Quenching of Polarized Jets

Shu-Yi Wei (Shandong University)
shuyi@sdu.edu.cn

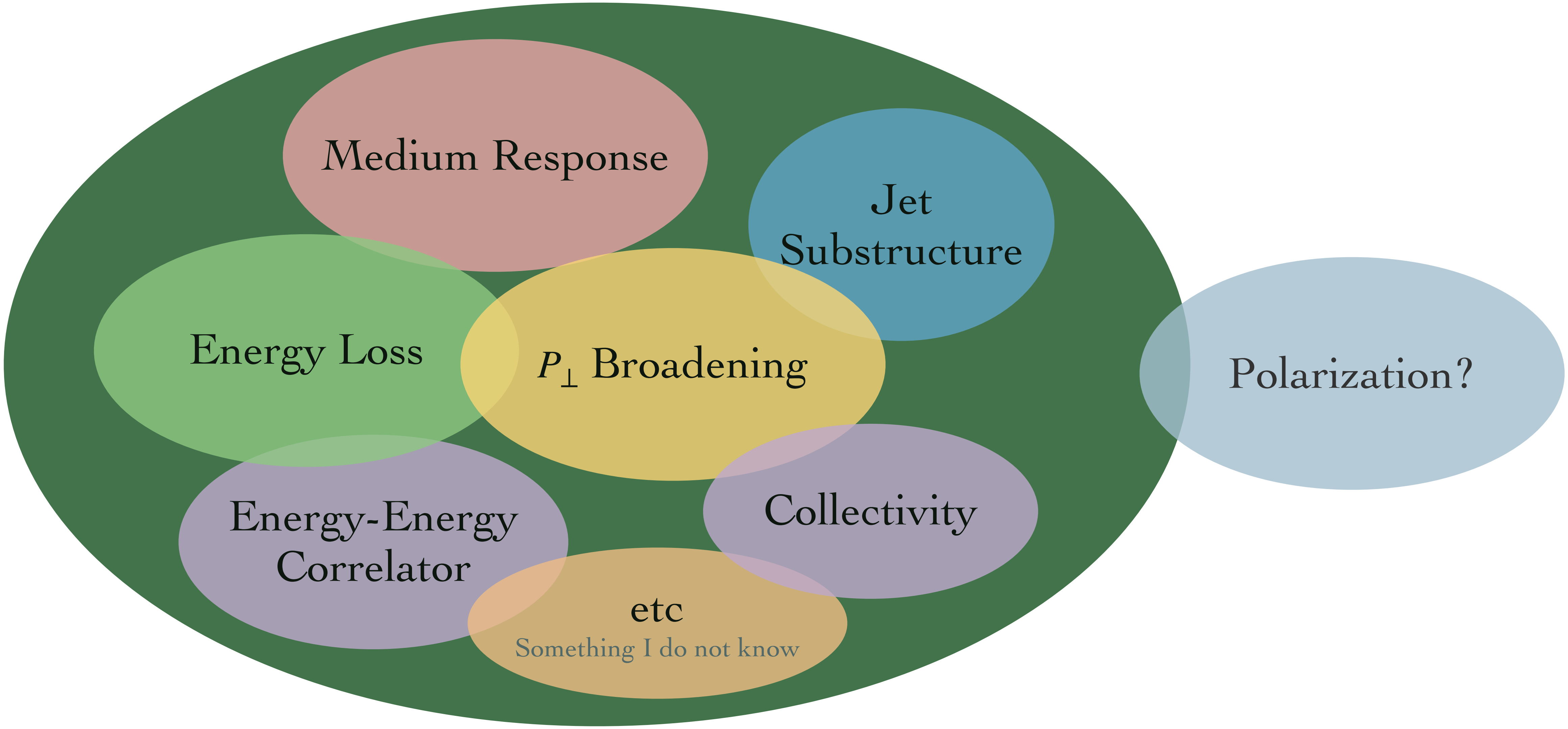
H.C. Zhang, S.Y. Wei; PLB 839, 137821 (2023)
X.W. Li, Z.X. Chen, S. Cao, S.Y. Wei, PRD 109, 014035 (2024)

Contents

- ☑ Introduction
- ☑ Polarization in Unpolarized Collisions
- ☑ Polarization and Jet Quenching
- ☑ Summary and Outlook

Introduction

Keywords of Jet Quenching



Unpolarized Beams
+
Strong Interaction

→ Unpolarized Jets

See also Siggi's talk.

Introduction

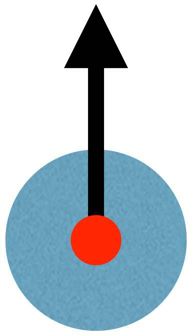
QCD factorization

partonic interaction, perturbative

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

non-perturbative, universal

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



$$\not{n}_+\left[f_1 - \frac{(\widehat{\boldsymbol{e}}_p \times \boldsymbol{k}_T)\cdot \boldsymbol{S}_\perp}{M} f_{1T}^\perp\right] + \gamma_5 \not{n}_+\left[\lambda g_{1L} + \frac{k_T \cdot S_\perp}{m} g_{1T}^\perp\right] +$$
$$\frac{i[\not{k}_T, \not{n}_+]}{2m} h_1^\perp + \frac{1}{2}[\not{S}_\perp, \not{n}_+]\gamma_5 h_{1T} + \frac{[\not{k}_T, \not{n}_+]\gamma_5}{2m}\left[\lambda h_{1L}^\perp + \frac{k_T \cdot S_\perp}{m} h_{1T}^\perp\right]$$

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

$$\not{n}_-\left[D_1 + \frac{(\widehat{\boldsymbol{e}}_j \times \boldsymbol{p}_T)\cdot \boldsymbol{S}_\perp}{zM} D_{1T}^\perp\right] + \gamma_5 \not{n}_-\left[\lambda G_{1L} + \frac{p_T \cdot S_\perp}{zM} G_{1T}^\perp\right] +$$
$$\frac{i[\not{p}_T, \not{n}_-]}{2M} H_1^\perp + \frac{1}{2}[\not{S}_\perp, \not{n}_-]\gamma_5 H_{1T} + \frac{[\not{p}_T, \not{n}_-]\gamma_5}{2M}\left[\lambda H_{1L}^\perp + \frac{p_T \cdot S_\perp}{M} H_{1T}^\perp\right]$$

Introduction

QCD factorization

Baryons

Quarks

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

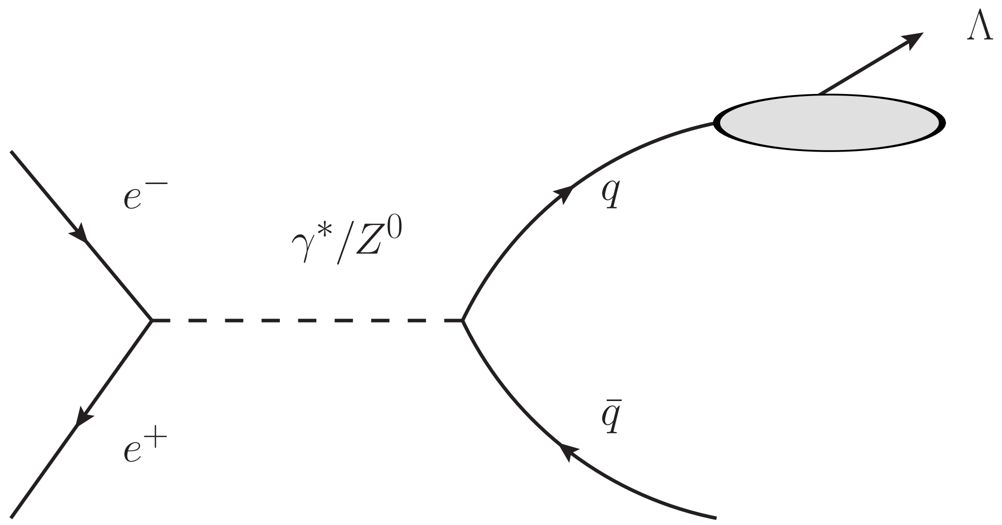
☑ **G_{1L}, aka, the longitudinal spin transfer**

