Today we will continue to discuss physics of color,
from a complementary perspective

"eRHIC"

Physics of *Lepton*-Ion Collisions

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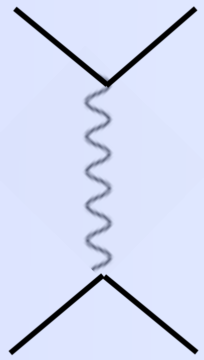
The Berkeley School 2014

Consider (electro-)production of muons and "hadrons",

$$e^+ + e^- \rightarrow \mu^+ + \mu^-$$

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



The same diagram!

Now, consider the cross-section ratio:

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

as a function of energy.

For the three light flavors,

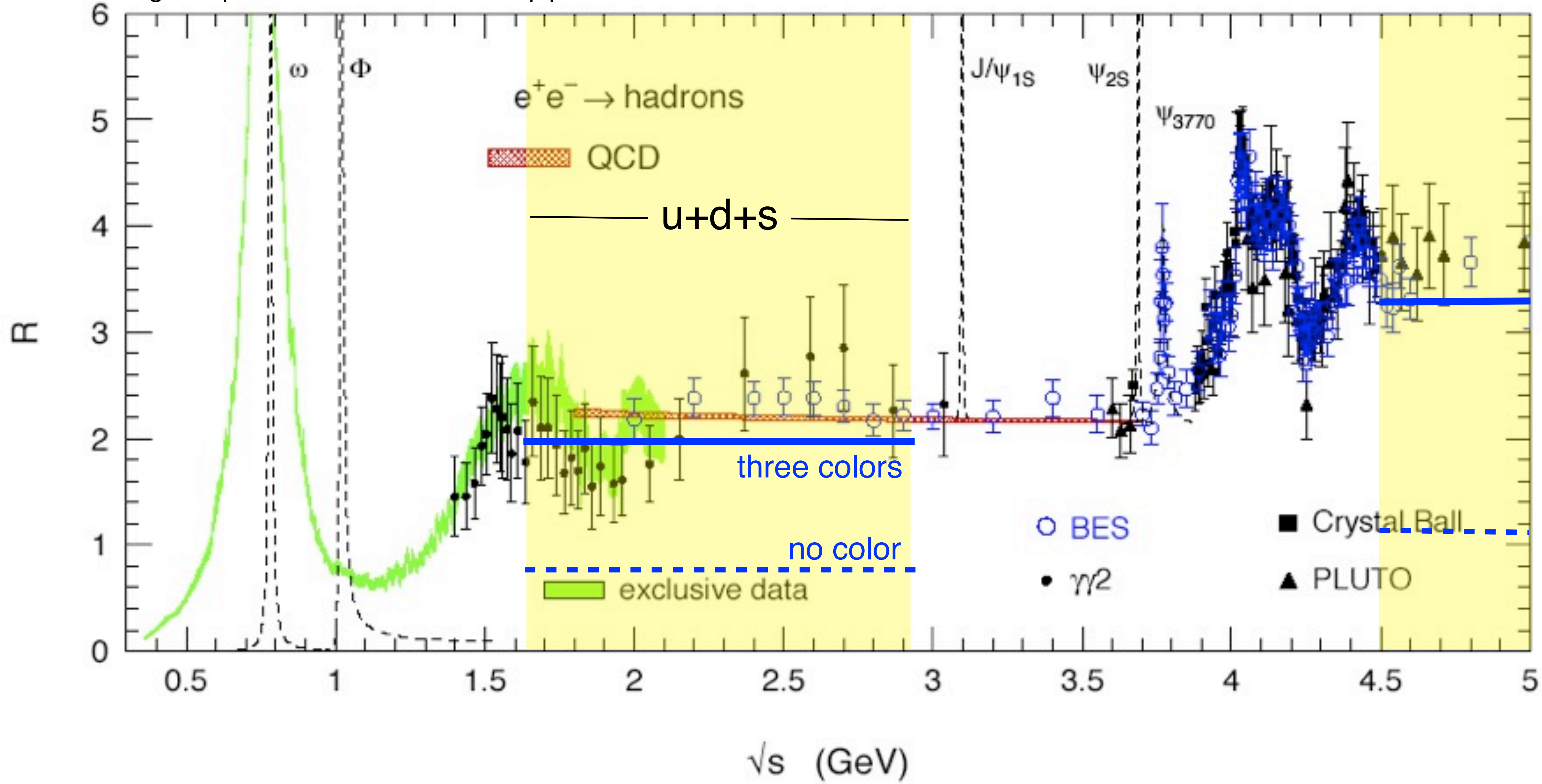
$$R = n_{\text{color}} \left[\left(\frac{2}{3}\right)^2 + \left(-\frac{1}{3}\right)^2 + \left(-\frac{1}{3}\right)^2 \right] = n_{\text{color}} \cdot \frac{2}{3} = 2$$

Between the charm and beauty threshold,

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

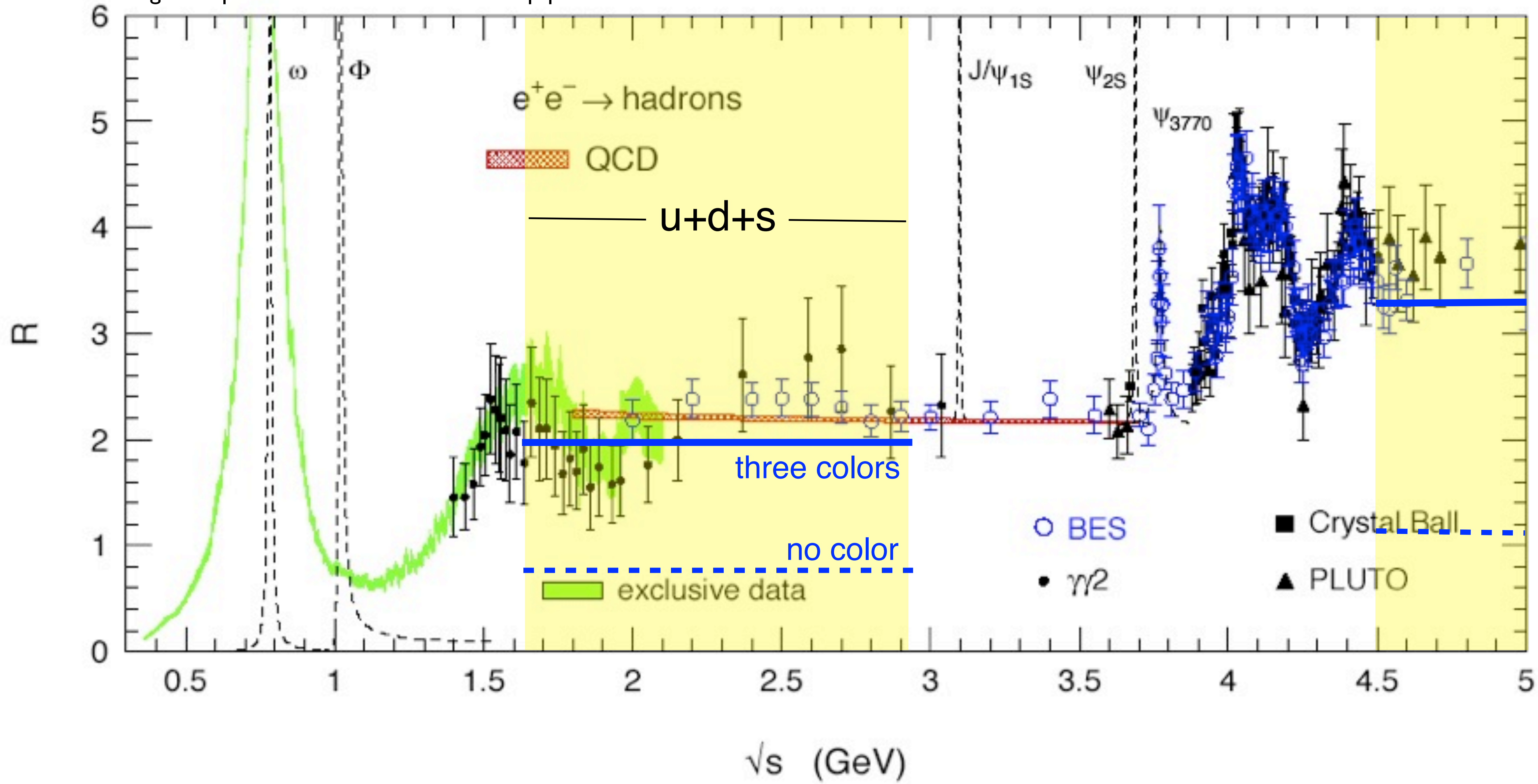
Data:

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



Data:

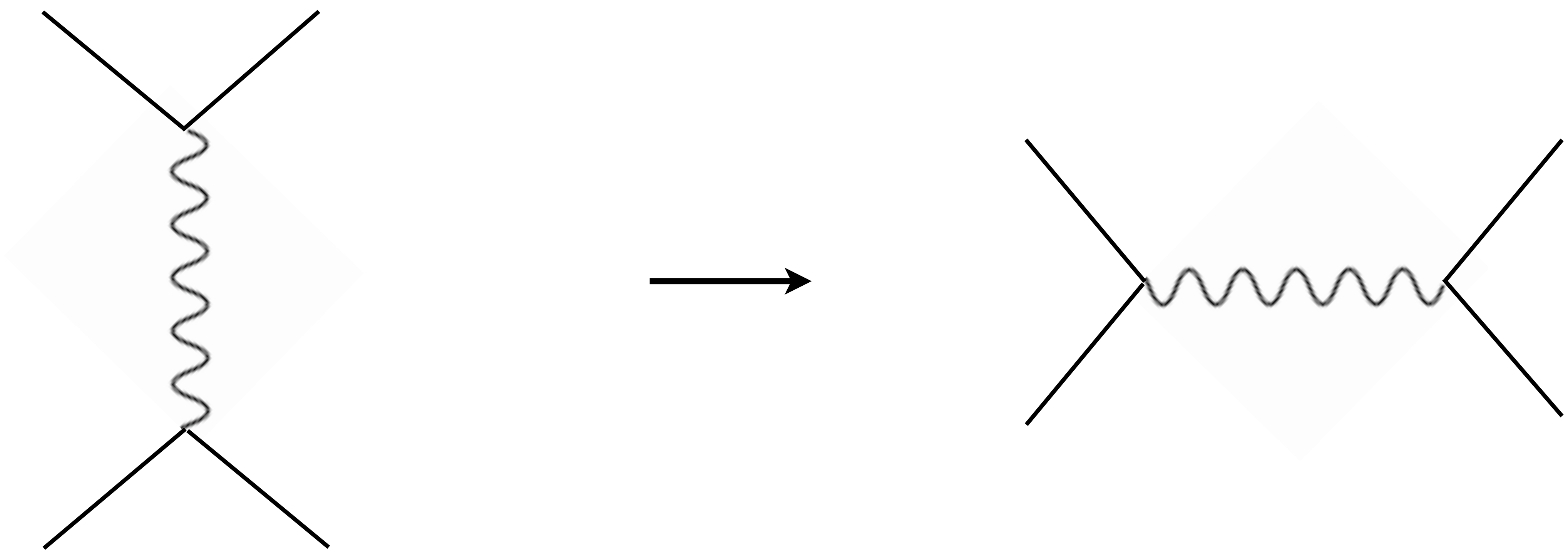
Figure reproduced from Davier et al. hep-ph/0208177



What about the fractional charges?

What about spin?

Much of the next ~75 mins will be about:



Physics with Lepton-Ion Collisions

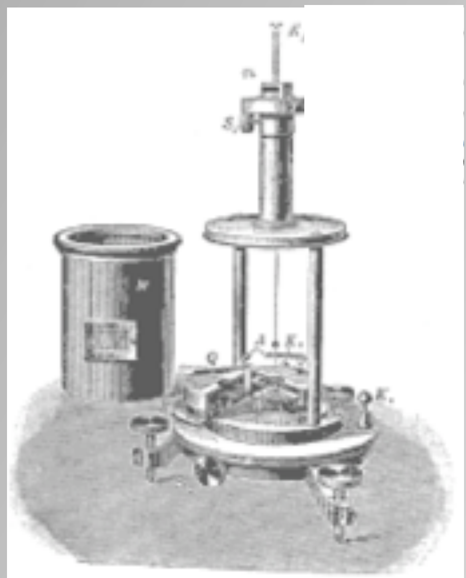
1. Deep-Inelastic Scattering

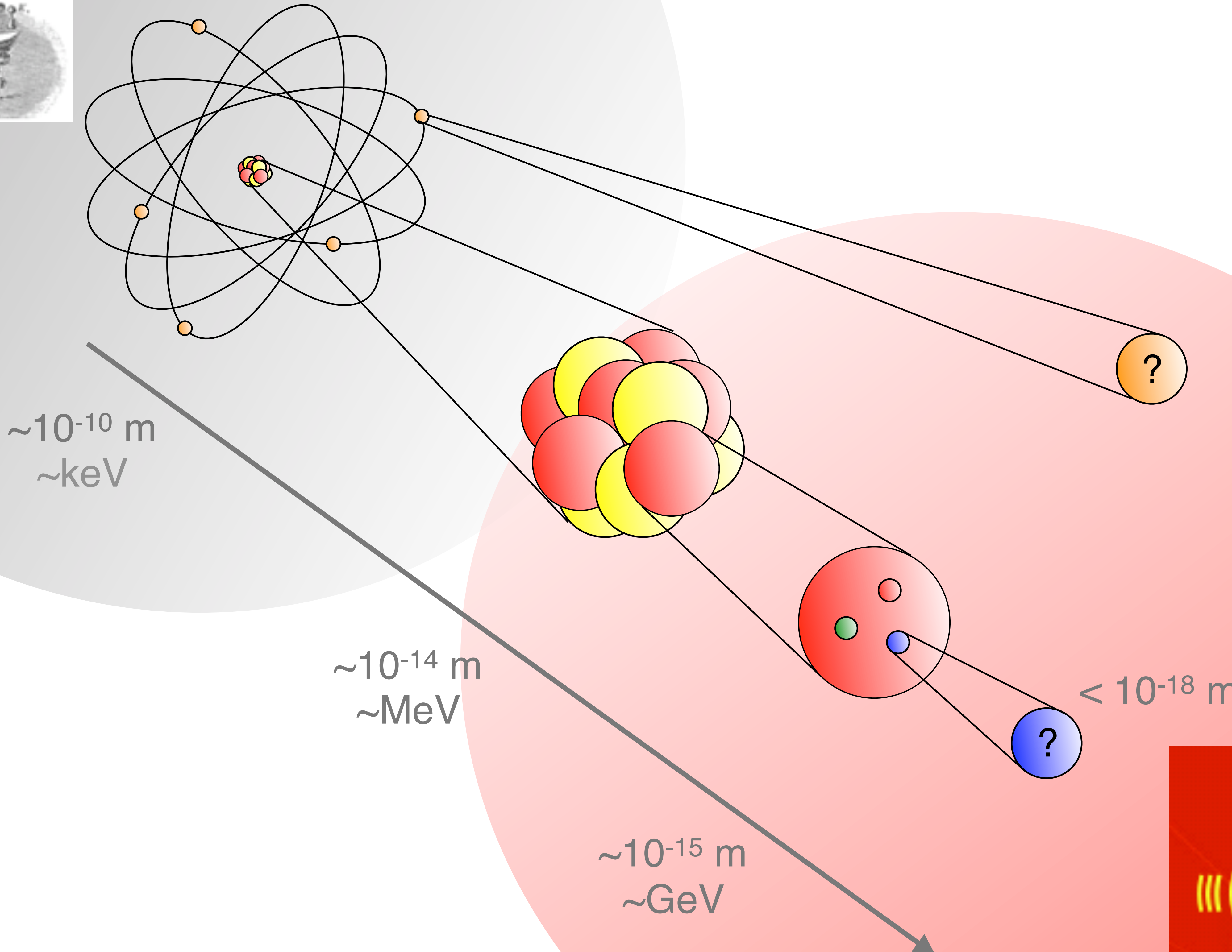
1. Deep-Inelastic Scattering

2. Applications at RHIC


1. Deep-Inelastic Scattering
3. Towards an EIC
2. Applications at RHIC

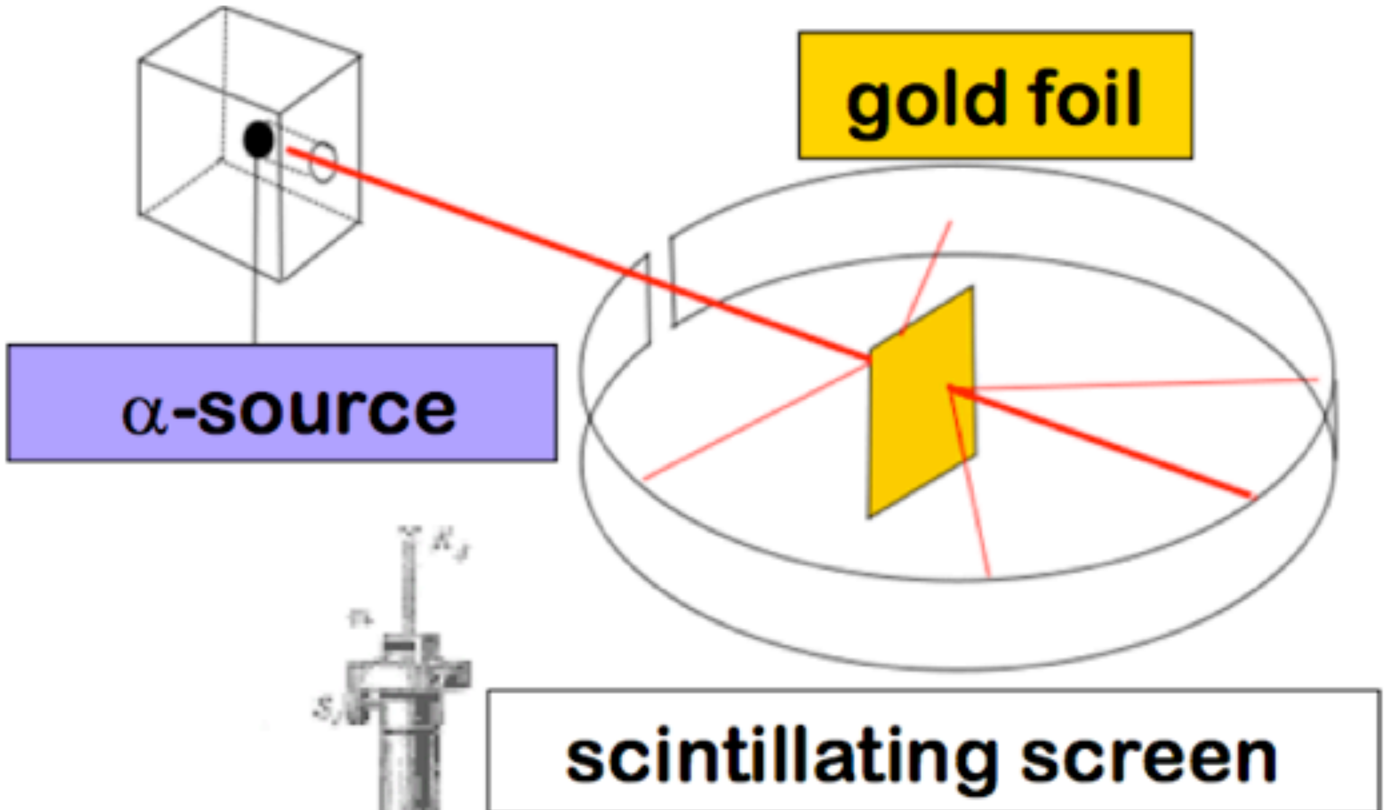
I - Deep-Inelastic Scattering

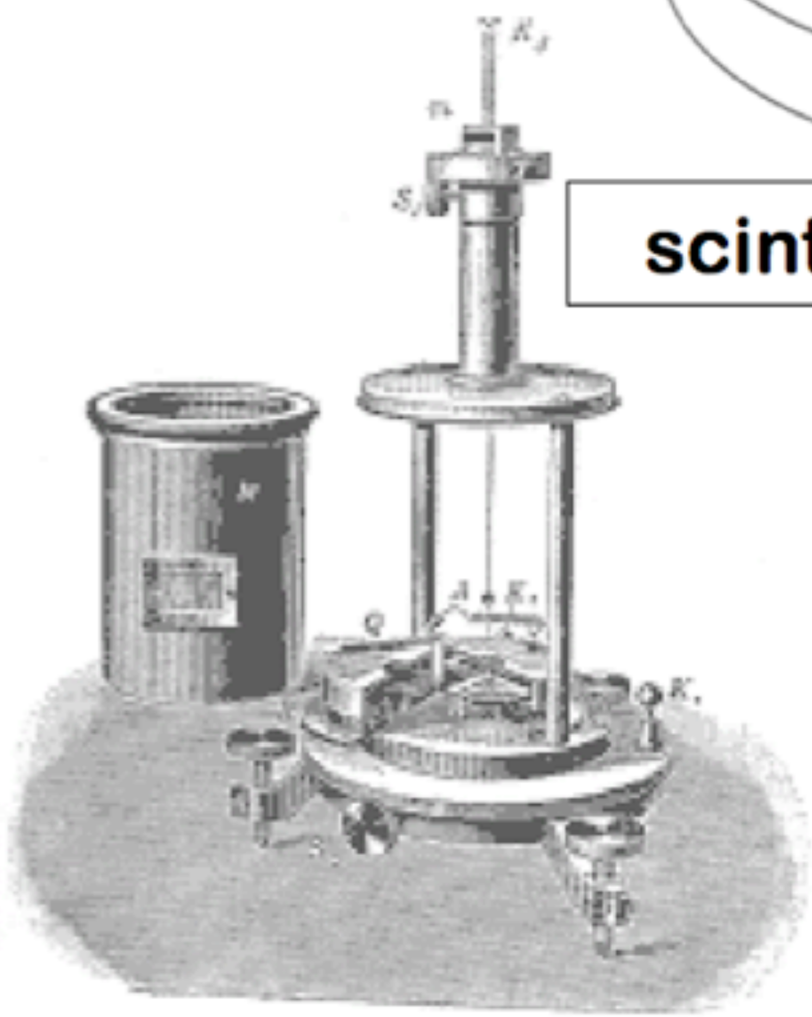



?
~10^{-10} m
~keV
~10^{-14} m
~MeV
~10^{-15} m
~GeV
< 10^{-18} m
?

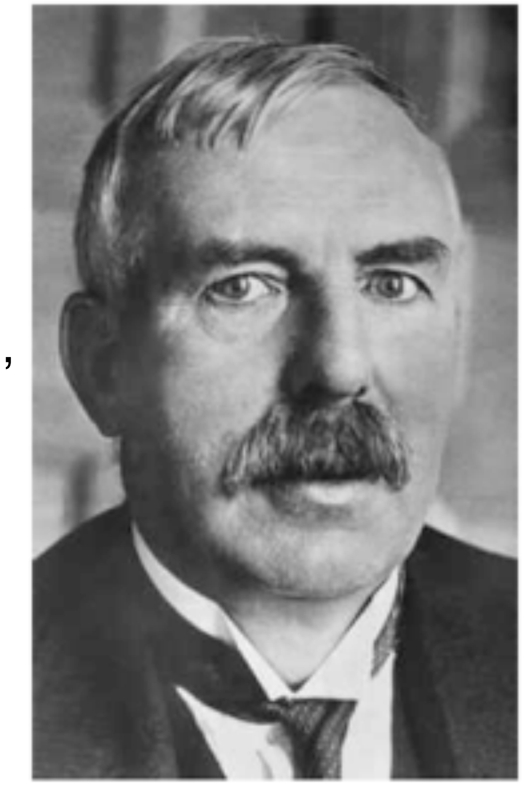
Rutherford Scattering

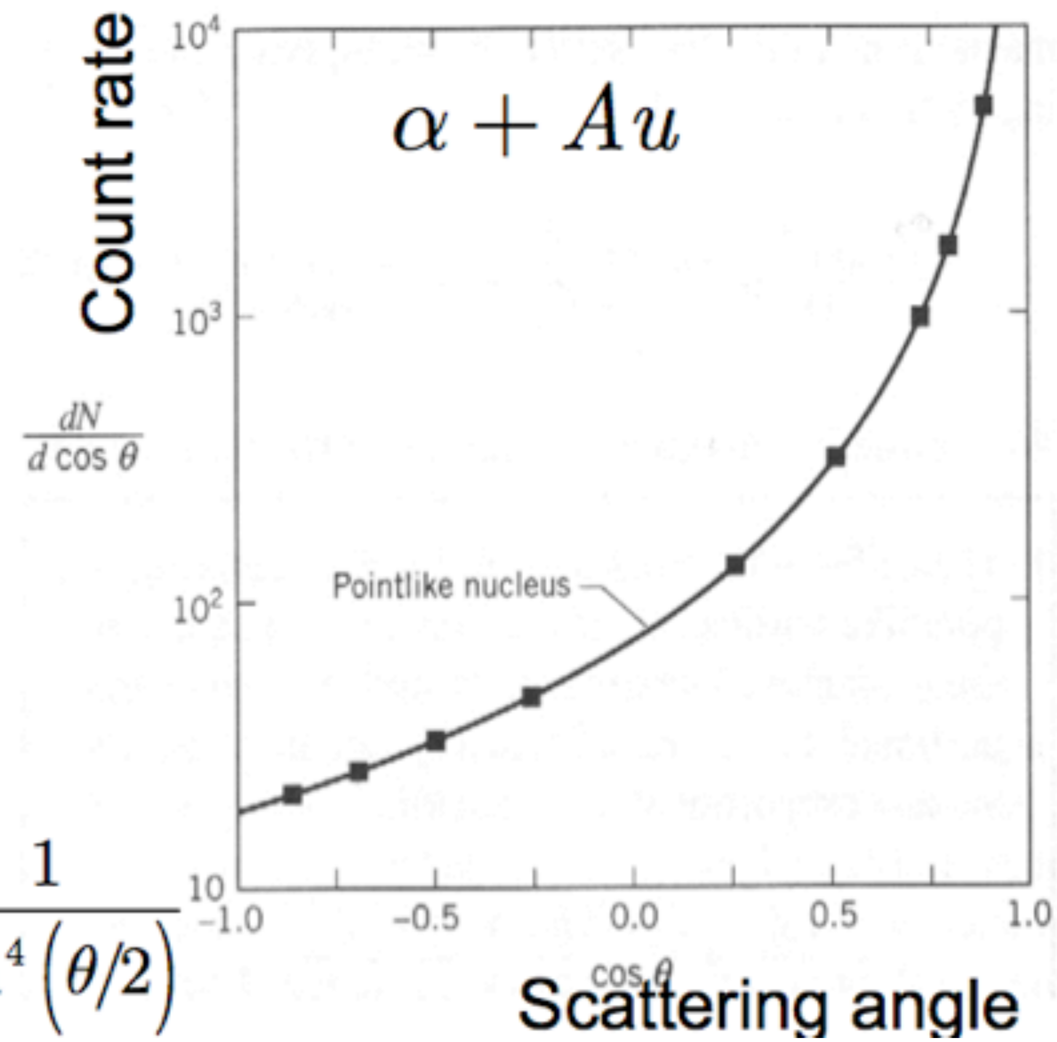
~5 MeV





Ernest Rutherford,
Nobel Prize 1908



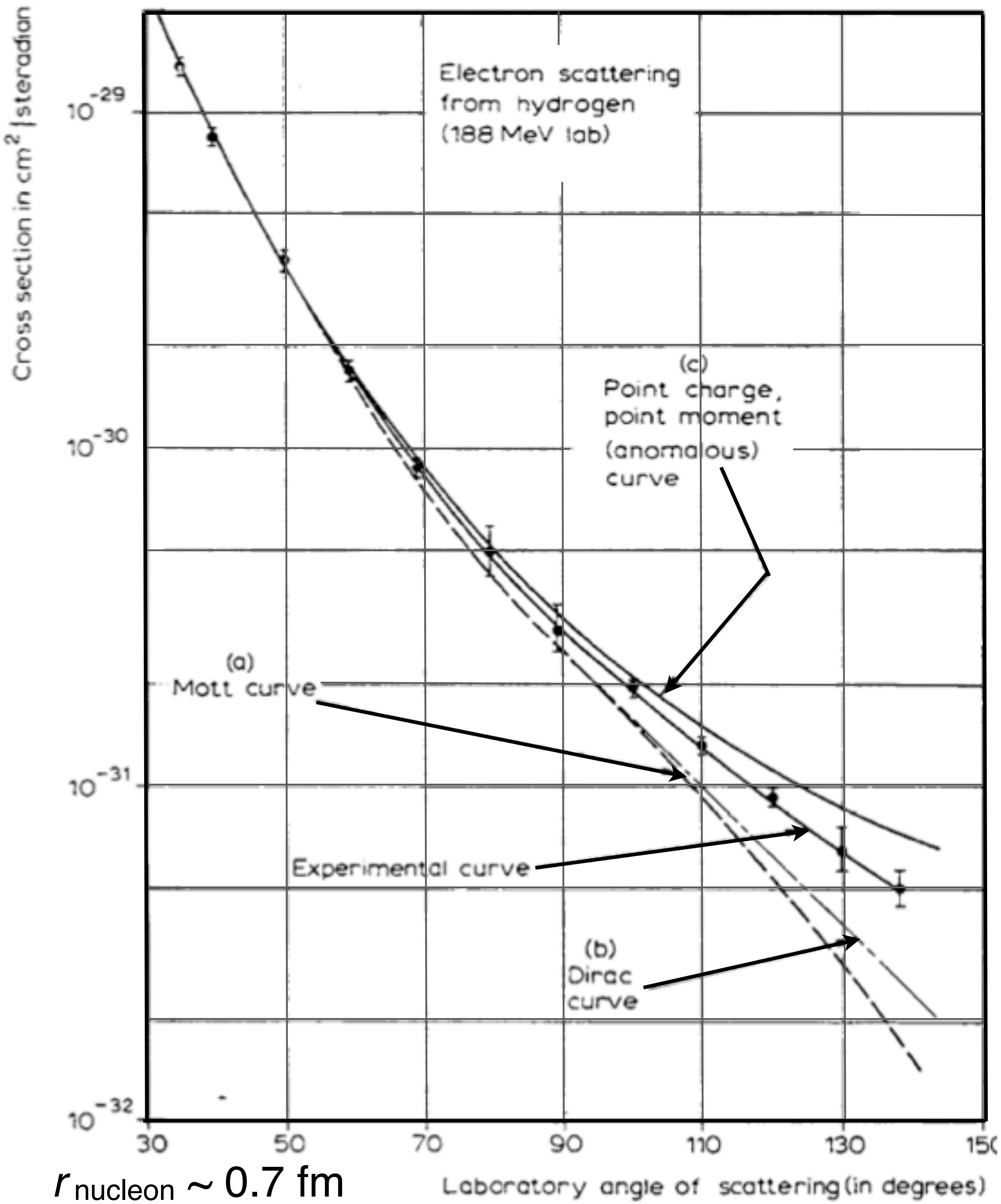


$$\frac{d\sigma}{d\Omega} = (zZ\alpha)^2 \left(\frac{\hbar c}{4E_{\text{kin}}}\right)^2 \frac{1}{\sin^4(\theta/2)}$$

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

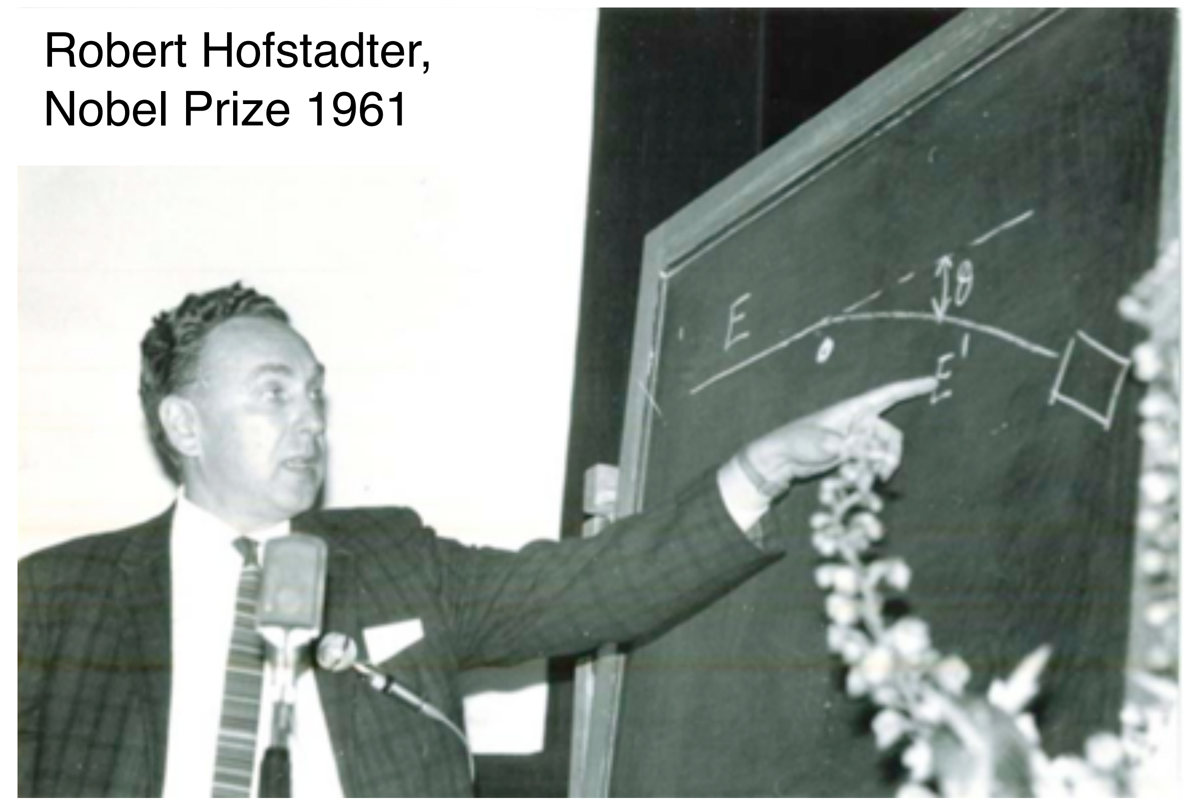
~200 MeV

Elastic Electron Scattering



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

Robert Hofstadter, Nobel Prize 1961



Scattering off a spin-1/2 Dirac particle:

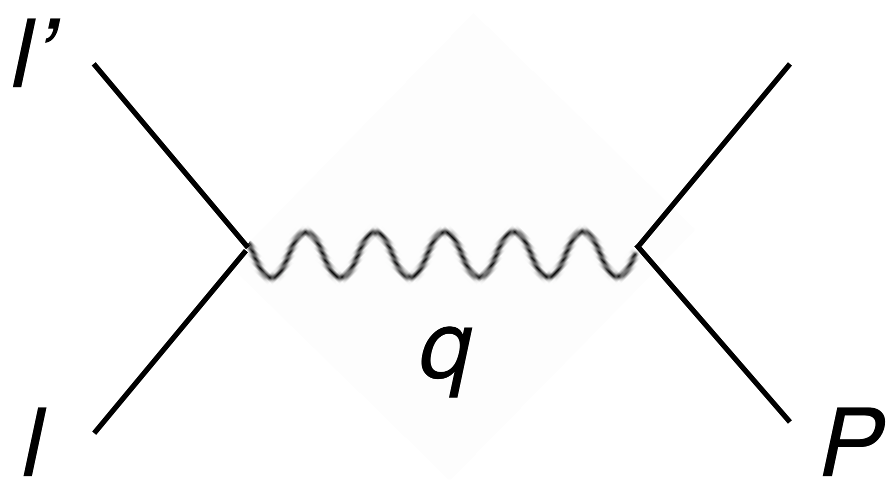
$$\frac{d\sigma}{d\Omega} = \left(\frac{\alpha}{4ME\sin^2(\theta/2)}\right)^2 \frac{E'}{E}\left[\frac{q^2}{2M}\sin^2(\theta/2) + \cos^2(\theta/2)\right]$$

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:

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

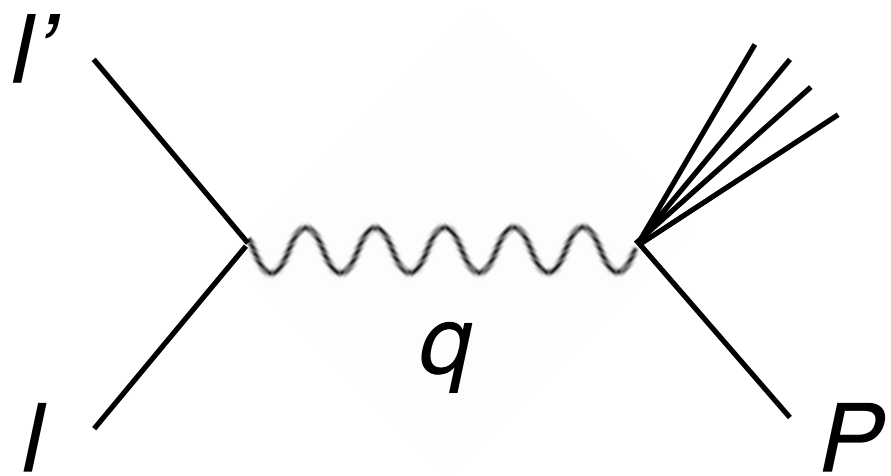
Charge conservation at the proton vertex reduces the number of structure functions:

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

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:

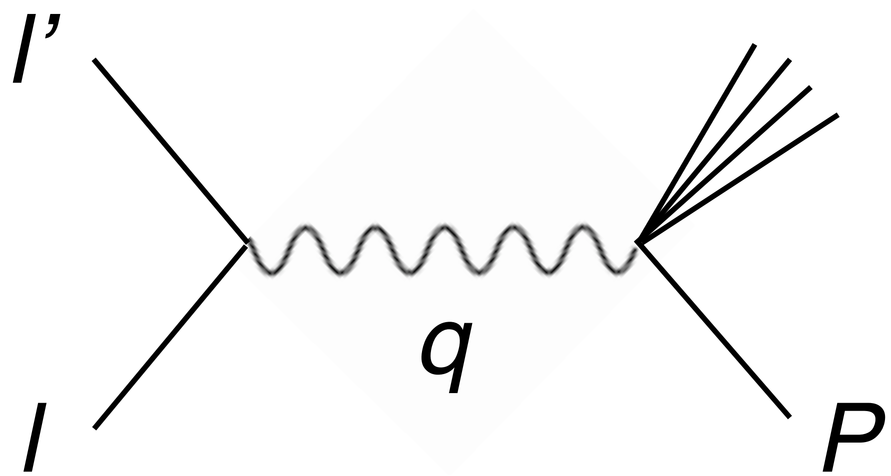
$$W_1, W_2 \;\; \text{or, alternatively expressed,} \;\; F_1, F_2$$

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

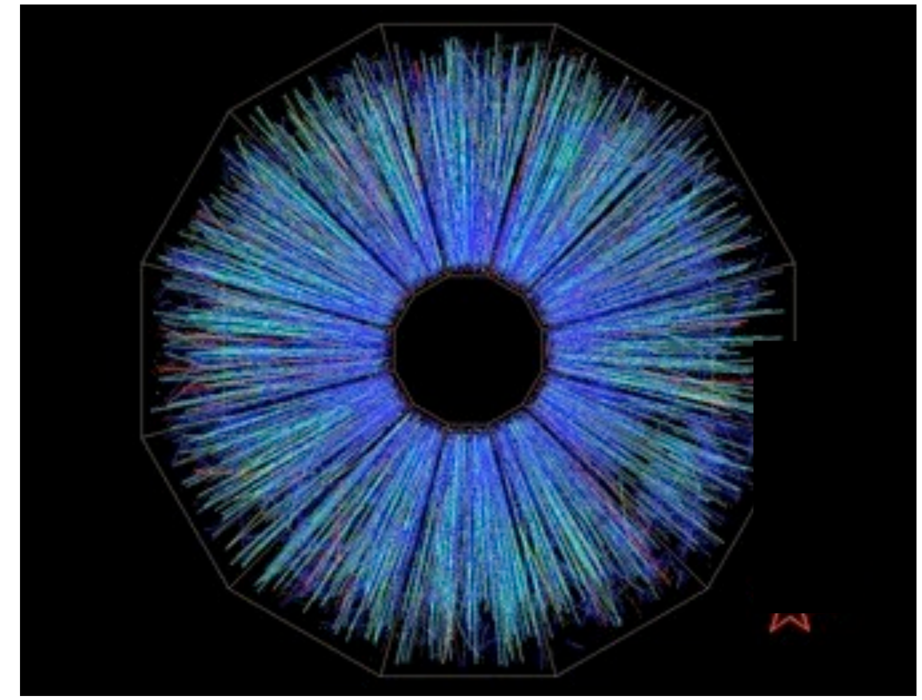
$$Q^2 = -q^2, \qquad x = -\frac{q^2}{2q.p}, \;\; 0 < x < 1$$

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!

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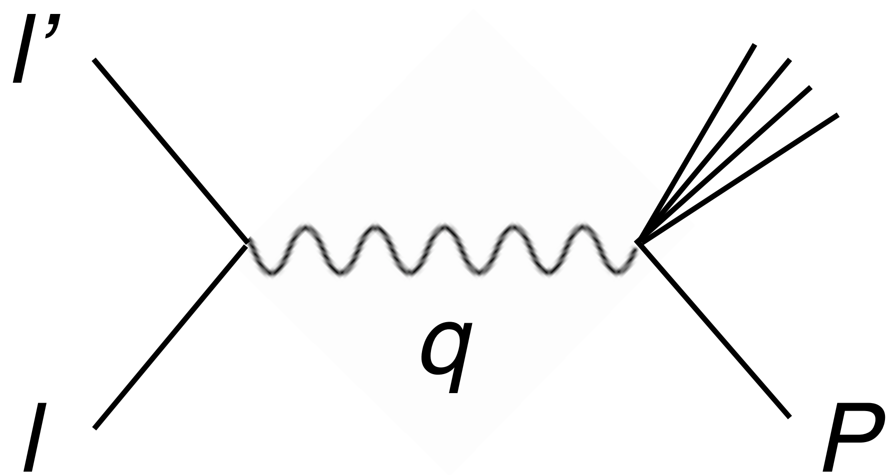

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So much for the structure, <u>the physics is in the structure functions.</u>

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

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

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

Now,

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

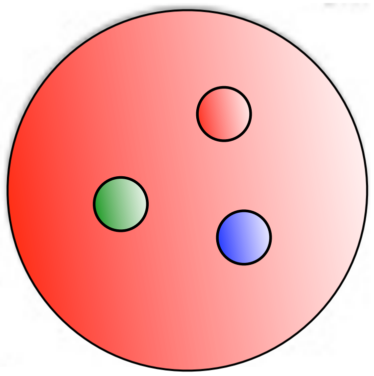
$$-\frac{q^2}{2Mx}W_2 = \sum_q \int_0^1 x e_q^2 \delta(x - z_q)\, f_q(z_q)\, dz_q = x \sum_q e_q^2 f_q(x) \equiv F_2(x)$$

Two important *observable* consequences,

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

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

Elastic scattering off Dirac Partons



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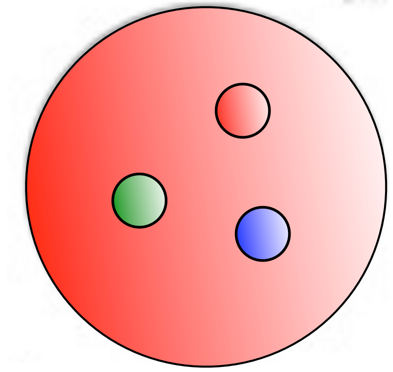

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Now,

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

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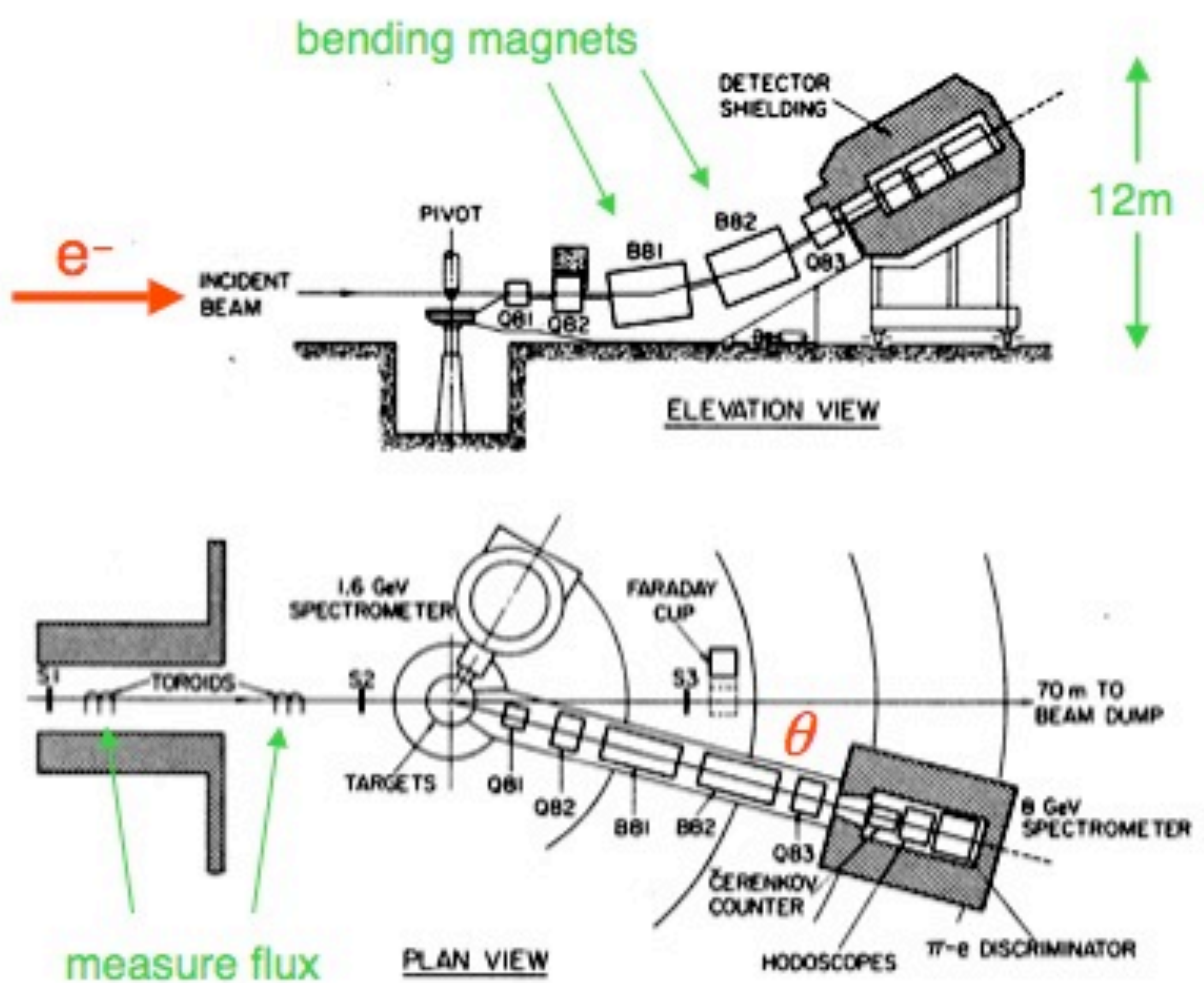
~10 GeV *Deep-Inelastic* Electron Scattering



