Workshop on Light-Cone QCD and Nonperturbative Hadron Physics
Cairns, July 14, 2005

Jefferson Lab Phenomenology

- selected highlights -

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Jefferson Lab

DEPARTMENT OF ENERGY
UNITED STATES OF AMERICA

Outline

- Introduction
- Baryon spectroscopy
- Electromagnetic form factors
- Quark distributions and duality
- Outlook

Introduction to JLab

JLab experimental program touches key problems in nuclear & particle physics, and beyond...

⇨ confinement in QCD - spectra and decays of hadrons

⇨ hadronic form factors & quark-gluon distributions

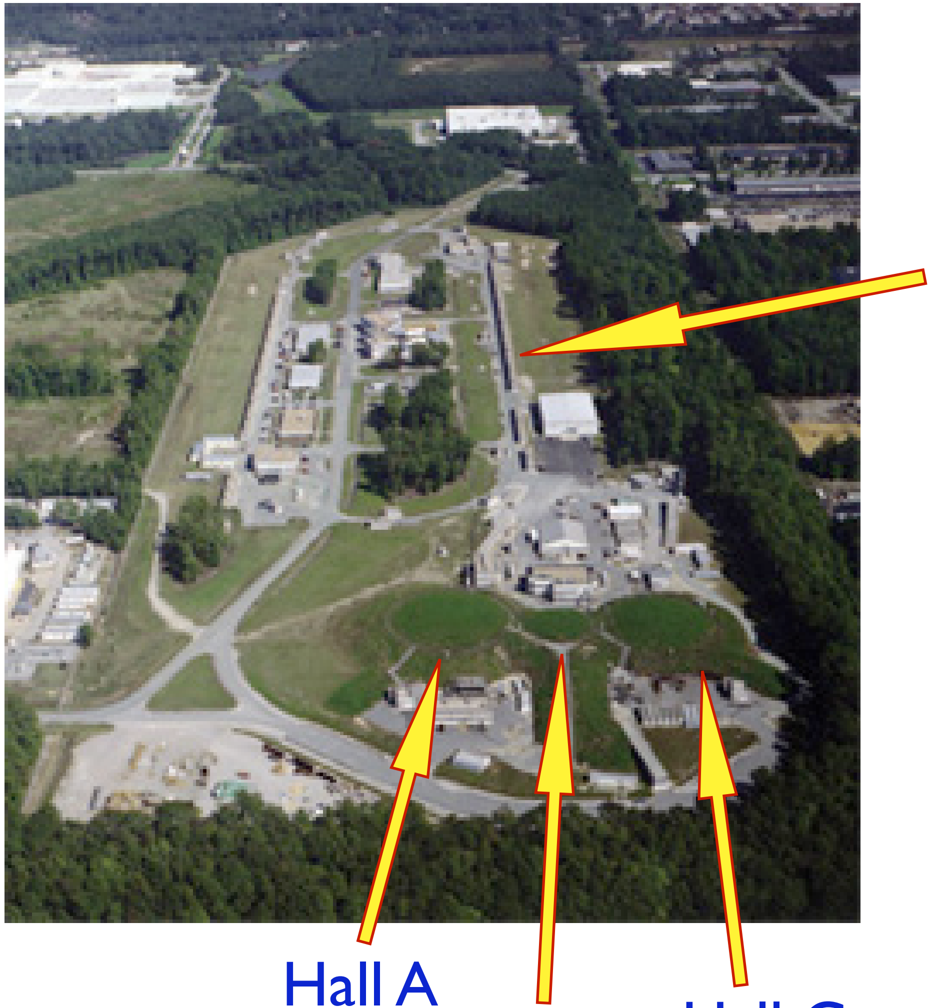
⇨ strangeness & parity violation in hadrons & nuclei

⇨ few-body nuclear physics & the NN force

⇨ many-body nuclear physics & the nuclear medium

⇨ Standard Model tests & beyond

Continuous Electron Beam Accelerator Facility at JLab



0.6 GeV electrons / linac

x 10 ⟶ 6 GeV

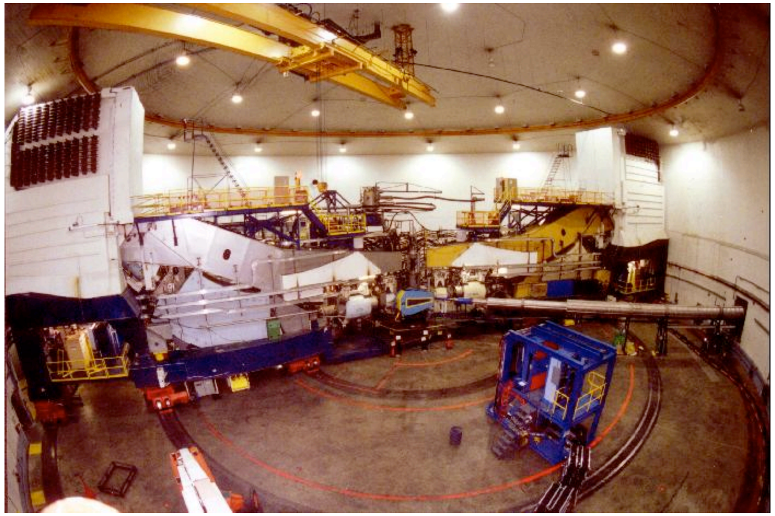
Hall A

Hall B

Hall C

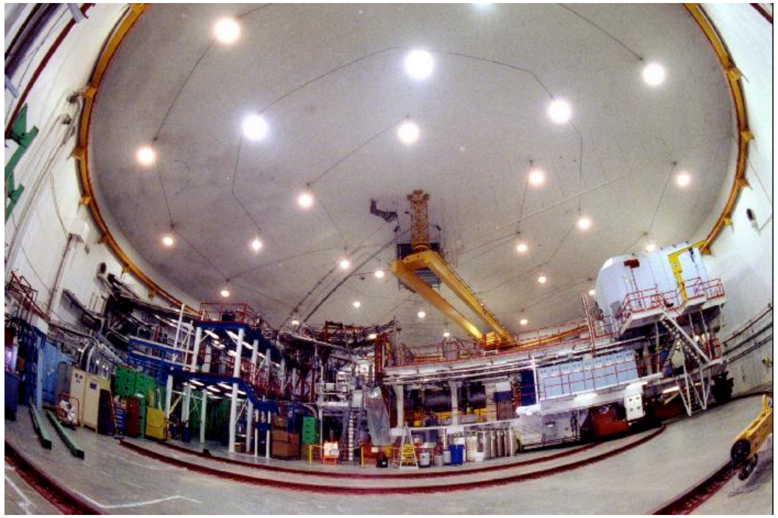
Experimental Halls

Hall A

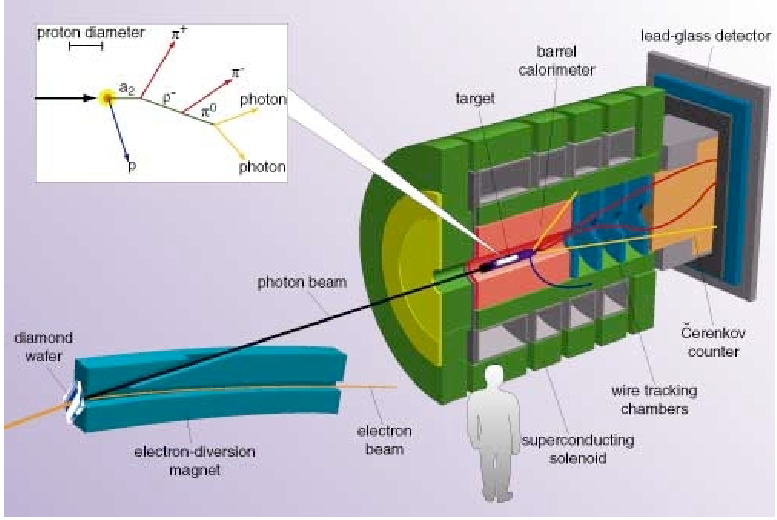


Hall B

Hall C

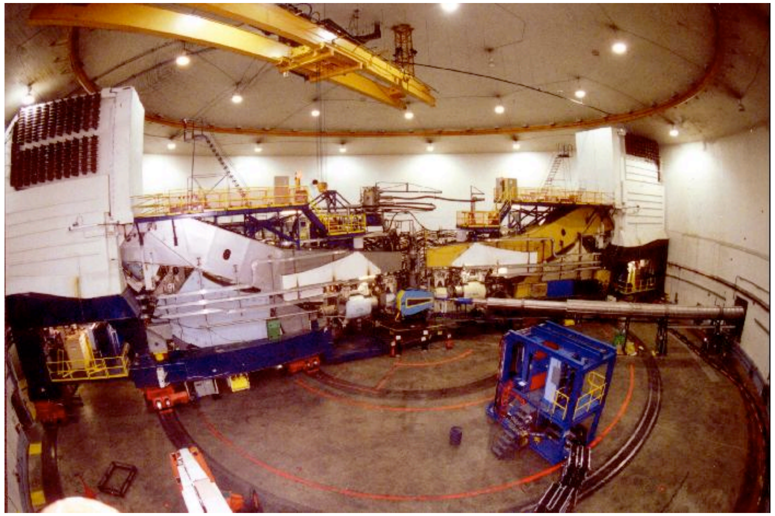


Hall D

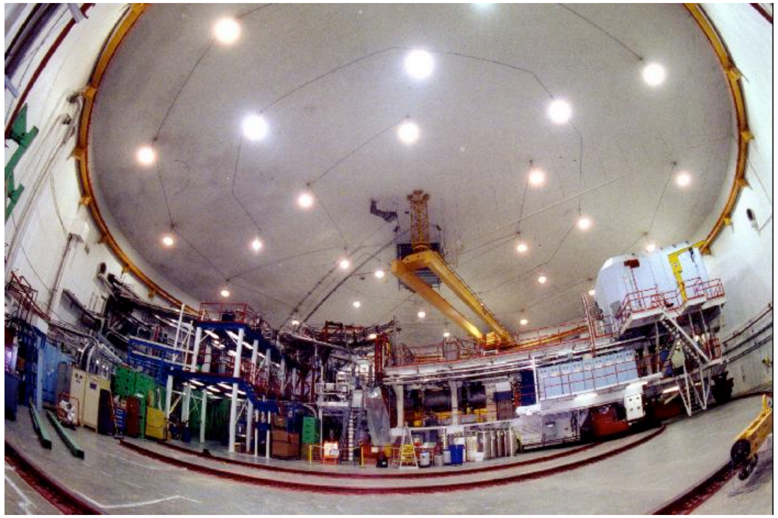


Experimental Halls

Hall A



Hall C



high luminosity

$> 10^{38}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$

very high precision measurements

high Q^2 form factors,
parity-violating e scattering,
precision structure functions,
...

Experimental Halls

Hall B

CLAS

(CEBAF Large Acceptance Spectrometer)

large acceptance

lower luminosity

$\sim 10^{35}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$

collect all data “at once”

N^* spectroscopy

(multi-hadron final states),

structure function moments,

...

Experimental Halls

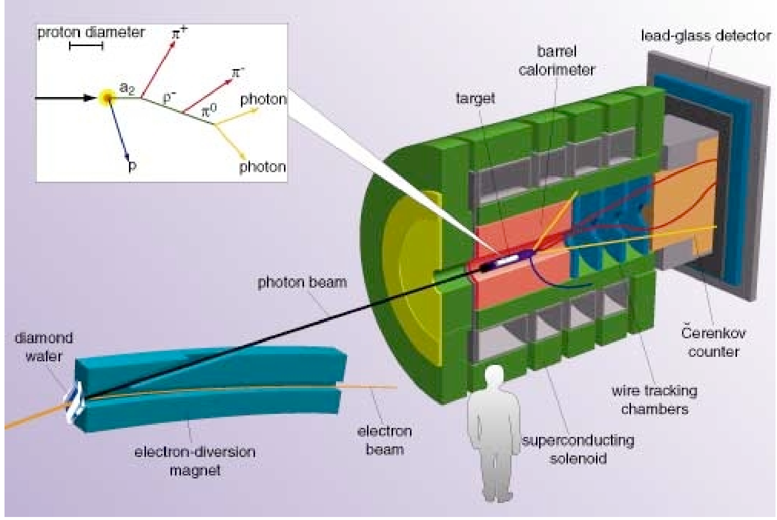
proposed new Hall
as part of 12 GeV upgrade

4π acceptance

photon beam

exotic meson spectroscopy
(GlueX Collaboration)
“origins of confinement”

Hall D



Baryon Spectroscopy

→ Hall B (CLAS Collaboration)

Search for Pentaquarks at CLAS

A comprehensive program to search for pentaquarks with high statistics and high resolution photoproduction experiments is in progress at Jefferson Lab

New experiments seeking evidence of pentaquarks with the CLAS detector were approved in 2003-2004 with the goal of confirming previous results and explore new kinematics with at least a factor 10 increase in statistics

g10	deuteron data taking completed in 2004	E_γ ~ 1.0–3.5 GeV	$\gamma d \rightarrow K^+ n K^- p$
g11	proton data taking completed in 2004	E_γ ~ 1.6–3.8 GeV	$\gamma p \rightarrow K^+ n K^0$
eg3	deuteron data taking completed in 2005	E_γ ~ 4.0–5.4 GeV	
Super-g	proton planned for 2006	E_γ ~ 3.8 - 5.7 GeV	

Comparison with SAPHIR results

R. DeVita (2005)

Observed Yields

SAPHIR

$N(\Theta^+)/N(\Lambda^*) \sim 9\%$

CLAS

$N(\Theta^+)/N(\Lambda^*) < 0.5\%$ (95%CL)

Cross Sections

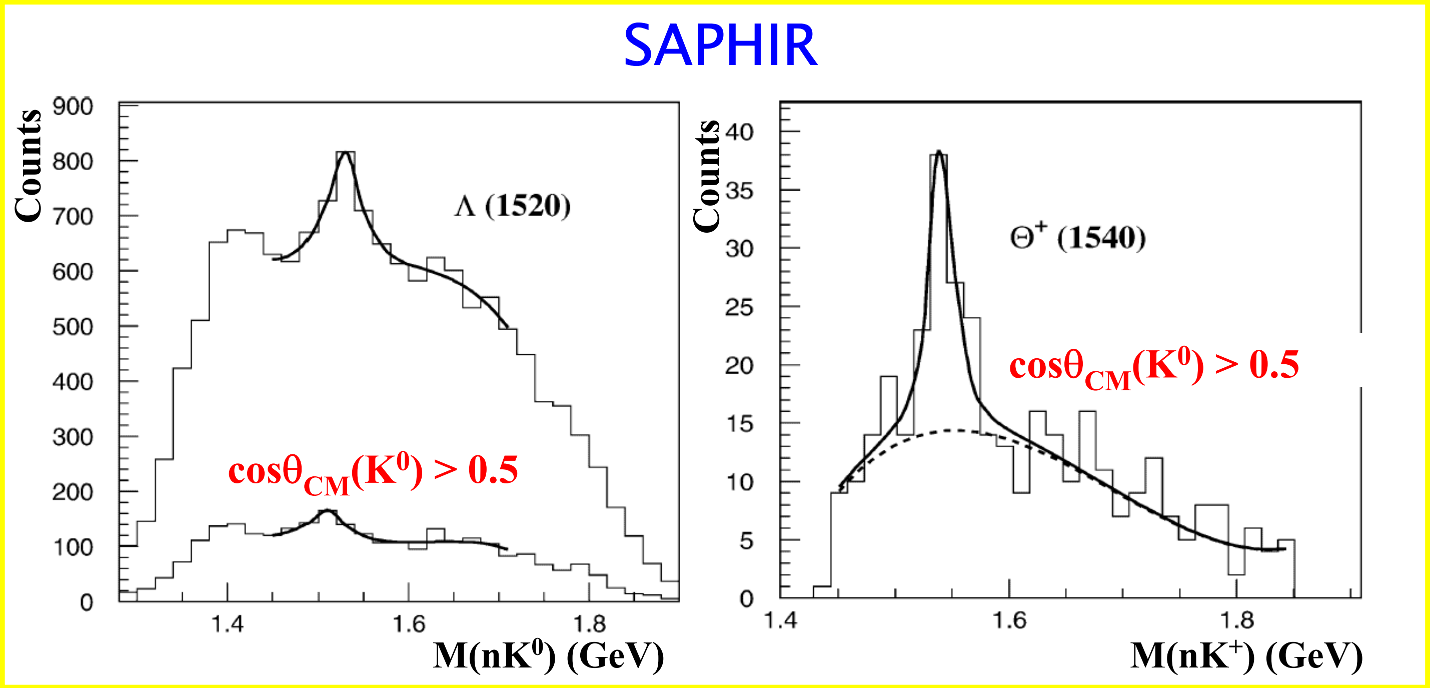
SAPHIR

$\sigma_{\gamma p \to \Theta^+ K^0} \sim 300$ nb

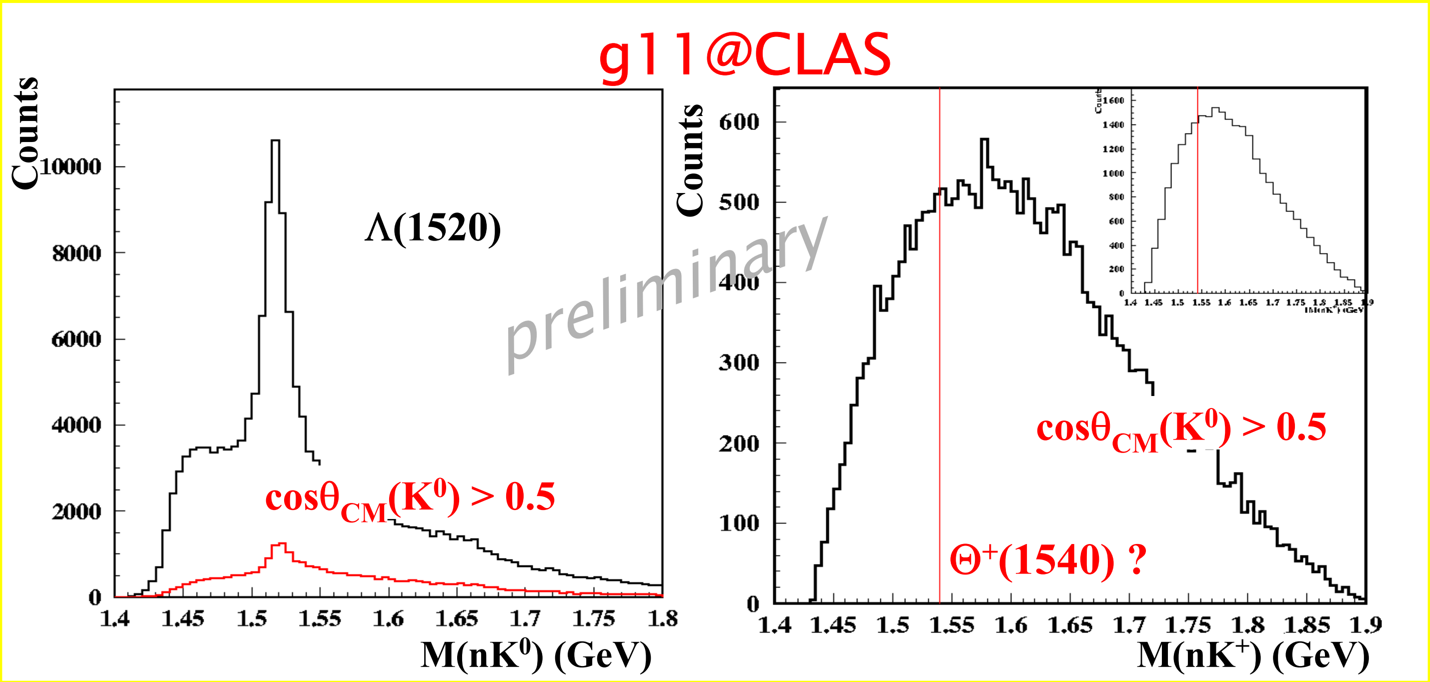
reanalysis 50 nb

CLAS

$\sigma_{\gamma p \to \Theta^+ K^0} < 1$- 4 nb



SAPHIR

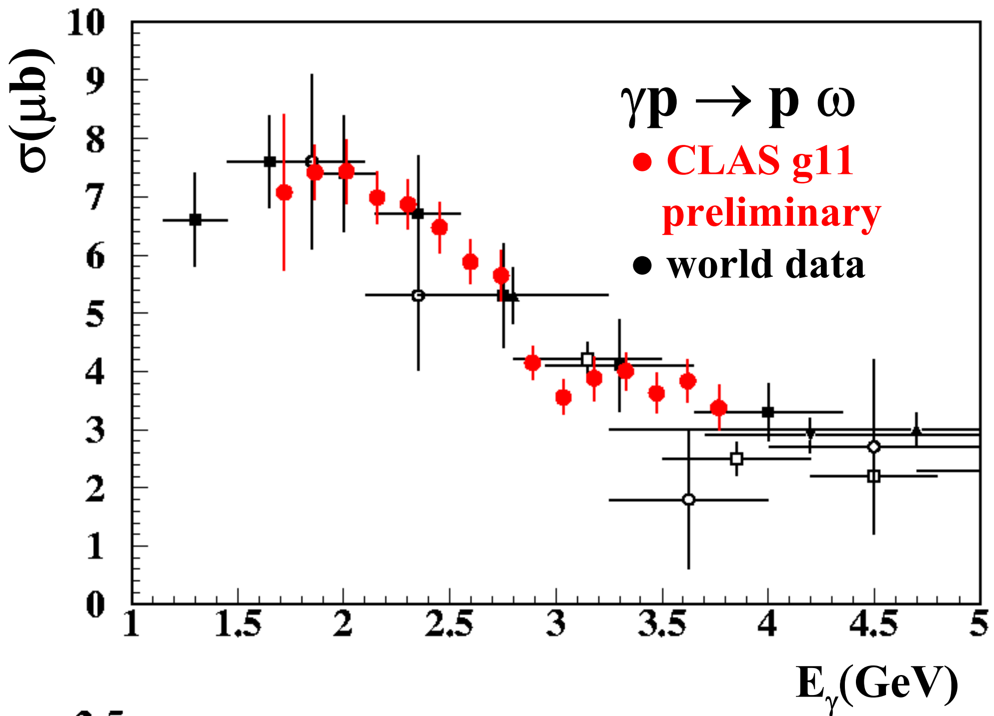


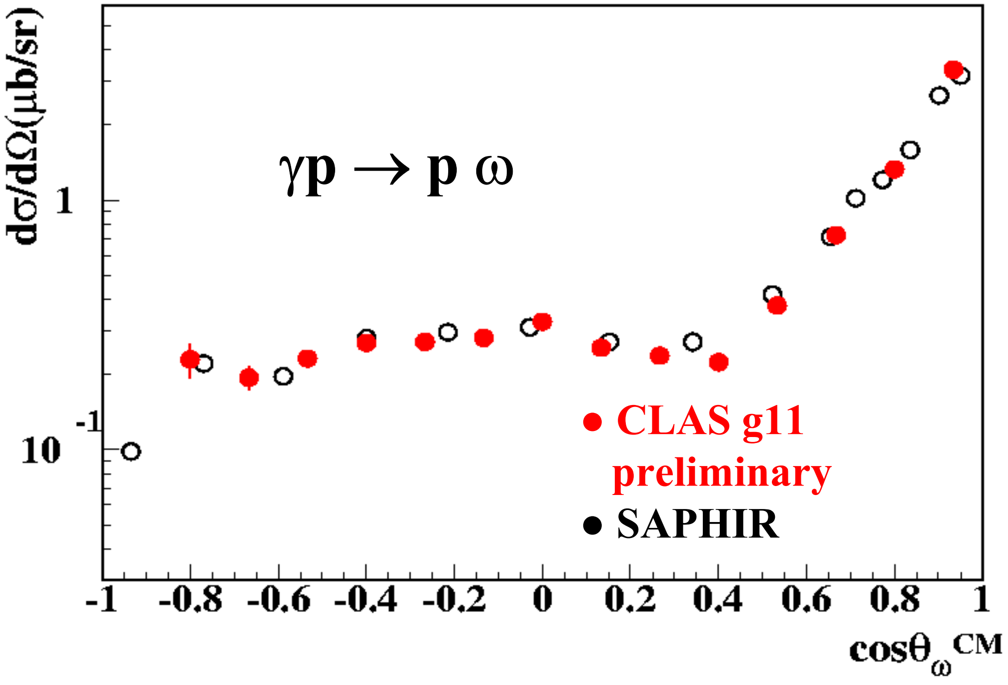
g11@CLAS

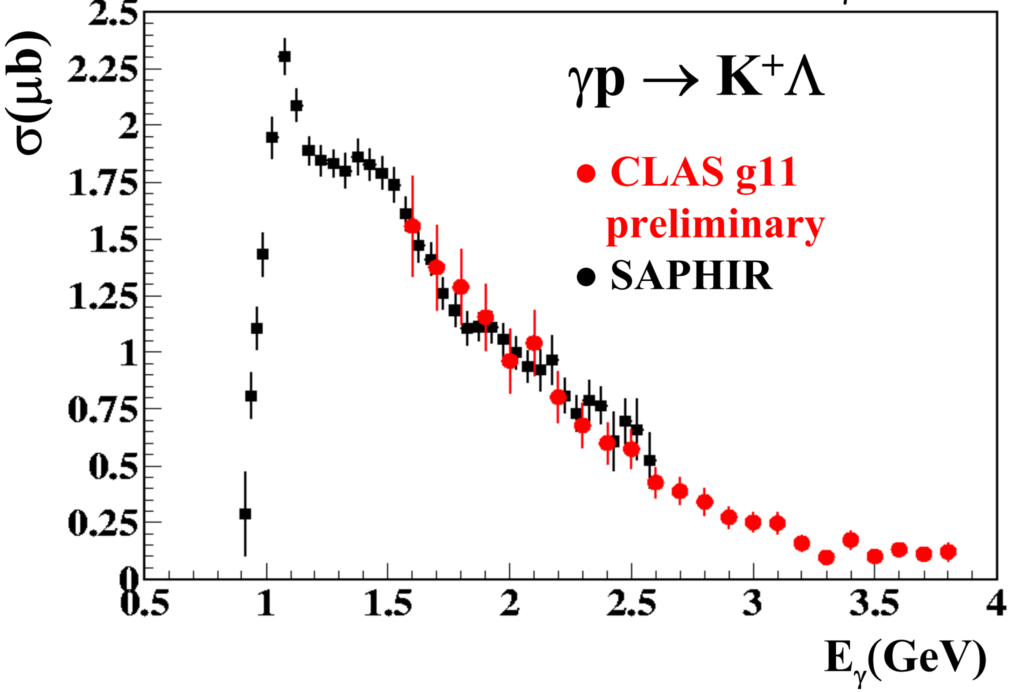
Cross Section Extraction

R. DeVita (2005)

- Different final states are measured simultaneously in the CLAS detector
- Cross section for known reactions have been extracted to test the accuracy of the analysis procedure
- 1% of statistics







