Polarized TMD Fragmentation Functions

宋玉坤（济南大学）

2025.8.10

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. P-odd FFs

V. Conclusion and outlook

Outline

I. **Introduction**

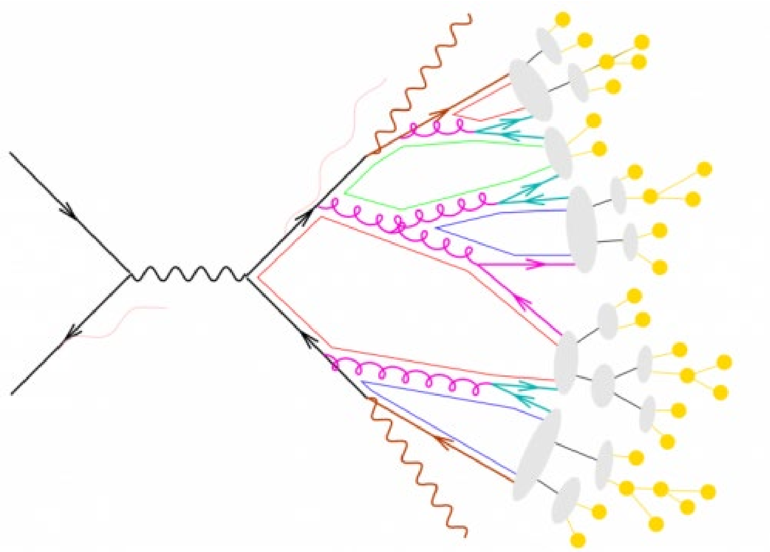
II. Flavor structure of $D_{1T,q}^{\perp\Lambda}$ from various processes

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

IV. P-odd FFs

V. Conclusion and outlook

I Introduction

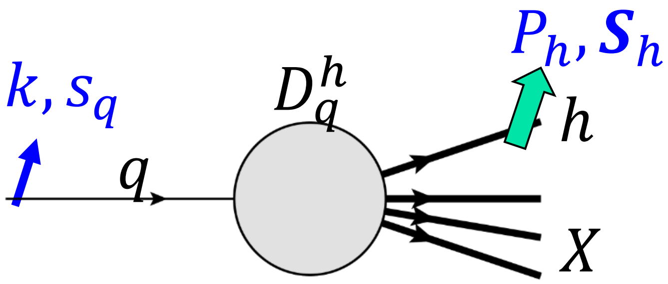


➢ QCD因子化定理 (Collins 2011)

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

➢ 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 ?

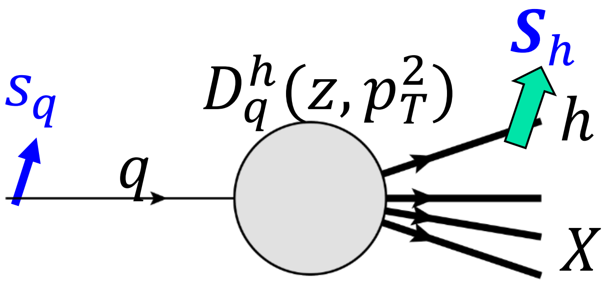


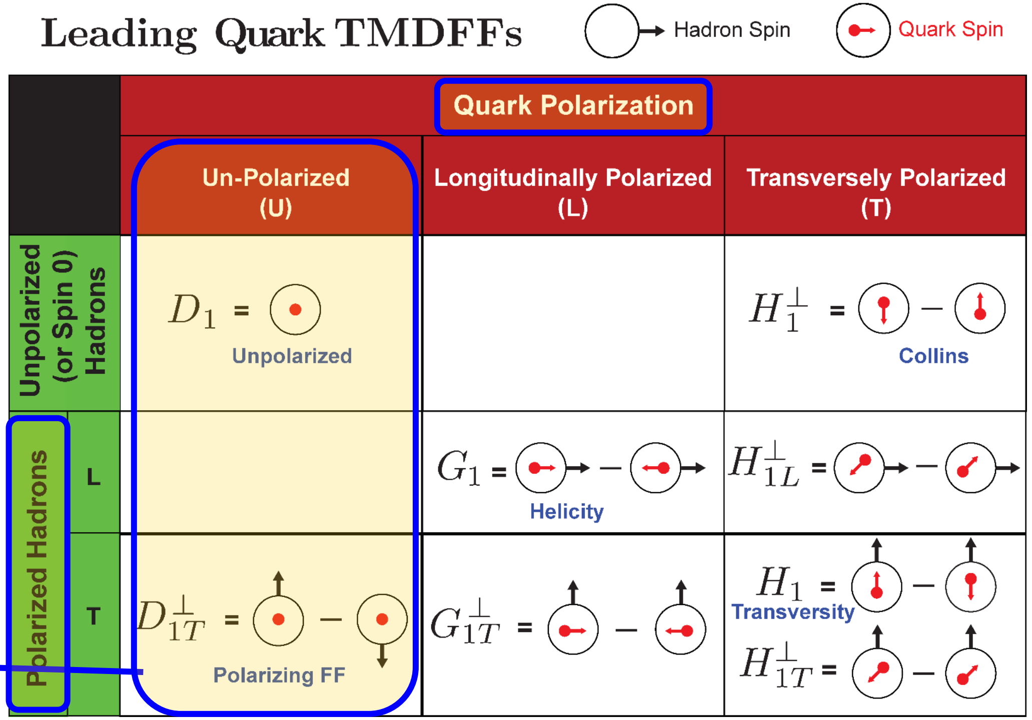
➢ $D_j^h(k, s_q; P_h, S_h)$

- 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

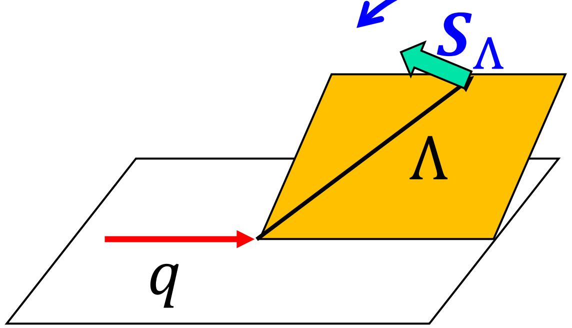
- Λ超子的横动量依赖的（TMD）碎裂函数





TMD handbook
2304.03302

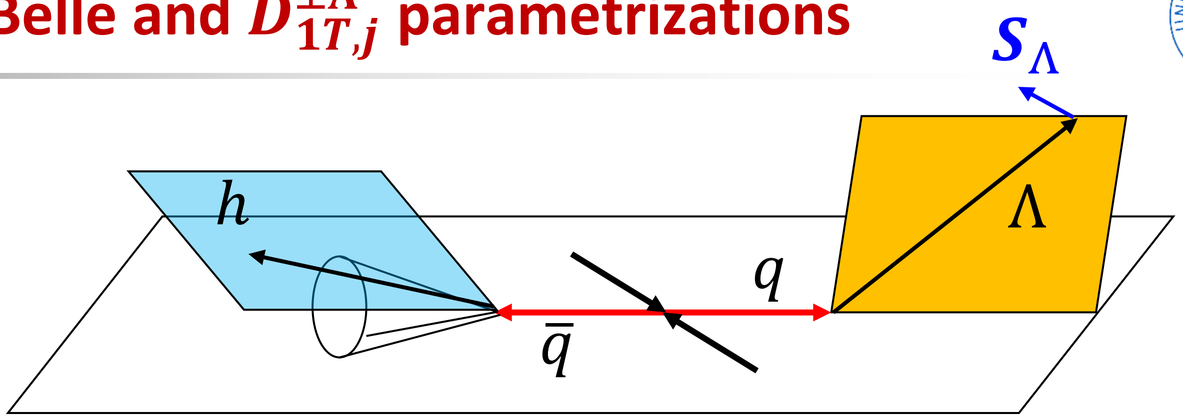
- 横向极化的Λ超子碎裂函数$D_{1T}^{\perp}(z, p_T^2)$



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

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

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 $0.2 < z_\Lambda < 0.4$

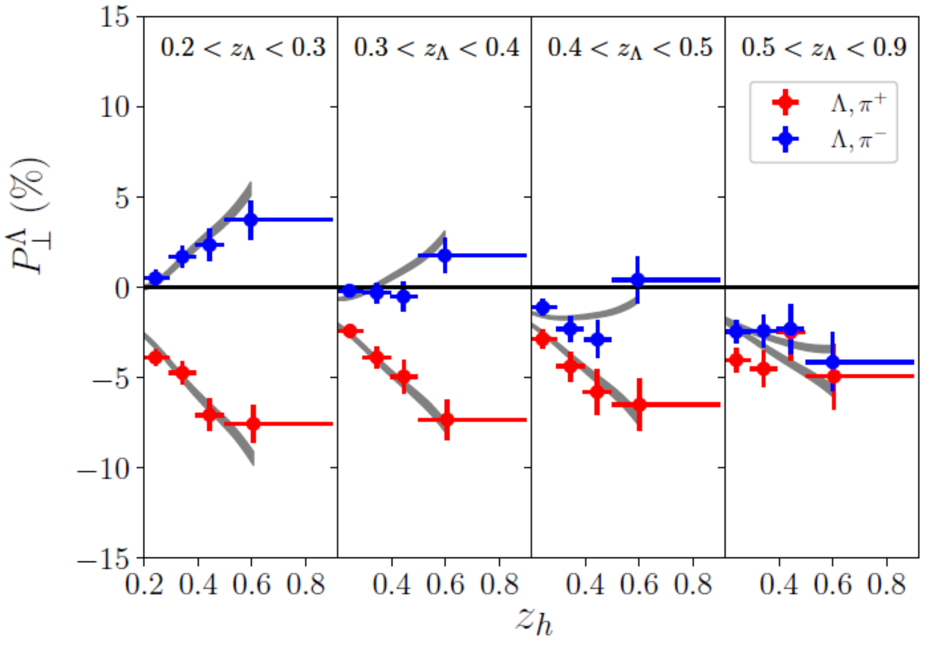
$$e^+e^- \to \Lambda(u\mathbf{d}s)\pi^+(u\bar{\mathbf{d}})X, \qquad e^+e^- \to \Lambda(\mathbf{u}ds)\pi^-(d\bar{\mathbf{u}})X$$

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

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

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?

