Overview of spin physics at EIC

Daniël Boer

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university of groningen

Outline

- Proton & deuteron spin structure (SFs, PDFs)
- 3-D Spin Structure (TMDs, Sivers effect)
- Gluon polarization effects in unpolarized ep
- Fragmentation functions (DiFF, Λs)
- GTMDs & GPDs

1-D Spin Structure

Classic DIS objectives: polarized structure functions

$$W_{\mu\nu} = \left(-g_{\mu\nu} + \frac{q_\mu q_\nu}{q^2}\right) F_1(x,Q^2) + \frac{\hat{P}_\mu \hat{P}_\nu}{P\cdot q} F_2(x,Q^2) - i\varepsilon_{\mu\nu\lambda\sigma}\frac{q^\lambda P^\sigma}{2P\cdot q} F_3(x,Q^2)$$
$$+ i\varepsilon_{\mu\nu\lambda\sigma}\frac{q^\lambda S^\sigma}{P\cdot q} g_1(x,Q^2) + i\varepsilon_{\mu\nu\lambda\sigma}\frac{q^\lambda(P\cdot q S^\sigma - S\cdot q P^\sigma)}{(P\cdot q)^2} g_2(x,Q^2)$$
$$+ \left[\frac{\hat{P}_\mu \hat{S}_\nu + \hat{S}_\mu \hat{P}_\nu}{2} - S\cdot q \frac{\hat{P}_\mu \hat{P}_\nu}{(P\cdot q)}\right] \frac{g_3(x,Q^2)}{P\cdot q}$$
$$+ S\cdot q \frac{\hat{P}_\mu \hat{P}_\nu}{(P\cdot q)^2} g_4(x,Q^2) + \left(-g_{\mu\nu} + \frac{q_\mu q_\nu}{q^2}\right)\frac{(S\cdot q)}{P\cdot q} g_5(x,Q^2),$$

E.g. Blümlein, Kochelev, Nucl. Phys. B 498 (1997) 285

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$g_1 \to \Delta q, \Delta g$ — spin sum rule — $\Delta\Sigma = \Delta u + \Delta d + \Delta s$

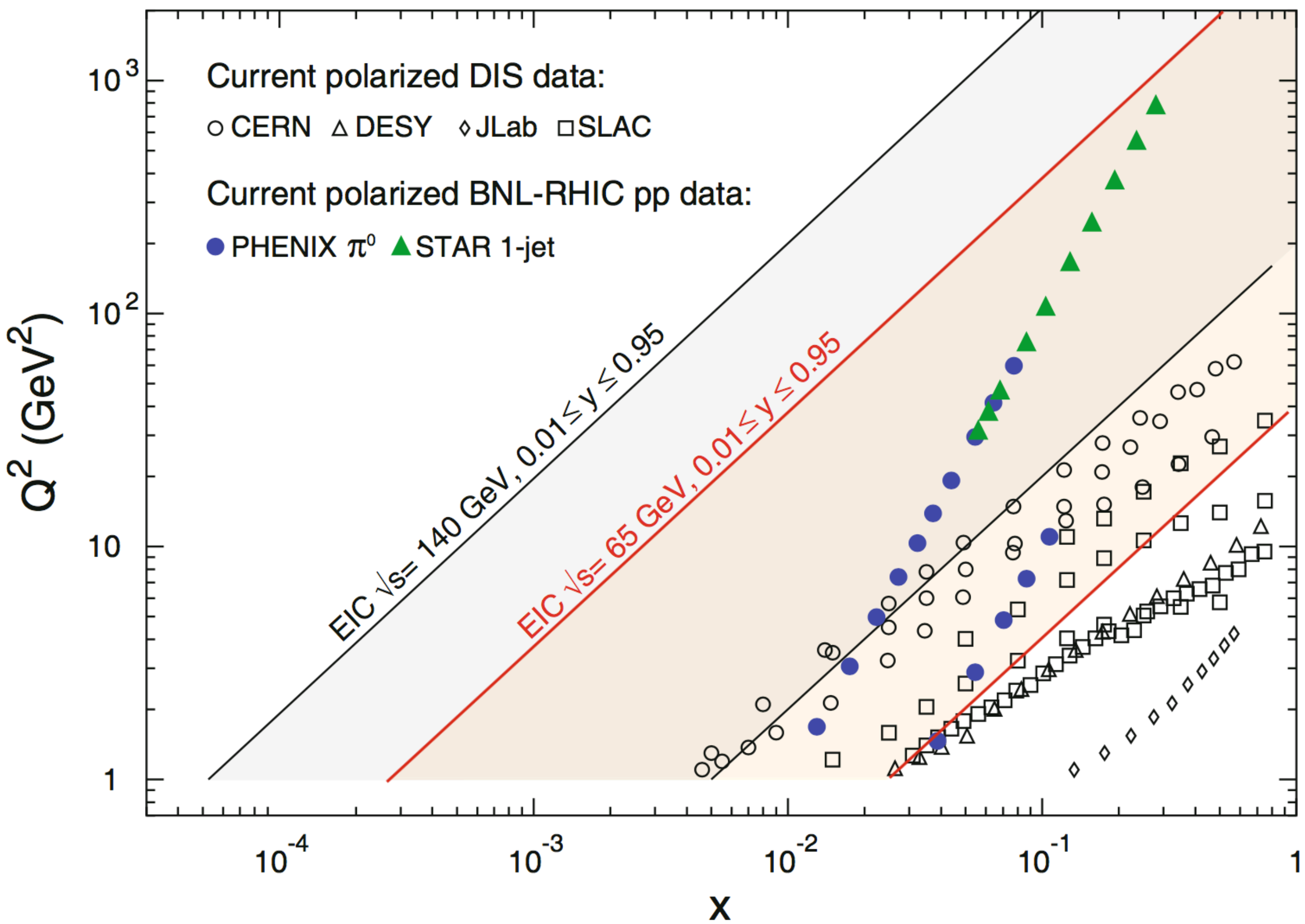
$g_2 \to \int_0^1 dx\; g_2(x,Q^2) = 0$ — Burkhardt-Cottingham sum rule

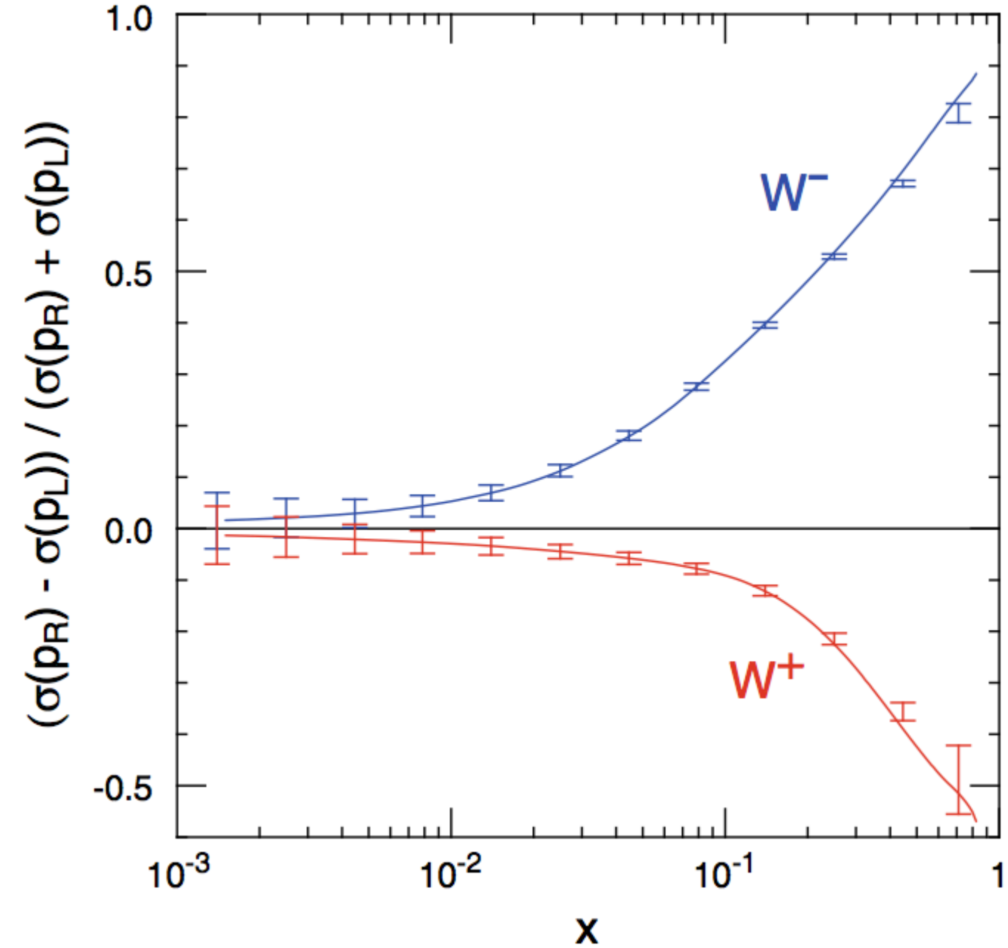
$g_2 \to d_2 = 3\int_0^1 dx\; x^2\, g_2(x,Q^2)\big|_{\text{twist}-3}$ — lattice, E155x

g_3, g_4, g_5 — weak interactions

Classic DIS objectives: polarized structure functions

g_3, g_4, g_5 weak interactions, hence high Q^2 and high x





$$g_1^{W^-}(x,Q^2) = \left[\Delta u + \Delta \bar{d} + \Delta c + \Delta \bar{s}\right](x,Q^2),$$
$$g_5^{W^-}(x,Q^2) = \left[-\Delta u + \Delta \bar{d} - \Delta c + \Delta \bar{s}\right](x,Q^2)$$

Parity violating SSA

$$g_4(x,Q^2) = 2x g_5(x,Q^2)$$

Dicus relation, analogous to Callan-Gross (PM)

g_3 Similar to g_2 part twist 2 and twist 3

Polarized deuteron

$$W_{\mu\nu} = -F_1 g_{\mu\nu} + F_2 \frac{p_\mu p_\nu}{\nu} - b_1 r_{\mu\nu} + \tfrac{1}{6} b_2 (s_{\mu\nu} + t_{\mu\nu} + u_{\mu\nu}) + \tfrac{1}{2} b_3 (s_{\mu\nu} - u_{\mu\nu})$$

$$+ \tfrac{1}{2} b_4 (s_{\mu\nu} - t_{\mu\nu}) + i \frac{g_1}{\nu} \epsilon_{\mu\nu\lambda\sigma} q^\lambda s^\sigma + i \frac{g_2}{\nu^2} \epsilon_{\mu\nu\lambda\sigma} q^\lambda (p \cdot q s^\sigma - s \cdot q p^\sigma),$$

Hoodbhoy, Jaffe, Manohar, Nucl. Phys. B 312 (1989) 571

b_1, b_2 leading twist, longitudinal tensor polarization

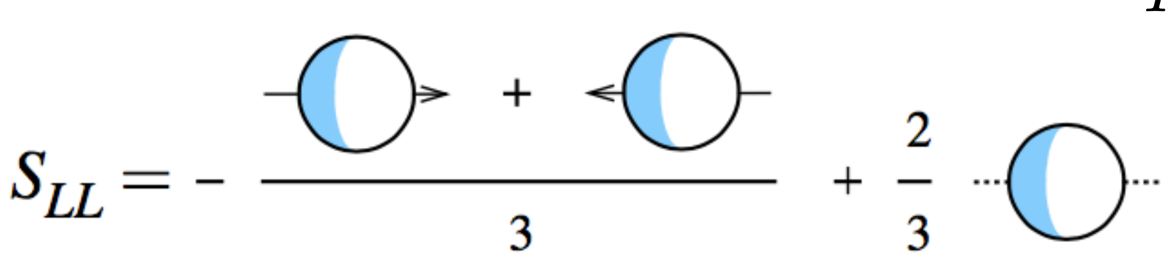
$b_2 = 2x b_1$ Parton model relation analogous to Callan-Gross

b_1 can be extracted using unpolarized leptons and using a spin-1 hadron polarized along the beam (and subtracting the unpolarized contribution)

$$b_1(x) = \frac{1}{2}\left(q^0(x) - q^1(x)\right)$$

$$q^0(x) = \left(q^0_\uparrow + q^0_\downarrow\right) = 2q^0_\uparrow$$

$$q^1(x) = \left(q^1_\uparrow + q^1_\downarrow\right) = \left(q^1_\uparrow + q^{-1}_\uparrow\right)$$

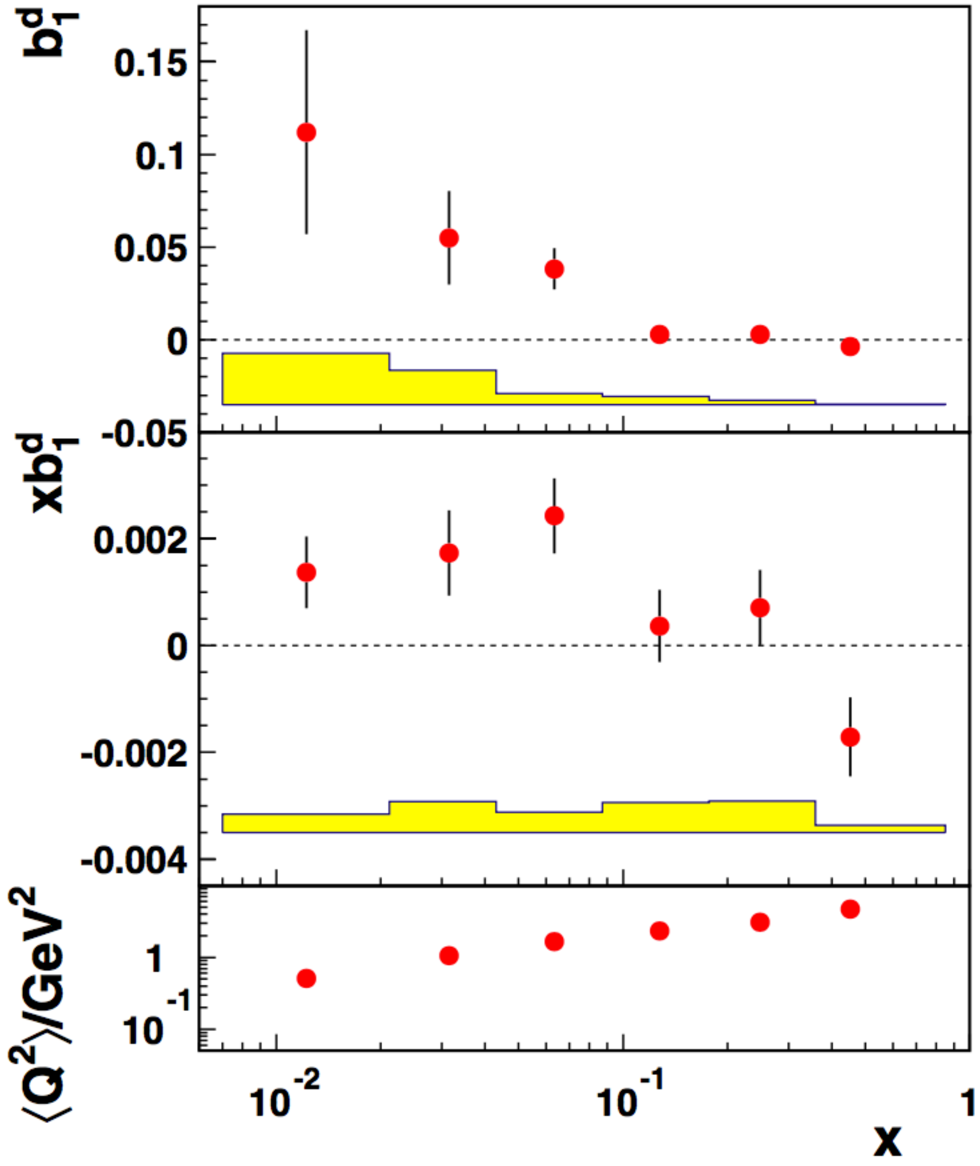


S_{LL} called "alignment"

Bacchetta, Mulders, PRD 62 (2000) 114004

Polarized deuteron

A. Airapetian et al. (HERMES Collaboration)
Phys. Rev. Lett. 95 (2005) 242001



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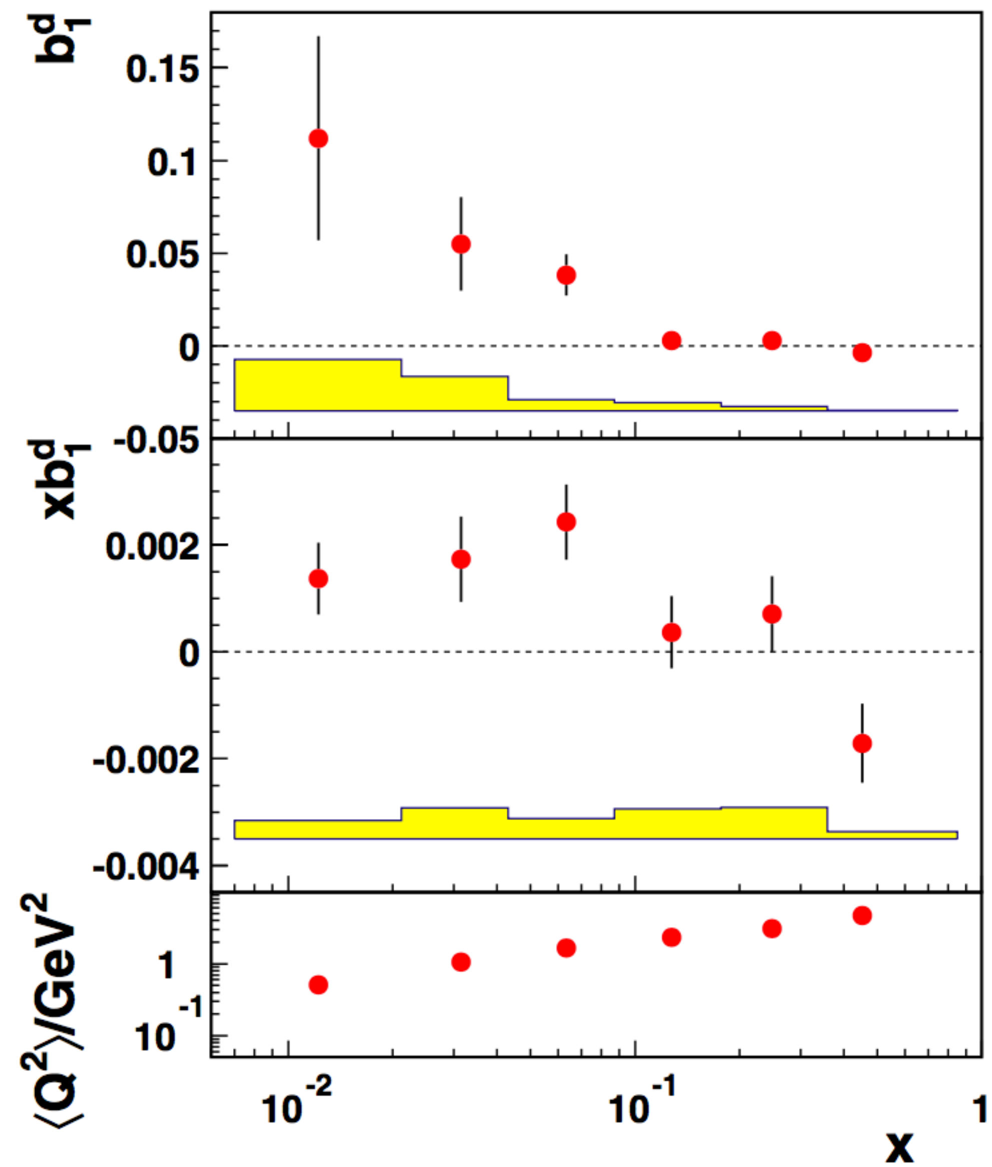


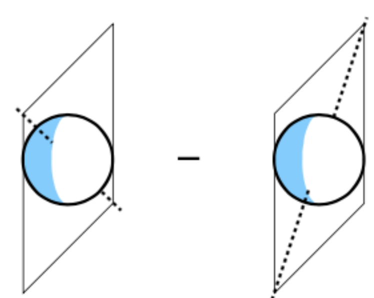
For gluons there is also an S_{TT} contribution

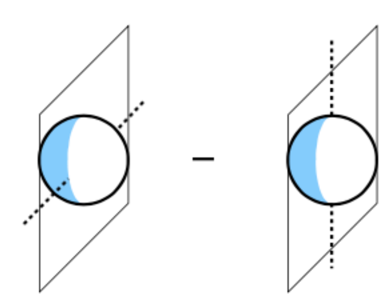
leading twist, transverse tensor polarization

Jaffe, Manohar, Phys. Lett. B 223 (1989) 218

Artru, Mekhfi, Z. Phys. C 45 (1990) 669

$$\Gamma^{ij}(x) = \frac{x}{2}\left[- g_T^{ij}\, f_1(x) + i\epsilon_T^{ij} S_L\, g_1(x) - g_T^{ij} S_{LL}\, f_{1LL}(x) + S_{TT}^{ij}\, h_{1TT}(x)\right]$$

