Heavy Quark and Spin Physics in p+p and e+n Collisions

Jianwei Qiu
Brookhaven National Laboratory

Workshop on “Heavy quark production in heavy-ion collisions”
Purdue University, IN, January 4 – 6, 2011

Outline

- Why spin?
- Role of heavy quark production in spin physics
- Single spin asymmetry of heavy quark production

  – beyond the probability – QCD quantum interference
- Heavy quark is an excellent probe of glue at EIC
- Summary and outlook

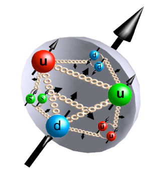
Spin

- **Spin of an elementary particle:**

  An intrinsic quantum property of the particle

- **Spin of a composite particle:**

  Angular momentum when the particle is at rest



- **Spin in QCD:**

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

✧ **Quark angular momentum operator:**

$$\vec{J}_q = \int d^3x \left[\psi_q^\dagger \vec{\gamma}\gamma_5 \psi_q + \psi_q^\dagger (\vec{x} \times (-i\vec{D}))\, \psi_q \right] \Rightarrow J_q(\mu) \to \frac{1}{2}\Delta q(\mu) + L_q(\mu)$$

✧ **Gluon angular momentum operator:**

$$\vec{J}_g = \int d^3x \left[\vec{x} \times (\vec{E} \times \vec{B}) \right] \Rightarrow J_g(\mu) \to \Delta G(\mu) + L_g(\mu)$$

Jaffe-Manohar, Ji, Chen et al, Wakamatsu, …

The decomposition is not unique!

– link individual pieces to other observables?

Proton Spin

❑ Complexity of the proton state:

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

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

$$\mu \Rightarrow \infty$$

❑ Qaurk Model:

$$S_p \equiv \langle p \uparrow | S | p \uparrow \rangle = \frac{1}{2}, \qquad S = \sum_i S_i$$

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

❑ Asymptotic limit:

Ji, 2005

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

❑ Proton spin structure:

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

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

If they could be measured separately

Cross sections and asymmetries

❑ Cross section:

Scattering amplitude square – Probability – Positive definite

A function of in-state and out-state variables: momentum, spin, …

❑ Spin-averaged cross section:

$$\sigma = \frac{1}{2}\left[\sigma(\vec{s}) + \sigma(-\vec{s})\right]$$ – Positive definite probability

❑ Asymmetries or difference of cross sections:

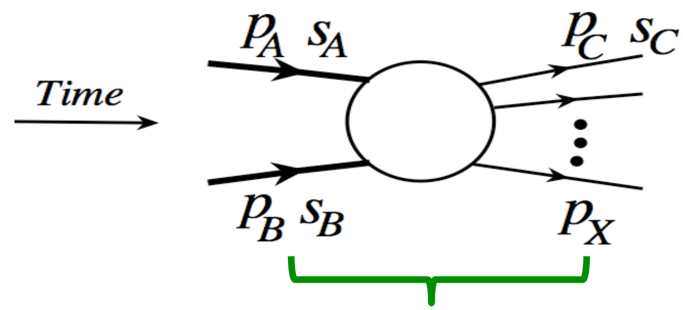
$$A(\vec{s}) = \frac{\Delta\sigma(\vec{s})}{\sigma} = \frac{\sigma(\vec{s}) - \sigma(-\vec{s})}{\sigma(\vec{s}) + \sigma(-\vec{s})} \qquad \Delta\sigma(\vec{s}) = \frac{1}{2}\left[\sigma(\vec{s}) - \sigma(-\vec{s})\right]$$

Difference of two probabilities – Not necessary positive!

Chance to see quantum interference directly

Connecting hadrons to QCD partons

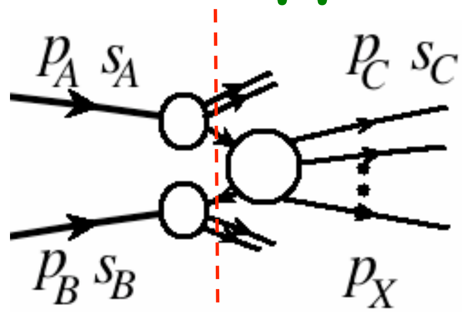
- **QCD confinement:**



Do not see partons in the detector!

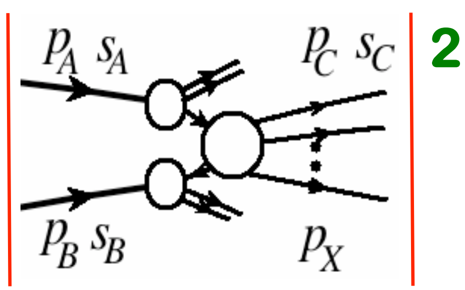
QCD parton dynamics

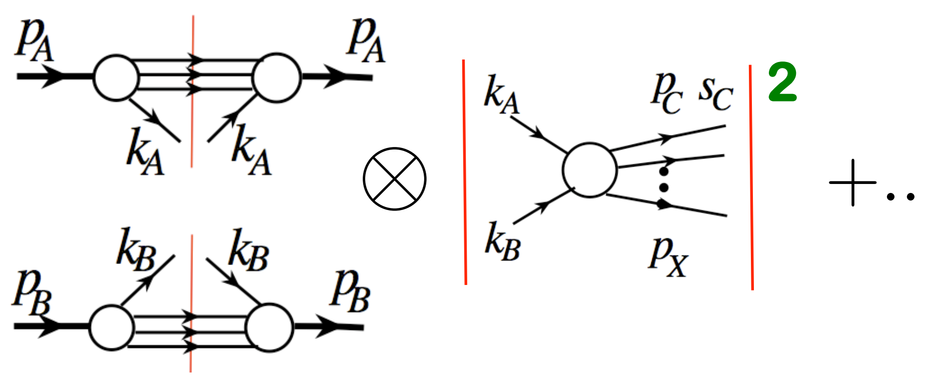
- **Factorization - approximation:**



$+\ldots$ (Diagrams with more active partons from each hadron!)

Single active parton from each hadron!

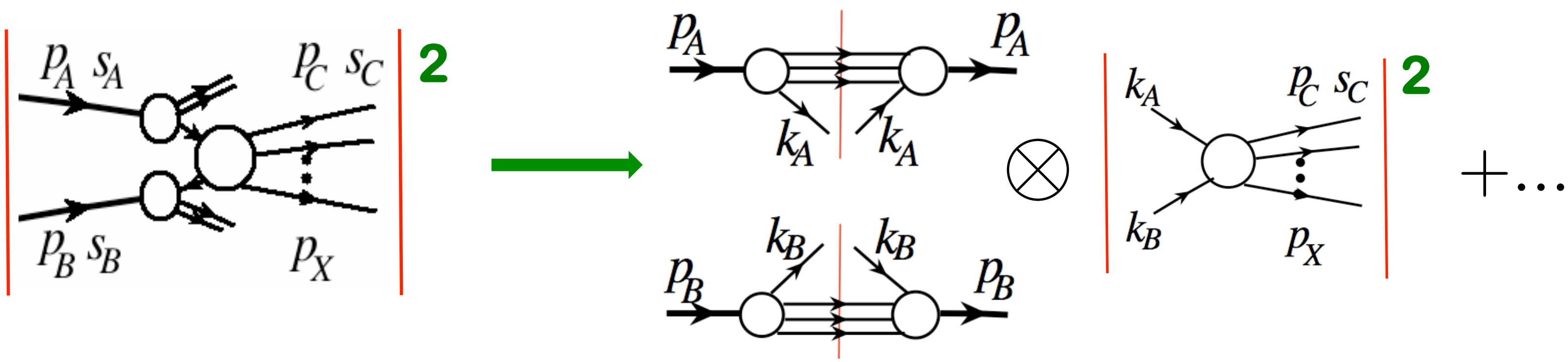




A Probability ~ A Product of probabilities!

Hadron vs parton spin states

❑ Partonic dynamics is insensitive to the hadron spin:



But, it is sensitive to parton's spin state !

