Shape and Structure of the Nucleon

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Outline:

- From form factors & quark distributions to GPDs
- Shape of the proton
  - Elastic scattering
  - NΔ(1232) transition
- The size of constituent quarks
- "Tomography" of the nucleon
  - Deeply Virtual Compton Scattering
  - Real Compton Scattering at high momentum transfer
- Conclusions

From form factors & quark distributions to GPDs

1950 Does the proton have finite size and structure?

- Elastic electron-proton scattering
  - charge and current distribution in the proton, F_1/F_2

1960 What is the internal structure of the proton?

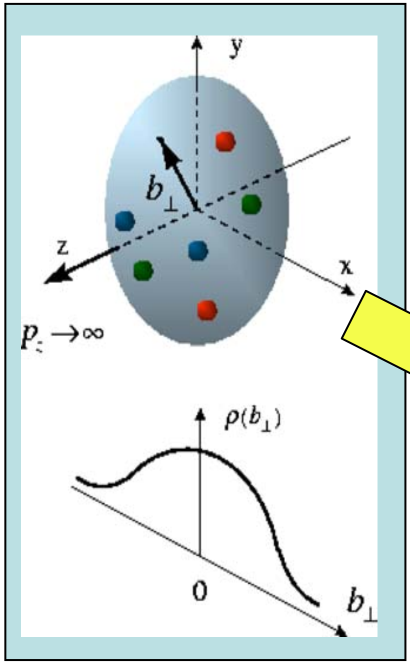
- Constituent quarks
- Elementary quarks (and gluons)
  - momentum & helicity distributions

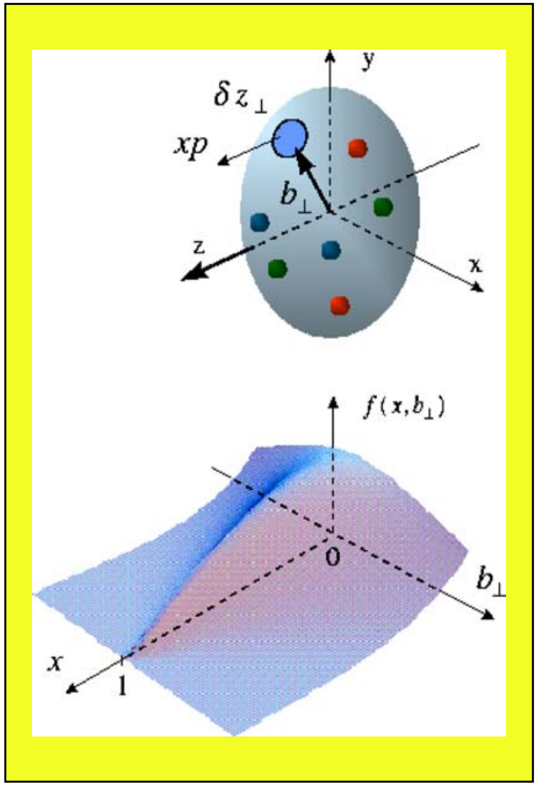
Today Beyond form factors and quark distributions

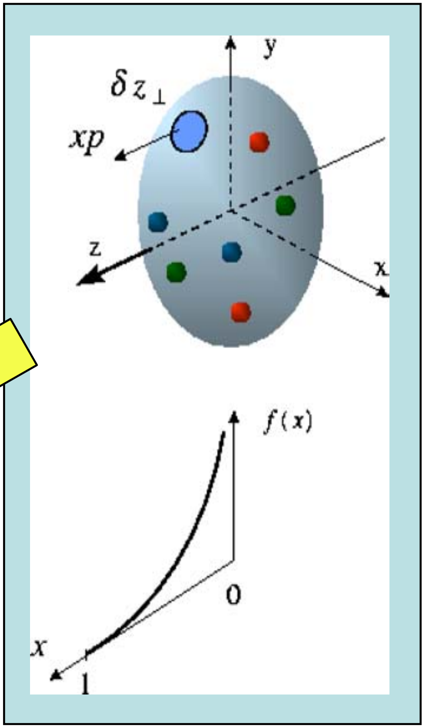
- How are these representations of the proton, form factors and quark distributions, connected?

Beyond form factors and quark distributions – Generalized Parton Distributions (GPDs)

X. Ji, D. Mueller, A. Radyushkin (1994-1997)







Proton form factors, transverse charge & current densities

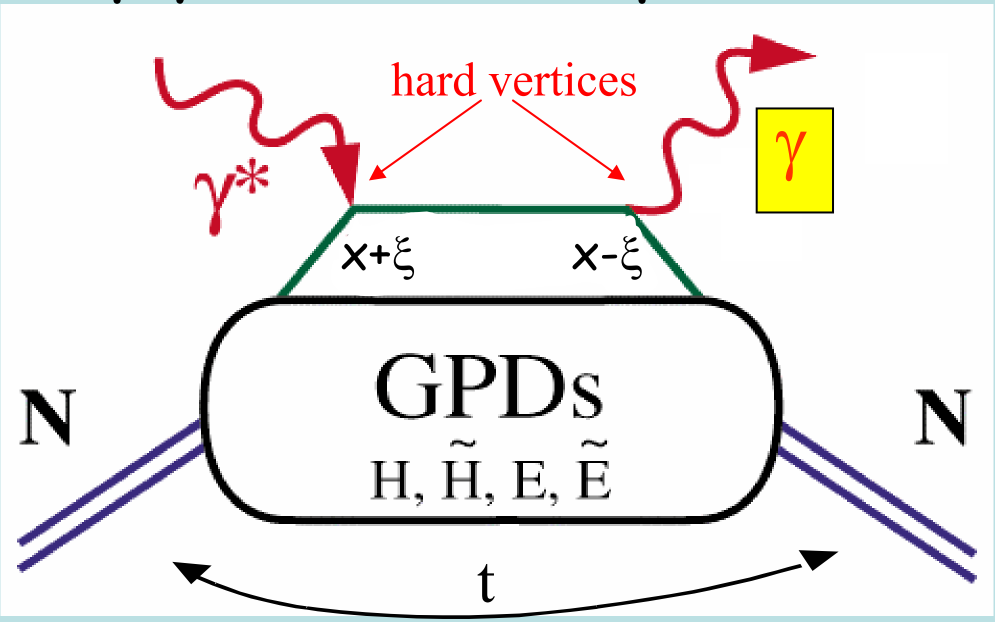
Correlated quark momentum and helicity distributions in transverse space - GPDs

Structure functions, quark longitudinal momentum & helicity distributions

GPDs & Deeply Virtual Exclusive Processes

"handbag" mechanism

Deeply Virtual Compton Scattering (DVCS)



x – quark momentum fraction

ξ– longitudinal momentum transfer

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

$H(x,\xi,t), E(x,\xi,t), \ldots$

Link to DIS and Elastic Form Factors

$$H^q, E^q, \widetilde{H}^q, \widetilde{E}^q(x,\xi,t)$$

DIS at $\xi = t = 0$

$$H^q(x,0,0) = q(x), \quad -\bar{q}(-x)$$

$$\widetilde{H}^q(x,0,0) = \Delta q(x), \quad \Delta\bar{q}(-x)$$

Form factors (sum rules)

$$\int^1 dx \sum_q \left[H^q(x,\xi,t) \right] = F_1(t) \quad \text{Dirac f.f.}$$

$$\int^1 dx \sum_q \left[E^q(x,\xi,t) \right] = F_2(t) \quad \text{Pauli f.f.}$$

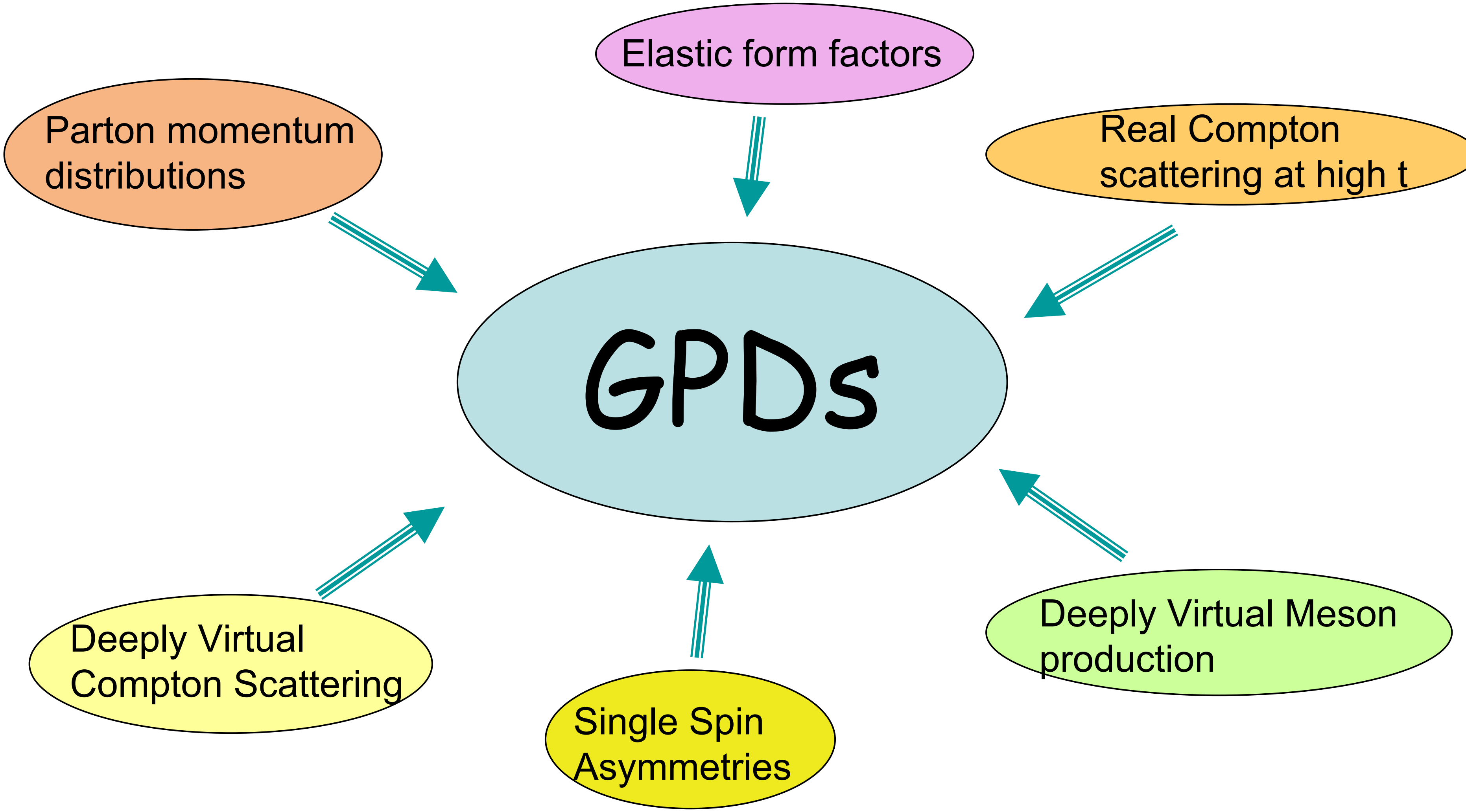
$$\int_{-1}^{1} dx\, \widetilde{H}^q(x,\xi,t) = G_{A,q}(t), \quad \int_{-1}^{1} dx\, \widetilde{E}^q(x,\xi,t) = G_{P,q}(t)$$

Quark angular momentum (Ji's sum rule)

