Polarized TMD FFs with QCD evolution

Yu-Kun Song (University of Jinan)

2025.9.23

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. Transverse polarization of Λ from QGP as a probe of nuclear matter

IV. Conclusion and outlook

Outline

I. **Introduction**

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

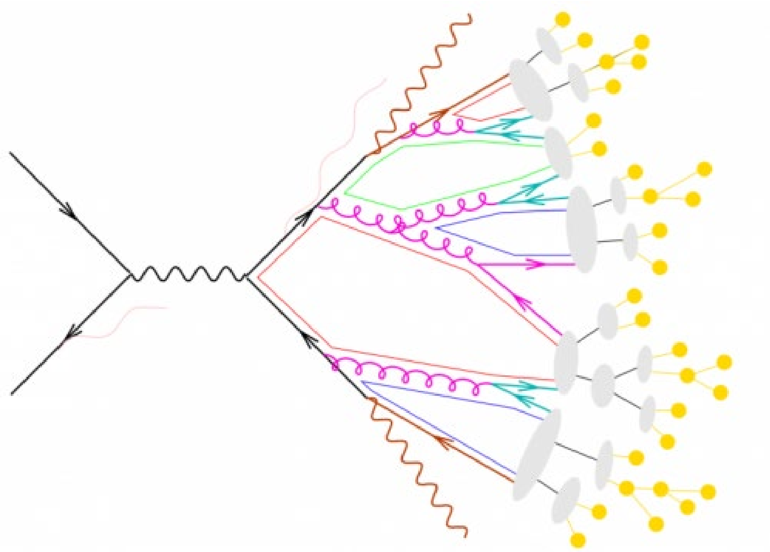
III. Transverse polarization of Λ from QGP as a probe of nuclear matter

IV. Conclusion and outlook

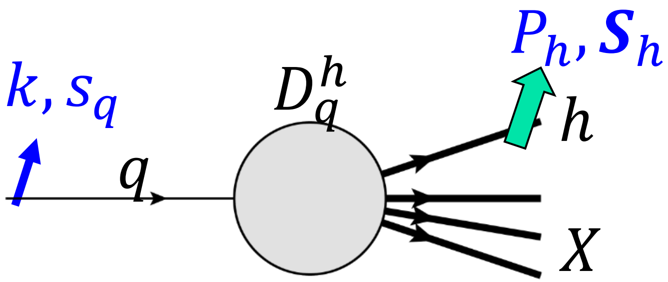
I Introduction

- QCD factorization formulae (Collins 2011)

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



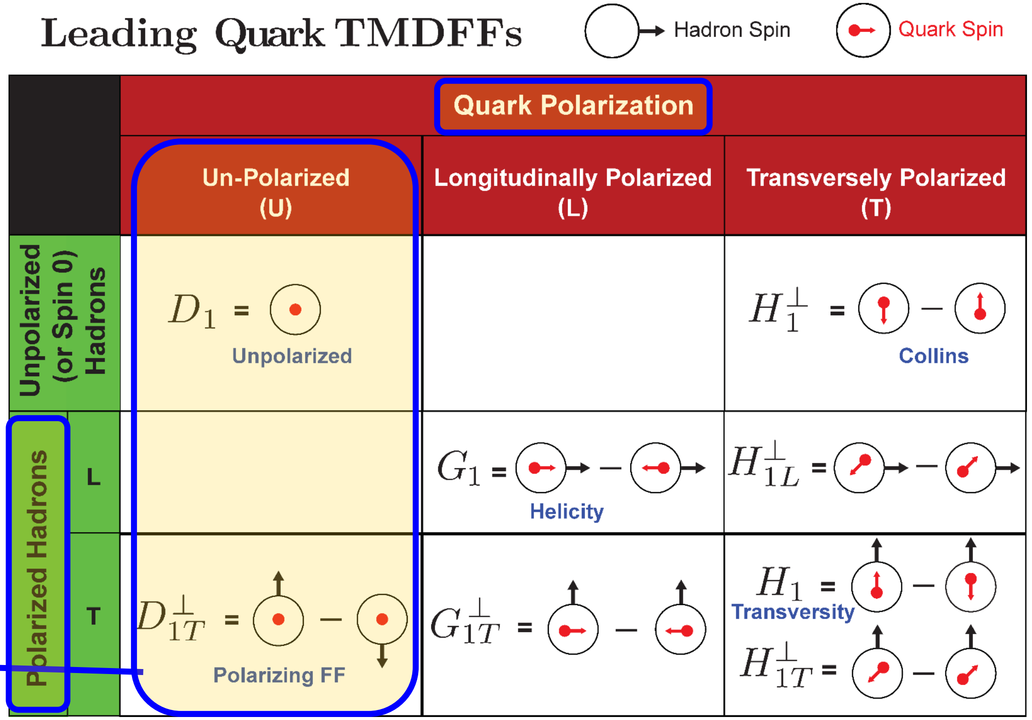
- D_j^h: fragmentation functions(FFs) (Metz, Vossen, PPNP2016)
  - Global analysis of exp data
  - Quark model calculations
  - Lattice QCD ?



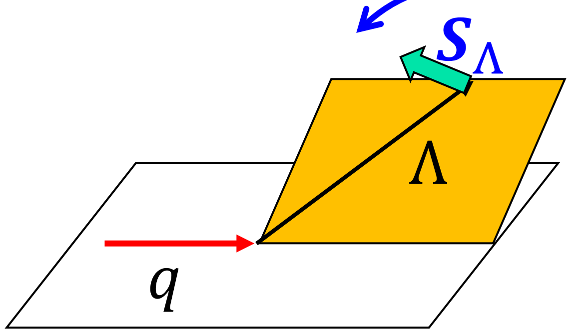
- $D_j^h(k, s_q; P_h, S_h)$: polarized FFs, various SS/LS-coupling
  - Transverse-momentum-dependent (TMD) FFs $D(z, p_T^2)$
  - Leading Twist vs Higher twist FFs
  - Unpolarized vs spin-dependent FFs

Spin-dependent TMD FFs of Λ

- Polarized TMD FF $D_{1T}^{\perp}(z, p_T^2)$ of Λ



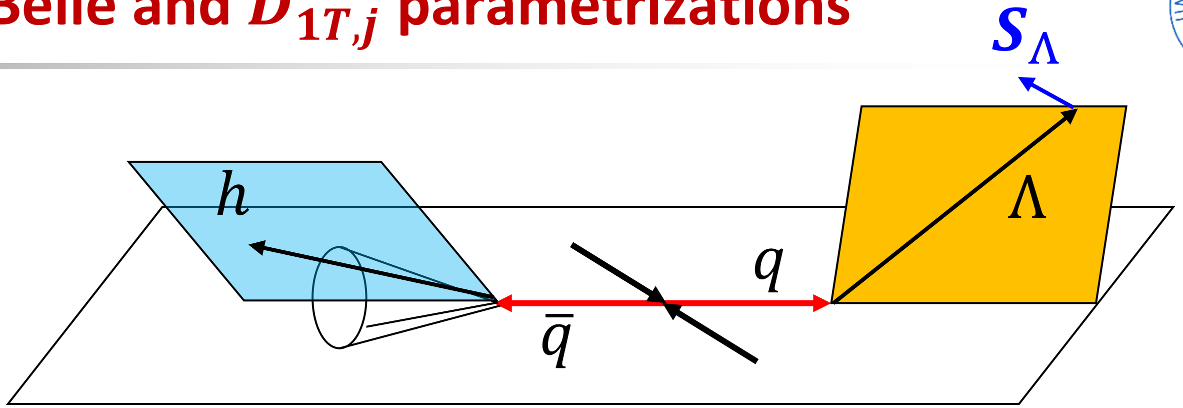
TMD handbook
2304.03302



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

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

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 $0.2 < z_\Lambda < 0.4$

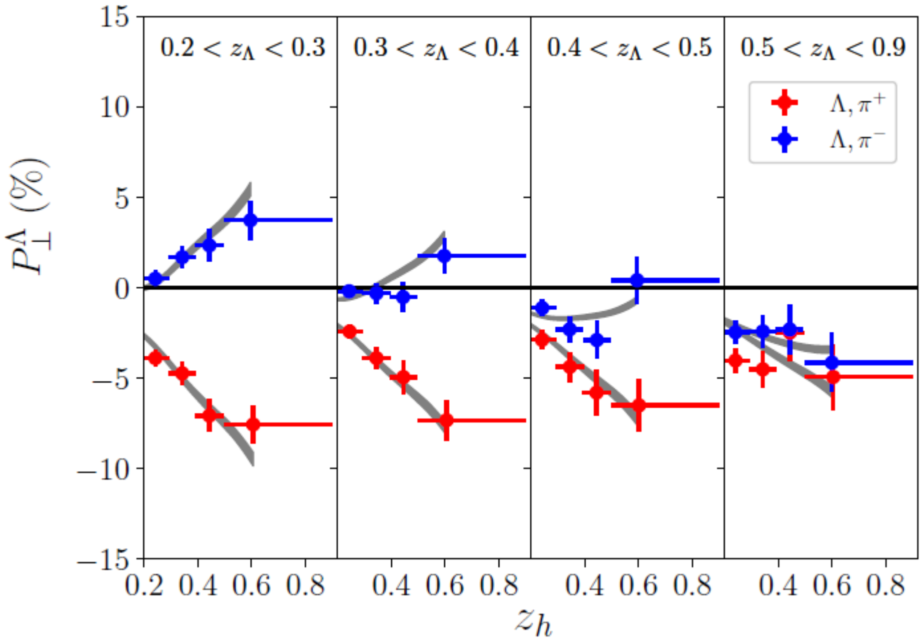
$$e^+e^- \to \Lambda(u\boldsymbol{d}s)\pi^+(u\bar{\boldsymbol{d}})X, \qquad e^+e^- \to \Lambda(\boldsymbol{u}ds)\pi^-(d\bar{\boldsymbol{u}})X$$

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

- 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



CKT

Isospin symmetry violation?