$S_{TT}^{xy} =$ 

$S_{TT}^{xx} =$ 

not yet measured

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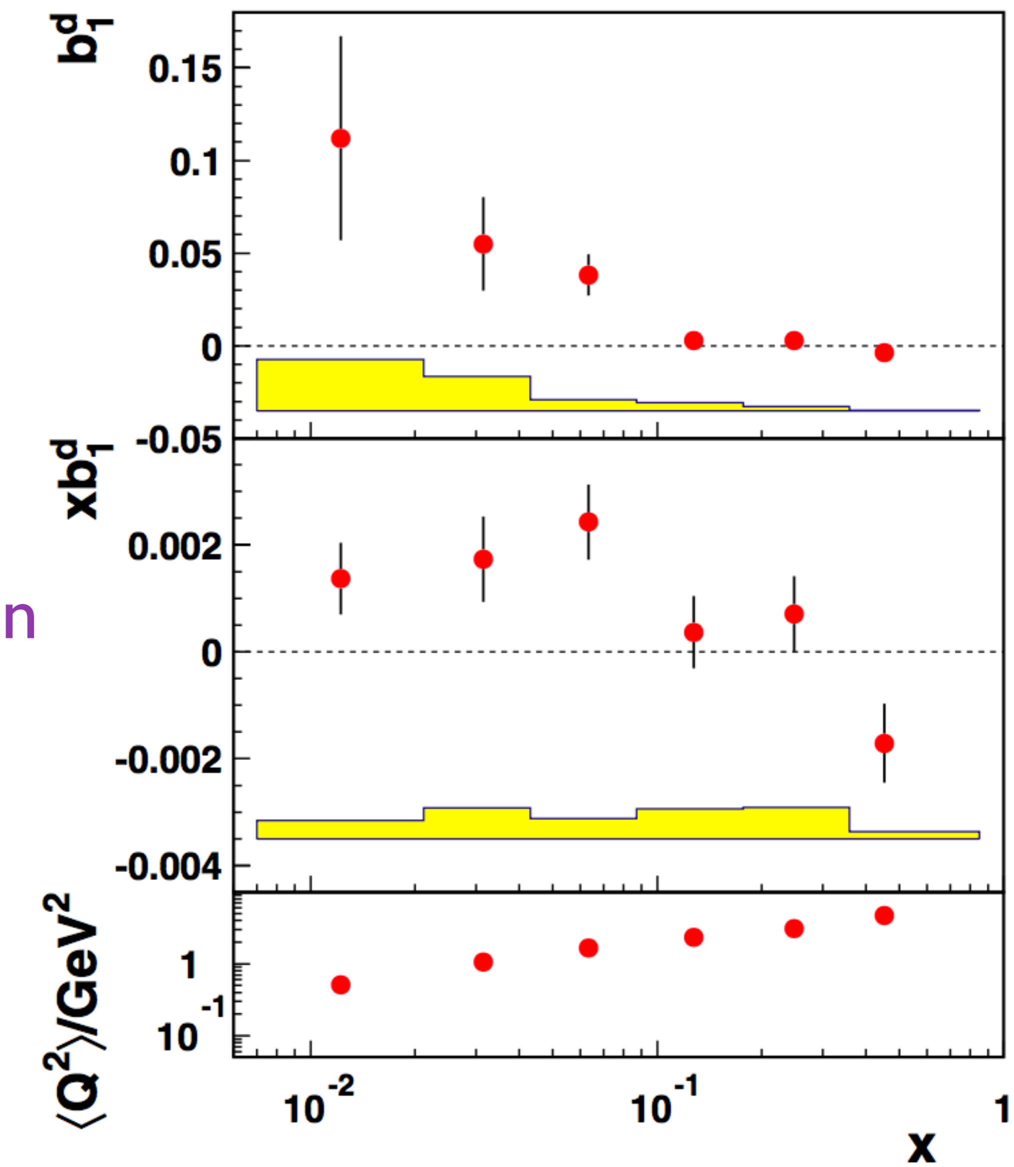

Also: eD →epX spectator tagging
to access polarized neutron structure

Cosyn, Sargsian, Weiss, …, 2011-…; → Cosyn's talk

Also polarized Helium-3 ≈ polarized neutron

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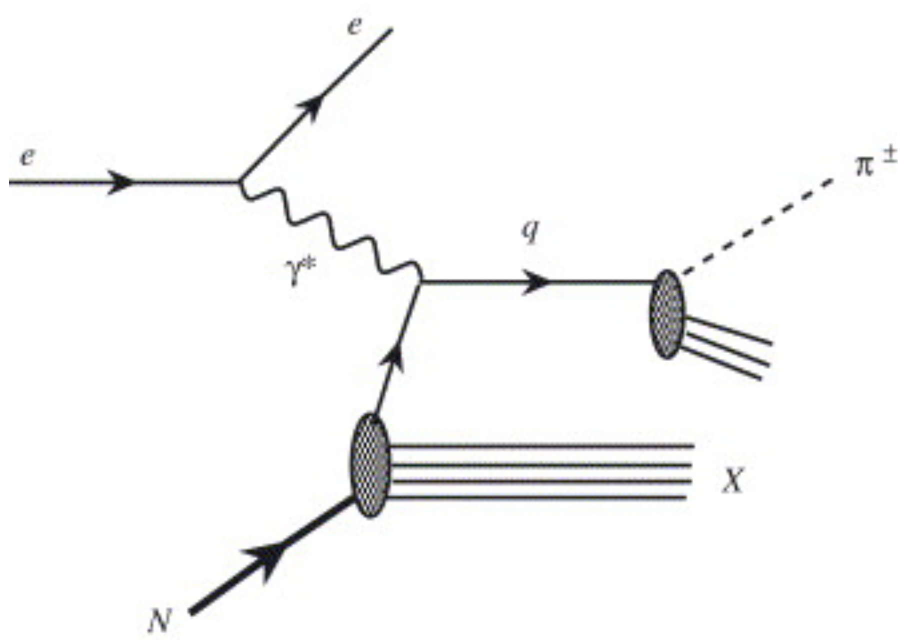
3-D Spin Structure

Typical TMD processes

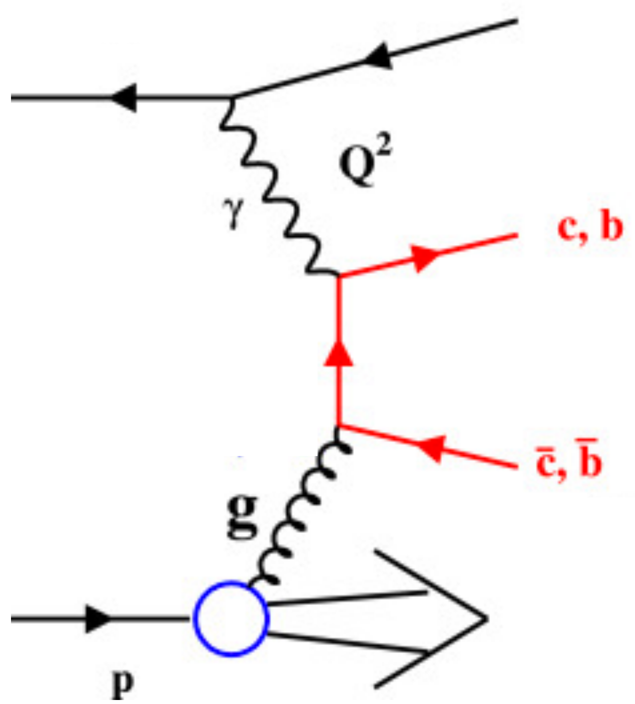
Semi-inclusive DIS is a process sensitive to the transverse momentum of quarks

$$e\,p \to e'\,h\,X$$



D-meson pair production is sensitive to transverse momentum of gluons

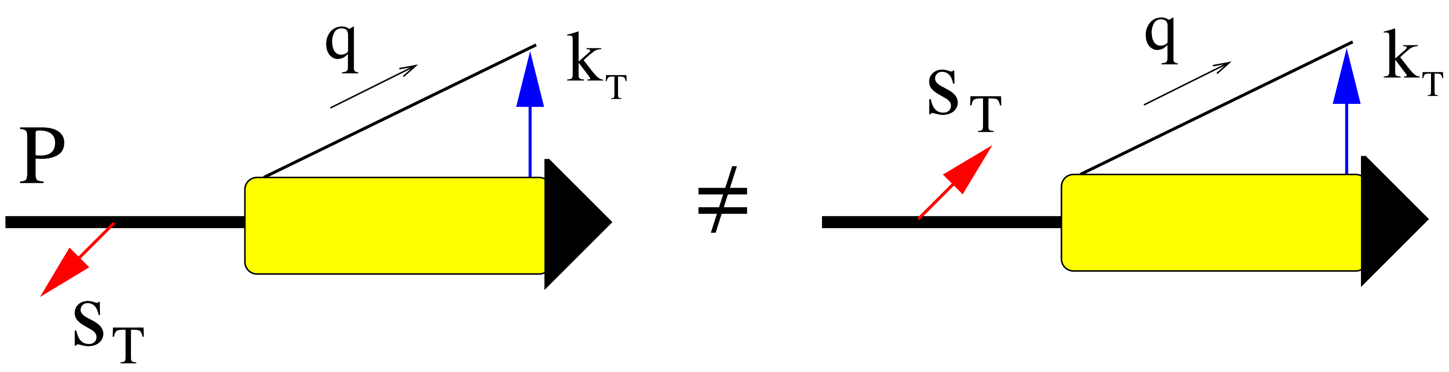
$$e\,p \to e'\,D\,\bar{D}\,X$$



Sivers effect

The transverse momentum dependence can be correlated with the spin, e.g.

D. Sivers ('90):



$k_T \times S_T$

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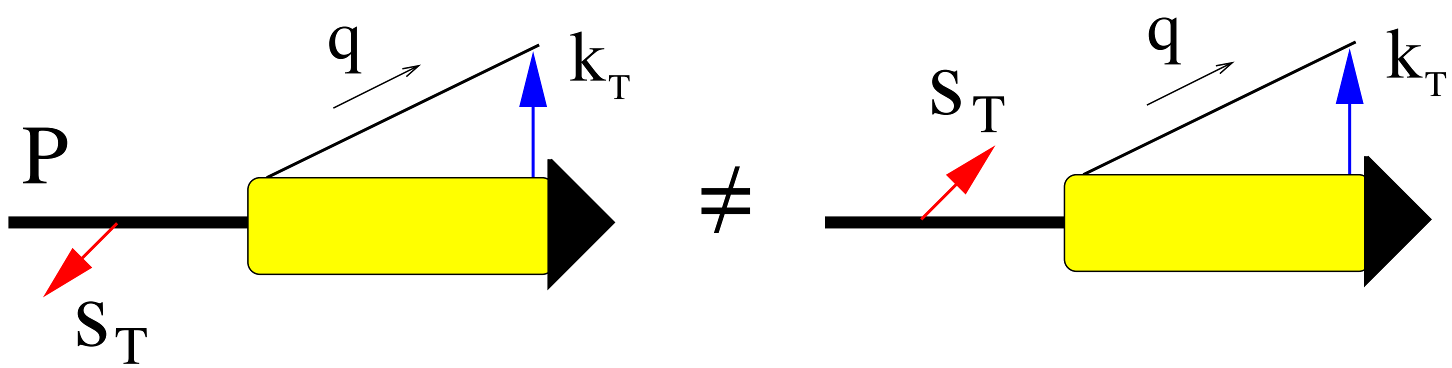

$k_T \times S_T$

Sivers TMD can be measured in semi-inclusive DIS through a single spin asymmetry

[Boer & Mulders, '98]

$$e\,p^{\uparrow} \to e'\,\text{jet}\,X$$

$$\frac{d\sigma(e\,p^{\uparrow} \to e'\,\text{jet}\,X)}{d^2\boldsymbol{q}_T} \propto\ |\boldsymbol{S}_T|\ \sin(\phi^e_{\text{jet}} - \phi^e_S)\,\frac{Q_T}{M} f_{1T}^{\perp}(x, Q_T^2) \qquad Q_T^2 = |\boldsymbol{P}_{\perp}^{\text{jet}}|^2$$

One can probe the k_T-dependence of the Sivers function directly in this way!

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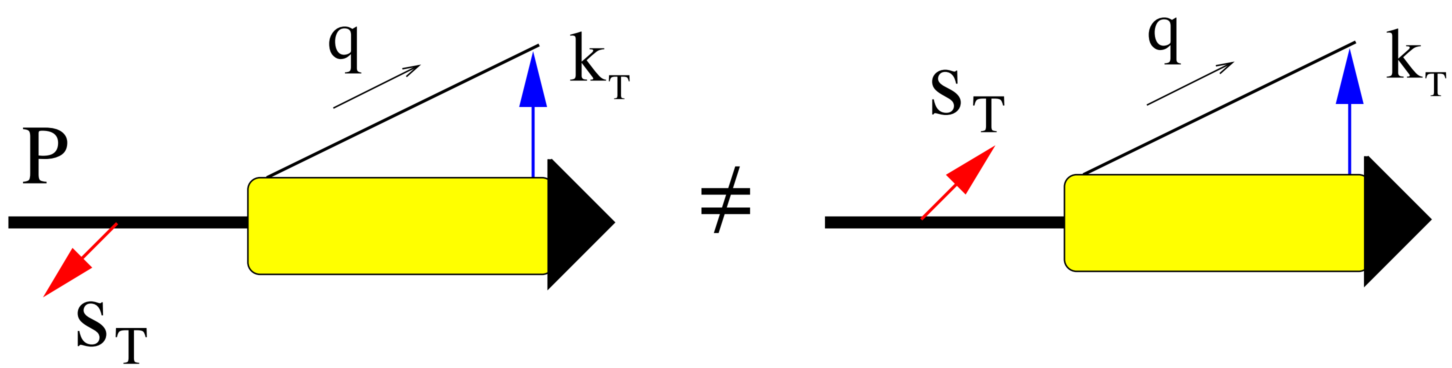

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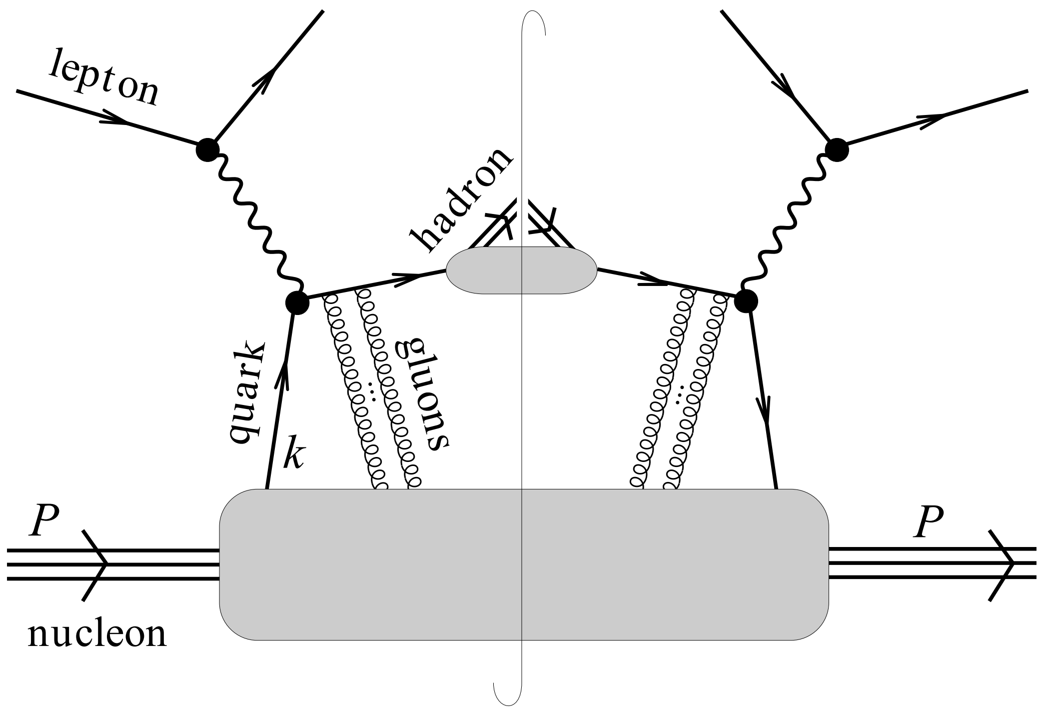
EIC advantage: measurement possible in the same kinematic region as Drell-Yan

This is important for a clean test of the predicted sign change relation

$$f_{1T}^{\perp q [\mathrm{SIDIS}]}(x, k_T^2) = - f_{1T}^{\perp q [\mathrm{DY}]}(x, k_T^2)$$

[Collins '02]

Initial and final state interactions



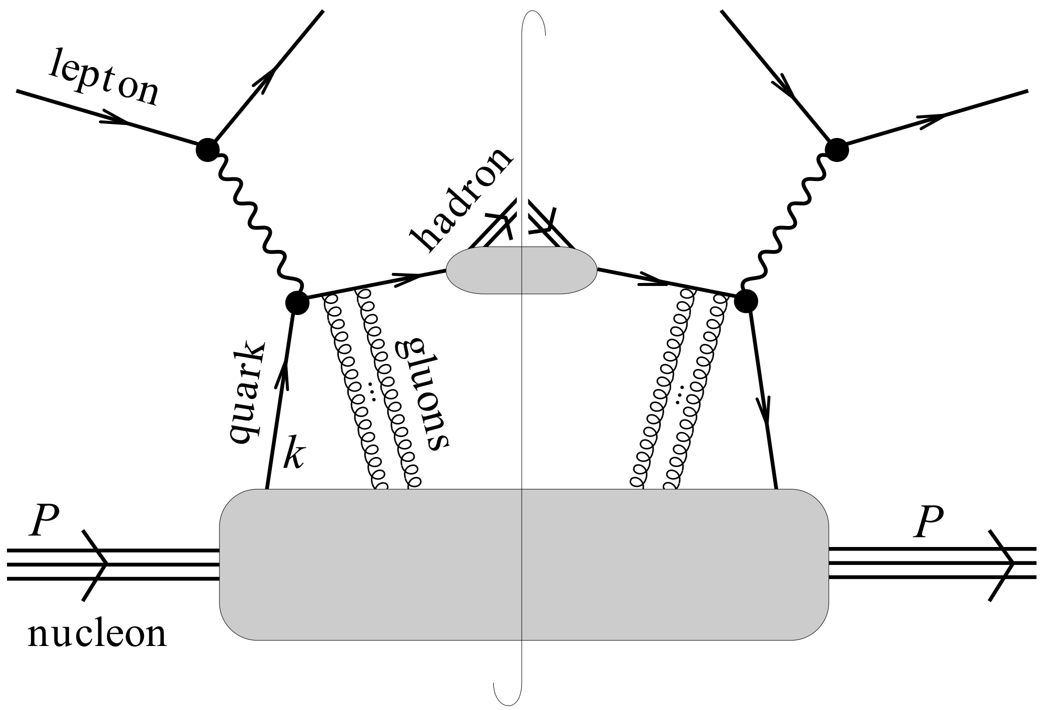
summation of all gluon rescatterings leads to path-ordered exponentials in correlators

$$\mathcal{L}_{\mathcal{C}}[0,\xi] = \mathcal{P}\exp\left(-ig\int_{\mathcal{C}[0,\xi]} ds_\mu\, A^\mu(s)\right)$$

$$\Phi \propto \langle P|\overline{\psi}(0)\mathcal{L}_{\mathcal{C}}[0,\xi]\psi(\xi)|P\rangle$$

Efremov & Radyushkin, Theor. Math. Phys. 44 ('81) 774

Initial and final state interactions



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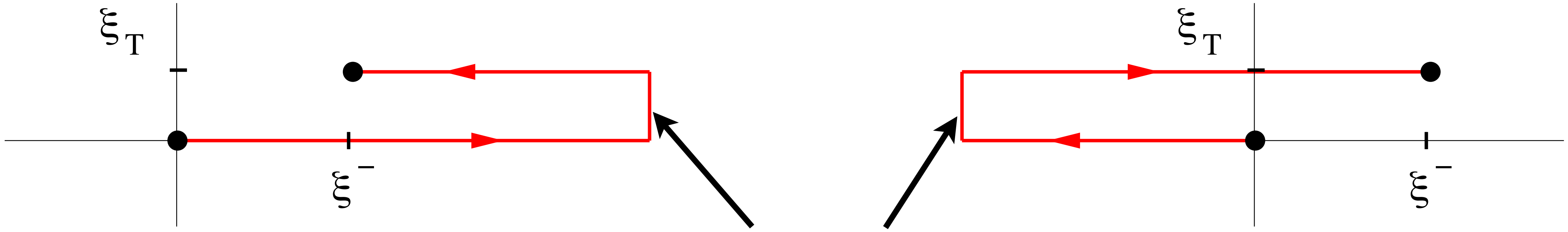
Efremov & Radyushkin, Theor. Math. Phys. 44 ('81) 774

