Polarized Heavy Quarkonium Production in the Color Evaporation Model

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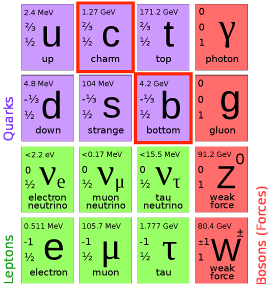
Overview

Introduction



Quarks	2.4 MeV ⅔ ½ u up	1.27 GeV ⅔ ½ c charm	171.2 GeV ⅔ ½ t top	0 0 1 γ photon
	4.8 MeV -⅓ ½ d down	104 MeV -⅓ ½ s strange	4.2 GeV -⅓ ½ b bottom	0 0 1 g gluon
Leptons	<2.2 eV 0 ½ ν_e electron neutrino	<0.17 MeV 0 ½ ν_μ muon neutrino	<15.5 MeV 0 ½ ν_τ tau neutrino	91.2 GeV 0 1 Z^0 weak force
	0.511 MeV -1 ½ e electron	105.7 MeV -1 ½ μ muon	1.777 GeV -1 ½ τ tau	80.4 GeV ±1 1 $W^\pm$ weak force

Quarkonium Polarization Problem

- The mechanism of producing Quarkonium has not been solved
- Non Relativistic QCD (NRQCD), a common method to predict quarkonium production, has difficulties describing production and polarization simutaneously
- No polarization prediction has been made using the Color Evaporation Model (CEM) until now (submitted)

Quarkonium Production Models

Non Relativistic QCD (NRQCD)

- e.g. for J/ψ, $\sigma_{J/\psi} = \sum_n \sigma_{c\bar{c}[n]} \langle \mathcal{O}^{J/\psi}[n] \rangle$
- $\sigma_{c\bar{c}[n]}$ are cross sections in a particular color and spin state n calcuated by perturbative QCD
- $\langle \mathcal{O}^{J/\psi}[n] \rangle$ are nonperturbative Long Distance Matrix Elements (LDMEs) that describe the conversion of $c\bar{c}[n]$ state into final state J/ψ, assuming that the hadronization does not change the spin or momentum
- LDMEs are assumed to be universal and are expanded in powers of v/c
- leading term is $n = {}^3S_1^{[1]}$, corresponds to the color singlet model
- color octet states are subleading terms ${}^1S_0^{[8]}$, ${}^3S_1^{[8]}$, and ${}^3P_J^{[8]}$
- mixing of LDMEs are determined by fitting to data, usually p_T distributions above some p_T cut

NRQCD LDMEs[1] depend on p_T cut/experiment

Included in fits

e^+e^-

ep

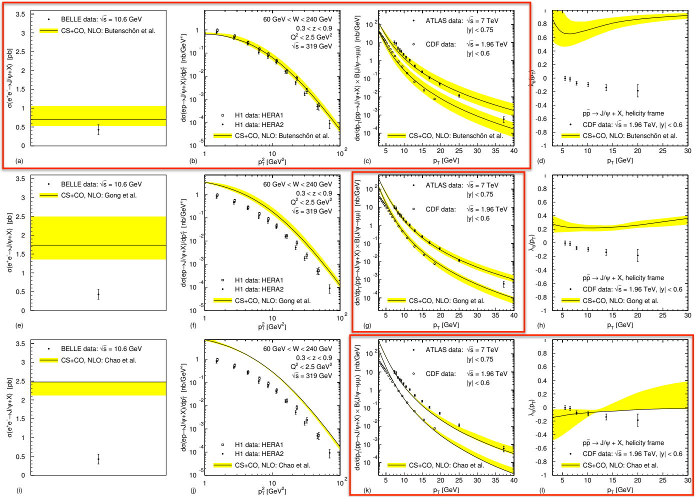
pp p_T distribution

pp polarization

Butenschon & Kniehl
$p_T > 3$ GeV

Gong et al.
$p_T > 5$ GeV

Chao et al.
$p_T > 7$ GeV



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[1] N. Brambilla et al., Eur. Phys. J. C **74**, 2981 (2014)

