Physics in Electron-Ion Collider Experiments
II: From Factors and Parton Distributions

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Huada School on QCD 2016: QCD in the EIC Era , May 23 – June 3, 2016

- Electron Scattering
- Elastic Scattering: From Factors

  Surprise: G_E^p @ high Q^2 : proton shape, 2-γ exchange

  Proton radius puzzle
- Deep-Inelastic Scattering:

  Unpolarized Structure Functions → Parton Distribution Functions

  High-x physics

  Sea asymmetry

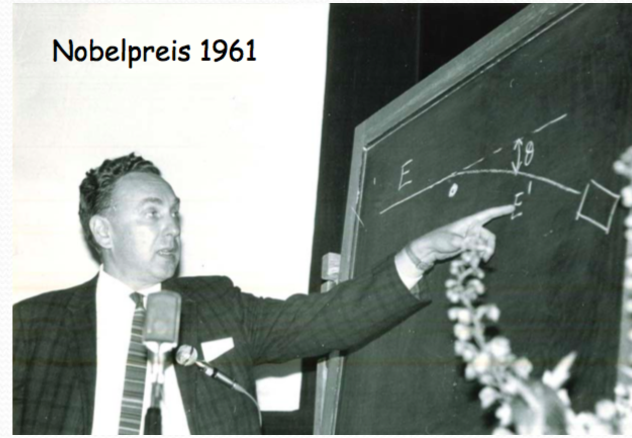
Electron Scattering

A Clean Probe To Study Nucleon Structure and QCD

Electron Scattering and Nucleon Structure

- Clean probe to study nucleon structure
  only electro-weak interaction, well understood

- Elastic Electron Scattering: Form Factors
  → 60s: established nucleon has structure (Nobel Prize)
  electrical and magnetic distributions

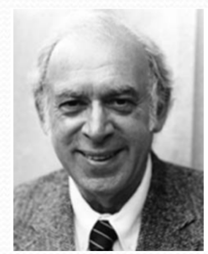


Robert Hofstadter,
Nobel Prize 1961

- Resonance Excitations
  → internal structure, rich spectroscopy (new particle search)
  constituent quark models

- Deep Inelastic Scattering
  → 70s: established quark-parton picture (Nobel Prize)
  parton distribution functions (PDFs)
  polarized PDFs : spin Structure
  TMDs, GPDs: 3-d structure:

Factorization: observable $A \sim H \otimes S$



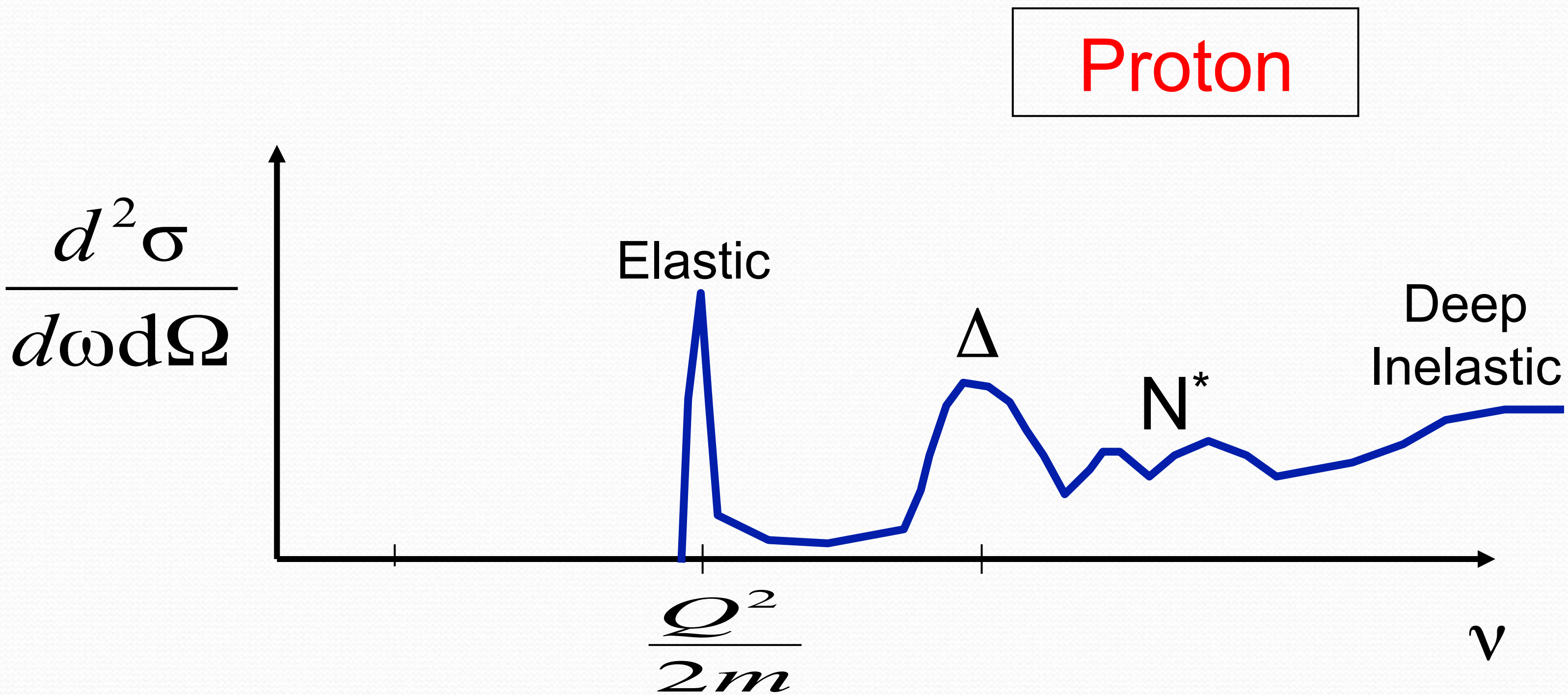
J.T. Friedman

R. Taylor

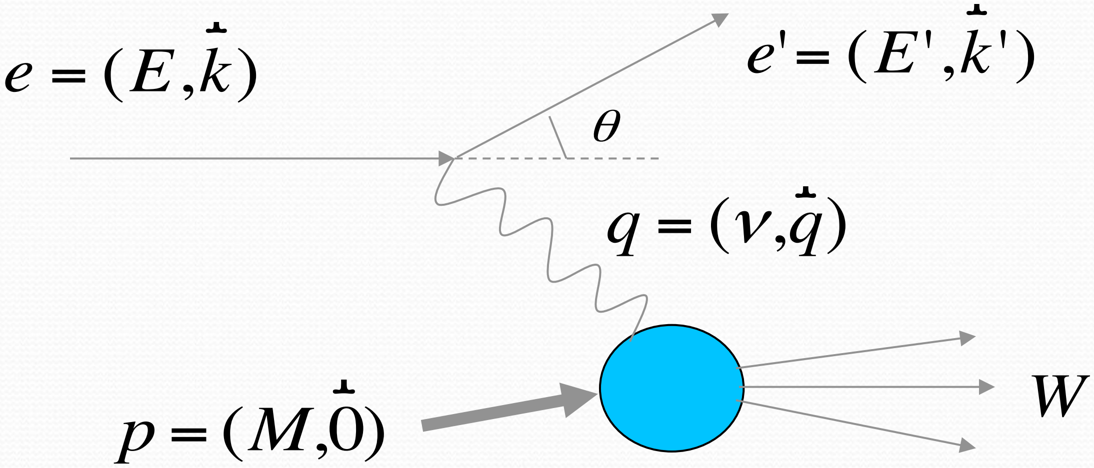
H.W. Kendall

Nobel Prize 1990

Typical Electron Scattering Spectra at Fixed Q^2



Inclusive Electron Scattering



4-momentum transfer squared

$$Q^2 = -q^2 = 4EE'\sin^2\tfrac{\theta}{2}$$

Invariant mass squared

$$W^2 = M^2 + 2M\nu - Q^2$$

Unpolarized:

$$\frac{d^2\sigma}{d\Omega dE'} = \sigma_M \left[\frac{1}{\nu} F_2(\nu, Q^2) + \frac{2}{M} F_1(\nu, Q^2) \tan^2\tfrac{\theta}{2} \right]$$

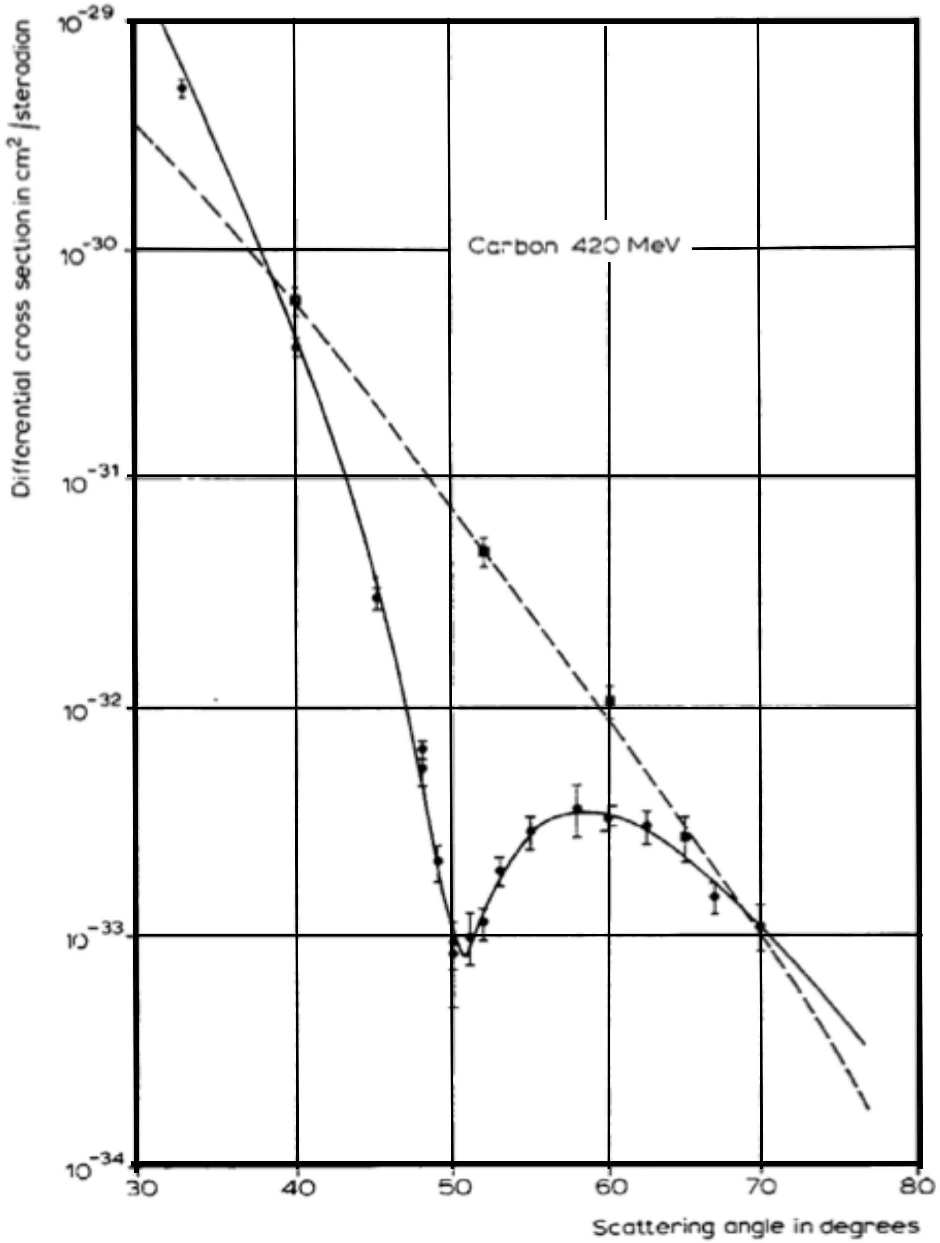
$$\sigma_M = \frac{\alpha^2 E' \cos^2(\theta/2)}{4E^3 \sin^4(\theta/2)}$$

F_1 and F_2: information on the nucleon/nuclear structure

Nucleon Form Factors

Charge and Magnetization Distributions

Elastic Electron Scattering



Robert Hofstadter,
Nobel Prize 1961

Scattering cross section of nuclei:

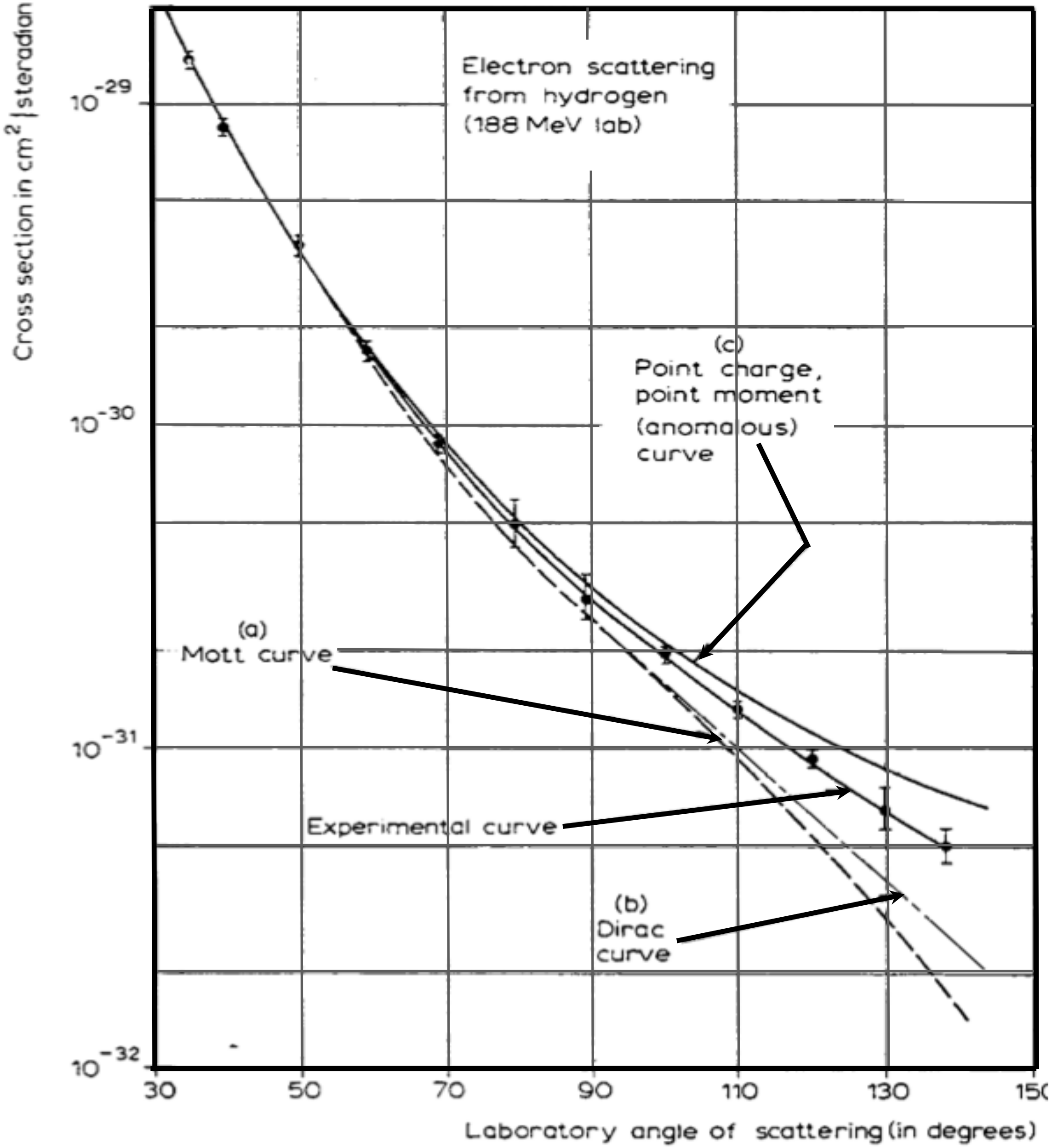
$$\frac{d\sigma}{d\Omega} = \left.\frac{d\sigma}{d\Omega}\right|_{\mathrm{Ruth.}} \frac{E'}{E} \cos^2\frac{\theta}{2} \left|F(q^2)\right|^2$$

Structure reflects finite charge radius, through Fourier transform, of ~4 fm.

Elastic Electron Scattering

~200 MeV

Discovery: Proton Has Structure



Robert Hofstadter,

Nobel Prize 1961

Scattering off a spin-1/2 Dirac particle:

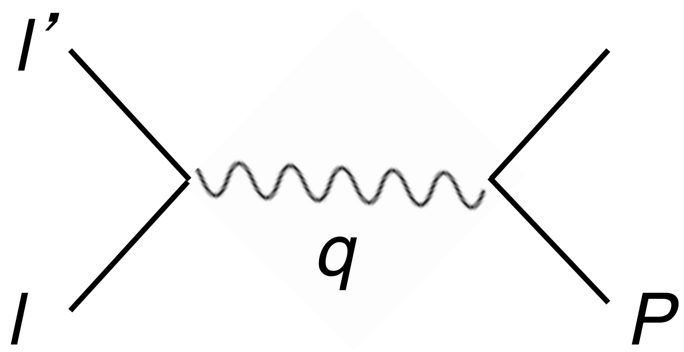
$$\frac{d\sigma}{d\Omega} = \left(\frac{\alpha}{4ME\sin^2(\theta/2)}\right)^2 \frac{E'}{E}\left[\frac{q^2}{2M}\sin^2(\theta/2) + \cos^2(\theta/2)\right]$$

The proton has an anomalous magnetic moment,

$$g_p \neq 2, \quad g_p \simeq 5.6$$

and, hence, internal (spin) structure.

Elastic Electron Scattering



$$d\sigma \propto \left\langle |\mathcal{M}|^2 \right\rangle = \frac{g_e^4}{q^4} L^{\mu\nu}_{\text{lepton}} K_{\mu\nu\,\text{nucleon}}$$

The lepton tensor is calculable:

$$L^{\mu\nu}_{\text{lepton}} = 2\left(k^\mu k'^\nu + k^\nu k'^\mu + g^{\mu\nu}(m^2 - k\cdot k')\right)$$

The nucleon tensor is not; it's general (spin-independent, parity conserved) form is:

$$K_{\mu\nu\,\text{nucleon}} = -K_1 g_{\mu\nu} + \frac{K_2}{M^2} p_\mu p_\nu + \frac{K_4}{M^2} q_\mu q_\nu + \frac{K_5}{M^2}\left(p_\mu q_\nu + p_\nu q_\mu\right)$$

Charge conservation at the proton vertex reduces the number of structure functions:

$$q_\mu K^{\mu\nu}_{\text{nucleon}} \quad \to \quad K_4 = f(K_1, K_2), \quad K_5 = g(K_2)$$

and one obtains the Rosenbluth form, with electric and magnetic form factors:

$$\frac{d\sigma}{d\Omega} = \left(\frac{\alpha}{4ME\sin^2(\theta/2)}\right)^2 \frac{E'}{E}\left[2K_1 \sin^2(\theta/2) + K_2\cos^2(\theta/2)\right], \qquad K_{1,2}(q^2)$$

Elastic Scattering on a Proton

From relativistic quantum mechanics one can derive the the formula electron-proton scattering where one has assumed the exchange of a single virtual photon.

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} \cdot \frac{E'}{E}\left[\frac{G_E^2 + \tau G_M^2}{1+\tau} + 2\tau G_M^2 \tan^2\frac{\theta}{2}\right]$$

where G_E and G_M form factors take into account the finite size of the proton.

