Theoretical overview of current status and future directions of spin studies

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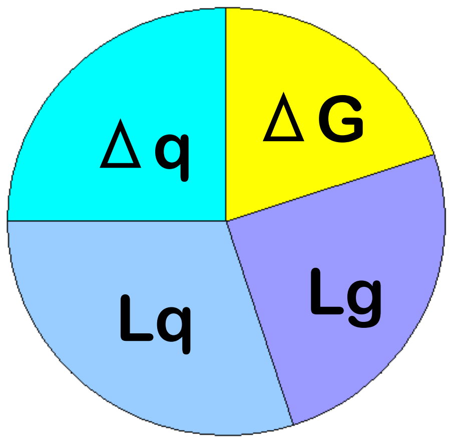
Outline of my talk

I will concentrate on two features of spin physics:

- ❑ Spin sum rule: the proton's spin budget?



- ❑ Spin as a tool to probe the hadron's partonic structure and QCD dynamics

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:

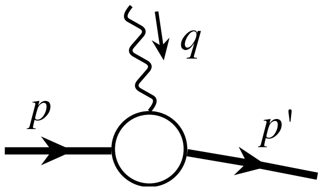
  Could calculate all hadron properties in principle!
  Has done an excellent job in reproducing the hadron mass spectrum

- But,

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

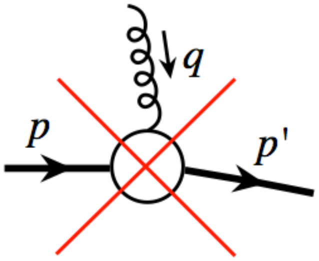
Hadron properties – parton dynamics

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



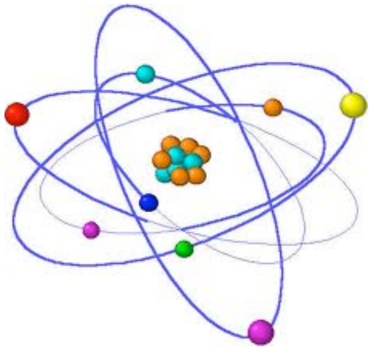
- ✧ Electric form factor ➡ charge distribution

  But, no color form factor!



- ✧ Hadron is a color singlet, but, gluon carries color

- ❑ 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

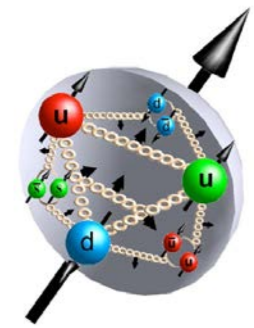
Something special about spin

- ❑ **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, …

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

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

Spin as a hadron property

- Complexity of the proton state – scale dependence:

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

$$\mu \Rightarrow \infty$$

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

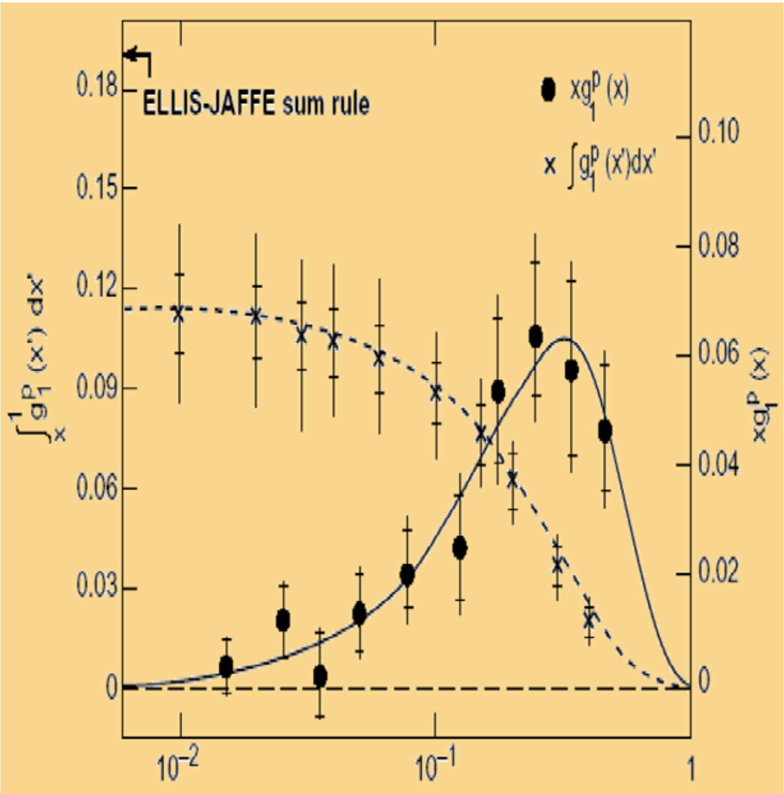
dynamical parton motion: $L_q(Q^2), \quad L_g(Q^2)$

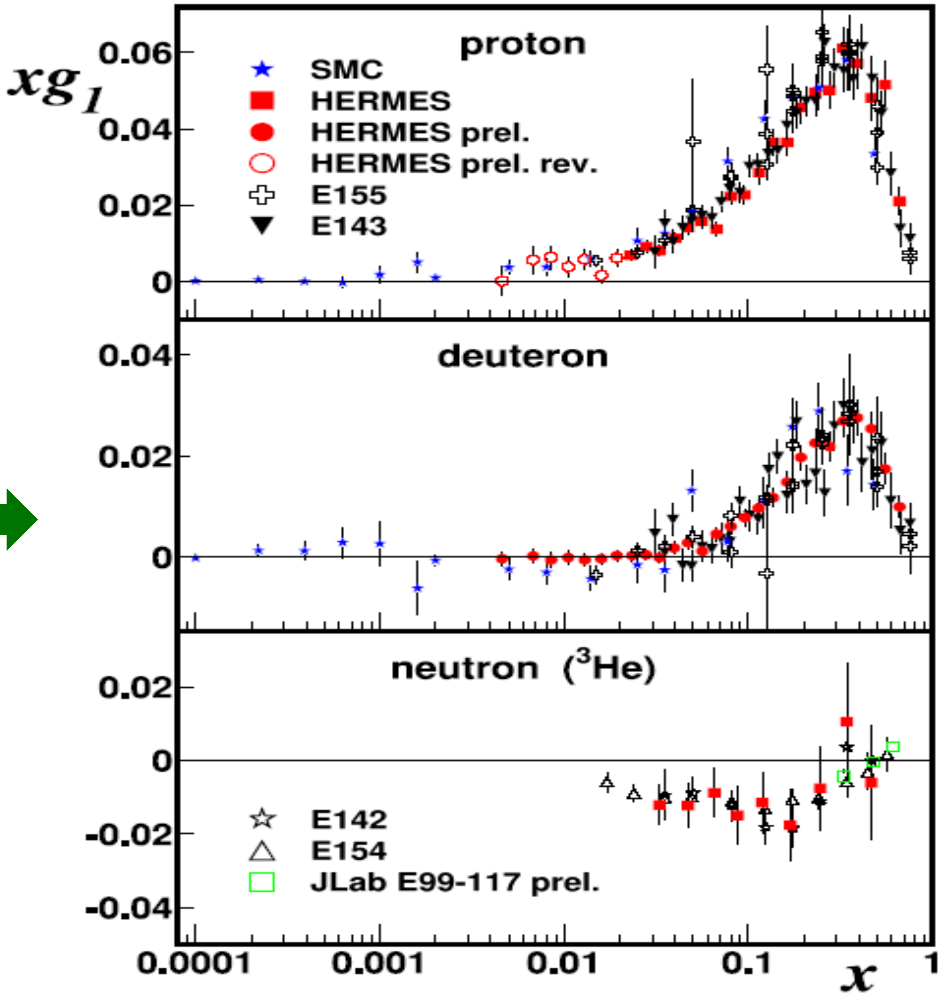
- Spin decomposition – at different distance scales:

Learn QCD dynamics, not much details in partonic structure!

Role of quark's spin – twenty years' effort

❑ The EMC's "Plot" is improved:





❑ But, the puzzle remains!

$$\Delta\Sigma(Q^2) = \sum_q \left[\Delta q(Q^2) + \Delta\bar{q}(Q^2)\right] \ll 1$$

Quark spin ~ 25%

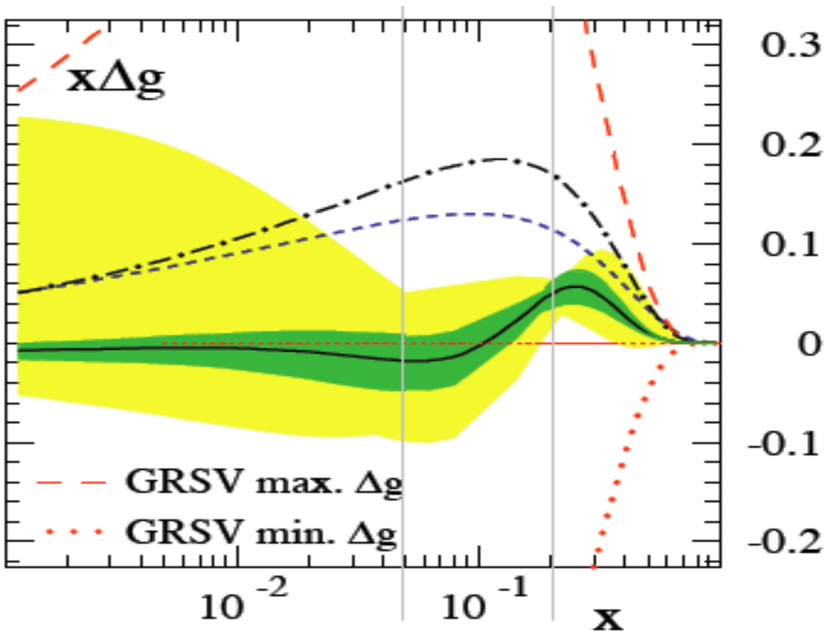
Role of gluon's spin – RHIC's spin program

- Definition – in terms of an non-local operator! – small x?

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

- NLO QCD global fit - DSSV:

PRL101,072001(2008)



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

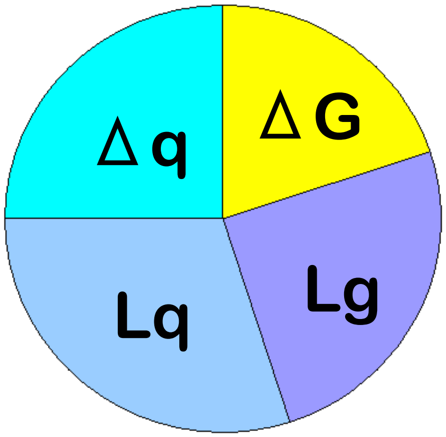
Strong constraint on ΔG from

$$0.05 \lesssim x \lesssim 0.2$$

Physics of the node?