Conventional N^* Spectroscopy

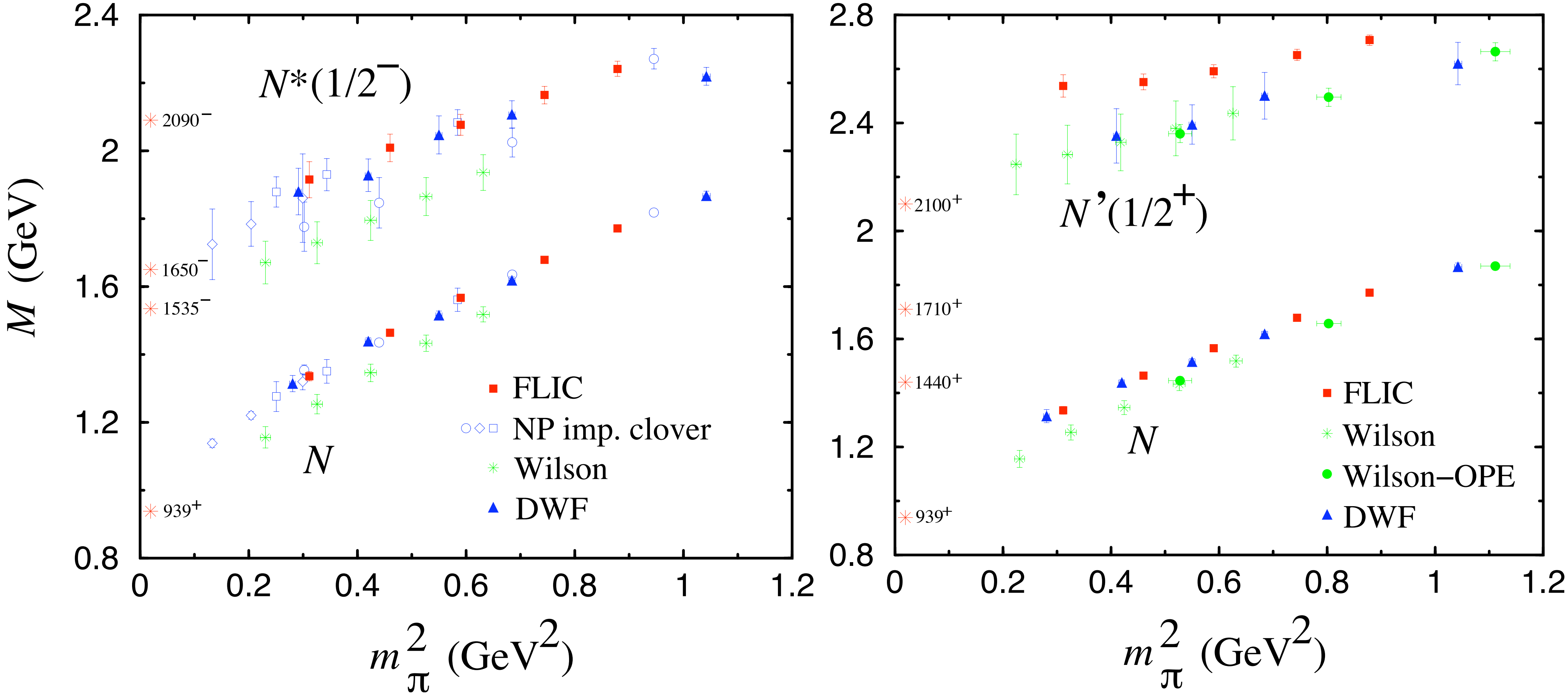
- Why are lowest positive parity (Roper) excitations ($N^{1/2+}(1440)$, $\Delta^{3/2+}(1600)$, $\Sigma^{1/2+}(1690)$) lighter than lowest negative parity states?
  $\longrightarrow$ "breathing modes"?

- What is the nature of $\Lambda^{1/2-}(1405)$?
  $\longrightarrow$ $\Sigma\pi$ channel coupling?

- Are mass splittings & level orderings governed by *colour-magnetic* or *spin-flavor* (Goldstone boson exchange) interaction?

- Where are "missing" CQM resonances?
  $\longrightarrow$ is a quark–diquark picture (fewer degrees of freedom) more relevant?

*N** on the Lattice

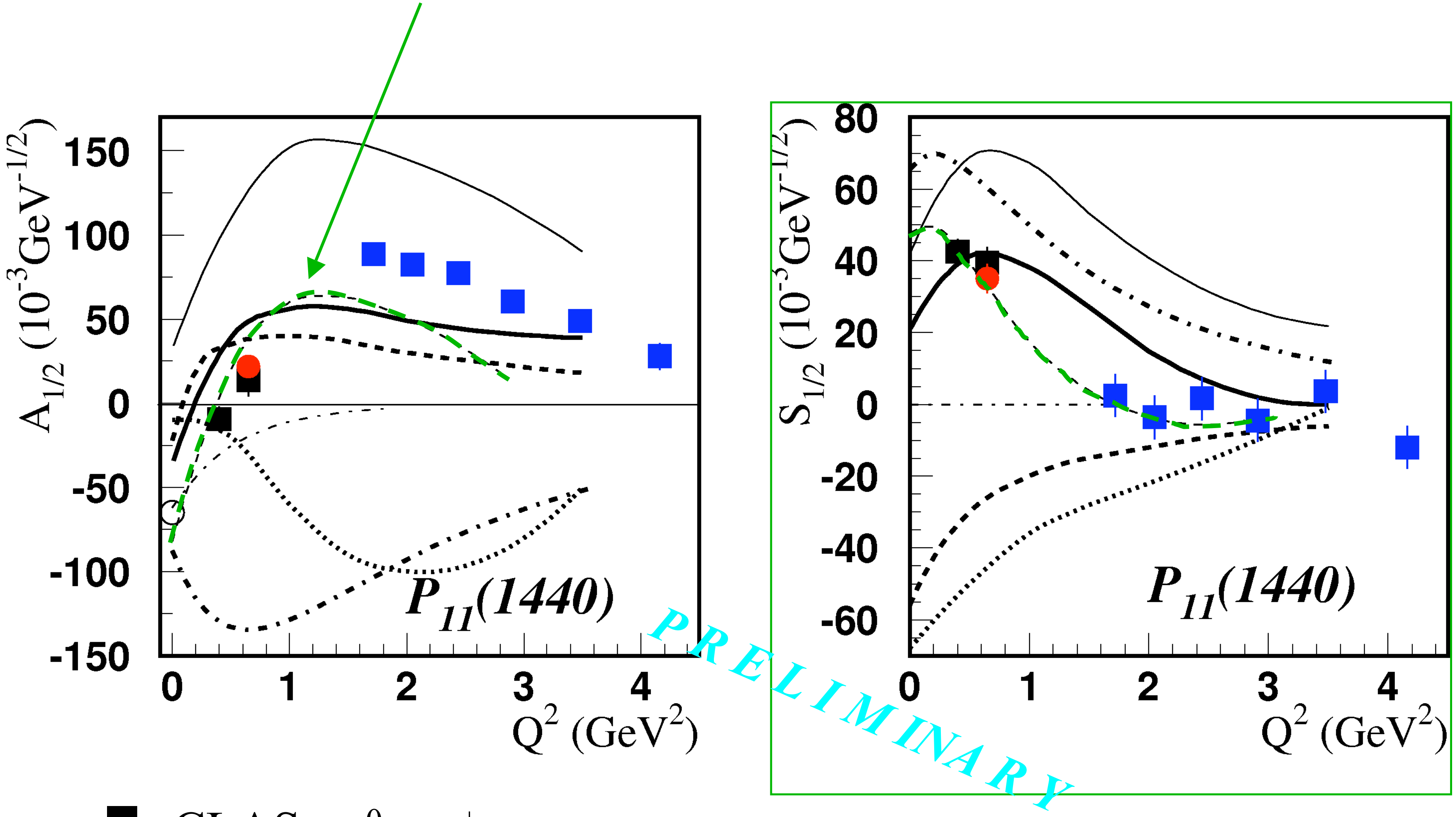


WM et al. (CSSM Lattice Collaboration)
Phys. Rev. D67 (2003) 114506

Leinweber et al., nucl-th/0406032

CLAS – N* analysis of Roper excitation

Best description by model with meson cloud (low Q^2) and quark core (high Q^2)



■ CLAS $p\pi^0$, $n\pi^+$

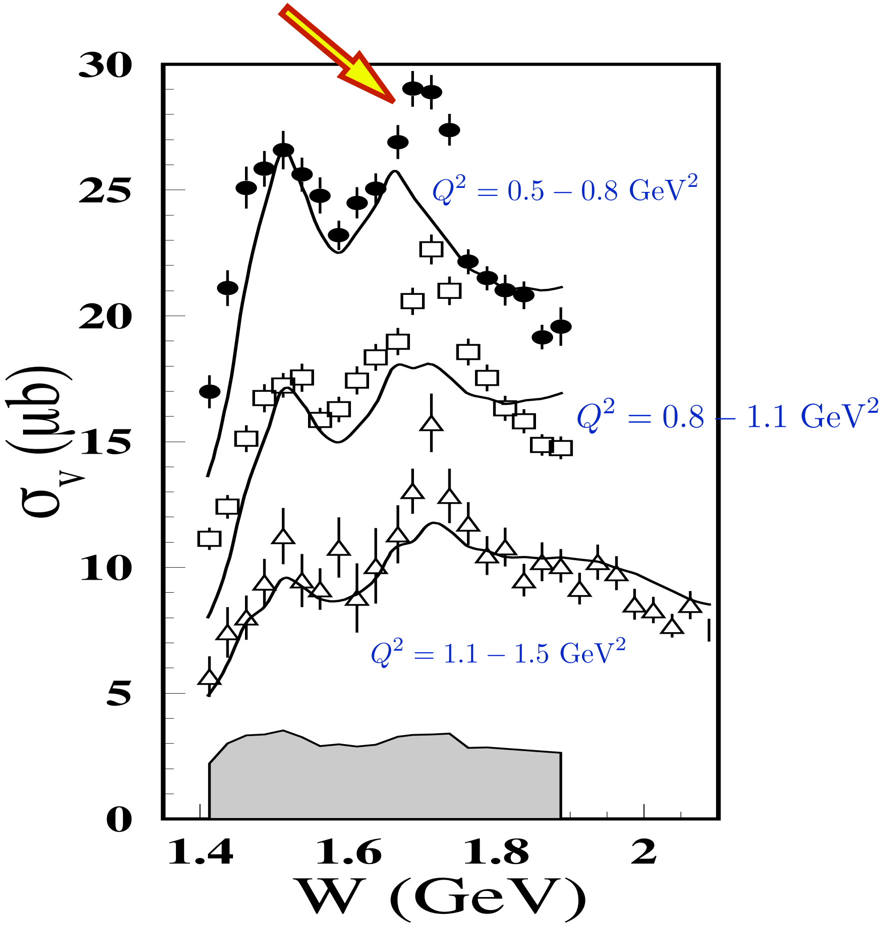
■ CLAS $n\pi^+$ (preliminary)

● CLAS $N\pi$, $p\pi^+\pi^-$

Conventional N^* Spectroscopy

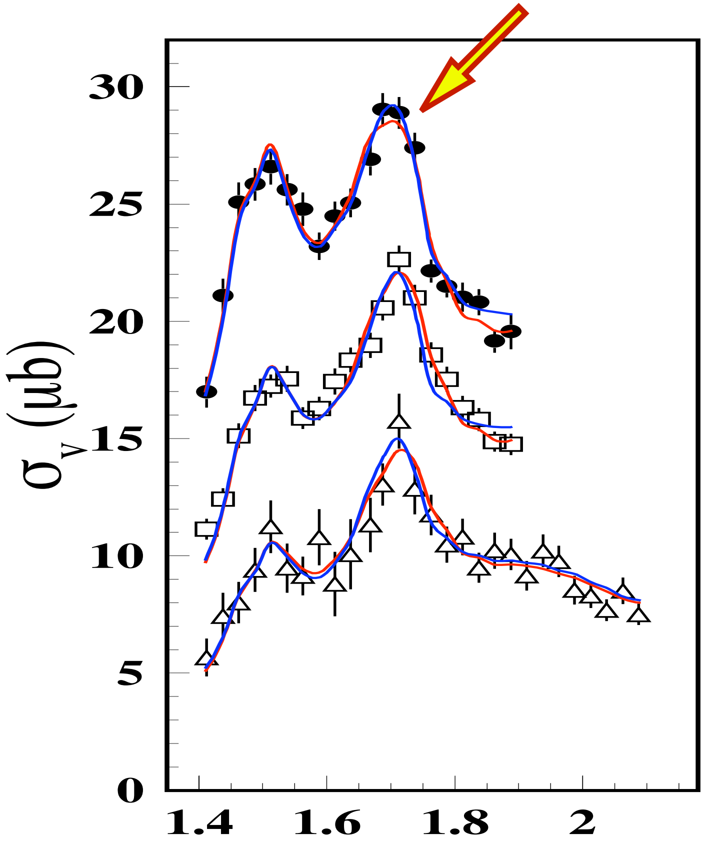
New state seen in $\gamma^* p \to p \pi^+ \pi^-$?

missing strength
with PDG input



Ripani et al, PRL91, 022002

including new state $P_{13}(1720)$
with $\Gamma = 114 \pm 19$ MeV



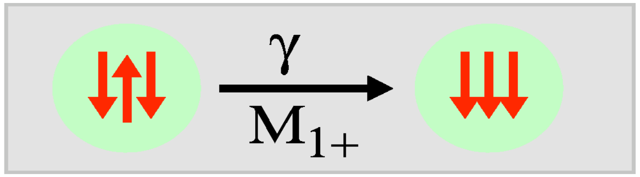
hybrid *qqqg* state predicted in FTM ?

Capstick, Page, PRC66, 065204

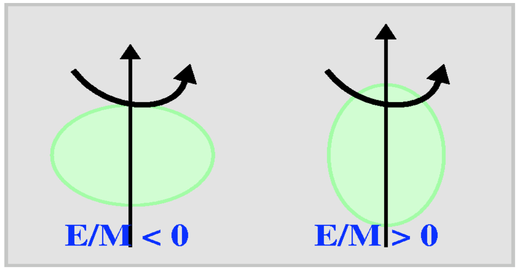
P_{13} pentaquark with $M \sim 1.77$ MeV ?

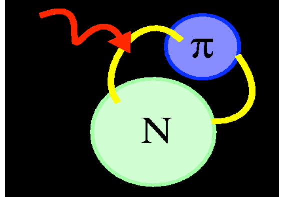
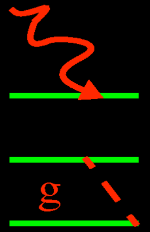
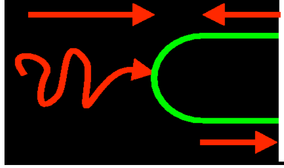
Walliser, Kopeliovich, JETP97, 433

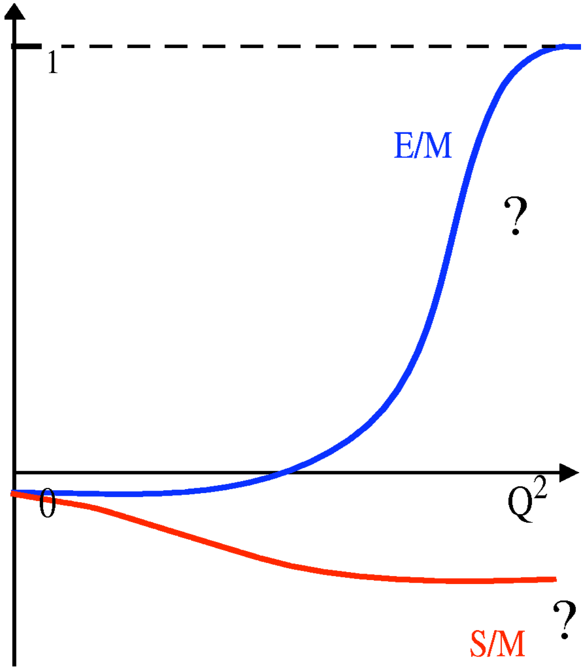
$N \to \Delta$ Transition Form Factor



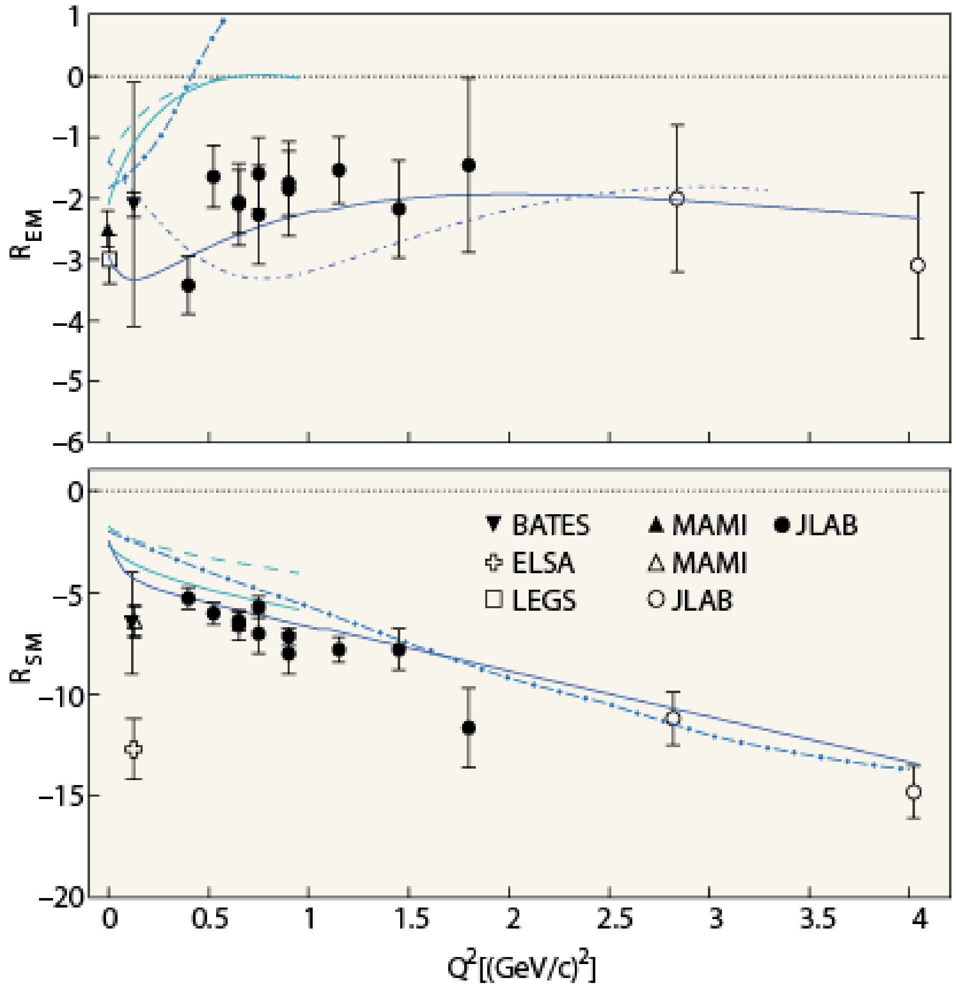
SU(6): $E_{1+}=S_{1+}=0$



		E/M	S/M
	pion cloud	~0.03	~0.1
	one-gluon exch.	< 0.01	
	pQCD	+1	const.



$N \rightarrow \Delta$ Transition Form Factor



Hall B & Hall C

- R_{EM} remains small and < 0 at high Q^2 with trend towards R_{EM} ~ 0, and possible sign change.

- R_{SM} continues to rise in magnitude with Q^2. No trend seen towards Q^2-independence.

- Pion cloud models describe data well (fitted to low and high Q^2 points).

