Transversely polarized Λ production within a jet in unpolarized proton-proton collisions

TRANSVERSITY 2024

MARCO ZACCHEDDU – JEFFERSON LAB

IN COLLABORATION WITH: U. D'ALESIO, L. GAMBERG & F. MURGIA

Based on: *Phys.Lett.B* 851 (2024) 138552

Outline

- Motivations
- Hadron in jet in unpolarized proton-proton collisions $pp \to h(jet)X$
- Polarizing FF from Belle e^+e^-
- Predictions and comparison against STAR data

Motivations

Lambda Transverse Polarization: longstanding problem!

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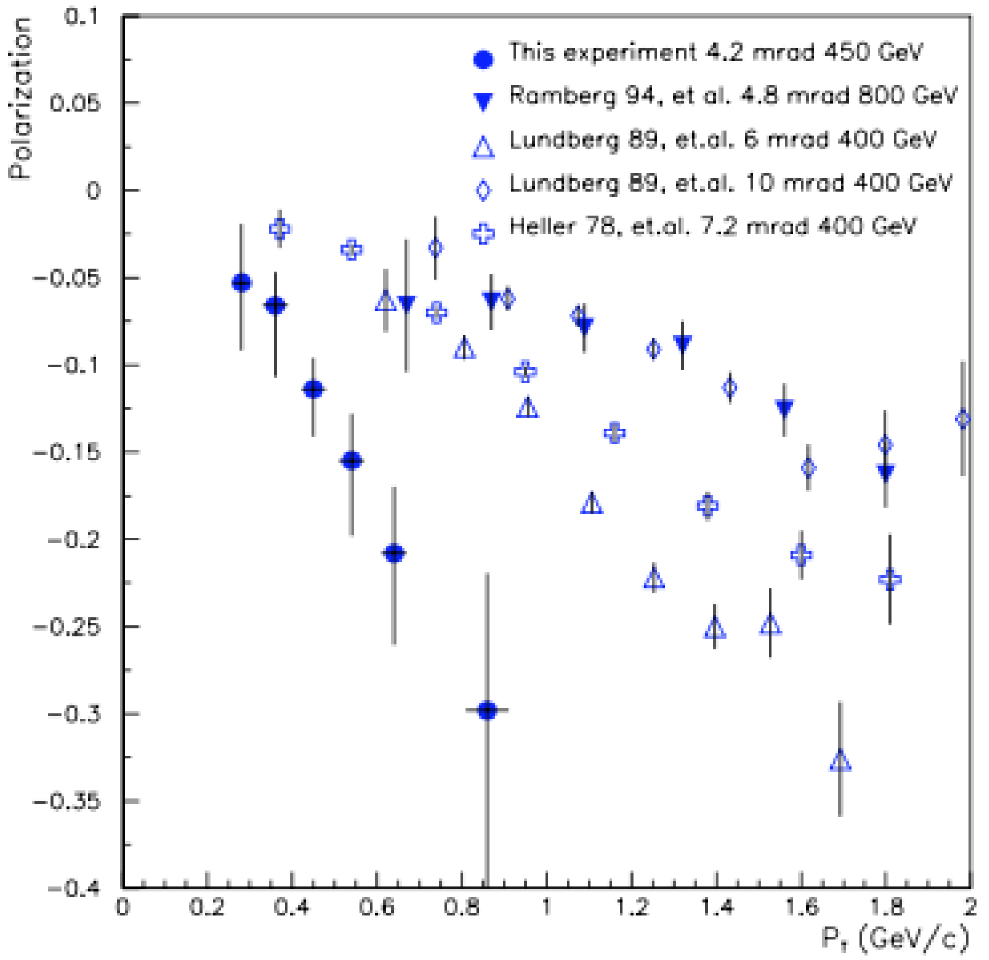

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Collinear pQCD not able to describe the size of the Polarization (at leading-twist)

$P_T \simeq 1 - 2\ \%$

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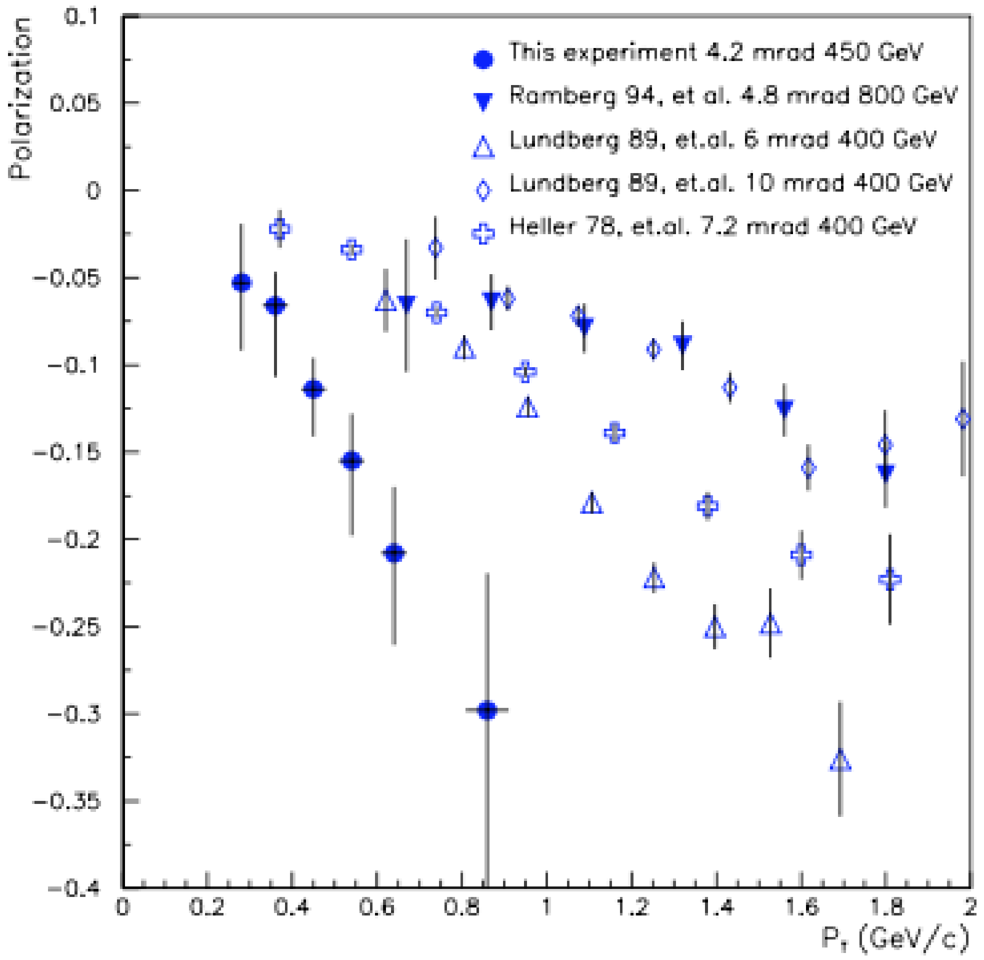

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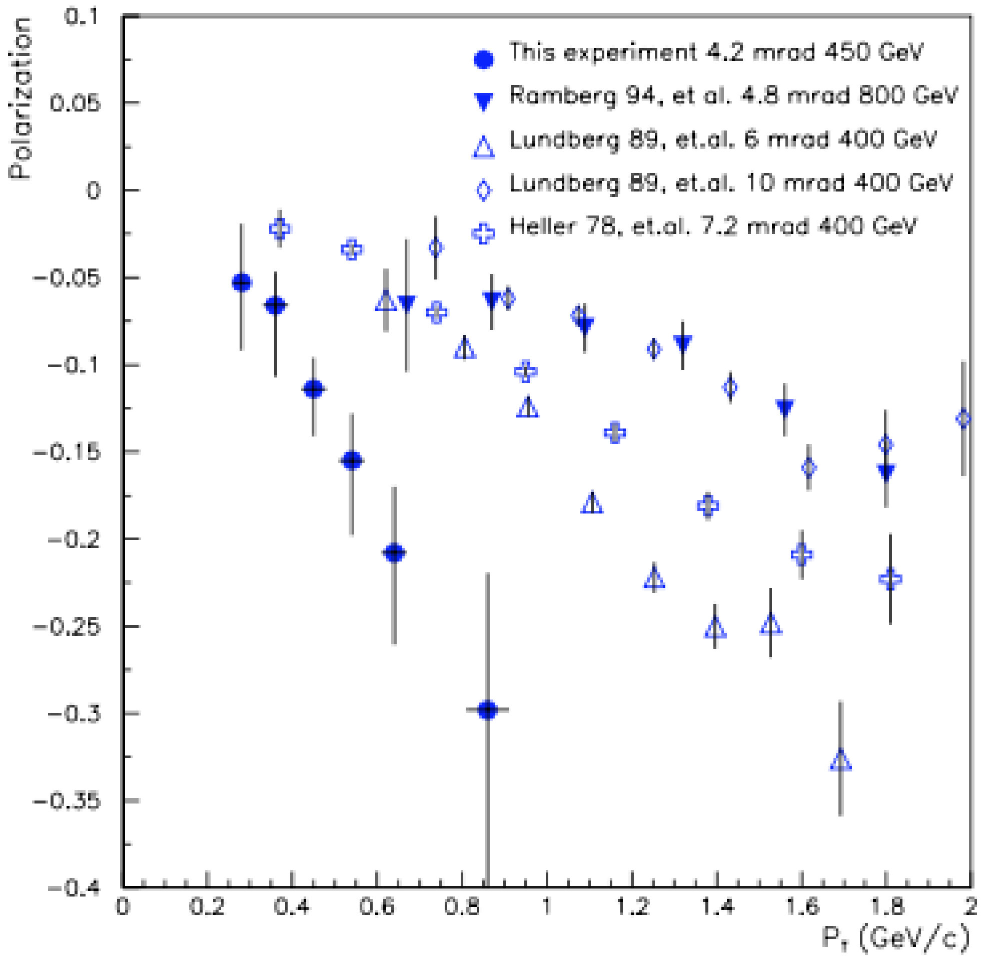

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Polarizing TMD-FF introduced

[P.J. Mulders and R.D. Tangerman, Nucl. Phys. B461, 197 (1996)]

Studied phenomenologically in a simplified TMD approach

[M. Anselmino, D. Boer, U. D'Alesio, and F. Murgia. Phys. Rev. D 63. 054029 (2001)]

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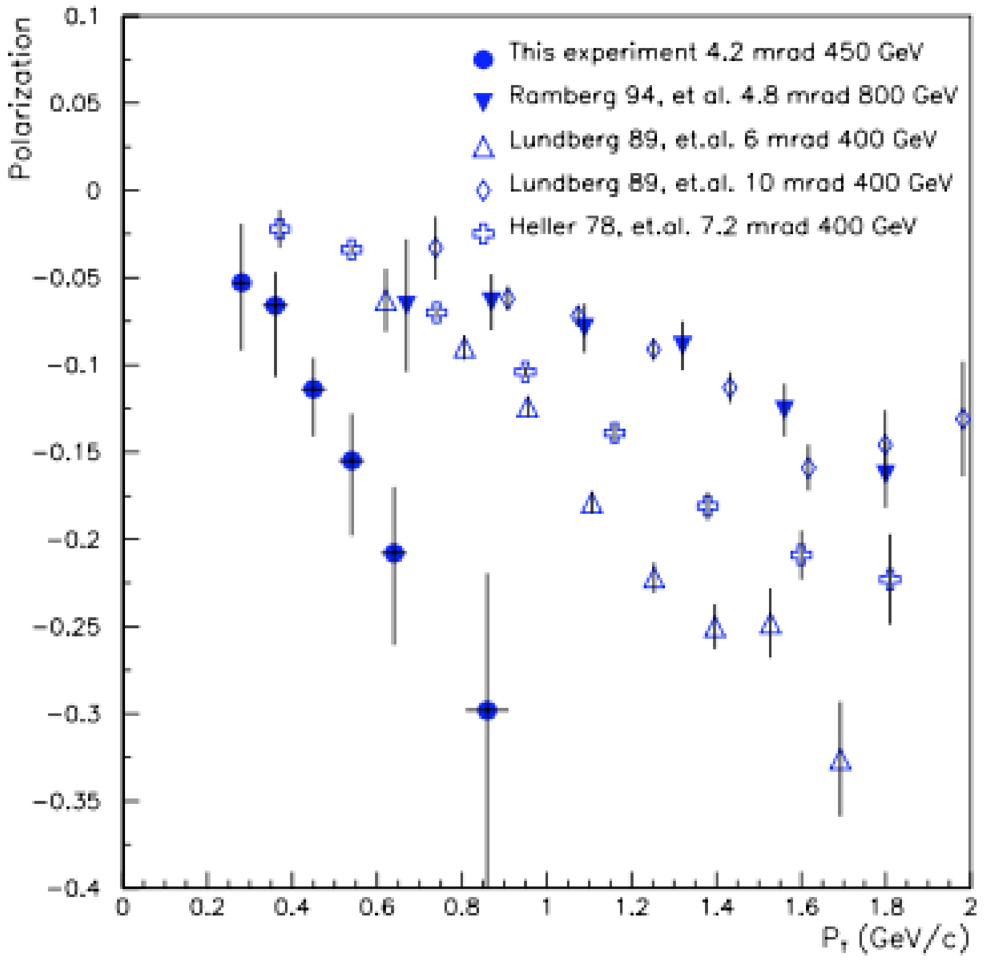

