

Opportunities for spin physics at EIC

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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, Λ_s)
- GTMDs & GPDs

1-D Spin Structure

Classic DIS objectives: polarized structure functions

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

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

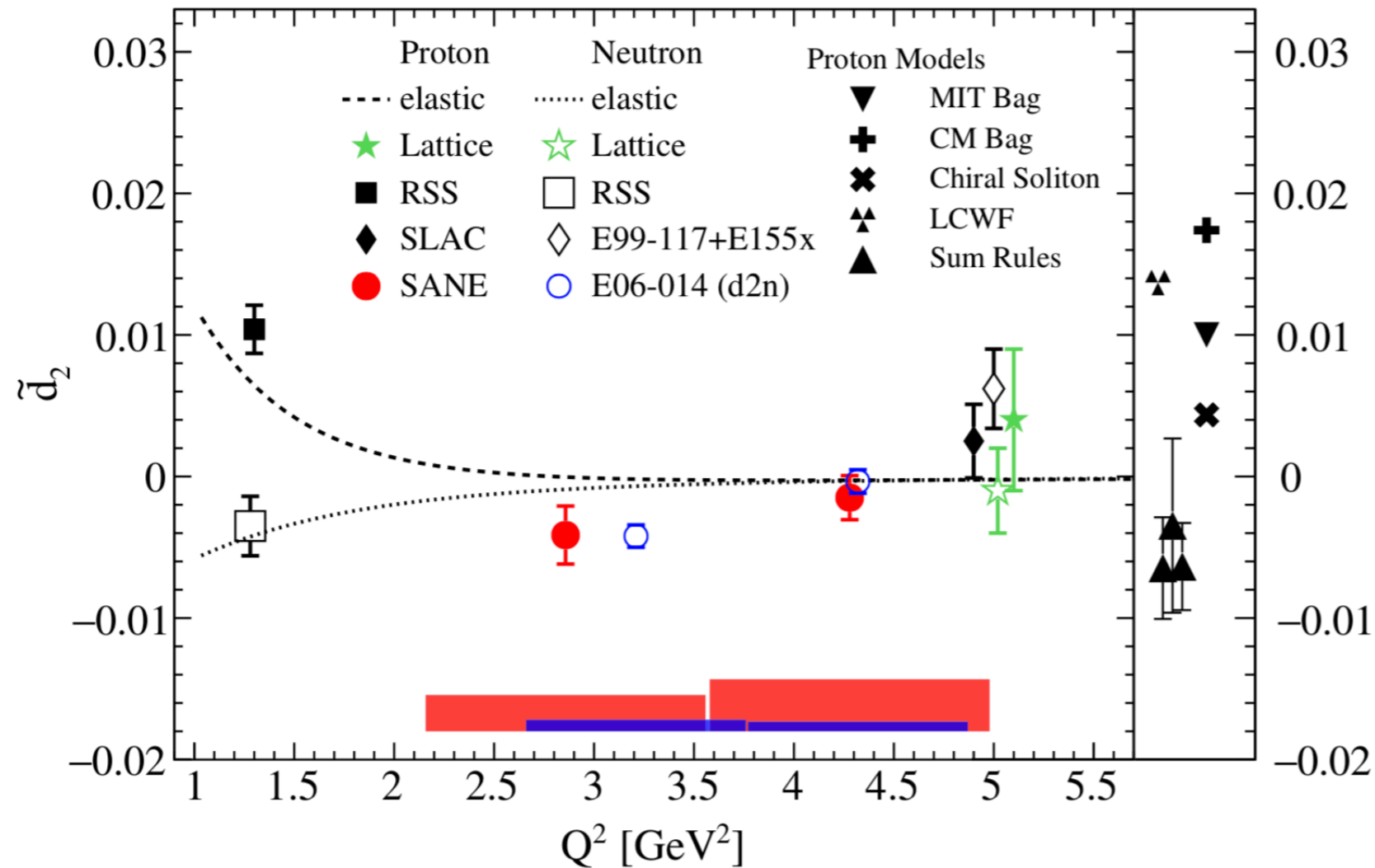
$$g_1 \rightarrow \Delta q, \Delta g \quad \text{spin sum rule} \quad \Delta\Sigma = \Delta u + \Delta d + \Delta s$$

$$g_2 \rightarrow \int_0^1 dx g_2(x, Q^2) = 0 \quad \text{Burkhardt-Cottingham sum rule}$$

$$g_2 \rightarrow d_2 = 3 \int_0^1 dx x^2 g_2(x, Q^2) \Big|_{\text{twist-3}} \quad \text{lattice, E155x, ...}$$

$$g_3, g_4, g_5 \quad \text{weak interactions}$$

Classic DIS objectives: polarized structure functions



$$\tilde{d}_2 = \int_0^1 x^2 [3g_T(x) - g_1(x)] dx$$

SANE Collab (Hall-C JLab)
 PRL 122 (2019) 022002

$$d_2 = 3 \int_0^1 dx x^2 g_2(x, Q^2) \Big|_{\text{twist-3}} = \int_0^1 dx x^2 [3g_2(x, Q^2) + 2g_1(x, Q^2)]$$

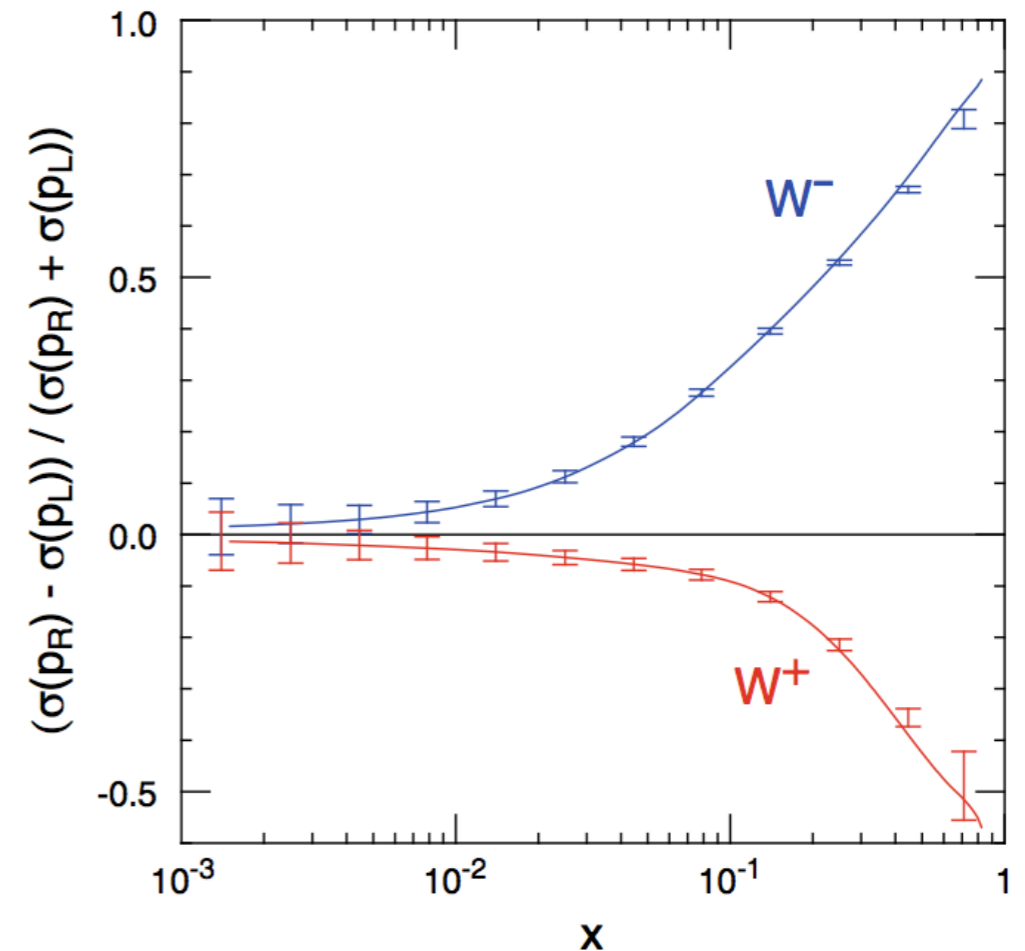
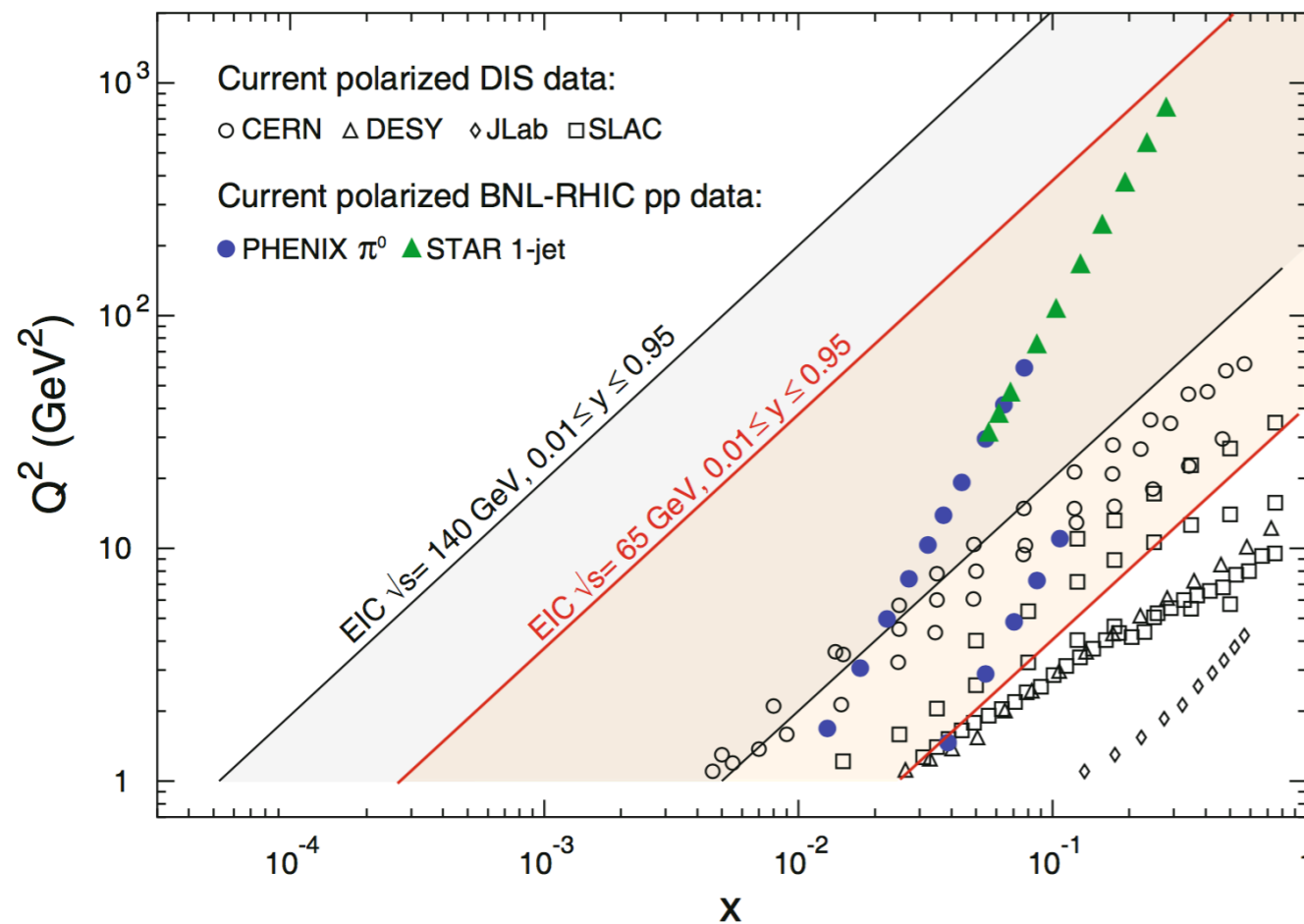
small ± 0.01 : twist-3 not very important in this quantity

polarized Helium-3 \approx polarized neutron

Classic DIS objectives: polarized structure functions

g_3, g_4, g_5

weak interactions, hence high Q^2 and high x



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

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

Parity violating SSA

see e.g. Zhao, Deshpande, Huang, Kumar & Riordan, EPJ A 53 (2017) 55

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

Dicus relation, analogous to Callan-Gross (PM)

g_3

Similar to g_2 part twist 2 and twist 3

Polarized deuteron

$$W_{\mu\nu} = -F_1 g_{\mu\nu} + F_2 \frac{p_\mu p_\nu}{\nu} - b_1 r_{\mu\nu} + \frac{1}{6} b_2 (s_{\mu\nu} + t_{\mu\nu} + u_{\mu\nu}) + \frac{1}{2} b_3 (s_{\mu\nu} - u_{\mu\nu}) \\ + \frac{1}{2} b_4 (s_{\mu\nu} - t_{\mu\nu}) + i \frac{g_1}{\nu} \epsilon_{\mu\nu\lambda\sigma} q^\lambda s^\sigma + i \frac{g_2}{\nu^2} \epsilon_{\mu\nu\lambda\sigma} q^\lambda (p \cdot q s^\sigma - s \cdot q p^\sigma),$$

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

b_1, b_2 Leading twist, longitudinal tensor polarization

$b_2 = 2xb_1$ 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)

$$b_1(x) = \frac{1}{2} (q^0(x) - q^1(x)) \quad q^0(x) = (q_{\uparrow}^0 + q_{\downarrow}^0) = 2q_{\uparrow}^0 \\ q^1(x) = (q_{\uparrow}^1 + q_{\downarrow}^1) = (q_{\uparrow}^1 + q_{\uparrow}^{-1})$$

$$S_{LL} = - \frac{\text{Diagram 1} + \text{Diagram 2}}{3} + \frac{2}{3} \text{Diagram 3}$$

S_{LL} called “alignment”

Polarized deuteron

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



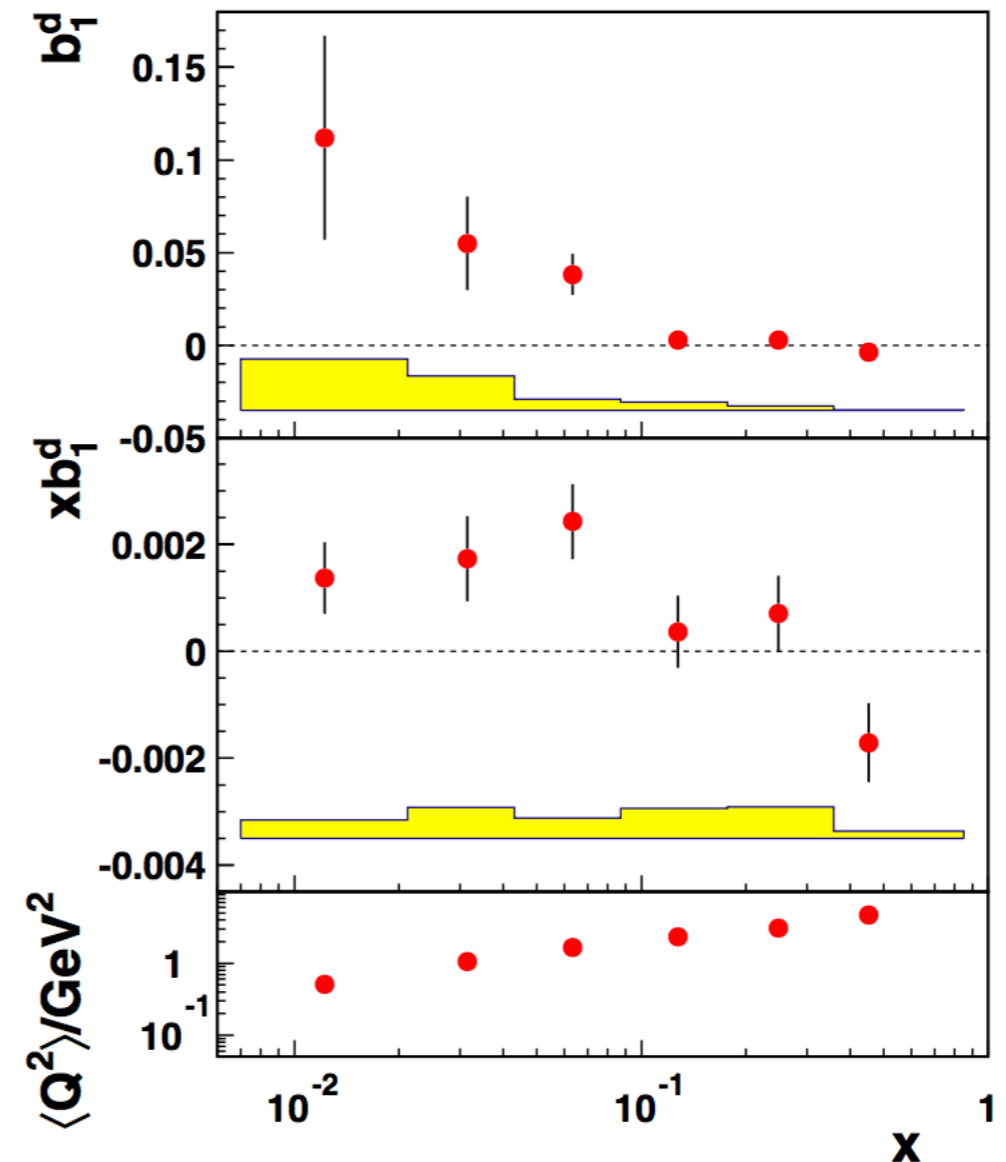
Also: eD → epX spectator tagging
 to access polarized neutron structure

Cosyn, Sargsian, Weiss, ..., 2011-...

