Optimal Spin Quantization Axes for Dileptons and Quarkonium with Large Q_T

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[PRD 79, 014025 and PRD 79, 054013]

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Information of particle spin

- How can we measure spin information of unstable particles?
  Angular distribution of decay products
  For example, $\gamma^* \to l^+ l^-$

  $$\frac{d\sigma}{d\Omega} \propto 1 + \alpha \cos^2\theta + \beta \sin 2\theta \cos\phi + \cdots$$

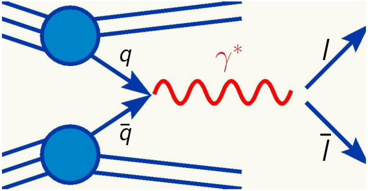
  $\Rightarrow$ Coefficients depend on choice of
  Spin Quantization Axes (SQA)
- Difficulties
  - Often not enough data in practice
  - Dilution of the information due to varying parton momenta in hadron collisions
  - Large high-order corrections

Spin Quantization axis

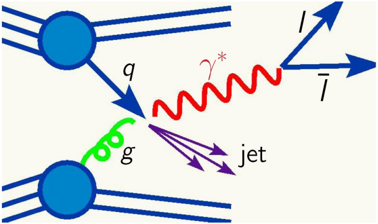
- How can we maximize the spin information?
  Can we maximize with proper choice of SQA?

- Dilepton production from virtual photon

Drell-Yan



LO parton: $qg \longrightarrow \gamma^* g$



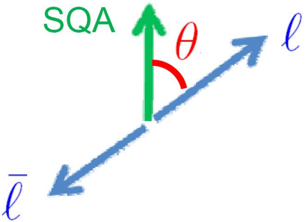
Which SQA is optimal to these processes?

Spin Quantization axis

- Dilepton production from a virtual photon

$$\frac{d\sigma}{d\cos\theta} \propto 1 + \left(\frac{\sigma_T - 2\sigma_L}{\sigma_T + 2\sigma_L}\right)\cos^2\theta$$

SQA determines σ_T and σ_L.
SQA is $\hat{\epsilon}_L$ in virtual photon rest frame.



virtual photon rest frame

- Longitudinal polarization vector ϵ_L

$$\epsilon_L^\mu \propto \left(-g^{\mu\nu} + \frac{Q^\mu Q^\nu}{Q^2}\right) X_\nu,$$

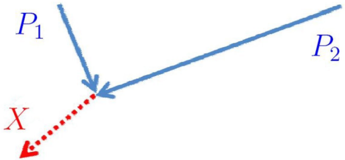
satisfies $\epsilon_L \cdot Q{=}0$ and $\epsilon_L^2 = -1$.
(Q = virtual photon momentum)

SQA in the hadron collision plane

$$\epsilon_L^\mu \propto \left(-g^{\mu\nu} + \frac{Q^\mu Q^\nu}{Q^2}\right) X_\nu = \left(-X^\mu + Q^\mu \frac{Q \cdot X}{Q^2}\right)$$

- In Q rest frame SQA $= \hat{\epsilon}_L = -\hat{\mathbf{X}}$
- In X rest frame $\hat{\epsilon}_L = \hat{\mathbf{Q}}$
  $\Rightarrow$ Helicity $=$ Spin projection along SQA
- Collision of hadrons with momenta $\mathbf{P}_1$ and $\mathbf{P}_2$:
  In general $\mathbf{X}$ is chosen to lie in the collision plane in Q rest frame.