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Observation of Transverse $\Lambda/\bar{\Lambda}$ Hyperon Polarization in e^+e^- Annihilation at Belle

- 2 data set @$\sqrt{s} = 10.58$ GeV

[Y. Guan et al., Phys. Rev. Lett. 122. 042001 (2019)]

Double hadron production:

- $e^+e^- \rightarrow \Lambda\pi/K + X$

Single-inclusive hadron production:

- $e^+e^- \rightarrow \Lambda(jet) + X$

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- Chen, Liang, Pan, Song, Wei; *Phys.Lett.B 816 (2021) 136217* → *SU(2) isospin symmetry issue*

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Phenomenological analysis:

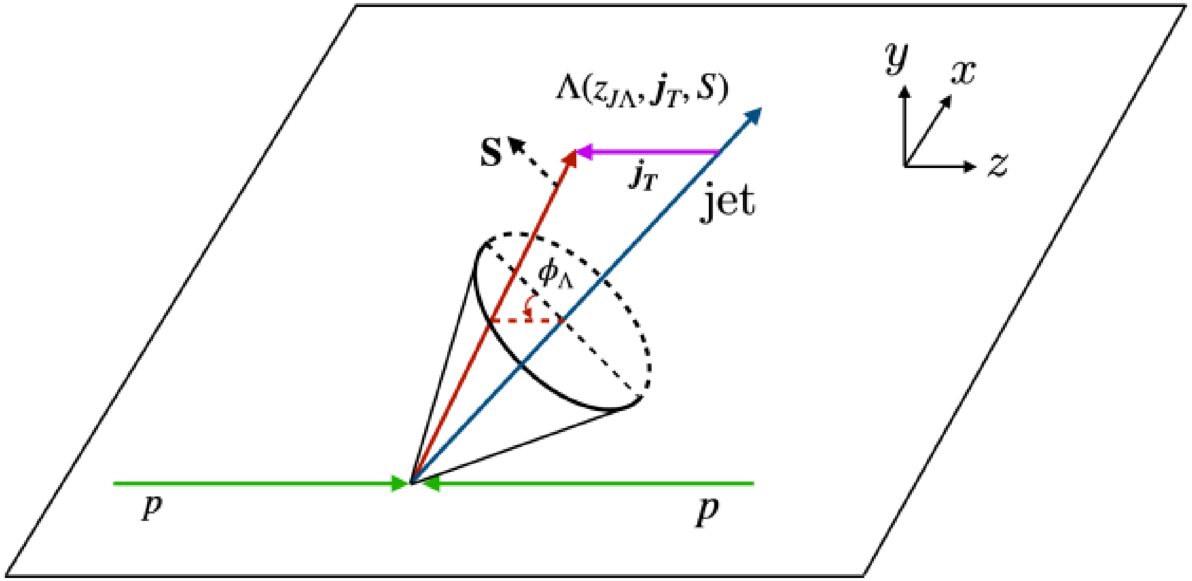
CSS scheme:

- D'Alesio, Gamberg, Murgia, MZ; *JHEP* 12 (2022) , PRD 108 (2023), → SU(2) isospin issue and predictions for SiDIS
- Li, Wang, Yang, Lu '21
- Gamberg, Kang, Shao, Terry, Zhao ,21

Unpolarized proton-proton collisions: $pp \to \Lambda\,(jet)X$

- Complementary to SiDIS and e^+e^-
- 2 scales:
  - p_{jT} T.M. of the jet
  - $\mathrm{p}_{\perp\Lambda}$ Lambda T.M. w.r.t. the jet
- Transverse momentum effects considered only for FFs

$$A(p_A)\,B(p_B) \to \mathrm{jet}(p_\mathrm{j})\,\Lambda^\uparrow(p_\Lambda)\,X$$



- Different studies for hadron in jet production:
  - Collins effect in pp collisions [Yuan ’08, D’Alesio, Murgia, Pisano ’11,’17; Kang et al.‘17]
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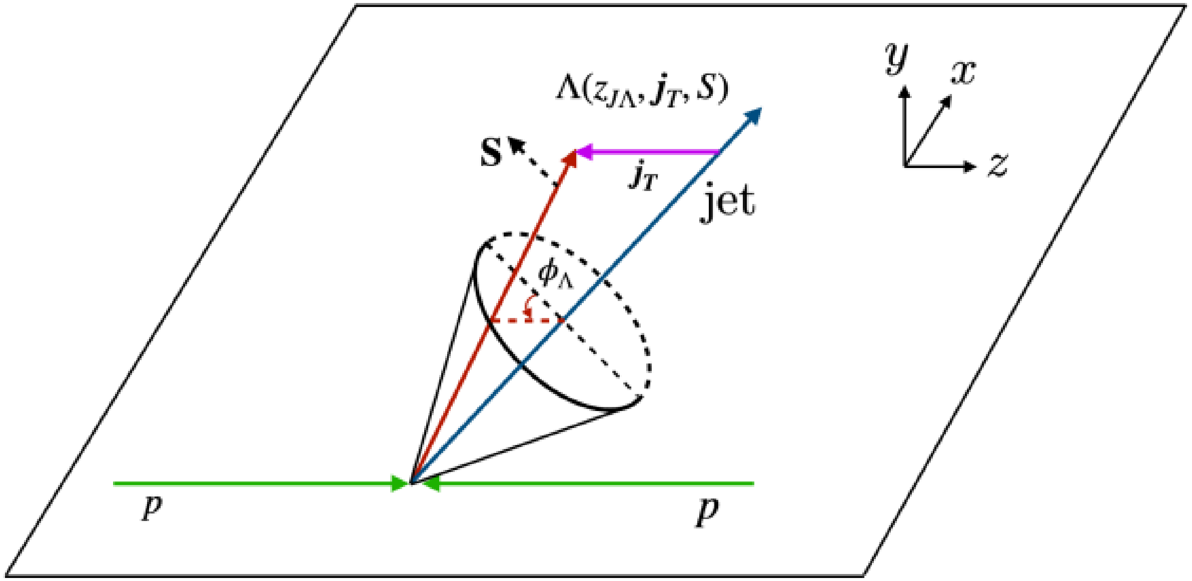

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NEW DATA from STAR for Λ transverse polarization

T. Gao @ SPIN2023: arxiv/2402.01168

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Transverse Polarization:

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

For more details see:
D'Alesio, Gamberg, Murgia, MZ; *Phys.Lett.B* 851 (2024) 138552

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Scaling variables

$$\begin{aligned} z_\Lambda &= E_\Lambda/E_{\rm j} \quad \text{(energy fraction)}\\ z_p &= |\boldsymbol{p}_\Lambda|/E_{\rm j} \quad \text{(momentum fraction)} \end{aligned}$$

Long. mom. fraction

$$z = \frac{\boldsymbol{p}_\Lambda\cdot\boldsymbol{p}_{\rm j}}{\boldsymbol{p}_{\rm j}^2} = \frac{\boldsymbol{p}_\Lambda\cdot\hat{\boldsymbol{p}}_{\rm j}}{E_{\rm j}} = \frac{\tilde{p}_{L\Lambda}}{E_{\rm j}}$$

Light-cone mom. fraction

$$\xi = \frac{E_\Lambda + \tilde{p}_{L\Lambda}}{2E_{\rm j}} = \frac{1}{2}\left[\sqrt{z^2 + (p_{\perp\Lambda}^2 + m_\Lambda^2)/E_{\rm j}^2} + z\right]$$

- Factorization scale al LO: $\mu = p_{jT}$
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Collinear PDFs

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Unp. Partonic cross section for quarks and gluons

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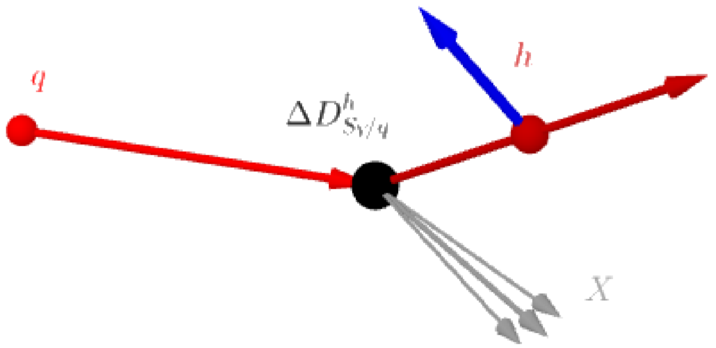
Polarizing FF

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



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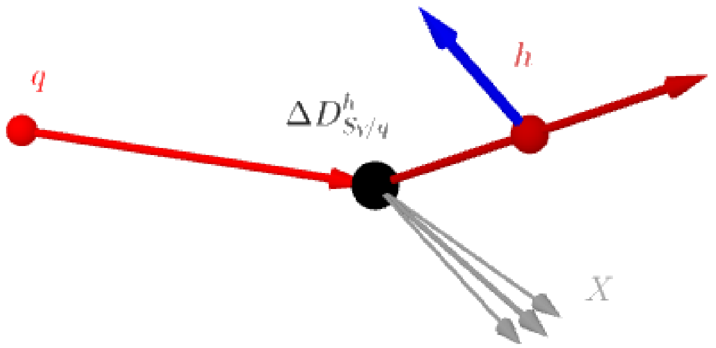
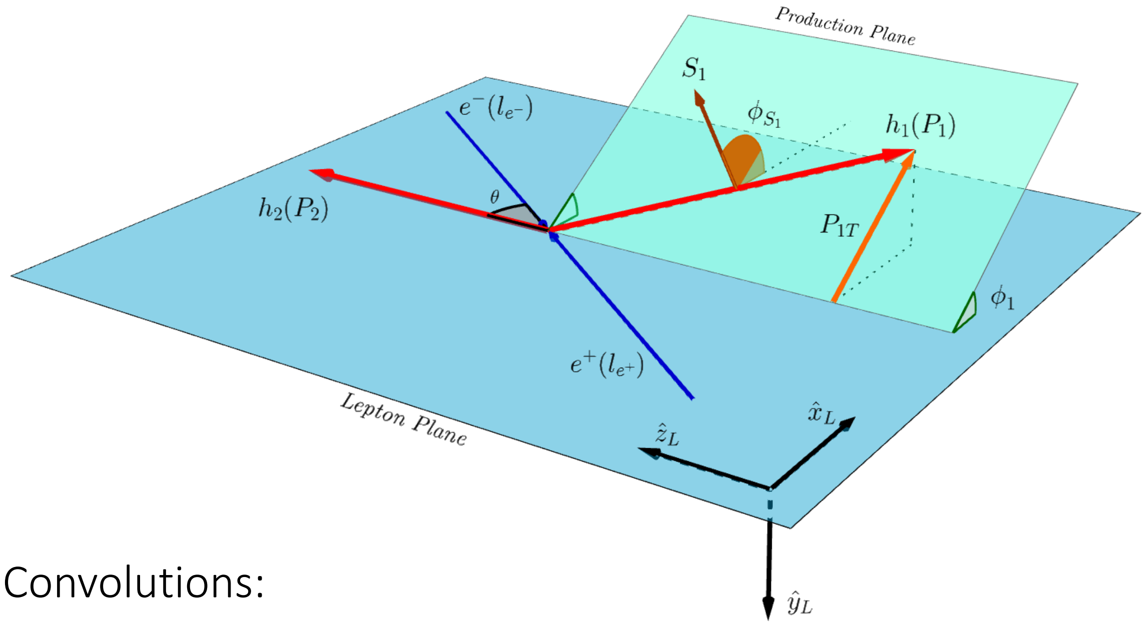


→ Extracted from e^+e^- Belle data
D'Alesio, Gamberg, Murgia, MZ; *JHEP* 12 (2022) , PRD 108 (2023)

Double hadron production in e^+e^- processes



Polarization:

$$P_n^{h_1}(z_{h_1}, z_{h_2}) = \frac{M_1 \int dq_T\, q_T\, d\phi_1\, \mathcal{B}_1\left[\widetilde{D}_{1T}^{\perp(1)}\, \widetilde{\bar{D}}_1\right]}{\int dq_T\, q_T\, d\phi_1\, \mathcal{B}_0\left[\widetilde{D}_1 \widetilde{\bar{D}}_1\right]}$$

Convolutions:

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

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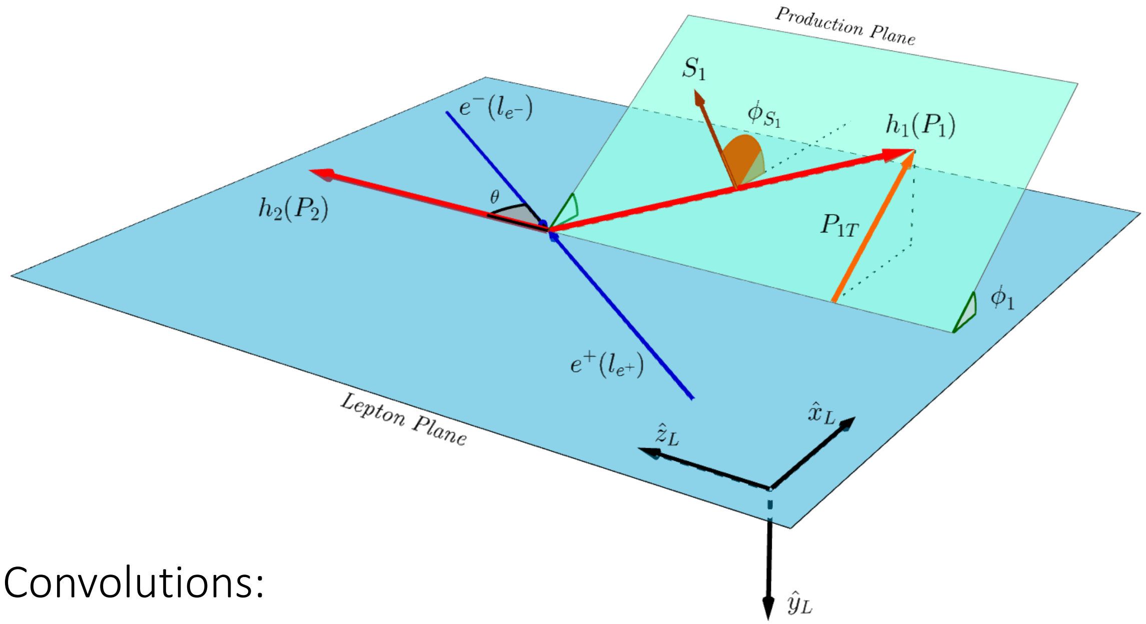

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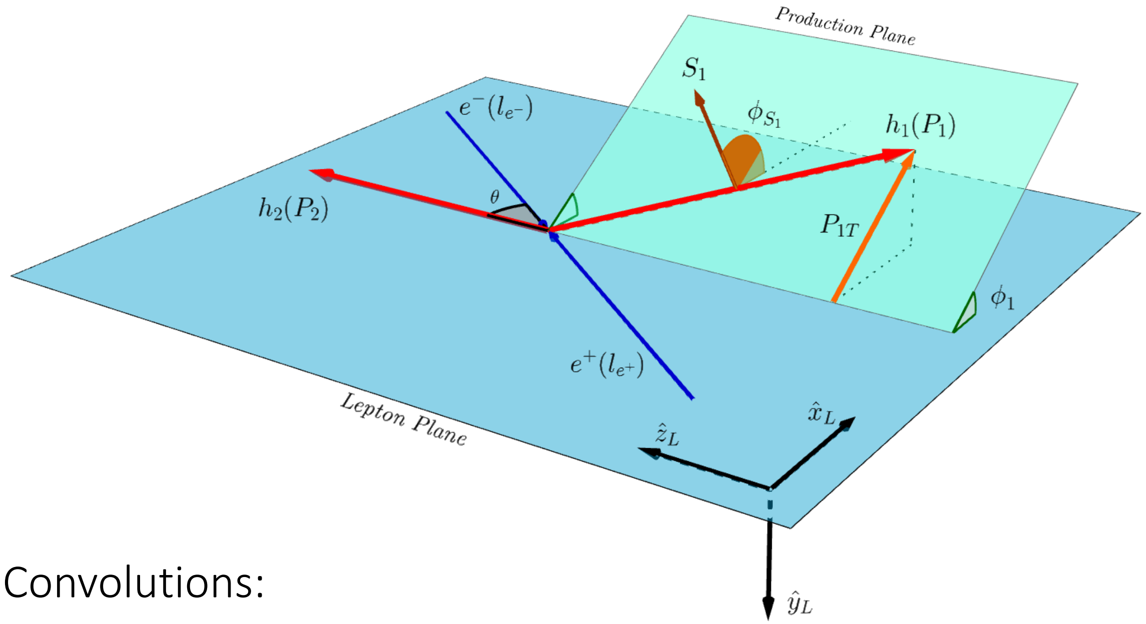

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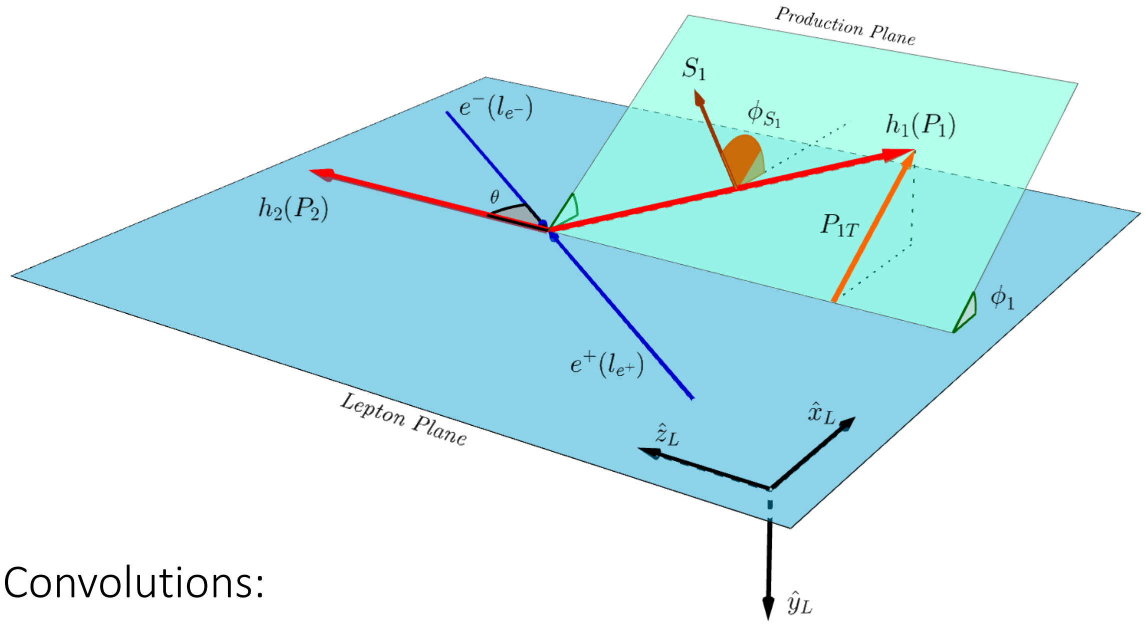

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$$\mathcal{B}_1\left[\widetilde{D}_{1T}^{\perp(1)}\,\widetilde{\bar{D}}_1\right] = \frac{1}{z_1^2 z_2^2}\sum_q e_q^2 \int \frac{db_T}{(2\pi)}\, b_T^2 J_1(b_T\, q_T)\, D_{1T}^{\perp(1)}(z_1;\bar{\mu}_b)\, d_{\bar{q}/h_2}(z_2;\bar{\mu}_b)$$
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Unpolarized FFs:
DSS set for π/K
AKK set for Λ

Non-perturbative functions from
Bacchetta et al., *JHEP* 06 (2017) 081

Double hadron production in e^+e^- processes

Data selection:

- $\Lambda + \pi/K$: $z_{\pi.K} = [0.5 \ - 0.9]$ bin excluded → 96 data points

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Functions to be extracted:

Polarizing FF first moment

$$\widetilde{D}^{\perp(1)}_{1T,\,\Lambda/q}(z;\mu_b) = \mathcal{N}^p_q(z) d_{q/\Lambda}(z;\mu_b)$$

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

Polarizing FF non-perturbative function

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

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u, d, s

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u, d, s + charm

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u, d, s + charm

Isospin symmetry

- No SU(2): N_u, N_d, N_s, N_{sea}
- SU(2): $N_u = N_d, N_{\bar{u}} = N_{\bar{d}}, N_s, N_{\bar{s}}$

See also:
Chen, Liang, Pan, Song, Wei;
Phys.Lett.B 816 (2021) 136217

Double hadron production in e^+e^- processes

Scenarios considered:

1. No Charm, No SU(2) sym.
   pFFs for: $up, down\ strange\ and\ sea;$

2. Charm, No SU(2) sym.
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3. Charm, SU(2) sym.
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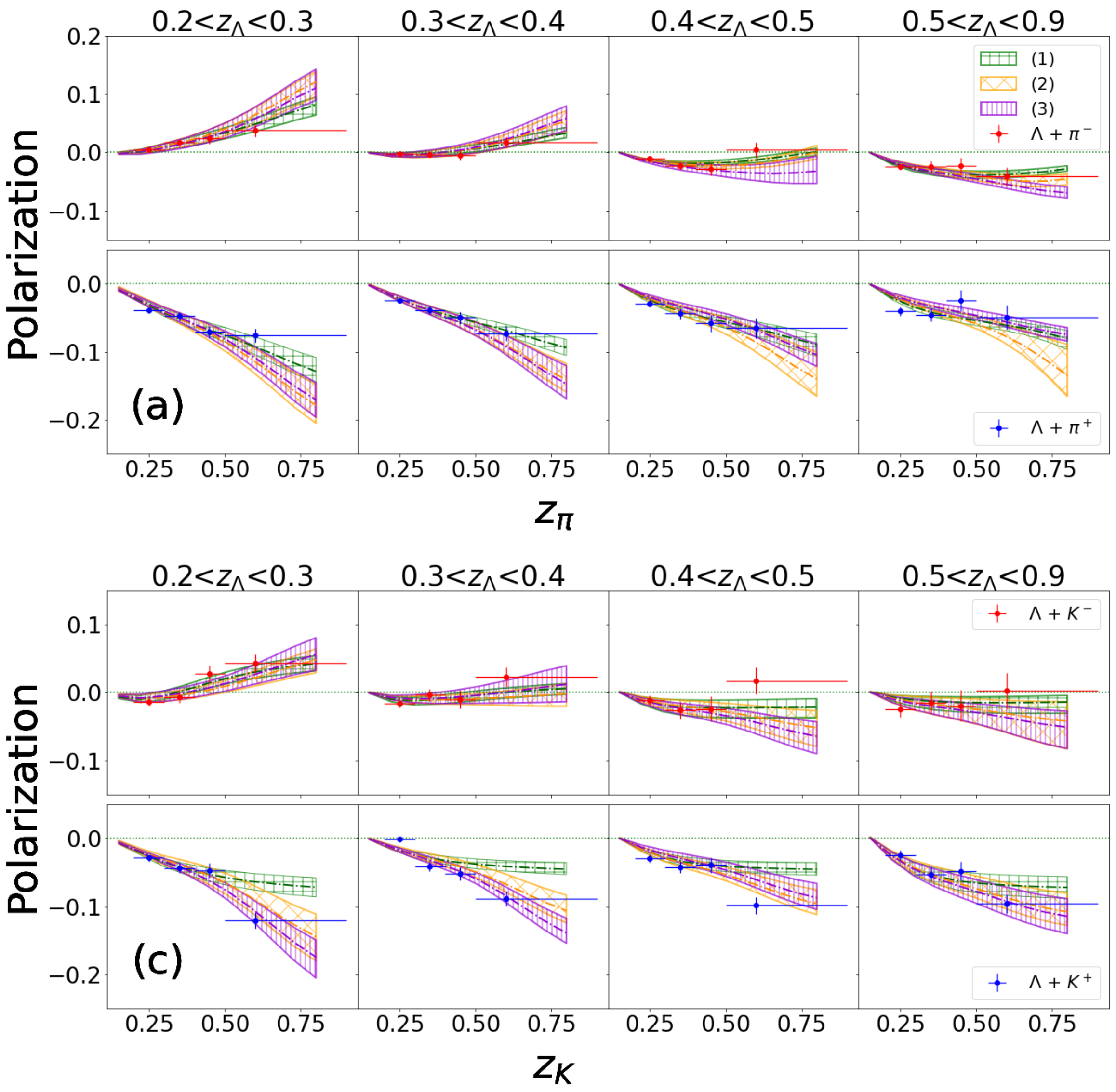
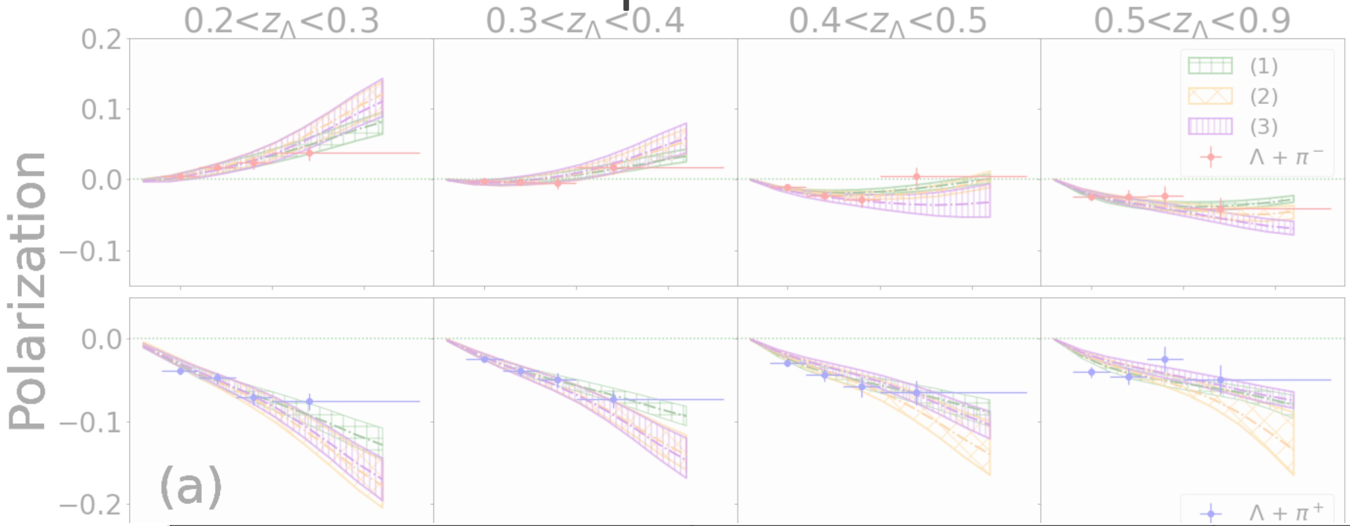
χ^2_{dof}
96 points
1,174
1,259
1,361

