Understanding the quarkonium production mechanism from polarization measurements

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Outline

I. J/ψ polarization puzzle

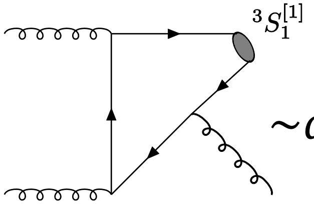
II. Recent progress

III. Rotation-invariant observables

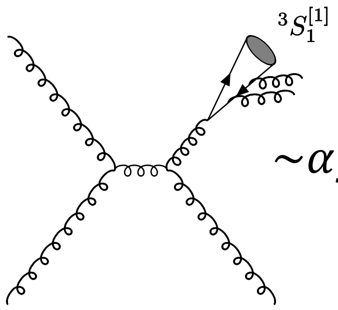
IV. Summary

➢ ψ' surplus at Tevatron

- Data overshoot CSM calculation by a factor of 30 at high p_T
- Fragmentation contribution included
- Other mechanism is needed



$\sim\alpha_s^3 \frac{m_Q^4}{p_T^8}$



$\sim\alpha_s^5 \frac{1}{p_T^4}$

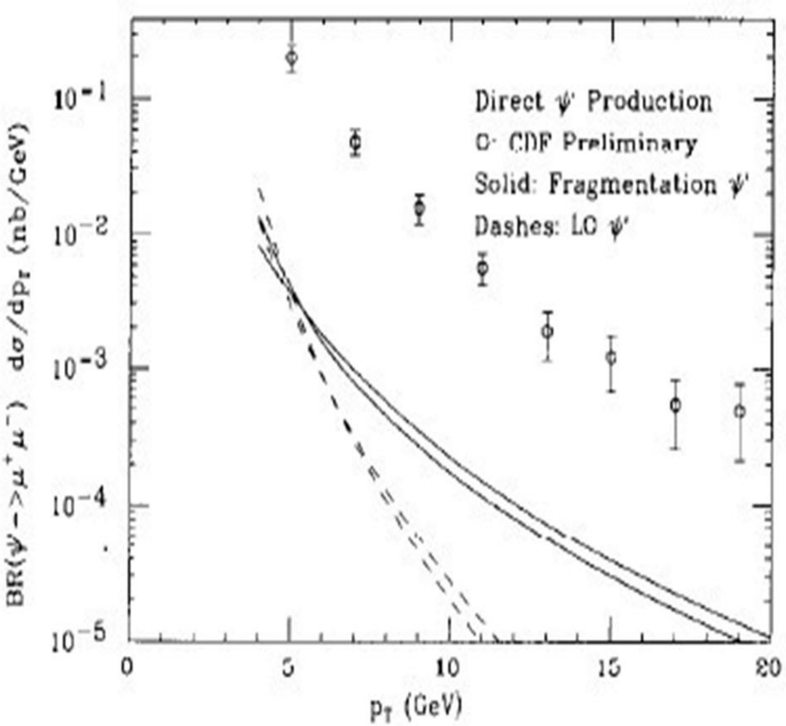


Fig. 4. Preliminary CDF data for prompt ψ' production (O) compared with theoretical predictions of the total fragmentation contribution (solid curves) and the total leading-order contribution (dashed curves).

NRQCD and CO mechanism

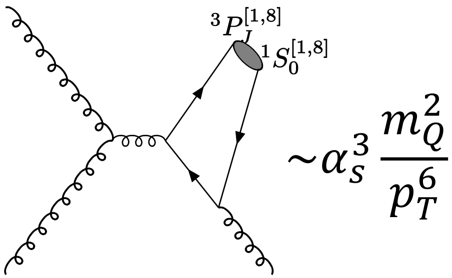
Bodwin, Braaten, Lepage, 9407339

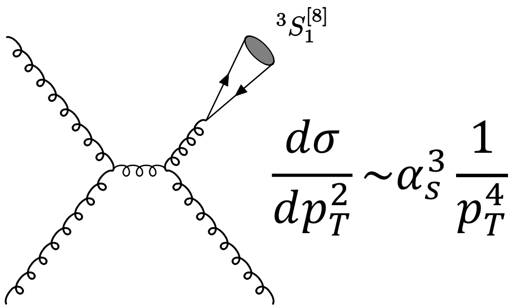
➢ NRQCD factorization

$$d\sigma_\psi = \sum_{i,j,n} \int \underbrace{dx_1 dx_2 \, G_{i/A} G_{j/B}}_{\Lambda_{QCD}} \times \underbrace{\hat{\sigma}[ij \to c\bar{c}[n] + X]}_{m_c} \times \underbrace{\langle O_n^\psi \rangle}_{m_c v}$$

