QPT-2025

Spin Polarization as a Novel Probe of Jet Quenching

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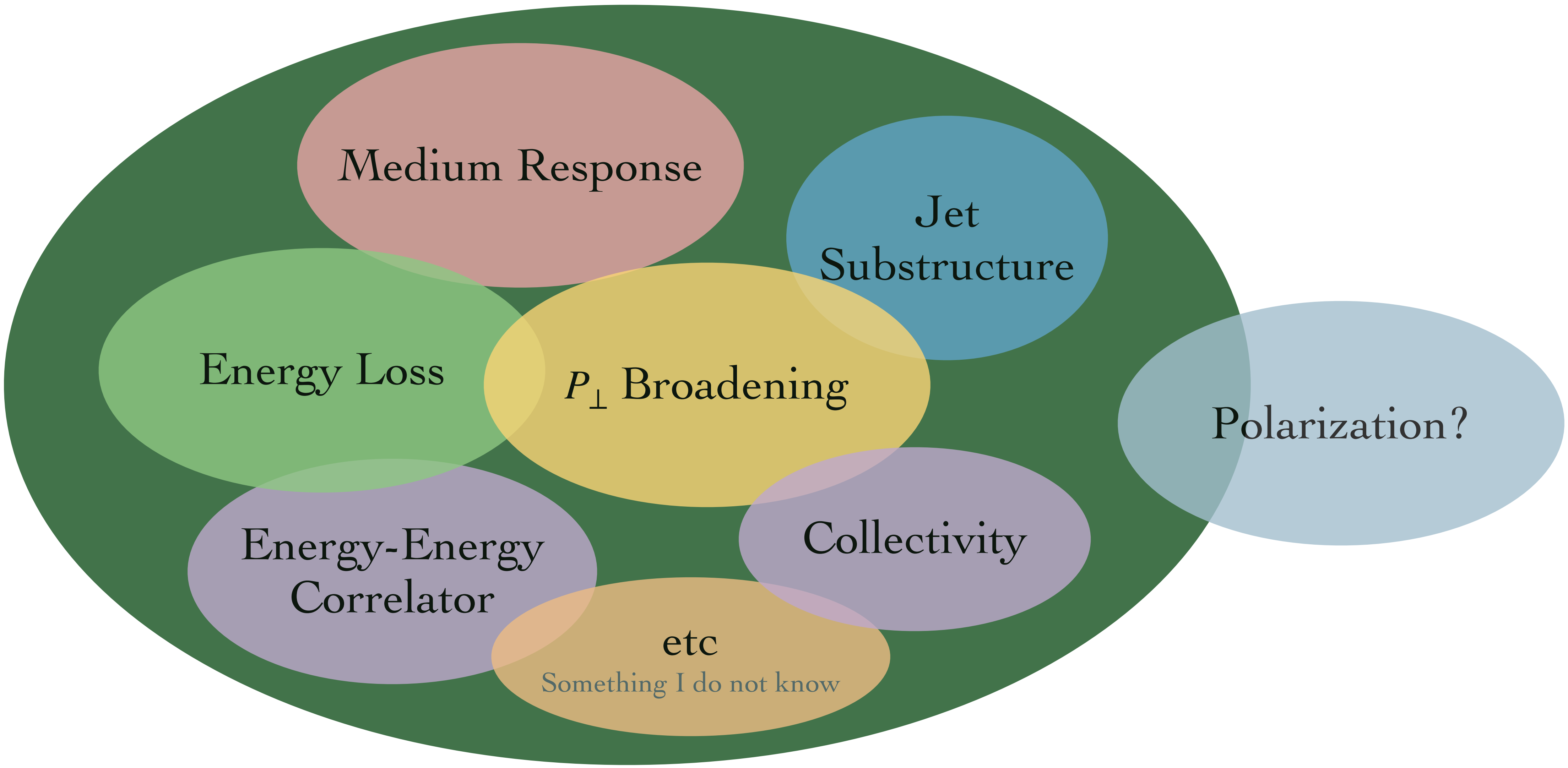
K.B. Chen, Z.T. Liang, Y.L. Pan, Y.K. Song, S.Y. Wei; Phys.Lett.B816, 136217 (2021).
K.B. Chen, Z.T. Liang, Y.K. Song, S.Y. Wei; Phys.Rev.D105, 034027 (2022).
Y. Gao, K.B. Chen, Y.K. Song, S.Y. Wei; Phys.Lett.B 858, 139026 (2024).
X.Y. Qin, Y.K. Song, S. Y. Wei; arXiv:2504.00739.

Keywords of Jet Quenching



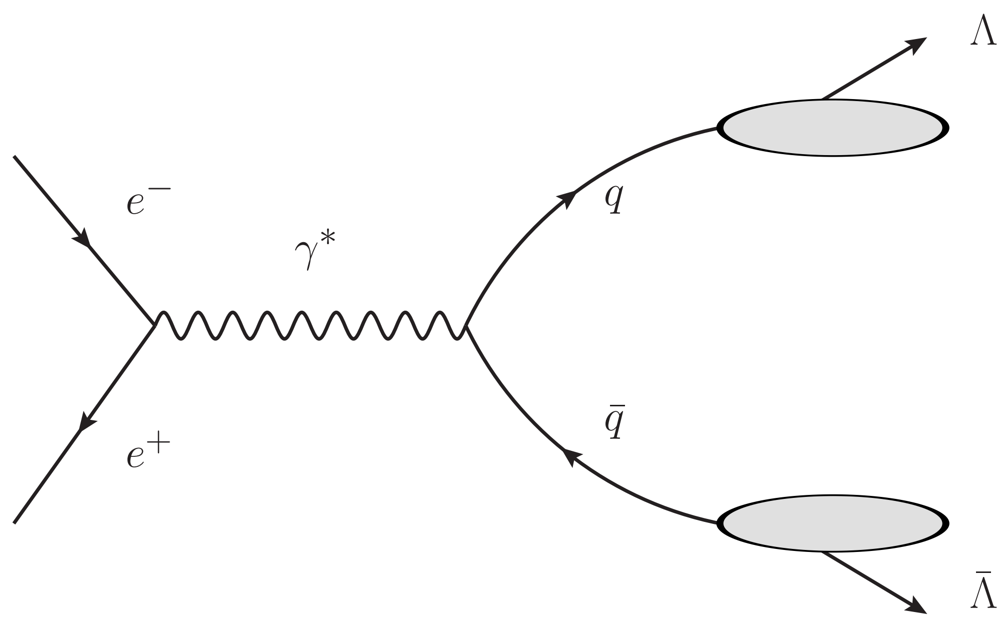
Unpolarized Initial State + QCD dominant ⇒ Unpolarized JET

Contents

- ☑ The ubiquitous Spin Correlation
- ☑ Emerging transverse polarization
- ☑ Z/W associated jet production see Wen-Hao-Yao's poster (A1)
- ☑ Summary

The ubiquitous Spin Correlation

$\Lambda\bar{\Lambda}$-pair Production in e⁺e⁻ Annihilation Experiment



Belle Energy

$$\frac{d\sigma}{dPS} = \sigma_0 \left[D_{1q}^{\Lambda}(z_1) D_{1\bar{q}}^{\bar{\Lambda}}(z_2) - \lambda_\Lambda \lambda_{\bar{\Lambda}} G_{1Lq}^{\Lambda}(z_1) G_{1L\bar{q}}^{\bar{\Lambda}}(z_2) \right]$$

☑ **Helicity Conservation**

q and $\bar{q}$ are on the same fermion line.
They must have opposite helicities.

☑ **Helicity Correlation**

A novel probe to the spin-dependent fragmentation functions

☑ **Entangled states**

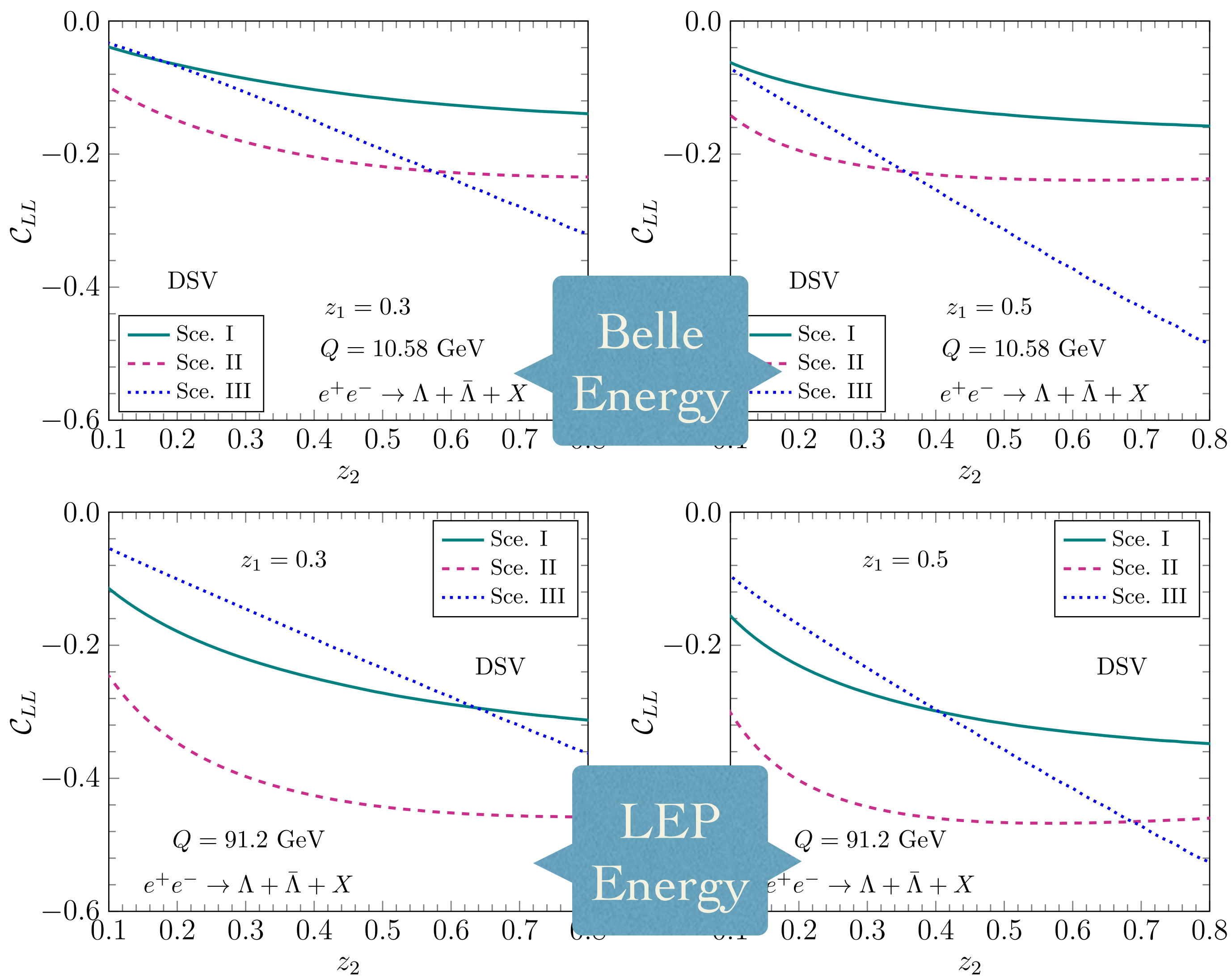
$$\frac{1}{\sqrt{2}} |A^\uparrow B^\downarrow \pm A^\downarrow B^\uparrow\rangle$$

$$\frac{1}{\sqrt{2}} |A^\uparrow B^\uparrow \pm A^\downarrow B^\downarrow\rangle$$

H.C. Zhang, SYW, PLB 839 (2023) 137821
see also Nucl. Phys. B 445 (1995) 380.

