Transverse Λ production at the EIC

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Λ baryons for TMD FFs

TMD PDFs

Quark Pol (columns), Proton Pol (rows)

Φ	U	L	T
U	f		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$

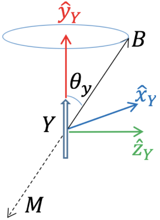
TMD FFs

Quark Pol (columns), Hadron Pol (rows)

Δ	U	L	T
U	D		$H_1^\perp$
L		G_1	$H_{1L}^\perp$
T	$D_{1T}^\perp$	G_{1T}	H_1 $H_{1T}^\perp$

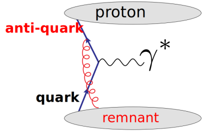
Λ baryon decay

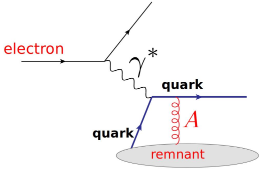
- Many of the TMD PDFs can be probed through precision beam polarization.
- There has been progress in terms of extracting the unpolarized TMD FF as well as the Collins fragmentation function.
- Measuring TMD FFs for hadrons with polarized final states introduces additional complications due to spin reconstruction.
- $\Lambda \to p\,\pi$ is self-analyzing. Allows reconstruction of the final state hadron spin.

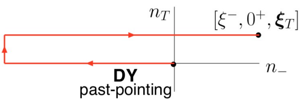


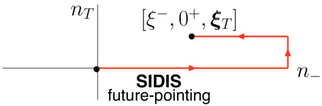
$$\frac{1}{N}\frac{dN}{\cos\theta} = 1 + \alpha P \cos\theta$$

Process dependence of the Sivers function



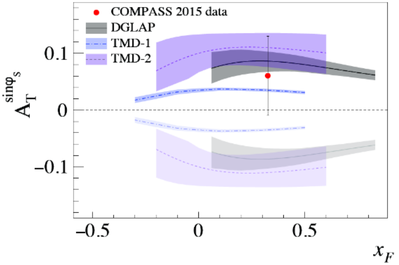






Repulsion between anti-quark and remnant in $p\,p$ collisions. Attraction between quark and remnant in SIDIS [1-4].

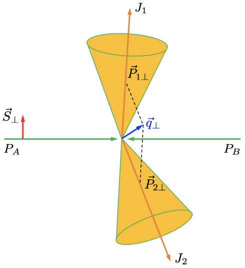
$$f_{1T,q/p}^{\perp,\mathrm{DY}} = -f_{1T,q/p}^{\perp,\mathrm{SIDIS}}$$

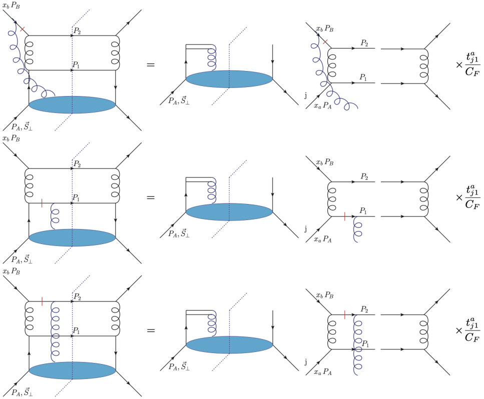


[1] Collins 02, [2] Boer-Mulders-Pijlman 03, [3] Collins-Metz 04, [4] Kang-Qiu 09

Process dependence of the Sivers function continued

Processes with additional hadrons lead to much more complicated process dependence



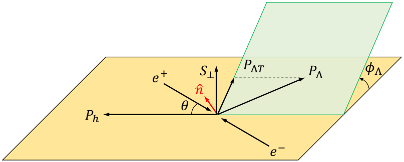


[5] Qiu, Vogelsang, Yuan 2007, [6] Liu, Ringer, Vogelsang, Yuan 2020, [7] Kang, Lee, Shao, J.T 2020

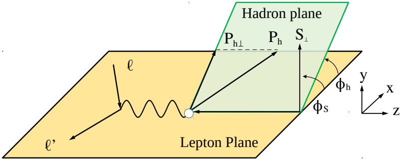
Experimental Observables

Recent work involving standard processes

$$e^- + e^+ \to \Lambda/\bar{\Lambda} + h + X$$



$$e + p \to e + \Lambda + X$$



- $\Lambda/\bar{\Lambda}$ polarizations at Belle [8] at 100 fb^{-1}.
- Three extractions performed in the literature for $D_{1T}^{\perp}$ from Belle data [9-11].
- Experimental measurements in SIDIS are vital for verifying universality prediction for TMD PFF.
- Recent COMPASS measurement for the transverse spin transfer [12].