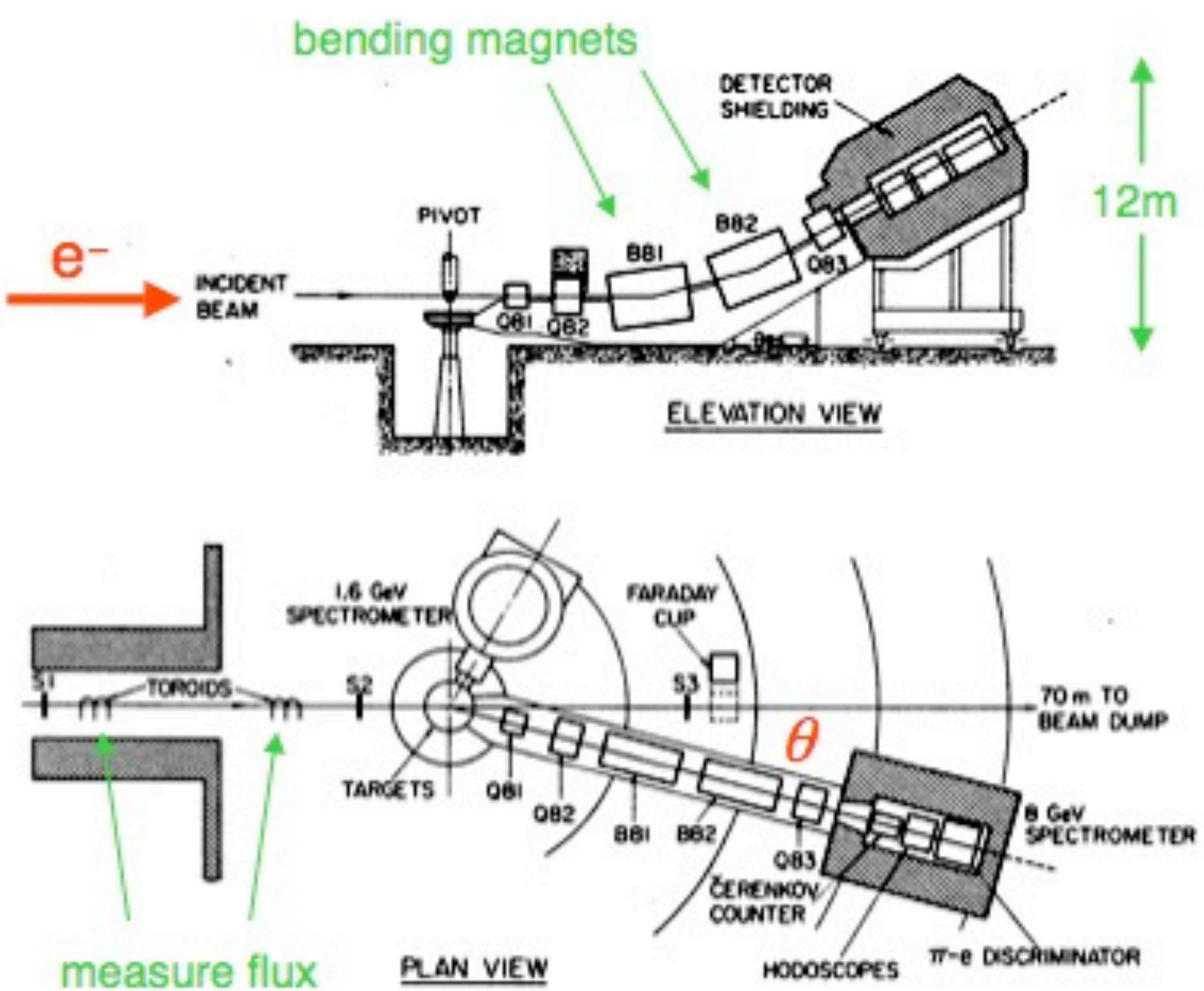
Scattered electron is deflected by a known *B*-field and a fixed vertical angle:

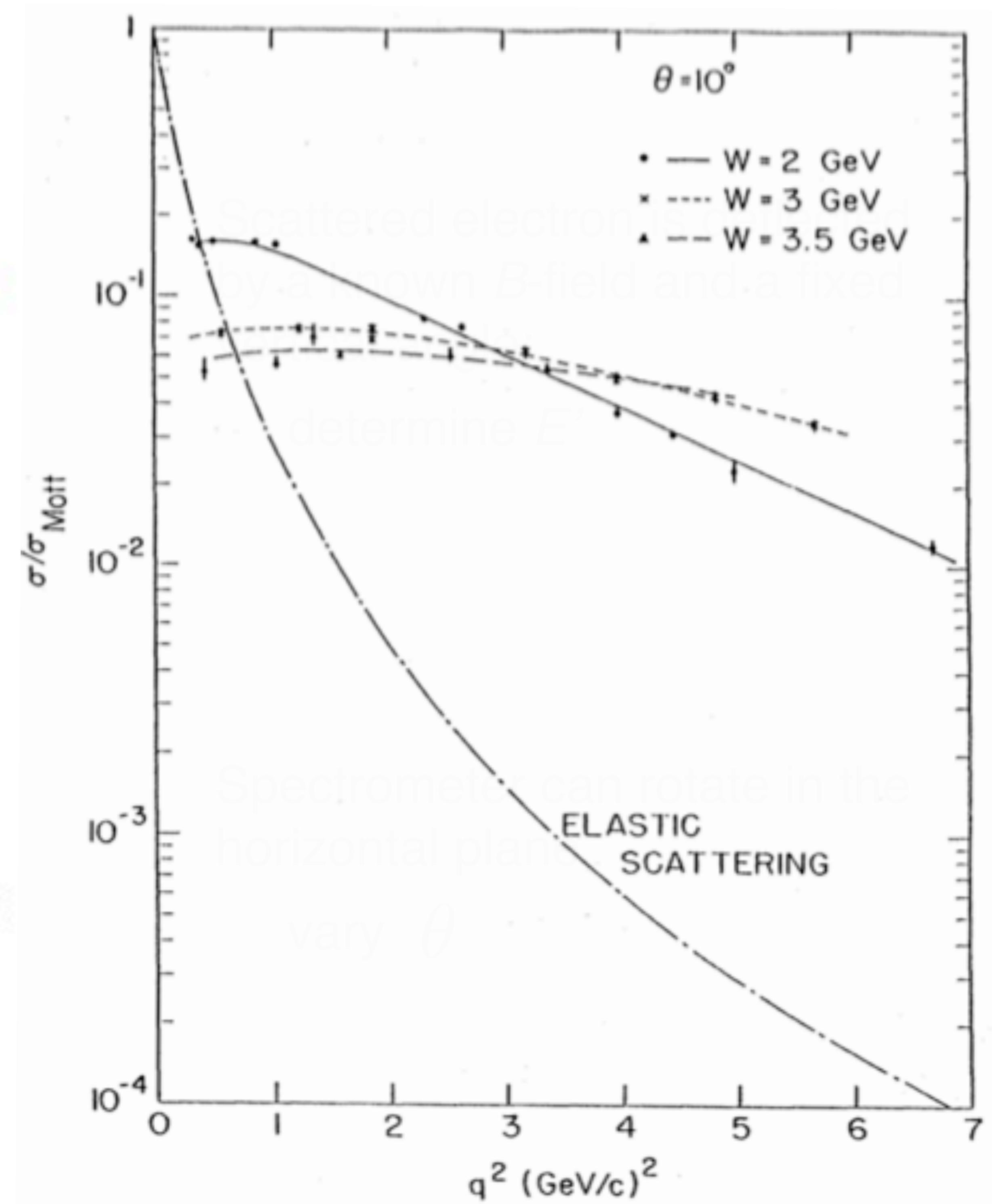
determine *E'*

Spectrometer can rotate in the horizontal plane,

vary θ

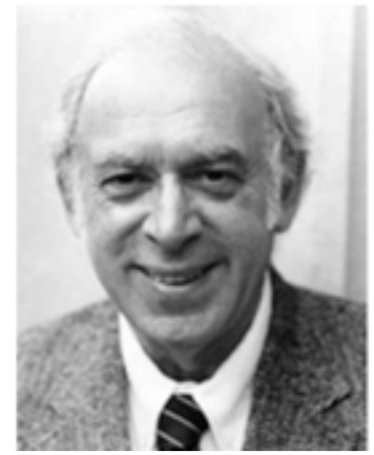
~10 GeV *Deep-Inelastic* Electron Scattering





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

Deep-Inelastic Electron Scattering

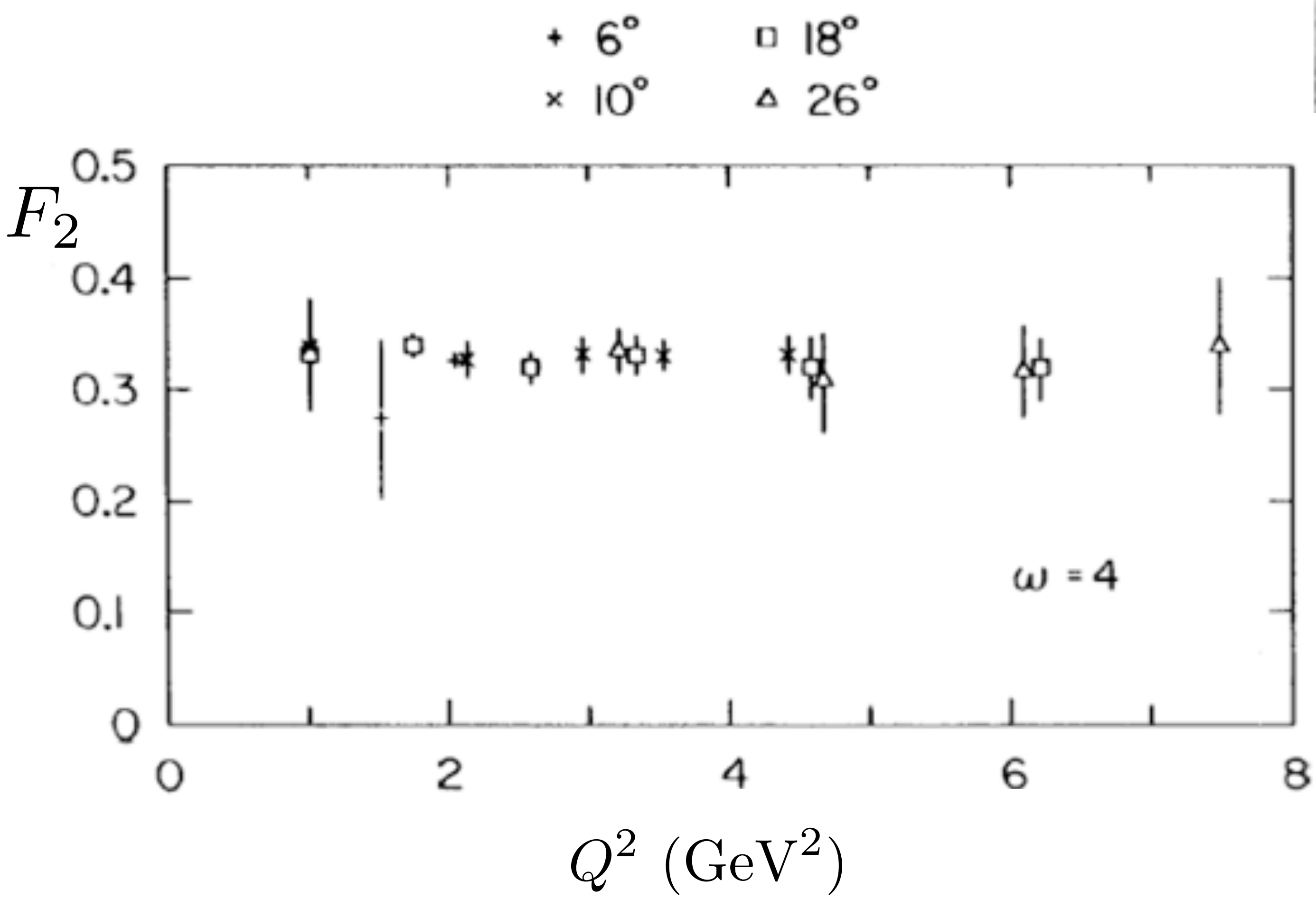


J.T. Friedman

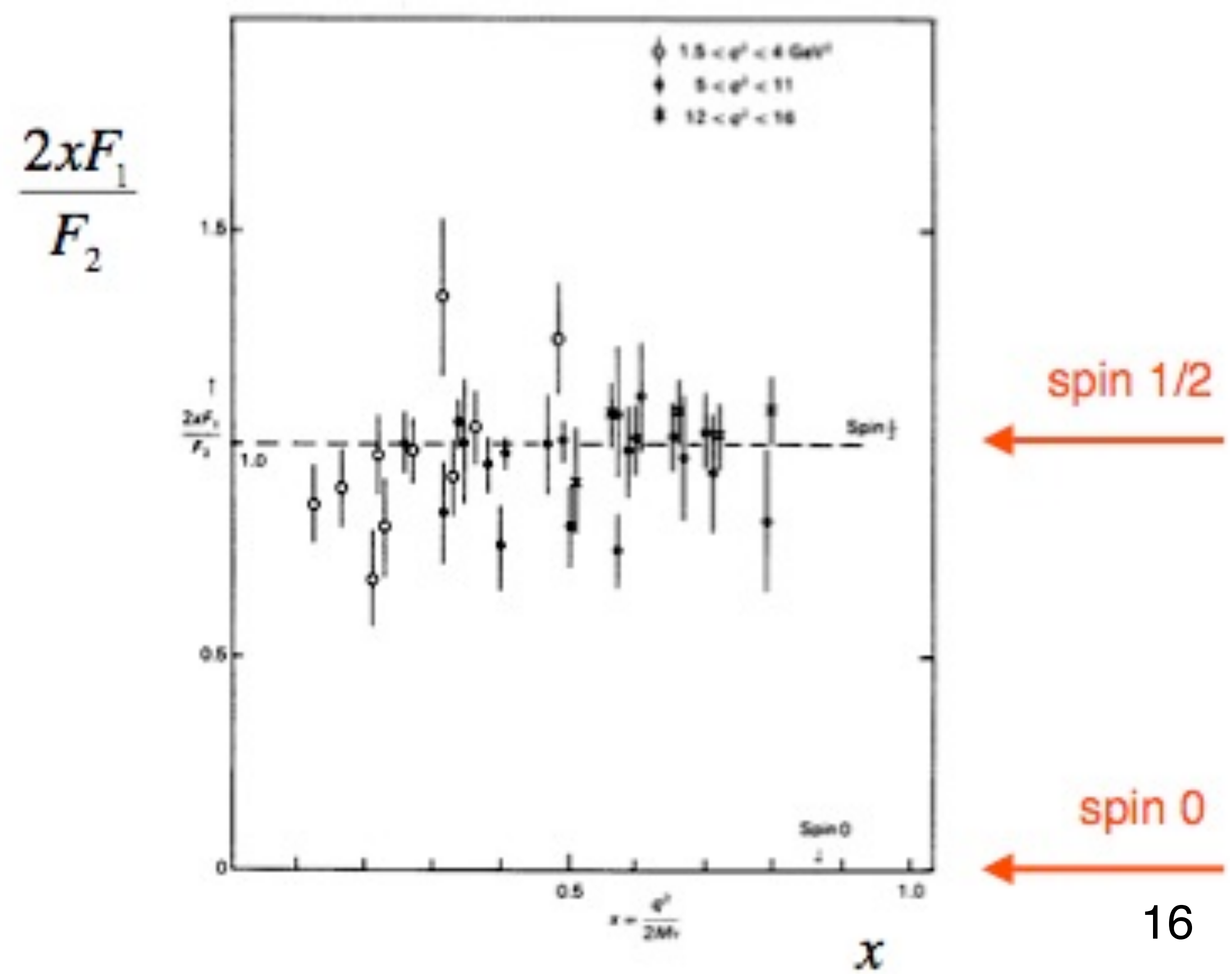
R. Taylor
Nobel Prize 1990

H.W. Kendall

Bjorken scaling:



Callan-Gross relation:



*Point particles cannot be further resolved; their measurement does not depend on wavelength, hence Q², *

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

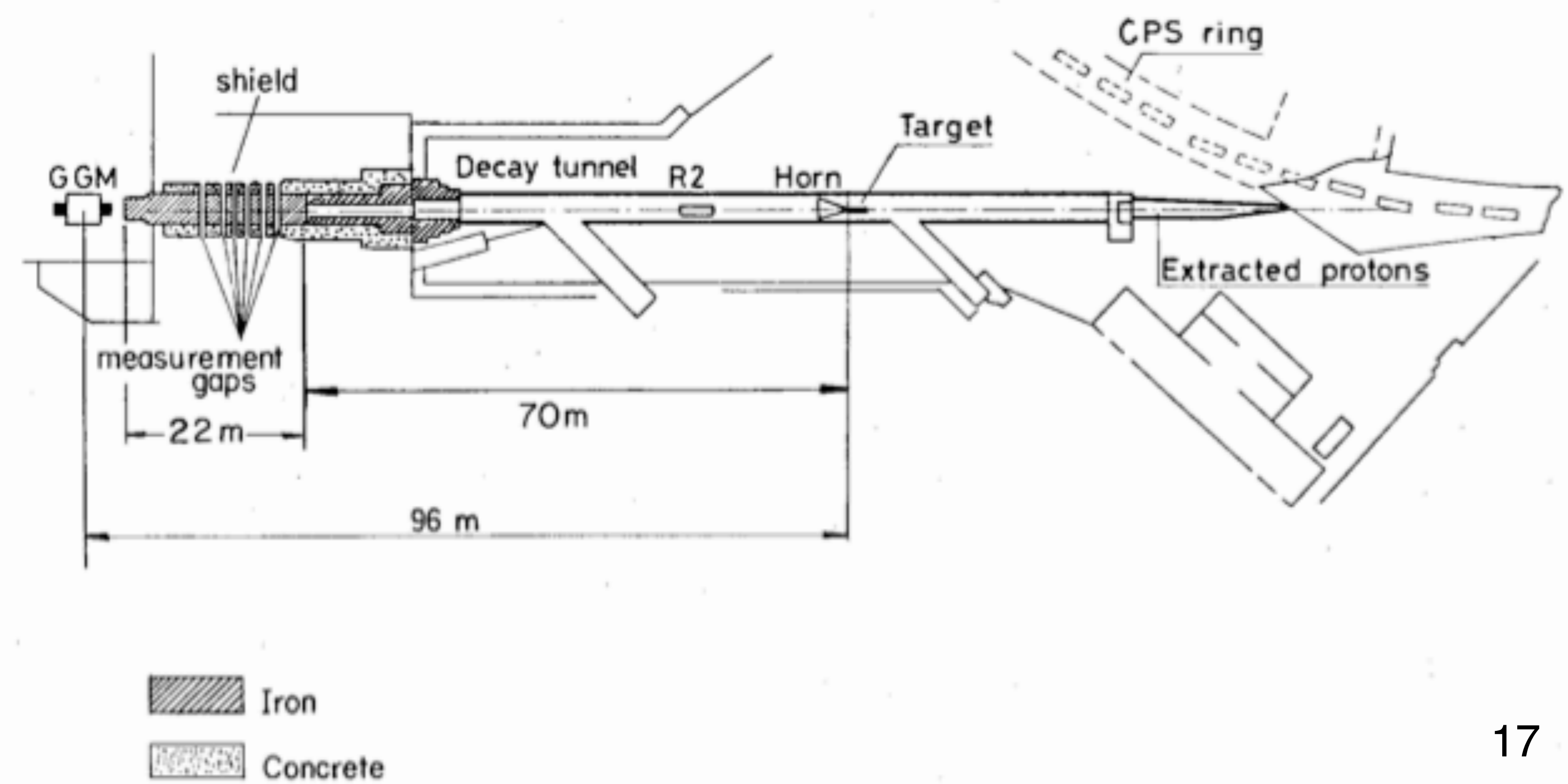
Deep-Inelastic *Neutrino* Scattering

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

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

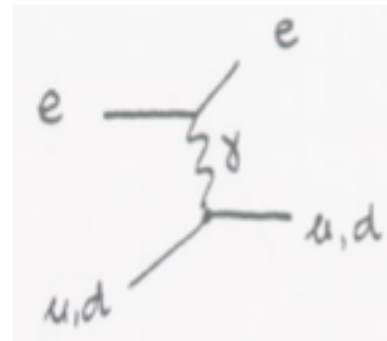
Charged-current DIS!

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



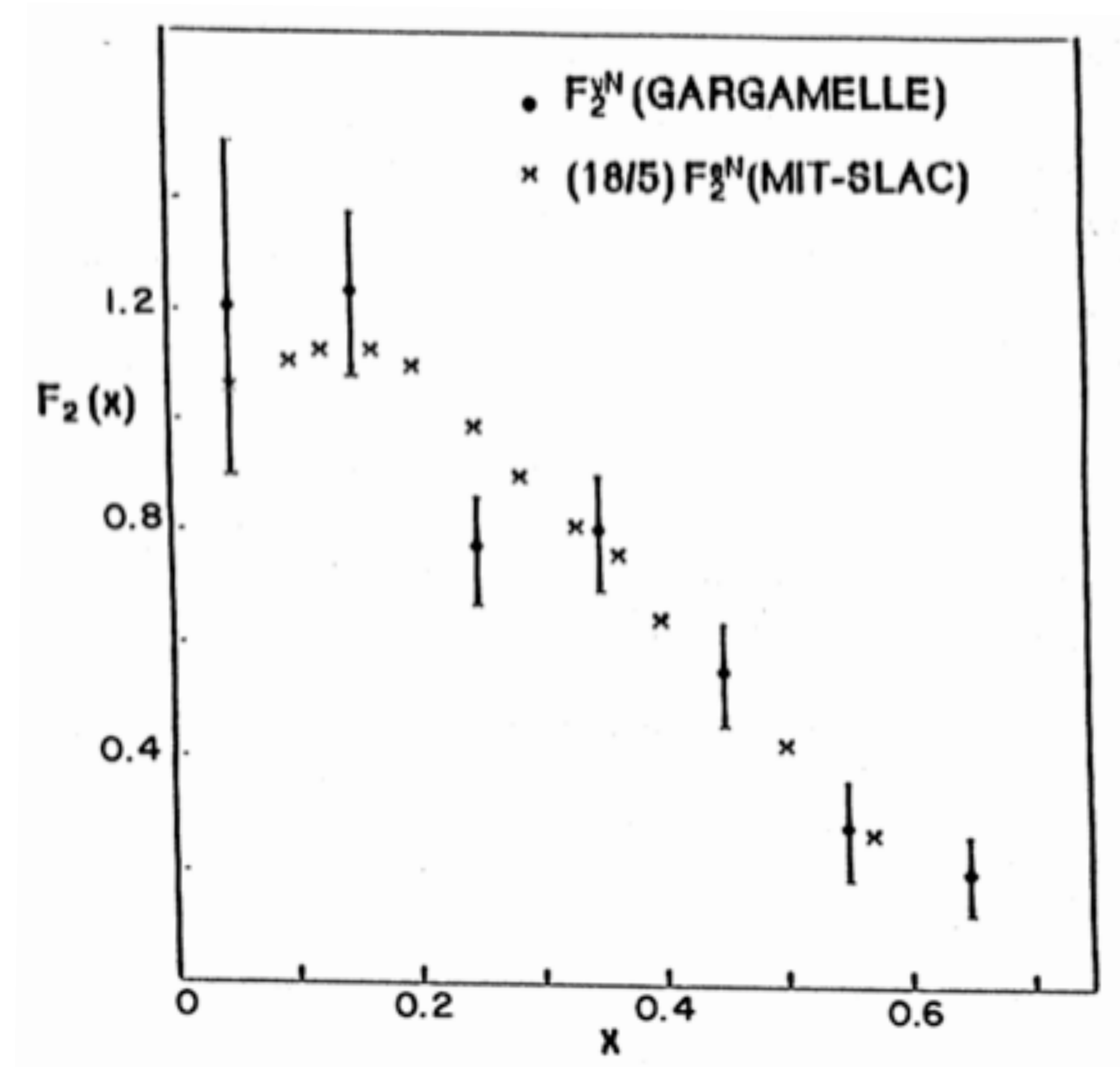
Deep-Inelastic Scattering - Fractional Electric Charges

Neutral-current (photon) DIS:



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

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



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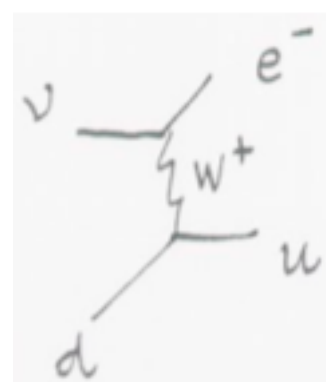

$$F_2^{\nu p} = 2x(d + \bar{u}), \quad F_2^{\nu n} = 2x(u + \bar{d})$$

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Deep-Inelastic Scattering - Fractional Electric Charges

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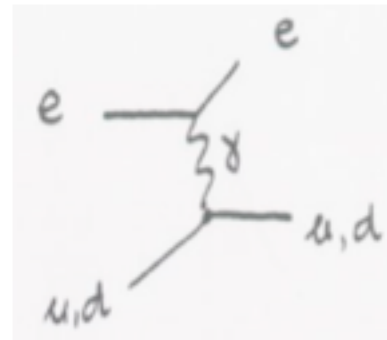

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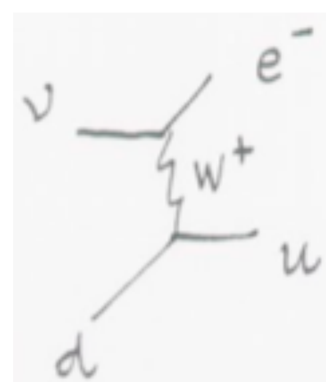

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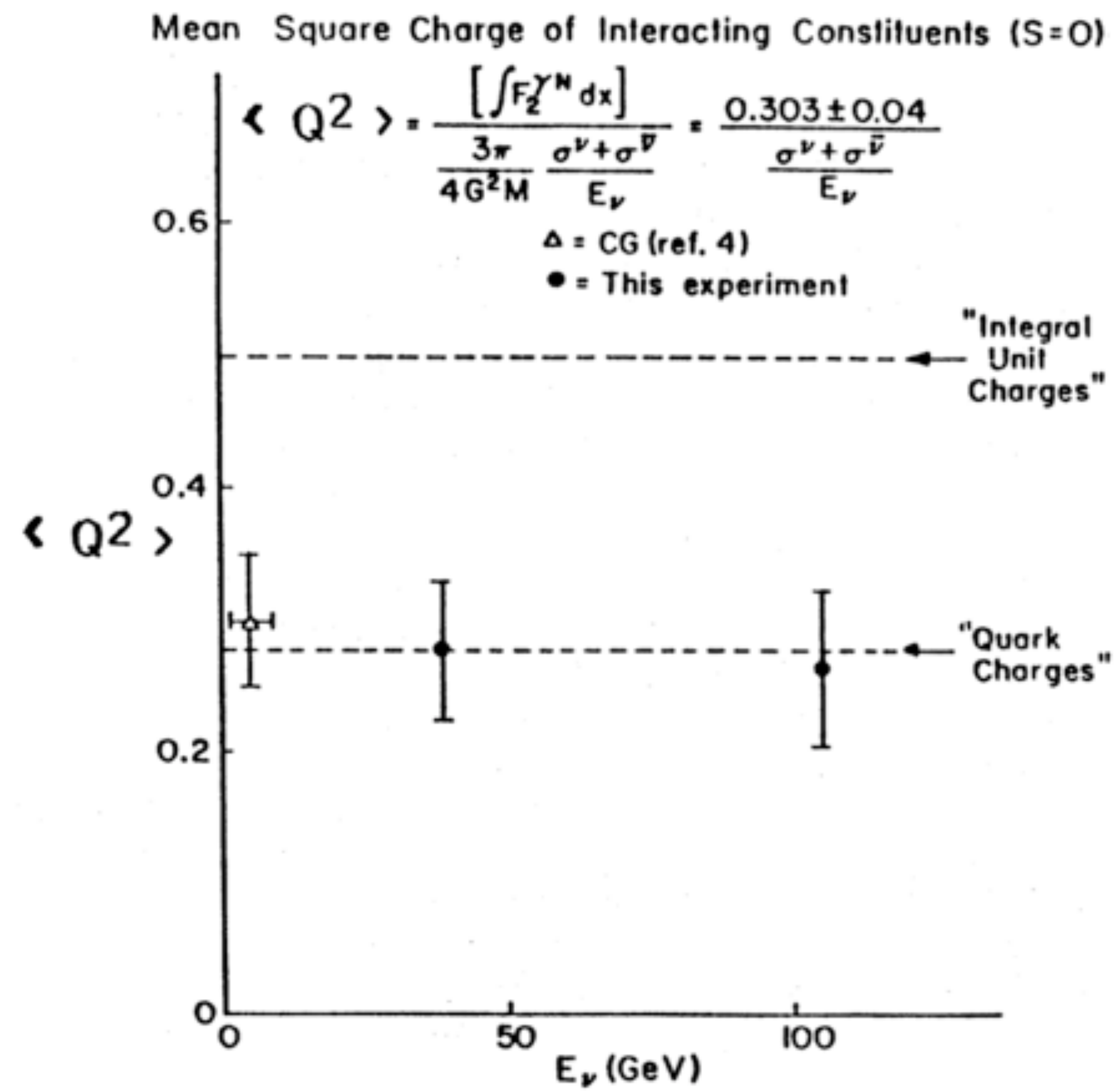
Ratio:

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



Deep-Inelastic Scattering - Valence and Sea Quarks

Charged-current DIS:

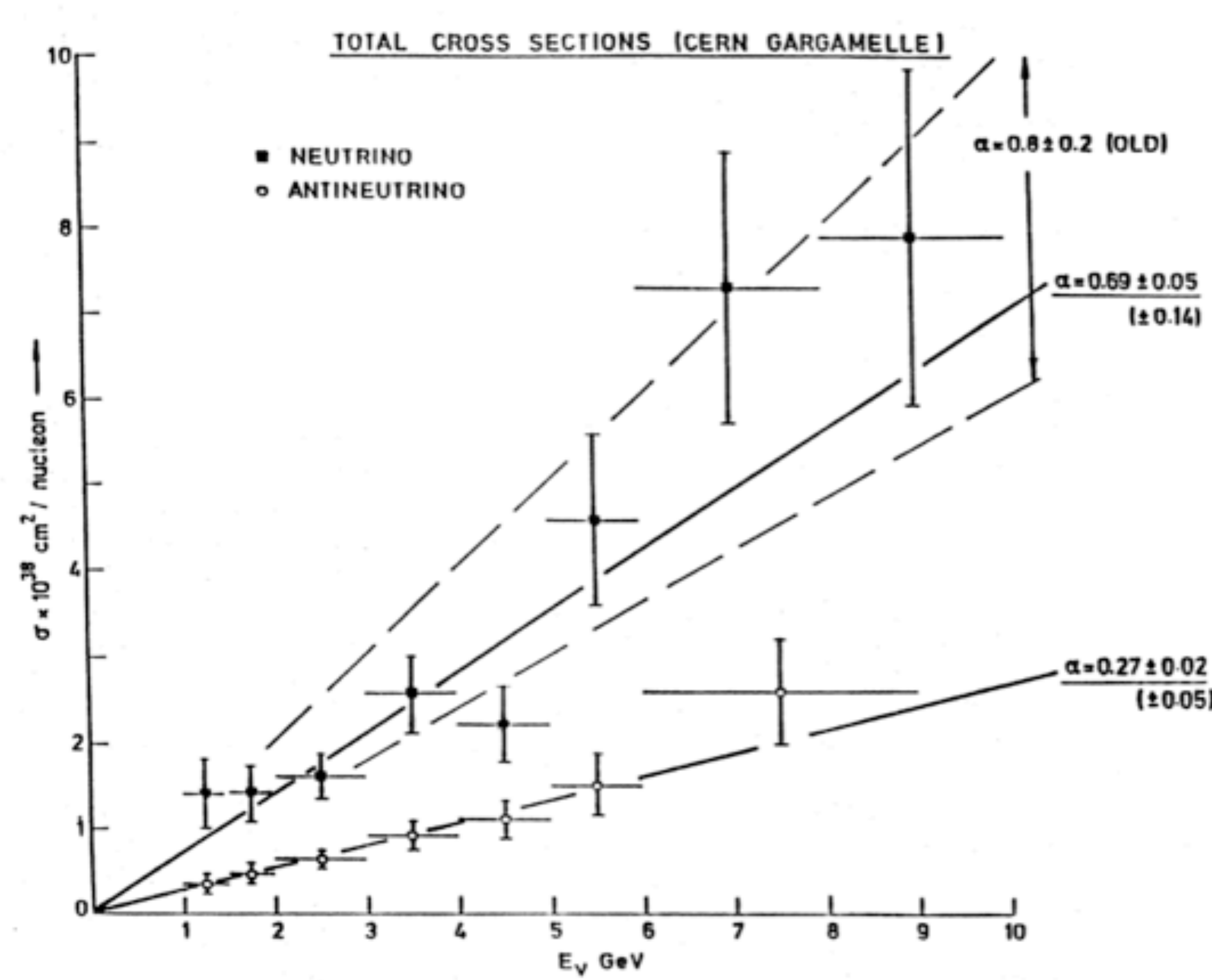
$$F_2^{\nu} = 2x \sum (q + \bar{q})$$

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

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

Gross Llewellyn-Smith: 3

Gargamelle: 3.2 +/- 0.6



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

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

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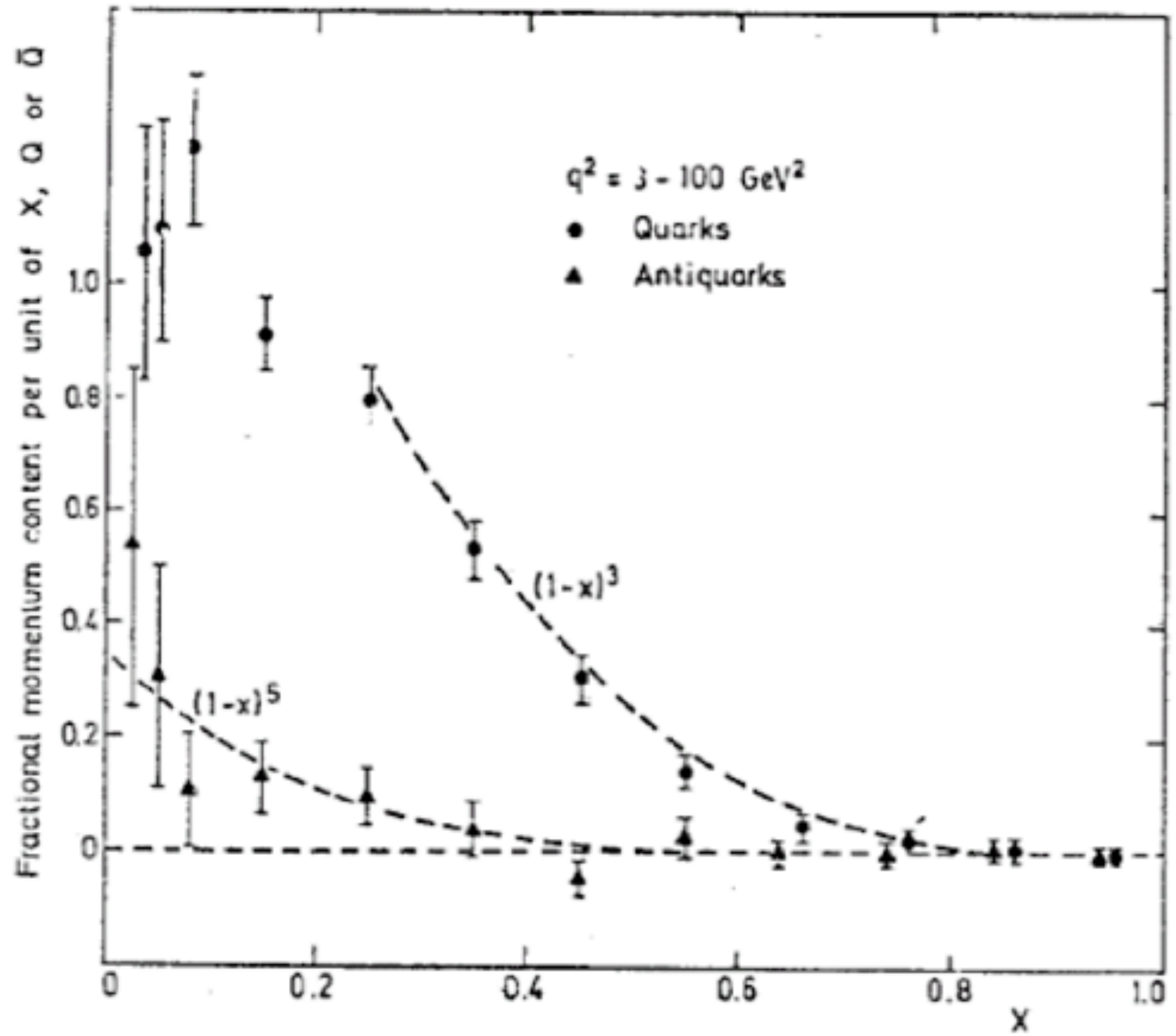
Gross Llewellyn-Smith: 3

Gargamelle: 3.2 +/- 0.6

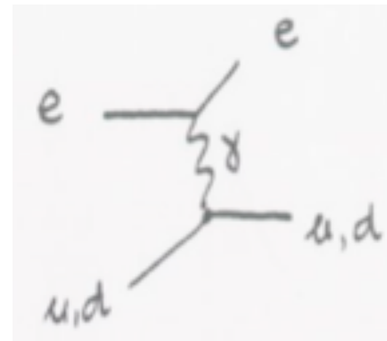


$$\frac{d^2\sigma^{\bar{\nu}N}}{dxdy} \propto \left[\bar{u} + \bar{d} + (u + d)(1 - y)^2\right]$$

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

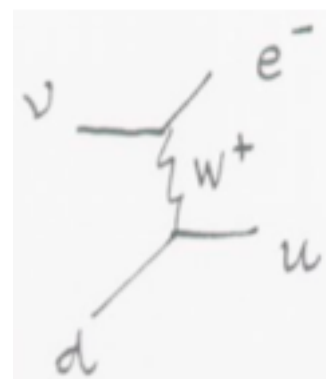
Deep-Inelastic Scattering - Momentum Conservation

Neutral-current (photon) DIS:



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

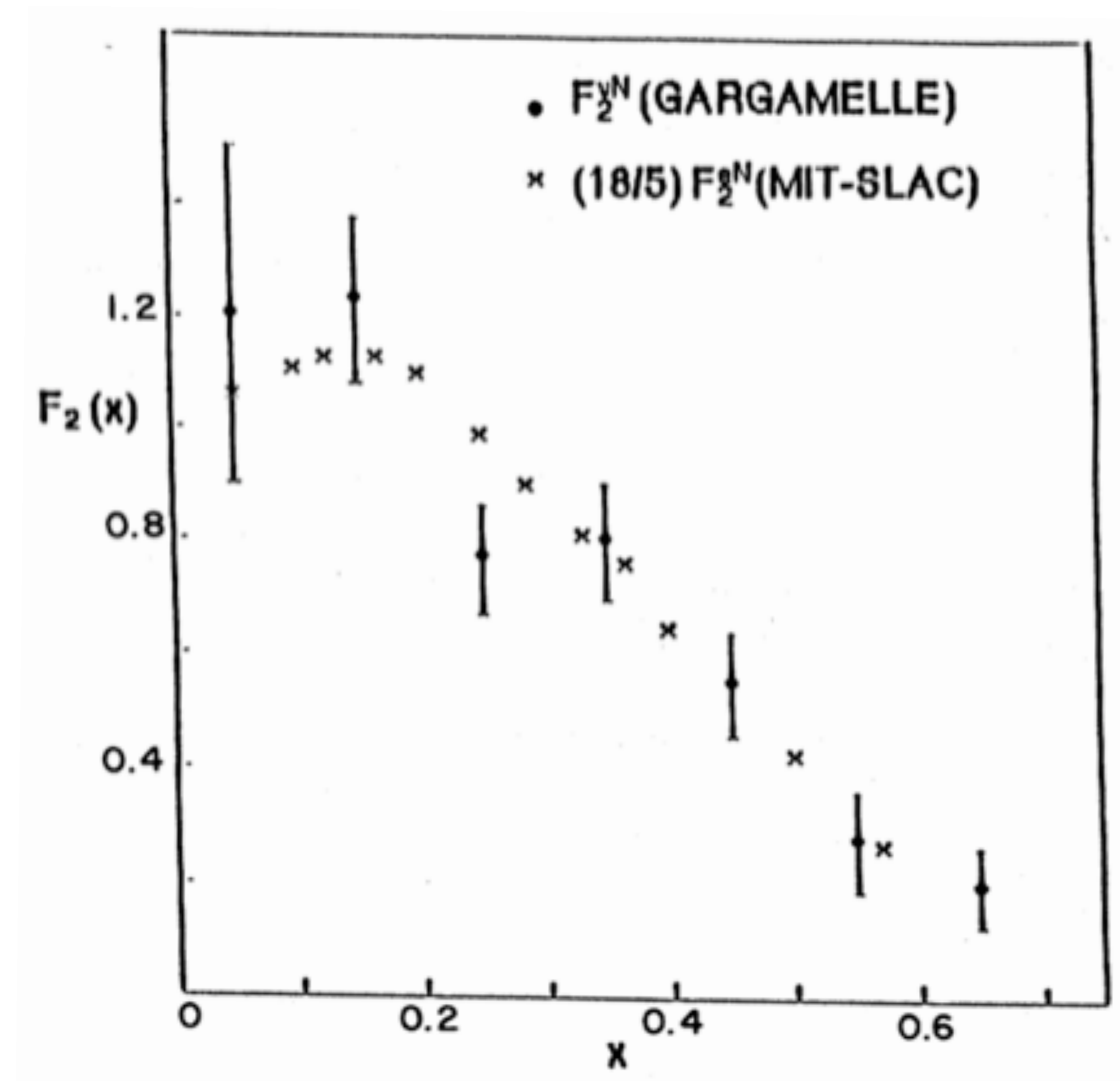
Charged-current DIS:



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

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

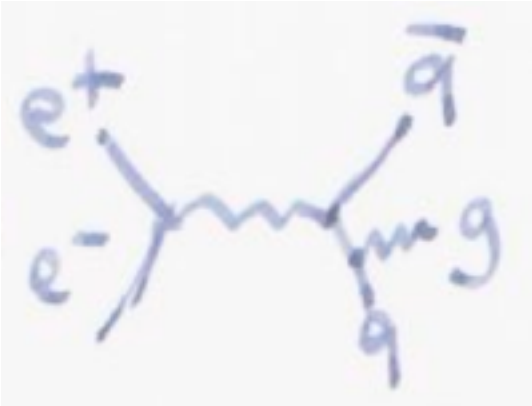
SLAC: 0.14 +/- 0.05

Quarks carry half of the nucleon momentum!

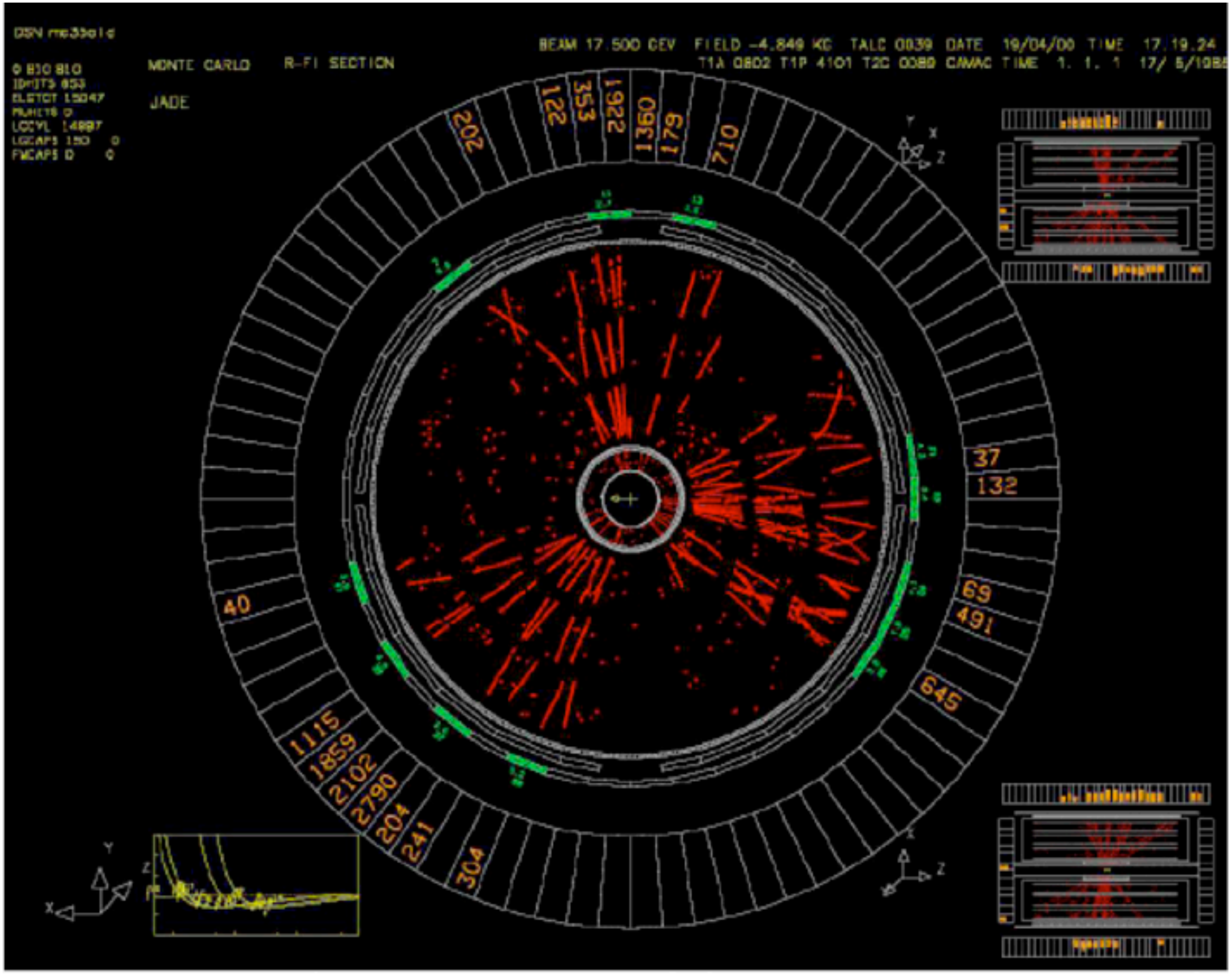
3-jet events at PETRA

Recall the intro on colour:

Observation of its higher order process,

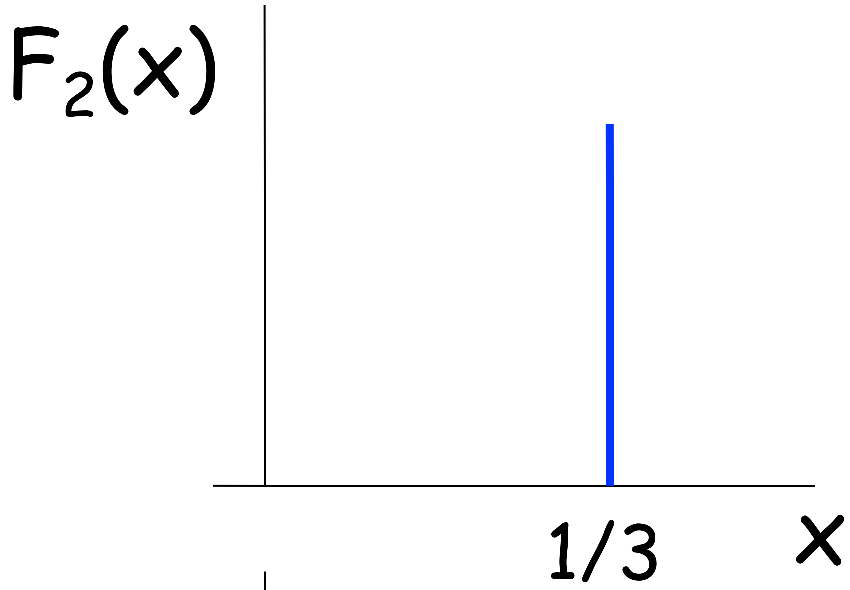


marks the discovery of the gluon.