Helicity Correlation of $\Lambda\bar{\Lambda}$-pair

$$C_{LL} = \frac{\text{same signs} - \text{opposite signs}}{\text{total cross section}} = -\frac{\sum_q \sigma_0 G_{1Lq}^{\Lambda}(z_1) G_{1L\bar{q}}^{\bar{\Lambda}}(z_2)}{\sum_q \sigma_0 D_{1q}^{\Lambda}(z_1) D_{1\bar{q}}^{\bar{\Lambda}}(z_2)} \propto \langle \cos\theta_1^* \cos\theta_2^* \rangle$$

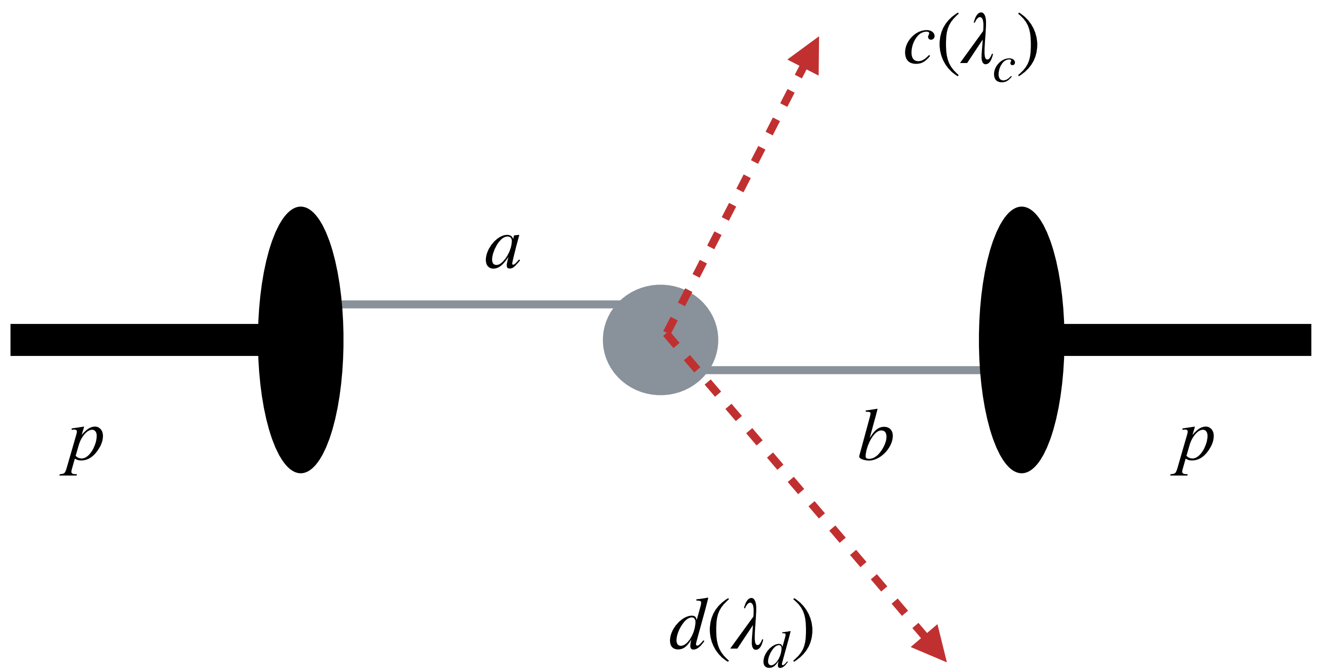


- ☑ The helicity correlation at the Belle has a similar magnitude with that at LEP.
- ☑ It is indeed possible to study the hadronization of polarized quark in unpolarized experiments.

H.C. Zhang, SYW, PLB 839 (2023) 137821

The ubiquitous Spin Correlation

Apply to the unpolarized pp collisions

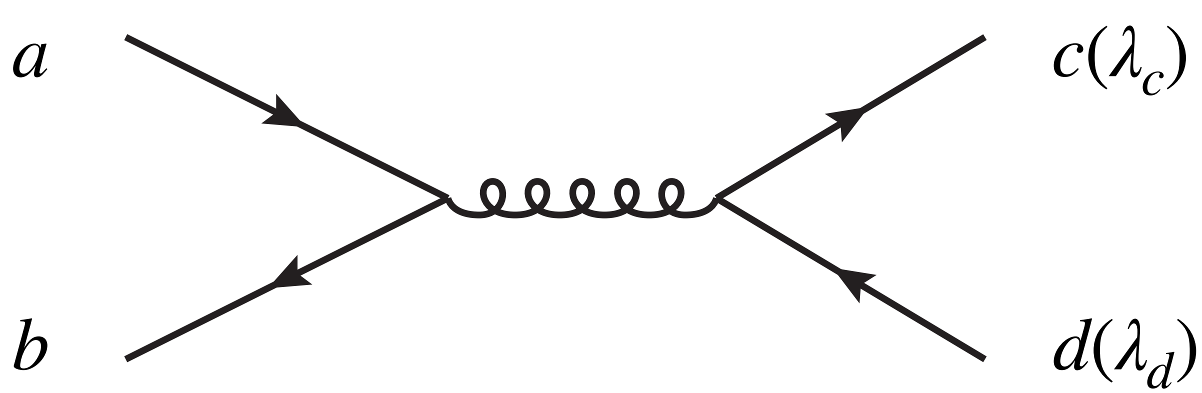


$$a + b \to c(\lambda_c) + d(\lambda_d)$$

☑ **Are λ_c and λ_d correlated?**

Yes!

"Connected channels": just like e^+e^- annihilation, maximum correlation



$$g + g \to q + \bar{q}$$

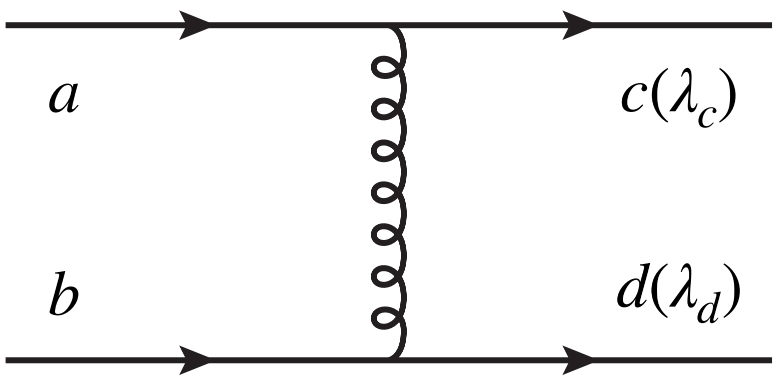
$$q_i + \bar{q}_i \to q_j + \bar{q}_j$$

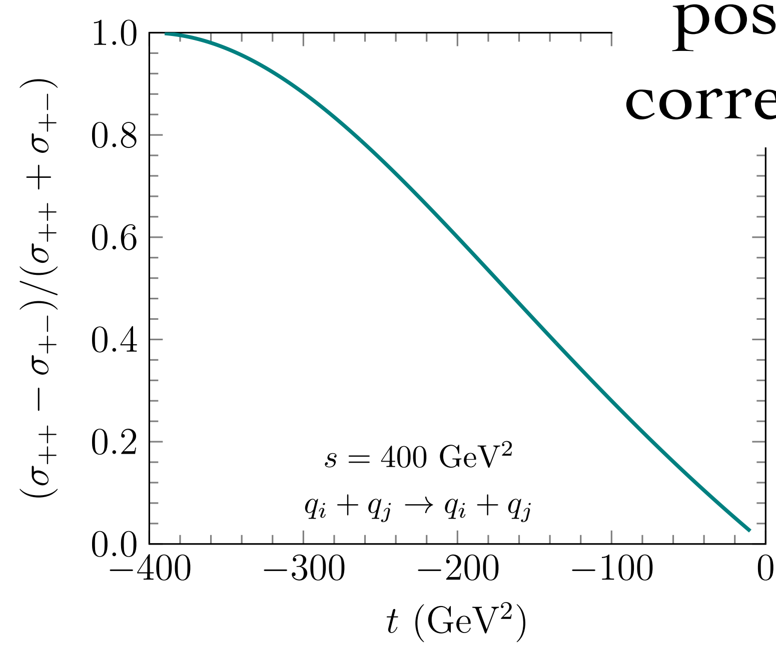
$$q + \bar{q} \to g + g$$

negative correlation

H.C. Zhang, SYW, PLB 839 (2023) 137821

"Unconnected channels": prefer same-sign correlation





positive correlation

$q + g \to q + g$

$q_i + q_j \to q_i + q_j$

$g + g \to g + g$

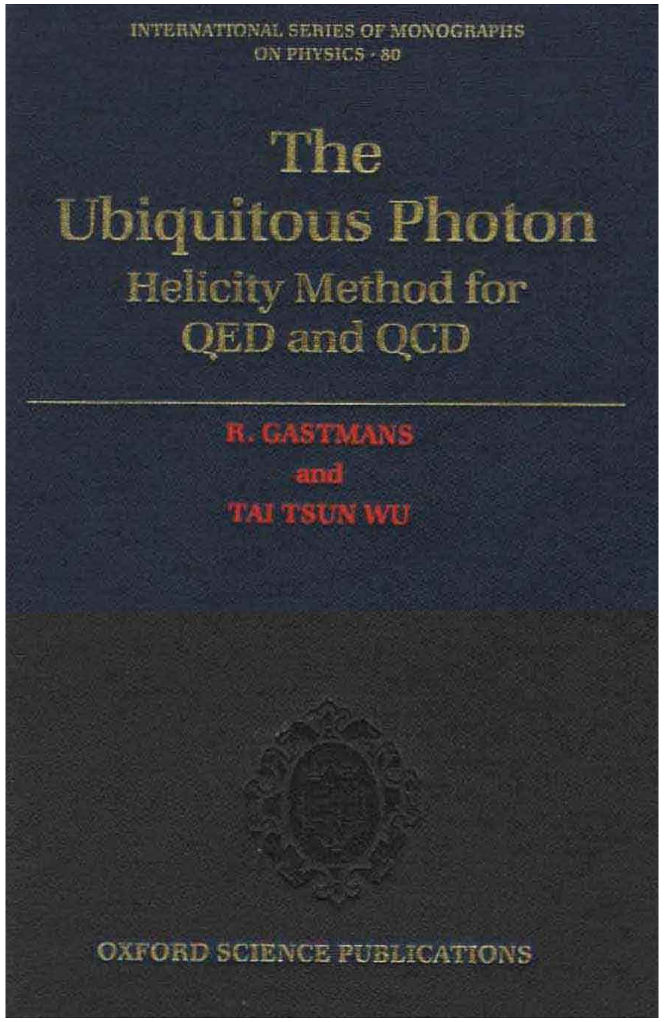
$q_i + q_i \to q_i + q_i$

$q_i + \bar{q}_i \to q_i + \bar{q}_i$

To summarize

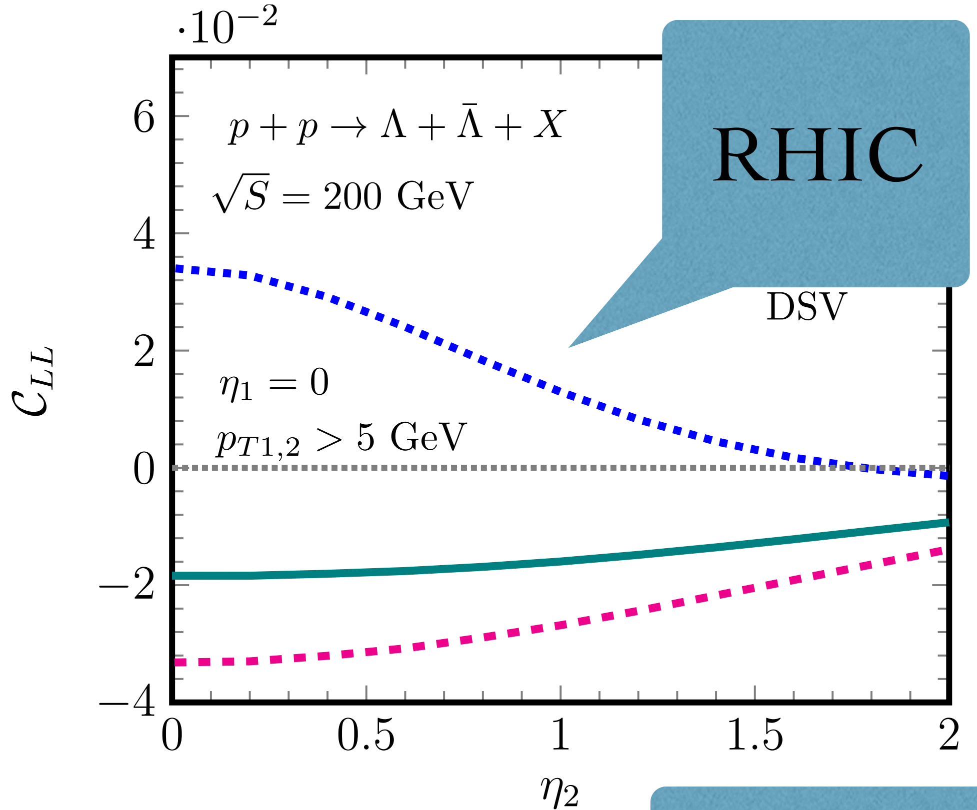
- ☑ "Connected": $\sigma_{+-} = \sigma_{-+} > \sigma_{++} = \sigma_{--} = 0$
- ☑ "Unconnected": $\sigma_{++} = \sigma_{--} > \sigma_{+-} = \sigma_{-+} > 0$
- ☑ Probe polarized FF in unpolarized pp collisions
- ☑ Explore the circularly polarized gluon FF

