Theoretical Overview of e+p physics at an EIC

Jianwei Qiu
Brookhaven National Laboratory

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Outline of my talk

- ❑ Question(s)
- ❑ Challenges for theorists
- ❑ Why EIC – EIC advantages?
- ❑ Physics opportunities
- ❑ Summary

Challenges of strong interaction

- Hadron properties in terms of dynamics of quarks and gluons:

Hadron properties		QCD		
Charge, Mass, Spin, Magnetic moment, …	⟷	Quarks Color, Flavor, Charge, Mass, Spin, …	+	Gluons Color, Spin, …

- Lattice QCD:

  Could calculate all hadron properties in principle!

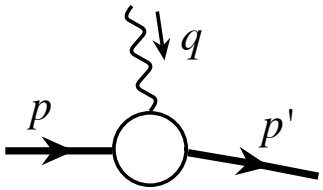
  Has done an excellent job in reproducing the hadron mass spectrum

- But,

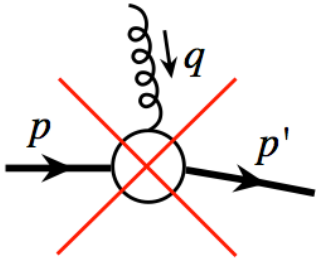
  It does not reveal the space-time distribution of partons inside a hadron, details of interactions, reasons of confinement, …

The “big” question(s)

- How color is distributed inside a hadron?
  (possible clue for color confinement, …)



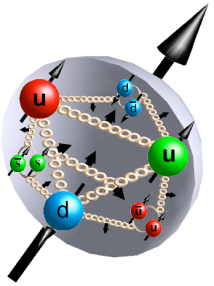
  - ✧ Electric form factor ➡ charge distribution

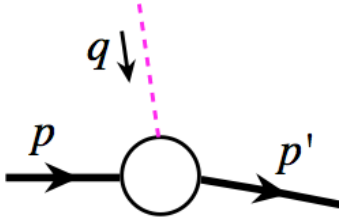


  But, no color form factor!

  Hadron is color singlet and gluon carries color

- How partons are distributed inside a hadron?
  (hadron’s partonic structure, …)





Need an effective strong interacting, but, color singlet current to keep the proton intact

OR use an inclusive process with a “localized” probe

Hadron's partonic structure

- **Ideal solution:**
  - ✧ **Measure or calculate matrix elements:**

$$\langle p, s|\mathcal{O}(\overline{\psi}_q, \psi_q, A^\mu)|p, s\rangle$$

with ALL possible combinations of parton fields

  - ✧ **Two parton correlations – parton densities:**

$$\langle p, s|\overline{\psi}_q(0)\,\Gamma\,\psi_q(y)|p, s\rangle \quad \langle p, s|F^{+\alpha}(0)F^{+\beta}(y)|p, s\rangle$$

  - ✧ **Three parton correlations – measure of color forces:**

$$\langle p, s|\overline{\psi}_q(0)\,\Gamma\,\left[\epsilon_\perp^{s_T\sigma}F^+_\sigma(y')\right]\psi_q(y)|p, s\rangle$$

$$\langle p, s|\overline{\psi}_q(0)\,\Gamma\,\left[s_T^\sigma F^+_\sigma(y')\right]\psi_q(y)|p, s\rangle, \ldots$$

  - ✧ **Multi-parton correlations – coherence of parton fields:**

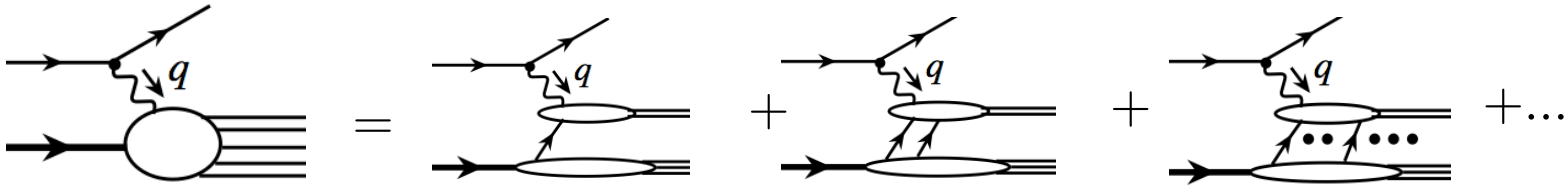
$$\langle p, s|\overline{\psi}_q(0)\,\Gamma\,\left[F^+_\alpha(y_1)F^+_\beta(y_2)\right]\psi_q(y)|p, s\rangle, \ldots$$

- **Problem:**

None of these matrix elements is a direct observable!
– color confinement

Challenges

- Hadronic cross sections:



  - ✧ Every parton can participate the hard collision!
  - ✧ Hadronic cross section depends on matrix elements of all fields

- Approximation – large momentum transfer: Q >> 1/fm

$$\sigma(Q) = \sigma^{\rm LP}(Q) + \frac{Q_s}{Q}\sigma^{\rm NLP}(Q) + \frac{Q_s^2}{Q^2}\sigma^{\rm NNLP}(Q) + ... \approx \sigma^{\rm LP}(Q)$$

- Factorization - approximation:

$$\sigma(Q) \approx \sigma^{\rm LP}(Q) \propto \hat{\sigma}(Q) \otimes \langle p,s|\tilde{\phi}^\dagger(k)\tilde{\phi}(k)|p,s\rangle + ...$$

Hadron's partonic structure!

- Challenges for theorists:

To identify measurable and factorizable physical quantities
– carry rich information on hadron's partonic structure

Why EIC?

- Probes for hadron's partonic structure need:
  - A large momentum transfer: Q >> 1/fm

    Localized probe, suppress contribution of complicate matrix elements
  - A small momentum scale: Q_2 ~ 1/fm

    Sensitive to parton's motion inside a hadron
  - QCD factorization can be applied!

$$\sigma(Q) \approx \sigma^{\rm LP}(Q) \propto \hat{\sigma}(Q) \otimes \langle p, s|\tilde{\phi}^\dagger(k)\tilde{\phi}(k)|p, s\rangle + \ldots$$

Calibrated local probe!

Hadron's partonic structure!

  - Polarization – probe different parton operators/structure:

$$\langle p, s|\mathcal{O}(\psi_q, A^\mu)|p, s\rangle - \langle p, -s|\mathcal{O}(\psi_q, A^\mu)|p, -s\rangle$$

- EIC has advantages on all these requirements!

Some EIC e+p opportunities

Still interesting beyond 2020

- ❑ Inclusive DIS – Spin, F_L, …
- ❑ SIDIS – TMDs, spin-orbital correlations, …
- ❑ GPDs – parton spatial distributions
- ❑ …

(A personal selection of limited topics in a limited time)

Many excellent talks in this conferences!

EIC webpages: http://web.mit.edu/eicc/index.html
http://www.int.washington.edu/PROGRAMS/10-3/
…

Golden PDF measurements

Science Deliverable	Basic Measurement	Uniqueness Feasibility Relevance	Requirements
spin structure at small x contribution of Δg, $\Delta\Sigma$ to spin sum rule	inclusive DIS	✔	need to reach $x=10^{-4}$ large x, Q^2 coverage about $10 fb^{-1}$
full flavor separation in large x, Q^2 range strangeness, $s(x)-\bar{s}(x)$ polarized sea	semi-inclusive DIS	✔	very similar to DIS excellent particle ID improved FFs (Belle,LHC,...)
electroweak probes of proton structure flavor separation electroweak parameters	inclusive DIS at high Q^2	✔ some unp. results from HERA	20x250 to 30x325 positron beam ? polarized ^{3}He beam ?