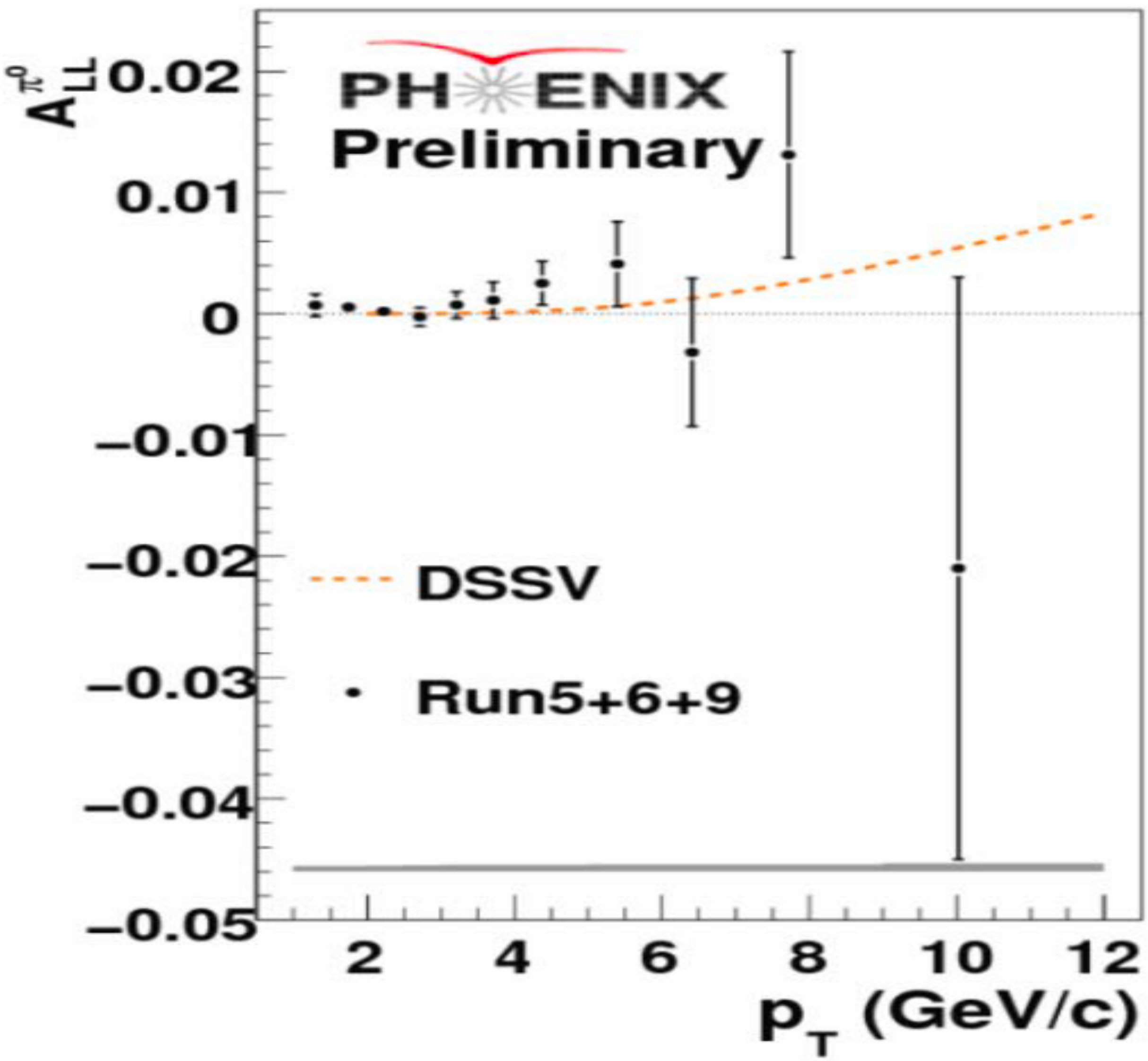
- Proton's spin budget:

Quark spin ~ 25%, Gluon spin ~ 0%



New PHENIX data – Run 9

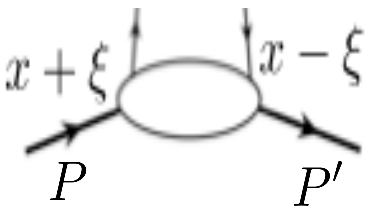
- Combine data from Run 5, 6, and 9:



Contribution from parton's orbital motion

❑ Generalized parton distributions (GPDs) - quark:

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

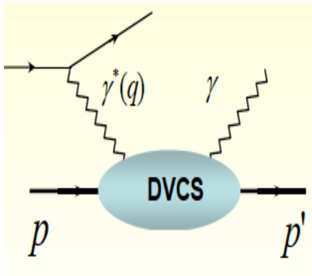


with $\xi = (P'-P)\cdot n/2$ and $t = (P'-P)^2 \Rightarrow -\Delta_\perp^2$ if $\xi \to 0$

❑ Net quark's orbital motion:

Ji, PRL78, 1997

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



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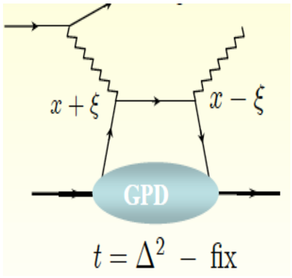


$, \ldots$

❑ Similarly, for gluon GPDs

C. Weiss' talk on exclusive process tomorrow

Need to measure the exclusive processes – DIS is ideal

(no factorization for hadronic diffractive processes!)

Contribution from parton's orbital motion

Negele et al

- ❑ **Moments of GPDs on lattice:**

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

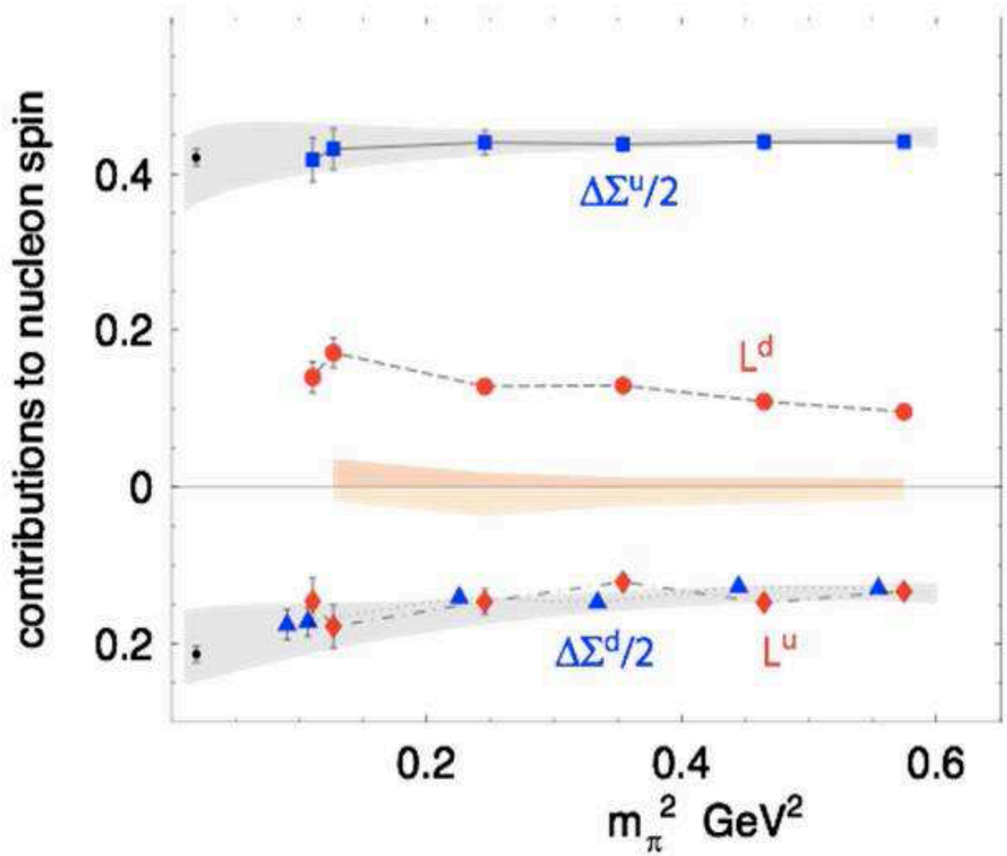
- ❑ **Ji's relation:**

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

- ❑ **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 luminosity

Challenges in determining the sum rule

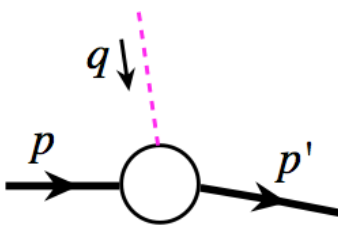
❑ "Proper" definition:

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

- ✧ Confinement – No free quarks and gluons – only the "sum" is physical
- ✧ A good or meaningful decomposition:

  Every term is connected to the physically measurable quantities with controllable approximation

❑ Exclusive processes – GPDs:



- ✧ Exchange a "vacuum" quantum number

  Any partonic combination with a "vaccum" quantum number can contribute

  $$q\bar{q},\ q(g)^n\bar{q},\ gg,\ g(g)^n g, \ldots$$

- ✧ Both real and imaginary part of amplitude contribute

Require a large Q^2 – "localized" probe, and a large range of Q^2, …

Spin as a powerful tool

- ❑ The sum rule, such as the proton's spin budget, is interesting and important

- ❑ BUT, the x- and k_T-dependence of the distributions (the motion of a parton), and the correlation of multiple partons inside a hadron are even more interesting, more rich in dynamics

  - ✧ Transverse momentum dependent (TMD) distributions

    3-D motion of partons

  - ✧ Multi-parton correlation functions

    Measurement of quantum interference

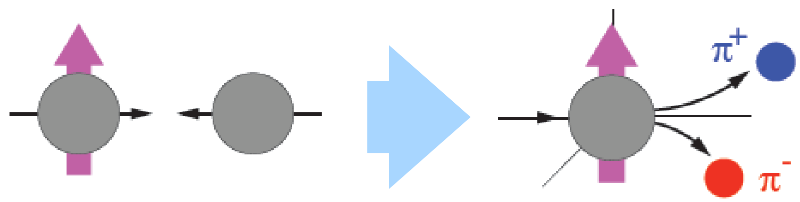
Spin helps to separate and extract these information