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

polarized beams
or
weak interaction

Introduction

Single Inclusive Λ Production in e⁺e⁻ Annihilation Experiment



Final state quarks gain polarization through weak interaction

γ^* Z^0

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

Belle Energy

LEP Energy

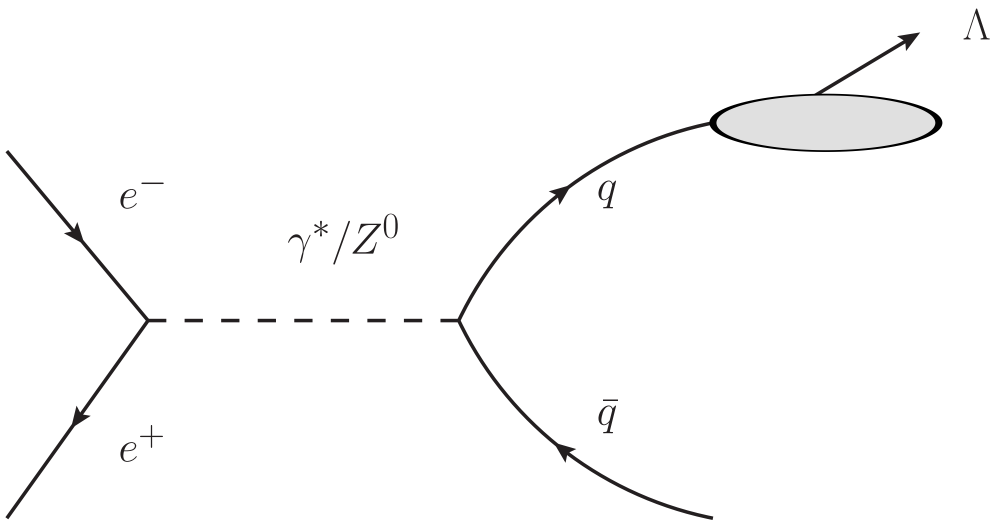
spin transfer

$$\mathscr{P}_L^{\Lambda} = \lambda_q \frac{G_{1Lq}^{\Lambda}}{D_{1q}^{\Lambda}}$$

quark polarization

Introduction

Single Inclusive Λ Production in e⁺e⁻ Annihilation Experiment

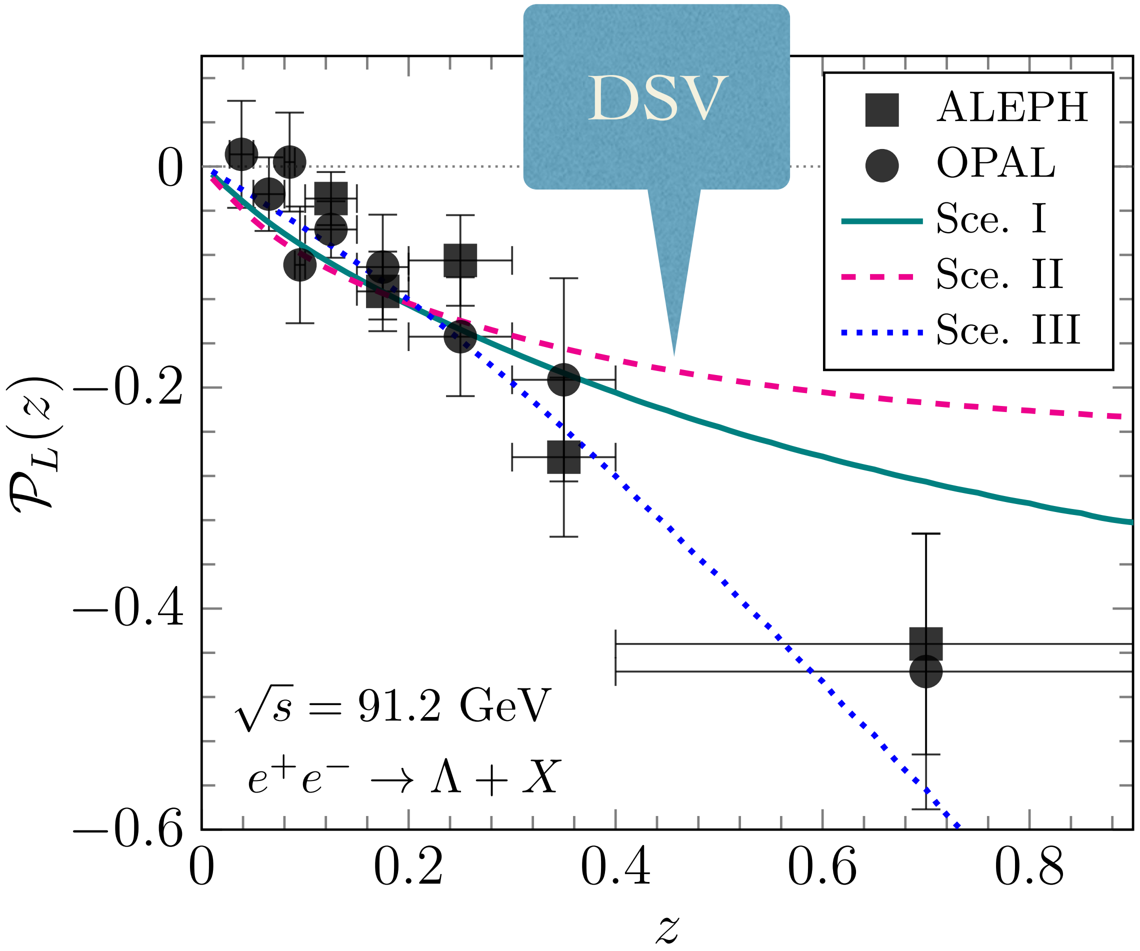


Final state quarks gain polarization through weak interaction

spin transfer

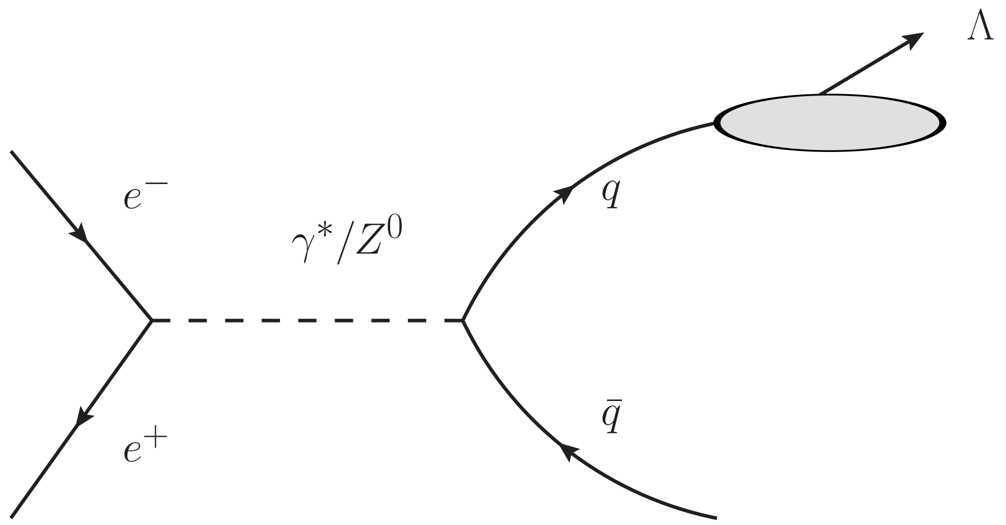
$$\mathscr{P}_L^\Lambda = \lambda_q \frac{G_{1Lq}^\Lambda}{D_{1q}^\Lambda}$$