Stratmann's talk to EICAC review

The "money" plot – inclusive DIS

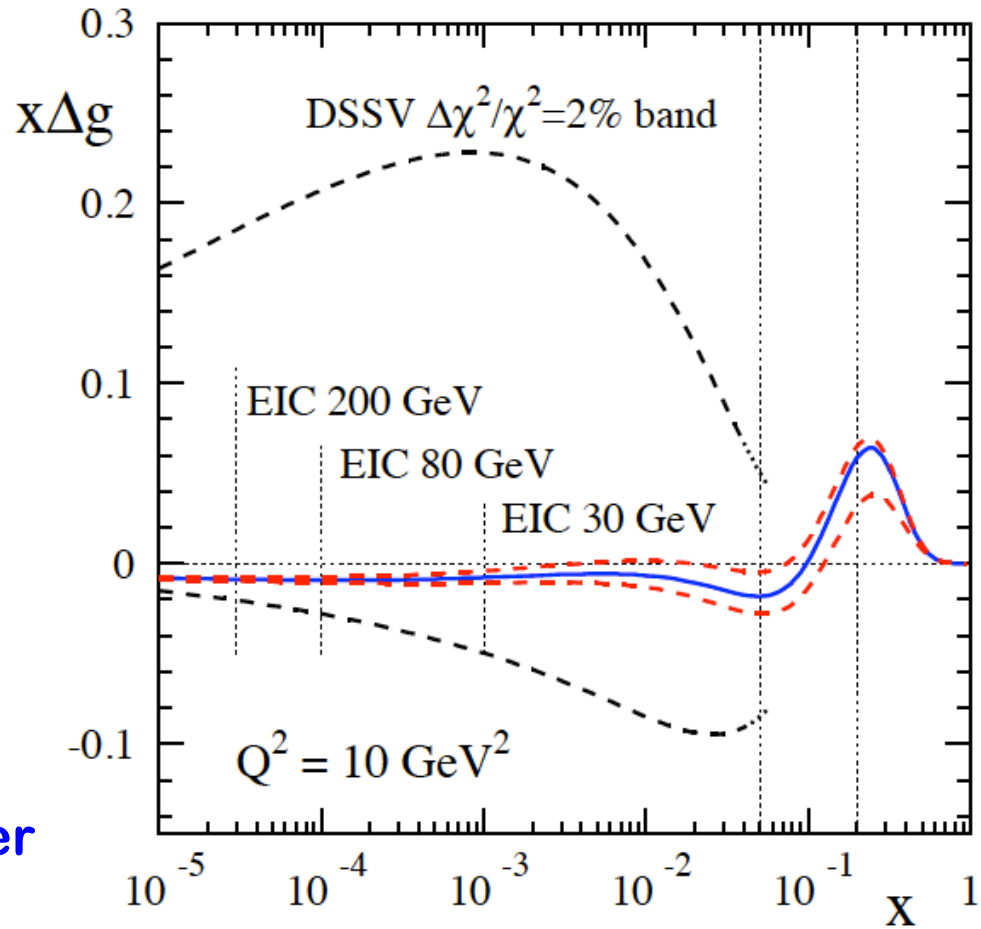
- **Precision of $\Delta g(x,Q^2)$:**

$$\frac{dg_1}{d\ln Q^2} \propto \Delta g(x,Q^2)$$

Expectation:

$$\int_0^1 dx\, \Delta g(x,Q^2)$$ **to 10% level?**

- **Questions:**
  - ✧ **Physics behind the node?**
  - ✧ **Factorization at small-x?**
  - ✧ **Dominance of leading power when it is so small?**
  - ✧ **…**



See stratmann's talk

$F_L(x,Q^2)$ – Inclusive DIS

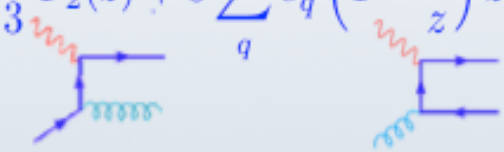
- Unfinished business of HERA:

Test of pQCD expansion

(NNLO – three loops)

No small-x growth until NNLO

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



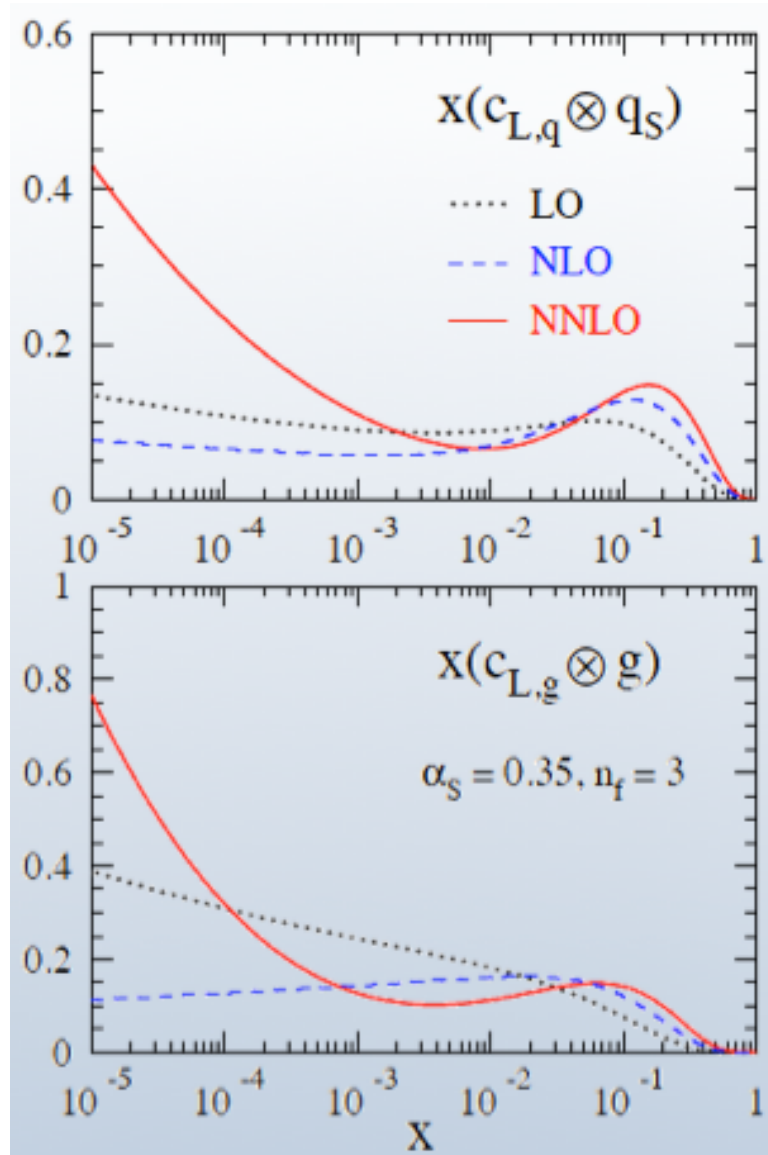
Direct measurement of gluon

NO scheme to eliminate

The gluon contribution to F_L

(DIS scheme: no gluon for F_2)

See stratmann's talk



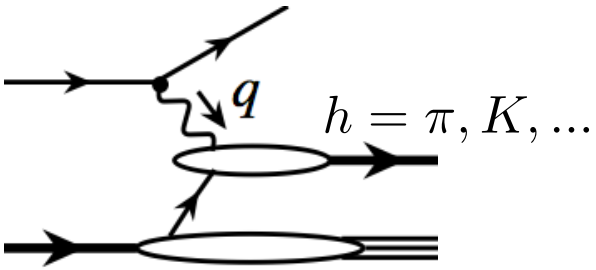
Quark flavor separation – SIDIS

- Integrate over final-state hadron's transverse momentum:

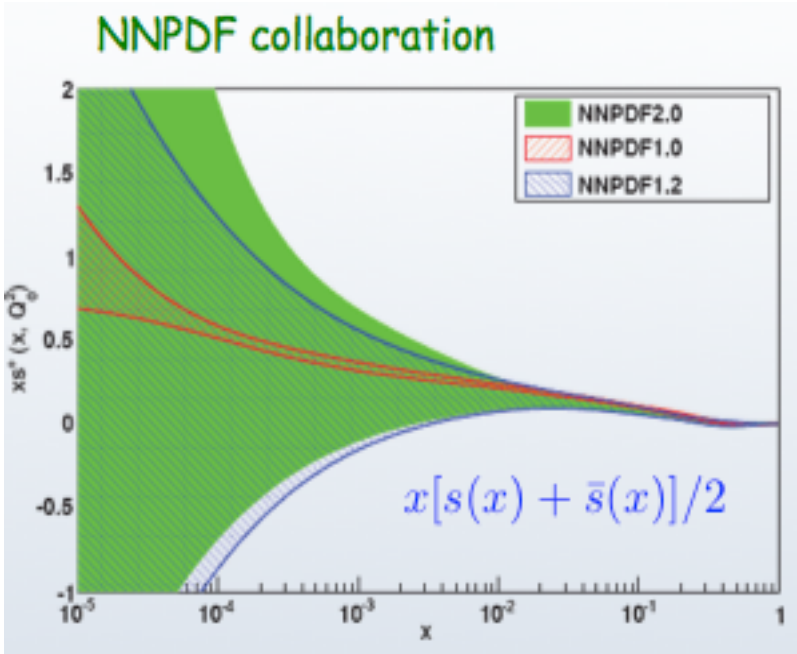
  One hard scale – collinear factorization