$G_E = G_E(Q^2)$, $G_M = G_M(Q^2)$; $G_E(0)=1$, $G_M(0) = \mu_p$

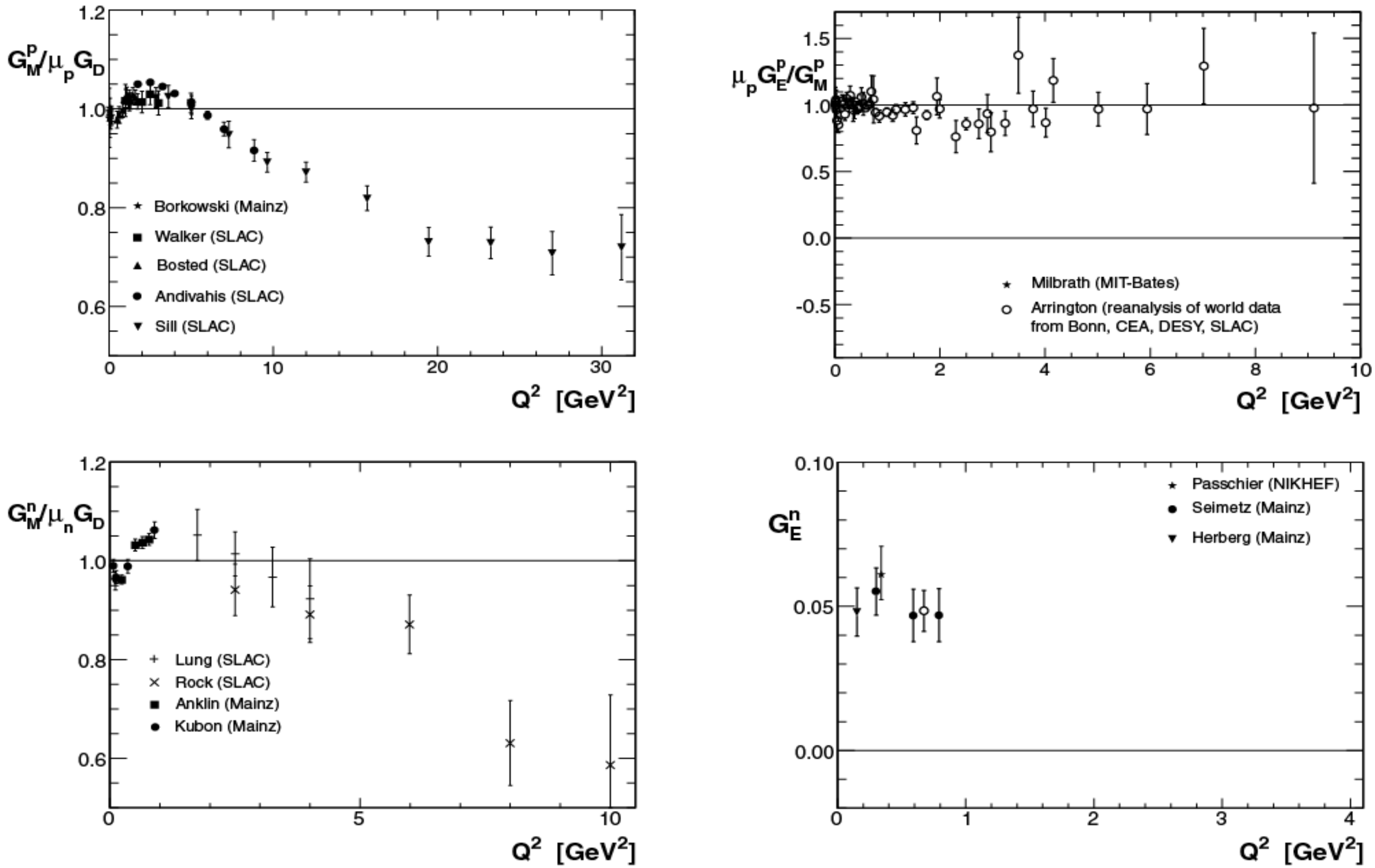
$Q^2 = 4\,E\,E'\sin^2(\theta/2)$ and $\tau = Q^2/4m_p^2$

Elastic cross sections at small angles and small Q^2's are dominated by G_E (Prad Hall B)

Elastic cross Sections at small angles and small Q^2's are dominated by G_M (GMP Hall A)

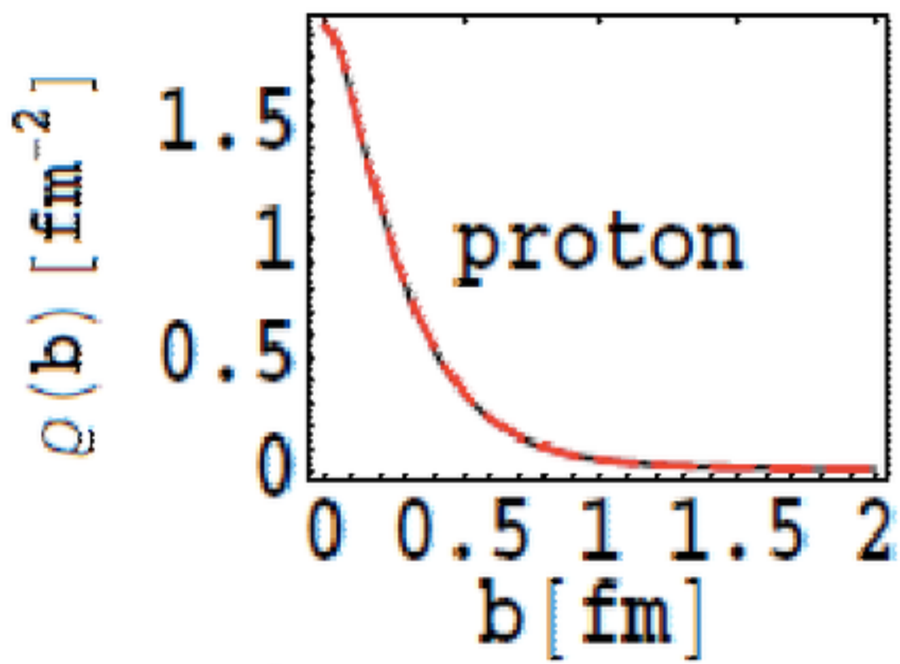
For moderate Q^2's one can separate G_E and G_M with Rosenbluth or asymmetry measurements.

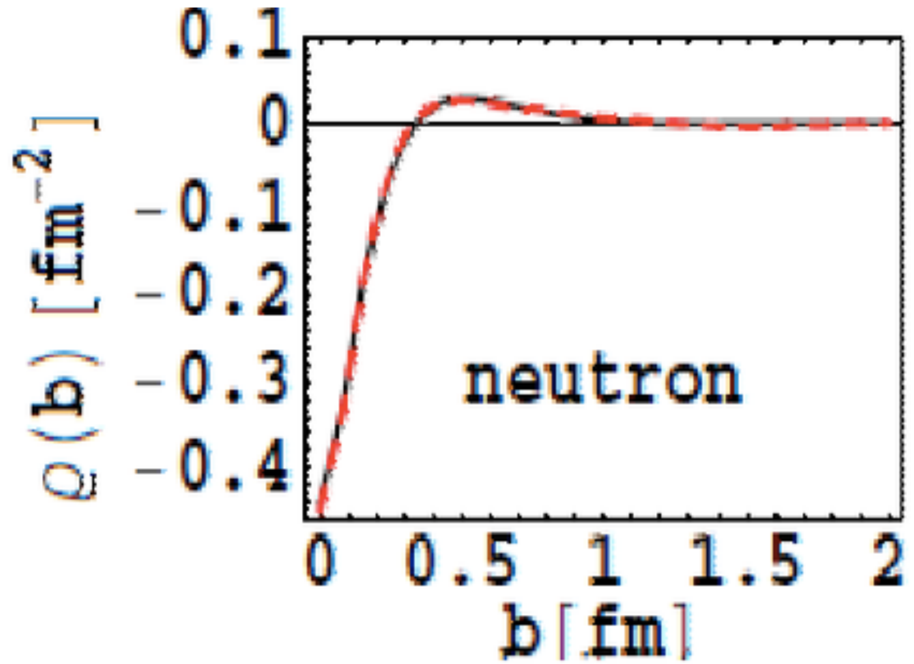
Before JLab and Recent non-JLab Data



Form Factors → Charge/Current Distributions

Elastic electric form factor ➡ **Charge distributions**



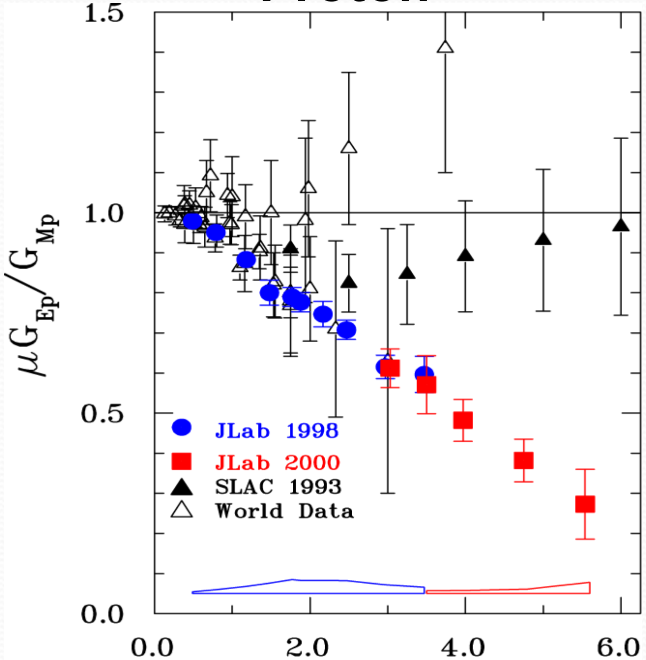


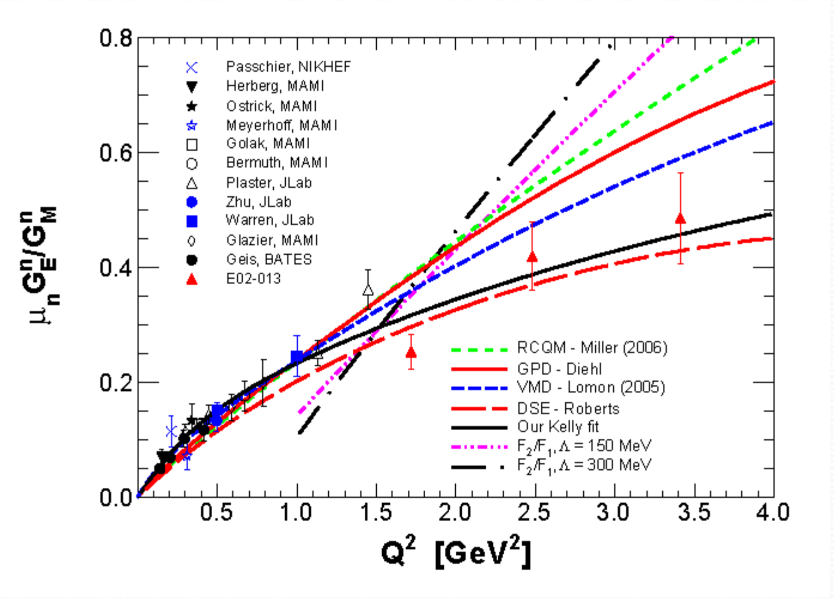
JLab Data on EM Form Factors

Testing Ground for Theories of Nucleon Structure

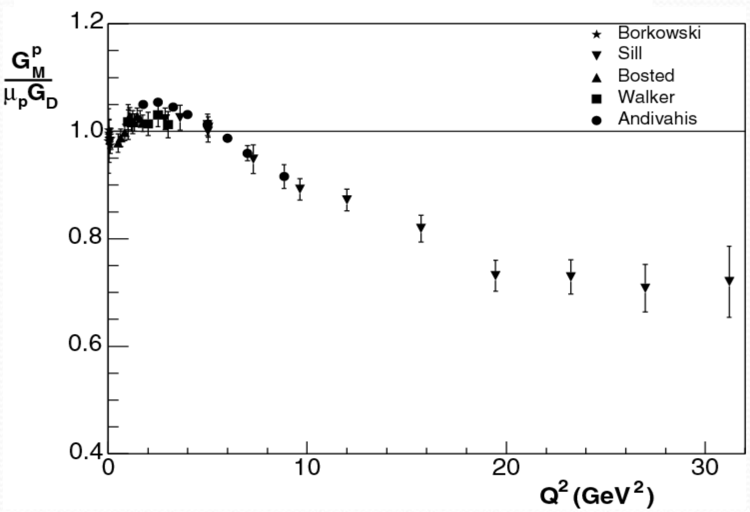
Proton | **Neutron**

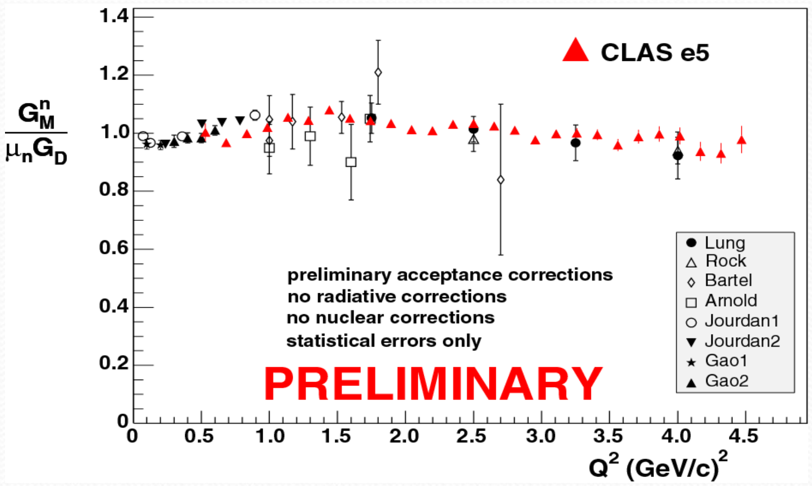
Electric





Magnetic



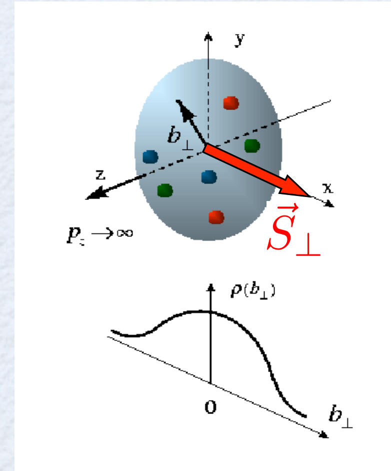


Form factors: 2D light-front densities of hadrons

$$\rho^N(\vec{b}) = \int_0^\infty \frac{dQ}{2\pi} Q\, J_0(b\,Q) F_1(Q^2)$$
$$+ \sin(\phi_b - \phi_S) \int_0^\infty \frac{dQ}{2\pi} \frac{Q^2}{2M_N} J_1(b\,Q) F_2(Q^2)$$

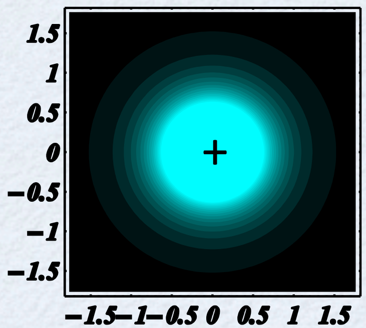
→ unpolarized Dirac FF F_1

→ transverse polarization Pauli FF F_2

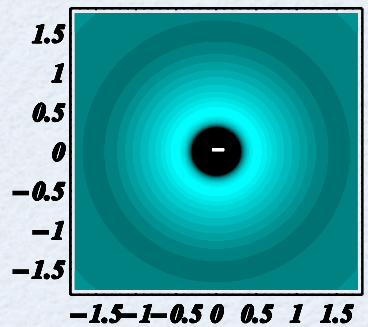


proton | neutron

unpolarized charge density



b (fm)

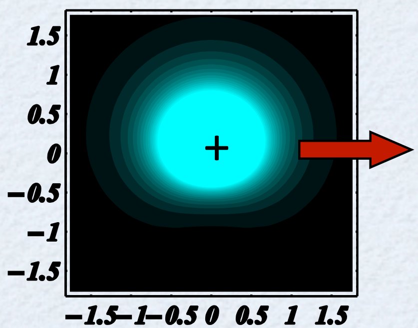


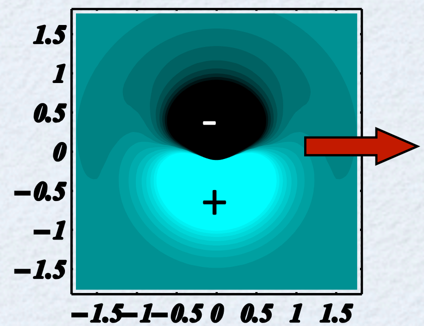
b (fm)

Burkardt (2000,2003)

Miller(2007)

density for transverse polarization





Carlson, Vdh(2008)

G_E^p: JLab Polarization-Transfer Data

Using Focal Plane Polarimeter in Hall A

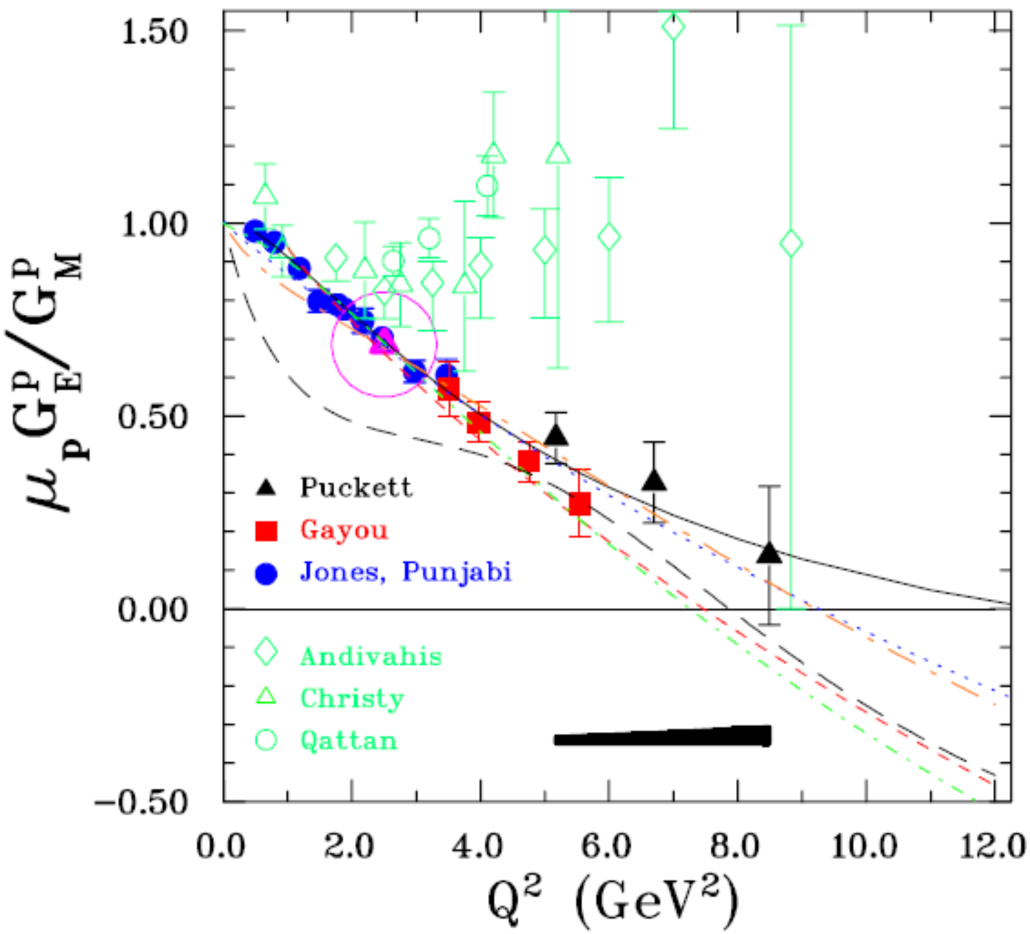
- E93-027 PRL 84, 1398 (2000)
- E99-007 PRL 88, 092301 (2002)
- E04-108, arXiv:1005.3419v2 (2010)

Clear discrepancy between polarization transfer and Rosenbluth data

- Investigate possible theoretical sources for discrepancy
  → likely two-photon contributions

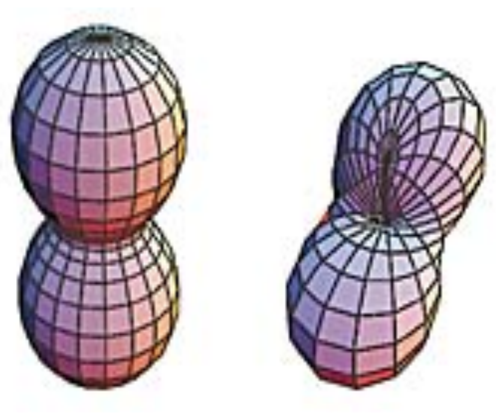
Information on the shape of the proton and the orbital angular momentum.