Quark Pol (columns) / Hadron Pol (rows)

Δ	U	L	T
U	D		$H_1^{\perp}$
L		G_1	$H_{1L}^{\perp}$
T	$D_{1T}^{\perp}$	G_{1T}	H_1 $H_{1T}^{\perp}$

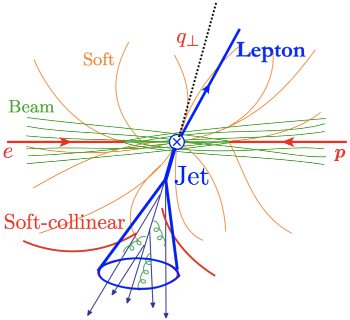
[8] PRL 122 (2019) 4, 042001

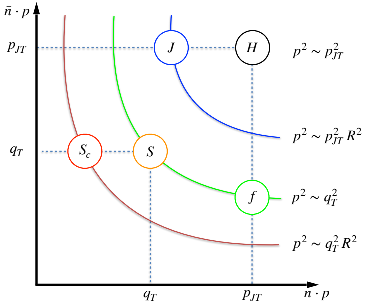
[9] D'Alesio, Murgia, Zaccheddu 2020, [10] Callos, Kang, J.T 2020, Chen, Liang, Pan, [11] Song, Wei 2021

[12] 2104.13585

Experimental Observables Continued

Process: Back-to-back lepton-jet production [13].





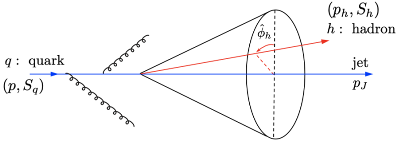
Factorization and resummation

$$\frac{d^5\sigma(\ell p \to \ell' J)}{dy_\ell d^2k_{\ell\perp} d^2q_\perp} = \sigma_0 \int d^2k_\perp d^2\lambda_\perp x f_q(x, k_\perp, \zeta_c, \mu_F)$$
$$\times H_{\rm TMD}(Q,\mu_F) S_J(\lambda_\perp,\mu_F)\, \delta^{(2)}(q_\perp - k_\perp - \lambda_\perp)\ .$$

[13] Liu, Ringer, Vogelsang, Yuan 2019

Experimental Observables Continued

TMD Jet FF: provides three dimensional distribution of hadrons in a jet [14]



Mode analysis:

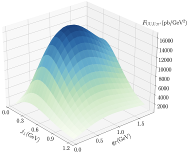
Collinear: $p_{j\perp} R(1, R^2, R)$

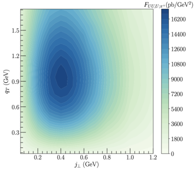
Soft: $j_\perp / R(1, R^2, R)$

$$\mathcal{D}_1^{h/q}(z_h, j_\perp^2, \mu, \zeta_J) = \int_{\boldsymbol{k}_\perp, \boldsymbol{\lambda}_\perp} D_1^{h/q,\,\mathrm{unsub}}(z_h, k_\perp^2, \mu, \zeta'/\nu^2) S_q(\lambda_\perp^2, \mu, \nu\mathcal{R})$$

Recently applied for lepton-jet correlations in [15]. Full spin dependence by in [16].

$$F_{UU}^h = \sigma_0\, H_q(Q,\mu) \sum_q e_q^2\, \mathcal{G}_q^h(z_h, \vec{j}_T, p_T^{\mathrm{jet}} R, \mu)$$
$$\times \int \frac{\mathrm{d}^2 \vec{b}_T}{(2\pi)^2}\, e^{i\vec{q}_T\cdot\vec{b}_T}\, f_q^{\mathrm{TMD}}(x, \vec{b}_T, \mu)\, S_q(\vec{b}_T, y_{\mathrm{jet}}, R, \mu)$$