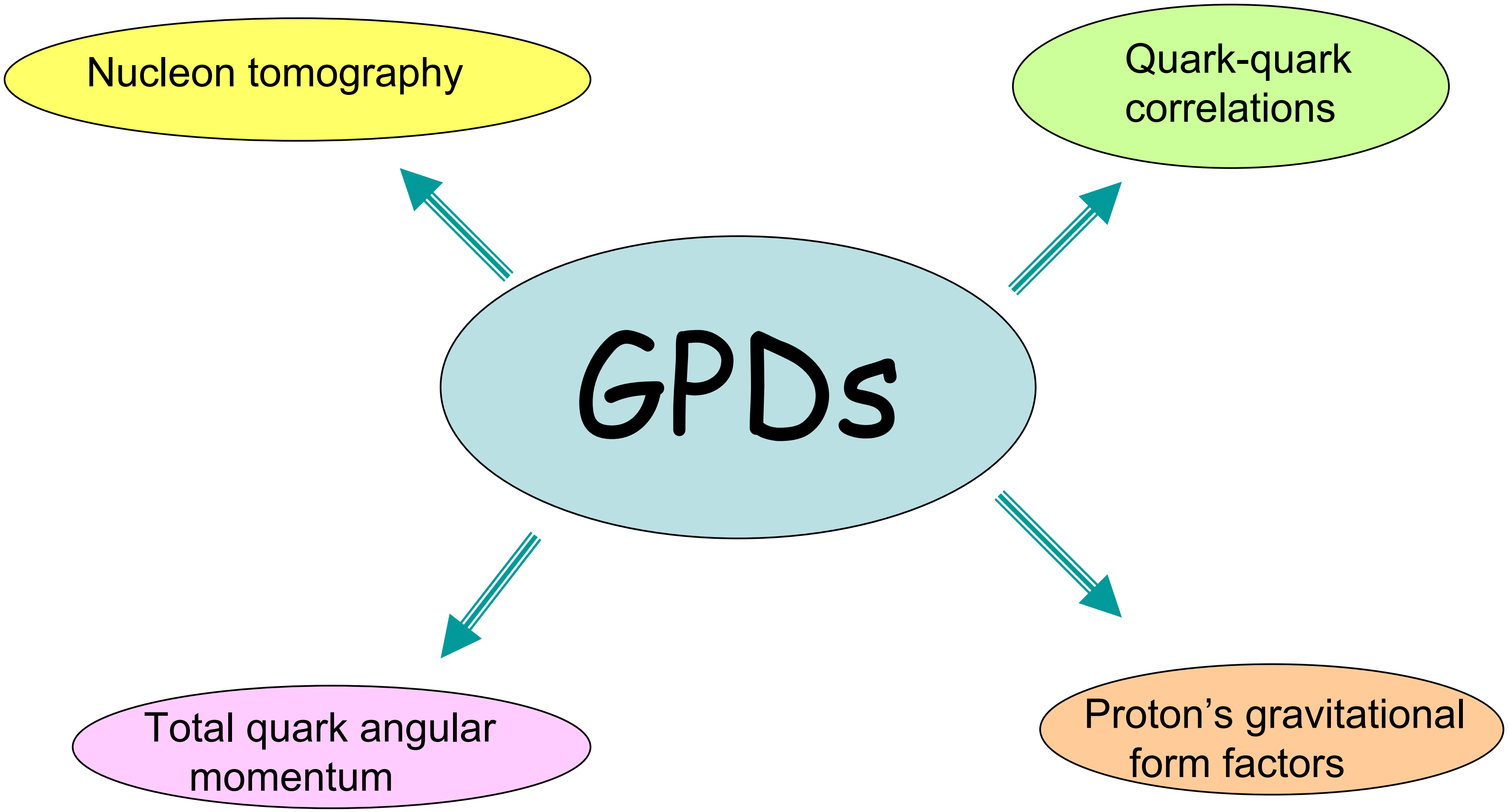
$$J^q = \frac{1}{2} - J^G = \frac{1}{2} \int_{-1}^{1} x dx \left[H^q(x,\xi,0) + E^q(x,\xi,0) \right]$$

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

Universality of Generalized Parton Distributions

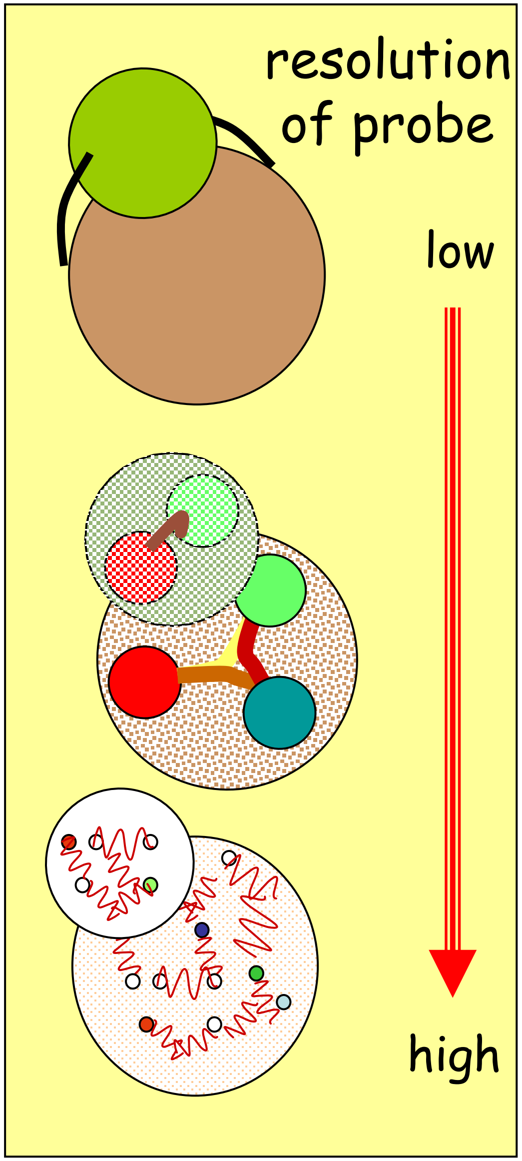


Universality of Generalized Parton Distributions

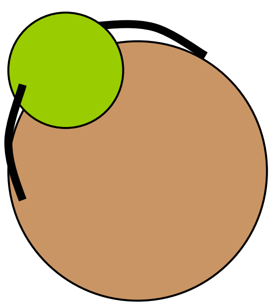


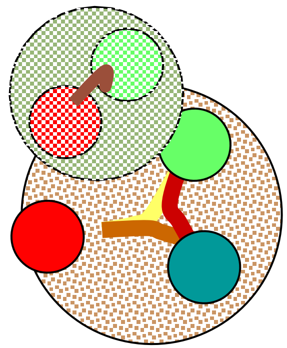
Towards a consistent description and fundamental interpretation of nucleon structure

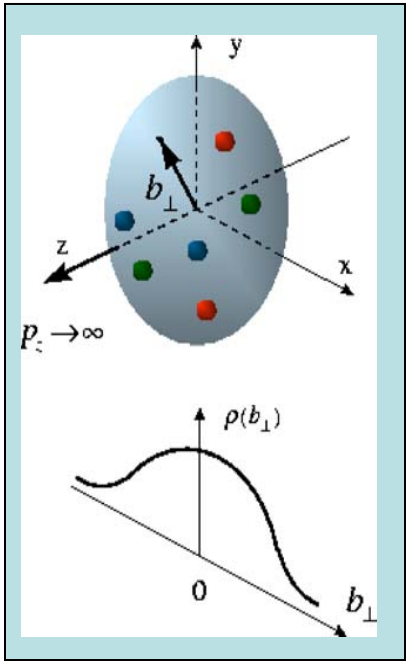
- Interpretation of precise data on e.m. form factors and NΔ transition within hadronic models and Lattice QCD.
- Moments of inclusive structure functions probe constituent quarks as extended objects.
- Analysis of JLab (and DESY) data in terms of GPDs is leading to fundamentally new insights into nucleon structure at the amplitude level.

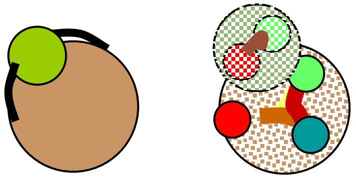


Elastic Form Factors and NΔ(1232) Transition at low and intermediate Q^2



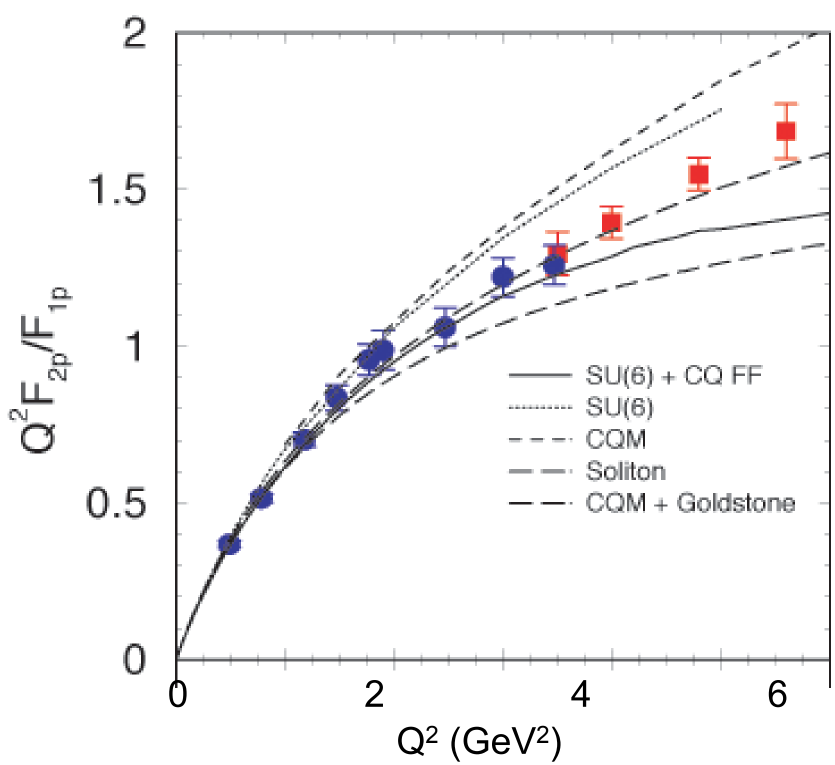






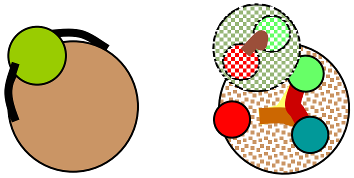
Elastic Electron Proton Scattering

JLab/Hall A



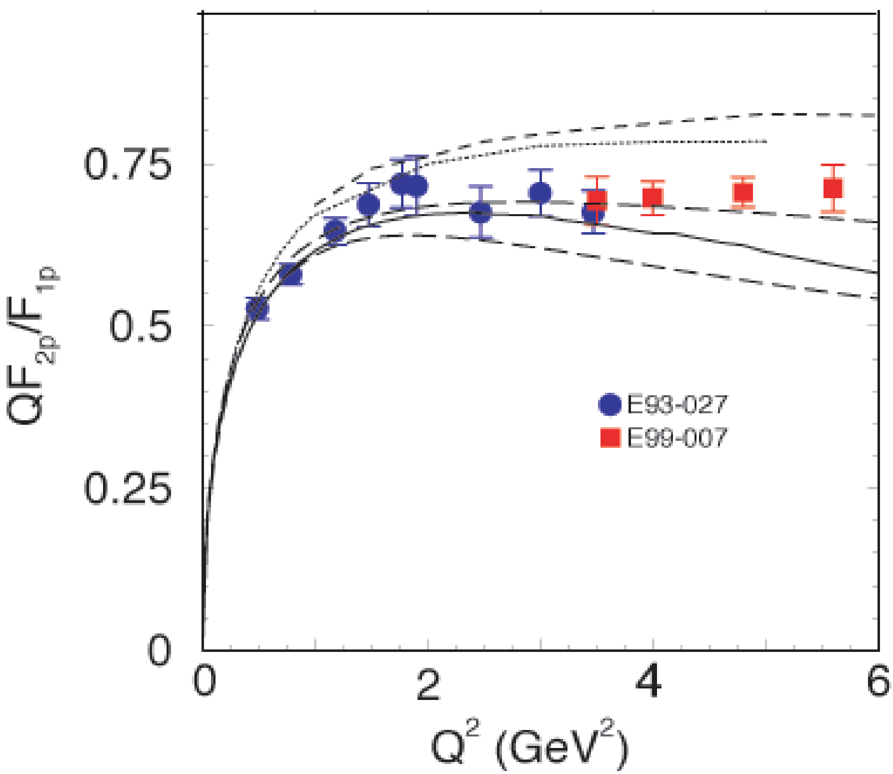
M. Jones et al., PRL84 (2000) 1398
O. Gayou et al., PRL88 (2002) 092301

- Data exclude asymptotic pQCD scaling (Brodsky et al.) for the ratio of Pauli and Dirac form factors
  $F_2(Q^2)/F_1(Q^2) \sim 1/Q^2$
  at $Q^2 < 6$ GeV².
- In relativistic constituent quark models this is explained by $K_\perp \neq 0$ contributions of the quarks leading to orbital angular momentum. At moderate Q^2 one predicts "scaling" like
  $F_2(Q^2)/F_1(Q^2) \sim 1/Q$



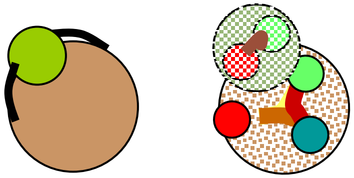
Elastic Electron Proton Scattering

JLab/Hall A



- $F_2(Q^2)/F_1(Q^2) \sim 1/Q$ scaling works for $Q^2 \sim$ 2-6 GeV^2
- Data can also be described with pQCD scaling if orbital angular momentum effects are included (A. Belitsky, X. Ji, F. Yuan, 2003) $F_2(Q^2)/F_1(Q^2) \sim \ln^2(Q^2/\Lambda^2_{QCD})/Q^2$ Absolute normalization uncertain.

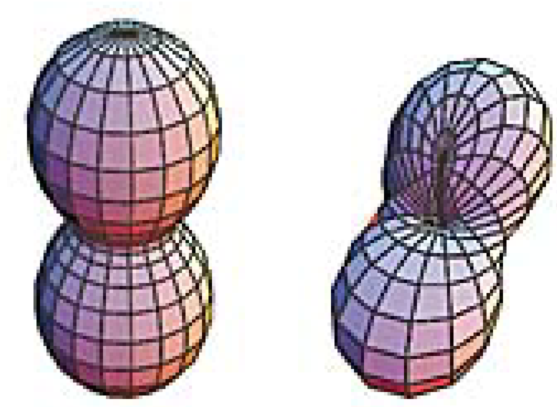
These data generated much interest in the community, are leading to numerous theoretical papers, and ……



The Proton's Shape and JLab in The New York Times

It's a Ball. No, It's a Pretzel. Must Be a Proton. (K. Chang, NYT, May 6, 2003)

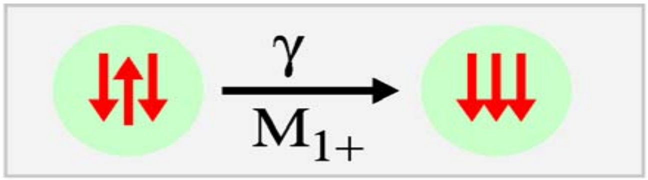
In relativistic constituent quark models with orbital angular momentum, the proton's shape is found to depend on the specific spin-polarization of the quarks relative to the proton polarization.



