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Quenching of polarized jets

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September 24, 2025

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manuscript in preparation (2025)

100 YEARS SPIN 2025

26th International Symposium on Spin Physics

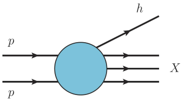
A Century of Spin

Contents

Introduction

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.

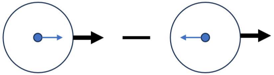
Leading Twist Collinear Fragmentation Functions

$$\textbf{Quarks} \xrightarrow{\text{Hadronization}} \textbf{Hadrons}$$

$$D_q^h(z) = D_1^h(z) + \lambda_q \lambda_h G_{1L}^h(z) + S_{Tq} \cdot S_{Th} H_{1T}(z)$$

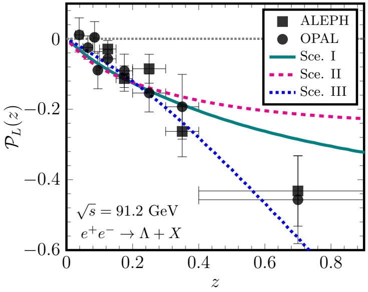
Longitudinal Spin Transfer G_{1L}

G_{1L} =



Introduction

DSV Parameterization

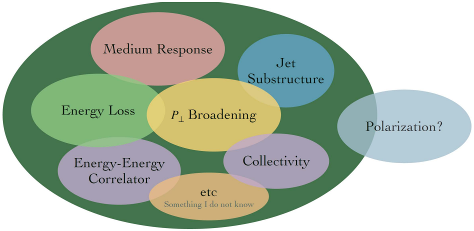


D. de Florian, M. Stratmann, W. Vogelsang, Phys. Rev. D **57**, (1998)5811–5824
K. B. Chen, W. H. Yang, Y. J. Zhou and Z. T. Liang, Phys. Rev. D **95** (2017)3, 034009

DSV Scenarios - flavor dependence?

Sce. I: only s quark contributes to Λ polarization.
Sce. II: s quark contributes positively, while u and d quarks contribute slightly negatively.
Sce. III: u, d, and s quarks contribute equally.

Keywords of Jet Quenching



Λ polarization in $p+p \to Z^0/W^\pm$+ jet ($\to \Lambda$) process

Polarized Jets

Unpolarized collisions

+

Weak interaction

⇓

Polarized jets

⇓

Λ Hyperons

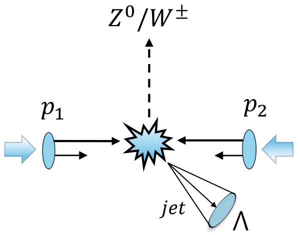
Jet Associated with a Vector Boson Production

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

Partonic Cross Section with Helicity-amplitude Method

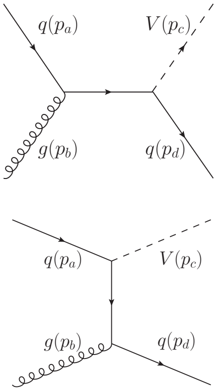
$$\frac{d\hat{\sigma}_+^{ab\to Vd}}{d\hat{t}} : \quad \text{probability for } |d,\uparrow\rangle$$