Electromagnetic Form Factors

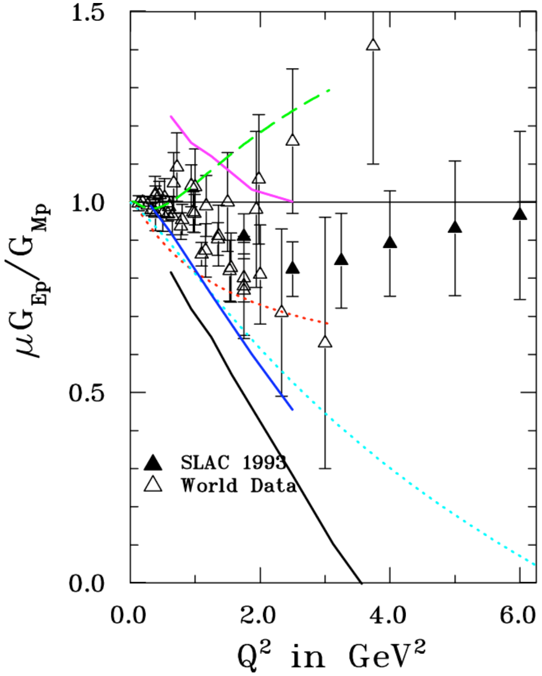
→ Halls A and C

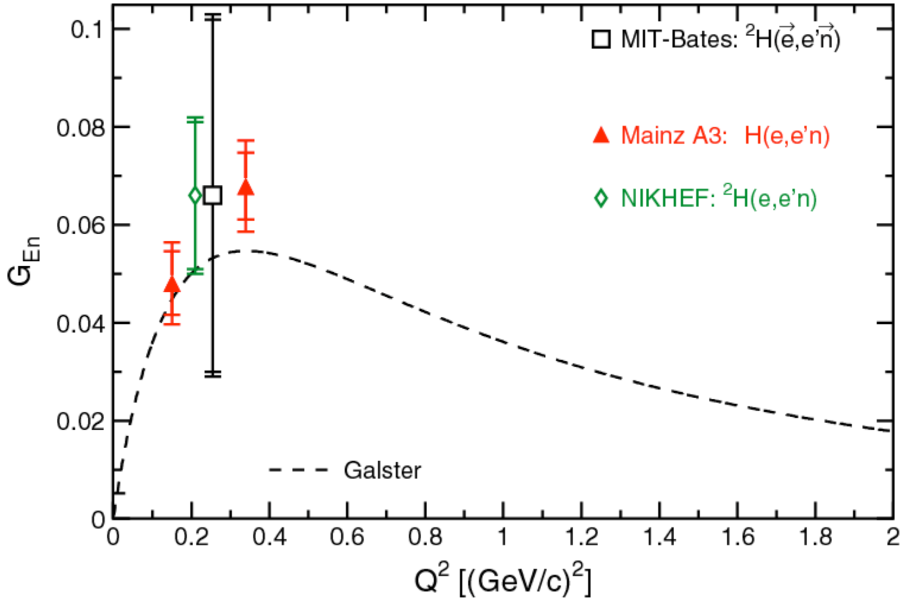
Before JLab

proton

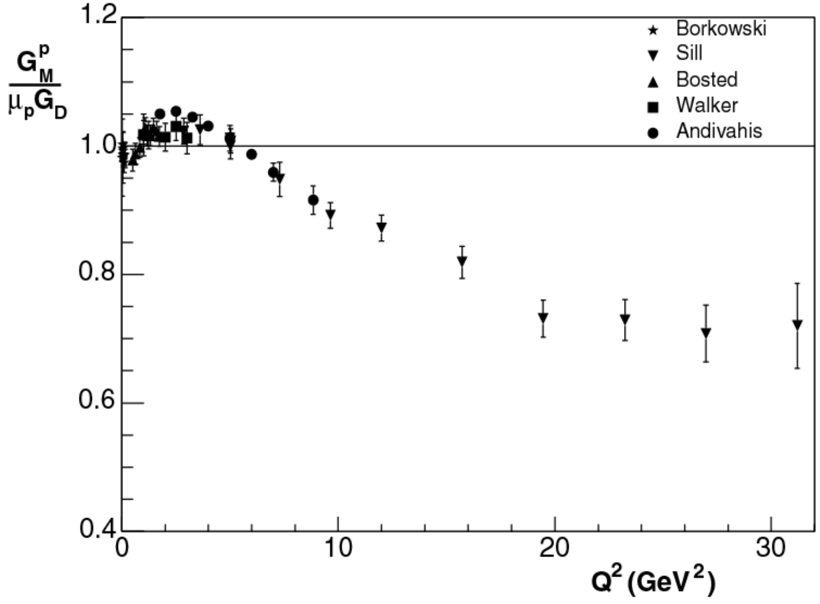
neutron

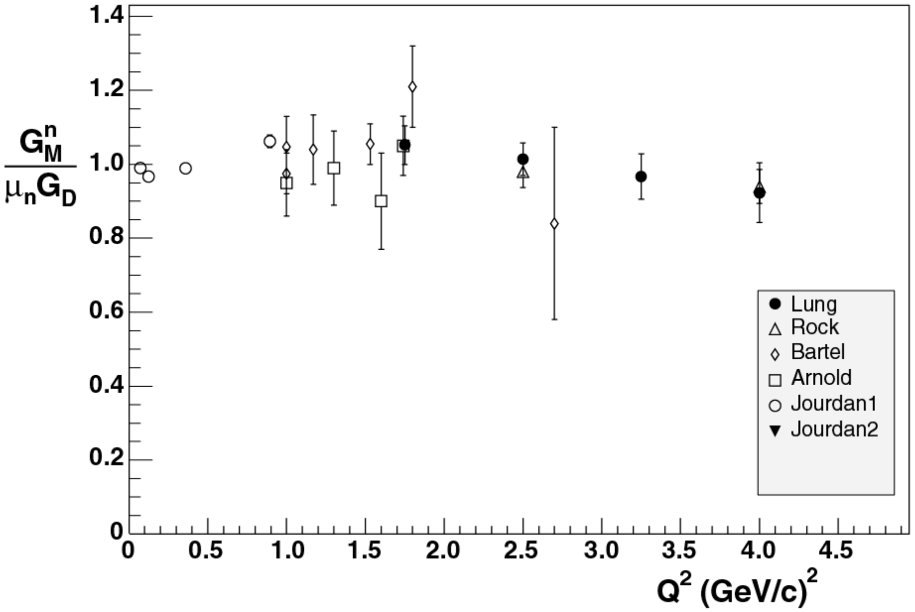
Electric





Magnetic



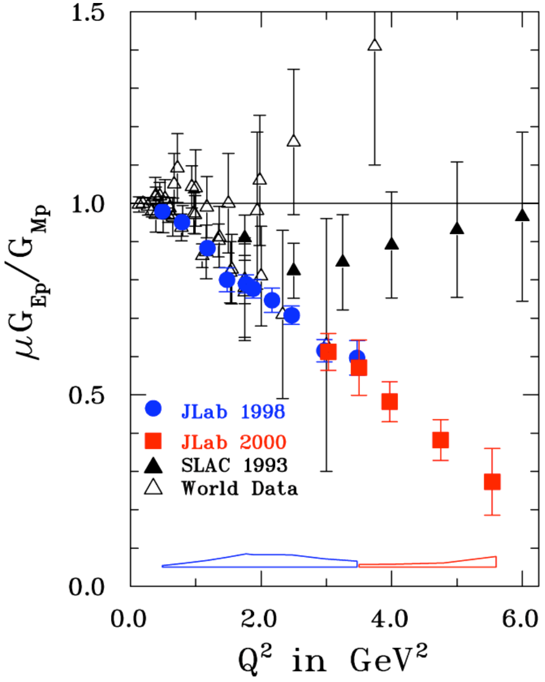


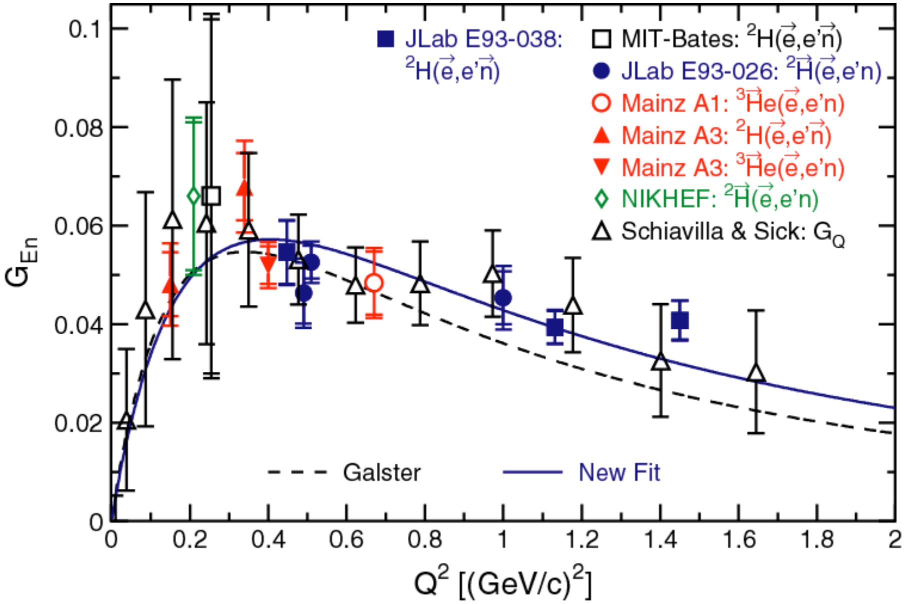
Today

proton

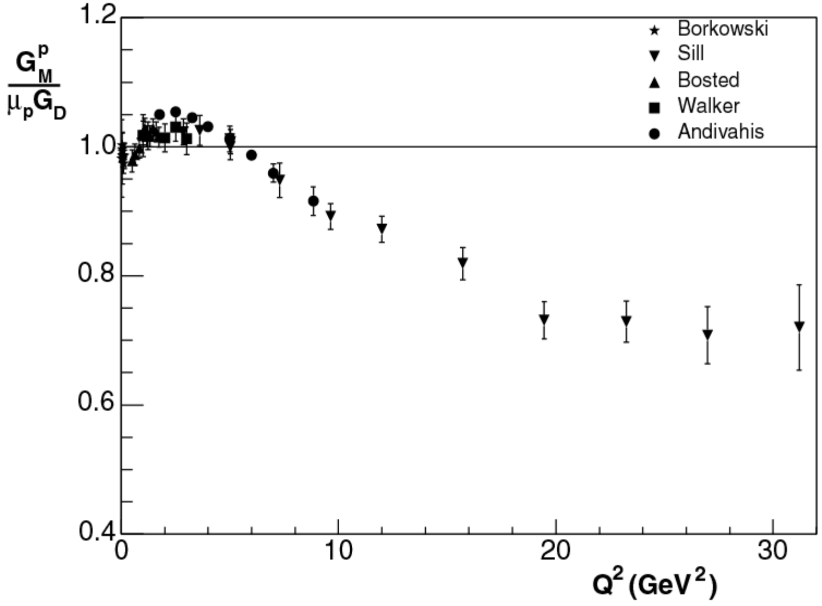
neutron

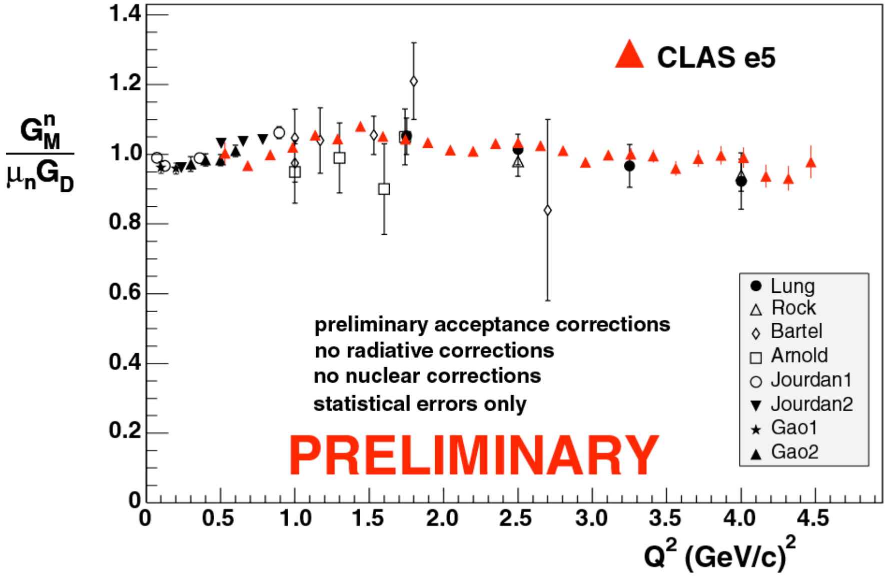
Electric



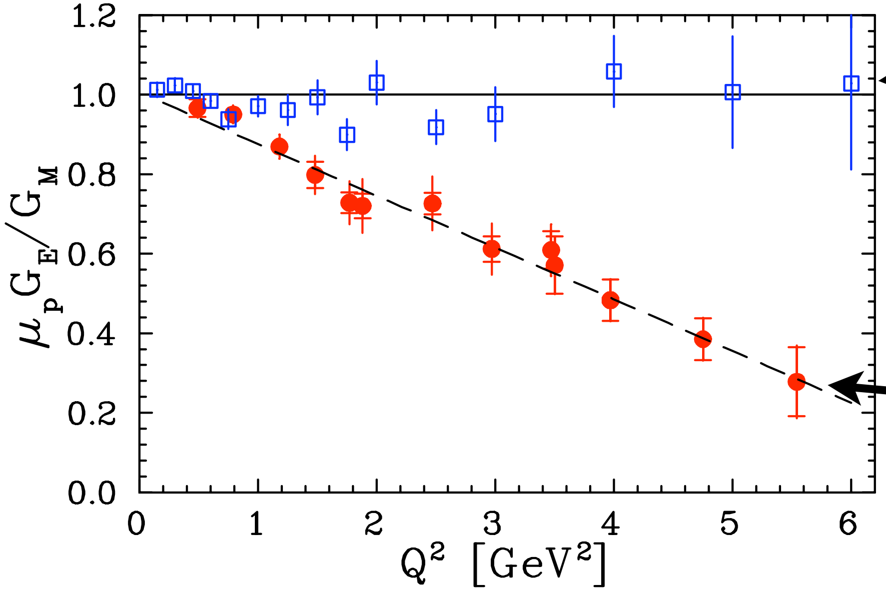


Magnetic





Proton G_E/G_M Ratio



Rosenbluth (Longitudinal-Transverse) Separation

Polarization Transfer

LT

$$\sigma_R = G_M^2(Q^2) + \frac{\varepsilon}{\tau} G_E^2(Q^2)$$

$$\tau = Q^2/4M^2$$
$$\varepsilon = \left[1 + 2(1+\tau)\tan^2\theta/2\right]^{-1}$$

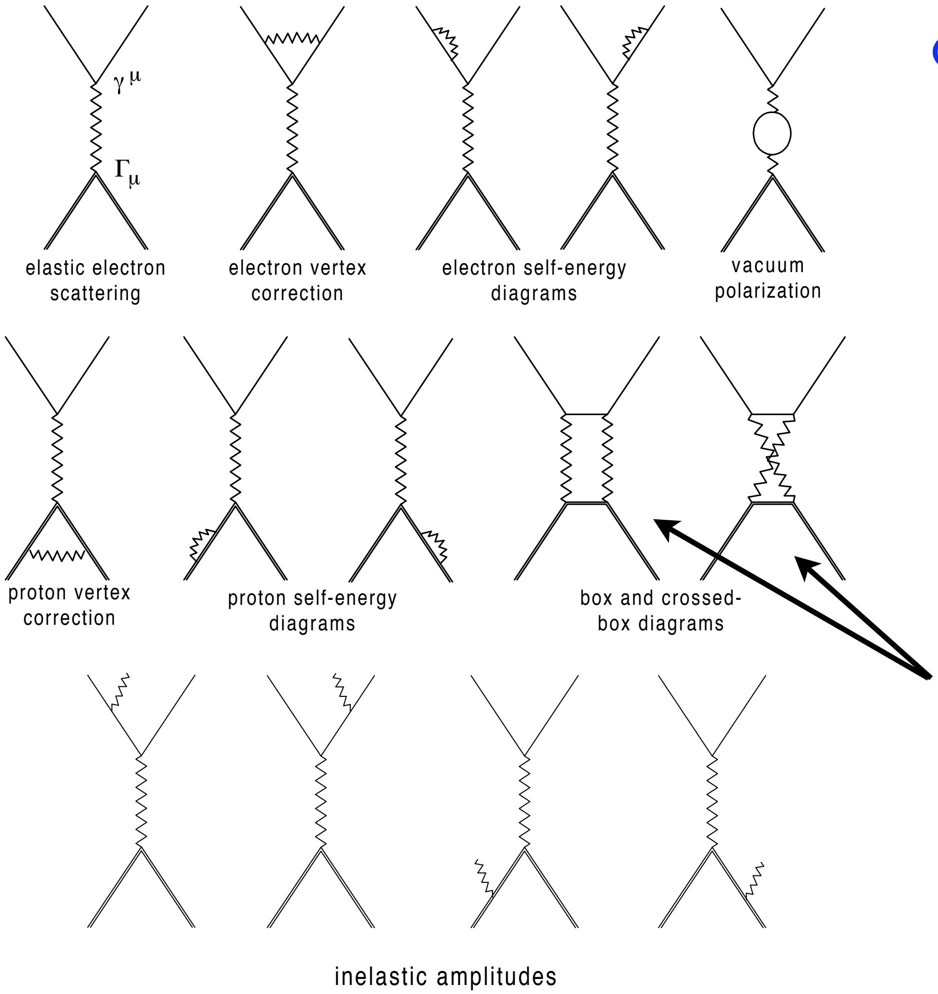
G_E/G_M from slope in ε plot

PT

$$\frac{G_E}{G_M} = -\sqrt{\frac{\tau(1+\varepsilon)}{2\varepsilon}}\,\frac{P_T}{P_L}$$

$P_{T,L}$ polarization of recoil proton

QED Radiative Corrections



Cross section modified by 1γ-loop effects

$$d\sigma = d\sigma_0 \; (1 + \delta)$$

δ contains additional ε dependence

mostly from box (and crossed box) diagram

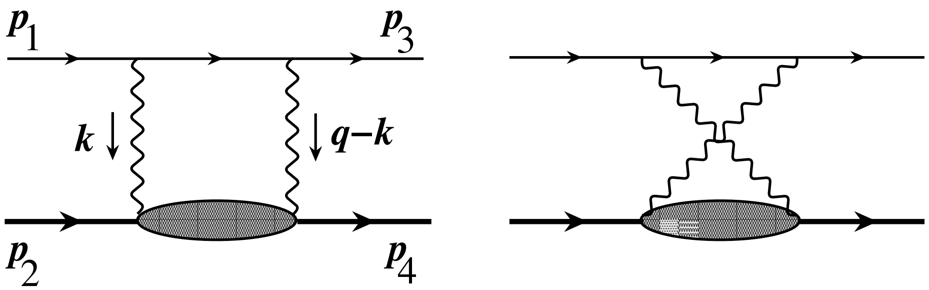
$\longrightarrow$ can modify ε dependence in $d\sigma_0$

Guichon, Vanderhaeghen, Phys. Rev. Lett. 91 (2003) 142303

Blunden, WM, Tjon, Phys. Rev. Lett. 91 (2003) 142304

Chen, Afanasev, Brodsky, Carlson, Vanderhaeghen, Phys. Rev. Lett. 93 (2004) 122301

Box diagram



$$\mathcal{M}_{\gamma\gamma} \;=\; e^4 \int \frac{d^4k}{(2\pi)^4} \frac{N(k)}{D(k)}$$

where

$$\begin{aligned} N(k) \;&=\; \bar{u}(p_3)\ \gamma_\mu(\not{p}_1 - \not{k} + m_e)\gamma_\nu\ u(p_1) \\ &\quad \times\ \bar{u}(p_4)\ \Gamma^\mu(q-k)\ (\not{p}_2 + \not{k} + M)\ \Gamma^\nu(k)\ u(p_2) \end{aligned}$$

and

$$\begin{aligned} D(k) \;&=\; (k^2 - \lambda^2)\ ((k-q)^2 - \lambda^2) \\ &\quad \times\ ((p_1 - k)^2 - m^2)\ ((p_2 + k)^2 - M^2) \end{aligned}$$

with λ an IR regulator, and e.m. current is

$$\Gamma^\mu(q) \;=\; \gamma^\mu\ F_1(q^2) + \frac{i\sigma^{\mu\nu}q_\nu}{2M}\ F_2(q^2)$$

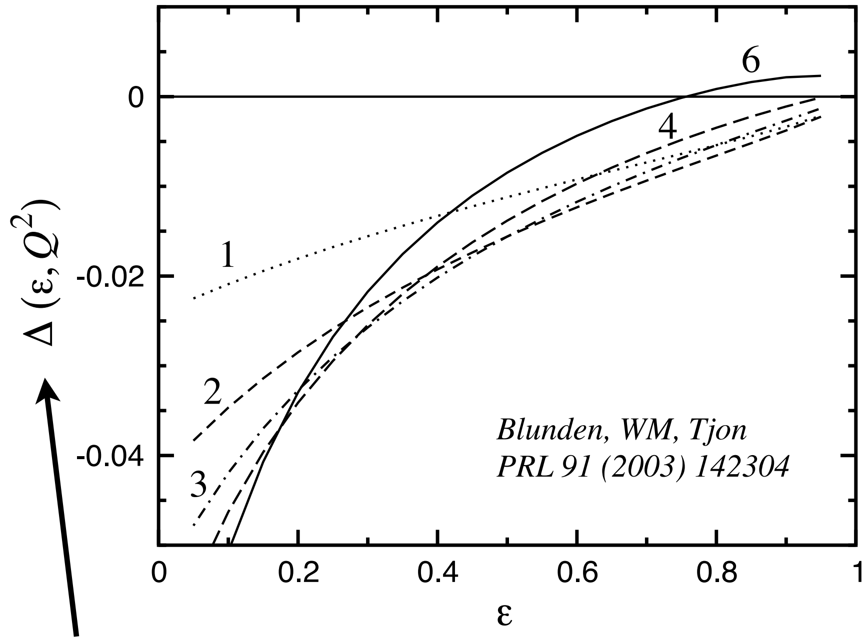
Various approximations to $\mathcal{M}_{\gamma\gamma}$ used

- Mo-Tsai: soft γ approximation
  - $\longrightarrow$ integrand most singular when $k = 0$ and $k = q$
  - $\longrightarrow$ replace γ propagator which is not at pole by $1/q^2$
  - $\longrightarrow$ approximate numerator $N(k) \approx N(0)$
  - $\longrightarrow$ neglect all structure effects

- Maximon-Tjon: improved loop calculation
  - $\longrightarrow$ exact treatment of propagators
  - $\longrightarrow$ still evaluate $N(k)$ at $k = 0$
  - $\longrightarrow$ first study of form factor effects
  - $\longrightarrow$ additional ε dependence

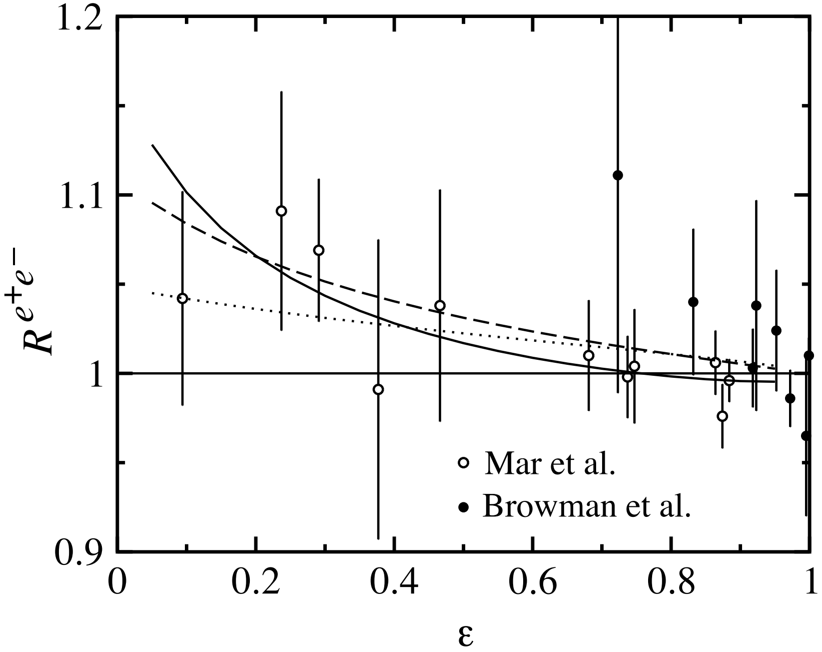
- Blunden-WM-Tjon: exact loop calculation
  - $\longrightarrow$ no approximation in $N(k)$ or $D(k)$
  - $\longrightarrow$ include form factors

Two-photon correction



Blunden, WM, Tjon
PRL 91 (2003) 142304

$\delta^{(2\gamma)}_{\rm full} - \delta^{(2\gamma)}_{\rm Mo-Tsai}$



$$R^{e^+e^-} = \frac{d\sigma^{e^+}}{d\sigma^{e^-}} \approx 1 - 2\Delta$$

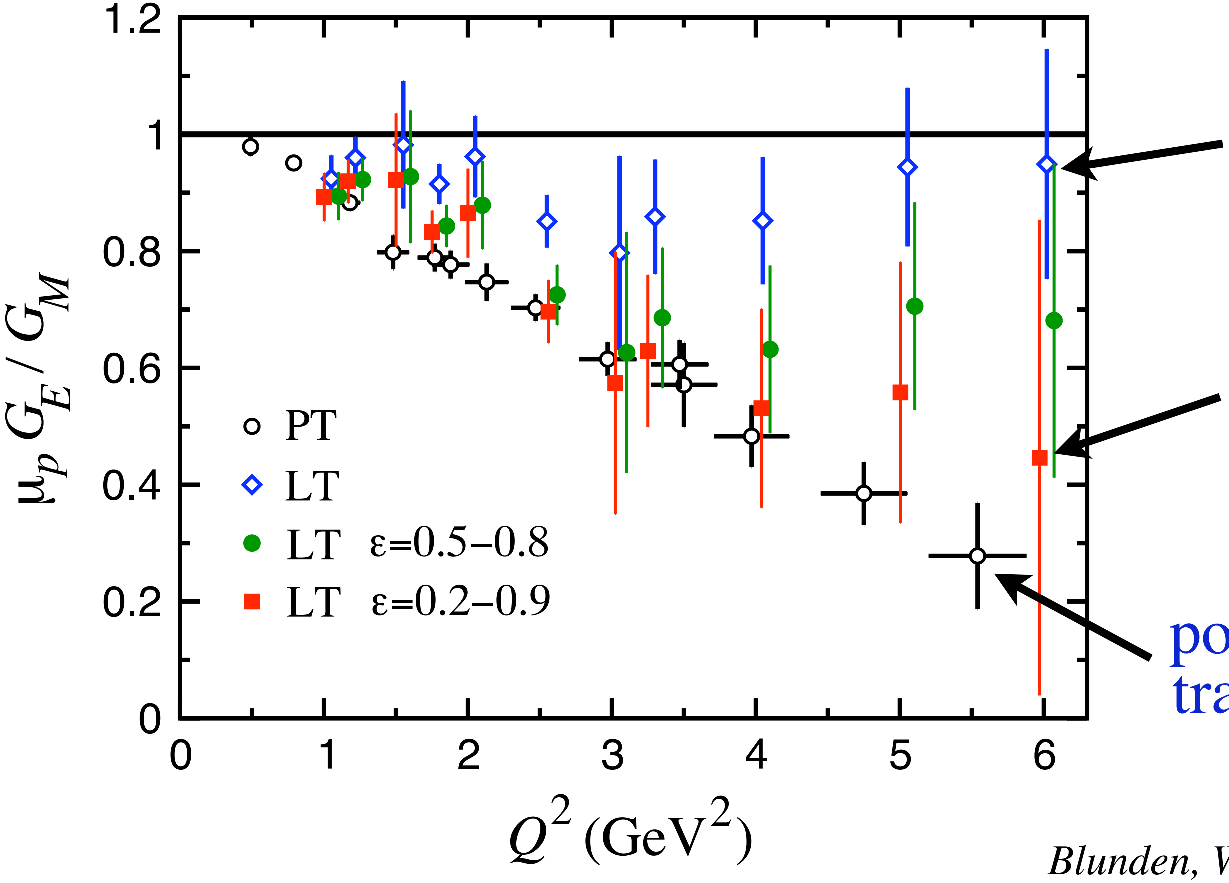
few % effect

non-linearity in ε

isolate 2γ effect in difference between e^+p and e^-p scattering

⇨ simultaneous e^-p/e^+p measurement planned in Hall B (to Q^2 ~ 1 GeV^2)

Two-photon exchange in elastic scattering



Rosenbluth separation

Rosenbluth corrected for 2γ exchange

polarization transfer

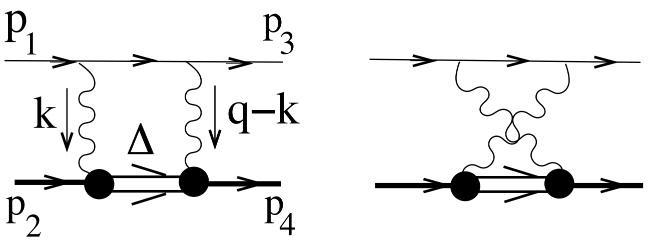
Blunden, WM, Tjon, nucl-th/0506039

⇨ *resolves much of the form factor discrepancy*

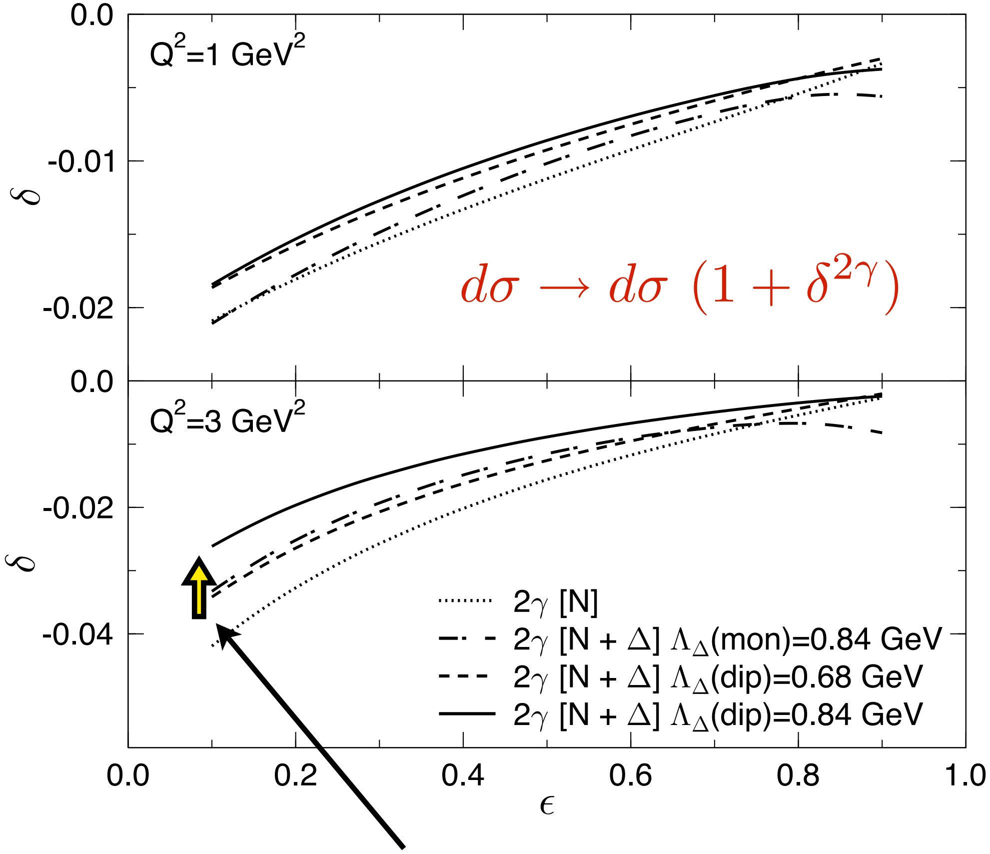
BUT nucleon elastic intermediate states only

⇨ what about higher mass states?