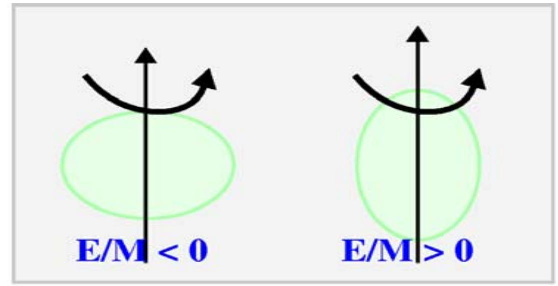
quark spin parallel to that of the proton (left), quark spin perpendicular to the proton spin (right).

G. Miller, arXiv:nucl-th/0304076

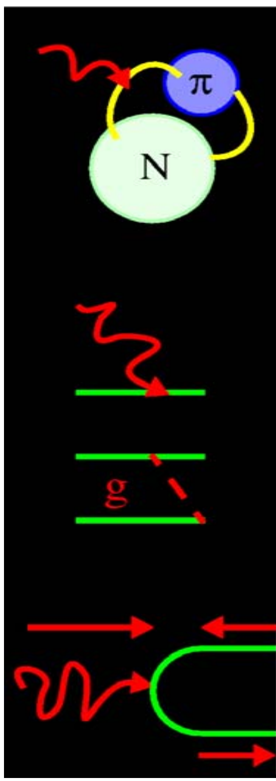
NΔ(1232) Quadrupole Transition



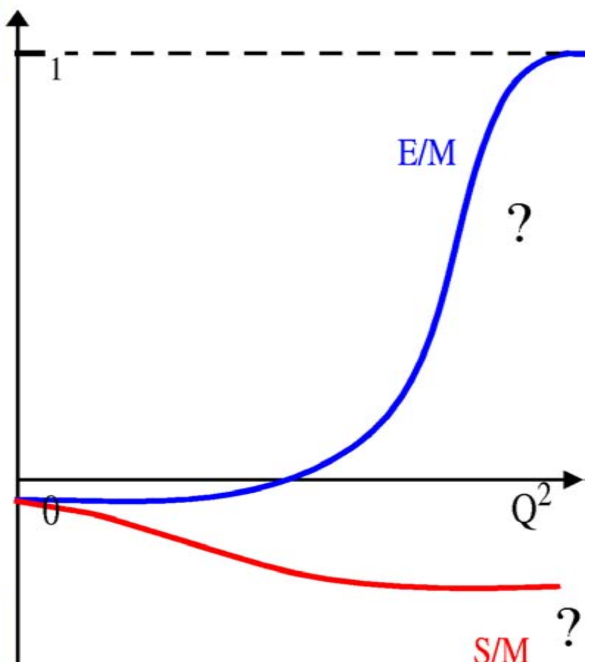
$$SU(6): E_{1+} = S_{1+} = 0$$



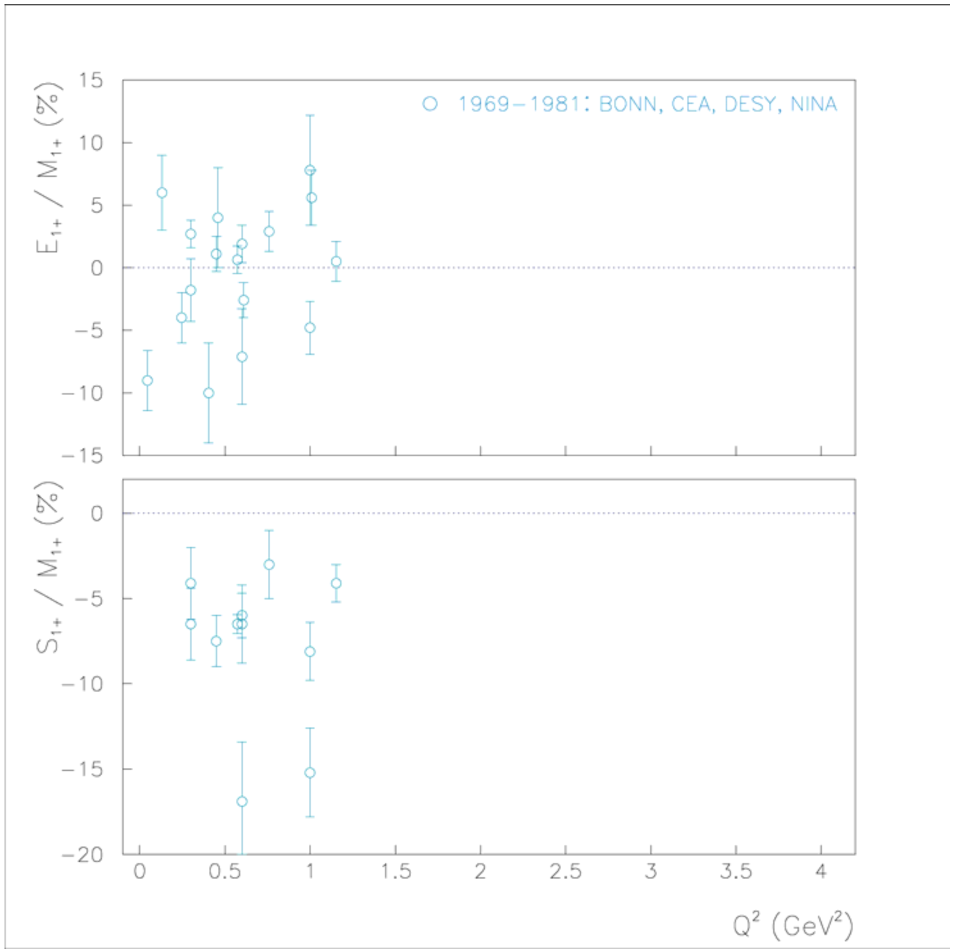
(A. Buchmann, E. Henley, 2000)



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



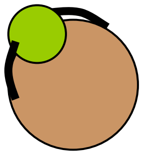
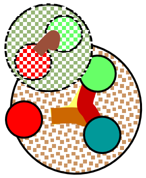
Multipole Ratios R_{EM}, R_{SM} before 1999



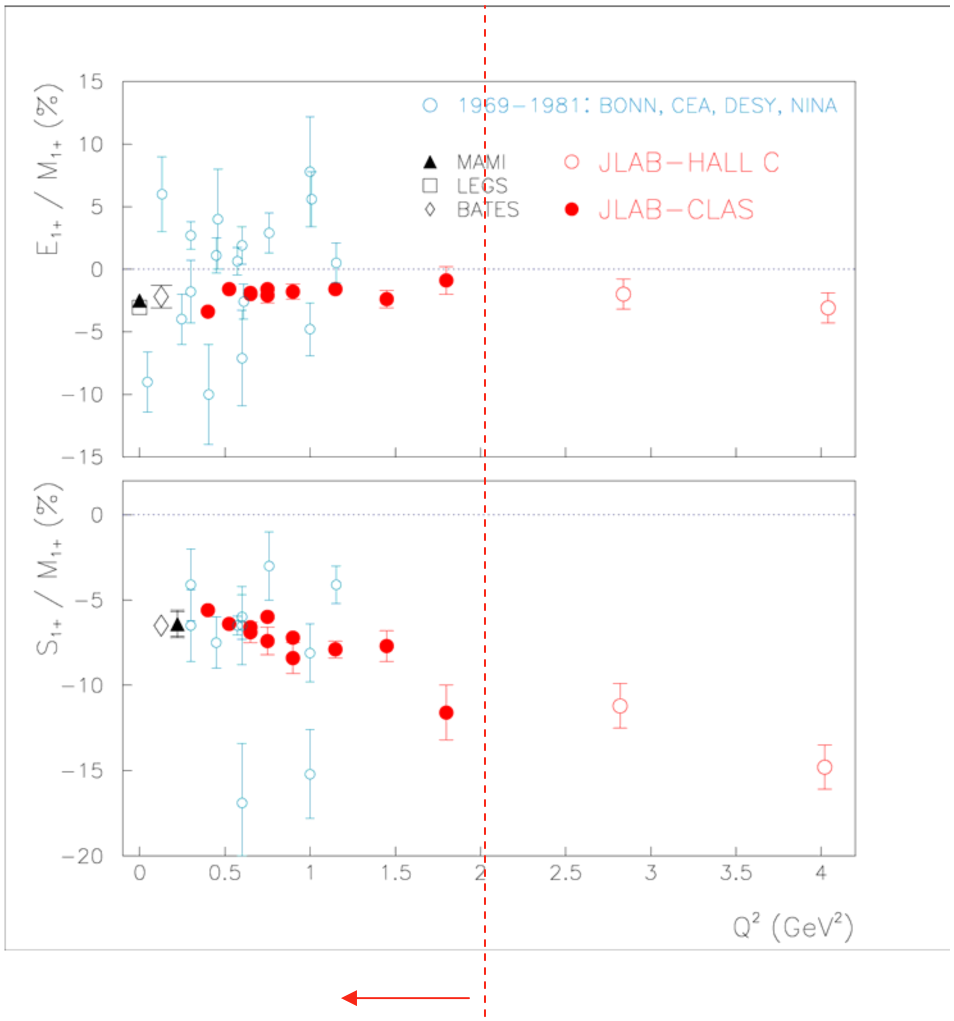
Sign?

Q^2 dependence?

- Data could not determine sign or Q^2 dependence

Multipole Ratios R_{EM}, R_{SM} in 2002



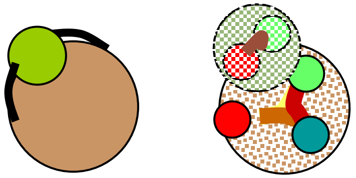
Sign?

< 0 !

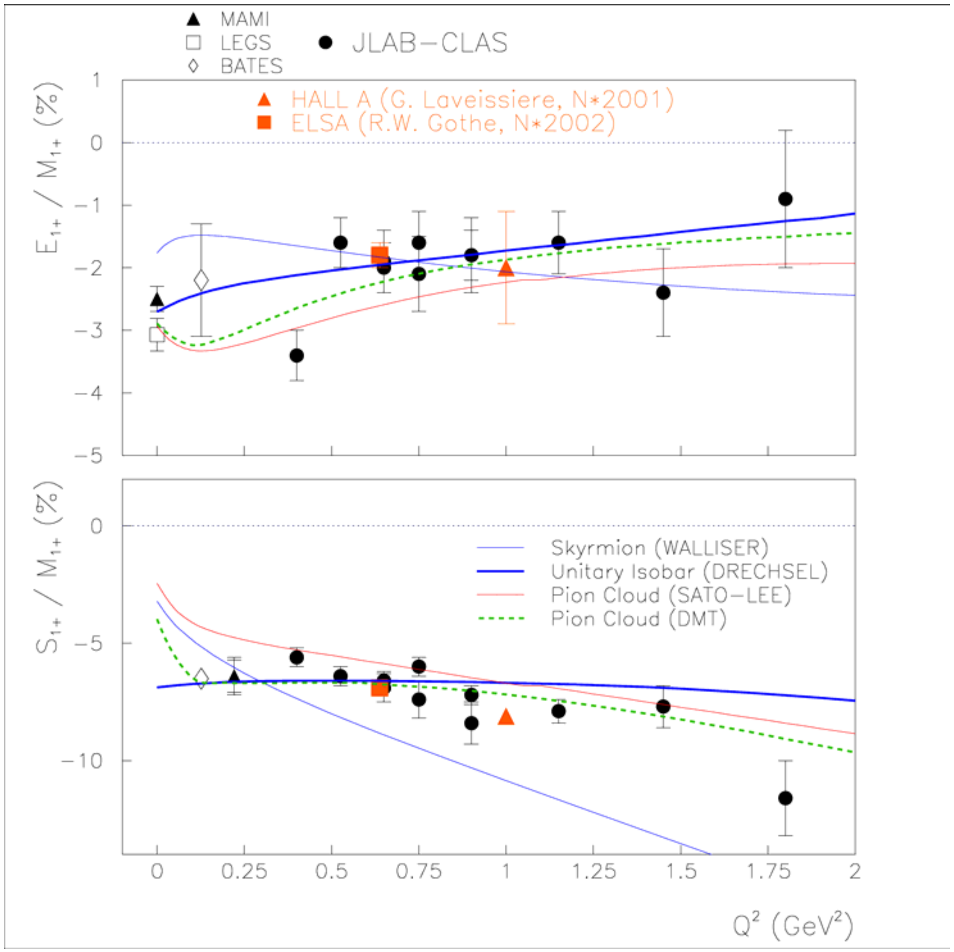
Q^2 dependence !

Slope < 0

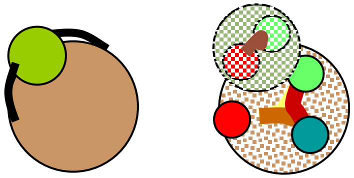
➢ No trend towards pQCD behavior is observed for Q^2 up to 4 GeV^2.