  $h = \pi, K, \ldots$

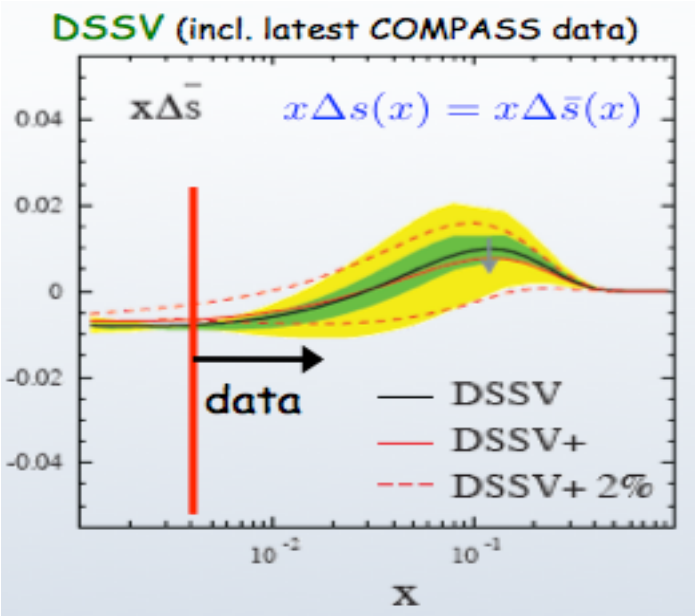
  Separation of parton flavors



- Strangeness distributions:



NuTeV anomaly on $\sin^2\theta_W$



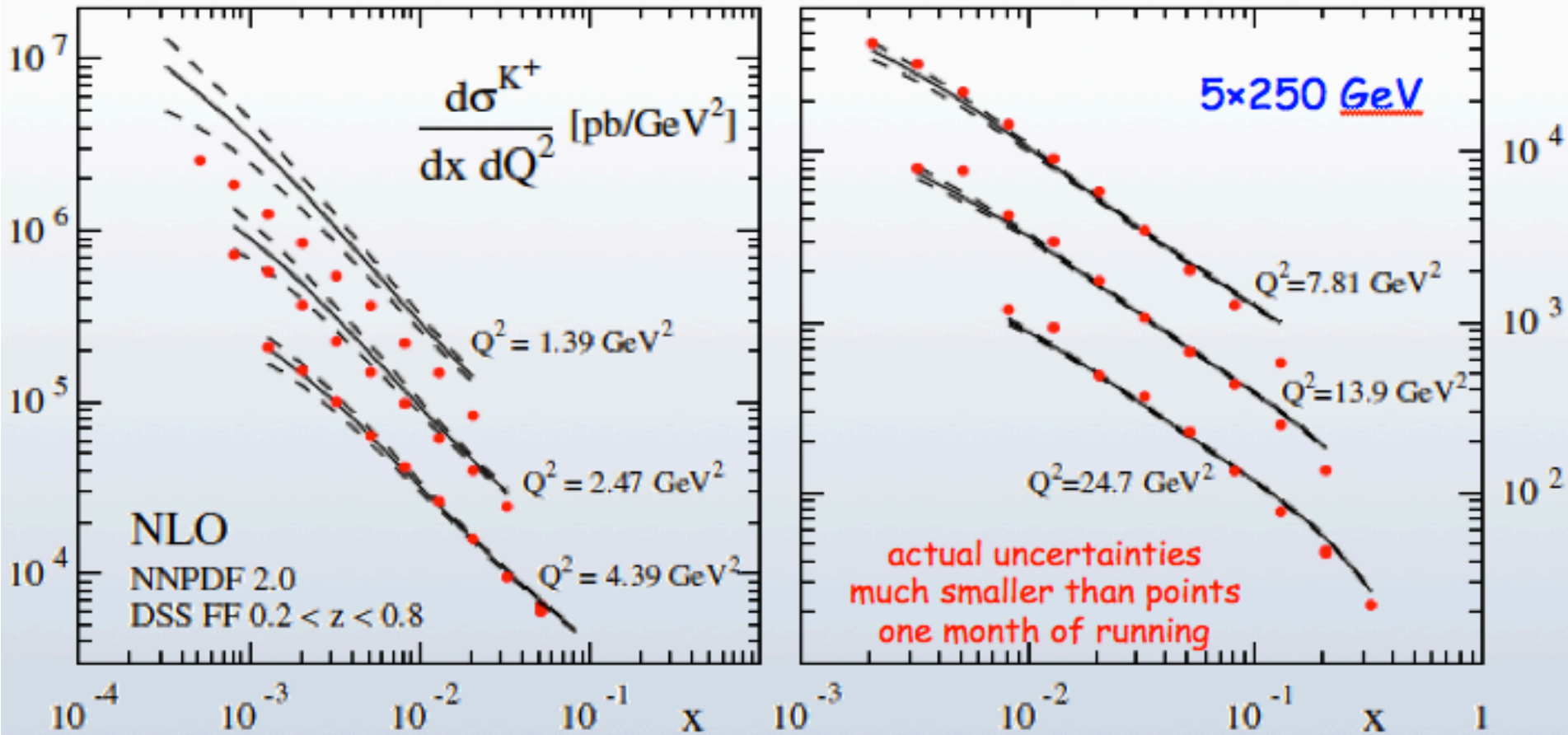
Tension with the 1st moment

EIC for charged kaons

compute K^+ yields at NLO with 100 NNPDF replicas

z integrated to minimize FF uncertainties (work in progress)

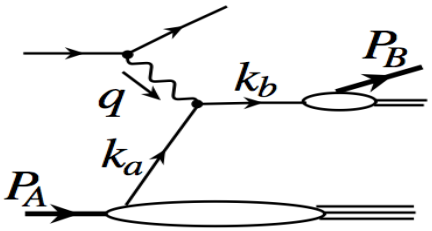
Aschenauer
Stratmann



PYTHIA agrees very well (despite ***very*** different hadronization model)

--> confidence that we can use MC to estimate yields & generate toy data

TMD factorization – SIDIS

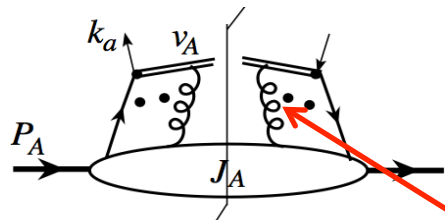


$$\sigma_0\, \phi(x,\mu) \otimes D(z,\mu)\delta^2(p_{BT})$$

$$\sigma_0\ \widetilde{\phi}(x,k_{aT}) \otimes \widetilde{D}(z,k_{bT})\ \delta^2(p_{BT} - k_{aT} - k_bT)$$

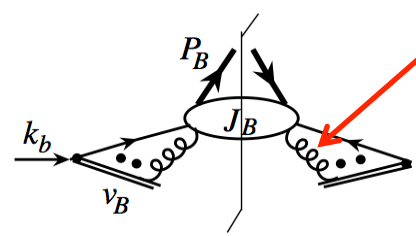
- **TMD parton distribution:**

$$\widetilde{\phi}^{(0)}_{f/A}(x,k_{aT}) = \mathrm{Tr}_{\mathrm{color}}\mathrm{Tr}_{\mathrm{Direc}}\frac{\gamma^+}{2}\int\frac{dk_a^-}{2\pi}$$



- **TMD fragmentation function:**

$$\widetilde{D}^{(0)}_{f\to B}(z,k_{bT}) = \frac{\mathrm{Tr}_{\mathrm{color}}}{N_c}\frac{\mathrm{Tr}_{\mathrm{Direc}}}{4}\frac{\gamma^+}{z}\int\frac{dk_b^-}{2\pi}$$