$$X^\mu = aP_1^\mu + bP_2^\mu$$



SQA in the hadron collision plane

$$X^{\mu} = aP_1^{\mu} + bP_2^{\mu}$$

where a and b are scalar functions of Q, P_1, P_2, and $\cdots$

- Specifying a/b determines $\hat{X}$ hence, SQA $\Rightarrow \sigma_L$ and σ_T
- Examples of well known SQA's

$$a/b = 1 \quad \text{(c.m. helicity axis)}$$
$$a/b = -Q \cdot P_2/Q \cdot P_1 \quad \text{(Collins-Soper axis)}$$
$$a/b = +Q \cdot P_2/Q \cdot P_1 \quad \text{(perpendicular helicity axis)}$$

c.m. helicity axis

$$X^{\mu}_{cmh} = P^{\mu}_{1} + P^{\mu}_{2}$$

Collins-Soper axis

[Collins and Soper PRD (1977)]

$$X^{\mu}_{CS} = \frac{P^{\mu}_{1}}{Q\cdot P_1} - \frac{P^{\mu}_{2}}{Q\cdot P_2}$$

perpendicular helicity axis

$$X^{\mu}_{\perp h} = \frac{P^{\mu}_{1}}{Q\cdot P_1} + \frac{P^{\mu}_{2}}{Q\cdot P_2}$$

CS axis is orthogonal to $\perp h$ axis.

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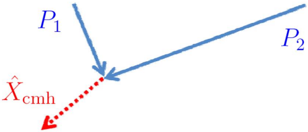
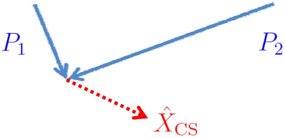
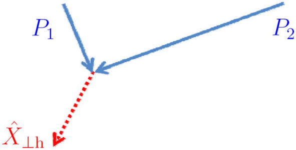
In Q rest frame







$\hat{\mathbf{X}}_{cmh} \parallel \mathbf{P}_1 + \mathbf{P}_2$

$\hat{\mathbf{X}}_{CS} \parallel \mathbf{v}_1 - \mathbf{v}_2$

$\hat{\mathbf{X}}_{\perp h} \parallel \mathbf{v}_1 + \mathbf{v}_2$

c.m. helicity axis

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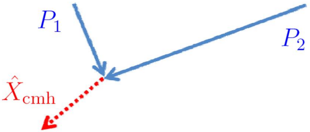

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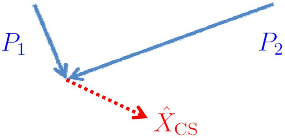
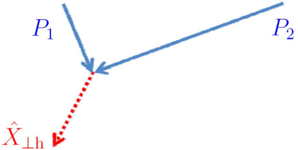


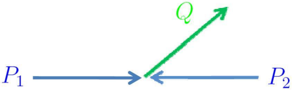
$\hat{\mathbf{X}}_{CS} \parallel \mathbf{v}_1 - \mathbf{v}_2$



$\hat{\mathbf{X}}_{\perp h} \parallel \mathbf{v}_1 + \mathbf{v}_2$

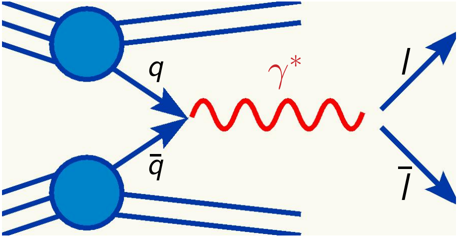
In X rest frame

hadron c.m. frame



perpendicular frame

Drell-Yan process at small Q_T [Drell and Yan PRL (1970)]



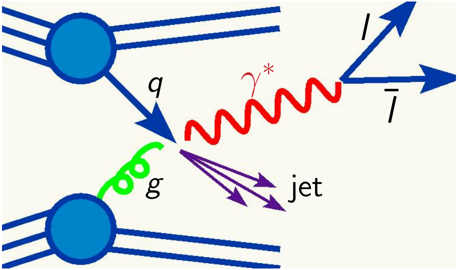
- For collinear partons at LO, $\hat{\sigma}_{tot} = \hat{\sigma}_T$ and $\hat{\sigma}_L = 0$
- For partons with intrinsic transverse momentum $\mathbf{k}_\perp$

$$\hat{\sigma}_L \propto \frac{4\pi e_q^2 \alpha \langle k_\perp^2 \rangle}{Q^2} \frac{a^2 x_2^2 + b^2 x_1^2}{(a x_2 - b x_1)^2}$$

