Partonic Hadron Structure II

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I. Where are we now?
II. Longitudinal Parton Distributions
III. Nuclear Effects
IV. Spin

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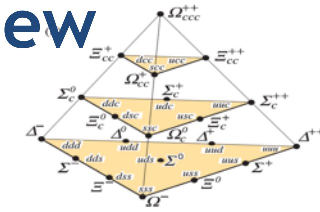
Partonic Hadron Structure I Review



1. **Physicists seek organization and order**
2. The quark model can explain many of the properties of the observed hadronic spectra.
3. Elastic scattering shows that the proton is not a point particle

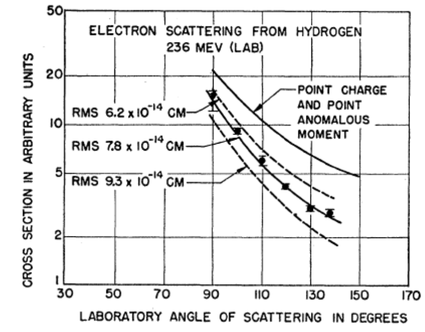


FIG. 6. This figure shows the experimental points at 236 Mev and the attempts to fit the shape of the experimental curve. The best fit lies near 0.78×10^{-13} cm.

4. **Richard Feynman was a genius.**
   - Hadron-hadron scattering is a collision of many point-like particles (partons)
   - Each parton carries a fraction of the hadron's momentum
   - Parton distributions can be described in terms of a probability distribution of a parton existing with momentum fraction in [x, x+dx]
5. Deep Inelastic Scattering cam be described in terms of a summation over point-like scattering from partons.
6. Parton distributions may be extracted from hard scattering data.
   - Generally requires data from multiple measurements
   - **Care must be taken to avoid false assumptions**

$$F_2^{\mu p}(x) \propto \sum_{q\in\{u,d,\dots\}} e_q^2 x \left[q(x,Q^2)+\bar{q}(x,Q^2)\right]$$

$$F_2^{\nu p}(x) + F_2^{\nu n} \propto \sum_{q\in\{u,d,\dots\}} x \left[q(x,Q^2)+\bar{q}(x,Q^2)\right]$$

$$xF_3^{\nu N}(x) \propto \sum_{q\in\{u,d,\dots\}} x \left[q(x,Q^2)-\bar{q}(x,Q^2)\right]$$

Becky is now Happy!


Dusty: Not so happy—things I left out yesterday

Infinite Momentum Frame

- Feynman:

  "By Lorentz transformation, the fields to be radiated are becoming narrower and narrower in the *z* direction as *W* rises. The energy in this field is therefore distributed as a δ function in *z*."
- The concept of longitudinal parton distributions exists in a Lorentz frame in which the hadron is moving fast enough that transverse momentum of the partons within the hadron can be neglected, or $P_z >>> M$.

- The proton is Lorentz contracted which implies that during the Δt of the reaction, the partons do not communicate with each other. That is, they are quasi-free particles

Gluons are partons too!

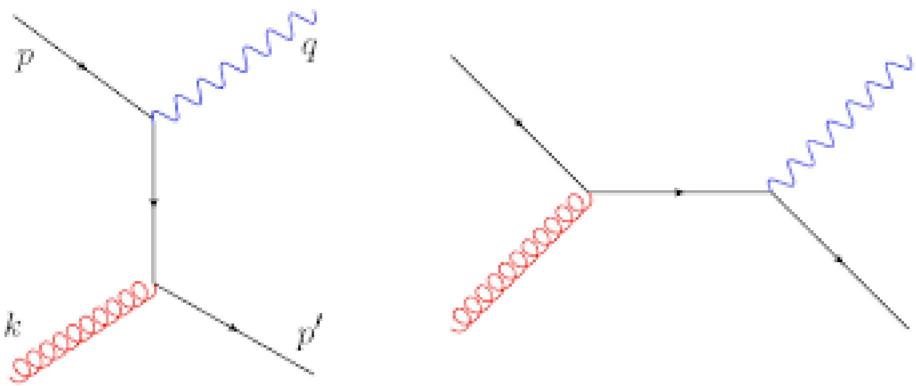
- Gluons also form partons and carry a fraction (possibly large) of the proton's momentum

Momentum conservation $$\int_0^1 x\left[u(x)+\bar{u}(x)+d(x)+\bar{d}(x)+\cdots\right]dx = 1$$

- Part of the "..." in the momentum constraint. Sometimes written out explicitly as g(x).

- Difficult to measure because
  - They do not couple to the electromagnetic force (hard to probe)
  - They are suppressed by $1/\alpha_{EM}$

- Observation of direct photons



Scaling

- Bjorken limit

  $Q^2 \to \infty$ and $\nu \to \infty$ at fixed x

  The structure functions were measured to be relatively constant over many decades of Q^2

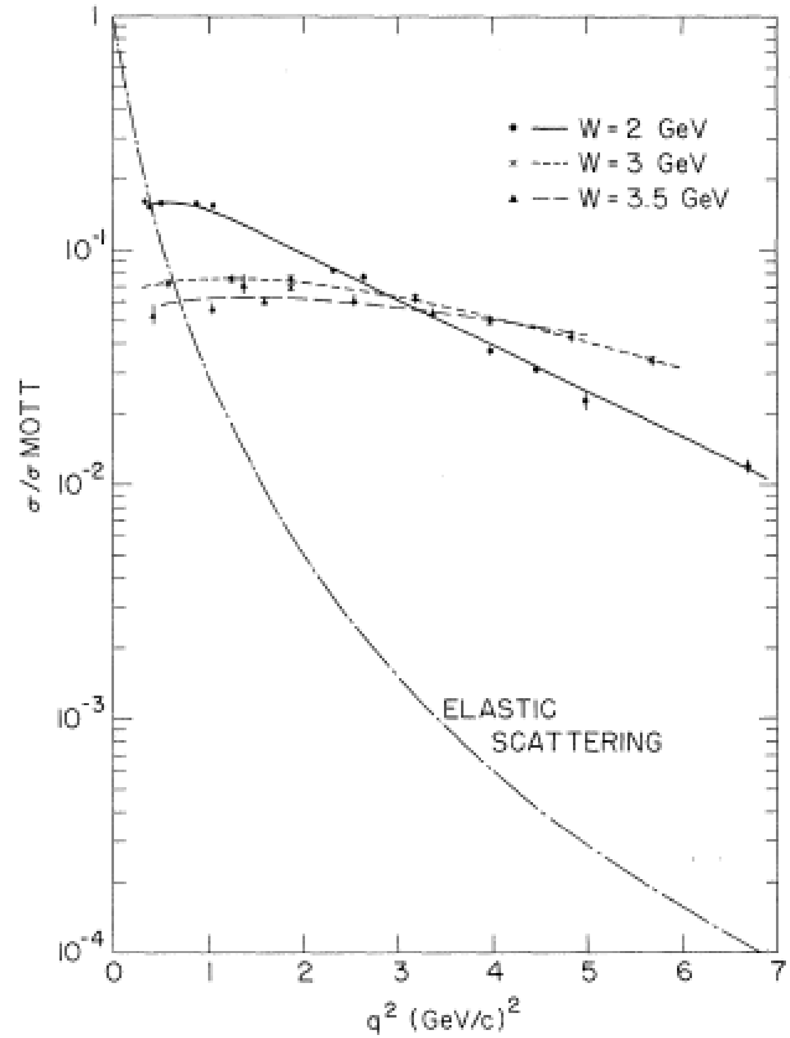
VOLUME 23, NUMBER 16 PHYSICAL REVIEW LETTERS 20 OCTOBER 1969

OBSERVED BEHAVIOR OF HIGHLY INELASTIC ELECTRON-PROTON SCATTERING

M. Breidenbach, J. I. Friedman, and H. W. Kendall
Department of Physics and Laboratory for Nuclear Science,*
Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

and

E. D. Bloom, D. H. Coward, H. DeStaebler, J. Drees, L. W. Mo, and R. E. Taylor
Stanford Linear Accelerator Center,† Stanford, California 94305
(Received 22 August 1969)



Scaling

- Bjorken limit

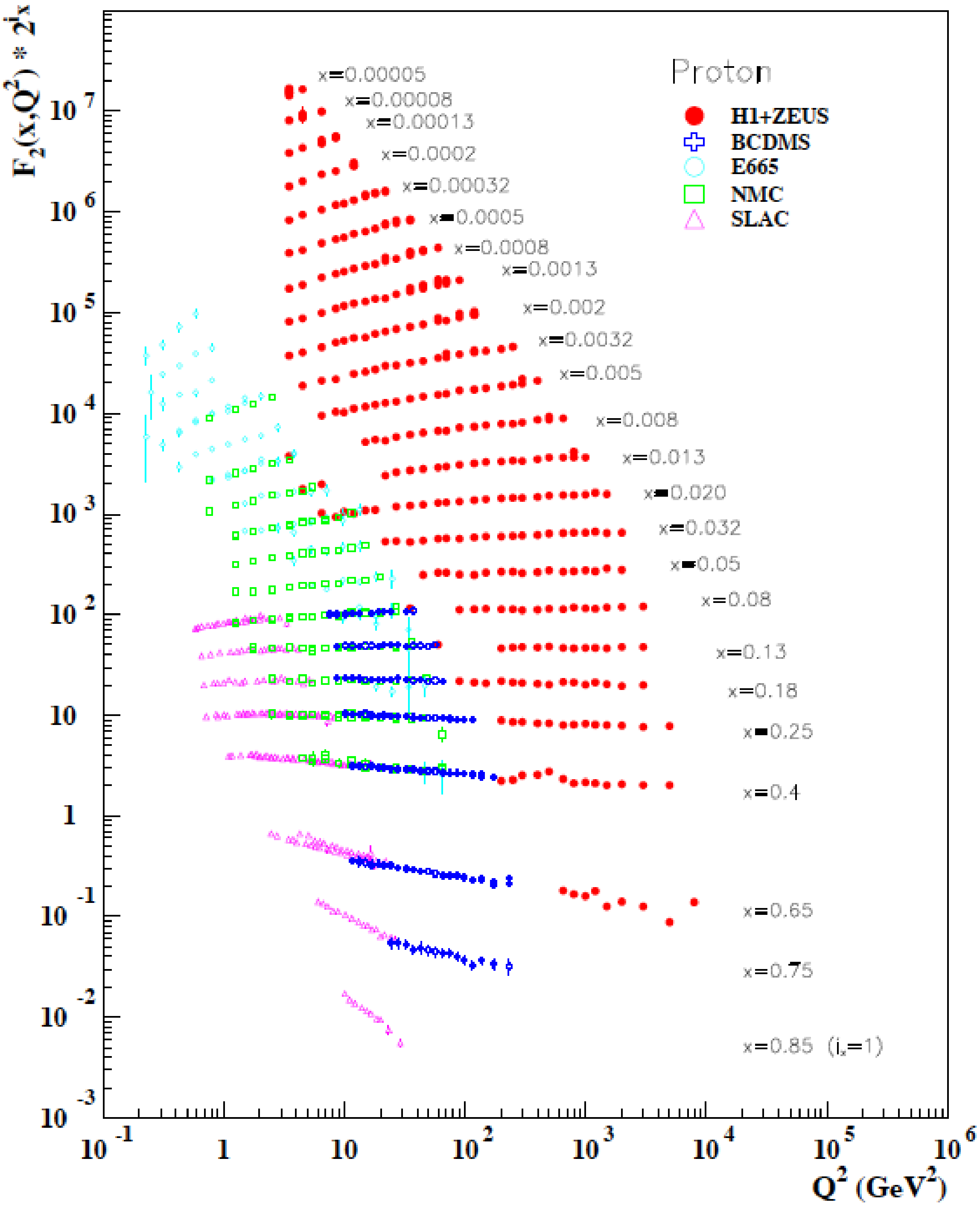
  $Q^2 \to \infty$ and $\nu \to \infty$ at fixed x

  The structure functions were measured to be relatively constant over many decades of Q^2

- Field theories predicted gross violation of scaling except in a special case:

  Asymptotically Free

  theories



What parton distributions are available?

- CTEQ
  - Coordinated Theor.-Exp. Project on QCD
  - https://www.physics.smu.edu/scalise/cteq/
- MRSTW—Martin, Roberts, Stirling, Thorne, Watt
- GRV—Gluck, Reya, Vogt
- NNPDF—Neural Network PDF
  - Goal: reduce assumption/theory bias
  - https://nnpdf.hepforge.org/
- HERA
  - using only data from the H1 and Zeus experiments at DESY HERA
- BS15
  - Statistical model to constrain PDFs
- Others. . .

For "black box" use, LHAPDF compiles most available PDF sets into a common interface

- Currently 773 different PDF sets available
- Many superseded by newer versions as more data becomes available
- Many exploring different constraints on QCD
- https://lhapdf.hepforge.org/

If you want to fit your own, there is a data archive at Durham called HEPDAT

- http://hepdat.net
- **Also, be sure that your data makes it into this archive. . .**

Example fits: CTEQ14NNLO

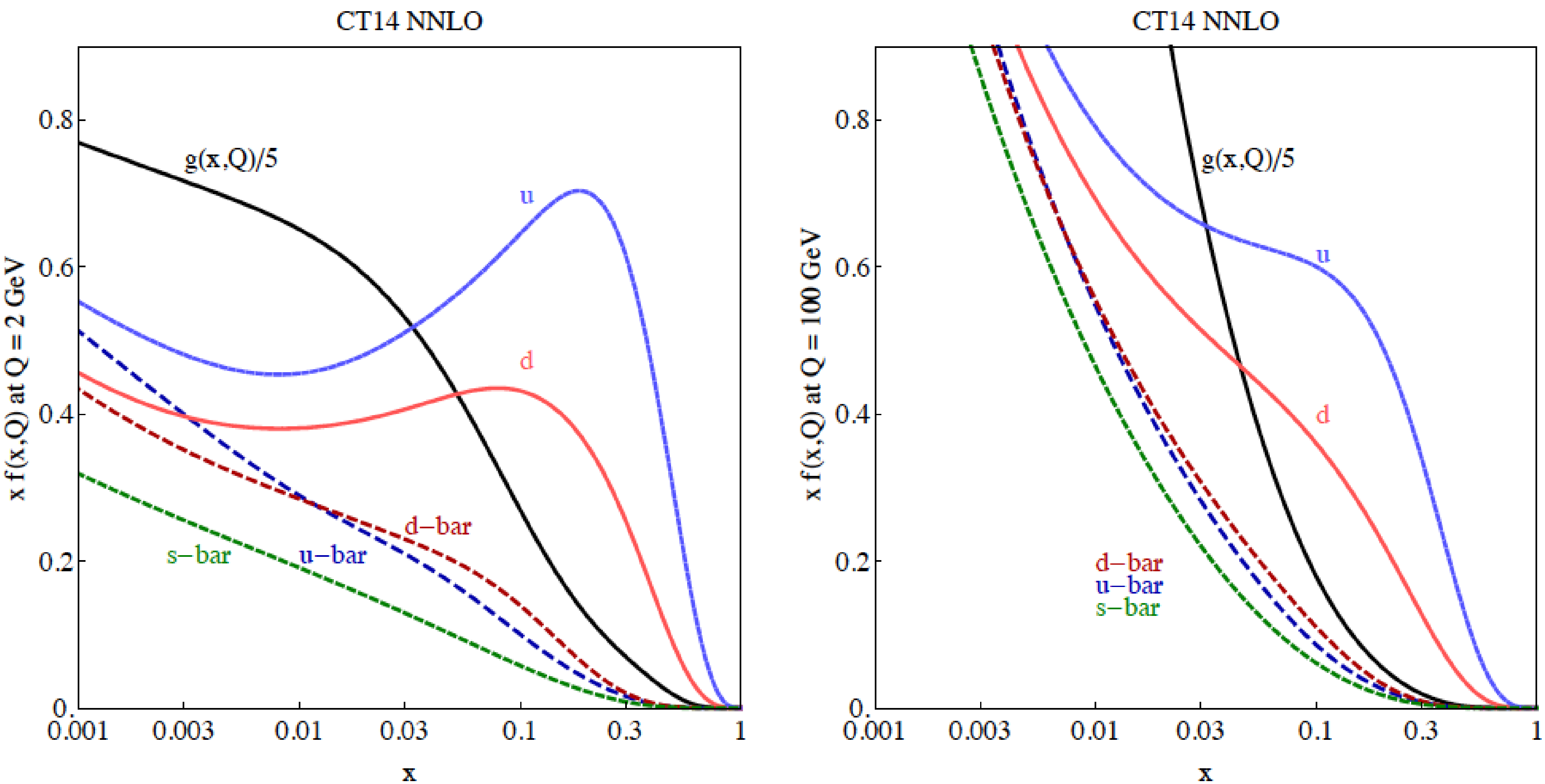


FIG. 5: The CT14 parton distribution functions at $Q = 2$ GeV and $Q = 100$ GeV for $u, \overline{u}, d, \overline{d}, s = \overline{s}$, and g.