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., $\boldsymbol{D_u^\Lambda = D_d^\Lambda}$

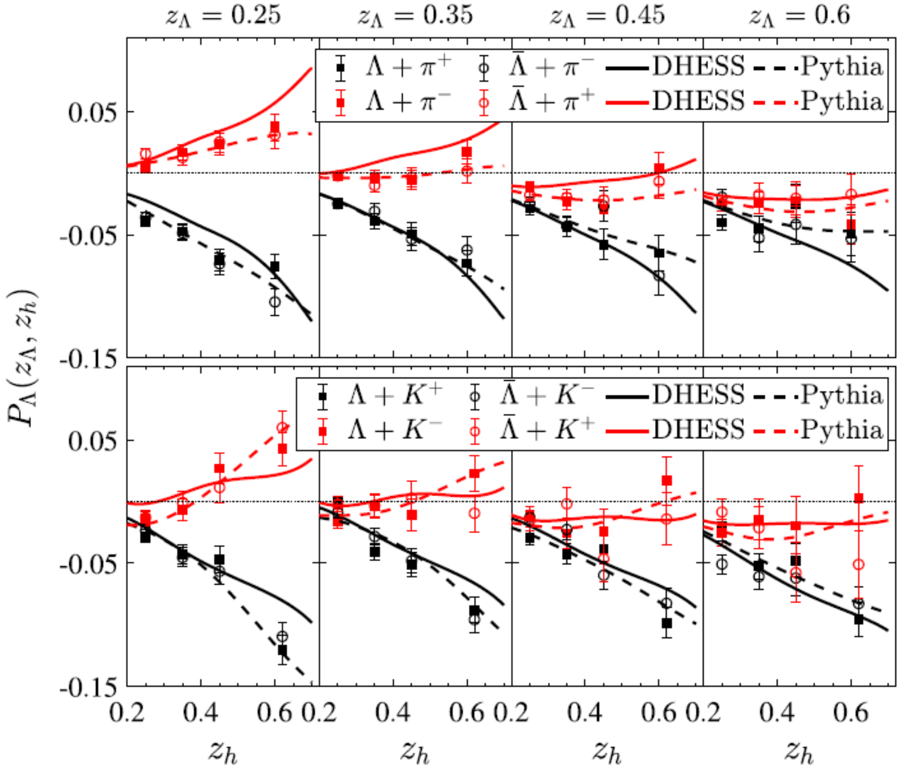
- Based on an **isospin symmetric** formalism, we fit the Belle data well using CLPSW parametrizations.

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

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

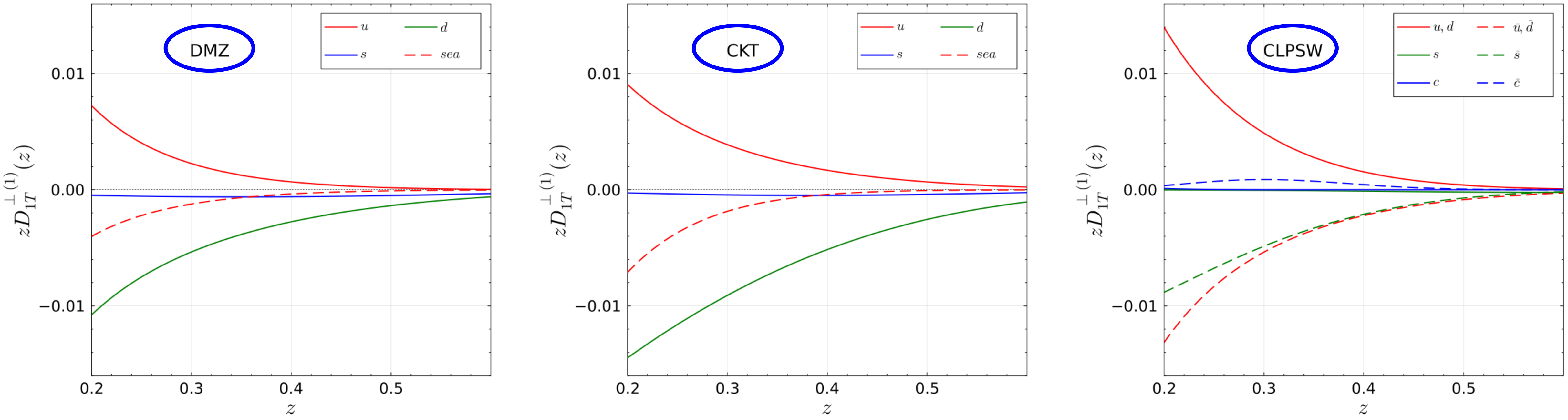
$$D_{1T\bar{u}}^{\perp\Lambda} = D_{1T\bar{d}}^{\perp\Lambda},$$

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



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 $D_{1T,q}^{\perp\Lambda}$?

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

  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

- A precise theoretical formalism with
  - QCD evolution effects

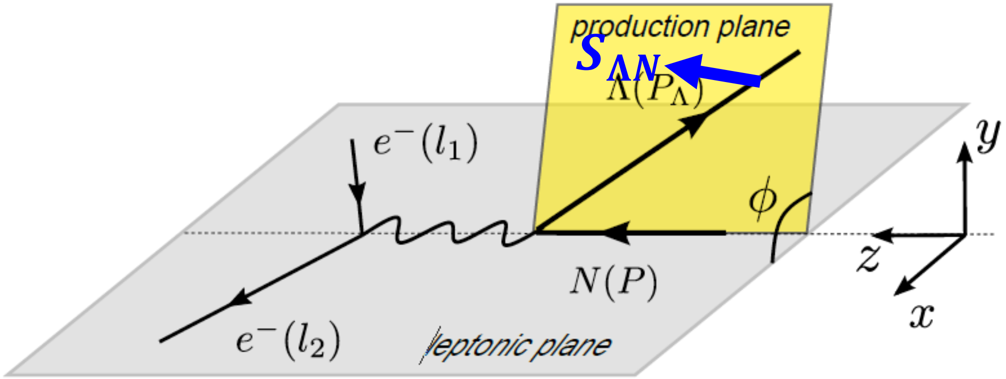
    $D_{1T}^{\perp}(z, p_T^2; \mu, \zeta)$： dependences on renormalization scale μ and C-S parameter ζ

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

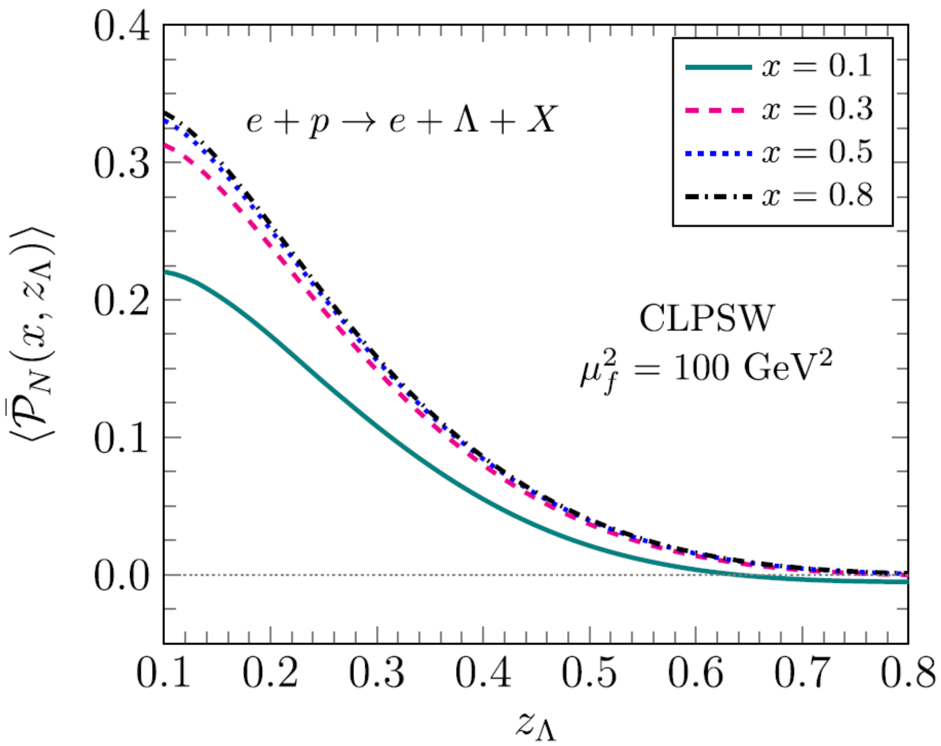
  important to incorporate data from lower energy experiment

Outline

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

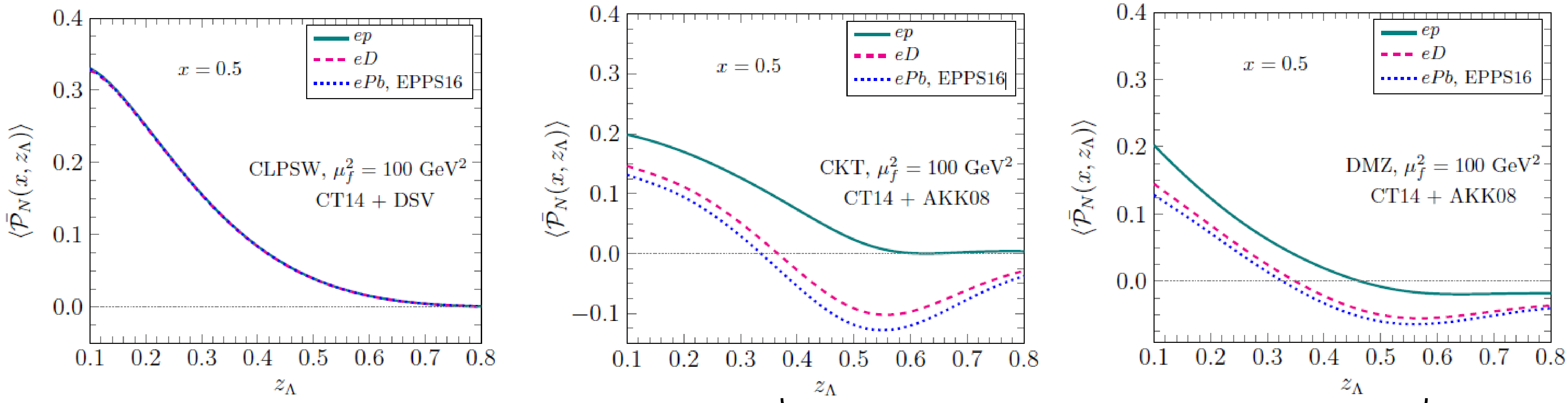
Z. Ji, X.Y.Zhao, A.Q.Guo, Q.H.Xu, J.L.Zhang, Nucl.Sci.Tech. 34 (2023) 155