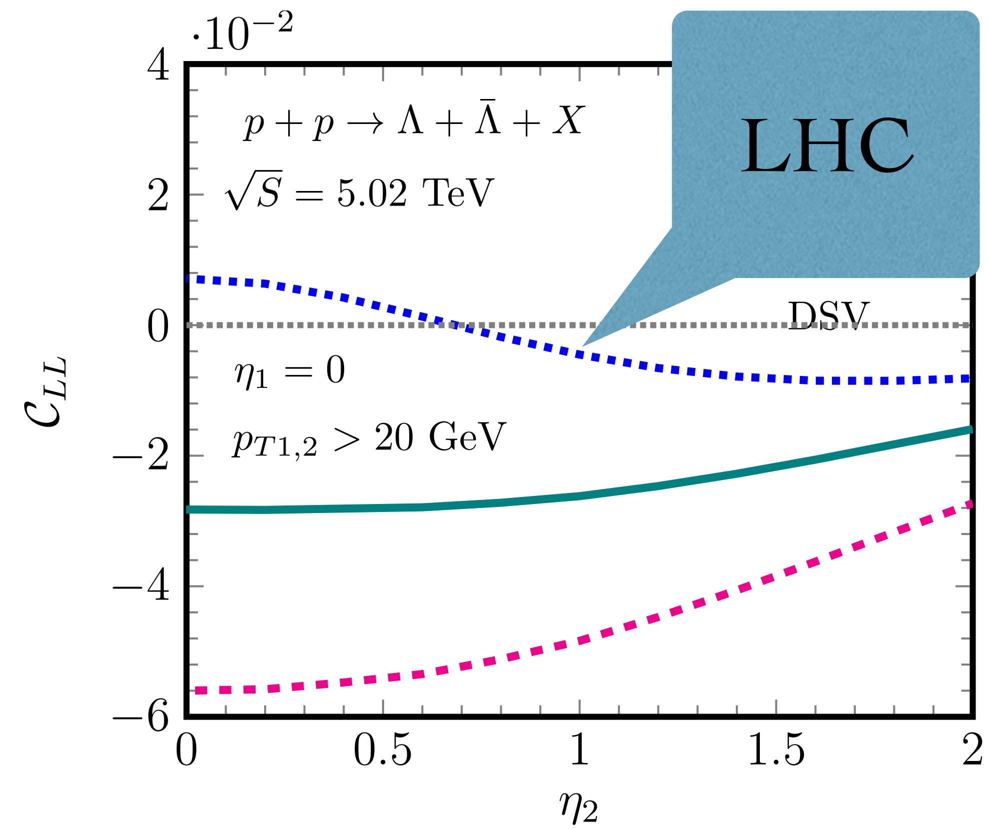
H.C. Zhang, SYW; PLB 839 (2023) 137821

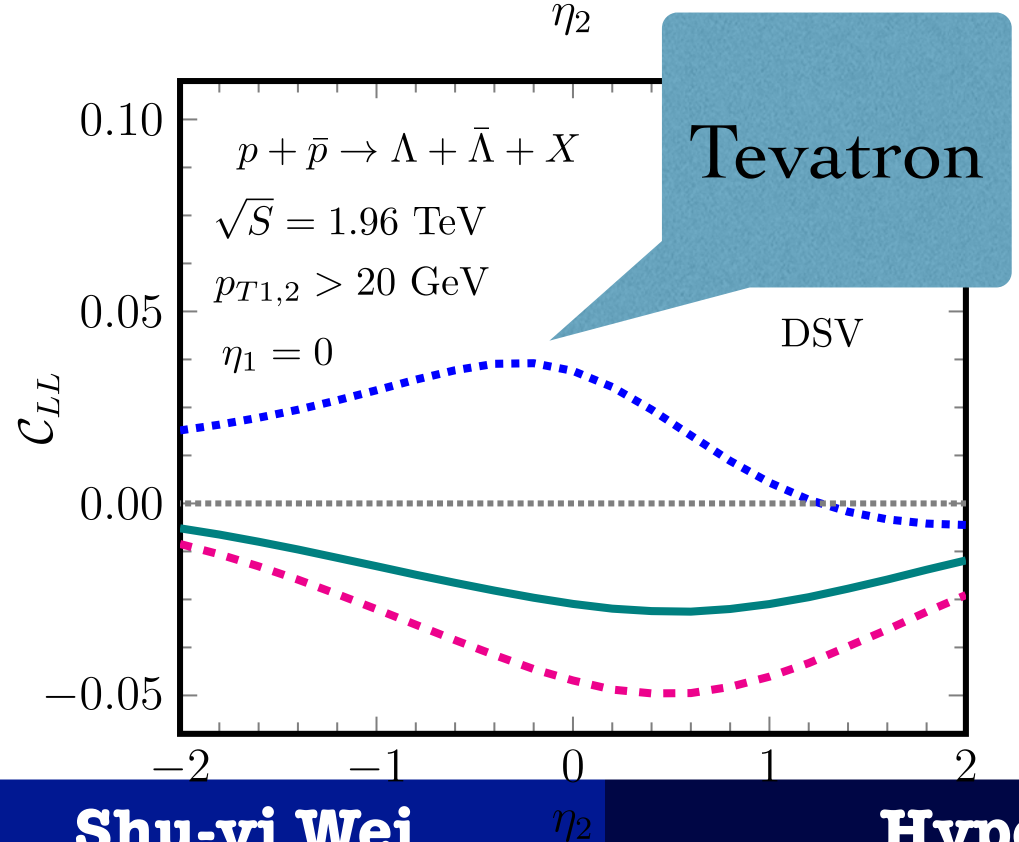


The ubiquitous Spin Correlation

Polarization Correlation in unpolarized pp collisions







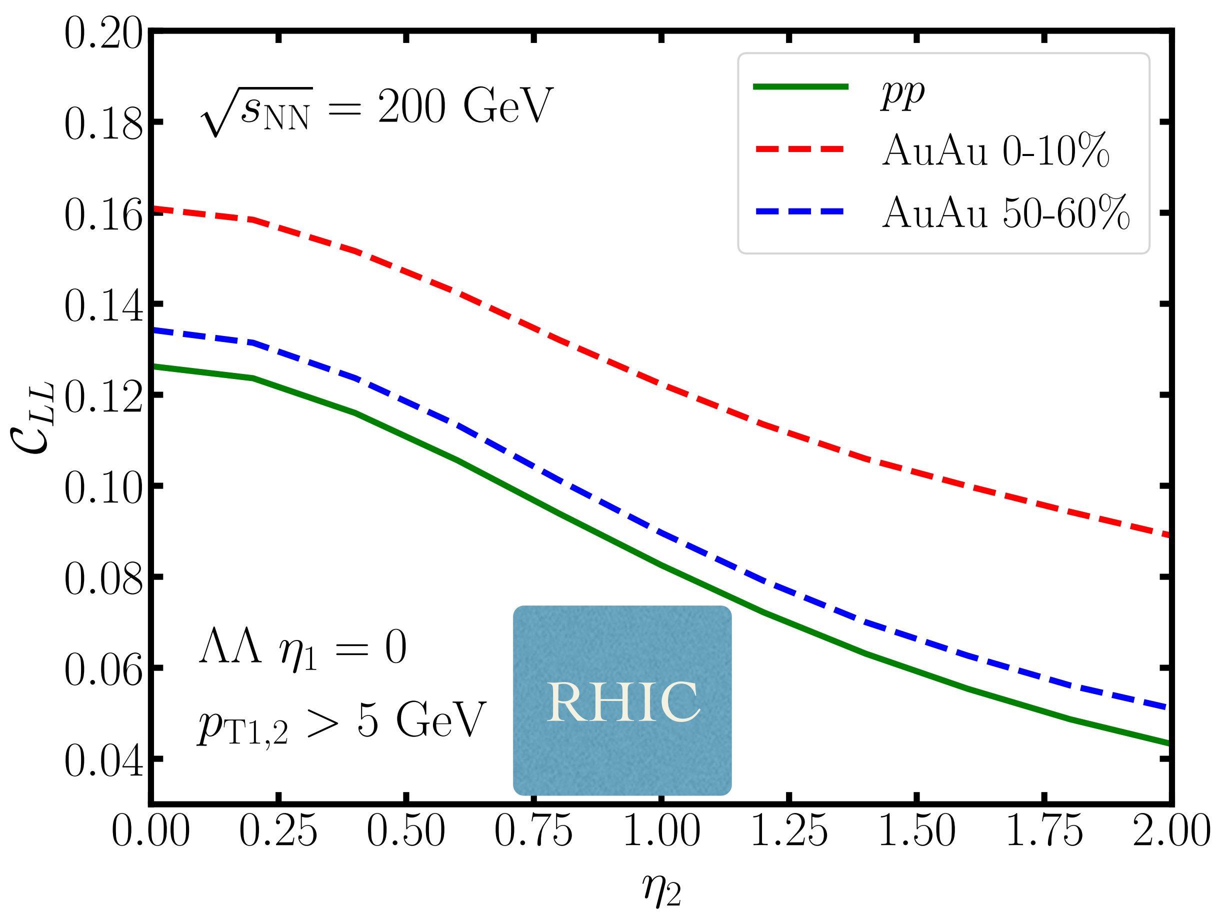
- ☑ Smaller, but none-zero
- ☑ Distinguish different scenarios
- ☑ Avoid contamination of polarized PDF
- ☑ Probe gluon spin transfer

H.C. Zhang, SYW, PLB 839 (2023) 137821

Helicity Correlation in central and peripheral AA collisions

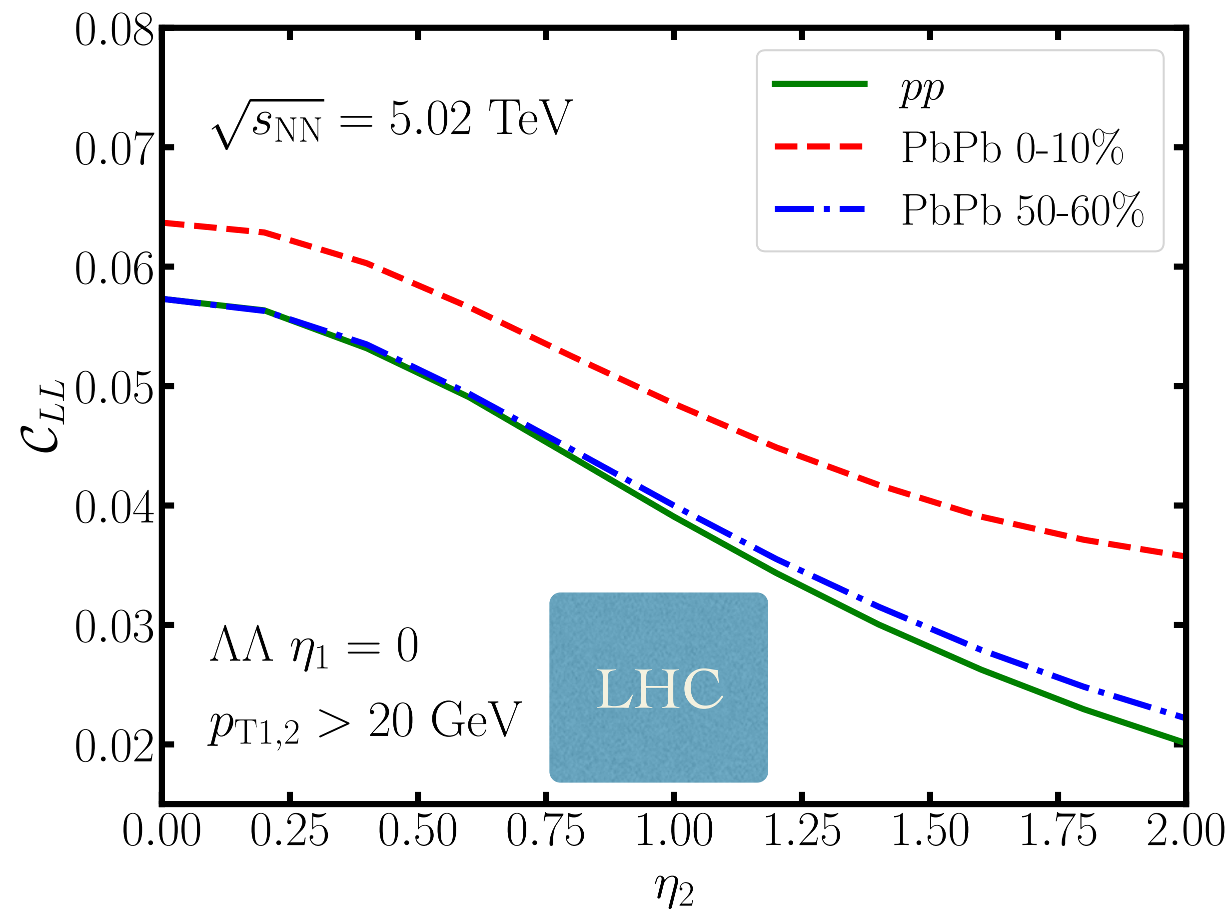
$$\text{A toy model: } \left.\frac{d\sigma}{d\mathrm{PS}}\right|_{AA} = \text{Energy Loss} \otimes \left.\frac{d\sigma}{d\mathrm{PS}}\right|_{pp}$$

