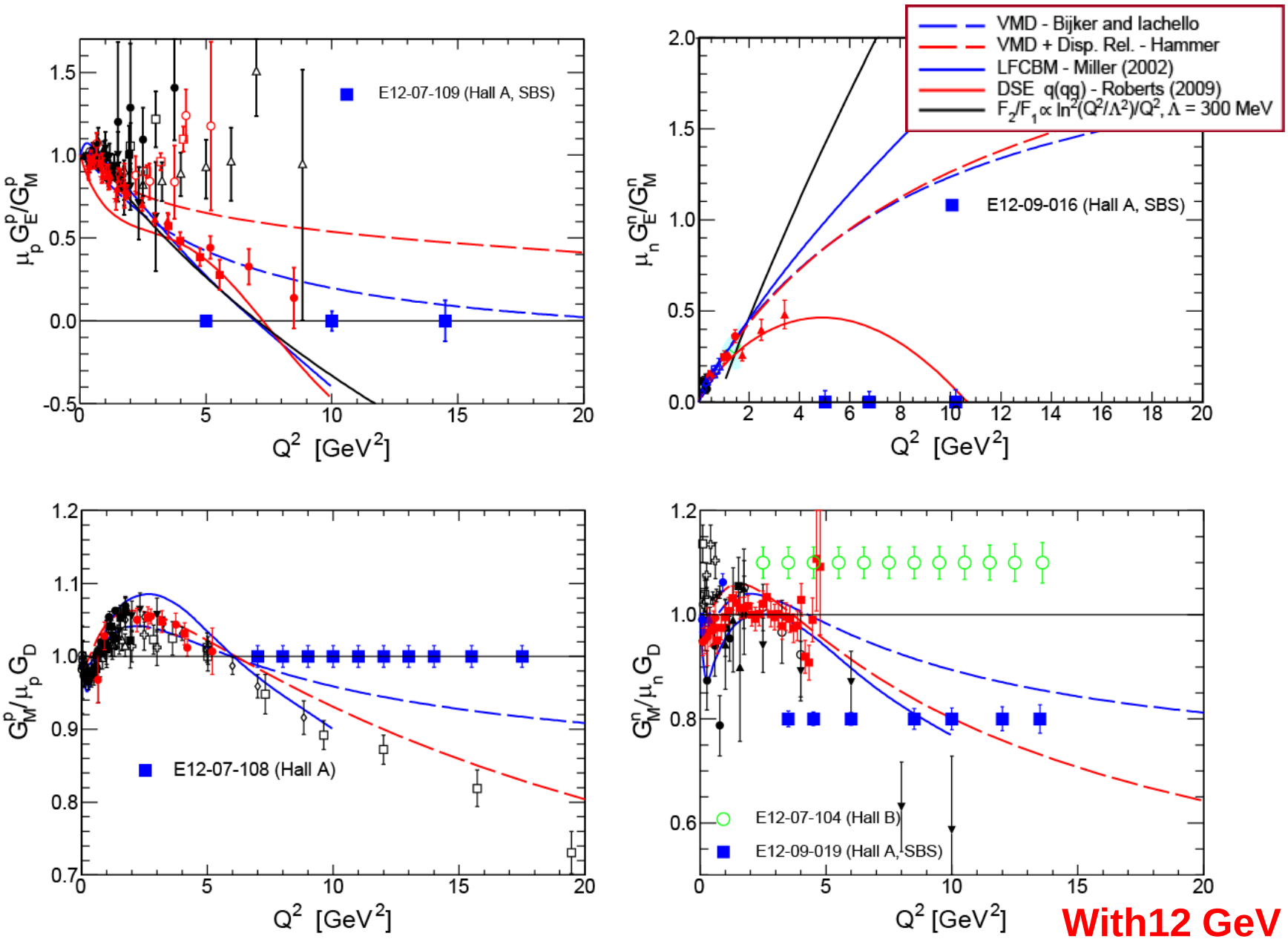
$$\rho_{Dirac}(b) = \int_0^\infty \frac{QdQ}{2\pi} J_o(bQ) F_1(Q^2)$$

Form Factors – Plans for 12 GeV



Today

Form Factors – Plans for 12 GeV



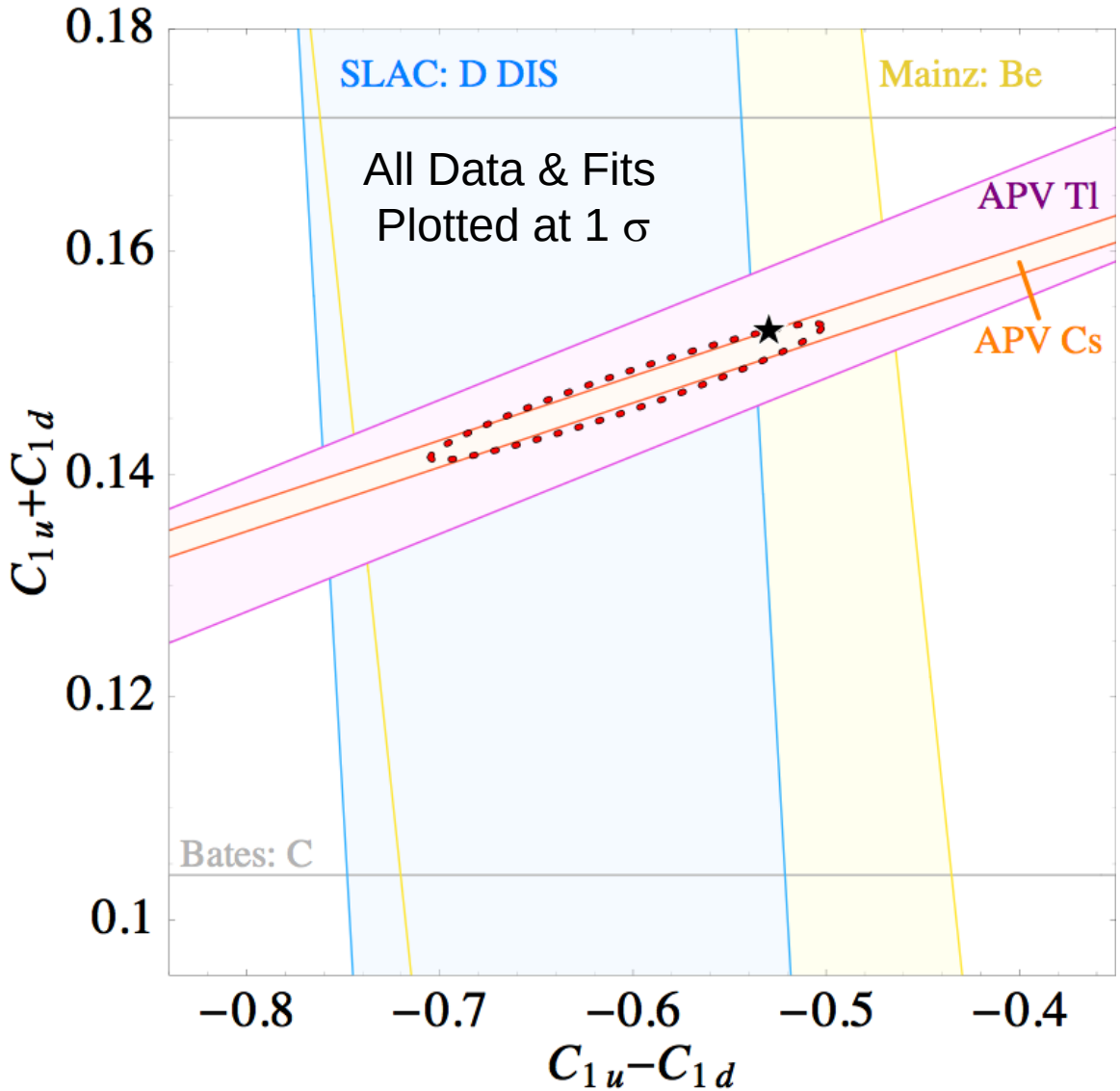
With12 GeV

Highlights from the first 10 Years

- **Quantum Chromodynamics and the Structure of Hadrons**
  - Discovery of unexpected behavior of G_e^p
  - Strangeness content of the proton
  - The deformation of Δ and N* transition form factors
  - Spin dependent structure functions:
    Bjorken & GDH sum rule; g_1^n; $|\Delta G|$
  - Measurement of the pion form factor
  - Exploration of duality, pQCD counting rules, color transparency
  - Initial exploration of Generalized Parton Distributions (GPDs) towards mapping of angular momentum in the proton
- **Nuclei: From Structure to Exploding Stars**
  - New information on correlations in nuclei and the role of the tensor force
  - Studies of hypernuclei – better than 400keV resolution
- **In Search of the New Standard Model**
  - Factor 5 increase in precision of Standard Model couplings

These Experiments Have Impact Beyond Our Understanding of Nucleon Structure: e.g. for C_{1q} couplings in the Standard Model

$$\mathcal{L}_{\rm NC}^{eq} = -\frac{G_F}{\sqrt{2}}\bar{e}\gamma_\mu\gamma_5 e \sum_q C_{1q}\bar{q}\gamma^\mu q\,.$$



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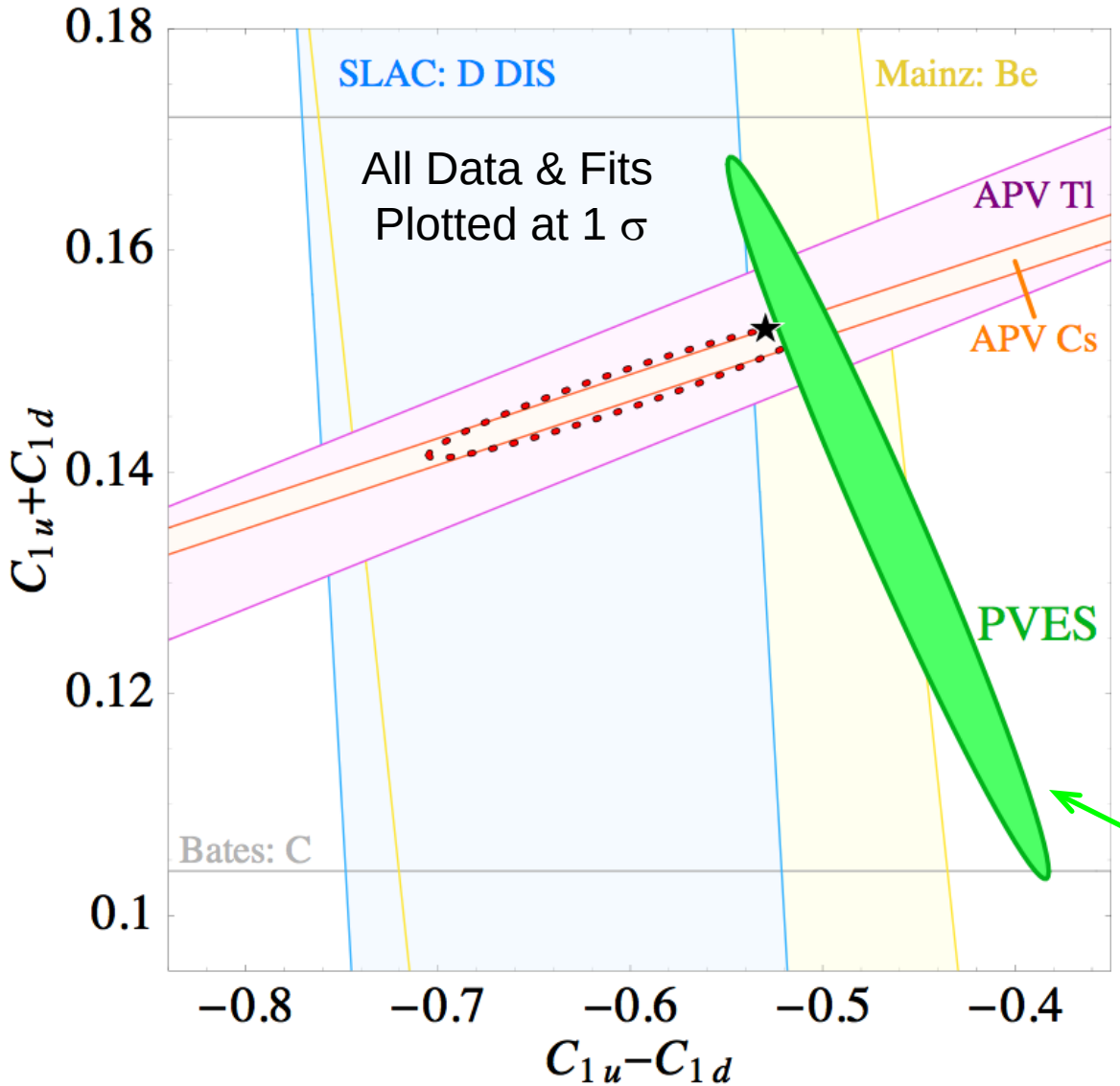

HAPPEx: H, He
G^0: H,
PVA4: H
SAMPLE: H, D

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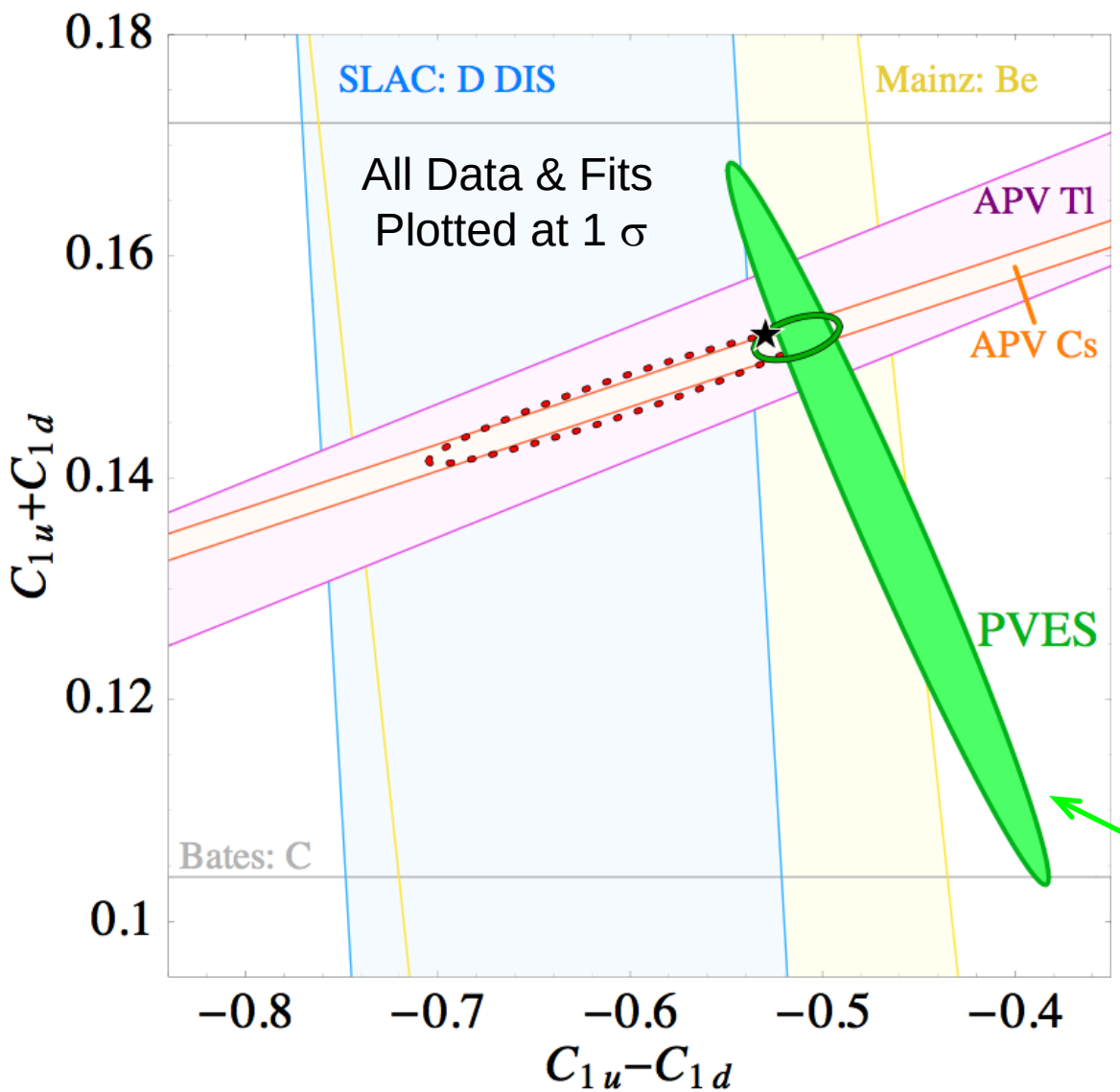

R. Young, R. Carlini, A. Thomas & J. Roche, PRL **99**, 122003 (2007)

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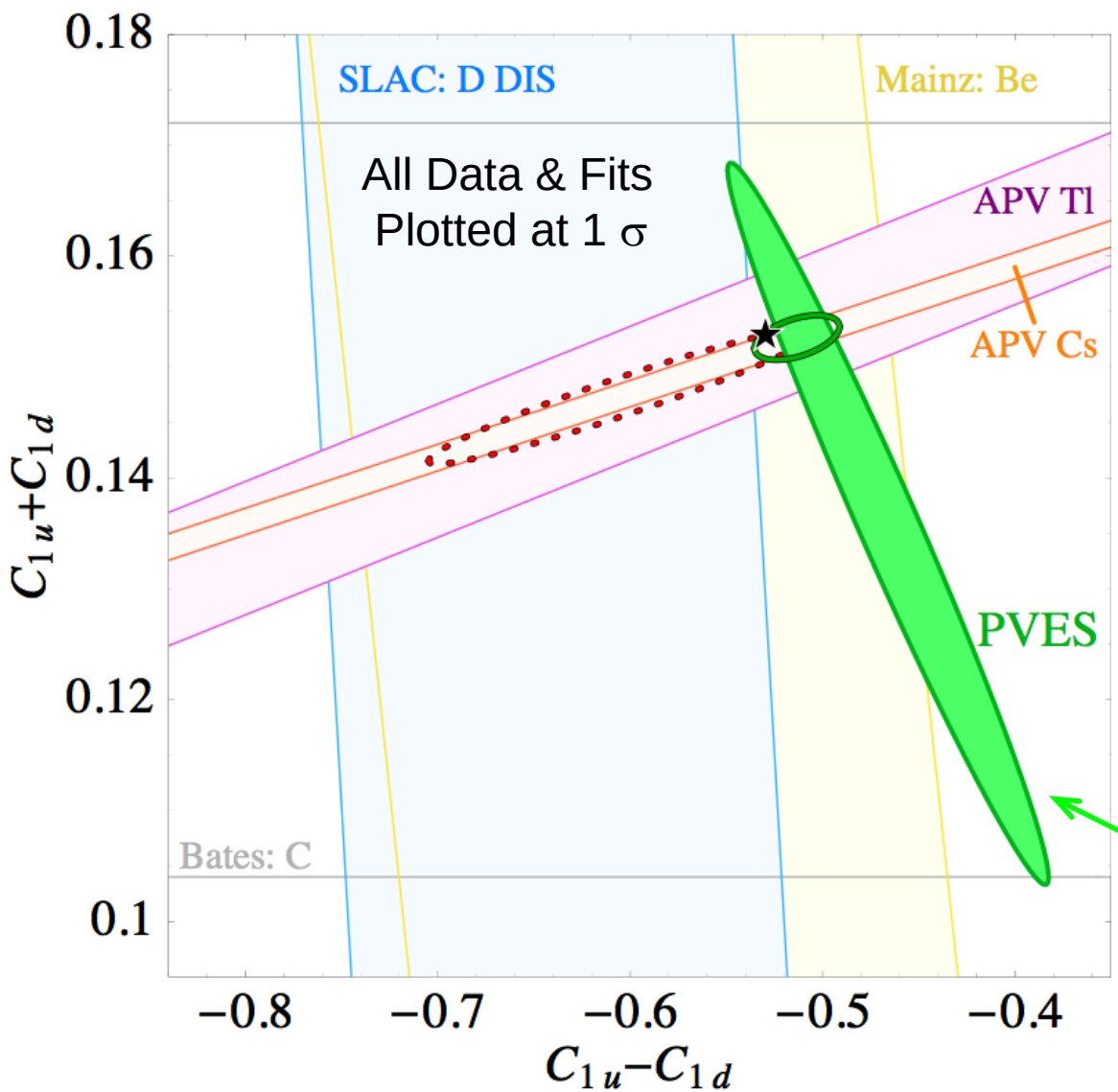

R. Young, R. Carlini, A. Thomas & J. Roche, PRL **99**, 122003 (2007)

A dramatic improvement in our knowledge of weak couplings!