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

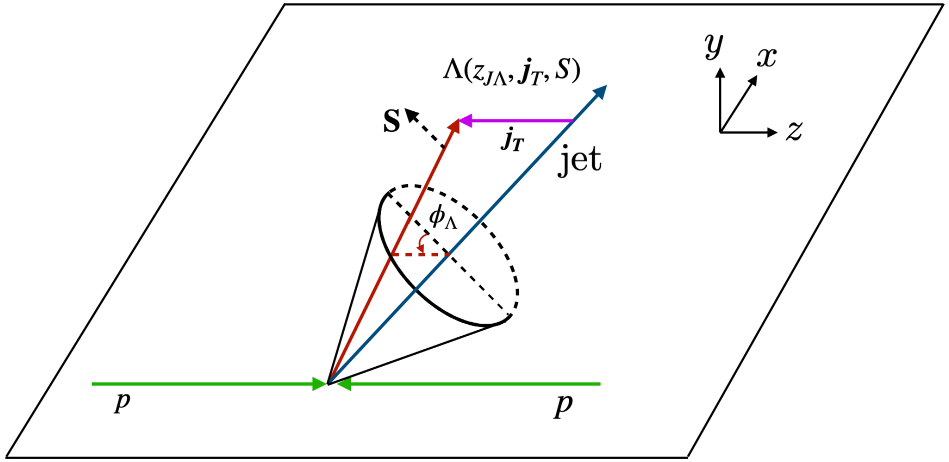
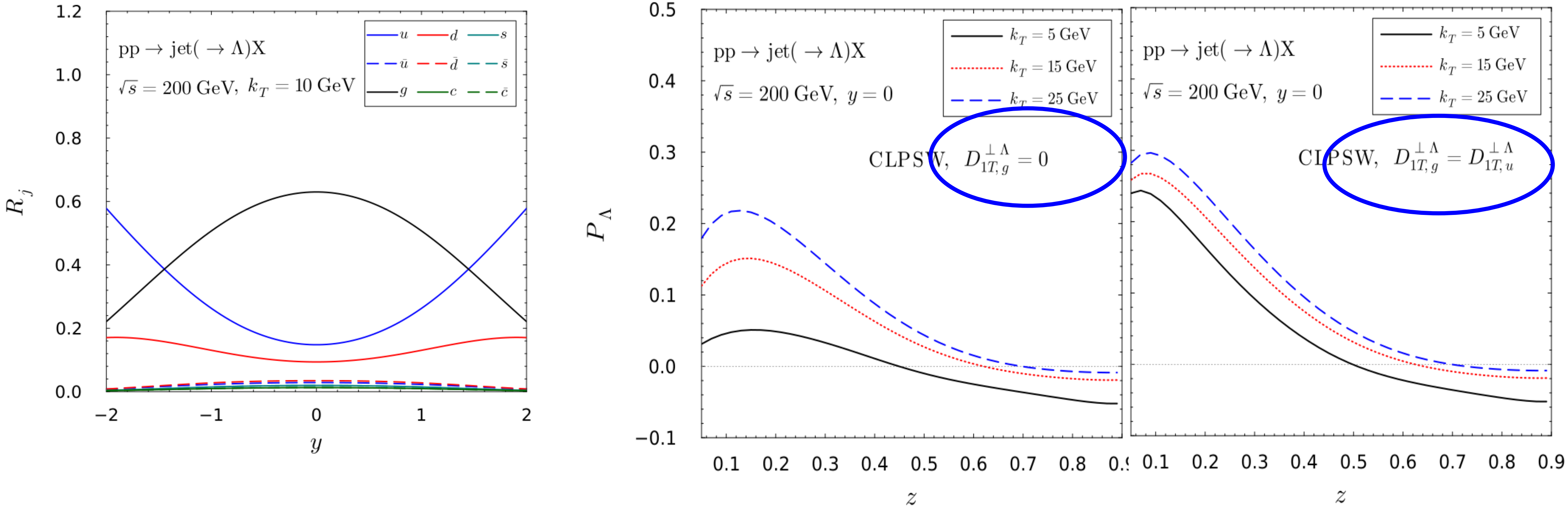


Figure from STAR

pp collisions

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

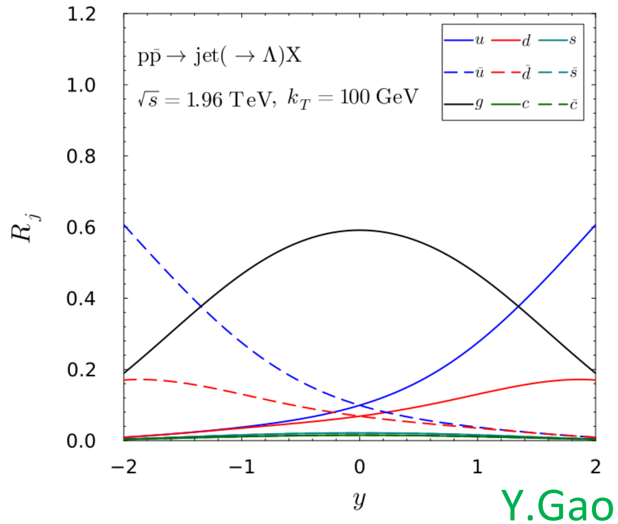


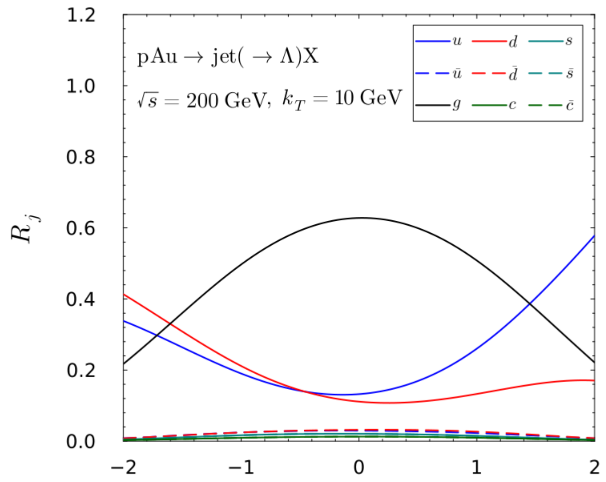
Central rapidity & small k_T region, **gluon dominate**!

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

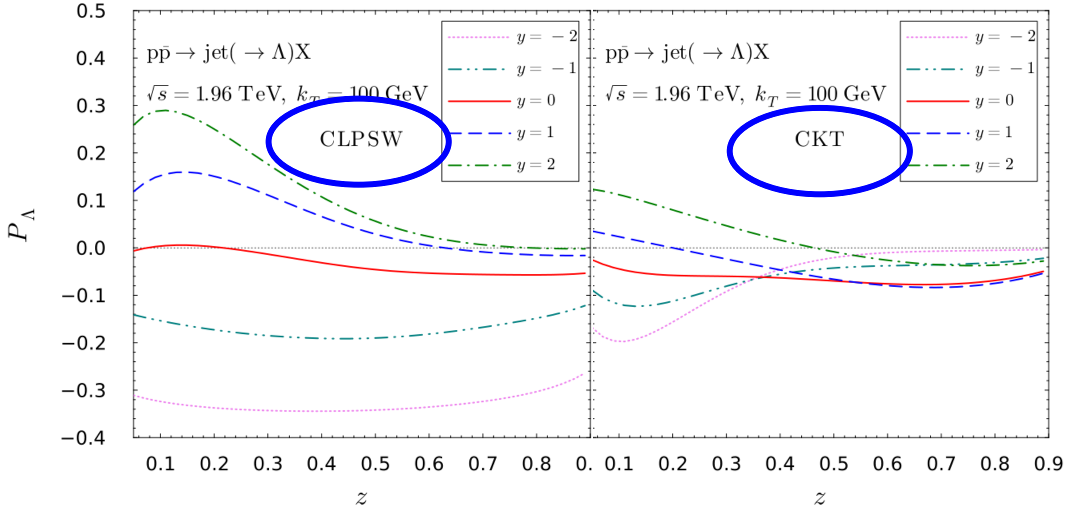
CT18 PDF, DSV FF D_1^Λ, CLPSW $D_{1T}^\perp$

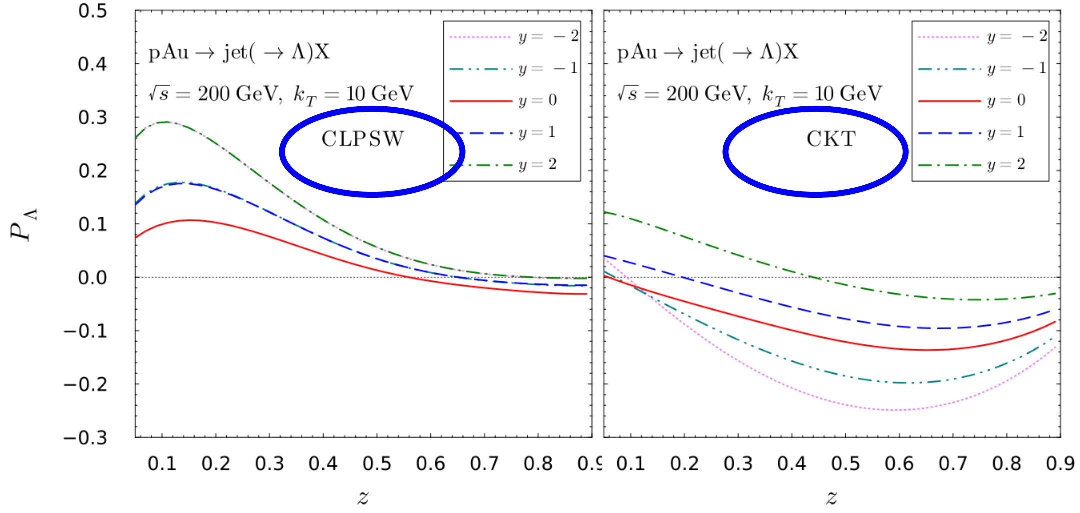
$p\bar{p}$ pA





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

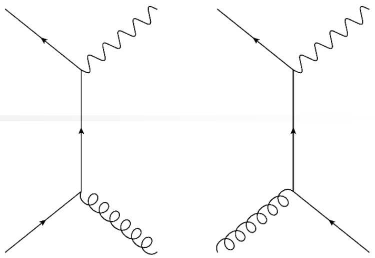




Forward rapidity region, ***u* quark dominate**;
backward rapidity region, **$\bar{u}$ quark dominate**

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

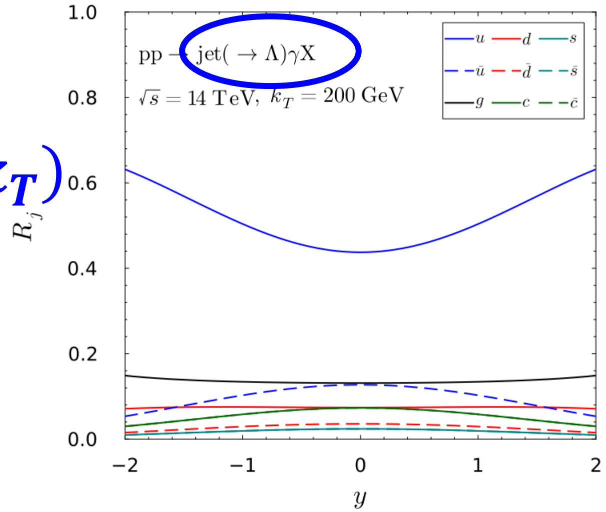
γ/Z^0-associated Λ production

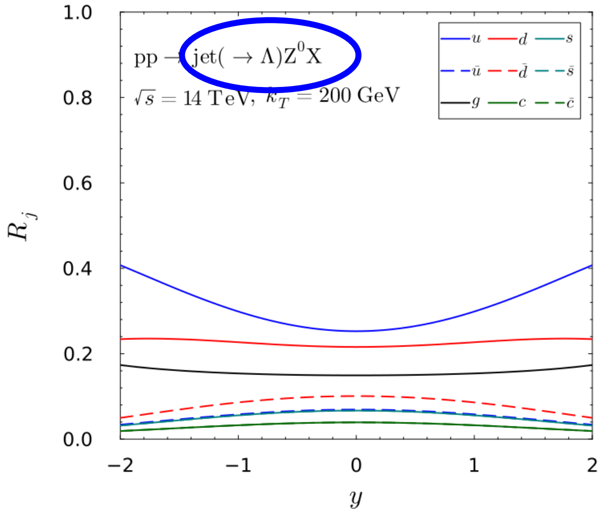


- Quarks dominate over gluons
- u dominate in γ-associated process, while $u \sim d$ in Z-associated process

