Transverse Λ polarization in semi-inclusive DIS, e^+e^- and pp collisions and the TMD polarizing fragmentation function $D_{1T}^{\perp}$

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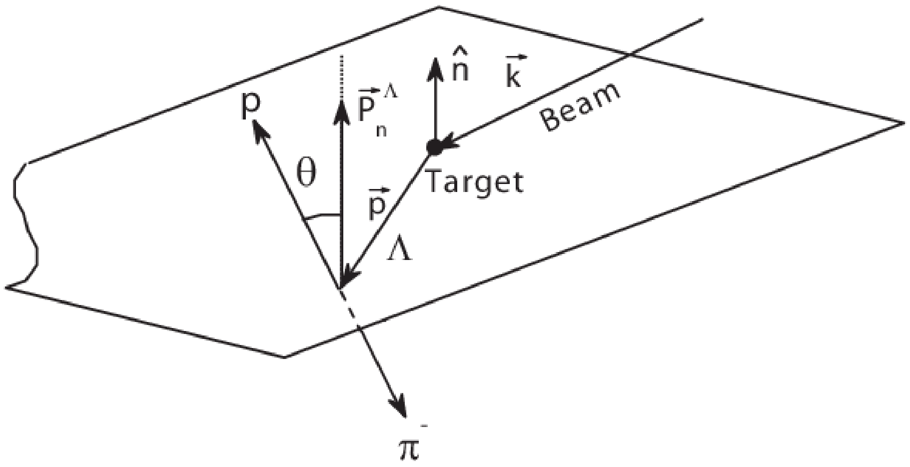
QCD@Work 2024, 18-21 June 2024, Trani - Italy

Outline

- **Physical motivation and early experimental results [1970-90]**
- **Models and a first simplified TMD model interpretation in pQCD [2000]**
- **New results from Belle in $e^+e^- \to \Lambda(\bar{\Lambda}) + \pi, K + X$ and $e^+e^- \to \Lambda(\bar{\Lambda})\ in\ jet + X$ [2019]**
- **First phenom. extractions of the transverse momentum dependent (TMD) Λ polarizing FF [2020]**
- **TMD factorization with full TMD (CSS) evolution with scale and estimates for EIC [2001-today]**
- **Role of $SU(2)$ isospin symmetry and charm fragmentation contribution**
- **New preliminary results from STAR at RHIC in $pp \to \Lambda(\bar{\Lambda})\ in\ jet + X$ [2023]**
- **Universality test for the TMD polarizing fragmentation function**
- **Outlook and conclusions**

Hyperon decay in a spin 1/2 and a spin 0 particle is self-analyzing, e.g. $pp, pA \rightarrow \Lambda + X \rightarrow p\,\pi^- + X$

$\hat{\boldsymbol{n}} = \boldsymbol{p}_{\mathrm{beam}} \times \boldsymbol{p}_{\Lambda}$



$\theta_{\hat{n}}$ measured w.r.t. the normal to the production plane

$$\frac{dN(\theta_p,\phi_p)}{N} = \frac{1}{4\pi}\left[1 + \alpha_\Lambda P^\Lambda \cdot \hat{\boldsymbol{n}}(\theta_p,\phi_p)\right] = \frac{1}{4\pi}\left[1 + \alpha_\Lambda P^\Lambda_n \cos\theta_{\hat{n}}\right]$$

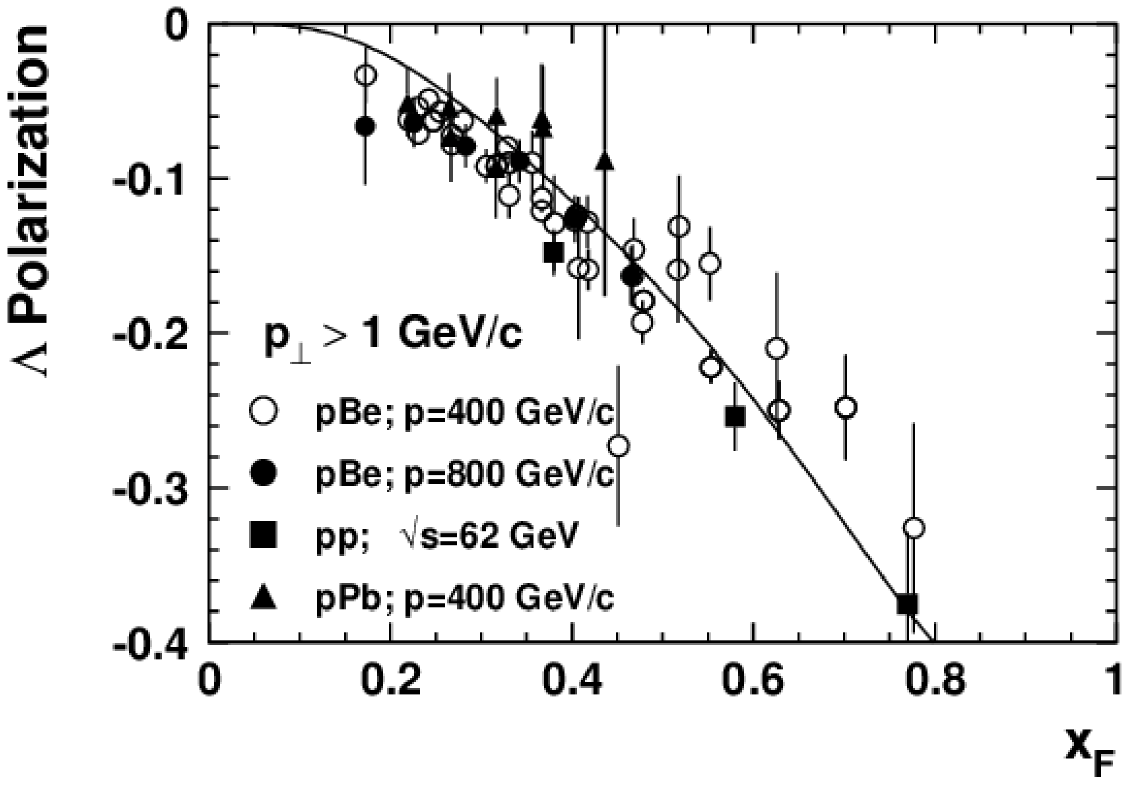
θ_p, ϕ_p measured in the Λ helicity rest frame

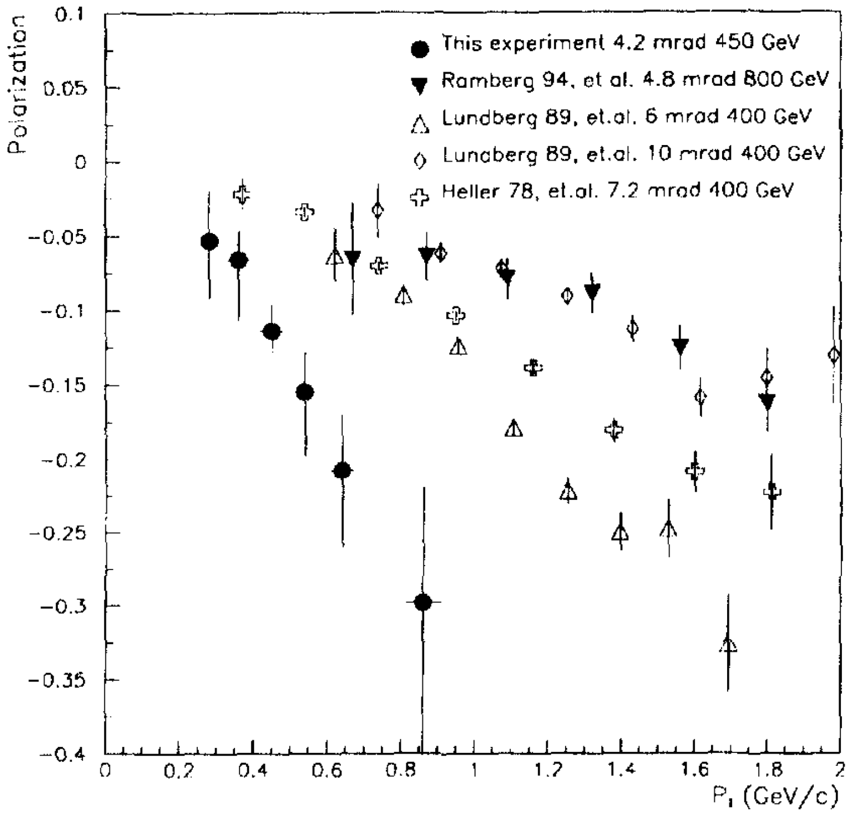
- Parity conserving unpolarized production process: Only polarization transverse to the production plane allowed
- What is actually measured is the product $\alpha_\Lambda P^\Lambda_n$; requires independent determination of α_Λ
- Notice: $\alpha_\Lambda = 0.642$ and $\alpha_{\bar{\Lambda}} = 0.71$ until PDG 2018, BUT $\alpha_\Lambda = 0.747$ and $\alpha_{\bar{\Lambda}} = 0.757$ in PDG 2024

BESIII, LHCb, CLAS

- $\Longrightarrow$ Older $\Lambda, \bar{\Lambda}$ polarization measurements should be accordingly rescaled!

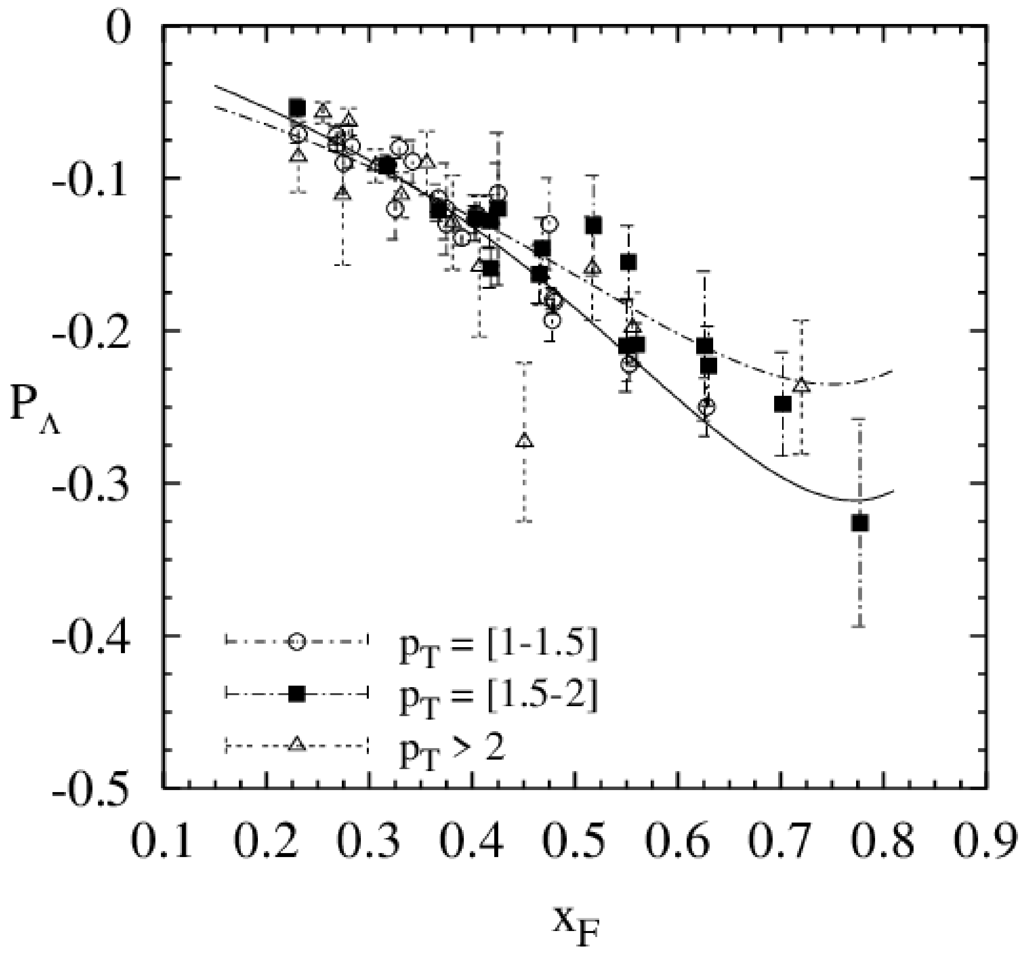
A (very partial) collection of older results on spontaneous Λ transverse polarization in unpolarized pp, pA collisions (fixed target)

