Selected Physics Topics with a Polarized Electron Ion Collider

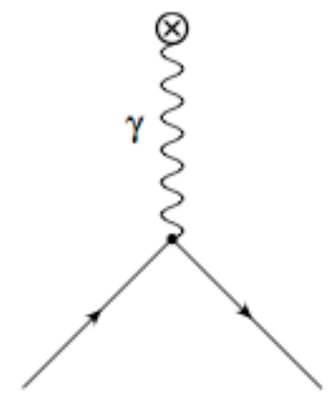
Ernst Sichtermann
Relativistic Nuclear Collisions Program, NSD

(Early) Monday Morning Meeting
November 9, 2009

Proton Magnetic Moment - circa 1935

- The magnetic moment $\vec{\mu}$ of a particle is related to its spin $\vec{S}$ according to:

$$\vec{\mu} = g\frac{e}{2mc}\vec{S}$$



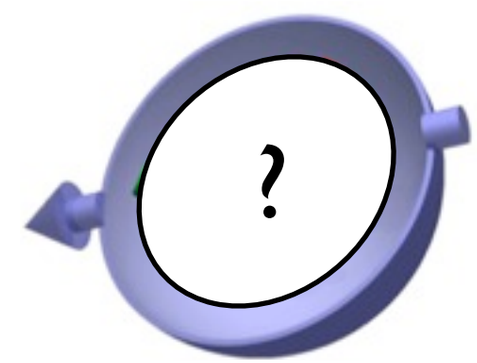
$$g = 2 + \mathcal{O}(\alpha_{\mathrm{e}})$$

for Dirac particles

- 1933 - Frisch and Stern:

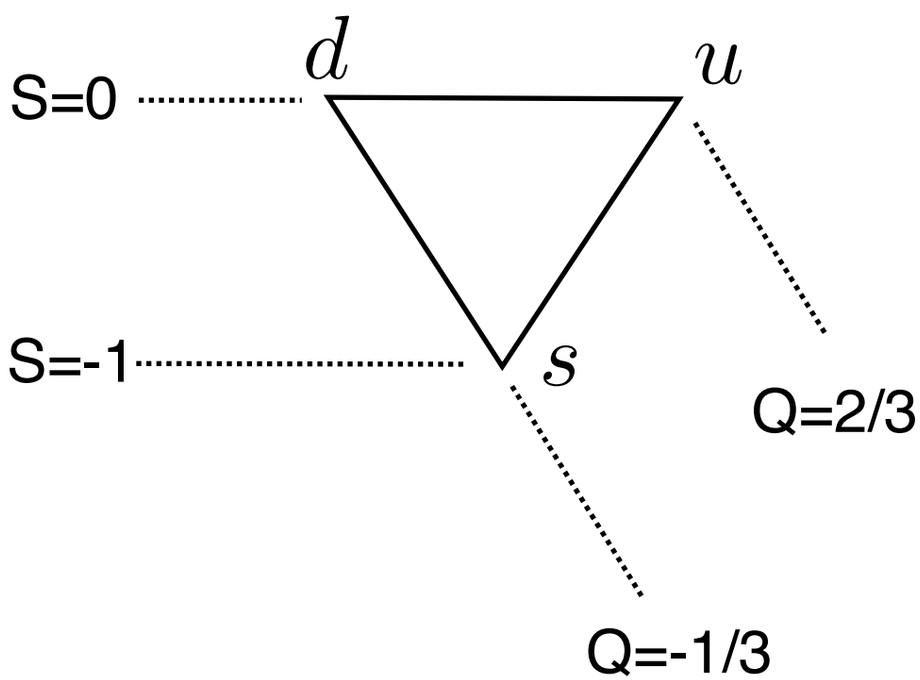
$$\vec{\mu}_p = 5.8\frac{e}{2mc}\vec{S}_p$$ - *Proton has (spin-)substructure*

But, what is it?

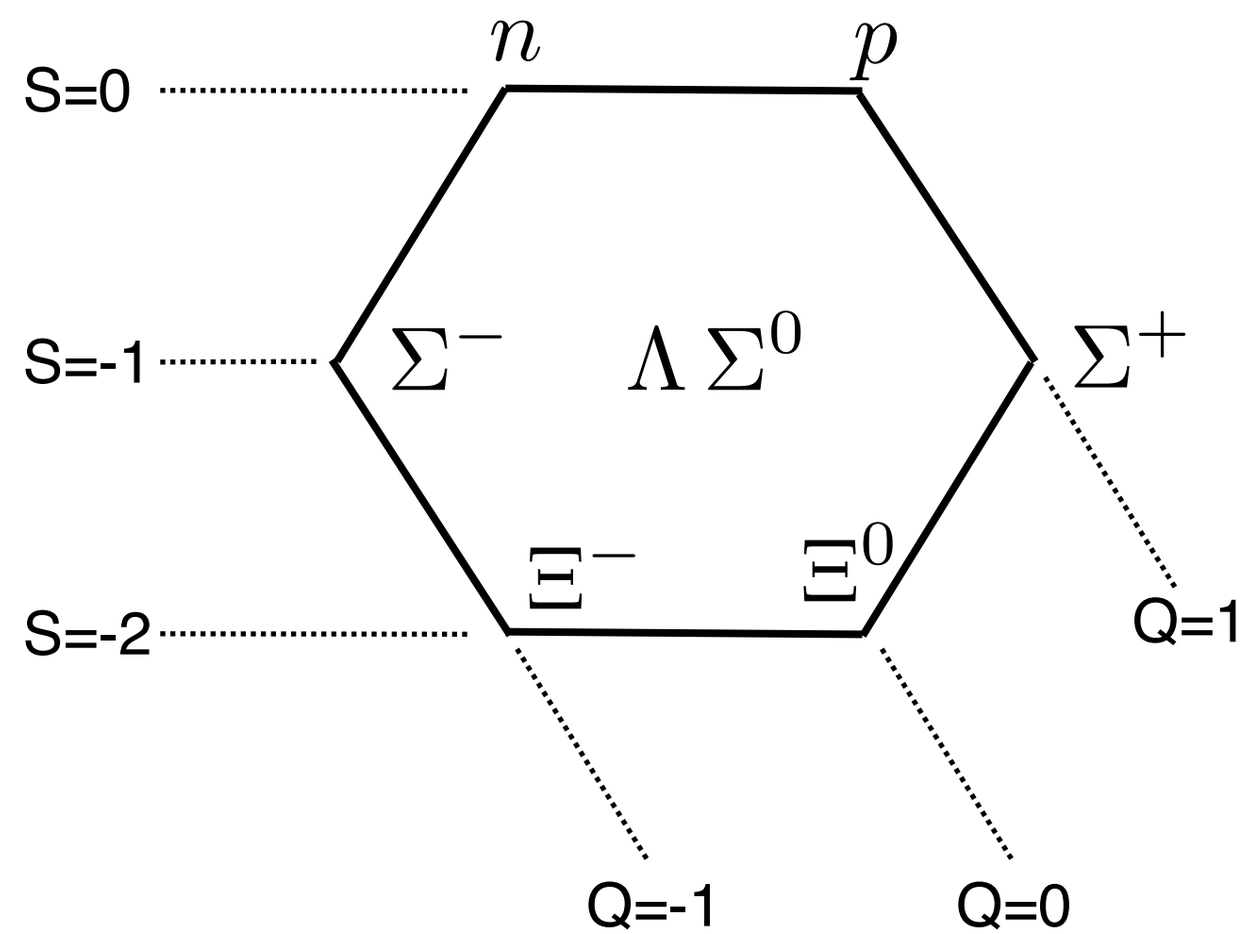


Quark-parton Structure - circa 1960

3 light Quarks



L=0, S=1/2 Baryon Octet

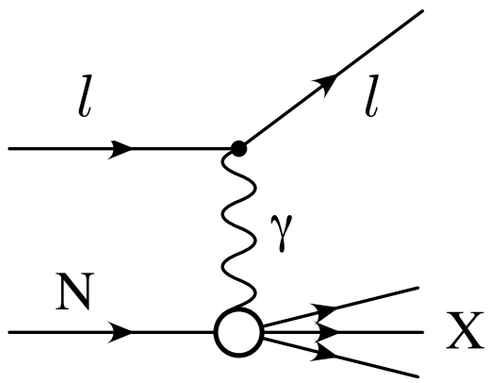


Highly successful in describing spectroscopy, *magnetic moments*, ...

$$|p:\frac{1}{2}\frac{1}{2}>=\frac{2}{3\sqrt{2}}\left(u(\uparrow)u(\uparrow)d(\downarrow)\right)-\frac{1}{3\sqrt{2}}\left(u(\uparrow)u(\downarrow)d(\uparrow)\right)-\frac{1}{3\sqrt{2}}\left(u(\downarrow)u(\uparrow)d(\uparrow)\right)\ +\ \text{permutations}$$

Deep Inelastic Scattering - circa 1970

- SLAC-MIT experiment - start of deep-inelastic scattering,

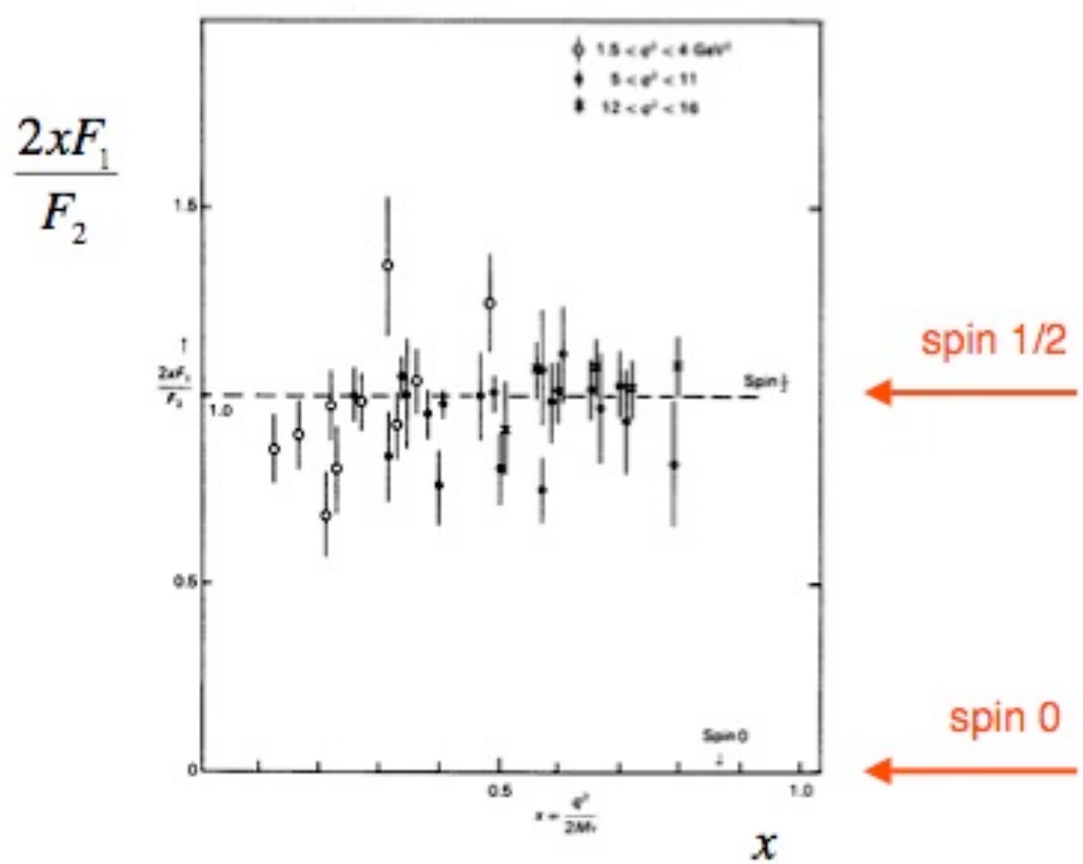


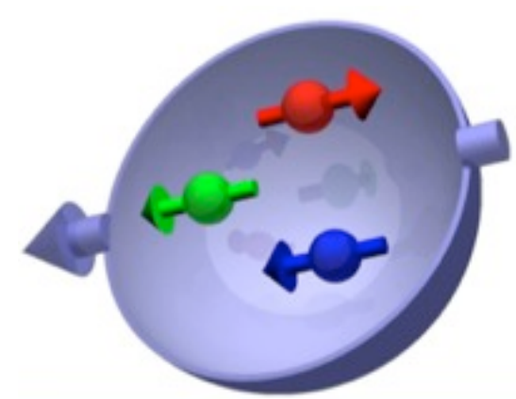
Q^2 ~ wavelength (in Compton sense) of the photon,

x ~ fraction of the proton momentum carried by the struck 'quark' in the proton inf. mom. frame,

F_1, F_2 structure functions, parametrizations of the (spin-averaged) inclusive cross-section

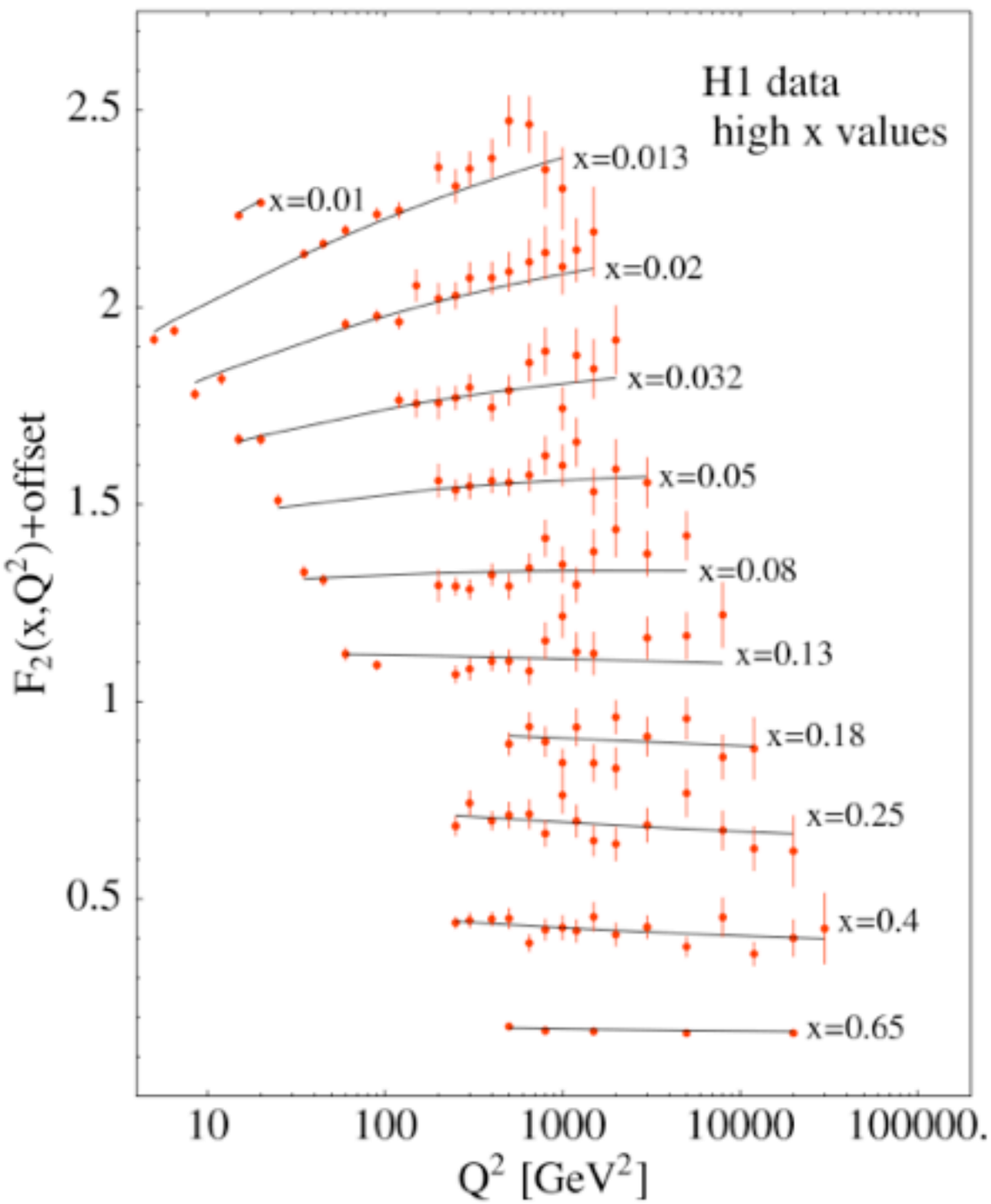
- among the early results: the partons (quarks) are indeed spin $\frac{1}{2}$





