Fondazione di Sardegna

STRONG 2020

Center for Frontiers in Nuclear Science

WORKSHOP ON
TMDs: Towards a Synergy between
Lattice QCD and Global Analyses

TRANSVERSE Λ POLARIZATION IN e^+e^- ANNIHILATION AND SIDIS PROCESSES WITHIN A TMD FRAMEWORK

Umberto D'Alesio

in coll. with

L. Gamberg, F. Murgia & M. Zaccheddu

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OUTLINE

- Motivations
- $e^+e^- \to h_1\ h_2 + X$:
  - ✓ TMD formulation and fit of transverse Λ polarization Belle data
  - ✓ Extraction of the polarizing FF
  - ✓ *SU(2)* symmetry and role of charm contribution
- SIDIS
  - ✓ TMD formalism
  - ✓ Predictions for EIC
- Concluding remarks

MOTIVATIONS AND MORE

- Transverse Λ polarization in *unpolarized pp* collisions: [Bunce *et al.* 1976]
  sizeable, rising with x_F, p_T plateau…still challenging
- First attempt within a TMD scheme: [Anselmino, Boer, UD, Murgia 2001]
  good description … no formal theory behind
- Breakthrough: Belle e^+e^- data [Guan *et al.* (Belle Coll.) 2019]
- e^+e^- collisions:

  2h, TMD fact. [Collins 2011; Echevarria, Idilbi, Scimemi 2012]

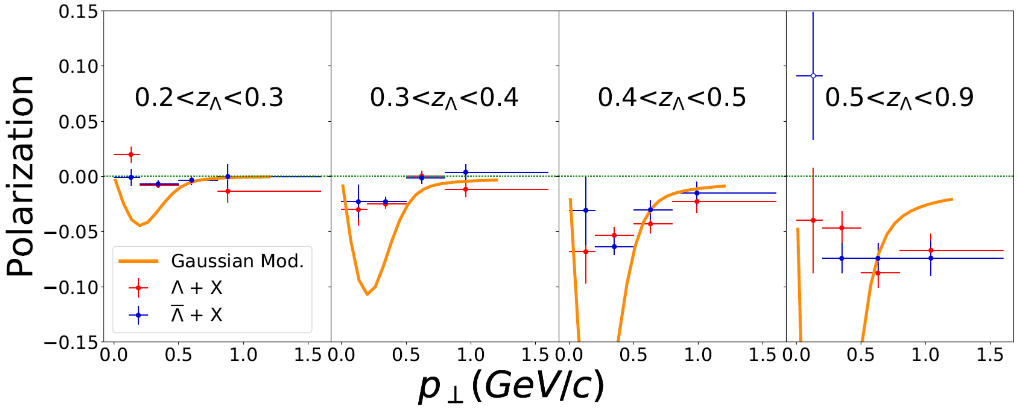
  1h: new TMD scheme? [Kang, Shao, Zhao 2020; Boglione, Simonelli 2021, 2022]
- First analysis of Belle data: extraction of the polarizing FF (fixed scale)

  2h and 2h+1h fits [UD, Murgia, Zaccheddu 2020]
  2h fit [Callos, Kang, Terry 2020]
- Analysis w/ CSS scheme [Li, Wang, Yang, Lu 2021; Gamberg, Kang, Shao, Terry, Zhao 2021; UD, Gamberg, Murgia, Zaccheddu 2022]
- *SU(2)* issue: [Chen, Liang, Pan, Song, Wei 2021; Chen, Liang, Song, Wei 2022]

OPEN ISSUES (THE LAST ANALYSIS)

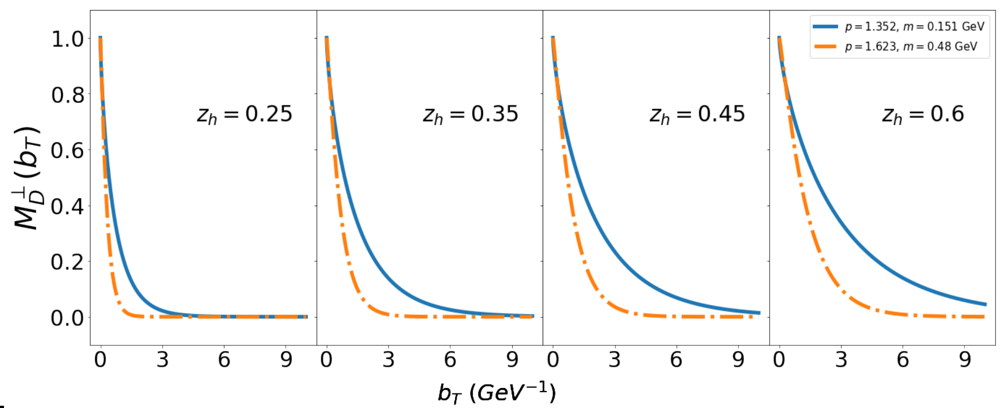
[UD, Gamberg, Murgia, Zaccheddu 2022]