Factor of 5 increase in precision of Standard Model test

HAPPEx: H, He
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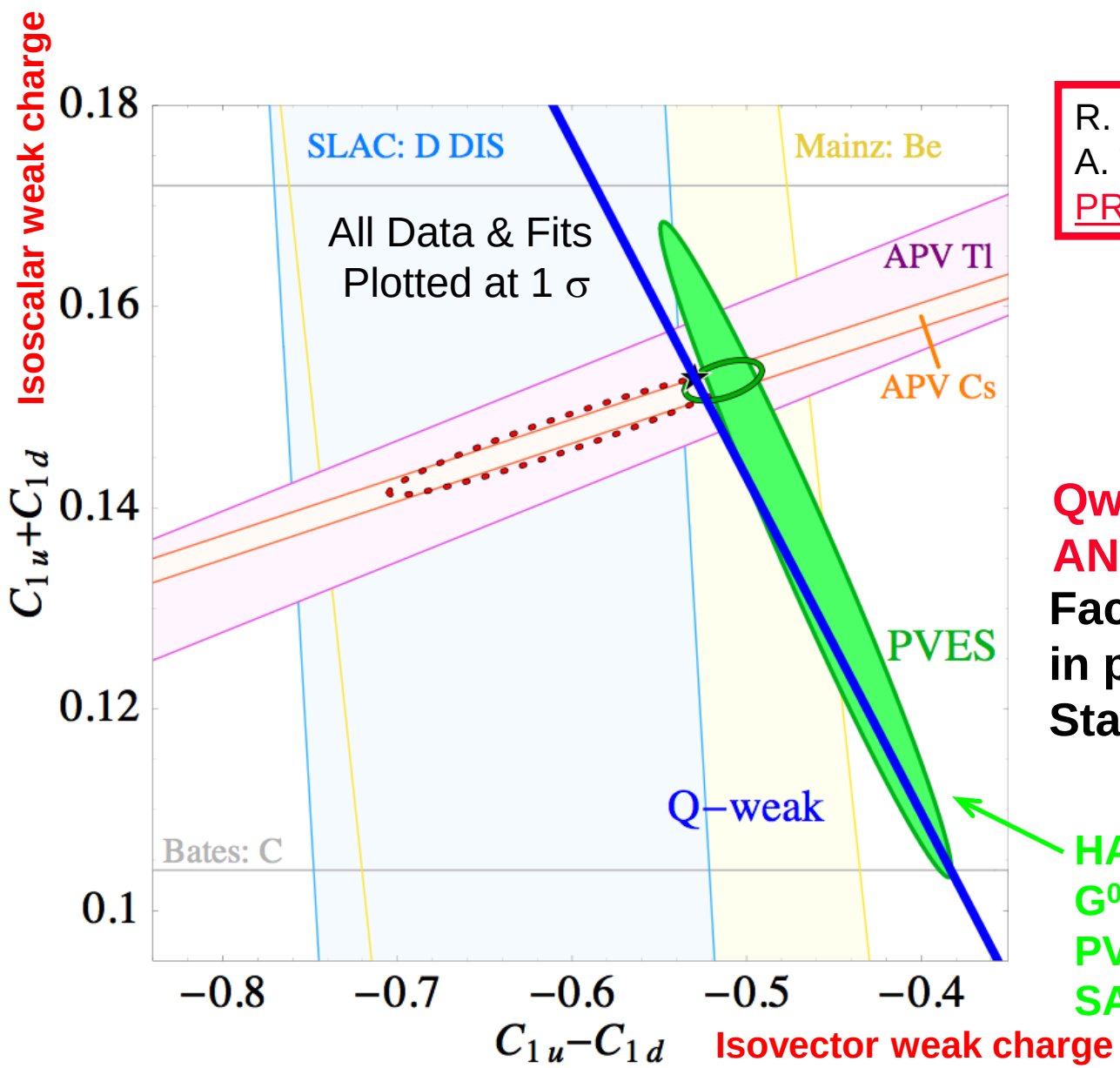
Q_{Weak} will further test our understanding of the C_{1q} couplings in the Standard Model



R. Young, R. Carlini, A. Thomas & J. Roche, PRL **99**, 122003 (2007)

Qweak will provide ANOTHER

Factor of 5 increase in precision of Standard Model test

HAPPEx: H, He
G^0: H,
PVA4: H
SAMPLE: H, D

And also Determine the Weak Charge of the Proton

- Precise measurement of the proton's weak charge in PVES

$$Q^p_{\text{weak}} = -2(2C_{1u} + C_{1d}) \qquad Q^2 = 0.03\,\text{GeV}^2,\ \theta = 8^\circ$$

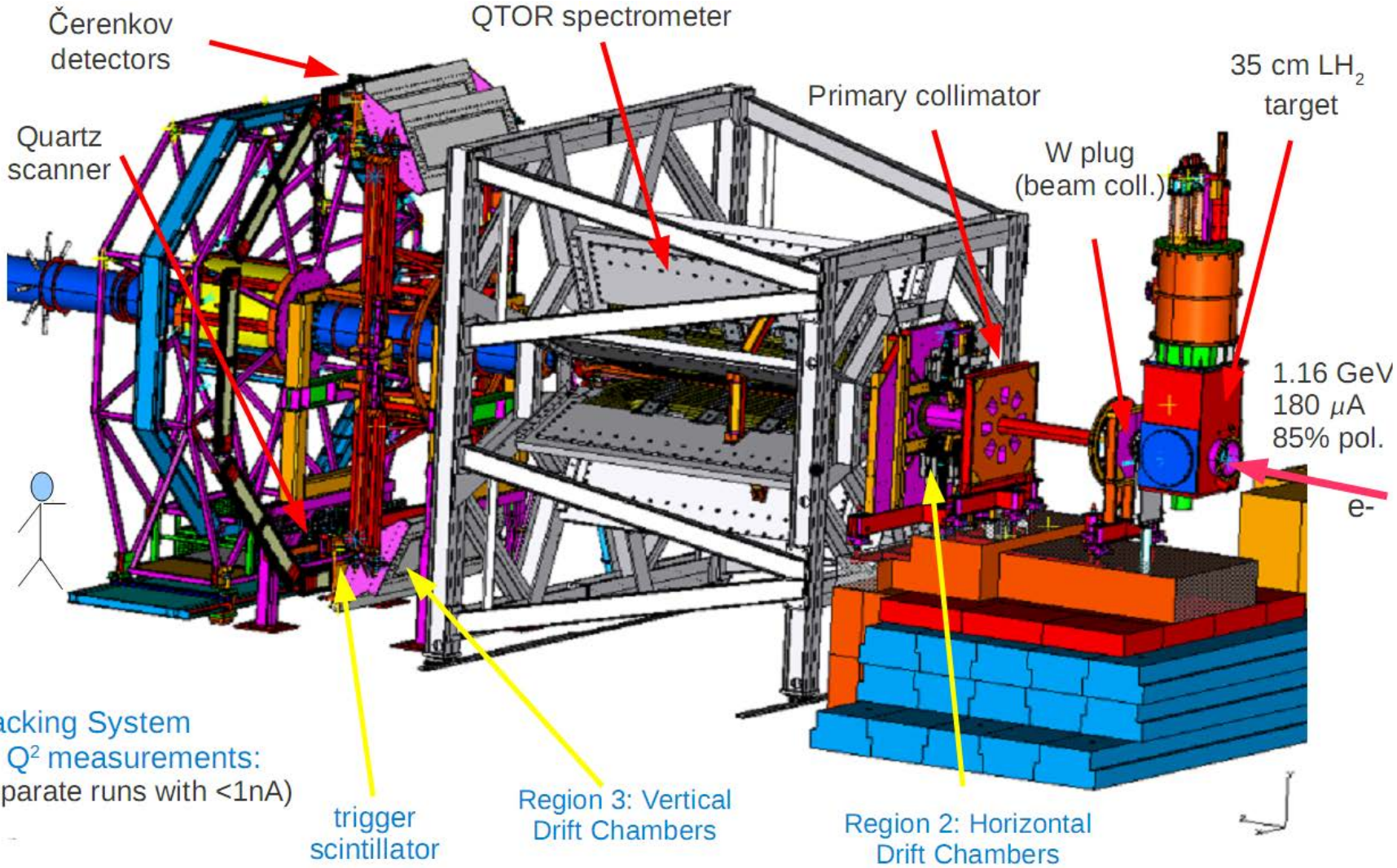
- Feasible because at low energy and small scattering angles the parity-violating asymmetry is given by:

$$A_{LR} \Rightarrow -\frac{G_\mu Q^2}{4\pi\alpha\sqrt{2}}\left[Q_{\text{weak}} + \beta_A \tilde{G}^p_A \sqrt{Q^2} + \beta_V Q^2 + \ldots\right]$$

$$\beta_A \propto \theta + O(\theta^3)$$

Anapole uncertainty

Strangeness uncertainty

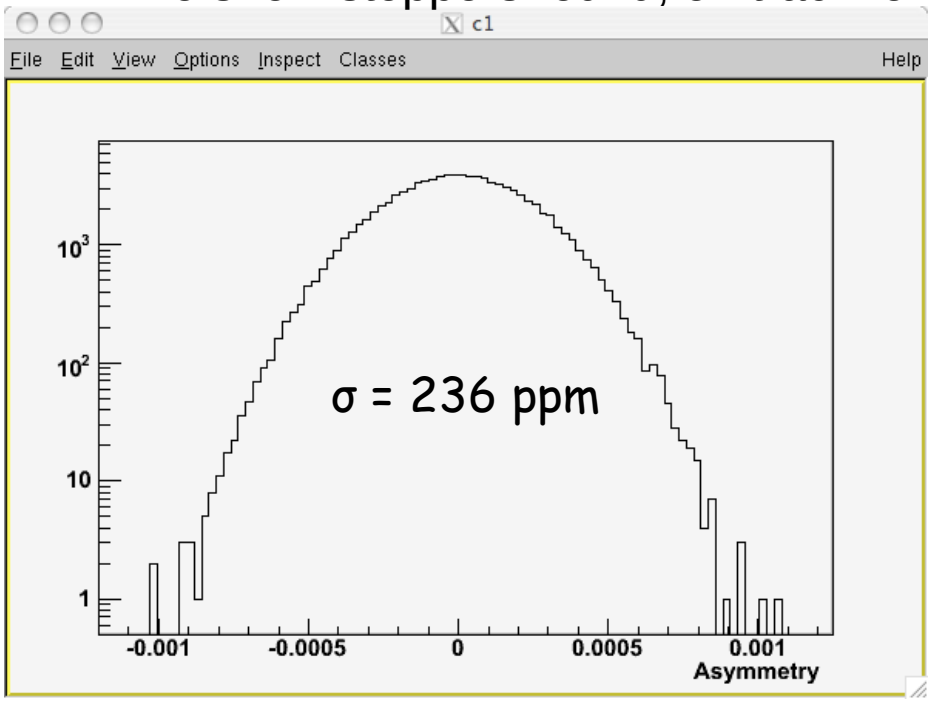

Čerenkov detectors
QTOR spectrometer
35 cm LH_2 target
Primary collimator
Quartz scanner
W plug (beam coll.)
1.16 GeV
180 μA
85% pol.
e-
Tracking System for Q^2 measurements:
(separate runs with <1nA)
trigger scintillator
Region 3: Vertical Drift Chambers
Region 2: Horizontal Drift Chambers

Canadian Contributors to Qweak

- Physicists:
  - S. Page (co-spokesperson), W. van Oers, J. Birchall, W. Falk, M. Gericke, L. Lee, D. Ramsay, C. Davis, E. Korkmaz, J. Martin, V. Tvaskis, R. Mahurin
- Students:
  - S. MacEwan, J. Pan, P. Wang
- Technical:
  - George Clark (QTOR)
  - Namit Kahn (QTOR)
  - Bill Roberts -Electronics group (pre-amps & 18 bit ADCs
- Procurement Support:
  - Christy Clark, Gordon Campbell

Qweak Status after 1st Run

- Precision measurement of the proton's weak charge in the simplest system
- Search for parity-violating new physics up to the ~ 2 TeV scale
- No show-stoppers found, on track for proposed 4% precision on Q^p_{Weak}



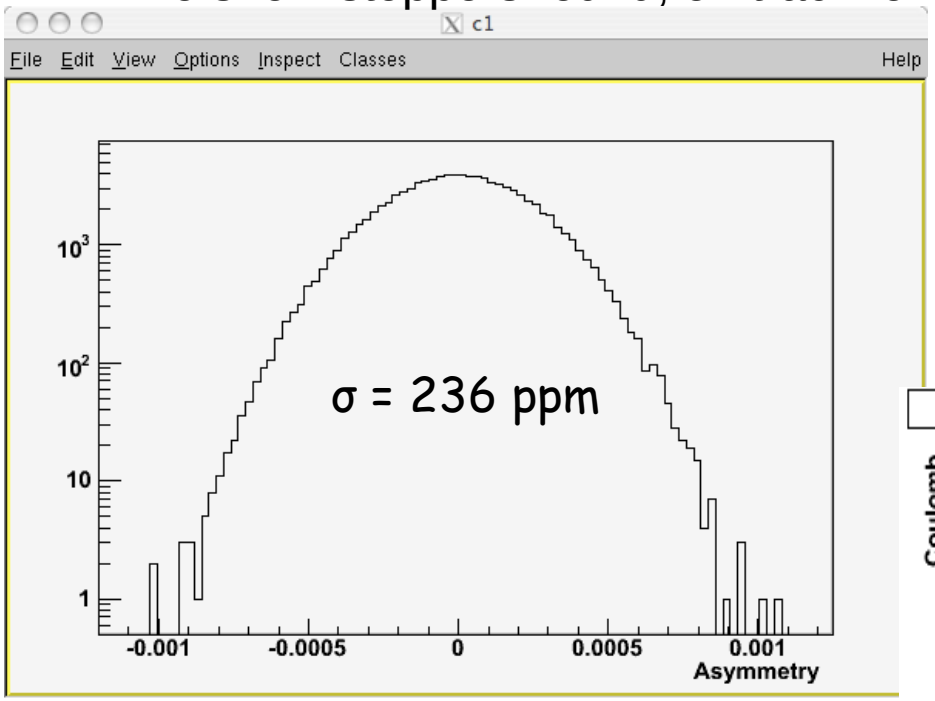
Asymmetry Width

- Beam: routine data-taking at 165μA @ ~88% polarization (and tests up to 180 μA)
- Helicity-correlated properties acceptable!

Above: 6.5 minutes of data @ 165 μA
Total detected rate = ~5.83 GHz
Pure counting statistics: ~215 ppm
+ detector energy resolution → 232 ppm
+ beam current normalization → 235 ppm
agrees with data

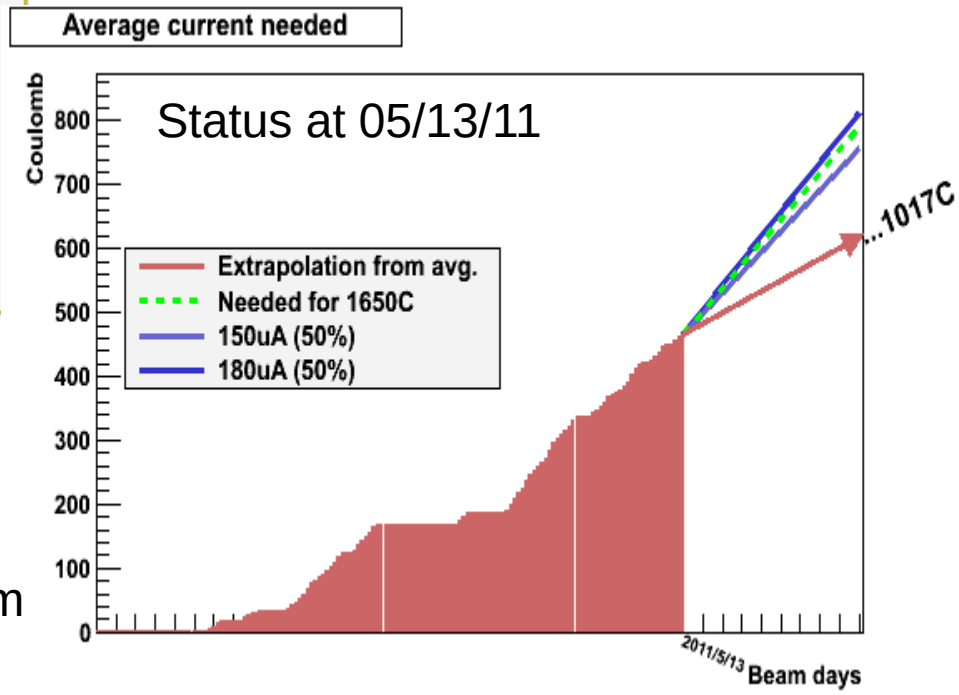
Qweak Status after 1st Run

- Precision measurement of the proton's weak charge in the simplest system
- Search for parity-violating new physics up to the ~ 2 TeV scale
- No show-stoppers found, on track for proposed 4% precision on Q^p_{Weak}



Asymmetry Width

- Beam: routine data-taking at 165μA @ ~88% polarization (and tests up to 180 μA)
- Helicity-correlated properties acceptable!



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Evolution of PVES Helicity Correlated Beam Properties

Experiment	Energy (GeV)	I (μA)	Target	A_{pv} (ppb)	Maximum Charge Asym (ppb)	Maximum Position Diff (nm)	Maximum Angle Diff (nrad)	Maximum Size Diff (δσ/σ)
HAPPEx-II (Achieved)	3.0	55	^{1}H (20 cm)	1400	400	1	0.2	Was not specified
HAPPEx-III (Achieved)	3.484	100	^{1}H (25 cm)	16900	200±100	3±3	0.5±0.1	10^{-3}
PREx	1.063	70	^{208}Pb (0.5 mm)	500	100±10	2±1	0.3±0.1	10^{-4}
QWeak	1.162	180	^{1}H (35 cm)	234	100±10	2±1	30±3	10^{-4}
Qweak Run Average					**8 ± 15**	**x: 3.9 ± 0.5 y: -5.7 ± 0.5**	**x': -0.11 ± 0.02 y': -0.00 ± 0.02**	
Møller	11.0	75	^{1}H (150 cm)	35.6	10±10	0.5±0.5	0.05±0.05	10^{-4}

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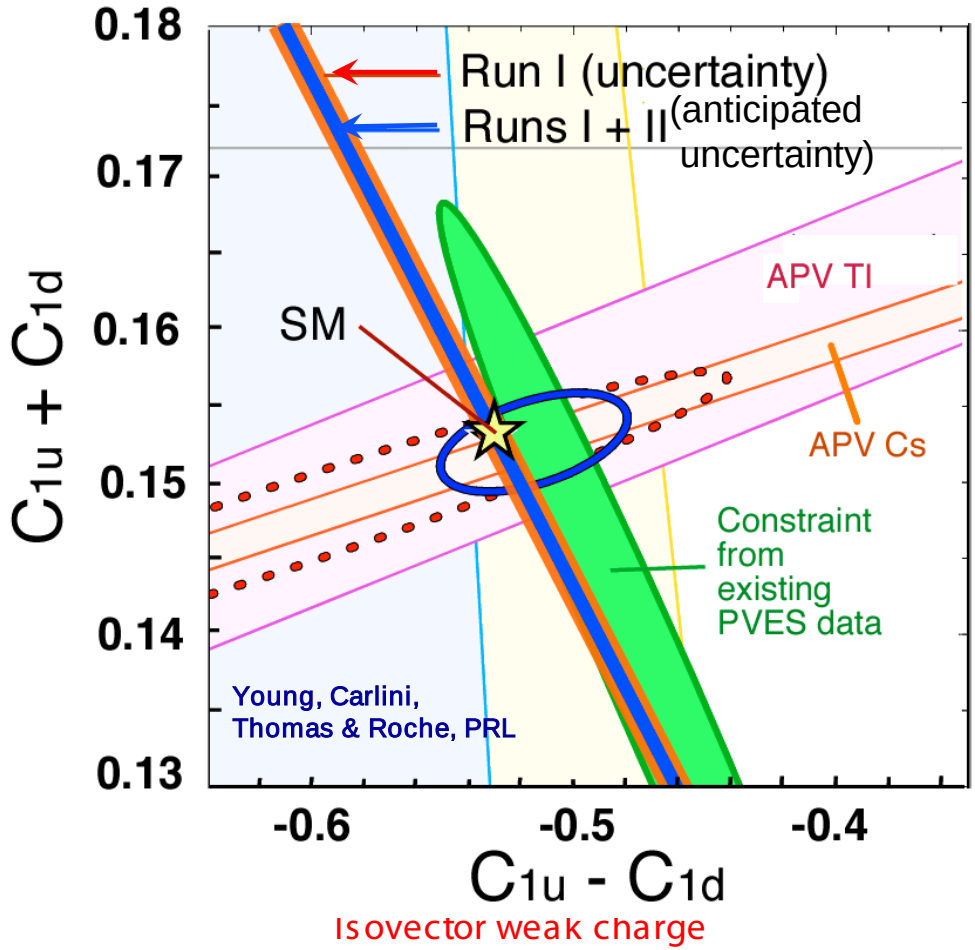
Thank you Chao!

Q_{Weak} Status After Run I



Anticipated constraints if Q^P_W is consistent with the Standard Model.

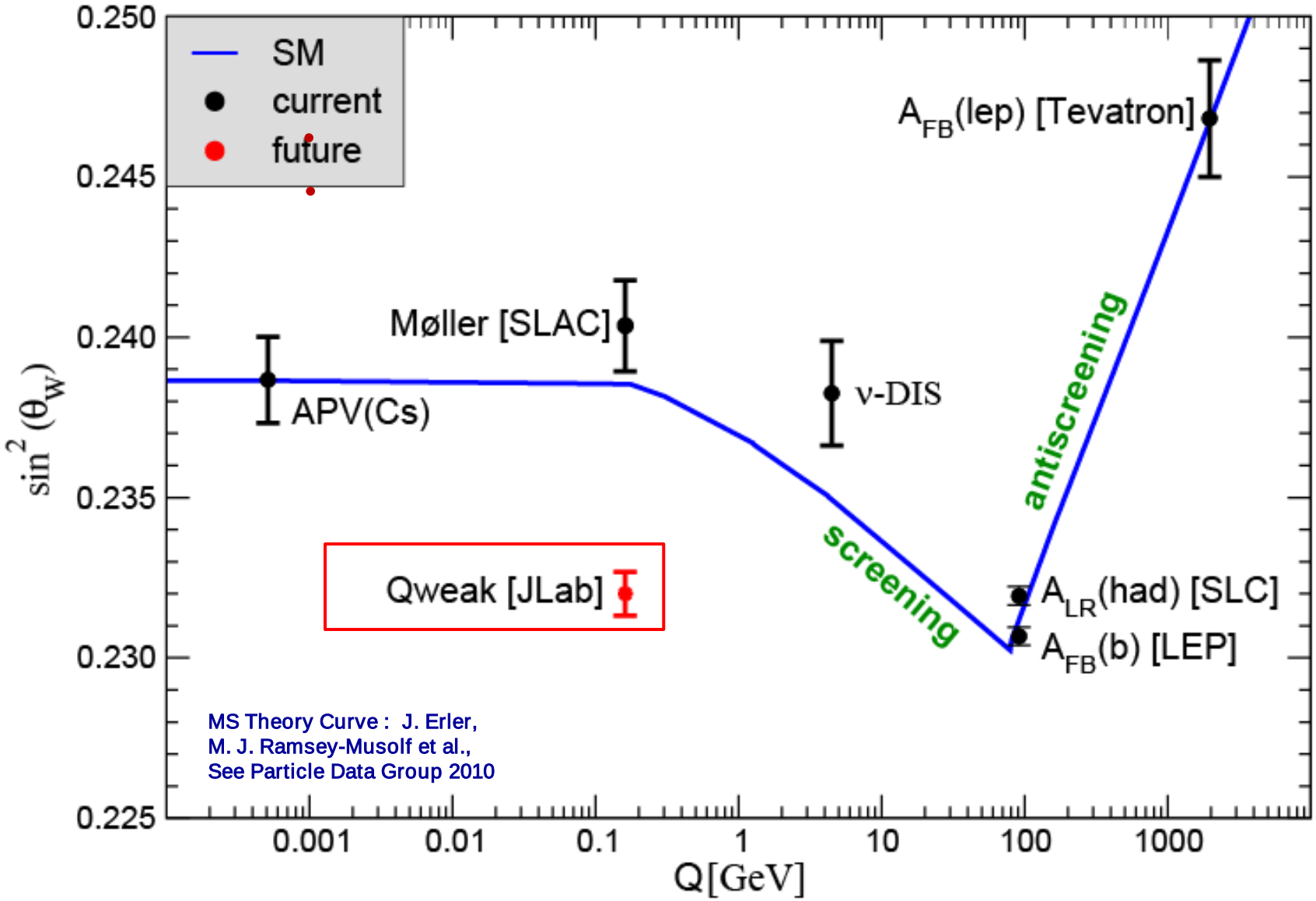
Q_{Weak} Goals:

- First direct measurement of the proton's weak charge.

  $$Q^P_W = -2\,(2C_{1u} + C_{1d})$$

- Precision determination of the neutral current weak couplings to the quarks (C_{1u} & C_{1d}).
- Mass scale reach for parity-violating new physics at expected final uncertainty (95% CL) is ~2.3 TeV.

