Open questions in spin, e-p and e-A physics

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Outline of my talk

- ❑ **Questions and opportunities for**

  - ✧ **Spin**
  - ✧ **e-p**
  - ✧ **e-A**

  A limited personal selection for this talk

- ❑ **References:**

  INT workshop:

  http://www.int.washington.edu/PROGRAMS/10-3/

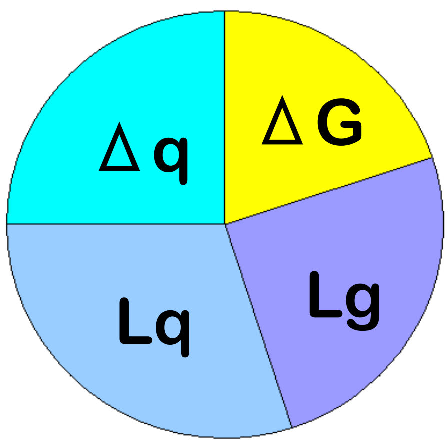
  Report: arXiv: 1108.1713

Spin

I will concentrate on two features of spin physics:

- ❑ **Spin as a fundamental hadron property:**

  Spin sum rule: the proton's spin budget?



- ❑ **Spin as an experimental tool to probe hadron's partonic structure and QCD dynamics**

Key challenge to strong interaction

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

Hadron properties		QCD		
Charge, Mass, Spin, Magnetic moment, …	$\longleftrightarrow$	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

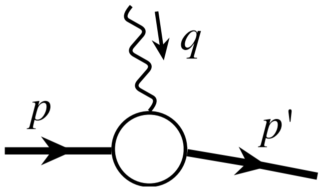
- But,

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

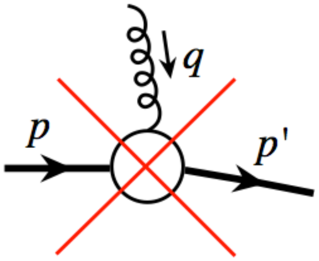
Hadron properties – parton dynamics

❑ EM charge distribution:

✧ Electric form factor ➡ charge distribution



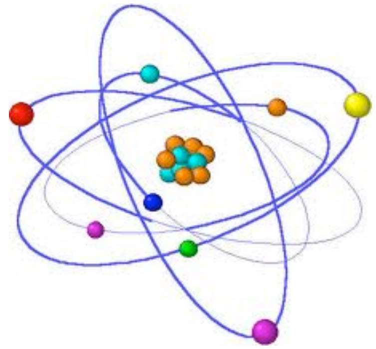
❑ How color is distributed inside a hadron?
(possible clue for color confinement, …)



But, no color form factor!

❑ How partons and their interaction build up the hadron mass?

✧ Atom mass – heavy nucleus + light electrons
– concentrated mass and "localized" charge source



No "localized" color source for light hadrons!

✧ Hadron mass < Energy scale to "see"
localized partons (live long enough) - hard for pQCD approach

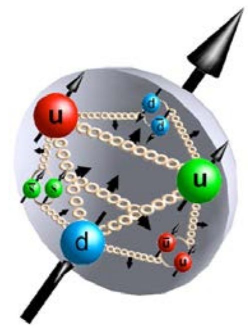
Something special about spin

- Spin of an elementary particle:

  An intrinsic quantum property of the particle

- Spin of a composite particle – like a proton:

  Angular momentum when the particle is at rest



  = Spin of elementary partons
  (intrinsic quantum effect)

  \+

  Motion of the partons
  (dynamical – fundamental interaction)

- Proton's spin budget in QCD: Jaffe-Manohar, Ji, Chen et al, Wakamatsu, …

$$S(\mu) = \sum_f \langle P,S|\hat{J}^z_f(\mu)|P,S\rangle = \frac{1}{2} \equiv J_q(\mu) + J_g(\mu) \;\; \rightarrow \frac{1}{2}\Sigma_q + L_q + (\Delta G + L_g)$$

The decomposition is not unique! Only the total sum is physical!

Proton spin

- Spin is the same for any probing energy:

$$S(\mu) = \frac{1}{2}$$

$$\mu \Rightarrow \infty$$

- Asymptotic limit:

Ji, 2005

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

- Spin sum rule – not unique!

$$S(\mu) = \frac{1}{2}\Sigma(\mu) + L_q(\mu) + \Delta G(\mu) + [J_g(\mu) - \Delta G(\mu)]$$

Intrinsic parton's spin: $\Sigma(Q^2) = \sum_q \left[\Delta q(Q^2) + \Delta\bar{q}(Q^2)\right], \quad \Delta G(Q^2)$

dynamical parton motion: $L_q(Q^2), \quad L_g(Q^2)$

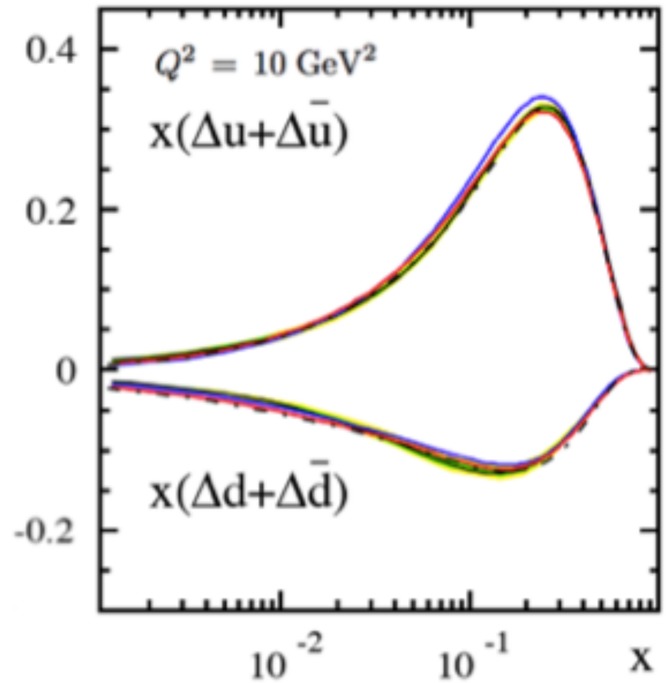
- Spin decomposition – at different distance scales:

Learn QCD dynamics, not much details in partonic structure!

Proton spin budget - status

- Over 20 years' effort since EMC's discovery:
  - ✧ Quark spin makes up about 30% of proton spin
- 20 years later: RHIC's discovery:
  - ✧ Gluon spin contributes "a little" to proton spin

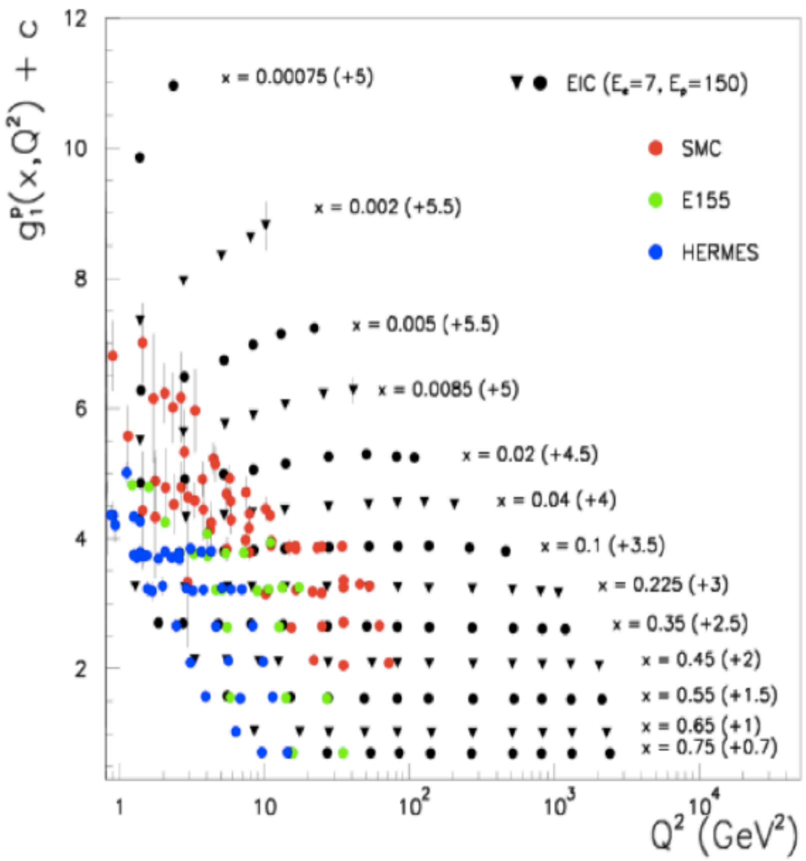
    But, the fraction increases?!

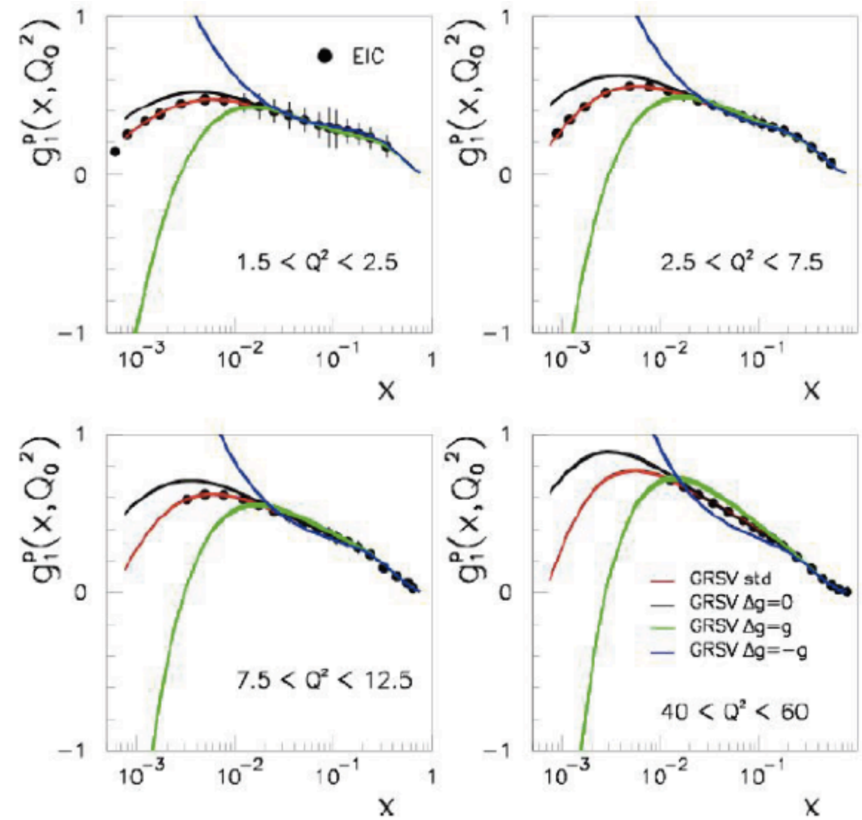


- Future challenges – role of EIC:
  - ✧ Better determination of $\Delta G(\mu)$ - extrapolation to small x?!
  - ✧ Measure the orbital contribution – transverse motion of partons?!

