Flavor dependence of Lambda polarized fragmentation functions

宋玉坤（济南大学）

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X,Y.Qin, **YKS**, S.Y.Wei, 2504.00739
Y.Gao, K.B.Chen, **YKS**, S.Y.Wei, PLB 858 (2024) 139026
Y.L.Pan, K.B.Chen, **YKS**, S.Y.Wei, PLB 850 (2024) 138509
K.B.Chen, Z.T.Liang, **YKS**, S.Y.Wei, PRD 105 (2022) 034027
K.B.Chen, Z.T.Liang, Y.L.Pan, **YKS**, S.Y.Wei, PLB 816 (2021) 136217

Outline

I. Introduction

II. Flavor structure of $D_{1T,q}^{\perp\Lambda}$ from various processes

III. QCD evolution of $D_{1T,q}^{\perp\Lambda}$ and its nuclear dependence as a probe of nuclear matter

IV. Conclusion and outlook

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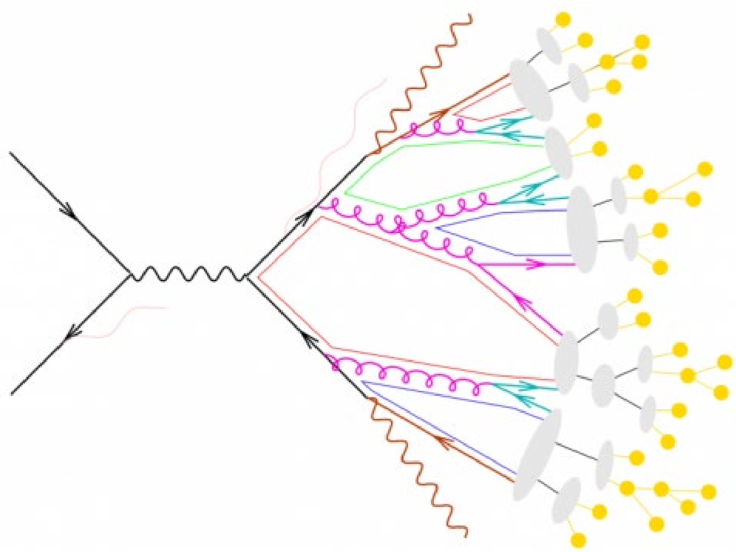
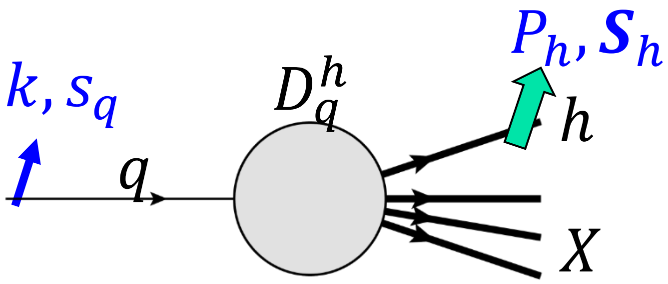
I Introduction



- QCD因子化定理 (Collins 2011)

$$\sigma_{e^+e^-\to hX} = \hat{\sigma}_{e^+e^-\to jX} \otimes D_j^h$$

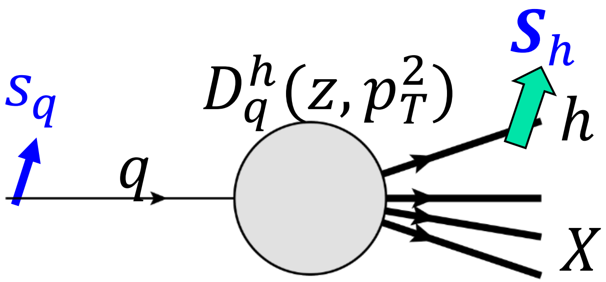
- D_j^h：碎裂函数(FF)，描述部分子碎裂产生强子的数密度，非微扰物理量 (Metz, Vossen, PPNP2016)
  - Global analysis of exp data
  - Quark model calculations
  - Lattice QCD ?



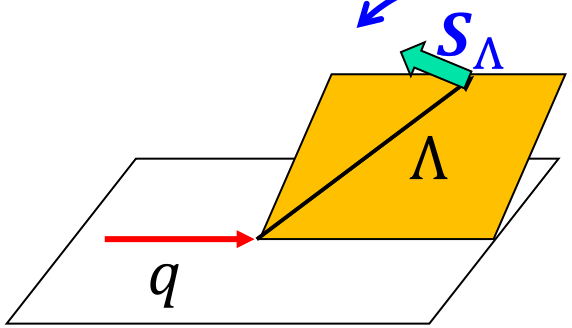
- $D_j^h(k, s_q; P_h, S_h)$
  - Collinear $D(z)$ vs TMD FFs $D(z, p_T^2)$
  - Leading Twist vs Higher twist FFs
  - Unpolarized vs spin-dependent FFs