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

❑ Hadron matrix element of different parton operators:

New information on hadron's partonic structure
– complimentary to spin-averaged experiments

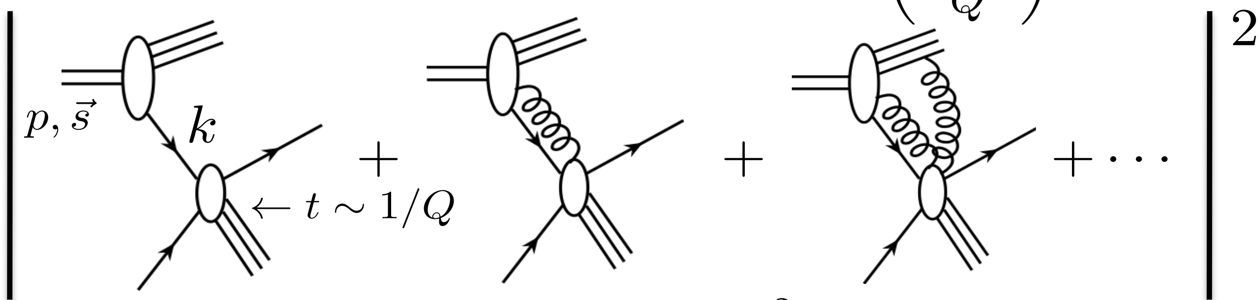
Unpol: $\langle p,\vec{s}|\overline{\psi}(0)\,\dfrac{\gamma\cdot n}{p\cdot n}\,\psi(yn)|p,\vec{s}\rangle$ $\quad \langle p,\vec{s}|F^{+\alpha}(0)F^{+\beta}(yn)|p,\vec{s}\rangle(-g_{\alpha\beta})$

Pol: $\langle p,\vec{s}|\overline{\psi}(0)\,\dfrac{\gamma\cdot n\,\gamma_5}{p\cdot n}\,\psi(yn)|p,\vec{s}\rangle$ $\quad \langle p,\vec{s}|F^{+\alpha}(0)F^{+\beta}(yn)|p,\vec{s}\rangle(i\epsilon_{\alpha\beta})$

Probe of QCD quantum interference

❑ Cross section with single hard scale: $\left(\frac{\langle k_\perp \rangle}{Q}\right)^n$ – expansion

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

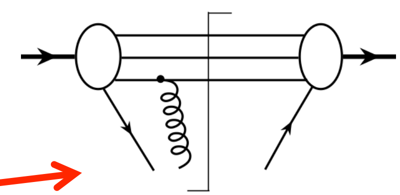


$$\sigma_{AB}(Q, \vec{s}) \approx \sigma^{(2)}_{AB}(Q, \vec{s}) + \frac{Q_s}{Q}\sigma^{(3)}_{AB}(Q, \vec{s}) + \frac{Q_s^2}{Q^2}\sigma^{(4)}_{AB}(Q, \vec{s}) + \cdots$$

single active collinear parton

❑ Single transverse spin asymmetry:

It is sensitive to parton's transverse motion!



$$\Delta\sigma(Q, s_T) \equiv [\sigma(Q, s_T) - \sigma(Q, -s_T)]/2$$

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

Direct information on QCD quantum interference

– spin-averaged experiment cannot "see" – different phase

Contribution from intrinsic parton's spin

- **DSSV – 2008:** $\Delta f_j^{1,[x_{\min}-1]}$ at $Q^2 = 10\,\mathrm{GeV}^2$

	$x_{\min}=0$ best fit	$x_{\min}=0.001$ $\Delta\chi^2=1$	$\Delta\chi^2/\chi^2=2\%$
$\Delta u+\Delta\bar{u}$	0.813	$0.793^{+0.011}_{-0.012}$	$0.793^{+0.028}_{-0.034}$
$\Delta d+\Delta\bar{d}$	-0.458	$-0.416^{+0.011}_{-0.009}$	$-0.416^{+0.035}_{-0.025}$
$\Delta\bar{u}$	0.036	$0.028^{+0.021}_{-0.020}$	$0.028^{+0.059}_{-0.059}$
$\Delta\bar{d}$	-0.115	$-0.089^{+0.029}_{-0.029}$	$-0.089^{+0.090}_{-0.080}$
$\Delta\bar{s}$	-0.057	$-0.006^{+0.010}_{-0.012}$	$-0.006^{+0.028}_{-0.031}$
Δg	-0.084	$0.013^{+0.106}_{-0.120}$	$0.013^{+0.702}_{-0.314}$
$\Delta\Sigma$	0.242	$0.366^{+0.015}_{-0.018}$	$0.366^{+0.042}_{-0.062}$

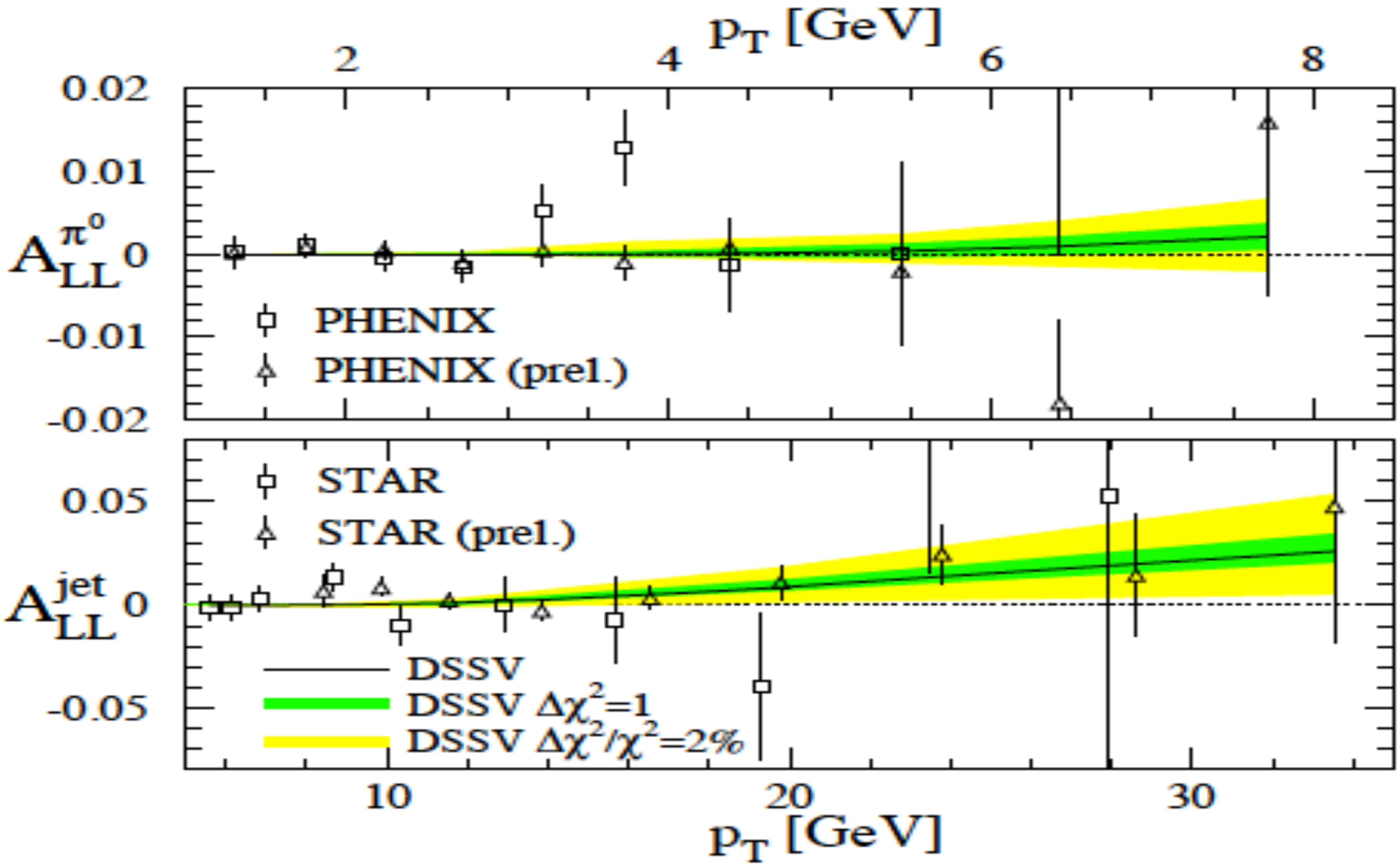
- **Hirai-Kumano – 2008:**

at $Q^2 = 1\ \mathrm{GeV}^2$

Analysis set	DIS	RHIC π^0	E07-011
A	○	–	–
B	○	○	–
C	○	–	○

	Set A Positive	Set A Node	Set B Positive	Set B Node	Set C Positive	Set C Node
$\Delta\Sigma$	$0.24\ \pm 0.07$	0.22 ± 0.08	$0.26\ \pm 0.06$	0.25 ± 0.07	$0.24\ \pm 0.05$	0.22 ± 0.05
ΔG	$0.63\ \pm 0.81$	0.94 ± 1.66	$0.40\ \pm 0.28$	-0.12 ± 1.78	$0.63\ \pm 0.45$	0.94 ± 1.09

