中国物理学会高能物理分会第十二届全国会员代表大会暨学术年会

Flavor Dependences of Polarized Fragmentation Functions

Yu-Kun Song (University of Jinan)

2026.7.17

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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

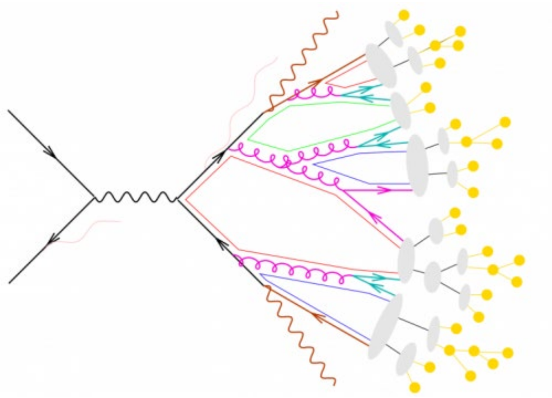
I. Introduction

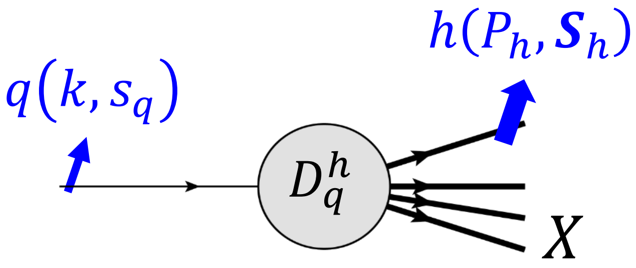
II. Flavor structure of $D_{1T,q}^{\perp\Lambda}$ from various processes

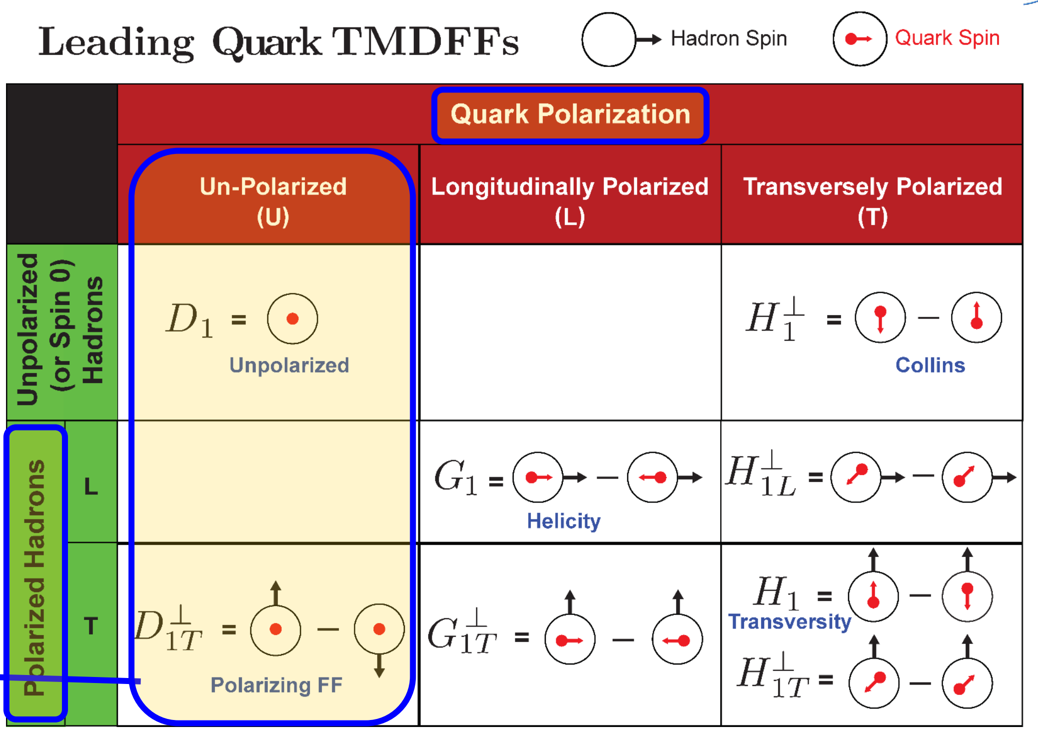
III. Transverse polarization of Λ from QGP as a probe of nuclear matter