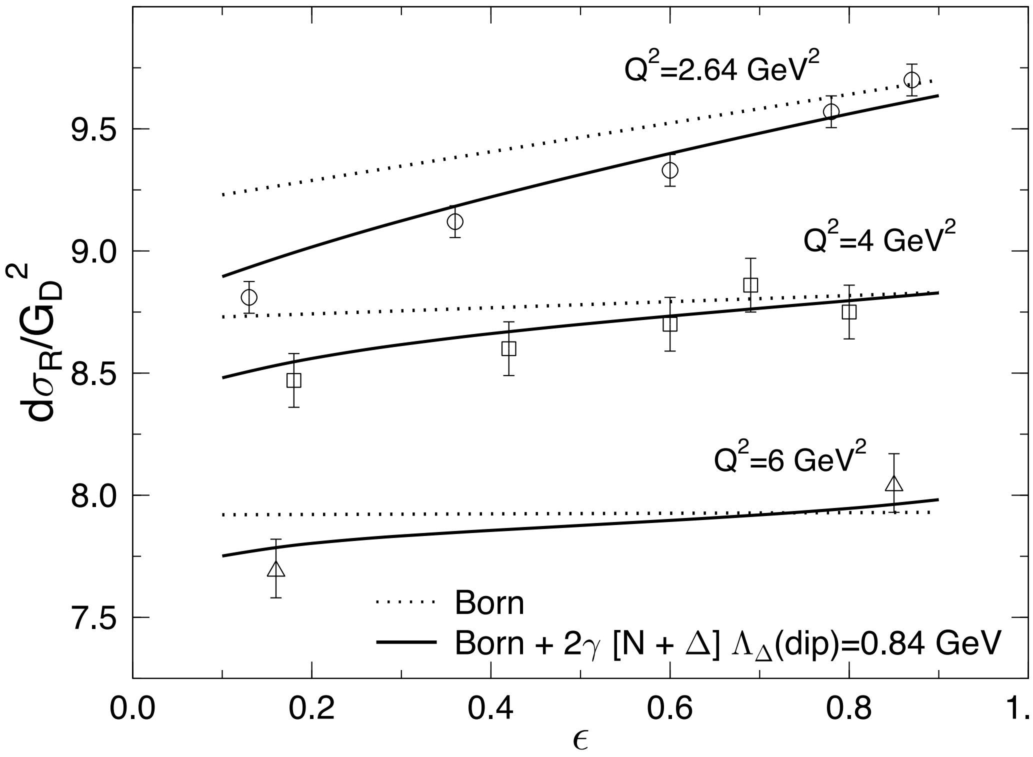
e.g. Δ intermediate states



Kondratyuk, Blunden, Melnitchouk, Tjon, nucl-th/0506026



$$d\sigma \rightarrow d\sigma\ (1 + \delta^{2\gamma})$$



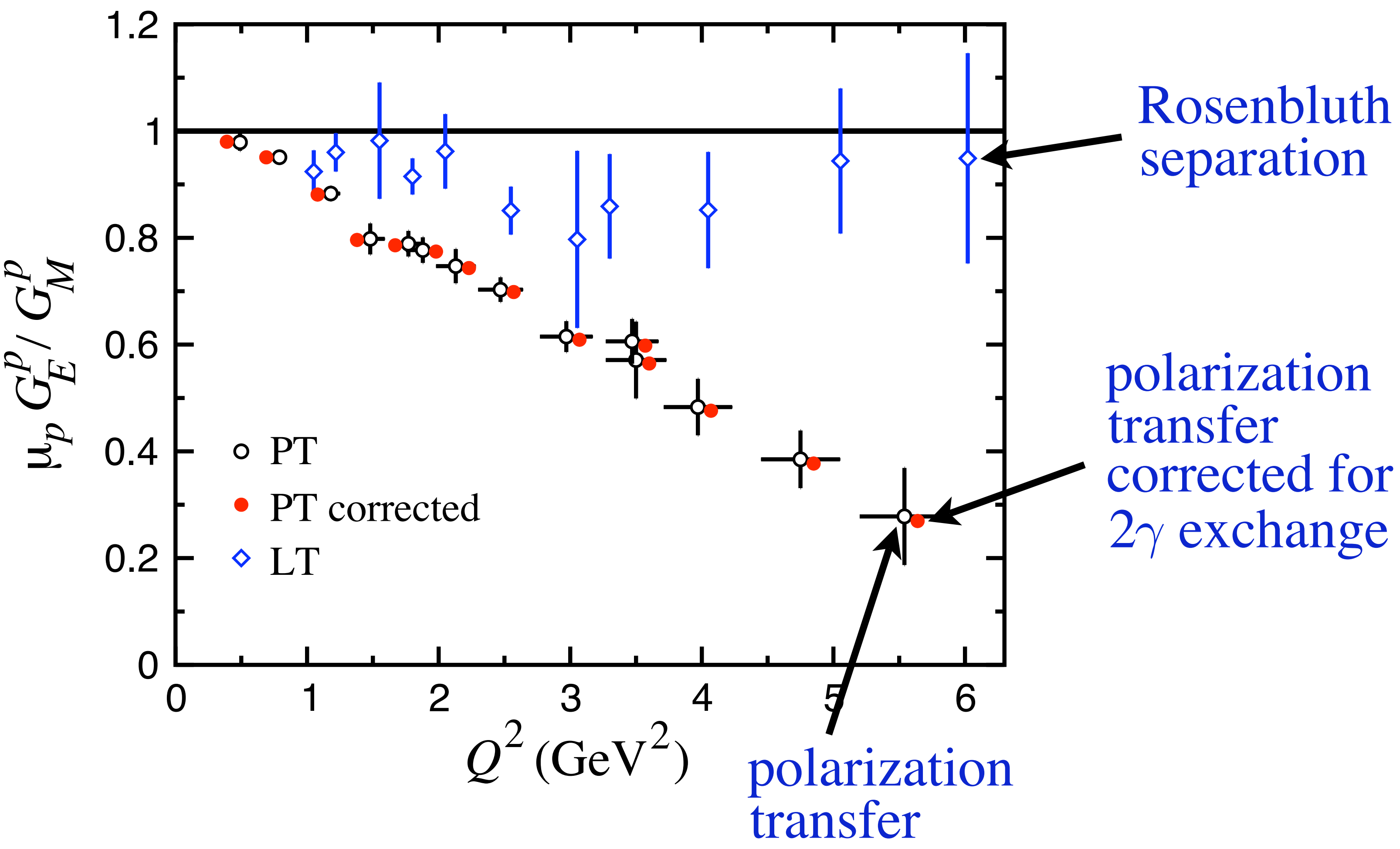
cancels some of the *N* contribution

good description of ϵ-dependence of JLab & SLAC data

⇒ room for higher-mass excitations ?

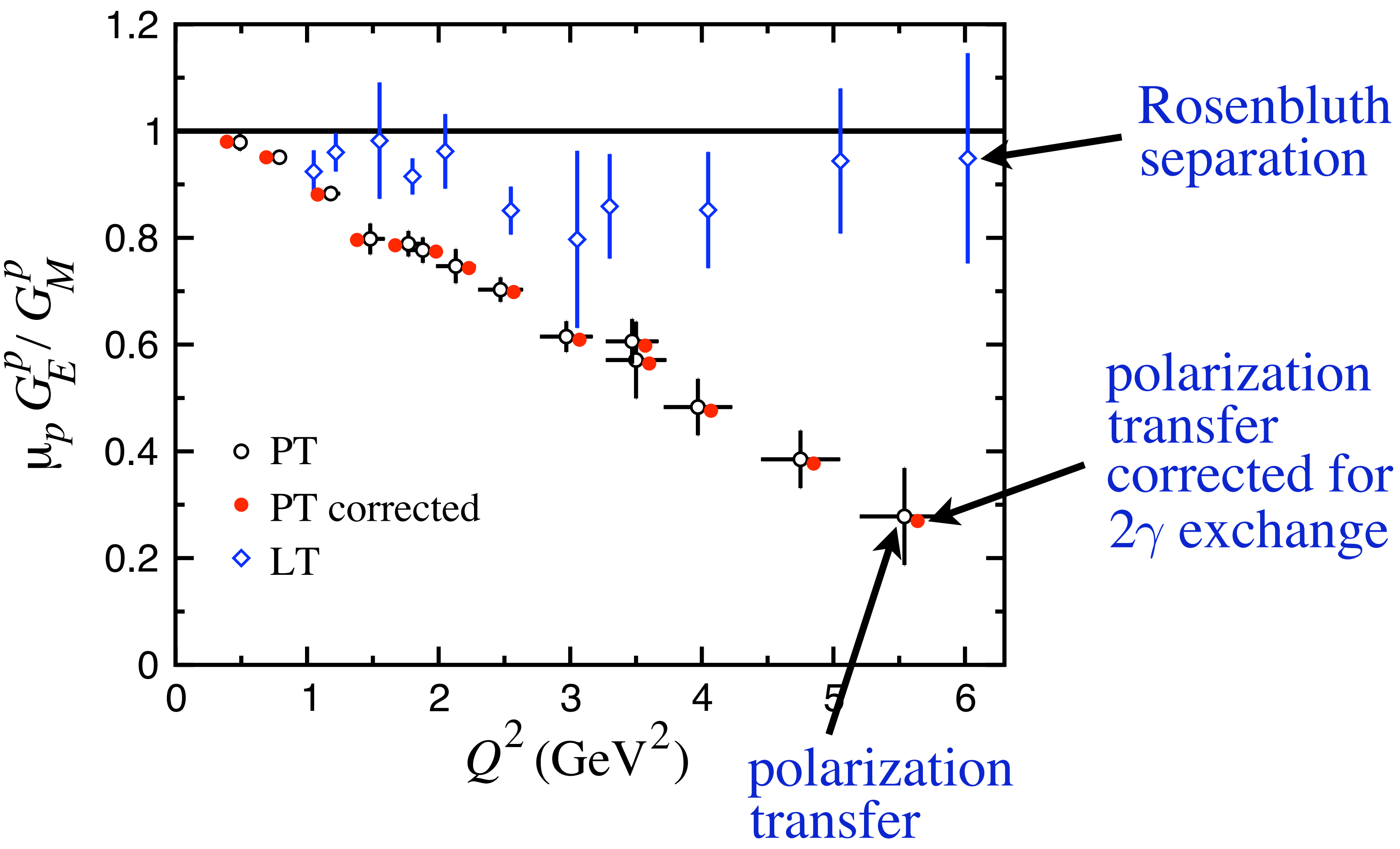
Chen et al, Phys. Rev. Lett. 93 (2004) 122301

Does 2γ exchange affect *polarization transfer* data ?



⇨ negligible effect

Does 2γ exchange affect *polarization transfer* data ?



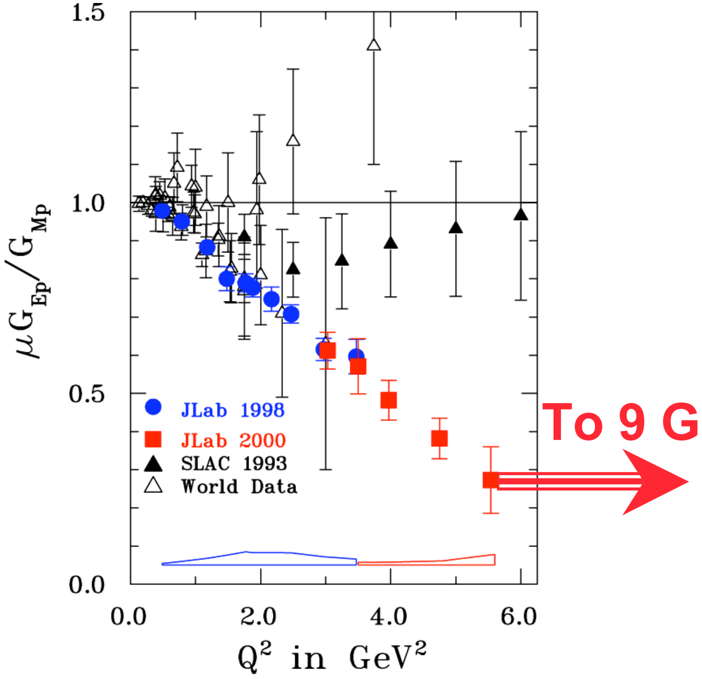
⇒ have reached a limit to usefulness of Rosenbluth technique for measuring G_E/G_M

Next 5 years

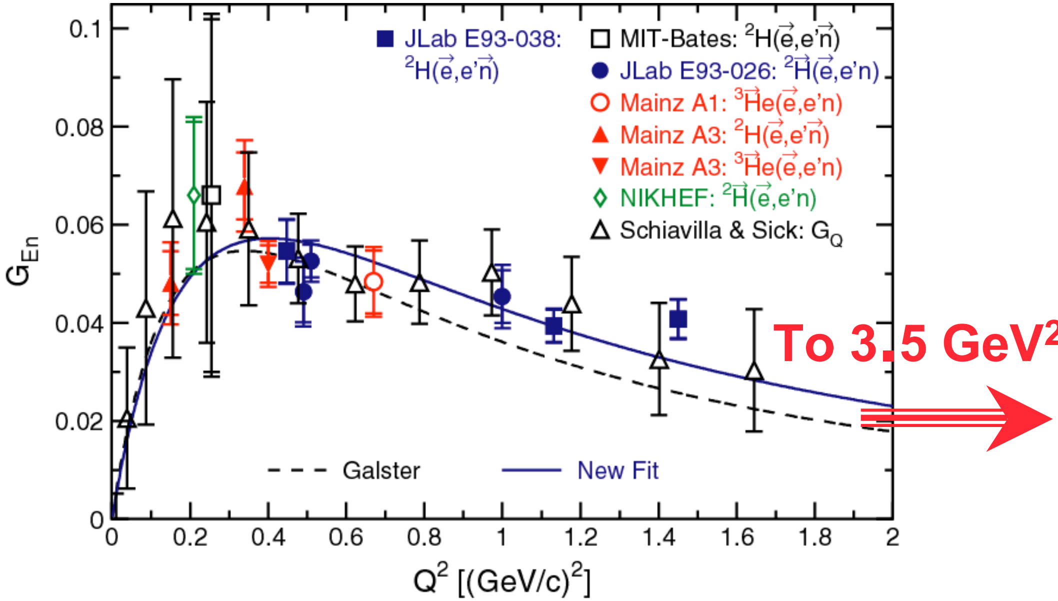
proton

neutron

Electric

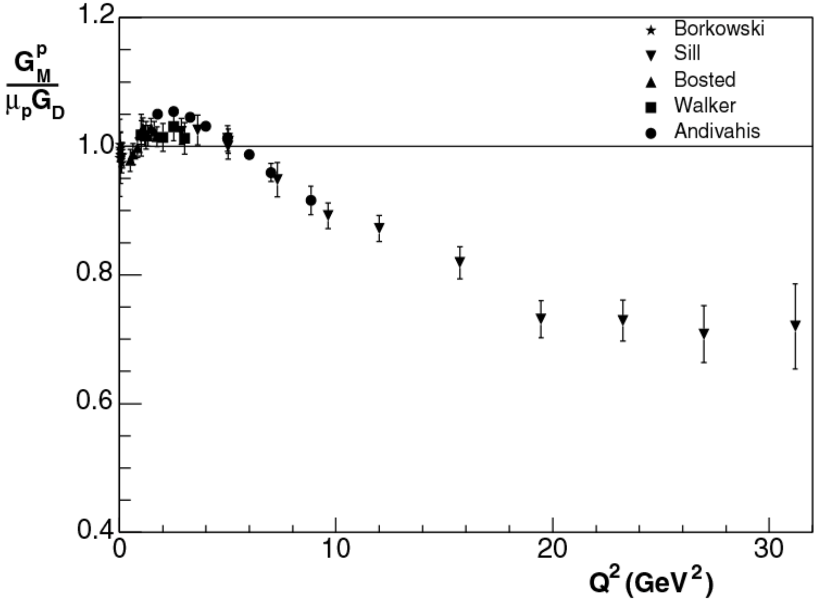


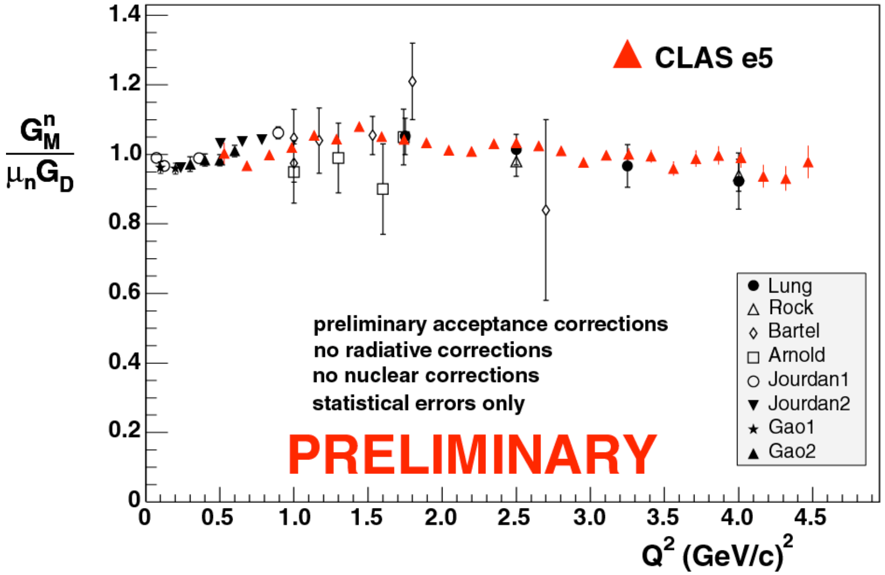
To 9 GeV^2



To 3.5 GeV^2

Magnetic

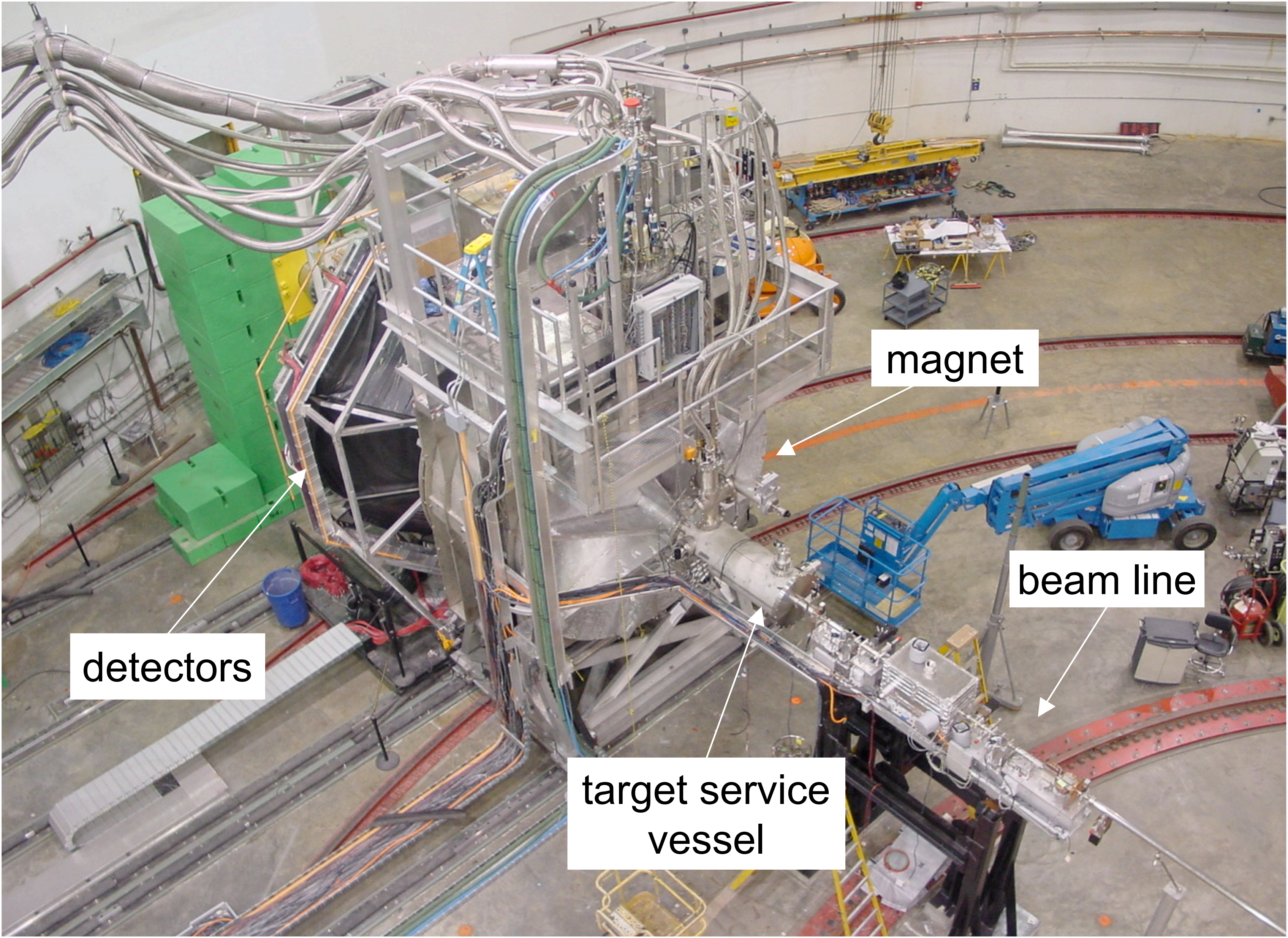




preliminary acceptance corrections
no radiative corrections
no nuclear corrections
statistical errors only

PRELIMINARY

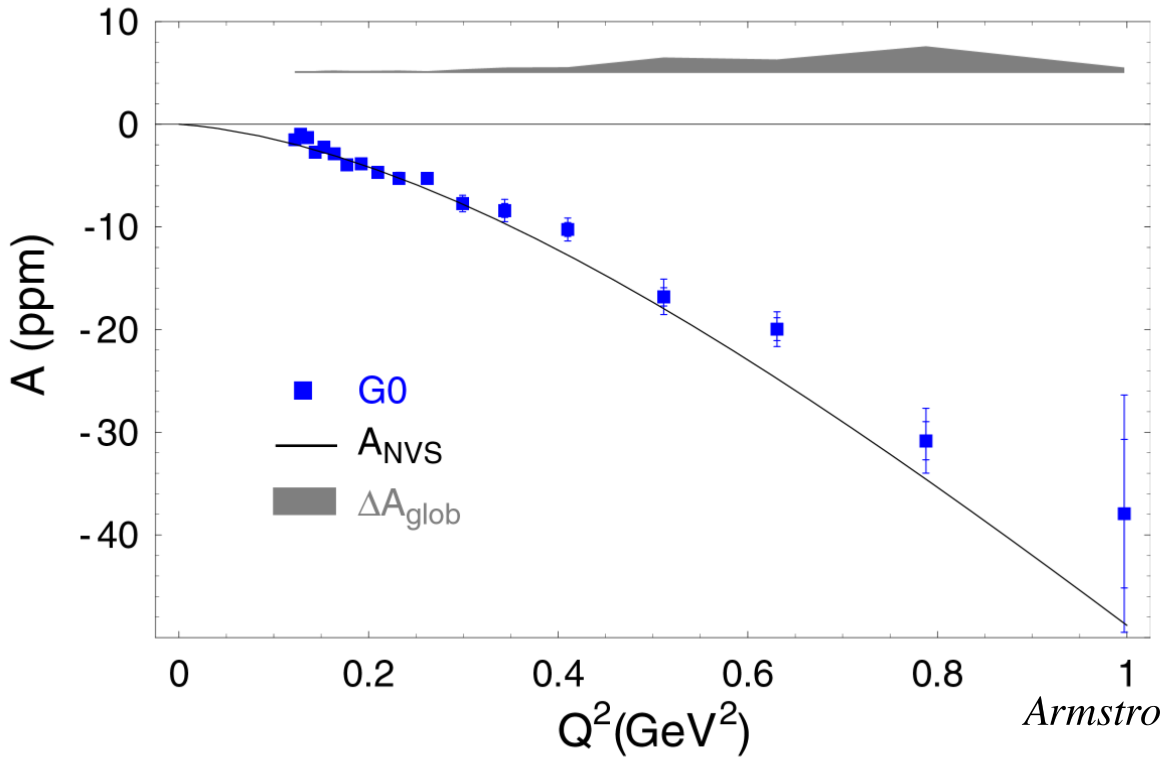
G0 Experiment at Jefferson Lab



Strangeness in the Nucleon

Parity-violating e scattering

$$A = \frac{d\sigma_R - d\sigma_L}{d\sigma_R + d\sigma_L} = -\frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\,\frac{\varepsilon G_E^\gamma G_E^Z + \tau G_M^\gamma G_M^Z - (1-4\sin^2\theta_W)\varepsilon' G_M^\gamma G_A^e}{\mathcal{D}}$$