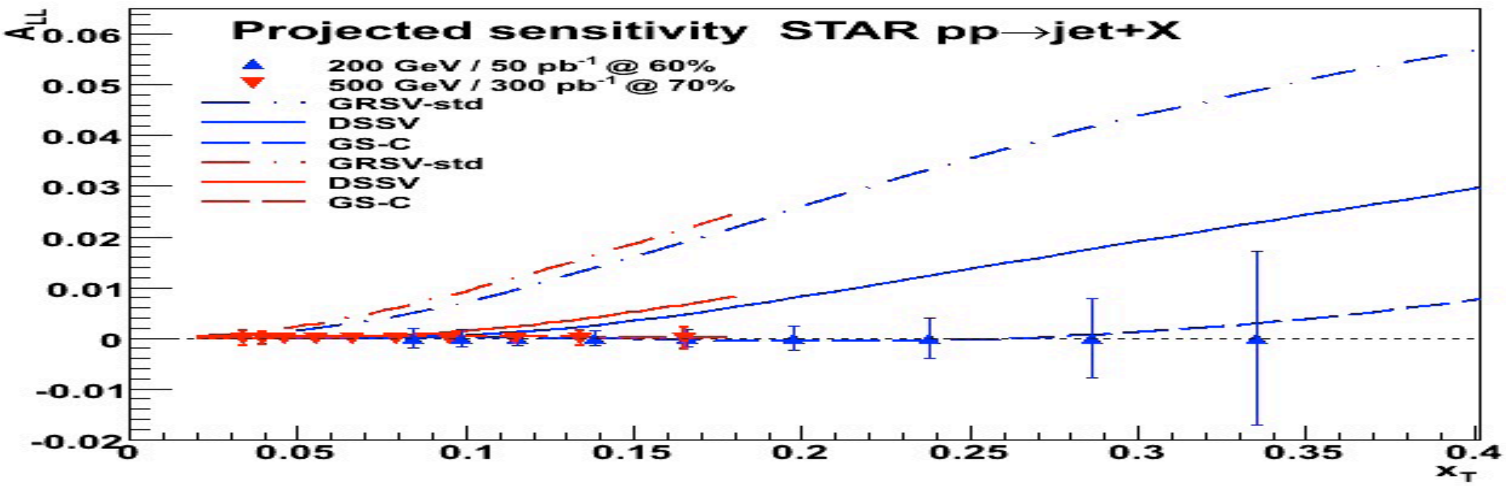
RHIC measurement of ΔG



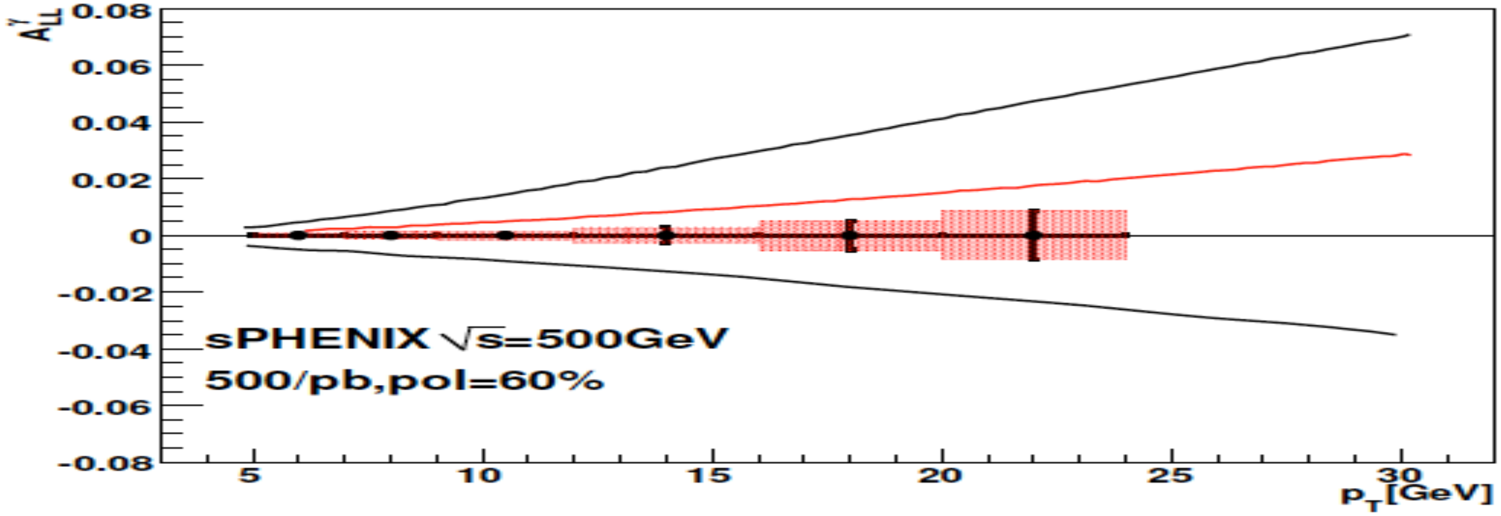
Small asymmetry leads to small gluon "helicity" distribution

Future RHIC measurement of ΔG

- STAR – multiple channels – inclusive jet:



- PHENIX – multiple channels – γ:



Role of heavy quark production in p+p

- **Gluon fusion dominates heavy quark production:**

  Provide the complimentary constraint on ΔG

  But, unlikely to be the channel to give the best precision on ΔG

- **A_N – beyond leading collinear parton approximation:**

  - **P_T distribution of open Charm meson production**

    – tri-gluon correlation

  - **Heavy quarkonium production**

    – Sensitivity on the production mechanism

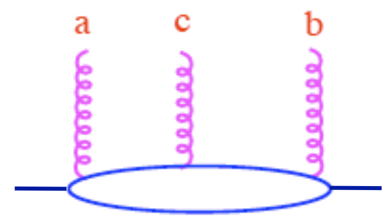
Open charm meson production

❑ Tri-gluon correlation function:

✧ **interference between a single gluon and a double gluon states**

$$T_G(x,x) = \int \frac{dy_1^- dy_2^-}{2\pi} e^{ixP^+y_1^-} \frac{1}{xP^+} \langle P, s_T | F^+{}_\alpha(0) \left[\epsilon^{s_T\sigma n\bar{n}} F_\sigma{}^+(y_2^-)\right] F^{\alpha+}(y_1^-) | P, s_T \rangle$$