IV. Conclusion and outlook

Spin-dependent TMD FFs of Λ

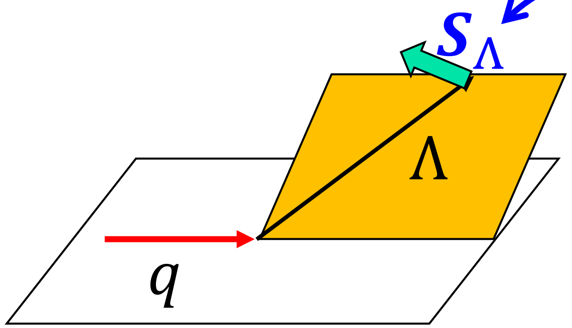






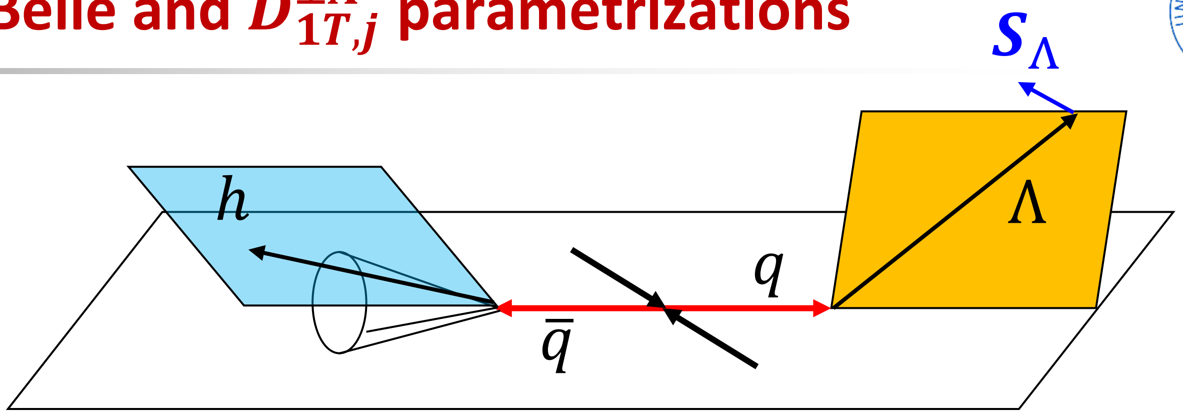
TMD handbook
2304.03302

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



$D_{1T}^\perp(z, p_T^2)$
$\boldsymbol{S}_\Lambda \cdot (\boldsymbol{k} \times \boldsymbol{p}_\Lambda)$

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 $0.2 < z_\Lambda < 0.4$

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

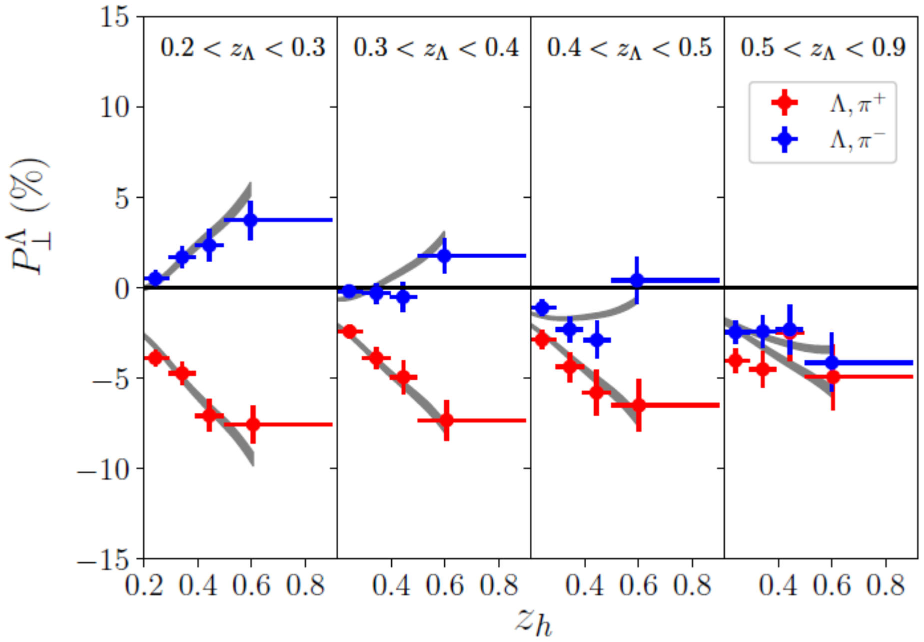
$$P_\Lambda \propto \sum_q e_q^2 D_{1T,q}^{\perp\Lambda} \quad \Longrightarrow \quad \boldsymbol{D_{1T,u}^{\perp\Lambda} \sim -D_{1T,d}^{\perp\Lambda}} \quad ???$$

- 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?



CKT

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

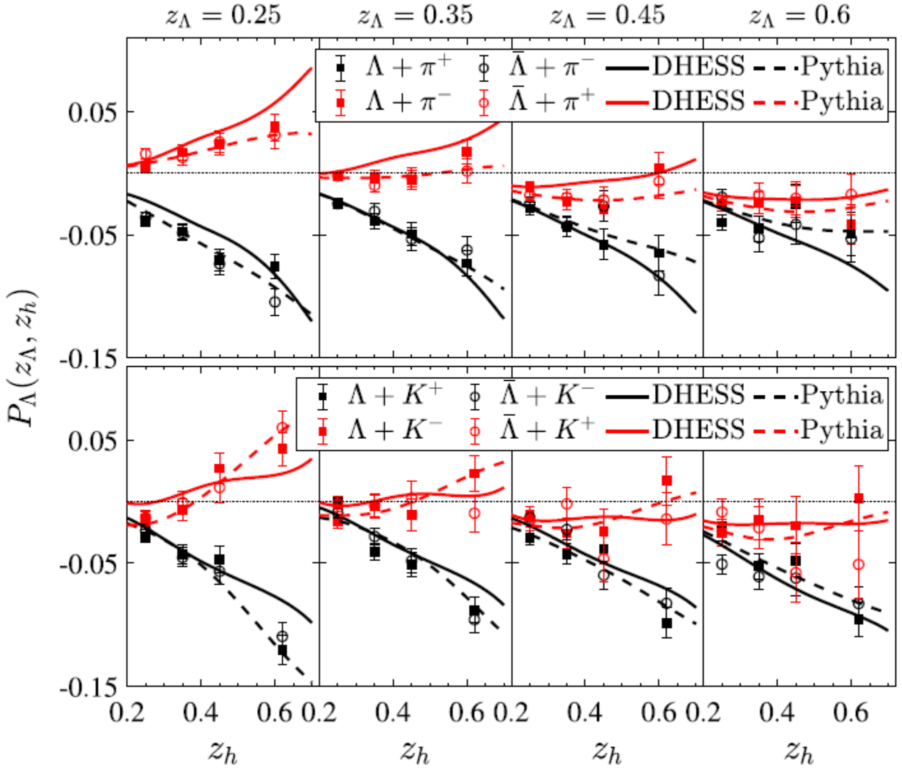
- Based on an **isospin symmetric** formalism, we fit the Belle data well using CLPSW parametrizations.