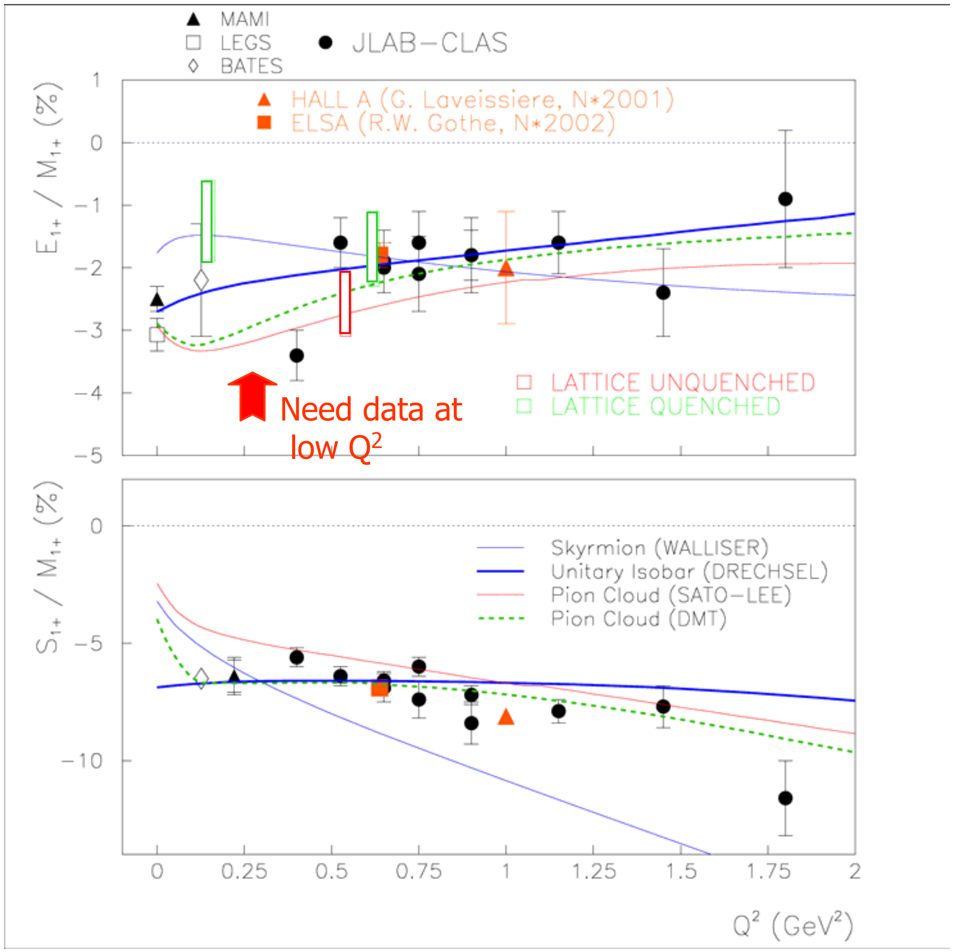
NΔ(1232) Transition



Preliminary results from ELSA and Hall A using different techniques confirm CLAS data.



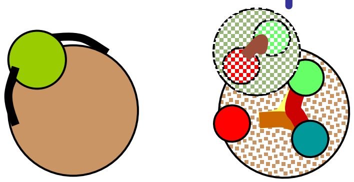
NΔ(1232) Transition



Lattice QCD indicates that the pion cloud makes E_{1+}/M_{1+} more negative at small Q^2, consistent with dynamical models.

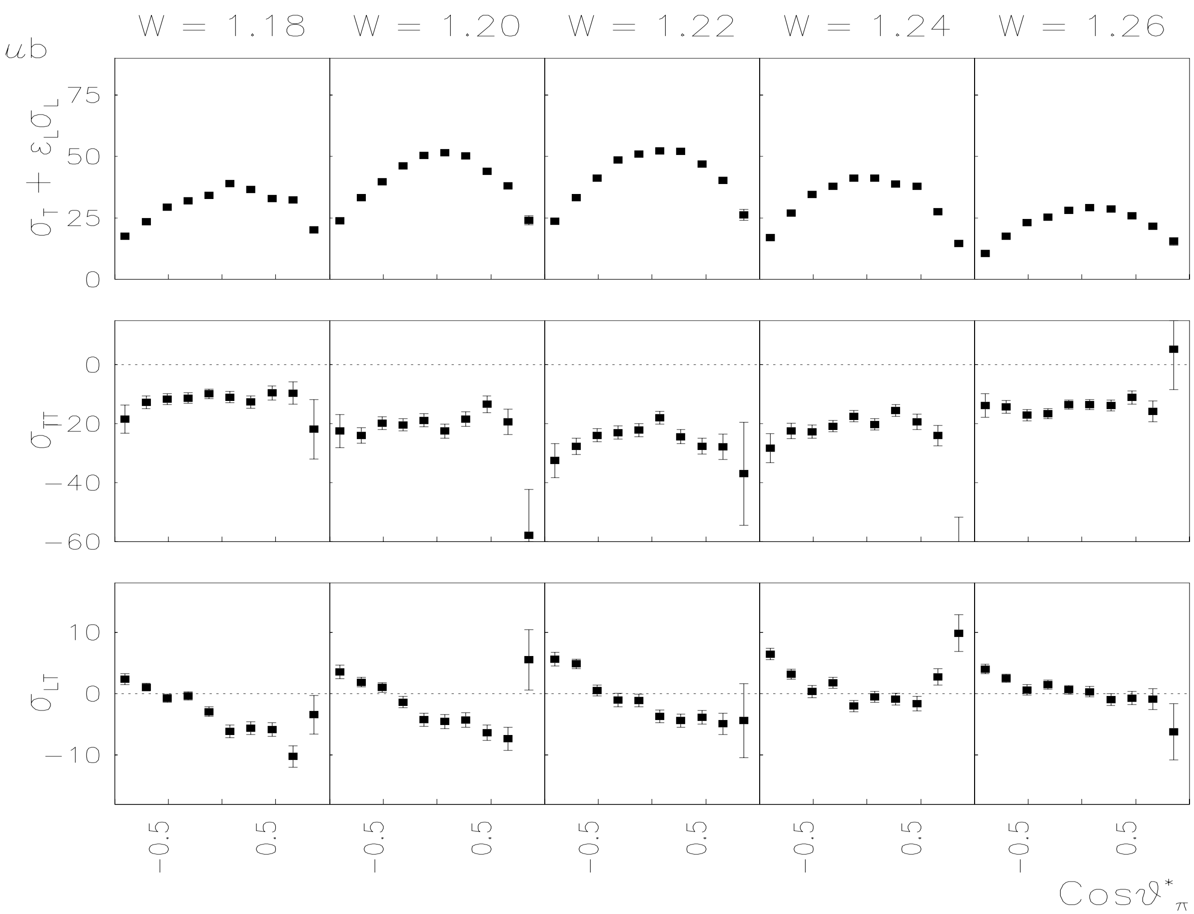
Data at low Q^2 needed to study effect of pion cloud.

Response Functions from π^0 Electroproduction in the $\Delta(1232)$ Region

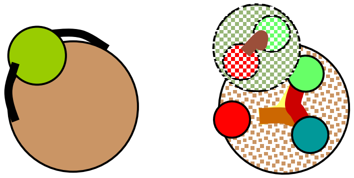


$$d\sigma/d\Omega = \sigma_T + \varepsilon\sigma_L + \varepsilon\sigma_{TT}\cos 2\phi + \sqrt{\varepsilon(\varepsilon+1)}\sigma_{LT}\cos\phi; \quad \sigma_i(\cos\theta^*, W)$$

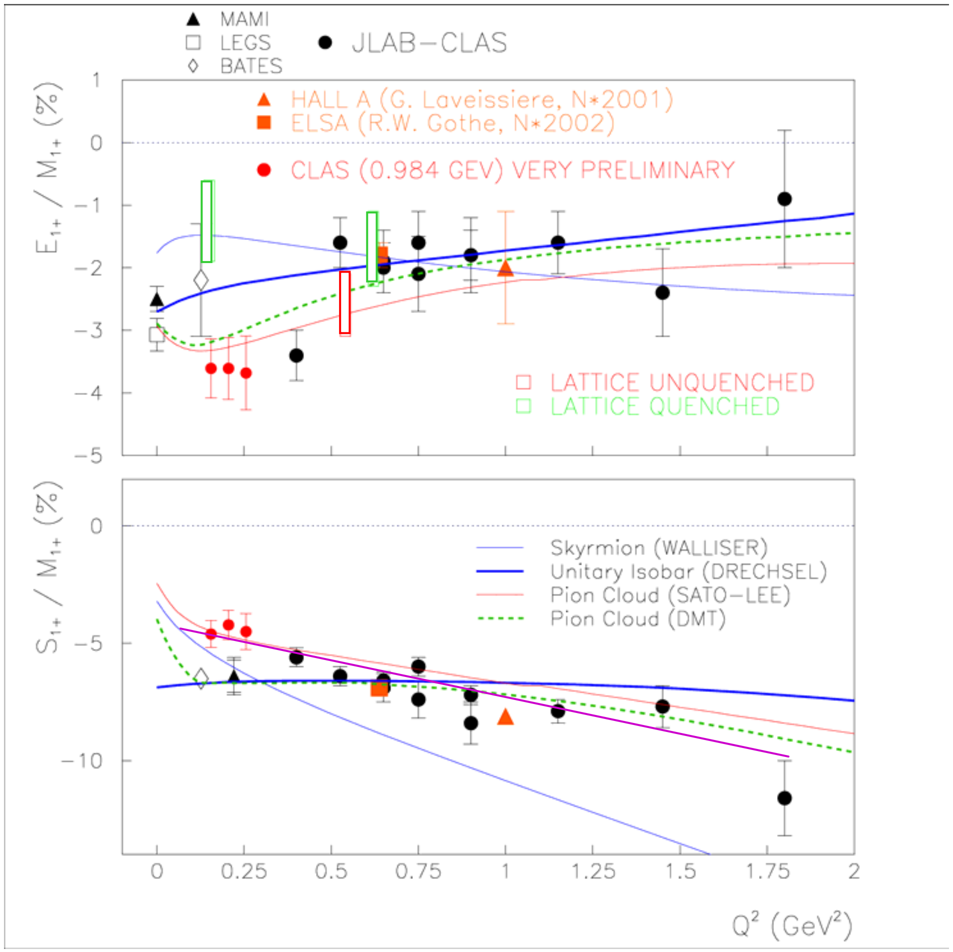
Q^2=0.2 GeV^2



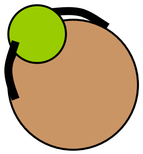
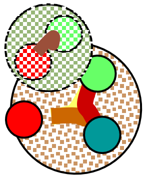
CLAS Preliminary



NΔ(1232) Transition



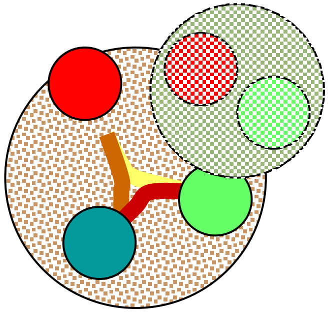
- R_{EM} < 0, and shows little indication of a zero crossing for Q^2 < 4 GeV^2; asymptotic pQCD not relevant in this Q^2 regime.
- Dynamical models and full LQCD calculations indicate the importance of the pion cloud at low Q^2 consistent with the trend of data.
- Full LQCD results indicate a small oblate deformation of the Δ(1232).

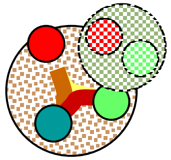
NΔ(1232) - Current experiments and future prospects

- Data with much higher statistics currently being analyzed (CLAS) covering Q^2 = 0.1 – 5.5 GeV^2
- Experiment E-01-002 in (Hall C), currently taking data at highest Q^2 = 6.5 – 7.7 GeV^2 reachable with presently available beam
- R_{EM} and R_{SM} can be measured up to Q^2 ~ 12 GeV^2 after the energy upgrade to 12 GeV

Constituent Quarks as Extended Objects?



How Big are Constituent Quarks ?



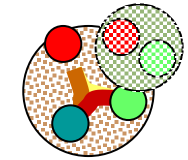
- The Constituent Quark Model has been the most successful model in hadronic physics, describing many properties of baryons and mesons.

- Constituent Quark (CQ) masses are inferred from baryon masses: $M_{u/d}$~330MeV, M_s~500MeV.

- If CQs have masses much larger than elementary quarks, do they have a physical size?

- CQs may be probed in inclusive electron scattering at intermediate energies and momentum transfer.