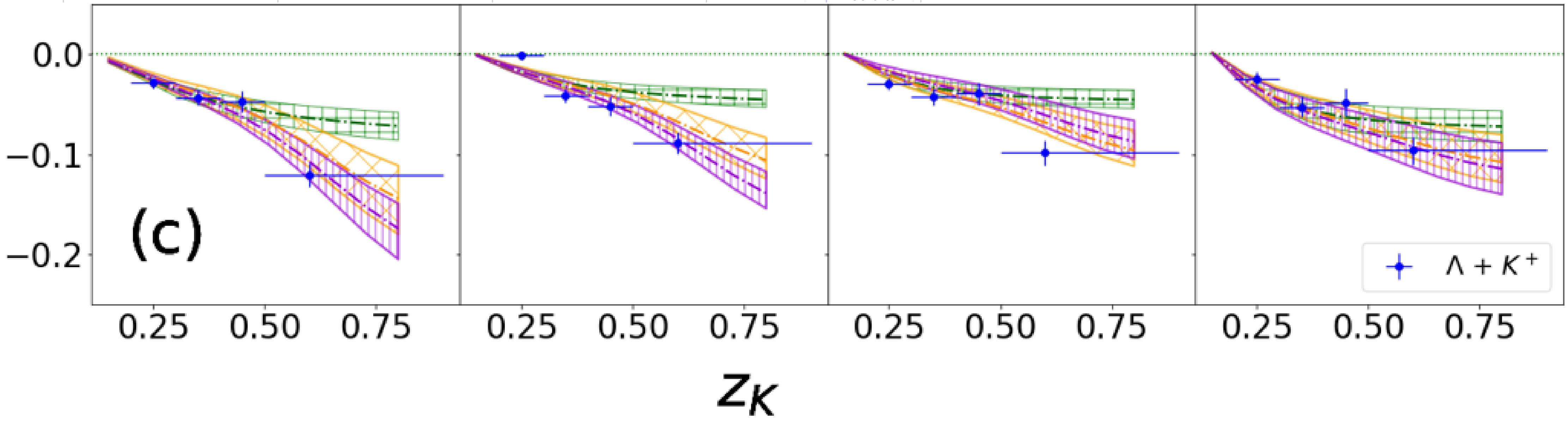
Double hadron production in e^+e^- processes



- All scenarios can describe $\Lambda\pi^\pm, \bar{\Lambda}\pi^\pm, \Lambda K^-, \bar{\Lambda}K^+$ data;
- Scenario (1) cannot describe $\Lambda K^+, \bar{\Lambda}K^-$ data with $z_K > 0{,}5$;
- With the Charm contribution we obtain similar good fits and description

Double hadron production in e^+e^- processes





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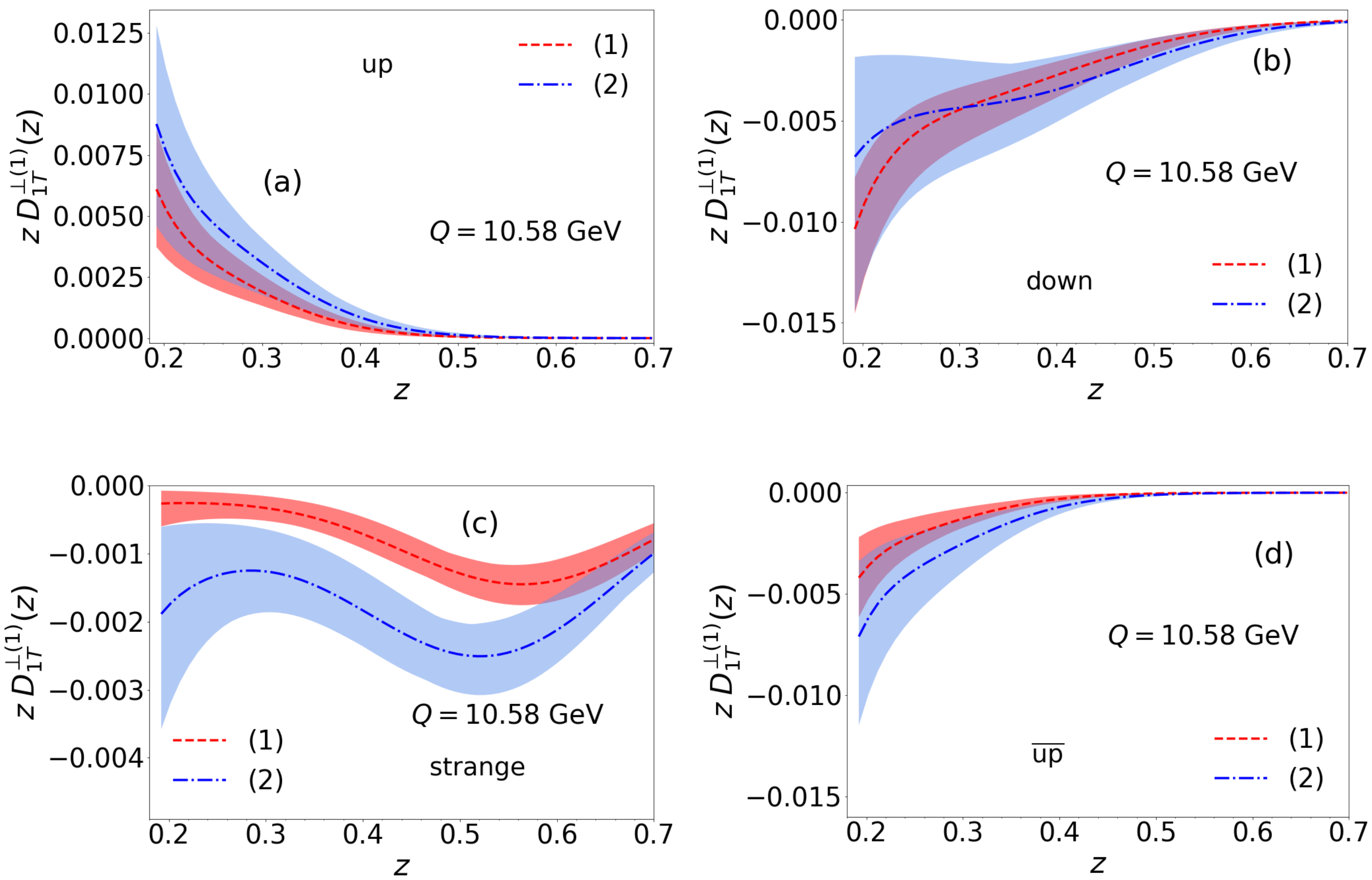
- With the Charm contribution we obtain similar good fits and description (SC 2 and 3)

Double hadron production in e^+e^- processes

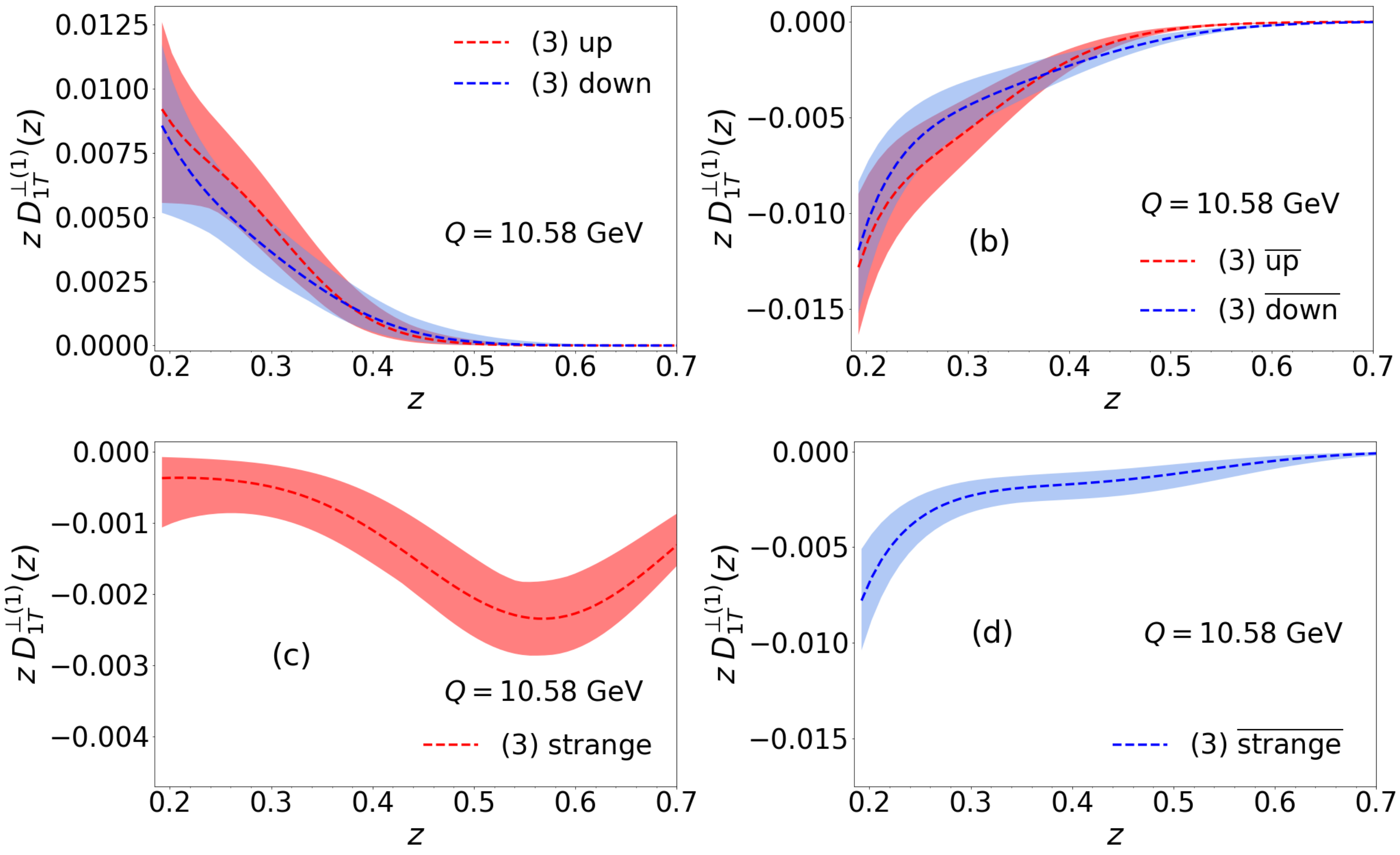
First moments: (1) & (2) scenarios



- pFFs are different in magnitude due to the charm contribution;
- up pFF is positive;
- First moments are compatible, except for the strange f.m.
- Similar size for the Gaussian width.

Double hadron production in e^+e^- processes

First moments: (3) scenario



- $up/down$ pFFs are positive;
- $\overline{up}/\overline{down}$ pFFs are negative;
- $strange/\overline{strange}$ pFFs are negative;
- up & $\overline{strange}$ compatible with (1,2) scn.
- The negative sea contribution is larger in size;
- Similar size for the Gaussian width.

Double hadron production in e^+e^- processes

Some remarks:

- Charm contribution in the unpolarized C.S. is necessary;
  Attempts were made to include this contribution also in the polarized c.s.

