Proton Structure and Insights from RHIC

Ernst Sichtermann

UCB PHY290E
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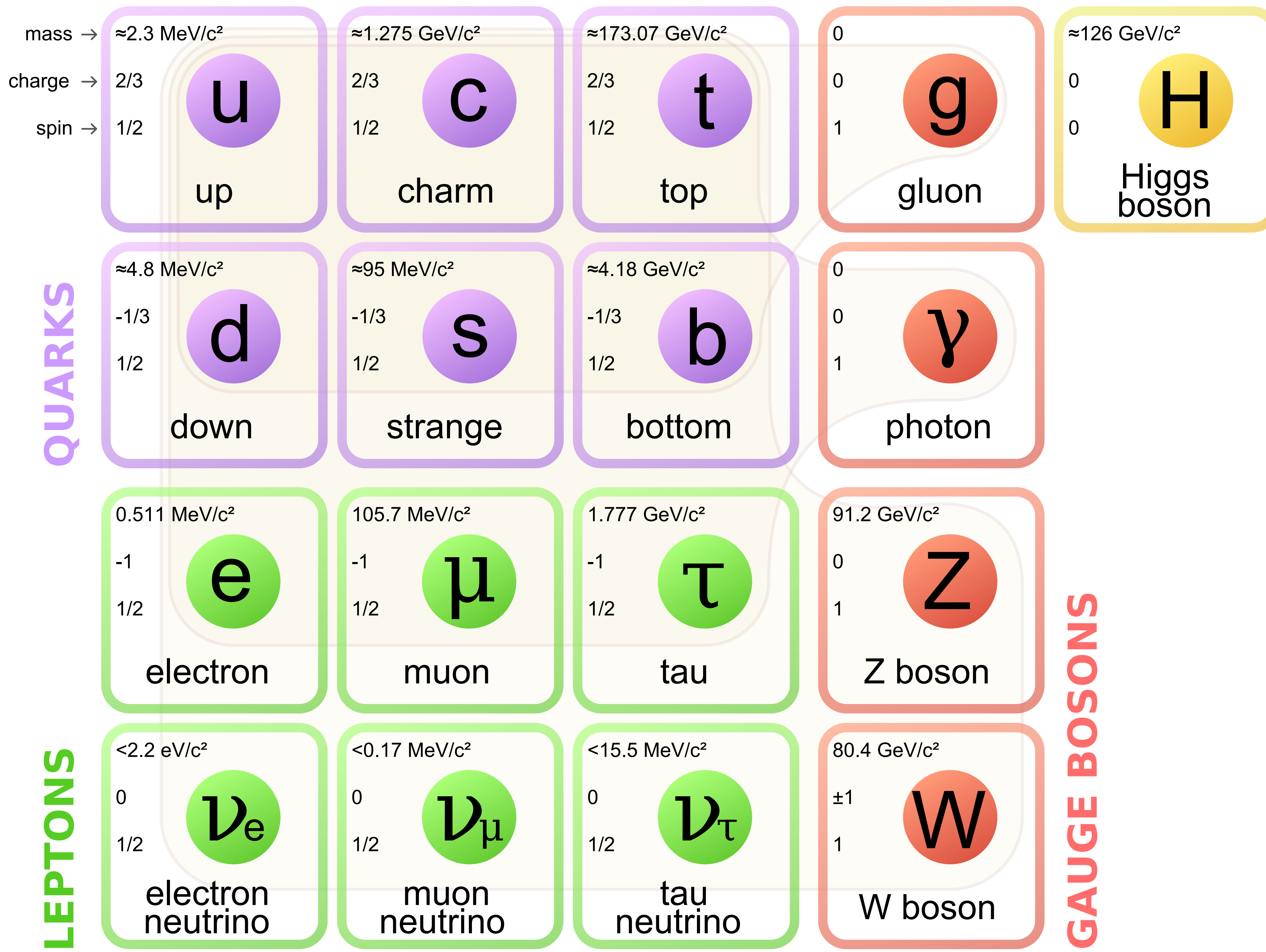
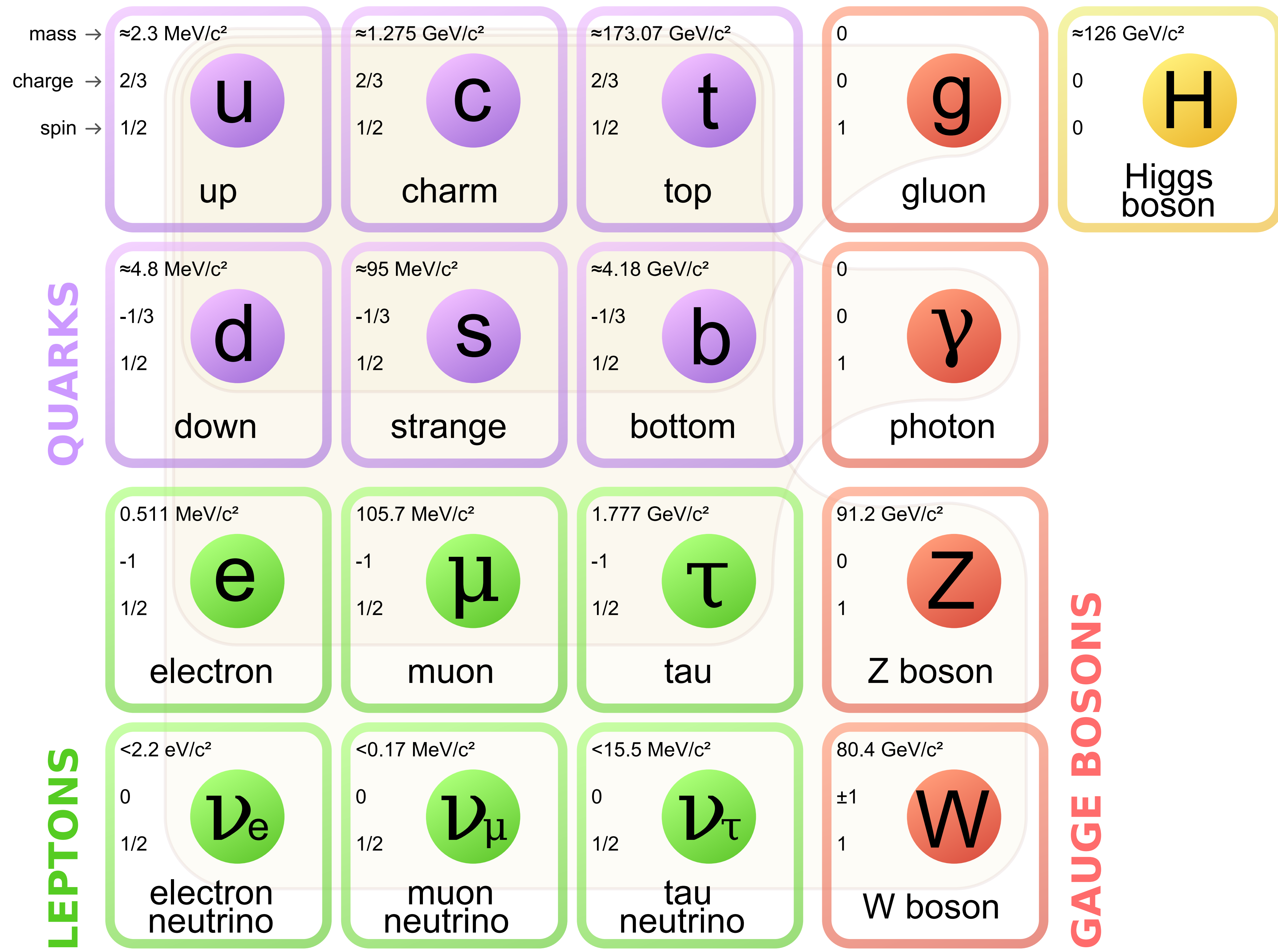

mass →
charge →
spin →
≈2.3 MeV/c²
2/3
1/2
u
up
≈1.275 GeV/c²
2/3
1/2
c
charm
≈173.07 GeV/c²
2/3
1/2
t
top
0
0
1
g
gluon
≈126 GeV/c²
0
0
H
Higgs boson
≈4.8 MeV/c²
-1/3
1/2
d
down
≈95 MeV/c²
-1/3
1/2
s
strange
≈4.18 GeV/c²
-1/3
1/2
b
bottom
0
0
1
γ
photon
0.511 MeV/c²
-1
1/2
e
electron
105.7 MeV/c²
-1
1/2
μ
muon
1.777 GeV/c²
-1
1/2
τ
tau
91.2 GeV/c²
0
1
Z
Z boson
<2.2 eV/c²
0
1/2
νe
electron neutrino
<0.17 MeV/c²
0
1/2
νμ
muon neutrino
<15.5 MeV/c²
0
1/2
ντ
tau neutrino
80.4 GeV/c²
±1
1
W
W boson
QUARKS
LEPTONS
GAUGE BOSONS



Today's discussion will be about (light) quarks, gluons, and their (color-)interactions.

Color in QCD

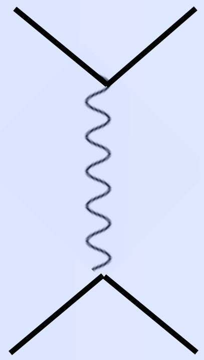
Color at sub-nucleonic scales, ~10^{-15}m

Just three?

Consider (electro-)production of muons and “hadrons”,

$$e^+ + e^- \to \mu^+ + \mu^-$$

$$e^+ + e^- \to q + \bar{q}$$



The same diagram!

Now, consider the cross-section ratio:

$$R = \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)} = n_{\text{color}} \sum_{\text{flavor}} Q_f^2$$

as a function of energy.

For the three light flavors,

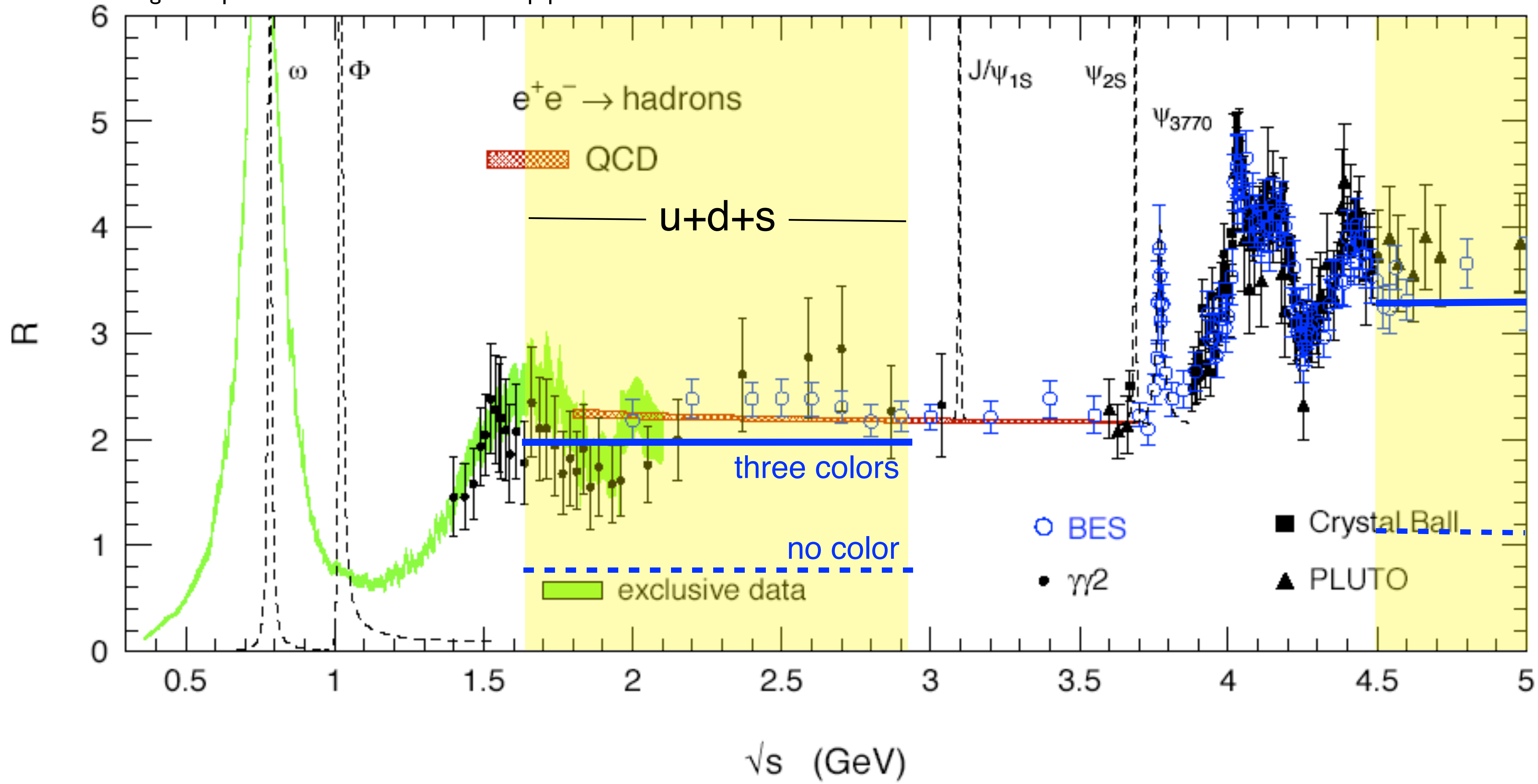
$$R = n_{\text{color}} \left[\left(\frac{2}{3}\right)^2 + \left(-\frac{1}{3}\right)^2 + \left(-\frac{1}{3}\right)^2 \right] = n_{\text{color}} \cdot \frac{2}{3} = 2$$

Between the charm and beauty threshold,

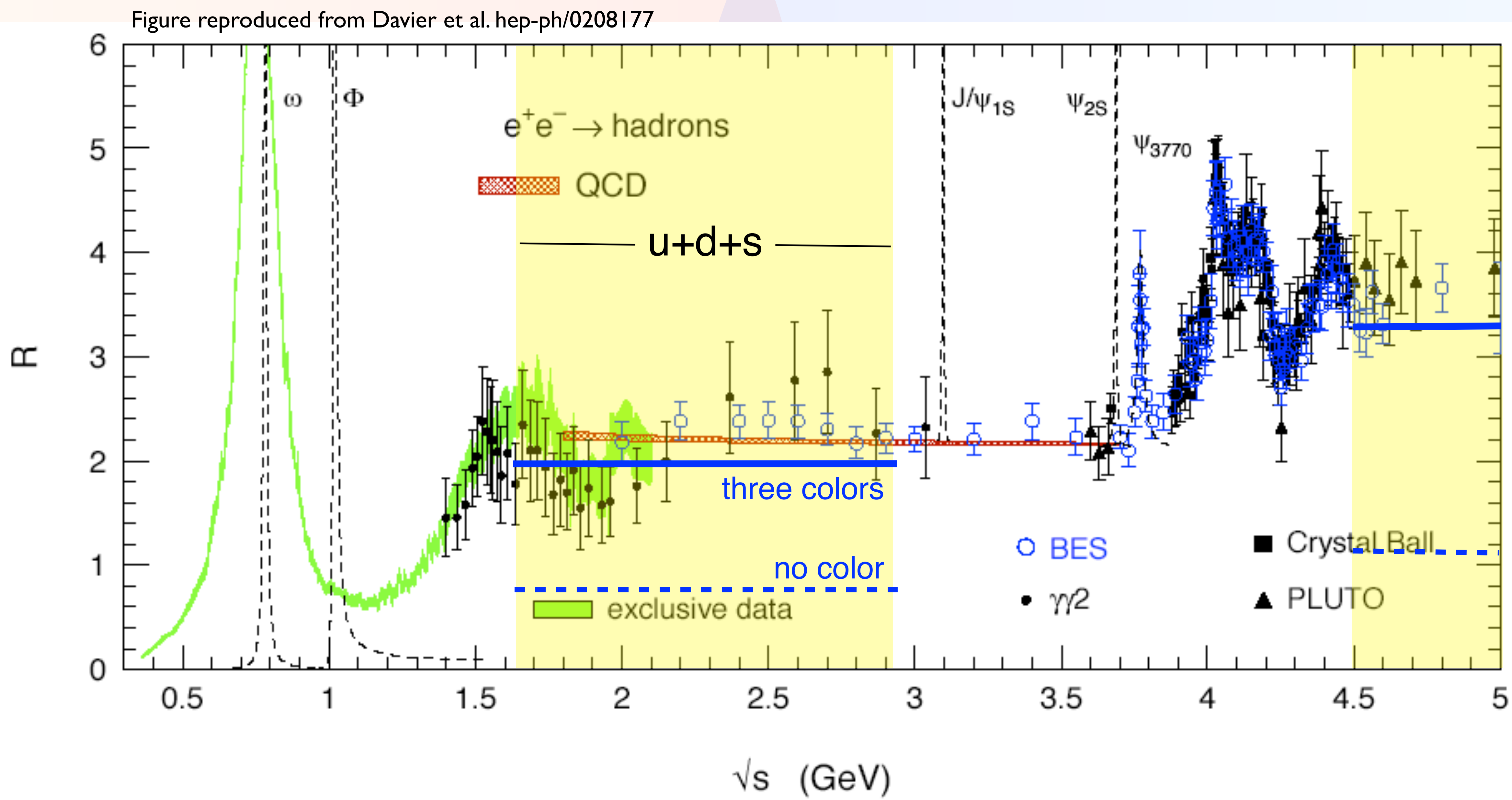
$$R = n_{\text{color}} \left[\left(\frac{2}{3}\right)^2 + \left(-\frac{1}{3}\right)^2 + \left(-\frac{1}{3}\right)^2 + \left(\frac{2}{3}\right)^2 \right] = \frac{10}{9} \cdot n_{\text{color}}$$

Data:

Figure reproduced from Davier et al. hep-ph/0208177



Data:



What about the fractional quark charges?

What about quark spins?

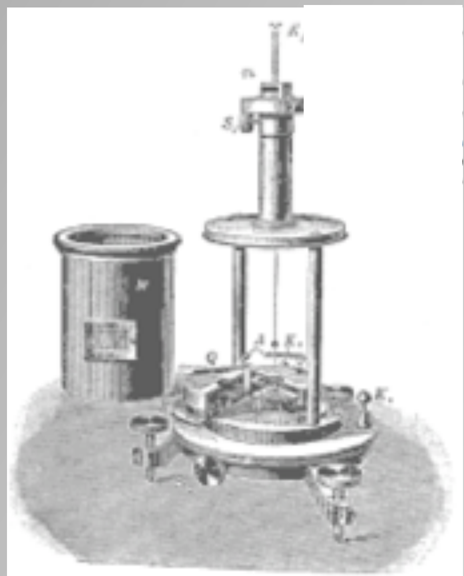
1. Deep-Inelastic Scattering

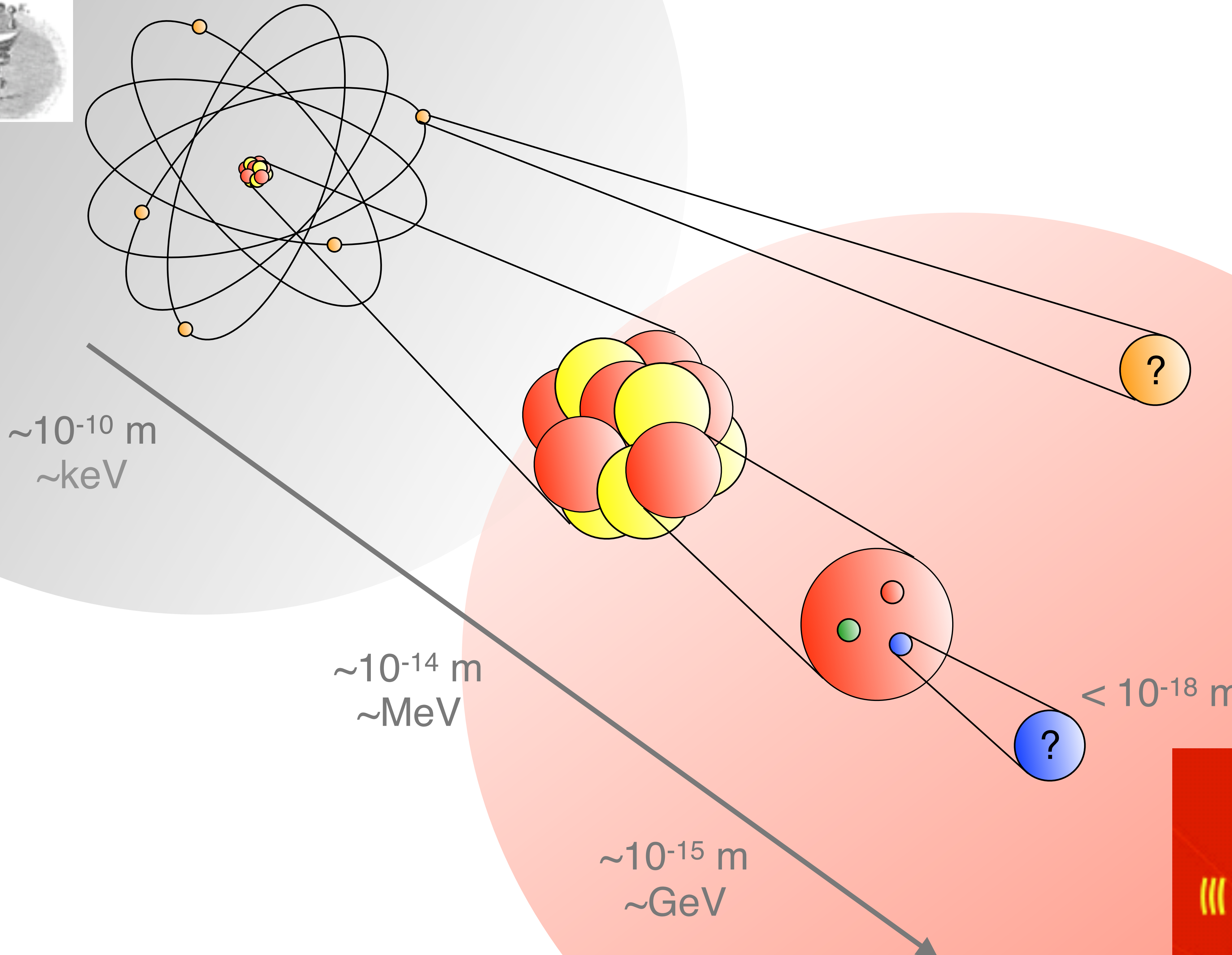
1. Deep-Inelastic Scattering

2. Insights from RHIC


1. Deep-Inelastic Scattering
3. A few words on EIC
2. Applications at RHIC

I - (Deep-Inelastic) Scattering

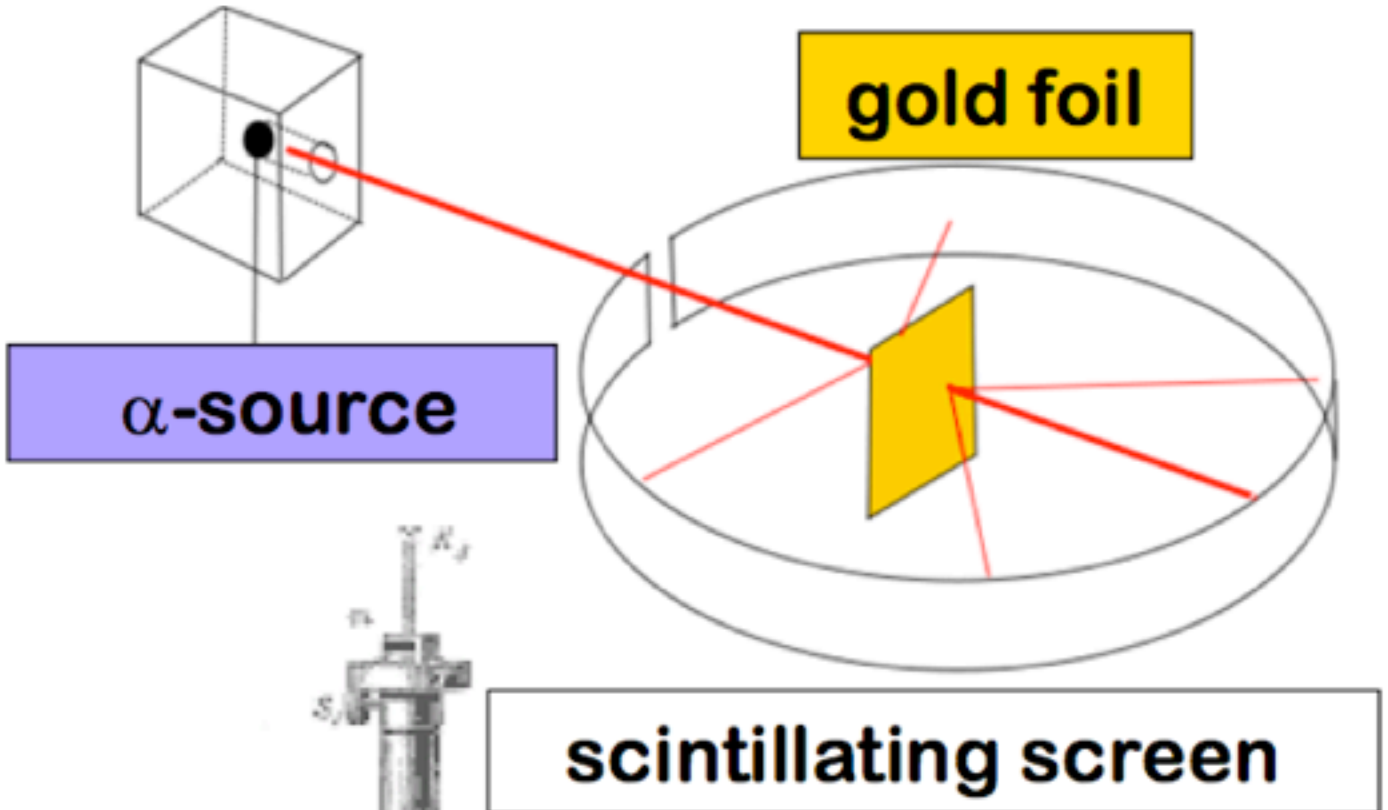


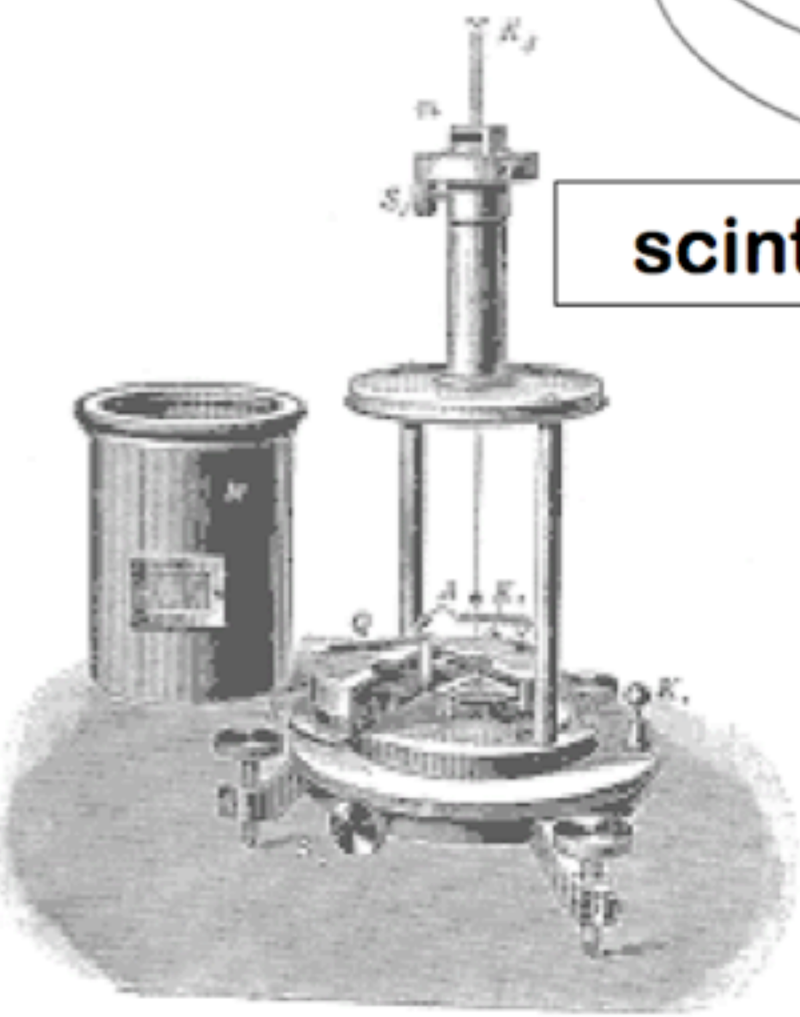


~10-10 m
~keV
~10-14 m
~MeV
~10-15 m
~GeV
< 10-18 m
?
?

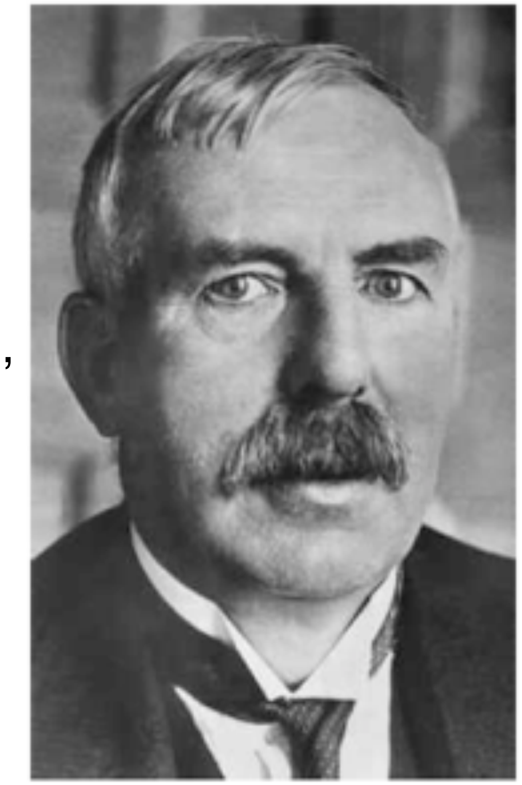
Rutherford Scattering

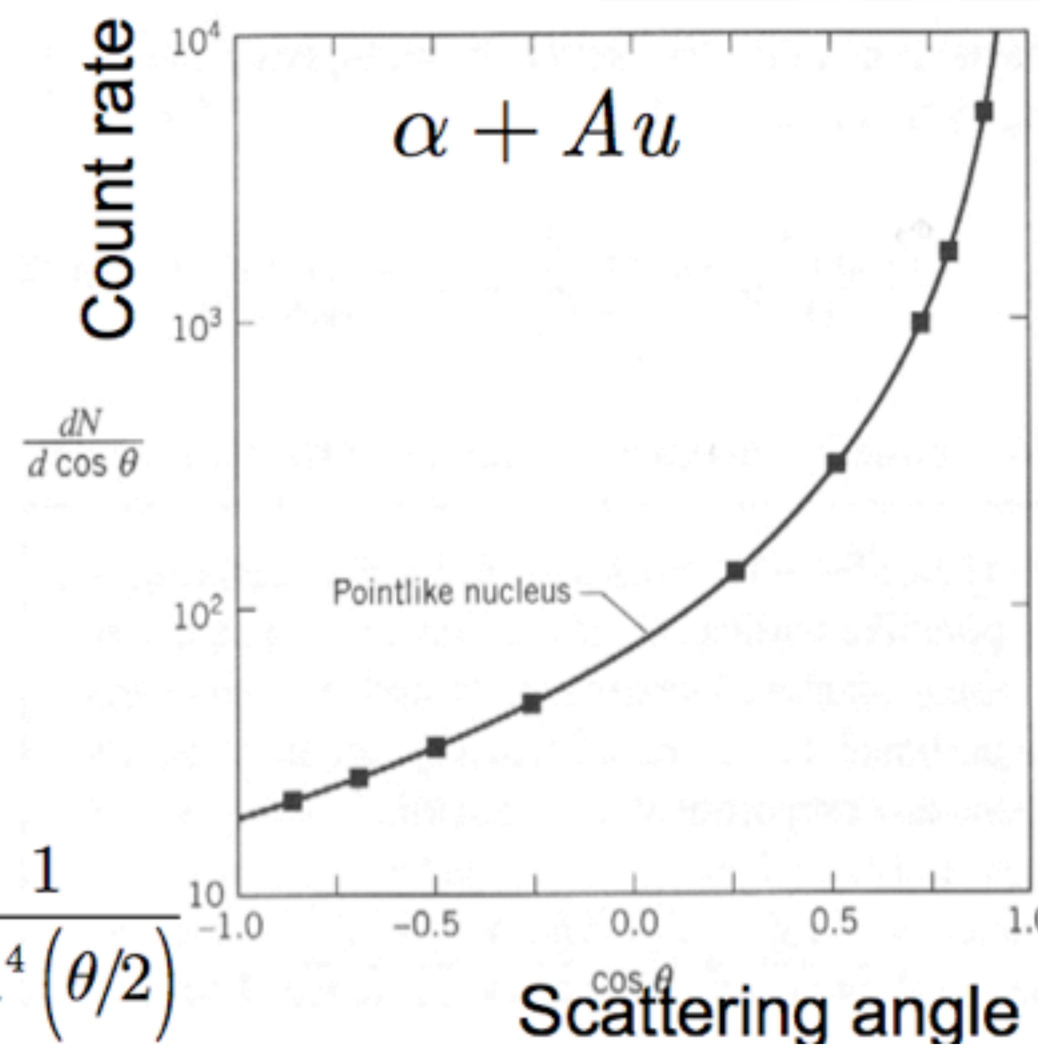
~5 MeV





Ernest Rutherford,
Nobel Prize 1908



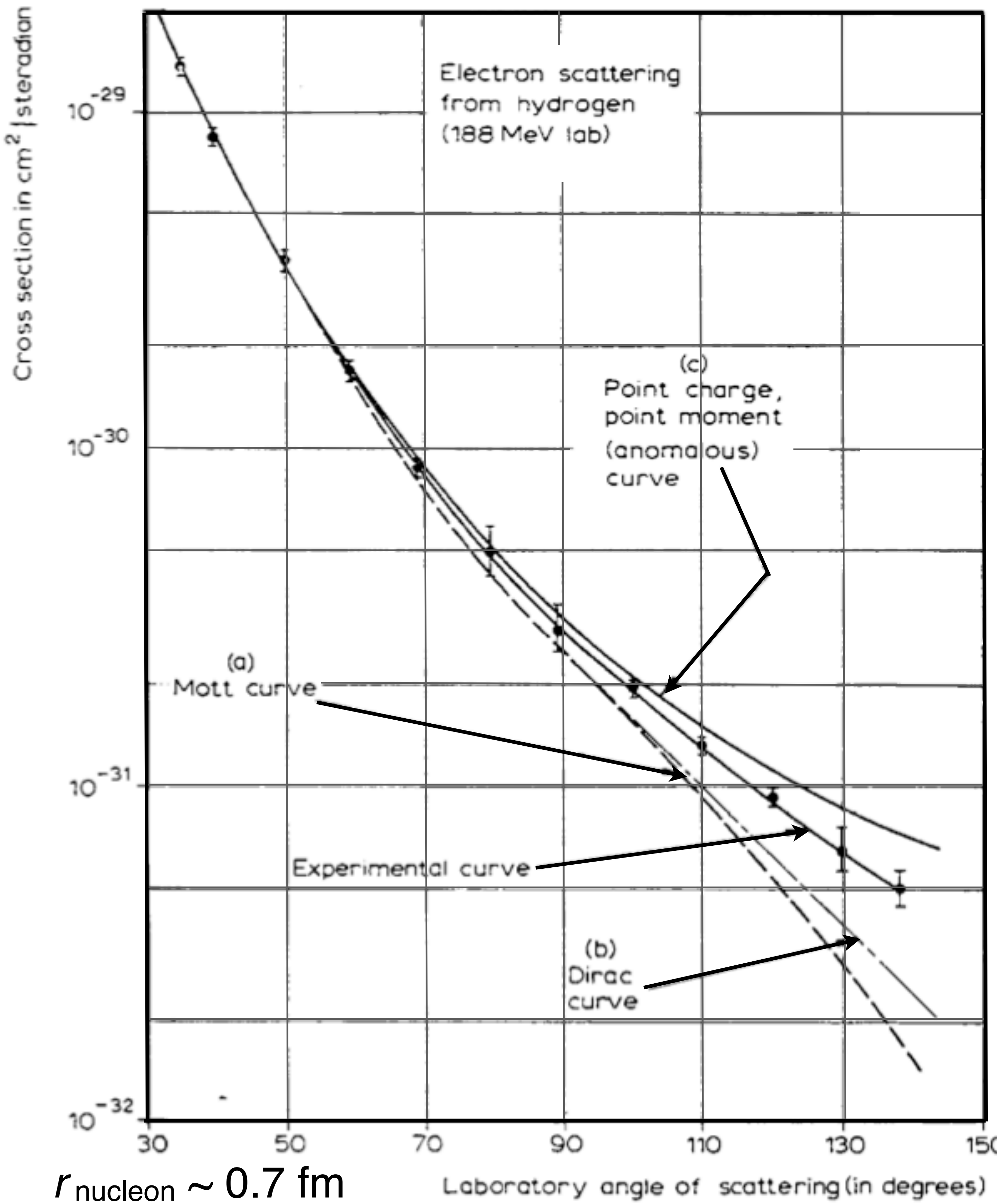


$$\frac{d\sigma}{d\Omega} = (zZ\alpha)^2 \left(\frac{\hbar c}{4E_{\text{kin}}}\right)^2 \frac{1}{\sin^4(\theta/2)}$$

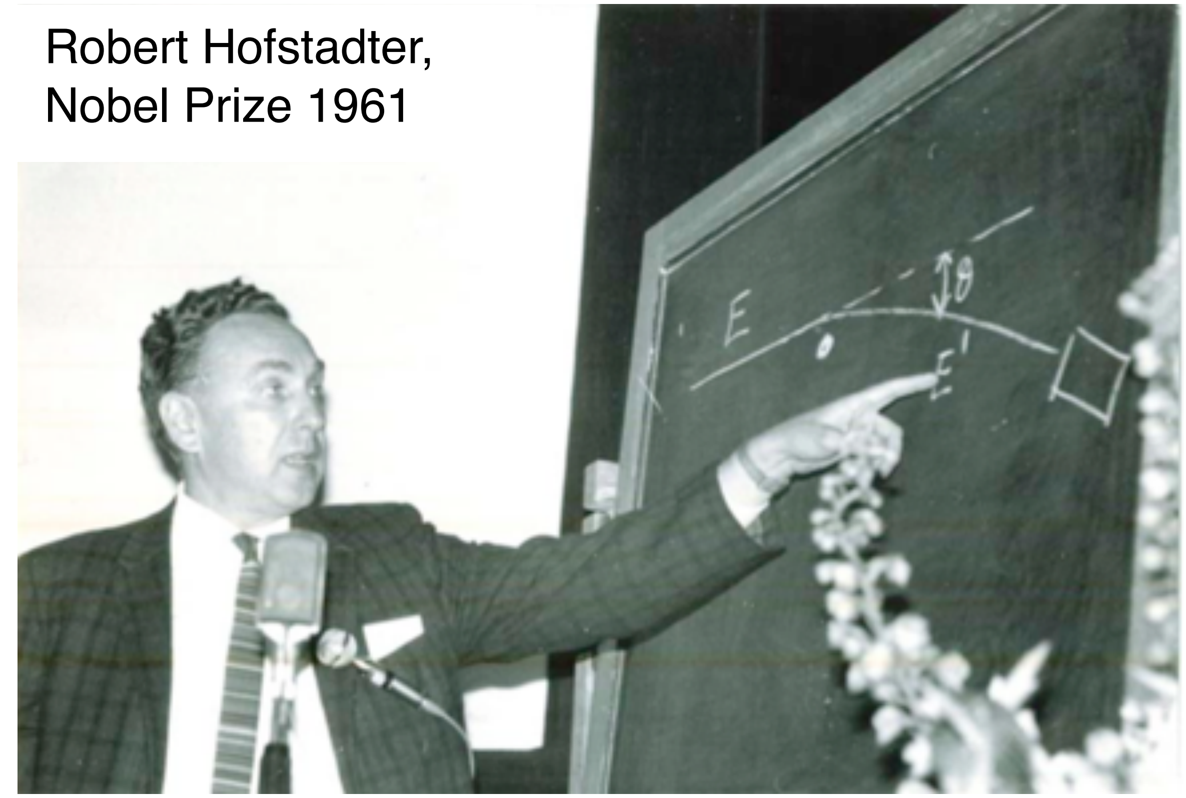
Scattering off a hard sphere; $r_{\text{nucleus}} \sim (10^{-4} \,.\, r_{\text{atom}}) \sim 10^{-14}$ m