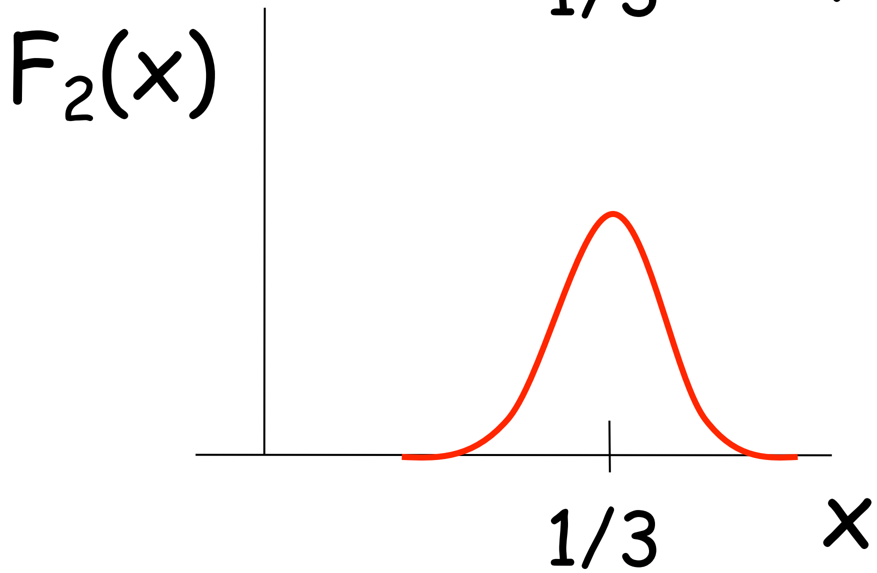


Mom. Conservation: *Gluons carry the other half of the nucleon momentum.*

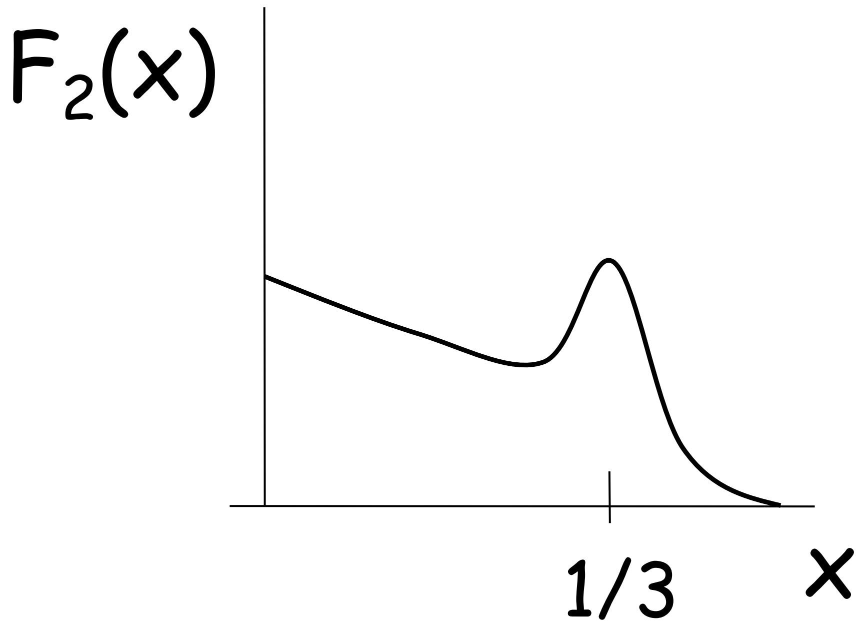
Nucleon Structure



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

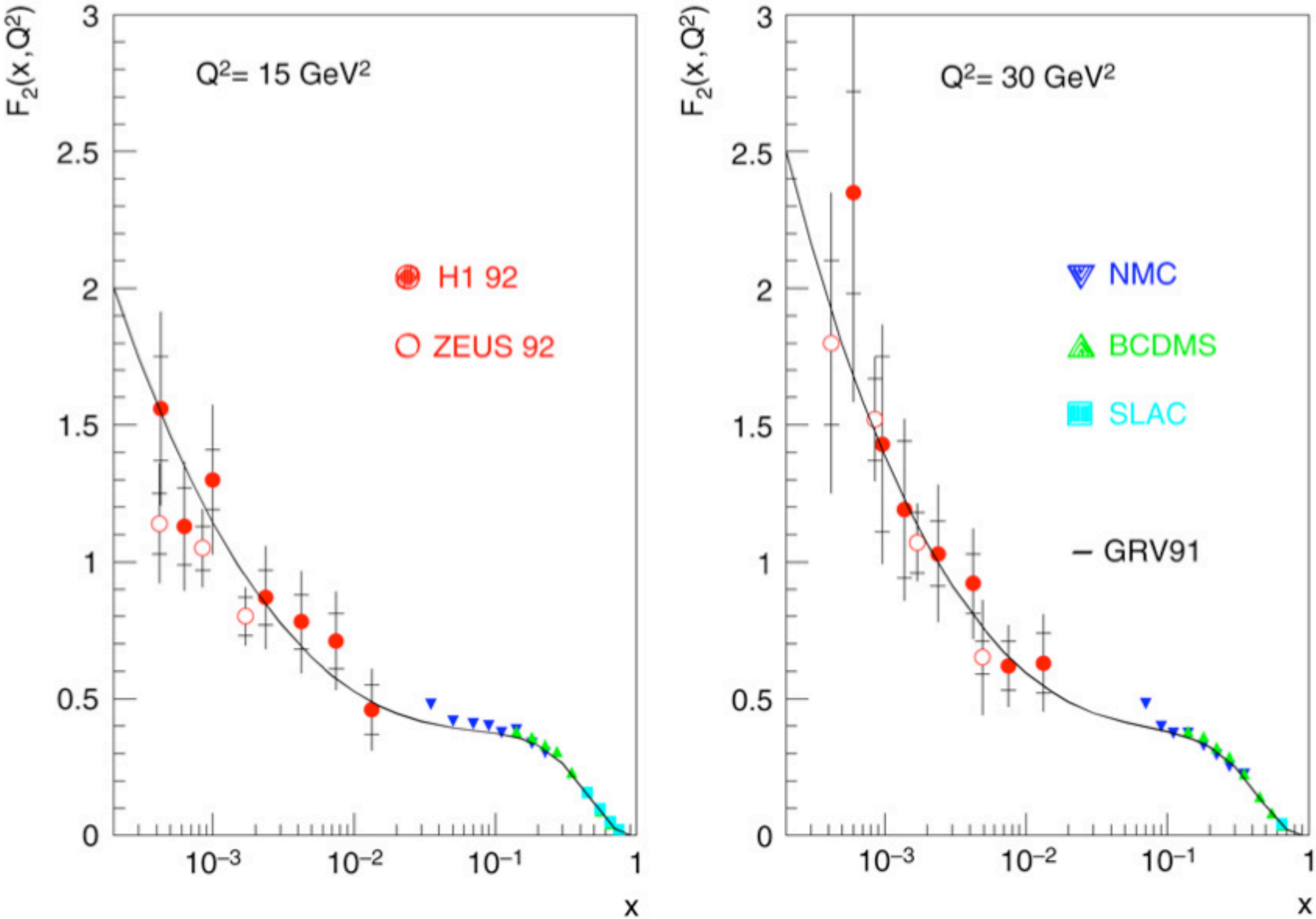


Three quarks with some momentum smearing.

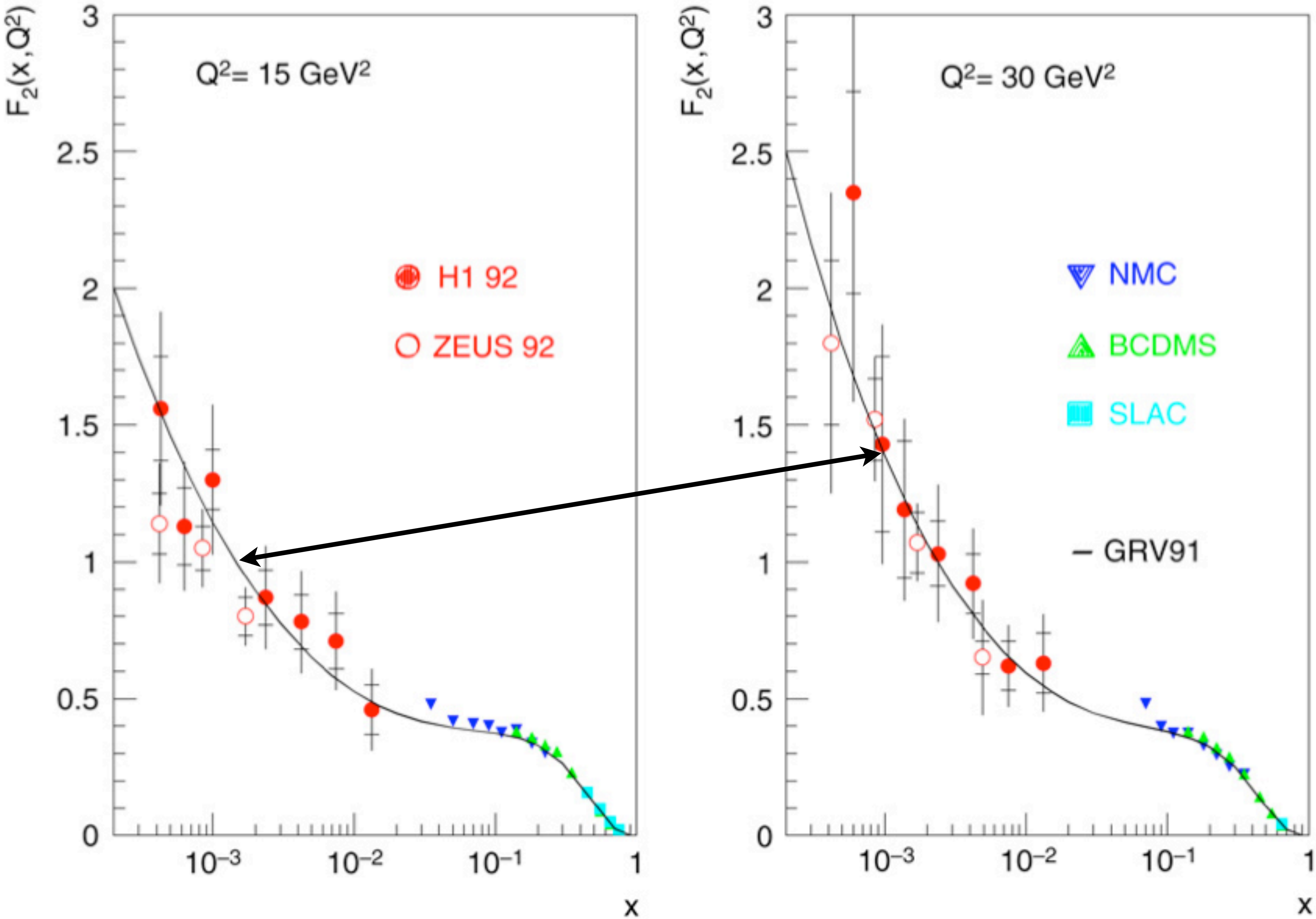


The three quarks radiate partons to lower momentum fractions *x*.

HERA - Early Measurements



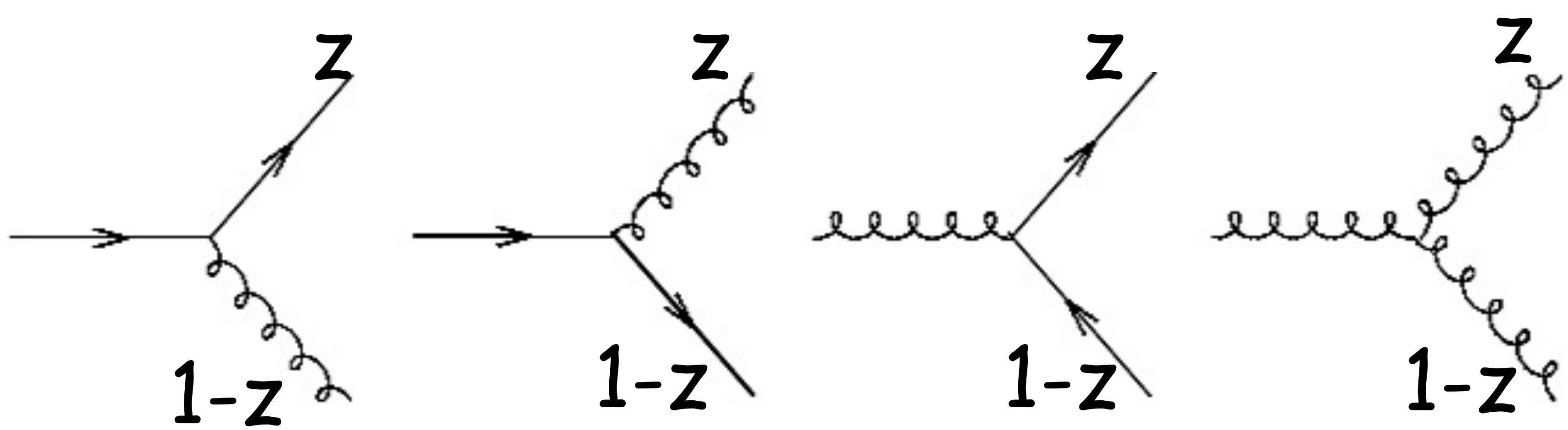
HERA - Early Measurements



Can these observations be related?

QCD Radiation

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

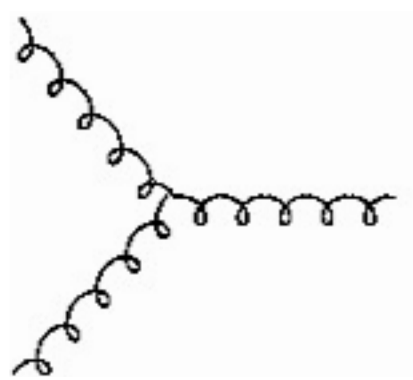


$P_{ab}(z)$: the probability that parton a will radiate a parton b with the fraction z of the original momentum carried by a.

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:

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

convolution

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*.

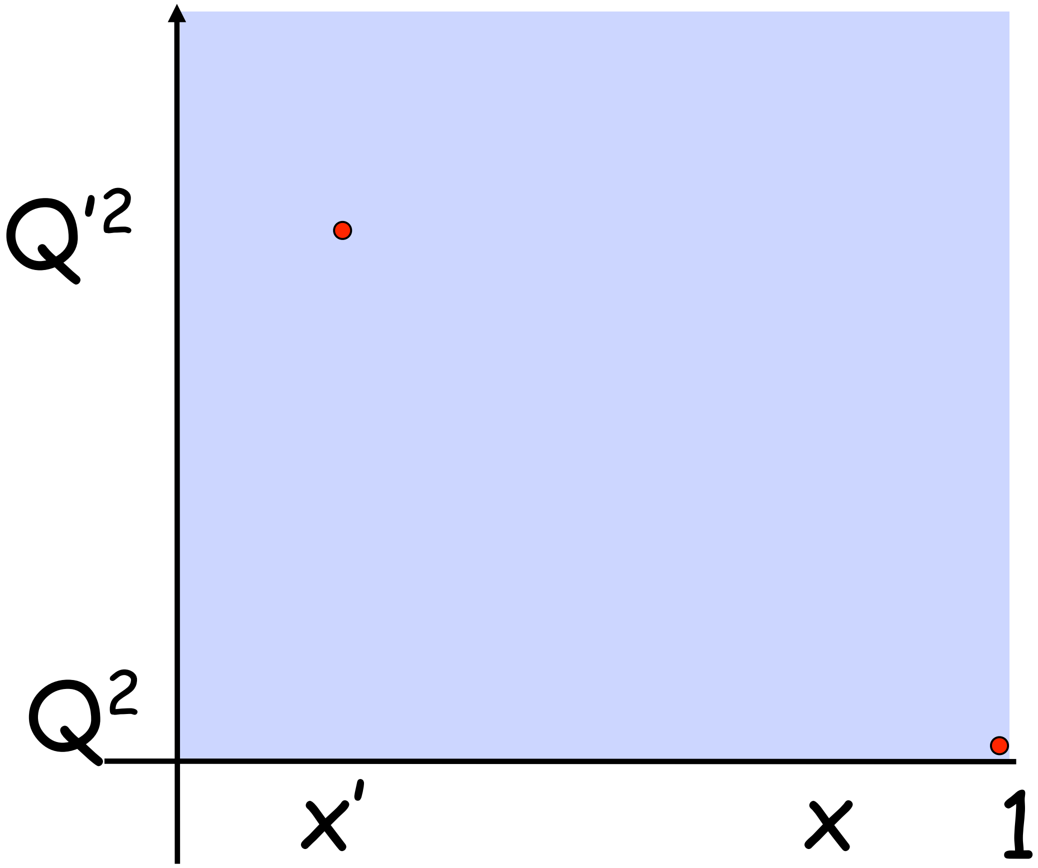
Similarly, for gluons:

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

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 $Q'^2 > Q^2$.



QCD Radiation

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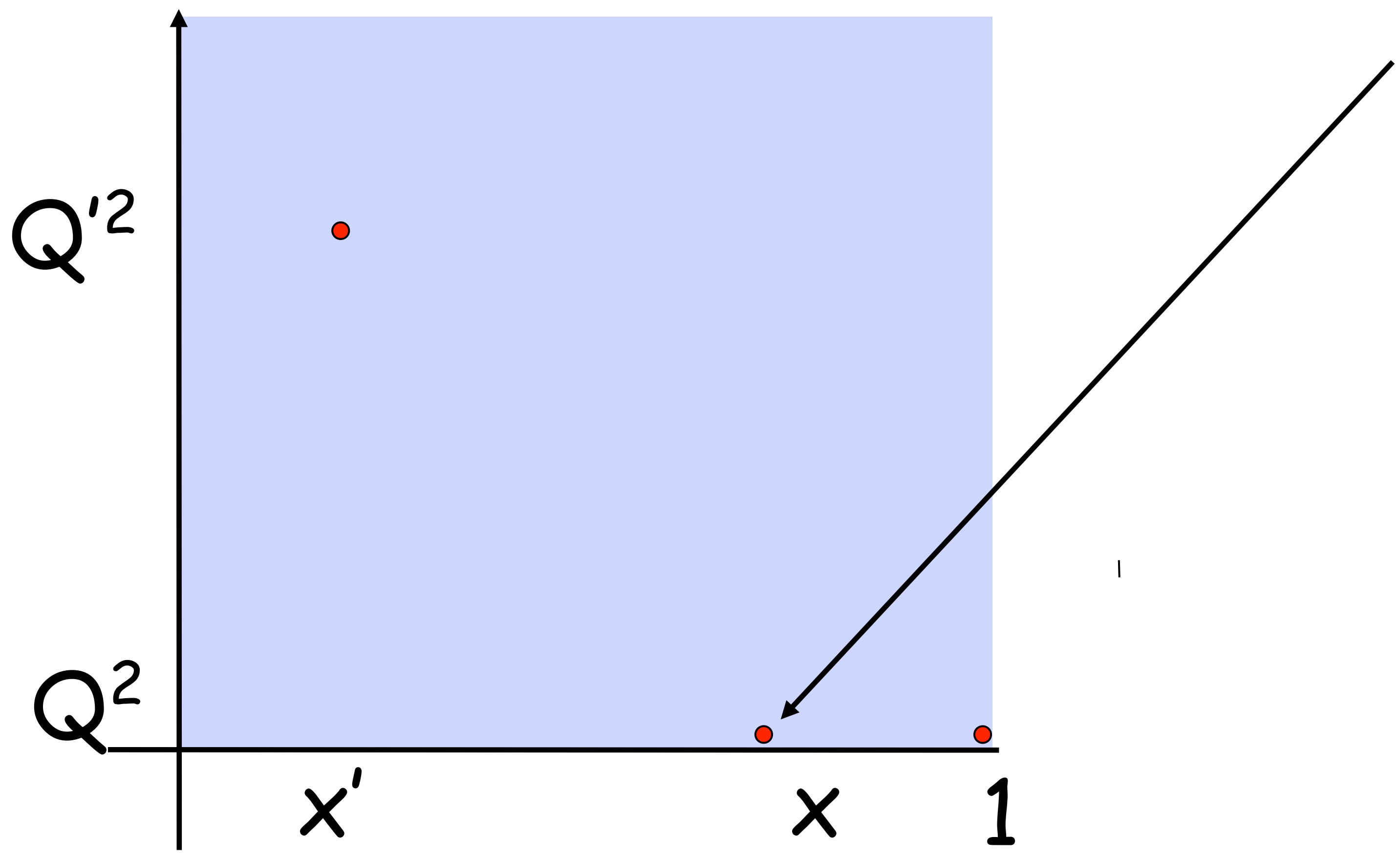

Any parton at $x > x'$ at Q^2 is a source.

QCD Radiation

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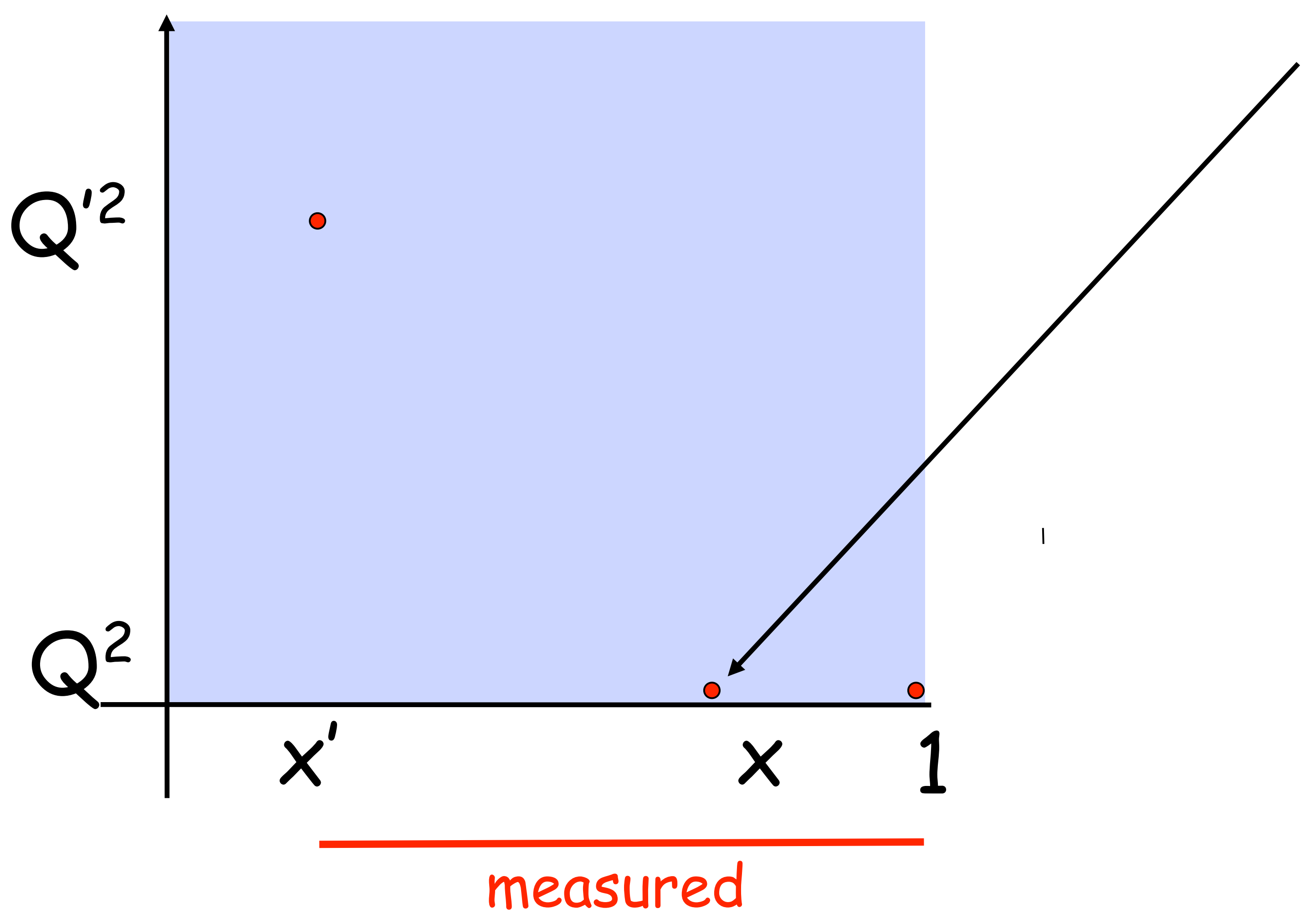

Any parton at $x > x'$ at Q^2 is a source.

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.

QCD Radiation

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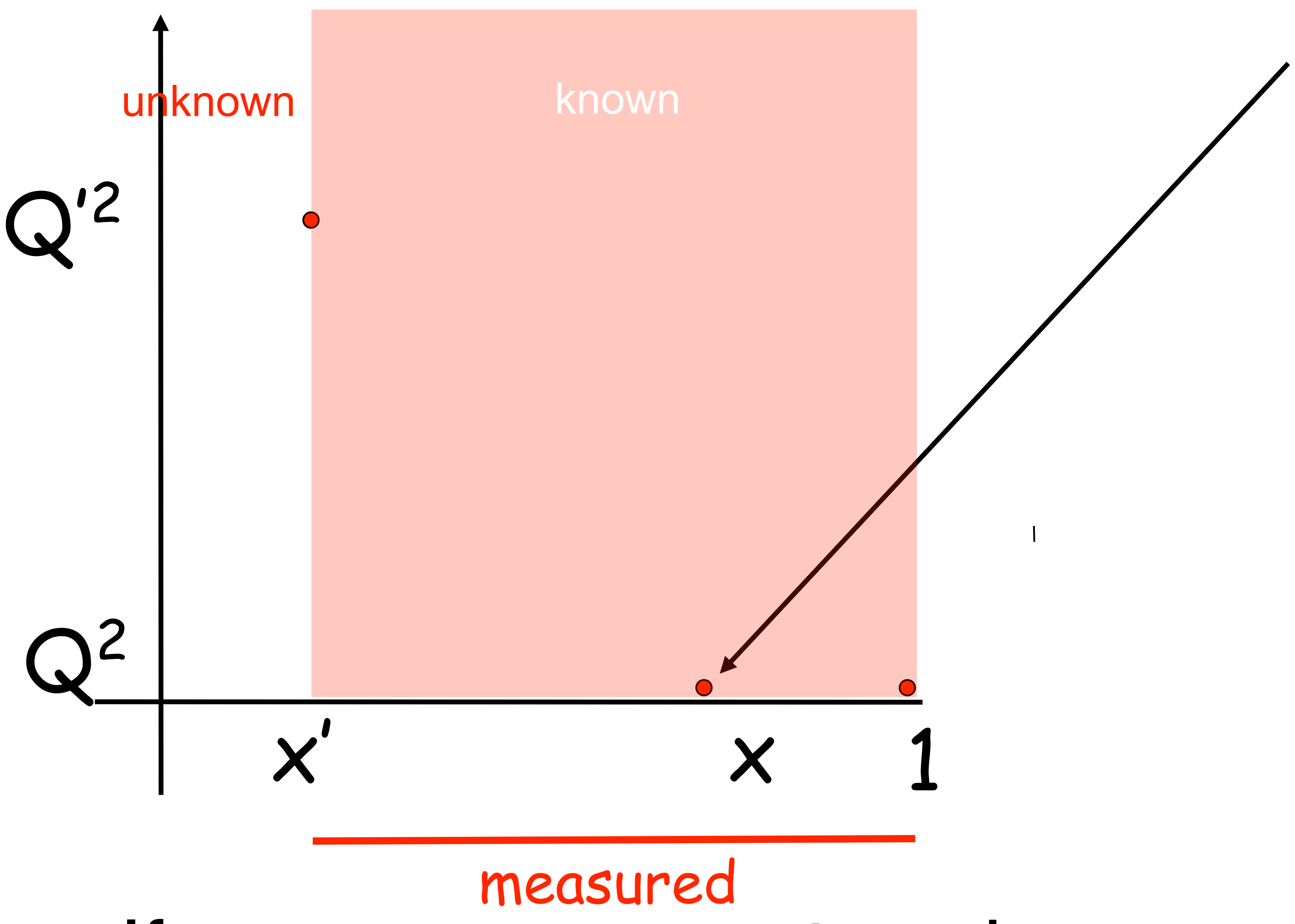

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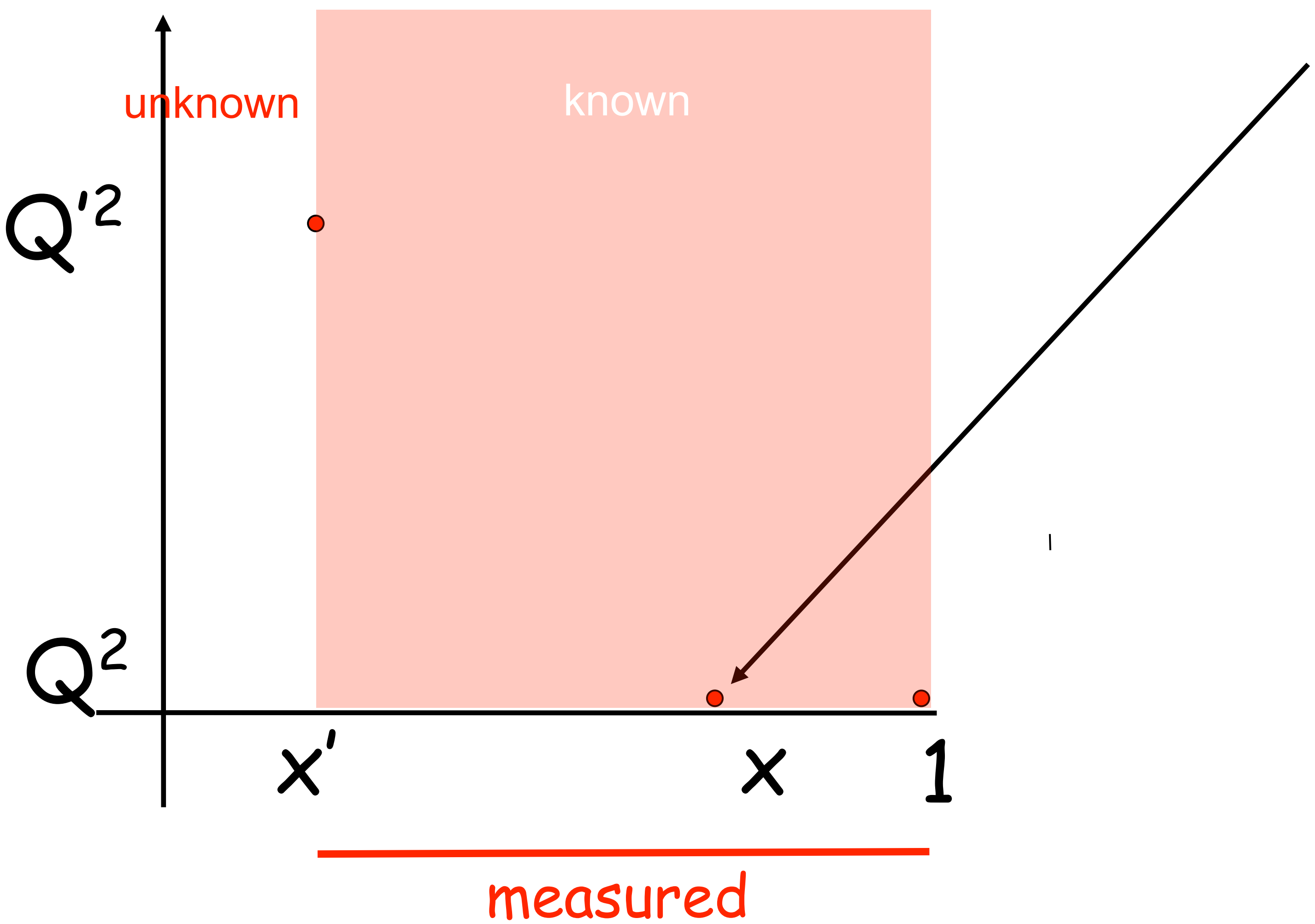
If you measure partons in range $x' \leq x \leq 1$ at some Q^2 then you know them in that range, and only that range, for all Q'^2.

QCD Radiation

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



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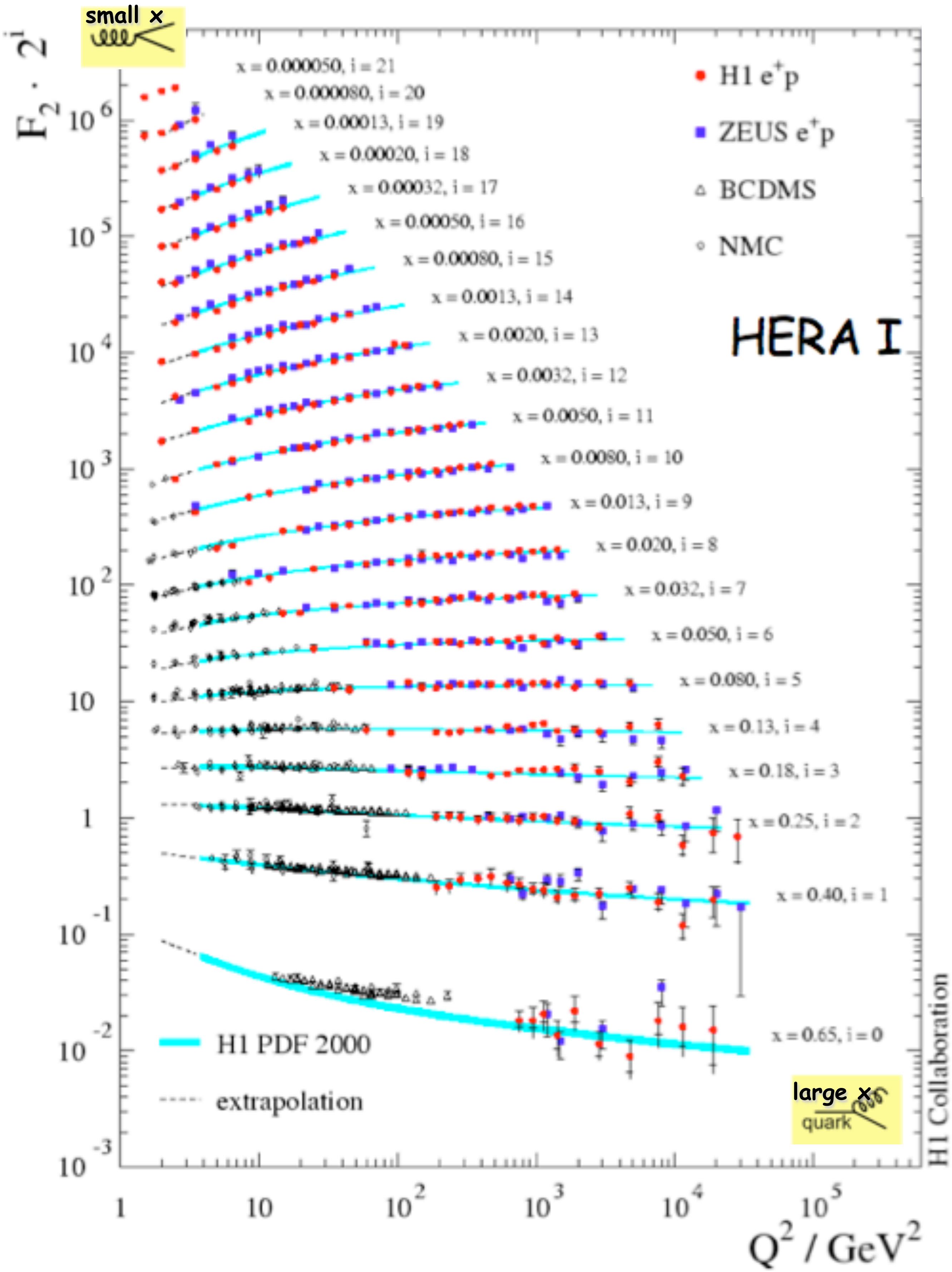
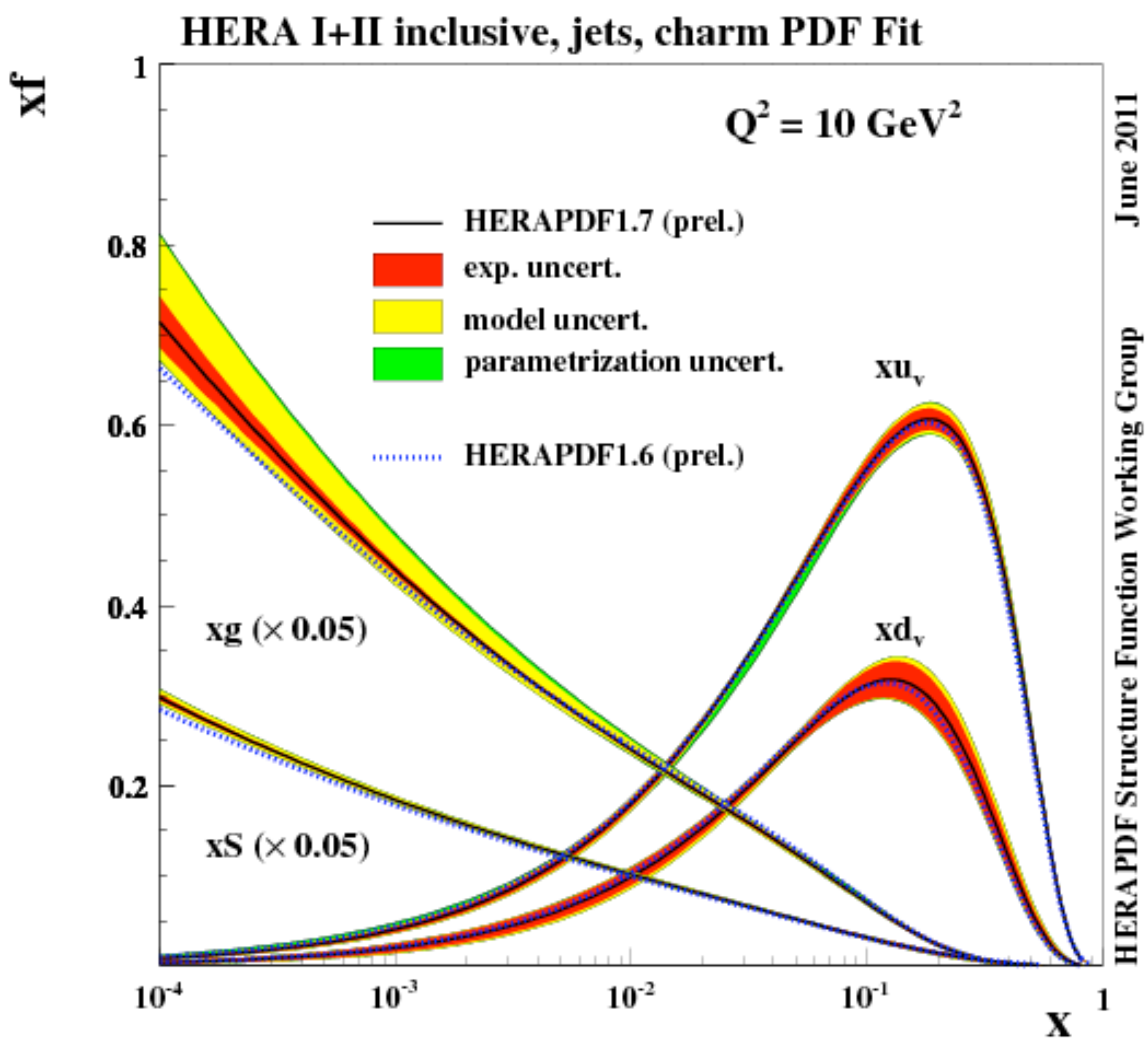
Asymptotic solutions exist to the DGLAP equations that may overwhelm the intrinsic contributions.

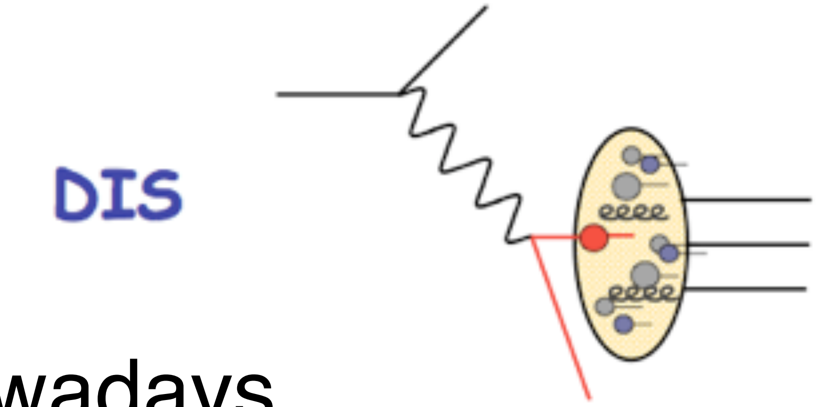
Bjorken scaling vis-a-vis QCD Radiation



Modern understanding of nucleon composition



Brief recap:



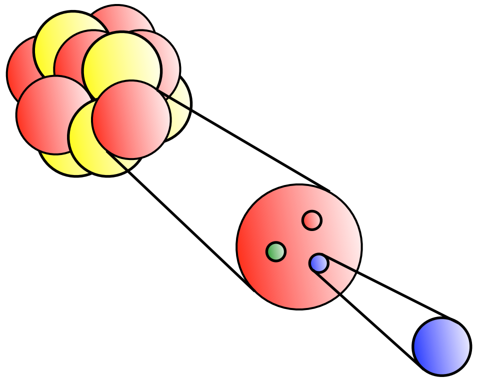
- DIS is about nucleon or nuclear structure, nowadays described in terms of quarks and gluons,
- Feynman's parton model - point like partons, which behave *incoherently* - combined with QCD radiation are remarkably successful in describing DIS cross sections.
- Parton distributions *f(x)* are intrinsic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

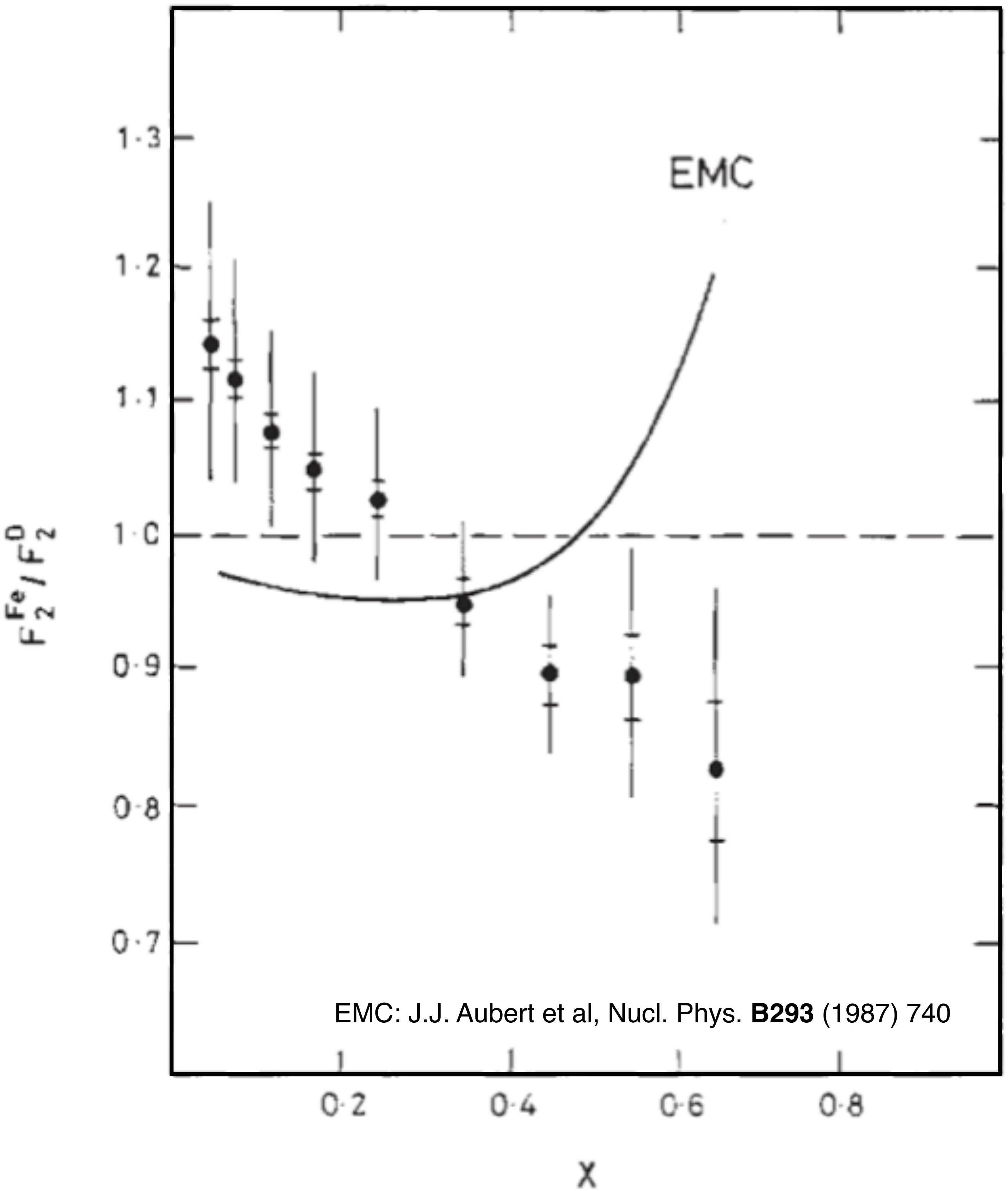
This is great for RHIC, LHC, and many other areas.

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

Questions or comments, before we move on?

DIS - Surprises with Nuclei



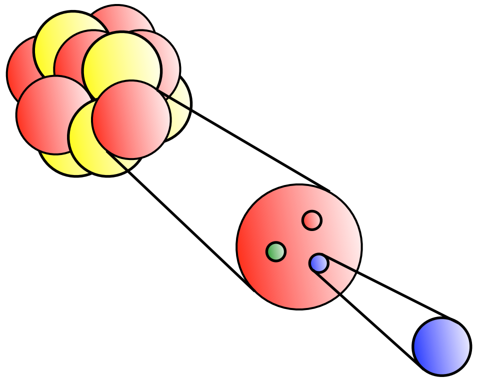


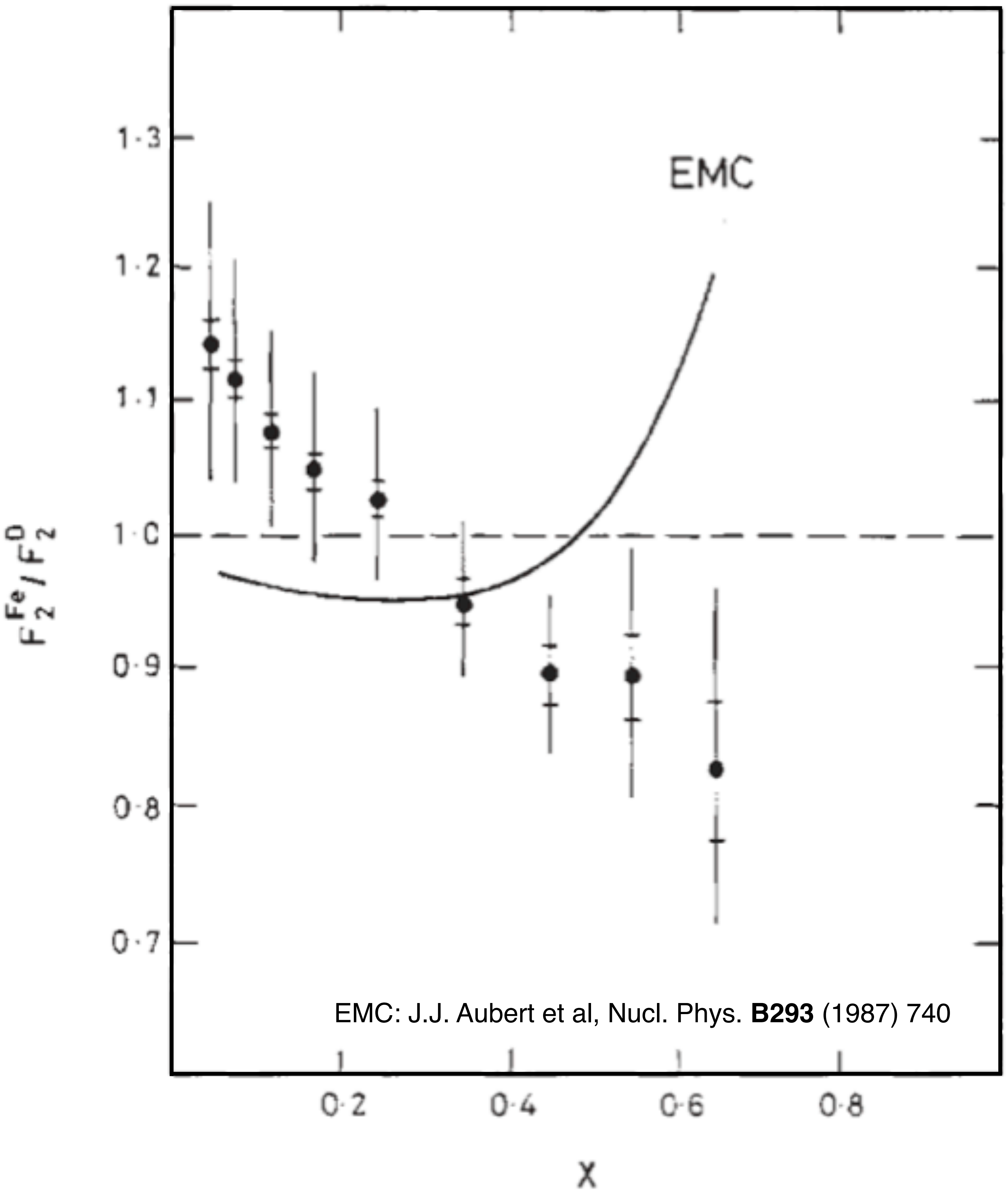
~10 times *higher* beam energy than earlier DIS experiments,

An iron target to boost luminosity...