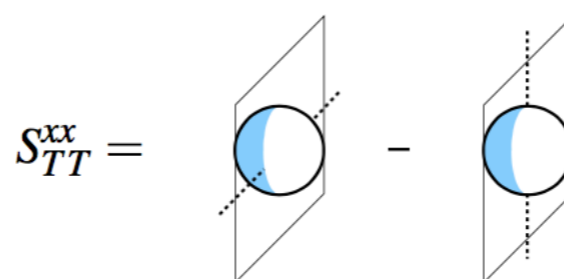
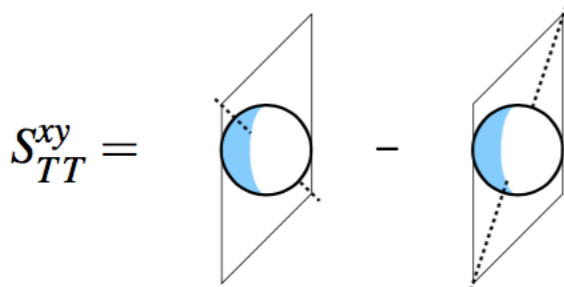
For gluons there is also an S_{TT} contribution
 leading twist, transverse tensor polarization

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

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



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



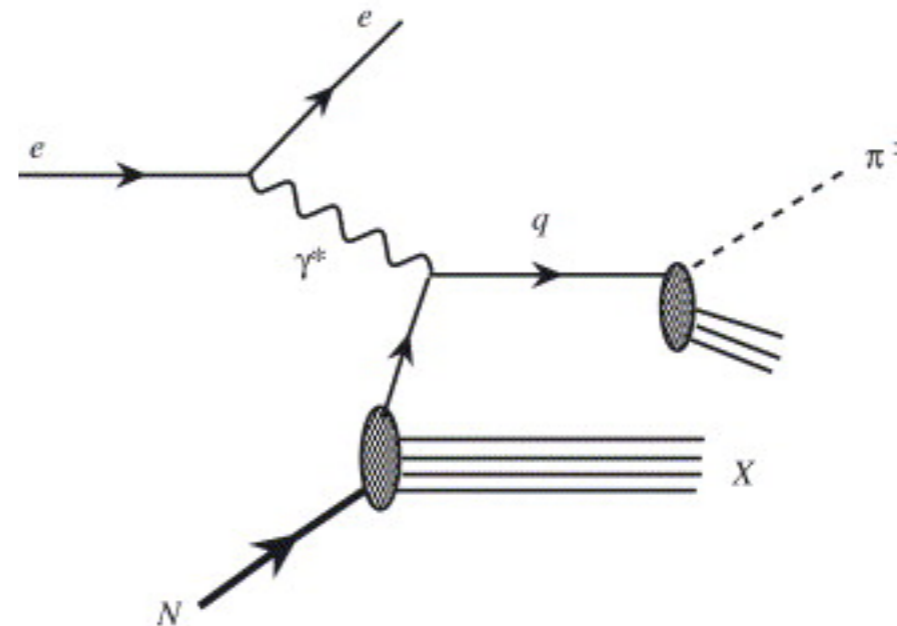
not yet measured

3-D Spin Structure

Typical TMD processes

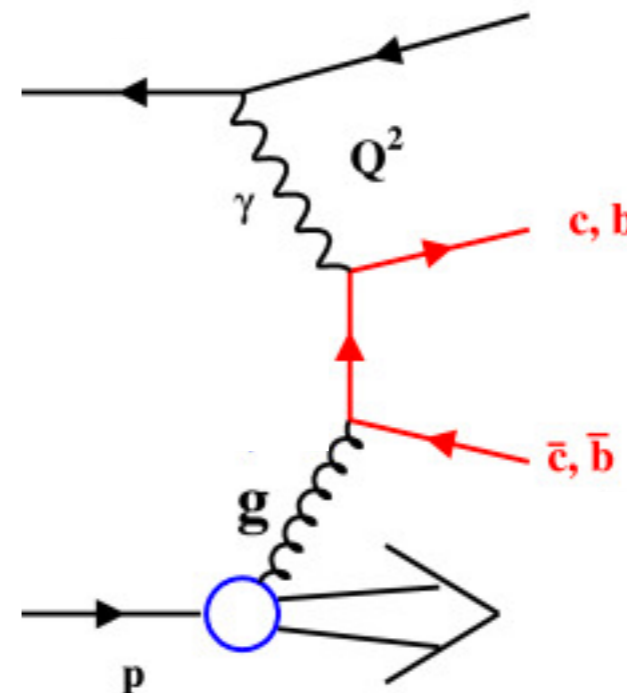
Semi-inclusive DIS is a process sensitive to the transverse momentum of quarks

$$e p \rightarrow e' h X$$



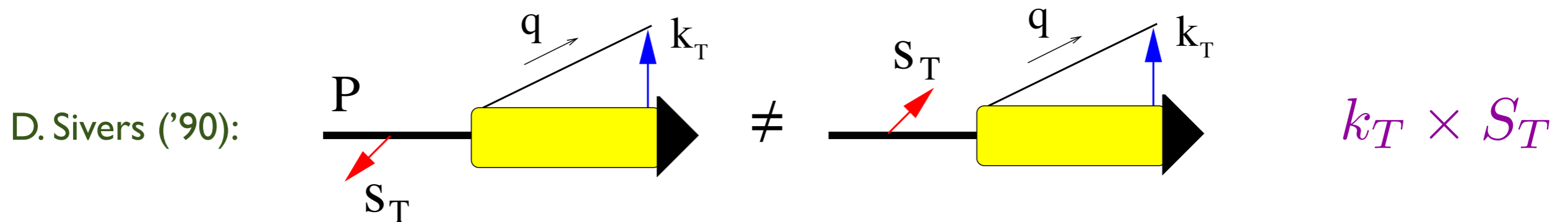
D-meson pair production is sensitive to transverse momentum of gluons

$$e p \rightarrow e' D \bar{D} X$$



Sivers effect

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



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

[Boer & Mulders, '98]

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

$$\frac{d\sigma(e p^\uparrow \rightarrow e' \text{ jet } X)}{d^2 \mathbf{q}_T} \propto |\mathbf{S}_T| \sin(\phi_{\text{jet}}^e - \phi_S^e) \frac{Q_T}{M} f_{1T}^\perp(x, Q_T^2) \quad Q_T^2 = |\mathbf{P}_\perp^{\text{jet}}|^2$$

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

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

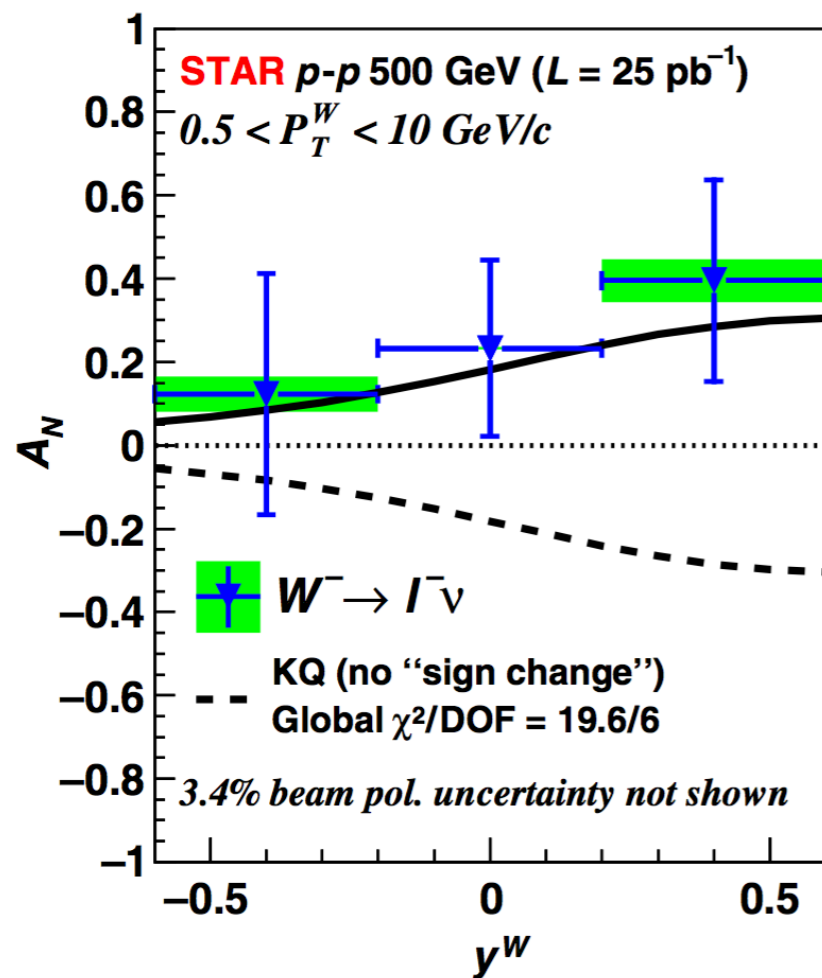
$$f_{1T}^{\perp q[\text{SIDIS}]}(x, k_T^2) = -f_{1T}^{\perp q[\text{DY}]}(x, k_T^2) \quad [\text{Collins '02}]$$

Measurements of the Sivers TMD

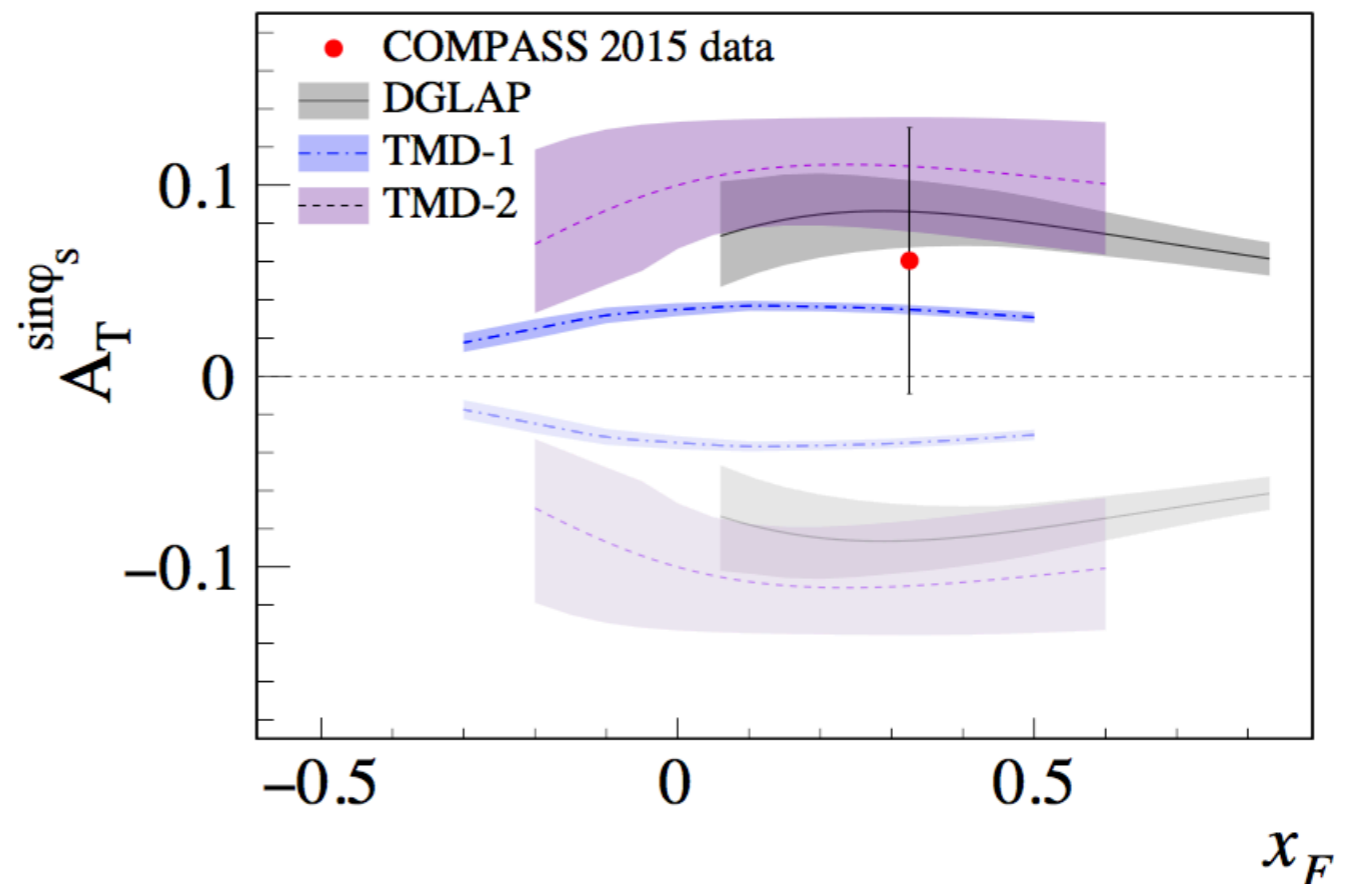
The Sivers effect in SIDIS has been clearly observed by HERMES at DESY (PRL 2009) & COMPASS at CERN (PLB 2010)

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, PRL 2017

Process dependence of Sivers TMDs

A similar sign change relation for gluon Sivers functions holds

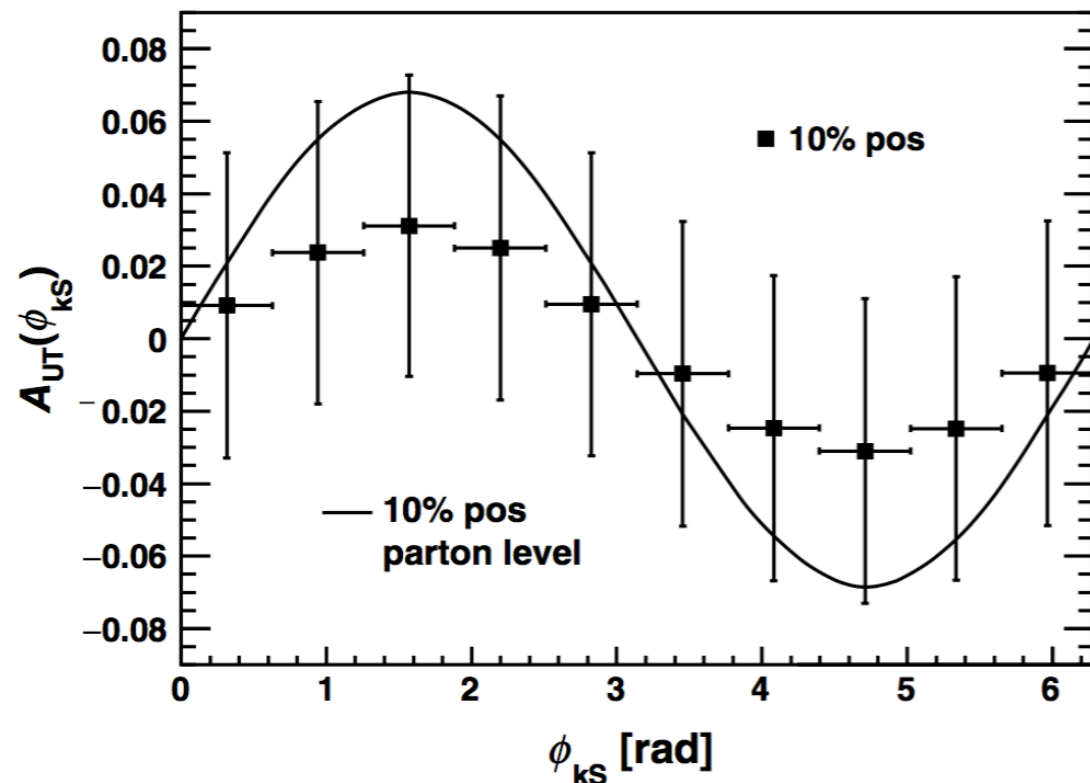
$$f_{1T}^{\perp g} [e p^{\uparrow} \rightarrow e' Q \bar{Q} X] (x, p_T^2) = -f_{1T}^{\perp g} [p^{\uparrow} p \rightarrow \gamma \gamma X] (x, p_T^2)$$