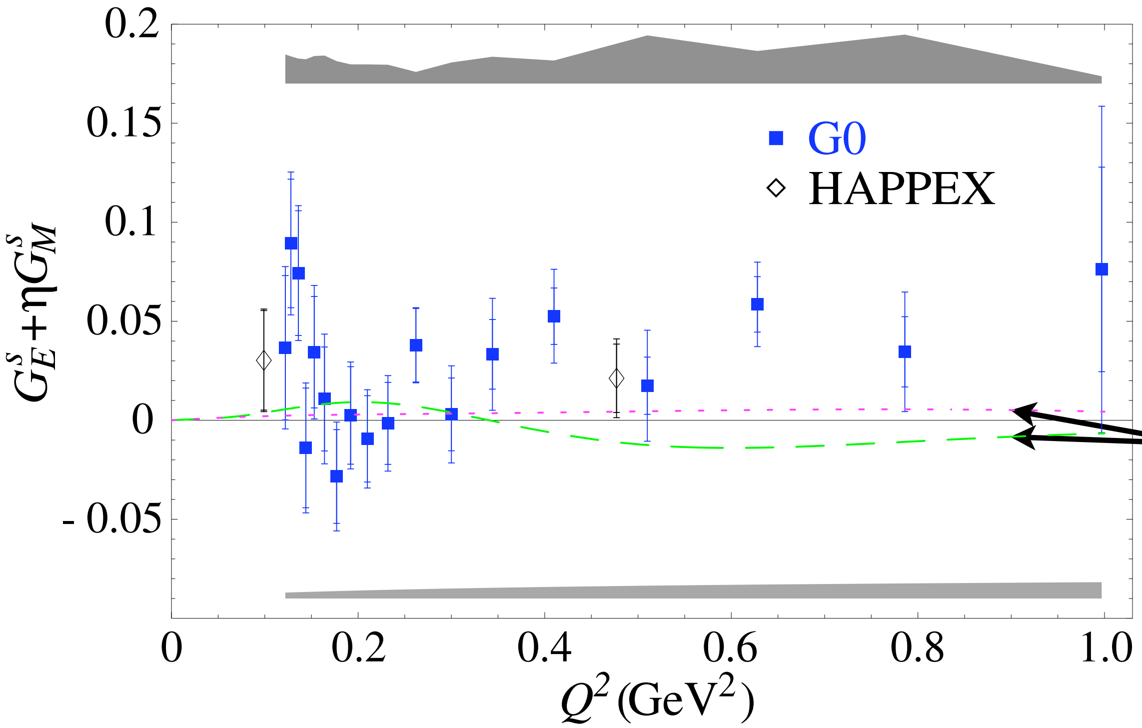
Armstrong et al. [G0 Collaboration]
nucl-ex/0506021

http://www.npl.uiuc.edu/exp/G0Forward

Strangeness in the Nucleon

Parity-violating e scattering

$$A = \frac{d\sigma_R - d\sigma_L}{d\sigma_R + d\sigma_L} = -\frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\,\frac{\varepsilon G_E^\gamma G_E^Z + \tau G_M^\gamma G_M^Z - (1-4\sin^2\theta_W)\varepsilon' G_M^\gamma G_A^e}{\mathcal{D}}$$



$$\eta = \tau G_M/\varepsilon G_E$$

$$\sim\ 0.94\ Q^2$$

dependence of "zero-point" on e.m. form factors

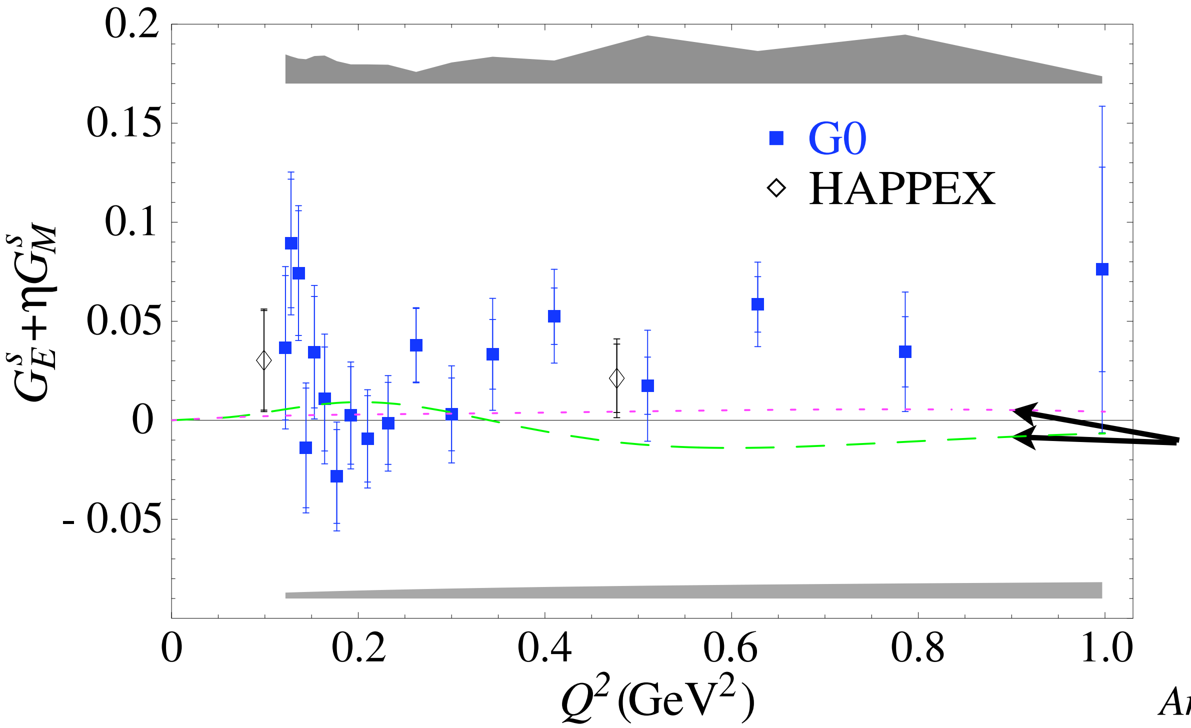
Armstrong et al. [G0 Collaboration] nucl-ex/0506021

- intriguing Q^2 dependence !
- trend to positive values at larger Q^2

Strangeness in the Nucleon

Parity-violating e scattering

$$A = \frac{d\sigma_R - d\sigma_L}{d\sigma_R + d\sigma_L} = -\frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\,\frac{\varepsilon G_E^\gamma G_E^Z + \tau G_M^\gamma G_M^Z - (1 - 4\sin^2\theta_W)\varepsilon' G_M^\gamma G_A^e}{\mathcal{D}}$$



$\eta = \tau G_M / \varepsilon G_E$

$\sim\ 0.94\ Q^2$

dependence of "zero-point" on e.m. form factors

Armstrong et al. [G0 Collaboration]
nucl-ex/0506021

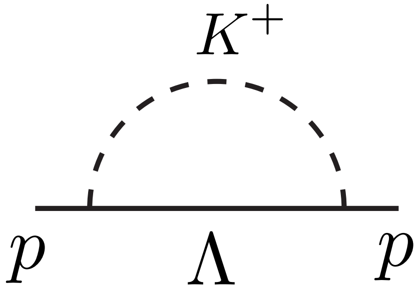
⟹ can one understand this theoretically?

Strangeness in the Nucleon

K cloud model of strangeness in N

$$p^{\uparrow} \to \Lambda^{\downarrow} K^{+} \to p^{\uparrow}$$

$$(uud)^{\uparrow} \to \left[(ud)_0 \; s^{\downarrow}\right] \; (u\bar{s})_0$$



Thomas, Signal; Brodsky, Ma;
WM, Malheiro; ...

covariant formulation on light-cone

$$J^s_\mu = F^s_1 \; \gamma_\mu \; + \; F^s_2 \; \frac{i\sigma_{\mu\nu} q^\nu}{2M}$$

$$+ \; B^s_1 \left(\frac{n \cdot \gamma}{n \cdot p} - \frac{1}{(1+\eta)M} \right) p_\mu \; + \cdots$$

spurious form factor
(associated with violation of Lorentz covariance
arising from use of one-body currents)

Karmanov, Mathiot, Nucl. Phys. A602 (1996) 388

Carbonell, Desplanques, Karmanov, Mathiot, Phys. Rep. 300 (1998) 215

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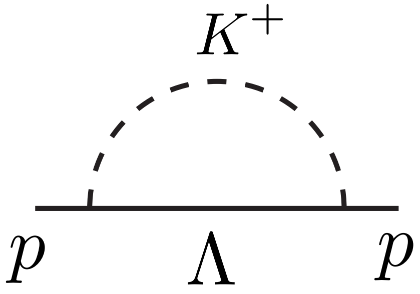

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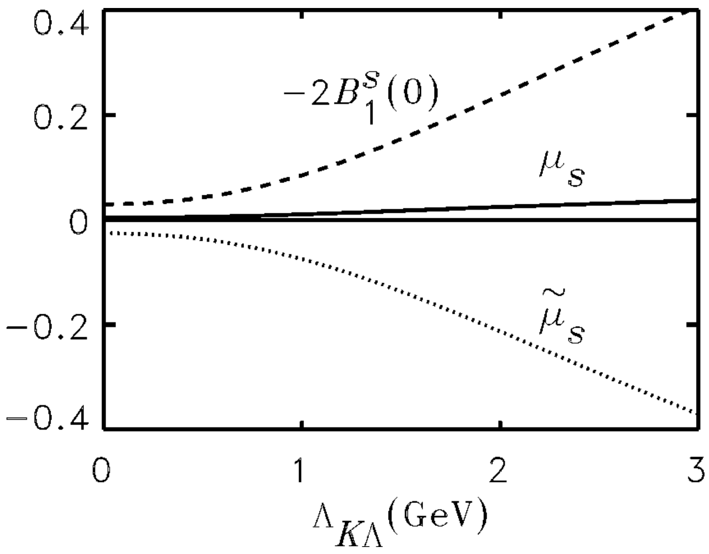

$$G^2_M = \widetilde{G}^s_M - 2B^s_1$$

⇒ large correction

Karmanov, Mathiot, Nucl. Phys. A602 (1996) 388

Carbonell, Desplanques, Karmanov, Mathiot, Phys. Rep. 300 (1998) 215

Strangeness in the Nucleon

K cloud model of strangeness in *N*

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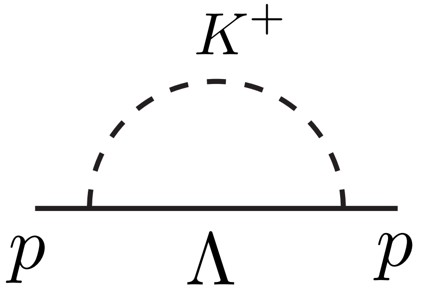
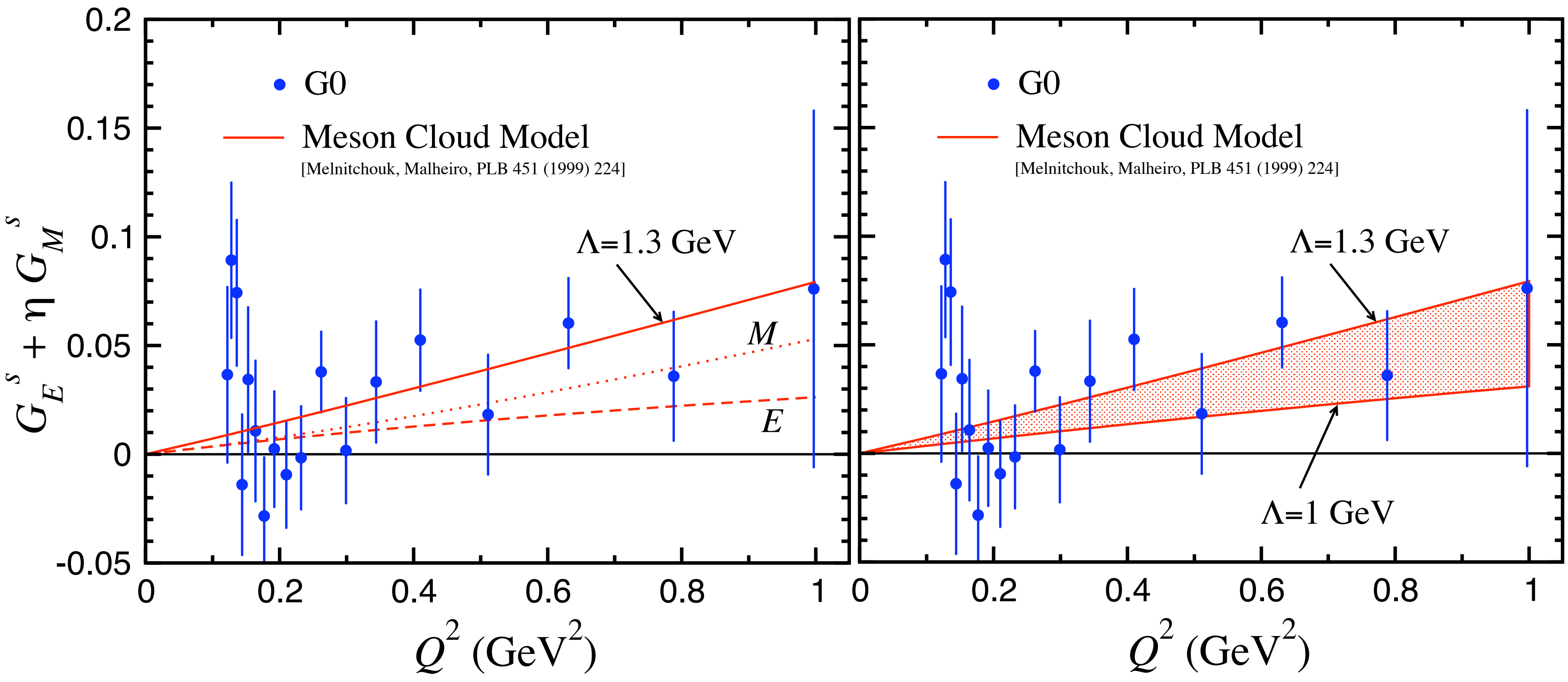
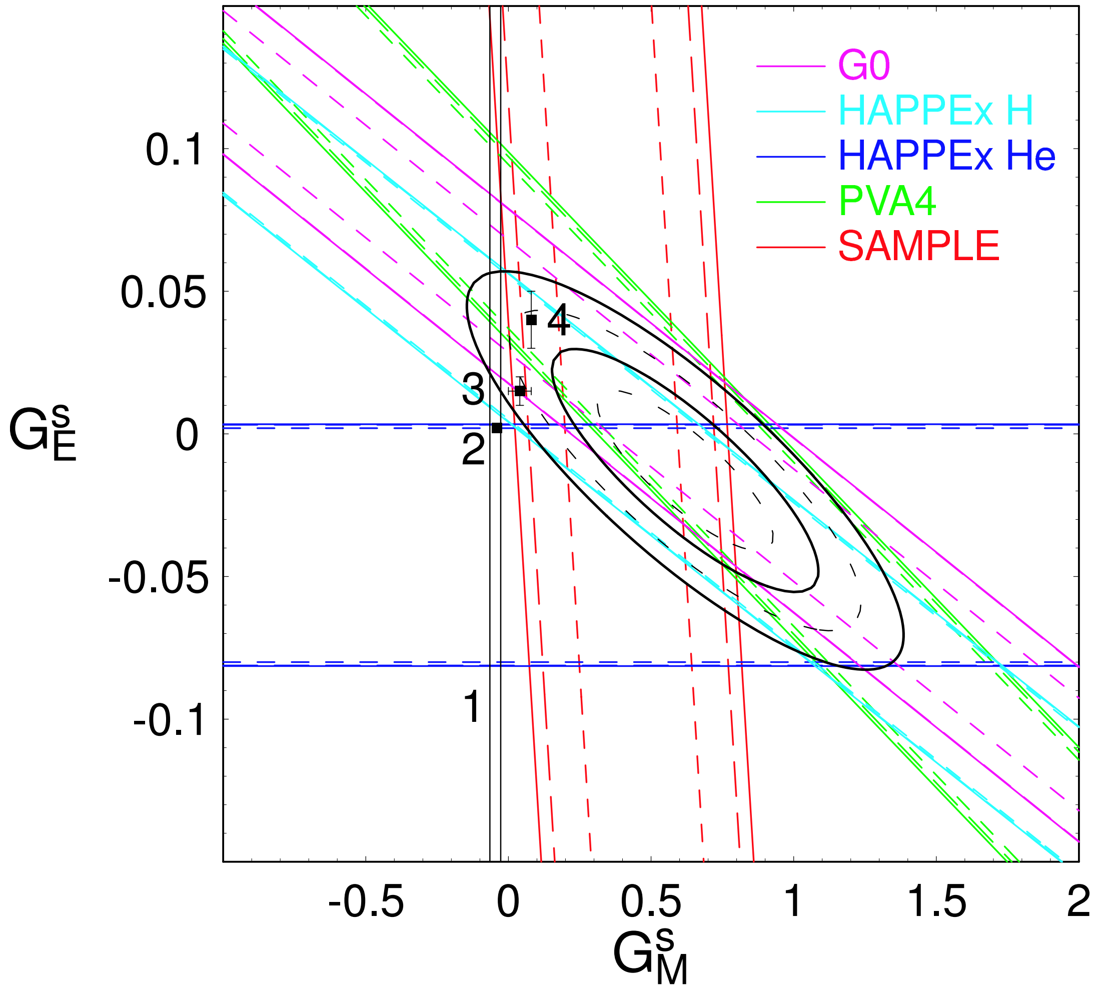




Strangeness in the Nucleon

combined world data at $Q^2 = 0.1\ \mathrm{GeV}^2$



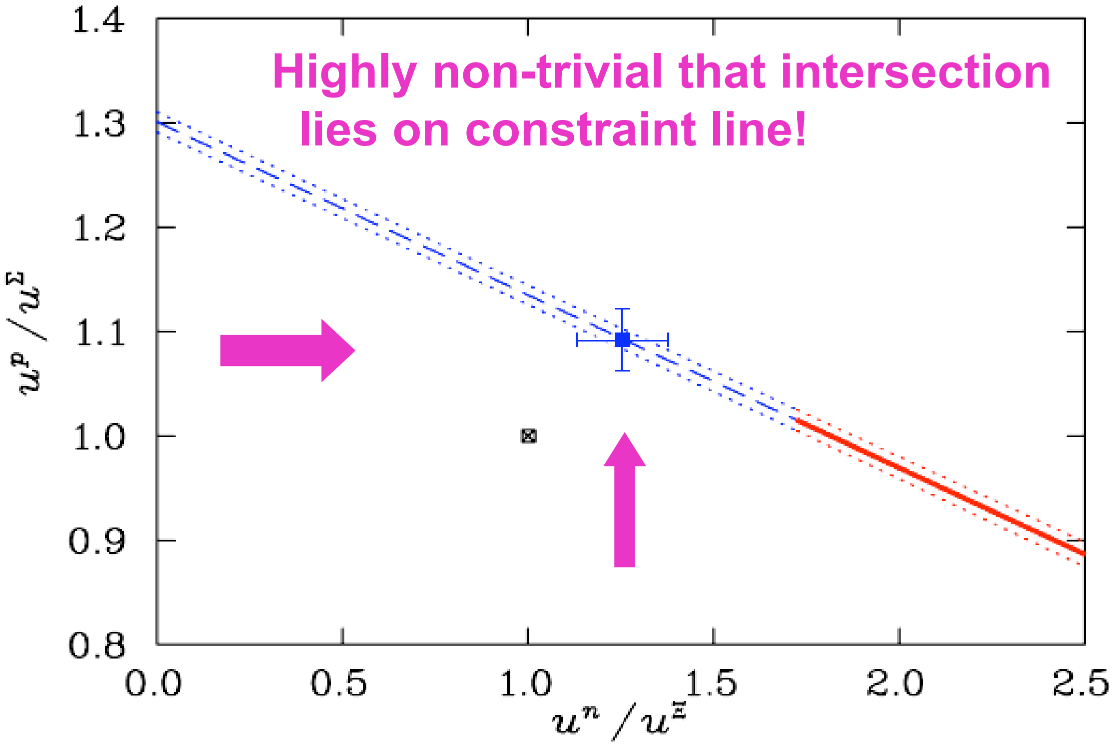
$$G_E^s = -0.013 \pm 0.028$$
$$G_M^s = +0.62 \pm 0.31$$
$$\pm 0.62\ 2\sigma$$

Theories

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

⇨ no theory can explain result (?)

Strangeness in the Nucleon



Highly non-trivial that intersection lies on constraint line!

1.10±0.03

1.25±0.12

Yields :G_M^s = -0.046 ± 0.019 μ_N

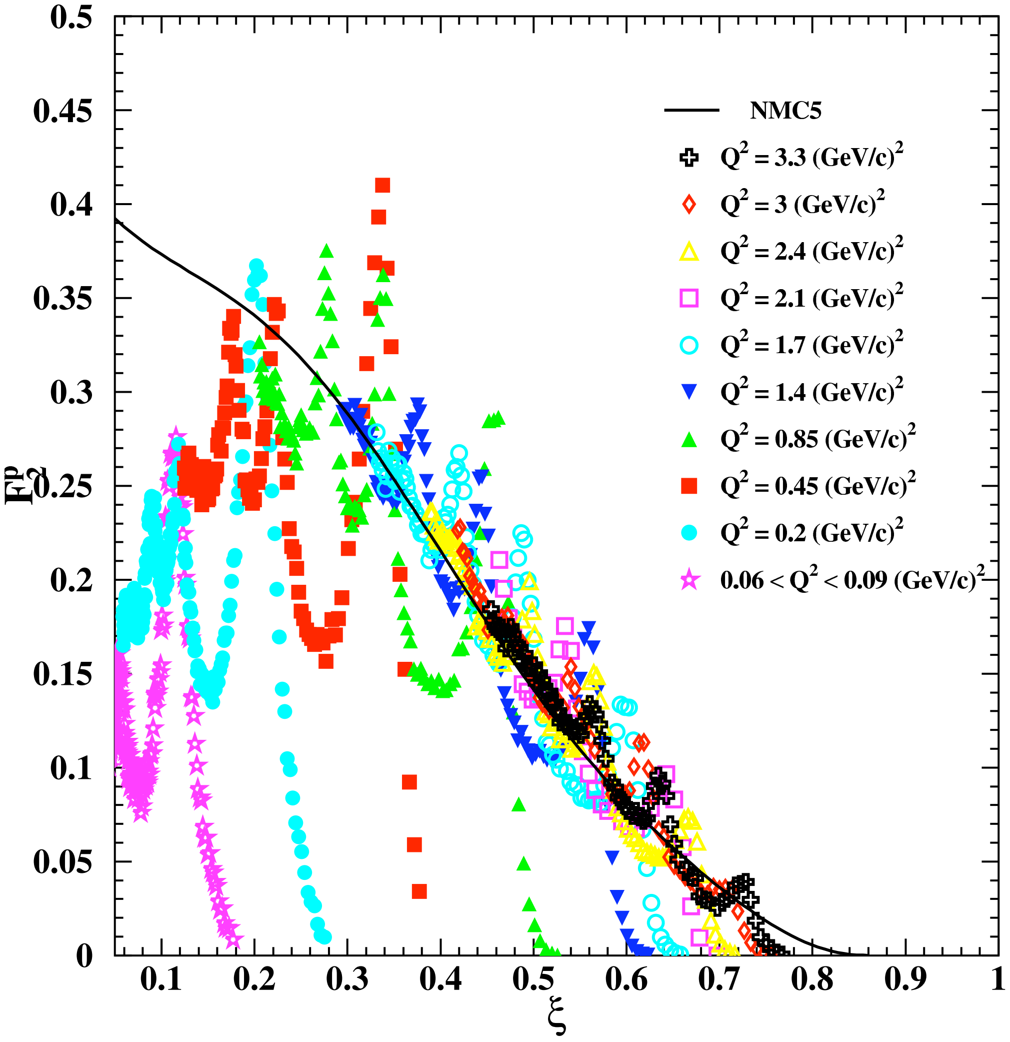
Leinweber et al., hep-lat/0406002
Phys. Rev. Lett. 94 (2005) 212001

⇒ sign and magnitude of G_M^s
would violate universality by 70% !