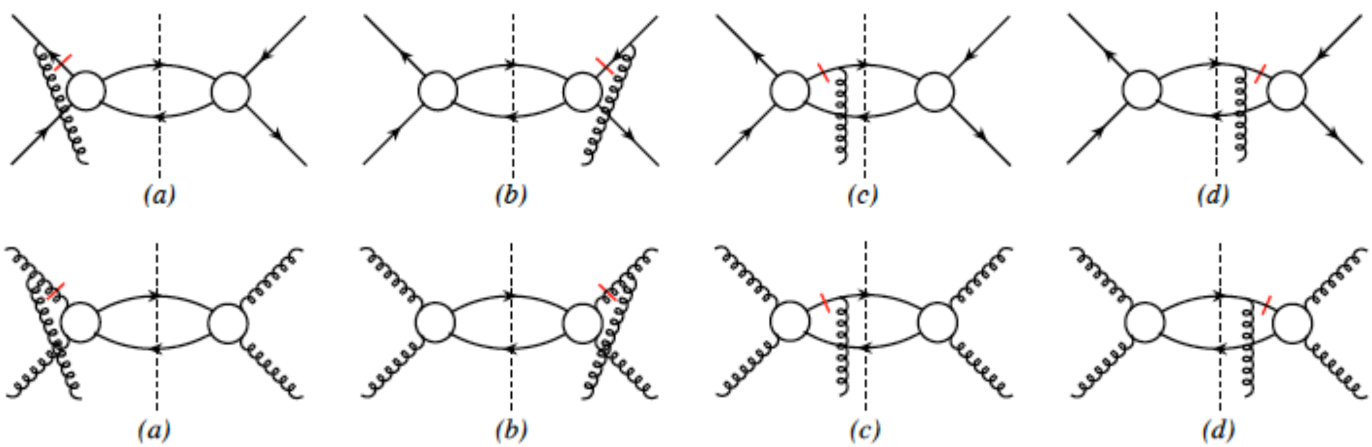
✧ **Different color contractions**



$$T_G^{(f)}(x,x) \propto i f^{ABC} F^A F^C F^B = F^A F^C (\mathcal{T}^C)^{AB} F^B$$

$$T_G^{(d)}(x,x) \propto d^{ABC} F^A F^C F^B = F^A F^C (\mathcal{D}^C)^{AB} F^B$$

❑ P_T distribution of charm meson:



s-channel

t,u-channel

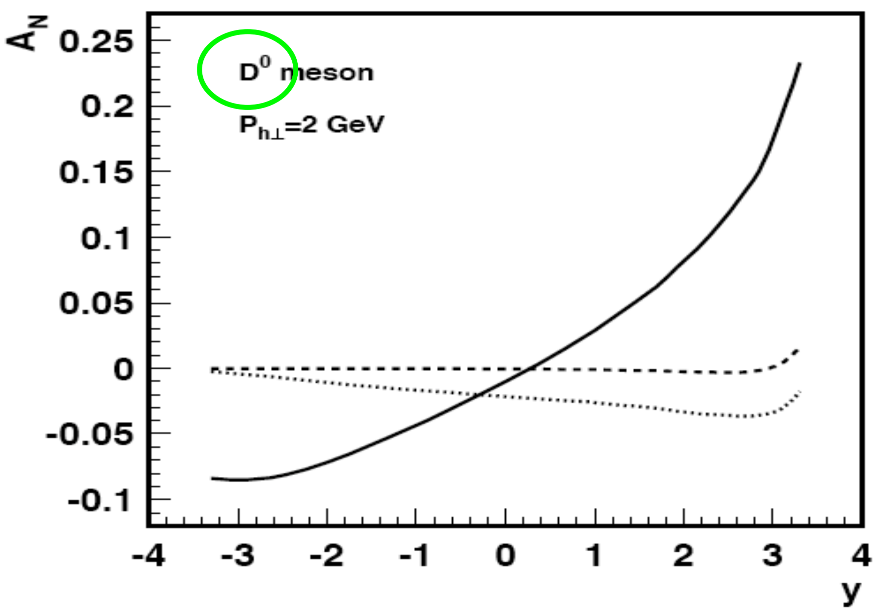
SSA of D-meson production at RHIC

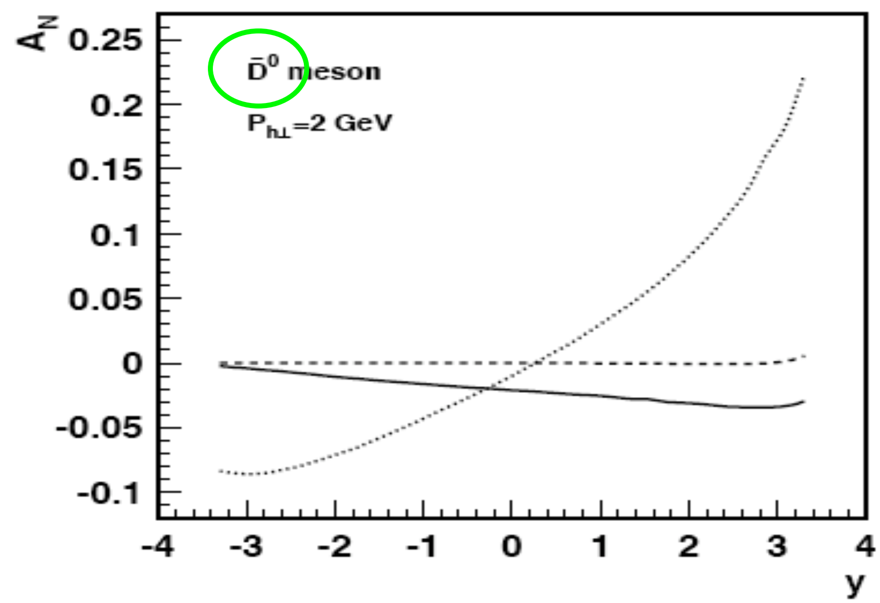
- **Model for tri-gluon correlation functions:**

$$T_G^{(f,d)}(x,x) = \lambda_{f,d} G(x) \qquad \lambda_{f,d} = \pm\lambda_F = \pm 0.07\text{GeV}$$

$$D - \text{meson} \propto T_G^{(f)} + T_G^{(d)} \qquad \overline{D} - \text{meson} \propto T_G^{(f)} - T_G^{(d)}$$

- **Rapidity:** $\sqrt{s} = 200 \text{ GeV} \quad \mu = \sqrt{m_c^2 + P_{h\perp}^2} \quad m_c = 1.3 \text{ GeV}$





Solid: (1) $\lambda_f = \lambda_d = 0.07$ GeV $\quad T_G^{(f)} = T_G^{(d)}$

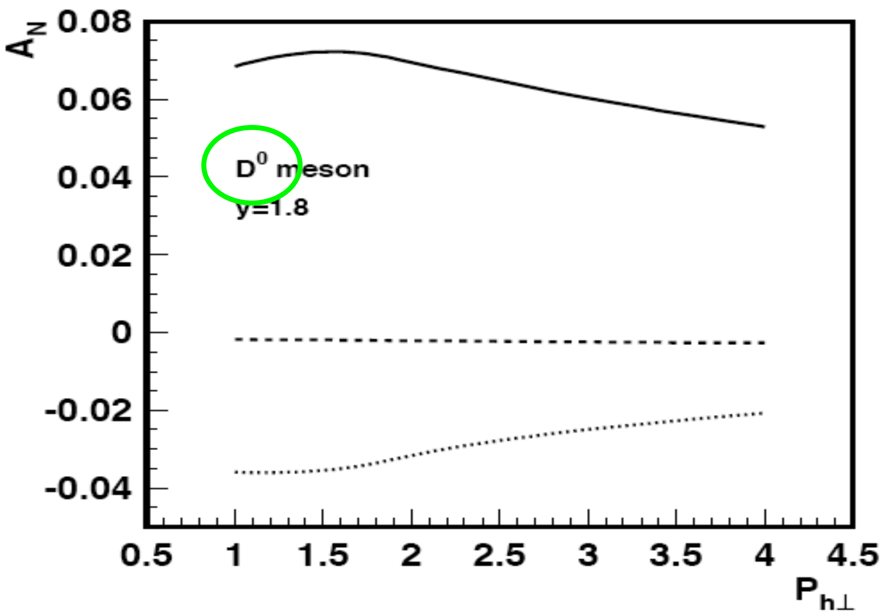
Dashed: (2) $\lambda_f = \lambda_d = 0$ $\quad T_G^{(f)} = T_G^{(d)} = 0$