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

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

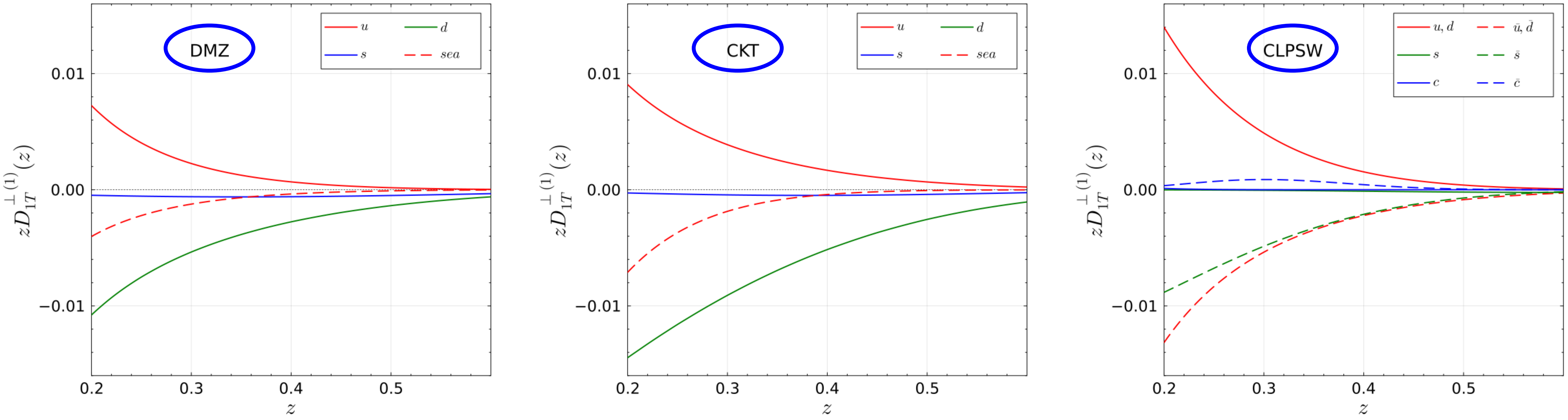
$$D_{1T\bar{u}}^{\perp\Lambda} = D_{1T\bar{d}}^{\perp\Lambda},$$

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



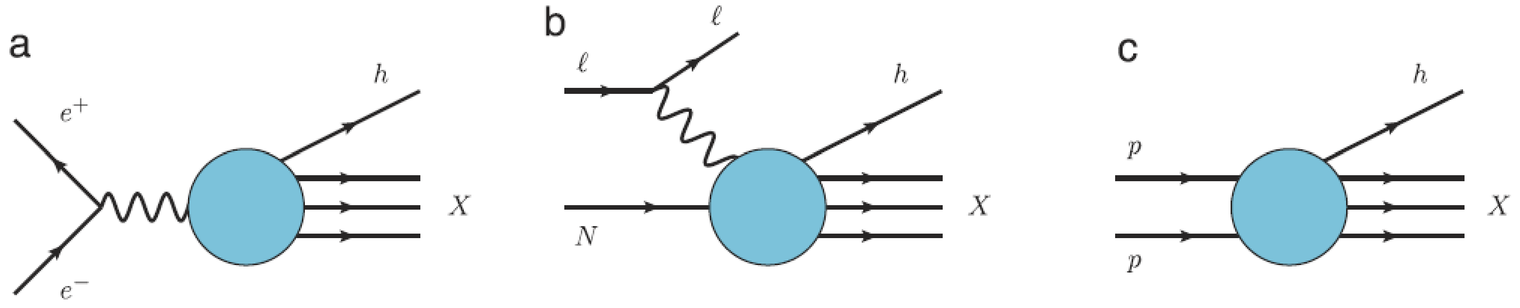
Different flavor structures of $D_{1T,q}^{\perp\Lambda}$ from various parametrizations

- Comparison of parametrizations



Flavor structure (Isospin symmetry) of the polarized FFs $D_{1T,q}^{\perp\Lambda}$?

Global analysis of $D_{1T,q}^{\perp\Lambda}$ 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

- 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

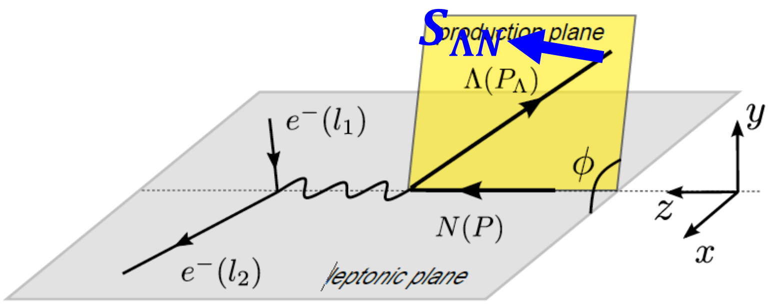
  U.D'Alesio, L.Gamberg, F.Murgia, M.Zaccheddu, PRD 108 (2023) 094004

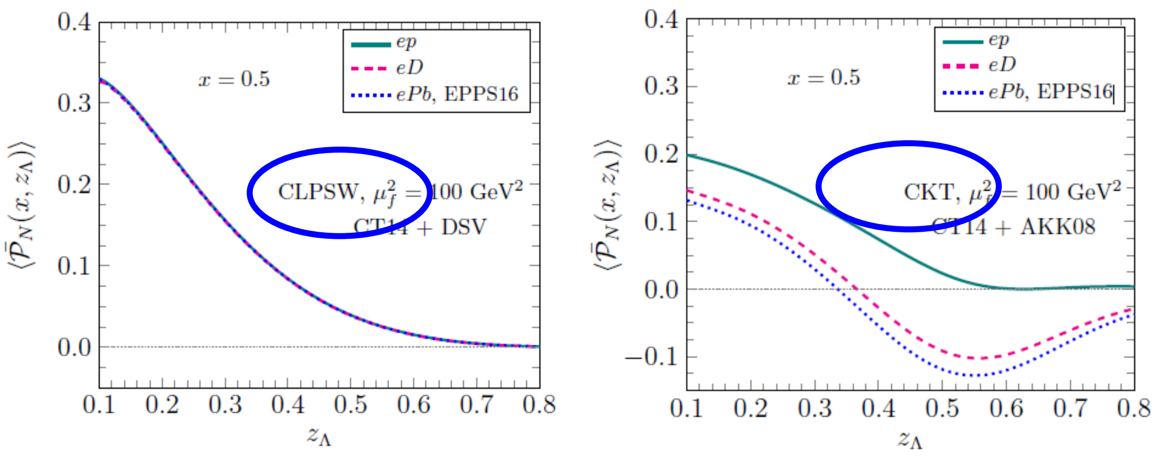
  Z. Ji, X.Y.Zhao, A.Q.Guo, Q.H.Xu, J.L.Zhang, Nucl.Sci.Tech. 34 (2023) 155

