Probing the polarized fragmentation function in unpolarized pp and AA collisions at the LHC

Shu-yi Wei (魏树一)

Shandong University

shuyi@sdu.edu.cn

H.C. Zhang, S.Y. Wei; Physics Letters B 839 (2023) 137821

X.W. Li, Z.X. Chen, S. Cao, S.Y. Wei, arXiv:2309.09487

Contents

Introduction

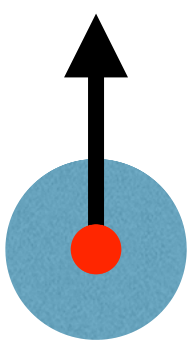
QCD factorization

partonic interaction, perturbative

$$\text{Cross Section} = \text{short distance} \otimes \text{long distance}$$

non-perturbative, universal

TMD PDFs: $\mathcal{FT}\langle p|\bar{\psi}(0)\psi(x^-,\vec{x}_\perp)|p\rangle$



$$\slashed{n}_+\left[f_1 - \frac{(\widehat{\boldsymbol{e}}_p \times \boldsymbol{k}_T)\cdot \boldsymbol{S}_\perp}{M} f_{1T}^\perp\right] + \gamma_5\slashed{n}_+\left[\lambda g_{1L} + \frac{k_T\cdot S_\perp}{m} g_{1T}^\perp\right] + \frac{i[\slashed{k}_T,\slashed{n}_+]}{2m} h_1^\perp + \frac{1}{2}[\slashed{S}_\perp,\slashed{n}_+]\gamma_5 h_{1T} + \frac{[\slashed{k}_T,\slashed{n}_+]\gamma_5}{2m}\left[\lambda h_{1L}^\perp + \frac{k_T\cdot S_\perp}{m} h_{1T}^\perp\right]$$

TMD FFs: $\mathcal{FT}\langle 0|\psi(0)|hX\rangle\langle hX|\bar{\psi}(x^-,\vec{x}_\perp)|0\rangle$

$$\slashed{n}_-\left[D_1 + \frac{(\widehat{\boldsymbol{e}}_j \times \boldsymbol{p}_T)\cdot \boldsymbol{S}_\perp}{zM} D_{1T}^\perp\right] + \gamma_5\slashed{n}_-\left[\lambda G_{1L} + \frac{p_T\cdot S_\perp}{zM} G_{1T}^\perp\right] + \frac{i[\slashed{p}_T,\slashed{n}_-]}{2M} H_1^\perp + \frac{1}{2}[\slashed{S}_\perp,\slashed{n}_-]\gamma_5 H_{1T} + \frac{[\slashed{p}_T,\slashed{n}_-]\gamma_5}{2M}\left[\lambda H_{1L}^\perp + \frac{p_T\cdot S_\perp}{M} H_{1T}^\perp\right]$$

QCD factorization

Baryons

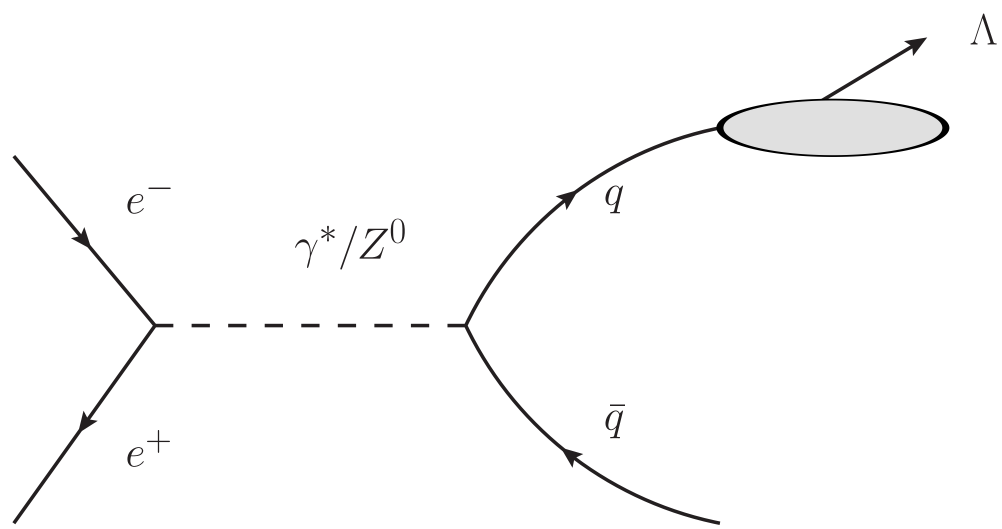
Quarks	Unpolarized	L	T
Unpolarized	D_1		$D_{1T}^{\perp}$
L		G_{1L}	$G_{1T}^{\perp}$
T	H_1	H_{1L}	$H_{1T}, H_{1T}^{\perp}$

polarized beams
or
weak interaction

☑ **G_{1L}, aka, the longitudinal spin transfer**

Number density of longitudinally polarized hadrons produced from longitudinally polarized quarks.