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



Helicity-dependent Partonic Cross Sections for Quark Jet

$q + g \to V + q$



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

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

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

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

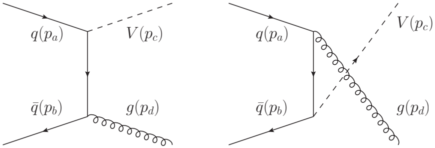
$q(\bar{q}) + g \to W^\pm + q(\bar{q})$

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

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

Helicity-dependent Partonic Cross Sections for Gluon Jet

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



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

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

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

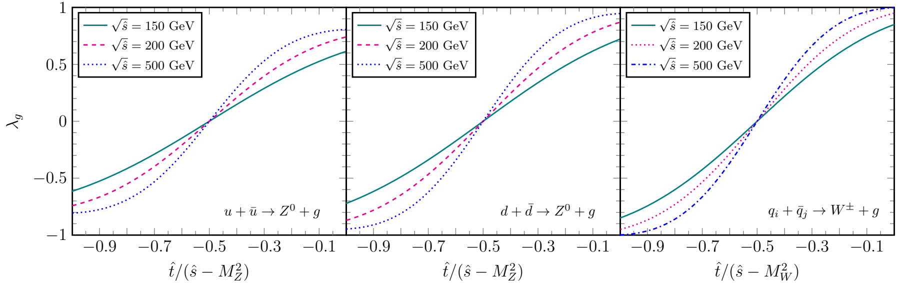
$q+\bar{q} \to Z^0 + g$

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

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

Partonic Helicity of Gluon

The Gluon Helicity

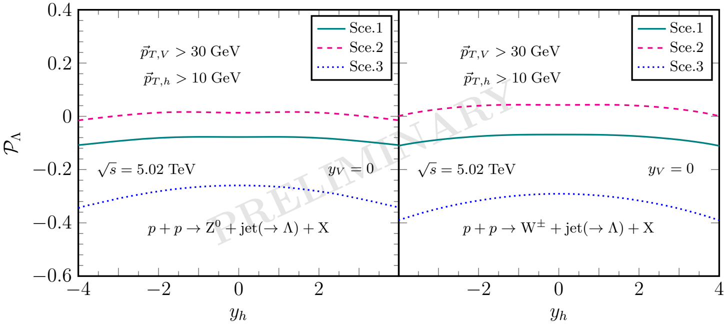


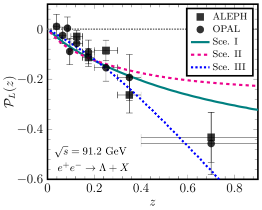
At high energy limit and $\hat{t} \sim 0$ or $\hat{u} \sim 0$: $\lambda_{g,Z^0} = \pm \frac{2c_V^q c_A^q}{(c_V^q)^2 + (c_A^q)^2}$ and $\lambda_{g,W^\pm} = \pm 1$.

At the symmetric point, $\hat{u} = \hat{t} = -(\hat{s} - M^2_{Z/W})/2$, the gluon polarization vanishes.

Numerical Results

Polarization of Lambda Hyperons





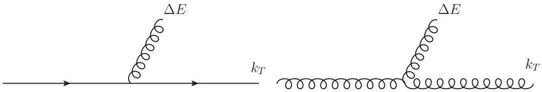
LEP data and DSV global fit results

- Λ polarization is highly sensitive to the flavor dependence of the polarized fragmentation function.

Λ polarization in A + A $\to Z^0/W^\pm + \text{jet}(\to \Lambda)$ process

Spin Quenching

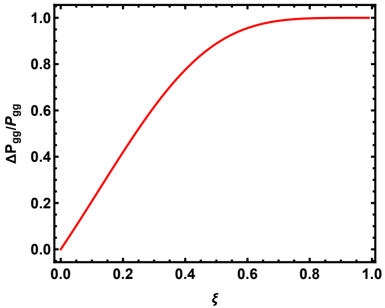
- Quark jet $\longrightarrow$ helicity is conserved in gluon radiation $\longrightarrow$ no spin quenching
- Gluon jet $\longrightarrow$ spin quenching



- A single splitting for gluon:

$$\frac{\Delta P_{gg}(\xi)}{P_{gg}(\xi)} = \frac{\xi[1-\xi(1-\xi)+(1-\xi)^2]}{[1-\xi(1-\xi)]^2}$$

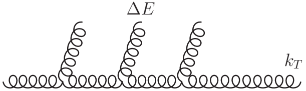
ΔE : total energy loss
ξ: final gluon carried momentum fraction
$\Delta P_{gg}(\xi)$: polarized gluon splitting functions
$P_{gg}(\xi)$: unpolarized gluon splitting functions



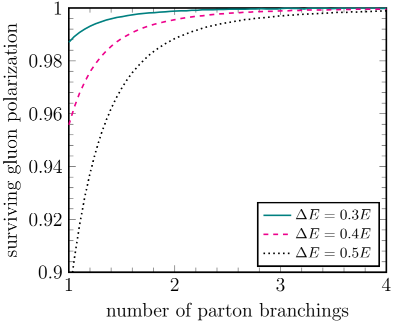
Λ polarization in A + A $\to Z^0/W^\pm$ + jet($\to \Lambda$) process

Spin Quenching

- Gluon jet $\longrightarrow$ spin quenching
- After n successive splittings:



$$\frac{\lambda_g^{after}}{\lambda_g^{initial}} = \left(\frac{\Delta_L P_{gg}(\xi)}{P_{gg}(\xi)}\right)^n$$



- The larger the ΔE, the stronger the quenching.
- The overall polarization loss is small and approaches zero under multiple splittings.