➢ CO mechanism

States	p_T behavior at LO
$^3S_1^{[1]}$	p_T^{-8}
$^3S_1^{[8]}$	p_T^{-4}
$^1S_0^{[8]}$	p_T^{-6}
$^3P_J^{[8]}$	p_T^{-6}

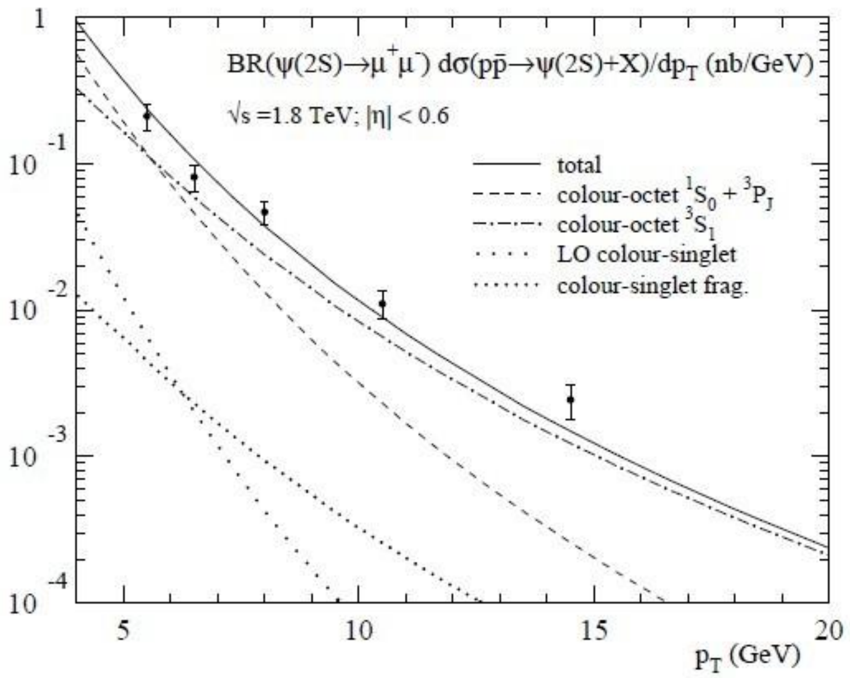


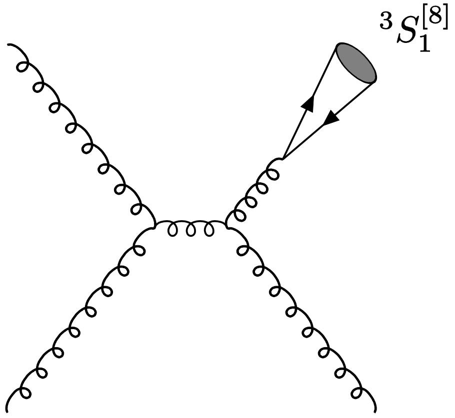


${}^3S_1^{[8]}$ dominance

➢ **LO NRQCD calculation**

- ${}^3S_1^{[8]}$ dominant at high p_T
- Predicts transverse polarization



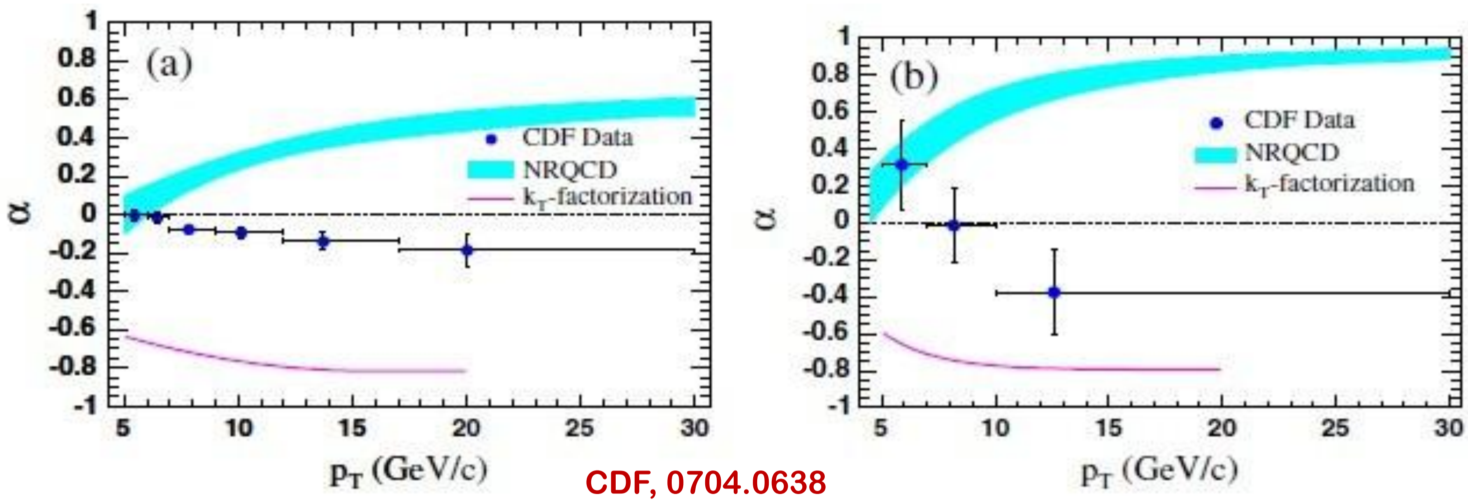


Kramer, 0106120

Polarization puzzle

➤ $\psi \to l^+ l^-$

- $W(\cos\theta, \phi) \propto \frac{1}{3+\alpha}(1 + \alpha \cos^2\theta)$
- **LO NRQCD prediction contradicts with CDF data**



CDF, 0704.0638

FIG. 4 (color online). Prompt polarizations as functions of p_T: (a) J/ψ and (b) $\psi(2S)$. The band (line) is the prediction from NRQCD [4] (the k_T-factorization model [9]).

