J/ψ Production with NRQCD

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Production and Decay Rates of Heavy Quarkonia

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

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

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: $c\bar{c}[^3S_1^{[1]}]$
- Multiply by quarkonium wave function (or its derivative) at origin
- Strong disagreement with Tevatron data

Nonrelativistic QCD (NRQCD):

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

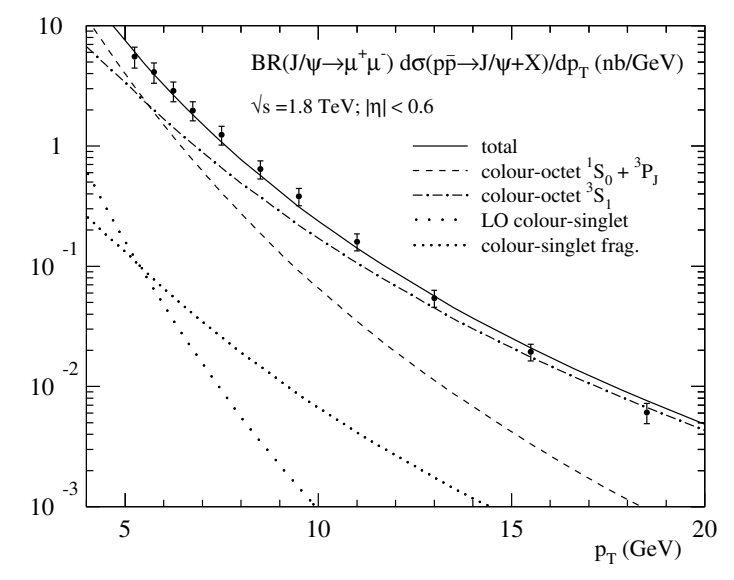
Scaling rules: MEs scale with relative velocity v ($v^2 \approx 0.2$):

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

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

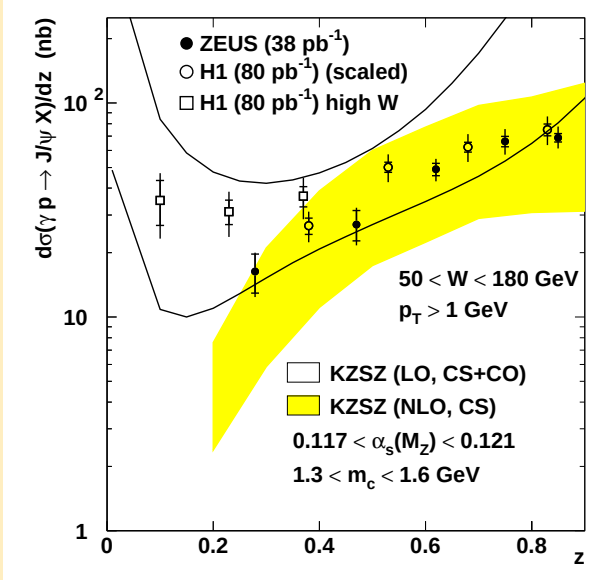
Production of J/ψ: NRQCD vs. Experiment (History)

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

This work: NLO NRQCD calculation for photo- and hadroproduction
$\Longrightarrow$ 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)	Cacciari, Krämer (1996)
NLO	Campbell et al. (2007)	M.B., Kniehl (2010)

Photoproduction:

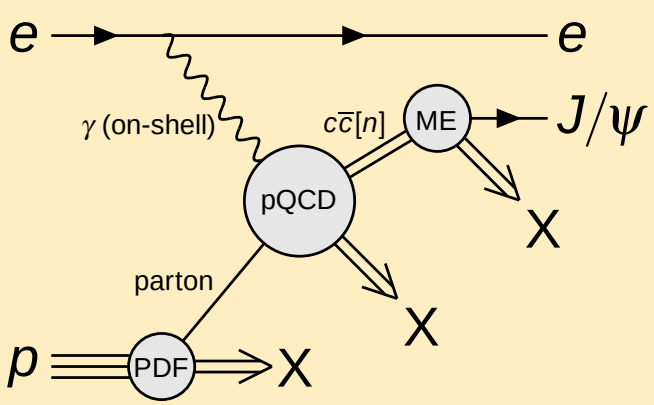
	$^3S_1^{[1]}$	$^1S_0^{[8]}, {}^3S_1^{[8]}, {}^3P_{0/1/2}^{[8]}$
Born	Berger, Jones (1981)	Ko, Lee, Song (1996)
NLO	Krämer (1995)	M.B., Kniehl (2009)