Power of various spin asymmetries

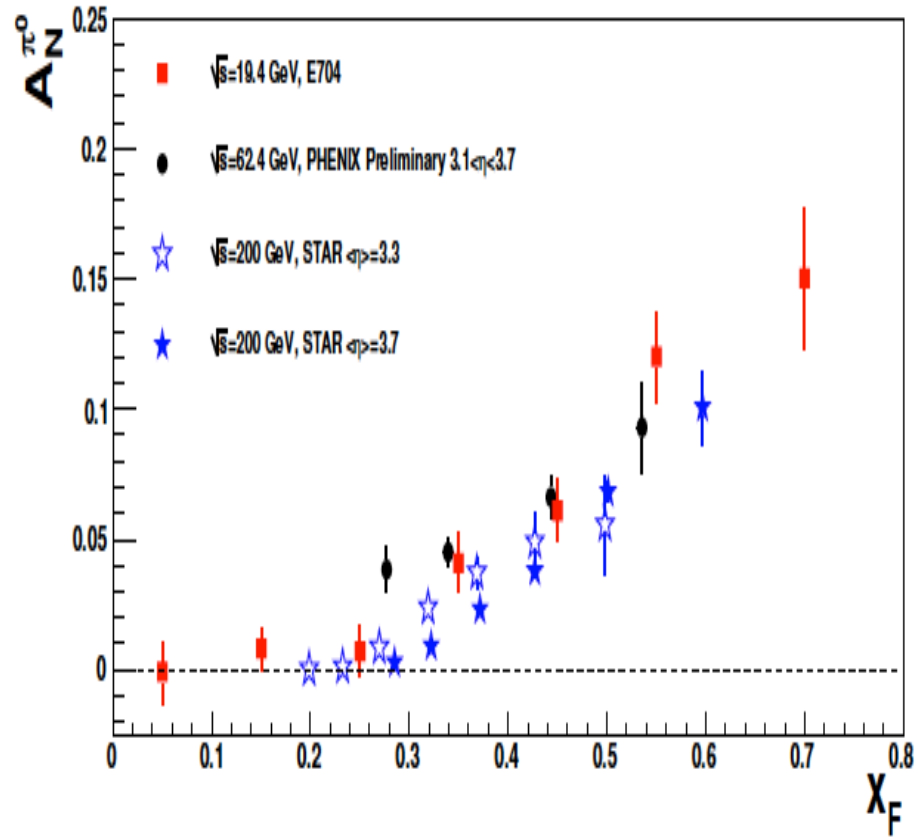
Parton's transverse motion

- Transverse single spin asymmetry (SSA):

$$A(p_A, s_\uparrow) + B(p_B) \to \pi(p) + X$$



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



- Vanish without parton's transverse motion:

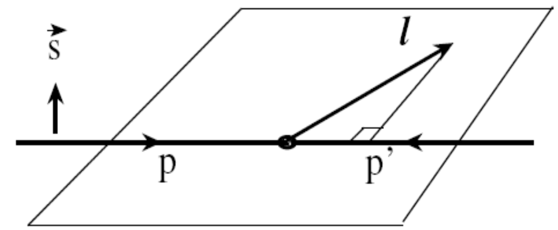
➡ A direct probe for parton's transverse motion,

Spin-orbital correlation, QCD quantum interference

SSA in collinear parton model

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

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

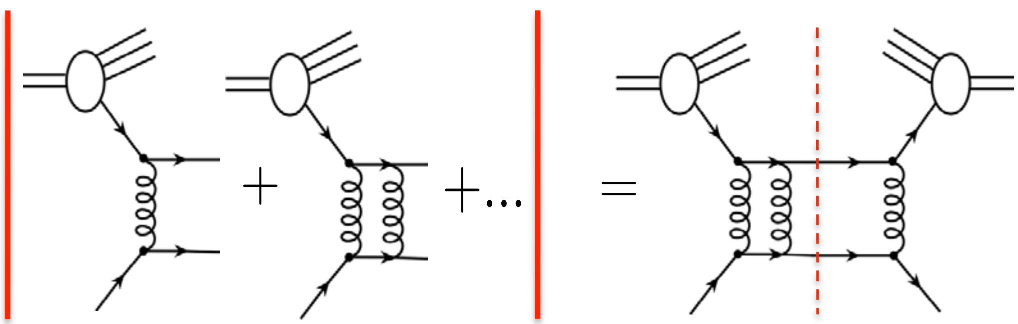


Novanish A_N requires a phase, enough vectors to fix a scattering plan, and a spin flip at the partonic scattering

- **Leading power in QCD:**

Kane, Pumplin, Repko, PRL, 1978

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

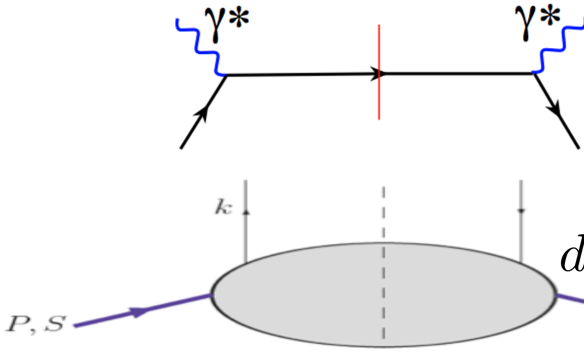


$$\propto \alpha_s \frac{m_q}{p_T}$$

A_N connects to parton's transverse motion!

TMD parton distributions

❑ Quark TMD distributions:



$$\hat{k}^\mu = xp^\mu + \frac{k_T^2}{2xp^+}n^\mu + k_T^\mu$$

$$dk^2 dk^+ \delta(x - k^+/P^+)$$

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

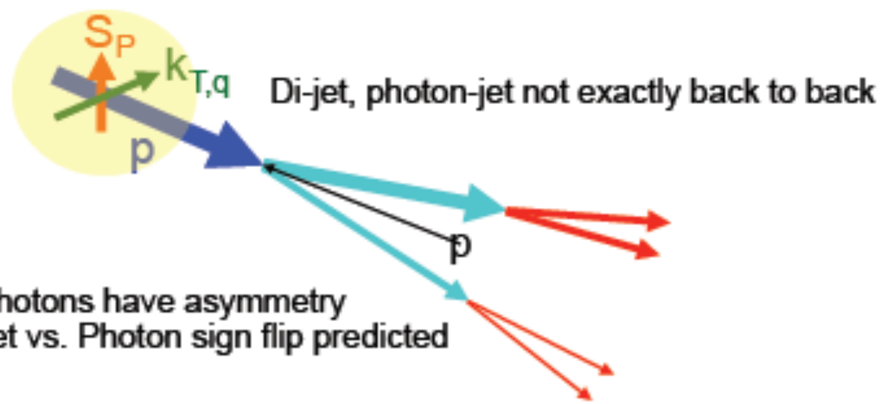
Total 8 TMD quark distributions

❑ Gluon TMD distributions, …

Production of quarkonium, two-photon, …

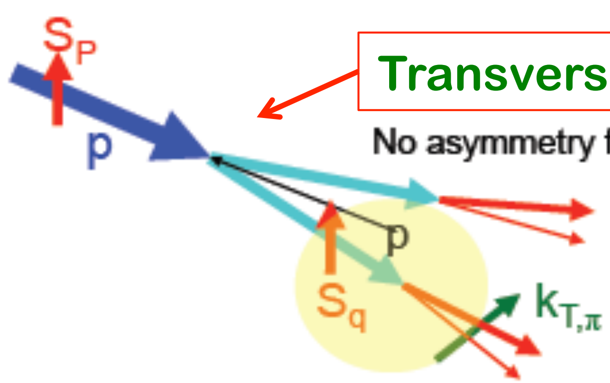
Measure TMD's

❑ Sivers' effect – Sivers' function:



Hadron spin influences parton's transverse motion

❑ Collin's effect – Collin's function:



Parton's transverse spin affects its hadronization

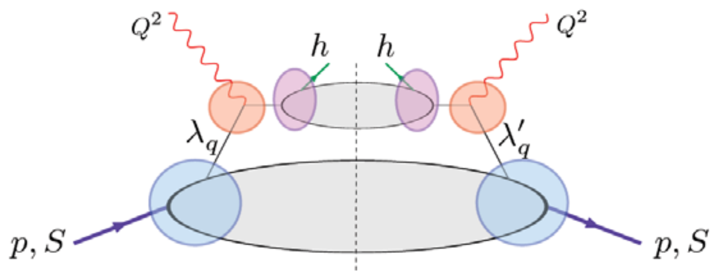
Separation of different effects?

❑ Need TMD factorization to quantify parton transverse motion!

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

SIDIS is ideal for studying TMDs

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



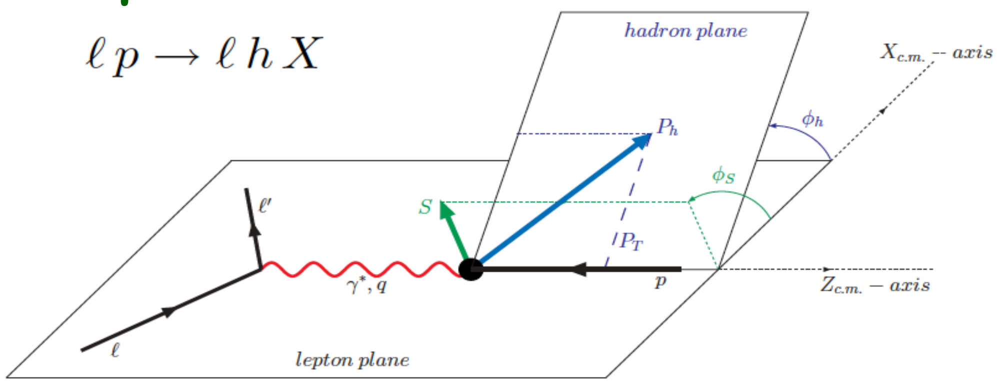
$$\ell(s_e) + p(s_p) \to \ell + h(s_h) + X$$

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

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

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

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

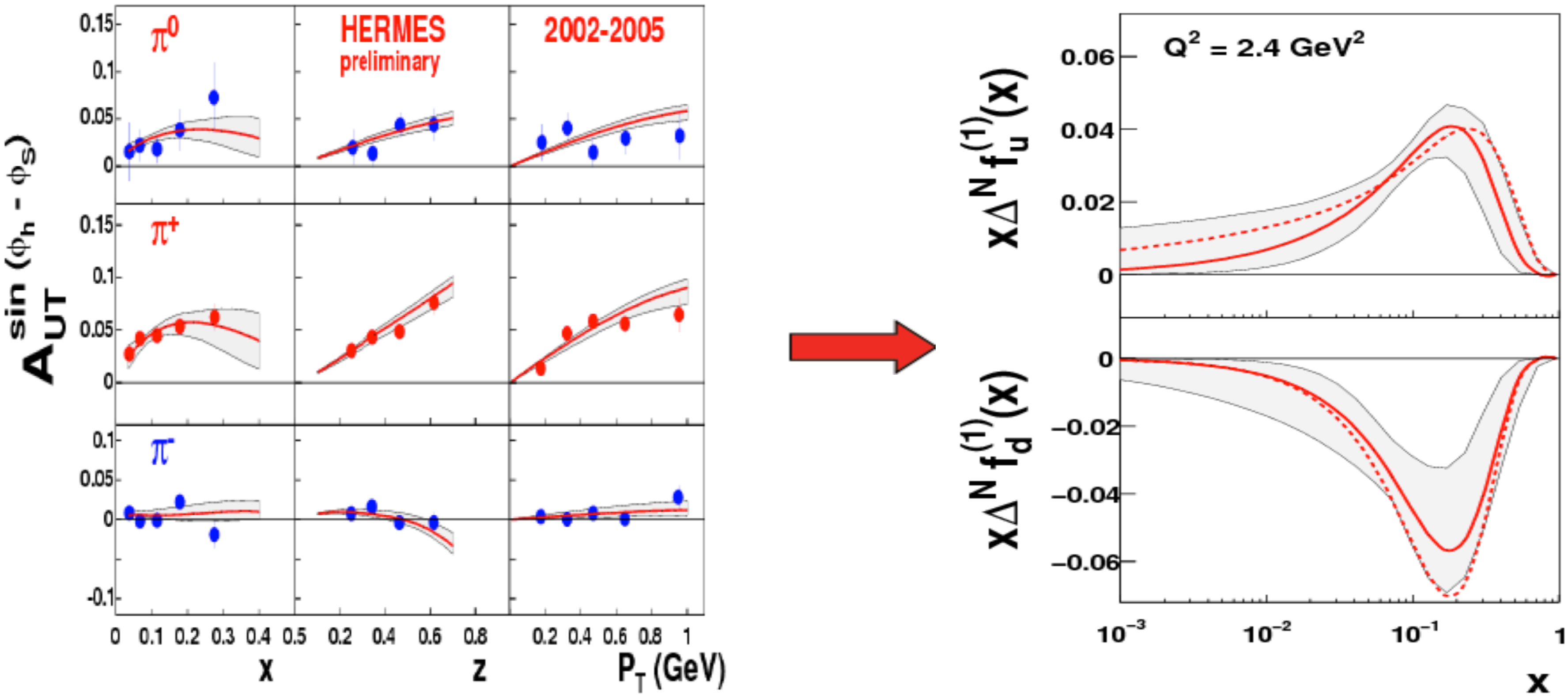
$$A_{UT}^{Collins} \propto \langle \sin(\phi_h + \phi_S) \rangle_{UT} \propto h_1 \otimes H_1^{\perp}$$

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

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

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!