Single Inclusive Λ Production in e⁺e⁻ Annihilation Experiment



Final state quarks gain polarization through weak interaction

γ^* Z^0

$$\frac{d\sigma}{dPS} = \sigma_0 \left[D_{1q}^{\Lambda}(z) + \lambda_q P_L^{\Lambda} G_{1Lq}^{\Lambda}(z) \right]$$

Belle Energy

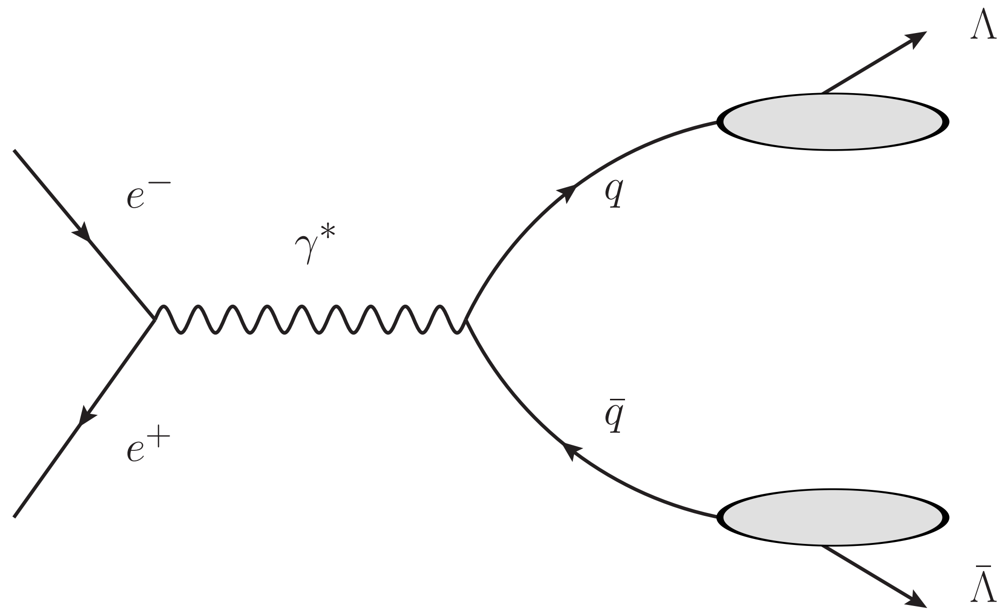
LEP Energy

spin transfer

$$P_L^{\Lambda} = \lambda_q \frac{G_{1Lq}^{\Lambda}}{D_{1q}^{\Lambda}}$$

quark polarization

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



Belle Energy

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

- ☑ **Helicity Conservation**

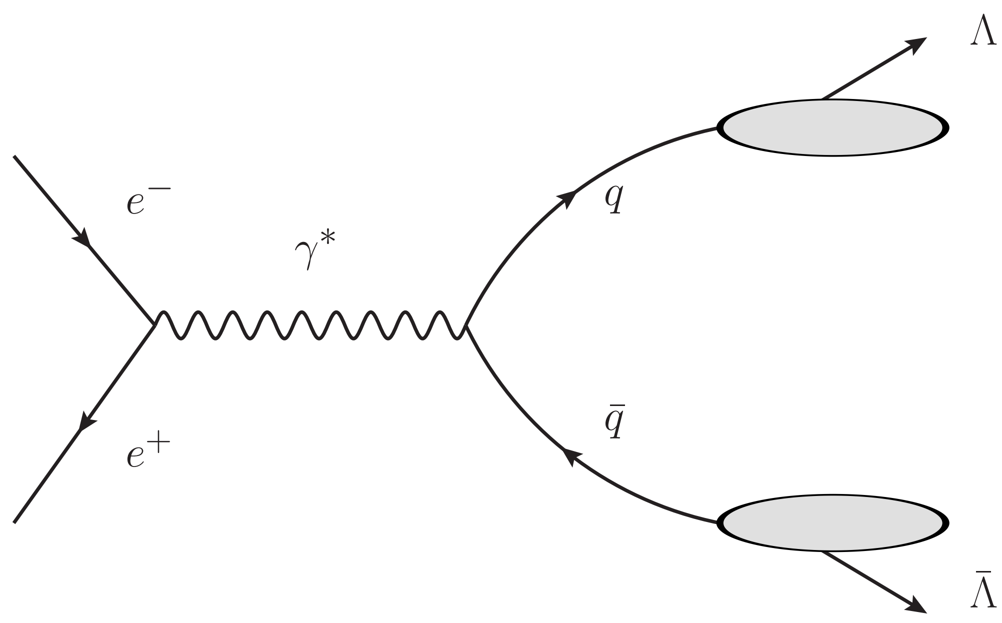
  q and $\bar{q}$ are on the same fermi line. They must have opposite helicities.

- ☑ **Polarization Correlation**

  A novel probe to the spin-dependent fragmentation functions

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

Helicity Amplitude Approach



$\sigma_{\lambda_q \lambda_{\bar{q}}}$ denotes the differential X of $q\bar{q}$-pair production

$$\sigma_{+-} = \sigma_{-+} = \sigma_0/2$$
$$\sigma_{++} = \sigma_{--} = 0$$

$\mathscr{D}$ denotes the helicity dependent fragmentation function

$$\mathscr{D}(\lambda_q, \lambda_\Lambda, z) = D_{1q}(z) + \lambda_q P_L^\Lambda G_{1Lq}(z)$$