SIDIS — DY

FSI lead to a future pointing Wilson line (+ link), whereas ISI to past pointing (− link)



lightcone infinity ∞^- $-\infty^-$

Leads to observable effects, such as nonzero Sivers asymmetry

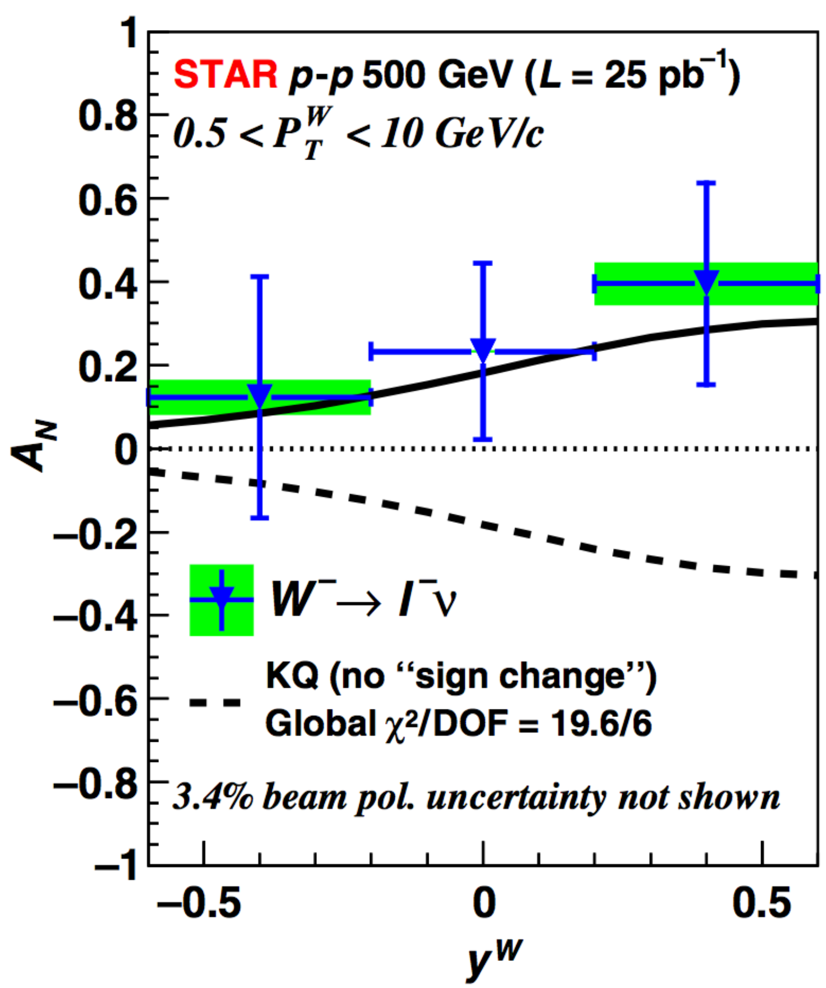
Brodsky, Hwang & Schmidt, 2002; Collins, 2002

Measurements of the Sivers TMD

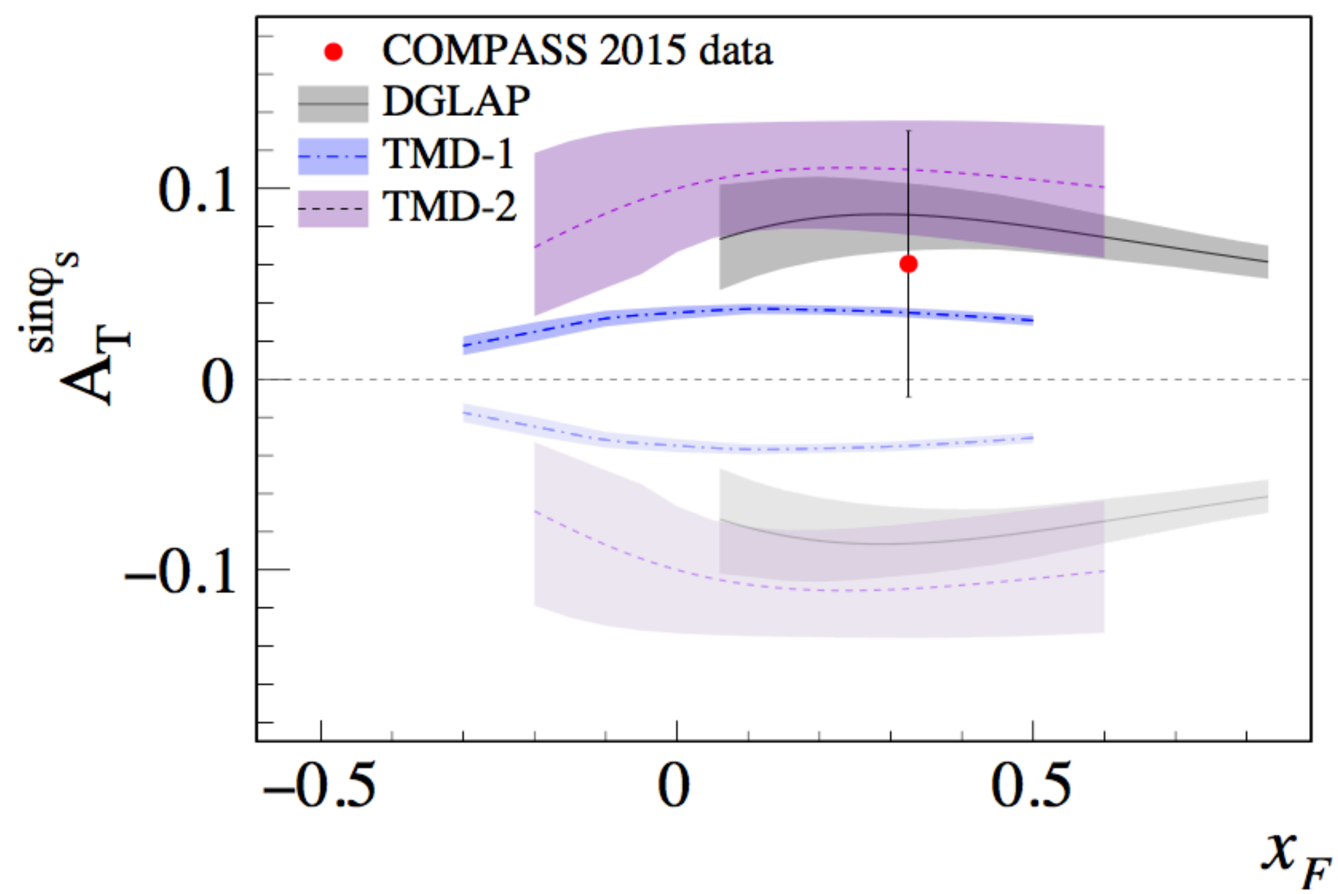
The Sivers effect in SIDIS has been clearly observed by HERMES at DESY (PRL 2009) & COMPASS at CERN (PLB 2010)

The corresponding DY experiments are investigated at CERN (COMPASS), Fermilab (SeaQuest) & RHIC (W-boson production rather) & planned at NICA (Dubna) & IHEP (Protvino)

The first data is compatible with the sign-change prediction of the TMD formalism



STAR, PRL 2016



COMPASS, arXiv:1704.00488

Process dependence of Sivers TMDs

A similar sign change relation for gluon Sivers functions holds

$$f_{1T}^{\perp\, g\, [e\, p^{\uparrow} \to e'\, Q\, \overline{Q}\, X]}(x, p_T^2) = -f_{1T}^{\perp\, g\, [p^{\uparrow}\, p \to \gamma\, \gamma\, X]}(x, p_T^2)$$

D.B., Mulders, Pisano, Zhou, 2016

Important role for EIC, but challenging (the r.h.s. is challenging for RHIC)

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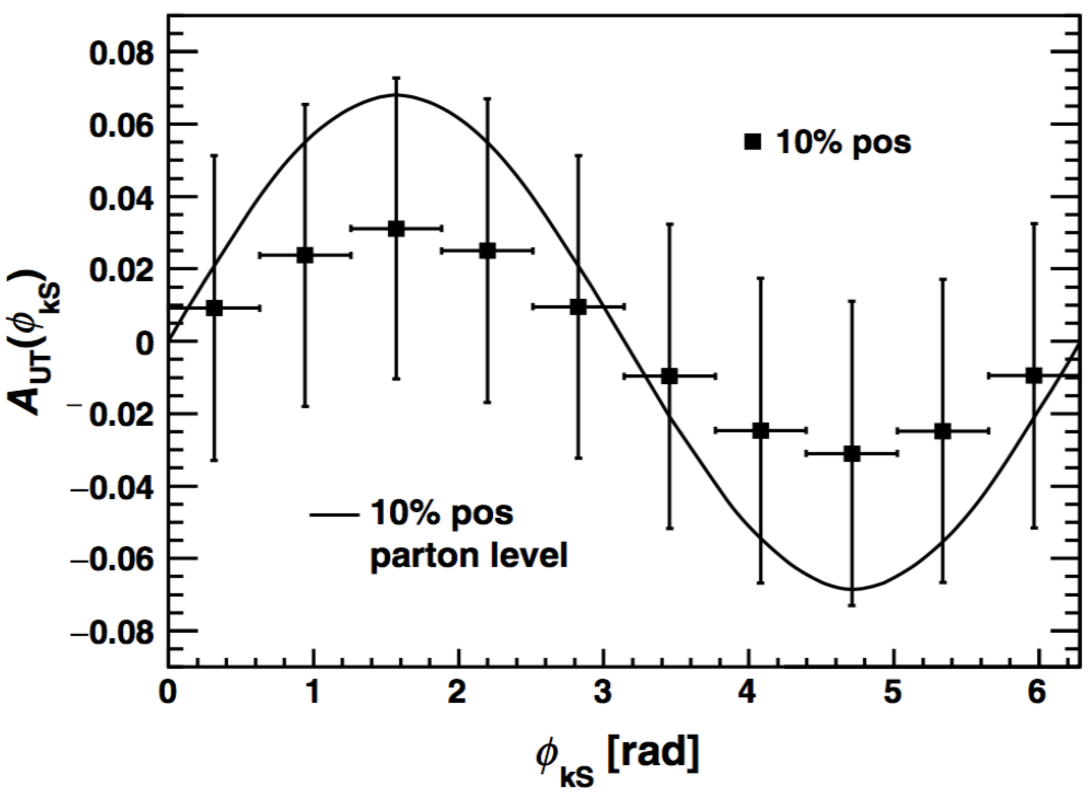
Important role for EIC, but challenging (the r.h.s. is challenging for RHIC)

The Sivers asymmetry in open heavy quark production is bounded by 1

$$e\,p^\uparrow \to e'\,Q\bar{Q}\,X \qquad A_N^{\sin(\phi_S-\phi_T)} = \frac{|\boldsymbol{q}_T|}{M_p}\,\frac{f_{1T}^{\perp g}(x, \boldsymbol{q}_T^2)}{f_1^g(x, \boldsymbol{q}_T^2)}$$

D.B., Pisano, Mulders, J. Zhou, 2016



Lint = 10 fb^{-1}

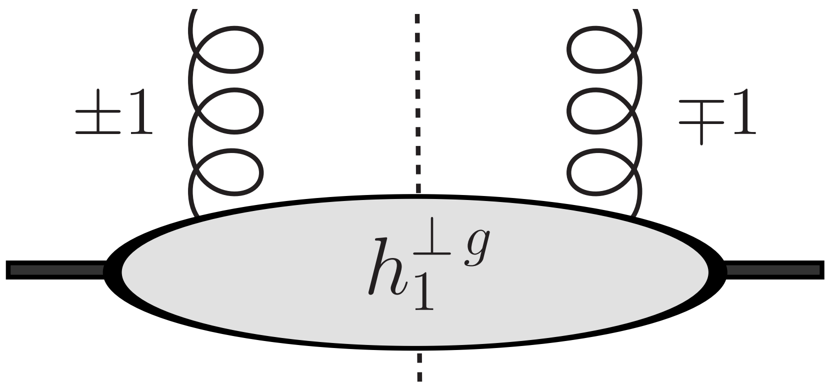
Conclusion: if function is 10% of the positivity bound, then it cannot be discerned within the statistics

Zheng, Aschenauer, Lee, Xiao, Yin, PRD 98 (2018) 034011

The situation for dijets is more promising, but theoretically less clean

Open heavy quark electro-production

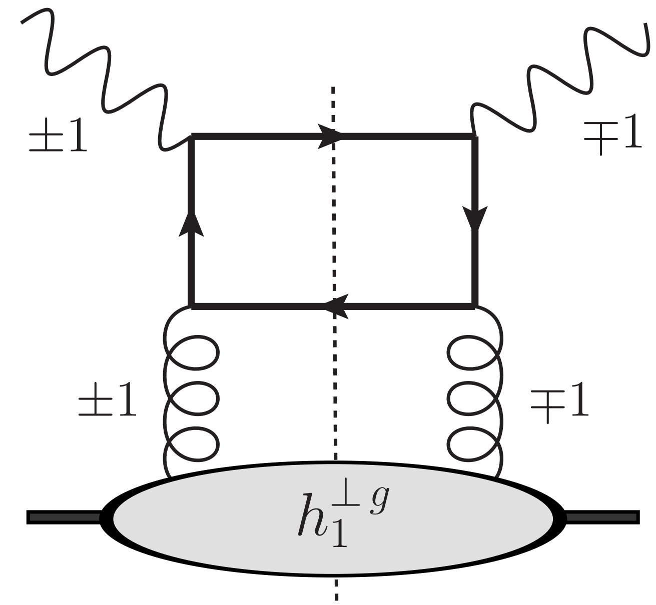
Unpolarized open heavy quark production also offers an interesting opportunity: to probe linearly polarized gluons in *unpolarized* hadrons



an interference between ±1 helicity gluon states

[Mulders, Rodrigues, 2001]

$$ep \to e' Q\bar{Q} X$$



[D.B., Brodsky, Mulders & Pisano, 2010]

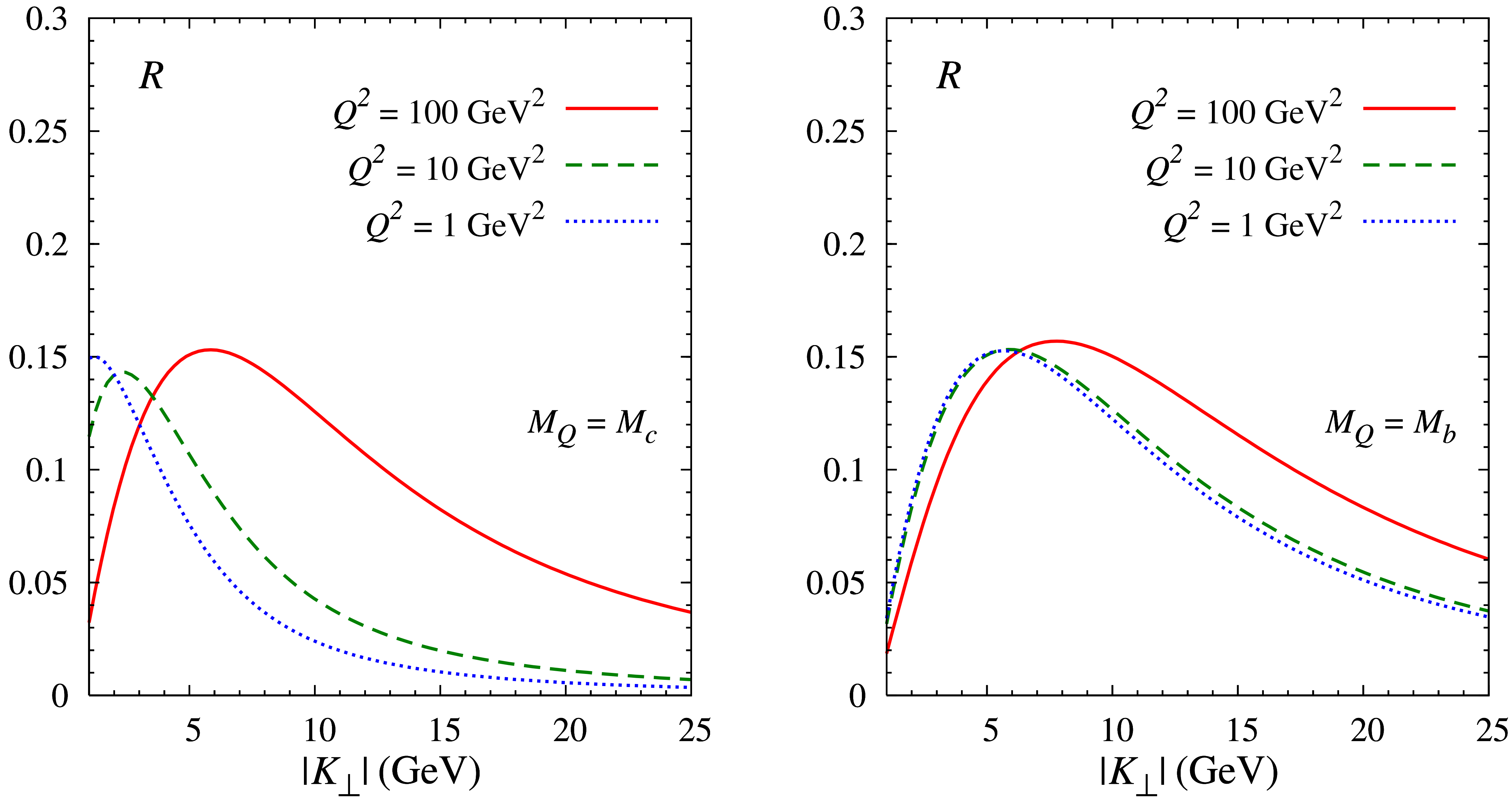
It gives rise to an angular distributions: a cos $2(\phi_T - \phi_\perp)$ asymmetry, where $\phi_{T/\perp}$ are the angles of $K_\perp^Q \pm K_\perp^{\bar{Q}}$

$h_1^{\perp g}$ appears by itself, so effects could be significant, especially towards smaller x

It is expected to keep up with the growth of the unpolarized gluons as x → 0

Maximum asymmetries in heavy quark production

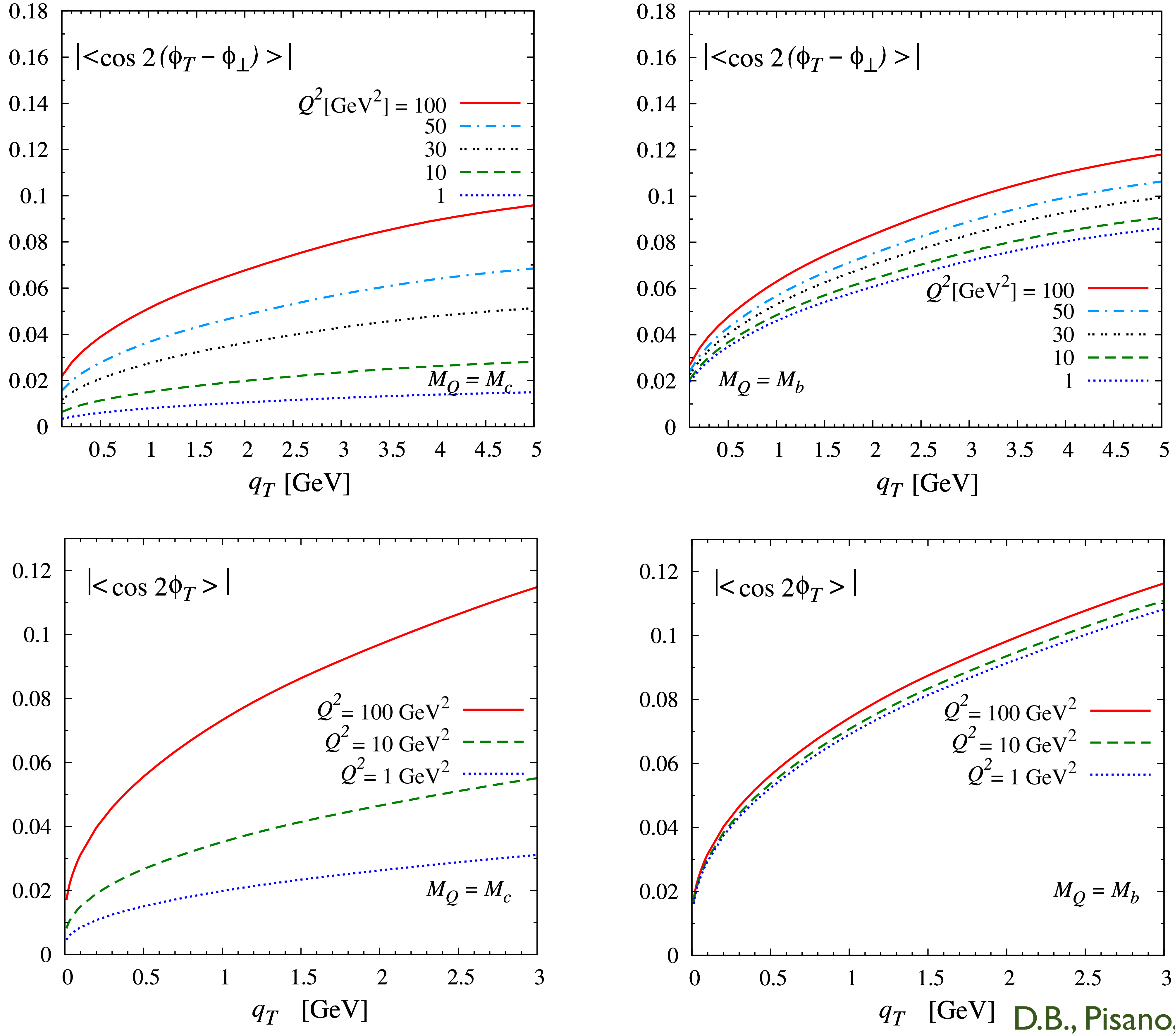
$ep \to e'Q\bar{Q}X$ $\qquad$ $R = \text{bound on } |\langle \cos 2(\phi_T - \phi_\perp) \rangle|$