- Tension between *2h* & *1h* data description



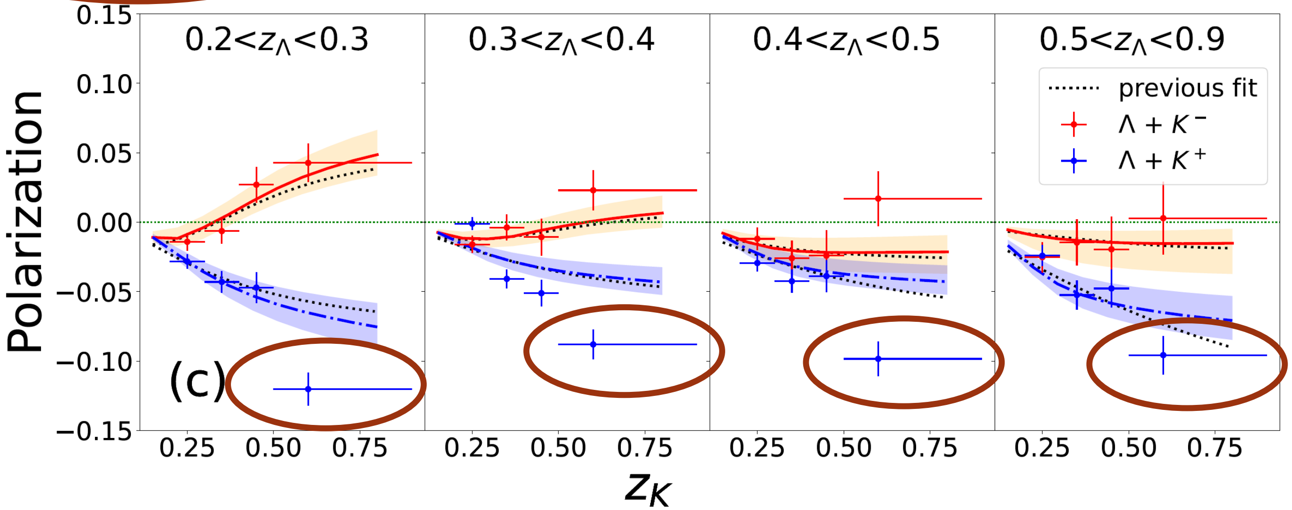
1h estimates from *2h*-fit

Non perturbative models to fit *2h* and *1h* data



Maybe two factorization schemes

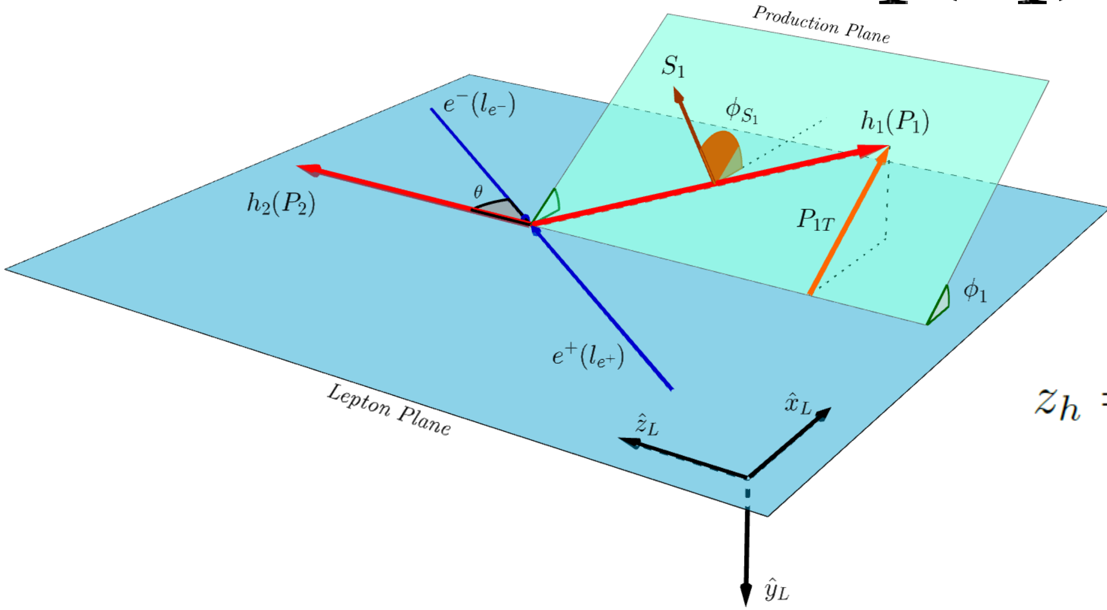
- Large-z $K\Lambda$ data: failure w/ or w/o proper TMD framework



- Free three-flavor (u, d, s) fit → strong *SU(2)* violation ($d \cong -u$)

HERE, focus on: *SU(2)* symmetry and role of charm

$e^+e^- \rightarrow h_1(P_1)\,h_2(P_2) + X$



$$z_p = \frac{2|\boldsymbol{P}_h|}{Q} \simeq z\left(1 - \frac{M_h^2}{z^2Q^2}\right)$$

$$z_h = \frac{2P_h\cdot q}{Q^2} = \frac{2E_h}{Q} \simeq z\left(1 + \frac{M_h^2}{z^2Q^2}\right)$$