Transverse density .



The Proton's Shape

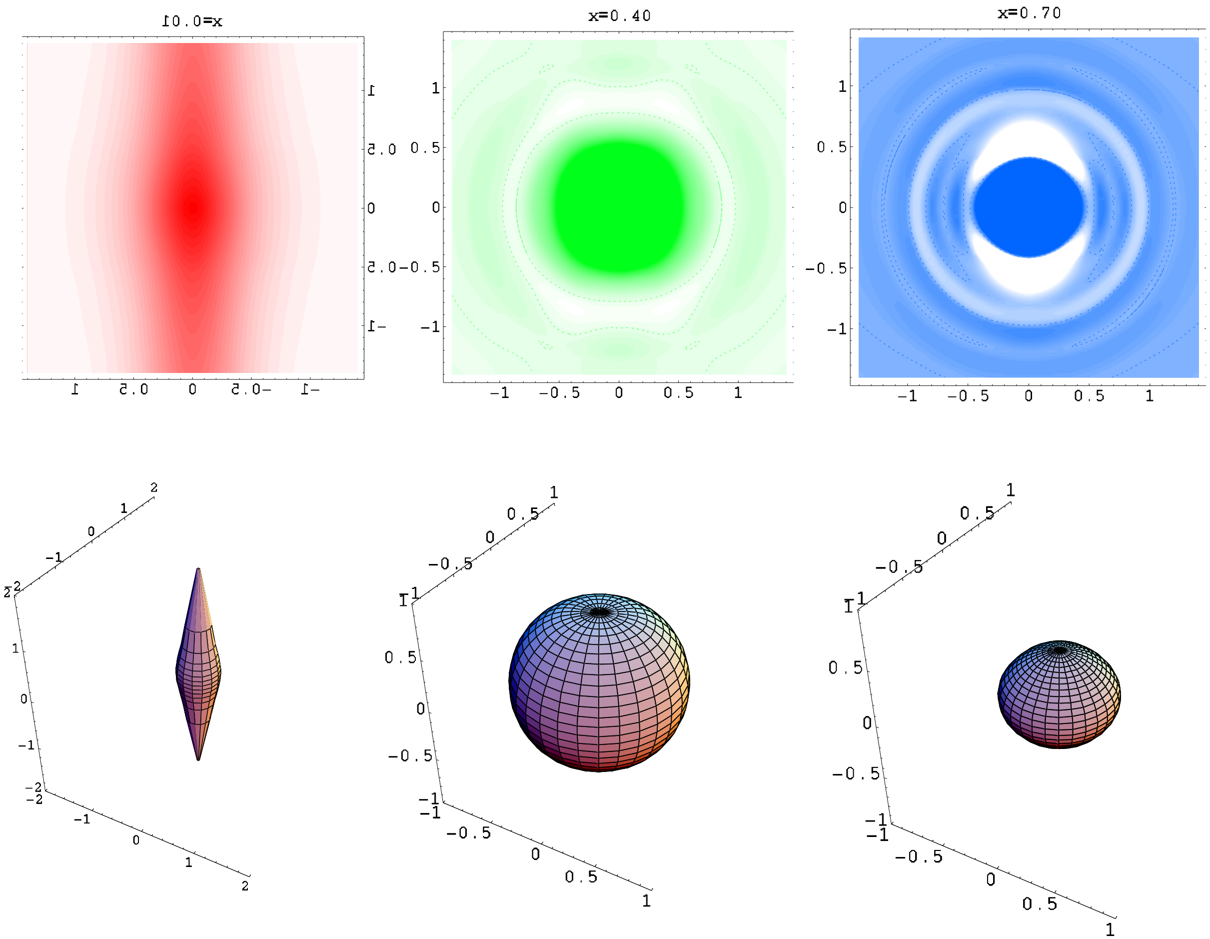
It's a Ball. No, It's a Pretzel.
Must Be a Proton.
(K. Chang, NYT, May 6, 2003)



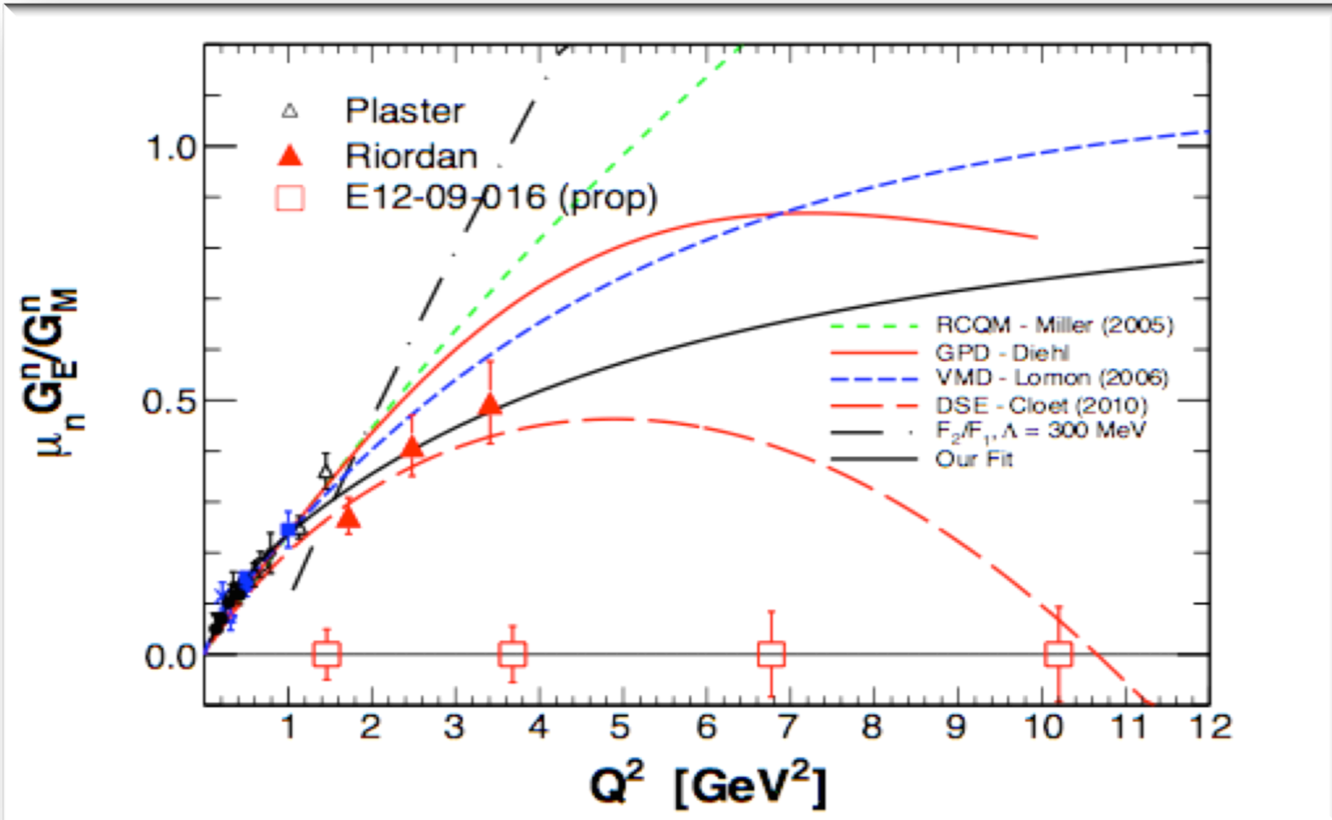
quark spin parallel to that of the proton (left), quark spin perpendicular to the proton spin (right).

G. Miller, PRC 68, 022201 (03)

Belitsky, Ji and Yuan: PRD 69, 074014(04)



G_E^n: 6 GeV Results and 12 GeV Plan



- *The dramatic turnover of the Argonne DSE model would be clearly visible.*
- *If the turnover is seen, it would provide strong evidence for the importance of diquark degrees of freedom in the nucleon form factors.*

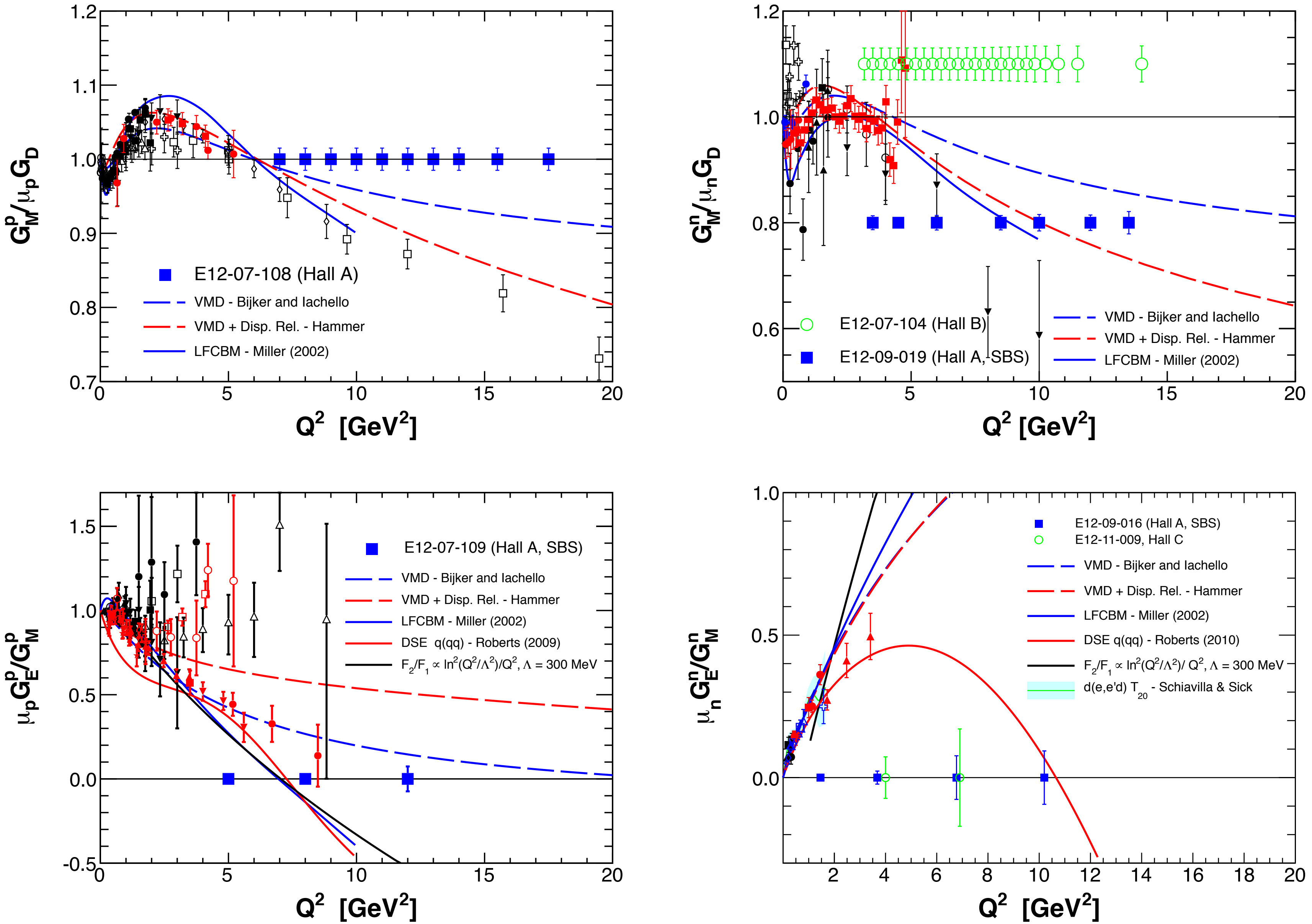
Planned JLab Measurements of Form Factors

Proton

Neutron

G_M

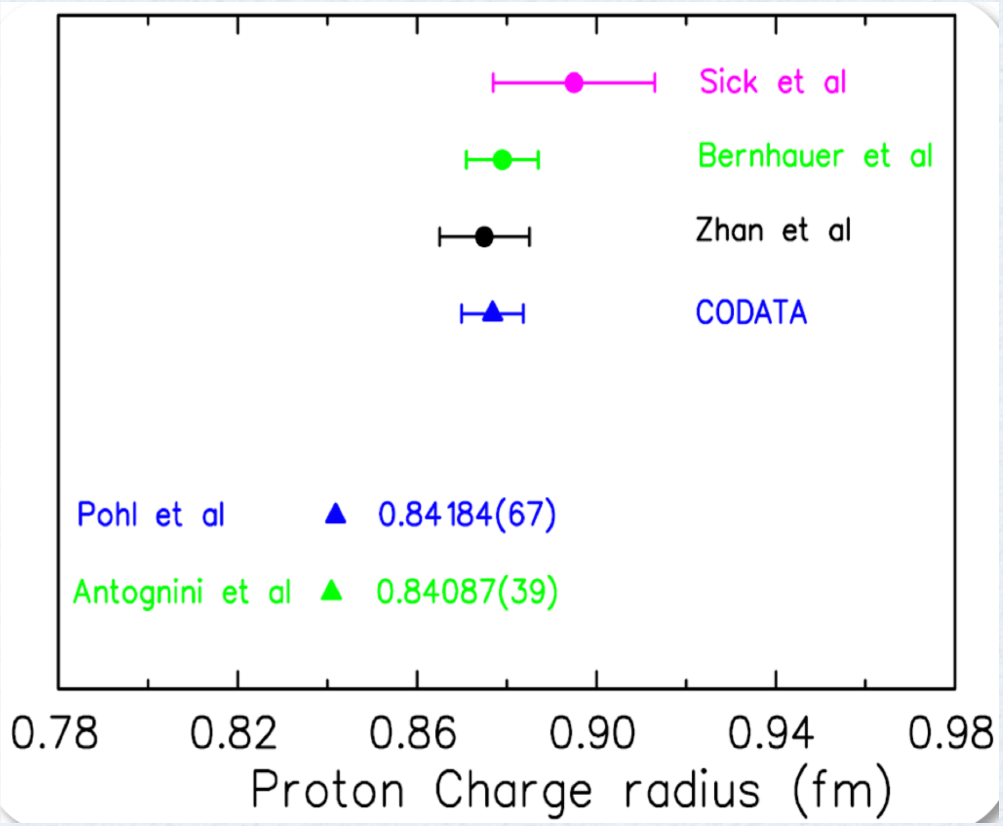
G_E

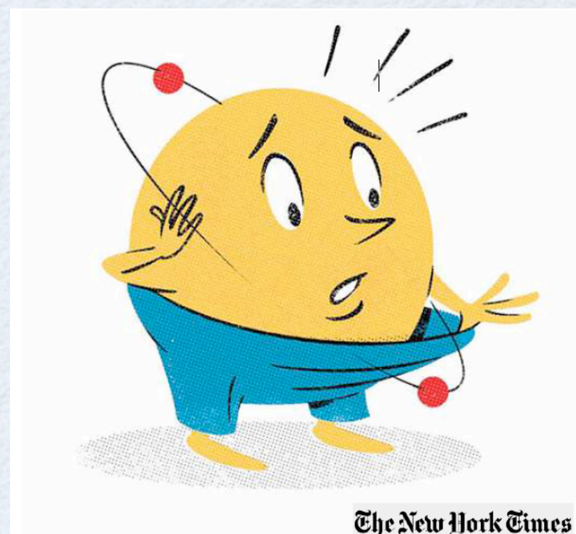


Proton Radius Puzzle

Electron probe vs. muon probe

Proton radius puzzle





μH data: $R_E = 0.8409 \pm 0.0004$ fm

Pohl et al.(2010)

Antognini et al.(2013)

7 σ difference !?

ep data: $R_E = 0.8775 \pm 0.0051$ fm

Charge Radius of the Proton

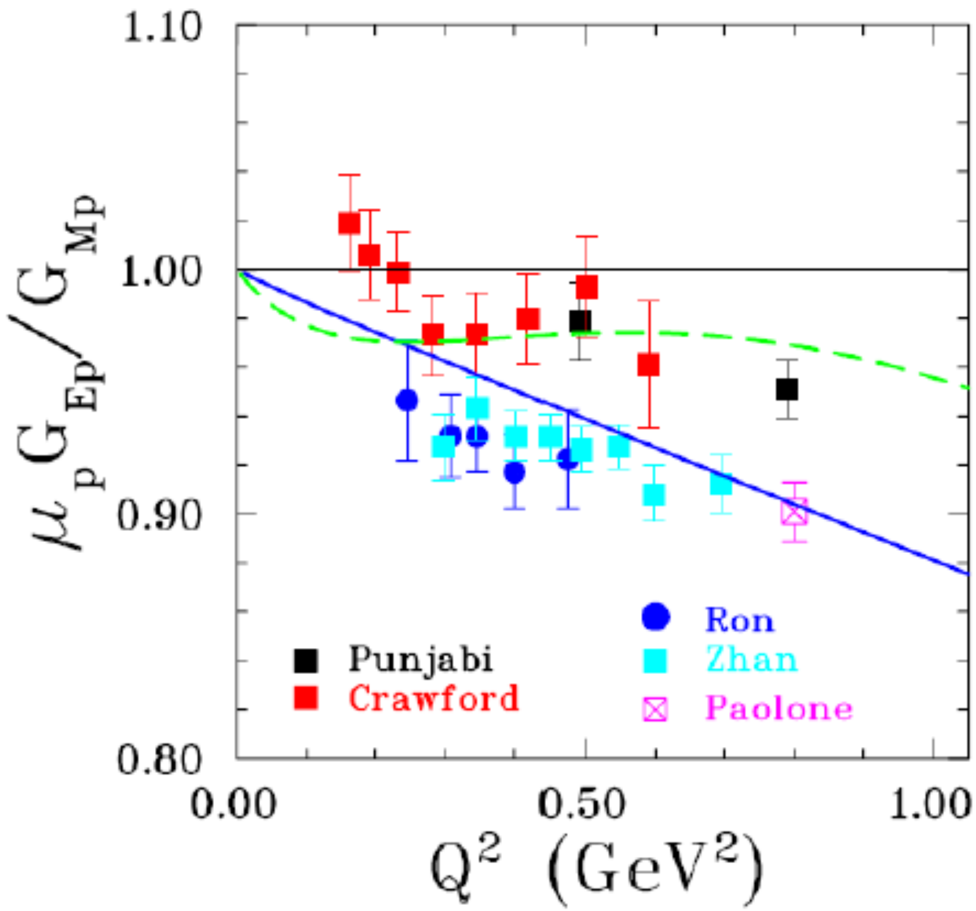
- Proton G_E has no measured minima and it is too light for the Fourier transformation to work in a model independent way.
- Thus for the proton we make use of the fact that as Q^2 goes to zero the charge radius is proportional to the slope of G_E

$$G_E(Q^2) = 1 + \sum_{n \geq 1} \frac{(-1)^n}{(2n+1)!} \langle r^{2n} \rangle \, Q^{2n}$$

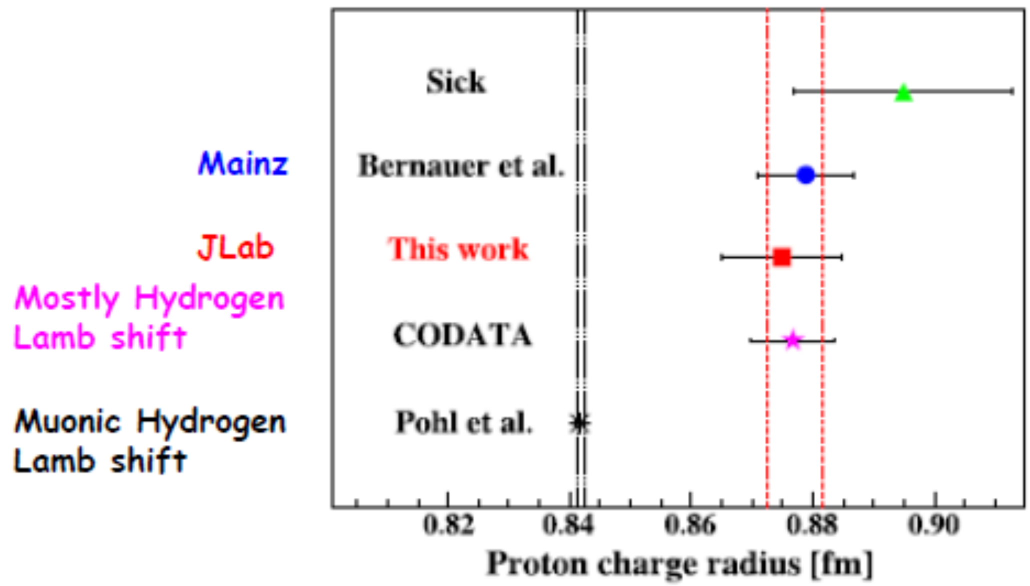
$$r_p \equiv \sqrt{\langle r^2 \rangle} = \left(-6 \, \frac{\mathrm{d}G_E(Q^2)}{\mathrm{d}Q^2} \Big|_{Q^2=0} \right)^{1/2}$$

We don't measure to Q^2 of zero, so this is going to be an extrapolation problem.