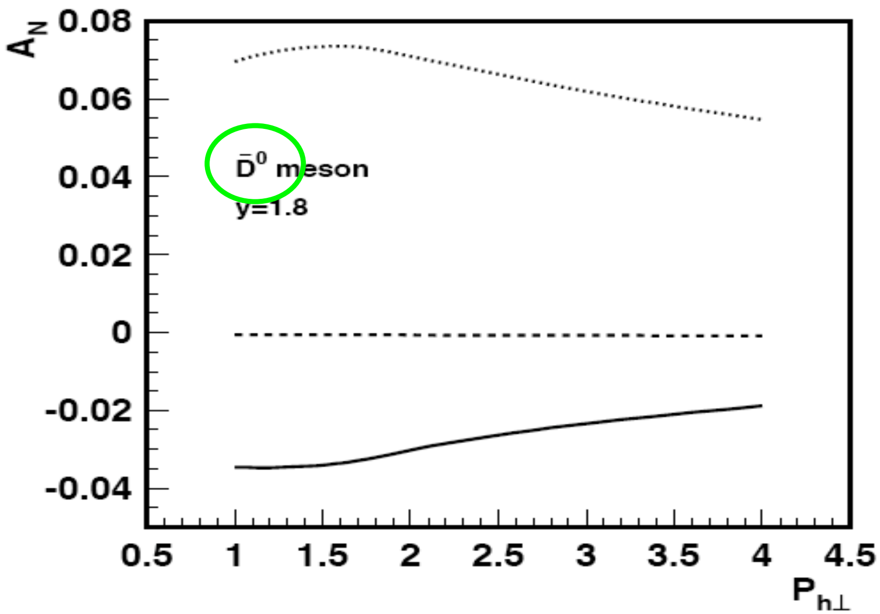
Dotted: (3) $\lambda_f = -\lambda_d = 0.07$ GeV $\quad T_G^{(f)} = -T_G^{(d)}$

No intrinsic Charm included

SSA of D-meson production at RHIC

❑ **P_T dependence:** $\sqrt{s} = 200\ \text{GeV}$ $\mu = \sqrt{m_c^2 + P_{h\perp}^2}$ $m_c = 1.3\ \text{GeV}$





Solid: $(1)\ \lambda_f = \lambda_d = 0.07\ \text{GeV}$ $T_G^{(f)} = T_G^{(d)}$

Dashed: $(2)\ \lambda_f = \lambda_d = 0$ $T_G^{(f)} = T_G^{(d)} = 0$

Dotted: $(3)\ \lambda_f = -\lambda_d = 0.07\ \text{GeV}$ $T_G^{(f)} = -T_G^{(d)}$

No intrinsic Charm included

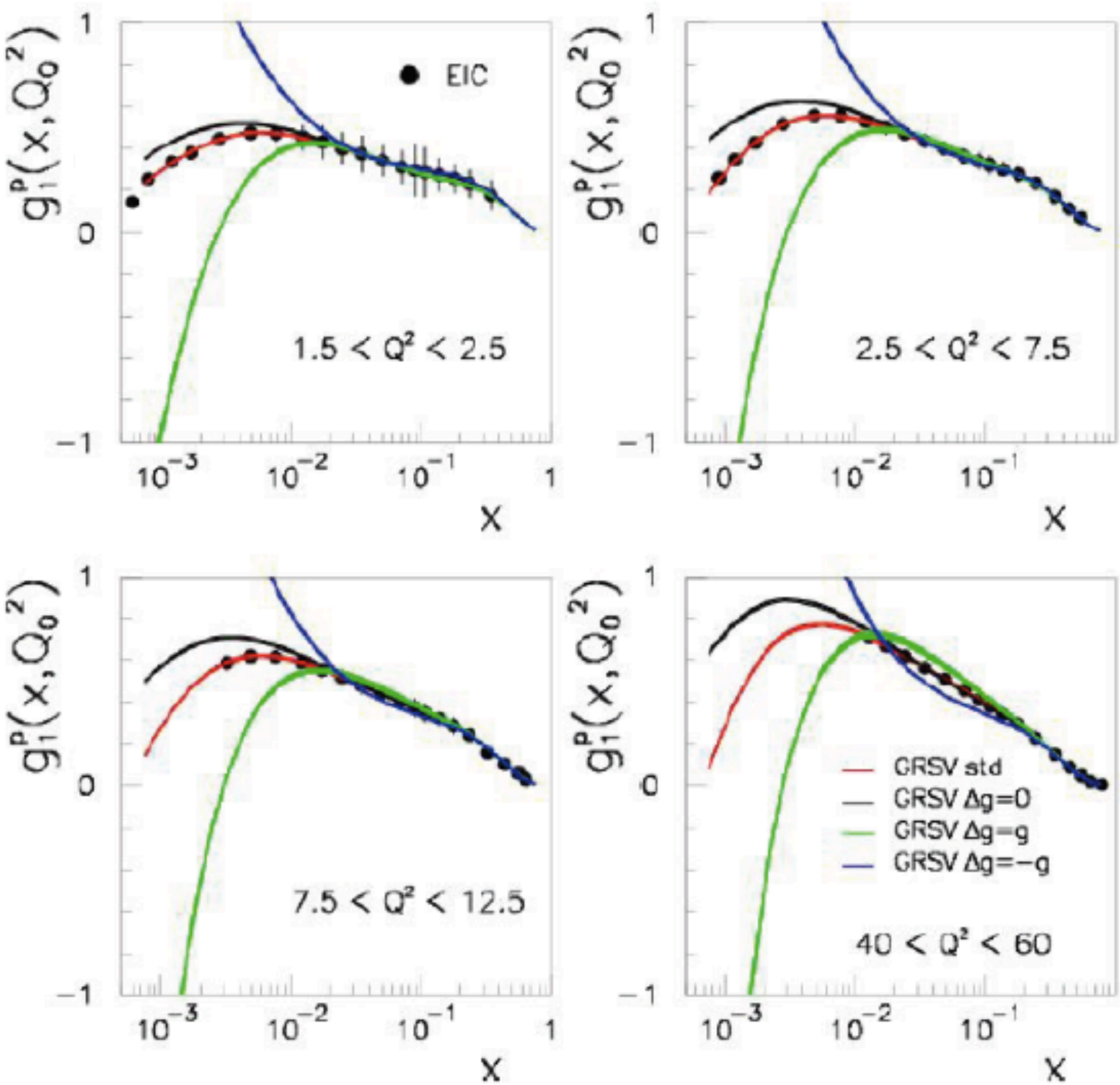
Nonzero A_N = tri-gluon correlation = "direct" interference

Separate $T_G^{(f)}$ and $T_G^{(d)}$ by the difference between D and $\bar{D}$

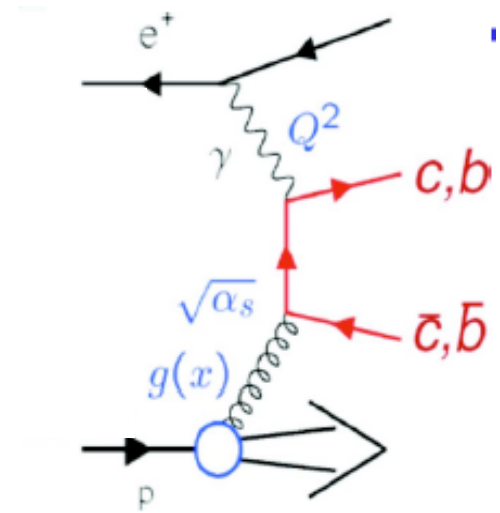
Heavy quark production in e+p/n

❑ Better probe of ΔG – future EIC:

PHENIX decadal plan

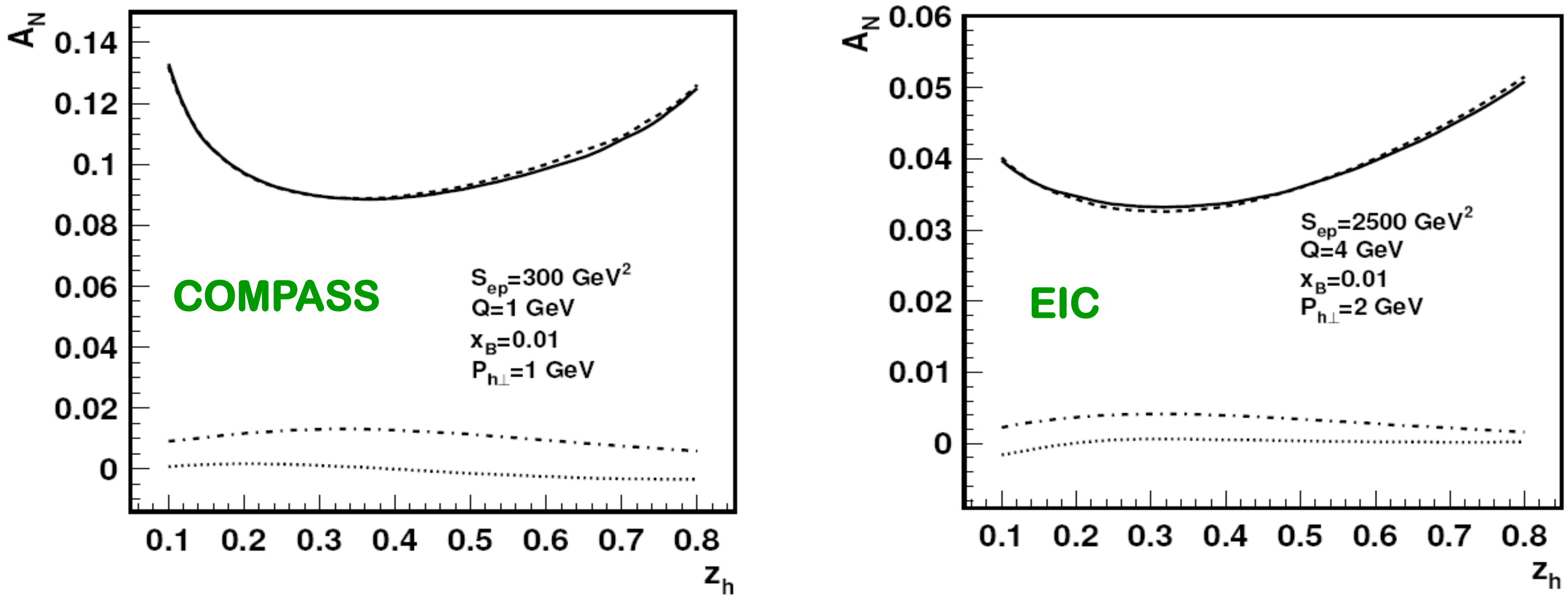


Direct probe:
– trigger on charm



SSA of D-meson production in e+p/n

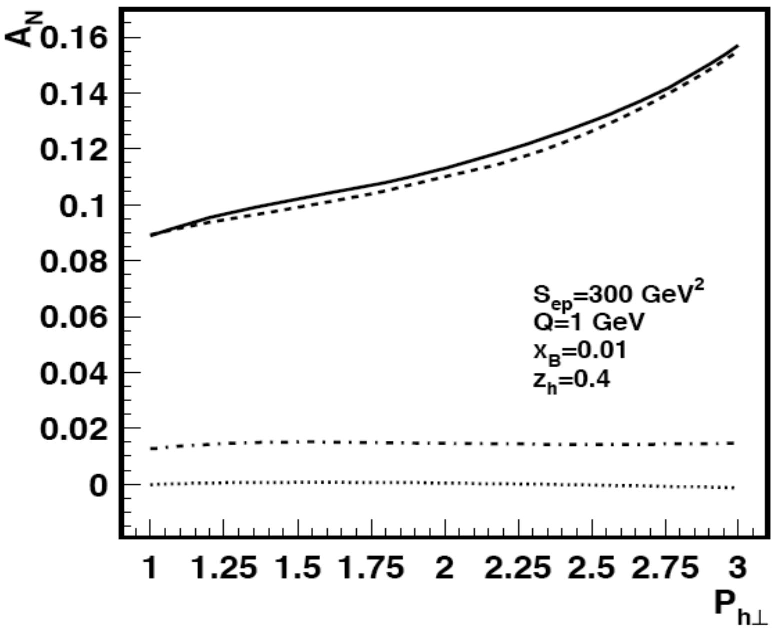
❑ SSA for D^0 production (λ_f only):

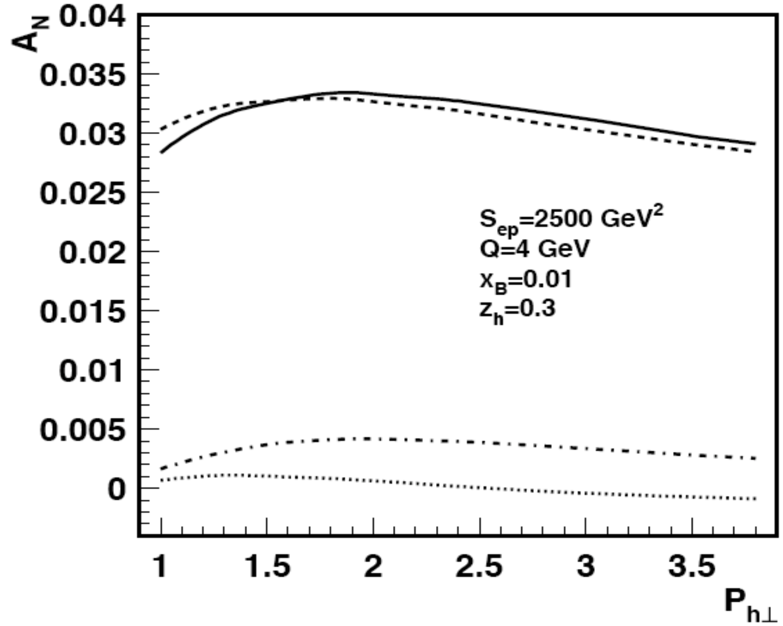


- ✧ Derivative term dominates, and small φ dependence
- ✧ Asymmetry is twice if $T_G^{(f)} = +T_G^{(d)}$, or zero if $T_G^{(f)} = -T_G^{(d)}$
- ✧ Opposite for the $\bar{D}$ meson
- ✧ Asymmetry has a minimum ~ z_h ~ 0.5

SSA of D-meson production in e+p/n

❑ SSA for D^0 production (λ_f only):





- ✧ SSA is a twist-3 effect, it should fall off as $1/P_T$ when $P_T \gg m_c$
- ✧ For the region, $P_T \sim m_c$,

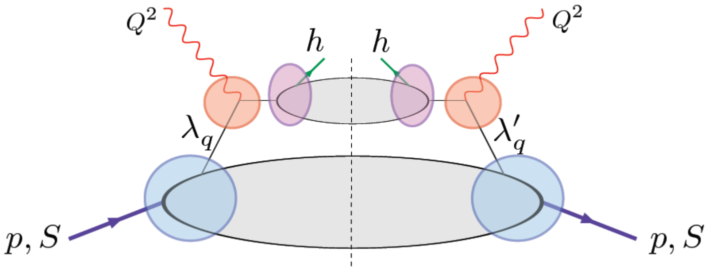
$$A_N \propto \epsilon^{P_h s_\perp n \bar{n}} \frac{1}{\tilde{t}} = -\sin\phi_s \frac{P_{h\perp}}{\tilde{t}}$$

$$\tilde{t} = (p_c - q)^2 - m_c^2 = -\frac{1-\hat{z}}{\hat{x}} Q^2$$

$$\hat{z} = z_h/z, \quad \hat{x} = x_B/x$$

EIC is ideal for studying TMDs

❑ SIDIS has the natural kinematics for TMD factorization:



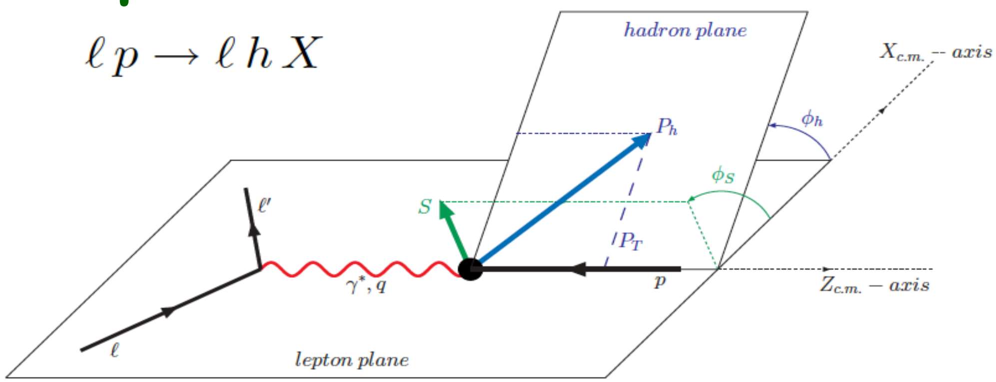
$$\ell(s_e) + p(s_p) \to \ell + h(s_h) + X$$

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

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

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

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

$\longrightarrow$

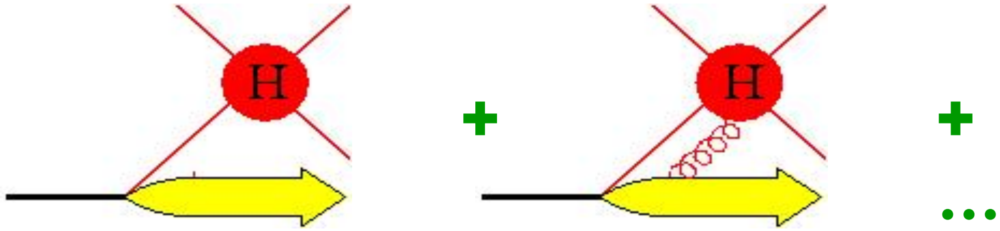
$$A_{UT}^{Collins} \propto \left\langle \sin(\phi_h + \phi_S) \right\rangle_{UT} \propto h_1 \otimes H_1^{\perp}$$

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

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

Gauge invariance and universality of PDFs

❑ 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:

$$\phi(x,p,s) = \int \frac{dy^-}{2\pi} e^{ixp^+y^-} \langle p,s|\underbrace{\overline{\psi}(0)_j \hat{\Gamma}_{ji} \Phi_n^\dagger(\infty,0)\Phi_n(\infty,y^-)\psi_i(y^-)}_{\text{“Localized” operator with size} \sim 1/xp \sim 1/Q}|p,s\rangle$$

Collinear PDFs:

“localized” color flow

❑ Universality of PDFs – predictive power of pQCD:

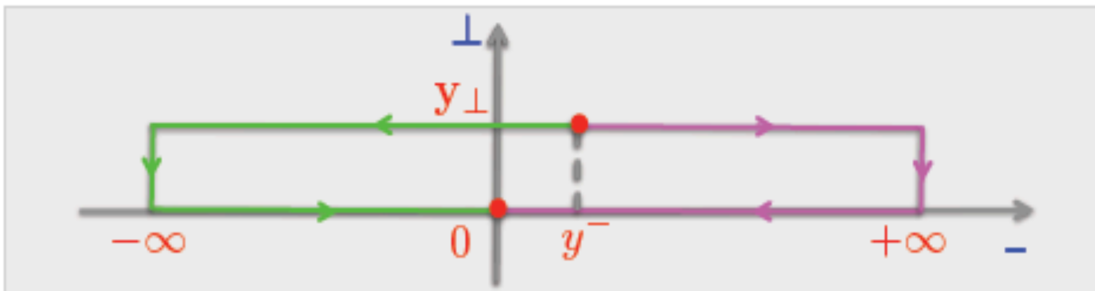
Gauge link should be process independent!

Process dependence of TMDs

❑ The form of gauge link is a result of factorization:

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

- SIDIS: $\Phi_n^\dagger(\{+\infty,0\},\mathbf{0}_\perp)\Phi_{\mathbf{n}_\perp}^\dagger(+\infty,\{\mathbf{y}_\perp,\mathbf{0}_\perp\})\Phi_n(\{+\infty,y^-\},\mathbf{y}_\perp)$
- DY: $\Phi_n^\dagger(\{-\infty,0\},\mathbf{0}_\perp)\Phi_{\mathbf{n}_\perp}^\dagger(-\infty,\{\mathbf{y}_\perp,\mathbf{0}_\perp\})\Phi_n(\{-\infty,y^-\},\mathbf{y}_\perp)$



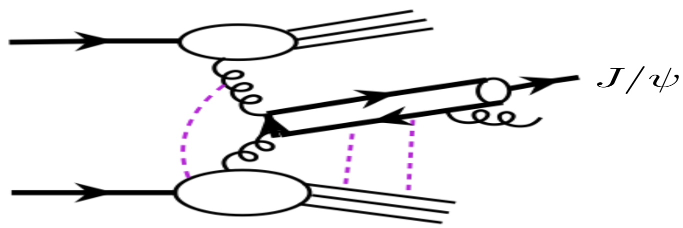
Wilson Loop ~ $\exp\left[-ig\int_\Sigma d\sigma^{\mu\nu}F_{\mu\nu}\right]$ Area is NOT zero

- For a fixed spin state:

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

SSA of J/ψ production at RHIC

- ❑ **Sensitive to color neutralization of J/ψ production:**



Final-state interaction proportional to color dipole moment of the heavy quark pair

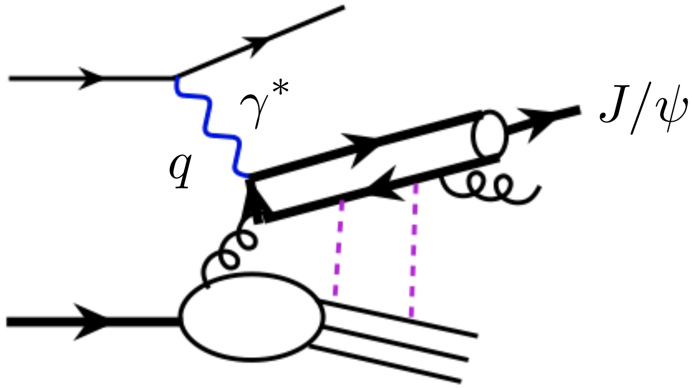
- ❑ **If neglect final-state interaction – "color singlet" pair:**

  - ✧ TMD factorization with the phase from initial-state interaction
  - ✧ A_N at low P_T is proportional to the gluon Sivers function
    - – PHENIX data indicates that gluon Sivers does not vanish
  - ✧ Sign change of gluon Sivers function – PT invariance
    - – Opposite sign A_N for J/ψ in SIDIS only if the pair is in octet?!

SSA of J/ψ production at e+p/n

- SSA requires a phase from final-state interaction

Feng



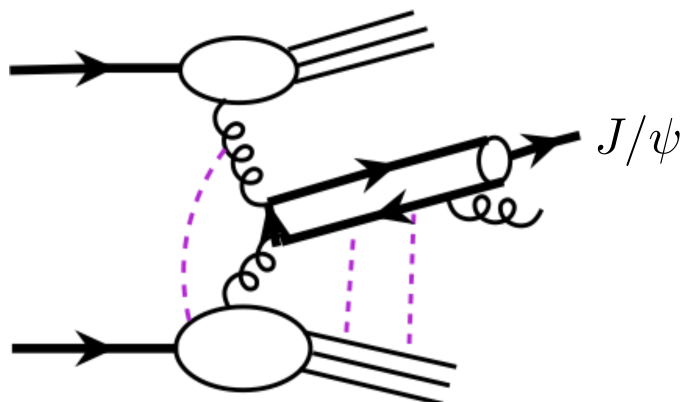
$$Q^2 \gtrsim M_{J/\psi}^2$$

✧ Ward identity – TMD fact.

✧ Pair “behaves” like a gluon

- SSA requires a phase from final-state interaction

Collins et al.