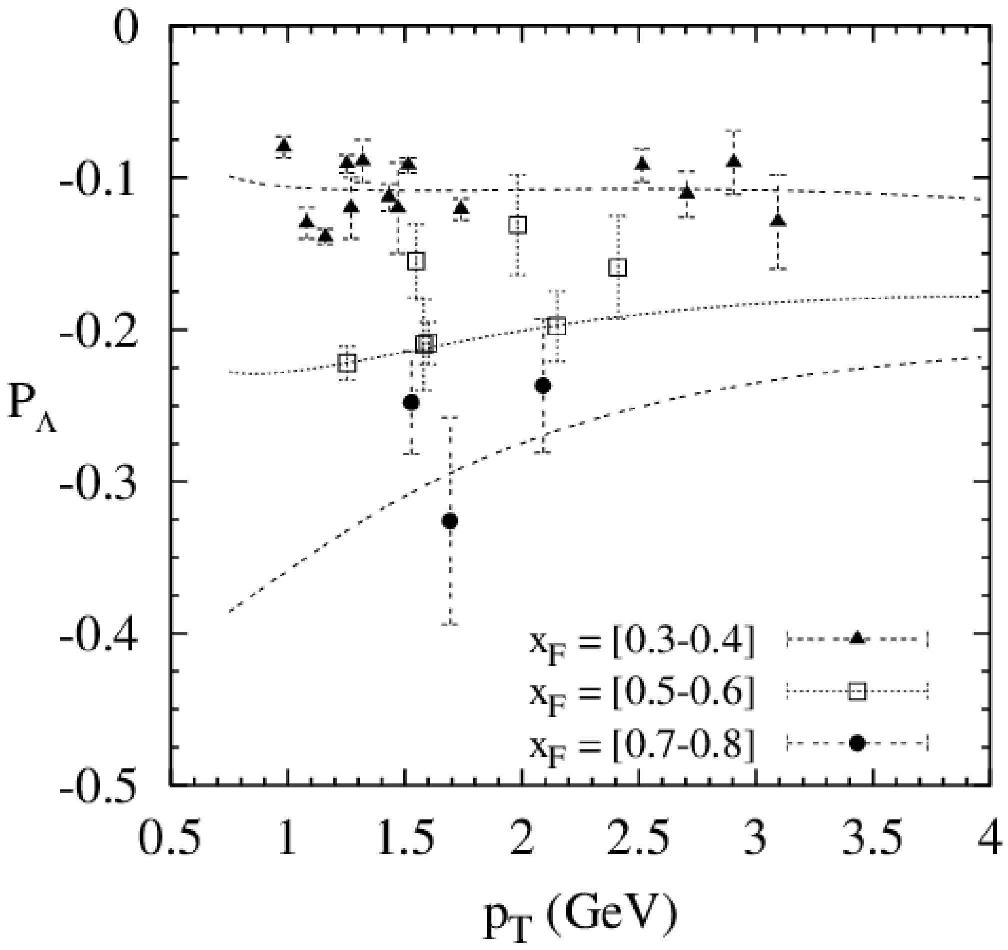




NA48 Collaboration
EPJC 6, 265 (1999)

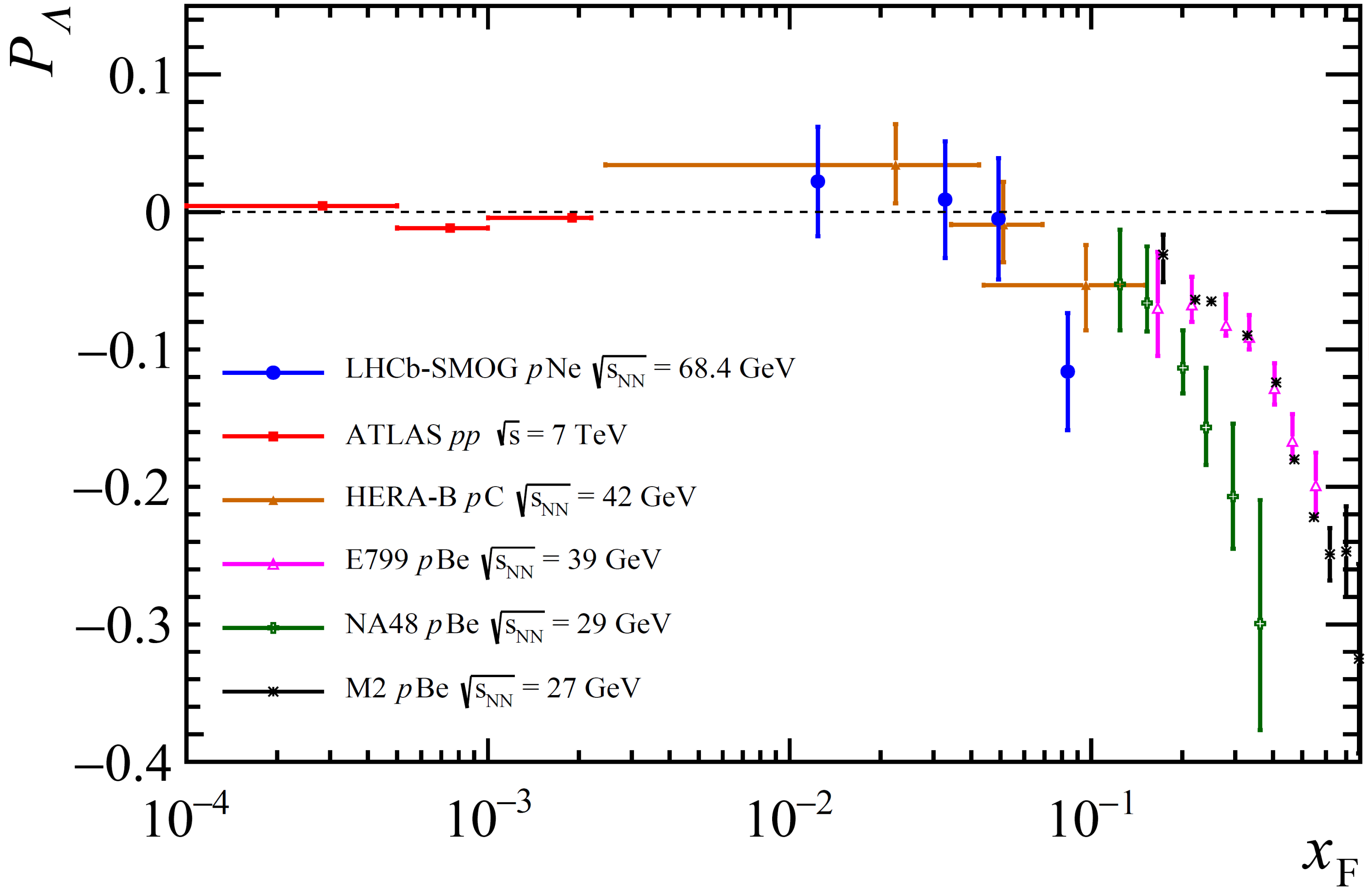
A (very partial) collection of older results on spontaneous Λ transverse polarization in unpolarized pp, pA collisions (fixed target)





Anselmino, Boer, D'Alesio, FM - PRD 63 054029 (2001)
PRD 65 114014 (2002) for SIDIS

Some older/new results on spontaneous Λ transverse polarization in unpolarized pp, pA collisions (fixed target and collider - LHC)



LHCb-SMOG Collab.
2405.11324 [hep-ex]

Some qualitative remarks

- All available data (except for ATLAS) are at relatively small $p_T \lesssim 1.0 - 3.0$ GeV
- Λ Polarization negative and sizable, increases in size with increasing of Feynman variable x_F
- Λ polarization increases with p_T – It seems to reach a plateau at the largest p_T values available
- The absolute value on the plateau increases at larger x_F values
- $\bar{\Lambda}$ polarization mostly consistent with zero
- In unpolarized pp collisions, e.g. ATLAS, $P_T^\Lambda(-x_F) = -P_T^\Lambda(-x_F) \Longrightarrow P_T^\Lambda(x_F = 0) \equiv 0$
- (Scarce) Polarization measurements for other hyperons contradictory and puzzling – No unifying scheme; nonpertubative models unable to explain the full picture

Early models on spontaneous hyperon polarization in unpolarized pp, pA collisions

- **Several nonperturbative, mostly semiclassical models have been proposed**
- **Degrand-Miettinen, Heller, Moriarty et al., Andersson et al., Szwed, Troshin-Tyurin, Soffer, Barni et al., Goldstein et al, Liang et al,....**
- **None of these models is able to explain (even partially) the full experimental data set**
- **Main issues: Wrong behaviour of polarization as a function of either p_T or x_F(or both), wrong polarization (sign and size) for some hyperons.**
- **Notice: most of these issues are still not clarified**
- **More recently spectator diquark models, e.g. Tashiro et al. (2006), Schmidt et al. (2017) within the TMD framework**

TMD Approach to single/azimuthal spin asymmetries in semi-inclusive DIS, Drell-Yan processes and e^+e^- annihilations

- **Introduced around 1990 to explain the large transverse single spin asymmetries in $p^\uparrow p \to \pi, K + X$ processes (Sivers, Collins; alternative approach: collinear twist-three, Qiu-Sterman et al.)**
- **Explicit inclusion of intrinsic motion of partons inside hadrons in a LO QCD improved parton model**
- **Accounts for correlations among intrinsic parton motion and the polarization of the particles involved in the process (parton and hadrons)**
- **Introduces a new class of transverse momentum dependent parton distributions and fragmentation functions (known as TMD PDFs and FFs or just TMDs)**
- **Allows for the existence of the so-called polarizing fragmentation function, describing the fragmentation of an unpolarized parton (quark, gluon) into a transversely polarized spin 1/2 hadron. Can potentially explains spontaneous hyperon polarization.**

For an updated and very comprehensive review on TMDs see: TMD Handbook 2304.03332 [hep-ph]

TMD Approach to single/azimuthal spin asymmetries in semi-inclusive DIS, Drell-Yan processes and e^+e^- annihilations

- **Applies to processes with two relevant scales: a large, perturbative one and a small, soft one sensitive to intrinsic parton motion**

- **E.g.: small p_T spectrum of the dilepton pair in DY processes at large invariant mass**
- **Small p_T (in the $\gamma^* p$ ref. frame) hadrons produced in SIDIS at large Q^2**
- **Almost back-to-back hadron, jet, jet-hadron pairs produced in e^+e^- annihilations**