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

$R_j(y, k_T)$

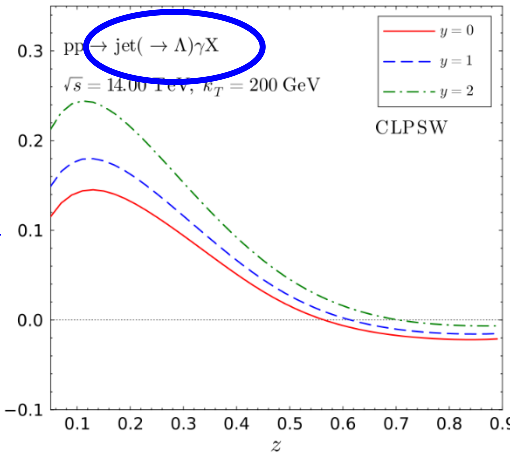


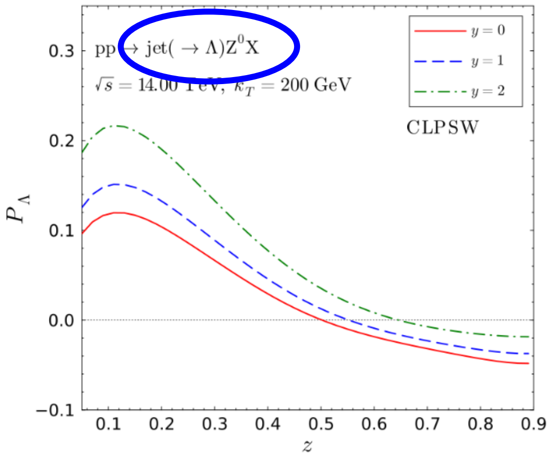


$$D_{1T,u}^{\perp\Lambda} = D_{1T,d}^{\perp\Lambda}$$

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

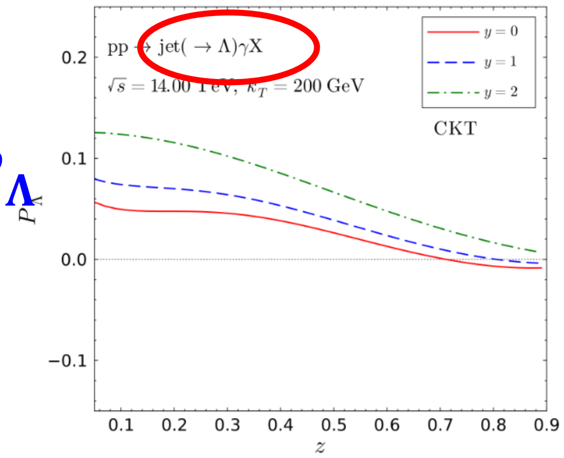
P_Λ

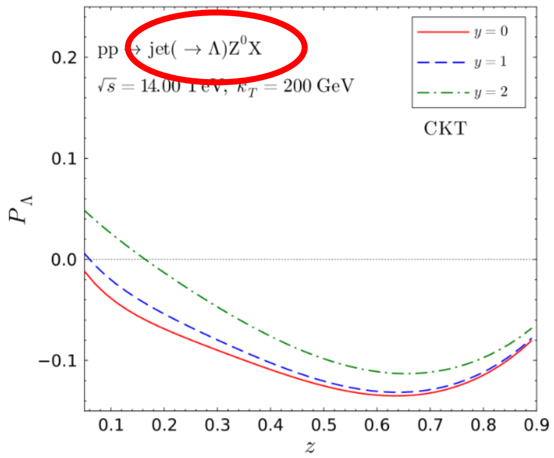




CLPSW

P_Λ



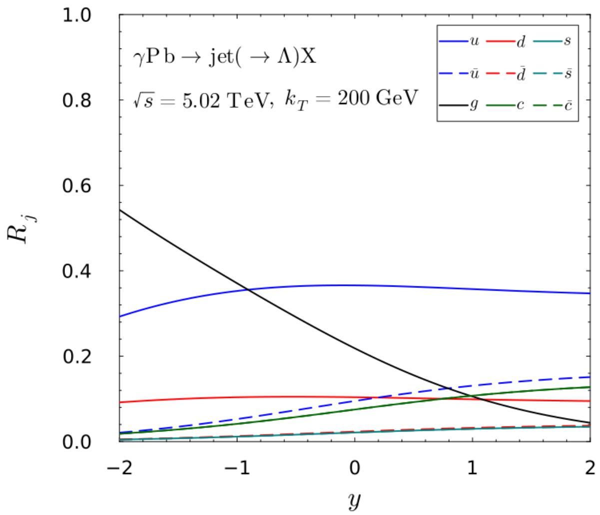


CKT

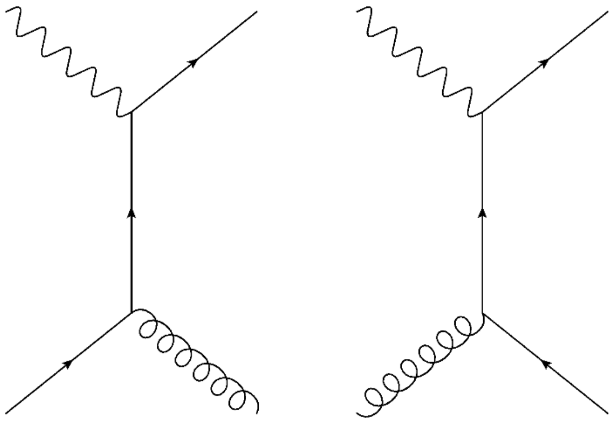
Λ production in UPC

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

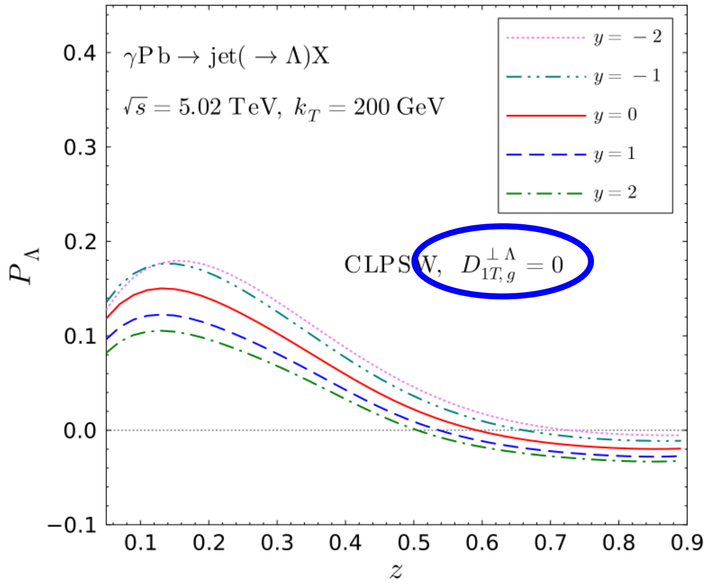
$R_j(y, k_T)$

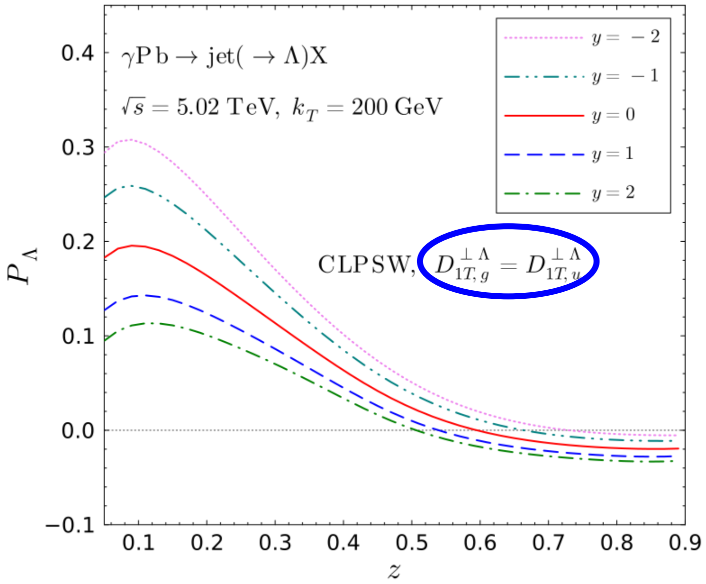


$$xf_\gamma(x) = \frac{2Z^2\alpha}{\pi}\left[\zeta K_0(\zeta)K_1(\zeta) - \frac{\zeta^2}{2}\left(K_1^2(\zeta) - K_0^2(\zeta)\right)\right]$$



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. P-odd FFs

V. 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

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

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

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

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

- The p_T-broadening functions is given by two forms

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

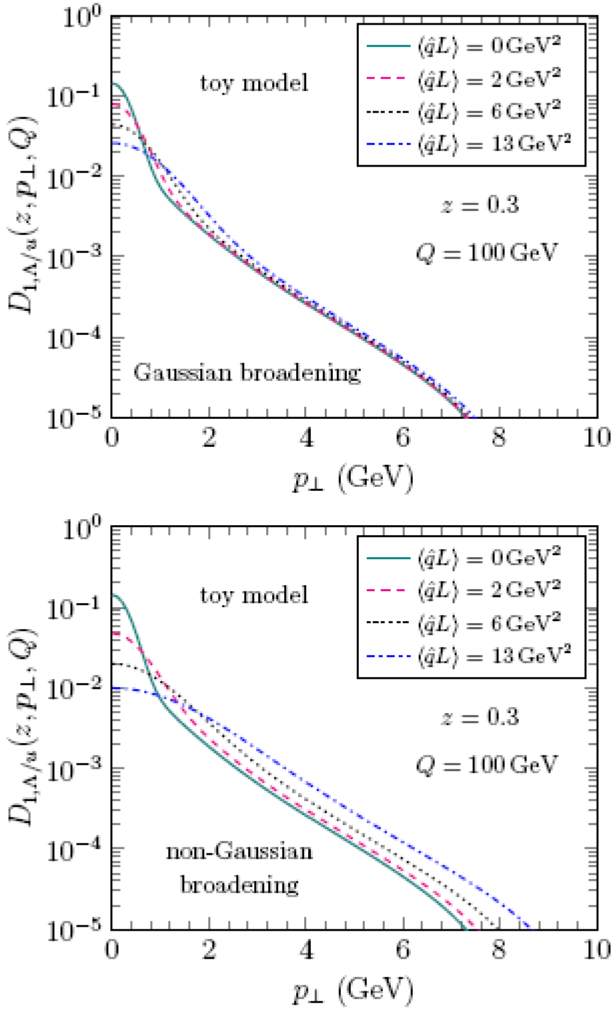
Non-Gaussian: $$\tilde{B}_{nG}(b_T) = \exp\left[-\frac{1}{4}\langle\hat{q}L\rangle b_T^2 \ln\left(e + \frac{2}{\Lambda b_T}\right)\right]$$

