Exploring the fundamental properties of matter with an Electron-Ion Collider

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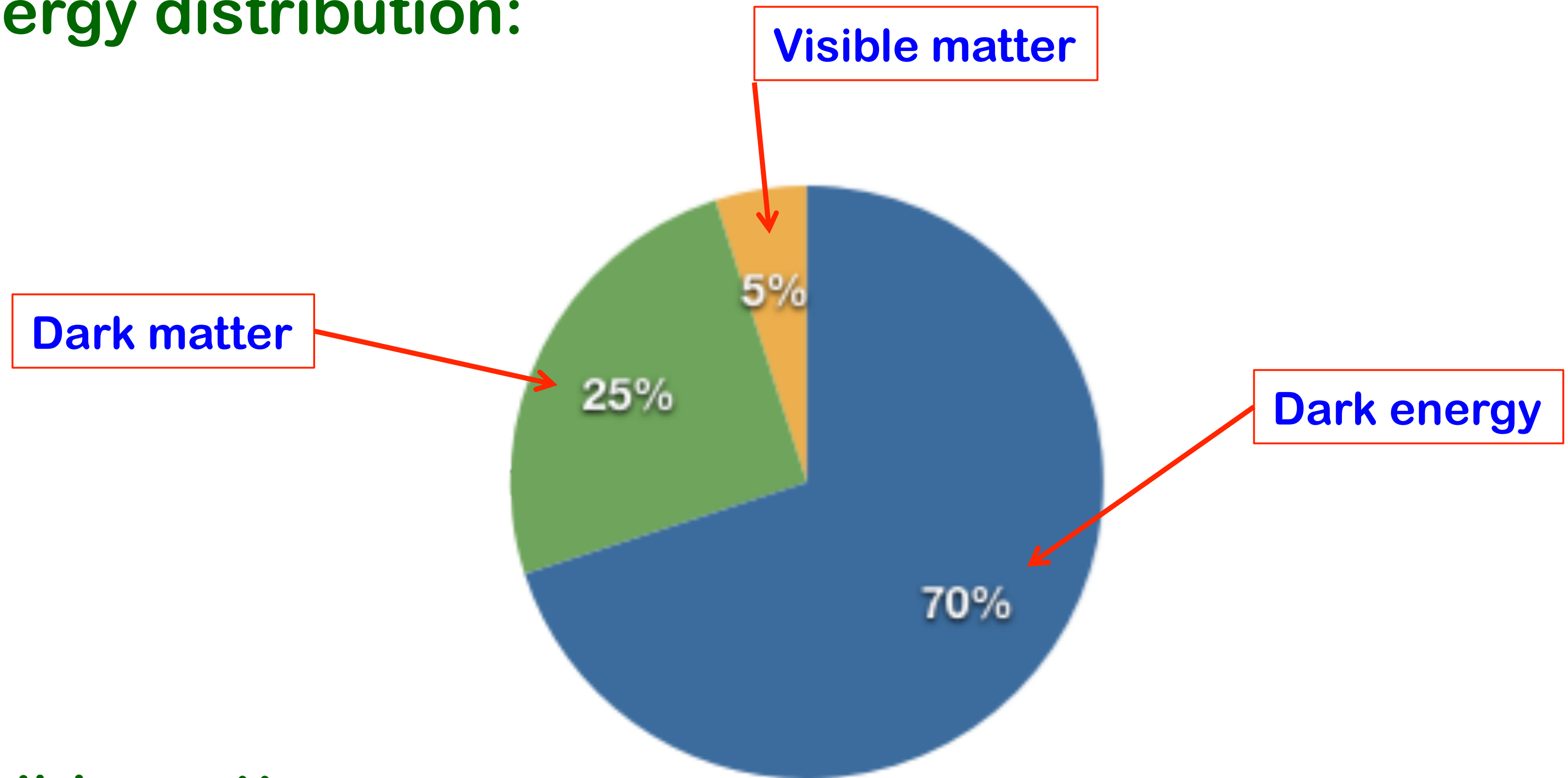
Outline of my talk

- Hadrons – the visible matter in our universe
- Why we believe QCD and its quarks and gluons?
- New frontier of QCD dynamics – probed by an EIC:
  - Hadron properties in QCD – confinement?
  - Direct QCD quantum interference – A_N
  - Saturation of glue at high energy – mass scale?
  - ----
- Summary

Matter in our universe

❑ Energy distribution:



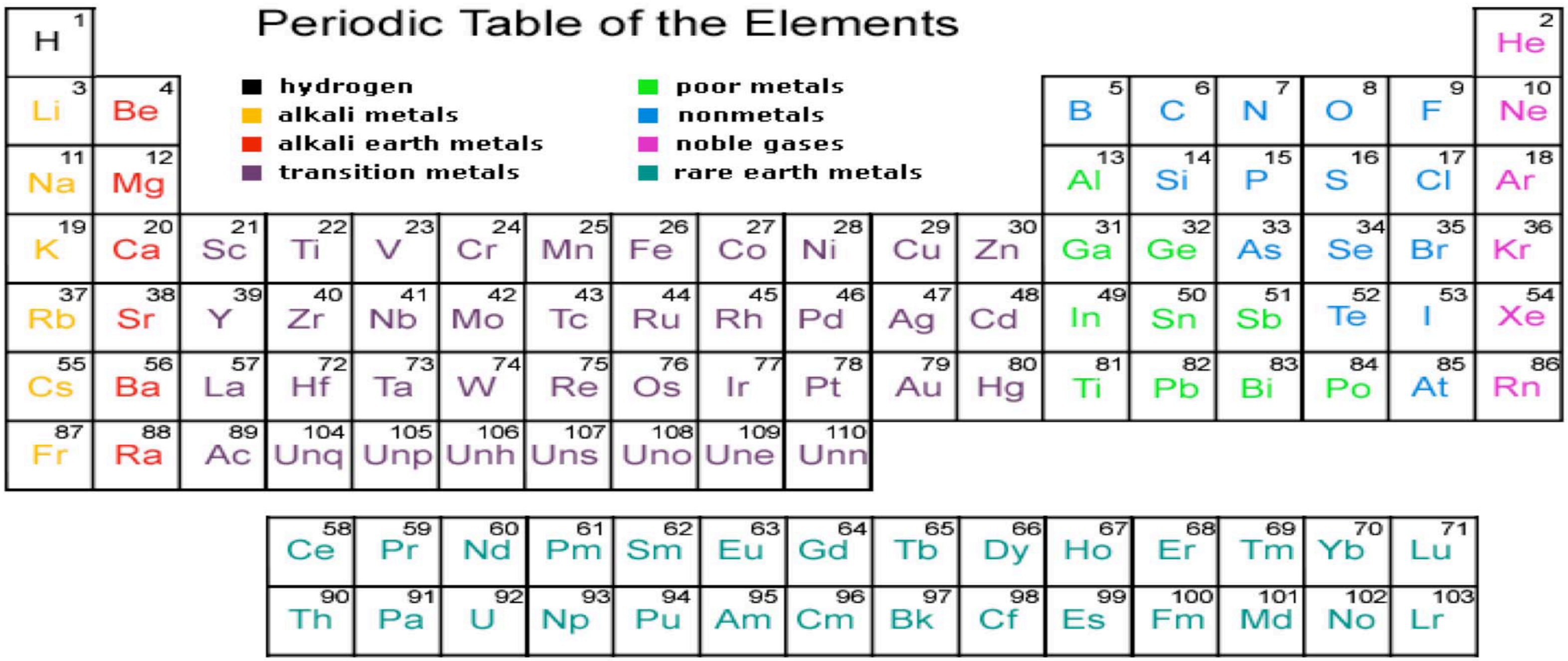
❑ Visible matter:

✧ It is the most important to our life – it is what we are made of although it makes up only 5% energy of our universe

✧ More than 95% mass of all visible matter is made up of protons and neutrons – the hadrons

Hadronic matters

- Proton and neutron are building blocks of all elements:



- But, themselves are not elementary:

Magnetic moment: $\mu = g\left(Q\frac{e}{2m}\right)$ $\quad g_p = 2.792 \neq 2 \quad g_n = -1.913 \neq 0$

We believe: proton and neutron are made of quarks and gluons of QCD!

Challenge: understand the hadron properties, mass, spin,… in terms of the properties and dynamics of quarks and gluons of QCD!

Quantum Chromodynamics (QCD)

= A quantum field theory of quarks and gluons =

❑ Fields:

$\psi_i^f(x)$

Quark fields: spin-½ Dirac fermion (like electron)
Color triplet: $i = 1, 2, 3 = N_c$
Flavor: $f = u, d, s, c, b, t$

$A_{\mu,a}(x)$

Gluon fields: spin-1 vector field (like photon)
Color octet: $a = 1, 2, ..., 8 = N_c^2 - 1$

❑ QCD Lagrangian density:

$$\mathcal{L}_{QCD}(\psi, A) = \sum_f \overline{\psi}_i^f \left[(i\partial_\mu \delta_{ij} - gA_{\mu,a}(t_a)_{ij})\gamma^\mu - m_f \delta_{ij} \right] \psi_j^f$$
$$- \frac{1}{4} \left[\partial_\mu A_{\nu,a} - \partial_\nu A_{\mu,a} - gC_{abc}A_{\mu,b}A_{\nu,c} \right]^2$$
$$+ \text{gauge fixing} + \text{ghost terms}$$

❑ QED Lagrangian density – most successful QFT:

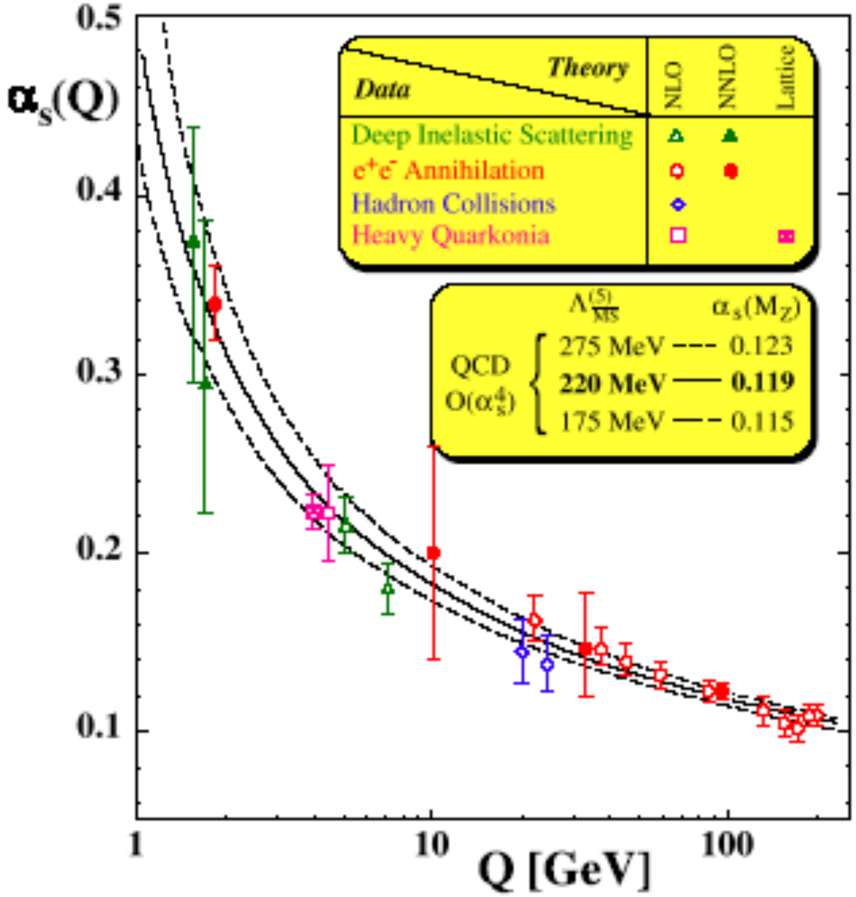
$$\mathcal{L}_{QED}(\phi, A) = \sum_f \overline{\psi}^f \left[(i\partial_\mu - eA_\mu)\gamma^\mu - m_f \right] \psi^f - \frac{1}{4} \left[\partial_\mu A_\nu - \partial_\nu A_\mu \right]^2$$

✧ **QCD is much richer in dynamics than QED, but no free quarks and gluons**

✧ **Why should we believe the existence of quarks, gluons, and QCD?**

QCD in asymptotic regime

- **QCD asymptotic freedom:** $\alpha_s(\mu_2) = \dfrac{\alpha_s(\mu_1)}{1 - \frac{\beta_1}{4\pi}\alpha_s(\mu_1)\ln\left(\frac{\mu_2^2}{\mu_1^2}\right)} \equiv \dfrac{4\pi}{-\beta_1 \ln\left(\frac{\mu_2^2}{\Lambda_{QCD}^2}\right)}$



Asymptotic Freedom ⇔ antiscreening

QCD: $\dfrac{\partial \alpha_s(Q^2)}{\partial \ln Q^2} = \beta(\alpha_s) < 0$

Compare

QED: $\dfrac{\partial \alpha_{EM}(Q^2)}{\partial \ln Q^2} = \beta(\alpha_{EM}) > 0$

D.Gross, F.Willczek, Phys.Rev.Lett 30, (1973)
H.Politzer, Phys.Rev.Lett. 30, (1973)

2004 Nobel Prize in Physics

- **Hard probe – large momentum transfer:**
  - ✧ Short-distance partonic dynamics < 1/10 fm (~ 2 GeV)
  - ✧ Connecting partons to hadrons – QCD factorization

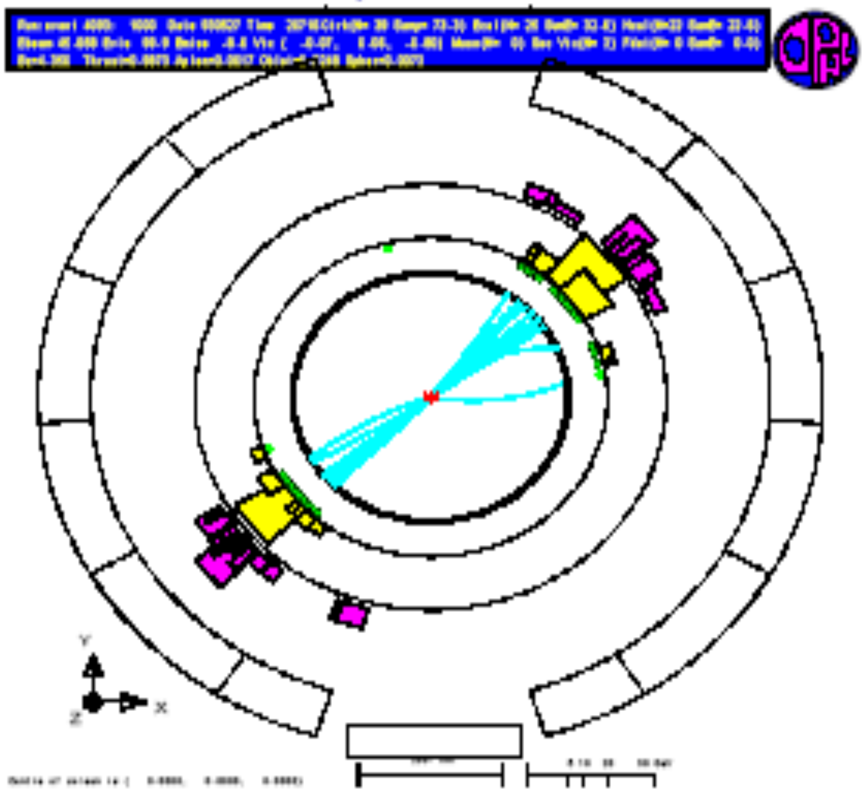
Question

Why should we believe QCD?

“See” the trace of quarks and gluons

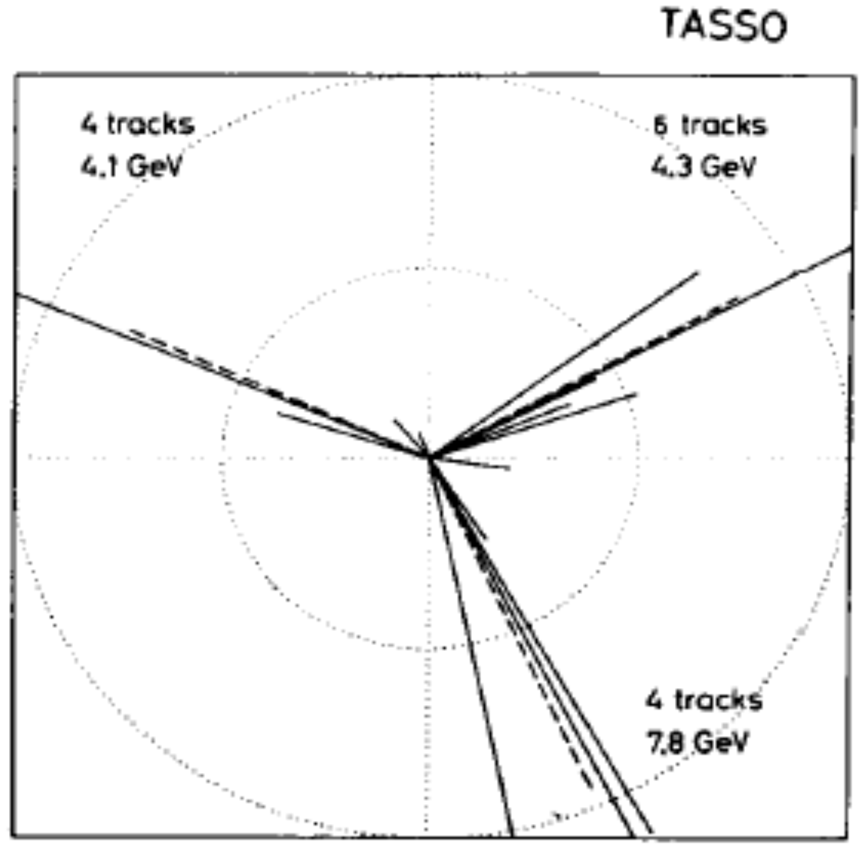
- Jets in e^+e^-:

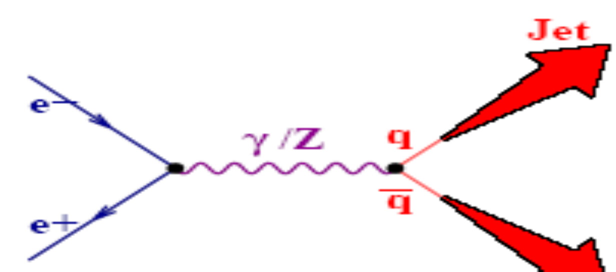
LEP ($\sqrt{s} = 90 - 205$ GeV)



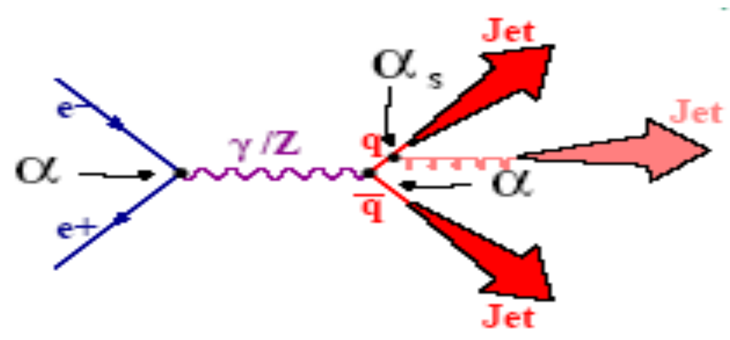
PETRA e^+e^- storage ring at DESY:

$E_{c.m.} \gtrsim 15$ GeV





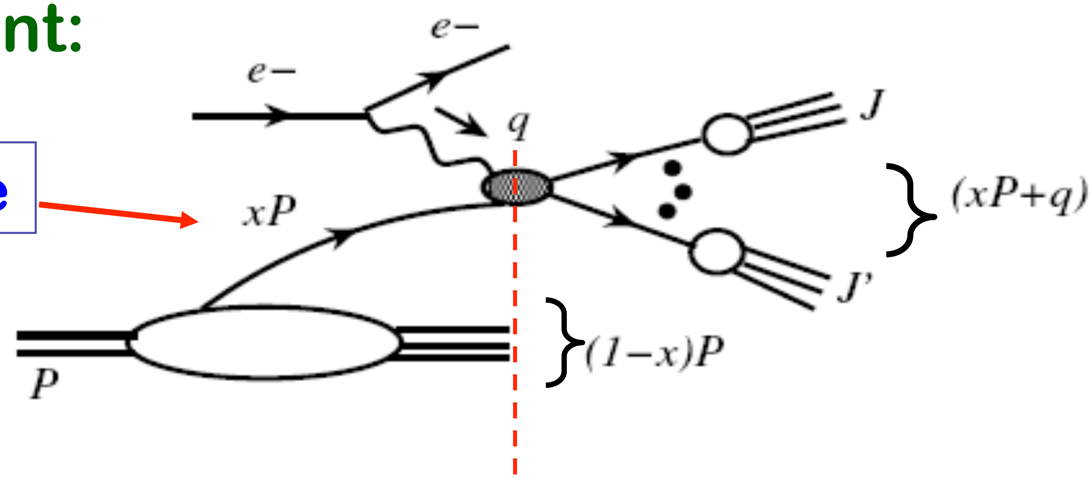
$e^+e^- \rightarrow$ jet + jet



"See" quarks and gluons inside a hadron

- "Rutherford" experiment:

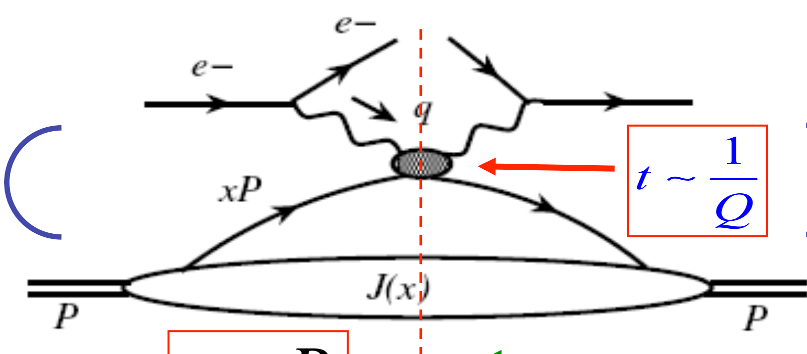
Long-lived parton state



Time: "Past" Now "Future"

- Unitarity – summing over all hard jets:

$$\sigma_{\rm tot}^{\rm DIS} \propto {\rm Im}\left(\right.$$



$$\left. \right)$$

$t \sim \frac{1}{Q}$

$t \sim R$

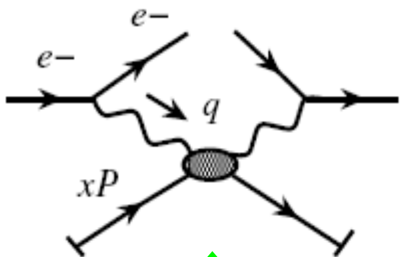
Not IR safe

Interaction between the "past" and "now" are suppressed!