Gauge links

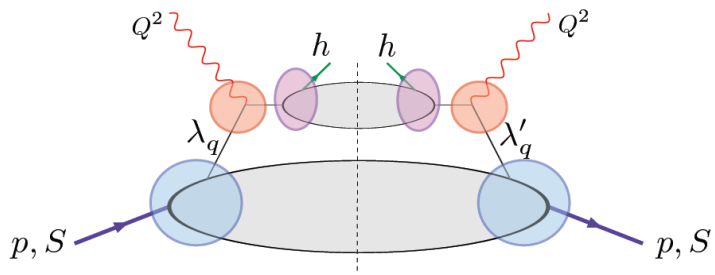
Phase for SSA

- **TMDs are more fundamental if we can measure them:**

Carry more information on hadron's partonic structure

EIC is ideal for studying TMDs

- **SIDIS has the natural kinematics for TMD factorization:**

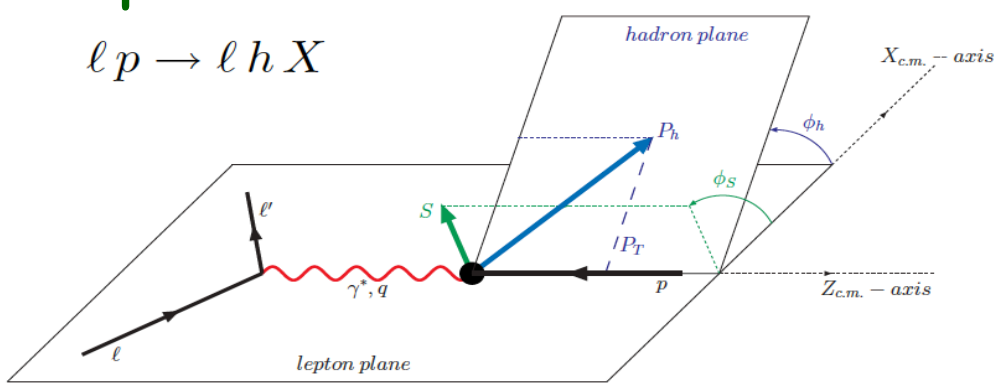


$$\ell(s_e) + p(s_p) \to \ell + h(s_h) + X$$

Natural event structure:

high Q and low p_T jet (or hadron)

- **Separation of various TMD contribution by angular projection:**



Lepton plane vs. hadron plane

$$A_{UT}(\varphi_h^l, \varphi_S^l) = \frac{1}{P}\frac{N^\uparrow - N^\downarrow}{N^\uparrow + N^\downarrow}$$

$$= A_{UT}^{Collins} \sin(\phi_h + \phi_S) + A_{UT}^{Sivers} \sin(\phi_h - \phi_S)$$

$$+ A_{UT}^{Pretzelosity} \sin(3\phi_h - \phi_S)$$

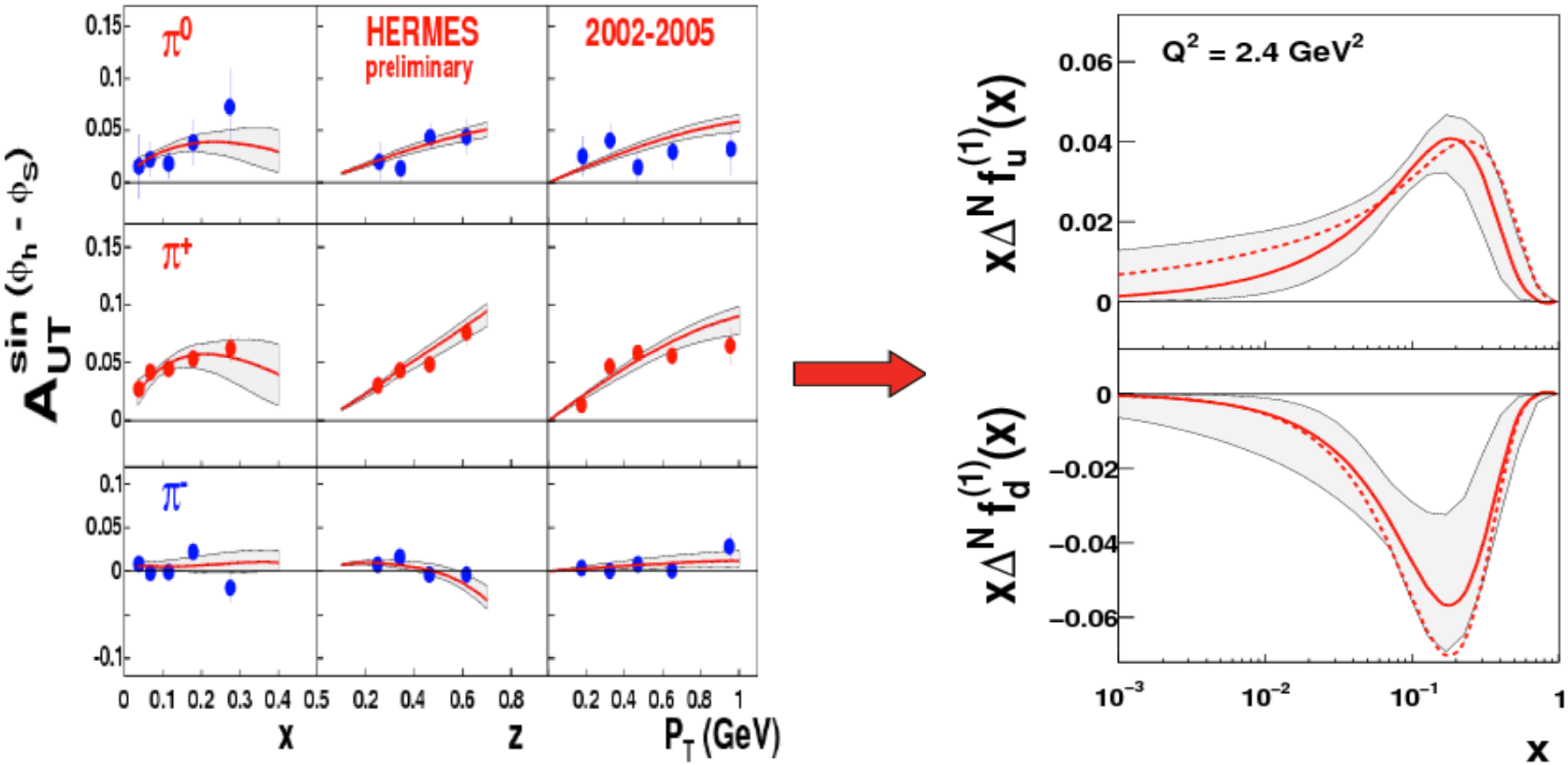
$$A_{UT}^{Collins} \propto \langle \sin(\phi_h + \phi_S) \rangle_{UT} \propto h_1 \otimes H_1^\perp$$

$$A_{UT}^{Sivers} \propto \langle \sin(\phi_h - \phi_S) \rangle_{UT} \propto f_{1T}^\perp \otimes D_1$$

$$A_{UT}^{Pretzelosity} \propto \langle \sin(3\phi_h - \phi_S) \rangle_{UT} \propto h_{1T}^\perp \otimes H_1^\perp$$

Our current knowledge on TMDs

- Sivers function from SIDIS:



EIC can do much better job in extracting TMDs

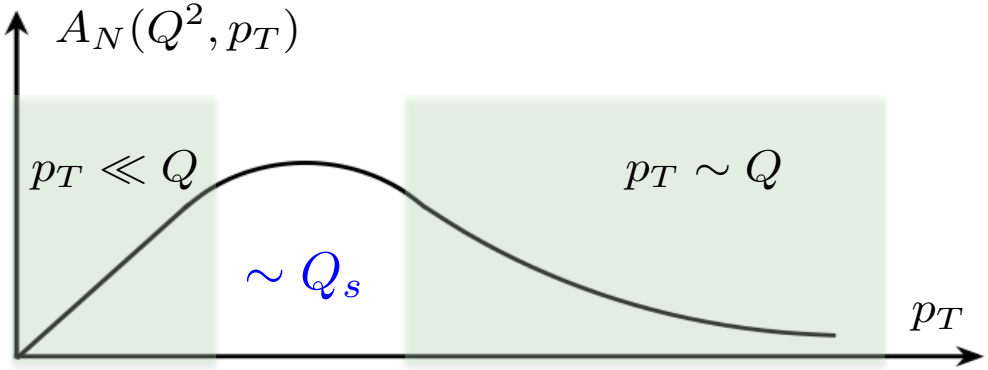
- NO TMD factorization for hadron production in p+p collisions