Quarkonium Production Models

Color Evaporation Model

- all Quarkonium states are treated like $Q\overline{Q}$ ($Q = c, b$) below $H\overline{H}$ ($H = D, B$) threshold
- does not separate states into color or spin
- color is said to be 'evaporated' away during transition from pair to Quarkonium state while preserving the kinematics
- mostly calculated by perturbative QCD
- fewer parameters than NRQCD (one F_Q for each Quarkonium state)
- F_Q is fixed by comparison of NLO calculation of σ_Q^{CEM} to $\sqrt{s}$ for J/ψ and Υ, $\sigma(x_F > 0)$ and $Bd\sigma/dy|_{y=0}$ for J/ψ, $Bd\sigma/dy|_{y=0}$ for Υ
- spin has been averaged over, no previous prediction of polarization in CEM

Color Evaporation Model

Leading Order Total Cross Section

$$\sigma = F_Q \sum_{i,j} \int_{4m_Q^2}^{4m_H^2} d\hat{s} \int dx_1 dx_2 f_{i/p}(x_1, \mu^2) f_{j/p}(x_2, \mu^2) \hat{\sigma}_{ij}(\hat{s}) \delta(\hat{s} - x_1 x_2 s) \ ,$$

F_Q is a universal factor for the quarkonium state and is independent of the projectile, target, and energy.

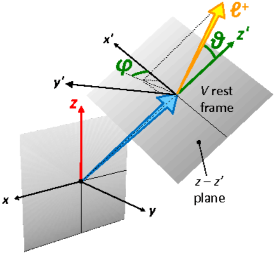
Leading Order Rapidity Distribution

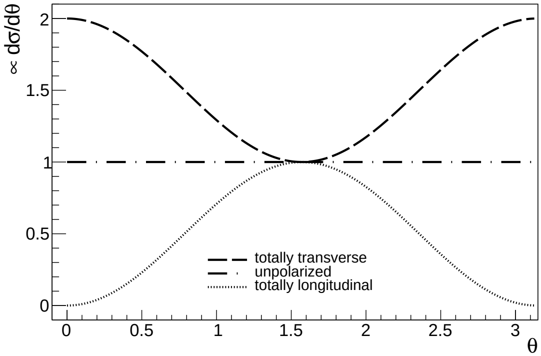
$$\frac{d\sigma}{dy} = F_Q \sum_{i,j} \int_{4m_Q^2}^{4m_H^2} \frac{d\hat{s}}{s} f_{i/p}(x_1, \mu^2) f_{j/p}(x_2, \mu^2) \hat{\sigma}_{ij}(\hat{s}) \ ,$$

where $x_{1,2} = (\sqrt{\hat{s}/s}) \exp(\pm y)$.

We take the factorization and renormalization scales to be $\mu^2 = \hat{s}$.

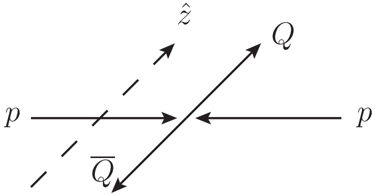
Polarization of Quarkonium





- defined as the tendency of quarkonium to be in a certain total angular momentum state
- e.g. an unpolarized $J = 1$ production means yielding J_z = -1, 0, +1 equally
- longitudinal → peak at $\vartheta = \pi/2$
- transverse → peaks at $\vartheta = 0, \pi$

Defining Polarization



Polarization in the Helicity Basis

- helicity is the projection of angular momentum onto the direction of momentum
- if the helicities are the same, then $J_z = 0$ (longitudinal)
- if the helicities are the opposite, then $J_z = \pm 1$ (transverse)

Polarized Partonic Cross Section

The individual partonic cross sections for the longintudinal and transverse polarizations are