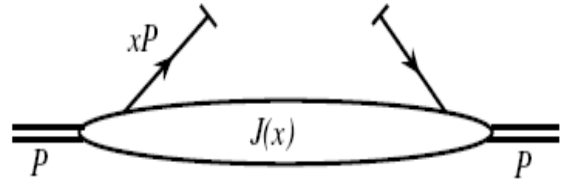
Connecting quark and gluon to hadrons

❑ One hadron:

$\sigma_{\text{tot}}^{\text{DIS}} \sim$



$\otimes$



$+ \, O\left(\frac{1}{QR}\right)$

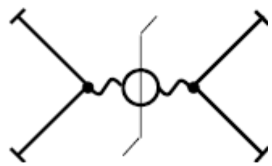
Now
Hard-part

Past
Parton-distribution

Connection
Power corrections

❑ Two hadrons:

$\sigma_{\text{tot}}^{\text{DY}} \sim$



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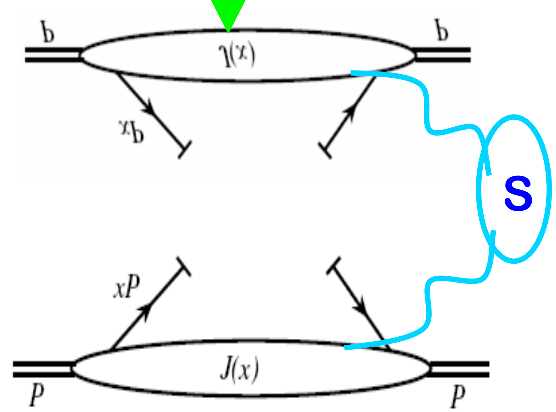


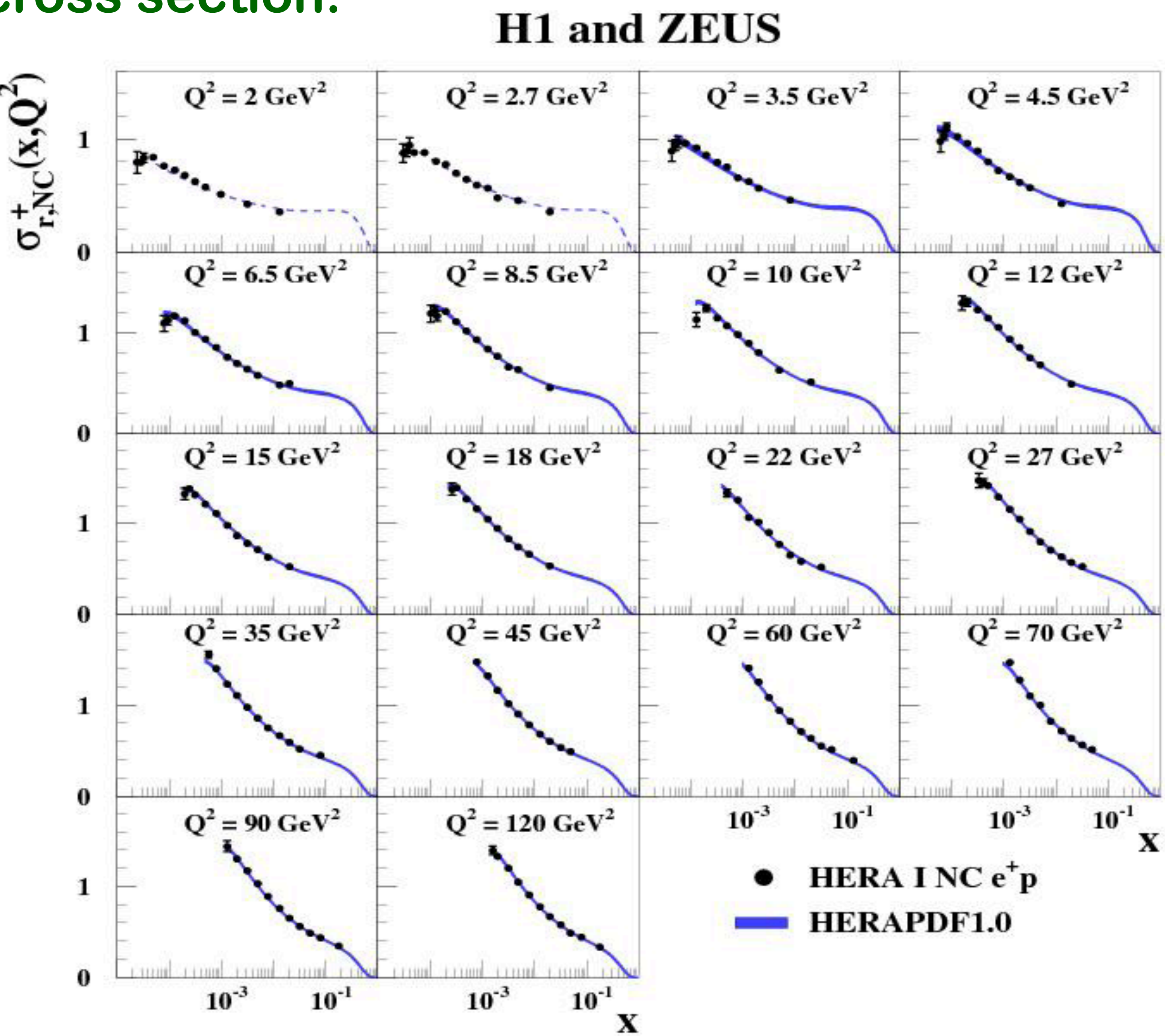
$+ \, O\left(\frac{1}{QR}\right)$

❑ Predictive power - factorization:

- ✧ Calculable short-distance partonic dynamics
- ✧ Universality of long-distance distribution functions

From HERA – single hadron

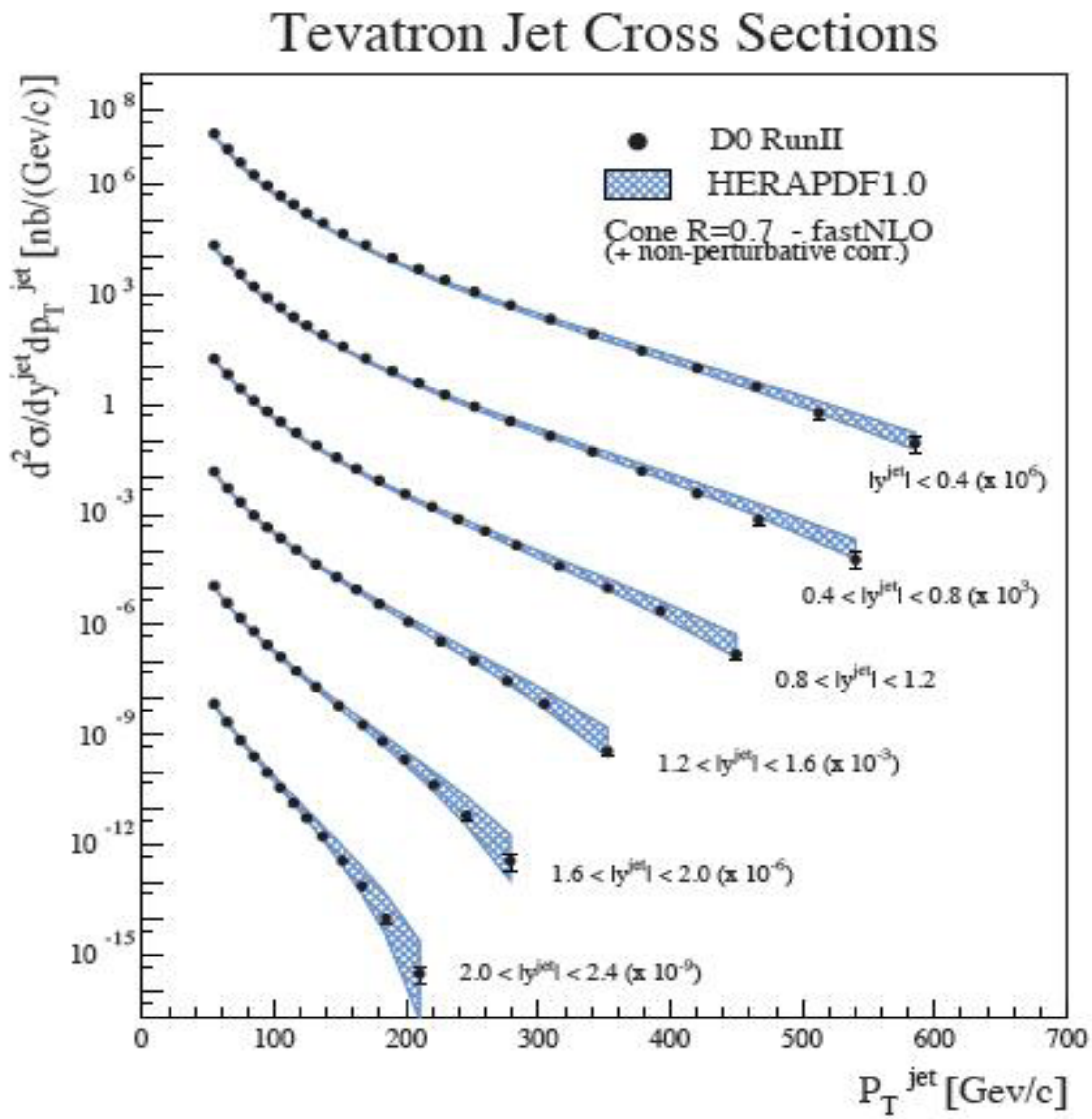
- DIS cross section:

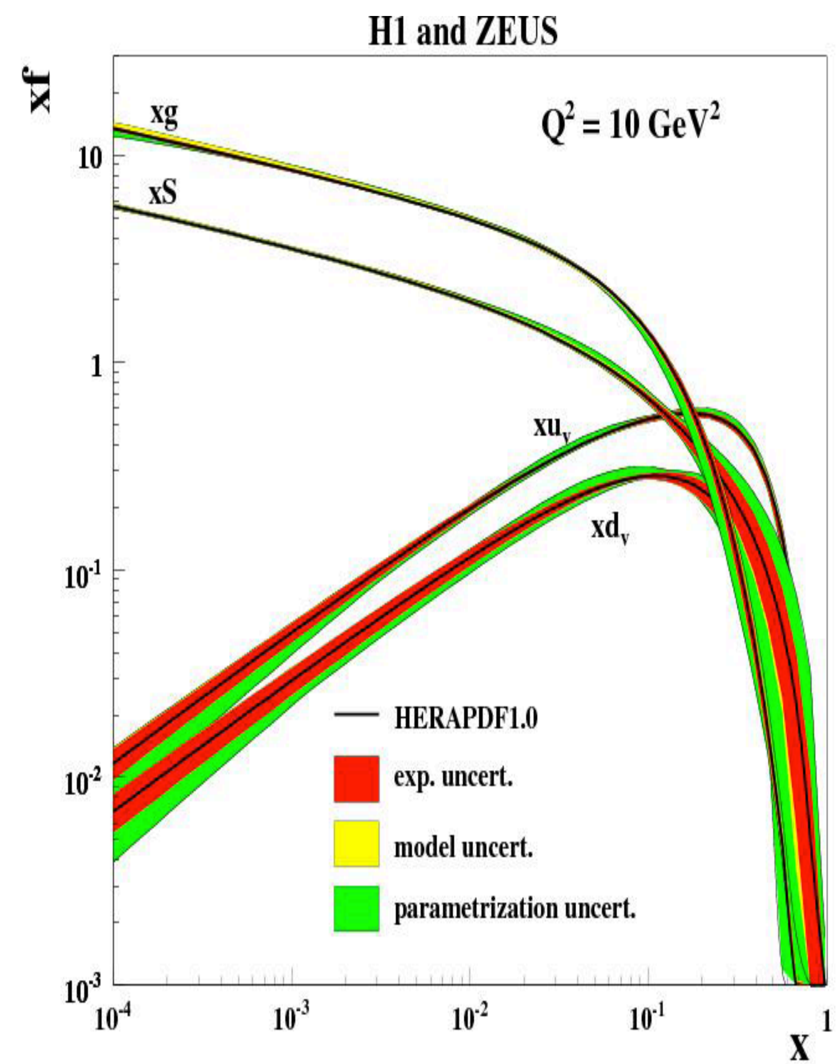


To Tevatron – multiple hadrons

- **Jet cross section:**

With one set universal PDFs





QCD is successful in last 30 years – we now believe it

Are there anything left to do in QCD?

- QCD is "right" – no longer interesting or challenging:

  became the background for the search of new physics beyond SM

  no more discovery or "Nobel prize" level work left?

- QCD is only tested in the most trivial regime of its dynamics!

  the asymptotic regime: < 1/10 fm (~ 2 GeV)

  Leading power dynamics from single parton scattering

- New measurements and new questions:

  Hints in disagreement when extrapolating to Q < 1 GeV,

  Multi-parton dynamics when s >> Q^2 – the unitarity limit?,

  Novel and puzzling phenomena with spin, nuclei, …

  Thermodynamics, hydrodynamics, and CMP of color forces, …

How many Nobel Prizes have been awarded to CMP after QED?

Challenges for QCD in next 30 years

- **Hadron properties – the origin of the visible matter:**

  in terms of the properties of quarks and gluons, and its dynamics

  Mass: the role of glue – $m_q \ll m_N \ll Q$ – energy exchange,

  Spin: could be the first complete example for QCD to describe, ...

- **QCD bound states – color confinement?**

  QED: nucleons is so much heavier than electron – localized charge

  QCD: heavy quarkonium – localized color source – but, unstable

  proton and neutron – no localized color source – but, stable

  Probe the spatial distribution of parton/color?

- **QCD in extreme conditions:**

  Multi-particle dynamics, saturation ($s \gg Q^2$), sQGP, phase transition, ...

An EIC with polarization could meet some of these challenges

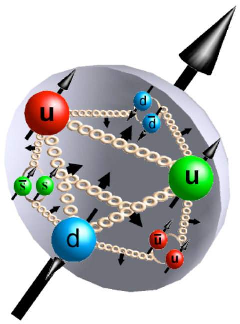
Proton spin

❑ Spin of an elementary particle:

An intrinsic quantum property of the particle

❑ Spin of a composite particle:

Angular momentum when the particle is at rest



Elementary particles' spin

(intrinsic quantum effect)

+

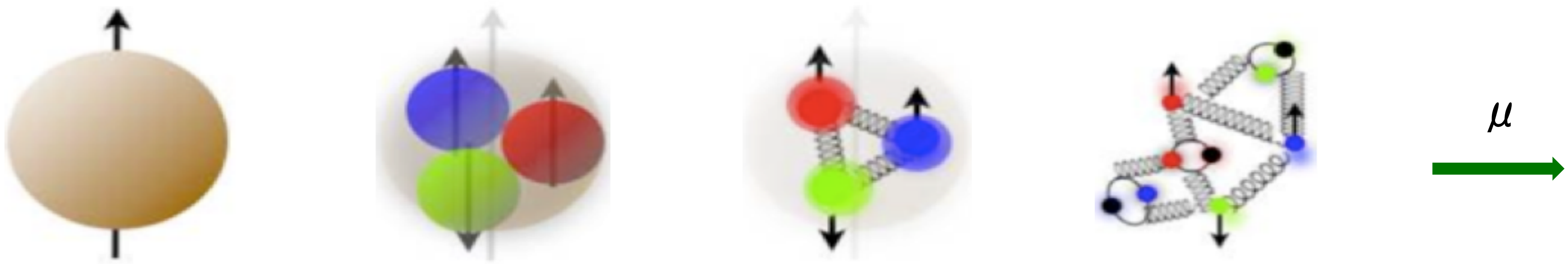
Motion of the particles

(dynamical – fundamental interaction)

Proton spin

❑ in QCD – complexity of the proton state:

$$S(\mu) = \sum_f \langle P,S|\hat{J}^z_f(\mu)|P,S\rangle = \frac{1}{2} \equiv J_q(\mu) + J_g(\mu) = \frac{1}{2}\Sigma(\mu) + L_q(\mu) + J_g(\mu)$$



❑ in Qaurk Model: $S_p \equiv \langle p\uparrow|S|p\uparrow\rangle = \frac{1}{2}, \quad S = \sum_i S_i$

$$|p\uparrow\rangle = \sqrt{\frac{1}{18}}\left[u\uparrow u\downarrow d\uparrow + u\downarrow u\uparrow d\uparrow - 2u\uparrow u\uparrow d\downarrow + \text{perm.}\right]$$

❑ Asymptotic limit:

Ji, 2005

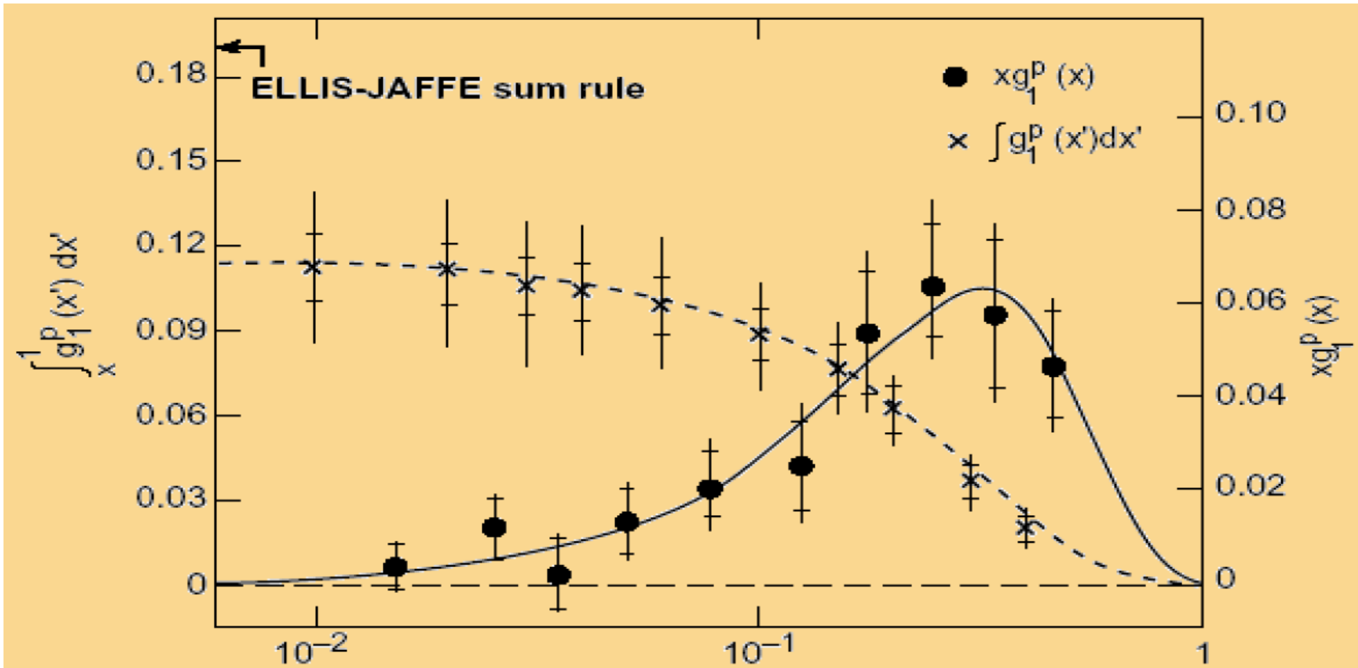
$$J_q(\mu\to\infty) \Rightarrow \frac{1}{2}\frac{3N_f}{16+3N_f} \sim \frac{1}{4} \qquad J_g(\mu\to\infty) \Rightarrow \frac{1}{2}\frac{16}{16+3N_f} \sim \frac{1}{4}$$

❑ Proton spin structure:

Role of the intrinsic parton's spin vs. the dynamical parton's motion

The role of quark's spin

- **EMC experiment in 1988/1989 – "the plot":**



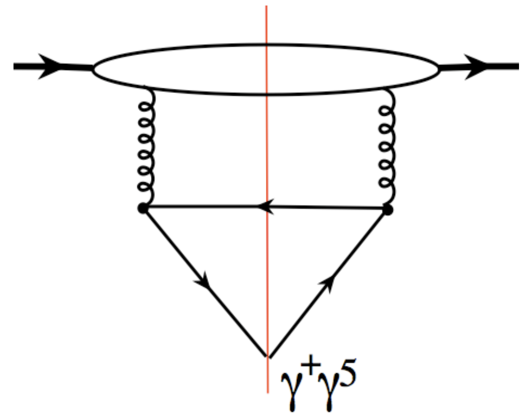
$$g_1(x) = \frac{1}{2}\sum_q e_q^2\,[\Delta q(x) + \Delta\bar{q}(x)] + \mathcal{O}(\alpha_s) + \mathcal{O}(1/Q)$$

$$\Delta q = \int_0^1 dx \Delta q(x) = \langle P, s_\parallel|\overline{\psi}_q(0)\gamma^+\gamma_5\psi_q(0)|P, s_\parallel\rangle$$

- **"Spin crisis" or puzzle:** $\Delta\Sigma = \sum_q [\Delta q + \Delta\bar{q}] = 0.12 \pm 0.17$

Early "solution" to the "crisis"

- **Large ΔG to cancel the "true" Δq:**



$$\Delta q = \int_0^1 dx \Delta q(x) = \langle P, s_\parallel | \overline{\psi}_q(0) \gamma^+ \gamma_5 \psi_q(0) | P, s_\parallel \rangle$$

$$\Delta\Sigma \rightarrow \Delta\Sigma - \frac{n_f \alpha_s(Q^2)}{2\pi} \Delta G(Q^2)$$

Need $\Delta G(Q^2) \sim 2$ **at Q ~ 1 GeV**

- **Role of gluon's spin:**

$$J_g(\mu^2 \rightarrow \infty) \rightarrow \frac{1}{2} \frac{16}{16 + 3N_f} \sim \frac{1}{4}$$

It is not a large number!

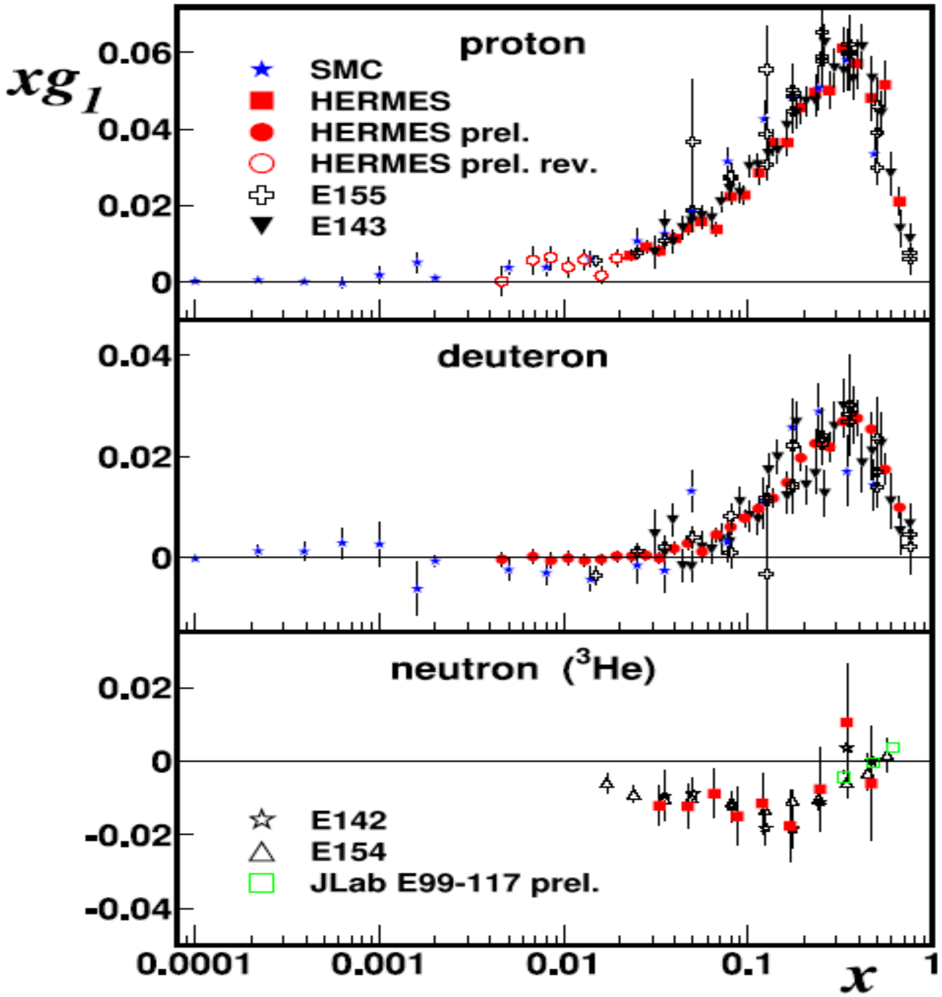
Need a large negative gluon orbital angular momentum if ΔG ~ 2?