- **Proper TMD Factorization theorems and evolution equations available for these three processes [starting from 2001-2003] (alternative route via SCET approaches]**

- **For SIDIS hadron multiplicities and DY cross sections extensive global fits now available up to N3LO and N3LL (MAP, JAM, Artemide collaborations)**

- **TMDs are nonperturbative objects, to be parametrized and fitted, just like ordinary collinear PDFs and FFs (with additional explicit dependence on transverse momentum) [additional input from nonpert. models and Lattice QCD]**

Leading twist quark TMD PDFs and FFs for spin 1/2 hadrons

Leading Quark TMDPDFs

Nucleon Spin   Quark Spin

		Quark Polarization		
		Un-Polarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	f_1 = Unpolarized		$h_1^\perp$ = Boer-Mulders
	L		g_1 = Helicity	$h_{1L}^\perp$ = Worm-gear
	T	$f_{1T}^\perp$ = Sivers	$g_{1T}^\perp$ = Worm-gear	h_1 = Transversity $h_{1T}^\perp$ = Pretzelosity

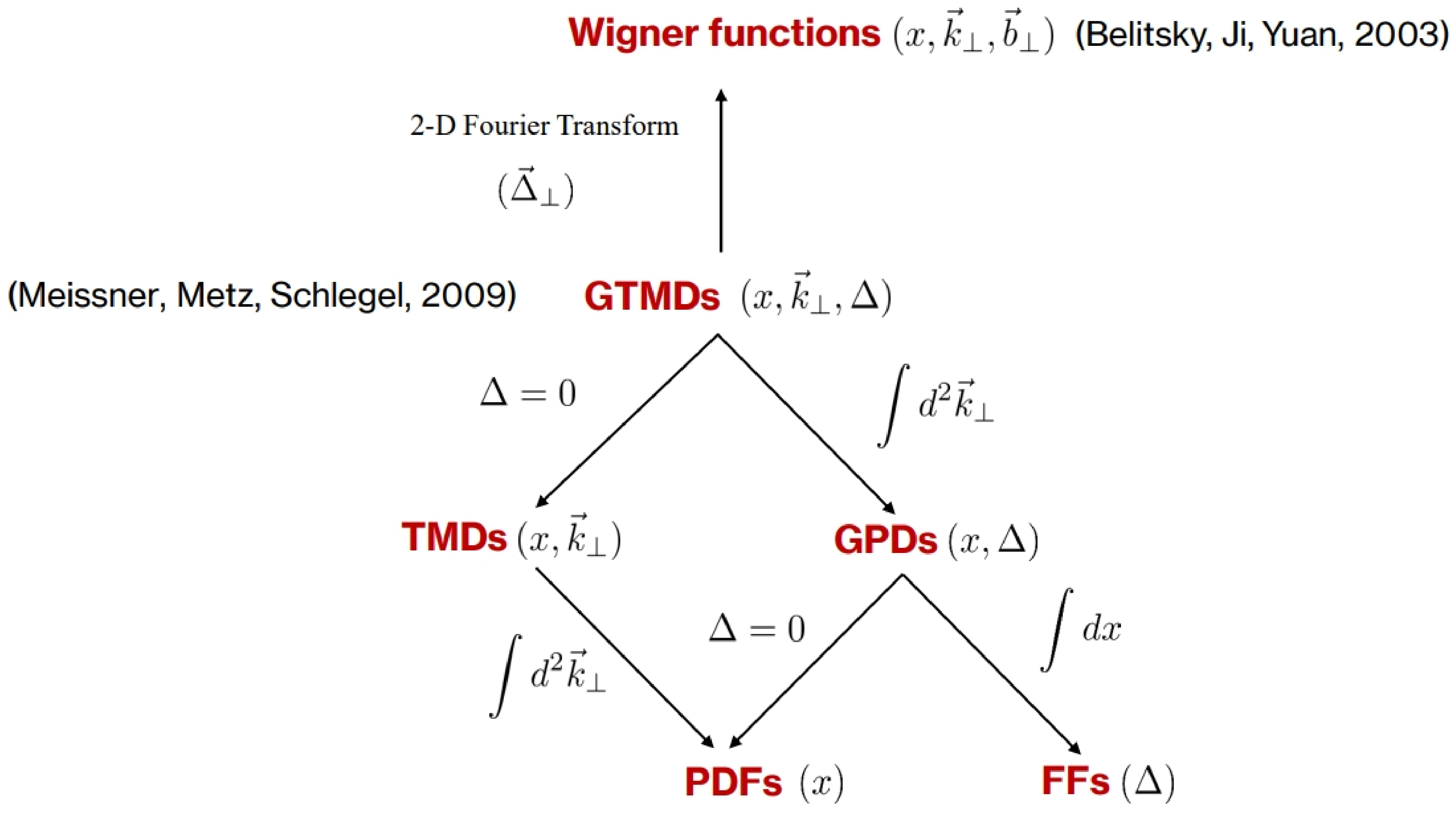
Leading Quark TMDFFs

Hadron Spin   Quark Spin

		Quark Polarization		
		Un-Polarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Unpolarized (or Spin 0) Hadrons		D_1 = Unpolarized		$H_1^\perp$ = Collins
Polarized Hadrons	L		G_1 = Helicity	$H_{1L}^\perp$ =
	T	$D_{1T}^\perp$ = Polarizing FF	$G_{1T}^\perp$ =	H_1 = Transversity $H_{1T}^\perp$ =

Analogous tables for leading twist gluon TMD PDFs and FFs in spin 1/2 hadrons, for leading twist quark and gluon TMDs in spin 1 hadrons, for twist 3 TMDs, ….

Connection among TMDs and other hadron distributions



TMD Factorization and evolution (CSS formalism): basic ideas

- Fourier transform from k_T to b_T space [convolutions → products of TMDs]
- Renormalize ultraviolet and rapidity divergences (due to required gauge links)
- RG evolution equations with proper anomalous dimensions (Collins-Soper kernel for rapidity)
- Avoid large b_T regime and Landau pole in perturbative expansion (b_* prescription)
- Perform OPE to evolve from the initial to the final (b_* implemented) scales
- Require nonperturbative input for CS kernel [$g_K(b_T^2)$] and for the OPE part
- The nonperturbative factor at the initial Q_0 scale effectively incorporates also unknown soft factors S

$$\hat{f}_1^a(x, \boldsymbol{b}_T^2; \mu_f, \zeta_f) = [C \otimes f_1](x, b_*; \mu_{b_*}, \mu_{b_*}^2) \exp\left\{ \int_{\mu_{b_*}}^{\mu_f} \frac{d\mu}{\mu} \gamma(\mu, \zeta_f) \right\} \left(\frac{\zeta_f}{\mu_{b_*}^2} \right)^{K(b_*, \mu_{b_*})/2} f_{1NP}(x, \boldsymbol{b}_T^2; \zeta_f, Q_0),$$

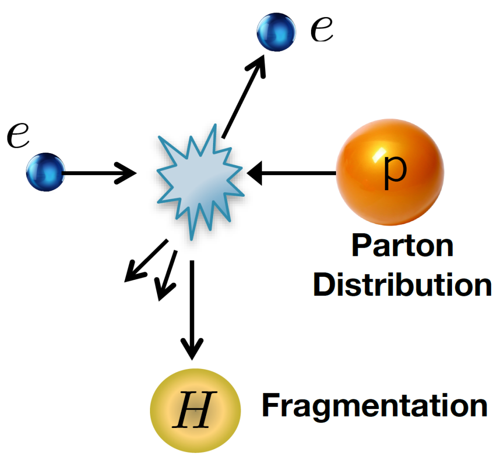
b_* prescription: $\quad \boldsymbol{b_T} \to \boldsymbol{b_*}(\boldsymbol{b_T}) = \dfrac{\boldsymbol{b_T}}{\sqrt{1 + (\boldsymbol{b_T}/\boldsymbol{b}_{\max})^2}}, \quad \boldsymbol{f}(\boldsymbol{b_T}) \to \left[\dfrac{\boldsymbol{f}(\boldsymbol{b_T})}{\boldsymbol{f}(\boldsymbol{b_*})} \right] \boldsymbol{f}(\boldsymbol{b_*})$

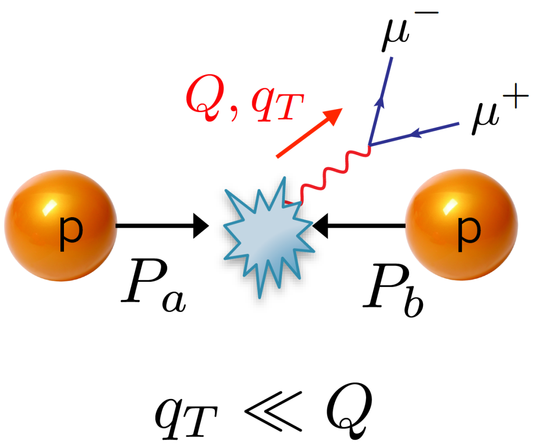
TMD Factorization and evolution (CSS formalism) basic ideas

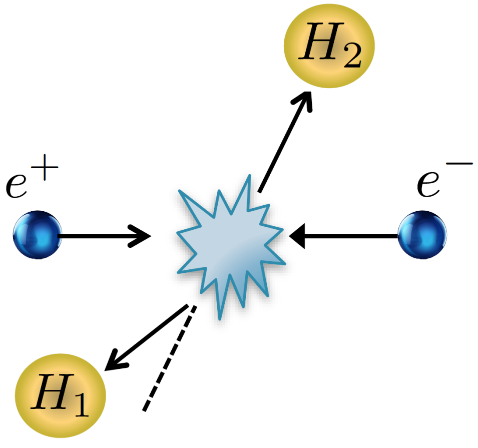
Phenomenological approaches differ in the choice of required ingredients:

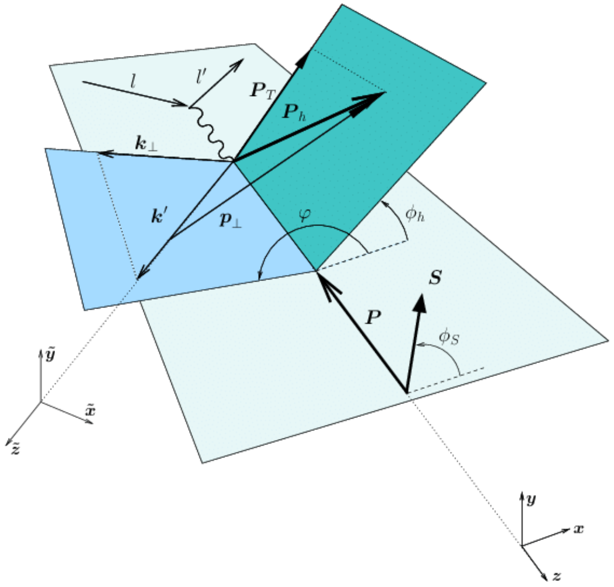
- **Order of perturbative expansion in the strong coupling costant (LO, NLO, NNLO, N3LO)**
- **Order in the resummation of large logarithms (LL, NLL, NNLL, N3LL, N4LL⁻)**
- **Parametrization of nonperturbative input: $g_K(b_T^2)$, functional form of distributions at the initial scale (e.g. combinations of Gaussians and weighted Gaussians, flavor dependence, ...)**
- **Choice of data sets to be fitted for SIDIS, DY, e^+e^- annihilation, pp collisions...**
- **Data selection criteria for the validity of the factorization approach (safe kinematical regions)**
- **Choice of collinear PDFs and FFs**
- **Evaluation of statistical uncertainty bands**
- **....**