How much better an EIC can do?

❑ Coverage for inclusive measurement:





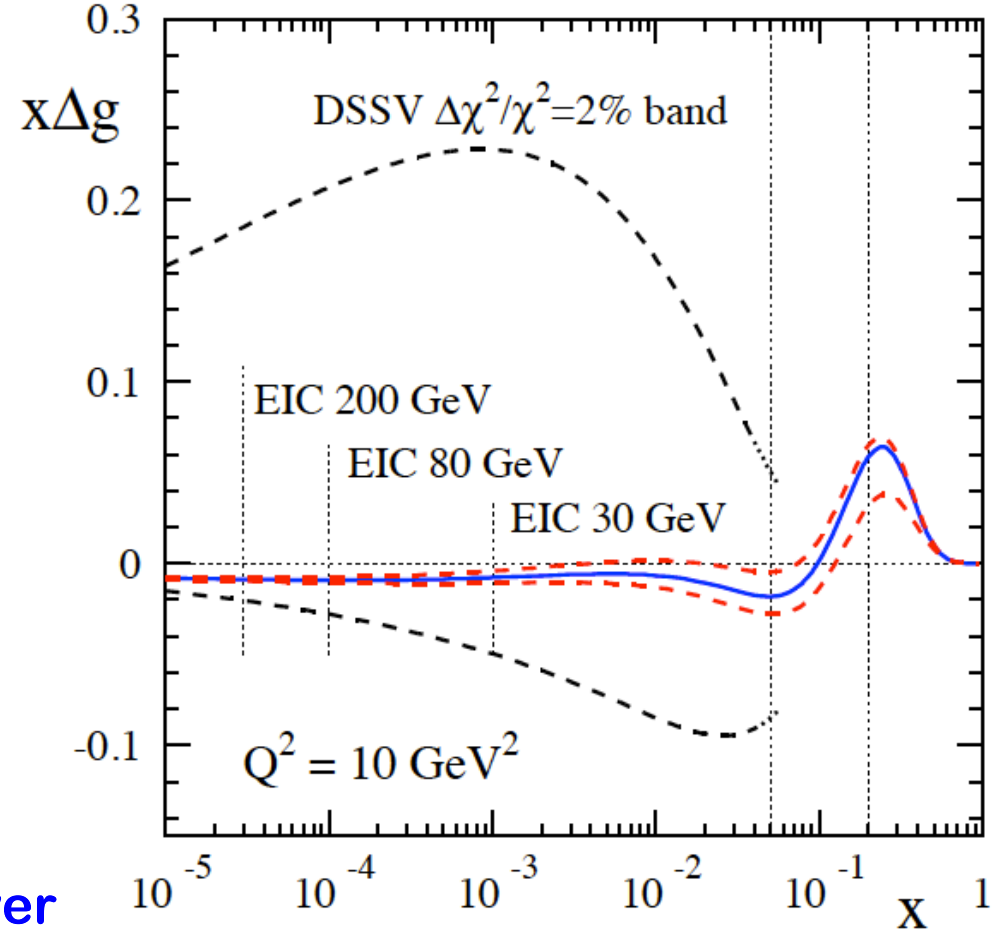
Golden measurement at EIC

- **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 for theorists:**
  - ✧ Physics behind the node if there is one?
  - ✧ Factorization at small-x?
  - ✧ Dominance of leading power when it is so small?
  - ✧ …

INT Yellow Book

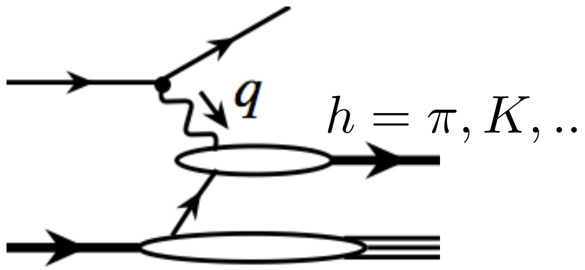
Quark flavor separation – SIDIS

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

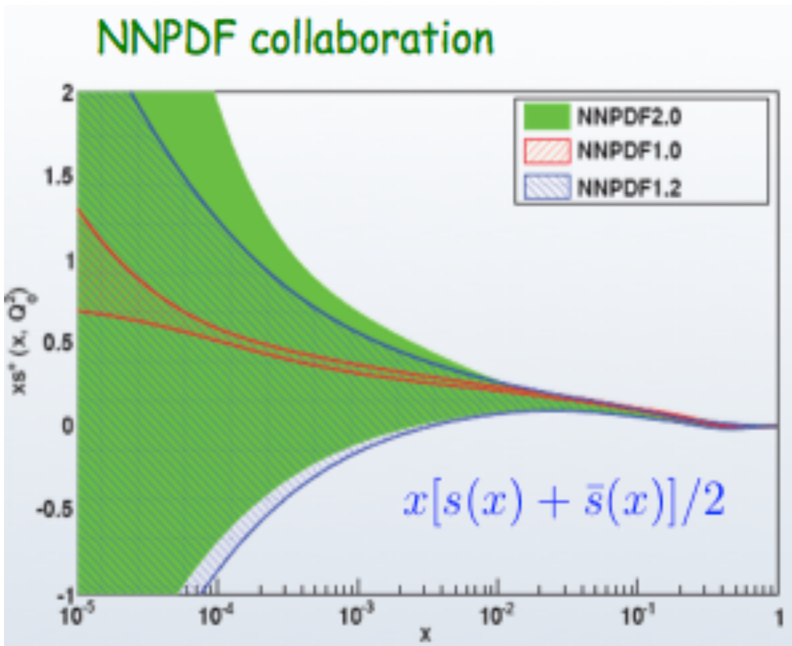
  One hard scale – collinear factorization

  $h = \pi, K, \ldots$

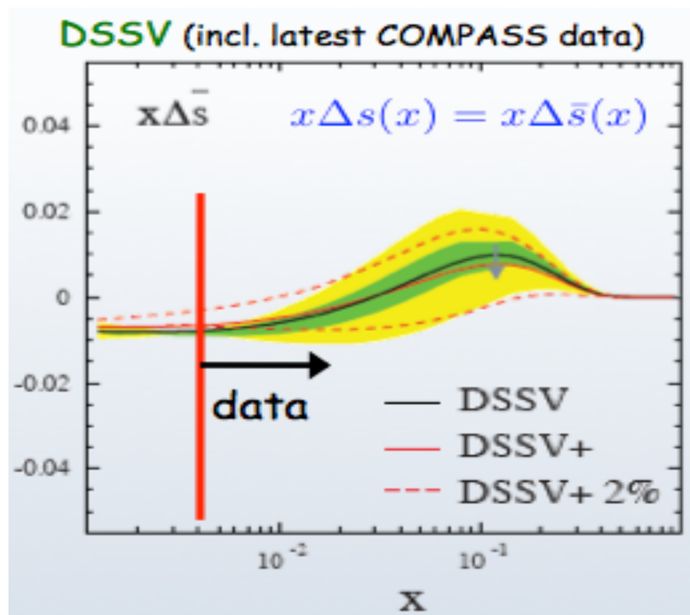
  Separation of parton flavors



- Strangeness distributions:



NuTeV anomaly on $\mathrm{Sin}^2\,\theta_W$



Tension with the 1st moment

Go beyond the collinear PDFs

- Proton's spin budget – sum rule is interesting and important

- BUT, the x- and k_T-dependence of the distributions, and the correlation of multiple partons are more interesting

  - ✧ How partons are distributed inside a hadron?
    – 3D imaging – partonic structures

  - ✧ How partons are moving or confined inside a hadron?
    – TMD distributions – orbital motion

  - ✧ What are correlations between hadron's spin and partons' spin and their motion?
    – Spin-orbital, spin-spin, correlations

  …

- Can we answer these questions without seeing partons?

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:**

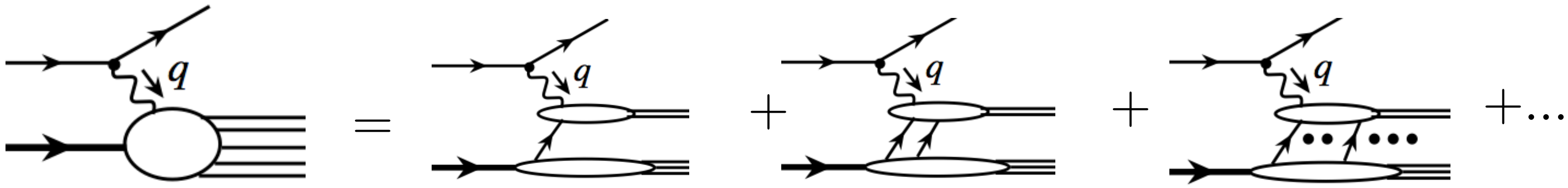
$$\langle p,s|\overline{\psi}_q(0)\,\Gamma\,\left[F^+_{\ \alpha}(y_1)F^+_{\ \beta}(y_2)\right]\psi_q(y)|p,s\rangle, \ldots$$

❑ 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**

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

❑ **Factorization - approximation:**

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

Hadron's partonic structure!