$$
\begin{aligned}
\hat{\sigma}_{q\bar{q}}^{J_z=0}(\hat{s}) &= \frac{16\pi\alpha_s^2}{27\hat{s}^2} M^2 \chi \,, \\
\hat{\sigma}_{q\bar{q}}^{J_z=\pm 1}(\hat{s}) &= \frac{4\pi\alpha_s^2}{27\hat{s}^2} \hat{s} \chi \,, \\
\hat{\sigma}_{gg}^{J_z=0}(\hat{s}) &= \frac{\pi\alpha_s^2}{12\hat{s}} \Big[\Big(4 - \frac{31M^2}{\hat{s}} + \frac{33M^2}{\hat{s}-4M^2} \Big) \chi \\
&+ \Big(\frac{4M^4}{\hat{s}^2} + \frac{31M^2}{2\hat{s}} - \frac{33M^2}{2(\hat{s}-4M^2)} \Big) \ln \frac{1+\chi}{1-\chi} \Big] \,, \\
\hat{\sigma}_{gg}^{J_z=\pm 1}(\hat{s}) &= \frac{\pi\alpha_s^2}{24\hat{s}} \Big[-11 \Big(1 + \frac{3M^2}{\hat{s}-4M^2} \Big) \chi \\
&+ \Big(4 + \frac{M^2}{2\hat{s}} + 33 \frac{M^2}{2(\hat{s}-4M^2)} \Big) \ln \frac{1+\chi}{1-\chi} \Big] \,,
\end{aligned}
$$

where $\chi = \sqrt{1 - 4M^2/\hat{s}}$.

Total Partonic Cross Section

The sum of the results, $\hat{\sigma}_{ij}^{J_z=0} + \hat{\sigma}_{ij}^{J_z=+1} + \hat{\sigma}_{ij}^{J_z=-1}$, is equal to the total partonic cross section[2]

$$\begin{aligned}
\hat{\sigma}_{q\bar{q}}^{\text{tot.}}(\hat{s}) &= \frac{8\pi\alpha_s^2}{27\hat{s}^2}(\hat{s}+2M^2)\chi \,, \\
\hat{\sigma}_{gg}^{\text{tot.}}(\hat{s}) &= \frac{\pi\alpha_s^2}{3\hat{s}}\Big[-\Big(7+\frac{31M^2}{\hat{s}}\Big)\frac{1}{4}\chi \\
&\quad +\Big(1+\frac{4M^2}{\hat{s}}+\frac{M^4}{\hat{s}^2}\Big)\ln\frac{1+\chi}{1-\chi}\Big] \,.
\end{aligned}$$

- convoluted with the CTEQ6L1 parton distribution functions (PDFs)
- obtain cross section σ as a function of $\sqrt{s}$ and the rapidity distribution, $d\sigma/dy$
- $\alpha_s = g_s^2/(4\pi)$ is calculated at one-loop level
- assume that the polarization is unchanged by the transition from the parton level to the hadron level

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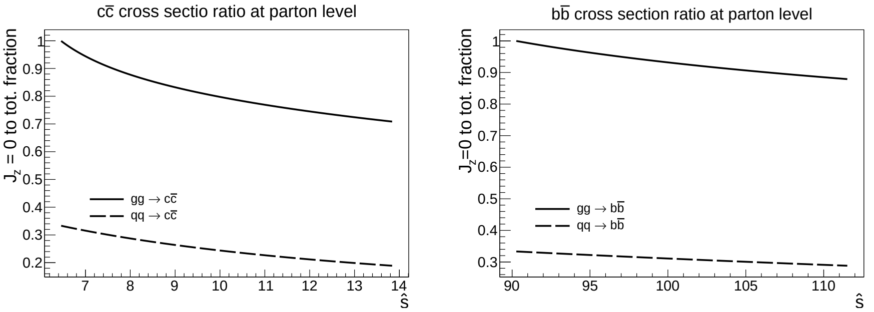
[2] B. L. Combridge, Nucl. Phys. B **151**, 429 (1978)

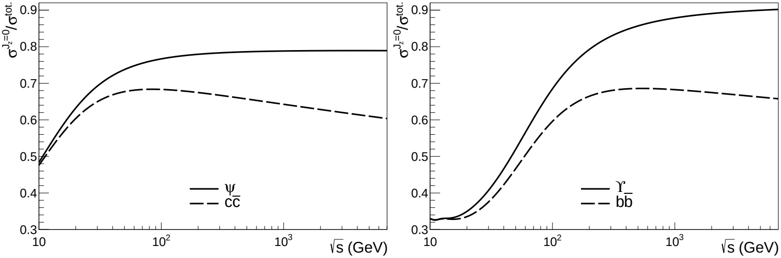
Longitudinal polarization fraction at parton level