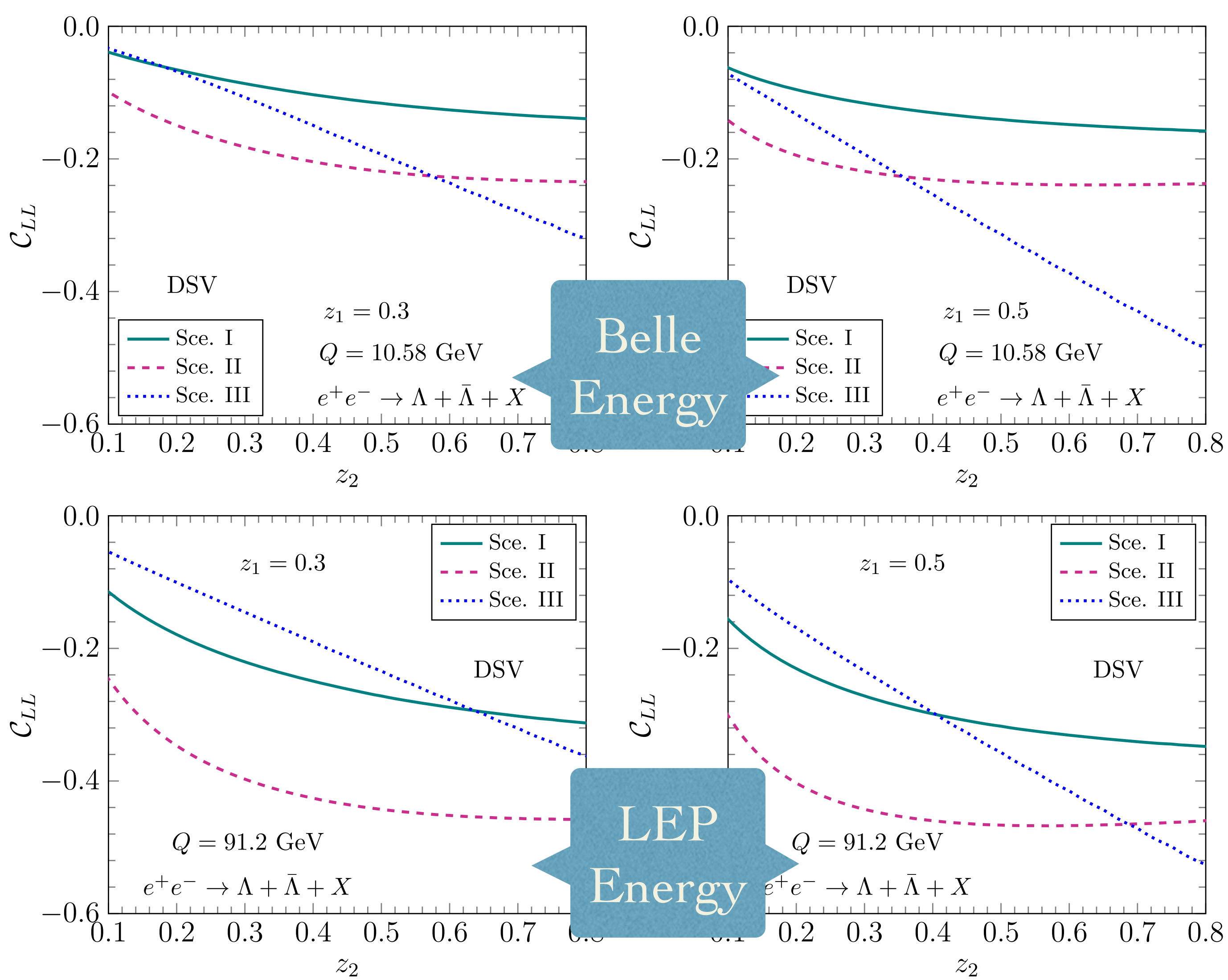
Physical interpretation:

$$\frac{d\sigma}{dPS} = \sigma_{+-} \otimes \mathscr{D}_q(+, \lambda_\Lambda, z_1) \otimes \mathscr{D}_{\bar{q}}(-, \lambda_{\bar{\Lambda}}, z_2) + \sigma_{-+} \otimes \mathscr{D}_q(-, \lambda_\Lambda, z_1) \otimes \mathscr{D}_{\bar{q}}(+, \lambda_{\bar{\Lambda}}, z_2)$$
$$= \sigma_0 \left[D_{1q}^\Lambda(z_1) D_{1\bar{q}}^{\bar{\Lambda}}(z_2) - P_L^\Lambda P_L^{\bar{\Lambda}} G_{1Lq}^\Lambda(z_1) G_{1L\bar{q}}^{\bar{\Lambda}}(z_2) \right]$$