- Optimal Spin Quantization Axes
  - $\hat{\sigma}_L$ is minimized when $a/b = -x_1/x_2 = -\frac{Q\cdot P_2}{Q\cdot P_1}$.
    $\Rightarrow$ Collins-Soper axis [Lam, Tung PRD (1979)]
  - $\hat{\sigma}_L$ is maximized when $a/b = x_1/x_2 = \frac{Q\cdot P_2}{Q\cdot P_1}$.
    $\Rightarrow$ perpendicular helicity axis

Dilepton Production at large Q_T

LO parton processes :
$q\bar{q} \to \gamma^* g$, $qg \to \gamma^* q$, and $\bar{q}g \to \gamma^* \bar{q}$



- $qg \to \gamma^* q$ and $\bar{q}g \to \gamma^* \bar{q}$ are dominant at Tevatron
- Longitudinal Cross Section :

$$\hat{\sigma}_L \propto \frac{(ax_2 - bx_1)^2 + b^2 x_1^2}{(aQ \cdot P_1 + bQ \cdot P_2)^2 - abQ^2}$$

- a/b extremizing $\hat{\sigma}_L \Rightarrow$ Optimal qg axes

a/b depends on momentum fractions x_1 and x_2.

$\to$ x_1 and x_2 can be estimated from measurements. (later)

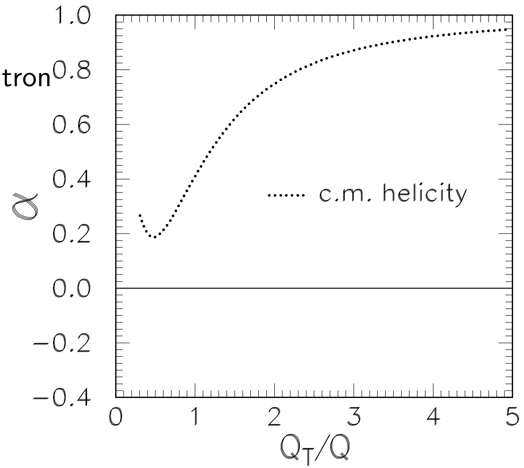
Dilepton Production at large Q_T

- Dilepton production at Tevatron $\sqrt{s} = 1.96$ TeV
- Polarization variable α

$$\alpha = \frac{\sigma_T - 2\sigma_L}{\sigma_T + 2\sigma_L}$$

$$\Rightarrow -1 \leq \alpha \leq +1$$

- *c.m.* helicity axis



- Orthogonal SQA's : ⊥ *helicity* and Collins-Soper axes
- Optimal SQA's : maximal and minimal *qg* axes

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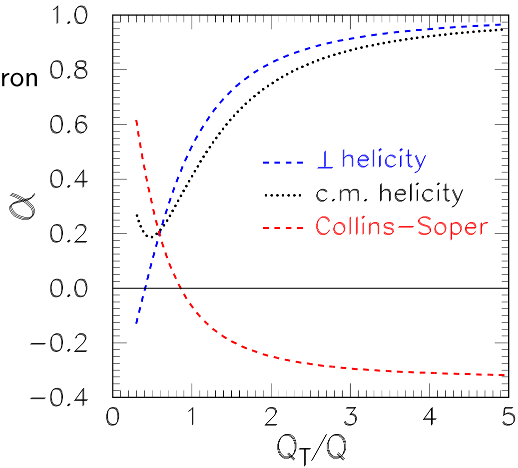

