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Λ Polarization in Weak-Boson-Tagged Jets as a Probe of Polarized Hadronization and Jet Quenching

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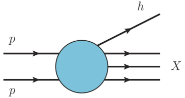
· W. H. Yao, X. Li, H. Dong, S. Y. Wei, Phys. Rev. D 113, 074014 (2026)

Contents

Introduction: Polarized Fragmentation Functions

QCD Factorization

- Cross Section = Short Distance (p-QCD calculable) $\otimes$ Long Distance (non-perturbative)



$$\hat{\sigma}^{pp\to hX} = \text{PDF} \otimes \text{PDF} \otimes \hat{\sigma} \otimes \text{FF}$$

- Non-perturbative inputs: Parton Distribution Functions and Fragmentation Functions.

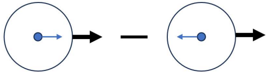
Leading Twist Collinear FFs: quark example

Quark $\xrightarrow{\text{Hadronization}}$ **Hadron**

$$D^{q\to h} = D_1^{q\to h} + \lambda_q \lambda_h G_{1L}^{q\to h} + \vec{S}_{q\perp} \cdot \vec{S}_{Th} H_{1T}^{q\to h}$$

Longitudinal Spin Transfer G_{1L}

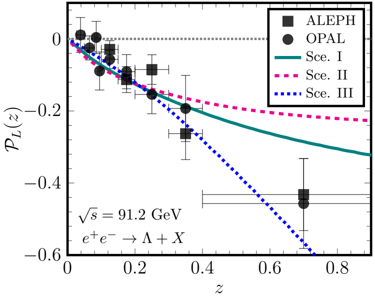
G_{1L} =



Polarized $q/g(\lambda)$ $\xrightarrow{\text{fragmentation}}$ Polarized $\Lambda(\lambda_\Lambda)$

Introduction: Current constraints on G_{1L} and the motivation for hadron-collider measurements

Current Knowledge: DSV Parameterization



D. de Florian, M. Stratmann, W. Vogelsang, Phys. Rev. D **57**, (1998)5811–5824
K. B. Chen, W. H. Yang, Y. J. Zhou and Z. T. Liang, Phys. Rev. D **95** (2017)3, 034009

DSV Scenarios

·Sce. I: only s quark contributes to Λ polarization.
·Sce. II: s positive, u, d slightly negative.
·Sce. III: u, d and s quarks contribute equally.
·Gluon contribution is set to zero at the initial scale.

Why Hadron Colliders?

- Three significantly different scenarios all could describe LEP data indicates that the flavor dependence of G_{1L} is still poorly constrained.
- Existing e^+e^- annihilation and polarized SIDIS data provide only very limited information on the gluon contribution to G_{1L}.
- Hadron colliders can provide broad kinematic coverage and abundant gluon jets.

Weak-Boson-Tagged Processes as the Source of Polarized Partons

Polarized Parton

Unpolarized collisions

+

Parity-violating weak interaction

$\Downarrow$

Polarized parton

$\Downarrow$

Λ polarization

$$P_\Lambda \sim \lambda \frac{G_{1L}}{D_1}$$

Jet Associated with a Vector Boson Production

$$p + p \to Z^0/W^\pm + \text{jet}(\to \Lambda) + X$$

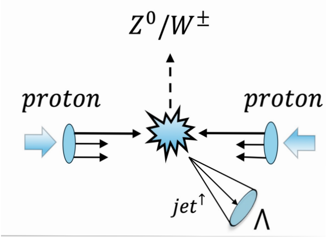
Partonic Cross Section with the Helicity Amplitude Method

Parton polarization : $\lambda = \dfrac{\hat{\sigma}_+ - \hat{\sigma}_-}{\hat{\sigma}_+ + \hat{\sigma}_-}$

$\dfrac{d\hat{\sigma}_+^{ab\to Vd}}{d\hat{t}}$: probability for $|d,\uparrow\rangle$

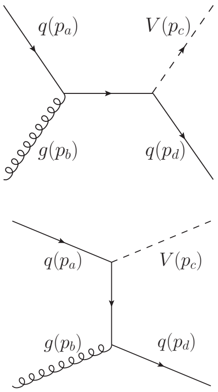
$\dfrac{d\hat{\sigma}_-^{ab\to Vd}}{d\hat{t}}$: probability for $|d,\downarrow\rangle$