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

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

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

$$e p^{\uparrow} \rightarrow e' Q \bar{Q} X \quad A_N^{\sin(\phi_S - \phi_T)} = \frac{|\mathbf{q}_T|}{M_p} \frac{f_{1T}^{\perp g}(x, \mathbf{q}_T^2)}{f_1^g(x, \mathbf{q}_T^2)} \quad \text{D.B., Pisano, Mulders, J. Zhou, 2016}$$



$$\text{Lint} = 10 \text{ fb}^{-1}$$

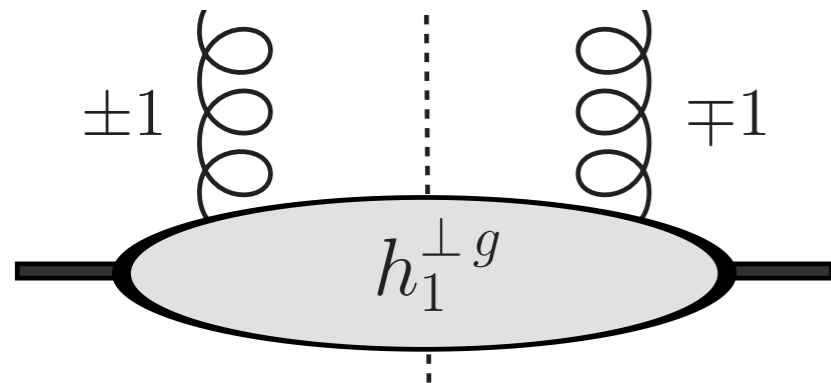
Conclusion: if function is 10% of the positivity bound, then it cannot be discerned within the statistics

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

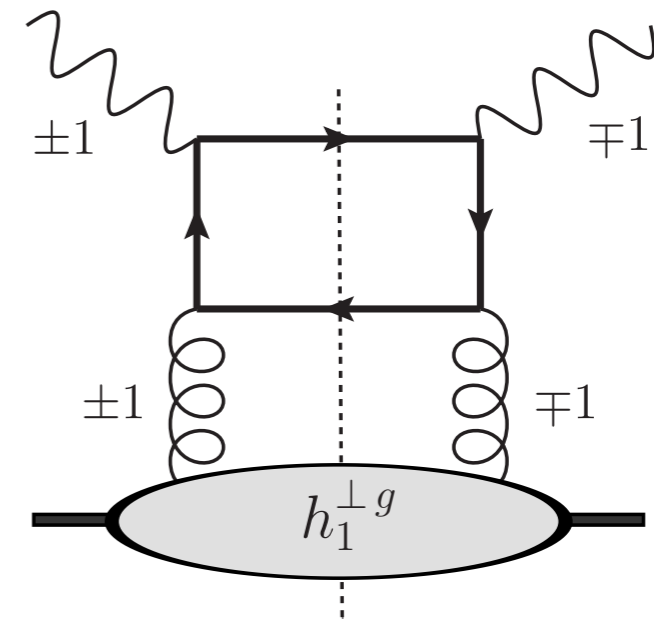
Unpolarized open heavy quark production also offers an interesting opportunity: to probe linearly polarized gluons in *unpolarized* hadrons



an interference between ± 1 helicity gluon states

[Mulders, Rodrigues, 2001]

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



[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 $K_{\perp}^Q \pm K_{\perp}^{\bar{Q}}$

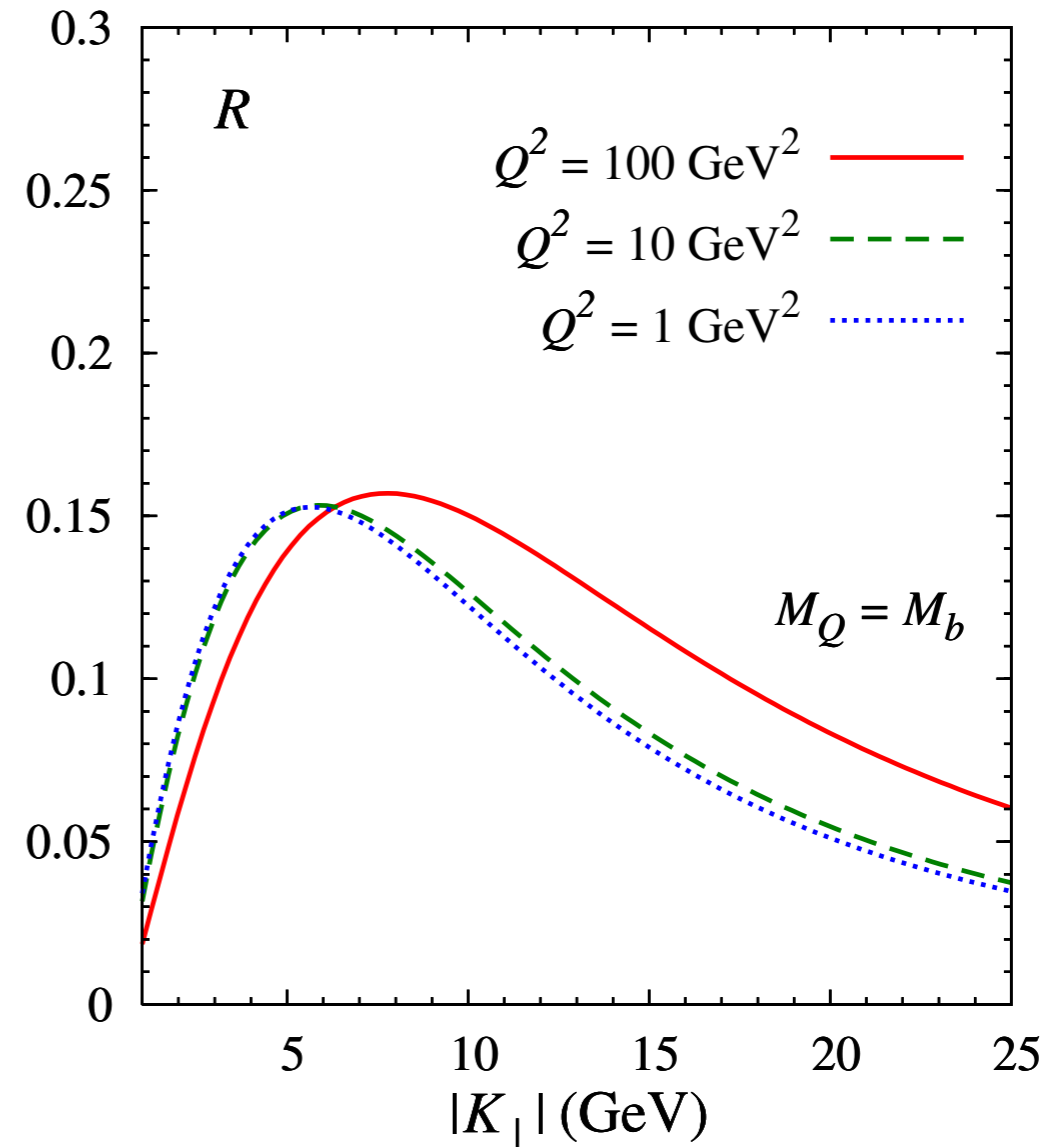
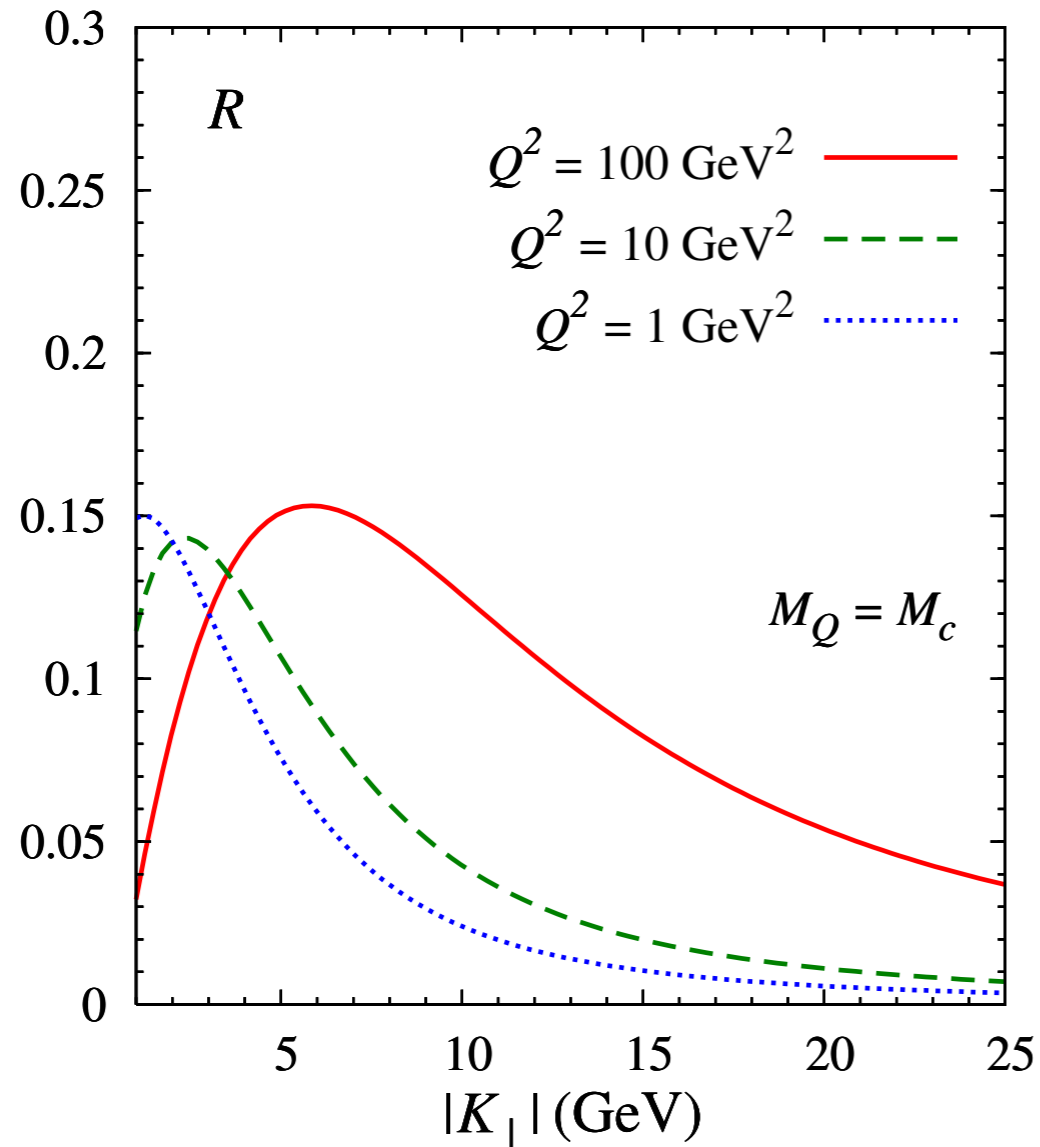
$h_{1\perp g}$ appears by itself, so effects could be significant, especially towards smaller x

It is expected to keep up with the growth of the unpolarized gluons as $x \rightarrow 0$

Maximum asymmetries in heavy quark production

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

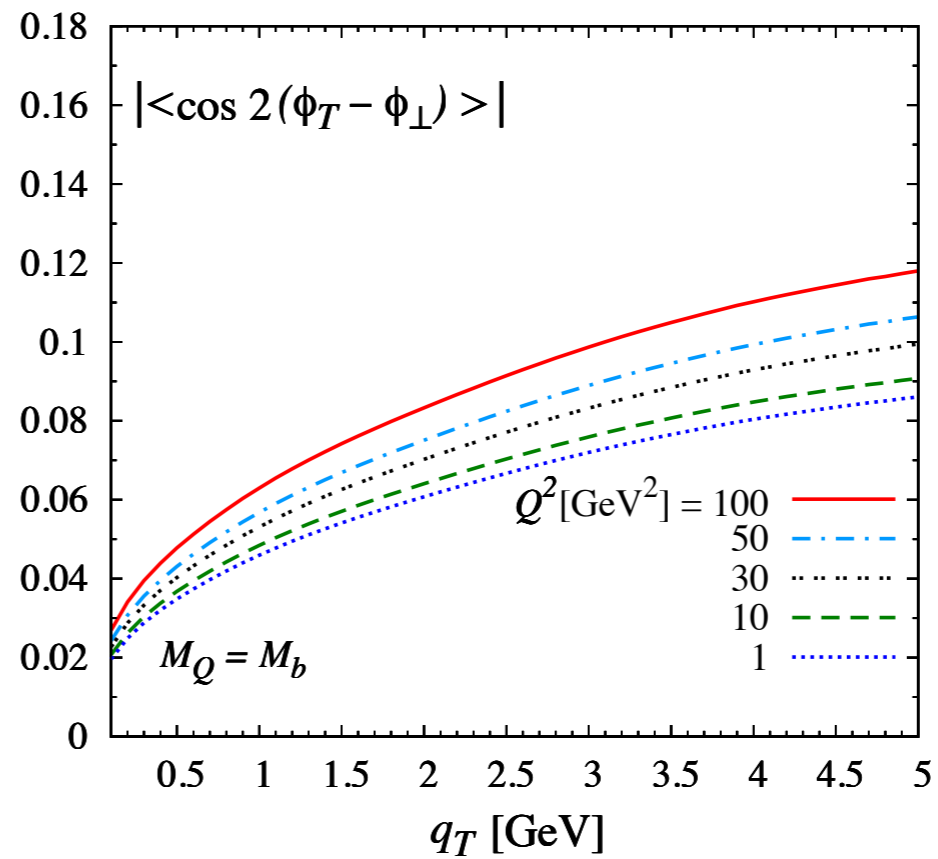
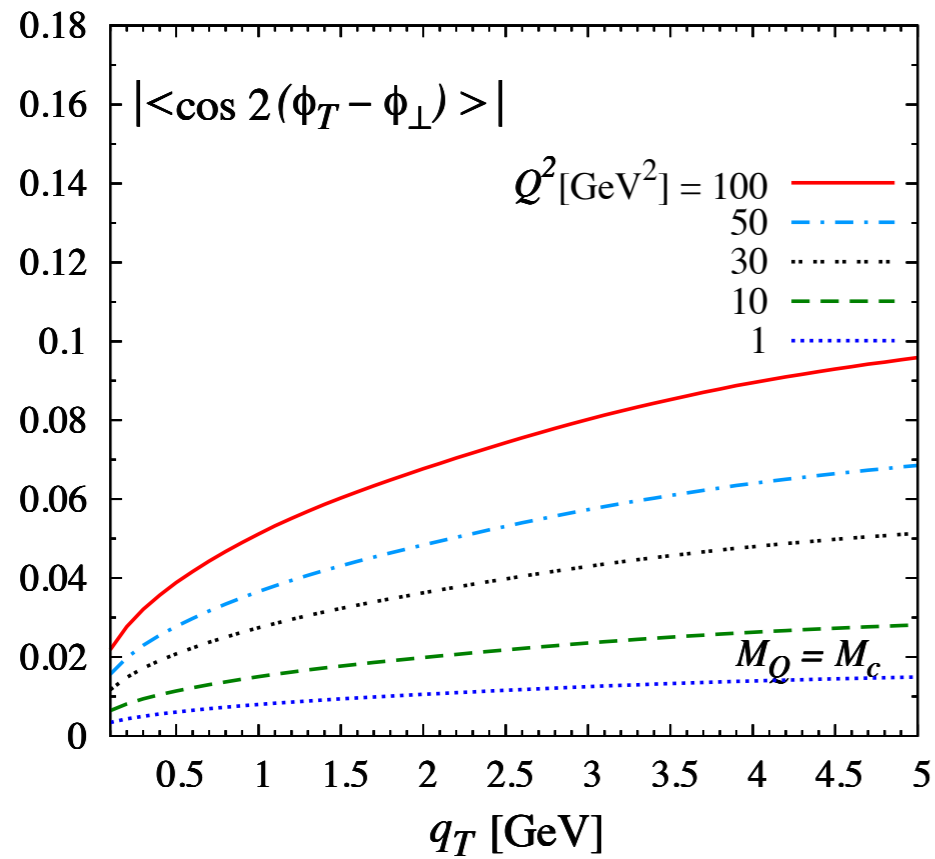
$$R = \text{bound on } |\langle \cos 2(\phi_T - \phi_\perp) \rangle|$$