Spin-dependent TMD FFs of Λ

- Λ超子的横动量依赖的（TMD）碎裂函数

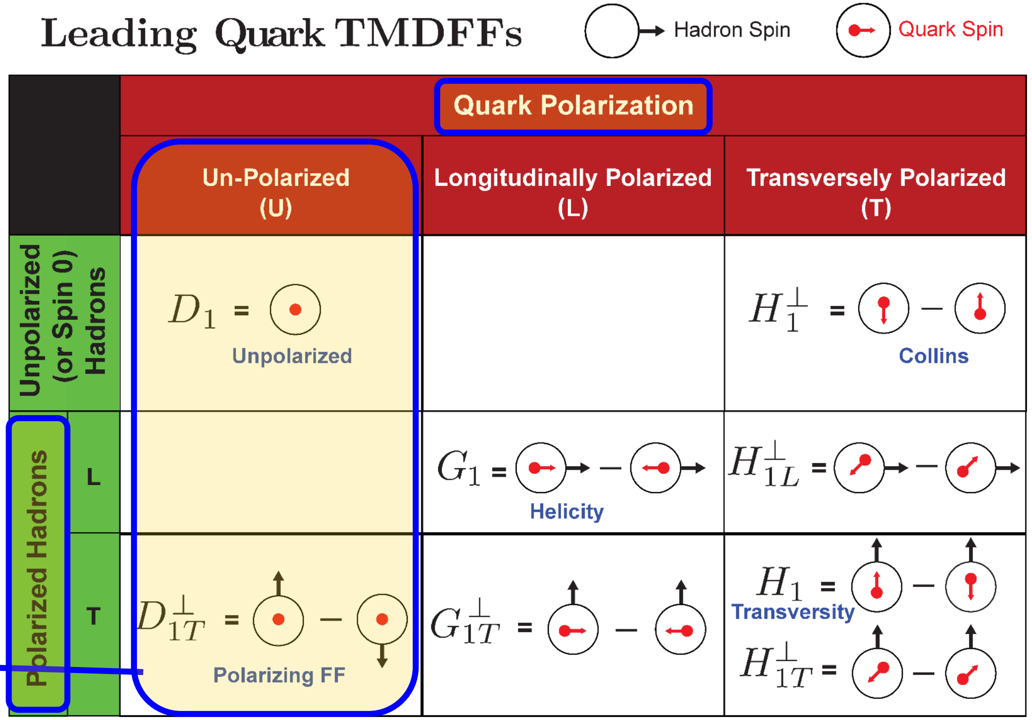


- 横向极化的Λ超子碎裂函数$D_{1T}^{\perp}(z, p_T^2)$



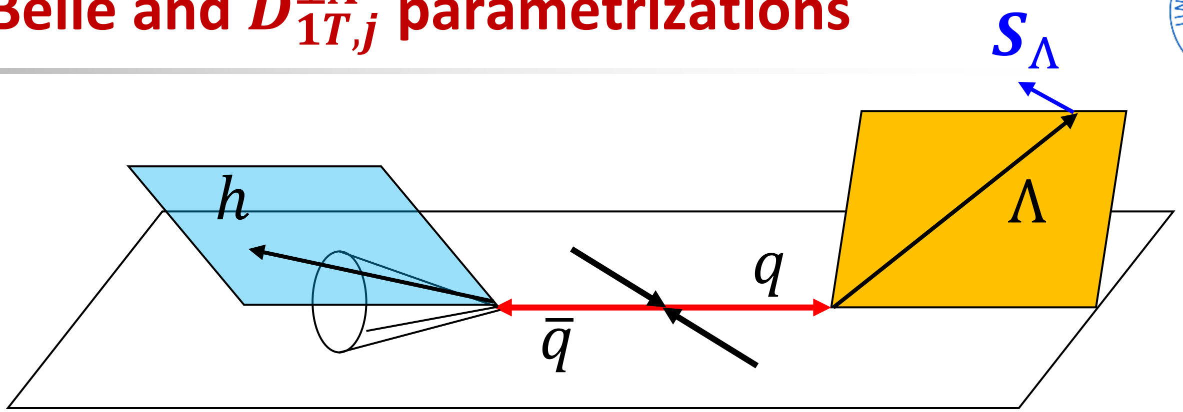
$D_{1T}^{\perp}(z, p_T^2)$

$\boldsymbol{S}_\Lambda \cdot (\boldsymbol{k} \times \boldsymbol{p}_\Lambda)$



TMD handbook
2304.03302

Λ Transverse polarization at Belle and $D_{1T,j}^{\perp\Lambda}$ parametrizations



- Belle collaboration PRL 122 (2019) 042001

1. Inclusive process in thrust frame

$$e^+e^- \to \Lambda(\bar{\Lambda})X$$

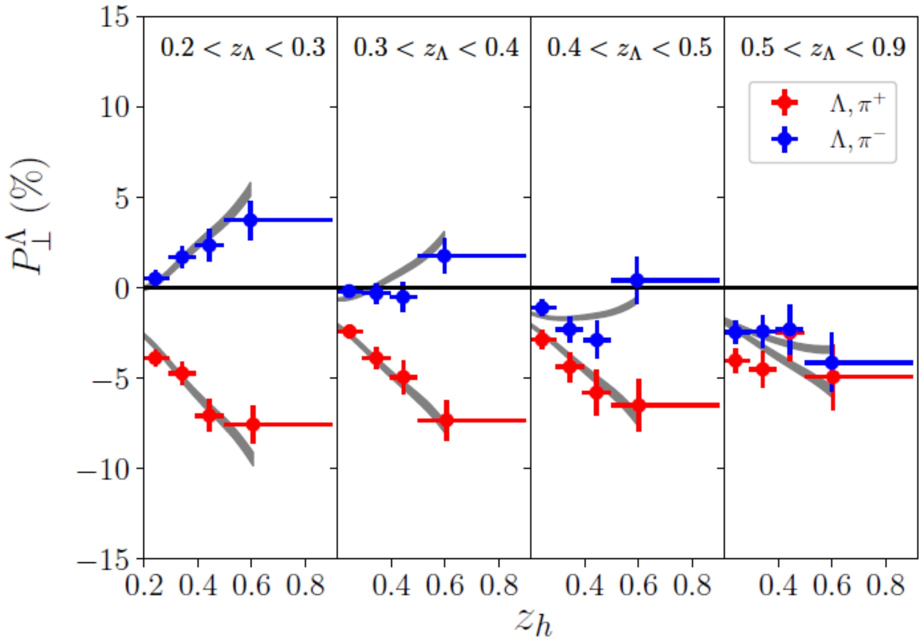
2. Semi-inclusive process

$$e^+e^- \to \Lambda(\bar{\Lambda})hX, \qquad h = \pi^\pm, K^\pm$$

- P_Λ for $\Lambda\pi^+$ and $\Lambda\pi^-$ are of opposite sign with $0.2 < z_\Lambda < 0.4$

$$e^+e^- \to \Lambda(u\boldsymbol{d}s)\pi^+(u\boldsymbol{\bar{d}})X, \qquad e^+e^- \to \Lambda(\boldsymbol{u}ds)\pi^-(d\boldsymbol{\bar{u}})X$$

$$P_\Lambda \propto \sum_q e_q^2 D_{1T,q}^{\perp\Lambda} \quad \Rightarrow \quad \boldsymbol{D_{1T,u}^{\perp\Lambda} \sim -D_{1T,d}^{\perp\Lambda}} \;\; ???$$



CKT

- Parametrizations with $\boldsymbol{D_{1T,u}^{\perp\Lambda} \neq D_{1T,d}^{\perp\Lambda}}$

U.D'Alesio, F.Murgia, M.Zaccheddu (DMZ), PRD 102 (2020) 05400

D.Callos, Z.B.Kang, J.Terry (CKT), PRD 102 (2020) 096007

Isospin symmetry violation?

Isospin symmetry conserved $D_{1T,j}^{\perp\Lambda}$ parametrizations

- However, all q's carry same color charges, and

  (1) $m_u \sim m_d \sim$ several MeV (2) Λ is a isospin singlet with $I = 0$

Isospin symmetry should apply to D_q^{Λ}, i.e., $\boldsymbol{D_u^{\Lambda} = D_d^{\Lambda}}$

- Based on an **isospin symmetric** formalism, we fit the Belle data well using CLPSW parametrizations.