Illustration



Quark Polarization in Weak-Boson-Tagged Processes

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



$q/\bar{q}+g \to Z^0+q/\bar{q}$

$$\frac{d\hat{\sigma}_+^{qg\to Z^0 q}}{d\hat{t}} = \frac{d\hat{\sigma}_-^{\bar{q}g\to Z^0 \bar{q}}}{d\hat{t}} = -\frac{\pi\alpha_s\alpha_{\rm em}}{6\hat{s}^2\sin^2 2\theta_W}(c_1^q - c_3^q)\left[\frac{2M_Z^2\hat{u}}{\hat{t}\hat{s}} + \frac{\hat{s}}{\hat{t}} + \frac{\hat{t}}{\hat{s}}\right]$$

$$\frac{d\hat{\sigma}_-^{qg\to Z^0 q}}{d\hat{t}} = \frac{d\hat{\sigma}_+^{\bar{q}g\to Z^0 \bar{q}}}{d\hat{t}} = -\frac{\pi\alpha_s\alpha_{\rm em}}{6\hat{s}^2\sin^2 2\theta_W}(c_1^q + c_3^q)\left[\frac{2M_Z^2\hat{u}}{\hat{t}\hat{s}} + \frac{\hat{s}}{\hat{t}} + \frac{\hat{t}}{\hat{s}}\right]$$

where $c_1^q = (c_V^q)^2 + (c_A^q)^2$ $\quad c_3^q = 2c_V^q c_A^q$ $\quad \boxed{\lambda_{q/\bar{q}} = \mp c_3^q/c_1^q}$

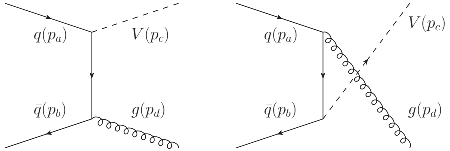
$q/\bar{q}+g \to W^\pm+q/\bar{q}$

$$\frac{d\hat{\sigma}_-^{q_i g\to W^\pm q_j}}{d\hat{t}} = \frac{d\hat{\sigma}_+^{\bar{q}_i g\to W^\pm \bar{q}_j}}{d\hat{t}} = -V_{ij}^2\frac{\pi\alpha_s\alpha_{\rm em}}{12\hat{s}^2\sin^2\theta_W}\left[\frac{2M_W^2\hat{u}+\hat{s}^2+\hat{t}^2}{\hat{t}\hat{s}}\right]$$

$$\boxed{\lambda_{q/\bar{q}} = \mp 1}$$

Gluon Polarization in Weak-Boson-Tagged Processes

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



$q+\bar{q}\to W^{\pm}+g$

$$\frac{d\hat{\sigma}_{+}^{q_i\bar{q}_j\to W^{\pm}g}}{d\hat{t}} = V_{ij}^2\frac{2\pi\alpha_s\alpha_{em}}{9\hat{s}^2\sin^2\theta_W}\frac{(M_W^2-\hat{u})^2}{\hat{t}\hat{u}}$$

$$\frac{d\hat{\sigma}_{-}^{q_i\bar{q}_j\to W^{\pm}g}}{d\hat{t}} = V_{ij}^2\frac{2\pi\alpha_s\alpha_{em}}{9\hat{s}^2\sin^2\theta_W}\frac{(M_W^2-\hat{t})^2}{\hat{t}\hat{u}}$$

$q+\bar{q}\to Z^0+g$

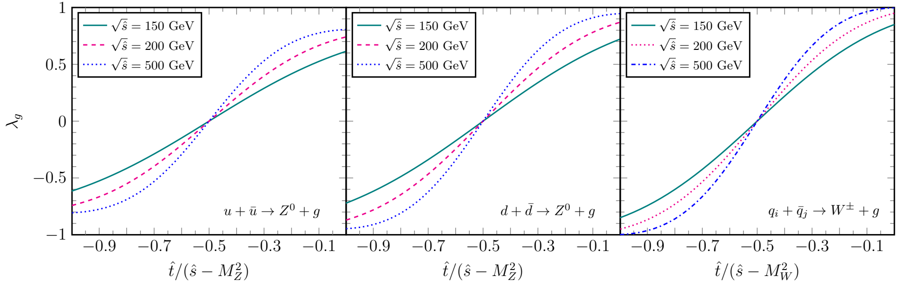
$$\frac{d\hat{\sigma}_{+}^{q\bar{q}\to Z^0 g}}{d\hat{t}} = \frac{4\pi\alpha_s\alpha_{em}}{9\hat{s}^2\sin^2 2\theta_W}\left\{c_1^q\left[\frac{2M_Z^2\hat{s}}{\hat{t}\hat{u}}+\frac{\hat{t}}{\hat{u}}+\frac{\hat{u}}{\hat{t}}\right]+c_3^q\left[\frac{2M_Z^2(\hat{t}-\hat{u})}{\hat{t}\hat{u}}-\frac{\hat{t}}{\hat{u}}+\frac{\hat{u}}{\hat{t}}\right]\right\}$$