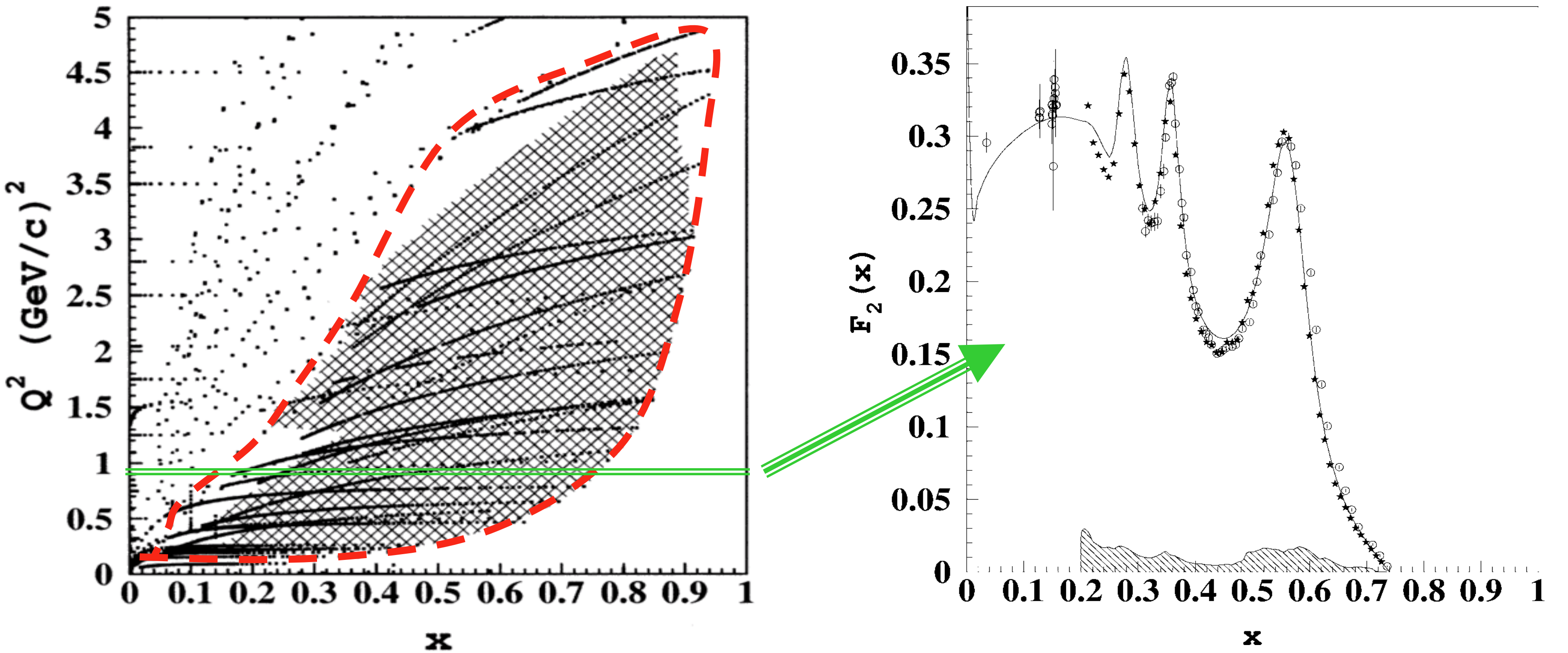
Evidence for Constituent Quarks as Extended Objects?



I. Niculescu et al., PRL 85 ,2000
C. S. Armstrong et al., PRD 63, 2001
M. Osipenko et al., PRD 67, 2003

CLAS, Hall C & world data on F_2

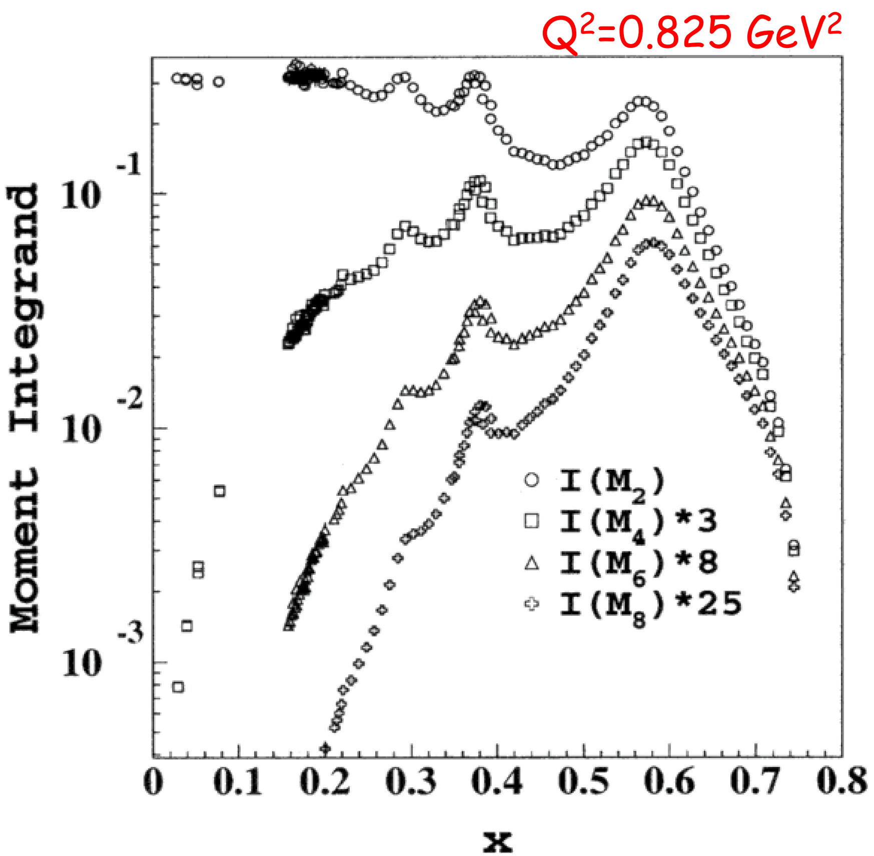
$F_2(x, Q^2)$ @ Q^2=0.825 GeV^2

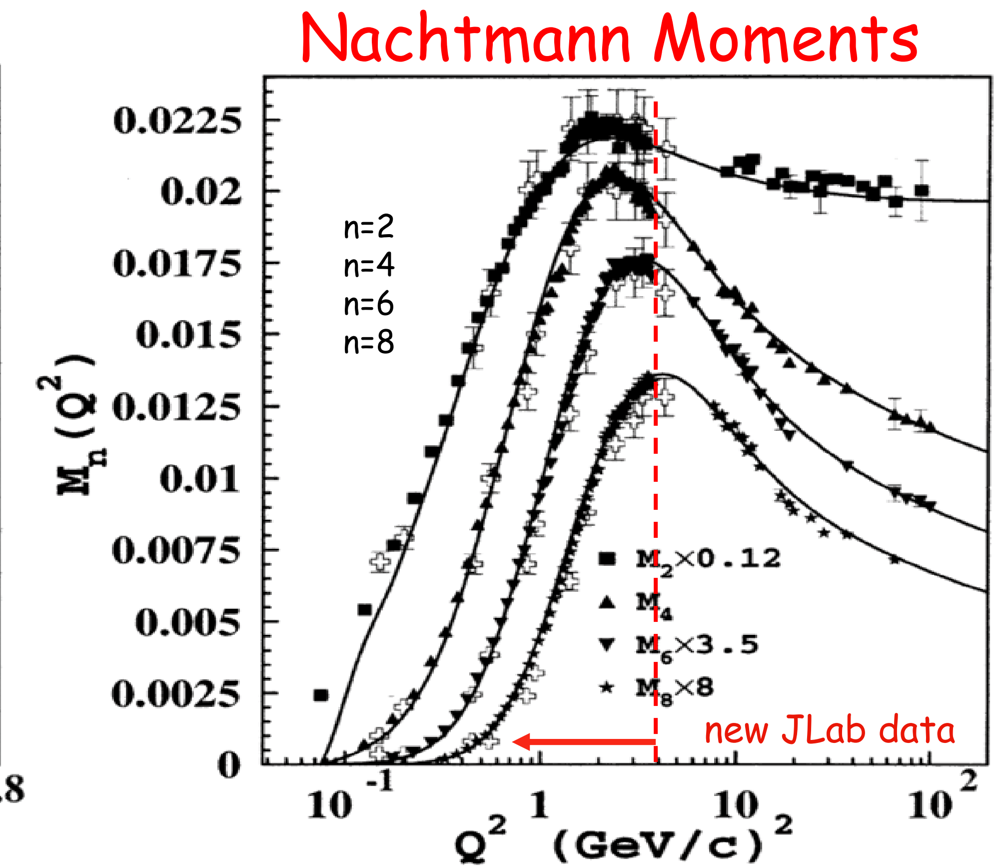


$$M_n(Q^2) = \int_0^1 dx F_2(x,Q^2) \frac{\xi^{n+1}}{x^3} \frac{3+3(n+1)r + n(n+2)r^2}{(n+2)(n+3)},$$

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

Evidence for Constituent Quarks as Extended Objects?

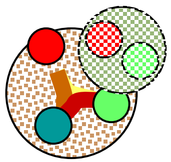




In the Nachtmann moments of $F_2^p(Q^2)$ all kinematical corrections which are due to the finite target mass, cancel.

- Moments at $Q^2 < 4$ GeV^2 are dominated by JLab data

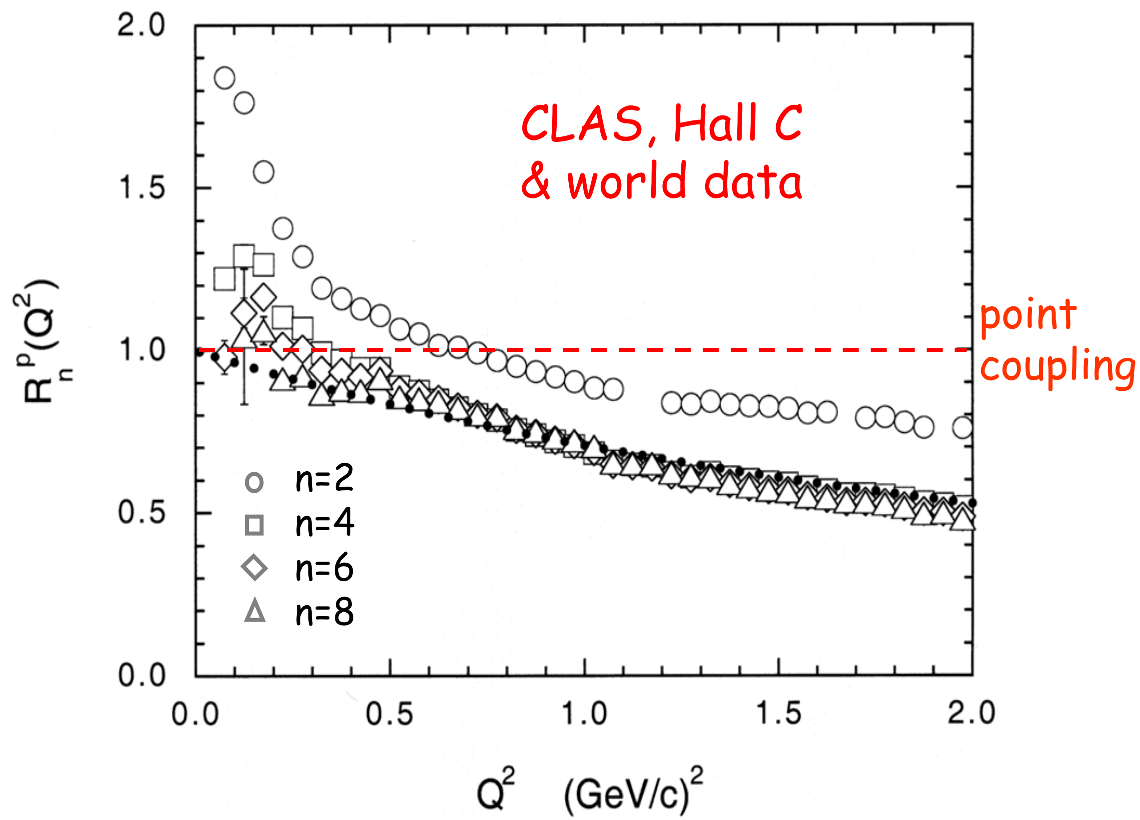
Evidence for Constituent Quarks as Extended Objects?



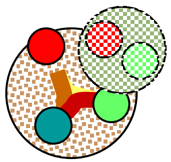
$R_n^p(Q^2) = M_n^p(Q^2)/\overline{M}_n^p(Q^2)$

$\overline{M}_n^p$ - Theoretical moments of the model with pointlike CQs

R. Petronzio, S. Simula, G. Ricco, PRD 67, 09404 (2003)



Evidence for Constituent Quarks as Extended Objects?