Systematic issues with low-Q^2 G_{Ep} polarization data!



Beam-target asymmetry and recoil polarization data disagree at low Q^2!



r_p from muonic hydrogen Lamb shift disagrees with ep scattering and electronic hydrogen Lamb shift determinations

Tension among low-Q^2 G_E/G_M ratios from polarization observables not yet understood, but at least one of these experiments has to have an unaccounted-for source of systematic error!

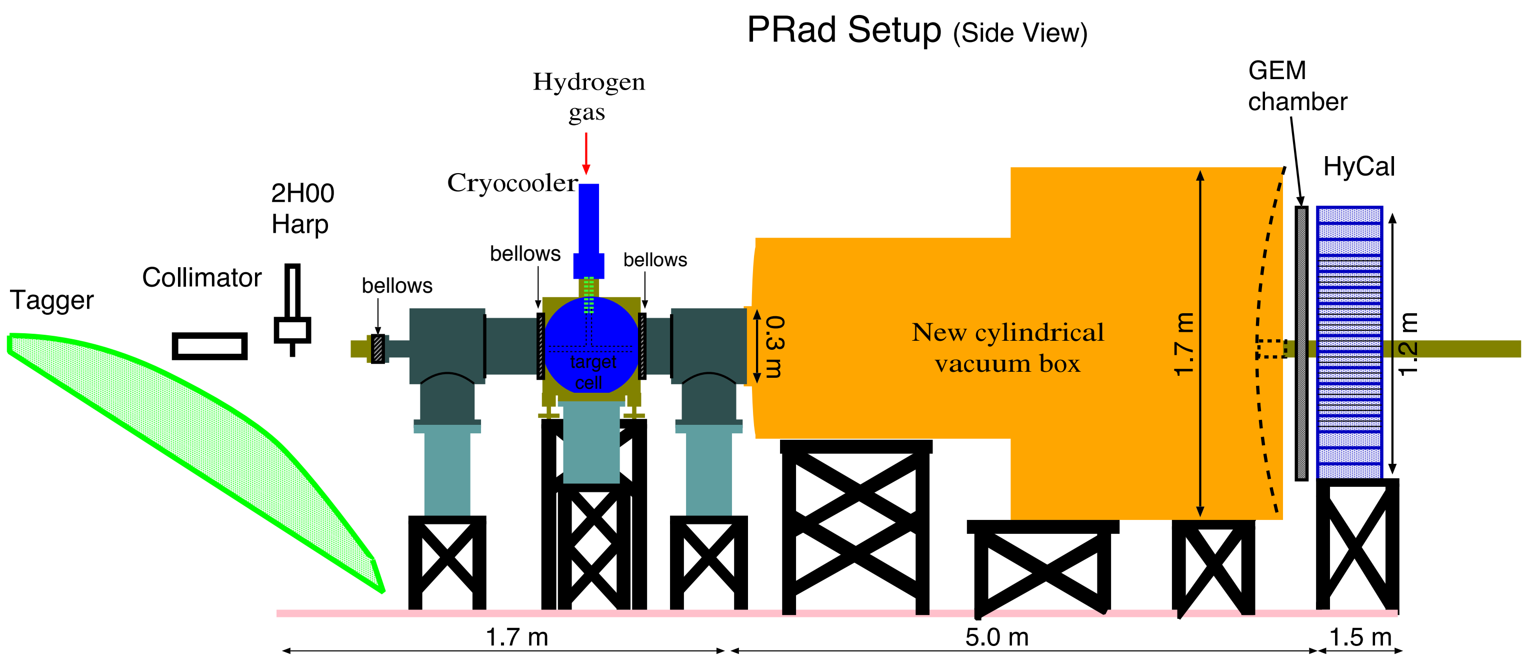
Proton radius puzzle: what's next ?

- μH Lamb shift: muonic D, muonic ^{3}He, ^{4}He have been performed
- electronic H Lamb shift: higher accuracy measurements underway
- electron scattering analysis: Lorenz et al.
  - radius extraction fits (use fits with correct analytical behavior: 2π cut)
  - radiative corrections, two-photon exchange corrections

  new fit $R_E = 0.904$ (15) fm (4σ from μH) Lee, Arrington, Hill (2015)
- electron scattering experiments:
  new G_{Ep} experiments down to $Q^2 \approx 2 \times 10^{-4}$ GeV^2
  - MAMI/A1: Initial State Radiation (2013/4)
  - JLab/Hall B: HyCal, magnetic spectrometer-free experiment, norm to Møller (2016/7)
  - MESA: low-energy, high resolution spectrometers (2019)

  see talk: H. Gao
- muon scattering experiments: MUSE@PSI (2017/8)
- e^-e^+ versus $\mu^-\mu^+$ photoproduction: lepton universality test

PRad Experimental Setup in Hall B at JLab



- **High resolution, large acceptance calorimeter**
- **Windowless H_2 gas flow target**
- **Simultaneous detection of elastic and Moller electrons**
- **GEM detectors**
- **Q^2 range of 2×10^{-4} – 0.14 GeV^2**

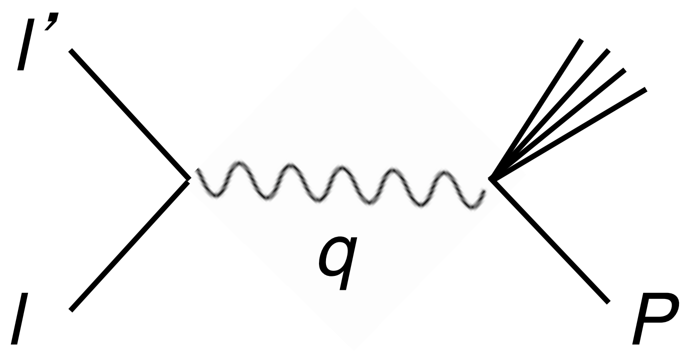
Future sub 1% measurements:
(1) ep elastic scattering at Jlab (PRad)
(2) μp elastic scattering at PSI - 16 U.S. institutions! (MUSE)
(3) ISR experiments at Mainz

Ongoing H spectroscopy experiments

Deep-Inelastic Scattering
Unpolarized Nucleon Structure

Parton Distributions:
Flavor Structure: Valence and Sea
Gluons

Inelastic Scattering



Considerably more complex, indeed!

Simplify - consider *inclusive* inelastic scattering,

$$d\sigma \propto \left\langle |\mathcal{M}|^2 \right\rangle = \frac{g_e^4}{q^4} L^{\mu\nu}_{\text{lepton}} W_{\mu\nu\,\text{nucleon}}, \qquad W_{\mu\nu\,\text{nucleon}}(p, q)$$

Again, two (parity-conserving, spin-independent) structure functions:

$$W_1, W_2 \;\; \text{or, alternatively expressed,} \;\; F_1, F_2$$

which may depend on two invariants,

$$Q^2 = -q^2, \qquad x = -\frac{q^2}{2q.p}, \; 0 < x < 1$$

So much for the structure, the physics is in the structure functions.

Elastic scattering off Dirac Protons

Compare:

$$L^{\mu\nu}_{\text{lepton}} = 2\left(k^\mu k'^\nu + k^\nu k'^\mu + g^{\mu\nu}(m^2 - k\cdot k')\right)$$

with:

$$K_{\mu\nu\,\text{nucleon}} = K_1\left(-g_{\mu\nu} + \frac{q^\mu q^\nu}{q^2}\right) + \frac{K_2}{M^2}\left(p^\mu + \frac{1}{2}q^\mu\right)\left(p^\nu + \frac{1}{2}q^\nu\right)$$

which uses the relations between $K_{1,2}$ and $K_{4,5}$

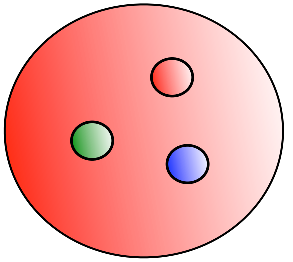
Then, e.g. by substitution of $k' = k-q$ in L:

$$K_1 = -q^2, \quad K_2 = 4M^2$$

Note, furthermore, that inelastic cross section reduces to the elastic one for:

$$W_{1,2}(q^2, x) = -\frac{K_{1,2}(q^2)}{2Mq^2}\delta(x-1)$$

Elastic scattering off Dirac Partons



Imagine *incoherent* scattering off *Dirac* Partons (quarks) q :

$$W_1^q = \frac{e_q^2}{2m_q}\delta(x_q - 1), \quad W_2^q = -\frac{2m_q e_q^2}{q^2}\delta(x_q - 1) \text{ and } x_q = -\frac{q^2}{2q\cdot p_q}$$

and, furthermore, suppose that the quarks carry a fraction, z, of the proton momentum

$$p_q = z_q p, \quad \text{so that } x_q = \frac{x}{z_q} \quad (\text{also note } m_q = z_q M\,!)$$

which uses the relations between $K_{1,2}$ and $K_{4,5}$

Now,

$$MW_1 = M\sum_q \int_0^1 \frac{e_q^2}{2M}\delta(x - z_q)\, f_q(z_q)\, dz_q = \frac{1}{2}\sum_q e_q^2 f_q(x) \equiv F_1(x)$$

$$-\frac{q^2}{2Mx}W_2 = \sum_q \int_0^1 x e_q^2 \delta(x - z_q)\, f_q(z_q)\, dz_q = x\sum_q e_q^2 f_q(x) \equiv F_2(x)$$

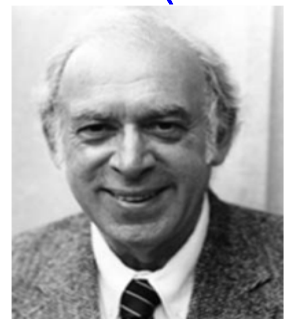
Two important *observable* consequences,

Bjorken scaling: $F_{1,2}(x), \quad \text{not } F_{1,2}(x, Q^2)$

Callan-Gross relation: $F_2 = 2xF_1(x)$

Deep-Inelastic Electron Scattering

Discovery of Quarks (Partons)



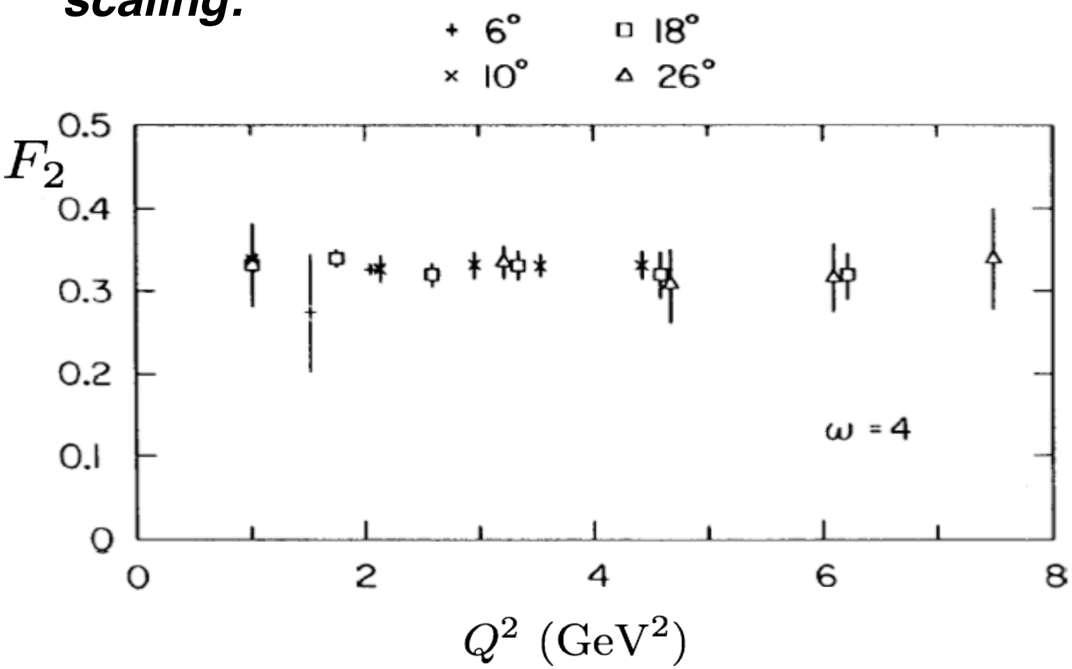
J.T. Friedman

R. Taylor

H.W. Kendall

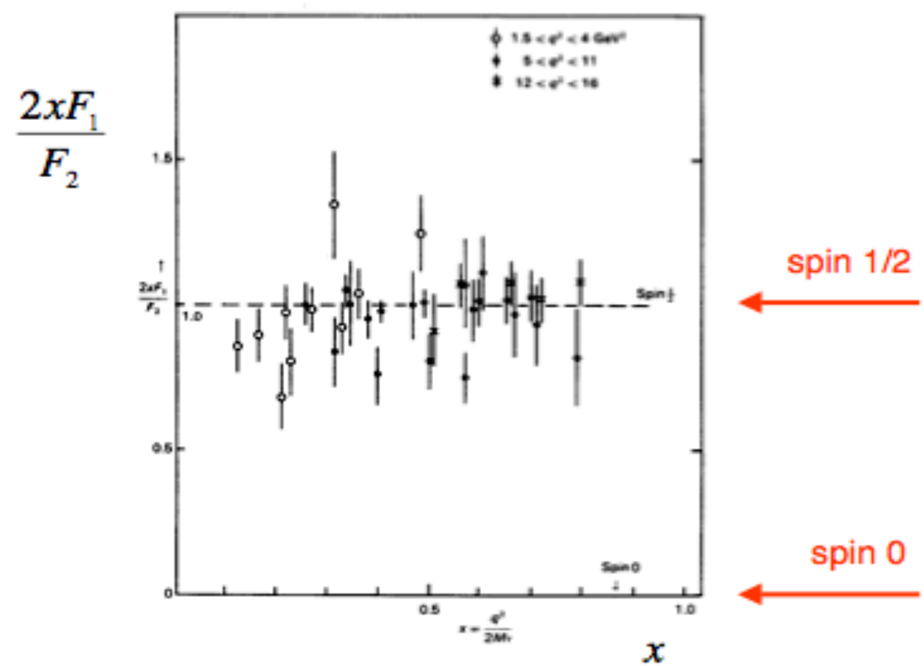
Nobel Prize 1990

Bjorken scaling:



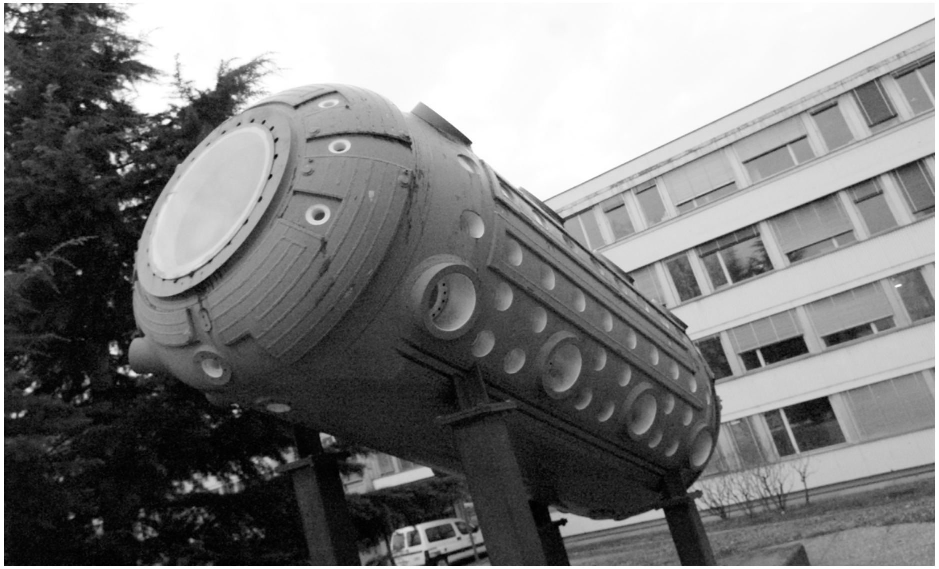
Point particles cannot be further resolved; their measurement does not depend on wavelength, hence Q^2,

Callan-Gross relation:



Spin-1/2 quarks cannot absorb longitudinally polarized vector bosons and, conversely, spin-0 (scalar) quarks cannot absorb transversely polarized photons.