Elastic Electron Scattering

~200 MeV



$r_{\text{nucleon}} \sim 0.7$ fm



Robert Hofstadter, Nobel Prize 1961

Scattering off a spin-1/2 Dirac particle:

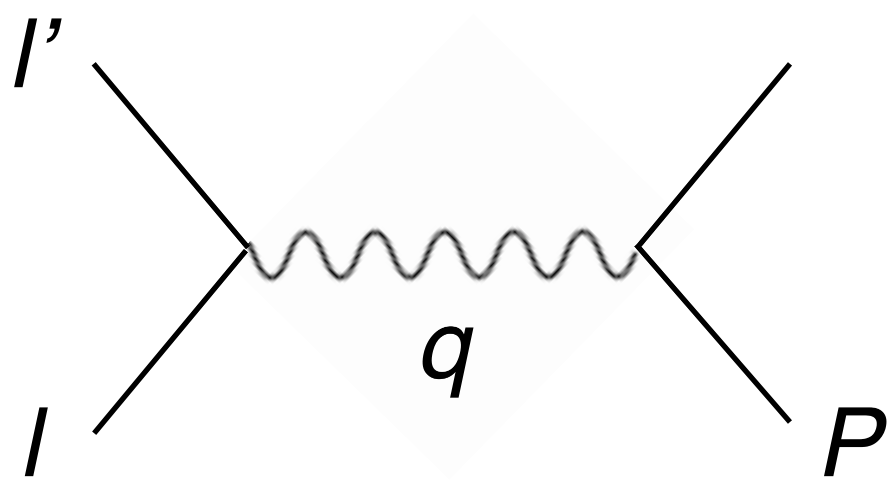
$$\frac{d\sigma}{d\Omega} = \left(\frac{\alpha}{4ME\sin^2(\theta/2)}\right)^2 \frac{E'}{E}\left[\frac{q^2}{2M}\sin^2(\theta/2) + \cos^2(\theta/2)\right]$$

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-averaged, parity conserved) form is:

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

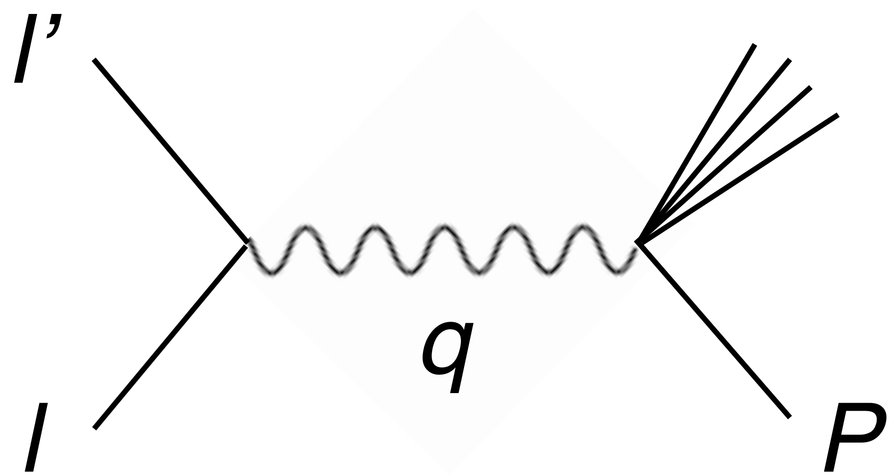
Charge conservation at the proton vertex reduces the number of structure functions:

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

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

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

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, <u>two</u> (parity-conserving, spin-averaged) structure functions:

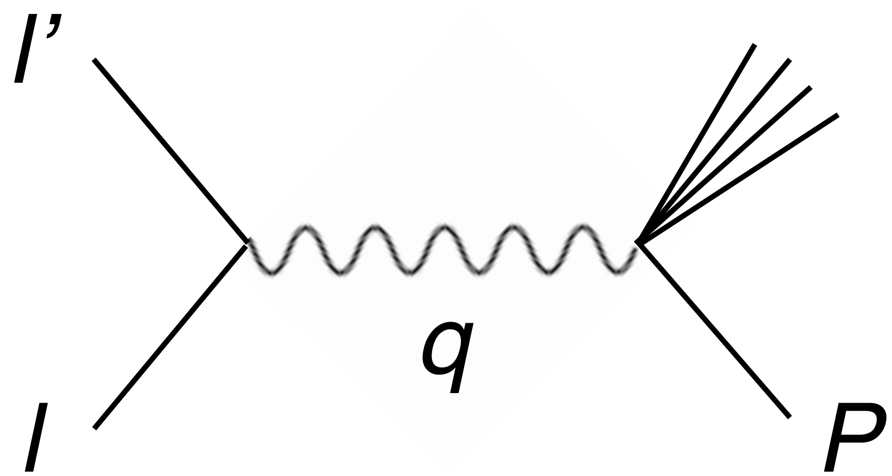
$$W_1, W_2 \;\; \text{or, alternatively expressed,} \;\; F_1, F_2$$

which may depend on <u>two</u> invariants,

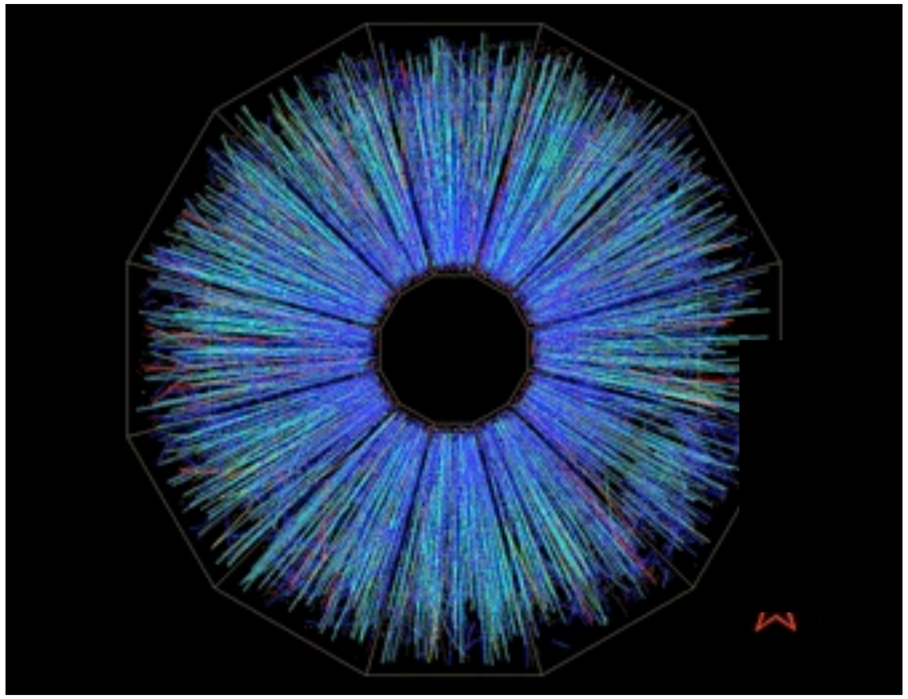
$$Q^2 = -q^2, \qquad x = -\frac{q^2}{2q.p}, \;\; 0 < x < 1$$

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

Inelastic Scattering



Not convinced of additional complexity?



Then forget this talk, and calculate this!

Simplify - consider *inclusive* inelastic scattering,

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

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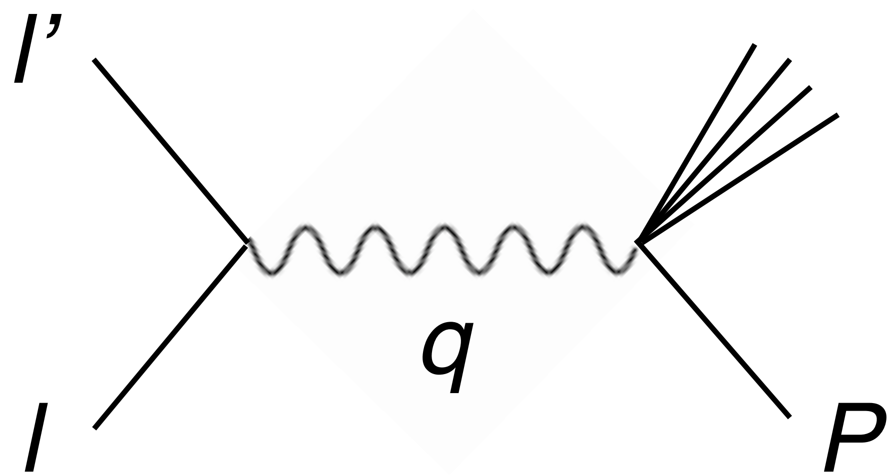
Inelastic Scattering



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So much for the structure, <u>the physics is in the structure functions.</u>

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 $K_{4,5}$

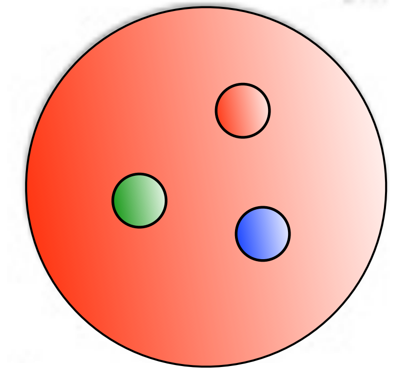
Then, e.g. by substitution of $k' = k-q$ in L:

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

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

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

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

Now,

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

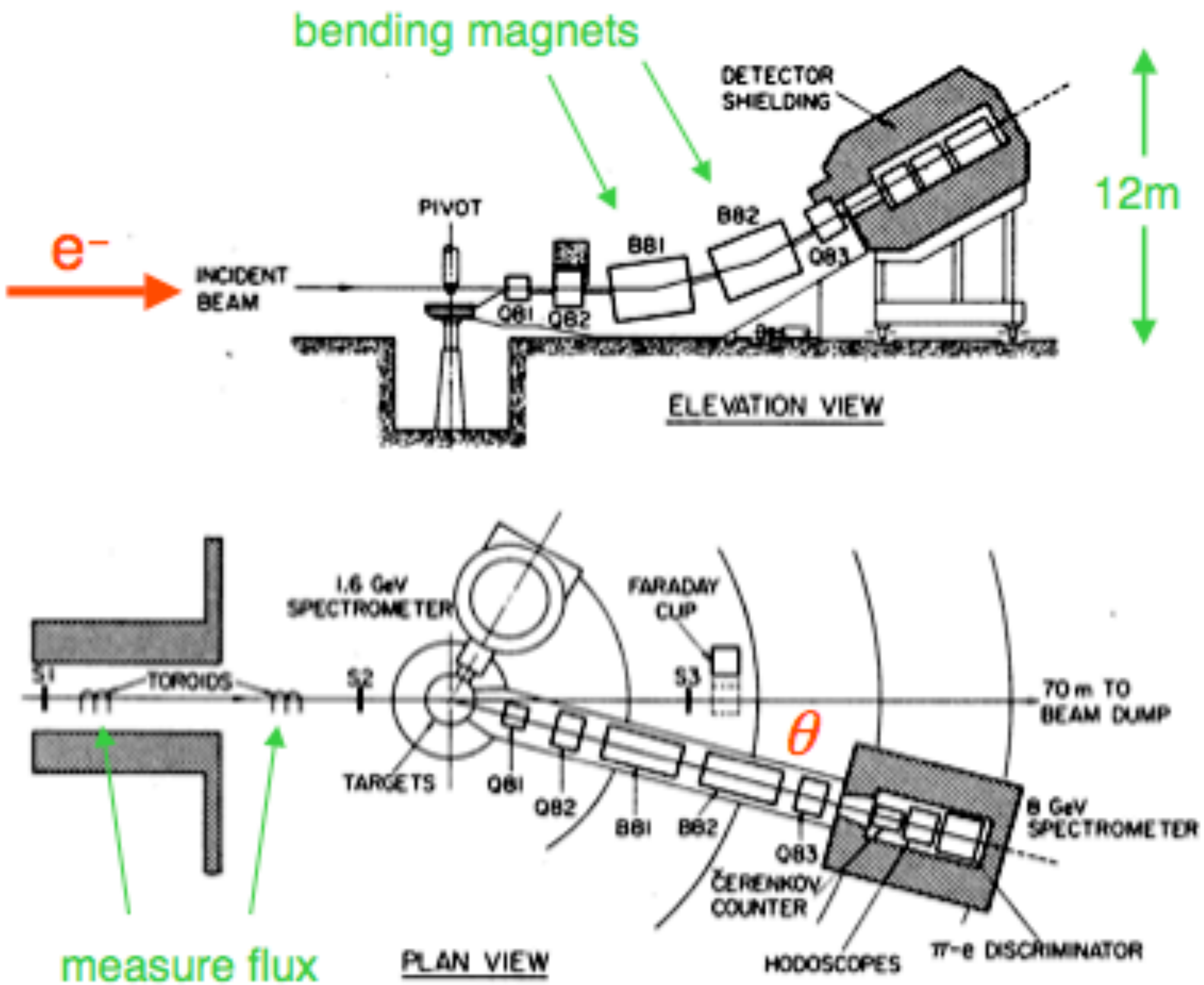
$$-\frac{q^2}{2Mx}W_2 = \ldots\int_0^1 x e_q^2 \delta(x - z_q)\, f_q(z_q)\, dz_q = x\sum_q e_q^2 f_q(x) \equiv F_2(x)$$

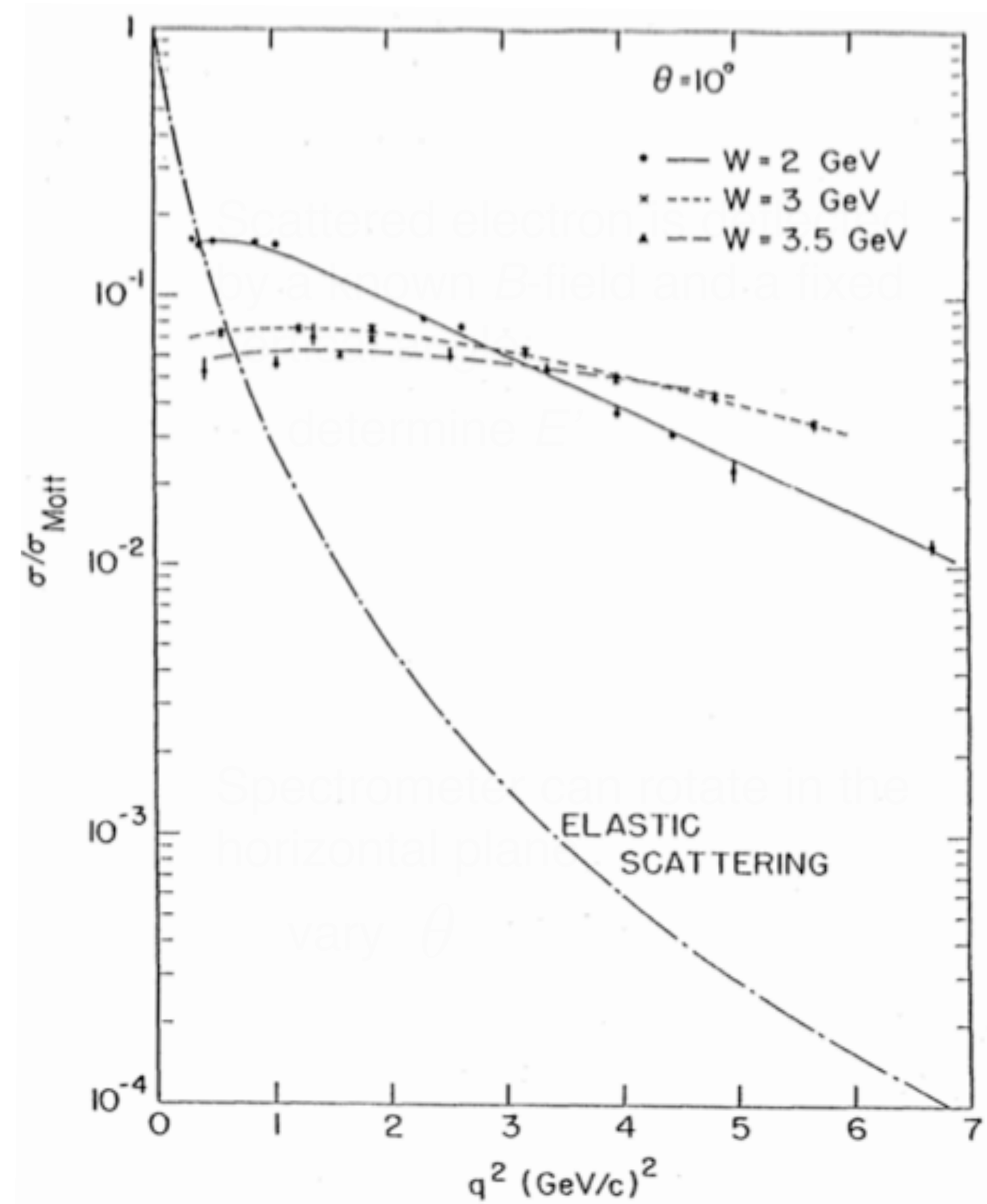
Two important *observable* consequences,

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

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

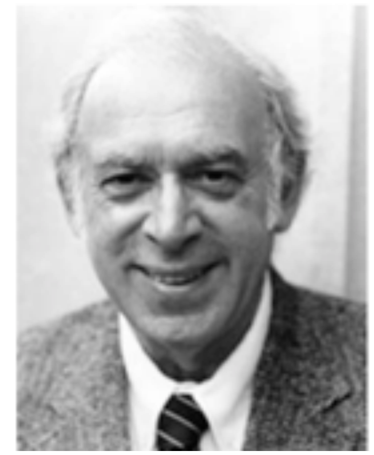
~10 GeV *Deep-Inelastic* Electron Scattering





e.g. J.T.Friedman and H.W. Kendall, Ann.Rev.Nucl.Sci. 22 (1972) 203

Deep-Inelastic Electron Scattering

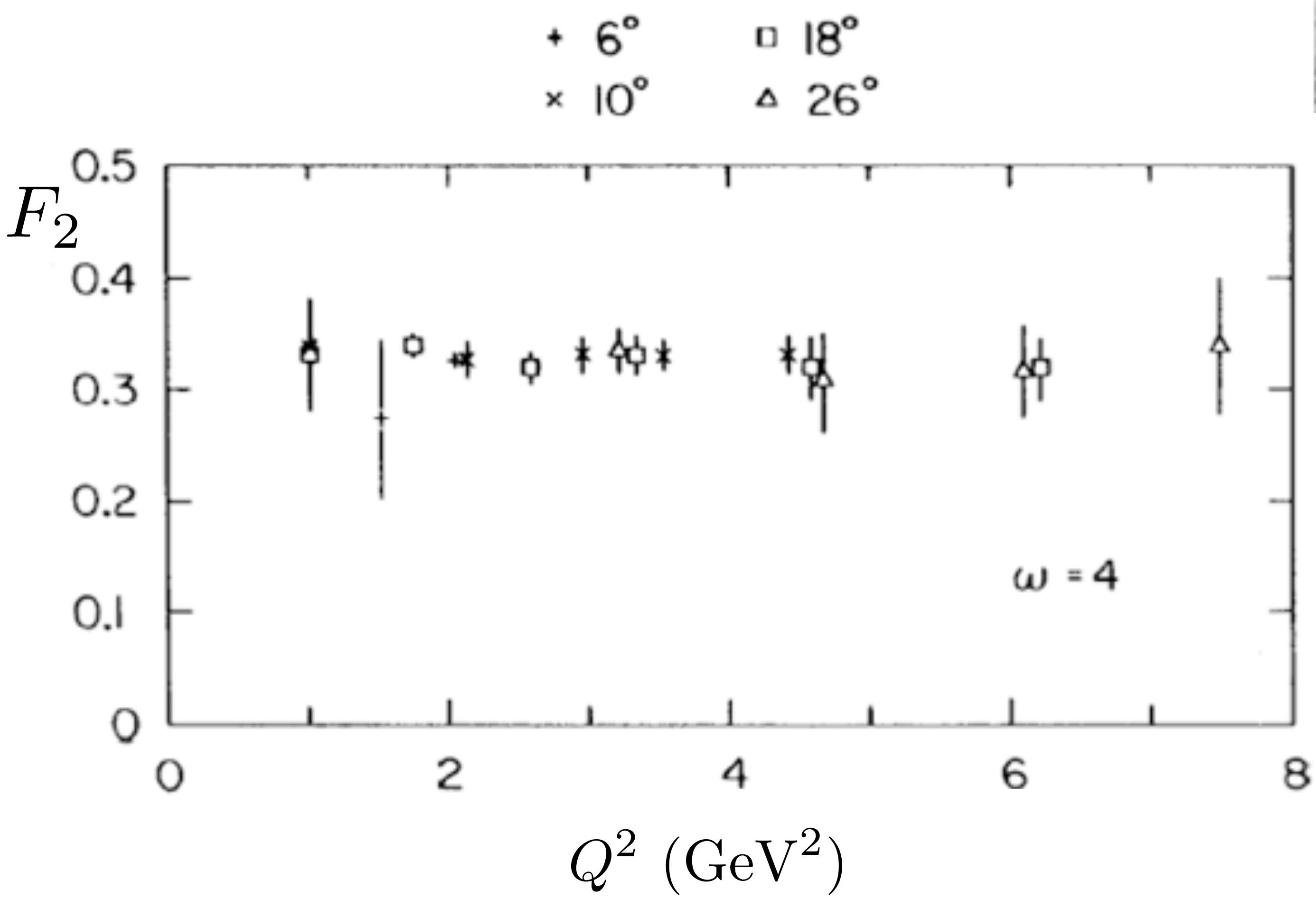


J.T. Friedman

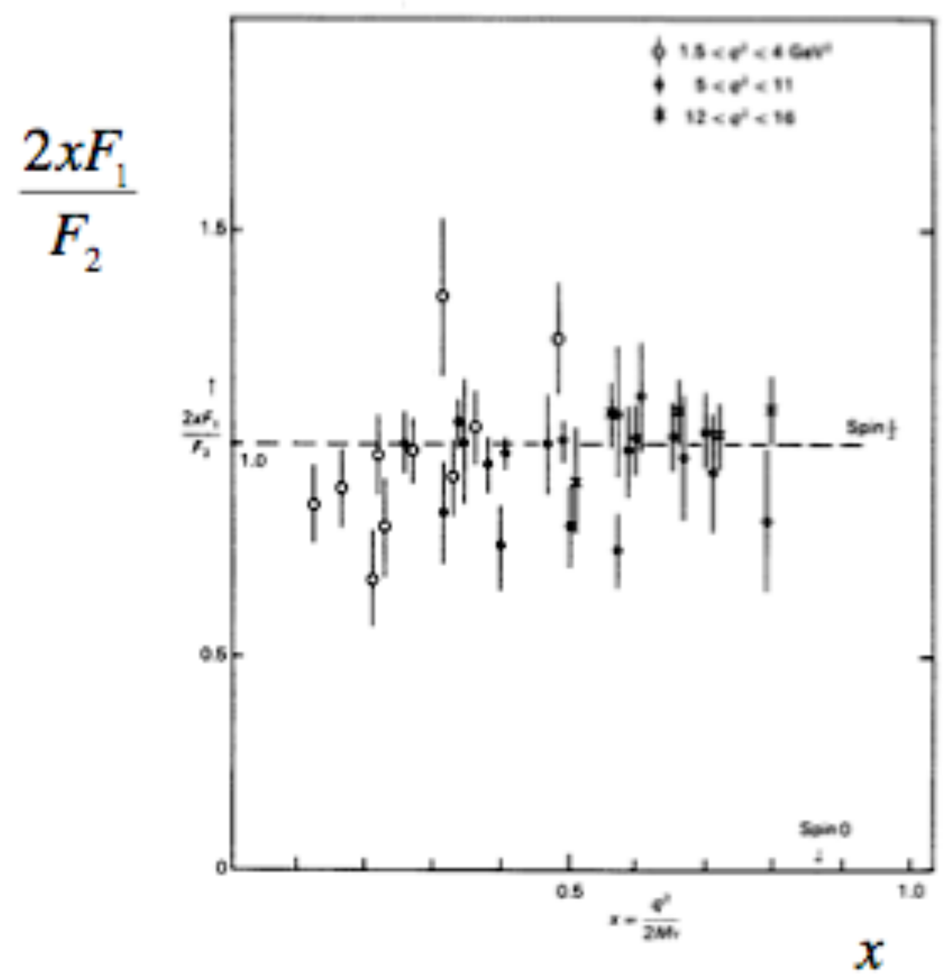
R. Taylor
Nobel Prize 1990

H.W. Kendall

Bjorken scaling:



Callan-Gross relation:



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

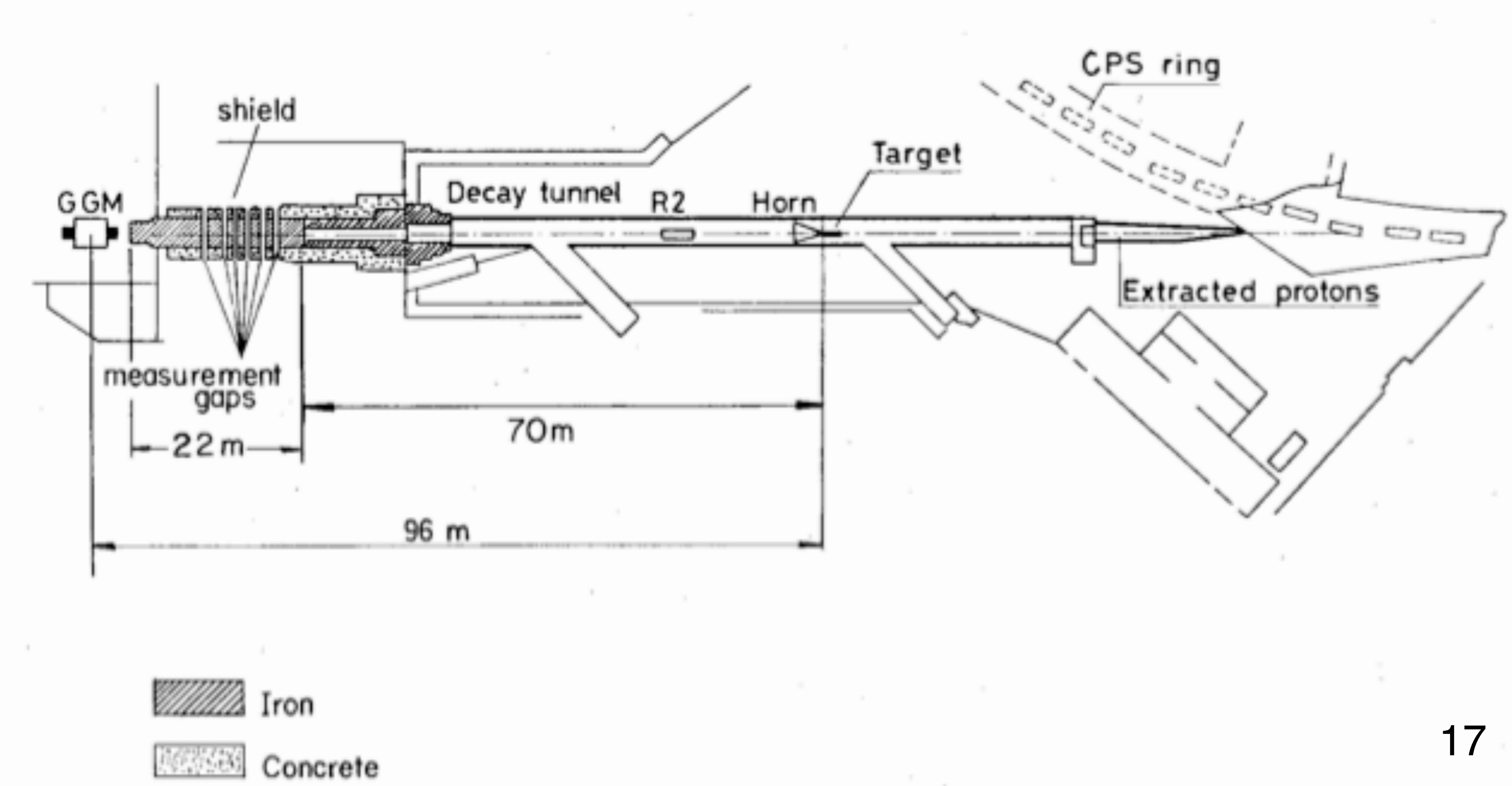
Spin-1/2 quarks cannot absorb longitudinally polarized vector bosons and, conversely, spin-0 (scalar) quarks cannot absorb transversely polarized photons.

Deep-Inelastic *Neutrino* Scattering

Some of you may recognize this picture from CERN...

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

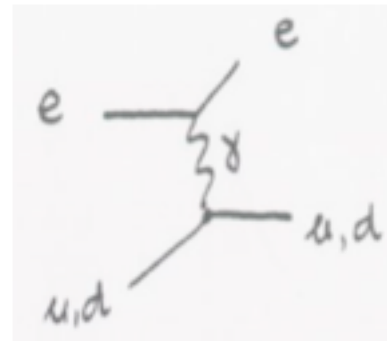
Charged-current DIS!



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

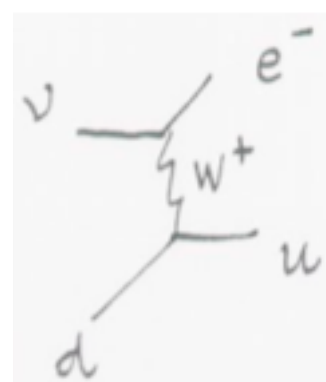
Neutral-current (photon) DIS:



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

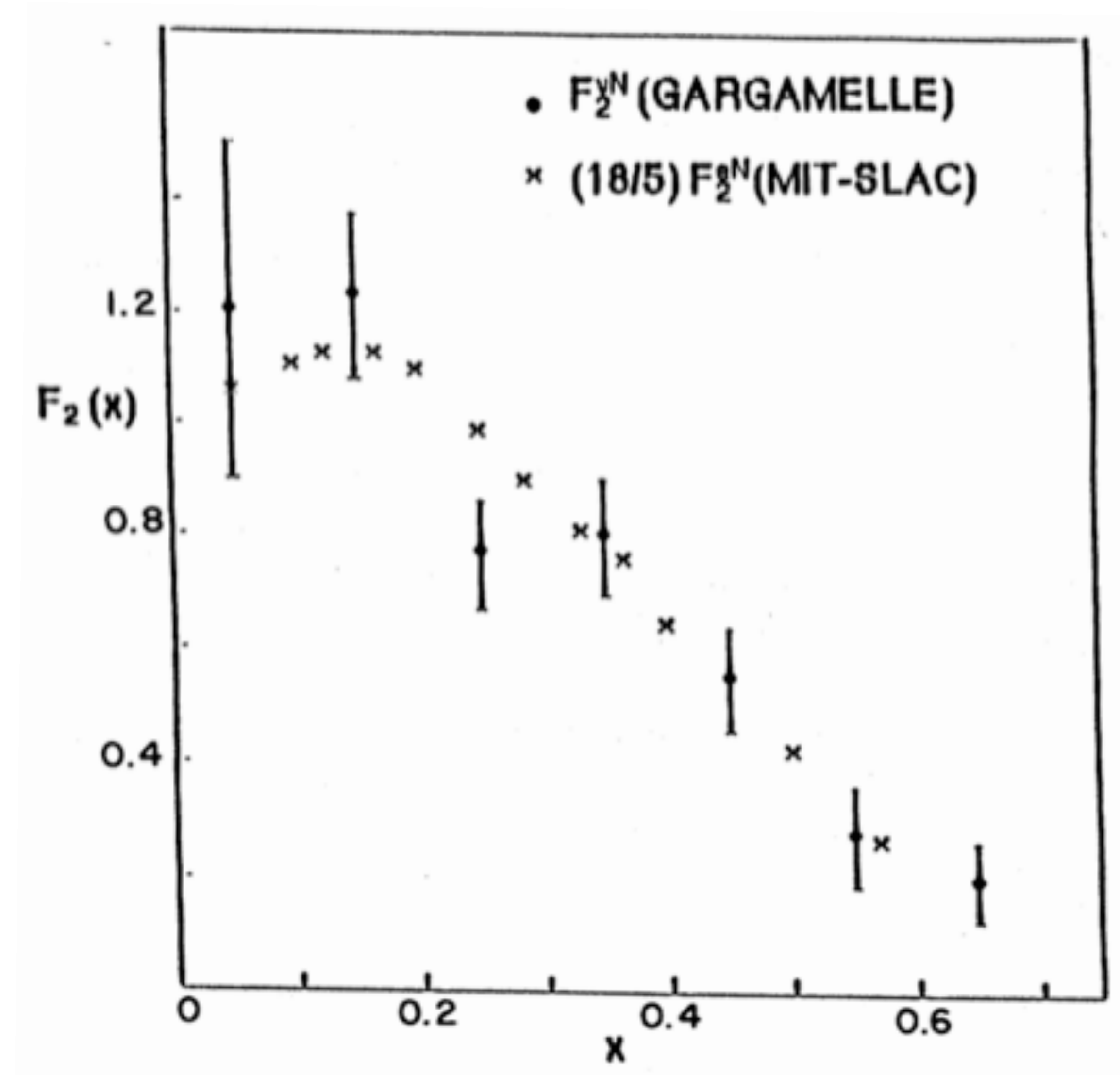
$$F_2^N = x \, \frac{e_u^2 + e_d^2}{2} \, (u + \bar{u} + d + \bar{d})$$

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

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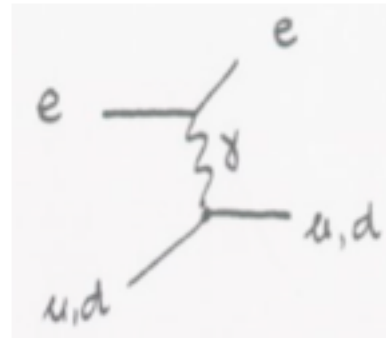

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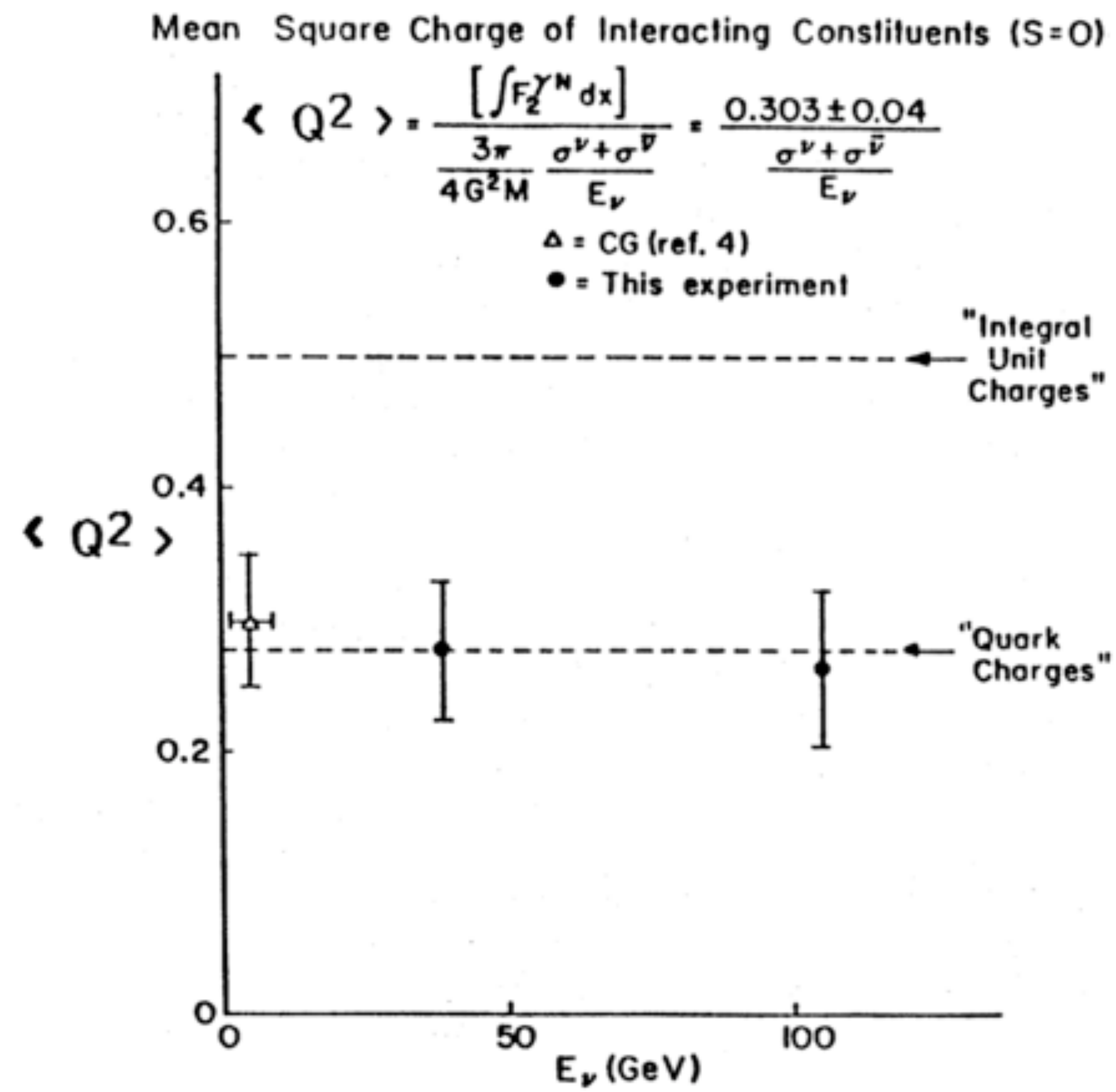
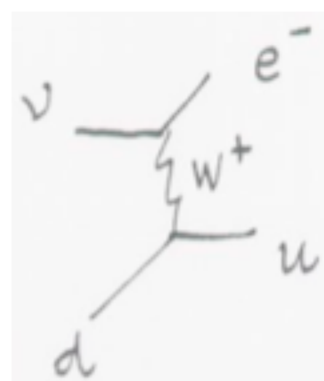


Charged-current DIS:



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

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

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 - Valence and Sea Quarks

Charged-current DIS:

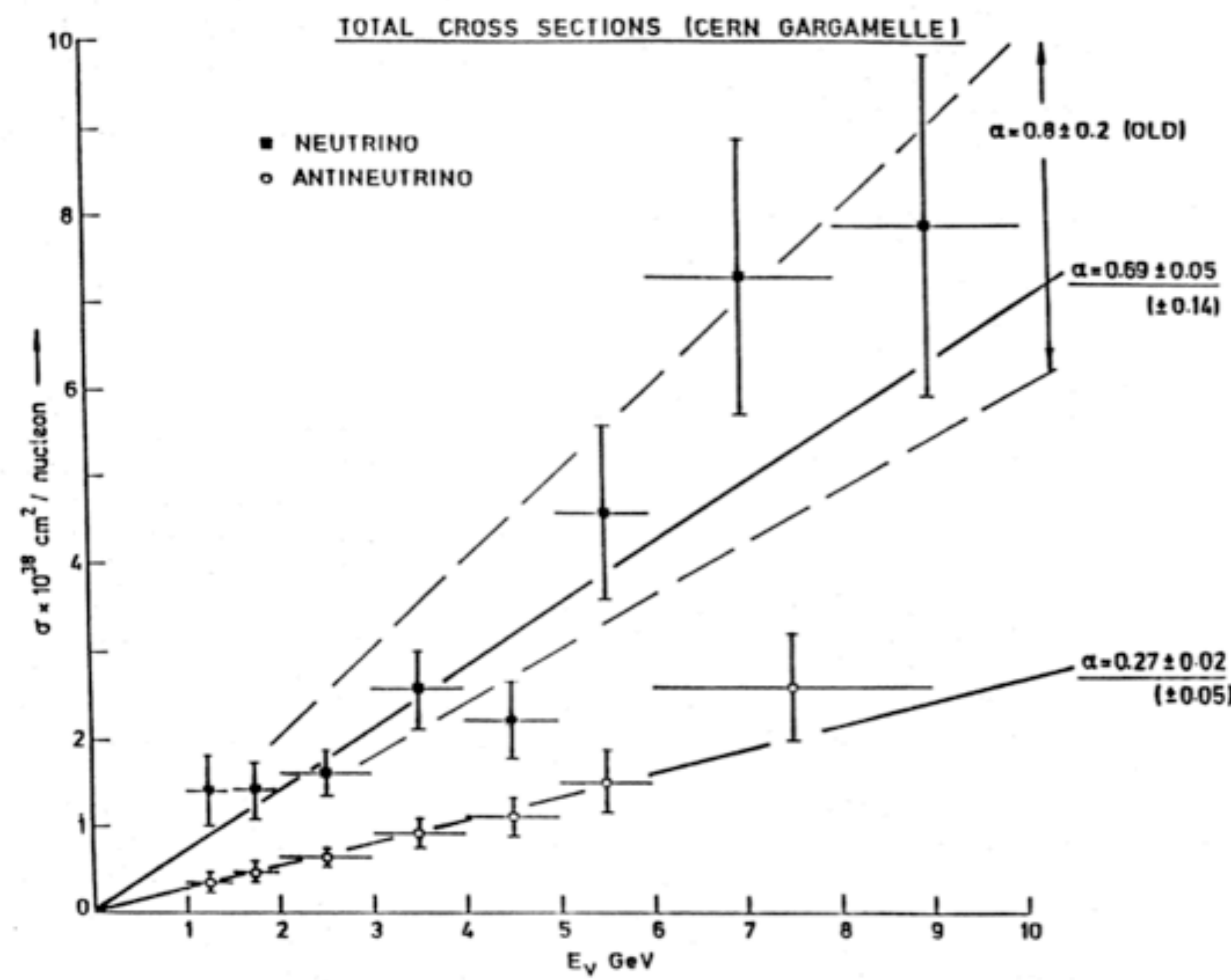
$$F_2^{\nu} = 2x \sum (q + \bar{q})$$

$$xF_3^{\nu N} = 2x \sum (q - \bar{q})$$

$$\int_0^1 xF_3^{\nu \mathrm{N}} \frac{dx}{x} = \int_0^1 (u_v + d_v) dx$$

Gross Llewellyn-Smith: 3

Gargamelle: 3.2 +/- 0.6



$$\frac{d^2\sigma^{\bar{\nu}N}}{dxdy} \propto \left[\bar{u} + \bar{d} + (u + d)(1 - y)^2\right]$$

$$\frac{d^2\sigma^{\nu N}}{dxdy} \propto \left[u + d + (\bar{u} + \bar{d})(1 - y)^2\right]$$