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Theoretical side: high order calculation

- 0703113: Campbell, Maltoni, Tramontano

NLO, cross section, S-wave

- 0802.3727: Gong, Wang

NLO, polarization, S-wave

- 0806.3282: Artoisenet, Campbell, Lansberg, Maltoni, Tramontano

$\mathrm{NNLO}^{\star}$, S-wave

- 1002.3987: YQM, Wang, Chao
- 1009.3655: YQM, Wang, Chao
- 1009.5662: Butenschöen, Kniehl

Complete NLO (S- and P-wave), cross section

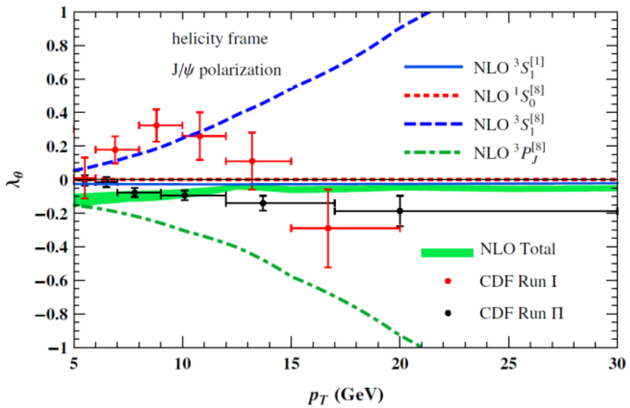
- 1201.1872: Butenschöen, Kniehl
- 1201.2675: Chao,YQM,Shao,Wang,Zhang
- 1205.6682: Gong,Wan,Wang,Zhang

Complete NLO (S- and P-wave), with polarization

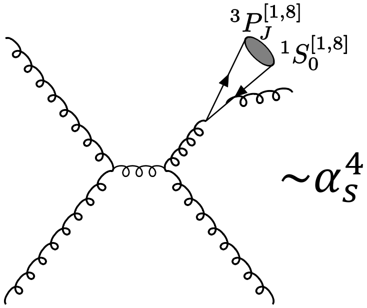
NOT fully comprehensive!!!