X. Li, Z.X. Chen, S. Cao, S.Y. Wei;
Phys.Rev.D 109, 014035 (2024)



Clear Enhancement in central AA collisions

- ☑ Much larger luminosity
- ☑ Jet Quenching + Polarization



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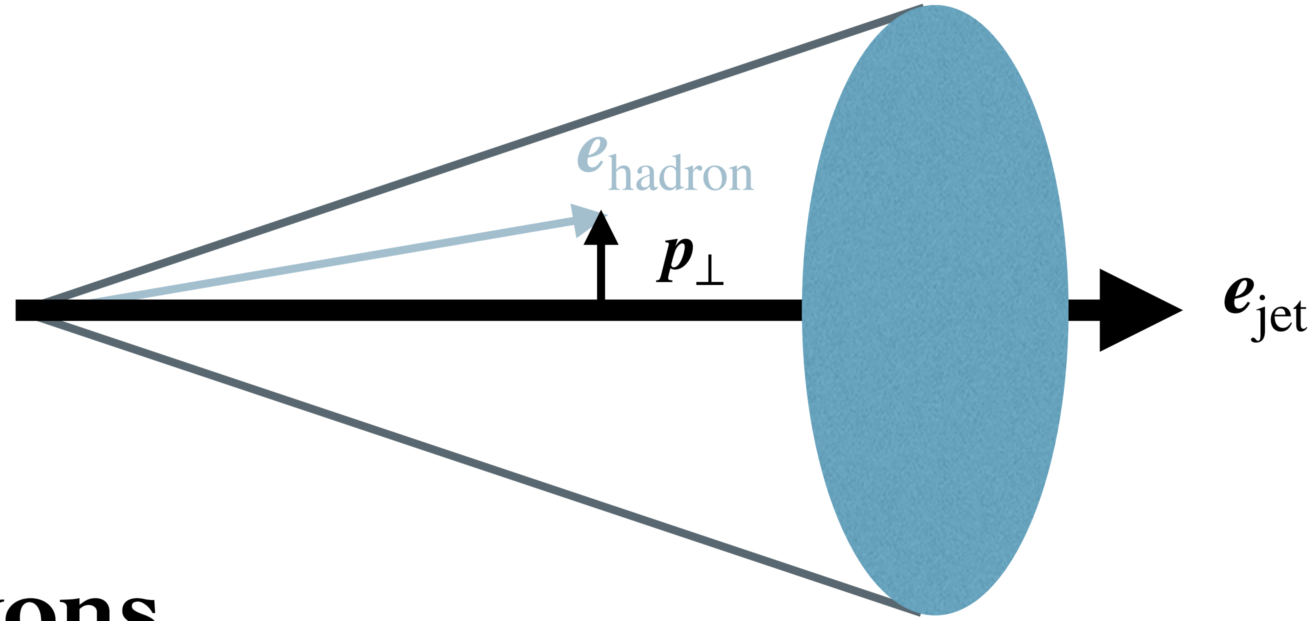
Hadron in Jet: TMD factorization

$$p_\perp \ll E_{\text{hadron}} \sim E_{\text{jet}}$$

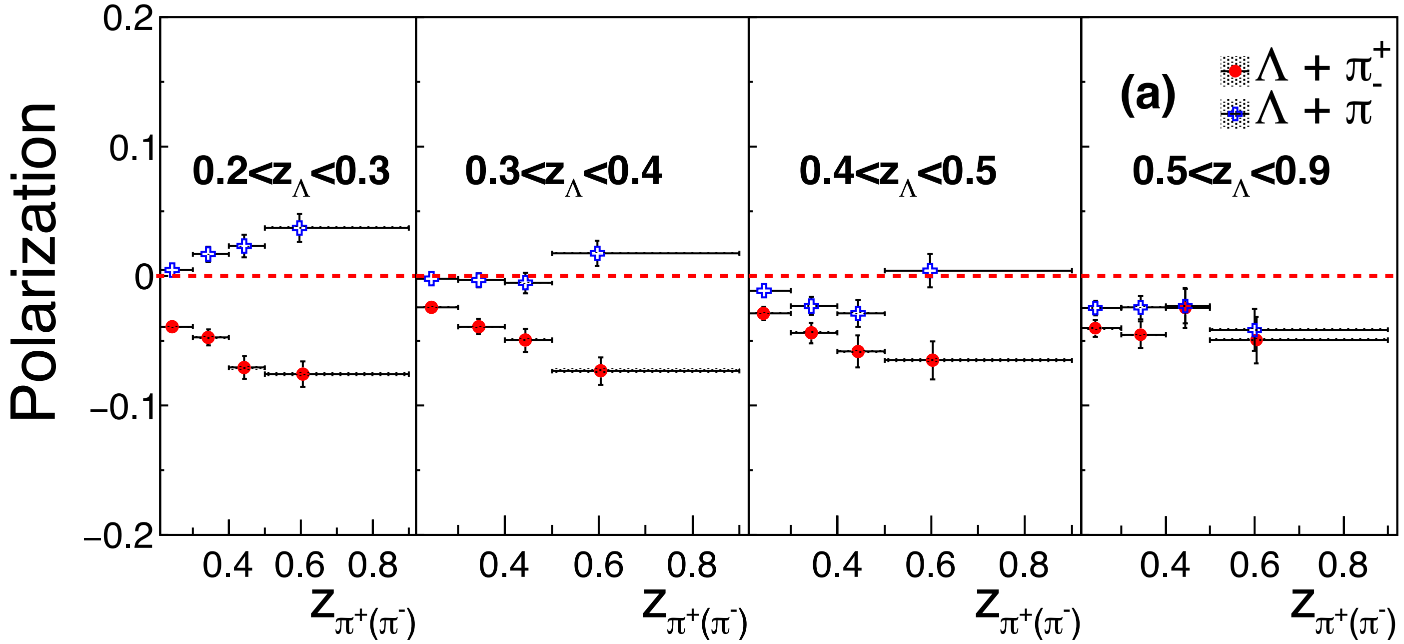


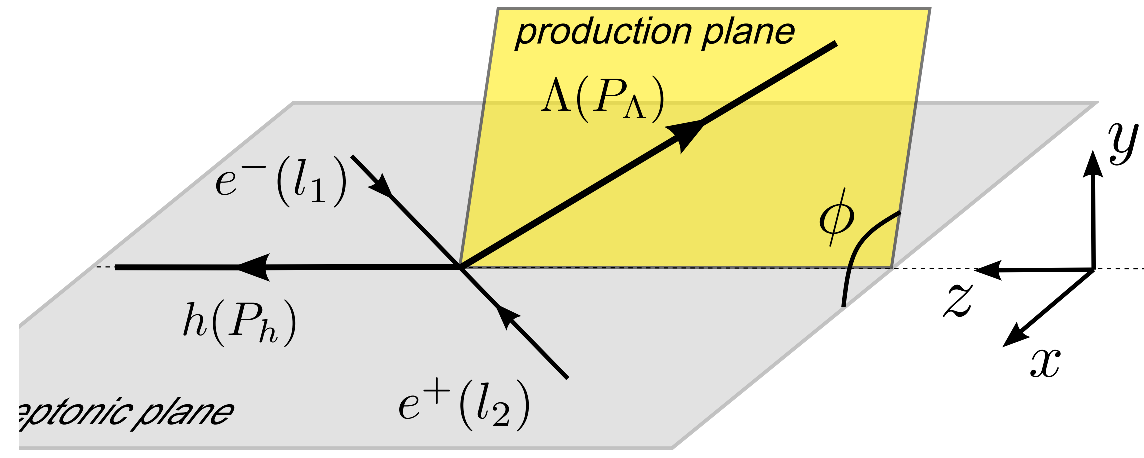
Baryons

Quarks	Unpolarized	L	T
Unpolarized	D_1		$D_{1T}^\perp$
L		G_{1L}	$G_{1T}^\perp$
T	H_1	H_{1L}	$H_{1T}, H_{1T}^\perp$

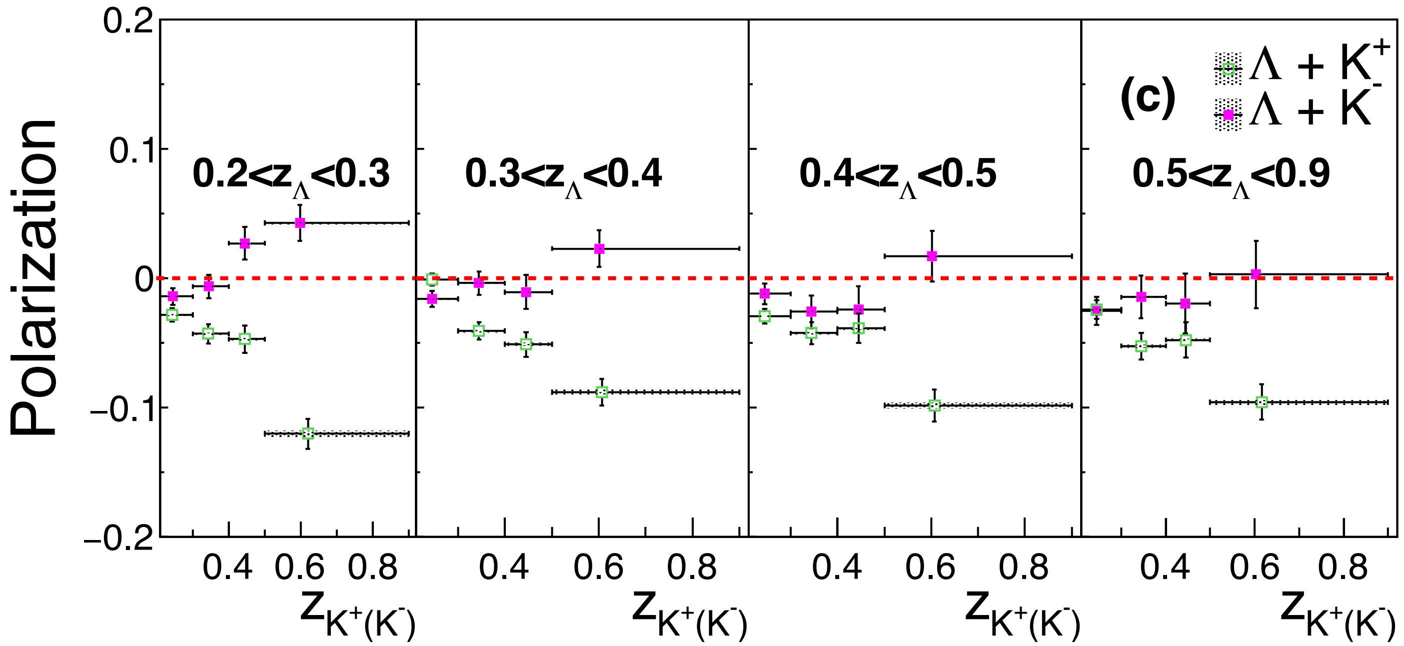
☑ $\boldsymbol{D_{1T}^\perp}$, Producing Transversely polarized hadron from unpolarized quark

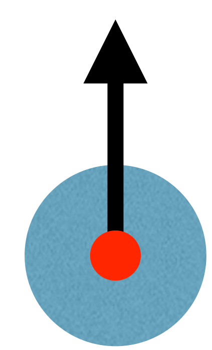
Transverse Polarization of Λ





$$\left[D_{1q}^{\Lambda}(z_\Lambda, p_T) + \frac{(\widehat{\boldsymbol{e}}_j \times \boldsymbol{p}_T)\cdot \boldsymbol{S}_{\Lambda\perp}}{z_\Lambda M_\Lambda} D_{1Tq}^{\perp\Lambda}(z_\Lambda, p_T)\right]$$