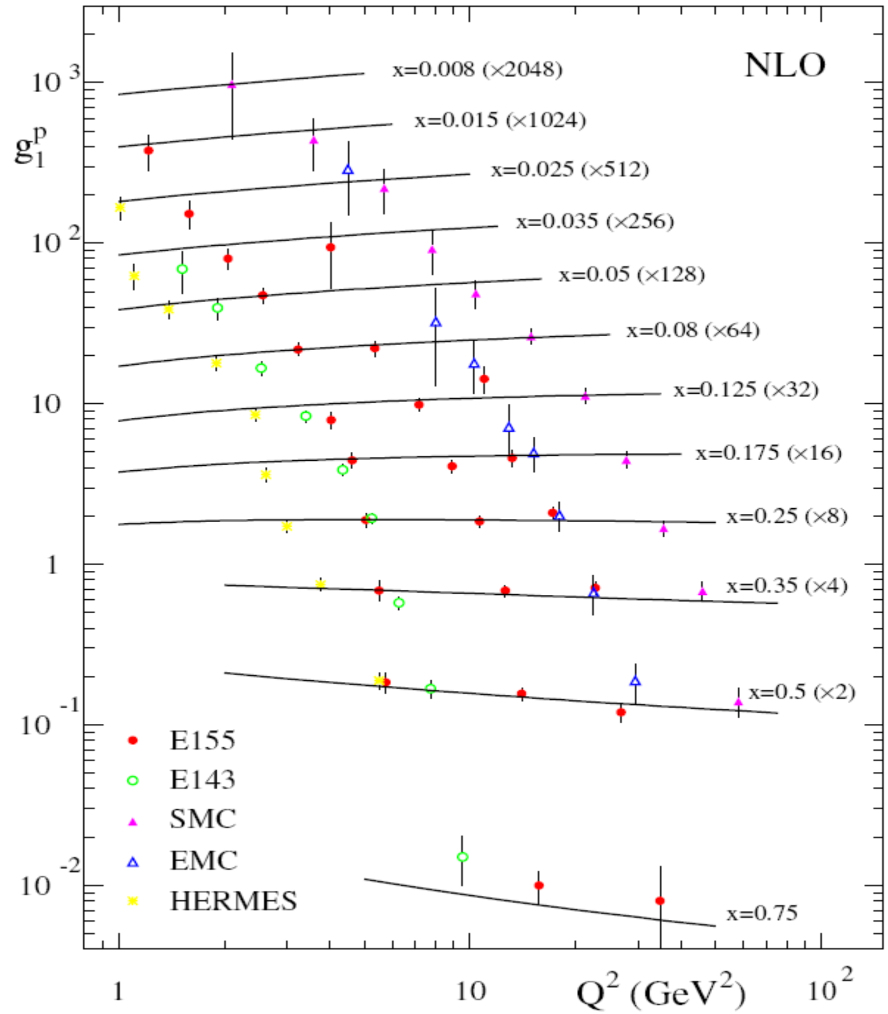
- **Question: How to measure ΔG independently?**

  - ✧ **Precision inclusive DIS**
  - ✧ **Jets in SIDIS**
  - ✧ **Hadronic collisions – RHIC spin**
  - ✧ **…**

Polarized inclusive DIS

- The "Plot" is now much improved:



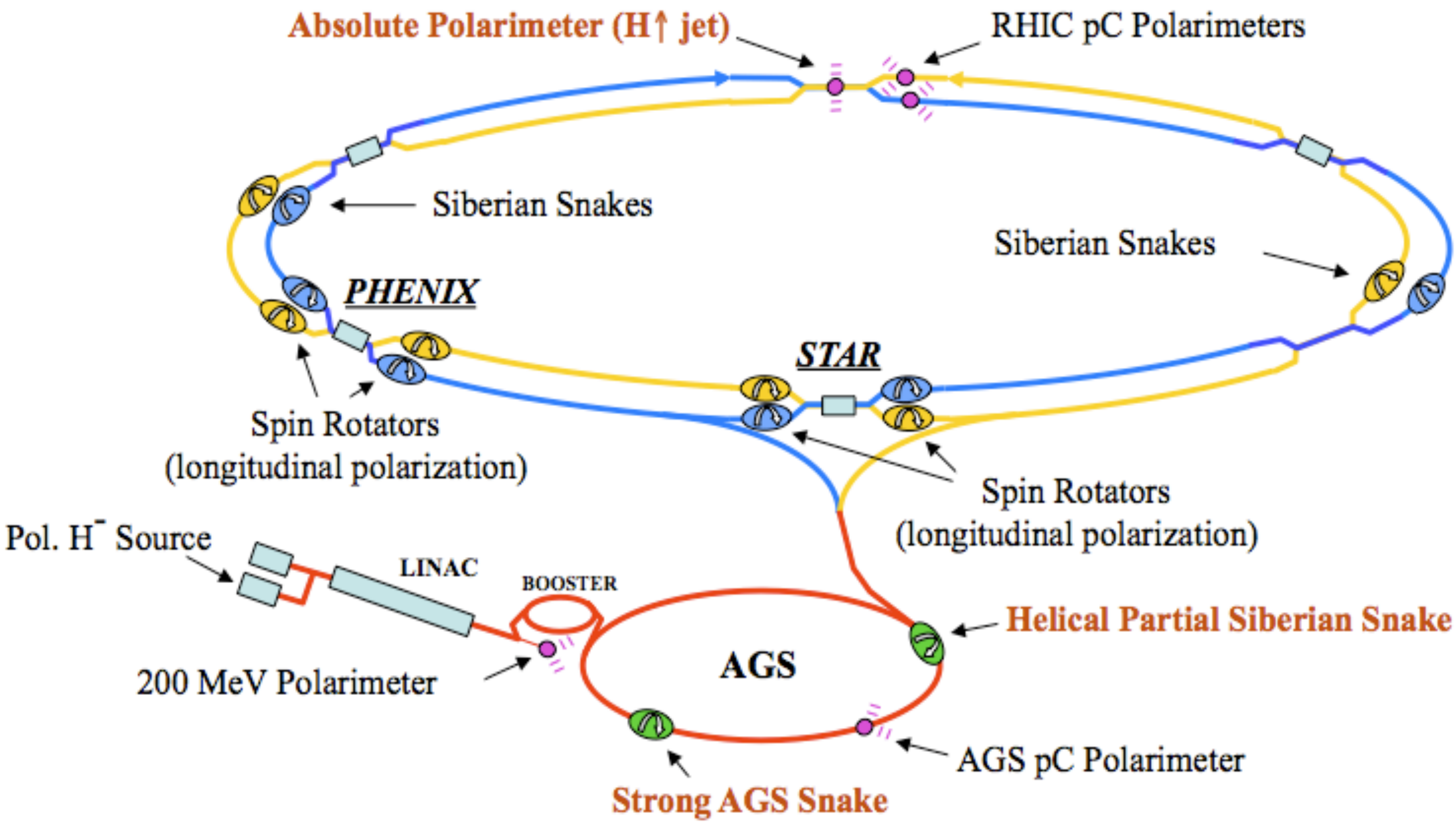


- Flavor separation – SIDIS, RHIC spin:

Compare to spin-averaged case, more data are needed!

RHIC spin program

❑ The machine:



Collider of two 100 GeV (250 GeV) polarized proton beams

Determination of ΔG

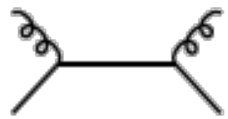
- **Physical channels sensitive to ΔG:**

$\vec{p} + \vec{p} \to \pi + X$

$\vec{p} + \vec{p} \to \text{jet} + X$

$\vec{g}\vec{g} \to gg$

$\vec{q}\vec{g} \to qg$



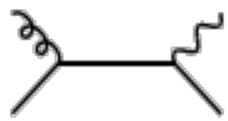
Pion or jet production

high rates

$\vec{p} + \vec{p} \to \gamma + X$

$\vec{p} + \vec{p} \to \gamma + \text{jet} + X$

$\vec{q}\vec{g} \to \gamma q$



Direct photon production

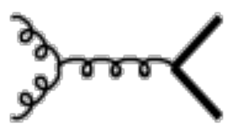
low rates

$\vec{p} + \vec{p} \to D + X$

$\vec{p} + \vec{p} \to B + X$

$\vec{g}\vec{g} \to c\bar{c}$

$\vec{g}\vec{g} \to b\bar{b}$

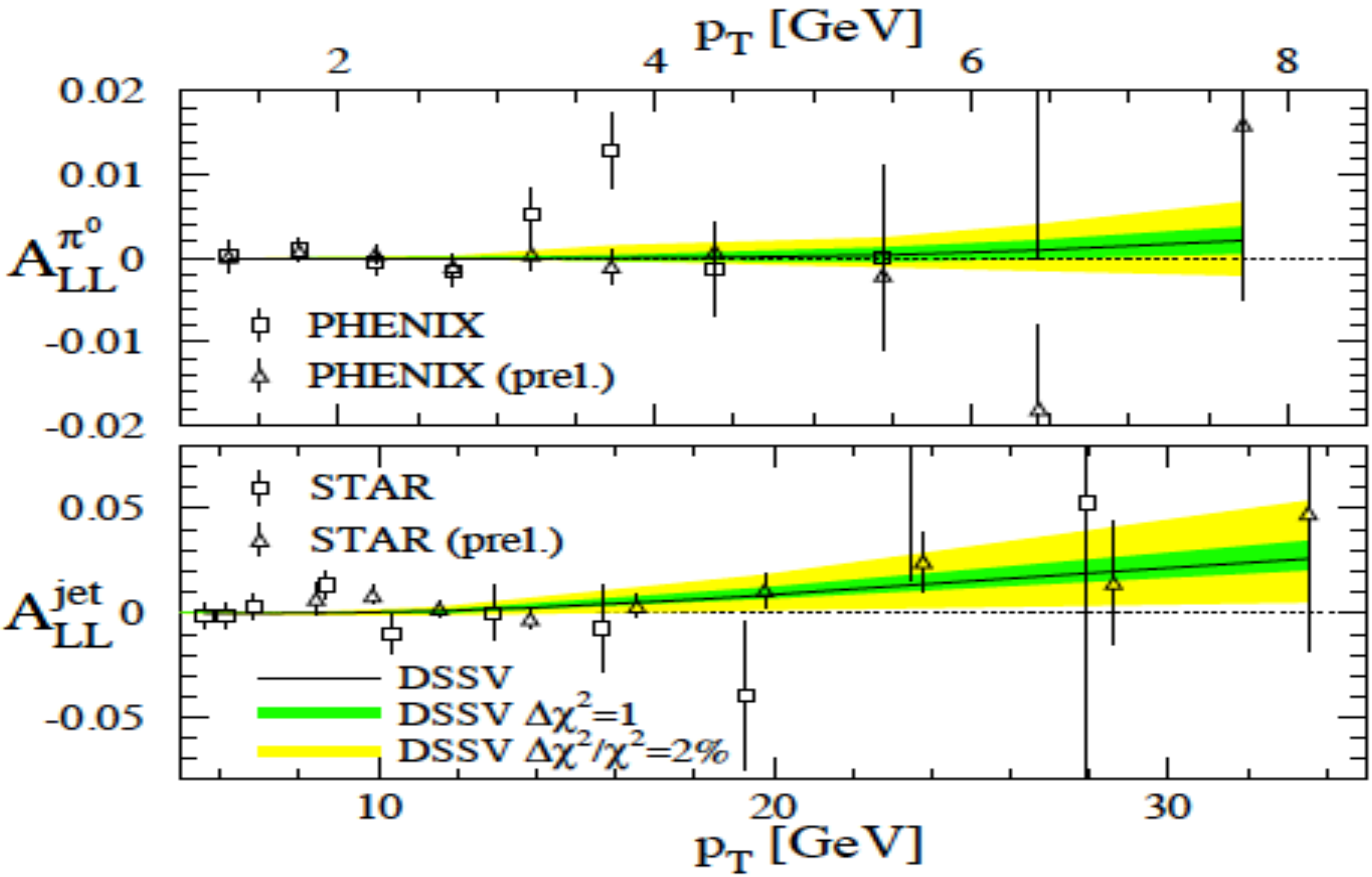


Heavy-flavour production

separated vertex detection required

Many NLO pQCD calculations are available

RHIC Measurements on ΔG



Small asymmetry leads to small gluon "helicity" distribution

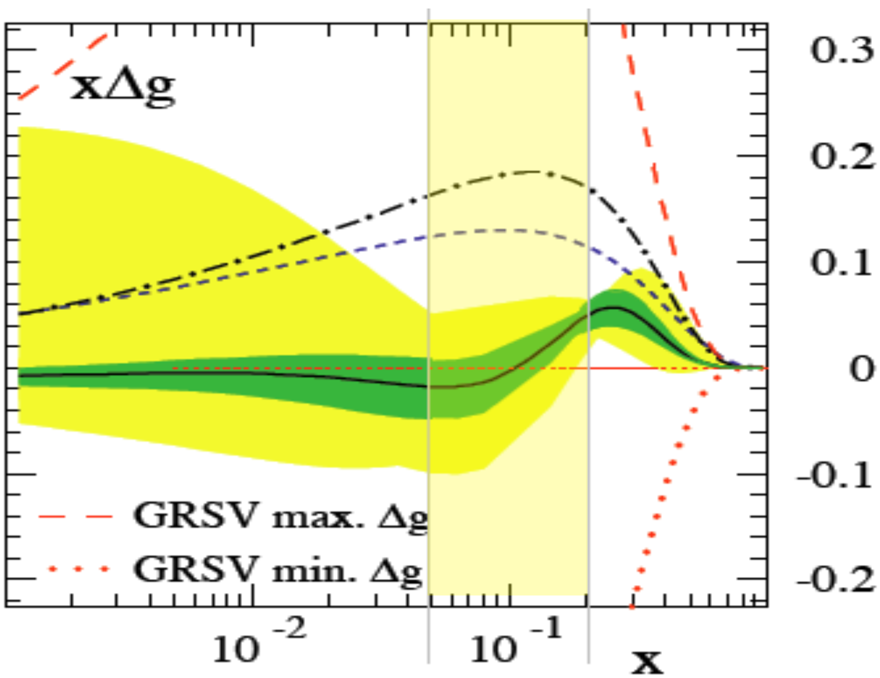
Current status on ΔG

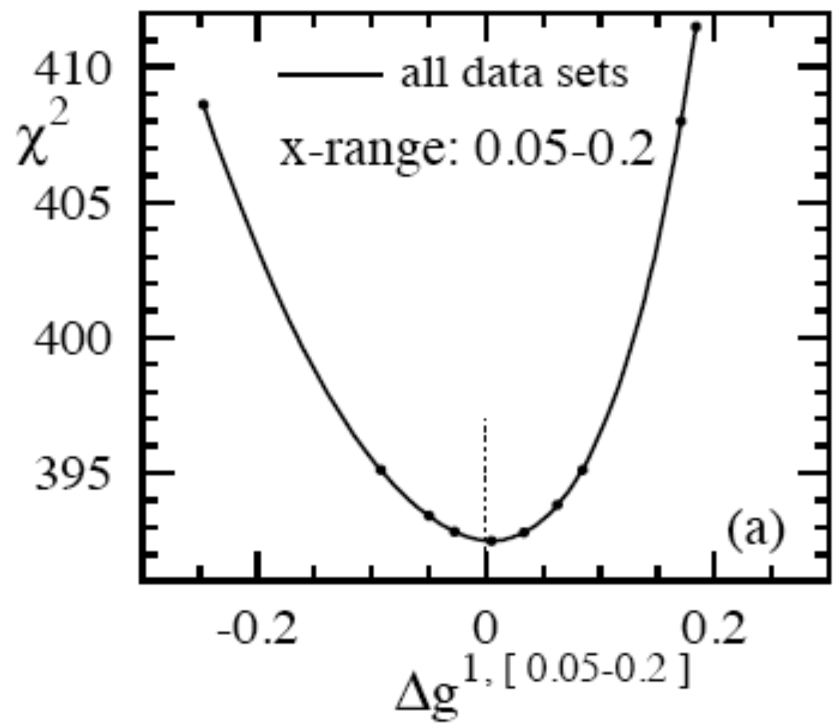
- Definition:

$$\Delta G = \int_0^1 dx\,\Delta G(x) \;= \int_0^1 \frac{dx}{xp^+}\int \frac{dy^-}{2\pi}\, e^{ixp^+y^-}\langle p,s|F^{+\mu}(0)F^{+\nu}(y^-)|p,s\rangle(-i\epsilon_{\mu\nu})$$

- NLO QCD global fit - DSSV:

PRL101,072001(2008)



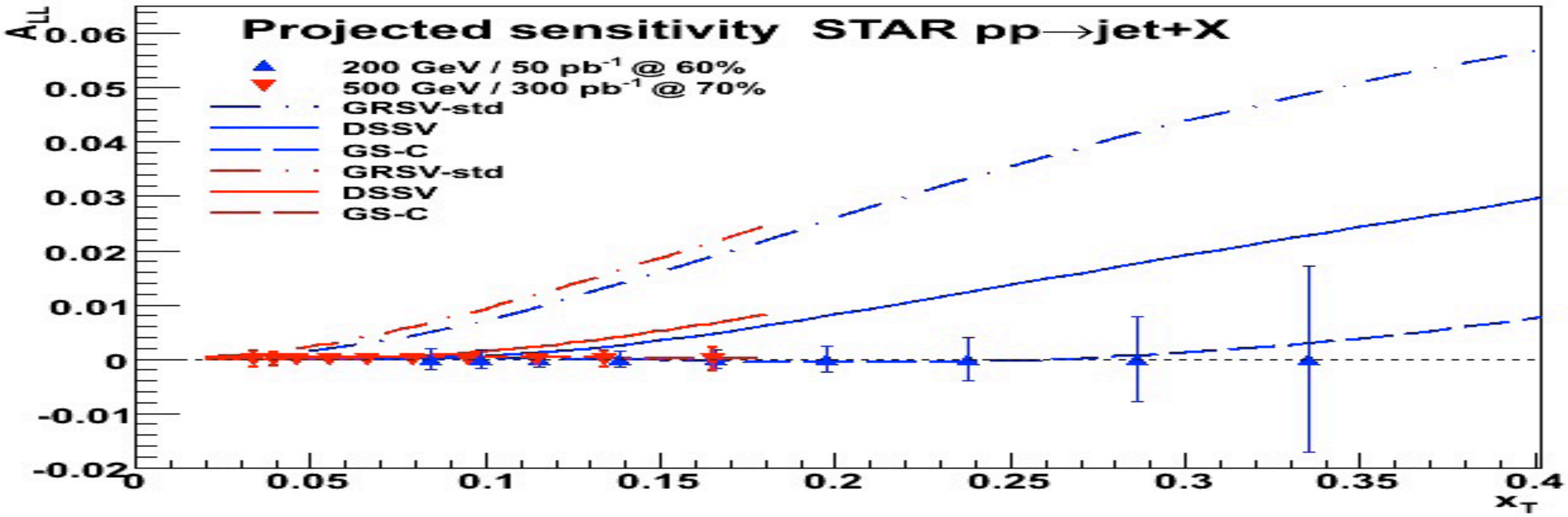


$$\Delta G \approx \int_{0.001}^{1} dx\,\Delta G(x) = -0.084$$

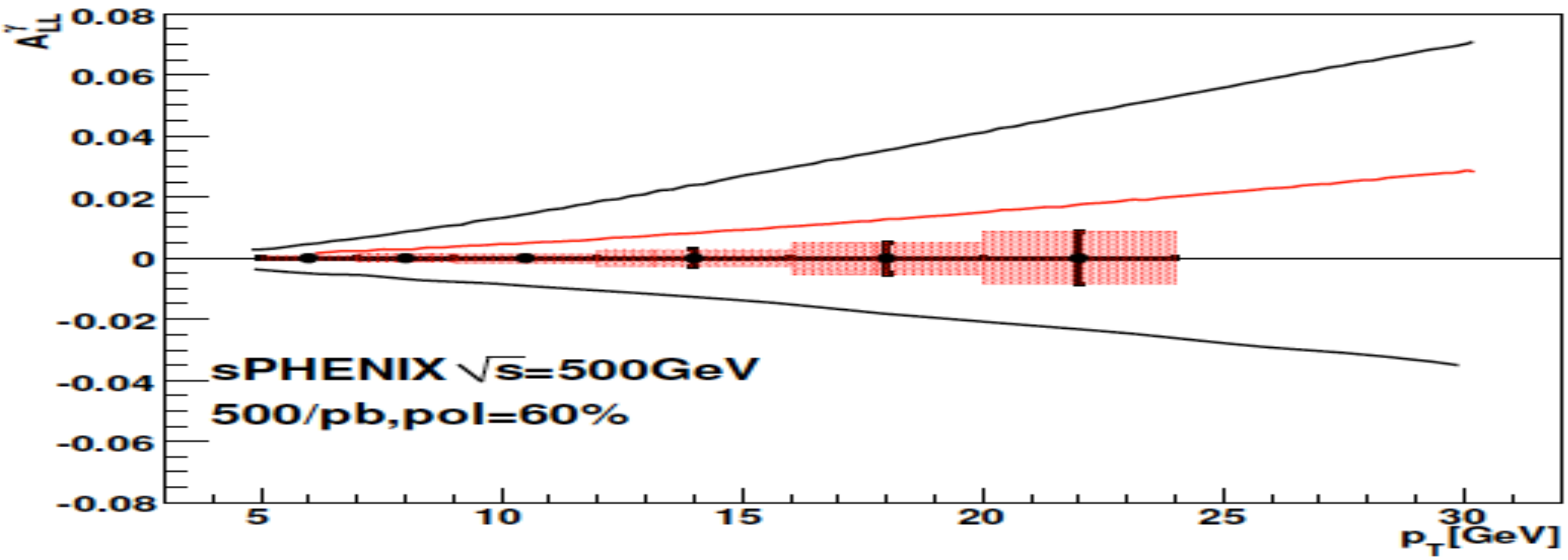
Strong constraint on ΔG from $0.05 \lesssim x \lesssim 0.2$

Future measurement on ΔG

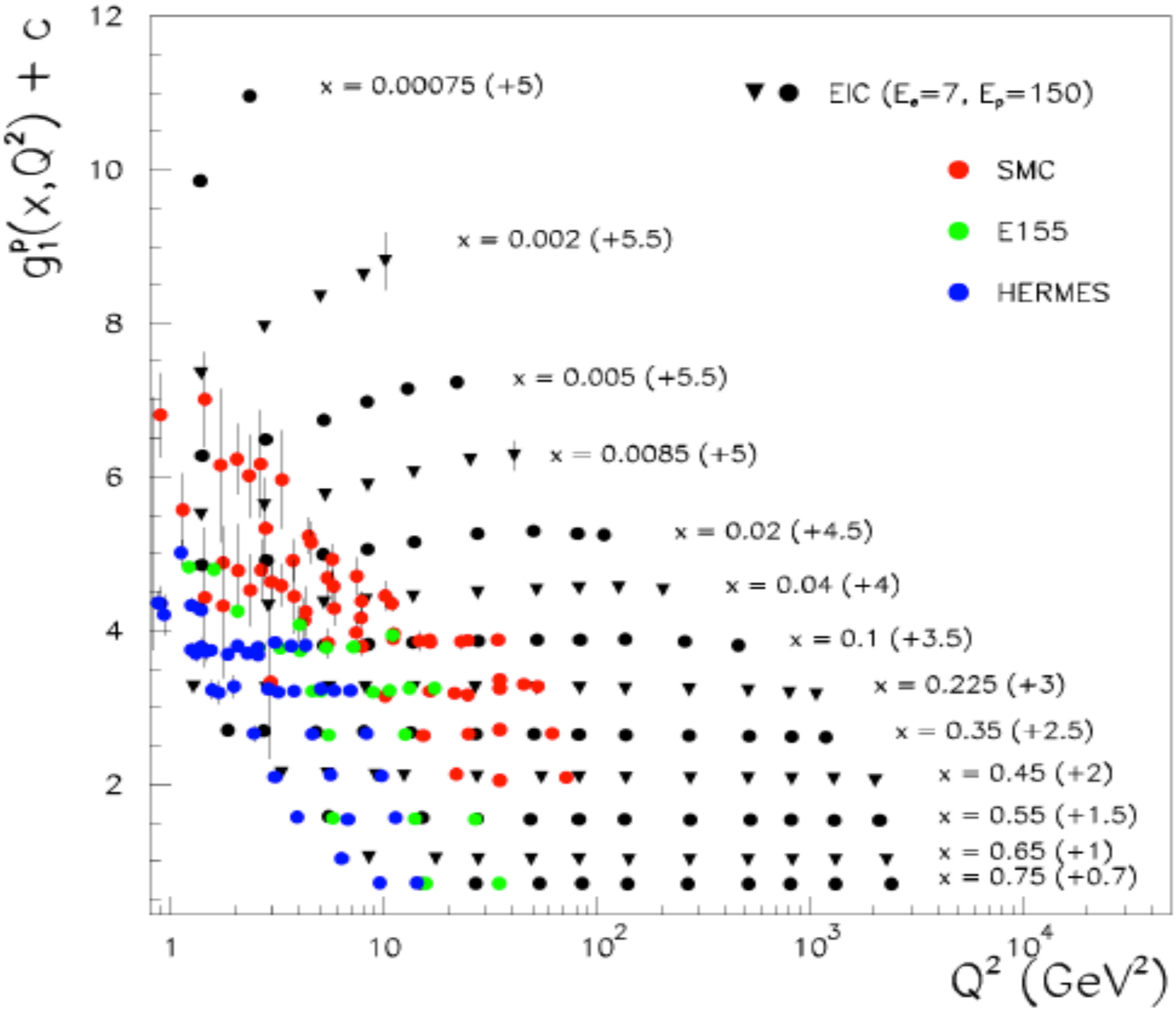
- STAR – multiple channels – inclusive jet:



- PHENIX – multiple channels – γ:



EIC coverage



Bruell, Ent

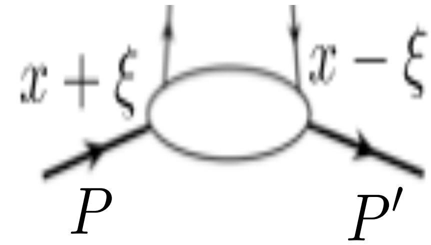
If intrinsic spin of quarks and gluons do not contribute much to proton's spin,

Need to exam parton's transverse motion inside a proton?