quark polarization



Introduction

Single Inclusive Λ Production in e^+e^- Annihilation Experiment



Final state quarks gain polarization through weak interaction

spin transfer

$$\mathscr{P}_L^\Lambda = \lambda_q \frac{G_{1Lq}^\Lambda}{D_{1q}^\Lambda}$$

quark polarization

γ^* Z^0

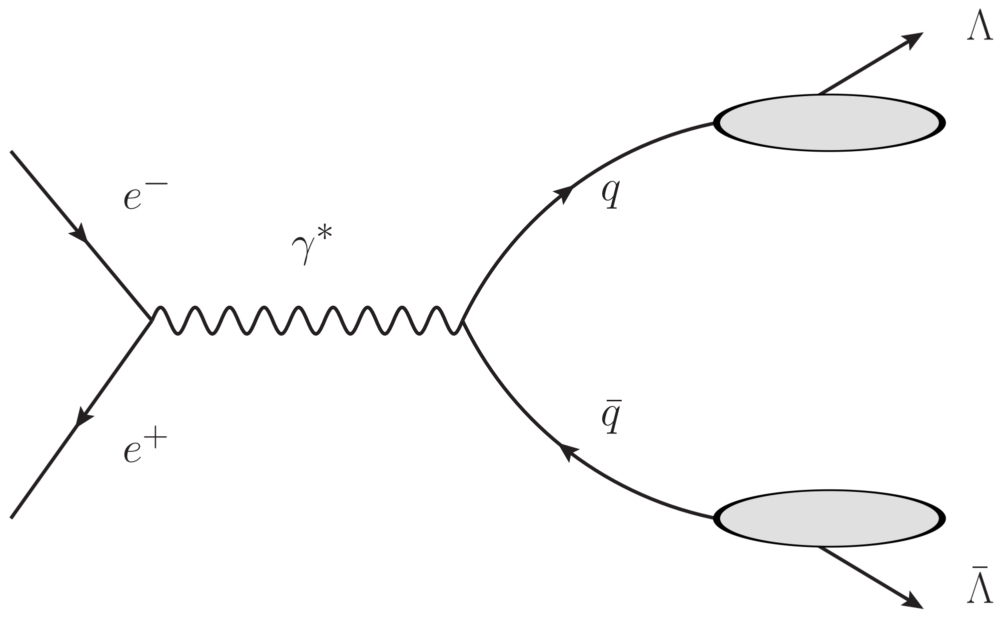
$$\frac{d\sigma}{dPS} = \sigma_0 \left[D_{1q}^\Lambda(z) + \cancel{\lambda_q \lambda_\Lambda G_{1Lq}^\Lambda(z)} \right]$$

Belle Energy

LEP Energy

Introduction

$\Lambda\bar{\Lambda}$-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 fermi line. They must have opposite helicities.

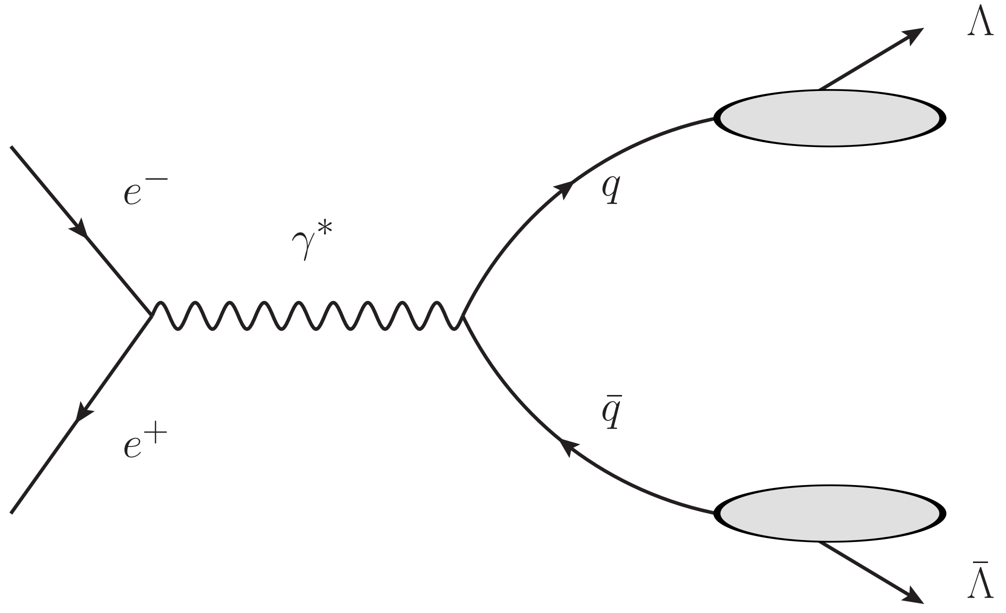
☑ **Polarization Correlation**

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

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

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

Physical interpretation:

$$\frac{d\sigma}{dPS} = \sigma_{+-} \otimes \mathscr{D}_q(+, \lambda_\Lambda, z_1) \otimes \mathscr{D}_{\bar{q}}(-, \lambda_{\bar{\Lambda}}, z_2) + \sigma_{-+} \otimes \mathscr{D}_q(-, \lambda_\Lambda, z_1) \otimes \mathscr{D}_{\bar{q}}(+, \lambda_{\bar{\Lambda}}, z_2)$$