[14] Kang, Liu, Ringer, Xing 2017
[15] Arratia, Kang, Prokudin, Ringer 2020
[16] Kang, Lee, Shao, Zhao 2021

Goals of this study

Spontaneous Λ polarization $\left(d\sigma \sim D_{1T\,\Lambda/q}^{\perp} \otimes f_{q/p}\right)$

- Provide predictions for spontaneous Λ polarization at the future EIC for both SIDIS as well as back-to-back lepton-jet production.
- Use a Monte Carlo event generator to provide projections for the statistical uncertainties at the future EIC.
- Characterize the requirements for the integrated luminosity for significantly reducing the theoretical uncertainty for the TMD PFFs.
- Identify which kinematic regions are optimal for the previous goal.

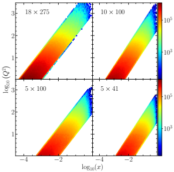
Transverse spin transfer $\left(d\sigma \sim H_{\Lambda/q} \otimes h_{q/p}\right)$

- Obtain the theoretical uncertainties for the TMD transversity FF from the recent COMPASS measurement in [12].
- Provide theoretical predictions at the future EIC for both processes.

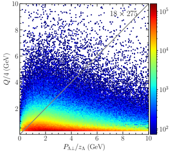
[12] 2104.13585

Monte Carlo Simulation

General kinematic restrictions

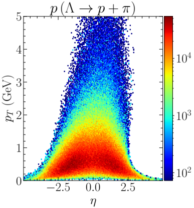


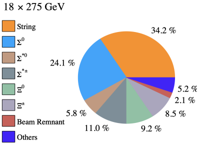
- Monte-Carlo generator: PYTHIA_eRHIC
- 18×275, 10×100, 5×100, 5×41 GeV^2 energy configurations.
- Restricted to $0.05 < y < 0.95$, $Q^2 > 1$ GeV^2, and $W > 2$ GeV.
- Jet reconstruction: Fastjet, anti-kT algorithm, $R = 1$.
- TMD region (SIDIS) $P_{\Lambda\perp}/z < Q/4$, (lepton-jet) $q_\perp < p_{J\perp}/4$, $j_\perp < p_{J\perp} R/4$



Λ *reconstruction*

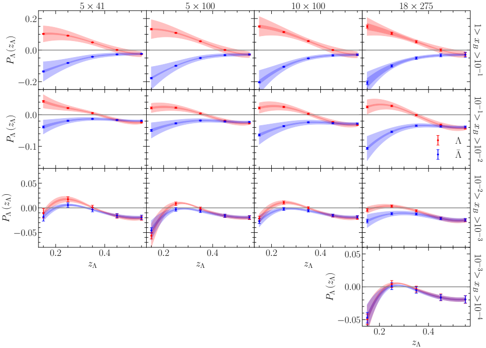
- Reconstructed from $\Lambda \to p\,\pi$.
- Previous analysis was integrated over feed-down.
- Rapidity requirement $|\eta_\Lambda| < 3.5$.
- Detector efficiency was placed at 50%.

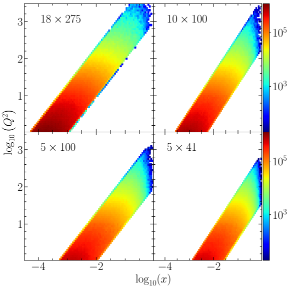




Spontaneous Λ polarization: Reweighting analysis in SIDIS

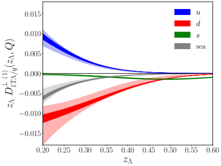
Generating the data at the EIC at 40 fb^{-1}

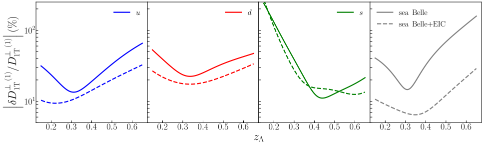




Light band: theoretical prediction using the data at Belle. Dark band: simultaneous analysis to EIC and Belle data.