  STAR, JHEP 06 (2026) 050

Potential to extract flavor-dependent $D_{1T,f}^{\perp\Lambda}$

SIDIS





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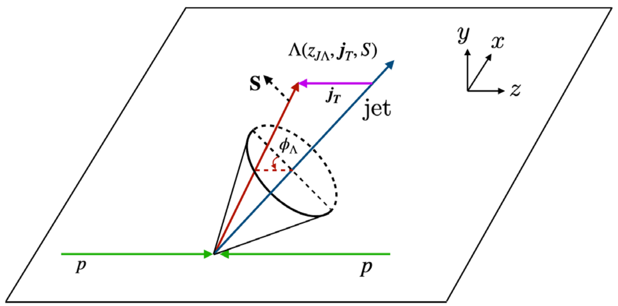
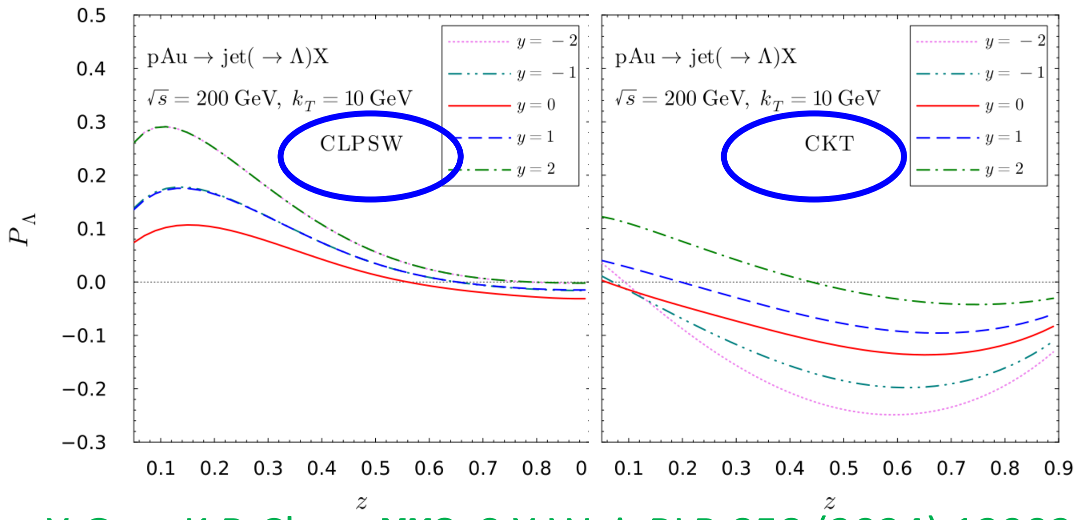
pp/pA/AA





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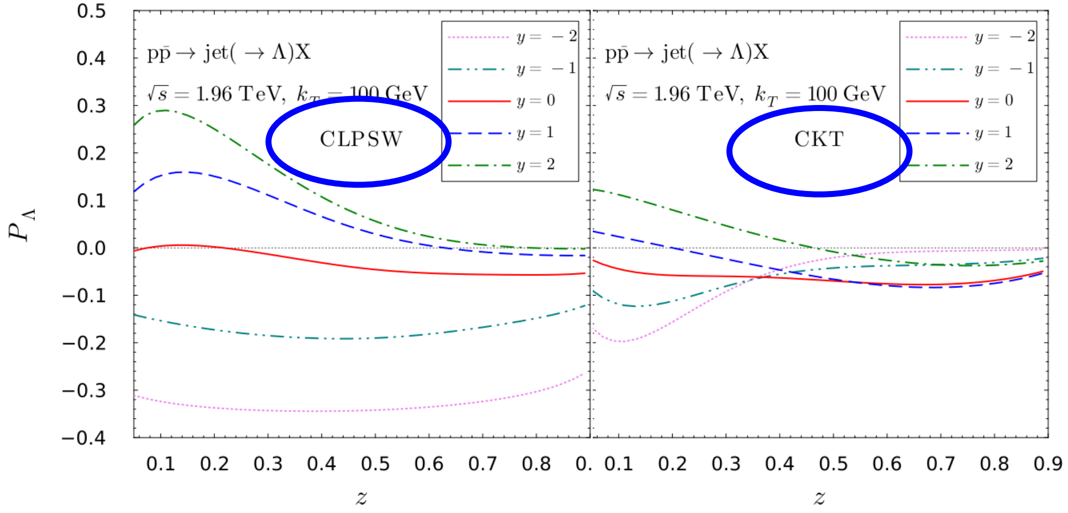
Potential to extract flavor-dependent $D_{1T,f}^{\perp\Lambda}$