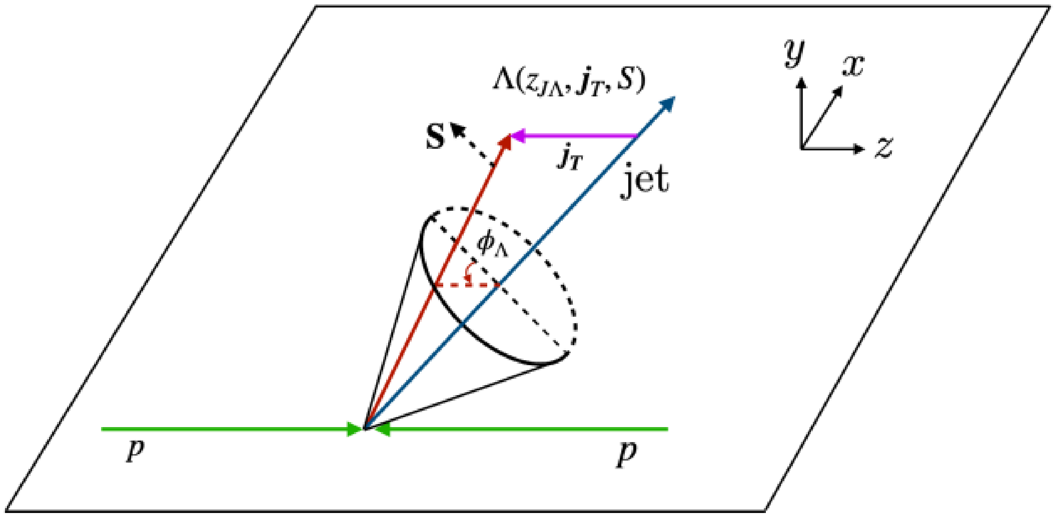
- We cannot distinguish between the (2) and (3) scenarios.
  If Normalization factors are free,
  up & $down$ come out opposite, violating the SU(2) symmetry.

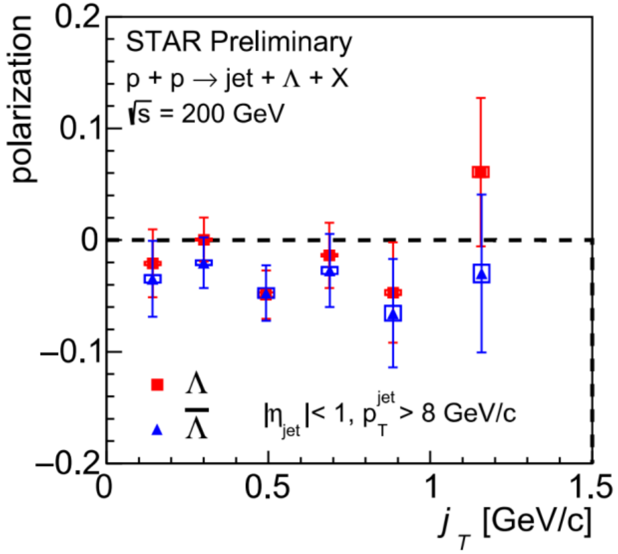
→ SiDIS and pp collisions

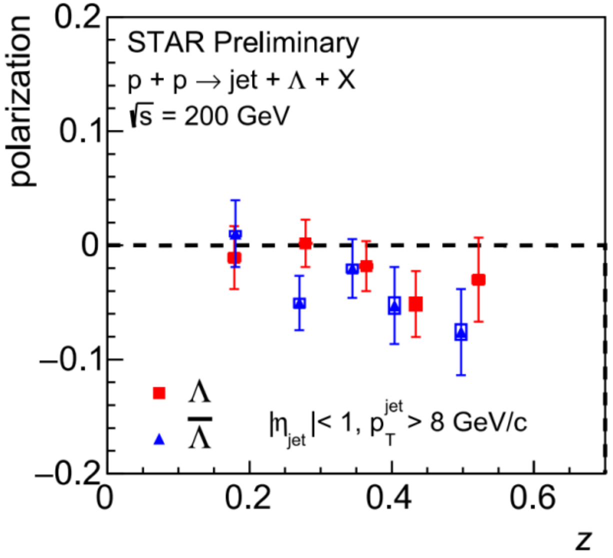
Unpolarized proton-proton collisions: $pp \to \Lambda\,(jet)X$

STAR data: arxiv/2402.01168

$$A(p_A)\,B(p_B) \to \text{jet}(p_\text{j})\,\Lambda^\uparrow(p_\Lambda)\,X \quad \sqrt{s} = 200\,\text{GeV}$$





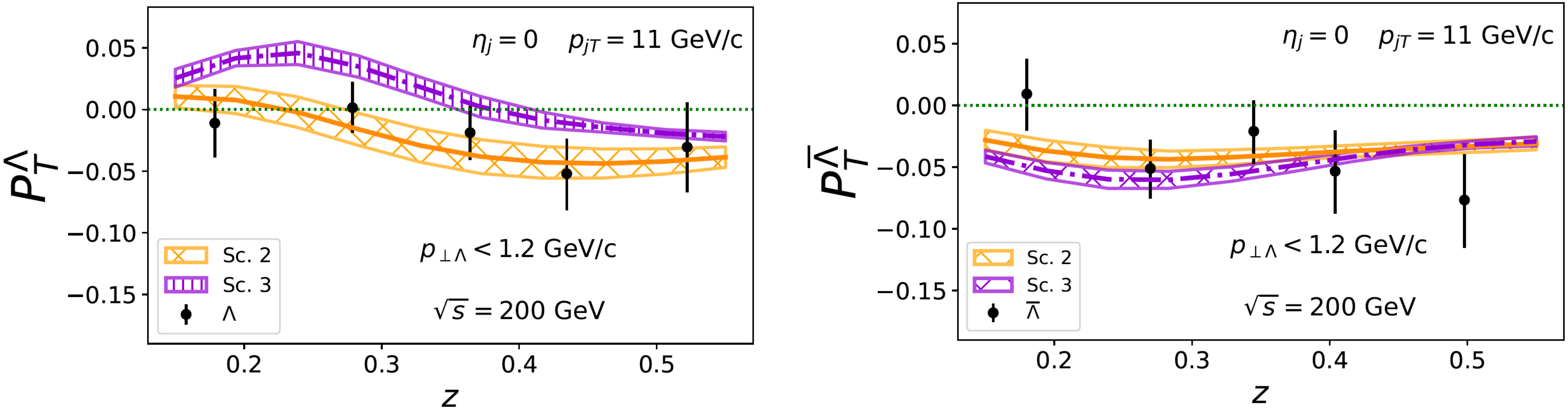


Kinematic cuts:

$$p_{\perp\Lambda} \le 1.6\,\text{GeV}/c, \quad 0 \le z \le 1,$$
$$8 \le p_{\text{jT}} \le 25\,\text{GeV}/c\,\text{with}\,\langle p_{\text{jT}}\rangle = 11\,\text{GeV}/c,$$
$$|\eta_\text{j}| \le 1.0,\; p_{T\Lambda} \le 10\,\text{GeV}/c,\; |\eta_\Lambda| \le 1.5$$

Anti-k_T algorithm with cone radius R = 0.6

Unpolarized proton-proton collisions: $pp \to \Lambda\,(jet)X$



The behaviour in z is driven by the relative contribution of the polFFs:

- In Sc. 1 and 2 only the up is positive → leads to a negative value of the polarization

In Sc . 3 both up and down are positive → leads to positive value of the polarization at small z and negative at intermediate values.

- Lambda-bar: the polarization is negative and is driven by the negative sign of the sea polFFs.

Unpolarized functions:
CT14nnlo set for proton
AKK set for Λ

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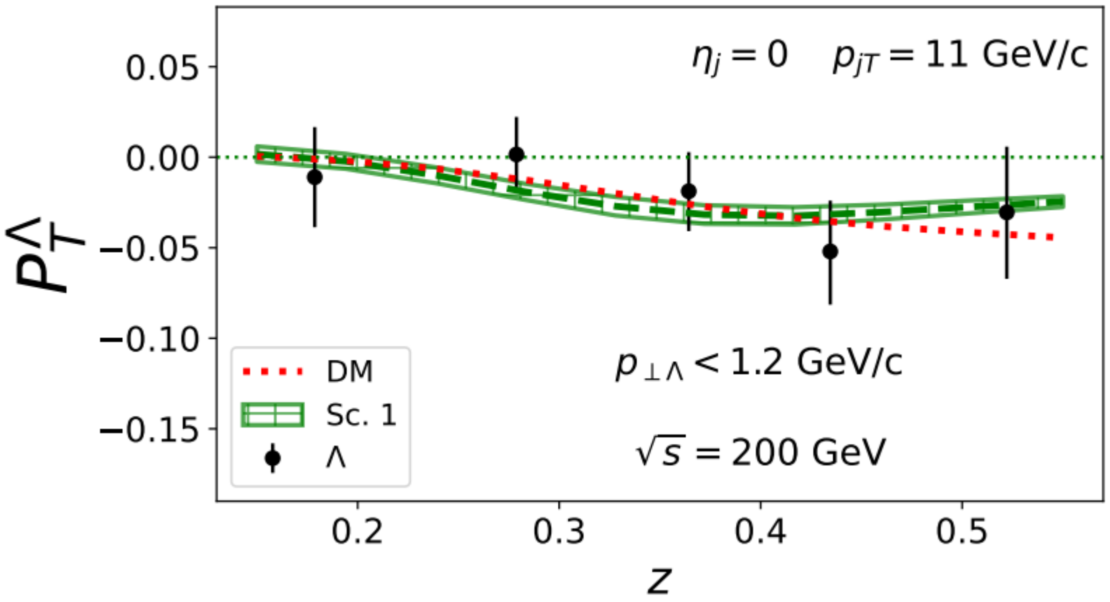