Explain J/ψ polarization

- Transverse polarization cancelled between ${}^3S_1^{[8]}$ and ${}^3P_J^{[8]}$ channel at NLO, ${}^1S_0^{[8]}$ may dominate



Chao,YQM,Shao,Wang,Zhang,1201.2675



$$\sim \alpha_s^4 \frac{1}{p_T^4}$$

- ${}^1S_0^{[8]}$ dominant mechanism: agreed by new studies

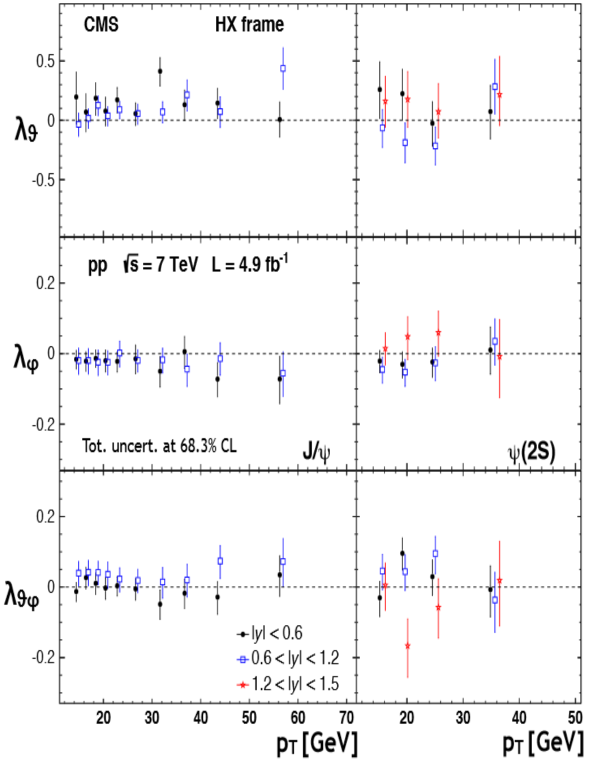
Bodwin, Chung, Kim, Lee, 1403.3612

Faccioli,Knunz,Lourenco,Seixas,Wohri,1403.3970

Experimental side: better measurements

- General observable distribution for dilepton decay of inclusive produced vector meson

$$W(\cos\vartheta,\varphi) \propto \frac{1}{(3+\lambda_\vartheta)}(1+\lambda_\vartheta\cos^2\vartheta+\lambda_\varphi\sin^2\vartheta\cos2\varphi + \lambda_{\vartheta\varphi}\sin2\vartheta\cos\varphi)$$