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

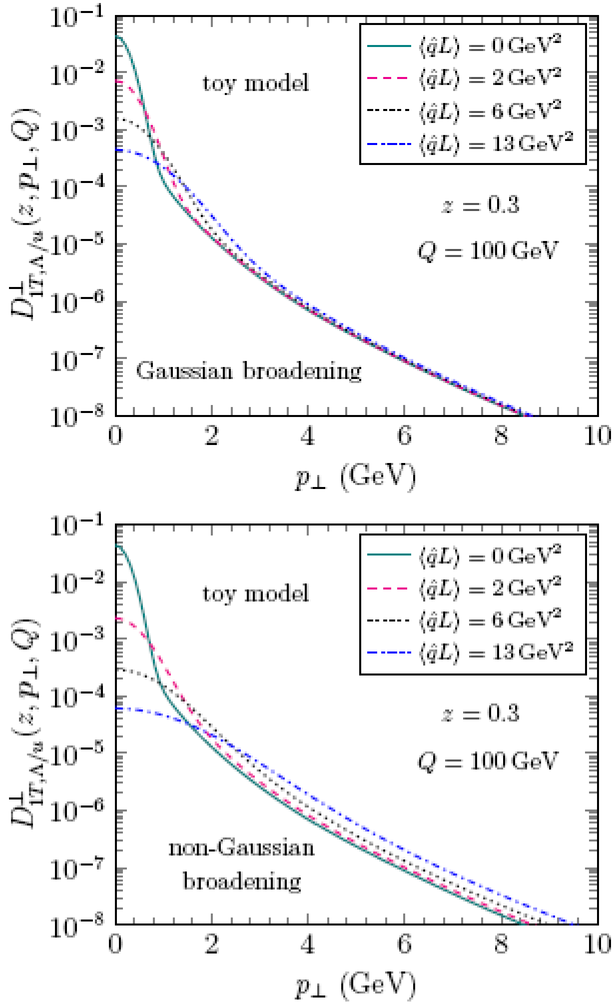
X,Y.Qin, **YKS**, S.Y.Wei, 2504.00739

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

- 2-step process

  (1) multiple scatterings and parton branchings inside the QGP

  (2) Hadronization of energetic parton outside the medium

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

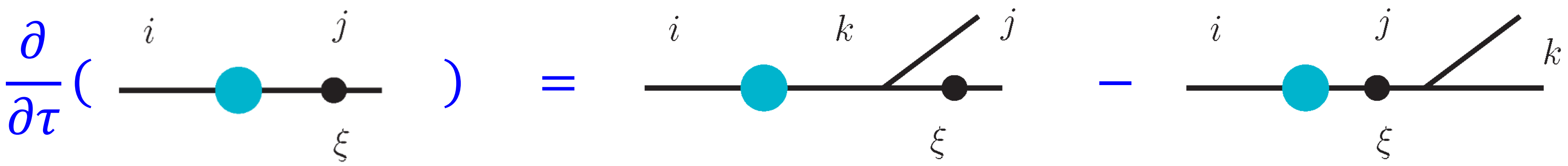
$$\tilde{D}_{1T,i}^{\perp(1)\mathrm{med}}(z, b_T, Q, \tau_{\max}) = \sum_j \int_z^1 C_{ji}(\xi, \tau_{\max}) \tilde{B}_j(b_T) D_{1T,j}^{\perp(1)\mathrm{vac}}\left(\frac{z}{\xi}, b_T, \xi Q\right)$$

- 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

Evolution equations for $C_{ij}(z,\tau)$



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

gain term　　loss term

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

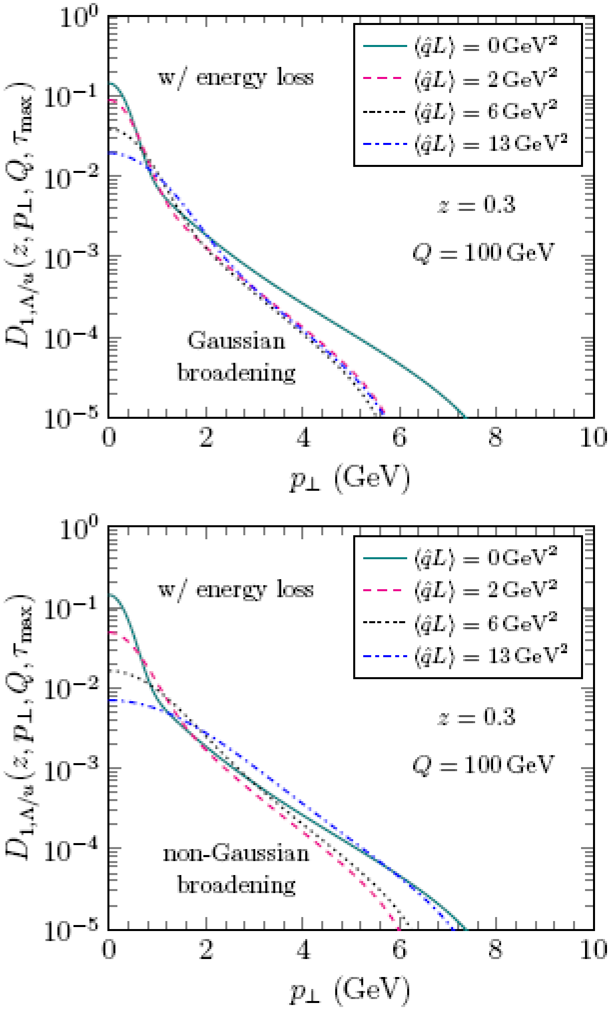
$$\mathcal{K}_{gg}(z) = \frac{1}{2}\hat{P}_{gg}(z)\sqrt{\frac{N_c(1-z+z^2)}{z(1-z)}}, \qquad \mathcal{K}_{qq}(z) = \frac{1}{2}\hat{P}_{qq}(z)\sqrt{\frac{N_c z + C_F(1-z)^2}{z(1-z)}}$$

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

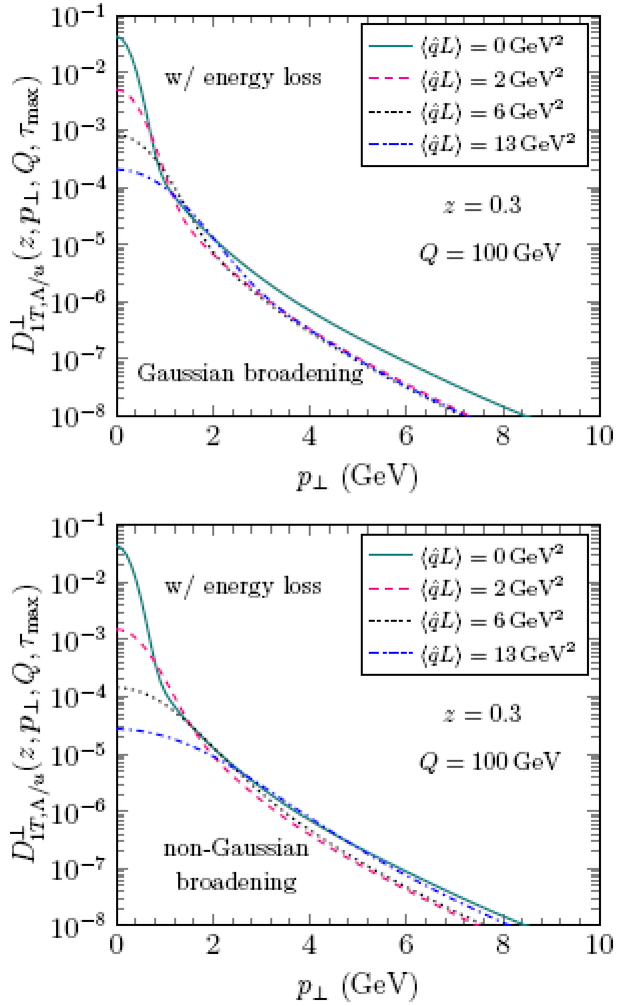
with $\hat{P}_{ij}$ the unregularized DGLAP splitting kernels.

QGP medium modification: the model with energy loss

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



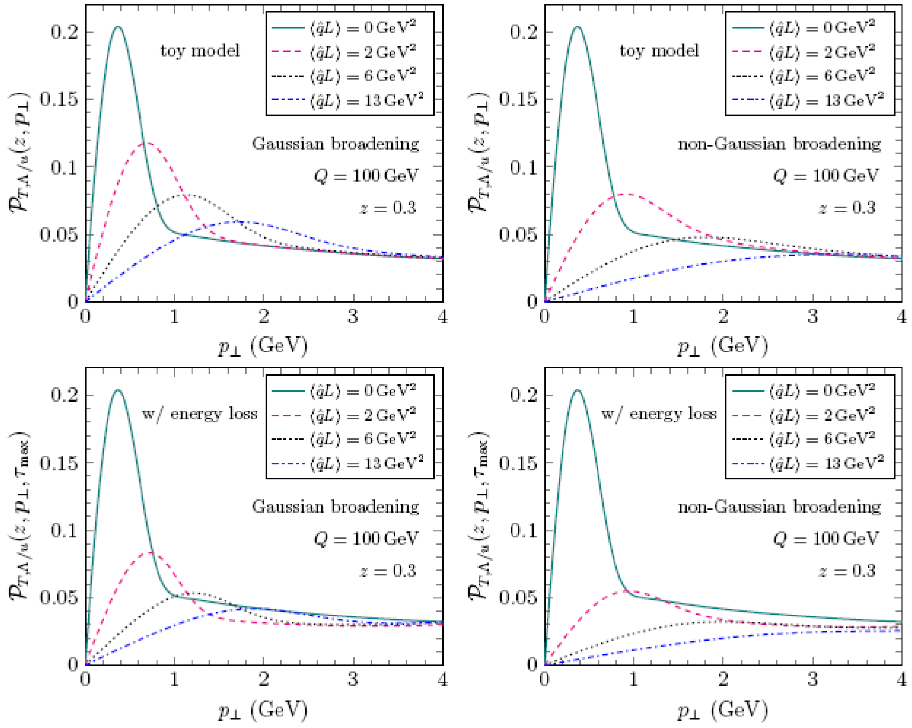
$D_{1T,u}^{\perp\Lambda}(z, p_\perp, Q)$



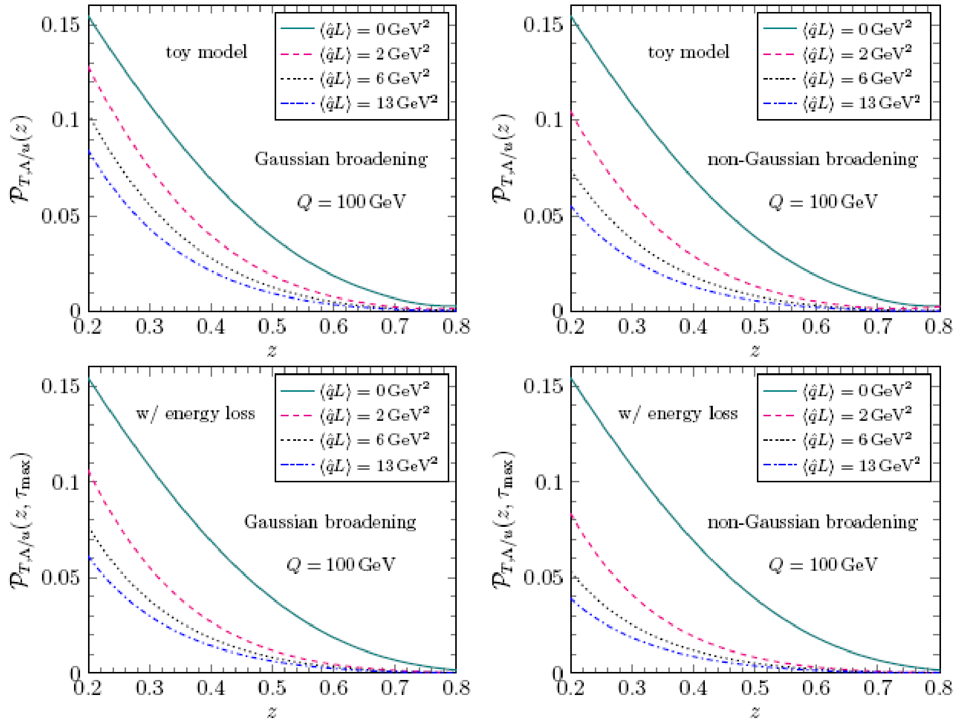
X,Y.Qin, **YKS**, S.Y.Wei, 2504.00739

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

Outline

I. Introduction

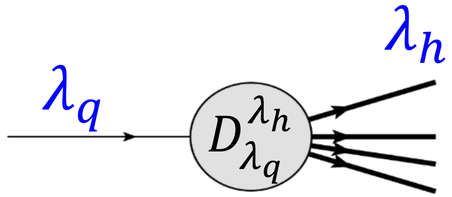
II. Flavor structure of $D_{1T,q}^{\perp\Lambda}$ from various processes