Q_{Weak} Will Also Tests the Running of $Sin^2\theta_W$



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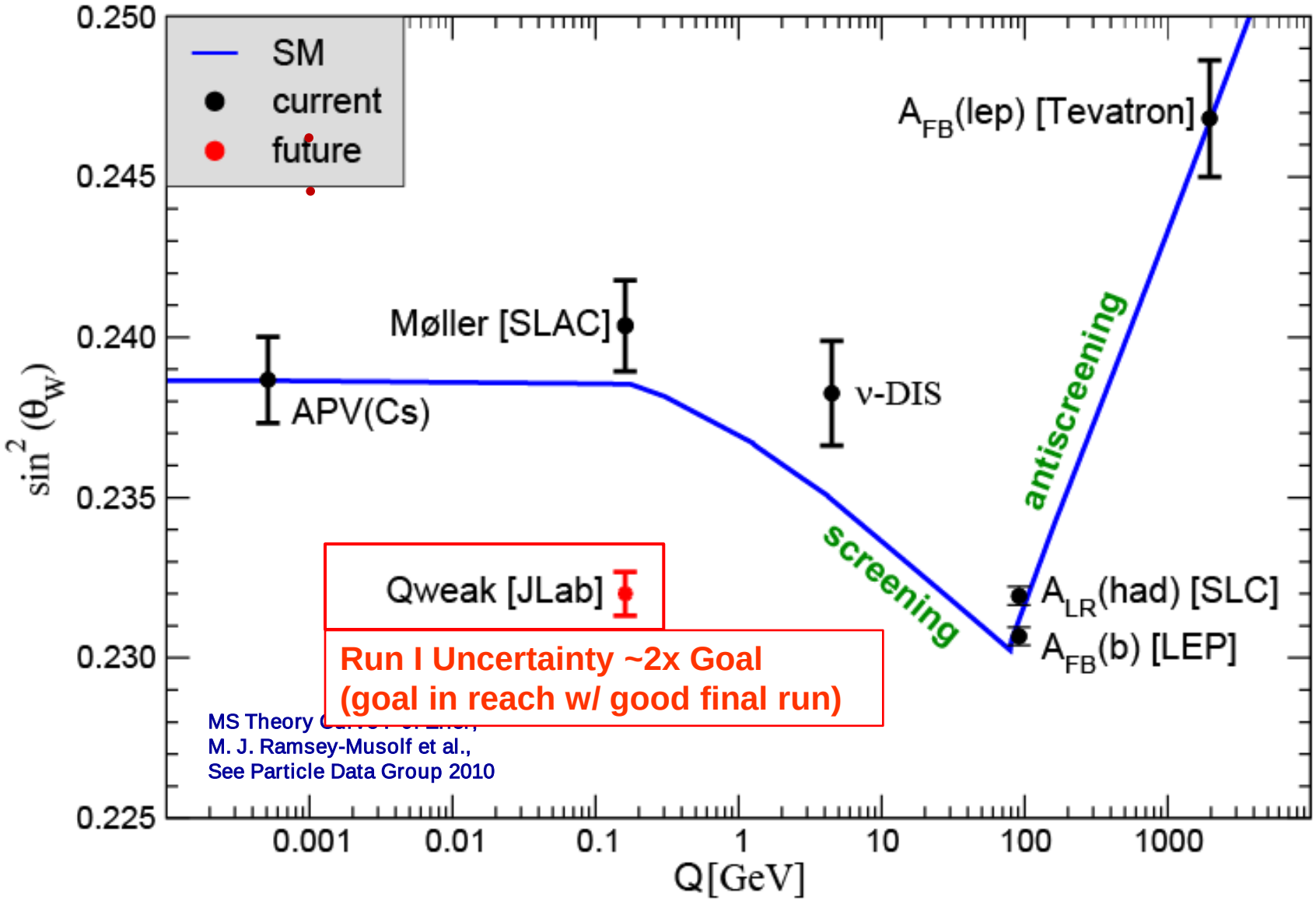
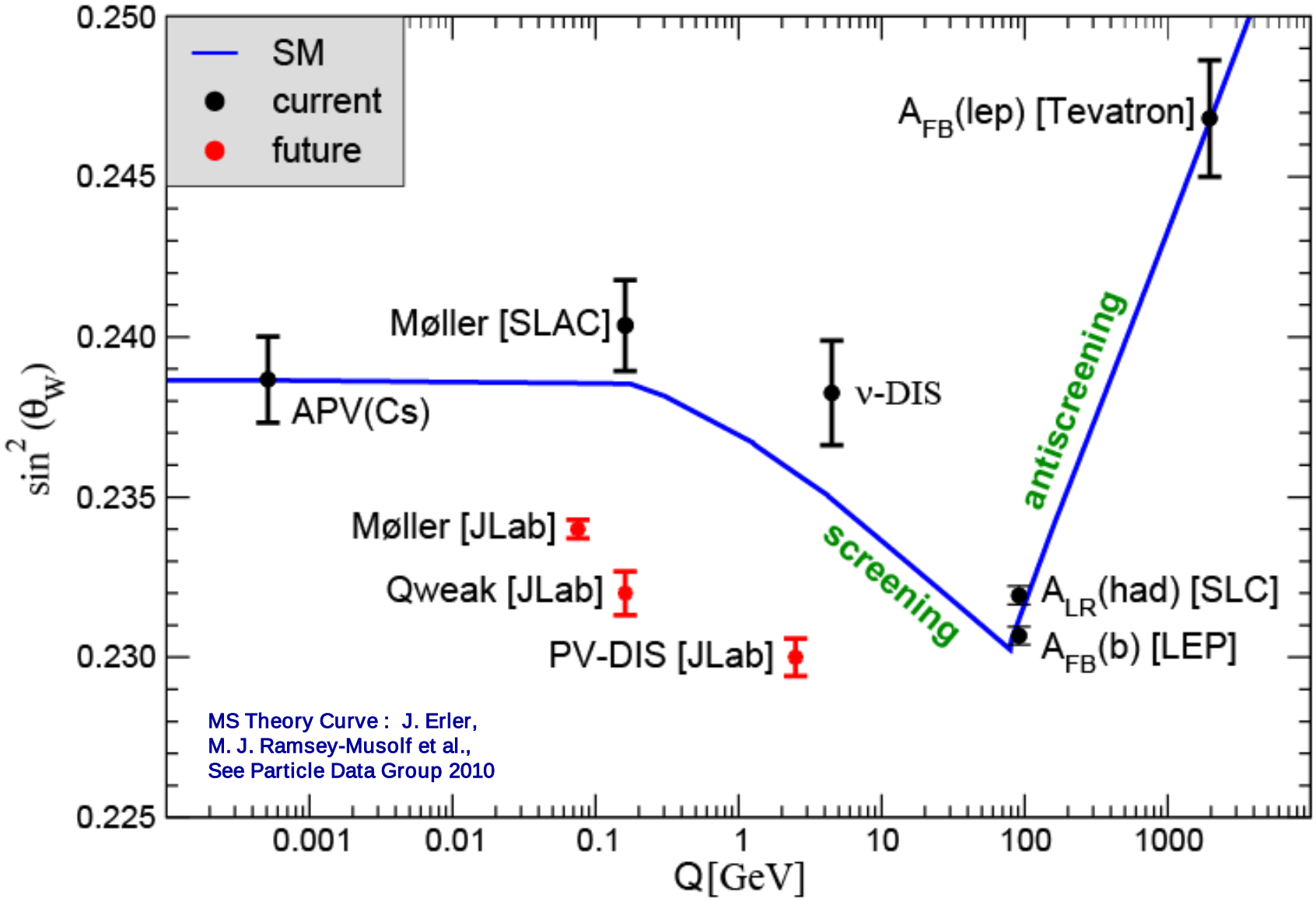


Further Precision Tests of Electro-Weak Theory Are Planned for 12 GeV



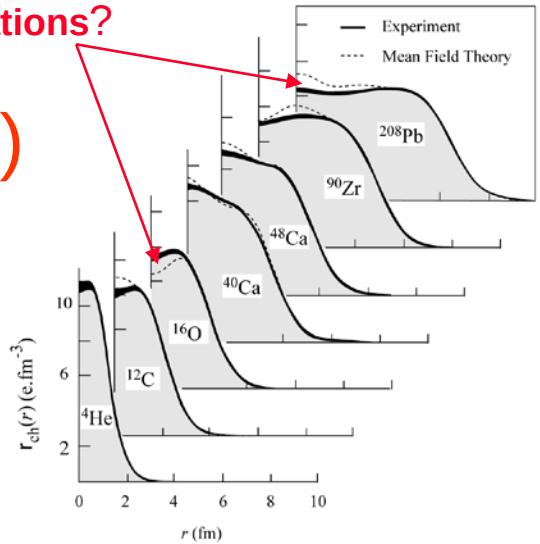
Highlights from the first 10 Years

- **Quantum Chromodynamics and the Structure of Hadrons**
  - Discovery of unexpected behavior of G_e^p
  - Strangeness content of the proton
  - The deformation of Δ and N* transition form factors
  - Spin dependent structure functions:
    Bjorken & GDH sum rule; g_1^n; $|\Delta G|$
  - Measurement of the pion form factor
  - Exploration of duality, pQCD counting rules, color transparency
  - Initial exploration of Generalized Parton Distributions (GPDs) towards mapping of angular momentum in the proton
- **Nuclei: From Structure to Exploding Stars**
  - New information on correlations in nuclei and the role of the tensor force
  - Studies of hypernuclei – better than 400keV resolution
- **In Search of the New Standard Model**
  - Factor 5 increase in precision of Standard Model couplings

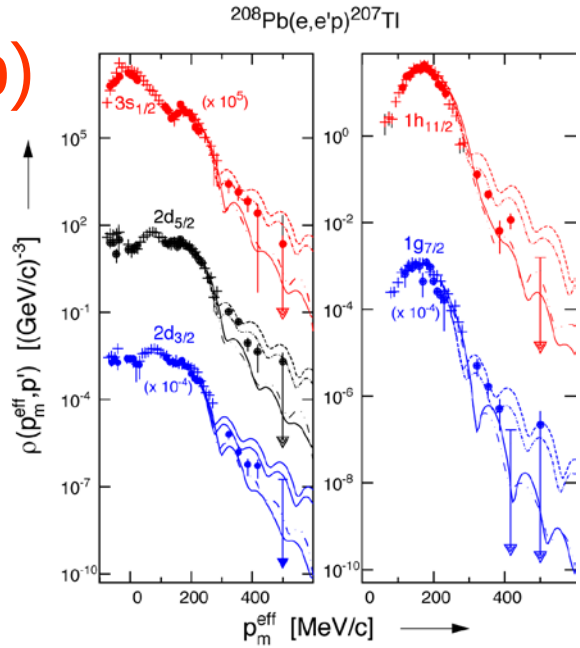
Recall Evidence for Correlations from (e,e) and (e,e'p) data

Correlations?

(e,e)



(e,e'p)



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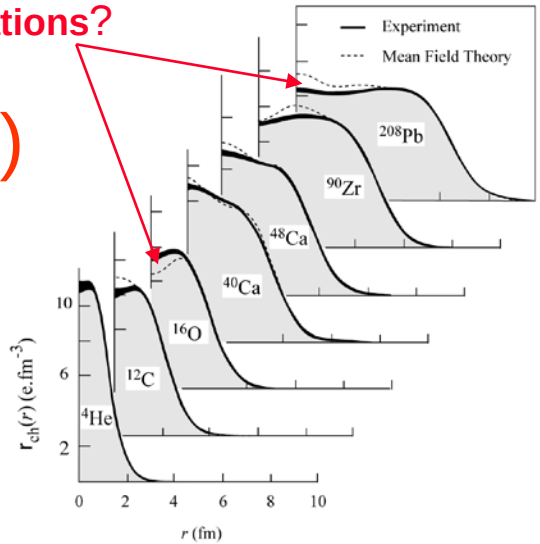
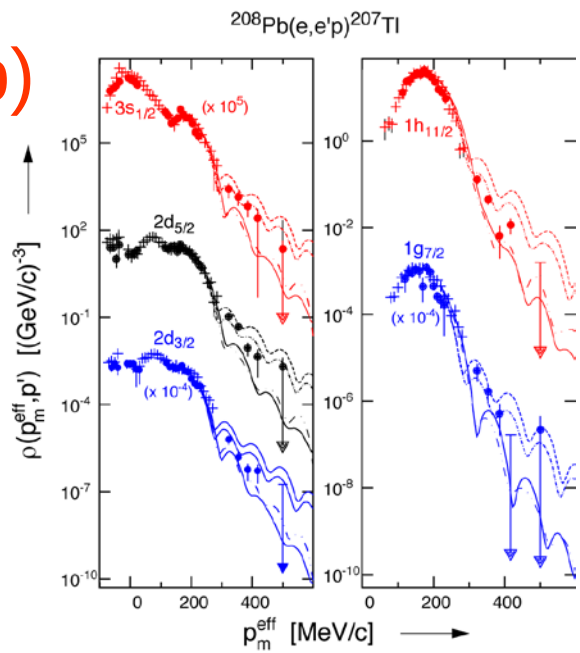
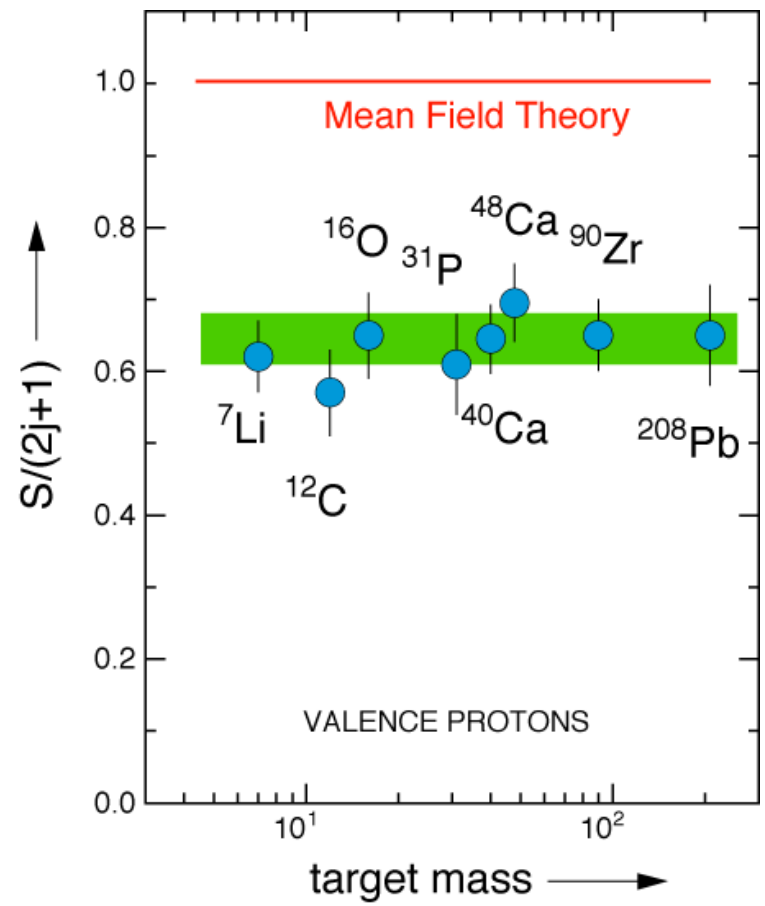


(e,e'p)

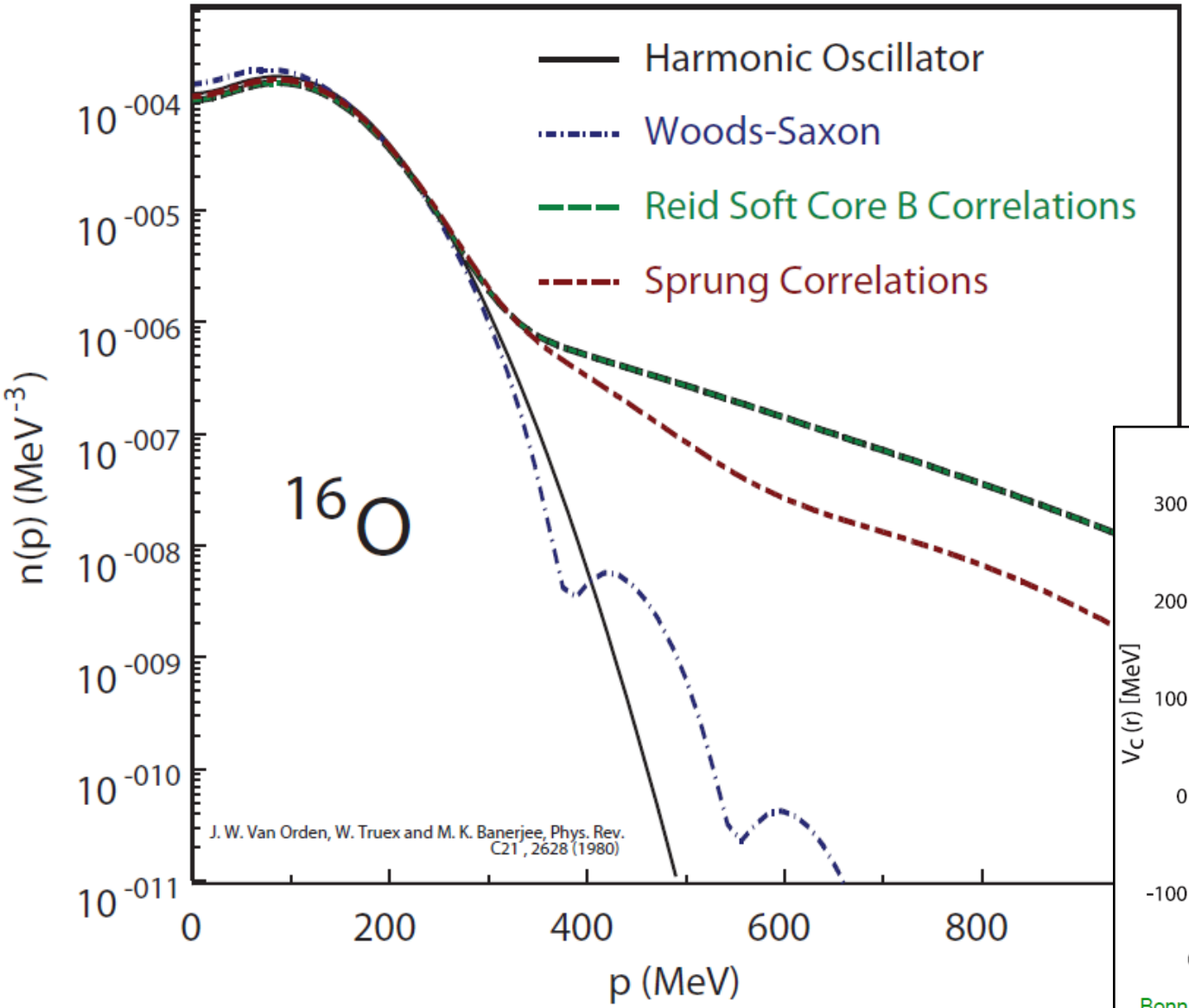


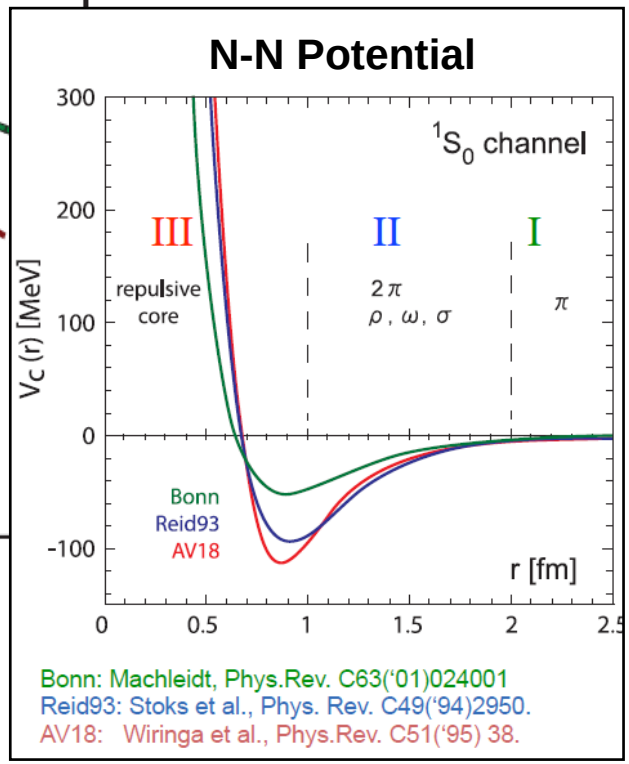
Spectroscopic Factors



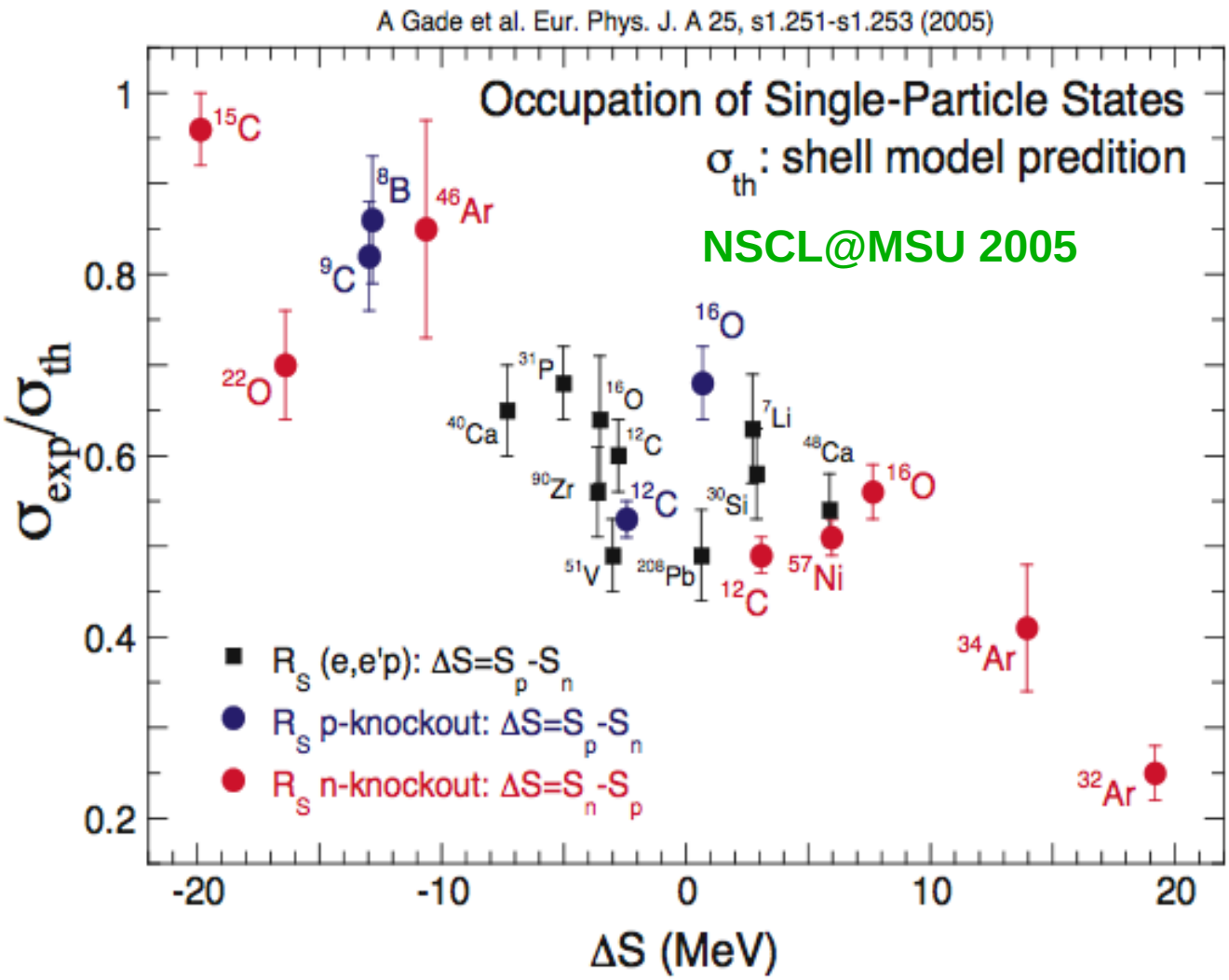
$$S_\alpha = 4\pi \int S(E_m, p_m) p_m^2 dp_m \delta(E_m - E_\alpha)$$