- "Full'' double angle analyses
- To avoid bias in single angle analyses

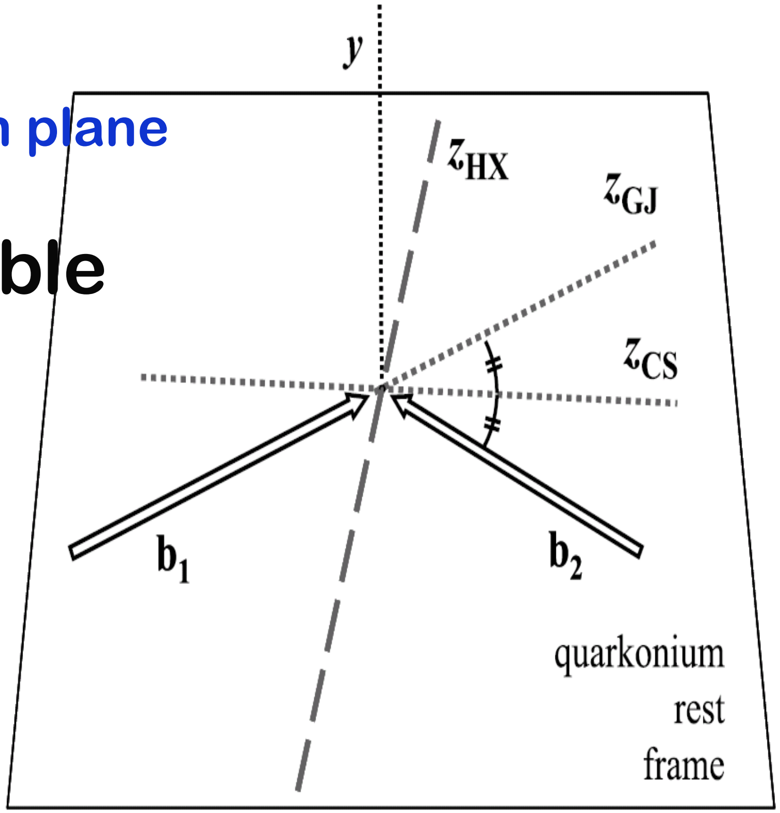
SO(2) rotation invariant observable

- Experimentally commonly used reference frames
  - S-channel helicity frame, Collins-Soper frame, Gottfried-Jakson frame
  - Related by a rotation in the production plane
- Frame independent observable

$$\tilde{\lambda} \equiv \mathcal{F}_{\{-3,0,1\}} = \frac{\lambda_\vartheta + 3\lambda_\varphi}{1 - \lambda_\varphi}$$

Faccioli, Lourenco, Seixas, Wohri, 1006.2738

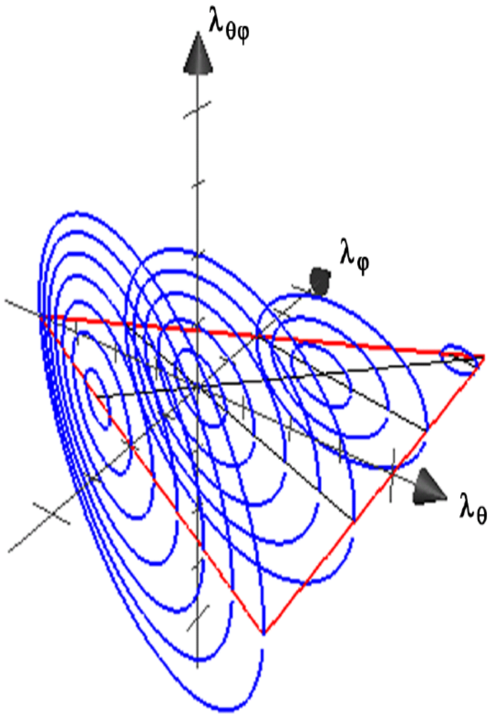
  - On behind the rotation invariant of Lam-Tung relation



Another SO(2) rotation invariant observable

- Using complicated algebra, another invariant is found

$$\lambda^* \equiv \frac{1+\Delta/4}{\sqrt{\Delta^2+4\lambda_{\theta\phi}{}^2}} = \frac{1+(\lambda_\theta-\lambda_\phi)/4}{\sqrt{(\lambda_\theta-\lambda_\phi)^2+4\lambda_{\theta\phi}{}^2}}$$