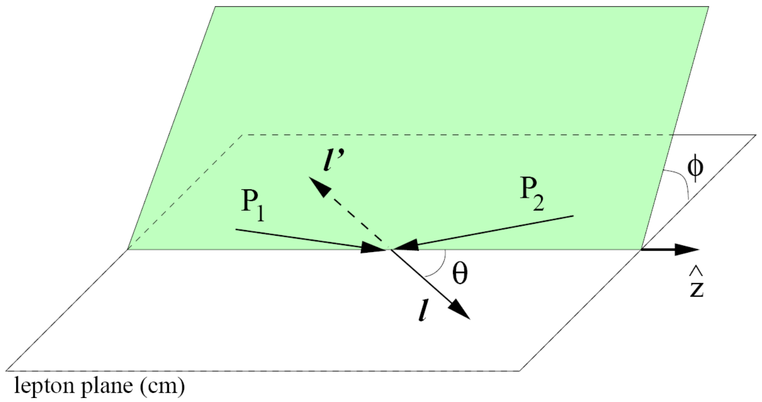
Semi-Inclusive DIS | Drell-Yan | Dihadron in e+e-

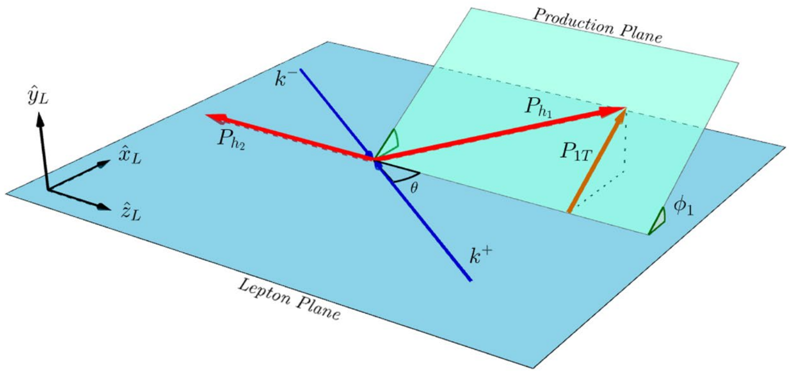




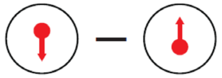




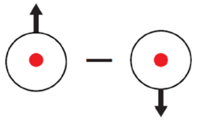




Cross section for SIDIS process, $e(\lambda_e)p(S) \to e'\,h + X$

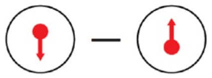
$h_1^\perp$ = 

Boer-Mulders,Cahn,...

$f_{1T}^\perp$ = 

Sivers

Collins

$H_1^\perp$ = 

Worm-gear $g_{1T}^\perp$

$$
\begin{aligned}
\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = \;& \frac{\alpha^2}{xyQ^2}\,\frac{y^2}{2\,(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Bigg\{F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h} \\
& + \varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h} + \lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h} \\
& + S_\parallel\left[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_h\,F_{UL}^{\sin\phi_h} + \varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\right] \\
& + S_\parallel\lambda_e\left[\sqrt{1-\varepsilon^2}\,F_{LL} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_h\,F_{LL}^{\cos\phi_h}\right] \\
& + |\boldsymbol{S}_\perp|\left[\sin(\phi_h-\phi_S)\left(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon\,F_{UT,L}^{\sin(\phi_h-\phi_S)}\right)\right. \\
& \quad + \varepsilon\,\sin(\phi_h+\phi_S)\,F_{UT}^{\sin(\phi_h+\phi_S)} + \varepsilon\,\sin(3\phi_h-\phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)} \\
& \quad \left. + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_S\,F_{UT}^{\sin\phi_S} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin(2\phi_h-\phi_S)\,F_{UT}^{\sin(2\phi_h-\phi_S)}\right] \\
& + |\boldsymbol{S}_\perp|\lambda_e\left[\sqrt{1-\varepsilon^2}\,\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_S\,F_{LT}^{\cos\phi_S}\right. \\
& \quad \left. + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos(2\phi_h-\phi_S)\,F_{LT}^{\cos(2\phi_h-\phi_S)}\right]\Bigg\},
\end{aligned}
$$

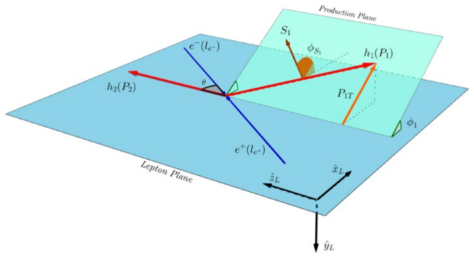
Boer-Mulders,Cahn,...

Worm-gear $h_{1L}^\perp$

Pretzelosity $h_{1T}^\perp$

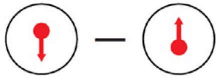
Most of them measured at HERMES, COMPASS, JLab

Cross section for SIA, $e^+e^- \to h_1(S_1)\, h_2 + X$



$$\frac{d\sigma^O(e^+e^- \to h_1 h_2 X)}{d\Omega\, dz_1\, dz_2\, d^2\boldsymbol{q}_T} = \frac{3\alpha^2}{Q^2} z_1^2 z_2^2 \Big\{ A(y)\mathcal{F}\left[D_1\overline{D}_1\right] + B(y)\cos(2\phi_1) \times \mathcal{F}\left[\left(2\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T\,\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T - \boldsymbol{k}_T\cdot\boldsymbol{p}_T\right)\frac{H_1^\perp \overline{H}_1^\perp}{M_1 M_2}\right]\Big\},$$

Collins azimuthal asymmetry

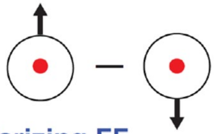
$H_1^\perp$ = 

Collins

Measured by Belle, BaBar, BESIII

$h_1 h_2$ both spin zero or unpolarized

$$\frac{d\sigma^O(e^+e^- \to h_1 h_2 X)}{d\Omega\, dz_1\, dz_2\, d^2\boldsymbol{q}_T} = \frac{3\alpha^2}{Q^2} z_1^2 z_2^2 \Big\{ \ldots + B(y)\lambda_1 \sin(2\phi_1) \times \mathcal{F}\left[\left(2\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T\,\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T - \boldsymbol{k}_T\cdot\boldsymbol{p}_T\right)\frac{H_{1L}^\perp \overline{H}_1^\perp}{M_1 M_2}\right]$$
$$- A(y)|\boldsymbol{S}_{1T}|\sin(\phi_1 - \phi_{S_1})\mathcal{F}\left[\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T\frac{D_{1T}^\perp \overline{D}_1}{M_1}\right]$$
$$+ B(y)|\boldsymbol{S}_{1T}|\sin(\phi_1 + \phi_{S_1})\mathcal{F}\left[\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T\frac{H_1 \overline{H}_1^\perp}{M_2}\right]$$
$$+ B(y)|\boldsymbol{S}_{1T}|\sin(3\phi_1 - \phi_{S_1}) \times \mathcal{F}\left[\left(4\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T)^2 - 2\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T\,\boldsymbol{k}_T\cdot\boldsymbol{p}_T - \hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T\,\boldsymbol{k}_T^2\right)\frac{H_{1T}^\perp \overline{H}_1^\perp}{2M_1^2 M_2}\right]\Big\}$$