- 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 symmetric FFs, $D_u^{\Lambda} = D_d^{\Lambda}$, are more reliable assumptions to us

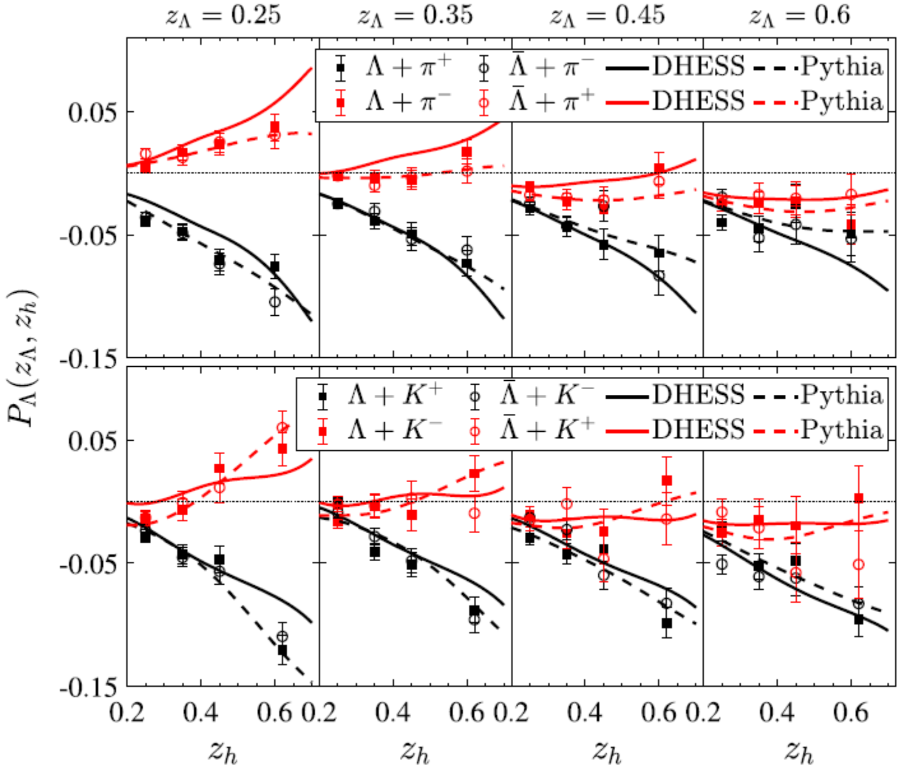
- Based on an **isospin symmetric** formalism, we fit the Belle data well using CLPSW parametrizations.

K.B.Chen, Z.T.Liang, Y.L.Pan, **YKS**, S.Y.Wei, PLB 816 (2021) 136217

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

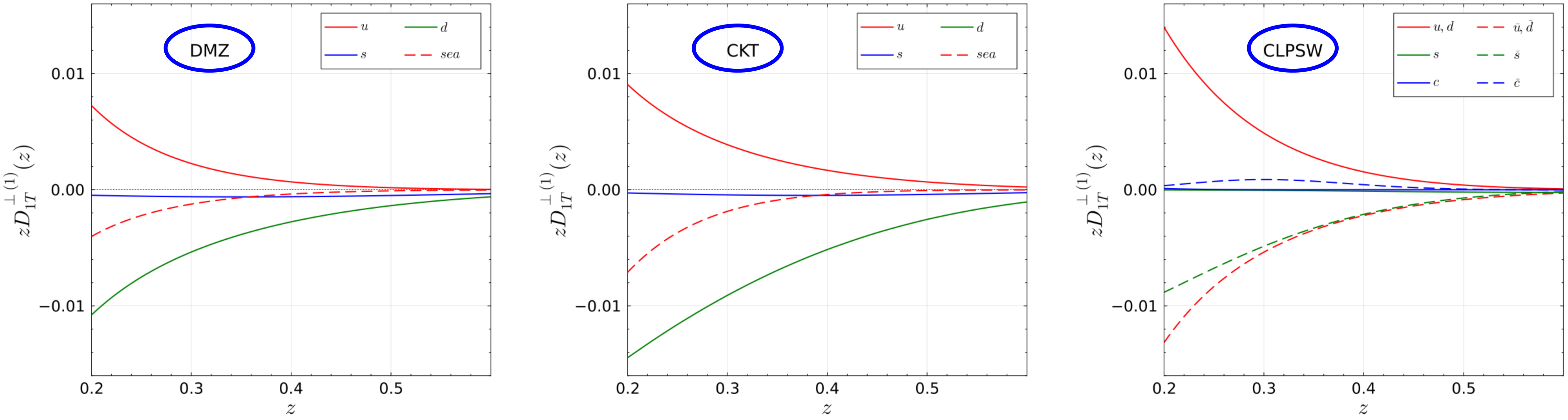
$$D_{1T\bar{u}}^{\perp\Lambda} = D_{1T\bar{d}}^{\perp\Lambda},$$

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



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 is in need

- $D_{1T}^{\perp}$-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

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

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

- The 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

    X,Y.Qin, **YKS**, S.Y.Wei, 2504.00739
  - NLO corrections
  - Higher twist FFs

  important to incorporate data from lower energy experiment

Outline

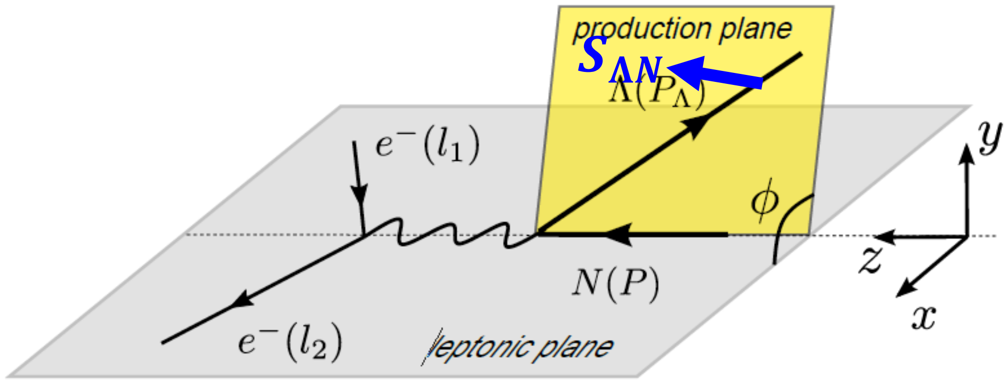
I. Introduction

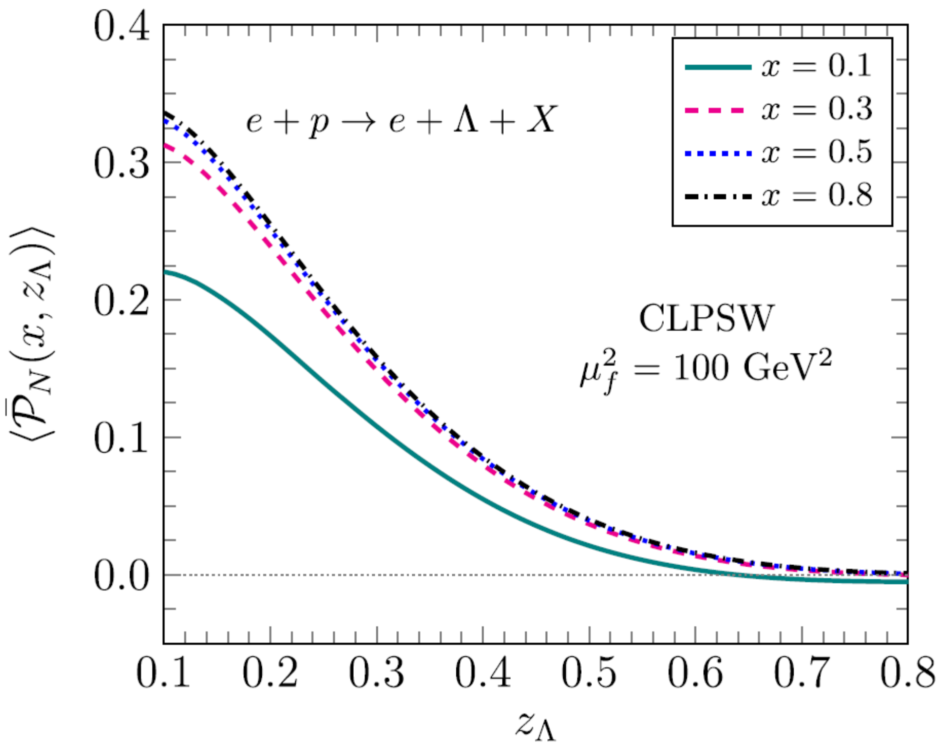
II. Flavor structure of $D_{1T,q}^{\perp\Lambda}$ from various processes