Collins and Qiu, 2007, Vogelsang and Yuan, 2007, Mulders and Rogers, 2010, …

From low p_T to high p_T

❑ TMD factorization to collinear factorization:

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



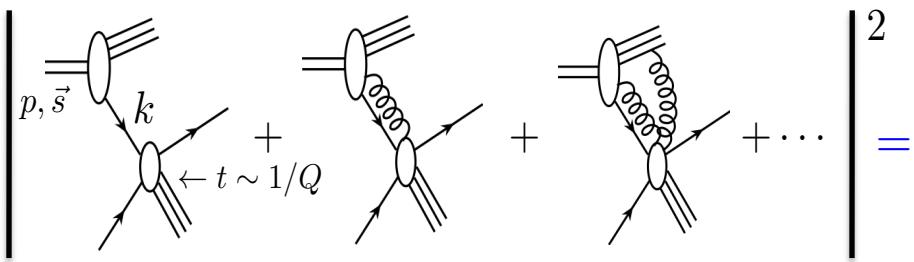
TMD **Collinear Factorization**

Two factorization are consistent in the overlap region where

$$\Lambda_{\rm QCD} \ll p_T \ll Q$$

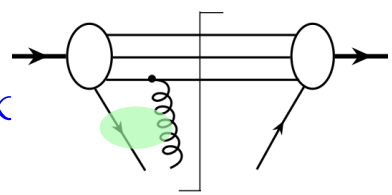
❑ Collinear factorization:

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

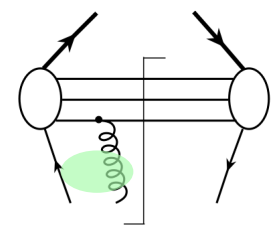
$\sigma(Q,\vec{s}) \propto$ 

$^2 = \sigma^{\rm LP}(Q,\vec{s}) + \frac{Q_s}{Q}\sigma^{\rm NLP}(Q,\vec{s}) + \ldots$

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

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

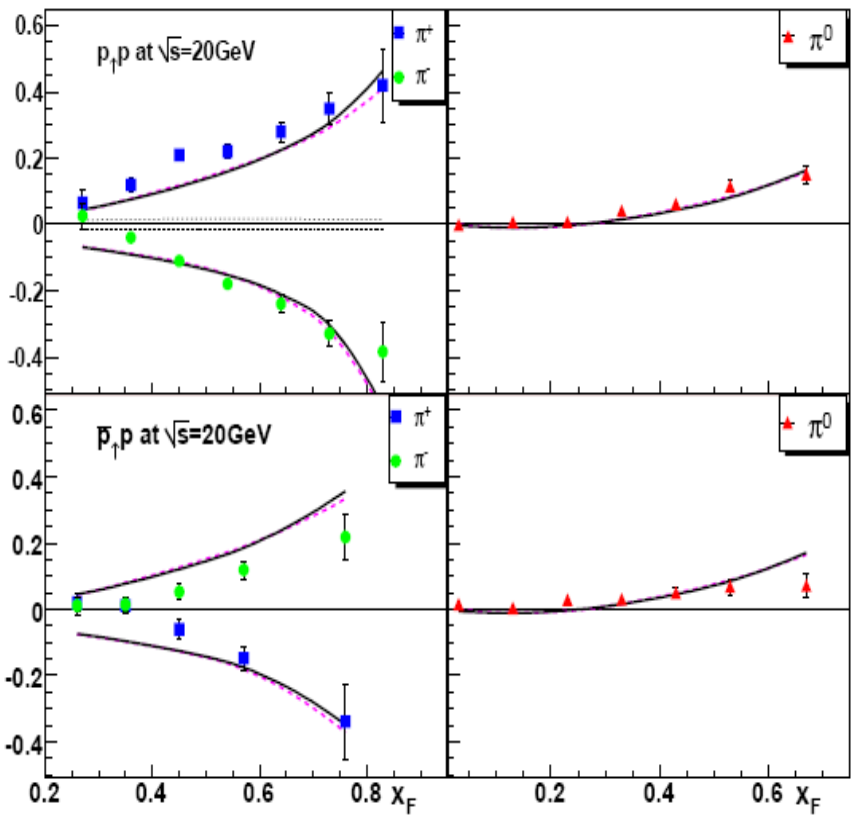
Qiu, Sterman, 1991, ...

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

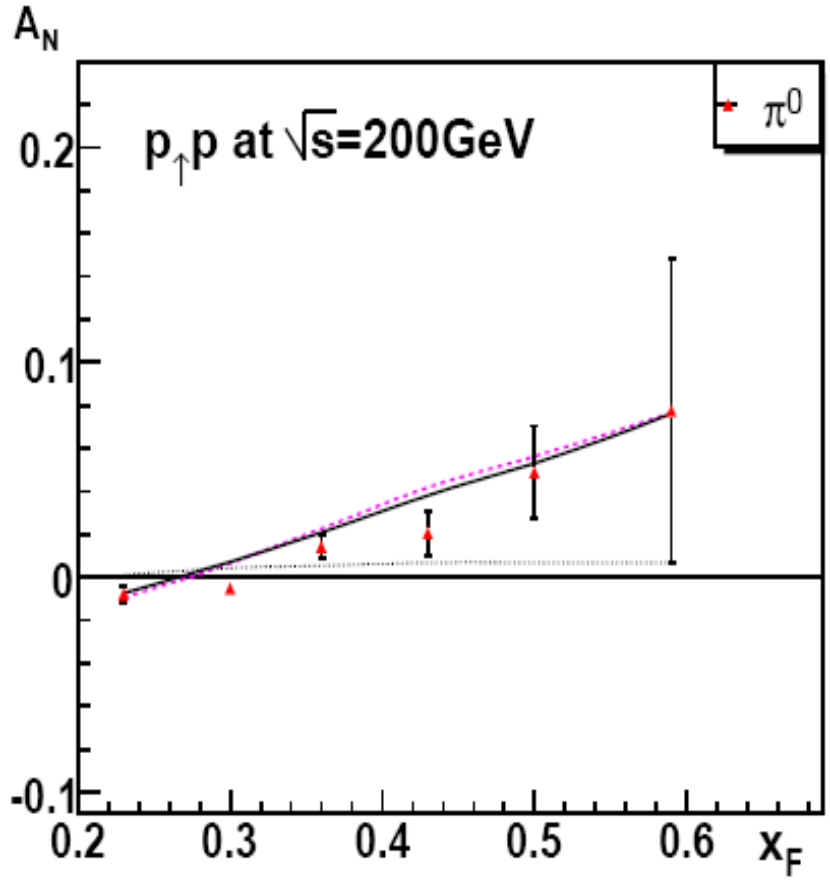
Kang, Yuan, Zhou, 2010

A_N from LO quark-gluon correlation

(FermiLab E704)



(RHIC STAR)



Kouvaris,Qiu,Vogelsang,Yuan, 2006

Nonvanish twist-3 function → Nonvanish transverse motion

Global QCD analysis for A_N

- **Universality of correlation functions:**

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

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

Same replacement for the gluons

Kang, Qiu, 2009

- **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

A sign "mismatch"