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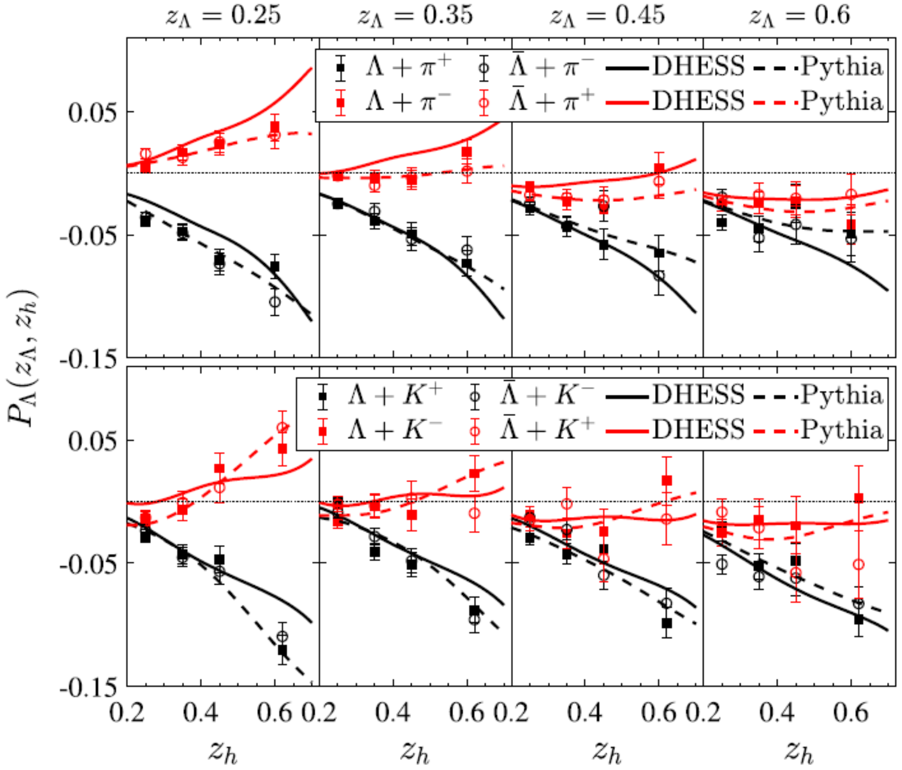
$$\boldsymbol{D_{1Tu}^{\perp\Lambda} = D_{1Td}^{\perp\Lambda},}$$

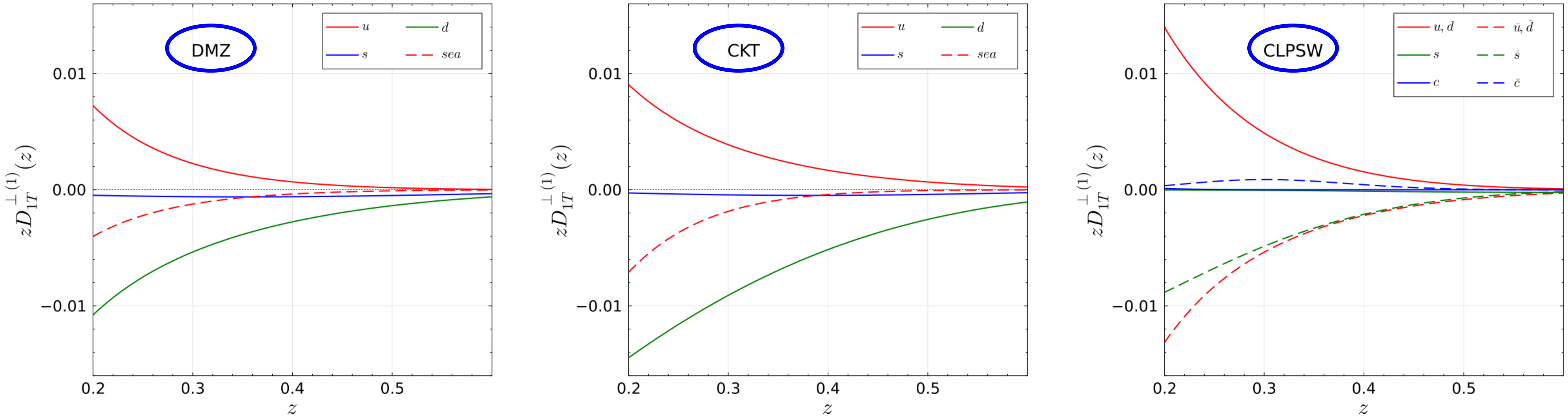
$$\boldsymbol{D_{1T\bar{u}}^{\perp\Lambda} = D_{1T\bar{d}}^{\perp\Lambda},}$$

$$\boldsymbol{D_{1Ts}^{\perp\Lambda},\ D_{1T\bar{s}}^{\perp\Lambda},\ D_{1Tc}^{\perp\Lambda},\ D_{1T\bar{c}}^{\perp\Lambda}}$$



Different flavor structures of $D_{1T,q}^{\perp\Lambda}$ from various parametrizations

➢ Comparison of parametrizations



How to decipher the flavor structure (Isospin symmetry) of the polarized FFs $\mathbf{D_{1T,q}^{\perp\Lambda}}$?

Analyzing the flavor structure of $D_{1T,q}^{\perp\Lambda}$

A **global analysis** of data from various experiments with a precise theoretical formalism

- $D_{1T}^{\perp}$-sensitive data from various processes

  Sensitive to specific flavored $D_{1T,q}^{\perp\Lambda}$ of transverse polarization in $\mathrm{ep/pp/pA/\gamma A}$ process

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  Y.Gao, K.B.Chen, **YKS**, S.Y.Wei, PLB 858 (2024) 139026

- A precise theoretical formalism with
  - QCD evolution effects

    $D_{1T}^{\perp}(z, p_T^2; \mu, \zeta)$： dependences on renormalization scale μ and C-S parameter ζ