Deep-Inelastic Scattering - Valence and Sea Quarks

Charged-current DIS:

$$F_2^{\nu} = 2x \sum (q + \bar{q})$$

$$xF_3^{\nu N} = 2x \sum (q - \bar{q})$$

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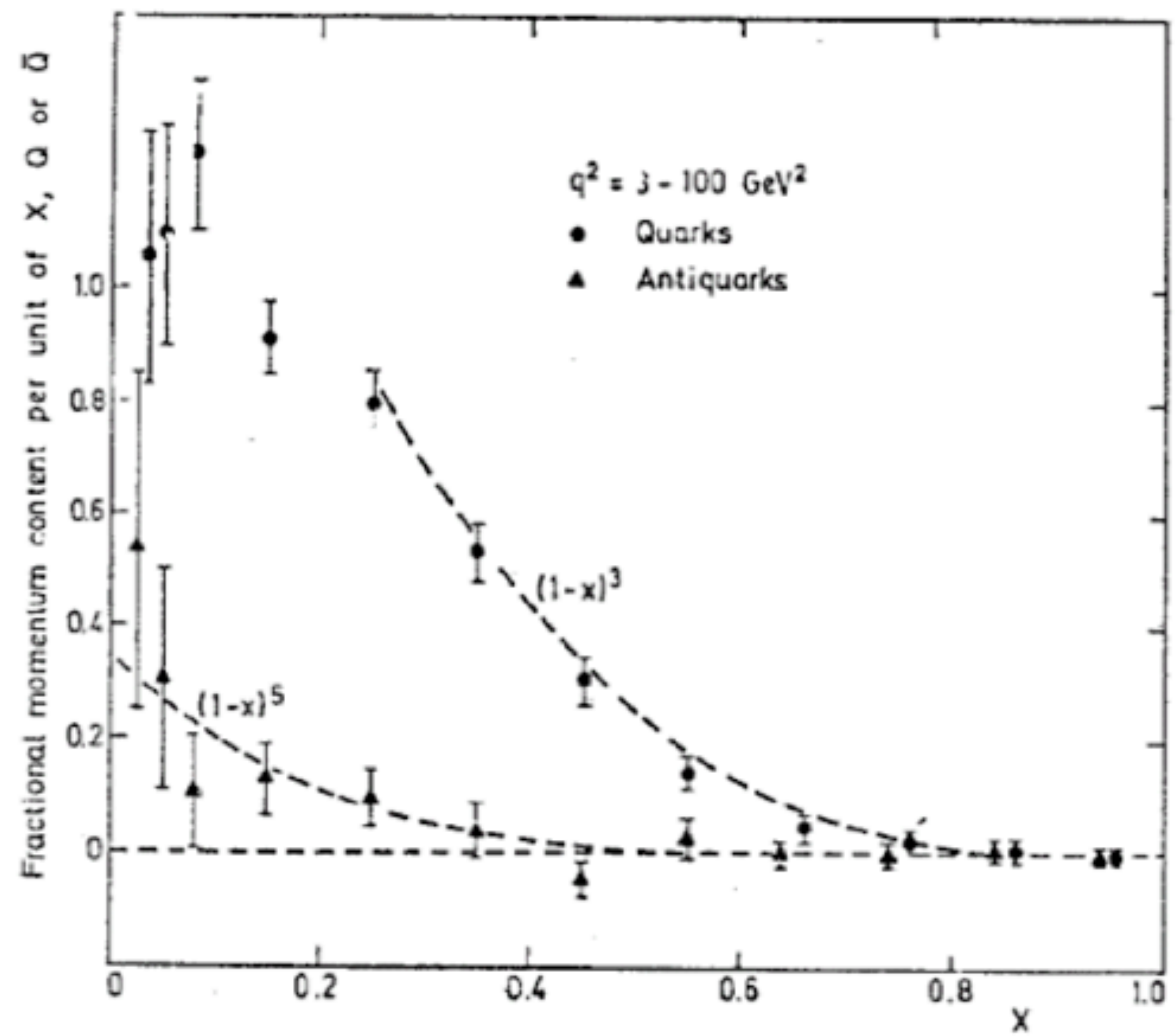

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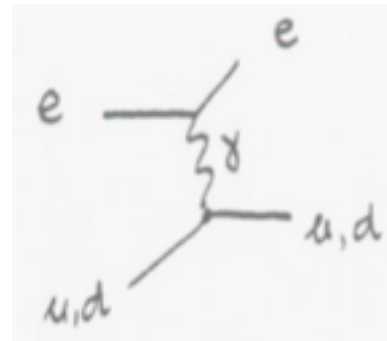
$$\frac{d^2\sigma^{\nu N}}{dxdy} \propto \left[u + d + (\bar{u} + \bar{d})(1 - y)^2\right]$$

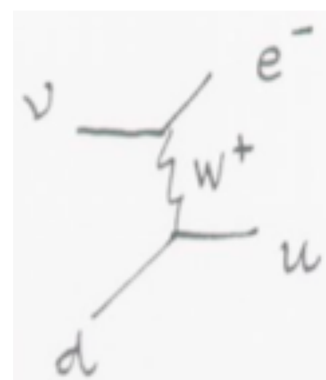
Deep-Inelastic Scattering - Momentum Conservation

Neutral-current (photon) DIS:



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

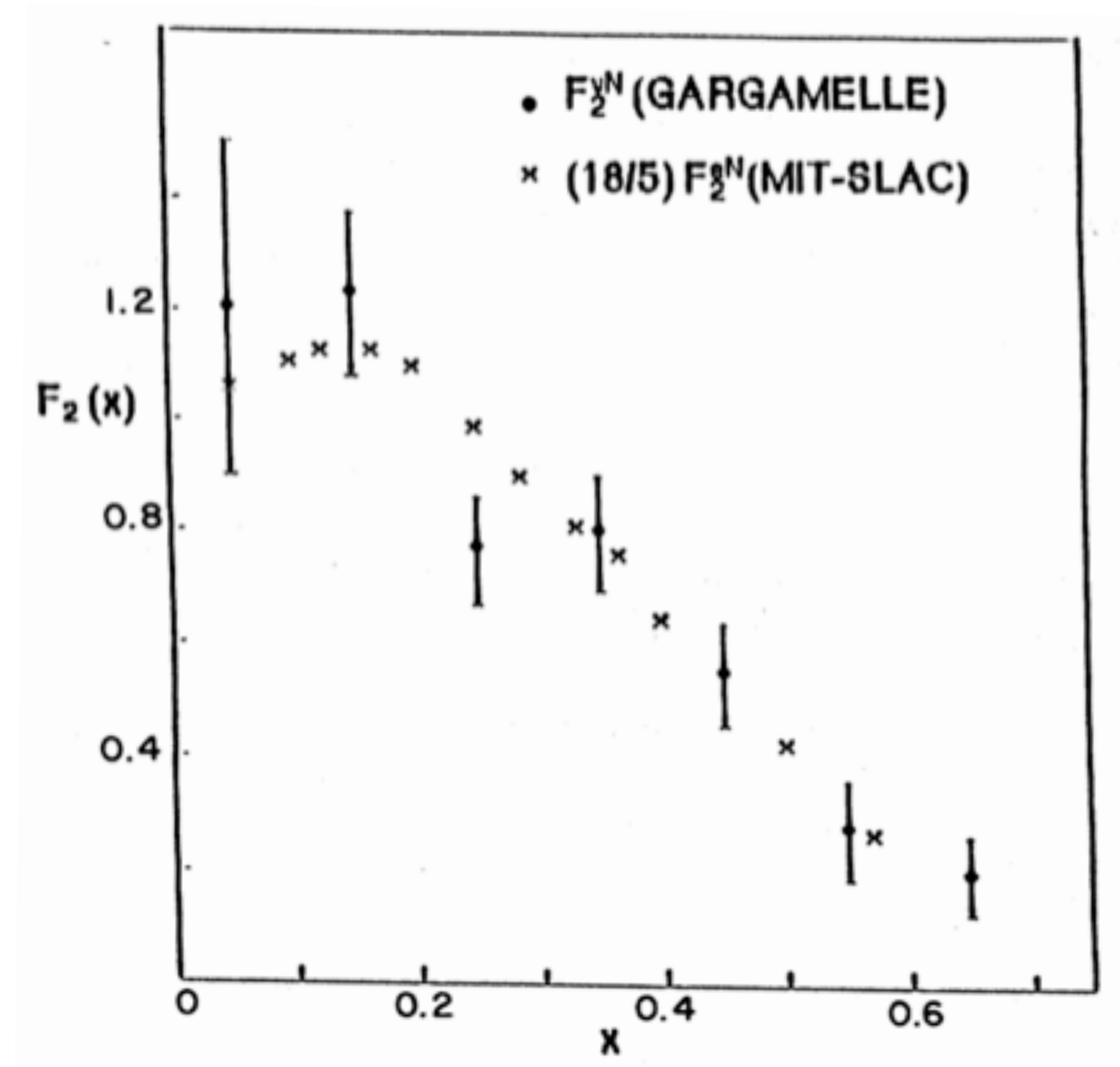
Charged-current DIS:



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

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

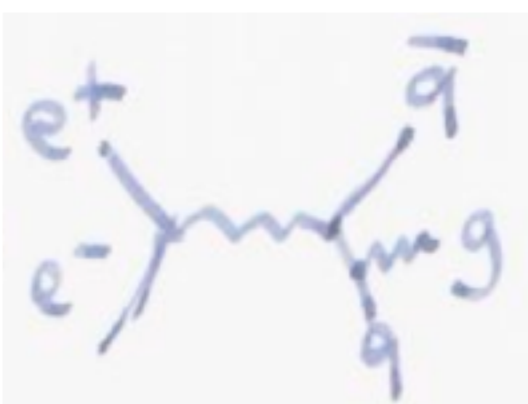
SLAC: 0.14 +/- 0.05

Quarks carry half of the nucleon momentum!

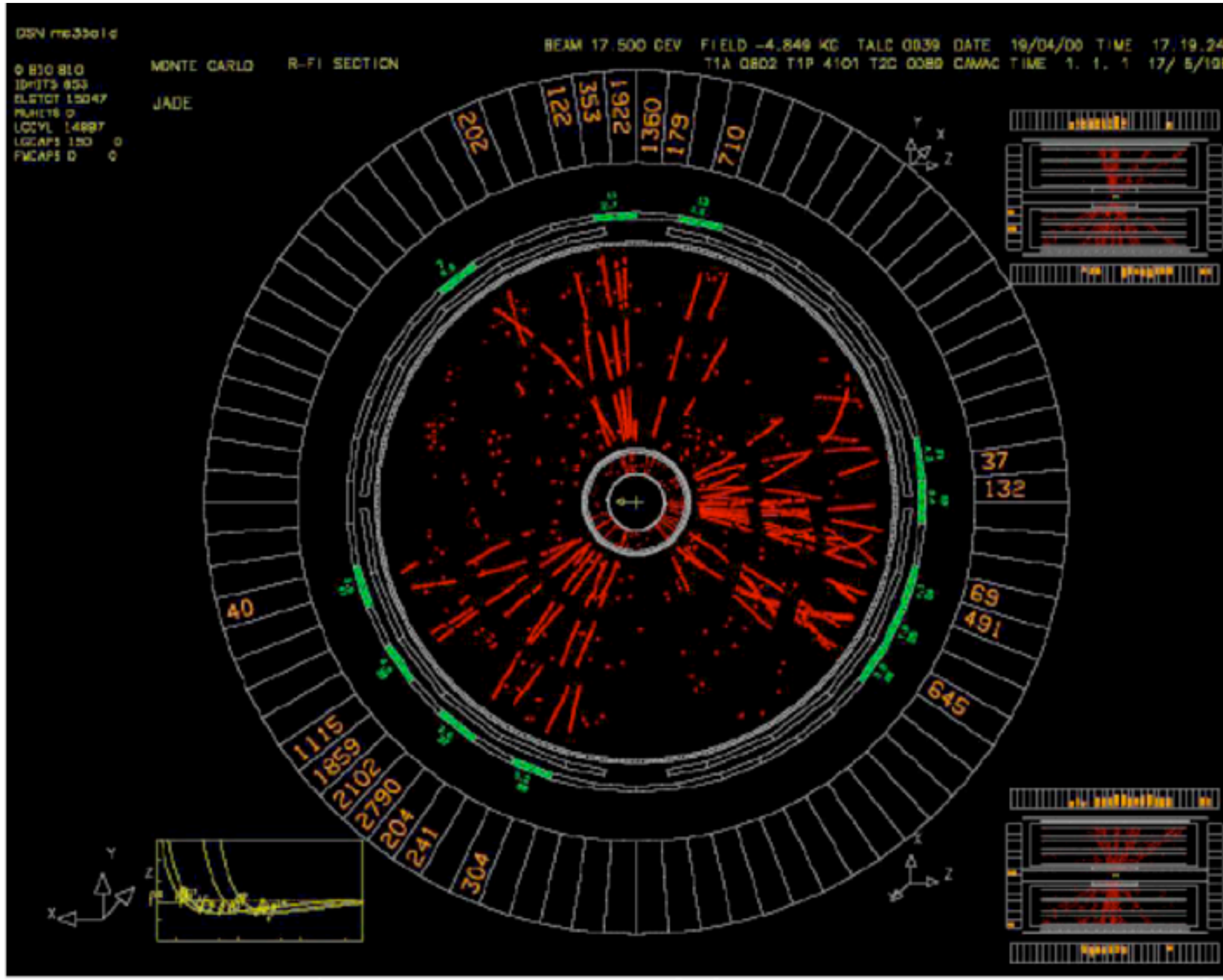
3-jet events at PETRA

Recall the intro on colour:

Observation of its higher order process,

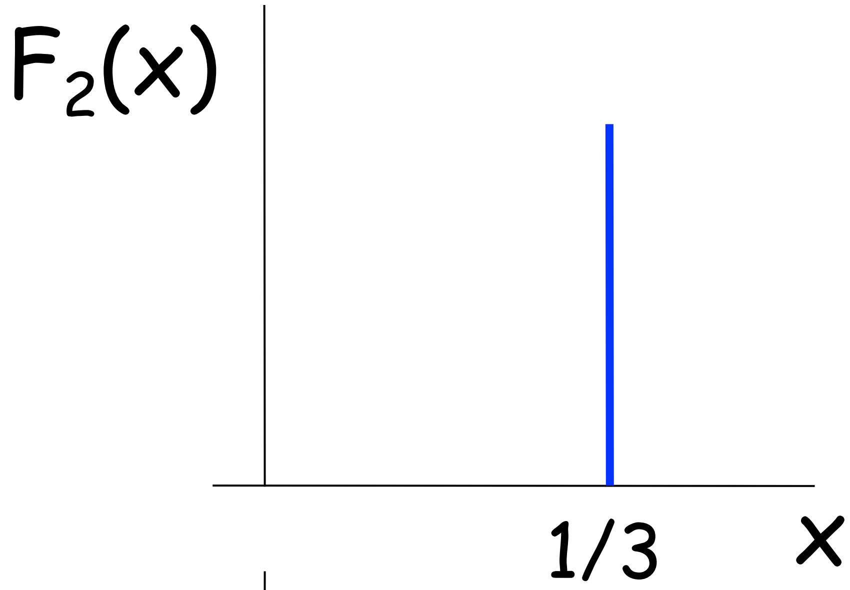


marks the discovery of the gluon.

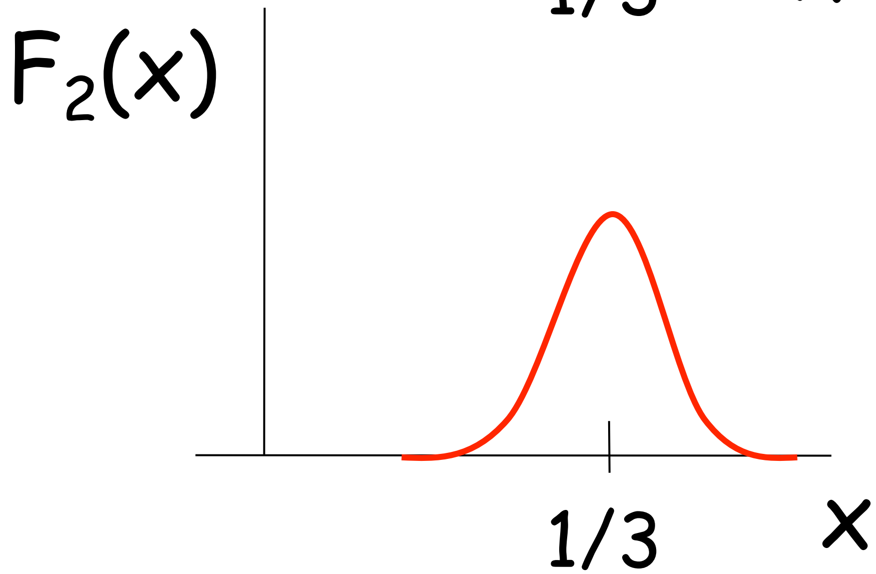


Mom. Conservation: *Gluons carry the other half of the nucleon momentum.*

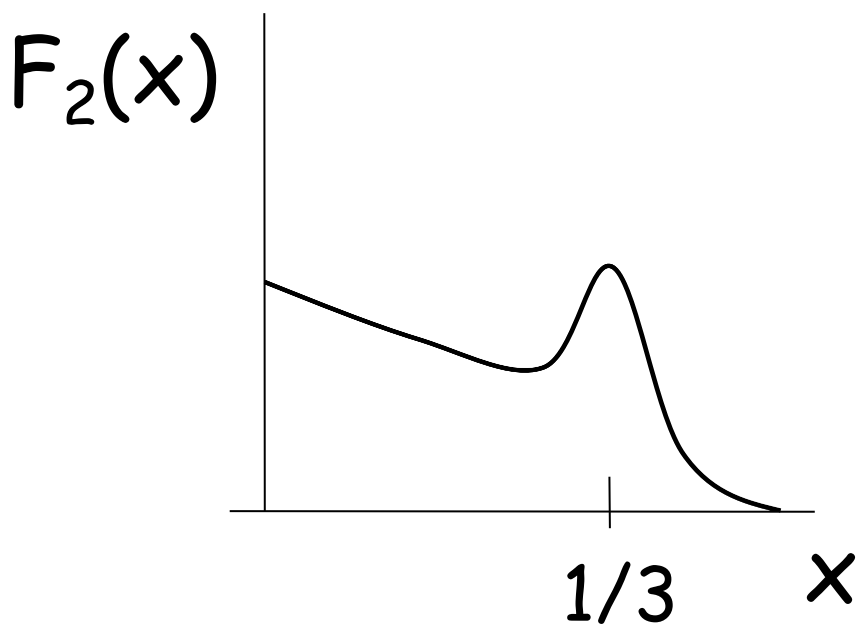
Nucleon Structure



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

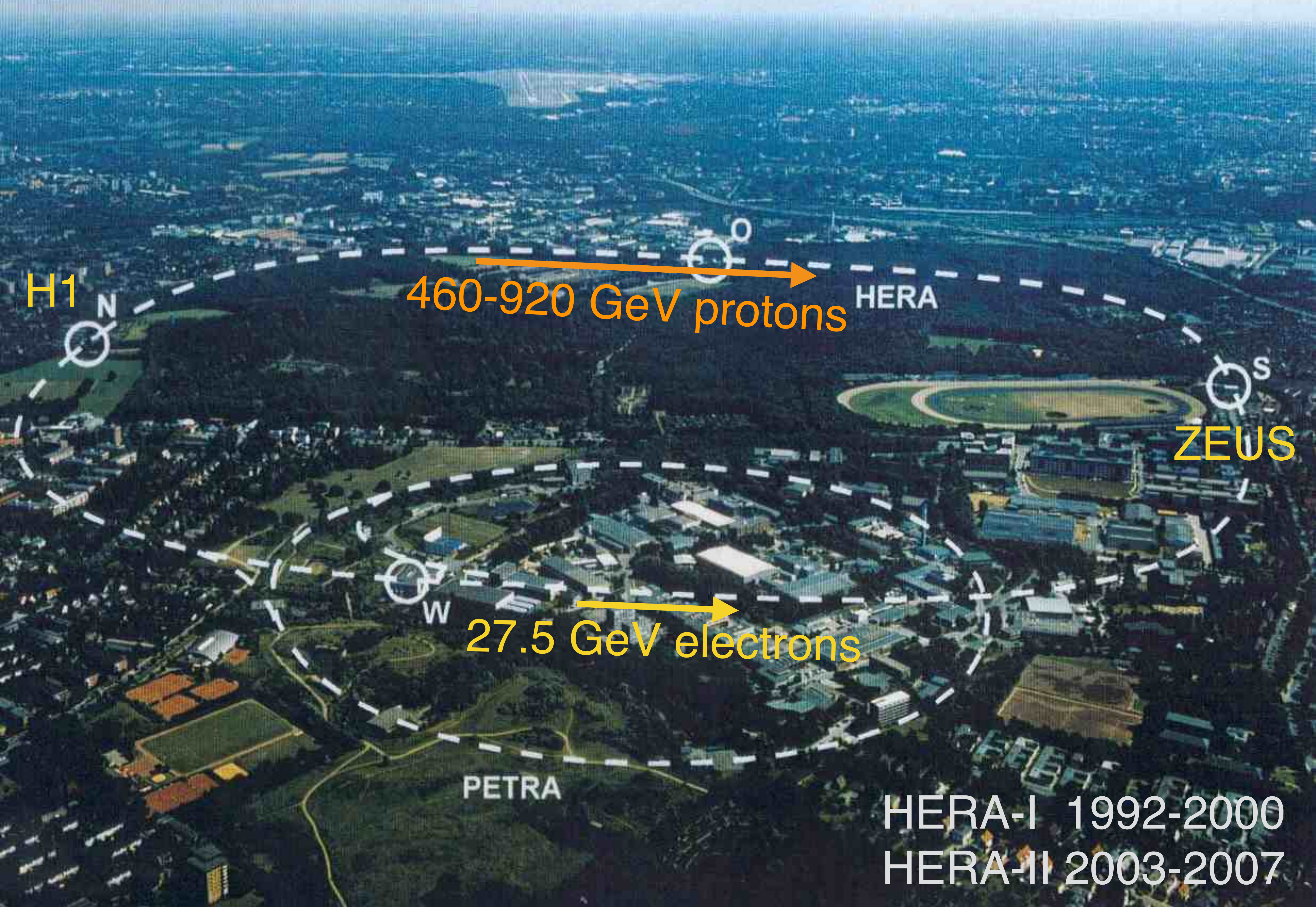


Three quarks with some momentum smearing.

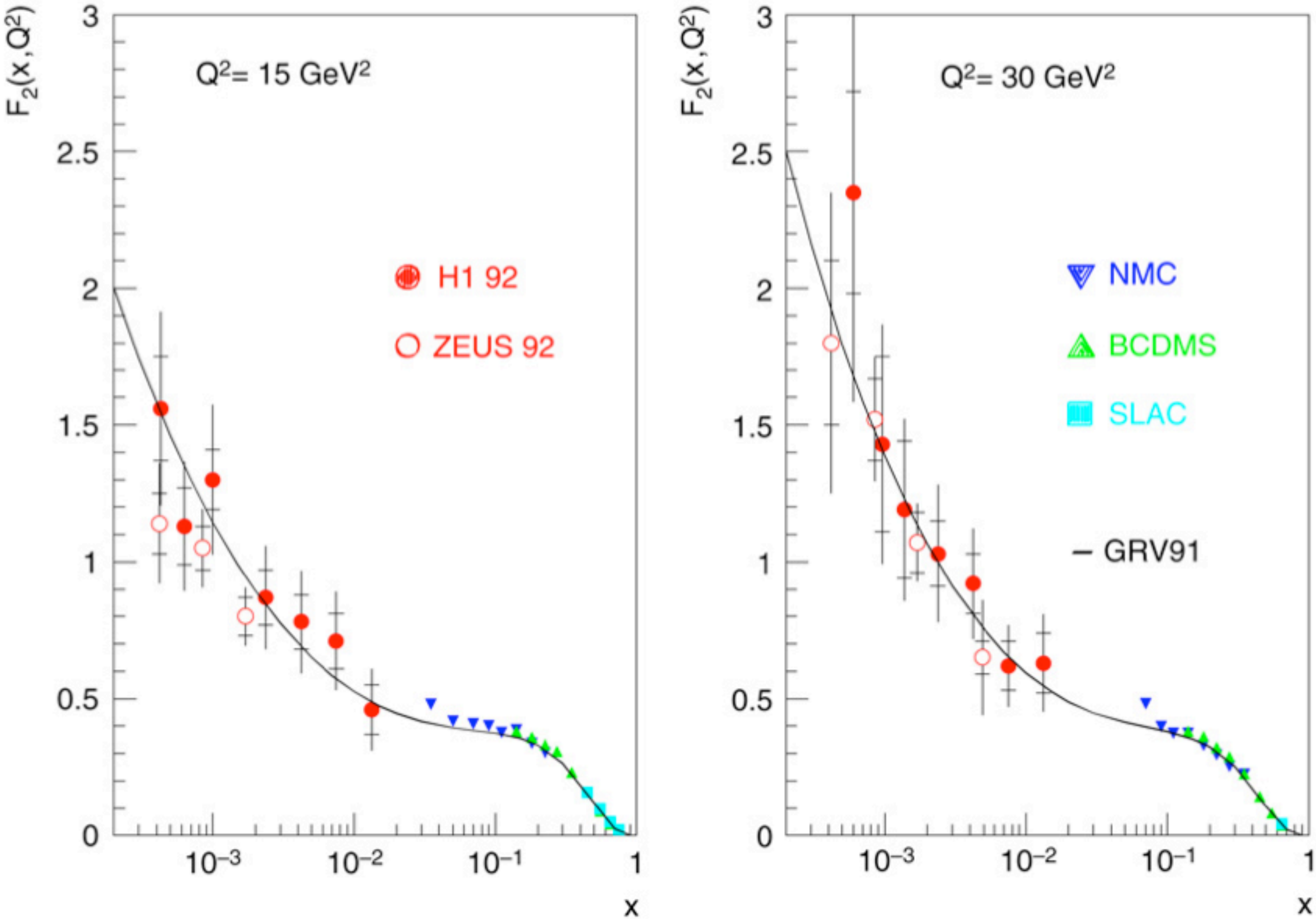


The three quarks radiate partons to lower momentum fractions *x*.

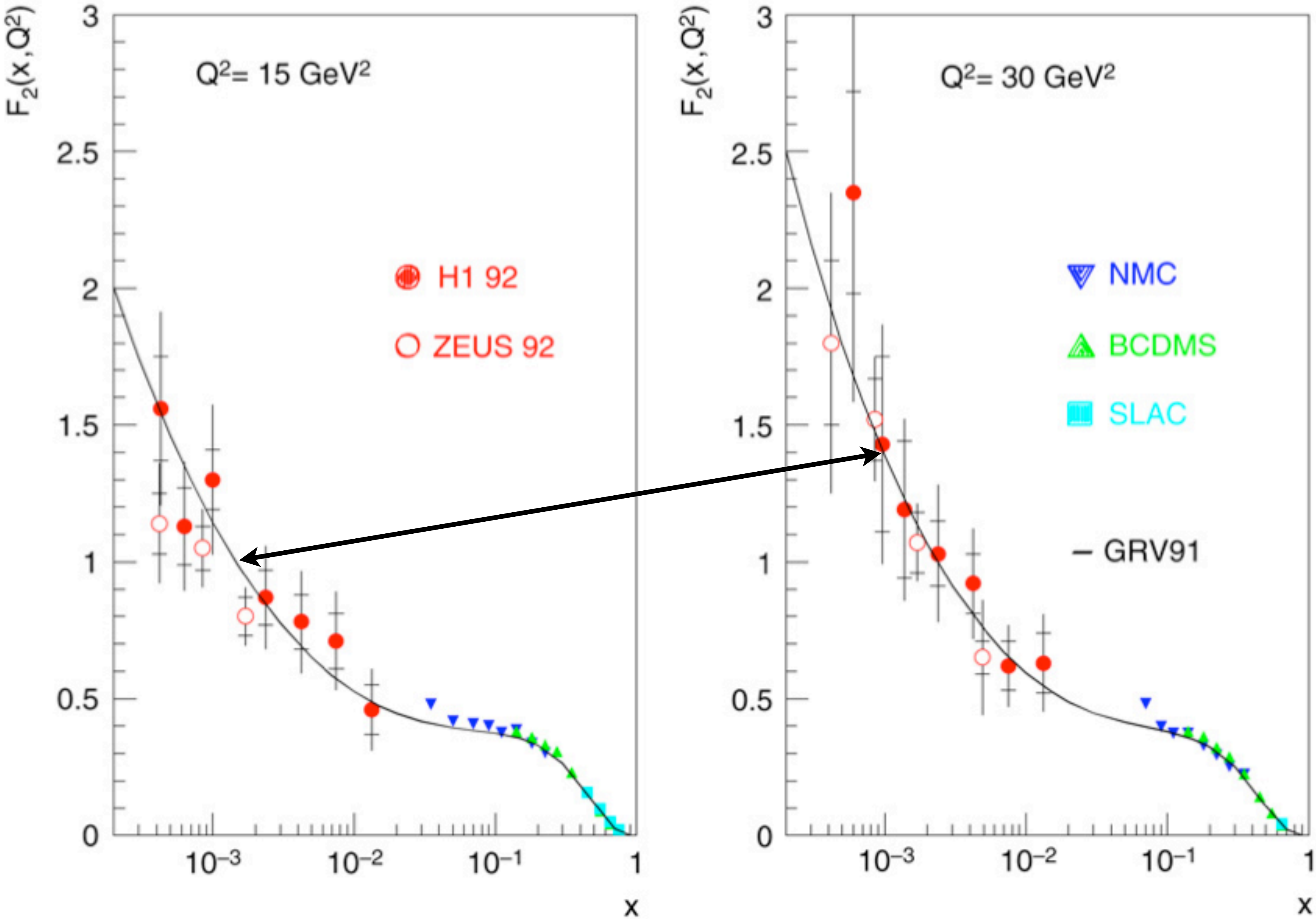
HERA - Electron Proton Collider



HERA - Early Measurements



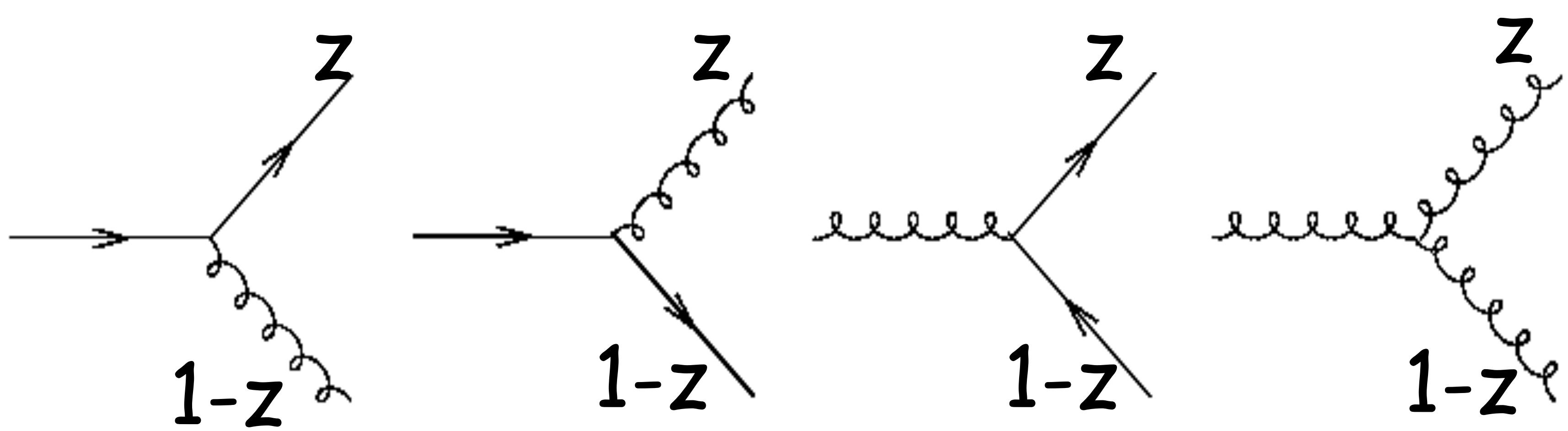
HERA - Early Measurements



Can these observations be related?

QCD Radiation

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

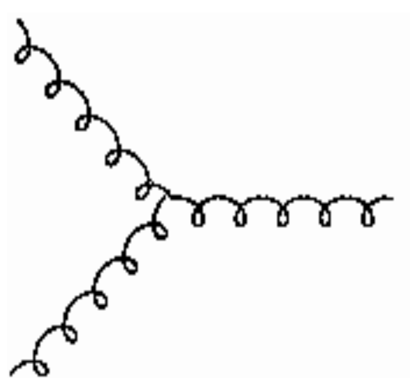


$P_{ab}(z)$: the probability that parton a will radiate a parton b with the fraction z of the original momentum carried by a.

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

DGLAP is highly successful, but not the only approach.



Gluons do not recombine, incoherence is preserved.

Gluon-dense environments?

Similarly, process-independent quarks, survive.

How does DGLAP work?

QCD Radiation

Schematically, DGLAP equations:

convolution

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

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*.

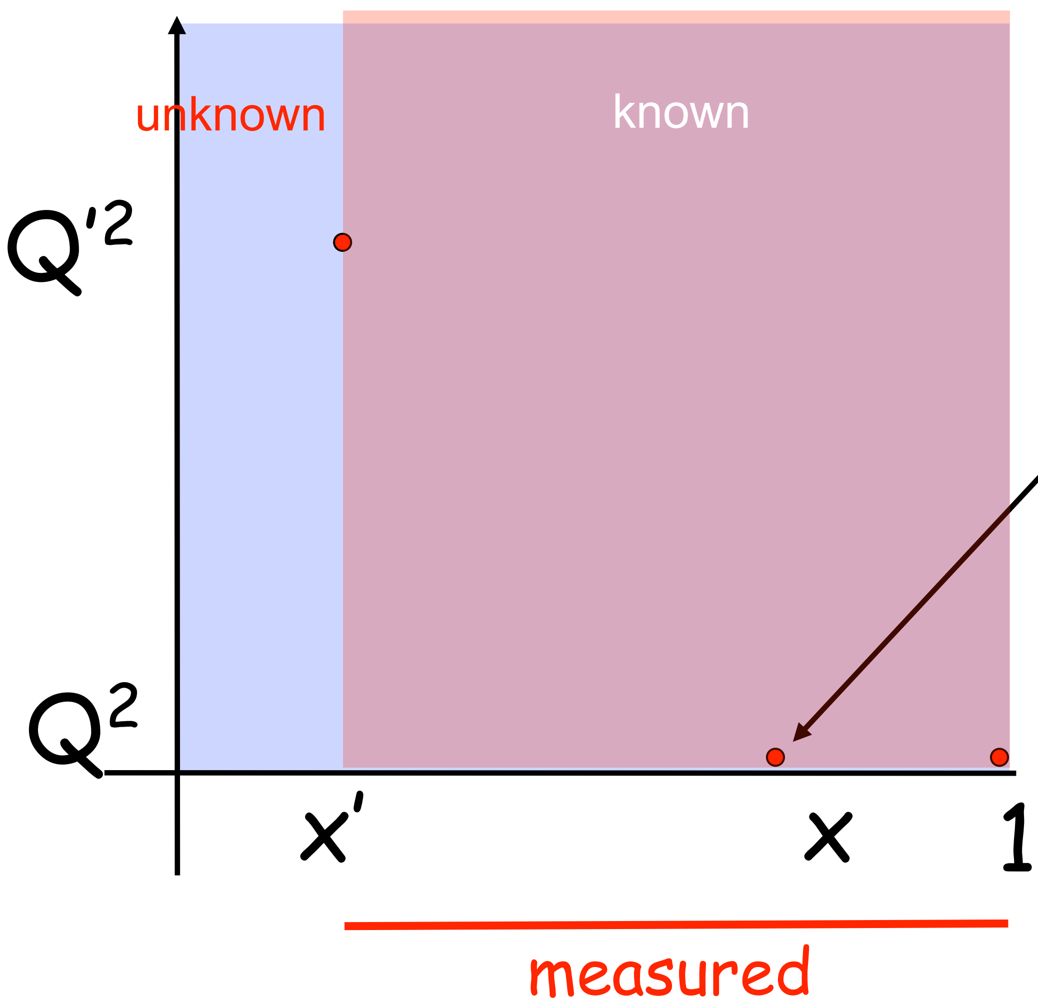
Similarly, for gluons:

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

Side-note: the spin-dependent splitting functions are different from the spin-averaged splitting functions; for example, they generate orbital momentum.

QCD Radiation

A parton at x at Q^2 is a source of partons at $x' < x$ at $Q'^2 > Q^2$.