Dusty: Still not sure if she is happy

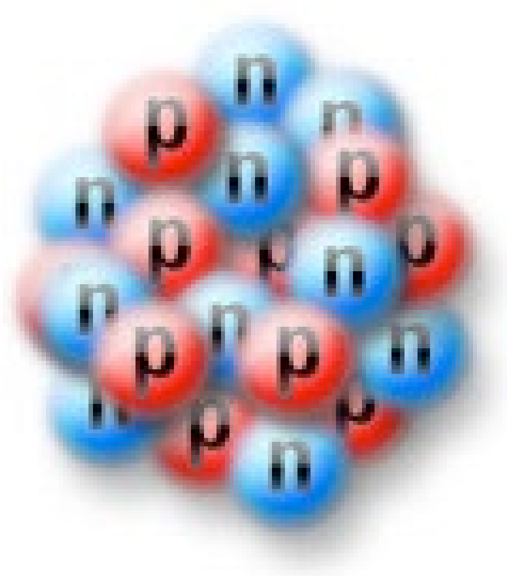
Nuclear effects

Guggenheim, Bilbao, Spain

Free proton vs. bound proton

Are the parton distributions of nucleons within a nucleus the same as free nucleons?

- Hard scattering assumption includes an implicit assumption that the interaction is so energetic that the binding of quarks in a proton is negligible
  - so surely, the binding of protons in the nucleus is also small
- Nuclear targets are used in many experiments
  - ν-DIS cross sections are small -> require dense targets
- Do the quarks change configuration?



The EMC Effect (European Muon Collaboration)

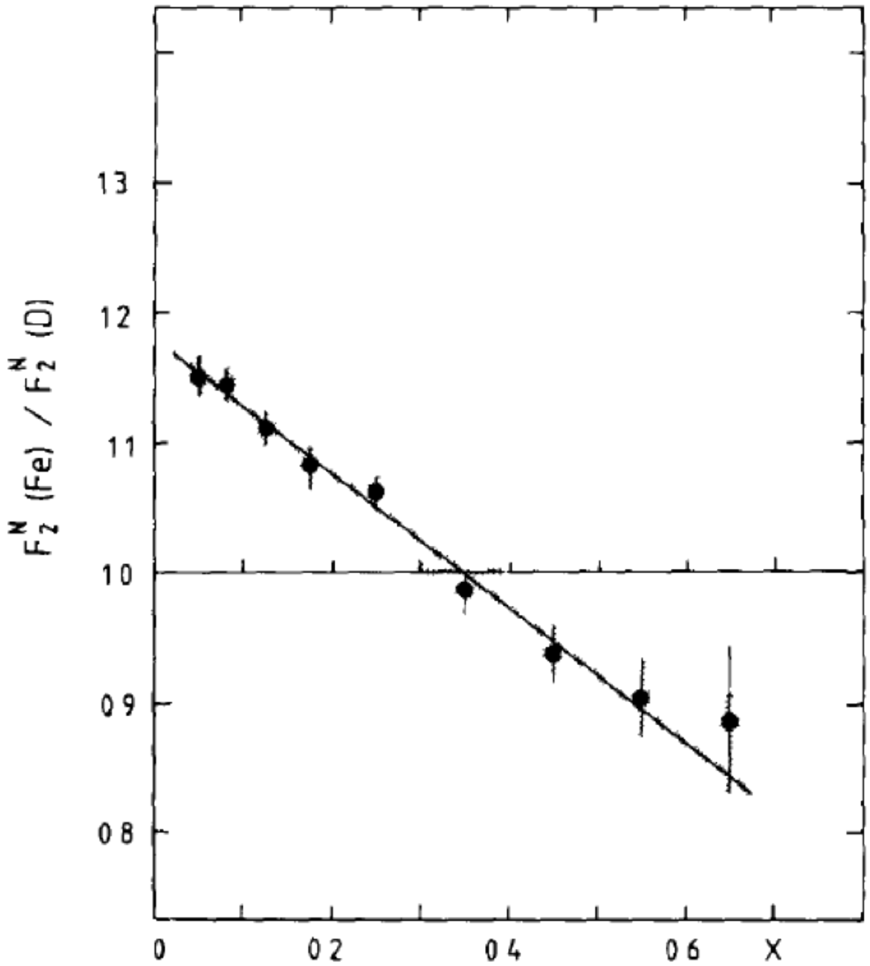
Volume 123B, number 3,4 PHYSICS LETTERS 31 March 1983

THE RATIO OF THE NUCLEON STRUCTURE FUNCTIONS F_2^N FOR IRON AND DEUTERIUM

The European Muon Collaboration

Attempt to increase integrated luminosity using a denser target.

Comparison iron data with earlier deuterium data found a striking difference



Systematics:

- Normalization uncertainty ^{2}H and Fe
- x-dependent uncertainties in slope
- Additional data helped clarify effect

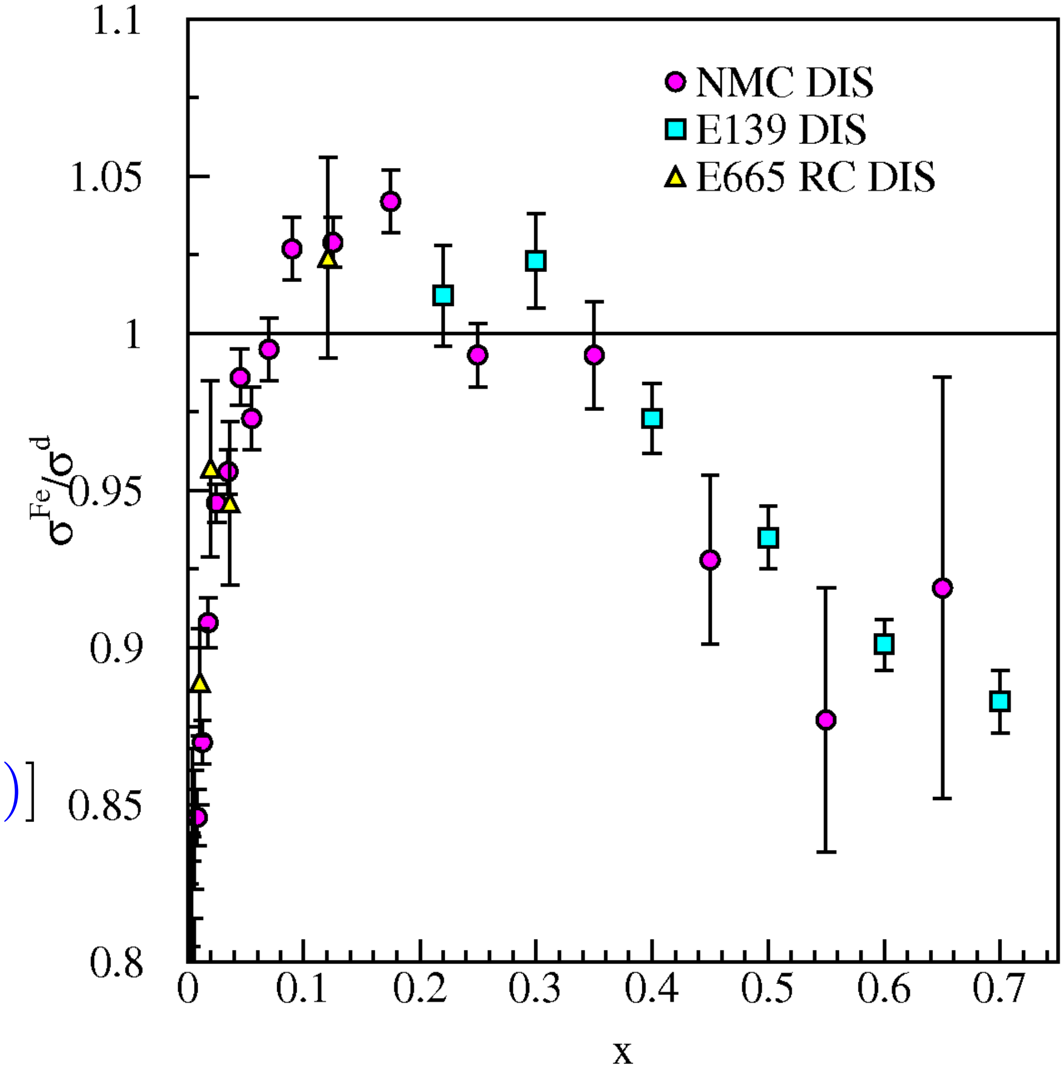
The EMC Effect

Additional data revealed

- Larger-x depletion in strength was correct
- Low-x structure was significantly different.

Are the parton distributions actually different?

$$F_2(x) = \sum_{q \in \{u,d\ldots\}} e_q^2 \left[q(x) + \bar{q}(x) \right]$$



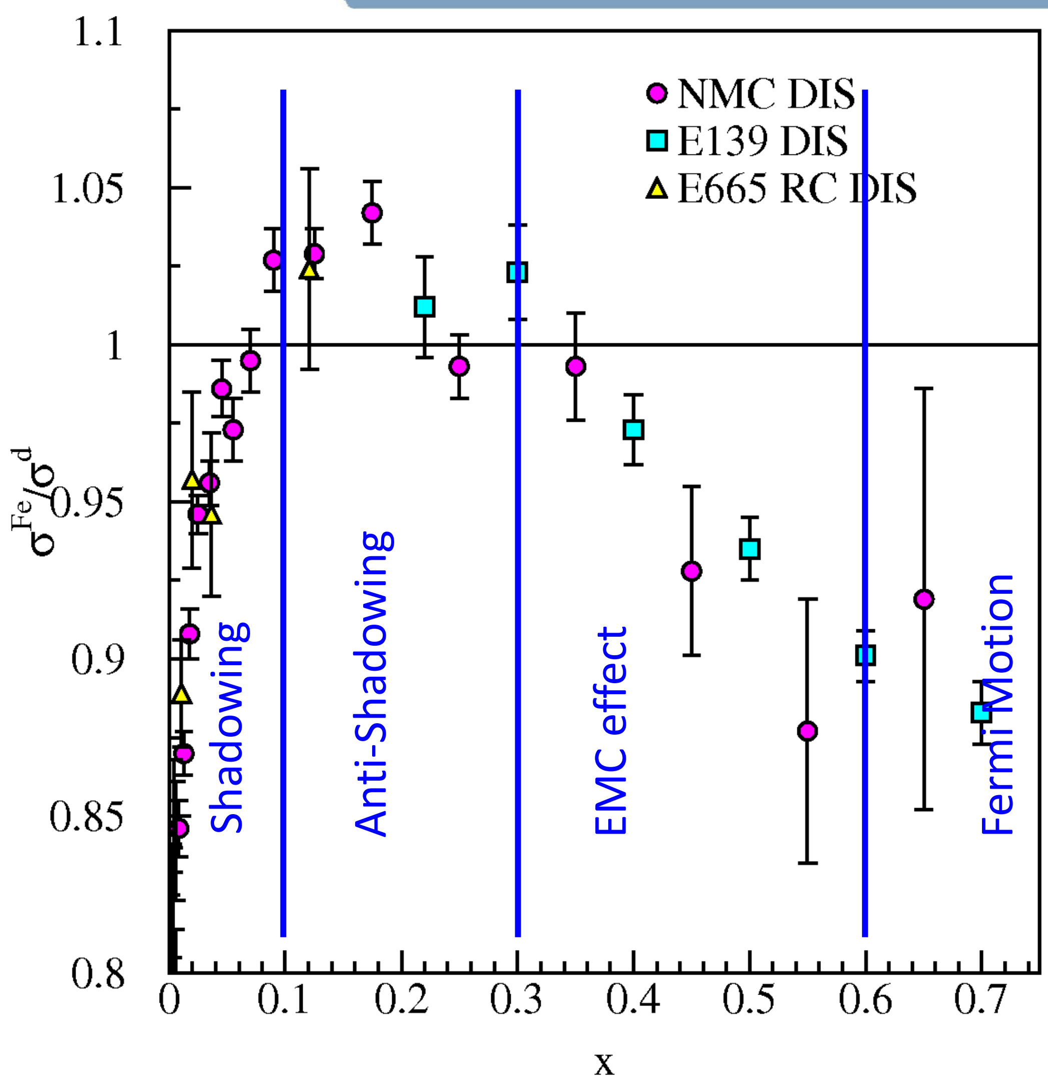
The EMC Effect

Effect generally divided into 4 regions

- x < 0.1 Shadowing Region
- 0.1 < x < 0.3 Anti-Shadowing
- 0.3 < x < 0.6 EMC effect
- 0.6 < x Fermi motion

What do we understand?