Open question of ME universality:

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

Direct J/ψ Production

Factorization formulas: (e.g. photoproduction)



- 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:

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

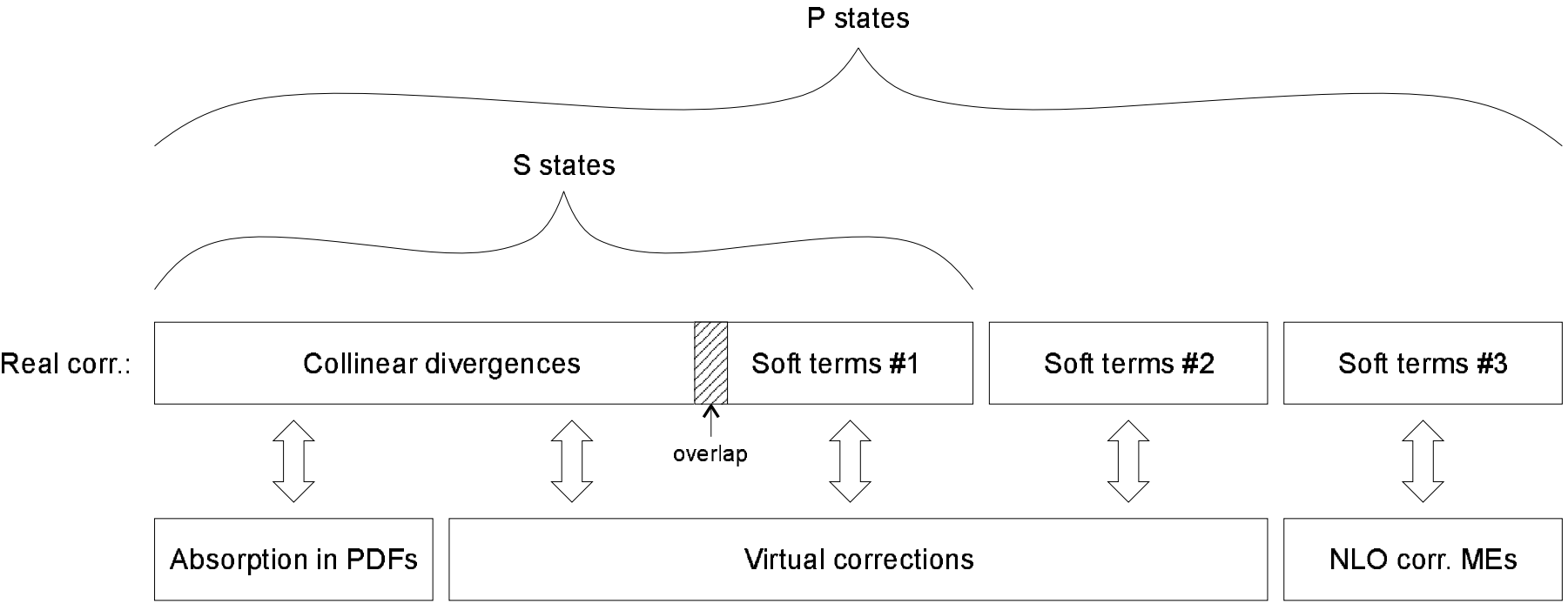
Amplitudes for $c\bar{c}[n]$ production by projector application, e.g.:

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

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

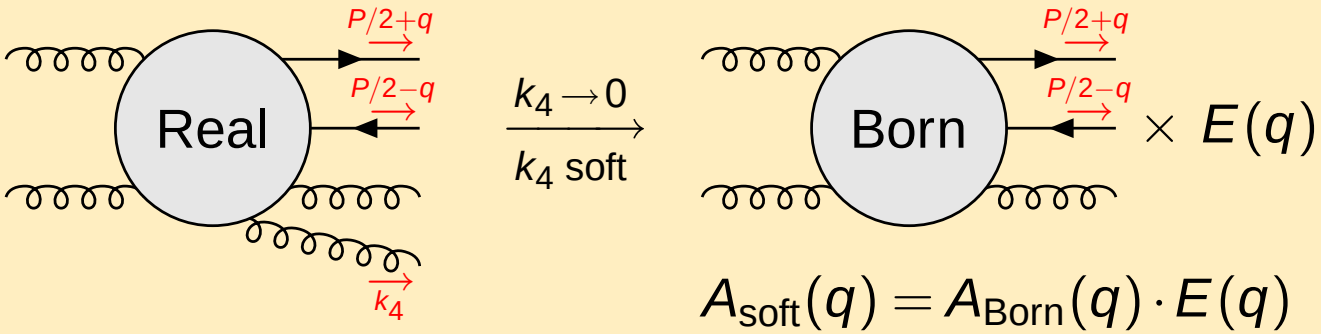
- $A_{c\bar{c}}$: Amputated pQCD amplitude for open $c\bar{c}$ production.
- q: Relative momentum between c and $\bar{c}$.

Overview of IR Singularity Structure



Structure of Soft Singularities

Soft limits of the real corrections:



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

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

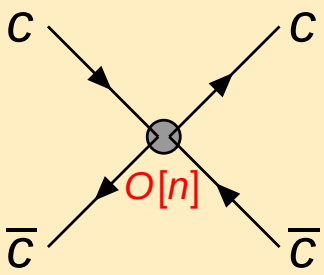
$$A_{\text{soft,s}} = A_{\text{soft}}(0) = A_{\text{Born,s}} \cdot E(0)$$
$$A_{\text{soft,p}} = A'_{\text{soft}}(0) = A_{\text{Born,p}} \cdot E(0) + A_{\text{Born,s}} \cdot E'(0)$$