$D_{1T}^\perp$ = 

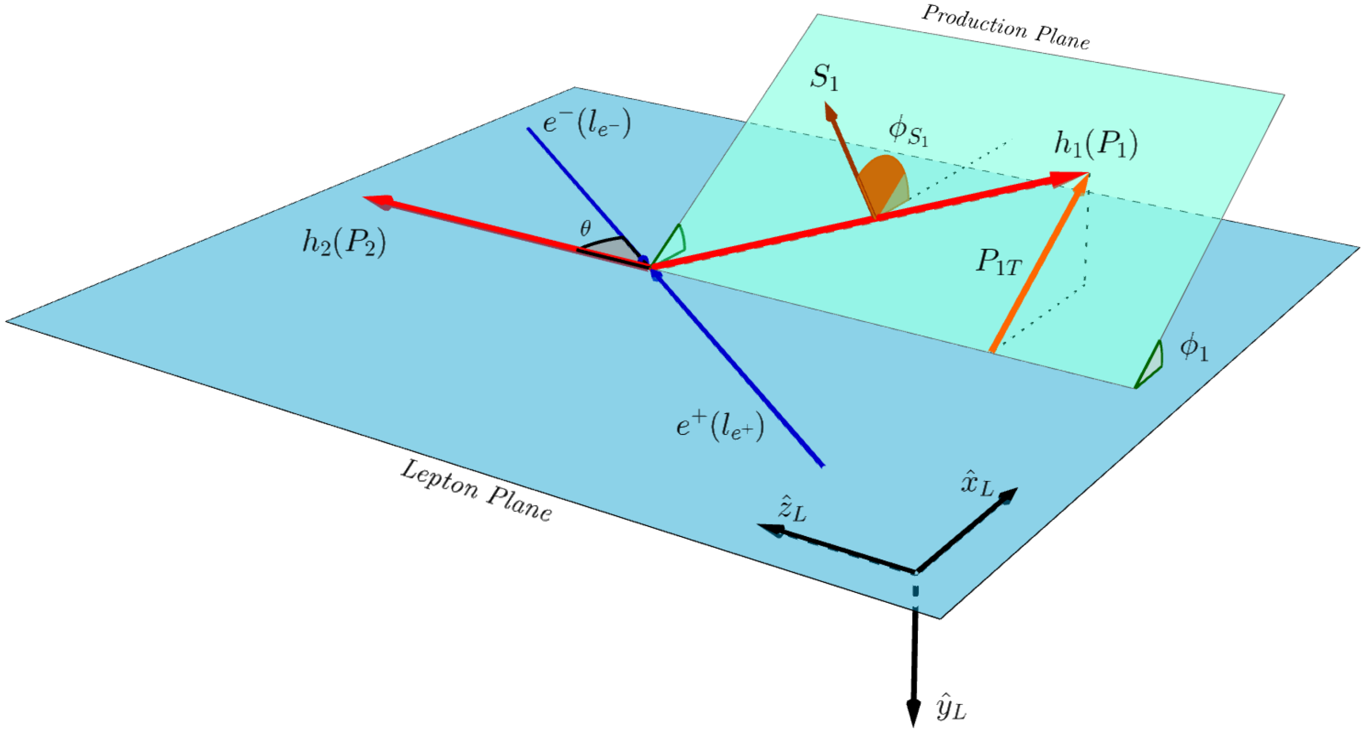
Polarizing FF

Transverse polarization with polFF

Measured by Belle

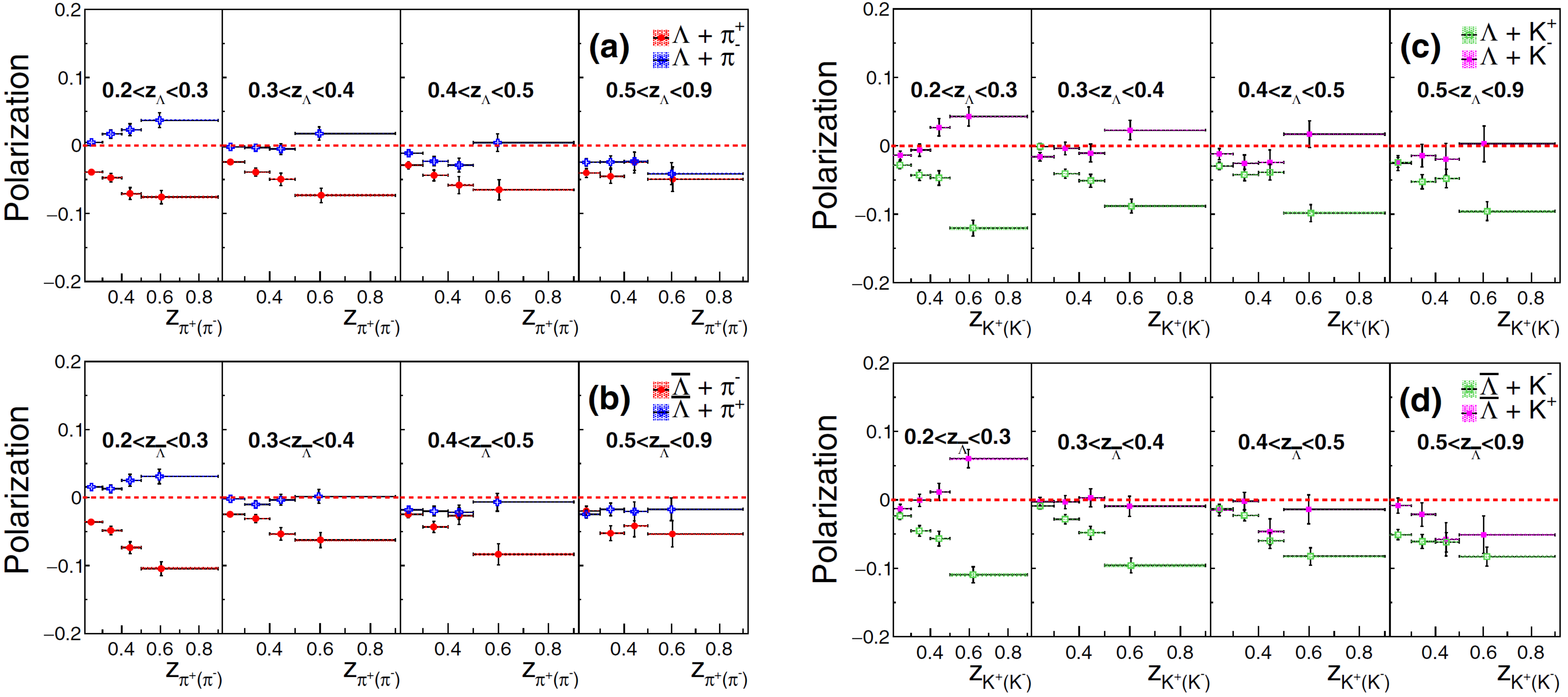
h_2 spin zero or unpolarized
h_1 polarized, spin 1/2

A Breakthrough: Belle results on transverse $\Lambda, \bar{\Lambda}$ polarization in $e^+e^- \to \Lambda(\bar{\Lambda}) + \pi^\pm, K^\pm + X$ [2019]



$$\frac{d\sigma^{e^+e^-\to h_1(S_1)h_2\,X}}{2dy\,dz_{h_1}dz_{h_2}d^2\boldsymbol{q}_T} = \sigma_0^{e^+e^-}\left[F_{UU} - |S_{1T}|\sin(\phi_1-\phi_{S_1})F_{TU}^{\sin(\phi_1-\phi_{S_1})} + \cdots\right]$$

Belle results on transverse $\Lambda, \bar{\Lambda}$ polarization in $e^+e^- \to \Lambda(\bar{\Lambda}) + \pi^\pm, K^\pm + X$



Belle Collaboration – PRL 122 042001 (2019)

Main ingredients of the TMD approach

$$P_n^{h_1}(z_{h_1}, z_{h_2}) = \frac{\int d^2\boldsymbol{q}_T\, F_{TU}^{\sin(\phi_1-\phi_{S_1})}}{\int d^2\boldsymbol{q}_T\, F_{UU}} = \frac{M_1 \int dq_T\; q_T\; d\phi_1\, \mathcal{B}_1\left[\widetilde{D}_{1T}^{\perp(1)}\,\widetilde{\bar{D}}_1\right]}{\int dq_T\; q_T\; d\phi_1\, \mathcal{B}_0\left[\widetilde{D}_1\,\widetilde{\bar{D}}_1\right]}$$

$$\mathcal{B}_0\left[\widetilde{D}_1\widetilde{\bar{D}}_1\right] = \frac{1}{z_1^2 z_2^2}\sum_q e_q^2 \int \frac{db_T}{2\pi}\, b_T J_0(b_T\, q_T)\, d_{h_1/q}(z_1;\bar{\mu}_b)\, d_{h_2/\bar{q}}(z_2;\bar{\mu}_b)$$
$$\times\; M_{D_1}(b_c(b_T), z_1)\, M_{D_2}(b_c(b_T), z_2)\, e^{-g_K(b_c(b_T);b_{\max})\ln\left(\frac{Q^2 z_1 z_2}{M_1 M_2}\right) - S_{\text{pert}}(b_*;\bar{\mu}_b)}$$

Collinear unpol FFs

b_T-dependent term for the FFs - parametrized

Collins-Soper kernel – parametrized
Lattice QCD calculations available

$$\mathcal{B}_1\left[\widetilde{D}_{1T}^{\perp(1)}\widetilde{\bar{D}}_1\right] = \frac{1}{z_1^2 z_2^2}\sum_q e_q^2 \int \frac{db_T}{2\pi}\, b_T^2 J_1(b_T\, q_T)\, D_{1T}^{\perp(1)}(z_1;\bar{\mu}_b)\, d_{h_2/\bar{q}}(z_2;\bar{\mu}_b)$$
$$\times\; M_{D_1}^{\perp}(b_c(b_T), z_1)\, M_{D_2}(b_c(b_T), z_2)\, e^{-g_K(b_c(b_T);b_{\max})\ln\left(\frac{Q^2 z_1 z_2}{M_1 M_2}\right) - S_{\text{pert}}(b_*;\bar{\mu}_b)}$$

Collinear term of polFF - parametrized

b_T-dependent term of polFF - parametrized

Sudakov factor pertubatively calculable

Main ingredients and parametrizations

$$D_{1T,\Lambda/q}^{\perp(1)}(z;\mu_b) = \mathcal{N}_q^{\rm p}(z)\, d_{\Lambda/q}(z;\mu_b)$$

$$\mathcal{N}_q^{\rm p}(z) = N_q z^{a_q}(1-z)^{b_q}\frac{(a_q+b_q)^{(a_q+b_q)}}{a_q^{a_q} b_q^{b_q}}$$

$$M_{D,\Lambda}^{\perp}(b_T,z) = \exp\left(-\frac{\langle p_\perp^2\rangle_{\rm p} b_T^2}{4z_p^2}\right)$$

For pions and kaons, from MAP coll.

$$M_D(b_T,z) = \frac{g_3\, e^{-b_T^2 \frac{g_3}{4z^2}} + \frac{\lambda_F}{z^2} g_4^2 (1 - g_4 \frac{b_T^2}{4z^2}) e^{-b_T^2 \frac{g_4}{4z^2}}}{g_3 + \frac{\lambda_F}{z^2} g_4^2}$$

$$M_D(b_T,z,p,m) = \frac{2^{2-p}}{\Gamma(p-1)}(b_T m/z_p)^{p-1} K_{p-1}(b_T m/z_p)$$

For Lambda's – Boglione, Simonelli

Data selection: $z_{\pi.K}$ [0.5-0.9] bin excluded → 96 data points (128)

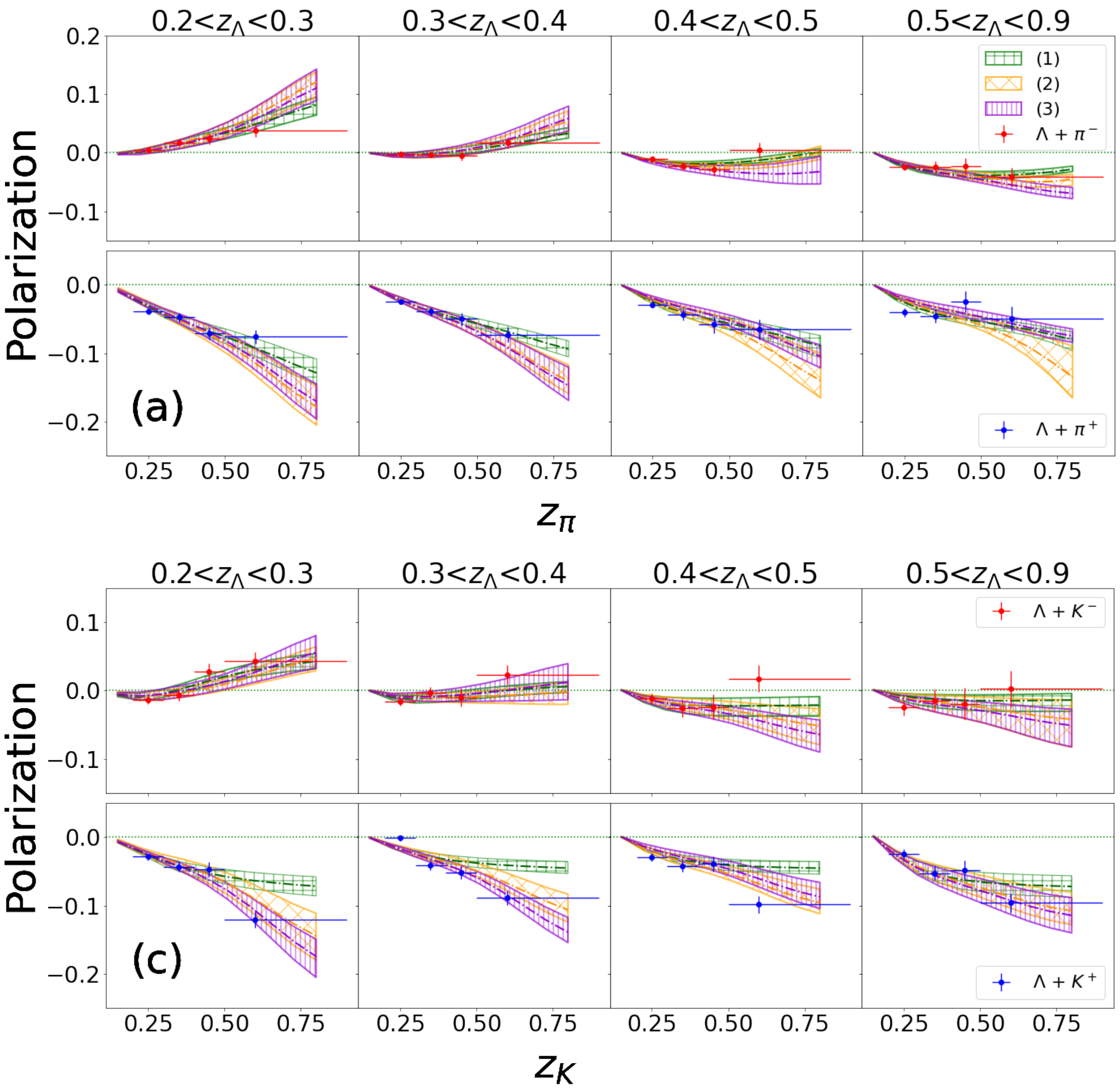
Three possible scenarios for TMD polarizing FFs:

- **Sc.1: No SU(2) isospin symmetry constraint for u,d quarks, no charm contribution (8 par.'s)**
- **Sc.2: No SU(2) symmetry constraint, charm contribution in the unpol. cross section (9 par.'s)**
- **Sc.3: SU(2) Symmetry, , charm contribution in the unpol. cross section(9 parameters)**

χ^2_{dof}
96 pts
1.17
1.26
1.36

Notice: Attempts to also include for Sc.s 2,3 the charm polFF, fits inconclusive, needs more data!