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

$$F_{UU} \;=\; z_{p_1}^2 z_{p_2}^2\,\mathcal{H}^{(e^+e^-)}(Q)\,\mathcal{F}[D_1\bar{D}_1] \qquad \mathcal{H}^{(e^+e^-)}(Q)|_{\rm LO} = 1$$

$$F_{TU}^{\sin(\phi_1-\phi_{S_1})} \;=\; z_{p_1}^2 z_{p_2}^2\,\mathcal{H}^{(e^+e^-)}(Q)\,\mathcal{F}\left[\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M_1}D_{1T}^{\perp}\bar{D}_1\right]$$

[Boer, Jakob, Mulders 1997; Pitonyak, Schlegel, Metz 2014; UD, Murgia, Zaccheddu 2021]

$e^+e^- \rightarrow h_1(P_1)\, h_2(P_2) + X$

Convolution in k_T space

$$\mathcal{F}[\omega D\bar{D}] = \sum_q e_q^2 \int d^2\boldsymbol{k}_T d^2\boldsymbol{p}_T\, \delta^{(2)}(\boldsymbol{k}_T + \boldsymbol{p}_T - \boldsymbol{q}_T)\, \omega(\boldsymbol{k}_T, \boldsymbol{p}_T) D(z_1, \boldsymbol{k}_\perp)\bar{D}(z_2, \boldsymbol{p}_\perp)$$

CSS approach…move to b_T space

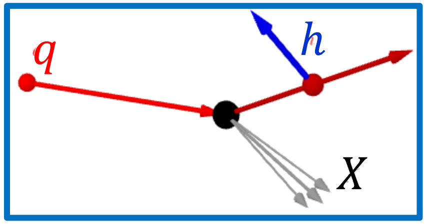
$$F_{UU} = z_{p_1}^2\, z_{p_2}^2 \mathcal{B}_0\left[\widetilde{D}_1 \widetilde{\bar{D}}_1\right] = z_{p_1}^2\, z_{p_2}^2 \sum_q e_q^2 \int \frac{db_T}{2\pi}\, b_T J_0(b_T\, q_T)\widetilde{D}_1(z_1, b_T)\widetilde{\bar{D}}_1(z_2, b_T)$$

$$\begin{aligned} F_{TU}^{\sin(\phi_1 - \phi_{S_1})} &= M_1 z_{p_1}^2\, z_{p_2}^2 \mathcal{B}_1\left[\widetilde{D}_{1T}^{\perp(1)} \widetilde{\bar{D}}_1\right] \\ &= M_1 z_{p_1}^2\, z_{p_2}^2 \sum_q e_q^2 \int \frac{db_T}{2\pi}\, b_T^2 J_1(b_T\, q_T)\widetilde{D}_{1T}^{\perp(1)}(z_1, b_T)\widetilde{\bar{D}}_1(z_2, b_T) \end{aligned}$$

1st moment of the pFF

$$\Delta^N D_{h^\uparrow/q}(z, k_\perp) = \frac{k_\perp}{z M_h} D_{1T}^\perp(z, k_\perp)$$

polarizing FF



$$e^+e^- \to h_1(P_1)\, h_2(P_2) + X$$

Polarization along ***n*** (⊥ to the production plane)

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

$q_T < 0.27\, Q$

TMD fact.

Denominator *(known)*

(small-b_T matching onto) collinear FFs

$$\mathcal{B}_0\left[\widetilde{D}_1 \widetilde{\bar{D}}_1\right] = \frac{1}{z_1^2 z_2^2} \sum_q e_q^2 \int \frac{db_T}{2\pi}\, b_T\, J_0(b_T\, q_T)\, d_{h_1/q}(z_1; \bar{\mu}_b)\, d_{h_2/\bar{q}}(z_2; \bar{\mu}_b)$$

$$\times\; M_{D_1}(b_c(b_T), z_1)\, M_{D_2}(b_c(b_T), z_2)\, e^{-g_K(b_c(b_T); b_{\max}) \ln\left(\frac{Q^2 z_1 z_2}{M_1 M_2}\right) - S_{\rm pert}(b_*; \bar{\mu}_b)}$$

Nonpert. funct.s

Nonpert. CS Kernel

Perturbative Sudakov factor

$$S_{\rm pert}(b_*;\bar\mu_b) = -\widetilde K(b_*;\bar\mu_b)\ln\frac{Q^2}{\bar\mu_b^2} - \int_{\bar\mu_b}^{Q}\frac{d\mu'}{\mu'}\left[2\gamma_D(g(\mu');1) - \gamma_K(g(\mu'))\ln\frac{Q^2}{\mu'^2}\right]$$

$$\bar\mu_b = \frac{C_1}{b_*(b_T)}$$

Perturb. CS Kernel

RG anomalous dimensions

cusp

$$C_1 = 2e^{-\gamma_E}$$

Nonperturbative functions from Bacchetta, Delcarro, Pisano, Radici, Signori 2017

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

$$b_* \equiv b_*(b_T;b_{\rm min},b_{\rm max}) = b_{\rm max}\left(\frac{1-e^{-b_T^4/b_{\rm max}^4}}{1-e^{-b_T^4/b_{\rm min}^4}}\right)^{1/4}$$

$$b_*(b_c(b_T)) \to \begin{cases} b_{\rm min} & b_T \ll b_{\rm min} \\ b_T & b_{\rm min} \ll b_T \ll b_{\rm max} \\ b_{\rm max} & b_T \gg b_{\rm max}\end{cases}$$