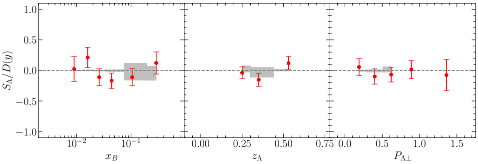
Theoretical uncertainties from the extraction

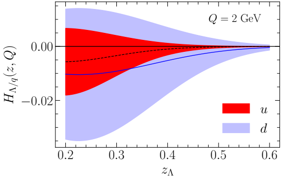




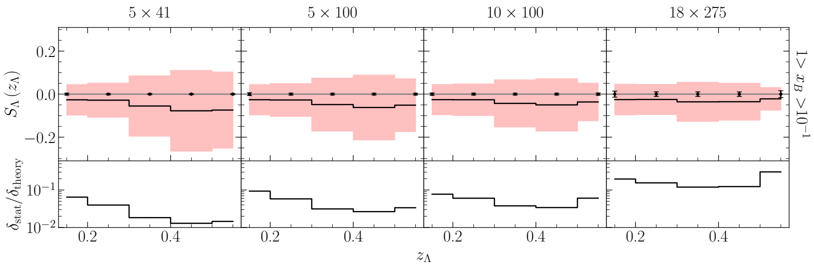
Transverse spin transfer: Fit to the COMPASS data

Fit to the COMPASS data:
Analysis performed at LO+NLL. Transversity TMD PDF taken from paramterization in [17].





Comparison with statistical projections at the EIC at 40 fb^{-1}



The EIC could be the first collider facility to obtain non-zero extraction of this distribution.

[17] Kang, Prokudin, Sun, Yuan 2015

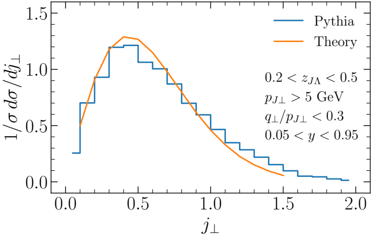
Back-to-back lepton-jet production: Unpolarized

Theoretical prediction is generated at NLL accuracy

$$W_{UU} = H(Q,\mu)\sum_q e_q^2\,\mathcal{G}_{\Lambda/q}(z_{J\Lambda}, j_\perp, \mu_J, \mu) \qquad \mathcal{G}_{\Lambda/q}(z_{J\Lambda}, j_\perp, \mu_J, \mu) = \exp\left[\int_{\mu_J}^{\mu}\frac{d\mu'}{\mu'}\gamma_J(\mu')\right]$$

$$\times \int \frac{d^2b}{(2\pi)^2}\, e^{i\boldsymbol{q}_\perp\cdot\boldsymbol{b}}\, f_{q/p}(x_B, b, \mu)\, S(b, y_J, R, \mu) \qquad \times \int \frac{d^2b}{(2\pi)^2} e^{i\boldsymbol{j}_\perp\cdot\boldsymbol{b}/z_{J\Lambda}} D_{\Lambda/q}(z_{J\Lambda}, b, \mu_J)\,,$$

Non-perturbative parameterization taken from [18].



[18] Sun, Isaacson, Yuan, Yuan 2014

Back-to-back lepton-jet production: Spontaneous polarization

Once again work at NLL accuracy

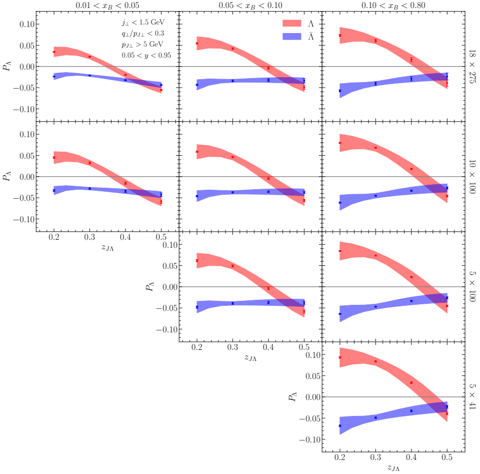
$$W_{UT}^{\sin(\phi_S-\phi_\Lambda)} = H(Q,\mu)\sum_q e_q^2\, \mathcal{G}_{1T,\Lambda/q}^{\perp}(z_{J\Lambda}, j_\perp, \mu_J, \mu) \times \int \frac{d^2b}{(2\pi)^2}\, e^{i\boldsymbol{q}_\perp\cdot\boldsymbol{b}}\, f_{q/p}(x_B, b, \mu)\, S(b, y_J, R, \mu) \quad (21)$$