Quark Distributions and Duality

→ Halls A, B and C

Bloom-Gilman duality

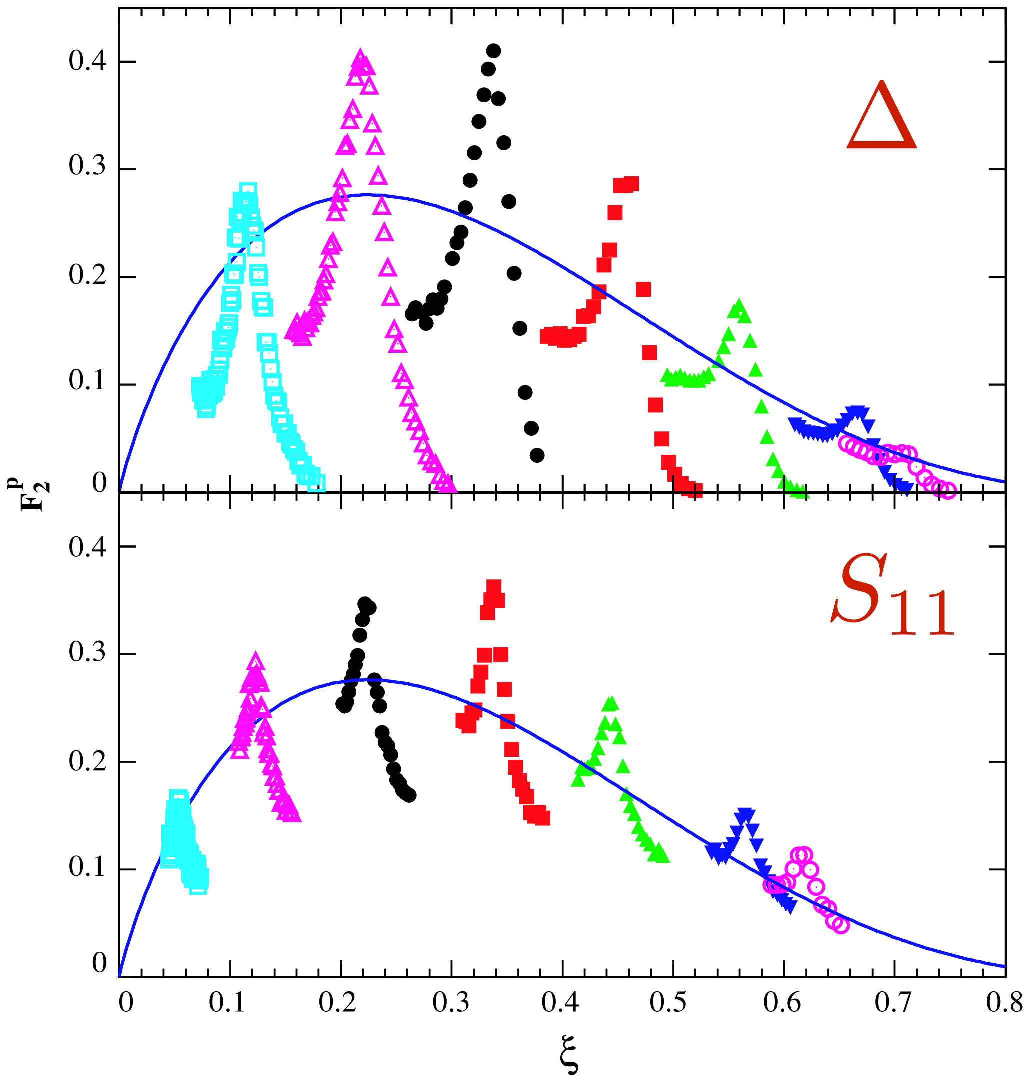


Jefferson Lab (Hall C)

Niculescu et al., Phys. Rev. Lett. 85 (2000) 1182

Average over
(strongly Q^2 dependent)
resonances
$\approx$ Q^2 independent
scaling function

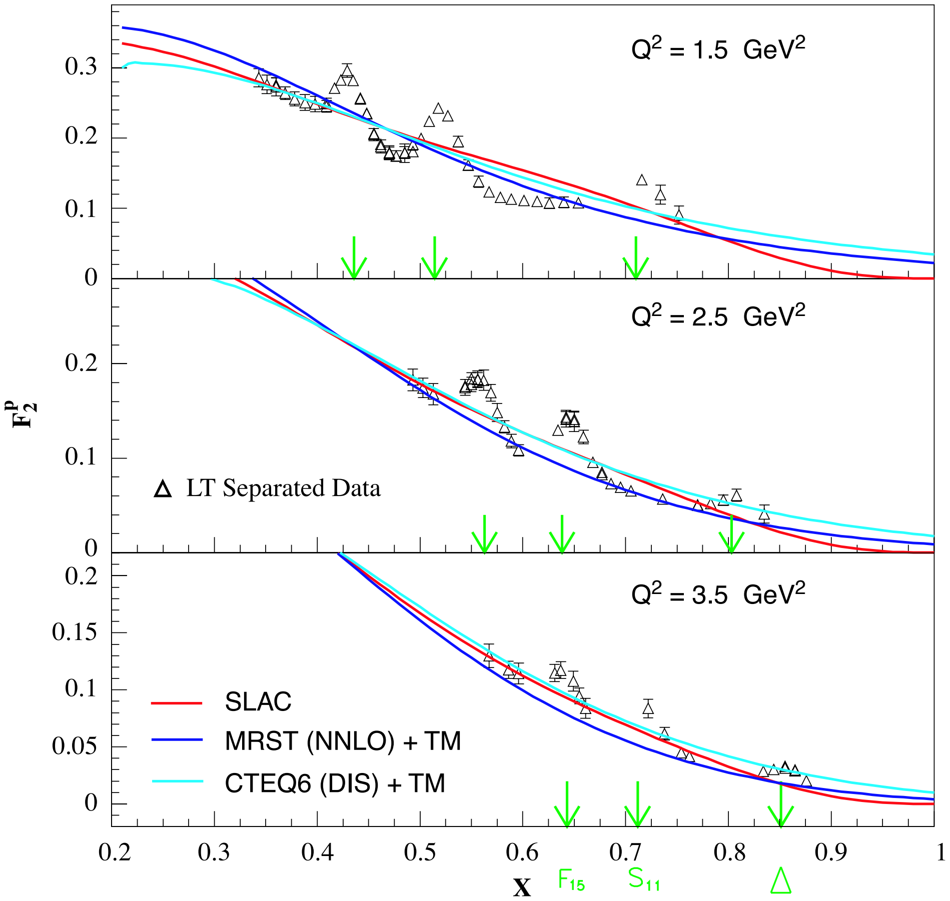
Local Bloom-Gilman duality

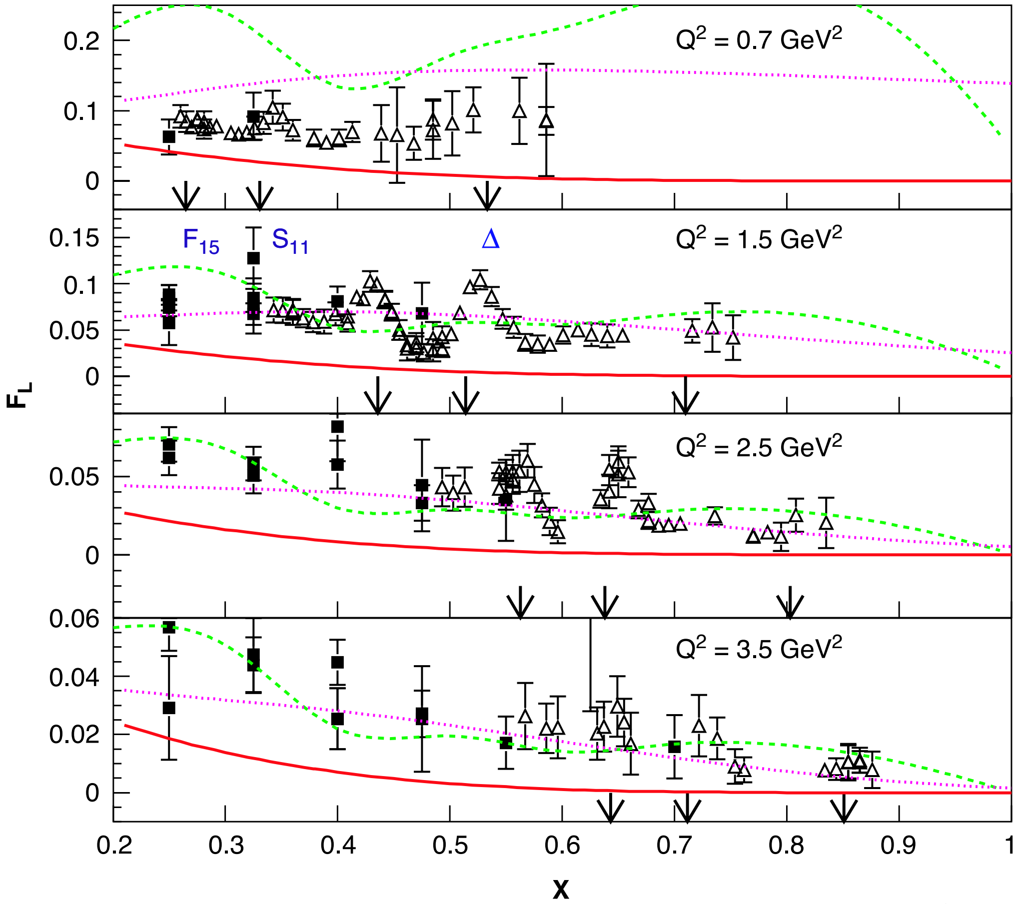


$$\xi = \frac{2x}{1+\sqrt{1+4M^2x^2/Q^2}}$$

Nachtmann scaling variable

Local Bloom-Gilman duality





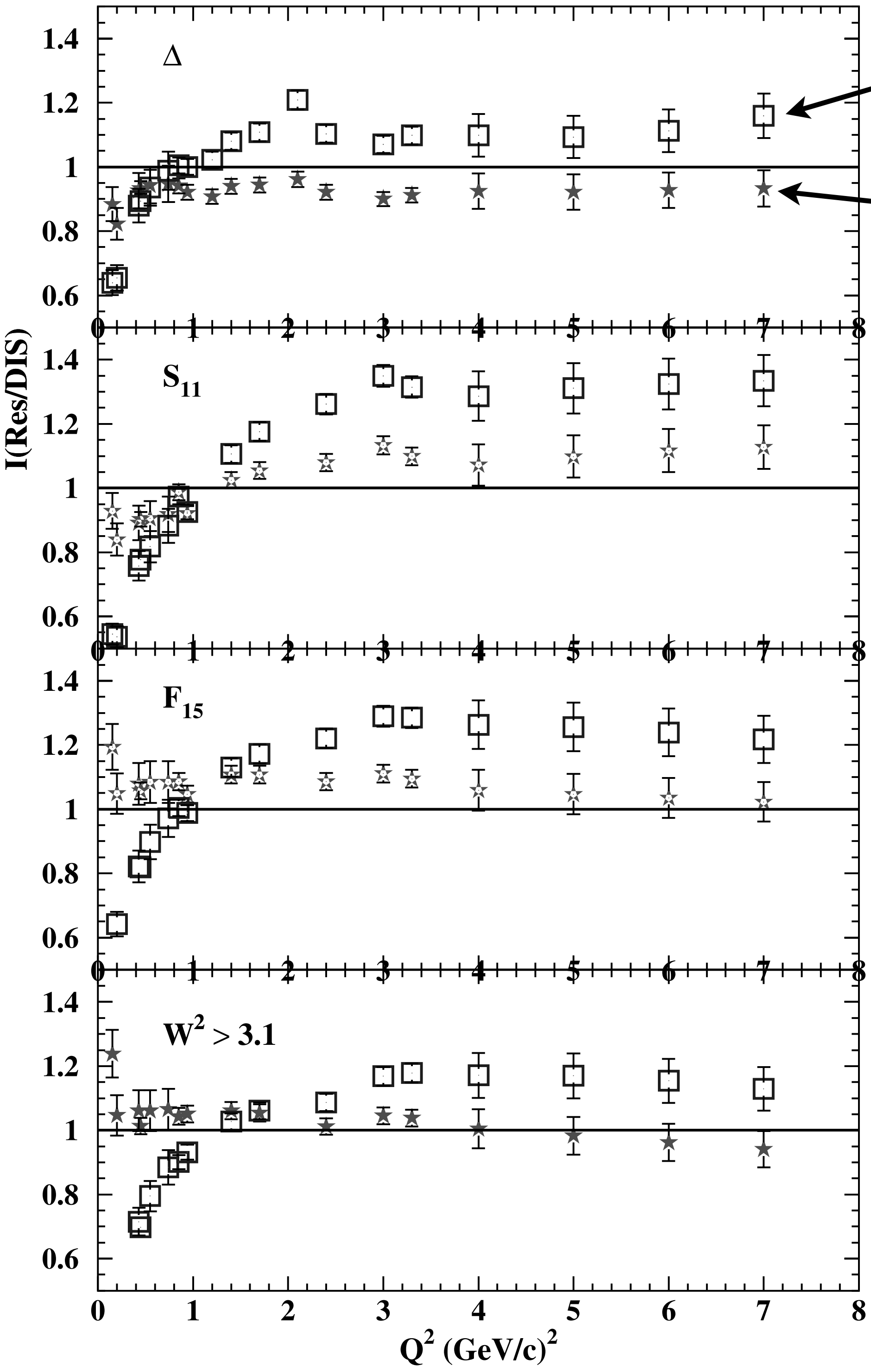
E. Christy et al. (2005)

duality in F_2 and F_L structure functions

(from longitudinal-transverse separation)

⇨ importance of target mass corrections

Integrated strength



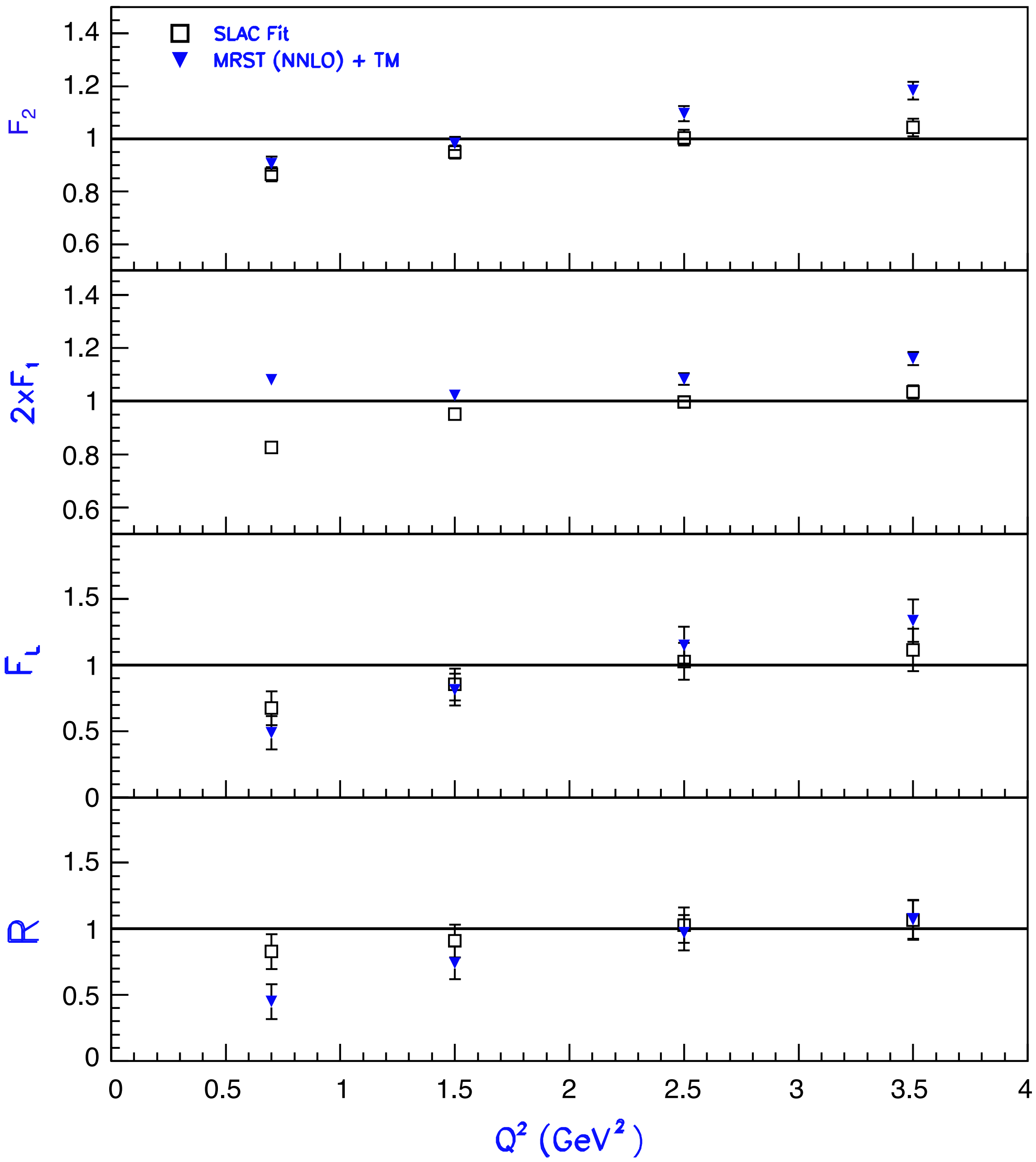
NMC fit

JLab resonance fit

~10% agreement for $Q^2 > 1$ GeV^2

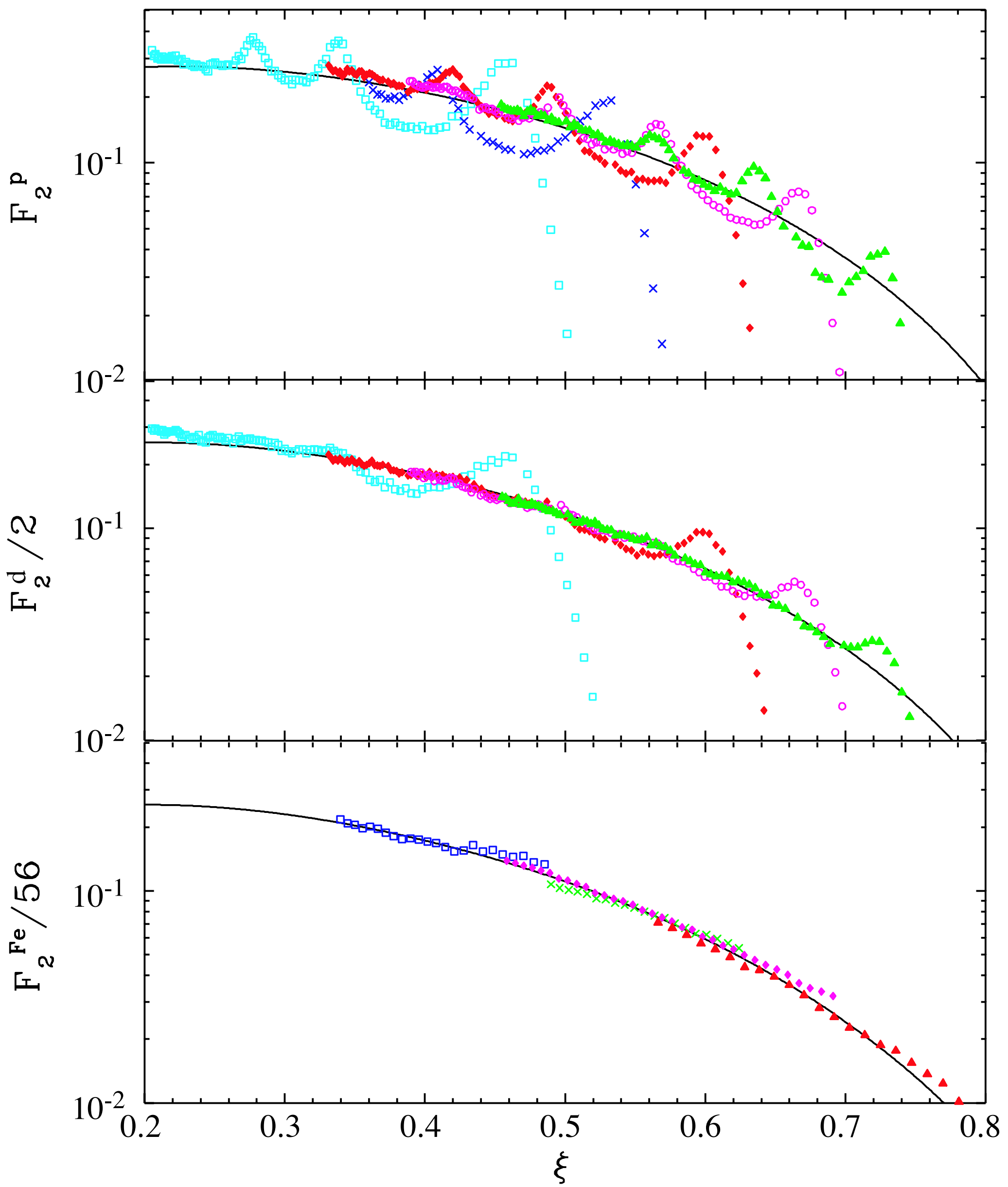
Moments

data from longitudinal-transverse separation !



Jefferson Lab (Hall C)

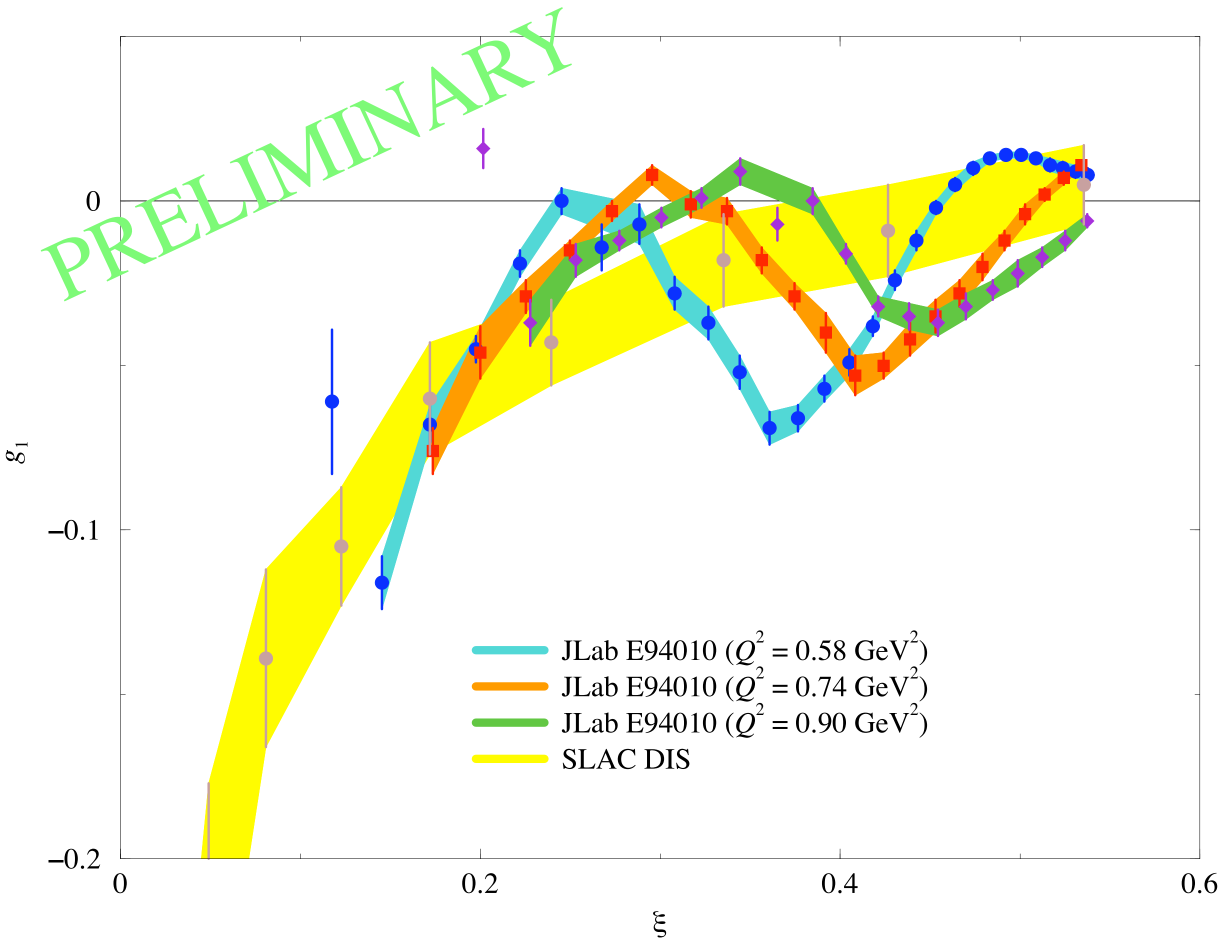
Nuclear structure functions



for larger nuclei, Fermi motion does resonance averaging automatically !