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  - NLO corrections
  - Higher twist FFs

  important to incorporate data from lower energy experiment

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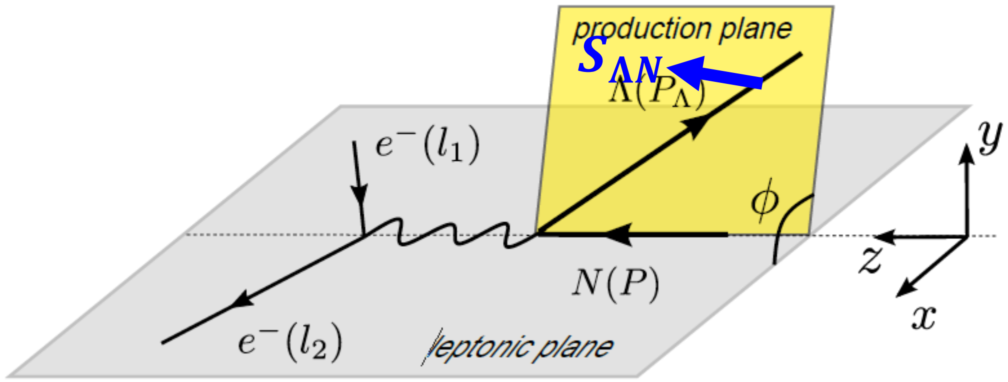
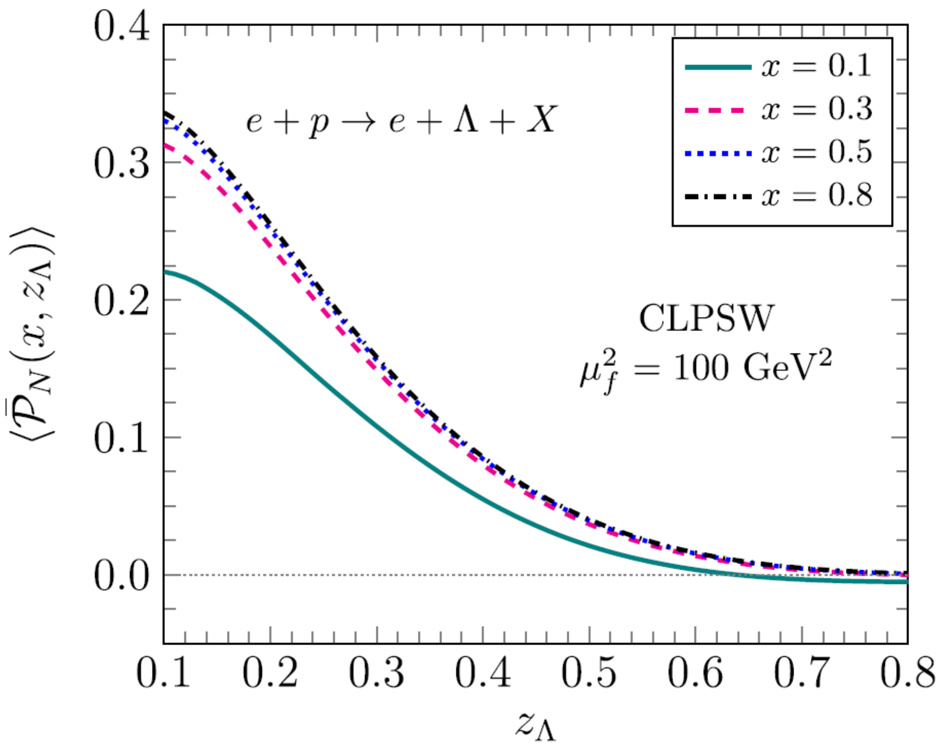
Transverse polarization of Λ in ep/eA collisions ($D_{1T}^{\perp}$)





$$\langle \bar{\mathcal{P}}_N(x, z_\Lambda) \rangle = \frac{\sqrt{\pi}\kappa_3(z_\Lambda)}{2z_\Lambda} \frac{\sum_q e_q^2 x f_{1q}(x) D_{1Tq}^{\perp\Lambda}(z_\Lambda)}{\sum_q e_q^2 x f_{1q}(x) D_{1q}^{\Lambda}(z_\Lambda)}$$

K.B.Chen, Z.T.Liang, **YKS**, S.Y.Wei, PRD 105 (2022) 034027

See also

Z.B.Kang, K.Lee, D.Y.Shao, F.Zhao, JHEP 11 (2021) 005

Z.B.Kang, J.Terry, A.Vossen, Q.H.Xu, J.L.Zhang, PRD 105 (2022) 094033

U.D'Alesio, L.Gamberg, F.Murgia, M.Zaccheddu, PRD 108 (2023) 094004

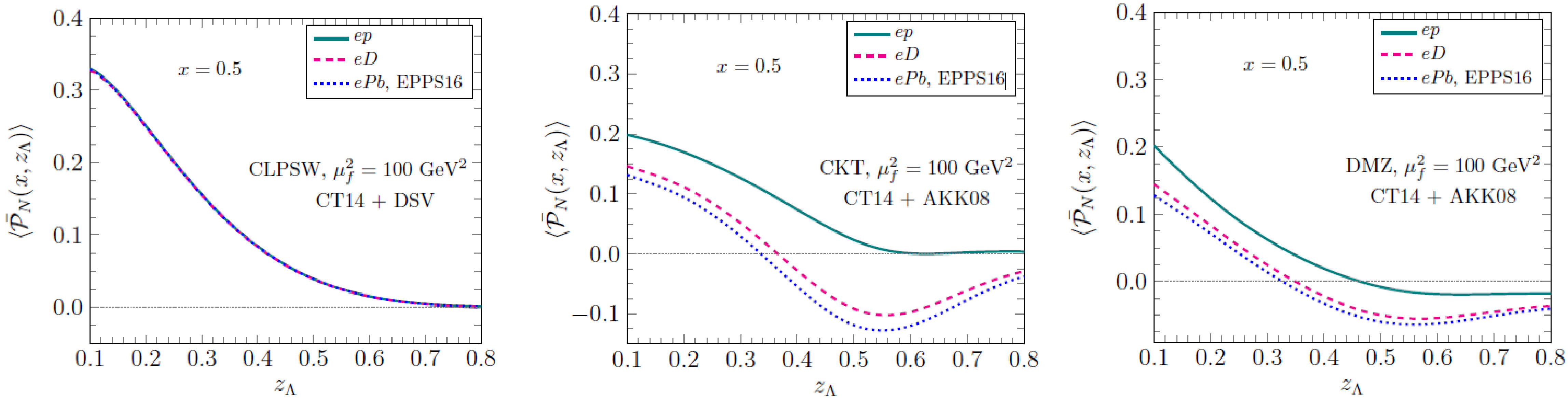
Z. Ji, X.Y.Zhao, A.Q.Guo, Q.H.Xu, J.L.Zhang, Nucl.Sci.Tech. 34 (2023) 155

Test of Isospin symmetry at the EIC with $\mathcal{P}_N$ for SIDIS

$$ep/eD/ePb \to e\Lambda X$$

Different u/d ratio→ $\begin{cases} \text{same } \mathcal{P}_N, & (D_{1u}^{\perp} = D_{1d}^{\perp}), \quad \text{CLPSW} \\ \text{different } \mathcal{P}_N, & (D_{1u}^{\perp} \neq D_{1d}^{\perp}), \quad \text{CKT, DMZ} \end{cases}$