Who ordered this?

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?

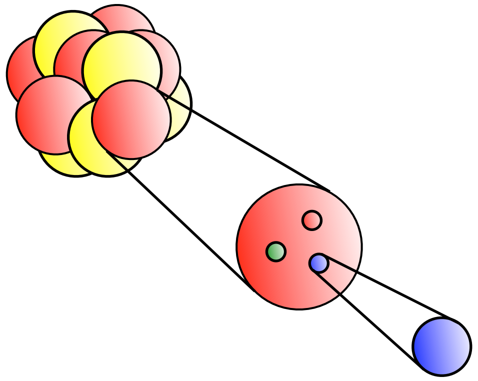
Numerous models, often based on:

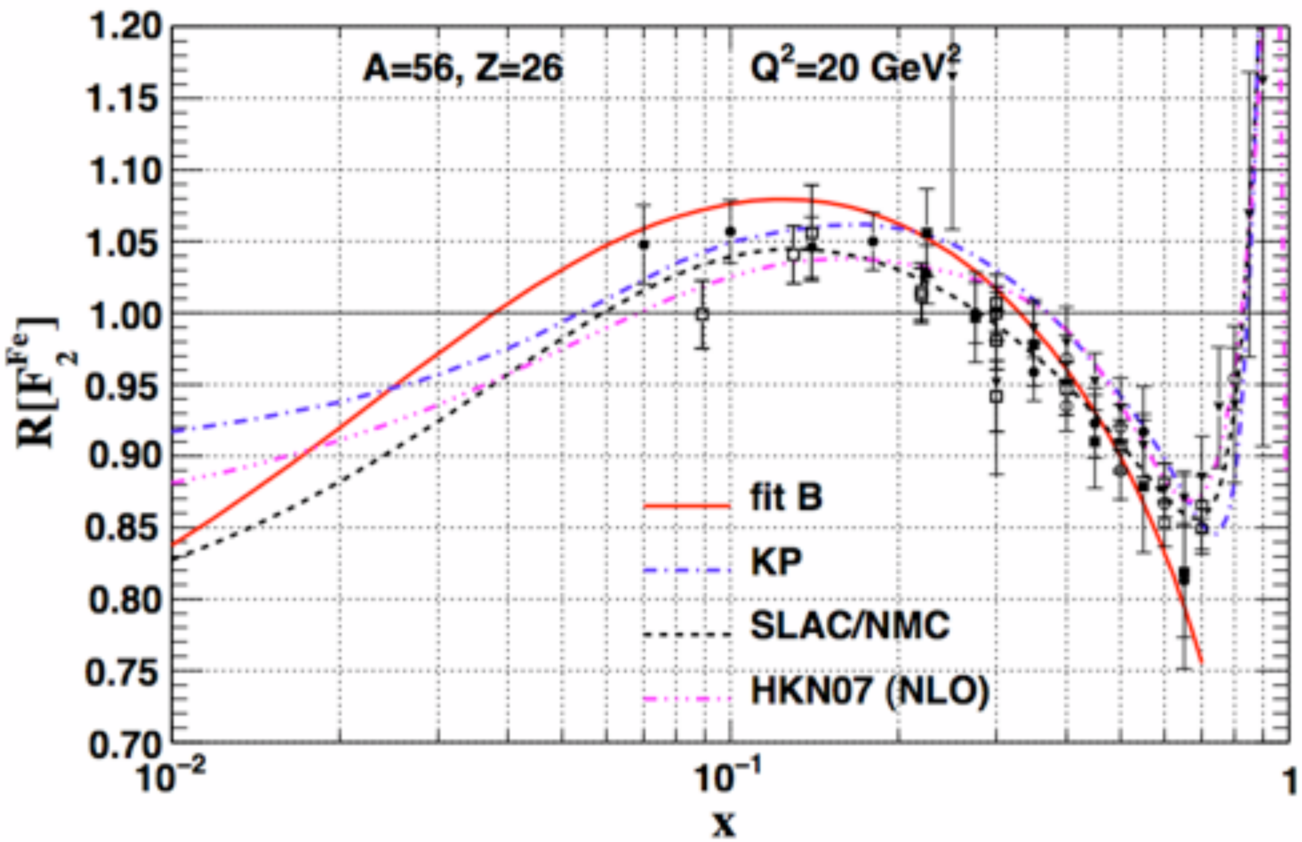
- single (bound) nucleons,
- pion enhancement,
- multiquark clusters,
- dynamic rescaling,
- shadowing

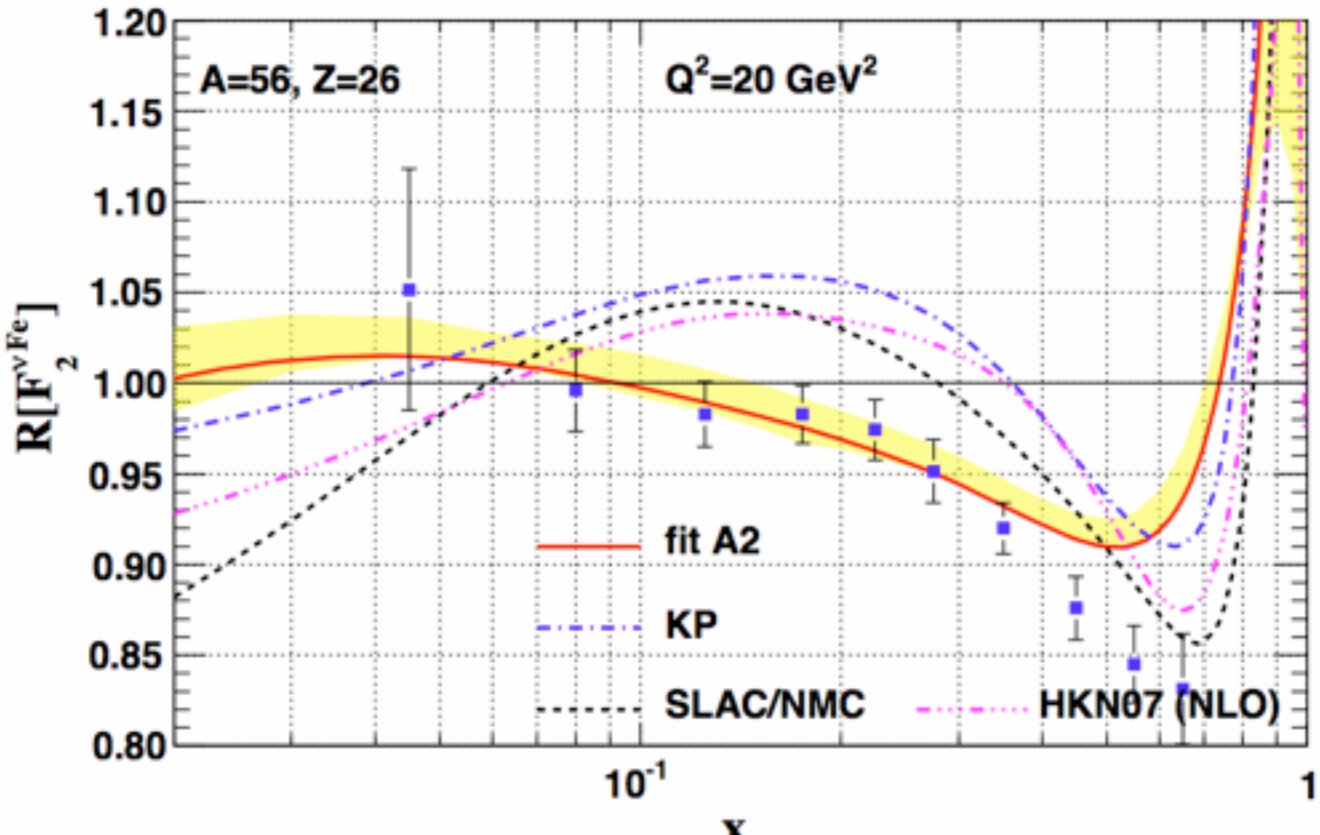
Textbook effect, remains in search of a comprehensive explanation.

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?

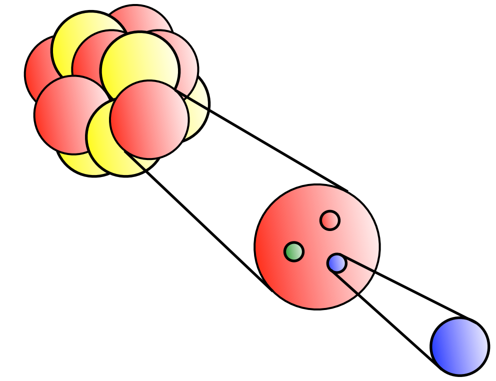
Nowadays,
~800 fixed target data points on F_2^A/F_2^D,
~200 $F_2^A/F_2^{A'}$,
~100 Drell-Yan.

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

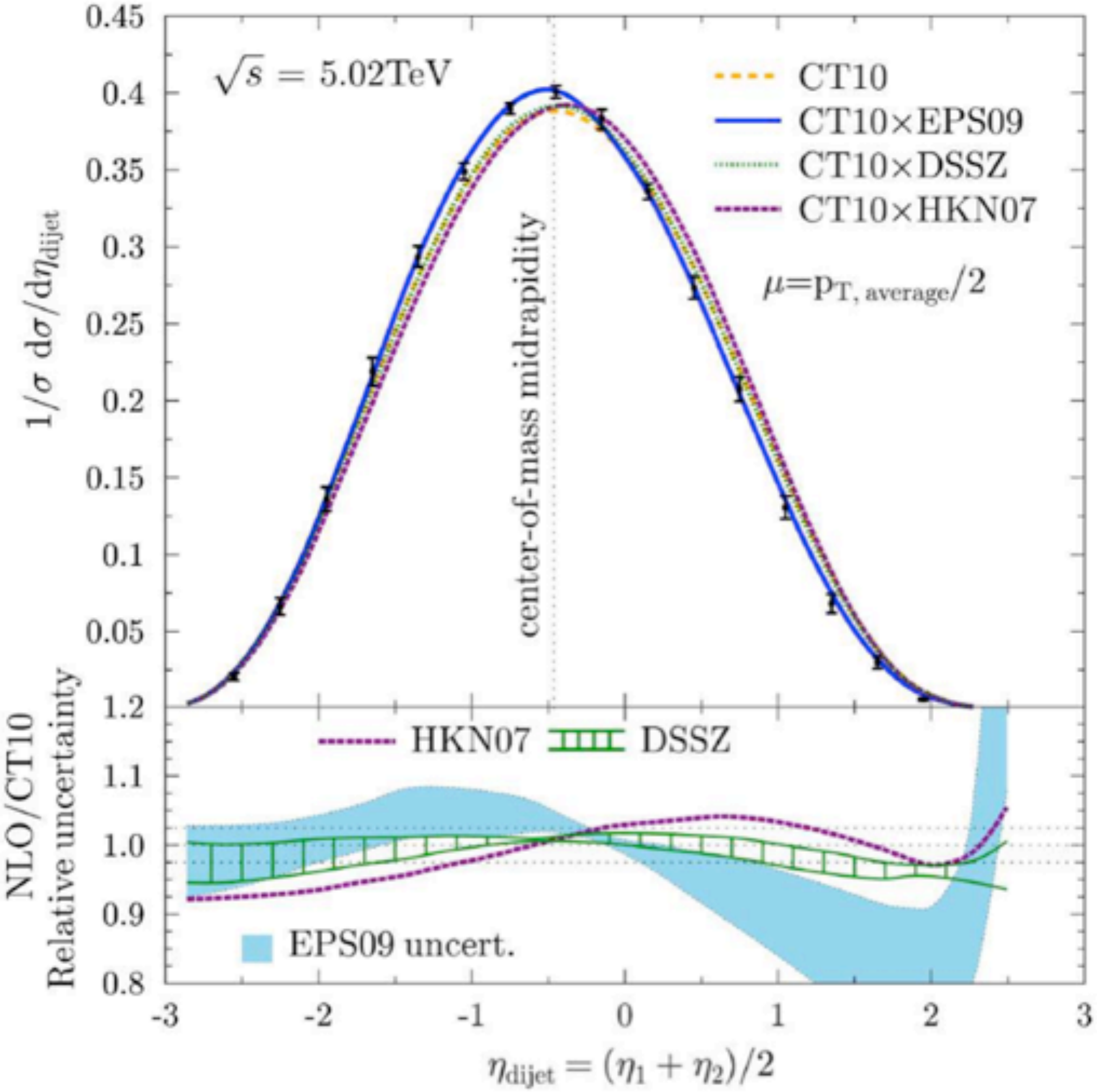
Physics or NuTeV experiment effect?

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.

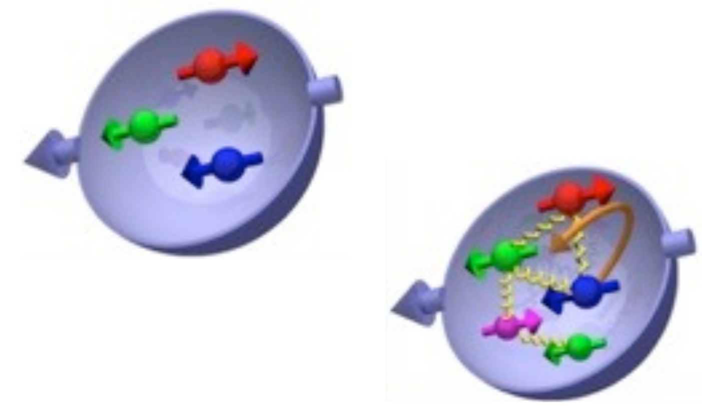
Experimental opportunities:

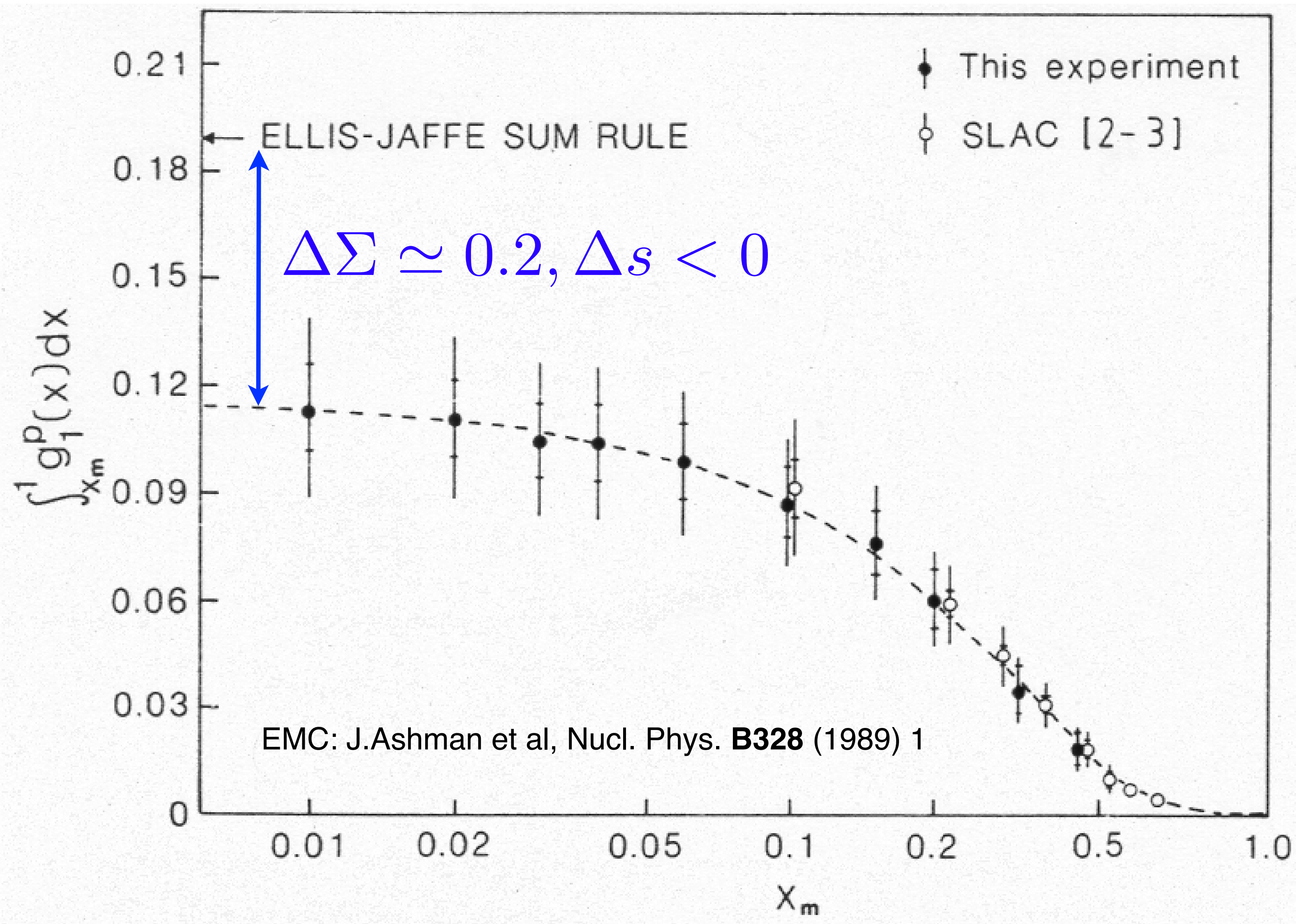
Near-term:
- (polarized) p+A scattering,
- continued DIS, DY,
- ...

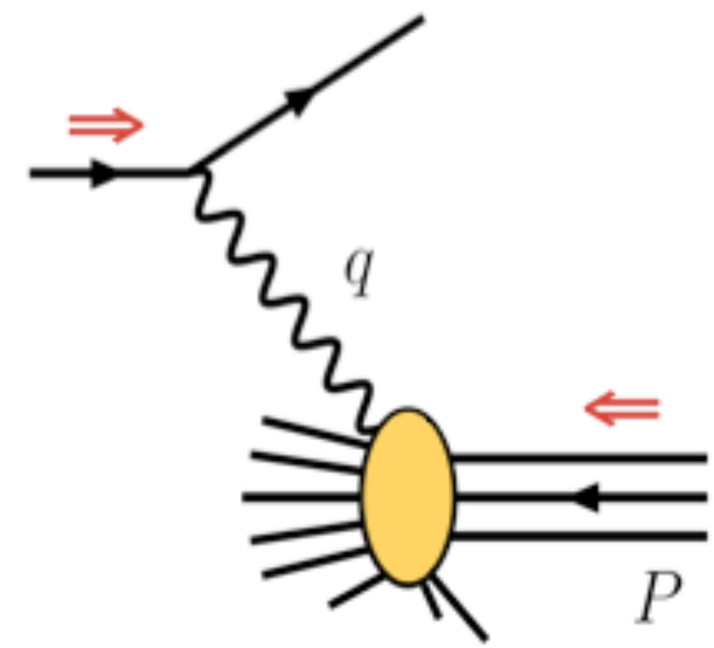
EIC-term:
- QCD-evolution, esp. gluon region,
- NC, CC probes,
- 1-particle semi-inclusive data,
- n-particle correlations,
- diffraction,
- exclusive reactions (imaging),
- ...

Simply this student’s list - input sought.

DIS - Surprises with Spin



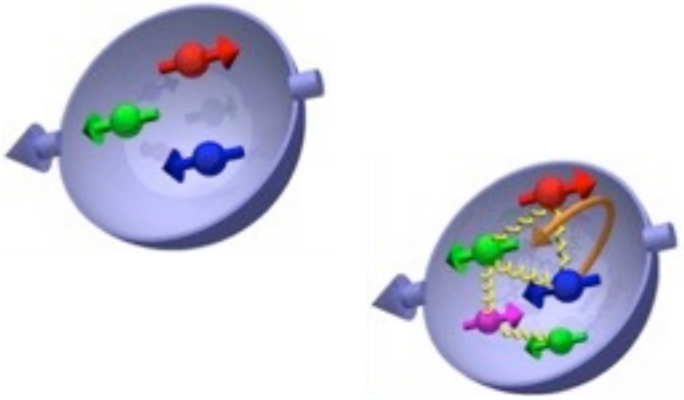




$$\sigma(\Rightarrow,\Leftarrow) - \sigma(\Rightarrow,\Rightarrow) \sim \mathbf{g_1(x, Q^2)}$$

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

DIS - Surprises with Spin



For the proton,

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

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

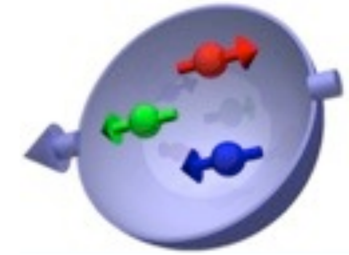
Unique to DIS, ΔΣ

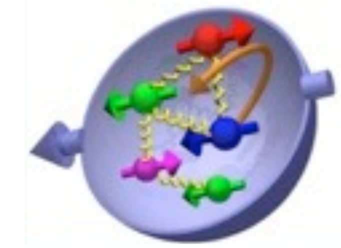
Known from weak neutron to proton decay, combined with weak Σ to neutron decay

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

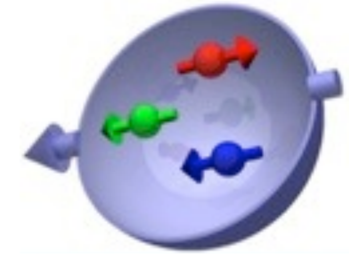
Since,

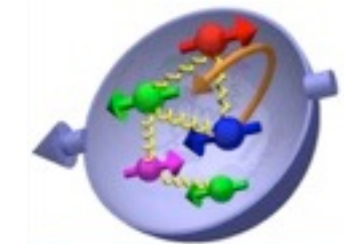
$$\left.\frac{\partial \Gamma_1}{\partial a_8}\right|_{\mathrm{Ellis-Jaffe}} \simeq \frac{5}{36}$$

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

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

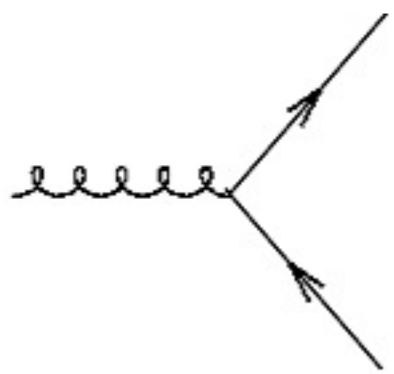
DIS - Surprises with Spin





Numerous follow-up questions and experiment programs,

Among the early attempts at a resolution,



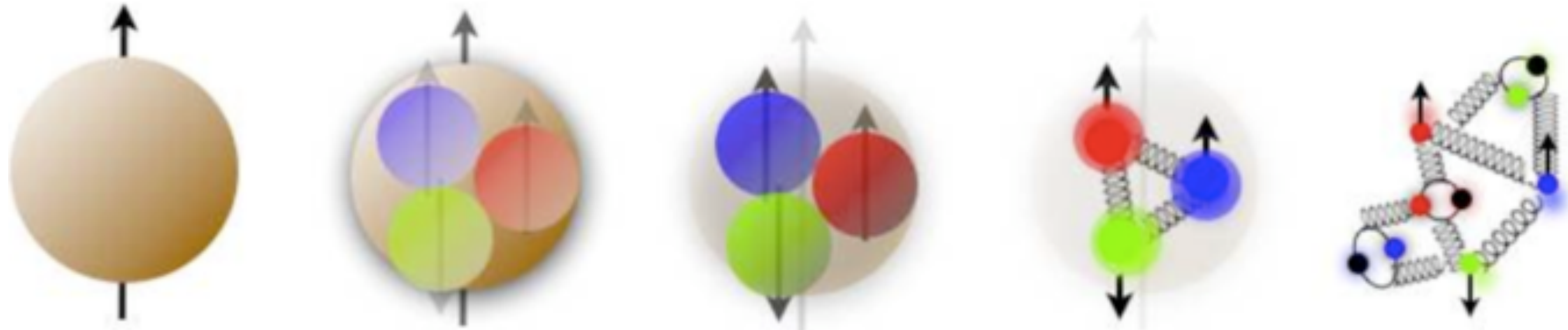
with the gluons *polarized*.

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

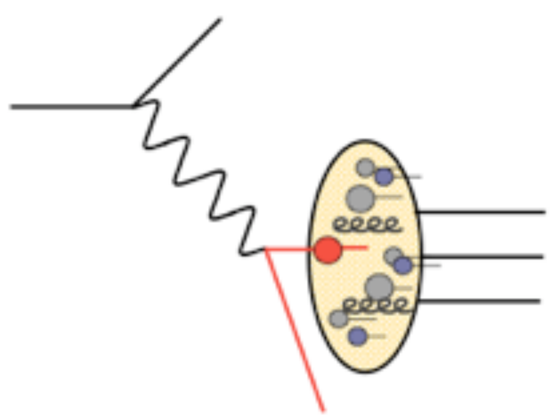
Note: this attempt requires *very* significant polarization,
factors larger than the nucleon spin itself, and
by inference, *huge* compensating orbital momenta.

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

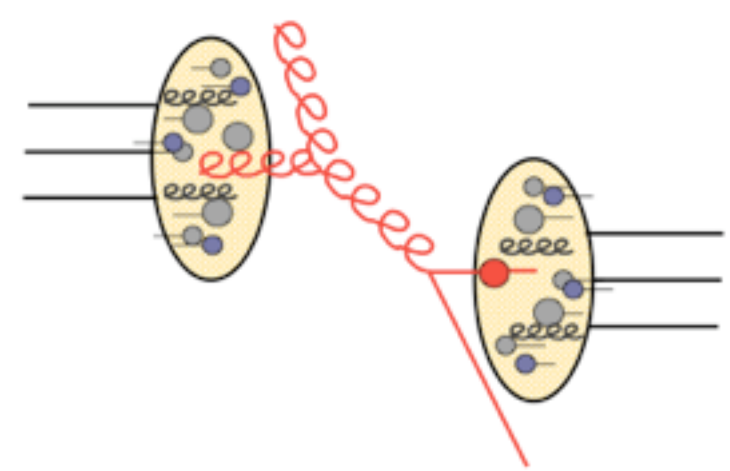
II - Applications at RHIC



DIS



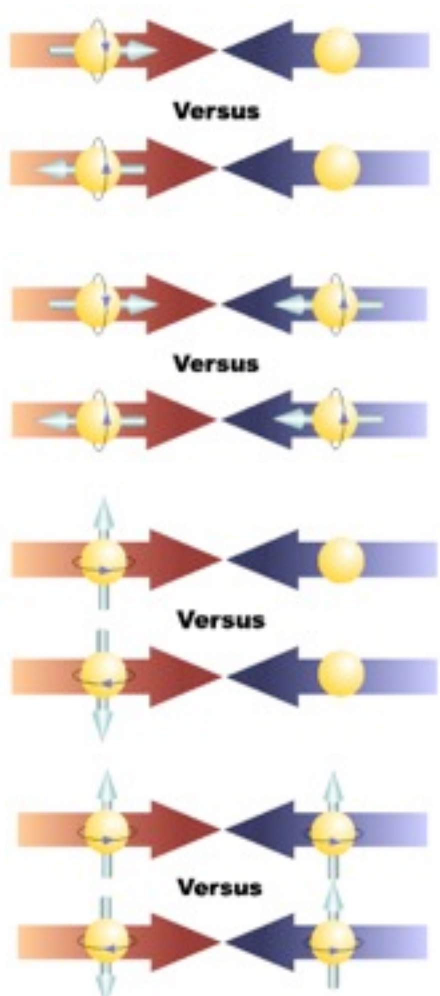
pp

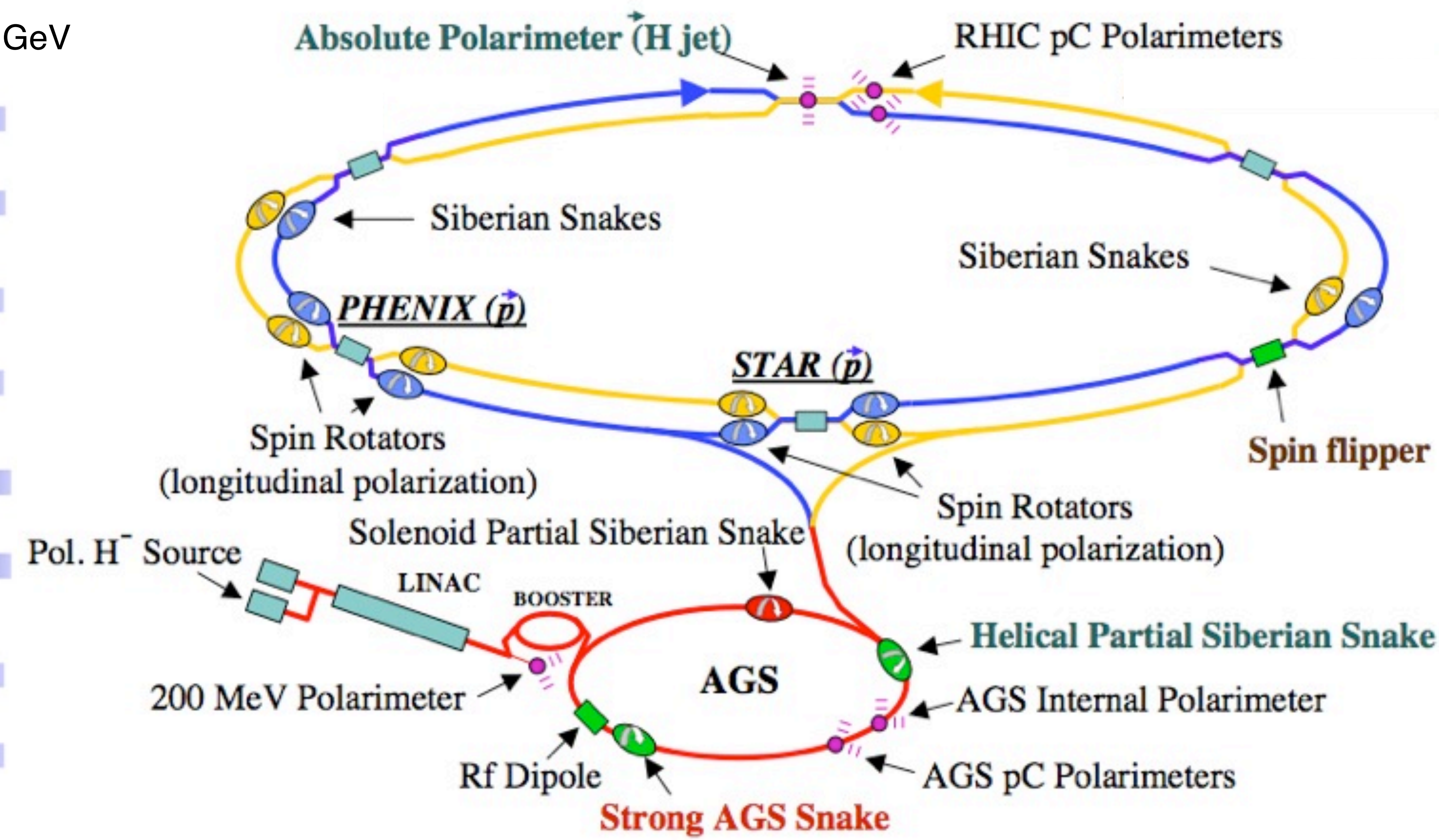


RHIC - Polarized Proton-Proton Collider

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.

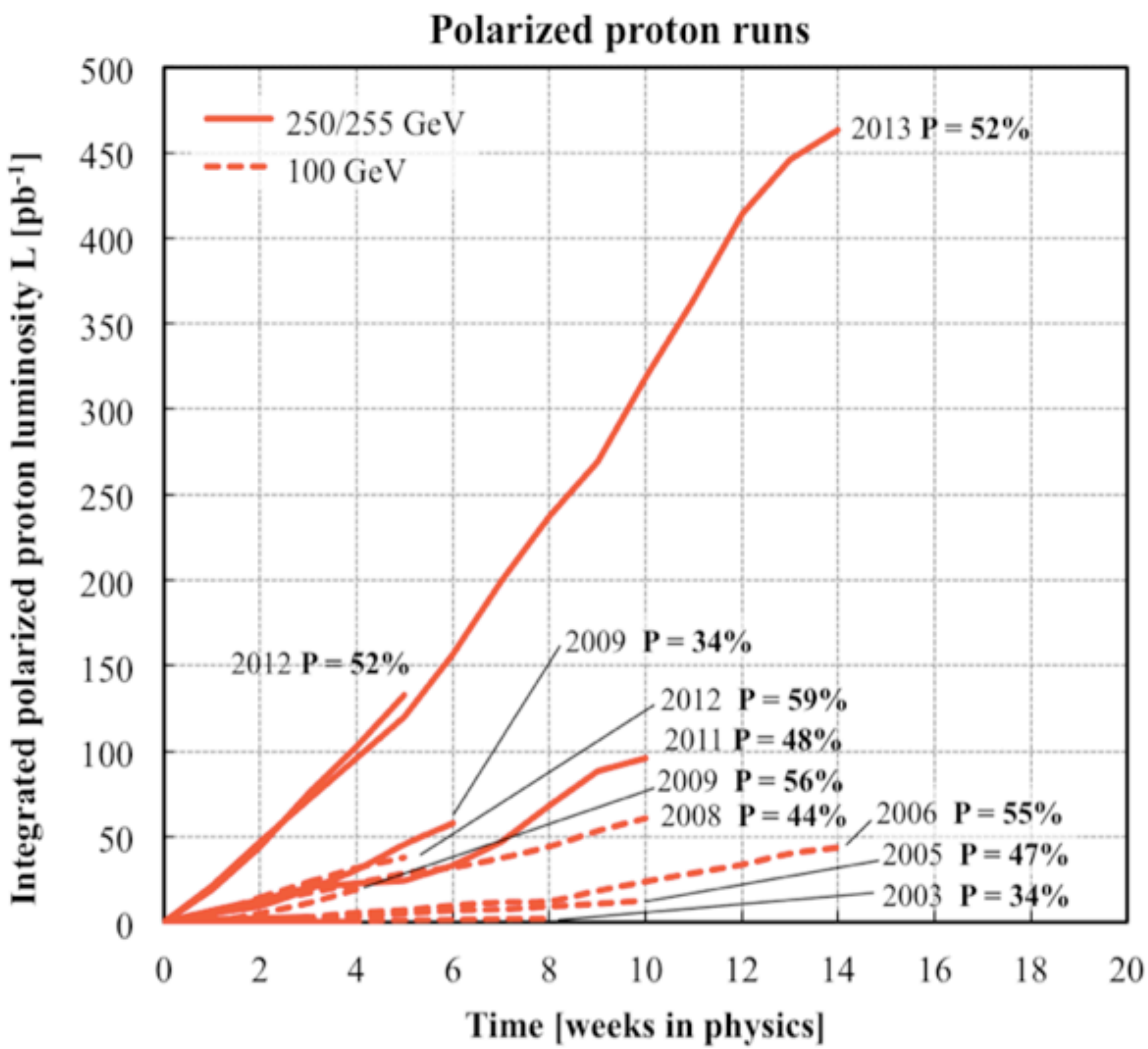
RHIC - Polarized Proton-Proton Collider

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

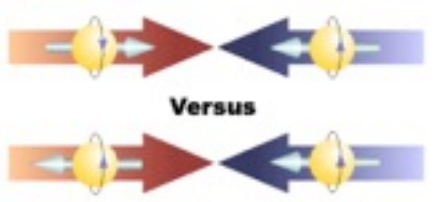
Longitudinal data	**STAR**
√s = **200 GeV**	
2005	
2006	35 pb^{-1}
2009	
(2015)	(50 pb^{-1})
√s = **500 GeV**	
2009	
2011	
2012	400 pb^{-1}
2013	

Transverse data	
√s = **200 GeV**	
2006	
2008	38 pb^{-1}
2012	
(2015)	(50 pb^{-1})
√s = **500 GeV**	
2011	25 pb^{-1}
(2016)	(400 pb^{-1})

50-60% polarization

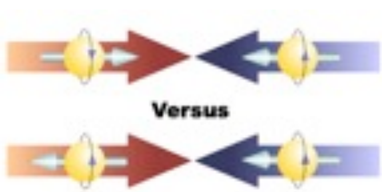


II - Applications at RHIC: Gluon Polarization



Gluon Polarization at RHIC

Measure double longitudinal spin asymmetries and establish the factorized framework,



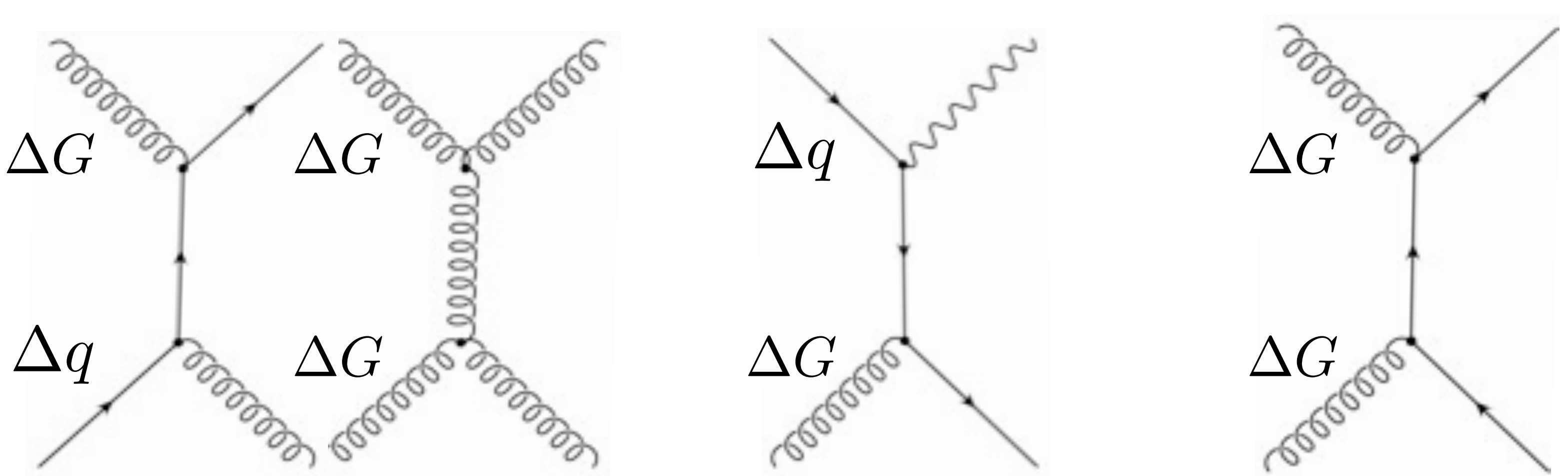
$$A_{LL} = \frac{\sigma^{\uparrow\uparrow} - \sigma^{\uparrow\downarrow}}{\sigma^{\uparrow\uparrow} + \sigma^{\uparrow\downarrow}} \stackrel{?}{=} \sum_{f=q,g} \frac{\Delta f_1}{f_1} \otimes \frac{\Delta f_2}{f_2} \otimes \hat{a}_{LL} \otimes (\text{fragmentation functions})$$

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,

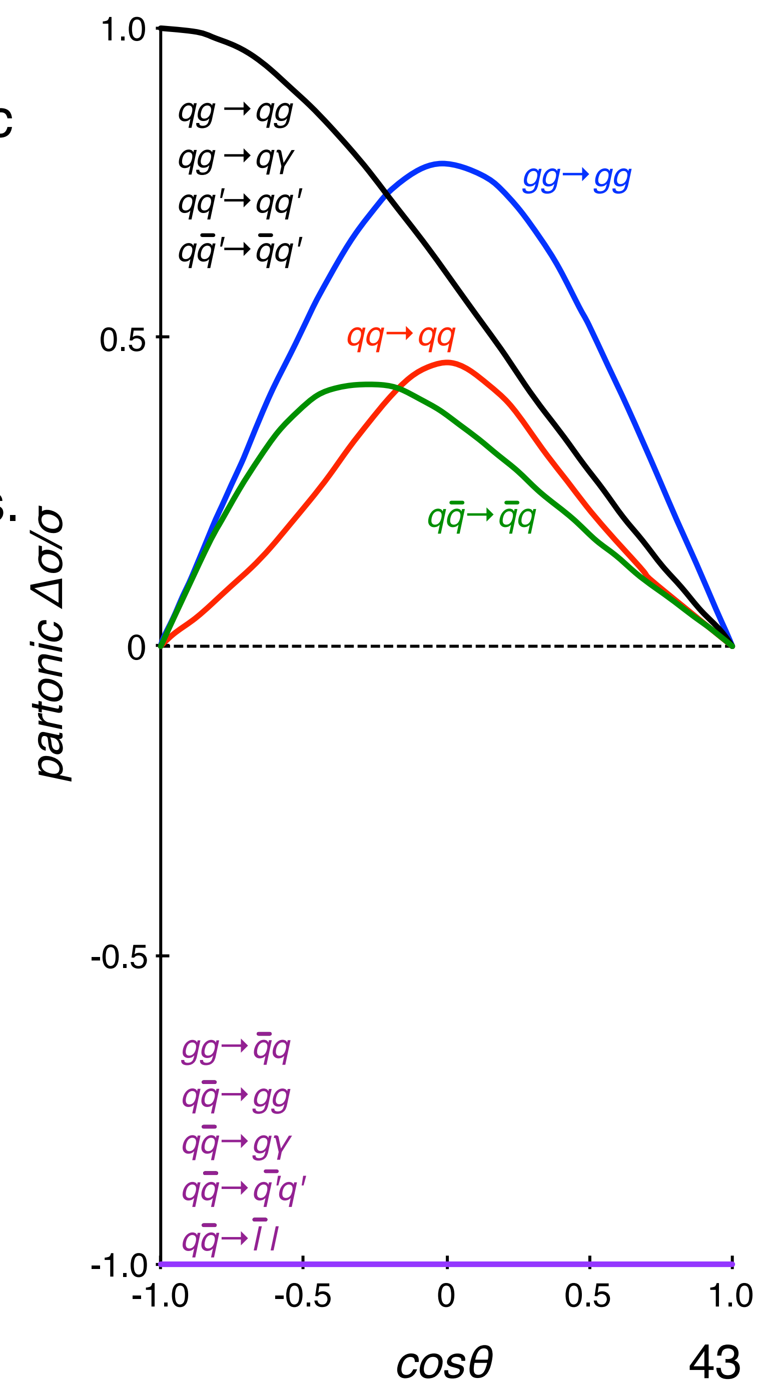
Path: precision, coverage, sensitivity to initial kinematics, and selective probes.