$p\bar{p}$

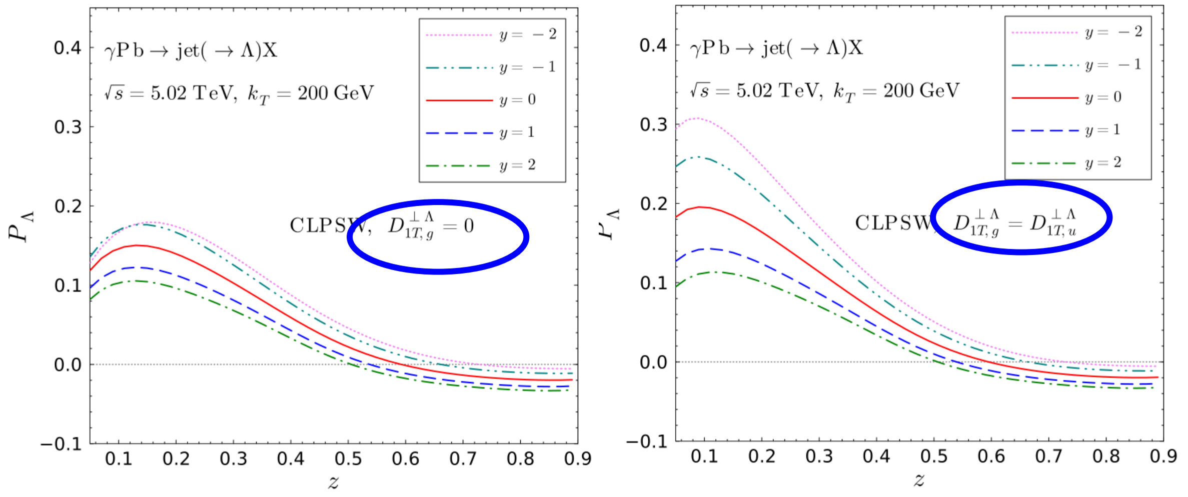
Calling for the Re-analysis of Tevatron data



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

UPC

Extraction of Gluon TMD $D_{1T,q}^{\perp\Lambda}$



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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

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

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

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

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

Where the perturbative and non-perturbative parts are given by

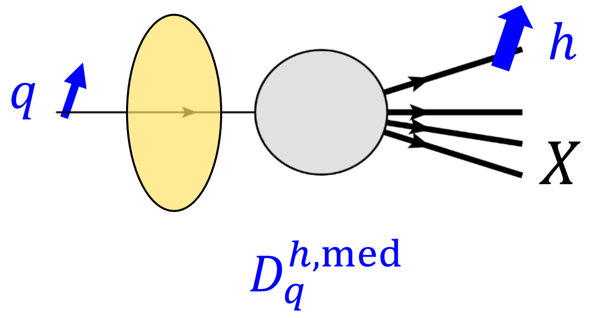
$$S_{pert} = -K(b_T^*, \mu_b) \ln \frac{Q}{\mu_b} - \int_{\mu_b}^{Q} \frac{d\mu'}{\mu'} \gamma_D\left(g(\mu'), \frac{Q^2}{\mu'^2}\right), \qquad S_{NP} = \frac{\langle p_\perp^2 \rangle}{4} \frac{b_T^2}{z^2}, \qquad S_{NP}^{\perp} = \frac{\langle p_\perp^2 \rangle}{4} \frac{b_T^2}{z^2},$$

P_Λ as a probe of QGP medium: 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

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

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



- 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, PRD113 (2026) 014007

P_Λ as a probe of QGP medium: refined model

- The refined model with 2-step process

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

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

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

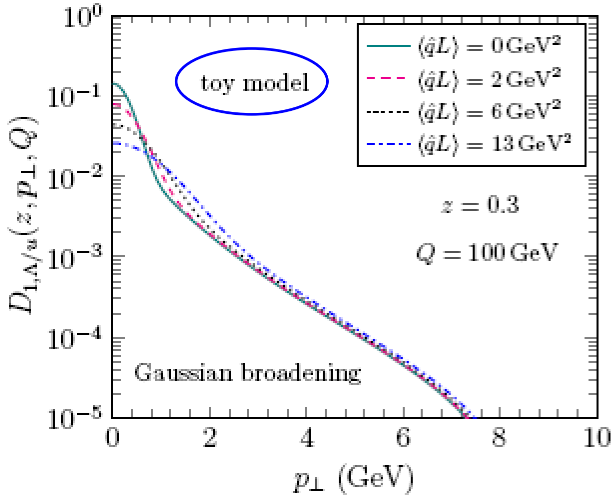
$$\widetilde{D}_{1T,i}^{\perp(1)\mathrm{med}}(z, b_T, Q, \tau_{\mathrm{max}}) = \sum_j \int_z^1 C_{ji}(\xi, \tau_{\mathrm{max}}) \tilde{B}_j(b_T) D_{1T,j}^{\perp(1)\mathrm{vac}}\left(\frac{z}{\xi}, b_T, \xi Q\right)$$

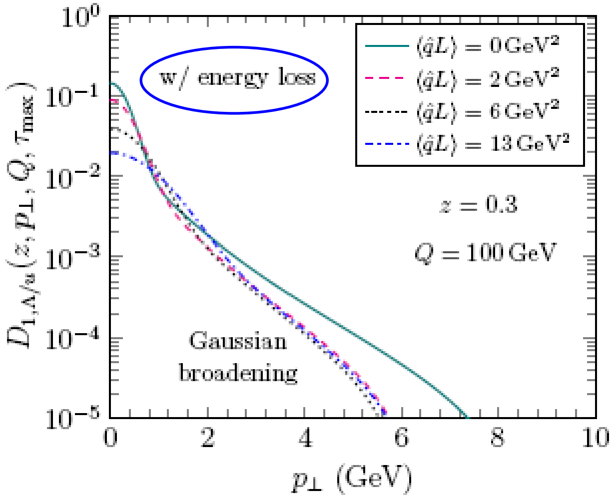
- The energy loss effect is accounted for through the cascade spectrum function C_{ji}. We obtain C_{ji} by solving the evolution equations developed in literature.