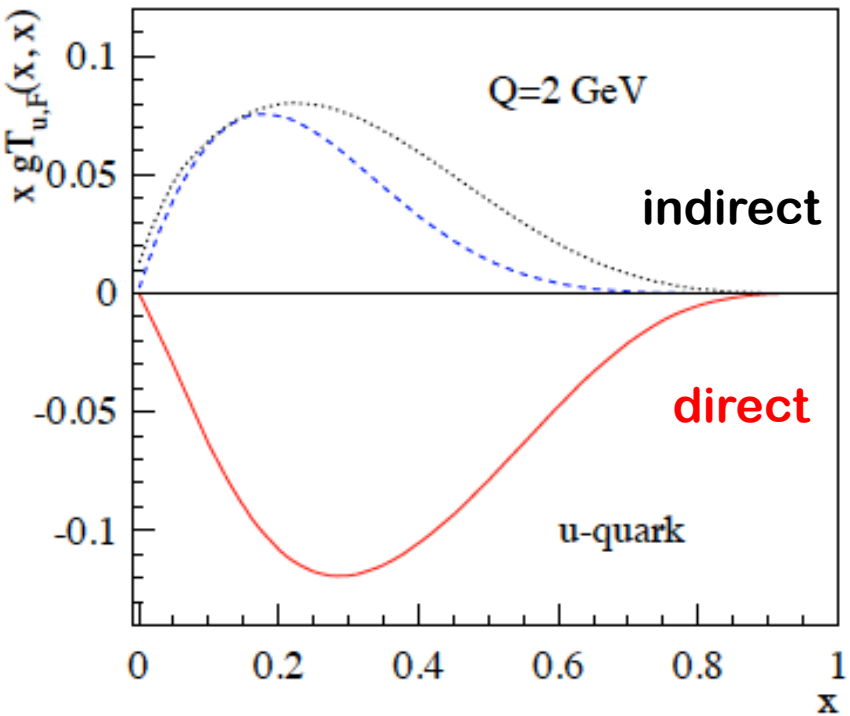
Kang, Qiu, Vogelsang, Yuan, 2011

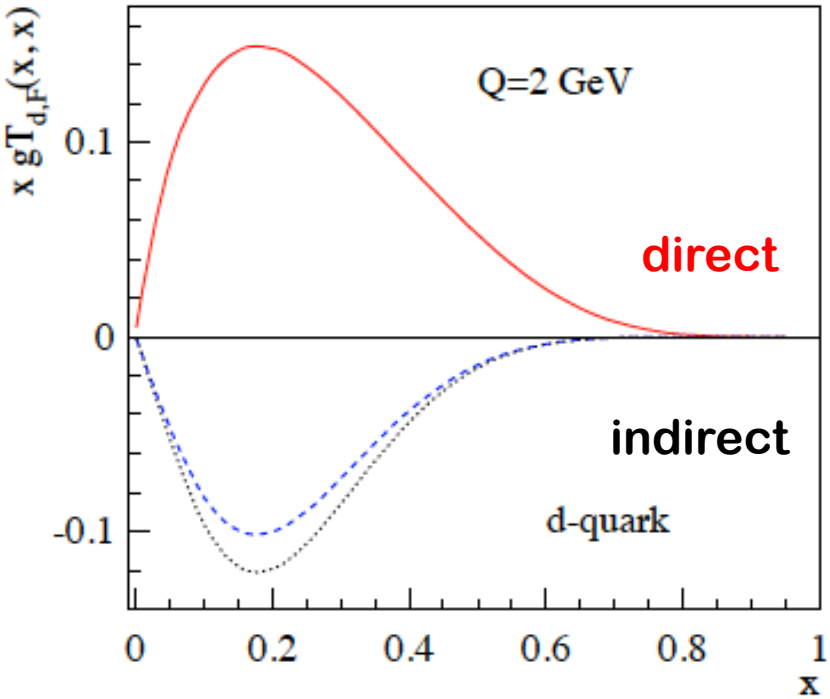
- Sivers function and twist-3 correlation:

$$gT_{q,F}(x,x) = -\int d^2k_\perp \frac{|k_\perp|^2}{M} f_{1T}^{\perp q}(x,k_\perp^2)|_{\rm SIDIS}$$ + UVCT

- "direct" and "indirect" twist-3 correlation functions:

Calculate $T_{q,F}(x,x)$ by using the measured Sivers functions

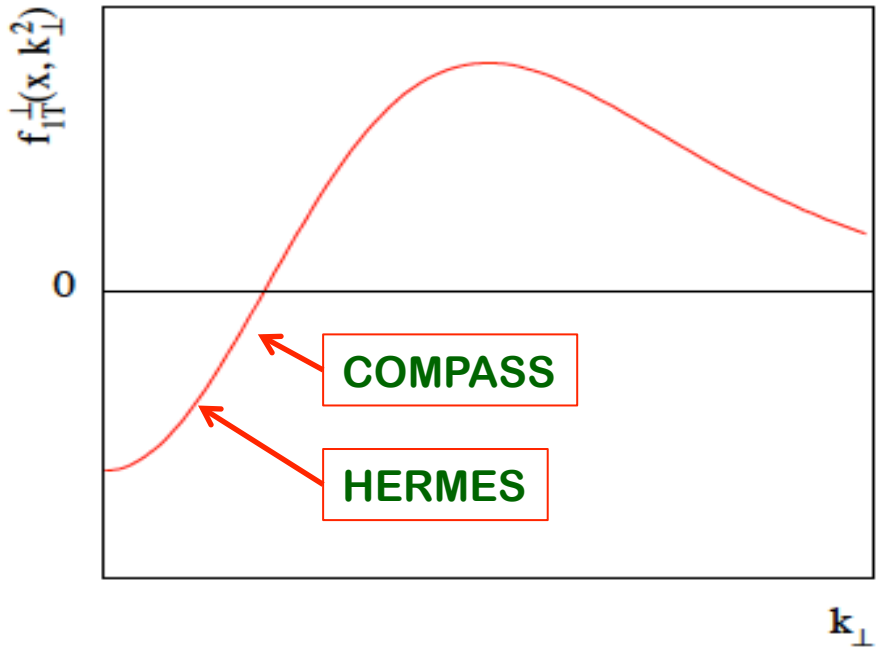




Possible interpretations

- A node in k_T-distribution:
  - Like the DSSV's $\Delta G(x)$
  - HERMES vs COMPASS
  - Physics behind the sign change

EIC can measure TMDs
for a wide range of k_T



- Large twist-3 fragmentation contribution in RHIC data:

If Sivers-type initial-state effect is much smaller than fragmentation Effect and two effects have an opposite sign

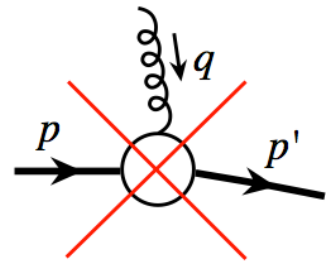
Can be tested by A_N of single jet or direct photon at RHIC

Parton's spatial distribution

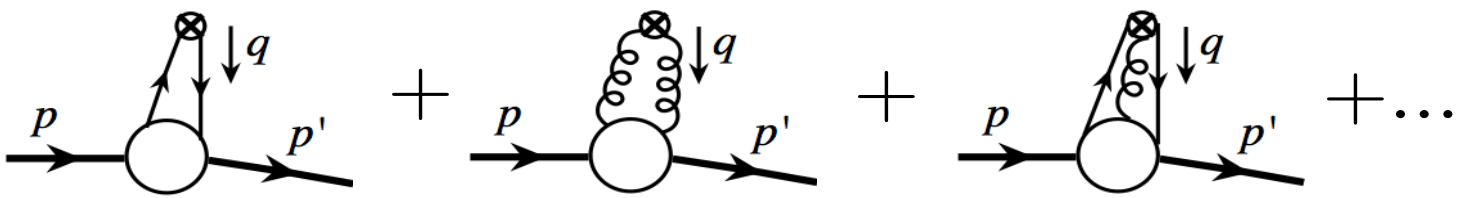
- Form factor – spatial distribution:

  Fourier transform of momentum transfer: $\Delta = p' - p$

  But, no color form factor!



- Need diffractive scattering:



But, every parton can participate – need a "localized" probe!

- Need a large scale Q and a large enough phase space for Δ

  EIC at high energy can provide both, as well as factorization!

  No natural large scale for hadronic diffractive scattering

  No factorization for hadron-hadron diffractive scattering!