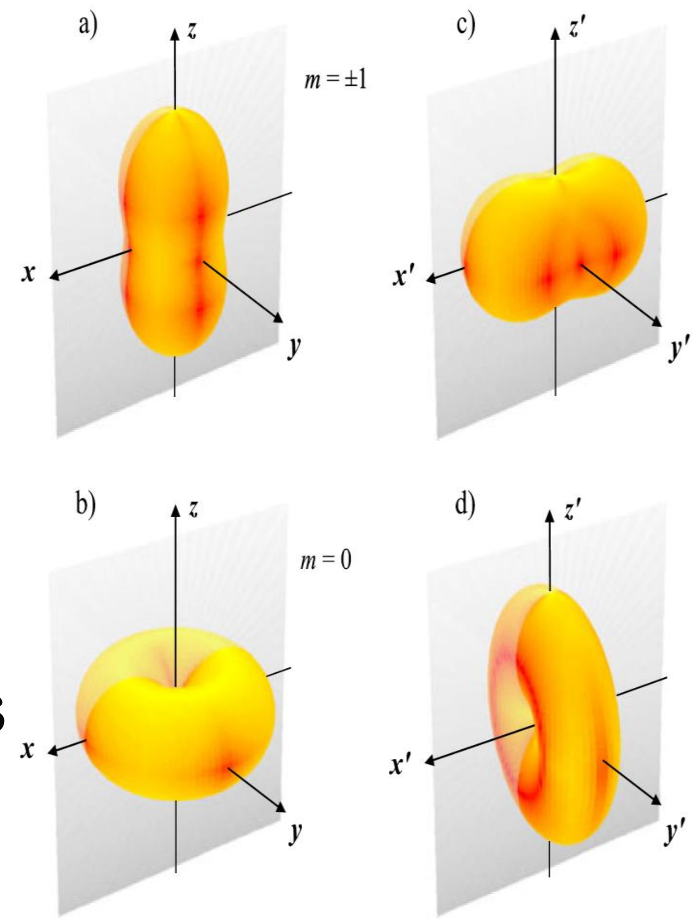
Palestini, 1012.2485

FIG. 1 (color online). Ellipses of rotation in the space of the coefficients of the angular distribution are illustrated, showing four sets corresponding to $\tilde{\lambda} = -1, 0, 3, 37$ (see Sec. V).

Properties of invariants

➢ Nice feature of rotation invariants

- Experimental axis can be different from natural axis
- Less sensitive to detector acceptances
- Can be checked between measurements from different reference frame



Faccioli, Lourenco, Seixas, Wohri, 1006.2738

➢ Find out all rotation invariants

- SO(3) rotation invariants can be even powerful

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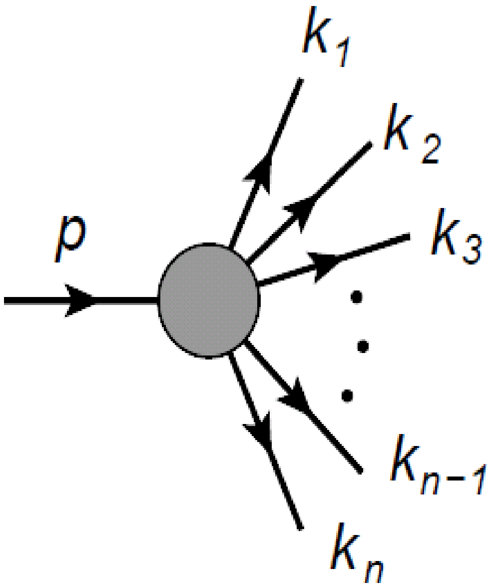
Angular distribution

- **General angular distribution of probe particle B in the rest frame of decay particle A**

YQM, Zhang, Qiu, in progress

$$\frac{1}{\Gamma}\frac{\mathrm{d}\Gamma}{\mathrm{d}\Omega_B} \equiv f(\theta,\phi) = \sum_{l=0}^{2J}\sum_{m=-l}^{l} f_{l,m} Y_{lm}(\theta,\phi)$$



$$f_{l,-m} = (-1)^m f_{l,m}^*$$

$$f_{0,0} = \frac{1}{\sqrt{4\pi}}$$

- Degree of freedom: $4J^2 + 4J$
- There should be $4J^2 + 4J - 3$ SO(3) rotation invariants, $4J^2 + 4J - 1$ SO(2) rotation invariants

SO(3) rotation invariants

- Invariants resulted from the unitarity of rotation

$$W_l = \sum_{m=-l}^{l} |f_{l,m}|^2, \qquad l = 1,\ 2,\ \cdots,\ 2J$$

- Invariants obtained by integration over all space angle

$$W_{J,n} = \int d\Omega \left[f(\theta,\phi) - \frac{1}{4\pi} \right]^n, \qquad n = 1,\ 2,\ \cdots$$

- All SO(3) rotation invariants can be found by this method

SO(2) rotation invariants

- Express distribution in bases of eigen functions of J_y

$$\frac{1}{\Gamma}\frac{\mathrm{d}\Gamma}{\mathrm{d}\Omega_B} = \sum_{l=0}^{2J}\sum_{m=-l}^{l} g_{l,m}\bar{Y}_{lm}(\theta,\phi)$$