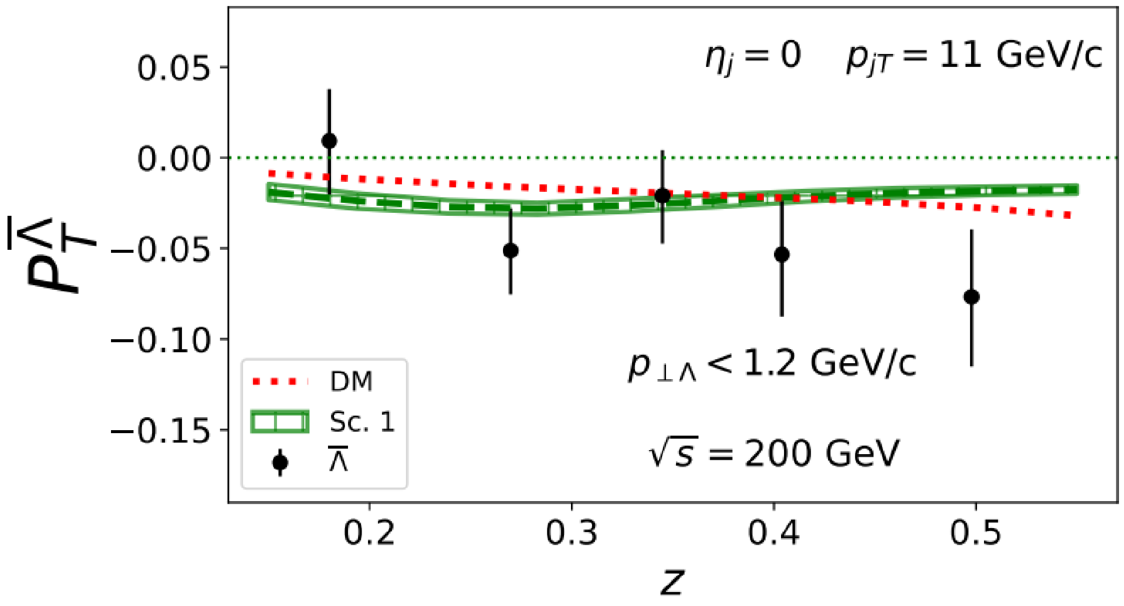

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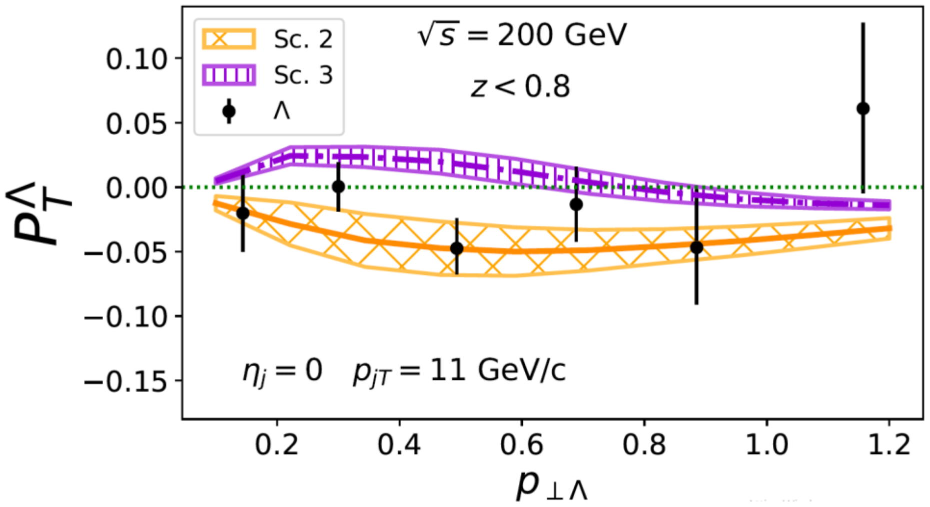
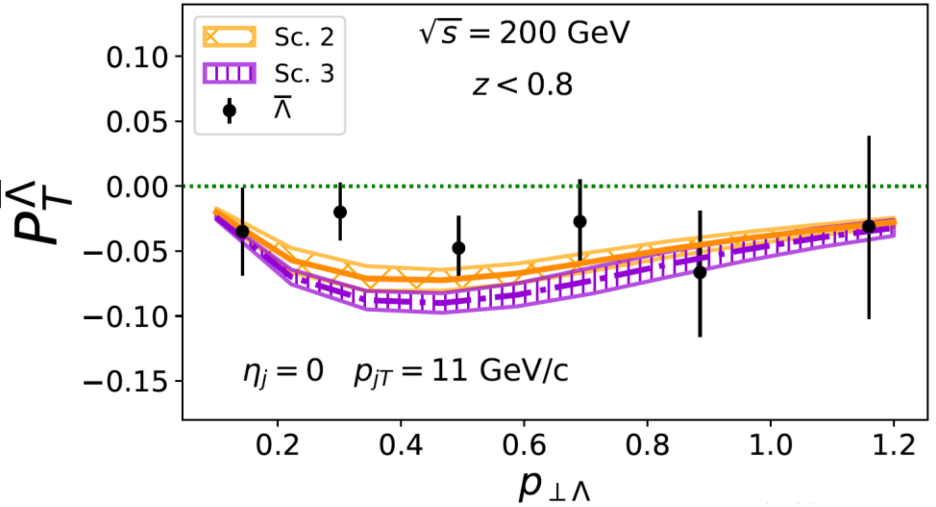
Similar comments as for the z behavior.





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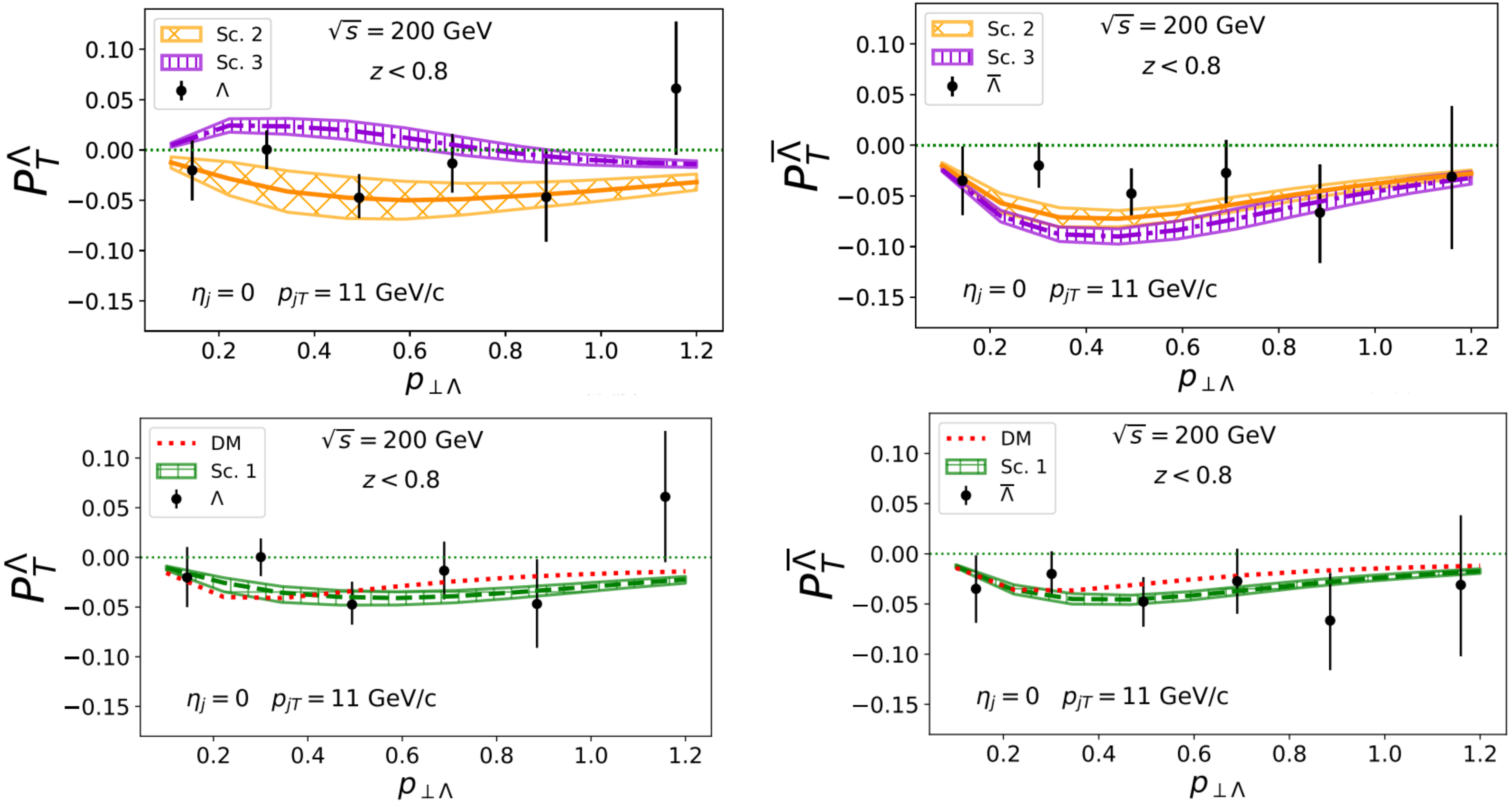

Unpolarized proton-proton collisions: $pp \to \Lambda\,(jet)X$

General remarks:

- Large experimental error bars: no strong conclusions
- General agreement with data in favor of the predicted universality of the polFF
- Sc. 1 & Sc. 2 (no SU(2)) a bit better than Sc. 3 at describing the data

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- Large experimental error bars: no strong conclusions
- General agreement with data in favor of the predicted universality of the polFF
- Sc. 1 & Sc. 2 (no SU(2)) a bit better than Sc. 3 at describing the data

First hint of the size of the Gluon polFF:

- UnpFF contribution to unpolarized cross sec. is about 50% ;
- Since quark contribution to polarization is about 5-8% ;

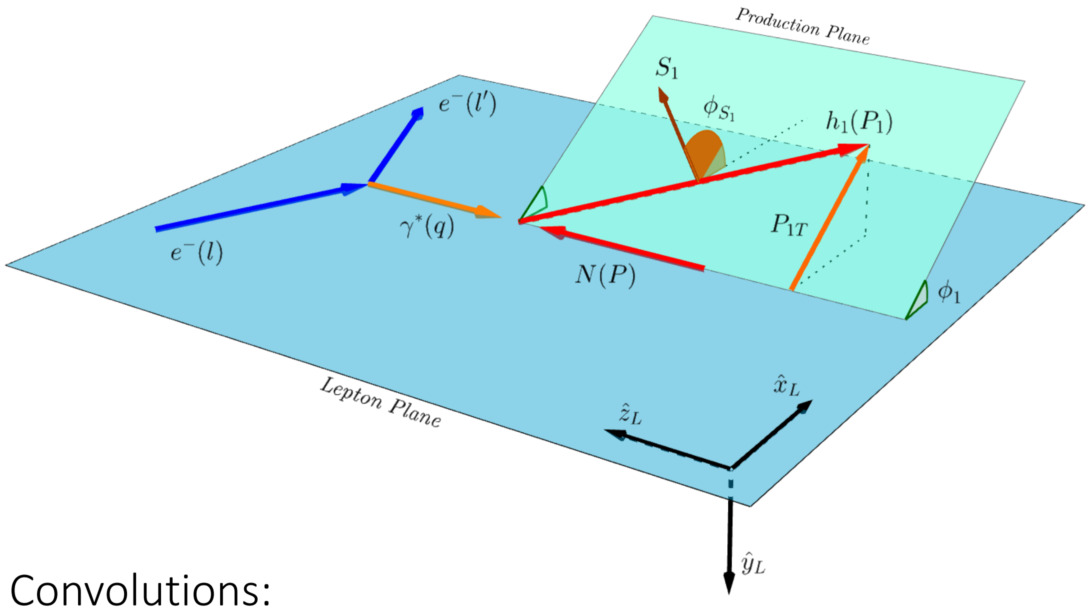
→Gluon polFF can be only around 10% of its positivity bound

Conclusions

- Λ in jet pp collisions: tool to test universality of the polFF
- TMD effects only in the fragmentation mechanism
- Estimates based on fits of Belle data on transverse Λ polarization:
  - Good agreement with STAR pp data
  - Test of universality and SU(2) symmetry issue
- First hint of the role of the polFF for gluons

Backup

Semi-inclusive Deep Inelastic Scattering



Polarization:

$$P_n^{h_1}(x_B, z_h) = \frac{M_1 \int dq_T\, q_T\, d\phi_1\, \mathcal{B}_1\left[\widetilde{f}_1 \widetilde{D}_{1T}^{\perp(1)}\right]}{\int dq_T\, q_T\, d\phi_1\, \mathcal{B}_0\left[\widetilde{f}_1 \widetilde{D}_1\right]}$$

Convolutions:

$$\mathcal{B}_0\left[\widetilde{f}_1 \widetilde{D}_1\right] = \frac{1}{z^2}\sum_q e_q^2 \int \frac{db_T}{(2\pi)}\, b_T J_0(b_T\, q_T)\, f_{N/q}(x;\bar{\mu}_b)\, d_{q/h}(z;\bar{\mu}_b)$$
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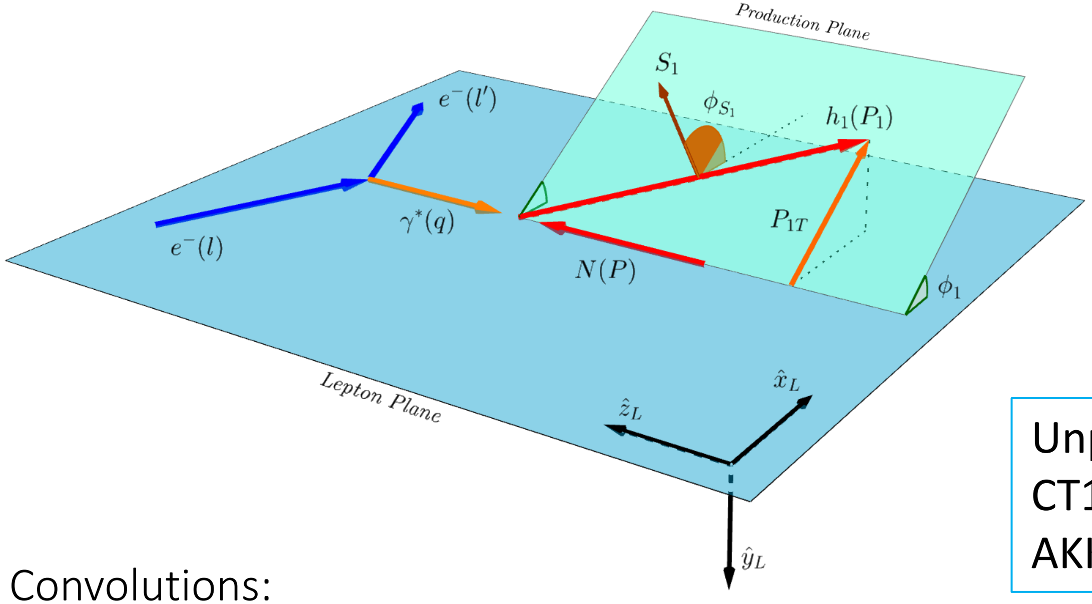