III. Transverse polarization of Λ from QGP as a probe of nuclear matter

IV. Conclusion and outlook

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

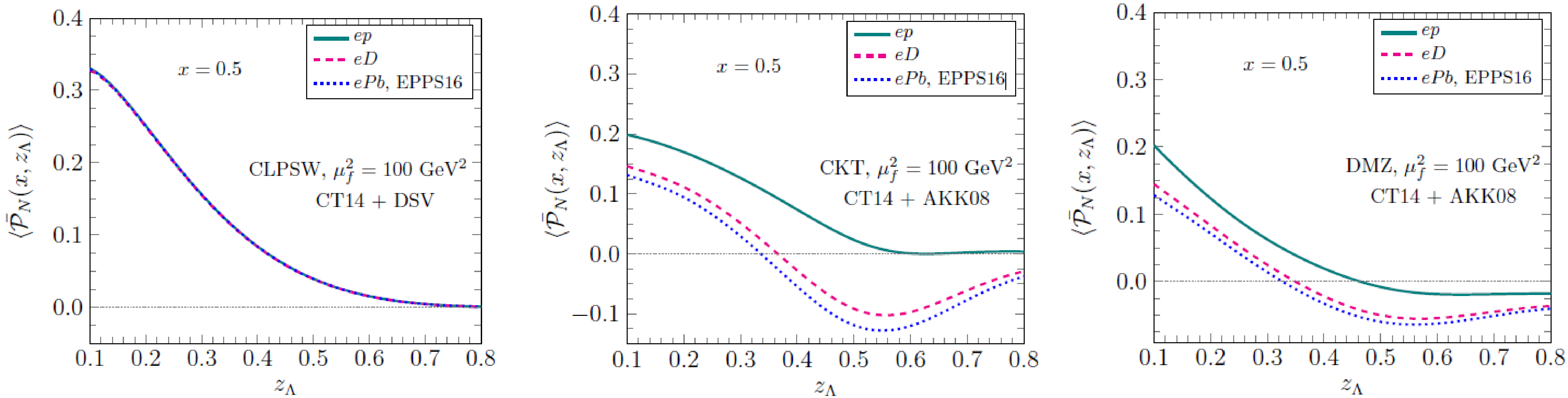
Z. Ji, X.Y.Zhao, A.Q.Guo, Q.H.Xu, J.L.Zhang, Nucl.Sci.Tech. 34 (2023) 155

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

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

Different u/d ratio→
- same $\mathcal{P}_N$, $(D_{1u}^{\perp} = D_{1d}^{\perp})$, CLPSW
- different $\mathcal{P}_N$, $(D_{1u}^{\perp} \neq D_{1d}^{\perp})$, CKT, DMZ

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



Isospin symmetric parametrization

Isospin symmetry violating parametrizations

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

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

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

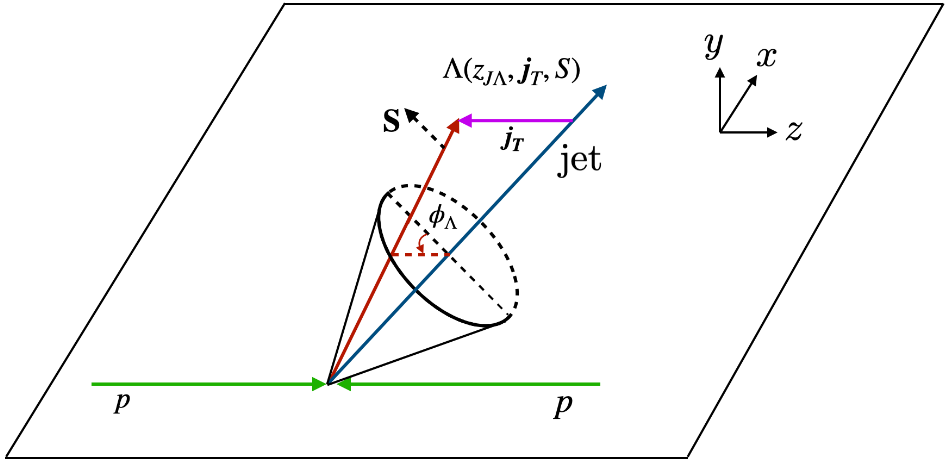
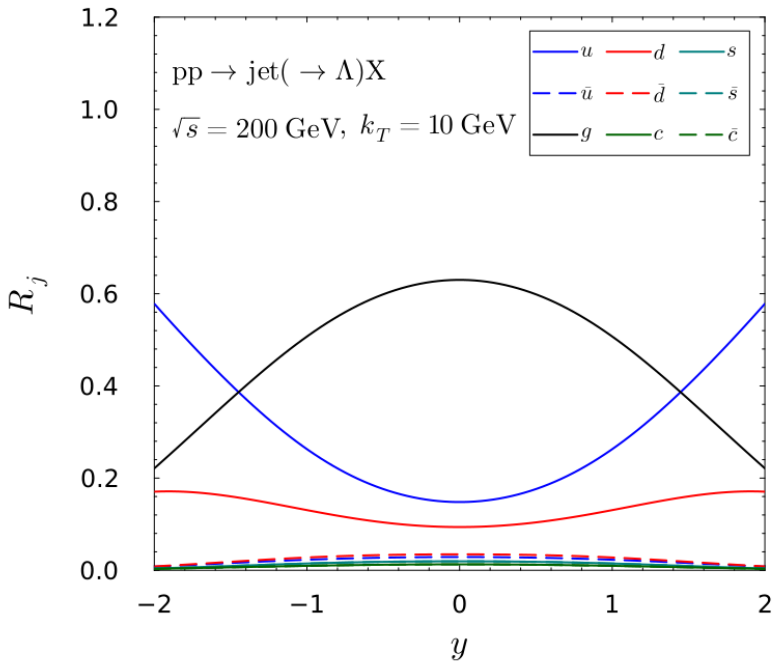
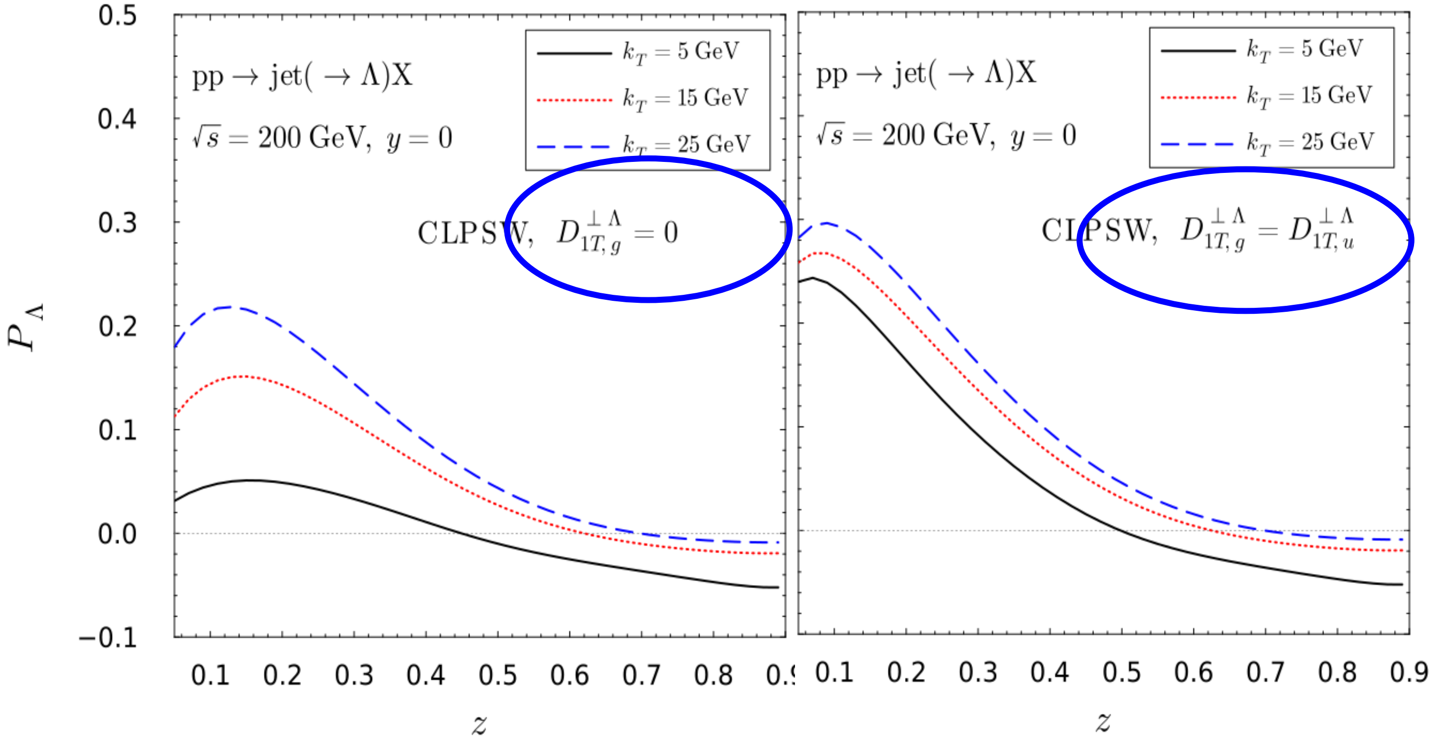