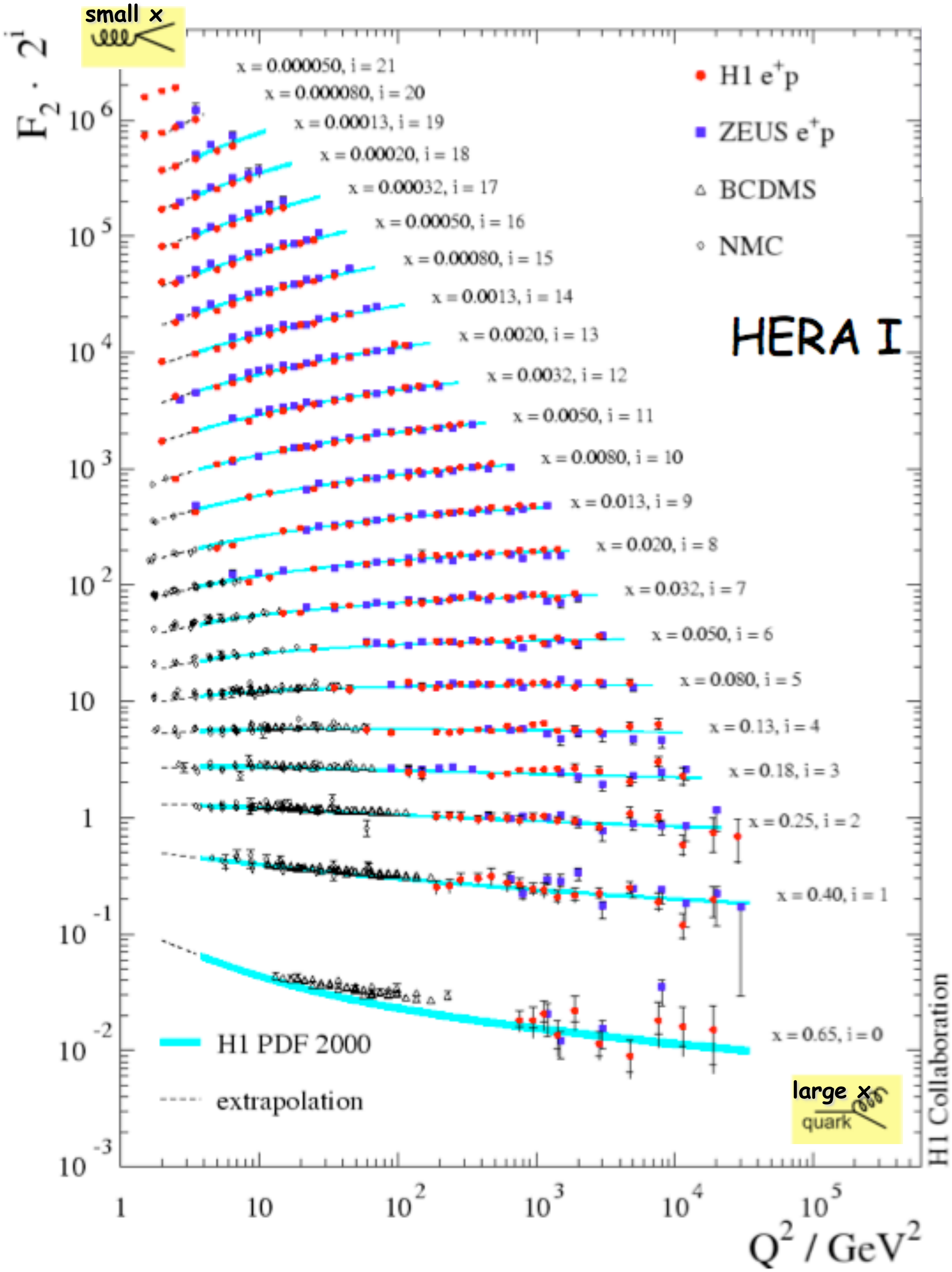
Any parton at $x > x'$ at Q^2 is a source.

It is necessary and sufficient to know the parton densities in the range $x' \leq x \leq 1$ at a lower Q^2 to determine the parton density at x', Q'^2.

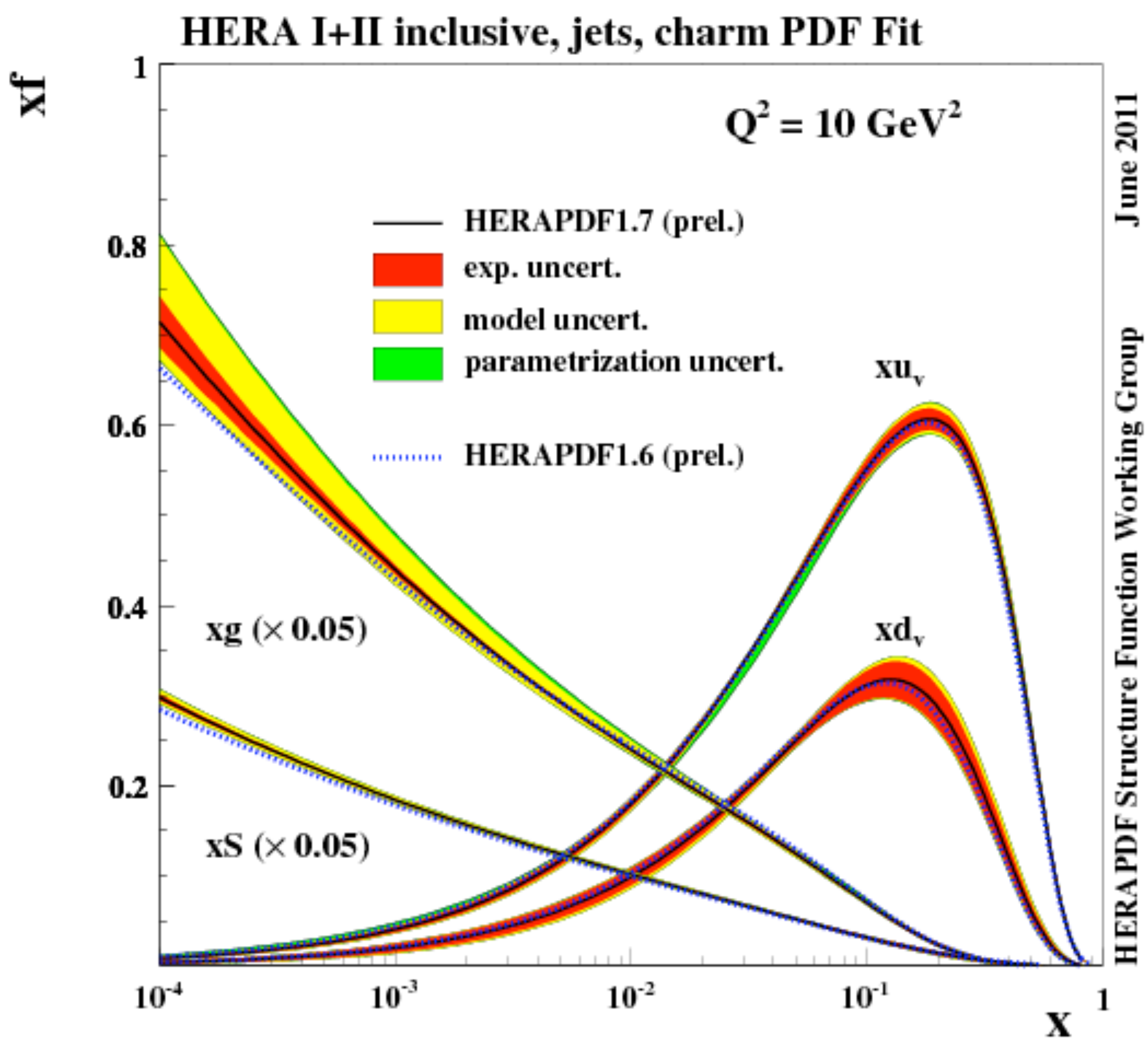
If you measure partons in range $x' \leq x \leq 1$ at some Q^2 then you know them in that range, and only that range, for all Q'^2.

Asymptotic solutions exist to the DGLAP equations that may overwhelm the intrinsic contributions.

Bjorken scaling vis-a-vis QCD Radiation

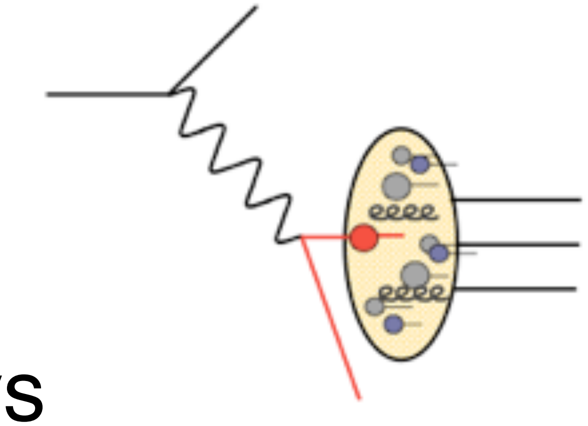


Modern understanding of nucleon composition



Brief recap:

DIS



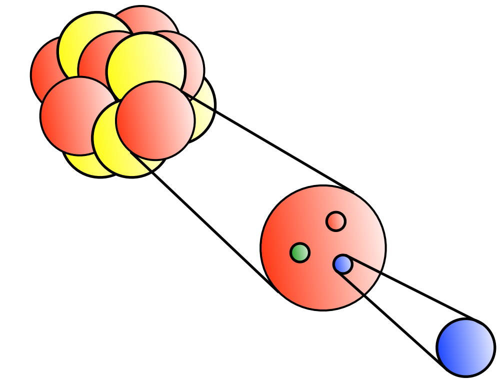
- DIS is about nucleon or nuclear structure, nowadays described in terms of quarks and gluons,
- Feynman's parton model - point like partons, which behave *incoherently* - combined with QCD radiation are remarkably successful in describing DIS cross sections.
- Parton distributions *f(x)* are intrinsic properties of the nucleon and (thus) process independent.
- QCD evolution allows one to relate quantitatively processes at different scales Q^2,

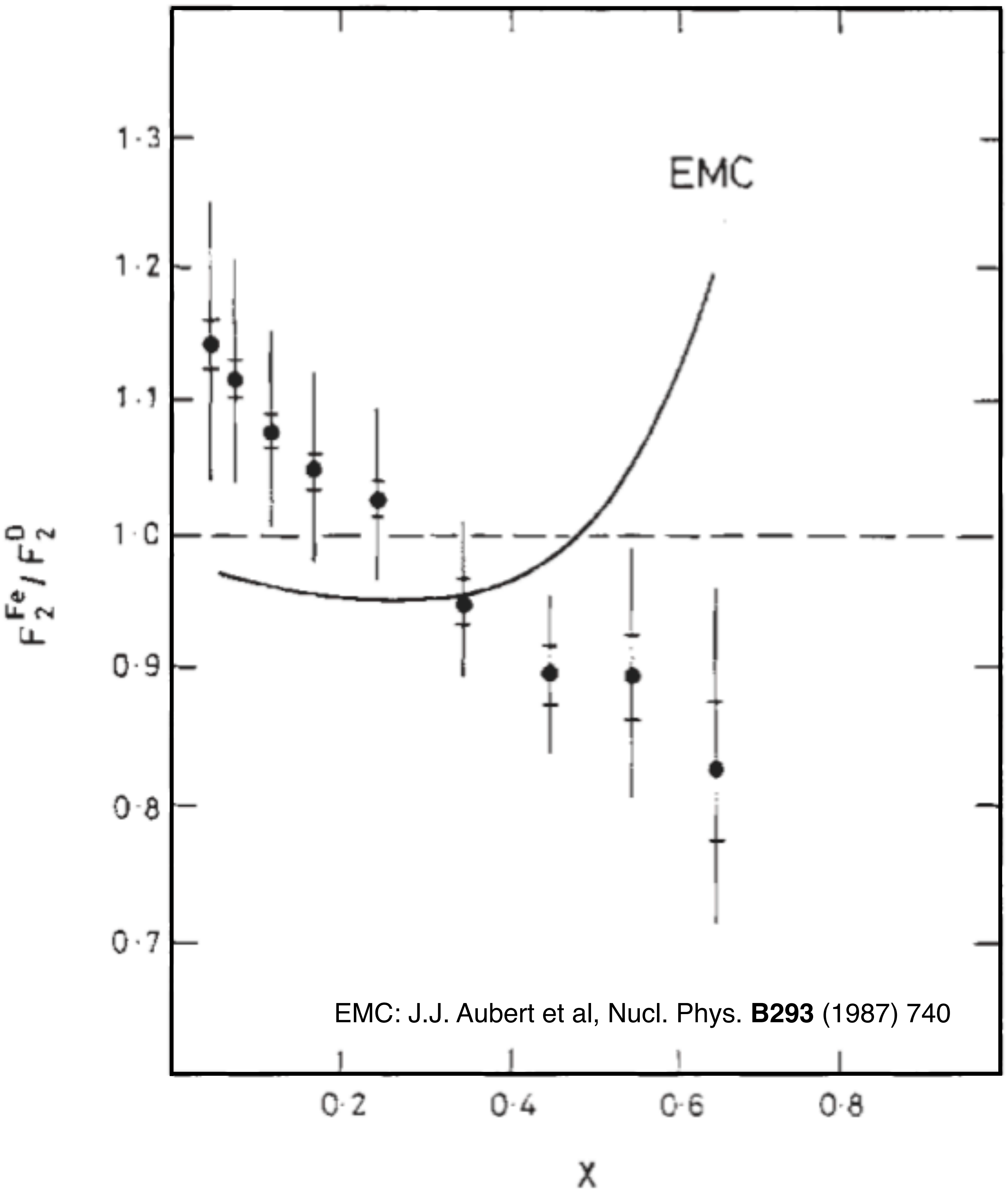
This is great for RHIC, LHC, and many other areas.

- Gluons are a *very* significant part of the nucleon

Questions or comments, before we move on?

DIS - Surprises with Nuclei





EMC: J.J. Aubert et al, Nucl. Phys. **B293** (1987) 740

~10 times *higher* beam energy than earlier DIS experiments,

An iron target to boost luminosity...

Who ordered this?

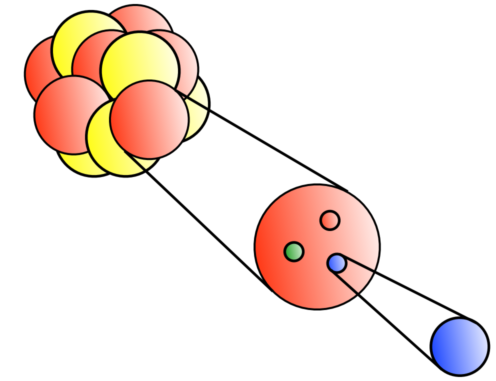
Numerous models, often based on:

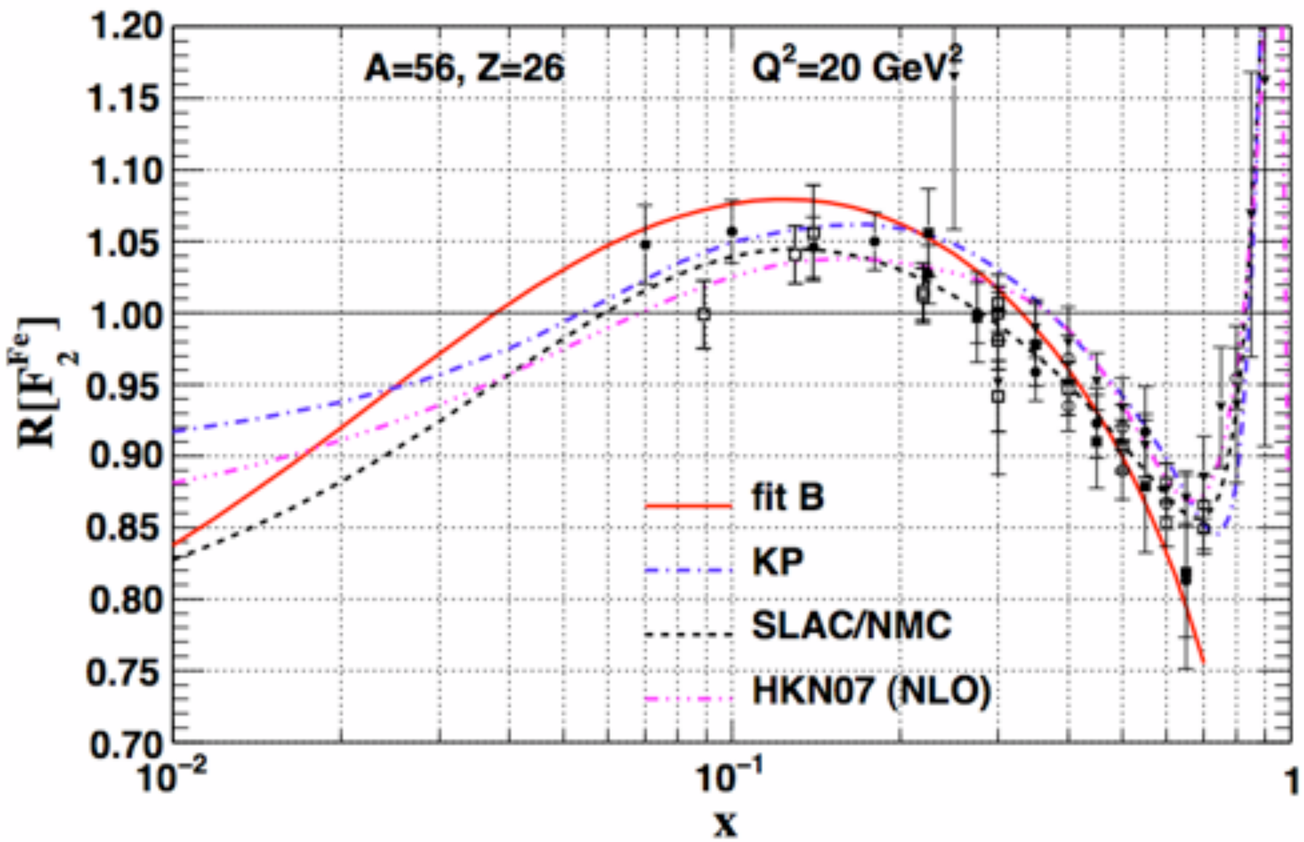
- single (bound) nucleons,
- pion enhancement,
- multiquark clusters,
- dynamic rescaling,
- shadowing

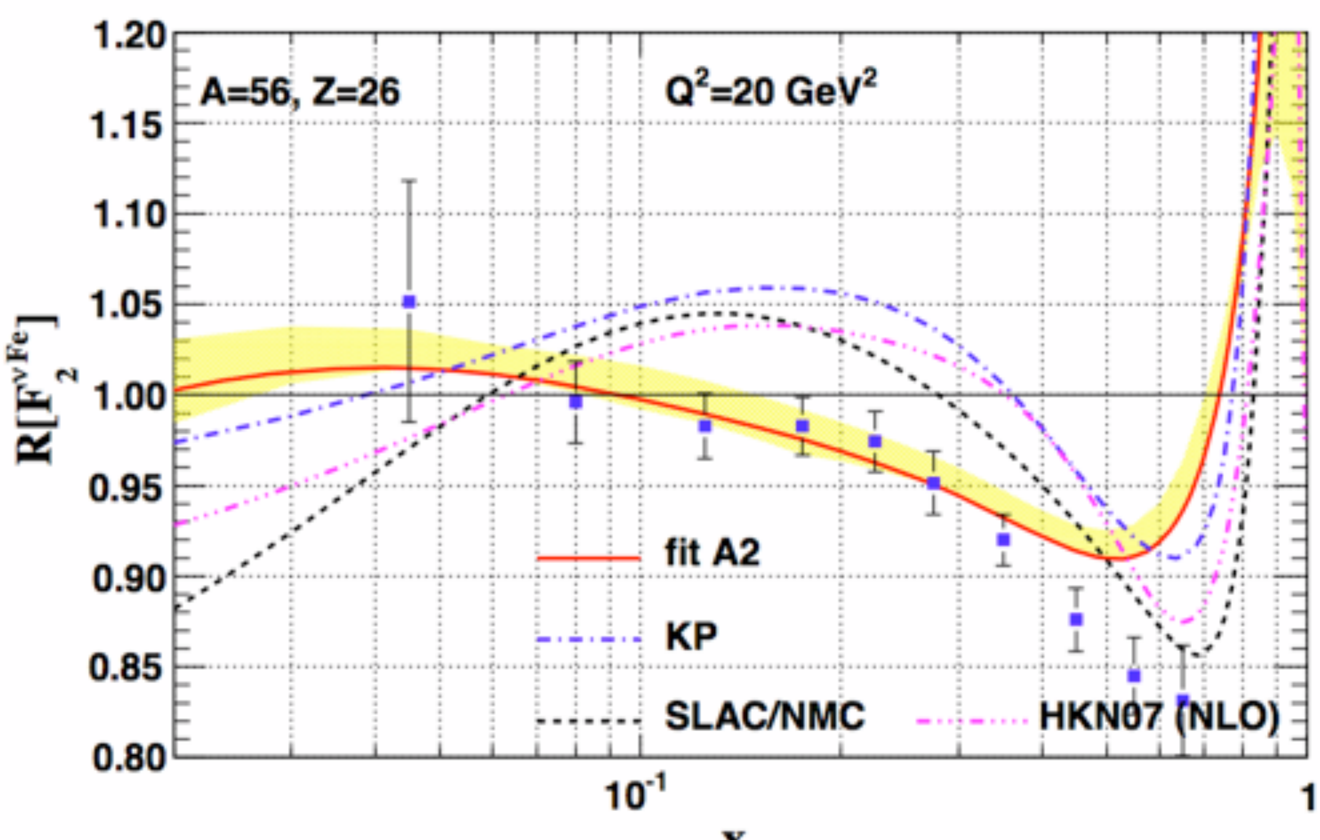
Textbook effect, remains in search of a comprehensive explanation.

See e.g. M. Arneodo, Phys. Rep. **240** (1994) 301

DIS - Surprises with Nuclei







I. Schienbein et al, Phys. Rev. **D80** (2009) 094004
K. Kovarik et al, Phys. Rev. Lett. **106** (2011) 122301

~10 times *higher* beam energy than earlier DIS experiments,

An iron target to boost luminosity...

Who ordered this?

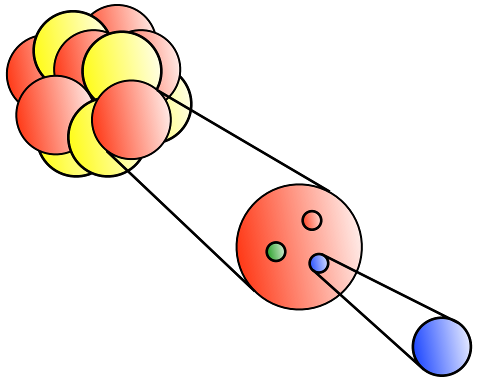
Nowadays,
~800 fixed target data points on F_2^A/F_2^D,
~200 $F_2^A/F_2^{A'}$,
~100 Drell-Yan.

And, neutrino-scattering data (~3000 pts).

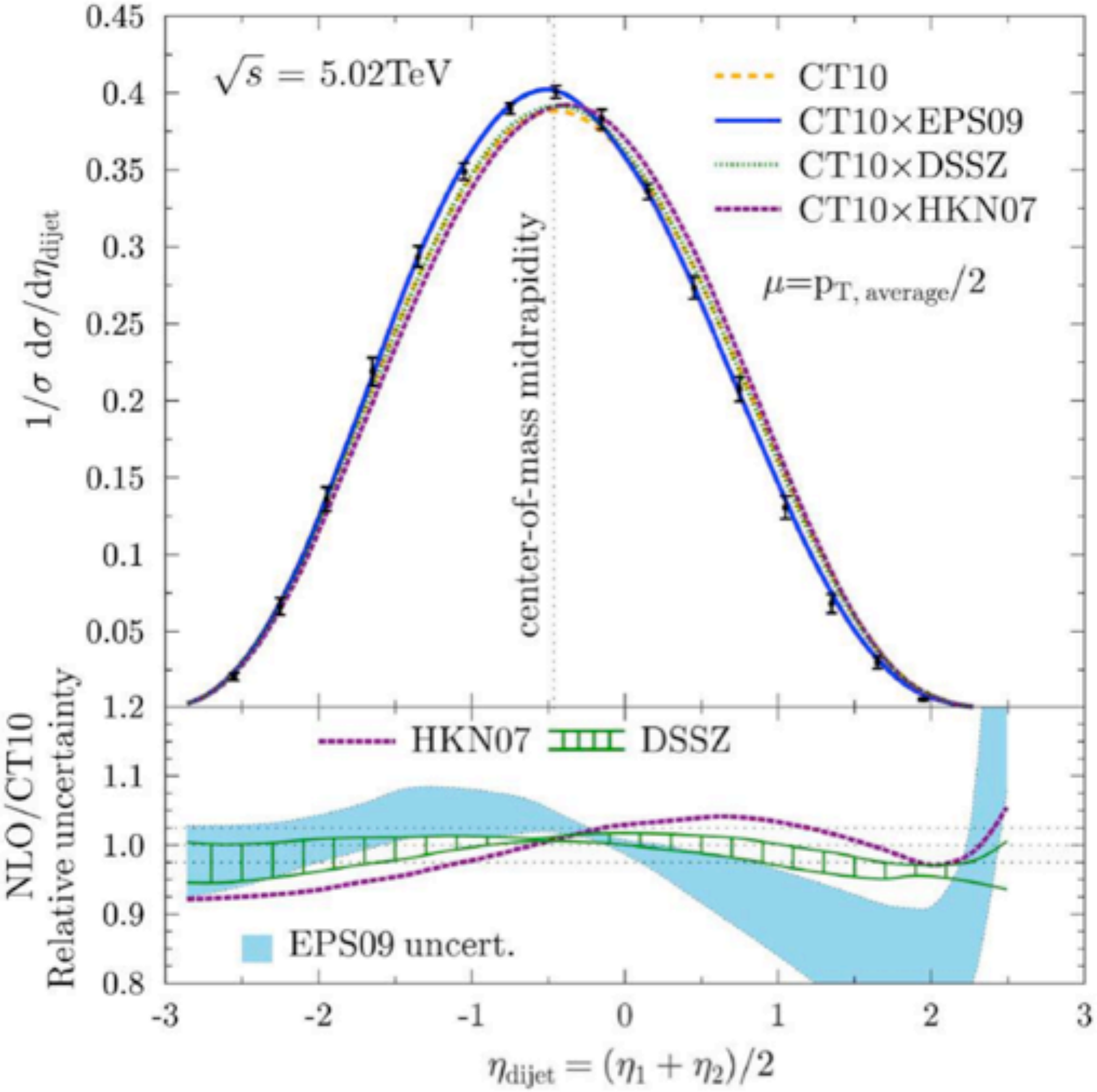
Physics or NuTeV experiment effect?

See e.g. H. Paukkunnen at QCD Frontier 2013

DIS - Surprises with Nuclei



CMS, ArXiv:1401.4433
H. Paukkunnen, ArXiv:1401.2345



Textbook effect, remains in search of a comprehensive explanation.

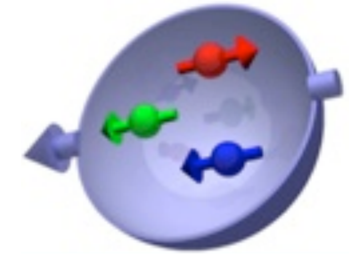
Experimental opportunities:

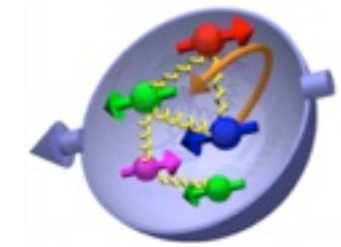
Near-term:
- (polarized) p+A scattering,
- continued DIS, DY,
- ...

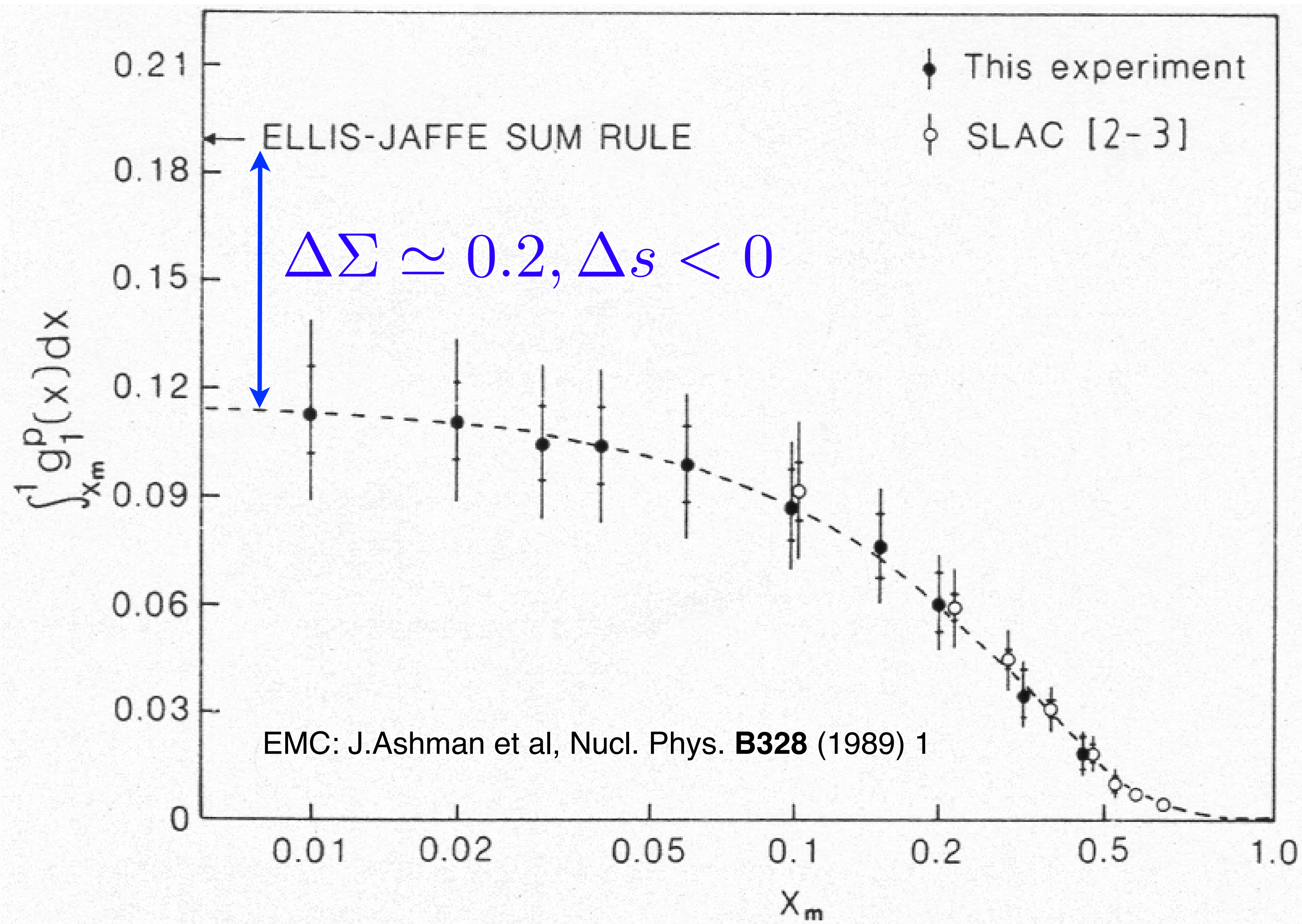
EIC-term:
- QCD-evolution, esp. gluon region,
- NC, CC probes,
- 1-particle semi-inclusive data,
- n-particle correlations,
- diffraction,
- exclusive reactions (imaging),
- ...

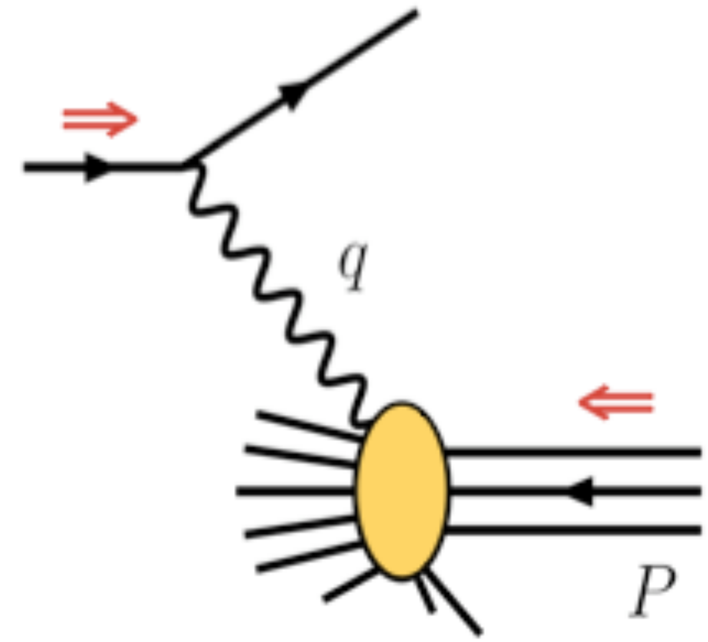
Simply this student's list - input sought.

DIS - Surprises with Spin





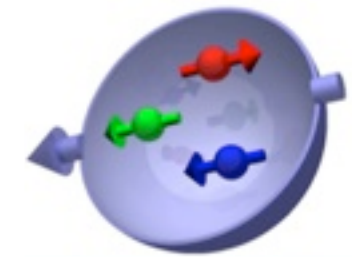


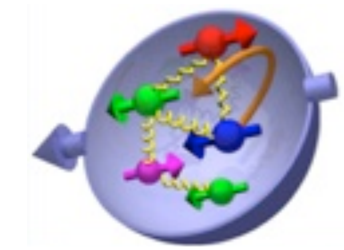


$$\sigma(\Rightarrow,\Leftarrow) - \sigma(\Rightarrow,\Rightarrow) \sim \mathbf{g_1(x,Q^2)}$$

The sum of Quark Spins contribute little to the proton spin, and strange quarks are negatively polarized.

DIS - Surprises with Spin





For the proton,

$$\Gamma_1 = \int_0^1 g_1(x)\mathrm{d}x = \int_0^1 \left(\frac{1}{2}\sum e_q^2 \Delta q(x)\right)\mathrm{d}x = \frac{1}{2}\left(\frac{4}{9}\Delta_1 u + \frac{1}{9}\Delta_1 d + \frac{1}{9}\Delta_1 s\right)$$

$$= \frac{1}{12}\left(\Delta_1 u - \Delta_1 d\right) + \frac{1}{36}\left(\Delta_1 u + \Delta_1 d - 2\Delta_1 s\right) + \frac{1}{9}\left(\Delta_1 u + \Delta_1 d + \Delta_1 s\right)$$

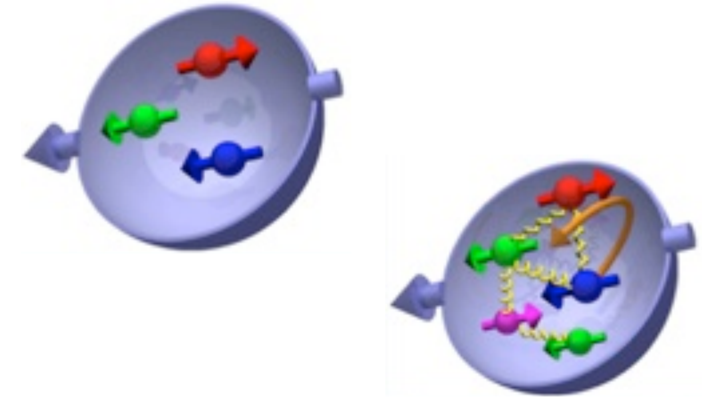
Unique to DIS, $\Delta\Sigma$

Known from weak neutron to proton decay, combined with weak Σ to neutron decay

Known from weak neutron to proton decay

which becomes a prediction if $\Delta_1 s = 0$

DIS - Surprises with Spin



For the proton,

$$\Gamma_1 = \int_0^1 g_1(x)\mathrm{d}x = \int_0^1 \left(\frac{1}{2}\sum e_q^2 \Delta q(x)\right)\mathrm{d}x = \frac{1}{2}\left(\frac{4}{9}\Delta_1 u + \frac{1}{9}\Delta_1 d + \frac{1}{9}\Delta_1 s\right)$$

$$= \frac{1}{12}(\Delta_1 u - \Delta_1 d) + \frac{1}{36}\underbrace{(\Delta_1 u + \Delta_1 d - 2\Delta_1 s)}_{a_8 \;=\; 3F-D \;=\; 0.59\pm 0.03} + \frac{1}{9}(\Delta_1 u + \Delta_1 d + \Delta_1 s)$$

✓ 9%

Known from weak neutron to proton decay,
combined with weak ∑ to neutron decay

Unique to DIS, ΔΣ

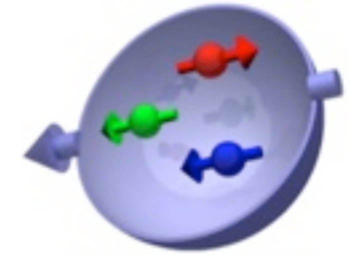
Since,

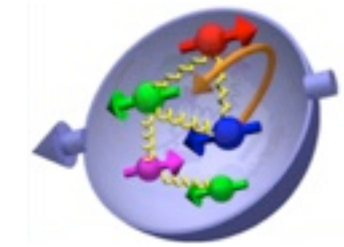
$$\left.\frac{\partial\Gamma_1}{\partial a_8}\right|_{\mathrm{Ellis-Jaffe}} \simeq \frac{5}{36}$$

$$\left.\frac{\partial\Gamma_1}{\partial a_8}\right|_{\mathrm{experiment}} \simeq 0$$

} one can recover the E-J expectation with a *sizable* shift of $a_8 = 3F - D,\ a_8 \simeq 0.2 \pm 0.1$

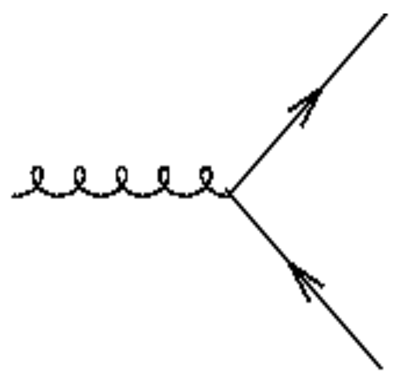
DIS - Surprises with Spin





Numerous follow-up questions and experiment programs,

Among the early attempts at a resolution,



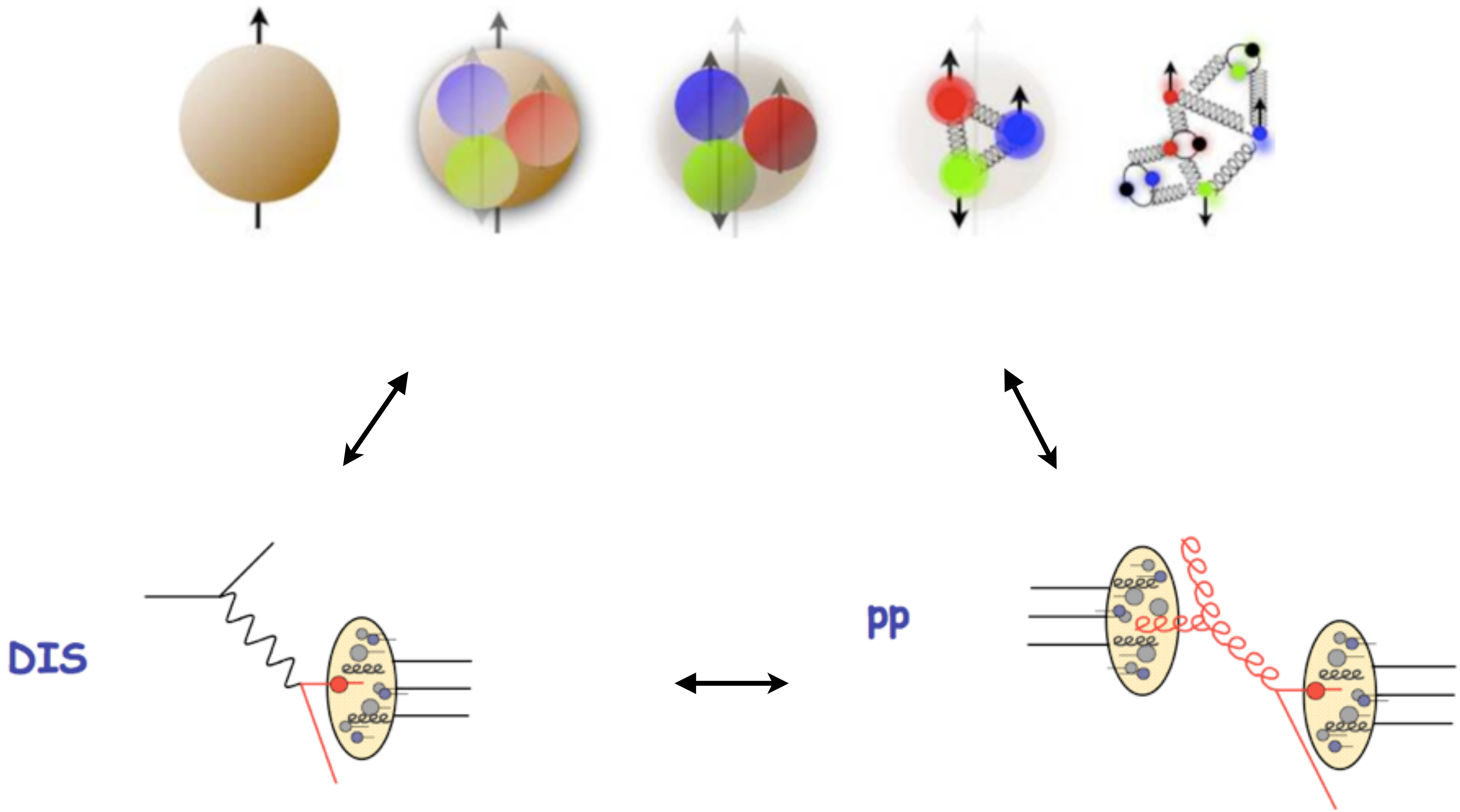
with the gluons *polarized*.