Deep Inelastic Scattering - circa 1970

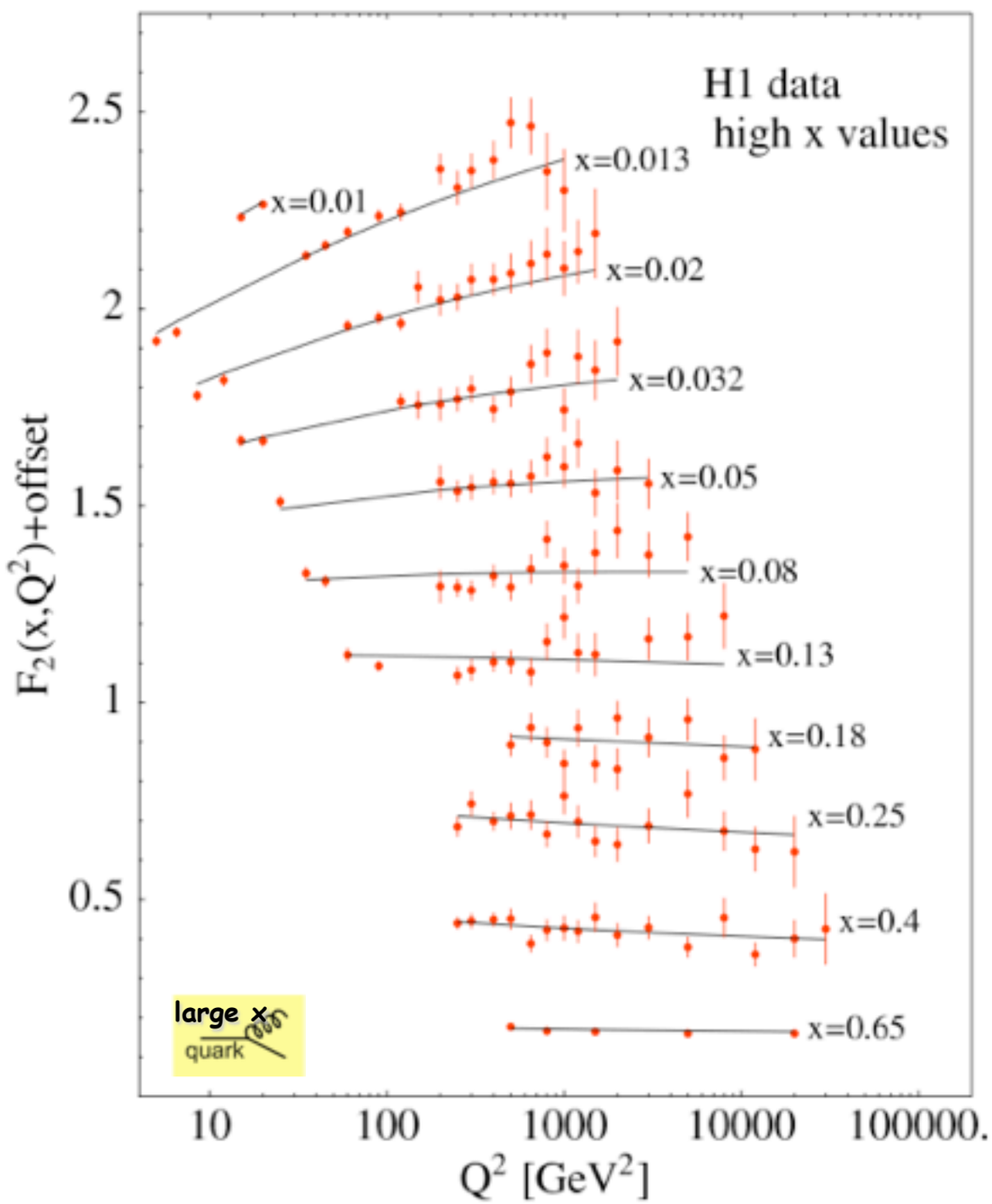
- and, perhaps better known, the structure function scales with Q^2

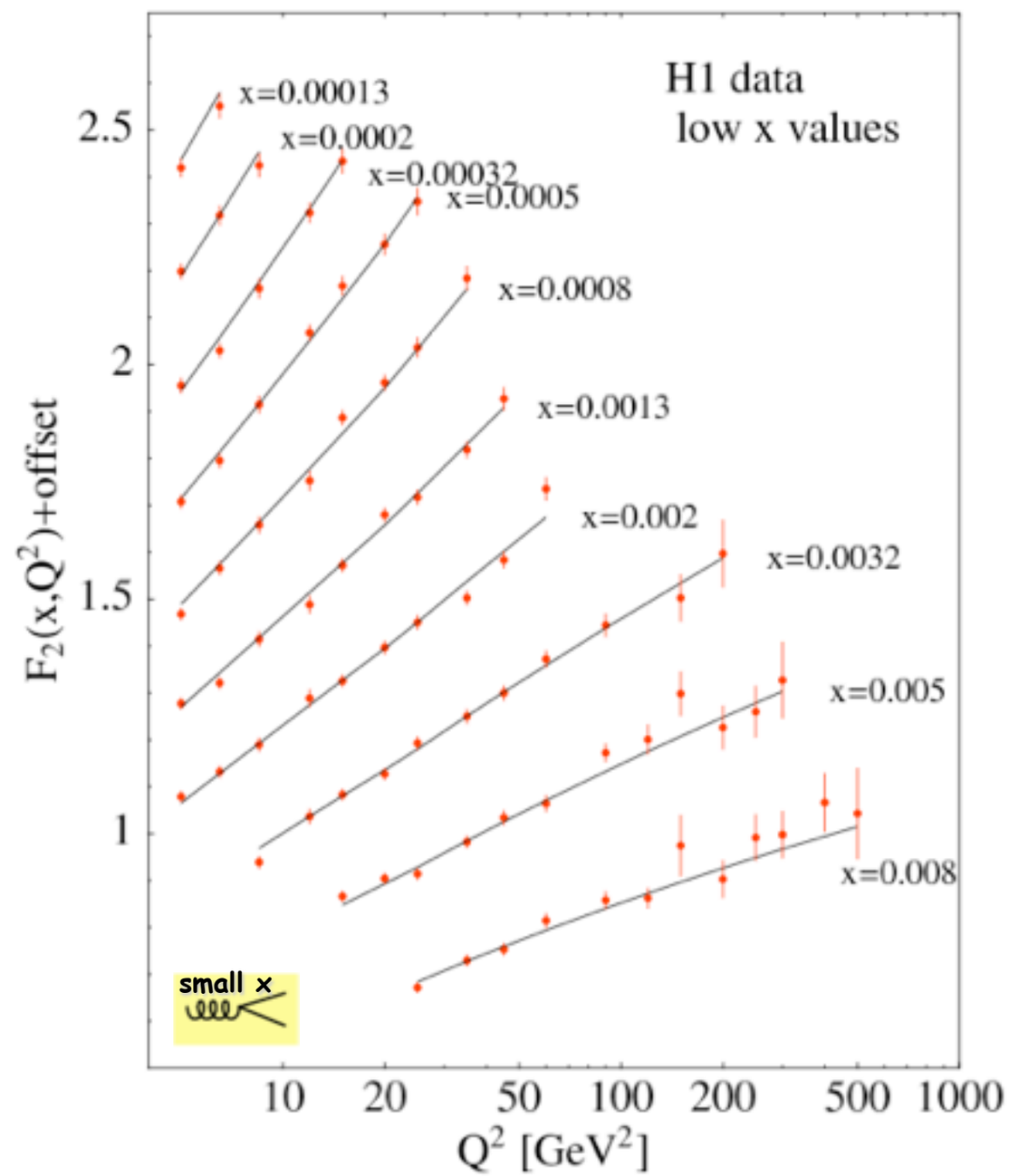


Shown are modern data from HERA, the world's only e-p collider.

Deep Inelastic Scattering

- F_2 shows approximately scaling with Q^2 at moderate x, and *pronounced* evolution for *smaller* x,





Deep Inelastic Scattering

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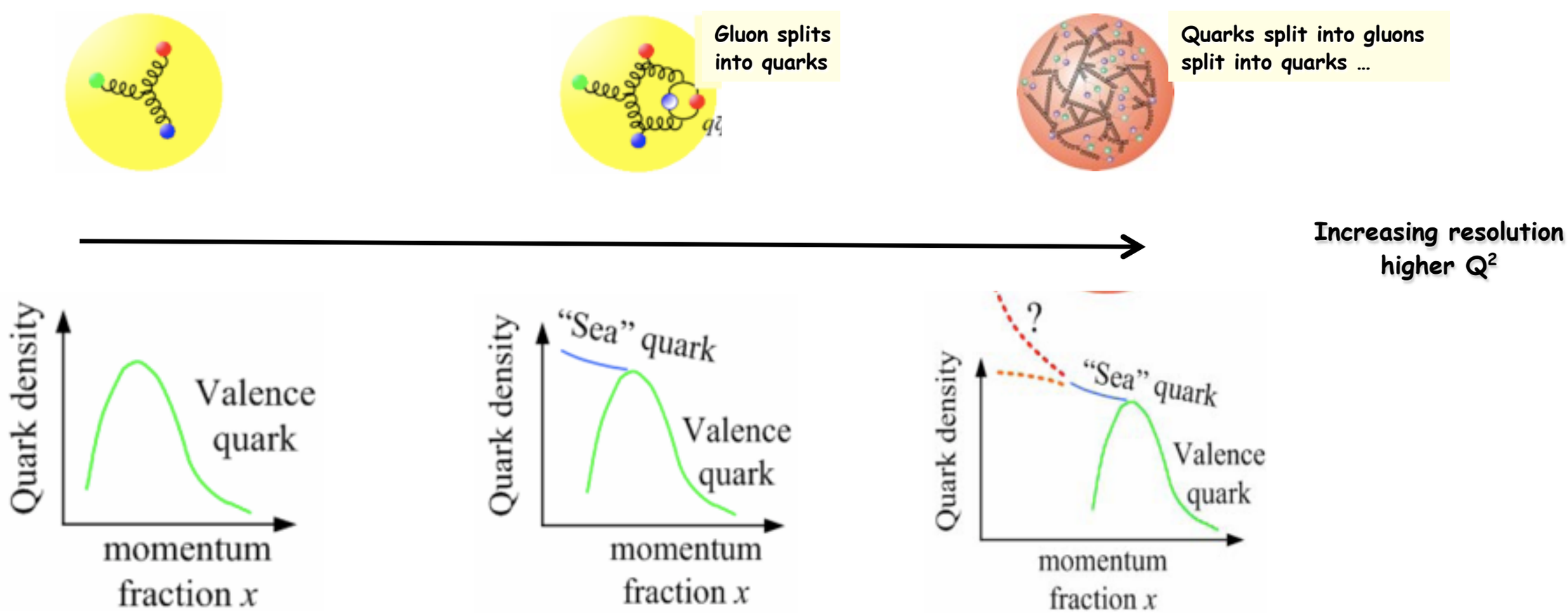


Proton Structure

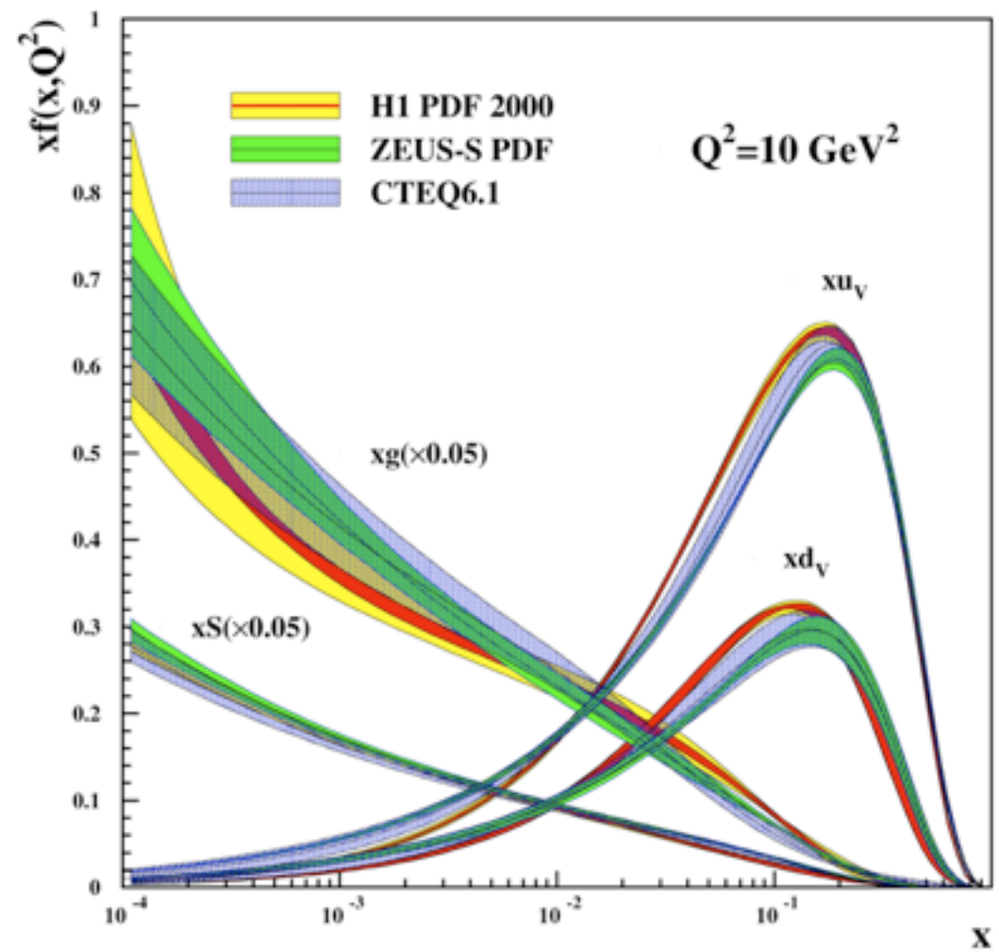
- Development of the initial quark-parton model,

$$F_1(x) = \frac{1}{2}\sum_q e_q^2 q(x)$$

$$F_2(x) = x\sum_q e_q^2 q(x) \qquad +\mathcal{O}(\alpha_s)$$

$$g_1(x) = \frac{1}{2}\sum_q e_q^2 \Delta q(x)$$

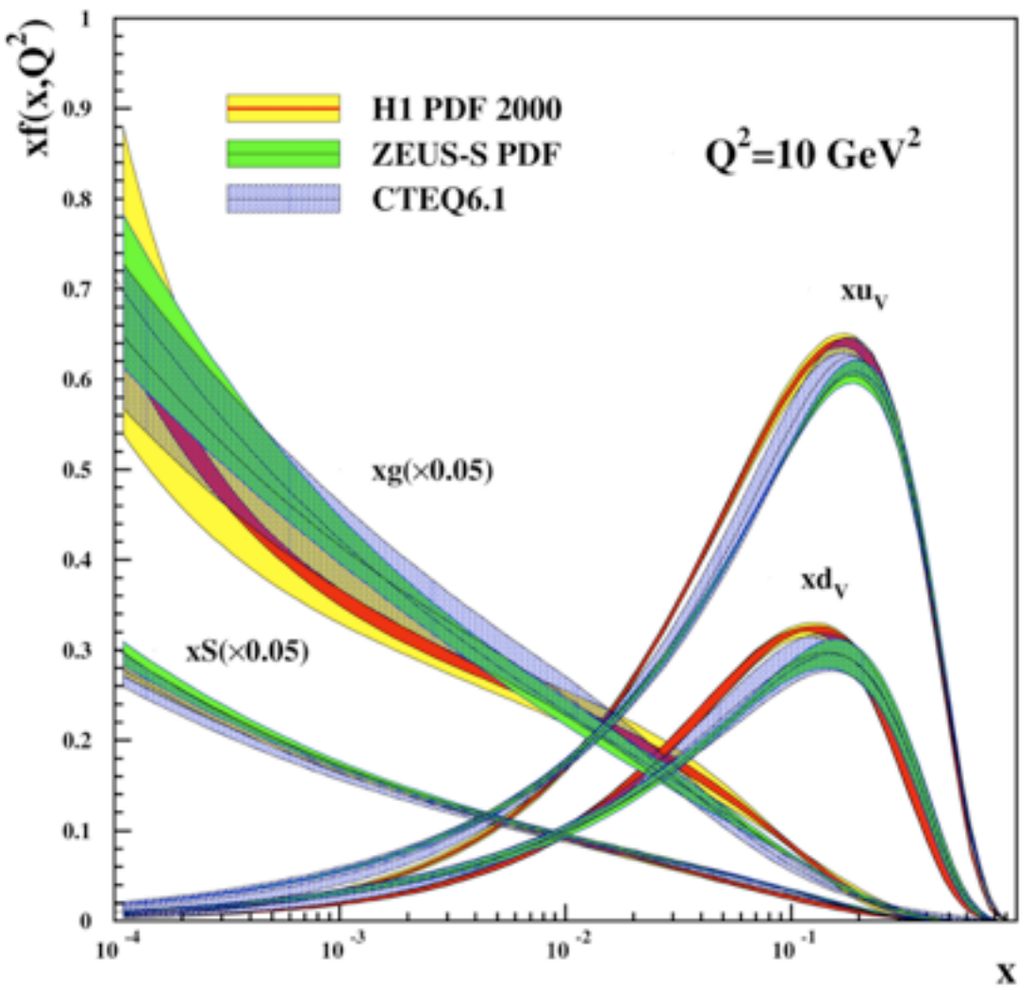
$$h_1(x) = \frac{1}{2}\sum_q e_q^2 \delta q(x)$$