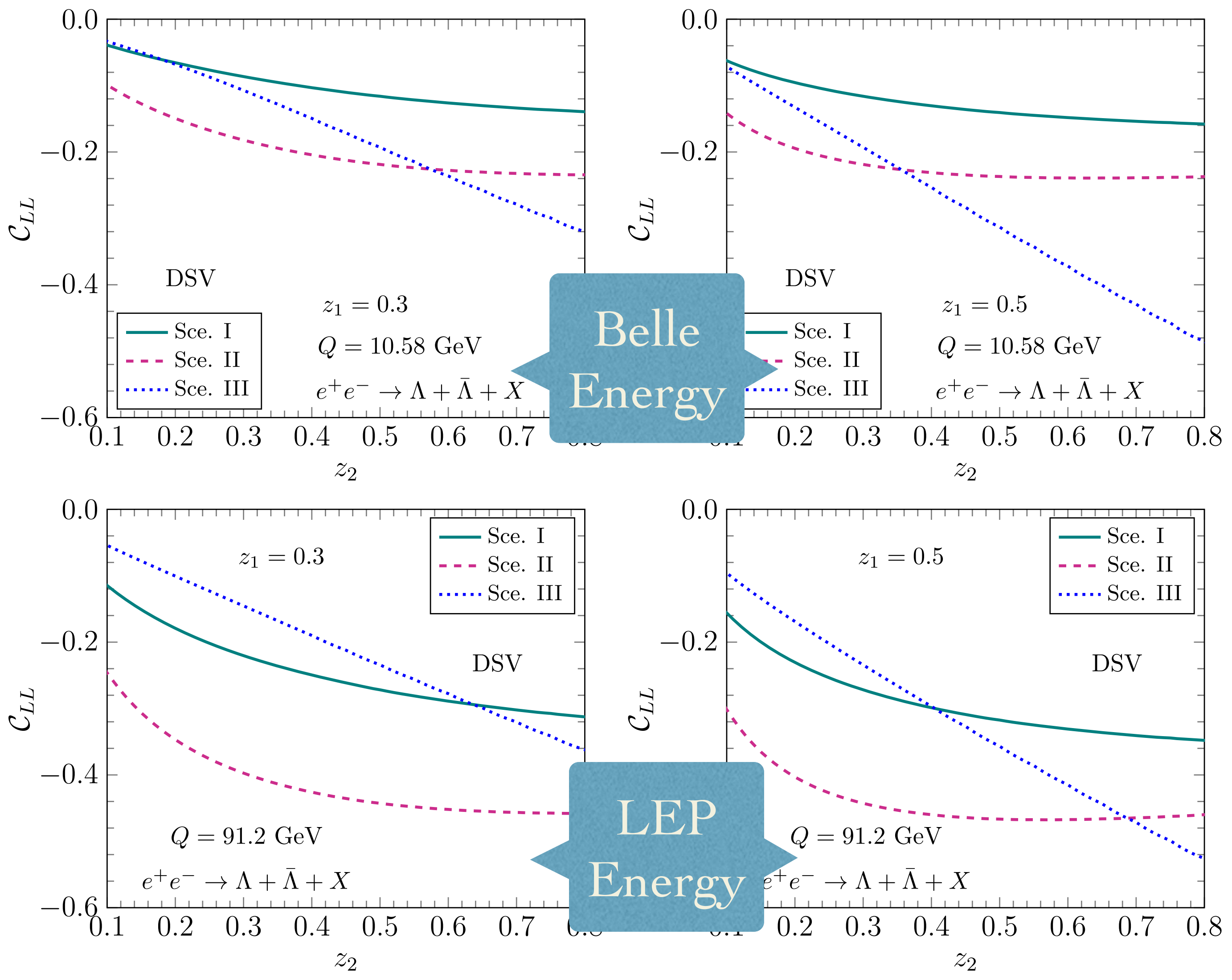
$$= \sigma_0 \left[D_{1q}^{\Lambda}(z_1) D_{1\bar{q}}^{\bar{\Lambda}}(z_2) - \lambda_\Lambda \lambda_{\bar{\Lambda}} G_{1Lq}^{\Lambda}(z_1) G_{1L\bar{q}}^{\bar{\Lambda}}(z_2) \right]$$

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

Helicity Amplitude Approach

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

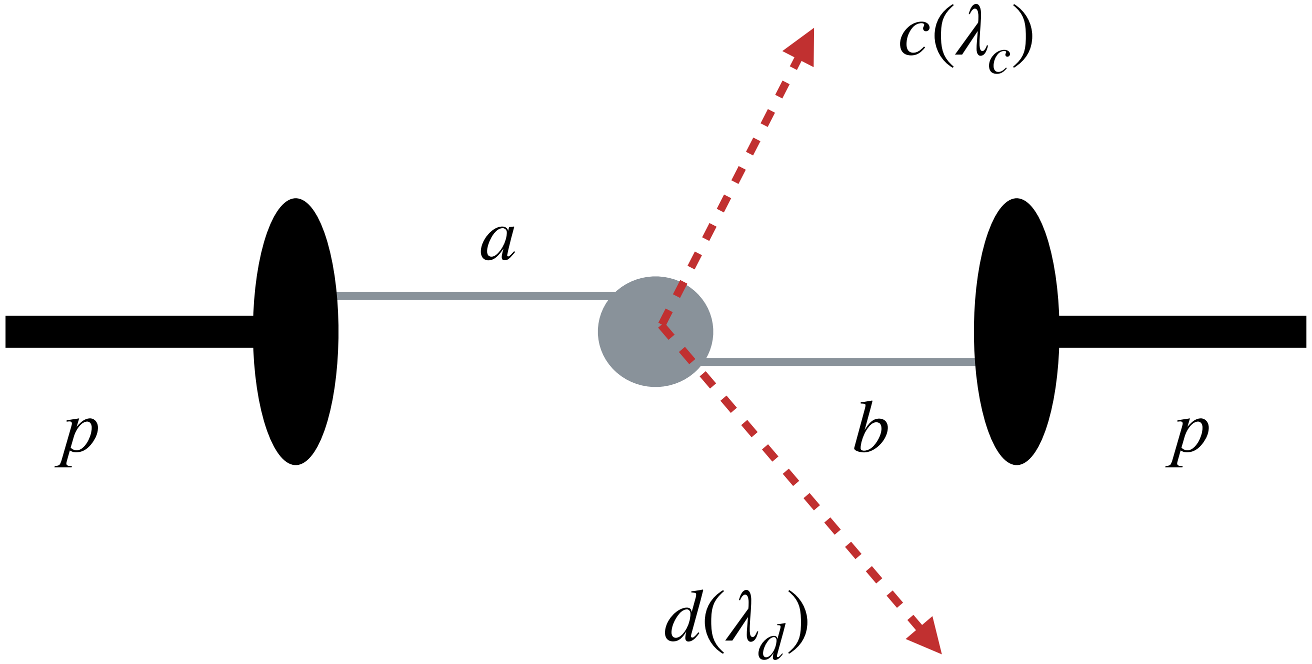
$$C_{LL} = \frac{\text{same signs} - \text{opposite signs}}{\text{total cross section}} = \frac{\sum_q \sigma_0 G_{1Lq}^{\Lambda}(z_1) G_{1L\bar{q}}^{\bar{\Lambda}}(z_2)}{\sum_q \sigma_0 D_{1q}^{\Lambda}(z_1) D_{1\bar{q}}^{\bar{\Lambda}}(z_2)} \propto \langle \cos\theta_1^* \cos\theta_2^* \rangle$$



- ☑ 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.

Helicity Amplitude Approach

Applying to the unpolarized pp collisions

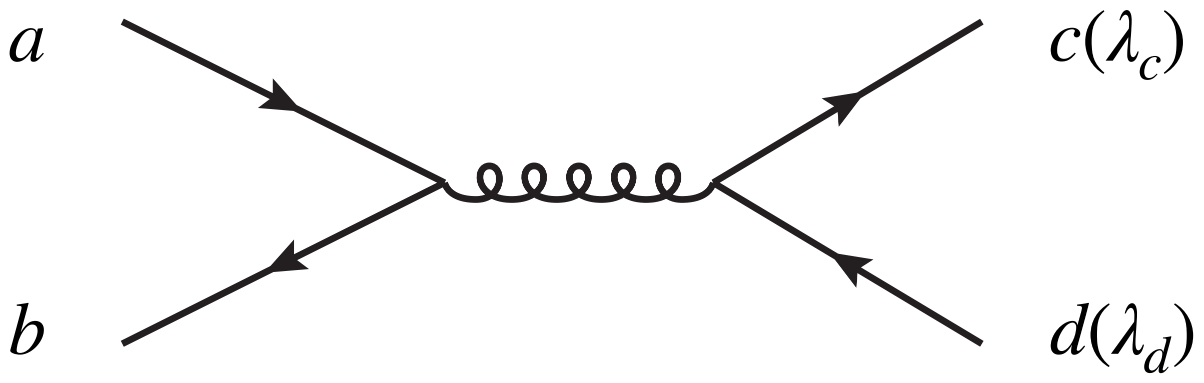


$$a + b \to c(\lambda_c) + d(\lambda_d)$$

☑ **Are λ_c and λ_d correlated?**

Yes!