[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

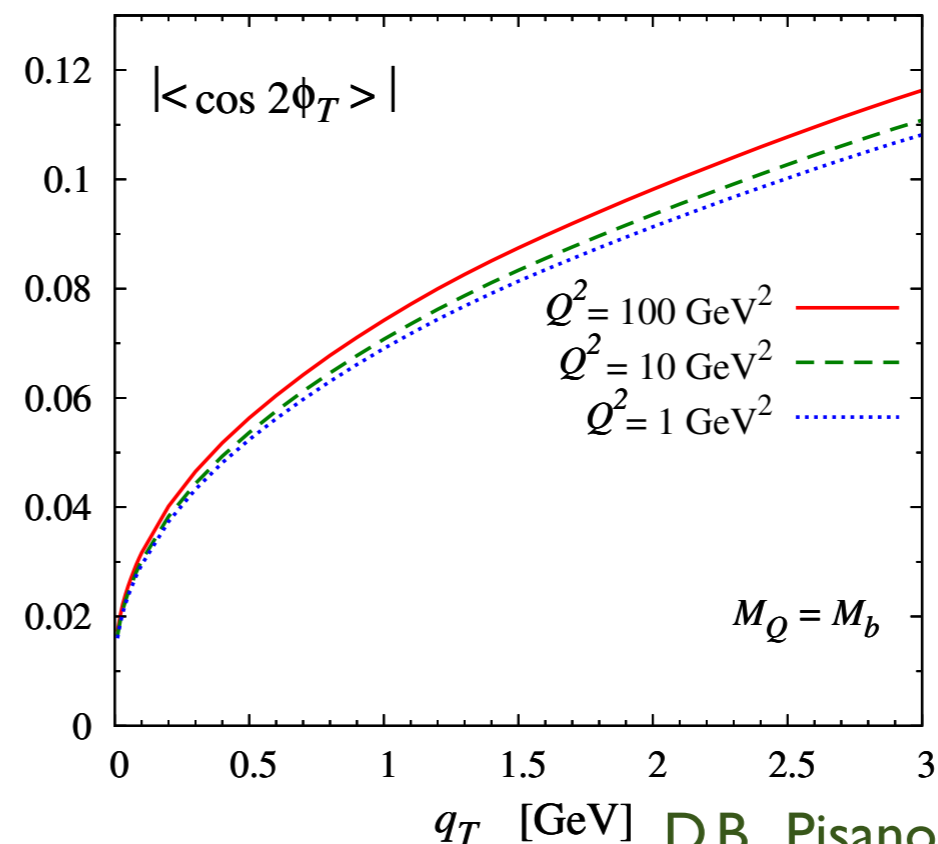
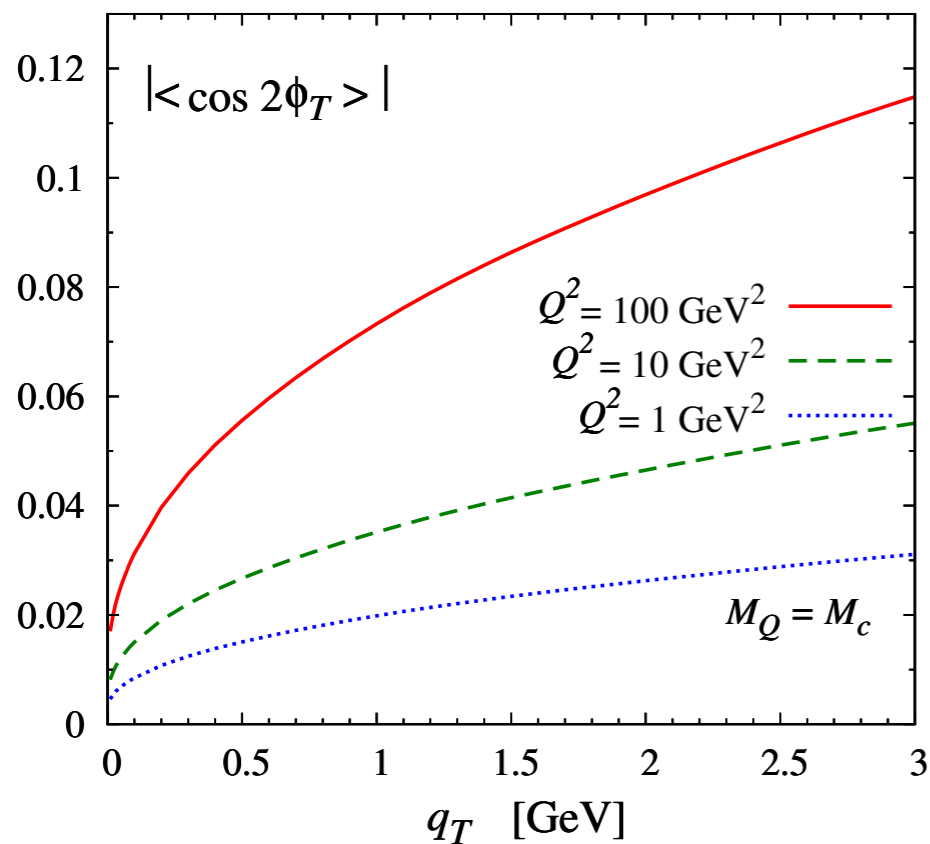


small x model
similar in size

$$|\mathbf{K}_\perp| = 10 \text{ GeV}$$

$$z = 0.5$$

$$y = 0.3$$



$$|\mathbf{K}_\perp| = 6 \text{ GeV}$$

$$z = 0.5$$

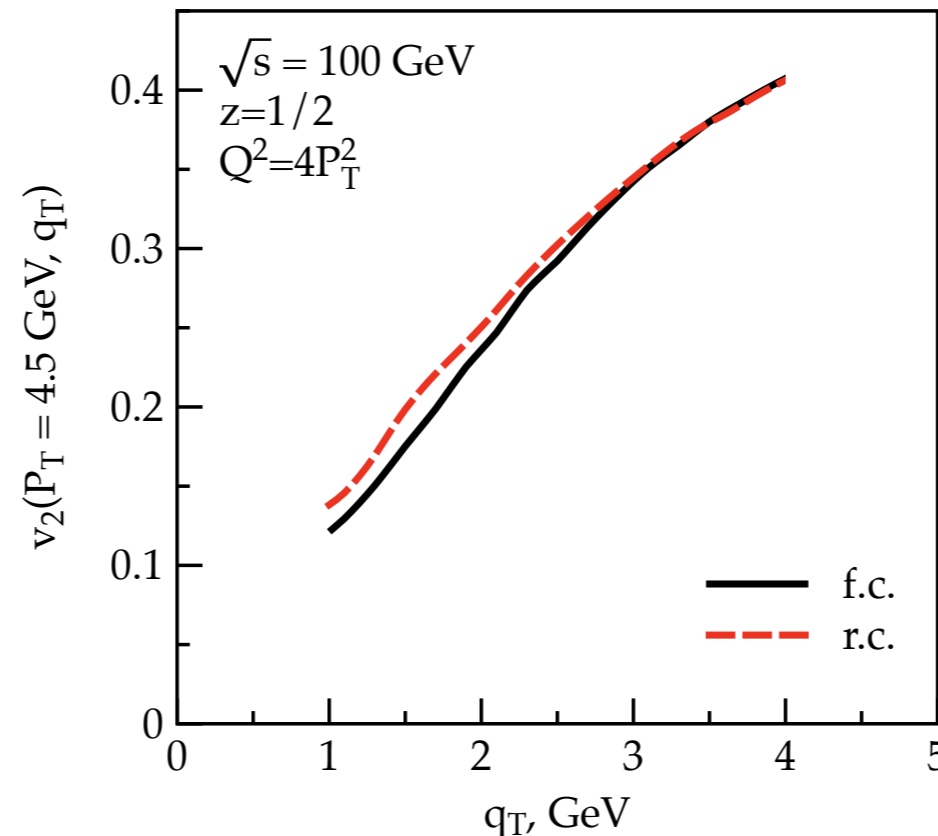
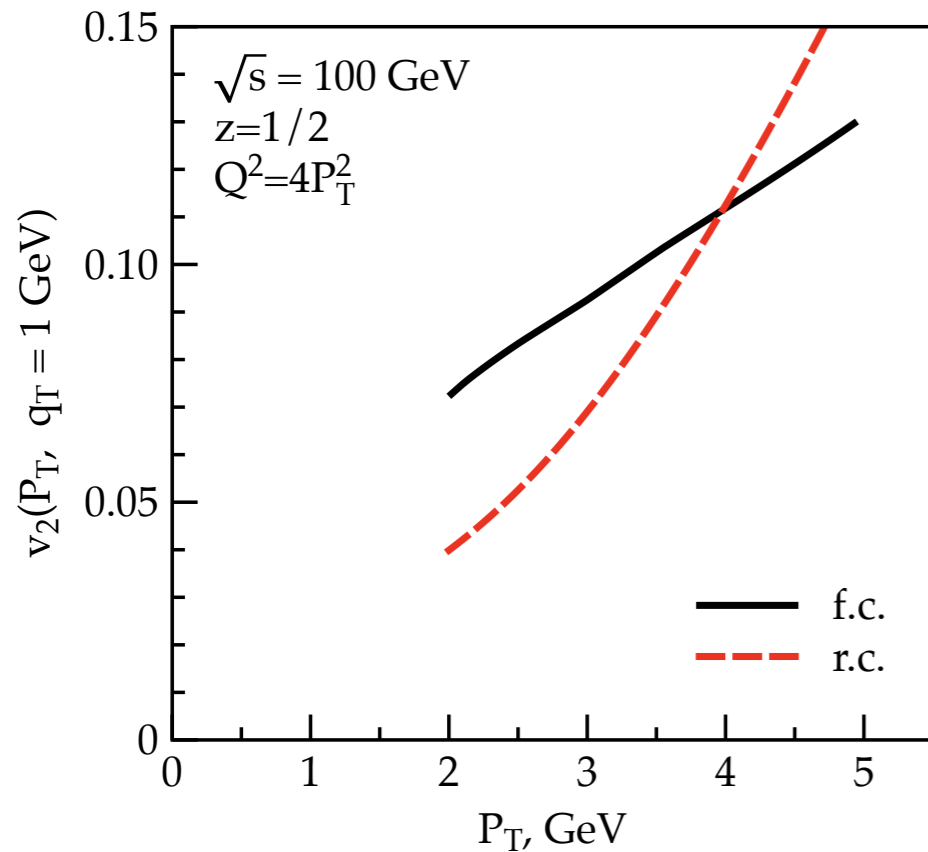
$$y = 0.1$$

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]

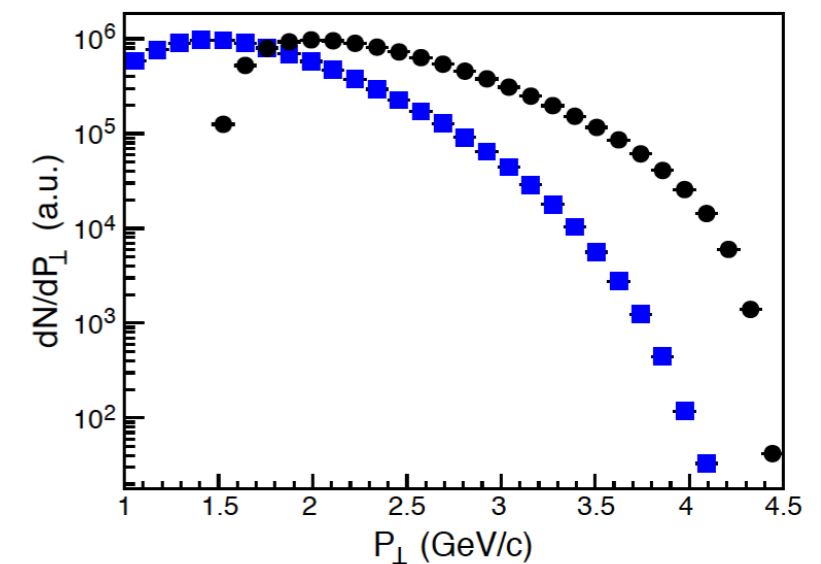
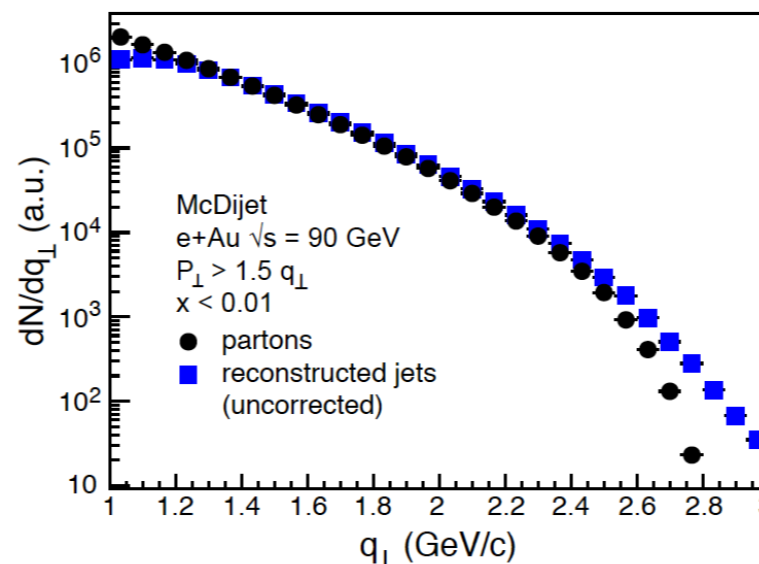
Polarization shows itself through a $\cos 2\phi$ distribution



Large effects are found
Dumitru, Lappi, Skokov, 2015

$\cos 2\phi$ has opposite signs for
L and T γ^* polarization

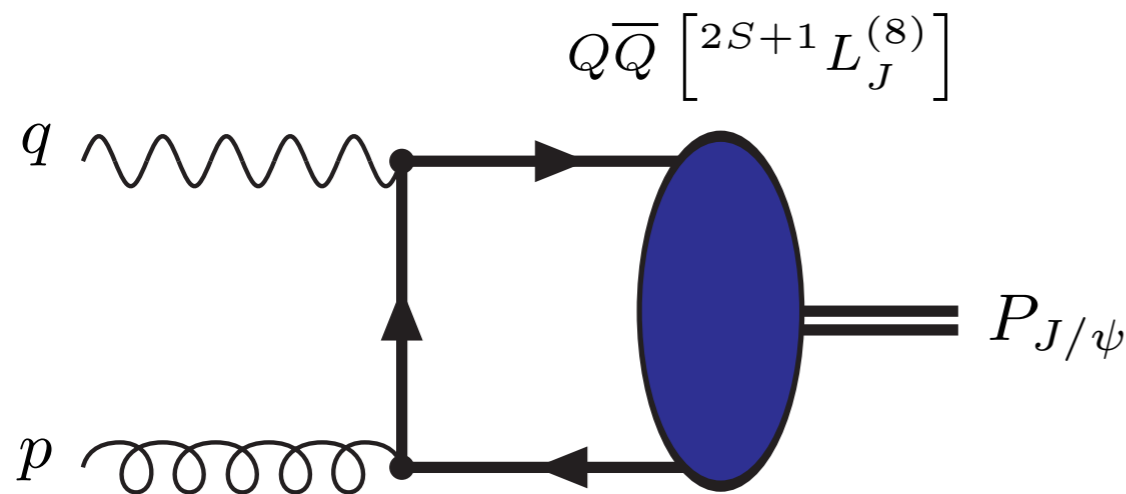
Dumitru, Skokov, Ullrich, 2018



Quarkonia

$e p^\uparrow \rightarrow e' Q X$ with 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

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

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

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

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

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

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

CO NRQCD LDMEs @ EIC

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

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

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

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

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, Taelis, arXiv:1809.02056]

Plus similar (but different) equations for polarized quarkonium production

Fragmentation Functions
as analyzers of spin
distributions

Di-hadron production

Two-hadron FF allows to probe **quark transversity**, as alternative to Collins FF