$$\frac{d\hat{\sigma}_{-}^{q\bar{q}\to Z^0 g}}{d\hat{t}} = \frac{4\pi\alpha_s\alpha_{em}}{9\hat{s}^2\sin^2 2\theta_W}\left\{c_1^q\left[\frac{2M_Z^2\hat{s}}{\hat{t}\hat{u}}+\frac{\hat{t}}{\hat{u}}+\frac{\hat{u}}{\hat{t}}\right]-c_3^q\left[\frac{2M_Z^2(\hat{t}-\hat{u})}{\hat{t}\hat{u}}-\frac{\hat{t}}{\hat{u}}+\frac{\hat{u}}{\hat{t}}\right]\right\}$$

- Direct probe of circularly polarized gluon fragmentation.

Kinematic Dependence of Gluon Polarization

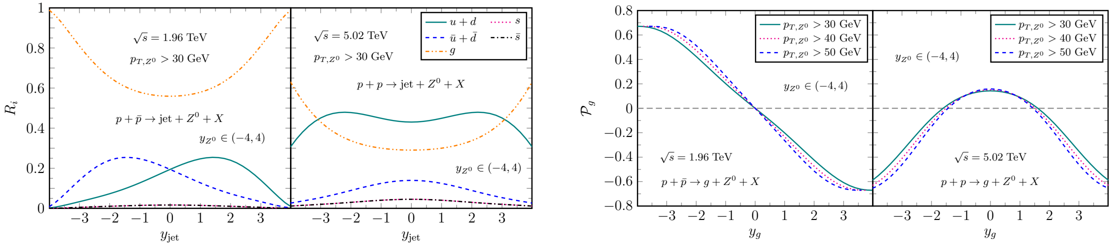
Gluon Polarization



- In the high-energy limit, $|\lambda_g|$ becomes sizable near $\hat{t} \sim 0$ or $\hat{u} \sim 0$.
- At the symmetric point $\hat{u} = \hat{t} = -(\hat{s} - M_V^2)/2$, the gluon polarization vanishes.
- A large rapidity gap between the vector boson and the jet is preferred.

Analysis of Gluon Jets at Hadron Colliders

Gluon Production and Polarization at Hadron Colliders



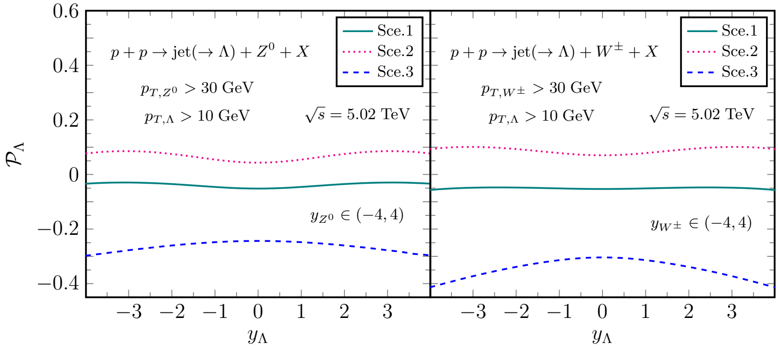
Production ratio of different flavor jets **Rapidity dependence of gluon polarization**

- Abundant gluon jets at hadron colliders, especially in $p\bar{p}$ collisions.
- Sizable P_g in forward/backward rapidity regions with clear kinematic dependence.
- Nonzero mid-rapidity P_g comes from the asymmetry of q & $\bar{q}$ PDF in the proton.

◇ Hadron colliders could provide a probe of circularly polarized gluon fragmentation.