G. Altarelli and G.G. Ross Phys. Lett. **B212** (1998) 391

Note: this attempt requires *very* significant polarization, *factors* larger than the nucleon spin itself, and by inference, *huge* compensating orbital momenta.

Other attempts include e.g extrapolation over unmeasured low-x.

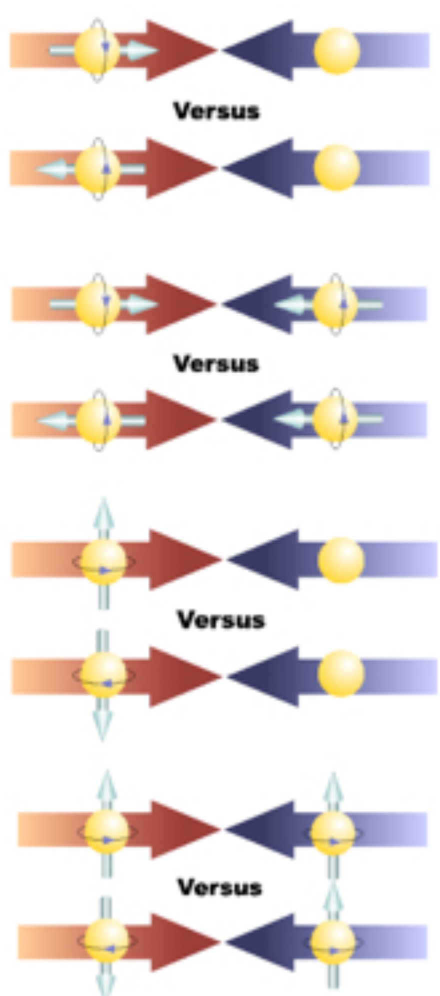
II - Insights from RHIC

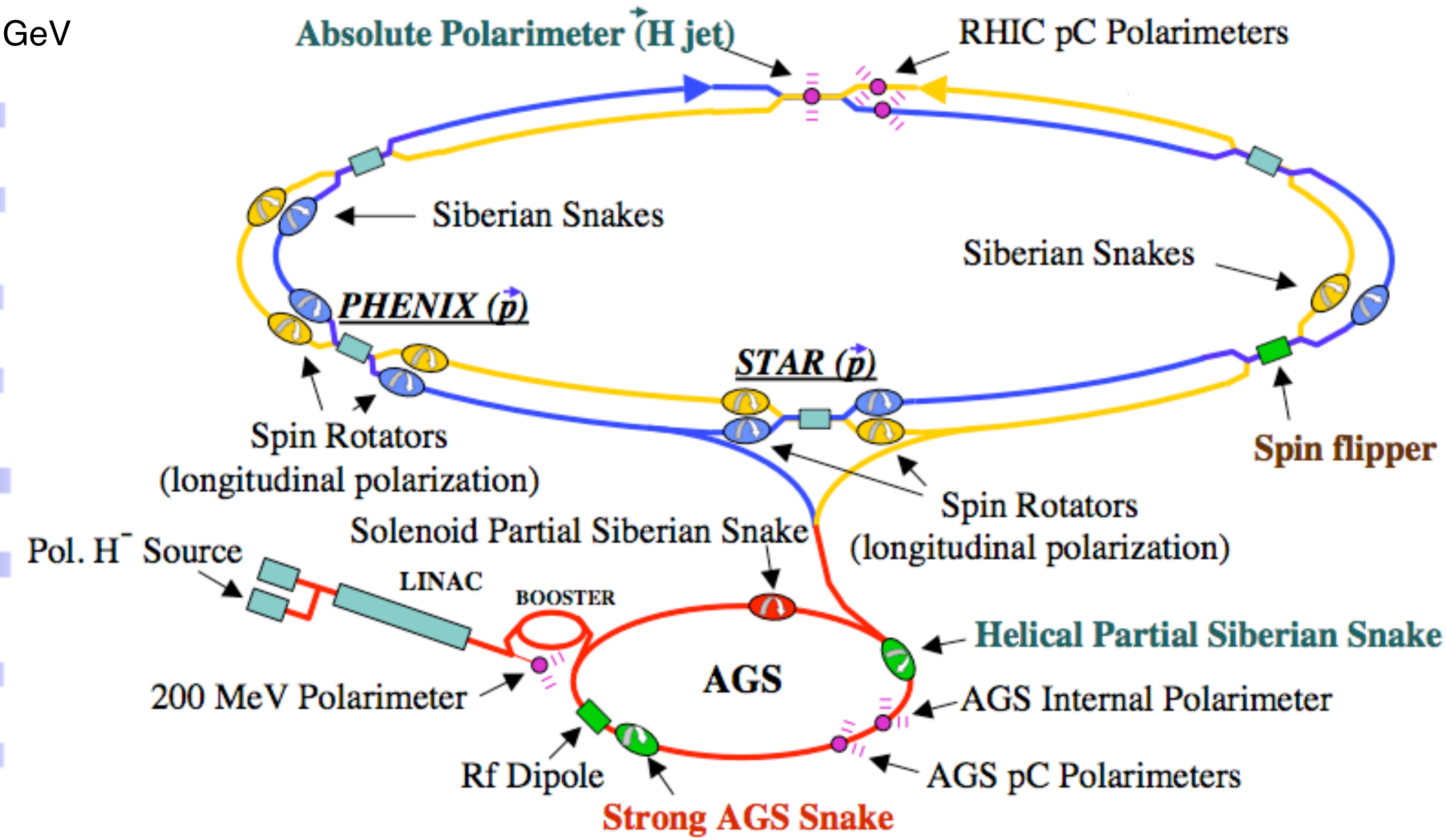

DIS
pp

RHIC - Polarized Proton-Proton Collider

Unique opportunities to study nucleon spin properties and spin in QCD,

$\sqrt{s}$ = 62, 200, and 500 GeV



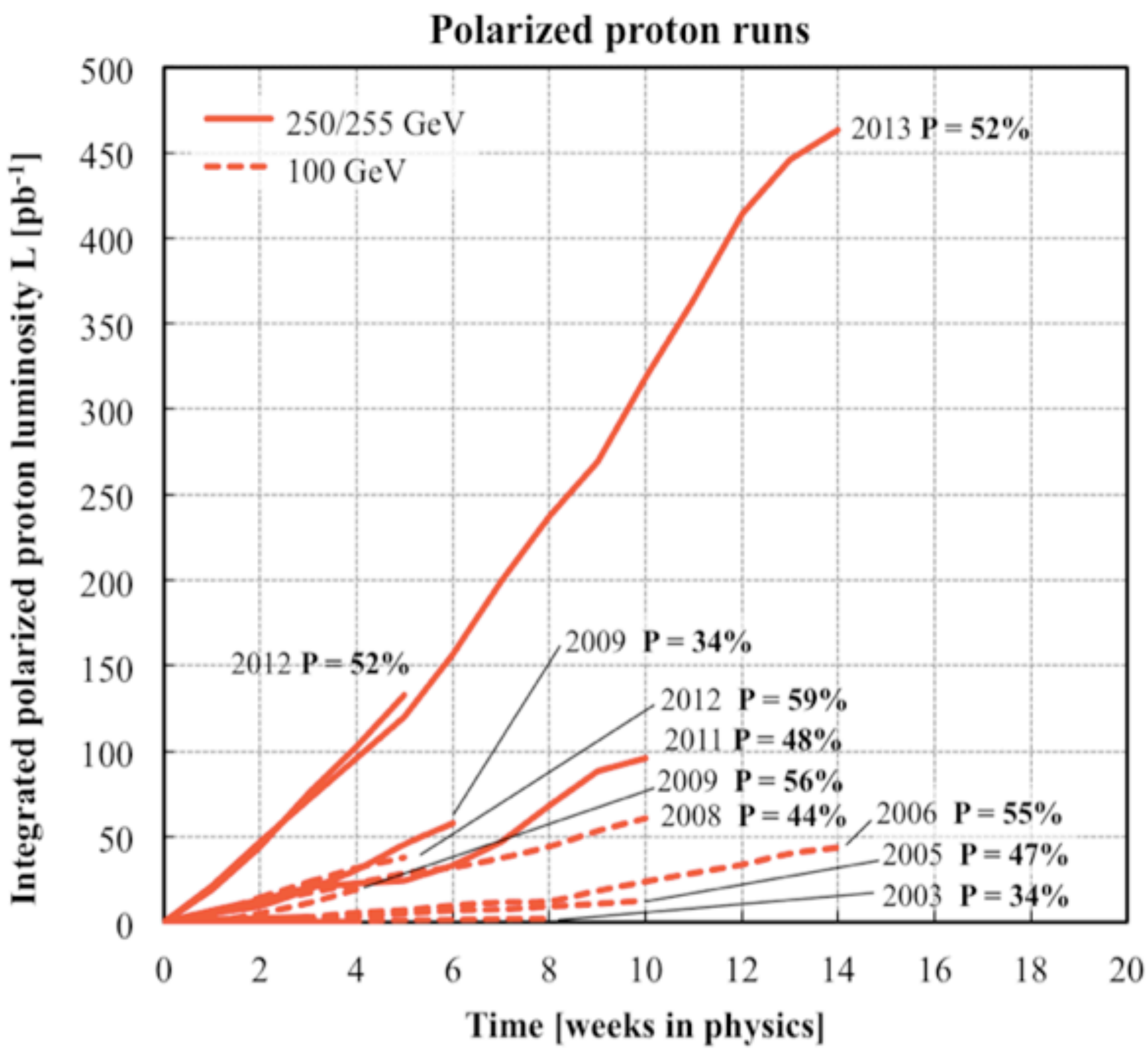


at hard (perturbative) scales with good systematic controls, e.g. from the ~100ns succession of beam bunches with alternating beam spin configurations.

RHIC - Polarized Proton-Proton Collider

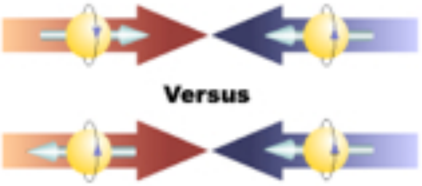
Unique opportunities to study nucleon spin properties and spin in QCD,

Longitudinal data	**STAR**
√s = **200 GeV**	
2005	
2006	35 pb^{-1}
2009	
(2015)	(50 pb^{-1})
√s = **500 GeV**	
2009	
2011	
2012	400 pb^{-1}
2013	
Transverse data	
√s = **200 GeV**	
2006	
2008	38 pb^{-1}
2012	
(2015)	(50 pb^{-1})
√s = **500 GeV**	
2011	25 pb^{-1}
(2017)	(400 pb^{-1})



50-60% polarization

II - Insights from RHIC: Gluon Polarization



Gluon Polarization at RHIC

Measure double longitudinal spin asymmetries and establish the factorized framework,

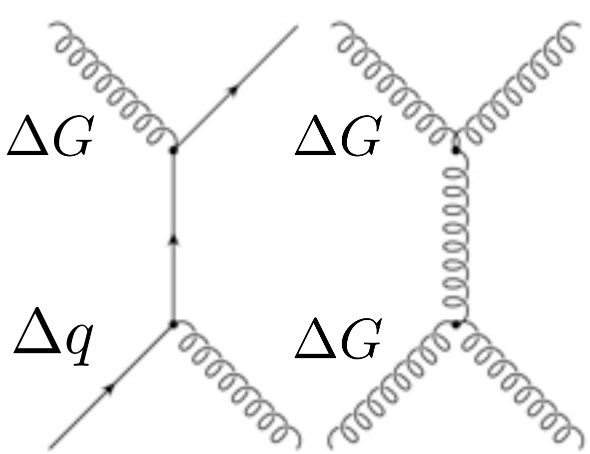
$$A_{LL} = \frac{\sigma^{\uparrow\uparrow} - \sigma^{\uparrow\downarrow}}{\sigma^{\uparrow\uparrow} + \sigma^{\uparrow\downarrow}} \overset{?}{=} \sum_{f=q,g} \frac{\Delta f_1}{f_1} \otimes \frac{\Delta f_2}{f_2} \otimes \hat{a}_{LL} \otimes (\text{fragmentation functions})$$

Start with abundantly produced jets or pions at mid-rapidity, where the partonic asymmetries are sizable,

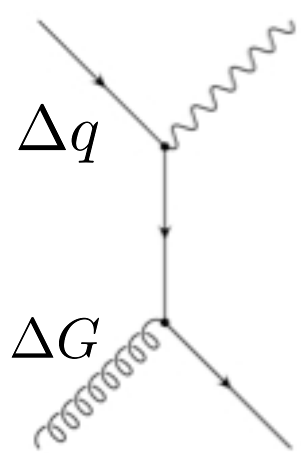
Gluon-gluon scattering contribution dominates up to jet $p_T \sim 8$ GeV, where quark-gluon scattering takes over,

Path: precision, coverage, sensitivity to initial kinematics, and selective probes.

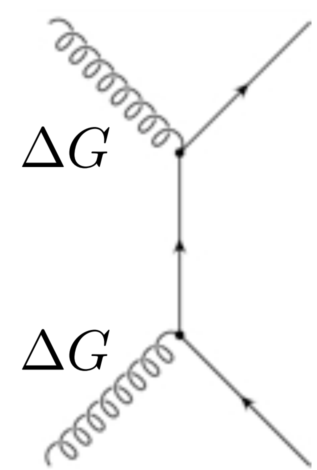
$\vec{p} + \vec{p} \rightarrow \text{jet(s)} + X$

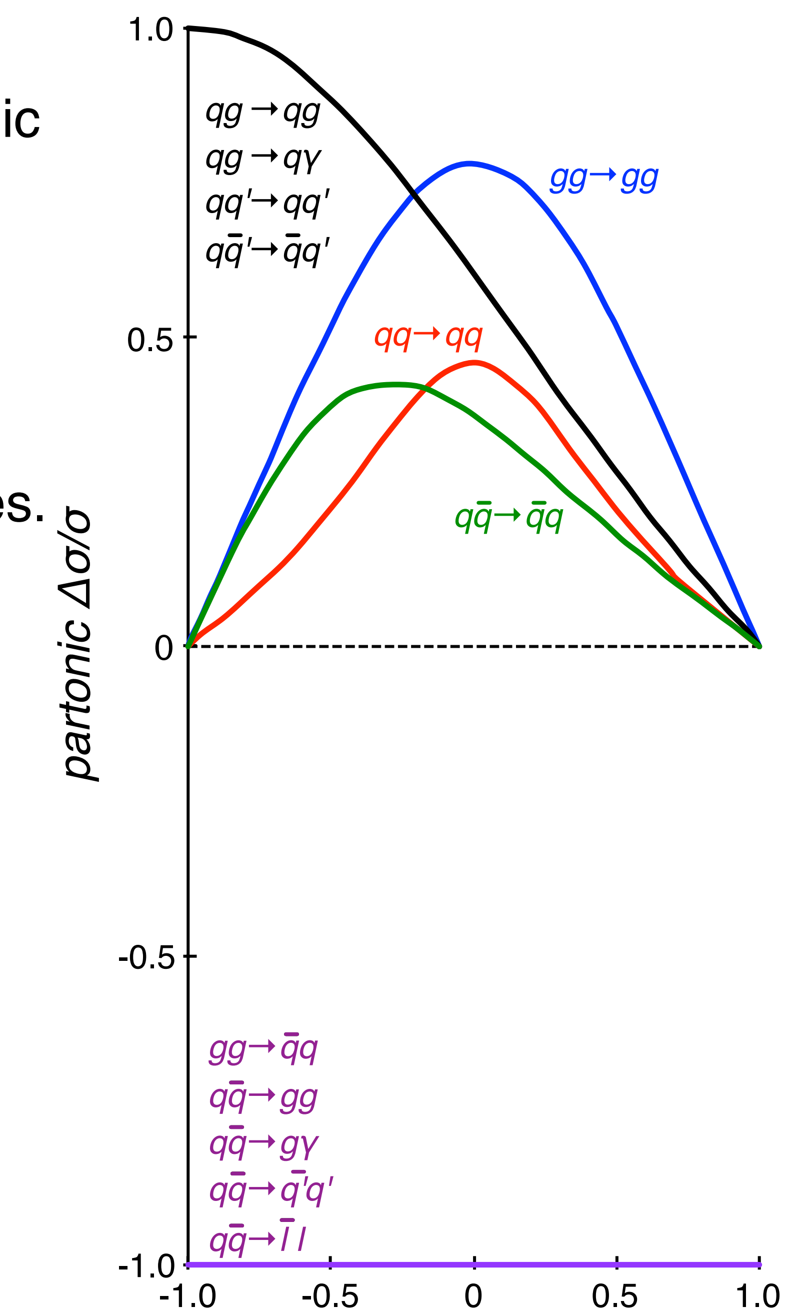


$\vec{p} + \vec{p} \rightarrow \gamma + \text{jet}$



$\vec{p} + \vec{p} \rightarrow c\bar{c}, b\bar{b} + X$

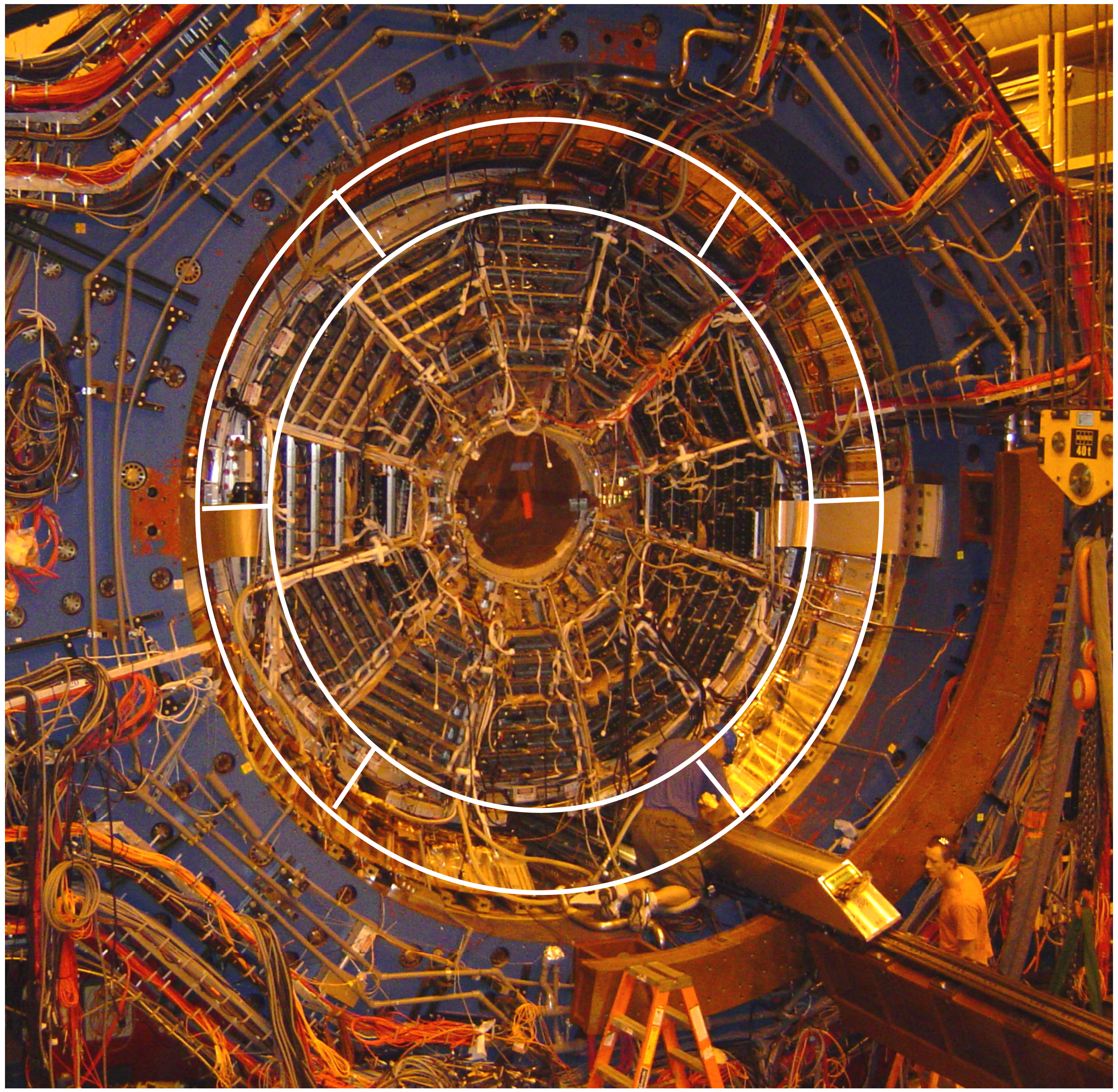


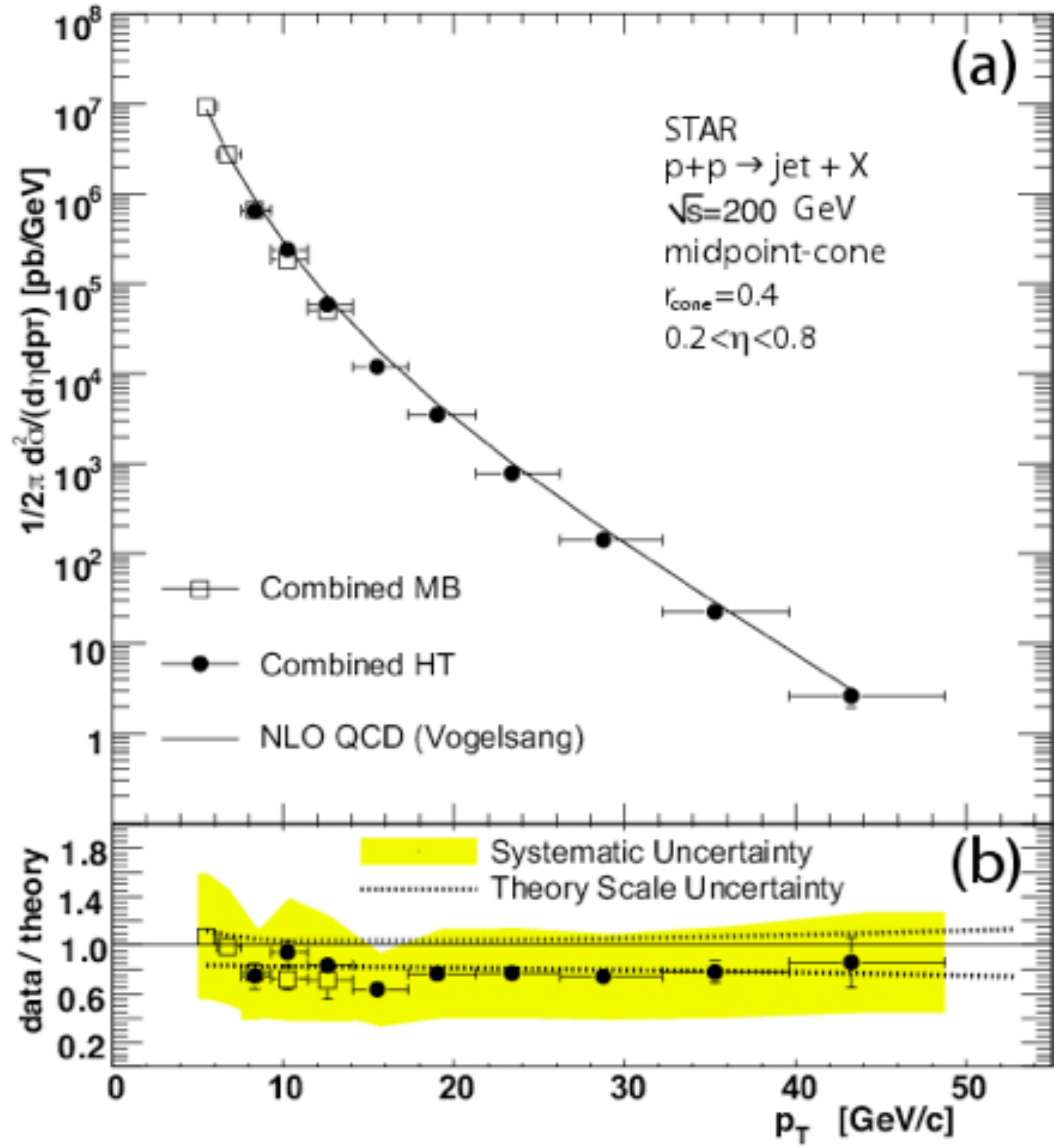


$$\mathcal{L} \simeq 3 - 8 \cdot 10^2\,\text{pb}^{-1}, \quad P = 0.4 - 0.7, \quad \sqrt{s} = 200 - 500\,\text{GeV}$$

→ time

Gluon Polarization at STAR - Inclusive Jets



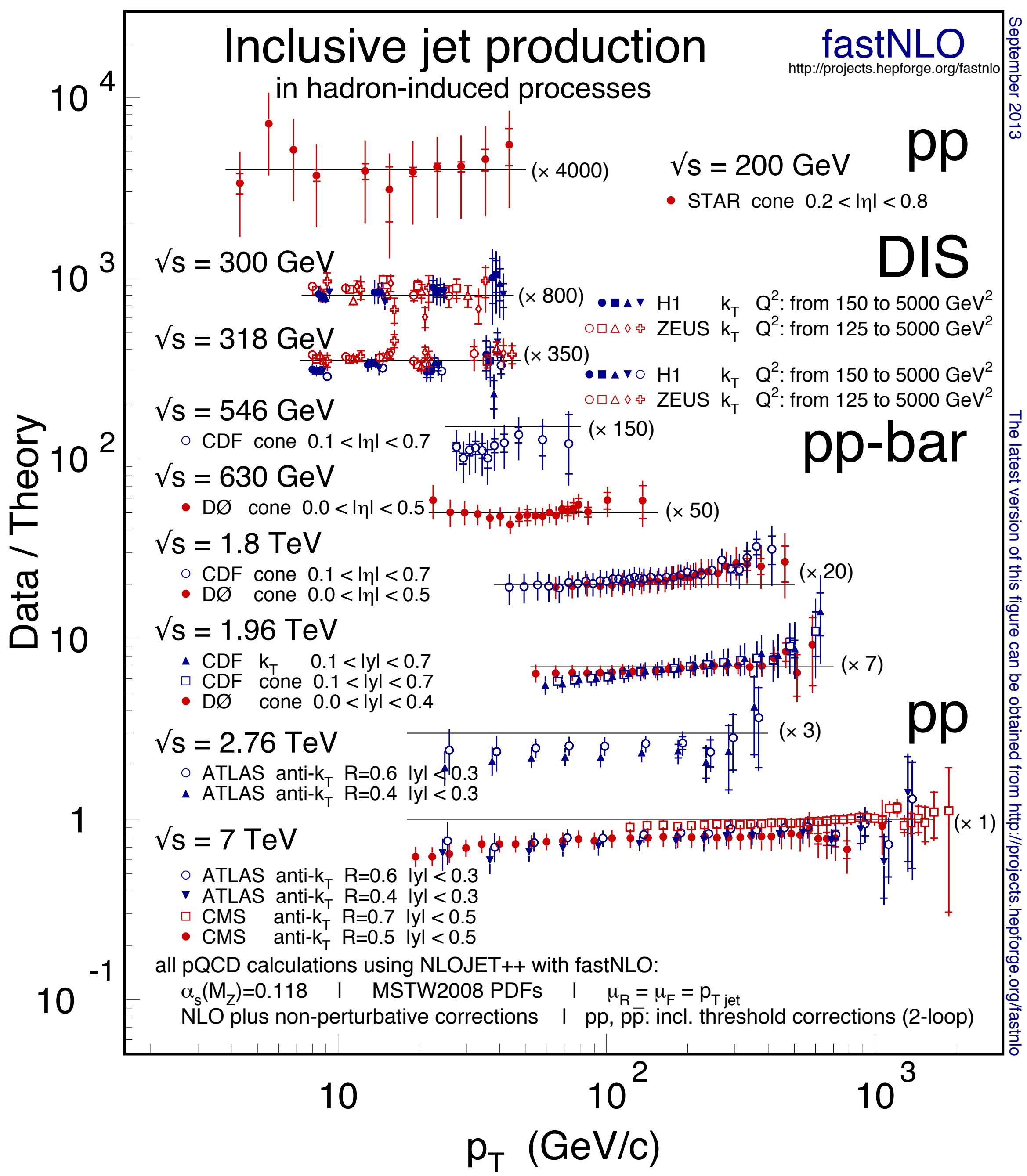


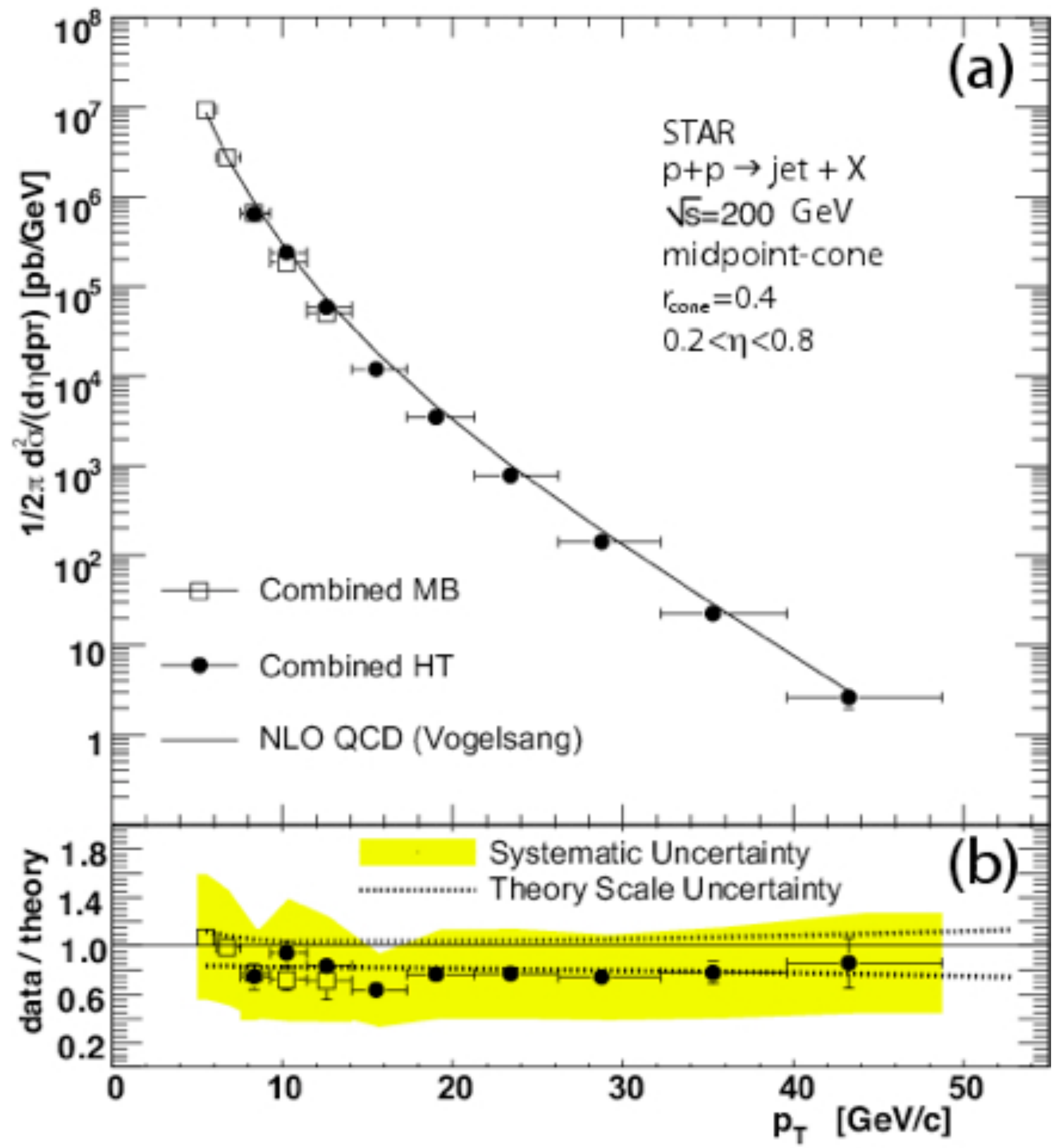
TPC: - charged track measurement over 2+ units in pseudo-rapidity

Phys. Rev. Lett. 97, 252001 (2006)

EMCs: - neutral energy measurement over an even wider range,
- triggering

Gluon Polarization at STAR - Inclusive Jets





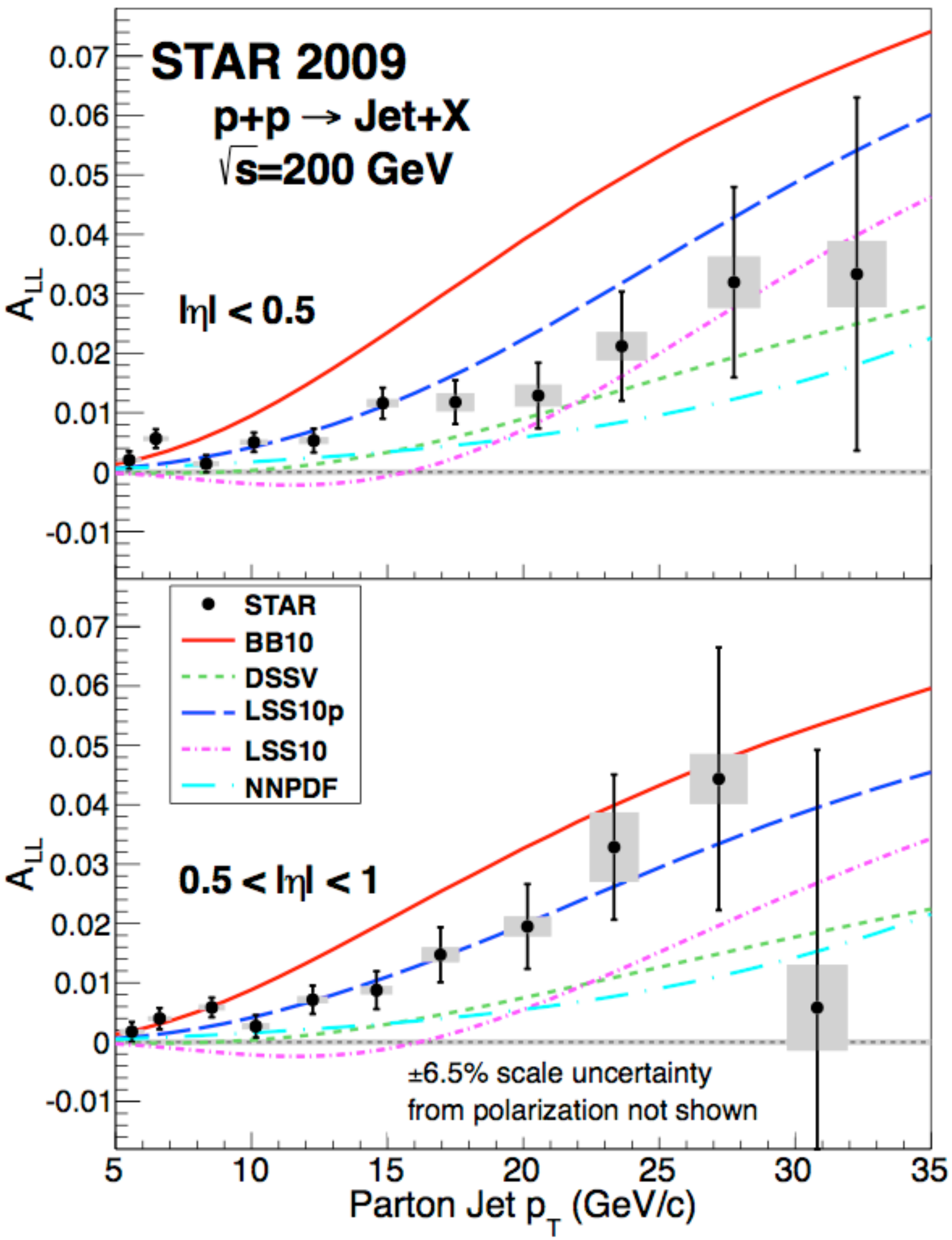
Phys. Rev. Lett. 97, 252001 (2006)

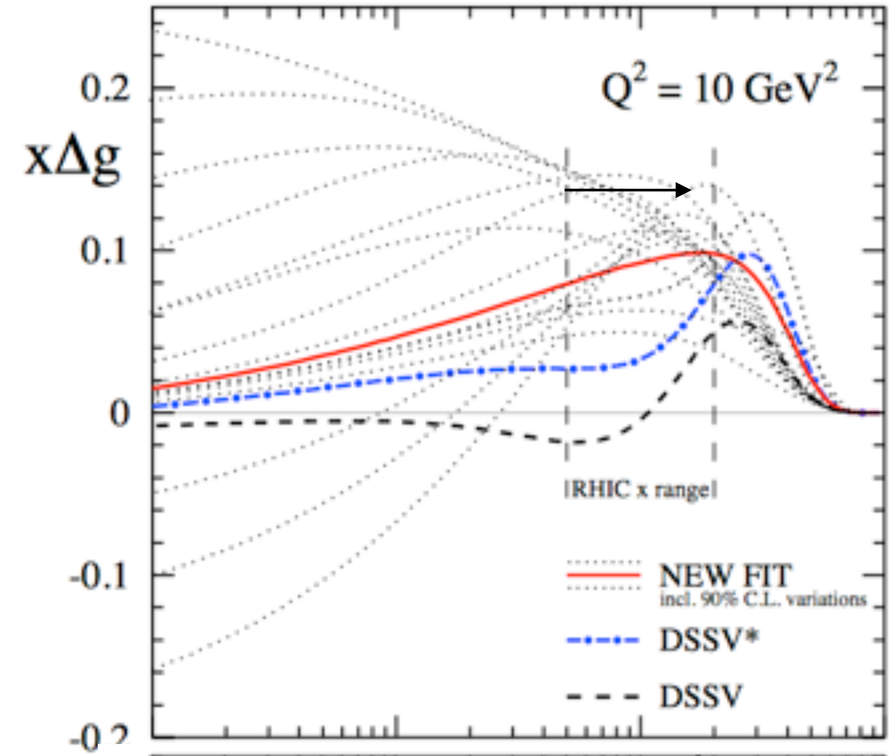
STAR is uniquely suited, at RHIC, for central-rapidity jet measurements,

Measured cross section is well-described by perturbative QCD evaluation at NLO.