Behavior within the integration limits

- contribution from gluon fusion process is longitudinal
- contribution from quark annihilation process is transverse
- both fractions decrease as a function of $\hat{s}$

Energy dependence of longitudinal polarization fraction[3]



Energy Dependence

- ψ production is more than 50% for $\sqrt{s} > 10$ GeV, and saturates at 80% at high energies
- Υ production is more than 50% for $\sqrt{s} > 50$ GeV, and saturates at 90% at high energies
- $c\bar{c}$ and $b\bar{b}$ production turnover, dominantly transversely polarized at high energies

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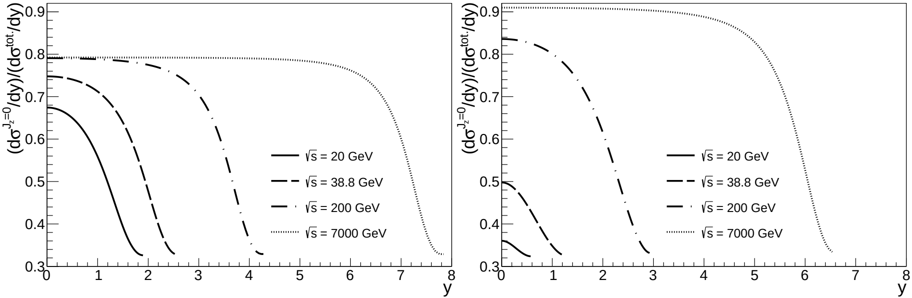
[3] V. Cheung & R. Vogt, submitted

Rapidity dependence of longitudinal polarization fraction[4]



Rapidity Dependence

- fraction is greatest at $y = 0$ and decreases as $|y|$ increases
- near transverse polarization of Υ at fixed-target energies

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[4] V. Cheung & R. Vogt, submitted

Ongoing

Separation of $S = 1, S_z = 0$ (triplet) from $S = 0, S_z = 0$ (singlet)

- sorted by J_z does not distinguish the triplet state from singlet state
- enforce $S = 1$

Extraction of $L = 0$

- enforce $L = 0$ so $S = 1, L = 0 \rightarrow J = 1$
- make sense to calculate the polarization parameter, λ_ϑ[5] for comparison

calculation of λ_ϑ

$$\lambda_\vartheta = \frac{\mathcal{N} - 3|a_0|^2}{\mathcal{N} + |a_0|^2} \,,$$

where $\mathcal{N}$ *is the total production amplitude*
and $|a_0|^2$ *is the longitudinal production amplitude.*

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[5] P. Faccioli, C. Lourenco, J. Seixas, and H. K. Wohri, Eur. Phys. J. C **69**, 657 (2010)

Conclusion and Future

Conclusion

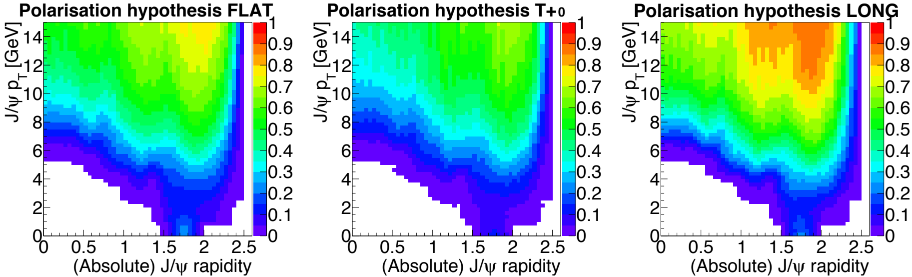
- presented the energy and rapidity dependence of the polarization of heavy quarkonium production in $p+p$ collisions
- longitudinal at most energies and around central rapidity
- transverse at the kinematic limits of the calculation where $q\overline{q}$ production is dominant
- enforcing $J=1$ is still in progress

Future

- leading order calculation → cannot speak to the p_T dependence
- explore the p_T and rapidity dependence of the polarization of a single heavy quark at leading order
- then investigate the high p_T polarization of heavy quark pairs

Backup Slides

Polarization and Experimental Acceptance[6]



from left to right: unpolarized, totally transverse, totally longitudinal.

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[6] The ATLAS Collaboration, Nucl. Phys. B **850**, 387 (2011).