❑ **Challenges for theorists:**

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

Power of spin and symmetries

- **Factorized cross sections – asymmetries:**

$$A \propto \sigma_{h(p)}(Q,\vec{s}) - \sigma_{h(p)}(Q,-\vec{s}) \propto \langle p,\vec{s}|\mathcal{O}(\psi_q, A^\mu)|p,\vec{s}\rangle - \langle p,-\vec{s}|\mathcal{O}(\psi_q, A^\mu)|p,-\vec{s}\rangle$$

$$e.g.\ \mathcal{O}(\psi, A^\mu) = \overline{\psi}(0)\,\hat{\Gamma}\,\psi(y^-) \qquad \text{with } \hat{\Gamma} = I, \gamma_5, \gamma^\mu, \gamma_5\gamma^\mu, \sigma^{\mu\nu}$$

- **Parity and Time-reversal invariance:**

$$\langle p,\vec{s}|\mathcal{O}(\psi, A^\mu)|p,\vec{s}\rangle = \langle p,-\vec{s}|\mathcal{P}\mathcal{T}\mathcal{O}^\dagger(\psi, A^\mu)\mathcal{T}^{-1}\mathcal{P}^{-1}|p,-\vec{s}\rangle$$

- **IF:** $\langle p,-\vec{s}|\mathcal{P}\mathcal{T}\mathcal{O}^\dagger(\psi, A^\mu)\mathcal{T}^{-1}\mathcal{P}^{-1}|p,-\vec{s}\rangle = \pm\langle p,-\vec{s}|\mathcal{O}(\psi, A^\mu)|p,-\vec{s}\rangle$

  or $\langle p,\vec{s}|\mathcal{O}(\psi, A^\mu)|p,\vec{s}\rangle = \pm\langle p,-\vec{s}|\mathcal{O}(\psi, A^\mu)|p,-\vec{s}\rangle$

Operators lead to the "+" sign ➡ spin-averaged cross sections

Operators lead to the "-" sign ➡ spin asymmetries

- **Example:**

$$\mathcal{O}(\psi, A^\mu) = \overline{\psi}(0)\,\gamma^+\,\psi(y^-) \;\Rightarrow\; q(x)$$

$$\mathcal{O}(\psi, A^\mu) = \overline{\psi}(0)\,\gamma^+\gamma_5\,\psi(y^-) \;\Rightarrow\; \Delta q(x)$$

$$\mathcal{O}(\psi, A^\mu) = \overline{\psi}(0)\,\gamma^+\gamma^\perp\gamma_5\,\psi(y^-) \;\Rightarrow\; \delta q(x) \to h(x)$$

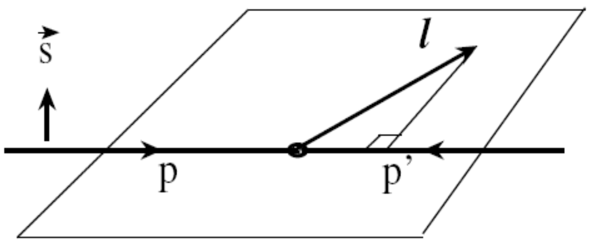
$$\mathcal{O}(\psi, A^\mu) = \frac{1}{xp^+}F^{+\alpha}(0)[-i\varepsilon_{\alpha\beta}]F^{+\beta}(y^-) \Rightarrow \Delta g(x)$$

Transverse SSA – parton transverse motion

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

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

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

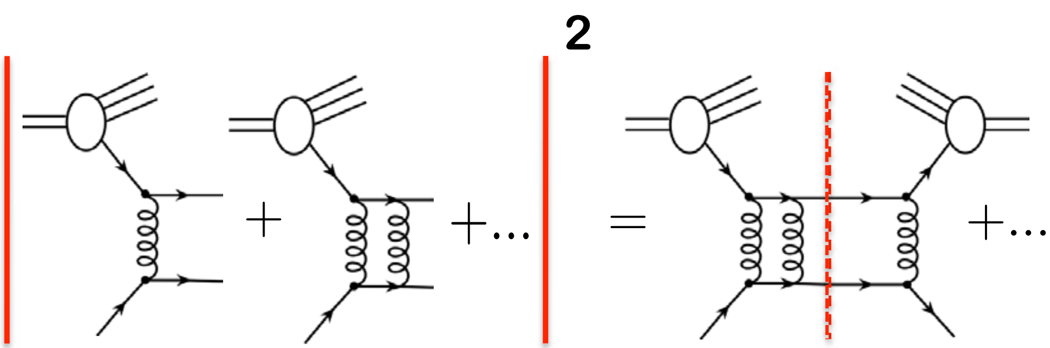


Novanish A_N requires a phase, enough vectors to fix a scattering plan, and a spin flip at the partonic scattering

❑ Leading power in QCD:

Kane, Pumplin, Repko, PRL, 1978

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



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

Need parton's transverse motion to generate the asymmetry!

(SI)DIS advantage

- **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!**

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

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 – F_L, F_2^c , …**
- ❑ **SIDIS – TMDs, spin-orbital correlations, …**
- ❑ **GPDs – 3D imaging, …**
- ❑ **…**

(Again, a selection of limited topics for this talk)

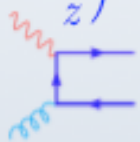
(Many more topics are discussed in the INT report)

"See" the gluon

❑ Glue contribution to F_2 is scheme dependent – No glue in DIS scheme

❑ F_L – a direct probe of glue:

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



No small-x growth until NNLO

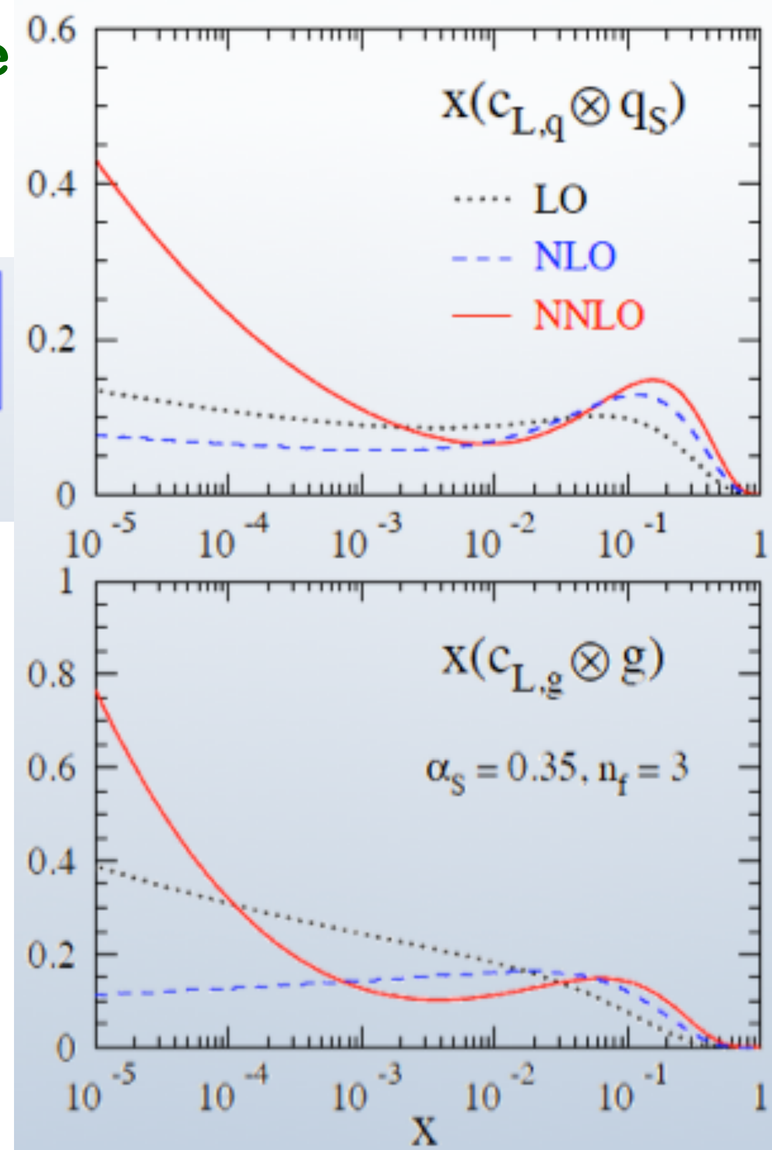
❑ Unfinished business at HERA:

Need good coverage on y-dependence

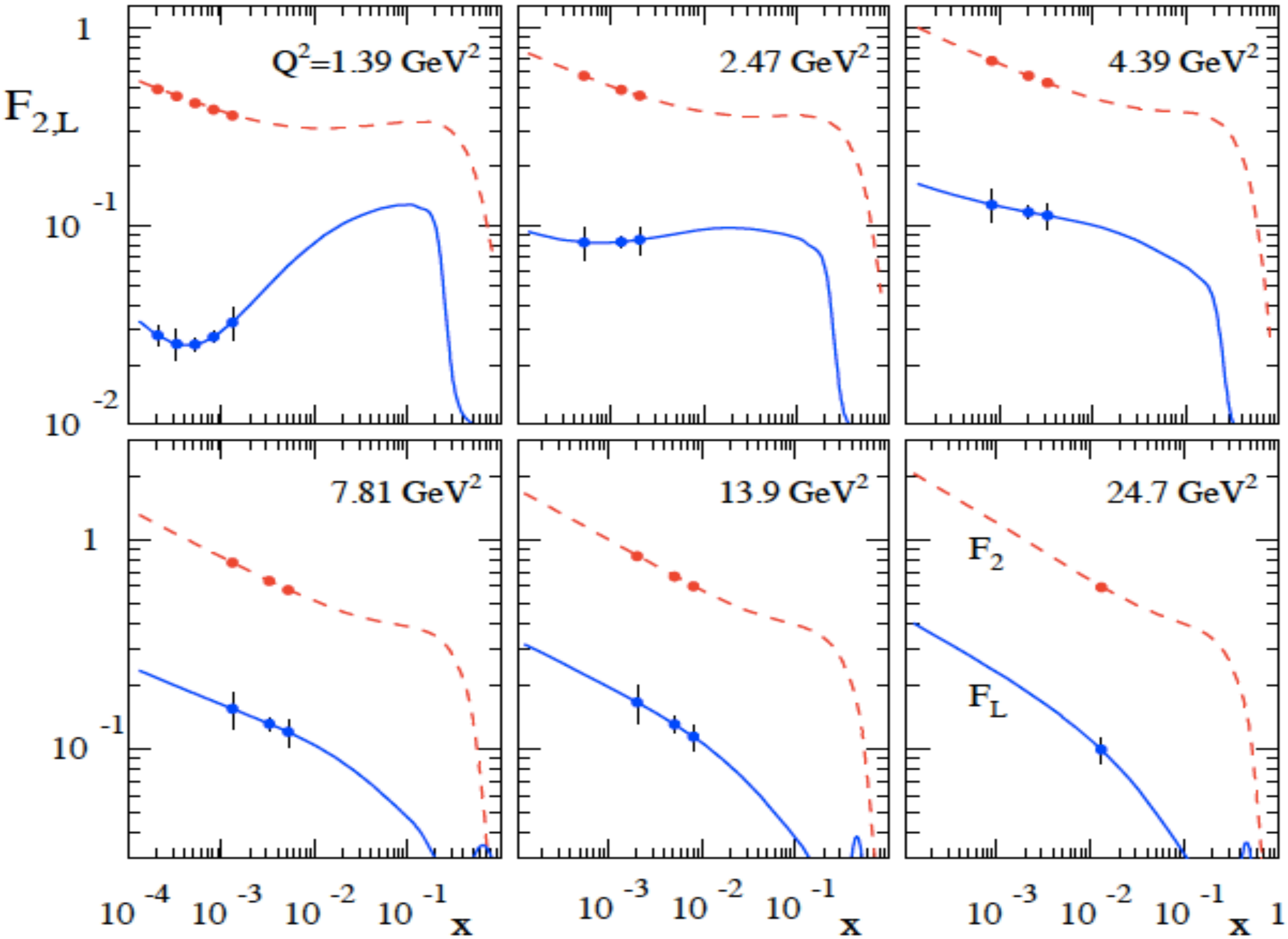
or energy scan

EIC should be able to do that

See stratmann's talk



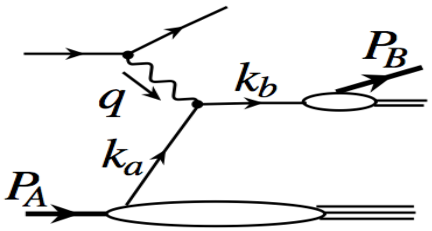
F_L measurement at EIC



Energy: 5 GeV + 100 (250, 325) GeV

INT report

TMD factorization – SIDIS

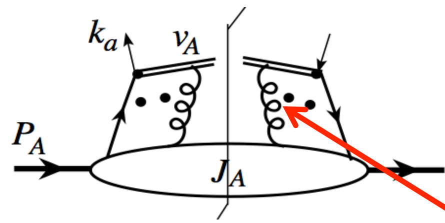


$$\sigma_0\, \phi(x,\mu) \otimes D(z,\mu)\delta^2(p_{BT})$$

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

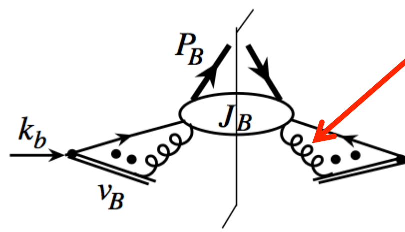
- **TMD parton distribution:**

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



- **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

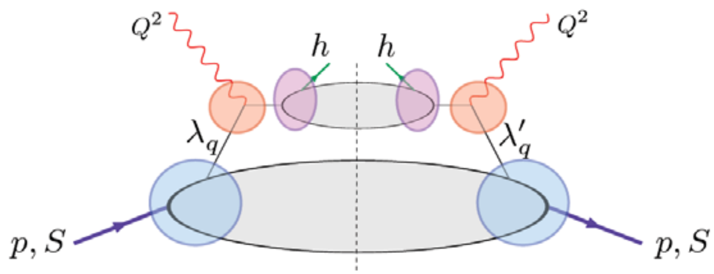
Phase for SSA

- **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:**

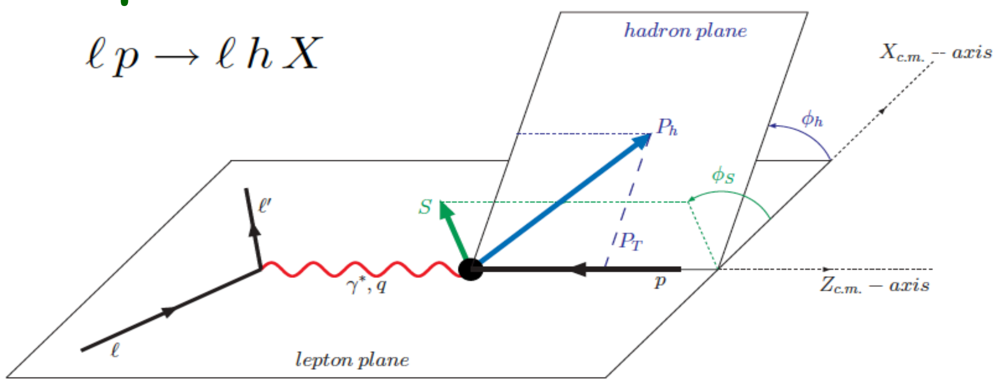


$$\ell(s_e) + p(s_p) \to \ell + h(s_h) + X$$

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

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

$$\ell\, p \to \ell\, h\, X$$



Lepton plane vs. hadron plane

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

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

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

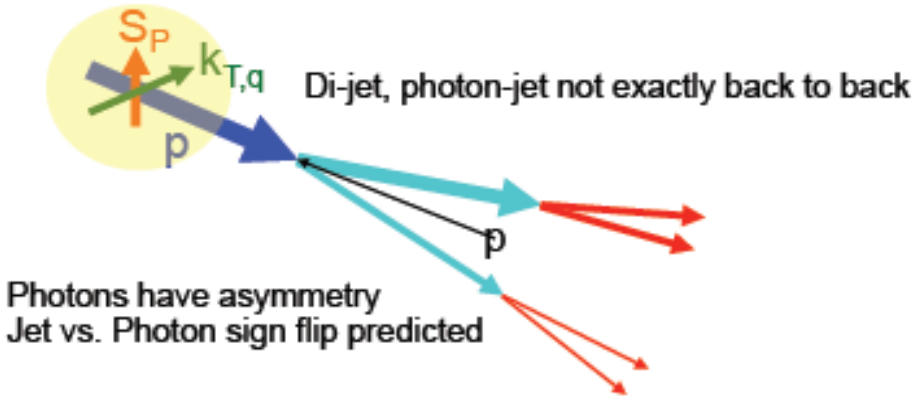
$$A_{UT}^{Collins} \propto \langle \sin(\phi_h + \phi_S) \rangle_{UT} \propto h_1 \otimes H_1^\perp$$

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

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

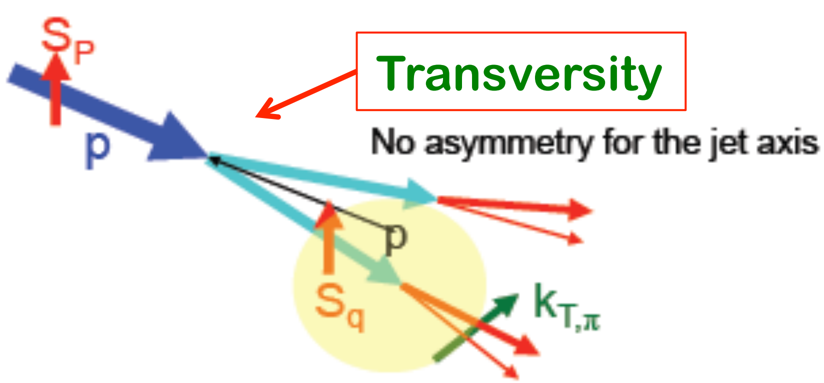
Measure TMD's

- **Sivers' effect – Sivers' function:**



Hadron spin influences parton's transverse motion

- **Collin's effect – Collin's function:**



Parton's transverse spin affects its hadronization

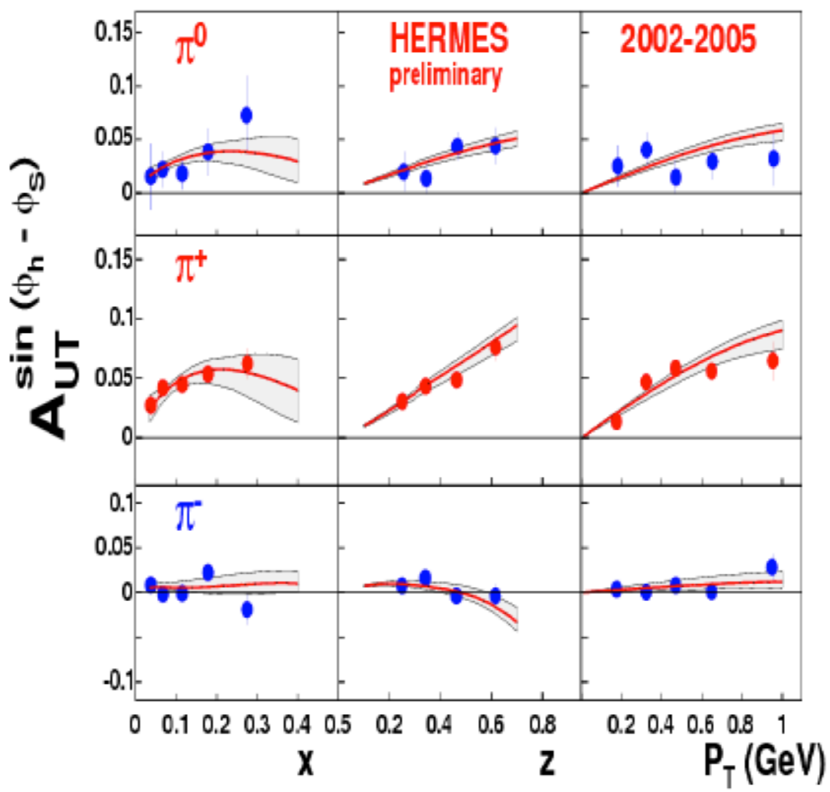
Separation of different effects?

