J/ψ Photoproduction at NLO with NRQCD

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Heavy Quarkonia

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

- Charmonia ($c\overline{c}$) and Bottomonia ($b\overline{b}$)
- Top decays too fast for bound state.

Charmonium spectrum ($c\overline{c}$):

$n\,^{2S+1}L_J$	Name	Mass
$1\,^1S_0$	η_c	2980 MeV
$1\,^3S_1$	J/ψ	3097 MeV
$1\,^3P_0$	χ_{c0}	3415 MeV
$1\,^3P_1$	χ_{c1}	3511 MeV
$1\,^1P_1$	h_c	3526 MeV
$1\,^3P_2$	χ_{c2}	3556 MeV
$2\,^1S_0$	η_c'	3637 MeV
$2\,^3S_1$	ψ'	3686 MeV

- 1974: Discovery of J/ψ: First observation of heavy quarks
- Long lifetime of $c\overline{c}$: Spectrum and radiative transitions seen $\Longrightarrow$ Potential models
- Calculation of energy spectrum: Challenge for lattice QCD.
- Production and decay rates: One of first applications for perturbative QCD.

Production and Decay Rates of Heavy Quarkonia

The classic approach: Color-singlet model

- Calculate cross section for $c\bar{c}$-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.
  $\Longrightarrow$ Theoretically inconsistent

Nonrelativistic QCD (NRQCD):

- 1995: Rigorous effective field theory by Bodwin, Braaten, Lepage
- Based on factorization of soft and hard scales
  (Scale hierarchy: $Mv^2, Mv \ll \Lambda_{\mathrm{QCD}} \ll M$)
- 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 $c\bar{c}[n] \to J/\psi$, universal, extracted from experiment.

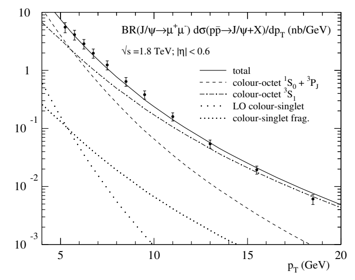
Scaling rules: MEs scale with relative velocity v ($v^2 \approx 0.2$):

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

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

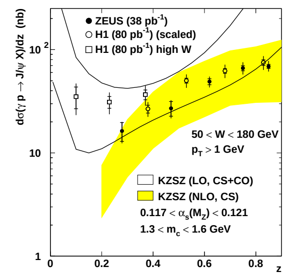
Production of J/ψ: NRQCD vs. Experiment

Hadroproduction at Tevatron:



- Color octet states important
  $\Longrightarrow$ 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
$\Longrightarrow$ 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:

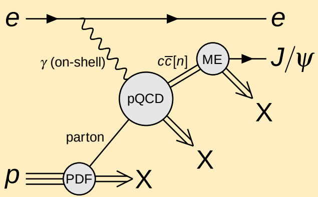
	$^3S_1^{[1]}$	$^1S_0^{[8]}, {}^3S_1^{[8]}, {}^3P_{0/1/2}^{[8]}$
Born	Berger, Jones (1981)	Ko, Lee, Song (1996)
NLO	Krämer (1995)	THIS WORK

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:

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

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

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

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

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

Cancellation of Divergences

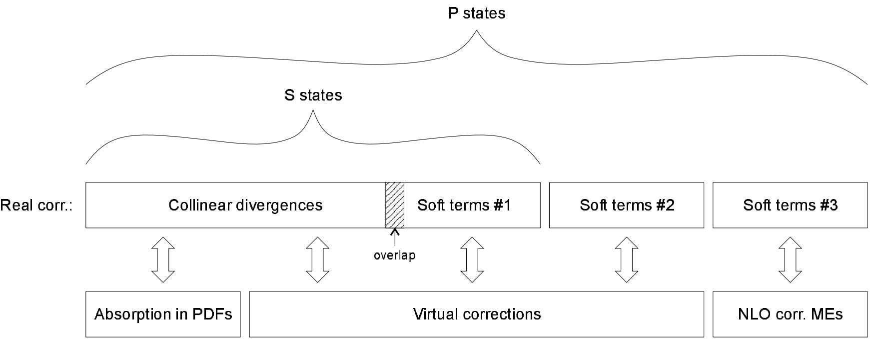
UV-divergences: Cancellation within virtual corrections:

- Loop integrals
- Charm mass renormalization
- Strong coupling constant renormalization
- Wave function renormalization of external particles

IR-divergences: Cancellation between:

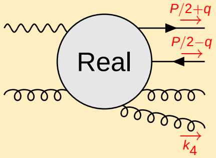
- Virtual corrections (loop integrals + wave function renormal.)
- Soft and collinear parts of real corrections
- Universal part absorbed into proton and photon PDFs
- Radiative corrections to long distance matrix elements

Overview of IR Singularity Structure

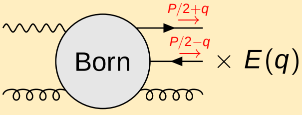


Structure of Soft Singularities

Soft limits of the real corrections:



$$\xrightarrow[k_4 \text{ soft}]{k_4 \to 0}$$



$$A_{\text{soft}}(q) = A_{Born}(q) \cdot E(q)$$

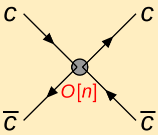
S and P states: Soft #1 + Soft #2 + Soft #3 terms:

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

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

Radiative Corrections to Long Distance MEs

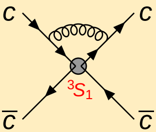
In NRQCD: Long distance MEs = $c\bar{c}$ scattering amplitudes:

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

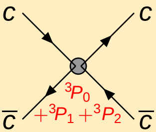
$O[n]$ = 4-fermion operators

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

Corrections to $\langle \mathbf{O}^{J/\psi}[{}^3\mathbf{S}_1^{[1/8]}] \rangle$ with NRQCD Feynman rules:



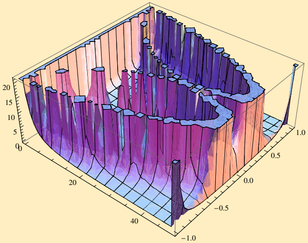
$+$ similar diagrams $\propto \frac{4\alpha_s}{3\pi m_c^2}\left(\frac{1}{\varepsilon_{\mathrm{UV}}} - \frac{1}{\varepsilon_{\mathrm{IR}}}\right) \cdot$



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

Real Corrections: Phase Space Slicing

Example: Squared amplitude for $\gamma + g \to c\bar{c}[^3S_1^{[8]}] + d + \bar{d}$:



- Infrared divergences: Cannot do complete integration numerically.
- Collinear and soft limits: Phase space and $|M|^2$ factorizes $\Longrightarrow$ Analytical D dimensional integration possible!

(Plotted against $(k_d + k_{\bar{d}})^2$ and $\cos\theta(c\bar{c}, d)$ in d-$\bar{d}$ rest frame for $s = 100$ GeV^2, $t = -20$ GeV^2.)

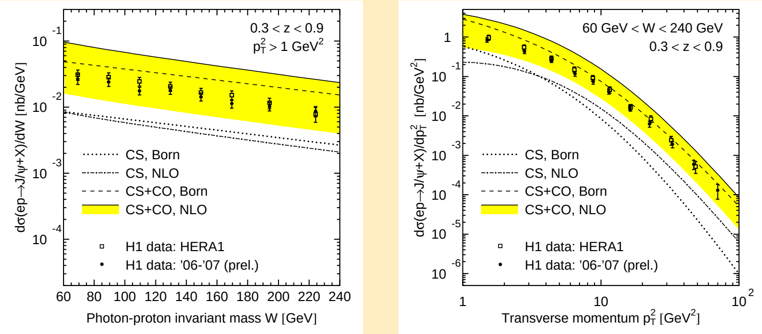
Idea: Split integration into two regions:

1. $\delta s < 100(k_i \cdot k_j)^2$ or $\delta\sqrt{s} < 2E_{3/4}$: Analytical integration.
2. $\delta s > 100(k_i \cdot k_j)^2$ and $\delta\sqrt{s} > 2E_{3/4}$: Numerical integration.

Both contributions: $\log\delta$ terms. These terms cancel for small δ!

Confront Results with Data (1)

Direct J/ψ photoproduction at HERA:

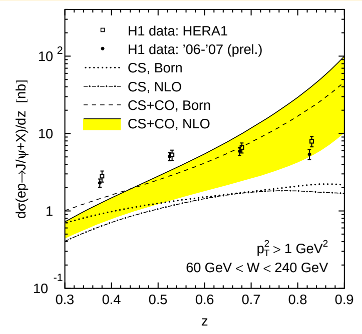


- Color-octet MEs from leading order Tevatron fit
- NLO Tevatron fit $\Longrightarrow$ Decrease of CO MEs: Yellow bands

$\Longrightarrow$ CS not enough! CS+CO better!

Confront Results with Data (2)

Direct J/ψ photoproduction at HERA:



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

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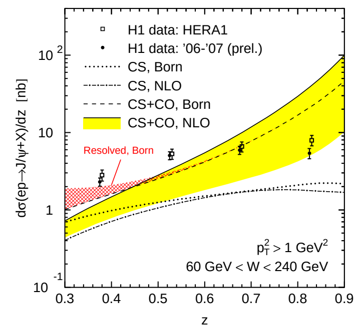

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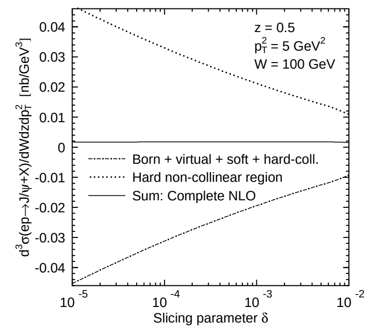
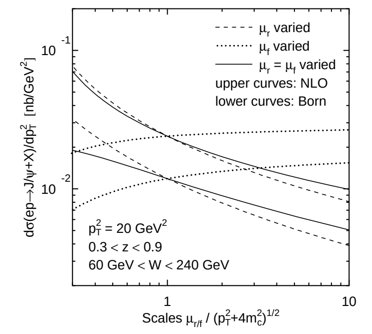
Parameter Dependences

Dependence on slicing parameter and unphysical scales:





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

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.