Data description



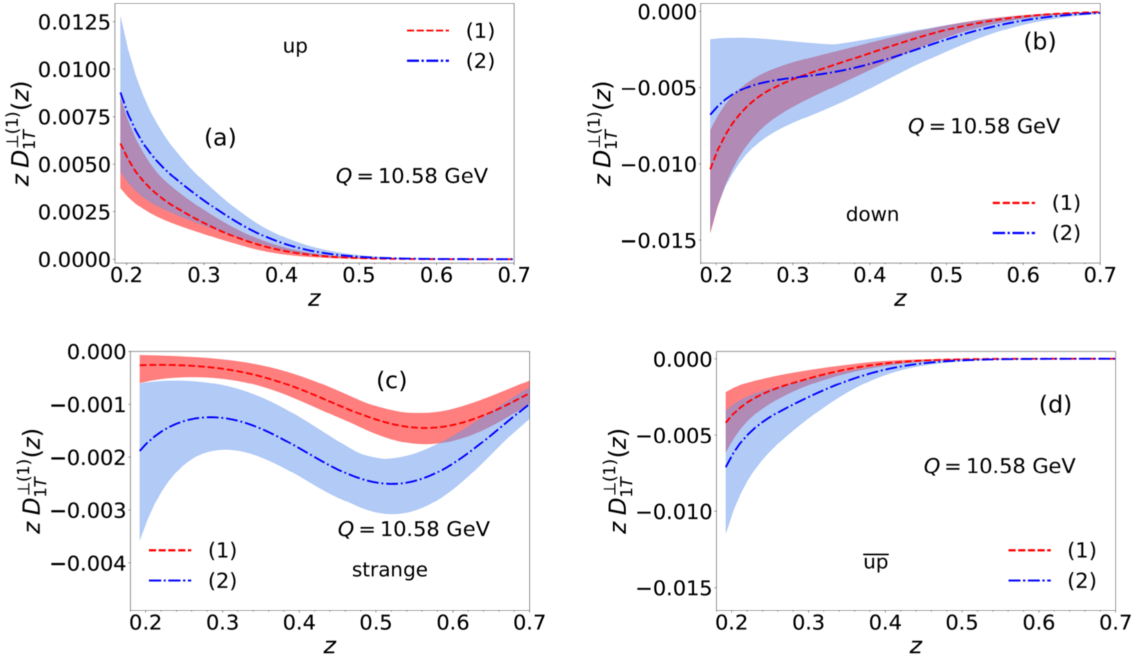
D'Alesio, FM, Zaccheddu – PRD 102 054001 (2020)
D'Alesio, Gamberg, FM, Zaccheddu – JHEP 12 (2022) 74, PRD 108 094004 (2023)

See also:
Callos, Kang, Terry, PRD 102 096007 (2020)
Gamberg, Kang, Shao, Terry, Zhao – PLB 818 136371 (2021)
Kang, Terry, Vossen, Xu, Zhang - PRD 105 094033 (2022)
Chen, Liang, Pang, Song, Wei – PLB 816 136217 (2021)
Li, Wang, Yang, Lu – EPJC 81 289 (2021)

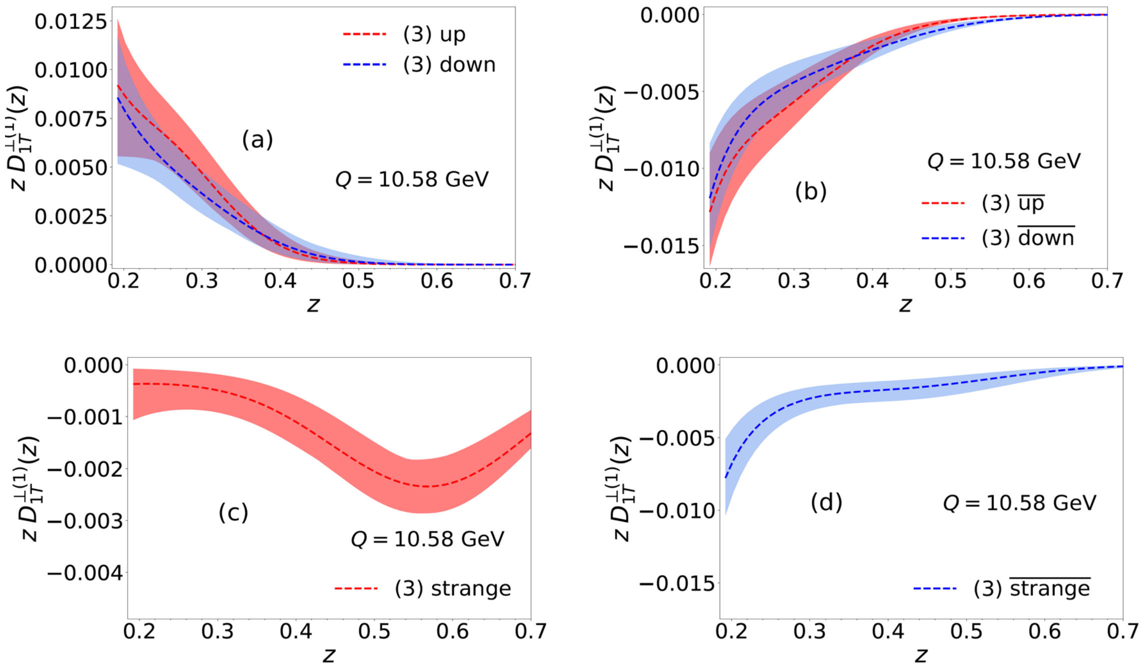
- **Good overall agreement with data for all 3 scenarios**
- **In all cases Sc.s 1,2,3 very similar at small z_π, z_K**
- **Sc. 1 [no SU(2)/no charm] unable to describe the $z_K > 0.5$ bins for $\Lambda + K^+$production (notice: $z_{\pi,K} > 0.5$ bins are NOT included in the fit!)**
- **Sc.s 2, 3 (charm included) give very similar results**
- **Uncertainty bands are only statistical**

First k_T-moments of the polFF in the 3 scenarios

Scenarios 1, 2 [NO SU(2) sym, without/with charm]

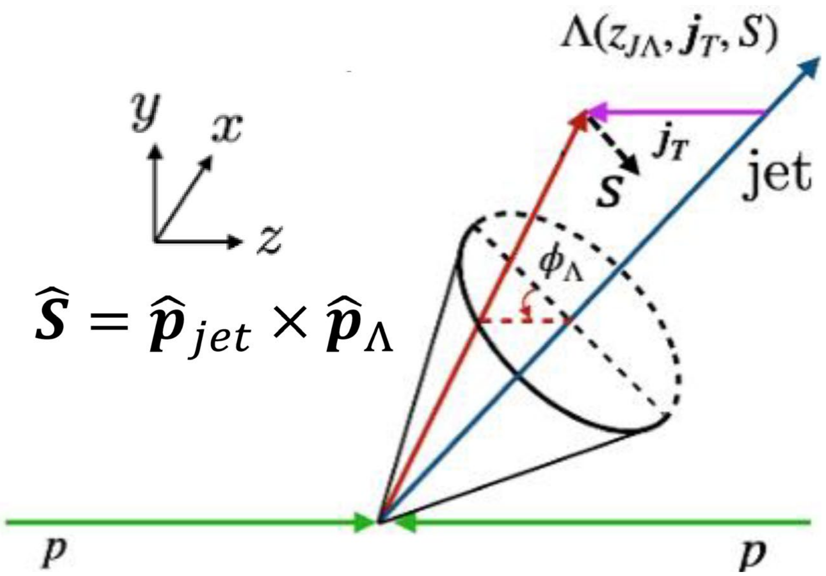


Scenario 3 [SU(2) sym with charm]

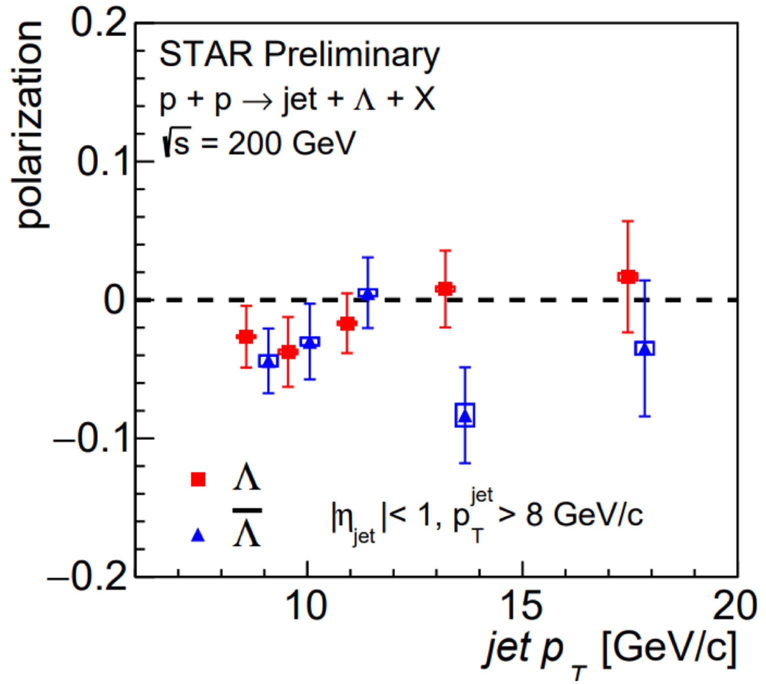


D'Alesio, Gamberg, FM, Zaccheddu – PRD 108 094004 (2023)

STAR preliminary results for transverse $\Lambda, \bar{\Lambda}$ polarization in unpolarized $pp \to \Lambda^{\uparrow} + jet + X$ [2023]

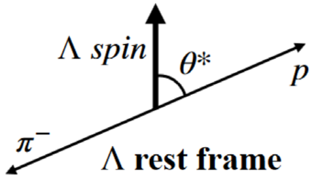


$$\hat{S} = \hat{p}_{jet} \times \hat{p}_{\Lambda}$$



$$\frac{dN}{d\cos\theta^*} \propto (1 + \alpha P \cos\theta^*)$$

$\alpha = 0.732 \pm 0.014$
P: Λ polarization
θ^*: angle between p and spin direction



