

J/ψ Photoproduction at NLO with NRQCD

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1 October 2009



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arXiv:0909.2798

Production and Decay Rates of Heavy Quarkonia

Heavy quarkonia: Bound states of heavy quark and its antiquark.

- Charmonia ($c\bar{c}$) and Bottomonia ($b\bar{b}$)

The classic approach: Color-singlet model

- Calculate cross section for heavy quark pair in physical **color-singlet** (= color neutral) state. In case of J/ψ : $c\bar{c}[{}^3S_1^{[1]}]$
- Then multiply by J/ψ wave function or its derivative at origin.
- Leftover infrared divergences at P wave quarkonia.

Nonrelativistic QCD (NRQCD):

- 1995: Rigorous effective field theory by Bodwin, Braaten, Lepage
- Based on **factorization of soft and hard scales**
(Scale hierarchy: $Mv^2, Mv \ll \Lambda_{\text{QCD}} \ll M$)
- Theoretically consistent: No leftover singularities.
- Can explain hadroproduction at Tevatron

J/ψ Production with NRQCD

Factorization theorem: $\sigma_{J/\psi} = \sum_n \sigma_{c\bar{c}[n]} \cdot \langle O^{J/\psi}[n] \rangle$

- n : Every possible Fock state, including **color-octet** states.
- $\sigma_{c\bar{c}[n]}$: Production rate of $c\bar{c}[n]$, calculated in perturbative QCD.
- $\langle O^{J/\psi}[n] \rangle$: Long distance matrix elements (ME): describe $c\bar{c}[n] \rightarrow J/\psi$, universal, extracted from experiment.

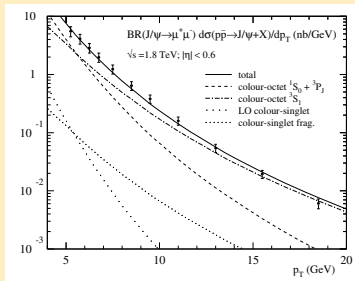
Scaling rules: MEs scale with relative velocity v ($v^2 \approx 0.2$):

scaling	v^3	v^7	v^{11}
n	$^3S_1^{[1]}$	$^1S_0^{[8]}, ^3S_1^{[8]}, ^3P_{0/1/2}^{[8]}$...

- **Double expansion** in v and α_s .
- Leading term in v ($n = ^3S_1^{[1]}$) equals **color-singlet model**.

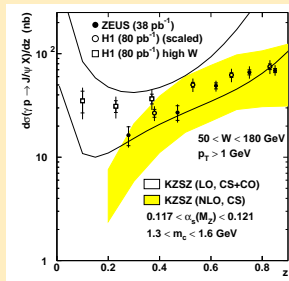
Production of J/ψ : NRQCD vs. Experiment

Hadroproduction at Tevatron:



- Color octet states important
 \Rightarrow **Great success** for NRQCD

Photoproduction at HERA:



- MEs from fits to Tevatron data.
- Importance of color octet **unclear**

Our work: NRQCD calculation for photoproduction at **NLO**
 \Rightarrow Aim: Establish universality of long distance matrix elements.

Production of J/ψ : Summary of Calculations

Hadroproduction:

	$3S_1^{[1]}$	$1S_0^{[8]}, 3S_1^{[8]}, 3P_{0/1/2}^{[8]}$
Born	Baier, Rückl (1980)	Cho, Leibovic (1996)
NLO	Campbell et al. (2007)	————

Photoproduction:

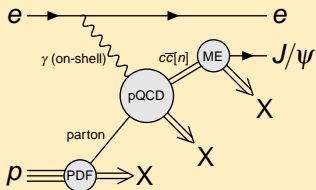
	$3S_1^{[1]}$	$1S_0^{[8]}, 3S_1^{[8]}, 3P_{0/1/2}^{[8]}$
Born	Berger, Jones (1981)	Ko, Lee, Song (1996)
NLO	Krämer (1995)	THIS WORK

Open question of ME universality:

- (Our) NLO NRQCD calculation: Only after **13 years!**
- Difficulty: Virtual corrections to **P states**

Direct J/ψ Photoproduction

Factorization formulas:



- Convolute partonic cross sections with **proton PDFs**:

$$\sigma_{\text{hadr}} = \sum_i \int dx f_{i/p}(x) \cdot \sigma_{\text{part},i}$$

- **NRQCD factorization**:

$$\sigma_{\text{part},i} = \sum_n \sigma(\gamma i \rightarrow c\bar{c}[n] + X) \cdot \langle O^{J/\psi}[n] \rangle$$