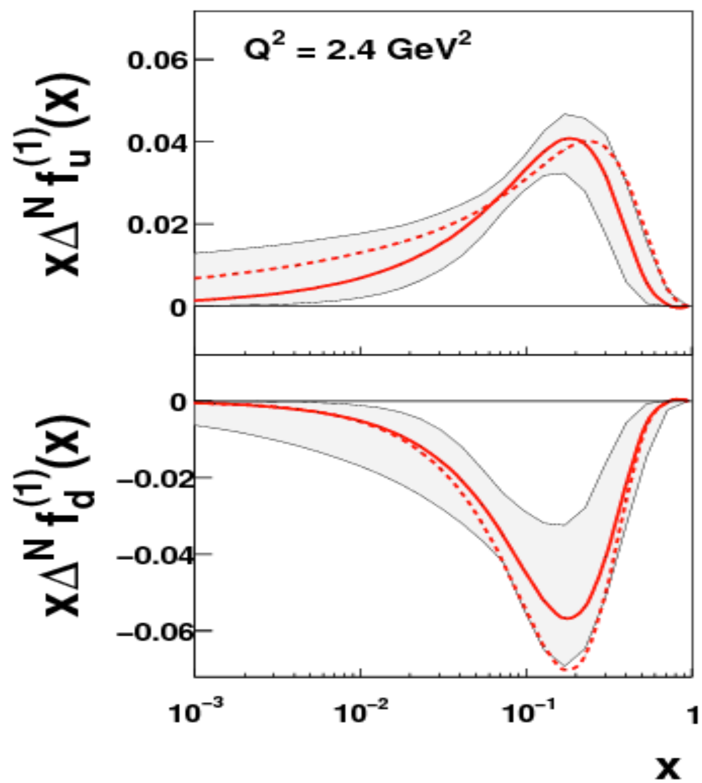
- **Need TMD factorization to quantify parton transverse motion!**

Two-scale problem in QCD: $Q_1 \gg Q_2 \sim \Lambda_{\rm QCD}$

Our knowledge of TMDs

❑ Sivers function from SIDIS:





EIC can do much better job in extracting TMDs

❑ NO TMD factorization for hadron production in p+p collisions!

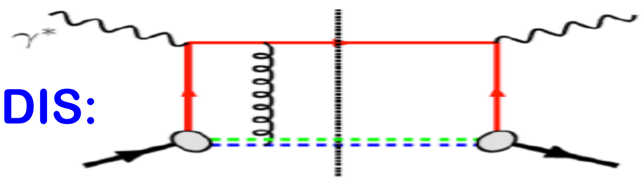
Collins and Qiu, 2007, Vogelsang and Yuan, 2007, Mulders and Rogers, 2010, …

Critical test of TMD factorization

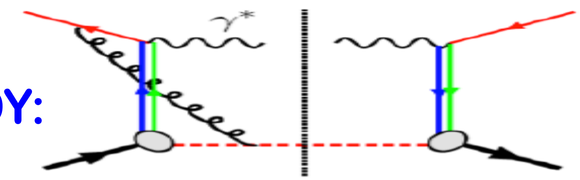
❑ TMD distributions with non-local gauge links:

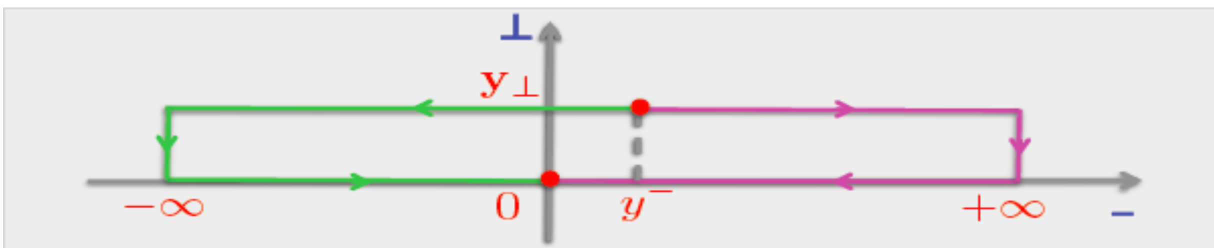
$$f_{q/h^\uparrow}(x, \mathbf{k}_\perp, \vec{S}) = \int \frac{dy^- d^2y_\perp}{(2\pi)^3} e^{ixp^+y^- - i\mathbf{k}_\perp\cdot\mathbf{y}_\perp} \langle p, \vec{S}|\overline{\psi}(0^-, \mathbf{0}_\perp) \boxed{\text{Gauge link}} \frac{\gamma^+}{2} \psi(y^-, \mathbf{y}_\perp)|p, \vec{S}\rangle$$

SIDIS:



DY:





- For a fixed spin state:

$$f^{\text{SIDIS}}_{q/h^\uparrow}(x, \mathbf{k}_\perp, \vec{S}) \neq f^{\text{DY}}_{q/h^\uparrow}(x, \mathbf{k}_\perp, \vec{S})$$

❑ Parity + Time-reversal invariance:

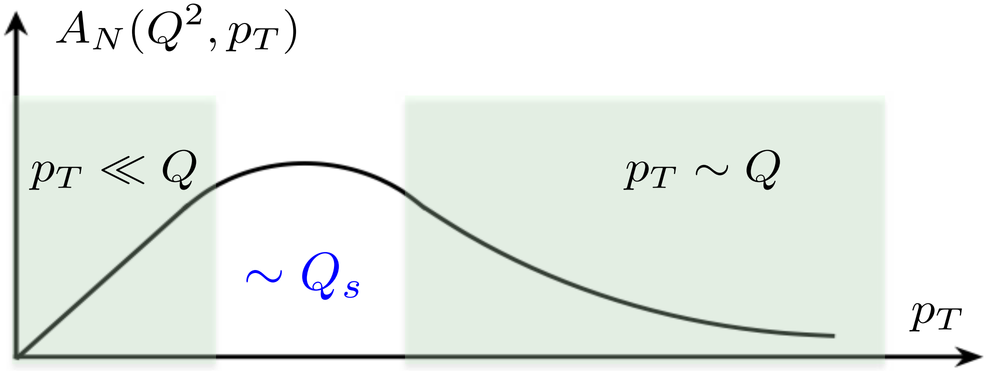
$$\Longrightarrow \quad f^{\text{Sivers}}_{q/h^\uparrow}(x, k_\perp)^{\text{SIDIS}} = -f^{\text{Sivers}}_{q/h^\uparrow}(x, k_\perp)^{\text{DY}}$$

It is a critical test of TMD factorization approach

From low p_T to high p_T

❑ TMD factorization to collinear factorization:

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



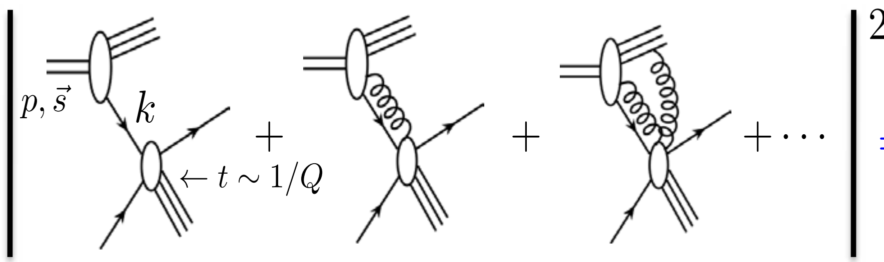
Two factorization are consistent in the overlap region where

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

❑ Collinear factorization:

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

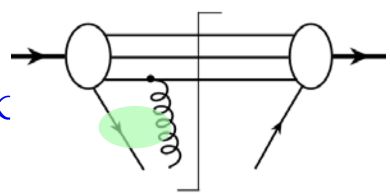
$\sigma(Q, \vec{s}) \propto$



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

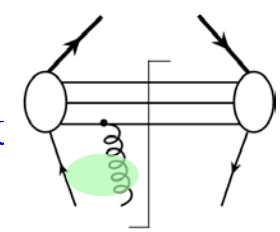
$$\Delta\sigma(s_T) \propto T^{(3)}(x,x) \otimes \hat{\sigma}_T \otimes D(z) + \delta q(x) \otimes \hat{\sigma}_D \otimes D^{(3)}(z,z) + \ldots$$

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



Qiu, Sterman, 1991, …

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



Kang, Yuan, Zhou, 2010

Role of color magnetic force

- Two-sets Twist-3 correlation functions:

No probability interpretation!

$$\widetilde{T}_{q,F} = \int \frac{dy_1^- dy_2^-}{(2\pi)^2} e^{ixP^+y_1^-} e^{ix_2P^+y_2^-} \langle P, s_T|\overline{\psi}_q(0) \frac{\gamma^+}{2} \left[\epsilon^{s_T\sigma n\bar{n}} F_\sigma{}^+(y_2^-)\right] \psi_q(y_1^-)|P, s_T\rangle$$

$$\widetilde{T}_{G,F}^{(f,d)} = \int \frac{dy_1^- dy_2^-}{(2\pi)^2} e^{ixP^+y_1^-} e^{ix_2P^+y_2^-} \frac{1}{P^+} \langle P, s_T|F^{+\rho}(0) \left[\epsilon^{s_T\sigma n\bar{n}} F_\sigma{}^+(y_2^-)\right] F^{+\lambda}(y_1^-)|P, s_T\rangle(-g_{\rho\lambda})$$

$$\widetilde{T}_{\Delta q,F} = \int \frac{dy_1^- dy_2^-}{(2\pi)^2} e^{ixP^+y_1^-} e^{ix_2P^+y_2^-} \langle P, s_T|\overline{\psi}_q(0) \frac{\gamma^+\gamma^5}{2} \left[i\, s_T^\sigma\, F_\sigma{}^+(y_2^-)\right] \psi_q(y_1^-)|P, s_T\rangle$$

$$\widetilde{T}_{\Delta G,F}^{(f,d)} = \int \frac{dy_1^- dy_2^-}{(2\pi)^2} e^{ixP^+y_1^-} e^{ix_2P^+y_2^-} \frac{1}{P^+} \langle P, s_T|F^{+\rho}(0) \left[i\, s_T^\sigma\, F_\sigma{}^+(y_2^-)\right] F^{+\lambda}(y_1^-)|P, s_T\rangle\, (i\epsilon_{\perp\rho\lambda})$$

Role of color magnetic force!

- Twist-2 distributions:
  - Unpolarized PDFs:

$$q(x) \propto \langle P|\overline{\psi}_q(0)\frac{\gamma^+}{2}\psi_q(y)|P\rangle$$

$$G(x) \propto \langle P|F^{+\mu}(0)F^{+\nu}(y)|P\rangle(-g_{\mu\nu})$$

  - Polarized PDFs:

$$\Delta q(x) \propto \langle P, S_\parallel|\overline{\psi}_q(0)\frac{\gamma^+\gamma^5}{2}\psi_q(y)|P, S_\parallel\rangle$$

$$\Delta G(x) \propto \langle P, S_\parallel|F^{+\mu}(0)F^{+\nu}(y)|P, S_\parallel\rangle(i\epsilon_{\perp\mu\nu})$$

- Twist-3 fragmentation functions:

See Kang, Yuan, Zhou, 2010, Kang 2010

Predictive power of TMD and CO approach

- **Universality of the nonperturbative functions**

  The sign change of Sivers function is a critical test for TMD approach

- **Ability to calculate and control the high order contribution**

  Factorization naturally introduces the factorization scale dependence

$$\sigma_{\rm phy}(Q,\Lambda_{\rm QCD}) \approx \sum_f \hat{\sigma}_f(Q,\mu)\otimes\phi_f(\mu,\Lambda_{\rm QCD})$$

$$\rightarrow \quad \frac{d}{d\mu}\sigma_{\rm phy}(Q,\Lambda_{\rm QCD}) = 0$$

Scaling violation of nonperturbative functions

NLO contribution is critical!