[Pisano, D.B., Brodsky, Buffing & Mulders, JHEP 10 (2013) 024]

Maximal asymmetries can be substantial (for any Q^2 and for both charm & bottom)

Heavy quark pair production at EIC



small x
MV model

$|\boldsymbol{K}_\perp| = 10\,\text{GeV}$
$z = 0.5$
$y = 0.3$

$|\boldsymbol{K}_\perp| = 6\,\text{GeV}$
$z = 0.5$
$y = 0.1$

D.B., Pisano, Mulders, Zhou, 2016

Dijet production at EIC

$h_1^{\perp g}$ (WW) is accessible in dijet production in eA collisions at a high-energy EIC

[Metz, Zhou 2011; Pisano, D.B., Brodsky, Buffing, Mulders, 2013; D.B., Pisano, Mulders, Zhou, 2016]

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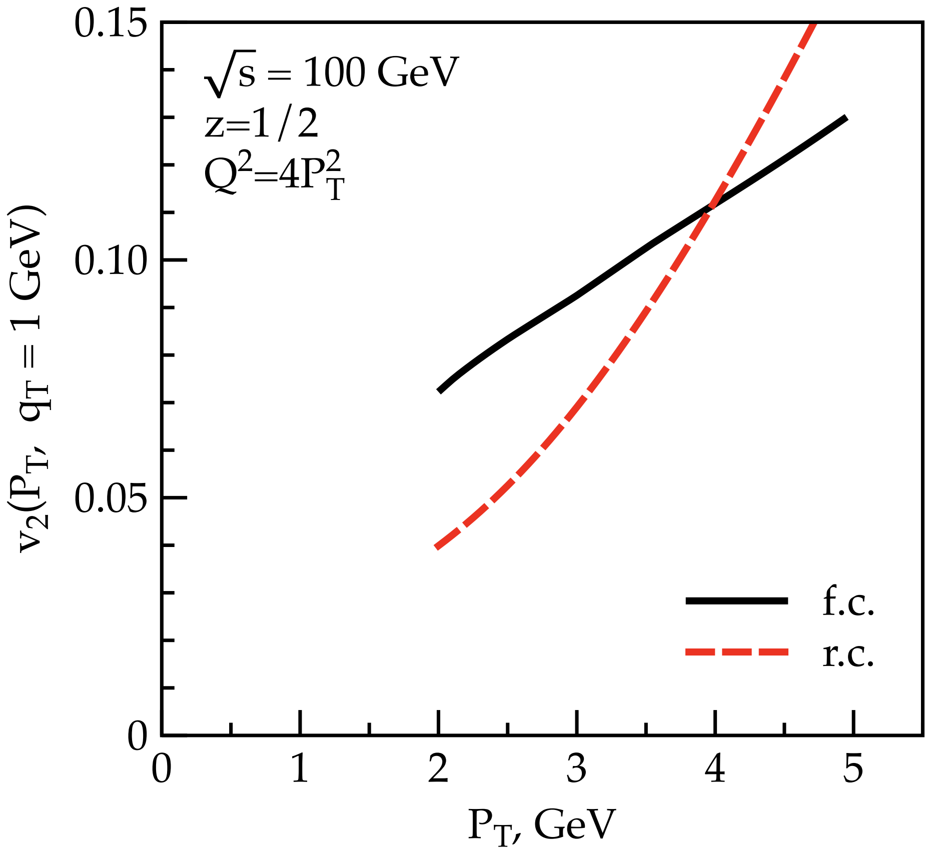
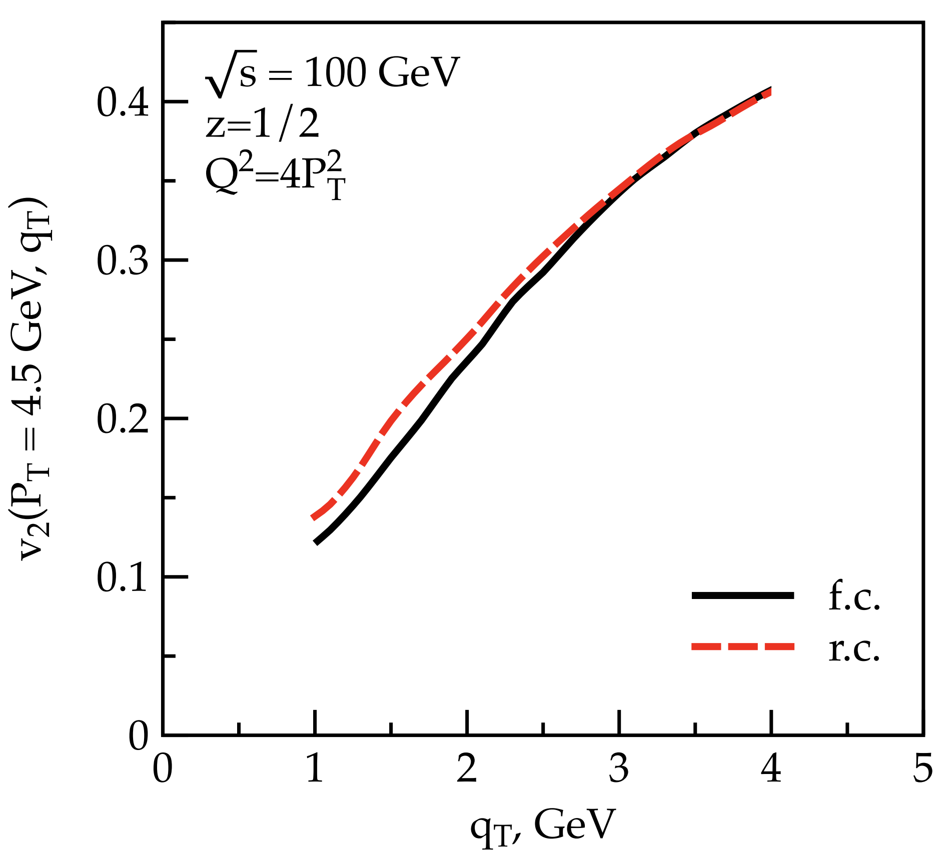
Polarization shows itself through a cos2ϕ distribution





Large effects are found

Dumitru, Lappi, Skokov, 2015

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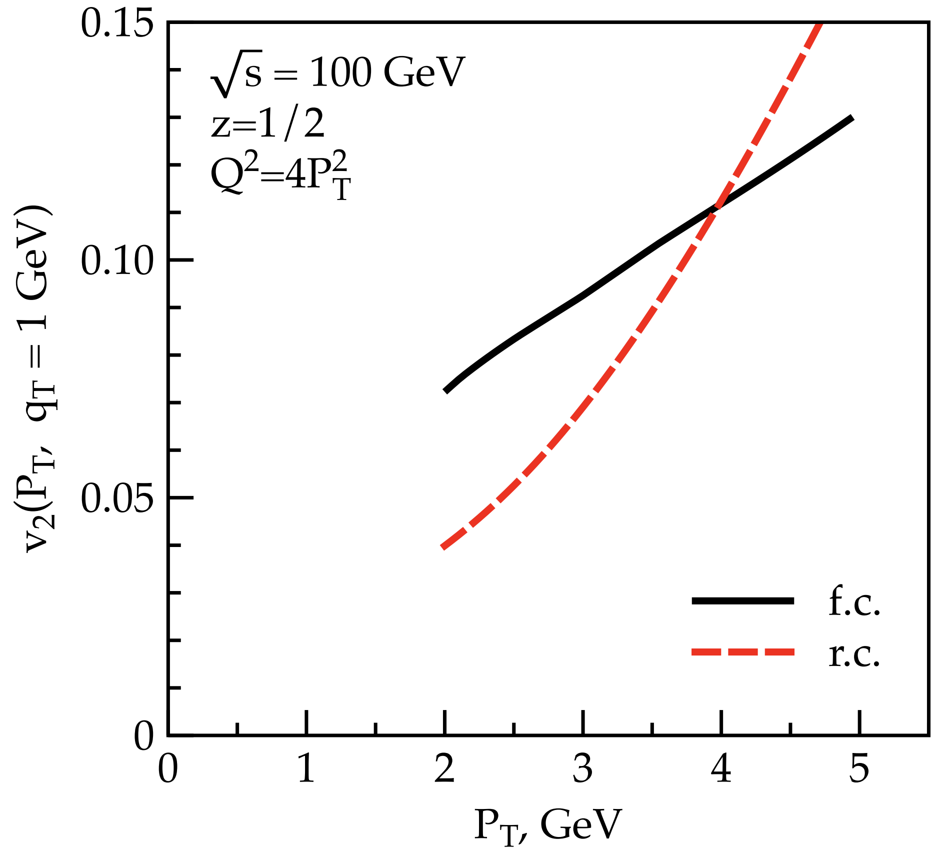

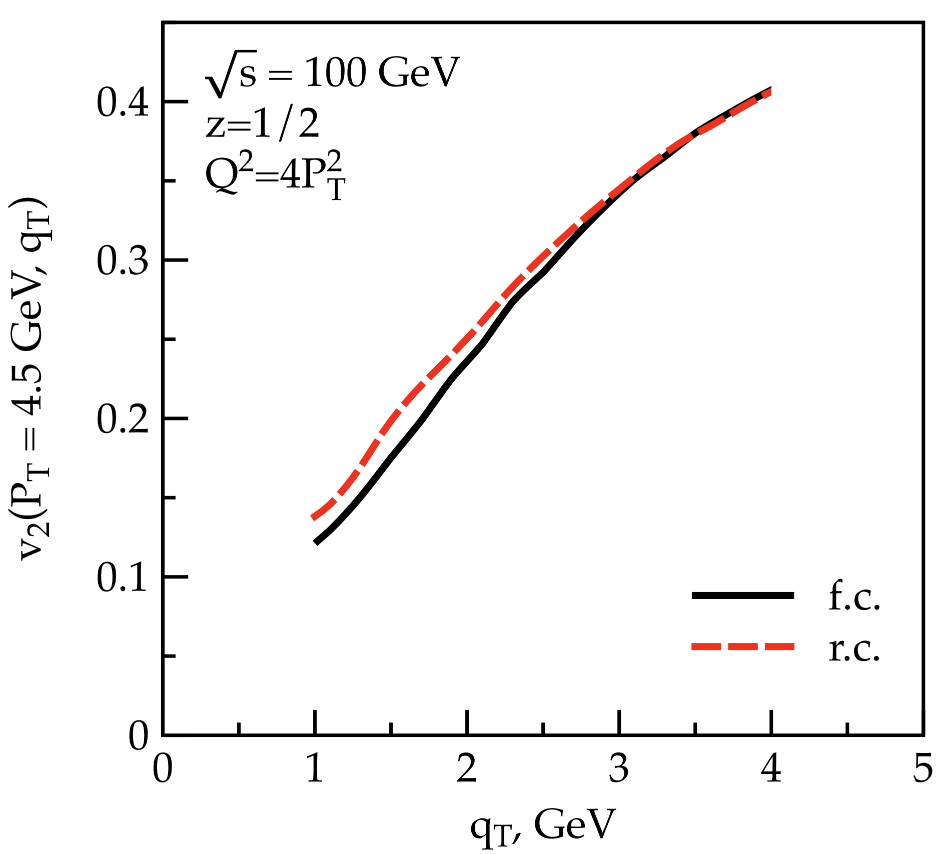

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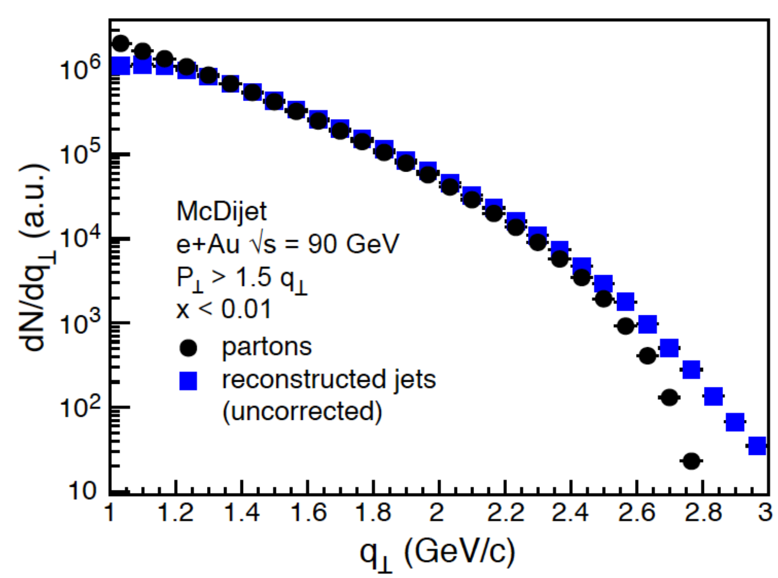
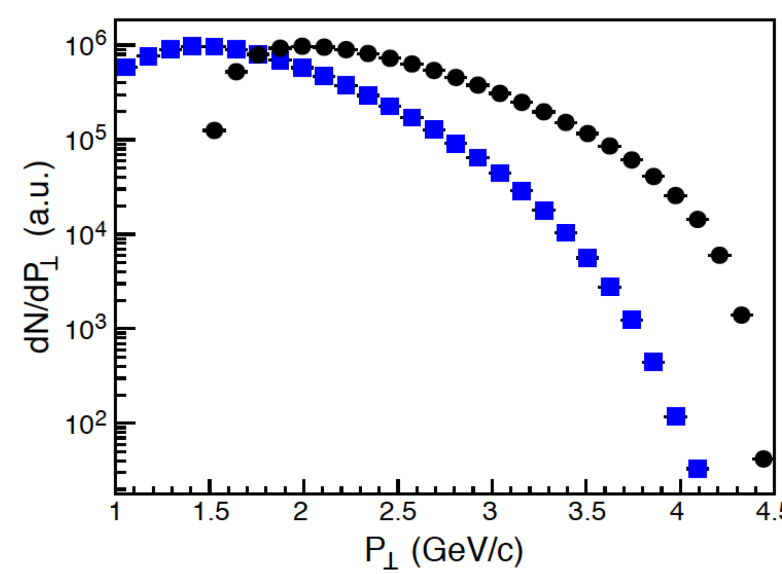
Dumitru, Lappi, Skokov, 2015

cos2ϕ has opposite signs for L and T γ^* polarization

Dumitru, Skokov, Ullrich, 2018

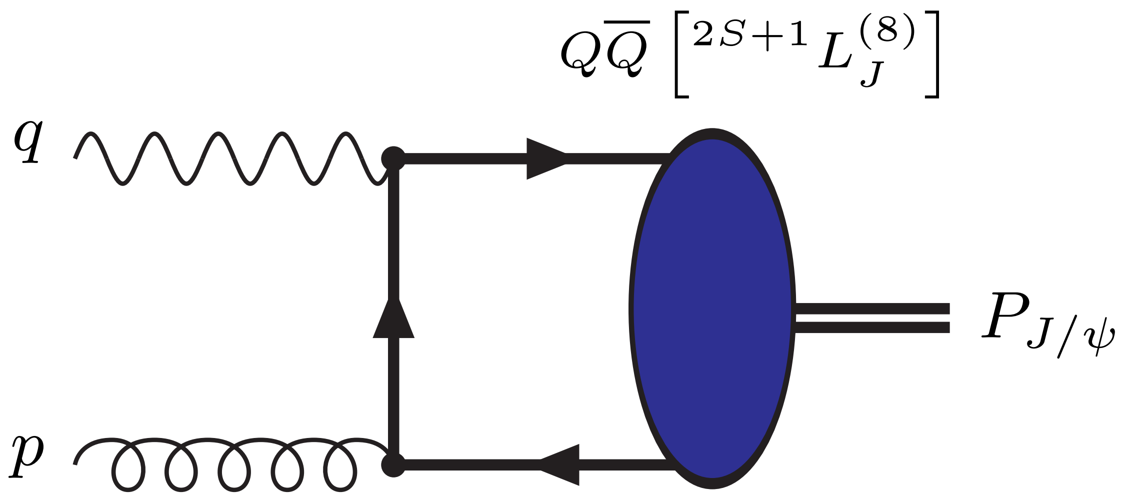




Quarkonia

$e\,p^{\uparrow} \to e'\,\mathcal{Q}\,X$ with $\mathcal{Q}$ either a J/ψ or a Υ meson

[Godbole, Misra, Mukherjee, Rawoot, 2012/3; Godbole, Kaushik, Misra, Rawoot, 2015; Mukherjee, Rajesh, 2017; Rajesh, Kishore, Mukherjee, 2018]



One either uses the Color Evaporation Model or NRQCD for Color Octet (CO) states

$$A^{\sin(\phi_S-\phi_T)} = \frac{|\boldsymbol{q}_T|}{M_p}\,\frac{f_{1T}^{\perp\,g}(x,\boldsymbol{q}_T^2)}{f_1^g(x,\boldsymbol{q}_T^2)}$$

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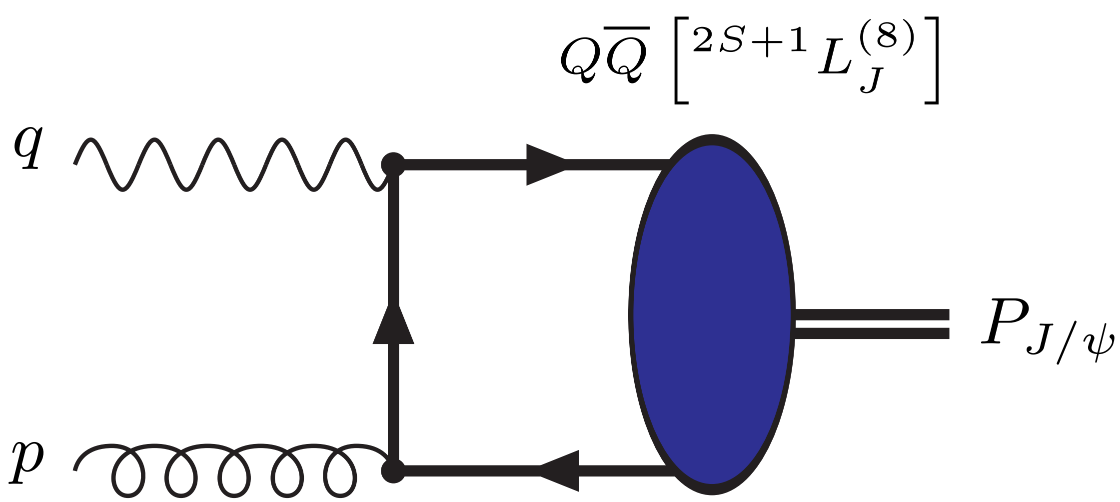

One either uses the Color Evaporation Model or NRQCD for Color Octet (CO) states

$$A^{\sin(\phi_S-\phi_T)} = \frac{|\boldsymbol{q}_T|}{M_p} \frac{f_{1T}^{\perp\, g}(x,\boldsymbol{q}_T^2)}{f_1^g(x,\boldsymbol{q}_T^2)}$$

Other asymmetries depend on the quite uncertain CO NRQCD LDMEs, but one can consider ratios of asymmetries to cancel them out

$$\frac{A^{\cos 2\phi_T}}{A^{\sin(\phi_S+\phi_T)}} = \frac{\boldsymbol{q}_T^2}{M_p^2} \frac{h_1^{\perp\, g}(x,\boldsymbol{q}_T^2)}{h_1^g(x,\boldsymbol{q}_T^2)}$$

$$\frac{A^{\cos 2\phi_T}}{A^{\sin(\phi_S-3\phi_T)}} = -\frac{1}{2} \frac{h_1^{\perp\, g}(x,\boldsymbol{q}_T^2)}{h_{1T}^{\perp\, g}(x,\boldsymbol{q}_T^2)}$$

$$\frac{A^{\sin(\phi_S-3\phi_T)}}{A^{\sin(\phi_S+\phi_T)}} = -\frac{\boldsymbol{q}_T^2}{2M_p^2} \frac{h_{1T}^{\perp\, g}(x,\boldsymbol{q}_T^2)}{h_1^g(x,\boldsymbol{q}_T^2)}$$

[Bacchetta, Boer, Pisano, Taels, arXiv:1809.02056]

CO NRQCD LDMEs @ EIC

But one can also consider ratios where the TMDs cancel out
and one can obtain new experimental information on the CO NRQCD LDMEs

This requires a comparison to the process $ep \to e' Q\bar{Q} X$

$$\mathcal{R}^{\cos 2\phi} = \frac{\int d\phi_T \cos 2\phi_T \, d\sigma^{\mathcal{Q}}(\phi_S, \phi_T)}{\int d\phi_T \, d\phi_\perp \cos 2\phi_T \, d\sigma^{Q\overline{Q}}(\phi_S, \phi_T, \phi_\perp)}$$

$$\mathcal{R} = \frac{\int d\phi_T \, d\sigma^{\mathcal{Q}}(\phi_S, \phi_T)}{\int d\phi_T \, d\phi_\perp \, d\sigma^{Q\overline{Q}}(\phi_S, \phi_T, \phi_\perp)}$$