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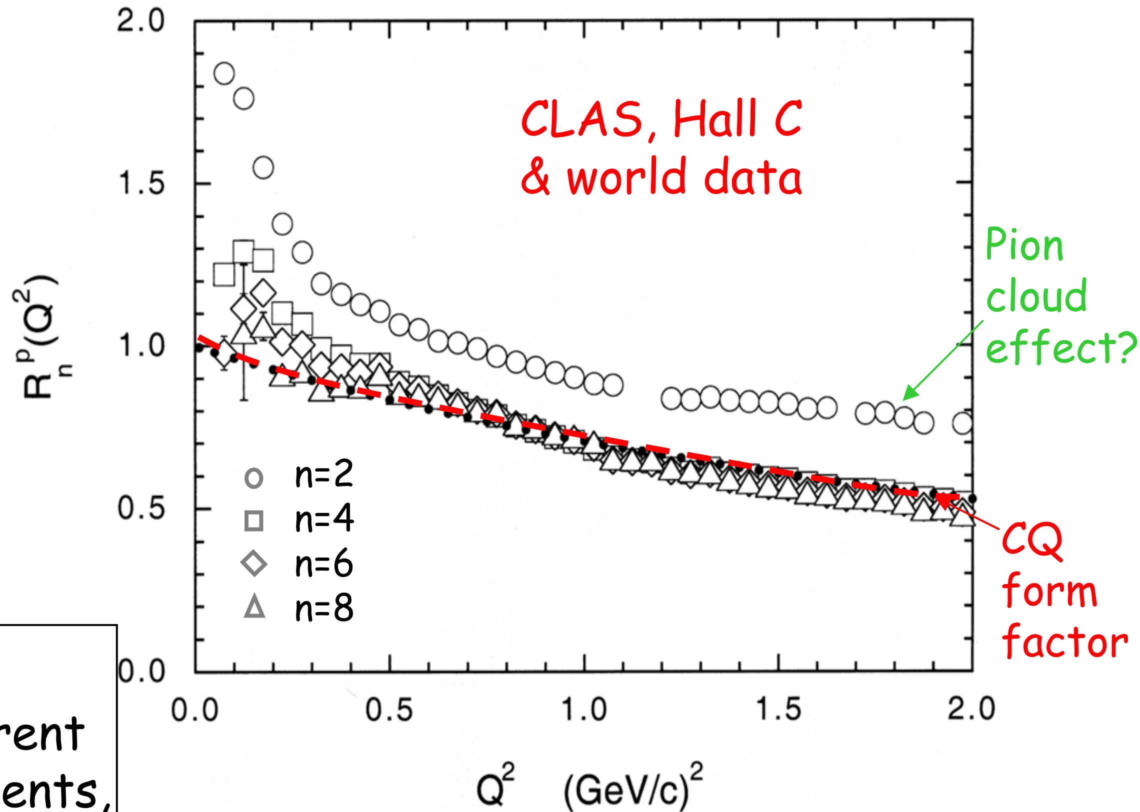
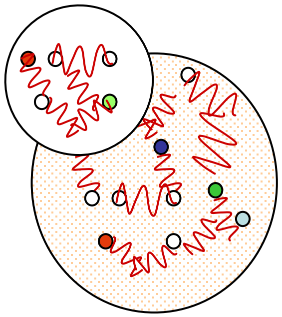


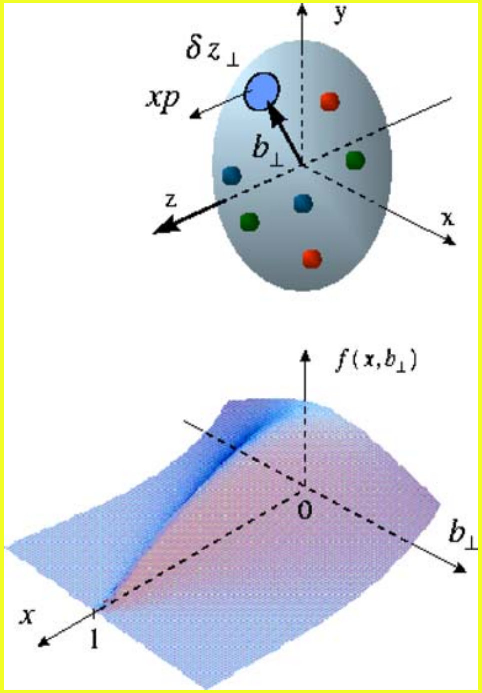
The scaling behavior in the Q^2-dependence observed for different orders n in the Nachtmann moments, is interpreted as "elastic" scattering off CQs with radius ~ 0.2-0.3 fm.

The model also makes predictions for the moments of polarized structure function $g_1(x,Q^2)$.

The Nucleon's Fundamental Structure



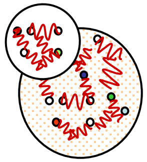
Generalized Parton Distributions



GPDs and the Proton Structure

- A description of the spatial distribution of quarks in the proton has been introduced by *M. Burkardt, M. Diehl, B. Pire and J. Ralston,* and others. It was shown that GPDs allow construction of 2-D images of the proton in the transverse plane for a specific quark momentum fraction x.

- *X. Ji and F. Yuan* have been extended this to 3-D images of the proton's quark distributions for a specific momentum slice.

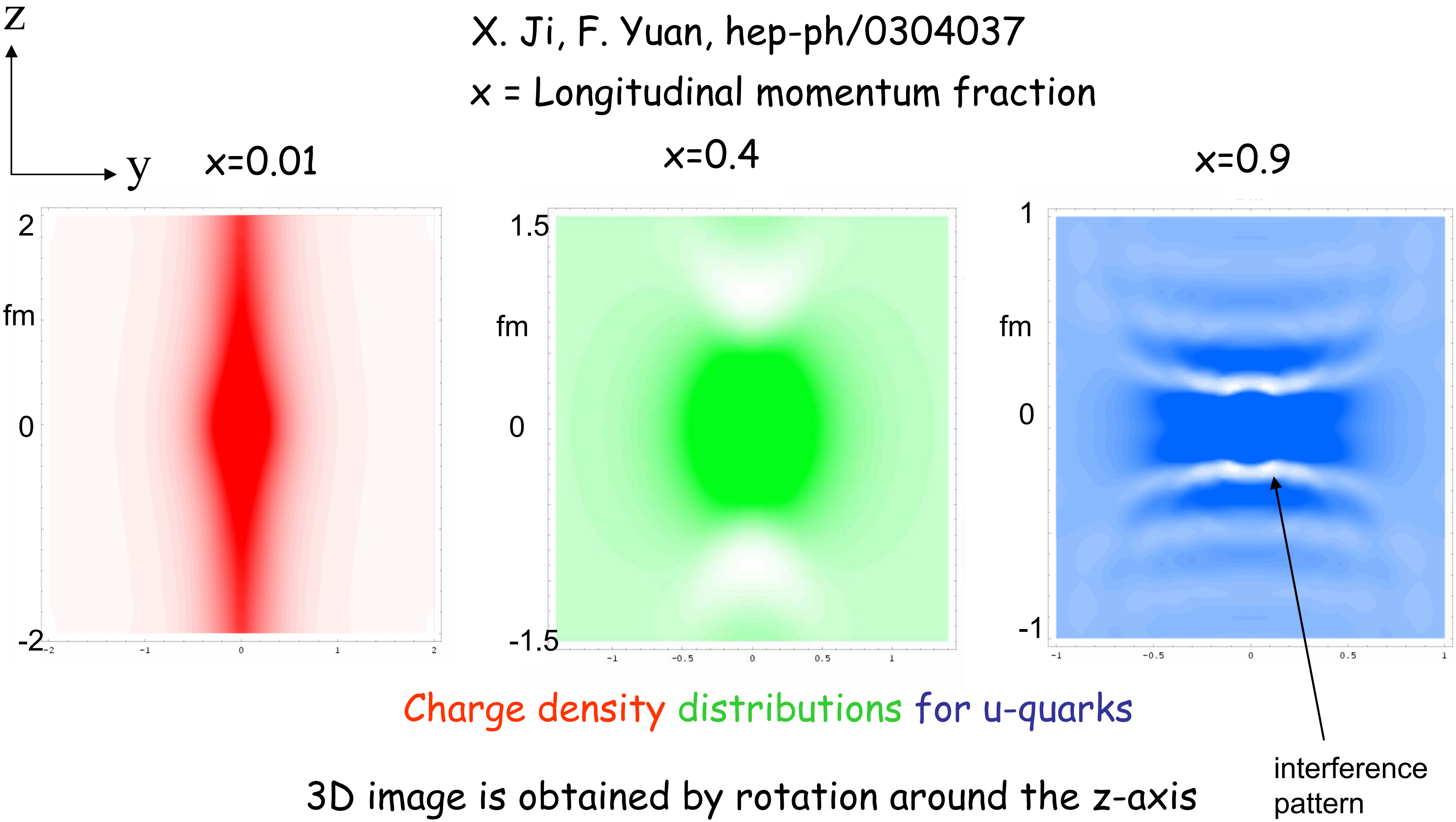


Tomography of u-quarks in the proton.

(using Model GPDs by: Goeke, Polyakov, Vanderhaeghen)