EPPS16: Eskola, Paakkinen, Paukkunen, Salgado, Eur.Phys.J.C 77 (2017) 163



Isospin symmetric parametrization

Isospin symmetry violating parametrizations

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Transverse Λ production in hadronic collisions ($D_{1T}^{\perp}$)

- A wealth of data from hadronic collisions, e.g., $pp, p\bar{p}, pA, AA, \gamma A(UPC)$, ...
- Direct extension with $pp \to \Lambda h X$ suffer from violation of QCD factorization theorem

J. Collins, J. W. Qiu, PRD 75 (2007) 114014

- "Hadron inside jets" proposed to study TMD JFFs in hadronic collisions

F.Yuan, PRL 100 (2008) 032003

Z. B. Kang, X. Liu, F. Ringer and H. Xing, JHEP 11 (2017), 068

Z. B. Kang, K. Lee and F. Zhao, PLB 809 (2020), 135756

(1) Reconstruct jets from pp collisions

(2) Measure the p_T distribution of hadrons with respect to jet axis.

To explore the potential for flavor separation for $D_{1T,q}^{\perp\Lambda}$, we perform a detailed phenomenological analysis on various hadronic collisions

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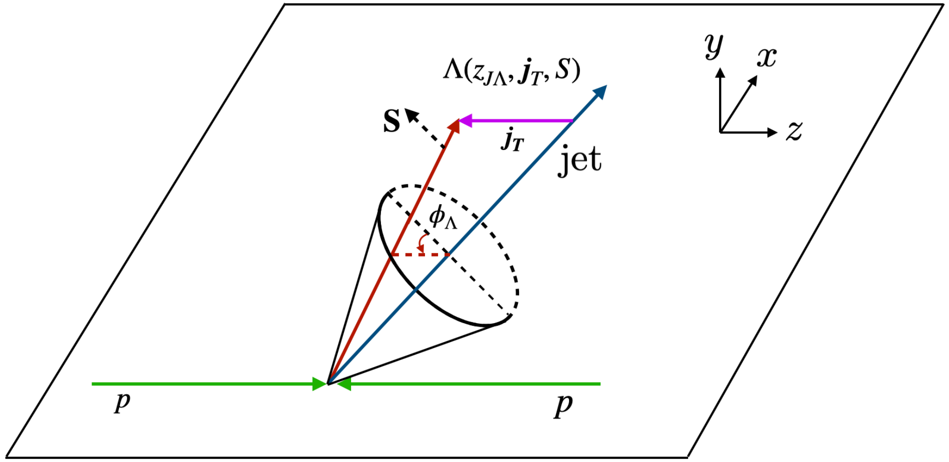

Figure from STAR

pp collisions

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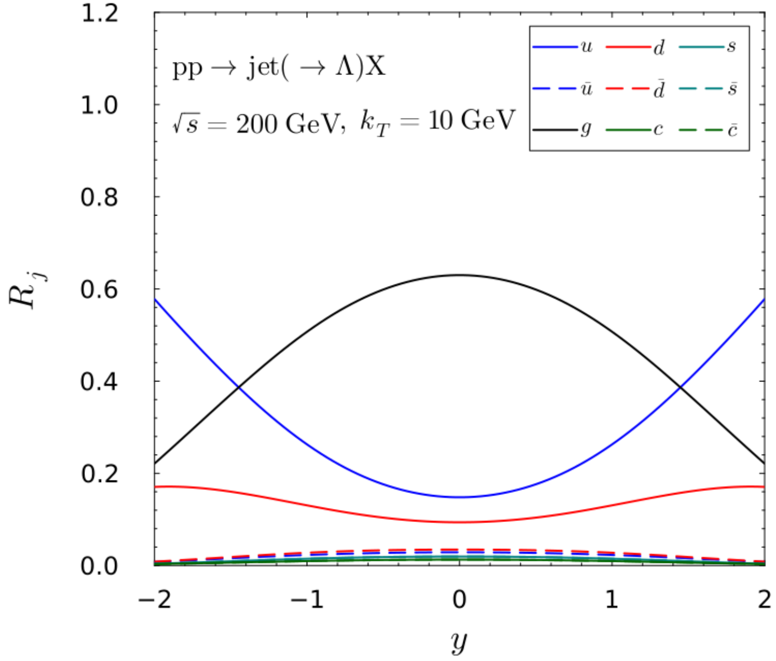
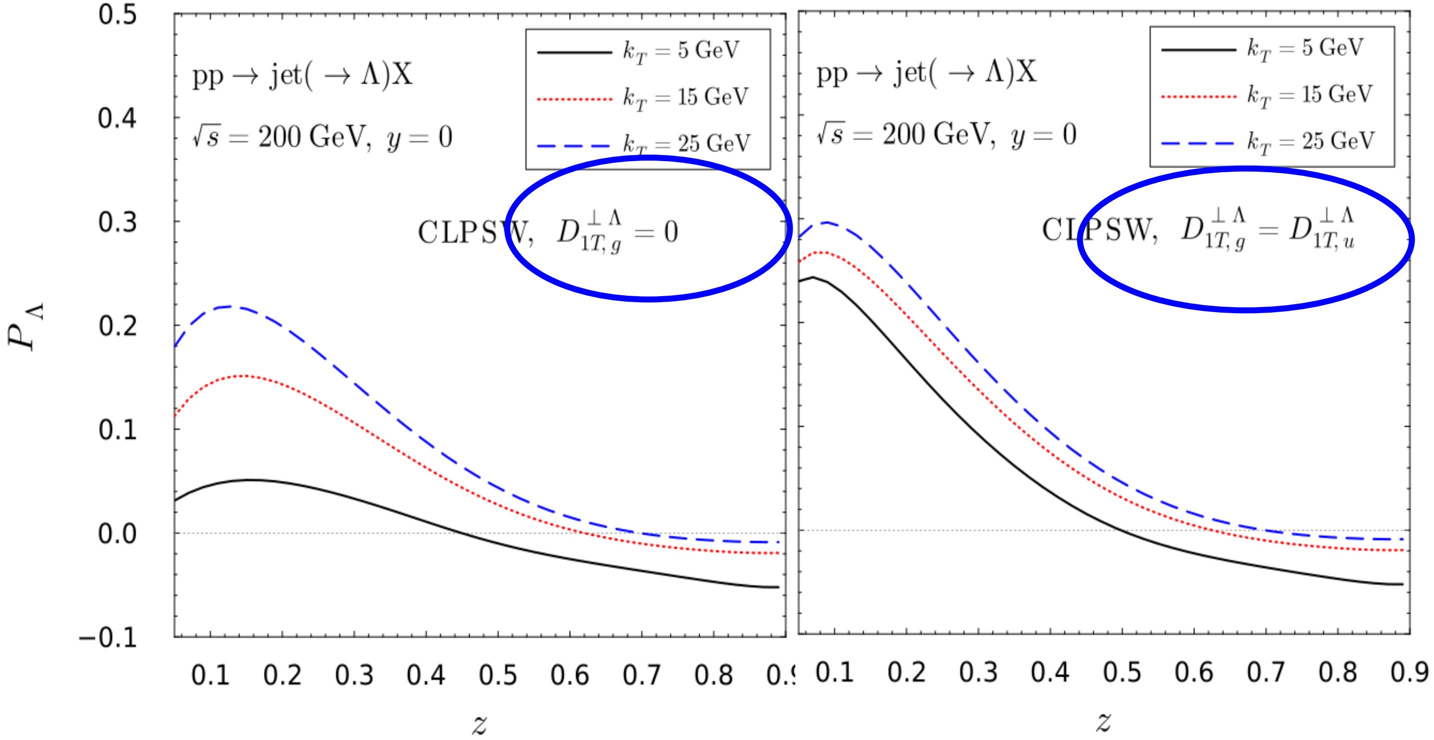