Two observables depending on two unknowns:

$$\mathcal{O}_8^S \equiv \langle 0 | \mathcal{O}_8^{\mathcal{Q}}(^1S_0) | 0 \rangle$$

$$\mathcal{O}_8^P \equiv \langle 0 | \mathcal{O}_8^{\mathcal{Q}}(^3P_0) | 0 \rangle$$

$$\mathcal{R}^{\cos 2\phi_T} = \frac{27\pi^2}{4} \frac{1}{M_Q} \left[\mathcal{O}_8^S - \frac{1}{M_Q^2} \mathcal{O}_8^P \right]$$

$$\mathcal{R} = \frac{27\,\pi^2}{4} \frac{1}{M_Q} \frac{[1 + (1-y)^2]\, \mathcal{O}_8^S + (10 - 10y + 3y^2)\, \mathcal{O}_8^P / M_Q^2}{26 - 26y + 9y^2}$$

[Bacchetta, Boer, Pisano, Taels, arXiv:1809.02056]

Plus similar (but different) equations for *polarized* quarkonium production

Fragmentation Functions

Di-hadron production

Two-hadron fragmentation functions can be exploited to probe quark transversity

Collins, Heppelmann, Ladinsky, 1993; Collins, Ladinsky, 1994; Jaffe, Jin, Tang, 1998;
Bianconi, Boffi, Jakob, Radici, 2000; Radici, Jakob, Bianconi, 2002; … ; Radici, Bacchetta, 2018

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"Handedness" fragmentation functions $G_1^\perp$ enters SIDIS with f_1 or g_1

$$\frac{d\sigma(lH \to l' h_1 h_2 X)_{LO}}{d\Omega\, dx\, dz_h\, d\xi\, d^2\vec{P}_{h\perp}\, d^2\vec{R}_\perp} \propto \left\{ \cdots - \lambda_e |\vec{R}_\perp| C(y) \sin(\phi_h - \phi_R) \mathcal{F}\left[\hat{\vec{h}} \cdot \vec{k}_T \frac{f_1 G_1^\perp}{2M_1 M_2} \right] \right\}$$

Bianconi, Boffi, Jakob, Radici, 2000

$$\frac{d\sigma(e\vec{p} \to e' h_1 h_2 X)_{OL}}{d\Omega dx dz d\xi d\boldsymbol{P}_{h\perp} d\boldsymbol{R}_T} \propto \left\{ \cdots - \lambda |\boldsymbol{R}_T| A(y) \sin(\phi_h - \phi_R) \mathcal{F}\left[\hat{h} \cdot \boldsymbol{k}_T \frac{g_1 G_1^\perp}{M_1 M_2} \right] + \cdots \right\}$$

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Bianconi, Boffi, Jakob, Radici, 2000

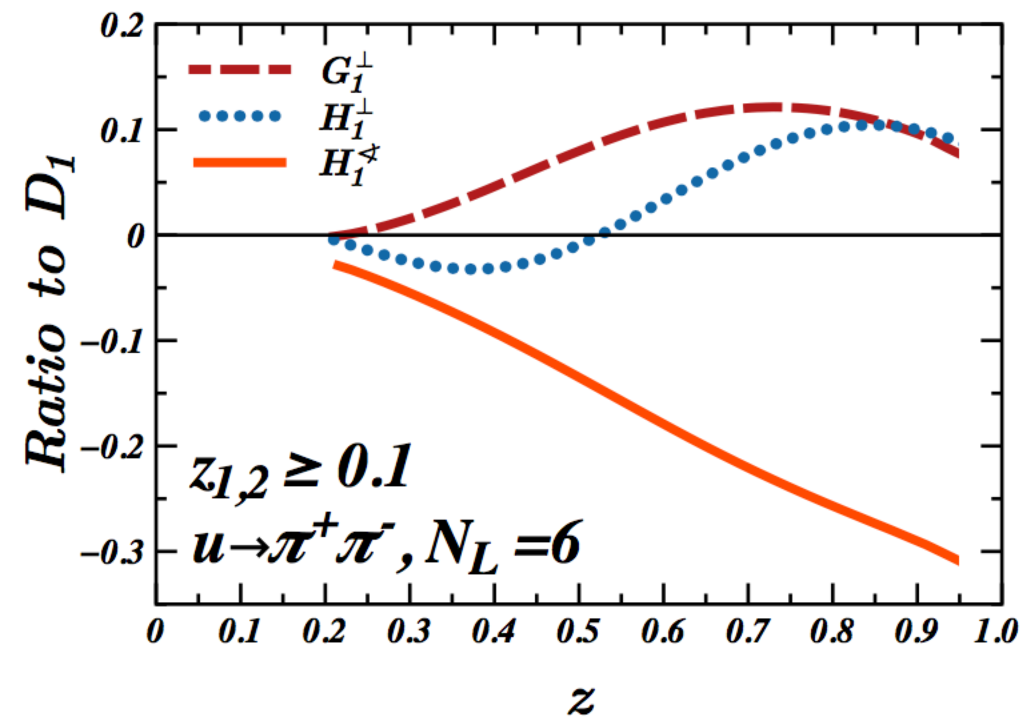
$G_1^\perp$ can be extracted from Belle data

Matevosyan, Kotzinian, Thomas, 2018; Matevosyan, Bacchetta, Boer, Courtoy, Kotzinian, Radici, Thomas, 2018
Belle Collaboration, arXiv:1505.08020

$$\langle \cos[2(\varphi_R - \varphi_{\bar{R}})] \rangle = 0$$

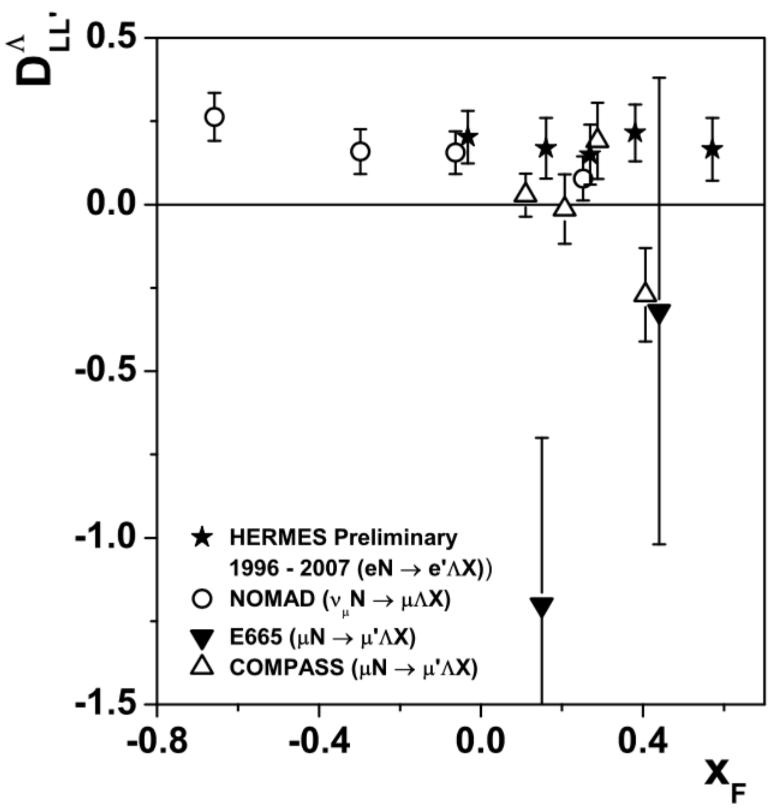
$$\begin{aligned} &\langle \boldsymbol{q}_T^2 (3\sin(\varphi_q - \varphi_R)\sin(\varphi_q - \varphi_{\bar{R}}) + \cos(\varphi_q - \varphi_R)\cos(\varphi_q - \varphi_{\bar{R}})) \rangle \\ &= \langle \boldsymbol{q}_T^2 (2\cos(\varphi_R - \varphi_{\bar{R}}) - \cos(2\varphi_1 - \varphi_R - \varphi_{\bar{R}})) \rangle \\ &= \frac{12\alpha^2}{\pi Q^2} A(y) \sum_{a,\bar{a}} e_a^2 M_h \bar{M}_h G_1^{\perp a}(z, M_h^2) \bar{G}_1^{\perp \bar{a}}(\bar{z}, \bar{M}_h^2), \end{aligned}$$

Matevosyan, arXiv:1807.11485

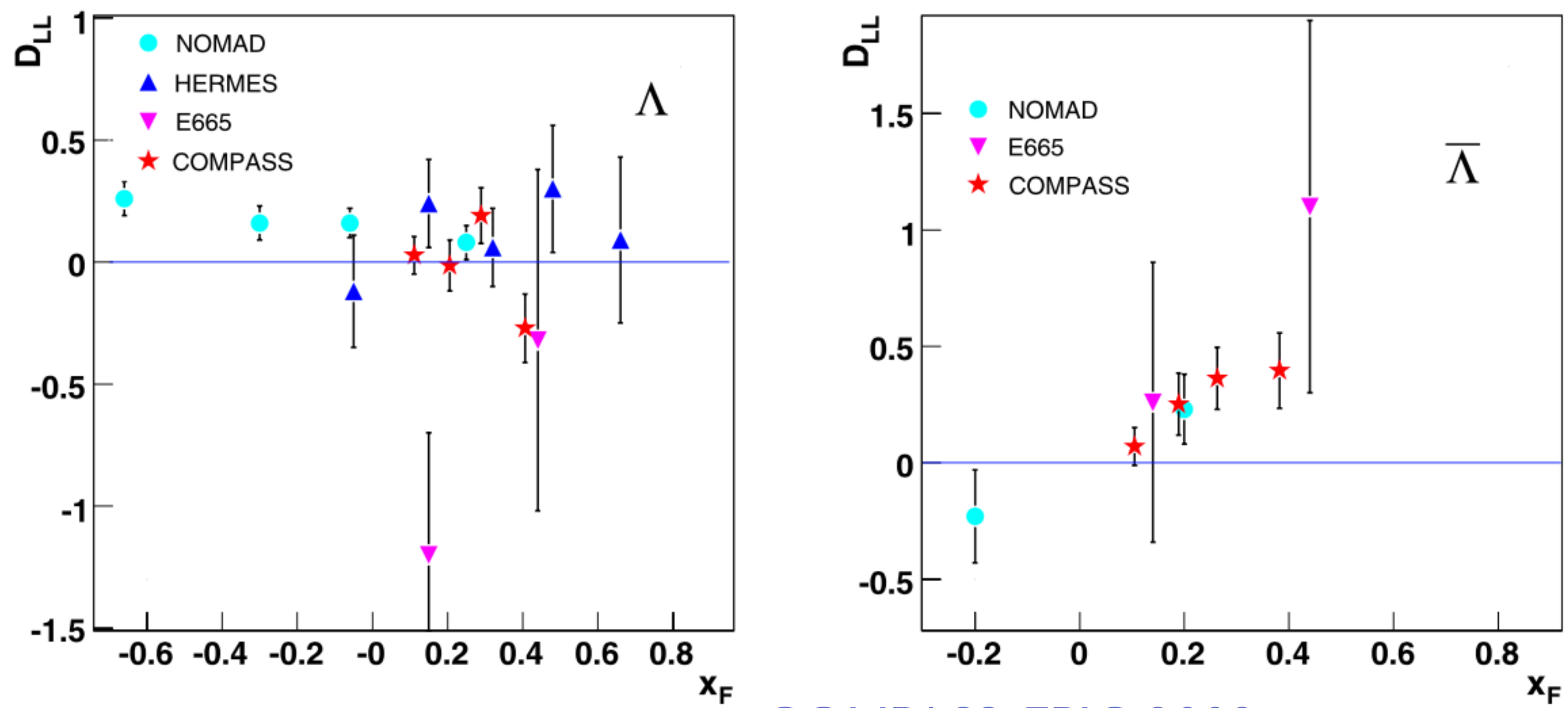


Lambda production

Polarized Λs can be used to probe g_1 via polarization *transfer* D_{LL}



HERMES@SPIN2010



COMPASS, EPJC 2009

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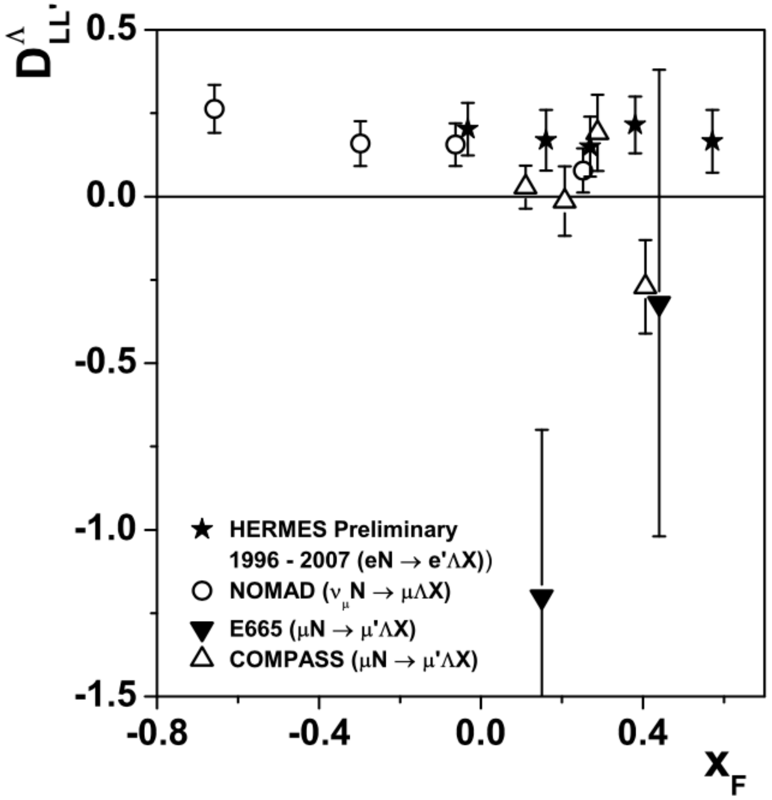
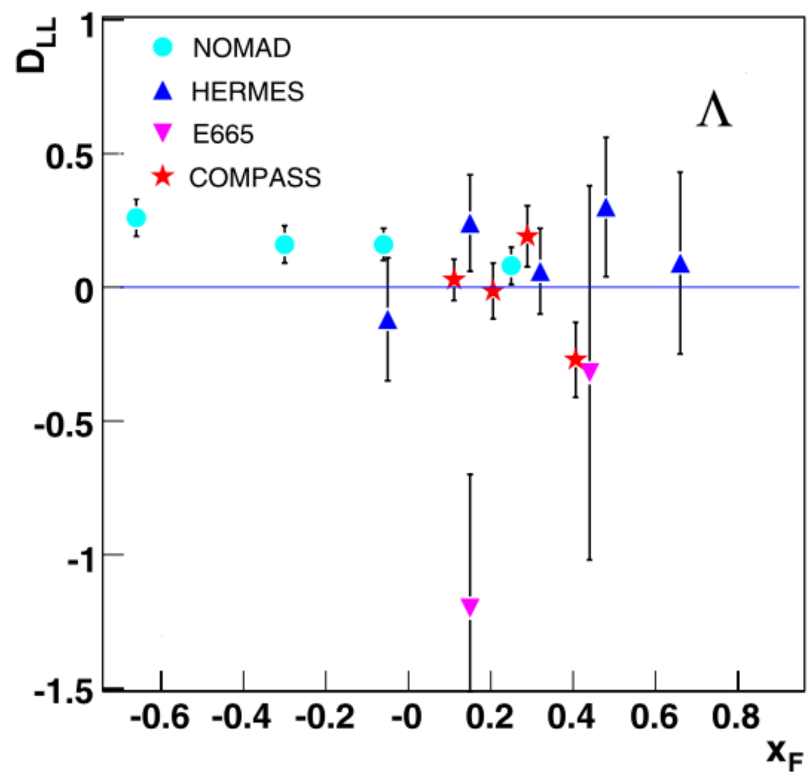
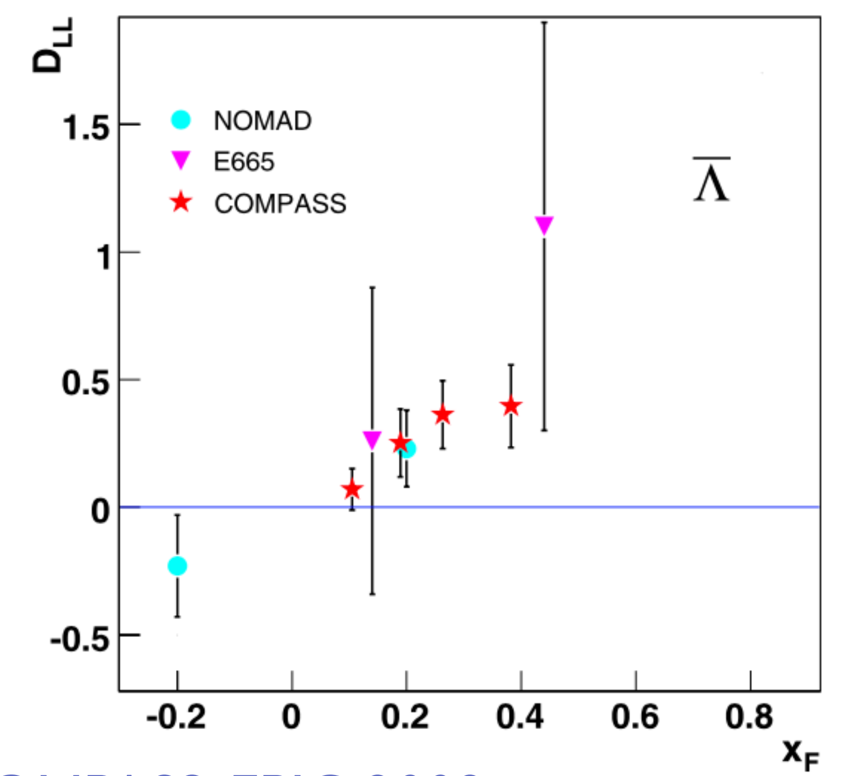
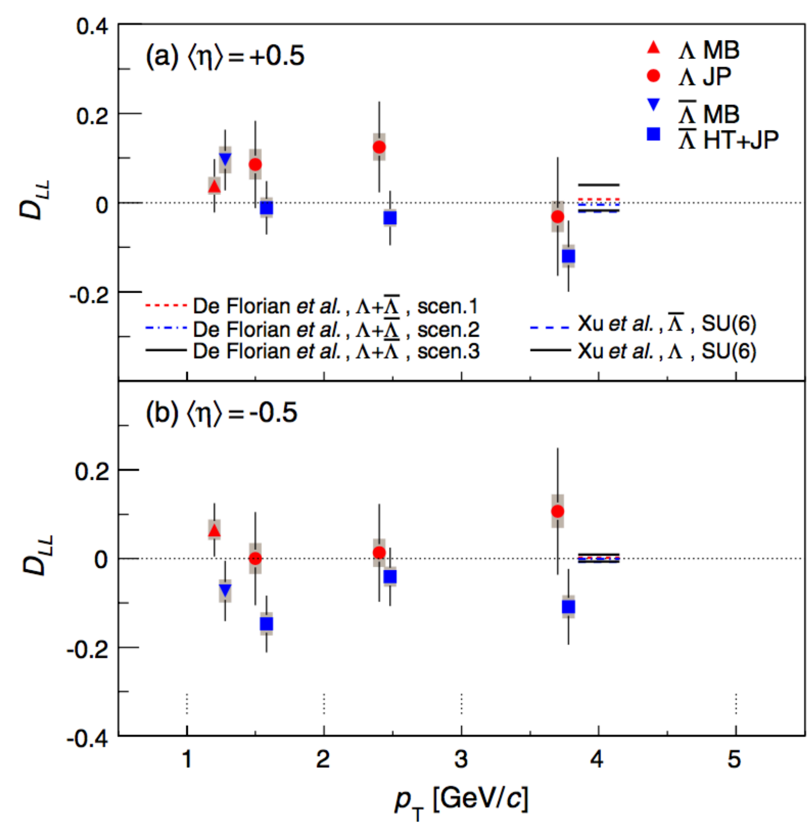