Figure from STAR

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



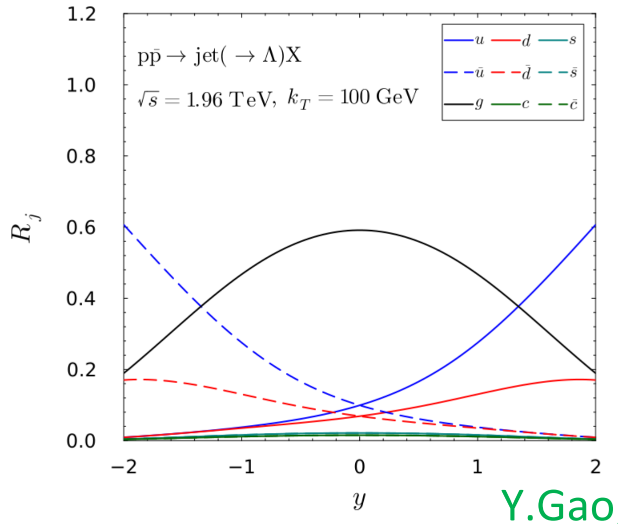


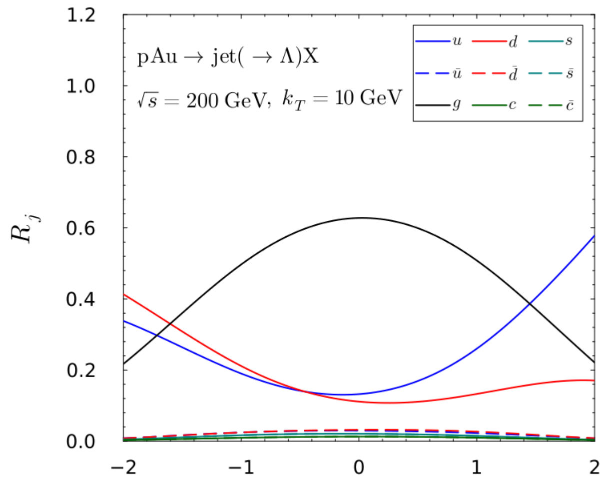
Central rapidity & small k_T region, **gluon dominate**!

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

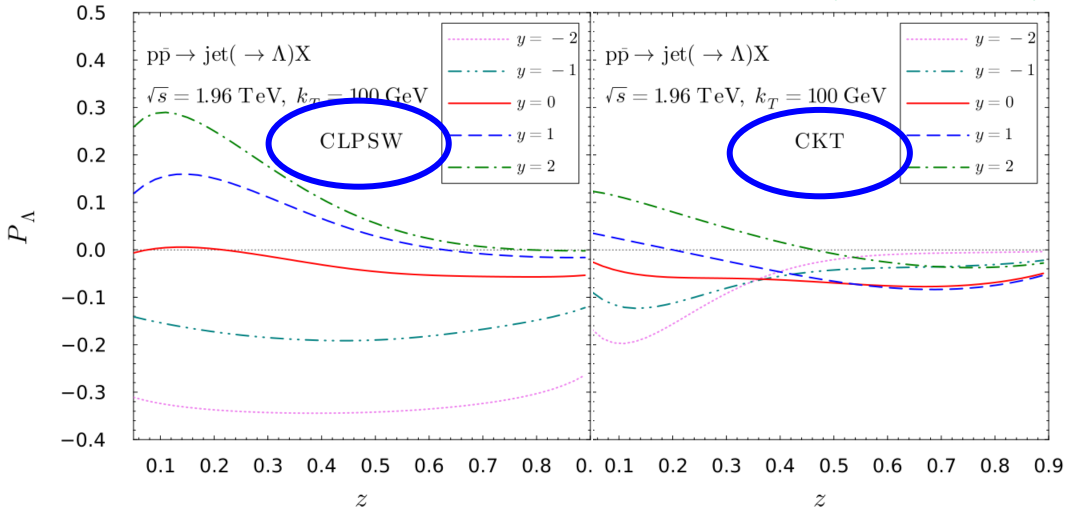
CT18 PDF, DSV FF D_1^{Λ}, CLPSW $D_{1T}^{\perp}$

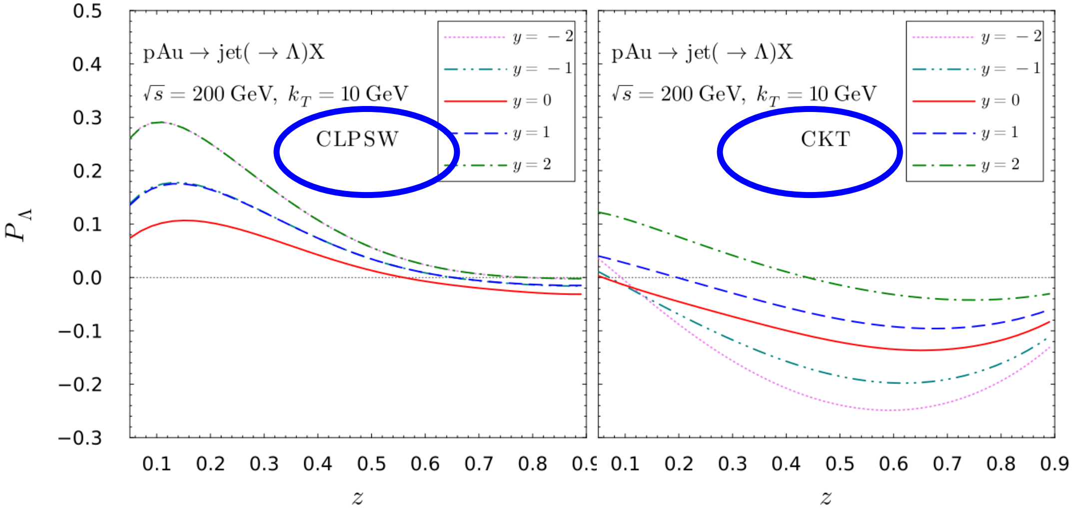
$p\bar{p}$ | pA





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

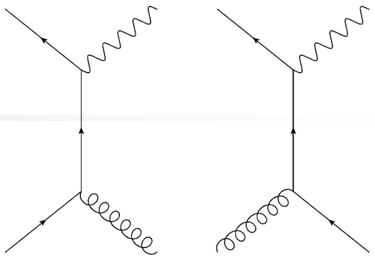




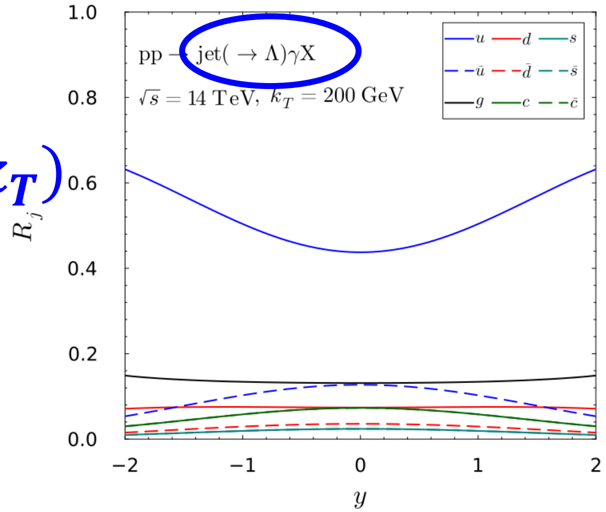
Forward rapidity region, ***u* quark dominate**;
backward rapidity region, **$\bar{u}$ quark dominate**

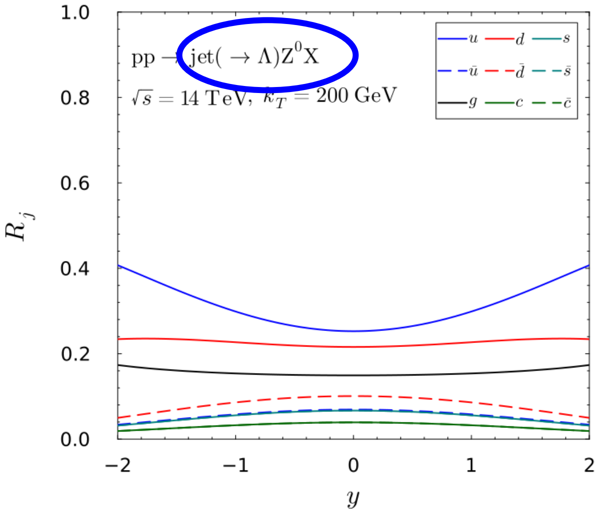
Forward rapidity region, ***u* quark dominate**;
backward rapidity region, **$u + d$ quark dominate**