Contribution from parton's orbital motion

- **Generalized quark distribution:**

$$F_q(x,\xi,t,\mu^2) = \int \frac{d\lambda}{2\pi} e^{-ix\lambda} \langle P' | \bar{\psi}_q(\lambda/2) \frac{\gamma \cdot n}{2P \cdot n} \psi_q(-\lambda/2) | P \rangle$$
$$\equiv \; H_q(x,\xi,t,\mu^2)\, [\bar{\mathcal{U}}(P')\gamma^\mu \mathcal{U}(P)]\, \frac{n_\mu}{2P\cdot n}$$
$$+ \; E_q(x,\xi,t,\mu^2) \left[\bar{\mathcal{U}}(P') \frac{i\sigma^{\mu\nu}(P'-P)_\nu}{2M} \mathcal{U}(P)\right] \frac{n_\mu}{2P\cdot n}$$



with $\quad \xi = (P'-P)\cdot n/2 \;\text{ and }\; t = (P'-P)^2 \;\Rightarrow\; -\Delta_\perp^2 \;\text{ if }\; \xi \to 0$

- **Net parton's orbital motion:**

$$J_q \;=\; \frac{1}{2} \lim_{t\to 0} \int dx\, x\, [H_q(x,\xi,t) + E_q(x,\xi,t)]$$
$$= \; \frac{1}{2}\Delta q + L_q$$

Ji, PRL78, 1997

- **Connection to normal quark distribution:**

$$H_q(x,0,0,\mu^2) = q(x,\mu^2)$$

Lattice calculation on parton's orbital motion

Negele et al

- Moments of GPDs on lattice:

$$\langle J_q^i \rangle = S^i \int dx \, [H_q(x,0,0) + E_q(x,0,0)] \, x$$

- Ji's relation:

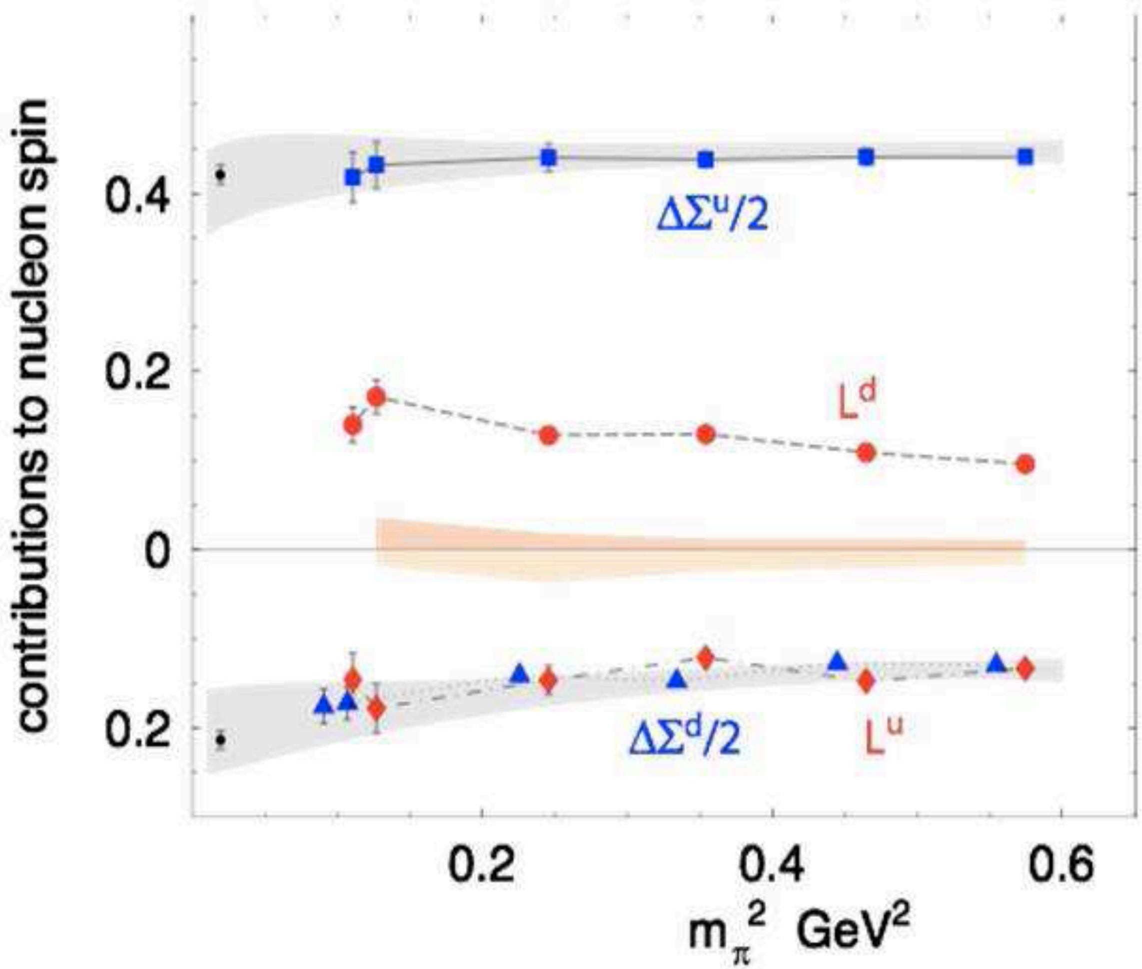
$$L_q^z = J_q^z - \frac{1}{2}\Delta q$$

- Both L_u and L_d large:

But, $L_u + L_d \sim 0$

- Role of disconnected diagram – cloud?

EIC is an ideal place
to measure GPDs – DVCS
– energy and luminocity



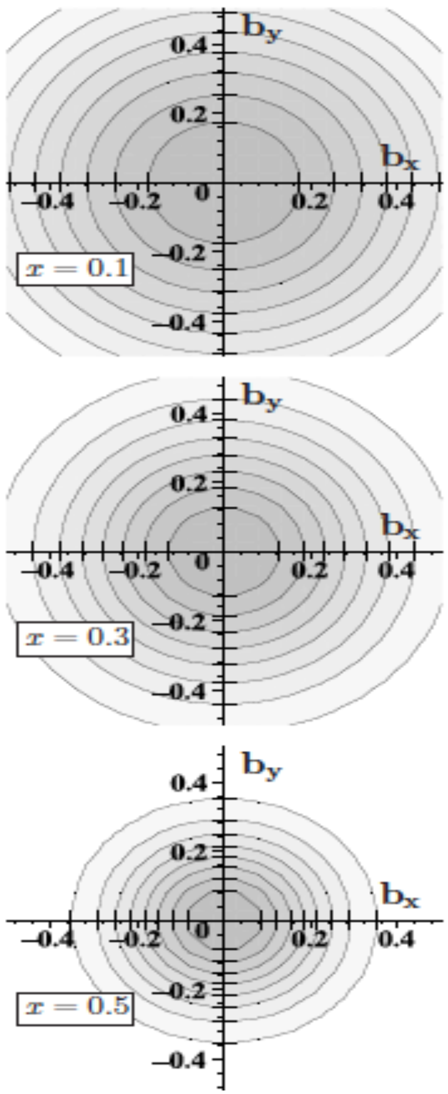
GPDs and transverse imaging

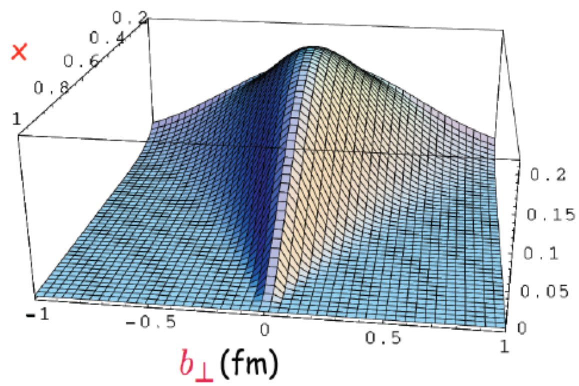
Burkardt, NPA711, 2002

- Spatial dependent quark distribution:

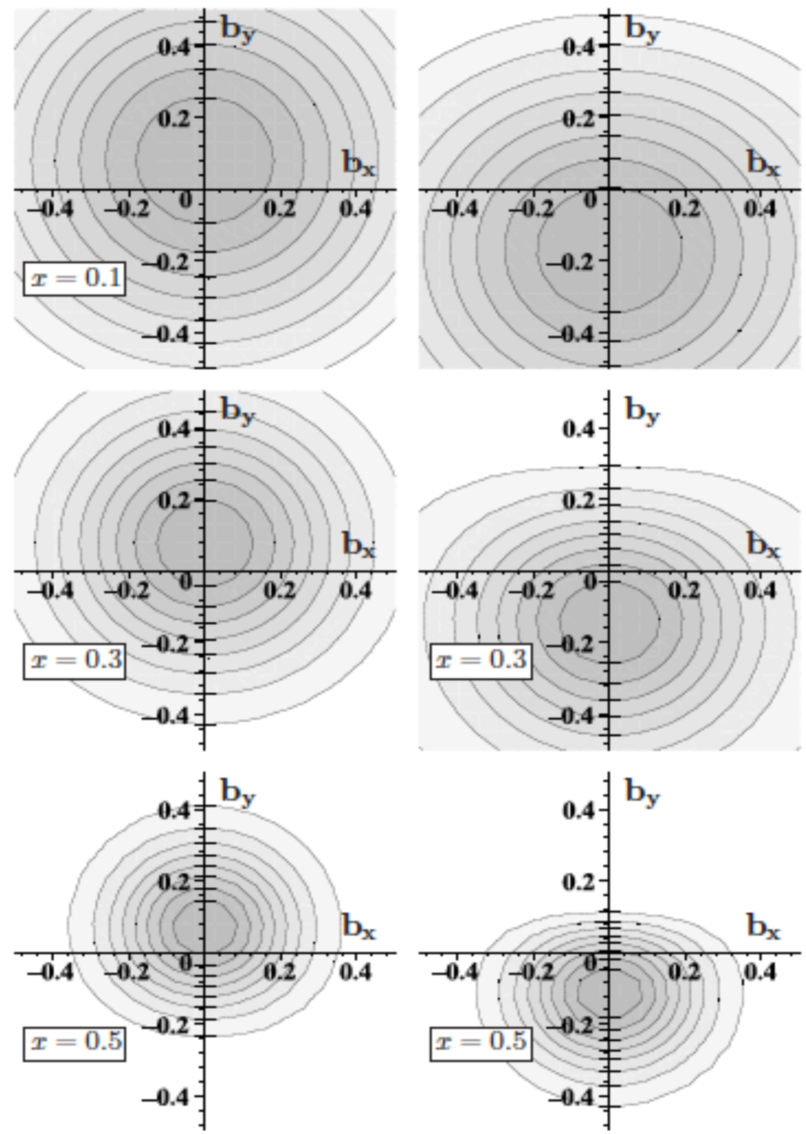
$$\int d^2\mathbf{\Delta}_\perp\, \mathrm{e}^{-i\mathbf{\Delta}_\perp\cdot\mathbf{b}_\perp}\; H_q(x,\xi=0,-\mathbf{\Delta}_\perp^2) = q(x,b_\perp)$$

$q(x,\mathbf{b}_\perp)$ for unpol. p



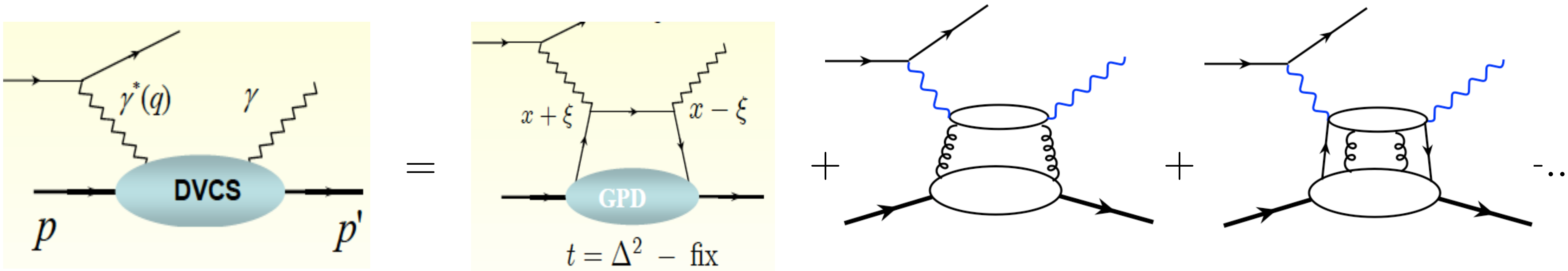


$u(x,\mathbf{b}_\perp)$ $d(x,\mathbf{b}_\perp)$



EIC is ideal for probing GPD's

- **DVCS – exchange vacuum quantum number:**



- **DVCS – Factorization is ok if** $Q^2 \gg -t^2$

ξ – Does not evolve

- **Evolution from color singlet ladder diagrams:**

x – convolution

- **DVCS – meson production:**

$$Q^2 \gg -t^2 \gg \Lambda^2_{\rm QCD}$$

Measured at H1, ZEUS, HERMES, JLAB CLAS and Hall A,

planned for COMPASS and JLAB 12 GeV

EIC has a better chance to cover the needed kinematics

Novel spin phenomena

Single Transverse-Spin Asymmetry (SSA)

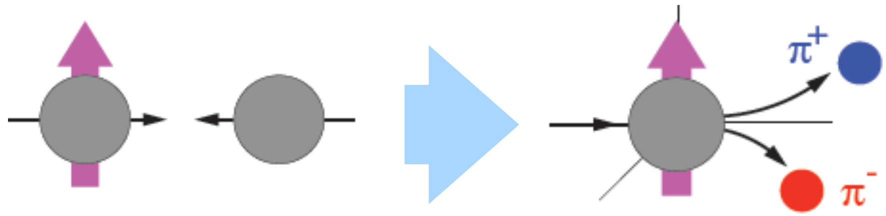
$$A(\ell, \vec{s}) \equiv \frac{\Delta\sigma(\ell, \vec{s})}{\sigma(\ell)} = \frac{\sigma(\ell, \vec{s}) - \sigma(\ell, -\vec{s})}{\sigma(\ell, \vec{s}) + \sigma(\ell, -\vec{s})}$$

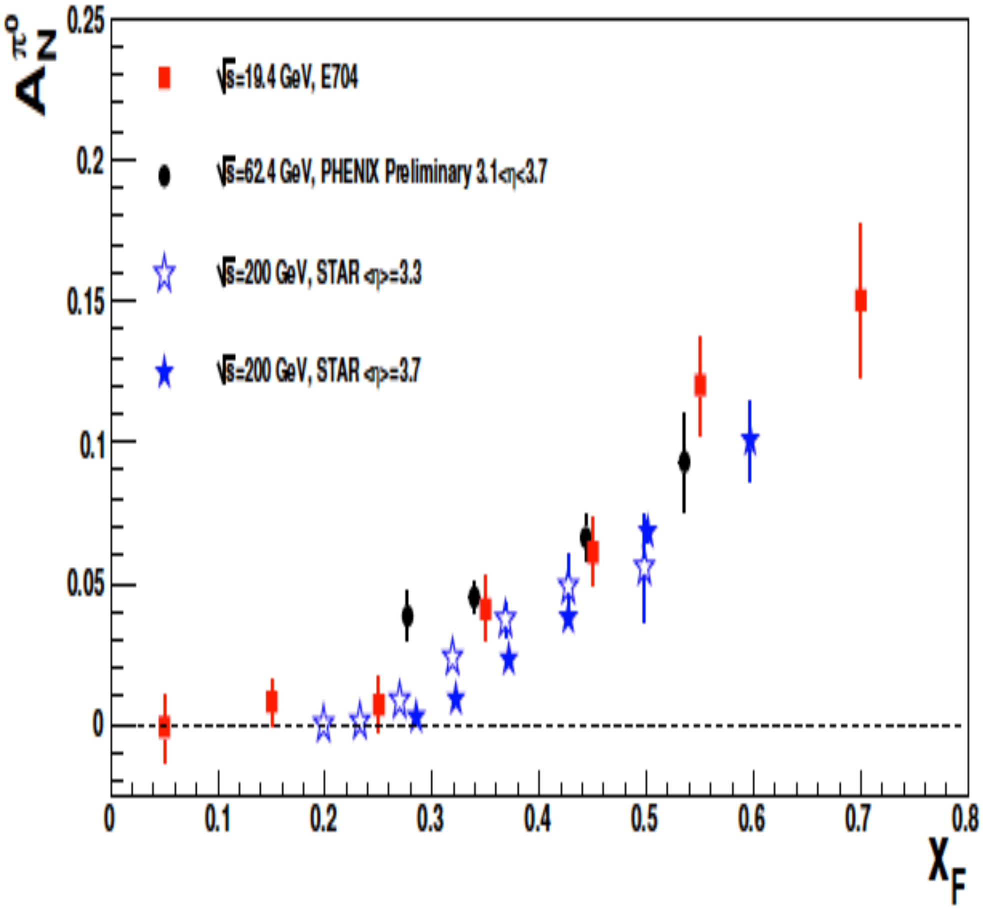
A direct probe for parton's transverse motion

A direct probe of QCD quantum interference

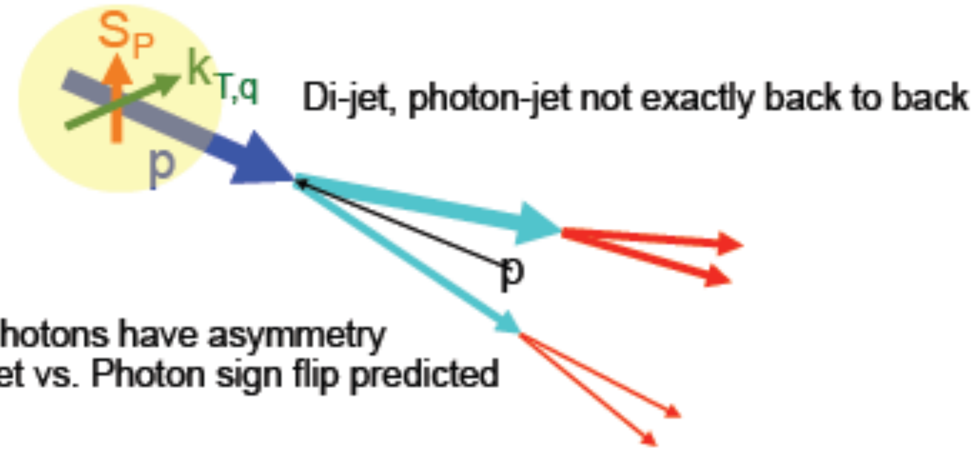
Transverse spin phenomena in QCD

❑ Left-right asymmetry:



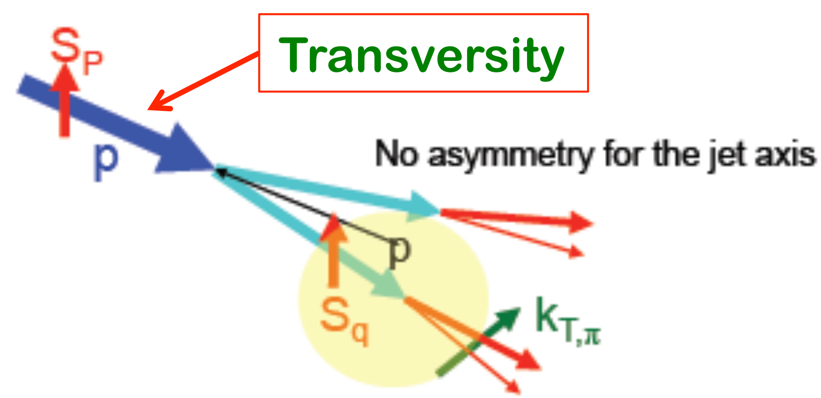


✧ Sivers effect:



Hadron spin influences parton's transverse motion

✧ Collins effect:



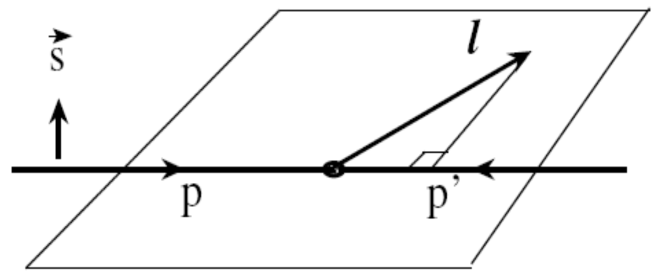
Parton's spin affects hadronization

Single transverse spin asymmetry

- **SSA corresponds to a naively T-odd triple product:**

$$A_N = [\sigma(p, s_T) - \sigma(p, -s_T)]/[\sigma(p, s_T) + \sigma(p, -s_T)]$$

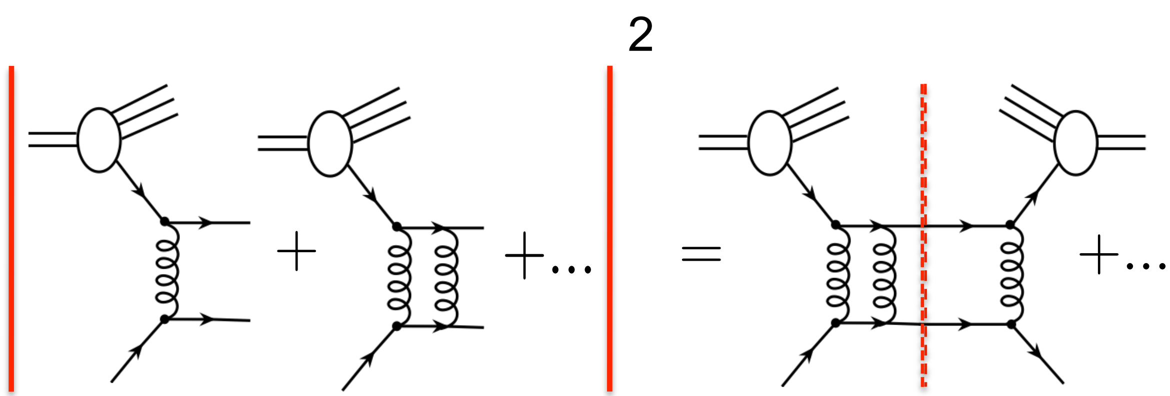
$$A_N \propto i\,\vec{s}_p \cdot (\vec{p} \times \vec{\ell}) \;\Rightarrow\; i\,\epsilon^{\mu\nu\alpha\beta}\, p_\mu s_\nu \ell_\alpha p'_\beta$$



Novanish A_N requires a phase, enough vectors to fix a scattering plan, and a spin flip at the partonic scattering