HERMES@SPIN2010



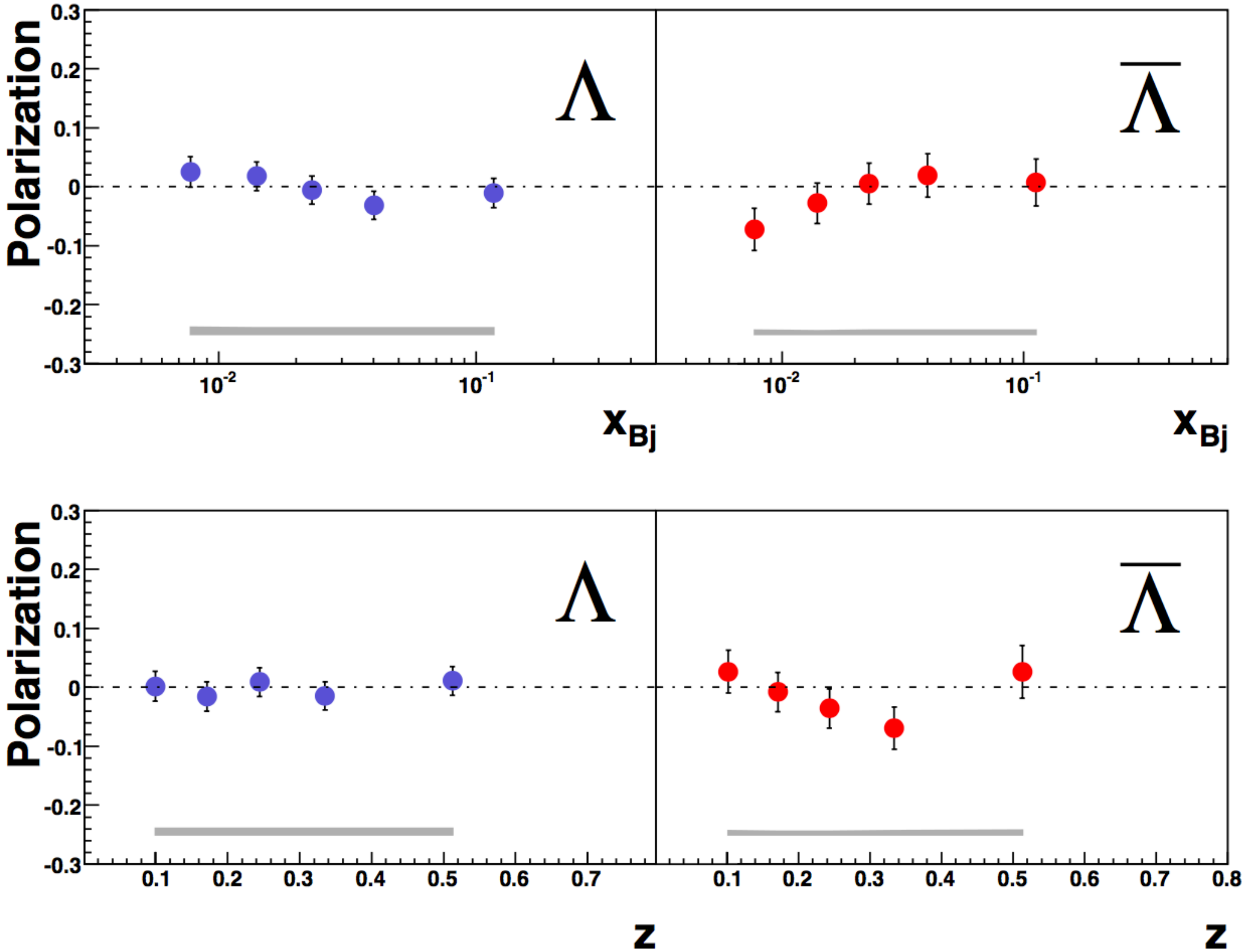


COMPASS, EPJC 2009



STAR, PRD 2009

D_{NN} in SIDIS ($\mu p^{\uparrow} \rightarrow \mu \Lambda^{\uparrow} X$)



T. Negrini, COMPASS, PhD thesis, 2009

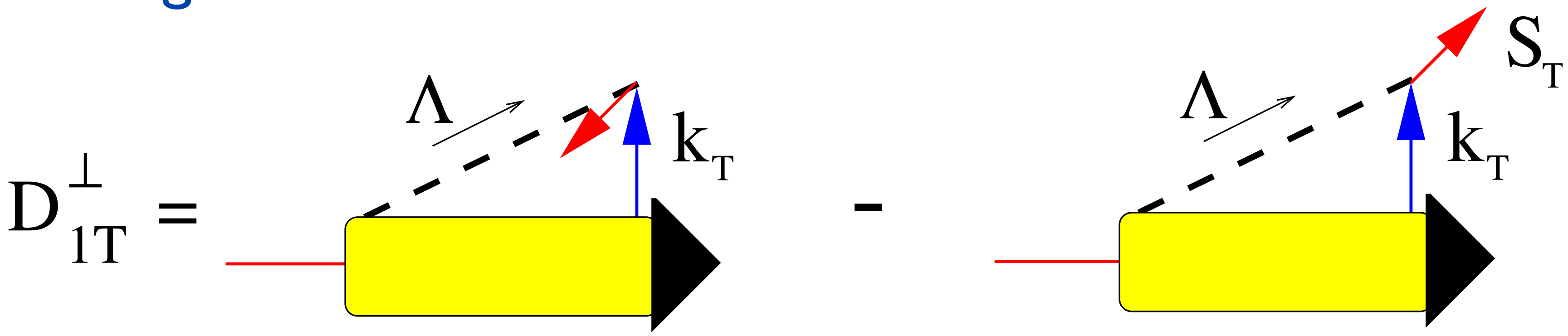
Figure 6.3: Λ and $\overline{\Lambda}$ polarizations with statistical errors as a function of x_{Bj} and z in the 2007 COMPASS data on a transversely polarized proton target with $Q^2 > 1$ $(\text{GeV/c})^2$ and $0.1 < y < 0.9$. The lower band shows the upper limit of the systematic error, estimated by the pulls distribution of false polarizations (same as Fig. 5.15).

Likely implies small $H_1^{u,d}(z)$ and/or small $h_1^{s}(x)$ in the measured range

Spontaneous Λ polarization

Produced Λs can also become "spontaneously" polarized, as long known from pp

Polarizing TMD fragmentation function $D_{1T}^{\perp}$



Mulders, Tangerman, 1996

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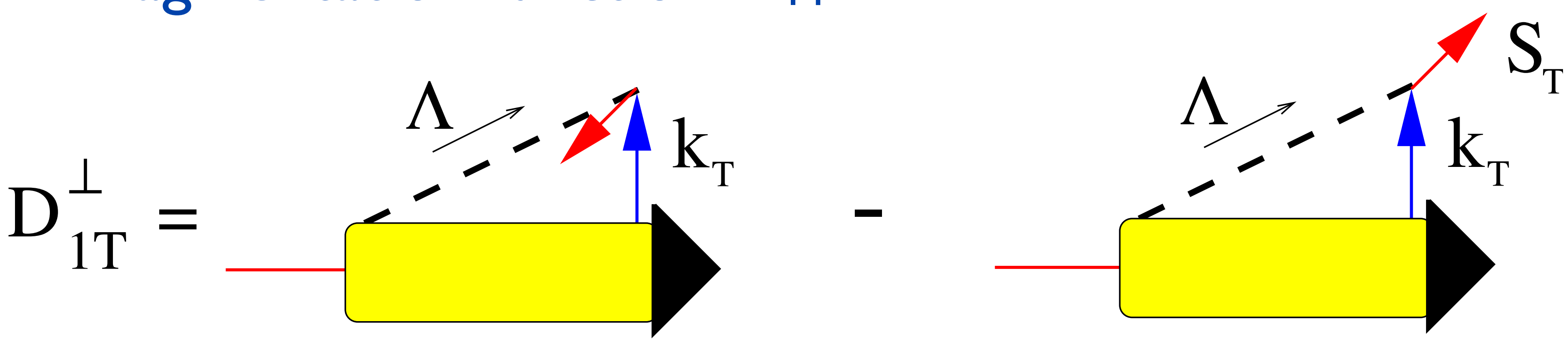

Mulders, Tangerman, 1996

Semi-inclusive DIS: ep → e' $\Lambda^{\uparrow}$ X (NC) and ν_{μ} p → $\mu\Lambda^{\uparrow}$ X (CC)

Anselmino, D.B., D'Alesio & Murgia, PRD 65 (2002) 114014

Only available SIDIS data in the current fragmentation region is from NOMAD ($\nu_{\mu}p \to \mu\Lambda^{\uparrow}X$) and from ZEUS ($ep \to e'\,\Lambda^{\uparrow}X$), both compatible with zero

Astier et al., NOMAD Collab., NPB 588 (2000) 3; ZEUS Collab., Eur. Phys. J. C 51 (2007) 1

Other ep data are either in the target fragmentation region or for quasi-real production (E665, HERMES)

Polarizing FFs from e⁺e⁻

$$\frac{d\sigma(e^+e^- \to h \text{ jet } X)}{d\Omega\, dz_h\, d^2\boldsymbol{q}_T} = \frac{3\alpha^2}{Q^2} z_h^2 \sum_{a,\bar{a}} {e_a}^2 \Big\{ A(y) \Big[D_1^a(z_h, z_h^2 Q_T^2) + |S_{hT}| \sin(\phi_h - \phi_{S_1}) \frac{Q_T}{M_h} D_{1T}^{\perp a}(z_h, z_h^2 Q_T^2) \Big]$$

in $e^+e^- \to (\Lambda^\uparrow \text{ jet})\, X$ it is not power suppressed

D.B., Jakob, Mulders, 1997

Polarizing FFs from e^+e^-

$$\frac{d\sigma(e^+e^- \to h \text{ jet } X)}{d\Omega\, dz_h\, d^2 q_T} = \frac{3\alpha^2}{Q^2} z_h^2 \sum_{a,\bar{a}} e_a{}^2 \Big\{ A(y) \Big[D_1^a(z_h, z_h^2 Q_T^2) + |S_{hT}| \sin(\phi_h - \phi_{S_1}) \frac{Q_T}{M_h} D_{1T}^{\perp a}(z_h, z_h^2 Q_T^2) \Big]$$

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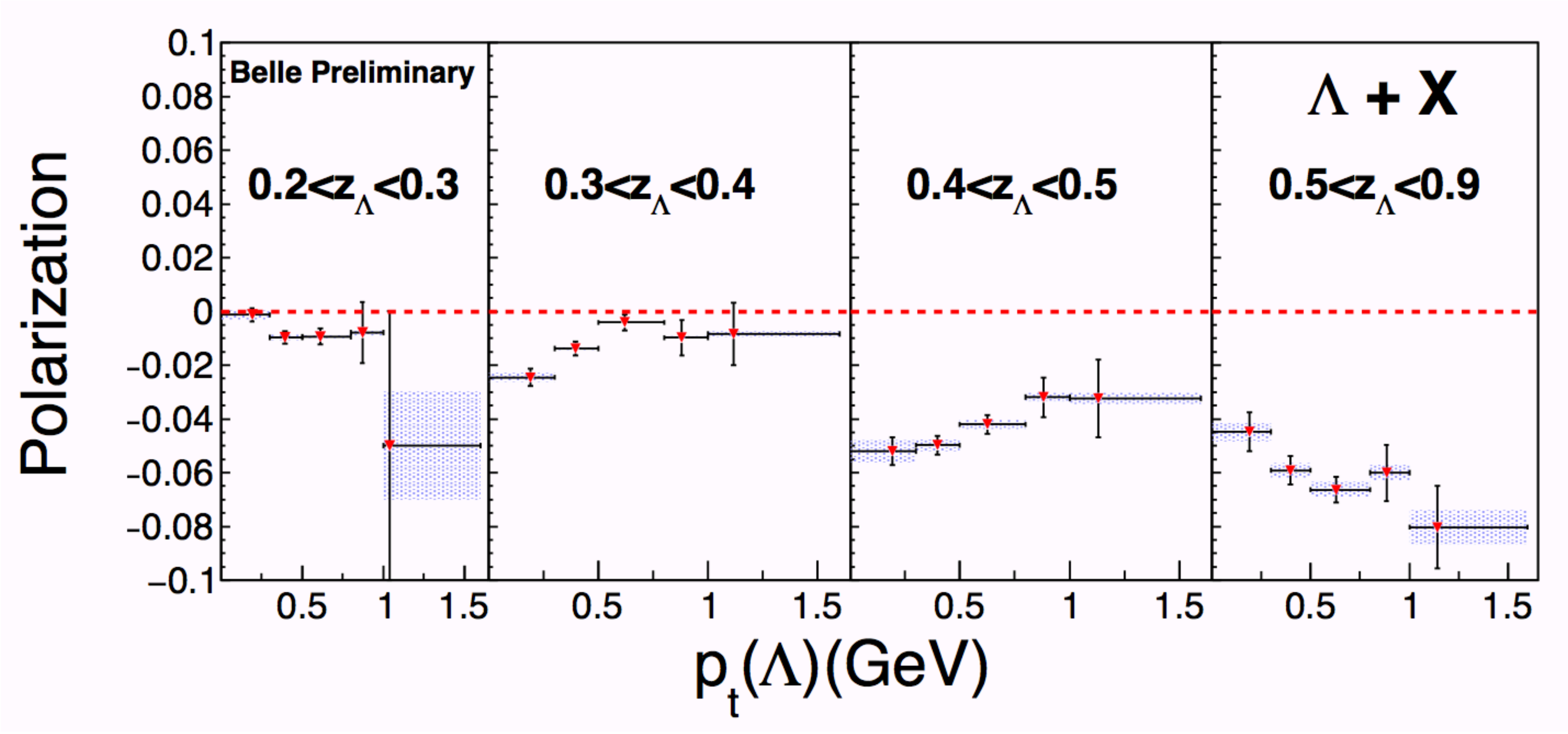
D.B., Jakob, Mulders, 1997

OPAL data $Q=M_Z$: compatible with zero at the ~3% level

Eur.Phys.J C2 (1998) 49



BELLE Collaboration arXiv:1611.06648

p_T w.r.t. thrust axis

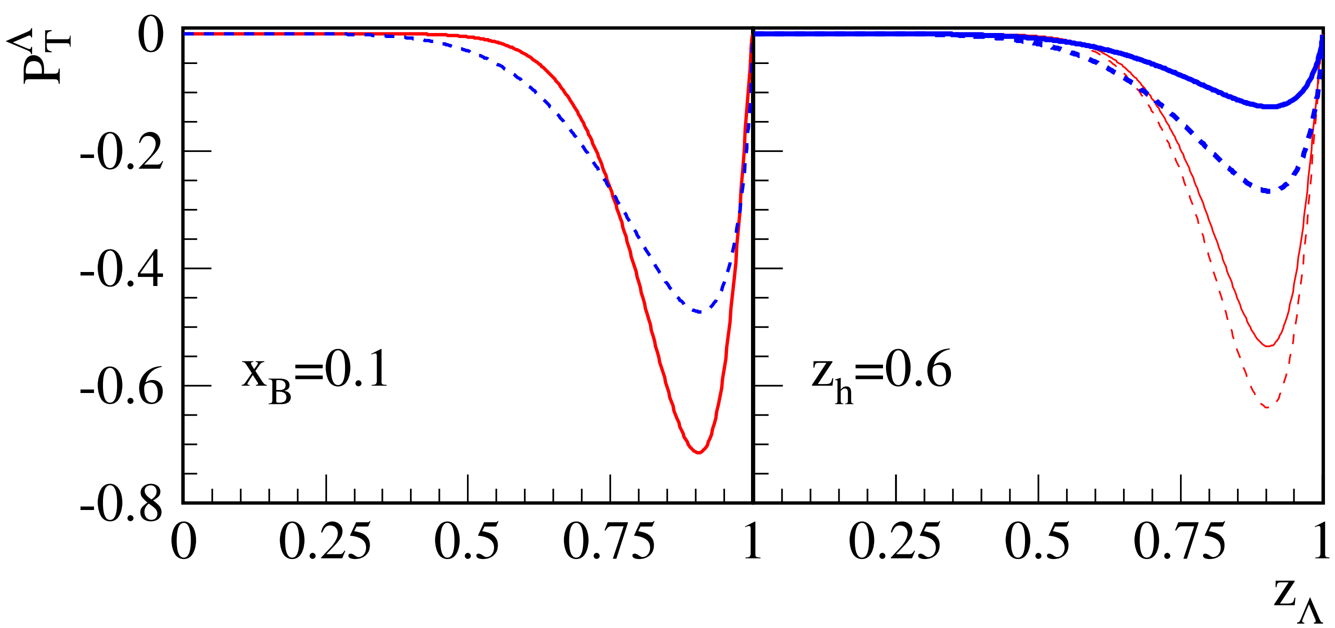
TMD evolution: polarization at BELLE expected to be 3 times larger than at $Q=M_Z$

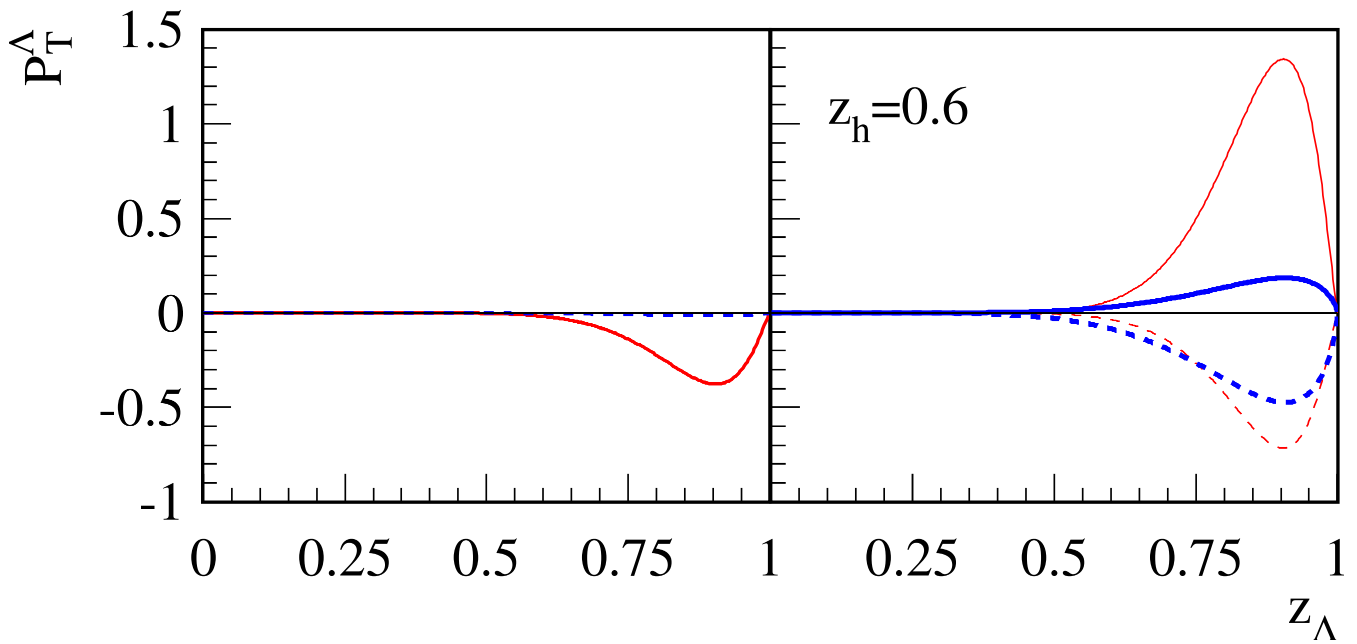
Associated production

$e^+e^- \to \Lambda^\uparrow X$ is very sensitive to cancellations between u, d and s contributions

It is better to study Λ produces in association with a π or K

This allows for flavor selection





D.B., Kang, Vogelsang, Yuan, PRL 2010

Fig 1: SIDIS, SU(3)-symmetric (solid) and broken (dashed) spin-averaged FFs

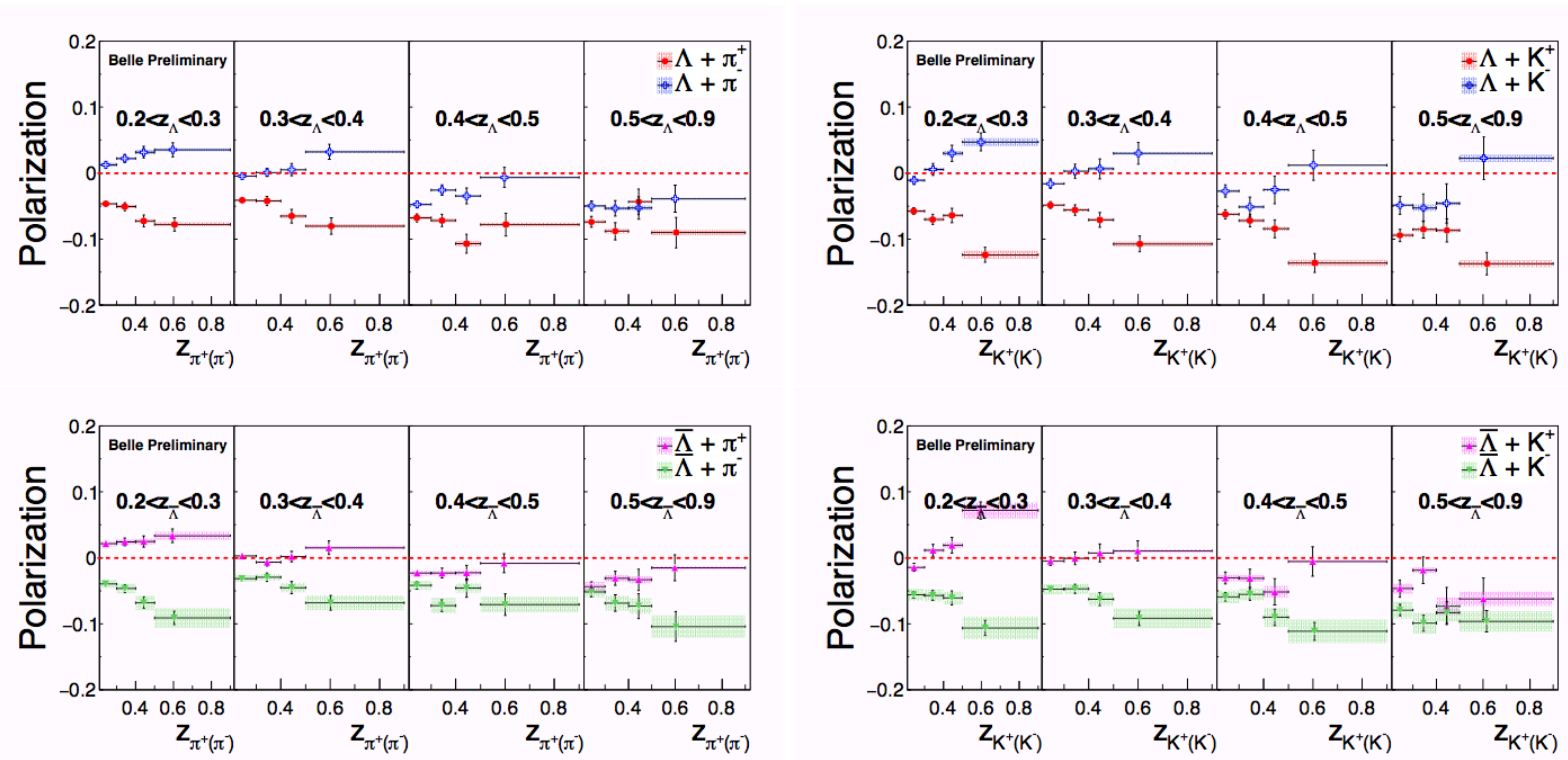
Fig 2: $e^+e^- \to \pi^\pm + \Lambda^\uparrow + X$, SU(3)-symmetric (thin) and broken (thick), solid/dashed is $\pi^\pm$