γ/Z^0-associated Λ production



$R_j(y, k_T)$





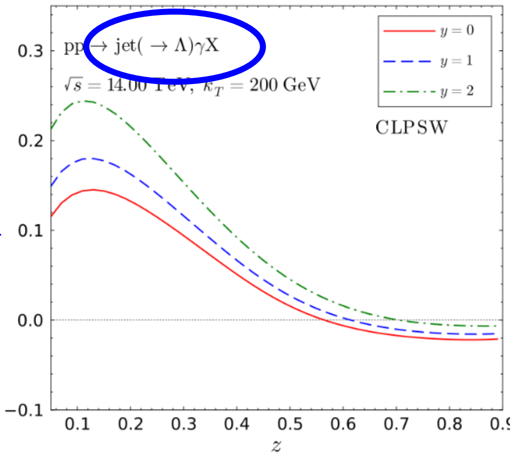
- Quarks dominate over gluons
- u dominate in γ-associated process, while $u \sim d$ in Z-associated process

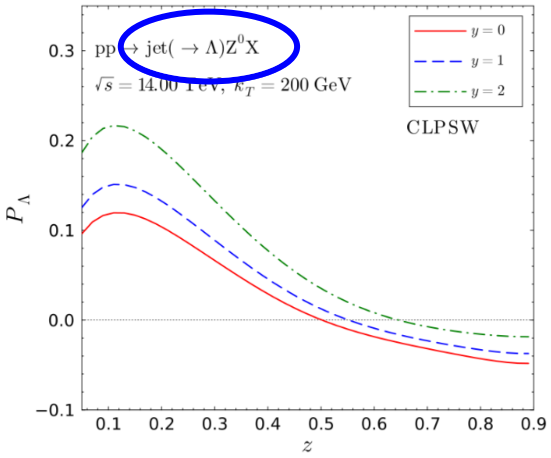
$\Longrightarrow$ a complementary place to study the difference between $D_{1T,u}^{\perp\Lambda}$ and $D_{1T,\bar{u}}^{\perp\Lambda}$

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

$$D_{1T,u}^{\perp\Lambda} \sim -D_{1T,d}^{\perp\Lambda}$$

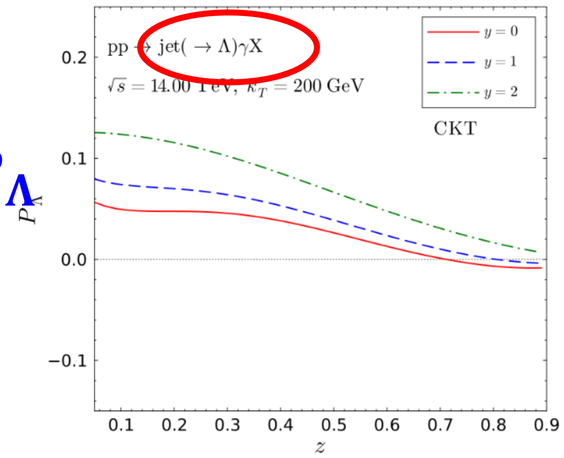
P_Λ

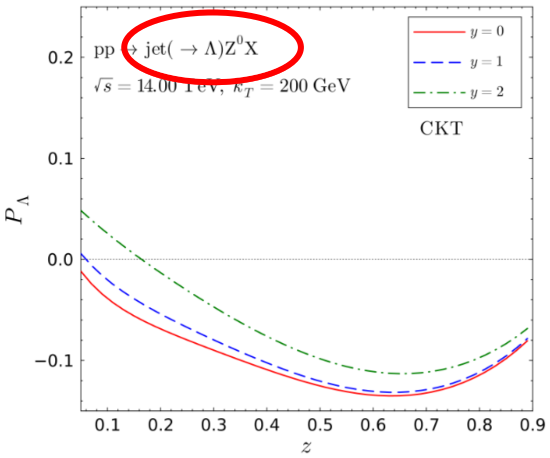




CLPSW

P_Λ





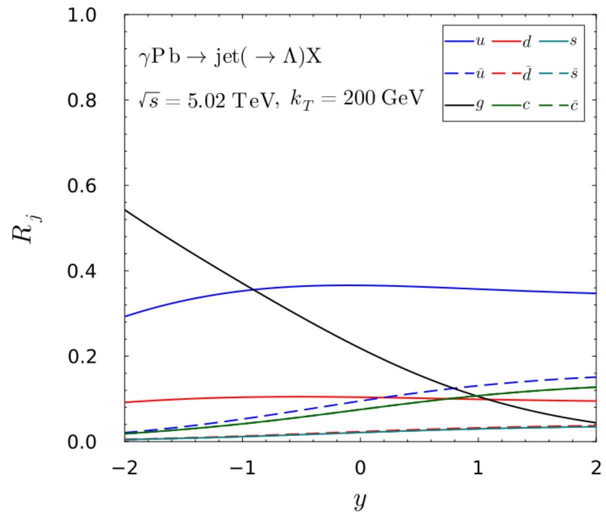
CKT

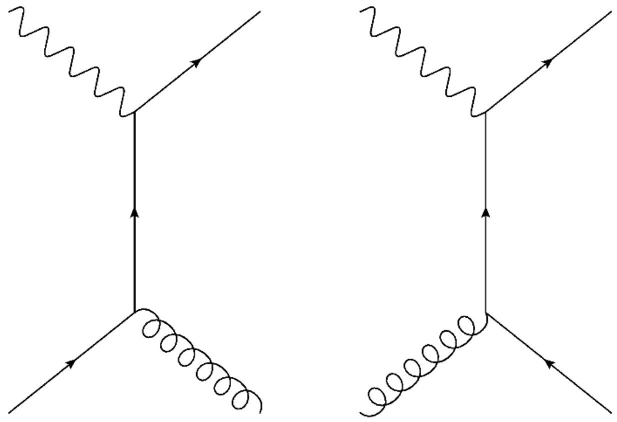
Λ production in UPC

- Highly energetic nucleus ⟺ quarks and gluons inside the nucleus
  + quasi-real photons surrounding the nucleus
- Equivalent Photon approximation (EPA)

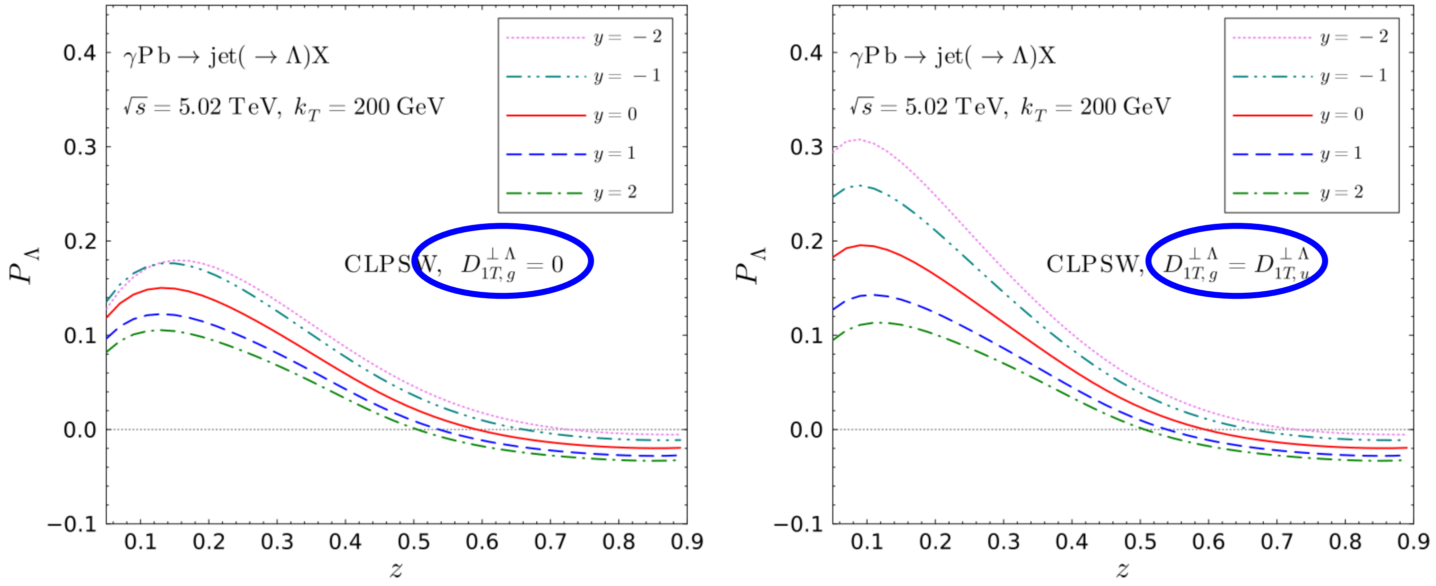
$$x f_\gamma(x) = \frac{2Z^2\alpha}{\pi}\left[\zeta K_0(\zeta)K_1(\zeta) - \frac{\zeta^2}{2}\left(K_1^2(\zeta) - K_0^2(\zeta)\right)\right]$$