$b_{\rm min} = 2e^{-\gamma_E}/Q$ and $b_{\rm max} = 0.6\,{\rm GeV}^{-1}$

$$g_K(b_T;b_{\rm max}) = \frac{g_2 b_T^2}{2}\,; \quad g_2 = 0.13\,{\rm GeV}^2$$

Coll. FF sets: for π/K de Florian. Sassot, Stratmann 2007; for Λ Albino, Kniehl, Kramer 2008

Numerator of P_n

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

- Polarizing FF first moment

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

$$q = u, d, s, \bar{u}, \bar{d}, \bar{s}$$

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

- nonperturbative pFF

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

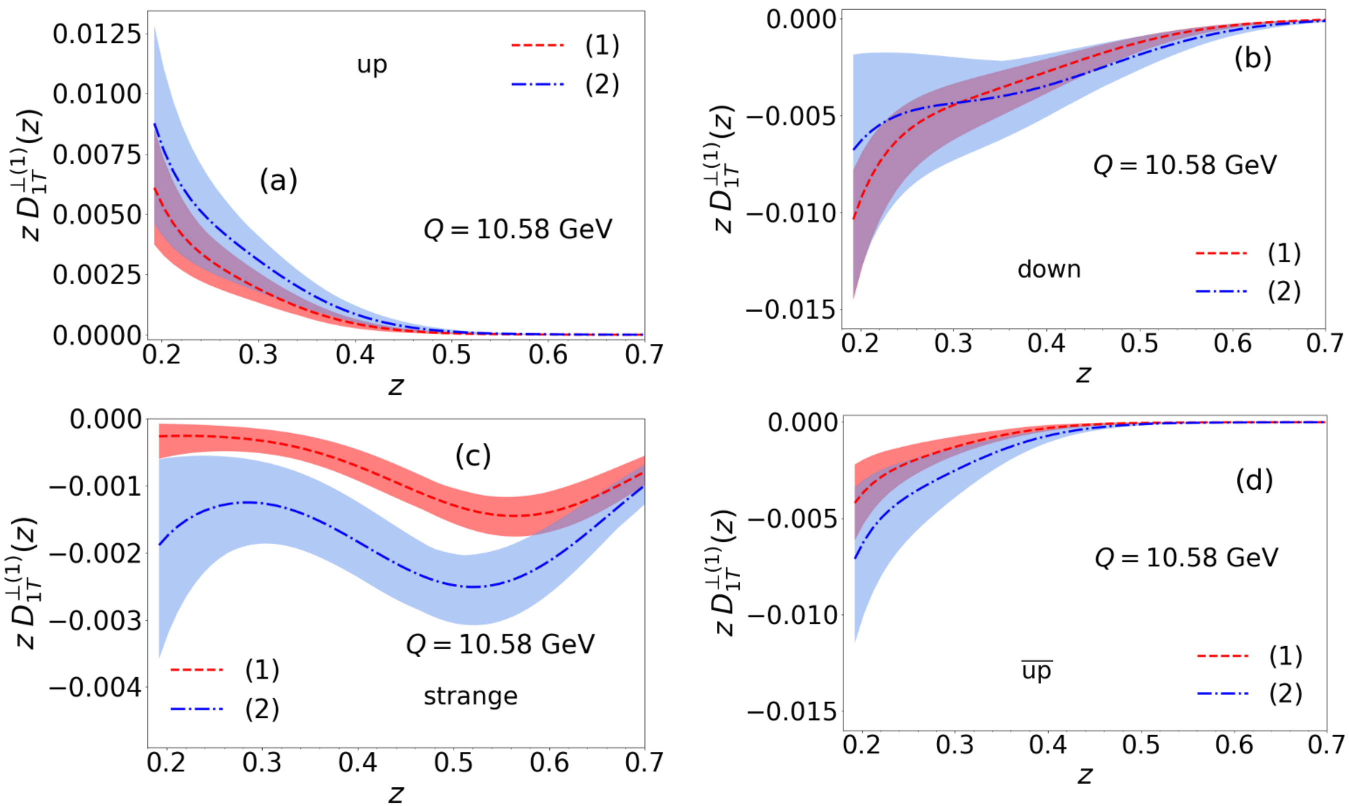
FIT OF BELLE DATA [NLL]

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

Scenarios considered:

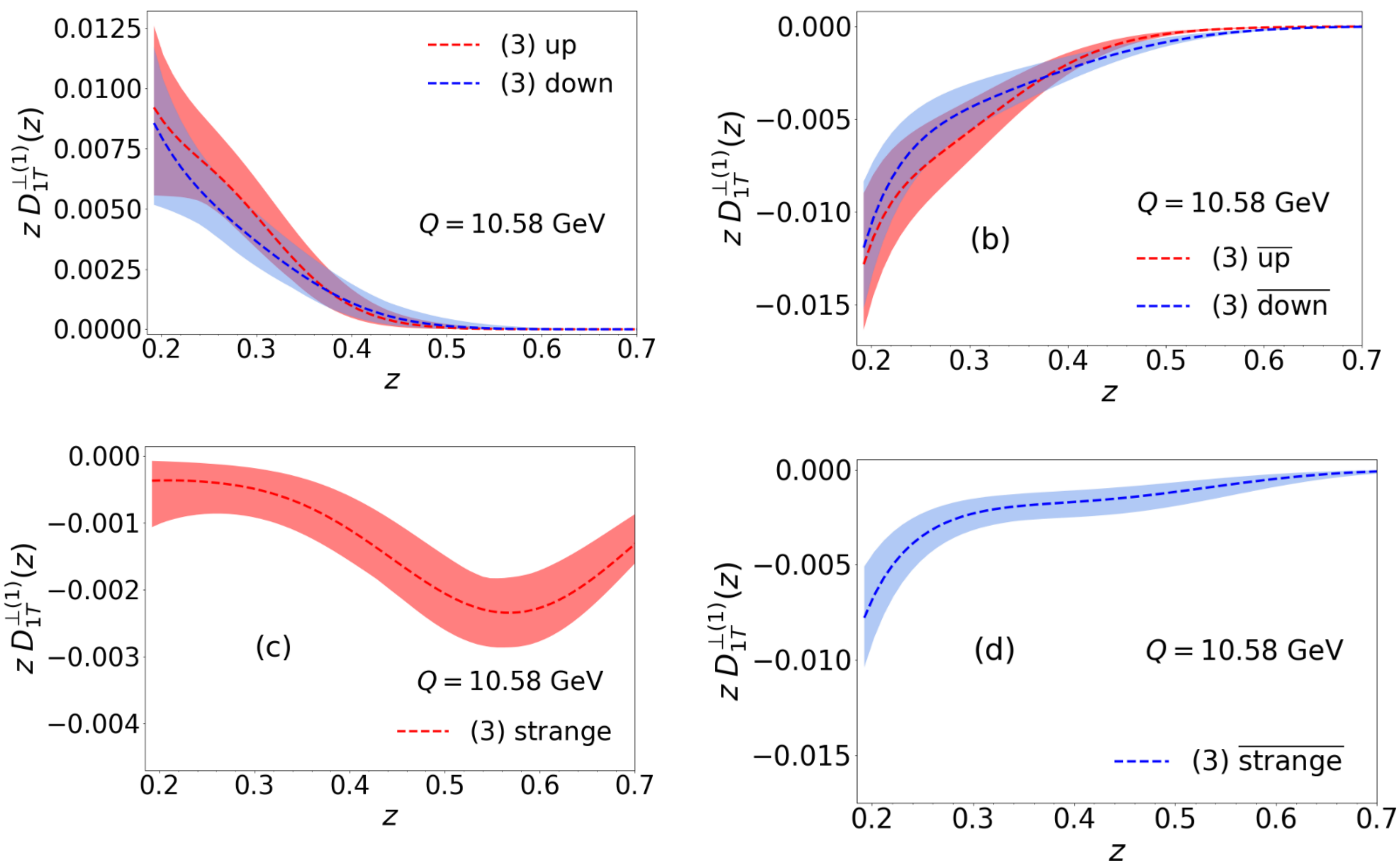
	χ^2_{dof} **96** pts	χ^2_{dof} **128** pts
1. Only light quarks & No *SU(2)* sym. pFFs for u, d, s, sea; [8 par]	1.17	1.90
2. Inclusion of charm in unpol. xsec, & No *SU(2)* sym. pFFs for u, d, s, sea; [9 par]	1.26	1.62
3. Inclusion of charm in unpol. xsec, *SU(2)* sym. pFFs for $d = u, \bar{d} = \bar{u}, s, \bar{s}$ [9 par]	1.36	1.64

FIRST MOMENTS: SC 1, 2 NO *SU(2)* SYMM.



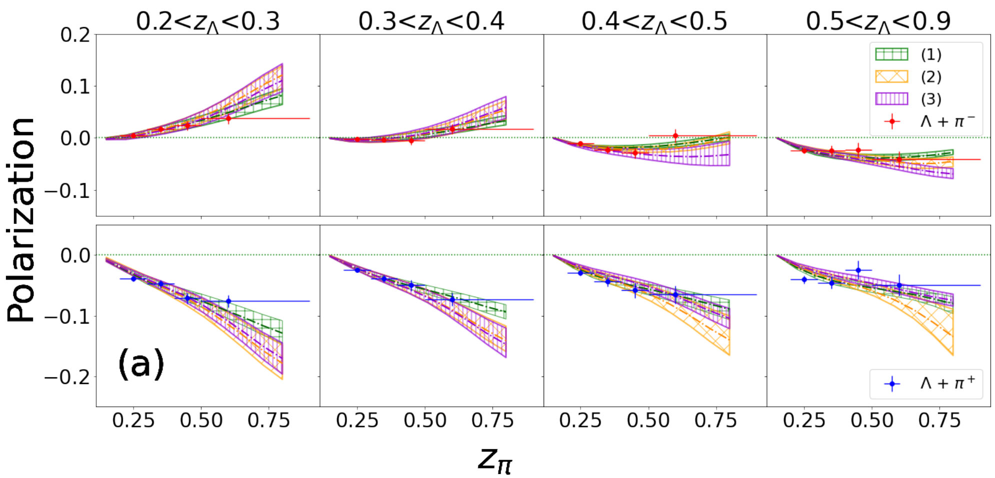
- different magnitudes, Sc 2 bigger in size: charm contribution;
- u pFF positive; d pFF negative — STRONG *SU(2)* violation
- Sc 1 and 2 compatible, except for strange
- Similar size for the Gaussian width.