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

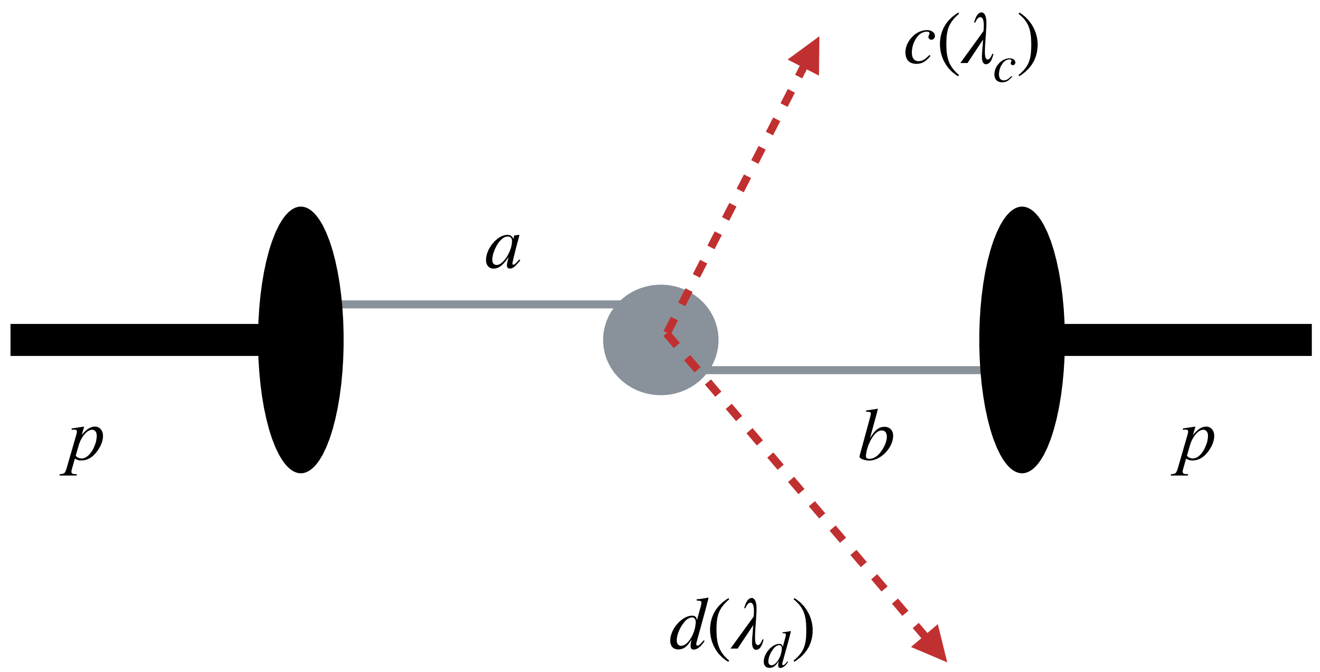
Polarization Correlation of $\Lambda\bar{\Lambda}$-pair

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



- ☑ The polarization correlation at the Belle energy has a similar magnitude with that at the LEP energy.
- ☑ It is now possible to extract the longitudinal spin transfer at Belle experiment.

Applying to the unpolarized pp collisions

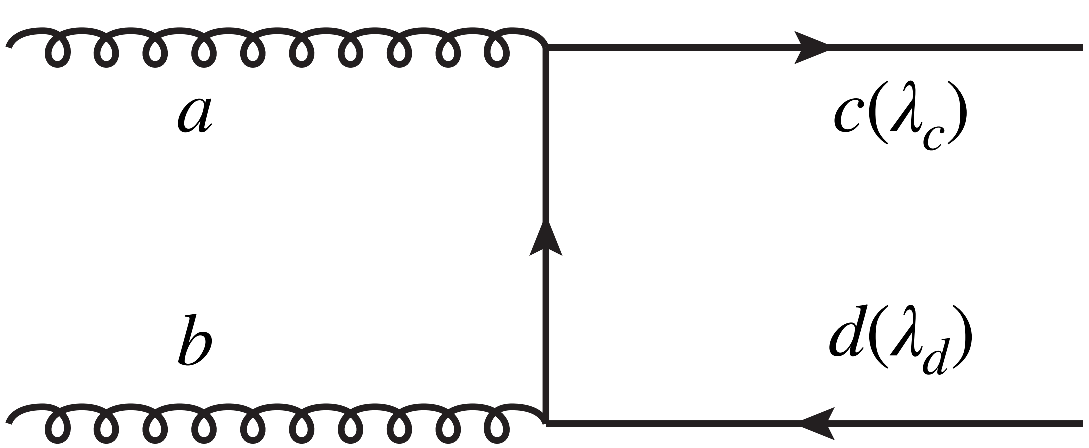


$$a + b \to c(\lambda_c) + d(\lambda_d)$$

☑ **Are λ_c and λ_d correlated?**

Yes!