Correlation Effects in ^{16}O (Theory)



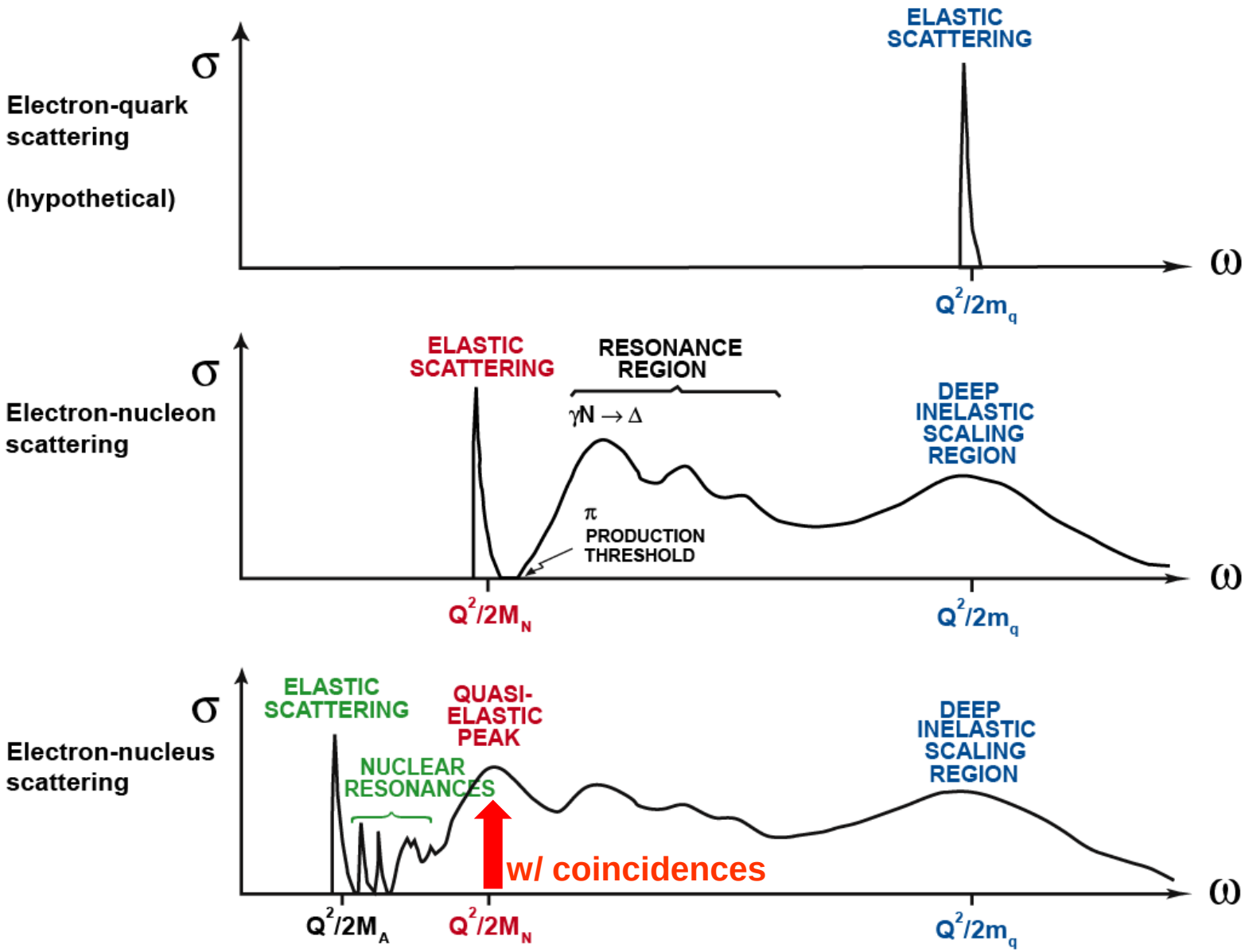


The Impact of Correlations on Nuclear Spectral Functions



Spectral functions derived from (e,e'p) provide reliable data on stable nuclei and a calibration for other techniques

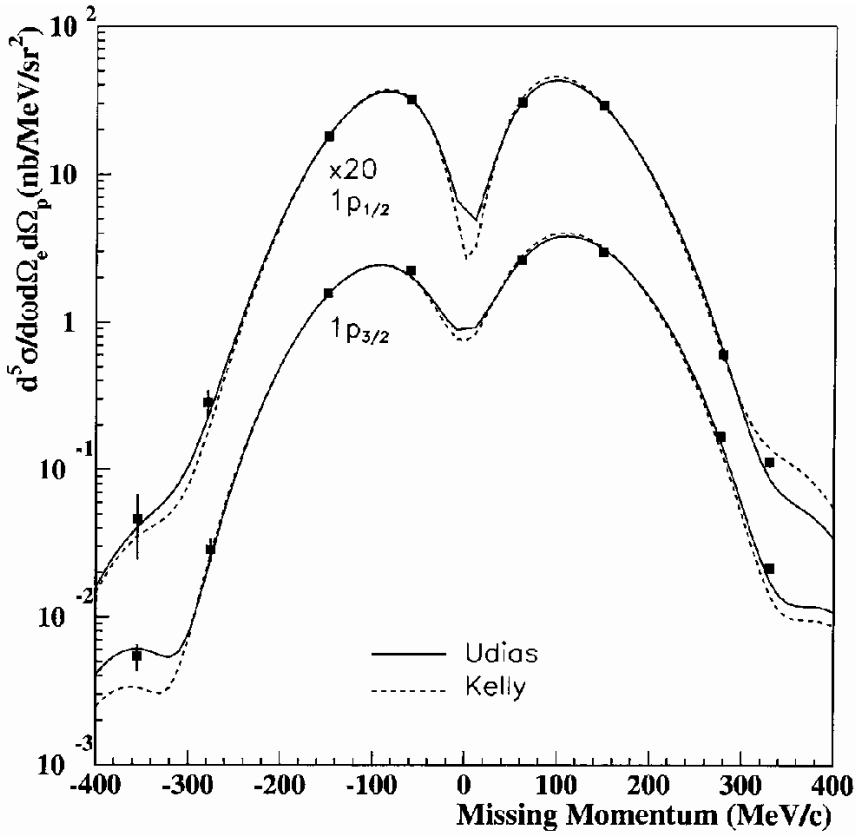
Electron Scattering



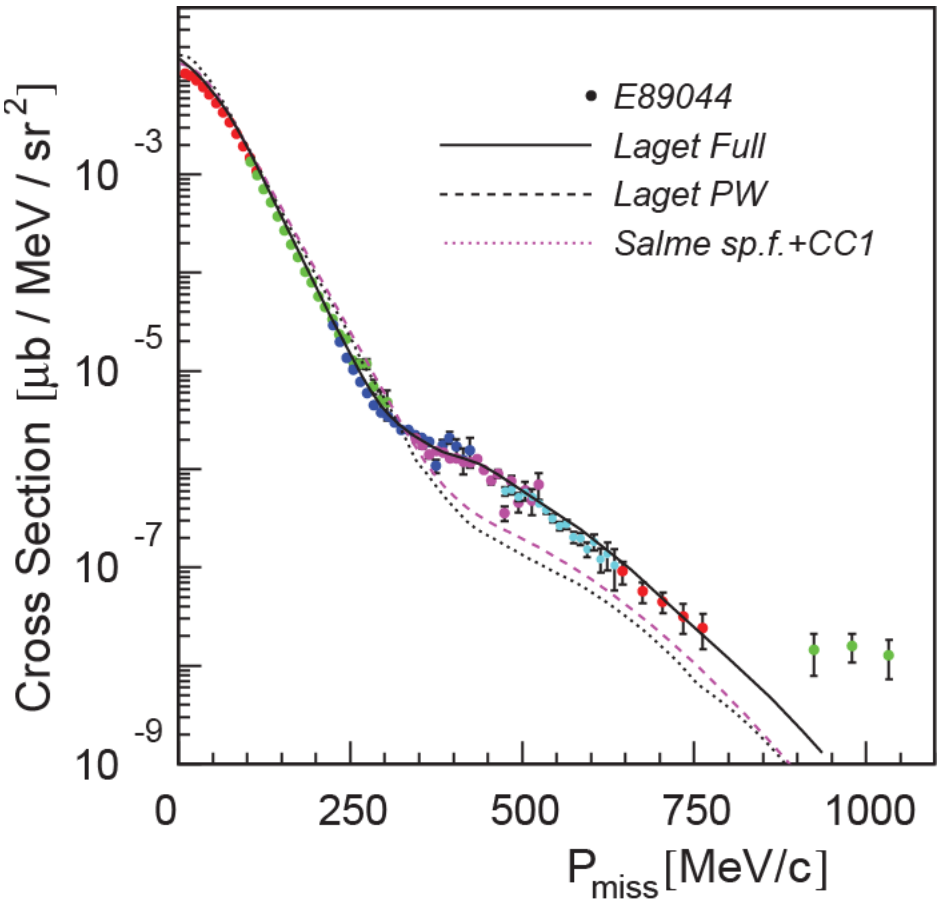
JLab's Higher Beam Energies Permit Us to Measure (e,e'p) at High Missing Momentum

And indeed the strength is found where theory predicted it would be

^{16}O(e,e'p)



^{3}He(e,e'p)

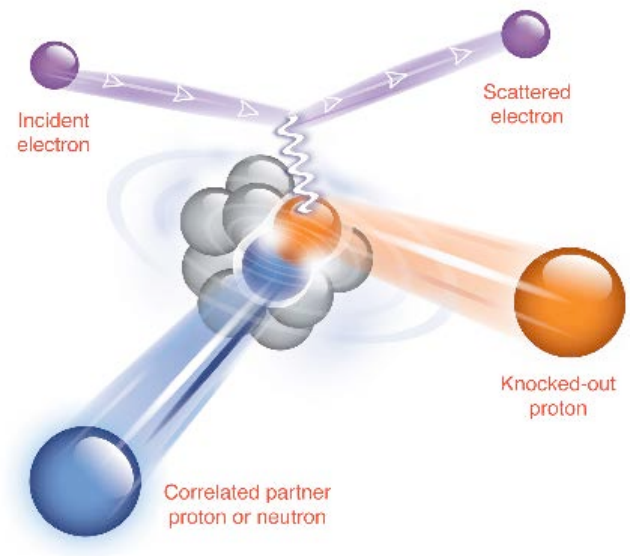


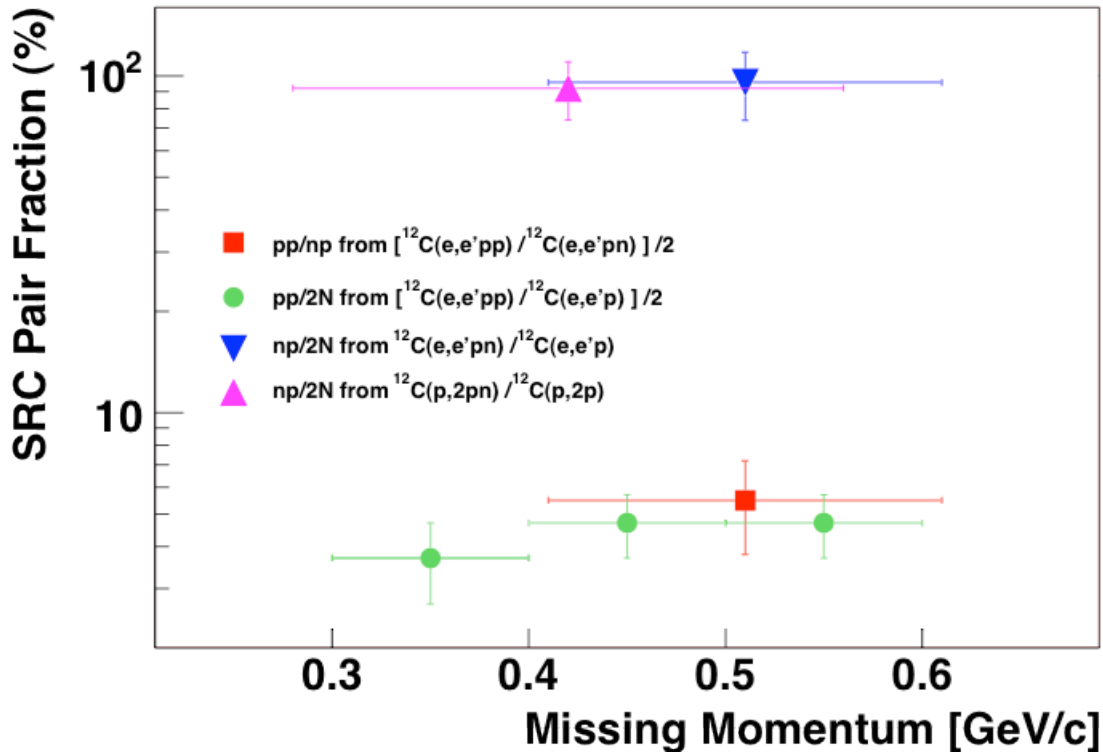
Next Step: Look for the Correlated Pairs Directly via (e,e'pN)

To study nucleon pairs at close proximity and their contributions to the large momentum tail of nucleons in nuclei.

R. Subedi *et al.*, Science **320** (2008) 1476.

A pair with "large" relative momentum between the nucleons and small center of mass momentum

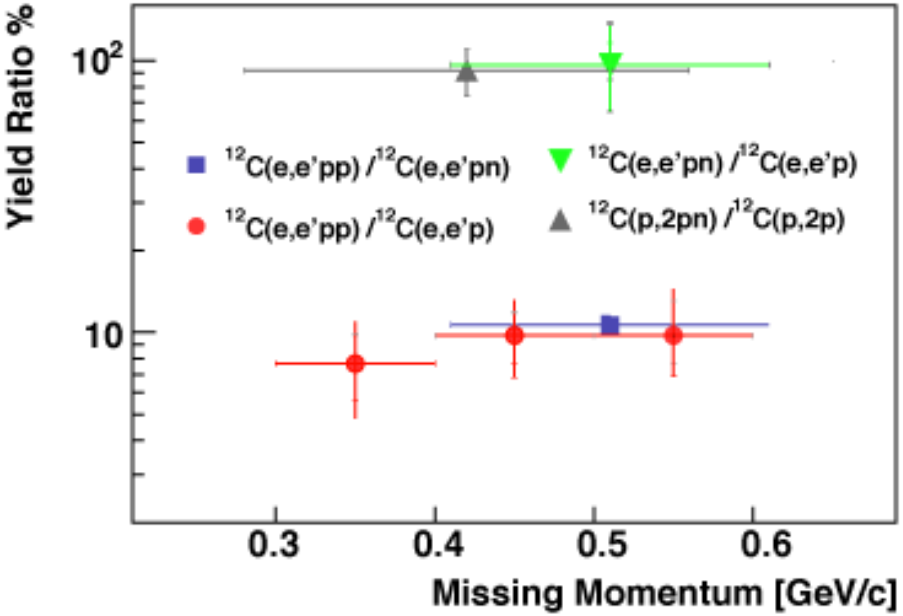


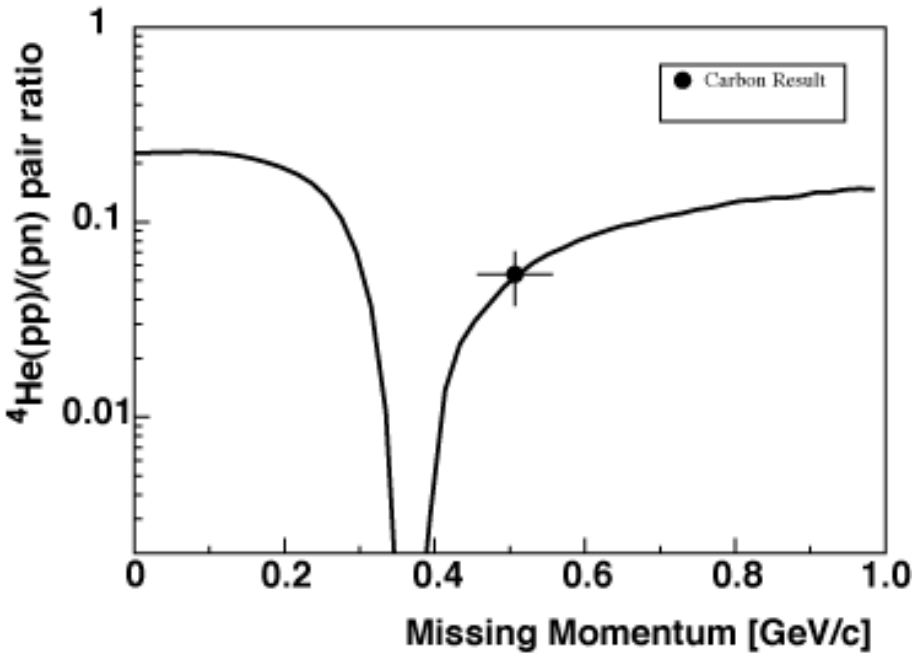


- High Q^2 to minimize MEC
- x>1 to suppress isobar contributions
- Parallel kinematics to suppress FSI

For high p_m, np pairs dominate over pp pairs by an order of magnitude, in agreement with the dominance of the tensor component in the kinematic region studied

Summary of E01-015 SRC findings in ^{12}C





For moderate p_m (<300 MeV/c):

- **60-70 % - independent-particle in a shell-model potential [from (e,e'p)]**
- **10-20 % - shell-model long-range correlations**

For high p_m (300-600 MeV/c):

- **9.5 ± 2 % of (e,e'p) events have a second (coincident) proton ejected back-to-back**
- **96 ± 23 % of (e,e'p) events have a coincident neutron ejected back-to-back**

Calculations by Rocco Schiavilla et al. indicate that the observed effect is due to tensor correlations

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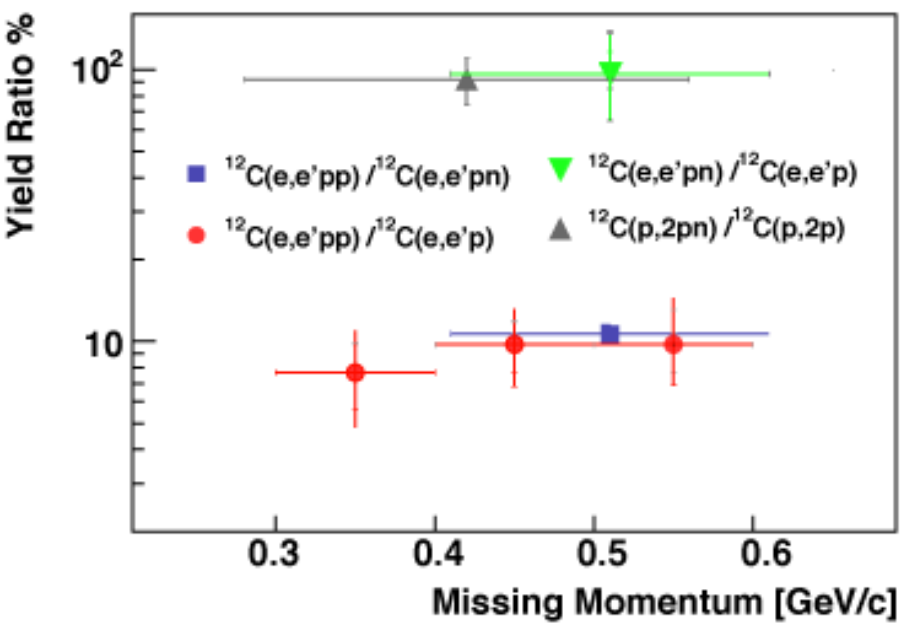

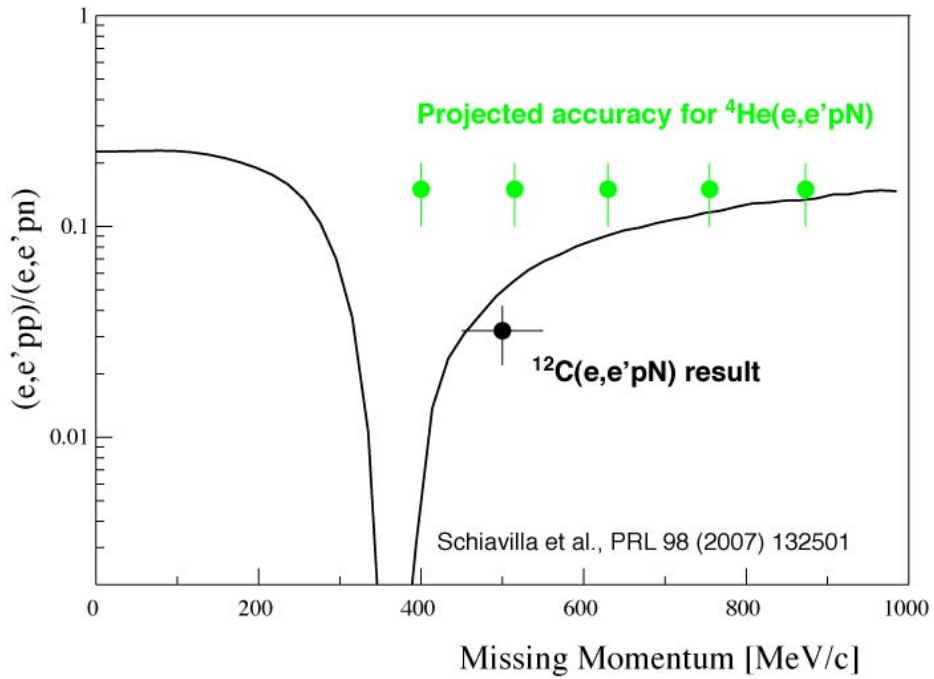

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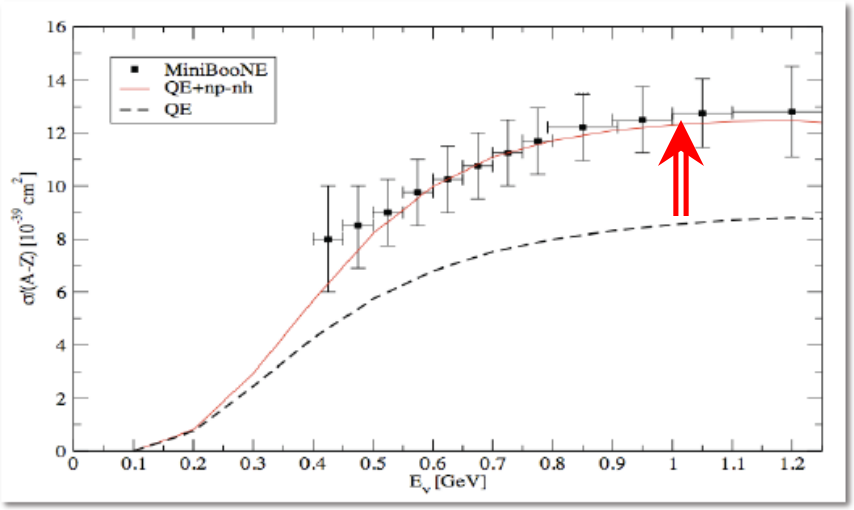
Calculations by Rocco Schiavilla et al. indicate that the observed effect is due to tensor correlations

E07-006 (just completed) will test that prediction

Understanding NN Correlations Has Important Implications for Other Physics (e.g. they resolve the MiniBoone discrepancy)

Nuclear Effects to the Rescue?