$\vec{p} + \vec{p} \rightarrow \text{jet(s)} + X$ $\quad$ $\vec{p} + \vec{p} \rightarrow \gamma + \text{jet}$ $\quad$ $\vec{p} + \vec{p} \rightarrow c\bar{c}, b\bar{b} + X$

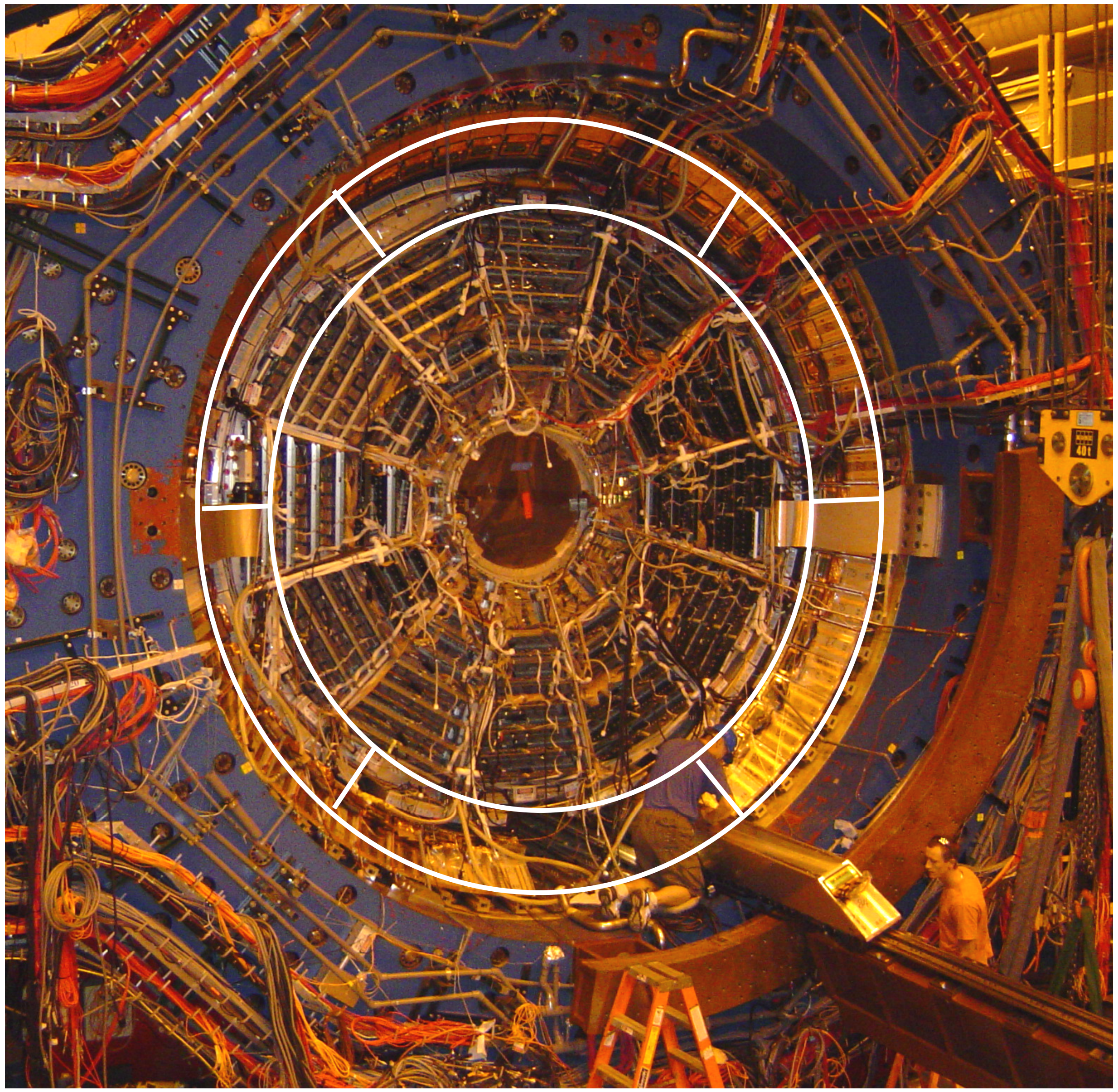


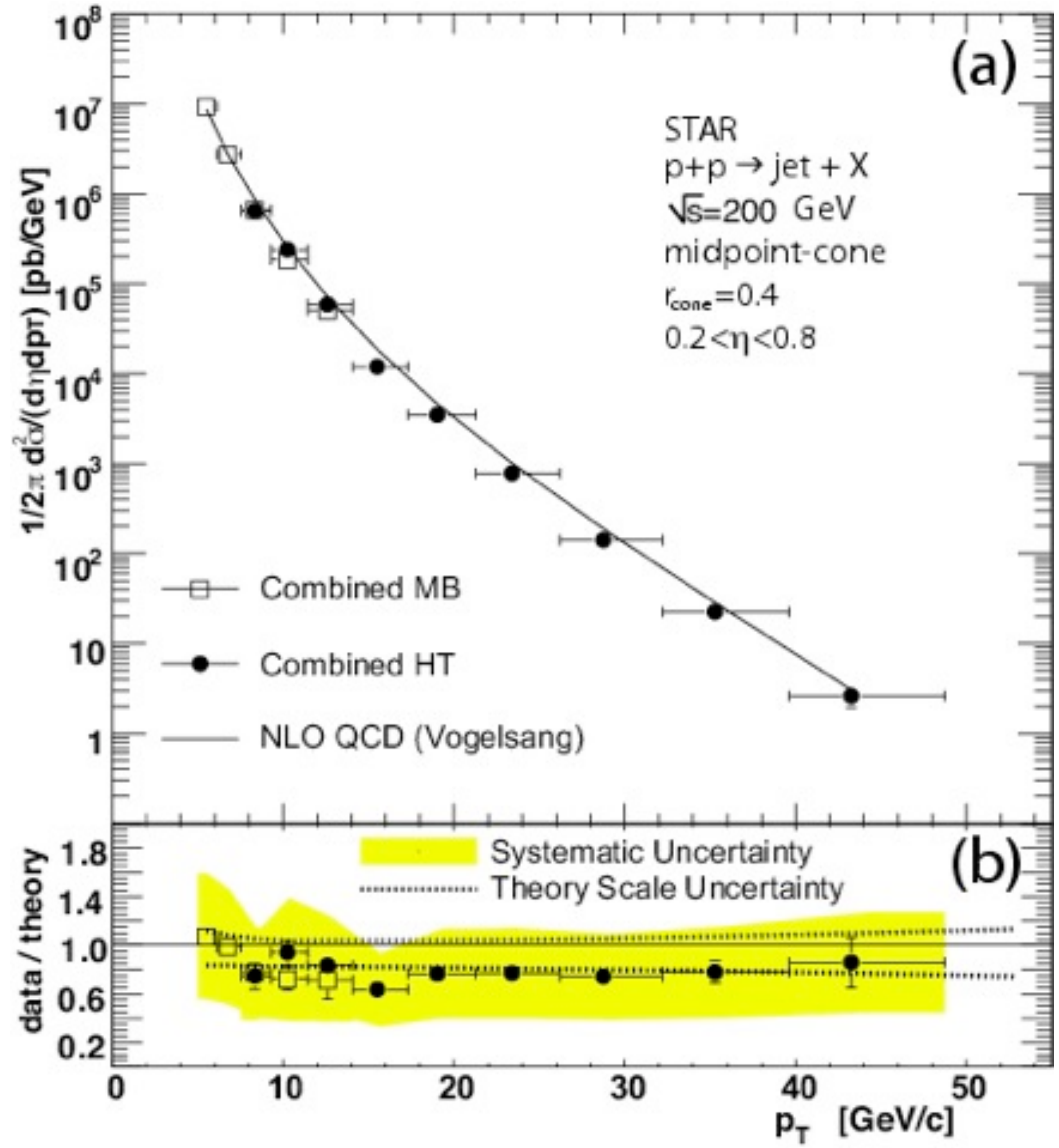
$$\mathcal{L} \simeq 3 - 8 \cdot 10^2\,\text{pb}^{-1}, \quad P = 0.4 - 0.7, \quad \sqrt{s} = 200 - 500\,\text{GeV}$$

time →



Gluon Polarization at STAR - Inclusive Jets



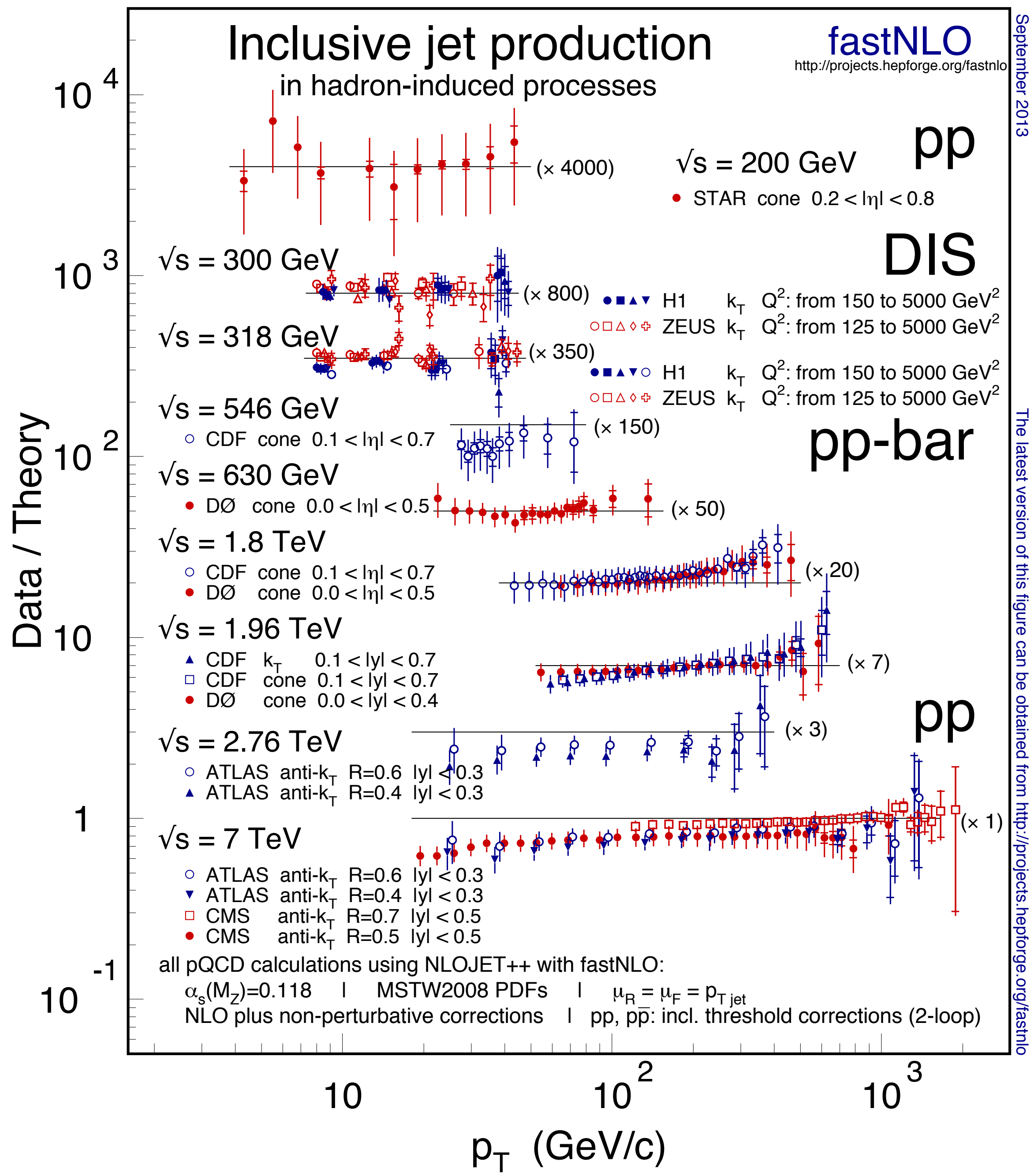


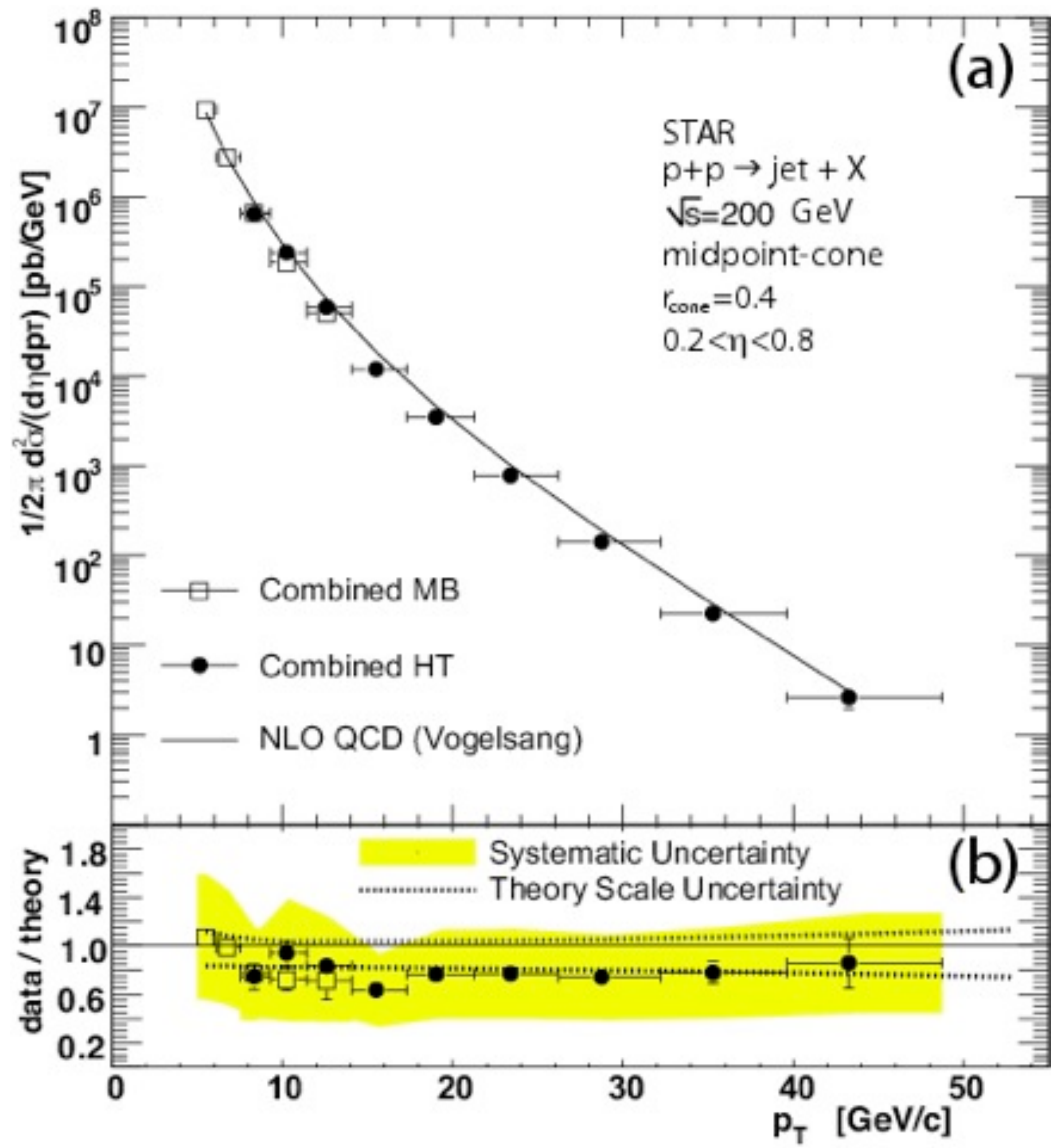
TPC: - charged track measurement over 2+ units in pseudo-rapidity

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

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

Gluon Polarization at STAR - Inclusive Jets





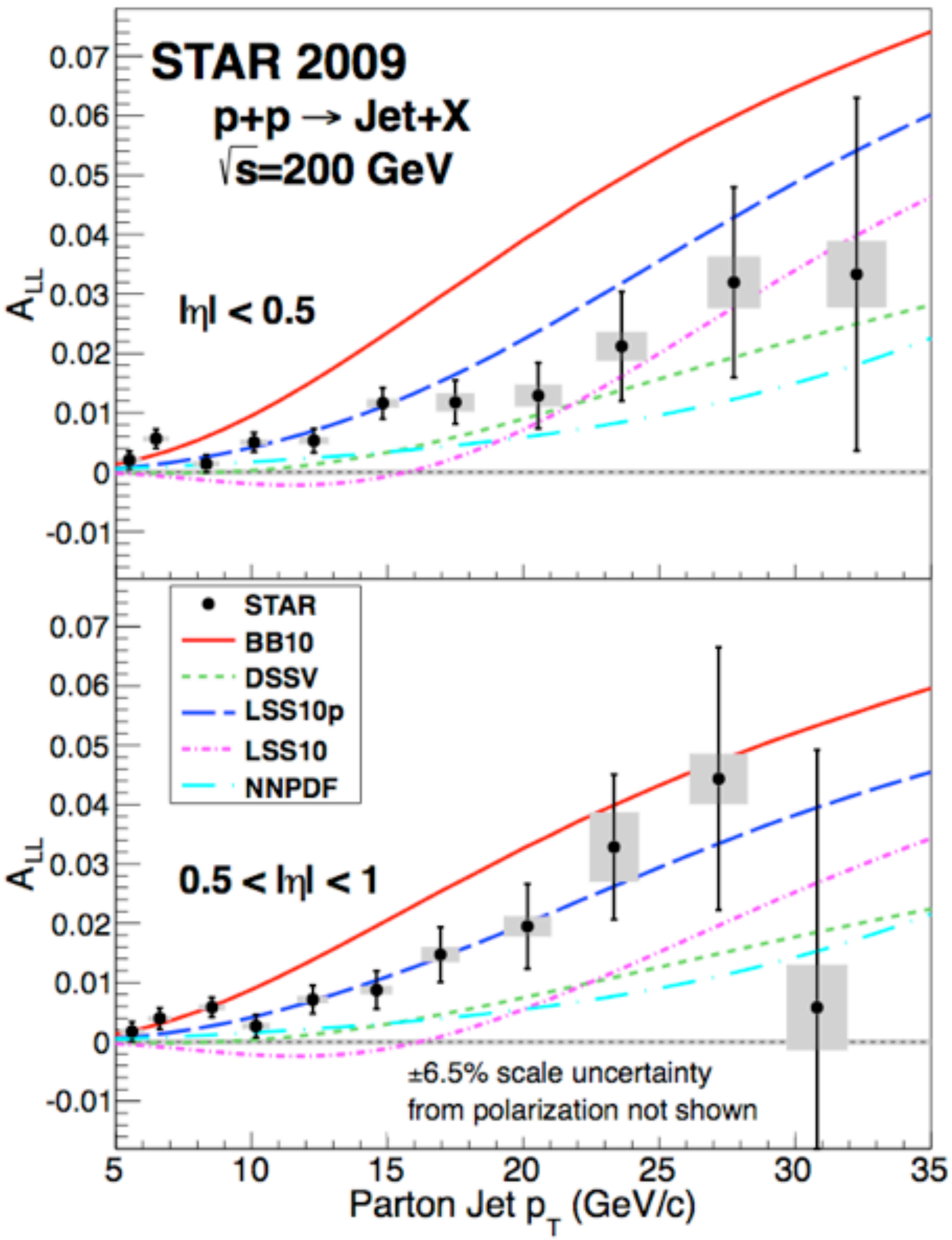
Phys. Rev. Lett. 97, 252001 (2006)

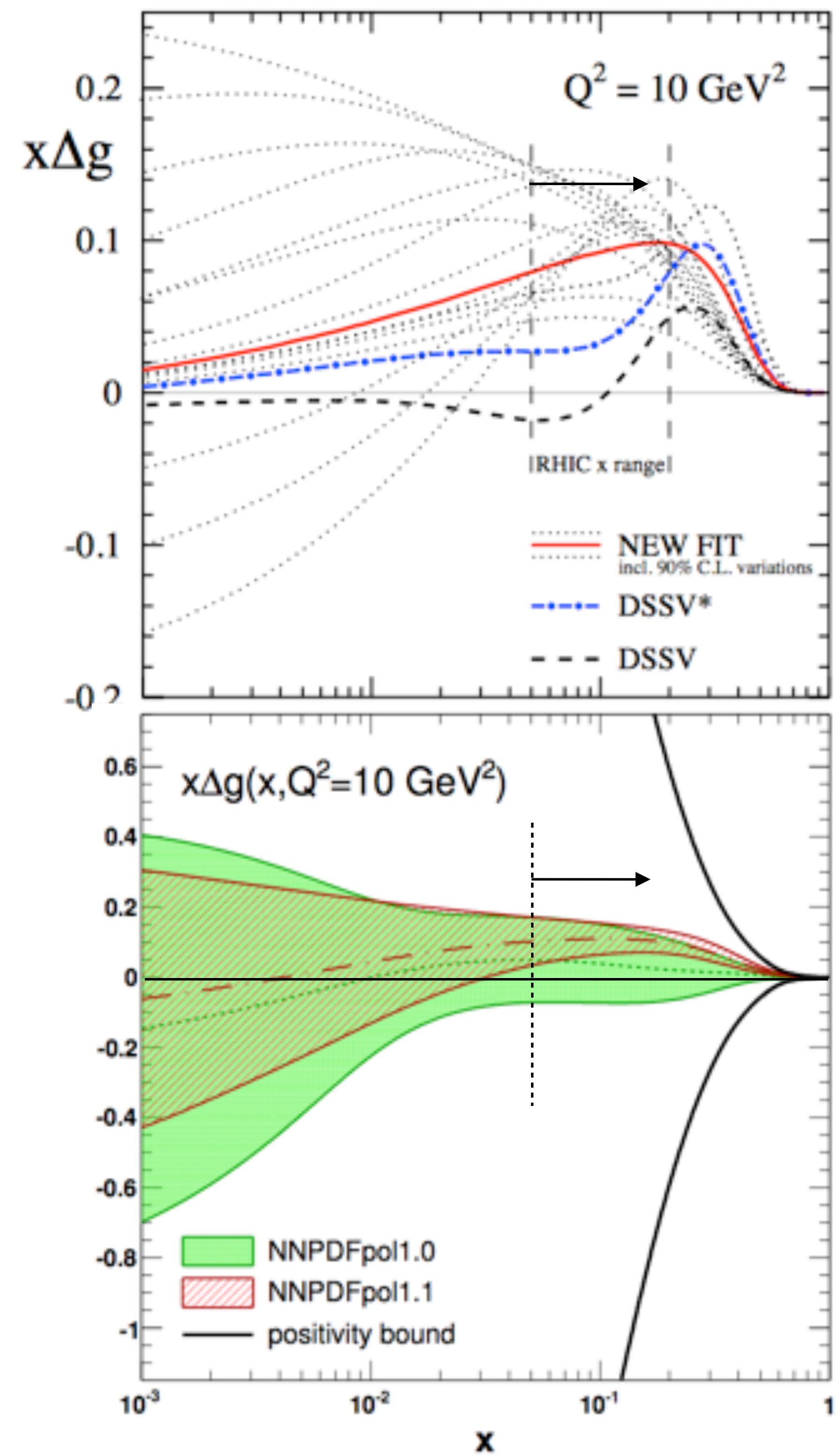
STAR is uniquely suited, at RHIC, for central-rapidity jet measurements,

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

Gluon Polarization from RHIC

ArXiv:1405.5134





0.20 ± 0.07

DSSV, ArXiv:1404.4293

0.21 ± 0.10

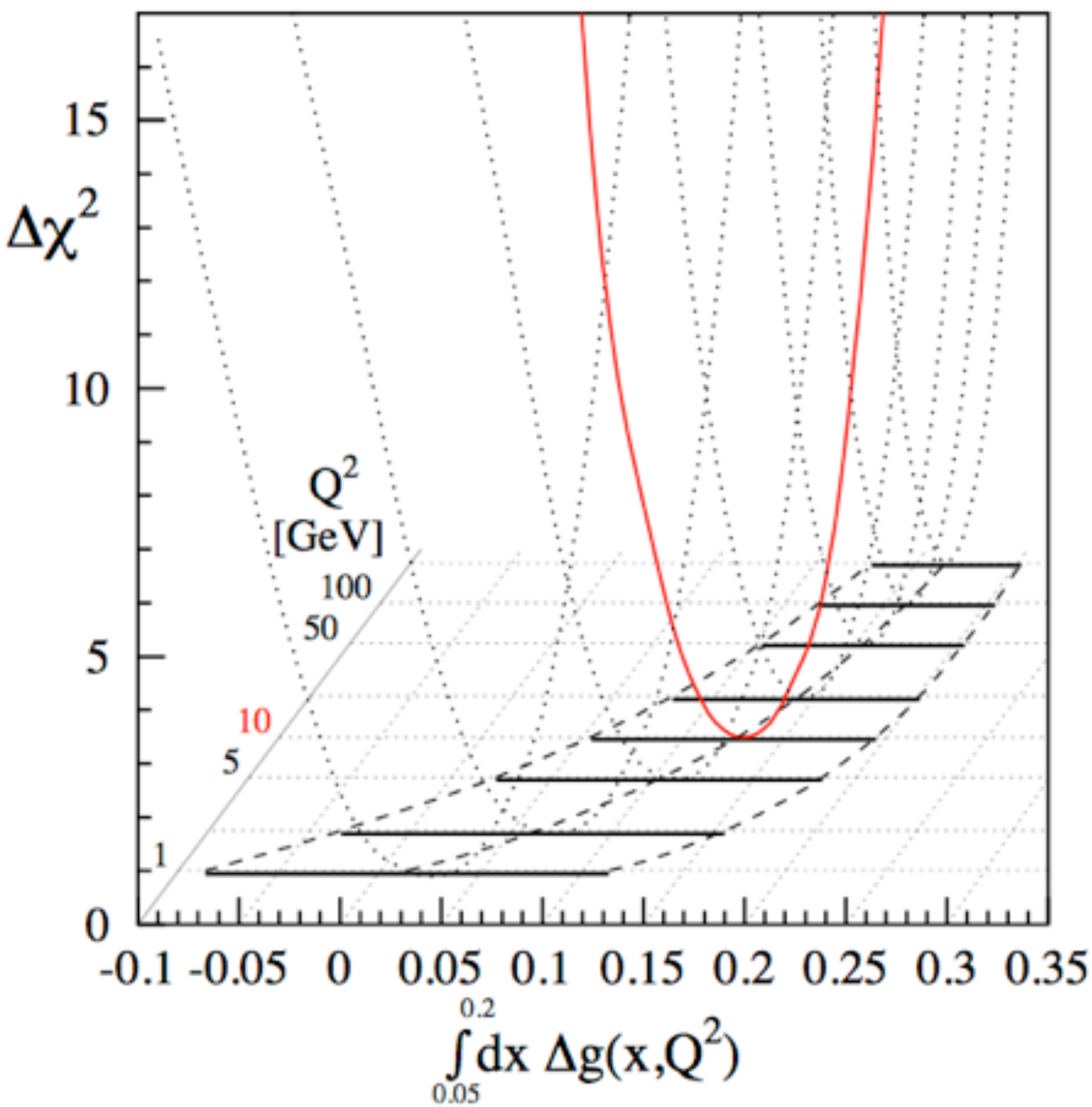
NNPDF, DIS 2014

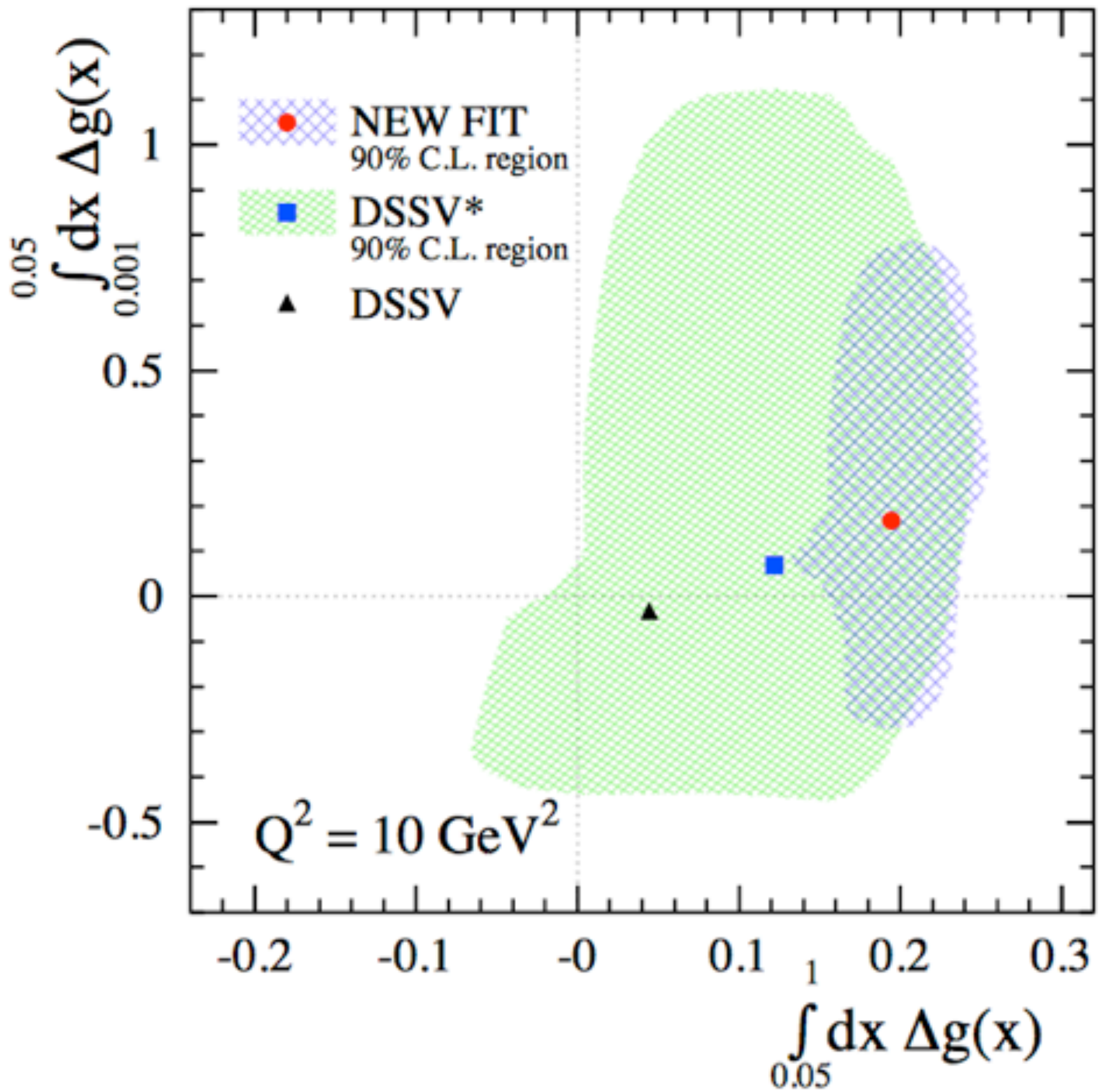
Gluon polarization is positive in the region of the data; ~0.2 ħ

Gluon Polarization - DSSV

Some properties of the DSSV polarized gluon:

DSSV, ArXiv:1404.4293

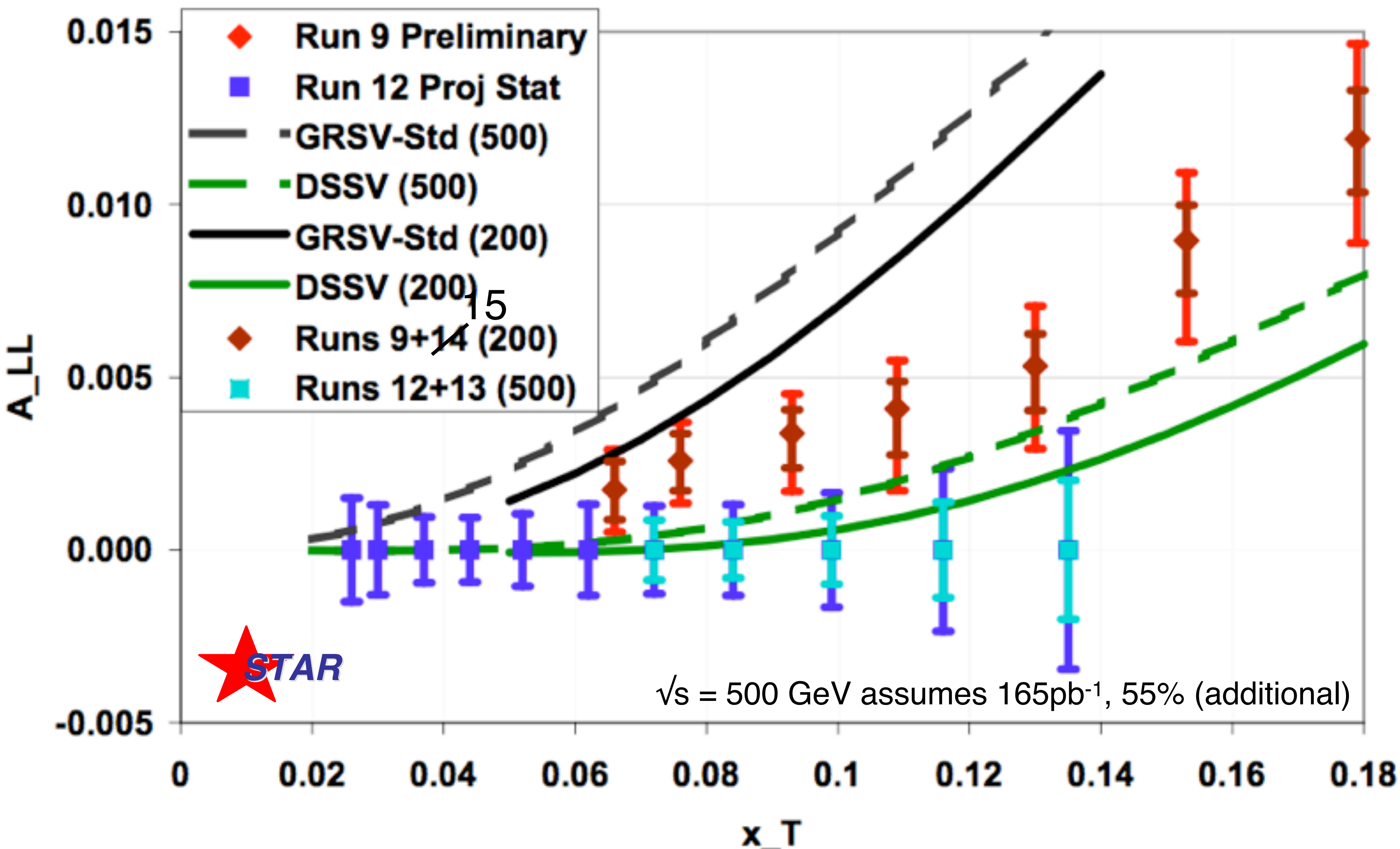




Strong scale dependence in the measured region

Easy to "hide" 1 ħ in the unmeasured region

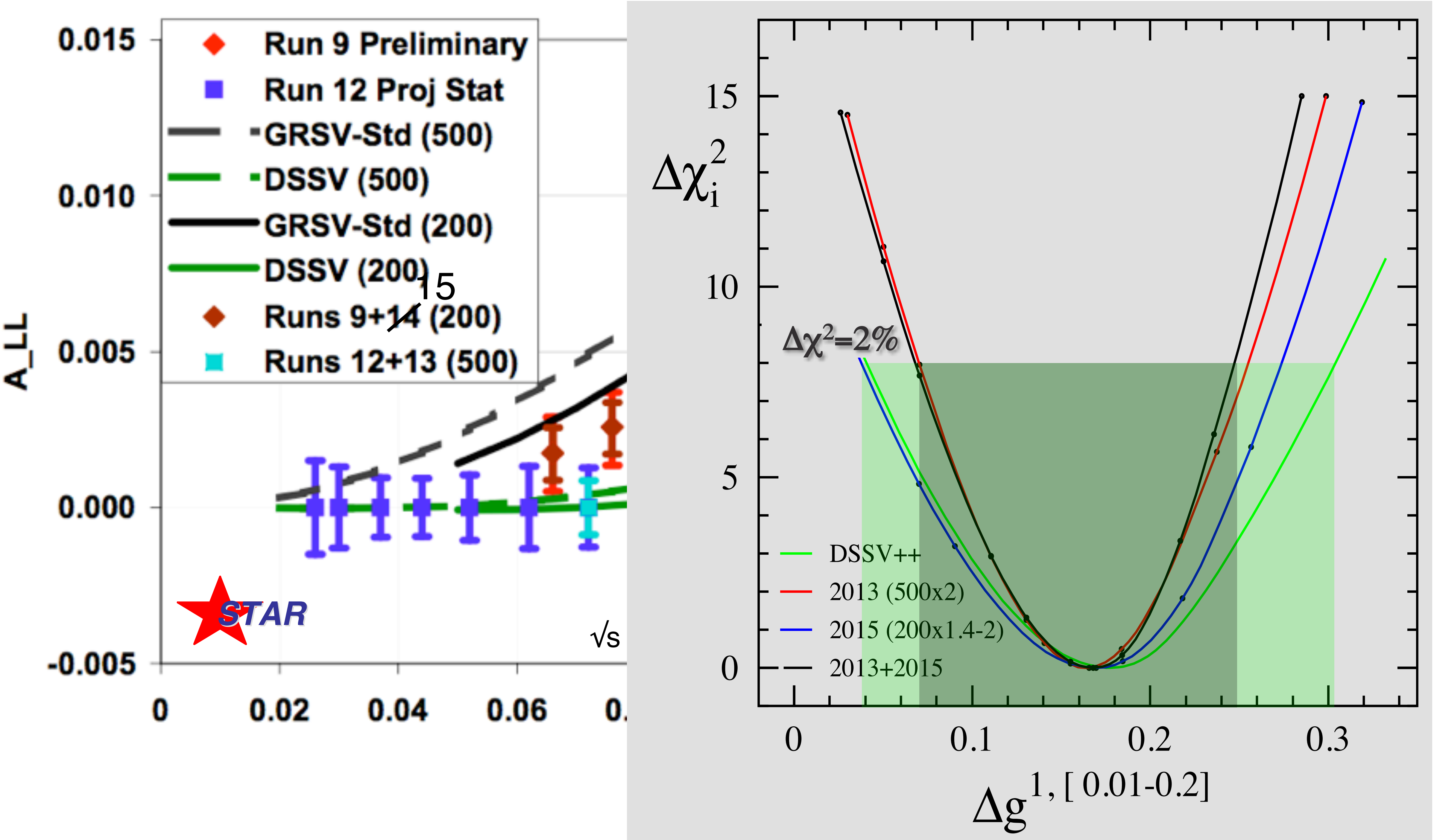
Gluon Polarization - Near Term Prospects



$\sqrt{s}$ = 500 GeV probes ~2.5 times smaller x_g than $\sqrt{s}$ = 200 GeV,

Longer term: forward instrumentation, EIC

Gluon Polarization - Near Term Prospects



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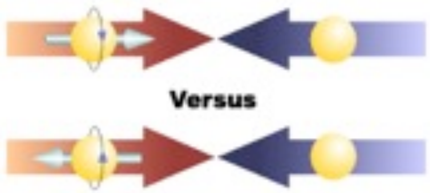
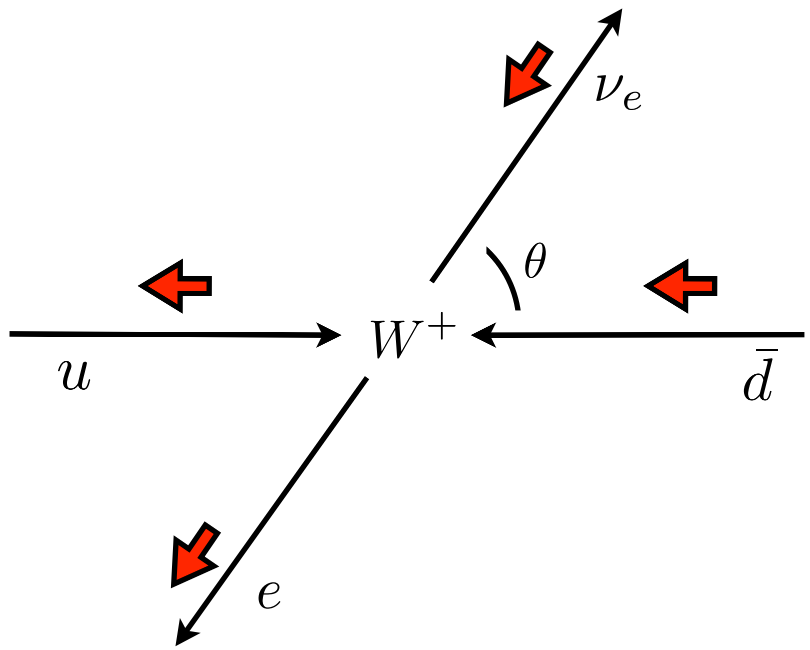
Longer term: forward instrumentation, EIC

Applications at RHIC: Quark Polarization



Quark Polarization at RHIC



√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

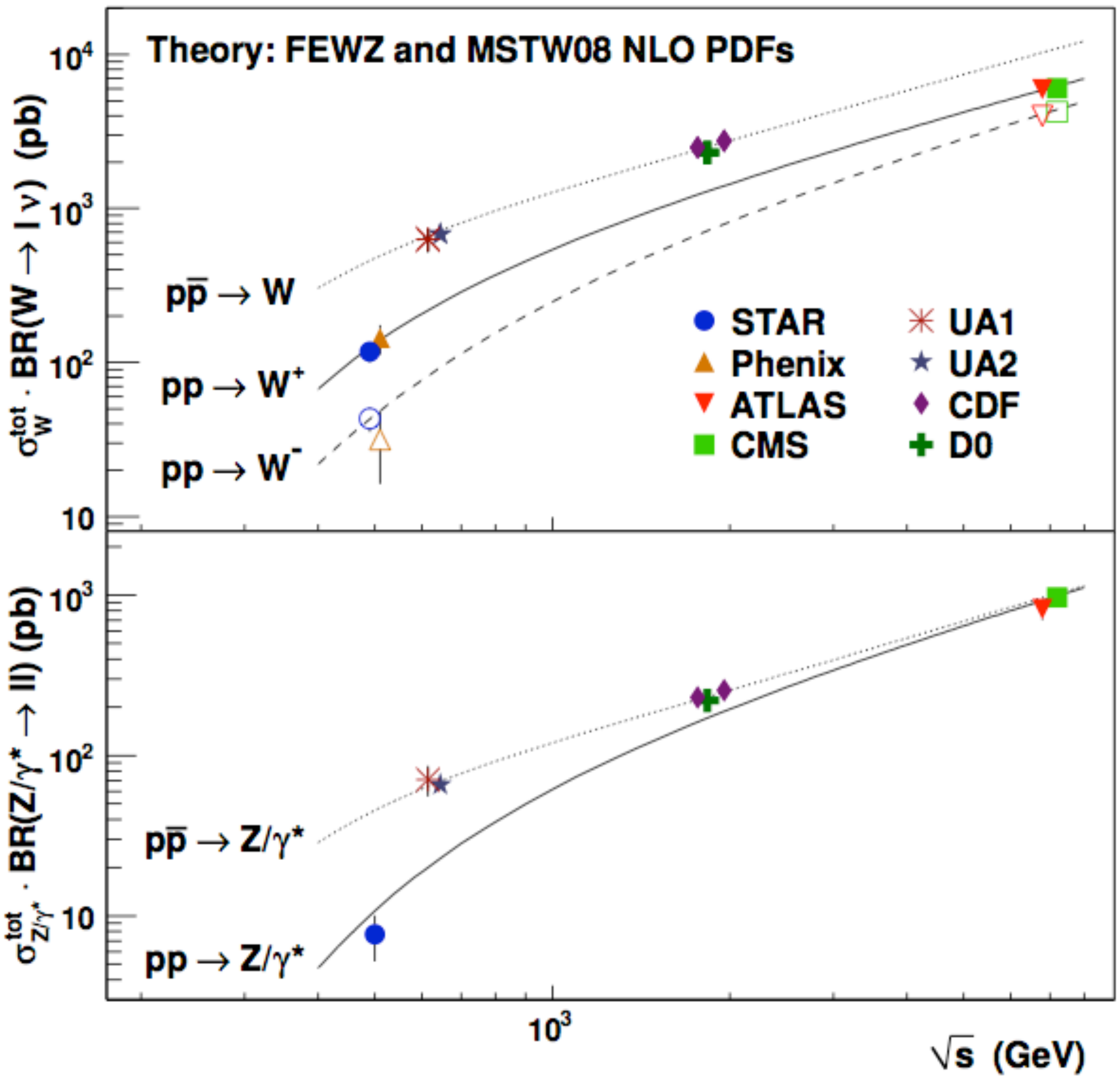
$$\Delta\sigma^{\rm Born}(\vec{p}p \to W^+ \to e^+\nu_e) \propto -\Delta u(x_a)\bar{d}(x_b)(1+\cos\theta)^2 + \Delta\bar{d}(x_a)u(x_b)(1-\cos\theta)^2$$

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,

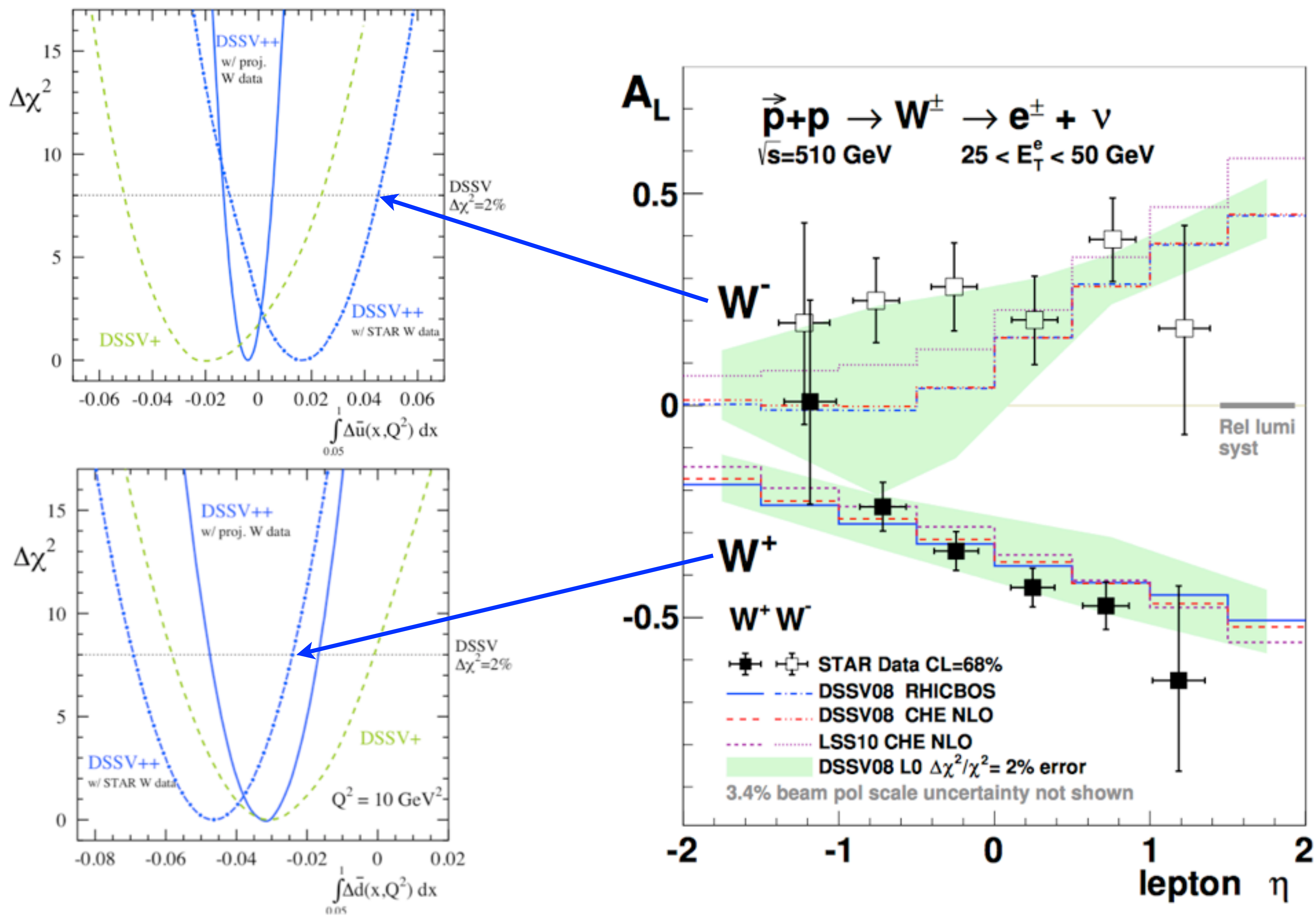
STAR: Initial NC cross section at RHIC, confirmation of PHENIX CC cross section measurements, Phys. Rev. **D85** (2012).

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

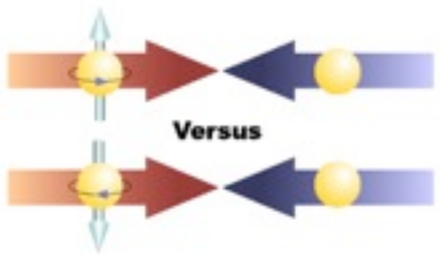
Necessary condition to interpret asymmetry measurements,

Future ratio measurements may provide insights in unpolarized light quark distributions

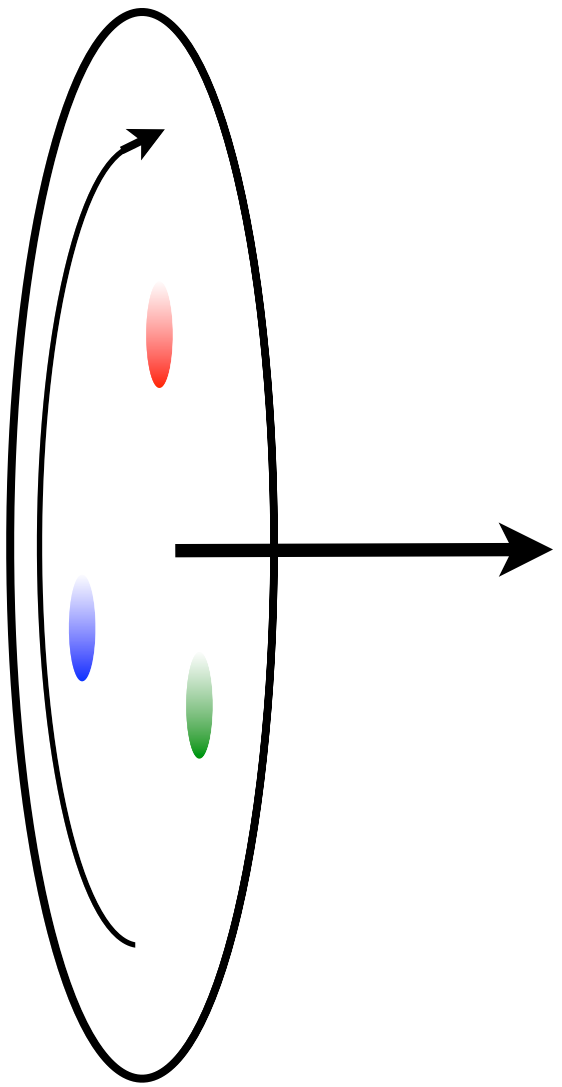
Quark Polarization at √s = 500 GeV



Applications at RHIC: Transverse Spin Phenomena

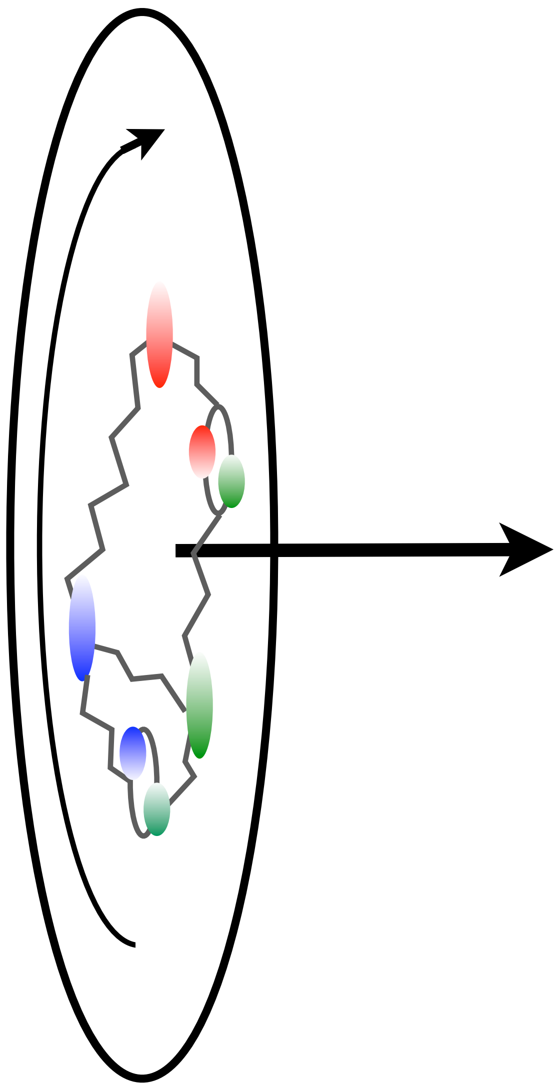


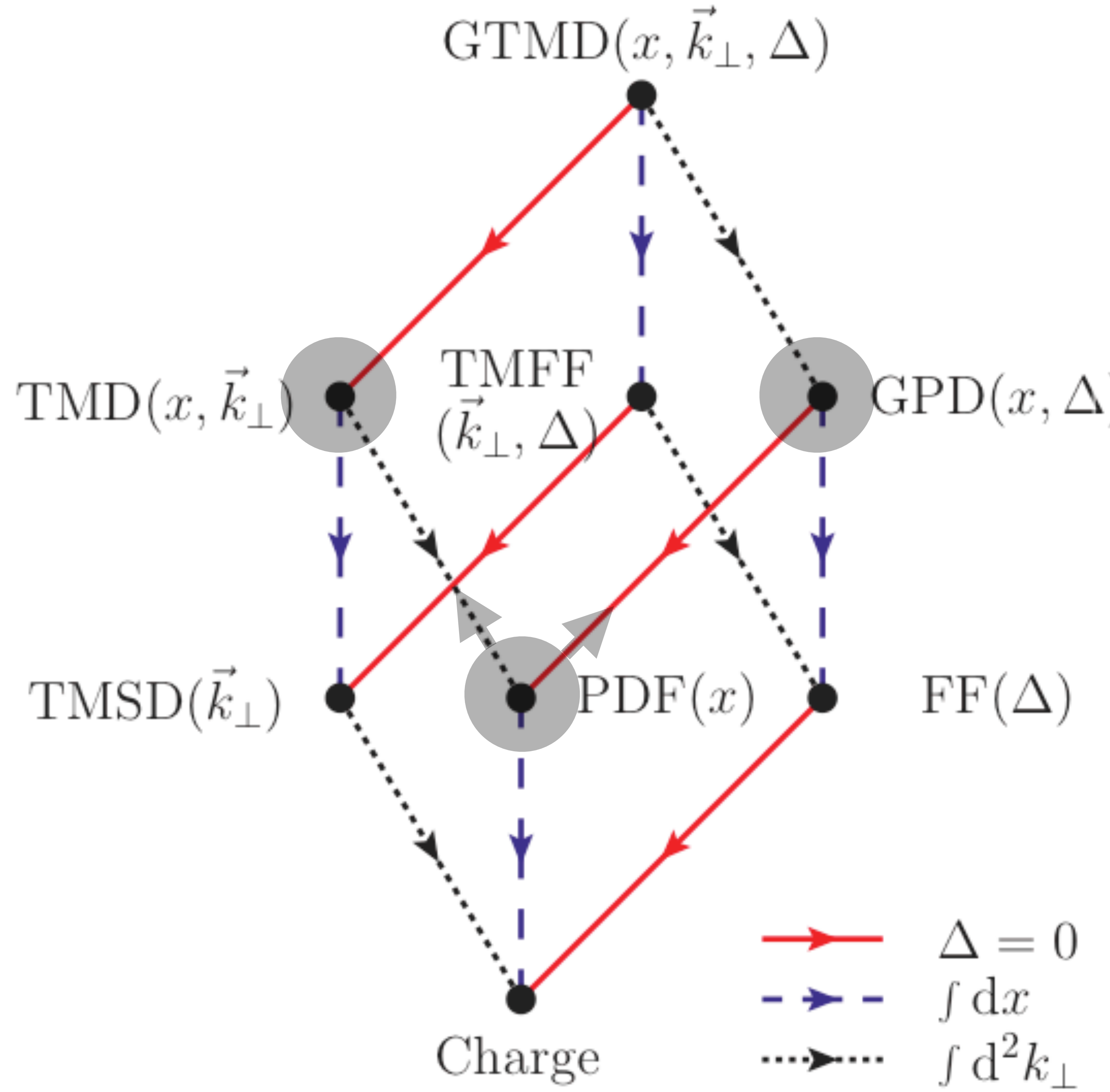
Beyond Helicity Distributions...