Gluon Polarization from RHIC

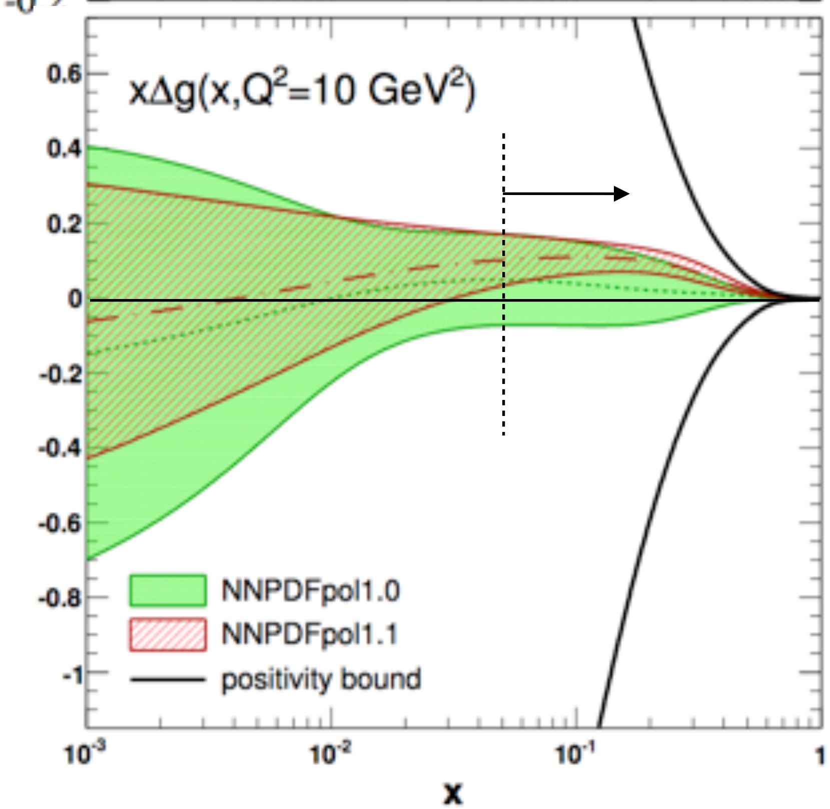
Phys.Rev.Lett 115 (2015) 092002





0.20 ± 0.07

DSSV, ArXiv:1404.4293



0.21 ± 0.10

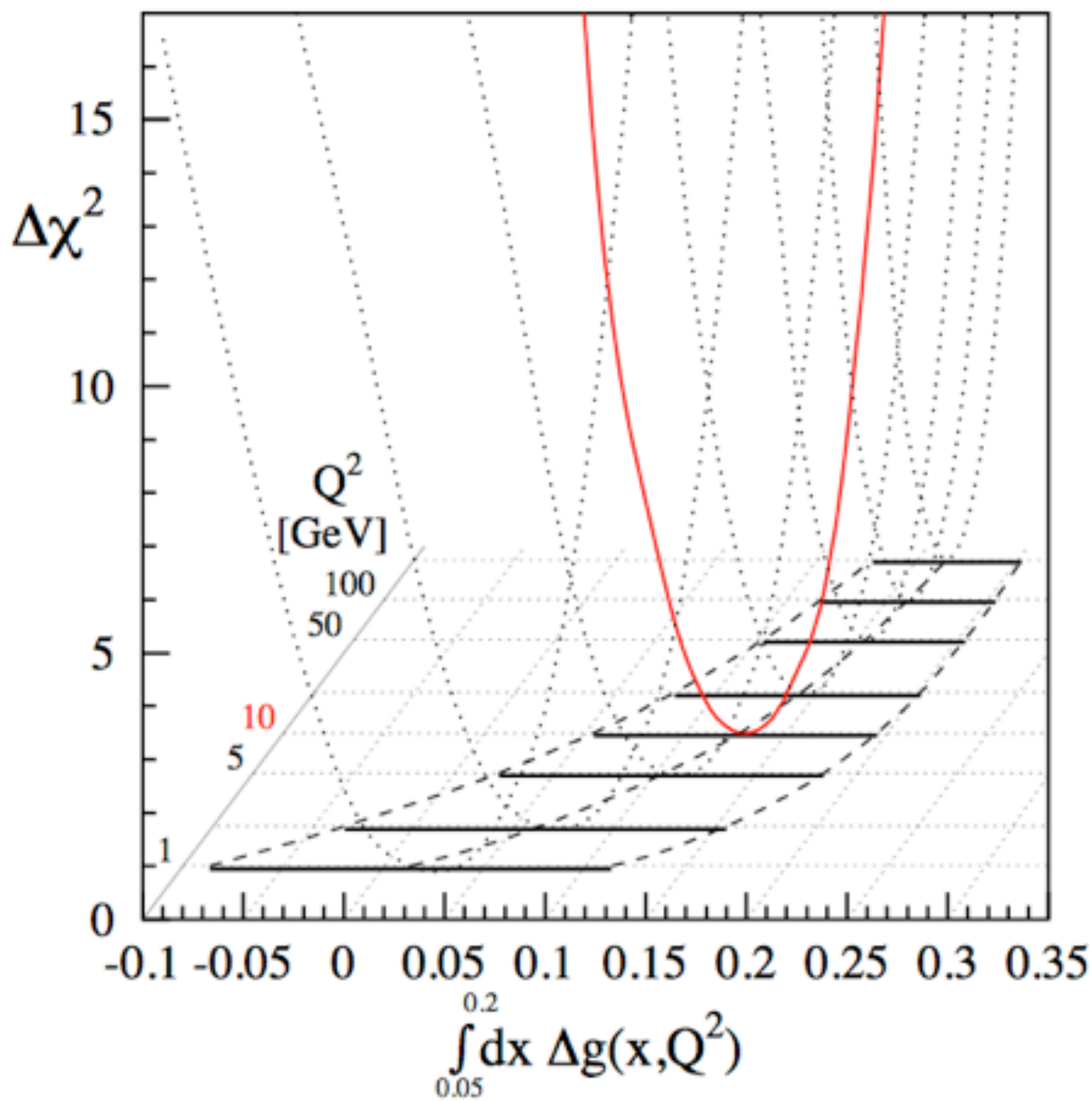
NNPDF, DIS 2014

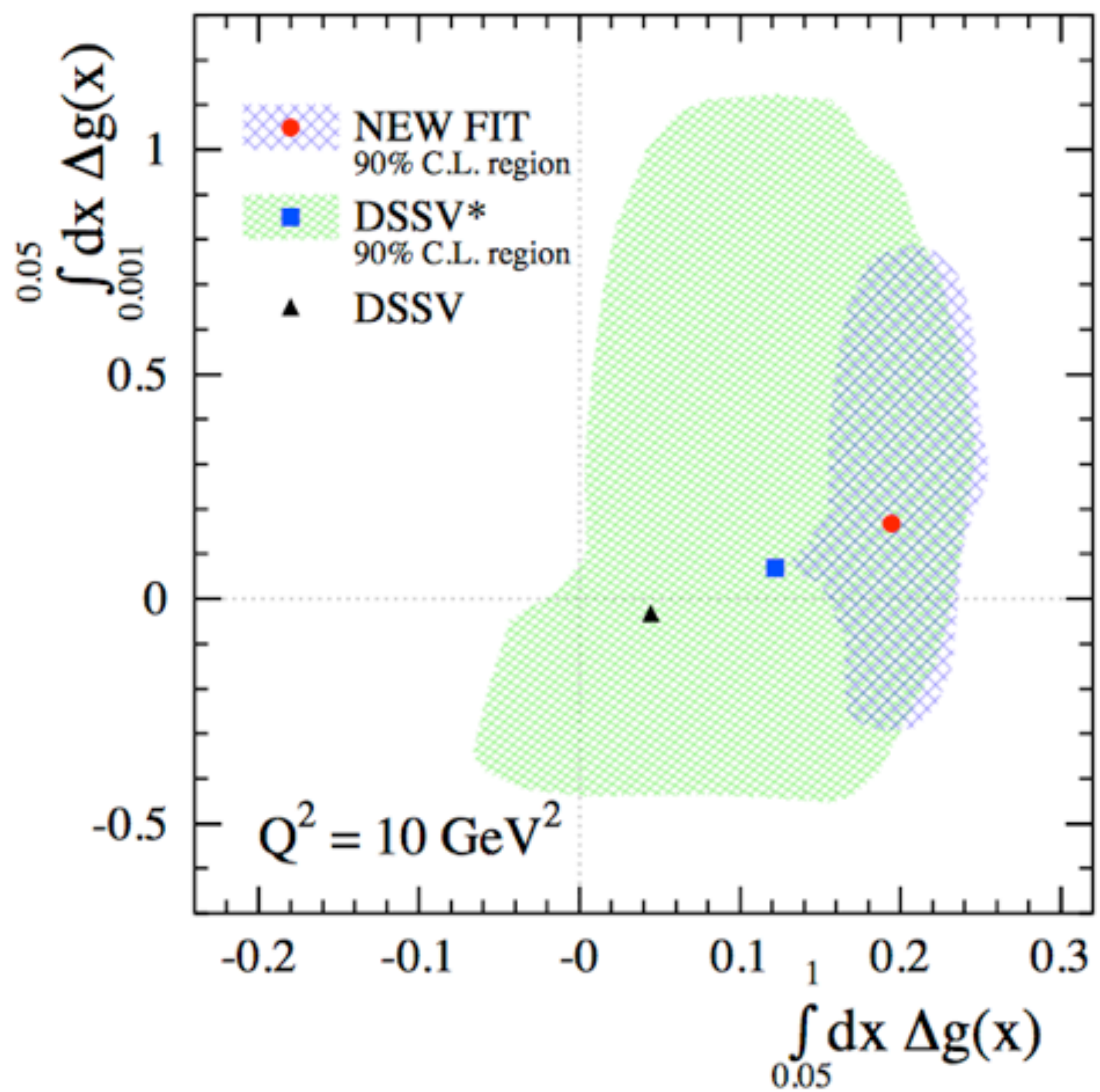
Gluon polarization is positive in the region of the data; ~0.2 ħ

Gluon Polarization - DSSV

Some properties of the DSSV polarized gluon:

DSSV, ArXiv:1404.4293

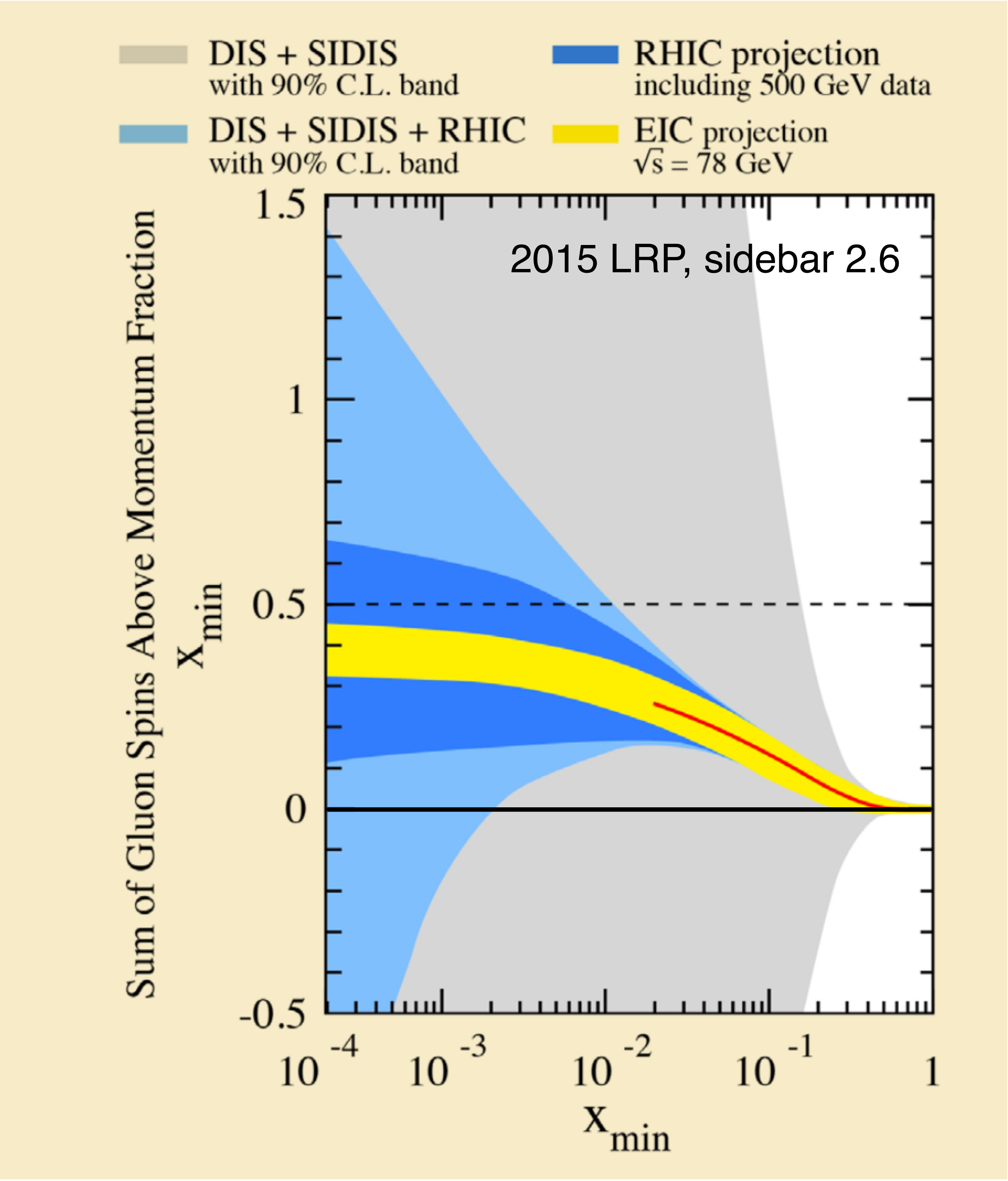




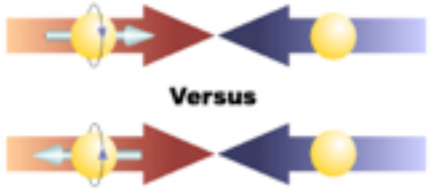
Strong scale dependence in the measured region

Easy to "hide" 1 ħ in the unmeasured region

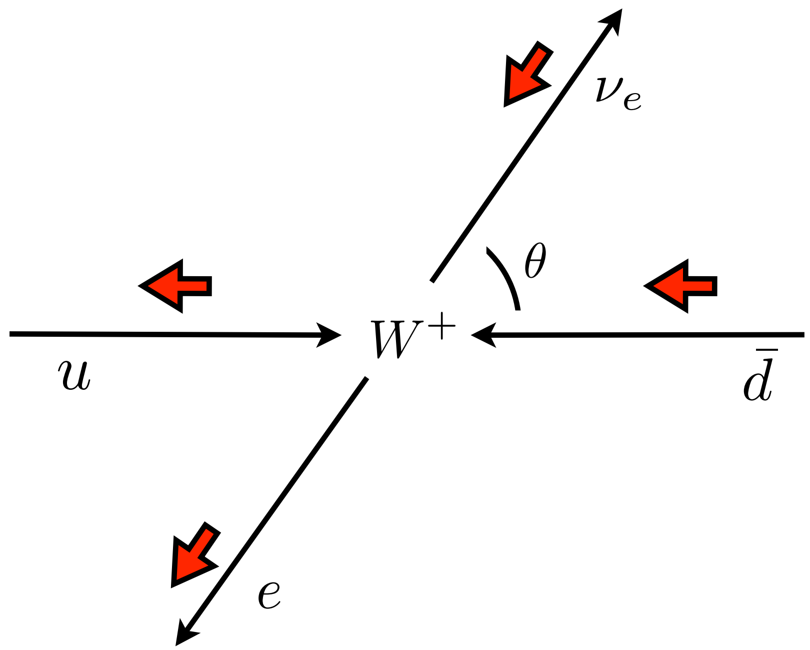
Gluon Polarization - Status and Prospects



Insights from RHIC: Quark Polarization



Quark Polarization at RHIC



$\sqrt{s}$ = 500 GeV above W production threshold,

Experiment Signature:

large p_T lepton, missing E_T

Experiment Challenges:

charge-ID at large Irapidityl
electron/hadron discrimination
luminosity hungry

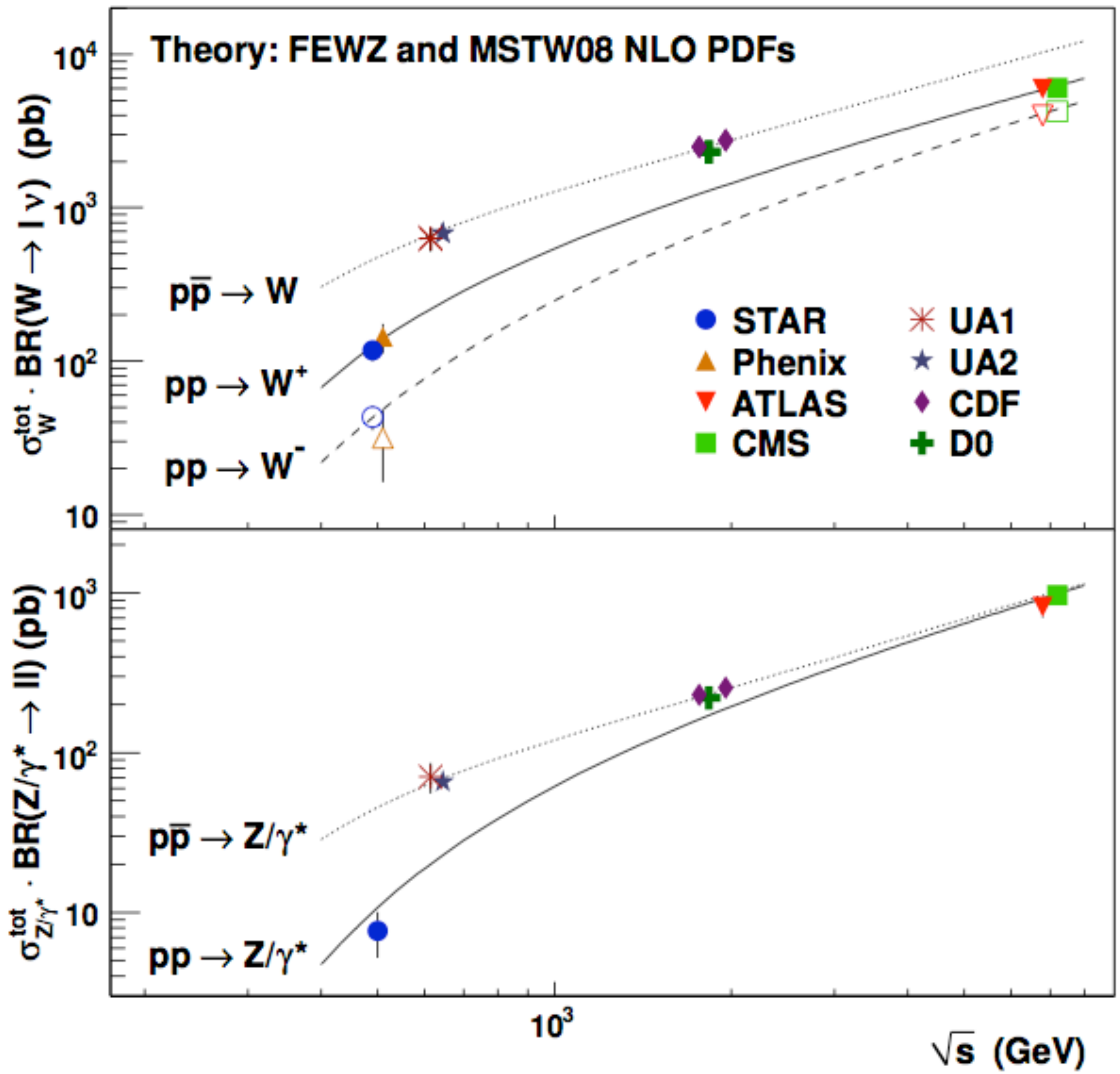
$$\Delta\sigma^{\text{Born}}(\vec{p}p \to W^+ \to e^+\nu_e) \propto -\Delta u(x_a)\bar{d}(x_b)(1+\cos\theta)^2 + \Delta\bar{d}(x_a)u(x_b)(1-\cos\theta)^2$$

Spin Measurements:

$$A_L(W^+) = \frac{-\Delta u(x_a)\bar{d}(x_b) + \Delta\bar{d}(x_a)u(x_b)}{u(x_a)\bar{d}(x_b) + \bar{d}(x_a)u(x_b)} = \begin{cases} -\dfrac{\Delta u(x_a)}{u(x_a)}, & x_a \to 1 \\ \dfrac{\Delta\bar{d}(x_a)}{\bar{d}(x_a)}, & x_b \to 1 \end{cases}$$

$$A_L(W^-) = \begin{cases} -\dfrac{\Delta d(x_a)}{d(x_a)}, & x_a \to 1 \\ \dfrac{\Delta\bar{u}(x_a)}{\bar{u}(x_a)}, & x_b \to 1 \end{cases}$$

W and *Z* Production Cross Sections



PHENIX: first W^+ and W^- production cross sections in proton-proton collisions, Phys.Rev.Lett. **106** (2011) 062001,

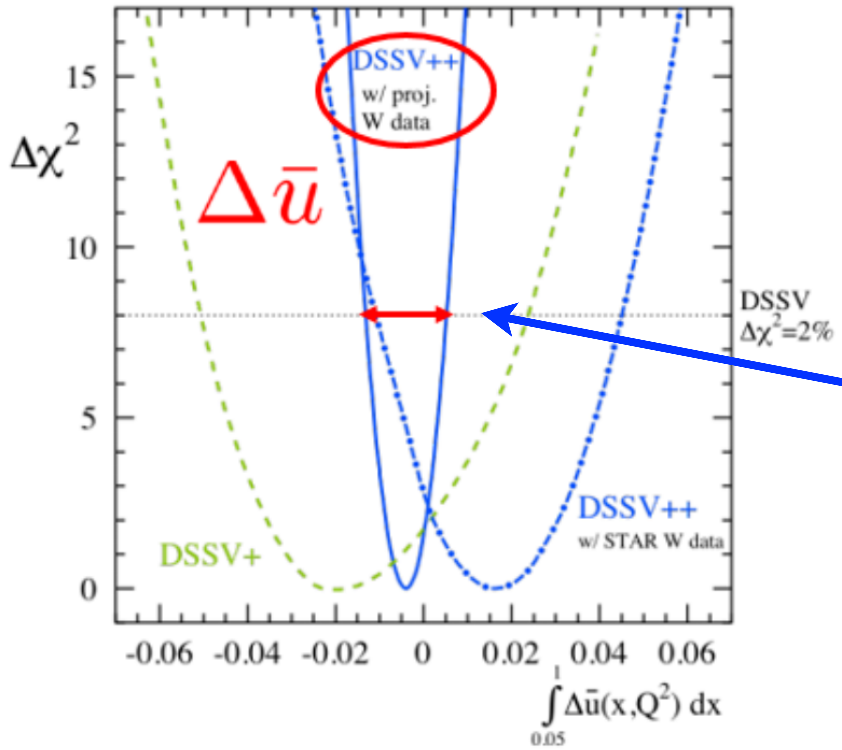
STAR: Initial NC cross section at RHIC, confirmation of PHENIX CC cross section measurements, Phys. Rev. **D85** (2012).

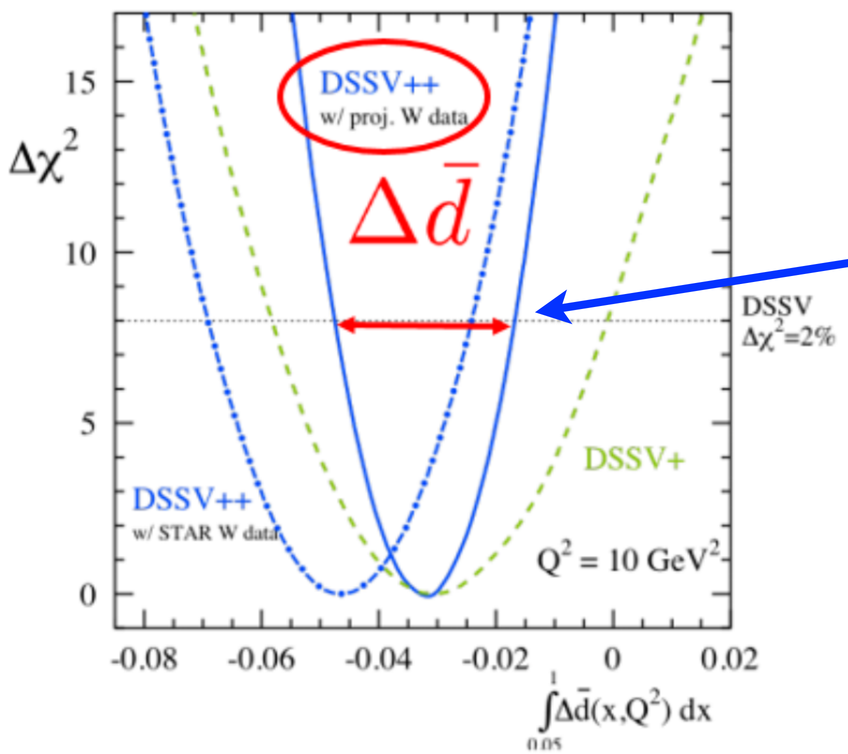
Data are well-described by NLO pQCD theory (FEWZ + MSTW08),

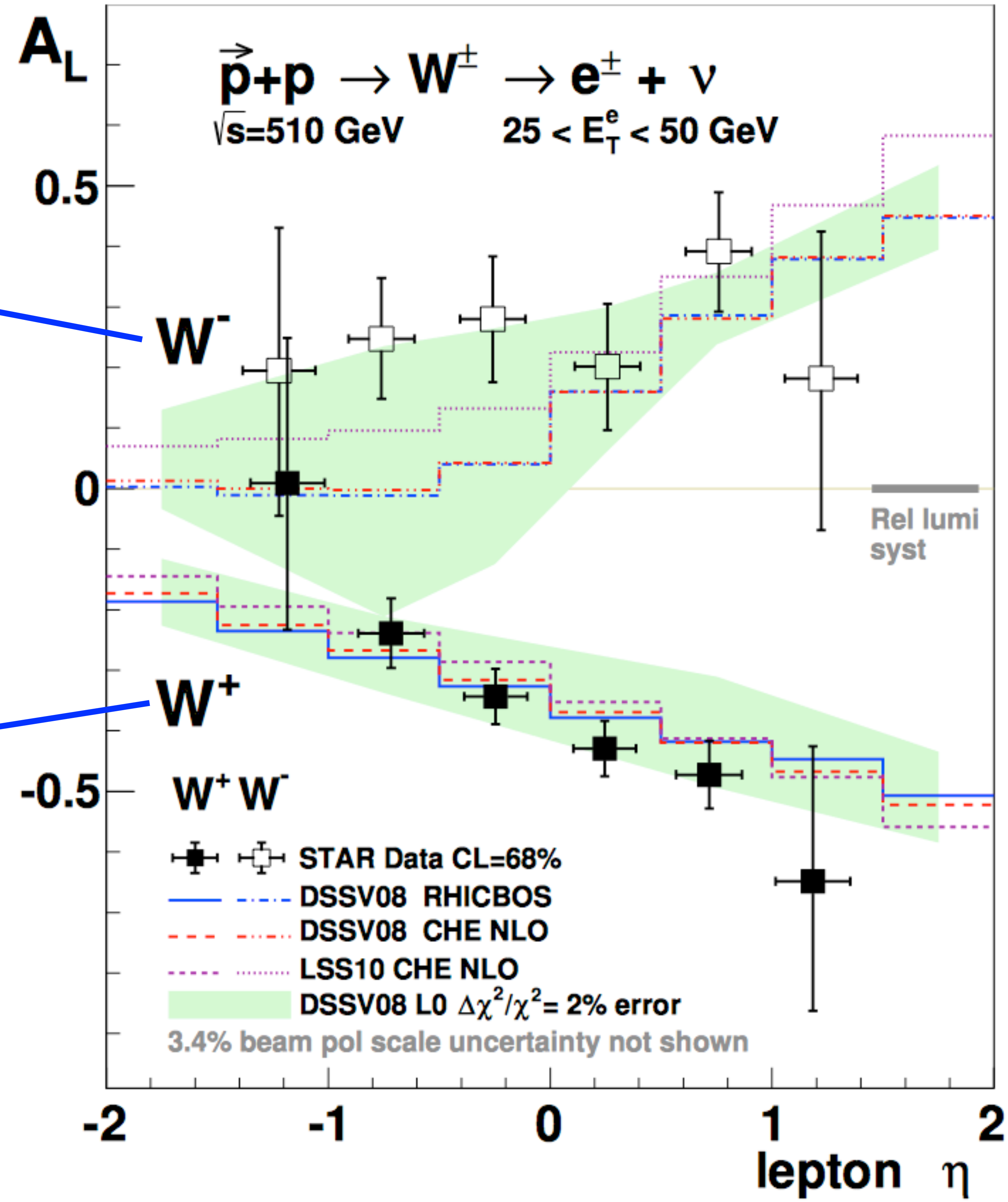
Necessary condition to interpret asymmetry measurements,

Future ratio measurements may provide insights in unpolarized light quark distributions

Quark Polarization at √s = 500 GeV

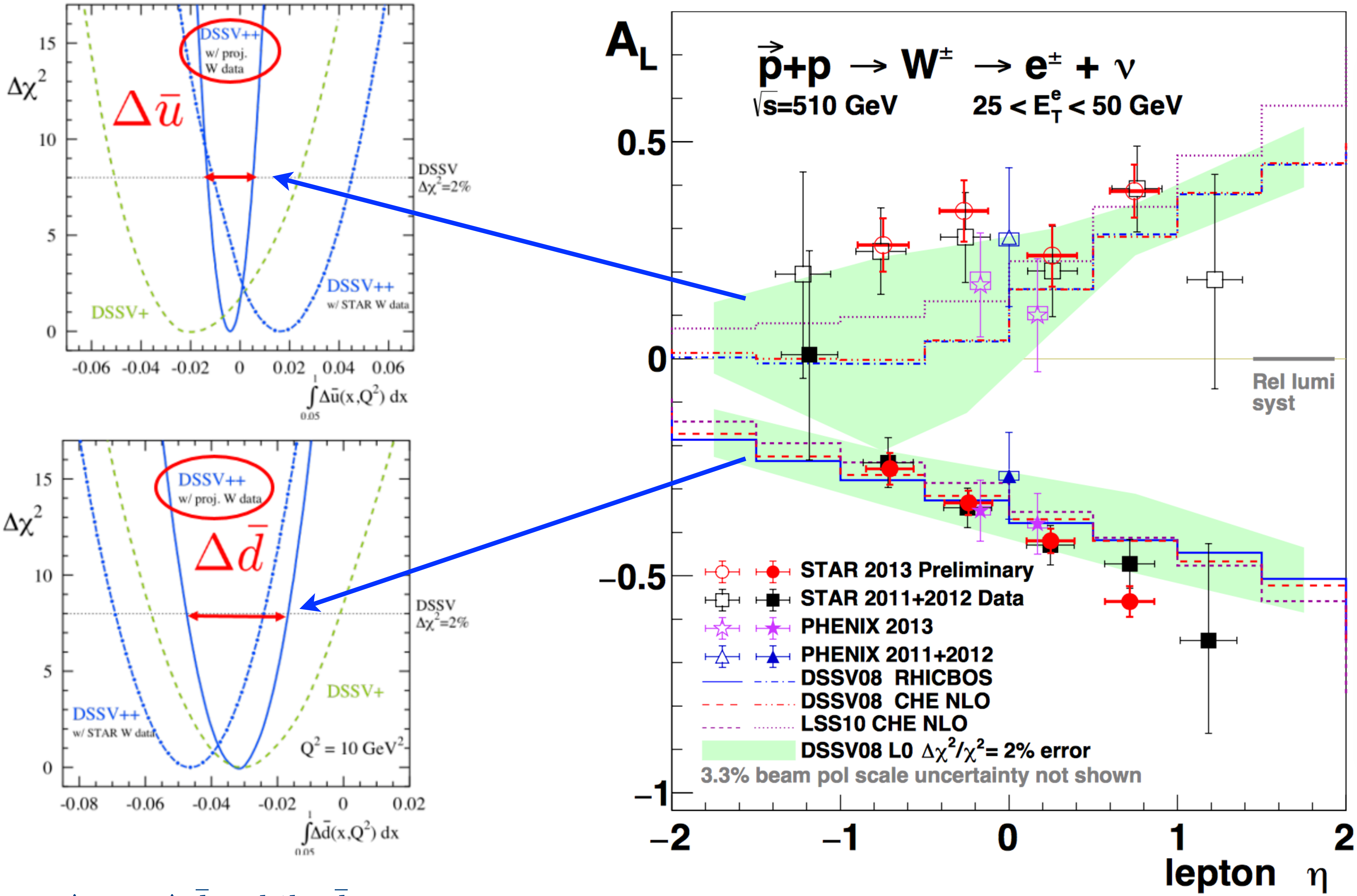






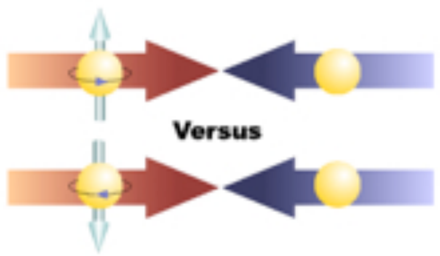
$\Delta\bar{u} > \Delta\bar{d}$, while $\bar{d} > \bar{u}$

Quark Polarization at √s = 500 GeV

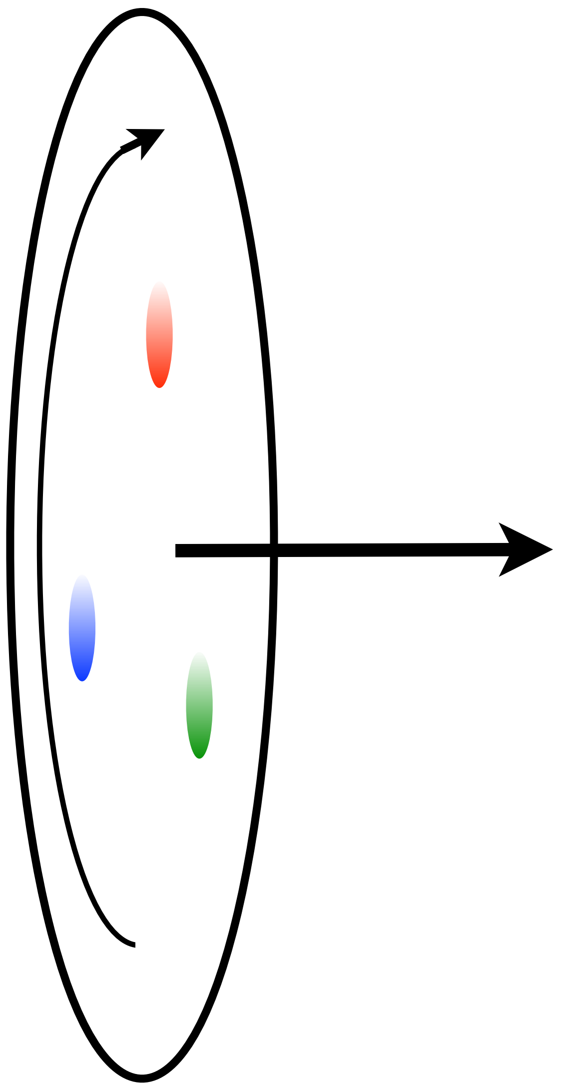


$\Delta\bar{u} > \Delta\bar{d},\ \text{while}\ \bar{d} > \bar{u}$

Insights from RHIC: Transverse Spin Phenomena

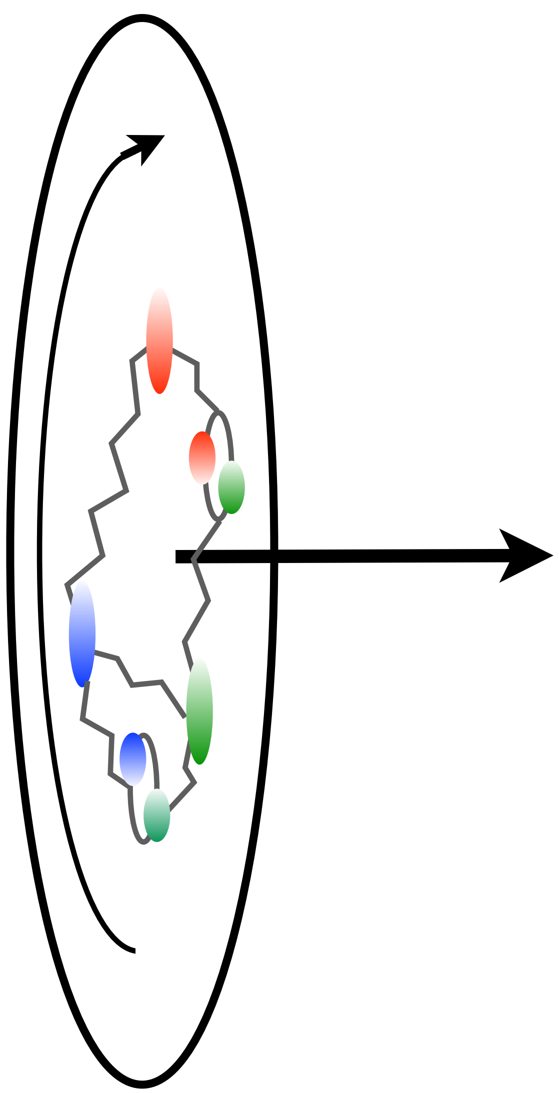


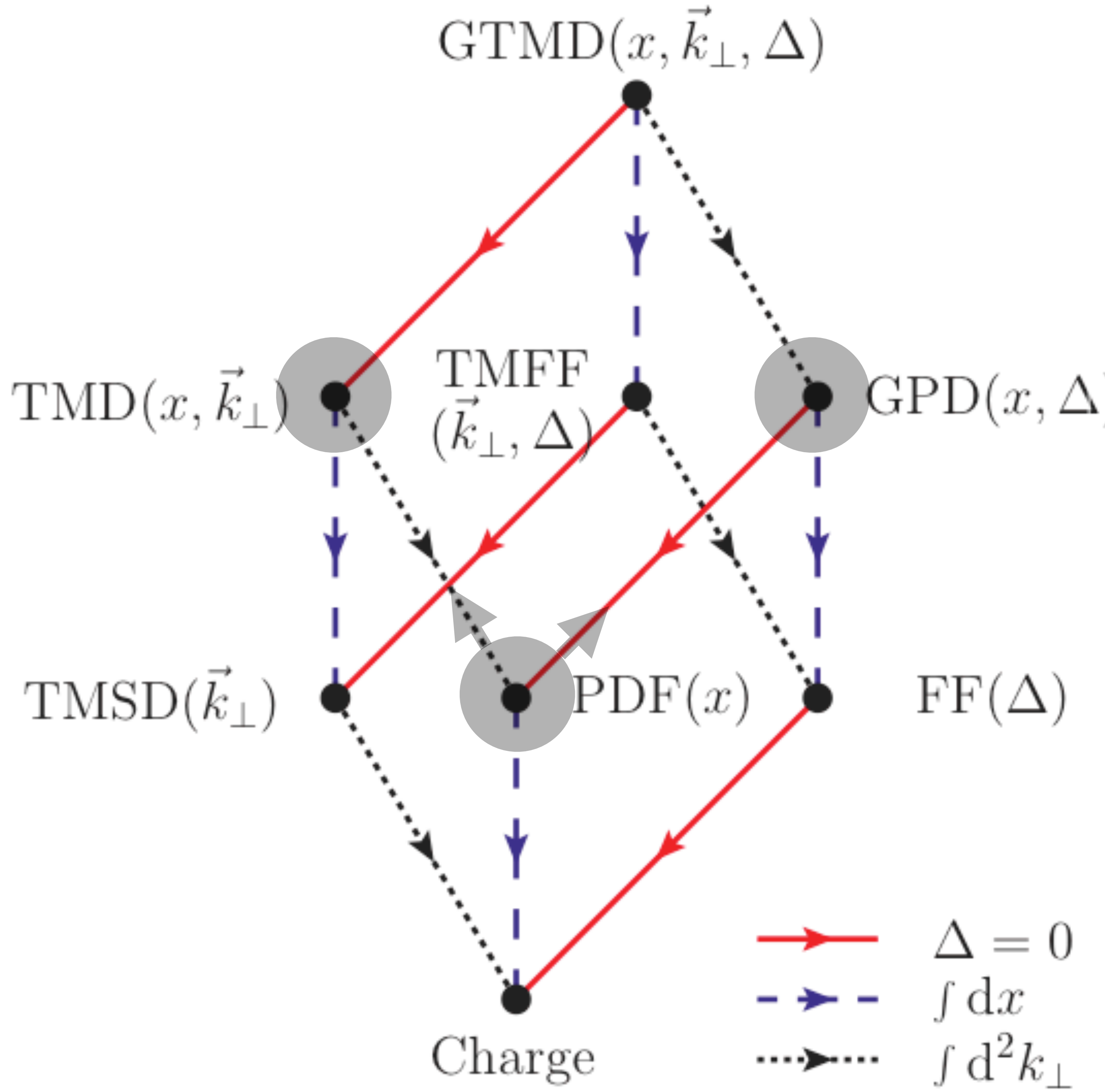
Beyond Helicity Distributions...



Simple concepts become involved...

Beyond Helicity Distributions...