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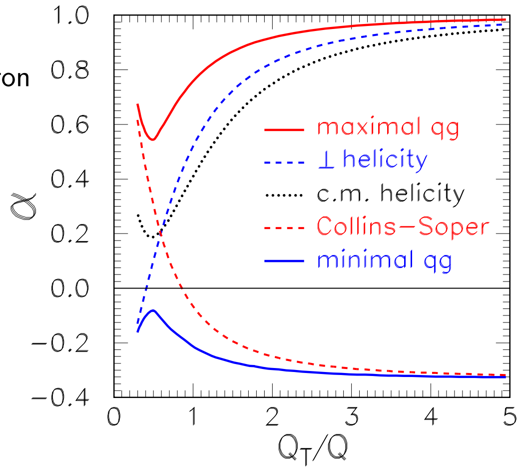

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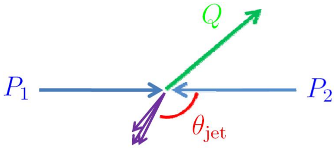
Momentum fractions of colliding partons

$$X^\mu = aP_1^\mu + bP_2^\mu$$

- For optimal SQA, a/b depends on the momentum fractions x_1 and x_2. However x_1 and x_2 are not direct measurables.
- Kinematic constraint gives
$$2\,(x_1 P_1 \cdot Q + x_2 P_2 \cdot Q) = x_1 x_2 s + Q^2$$
- x_1/x_2 can be estimated from angle θ_{jet} of the recoiling jet in the hadron c.m. frame.

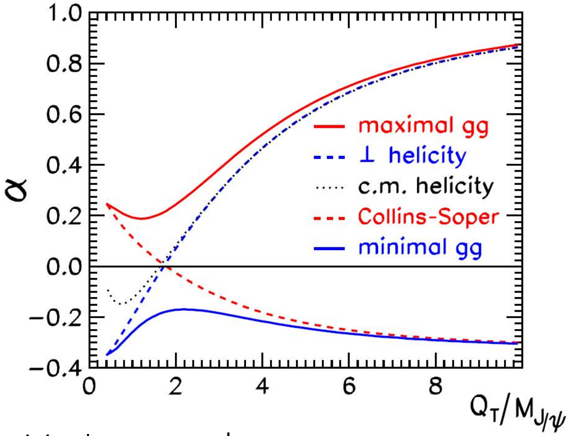
$$\frac{x_1}{x_2} = \frac{(Q_0 + Q_L)\sin\theta_{jet} + Q_T(1+\cos\theta_{jet})}{(Q_0 - Q_L)\sin\theta_{jet} + Q_T(1-\cos\theta_{jet})}$$



2 equations in 2 unknowns $\Rightarrow$ x_1, x_2

Quarkonium Production at LO

- J/ψ production at Tevatron, $\sqrt{s} = 1.96$ TeV
- CDF measurement and predictions : *c.m.* helicity axis
- Orthogonal SQA's : $\perp$ helicity and *CS* axes



- Optimal SQA's : maximal & minimal *gg* axes show greater contrast.
  angle of recoiling jet required.
- Large *NLO* corrections to α with *c.m.* helicity axis. [Artoisenet et al PRL 2008] [Gong et al PLB 2009]
  $\Rightarrow$ An optimal SQA less sensitive to *NLO* corrections ?

Conclusion

- Optimal SQA can improve spin information of particles.
- Drell-Yan process at small Q_T,
  Collins-Soper axis minimizes $\hat{\sigma}_L$ from parton transverse momentum.
  $\perp$ helicity axis maximizes $\hat{\sigma}_L$
- Dilepton (and J/ψ) production at large Q_T,
  Orthogonal SQA's : $\perp h$ and CS give contrast in polarization.
  see also [Faccioli et al hep-ph/0902.4462]
  Optimal SQA's: show greater contrast in polarization
  require angle of recoiling jet
- Further applications
  Optimal SQA's in Drell-Yan at NLO (in progress)
  SQA's *less sensitive* to higher-order corrections ?
  Optimal SQA's for $W^{\pm}$, Z^0, and t and new particles at LHC?