FIRST MOMENTS: SC 3 WITH *SU(2)* SYMM.

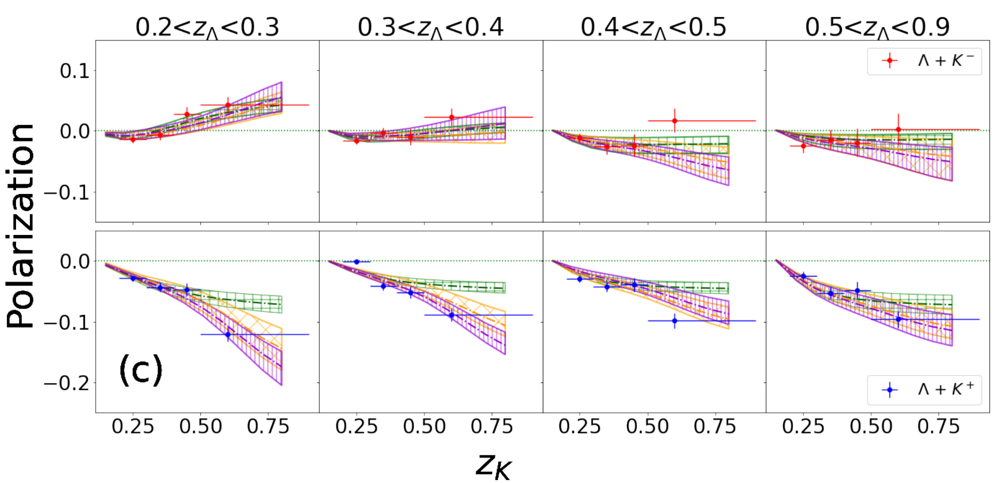


- u, d pFFs **positive**; all others pFFs negative
- sea contribution larger in size w.r.t. Sc. 1 & 2

DATA DESCRIPTION



- Good agreement for $\Lambda\pi^{\pm}, (\overline{\Lambda}\pi^{\pm})$ data, Sc. 1,2,3;



- Good agreement for $\Lambda K^-(\overline{\Lambda}K^+)$ data, Sc. 1,2,3;
- Sc. 1 (no charm/no *SU(2)*) cannot describe $\Lambda K^+(\overline{\Lambda}K^-)$ data with $z_K > 0{,}5$;
- Inclusion of charm allows for similar good fits (w/, w/o *SU(2)*)

A LOOK INTO ΛK^+ VS. $\Lambda\pi^+$ AT LARGE $z_{K/\pi}$

$$P_n(\Lambda K^+) \simeq 4D_{K^+/u}\Delta^N D_{\Lambda^\uparrow/\bar{u}} + D_{K^+/\bar{s}}\Delta^N D_{\Lambda^\uparrow/s}$$

$$P_n(\Lambda\pi^+) \simeq 4D_{\pi^+/u}\Delta^N D_{\Lambda^\uparrow/\bar{u}} + D_{\pi^+/\bar{d}}\Delta^N D_{\Lambda^\uparrow/d}$$

- Both negative and increasing at large z
- Sc 1: **down** pFF<0 …enough for $\Lambda\pi^+$
- Sc 2: inclusion of charm implies larger pFFs (**down** pFF stable):

  negative **strange** and the **sea** pFF larger
- Sc 3: inclusion of charm & *SU(2)* symmetry (**down** pFF>0)
  even larger size of the **sea** pFF (**strange** pFF stable w.r.t. Sc 2)

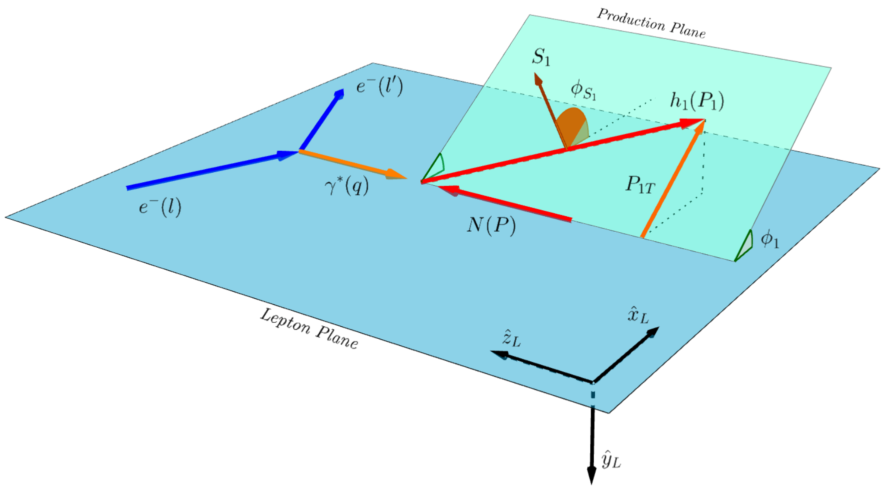
GENERAL REMARKS FROM e^+e^-

- Charm in unpol. xsec improves the quality of the fit (kaons)
- Polarizing FF for charm: tried but without any improvement
- Sc 2 and 3 (charm, w/ or w/o *SU(2)* symmetry) equally good
- If *SU(2)* not imposed, fits favor opposite pFFs for u, d

STRONG *SU(2)* symmetry violation

- Where/how can we check it?
- Different energies in e^+e^- do not help.