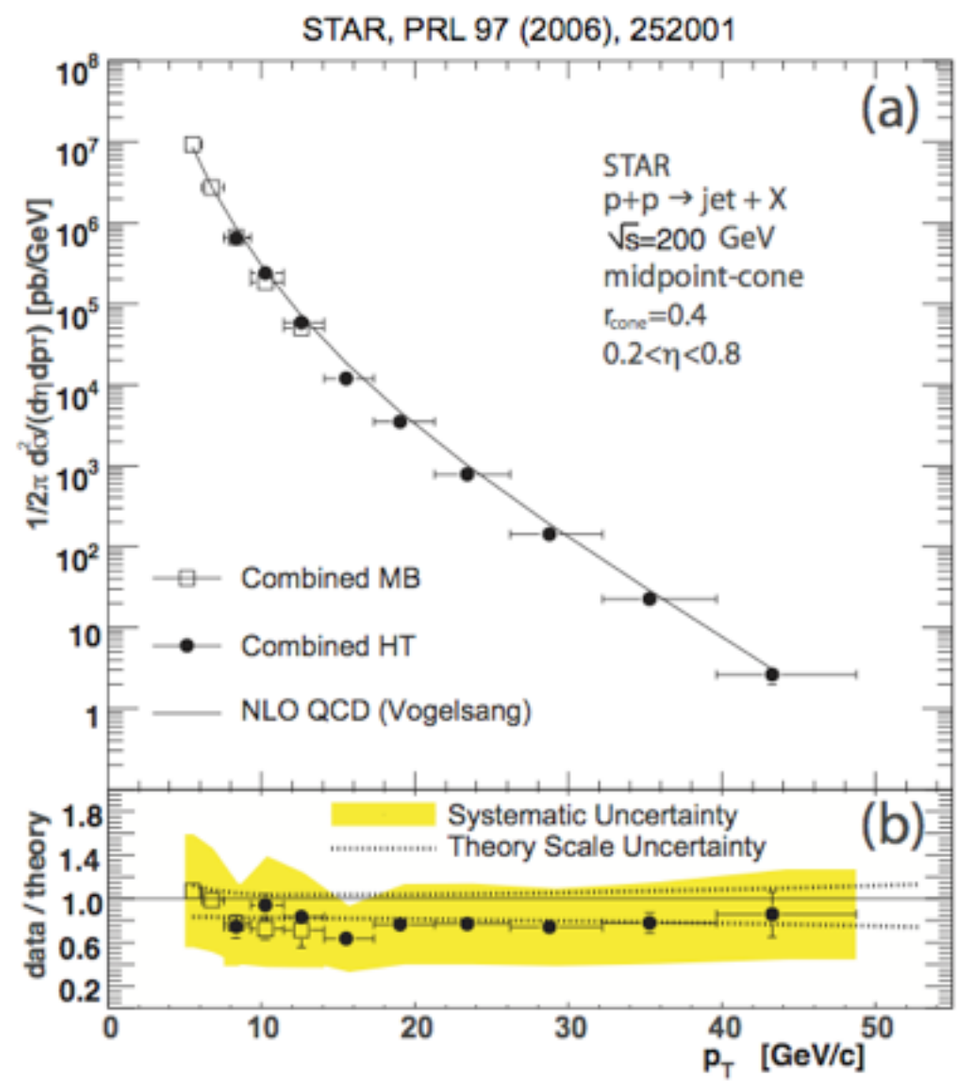


improved by perturbative QCD radiation.

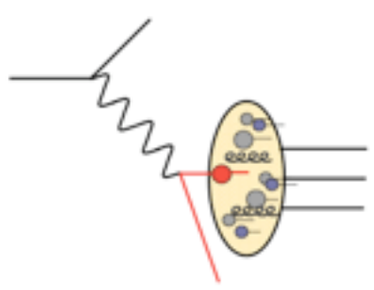
- Gluons dominate; responsible for ~98% of observed mass, carry ~50% of the proton momentum,

Parton Distributions - Powerful Predictors





DIS



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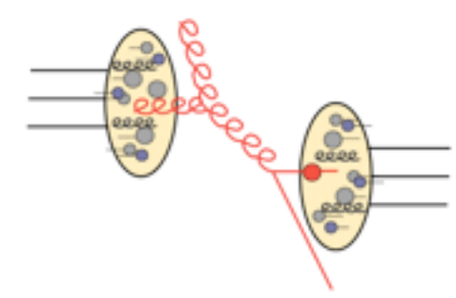
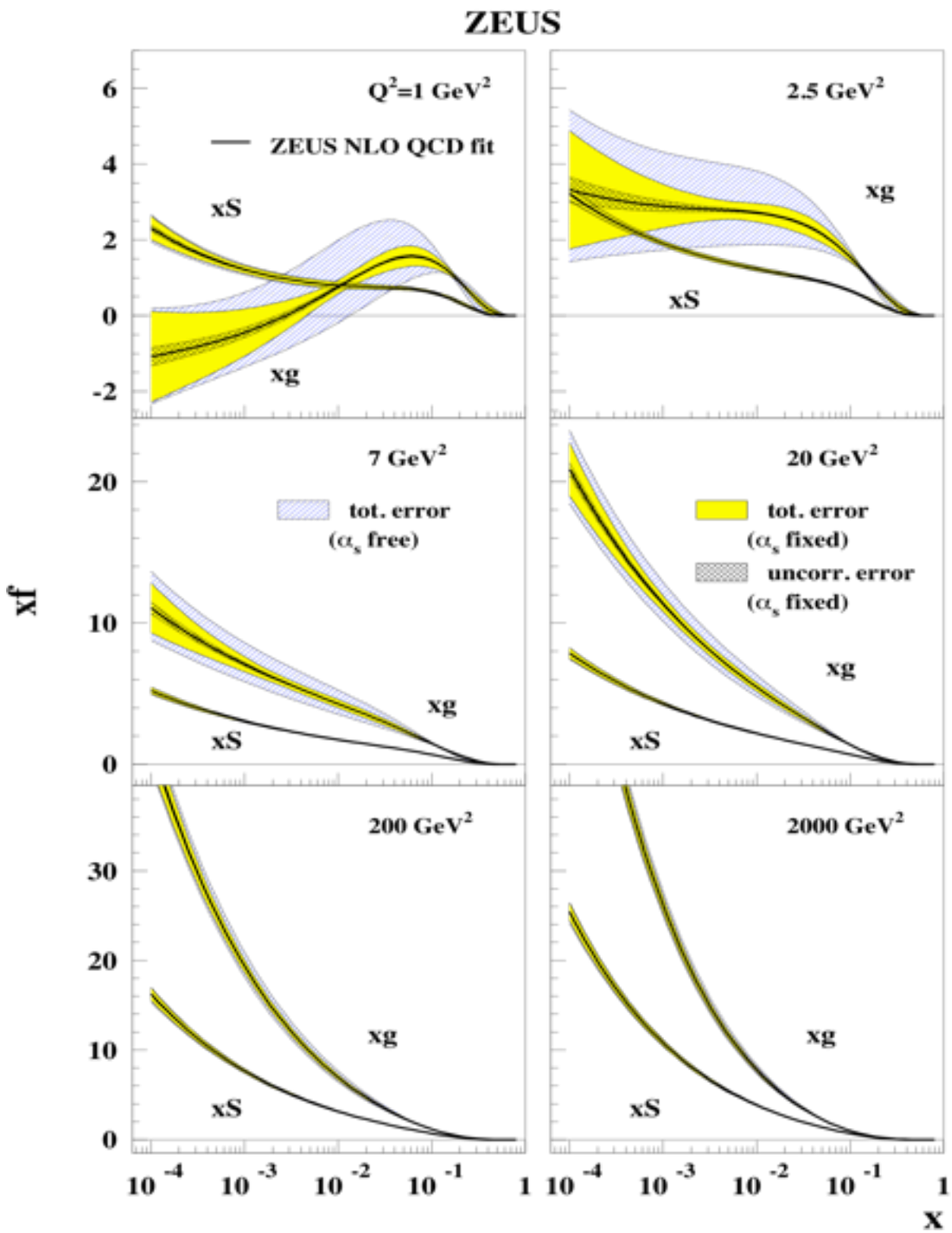


Parton Distributions - *not all is well*



NLO gluon distribution goes *negative* at small x, Q^2,

A *problem*?

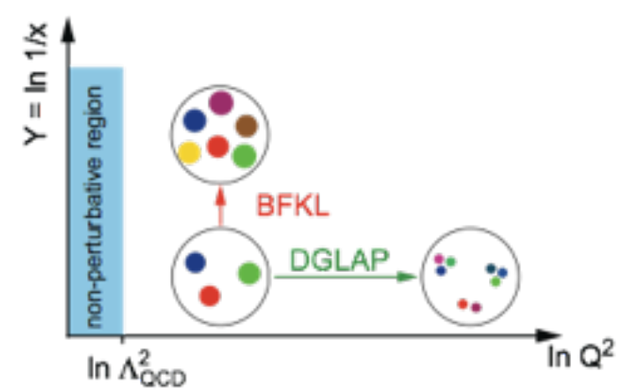
NLO distribution = renormalized probability,

Calls for precision measurements of F_L,

$$\frac{d^2\sigma^{ep\to eX}}{dxdQ^2} = \frac{4\pi\alpha^2}{xQ^4}\left[\left(1-y+\frac{y^2}{2}\right)F_2(x,Q^2)-\frac{y^2}{2}F_L(x,Q^2)\right]$$

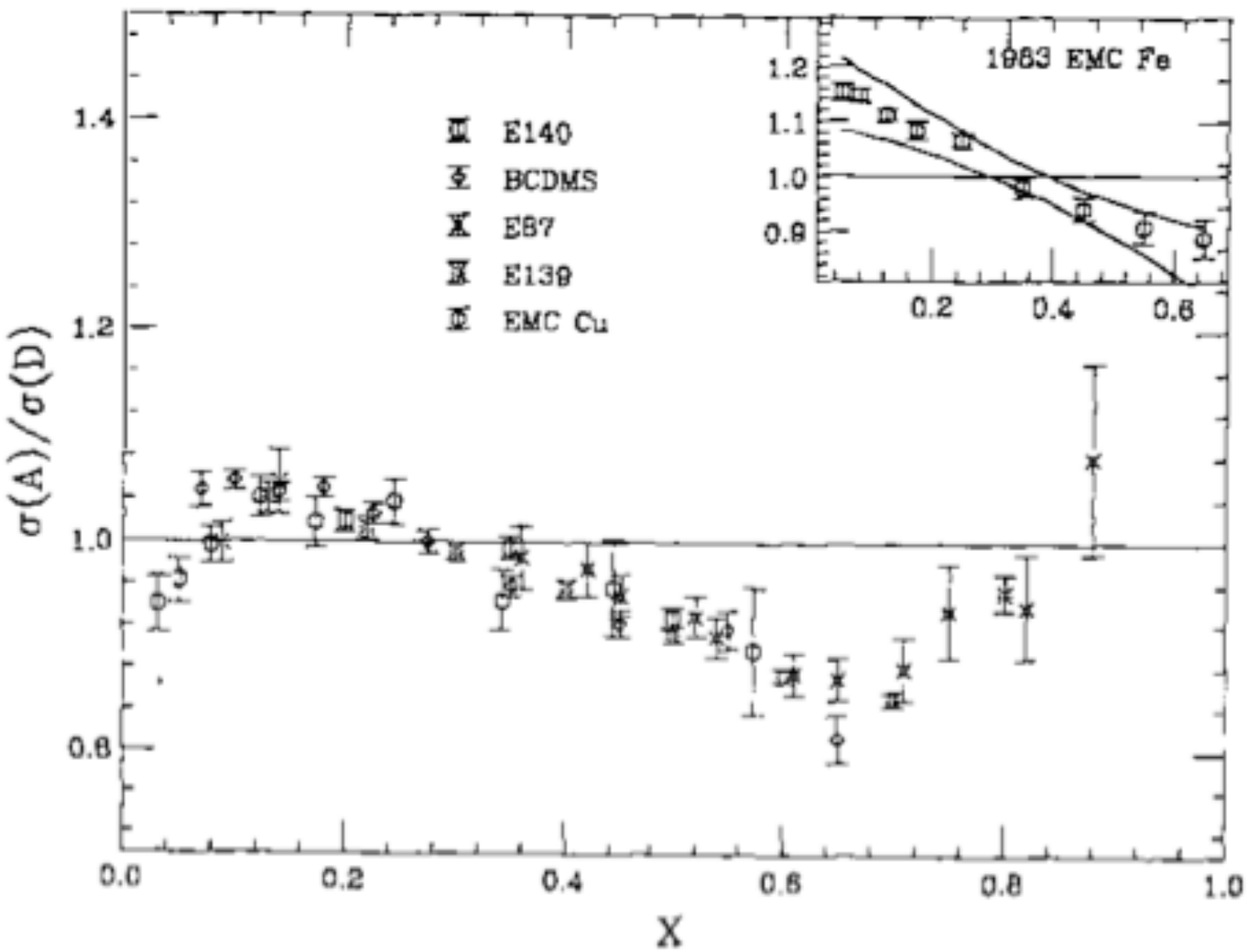
$F_L \sim \alpha_S G$

Breakdown of (DGLAP) evolution?



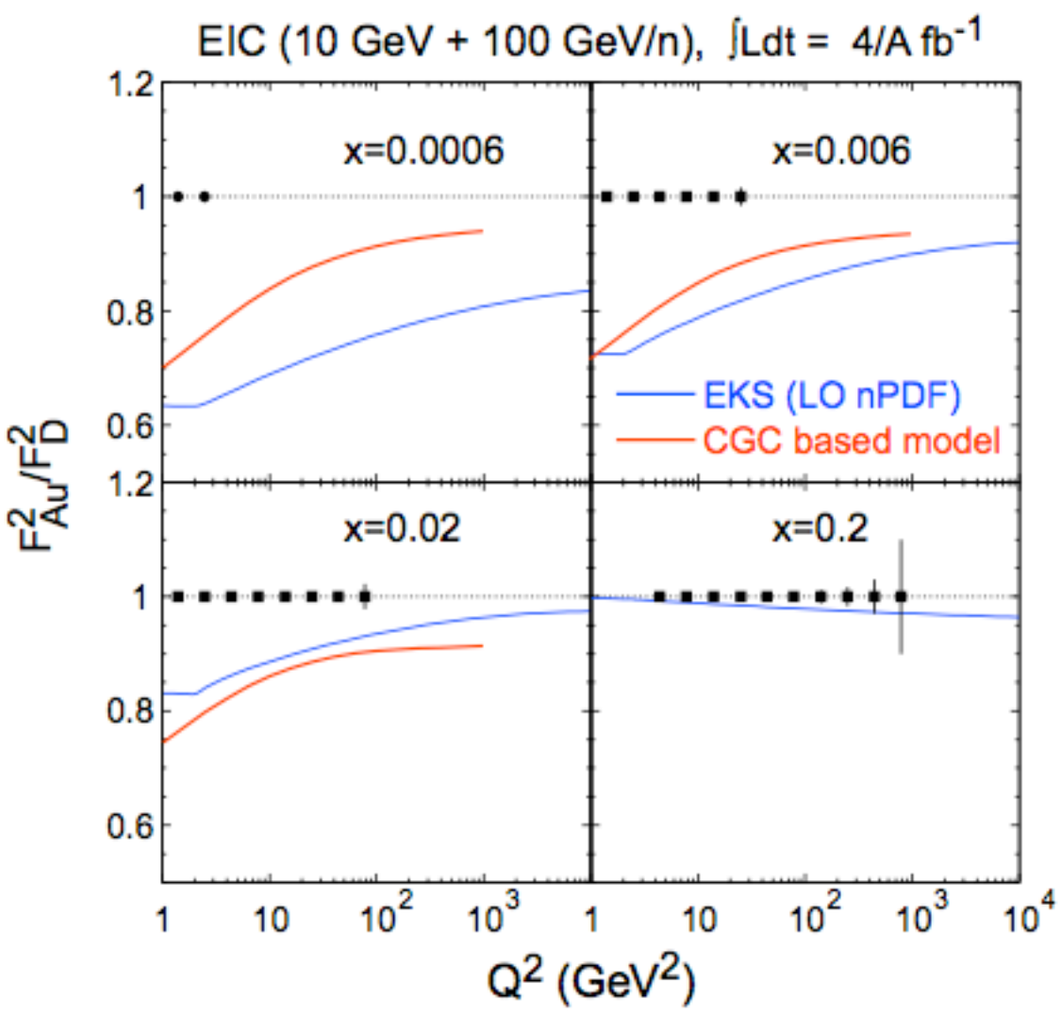
Parton Distributions - *a lot remains unknown / not understood*