Numerical Results

Λ Polarization in pp Collisions

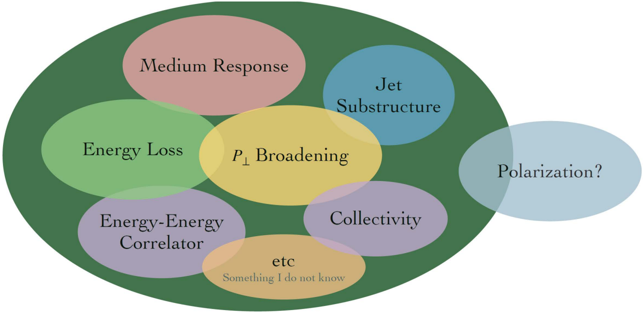


◇ P_Λ is sensitive to the flavor structure of G_{1L}.

◇ Measuring P_Λ can provide information about the hadronization of polarized partons.

From pp to AA: Polarized Jet Quenching

Keywords of Jet Quenching

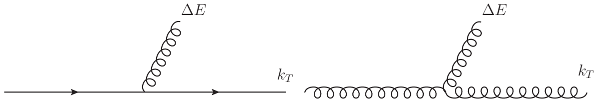


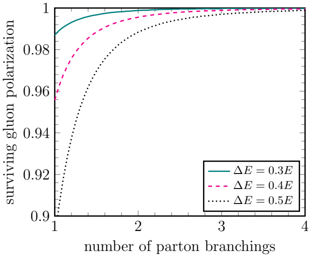
- ◇ The impact of jet quenching on polarization has received little attention.
- ◇ Λ polarization could provide a new spin-sensitive probe of jet–medium interactions.

What happens to the polarization of a polarized parton during splittings?

Spin Quenching for Quark and Gluon Splitting

- Polarized quark ⟶ helicity is conserved in gluon radiation ⟶ no spin quenching
- Polarized gluon ⟶ possible spin quenching

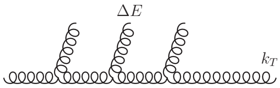




◇ A single hard splitting for gluon:
Larger energy loss (ΔE), stronger quenching.

$$\frac{\lambda_g^{\text{after}}}{\lambda_g^{\text{initial}}} = \frac{\Delta_L P_{gg}(\xi)}{P_{gg}(\xi)} = \frac{\xi[1-\xi(1-\xi)+(1-\xi)^2]}{[1-\xi(1-\xi)]^2}$$

◇ Multiple soft emissions carry away energy
but almost preserve the leading-gluon helicity.



Medium-induced Modification of Fragmentation Functions

Scheme I: Single-Hard-Branching

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

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

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

- Medium effects are absorbed into modified fragmentation functions.
- The parton loses energy through one relatively hard splitting.
- The average transverse energy loss ΔE_T is taken from the LBT model.

S. Cao, T. Luo, G. Y. Qin, X. N. Wang, Phys. Rev. C 94, 014909 (2016)
X. Y. Wu, L. G. Pang, G. Y. Qin, and X. N. Wang, Phys. Rev. C 98, 024913 (2018)

- For polarized gluons, an additional spin-quenching factor is included.

Medium-induced Modification of Fragmentation Functions

Scheme II: Multiple-Soft-Branching

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

- The parton loses energy through many soft emissions.
- The leading-parton helicity is approximately preserved.

$C_{ji}(\xi,\tau)$ describes the probability density of finding parton i with momentum fraction ξ in a cascade initiated by parton j and τ quantifies the magnitude of jet quenching.

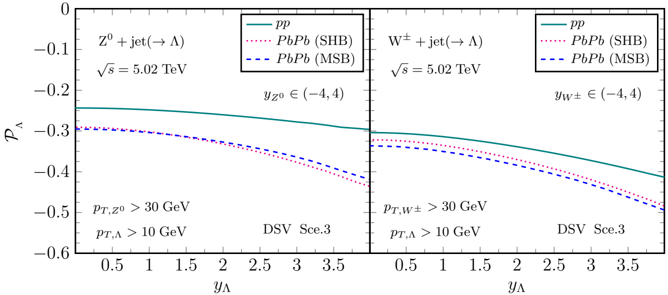
$$\frac{\partial C_{ji}(\xi,\tau)}{\partial \tau} = \sum_{k=g,q,\bar{q}} \int_\xi^1 dz K_{jk}(z) \sqrt{\frac{z}{\xi}} C_{ki}\left(\frac{\xi}{z}, \tau\right) - \int_0^1 dz \frac{1}{\sqrt{\xi}} C_{ji}(\xi,\tau)$$
$$\times \left\{ K_{qq}(z)\delta_{qj} + z[K_{gg}(z) + 2n_f K_{qg}(z)]\delta_{gj} \right\}$$

- Medium effects are incorporated through modified splitting kernels.