s-channel diagrams: just like e^+e^- annihilation, maximum correlation

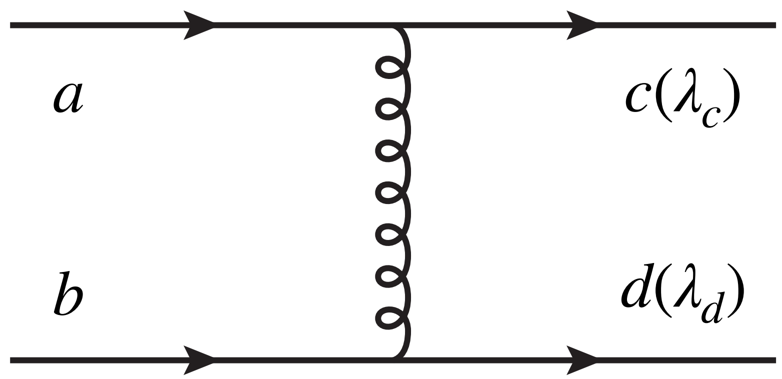


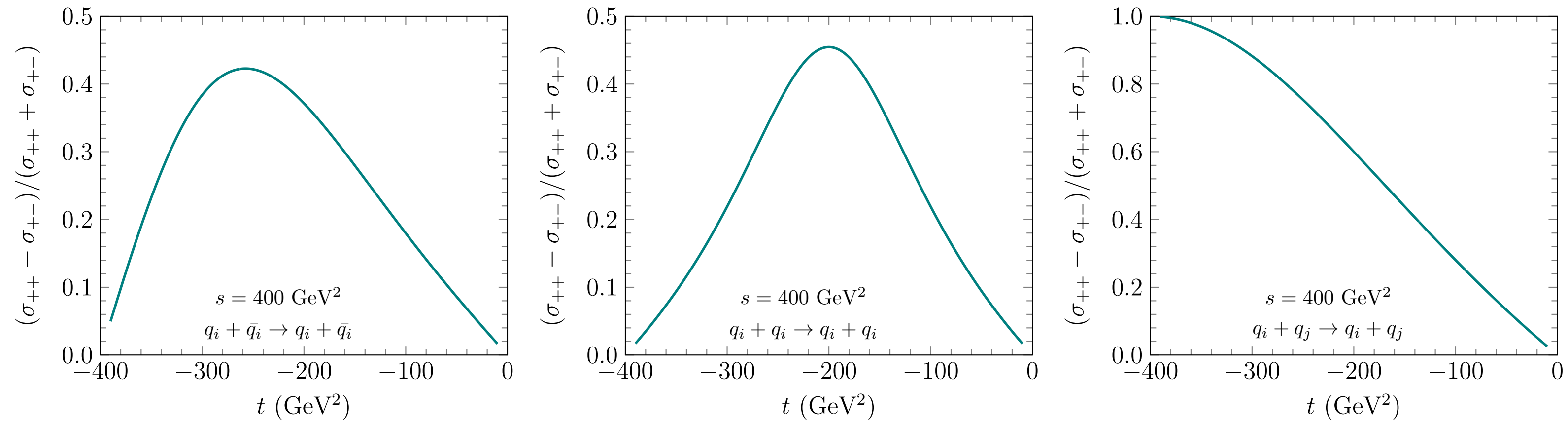
$$g + g \to q + \bar{q}$$

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

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

t-channel diagrams: prefer same-sign correlation

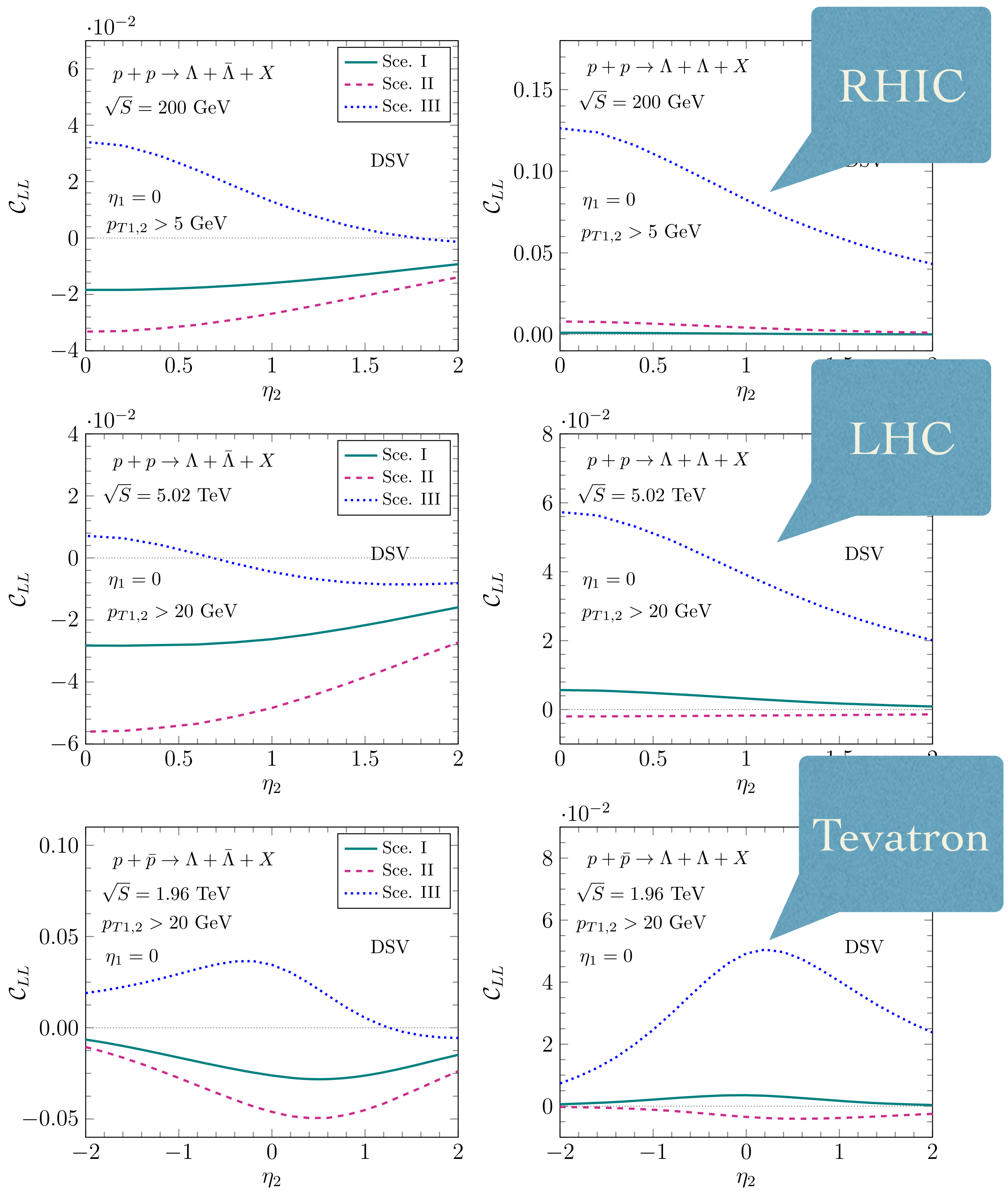




To summarize

- ☑ s-channel: $\sigma_{+-} = \sigma_{-+} > \sigma_{++} = \sigma_{--} = 0$
- ☑ t-channel: $\sigma_{++} = \sigma_{--} > \sigma_{+-} = \sigma_{-+} > 0$
- ☑ Probe polarized FF in unpolarized pp collisions
- ☑ Explore the circularly polarized gluon FF