Energy Loss: Single Hard Branching and Multiple Soft Branching

Medium-induced Modification of Fragmentation Functions (Single Hard Branching)

$$G_{1L,q}^{\text{med}}(z_d) = \int \frac{\mathrm{d}\xi}{\xi^2}\xi\delta\Big(\xi - \frac{k_T}{k_T+\Delta E_T}\Big)G_{1L,q}\Big(\frac{z_d}{\xi}\Big)$$

$$G_{1L,g}^{\text{med}}(z_d) = \int \frac{\mathrm{d}\xi}{\xi^2}\xi\delta\Big(\xi - \frac{k_T}{k_T+\Delta E_T}\Big)\boxed{\frac{\xi[1-\xi(1-\xi)+(1-\xi)^2]}{[1-\xi(1-\xi)]^2}}G_{1L,g}\Big(\frac{z_d}{\xi}\Big)$$

The average transverse energy loss ΔE_T is calculated by the Linear Boltzmann Transport (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)

Medium-induced Modification of Fragmentation Functions (Multiple Soft Branching)

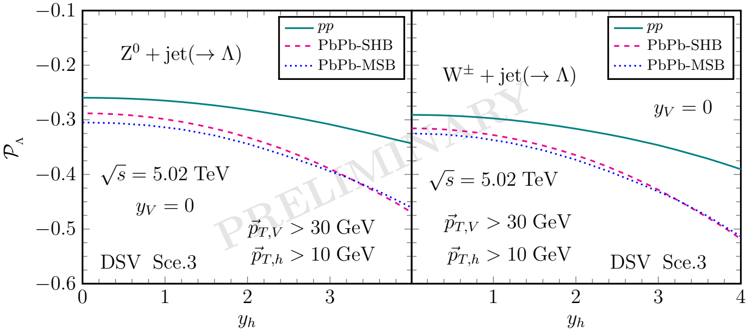
$$G_{1L}^{\text{med}}(z_d) = \int \frac{\mathrm{d}\xi}{\xi^2}C_{dd}(\xi,\tau_{\text{max}})G_{1L}\Big(\frac{z_d}{\xi}\Big)$$

$C_{ji}(\xi,\tau)$ is the momentum fraction density of parton i carrying the momentum fraction ξ inside the cascade initialized by parton j, and τ is a dimensionless time quantifying the magnitude of jet quenching.

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

Numerical Results

Polarization of Lambda Hyperons



- Clear enhancement in AA collisions.

$\Rightarrow$ A sensitive probe to the interaction between polarized-jet and 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.

- Λ polarization is sensitive to the flavor dependence of polarized FFs.
- Λ polarization is strongly enhanced in relativistic heavy-ion collisions due to jet-quenching energy loss.

THANKS!

BACKUP

Extra Details Spin quenching

Gluon Splitting Functions

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

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

The ratio $\Delta_L P_{gg}(\xi)/P_{gg}(\xi)$ characterizes the survival probability of the gluon's polarization after one splitting that losses energy fraction $1-\xi$.

Extra Details on Evolution Equations

Medium-induced Parton Evolution Equation

$$\frac{\partial C_{ji}(\xi,\tau)}{\partial\tau} = \sum_{k=g,q,\bar{q}} \int_{\xi}^{1} dz K_{jk}(z)\sqrt{\frac{z}{\xi}}C_{ki}\left(\frac{\xi}{z},\tau\right)$$

$$- \int_{0}^{1} dz\left\{K_{qq}(z)\delta_{qj} + z[K_{gg}(z) + 2n_f K_{qg}(z)]\delta_{gj}\right\}\frac{1}{\sqrt{\xi}}C_{ji}(\xi,\tau)$$

$$\tau_{\text{max}} = \bar{\alpha}\sqrt{\frac{\hat{q}L^2}{Q}} \qquad \bar{\alpha} = 0.2 \qquad L = 4\,\text{fm}$$

Extra Details on Evolution Equations

Kernels in the Coupled Evolution Equations

$$K_{gg}(z) = \frac{2N_c}{2} \frac{(1-z+z^2)^2}{z(1-z)} \sqrt{\frac{N_c(1-z+z^2)}{z(1-z)}}$$

$$K_{qq}(z) = \frac{C_F}{2} \frac{1+z^2}{1-z} \sqrt{\frac{N_c z + C_F(1-z)^2}{z(1-z)}}$$

$$K_{qg}(z) = \frac{T_F}{2} \left[z^2 + (1-z)^2\right] \sqrt{\frac{C_F - N_c z(1-z)}{z(1-z)}}$$

$$K_{gq}(z) = \frac{C_F}{2} \frac{1+(1-z)^2}{z} \sqrt{\frac{N_c(1-z) + C_F z^2}{z(1-z)}}$$

with $N_c = 3$, $C_F = 4/3$ and $T_F = 1/2$.