SIDIS



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

$$M_{f_1}(b_T, x) = \frac{1}{2\pi} e^{-g_1 \frac{b_T^2}{4}} \left(1 - \frac{\lambda g_1^2}{1+g_1} \frac{b_T^2}{4}\right)$$

Bacchetta, Delcarro, Pisano, Radici, Signori 2017

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

$$\times M_{f_1}(b_c(b_T), x) M_{D_h}(b_c(b_T), z)\; e^{-g_K(b_c(b_T); b_{\max}) \ln\left(\frac{Q^2 z}{x M_P M_h}\right) - S_{\text{pert}}(b_*; \bar{\mu}_b)}$$

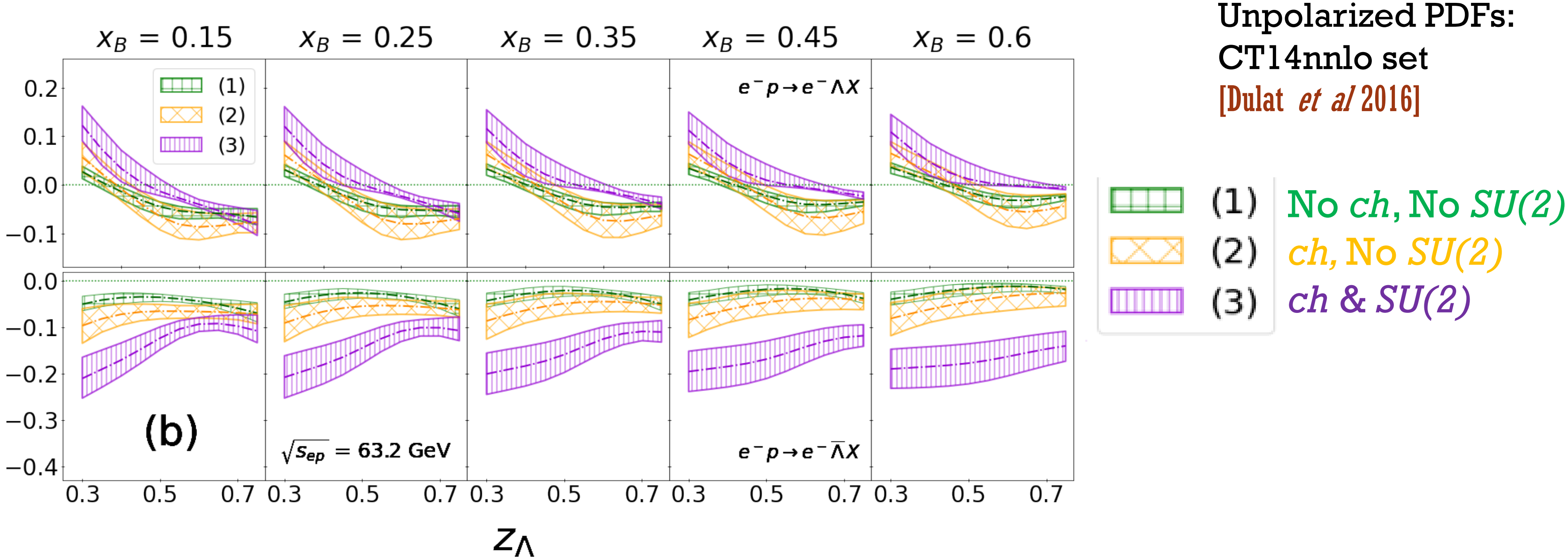
Coll PDF

$$\mathcal{B}_1\left[\widetilde{f}_1 \widetilde{D}_{1T}^{\perp(1)}\right] = \frac{1}{z^2} \sum_q e_q^2 \int \frac{db_T}{(2\pi)} b_T^2 J_1(b_T\, q_T) f_{q/N}(x; \bar{\mu}_b) D_{1T,q}^{\perp(1)}(z; \bar{\mu}_b)$$

$$\times M_{f_1}(b_c(b_T), x) M_{D_1}^{\perp}(b_c(b_T), z)\; e^{-g_K(b_c(b_T); b_{\max}) \ln\left(\frac{Q^2 z}{x M_P M_h}\right) - S_{\text{pert}}(b_*; \bar{\mu}_b)}$$

Nonpert funct.