Fig 3: $e^+e^- \to$ jet + $\Lambda^\uparrow + X$, SU(3)-symmetric (solid) and broken (dashed) spin-averaged FFs

Fig 4: $e^+e^- \to K^\pm + \Lambda^\uparrow + X$, SU(3)-symmetric (thin) and broken (thick), solid/dashed is $K^\pm$

Comparison to $ep \to e'\Lambda^\uparrow X$ can be used to test universality of $D_{1T}^\perp$

Associated production at Belle



BELLE Collaboration, arXiv:1611.06648

Data does not follow our expectations for the charges, e.g. for π^+ larger polarization than for π^-. Needs to be looked into

GTMDs & GPDs

Quark GTMDs

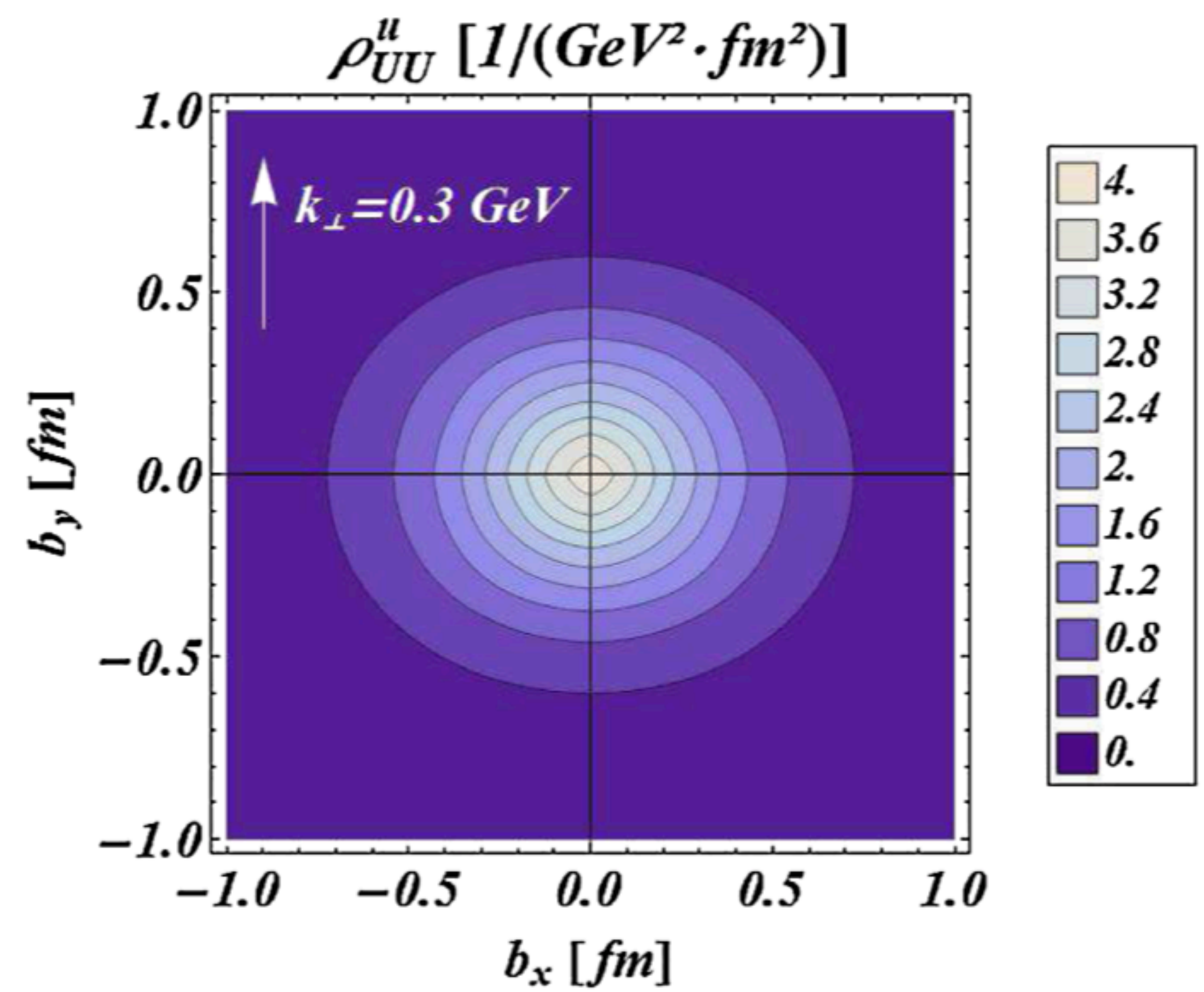
GTMD = off-forward TMD = Fourier transform of a Wigner distribution

$$G(x, \boldsymbol{k}_T, \boldsymbol{\Delta}_T) \xleftrightarrow{FT} W(x, \boldsymbol{k}_T, \boldsymbol{b}_T)$$

Meißner, Metz, Schlegel, 2009 Ji, 2003; Belitsky, Ji & Yuan, 2004

Quark Wigner distributions can display distortions in the b_T plane depending on k_T and vice versa, that vanish upon b_T or k_T integration

Lorce & Pasquini, 2011



Quark orbital angular momentum can be expressed as integrals over Wigner distributions

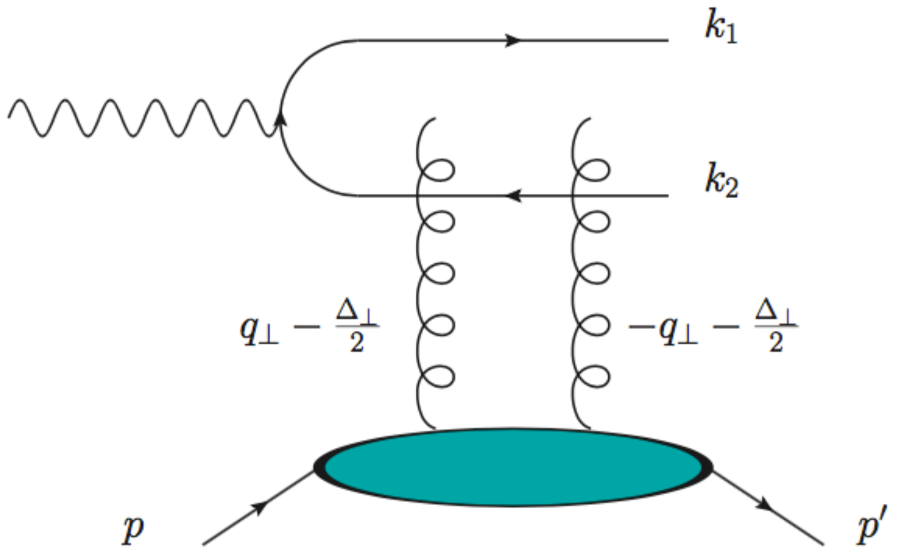
Analogously, gluon Wigner distributions and gluon GTMDs can be defined

See recent review: More, Mukherjee, Nair, Eur.Phys.J. C78 (2018)

Gluon GTMDs

First suggestion to measure gluon GTMDs: hard diffractive dijet production

Altinoluk, Armesto, Beuf, Rezaeian, 2016; Hatta, Xiao, Yuan, 2016



Extension of an earlier suggestion
to probe gluon GPDs

Braun, Ivanov, 2005

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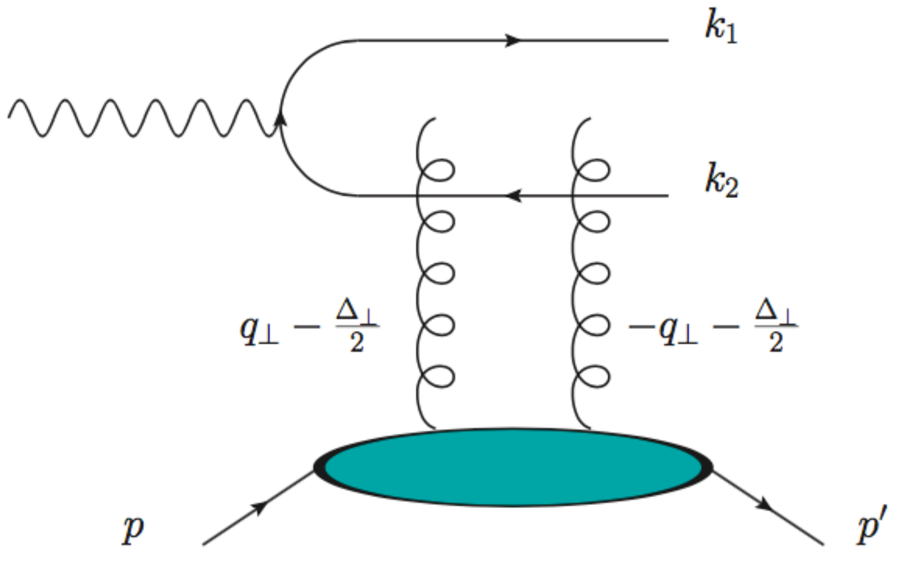

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In the limit x→0 there is only one gluon GTMD for an unpolarized proton (at leading twist)

D.B., van Daal, Mulders, Petreska, 2018

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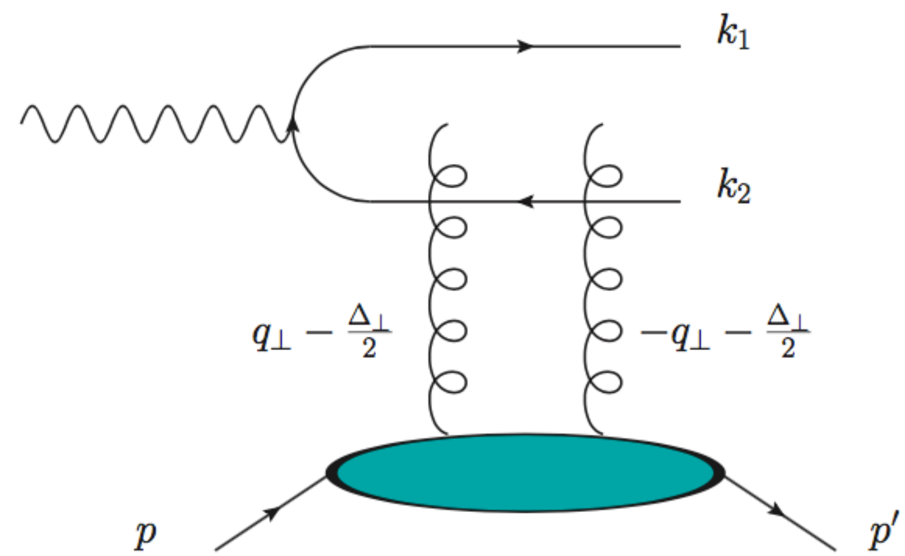

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D.B., van Daal, Mulders, Petreska, 2018

Part of it is the "elliptic" gluon GTMD $\propto \cos 2\phi_{\boldsymbol{k}\boldsymbol{\Delta}}$

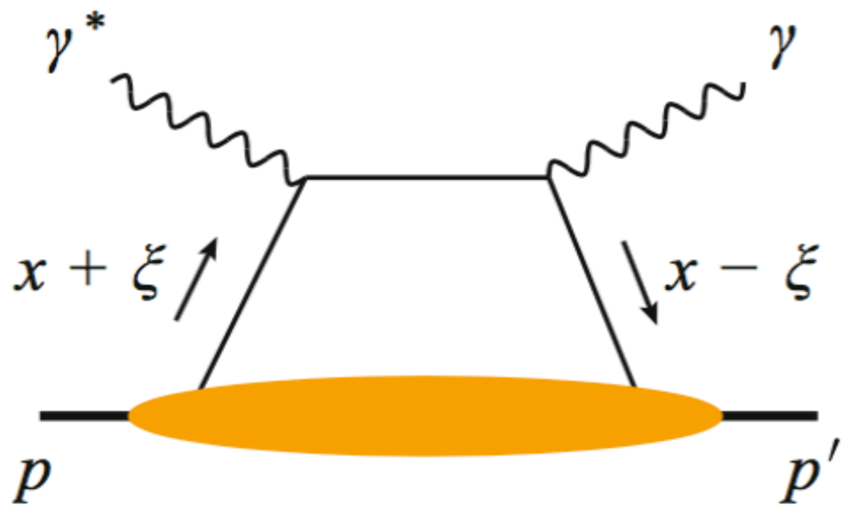
Hatta, Xiao, Yuan, 2016; J. Zhou, 2016

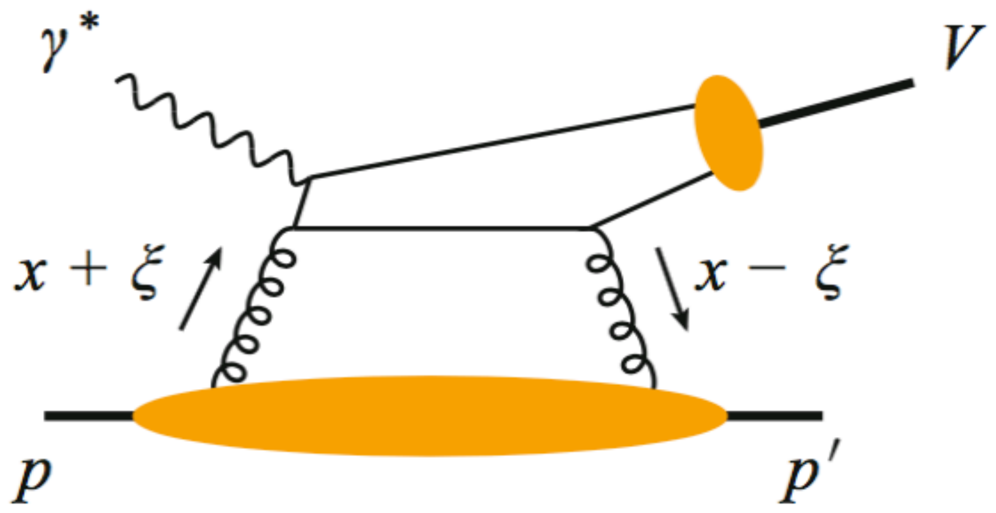
Small-x description of DVCS requires inclusion of the elliptic Wigner function

At small x it contributes to the helicity flip or transversity gluon GPD E_T

Hatta, Xiao, Yuan, 2017

GDPs

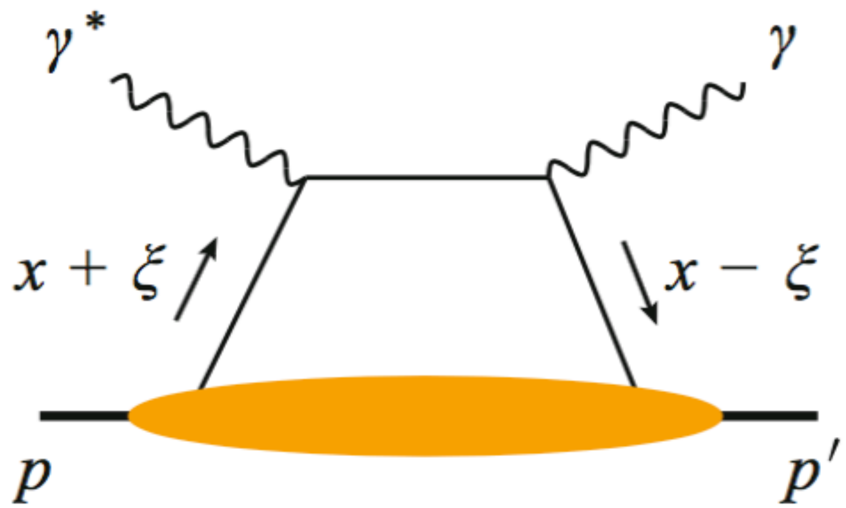


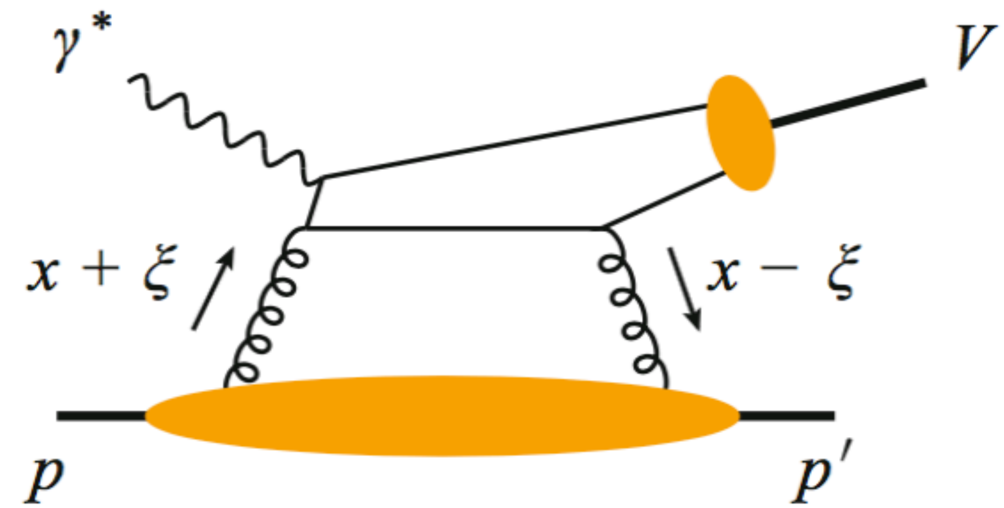


At EIC quark GPDs will be extracted in order to study quark OAM

$$J^q = \frac{1}{2}\int \mathrm{d}x\, x\, [H^q(x,\xi,t=0) + E^q(x,\xi,t=0)]$$

GDPs





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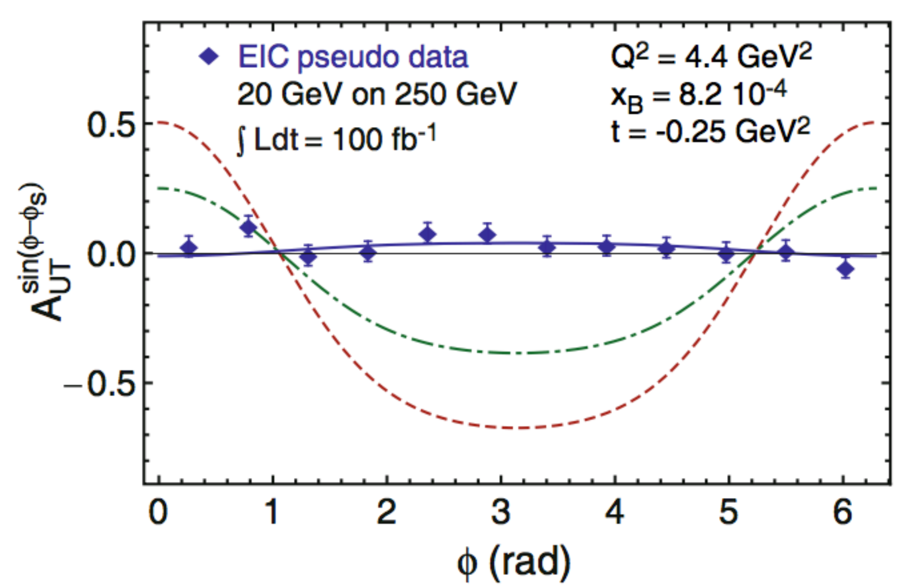
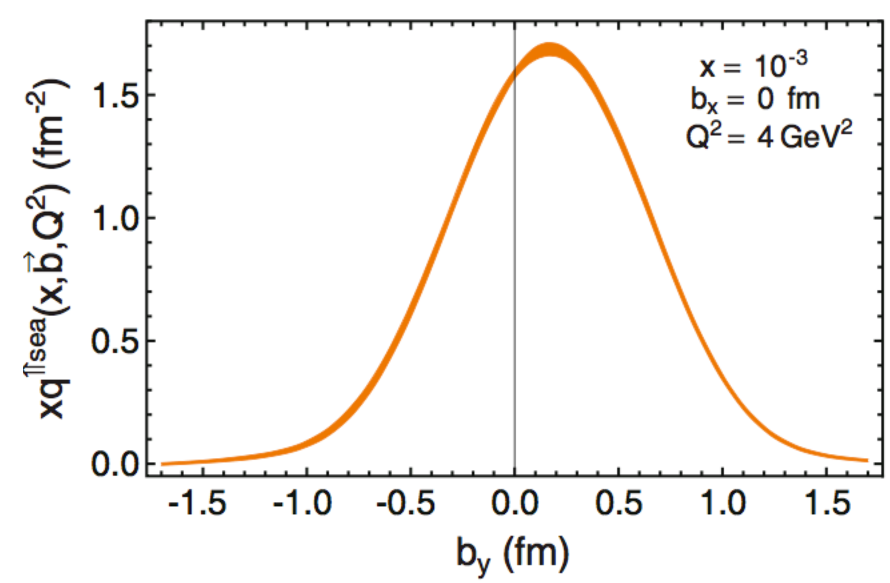
Sivers-like distortions ($b_T \times S_T$) and transversity GPDs can also be studied via transverse spin asymmetries





See Boer et al., arXiv:1108.1713; Accardi *et al.*, Understanding the glue that binds us all, EPJA (2016)

Conclusions

Conclusions

- Spin physics program at EIC is extremely rich: electroweak structure functions, numerous quark and gluon TMDs, GTMDs and GPDs
- Polarized deuterons and neutrons offer further opportunities
- Many possible final states allow to probe particular spin effects:
    - Heavy quarks (open and bound) could prove very useful analyzers of gluon TMDs but also of color-octet NRQCD long distance matrix elements
    - Λs and di-hadrons: polarization dependent fragmentation functions
- Lots of interplay & synergy with pp (polarized & unpolarized) and e^+e^- collisions
- Many more options not mentioned: higher twist and nuclear effects, large x, …
- EIC is essential for small-x and for high-Q^2 spin structure studies

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I can hardly wait!