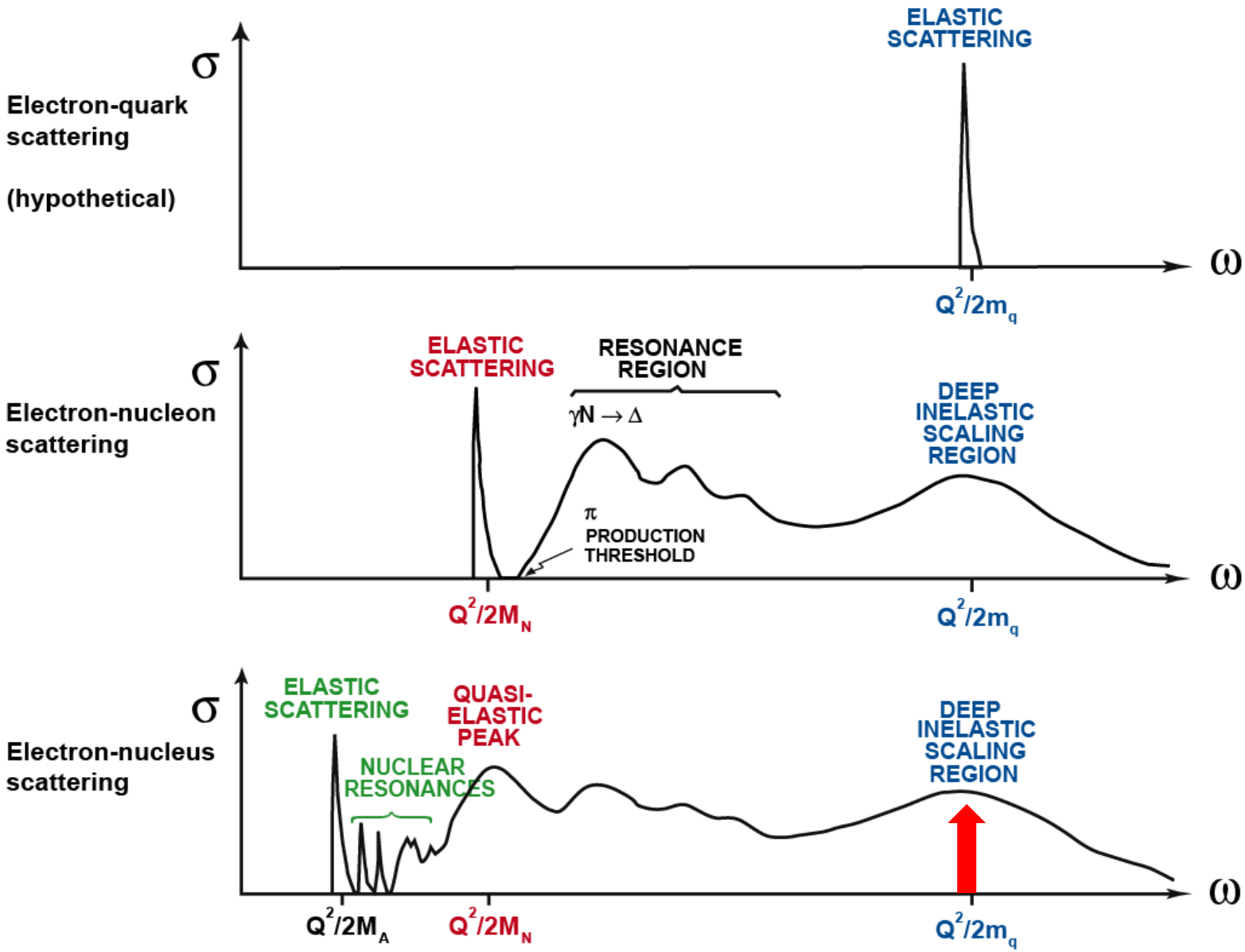
- another possible explanation has recently emerged
- while traditional nuclear effects <u>decrease</u> the σ, there are processes that can <u>increase</u> the total yield …



Martini *et al.*, PRC **80**, 065001 (2009)

- extra contributions coming from <u>nucleon correlations</u> in the nucleus
  (all prior calculations assume nucleons are independent particles)
- can predict MiniBooNE data without having to increase M_A *(here, M_A=1.0 GeV)*

Electron Scattering



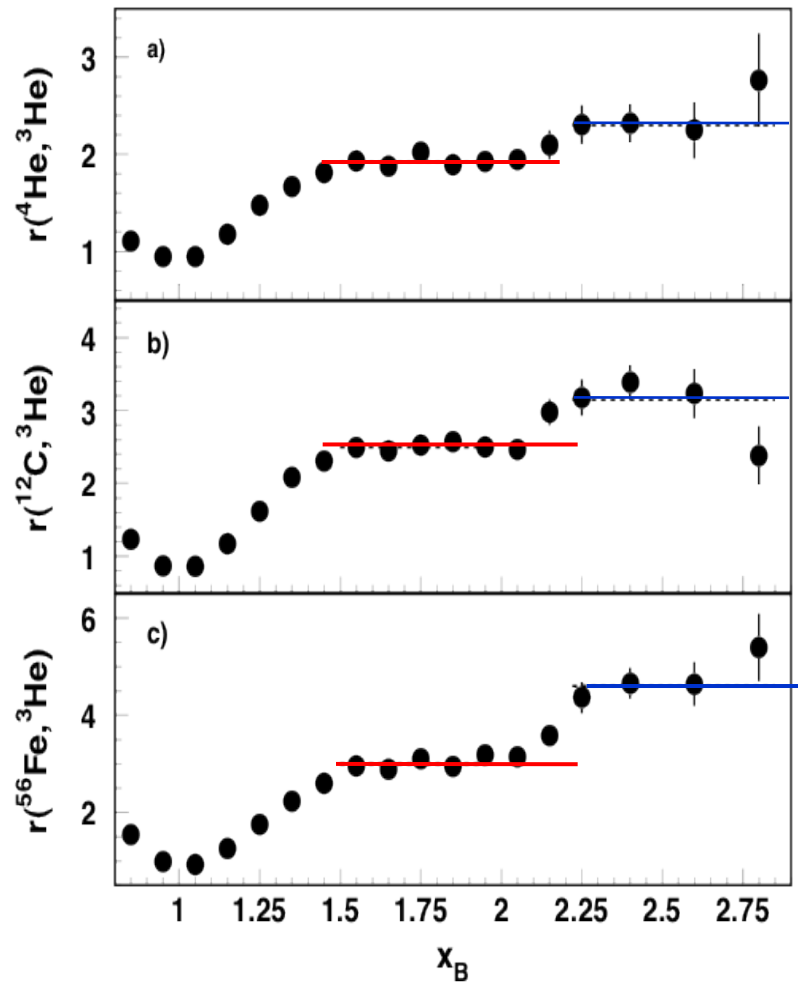
NN SRC via Inclusive Scattering at Large x_B

$$x = \frac{Q^2}{2M\omega} > 1.5 \text{ and } Q^2 > 1.4\ [\mathrm{GeV/c}]^2$$

then

$r(A,{}^3He) = a_{2n}(A)/a_{2n}({}^3He)$

a_{2n} 2N-probability above k_{Fermi}



The observed *scaling* means that the electrons probe the high-momentum nucleons in the 2N-SRC phase, and the scaling factors determine the per-nucleon probability of the 2N-SRC phase in nuclei with A>3 relative to ^{3}He

Analysis shows that 3-N SRC are 10 times smaller than 2-N SRC.

K. Sh. Egiyan *et al.*, PRC **68** (2003) 014313; PRL **96** (2006) 082501

Originally done with SLAC data by D.B. Day *et al.*, PRL 59 (1987) 427

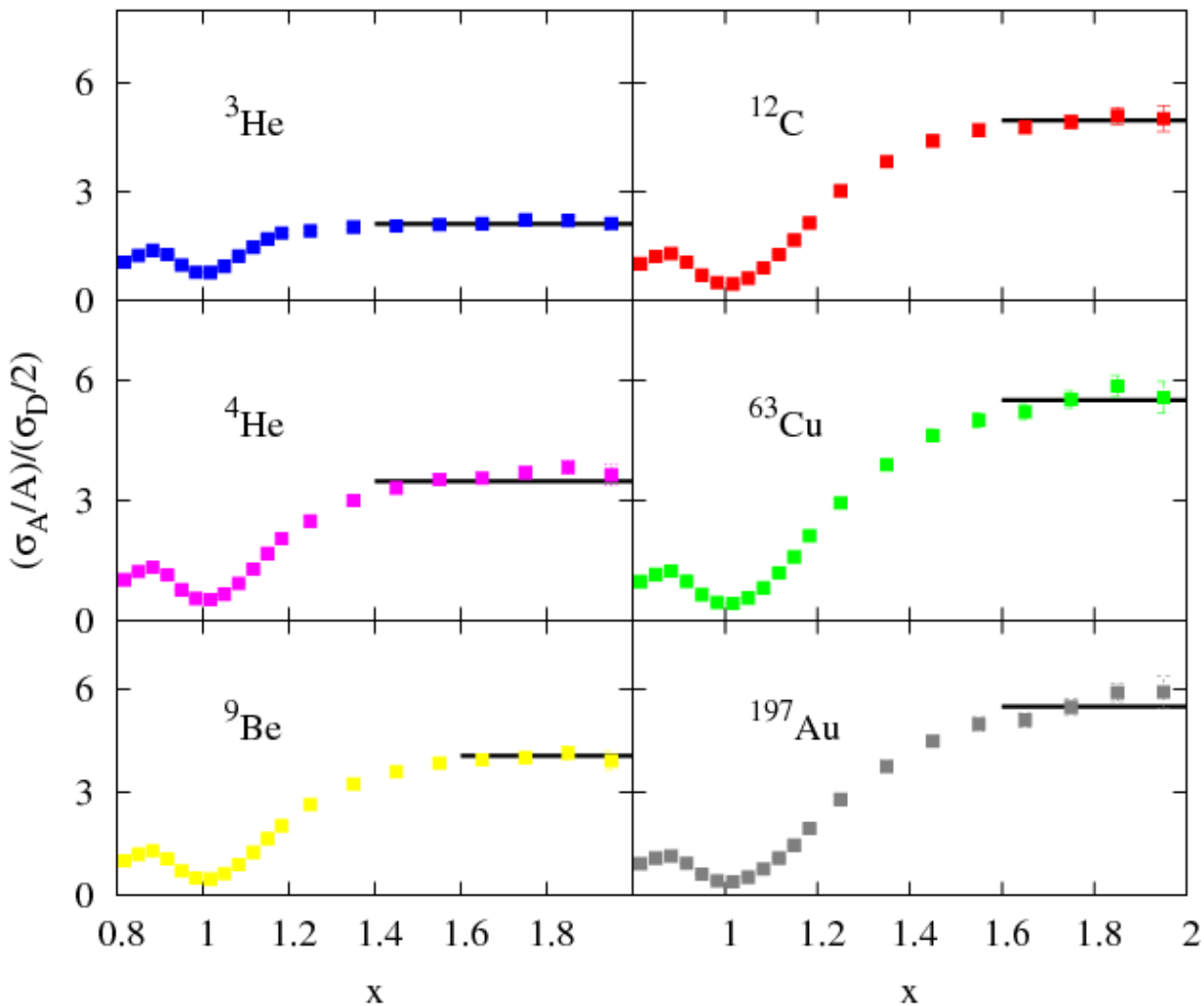
At any moment, the number of 2-nucleon SRC are 0.3, 1.2 and 6.7 in ^{4}He, ^{12}C and ^{56}Fe, respectively

Higher Precision, Higher Q^2 Follow-on Experiment E02-019: 2N correlations in A/D ratios

18° data

$\langle Q^2 \rangle = 2.72 GeV^2$

R(A, D)		
^{3}He	2.14(4)	1.93(10)
^{4}He	3.66(7)	3.02(17)
Be	4.00(8)	3.37(17)
C	4.88(10)	4.00(24)
Cu	5.37(11)	4.33(28)
Au	5.34(11)	4.26(29)



Raw cross section ratio

Correct for inelastics and high p_M tail due to pair motion to get relative 2N-SRC contribution . *Ratios are in excellent agreement with CLAS results for 2N correlations*

N. Fomin, et al, arXiv:1107.3583 (2011)

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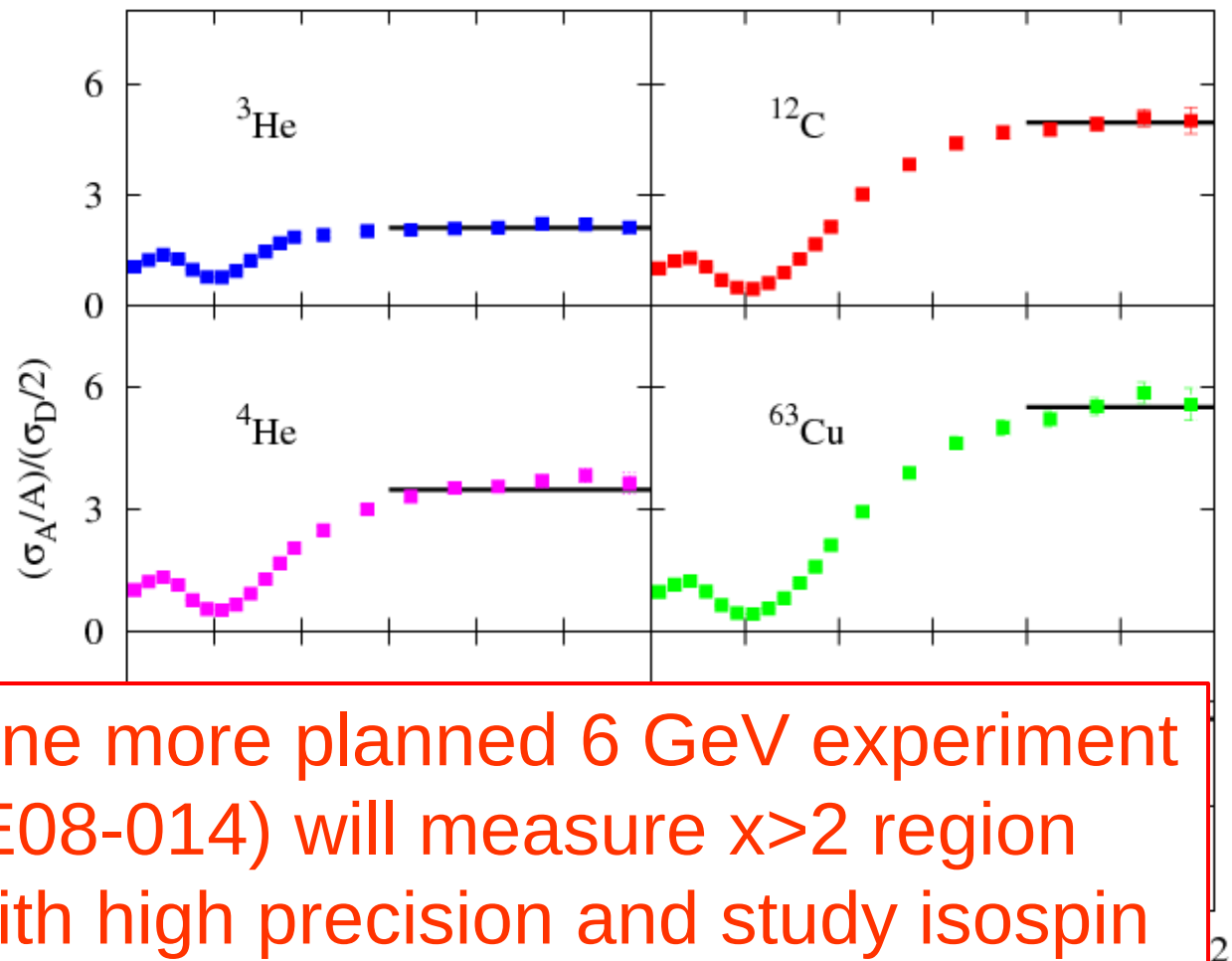
Raw cross section ratio

Cor
get
agr

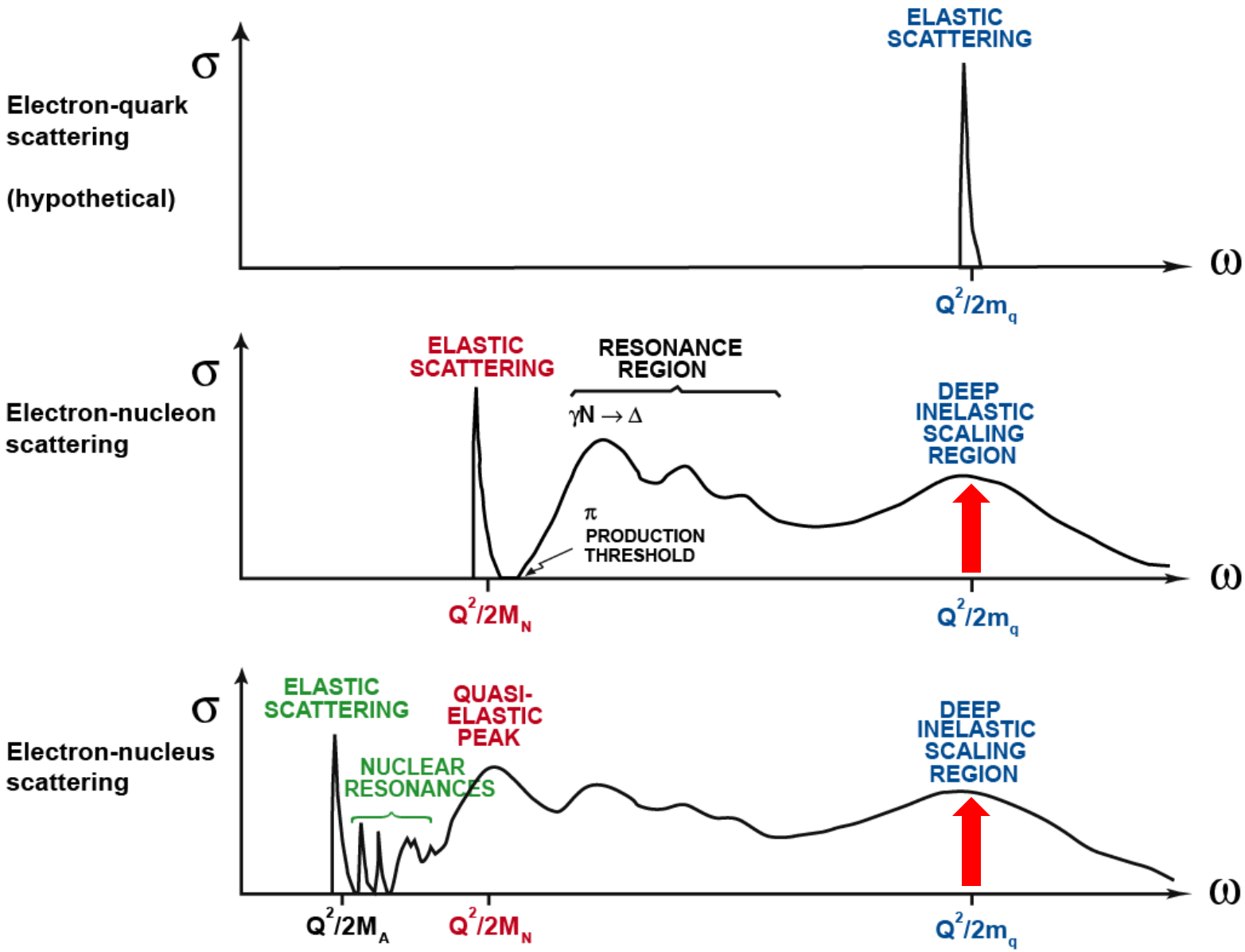


- One more planned 6 GeV experiment (E08-014) will measure x>2 region with high precision and study isospin effects (^{48}Ca & ^{40}Ca);
- Further studies planned for 12 GeV

Are the Free Protons and Neutrons Identical to the Protons and Neutrons in Nuclei????