PREDICTIONS FOR EIC



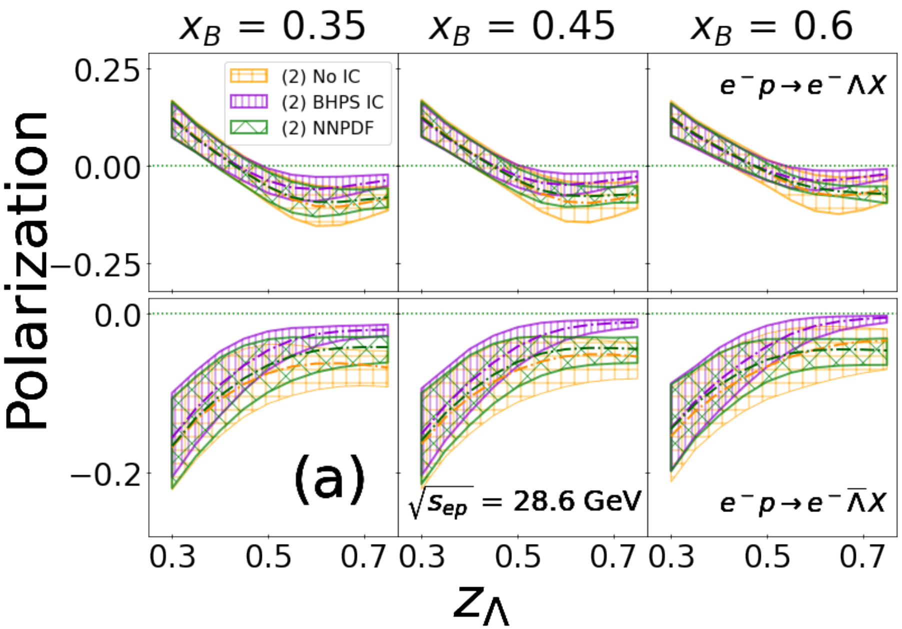
Unpolarized PDFs:
CT14nnlo set
[Dulat *et al* 2016]

- Sc. 1 & 2: no significant differences
- Λ pol. decreases and becomes negative
- $\bar{\Lambda}$ is always negative

- Sc. 3: similar size
- Λ pol. slightly greater
- $\bar{\Lambda}$ most significant difference

Impact study in SIDIS@EIC (Sc 1 at LO) Kang, Terry, Vossen, Xu, Zhang 2022

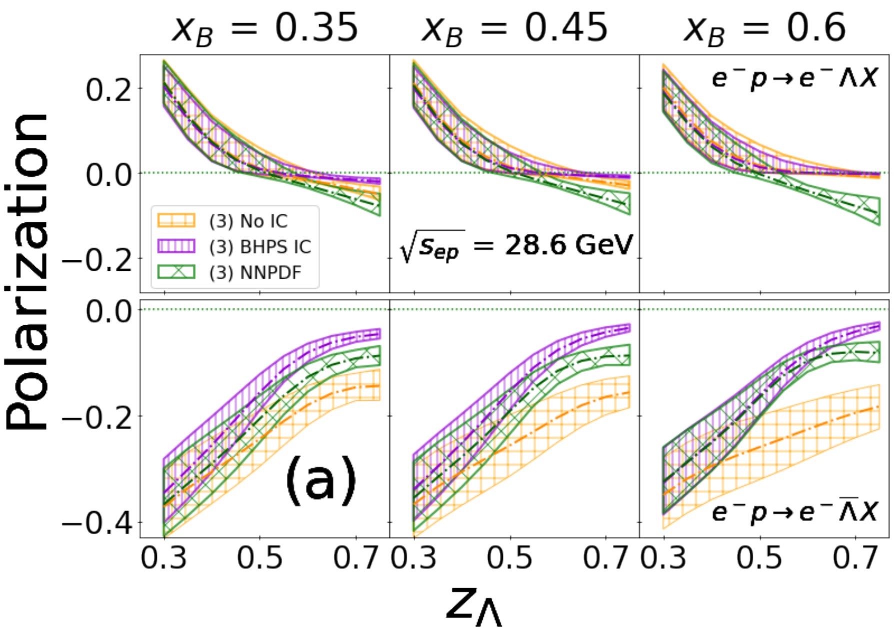
INTRINSIC CHARM IN THE PROTON WITHIN SCENARIO 2



- CT14 nnlo IC set with BHPS model [T.-J. Hou *et al.*, 2018]
- NNPDF4.0 nnlo set [NNPDF Coll. 2022]

- BHPS and NNPDF: similar polarization values
- compatible with no intrinsic charm case

INTRINSIC CHARM IN THE PROTON WITHIN SCENARIO 3



- CT14 nnlo IC set with BHPS model [T.-J. Hou *et al.*, 2018]
- NNPDF4.0 nnlo set [NNPDF Coll. 2022]

- Estimates vary significantly as x_B increases;
- $\bar{\Lambda}$ estimates different w.r.t. the no IC case;
- Similar behavior with perturbative charm contribution

CONCLUDING REMARKS

- New fit of Belle $e^+e^- \to h_1\ h_2 + X$ data on transverse Λ polarization within a TMD factorization at NLL accuracy
- Extraction of the polarizing FFs within three scenarios
- Charm contribution (seems) relevant
- *SU(2)* symmetry issue: no clear conclusion from e^+e^- data
- Predictions for SIDIS@EIC
  - ✓ *SU(2)* symmetry could be tested
  - ✓ $\bar{\Lambda}$ special role [Λ dominated by u and d]
  - ✓ check of the universality and scale evolution of the pFFs

THANKS for the ATTENTION

BACK-UP SLIDES