Simple concepts become involved...

Beyond Helicity Distributions...



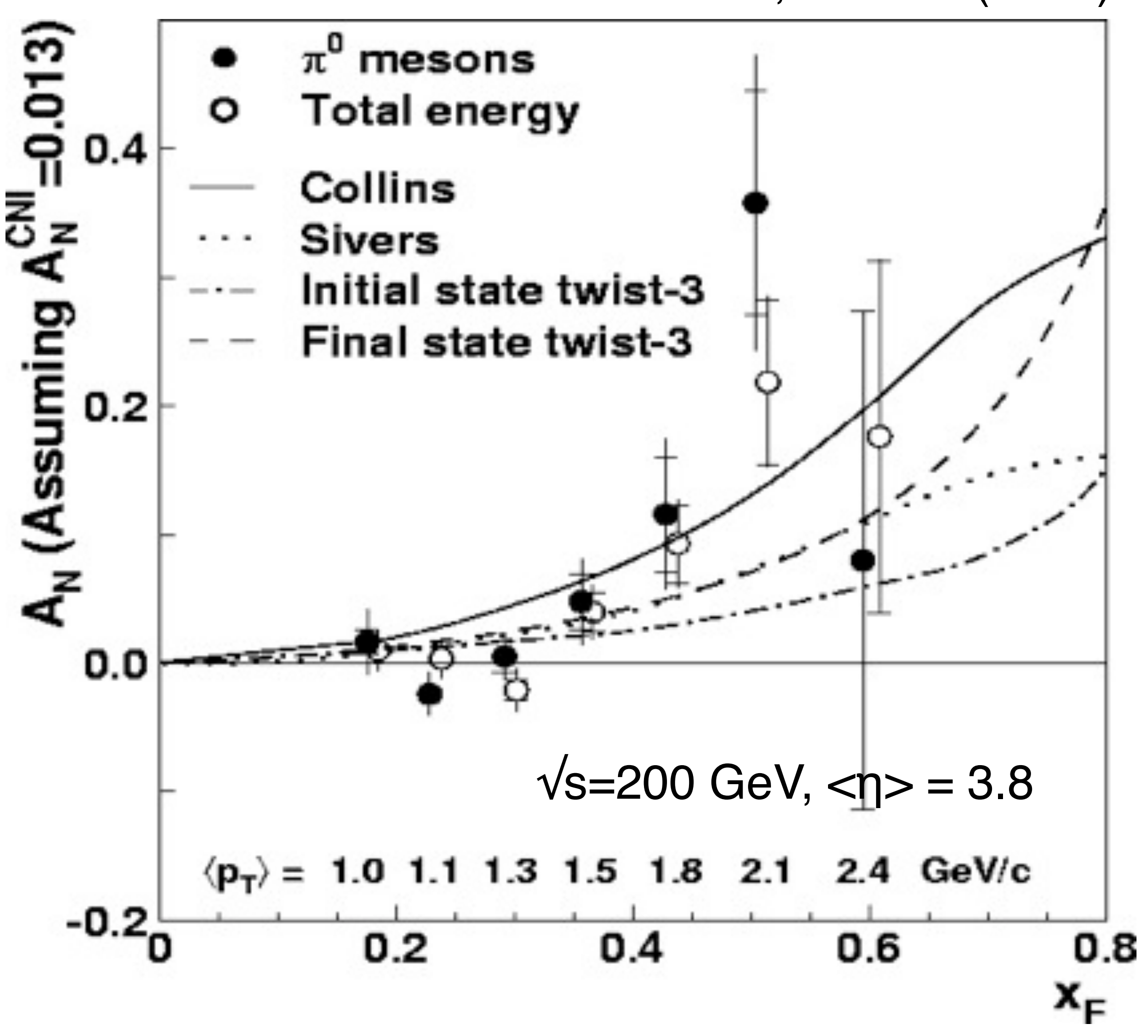


Lorce, Pasquini, Vanderhaeghen

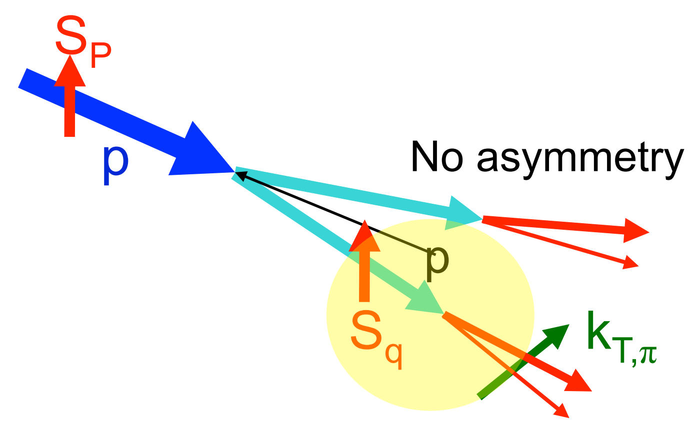
Transverse Spin Phenomena - A_N

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

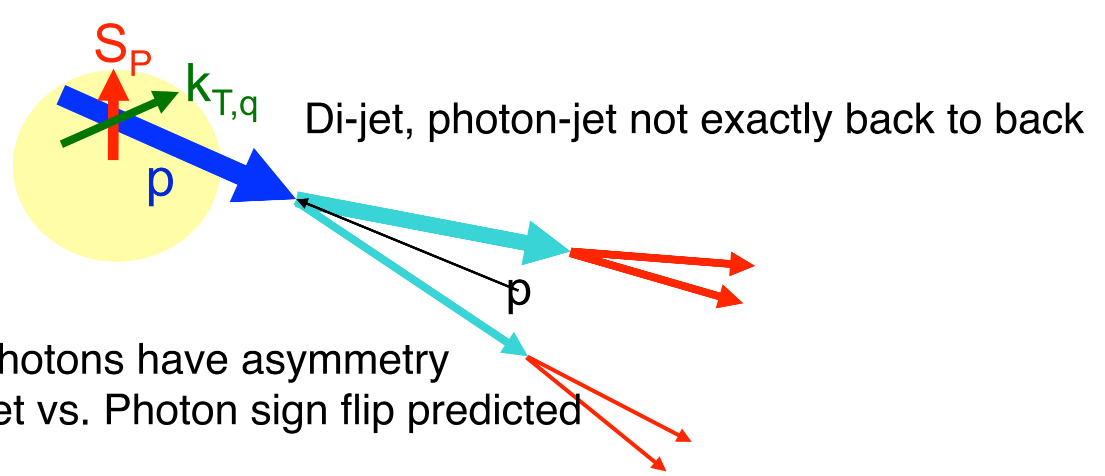
PRL 92, 171801 (2004)



- **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

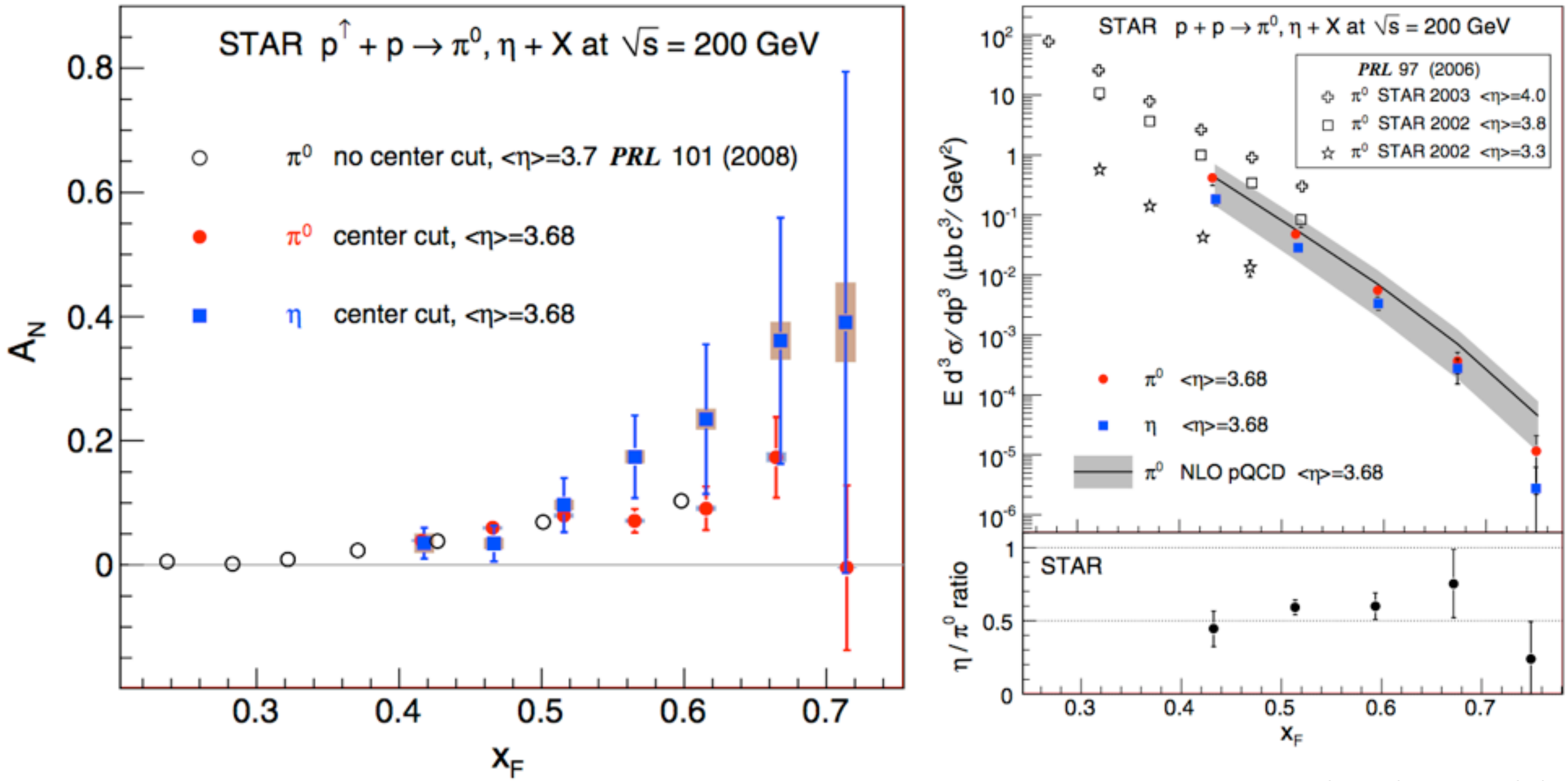


- **Other (?)**

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

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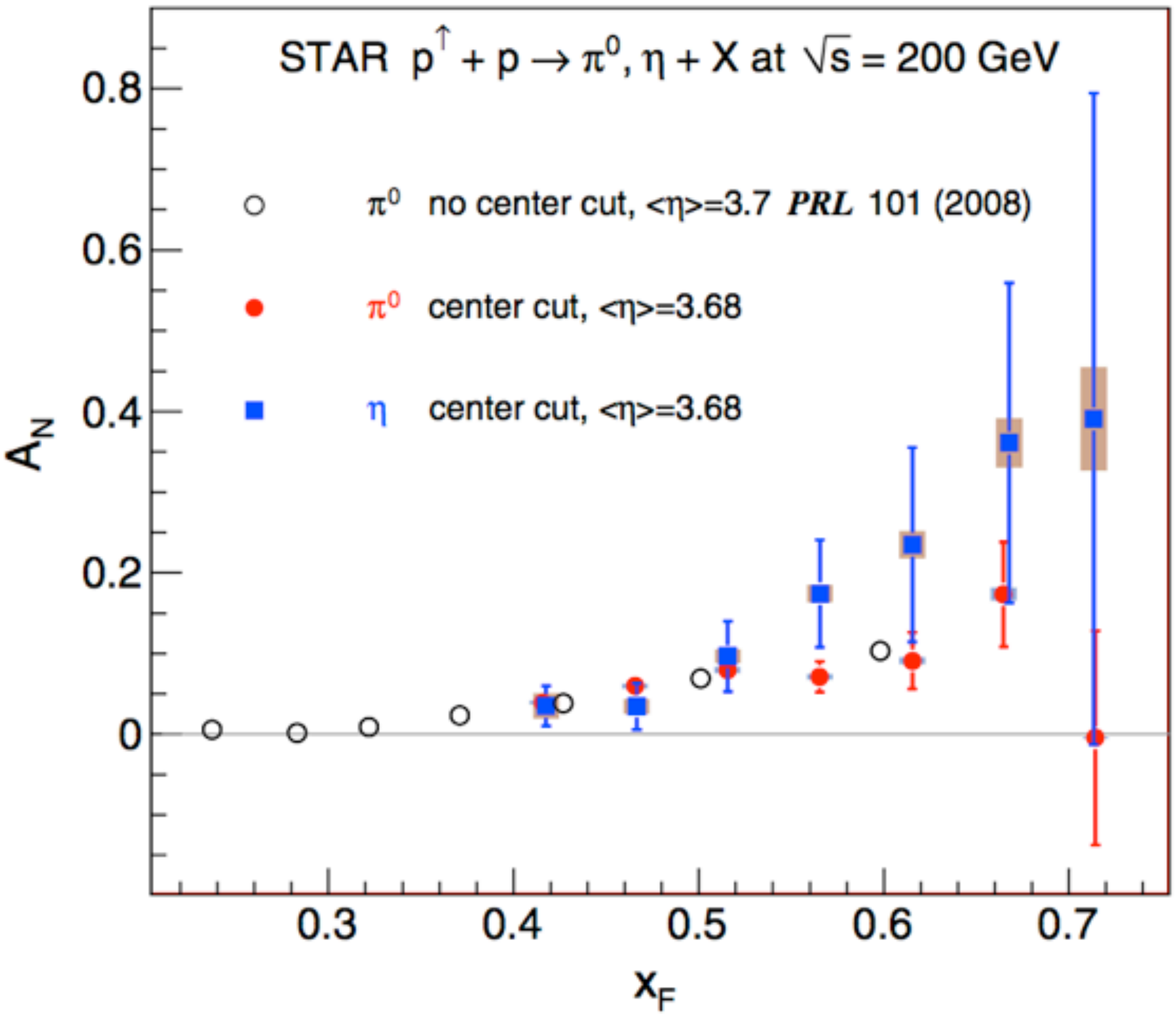
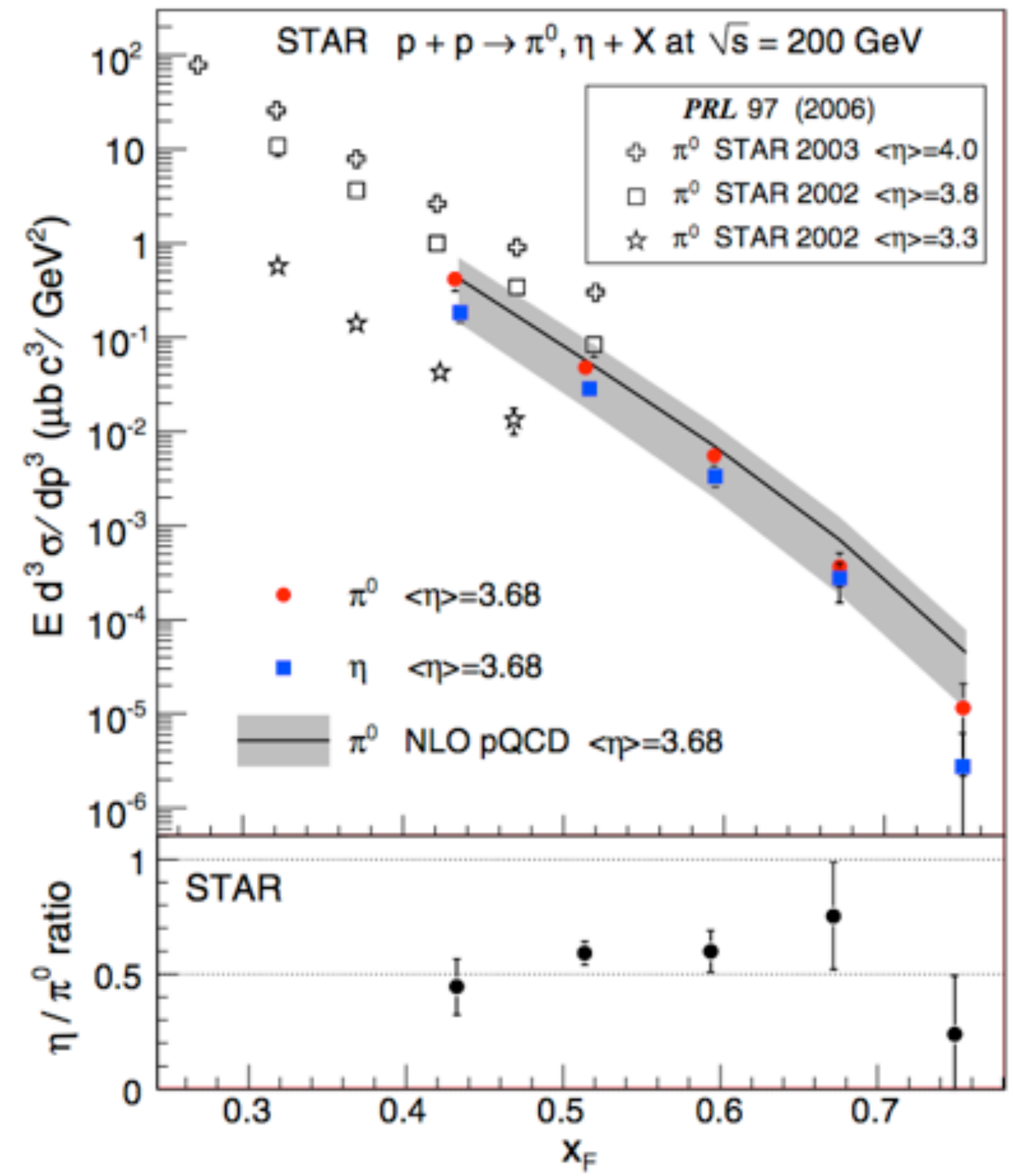
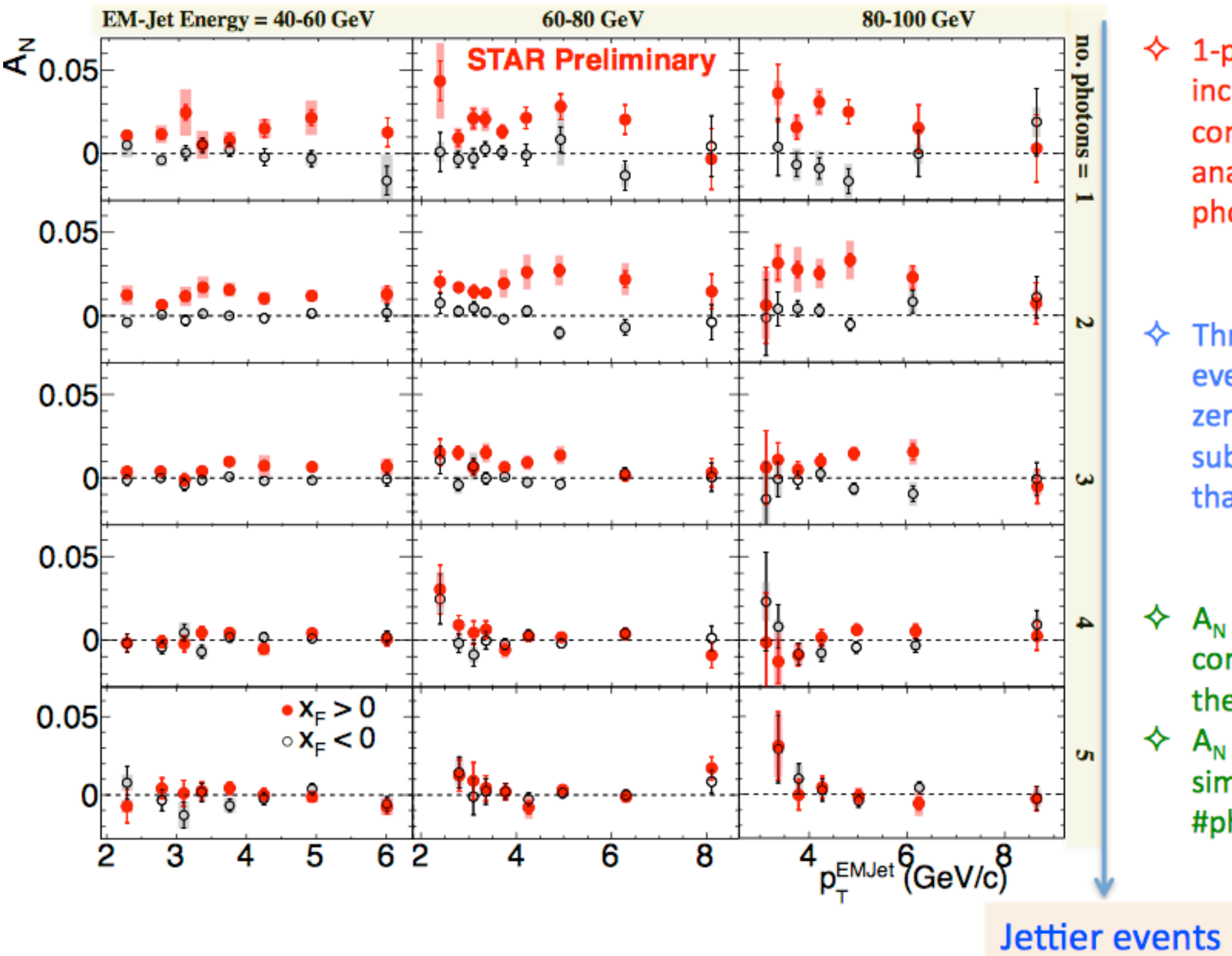




Phys. Rev. **D86** (2012) 051101(R)

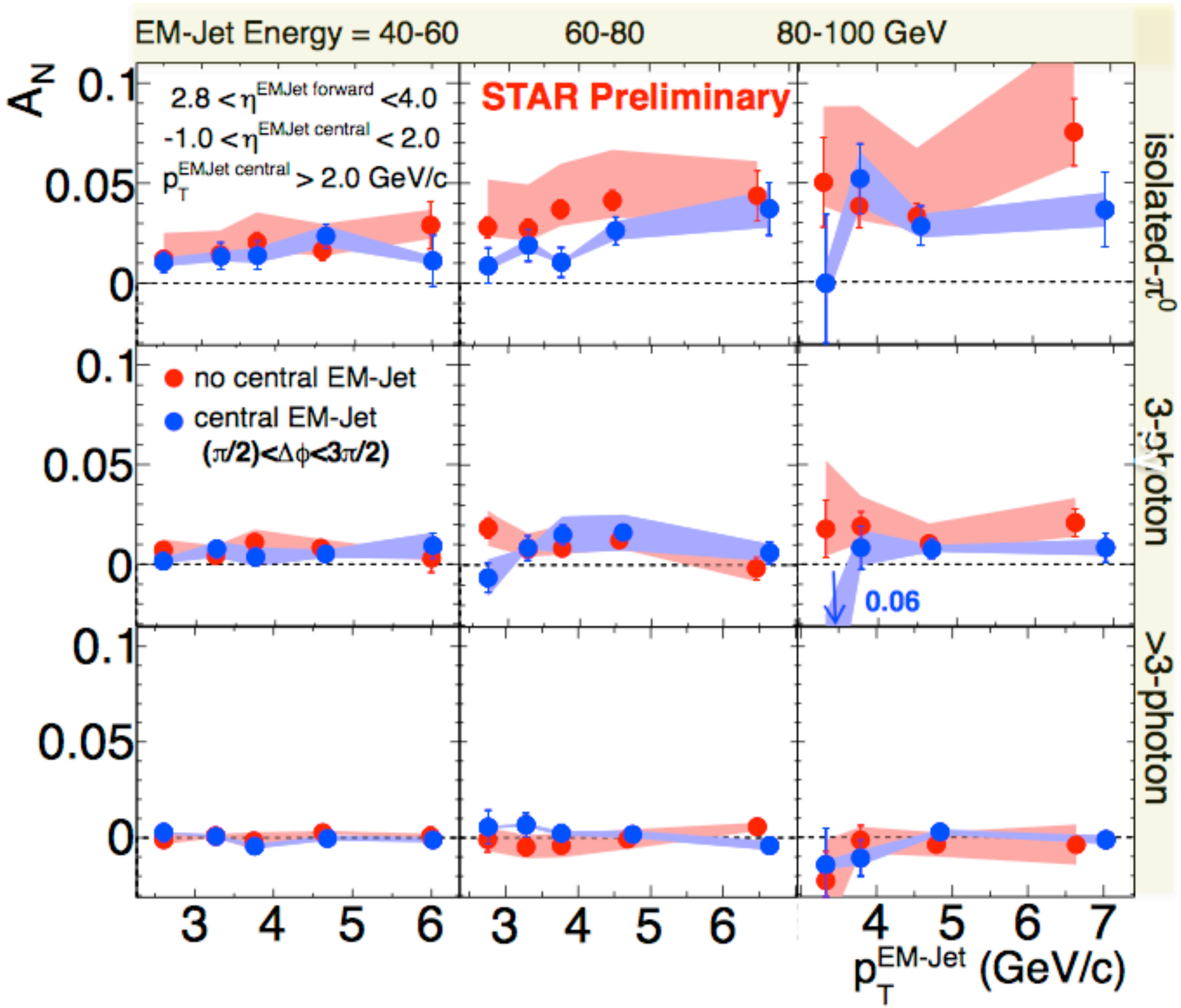
An intricate role for (anti-)strange quarks, also here?

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

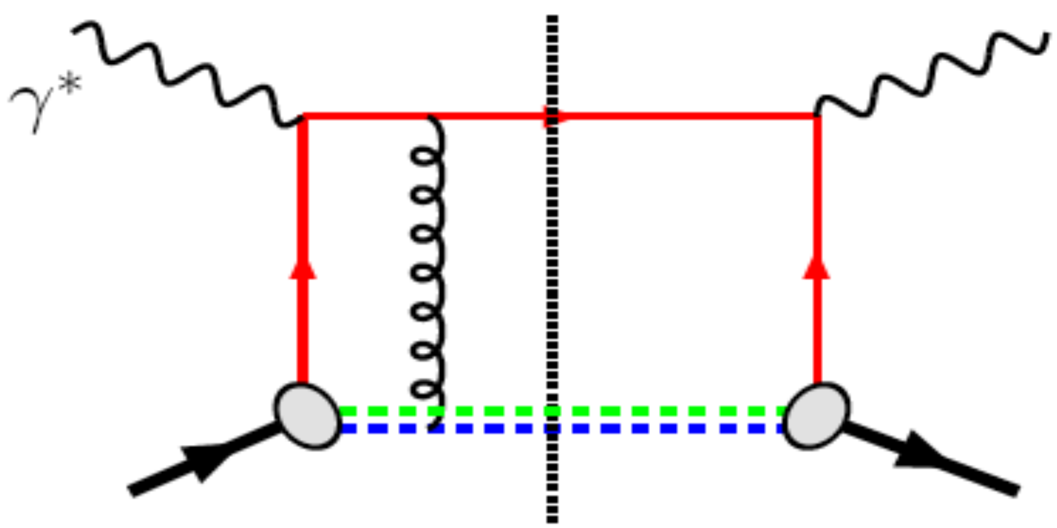
Transverse Spin Phenomena - A_N



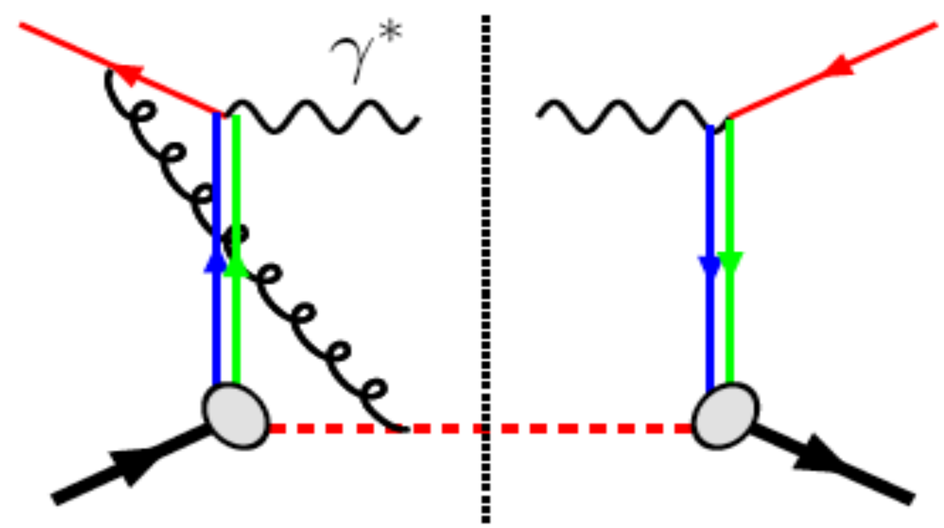
A_N tends to be larger for events without a mid-rapidity associated jet than for events with such a jet.

Transverse Spin Phenomena - Sivers Sign-Change

DIS, attractive FSI



DY, repulsive ISI

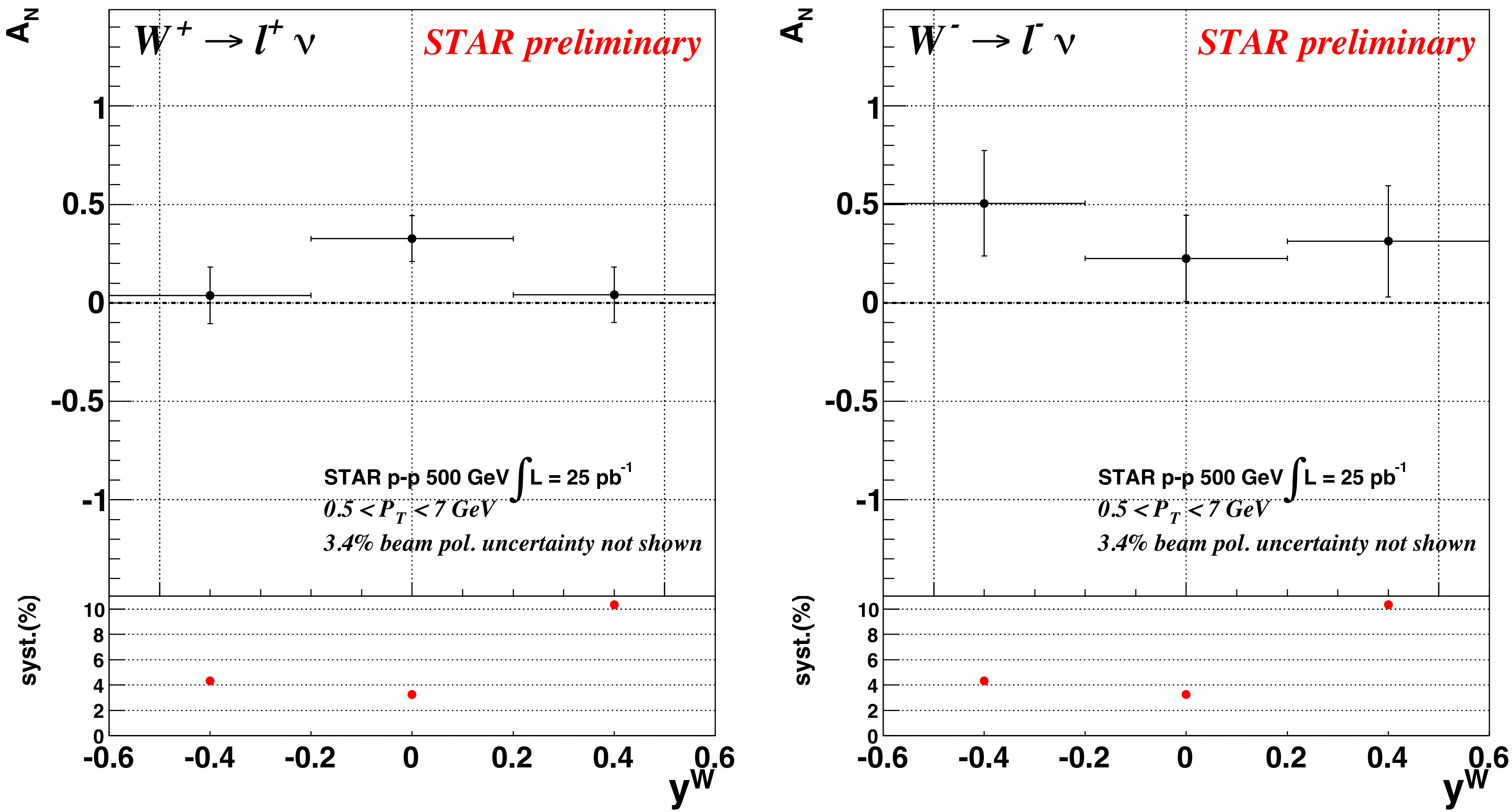


$\text{Sivers}_{\text{DIS}} = -\,\text{Sivers}_{\text{DY}}$

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

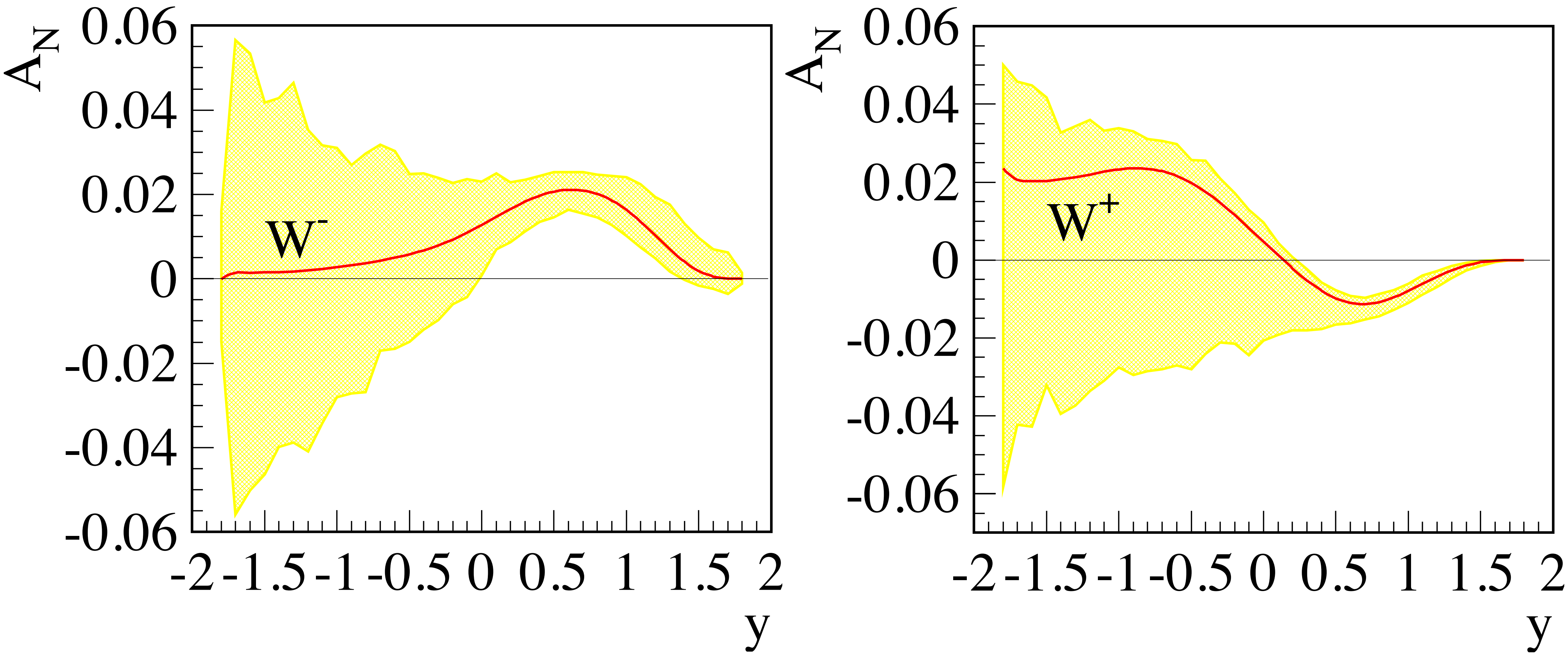
In colloquial english: Quarks with unlike color charge attract one another in QCD.

Transverse Spin Phenomena - Sivers Sign-Change

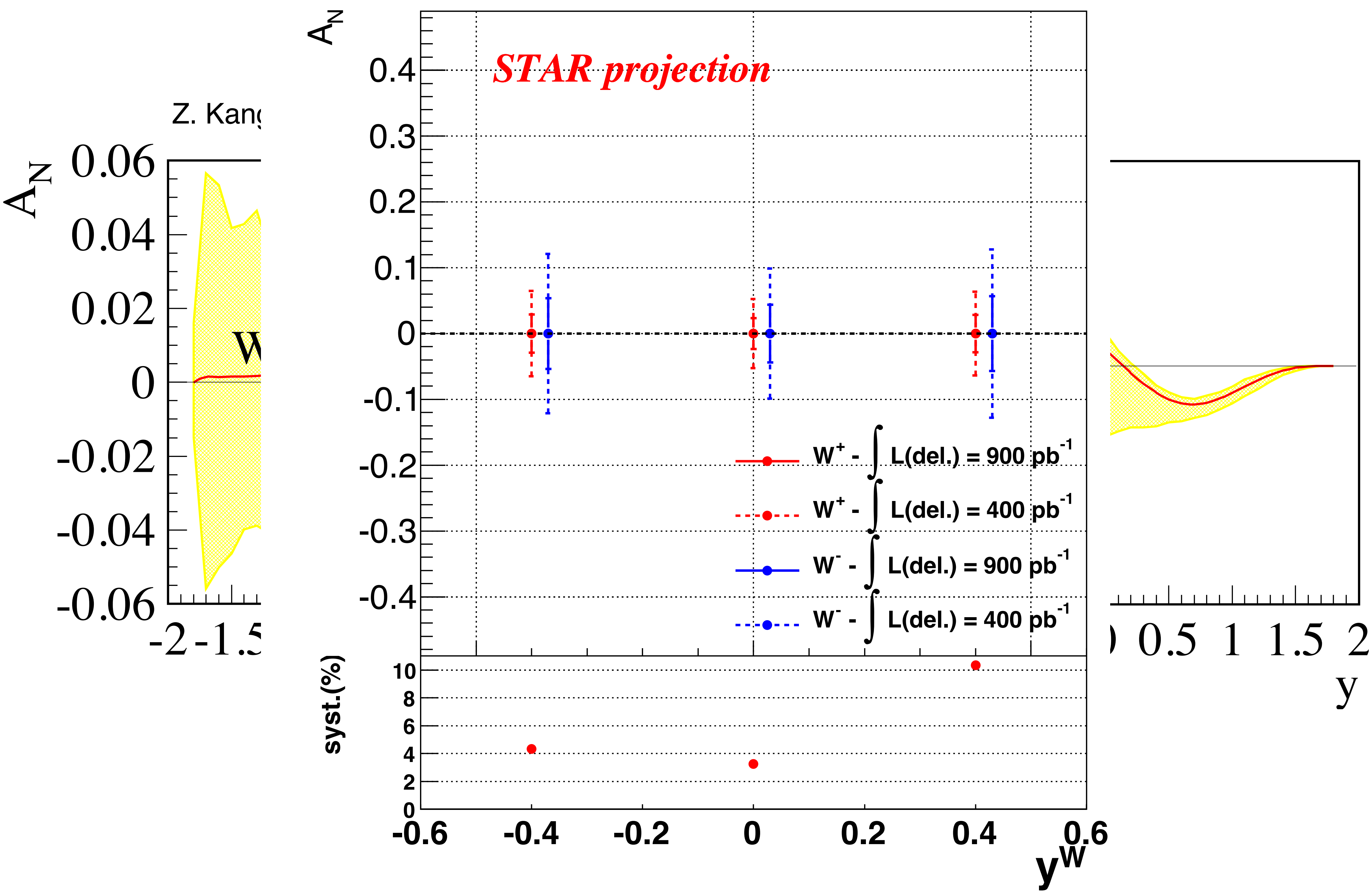


Transverse Spin Phenomena - Sivers Sign-Change

Z. Kang et al. arXiv:1401.5078v1



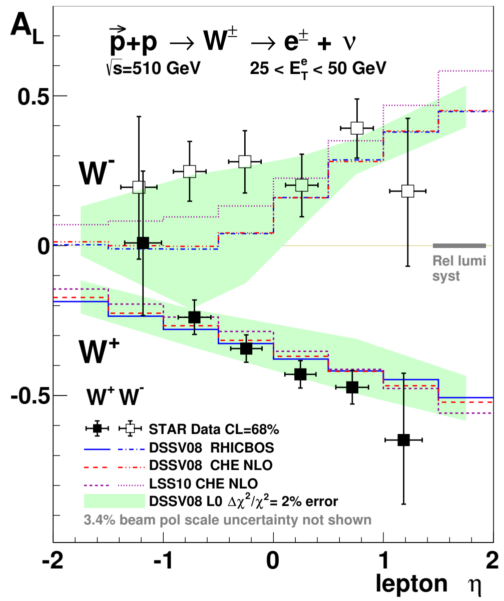
Transverse Spin Phenomena - Sivers Sign-Change



STAR Highlights at DIS 2014

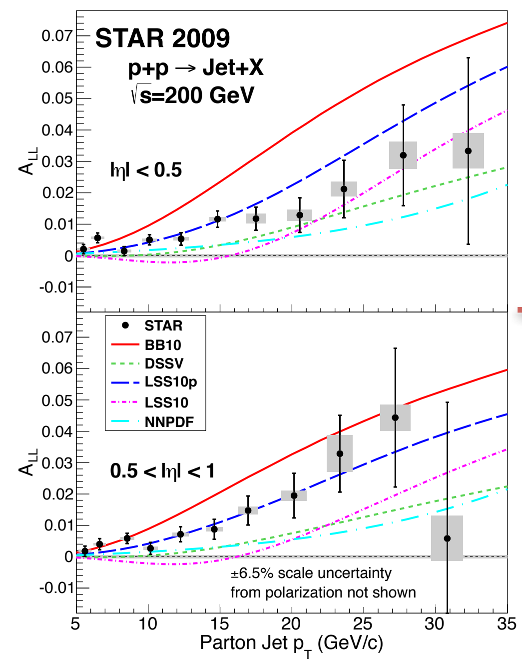
Warsaw, April 28 – May 2

Next Steps

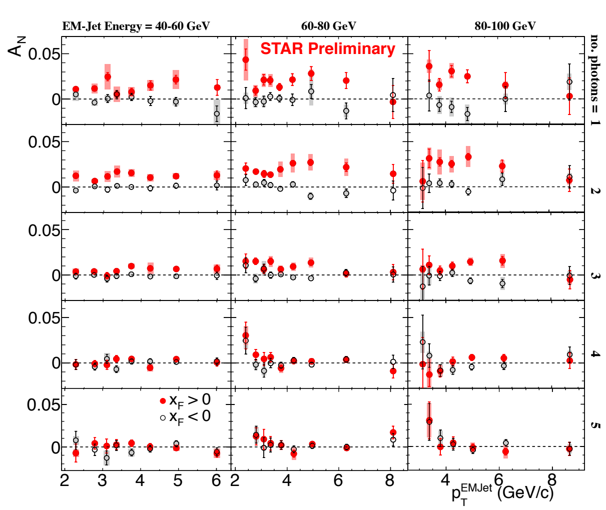


Justin Stevens (MIT)

Δu > Δd → ***Analyze Run-13***

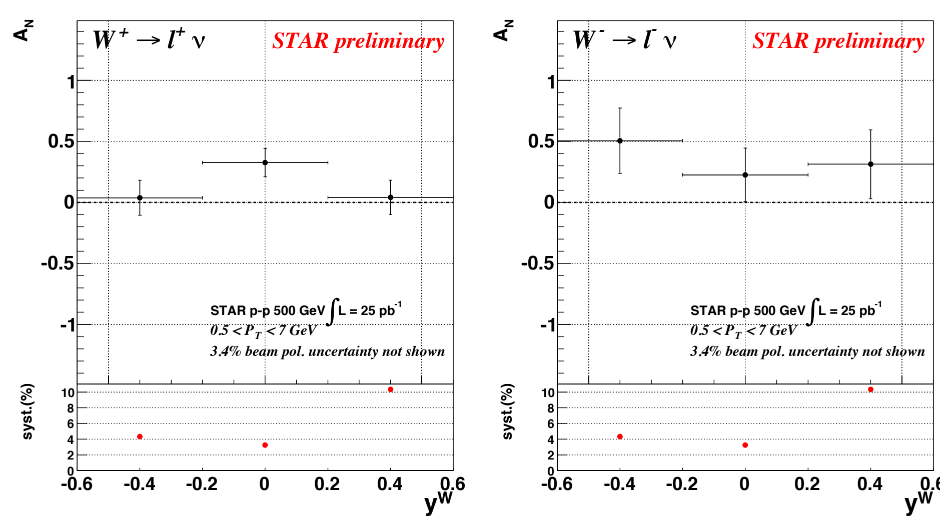


Non-zero ΔG → ***Increase precision in Run-15***



Mirganka Mondal (Texas A&M)

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



Salvatore Fazio (BNL)