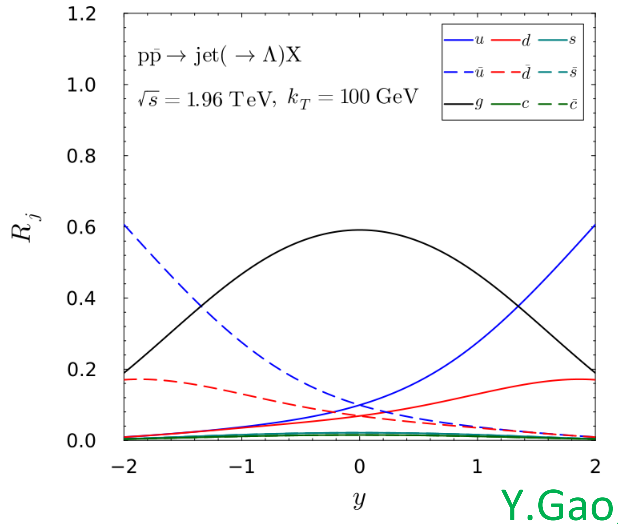


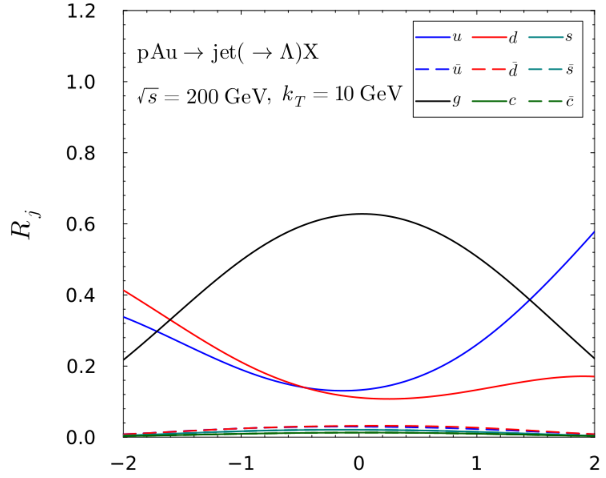
Central rapidity & small k_T region, **gluon dominate**!

$\Longrightarrow$ a nice place to study the gluon polarized FF $\boldsymbol{D_{1T,g}^{\perp\Lambda}}$

CT18 PDF, DSV FF D_1^{Λ}, CLPSW $D_{1T}^{\perp}$

$\mathbf{p\bar{p}}$ pA





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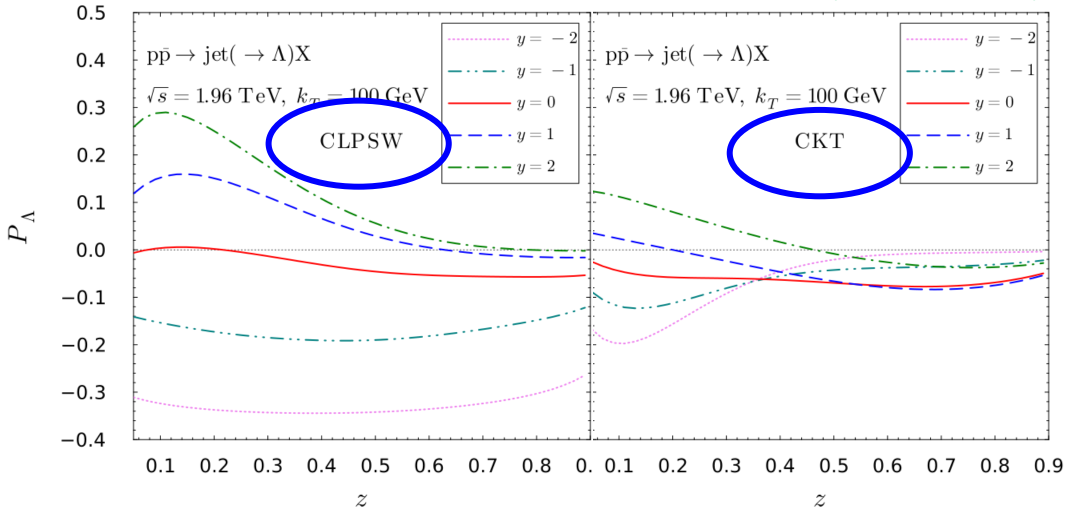