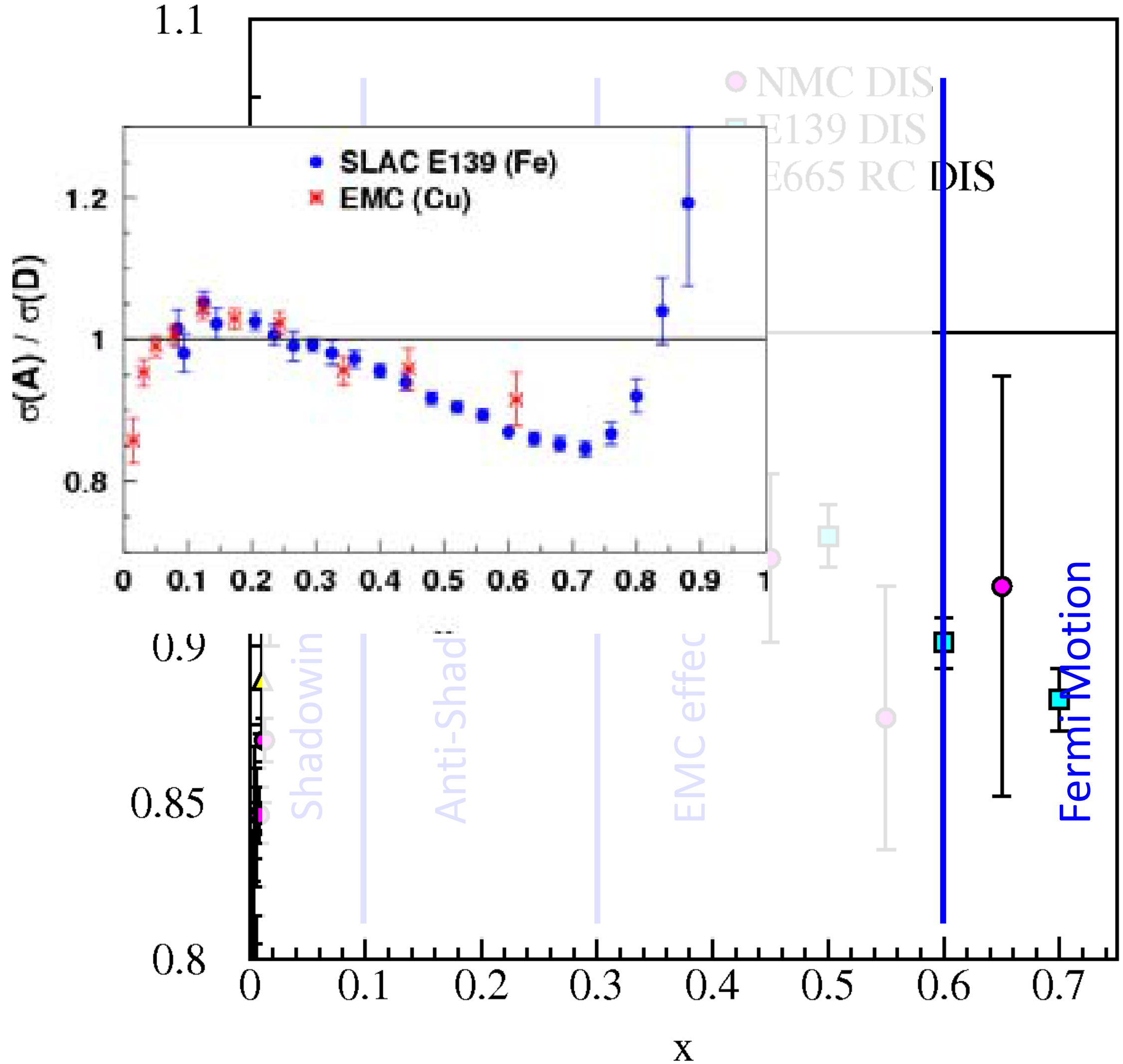
(or what are we guessing at?)



The EMC Effect

Fermi motion

- Intrinsic motion of nucleons in a nucleus at rest.



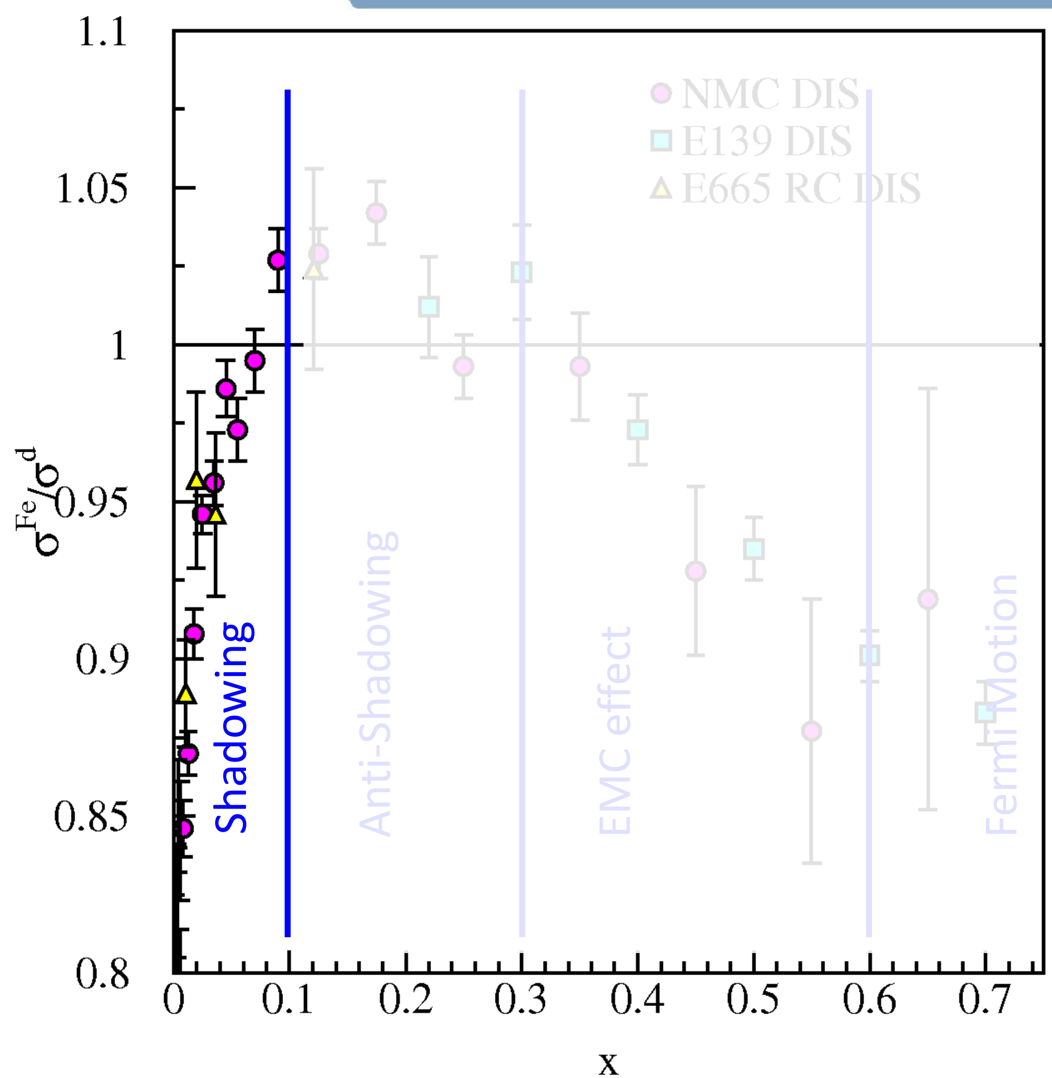
The EMC Effect

Fermi motion

- Intrinsic motion of nucleons in a nucleus at rest.

Shadowing

- Small-x partons (gluons) from one nucleus overlap with those of a neighboring nucleus
- Expect to start at some x_{onset} and saturate at x_{sat}~ ½ rM



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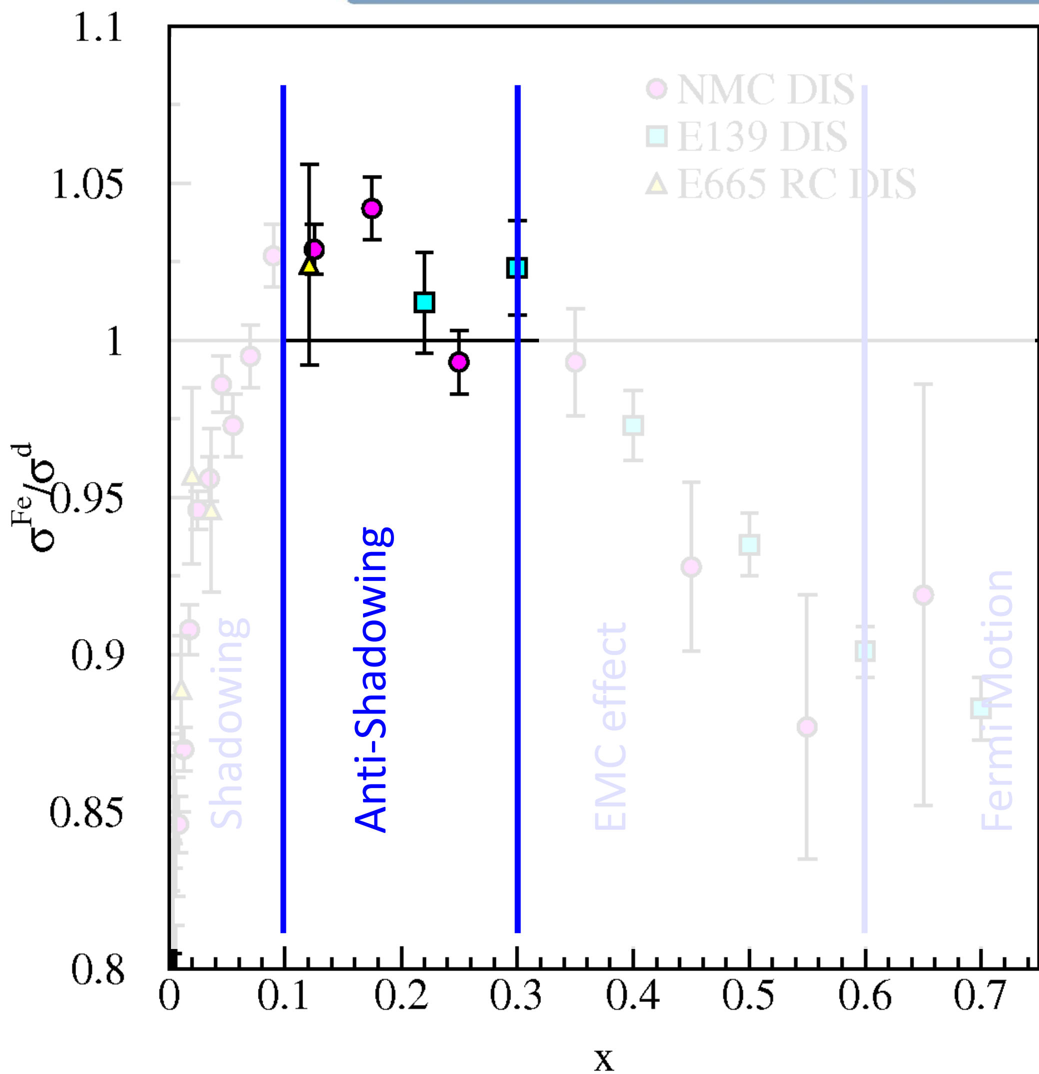
Anti-Shadowing

- Small-x parton (gluons) overlap?



The EMC Effect

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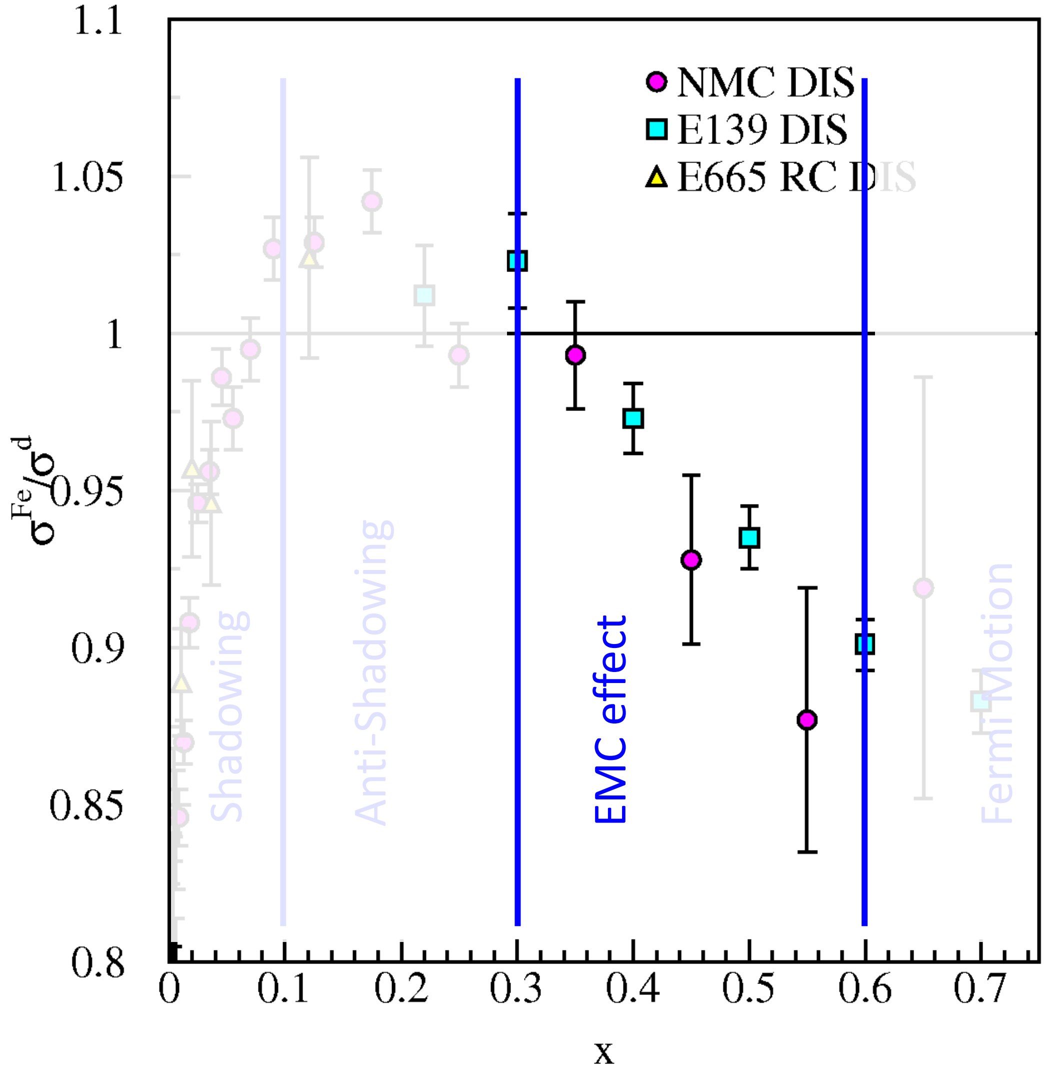
Anti-Shadowing

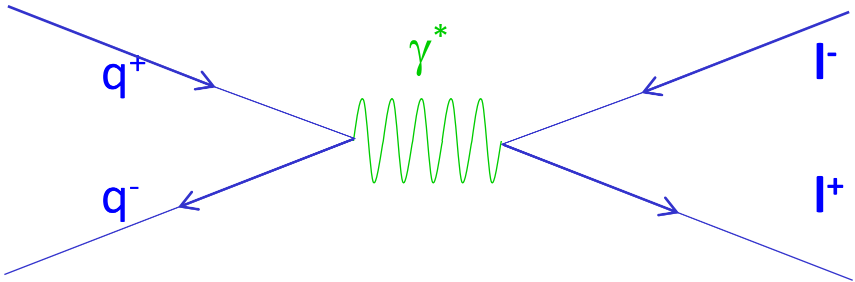
- Small-x parton (gluons) overlap?