Major theory effort in studying the scale-dependence of TMDs and twist-3 correlation functions

Boer, …

A sign "mismatch"

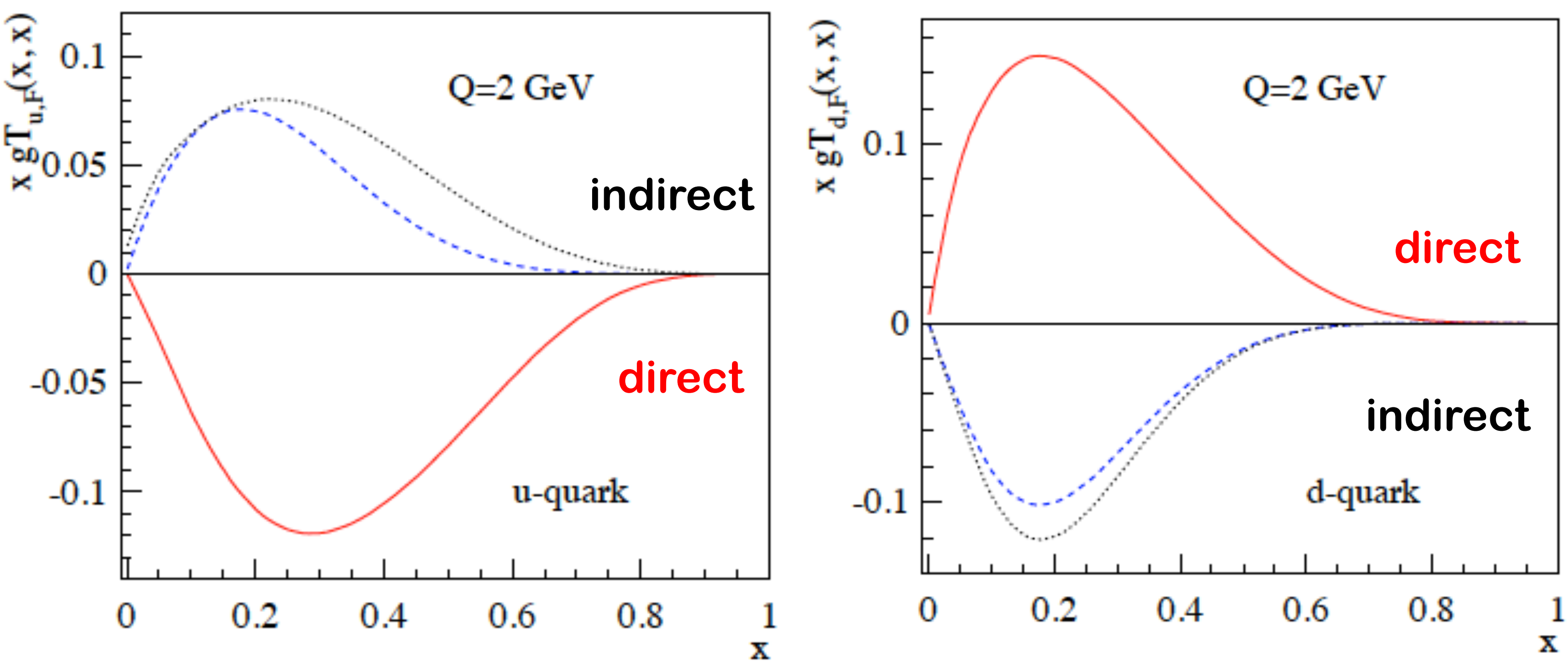
Kang, Qiu, Vogelsang, Yuan, 2011

- ❑ **Sivers function and twist-3 correlation:**

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

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

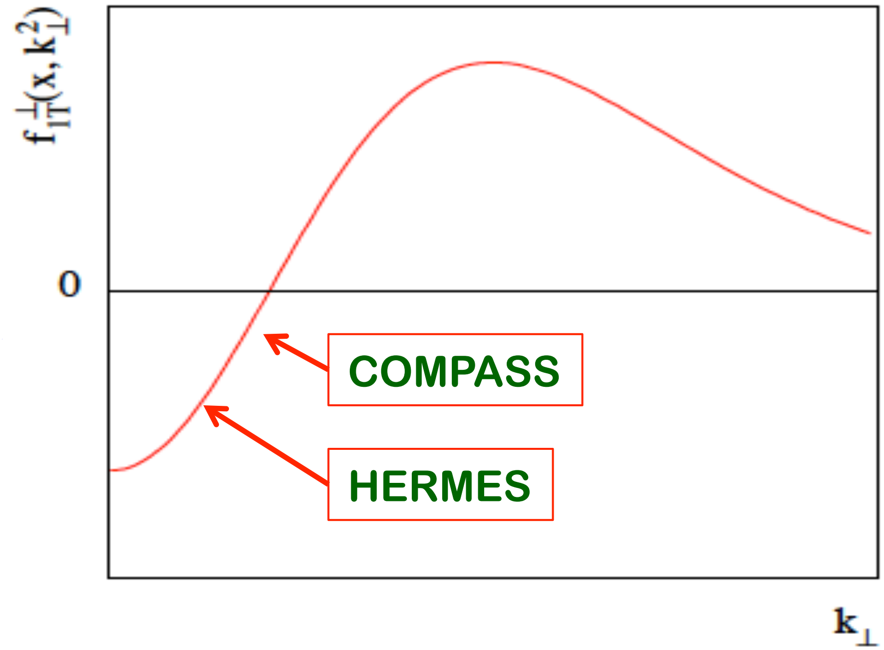
Calculate $T_{q,F}(x,x)$ by using the measured Sivers functions



Sensitivity to underline physics

- ❑ 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



- ❑ A node in x-dependence?
  - ✧ Existing experiments cover limited x-range
- ❑ 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

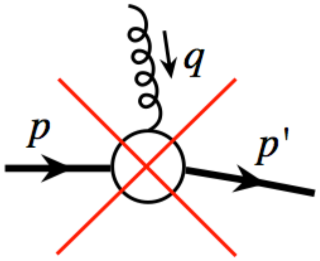
  Can be tested by A_N of single jet or direct photon at RHIC

3D-imaging of partons

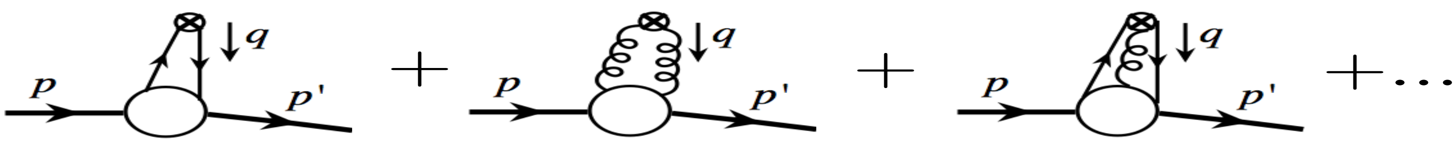
- Form factor – spatial distribution:

  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!

  EIC at high energy can provide large Q, phase-space for Δ !

  No natural large scale for hadronic diffractive scattering

  No factorization for hadron-hadron diffractive scattering!

- What do we learn from the imaging?

  e-p vs. e-A?

Generalized parton distributions (GPDs)

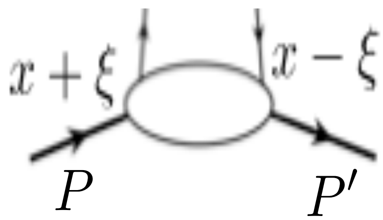
Muller, 94
Ji, 96, …

- **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 $\xi \to 0$

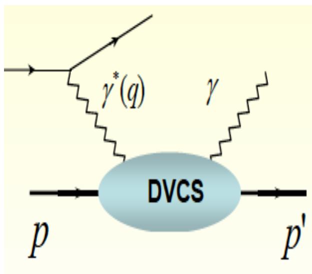
Like PDFs, GPDs are not physical observables, scheme dependent!

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

Ji, PRL78, 1997

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

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



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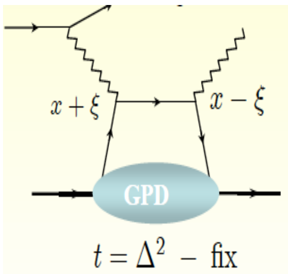


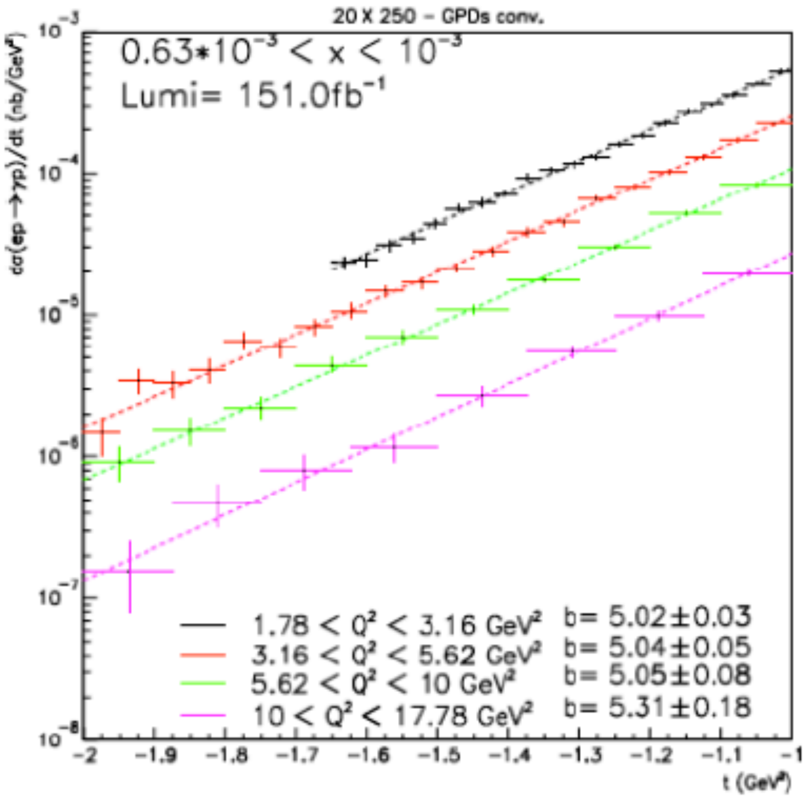
$, \ldots$

- **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})