Jefferson Lab (Hall C)

Neutron (^{3}He) g_1 structure function



Liyanage et al. (JLab Hall A)

Duality and the OPE

Operator product expansion

→ expand moments of structure functions in powers of $1/Q^2$

$$M_n(Q^2) = \int_0^1 dx\ x^{n-2}\ F_2(x, Q^2)$$

$$= A_n^{(2)} + \frac{A_n^{(4)}}{Q^2} + \frac{A_n^{(6)}}{Q^4} + \cdots$$

matrix elements of operators
with specific "twist" τ

$$\tau = \text{dimension} - \text{spin}$$

Duality and the OPE

Operator product expansion

➡ expand moments of structure functions in powers of $1/Q^2$

$$M_n(Q^2) = \int_0^1 dx\ x^{n-2}\ F_2(x, Q^2)$$
$$= A_n^{(2)} + \frac{A_n^{(4)}}{Q^2} + \frac{A_n^{(6)}}{Q^4} + \cdots$$

If moment $\approx$ independent of Q^2

➡ higher twist terms $A_n^{(\tau>2)}$ small

Applications of duality

If higher twists are small (duality "works")

⇒ can use single-parton approximation to describe structure functions

⇒ extract *leading twist* parton distributions

If duality is violated, and if violations are small

⇒ can use duality violations to extract *higher twist* matrix elements

⇒ learn about nonperturbative qq or qg correlations

Example: Lowest moment of g_1

$$\Gamma_1(Q^2) = \int_0^1 dx \; g_1(x, Q^2)$$

$$= \mu_2 + \frac{\mu_4}{Q^2} + \frac{\mu_6}{Q^4} + \cdots$$

Twist 2

$$\mu_2^{p(n)} = \left(\pm \frac{1}{12} g_A + \frac{1}{36} a_8 \right) C_{ns}(Q^2) + \frac{1}{9} \Delta\Sigma \; C_s(Q^2)$$

triplet

octet

RGI singlet
axial charge

Higher twist terms

$1/Q^2$ correction to g_1 moment

$$\mu_4 = \frac{1}{9} M^2 \left(a_2 + 4d_2 + 4f_2 \right)$$

target mass correction

quark-gluon correlations

Higher twist terms

$1/Q^2$ correction to g_1 moment

$$\mu_4 = \frac{1}{9} M^2 \left(a_2 + 4d_2 + 4f_2\right)$$

$$d_2 \;\rightarrow\; \langle N|\, \bar{\psi}\, \widetilde{G}^{\mu\{\nu}\gamma^{\alpha\}}\, \psi\, |N\rangle$$

twist 3

$$f_2 \;\rightarrow\; \langle N|\, \bar{\psi}\, \widetilde{G}^{\mu\nu}\gamma_\nu\, \psi\, |N\rangle$$

twist 4

Color polarizabilities

$1/Q^2$ correction to g_1 moment

$$\mu_4 = \frac{1}{9} M^2 \left(a_2 + 4d_2 + 4f_2\right)$$

color *electric* polarizability

$$\chi_E \;=\; \frac{1}{3}(4d_2 + 2f_2) \;\sim\; \langle \vec{j}_a \times \vec{E}_a \rangle_z$$

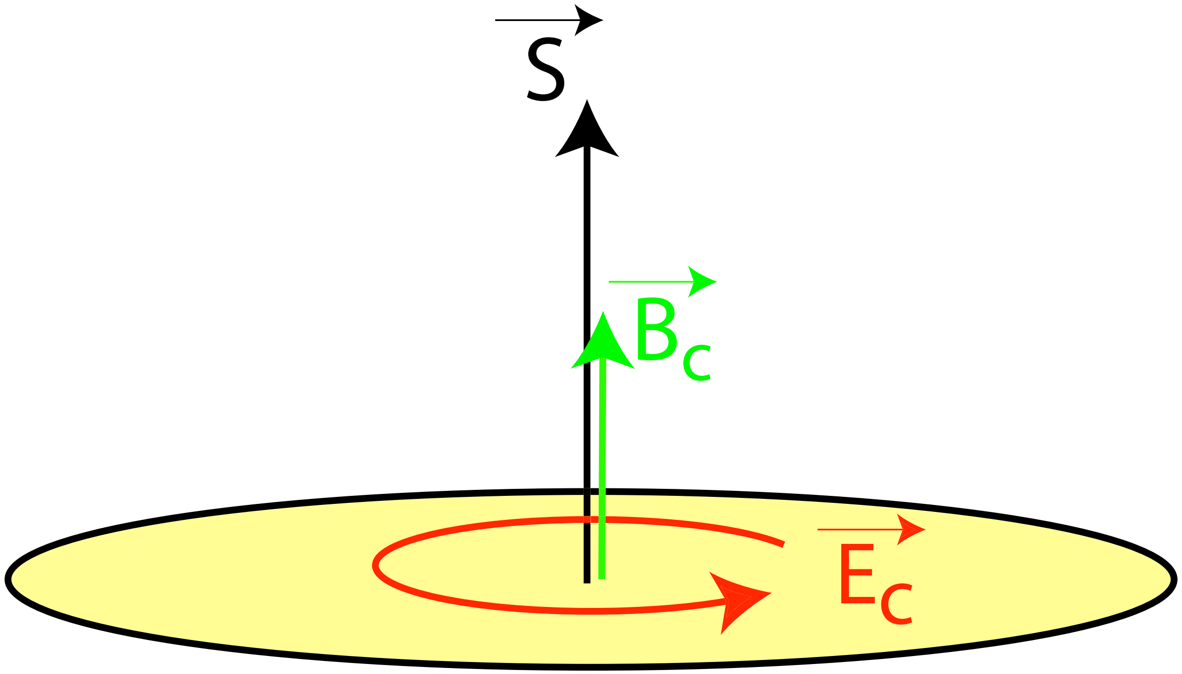
$$j_a^\mu = g_s \psi \gamma^\mu \mathbf{t}_a \psi$$

color *magnetic* polarizability

$$\chi_B \;=\; \frac{1}{3}(4d_2 - f_2) \;\sim\; \langle j_a^0 \; \vec{B}_a \rangle_z$$

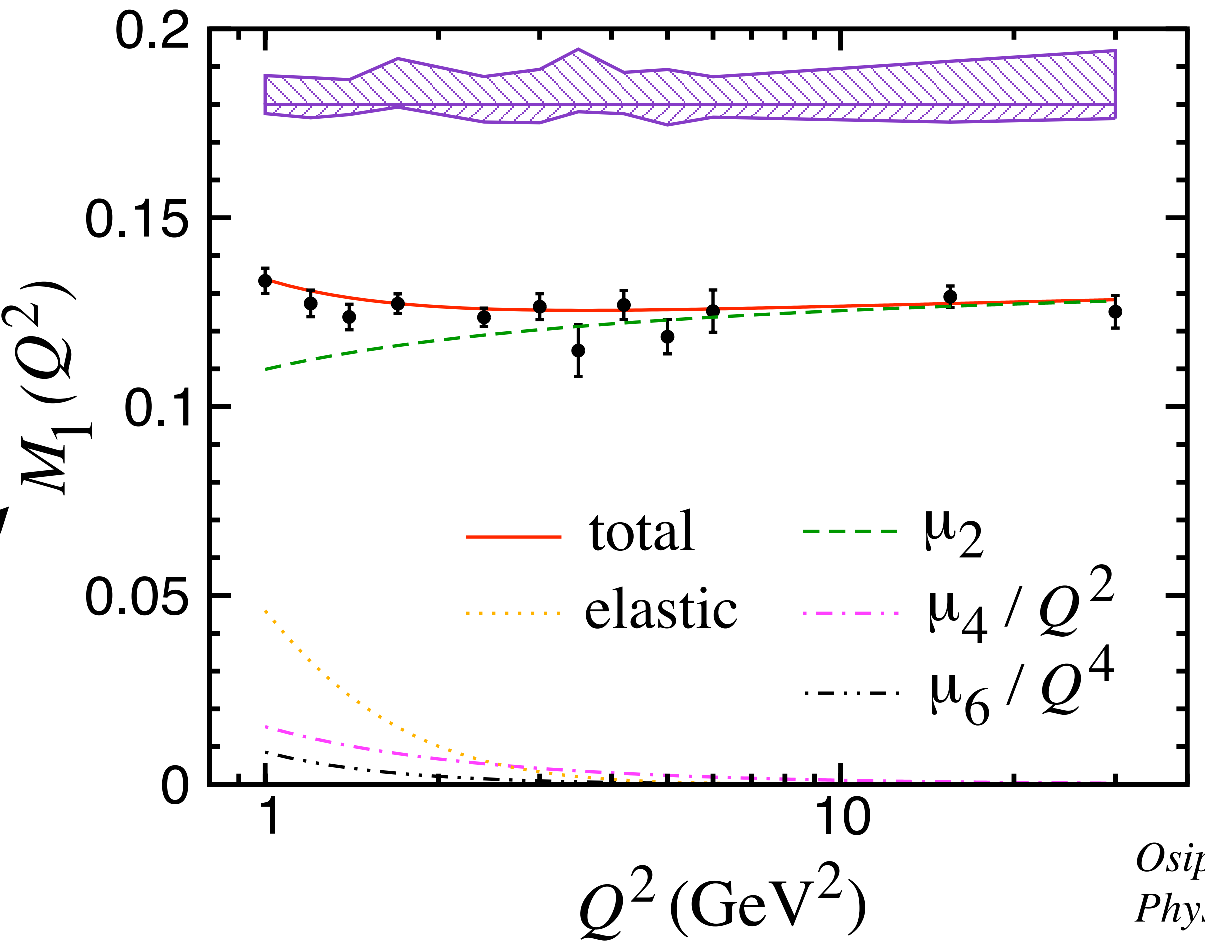
Ji (1995), Schafer, Mankiewicz, ... (1995)

Color polarizabilities



response of collective color electric and magnetic fields
to spin of nucleon

Proton g_1 moment



Nachtmann moment

Osipenko, WM et al,
Phys. Lett. B 609 (2005) 259

$$M_1 = \int_0^1 dx \frac{\xi^2}{x^2} \left[g_1 \left(\frac{x}{\xi} - \frac{M^2 x \xi}{9Q^2} \right) - g_2 \frac{4M^2 x^2}{3Q^2} \right] \;=\; \mu_2 + \frac{4M^2}{9Q^2} f_2 + \cdots$$

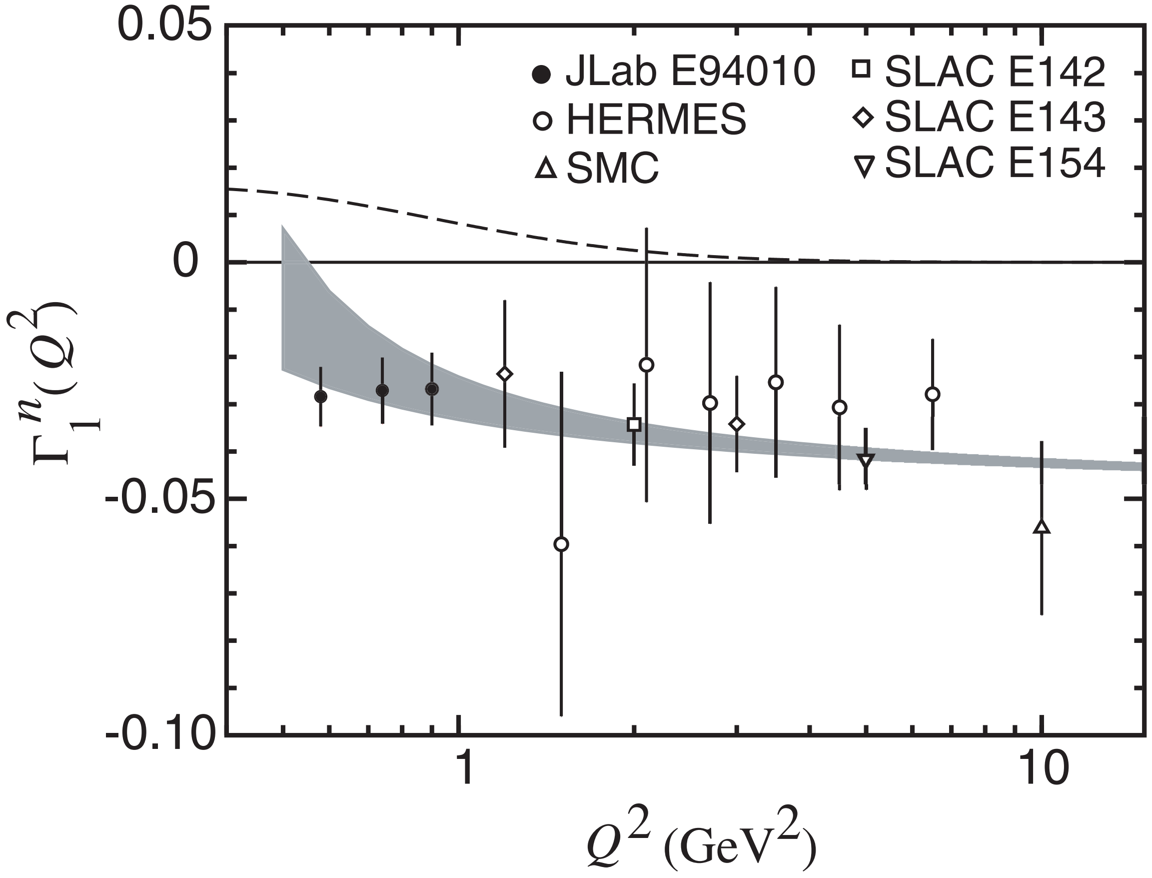
$$\chi_E^p = 0.026 \pm 0.015\ (\mathrm{stat}) \pm 0.021\ (\mathrm{sys})$$

$$\chi_B^p = -0.013 \pm 0.007\ (\mathrm{stat}) \pm 0.011\ (\mathrm{sys})$$

Compare with theoretical calculations:

	χ_E^p	χ_B^p
QCD sum rules	-0.04	0.01
MIT bag	0.05	0.02
Instanton	-0.03	0.02
Lattice	?	?

Neutron g_1 moment



Meziani, WM et al,
Phys. Lett. B613 (2005) 148

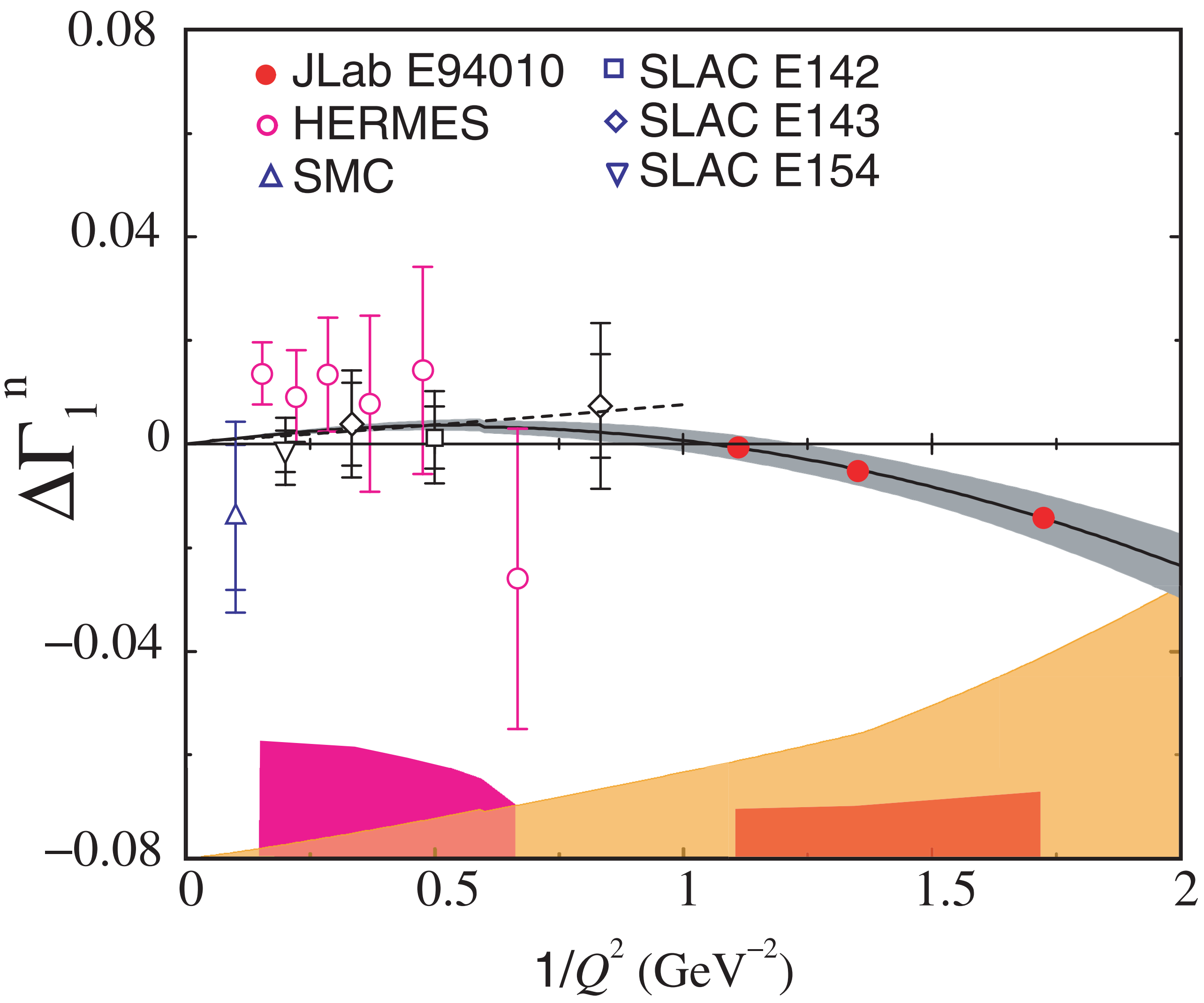
Γ_1^n extracted from $\Gamma_1^{^3\mathrm{He}}$ data

correcting for nuclear effects

$$\begin{aligned}\chi_E^n &= +0.033 \pm 0.029 \\ \chi_B^n &= -0.001 \pm 0.016\end{aligned}$$

Compare with theoretical calculations:

	χ_E^n	χ_B^n
QCD sum rules	-0.04	-0.02
MIT bag	0.00	0.00
Instanton	0.03	-0.01
Lattice	?	?



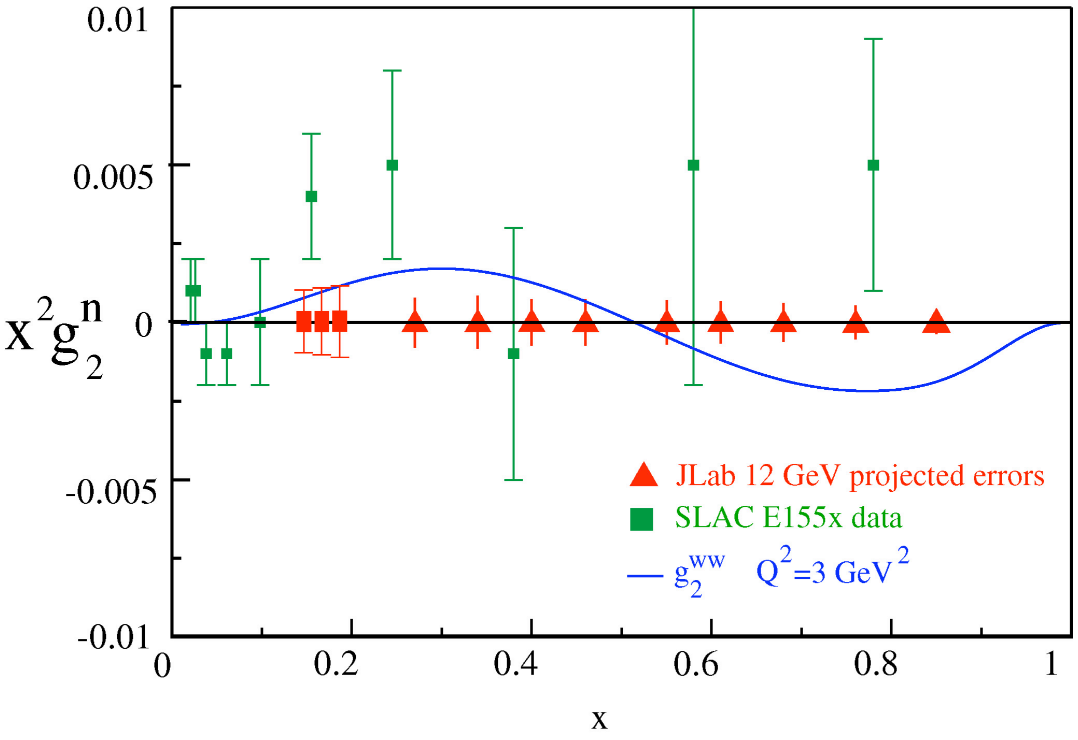
Higher twist contribution to neutron moment

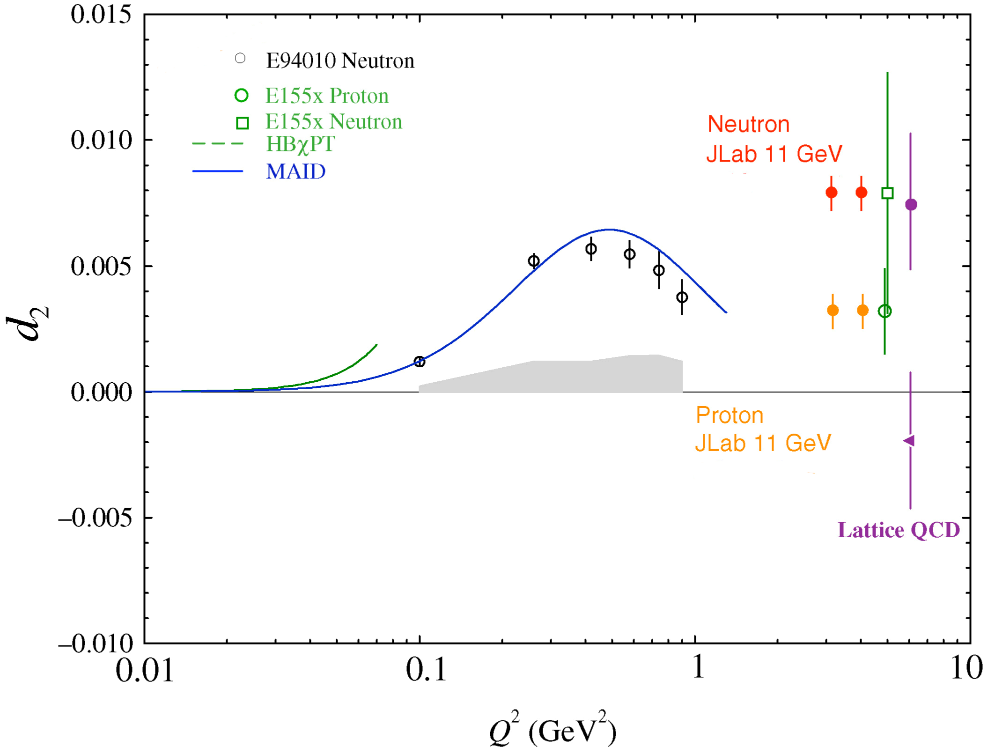
Total higher twist $\sim$ *zero* at $Q^2 \sim 1-2\ \mathrm{GeV}^2$

⟹ nonperturbative interactions between quarks and gluons not dominant at these scales