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

IV. **P-odd FFs**

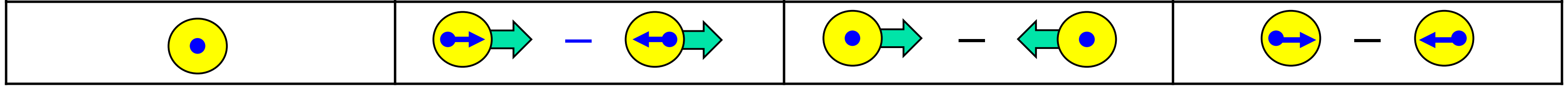
V. Conclusion and outlook

弱衰变导致的宇称破坏的极化碎裂函数 $\tilde{D}_{1L}, \tilde{G}_1$



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

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



$\tilde{D}_{1L}$: Difference of absolute values of hadron polarizations
$\tilde{G}_1$: 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 $\widetilde{D}_{1L}, \widetilde{G}_1$

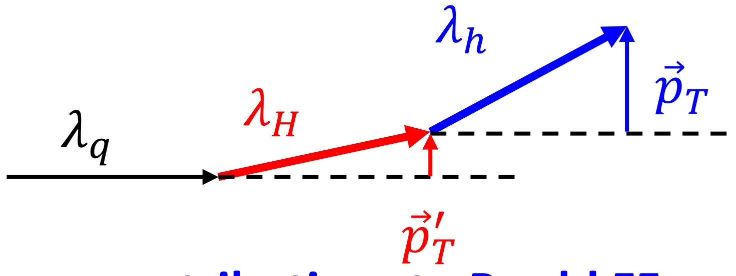
- QCD θ−vacuum breaks parity invariance $\Longrightarrow$ non−zero parity−odd FFs *[Kang, Kharzeev 2011]*

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

- 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.**

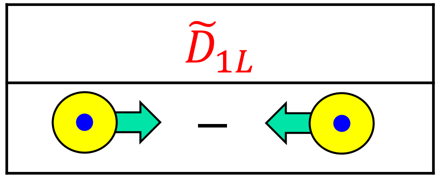
$$D_q^{\Lambda}:\ \Xi^0 \to \Lambda\pi^0, \Xi^- \to \Lambda\pi^-, \Omega^- \to \Lambda K^-, \ldots$$

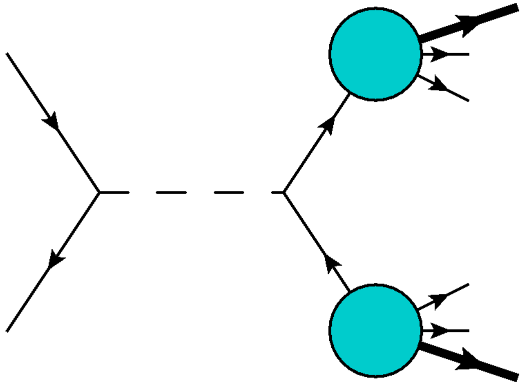
$$D_q^{\pi^+}: \Sigma^+ \to n\pi^+, \ldots$$

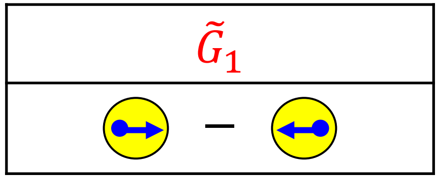
$$D_q^{\pi^-}: \Sigma^- \to n\pi^-, \Lambda \to p\pi^-, \Xi^- \to \Lambda\pi^-, \ldots$$

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

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

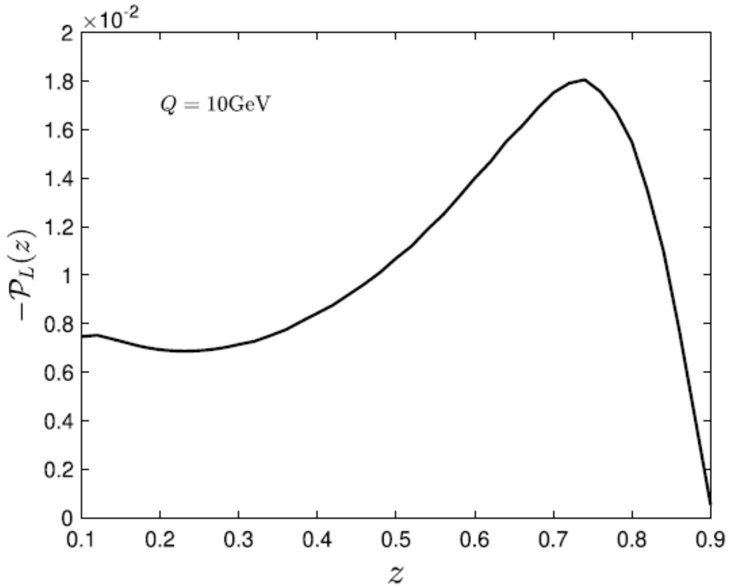


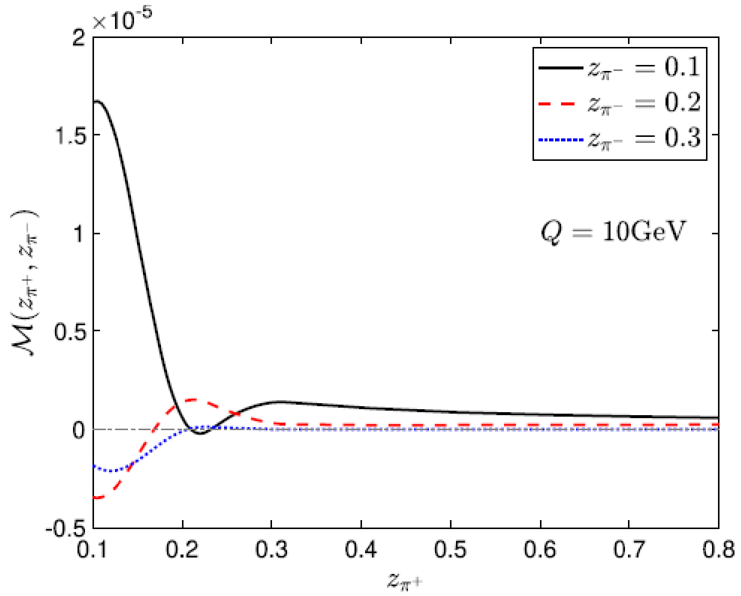




非极化$e^+e^- \to \Lambda X$
Λ自发纵向极化

非极化$e^+e^- \to \pi^+\pi^- X$
背对背双强子产额抑制





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

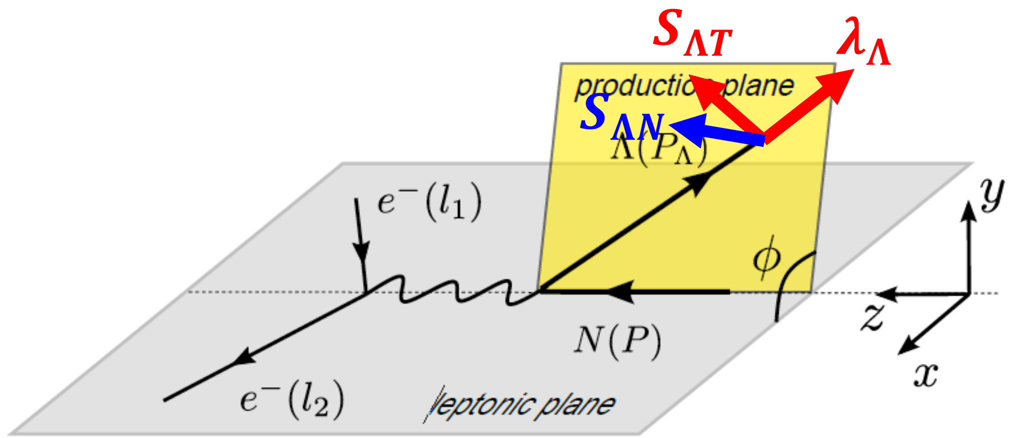
Conclusions and outlook

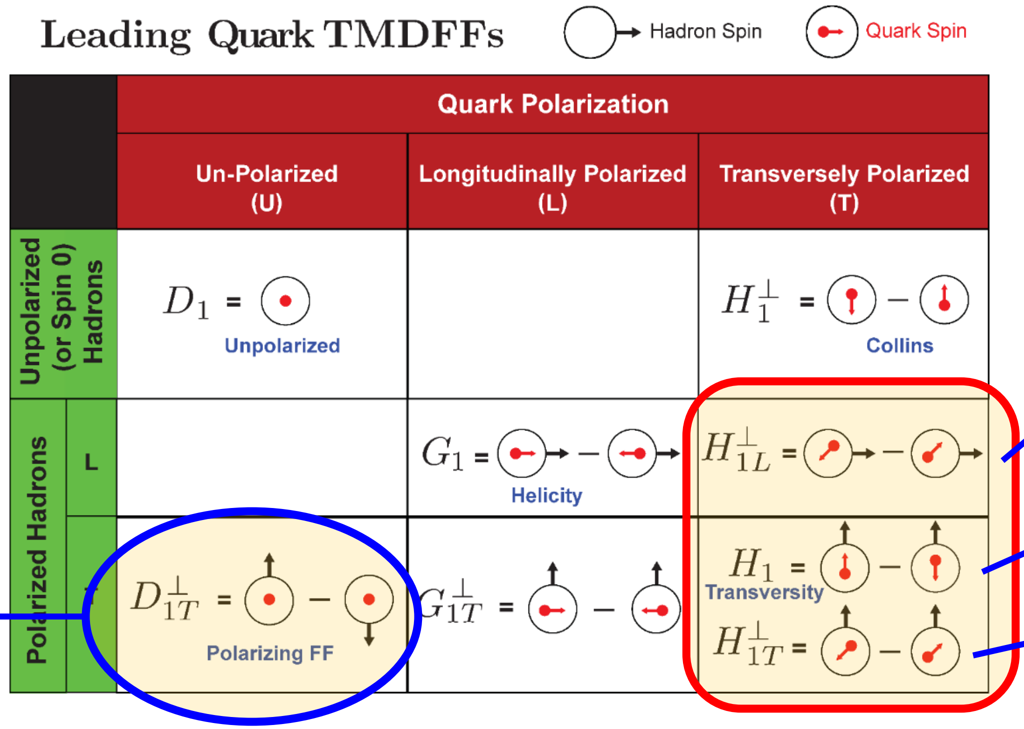
- Transverse polarization of Λ from Belle provoke the study of $D_{1T,q}^{\perp\Lambda}$, with current focus on the flavor structure/isospin symmetry
- Transverse polarization of Λ at different processes such as eA/pp/p$\bar{\text{p}}$/pA… are sensitive to $D_{1T,q}^{\perp\Lambda}$ of different flavors 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.
- P-odd FFs generated by weak decays are estimated and possible signals in e^+e^--annihilation are discussed.
- 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