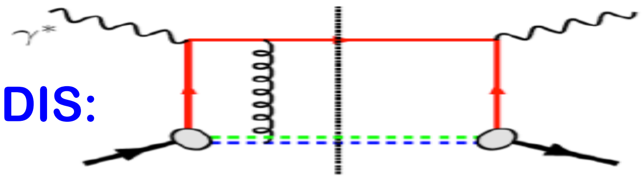
Collins and Qiu, 2007, Vogelsang and Yuan, 2007, Mulders and Rogers, 2010, …

Critical test of TMD factorization

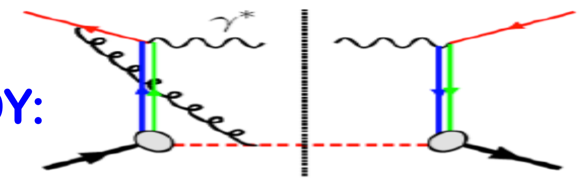
❑ **TMD distributions with non-local gauge links:**

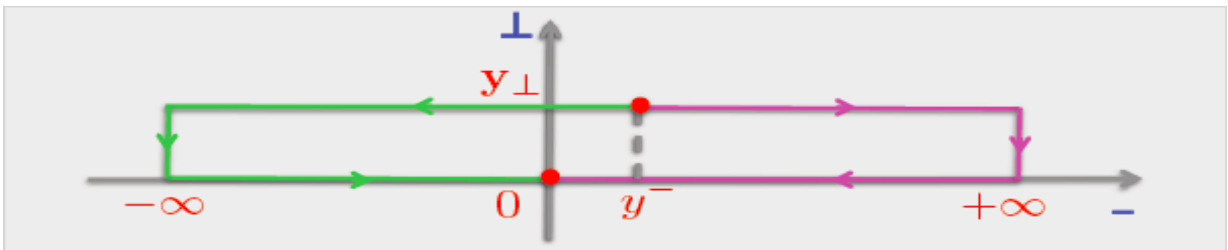
$$f_{q/h^\uparrow}(x,\mathbf{k}_\perp,\vec{S}) = \int \frac{dy^- d^2y_\perp}{(2\pi)^3}\, e^{ixp^+y^- - i\mathbf{k}_\perp\cdot\mathbf{y}_\perp} \langle p,\vec{S}|\overline{\psi}(0^-,\mathbf{0}_\perp)\, \boxed{\text{Gauge link}}\, \frac{\gamma^+}{2}\psi(y^-,\mathbf{y}_\perp)|p,\vec{S}\rangle$$

SIDIS:



DY:





- For a fixed spin state:

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

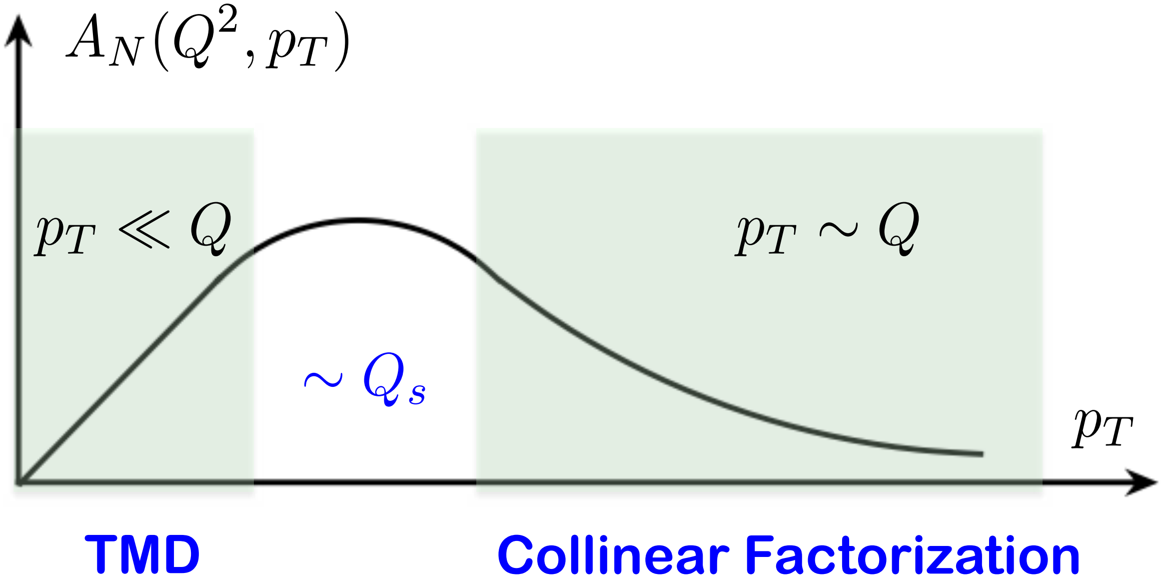
❑ **Parity + Time-reversal invariance:**

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

It is a critical test of TMD factorization approach

Transition from low pT to high pT

- Two-scale becomes one-scale:



- TMD factorization to collinear factorization:

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

Two approaches are consistent in the overlap region: $\Lambda_{\rm QCD} \ll p_T \ll Q$

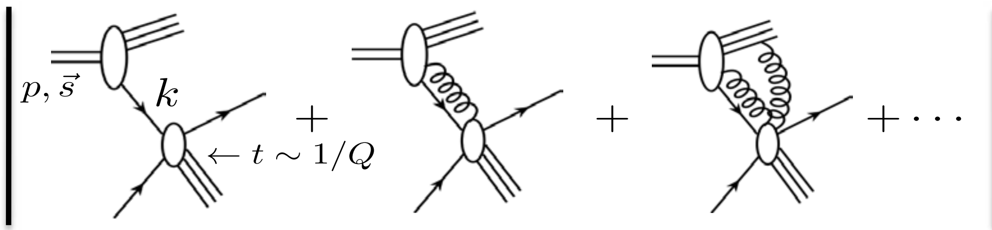
A_N finite – requires correlation of multiple collinear partons

New opportunities!

Collinear factorization for SSA

- **Collinear factorization beyond leading power:**

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



$\left(\frac{\langle k_\perp \rangle}{Q}\right)^n$ **– Expansion**

$$\sigma(Q, s_T) = H_0 \otimes f_2 \otimes f_2 + (1/Q)\, H_1 \otimes f_2 \otimes f_3 + \mathcal{O}(1/Q^2)$$

Too large to compete! (for H_0)

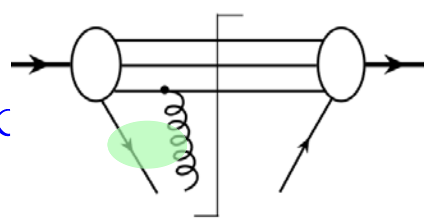
Three-parton correlation (for f_3)

- **Single transverse spin asymmetry:**

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

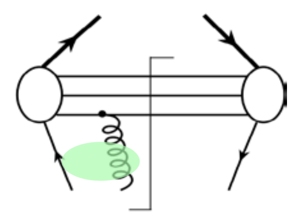
$$\Delta\sigma(s_T) \propto T^{(3)}(x,x) \otimes \hat{\sigma}_T \otimes D(z) + \delta q(x) \otimes \hat{\sigma}_D \otimes D^{(3)}(z,z) + \ldots$$