$$\mathcal{G}_{1T,\Lambda/q}^{\perp}(z_{J\Lambda}, j_\perp, \mu_J, \mu) = \frac{M_\Lambda}{z_{J\Lambda}} \exp\left[\int_{\mu_J}^{\mu} \frac{d\mu'}{\mu'}\gamma_J(\mu')\right] \times \frac{\partial}{\partial j_\perp}\int \frac{d^2b}{(2\pi)^2} e^{i\boldsymbol{j}_\perp\cdot\boldsymbol{b}/z_{J\Lambda}}\, D_{1T,\Lambda/q}^{\perp(1)}(z_{J\Lambda}, b, \mu_J)\,. \quad (22)$$

Non-perturbative parameterization taken from [10].

$$P_\Lambda = \frac{W_{UT}^{\sin(\phi_S-\phi_\Lambda)}}{W_{UU}}$$

Statistical uncertainties at 100 fb^{-1}.



[10] Callos, Kang, J.T 2020

Back-to-back lepton-jet production: Spin transfer

Structure function

$$W_{TT}^{\cos(\varphi_S-\phi_S)} = H_\perp(Q,\mu)\sum_q e_q^2\,\mathcal{G}^T_{\Lambda/q}(z_{J\Lambda}, j_\perp, \mu_J, \mu)$$

$$\times \int \frac{d^2b}{(2\pi)^2}\, e^{i\boldsymbol{q}_\perp\cdot\boldsymbol{b}}\, h_{q/p}(x_B, b, \mu)\, S(b, y_J, R, \mu)\,, \qquad (23)$$

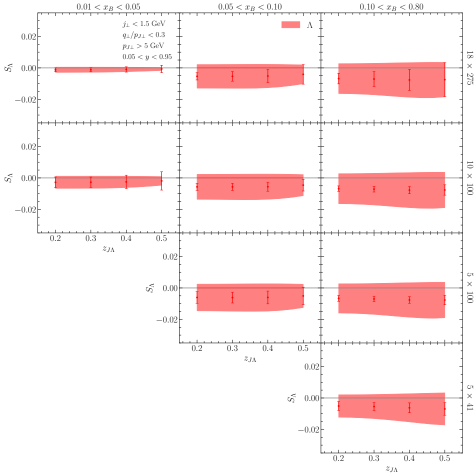
$$\mathcal{G}^T_{\Lambda/q}(z_{J\Lambda}, j_\perp, \mu_J, \mu) = \exp\left[\int_{\mu_J}^{\mu}\frac{d\mu'}{\mu'}\gamma_J(\mu')\right]$$

$$\times \int \frac{d^2b}{(2\pi)^2} e^{i\boldsymbol{j}_\perp\cdot\boldsymbol{b}/z_{J\Lambda}} H_{\Lambda/q}(z_{J\Lambda}, b, \mu_J)\,, \qquad (24)$$

Transversity TMD FF taken from fit to COMPASS data. Transversity TMD PDF taken from [17].

$$S_\Lambda = D(\hat{s},\hat{t},\hat{u})\,\frac{W_{TT}^{\cos(\varphi_S-\phi_S)}}{W_{UU}}$$

Statistical uncertainties at 100 fb^{-1}.



[17] Kang, Prokudin, Sun, Yuan 2020

Conclusion

Summary

- Λ baryons offer new possibilities for probing TMD FFs for polarized final-state hadrons as well as probing possible process dependences of TMD FFs.
- Both SIDIS as well as back-to-back lepton-jet production can be used as a probe for the TMD FFs.
- In this study we have provided projects at the future EIC for both processes for spontaneous Λ production as well as the transverse spin transfer.
- The EIC offers the possibility of significantly reducing the uncertainty from the TMD PFF as well as allowing the first non-zero extraction of the transversity TMD FF.