Deep-Inelastic Neutrino Scattering

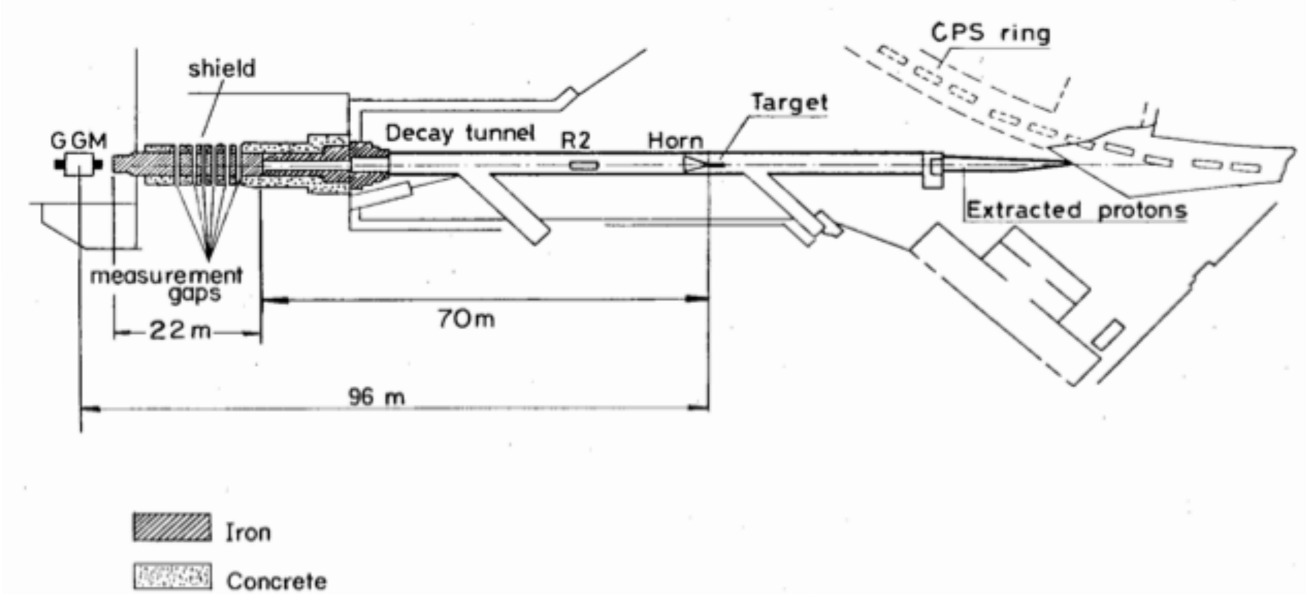


Picture from CERN...

Gargamelle bubble chamber, observation of weak neutral current (1973).

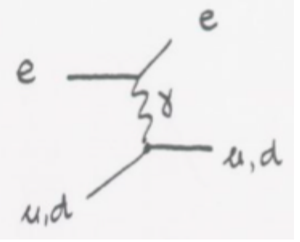
Charged-current DIS!

Nucl.Phys. **B73** (1974) 1
Nucl.Phys. **B85** (1975) 269
Nucl.Phys. **B118** (1977) 218
Phys.Lett. **B74** (1978) 134



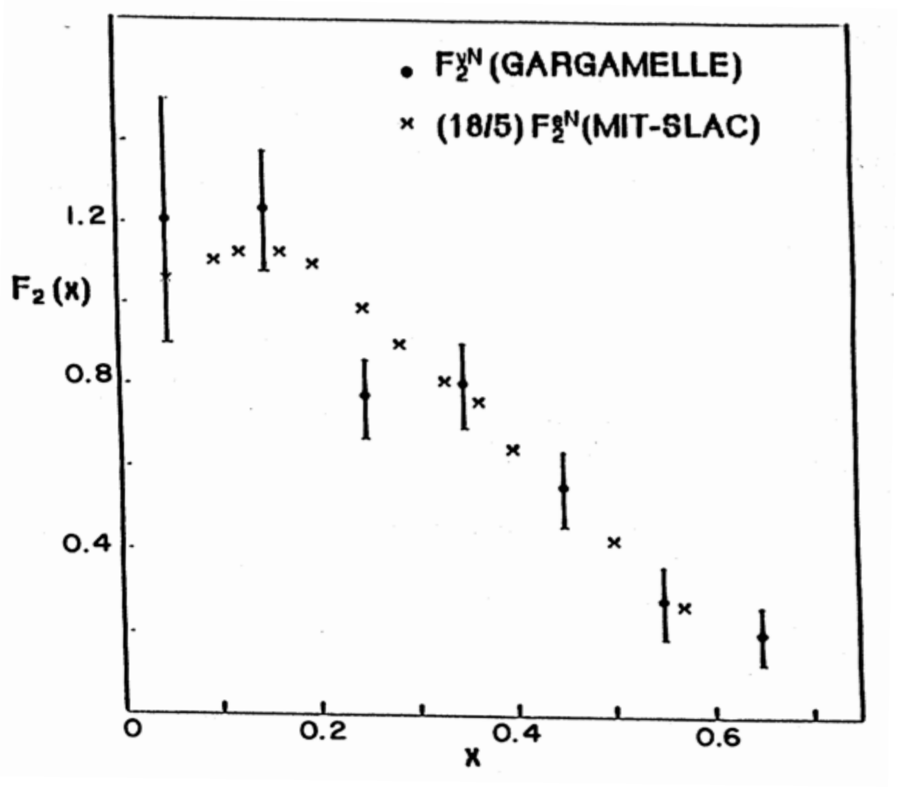
Deep-Inelastic Scattering - Fractional Electric Charges

Neutral-current (photon) DIS:

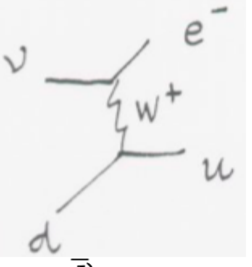


$$F_2 = x \sum e_q^2 (q + \bar{q}), \quad p : uud, \quad n : ddu$$

$$F_2^N = x \frac{e_u^2 + e_d^2}{2} (u + \bar{u} + d + \bar{d})$$



Charged-current DIS:

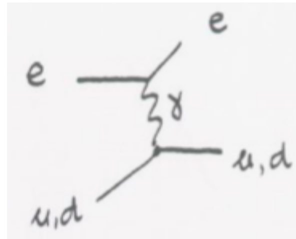


$$F_2^{\nu p} = 2x(d + \bar{u}), \quad F_2^{\nu n} = 2x(u + \bar{d})$$

$$F_2^{\nu N} = x(u + \bar{u} + d + \bar{d})$$

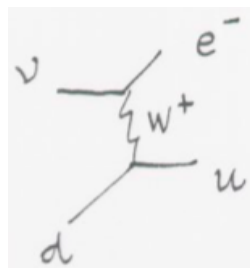
Deep-Inelastic Scattering - Fractional Electric Charges

Neutral-current (photon) DIS:



$$F_2 = x \sum e_q^2 (q + \bar{q}), \quad p: uud, \quad n: ddu$$

$$F_2^N = x \, \frac{e_u^2 + e_d^2}{2} \, (u + \bar{u} + d + \bar{d})$$



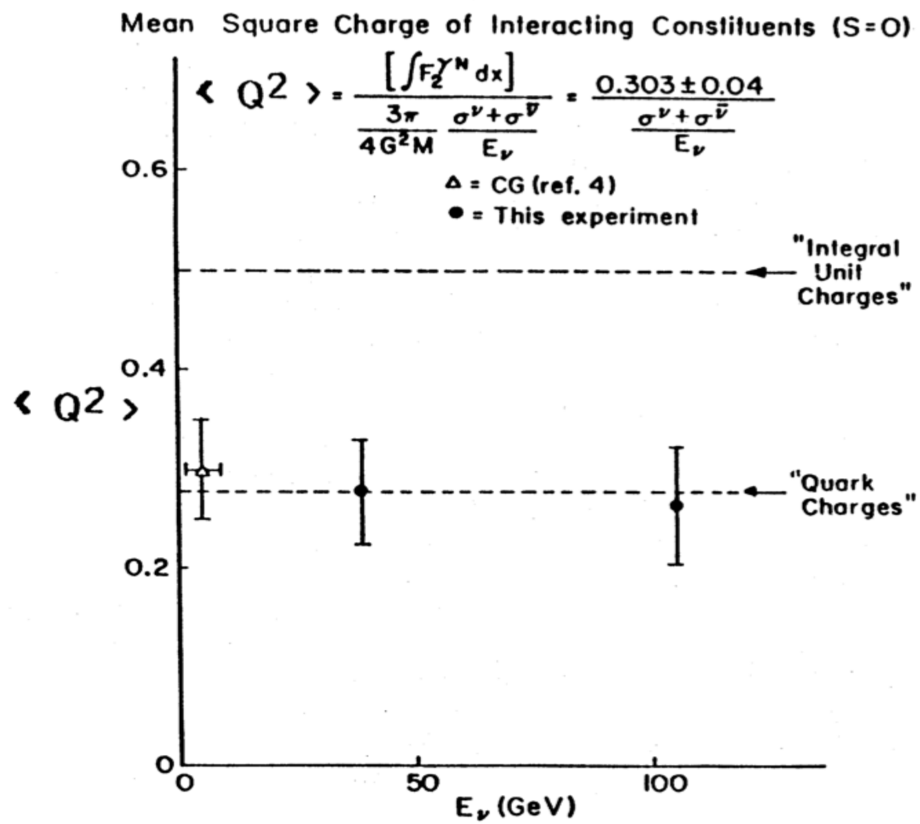
Charged-current DIS:

$$F_2^{\nu p} = 2x(d + \bar{u}), \quad F_2^{\nu n} = 2x(u + \bar{d})$$

$$F_2^{\nu N} = x(u + \bar{u} + d + \bar{d})$$

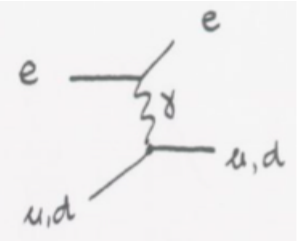
Ratio:

$$\frac{F_2^N}{F_2^{\nu N}} = \frac{1}{2}(e_u^2 + e_d^2) = \frac{5}{18} \simeq 0.28$$



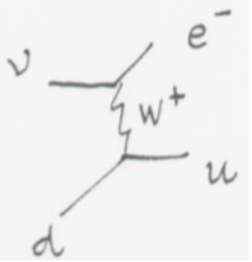
Deep-Inelastic Scattering - Momentum Conservation

Neutral-current (photon) DIS:



$$F_2^N = x \frac{e_u^2 + e_d^2}{2} (u + \bar{u} + d + \bar{d})$$

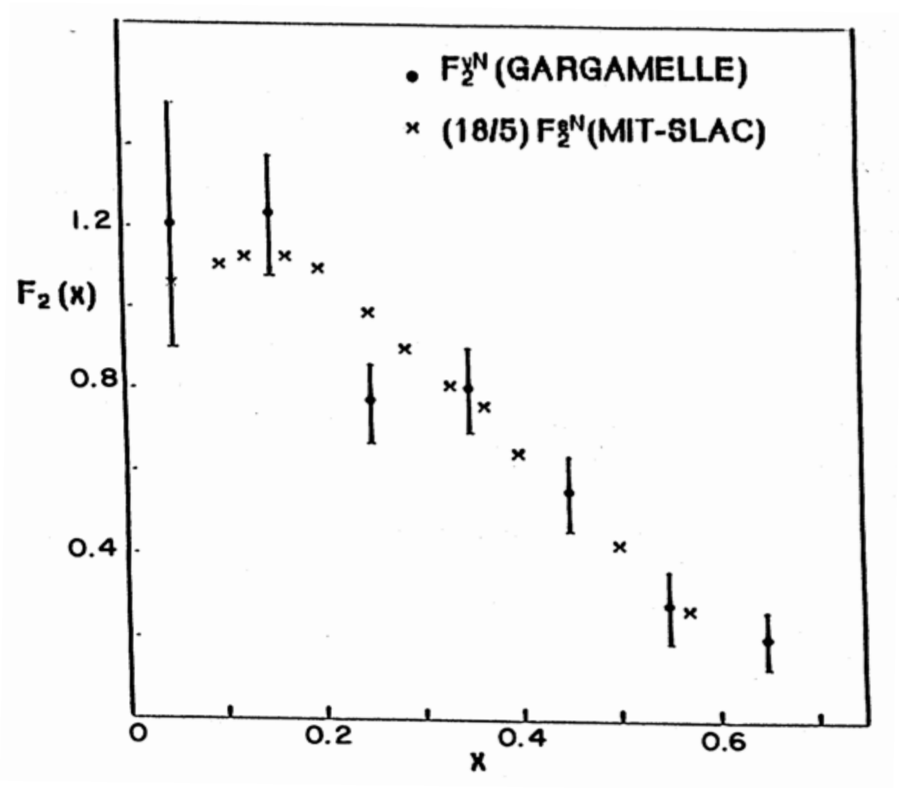
Charged-current DIS:



$$F_2^{\nu N} = x(u + \bar{u} + d + \bar{d})$$

Momentum fraction:

$$\int_0^1 F_2^N \, dx = \frac{e_u^2 + e_d^2}{2} \int_0^1 x(u + \bar{u} + d + \bar{d})$$



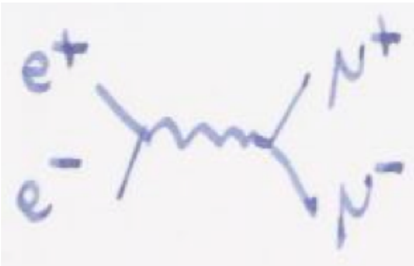
Gargamelle: 0.49 +/- 0.07

SLAC: 0.14 +/- 0.05

Quarks carry half of the nucleon momentum!

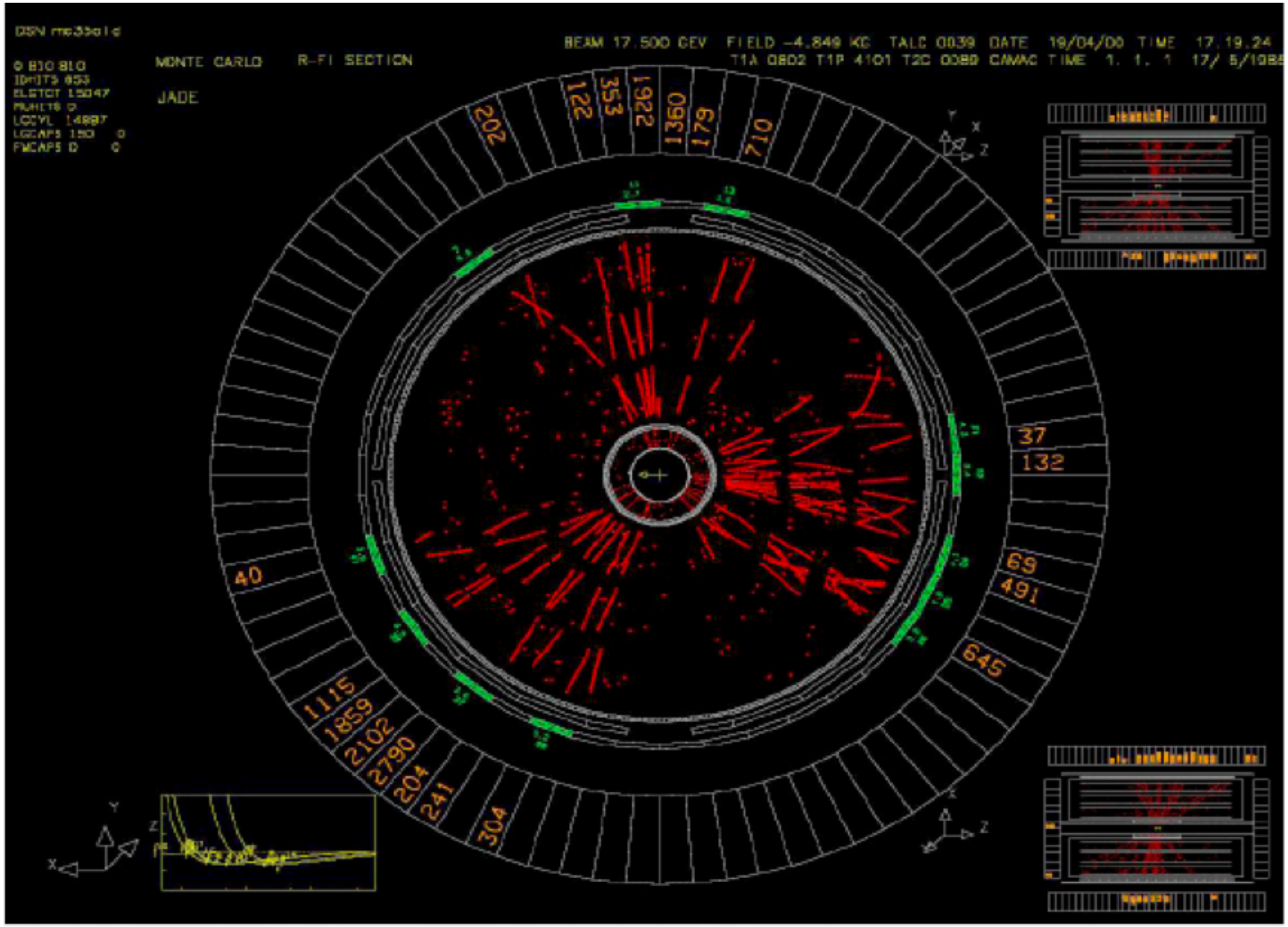
3-jet events at PETRA

Recall the intro on colour:



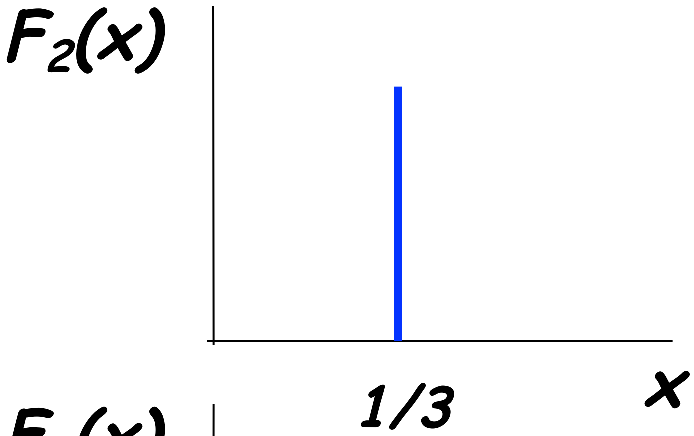
Observation of its higher order process,

marks the discovery of the gluon.

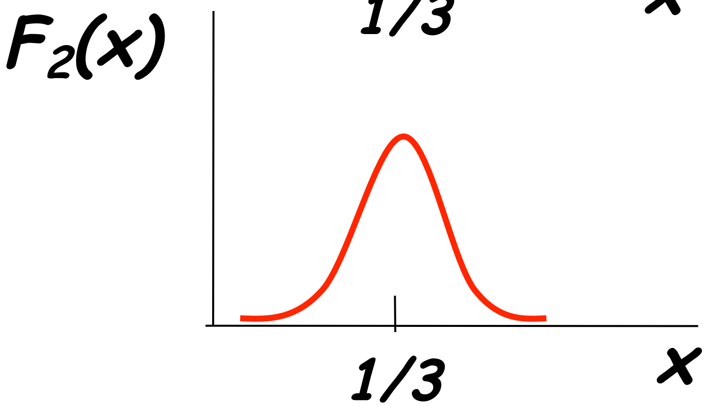


Mom. Conservation: *Gluons carry the other half of the nucleon momentum.*

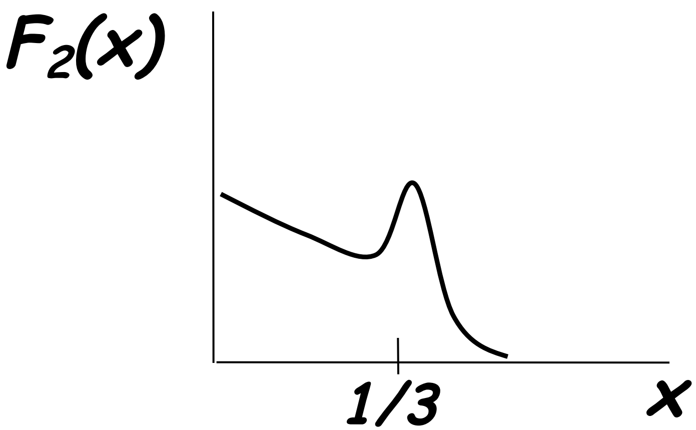
Nucleon Structure



Three quarks with 1/3 of total proton momentum each.