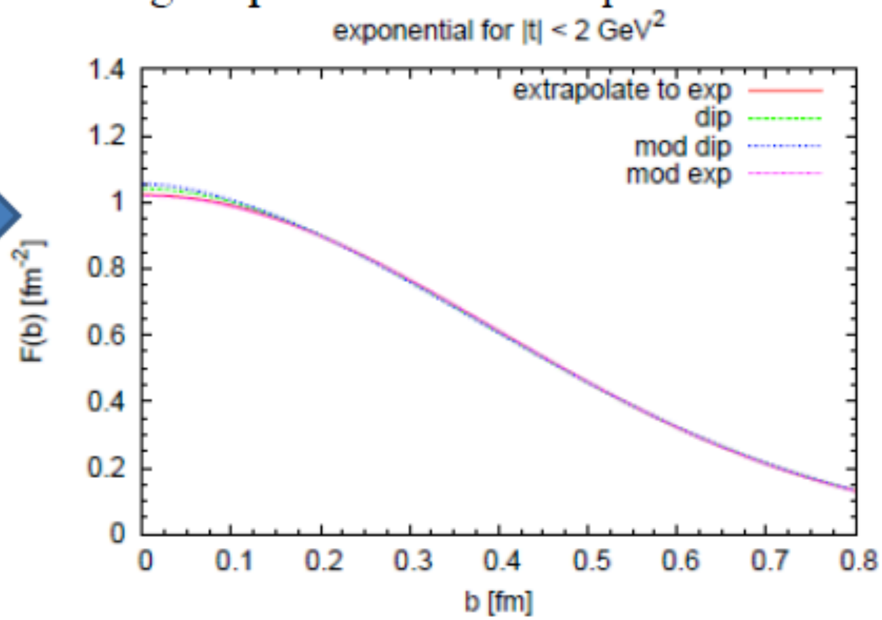


S. Fazio

F.T.

- 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



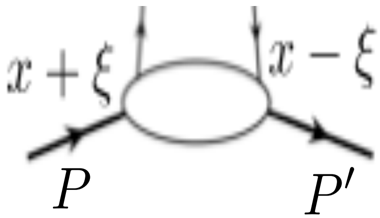
E. Aschenauer, M. Diehl, S. Fazio
(from the write-up of the INT10-03 program)

Guzey's talk at EICAC review

Spin sum rule - GPD E(x, ξ ,t)

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

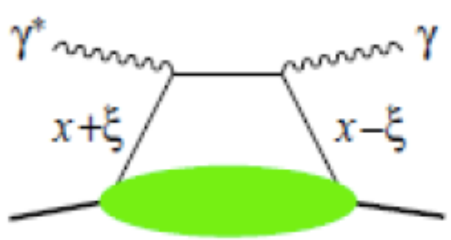
$$F_q(x,\xi,t,\mu^2) = \int \frac{d\lambda}{2\pi} e^{-ix\lambda} \langle P'|\bar{\psi}_q(\lambda/2)\frac{\gamma\cdot n}{2P\cdot n}\psi_q(-\lambda/2)|P\rangle$$
$$\equiv H_q(x,\xi,t,\mu^2)\,[\bar{\mathcal{U}}(P')\gamma^\mu \mathcal{U}(P)]\,\frac{n_\mu}{2P\cdot n}$$
$$+\; E_q(x,\xi,t,\mu^2)\left[\bar{\mathcal{U}}(P')\frac{i\sigma^{\mu\nu}(P'-P)_\nu}{2M}\mathcal{U}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

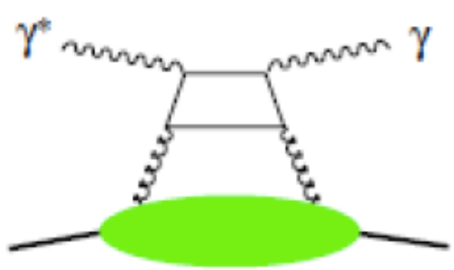


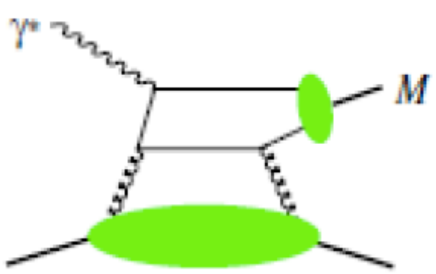
with $\xi = (P'-P)\cdot n/2$ and $t = (P'-P)^2 \Rightarrow -\Delta_\perp^2$ if $\xi \to 0$

- **Single target asymmetry:** A_{UT} **for** $\frac{d\sigma}{dt}$

Not much constraint on the E!







Can lattice QCD help?

Negele et al

- **Moments of GPDs on lattice:**

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

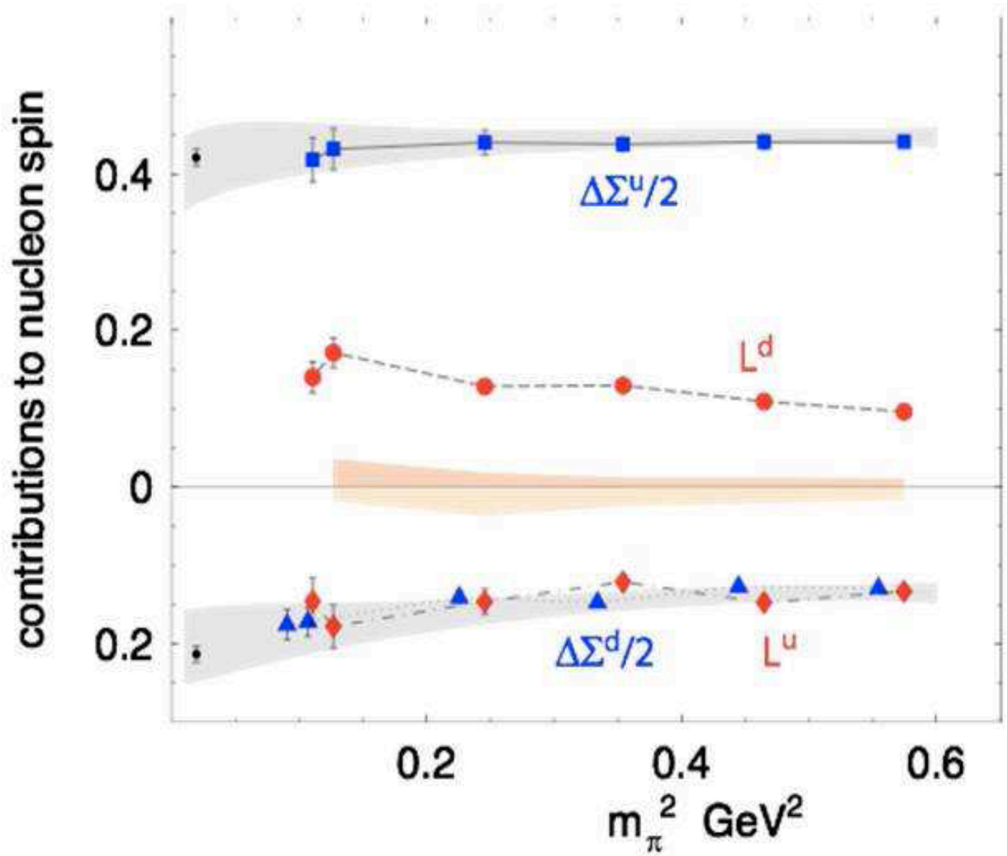
- **Ji's relation:**

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

- **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 luminosity

Quark-gluon nuclear physics

- **Can gluon density continuously grow as small x?**

  Inclusive: F_2, F_L and F_2^c for gluon, …

  Dima's talk

  Small-x, saturation, new dynamical scale, …

- **How hadrons form in a nuclear medium?**

  SIDIS: π, K, J/ψ, …

  Multiple scattering, energy loss, color neutralization, …

  Berndt's talk

- **Can we see quantum fluctuation in a large nucleus?**

  Diffractive meson production: J/ψ, …

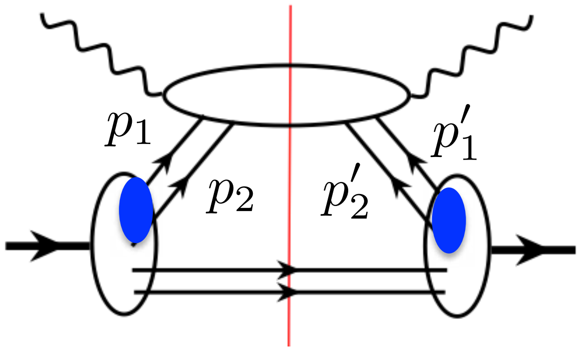
  Transverse imaging of gluon density in a nucleus, …

  Can we learn more than Woods-Saxon from EM form factors?

- **How strong is the long-range color correlation in a large nucleus?**

Color coherence inside a nucleus

- GPDs in nuclear collisions:



In a nucleus: $p_i \neq p_i'$

At large x: GPDs $\rightarrow$ PDFs

"color singlet nucleon"

At small x: GPDs with large Δ!

- A-dependence of structure functions, …

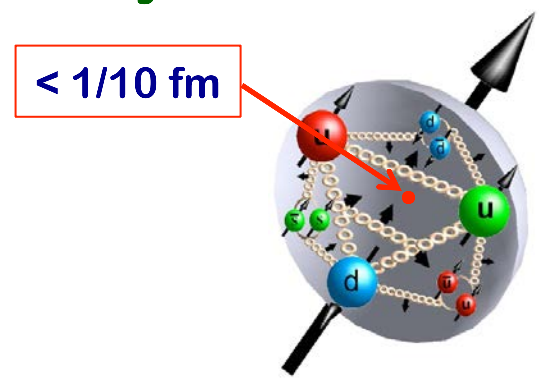
$A^{1/3}$ – No color coherence between amplitude and its c.c.