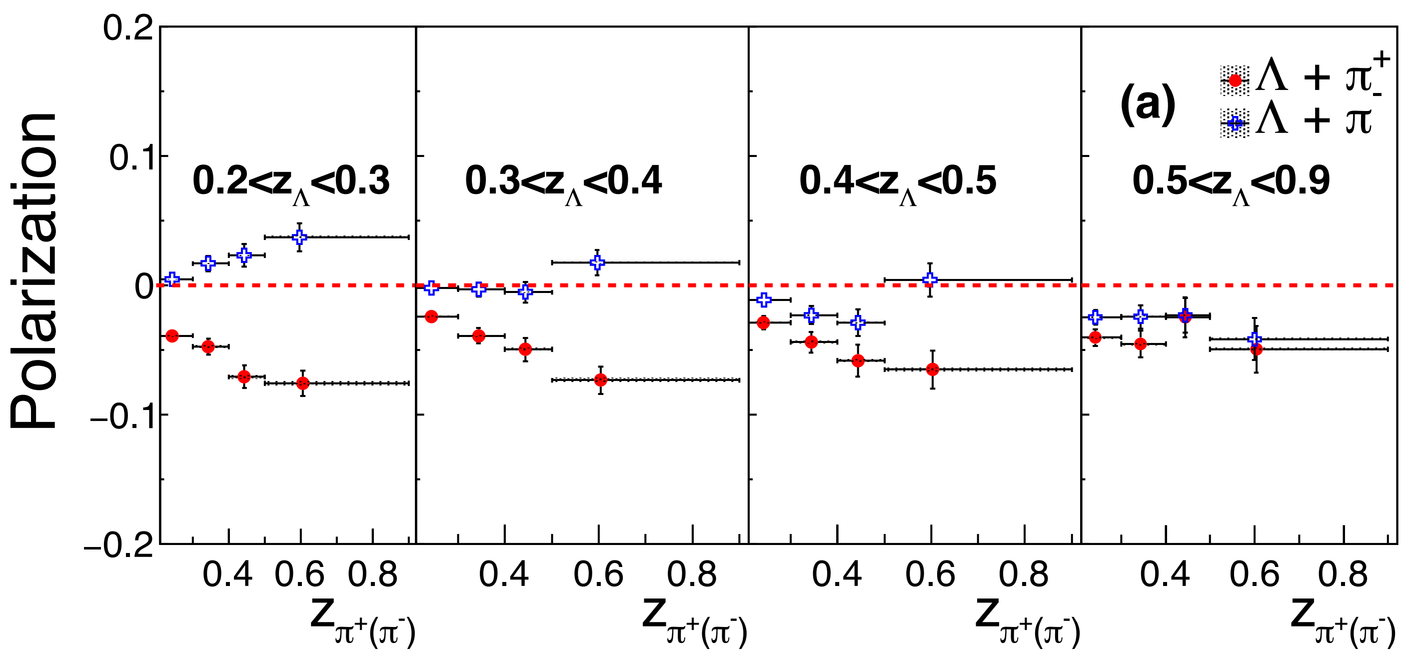


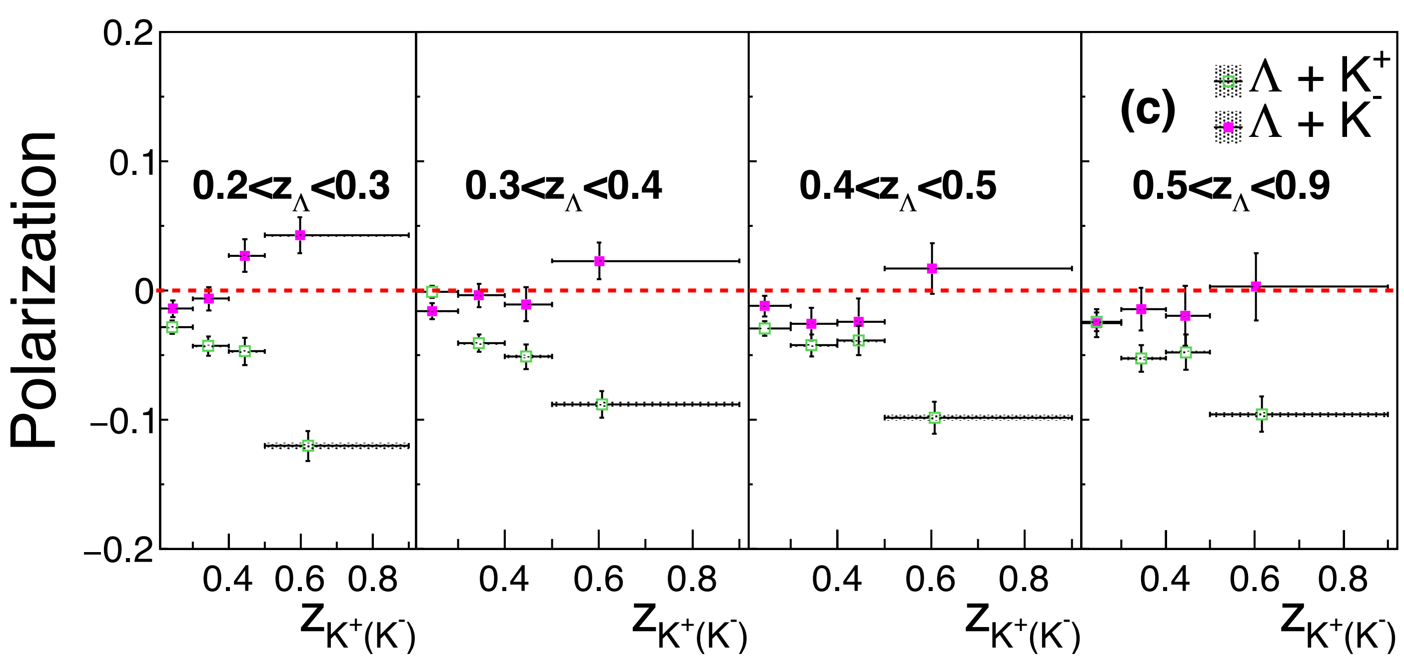


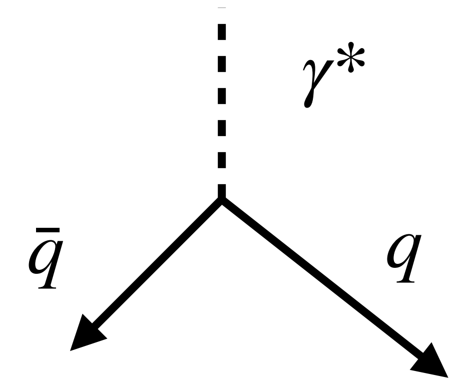
in analogue to Sivers function in TMD PDFs

[Belle], PRL122, 2019

Transverse Polarization of Λ







$\pi^+ : u\bar{d}; \quad d \to \Lambda$

$\pi^- : \bar{u}d; \quad u \to \Lambda$

$$D_{1T}^{\perp}(u) \neq D_{1T}^{\perp}(d)$$

$$D_{1T}^{\perp}(u) \neq D_{1T}^{\perp}(s)$$

$K^+ : u\bar{s}; \quad s \to \Lambda$

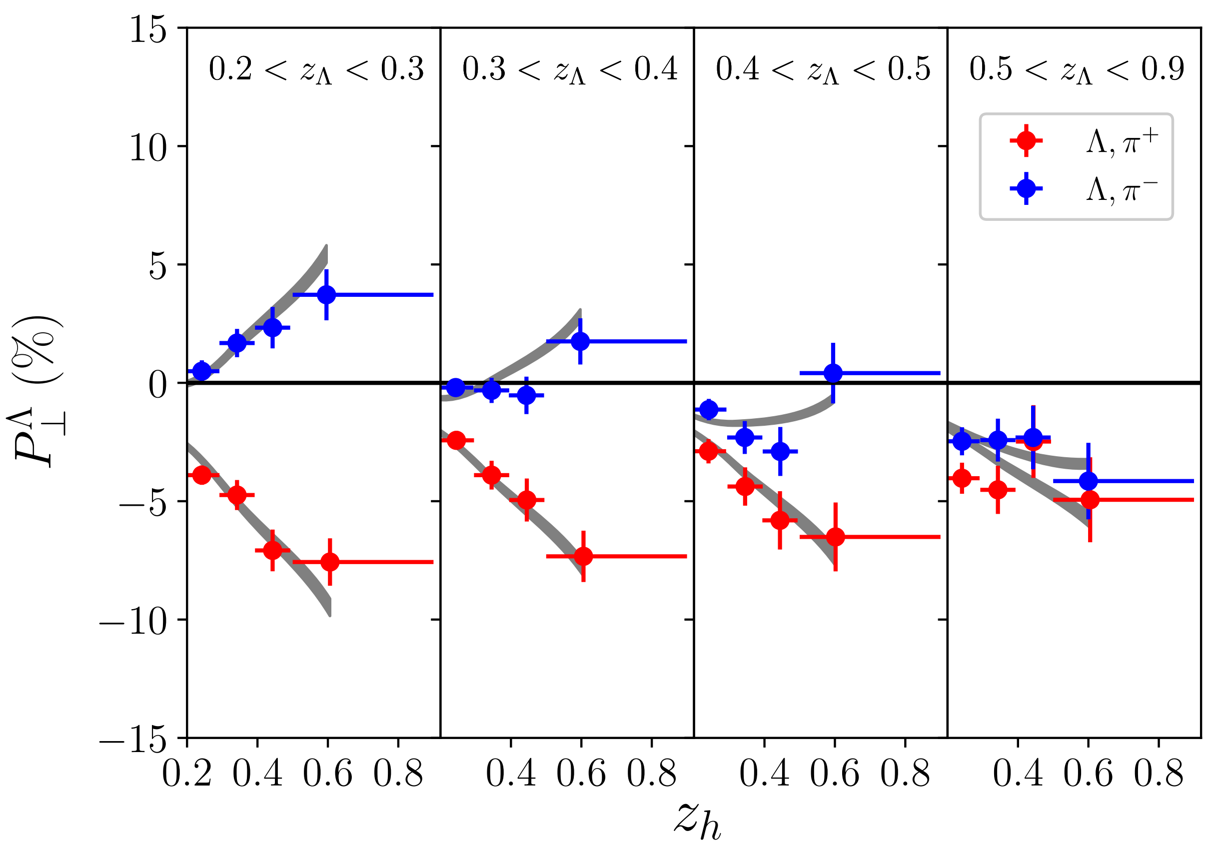
$K^- : \bar{u}s; \quad u \to \Lambda$

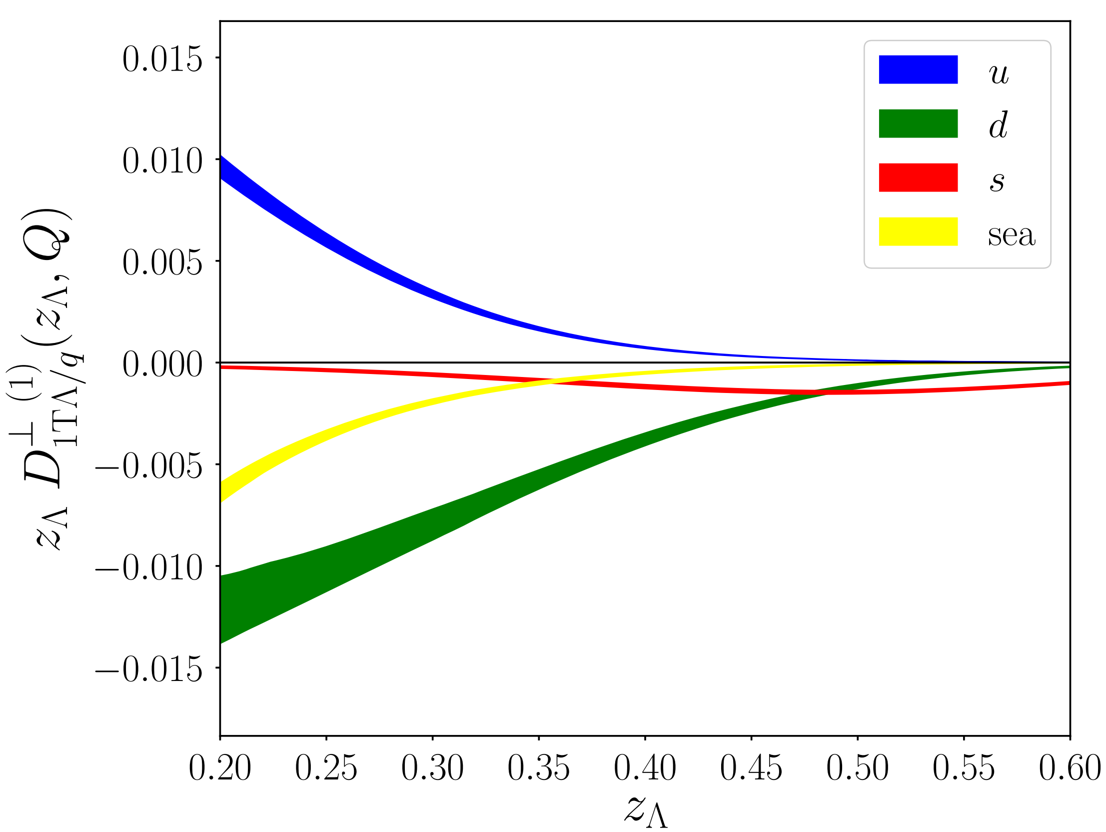
[Belle], PRL122, 2019

Transverse Polarization of Λ

differentiate valance quarks from sea quarks

$$D_{1T}^{\perp}(u) \neq D_{1T}^{\perp}(d) \neq D_{1T}^{\perp}(s) \neq D_{1T}^{\perp}(\text{sea})$$





Strong violation of isospin symmetry

Callos, Kang, Terry, PRD 102 (2020)

D'Alesio, Murgia, Zaccheddu, PRD 102 (2020)