$R_j(y, k_T)$





P_Λ



Outline

I. Introduction

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

III. **Transverse polarization of Λ from QGP as a probe of nuclear matter**

IV. Conclusion and outlook

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

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

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

- $\boldsymbol{D_1(z, b_T; \mu, \zeta)}$ 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

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

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

Where the perturbative and non-perturbative parts are given by

$$S_{pert} = -K(b_T^*,\mu_b)\ln\frac{Q}{\mu_b} - \int_{\mu_b}^{Q}\frac{d\mu'}{\mu'}\gamma_D\left(g(\mu'),\frac{Q^2}{\mu'^2}\right), \qquad S_{NP} = \frac{\langle p_\perp^2\rangle}{4}\frac{b_T^2}{z^2}, \qquad S_{NP}^{\perp} = \frac{\langle p_\perp^2\rangle}{4}\frac{b_T^2}{z^2},$$

QGP medium modification: Toy model

- QGP medium modify the QCD evolution, causing energy loss and p_T-broadening effects
- As a toy model, we consider only the p_T-broadening effect by

$$\widetilde{D}_{1,\Lambda/q}^{\text{med}}(z, b_T, Q) = \widetilde{D}_{1,\Lambda/q}^{\text{vac}}(z, b_T, Q)\tilde{B}(b_T)$$

$$\widetilde{D}_{1T,\Lambda/q}^{\perp(1),\text{med}}(z, b_T, Q) = \widetilde{D}_{1T,\Lambda/q}^{\perp(1),\text{vac}}(z, b_T, Q)\tilde{B}(b_T)$$

- The p_T-broadening functions is given by two forms

Gaussian： $\tilde{B}_G(b_T) = \exp\left[-\frac{1}{4}\langle\hat{q}L\rangle b_T^2\right]$

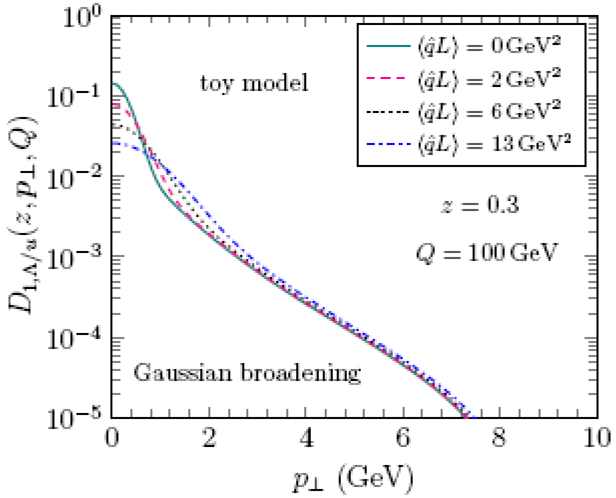
Non-Gaussian: $\tilde{B}_{nG}(b_T) = \exp\left[-\frac{1}{4}\langle\hat{q}L\rangle b_T^2 \ln\left(e + \frac{2}{\Lambda b_T}\right)\right]$

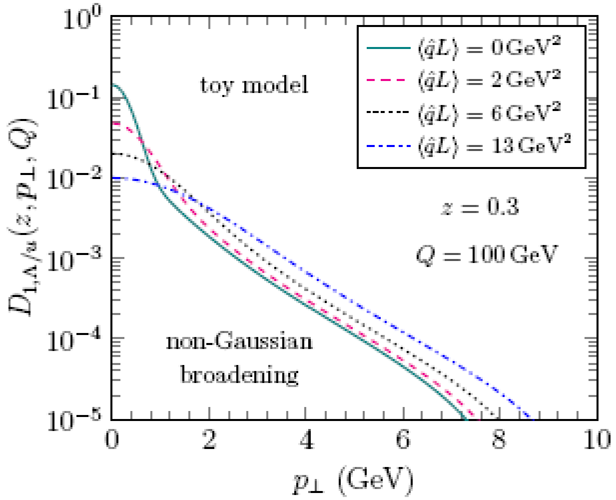
L. Chen, G. Y. Qin, S. Y. Wei, B. W. Xiao and H. Z. Zhang, PLB 773 (2017) 672
J. Barata, Y. Mehtar-Tani, A. Soto-Ontoso and K. Tywoniuk, PRD 104 (2021) 054047

X,Y.Qin, **YKS**, S.Y.Wei, 2504.00739

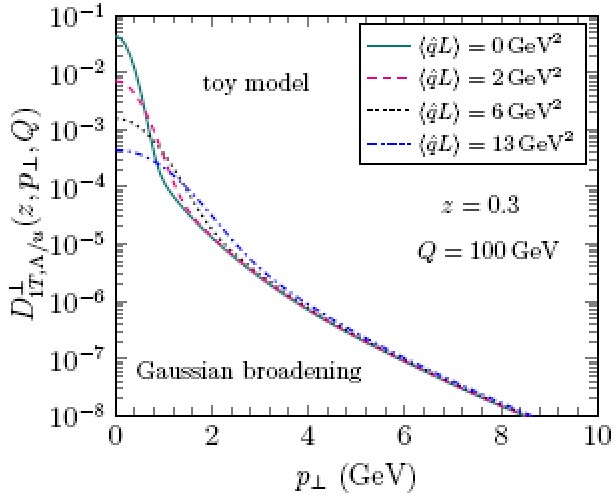
QGP medium modification: Toy model

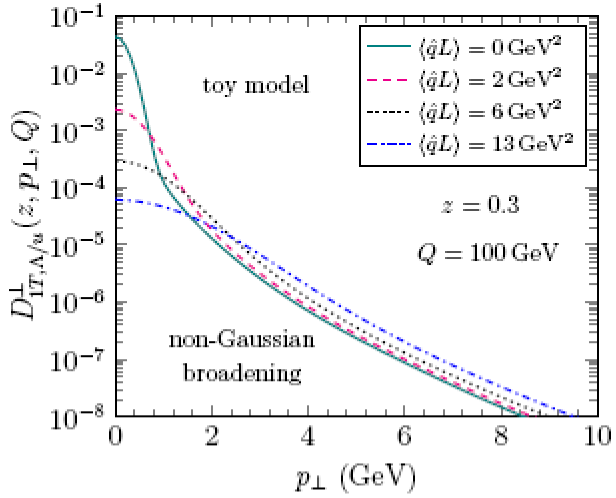
$D_{1u}^{\Lambda}(z, p_\perp, Q)$





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





X,Y.Qin, **YKS**, S.Y.Wei, 2504.00739

QGP medium modification: the model with energy loss

- The refined model with 2-step process

  (1) multiple scatterings and **parton branchings** inside the QGP

  (2) **Hadronization** of energetic parton outside the medium

$$\tilde{D}_{1,i}^{\text{med}}(z, b_T, Q, \tau_{\max}) = \sum_j \int_z^1 C_{ji}(\xi, \tau_{\max}) \tilde{B}_j(b_T) D_{1,j}^{\text{vac}}\left(\frac{z}{\xi}, b_T, \xi Q\right)$$

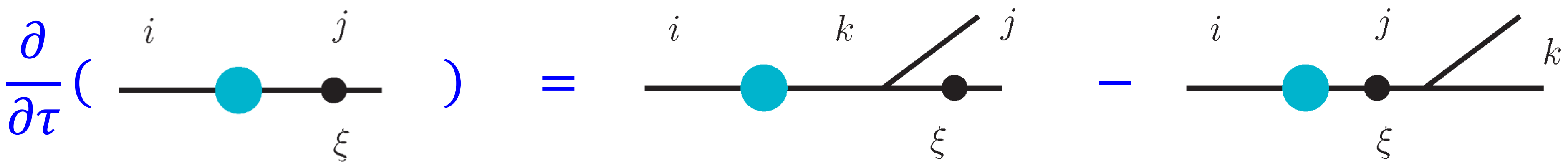
$$\tilde{D}_{1T,i}^{\perp(1)\text{med}}(z, b_T, Q, \tau_{\max}) = \sum_j \int_z^1 C_{ji}(\xi, \tau_{\max}) \tilde{B}_j(b_T) D_{1T,j}^{\perp(1)\text{vac}}\left(\frac{z}{\xi}, b_T, \xi Q\right)$$

- The energy loss effect is accounted for through the cascade spectrum function C_{ji}. We obtain C_{ji} by solving the evolution equations developed in literature.