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



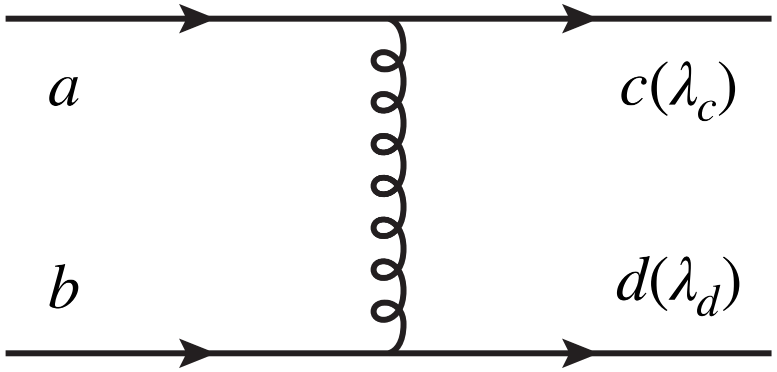
$$g + g \to q + \bar{q}$$

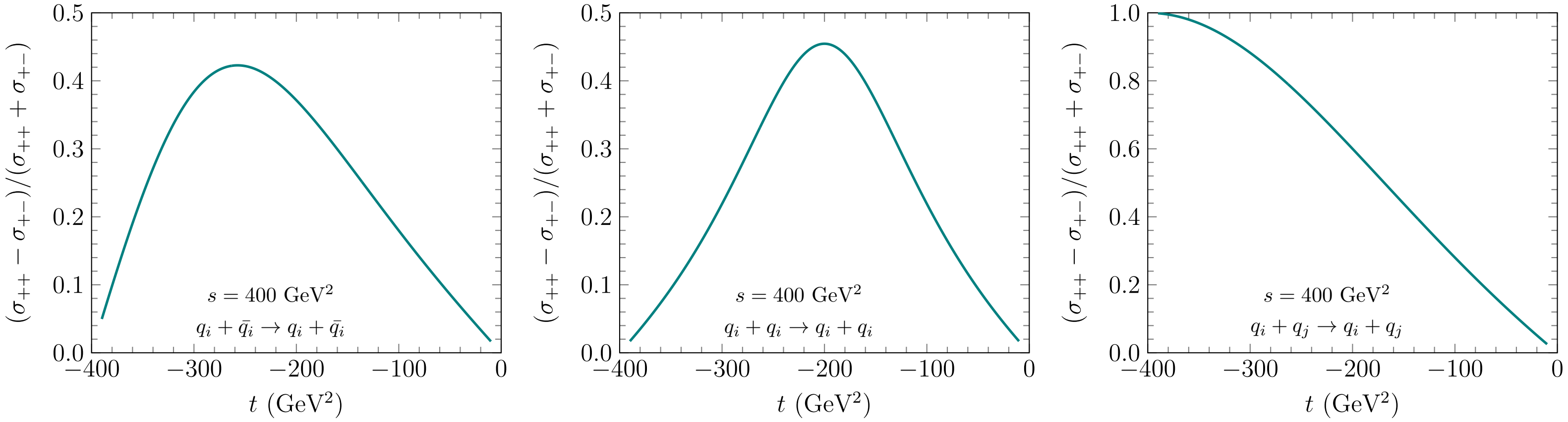
$$q_i + \bar{q}_i \to q_j + \bar{q}_j$$

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

Helicity Amplitude Approach

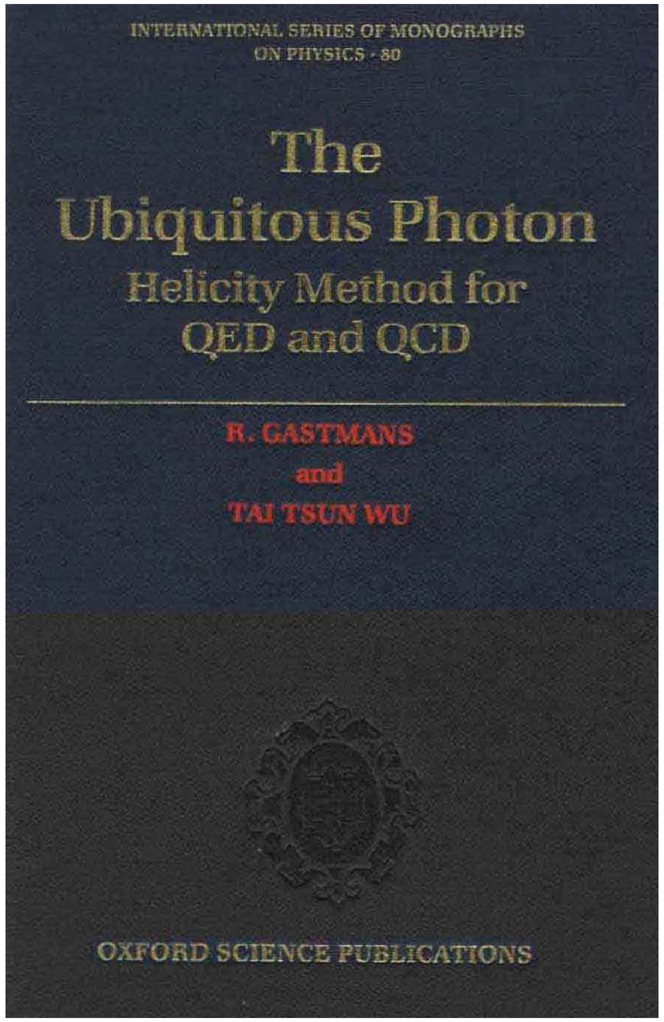
"t-channel diagrams": prefer same-sign correlation