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

Radiative Corrections to Long Distance MEs

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

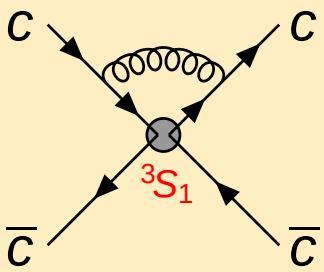
$$\langle O^{J/\psi}[n] \rangle =$$



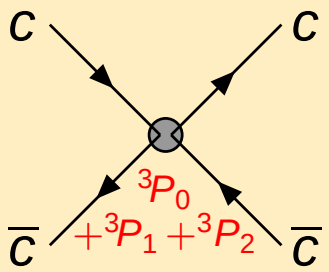
$O[n]$ = 4-fermion operators

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

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



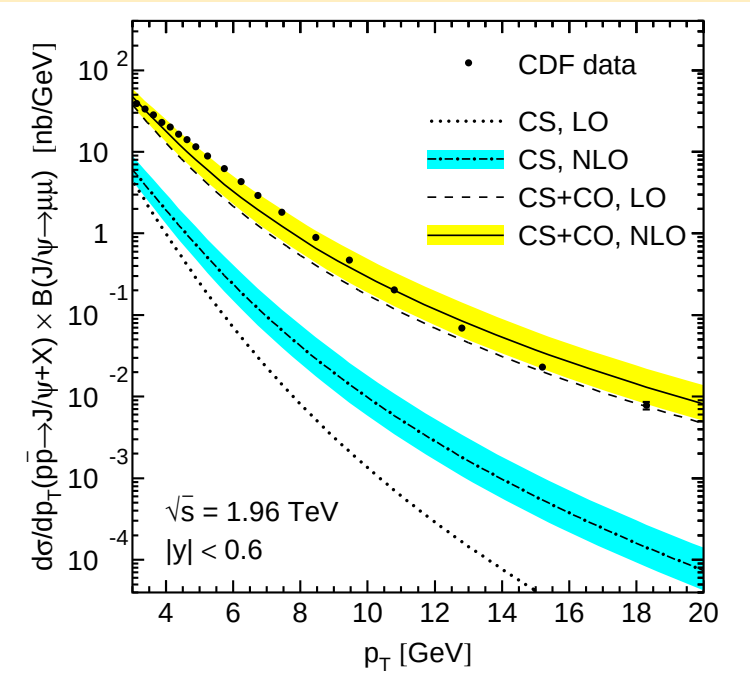
$+$ similar diagrams $\propto \frac{4\alpha_s}{3\pi m_c^2}\left(\frac{1}{\varepsilon_{\text{UV}}} - \frac{1}{\varepsilon_{\text{IR}}}\right) \cdot$

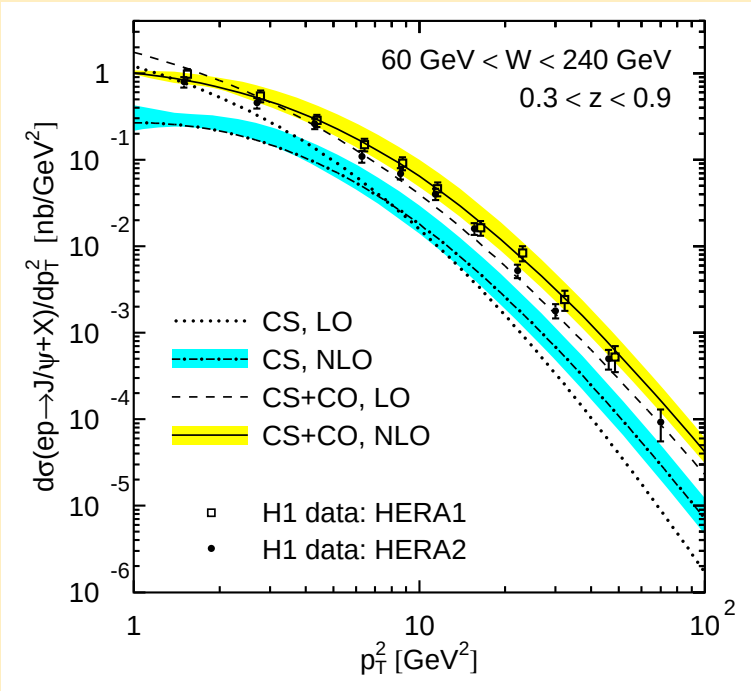


- UV singularity cancelled by renormalization of 4-fermion operat.
- IR singularity cancels soft #3 terms of p states.

Combined Fit to Tevatron and HERA (1)

Fit CO LDMEs to transverse momentum distributions:

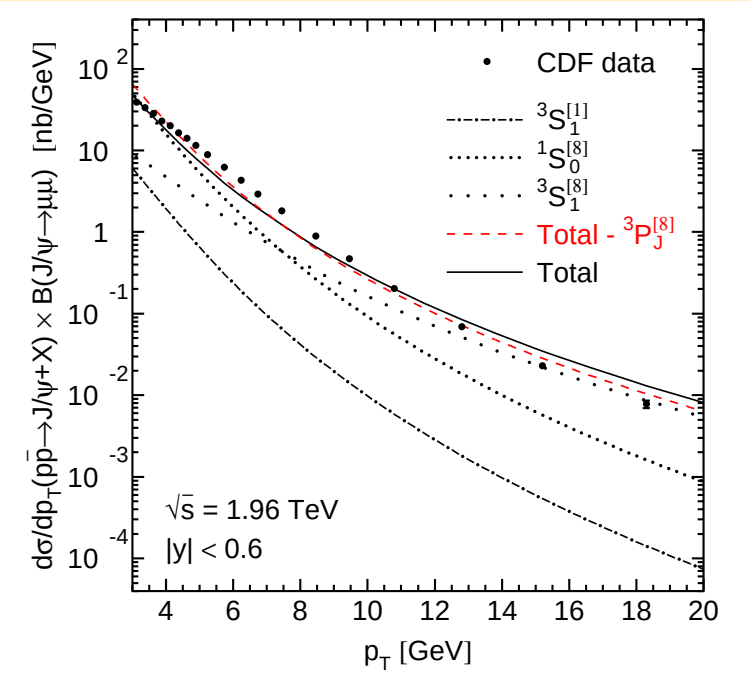


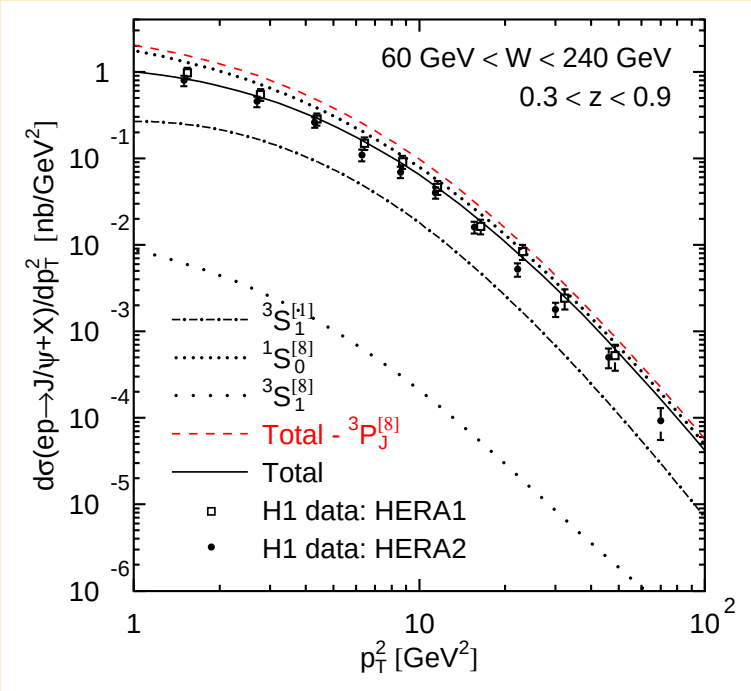


- Best fit values: $\langle O^{J/\psi}[^1S_0^{[8]}]\rangle = 0.033\ \text{GeV}^3$, $\langle O^{J/\psi}[^3S_1^{[8]}]\rangle = 0.0043\ \text{GeV}^3$, $\langle O^{J/\psi}[^3P_0^{[8]}]\rangle = -0.0072\ \text{GeV}^5$
- Fit very sensitive to input parameters: “Underconstrained”

Combined Fit to Tevatron and HERA (2)

Contribution of individual states:

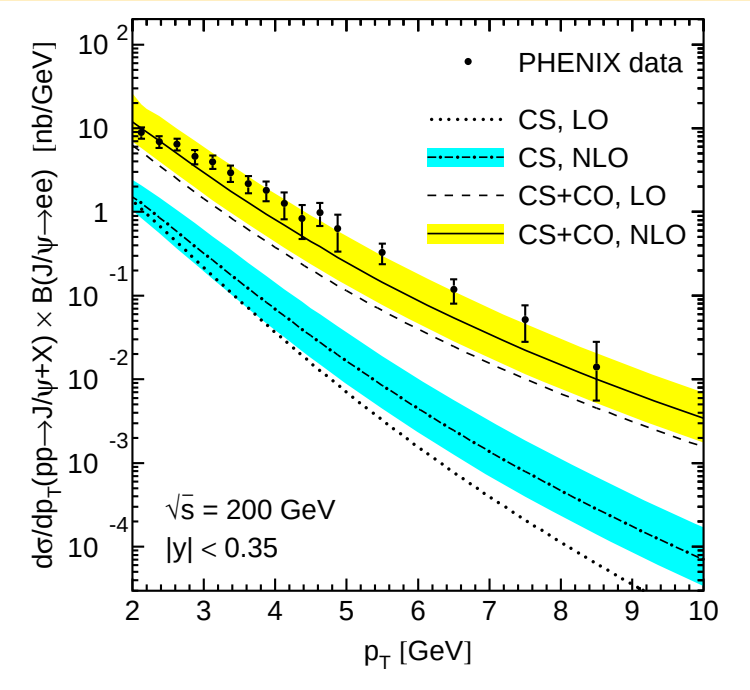


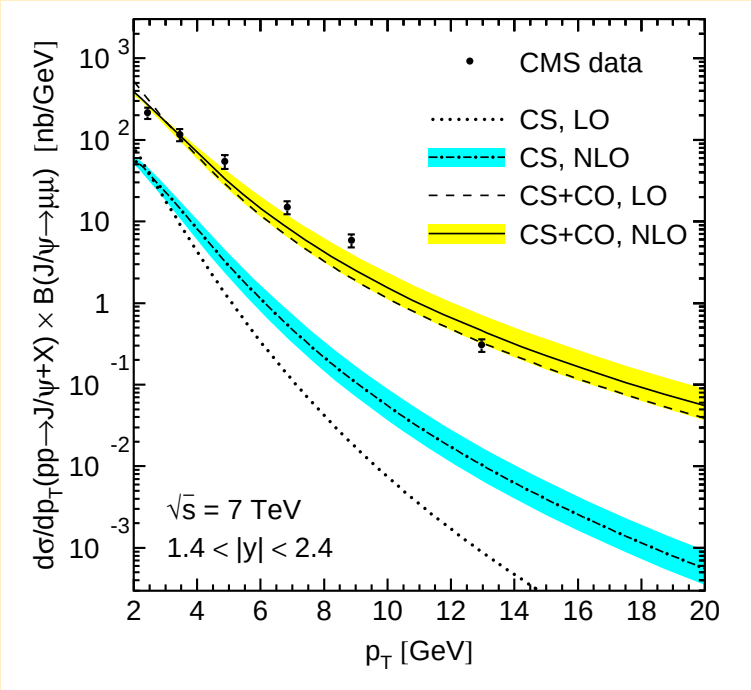


- Hadroprod.: Short-distance $\sigma(c\bar{c}[^3P_J^{[8]}])$ negative for $p_T \gtrapprox 7$ GeV
- But: Short-distance cross sections and LDMEs unphysical (NRQCD-scale dependence) $\Longrightarrow$ No problem!

Predictions for RHIC and LHC

Use LDMEs to make RHIC and LHC predictions:

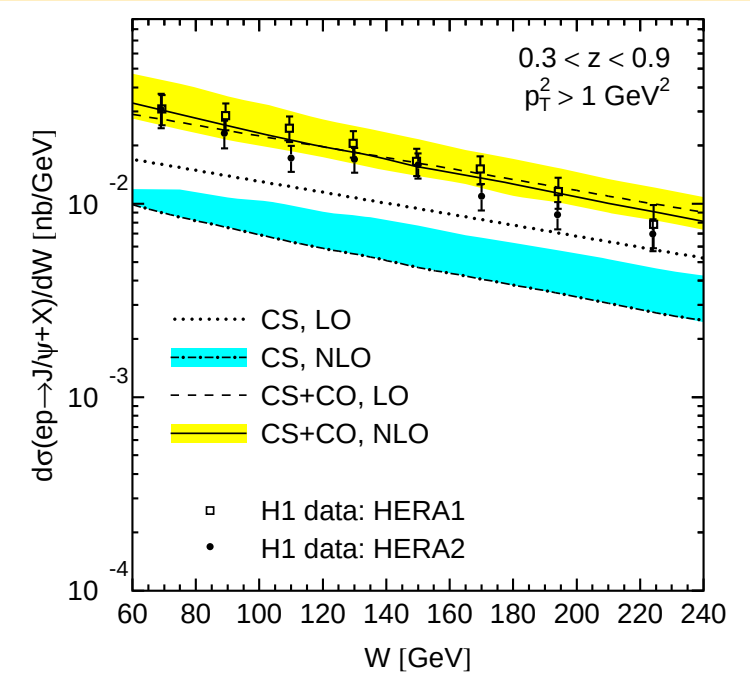


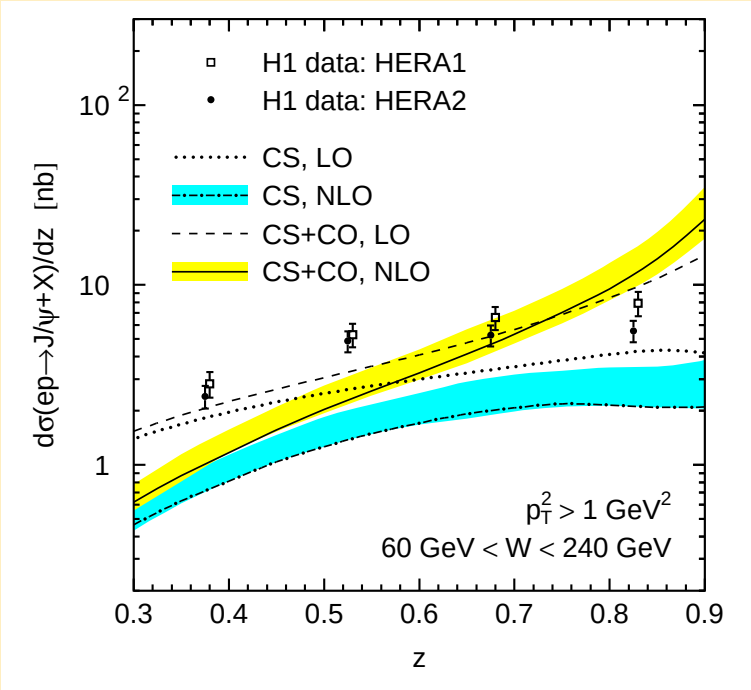


- Also RHIC and LHC data well described by CS+CO.
- Like at Tevatron: CS orders of magnitudes below the data.
- These data not part of the fit, outcome not trivial.

Further Predictions for HERA

Use LDMEs to make W and z distribution predictions:





- Proton rest frame: $z =$ Fraction of photon energy going to J/ψ.
- $z \lessapprox 0.45$: Resolved photoproduction important (not yet included).
- W distribution also well described. Data not part of the fit.

Summary (1)

Our project: Test NRQCD

- NRQCD provides rigorous factorization theorem for production and decay of heavy quarkonia: Include color-octet (CO) states.
- But: Need to proof universality of CO LDMEs.
- This work: Technological breakthrough: After 13 years finally NLO NRQCD photo- and hadroproduction calculation.

Our Results:

- CSM predictions: Could verify all previous results: CS contributions far below data in all considered experiments.
- Fitted CO LDMEs to p_T distributions at Tevatron and HERA.
- Used LDMEs for RHIC, LHC and HERA W and z distributions $\Longrightarrow$ CS+CO: Good agreement with data.

Summary (2)

Discussion of Fit:

- NLO hadroproduction p states: Shape changes, even negative.
  $\Longrightarrow$ Fit all three CO LDMEs (not linear combination like at LO).
- Negative unphysical quantities no problem.
- Photo- and hadroproduction consistently described by NRQCD.

Still to be done:

- Include resolved photoproduction.
- Extend analysis to e^+e^- collisions (LEP, B factories).
- Include feeddown processes.
- Do polarization analysis.