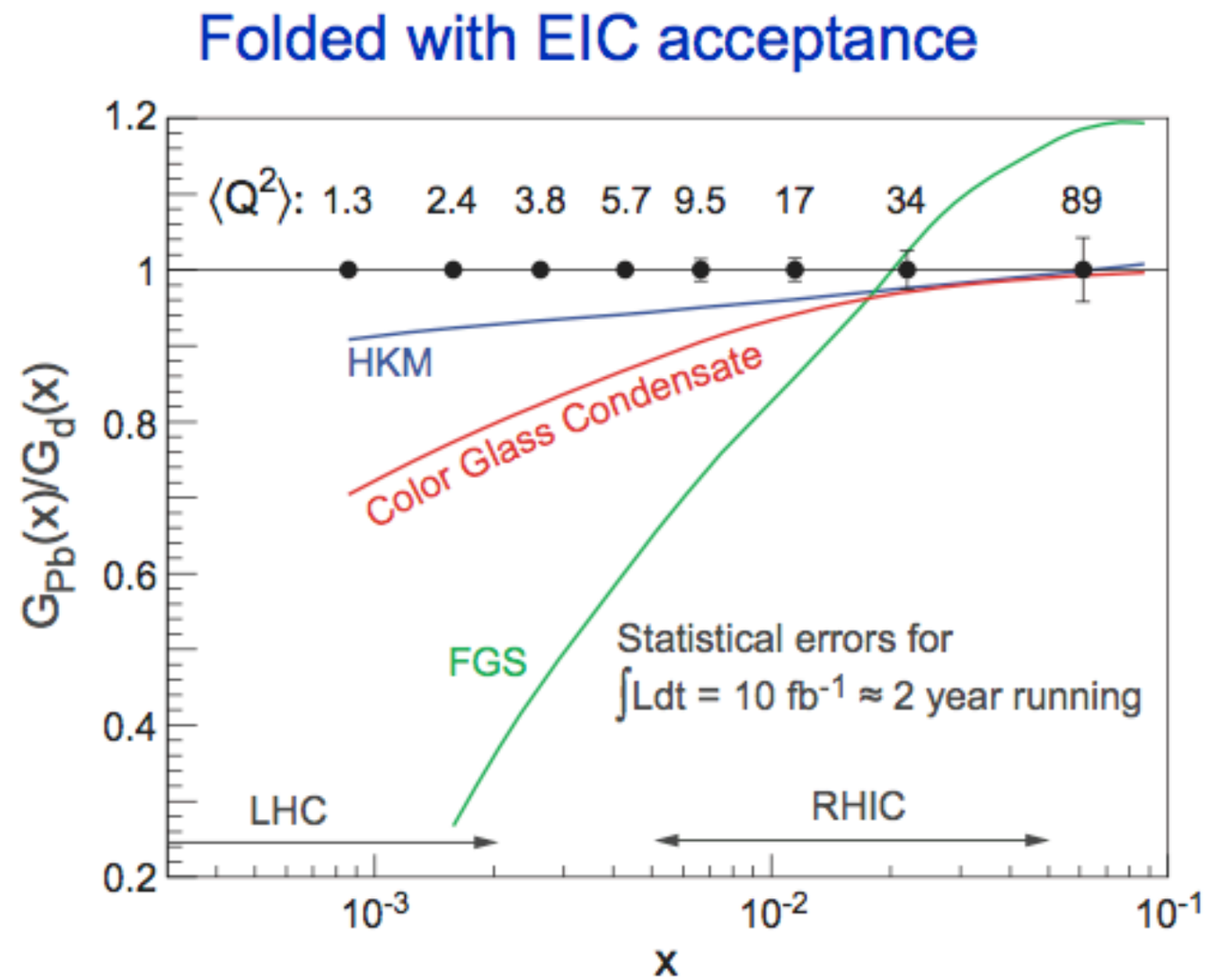
The Nuclear EMC Effect (incl. shadowing).



D. Geesaman et al, Annu. Rev. Nucl. Part. Sci. 1995:337-390

Nuclear Parton Distributions - *Key Role for EIC*





Assume:

L = 3.8 10^{33} cm^{-2} s^{-1} (100x Hera),

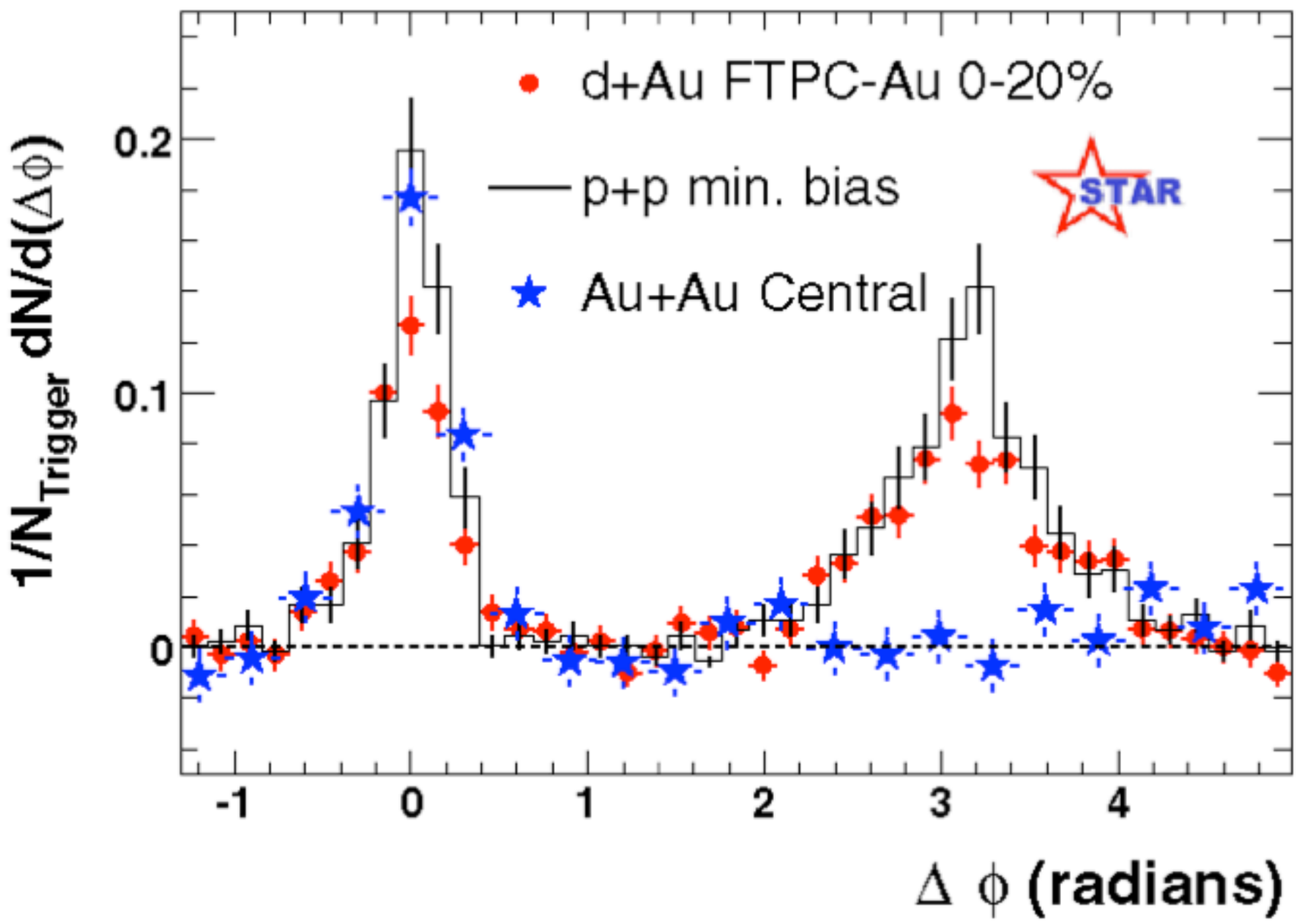
T = 4 weeks, duty cycle: 50%

$F_L \sim \alpha_s G(x,Q^2)$ requires $\sqrt{s}$ scan

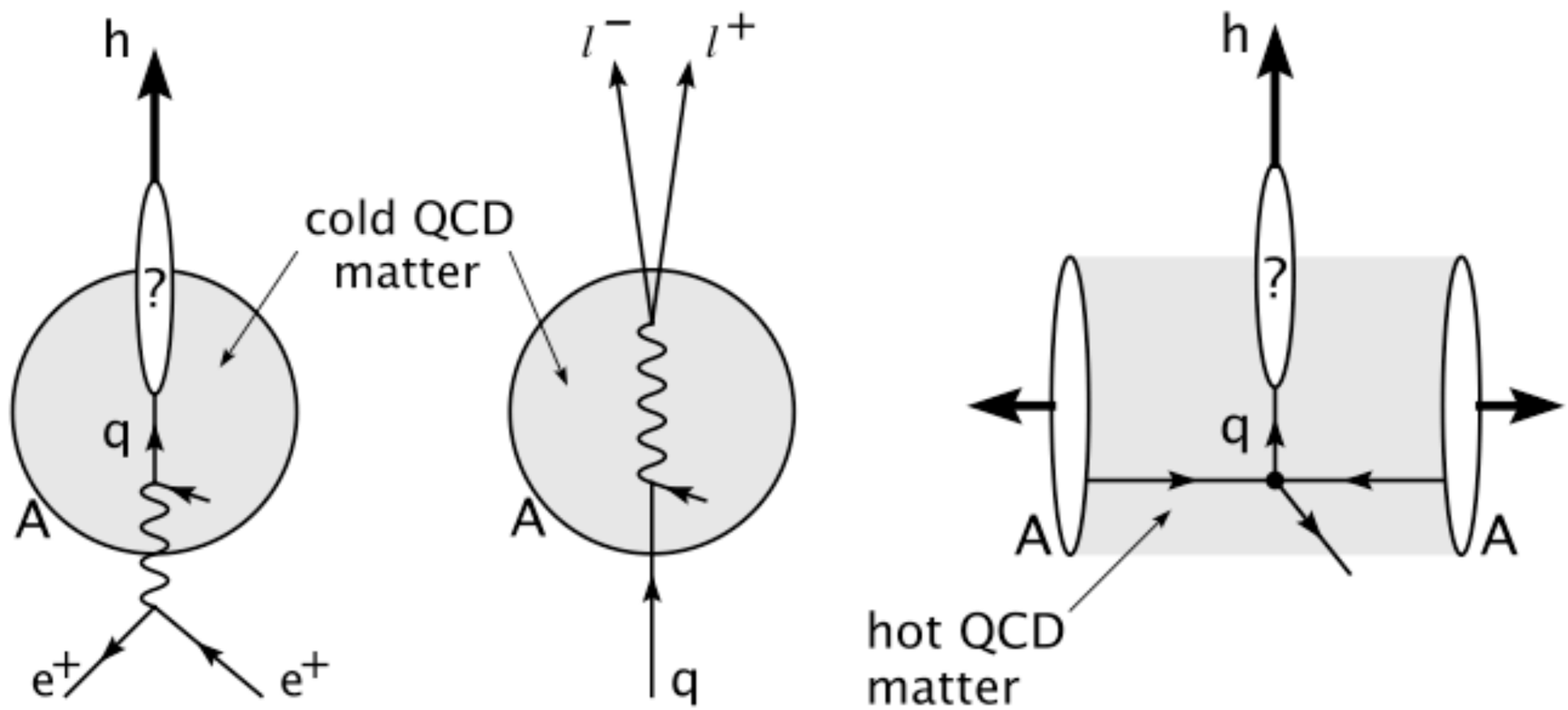
Here: 10+100, 10+50, 5+50 GeV

Note: Hadronic probes in RHIC/LHC A+A collisions are sensitive to pdf *and* "FF"

Parton Propagation and Fragmentation in Nuclear Matter



Parton Propagation and Fragmentation in Nuclear Matter



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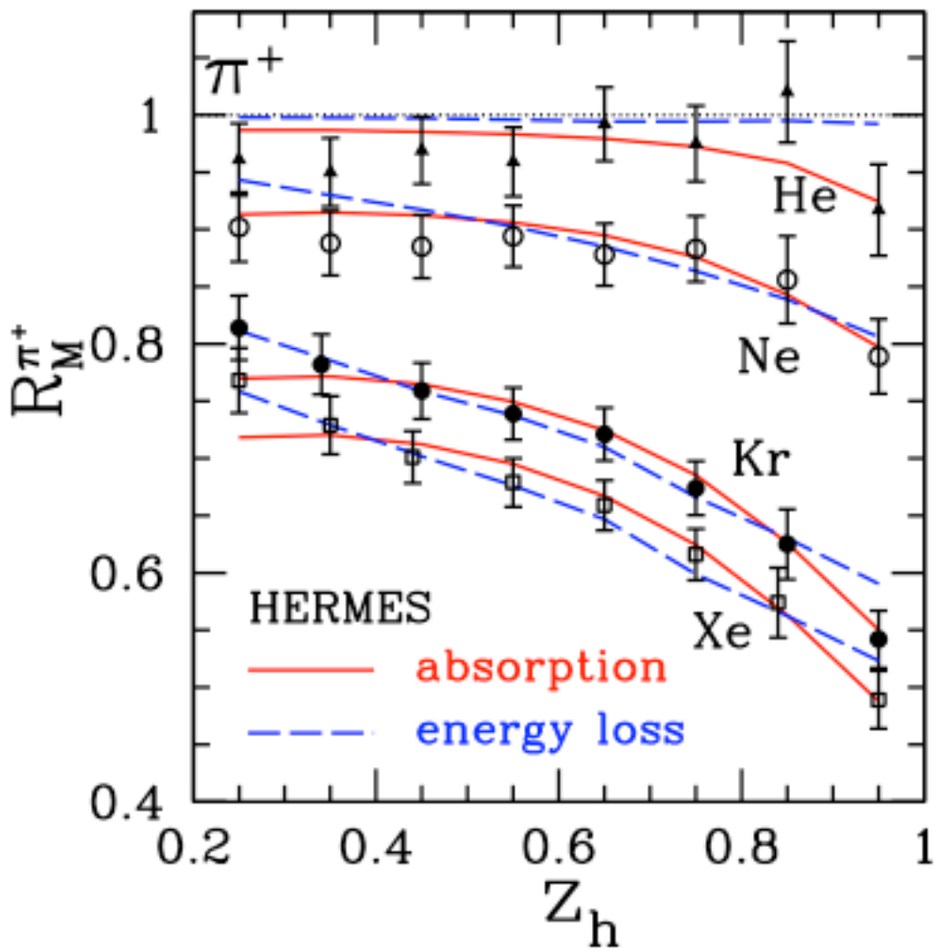
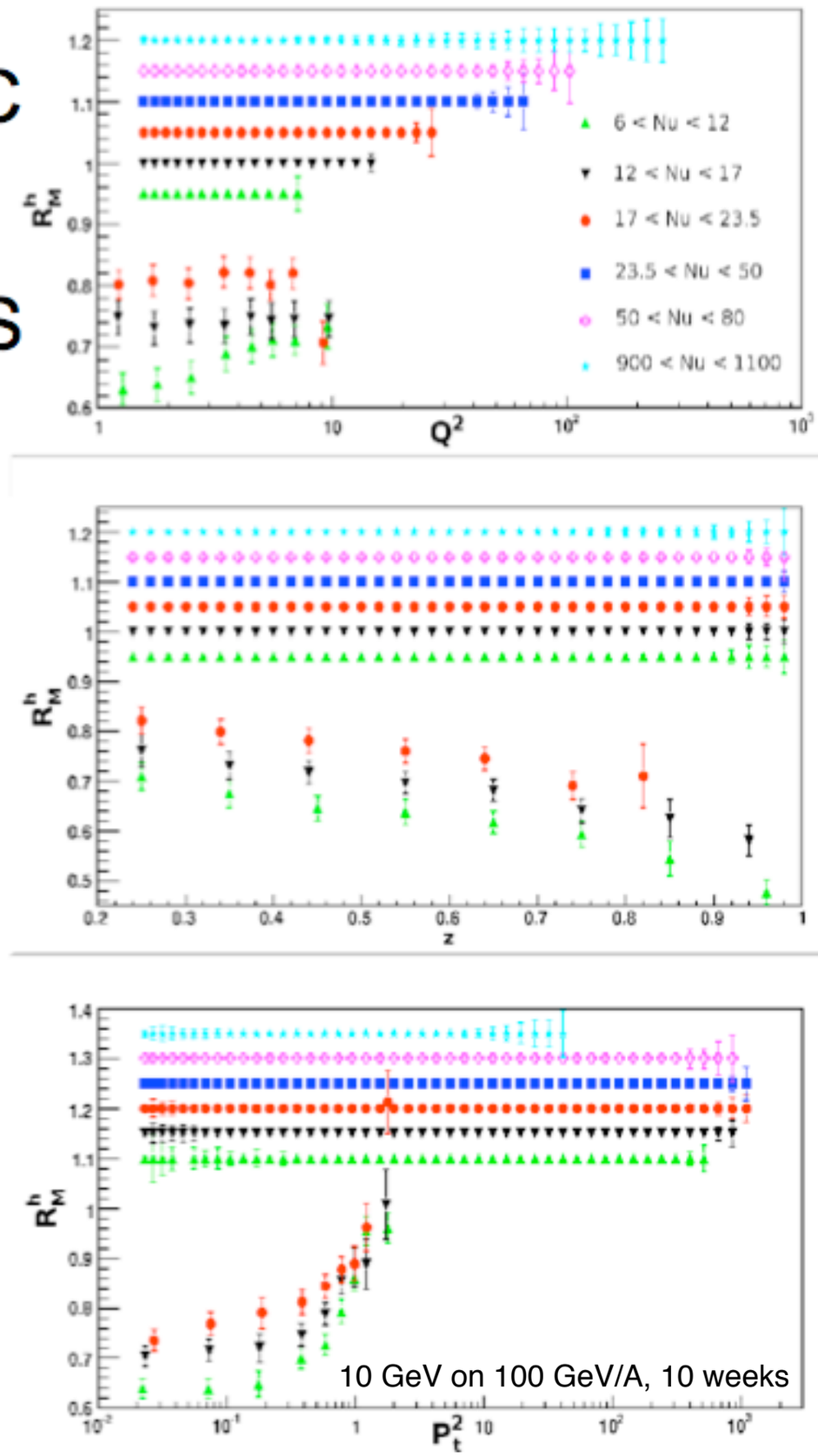