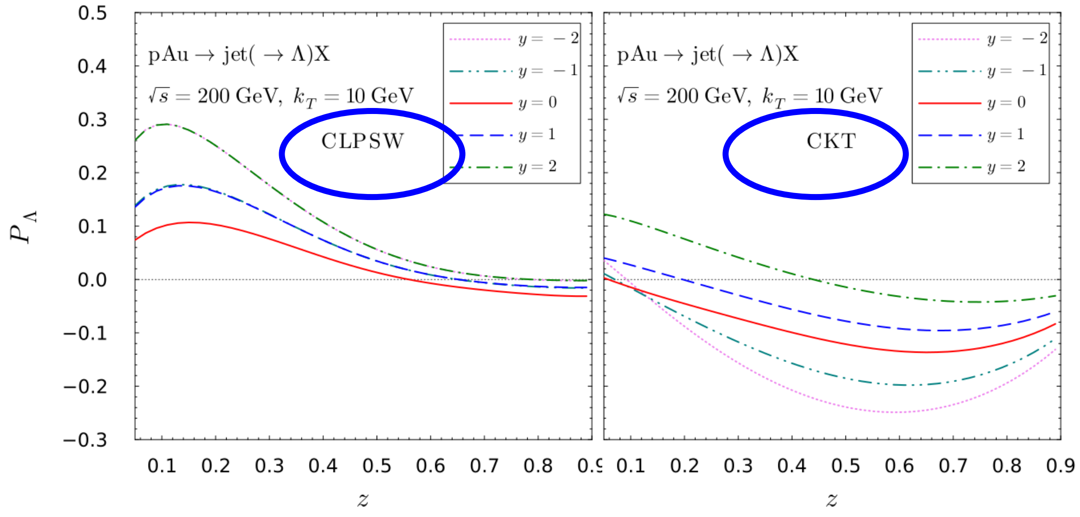

Forward rapidity region, $\boldsymbol{u}$ **quark dominate**;
backward rapidity region, $\bar{\boldsymbol{u}}$ **quark dominate**

Forward rapidity region, $\boldsymbol{u}$ **quark dominate**;
backward rapidity region, $\boldsymbol{u+d}$ **quark dominate**

Outline

QCD evolution of $D_{1T}^{\perp}(z, p_\perp; \mu, \zeta)$

$$\widehat{D}(z,\vec{p}_\perp) = \int \frac{d^2b}{(2\pi)^2} e^{i\vec{b}_T\cdot\vec{p}_\perp/z}\,\widehat{D}(z,\vec{b}_T), \qquad \widehat{D}(z,\vec{b}_T) = \frac{1}{2}\left[D_1(z,b_T) - \frac{iM\varepsilon_\perp^{bS}}{z^2} D_{1T}^{\perp(1)}(z,b_T)\right]$$

- $\boldsymbol{D_1(z, b_T; \mu, \zeta)}$ follow RG and CS evolution equations

$$\frac{d\ln D_1(z,b_T;\mu,\zeta)}{d\ln\mu} = \gamma_D\left(g(\mu),\frac{\zeta}{\mu^2}\right), \qquad \frac{d\ln D_1(z,b_T;\mu,\zeta)}{d\ln\sqrt{\zeta}} = K(b_T,\mu)$$

- Taking $\zeta = \mu^2 = Q^2$, the solution to above evolution equations

$$D_1(z,b_T,Q) = \frac{1}{z^2} D_1(z,\mu_b)\exp\{-S_{pert}(\mu_b,Q) - S_{NP}(b_T,z,Q_0,Q)\}$$

Where the perturbative and non-perturbative parts are given by

$$S_{pert}(\mu_b,Q) = -K(b_T^*,\mu_b)\ln\frac{Q}{\mu_b} - \int_{\mu_b}^{Q}\frac{d\mu'}{\mu'}\gamma_D\left(g(\mu'),\frac{Q^2}{\mu'^2}\right)$$

$$S_{NP}(b_T,z,Q_0,Q) = g_h\frac{b_T^2}{z^2} + \frac{g_2}{2}\ln\frac{Q}{Q_0}\ln\frac{b_T}{b_T^*}, \qquad g_h \simeq \frac{\langle p_\perp^2\rangle}{4}$$

L.Gamberg, Z.B.Kang, D.Y.Shao, J.Terry, F.Zhao, PLB 818 (2021) 136371

- Similarly for $D_{1T}^{\perp}$ L.Gamberg, Z.B.Kang, D.Y.Shao, J.Terry, F.Zhao, PLB 818 (2021) 136371

$$D_{1T}^{\perp}(z,b,Q) = \frac{\langle M_D^2\rangle}{2z^2M^2} D_{1T}^{\perp}(z,\mu_b)\exp\{-S_{pert}(\mu_b,Q) - S_{NP}^{\perp}(b,z,Q_0,Q)\}$$

$$S_{NP}^{\perp}(b,z,Q_0,Q) = \frac{\langle M_D^2\rangle}{4}\frac{b_T^2}{z^2} + \frac{g_2}{2}\ln\frac{Q}{Q_0}\ln\frac{b_T}{b_T^*}$$

- Modifications from QGP e.g., L. Chen, G. Y. Qin, S. Y. Wei, B. W. Xiao and H. Z. Zhang, PLB 773 (2017) 672

$$D_1^{med}(z,b_T,Q) = D_1^{vac}(z,b_T,Q)e^{-\langle\hat{q}L\rangle b_T^2/4}$$

$$D_{1T}^{\perp,med}(z,b_T,Q) = D_{1T}^{\perp,vac}(z,b_T,Q)e^{-\langle\hat{q}L\rangle b_T^2/4}$$

With $\hat{q}$ the jet transport coefficient.

- We study the QCD evolution effects and the nuclear effects on Λ transverse polarization.

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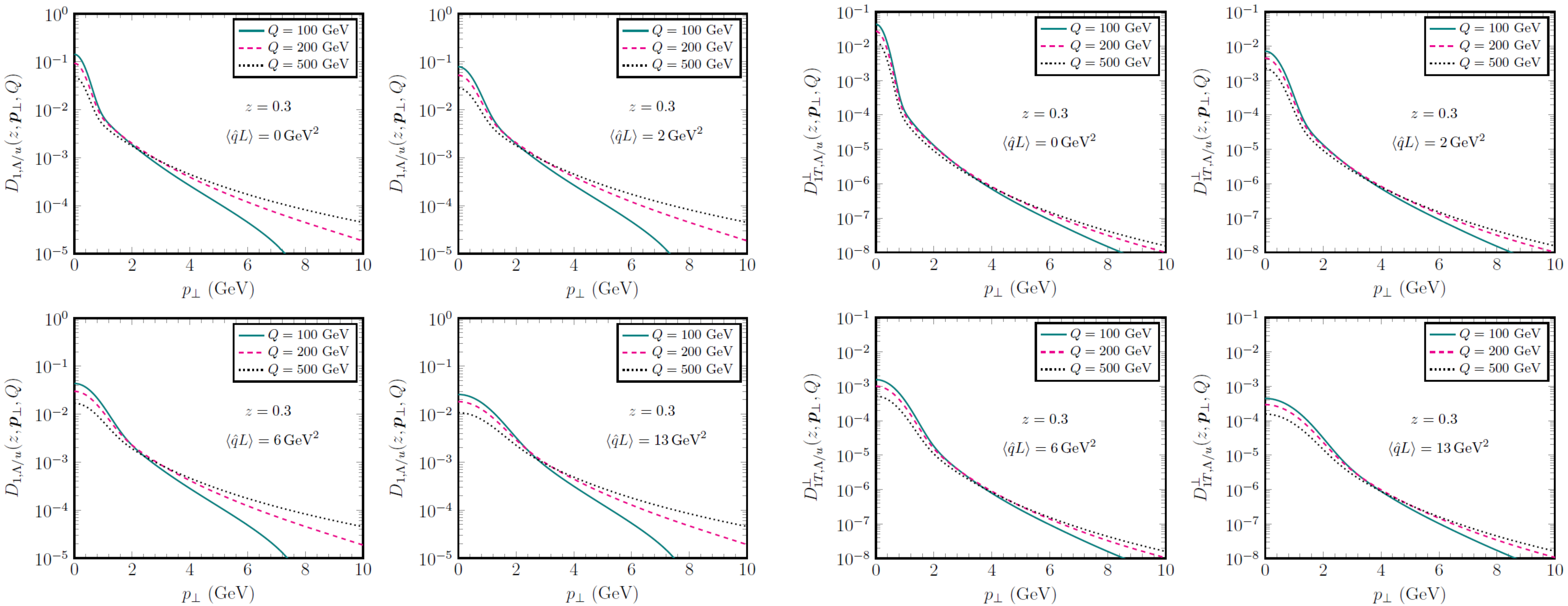
Evolution/Nuclear effects on D_1 and $D_{1T}^{\perp}$