Λ Polarization in pp Collisions

The Polarization of Λ Hyperon

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

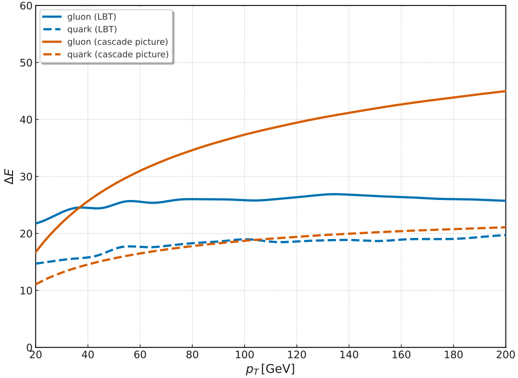
where $$\frac{\mathrm{d}\hat{\sigma}_U^{ab\to Vd}}{\mathrm{d}\hat{t}} = \frac{\mathrm{d}\hat{\sigma}_+^{ab\to Vd}}{\mathrm{d}\hat{t}} + \frac{\mathrm{d}\hat{\sigma}_-^{ab\to Vd}}{\mathrm{d}\hat{t}}$$

The Helicity of Parton d

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

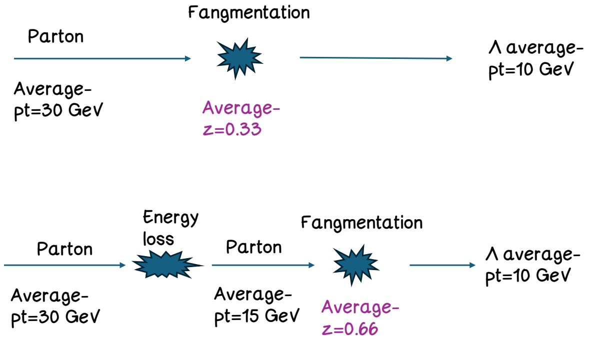
Extra Details on Energy Loss

Energy Loss and the Enhancement of Λ Polarization



Extra Details on Energy Loss

Energy Loss and the Enhancement of Λ Polarization



Extra Details on Fragmentation Functions

DSV Unpolarized Part

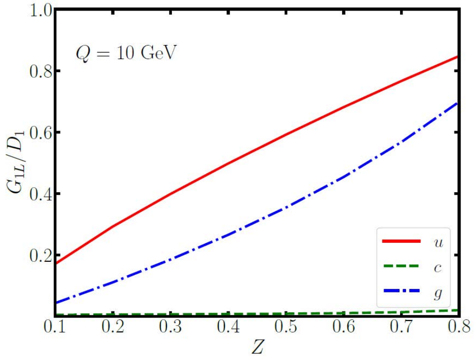
$$D_1^{u\to\Lambda+\bar{\Lambda}}(z) = D_1^{u\to\Lambda}(z) + D_1^{u\to\bar{\Lambda}}(z)$$

Decomposition

$$D_1^{u\to\Lambda}(z) = \frac{1}{1+(1-z)^2} D_1^{u\to\Lambda+\bar{\Lambda}}(z)$$

$$D_1^{u\to\bar{\Lambda}}(z) = \frac{(1-z)^2}{1+(1-z)^2} D_1^{u\to\Lambda+\bar{\Lambda}}(z)$$

DSV Scenario 3



Extra Details

Gluon Polarization Vector

$$\not\epsilon_g^{\pm}(p_d) = -\frac{\not p_d \not p_a \not p_b (1 \pm \gamma_5) + \not p_b \not p_a \not p_d (1 \mp \gamma_5)}{4\sqrt{(p_a \cdot p_b)(p_a \cdot p_d)(p_b \cdot p_d)}}$$

T. T. Wu and R. Gastmans, Int. Ser. Monogr. Phys. 80, 1–648 (1990)

Numerical Results

- nPDF: CTEQ PDFs + EPPS cold nuclear effects

CTEQ-TEA, Phys. Rev. D 93, 3, 033006 (2016)

K. J. Eskola, et al, Eur. Phys. J. C 77, 3, 163 (2017)