- Under SO(2) ration in the $x-z$ plane:

$$g'_{l,m} = e^{im\delta} g_{l,m}$$

- SO(2) rotation invariants

$$T_{l,0} = g_{l,0},$$
$$T_{l,l} = |g_{l,l}|^2$$

- Other SO(2) rotation invariants are not independent

Decay of spin$-\frac{1}{2}$ particle

➢ **Angular distribution**

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\Omega}=\frac{1}{4\pi}\left[1+2A_\theta\cos\theta+2A_\phi\sin\theta\cos\phi+2A_{\perp\phi}\sin\theta\sin\phi\right]$$

- **SO(3) rotation invariants**

$$W_1=\frac{A_\theta^2+A_\phi^2+A_{\perp\phi}^2}{3\pi}$$

- **SO(2) rotation invariants**

$$T_{1,0}=\frac{A_\phi^\perp}{\sqrt{3\pi}}$$

Decay of spin−1 particle

- **Angular distribution—assuming parity conseved**

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\Omega} = \frac{1}{4\pi(1+\frac{\lambda_\theta}{3})}\Big[1+\lambda_\theta\cos^2\theta+\lambda_\phi\sin^2\theta\cos 2\phi+\lambda_{\theta\phi}\sin 2\theta\cos\phi$$
$$+\lambda_{\perp\phi}\sin^2\theta\sin 2\phi+\lambda_{\perp\theta\phi}\sin 2\theta\sin\phi\Big].$$

- SO(3) rotation invariants

$$W_2 = \frac{1}{5\pi}\frac{\lambda_\theta^2+3(\lambda_\phi^2+\lambda_{\theta\phi}^2+\lambda_{\perp\phi}^2+\lambda_{\perp\theta\phi}^2)}{(3+\lambda_\theta)^2}$$

$$W_3 = \frac{(\lambda_\theta+3\lambda_\phi)(2\lambda_\theta^2-6\lambda_\theta\lambda_\phi+9\lambda_{\theta\phi}^2)+9(\lambda_\theta\lambda_{\perp\theta\phi}^2-2\lambda_\theta\lambda_{\perp\phi}^2+6\lambda_{\theta\phi}\lambda_{\perp\theta\phi}\lambda_{\perp\phi}-3\lambda_\phi\lambda_{\perp\theta\phi}^2)}{70\pi^2(3+\lambda_\theta)^3}$$

Decay of spin−1 particle (con.)

- SO(2) rotation invariants, equivalent to $\tilde{\lambda}$ and λ^*, respectively

$$T_{2,0} = -\frac{1}{2\sqrt{5\pi}} \frac{\lambda_\theta + 3\lambda_\phi}{3+\lambda_\theta},$$

$$T_{2,2} = \frac{3}{40\pi} \frac{(\lambda_\theta - \lambda_\phi)^2 + 4\lambda_{\theta\phi}^2}{(3+\lambda_\theta)^2}$$

- In frames where $\lambda_{\perp\phi}$ and $\lambda_{\perp\theta\phi}$ vanish, SO(3) invariants reduced to

$$\frac{\lambda_\theta^2 + 3\lambda_\phi^2 + 3\lambda_{\theta\phi}^2}{(3+\lambda_\theta)^2},$$

$$\frac{(\lambda_\theta + 3\lambda_\phi)(2\lambda_\theta^2 - 6\lambda_\theta\lambda_\phi + 9\lambda_{\theta\phi}^2)}{(3+\lambda_\theta)^3}$$

Equivalent to the two SO(2) invariants

Summary

- More observables are needed to fully understand polarization puzzle
- All SO(3) or SO(2) rotation-invariant observables are constructed
- These observables potentially useful for both quarkonium physics and other physics

Thank you!

Back up

Discovery: J/ψ polarization

- Fit to J/ψ cross section requires a very small

$$M_1 = \langle O\left({}^3S_1^{[8]}\right)\rangle - 0.56\,\langle O\left({}^3\boldsymbol{P}_0^{[8]}\right)\rangle/m_c^2$$

YQM, Wang, Chao, 1009.3655

- Transverse polarization proportional to

$$M'_1 = \langle O\left({}^3S_1^{[8]}\right)\rangle - 0.52\,\langle O\left({}^3\boldsymbol{P}_0^{[8]}\right)\rangle/m_c^2$$

Chao,YQM,Shao,Wang,Zhang,1201.2675

- **Cross section requires small transverse polarization— consistent with data!!!**