Emerging Transverse Spin Polarization

Isospin Symmetry Robust symmetry in QCD

$$u \leftrightarrow d$$
$$\bar{u} \leftrightarrow \bar{d}$$

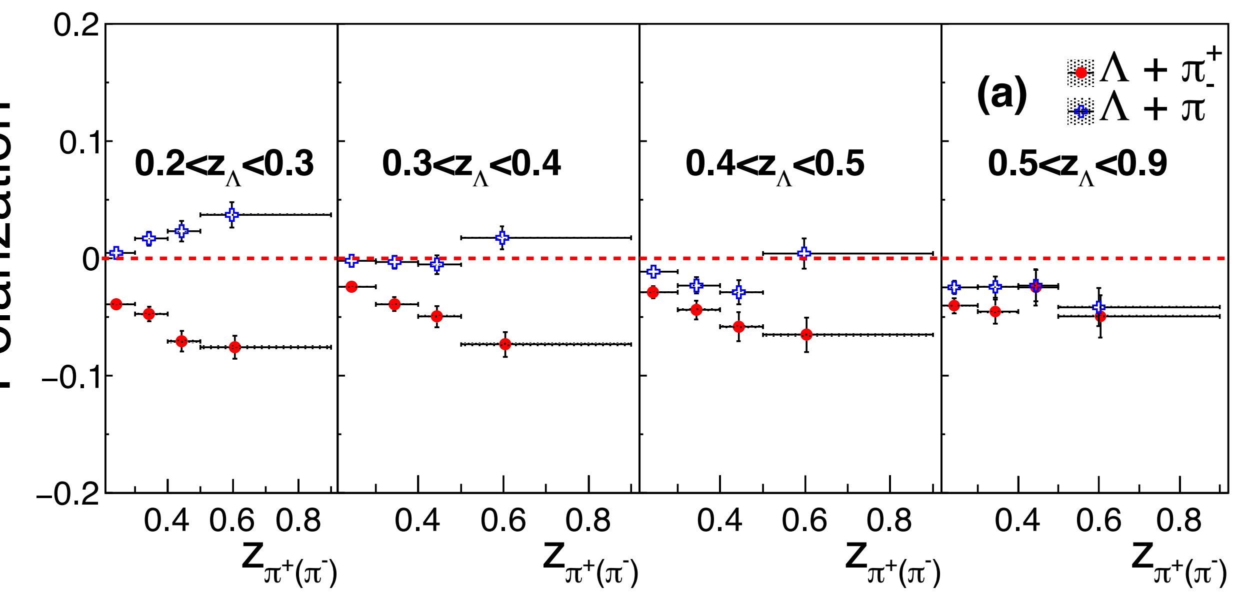
Example: proton (*uud*) ↔ neutron (*udd*)

$$f^u_{\text{proton}}(x) = f^d_{\text{neutron}}(x)$$
$$f^d_{\text{proton}}(x) = f^u_{\text{neutron}}(x)$$

isospin singlet

Lambda ↔ Lambda $\frac{1}{\sqrt{2}}(u^\uparrow d^\downarrow - u^\downarrow d^\uparrow)s^\uparrow$

$$D_{1T}^{\perp,u\to\Lambda}(z,p_T) = D_{1T}^{\perp,d\to\Lambda}(z,p_T)$$



- ☑ QED hard interaction
- ☑ QCD hadronization

Emerging Transverse Spin Polarization

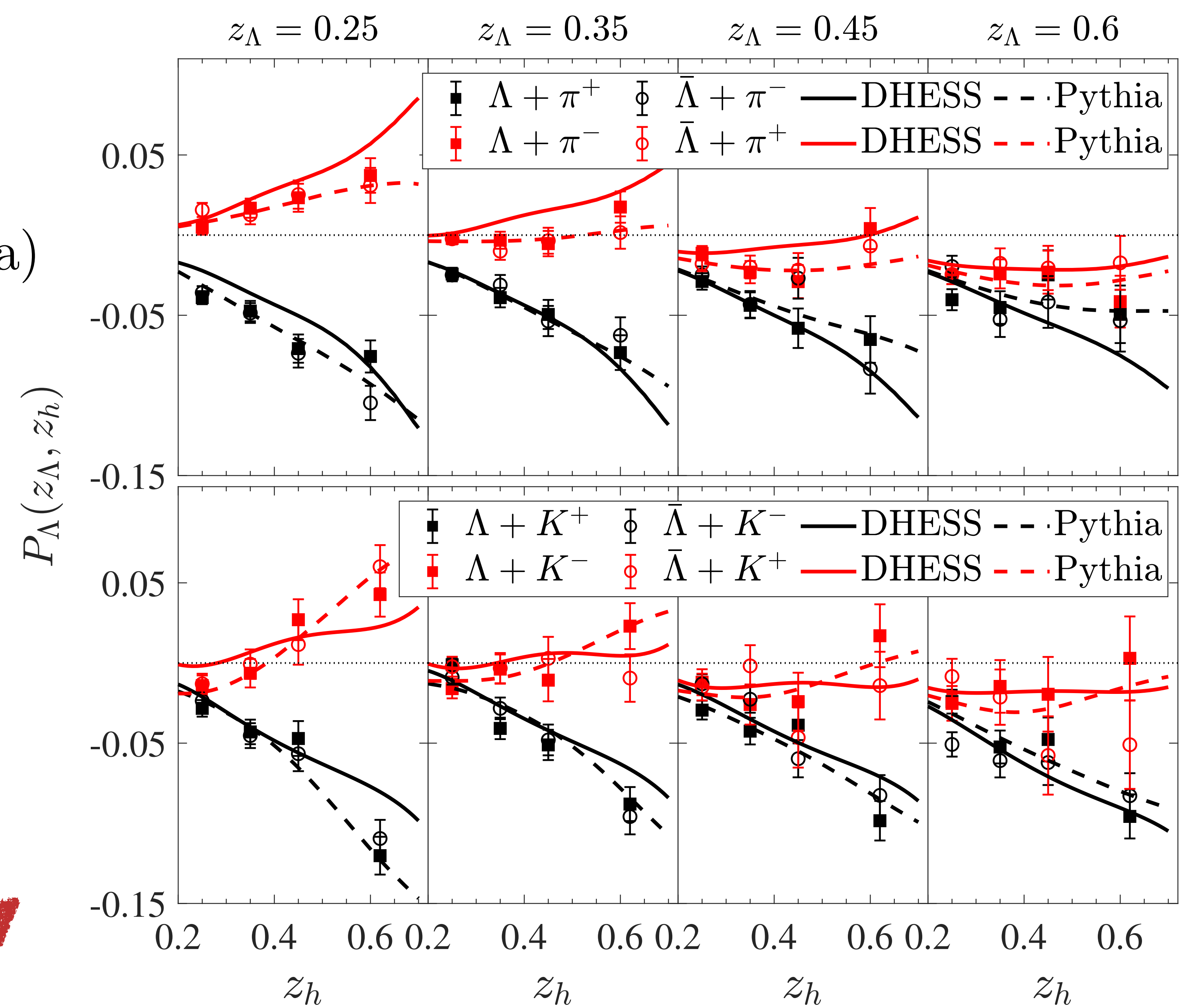
differentiate valance quarks from sea quarks

$$D_{1T}^{\perp}(u) \neq D_{1T}^{\perp}(d) \neq D_{1T}^{\perp}(s) \neq D_{1T}^{\perp}(\text{sea})$$

paradigm shift

enforce isospin symmetry

$$D_{1T}^{\perp}(u) = D_{1T}^{\perp}(d)$$
$$D_{1T}^{\perp}(\bar{u}) = D_{1T}^{\perp}(\bar{d})$$

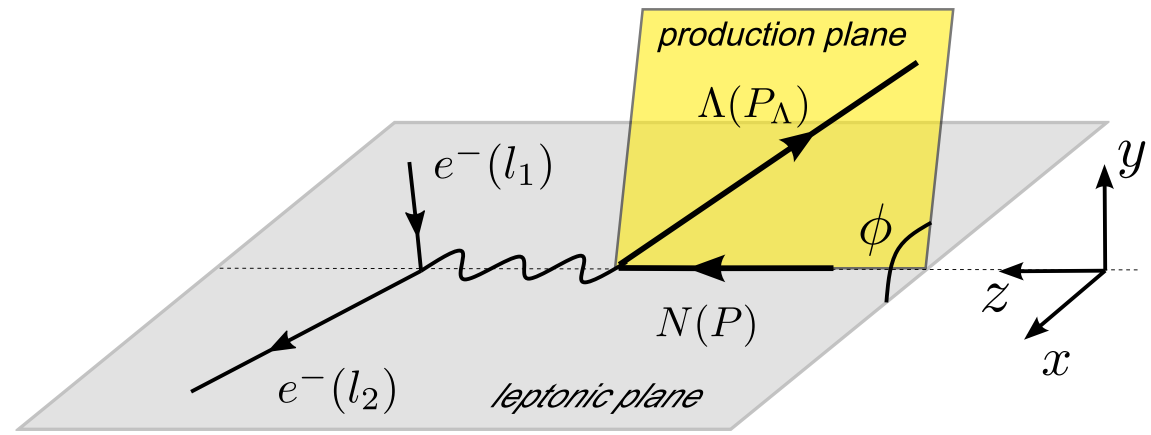


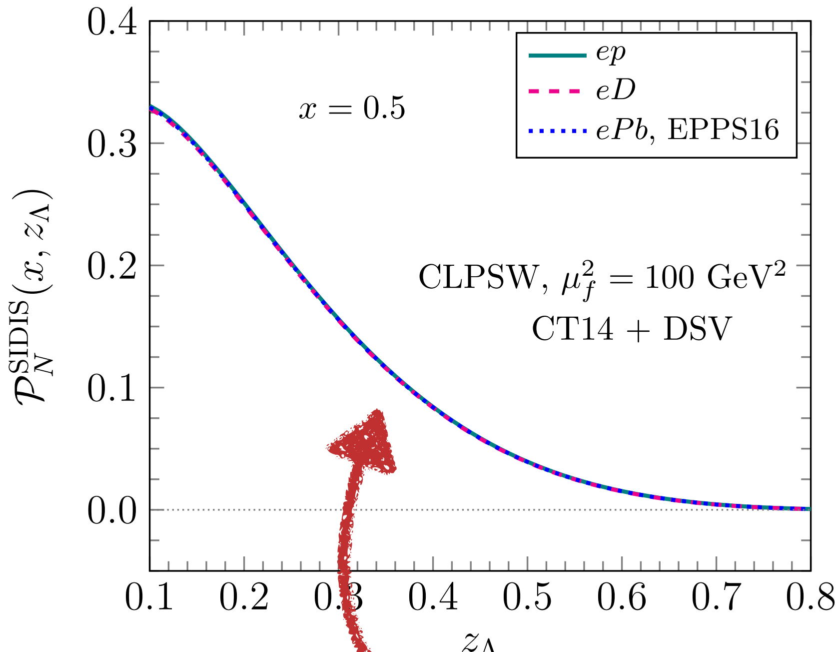
Belle data does not endorse isospin symmetry breaking.

Chen, Liang, Pan, Song, Wei, PLB816 (2021)