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

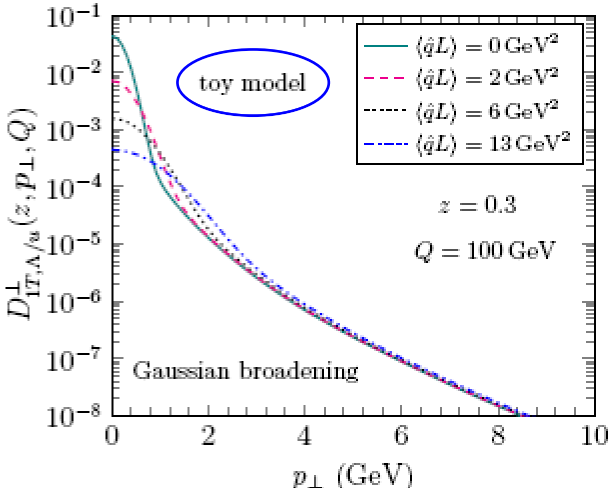
Medium modified FFs D_1 & $D_{1T}^{\perp}$

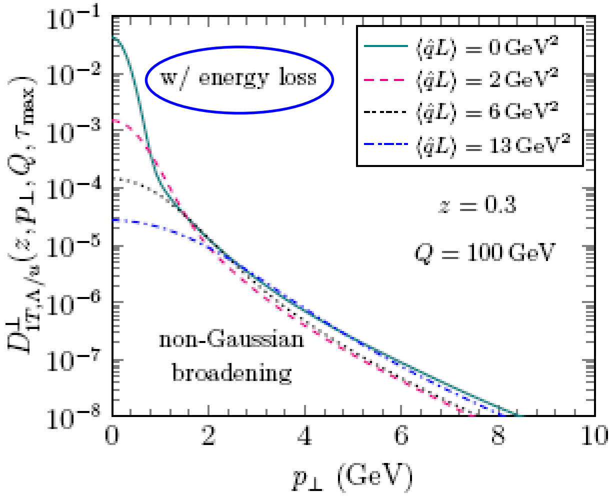
$D_{1u}^{\Lambda}(z, p_\perp, Q)$





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





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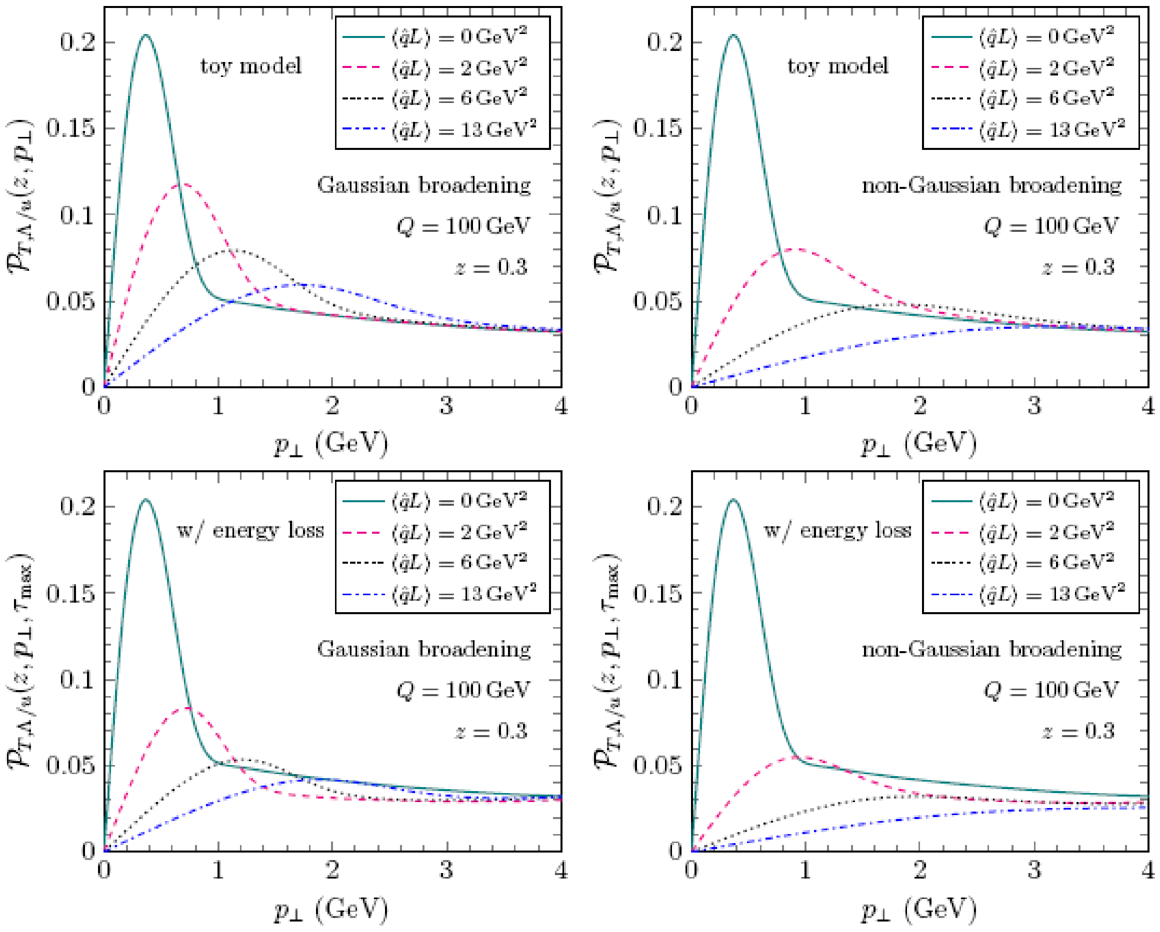
Medium effects on $\mathcal{P}_{T,\Lambda/u}(z, p_\perp)$