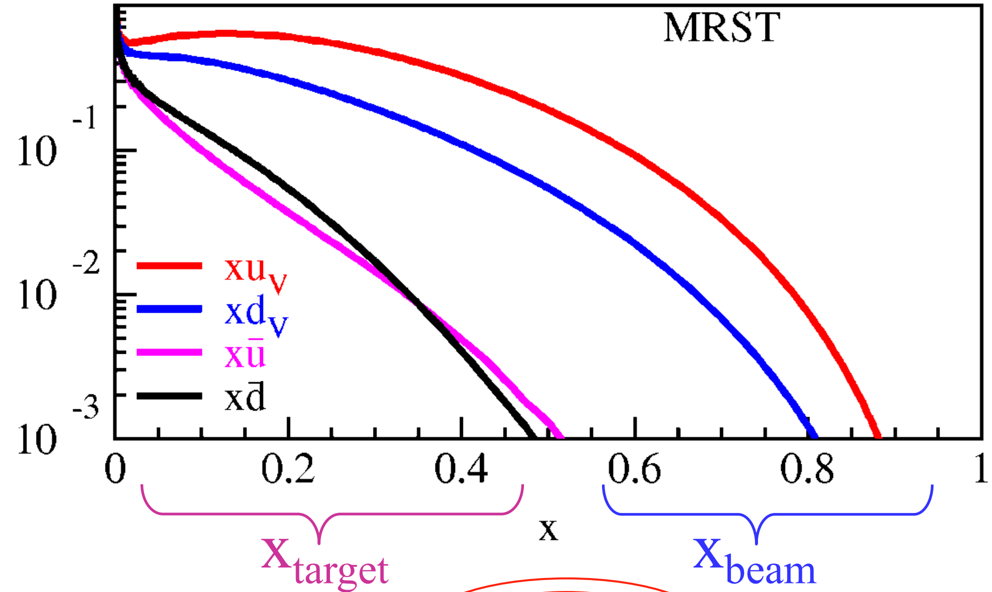
EMC Effect

- Many theories or models exist. None are satisfactory.



Drell-Yan Cross Section





- Cross section is a convolution of beam and target parton distributions

$$\frac{d^2\sigma}{dx_{\mathrm{b}}dx_{\mathrm{t}}} = \frac{4\pi\alpha^2}{x_{\mathrm{b}}x_{\mathrm{t}}s}\sum_{q\in\{u,d,s,\dots\}} e_q^2\left[\bar{q}_{\mathrm{t}}(x_{\mathrm{t}})q_{\mathrm{b}}(x_{\mathrm{b}}) + \cancel{\bar{q}_{\mathrm{b}}(x_{\mathrm{b}})q_{\mathrm{t}}(x_{\mathrm{t}})}\right]$$

Acceptance limited

(Fixed Target, Hadron Beam)

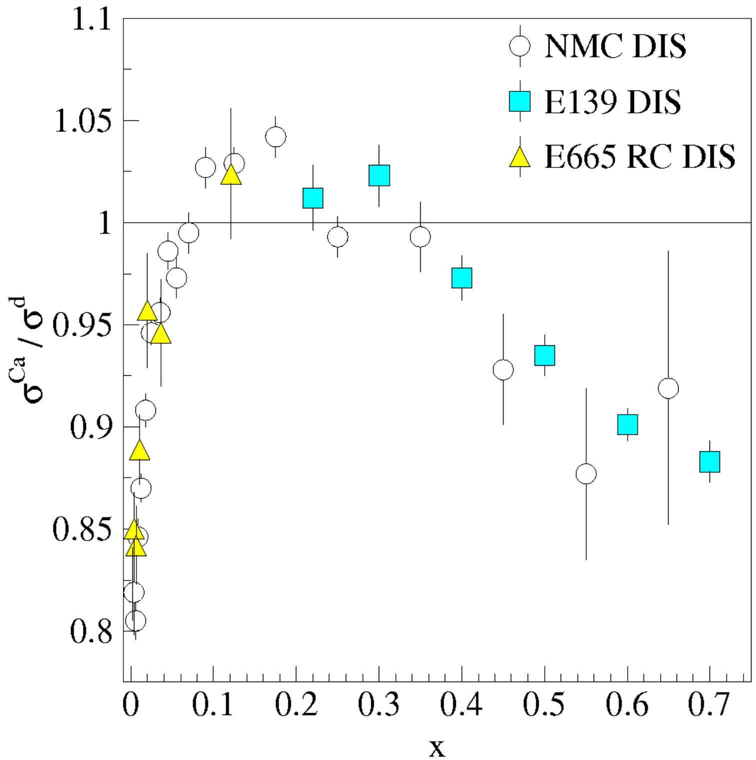
- u-quark dominance

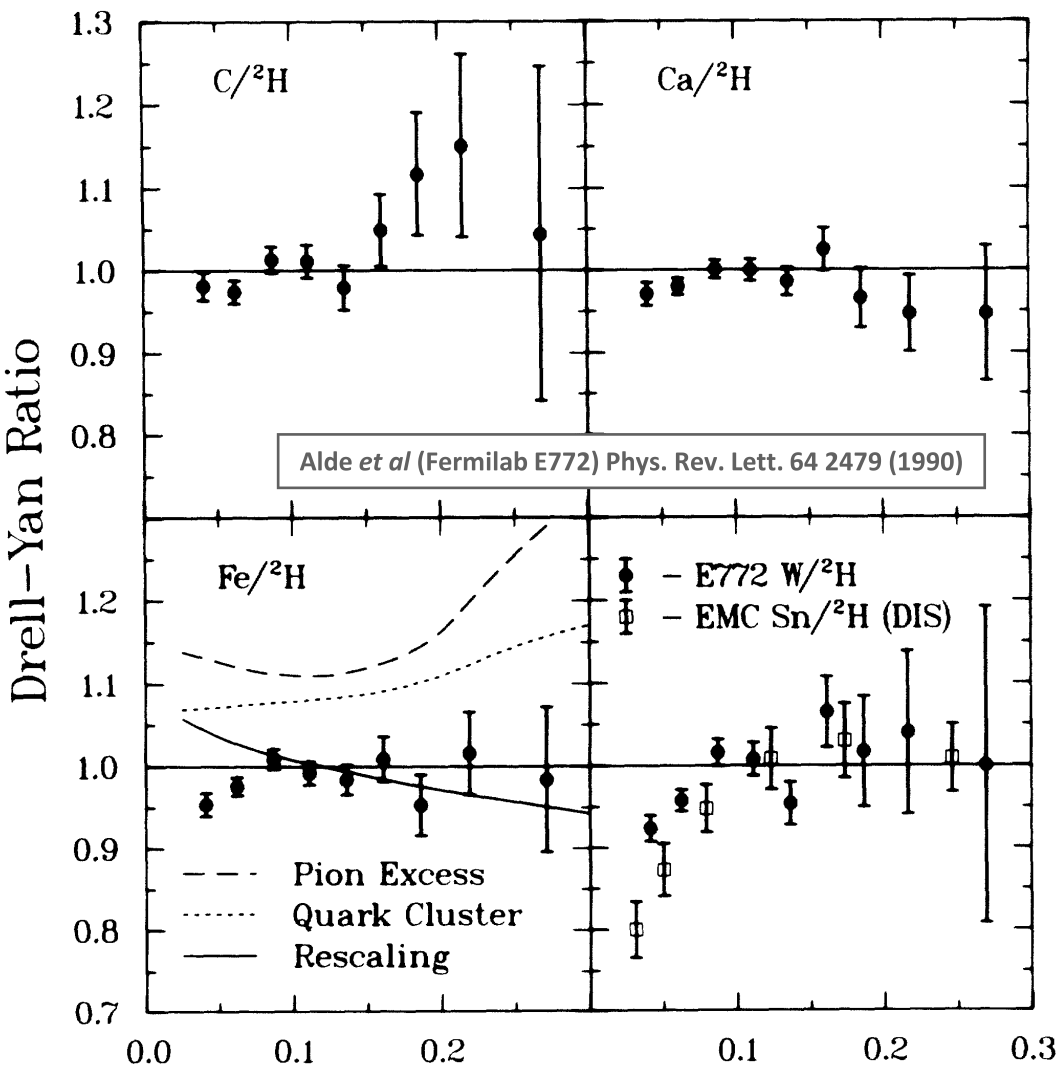
  $(2/3)^2$ vs. $(1/3)^2$

Beam	Sensitivity	Experiment
Hadron	Beam quarks target antiquarks	Fermilab, J-PARC RHIC (forward acpt.)
Anti-Hadron	Beam antiquarks Target quarks	J-PARC, GSI-FAIR Fermilab Collider
Meson	Beam antiquarks Target quarks	COMPASS, J-PARC

Structure of nucleonic matter: How do DIS and Drell-Yan data compare?

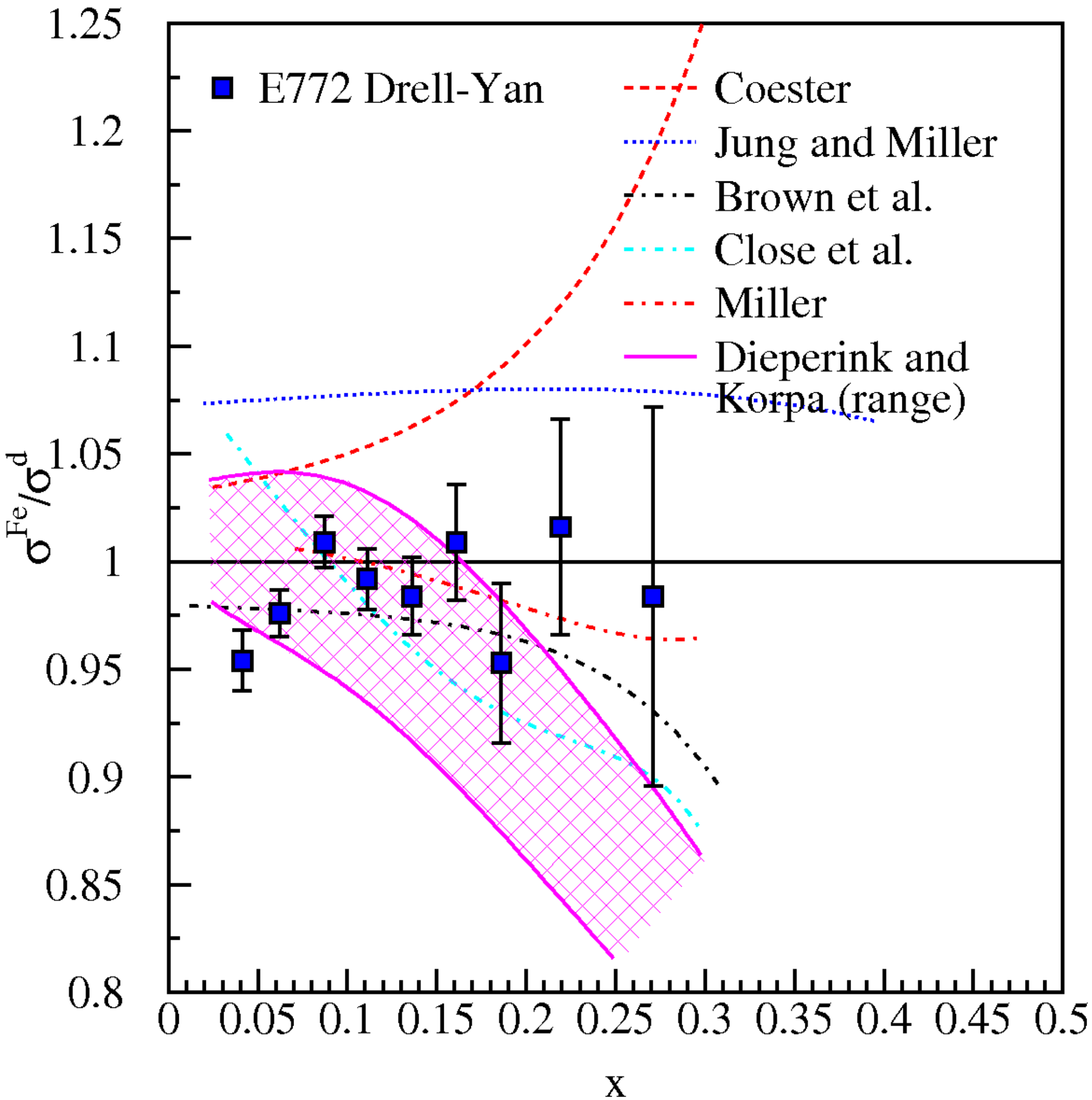
- Shadowing present in Drell-Yan
- Antishadowing not seen in Drell-Yan—Valence only effect?



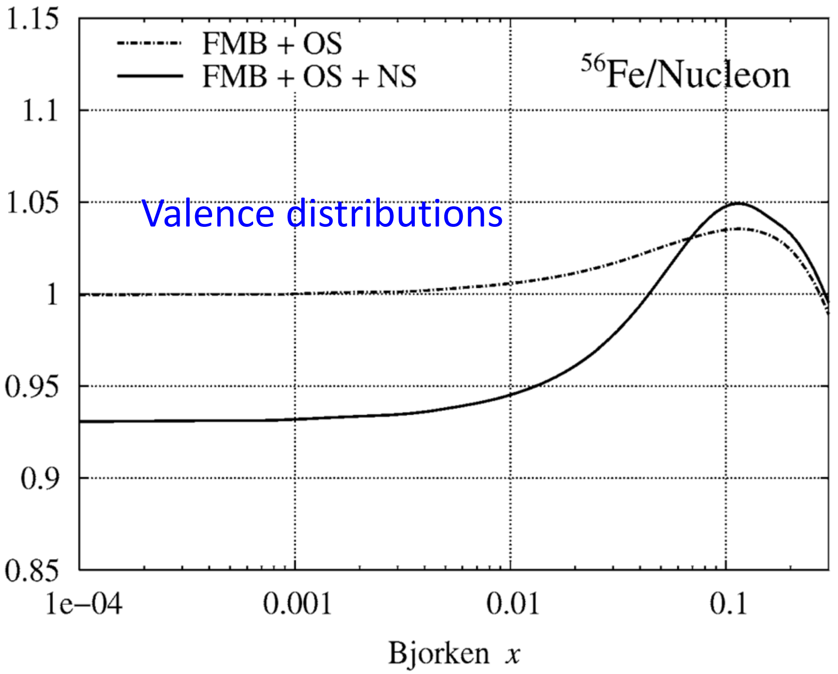


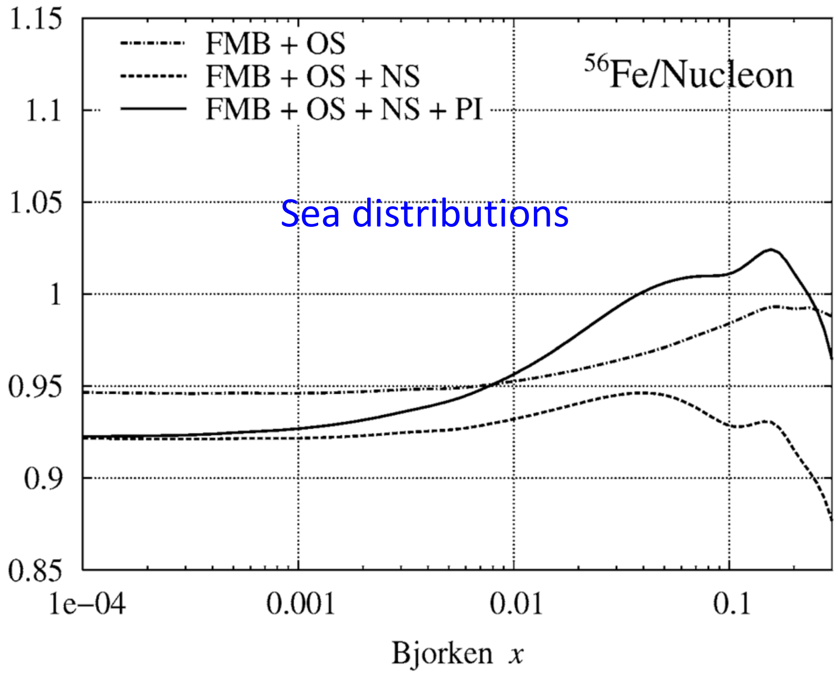
Structure of nucleonic matter: Where are the nuclear pions?