Y. Mehtar-Tani and S. Schlichting, JHEP 09 (2018) 144

Numerical Results: Medium Modification of Λ Polarization

Λ Polarization in AA Collisions



- AA collisions show an enhanced magnitude of Λ polarization compared with pp collisions.
- Parton energy loss shifts the observed Λ sample to a larger effective fragmentation fraction z_Λ. Since LEP data suggest stronger spin transfer at larger z_Λ, P_Λ is enhanced.

◇ P_Λ provides a spin-sensitive probe of the interaction between the polarized jet and the QGP.

Summary

- Jets produced with a vector boson in hadronic collisions are polarized due to the weak interaction, making this process ideal for extracting information about the longitudinal spin transfer G_{1L}, and for studying the quenching effects of polarized jets.

- Unpolarized hadron colliders offer a unique advantage for studying the hadronization of polarized gluons.
- Λ polarization is sensitive to the flavor dependence of polarized FFs.
- Λ polarization is enhanced in relativistic heavy-ion collisions due to the jet-quenching energy loss.

THANKS!

BACKUP

Λ Polarization in pp Collisions

The Polarization of Λ Hyperon

$$P_\Lambda(y_V, y_h) = \frac{\int \frac{\mathrm{d}z_d}{z_d^2} \int \mathrm{d}^2\vec{p}_{T,h} \sum_{ab\to Vd} x_a f_a(x_a)\, x_b f_b(x_b)\, \lambda_d \frac{1}{\pi} \frac{\mathrm{d}\hat{\sigma}_U^{ab\to Vd}}{\mathrm{d}\hat{t}} G_{1L,d}^{\Lambda}(z_d)}{\int \frac{\mathrm{d}z_d}{z_d^2} \int \mathrm{d}^2\vec{p}_{T,h} \sum_{ab\to Vd} x_a f_a(x_a)\, x_b f_b(x_b) \frac{1}{\pi} \frac{\mathrm{d}\hat{\sigma}_U^{ab\to Vd}}{\mathrm{d}\hat{t}} D_{1,d}^{\Lambda}(z_d)}$$

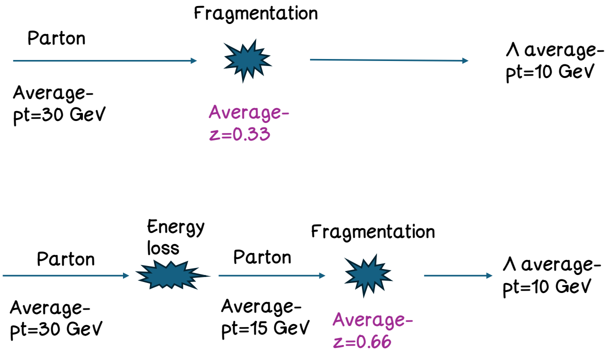
where $$\frac{\mathrm{d}\hat{\sigma}_U^{ab\to Vd}}{\mathrm{d}\hat{t}} = \frac{\mathrm{d}\hat{\sigma}_+^{ab\to Vd}}{\mathrm{d}\hat{t}} + \frac{\mathrm{d}\hat{\sigma}_-^{ab\to Vd}}{\mathrm{d}\hat{t}}$$

The Helicity of Parton d

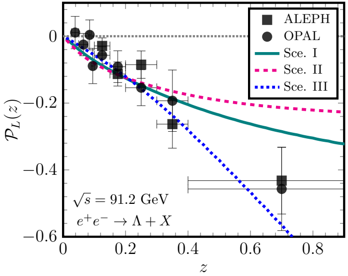
$$\lambda_d = \left(\frac{\mathrm{d}\hat{\sigma}_+^{ab\to Vd}}{\mathrm{d}\hat{t}} - \frac{\mathrm{d}\hat{\sigma}_-^{ab\to Vd}}{\mathrm{d}\hat{t}} \right) \Bigg/ \left(\frac{\mathrm{d}\hat{\sigma}_+^{ab\to Vd}}{\mathrm{d}\hat{t}} + \frac{\mathrm{d}\hat{\sigma}_-^{ab\to Vd}}{\mathrm{d}\hat{t}} \right)$$

Extra Details on Energy Loss

Transverse Energy Loss and the Enhancement of Λ Polarization



$$P_L^{\Lambda}(z) \sim \lambda_q \frac{G_{1L}}{D_1}$$



Extra Details on Energy Loss

Transverse Energy Loss