Use Deep Inelastic Scattering to Check

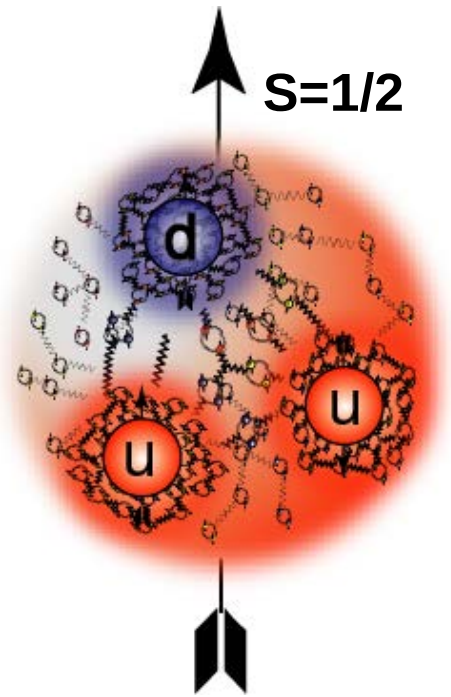
Electron Scattering



DIS Measures the Fraction of the Total Nucleon Momentum that the Struck Quark had at the Moment it was Struck

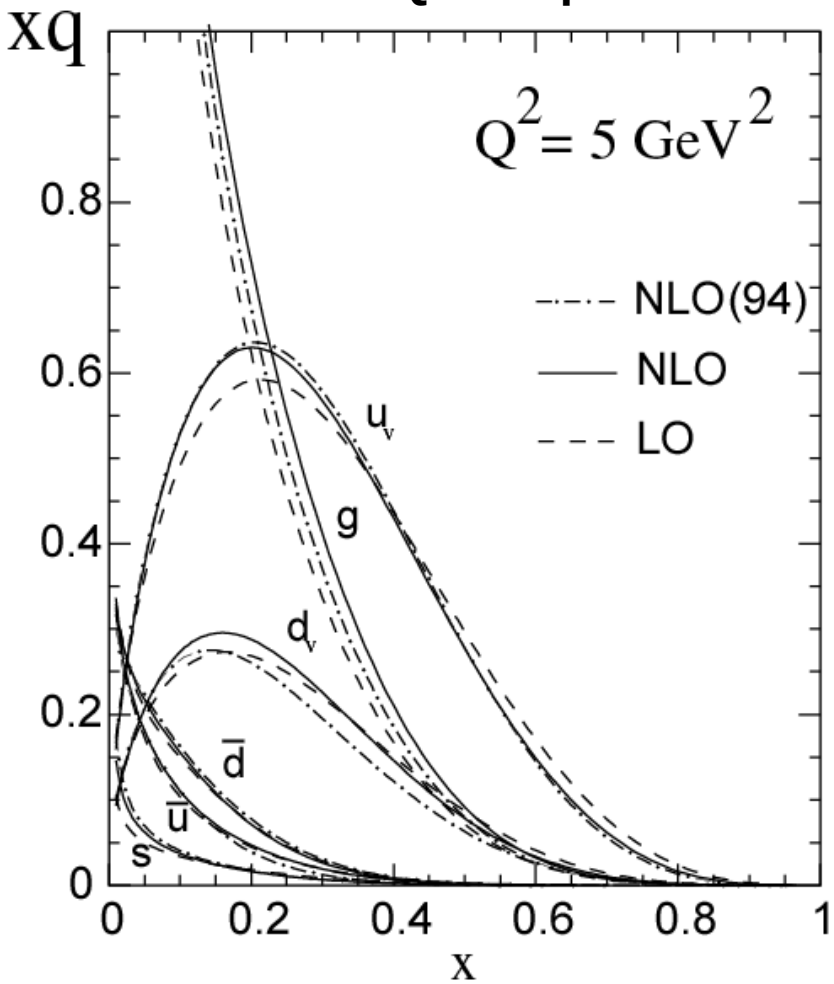
< 0.1 fm

"bare" quarks and glue

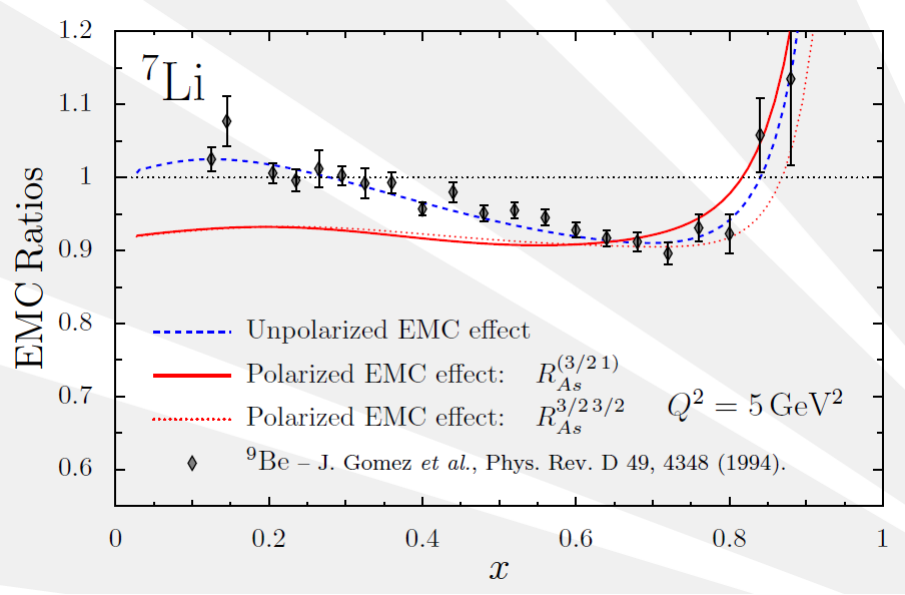


Measurement of quark's momentum component along the momentum transfer direction at the moment it was struck; complementary to elastic electron nucleon scattering data, which measures the transverse position of the struck quark

Analysis of the world's data on ep deep inleastic scattering by CTEQ Group



We Have Known Since the Late 1980's, when the EMC Effect was Discovered, that Nucleons in the Nucleus Differ from Free Nucleons



- EMC ratio

$$R_A = \frac{F_{2A}}{F_{2A}^{\text{naive}}} = \frac{F_{2A}}{Z\,F_{2p} + (A - Z)\,F_{2n}}$$

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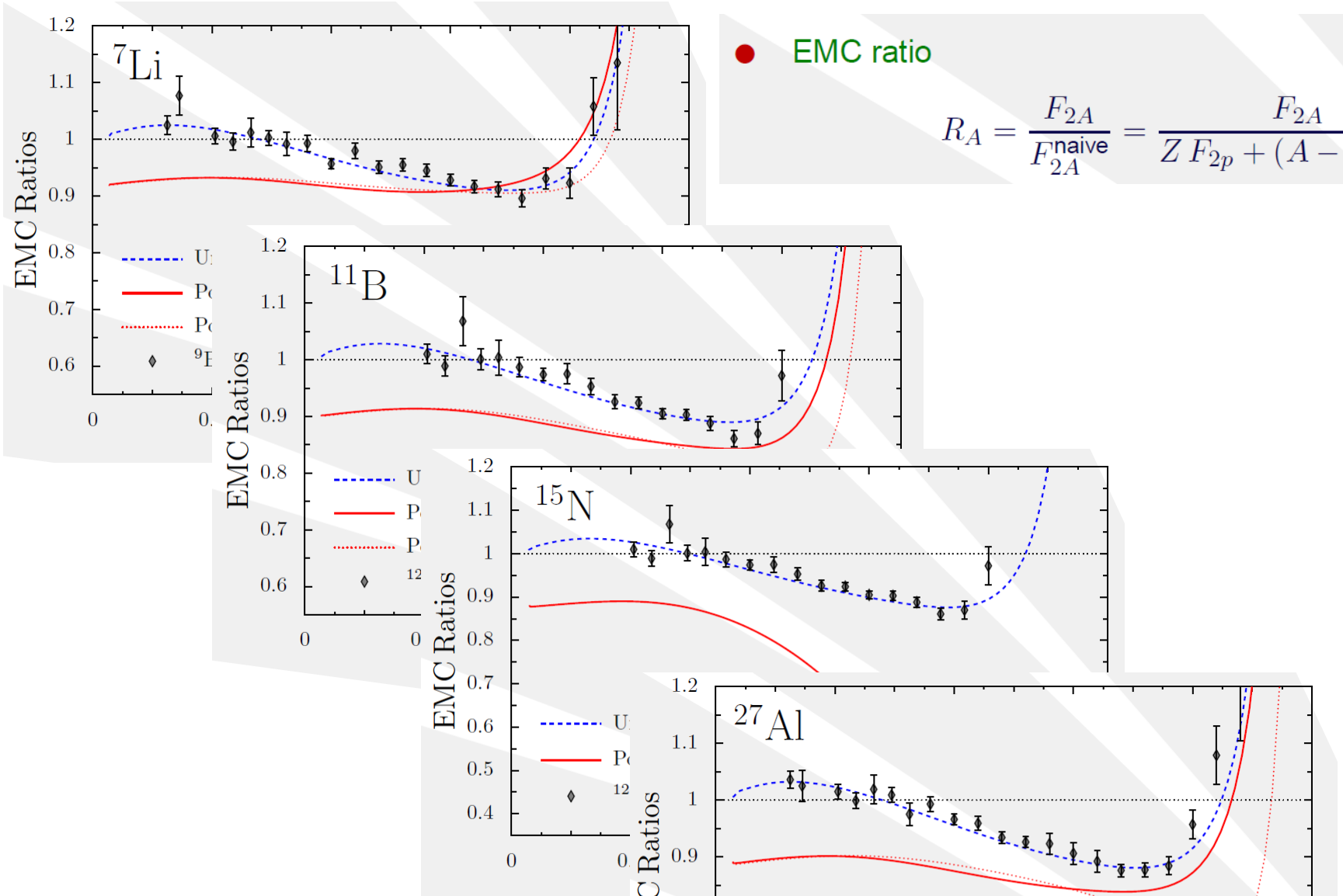


- EMC ratio

$$R_A = \frac{F_{2A}}{F_{2A}^{\text{naive}}} = \frac{F_{2A}}{Z\,F_{2p} + (A - Z)\,F_{2n}}$$

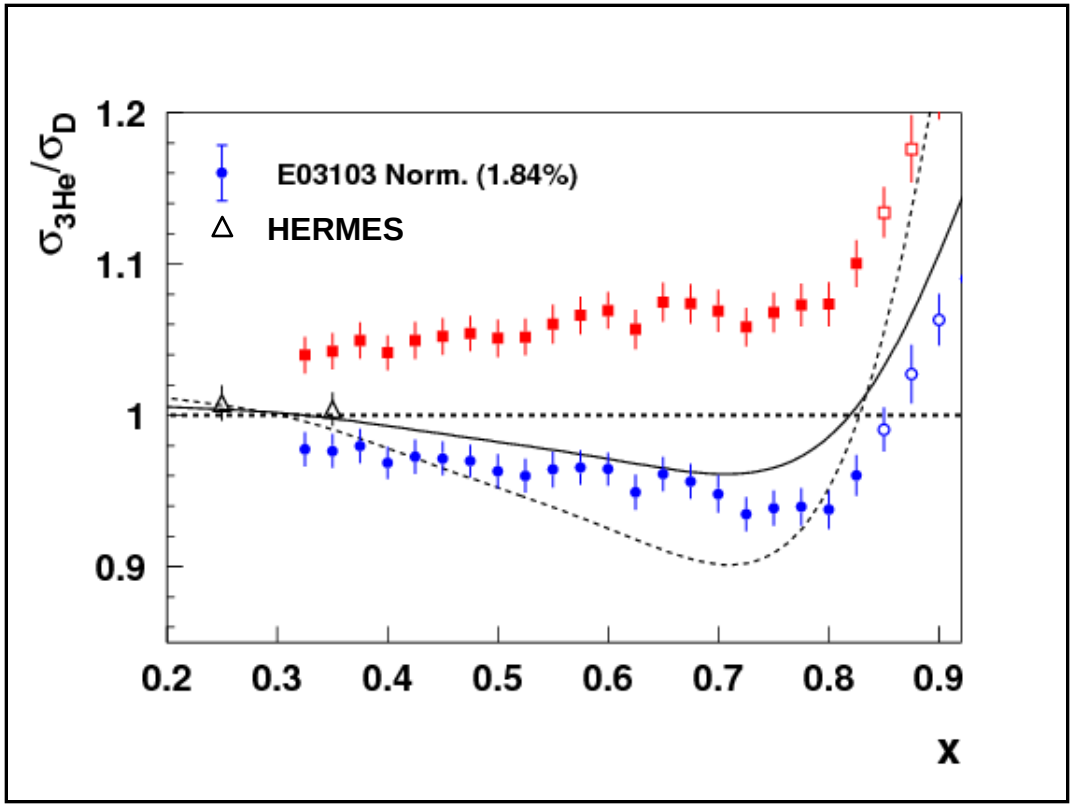
New JLab Data Extends EMC Effect Measurements to Very Light Nuclei

First measurement of EMC effect in ^{3}He at large *x*

Consistent with HERMES data in region of overlap

Large isoscalar correction – performed using fit to F_2^n/F_2^p combined with convolution calculation ***[J. Arrington et al, J. Phys. G36 025005 (2009)]***

Magnitude of EMC effect in ^{3}He much less than ^{4}He. Suggests EMC is density dependent, not A dependent.



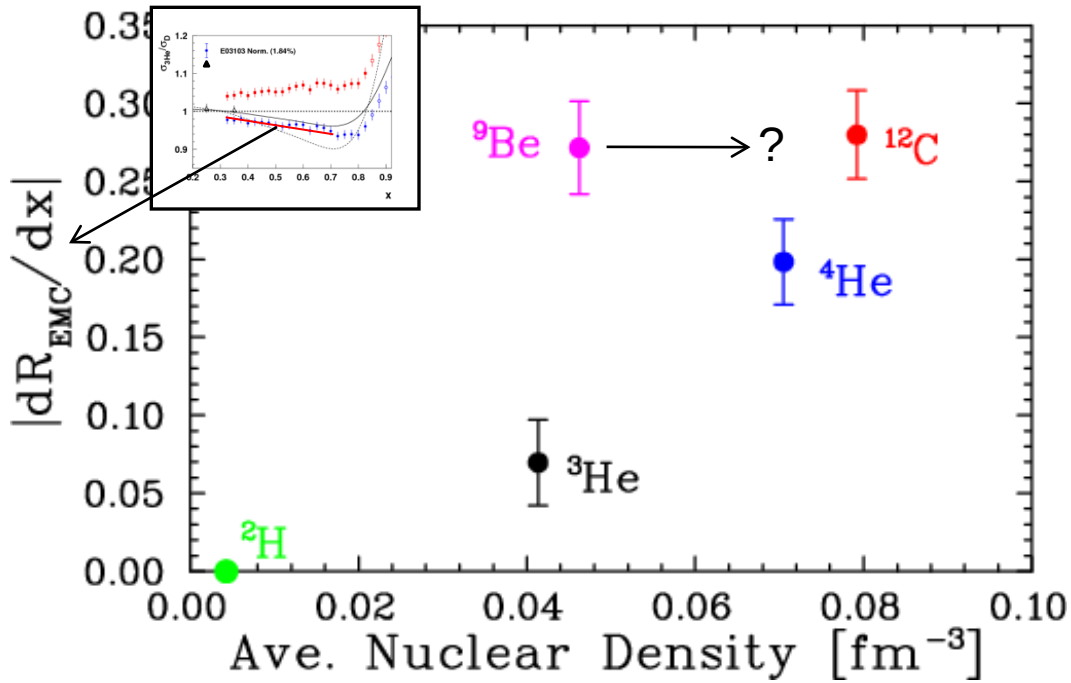
No isoscalar correction *Isocalar corrected*

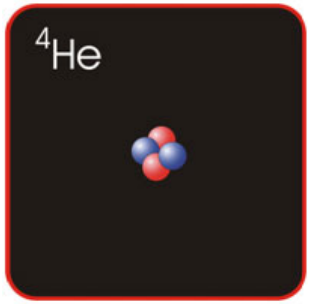
EMC Effect in very light nuclei

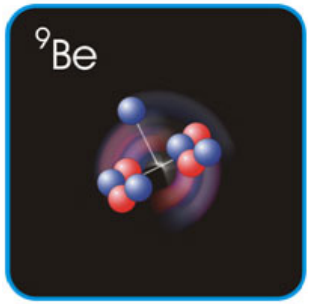
EMC effect scales with average nuclear density if we ignore Be

Be = 2 α clusters (^{4}He nuclei) + "extra" neutron

Suggests EMC effect depends on ***local*** nuclear environment





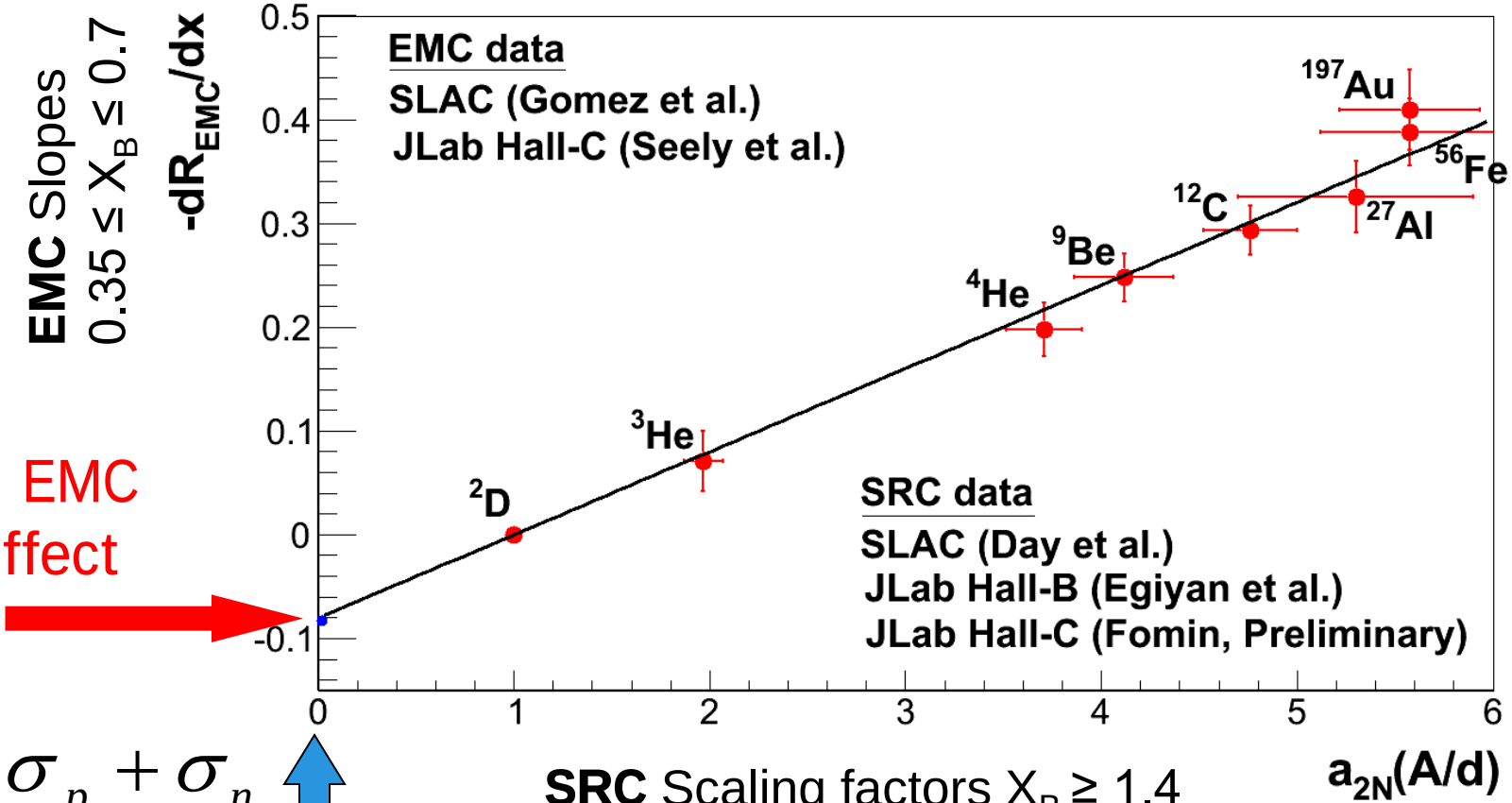


dR/dx = slope of line fit to *A/D* ratio over region *x=0.3* to *0.7*

Nuclear density extracted from *ab initio* GFMC calculation – scaled by *(A-1)/A* to remove contribution to density from "struck" nucleon

C. Seely, A. Daniel, et al, PRL 103, 202301 (2009)

The SRC Plateaus and EMC Effect Are Correlated



d EMC effect

$$\sigma_d \neq \sigma_p + \sigma_n$$

SRC Scaling factors $X_B \geq 1.4$

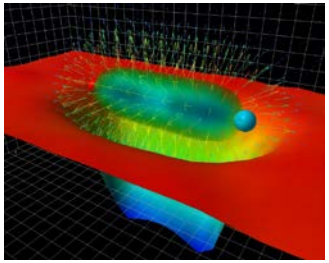
SRC=0
free nucleons

L. Weinstein *et al*, PRL 106, 052301 (2011)

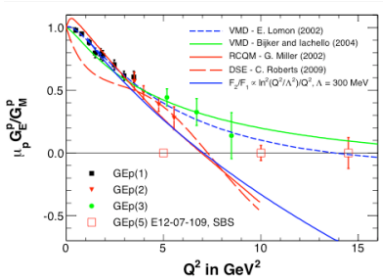
1. **The EMC effect and SRC are probably both dominated by high momentum (high virtuality) nucleons in nuclei**
2. **This strong correlation between them lets us extract both the *d* EMC effect [the slope of $\sigma_d/(\sigma_p+\sigma_n)$] and F^2_n/F^2_p for $0.3 < x < 0.7$**

Coming Next: The JLab 12 GeV Upgrade Major Programs in Six Areas

- **The Hadron spectra as probes of QCD**
  (GluEx and heavy baryon and meson spectroscopy)



- **The transverse structure of the hadrons**
  (Elastic and transition Form Factors)



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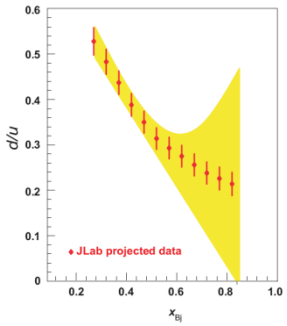

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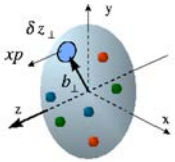
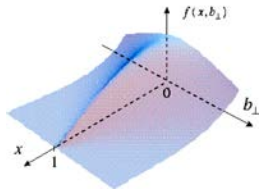
  (Generalized Parton Distributions and Transverse Momentum Distributions)





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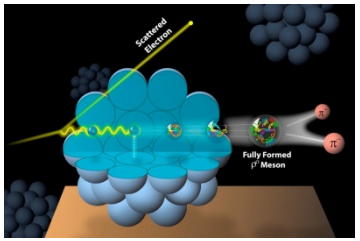
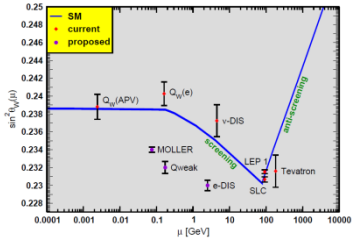
  (Medium modification of the nucleons, quark hadronization, N-N correlations, hypernuclear spectroscopy, few-body experiments)



- **Low-energy tests of the Standard Model and Fundamental Symmetries**
  (Møller, PVDIS, PRIMEX, ...)