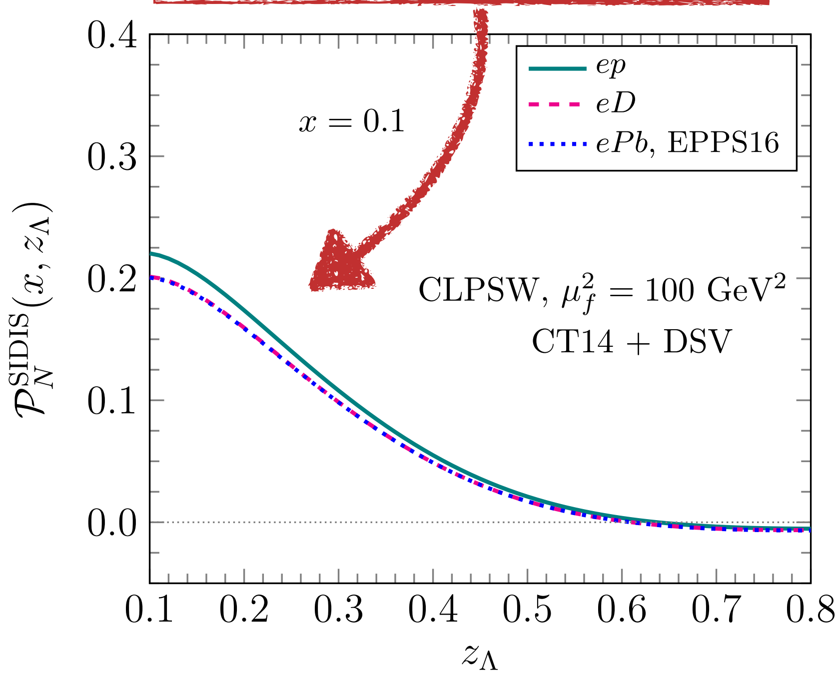
Emerging Transverse Spin Polarization

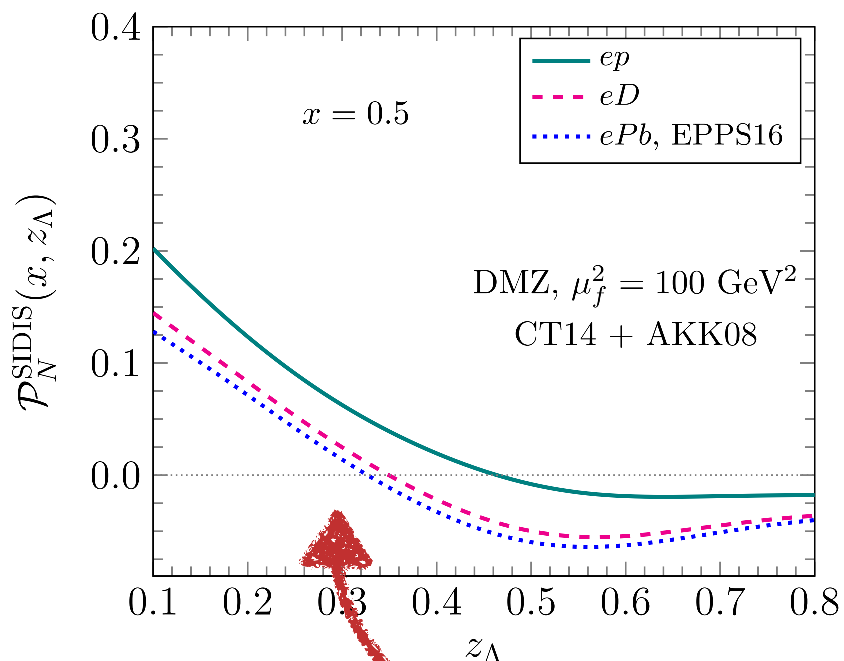
Testing Isospin Symmetry at EIC

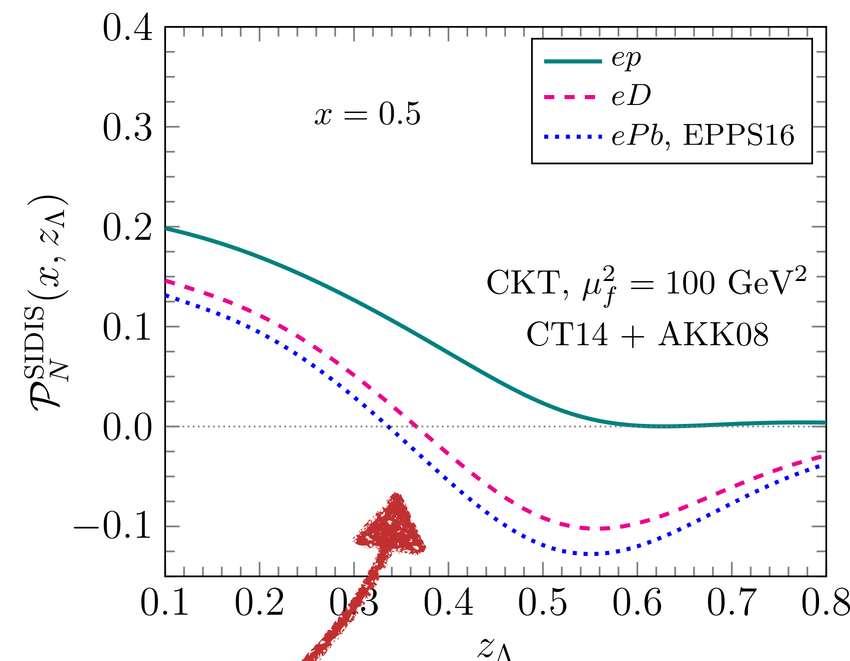




isospin symmetric







isospin-symmetry-violated parameterizations

Chen, Liang, Song, Wei, 2021

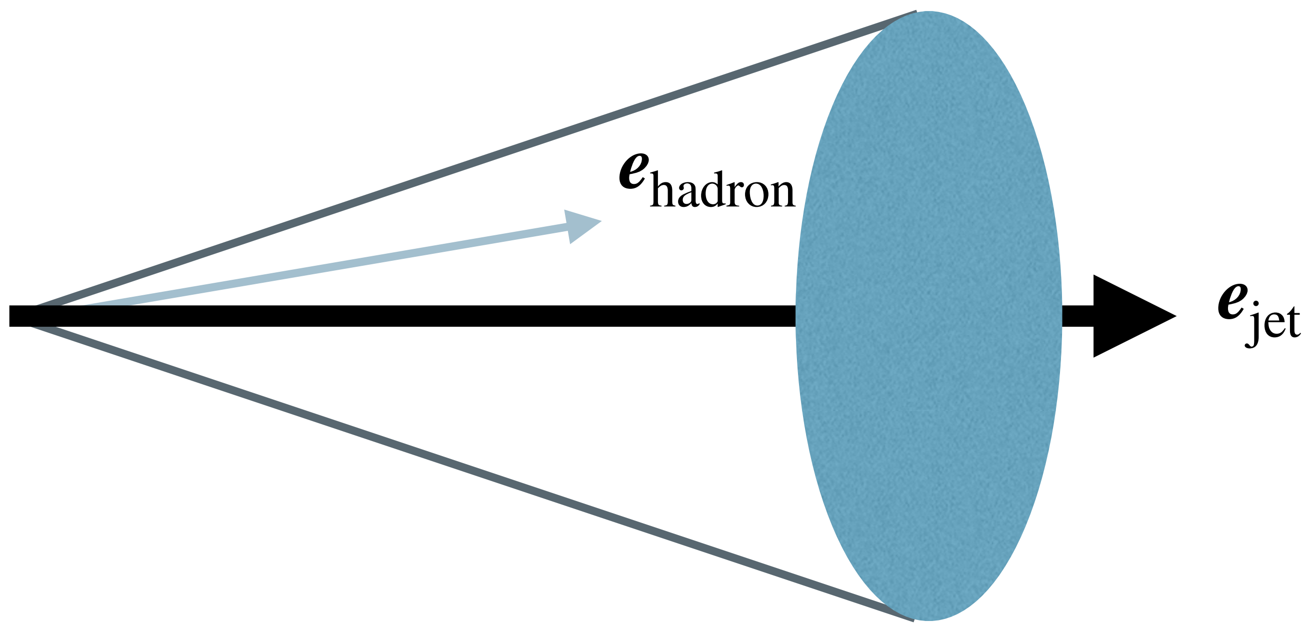
Emerging Transverse Spin Polarization

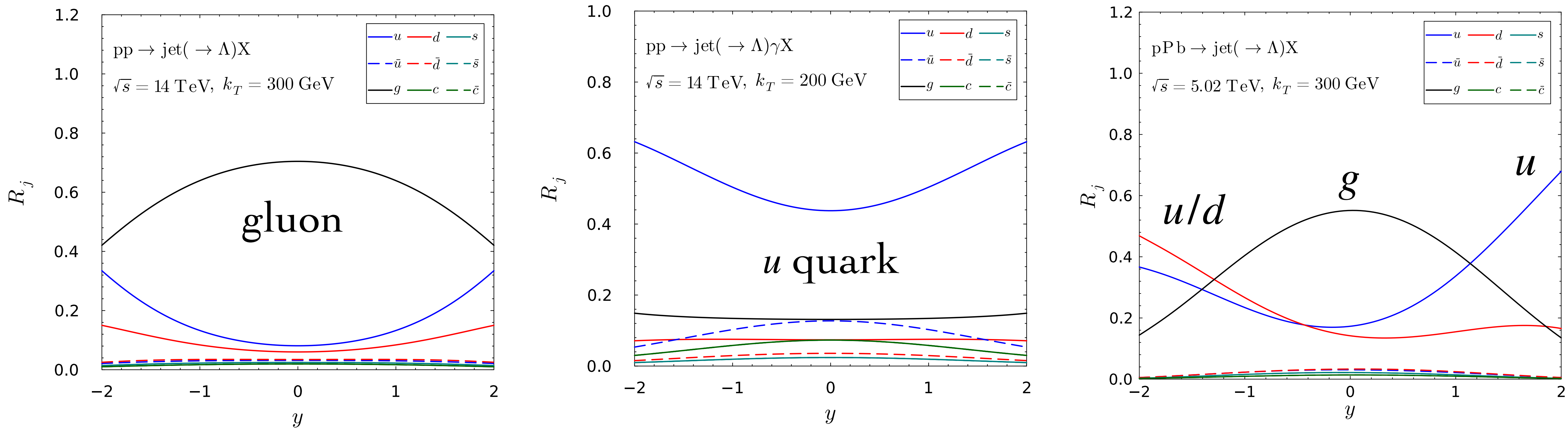
Hadron in Jet

measure the polarization of Λ along $\boldsymbol{e}_T = \boldsymbol{e}_{\rm jet} \times \boldsymbol{e}_{\rm hadron}$

arXiv:2403.06133

$$p + p \to \text{jet} + X$$
$$p + \bar{p} \to \text{jet} + X$$
$$p + A \to \text{jet} + X$$
$$p + p \to \text{jet} + \gamma + X$$
$$p + p \to \text{jet} + Z^0 + X$$
$$p + p \to \text{jet} + W^\pm + X$$





Emerging Transverse Spin Polarization

Hadron in Jet

$\boldsymbol{p}_\perp$: the relative transverse momentum of Λ momentum w.r.t. the jet momentum $\ll E_{\text{hadron}} \sim E_{\text{jet}}$

$\mathscr{P}_T$: the transverse polarization

$$\mathcal{P}_{T,\Lambda}(z,\boldsymbol{p}_\perp) = \frac{\mathcal{D}_{q\to\Lambda^\uparrow}(z,\boldsymbol{p}_\perp) - \mathcal{D}_{q\to\Lambda^\downarrow}(z,\boldsymbol{p}_\perp)}{\mathcal{D}_{q\to\Lambda^\uparrow}(z,\boldsymbol{p}_\perp) + \mathcal{D}_{q\to\Lambda^\downarrow}(z,\boldsymbol{p}_\perp)} = \frac{\frac{|\boldsymbol{p}_\perp|}{zM_\Lambda} D^\perp_{1T,\Lambda/q}(z,\boldsymbol{p}_\perp)}{D_{1,\Lambda/q}(z,\boldsymbol{p}_\perp)}$$

pp:
CSS evolution

$$\widetilde{D}^{\text{vac}}_{1,\Lambda/q}(z,b_T,Q) = \frac{1}{z^2} d_{1,\Lambda/q}(z,\mu_b)\exp\left[-S_p - S_{np}\right],$$

$$\widetilde{D}^{\perp(1),\text{vac}}_{1T,\Lambda/q}(z,b_T,Q) = \frac{1}{z^2}\frac{\langle M_D^2\rangle}{2M_\Lambda^2} d^\perp_{1T,\Lambda/q}(z,\mu_b)\exp\left[-S_p - S^\perp_{np}\right],$$

AA:
energy loss;
p_T-broadening

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

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

energy loss

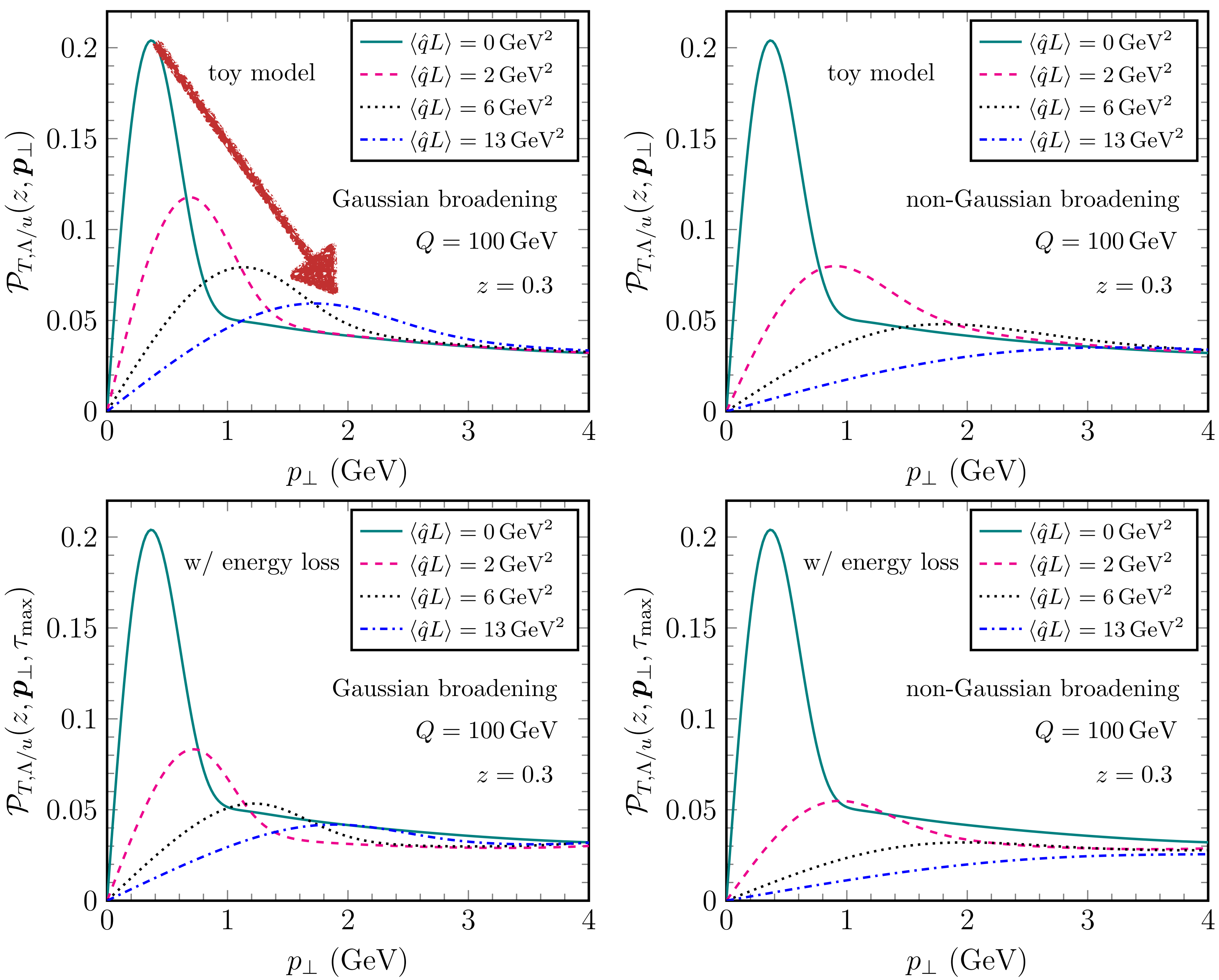
p_T-broadening

Emerging Transverse Spin Polarization

Hadron in Jet

$\boldsymbol{p}_\perp$: the relative transverse momentum of Λ momentum w.r.t. the jet momentum $\ll E_{\text{hadron}} \sim E_{\text{jet}}$