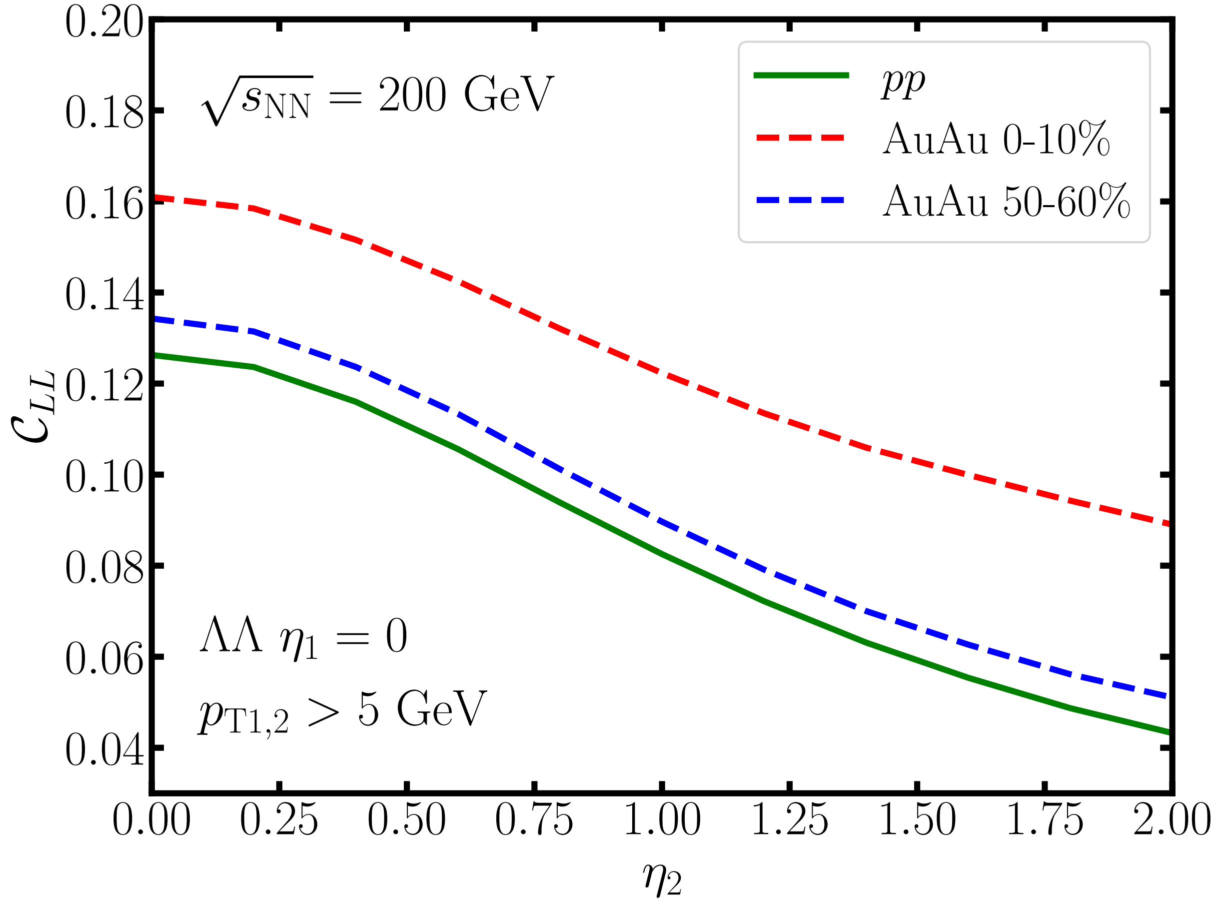
Polarization Correlation in pp collisions