$D_{1u}^{\Lambda}(z, p_\perp, Q)$ $D_{1T,u}^{\perp\Lambda}(z, p_\perp, Q)$



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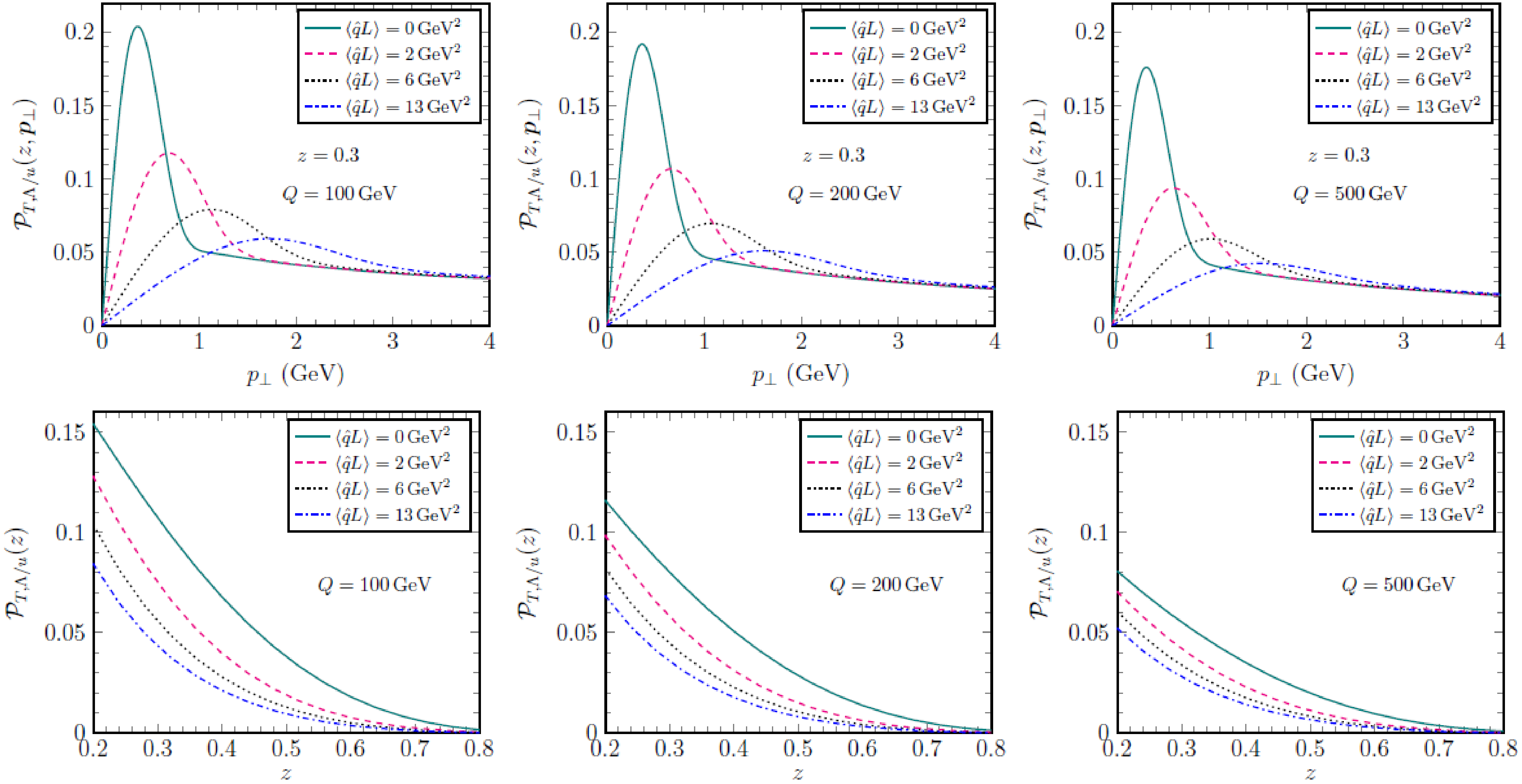
Evolution/Nuclear effects on Λ transverse polarization

$\mathcal{P}_{T,\Lambda/u}(z, p_\perp)$

$\mathcal{P}_{T,\Lambda/u}(z)$



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- Significant QCD evolution effects
- $\mathcal{P}_{T,\Lambda/u}$ can serve as a probe of QGP matter

Conclusions and outlook

- Transverse polarization of Λ from Belle provoke the study of $D_{1T,q}^{\perp\Lambda}$, with current focus on the flavor structure/isospin symmetry
- Transverse polarization of Λ at different processes such as eA/pp/p$\bar{\text{p}}$/pA… are sensitive to $D_{1T,q}^{\perp\Lambda}$ of different flavors of $\mathrm{u}, \mathrm{d}, \mathrm{g}, \bar{\mathrm{u}}, \bar{\mathrm{d}}$,…
- QCD evolution have evident effects on $D_{1T}^{\perp}$ at different energy scales. The QGP modify the gluon radiation in vacuum, leaving visible impact on the transverse polarization of Λ. This effect provide a new probe of nuclear matter.
- More experimental data and theoretical progress on the way, promising a nice prospect for the precise flavor structure of Λ polarized fragmentation function $D_{1T,q}^{\perp\Lambda}$

Thanks for you attention!