$p_{\perp\Lambda} \leq 1.6$ GeV/c, $0 \leq z \leq 1$,

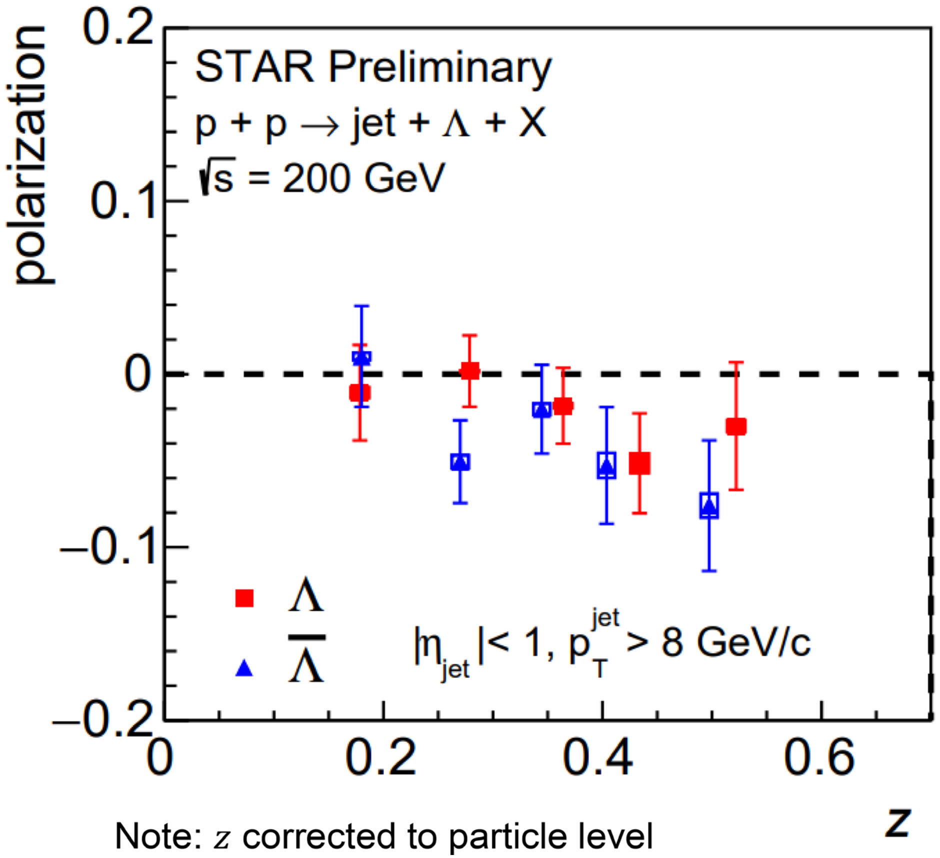
$8 \leq p_{jT} \leq 25$ GeV/c with $\langle p_{jT} \rangle = 11$ GeV/c

$|\eta_j| \leq 1.0$, $p_{T\Lambda} \leq 10$ GeV/c, $|\eta_\Lambda| \leq 1.5$,

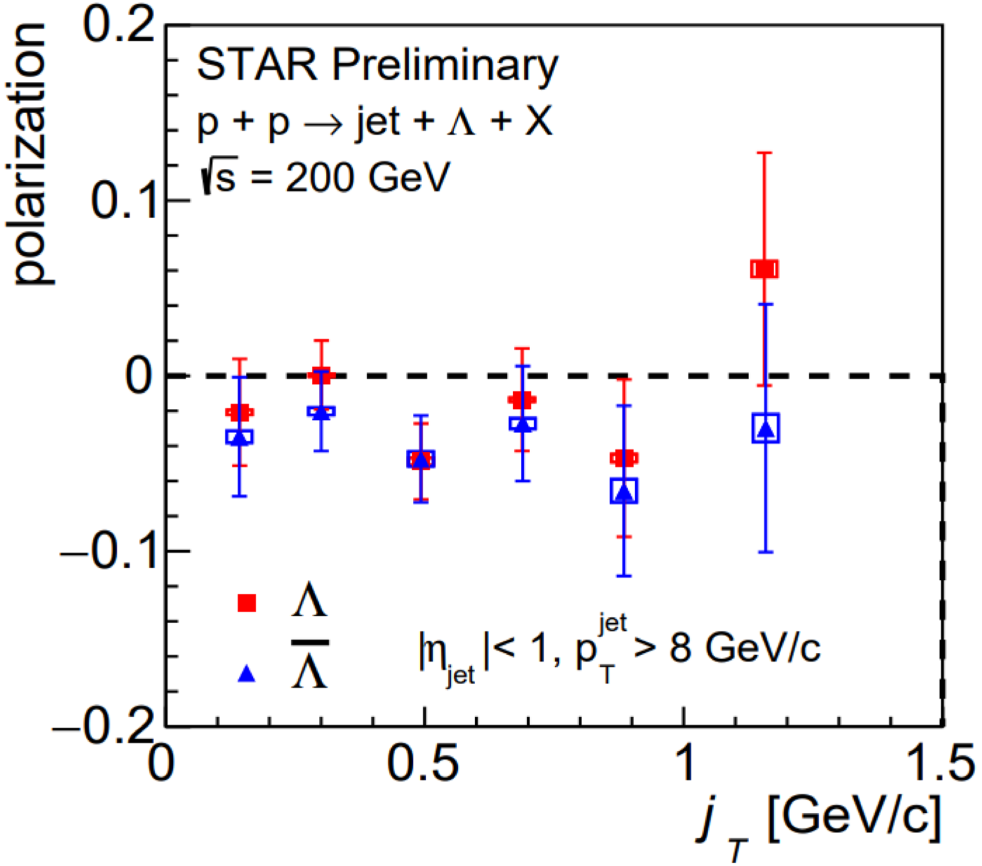
Jet reconstruction: Anti-k_T algorithm, $R = 0.6$

T. Gao, SPIN2023 - 2402.01168 [hep-ex]

STAR preliminary results for transverse $\Lambda, \bar{\Lambda}$ polarization in unpolarized $pp \to \Lambda^{\uparrow} + jet + X$



Note: z corrected to particle level



T. Gao, SPIN2023 - 2402.01168 [hep-ex]

TMD factorization for $pp \to H\ in\ jet + X$ proved in a hybrid scheme with TMD effects only in the fragmentation process

Yuan – PRL100 032003 (2008); see also D'Alesio, FM, Pisano – PRD 83 034021 (2011)

$$P_T^\Lambda(\boldsymbol{p}_\mathrm{j}, \xi, \boldsymbol{p}_{\perp\Lambda}) = \frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\uparrow + d\sigma^\downarrow} = \frac{d\Delta\sigma}{d\sigma_\mathrm{unp}}$$

$$d\sigma^{\uparrow(\downarrow)} \equiv E_\mathrm{j} \frac{d\sigma^{AB\to \mathrm{jet}\, \Lambda^{\uparrow(\downarrow)} X}}{d^3\boldsymbol{p}_\mathrm{j} d\xi d^2\boldsymbol{p}_{\perp\Lambda}}$$

$$\Delta D_{\Lambda^\uparrow/c}(\xi, p_{\perp\Lambda}) = \frac{p_{\perp\Lambda}}{\xi m_\Lambda} D_{1T}^{\perp c}(\xi, p_{\perp\Lambda})$$

$$d\Delta\sigma = \sum_{a,b,c,d} \int \frac{dx_a}{x_a s - \sqrt{s} E_\mathrm{j}(1+\cos\theta_\mathrm{j})} \frac{\alpha_s^2}{\hat{s}} \times f_{a/A}(x_a) f_{b/B}(x_b)\, |\overline{M}|^2\, \Delta D_{\Lambda^\uparrow/c}(\xi, p_{\perp\Lambda})$$

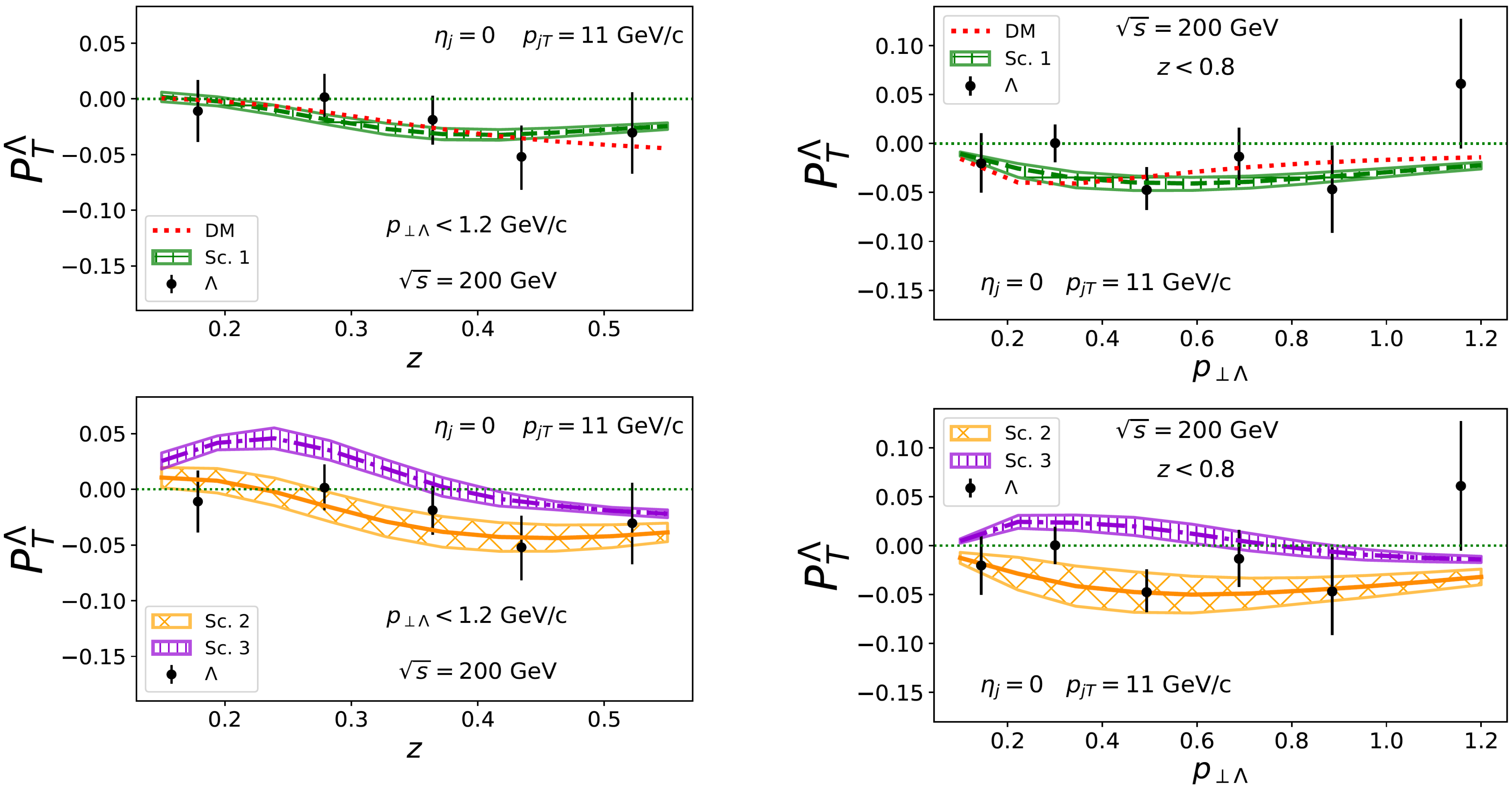
$$d\sigma_\mathrm{unp} = \sum_{a,b,c,d} \int \frac{dx_a}{x_a s - \sqrt{s} E_\mathrm{j}(1+\cos\theta_\mathrm{j})} \frac{\alpha_s^2}{\hat{s}} \times f_{a/A}(x_a) f_{b/B}(x_b)\, |\overline{M}|^2\, D_{\Lambda/c}(\xi, p_{\perp\Lambda}),$$

$$x_b = \frac{x_a E_\mathrm{j}(1-\cos\theta_\mathrm{j})}{x_a\sqrt{s} - E_\mathrm{j}(1+\cos\theta_\mathrm{j})}.$$