$A^{2/3}$ – Complete long range color coherence inside nucleus
– more like a large proton case

- Is there a "universality" for proton and nucleus
  - – long range color coherence – more close to $A^{2/3}$?
  - – or superposition of color singlet nucleons – to $A^{1/3}$?

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, …

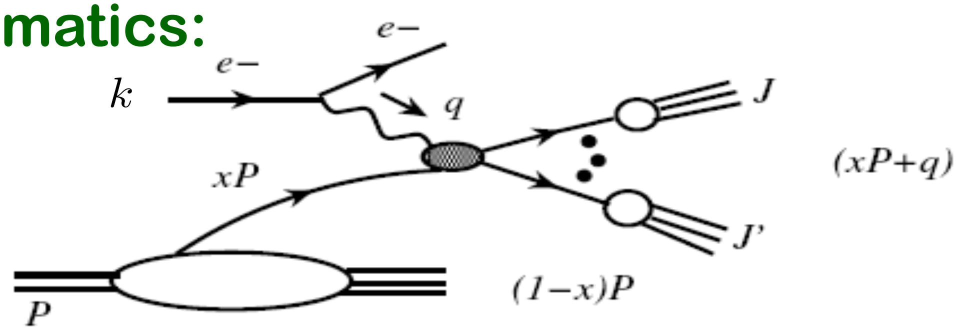
- The challenge for theorists:
  – to indentify new and calculable observables that carry rich information on hadron's partonic structure
  – to make measureable predictions

Thank you!

Backup slices

EIC Kinematics

- **DIS kinematics:**



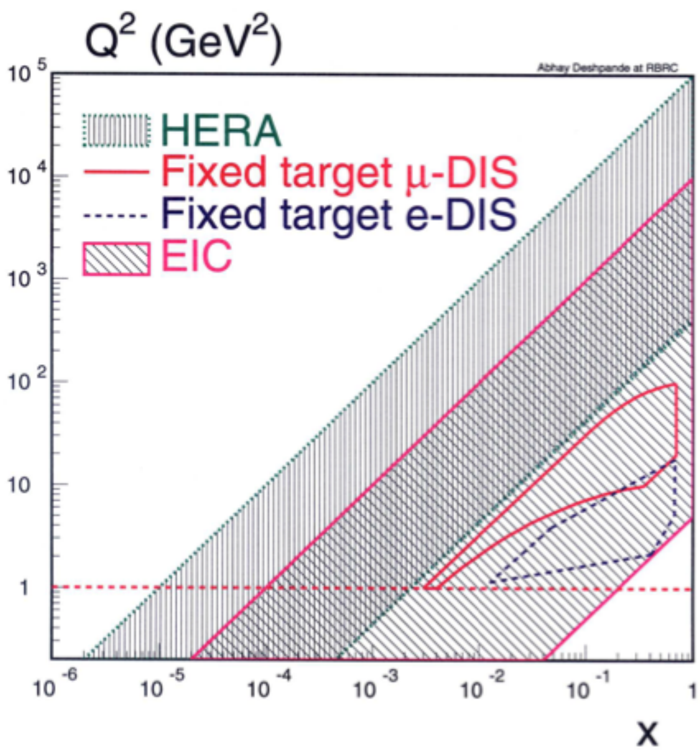
$$Q^2 = -q^2 = x_B\, y\, S$$

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

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

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

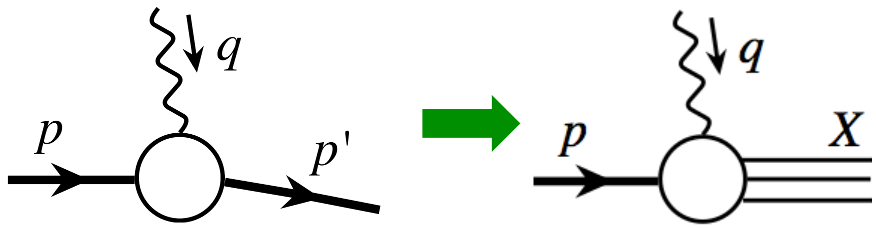
- **EIC (eRHIC – ELIC) basic parameters:**



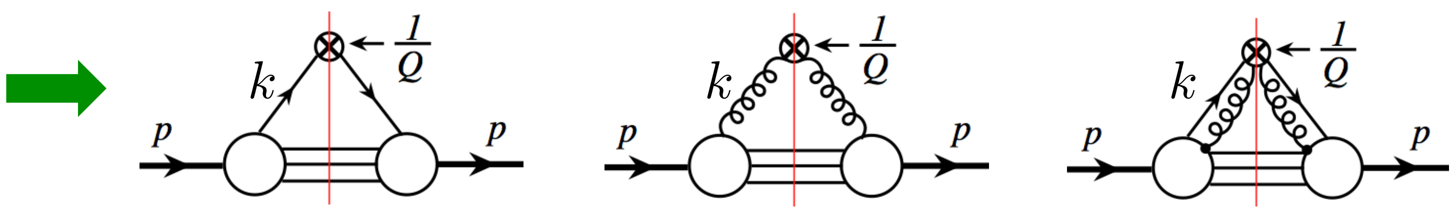
- $E_e = 10$ GeV (5-30 GeV available)
- $E_p = 250$ GeV (50-325 GeV available)
- $\sqrt{S} = 100$ GeV (30-200 GeV available)
- **"localized" probe:** $Q^2 \gtrsim 1$ GeV
- $x_{\min} \sim 10^{-4}$
- **Luminosity ~ 100 x HERA**
- **Polarization, heavy ion beam, …**

EIC advantages

- ❑ **Inclusive DIS – Spin:**



Forward scattering matrix elements:



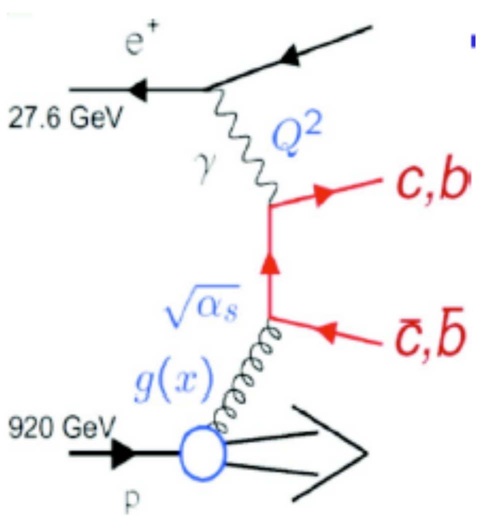
PDFs

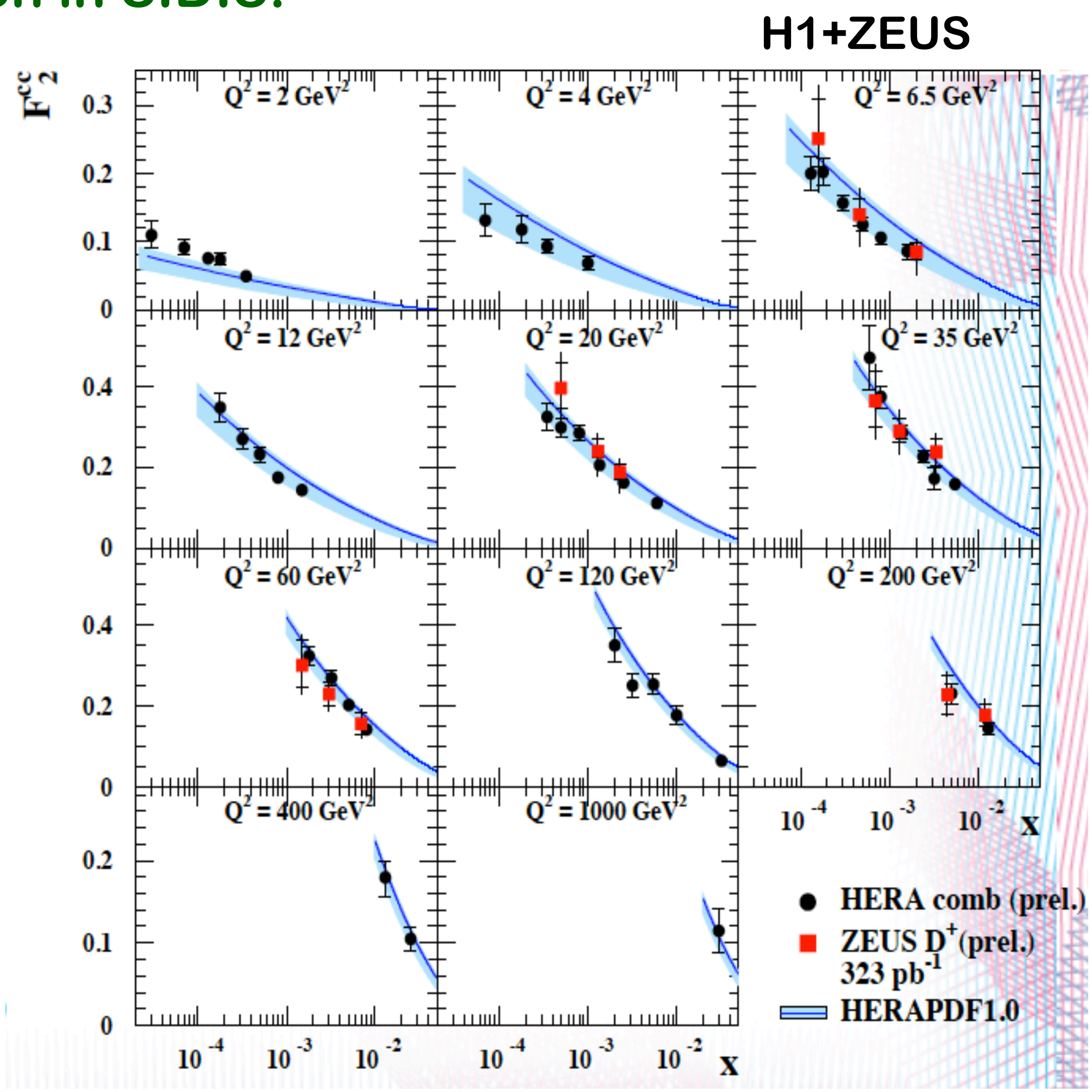
Correlation functions

- ❑ **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

Direct information on gluon distribution

- Heavy flavor production in SIDIS:





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

EIC could explore even smaller x region!