X. Ji, F. Yuan, hep-ph/0304037

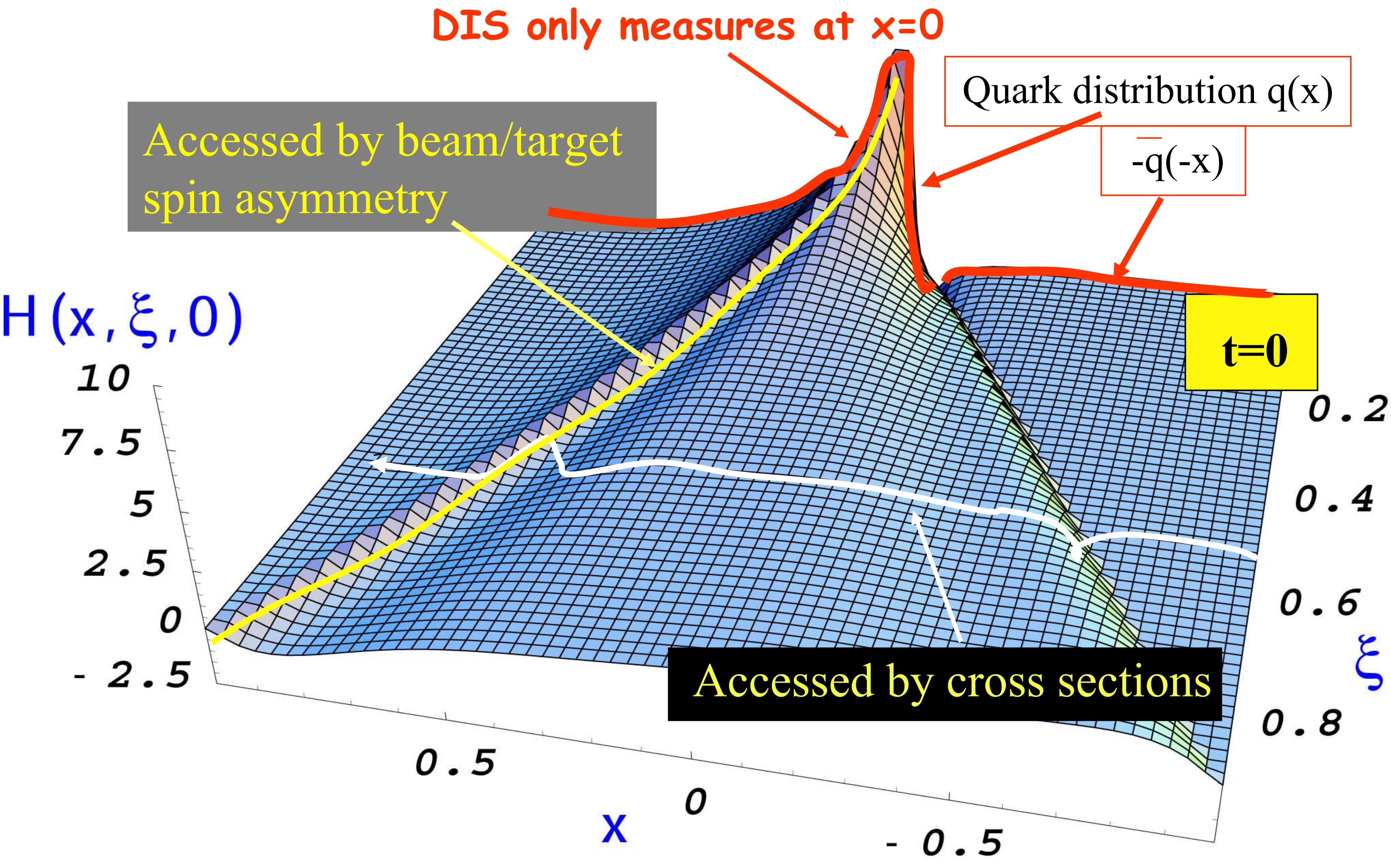
x = Longitudinal momentum fraction



Charge density distributions for u-quarks

3D image is obtained by rotation around the z-axis

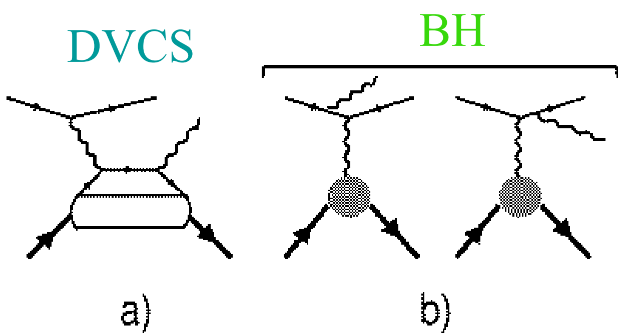
Experimental Access to GPDs

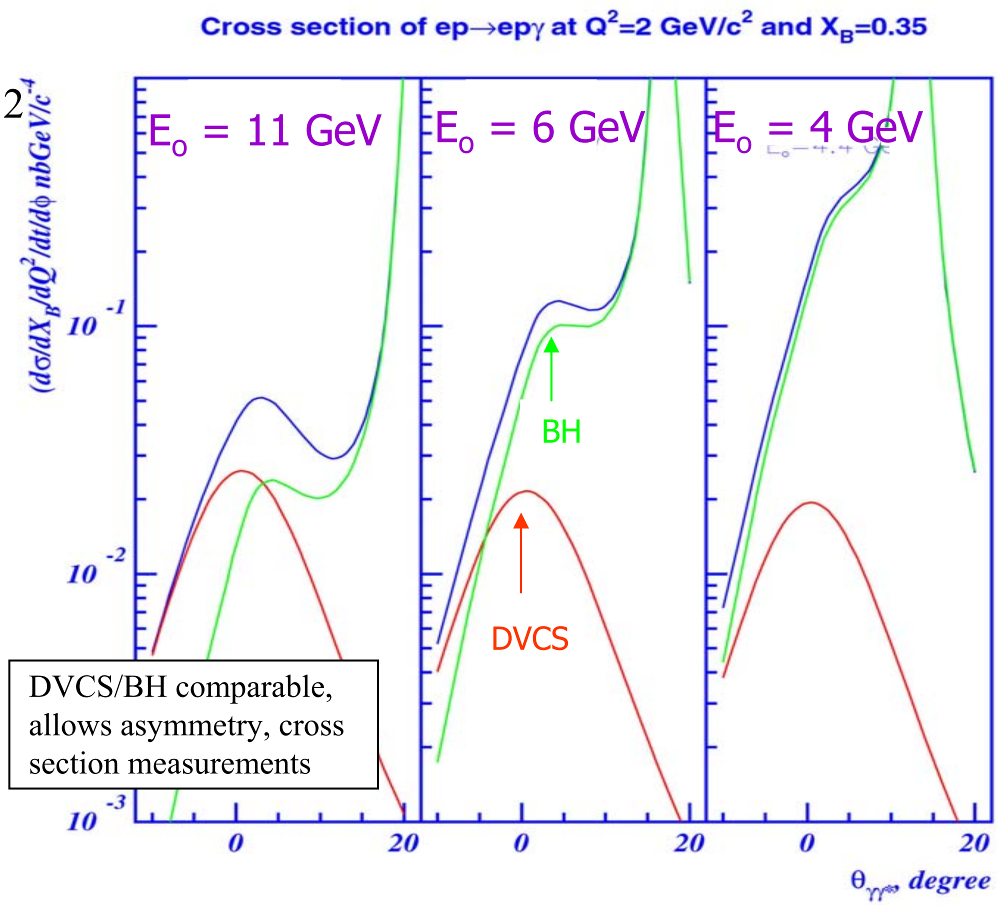


- Access GPDs through deeply virtual exclusive processes
- Initial experiments at JLab and at DESY have established the feasibility of such measurements

Small t : Access GPDs through DVCS

$$\frac{d^4\sigma}{dQ^2 dx_B dt d\phi} \sim |T^{DVCS} + T^{BH}|^2$$





T^{BH} : determined by Dirac & Pauli form factors

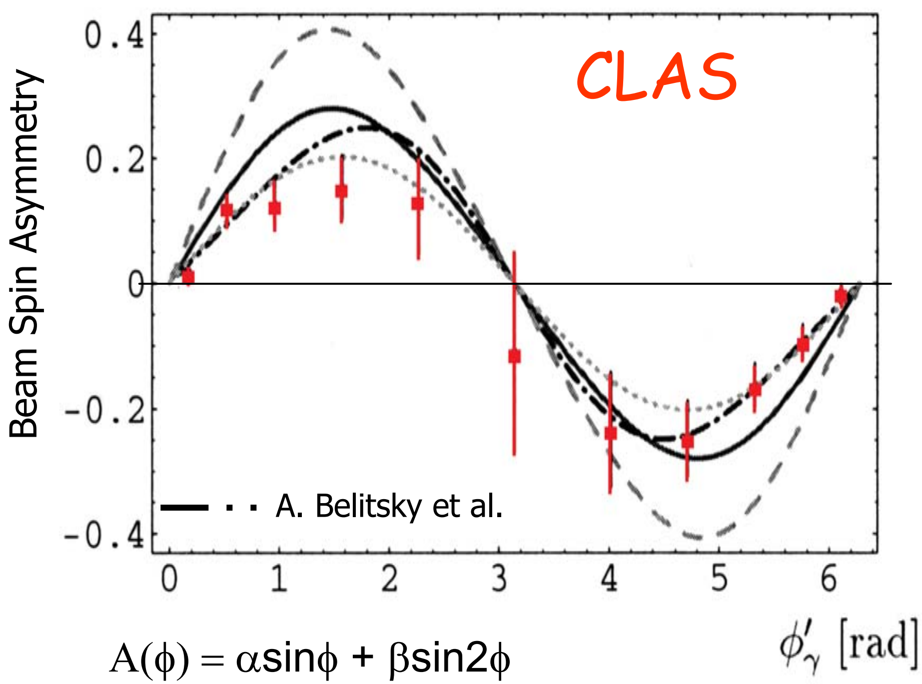
T^{DVCS}: determined by GPDs

Helicity difference:

Twist-2: $\Delta\sigma \sim \sin\phi \, \mathrm{Im}\{(F_1 H(\xi,\xi,t) + k_1(F_1+F_2)\tilde{H}(\xi,\xi,t) + k_2 F_2 E(\xi,\xi,t)\} d\phi$

Measurement of exclusive DVCS

1999 data, E=4.2GeV, $\langle Q^2 \rangle$=1.3GeV^2



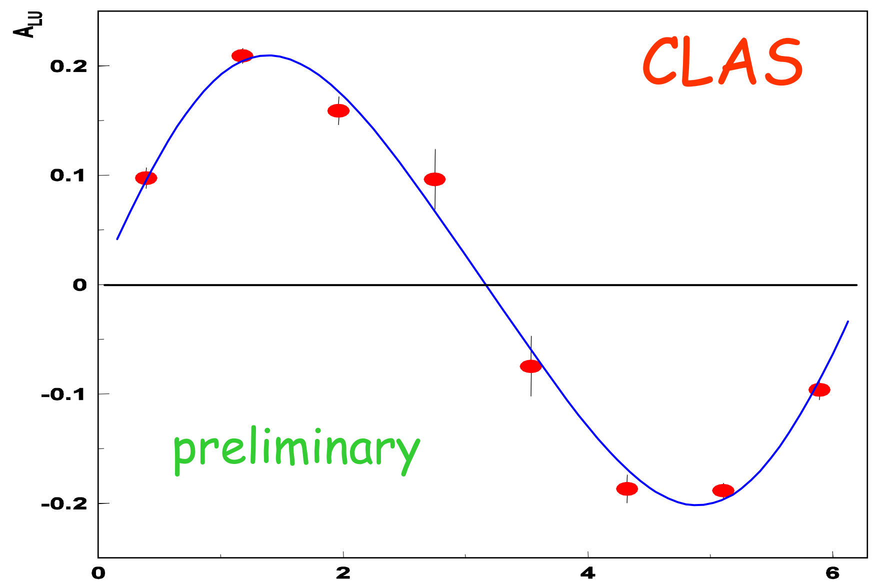
$A(\phi) = \alpha\sin\phi + \beta\sin2\phi$

- α = 0.202 ± 0.028^{stat} ± 0.013^{sys}
- β = -0.024 ± 0.021^{stat} ± 0.009^{sys}

S. Stepanyan et al. PRL **87**, 2001

GPD analysis of HERA/CLAS/HERMES data in LO/NLO , α = 0.20 for CLAS in LO
A. Freund, hep-ph/0306012 (2003)

2001 data, E=5.75GeV, $\langle Q^2 \rangle$=2.5GeV^2

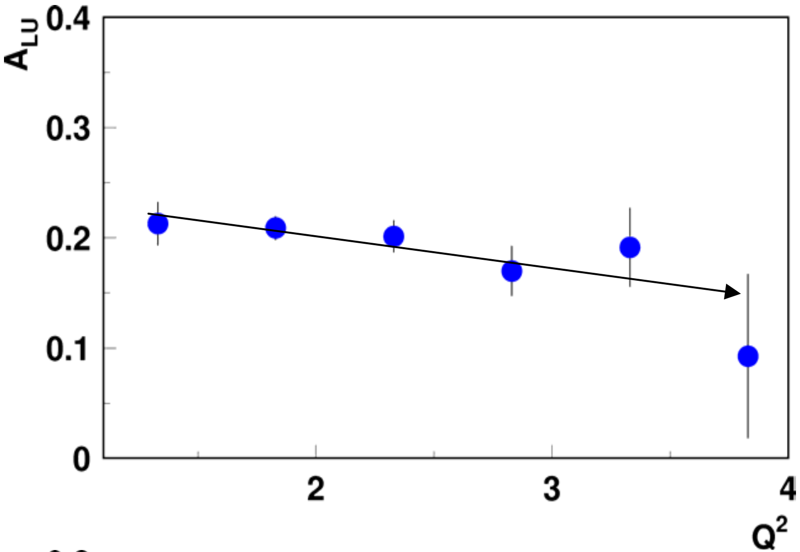


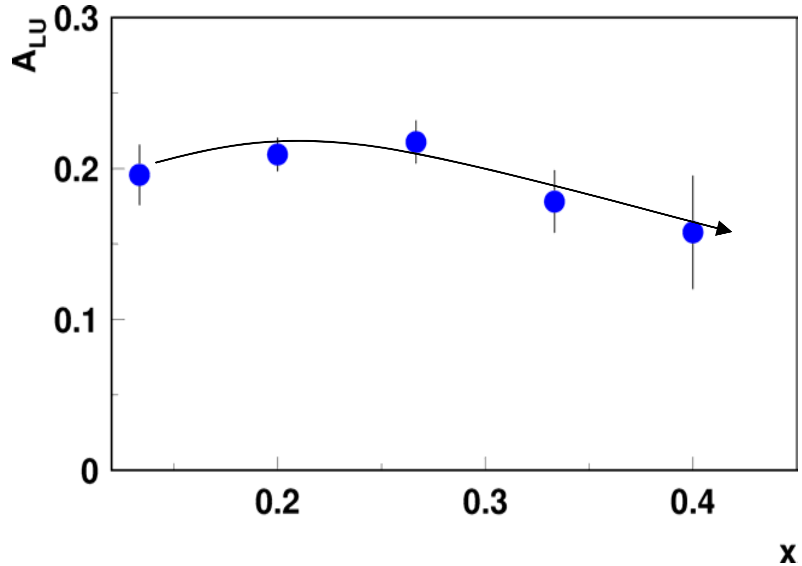
- Higher energy increases kinematics range.
- Higher statistics allows binning in Q^2, t, ξ

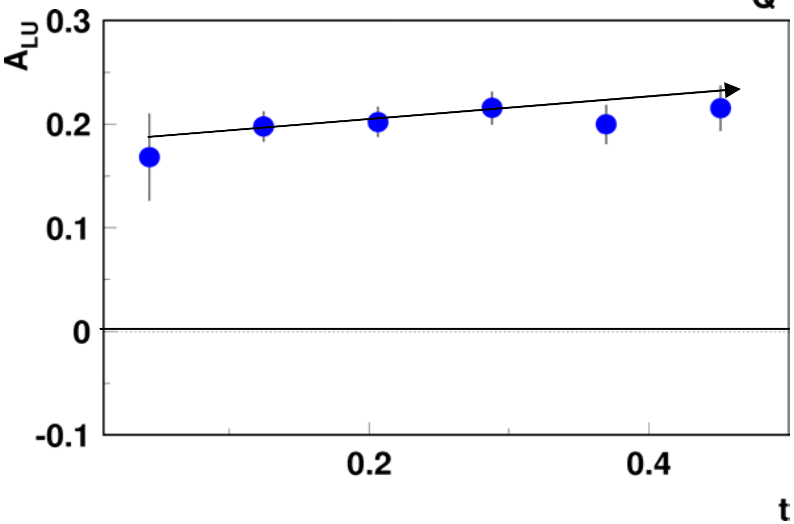
A. Freund: "..the twist-2 handbag contribution to DVCS is the leading contribution to SSA at CLAS."

DVCS/BH Beam Spin Asymmetry

CLAS very preliminary







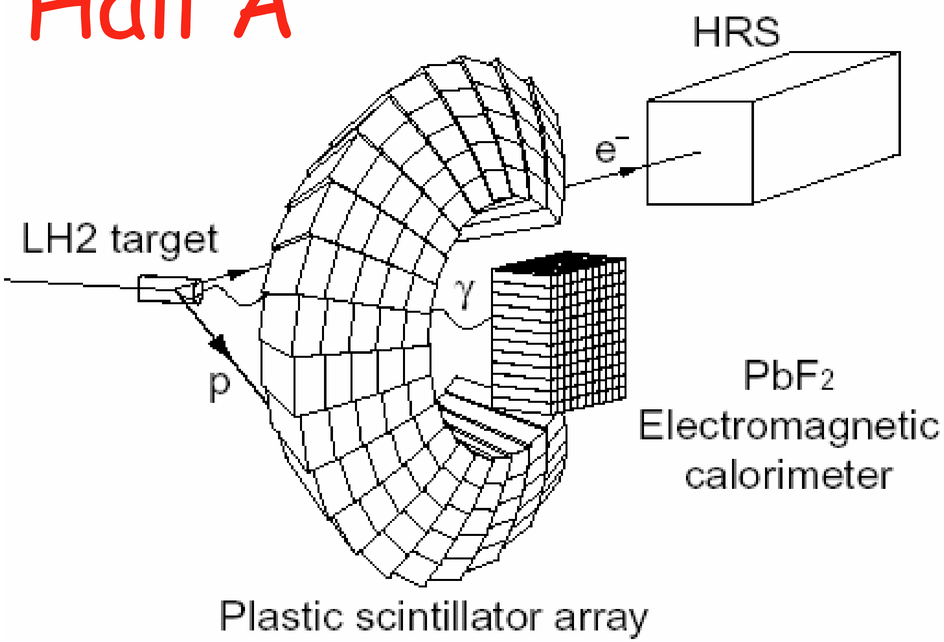
Data integrated over the other variables

- First significant kinematics dependencies for DVCS SSA.
- Results will serve as input to constrain GPDs.