- **Estimates provided at $\eta_j = 0, p_{jT} = 11\ \mathrm{GeV}/c, z \le 0.8, p_{\perp\Lambda} \le 1.2\ \mathrm{GeV}/c$**
- **Polarizing FFs as extracted from e^+e^- collisions (no evolution, very similar scales)**
- **Test of the theoretically predicted universality of TMD FFs**
- **Use of the three scenarios considered in e^+e^- collisions [+ one (DM) from a combined tentative fit to both inclusive Λ and $\Lambda+\pi, K\pi$ production]**

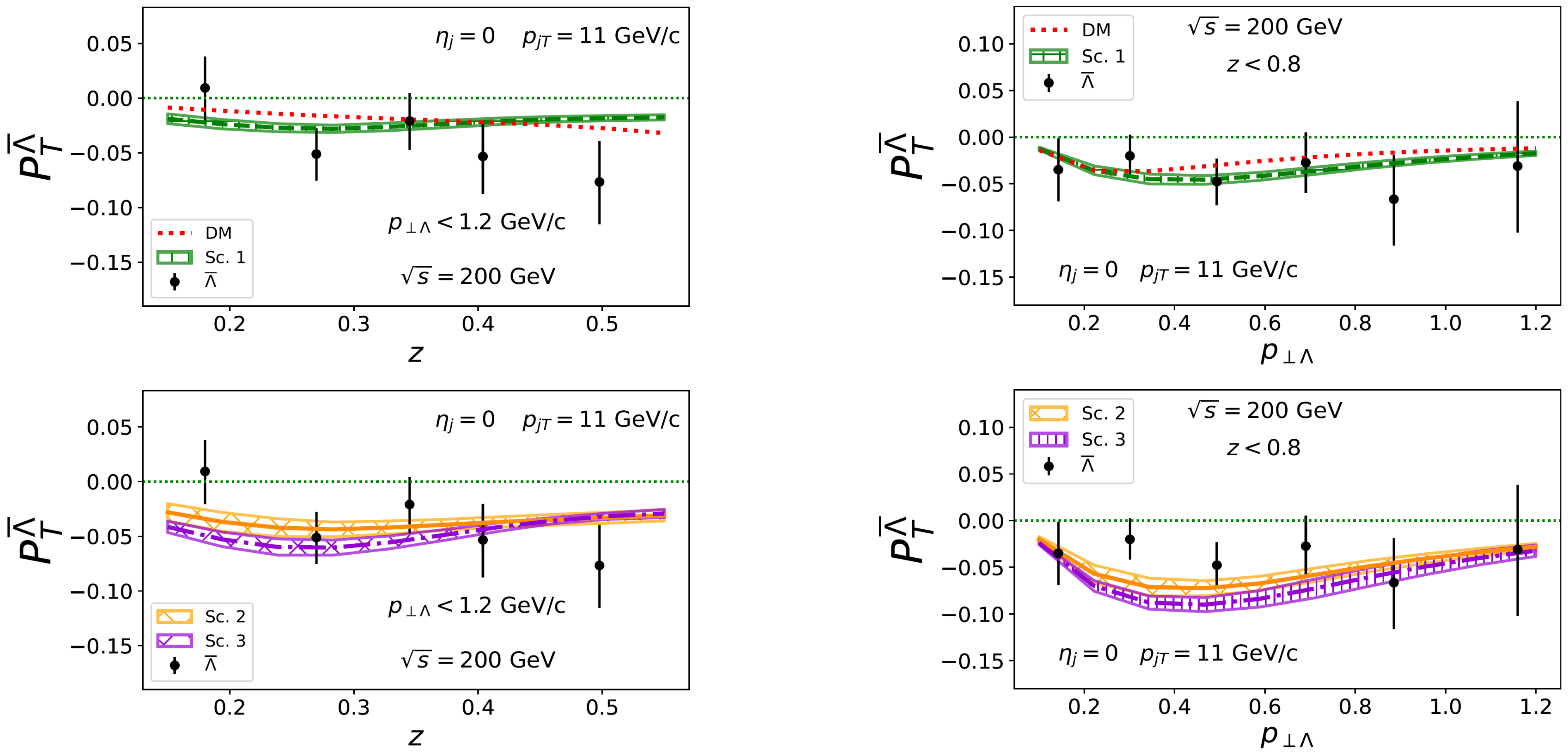
D'Alesio, Gamberg, FM, Zaccheddu PLB 851 138552 (2024)
See also similar studies with TMD jet functions (TMDJFFs):
Kang, Lee, Zhao – PLB 809 135756 (2020)

First theoretical estimates for $pp \to \Lambda^{\uparrow} + jet + X$



D'Alesio, Gamberg, FM, Zaccheddu – PLB 851 138552 (2024)

First theoretical estimates for $pp \to \bar{\Lambda}^{\uparrow} + jet + X$

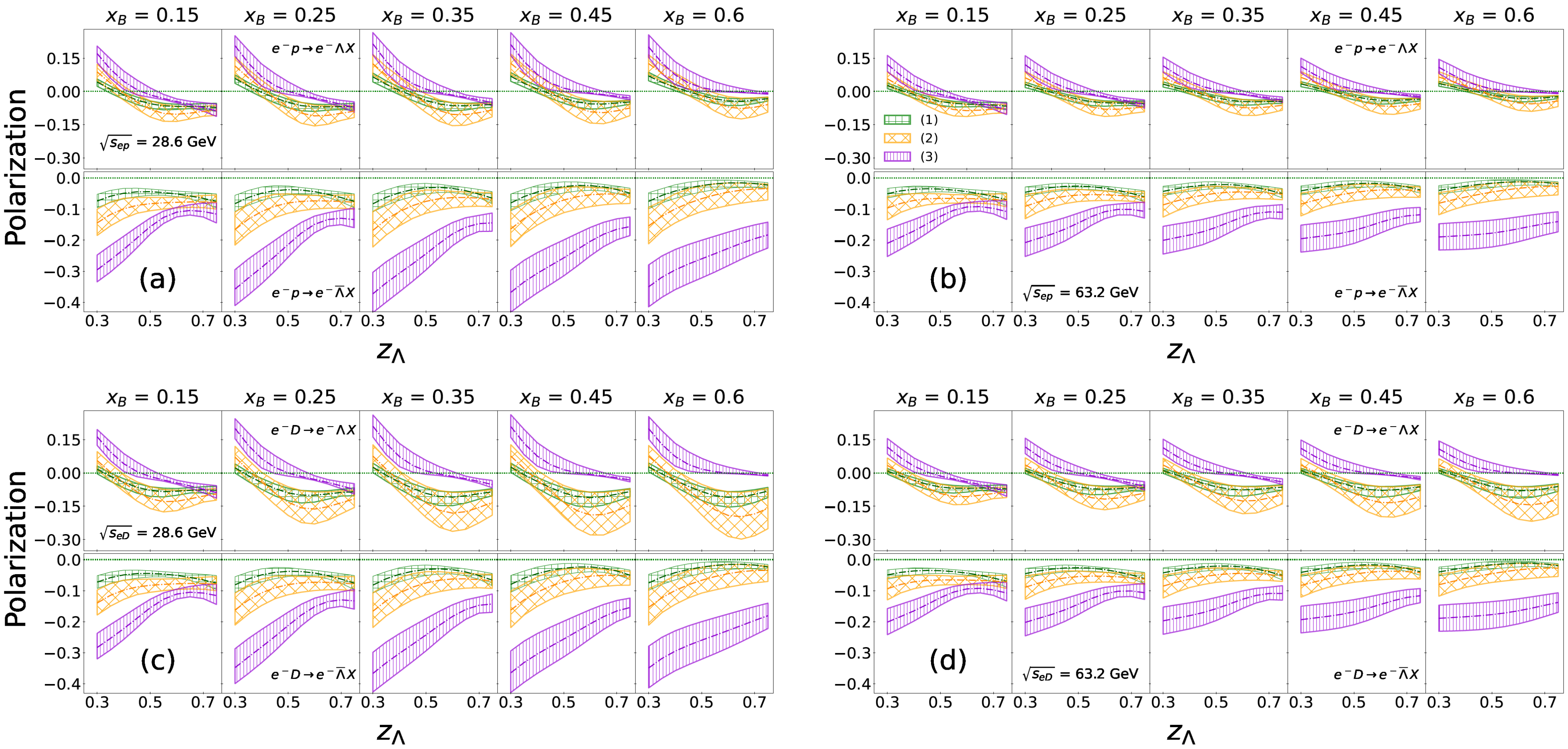


D'Alesio, Gamberg, FM, Zaccheddu – PLB 851 138552 (2024)

First theoretical estimates for $pp \to \Lambda^{\uparrow}, \bar{\Lambda}^{\uparrow} + jet + X$: remarks

- **Preliminary data, hybrid LO TMD approach at fixed scale: no strong conclusion on the results and the scenarios adopted**
- **General qualitative agreement with STAR data – in favour of the predicted universalilty of TMD FFs and the polarizing FF**
- **Sc. 1 [NO SU(2) symmetry, NO charm contribution] and SC. 2 [NO SU(2) symmetry, charm contr. In the unpol. cross section] describe reasonably well the data**
- **Sc. 3 [SU(2) symmetry, charm contribution] somewhat far from P_T^{Λ} data, both vs. z and $p_{\perp\Lambda}$**
- **Role of charm quark contribution apparently not so relevant as compared to e^+e^- case**
- **Role of SU(2) isospin symmetry remains to be clarified [SIDIS at EIC can help!]**

Theoretical estimates for $ep, eD \to \Lambda^{\uparrow}, \bar{\Lambda}^{\uparrow} + X$ at the EIC



Sc. 2 [NO SU(2) symmetry] and Sc. 3 [SU(2) constrained] are sizably different in some cases
EIC will be essential in claryfing the role of isospin symmetry for the polarizing FF!

Concluding remarks

- **Transverse hyperon polarization in unpolarized production processes: a longstanding puzzling phenomenon for pQCD approaches**

- **TMD approach can in principle provide a clean mechanism for spontaneous polarization in the hadronization phase through the TMD polarizing Fragmentation Function**

- **Older results from pp, pA collisions are more difficult to approach theoretically in pQCD (Factorization issues, one single scale, relatively small p_T range, …]**

- **Recent Belle data for $e^+e^- \rightarrow \Lambda^\uparrow, \bar{\Lambda}^\uparrow + \pi, K + X$ allowed for the first ever extraction of the Λ polFF in a full TMD approach (factorization and CSS evolution)**

- **Preliminary data from STAR at BNL on $pp \rightarrow \Lambda^\uparrow(\bar{\Lambda}^\uparrow)\ in\ jet + X$ offer the first chance to test the predicted universality of the TMD polarizing FF**

- **Future EIC results on spontaneous Lambda polarization will be crucial to clarify the role of SU(2) isospin symmetry and of charm contribution and reduce uncertainty bands**
- **Future Planned EIC-China**

Thanks for your attention!