Longitudinal and transverse Λ polarization in ep/eA collision ($H_{1T}, H_{1T}^{\perp}, H_{1L}^{\perp}$)





TMD handbook
2304.03302

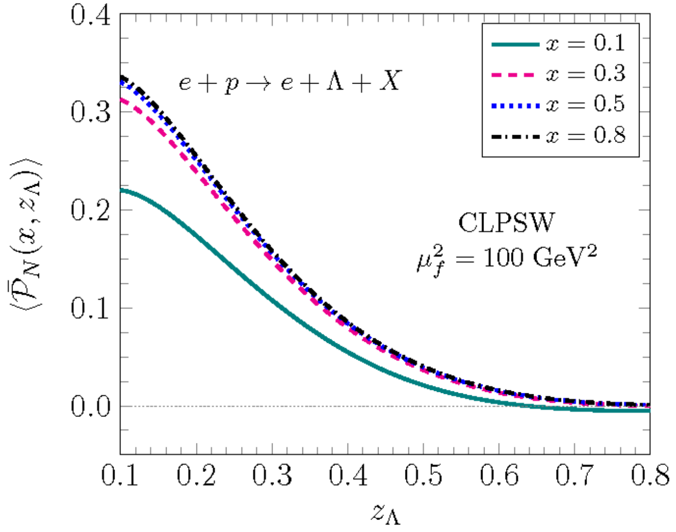
$S_\Lambda \cdot (k \times p_\Lambda)$

$(s_{qT} \cdot p_{\Lambda T})(S_\Lambda \cdot p_\Lambda)$

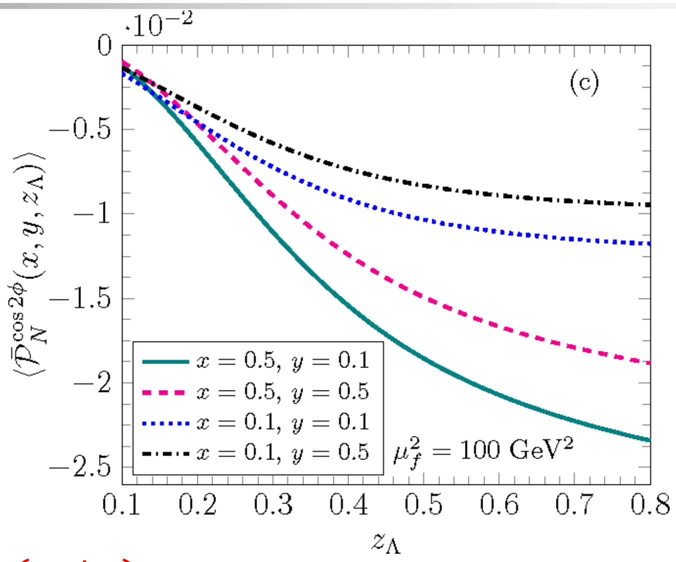
$s_{qT} \cdot S_{\Lambda T}$

$(s_{qT} \cdot p_{\Lambda T})(S_{\Lambda T} \cdot p_{\Lambda T})$

Longitudinal and transverse Λ polarization in ep/eA collision ($H_{1T}, H_{1T}^{\perp}, H_{1L}^{\perp}$)

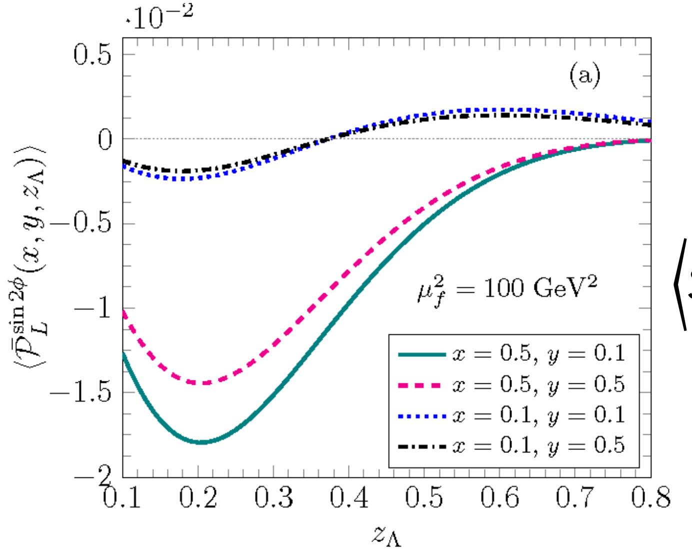


$$\langle \bar{\mathcal{P}}_N \rangle \propto \frac{f_{1q} D_{1T}^{\perp}}{f_1 D_1}$$

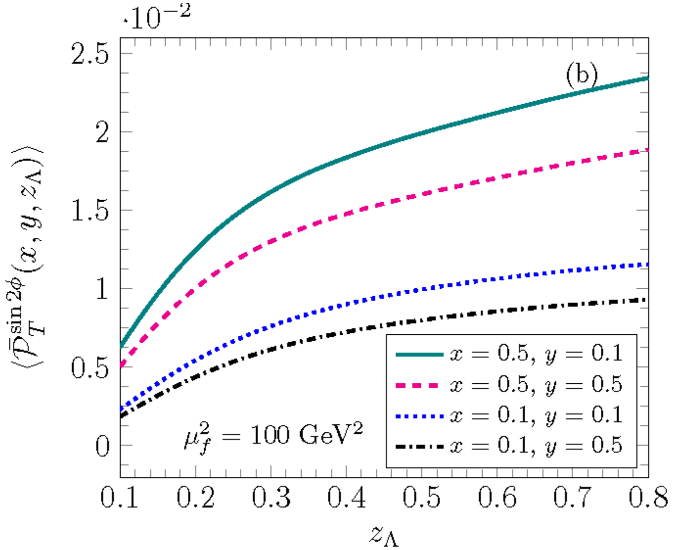


$$\left\langle \bar{\mathcal{P}}_N^{\cos 2\phi} \right\rangle \propto \frac{h_1^{\perp}(-H_{1T} + \kappa_5 H_{1T}^{\perp})}{f_1 D_1}$$

Assuming $H_{1L}^{\perp} \sim H_{1T}^{\perp} \sim \left(D_{1T}^{\perp}\right)/z$ and $H_{1T} \sim G_{1L}$



$$\left\langle \bar{\mathcal{P}}_L^{\sin 2\phi} \right\rangle \propto \frac{h_1^{\perp} H_{1L}^{\perp}}{f_1 D_1}$$



$$\left\langle \bar{\mathcal{P}}_T^{\sin 2\phi} \right\rangle \propto \frac{h_1^{\perp}(-H_{1T} + \kappa_4 H_{1T}^{\perp})}{f_1 D_1}$$

III 自旋 s=1 矢量介子的张量极化碎裂函数（矢量介子spin alignment）

- 矢量介子自旋态的描述，需要极化矢量$\vec{S}_h$和极化张量T^{ij}：$\hat{\rho}=\frac{1}{3}\left(\mathbf{1}+S^i\Sigma^i+T^{ij}\Sigma^{ij}\right)$
- 通过强衰变产物角分布即可测量极化张量。

  以$\rho\to\pi\pi$为例， 考虑到宇称守恒，跃迁概率为

$$\mathbf{T}=\frac{1}{2}\begin{pmatrix} -\frac{2}{3}S_{LL}+S_{TT}^{xx} & S_{TT}^{xy} & S_{LT}^{x} \\ S_{TT}^{xy} & -\frac{2}{3}S_{LL}-S_{TT}^{xx} & S_{LT}^{y} \\ S_{LT}^{x} & S_{LT}^{y} & \frac{4}{3}S_{LL} \end{pmatrix}$$

$$\mathrm{d}\Gamma\left(\vec{S}_h,T^{ij},\hat{p}^*\right)\propto A+B\,\mathrm{T}^{ij}\hat{p}_i^*\hat{p}_j^*$$

$$\Rightarrow\frac{dN}{d\cos\theta^*}\propto 1-\rho_{00}+(3\rho_{00}-1)\cos^2\theta^*$$

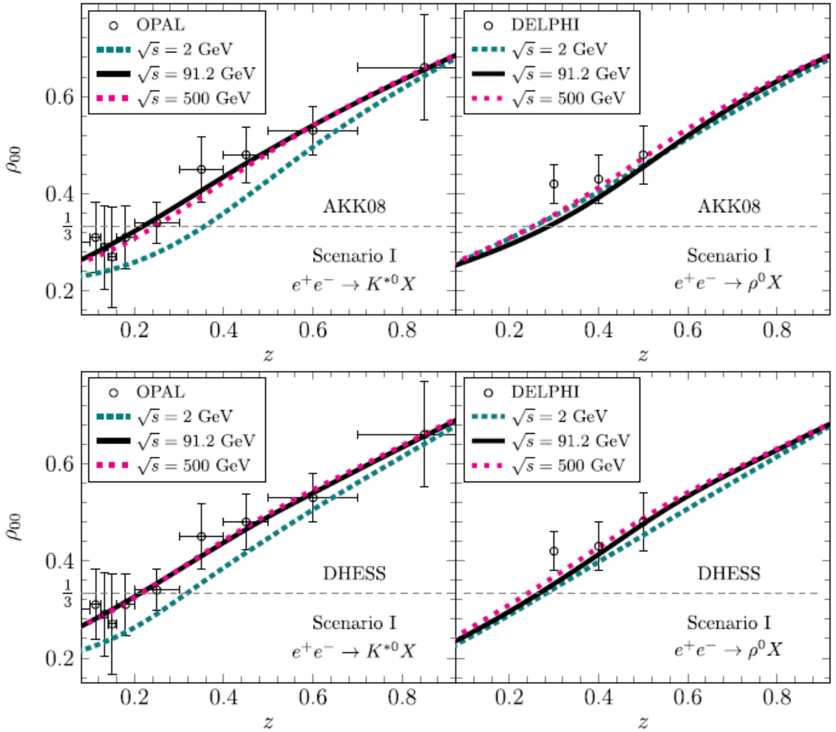
通过测量角分布，可以得到末态矢量介子的spin alignment ρ_{00}因子

- 矢量介子的共线张量极化碎裂函数，

$$D_j^V\left(k,s_q;zk,S_h,T^{ij}\right)=D_{1,j}^{\Lambda}(z)+\cdots+S_{LL}D_{1LL,j}^{V}(z)$$