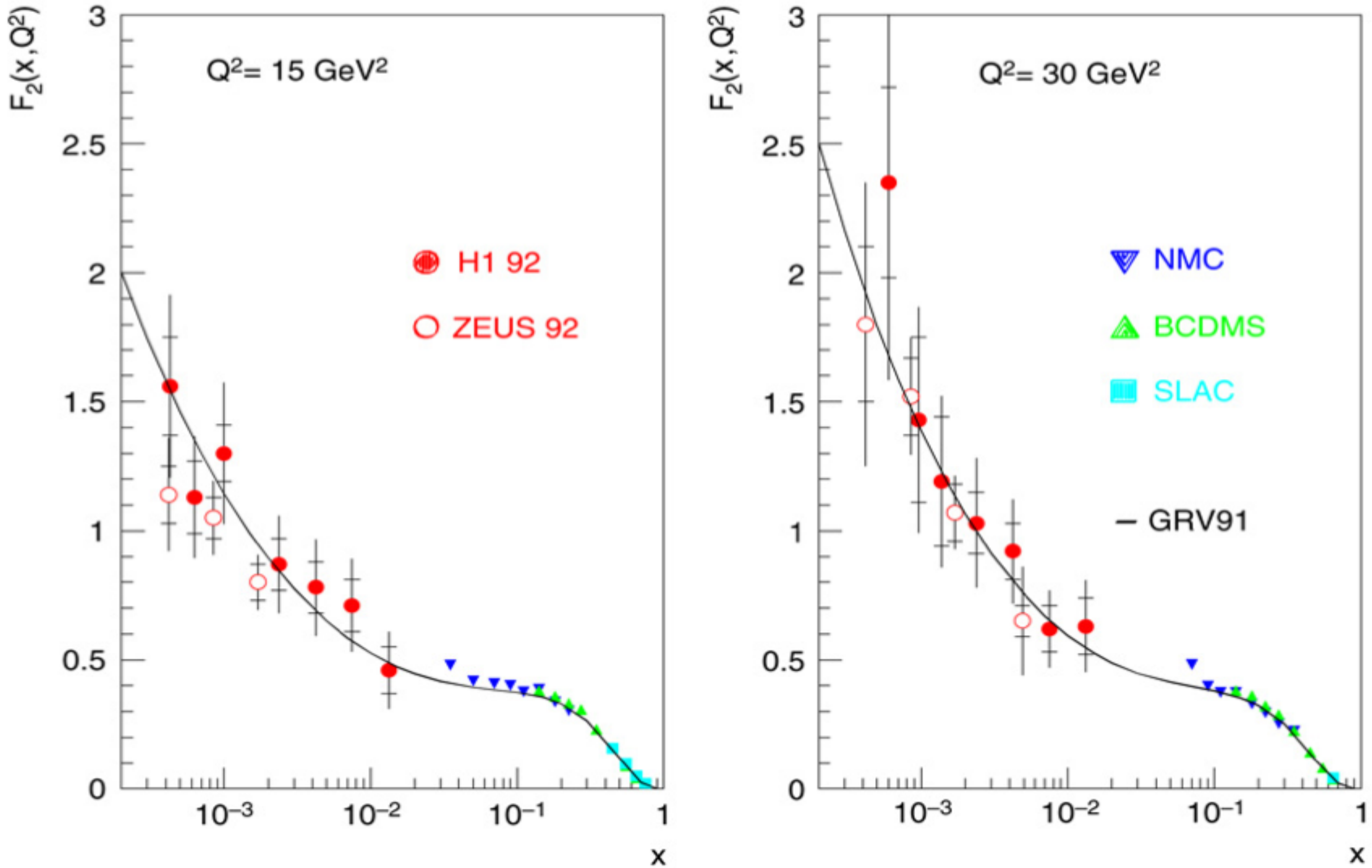


Three quarks with some momentum smearing.

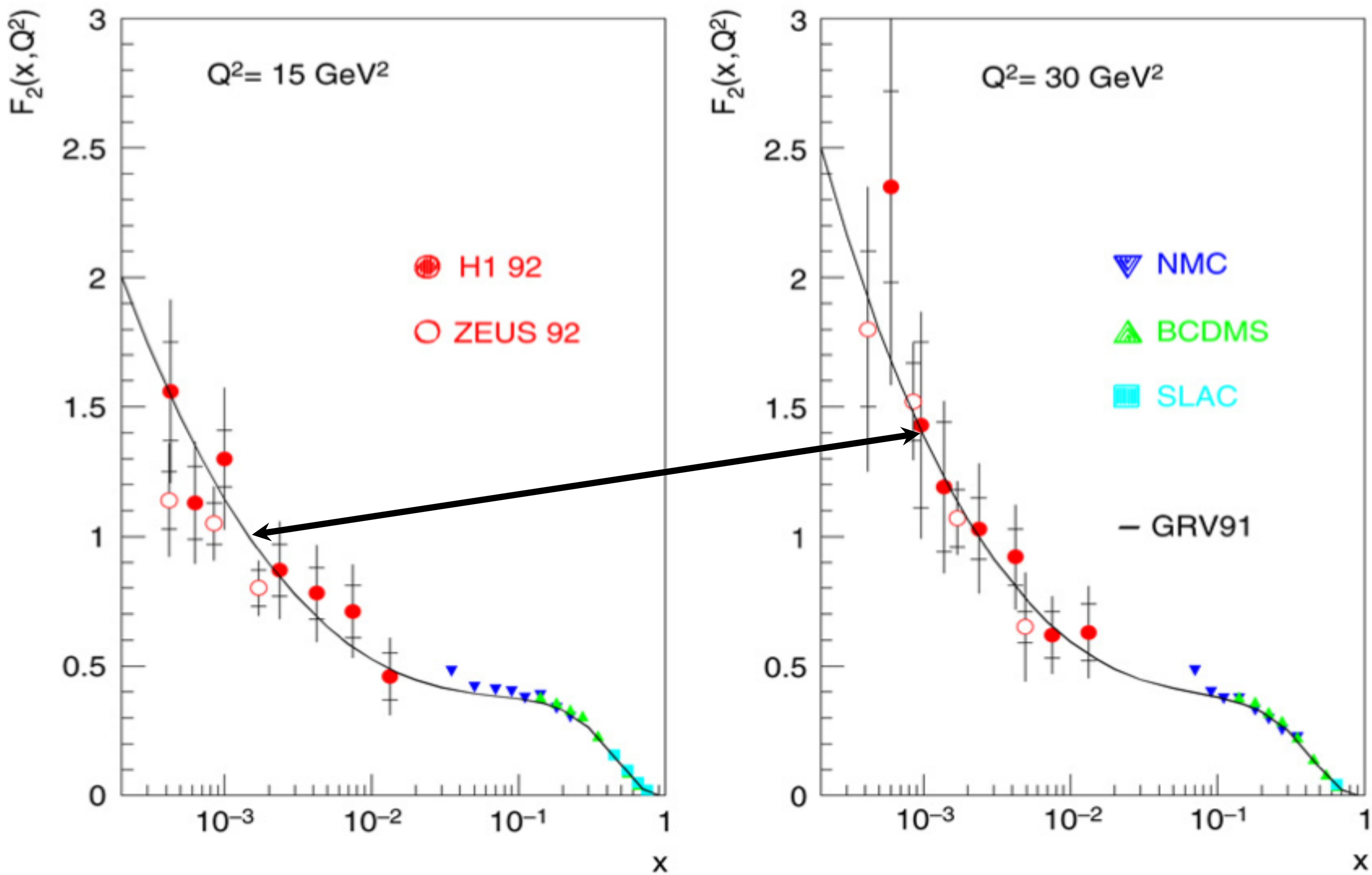


The three quarks radiate gluons to lower momentum fractions x.

HERA - Early Measurements



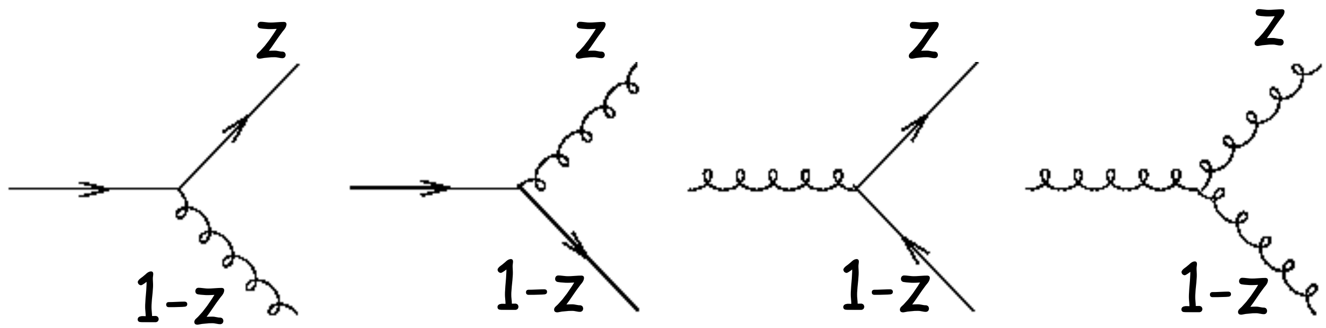
HERA - Early Measurements



Can these observations be related?

QCD Radiation

DGLAP equations are easy to "understand" intuitively, in terms of four "splitting functions",



$P_{ab}(z)$: the probability that parton a will radiate a parton b with the fraction z of the original momentum carried by a.

Yu.L. Dokshitzer, Sov.Phys. JETP **46** (1977) 641,
V.N. Gribov and L.N.Lipatov, Sov. Journ. Nucl. Phys. **15** (1972) 438; ibid **15** (1972) 675
G.Altarelli and G.Parisi, Nucl.Phys. **B126** (1977) 298

QCD Radiation

Schematically, DGLAP equations:

convolution

$$\frac{dq_f(x,Q^2)}{d\ln Q^2} = \alpha_s\,[q_f \otimes P_{qq} + g \otimes P_{gq}]$$

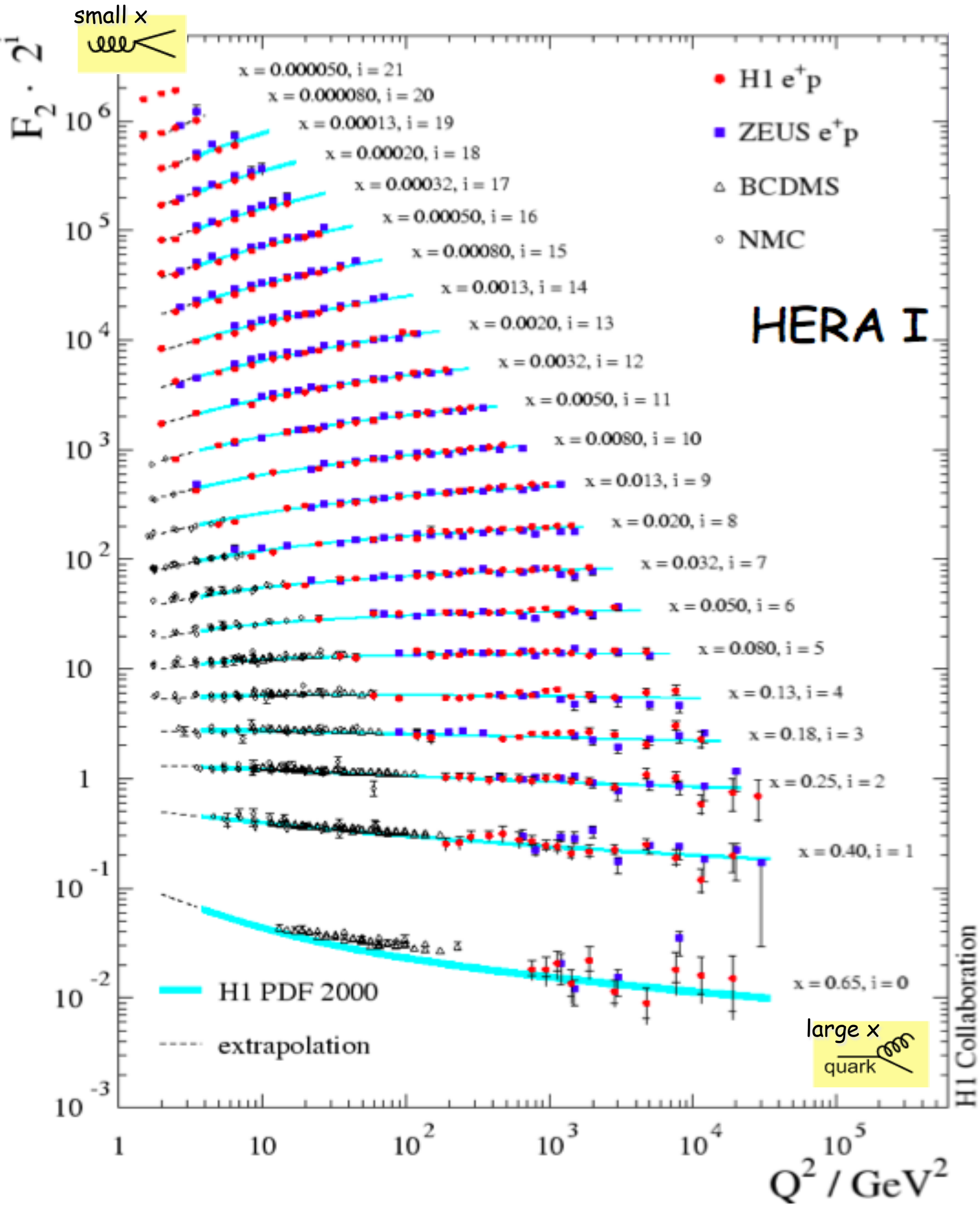
strong coupling constant

That is, the change of quark distribution q with Q^2 is given by the probability that q and g radiate q.

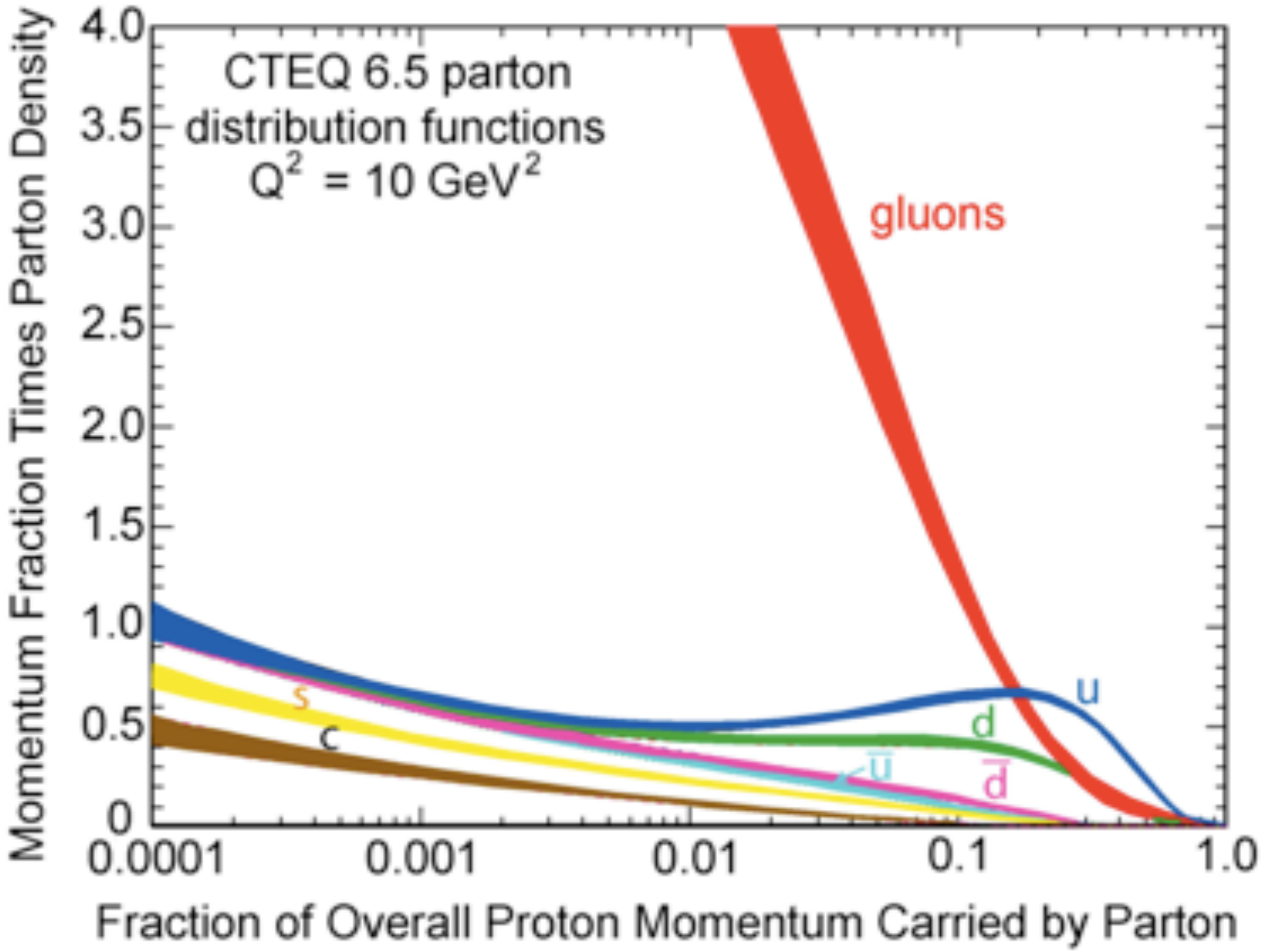
Similarly, for gluons:

$$\frac{dg(x,Q^2)}{d\ln Q^2} = \alpha_s\,[\sum q_f \otimes P_{qg} + g \otimes P_{gg}]$$

Bjorken scaling and QCD Radiation

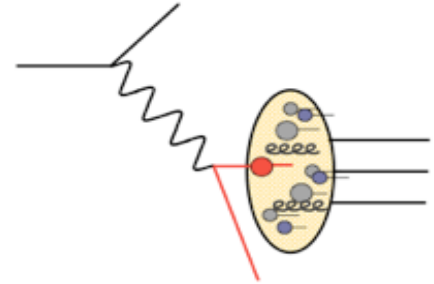


Modern understanding of nucleon composition



Brief Summary:

DIS



DIS probe nucleon or nuclear structure,
described in terms of quarks and gluons,

Feynman's parton model - point like partons, which
behave *incoherently* - combined with QCD radiation are remarkably successful in describing DIS cross sections.

QCD evolution allows one to relate quantitatively processes at different scales Q^2,

Parton distributions *f(x)* are intrinsic properties of the nucleon and (thus) process independent.
This is great for RHIC, LHC, and many other areas.

Gluons are a very significant part of the nucleon

Structure Functions at High x

Valence Quark Distributions

Why Are PDFs at High x Important?