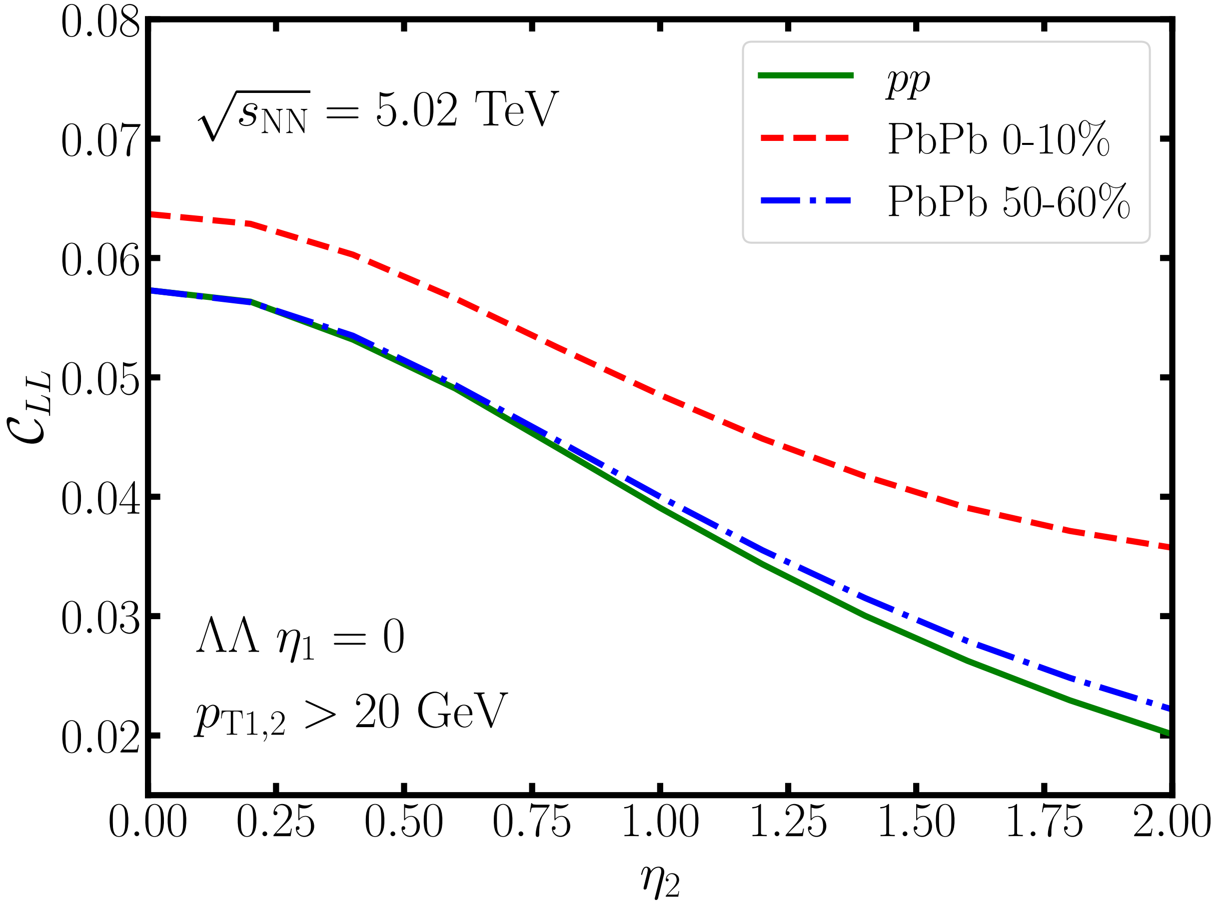
- Smaller, but none-zero
- Distinguish different scenarios
- Probe gluon spin transfer

Numerical Results

Polarization Correlation in central and peripheral AA collisions



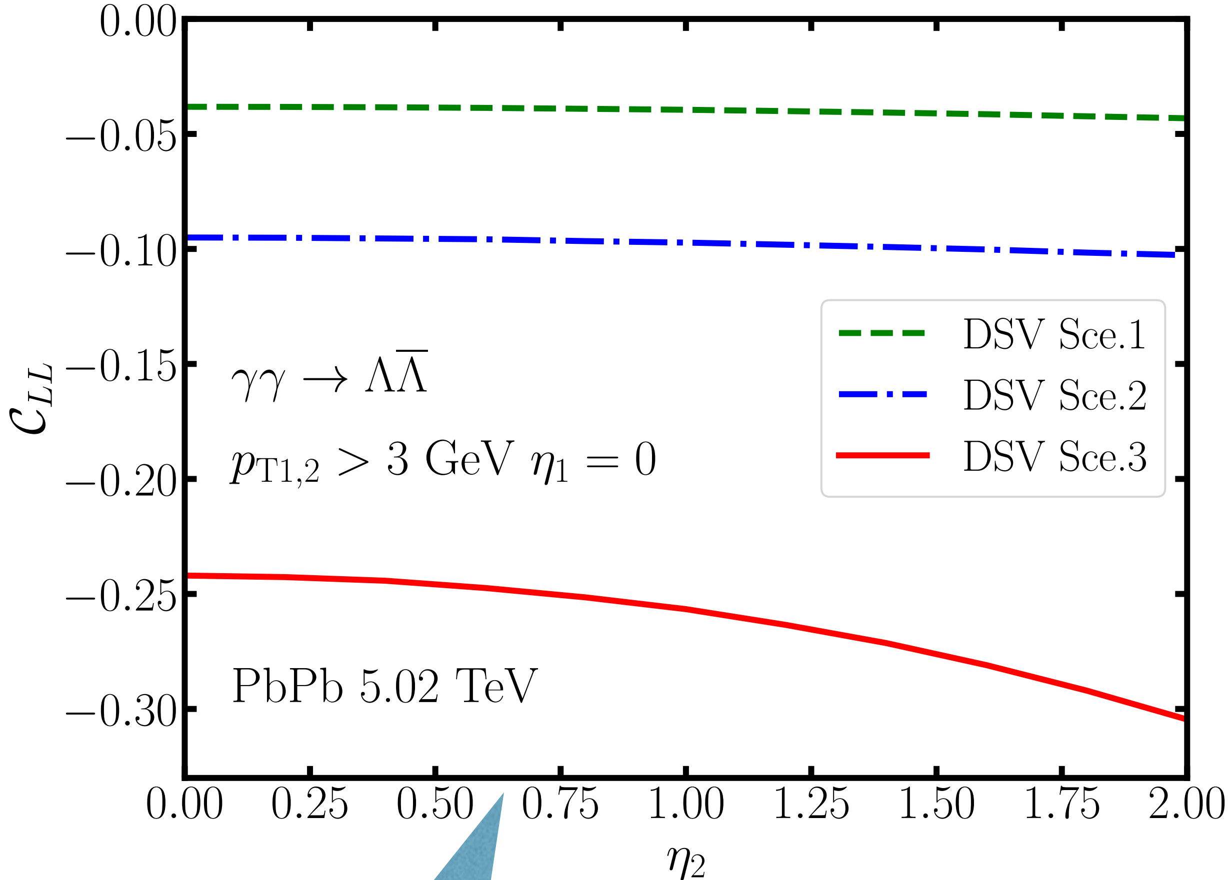
- ☑ Much larger luminosity
- ☑ Jet Quenching + Polarization