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



INTERNATIONAL SERIES OF MONOGRAPHS ON PHYSICS · 80

The Ubiquitous Photon

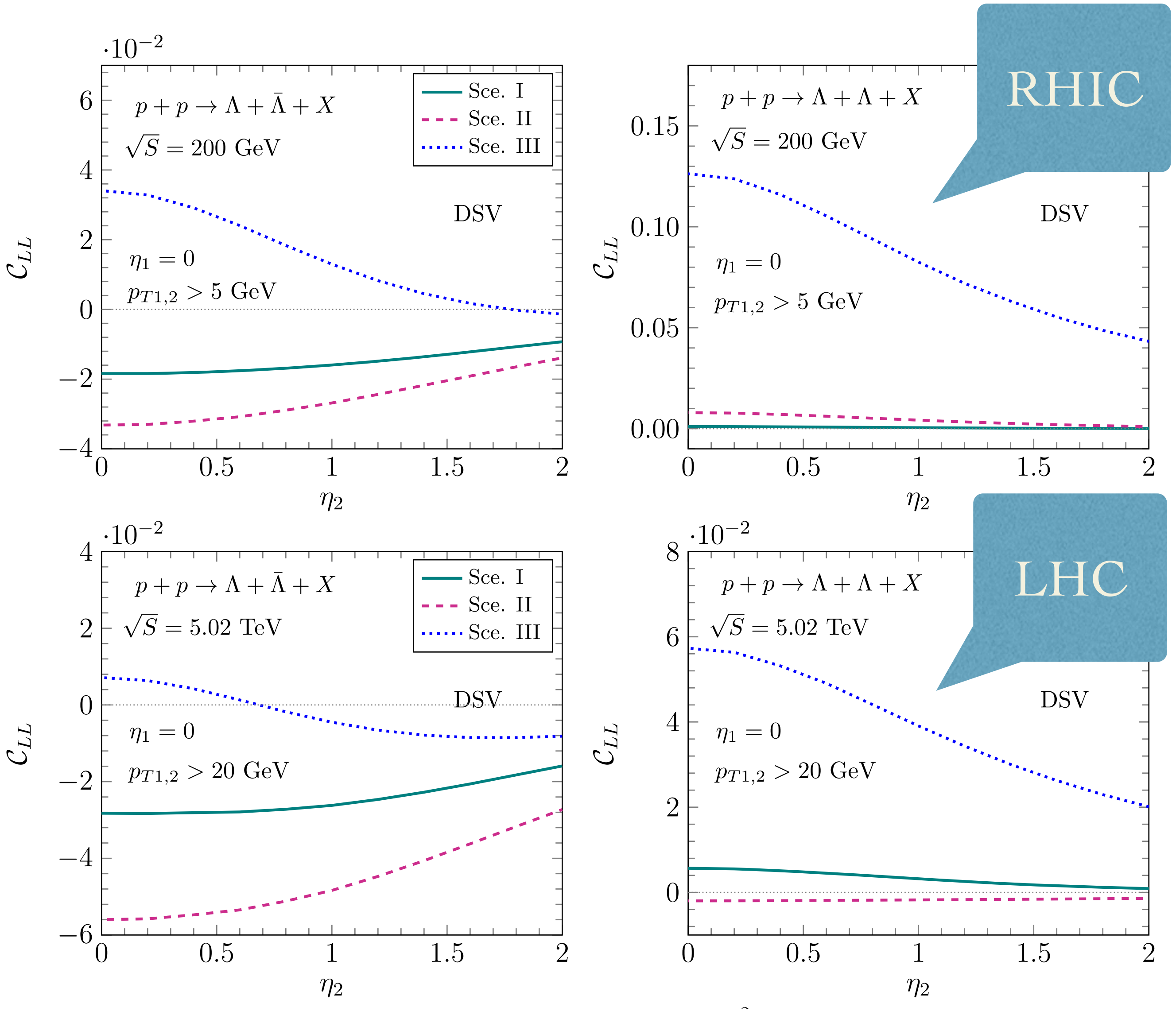
Helicity Method for QED and QCD

R. GASTMANS
and
TAI TSUN WU

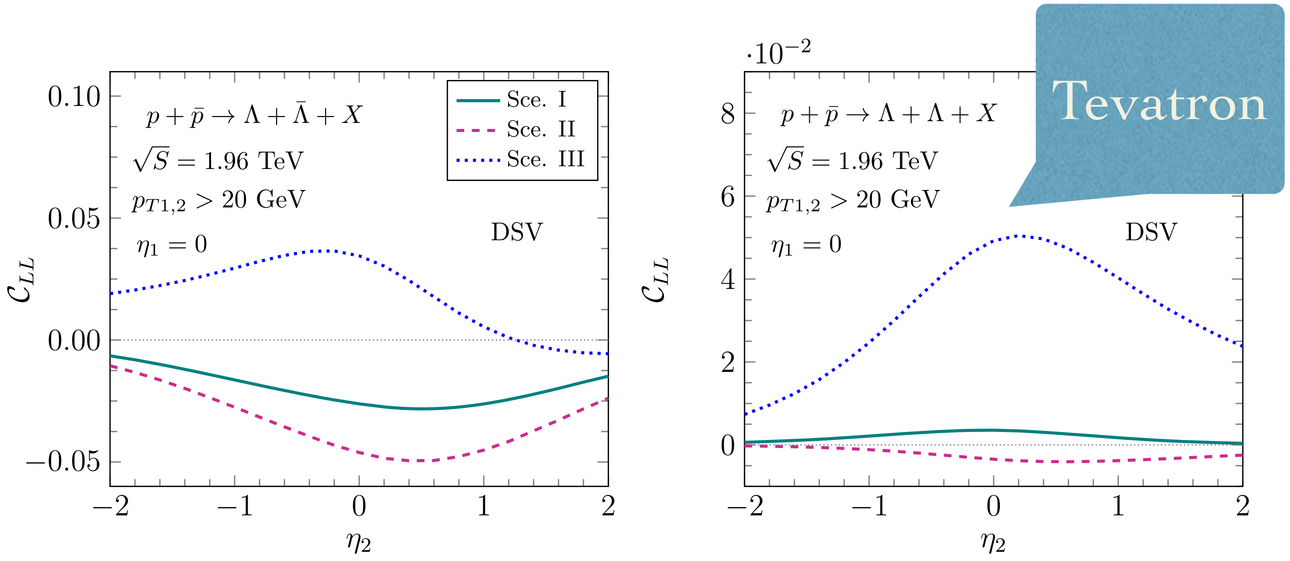
OXFORD SCIENCE PUBLICATIONS

Helicity Amplitude Approach