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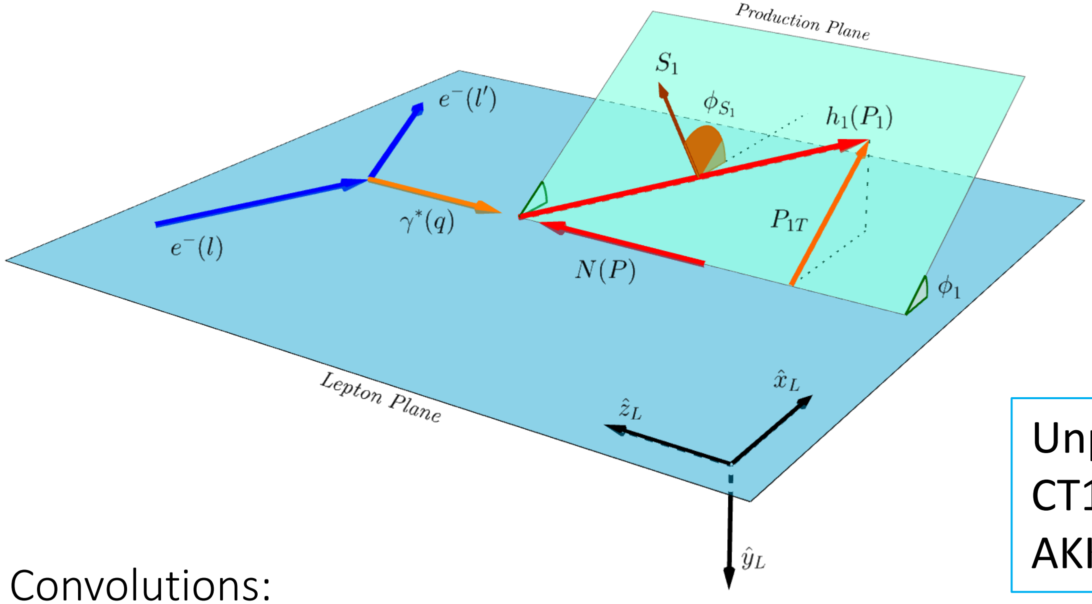

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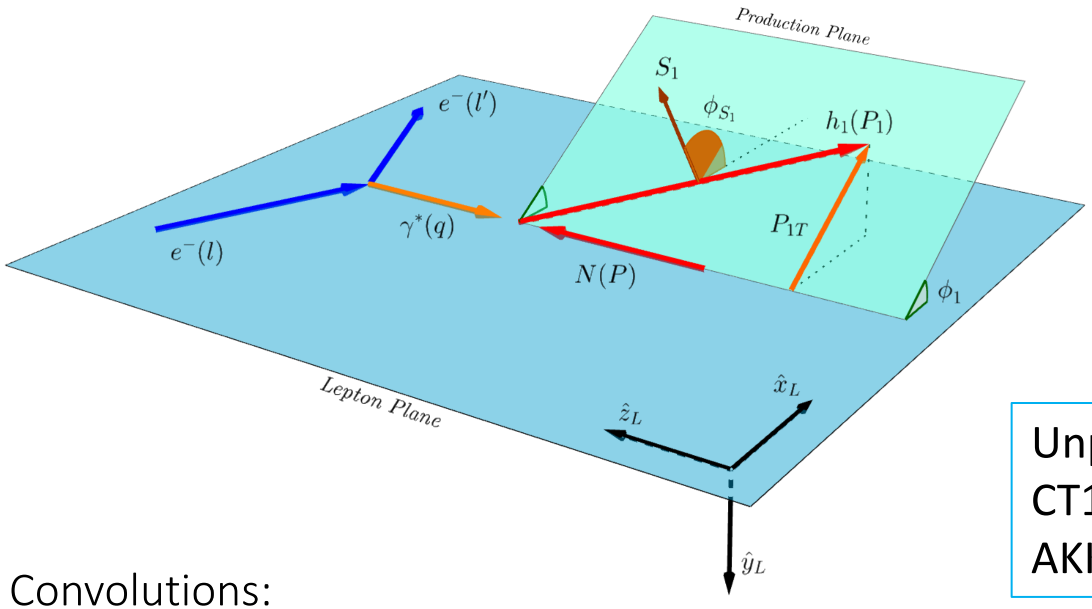

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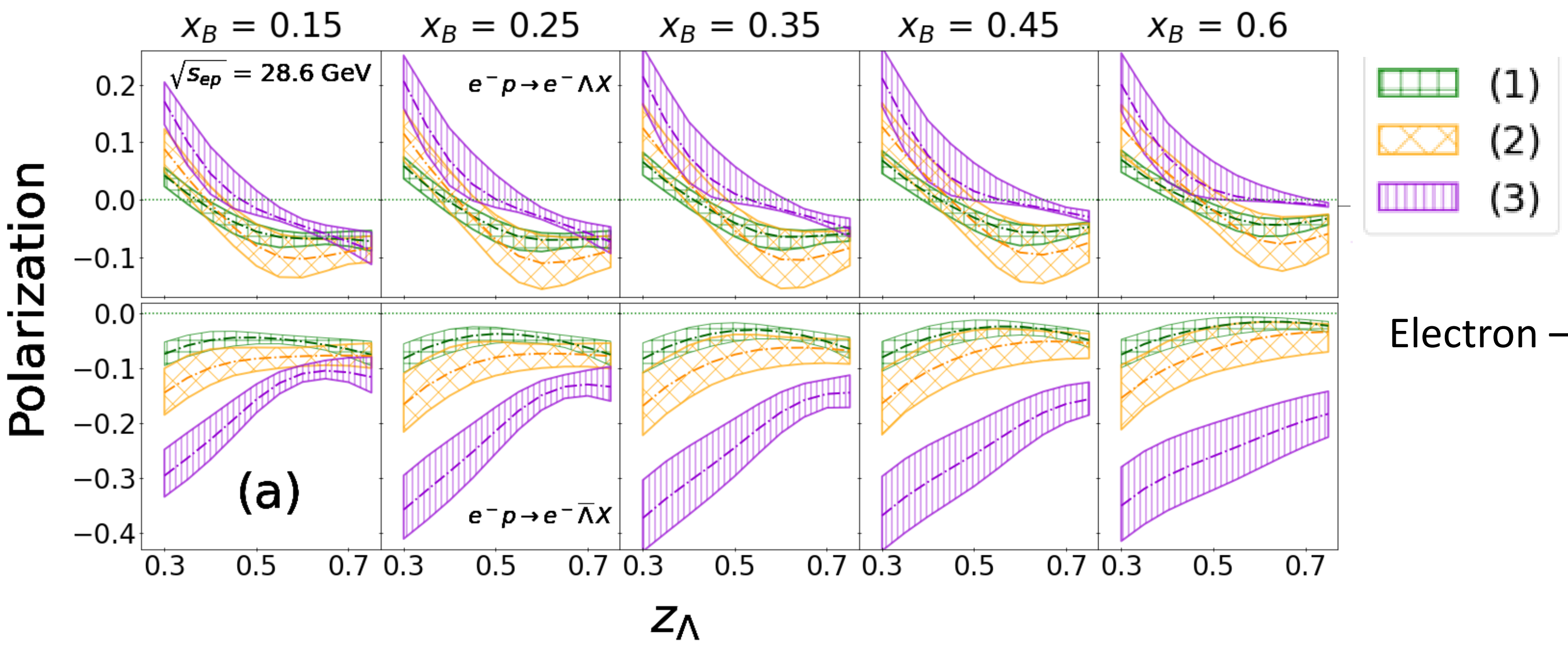
Predictions are given at different energies:

E_N (GeV)	E_{e^-} (GeV)	$\sqrt{s_{eN}}$ (GeV)
41	5	28.6
100	10	63.2

$$s = 4E_N E_e\,, \quad Q^2 = x_B y s$$

Semi-inclusive Deep Inelastic Scattering



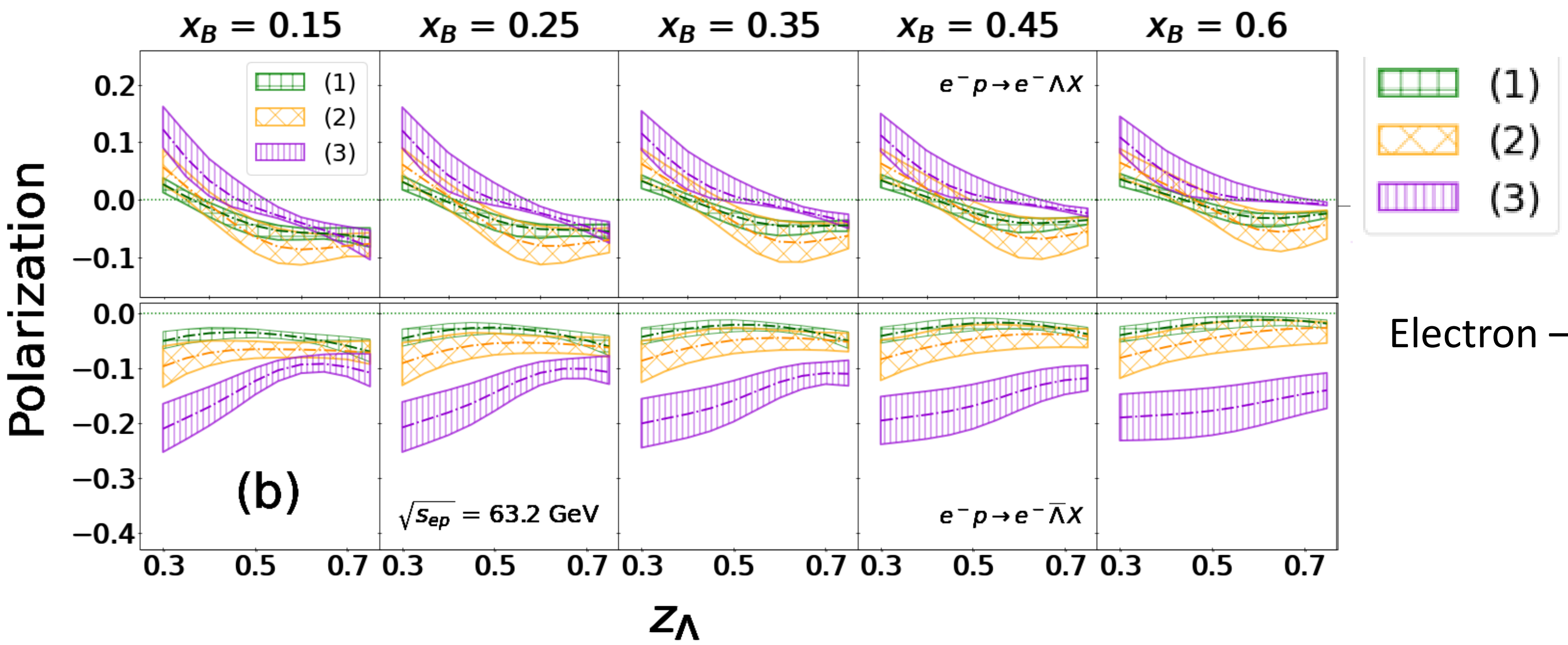
(1) No Charm, No SU2
(2) Charm, No SU2
(3) Charm, SU2

Electron – Proton

- (1) & (2) scenarios: polarization of similar size and behavior;
- Λ pol. decreases and becomes negative;
- $\bar{\Lambda}$ is always negative;
- $\sqrt{s_{ep}}$=28,6 pol. has the same size, for greater values there is a general reduction as x_B grows.

- (3) scenario: similar size;
- Λ pol. similar or slightly greater size;
- $\bar{\Lambda}$ most significant difference;

Semi-inclusive Deep Inelastic Scattering



(1) No Charm, No SU2
(2) Charm, No SU2
(3) Charm, SU2

Electron – Proton

- (1) & (2) scenarios: polarization of similar size and behavior;

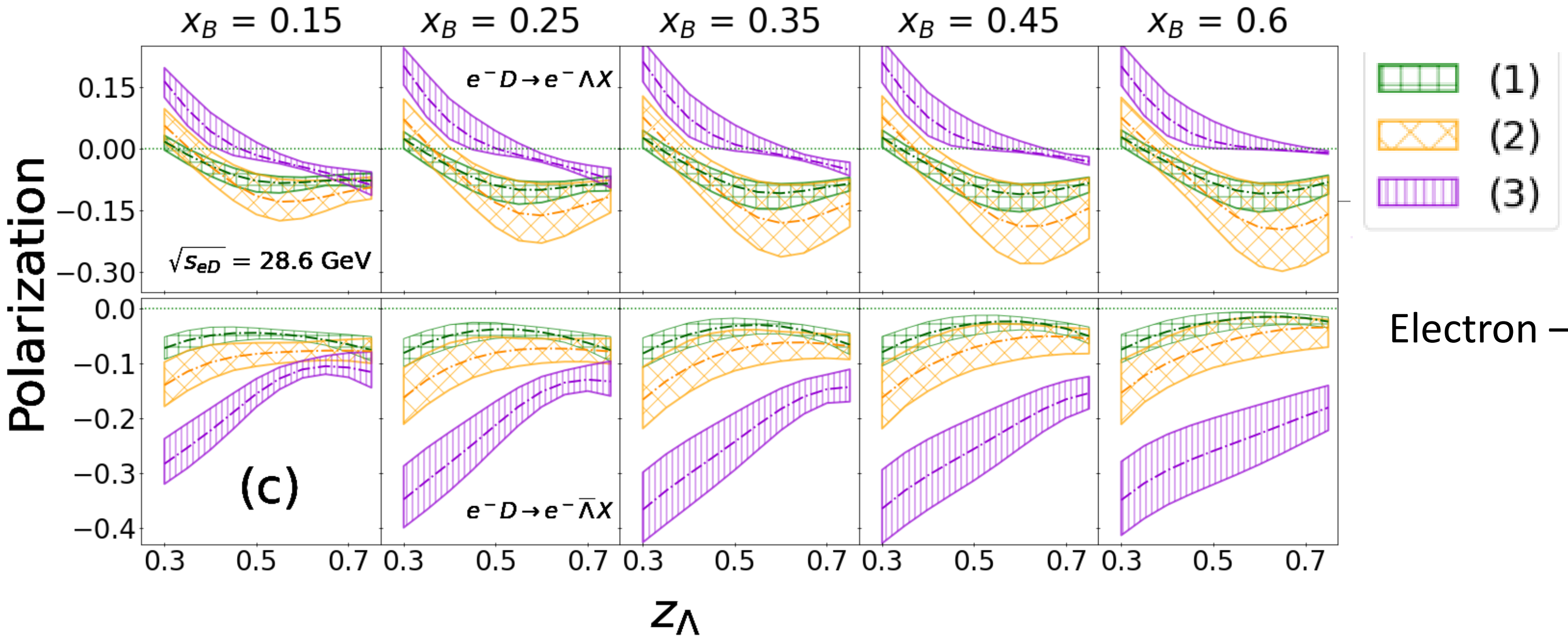
- Λ pol. decreases and becomes negative;
- $\bar{\Lambda}$ is always negative;

- $\sqrt{s_{ep}}$=28,6 pol. has the same size, for greater values there is a general reduction as x_B grows.