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

Similarly, the (k_T -dependent) “handedness” FF G_1^\perp allows to probe g_1

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

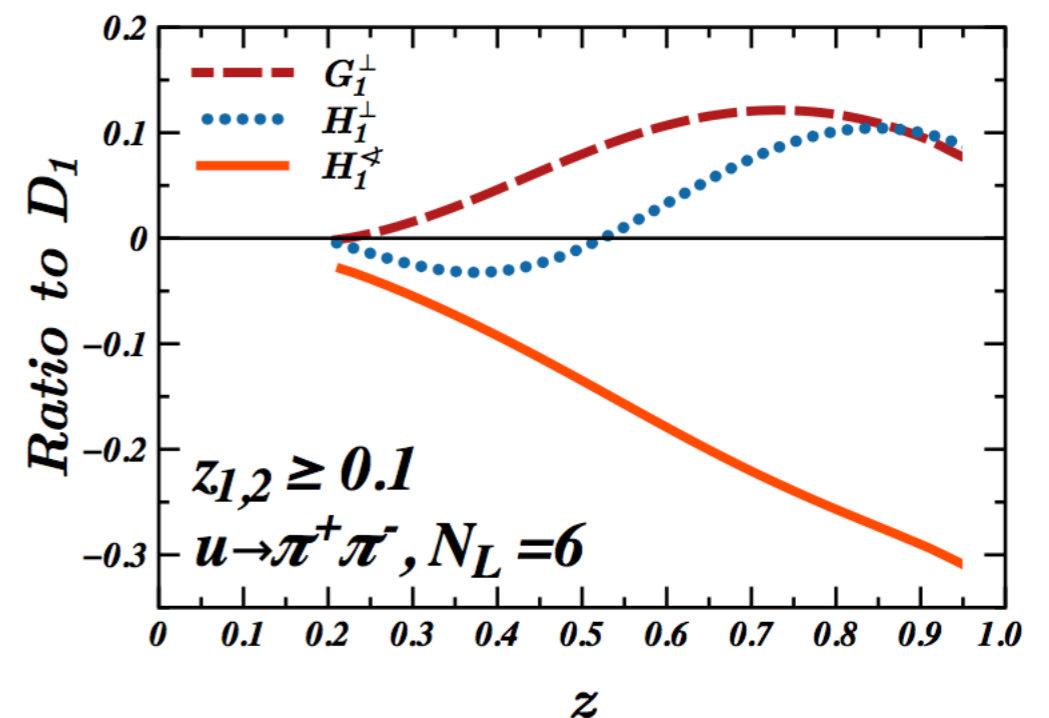
Bianconi, Boffi, Jakob, Radici, 2000

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

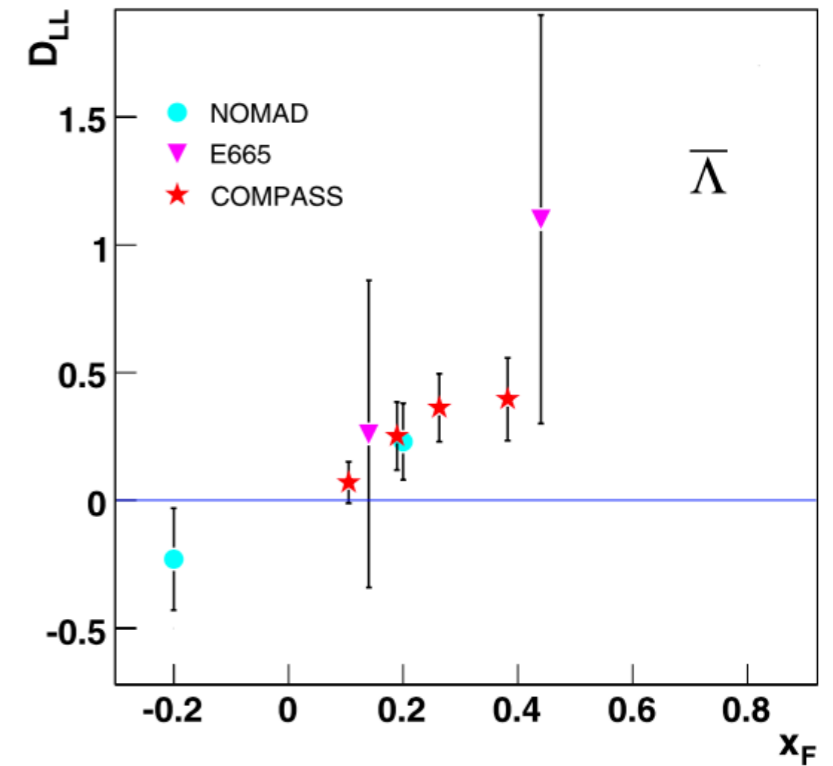
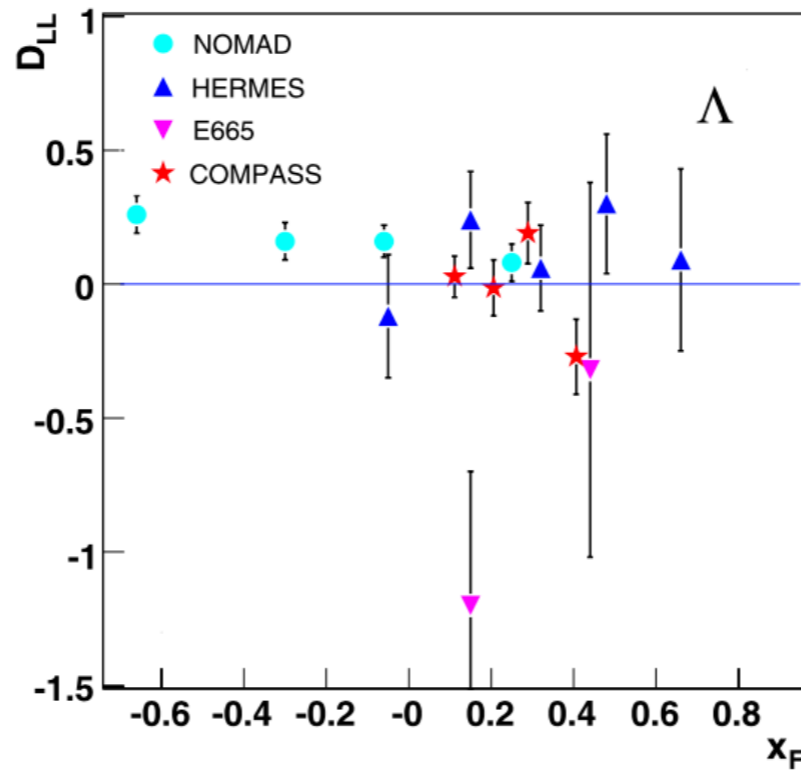
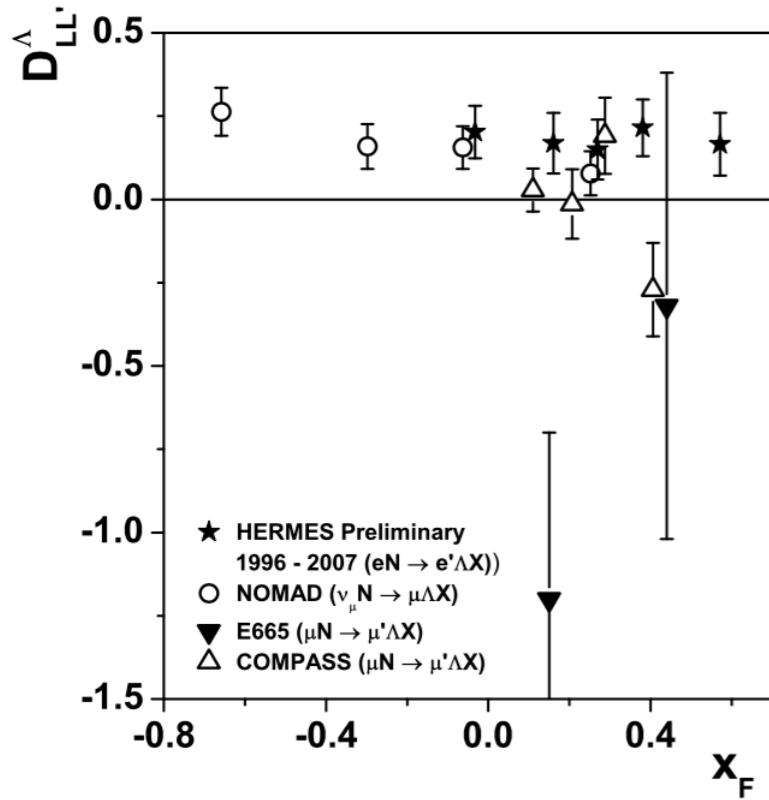
Model calculation indicates $G_1^\perp \approx D_1/10$

Matevosyan, arXiv:1807.11485



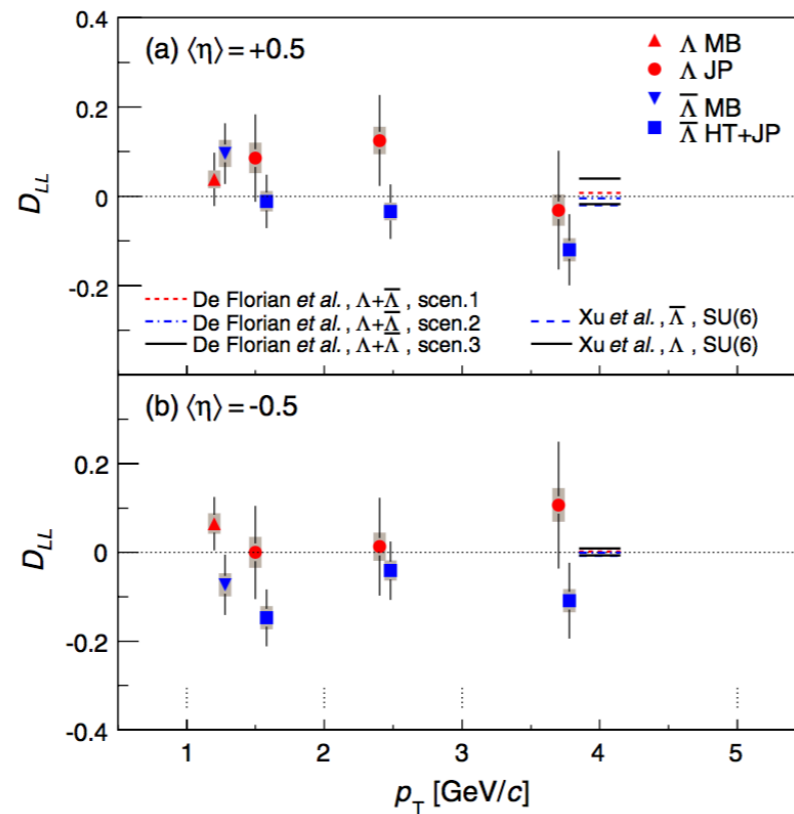
Lambda production

Polarized Λ s can be used to probe g_1 via polarization transfer D_{LL}



HERMES@SPIN2010

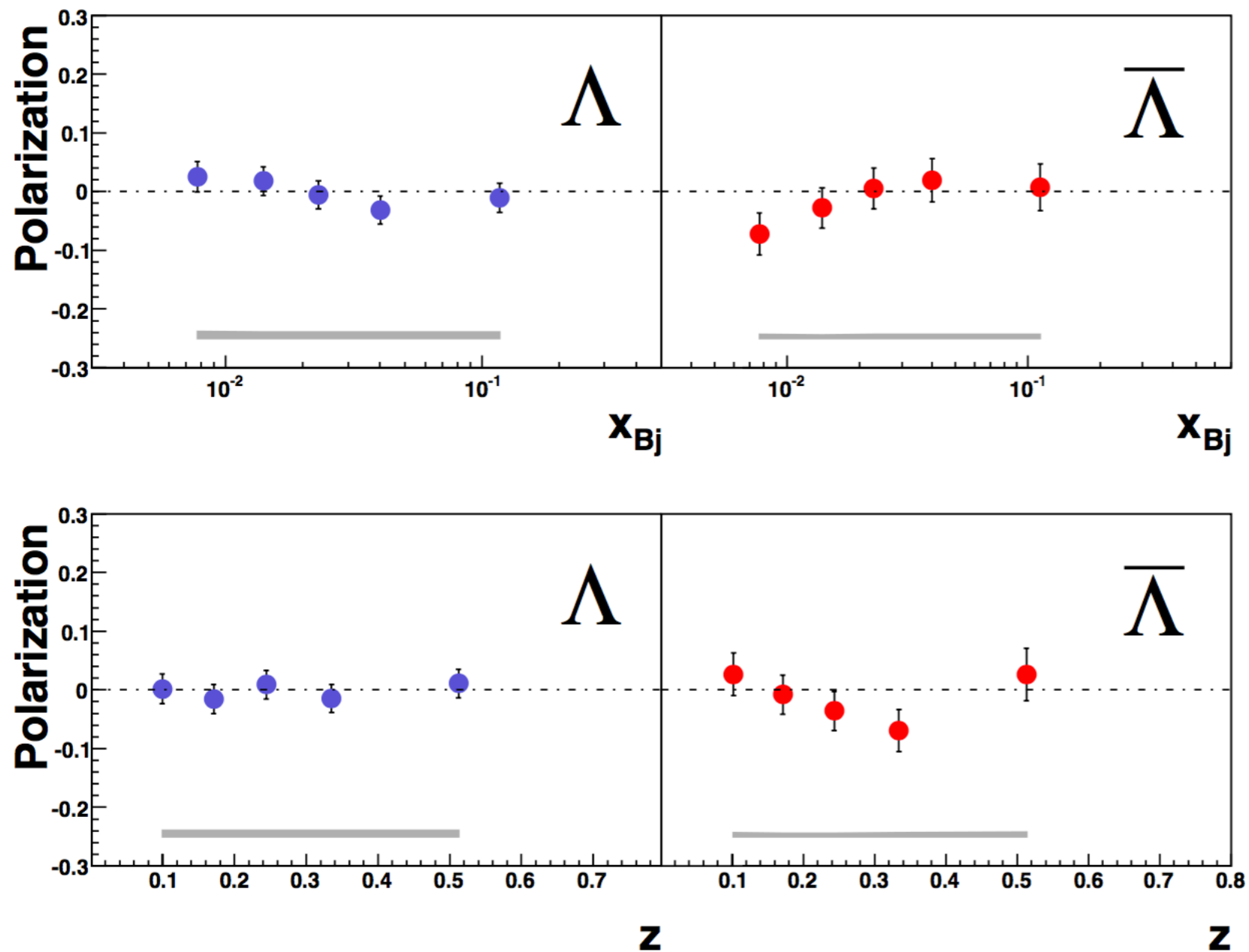
COMPASS, EPJC 2009



Also interesting for the spin sum rule for the Λ

STAR, PRD 2009

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



T. Negrini, COMPASS,
PhD thesis, 2009

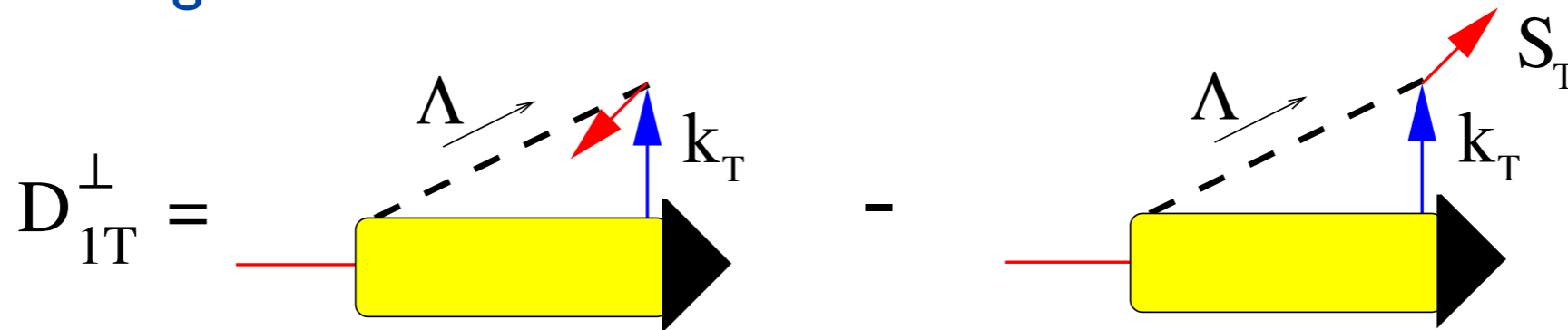
Figure 6.3: Λ and $\bar{\Lambda}$ polarizations with statistical errors as a function of x_{Bj} and z in the 2007 COMPASS data on a transversely polarized proton target with $Q^2 > 1$ (GeV/c)² and $0.1 < y < 0.9$. The lower band shows the upper limit of the systematic error, estimated by the pulls distribution 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 Λ s can also become “spontaneously” polarized, as long known from pp

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



Mulders, Tangerman, 1996

Accessible in semi-inclusive DIS: $ep \rightarrow e' \Lambda^\uparrow X$ (NC) and $\nu_\mu p \rightarrow \mu \Lambda^\uparrow X$ (CC)

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

SIDIS data in the current fragmentation region from NOMAD ($\nu_\mu p \rightarrow \mu \Lambda^\uparrow X$) and ZEUS ($ep \rightarrow e' \Lambda^\uparrow X$), both compatible with zero at the 20% and 5% level, resp.