$\mathscr{P}_T$: the transverse polarization



The peak position is altered due to $p_\perp$ broadening

arXiv:2504.00739

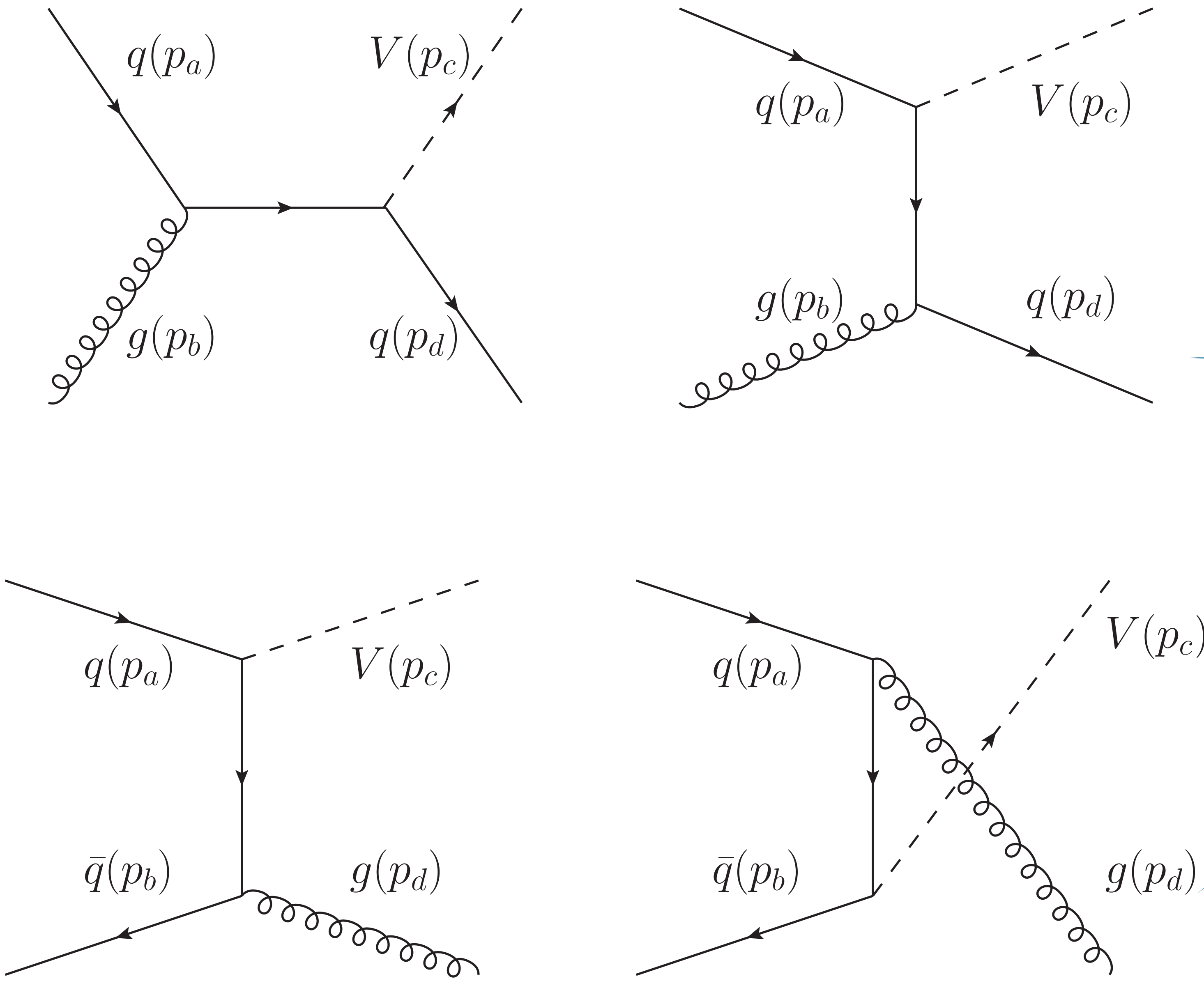
Contents

See Wen-Hao Yao's poster (A1)

Z/W-associated Jet Production

Parity is violated in weak interaction

See Wen-Hao Yao's poster (A1)



Polarized!

Z/W-associated Jet Production

Different Energy Loss Mechanisms

Single Hard Branching:

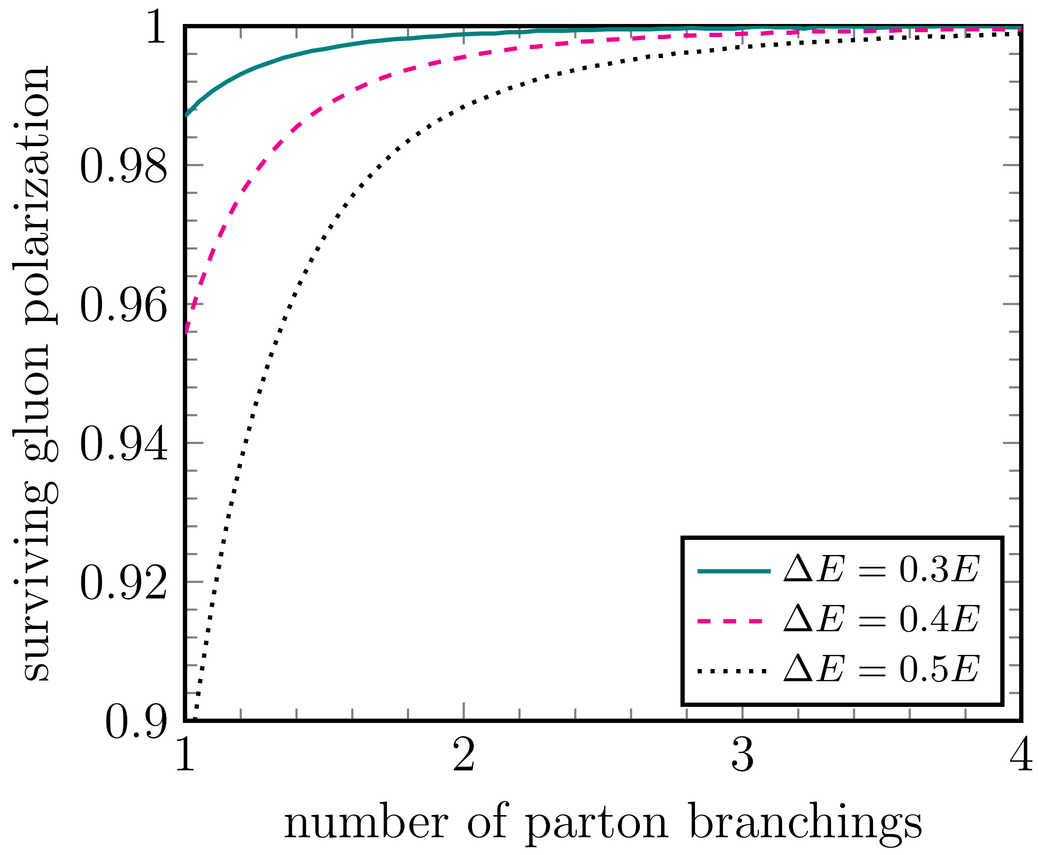
$$G_{1L,q/\bar{q}}^{\mathrm{med}}(z_d)\Big|_{\mathrm{SHB}} = \int \frac{d\xi}{\xi^2}\xi\delta\left(\xi - \frac{k_T}{k_T+\Delta E_T}\right) G_{1L,q\bar{q}}^{\mathrm{vac}}\left(\frac{z_d}{\xi}\right),$$

$$G_{1L,g}^{\mathrm{med}}(z_d)\Big|_{\mathrm{SHB}} = \int \frac{d\xi}{\xi^2}\xi\delta\left(\xi - \frac{k_T}{k_T+\Delta E_T}\right) \frac{\xi[1-\xi(1-\xi)+(1-\xi)^2]}{[1-\xi(1-\xi)]^2} G_{1L,g}^{\mathrm{vac}}\left(\frac{z_d}{\xi}\right).$$

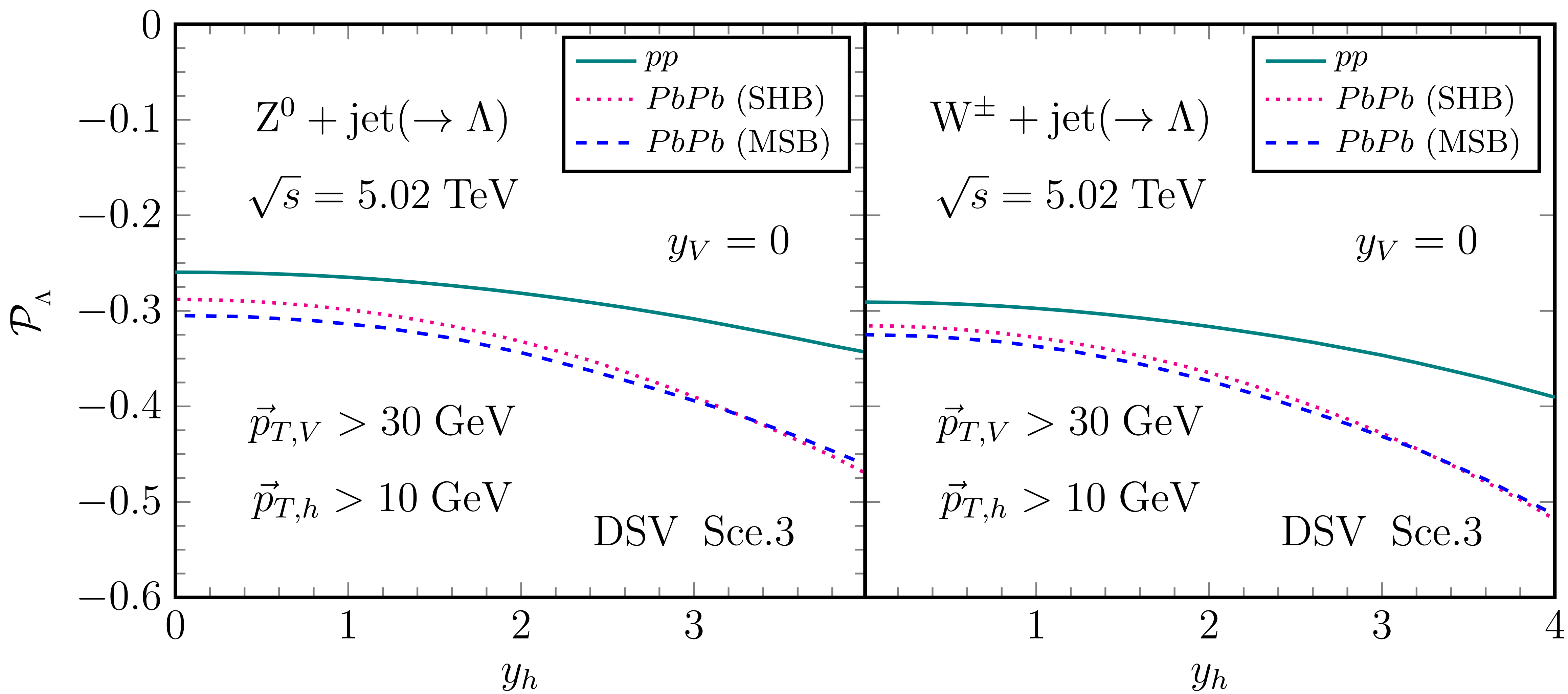
spin loss of the circularly polarized gluon

Multiple Soft Branchings:

$$G_{1L,d}^{\mathrm{med}}(z_d)\Big|_{\mathrm{MSB}} = \int \frac{d\xi}{\xi^2} C_{dd}(\xi,\tau_{\max}) G_{1L,d}^{\mathrm{vac}}\left(\frac{z_d}{\xi}\right)$$



Numerical Results



Preliminary

Summary

- ☑ Spin polarization can be studied in unpolarized collisions

- ☑ It is a novel probe of jet quenching.

Thanks for your attention!

The End