$$R_M^h(z) = \frac{\frac{1}{N_A^{DIS}} \frac{\mathrm{d}N_A^h(z)}{\mathrm{d}z}}{\frac{1}{N_D^{DIS}} \frac{\mathrm{d}N_D^h(z)}{\mathrm{d}z}}$$

Parton Propagation and Fragmentation in Nuclear Matter

EIC

HERMES



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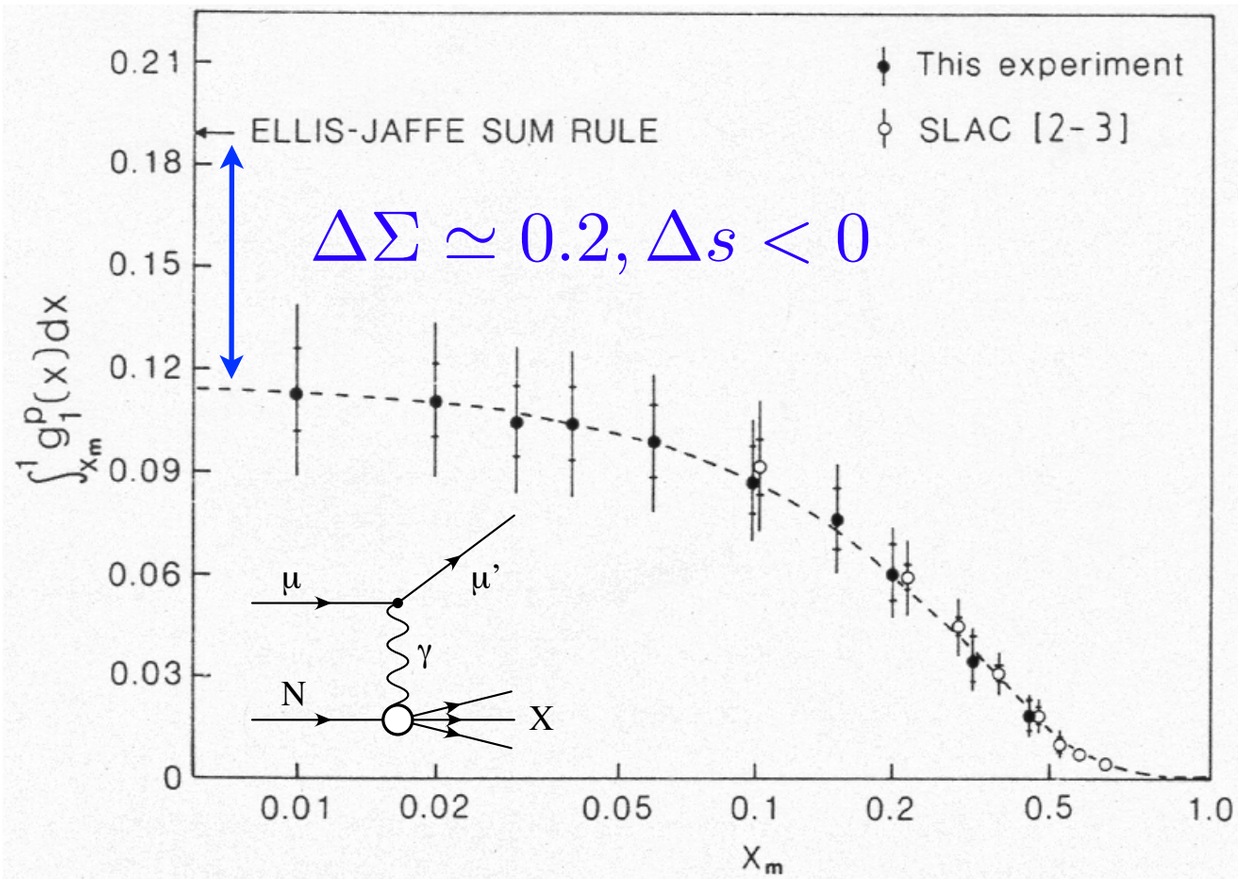
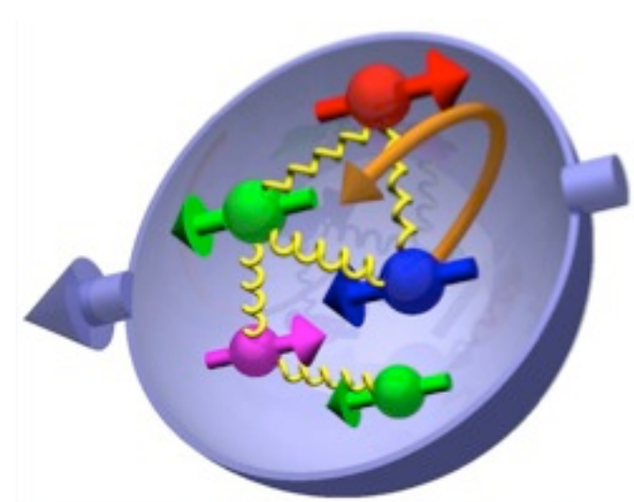
Parton Distributions - *a lot is unknown / not understood*

- *Polarized DIS* - European Muon Collaboration:



- *Quark spins carry only a small fraction of the proton spin,*
- *Strange sea is negatively polarized,*
- J. Ashman et al [EMC], Nucl. Phys. B 328:1 (1989)

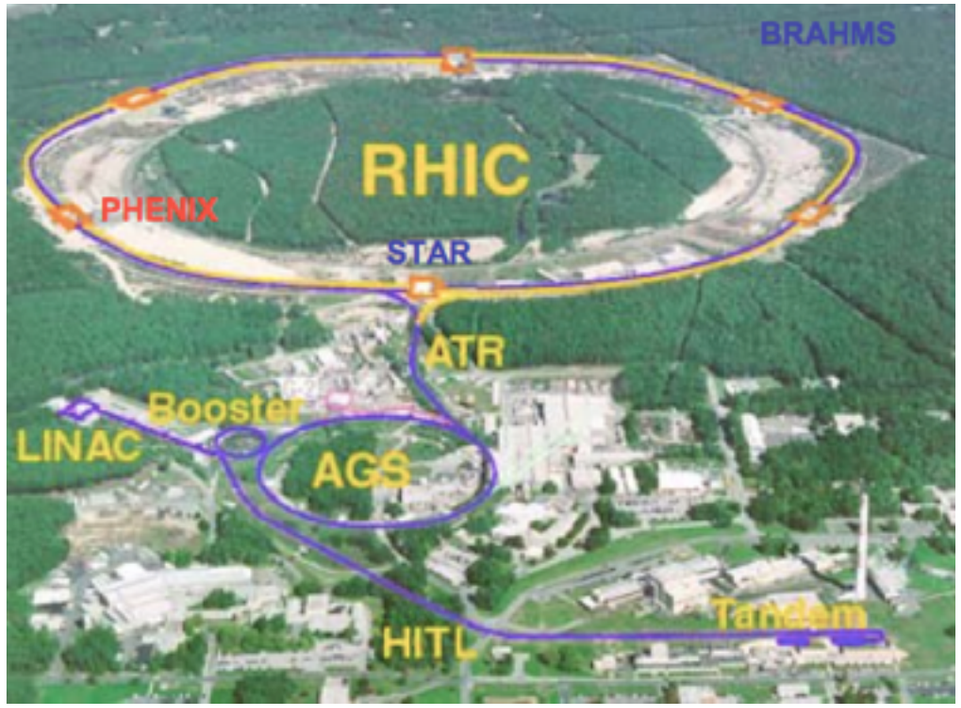


- SMC, E142, E143, E155, Hermes, and JLab have since confirmed the EMC data, and
- have tested the Bjorken Sum to ~7% precision.
- *forces to rethink nucleon (spin) structure.*

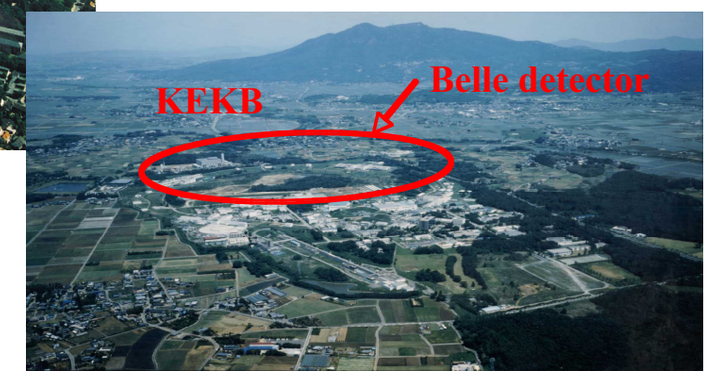
Some of the Open Questions on Nucleon Spin

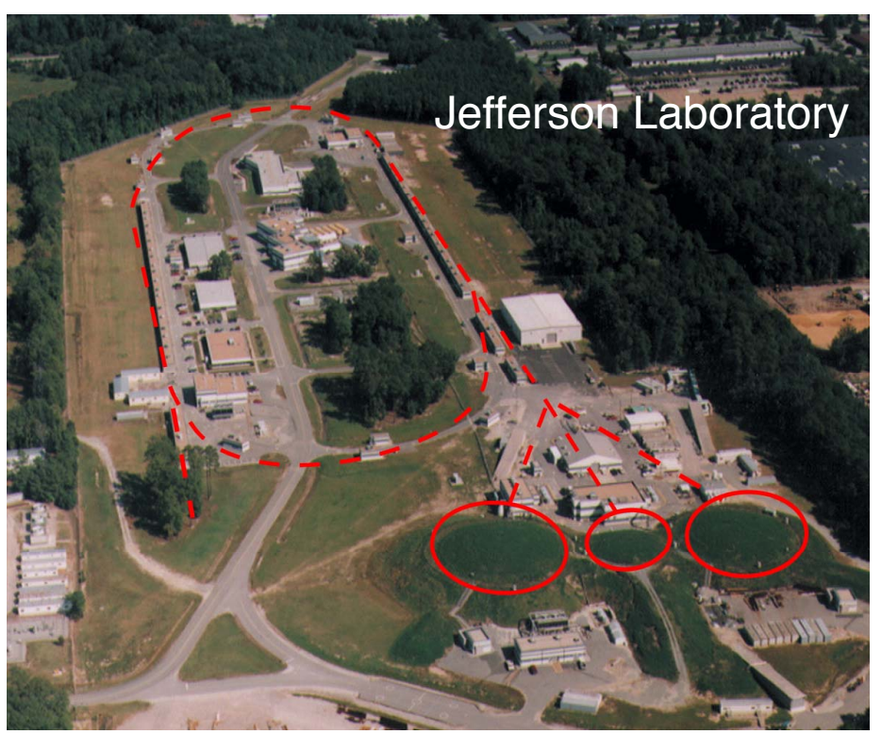
- How does gluon polarization contribute to the proton spin?
- What are the quark and anti-quark polarization by flavor?
- What orbital angular momenta do quarks and gluons carry?
- What is the role of transverse spins?

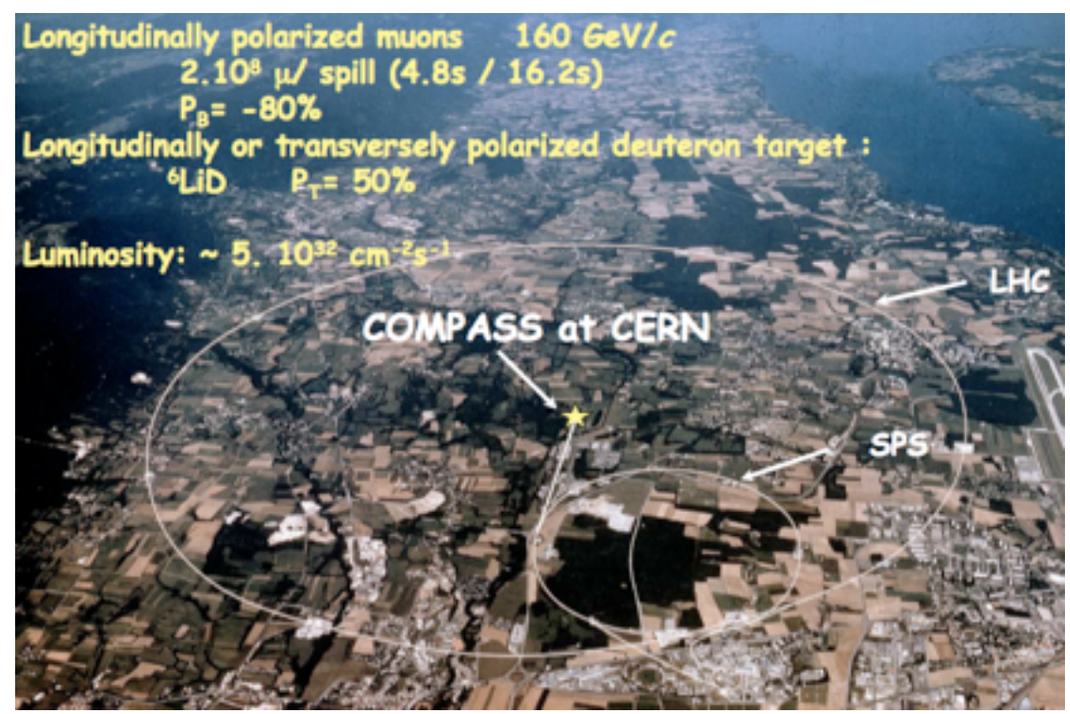
Some of the Open Questions on Nucleon Spin