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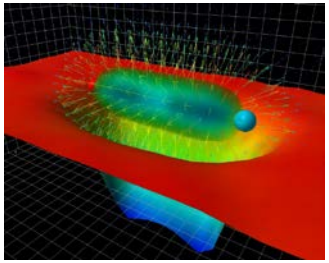
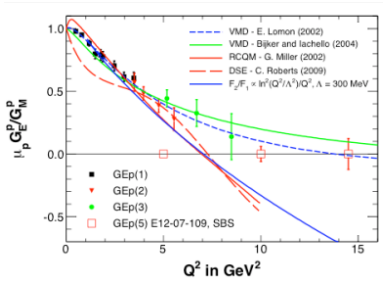
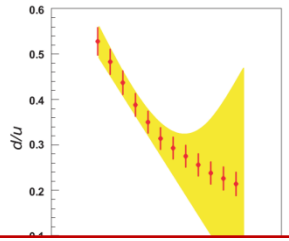
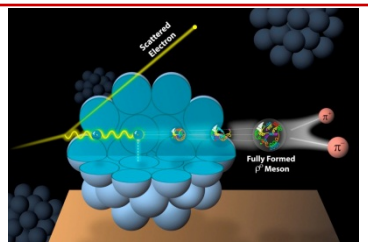
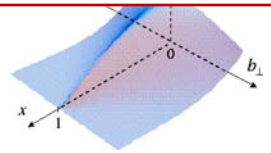


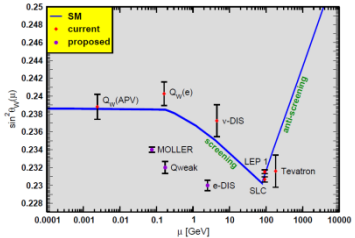




And other science we can't foresee



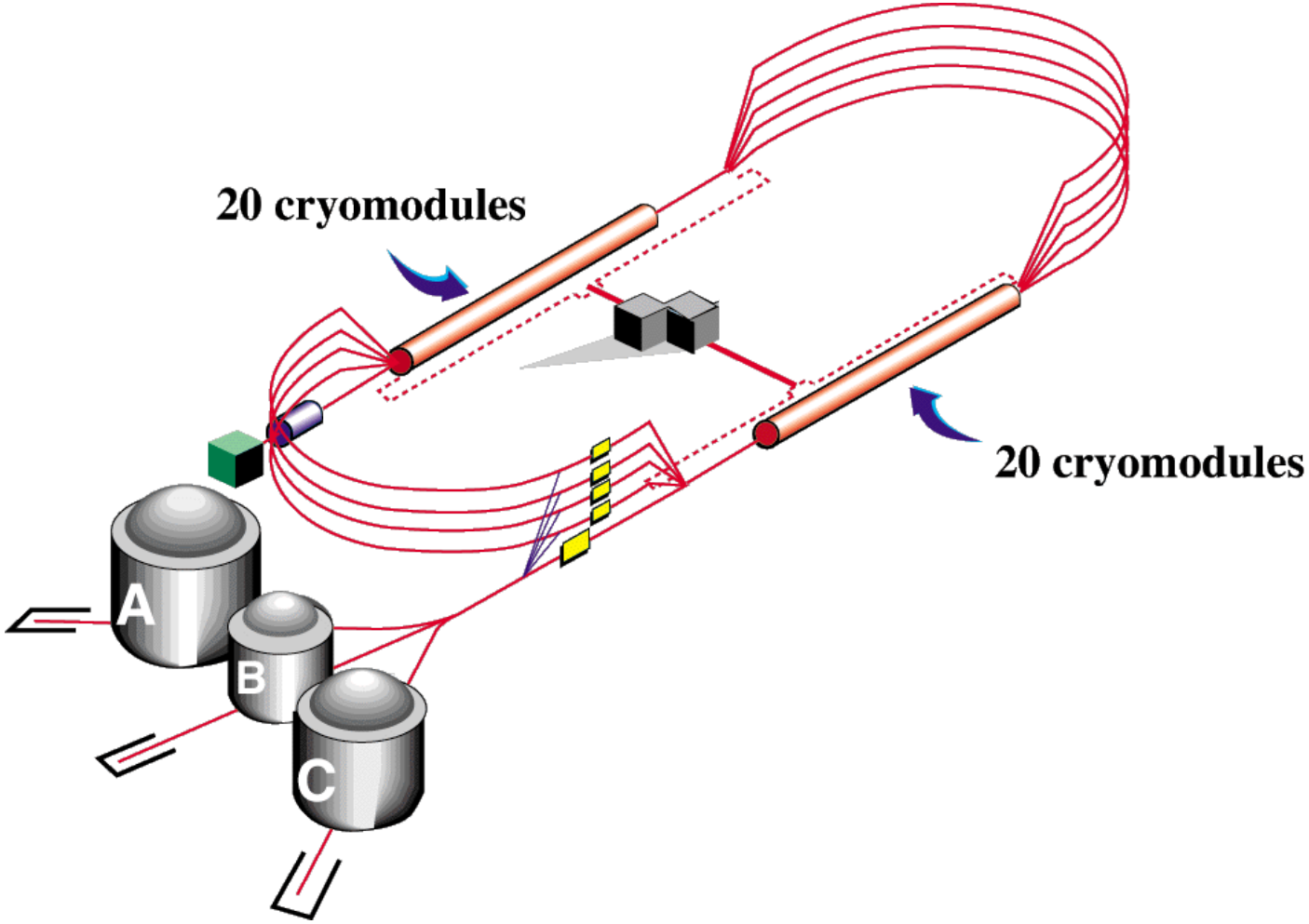




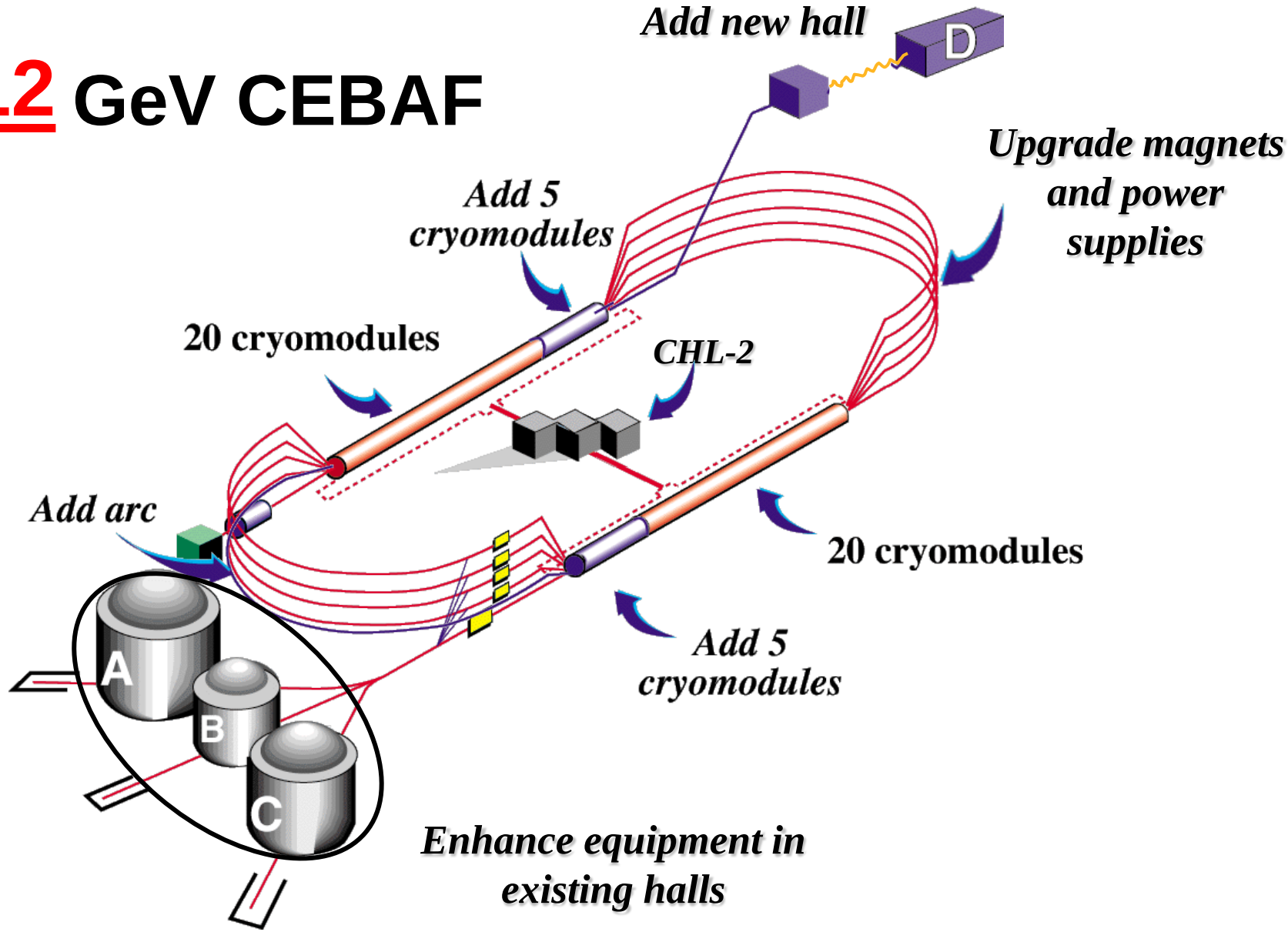
12 GeV Approved Experiments by Physics Topics

Topic	Hall A	Hall B	Hall C	Hall D	Total
The Hadron spectra as probes of QCD (GLUEx and heavy baryon and meson spectroscopy)		1		1	2
The transverse structure of the hadrons (Elastic and transition Form Factors)	4	2	3		9
The longitudinal structure of the hadrons (Unpolarized and polarized parton distribution functions)	2	2	5		9
The 3D structure of the hadrons (Generalized Parton Distributions and Transverse Momentum Distributions)	4	8	3		15
Hadrons and cold nuclear matter (Medium modification of the nucleons, quark hadronization, N-N correlations, hypernuclear spectroscopy, few-body experiments)	3	2	5		10
Low-energy tests of the Standard Model and Fundamental Symmetries	2			1	3
TOTAL	15	15	16	2	48

6 GeV CEBAF



12 GeV CEBAF


Add new hall
D
Upgrade magnets and power supplies
Add 5 cryomodules
20 cryomodules
CHL-2
Add arc
20 cryomodules
Add 5 cryomodules
A
B
C
Enhance equipment in existing halls

High-level Parameters

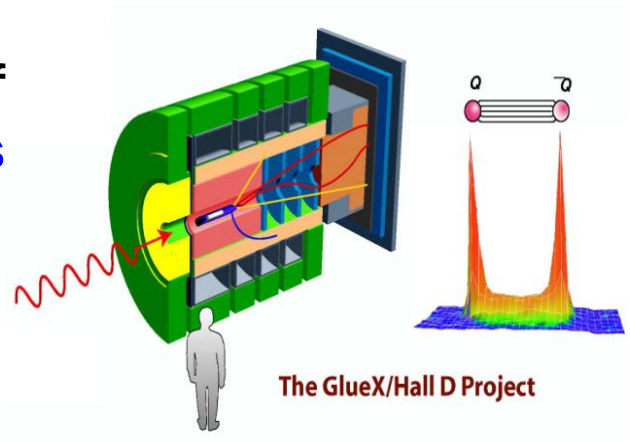
	Now
ACCELERATOR:	
Beam energy	6 GeV
Voltage of each linac	0.6 GV
Number of recirculations	5
Beam power (total program)	1 MW
Beam current (hybrid mesons)	-
Emittance	1 nm-rad
Energy spread	0.01%
CRYOPLANT	4.5 kW
EXPERIMENTAL HALLS	3

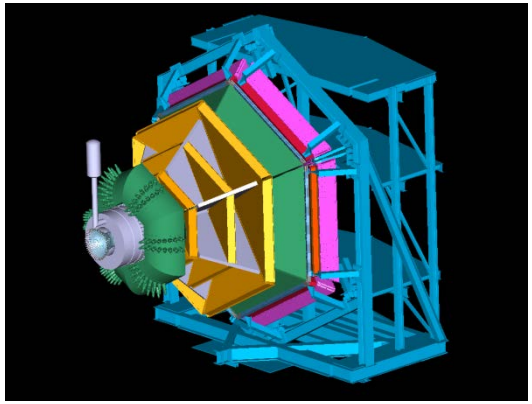
High-level Parameters

	Now	Upgrade
ACCELERATOR:		
Beam energy	6 GeV	12 GeV
Voltage of each linac	0.6 GV	1.1 GV
Number of recirculations	5	5 ½
Beam power (total program)	1 MW	1 MW
Beam current (hybrid mesons)	-	5 μA
Emittance	1 nm-rad	7 nm-rad
Energy spread	0.01%	0.02%
CRYOPLANT	4.5 kW	9 kW
EXPERIMENTAL HALLS	3	4

12 GeV Upgrade Physics Instrumentation

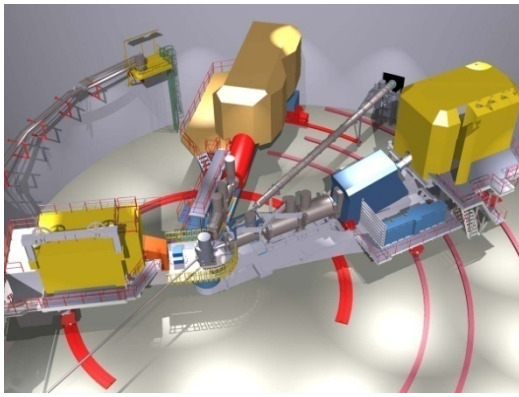
GLUEx (Hall D): **exploring origin of confinement by studying hybrid mesons**

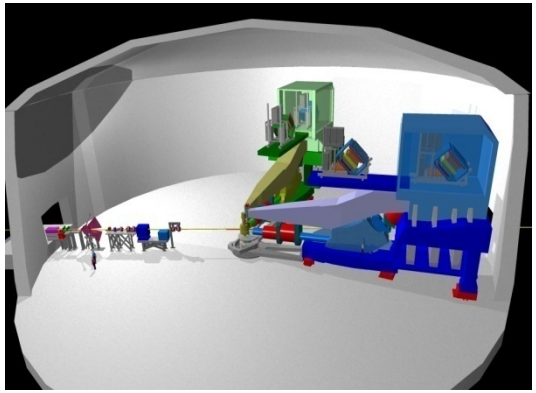




CLAS12 (Hall B): **understanding nucleon structure via generalized parton distributions**

SHMS (Hall C): **precision determination of valence quark properties in nucleons and nuclei**

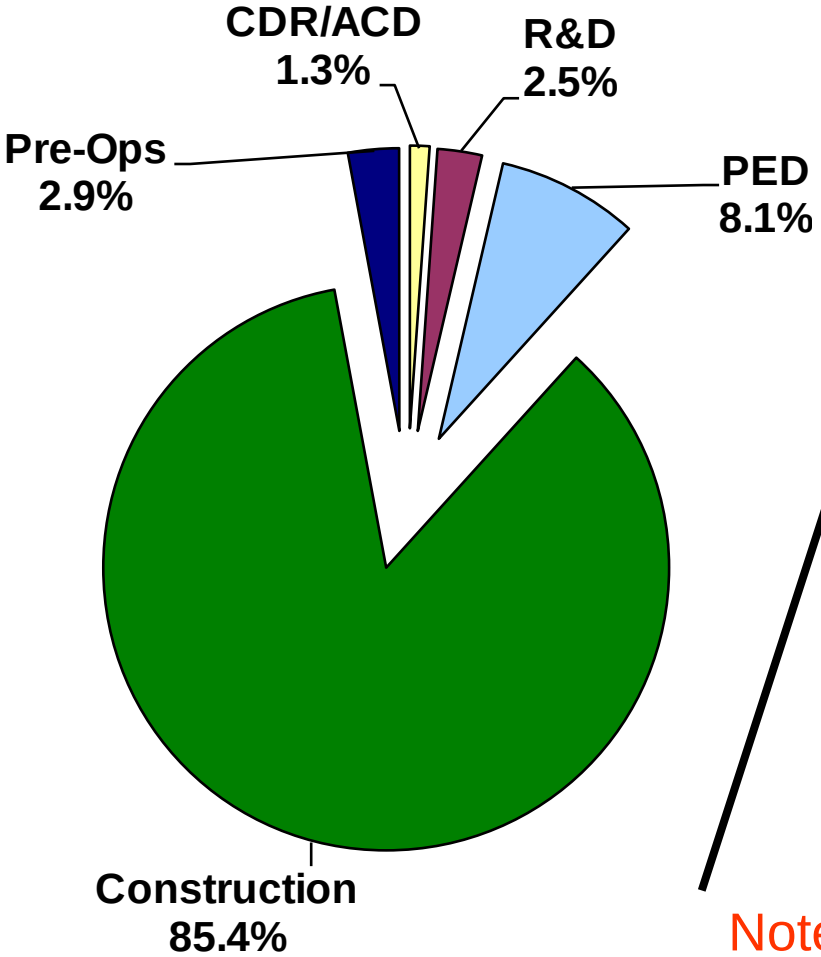




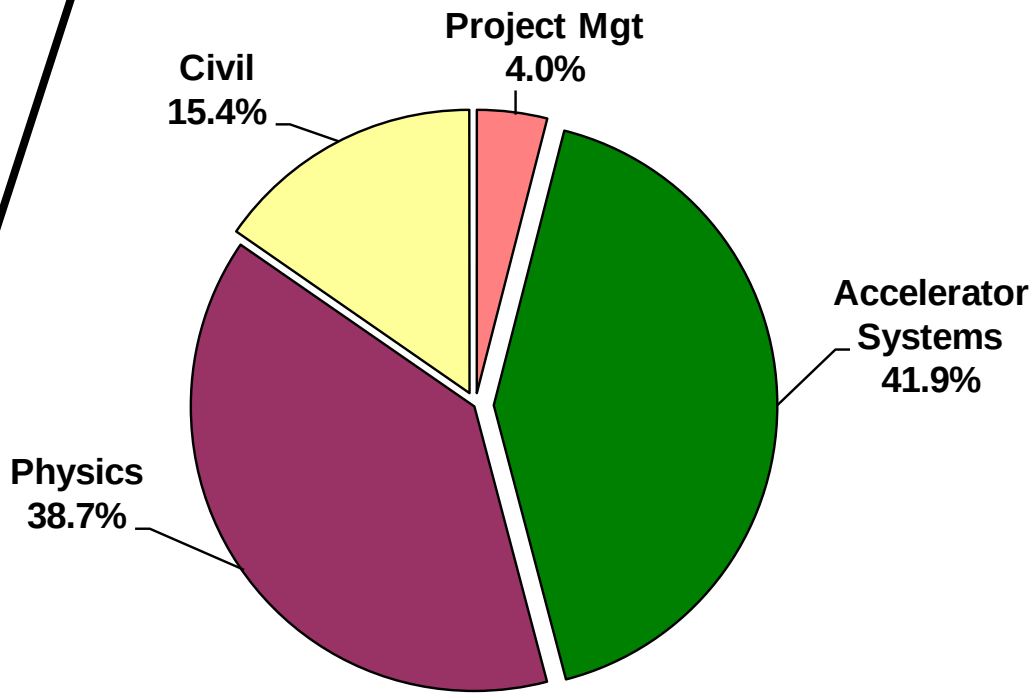
Hall A: **short range correlations, form factors, hypernuclear physics, *& future new experiments***

12 GeV CONSTRUCTION

TPC = $310M TEC = $287.5M



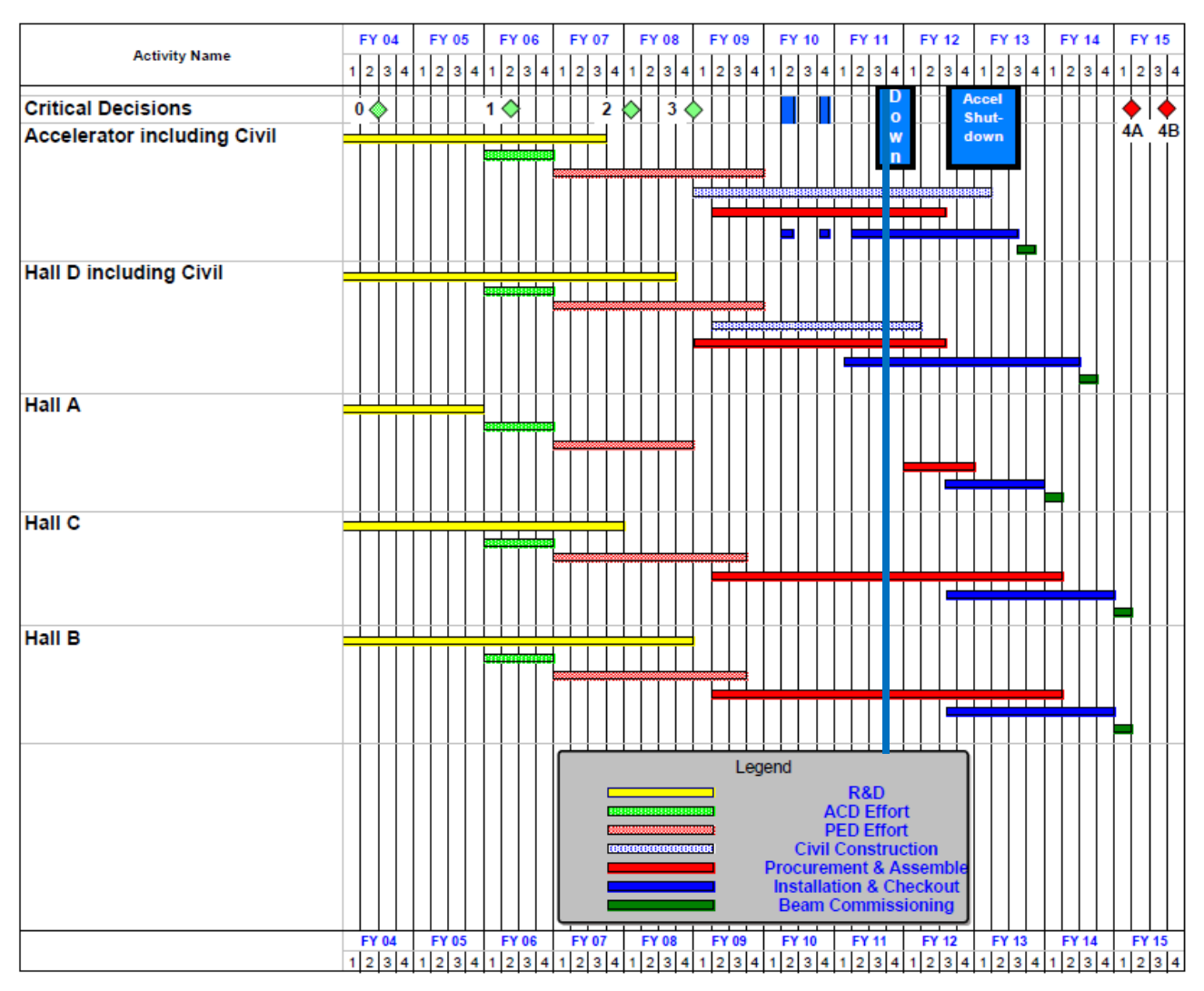
CONSTRUCTION = $266.5M



Note: 43% Contingency + Management Reserve

Project Unusual in that Accelerator and Experimental Apparatus Costs are Comparable: ***Due to SRF Improvements, Tunnel Space, and Dipole Reuse***