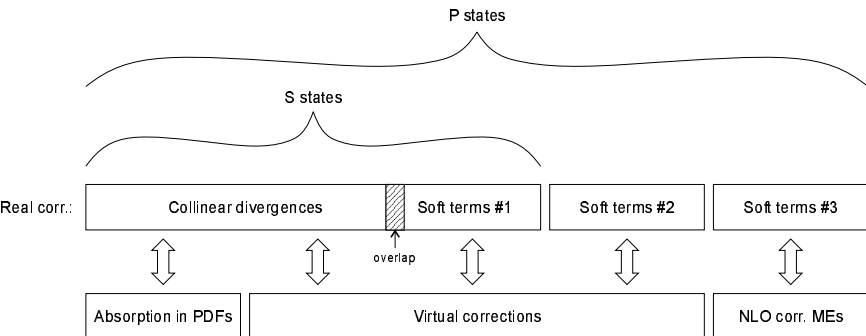
Amplitudes for $c\bar{c}[n]$ production by projector application, e.g.:

$$A_{c\bar{c}[3S_1^{[1/8]}]} = \varepsilon_\alpha \text{Tr} [C \Pi^\alpha A_{c\bar{c}}] |_{q=0}$$

$$A_{c\bar{c}[3P_J^{[8]}]} = \varepsilon_{\alpha\beta} \frac{d}{dq_\beta} \text{Tr} [C \Pi^\alpha A_{c\bar{c}}] |_{q=0}$$

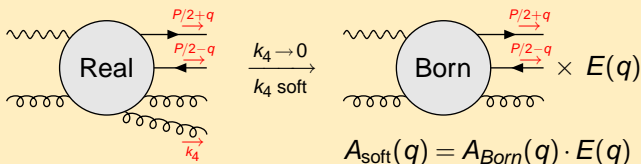
- $A_{c\bar{c}}$: Amputated pQCD amplitude for open $c\bar{c}$ production.
- q : Relative momentum between c and \bar{c} .

Overview of IR Singularity Structure



Structure of Soft Singularities

Soft limits of the real corrections:



S and P states: Soft #1 + Soft #2 + Soft #3 terms:

$$A_{\text{soft},s} = A_{\text{soft}}(0) = A_{\text{Born},s} \cdot E(0)$$

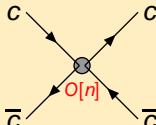
$$A_{\text{soft},p} = A'_{\text{soft}}(0) = A_{\text{Born},p} \cdot E(0) + A_{\text{Born},s} \cdot E'(0)$$

$$|A_{\text{soft},s}|^2 = |A_{\text{Born},s}|^2 \cdot E(0)^2$$

$$|A_{\text{soft},p}|^2 = |A_{\text{Born},p}|^2 \cdot E(0)^2 + 2 \operatorname{Re} A_{\text{Born},s}^* A_{\text{Born},p} \cdot E(0) E'(0) + |A_{\text{Born},s}|^2 \cdot E'(0)^2$$

Radiative Corrections to Long Distance MEs

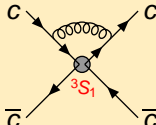
In NRQCD: Long distance MEs = $c\bar{c}$ scattering amplitudes:

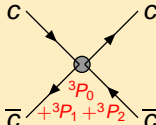
$$\langle O^{J/\psi}[n] \rangle =$$


$O[n]$ = 4-fermion operators

$$(n = {}^3S_1^{[1]}, {}^1S_0^{[8]}, {}^3S_1^{[8]}, {}^3P_{0/1/2}^{[8]}, \dots)$$

Corrections to $\langle O^{J/\psi}[{}^3S_1^{[1/8]}] \rangle$ with NRQCD Feynman rules:

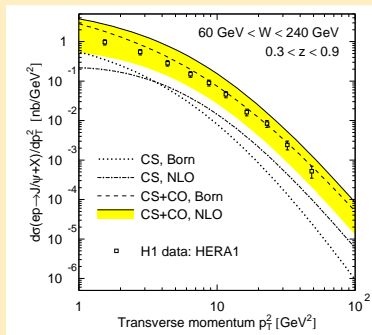
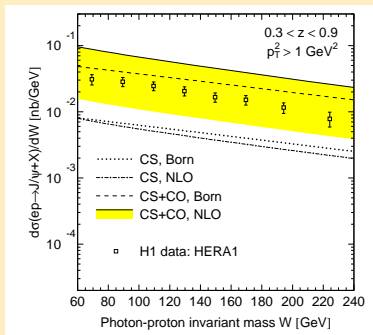


$$+ \text{similar diagrams} \propto \frac{4\alpha_s}{3\pi m_c^2} \left(\frac{1}{\epsilon_{UV}} - \frac{1}{\epsilon_{IR}} \right) \cdot$$


- UV singularity cancelled by renormalization of 4-fermion operat.
- IR singularity cancels soft #3 terms of p states!