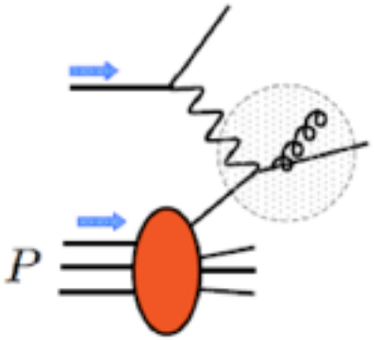


27 GeV e^+/e^- beam of HERA ep collider

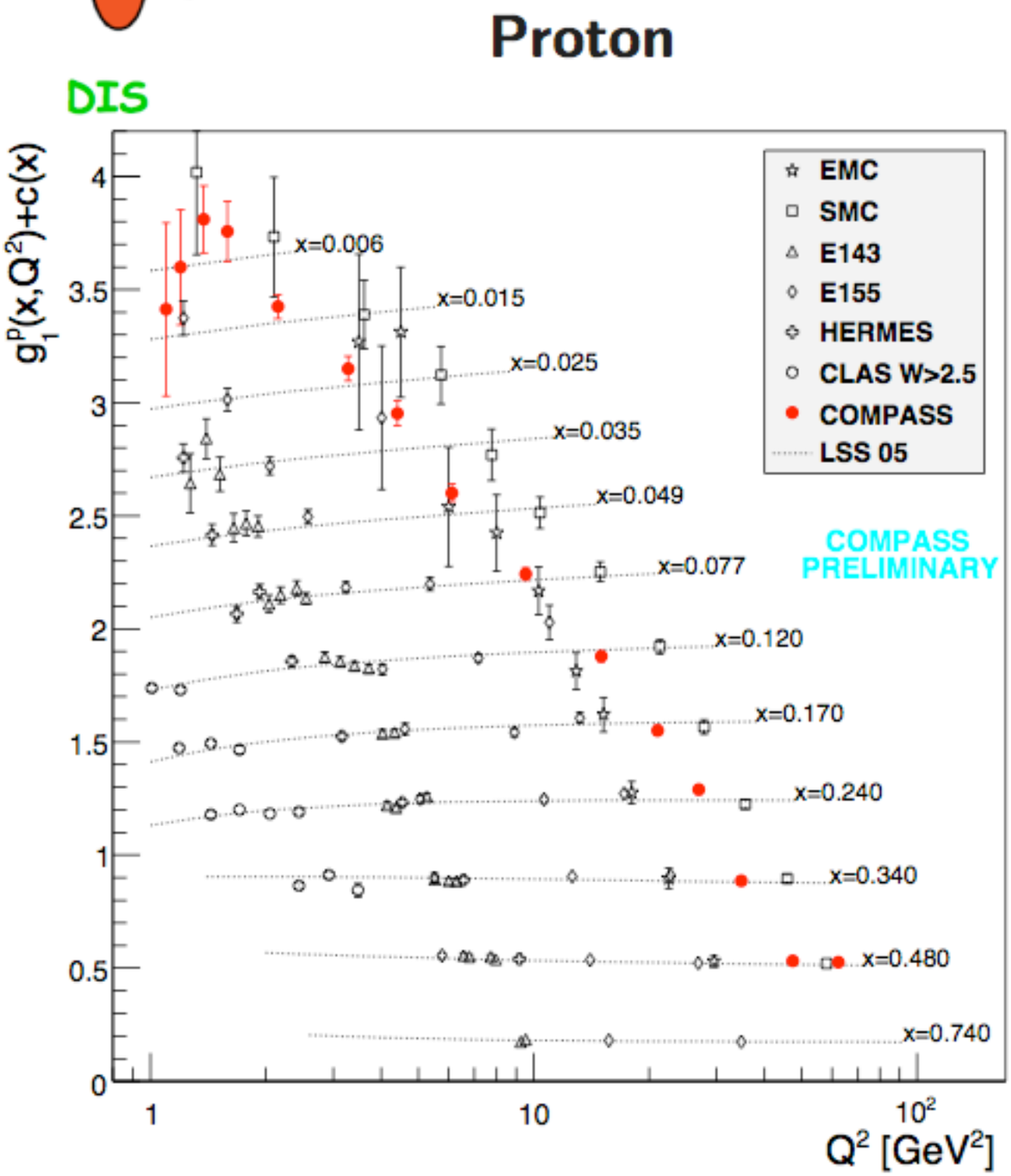


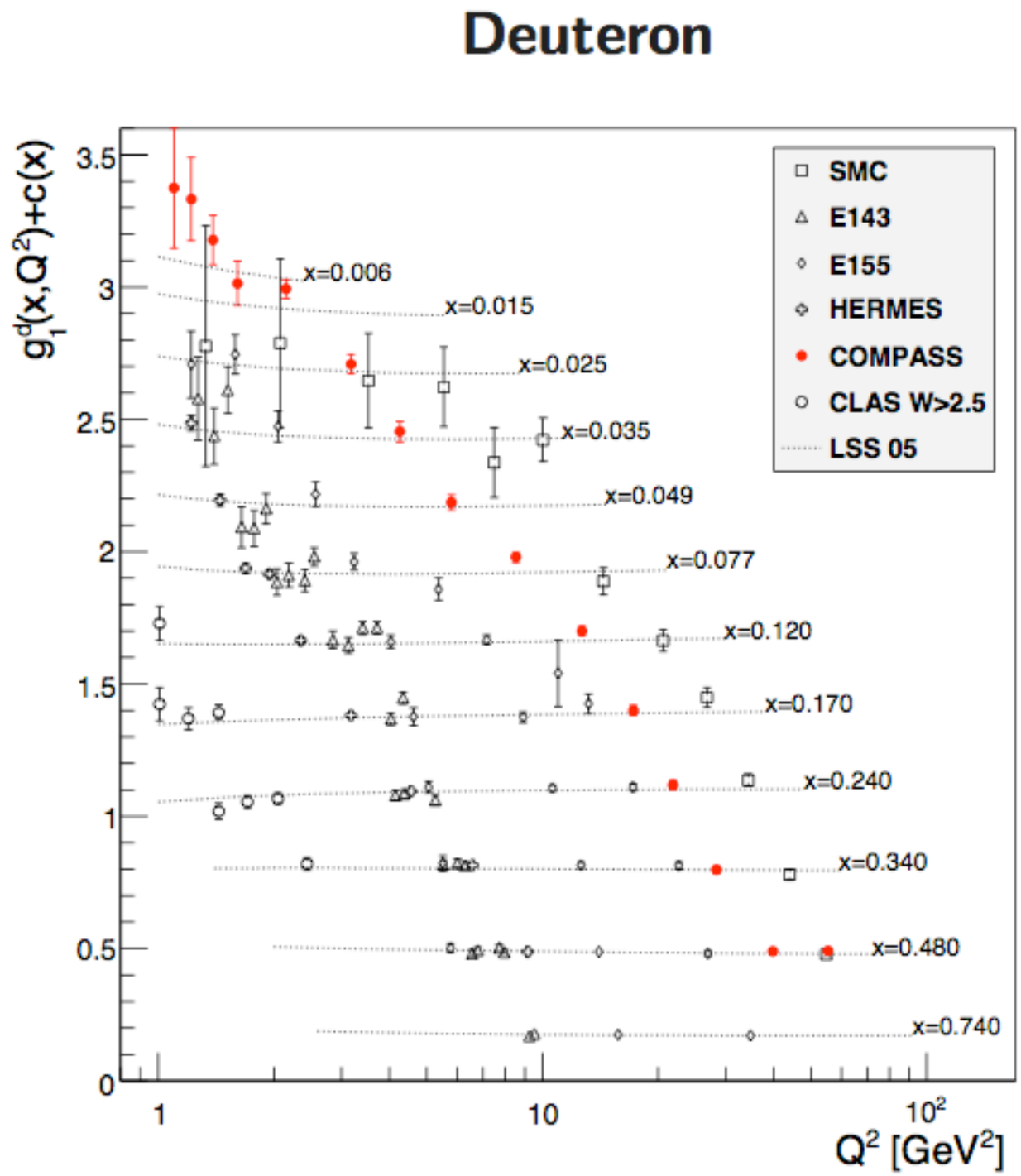




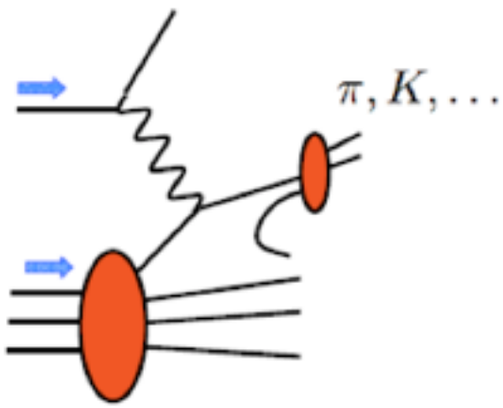


Inclusive Polarized DIS - 2009

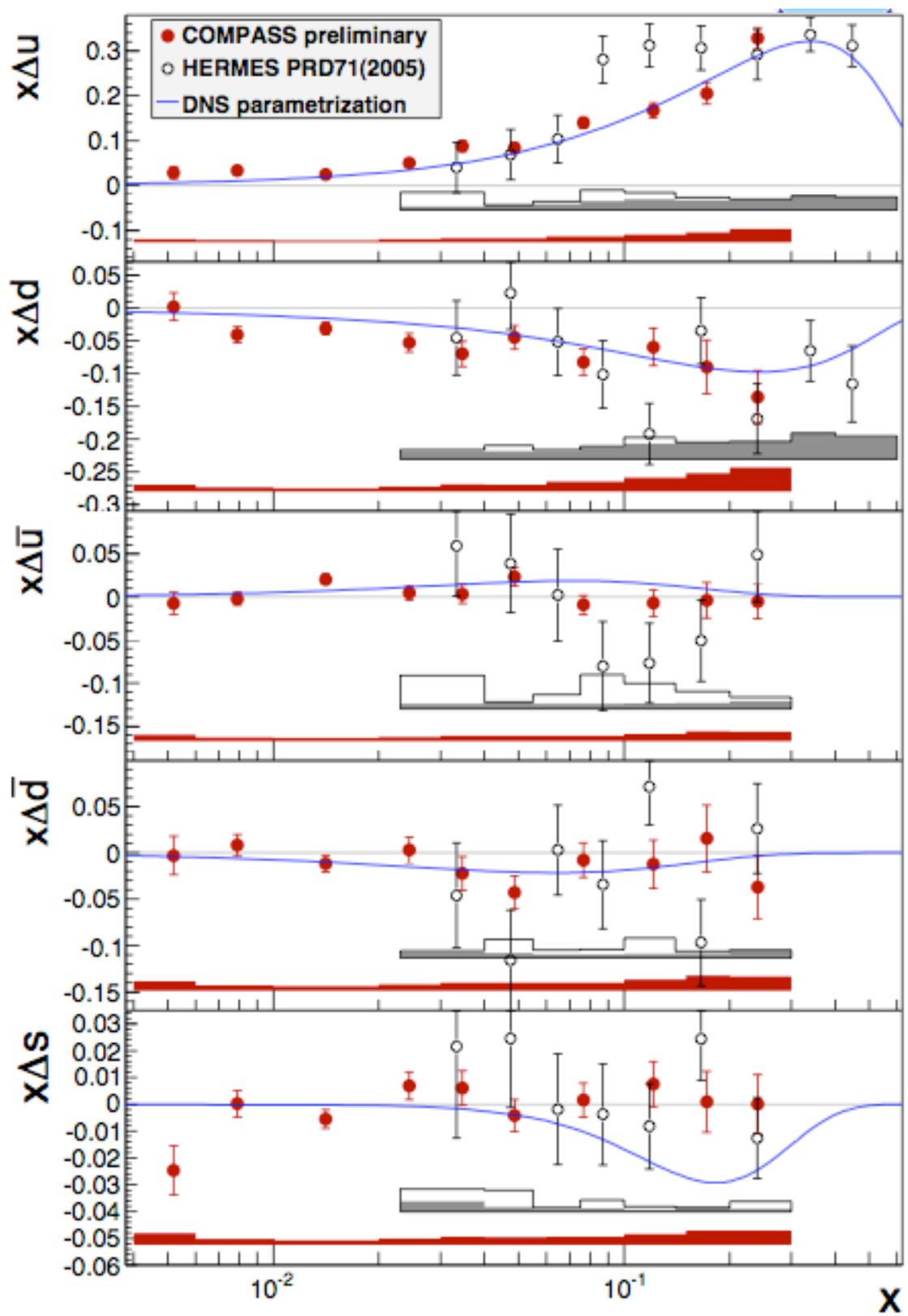




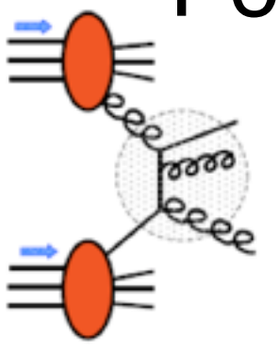
Semi-Inclusive Polarized DIS - 2009



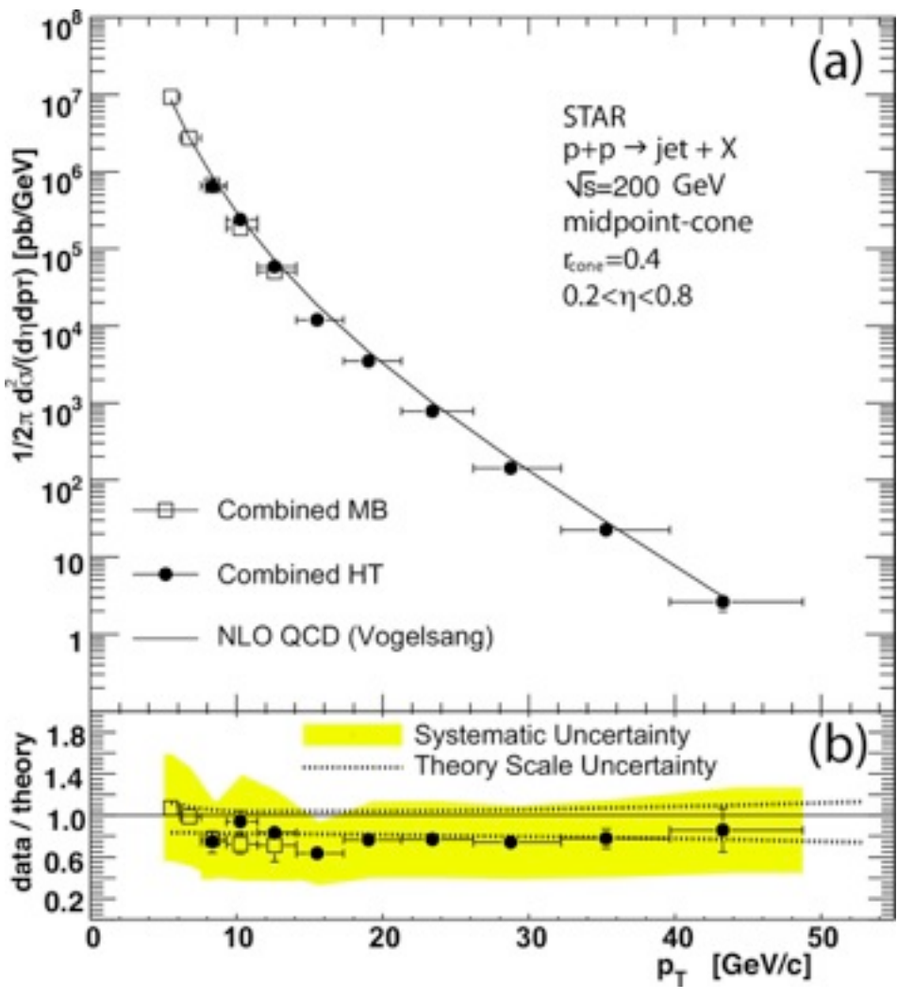
SIDIS



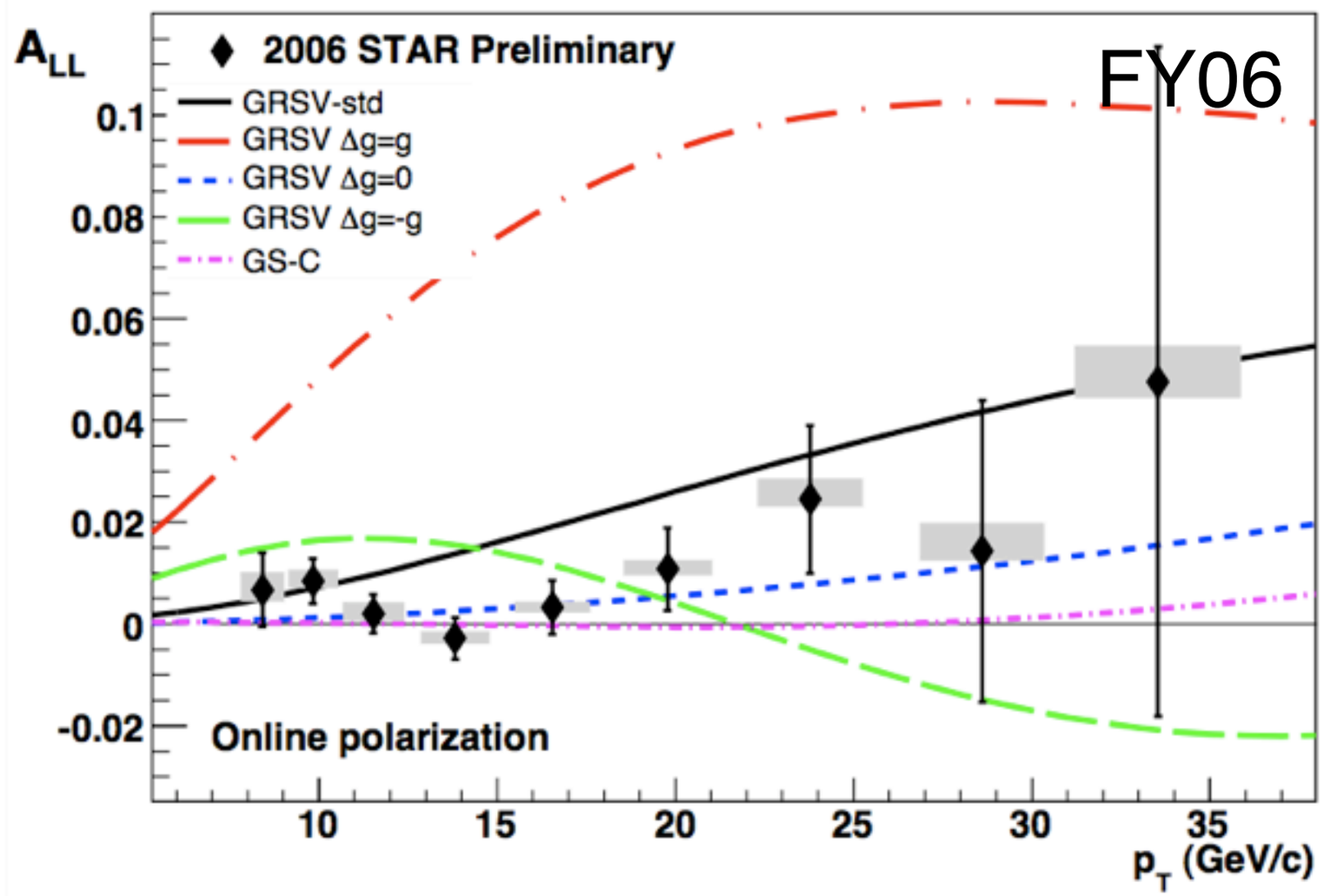
Polarized Proton+Proton Collisions at RHIC - 2009