- **Leading power in QCD:**

$$\sigma_{AB}(p_T, \vec{s}) \propto$$

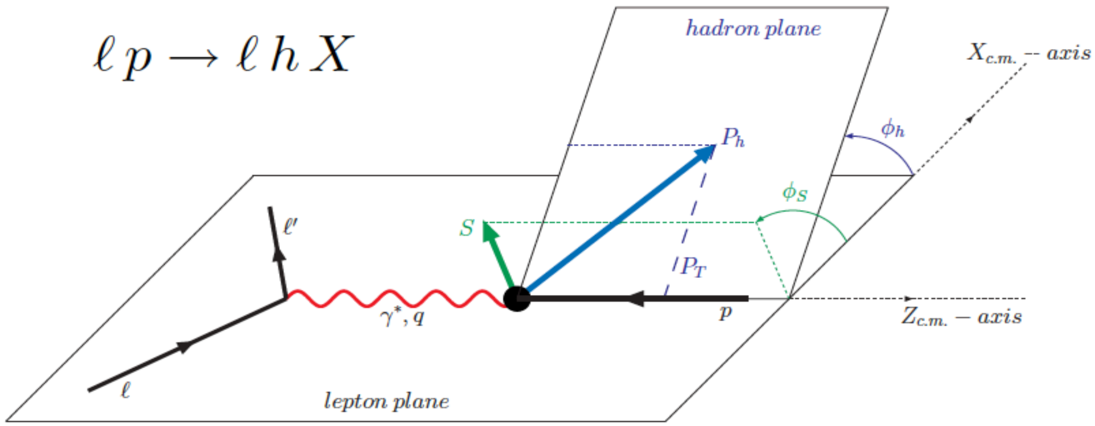


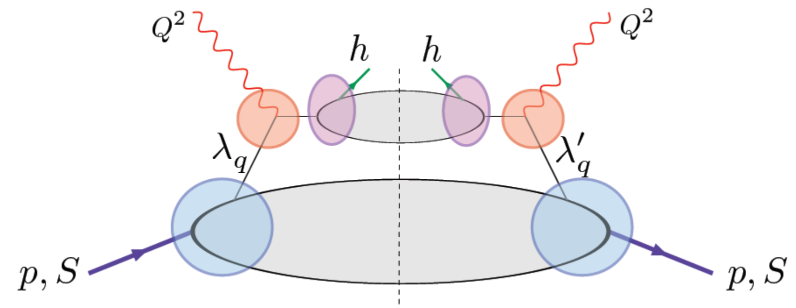
$$\propto \alpha_s \frac{m_q}{p_T}$$

Kane, Pumplin, Repko, PRL, 1978

EIC is ideal for studying TMDs

❑ SIDIS has the natural kinematics for TMD factorization:

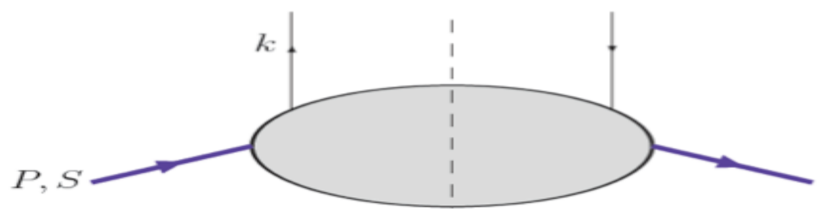




Natural event structure:
high Q and low p_T jet (or hadron)

❑ Quark TMD distributions:

$$\Phi(x, \boldsymbol{k}_\perp) = \frac{1}{2}\left[f_1 \not{n}_+ + f_{1T}^\perp \frac{\epsilon_{\mu\nu\rho\sigma}\gamma^\mu n_+^\nu k_\perp^\rho S_T^\sigma}{M} + \left(S_L g_{1L} + \frac{\boldsymbol{k}_\perp \cdot \boldsymbol{S}_T}{M} g_{1T}^\perp \right) \gamma^5 \not{n}_+ \right.$$
$$+ h_{1T} i\sigma_{\mu\nu}\gamma^5 n_+^\mu S_T^\nu + \left(S_L h_{1L}^\perp + \frac{\boldsymbol{k}_\perp \cdot \boldsymbol{S}_T}{M} h_{1T}^\perp \right) \frac{i\sigma_{\mu\nu}\gamma^5 n_+^\mu k_\perp^\nu}{M}$$
$$\left. + h_1^\perp \frac{\sigma_{\mu\nu} k_\perp^\mu n_+^\nu}{M} \right]$$



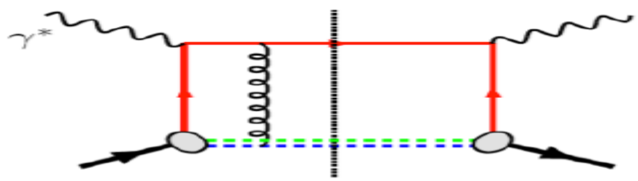
Total 8 TMD quark distributions

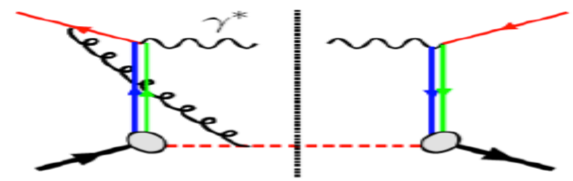
Similar decomposition for gluon TMD distribtutions

Critical test of TMD factorization

Collins et al. 2006

- Sign change:

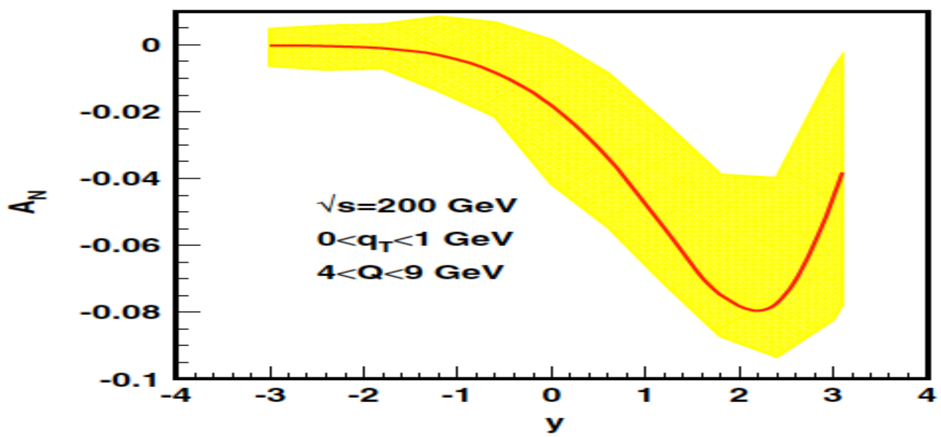


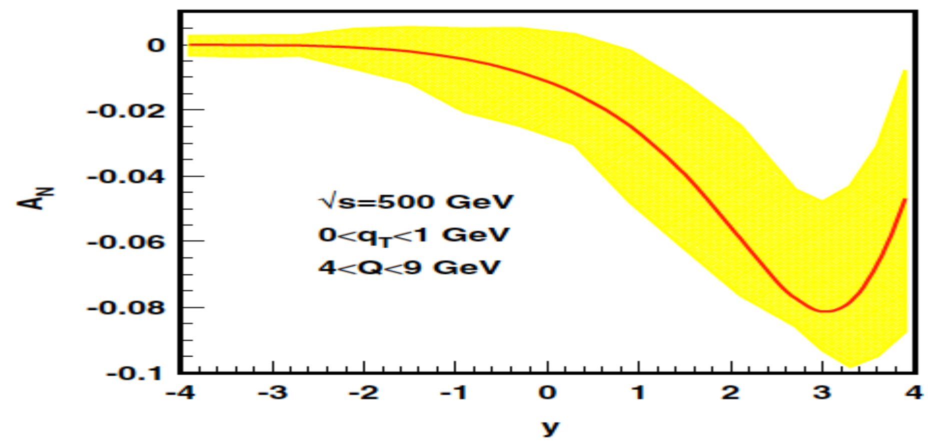


- Drell-Yan:

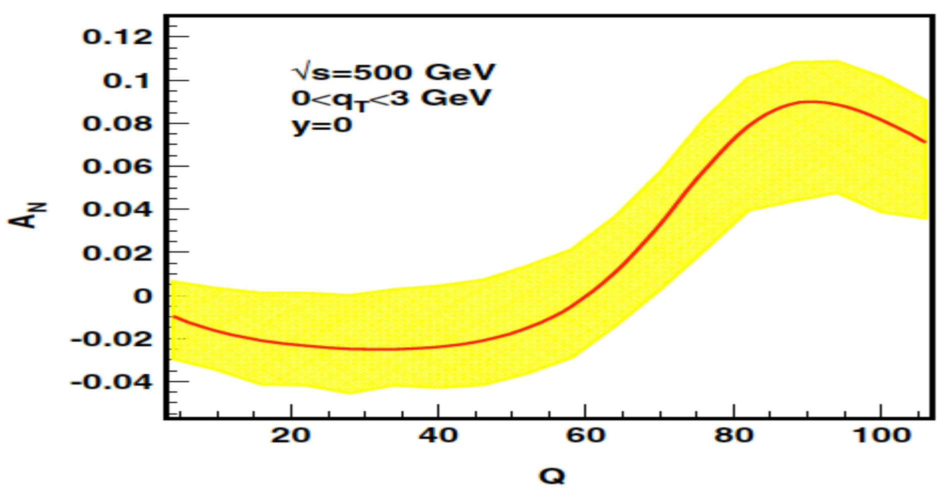
$$A_N^{\sin(\phi-\phi_s)} = -A_N$$

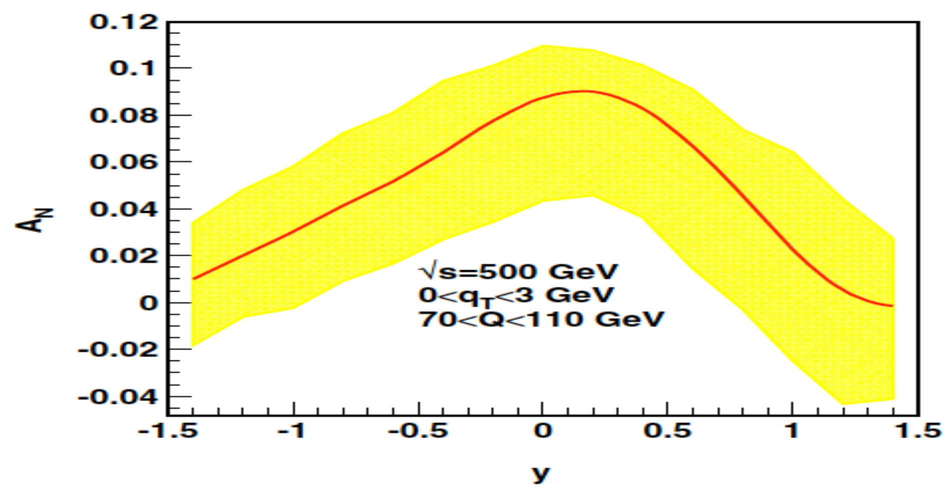
Kang, Qiu, 2009





- Z^0:





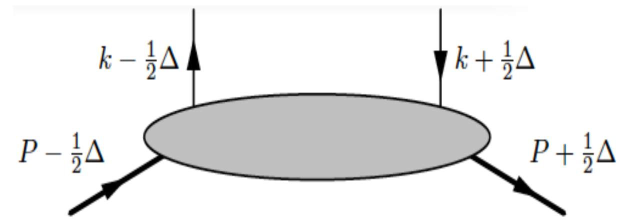
Map parton's motion by a hard probe

- **Fully unintegrated distribution:**

Meissner, Metz, Schiegel, 2009

$$W^{[\Gamma]}_{\lambda\lambda'}(P,k,\Delta,N;\eta) = \frac{1}{2}\int \frac{d^4z}{(2\pi)^4}\, e^{ik\cdot z}\, \langle p',\lambda'|\,\bar{\psi}(-\tfrac{1}{2}z)\,\Gamma\,\mathcal{W}(-\tfrac{1}{2}z,\tfrac{1}{2}z\,|\,n)\,\psi(\tfrac{1}{2}z)\,|p,\lambda\rangle$$

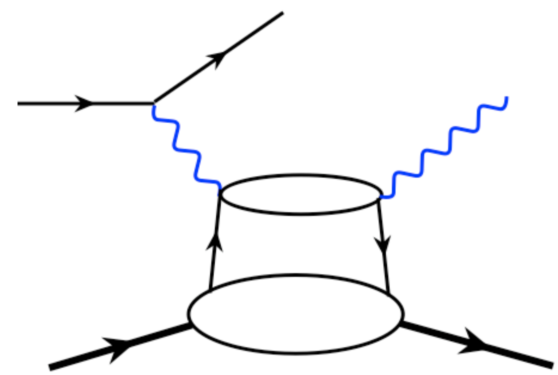
– not factorizable in general



- **Generalized TMDs – ideal distribution:**

$$H(x,k_T,\Delta)_\Gamma = \int dk^2\; W(P,k,\Delta)_\Gamma$$

– could be factorized assuming on-shell parton for the hard probe



Only EIC could have a chance to probe this!

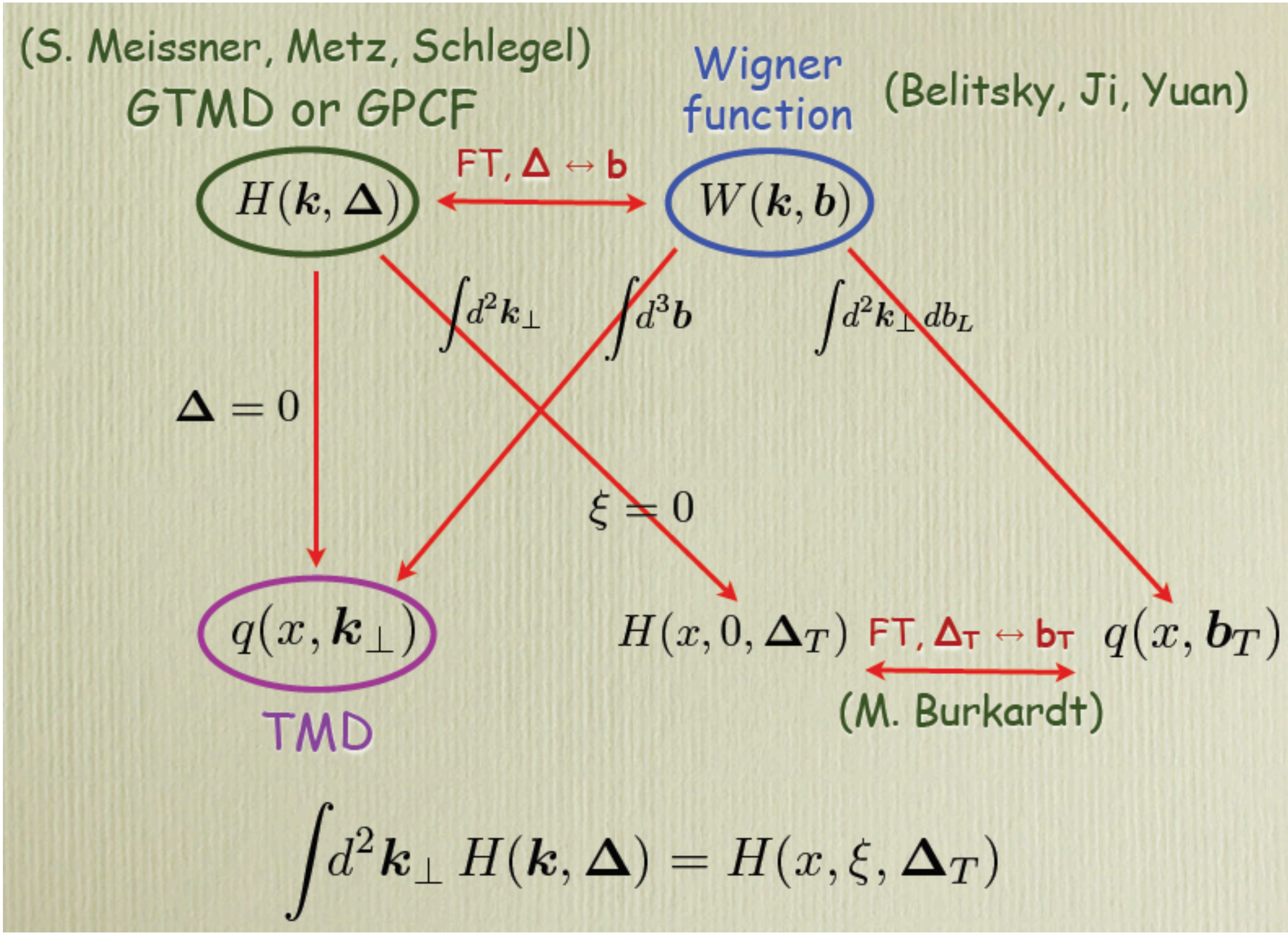
- **Wigner function:**

Belitsky, Ji, Yuan

$$W(x,k_T,b) \propto \int d^3\Delta\, e^{i\vec{b}\cdot\vec{\Delta}} H(x,k_T,\Delta)_{\Gamma=\gamma^+}$$

Connection to all other known distributions

Anselmino, INT

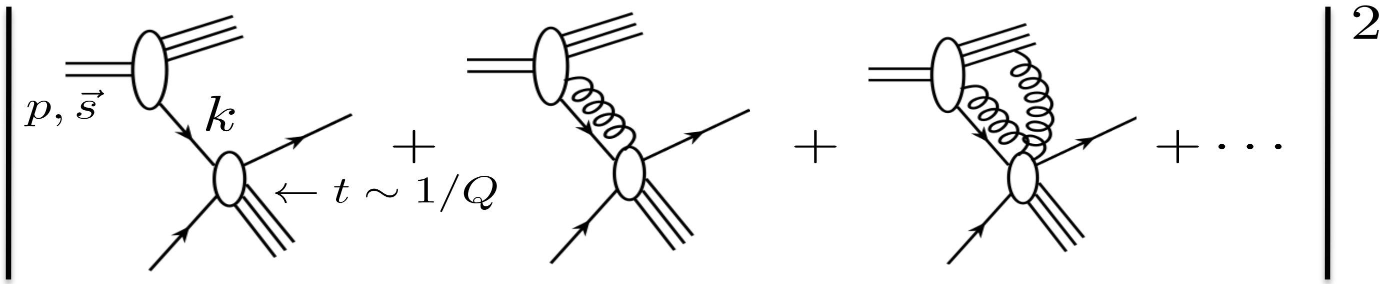


Cross section with ONE large scale

Efremov, Teryaev, 82; Qiu, Sterman, 91, etc.

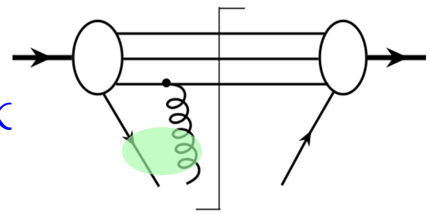
❑ A_N – twist-3 effect – when $P_T \sim Q$:

$$\sigma(Q,\vec{s}) \propto$$

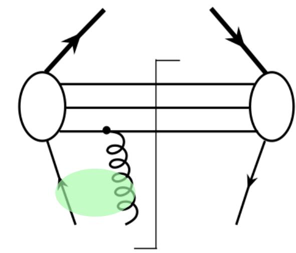


$$\Delta(s_T) \propto T^{(3)}(x,x) \otimes \hat{\sigma}_T \otimes D_f(z) + \delta q_f(x) \otimes \hat{\sigma}_D \otimes D^{(3)}(z,z)$$

$$T^{(3)}(x,x) \propto$$



$$D^{(3)}(z,z) \propto$$



Qiu, Sterman, 1991, …

Kang, Yuan, Zhou, 2010

❑ Spin flip:

– Interference of single parton and a two-parton composite state

❑ The phase:

– Interference of Real and Imaginary part of scattering amplitude

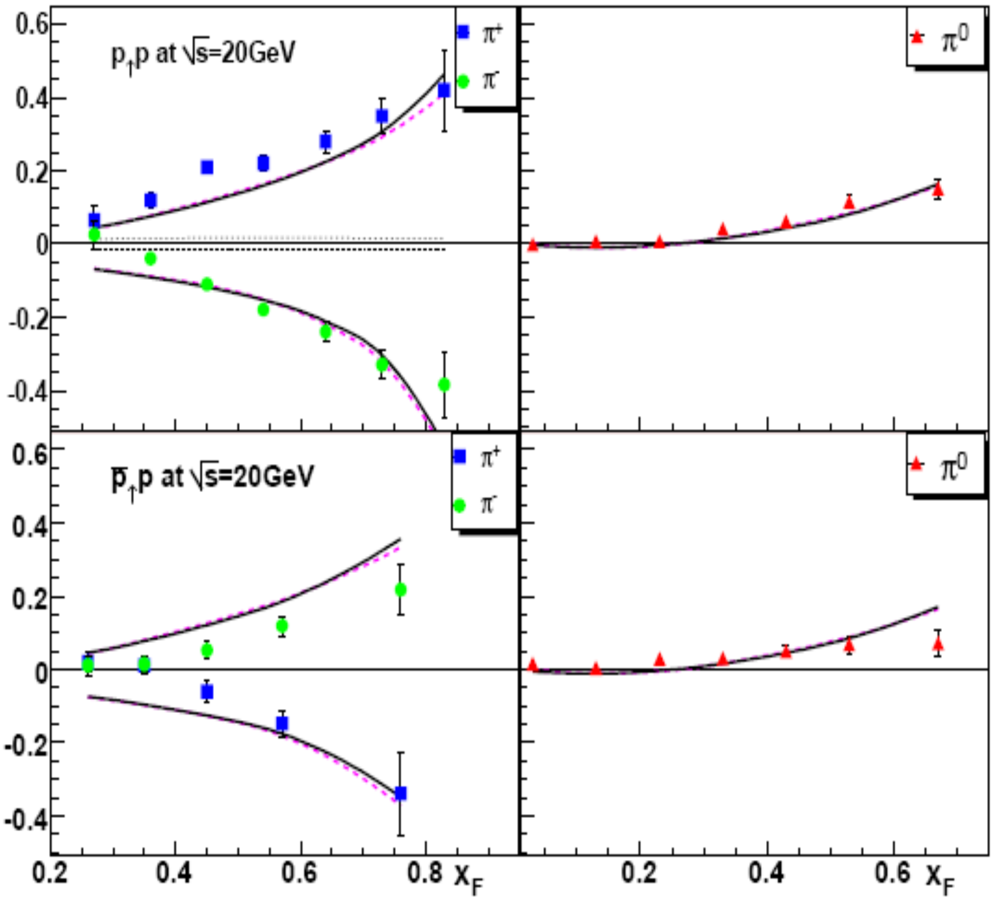
– gluonic pole: $\propto T^{(3)}(x,x)$

– fermionic pole contribution: $\propto T^{(3)}(x,0)$ or $T^{(3)}(0,x)$

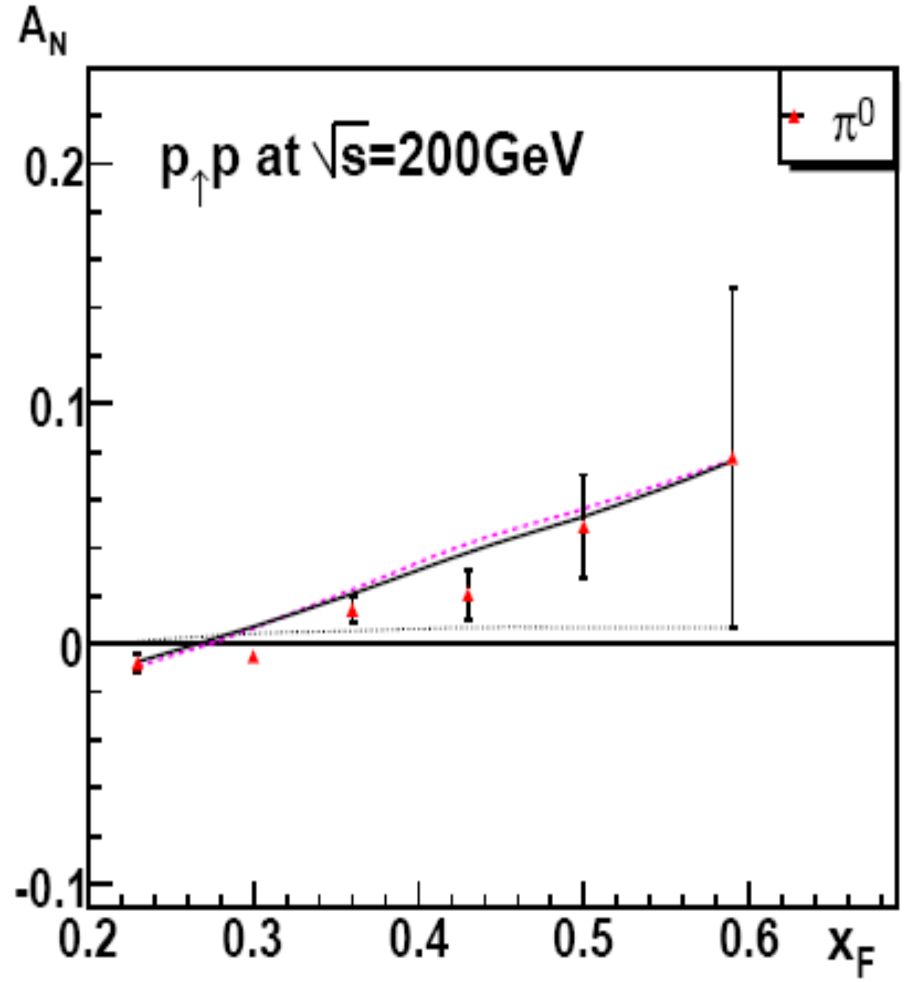
➡ Integrated information on parton's transverse motion!