Polarization Correlation in unpolarized pp collisions


RHIC

LHC

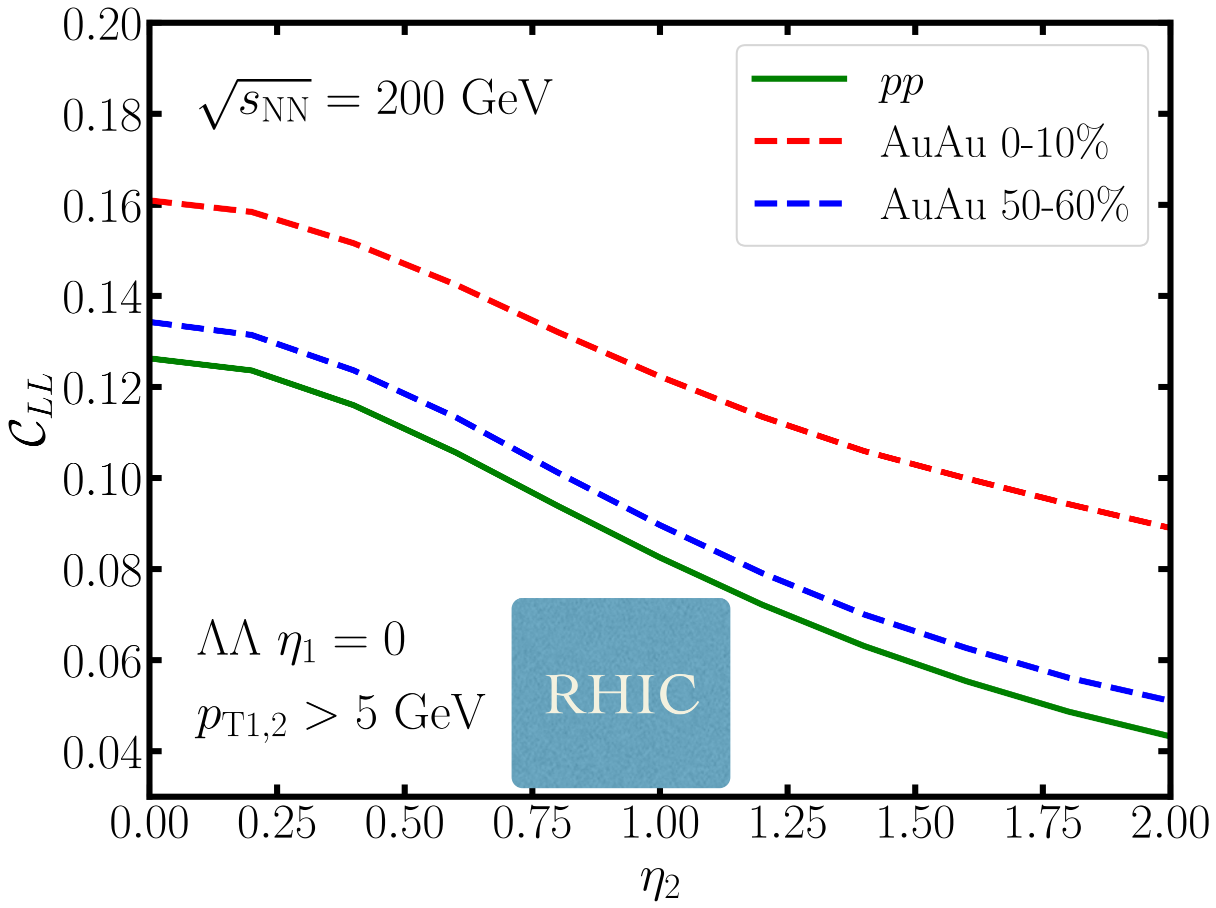

Tevatron

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

Polarization and Jet Quenching

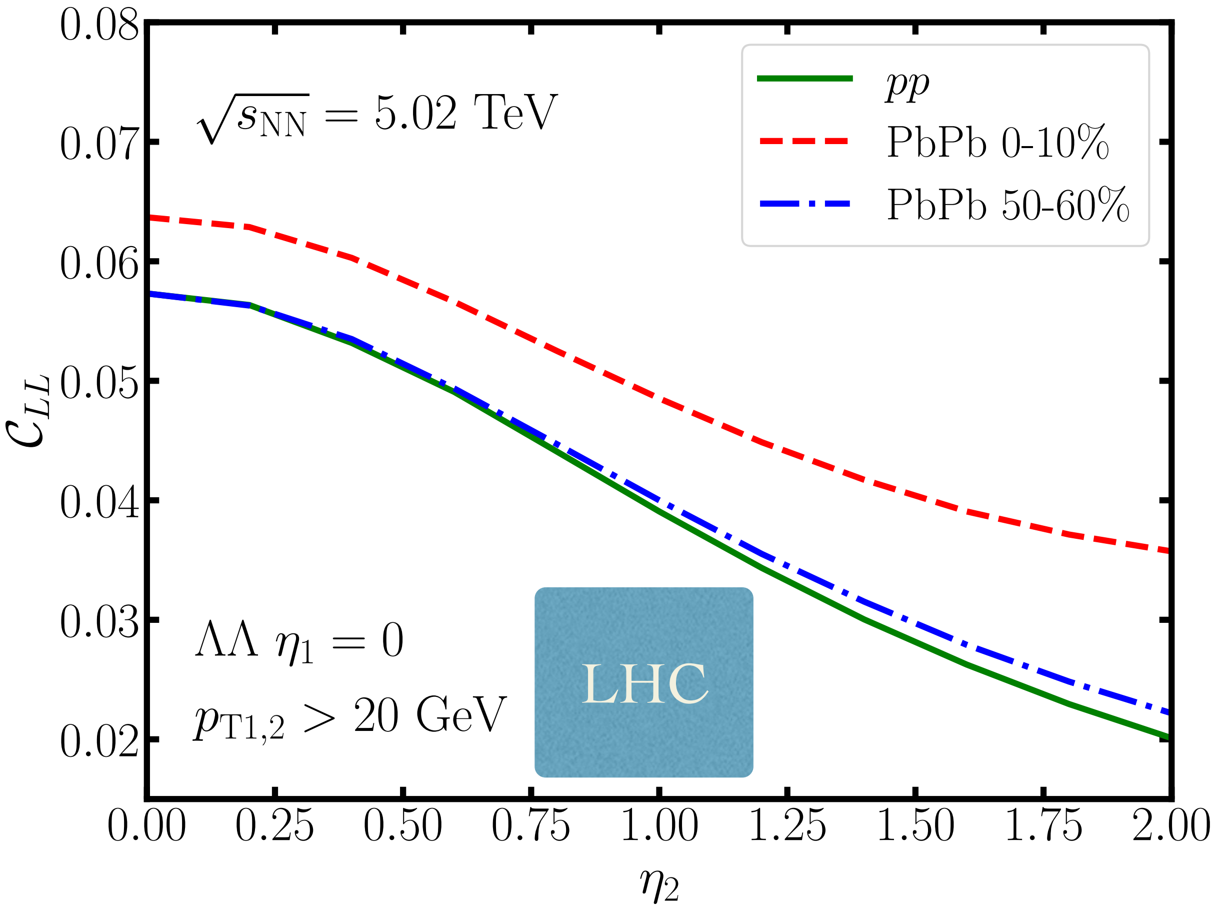
Polarization Correlation in central and peripheral AA collisions