- The binding of nucleons in a nucleus is expected to be governed by the exchange of virtual “Nuclear” mesons.
- No antiquark enhancement seen in Drell-Yan (Fermilab E772) data
- Contemporary models predict large effects to antiquark distributions as x increases.
- **Models must explain both DIS-EMC effect and Drell-Yan**



Kulagin and Petti sea vs. valence nuclear effects





Nuclear Physics A 765 (2006) 126–187

FMB—Fermi Motion and Nuclear Binding
OS—Off shell effects
NS—nuclear shadowing
PI—nuclear pions

Aside: Problem for PDF fits

Many experiments used nuclear targets

- Does this data need to be thrown out now?
- Information of d-quark distributions comes from Deuterium and isospin symmetry
- Neutrino DIS data?
  - Old H2 bubble chamber data OK
  - Modern experiments use iron target
  - Magnitude of Sea Quark distributions dominated by neutrino data

$$F_2^{\nu p}(x) + F_2^{\nu n} \propto \sum_{q\in\{u,d,\dots\}} x\left[q(x,Q^2) + \bar{q}(x,Q^2)\right]$$

$$xF_3^{\nu N}(x) \propto \sum_{q\in\{u,d,\dots\}} x\left[q(x,Q^2) - \bar{q}(x,Q^2)\right]$$

- Parameterize measurements?

K. J. Eskola, V. J. Kolhinen, and P. V. Ruuskanen, Nucl. Phys. B535, 351 (1998);

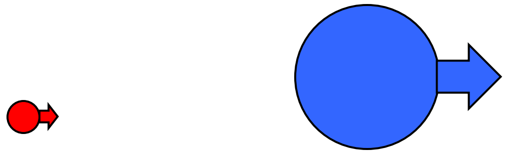

Becky has fallen asleep


Dusty: Not so happy

Now add Spin

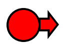
- Dynamics make things messy
- . . . Or more interesting?

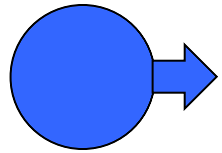
Spin dependent structure functions in Pictures



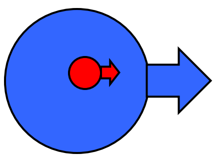
Polarized parton Polarized Proton

Spin dependent structure functions in Pictures



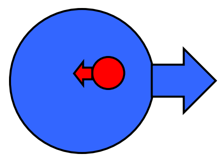


Polarized parton **Polarized Proton**



Parton and **Proton** both longitudinally polarized.

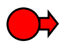
$$q_{\rightarrow}(x) \text{ or } q^{+}(x)$$



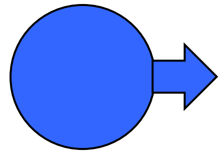
Parton and **Proton** oppositely, longitudinally polarized.

$$q_{\leftarrow}(x) \text{ or } q^{-}(x)$$

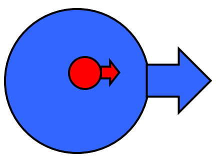
Spin dependent structure functions in Pictures



Polarized parton



Polarized Proton



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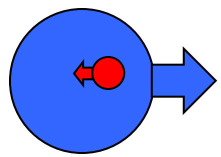
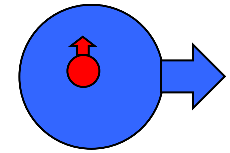
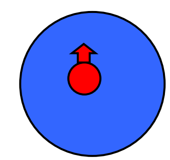


Parton and **Proton** oppositely, longitudinally polarized.

$$q_{\leftarrow}(x) \text{ or } q^{-}(x)$$

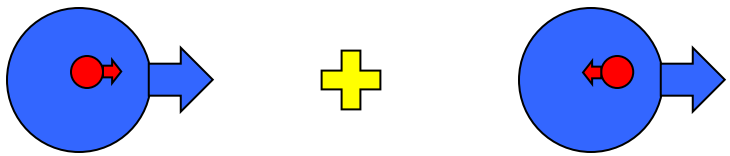


Parton polarized transversely and **Proton** longitudinally polarized.

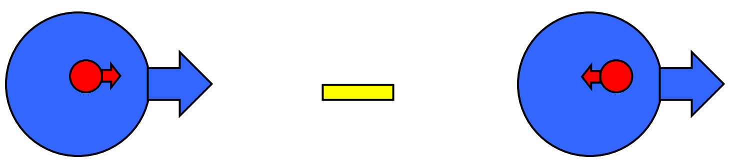


Parton polarized transversely and **Proton** unpolarized.

Spin dependent structure functions in Pictures

q(x) = 

$$q(x) = q_{\rightarrow}(x) + q_{\leftarrow}(x)$$

Δq(x) = 

$$\Delta q(x) = q_{\rightarrow}(x) - q_{\leftarrow}(x)$$

$$q \in \{u, \bar{u}, d, \bar{d}, s, \bar{s}, \ldots g\}$$

Note: Some authors separate

While others denote their sum by

Δq

Spin dependent structure functions

http://www.scholarpedia.org/article/Helicity_dependent_parton_distributions

$$g_1(x) = \frac{1}{2} \sum_{i\in\{u,\bar{u},d,\dots\}} e_i^2 \left[\Delta q(x) + \Delta\bar{q}(x)\right]$$

$$= \frac{1}{2}\left[\frac{4}{9}\Delta u(x) + \frac{4}{9}\Delta\bar{u}(x) + \frac{1}{9}\Delta d(x) + \frac{1}{9}\Delta\bar{d}(x) + \frac{1}{9}\Delta s(x) + \frac{1}{9}\Delta\bar{s}(x) + \cdots\right]$$

$$\Delta q_3 = (\Delta u + \Delta\bar{u}) - \left(\Delta d + \Delta\bar{d}\right) \qquad g_A^3 = \int_0^1 \Delta q_3 dx$$

$$\Delta q_8 = (\Delta u + \Delta\bar{u}) + \left(\Delta d + \Delta\bar{d}\right) - 2\left(\Delta s + \Delta\bar{s}\right) \qquad g_A^8 = \int_0^1 \Delta q_8 dx$$

$$\Delta\Sigma = (\Delta u + \Delta\bar{u}) + \left(\Delta d + \Delta\bar{d}\right) + \left(\Delta s + \Delta\bar{s}\right) \qquad g_A^0 = \int_0^1 \Delta\Sigma dx$$

$$g_1(x) = \frac{1}{9}\left[\frac{3}{4}\Delta q_3(x) + \frac{1}{4}\Delta q_8(x) + \Delta\Sigma(x)\right]$$

Spin dependent structure functions

Bjorken sum rule:

relates g^3_A and g^8_A to the axial and vector coupling constants G_A and G_V in β decay

$$g_A^3 \equiv g_A = 1.2670 \pm 0.0035 \text{ and } g_A^8 = 0.585 \pm 0.025$$

Elis-Jaffe Sum Rule: $$g_A^0 = g_A^8 + 3\left(\Delta s + \Delta\bar{s}\right)$$

$$\begin{aligned}\Gamma_1 &= \int_0^1 g_1(x)dx \\ &= \frac{1}{9}\left[\frac{3}{4}\int_0^1 \Delta q_3(x)dx + \frac{1}{4}\int_0^1 \Delta q_8(x)dx + \int_0^1 \Delta\Sigma(x)dx\right] \\ &= \frac{1}{9}\left[\frac{3}{4}g_A + \frac{1}{4}g_A^8 + \int_0^1 \Delta\Sigma(x)dx\right]\end{aligned}$$

The spin carried by the partons

Why do I care—I'm happy nibbling on clover

The proton's spin

- The proton is a spin-½ particle
- The quarks are spin-½ particles (this was also established in the parton model.)
- The gluons are spin-1 particles

How do the quarks' and gluons' angular momentum add to form a spin-½ proton?

Should be able to sum over all partons with appropriate Clepsch-Gordon coefficients , right??

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + \Delta G$$

Now,

- $\Delta\Sigma$ is integrated over x with a normalization convention requiring ½
- L_q is the orbital angular momentum of the quarks
- ΔG is the integral spin and orbital angular momentum of the glue

EMC Measures g_1

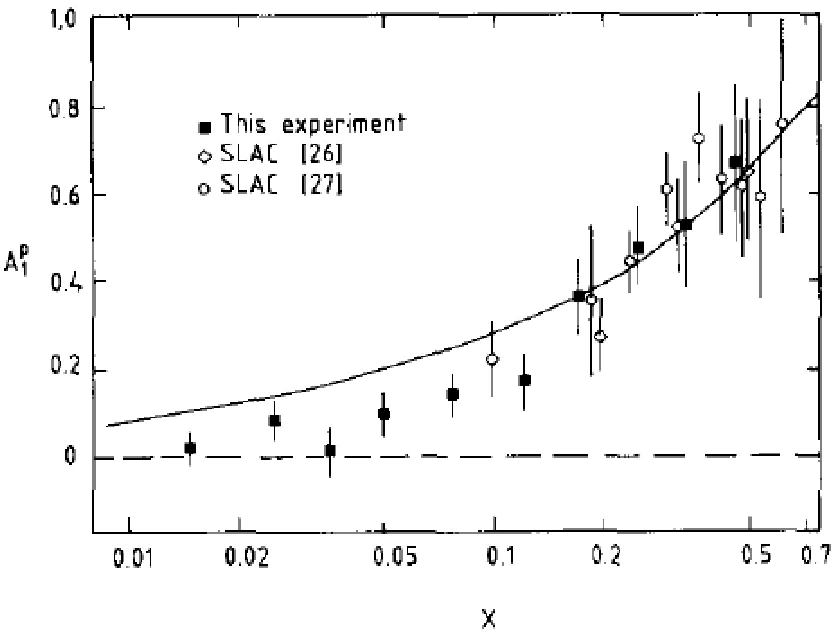
Volume 206, number 2 PHYSICS LETTERS B 19 May 1988

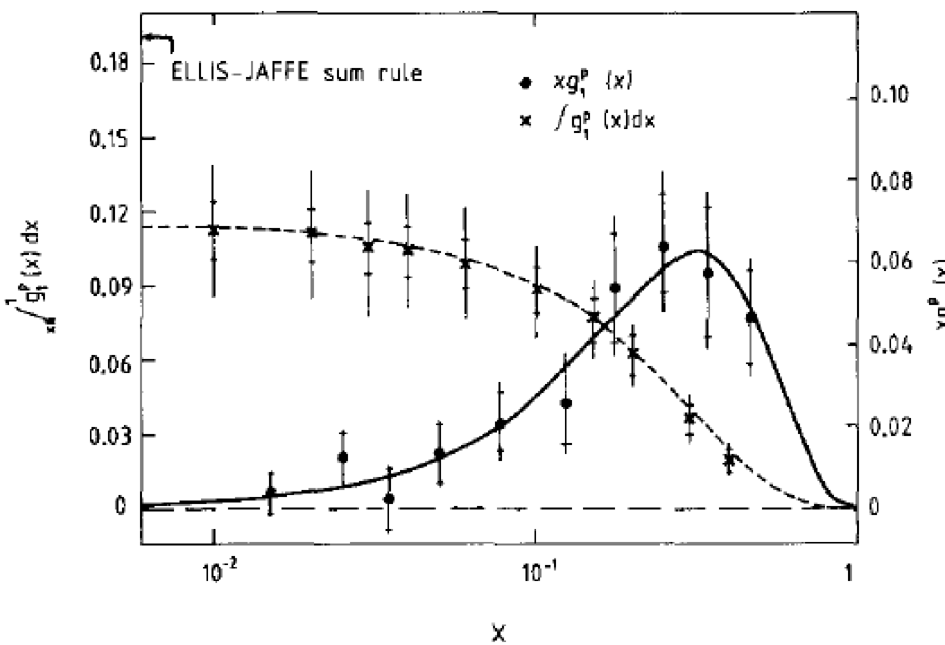
A MEASUREMENT OF THE SPIN ASYMMETRY AND DETERMINATION OF THE STRUCTURE FUNCTION g_1 IN DEEP INELASTIC MUON–PROTON SCATTERING

European Muon Collaboration

- scattered longitudinally polarized muons on a longitudinally polarized target
- measured the asymmetry in cross sections between the parallel and anti-parallel spins

$$A = \frac{\sigma^{\uparrow\downarrow} - \sigma^{\uparrow\uparrow}}{\sigma^{\uparrow\downarrow} + \sigma^{\uparrow\uparrow}}$$





The spin crisis

- Assuming that the missing spin for the Ellis-Jaffe sum rule is in the strange quarks:

$$\begin{aligned}
\langle S_z \rangle_u &= 0.373 \pm 0.019 \pm 0.039 \\
\langle S_z \rangle_d &= -0.254 \pm 0.019 \pm 0.039 \\
\langle S_z \rangle_s &= -0.113 \pm 0.019 \pm 0.039 \\
\langle S_z \rangle_{u+d+s} &= 0.006 \pm 0.058 \pm 0.117
\end{aligned}$$

- Compilation of recent experiments gives

$$\Delta\Sigma \approx 0.40$$

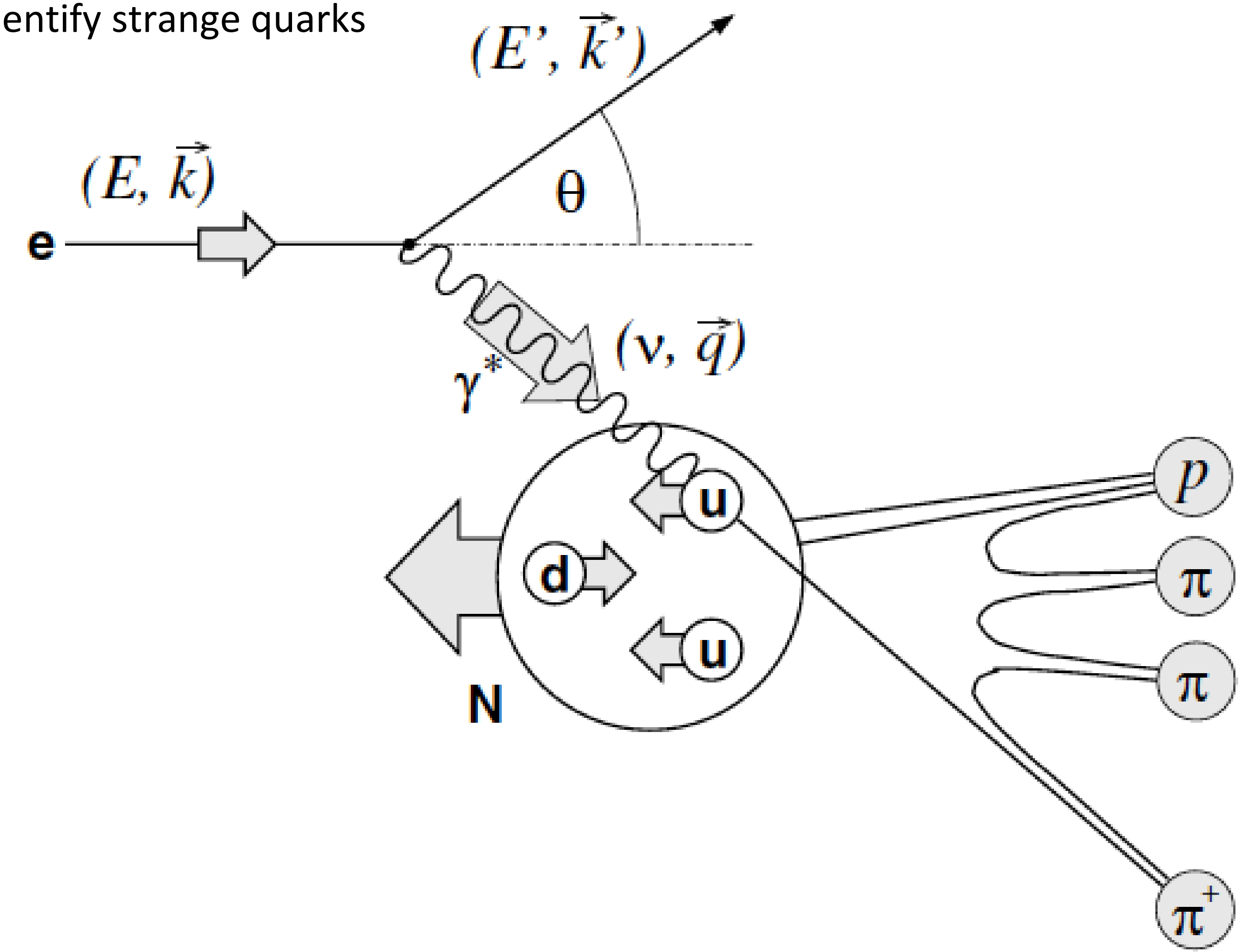
- Nevertheless, where is the proton's spin?