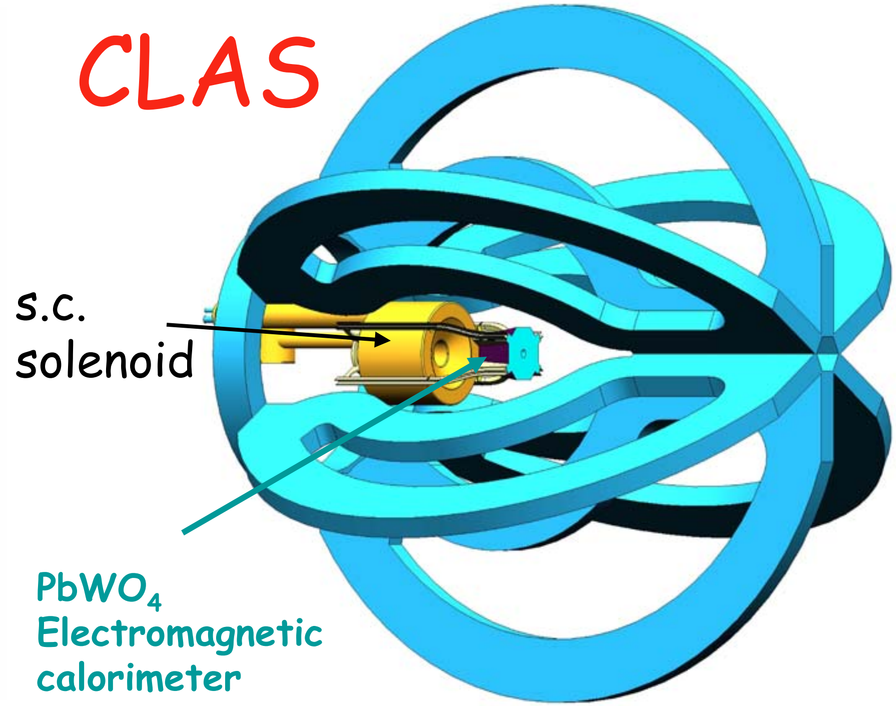
Near Term DVCS Experiments 2004/2005

Full reconstruction of all final state particles e, p, γ

Hall A



CLAS



Azimuthal and Q^2 dependence of Im(DVCS) at fixed ξ. Test Bjorken scaling.

ξ, t, Q^2 - dependence of Im(DVCS) in wide kinematics. Constrain GPD models.

Extending DVCS is one of the main physics motivations for the 12 GeV Upgrade

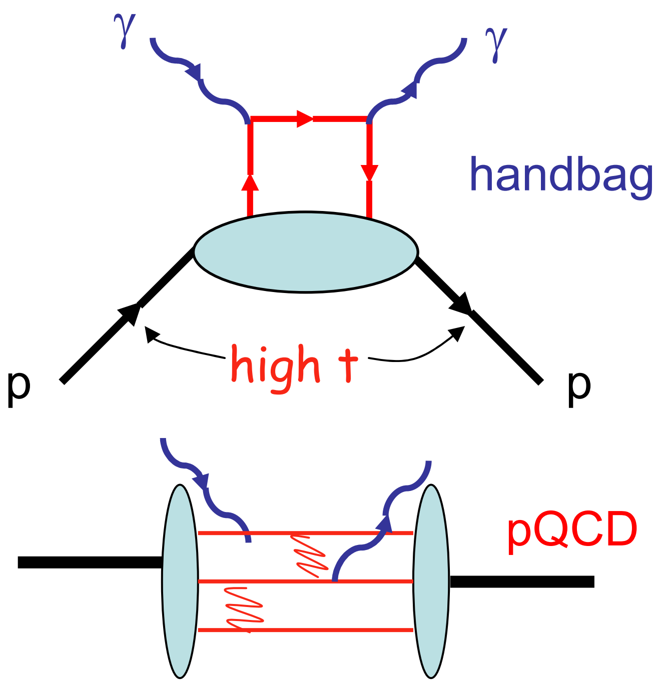
Real Compton Scattering & GPDs

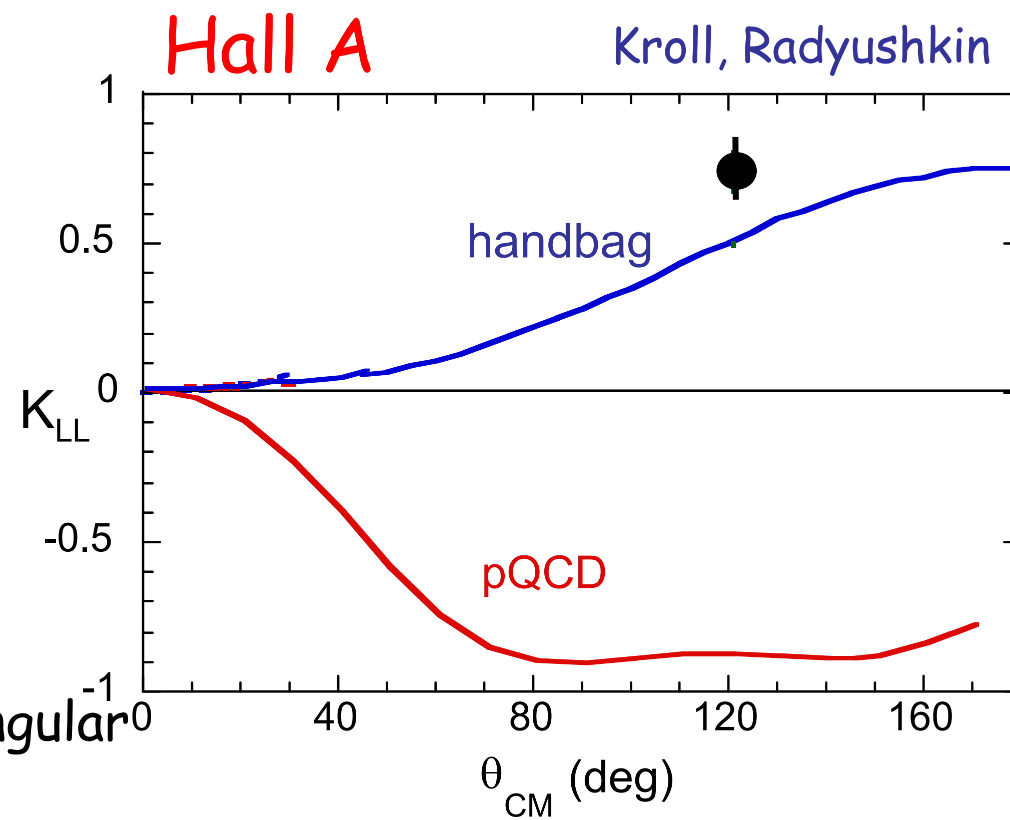
- Proton "Tomography" requires knowledge of GPDs in a large range of momentum transfer t.
  - DVCS probes low t kinematics
  - Compton Scattering with real photons (RCS) may probe the high t kinematics
- Important question: Can the "handbag" mechanism describe processes with real photons in the initial state, and high momentum transfer to the proton?
- This question is being addressed at JLab/Hall A.

Real Compton Scattering & GPDs

- Which mechanism is relevant for high t RCS ?

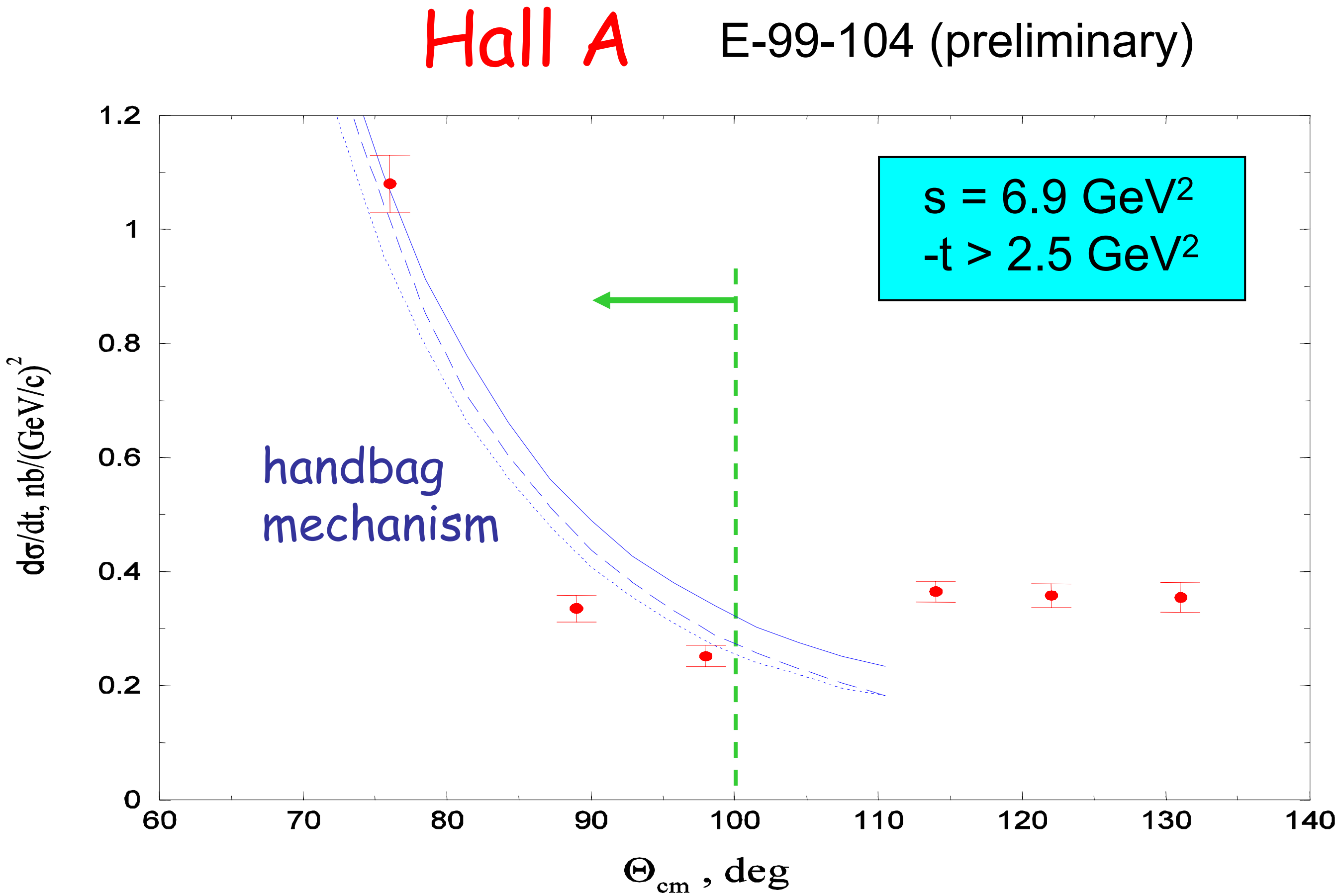
$$K_{LL} \sim A\,(R_A/R_V)$$
$$R_V(t) = \int \sum_q \frac{1}{x} H^q(x,t)\,dx$$





- Extension will measure the angular dependence of K_{LL}

RCS - preliminary cross sections



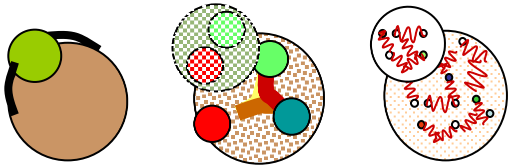
- Handbag mechanism dominates at this kinematics also for cross section

What are we learning about GPDs at 6GeV?

- Measurements of form factors constrain GPDs through moments, and in the DIS regime through improved parton distribution functions.
- Measure combinations of GPDs through DVCS at fixed $x = \xi$, t.
- Determine the kinematics where RCS may be used to constrain GPDs at high t.
- Understand the contribution meson production can make in determining GPDs at lower energies.

A growing community of experimentalists and theorists is addressing these issues.

The 12 GeV Upgrade will allow much broader access to GPDs



Conclusions

- The nucleon's shape and complex quark structure beyond longitudinal probability distributions, have become a major focus of hadron physics.

- JLab's experiments and theoretical analyses are having a strong impact on these groundbreaking developments, through accurate data on
  - Elastic nucleon form factors
  - $N\Delta(1232)$ transition multipoles (and higher mass N*)
  - Inclusive structure functions and their moments
  - Deeply Virtual Compton scattering
  - Real Compton scattering at high t

- The 12 GeV Upgrade will allow a much broader approach on dissecting the nucleon's fundamental structure.