⟹ suggests *strong cancellations* between resonances, resulting in dominance of *leading twist*

g_2 at JLab with 11 GeV





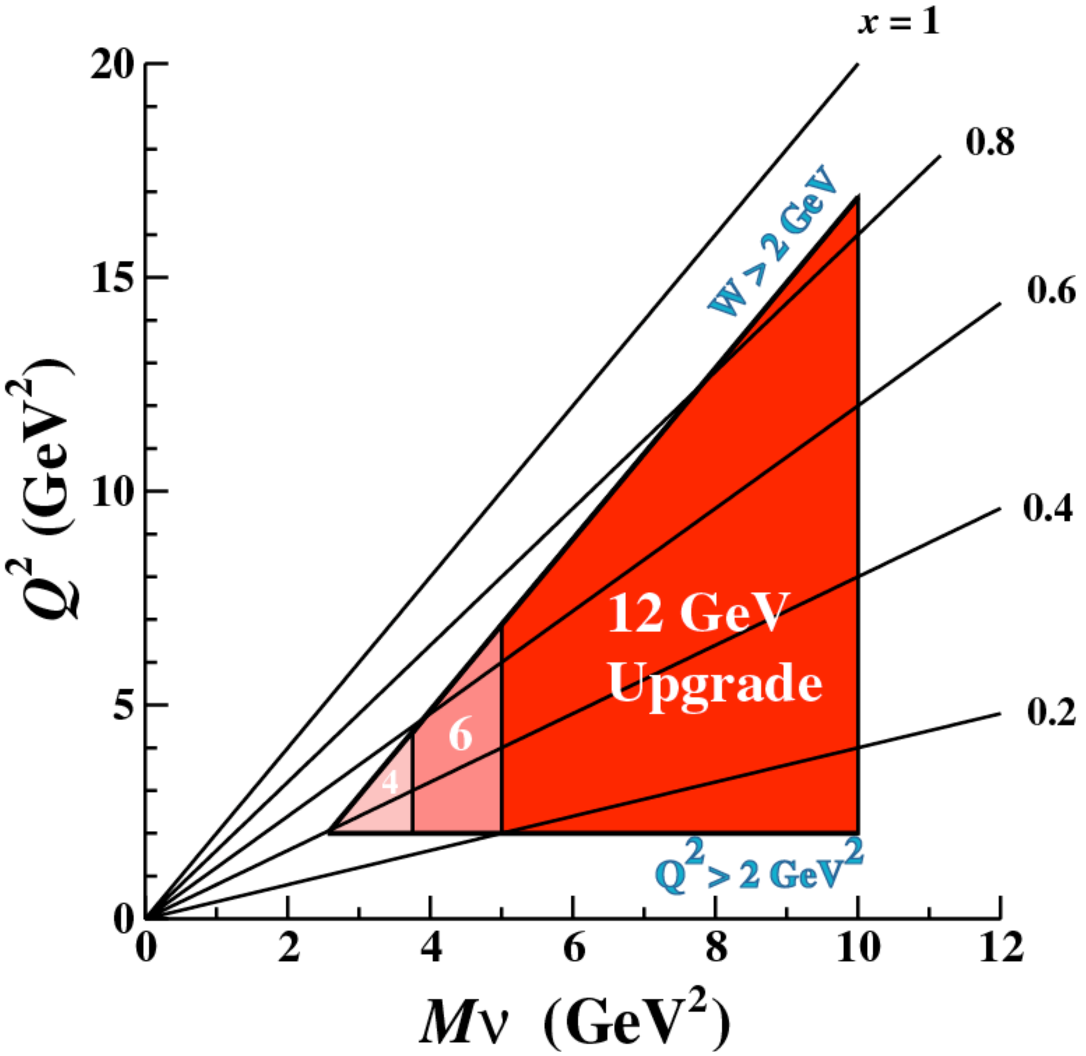
QCDSF (2005) $d_2^p = 0.004(5)$

$N_f = 2$ $d_2^n = -0.001(3)$

Outlook

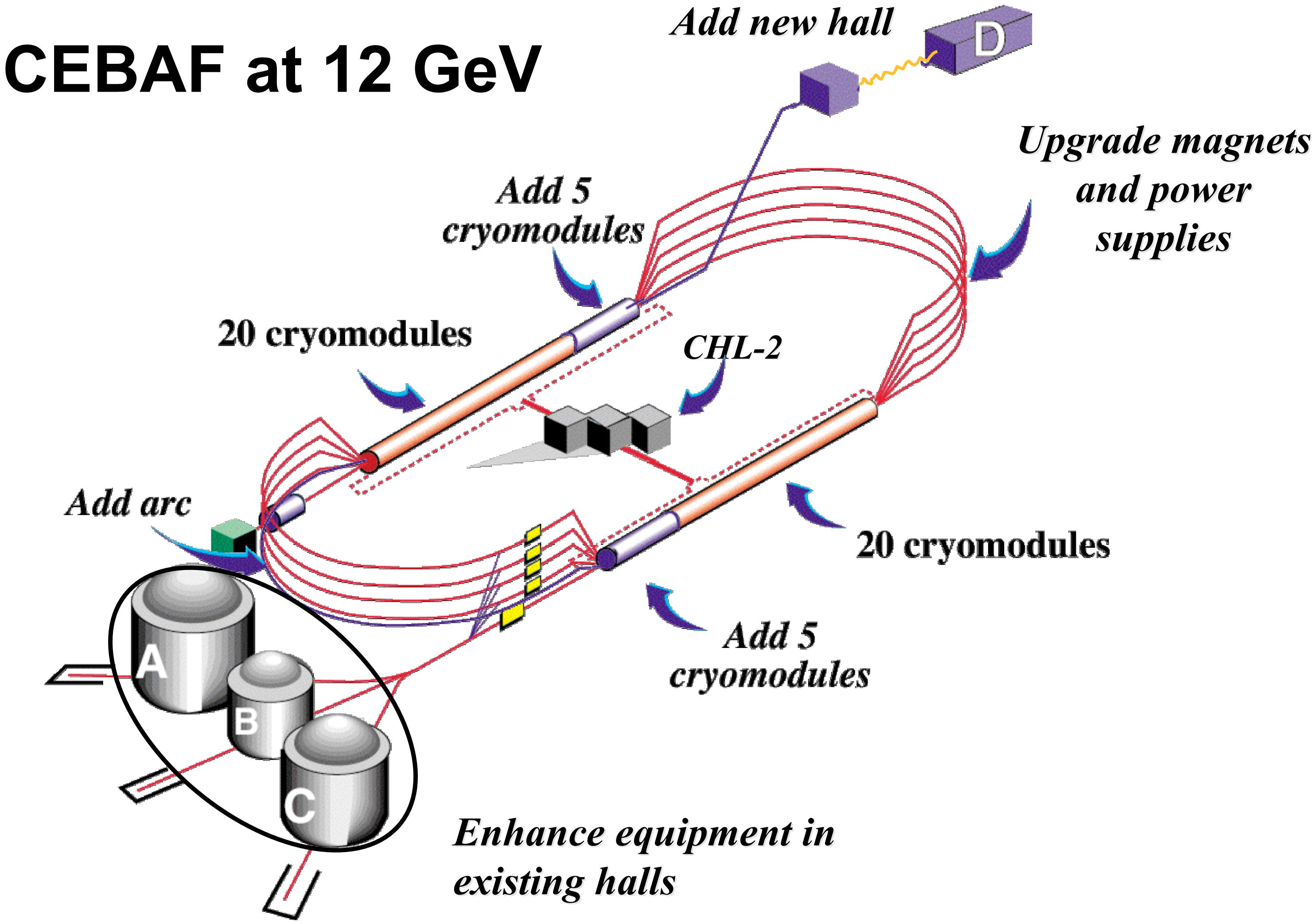
12 GeV JLab Upgrade

high luminosity with higher energy



⇨ unique probe of high-Q^2, high-x region

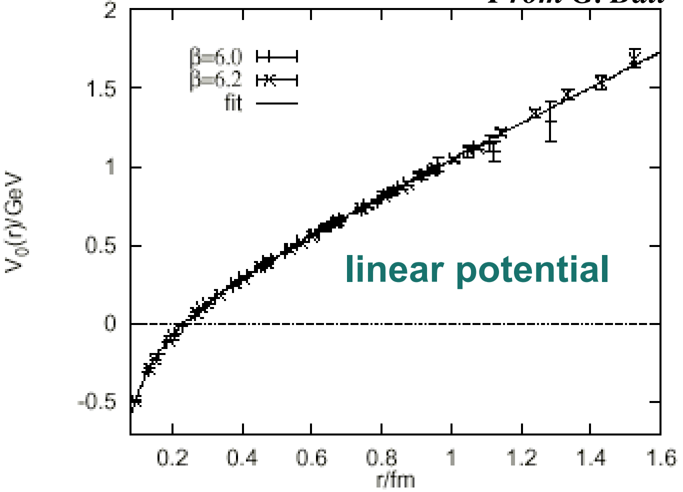
12 GeV JLab Upgrade

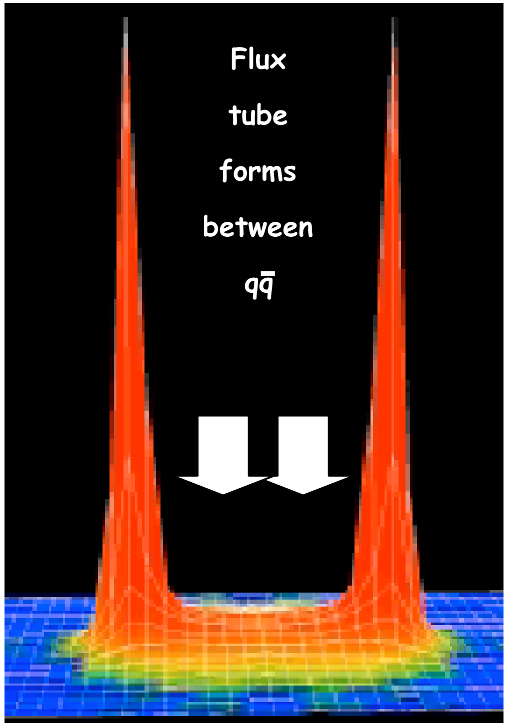


Gluonic Excitations and the Origin of Confinement

The quarks in a meson are sources of a color electric flux which is trapped in a flux tube connecting the quarks. The formation of the flux tube is related to the self-interaction of gluons via their color charge.

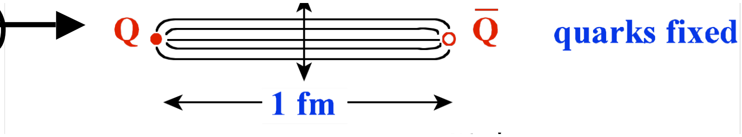
From G. Bali





G. Bali

- Flux tubes result in a linear confining potential
- Very little is known about gluonic (or flux-tube) excitations



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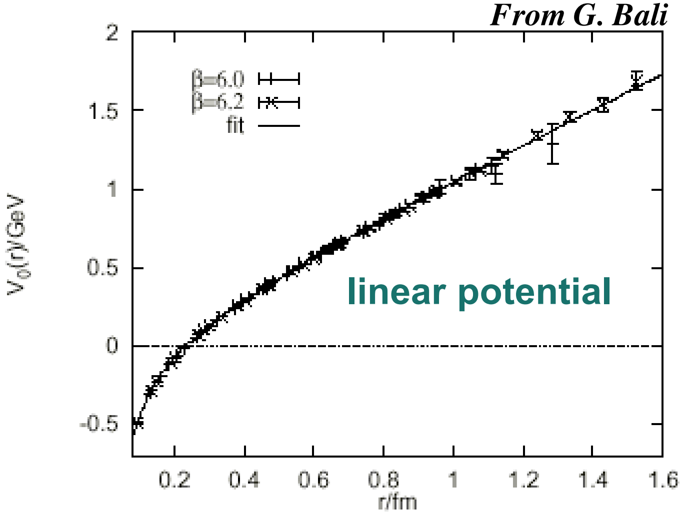


D. Leinweber

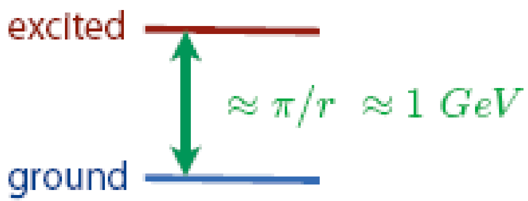
gluon field expunged from within flux tube

flux tube ≈ balloon under water

Masses and Widths of Hybrid Mesons

Masses and Widths

widths are expected to be of order 150-200 MeV



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

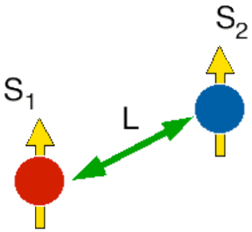
Author		1^{-+} Mass (GeV/c^2)	
Collab.	Year	$u\bar{u}/d\bar{d}$	$s\bar{s}$
UKQCD	(1997)	1.87 ± 0.20	2.0 ± 0.2
MILC	(1997)	$1.97 \pm 0.09 \pm 0.30$	$2.170 \pm 0.080 \pm 0.30$
MILC	(1999)	$2.11 \pm 0.10 \pm (sys)$	
SESAM	(1998)	1.9 ± 0.20	
Mei& Luo	(2003)	$2.013 \pm 0.026 \pm 0.071$	
Bernard *et al.*	(2004)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

Photons Preferred for Flux Tube Excitations

Normal mesons: $J^{PC} = 0^{-+} \quad 1^{+-} \quad 2^{-+}$

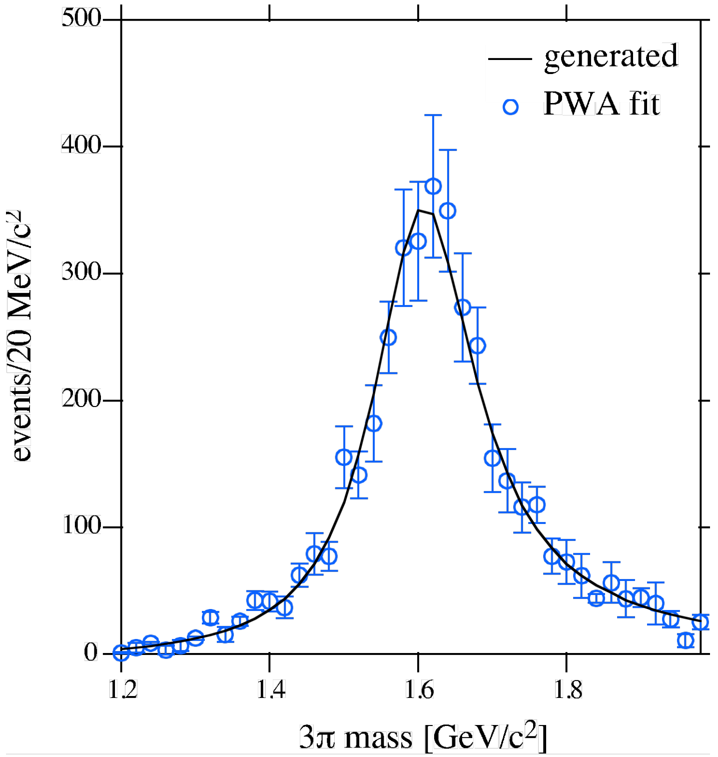


$S = S_1 + S_2$

$J = L + S$

$P = (-1)^{L+1}$

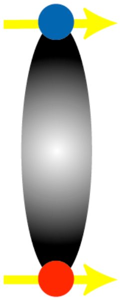
$C = (-1)^{L+S}$



First excited state of flux tube has $J^{PC}=1^{+-}$ or 1^{-+}

combined with S=1 for quarks results in

$J^{PC} = 0^{-+} \quad 0^{+-} \quad 1^{+-} \quad 1^{-+} \quad 2^{-+} \quad 2^{+-}$



exotic

(mass ~ 1.7 – 2.3 GeV)

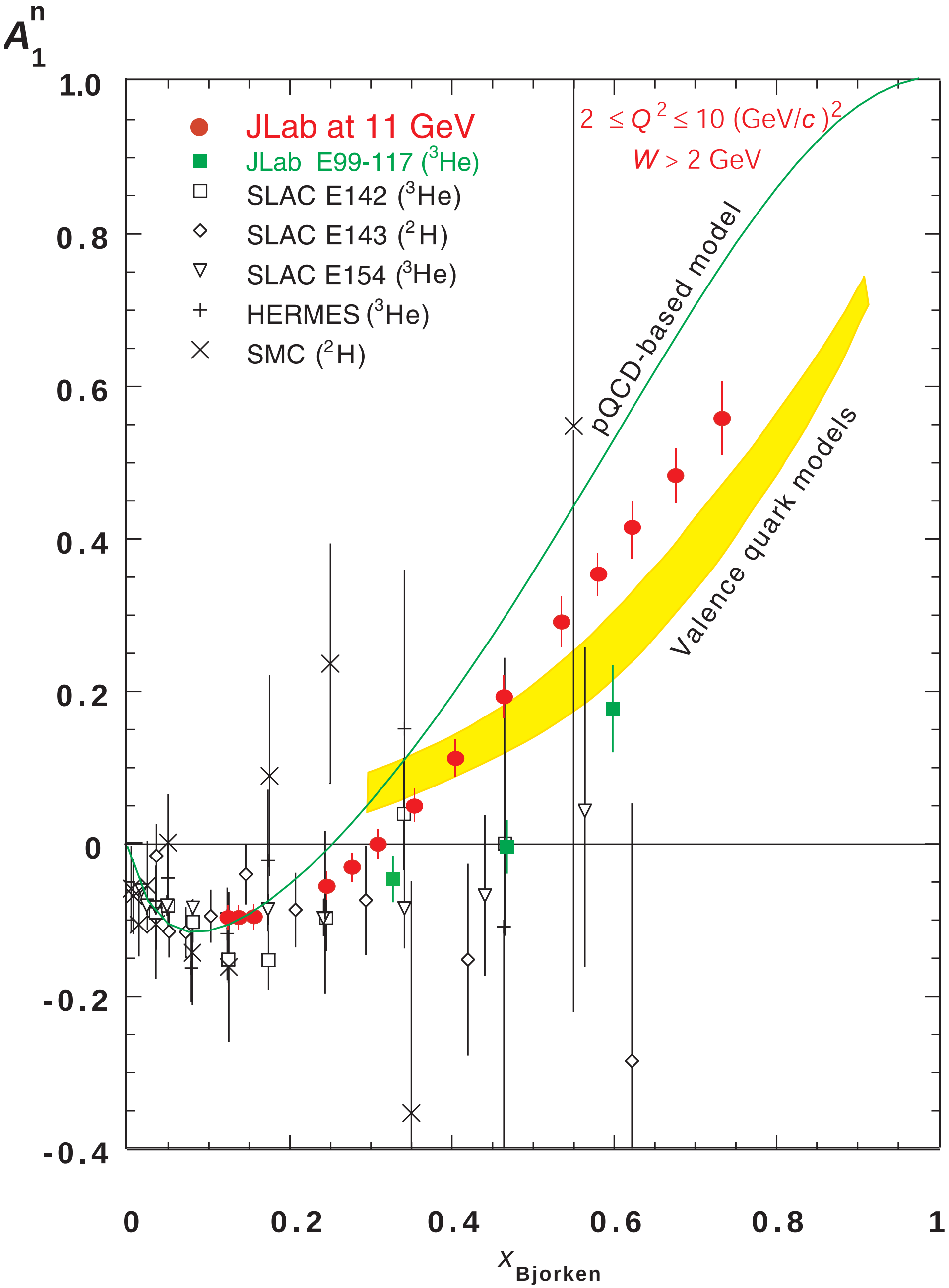
Double-blind Monte Carlo simulation:

2 % exotic signal clearly visible

A. Szczepaniak

Photons couple to exotic mesons via γ→ VM transition (same spin configuration)

Quark Distributions at Large x



pQCD (helicity conservation)

$$A_1^n \to 1$$

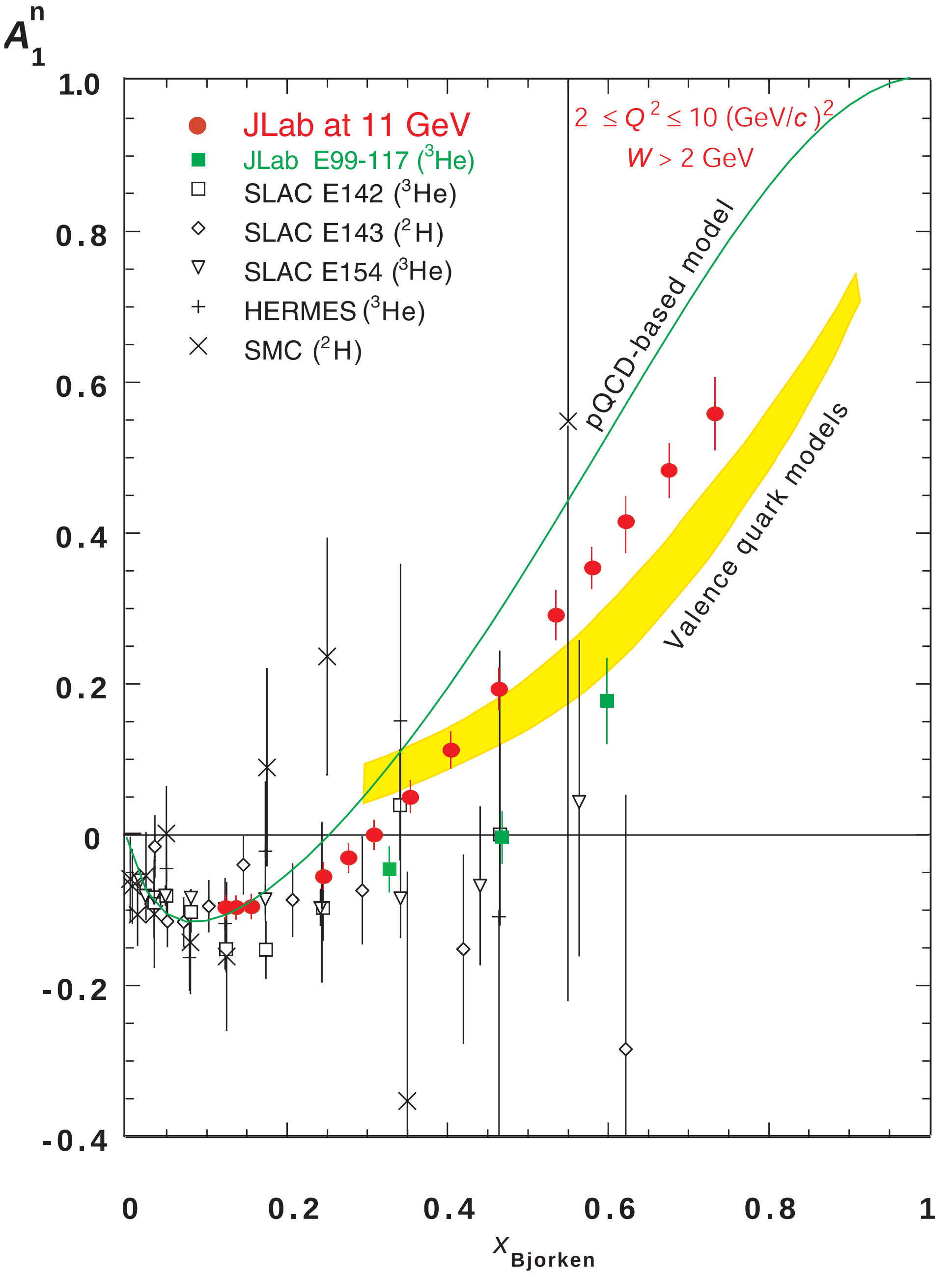
scalar diquark dominance

$$A_1^n \to 1$$

SU(6) symmetry

$$A_1^n = 0$$

Quark Distributions at Large x



pQCD (helicity conservation)

$$\frac{\Delta u}{u} \to 1\,, \quad \frac{\Delta d}{d} \to 1$$

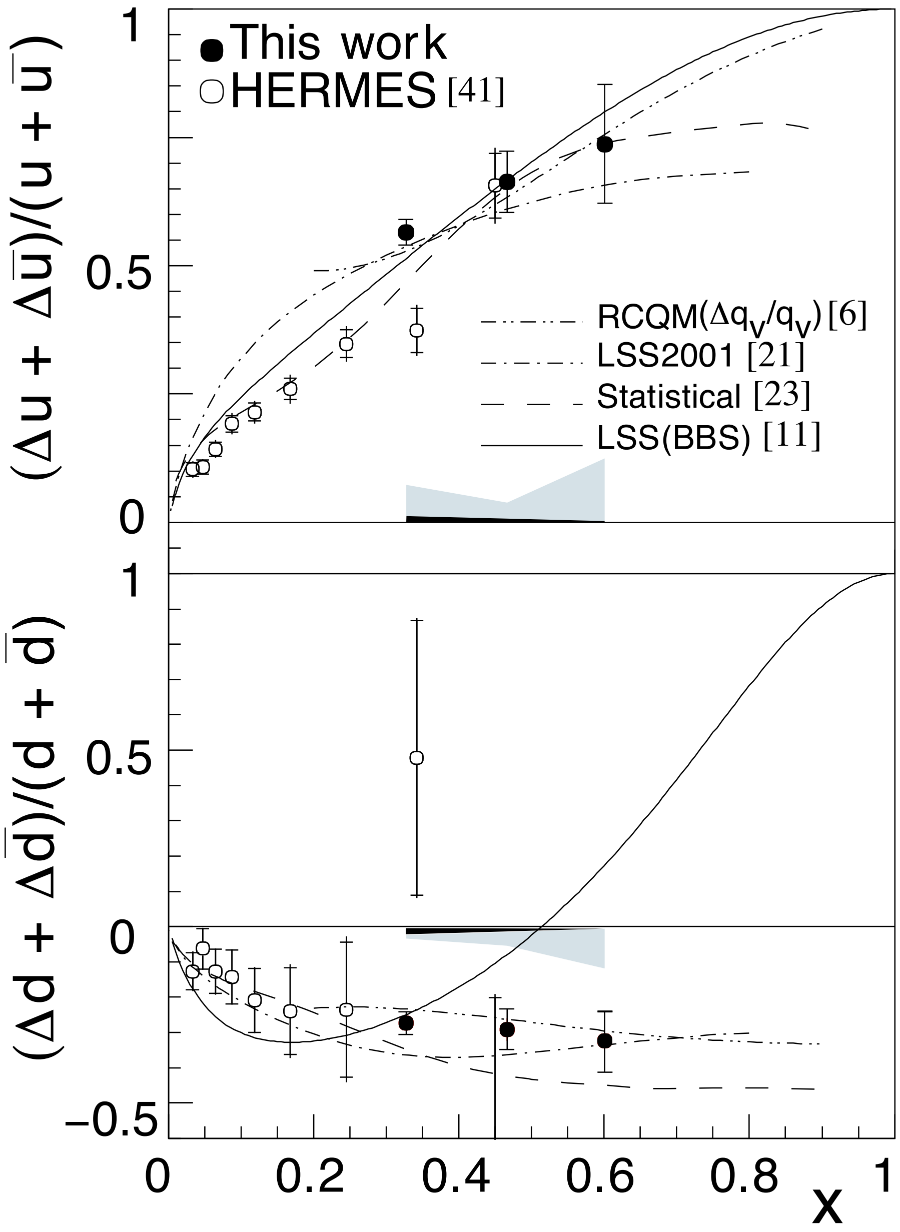
scalar diquark dominance

$$\frac{\Delta u}{u} \to 1\,, \quad \frac{\Delta d}{d} \to -\frac{1}{3}$$

SU(6) symmetry

$$\frac{\Delta u}{u} = \frac{2}{3}\,, \quad \frac{\Delta d}{d} = -\frac{1}{3}$$

Quark Distributions at Large *x*



pQCD (helicity conservation)

$$\frac{\Delta u}{u} \to 1\,, \quad \frac{\Delta d}{d} \to 1$$

scalar diquark dominance

$$\frac{\Delta u}{u} \to 1\,, \quad \frac{\Delta d}{d} \to -\frac{1}{3}$$

SU(6) symmetry

$$\frac{\Delta u}{u} = \frac{2}{3}\,, \quad \frac{\Delta d}{d} = -\frac{1}{3}$$

Other 12 GeV Campaigns

Generalized parton distributions
(deeply virtual Compton scattering/deep meson production)

Semi-inclusive DIS
(flavor decomposition, k_T dependent distributions)

Parity violation in DIS

Pion form factor at high Q^2

Nuclear EMC effect
(spin & flavor dependence)

Quark propagation through matter

DOE Critical Decisions

CD	DOE Meaning	Implications of CD Approval	Time
CD-0	Approve Mission Need	Formal CDR work begins using DOE funds R&D for CDR begins PED funds can be requested Acquisition plan developed Serious search for non-DOE/NP funding	April 2004
CD-1	Approve Preliminary Baseline Range	Lehman review of CDR and approval PED funds can be spent	~August 2005
CD-2	Approve Performance Baseline	Second Lehman review to establish budget, schedule and performance Long-lead procurements begin Request construction funding	2006/7 ??
CD-3	Approve Start of Construction	Construction begins in earnest	2008/9 ??
CD-4	Approve Start of Operations	**Science begins!**	2013 ??

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.

The End