J. P. Blaizot, E. Iancu and Y. Mehtar-Tani, PRL 111 (2013) 052001
J. P. Blaizot, F. Dominguez, E. Iancu and Y. Mehtar-Tani, JHEP 06 (2014), 075
Y. Mehtar-Tani and S. Schlichting, JHEP 09 (2018), 144

X,Y.Qin, **YKS**, S.Y.Wei, 2504.00739

Boltzmann-like evolution equations for $C_{ij}(z,\tau)$



$$\frac{\partial}{\partial \tau} C_{ji}(\xi,\tau) = \int_z \left[\mathcal{K}_{jk}(z)\, C_{ki}\left(\frac{\xi}{z}\right) - \mathcal{K}_{kj}(z)\, C_{ji}(\xi) \right]$$

gain term　　　loss term

➢ Kernel functions are given by Y. Mehtar-Tani and S. Schlichting, JHEP 09 (2018), 144

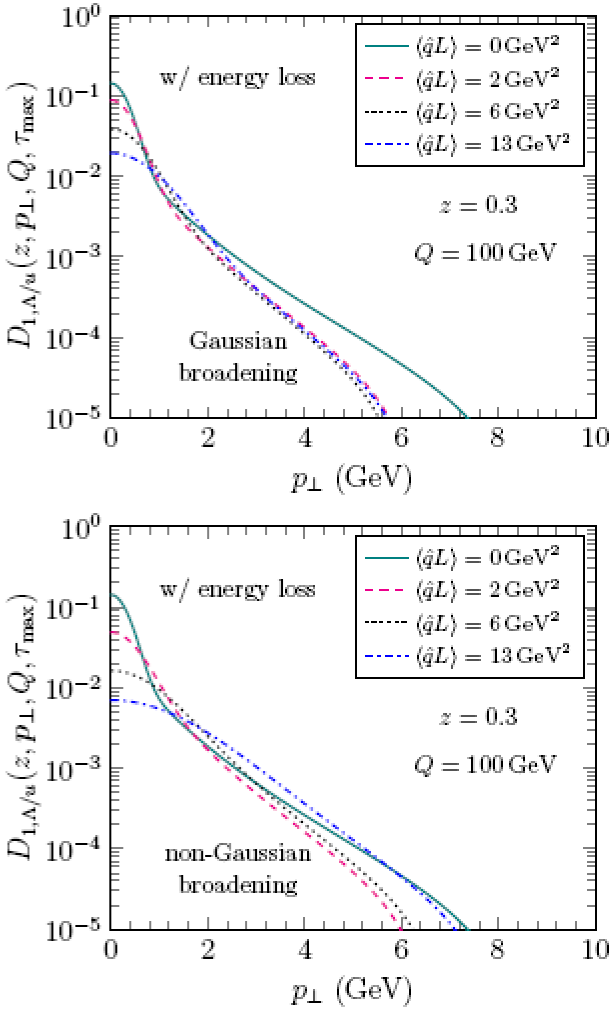
$$\mathcal{K}_{gg}(z) = \frac{1}{2}\hat{P}_{gg}(z)\sqrt{\frac{N_c(1-z+z^2)}{z(1-z)}}, \qquad \mathcal{K}_{qq}(z) = \frac{1}{2}\hat{P}_{qq}(z)\sqrt{\frac{N_c z + C_F(1-z)^2}{z(1-z)}}$$

$$\mathcal{K}_{qg}(z) = \frac{1}{2}\hat{P}_{qg}(z)\sqrt{\frac{C_F - N_c z(1-z)}{z(1-z)}}, \qquad \mathcal{K}_{gq}(z) = \frac{1}{2}\hat{P}_{gq}(z)\sqrt{\frac{N_c(1-z) + C_F z^2}{z(1-z)}}$$

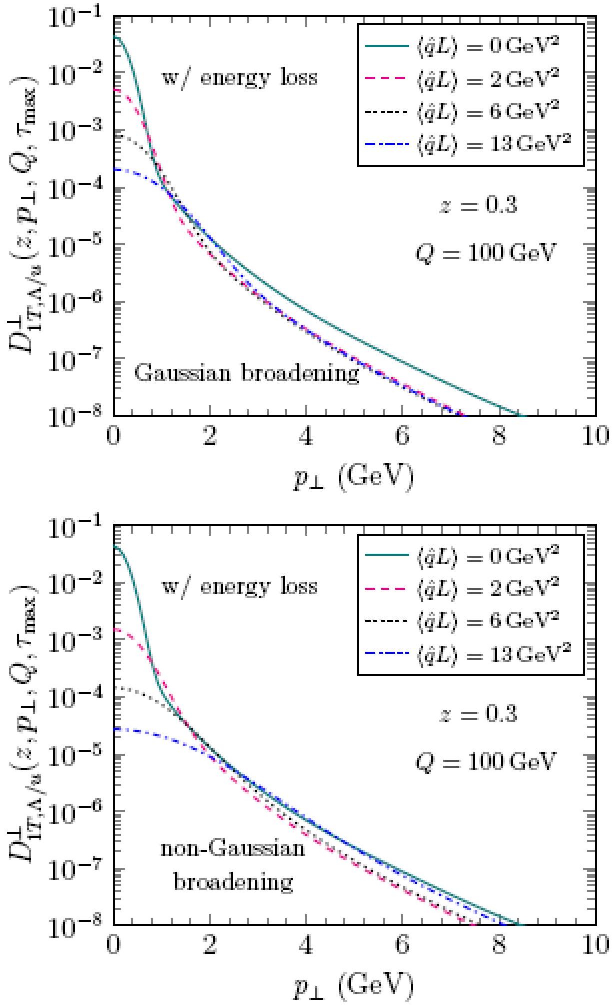
with $\hat{P}_{ij}$ the unregularized DGLAP splitting kernels.

QGP medium modification: the model with energy loss

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



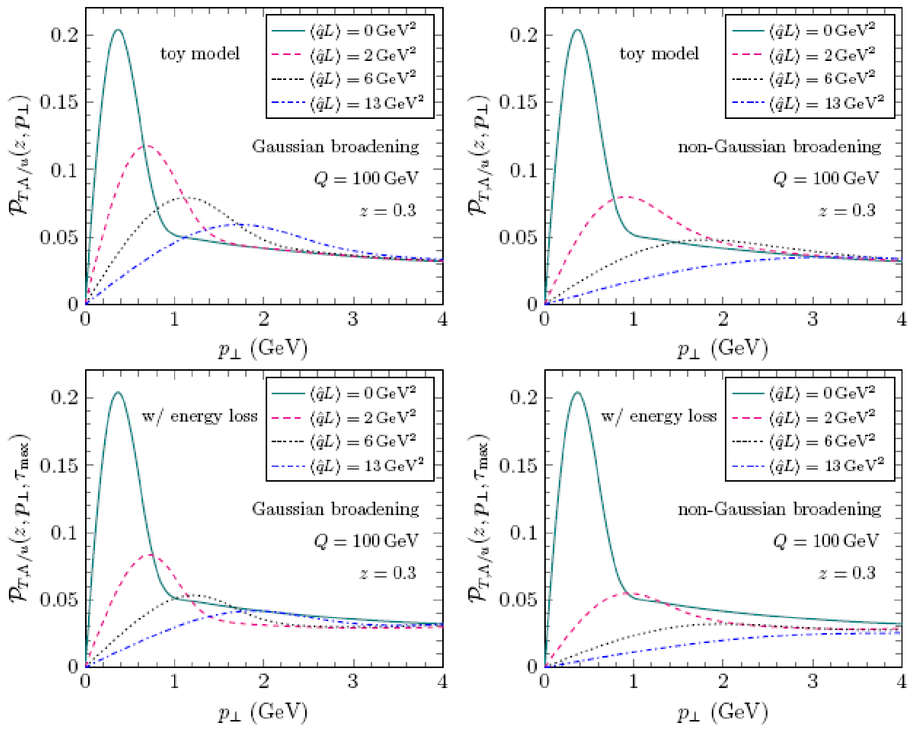
$D_{1T,u}^{\perp\Lambda}(z, p_\perp, Q)$



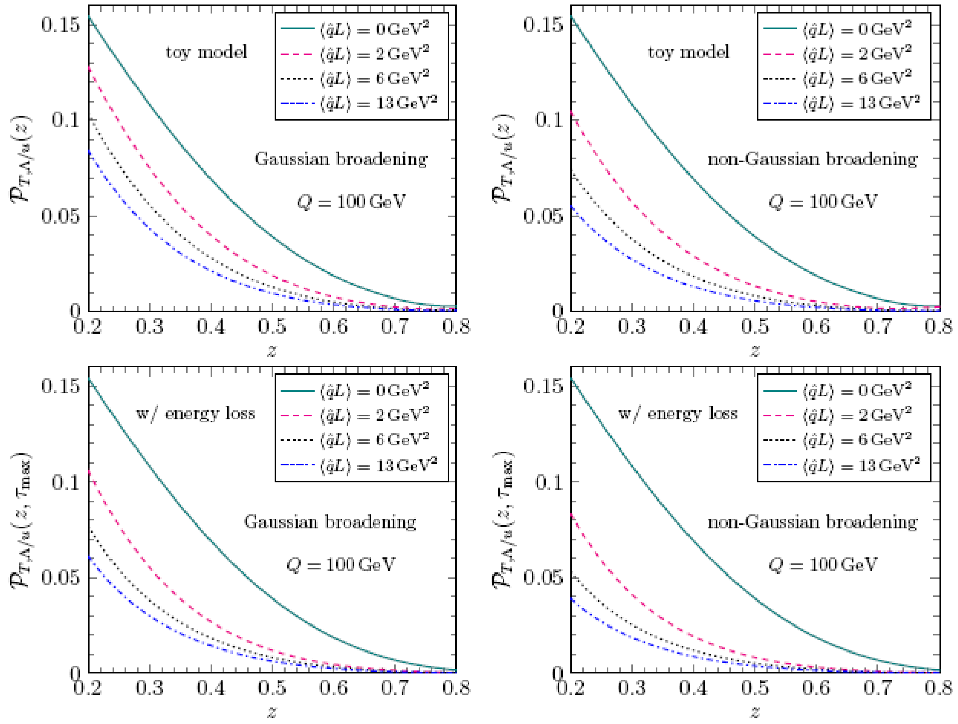
X,Y.Qin, **YKS**, S.Y.Wei, 2504.00739

Evolution/Nuclear effects on Λ transverse polarization

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



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



X,Y.Qin, **YKS**, S.Y.Wei, 2504.00739

- 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!