- Valence quark dominance: simpler picture
  - -- direct comparison with nucleon structure models
    SU(6) symmetry, broken SU(6), diquark
- $x \rightarrow 1$ region amenable to pQCD analysis
  - -- hadron helicity conservation?
- Clean connection with QCD, via lattice moments
- Input for search for physics beyond the Standard Model at high energy collider
  - -- evolution: high x at low $Q^2 \rightarrow$ low x at high Q^2
  - -- small uncertainties amplified
  - -- example: HERA 'anomaly' (1998)
- Input to nuclear, high energy and astrophysics calculations

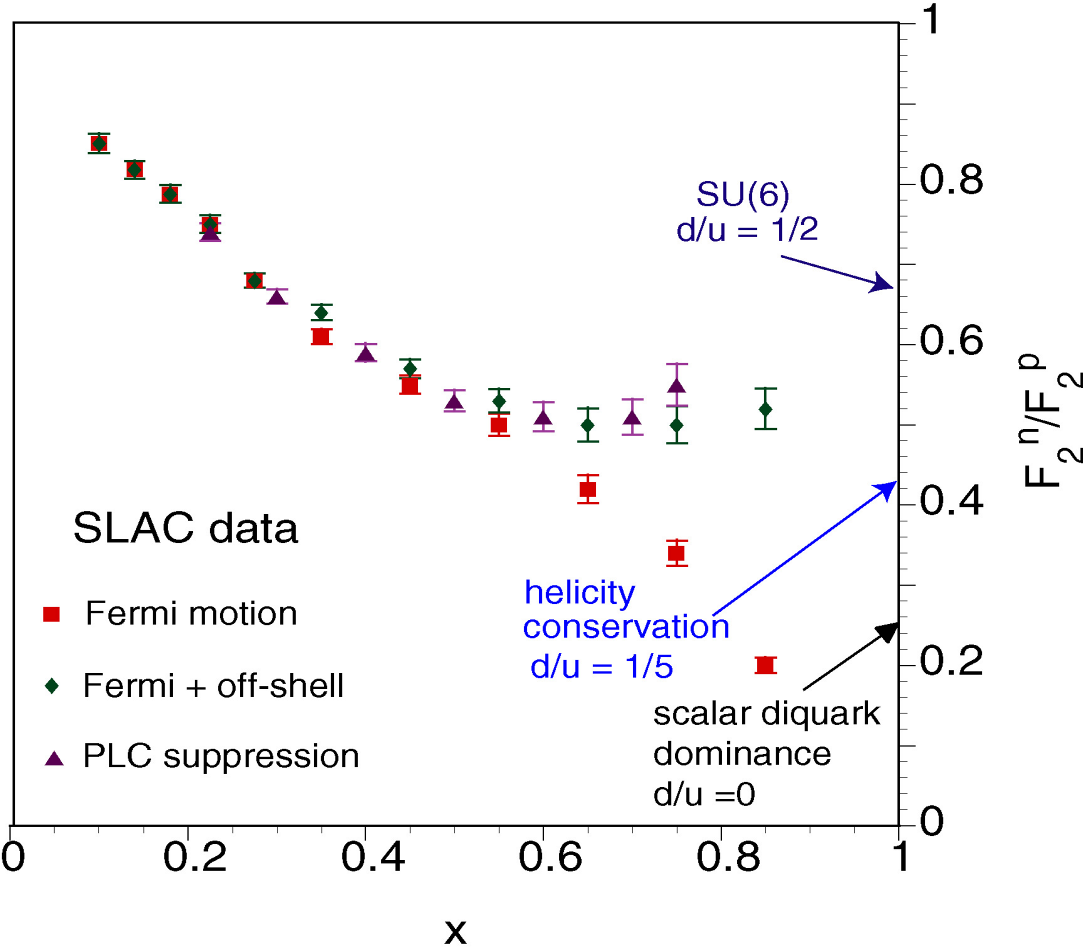
Predictions for High x

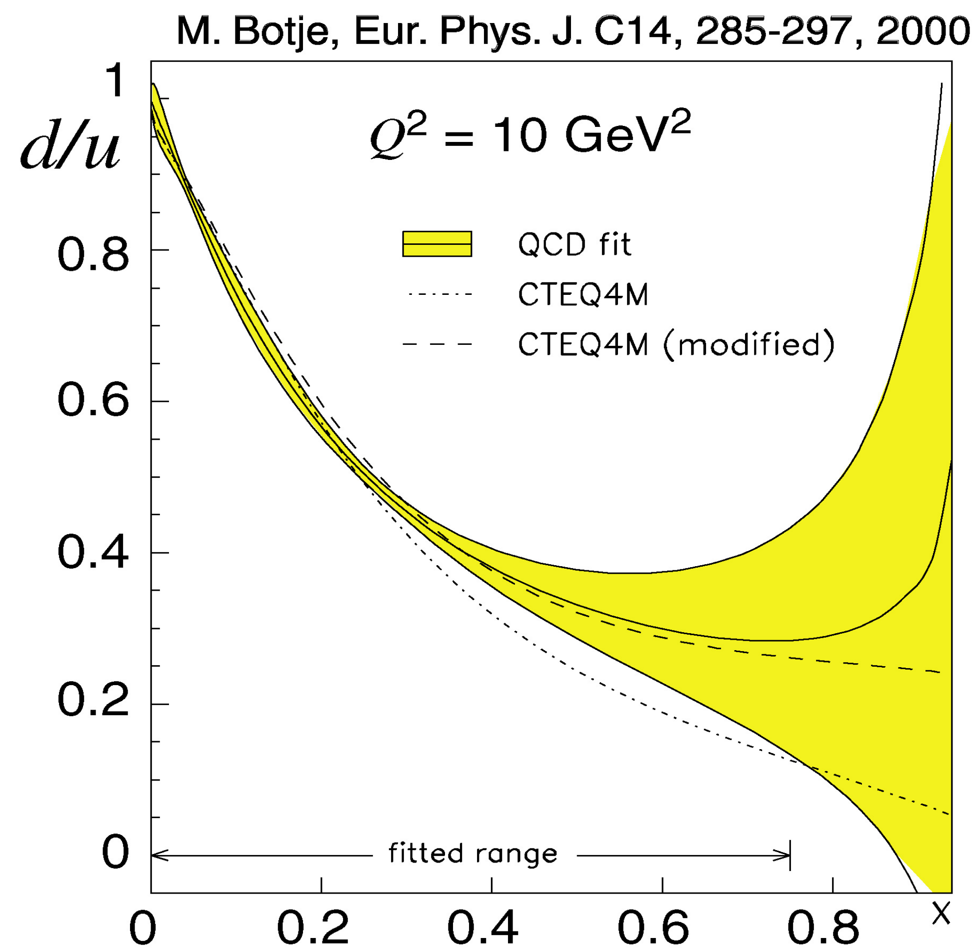
Proton Wavefunction (Spin and Flavor Symmetric)

$$|p\uparrow\rangle = \frac{1}{\sqrt{2}}|u\uparrow(ud)_{S=0}\rangle + \frac{1}{\sqrt{18}}|u\uparrow(ud)_{S=1}\rangle - \frac{1}{3}|u\downarrow(ud)_{S=1}\rangle - \frac{1}{3}|d\uparrow(uu)_{S=1}\rangle - \frac{\sqrt{2}}{3}|d\downarrow(uu)_{S=1}\rangle$$

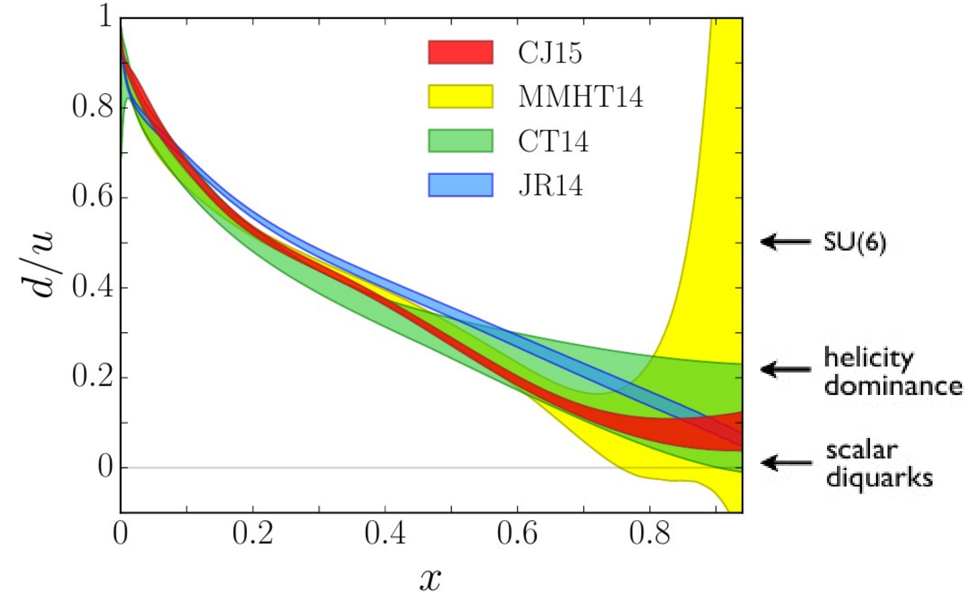
Nucleon Model	F_2^n/F_2^p	d/u	Δu/u	Δd/d	A_1^n	A_1^p
SU(6)	2/3	1/2	2/3	-1/3	0	5/9
Scalar diquark	1/4	0	1	-1/3	1	1
pQCD	3/7	1/5	1	1	1	1

F_2^n/F_2^p → d/u ratio at high-x





Hadronic physics output 1: d/u ratio



→ d/u ratio at high x of interest for nonperturbative models of nucleon

→ **CJ15:**

more flexible parametrization

$$d \rightarrow d + b\,x^c\,u$$

allows finite, nonzero $x = 1$ limit

(standard PDF form gives 0 or ∞ unless $a_2^d = a_2^u$)

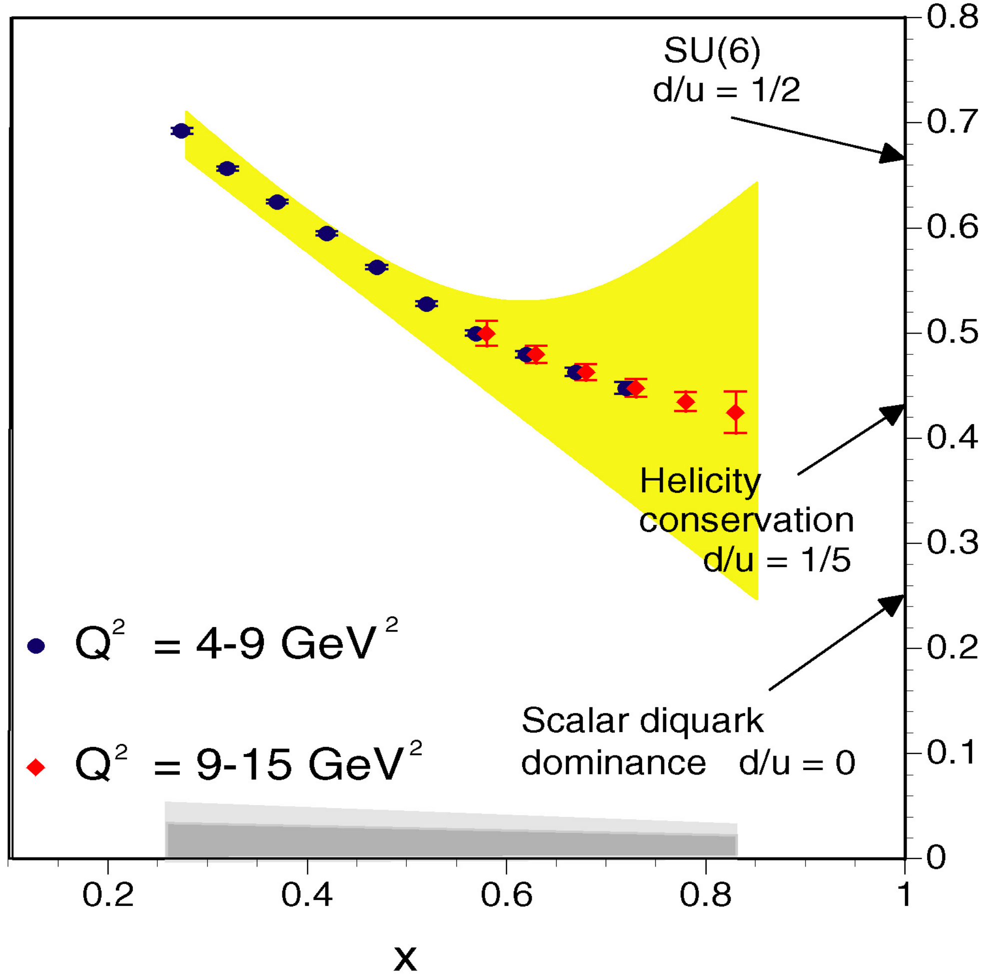
MMHT14: fitted deuteron corrections
standard *d* parametrization
→ "UNDERCONSTRAINED"

JR14 (and ABM12):
Similar deuteron corrections
standard *d* ; no lepton/W asym.
→ "OVERCONSTRAINED"

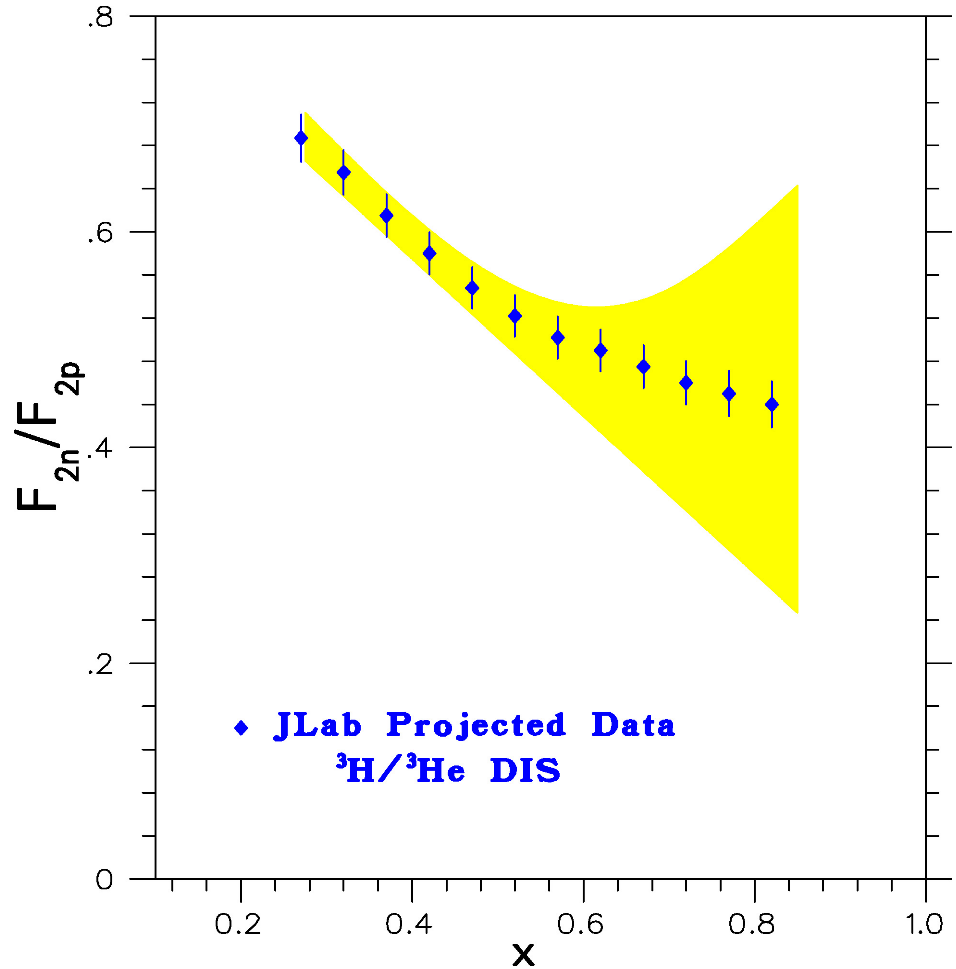
CT14: $\beta_u = \beta_d \implies d/u$ finite
No nuclear corrections

F_2^n/F_2^p → d/u ratio at high-x

BONUS at Hall B 11 GeV with CLAS12



Hall A 11 GeV with HRS



Longstanding issue in proton structure

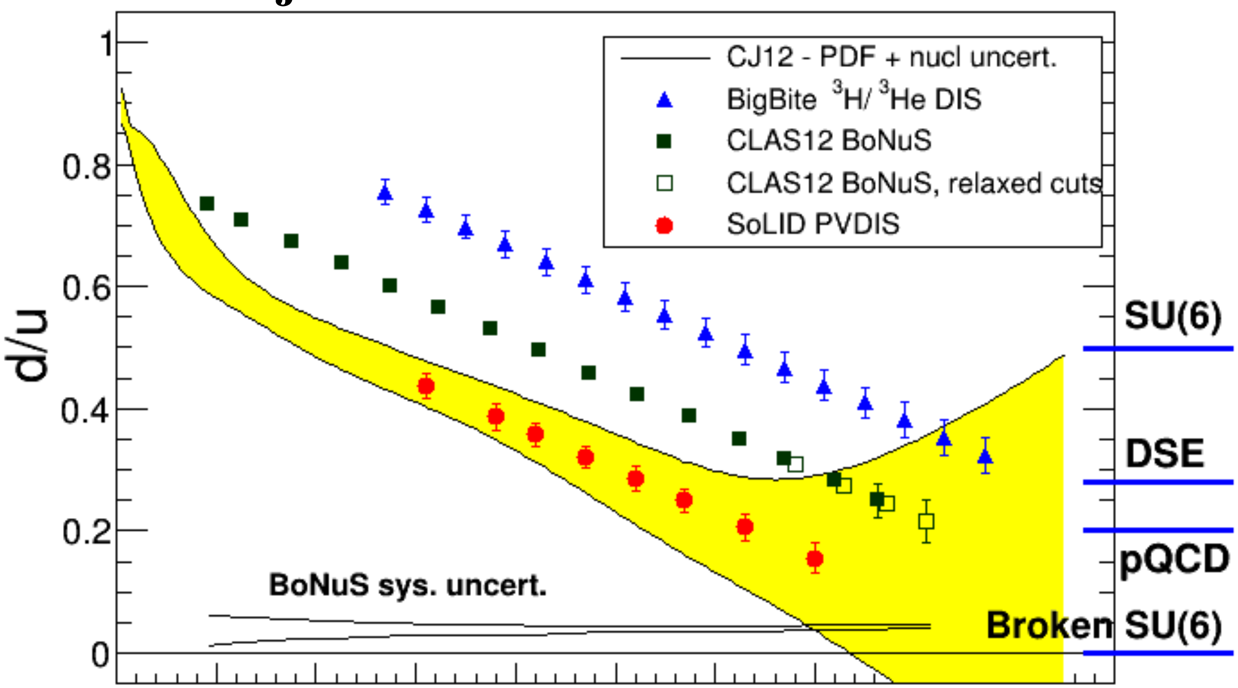
Proton PVDIS: d/u at high x

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

SU(6): d/u~1/2
Broken SU(6): d/u~0
Perturbative QCD: d/u~1/5

$$a^P(x) \approx \frac{u(x) + 0.91d(x)}{u(x) + 0.25d(x)}$$

Projected 12 GeV d/u extractions



- <u>3 JLab 12 GeV experiments</u>:

- CLAS12 BoNuS spectator tagging
- BigBite – DIS $^3H/^3He$ ratio
- **SoLID – PVDIS *ep***

- **The SoLID extraction of *d/u* is directly from *ep* DIS:**
  - **No nuclear corrections**
  - **No assumption of charge symmetry**