Asymmetries from the $T_F(x,x)$

(FermiLab E704)



(RHIC STAR)

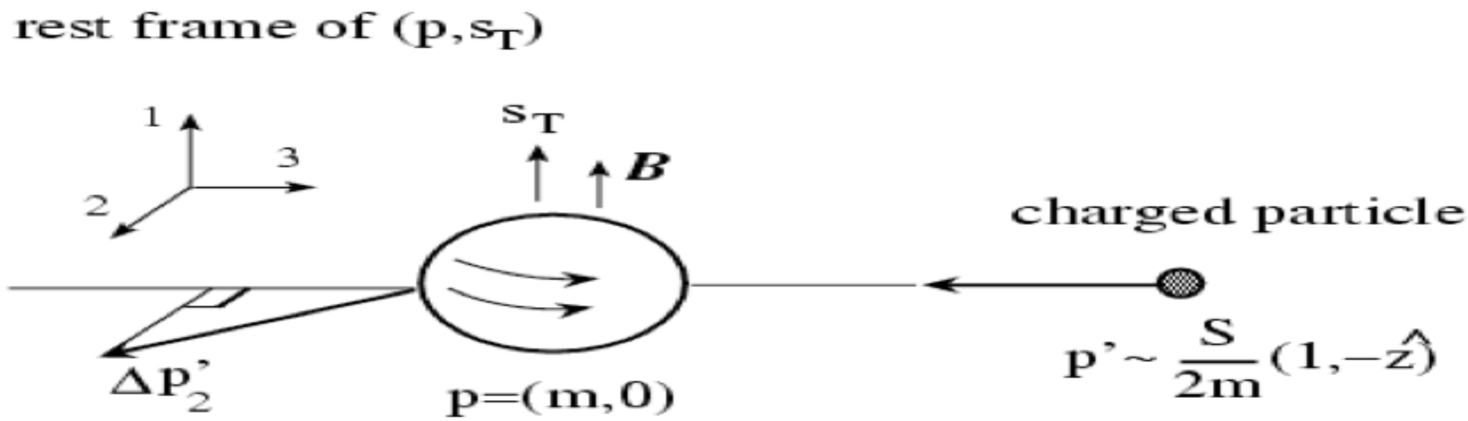


Kouvaris,Qiu,Vogelsang,Yuan, 2006

Nonvanish twist-3 function ➡ **Nonvanish transverse motion**

What the twist-3 distribution can tell us?

- The operator in Red – a classical Abelian case:



- Change of transverse momentum:

$$\frac{d}{dt}p_2' = e(\vec{v}' \times \vec{B})_2 = -ev_3B_1 = ev_3F_{23}$$

- In the c.m. frame:

$$(m,\vec{0}) \to \bar{n} = (1,0,0_T), \quad (1,-\hat{z}) \to n = (0,1,0_T)$$

$$\Longrightarrow \quad \frac{d}{dt}p_2' = e\,\epsilon^{s_T\sigma n\bar{n}}\,F_\sigma{}^+$$

- The total change: $\boxed{\Delta p_2' = e\int dy^-\epsilon^{s_T\sigma n\bar{n}}\,F_\sigma{}^+(y^-)}$

Net quark transverse momentum imbalance caused by color Lorentz force inside a transversely polarized proton

Global QCD analysis for SSA

- **Universality of correlation functions:**

$$\langle P,s|\overline{\psi}(0)\gamma^+\psi(y^-)|P,s\rangle \longrightarrow \langle P,s|\overline{\psi}(0)\gamma^+\left[\epsilon_\perp^{\alpha\beta}s_{T\alpha}\int dy_2^- F_\beta{}^+(y_2^-)\right]\psi(y^-)|P,s\rangle$$

$$\langle P,s|\overline{\psi}(0)\gamma^+\gamma_5\psi(y^-)|P,s\rangle \longrightarrow \langle P,s|\overline{\psi}(0)\gamma^+\left[i\,g_\perp^{\alpha\beta}s_{T\alpha}\int dy_2^- F_\beta{}^+(y_2^-)\right]\psi(y^-)|P,s\rangle$$

Kang, Qiu, 2009

Same replacement for the gluons

- **Scaling violation of correction functions:**

Leading order evolution kernels for all channels have been derived!

Kang, Qiu, 2009
Yuan, Zhou, 2009
Braun et al, 2009

- **What are urgently needed:**

NLO partonic contributions to SSA of all measureable observables!

Vogelsang, Yuan, 2009

- **A completely new domain to test QCD!**

From paton's transverse motion to direct QCD quantum interference

Collinear vs TMD factorization

❑ Relation between TMD and collinear parton distributions:

spin-averaged: $\int d^2k_T\, f_a^{\rm SIDIS}(x,k_T) + {\rm UVCT}\left(\mu^2\right) = q_a\left(x,\mu^2\right)$

Transverse-spin: $\frac{1}{M_P}\int d^2\vec{k}_\perp\; \vec{k}_\perp^2\; q_T(x,k_\perp) + {\rm UVCT}(\mu^2) = T_F(x,x,\mu^2)$

❑ Relation between two factorization schemes

They are valid for different kinematical regions:

Collinear: $Q_1 \ldots Q_n >> \Lambda_{QCD}$

TMD: $Q_1 >> Q_2 > \Lambda_{QCD}$

Common region – perturbative region:

$Q_1 >> Q_2 >> \Lambda_{QCD}$

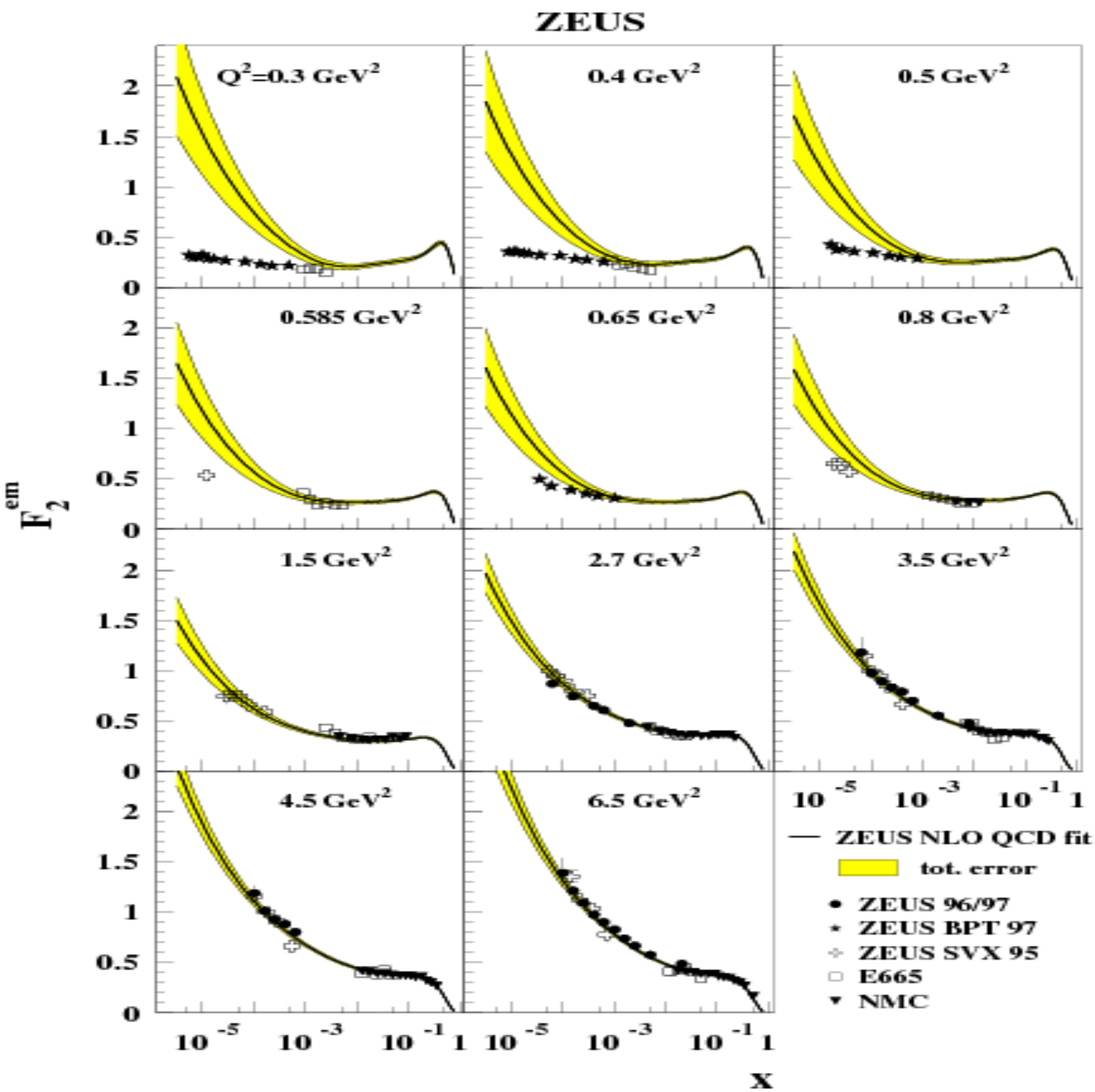
where both schemes are expected to be valid

Ji,Qiu,Vogelsang,Yuan,
Koike, Vogelsang, Yuan

QCD at an extreme condition

Saturation of glue inside a hadron
a new mass scale?

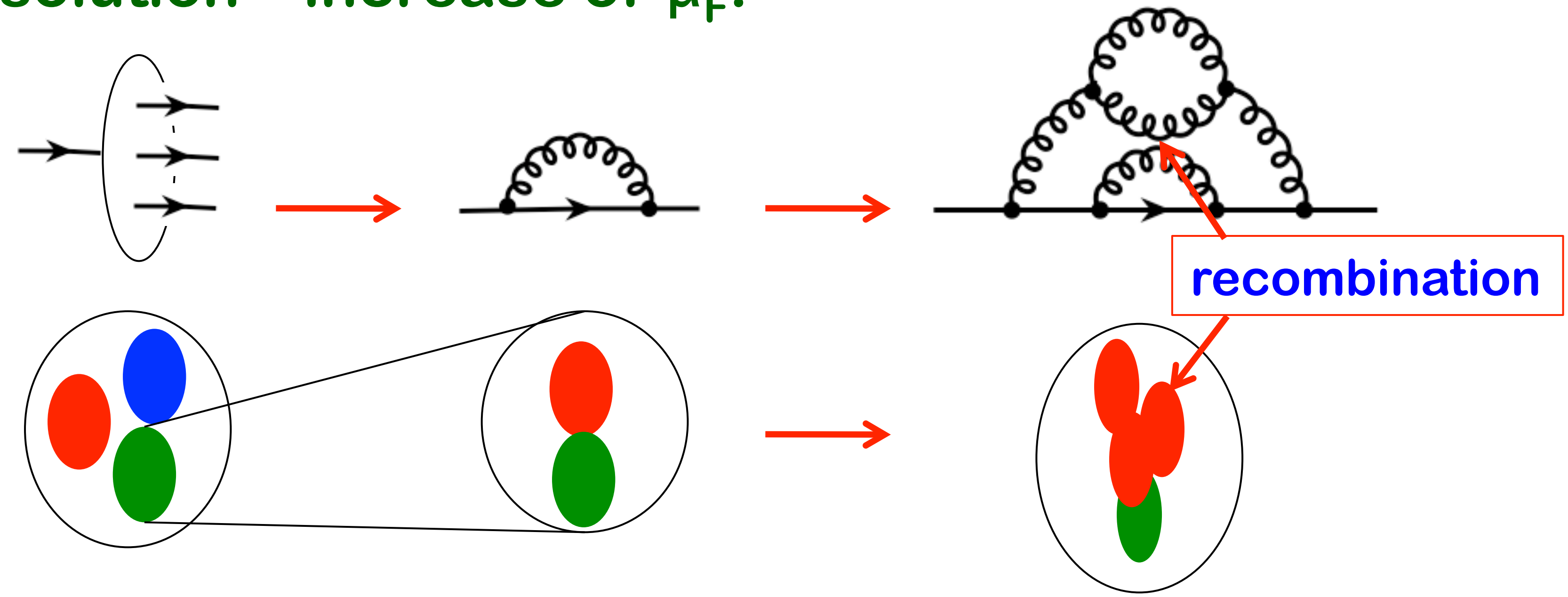
Breakdown of leading power pQCD



Only visible failure when Q < 1 GeV

Change Q^2

❑ Resolution – increase of μ_F:

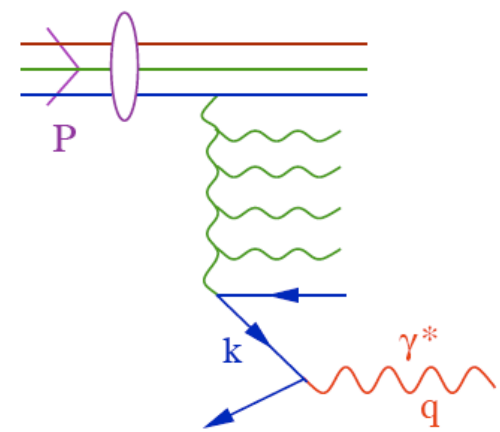


More partons at a smaller $1/\mu_F$

❑ DGLAP evolution:

$$\frac{\partial \phi_g(x,\mu^2)}{\partial \ln(\mu_F^2)} = P_{gg}(x) \otimes \phi_g(x,\mu^2) + \ldots$$

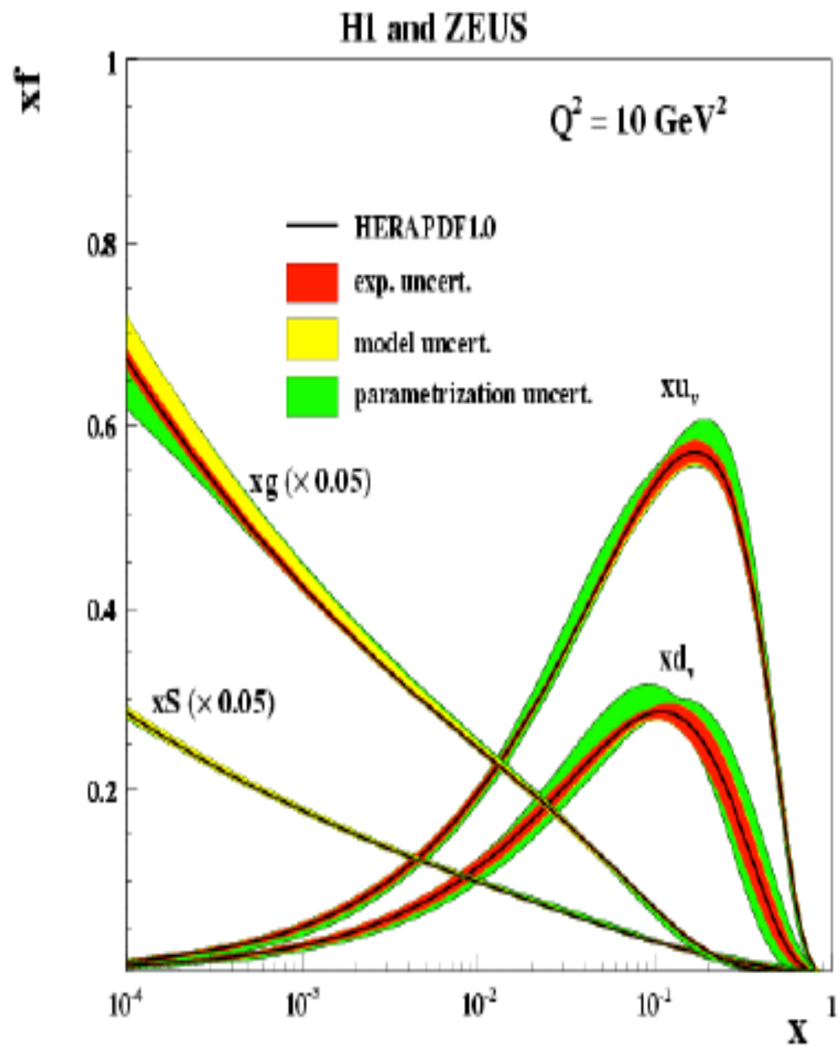
$$P_{gg}(x) \propto \frac{1}{x}$$

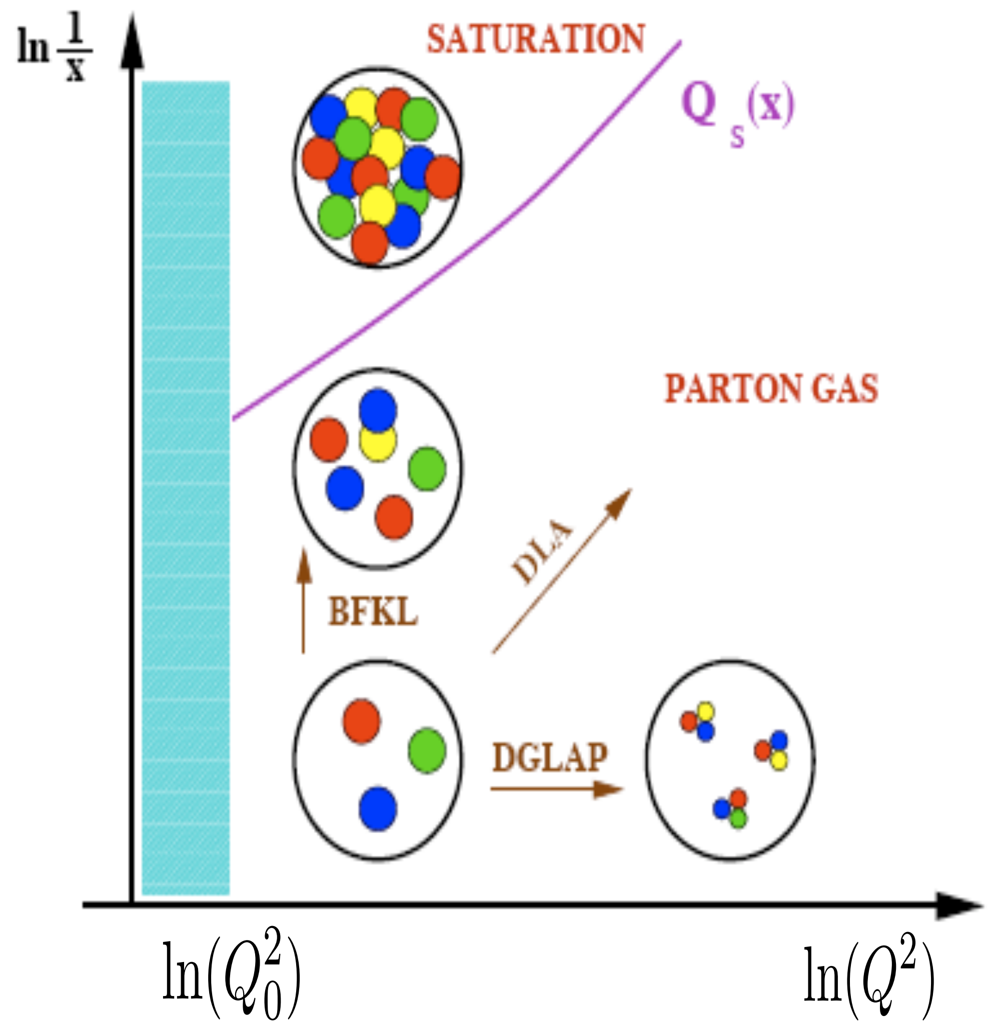


Large number gluons (sea quarks) at small x!

When s >> Q^2 - small x region

- Large gluon density – saturation?:





Important fact

Gluon distribution is not physical!

It is its connection to a physical observable that
makes the gluon distribution accessible – "physical"

Factorization is the key!

Factorization is an all order statement in perturbation theory

How to "see" the glue?

Charm and beauty can help!

Collinear factorization

- **Collinear gluon distribution is process independent!**

  Operator defining the collinear gluon is "local" – limited to 1/Q

- **Collinear gluon distribution is scheme dependent!**

  DIS scheme: No glue contribution to DIS F_2 structure function!

- **Limitation:**

  While it worked beautifully for observables with $Q^2 \gg Q_s^2(x)$,

  collinear factorization is expected to fail when $Q^2 \sim Q_s^2(x)$

Negative glue at a low Q^2

- **Negative gluon density at low x and low Q**

Does it mean that we have no gluon for $x < 10^{-3}$ at 1 GeV?

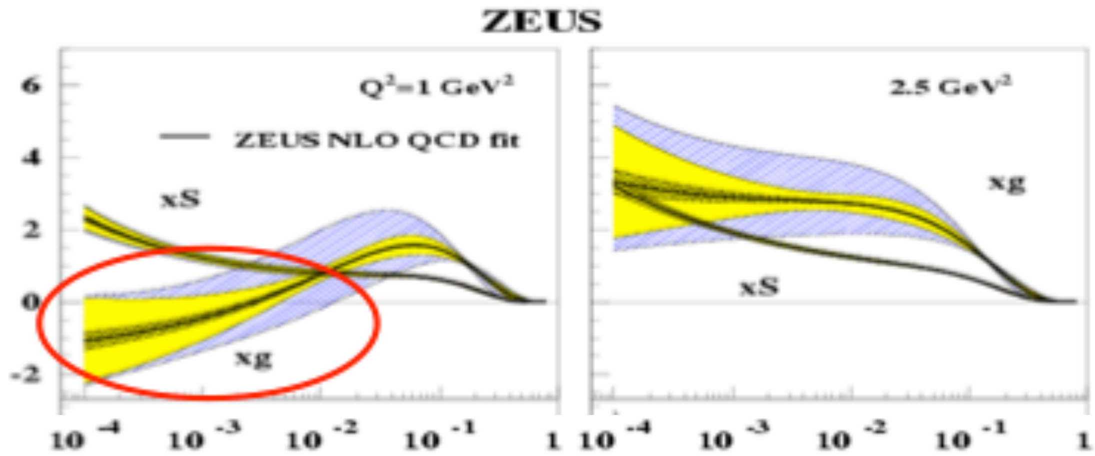
No!