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



Qiu, Sterman, 1991, …

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

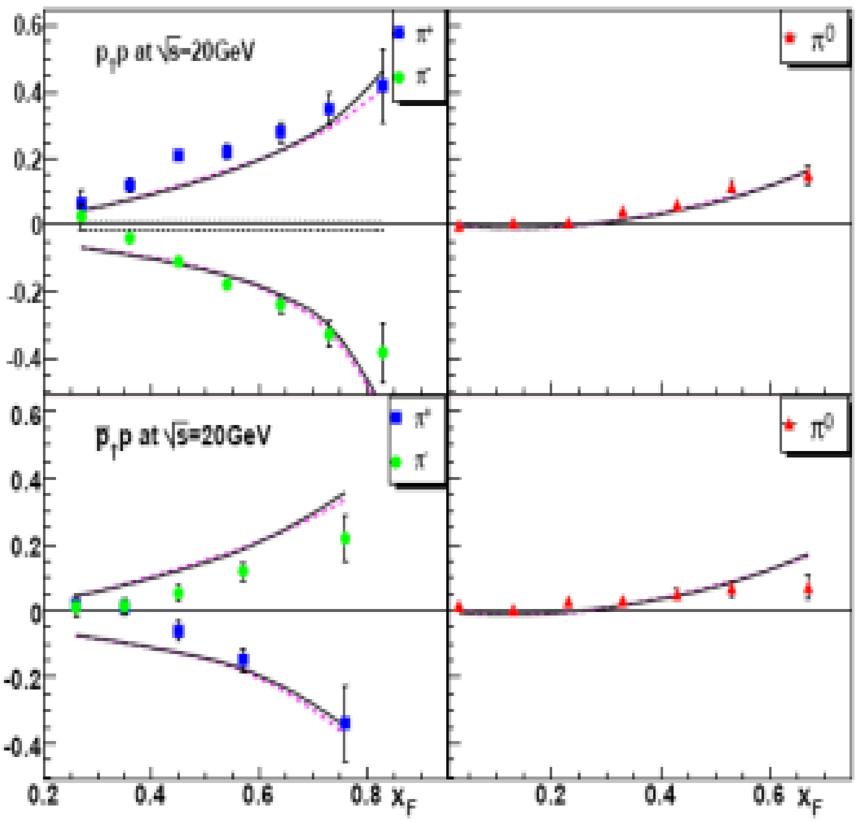


Kang, Yuan, Zhou, 2010

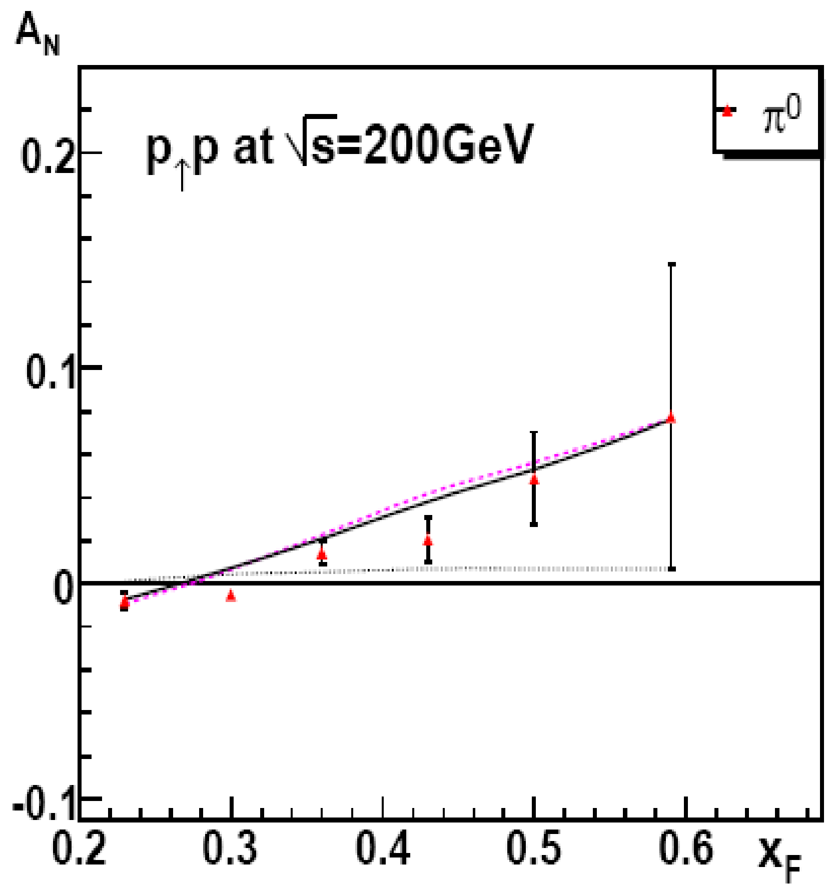
Integrated information on parton's transverse motion!

A_N from LO quark-gluon correlation

(FermiLab E704)



(RHIC STAR)



Kouvaris,Qiu,Vogelsang,Yuan, 2006

Nonvanish twist-3 function → Nonvanish transverse motion

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, …

Early surprise: a sign "mismatch"

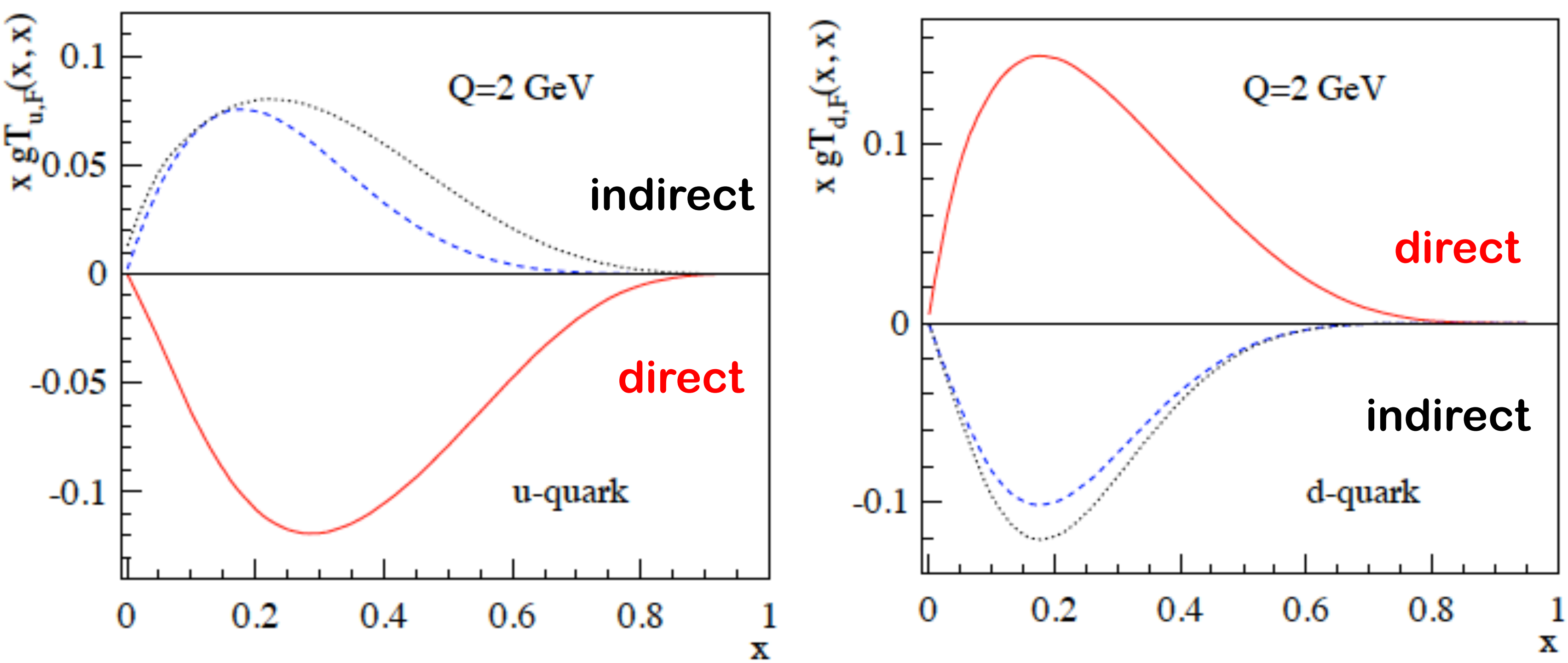
Kang, Qiu, Vogelsang, Yuan, 2011

- ❑ Sivers function and twist-3 correlation:

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

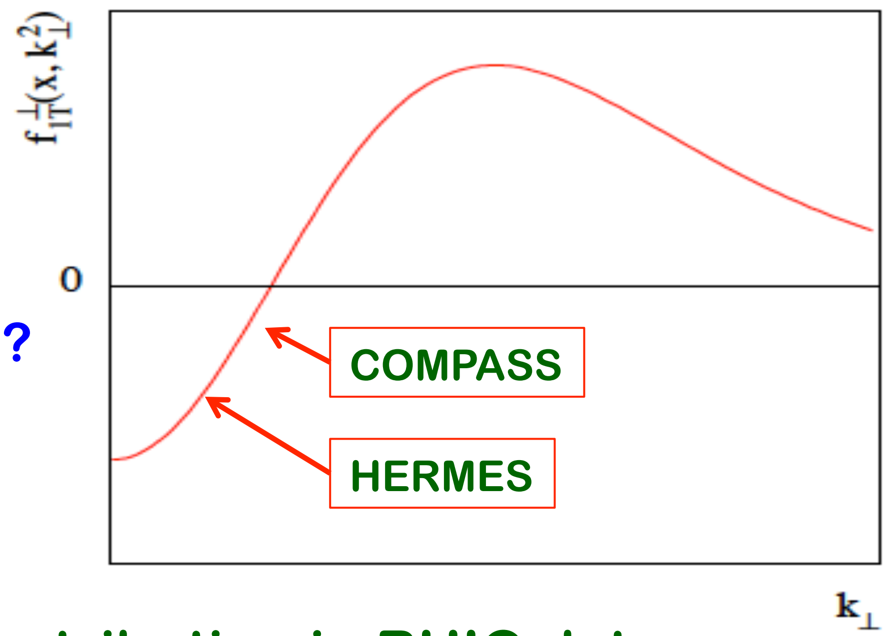
- ❑ "direct" and "indirect" twist-3 correlation functions:

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



Possible interpretations

Kang, Qiu, Vogelsang, Yuan, 2011



- 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

- A node in x-dependence of Sivers or twist-3 distributions

  Physics behind the node if there is any

  Boer, …

Scaling violation of twist-3 correlations

- Evolution equation is a consequence of factorization:

Factorization: $$\Delta\sigma(Q, s_T) = (1/Q)H_1(Q/\mu_F, \alpha_s) \otimes f_2(\mu_F) \otimes f_3(\mu_F)$$

DGLAP for f_2: $$\frac{\partial}{\partial \ln(\mu_F)} f_2(\mu_F) = P_2 \otimes f_2(\mu_F)$$

Evolution for f_3: $$\frac{\partial}{\partial \ln(\mu_F)} f_3 = \left(\frac{\partial}{\partial \ln(\mu_F)} H_1^{(1)} - P_2^{(1)}\right) \otimes f_3$$

- Evolution kernel is process independent:

  - ✧ Calculate directly from the variation of process independent twist-3 distributions

Kang, Qiu, 2009
Yuan, Zhou, 2009

  - ✧ Extract from the scale dependence of the NLO hard part of any physical process

Vogelsang, Yuan, 2009

  - ✧ Renormalization of the twist-3 operators

Braun et al, 2009

Scaling violation for twist-3 correlations

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

- ❑ Evolution kernels – "DGLAP":

Leading order evolution kernels for all channels have been derived!

$$\frac{\partial T_{q,F}(x,x,\mu_F)}{\partial \ln \mu_F^2} = \frac{\alpha_s}{2\pi}\int_x^1 \frac{d\xi}{\xi}\left\{\boxed{P_{qq}(z)\,T_{q,F}(\xi,\xi,\mu_F)}\right.$$
$$+\frac{C_A}{2}\left[\frac{1+z^2}{1-z}\left[T_{q,F}(\xi,x,\mu_F)-T_{q,F}(\xi,\xi,\mu_F)\right]+z\,T_{q,F}(\xi,x,\mu_F)\right]+\frac{C_A}{2}\left[T_{\Delta q,F}(x,\xi,\mu_F)\right]$$
$$\left.+P_{qg}(z)\left(\frac{1}{2}\right)\boxed{\left[T_{G,F}^{(d)}(\xi,\xi,\mu_F)+T_{G,F}^{(f)}(\xi,\xi,\mu_F)\right]}\right\}$$

- ✧ All kernels are infrared safe
- ✧ Diagonal contribution is the same as that of DGLAP
- ✧ Quark and antiquark evolve differently – caused by tri-gluon

- ❑ What are urgently needed:

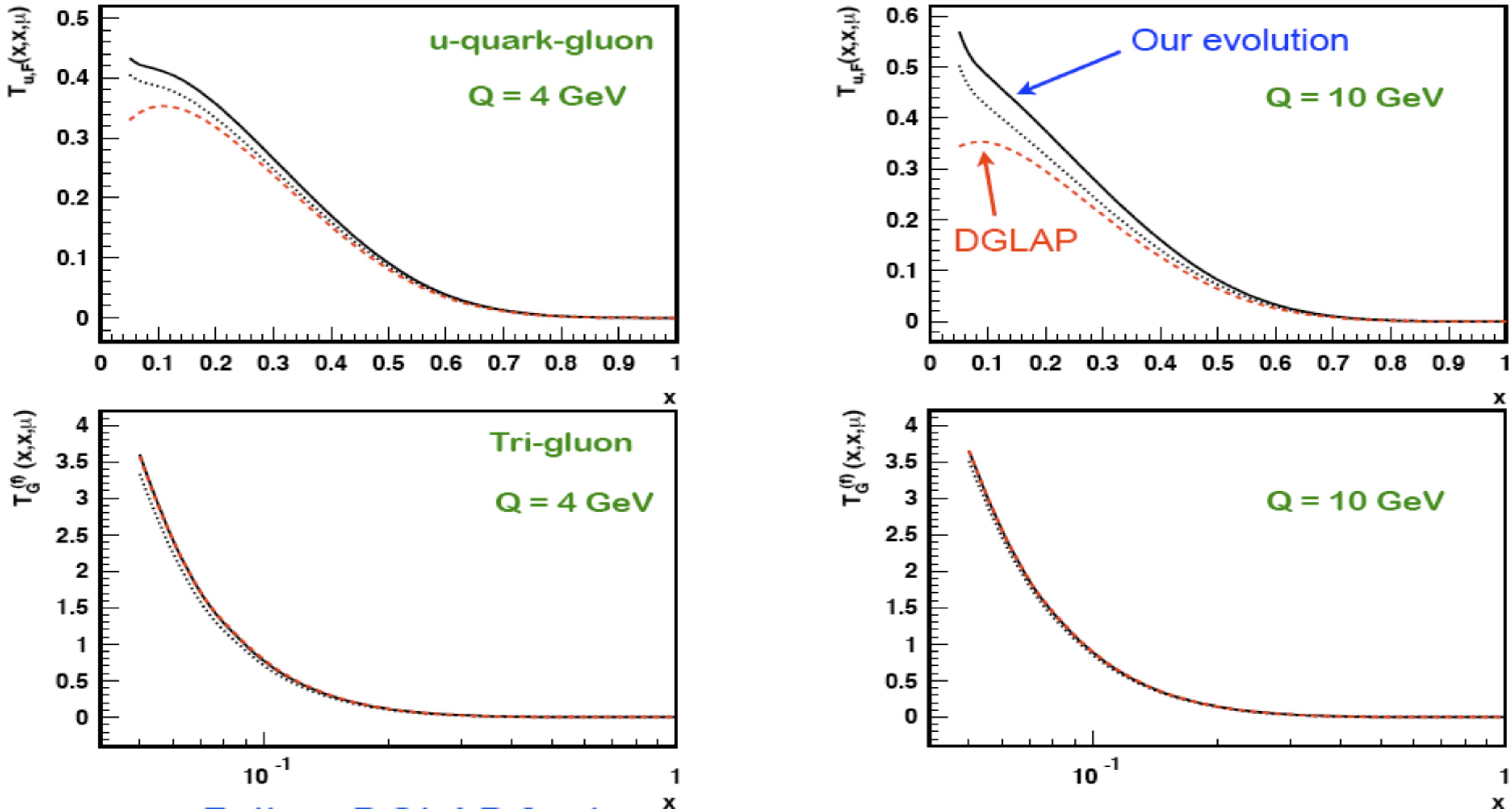
NLO partonic contributions to SSA of all measureable observables!

- ❑ A completely new domain to test QCD!

Vogelsang, Yuan, 2009

From paton's transverse motion to direct QCD quantum interference

Scale dependence



- ✧ **Follow DGLAP at large x**
- ✧ **Large deviation at low x (stronger correlation)**

We have all the tools to do NLO calculations, but, need man power!

Propose new observables for ep collisions

Kang, Metz, Qiu, Zhou, 2011

- **Process:** $e(\ell) + h(p) \to \mathrm{jet}(p_j)(\mathrm{or}\ \pi, ...) + X$

  Lepton-hadron scattering without measuring the scattered lepton

  Single hard scale: p_{jT} in lepton-hadron frame

- **Complement to SIDIS:** $e(\ell) + h(p) \to e'(\ell') + \mathrm{jet}(p_j)(\mathrm{or}\ \pi, ...) + X$

  Two scales: $Q,\ p_{jT}$ in virtual-photon-hadron frame

- **Key difference in theory treatment:**

  Collinear factorization for $e(\ell) + h(p) \to \mathrm{jet}(p_j)(\mathrm{or}\ \pi, ...) + X$

  TMD factorization for $e(\ell) + h(p) \to e'(\ell') + \mathrm{jet}(p_j)(\mathrm{or}\ \pi, ...) + X$

Test the consistency between TMD and Twist-3 to SSA
in the same experimental setting
Jlab, Compass, Future EIC, …

Analytical formulae

Kang, Metz, Qiu, Zhou, 2011

❑ Factorization is valid:

Same as hadron-hadron collision to jet + X

$$\frac{d\sigma^{lh\to \mathrm{jet}(P_J)X}}{dP_{JT}dy} \approx \sum_{ab}\int dx\, f_1^{a/l}(x,\mu)\int dx'\, f_1^{b/h}(x',\mu)\frac{d\hat\sigma^{ab\to \mathrm{Jet}(P_J)X}}{dP_{JT}dy}(x,x',P_{JT},y,\mu)$$

$$a = l,\gamma,q,\bar q,g$$
$$b = q,\bar q,g$$

❑ Leading order results:

$$\begin{aligned} P_J^0\frac{d^3\sigma}{d^3P_J} \;&=\; \frac{\alpha_{em}^2}{s}\sum_a\frac{e_a^2}{(s+t)\,x}\Big\{f_1^a(x)\,H_{UU}+\lambda_l\lambda_p\,g_1^a(x)\,H_{LL} \\ &\quad + 2\pi M\,\varepsilon_T^{ij}S_T^iP_{JT}^j\left[T_F^a(x,x)-x\frac{d}{dx}T_F^a(x,x)\right]\frac{\hat s}{\hat t\hat u}\,H_{UU} \\ &\quad + \lambda_l\,2M\,\vec S_T\cdot\vec P_{JT}\left[\left(\tilde g^a(x)-x\frac{d}{dx}\tilde g^a(x)\right)\frac{\hat s}{\hat t\hat u}\,H_{LL}+x\,g_T^a(x)\,\frac{2}{\hat t}\right]\Big\}\end{aligned}$$

$\lambda_l,\ \lambda_p$: Lepton, hadron helicity, respectively

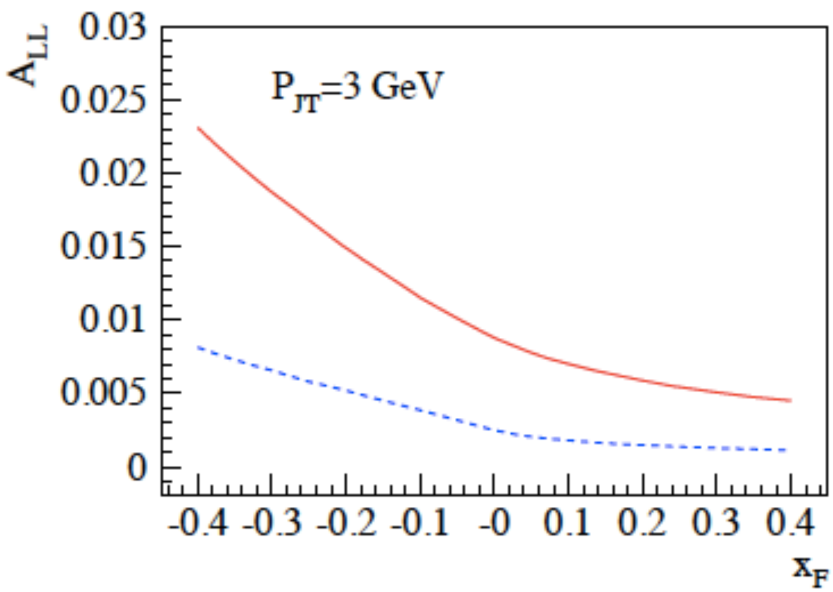
$\vec S_T$: Hadron's transverse spin vector

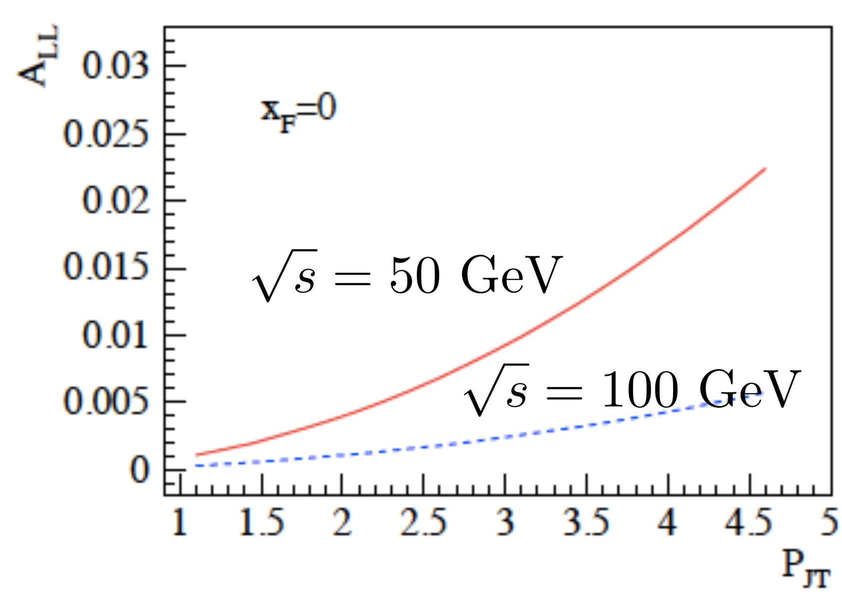
Numerical results

- Asymmetries:

$$A_{LL} = \frac{\sigma_{LL}}{\sigma_{UU}}\,, \qquad A_{UT} = \frac{\sigma_{UT}}{\sigma_{UU}}\,, \qquad A_{LT} = \frac{\sigma_{LT}}{\sigma_{UU}}$$

- Double spin asymmetries – very small:



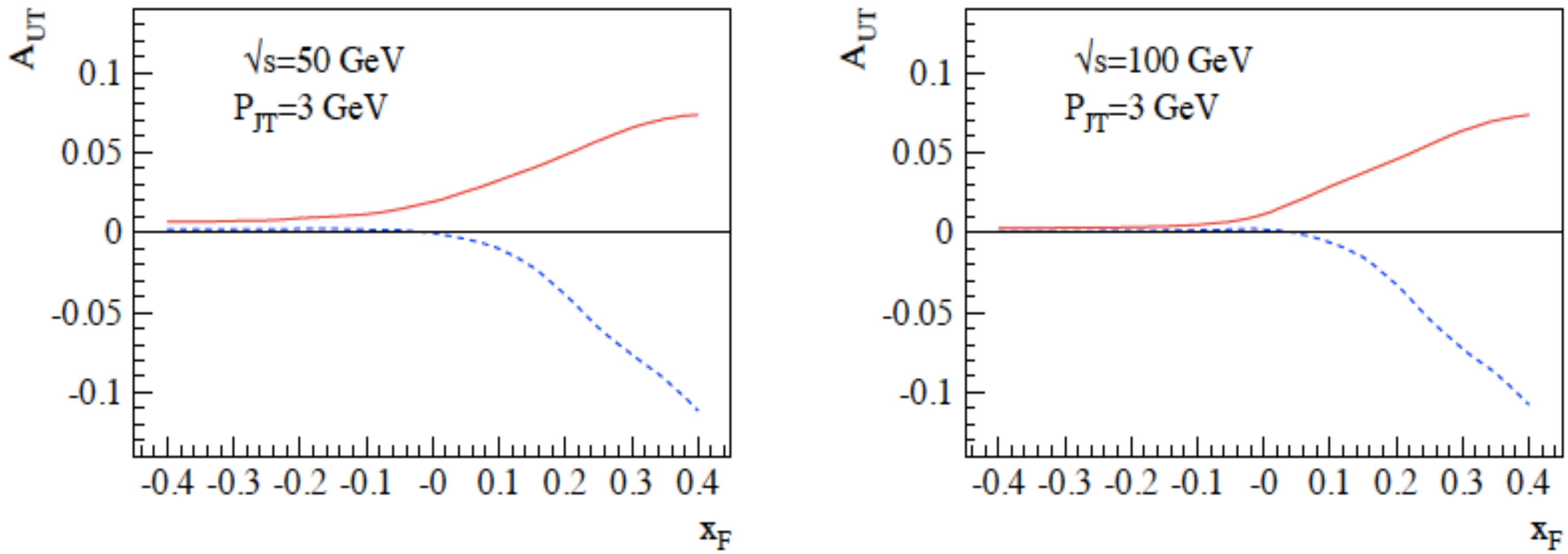


Wandzura-Wilczek approximation:

$$g_T(x) \approx \int_x^1 \frac{dy}{y}\, g_1(y) \qquad \tilde{g}(x) \approx x \int_x^1 \frac{dy}{y}\, g_1(y) \qquad \to \; A_{LT} \sim 0.001$$

Good probe of Sivers function

❑ Independent check of the "sign mismatch":



Red line: $T_F(x, \mu)$ extracted from fitting SSA in hadronic collisions

Blue line: $\pi T_F(x,x) = -\int d^2k_T \frac{\vec{k}_T^2}{2M^2} f_{1T}^{\perp}(x, \vec{k}_T^2)\Big|_{DIS}$ Sivers function

Excellent test for the mechanism of SSA
possibly at Jlab, surely at future EIC

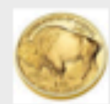
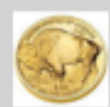
More on future directions

- ❑ RHIC spin, JLab at 12 GeV, possibly at Compass, …
- ❑ Future EIC:
  – a dedicated QCD machine for the visible matter

  Yellow book on EIC physics from INT workshop is available:

  arXiv: submit/0295324 [nucl-th]
- ❑ Physics opportunities at EIC:
  - ✧ Inclusive DIS – Spin, F_L, …
  - ✧ SIDIS – TMDs, spin-orbital correlations,
  - ✧ One jet or particle inclusive – multiparton quantum correlation, …
  - ✧ GPDs – parton spatial distributions
  - ✧ …
- ❑ More spin physics opportunities at low energy hadron machines around the world

Golden PDF measurements at EIC

Science Deliverable	Basic Measurement	Uniqueness Feasibility Relevance	Requirements
spin structure at small x contribution of Δg, ΔΣ 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, also in INT Yellow Book

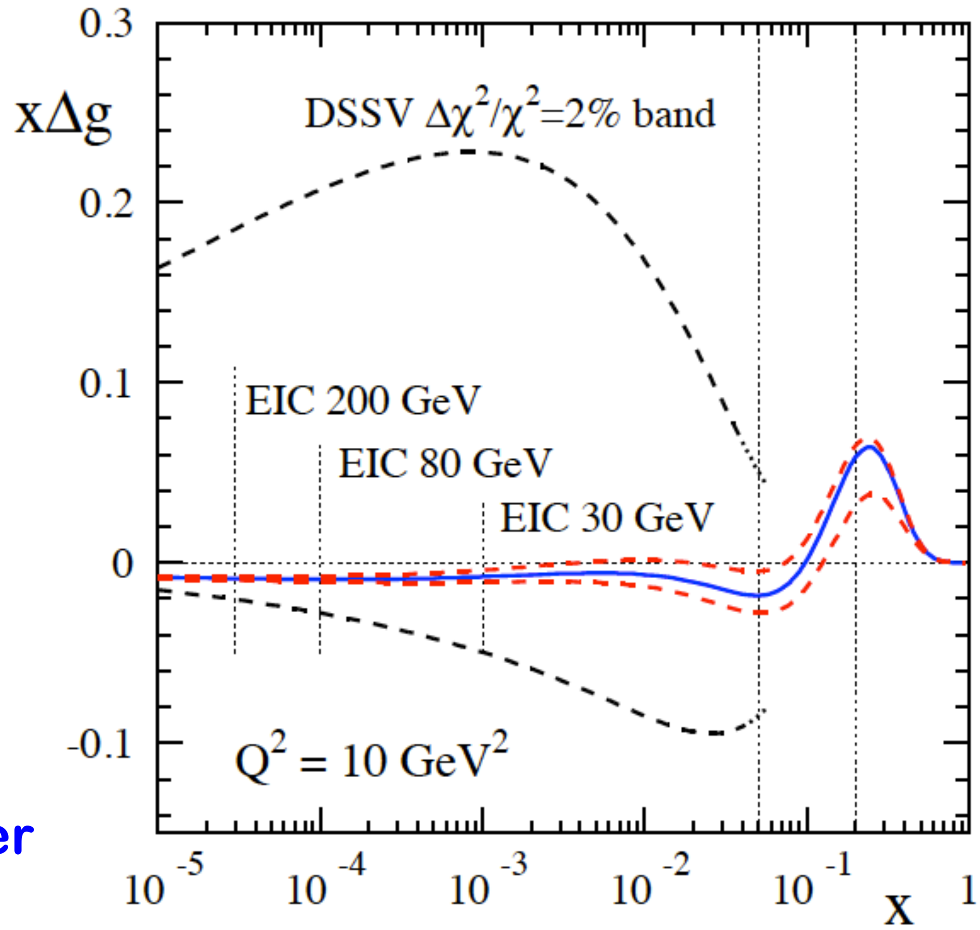
The “money” plot – inclusive DIS

❑ **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 for theorists:**

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

INT Yellow Book

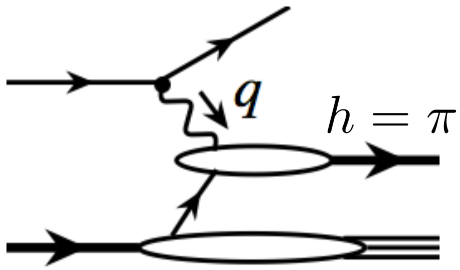
Quark flavor separation – SIDIS

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

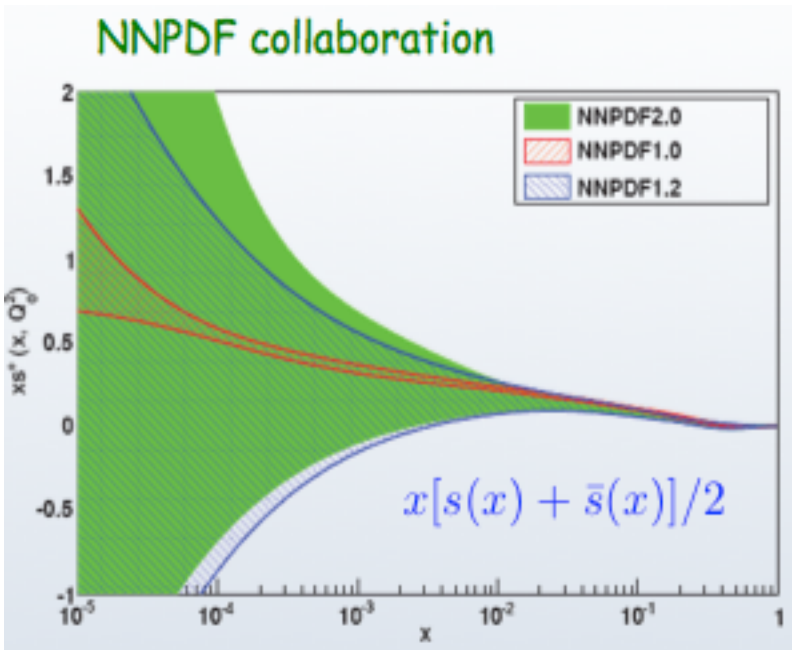
  One hard scale – collinear factorization

  $h = \pi, K, \ldots$

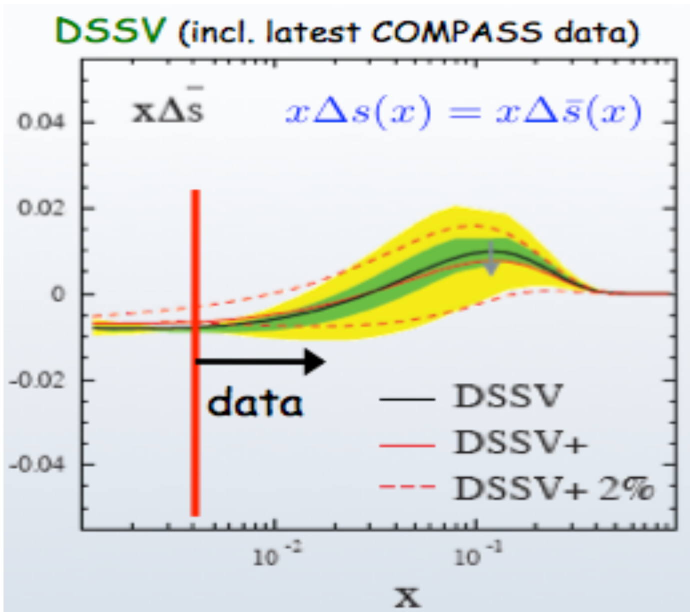
  Separation of parton flavors



- Strangeness distributions:



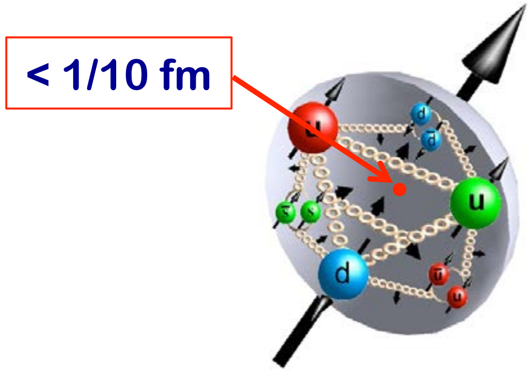
NuTeV anomaly on $\mathrm{Sin}^2\,\theta_W$



Tension with the 1st moment

Summary

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



- What about the hadron structure?

  Not much!