Backup Slides

Outline

I. Introduction

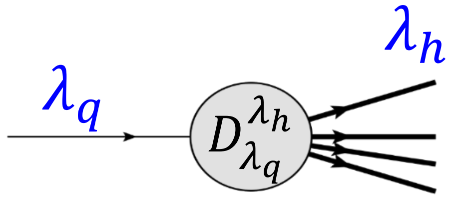
II. Flavor structure of $D_{1T,q}^{\perp\Lambda}$ from various processes

III. Transverse polarization of Λ from QGP as a probe of nuclear matter

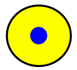
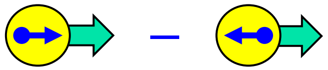
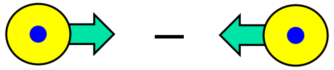
IV. **P-odd FFs**

V. Conclusion and outlook

Hadronic weak decay induced parivity-violation FFs $\widetilde{D}_{1L}, \widetilde{G}_1$



$$D_+^+, D_-^+, D_-^-, D_+^- \rightarrow \begin{cases} D_1 = \frac{1}{2}(D_+^+ + D_+^- + D_-^+ + D_-^-) \\ G_{1L} = \frac{1}{2}(D_+^+ - D_+^- - D_-^+ + D_-^-) \\ \widetilde{D}_{1L} = \frac{1}{2}(D_+^+ - D_+^- + D_-^+ - D_-^-) \\ \widetilde{G}_1 = \frac{1}{2}(D_+^+ + D_+^- - D_-^+ - D_-^-) \end{cases}$$

D_1	G_{1L}	$\widetilde{D}_{1L}$	$\widetilde{G}_1$
			

$\widetilde{D}_{1L}$: Difference of absolute values of hadron polarizations

$\widetilde{G}_1$: Difference of number of hadrons

} in jets initiated by helicity + and – quarks

Y.L.Pan, K.B.Chen, **YKS**, S.Y.Wei, PLB 850 (2024) 138509

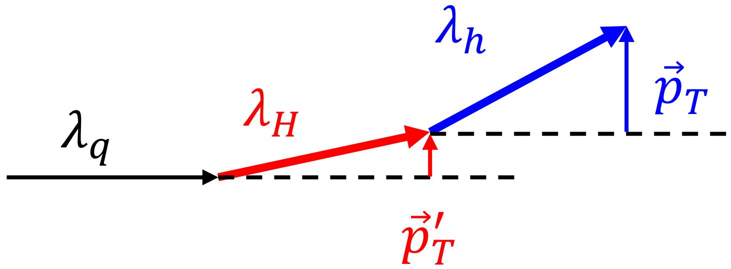
Weak decay contributions to TMD FFs $\widetilde{D}_{1L}, \widetilde{G}_1$

- QCD θ−vacuum breaks parity invariance $\Longrightarrow$ non−zero parity−odd FFs *[Kang, Kharzeev 2011]*

$$\mathcal{L} = \mathcal{L} + \frac{g^2}{32\pi^2}\theta(x,t)F_a^{\mu\nu}\tilde{F}_{\mu\nu}^a \quad \Longrightarrow \quad \Xi(z) \sim \gamma_\mu p^\mu\left(D_1 + \lambda_h \widetilde{D}_{1L}\right) + \gamma_\mu\gamma_5 p^\mu\left(\lambda_h G_{1L} + \tilde{G}_1\right)$$

- Hadrons detected in exps may contain weak decay contributions, thus violating parity invariance.

$$q \to H + X$$
$$\quad \hookrightarrow h + X'$$

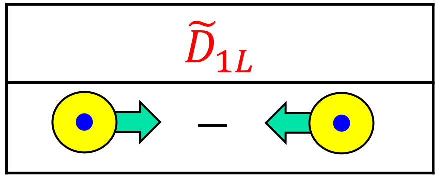


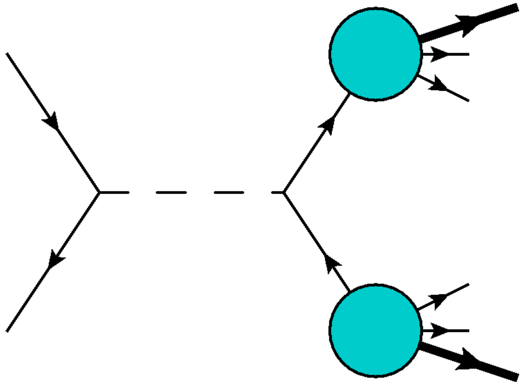
- **We perform a detailed calculation of weak decay contributions to P-odd FFs, and estimate the magnitudes of their observables in exps.**

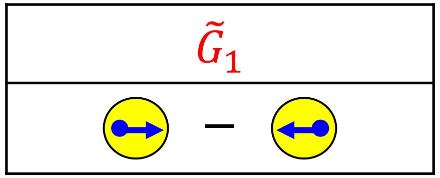
$$D_q^\Lambda:\ \Xi^0 \to \Lambda\pi^0, \Xi^- \to \Lambda\pi^-, \Omega^- \to \Lambda K^-, \ldots$$
$$D_q^{\pi^+}: \Sigma^+ \to n\pi^+, \ldots$$
$$D_q^{\pi^-}: \Sigma^- \to n\pi^-, \Lambda \to p\pi^-, \Xi^- \to \Lambda\pi^-, \ldots$$

Y.L.Pan, K.B.Chen, **YKS**, S.Y.Wei, PLB 850 (2024) 138509

Observables of $\widetilde{D}_{1L}, \widetilde{G}_1$

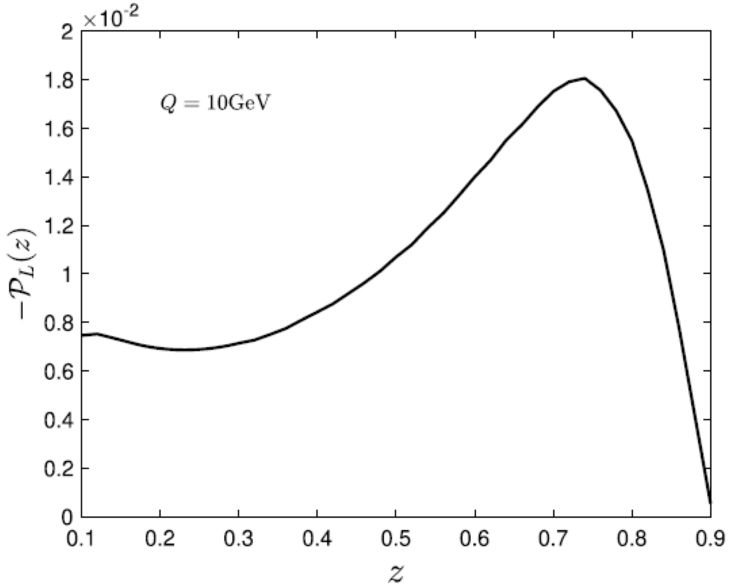






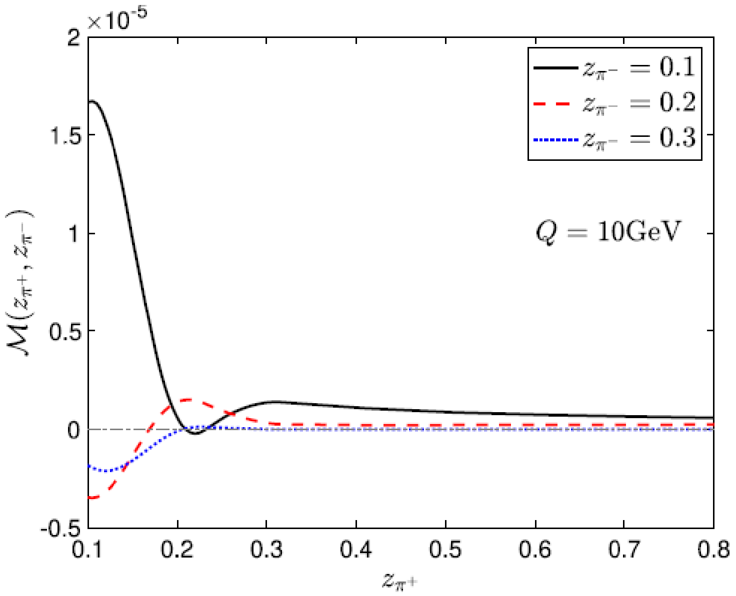
Unpolarized $e^+e^- \to \Lambda X$

Spontaneous Λ polarization



Unpolarized $e^+e^- \to \pi^+\pi^- X$

Suppression of back-to-back dihadron production



Y.L.Pan, K.B.Chen, **YKS**, S.Y.Wei, PLB 850 (2024) 138509