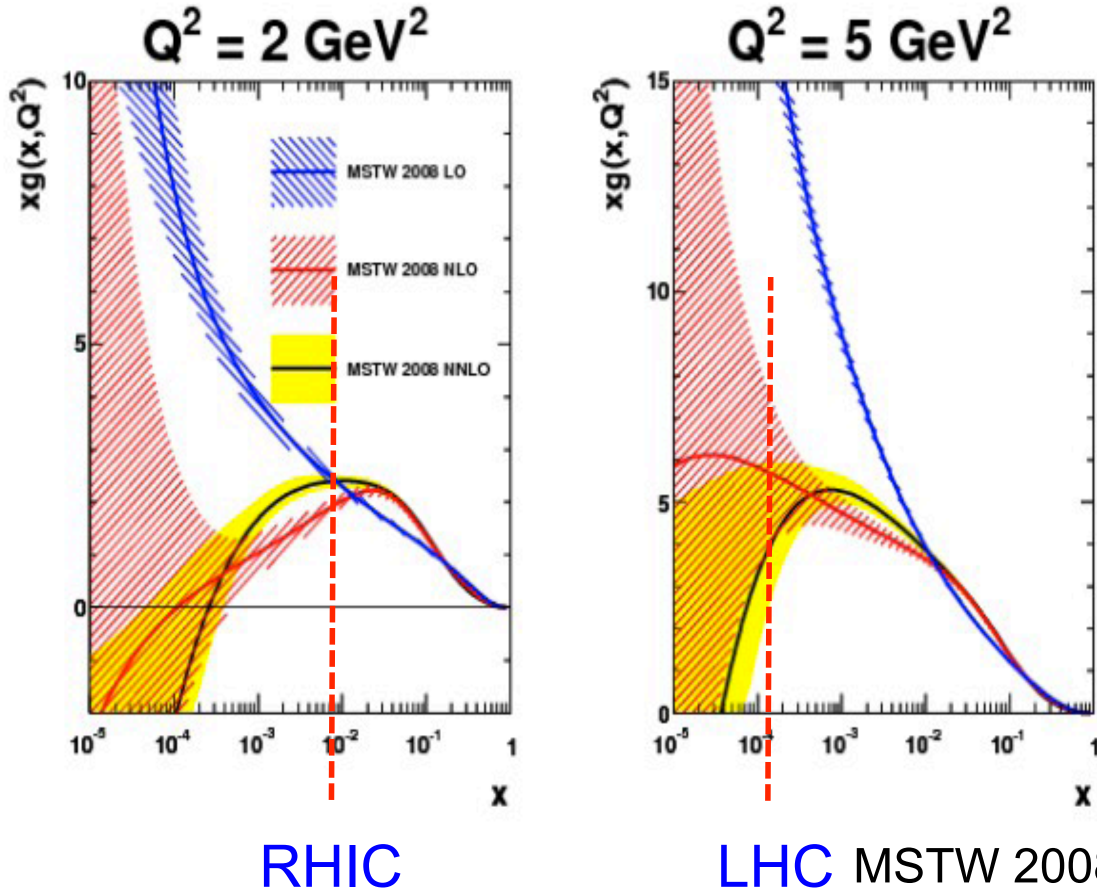
- **DGLAP evolution:**

$$P^{(1)}_{g/g}(x) \propto \frac{1}{x}$$

Gluon recombination slows down small-x evolution

More direct probe of glue!

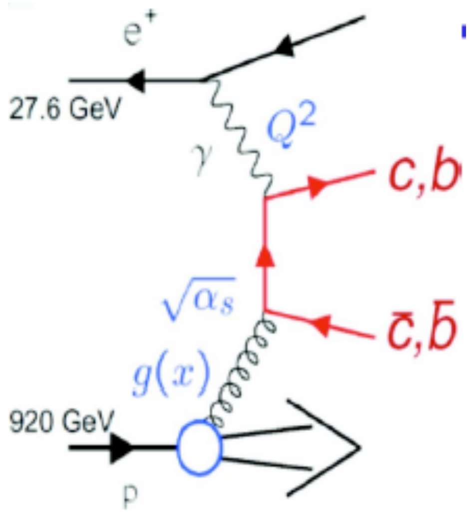


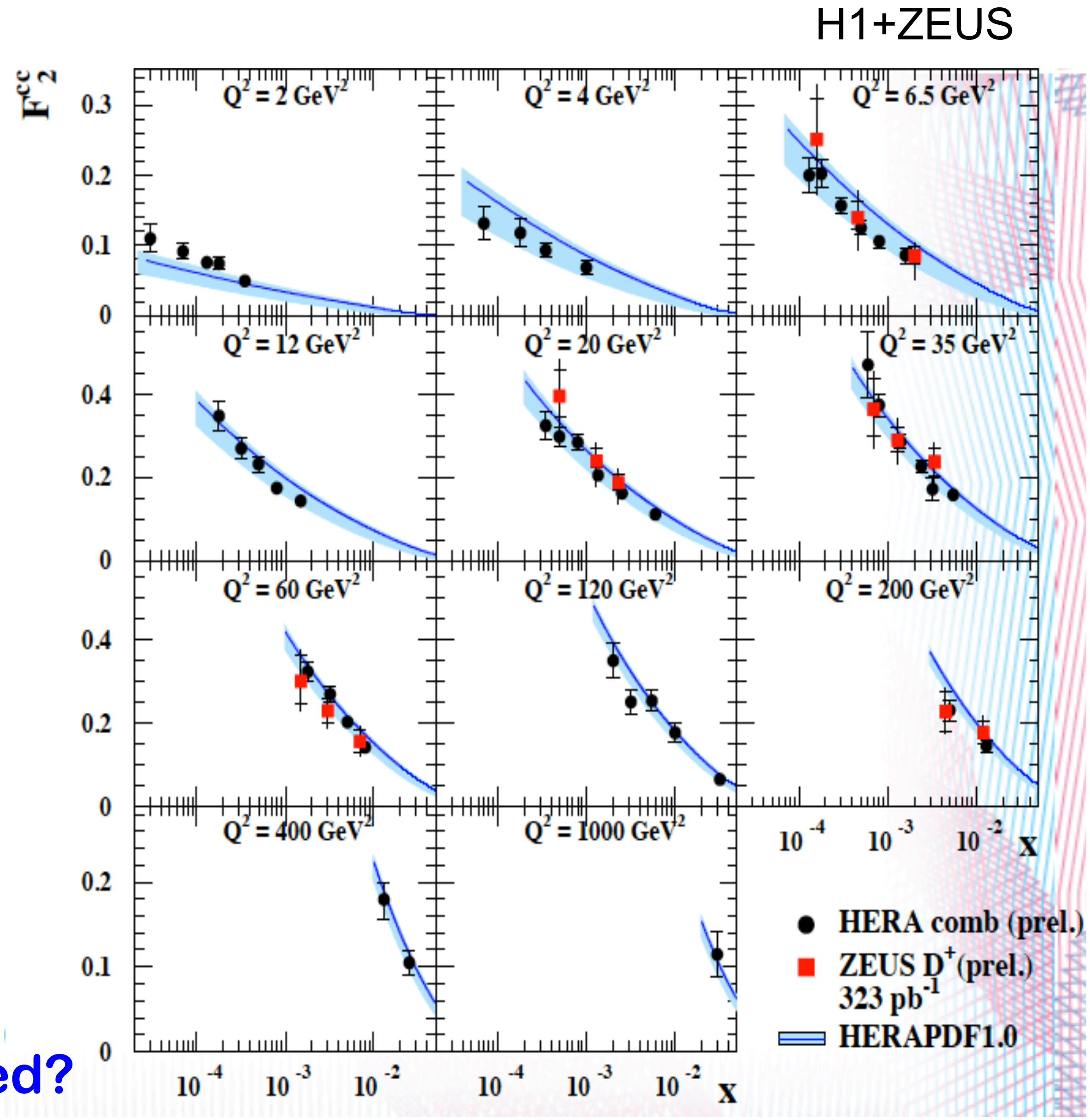


MSTW 2008

Direct information on gluon distribution

- Heavy flavor production in SIDIS:





Gluon continues to grow at $x=10^{-5}$ and $Q^2=2$ GeV^2

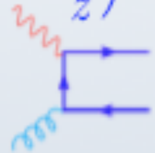
No sign of saturation yet at $Q^2=2$GeV^2!

What would happen if a nuclear target/beam is used?

Measurement of F_L

- F_L starts at $O(\alpha_s)$:

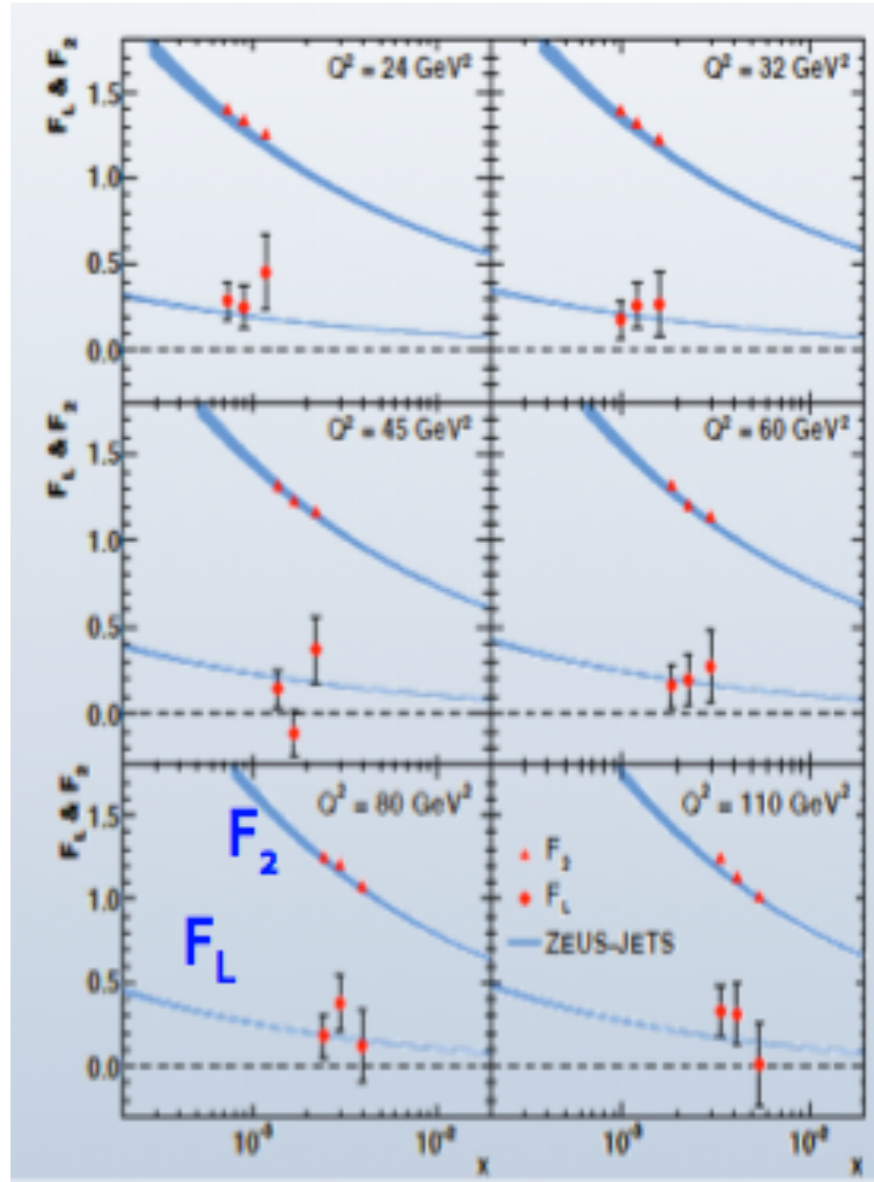
$$F_L = \frac{\alpha_s}{4\pi} x^2 \int_x^1 \frac{dz}{z^3} \left[\frac{16}{3} F_2(z) + 8 \sum_q e_q^2 \left(1 - \frac{x}{z}\right) z g(z) \right]$$



HERA data does not give new additional constraints on gluon

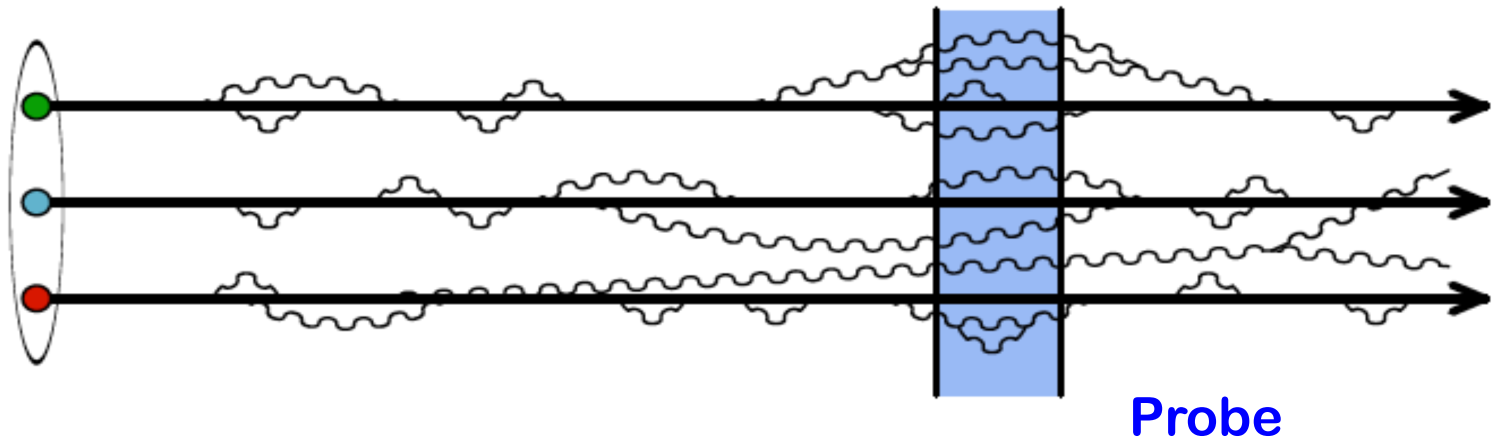
SIDIS could help!

EIC will have a much better reach in F_L



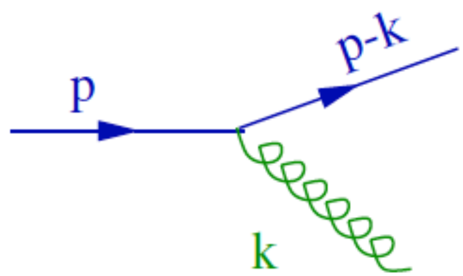
Low-x physics has to exist

❑ **Gluon recombination and saturation ought to be there:**



❑ **QCD color fluctuation taken place at various time scales:**

✧ **Radiation:**



$$dP \sim \alpha_s \frac{dk_T^2}{k_T^2} \frac{dx}{x}$$

✧ **Leads to change of distributions – evolution:**

DGLAP $\quad \frac{dk_T^2}{k_T^2} \rightarrow d\log(Q^2)$ $\qquad$ BFKL $\quad \frac{dx}{x} \rightarrow d\log(1/x)$

Direct HERA data seems to indicate that the saturation is not there yet

Can nucleus help?

- Hard probe – process with a large momentum transfer:

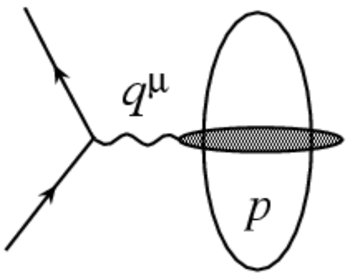
$$q^{\mu} \quad \text{with} \quad Q \equiv \sqrt{|q^2|} \gg \Lambda_{\mathrm{QCD}}$$

- Size of a hard probe is very localized and much smaller than a typical hadron at rest:

$$\frac{1}{Q} \ll 2R \sim \mathrm{fm}$$

- But, it might be larger than a Lorentz contracted hadron:

$$\frac{1}{Q} \sim \frac{1}{xp} \gg 2R\left(\frac{m}{p}\right) \quad \text{or equivalently} \quad x \ll x_c \equiv \frac{1}{2mR} \sim 0.1$$

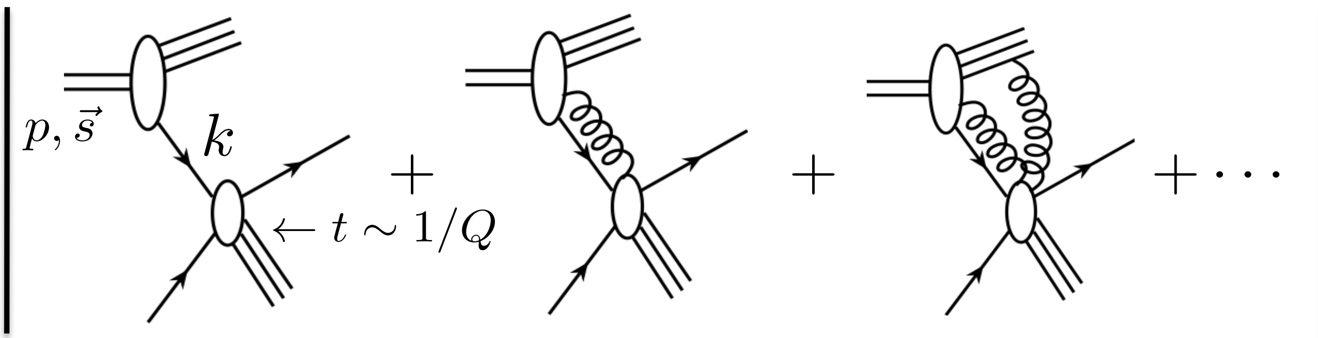


If an active parton x is small enough the hard probe could cover several nucleons in a Lorentz contracted large nucleus!

Power corrections become important

- **We measure cross sections – single hard scale:**

$$\sigma(Q,\vec{s}) \propto \left| \;\; \right|^2$$



$$\sigma_{AB}(Q,\vec{s}) \approx \sigma^{(2)}_{AB}(Q,\vec{s}) + \frac{Q_s}{Q}\sigma^{(3)}_{AB}(Q,\vec{s}) + \frac{Q_s^2}{Q^2}\sigma^{(4)}_{AB}(Q,\vec{s}) + \cdots$$

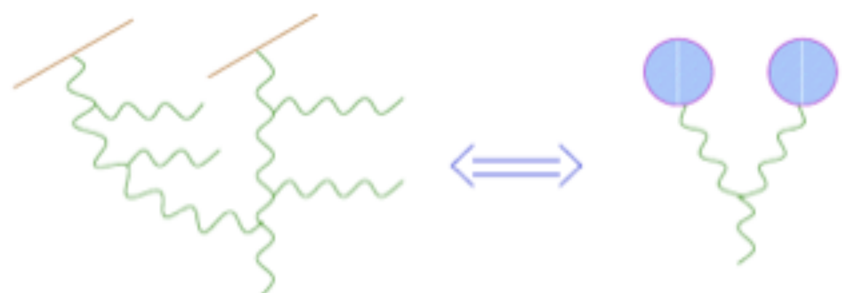
- **Saturation scale:**

  ✧ **Gluon shower: virtuality of the active parton before hard collision**

$$Q_s^2(x) \sim \langle k_T^2\rangle \sim \Lambda^2_{\rm QCD}\,\alpha_s\,\log\left(\frac{Q^2}{\Lambda^2_{\rm QCD}}\right)\log\left(\frac{s}{Q^2}\right) \propto \log(1/x)$$

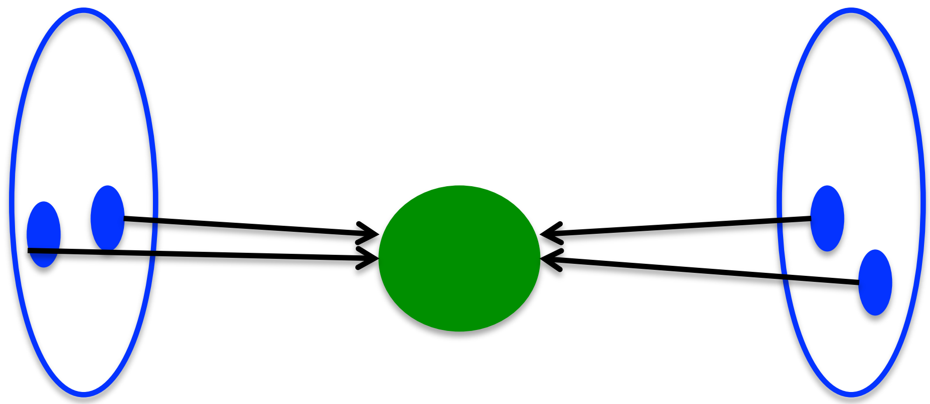
  ✧ **Gluon recombination:**

$$Q_s^2(x) \simeq \alpha_s\,\frac{xG(x,Q_s^2)}{\pi R^2} \sim \frac{1}{x^\lambda}$$



Color coherence between nucleons

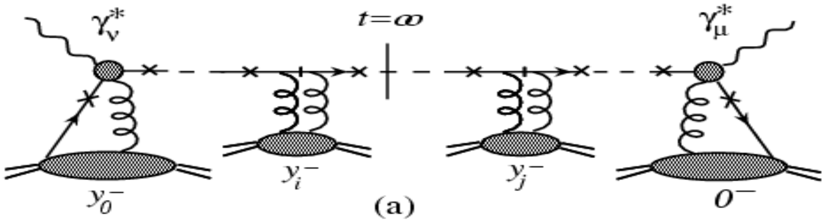
$A^{1/3}$ **No color coherence between amp and cc**



$A^{2/3}$ **Complete color coherence in nucleus**
– more like proton case

Additional multi-parton interaction

❑ Resummation of powers in $1/Q^2$



$$x_B^N\left[(-1)^N\frac{1}{N!}\frac{d^N}{dx^N}\delta(x-x_B)\right]$$

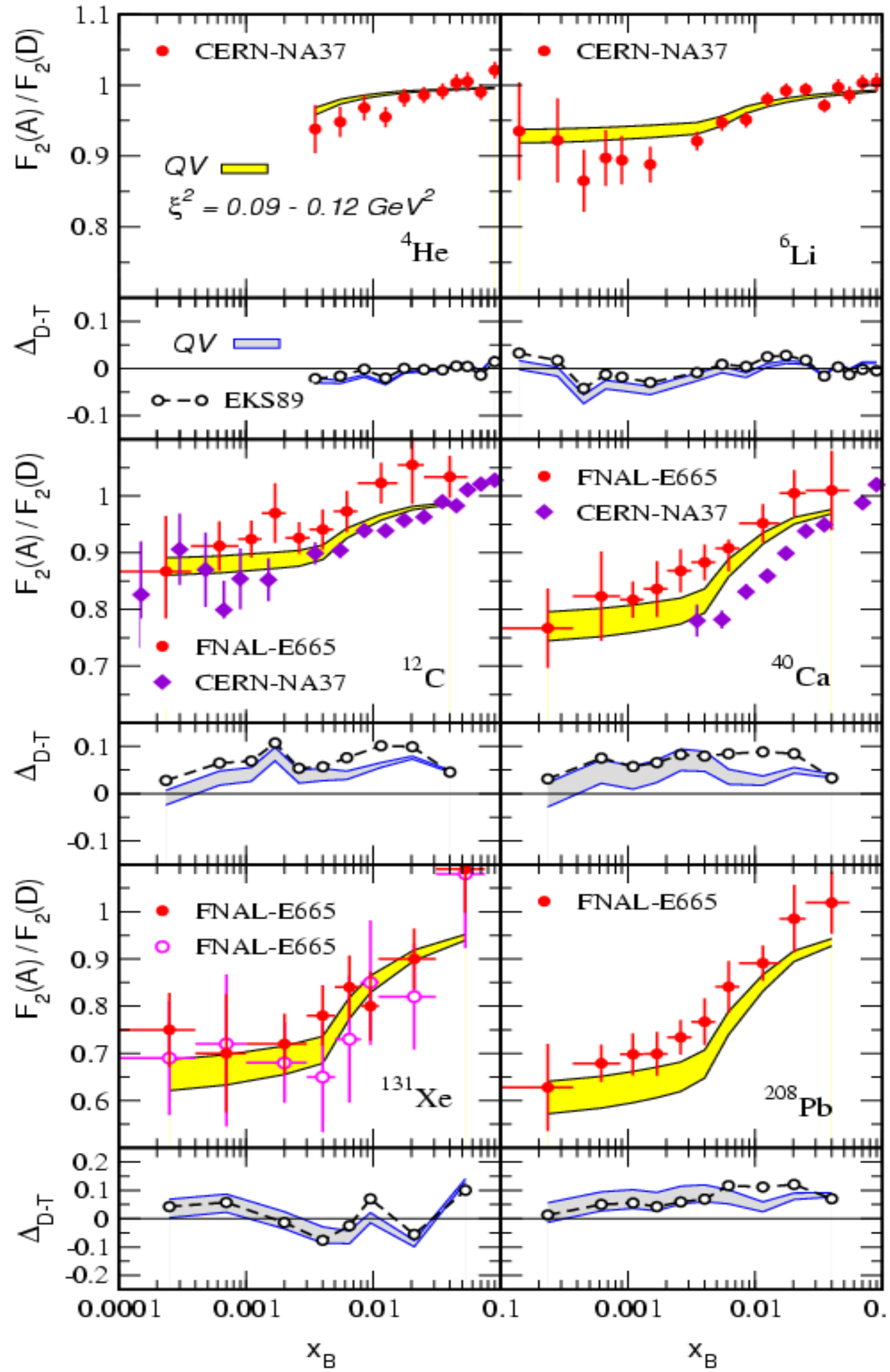
$$F_T(x_B,Q^2)=\sum_{n=0}^{N}\frac{1}{n!}\left[\frac{\xi^2}{Q^2}\left(A^{1/3}-1\right)\right]^n x_B^n\frac{d^n}{dx_B^n}F_T^{(0)}(x_B,Q^2)$$

$$\approx F_T^{(0)}(x_B(1+\Delta),Q^2)$$

$$\Delta\equiv\frac{\xi^2}{Q^2}\left(A^{1/3}-1\right)$$

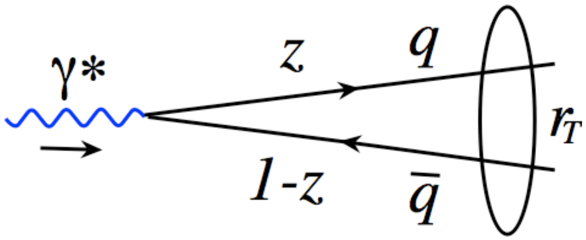
$$\xi^2=\frac{3\pi\alpha_s}{8R^2}\langle F^{+\alpha}F_\alpha{}^{+}\rangle$$