- Scattering with a polarized hadron beam opens up many new ways to test QCD and to study hadron structure:

  TMDs, GPDs, quark-gluon correlations, …

  EIC is the future for spin physics

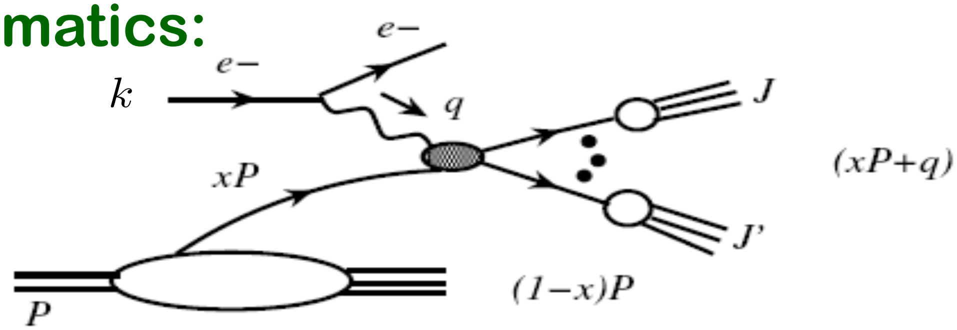
- The challenge for theorists is to indentify new, measurable, and factorizable observables that carry rich information on hadron’s partonic structure

Thank you!

Backup slices

EIC Kinematics

- **DIS kinematics:**



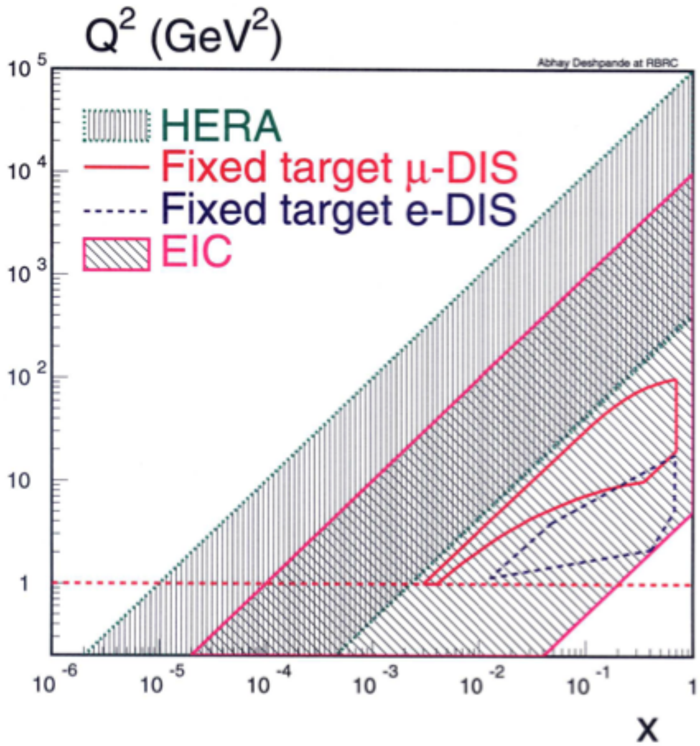
$$Q^2 = -q^2 = x_B\, y\, S$$

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

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

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

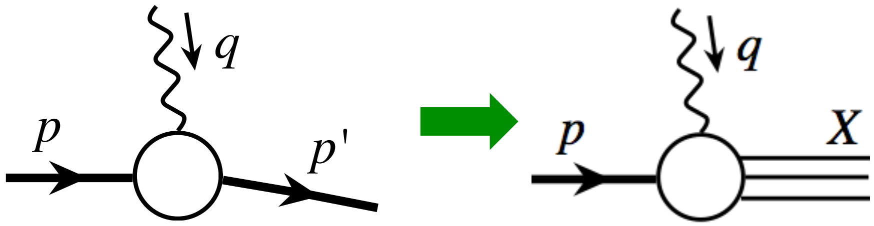
- **EIC (eRHIC – ELIC) basic parameters:**



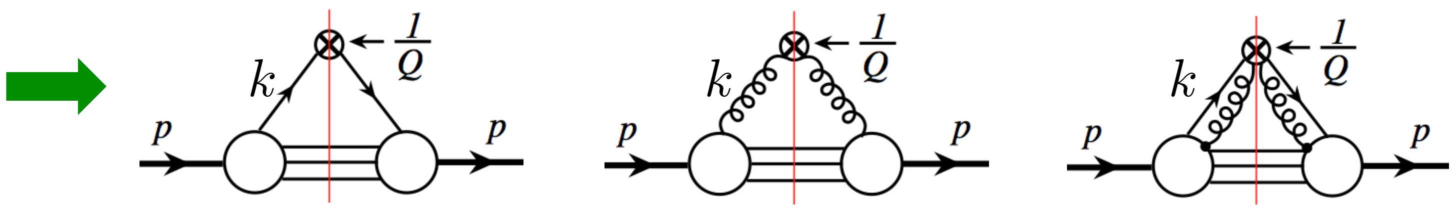
- $E_e = 10$ GeV (5-30 GeV available)
- $E_p = 250$ GeV (50-325 GeV available)
- $\sqrt{S} = 100$ GeV (30-200 GeV available)
- **"localized" probe:** $Q^2 \gtrsim 1$ GeV
- $x_{\min} \sim 10^{-4}$
- **Luminosity ~ 100 x HERA**
- **Polarization, heavy ion beam, …**

EIC advantages

- **Inclusive DIS – Spin:**



Forward scattering matrix elements:

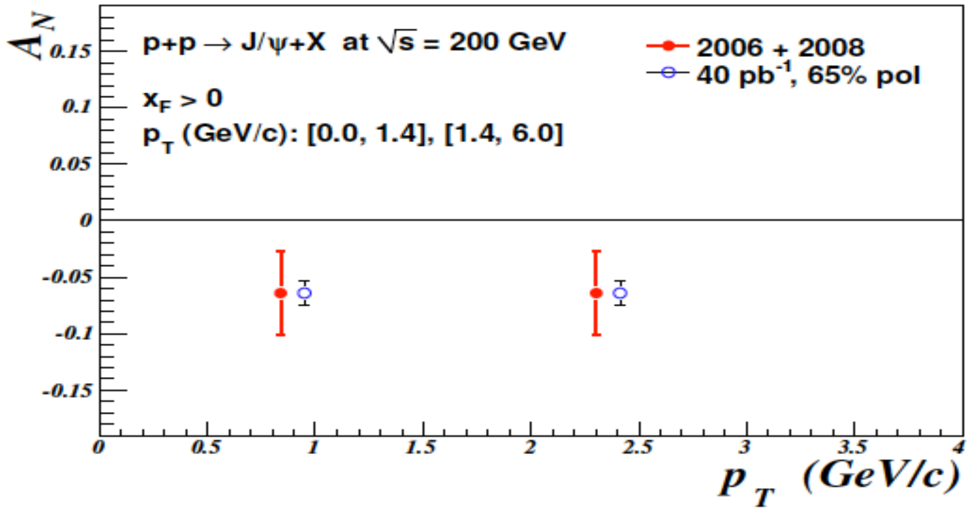


PDFs Correlation functions

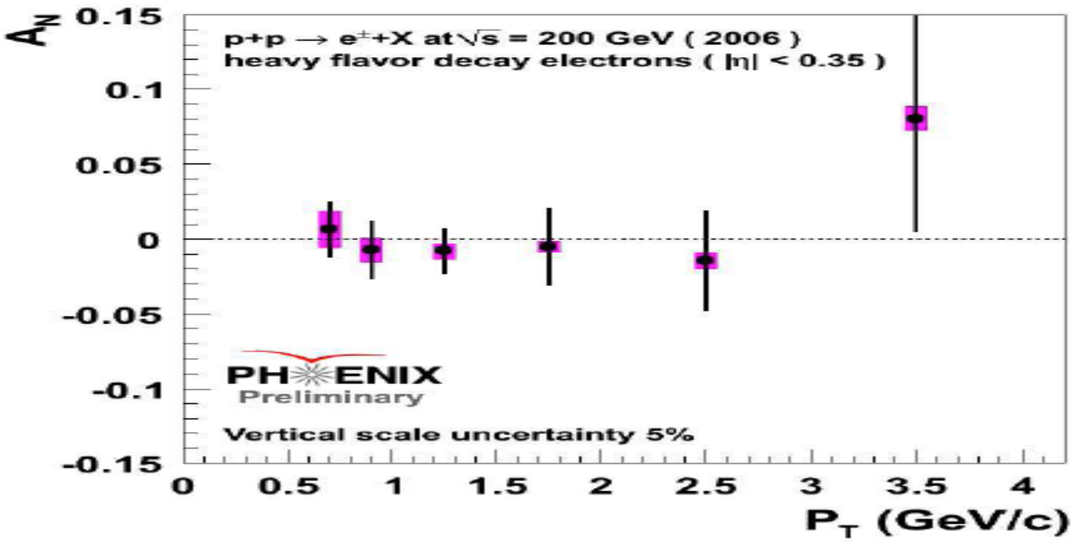
- **SIDIS – Best place to measure TMDs:**
  - ✧ TMD Factorization
  - ✧ Naturally two very different scales: Q, p_T
  - ✧ Well-defined lepton-plane and hadron-plane – separation of TMDs

First hint of tri-gluon correlation

- ❑ PHENIX data on J/psi:



- ❑ PHENIX data on open charm:



Collinear factorization:

- ✧ tri-gluon correlation – direct quantum interference

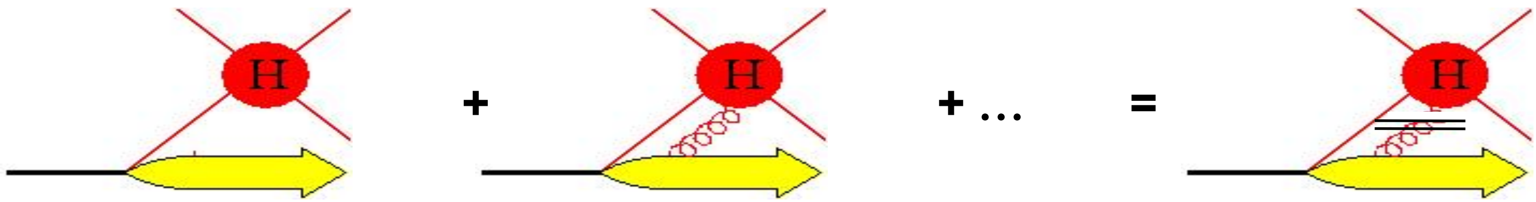
Challenges:

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

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

Color flow and gauge links

❑ **Gauge link – QCD phase:**



✧ **Summation of leading power gluon field contribution produces the gauge link:**

$$\Phi_n(\infty, y^-) = \mathcal{P}\exp\left(-ig\int_{y^-}^{\infty} d\lambda\, n\cdot A(\lambda n)\right)$$

✧ **Gauge invariant PDFs:**

$$\phi(x,p,s) = \int \frac{dy^-}{2\pi} e^{ixp^+y^-}\langle p,s|\overline{\psi}(0)_j\hat{\Gamma}_{ji}\Phi_n^\dagger(\infty,0)\Phi_n(\infty,y^-)\psi_i(y^-)|p,s\rangle$$

✧ **Collinear PDFs:**

"Localized" operator with size ~ 1/xp ~ 1/Q

"localized" color flow

✧ **Gauge link should be process dependent – color flow!**