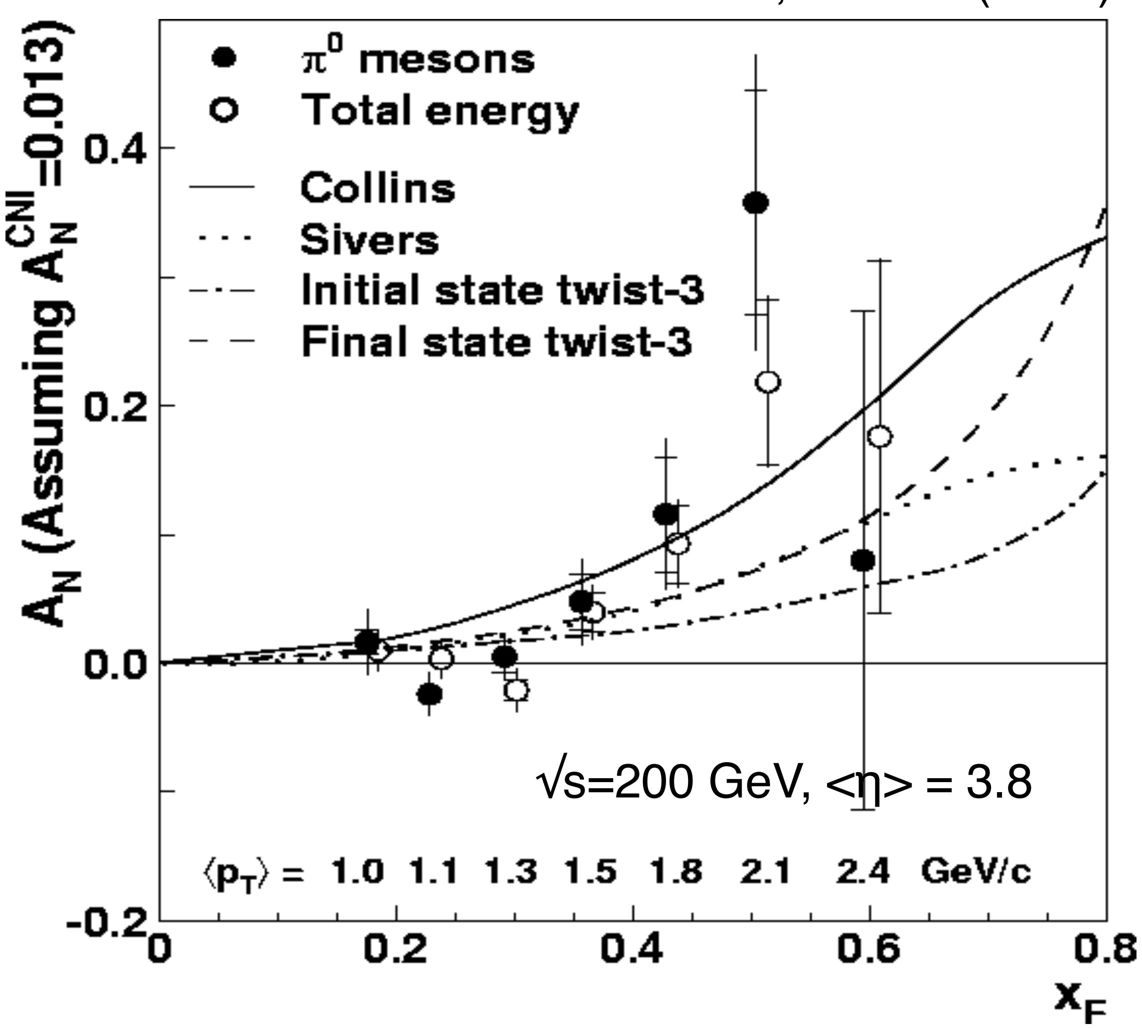


Lorce, Pasquini, Vanderhaeghen

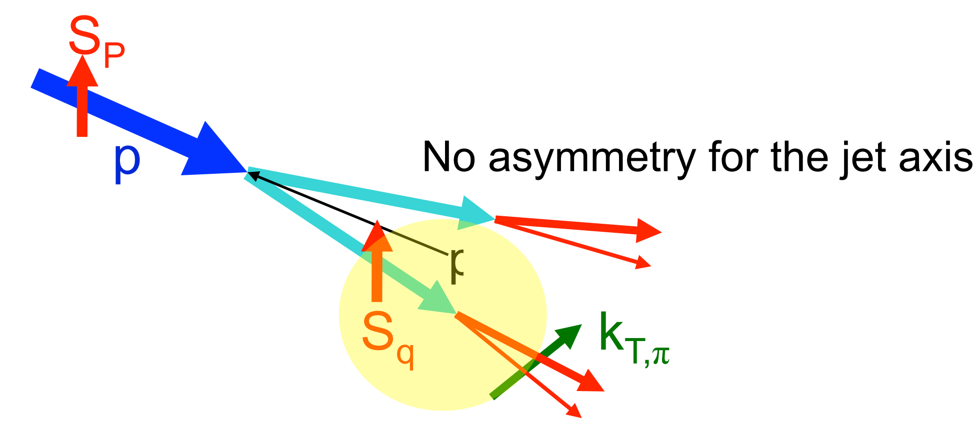
Transverse Spin Phenomena - A_N

Previously observed large A_N persist at $\sqrt{s}$ = 200 GeV,

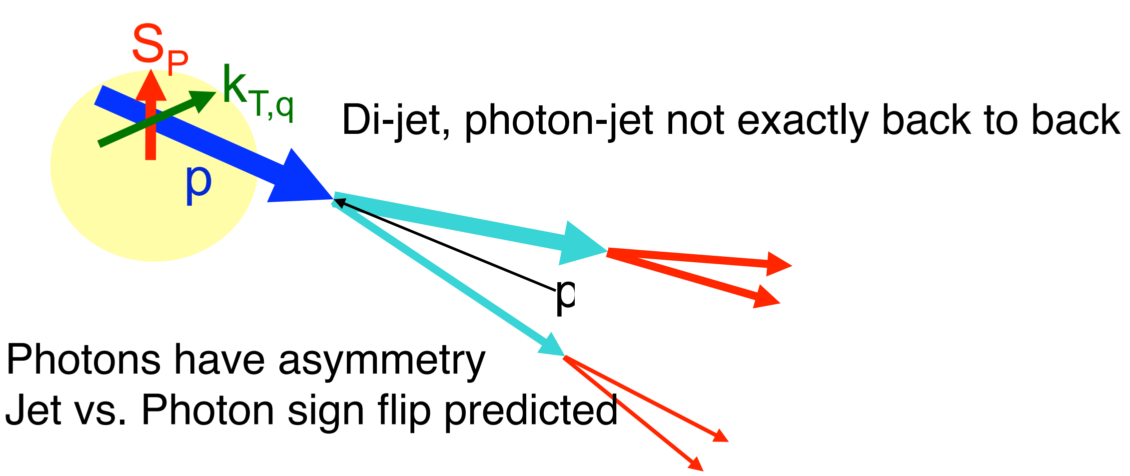
PRL 92, 171801 (2004)



• **Collins effect**: asymmetry comes from the transversity and the spin dependence of jet fragmentation.



• **Sivers effect**: asymmetry comes from spin-correlated k_T in the initial parton distribution

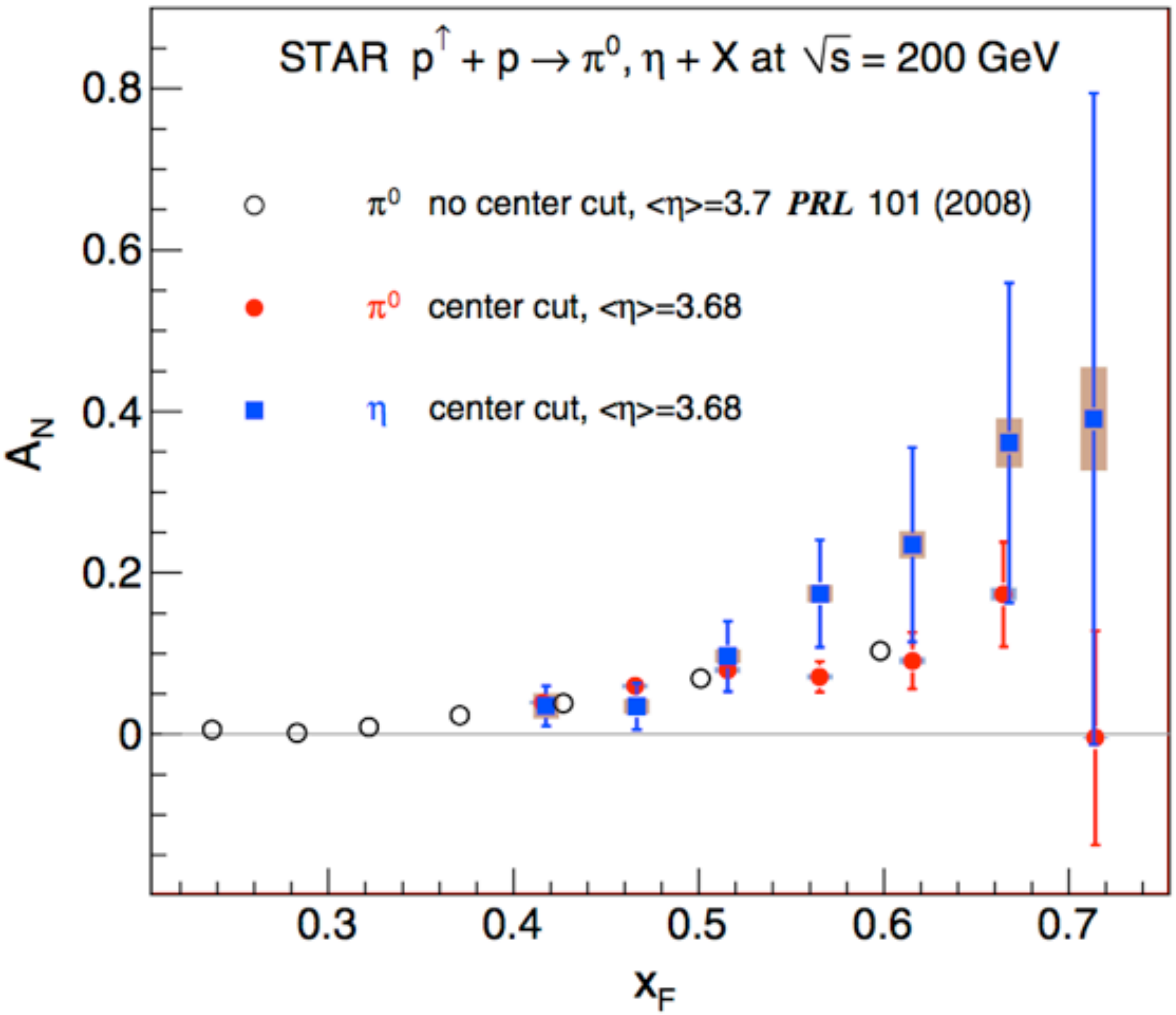


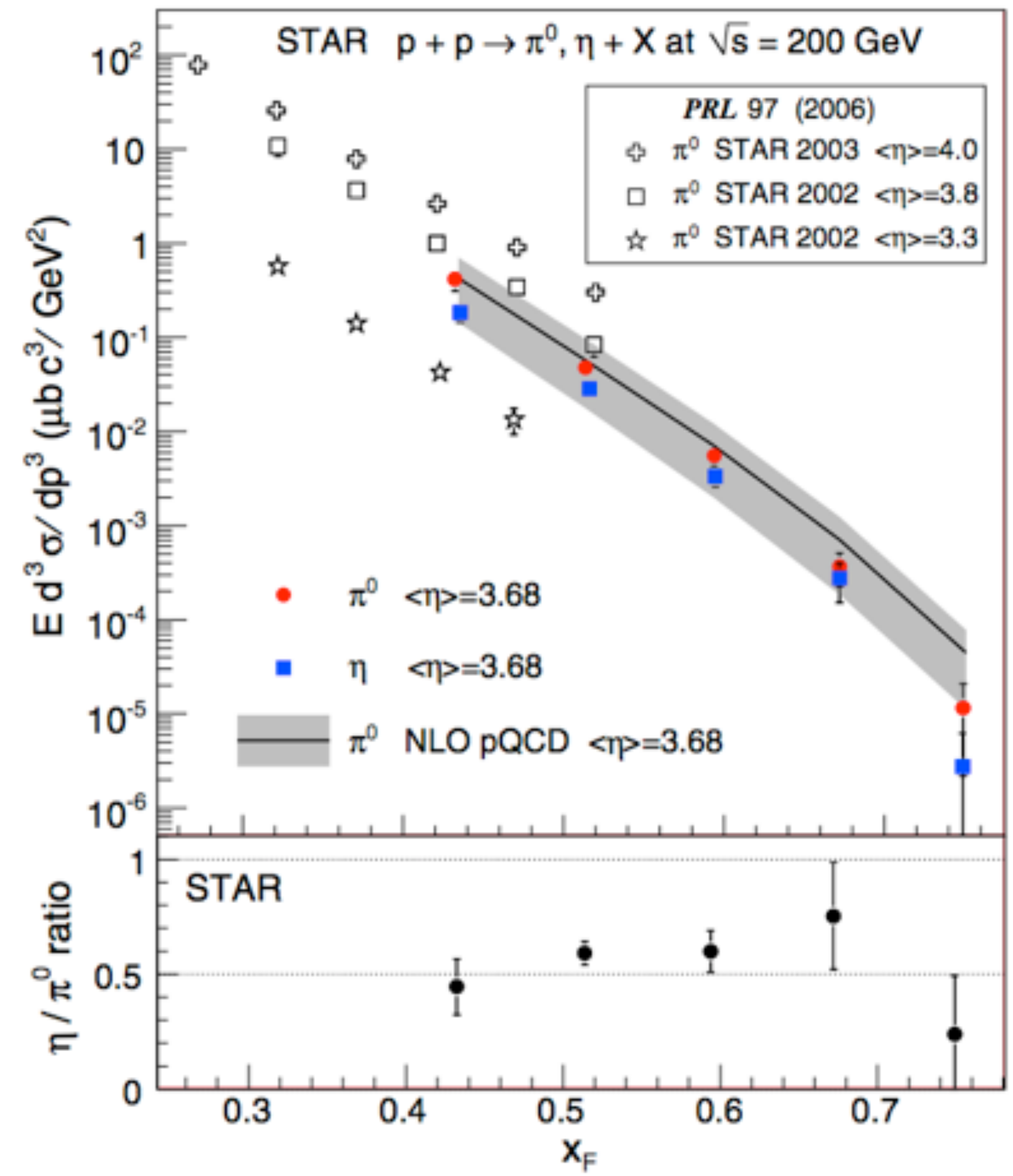
• **Other (?)**

Renewed interest in transverse spin phenomena in hadroproduction.

Transverse Spin Phenomena - A_N

Surprisingly, the η asymmetry is quite possibly even larger than π^0 A_N:

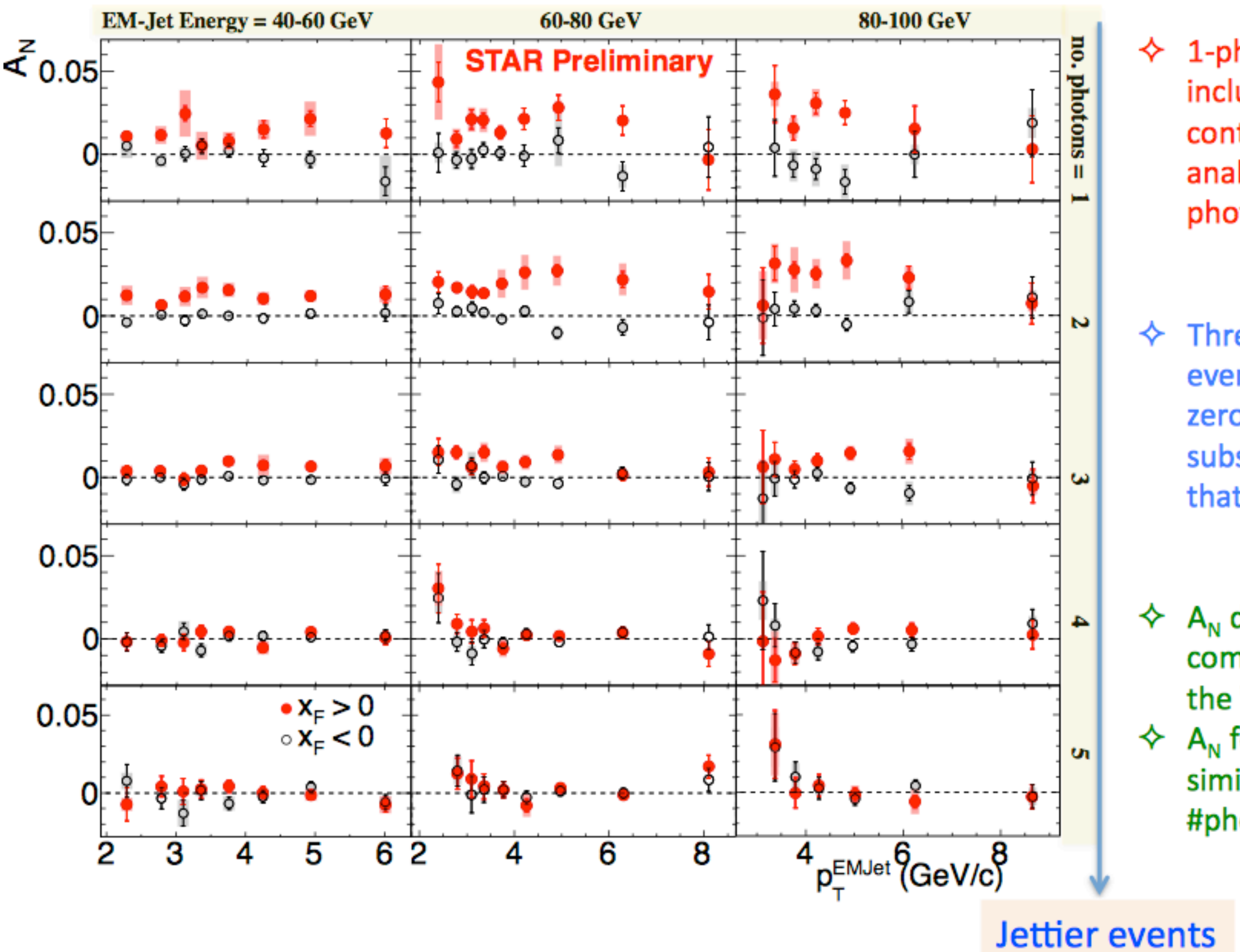




Phys. Rev. **D86** (2012) 051101(R)

An intricate role for (anti-)strange quarks, also here?

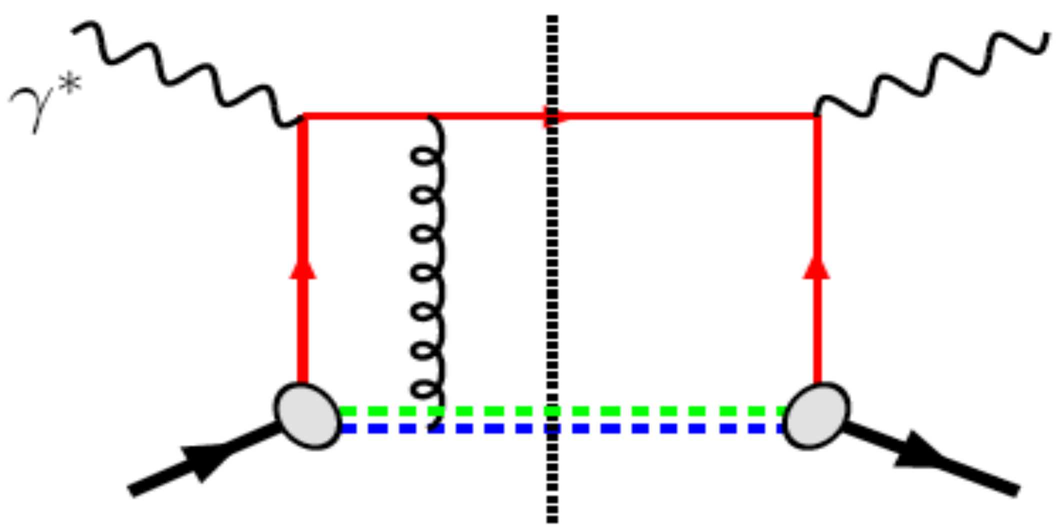
Transverse Spin Phenomena - A_N



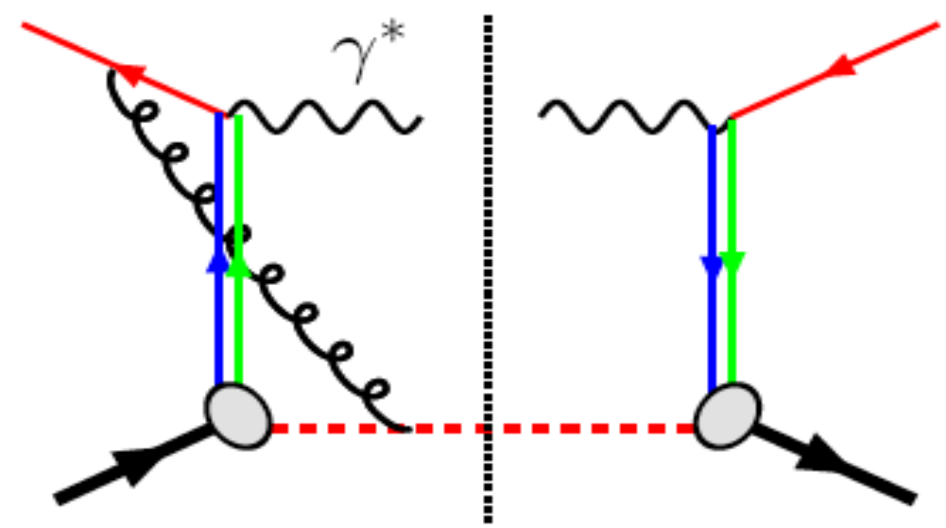
- 1-photon events, which include a large π^0 contribution in this analysis, are similar to 2-photon events
- Three-photon jet-like events have a clear non-zero asymmetry, but substantially smaller than that for isolated π^0's
- A_N decreases as the event complexity increases (i.e., the "jettiness"
- A_N for #photons >5 is similar to that for #photons = 5

Transverse Spin Phenomena - Sivers Sign-Change

DIS, attractive FSI



DY, repulsive ISI

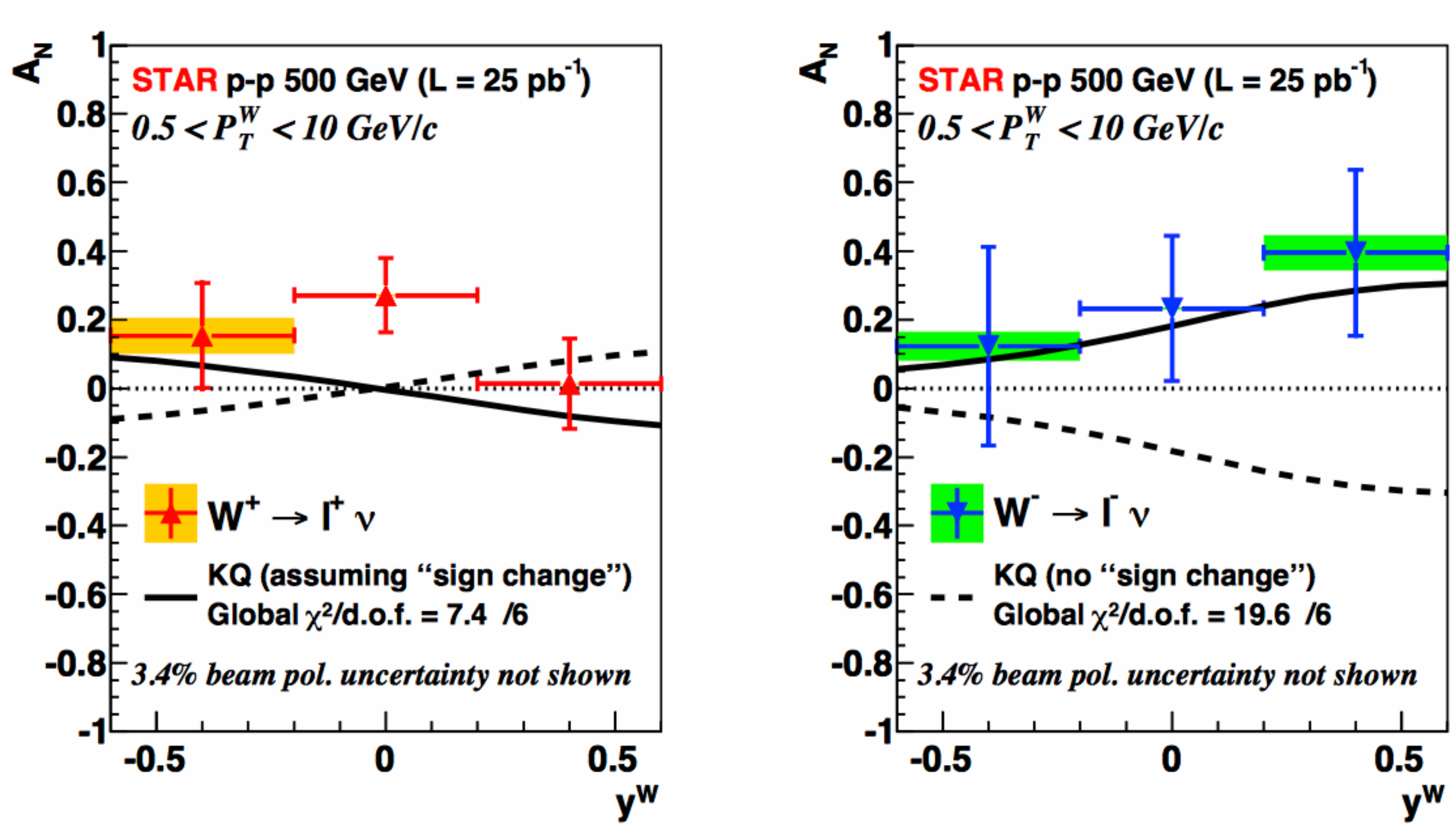


$\text{Sivers}_{\text{DIS}}$ = $-\text{Sivers}_{\text{DY}}$

HP13 (2015): Test unique QCD predictions for relations between single-transverse spin phenomena in p-p scattering and those observed in deep-inelastic lepton scattering

In colloquial english: Quarks with unlike color charge attract one another in QCD.

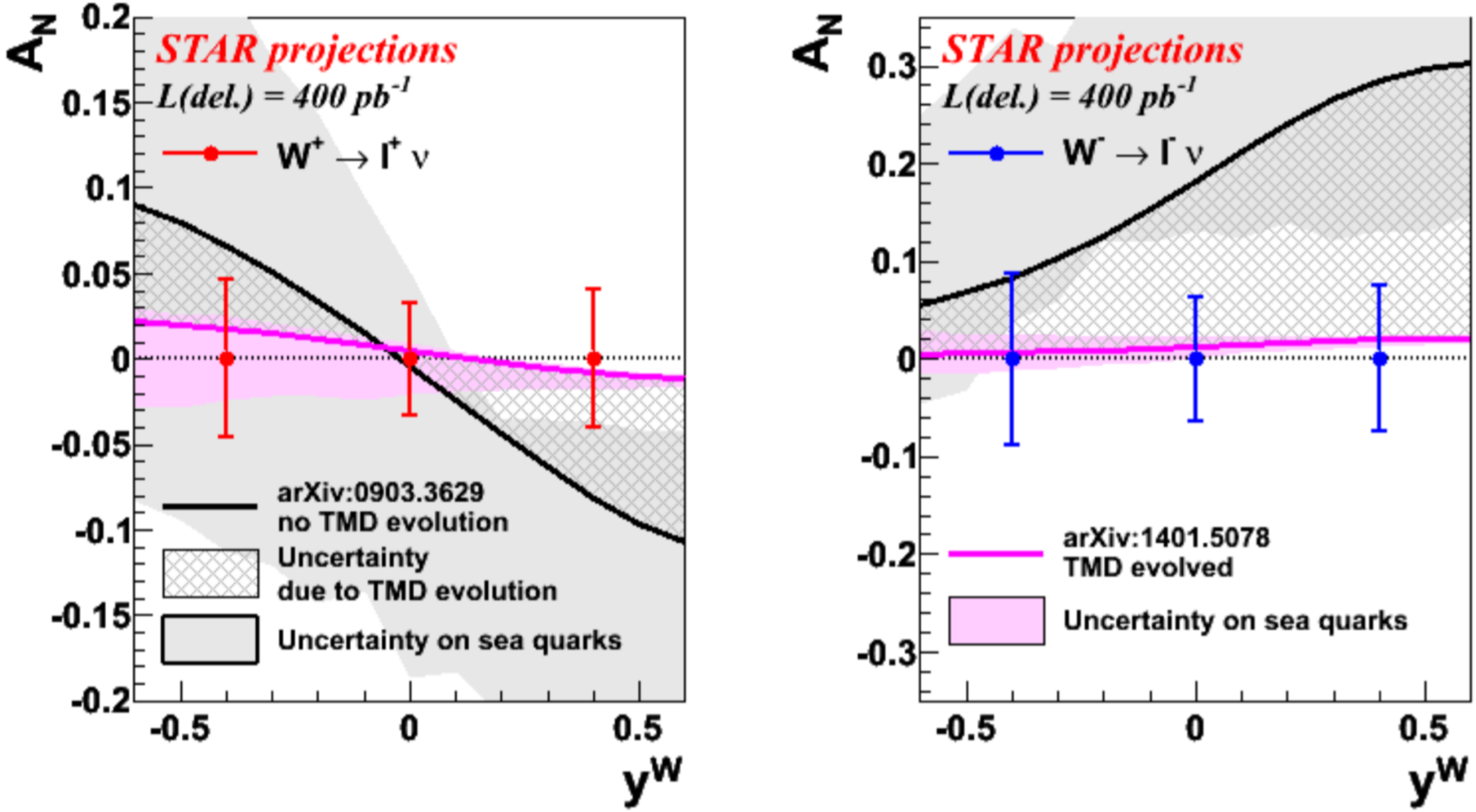
Transverse Spin Phenomena - Sivers Sign-Change



First hint of the anticipated sign-change between DIS and RHIC data,

In colloquial english: Quarks with unlike color charge attract one another in QCD.

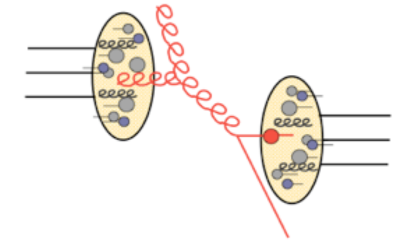
Transverse Spin Phenomena - Sivers Sign-Change



Main goal for RHIC beam-operations this year (2017),

Commissioning is progressing well - expect to see new collisions this upcoming weekend.

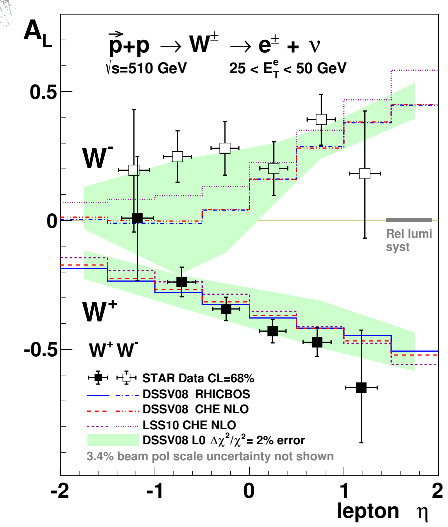
Brief recap:



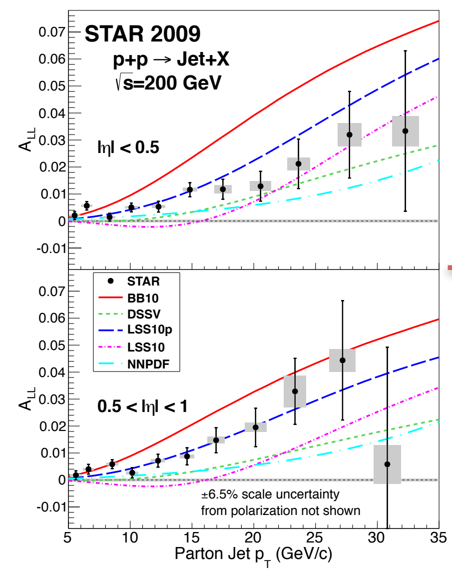
STAR Highlights at DIS2014

Warsaw, April 28 – May 2

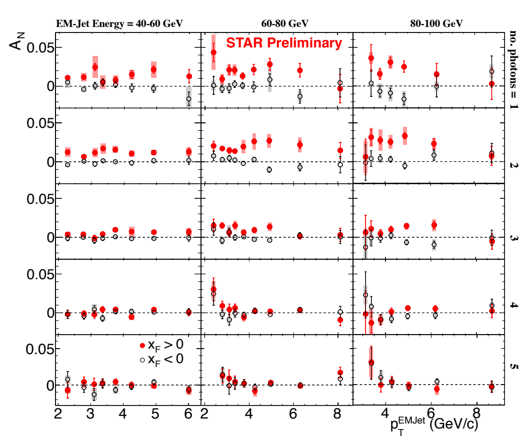
Next Steps



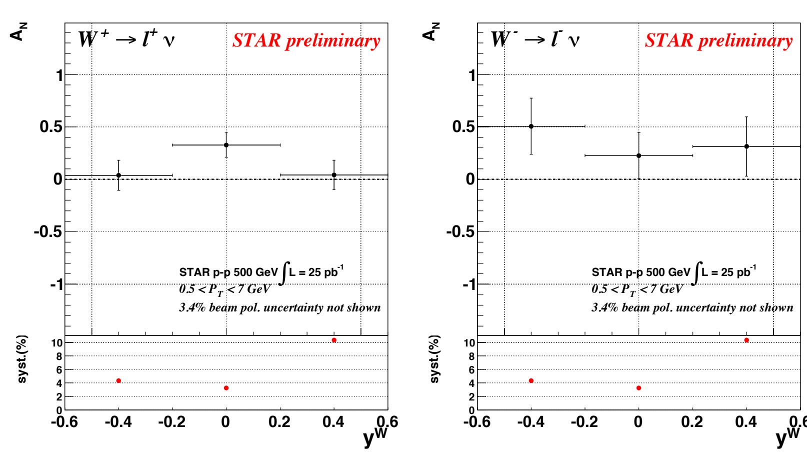
$\Delta\bar{u} > \Delta\bar{d}$ → ***Analyze Run-13***



Non-zero ΔG → ***Increase precision in Run-15***



A_N vanishes with increased jettiness → ***Measure Diffractive A_N with Roman Pots in Run-15***



Proof of concept A_N for W → ***Measure in Run-~~16~~ 7***

Salvatore Fazio (BNL)

Questions or comments, before we move on?

III - DIS, RHIC - A few words on EIC

Electron Ion Collider Initiatives

Past

Possible Future

	HERA @ DESY	LHeC @ CERN	HIAF @ CAS	ENC @ GSI	MEIC/ELIC @ JLab	eRHIC @ BNL
$\sqrt{s}$ [GeV]	320	800 - 1300	12 - 65	14	20 - 140	78 - 145
proton x_{min}	1×10^{-5}	5×10^{-7}	7×10^{-3} - 3×10^{-4}	5×10^{-3}	1×10^{-4}	5×10^{-5}
ion	p	p to Pb	p to U	p to ~^{40}Ca	p to Pb	p to U
polarization	-	-	p, d, ^{3}He	p, d	p, d, ^{3}He (^{6}Li)	p, ^{3}He
L [$cm^{-2}s^{-1}$]	2×10^{31}	10^{34}	10^{32-33} - 10^{35}	10^{32}	10^{33-34}	10^{33}
Interaction Points	2	1 (?)	1	1	2+	1-2
Year	1992 - 2007	post ALICE	2019 - 2030	upgrade to FAIR	post 12 GeV	2025

High-Energy Physics

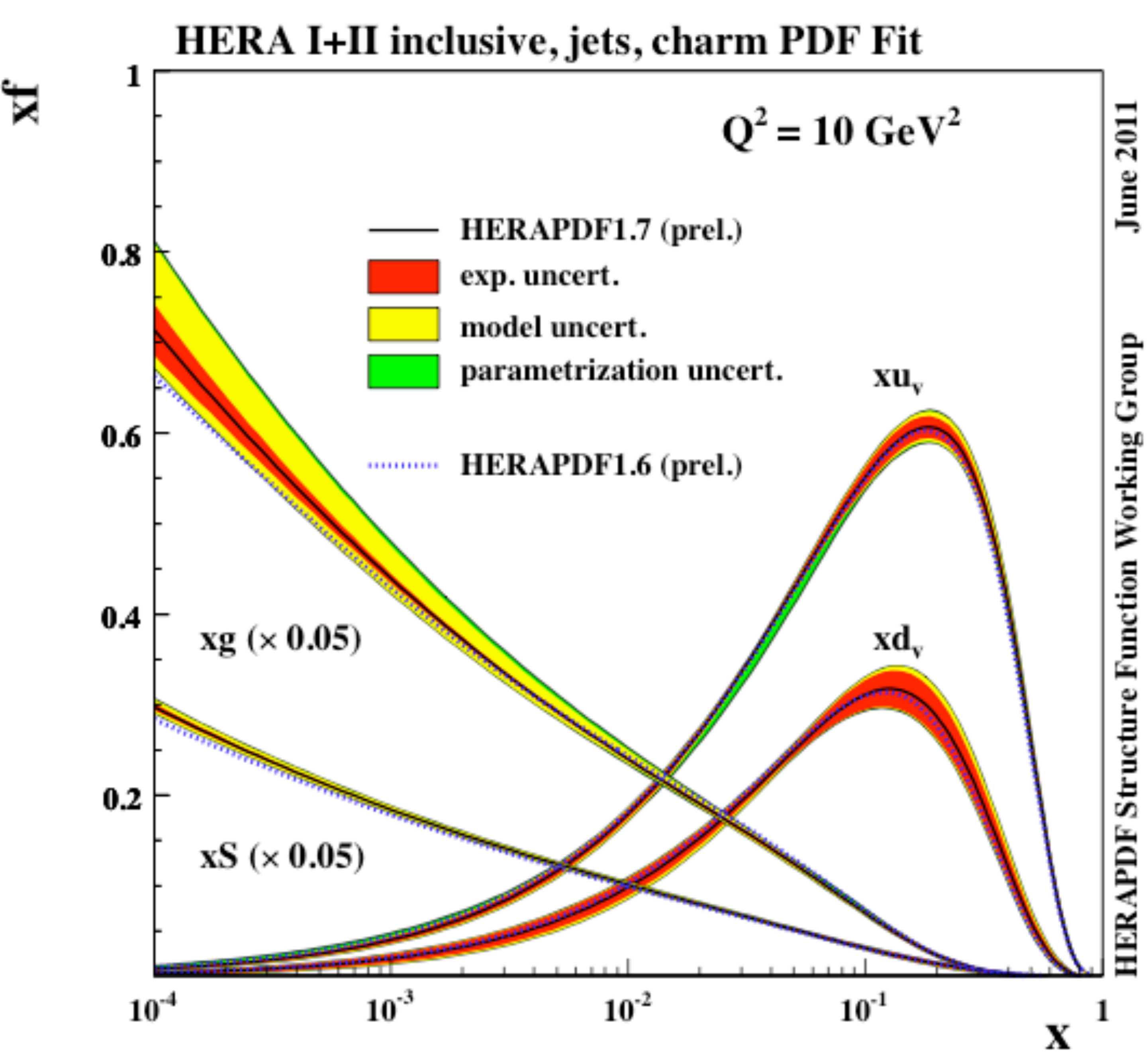
Nuclear Physics

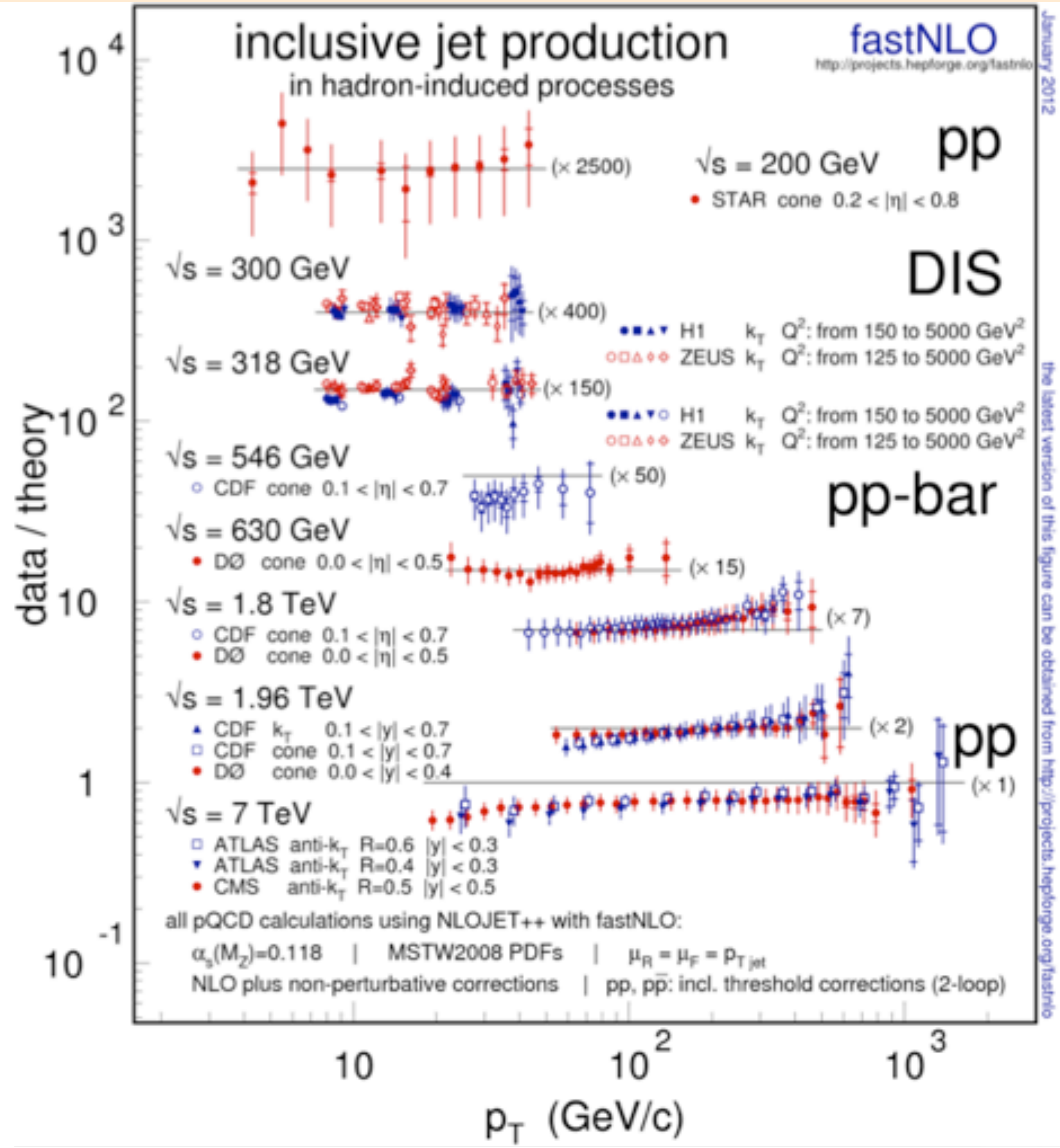
World Wide Interest

HERA's legacy

The proton in terms of gluons and quarks

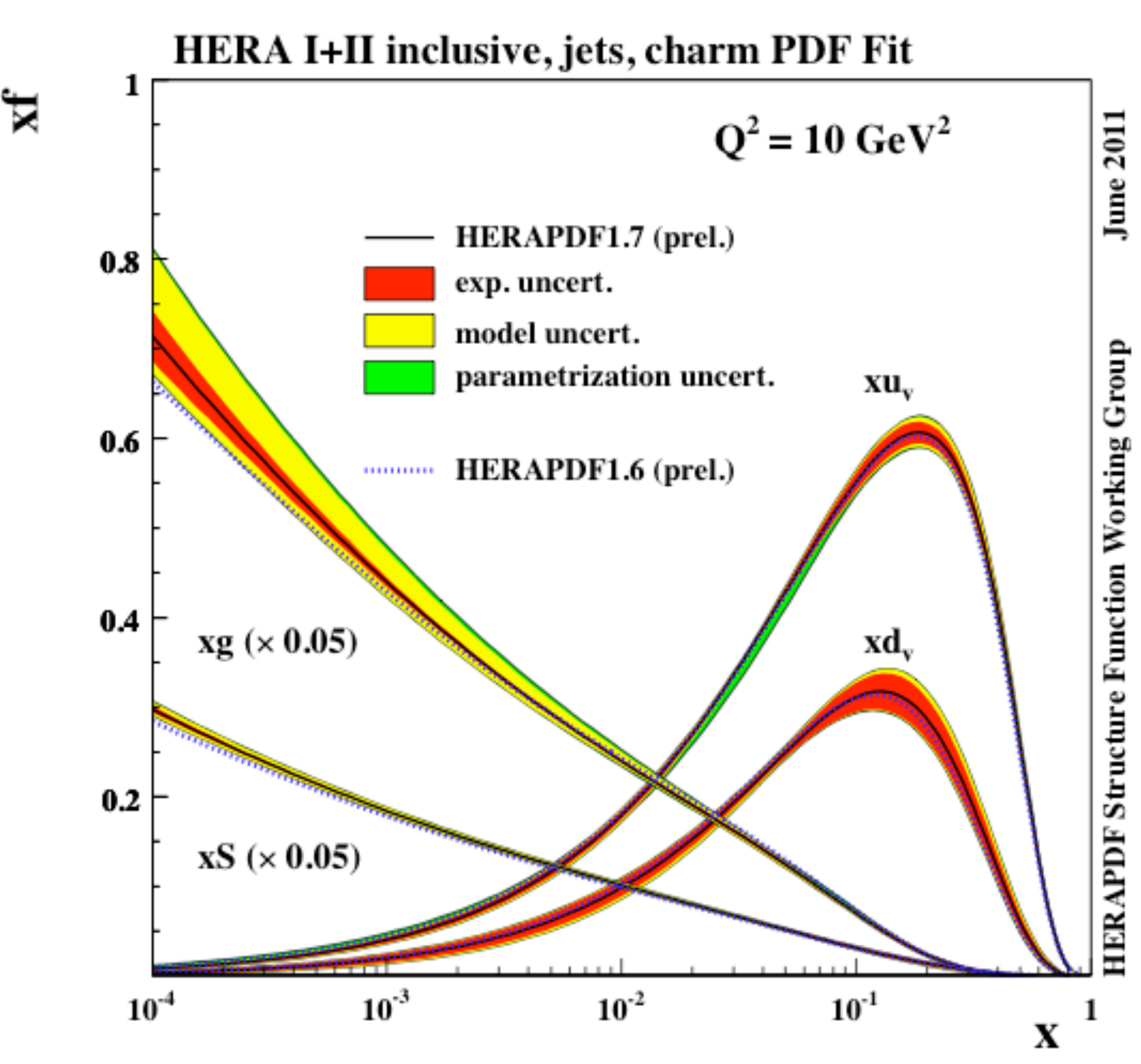
pQCD at work...