$\xi^2 \sim$ 0.09 - 0.12 GeV^2



Golec-Biernat and Wustoff Model

- In target rest frame:



$$\sigma_{T,L}^{\gamma^* p} = \int d^2 r_T \int dz \left|\psi_{T,L}(r_T, z, Q^2)\right|^2 \sigma_{q\bar{q}p}(r_T, x)$$
$$\sigma_{q\bar{q}p}(r_T, x) = \sigma_0 \left[1 - \exp(-r_T^2\, Q_s^2(x))\right]$$

- Saturation scale:

$$Q_s^2(x) \equiv Q_0^2 \left(\frac{x_0}{x}\right)^{\lambda}$$

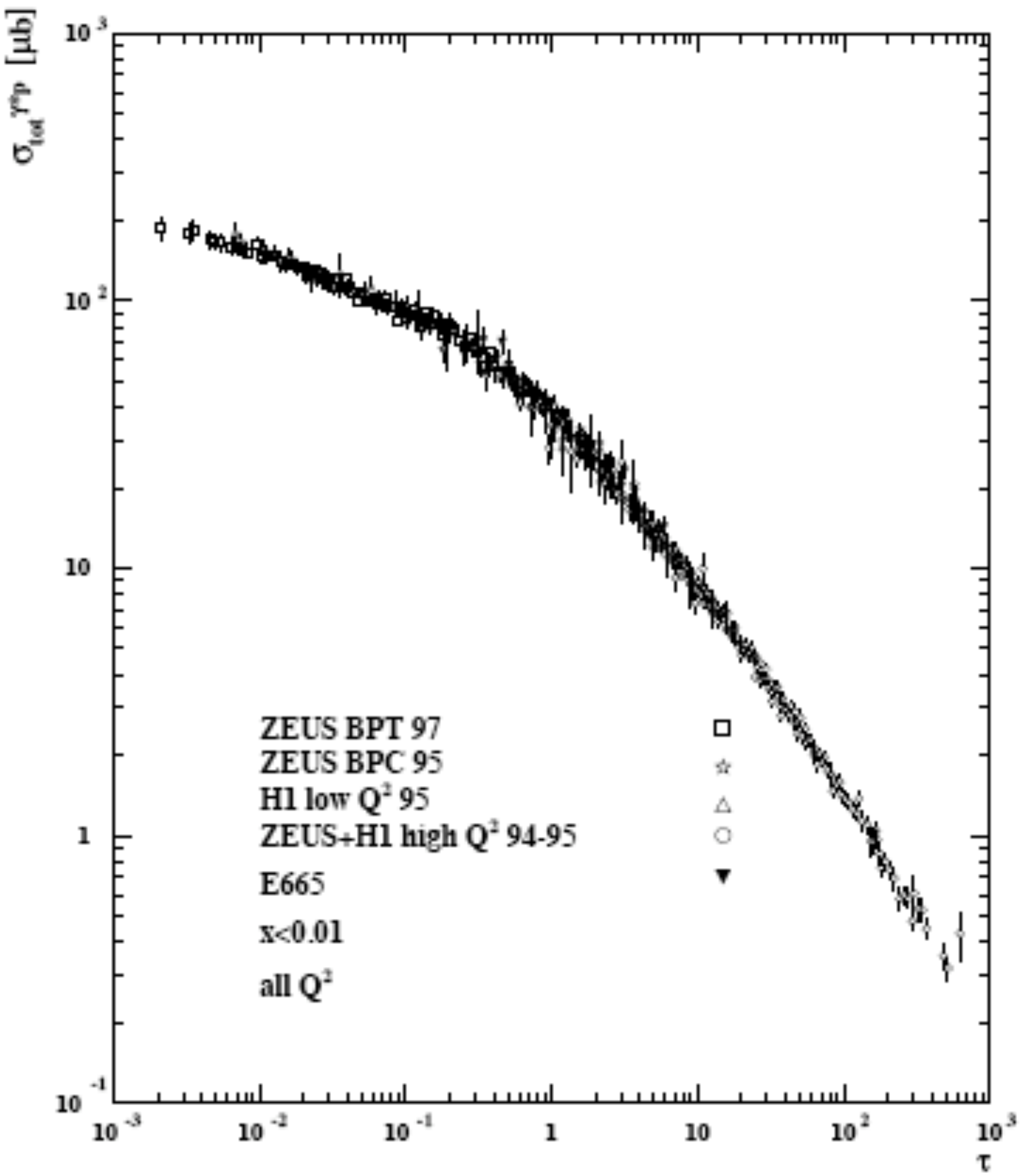
Fix all four parameters by fitting all HERA data with x<0.01 and all Q

$$Q_0 = 1\,\mathrm{GeV};\;\; \lambda = 0.3;\;\; x_0 = 3 \cdot 10^{-4};\;\; \sigma_0 = 23\,\mathrm{mb}$$

- Prediction - geometric scaling:

$$\sigma_{T,L}^{\gamma^* p} = f_{T,L}(Q^2/Q_s^2(x))$$

Geometric scaling in HERA data



$$\tau \equiv \frac{Q^2}{Q_s^2(x)}$$

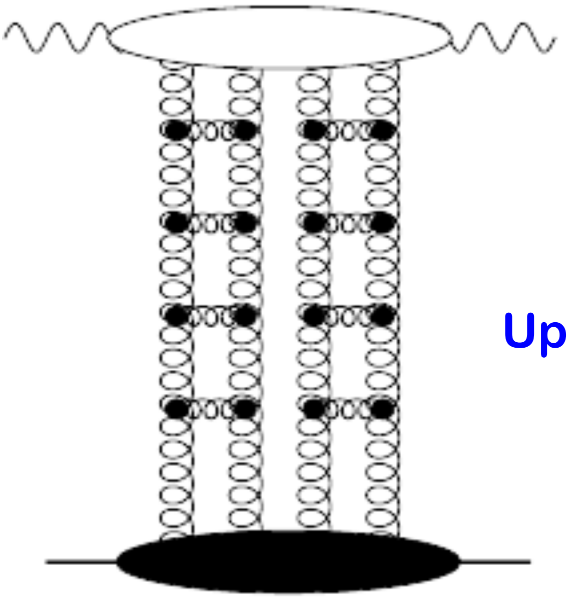
$$0.045 \leq Q^2 \leq 450 \mathrm{GeV}^2$$

Multi-gluon interaction

Bartels, INT

- Twist-4 contribution:

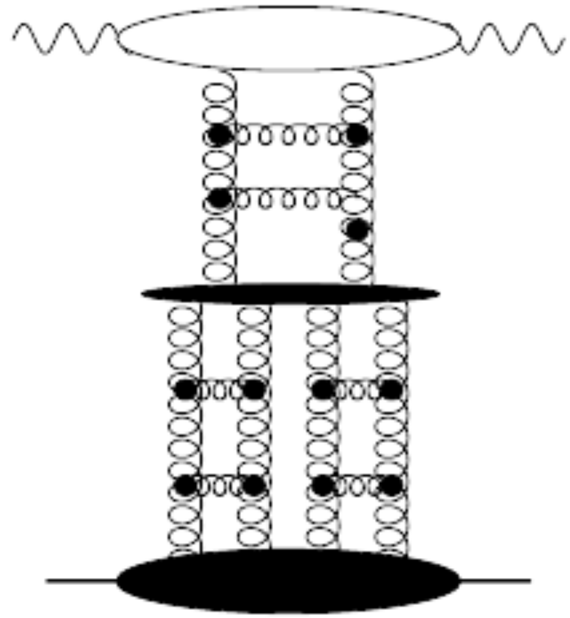
twist expansion



Up to $A^{2/3}$

Correlation at the collision point

log 1/x summation



BK equation, (saturation models)

Correlation in the history of a single gluon

- Twist-4 contribution is important:

Positive to F_T, negative to F_L, almost cancel for F_2

EIC measurement of F_T and F_L will be able to explore the difference

Summary

- After 35 years, we have learned a lot of QCD dynamics, but, only at very short-distance - less than 0.1 fm, and limited information on non-perturbative parton structure

- EIC with polarization provide a new program to test the new frontier research of QCD dynamics – key to the visible matter

- Understanding proton spin could provide the first complete example to describe the fundamental properties of hadrons

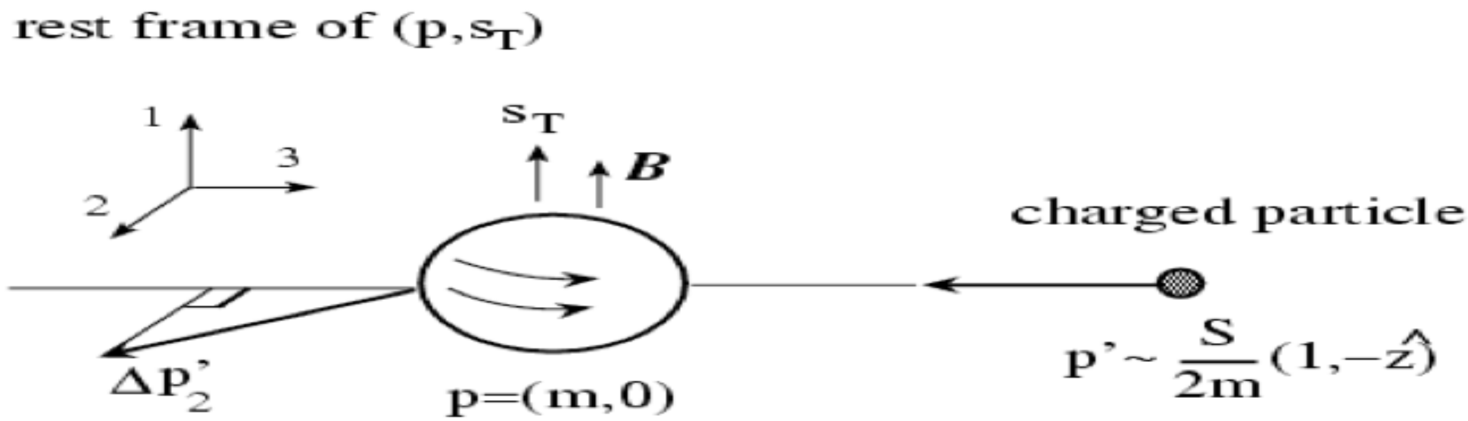
- Understanding the A-dependence of e+A collisions help understand the color distribution inside a large nucleus:
  - $A^{1/3}$ – color localized in nucleon,
  - $A^{2/3}$ – universal behavior between proton and a nucleus

Thank you!

Backup slices

What the twist-3 distribution can tell us?

- The operator in Red – a classical Abelian case:



- Change of transverse momentum:

$$\frac{d}{dt}p_2' = e(\vec{v}' \times \vec{B})_2 = -ev_3 B_1 = ev_3 F_{23}$$

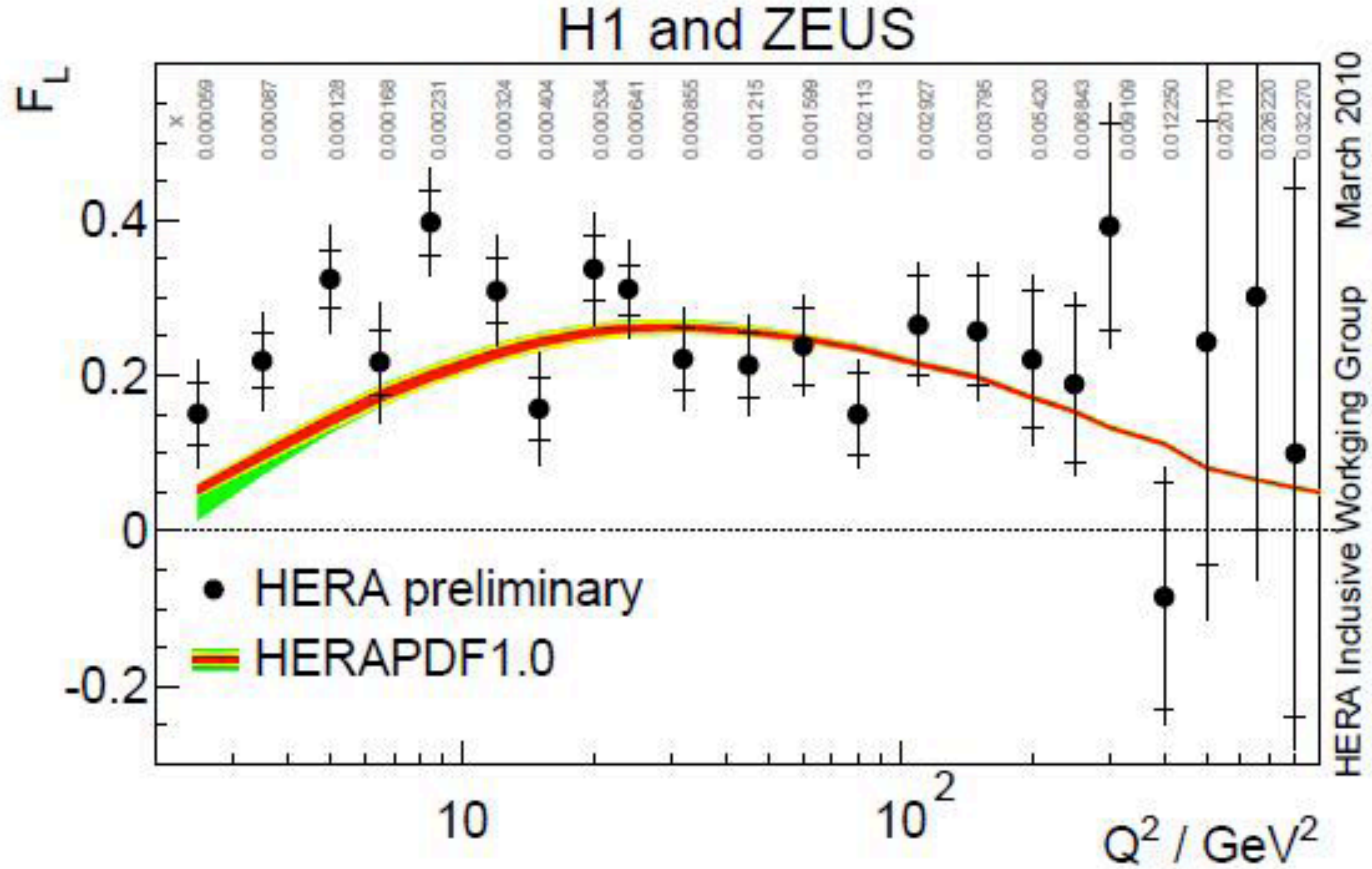
- In the c.m. frame:

$$(m, \vec{0}) \to \bar{n} = (1, 0, 0_T), \quad (1, -\hat{z}) \to n = (0, 1, 0_T)$$

$$\Longrightarrow \quad \frac{d}{dt}p_2' = e\, \epsilon^{s_T \sigma n \bar{n}}\, F_\sigma^{\ +}$$

- The total change: $\boxed{\Delta p_2' = e \int dy^- \epsilon^{s_T \sigma n \bar{n}}\, F_\sigma^{\ +}(y^-)}$

Net quark transverse momentum imbalance caused by color Lorentz force inside a transversely polarized proton



NLO DGLAP PDF (HERAPDF 1.0) give a
reasonable description
of the measured FL.
The FL data not in the HERAPDF 1.0 fit.

Improvement to ΔG

- **NNLO?** Probably not yet

- **Key: Extrapolation to low x and high x**
  - ✧ Large x: total contribution might be small due to the steep falling phase space
  - ✧ Small x: larger phase space for shower and smaller Q for a fixed collision energy

$$\Rightarrow \text{Large } \langle k_T^2 \rangle \quad \ln(s/Q^2) \sim \ln(1/x)$$

- **Collinear factorization does not work when** $Q \sim Q_s(x) \sim \langle k_T \rangle$

$$G(x) = G^+(x) + G^-(x) \propto \frac{1}{x^{1+\alpha}}$$ at small x

$$\Delta G(x) = G^+(x) - G^-(x)$$ Could be proportional to $\frac{1}{x^\alpha}$

Not positive definite!

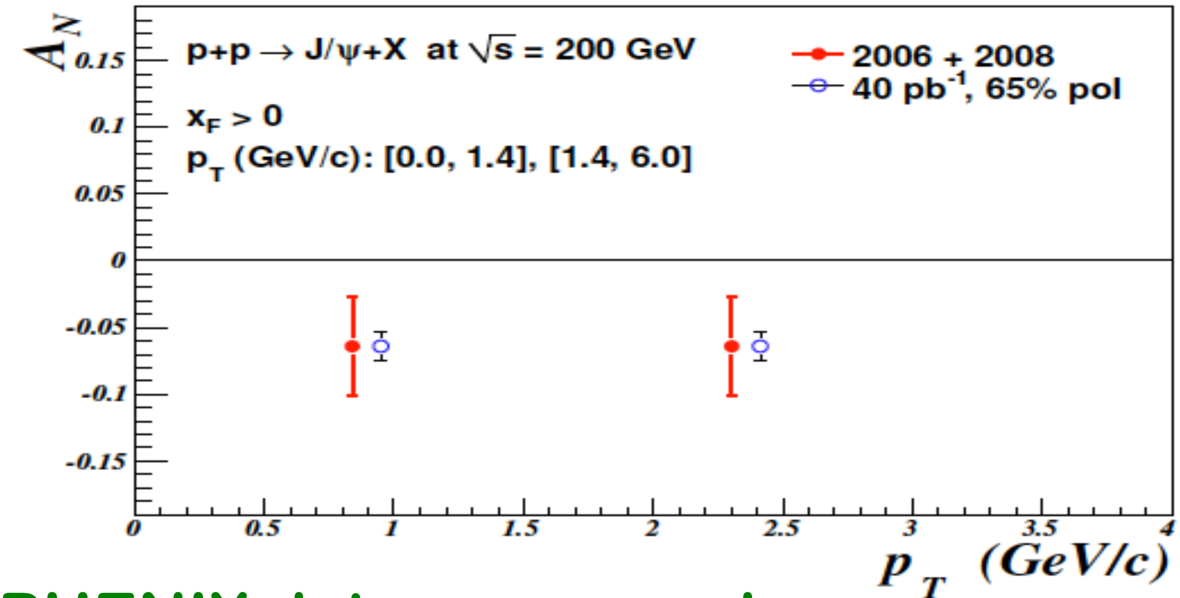
- **Current understanding of ΔG :**

ΔG ~ 2 is unlikely, but, ΔG ~ ¼ or ½ (¼) is still possible

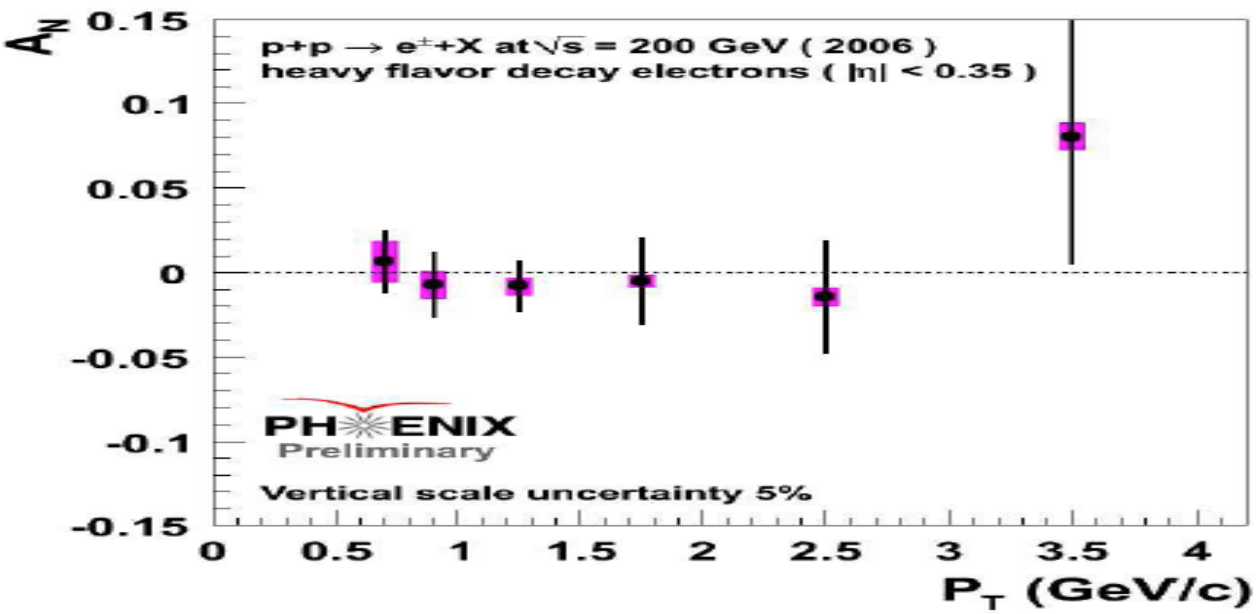
Theory effort is needed for understanding small-x behavior of ΔG !

SSA of charm production

- PHENIX data on J/psi:



- PHENIX data on open charm:



TMD factorization:

✧ Gluon Sivers function

✧ Initial-state vs final-state

Challenges:

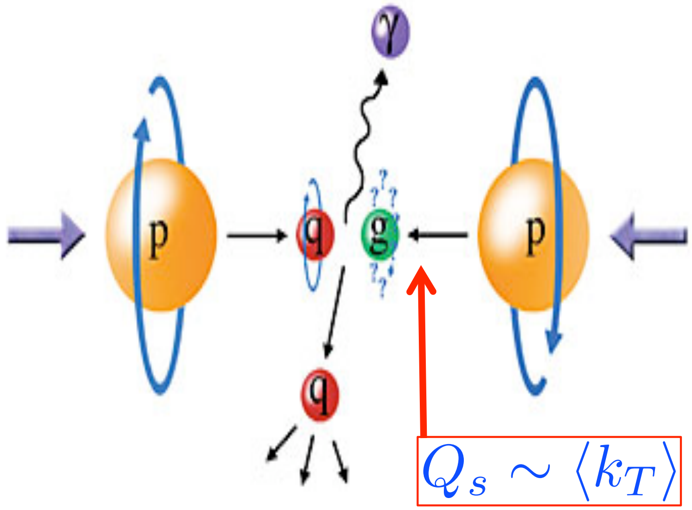
✧ J/psi production mechanism

✧ TMD factorization for hadornic coll.

Collins, Qiu, Vogelsang, Yuan, Rogers, Mulder, …

QCD factorization – approximation

❑ Collinear factorization – single hard scale:



$$\frac{d\sigma}{dy dp_T^2} = \int \frac{dx}{x} q(x) \int \frac{dx'}{x'} g(x') \frac{d\hat{\sigma}_{qg\to\gamma q}}{dy dp_T^2} + \mathcal{O}(\alpha_s^2) + \mathcal{O}\left(\frac{Q_s}{P_T}\right)^n$$

Convoluted with a fragmentation function for inclusive single particle production

❑ Transverse momentum dependent (TMD) factorization:

$$\frac{d\sigma}{dp_T^2 dq_T^2} = \int \frac{dx}{x} \int d^2k_T\, q(x,k_T) \int \frac{dx'}{x'} \int d^2k'_T\, g(x',k'_T) \frac{d\hat{\sigma}}{dp_T^2 dq_T^2} + \mathcal{O}(\alpha_s^2) + \mathcal{O}\left(\frac{q_T}{p_T}\right)$$

✧ Two very different physics scales: $p_T \gg q_T \gg \Lambda_{\rm QCD} \sim 1/{\rm fm}$

✧ Advantage: direct information on parton's transverse motion

✧ Challenges: theory effort needed to prove the factorization!