hadron-hadron

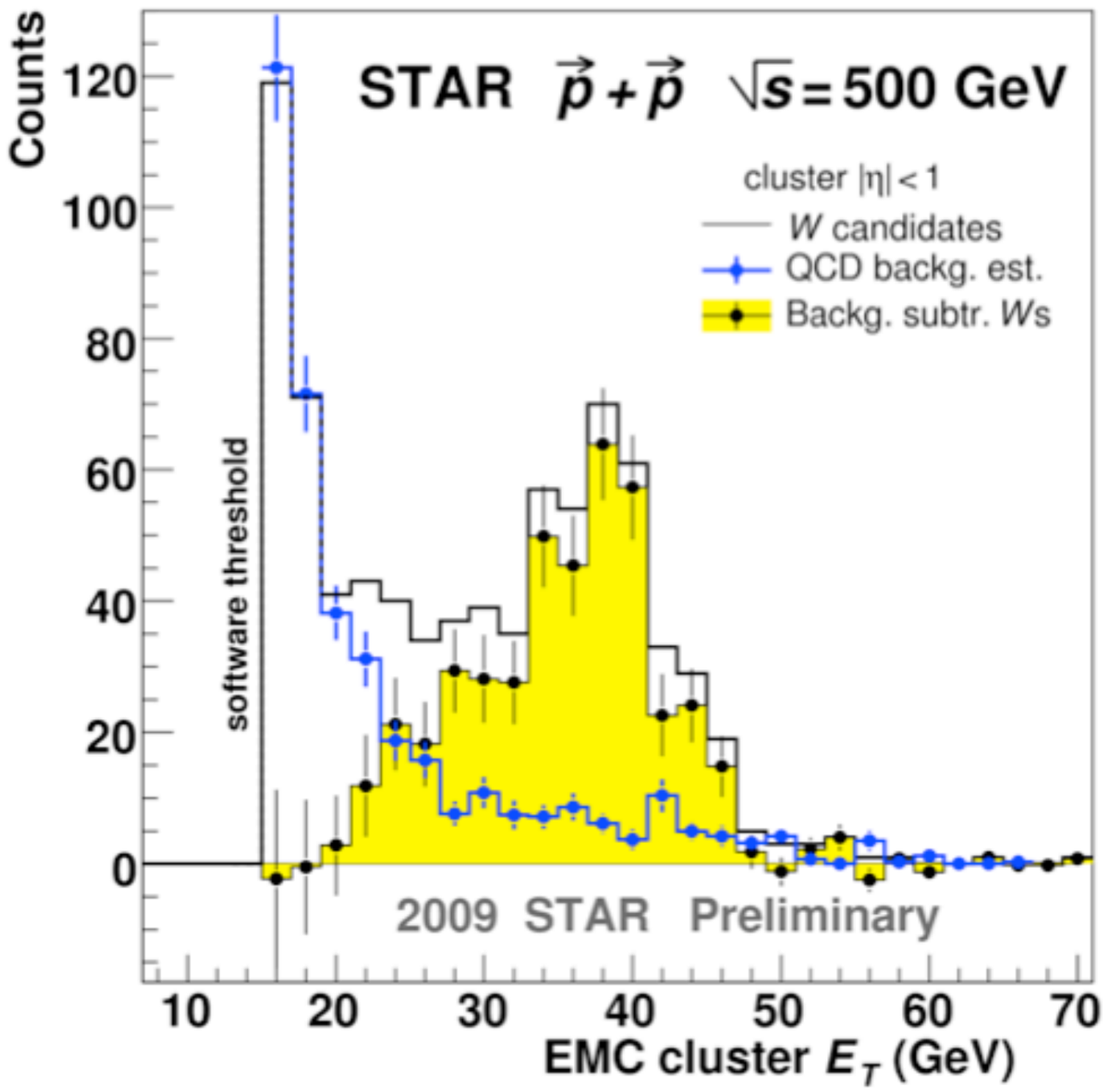


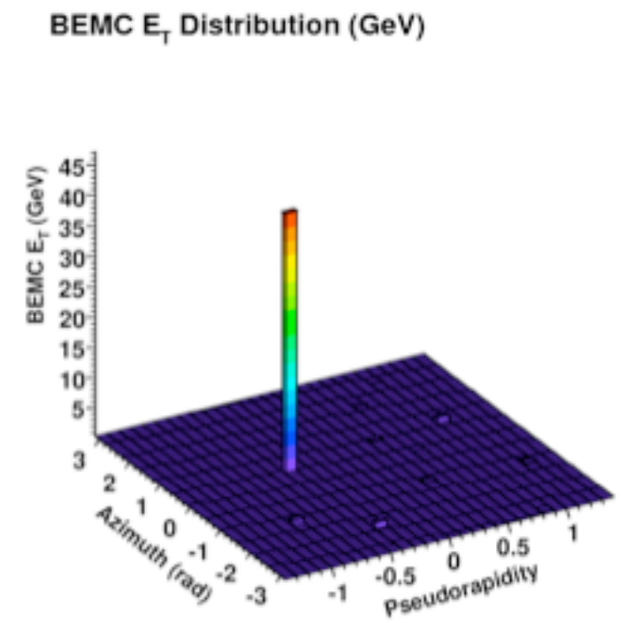
Inclusive jet production

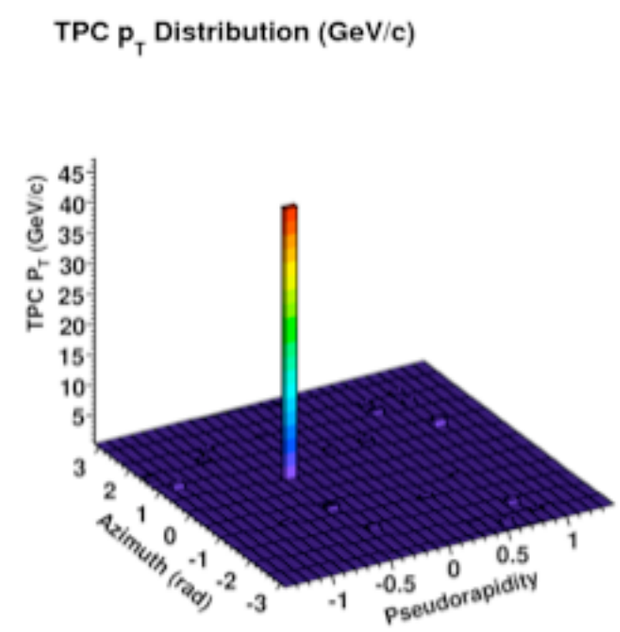


Primary goal: insight in gluon polarization using known quark polarizations

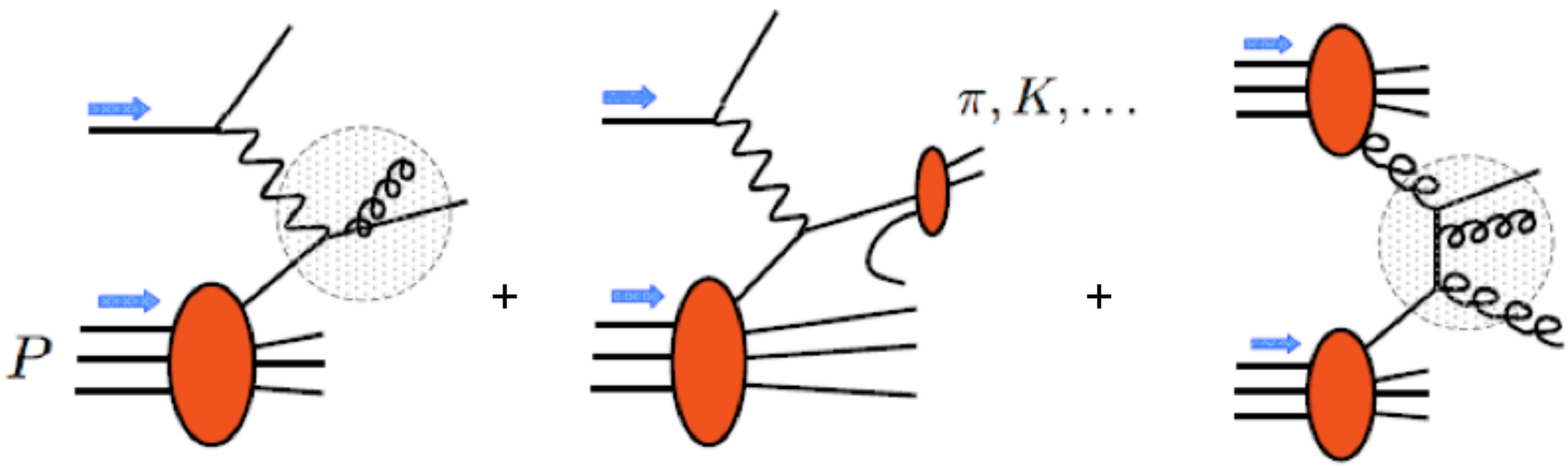
500 GeV - Early (2009) Data





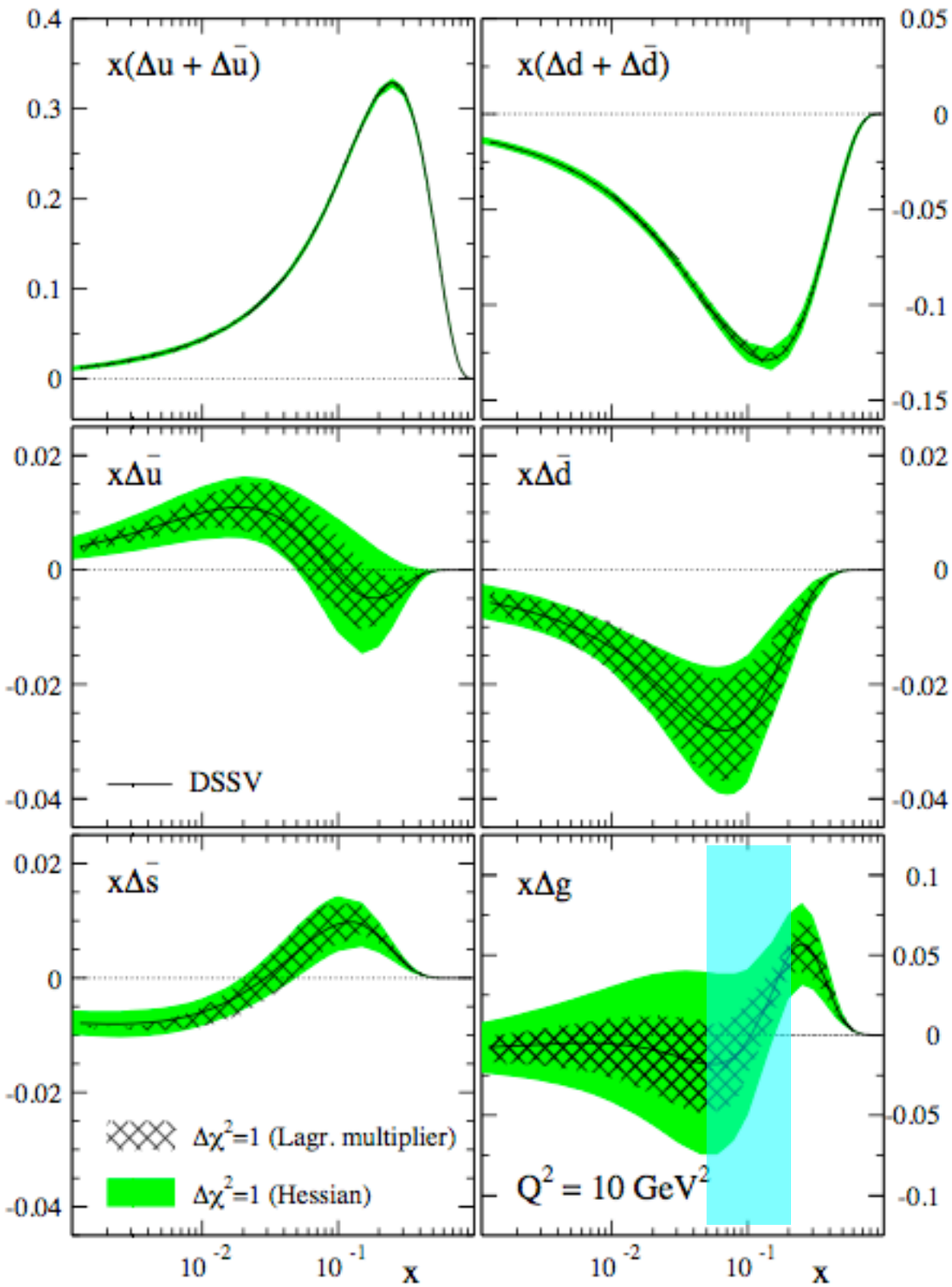


Present Picture of Nucleon Spin



DIS SIDIS hadron-hadron

Present Picture of Nucleon Spin



Approximate kinematic range of STAR jet data

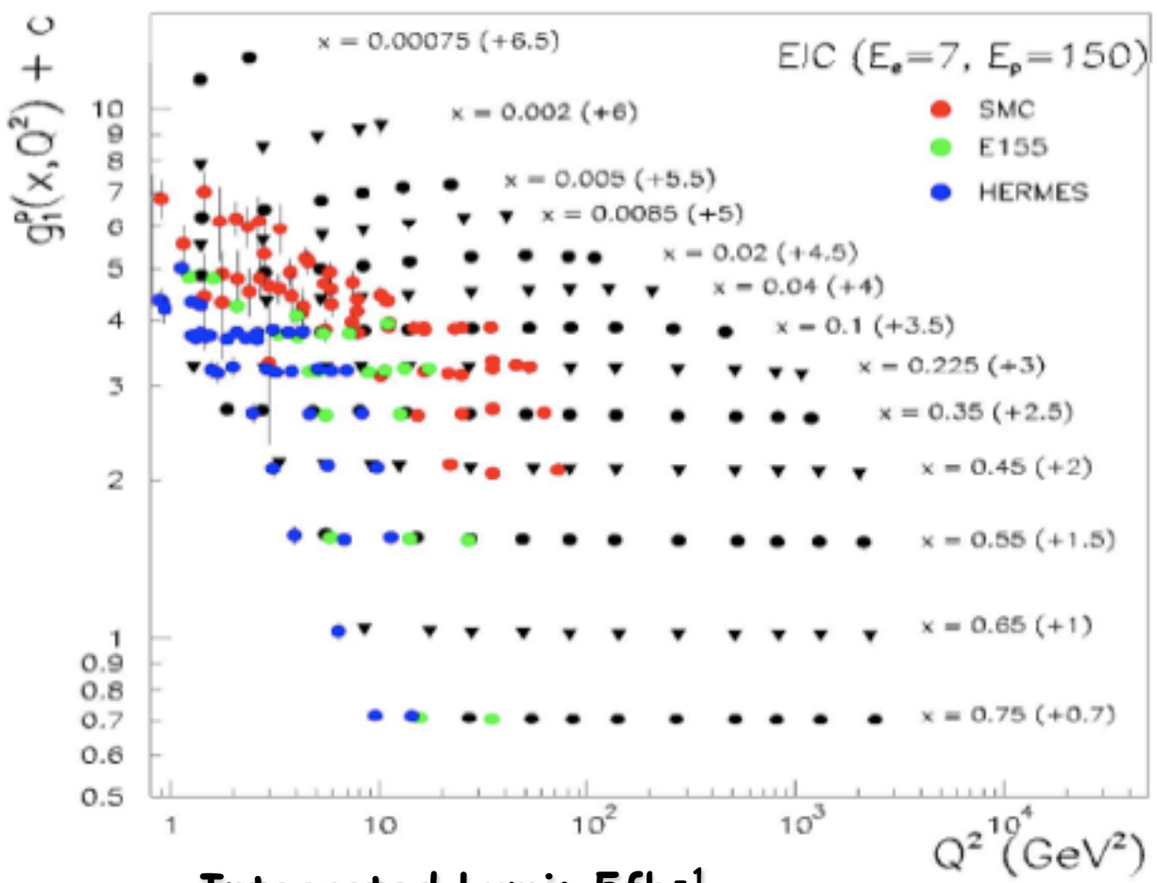
D. de Florian et al, Phys. Rev. Lett. 101:072001 (2008) and arXiv:0904.3821 [hep-ph],