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + \Delta G$$

- Could the problem be with strange quarks and the Ellis-Jaffe sum rule?

Semi-Inclusive Deep Inelastic Scattering SIDIS

- Try to tag the struck quark by detecting a fast outgoing particle
- Measure Kaons to identify strange quarks



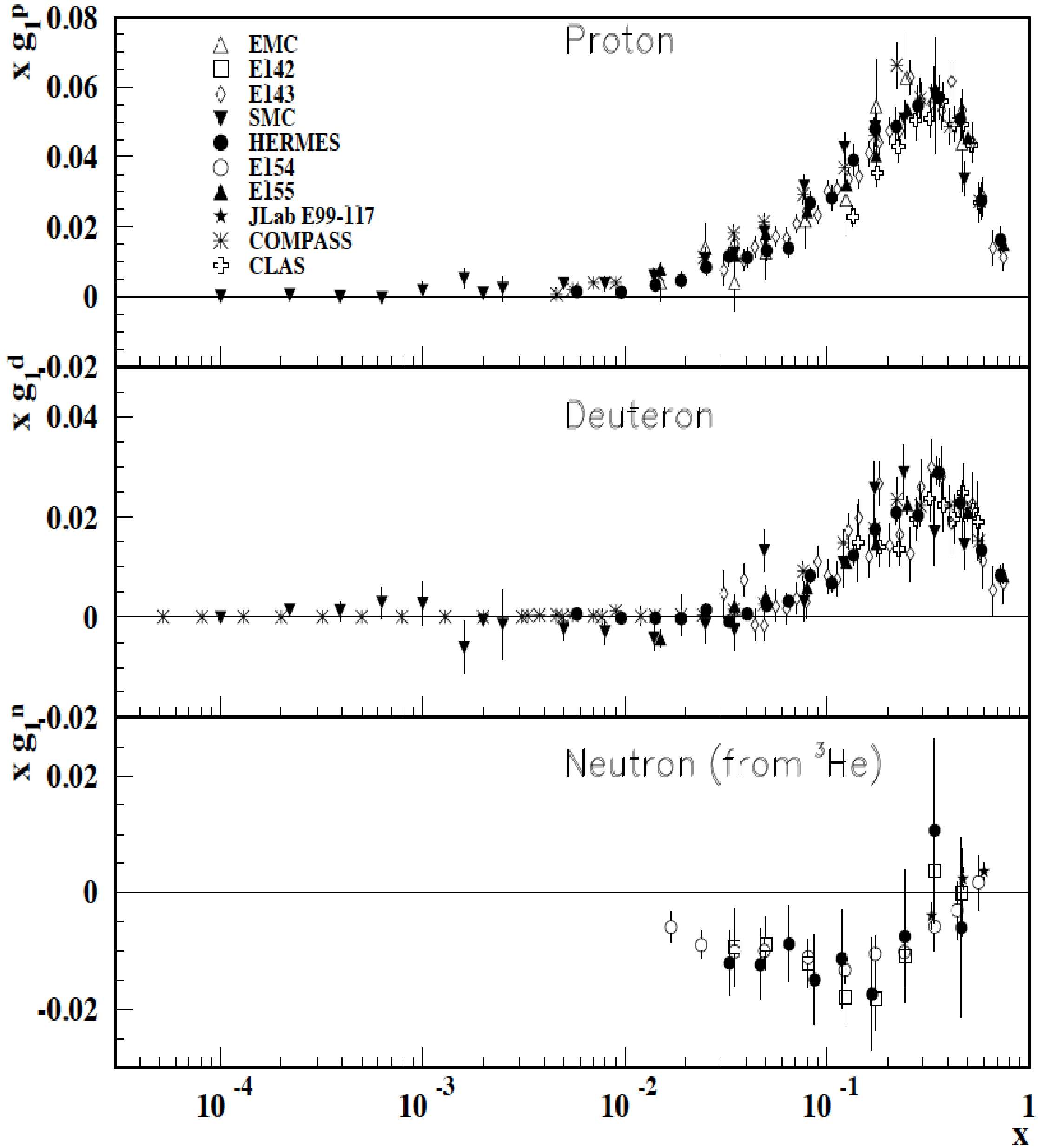
- HERMES (DESY)
- COMPASS (CERN)


hermes
HERA
PETRA


CERN Meyrin
LHCb
ATLAS
SUISSE
FRANCE
COMPASS
CERN
Prévessin
ALICE
CMS
LHC 27 km

Spin dependent structure function g_1

- World data compilation from PDG

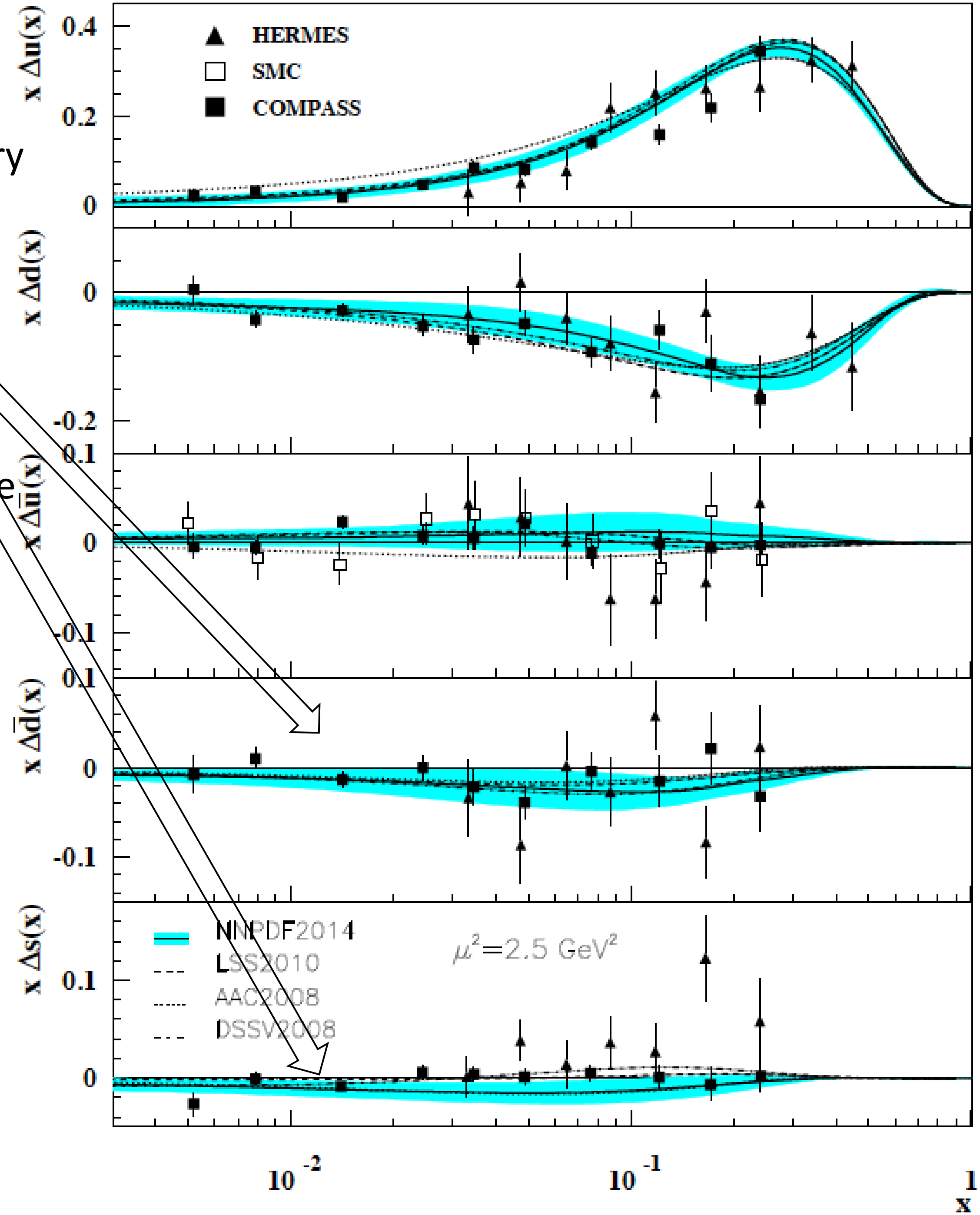


Where's the spin?

- The strange quarks seem to have very little of the proton's spin
- Again, turn to global parton distribution fits, as no one experiment or measurement tells the whole story.
- Nevertheless

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + \Delta G$$

$\Delta\Sigma$ is clearly not the whole story

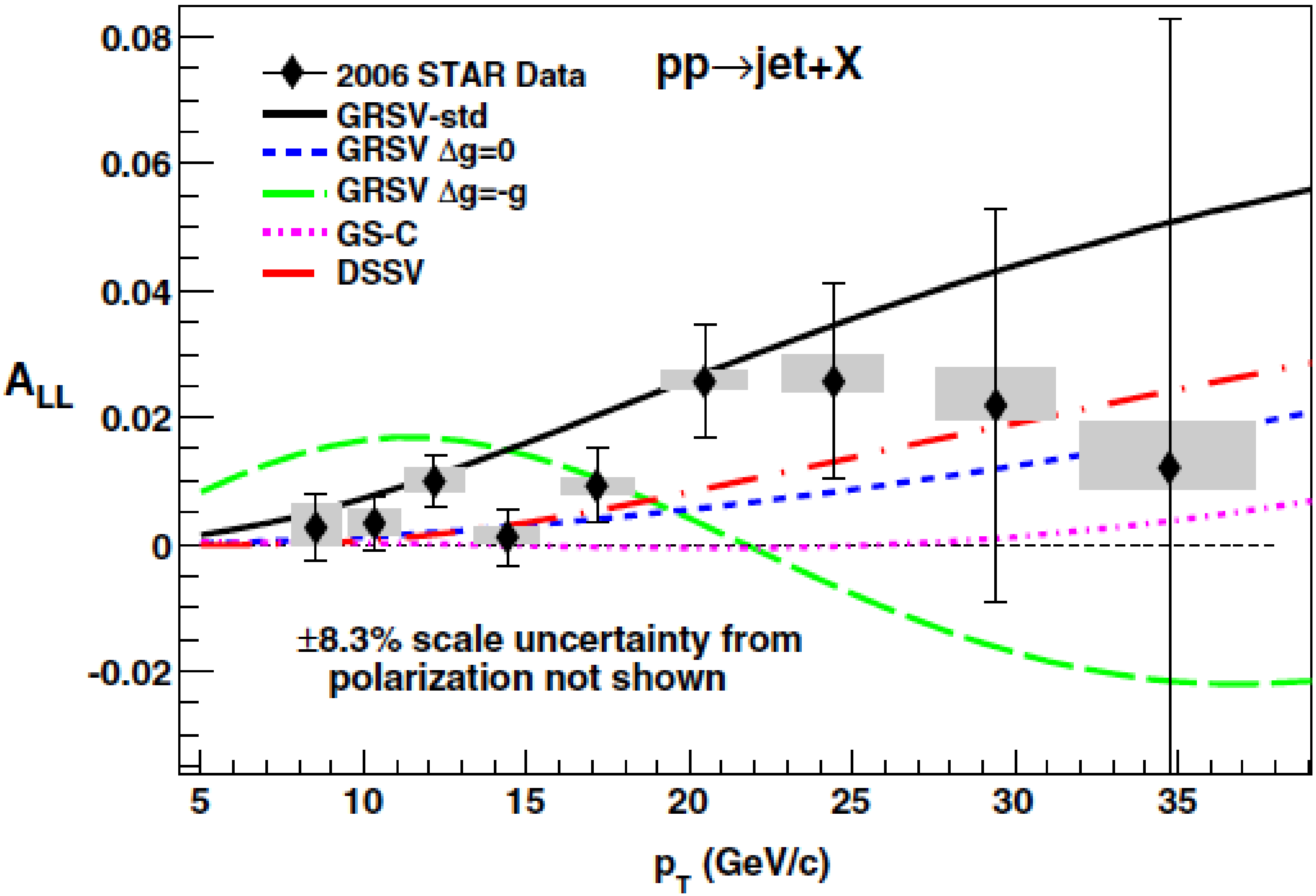


World data compilation from PDG


Cautious, but still somewhat interested
Could it be in the glue?