Confront Results with Data (1)

Direct J/ψ photoproduction at HERA:

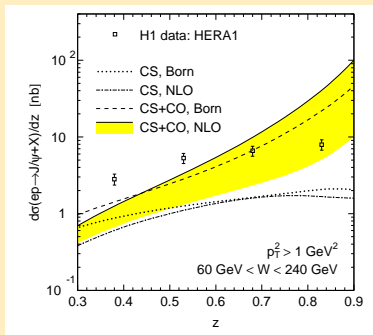


- Color-octet MEs from leading order Tevatron fit
- NLO Tevatron fit \implies Decrease of CO MEs: Yellow bands

\implies CS not enough! CS+CO better!

Confront Results with Data (2)

Direct J/ψ photoproduction at HERA:



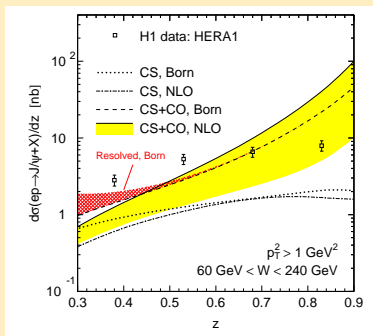
- $$z = \frac{P_{J/\psi} \cdot k_{\text{proton}}}{k_{\gamma} \cdot k_{\text{proton}}}$$
- Proton rest frame:
 $z =$ Fraction of photon energy going to J/ψ
- $z \lesssim 0.45$:
Expect contributions from **resolved** photoproduction

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\implies **CS not enough! CS+CO better!**

Confront Results with Data (2)

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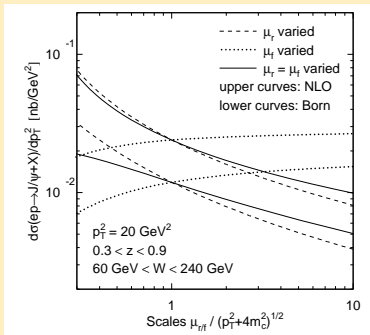
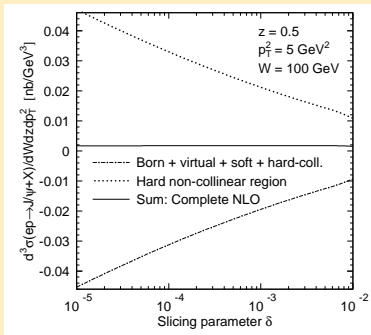
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Parameter Dependences

Dependence on slicing parameter and unphysical scales:



- Phase space slicing works!
 \implies Check on our kinematics and soft / collinear limits
- Dependence on renormalization and factorization scale:
 $0.7 \lesssim \sigma/\sigma_0 \lesssim 1.6$ if $0.5 < \mu_r/\mu_0 = \mu_f/\mu_0 < 2$.

Summary

Our project: Test NRQCD

- NRQCD provides rigorous **factorization theorem** for production and decay of heavy quarkonia.
- Inclusion of intermediate **color-octet** (= color charged) states, which explain Tevatron hadroproduction.
- But: Need to proof **universality** of CO MEs.
- Therefore: Since **13 years** want for NRQCD hadroproduction and photoproduction predictions at NLO.

Our results: Direct photoproduction at HERA

- **Color-singlet** contributions **not enough** to explain data
- Sum of color-singlet and **color-octet** seems to explain data better.
- But: **Uncertainty** due to CO MEs from **LO** Tevatron fit

Checks and Outlook

Checks on our calculation:

- 1 Checked **cancellation** of all **singularities** analytically.
- 2 Two different **reduction methods** for virtual corrections:
Checked analytically that results are equal.
- 3 Checked **real correction** amplitudes against MadOnia.
- 4 Checked phase space **slicing** parameter **independence**.
- 5 Could reproduce M. Krämer's **NLO color-singlet** results.

Outlook:

- Do second step: **Hadroproduction** at NLO.
- Furthermore: Calculate **J/ψ polarization**:
 - For photoproduction and hadroproduction at NLO
 - At high p_T both NLO CSM and LO NRQCD fail to describe data.