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)

Clearly nonzero in BELLE data

Polarizing FFs from e^+e^-

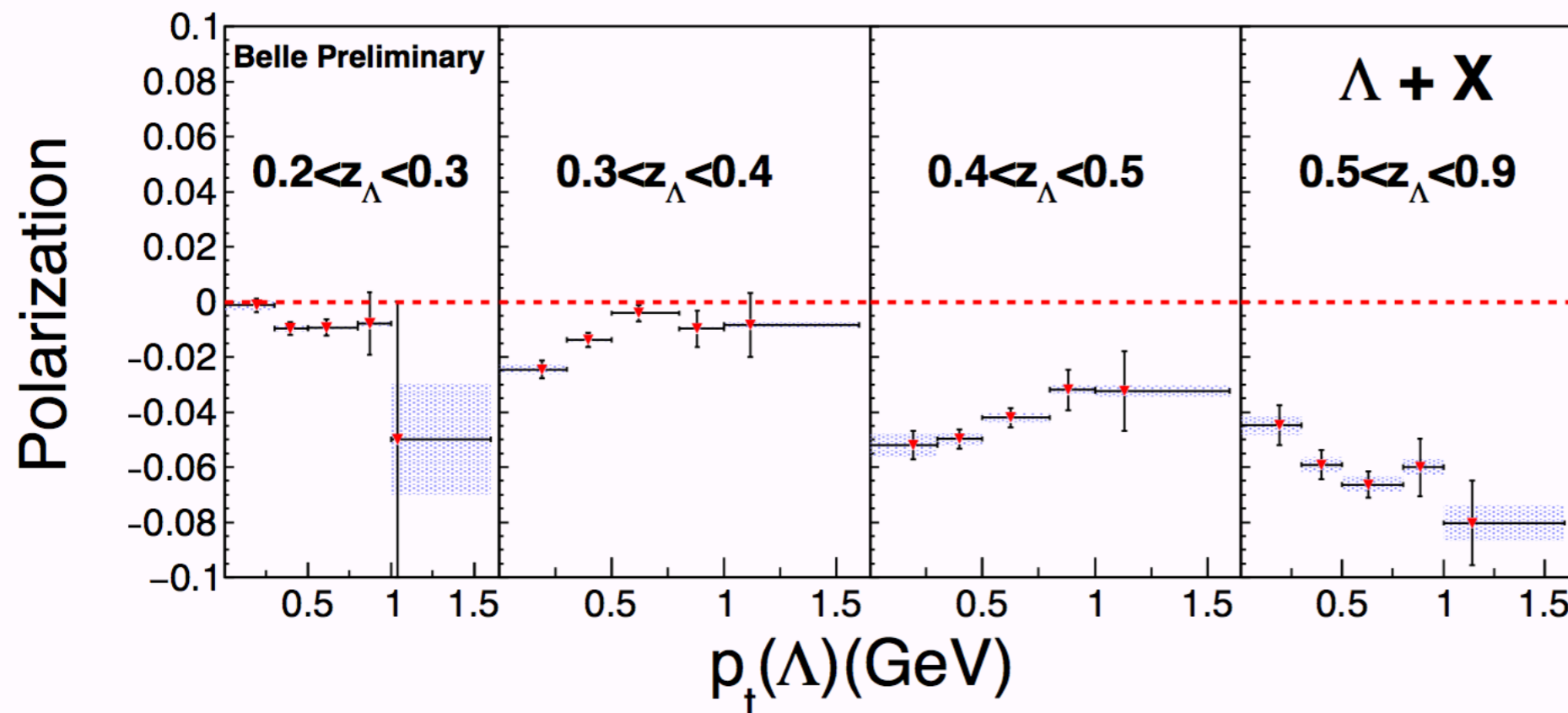
$$\frac{d\sigma(e^+e^- \rightarrow h \text{ jet } X)}{d\Omega dz_h d^2q_T} = \frac{3\alpha^2}{Q^2} z_h^2 \sum_{a,\bar{a}} e_a^2 \left\{ A(y) \left[D_1^a(z_h, z_h^2 Q_T^2) + |S_{hT}| \sin(\phi_h - \phi_{S_1}) \frac{Q_T}{M_h} D_{1T}^{\perp a}(z_h, z_h^2 Q_T^2) \right] \right\}$$

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

D.B., Jakob, Mulders, 1997

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

Eur.Phys.J C2 (1998) 49



BELLE Collaboration

arXiv:1611.06648

p_T w.r.t. thrust axis

(\approx jet axis)

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

GTMDs & GPDs

Quark GTMDs

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

$$G(x, \mathbf{k}_T, \Delta_T) \xleftrightarrow{FT} W(x, \mathbf{k}_T, \mathbf{b}_T)$$

Meißner, Metz, Schlegel, 2009

Ji, 2003; Belitsky, Ji & Yuan, 2004

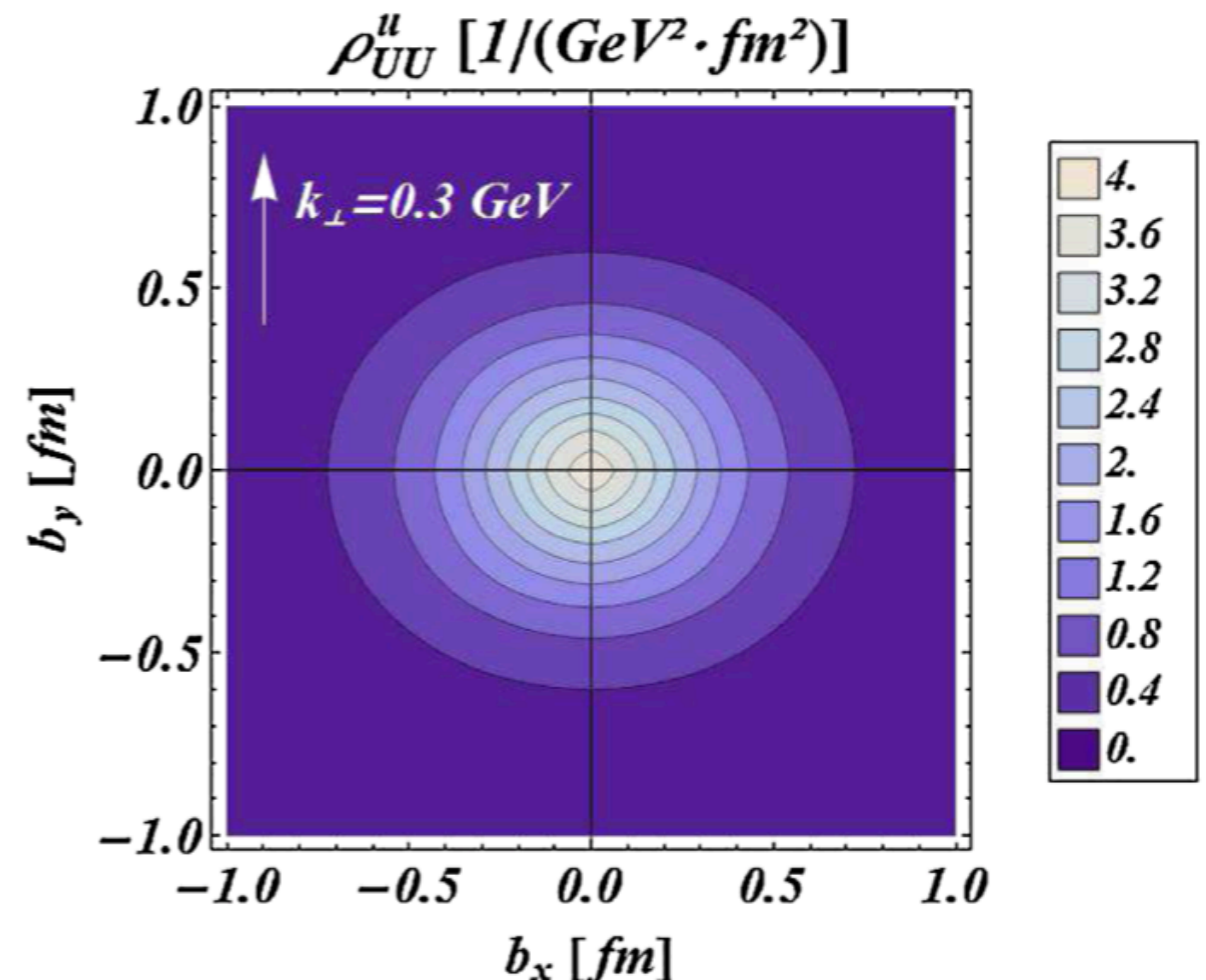
Quark Wigner distributions can display distortions in the \mathbf{b}_T plane depending on \mathbf{k}_T and vice versa, that vanish upon \mathbf{b}_T or \mathbf{k}_T integration

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)



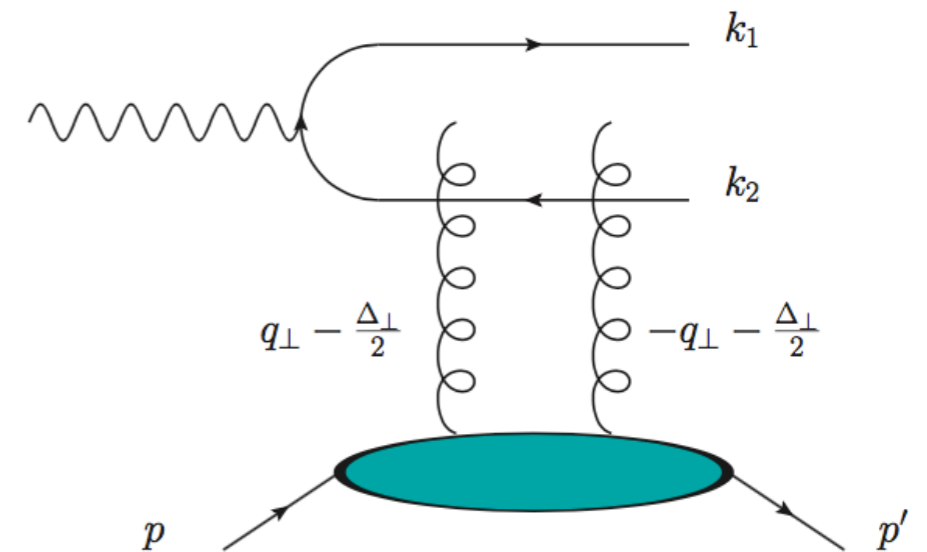
Gluon GTMDs

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



For an unpolarized proton there are four gluon GTMDs, of which one remains in the limit $x \rightarrow 0$ (at leading twist, without resummation of large logs in $1/x$)

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

Part of it is the “elliptic” gluon GTMD $\propto \cos 2\phi_{\mathbf{k}\Delta}$

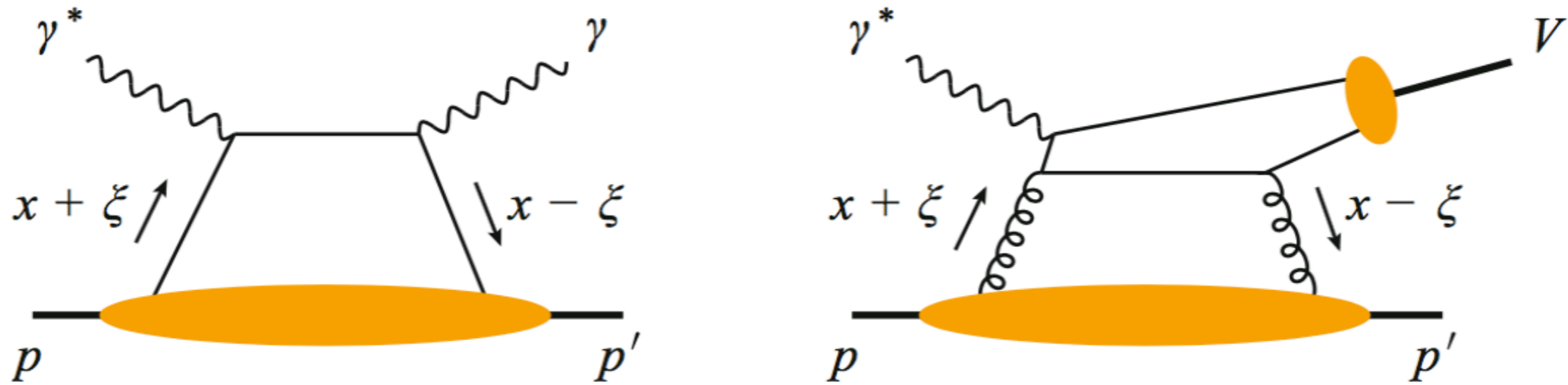
Hatta, Xiao, Yuan, 2016; J. Zhou, 2016

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

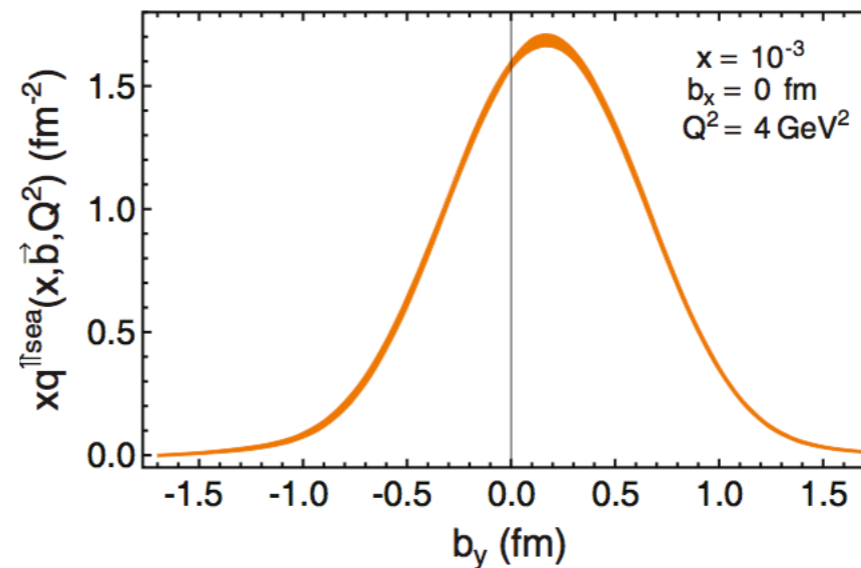
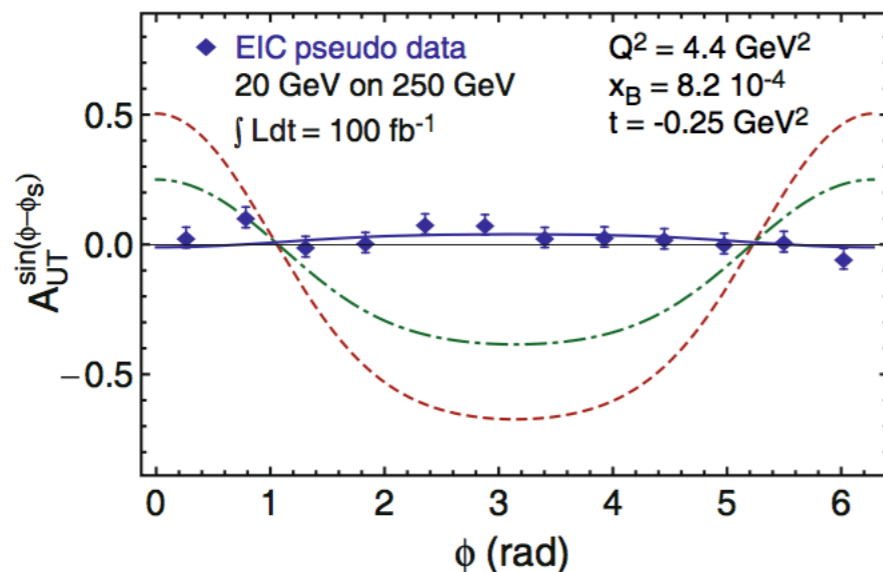
GDPs



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

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

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

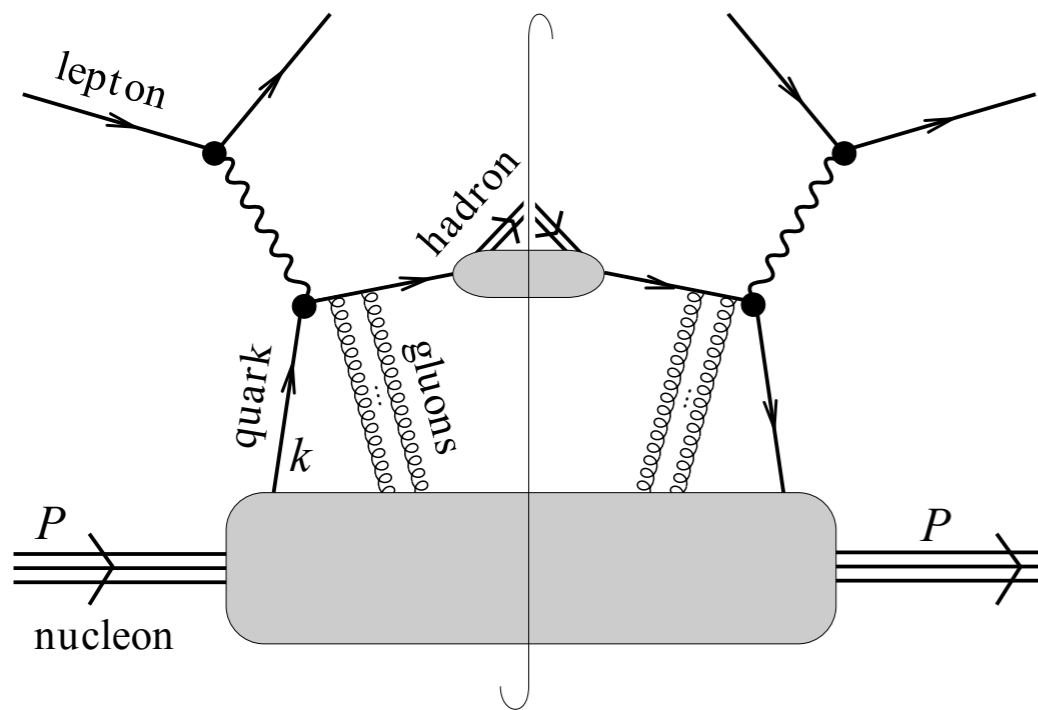
Conclusions

- 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
 - Λ s 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

I can hardly wait!