Clear Enhancement in central AA collisions

Numerical Results

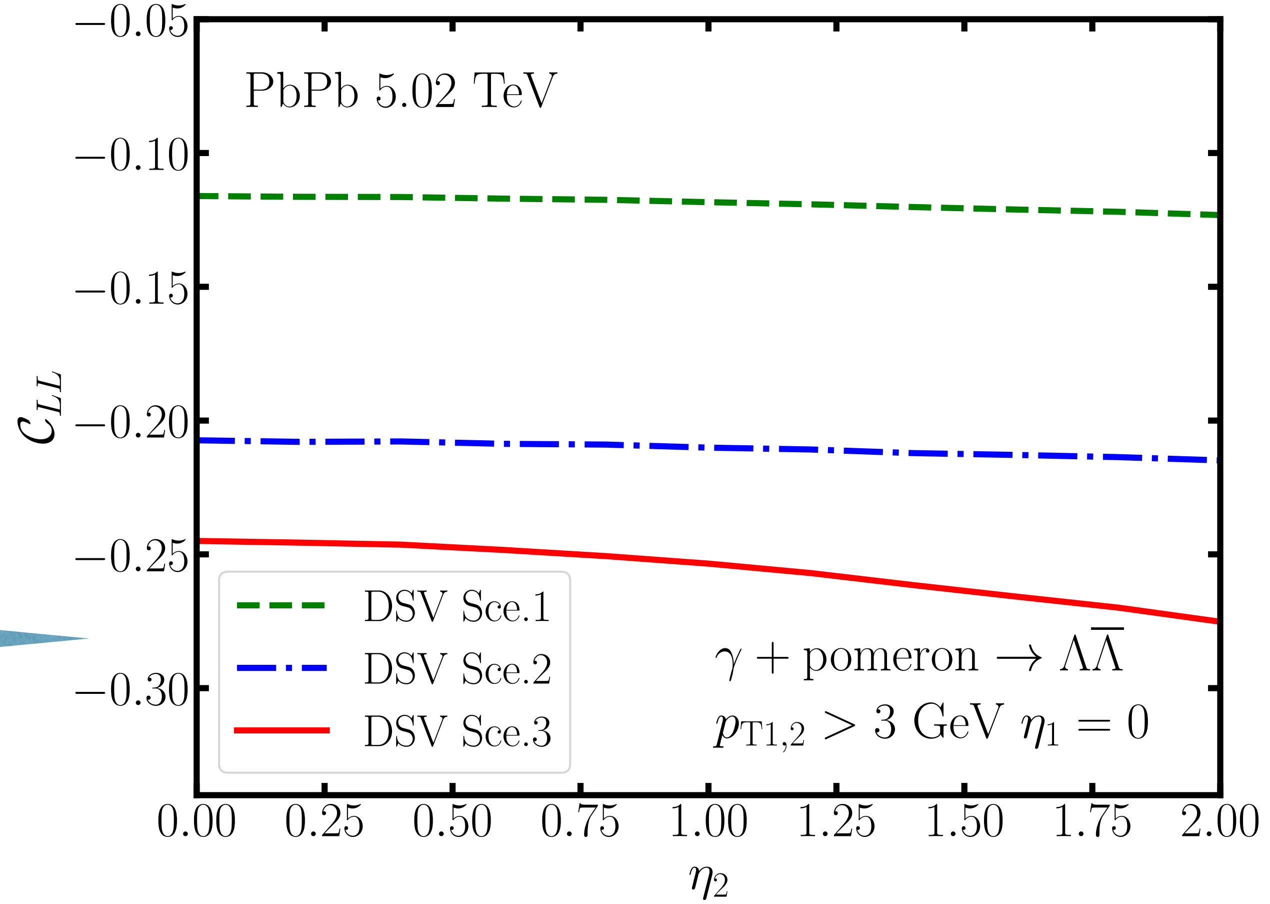
Polarization Correlation in ultra-peripheral AA collisions



- ☑ Much larger luminosity
- ☑ Pomeron + Polarization

$\gamma + \gamma$

$\gamma + \mathbb{P}$



Summary

- Polarization correlation servers as a novel probe to the polarized fragmentation functions.

- Polarized fragmentation functions can also be studied in unpolarized pp and AA collisions.

Besides this talk, we also studied the fragmentation of transversely polarized partons in unpolarized collisions.
Phys.Rev.D105, 034027. (2022)

Thanks for your attention!

The End