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

https://drupal.star.bnl.gov/STAR/presentations

III - Towards an Electron Ion Collider

Electron Ion Colliders

Past

Possible Future

	HERA @ DESY	LHeC @ CERN	HIAF @ CAS	ENC @ GSI	MEIC/ELIC @ JLab	eRHIC @ BNL
√s [GeV]	320	800 - 1300	12 - 65	14	20 - 140	45 - 175
proton x_{min}	1×10^{-5}	5×10^{-7}	7×10^{-3} - 3×10^{-4}	5×10^{-3}	1×10^{-4}	3×10^{-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^{33}	10^{32-33} - 10^{35}	10^{32}	10^{33-34}	10^{33-34}
Interaction Points	2	1 (?)	1	1	2+	2+
Year	1992 - 2007	2022 (?)	2019 - 2030	upgrade to FAIR	post 12 GeV	2022

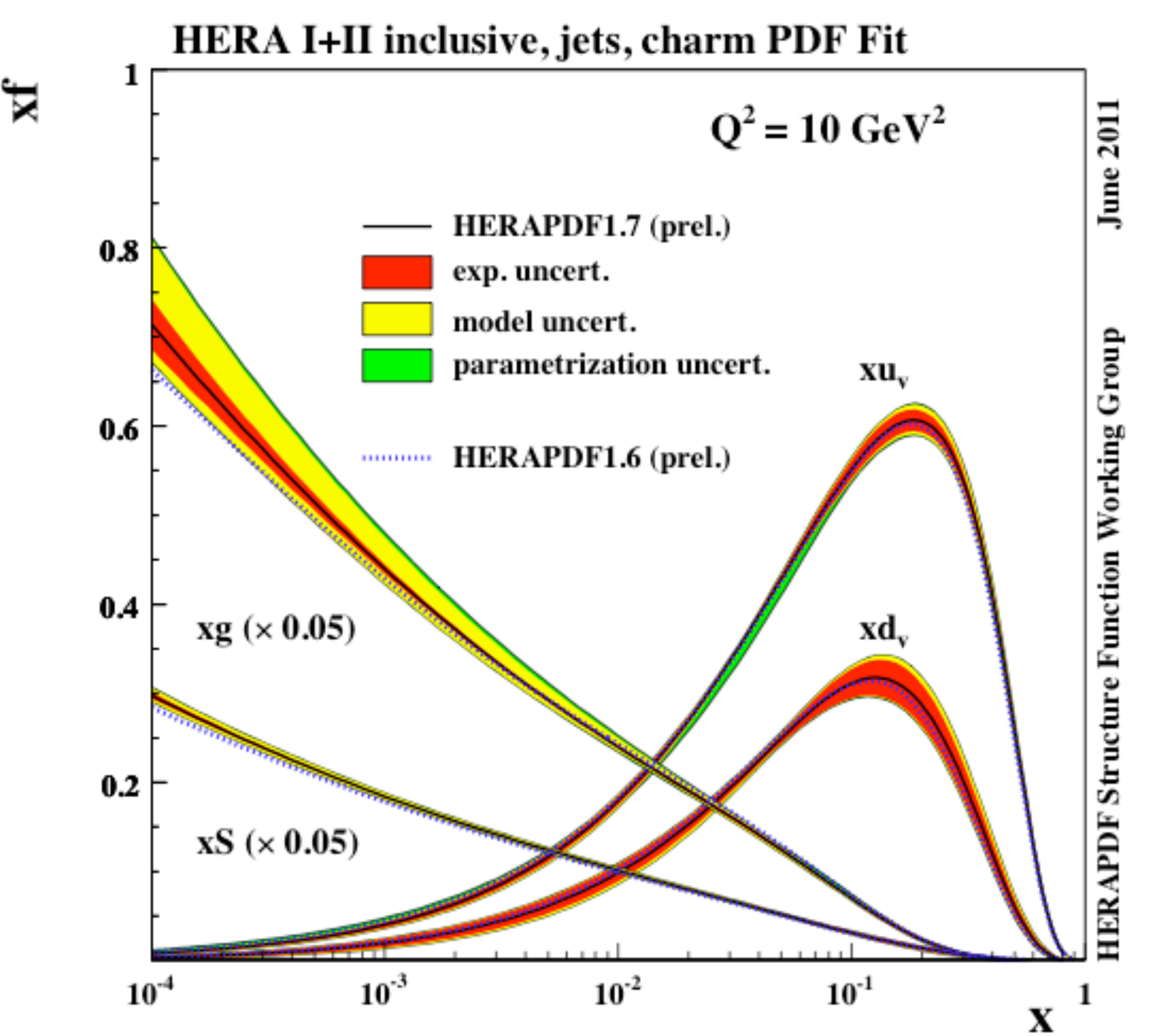
High-Energy Physics

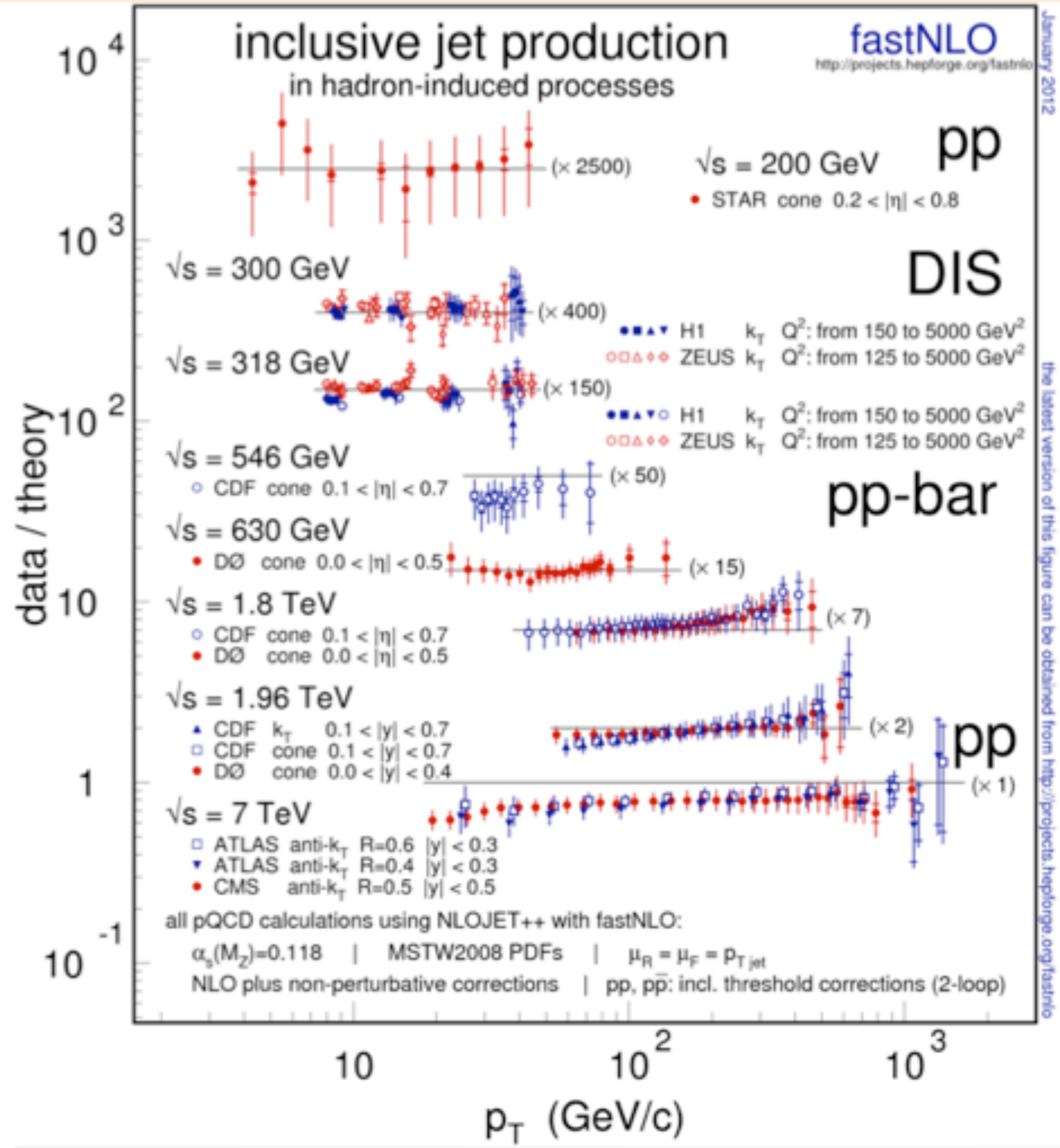
Nuclear Physics

HERA's legacy

The proton in terms of gluons and quarks

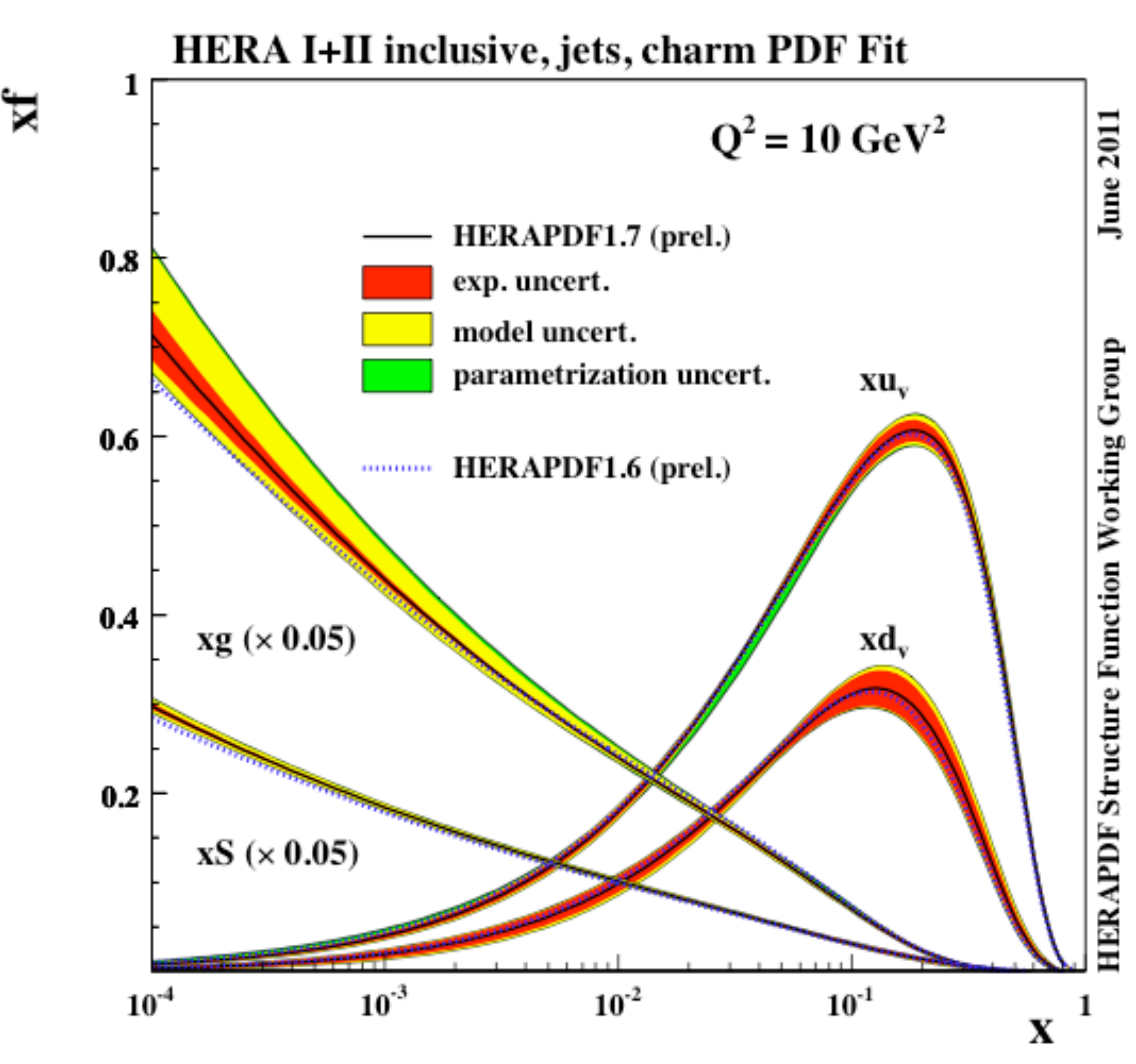
pQCD at work...





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,

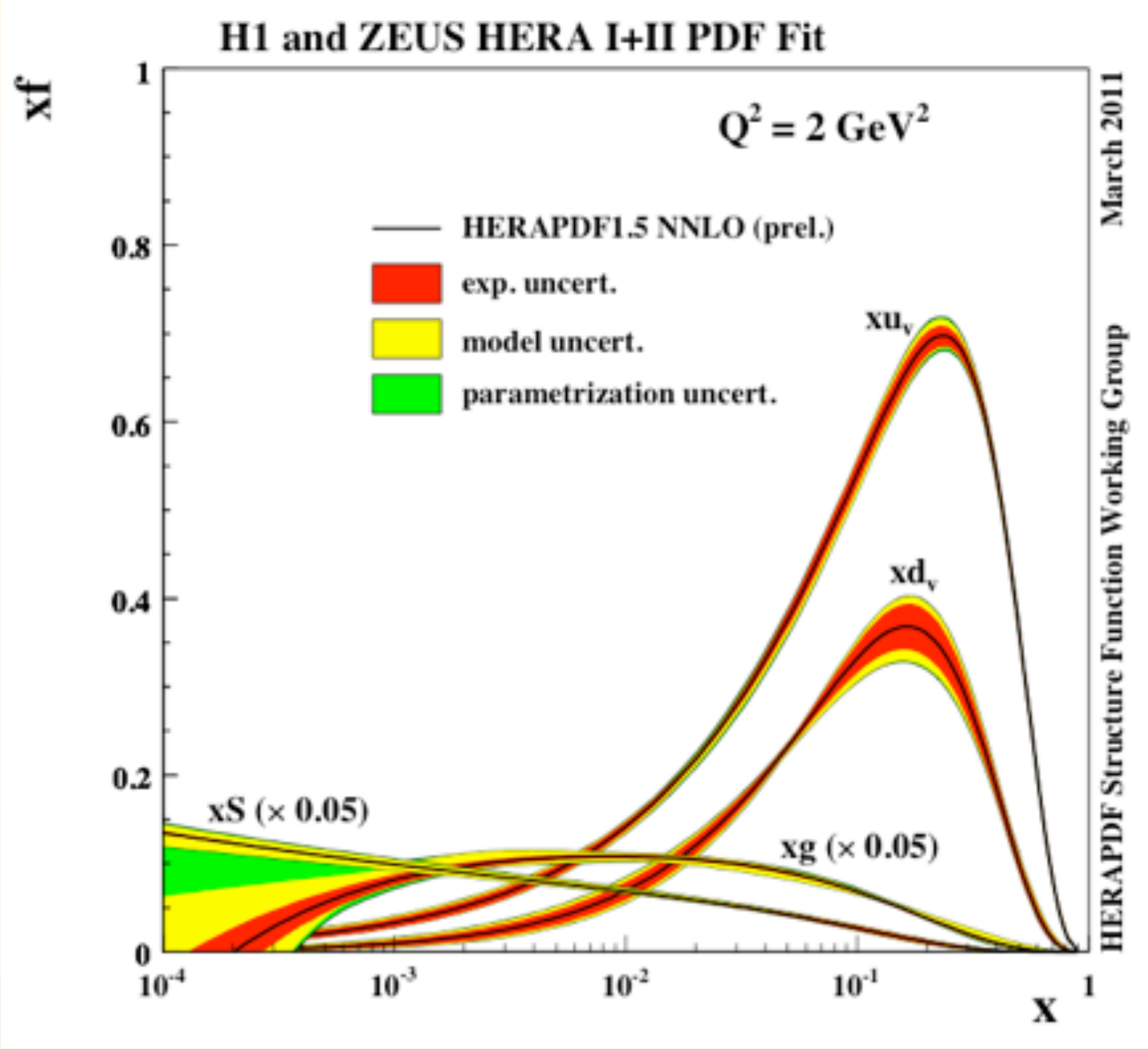
Saturation - insufficient √s / no nuclei,

...

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,



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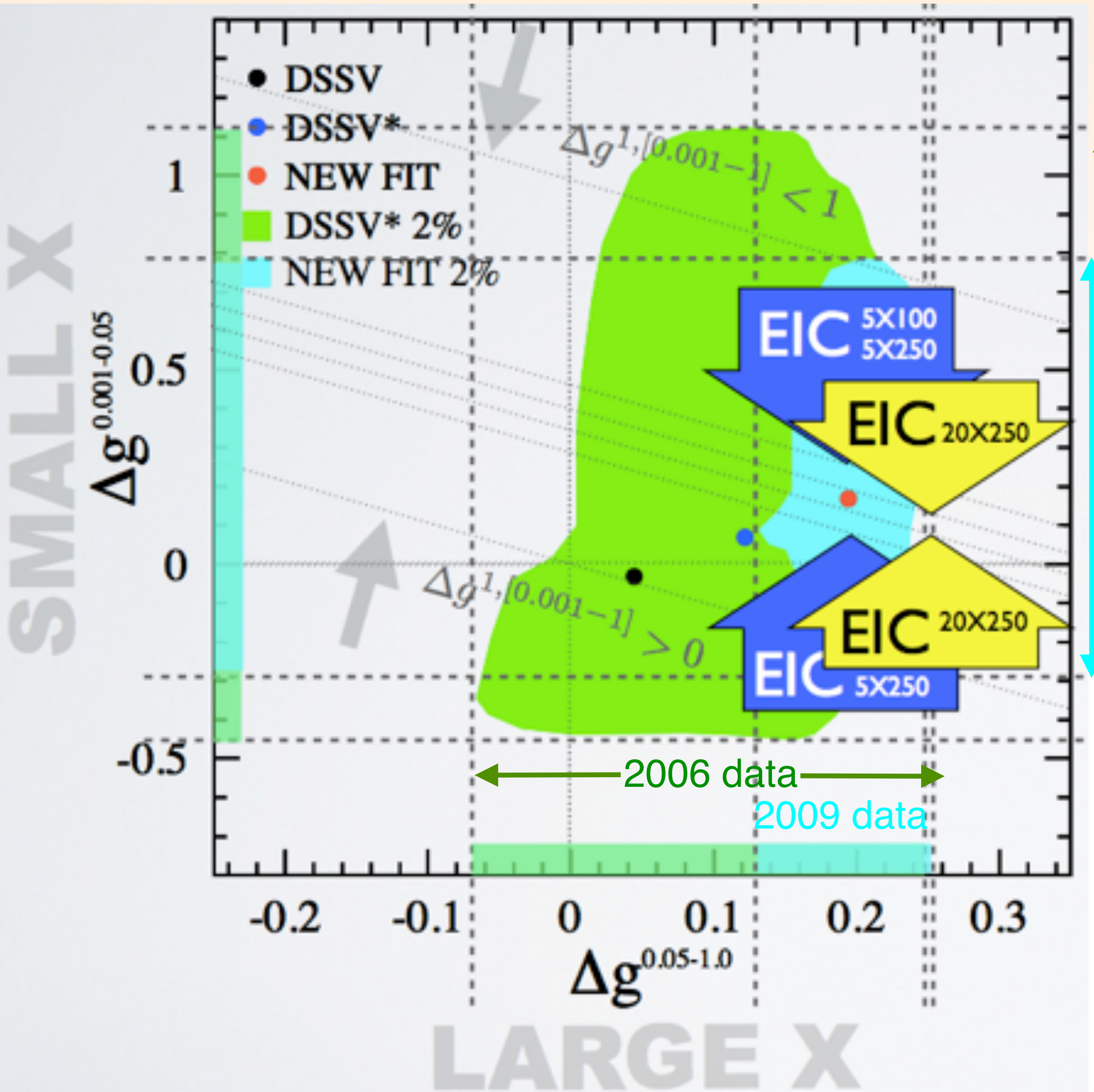
Spin puzzle:

- defining constraint on ΔG(x) for x > 0.05,
  smaller *x* is terra-icognita,
- fragmentation-free insight in Δu, Δd, Δū, Δd̄
  strange (anti-)quarks?
- large forward transverse-spin phenomena
  origin?

Mid-term: forward upgrade(s) at RHIC

Longer-term: EIC

Rodolfo Sassot at 2013 Spin Summer Program



HERA - RHIC, JLab

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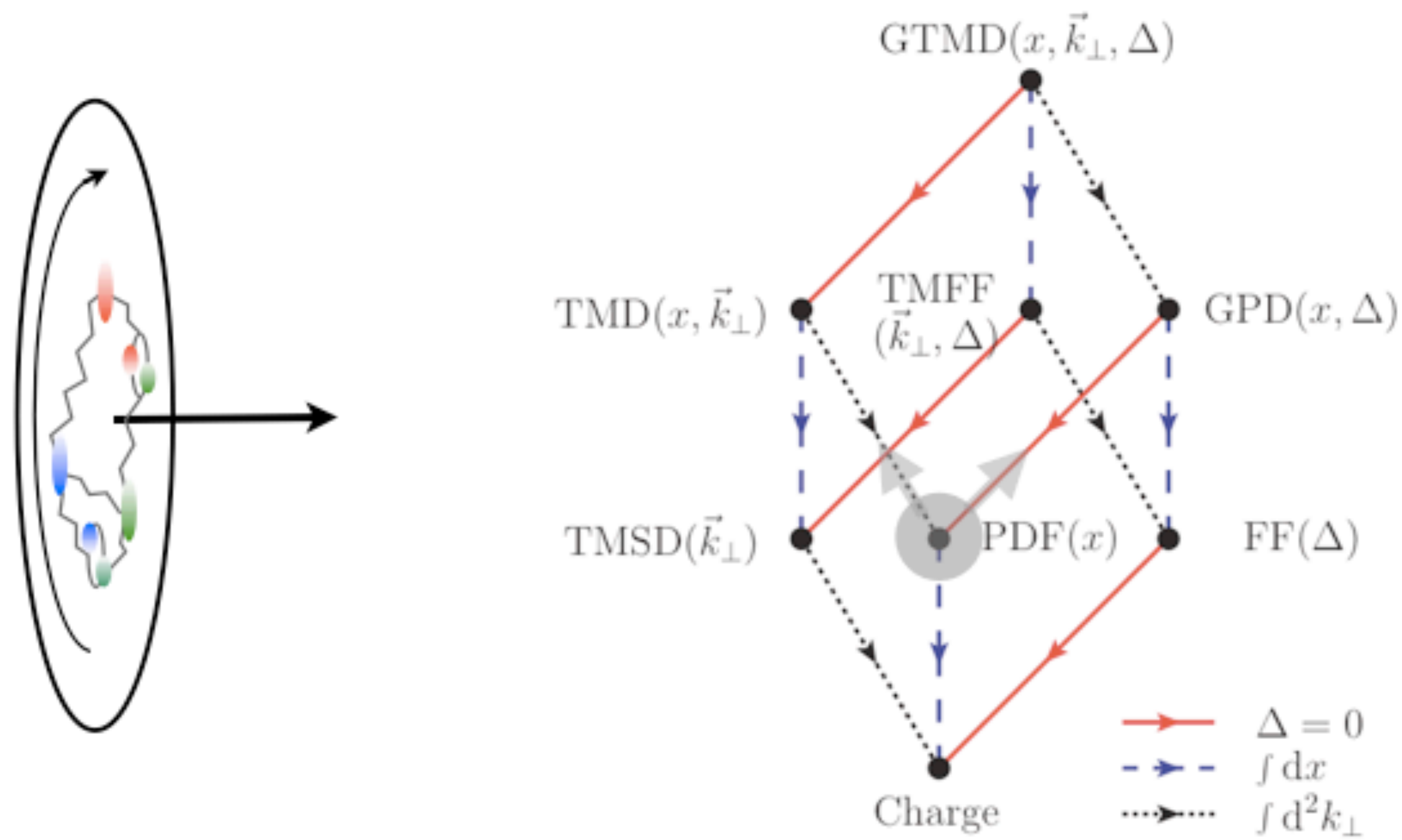
  strange (anti-)quarks?
- large forward transverse-spin phenomena
  origin?

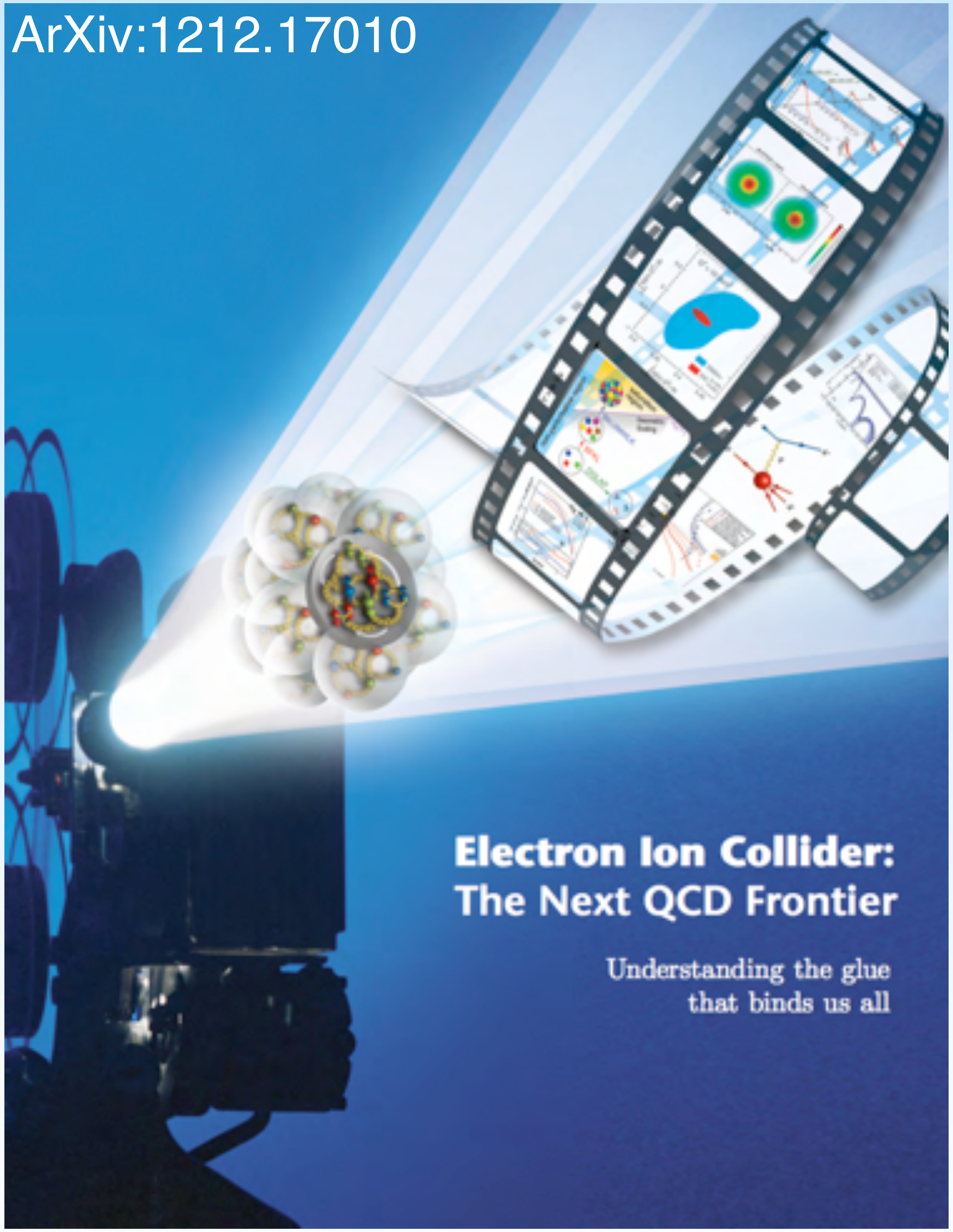
Imaging / tomography:

- valence quark region,
  gluon region?



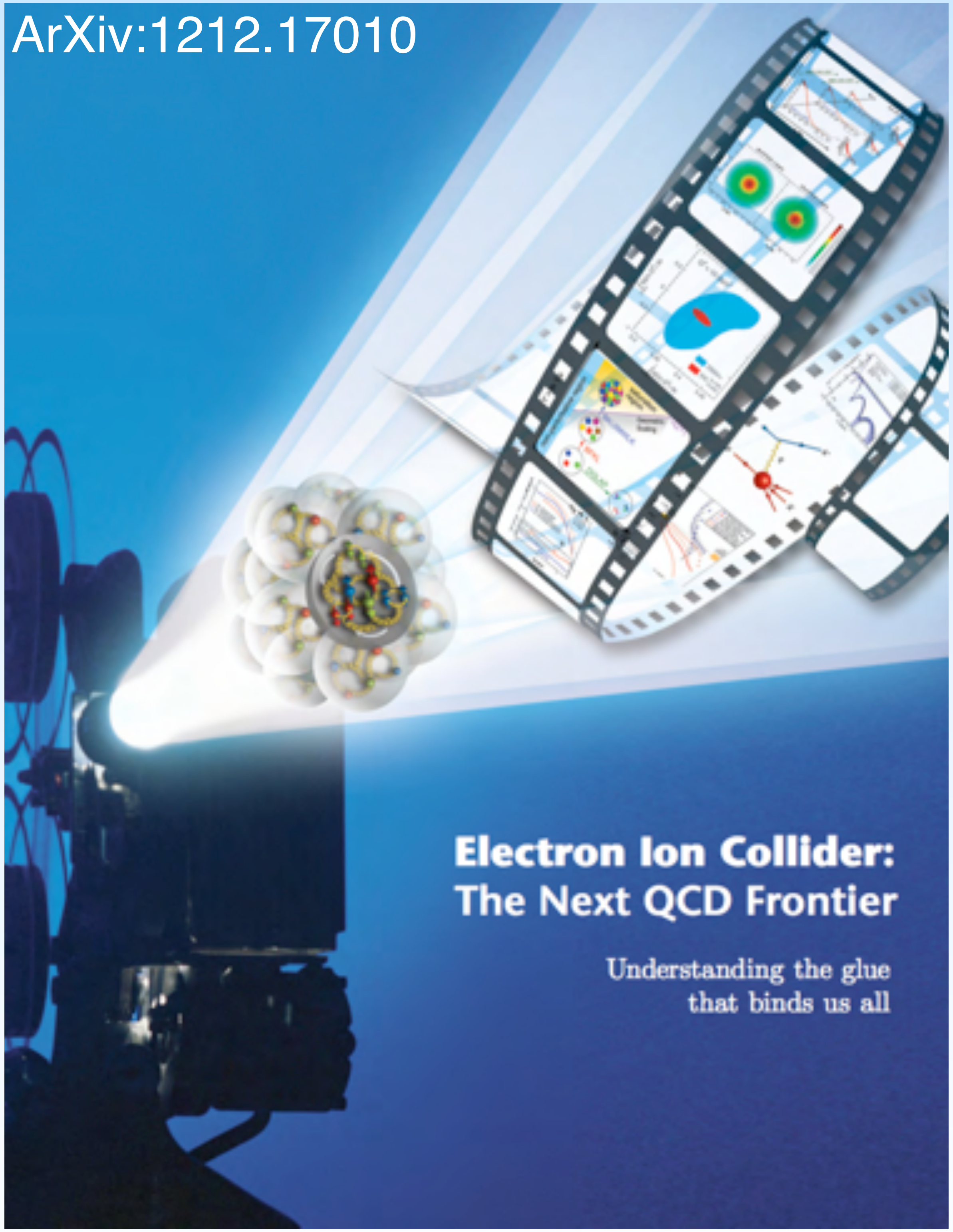
Lorce, Pasquini, Vanderhaeghen

U.S. EIC Science Case



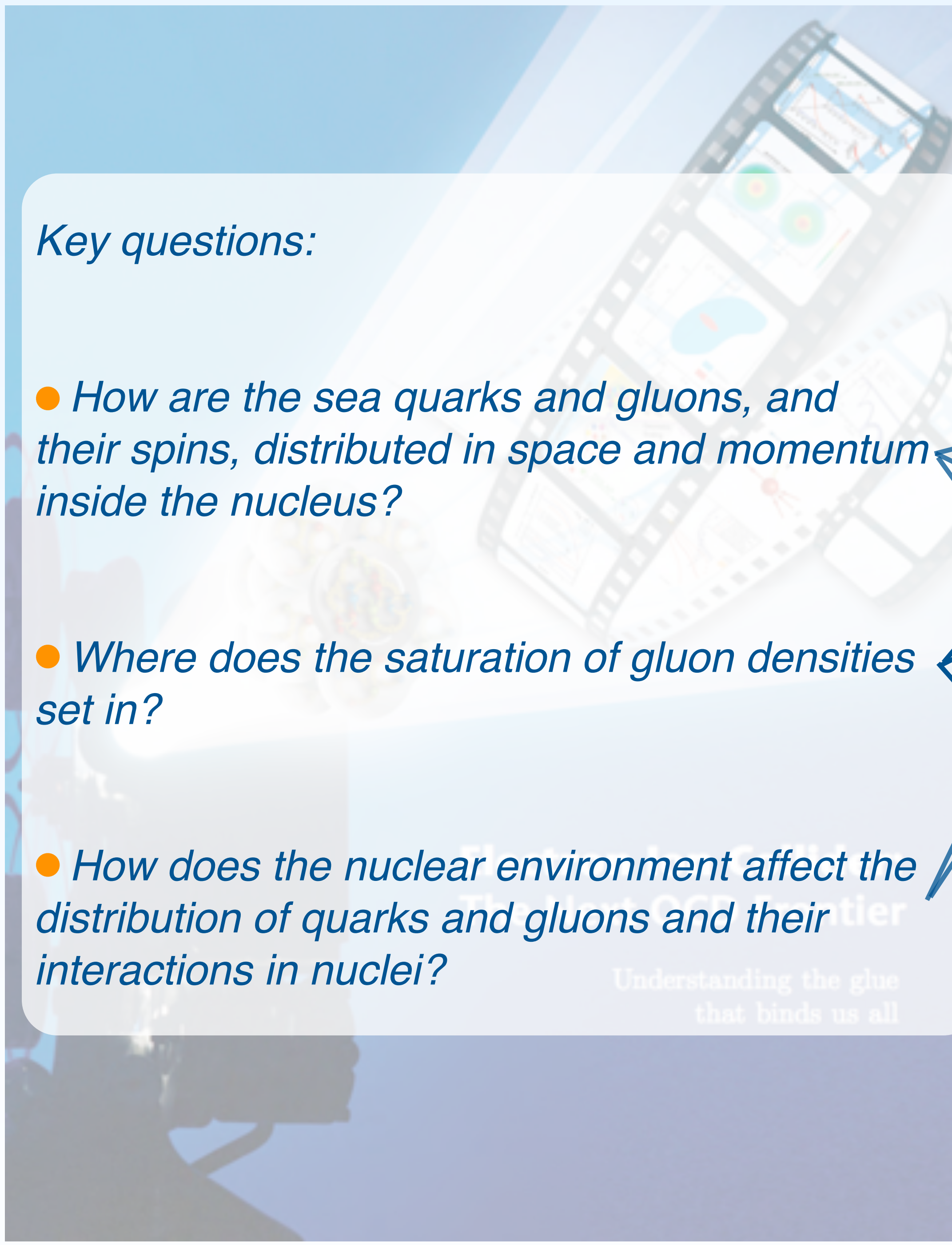
- *How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleus?*
- *Where does the saturation of gluon densities set in?*
- *How does the nuclear environment affect the distribution of quarks and gluons and their interactions in nuclei?*

U.S. EIC Capabilities



- *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.*

U.S. EIC Science Case and Measurements



Key questions:

- *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?*

Key measurements:

- *Inclusive Deep-Inelastic Scattering,*
- *Semi-inclusive deep-inelastic scattering with one or two of the particles in the final state,*
- *Exclusive deep-inelastic scattering,*
- *Diffraction.*

U.S. EIC Science Case and Measurements

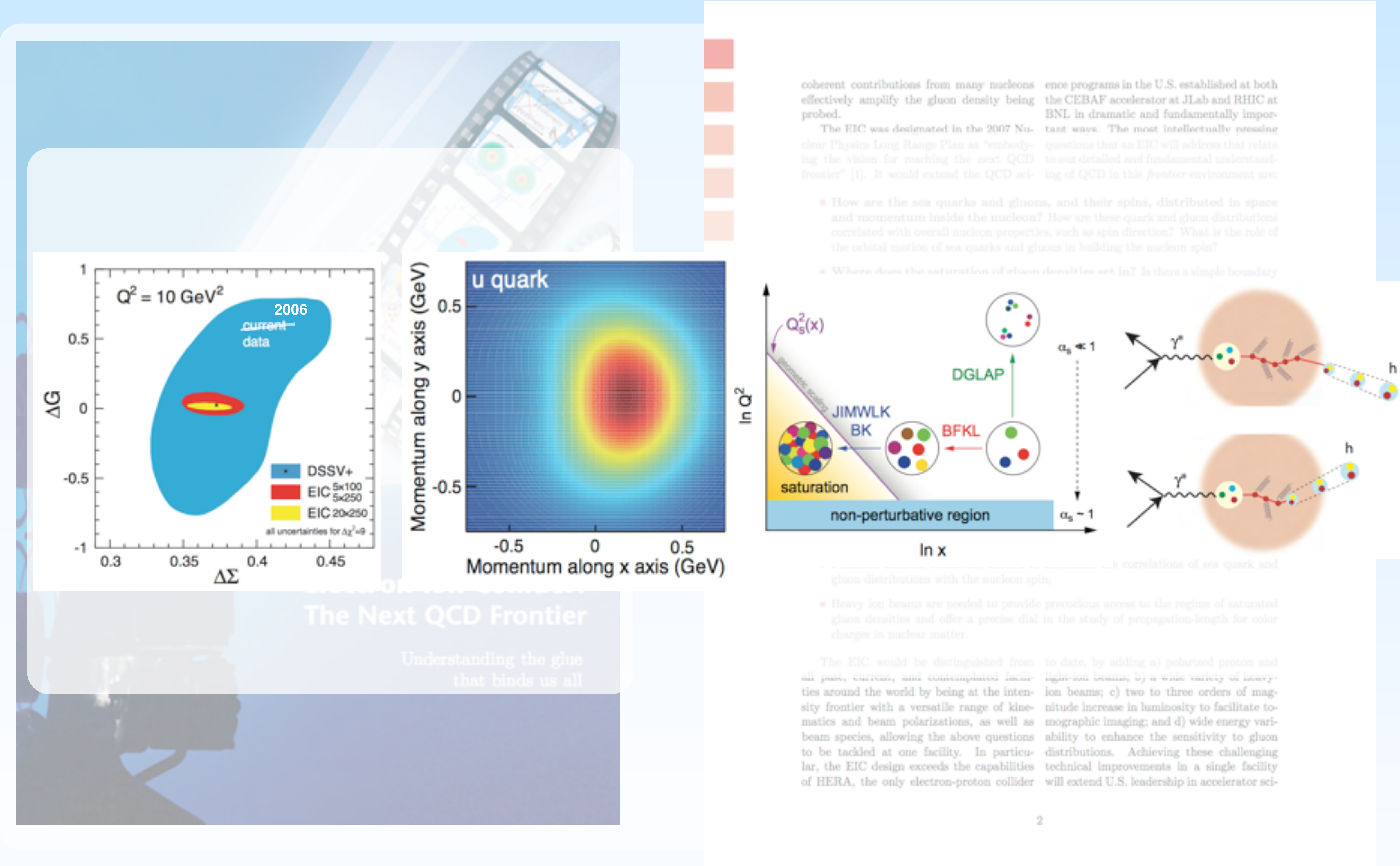
Key requirements:

- *Electron identification - scattered lepton*
- *Momentum and angular resolution - x,Q^2*
- *$\pi^+, \pi^-, K^+, K^-, p^+, p^-$, ... identification, acceptance*
- *Rapidity coverage, t-resolution*

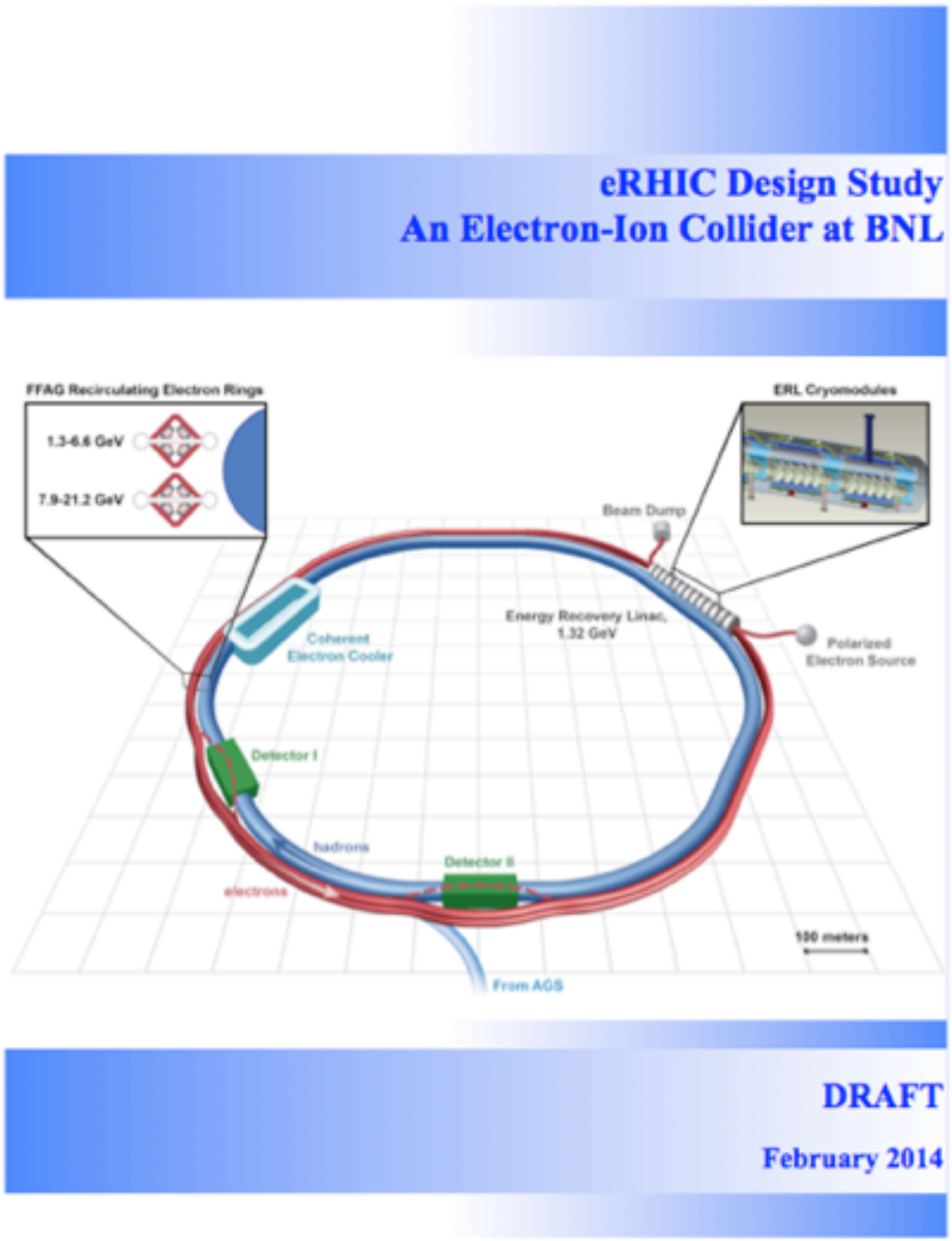
Key measurements:

- *Inclusive Deep-Inelastic Scattering,*
- *Semi-inclusive deep-inelastic scattering with one or two of the particles in the final state,*
- *Exclusive deep-inelastic scattering,*
- *Diffraction.*

U.S. EIC Science Case and Measurements



eRHIC: EIC at Brookhaven National Laboratory

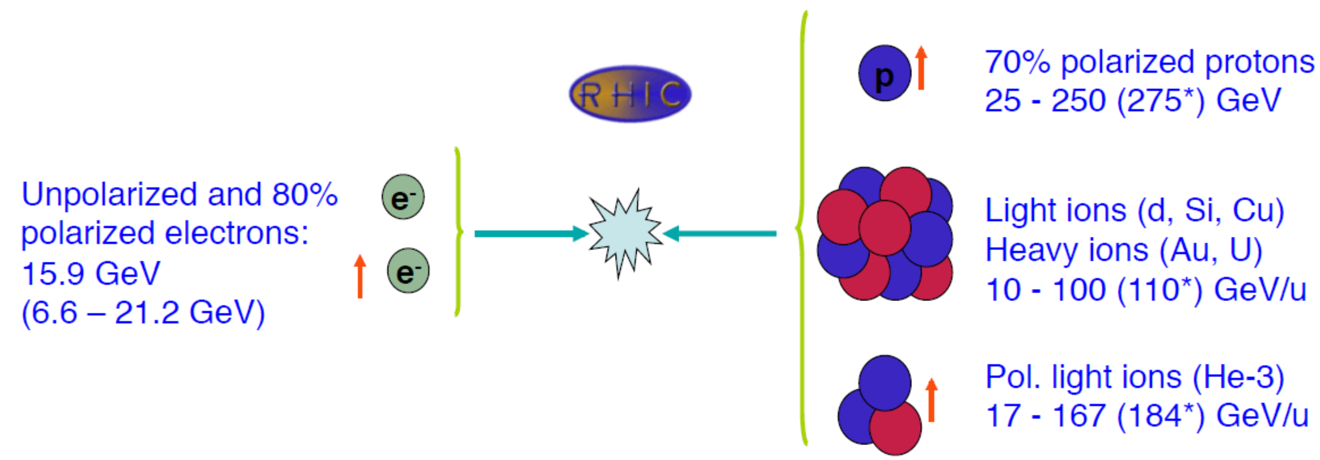


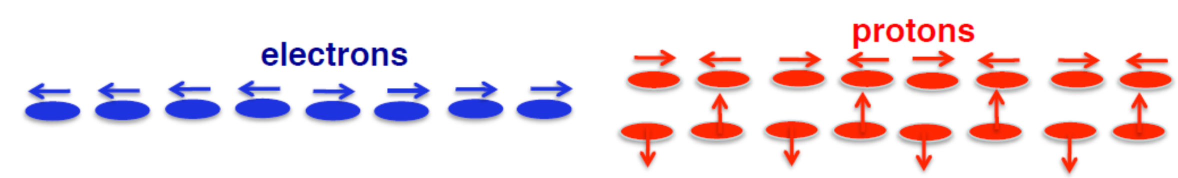
E.C. Aschenauer et al.

Numerous external contributions,

See talk by T. Roser at EIC-IAC meeting past February 28, 2014

The eRHIC accelerator ... design adds a high-current, multi-pass Energy Recovery Linac (ERL) and electron recirculation rings to the existing RHIC hadron facility:





* It is possible to increase RHIC ring energy by 10%

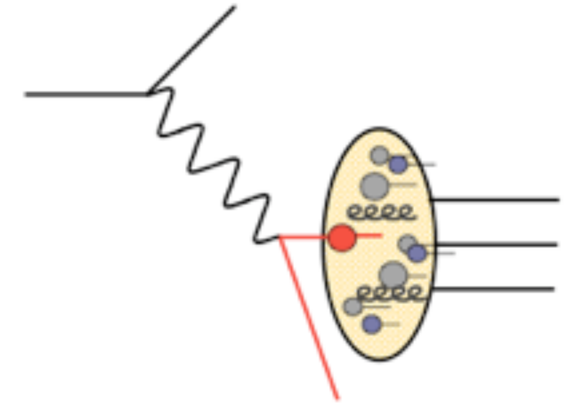
to provide a polarized electron beam with energy 15.9 GeV colliding with ion species ranging from polarized protons with a top energy of 250 GeV to fully stripped Uranium ions with energies up to 100 GeV/u, and e-nucleon luminosity of 10^{33} $cm^{-2}sec^{-2}$.