Generalized parton distributions (GPDs)

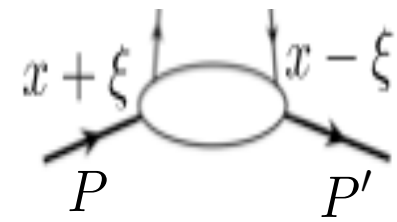
Muller, 94
Ji, 96, …

❑ Quark GPDs:

$$F_q(x,\xi,t,\mu^2) = \int \frac{d\lambda}{2\pi} e^{-ix\lambda} \langle P' | \bar{\psi}_q(\lambda/2) \frac{\gamma\cdot n}{2P\cdot n} \psi_q(-\lambda/2) | P \rangle$$

$$\equiv H_q(x,\xi,t,\mu^2) \left[\bar{\mathcal{U}}(P')\gamma^\mu \mathcal{U}(P)\right] \frac{n_\mu}{2P\cdot n}$$

$$+ E_q(x,\xi,t,\mu^2) \left[\bar{\mathcal{U}}(P') \frac{i\sigma^{\mu\nu}(P'-P)_\nu}{2M} \mathcal{U}(P)\right] \frac{n_\mu}{2P\cdot n}$$



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

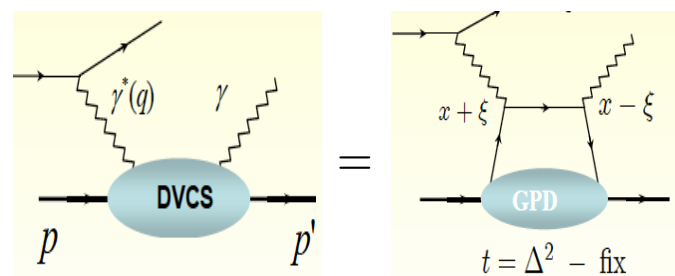
Like PDFs, GPDs are not physical observables, scheme dependent!

❑ Net parton's orbital motion:

Ji, PRL78, 1997

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

$$= \frac{1}{2}\Delta q + L_q$$

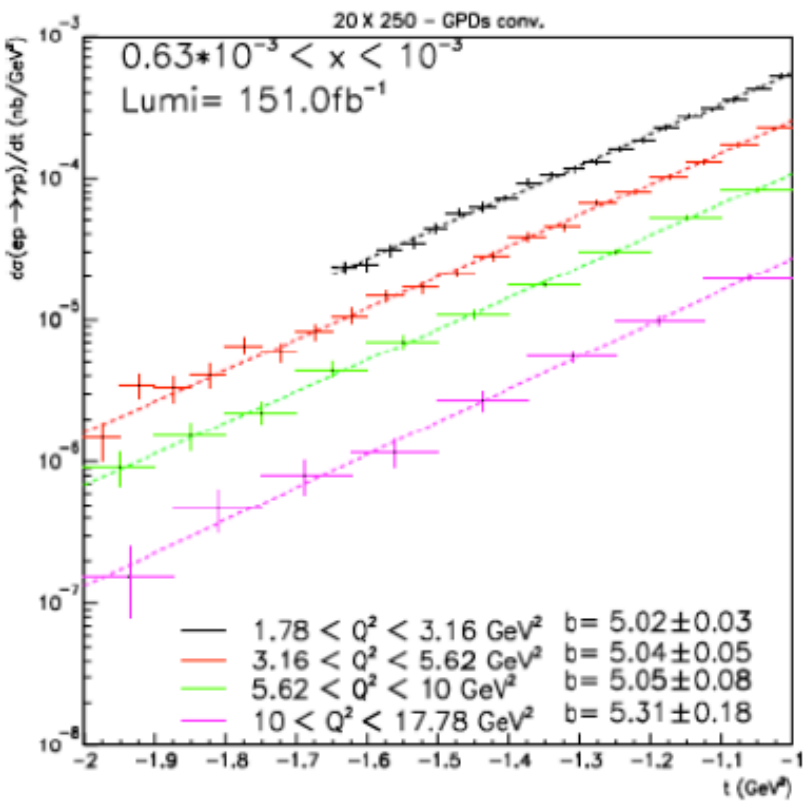


❑ Connection to normal quark distribution:

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

DVCS at EIC

Simulated DVCS cross section
(150 fb^{-1})

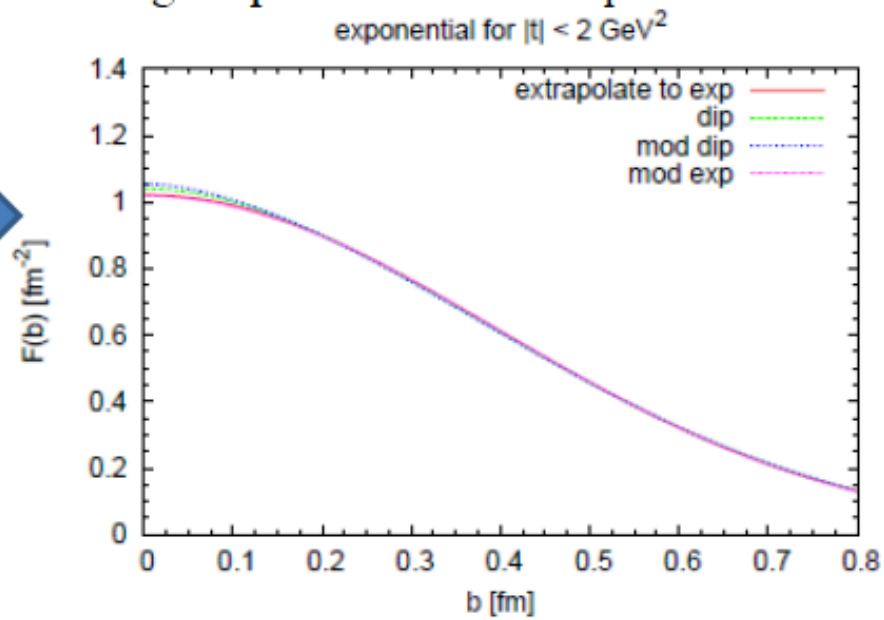


S. Fazio

- The slope of the t dependence can be extracted with 1% accuracy due to high luminosity!
(compare to ~10% accuracy at HERA)

- Extracted transverse distribution of "singlet quarks" down to $b_T \approx 0.05$ fm

F.T.

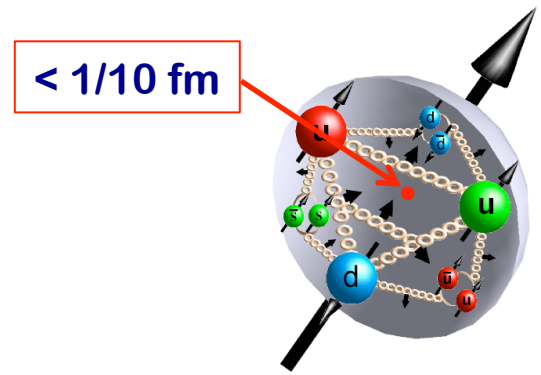


E. Aschenauer, M. Diehl, S. Fazio
(from the write-up of the INT10-03 program)

Guzey's talk at EICAC review

Summary

- QCD factorization/calculation have been very successful in interpreting HEP scattering data



- What about the hadron structure?

  Not much!

- EIC with a polarized hadron beam opens up many new ways to test QCD and to study hadron structure: TMDs, GPDs, …

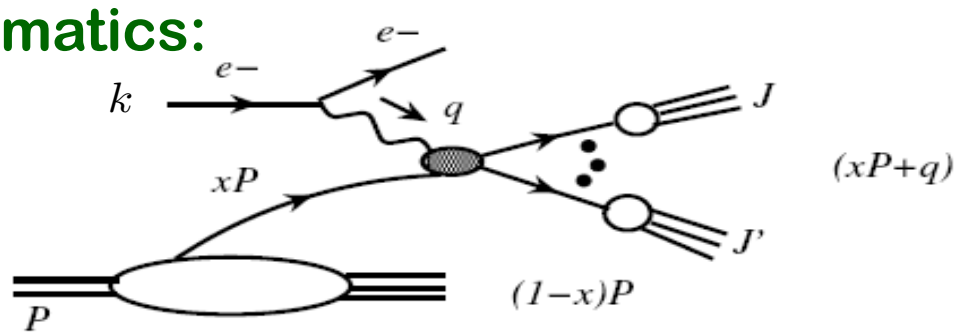
- The challenge for theorists is to indentify new, measurable, and factorizable observables that carry rich information on hadron's partonic structure

Thank you!