Back-up slides

Sign change relation for **gluon** Sivers TMD

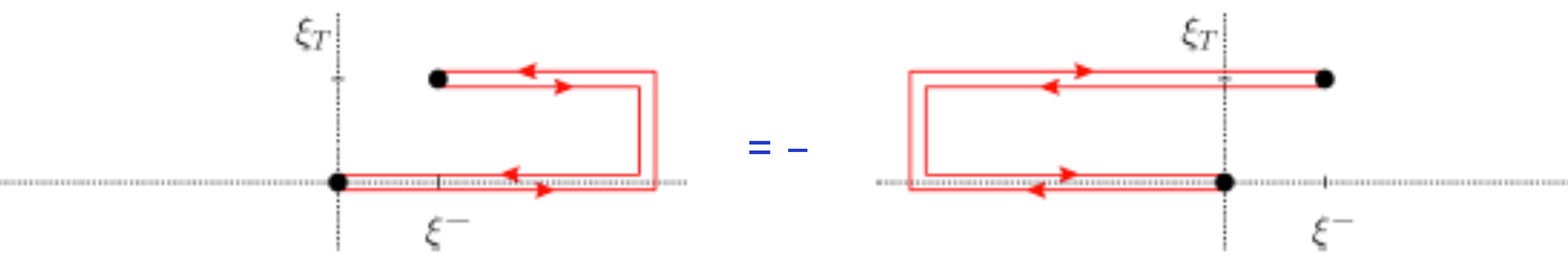
$e\,p^{\uparrow} \to e'\,Q\bar{Q}\,X$ $\gamma^*\,g \to Q\bar{Q}$ probes [+,+]

$p^{\uparrow}\,p \to \gamma\,\gamma\,X$

Qiu, Schlegel, Vogelsang, 2011

In the kinematic regime where pair rapidity is central, one effectively selects the subprocess:

$g\,g \to \gamma\,\gamma$ probes [−,−]



$$f_{1T}^{\perp\,g\,[e\,p^{\uparrow}\to e'\,Q\,\overline{Q}\,X]}(x,p_T^2) = -f_{1T}^{\perp\,g\,[p^{\uparrow}\,p\to\gamma\,\gamma\,X]}(x,p_T^2)$$

D.B., Mulders, Pisano, Zhou, 2016

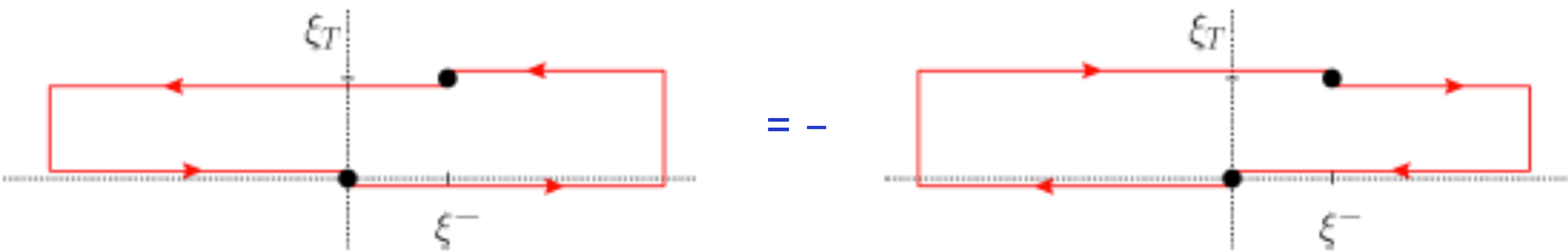
Important role for EIC

f and d type gluon Sivers TMD

$e\,p^{\uparrow} \to e'\,Q\bar{Q}\,X$ $\gamma^{*}\,g \to Q\bar{Q}$ probes [+,+]

$p^{\uparrow}\,p \to \gamma\,\mathrm{jet}\,X$

In the kinematic regime where gluons in the polarized proton dominate, one effectively selects the subprocess: $g\,q \to \gamma\,q$ probes [+,−]



These processes probe 2 distinct, **independent** gluon Sivers functions

Related to antisymmetric (f^{abc}) and symmetric (d^{abc}) color structures

Bomhof, Mulders, 2007; Buffing, Mukherjee, Mulders, 2013

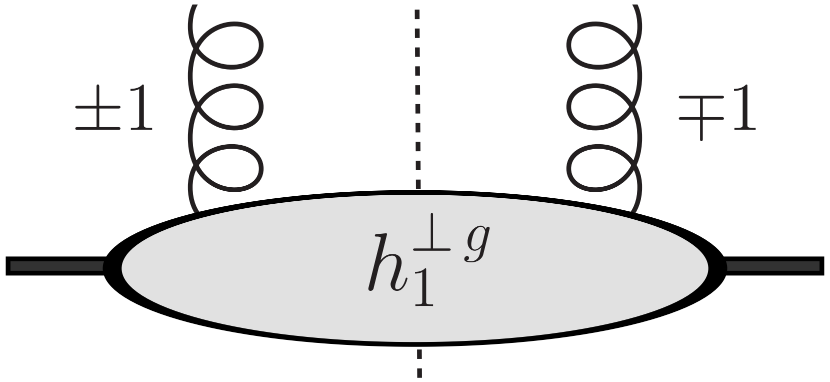
Conclusion: gluon Sivers TMD studies at EIC and at RHIC or AFTER@LHC can be related or complementary, depending on the processes considered

D.B., Lorcé, Pisano & Zhou, arXiv:1504.04332

Gluon polarization inside unpolarized protons

Linearly polarized gluons can exist in **unpolarized** hadrons

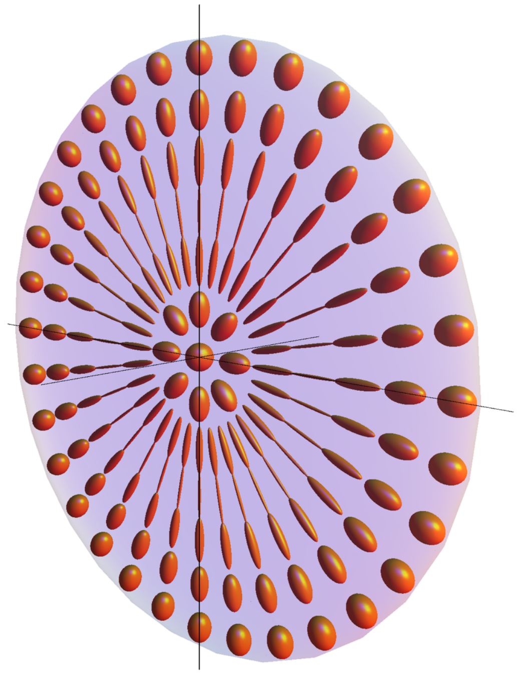
[Mulders, Rodrigues, 2001]



an interference between ±1 helicity gluon states

It requires nonzero transverse momentum: TMD

For $h_1^{\perp\, g} > 0$ gluons prefer to be polarized along k_T, with a *cos* 2ϕ distribution of linear polarization around it, where $\phi = \angle(k_T, \varepsilon_T)$



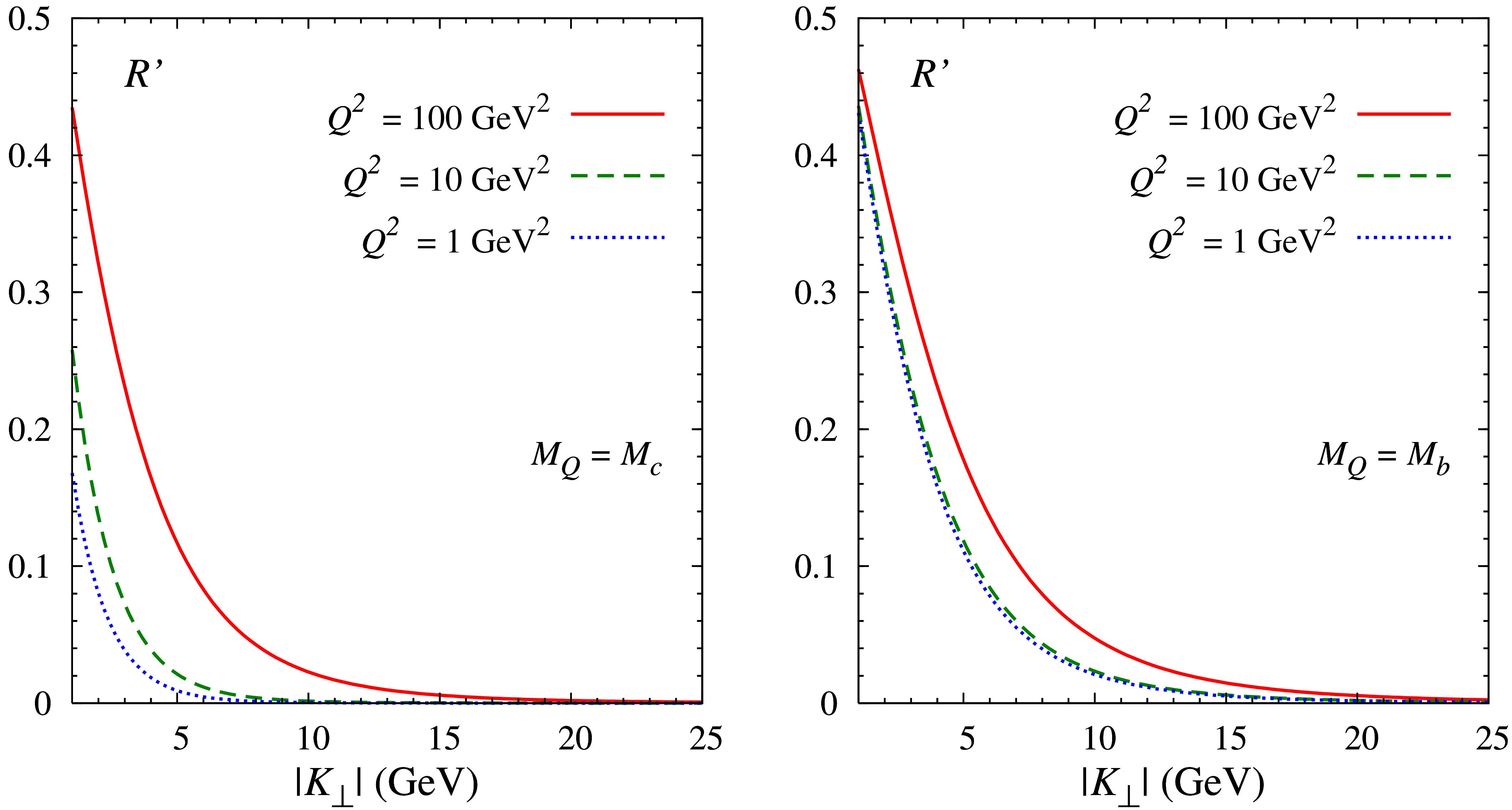
This TMD is k_T-even, chiral-even and T-even:

$$\Gamma_U^{\mu\nu}(x, \boldsymbol{p}_T) = \frac{x}{2} \left\{ -g_T^{\mu\nu}\, f_1^g(x, \boldsymbol{p}_T^2) + \left(\frac{p_T^\mu p_T^\nu}{M_p^2} + g_T^{\mu\nu} \frac{\boldsymbol{p}_T^2}{2M_p^2} \right) h_1^{\perp\, g}(x, \boldsymbol{p}_T^2) \right\}$$

Maximum asymmetries in heavy quark production

There are also angular asymmetries w.r.t. the lepton scattering plane, which are mostly relevant at smaller $|K_\perp|$

$$ep \to e' Q\bar{Q} X \qquad\qquad R' = \text{bound on } |\langle \cos 2(\phi_\ell - \phi_T)\rangle|$$



[Pisano, D.B., Brodsky, Buffing & Mulders, JHEP 10 (2013) 024]

Polarizing FFs from e^+e^-

ELSEVIER

Nuclear Physics B 504 (1997) 345–380

NUCLEAR PHYSICS B

Asymmetries in polarized hadron production in e^+e^- annihilation up to order $1/Q$

D. Boer [a], R. Jakob [a], P.J. Mulders [a,b]

$$\frac{d\sigma^O(e^+e^- \to hX)}{d\Omega\, dz_h} = \frac{3\alpha^2}{Q^2} \sum_{a,\bar{a}} e_a{}^2 \Big\{ A(y)\, D_1^a(z_h) + C(y)\, D(y)\, |S_{hT}| \sin(\phi_{S_h}) \frac{2M_h}{Q} \frac{D_T^a(z_h)}{z_h} \Big\} \qquad (80)$$

← Λ polarization in $e^+e^- \to \Lambda^\uparrow X$ is twist-3

$$\frac{d\sigma(e^+e^- \to h \text{ jet } X)}{d\Omega\, dz_h\, d^2\boldsymbol{q}_T} = \frac{3\alpha^2}{Q^2} z_h^2 \sum_{a,\bar{a}} e_a{}^2 \Big\{ A(y) \Big[D_1^a(z_h, z_h^2 Q_T^2) + |S_{hT}| \sin(\phi_h - \phi_{S_1}) \frac{Q_T}{M_h} D_{1T}^{\perp a}(z_h, z_h^2 Q_T^2) \Big]$$

← in $e^+e^- \to (\Lambda^\uparrow \text{ jet})\, X$ it is not power suppressed

Λ polarization in e^+e^-

OPAL data $Q=M_Z$

Eur.Phys.J C2 (1998) 49

Transverse polarization compatible with zero at the ~3 percent level

Table 6. Measured transverse polarization of Λ baryons as a function of p_T (the transverse momentum of the Λ measured relative to the event thrust axis). The first error is statistical, the second systematic

p_T (GeV/c)	P_T^Λ (%)
< 0.3	$-1.8 \pm 3.1 \pm 1.0$
$0.3 - 0.6$	$0.4 \pm 1.8 \pm 0.7$
$0.6 - 0.9$	$1.0 \pm 1.9 \pm 0.7$
$0.9 - 1.2$	$0.8 \pm 2.2 \pm 0.6$
$1.2 - 1.5$	$0.0 \pm 2.7 \pm 0.6$
> 1.5	$1.8 \pm 1.6 \pm 0.5$
> 0.3	$0.9 \pm 0.9 \pm 0.3$
> 0.6	$1.1 \pm 1.0 \pm 0.4$

This measurement is closer to $e^+e^- \to (\Lambda^\uparrow \text{ jet})\, X$ than to $e^+e^- \to \Lambda^\uparrow X$

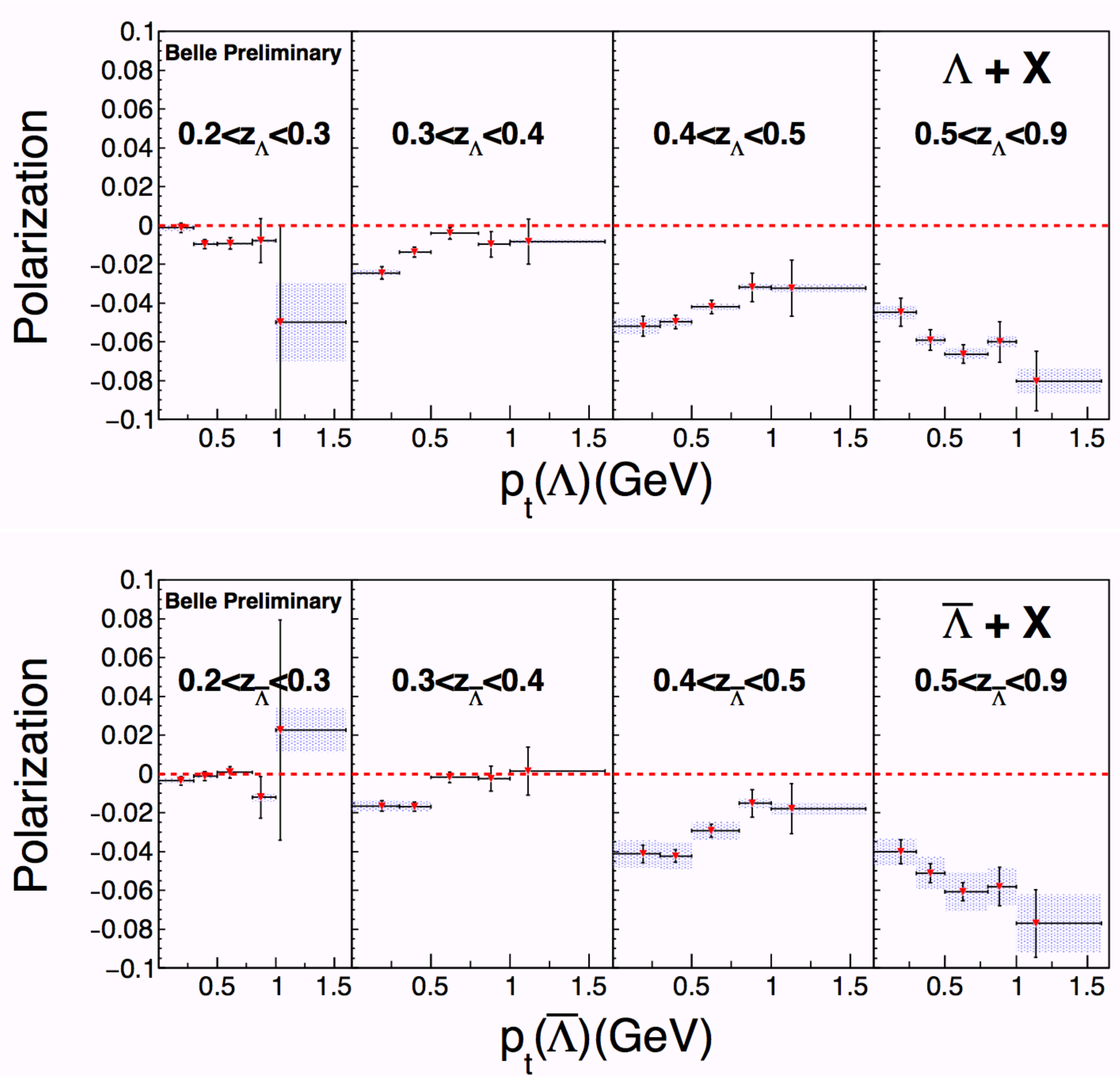
Twist-3 description applies to collinear factorization for p_T integrated case

Schlegel at Transversity 2018 (in collab with Gamberg, Kang, Pitonyak & Yoshida)

TMD evolution of observables with a single k_T-odd function is approx $1/\sqrt{Q}$

Belle polarization is then expected to be $\sqrt{(91.2/10.6)} \approx 3$ times larger than OPAL data (for z integrated)

Λ polarization in e^+e^-



p_T w.r.t. thrust axis

BELLE Collaboration
arXiv:1611.06648

Again: this is closer to $e^+e^- \to (\Lambda^\uparrow \text{ jet})\, X$ than to $e^+e^- \to \Lambda^\uparrow X$

As expected anti-Λ is similar to Λ, unlike the pp case