DIS Kinematics

Definitions: $e = (0, 0, -E_e, E_e)$

$$e' = (E'_e \sin\theta'_e, 0, E'_e \cos\theta'_e, E_e)$$

DIS



$$p = (0, 0, E_p, E_p)$$

angles w.r.t. hadron beam

Invariants: $s = (e+p)^2$

$$q = e - e' \quad Q^2 = -(e-e')^2$$

$$x = \frac{Q^2}{ys}$$

no substitute for c.m. energy

$$y = (q.p)/(e.p)$$

Resolutions:

$$\left(\frac{\delta Q_e^2}{Q_e^2}\right) = \frac{\delta E'_e}{E'_e} \otimes \tan\left(\frac{\theta'_e}{2}\right) \delta\theta'_e$$

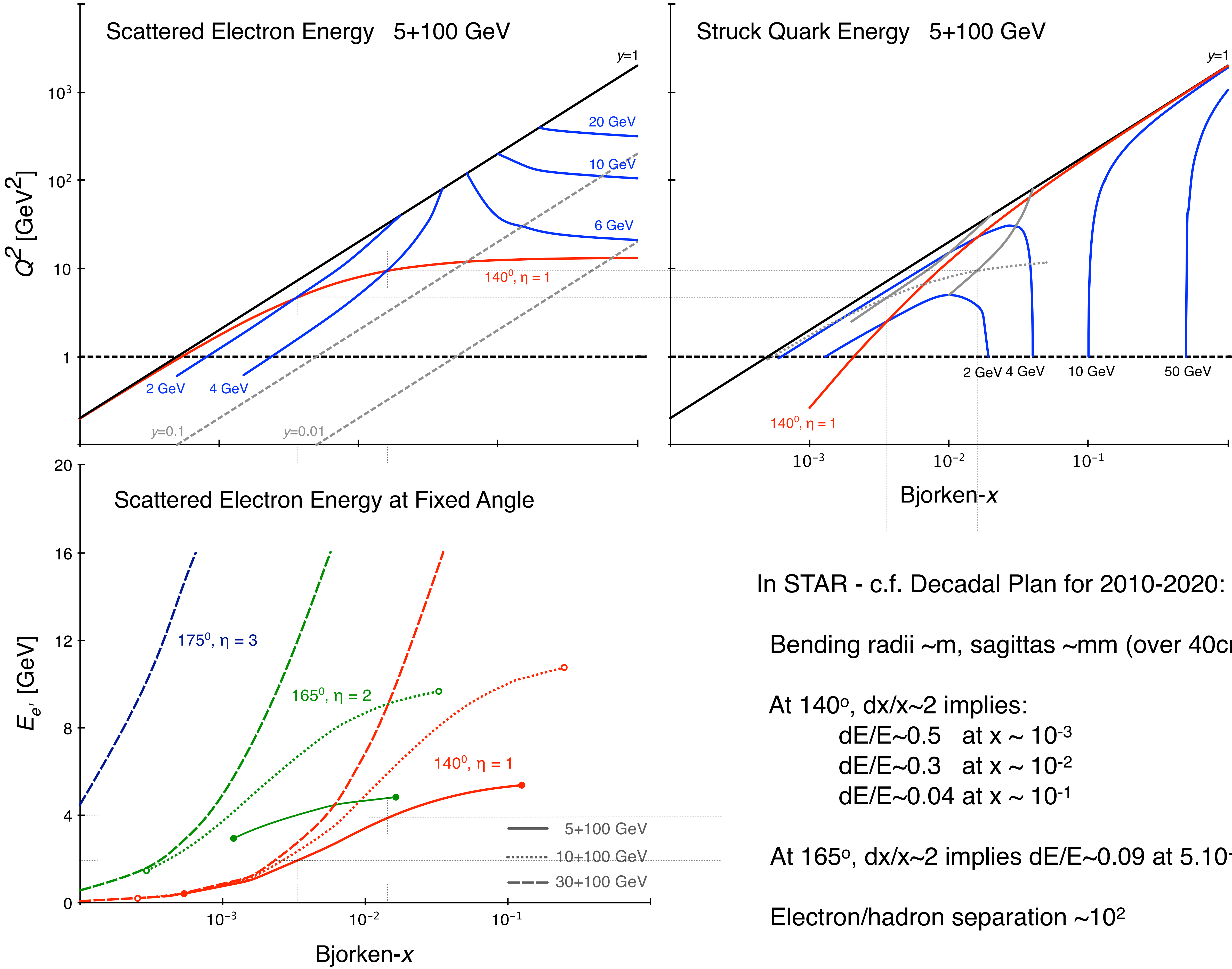
photoproduction

$$\left(\frac{\delta x_e}{x_e}\right) = \left(\frac{1}{y_e}\right) \frac{\delta E'_e}{E'_e} \otimes \left[\frac{x_e}{E_e/E_p} - 1\right] \tan\left(\frac{\theta'_e}{2}\right) \delta\theta'_e$$

low y

Note: kinematics can in principle be reconstructed also from the current jet; to be demonstrated in nuclear environments.

DIS Kinematic Considerations



In STAR - c.f. Decadal Plan for 2010-2020:

Bending radii ~m, sagittas ~mm (over 40cm),

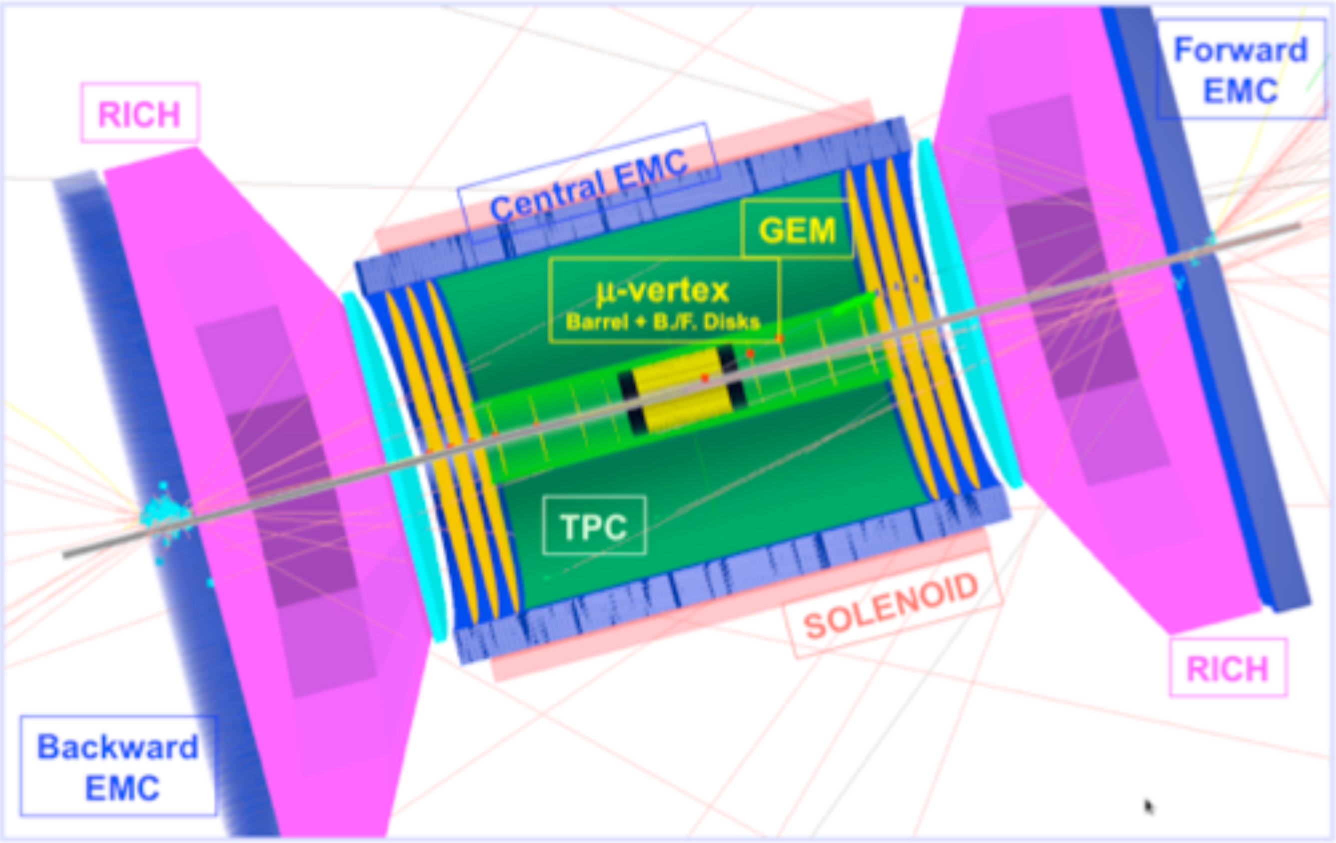
At 140°, dx/x~2 implies:
- dE/E~0.5 at x ~ 10^{-3}
- dE/E~0.3 at x ~ 10^{-2}
- dE/E~0.04 at x ~ 10^{-1}

At 165°, dx/x~2 implies dE/E~0.09 at 5.10^{-3}

Electron/hadron separation ~10^2

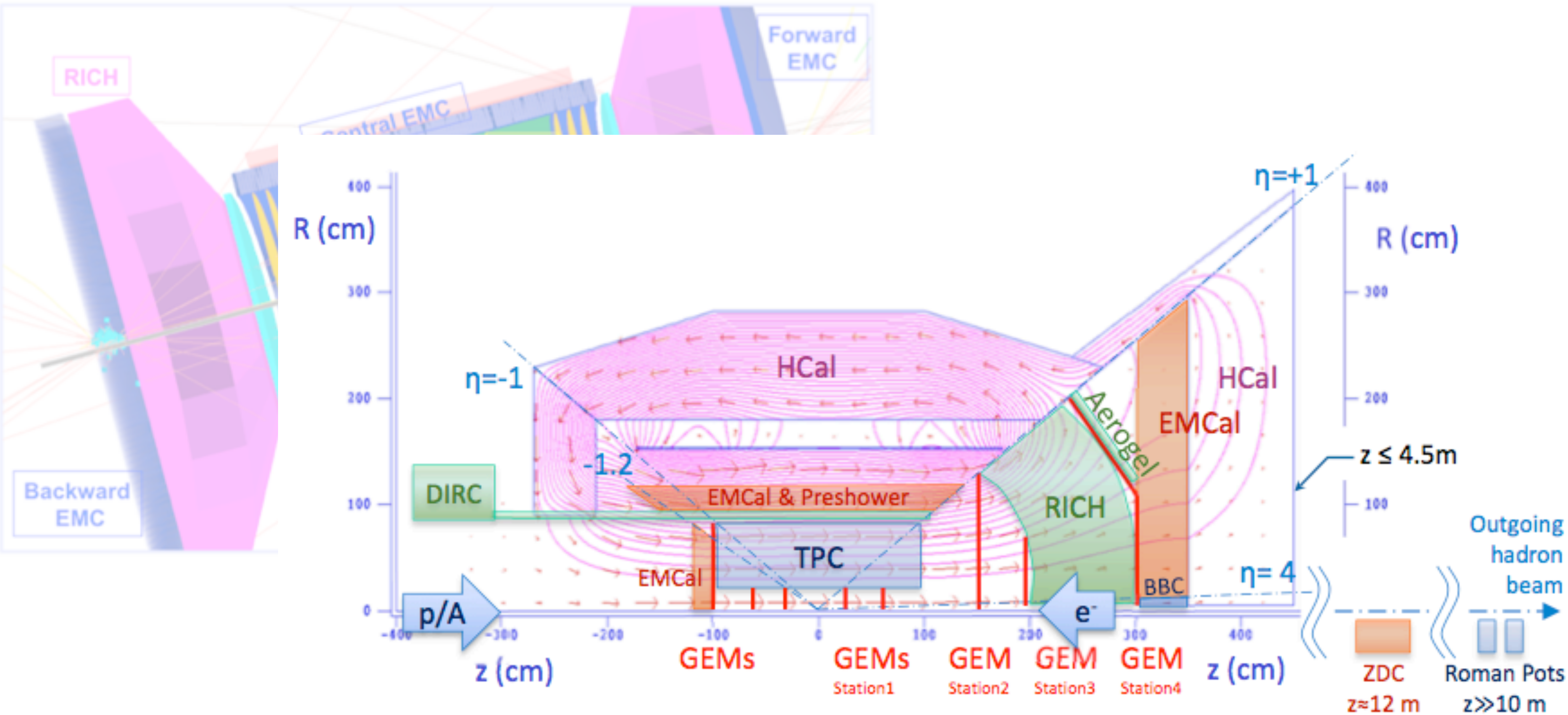
eRHIC - Detector Concepts

Optimized Detector



eRHIC - Detector Concepts

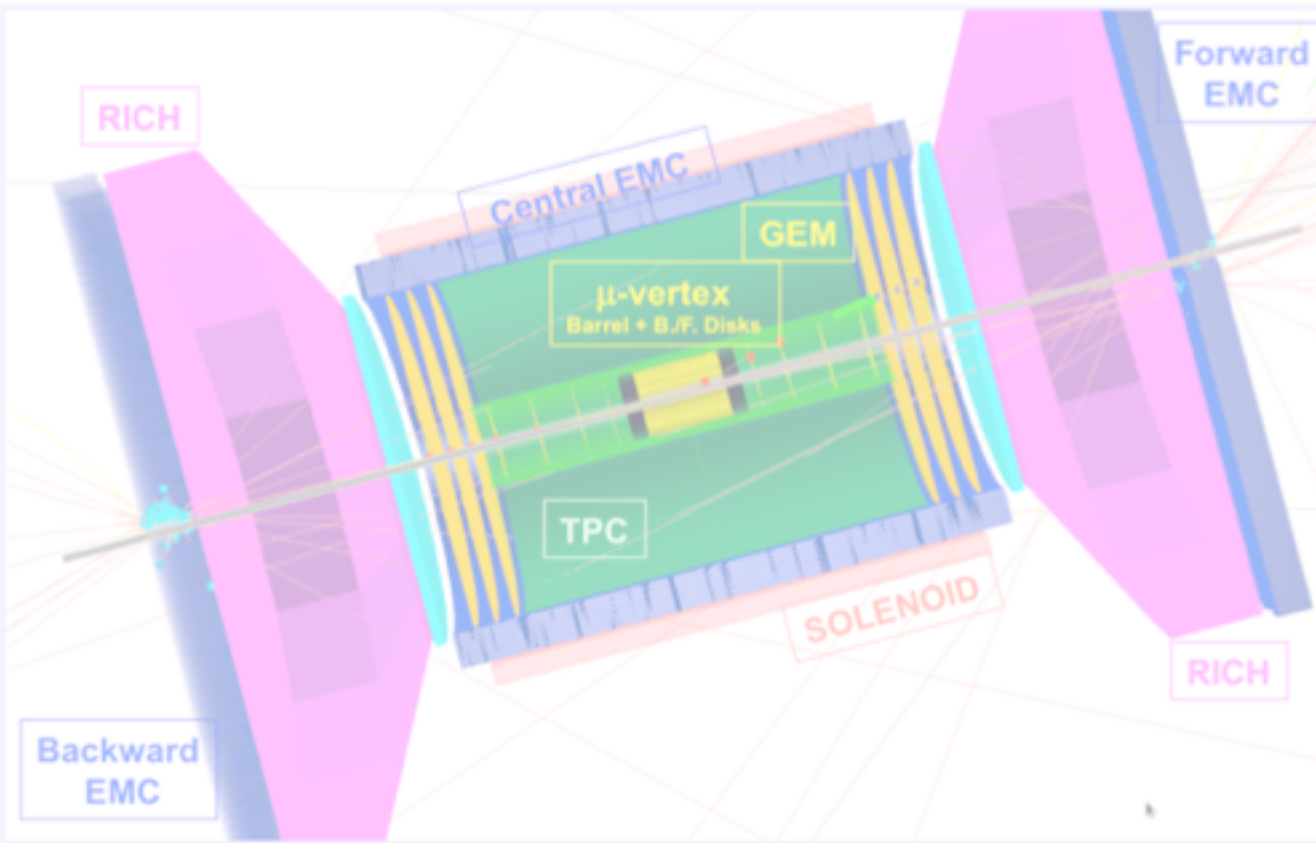
Optimized Detector



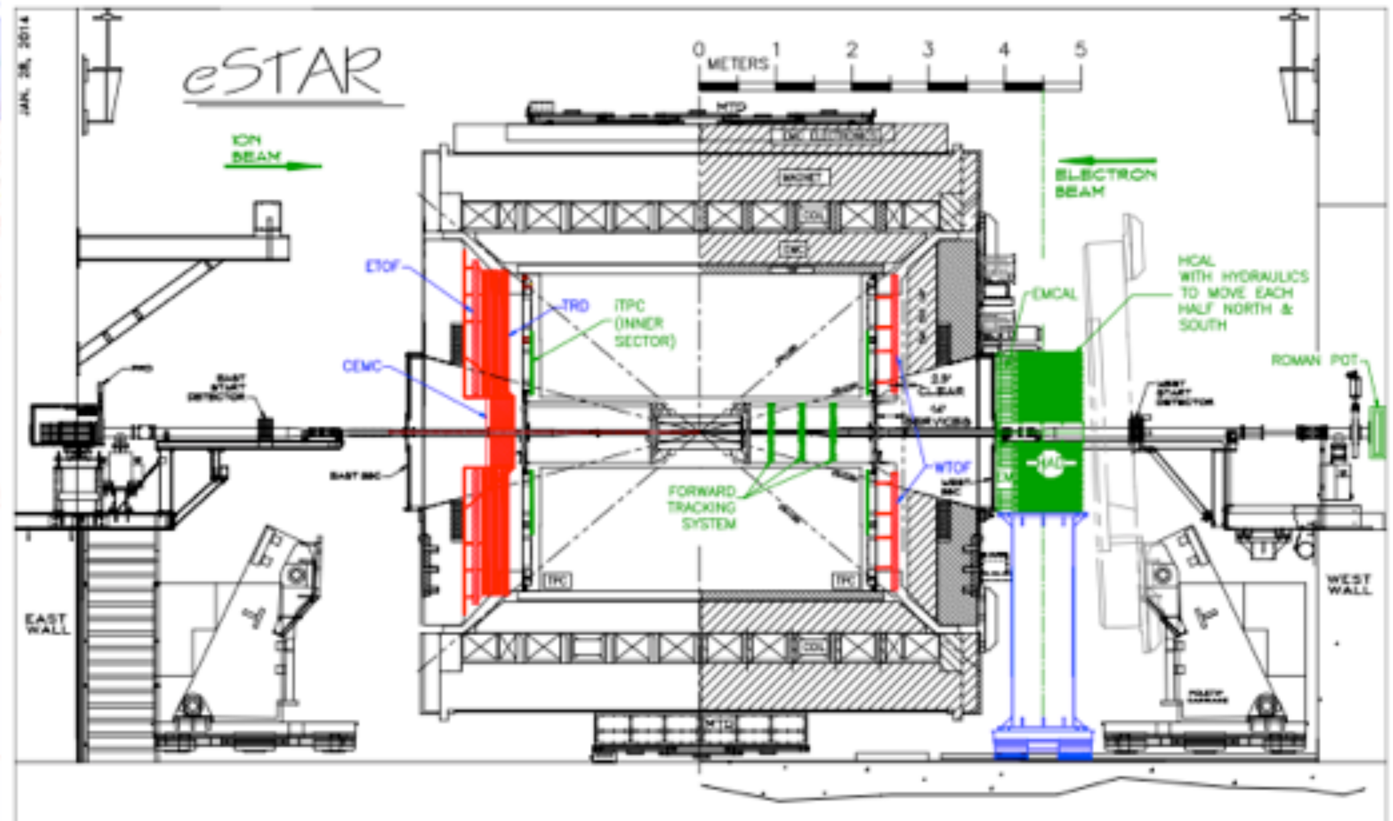
ePHENIX

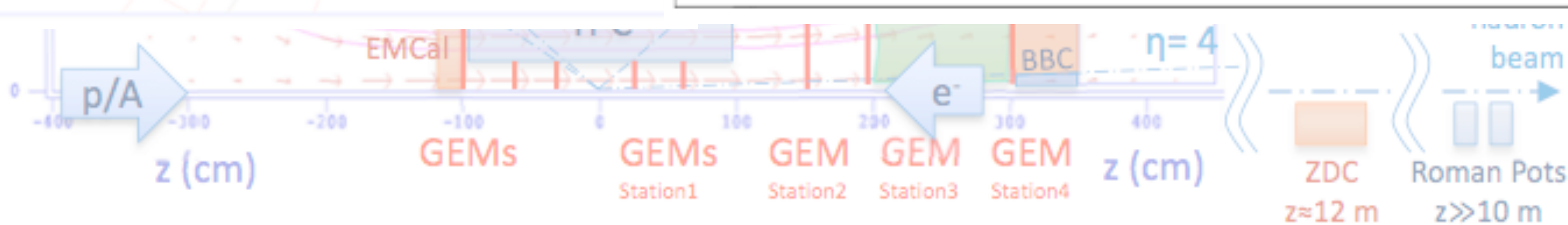
eRHIC - Detector Concepts

Optimized Detector



eSTAR





ePHENIX

eRHIC - Detector Concepts

Optimized Detector

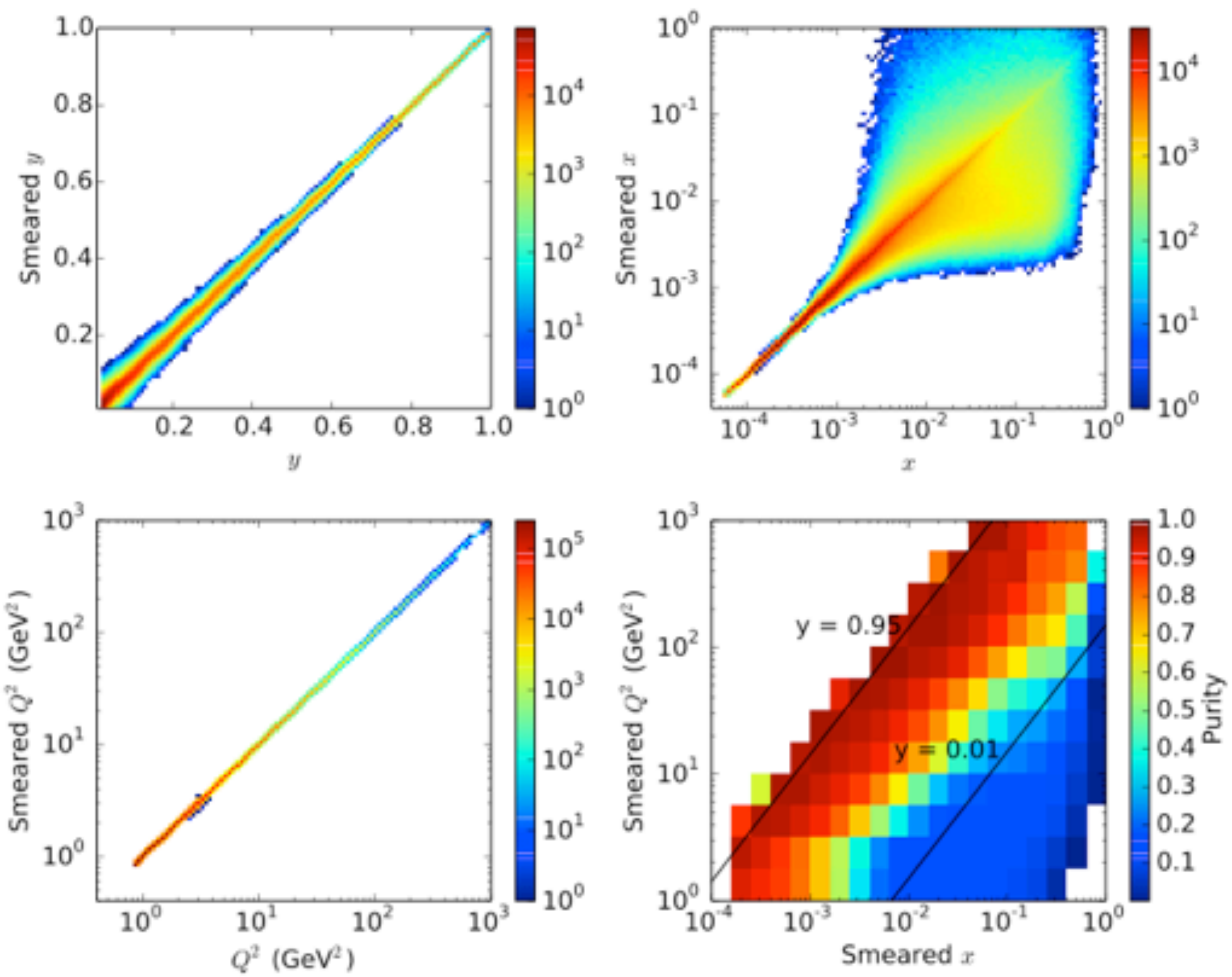
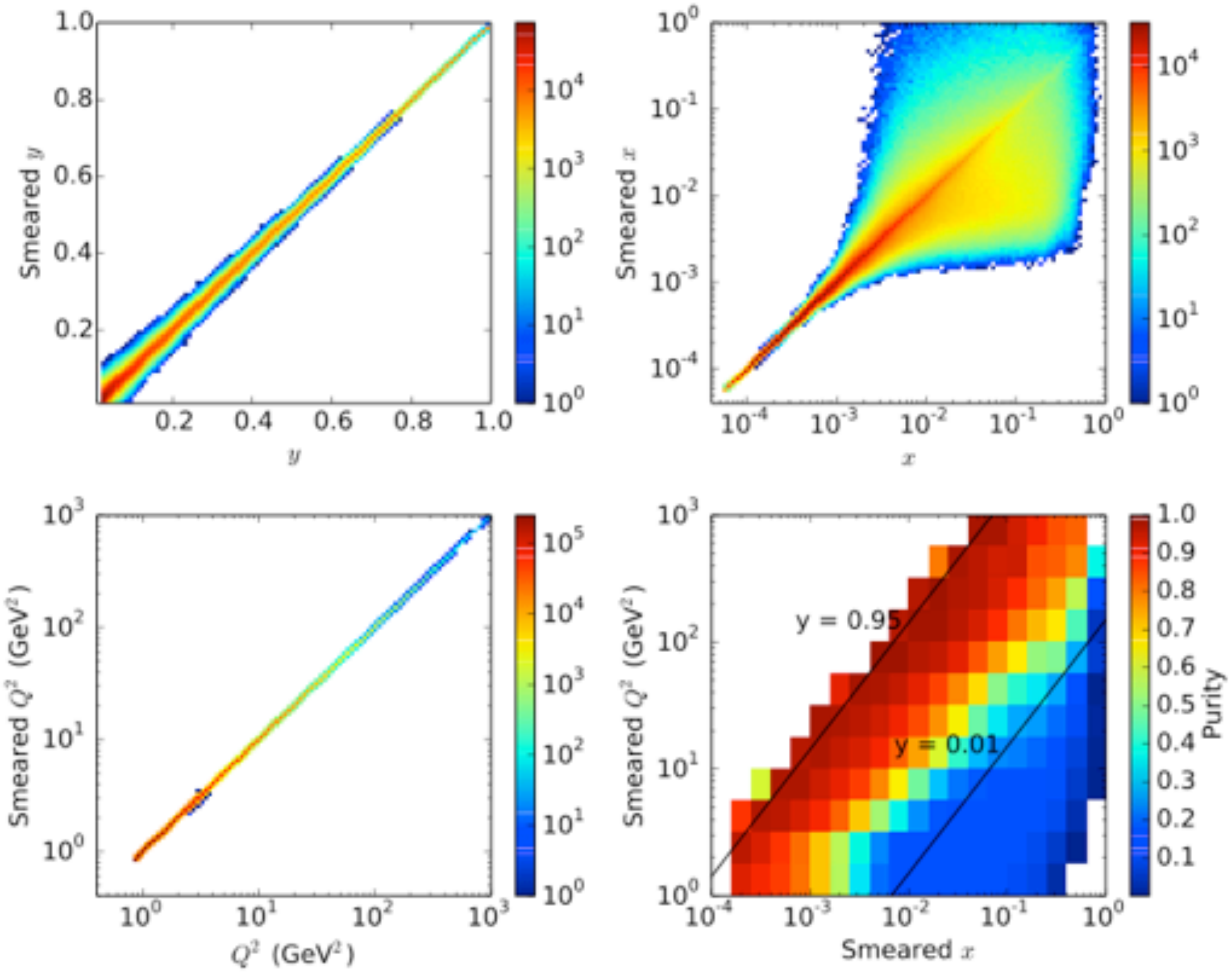


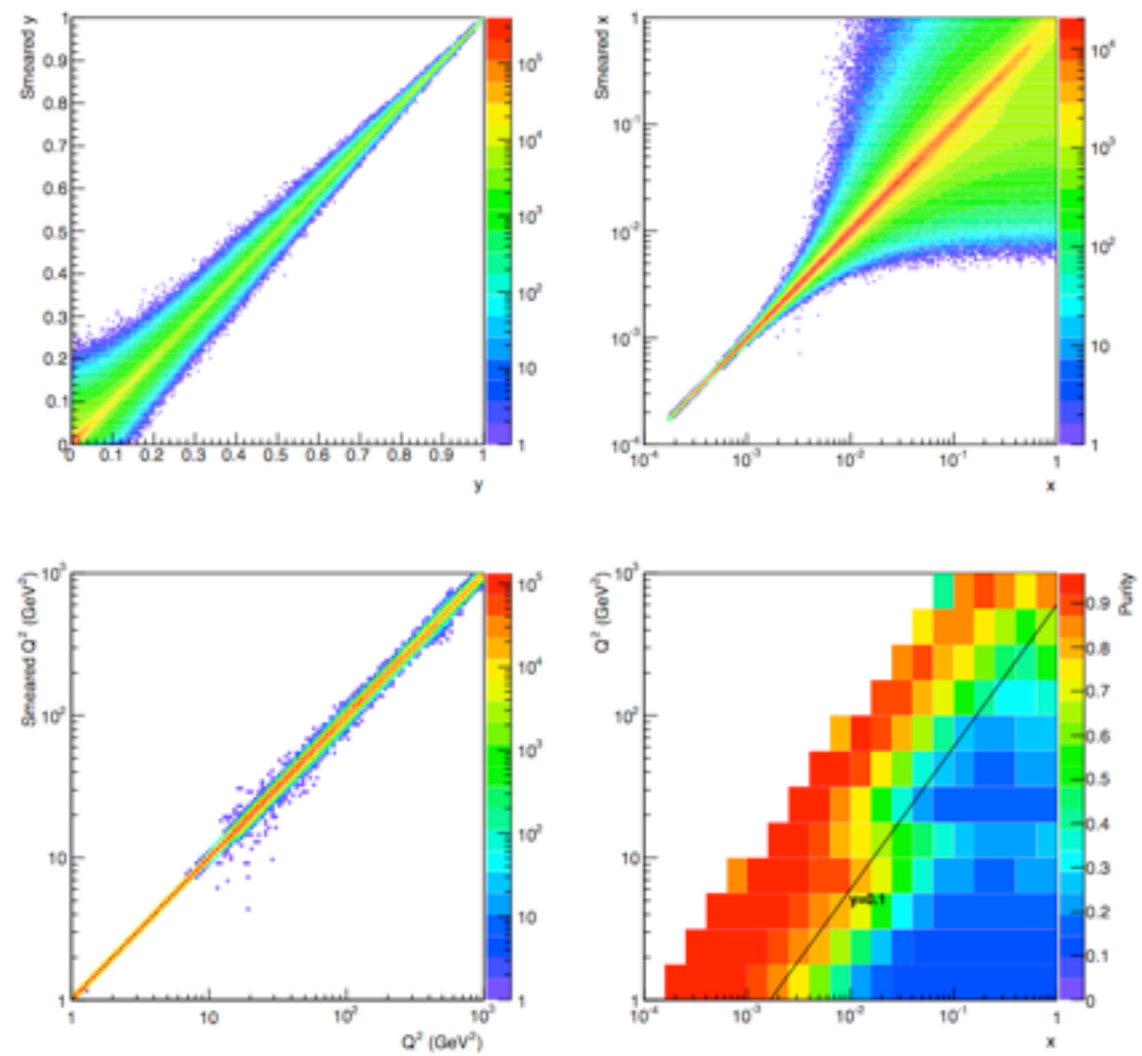
Figure 4-9: The correlation between smeared and true *y*, *x* and Q^2 (top to bottom left), and the resulting bin-by-bin event purity in the x-Q^2 plane (bottom right), reconstructed using the electron method. Purity is defined as (Ngen - Nout) / (Ngen - Nout + Nin), where Ngen, out, in are the number of events generated in a bin, smeared out of it, and smeared into it from other bins, respectively.

eRHIC - Detector Concepts

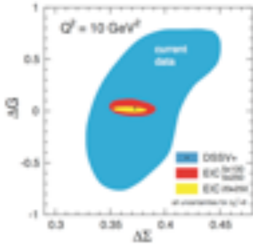
Optimized Detector



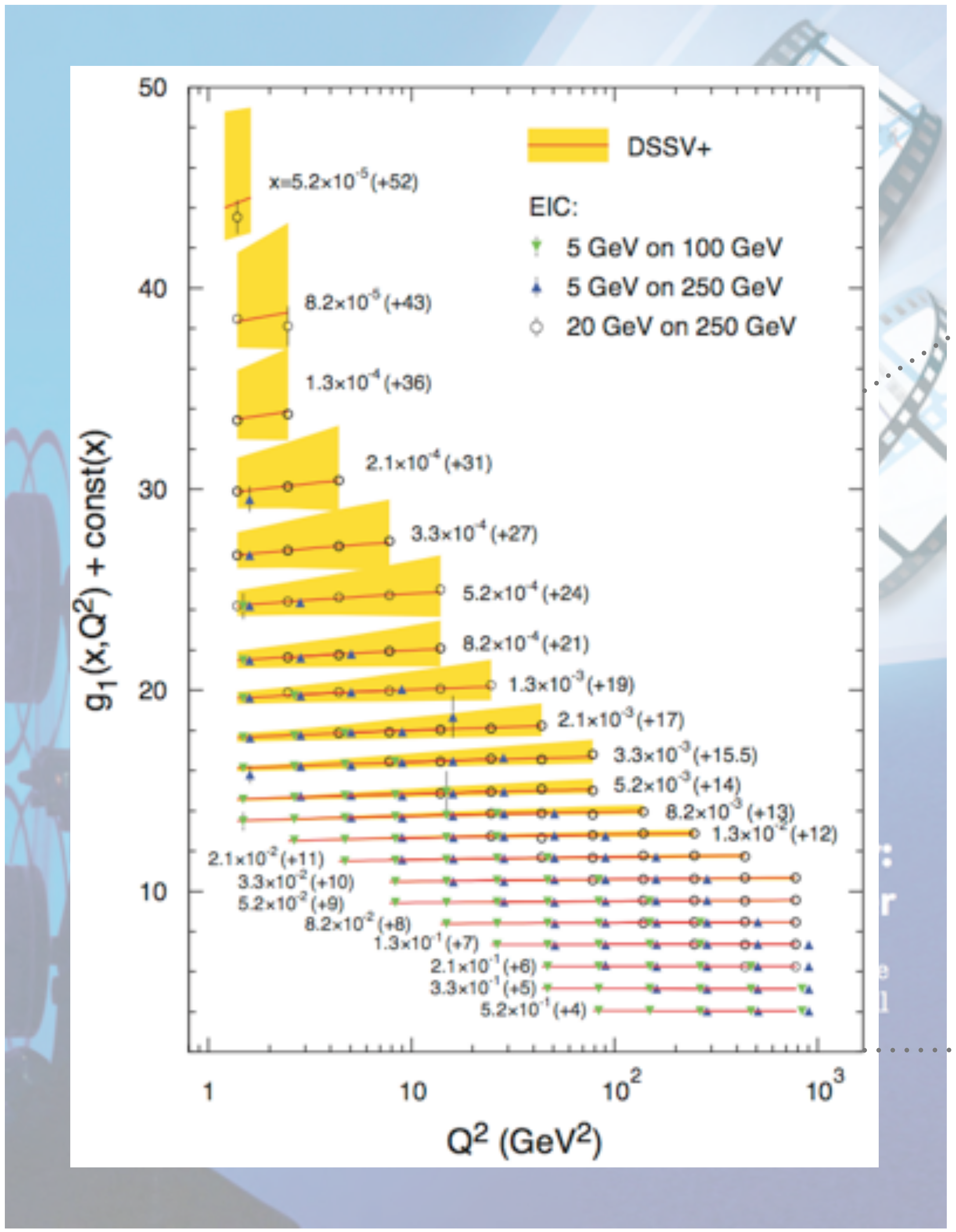
eSTAR

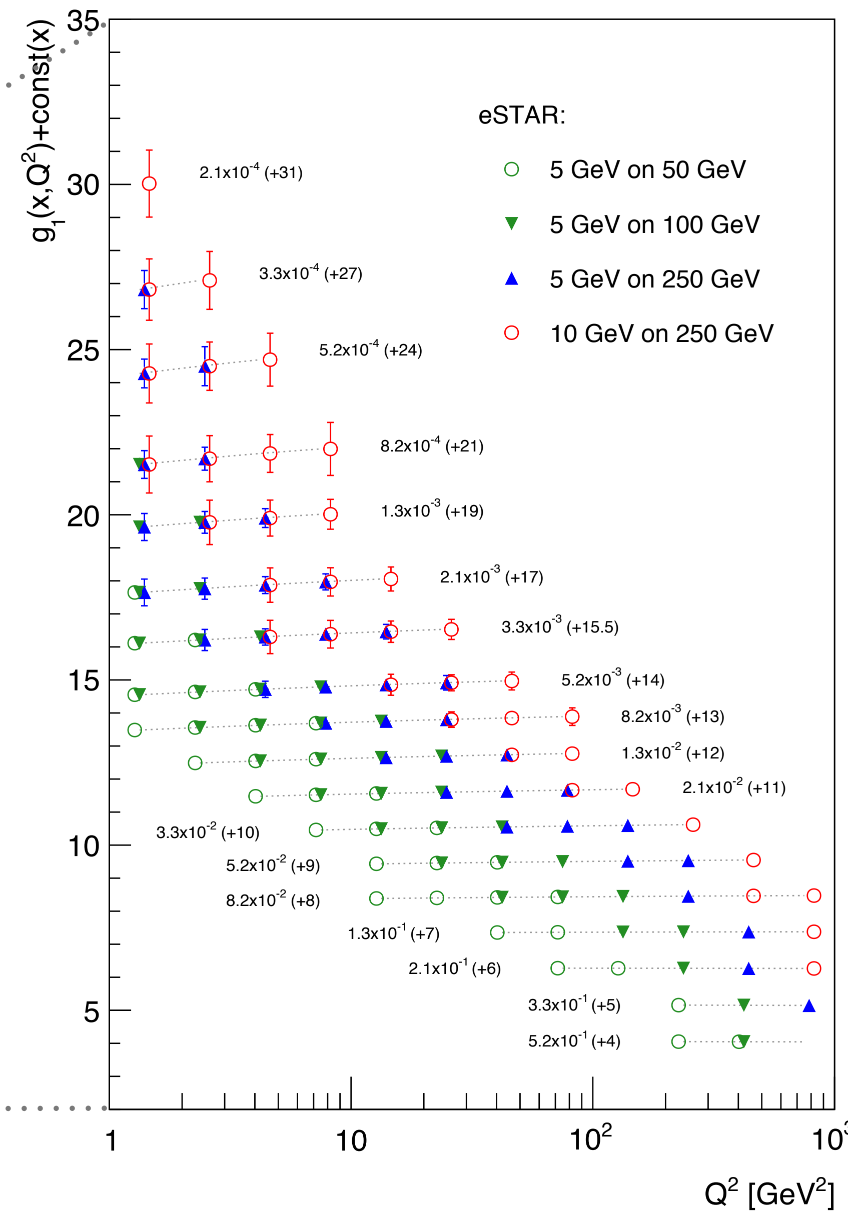


eRHIC - Inclusive Measurement Capabilities



Full eRHIC, dedicated detector → Initial stage eRHIC, eSTAR





Significant measurement capability for the unpolarized and polarized inclusive structure functions.

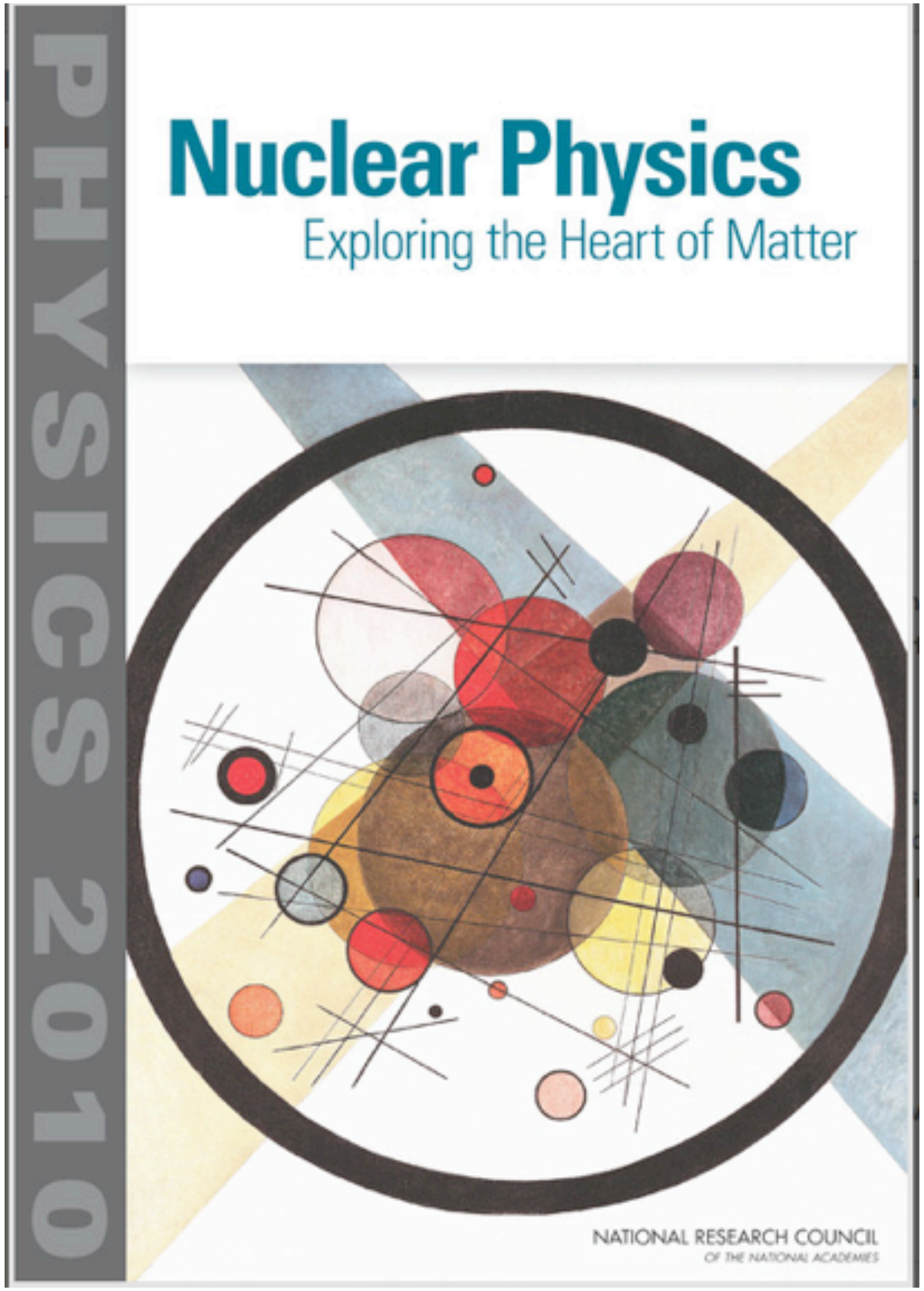
Page 236 - Recommendations,
Building a Foundation for the Future:

Without gluons, there would be no neutrons or protons and no atomic nuclei. Gluon properties in matter remain largely unexplored and mysterious.

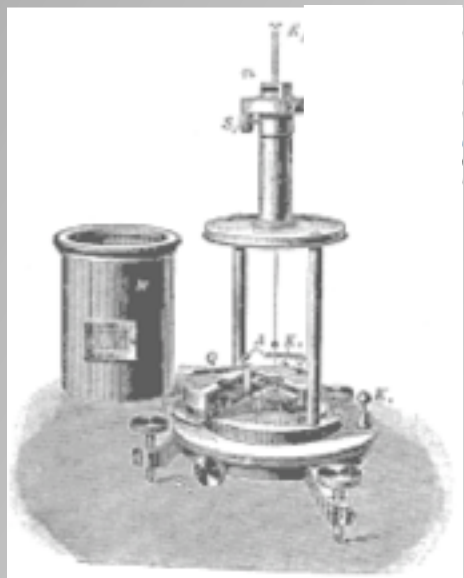
Finding: An upgrade to an existing accelerator facility that enables the colliding of nuclei and electrons at forefront energies would be unique for studying new aspects of quantum chromodynamics. In particular, such an upgrade would yield new information on the role of gluons in protons and nuclei. An electron-ion collider is currently under scrutiny as a possible future facility.

Recommendation: Investment in accelerator and detector research and development for an electron-ion collider should continue. The science opportunities and the requirements for such a facility should be carefully evaluated in the next Nuclear Science Long Range Plan.

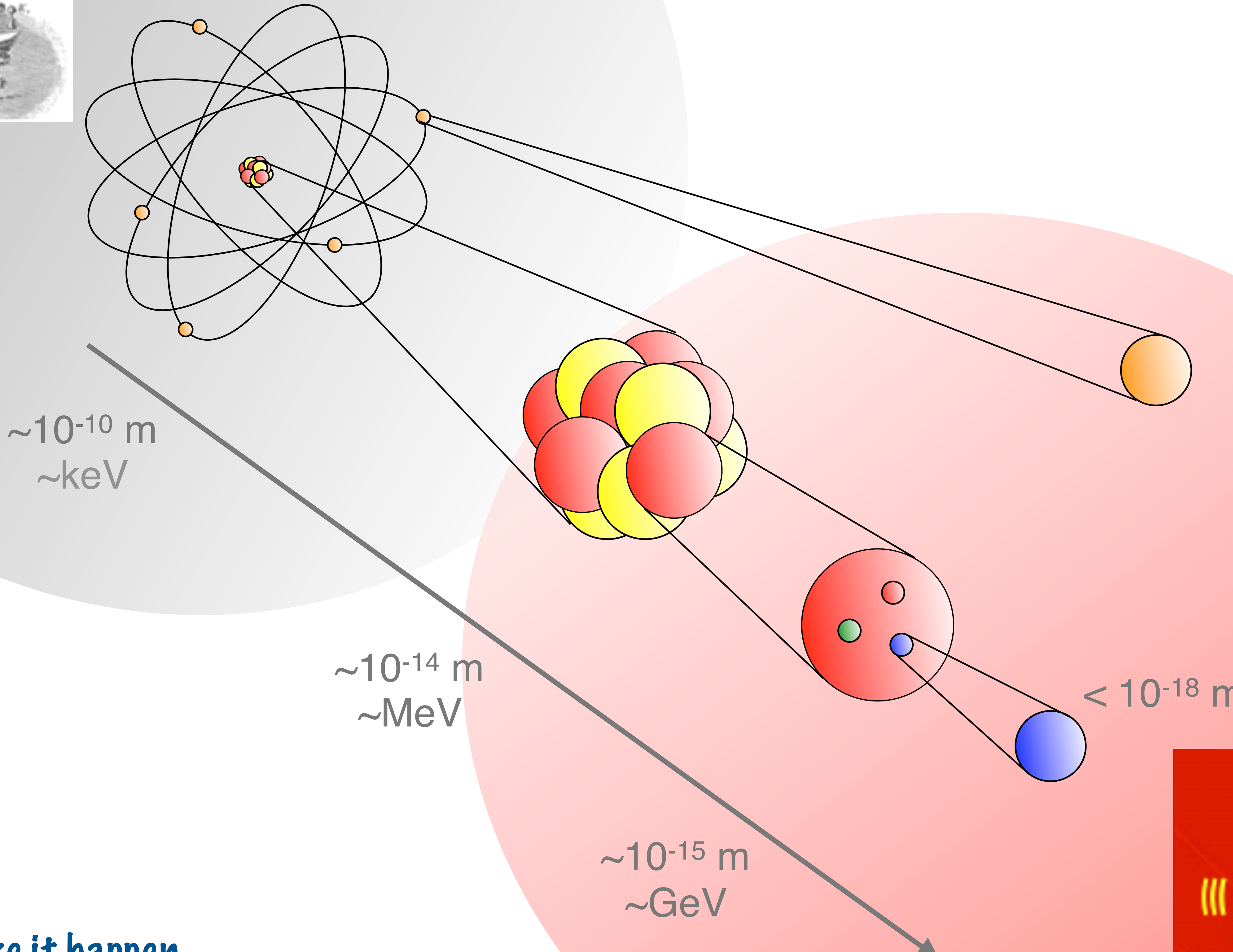
No other facility finding or recommendation.



National Research Council. *Nuclear Physics: Exploring the Heart of Matter*. Washington, DC: The National Academies Press, 2013.



The future for experimental QCD can be broad and bright.



Let's make it happen.