Backup slices

EIC Kinematics

- **DIS kinematics:**



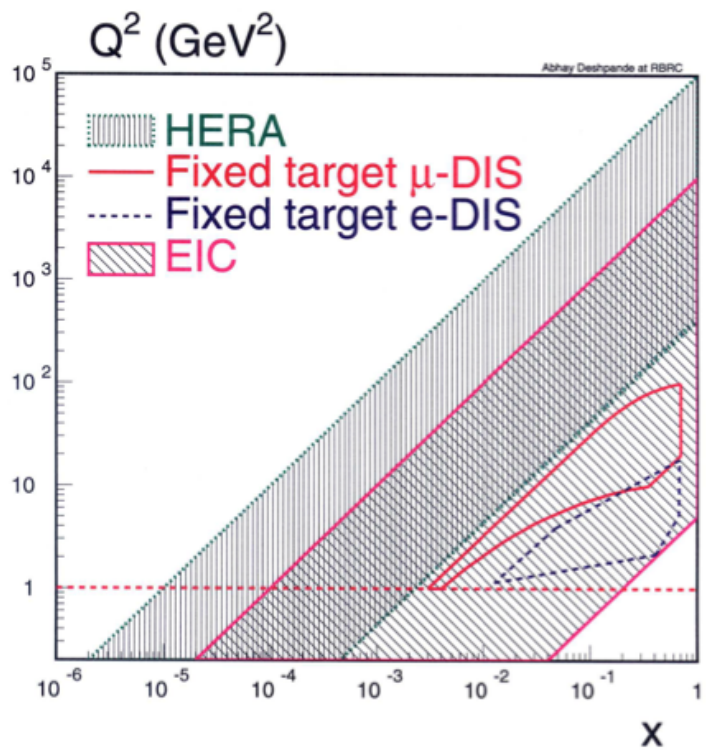
$$Q^2 = -q^2 = x_B\, y\, S$$

$$x_B = \frac{Q^2}{2p \cdot q}$$

$$y = \frac{p \cdot q}{p \cdot k}$$

$$S = (p+k)^2$$

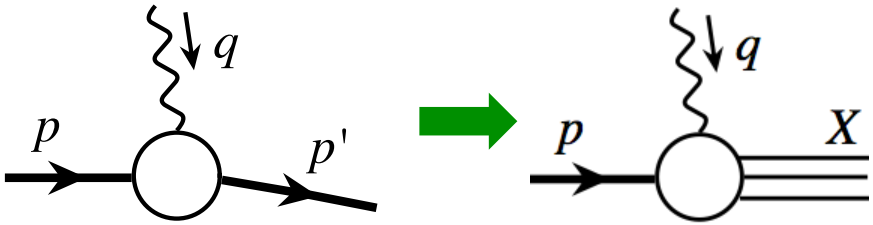
- **EIC (eRHIC – ELIC) basic parameters:**



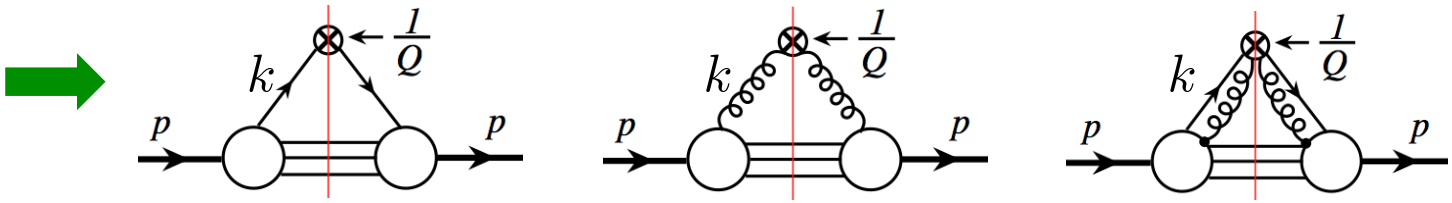
- $E_e = 10$ GeV (5-30 GeV available)
- $E_p = 250$ GeV (50-325 GeV available)
- $\sqrt{S} = 100$ GeV (30-200 GeV available)
- **"localized" probe:** $Q^2 \gtrsim 1$ GeV
- $x_{\min} \sim 10^{-4}$
- **Luminosity ~ 100 x HERA**
- **Polarization, heavy ion beam, …**

EIC advantages

- **Inclusive DIS – Spin:**



Forward scattering matrix elements:



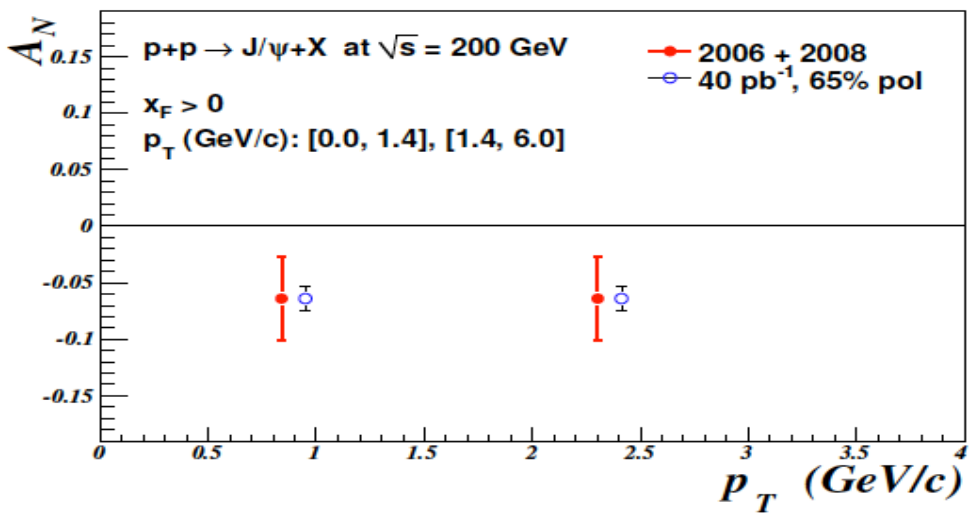
PDFs **Correlation functions**

- **SIDIS – Best place to measure TMDs:**

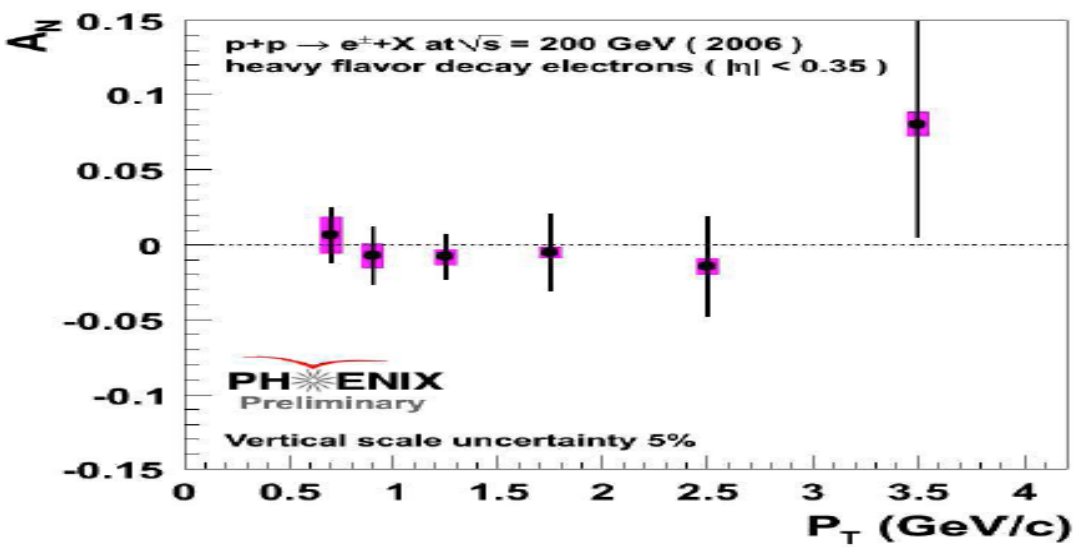
  - ✧ **TMD Factorization**
  - ✧ **Naturally two very different scales: Q, p_T**
  - ✧ **Well-defined lepton-plane and hadron-plane – separation of TMDs**

First hint of tri-gluon correlation

- PHENIX data on J/psi:



- PHENIX data on open charm:



Collinear factorization:

- ✧ tri-gluon correlation – direct quantum interference

Challenges:

- ✧ J/psi production mechanism
- ✧ Initial- vs final-state effect
- ✧ Connection to Gluon Sivers function

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