12 GeV Upgrade Schedule



Two short parasitic installation periods in FY10

6-month installation
May – Oct 2011

12-month installation
May 2012 – May 2013

Hall A commissioning start
October 2013

Hall D commissioning start
April 2014

Halls B/C commissioning start
October 2014

Project Completion
June 2015

Beam Transport: 6 GeV Arc w/ “C” Dipoles

West Arc July 2011: Dipoles ALL removed

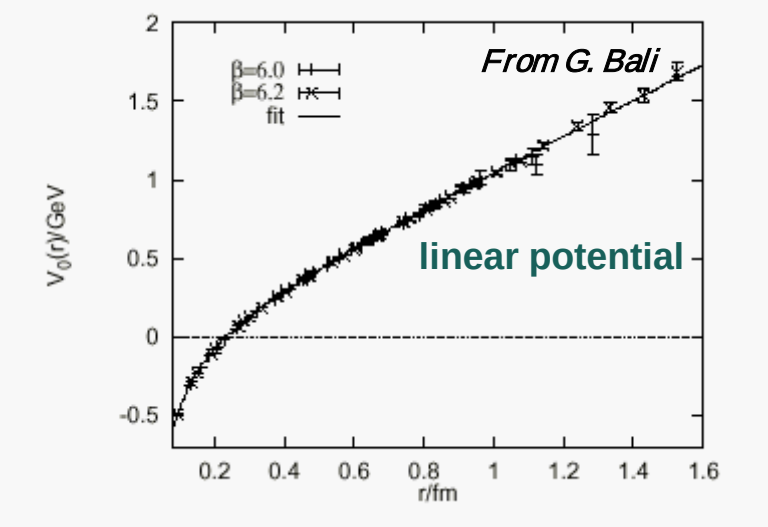
West Arc Today: All Dipoles Converted

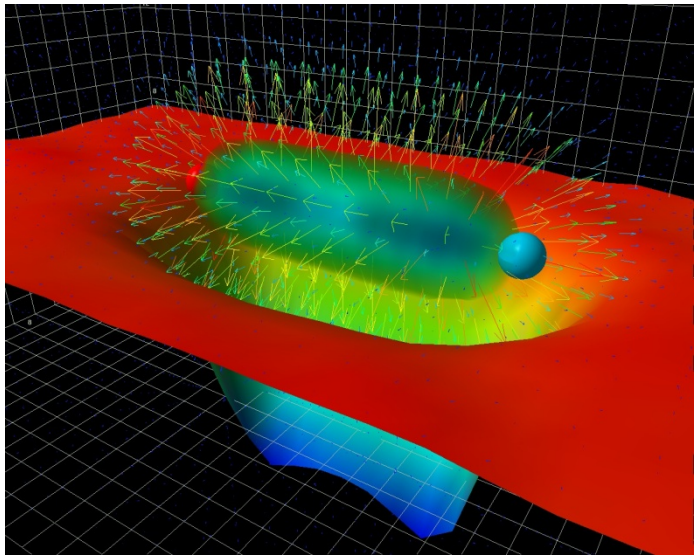
C100-1 Installed in Tunnel

100 MV vs 20 MV (now 30) for original cryomodules

Gluonic Excitations and the Origin of Confinement

Theoretical studies of QCD suggest that confinement is due to the formation of “Flux tubes” arising from the self-interaction of the glue, leading to a linear potential (and therefore a constant force)





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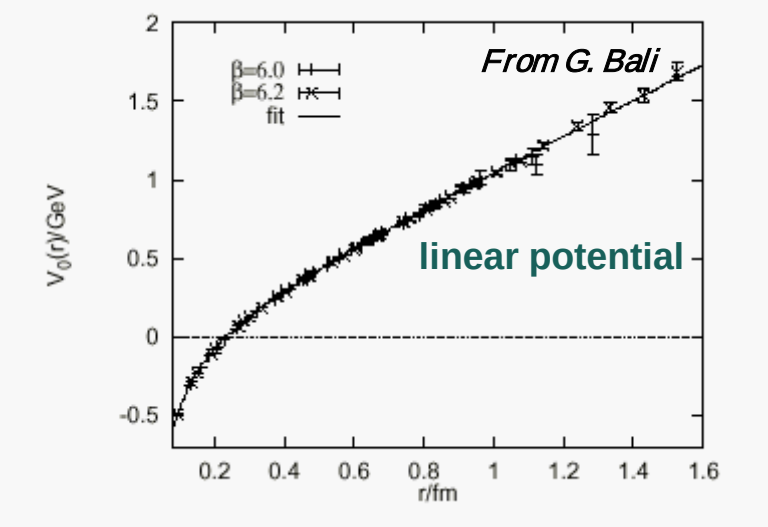
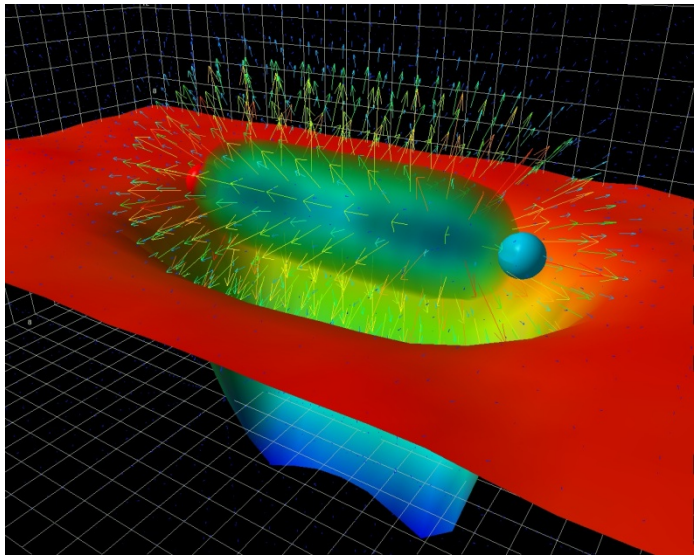
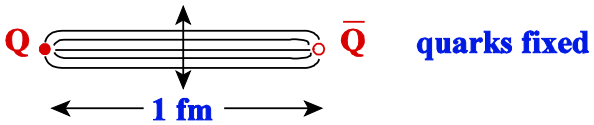




Experimentally, we want to “pluck” the flux tube



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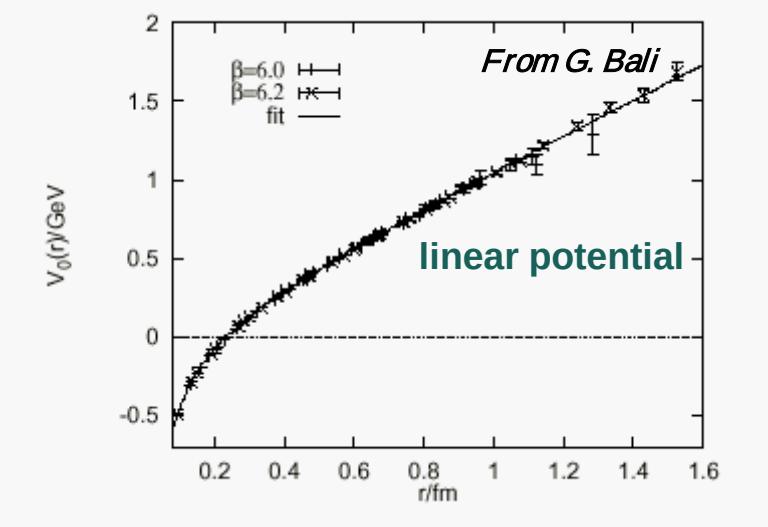
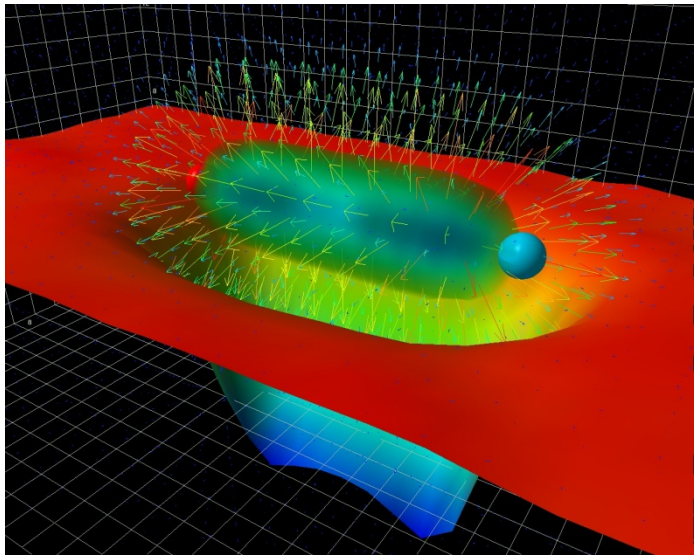
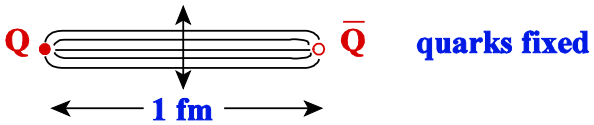
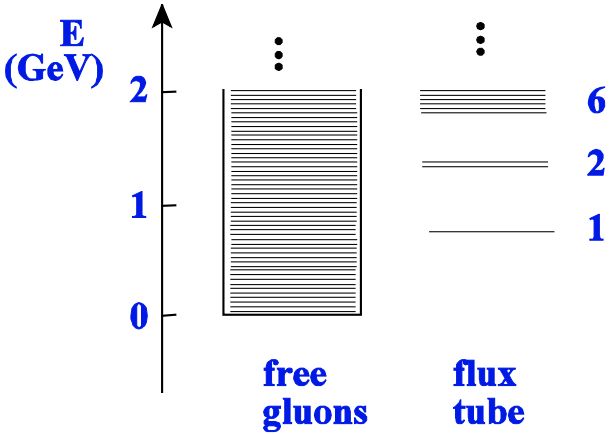




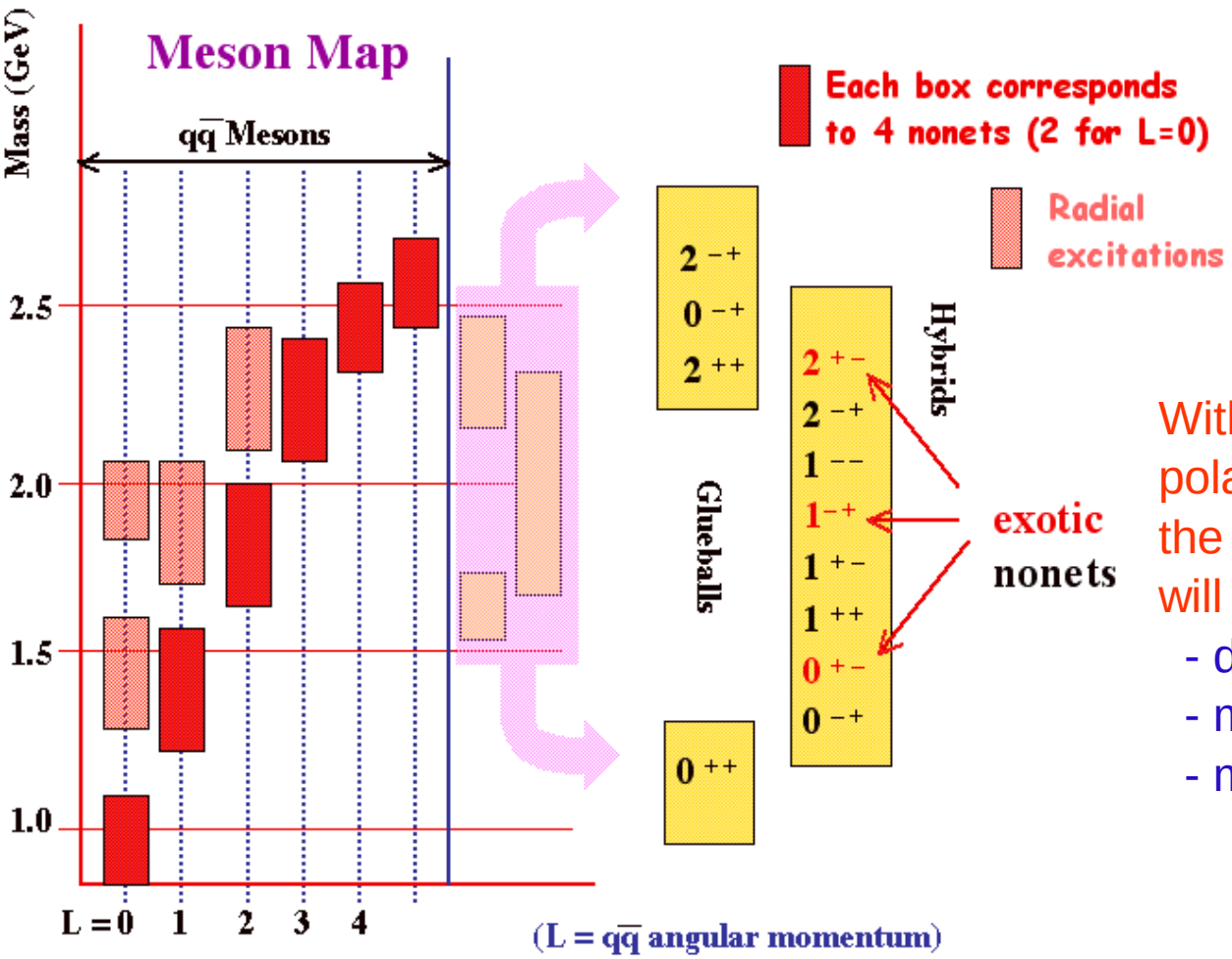
Experimentally, we want to “pluck” the flux tube (wiggle the hot dog?) and see how it responds





Glueballs and Hybrid Mesons

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.

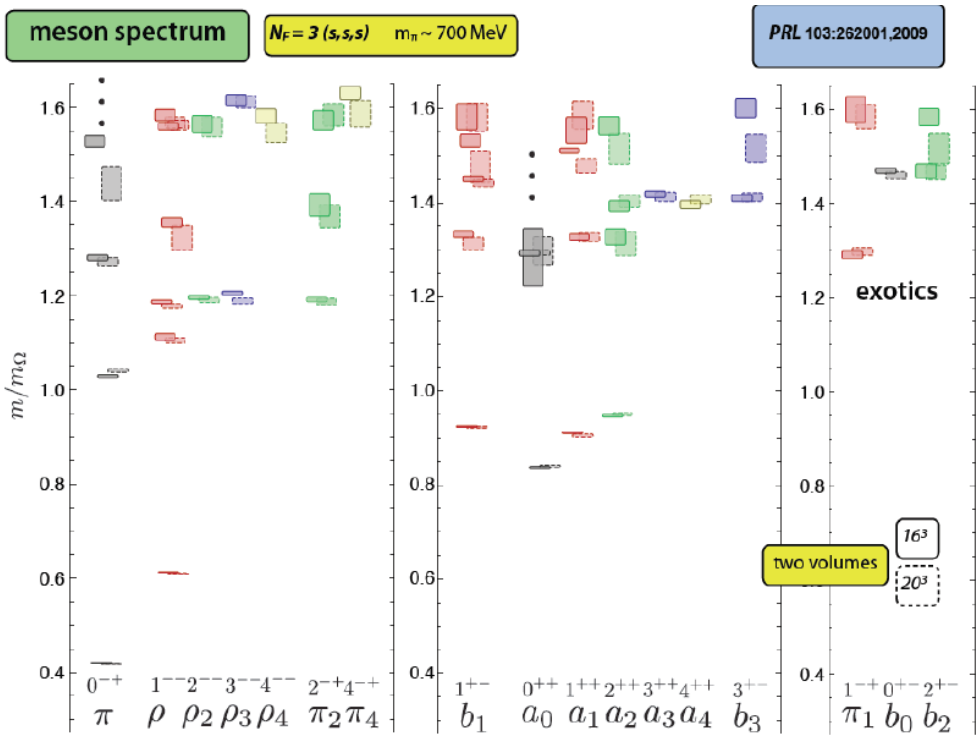


With 12 GeV, a linearly polarized photon beam, and the GlueX detector, Jlab will be uniquely poised to:

- discover these states,
- map out their spectra, and
- measure their properties

Colin Morningstar:
Gluonic Excitations workshop, 2003 (Jlab)

LQCD Developing Firm Predictions



Major challenge for lattice calculations: *the excited spectrum with quantum numbers of states identified.*

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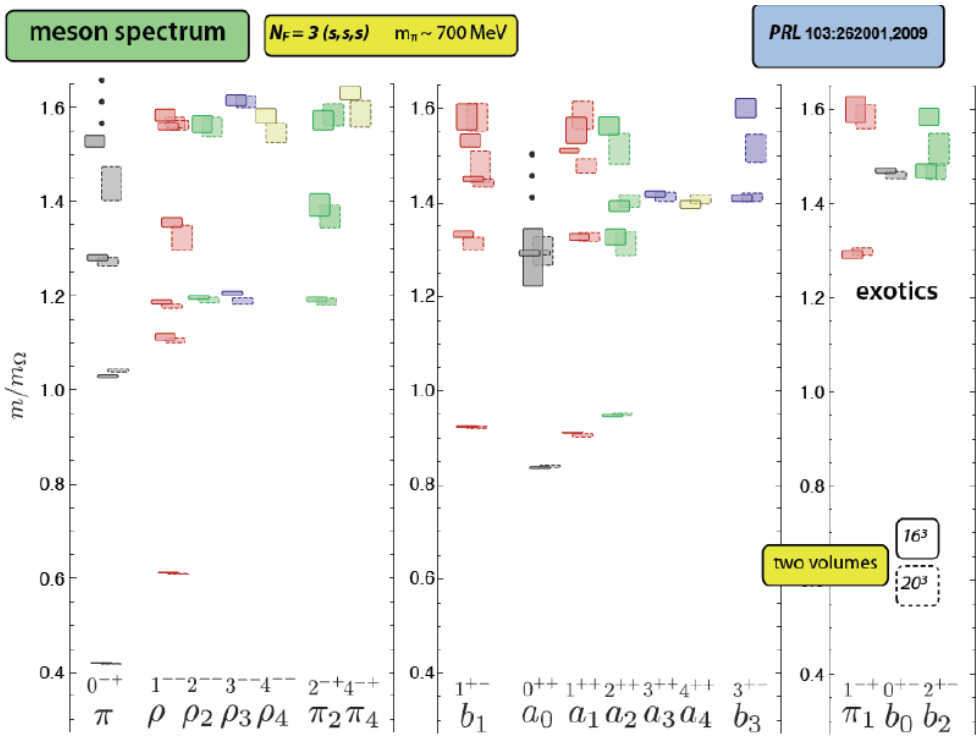

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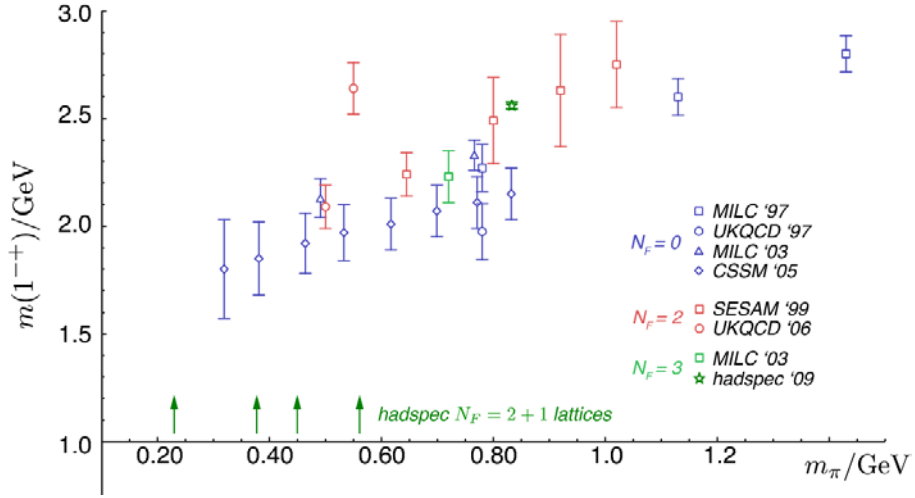
Spectrum of iso-vector mesons composed of strange quark and antiquark, in units of M_Ω



Mass of 1^{-+}, the lightest expected exotic: *ground-breaking advance in precision, laying groundwork for calculations for GlueX*

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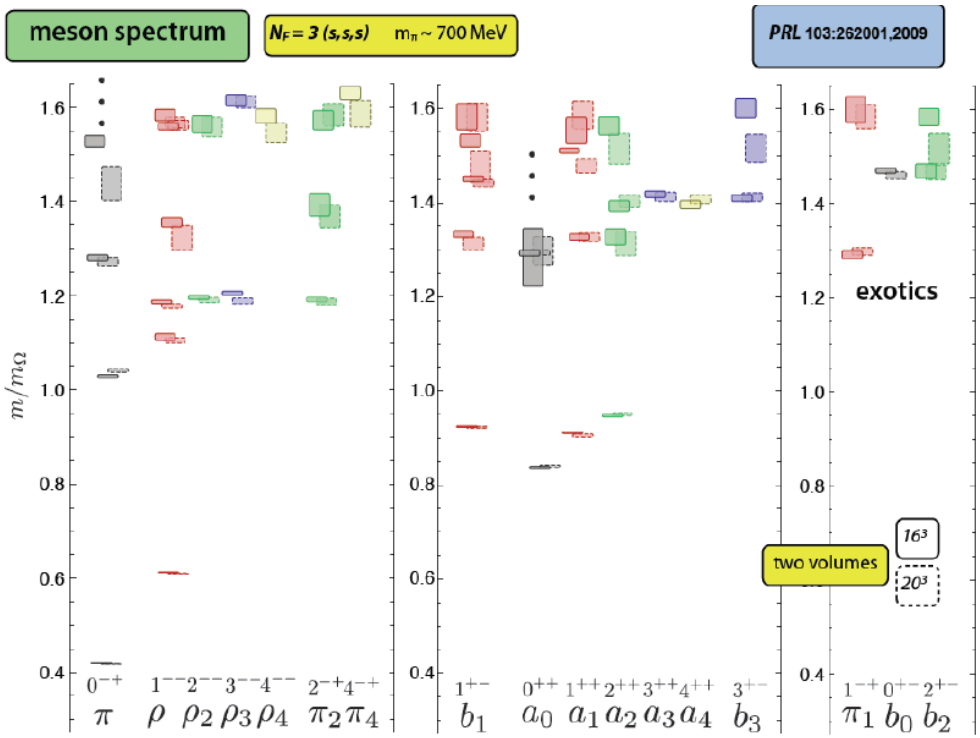

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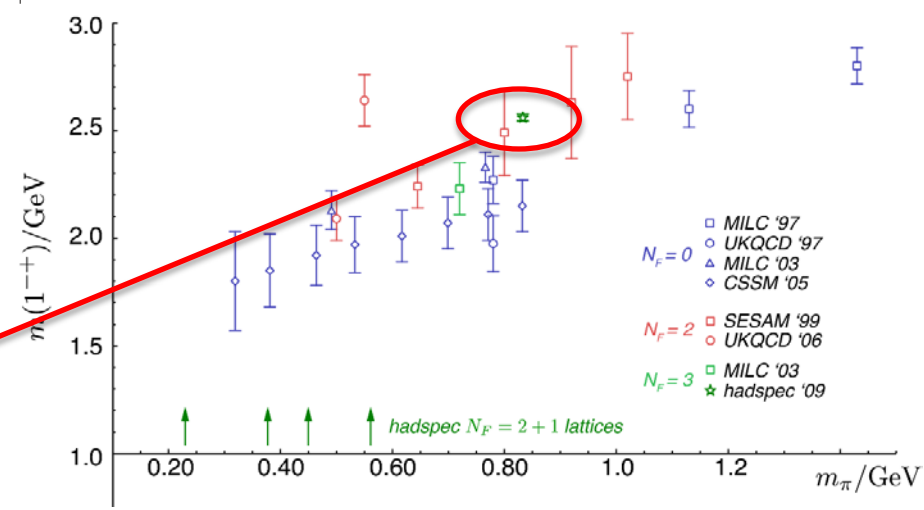

Dudek, Edwards, Peardon, Richards, Thomas, PRL103, 262001 (2009)

Summary and Perspectives

CEBAF@JLab is fulfilling its scientific mission:

- To understand how hadrons are constructed from the quarks and gluons of QCD
- To understand the QCD basis for the nucleon-nucleon force
- To explore the limits of our understanding of nuclear structure

  high precision

  short distances

  the transition from the nucleon-meson to the QCD description

The 12 GeV Upgrade will greatly enhance the scientific “reach” of the facility, supporting an exciting program of fundamental research

TRIUMF and Canadian Universities have played a critical role in this program and we look forward to continued collaboration in the 12 GeV era and beyond