Back-up slides

Initial and final state interactions



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

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

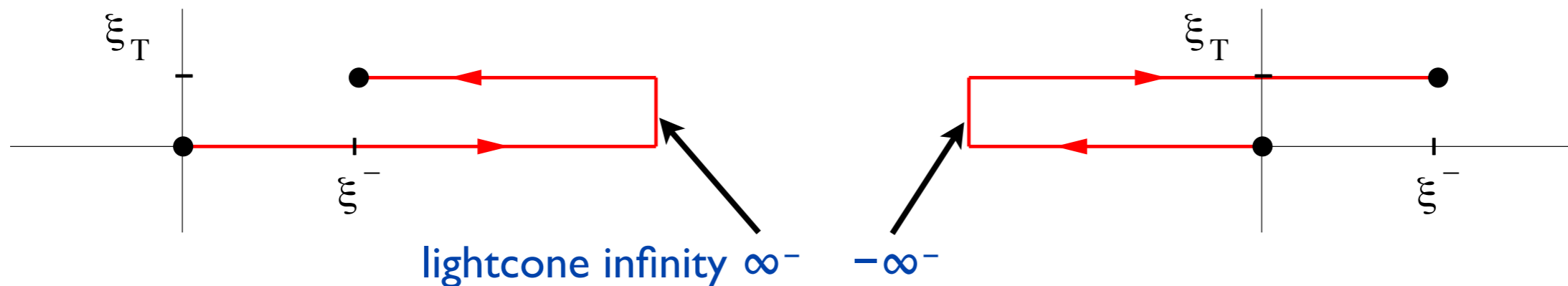
$$\Phi \propto \langle P | \bar{\psi}(0) \mathcal{L}_c[0, \xi] \psi(\xi) | P \rangle$$

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)



Leads to observable effects, such as nonzero Sivers asymmetry

Brodsky, Hwang & Schmidt, 2002; Collins, 2002

Sign change relation for gluon Sivers TMD

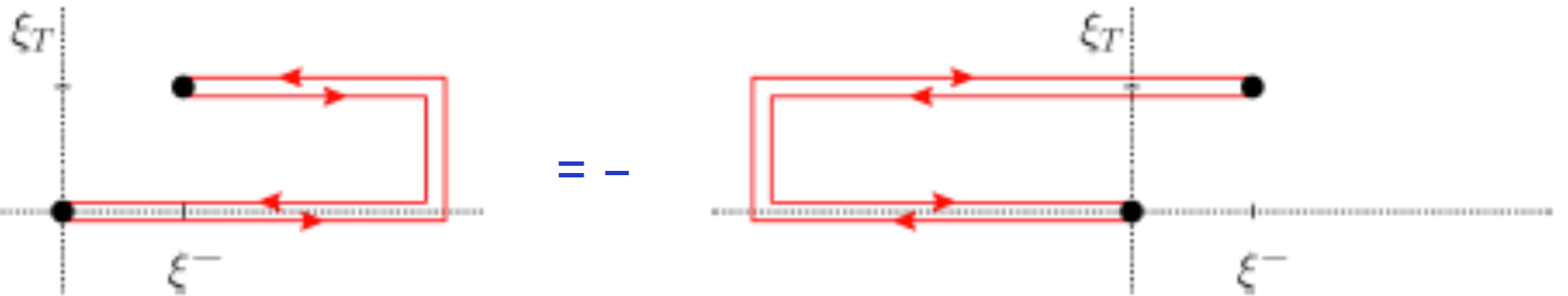
$$e p^\uparrow \rightarrow e' Q \bar{Q} X \quad \gamma^* g \rightarrow Q \bar{Q} \text{ probes } [+, +]$$

$$p^\uparrow p \rightarrow \gamma \gamma X$$

Qiu, Schlegel, Vogelsang, 2011

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

$$g g \rightarrow \gamma \gamma \text{ probes } [-, -]$$



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

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

Important role for EIC

f and d type gluon Sivers TMD

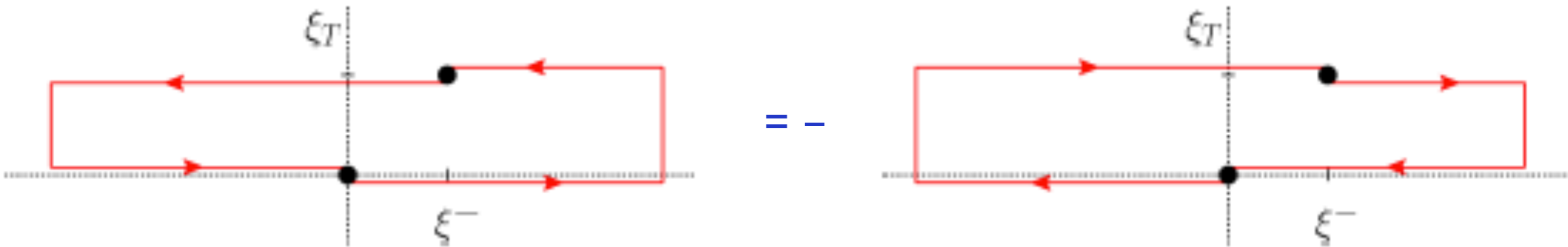
$$e p^\uparrow \rightarrow e' Q \bar{Q} X$$

$$\gamma^* g \rightarrow Q \bar{Q} \text{ probes } [+,+]$$

$$p^\uparrow p \rightarrow \gamma \text{ jet } X$$

In the kinematic regime where gluons in the polarized proton dominate, one effectively selects the subprocess:

$$g q \rightarrow \gamma q \text{ probes } [+,-]$$



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

Gluon polarization inside unpolarized protons

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

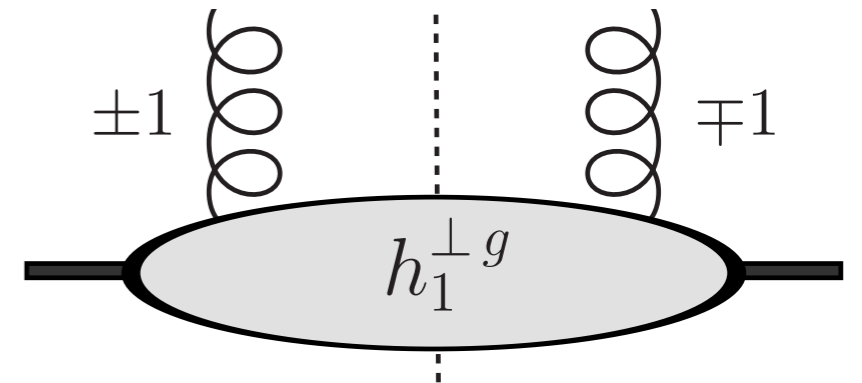
[Mulders, Rodrigues, 2001]

It requires nonzero transverse momentum: TMD

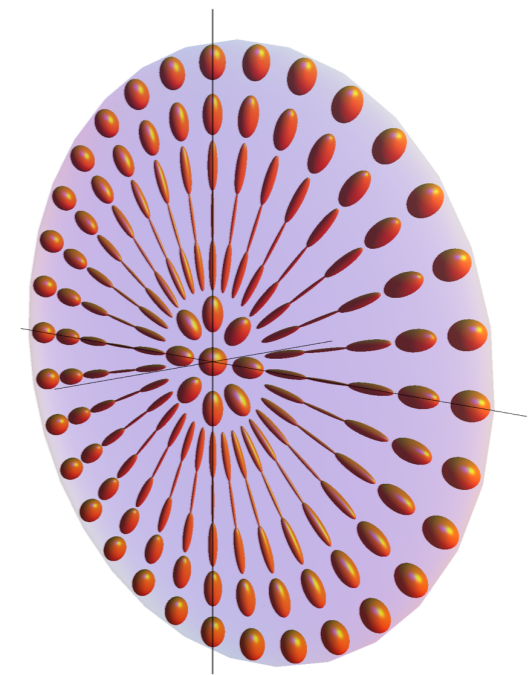
For $h_1^{\perp g} > 0$ gluons prefer to be polarized along \mathbf{k}_T , with a $\cos 2\phi$ distribution of linear polarization around it, where $\phi = \angle(\mathbf{k}_T, \boldsymbol{\varepsilon}_T)$

This TMD is \mathbf{k}_T -even, chiral-even and T-even:

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



an interference between ± 1 helicity gluon states

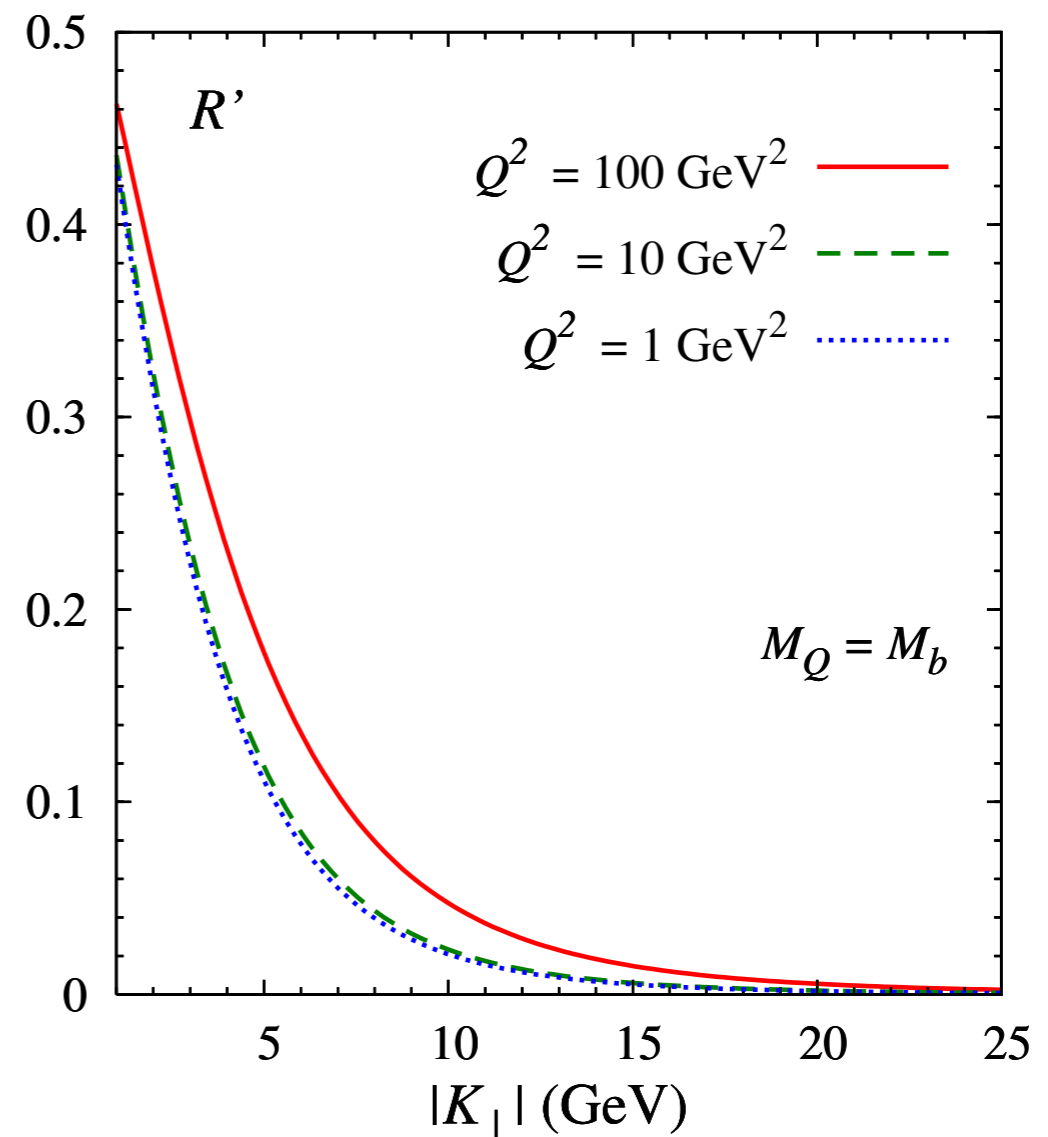
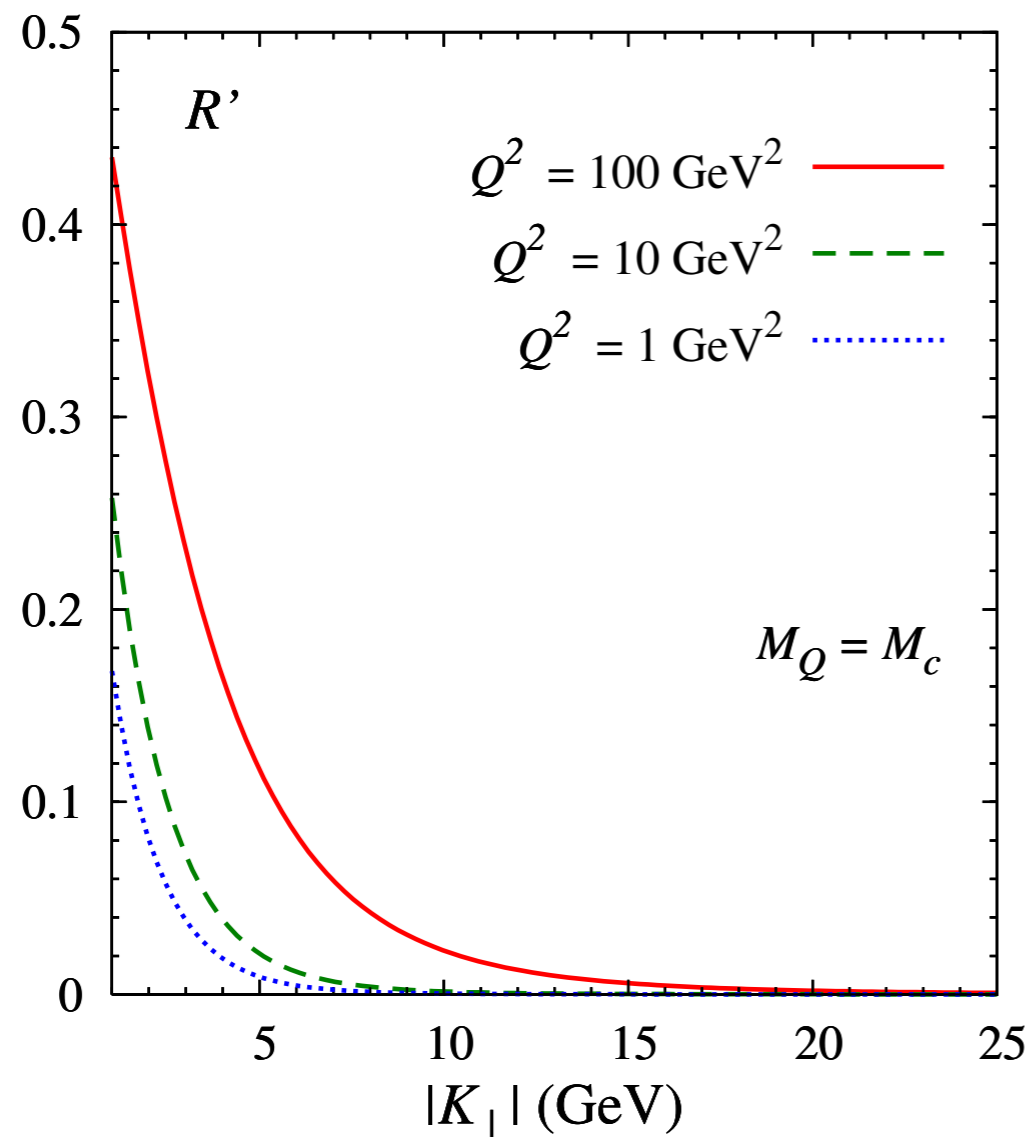