Polarized gluons

- RHIC $\vec{p} + \vec{p} \to \text{Jets} + X \quad A_{LL} = \dfrac{\sigma^{\uparrow\downarrow} - \sigma^{\uparrow\uparrow}}{\sigma^{\uparrow\downarrow} + \sigma^{\uparrow\uparrow}}$



Polarized gluons

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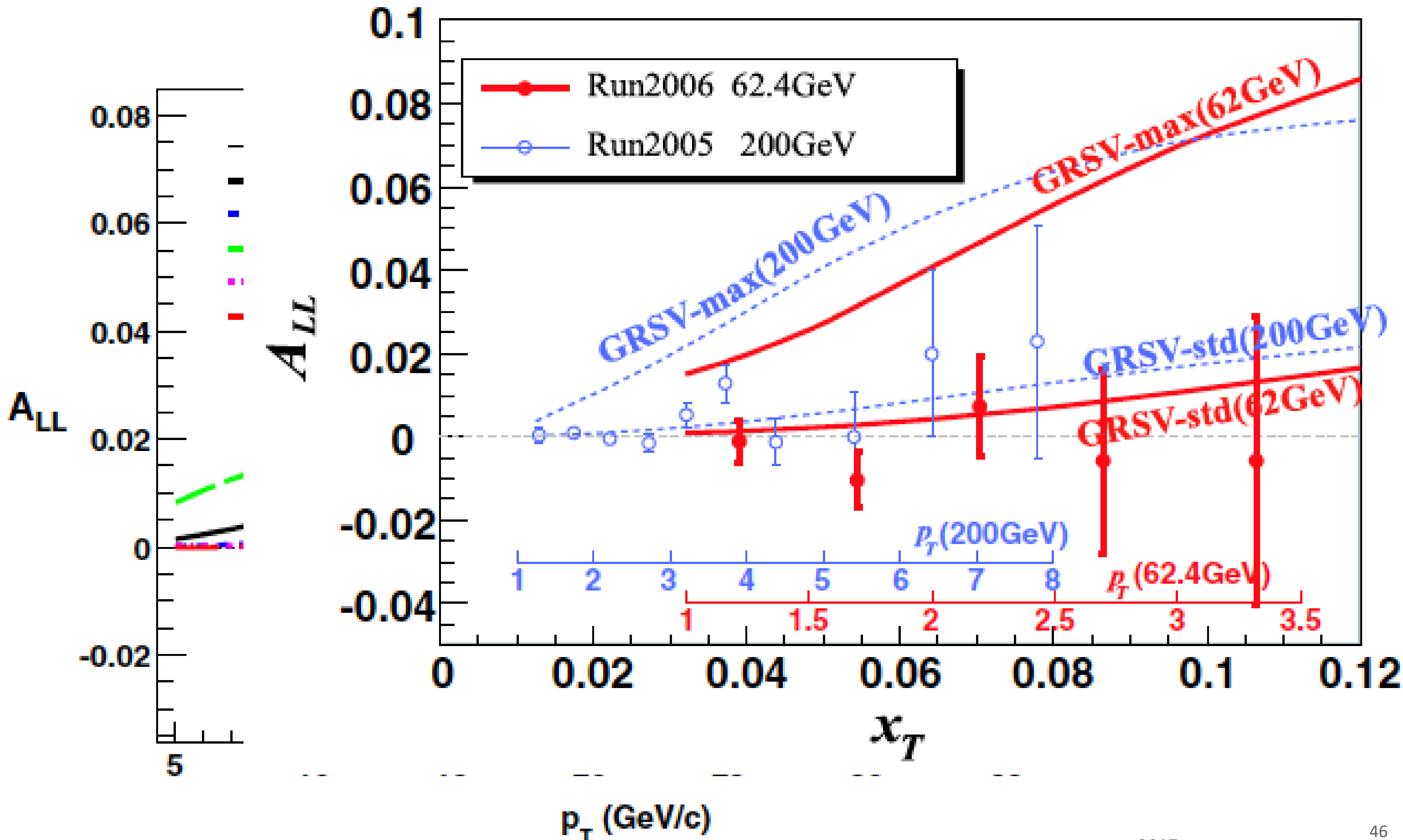

Global fit to spin density--DSSV

PRL **113,** 012001 (2014) PHYSICAL REVIEW LETTERS week ending 4 JULY 2014

Evidence for Polarization of Gluons in the Proton

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Global fit to spin density--DSSV

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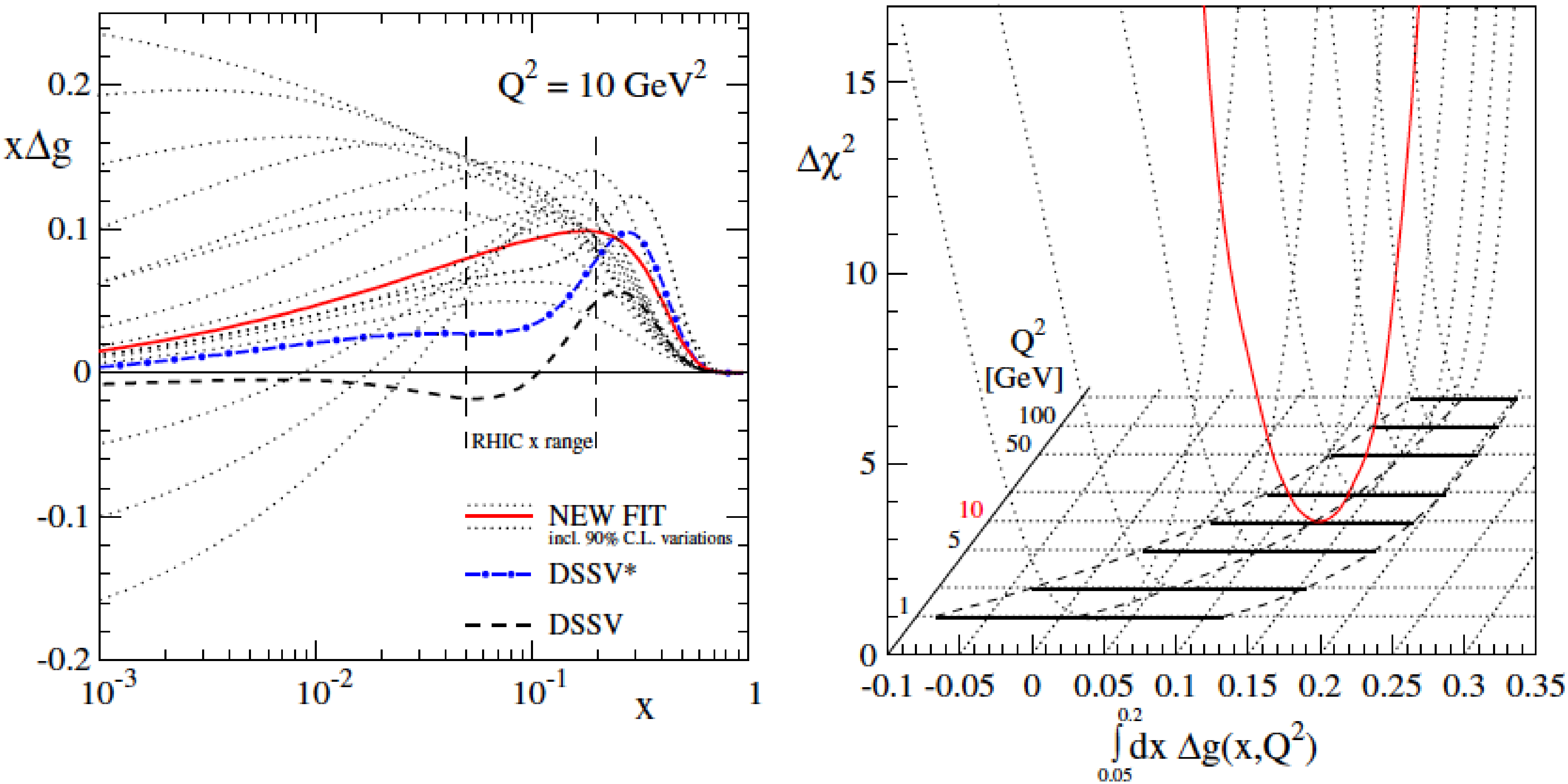
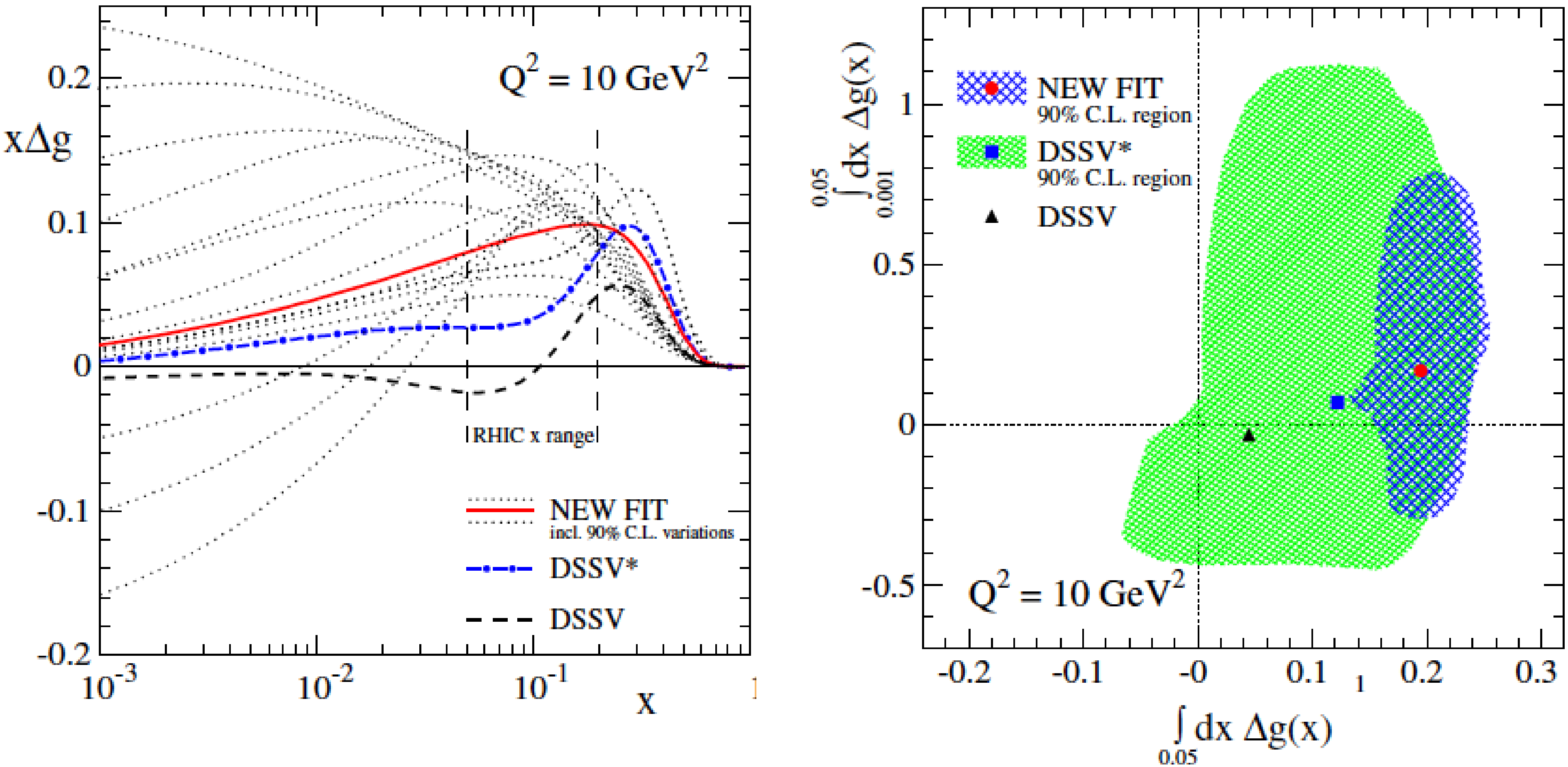
Evidence for Polarization of Gluons in the Proton



Global fit to spin density--DSSV

PRL **113,** 012001 (2014) PHYSICAL REVIEW LETTERS week ending 4 JULY 2014

Evidence for Polarization of Gluons in the Proton



Where are we?

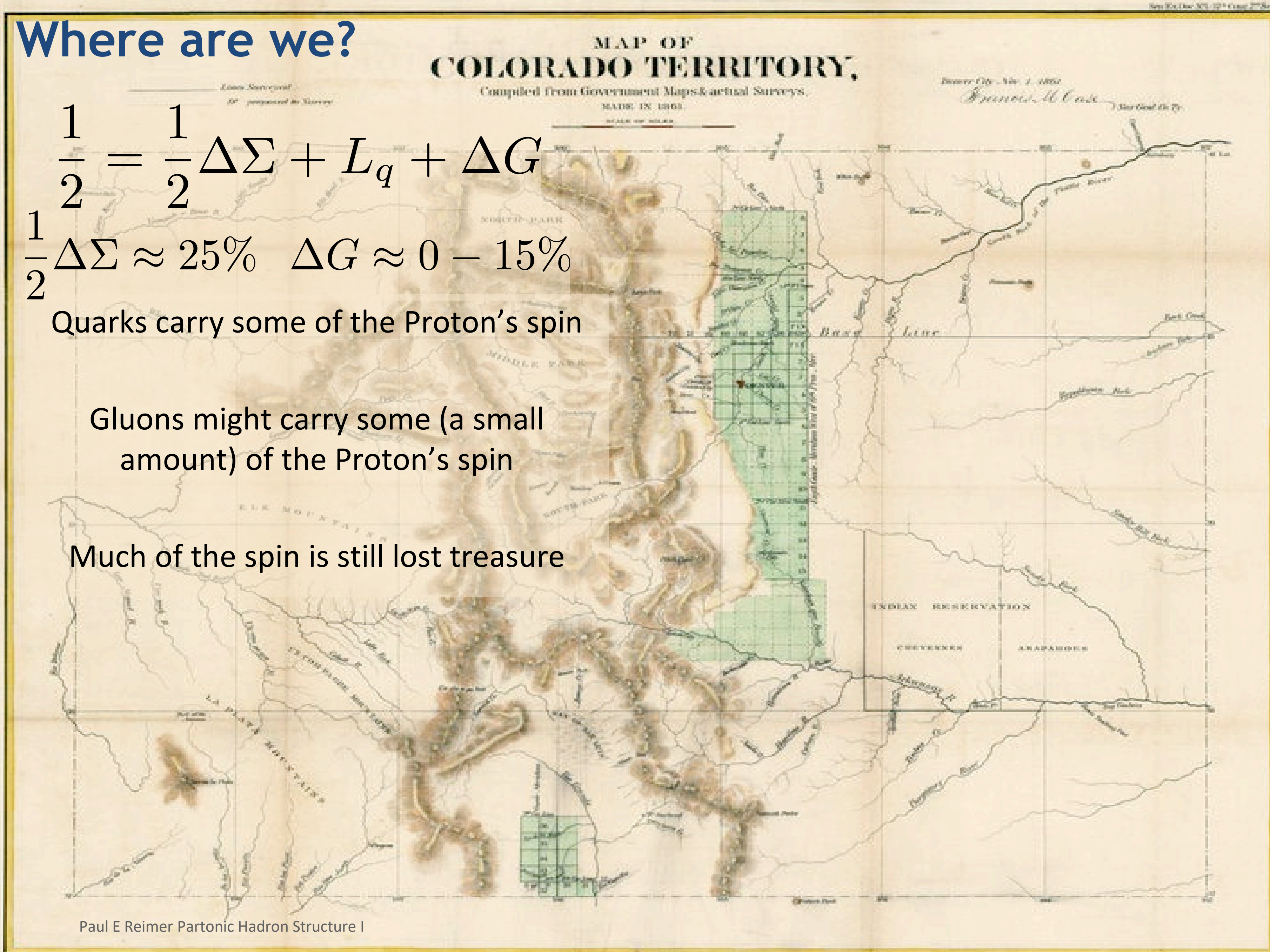
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + \Delta G$$

$$\frac{1}{2}\Delta\Sigma \approx 25\% \quad \Delta G \approx 0 - 15\%$$

Quarks carry some of the Proton's spin

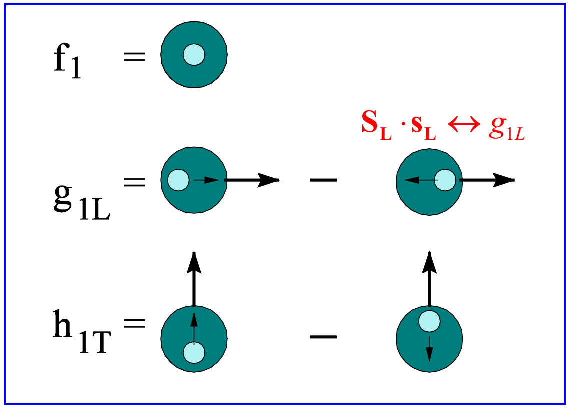
Gluons might carry some (a small amount) of the Proton's spin