- (3) scenario: similar size;

- Λ pol. similar or slightly greater size;
- $\bar{\Lambda}$ most significant difference;

Semi-inclusive Deep Inelastic Scattering



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Electron – Deuterium

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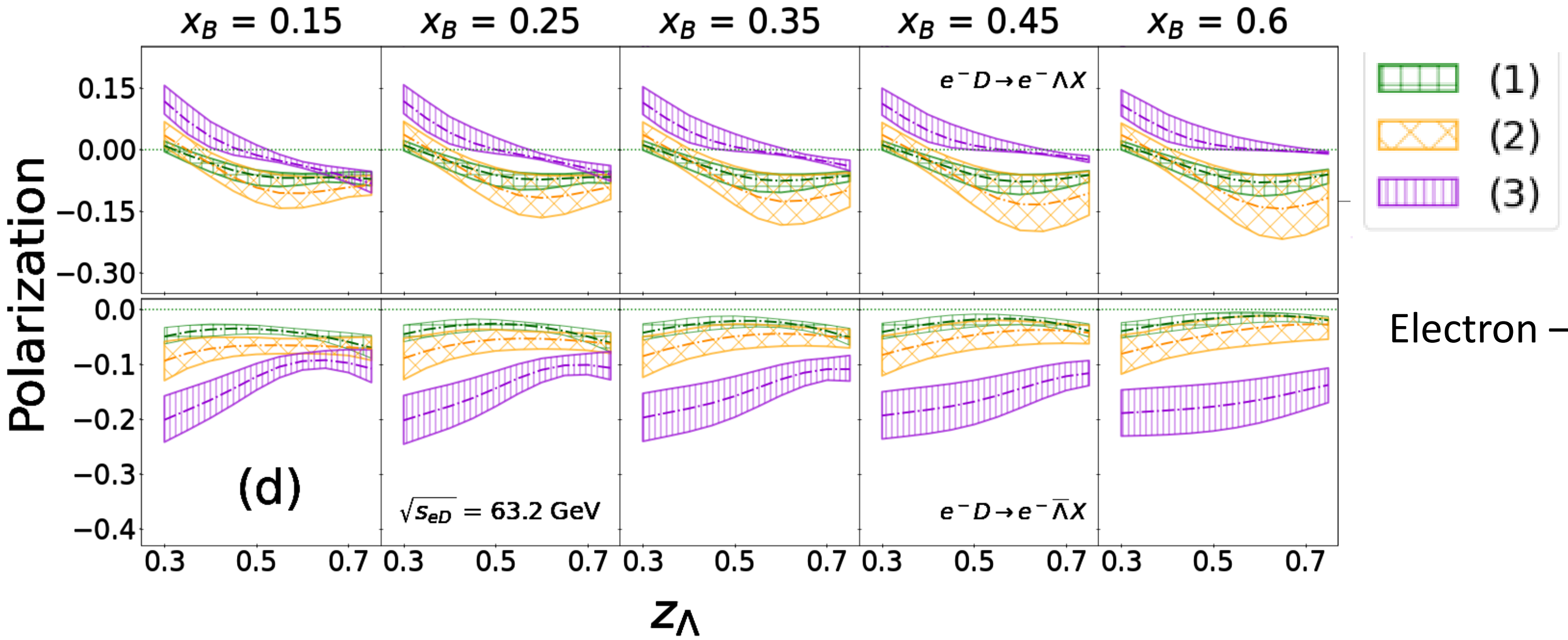
Semi-inclusive Deep Inelastic Scattering



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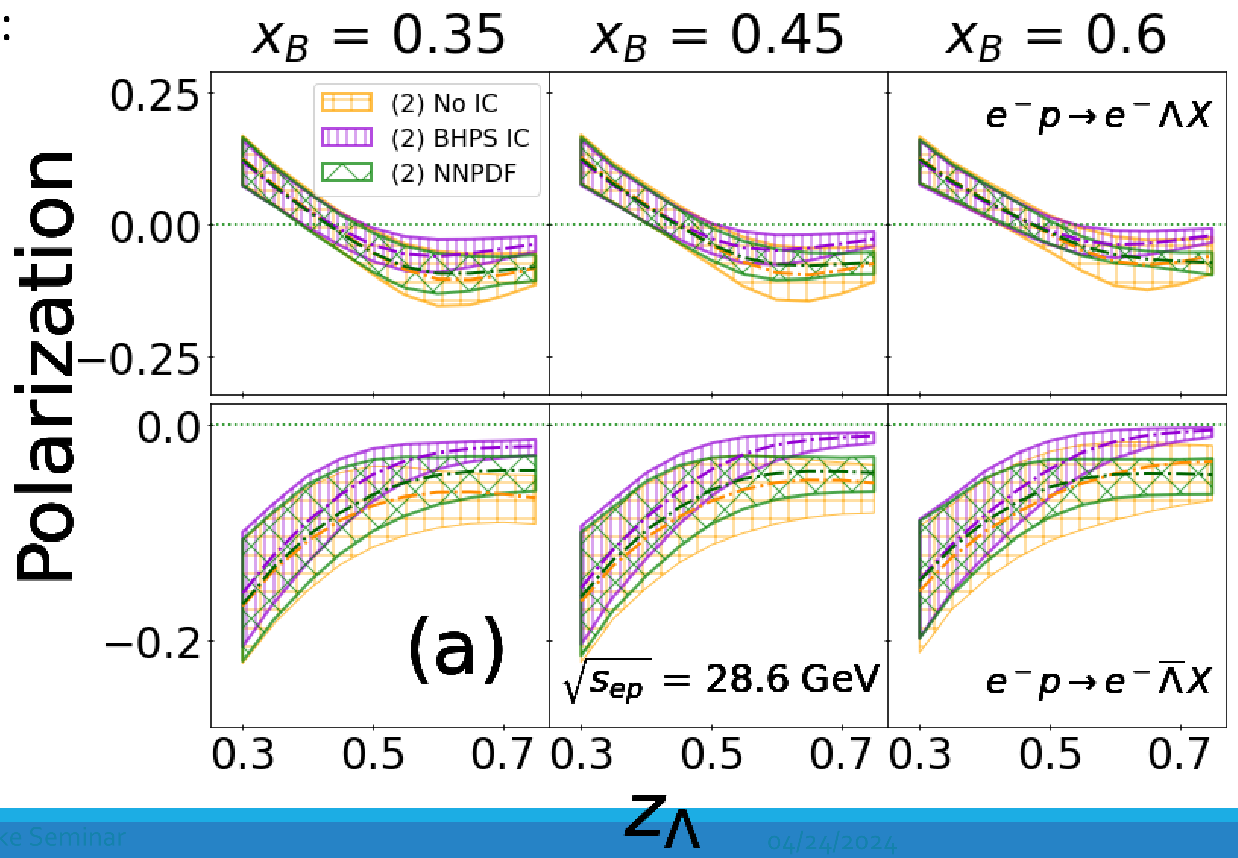
Semi-inclusive Deep Inelastic Scattering

The charm contribution in the fragmentation process is relevant

Intrinsic Charm (IC) component in the proton:
•CT14nnloIC set with BHPS model [T.-J. Hou et al., *JHEP* 02 (2018) 059]
•NNPDF4.0nnlo set [NNPDF Coll., *Eur.Phys.J.C* 82 (2022) 5, 428]

(2) Scenario:

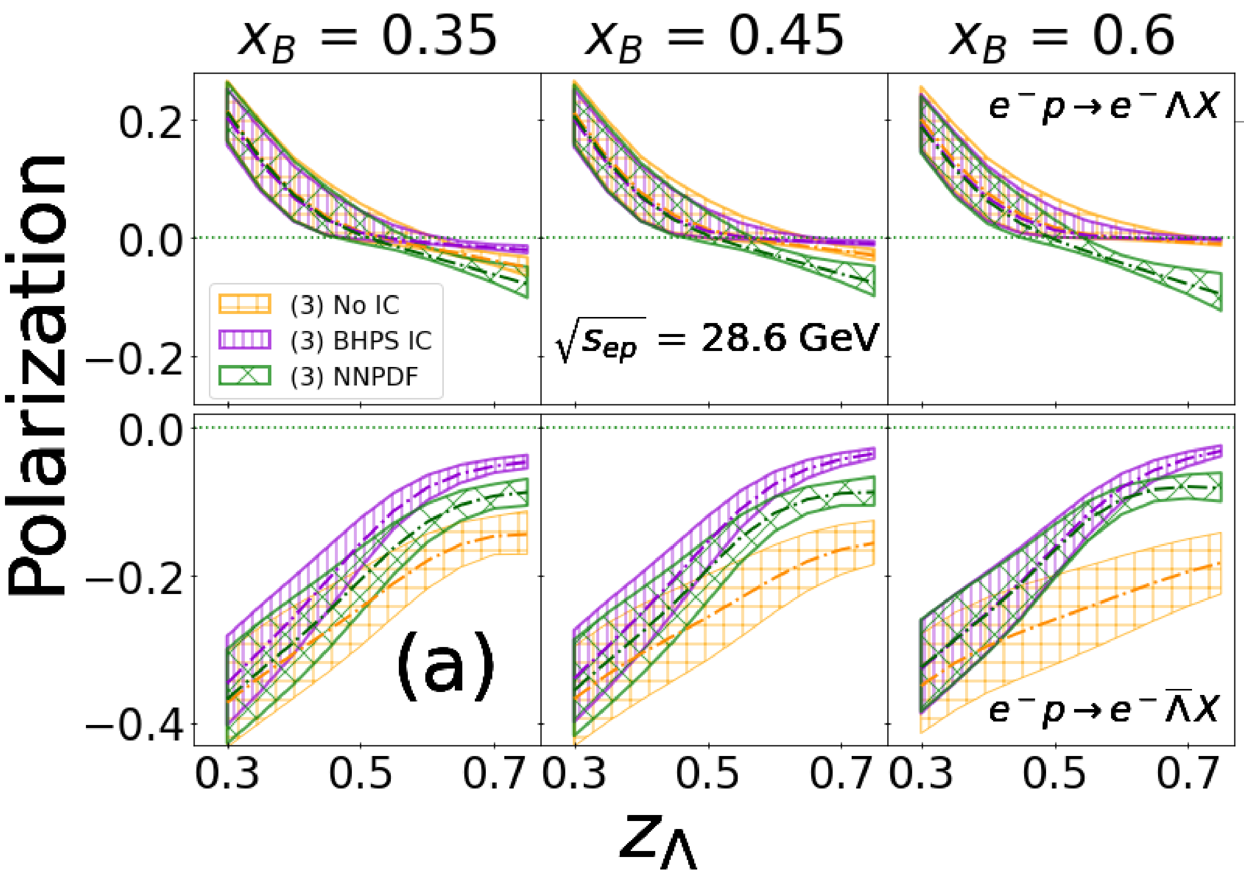


(2) Charm, No SU2

- BHPS and NNPDF: similar polarization of previous predictions
- Same behavior is present for greater values of the c.m. energy.

Semi-inclusive Deep Inelastic Scattering

(3) Scenario:



(3) Charm, SU2

- Estimates vary significantly as x_B increases;
- $\bar{\Lambda}$ estimates with BHPS and NNPDF different from the previous ones;
- Λ :decreases to zero
- Λ : NNPDF become negative