HERA's legacy

The proton in terms of gluons and quarks



... and quite remarkable voids:

Precision F_L - insufficient time,

Test isospin, u-d, - no deuterons,

d/u at large *x* - luminosity,

Strange quark distributions - luminosity,

Spin puzzle - no hadron beam polarization,

Quark-gluon dynamics in nuclei - no nuclei,

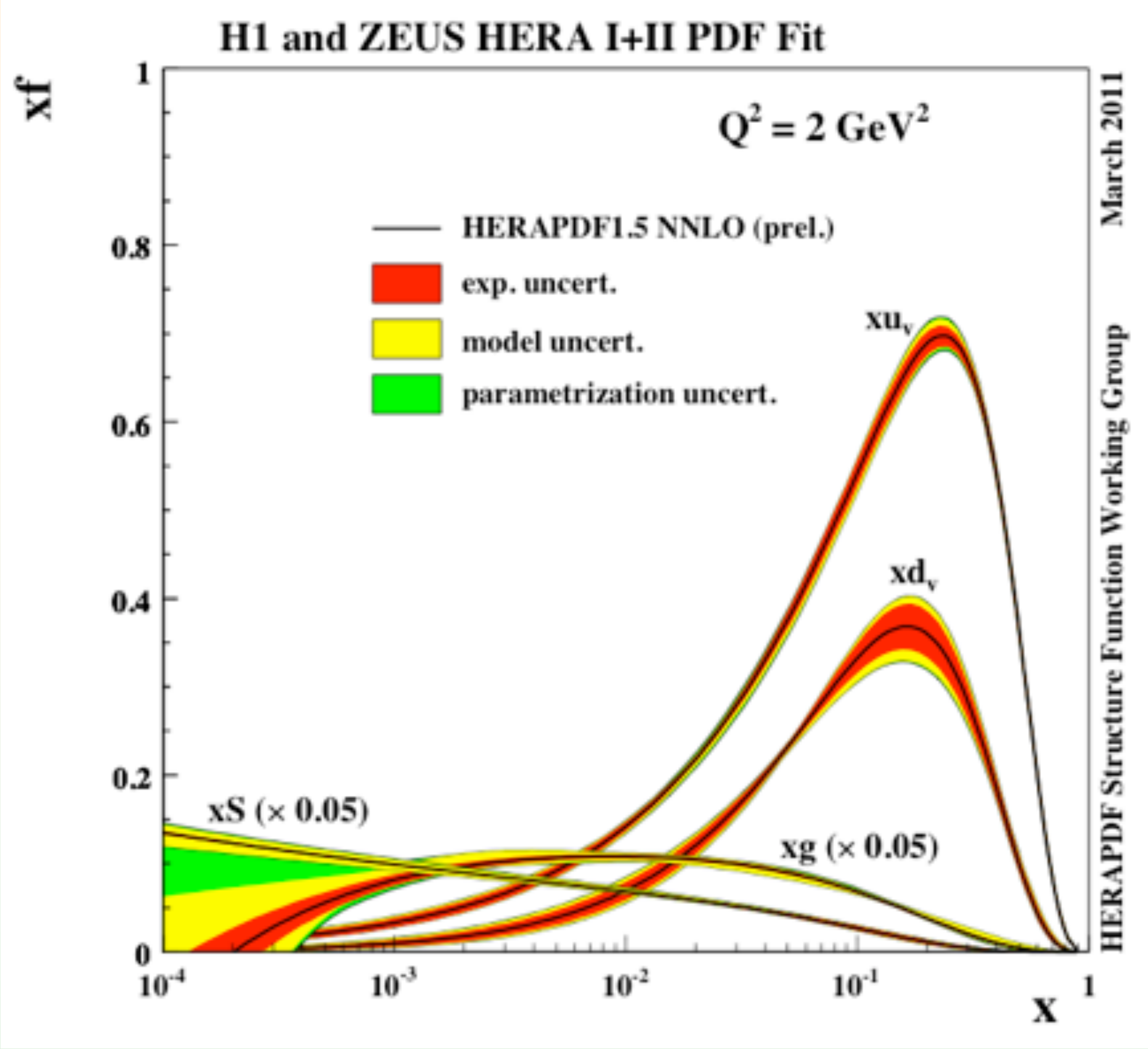
Saturation - insufficient √s / no nuclei,

...

HERA - RHIC

Saturation:

- geometric scaling of the cross section,
- diffractive cross-section independent of W and Q^2,
- hints of a negative gluon number distribution (at NLO),
- forward multiplicities and correlations at RHIC,

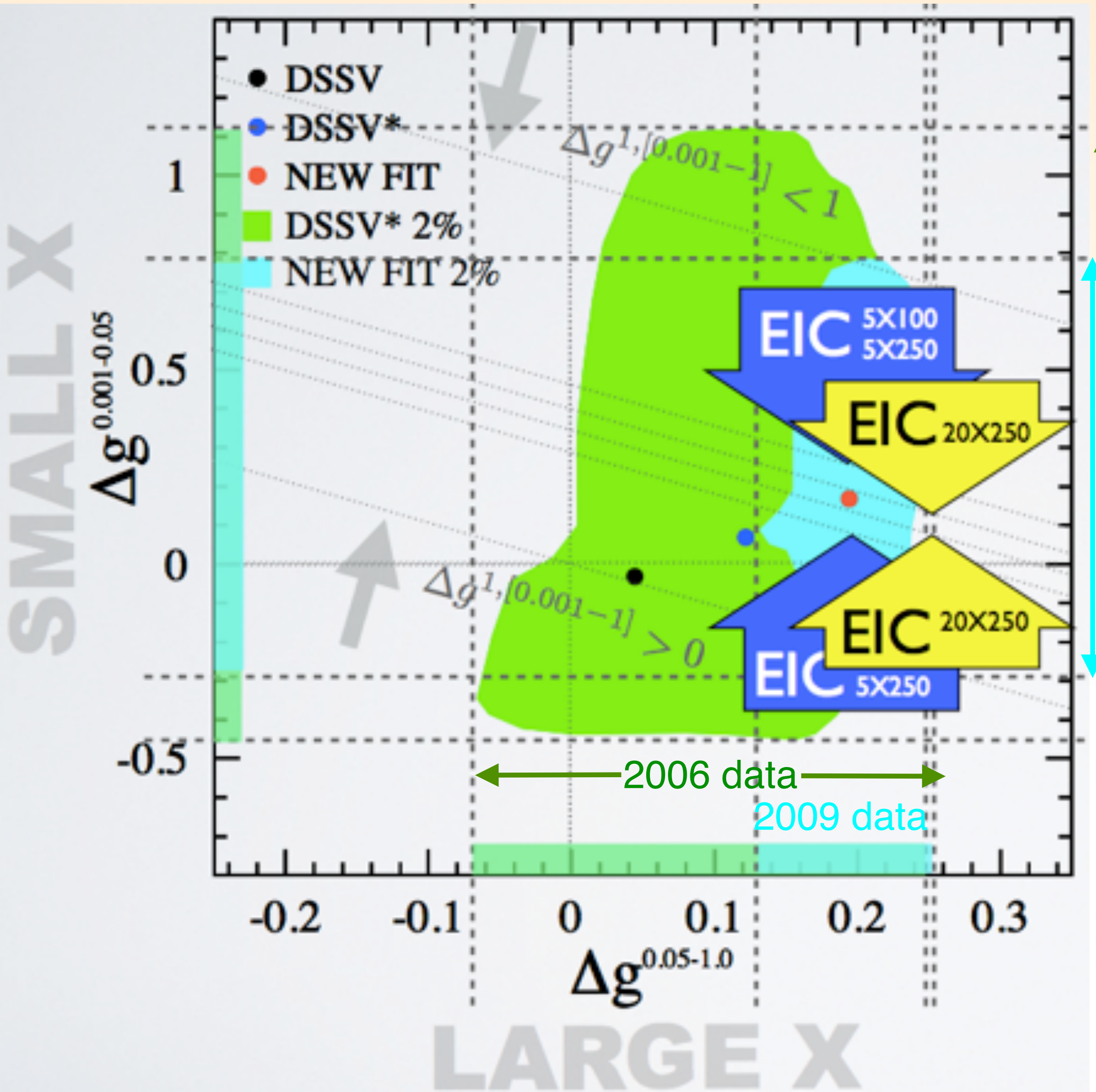


HERA - RHIC

Saturation:

- geometric scaling of the cross section,
- diffractive cross-section independent of W and Q^2,
- hints of a negative gluon number distribution (at NLO),
- forward multiplicities and correlations at RHIC,

Rodolfo Sassot at 2013 Spin Summer Program



Spin puzzle:

- defining constraint on $\Delta G(x)$ for $x > 0.05$, smaller *x* is terra-icognita,
- fragmentation-free insight in Δu, Δd, $\Delta\bar{u}$, $\Delta\bar{d}$ strange (anti-)quarks?
- large forward transverse-spin phenomena origin?

Mid-term: forward upgrade(s) at RHIC

Longer-term: EIC

HERA - RHIC, JLab

Saturation:

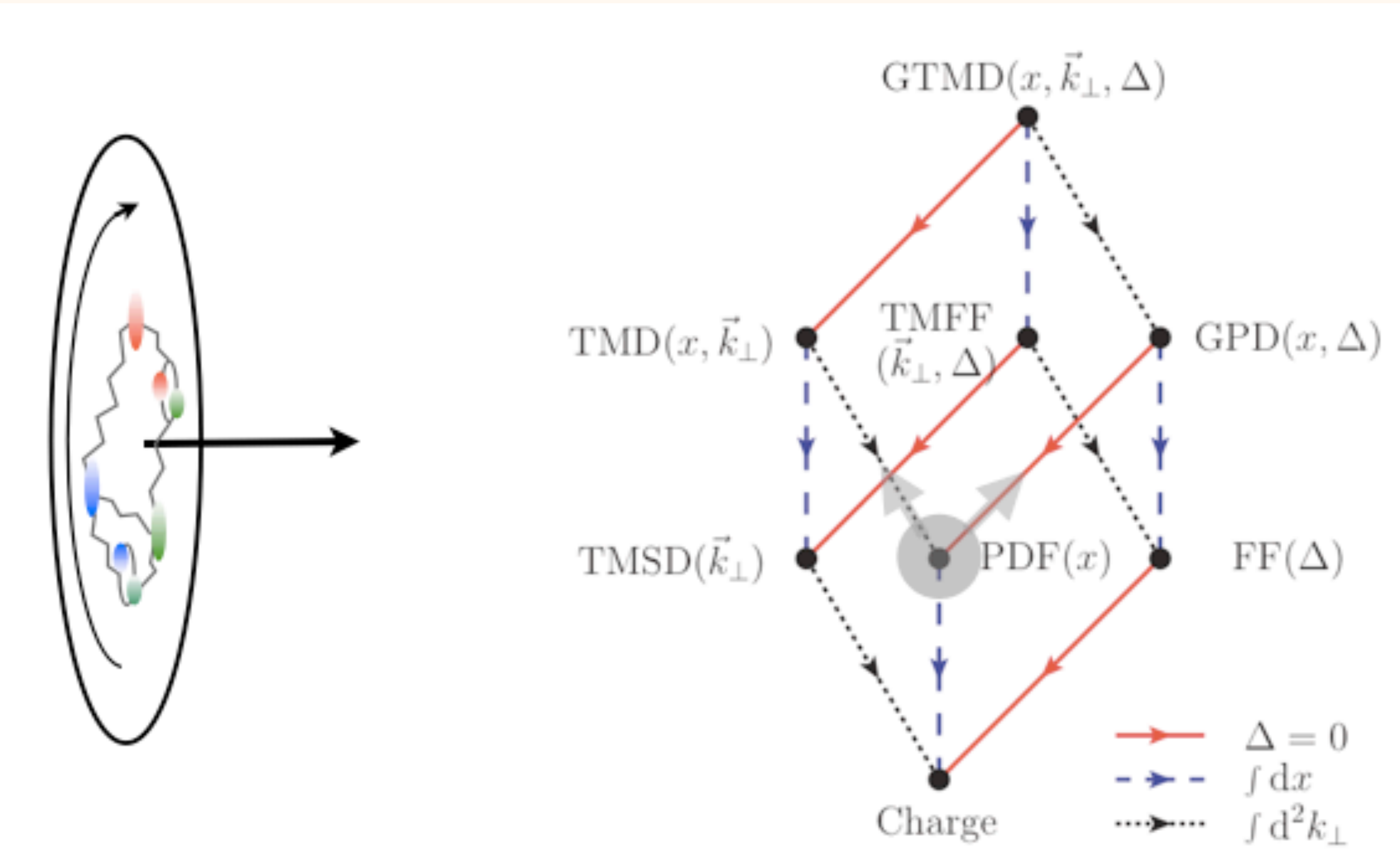
- geometric scaling of the cross section,
- diffractive cross-section independent of W and Q2,
- hints of a negative gluon number distribution (at NLO),
- forward multiplicities and correlations at RHIC,

Spin puzzle:

- defining constraint on $\Delta G(x)$ for $x > 0.05$,
  smaller *x* is terra-icognita,
- fragmentation-free insight in Δu, Δd, $\Delta\bar{u}$, $\Delta\bar{d}$
  strange (anti-)quarks?
- large forward transverse-spin phenomena
  origin?

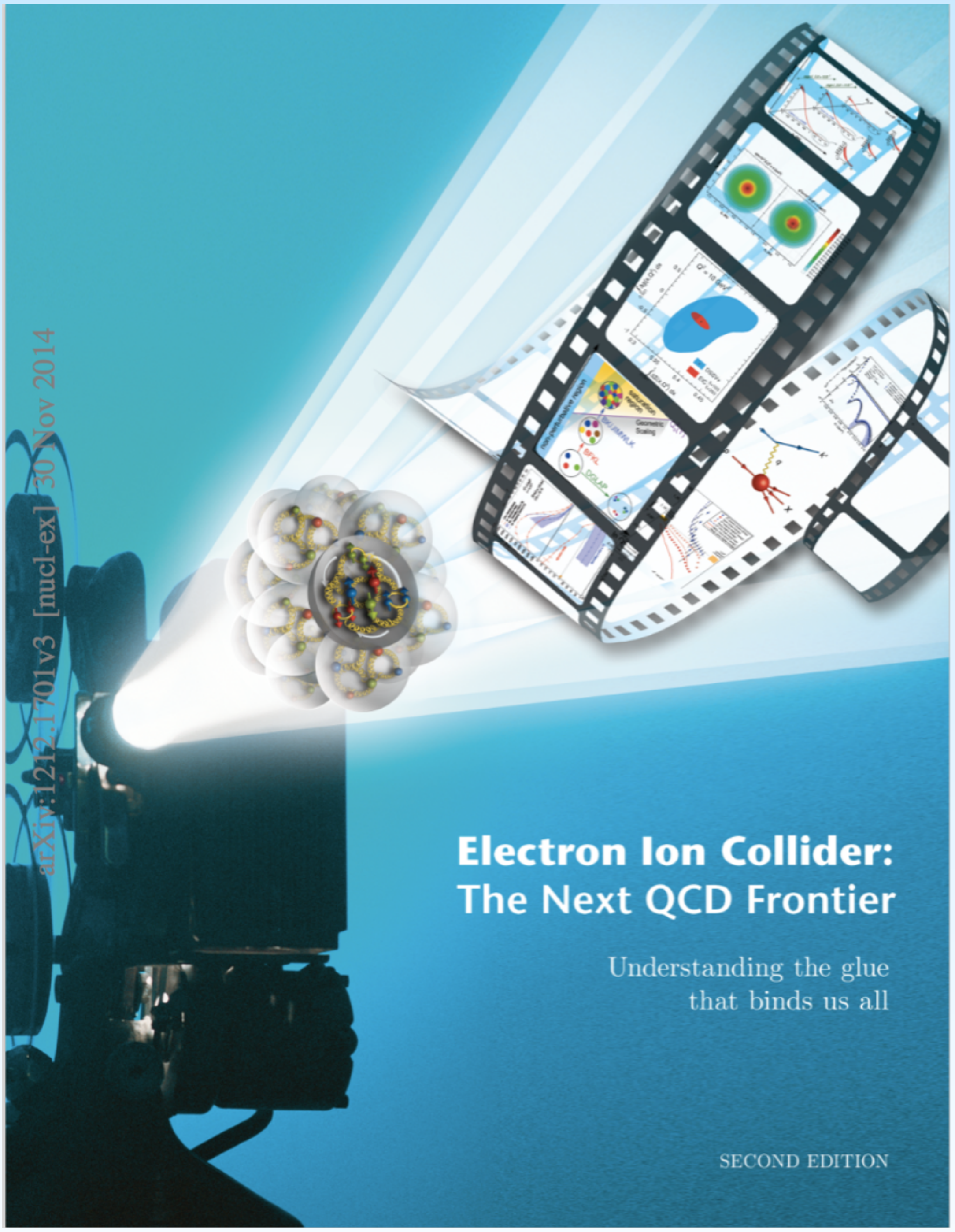
Imaging / tomography:

- valence quark region,
  gluon region?



Lorce, Pasquini, Vanderhaeghen

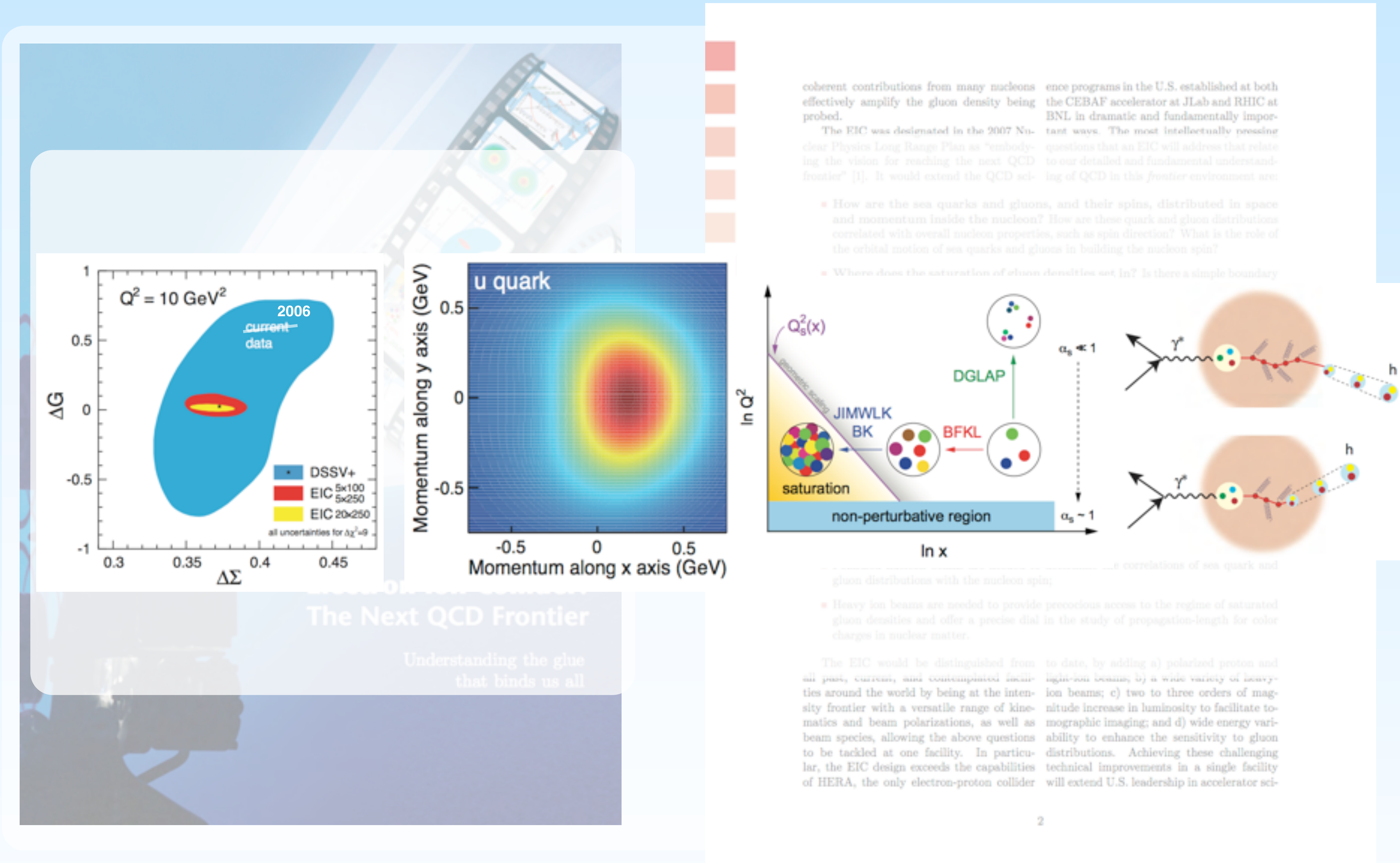
U.S. EIC Science Case



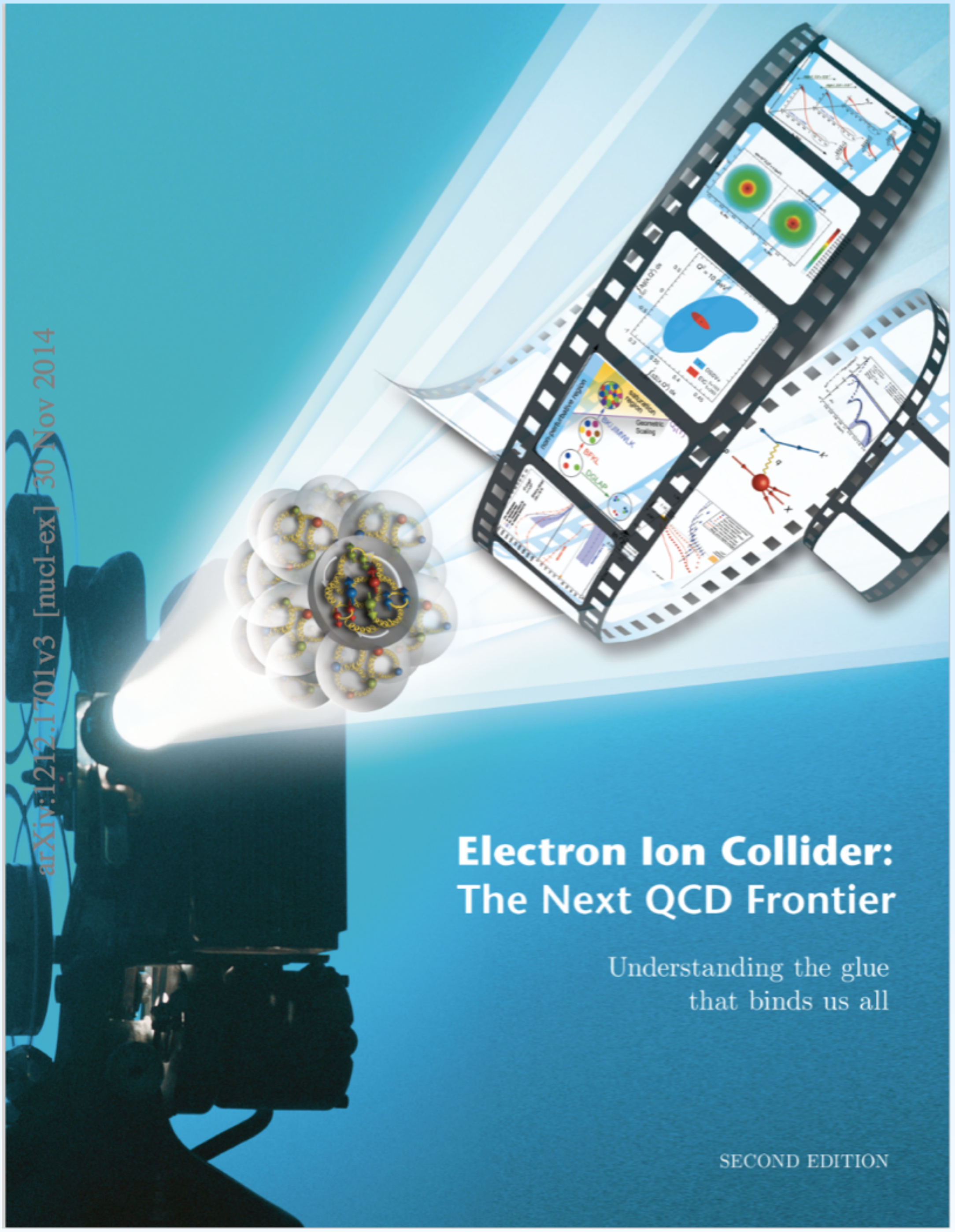
Eur. Phys. J. A52 (2016) no.9, 268 - 284 citations

- *How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleus?*
- *Where does the saturation of gluon densities set in?*
- *How does the nuclear environment affect the distribution of quarks and gluons and their interactions in nuclei?*

U.S. EIC Science Case and Measurements



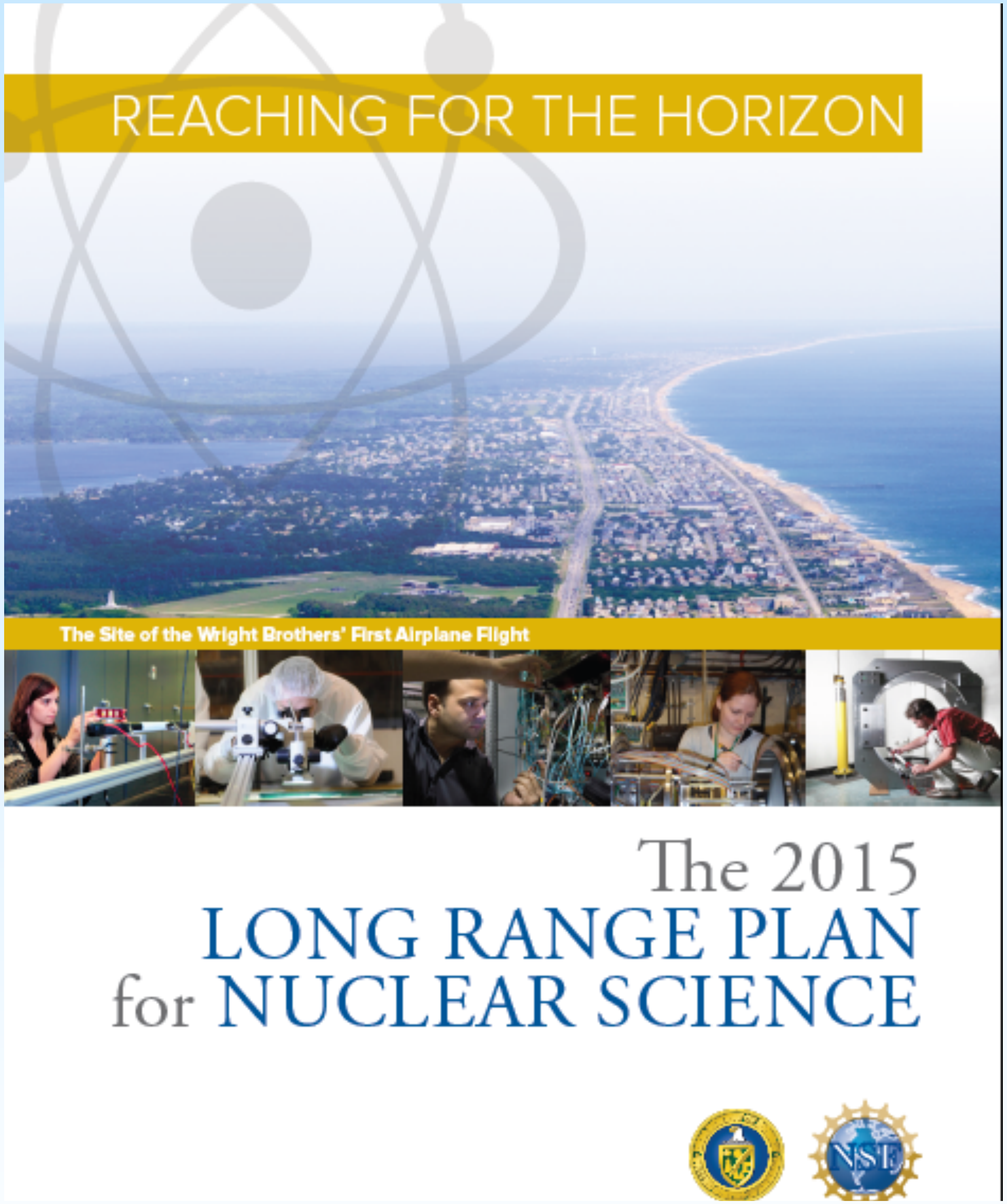
U.S. EIC Capabilities



Eur. Phys. J. A52 (2016) no.9, 268 - 284 citations

- *A collider to provide kinematic reach well into the gluon dominated regime,*
- *Electron beams provide the unmatched precision of the electromagnetic inter-action as a probe,*
- *Polarized nucleon beams to determine the correlations of sea quark and gluon distributions with the nucleon spin,*
- *Heavy Ion beams to access the gluon-saturated regime and as a precise dial to study propagation of color charges in nuclear matter.*
- *Facility concepts (upgrades) at RHIC and at Jefferson Laboratory.*

U.S. - Electron Ion Collider



Recommendation III

Gluons, the carriers of the strong force, bind the quarks together inside nucleons and nuclei and generate nearly all of the visible mass in the universe. Despite their importance, fundamental questions remain about the role of gluons in nucleons and nuclei. These questions can only be answered with a powerful new electron ion collider (EIC), providing unprecedented precision and versatility. The realization of this instrument is enabled by recent advances in accelerator technology.

We recommend a high-energy high-luminosity polarized EIC as the highest priority for new facility construction following the completion of FRIB.

The EIC will, for the first time, precisely image gluons in nucleons and nuclei. It will definitively reveal the origin of the nucleon spin and will explore a new quantum chromodynamics (QCD) frontier of ultra-dense gluon fields, with the potential to discover a new form of gluon matter predicted to be common to all nuclei.

This science will be made possible by the EIC's unique capabilities for collisions of polarized electrons with polarized protons, polarized light ions, and heavy nuclei at high luminosity.

April 2013
DIS at
Marseille

Possible QCD Developments

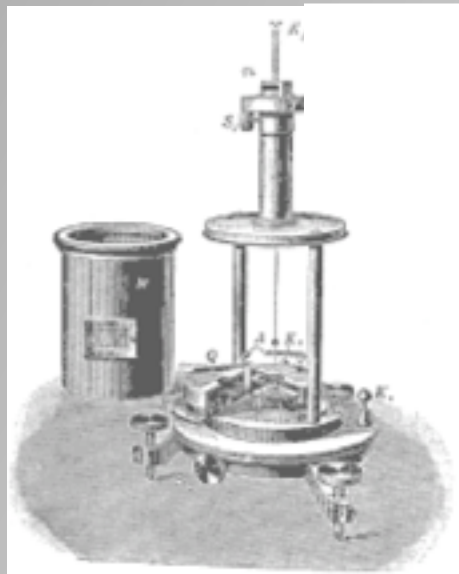
- AdS/CFT
- Instantons
- Odderons
- Non pQCD
- QGP
- N^kLO
- Resummation
- Non-conventional PDFs ...

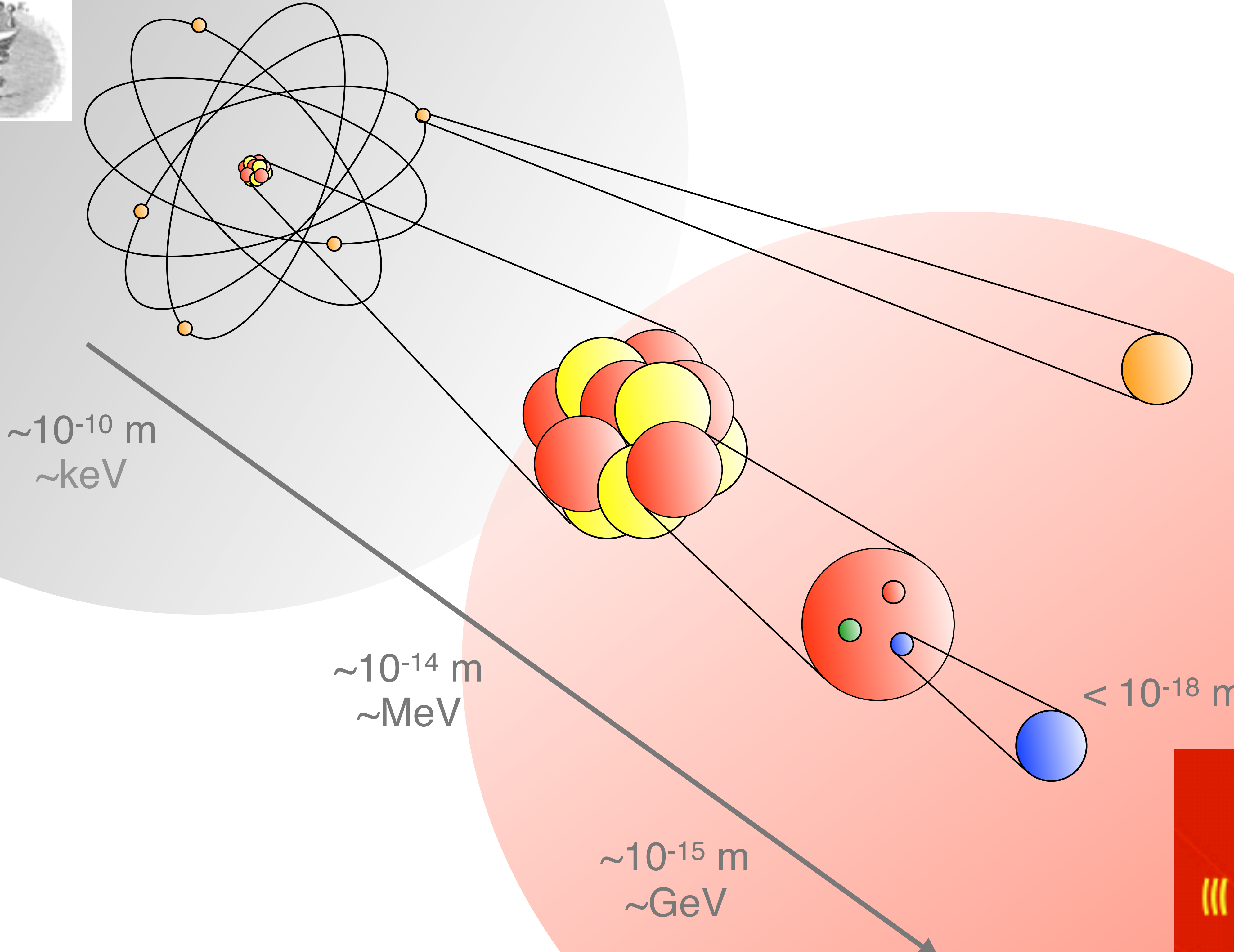
- Breaking of Factorisation
- Free Quarks
- Unconfined Color
- New kind of coloured matter
- Quark substructure
- New symmetry embedding QCD

QCD may break .. (Quigg DIS13)

QCD is the richest part of the Standard Model Gauge Field Theory and will (have to) be developed much further, on its own and as background

The future for experimental QCD can be broad and bright.





Let's make it happen.