✧ Potential pinch singularity

✧ Spectator - pair interaction
(prevents sum of final-states)

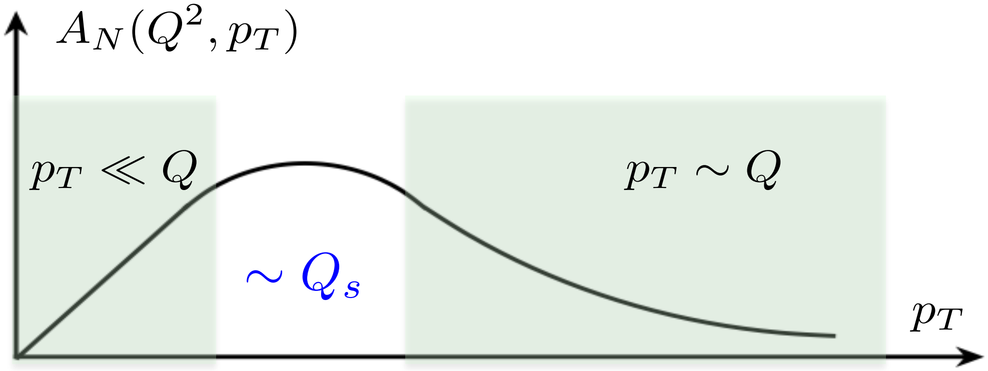
✧ No TMD for color octet!?

More theory work needed!

TMD vs collinear factorization

- **They cover different kinematic regimes:**

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



TMD Collinear Factorization

Two factorization are consistent in the overlap region where

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

- **"Formal" operator relation between TMD distributions and collinear factorized distributions:**

spin-averaged: $$\int d^2k_\perp \Phi_f^{\rm SIDIS}(x, k_\perp) + {\rm UVCT}(\mu_F^2) = \phi_f(x, \mu_F^2)$$

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

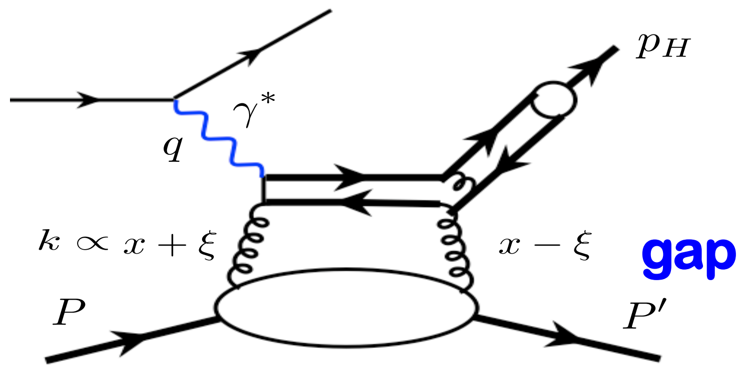
But, TMD factorization is only valid for low k_T – TMD PDFs at low k_T

Even a node at low p_T could be allowed !

Diffractive production of quarkonium

- **Exclusive production of J/ψ:**

Collins, etc.



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

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

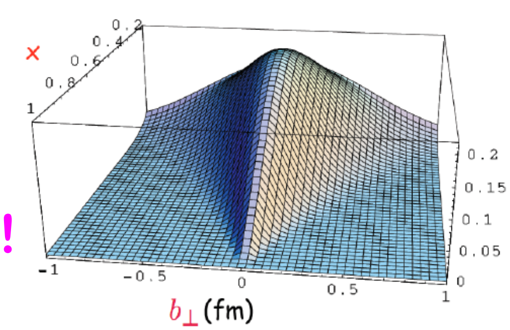
- **Collinear factorization – Gluon GPD:**

$$\langle k^2 \rangle \propto Q_s^2 \ll Q^2$$

Need EIC for a sufficient phase space in t

- **Parton spatial distribution – Fourier transform of GPDs:**

$$f(x,q_T) = \int \frac{d^2\Delta_T}{(2\pi)^2}\, e^{-i\vec{\Delta}_T\cdot\vec{q}_T}\, H_f(x,\xi=0,\Delta_T)$$



No factorization for diffractive production in p+p !

Summary

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

- Heavy flavor production at EIC with polarization provides more direct information on glue

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

- The program of measuring transverse spin asymmetries at EIC, which is complementary to RHIC, provides a new domain to test QCD dynamics, in particular, the parton’s transverse motion

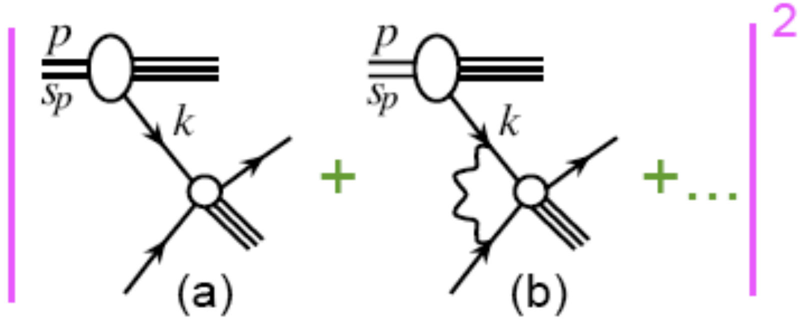
Thank you!

Backup slices

Leading power collinear factorization

- **One collinear parton per hadron in hard collision:**

$\sigma(s_T) \sim$



→ $\Delta\sigma(s_T) \sim \mathrm{Re}[(a)]\cdot\mathrm{Im}[(b)]$

- ❖ **Helicity – flip** ⟶ **quark mass term**
- ❖ **Generate the phase from the loop diagram** ⟶ α_s

⟶ **SSA vanishes in the parton model:**

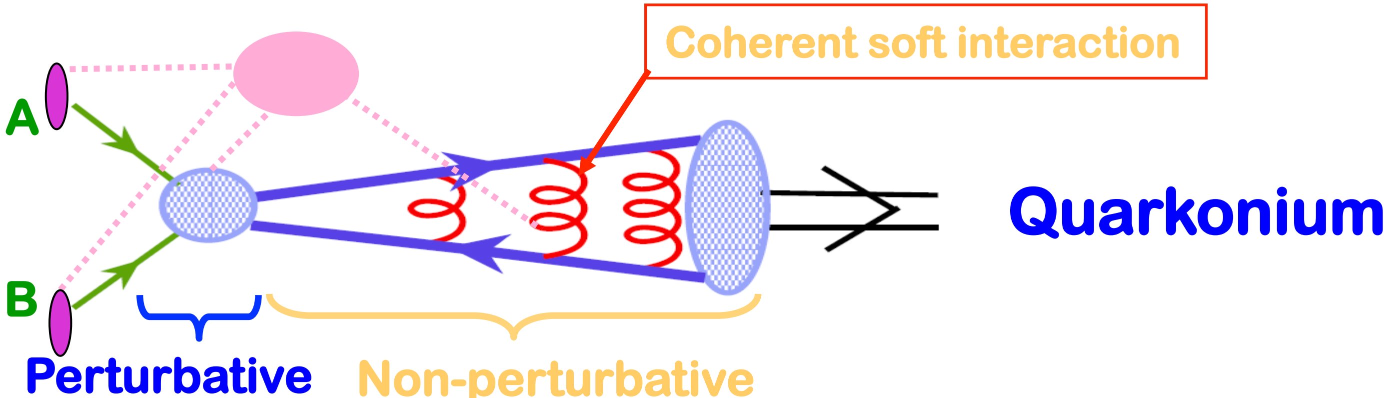
$$A_N \ \propto \ \alpha_s \frac{m_q}{Q} \ \rightarrow \ 0 \ \ \text{asymptotically}$$

- $A_N \ \neq \ 0$

⟶ **direct information on parton's transverse motion**

The basic production mechanism

- **Production of an off-shell heavy quark pair:**



$$\Delta r \leq \frac{1}{2m_Q}$$

- **Approximation: on-shell heavy quark pair + hadronization**

$$\sigma_{AB\to J/\psi} = \sum_{\text{states}} \int d\Gamma_{Q\bar{Q}} \left[\frac{d\hat{\sigma}(Q^2)}{d\Gamma_{Q\bar{Q}}}\right] F_{\text{states}(Q\bar{Q})\to J/\psi}(p_Q, p_{\bar{Q}}, P_{J/\psi})$$

Different models ⇔ Different assumptions/treatments on how the heavy quark pair becomes a quarkonium?