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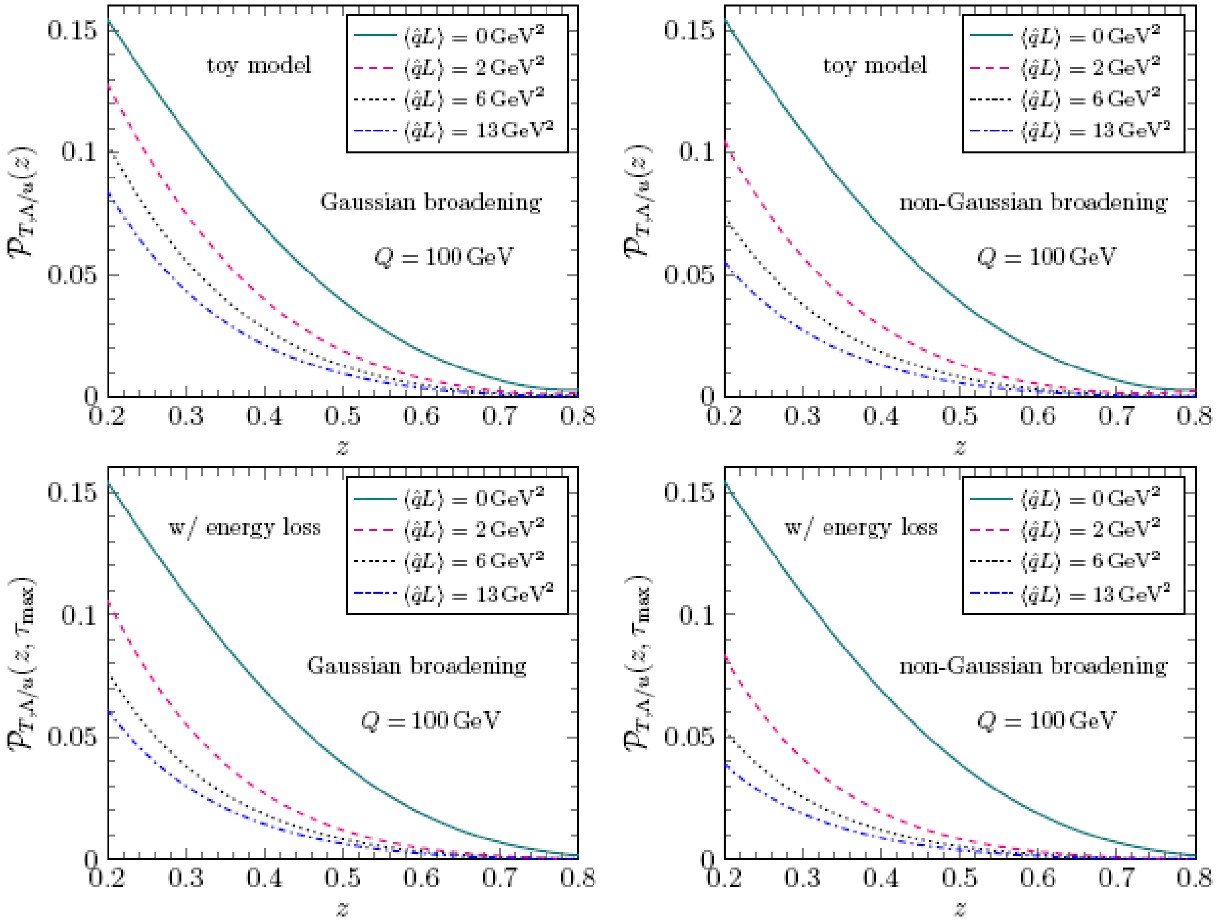
Medium effects on $\mathcal{P}_{T,\Lambda/u}(z)$



$\mathcal{P}_{T,\Lambda/u}$ can serve as a probe of QGP matter！

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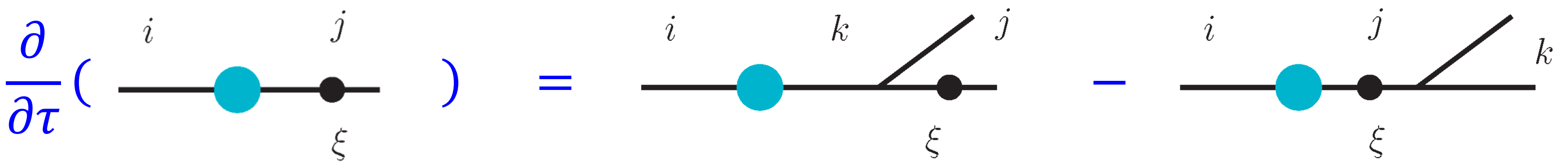
Conclusions and outlook

- Belle data attract much attention on $D_{1T,q}^{\perp\Lambda}$, and current focus lie on their flavor structure
- Global analysis of $D_{1T,q}^{\perp\Lambda}$ call for theoretical calculation and experimental study of various processes
- We performed phenomenological calculation P_{Λ} in various processes, e.g., eA/pp/p$\bar{\text{p}}$/pA…
- The QGP medium modify the gluon radiation in vacuum, leaving visible impact on the transverse polarization of Λ. We verify this effect as a new probe of nuclear matter.
- More experimental data and theoretical progress for $D_{1T,q}^{\perp\Lambda}$ are on the way. Keep tuned!

Thanks for you attention!