Maximum asymmetries in heavy quark production

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

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

$$R' = \text{bound on } |\langle \cos 2(\phi_{\ell} - \phi_T) \rangle|$$

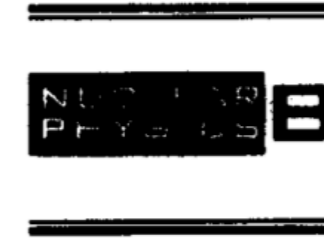


Polarizing FFs from e^+e^-



ELSEVIER

Nuclear Physics B 504 (1997) 345–380



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}

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

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

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

in $e^+e^- \rightarrow (\Lambda^\uparrow \text{ jet}) X$ 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 $e^+e^- \rightarrow (\Lambda^\uparrow \text{jet}) X$ than to $e^+e^- \rightarrow \Lambda^\uparrow X$

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)

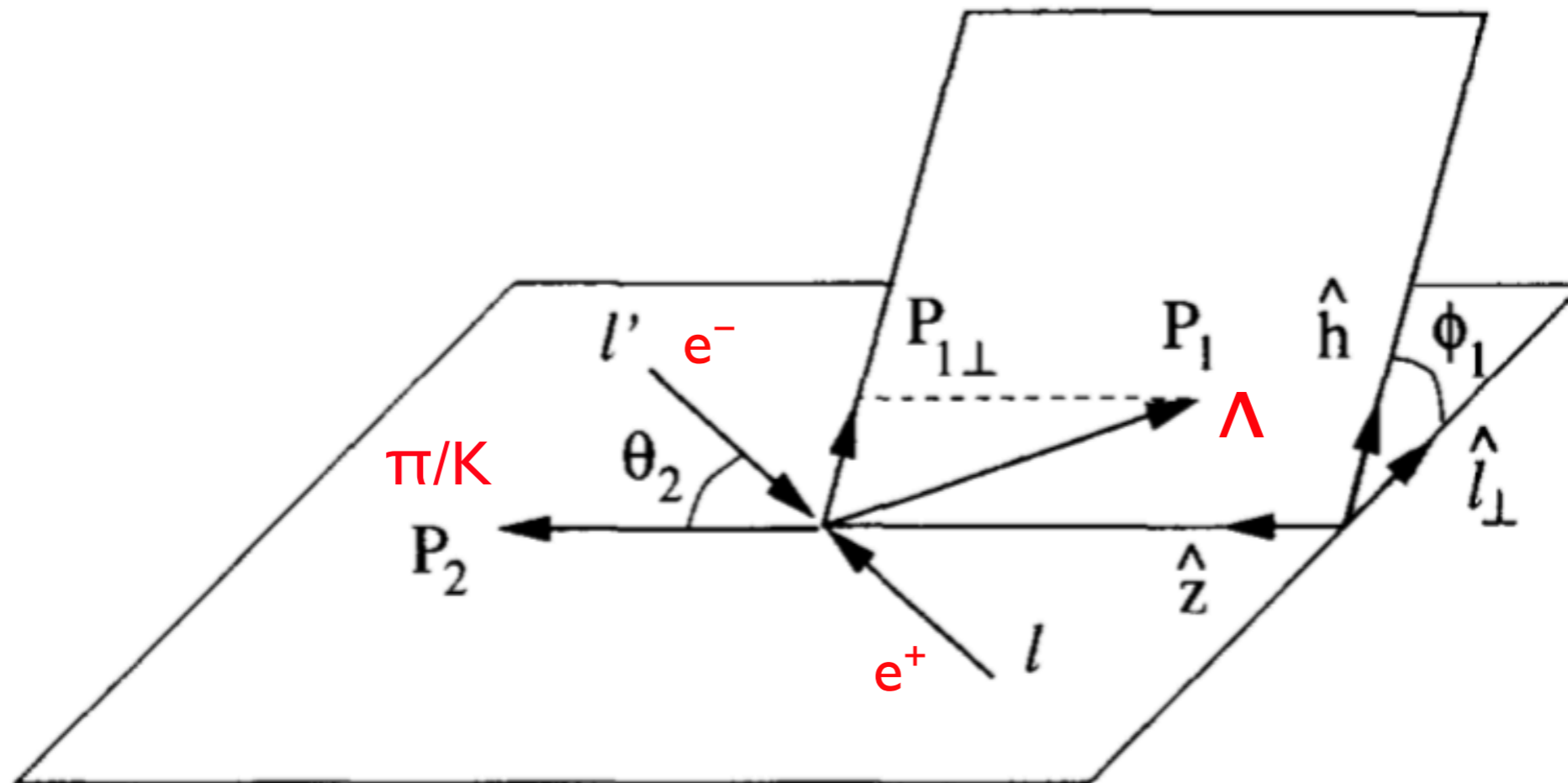
Associated production

$e^+e^- \rightarrow \Lambda^+ X$ 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



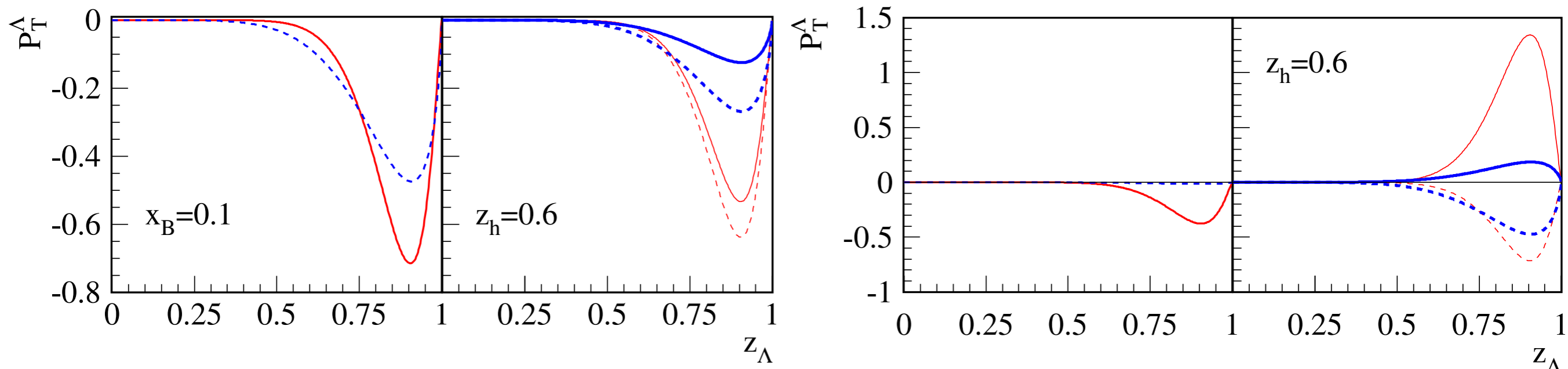
Comparison to $ep \rightarrow e'\Lambda^+ X$ can be used to test universality of $D_{\Lambda\pi^\pm}$

Associated production

$e^+e^- \rightarrow \Lambda^\uparrow X$ 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

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

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

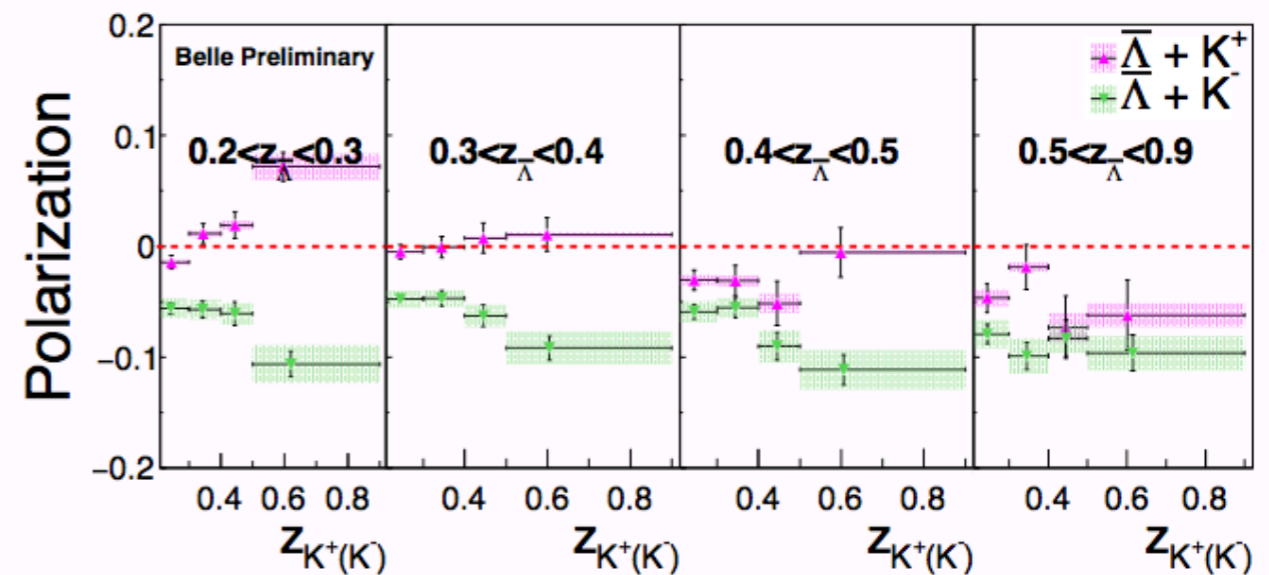
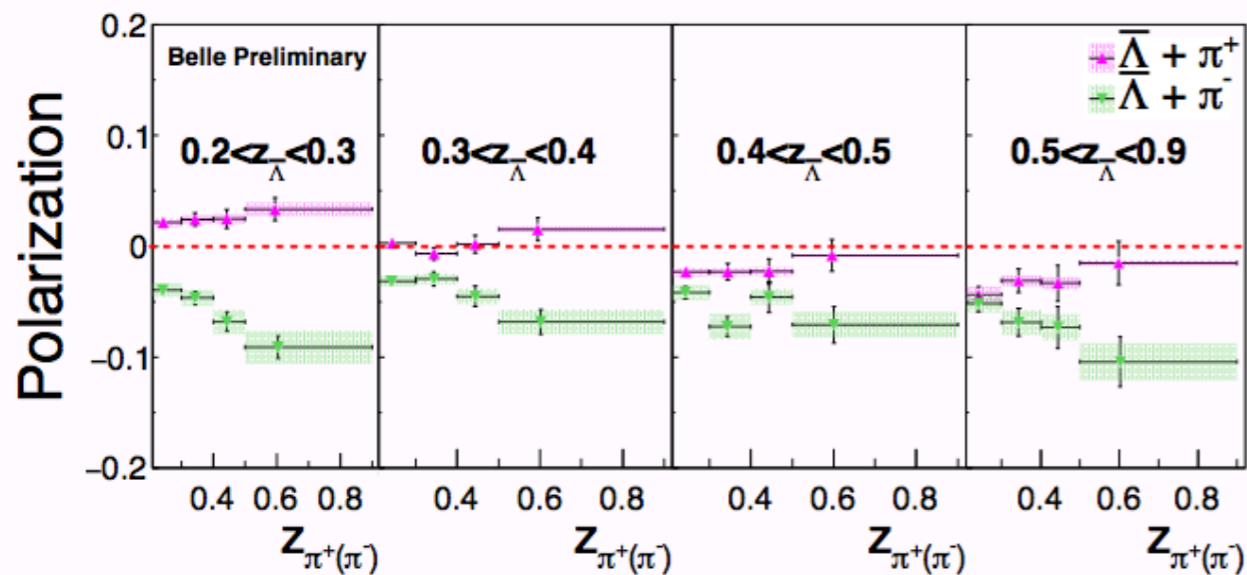
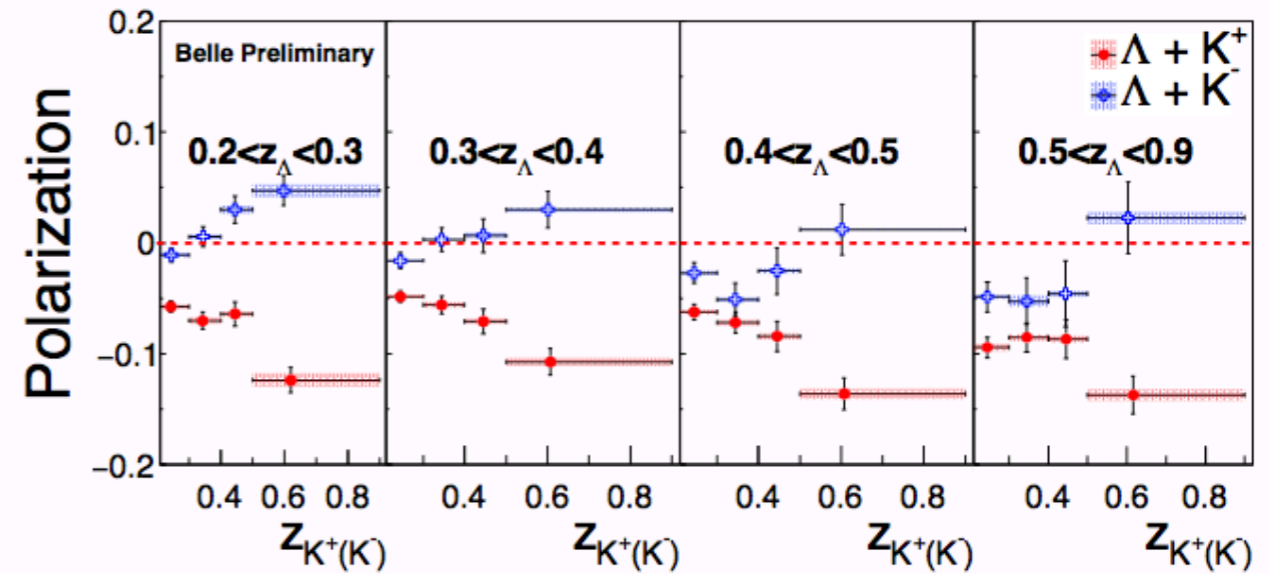
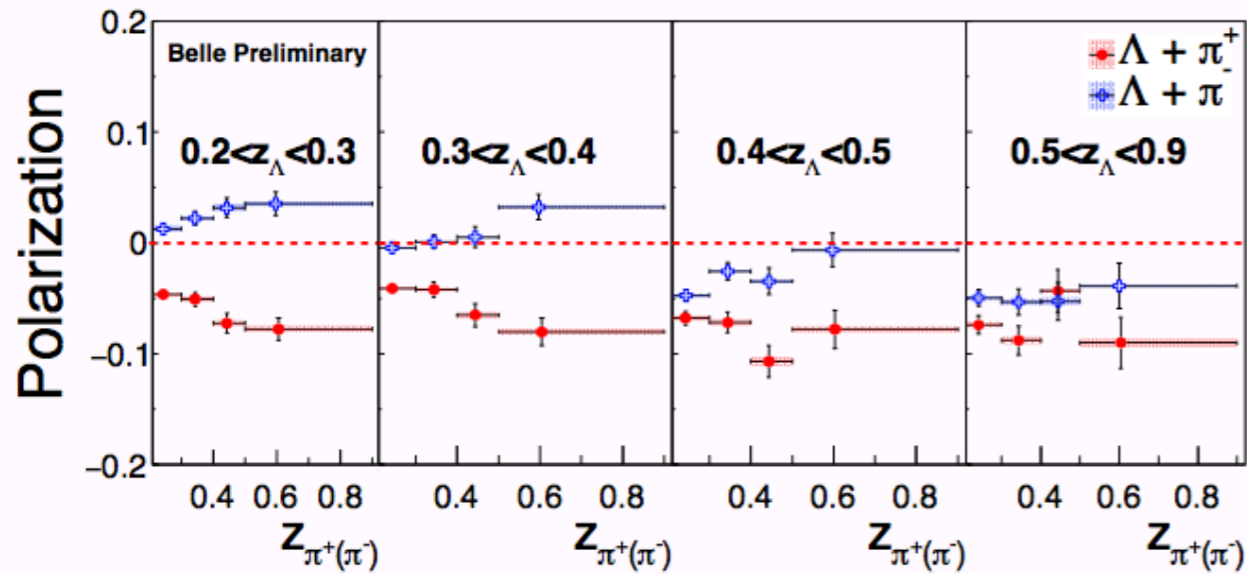
Fig 2: $e^+e^- \rightarrow \pi^\pm + \Lambda^\uparrow + X$, SU(3)-symmetric (thin) and broken (thick), solid/dashed is π^\pm

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

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

Comparison to $ep \rightarrow e'\Lambda^\uparrow X$ 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

Λ polarization in e^+e^-