"State-of-the-art": only polarized analysis that incorporates DIS, SIDIS, and RHIC data,

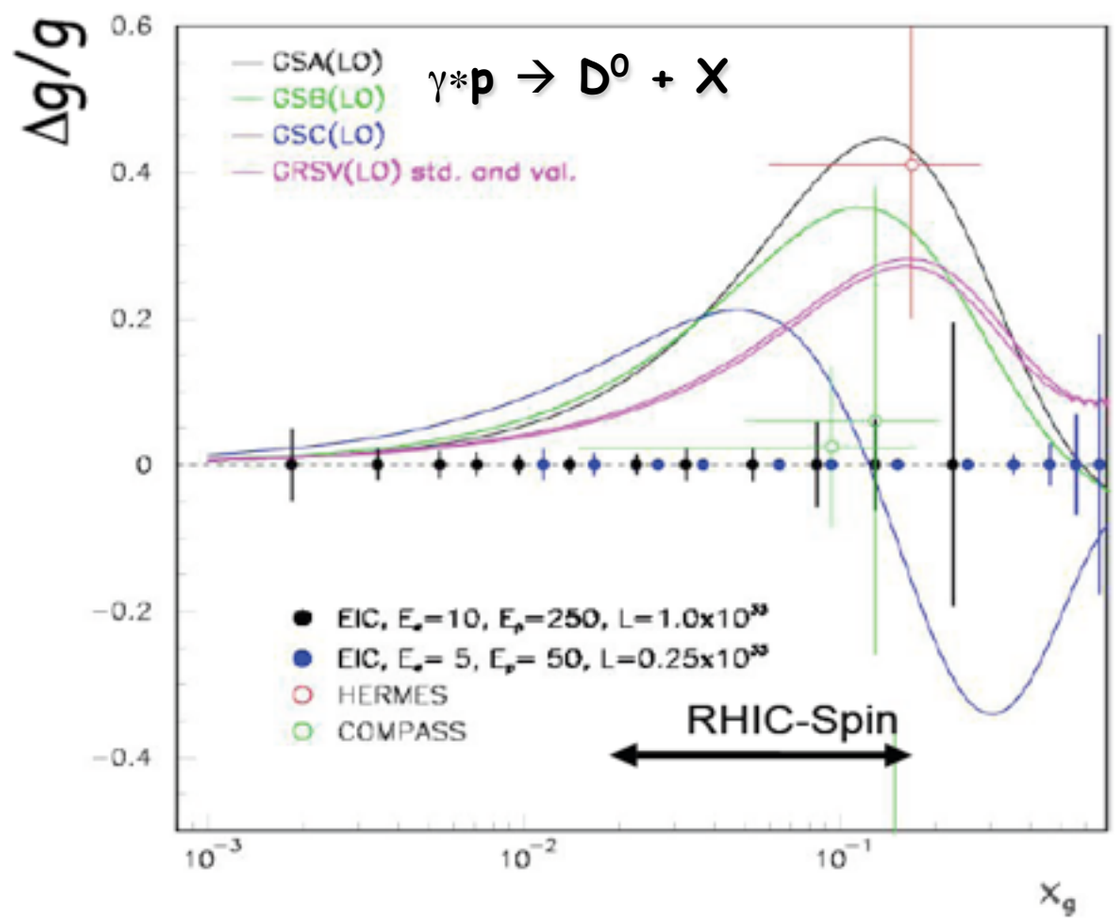
Quark + anti-quark distributions are well determined by DIS data; up quark spins preferentially point along the proton spin, whereas down quarks oppose it,

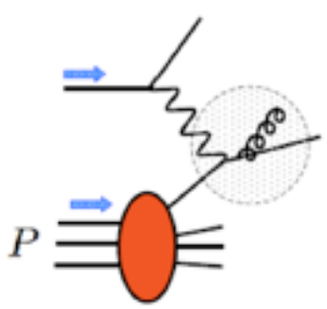
EIC role for sea quark and gluon polarizations; note in particular the nodes in the light-cone momentum fraction *x*

Role of a Polarized EIC



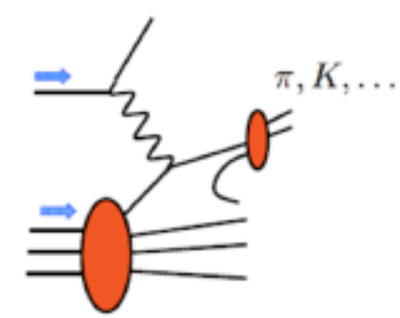
Integrated Lumi: 5fb^{-1}





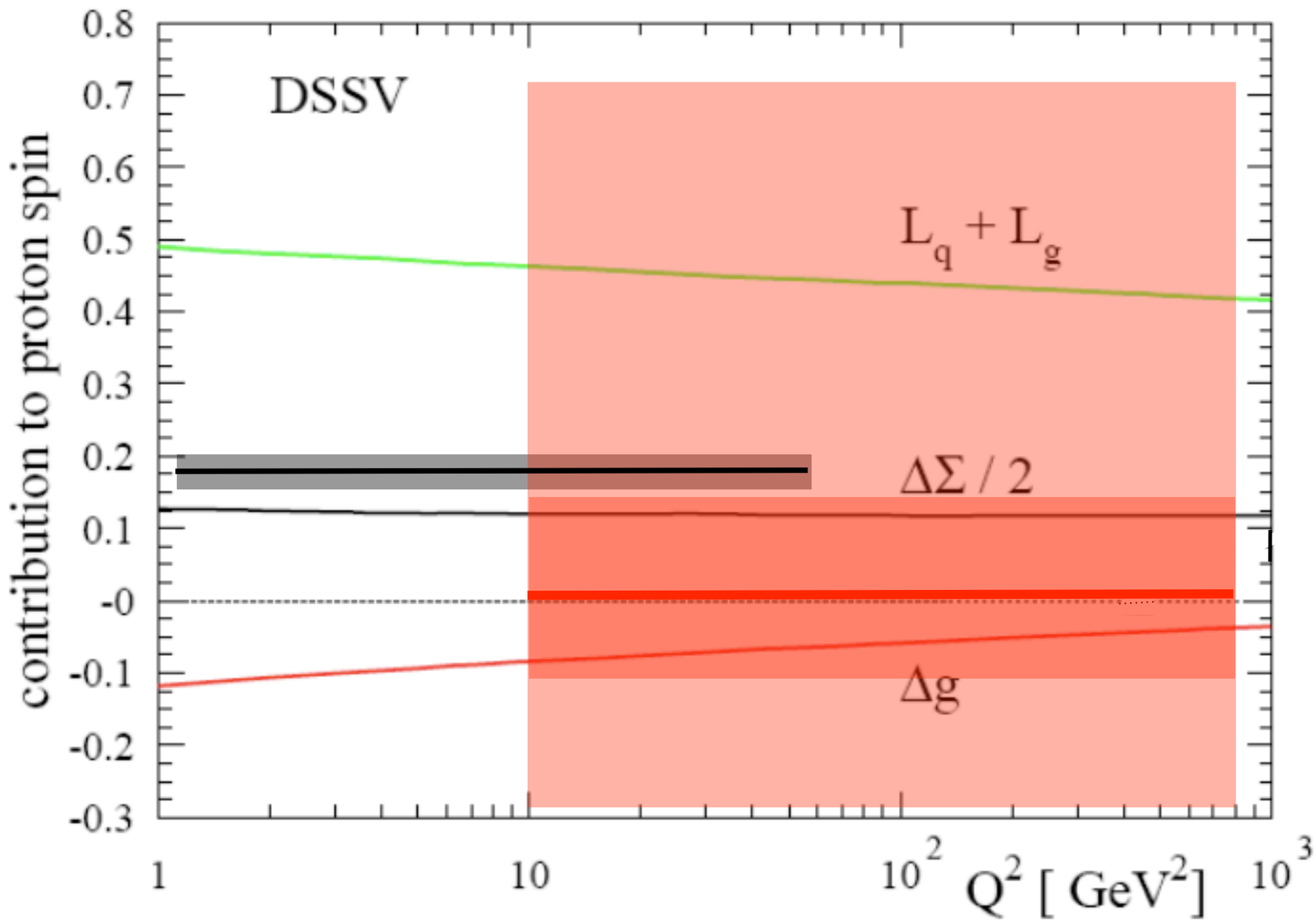
DIS

+



SIDIS

Present Picture of Proton Spin



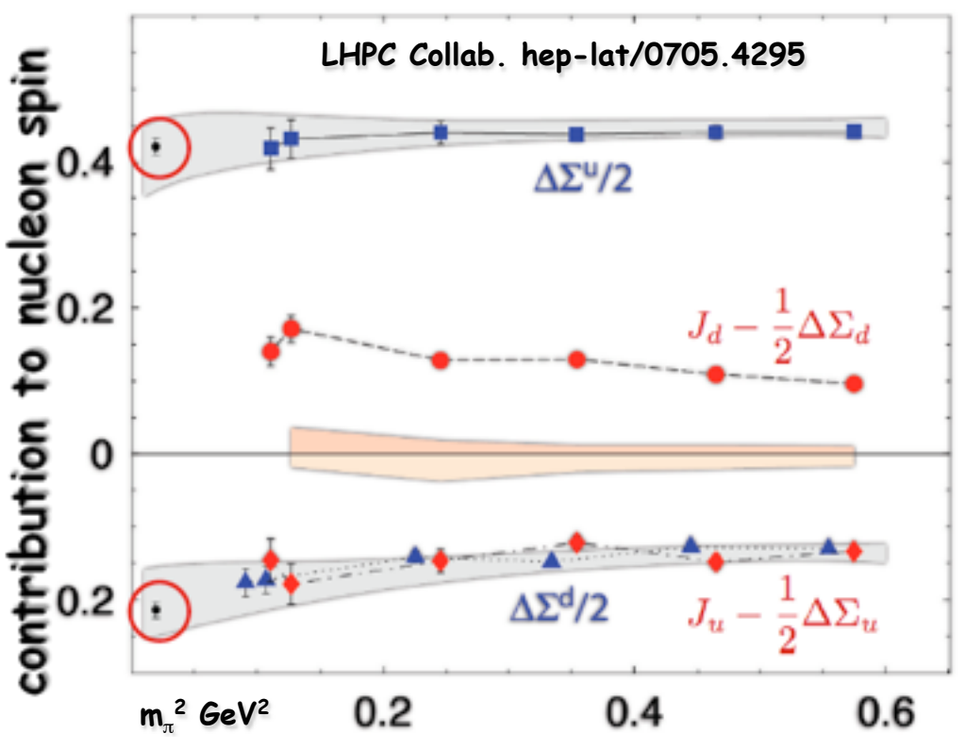
But, mind the uncertainties and extrapolations!

Is there (direct) evidence for orbital momenta?

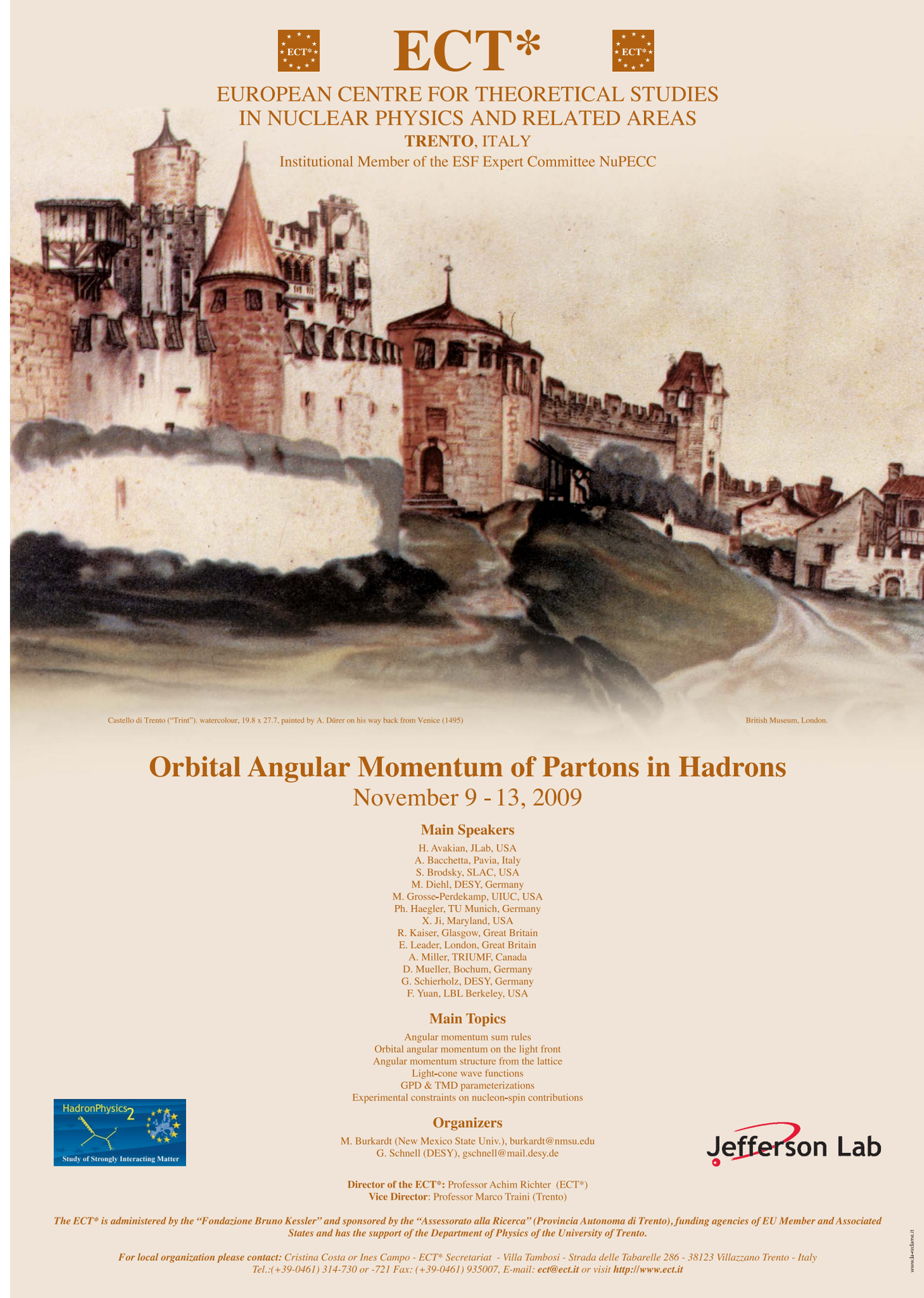
Orbital Angular Momenta

- *Possibly* related to large transverse spin phenomena observed at RHIC,

- *Rigorously* related to deeply virtual Compton scattering, pursued at the Jefferson Lab (for quarks) and in Lattice QCD:



- *I'll leave it to Feng to discuss at a future M3 :-)*



Concluding Remarks

Possibilities for electron-ion collisions are being studied at

LHC,

Brookhaven National Laboratory, using existing RHIC,

Jefferson Laboratory, using existing electron beam,

GSI

Overarching (NS) goal,

elucidate how QCD is the origin of observed matter;

how quark and gluon degrees of freedom form the coherent structures of nucleon structure and polarization, and nuclear structure,

Significant hurdles to get there,

discussed examples, F_L, eA, hadronization, spin,

not discussed e.g. diffraction, E.W.