Backup Slides



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

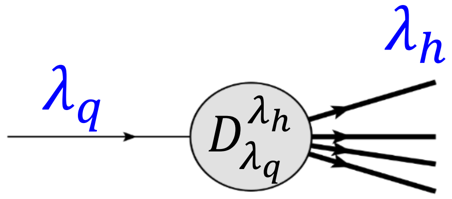
gain term loss term

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

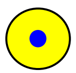
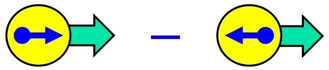
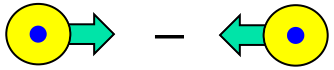
$$\mathcal{K}_{gg}(z) = \frac{1}{2}\hat{P}_{gg}(z)\sqrt{\frac{N_c(1-z+z^2)}{z(1-z)}}, \qquad \mathcal{K}_{qq}(z) = \frac{1}{2}\hat{P}_{qq}(z)\sqrt{\frac{N_c z + C_F(1-z)^2}{z(1-z)}}$$

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

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



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

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

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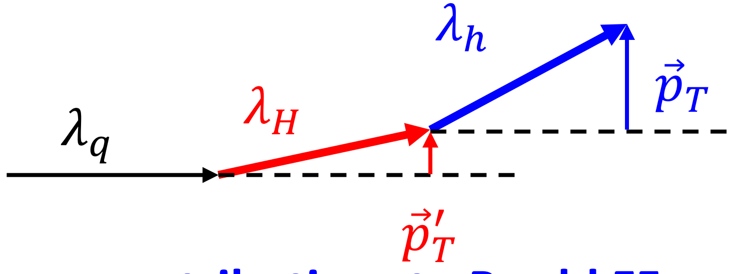
Weak decay contributions to TMD FFs $\widetilde{D}_{1L}, \widetilde{G}_1$

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

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

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

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



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

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

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

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

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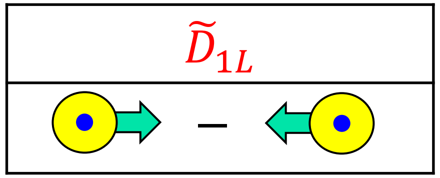
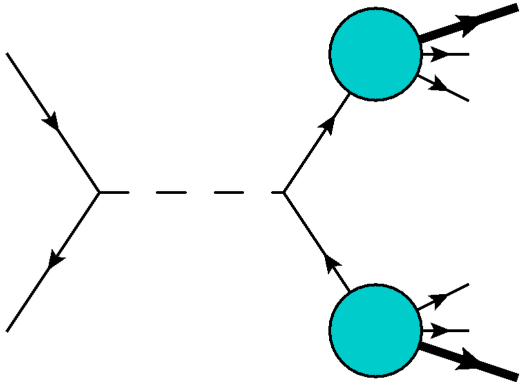
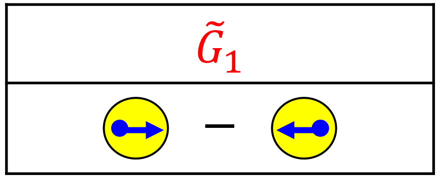
Observables of $\widetilde{D}_{1L}, \widetilde{G}_1$





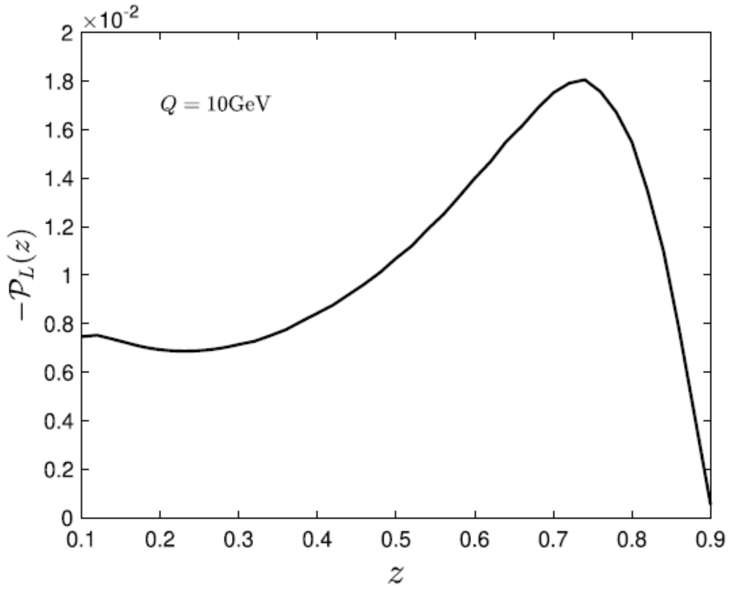


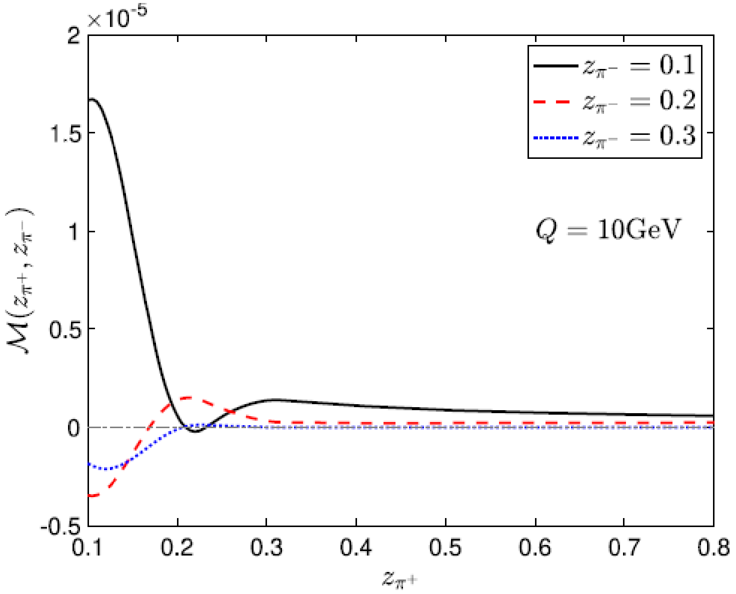
Unpolarized $e^+e^- \to \Lambda X$

Spontaneous Λ polarization

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

Suppression of back-to-back dihadron production





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