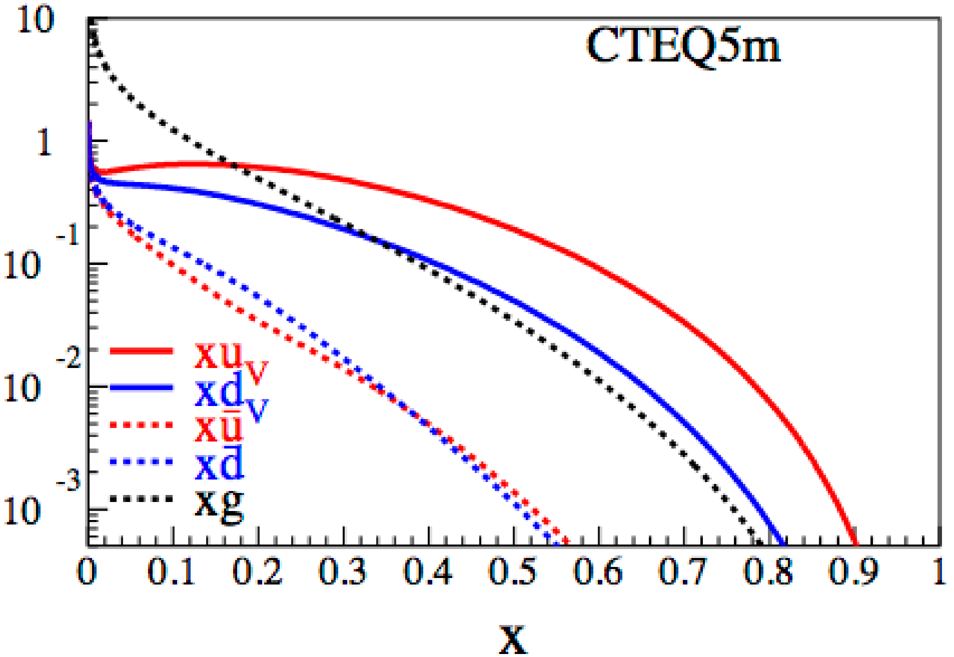
Much of the spin is still lost treasure

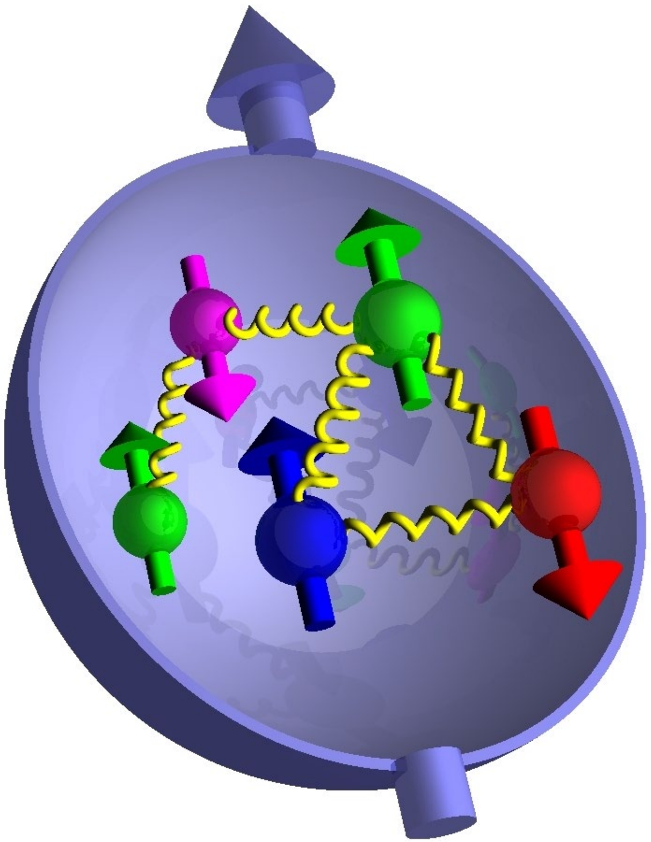


The proton in terms of all parton distributions

Survive k_T integration

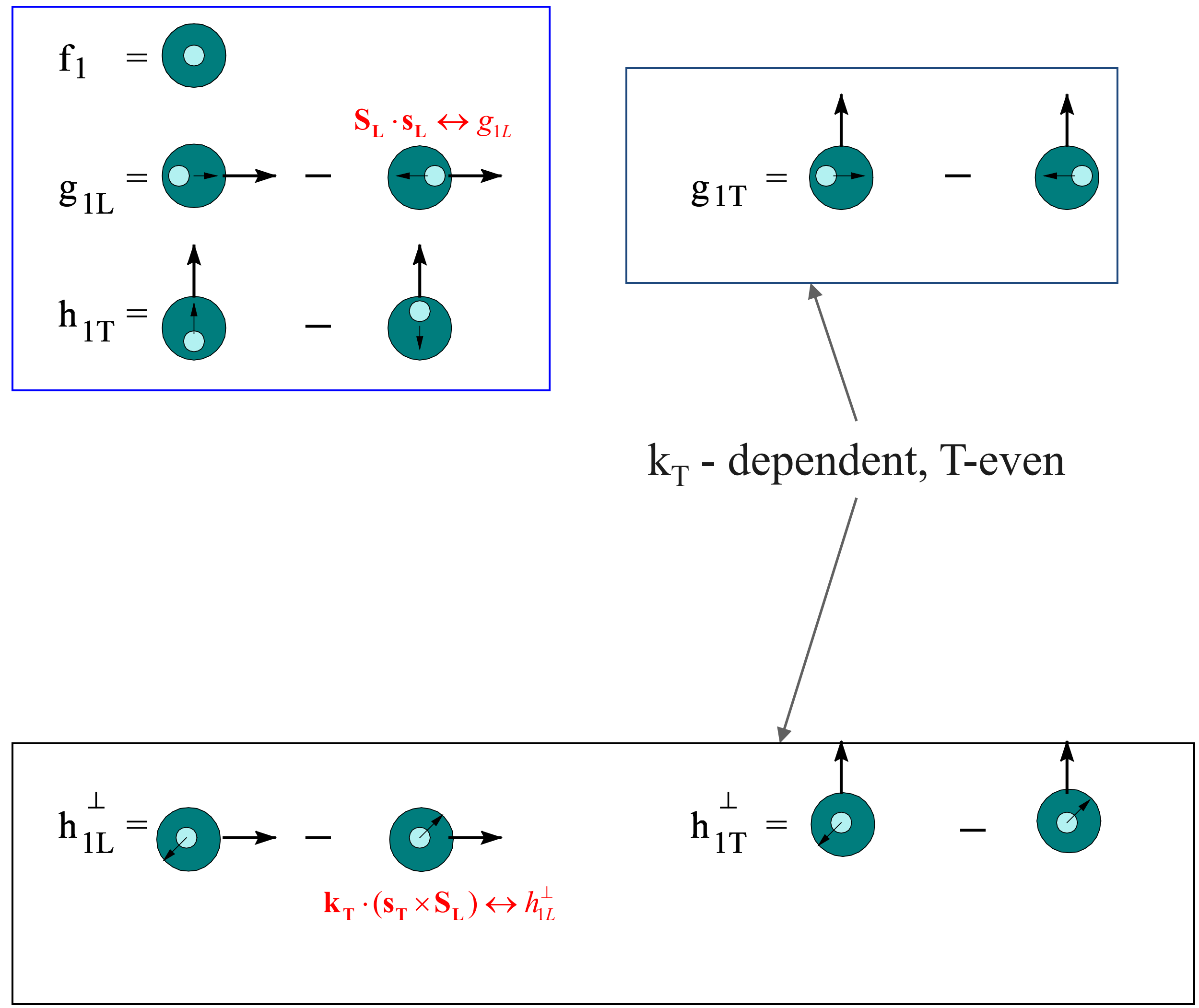




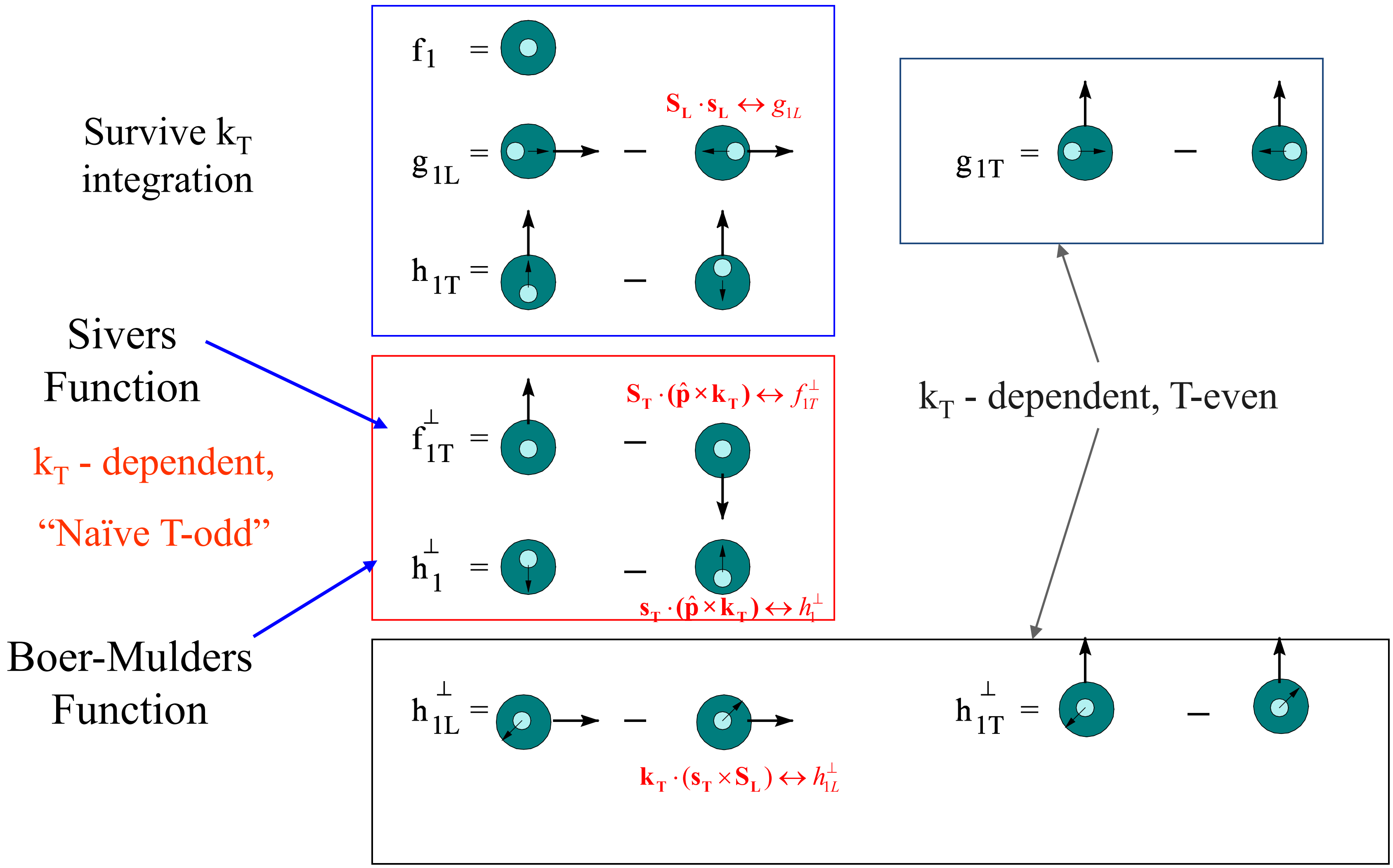


Transverse Momentum Distributions: Introduction

Survive k_T integration



Transverse Momentum Distributions: Introduction



Leave things spinning, but slowly getting there

Conclusions

- **Data** looks like scattering from many point particles (partons)
  - These distributions are universal and process independent
- **Data** allows the determination of the distributions of partons
  - But having the correct assumptions in interpreting data is critical!

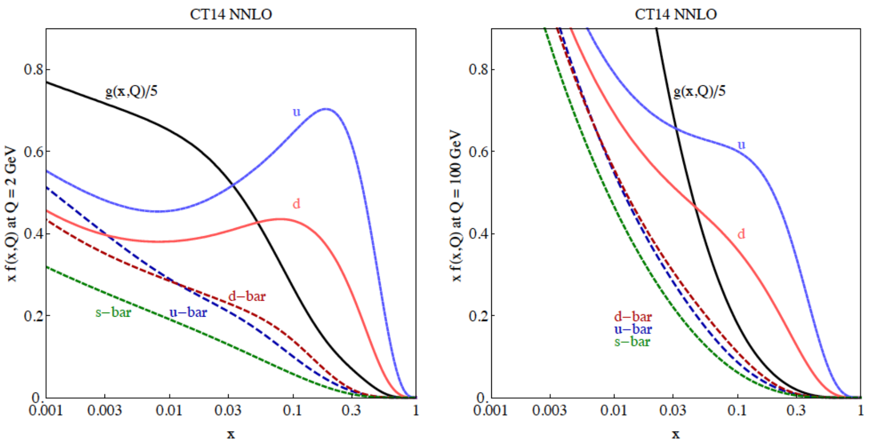
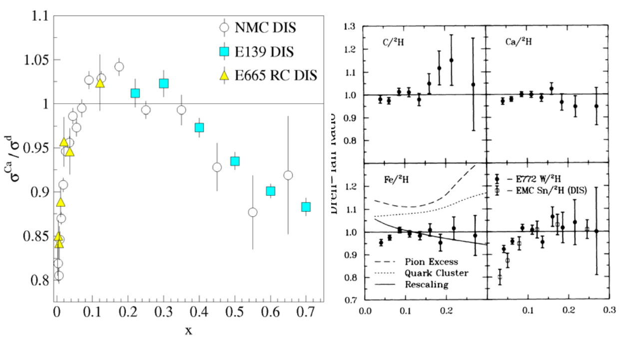


FIG. 5: The CT14 parton distribution functions at $Q = 2$ GeV and $Q = 100$ GeV for $u, \overline{u}, d, \overline{d}, s = \overline{s}$, and g.



- **Data** says that these distributions change when the proton is contained in a nucleus
  - Models of these effects are not satisfactory

- The proton's spin is not where we are looking, but the options are narrowing

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + \Delta G \qquad \frac{1}{2}\Delta\Sigma \approx 25\% \quad \Delta G \approx 0 - 15\%$$