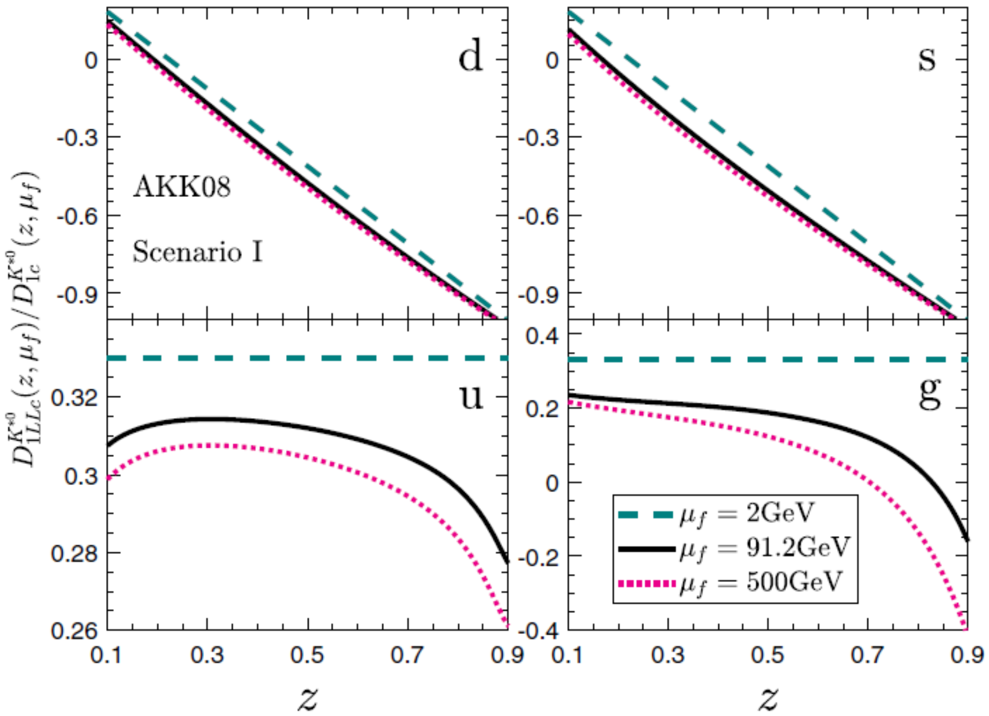
通过测量实验产生的矢量介子的ρ_{00}，可得$D_{1LL,j}^{V}(z)$的信息

- 两种Scenario
  - S1: $D_{1LL}^{\mathrm{unfav}}(z,\mu_0)=c_1D_1^{\mathrm{unfav}}(z,\mu_0)$, $D_{1LL}^{\mathrm{fav}}(z,\mu_0)=c_1(a_1z+1)D_1^{\mathrm{fav}}(z,\mu_0)$
  - S2: $D_{1LL}(z,\mu_0)=c_2\left(a_2z^{1/2}+1\right)D_1(z,\mu_0)$



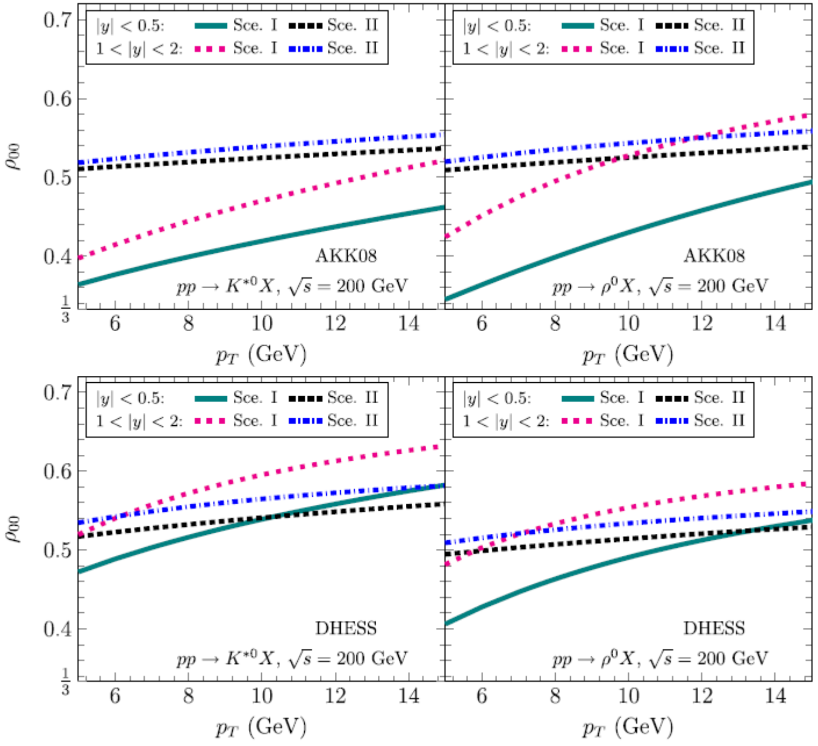
DELPHI, PLB1997
OPAL, PLB1997

D_{1LL}/D_1

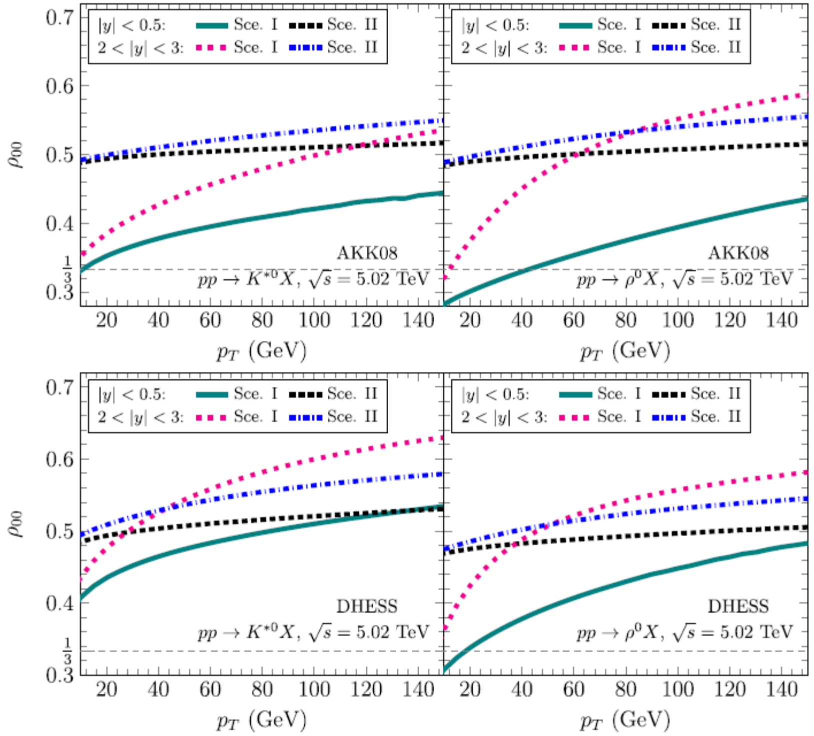


RHIC和LHC上对K^*, ρ^0 spin alignment的理论预言

RHIC



LHC



K.B.Chen, Z.T.Liang, YKS, S.Y.Wei, PRD102 (2020) 034001

Polarized TMD Fragmentation Functions

- $D_j^h(k, s_q; P_h, S_h)$：末态π, K, p, n等强子自旋S_h不容易测量，很难研究极化碎裂函数
- 超子$\Lambda, \Sigma, \Xi, \Omega$等，通过弱衰变产物角分布可以测量极化度。

  以$\Lambda \to p\pi$为例，Λ静止系中唯二矢量为极化矢量$\vec{\mathcal{P}}_\Lambda$和末态强子动量$\hat{p}^*$，跃迁概率为

$$\mathrm{d}\Gamma(\vec{\mathcal{P}}_\Lambda, \hat{p}^*) \propto A + B\,\vec{\mathcal{P}}_\Lambda \cdot \hat{p}^*$$
$$\propto 1 + \alpha \mathcal{P}_\Lambda \cos\theta^*$$

通过测量角分布，可以得到末态产物的极化矢量$\vec{\mathcal{P}}_\Lambda$

- Λ超子的共线碎裂函数，

$$D_j^\Lambda(k, s_q; zk, S_h) = D_{1,j}^\Lambda(z) + \lambda_q \lambda_h G_{1L,j}^\Lambda(z) + \vec{s}_{qT} \cdot \vec{S}_{\Lambda T}\, H_{1T,j}^\Lambda(z)$$

DSV98, de Florian, Stratmann, Vogelsang, PRD1998

AKK08, Albino, Kniehl, Kramer, NPB2008

Λ inside jets in hadronic collisions

(1) $p + p \to j + X$, with jet reconstructed

$$\frac{d\sigma_{pp\to jX}}{dy d^2\boldsymbol{k}_T} = \sum_{abc} \int dy_2 x_1 f_a(x_1, \mu_f) x_2 f_b(x_2, \mu_f) \frac{1}{\pi} \frac{d\hat{\sigma}_{ab\to jc}}{d\hat{t}}$$

$$R_j(y, k_T) \equiv \frac{d\sigma_{pp\to jX}}{\sum_i d\sigma_{pp\to iX}}$$

(2) $j \to \Lambda + X'$, described by TMD jet FFs

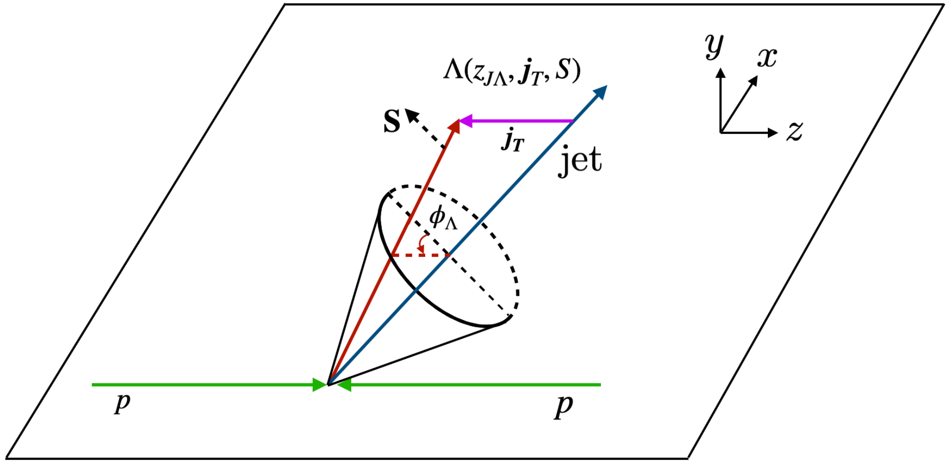


Figure from STAR

$$\frac{d\sigma_{pp\to j(\to\Lambda)X}}{dy d^2 k_T dz d^2 p_{\Lambda T}} = \sum_j \frac{d\sigma_{pp\to jX}}{dy d^2\boldsymbol{k}_T} \left(D_{1j}^{\Lambda}(z, p_{\Lambda T}) + \frac{\varepsilon_\perp^{\rho\sigma} p_{T\rho} S_{\Lambda T\sigma}}{zM} D_{1T,j}^{\perp\Lambda}(z, p_{\Lambda T}) \right)$$

$$P_\Lambda(y, k_T, z) = \frac{\sqrt{\pi}\Delta_\Lambda}{2zM} \frac{\sum_j R_j(y, k_T) D_{1T,j}^{\perp\Lambda}(z)}{\sum_j R_j(y, k_T) D_{1,j}^{\Lambda}(z)}$$

- We have quite different quark/gluon production $R_j(y, k_T)$ in different reaction/kinematic regions, which provide the potential for deciphering the flavor structure.