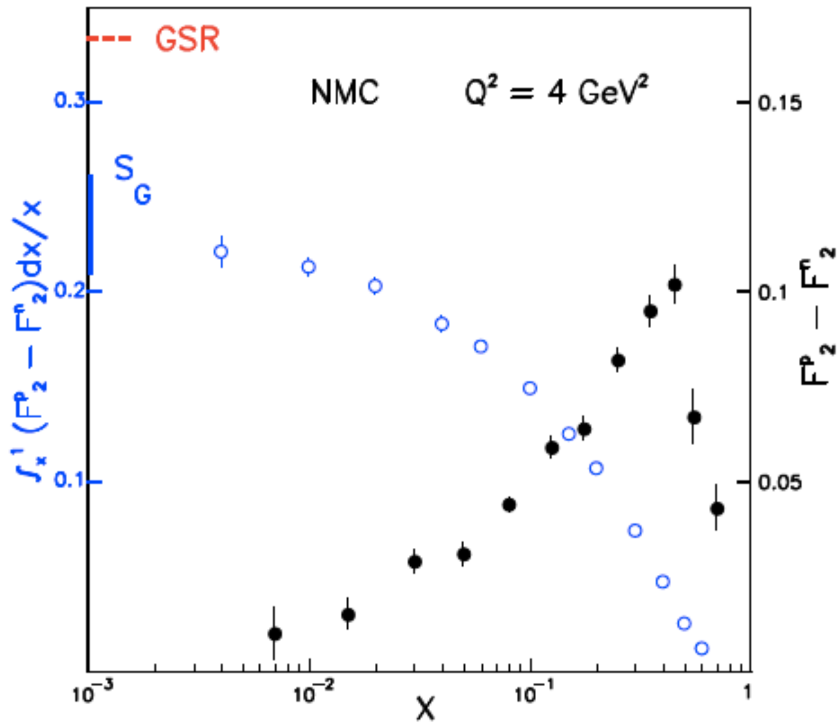
Sea Quark Distributions

Sea Asymmetry (d_bar/u_bar)
Strange Sea

Flavor structure of the proton sea

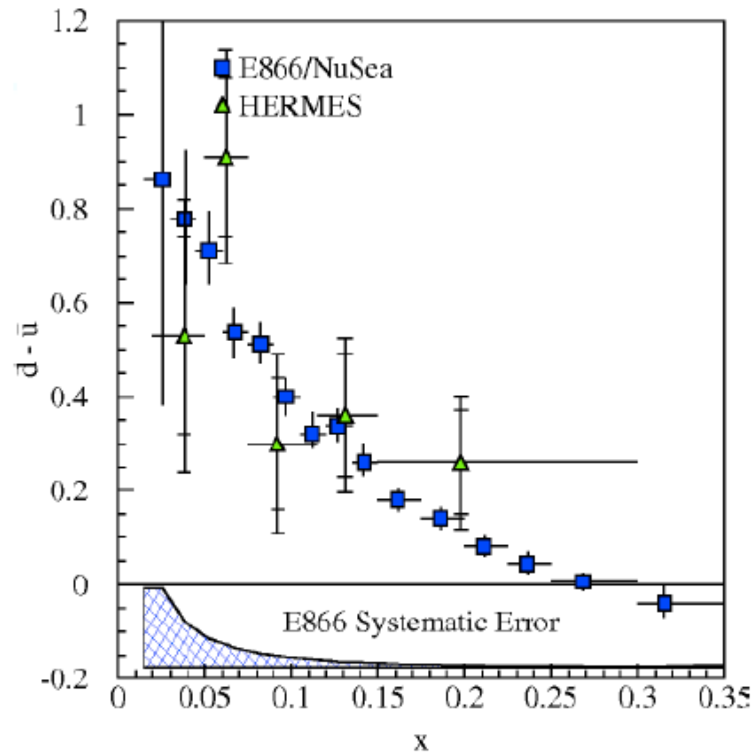
- The proton sea is not SU(3) symmetric!

Violation of Gottfried sum rule



$$S_G = \int_0^1 [(F_2^p(x) - F_2^n(x))/x]\,dx$$
$$= \frac{1}{3} + \frac{2}{3}\int_0^1 (\bar{u}_p(x) - \bar{d}_p(x))\,dx$$
$$= \frac{1}{3} \quad (if\ \bar{u}_p = \bar{d}_p) \quad \text{NMC: } S_G = 0.235 \pm 0.026$$

Confirmed by Drell-Yan exp't

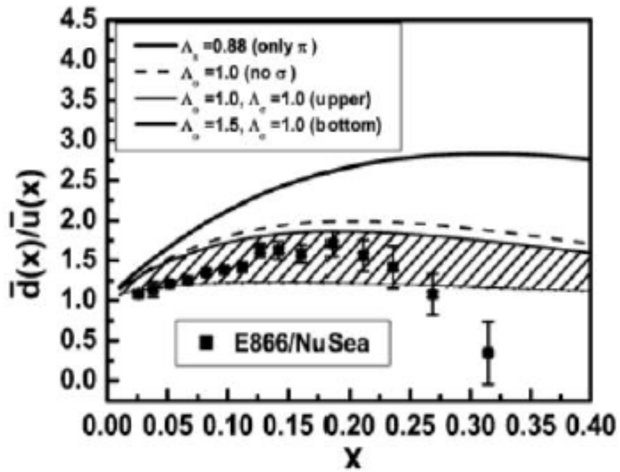


Why $\bar{d}(x) \neq \bar{u}(x)$ ***?***

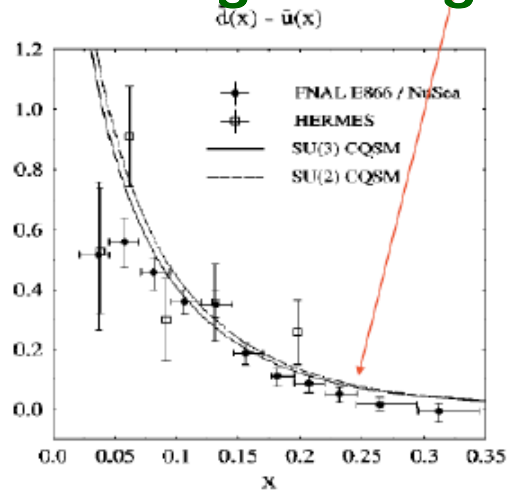
Why does $\bar{d}(x) - \bar{u}(x)$ ***change sign?***

Challenges for $\bar{d}(x) - \bar{u}(x)$

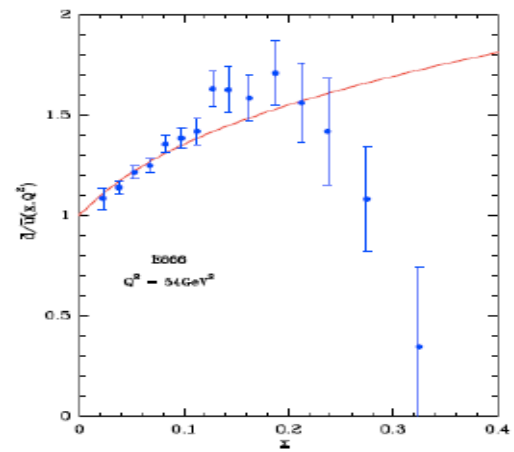
- ❑ All known models predict no sign change!



Meson cloud

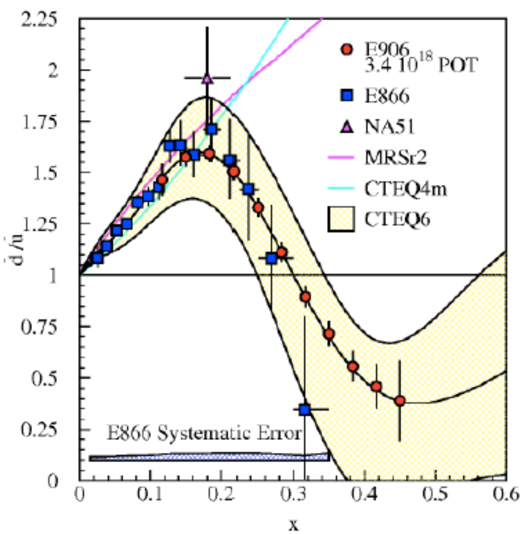


Chiral-quark soliton model

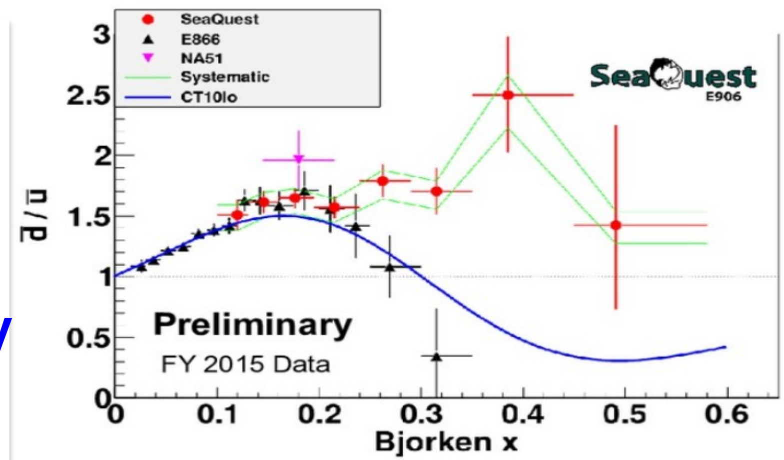


Statistic model

- ❑ Future experiments – E906, …

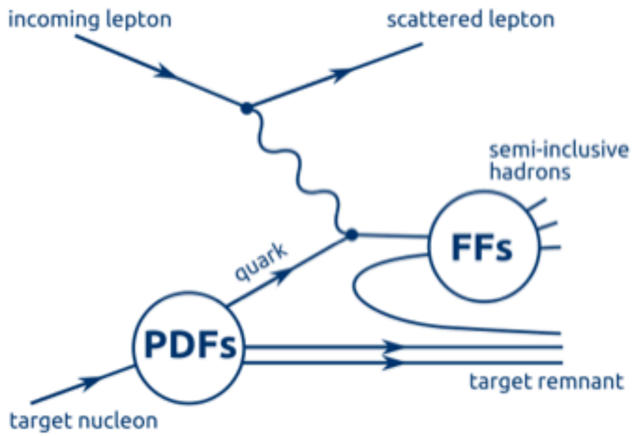


Preliminary From Seaquest



B.Kerns, DNP April 2016

Semi-Inclusive DIS



$$Q(x) \equiv u(x) + \bar{u}(x) + d(x) + \bar{d}(x)$$

$$S(x) \equiv s(x) + \bar{s}(x)$$

$$K = K^+ + K^-$$

isoscalar target (D)

Fragmentation function — Parton distribution function — Fragmentation function

$$\frac{d^2N^K(x)}{d^2N^{DIS}(x)} \overset{\text{LO}}{=} \frac{Q(x)\int D_Q^K(z)dz + S(x)\int D_S^K(z)dz}{5Q(x) + 2S(x)}$$

Parton distribution function

= Multiplicities

First Hermes extraction:
Phys.Lett. B666, 446 (2008)

Updated and final data now!

Q^2 Negative squared 4-momentum transfer to the target

x Parton fractional momentum

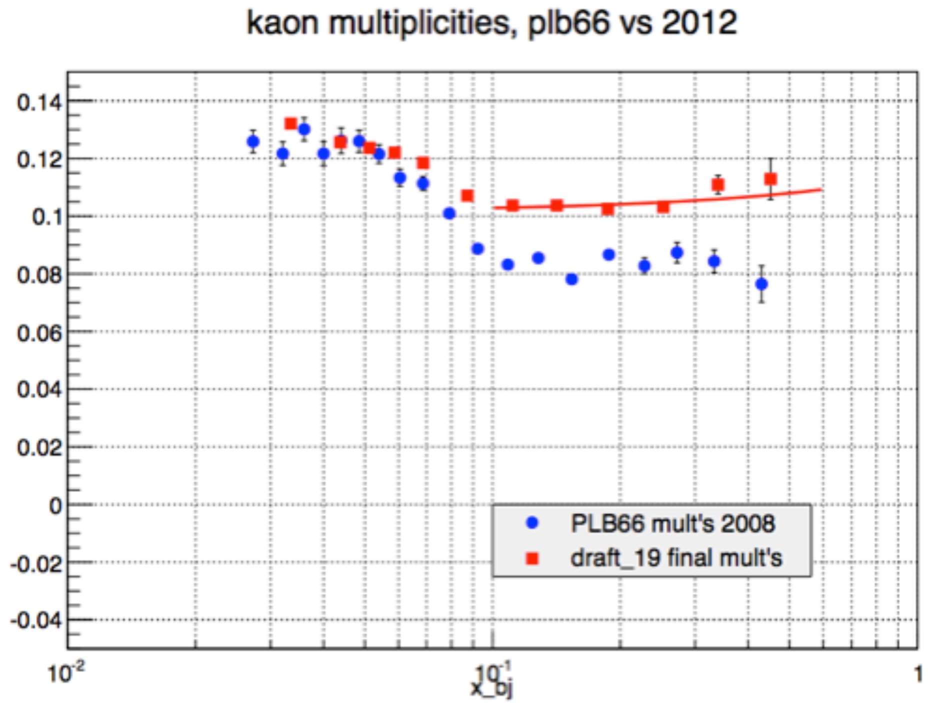
z Fractional energy transfer to the produced hadron

$P_{h\perp}$ Hadron transverse momentum with respect to the virtual photon direction

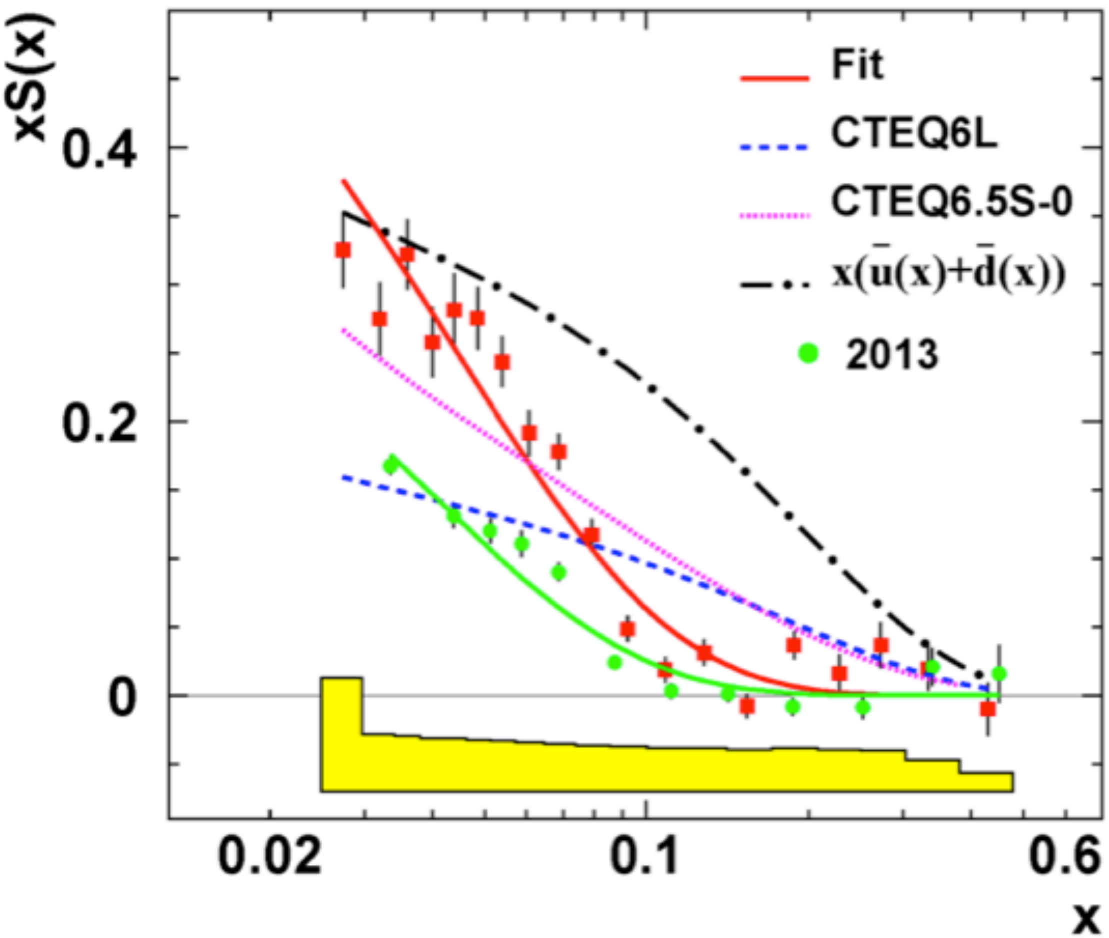
hermes

New multiplicities

- More data (~ factor 2)
- New 3-dimensional (x-z-$P_{h\perp}$) unfolding to correct for acceptance, radiative effects, smearing, decay in flight and secondary strong interactions
- Final 3-dimensional results corrected to 4π Born



Old versus new S(x)



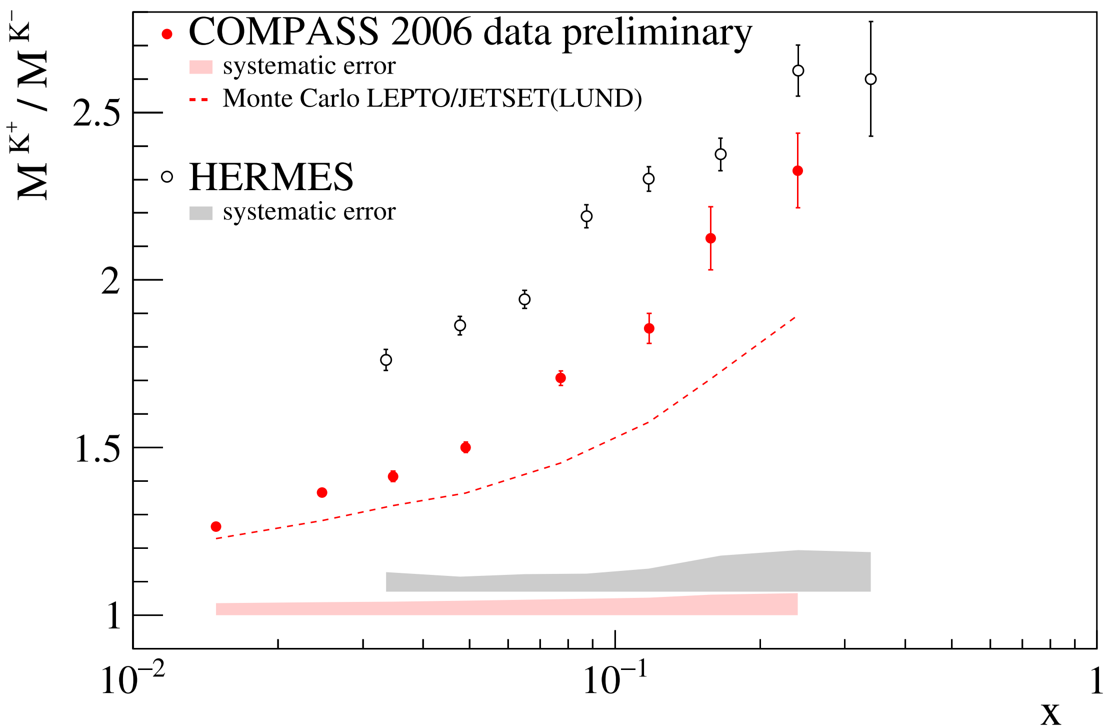
Kaon multiplicity ratio

- π case, there is a good agreement between COMPASS and HERMES for the π^+/π^- multiplicity ratio

  Despite the difference in the shape of π multiplicity sum

- K case: clear discrepancy between COMPASS and HERMES even for the K^+/K^- multiplicity ratio

- DSS next fit of Kaon FF



Summary

- Electron Scattering to study Nucleon Structure
- Elastic: Form Factors

  charge/current distributions

  transverse density

  G_E^p @ large Q^2 surprise → shape of proton, 2-γ effects

  proton radius puzzle

- Deep-Inelastic Scattering

  Unpolarized Structure functions → Parton Distributions

  High-x, valance quark distributions, d/u

  Sea distributions: d_bar/u-bar asymmetry

  poor knowledge on strange sea