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



☑ Much larger luminosity

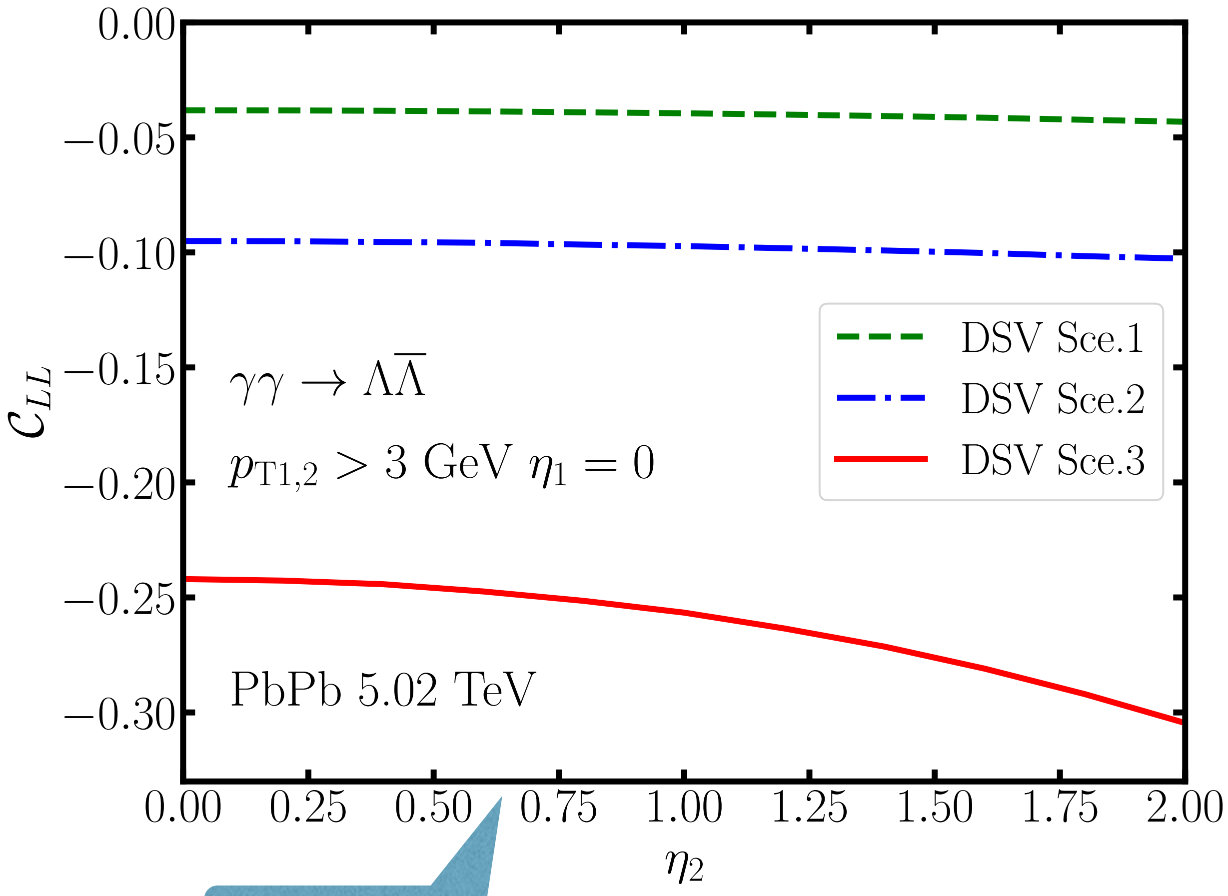
☑ Jet Quenching + Polarization



Clear Enhancement in central AA collisions

Polarization and Jet Quenching

Polarization Correlation in ultra-peripheral AA collisions

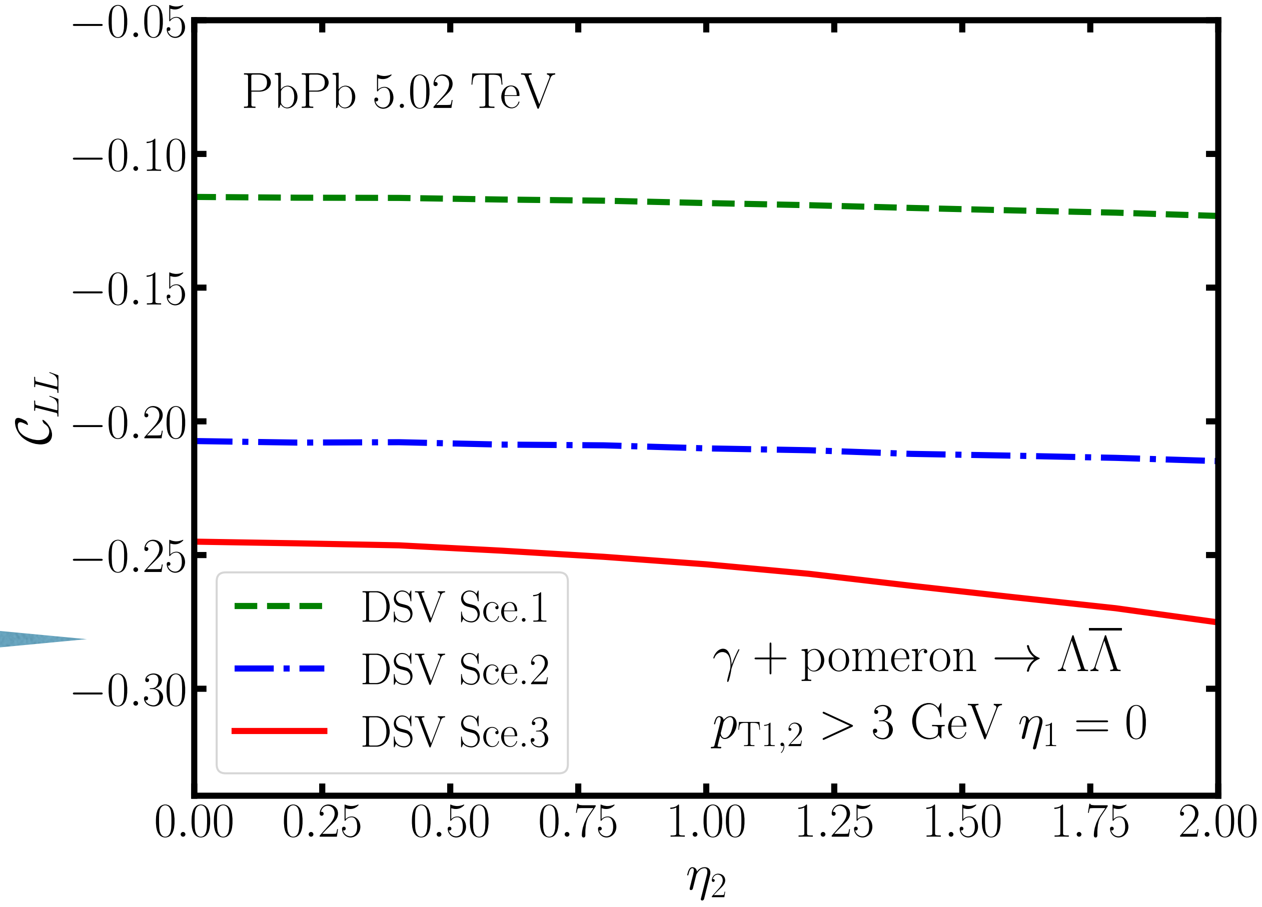


$\gamma + \gamma$

☑ Much larger luminosity

☑ Pomeron + Polarization

$\gamma + \mathbb{P}$



Polarization and Jet Quenching

Advantages?

Unpolarized Splitting Functions

$$P_{qq} = C_F \left[\frac{1+\xi^2}{(1-\xi)_+} + \frac{3}{2}\delta(1-\xi) \right]$$

$$P_{gg} = 2N_c \left[\frac{1-\xi}{\xi} + \xi(1-\xi) + \frac{\xi}{(1-\xi)_+} \right] + \frac{11N_c - 2\pi}{6}\delta(1-\xi)$$

$$P_{gq} = C_F \frac{1+(1-\xi)^2}{\xi}$$

$$P_{qg} = \frac{\xi^2 + (1-\xi)^2}{2}$$

Polarized Splitting Functions (L)

$$\Delta P_{qq} = C_F \left[\frac{1+\xi^2}{(1-\xi)_+} + \frac{3}{2}\delta(1-\xi) \right]$$

$$\Delta P_{gg} = N_c \left[(1+\xi^4)\left(\frac{1}{\xi} + \frac{1}{(1-\xi)_+} \right) - \frac{(1-\xi)^3}{\xi} \right] + \frac{11N_c - 2n_f}{6}\delta(1-\xi)$$

$$\Delta P_{gq} = C_F \frac{1-(1-\xi)^2}{\xi}$$

$$\Delta P_{qg} = \frac{\xi^2 - (1-\xi)^2}{2}$$

Summary and Outlook

- ☑ Spin effects can also be studied in unpolarized collisions.
- ☑ The combination of hadron polarization and jet quenching offers a new platform to study the jet medium interaction.
- ☑ Z^0-boson + Jet?
- ☑ MC simulation with the spin degree of freedom?

Besides this talk, we also studied other spin effects in unpolarized collisions.

Phys.Lett.B 816, 136217 (2021).

Phys.Rev.D105, 034027 (2022).

Thanks for your attention!

The End

Backups