Global analysis of J/ψ production at NLO in NRQCD

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Production and Decay Rates of 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

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: $c\overline{c}[^3S_1^{[1]}]$
- 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.

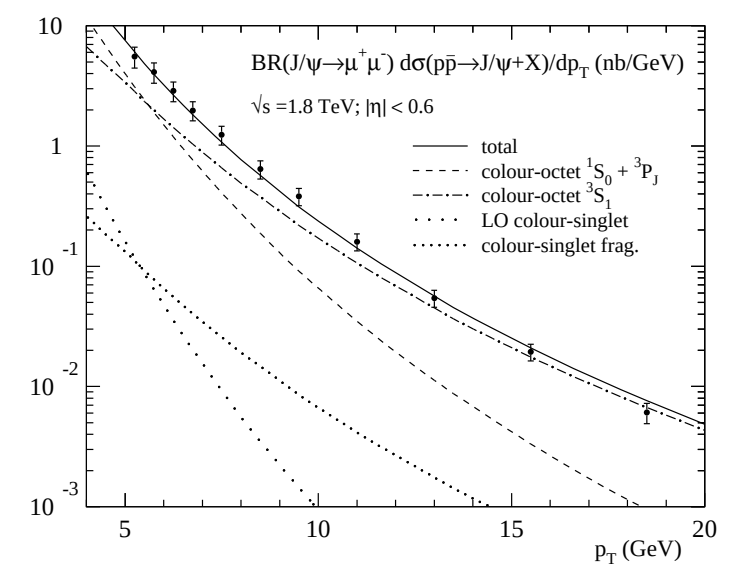
Scaling rules: MEs scale with relative velocity v ($v^2 \approx 0.2$):

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

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

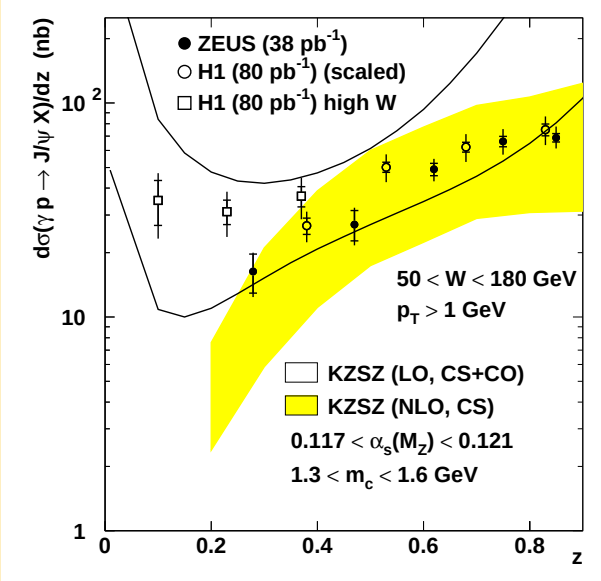
Production of J/ψ: NRQCD vs. Experiment (History)

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)	Butenschön, BK (2010) Ma et al. (2010)

Photoproduction:

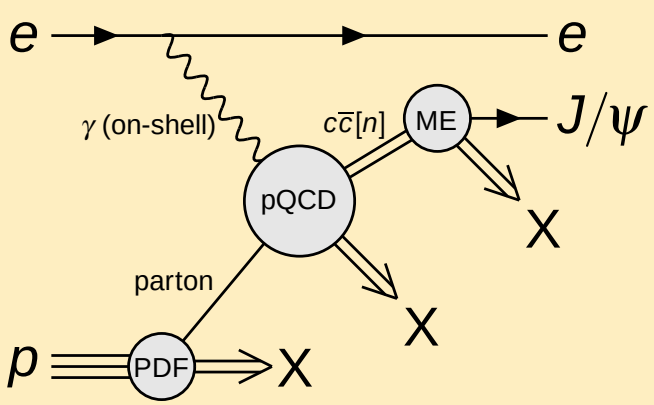
	$^3S_1^{[1]}$	$^1S_0^{[8]}$, $^3S_1^{[8]}$, $^3P_{0/1/2}^{[8]}$
Born	Berger, Jones (1981)	Ko, Lee, Song (1996)
NLO	Krämer (1995)	Butenschön, BK (2009)

Open question of ME universality:

- NLO NRQCD calculation: after 14 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:

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

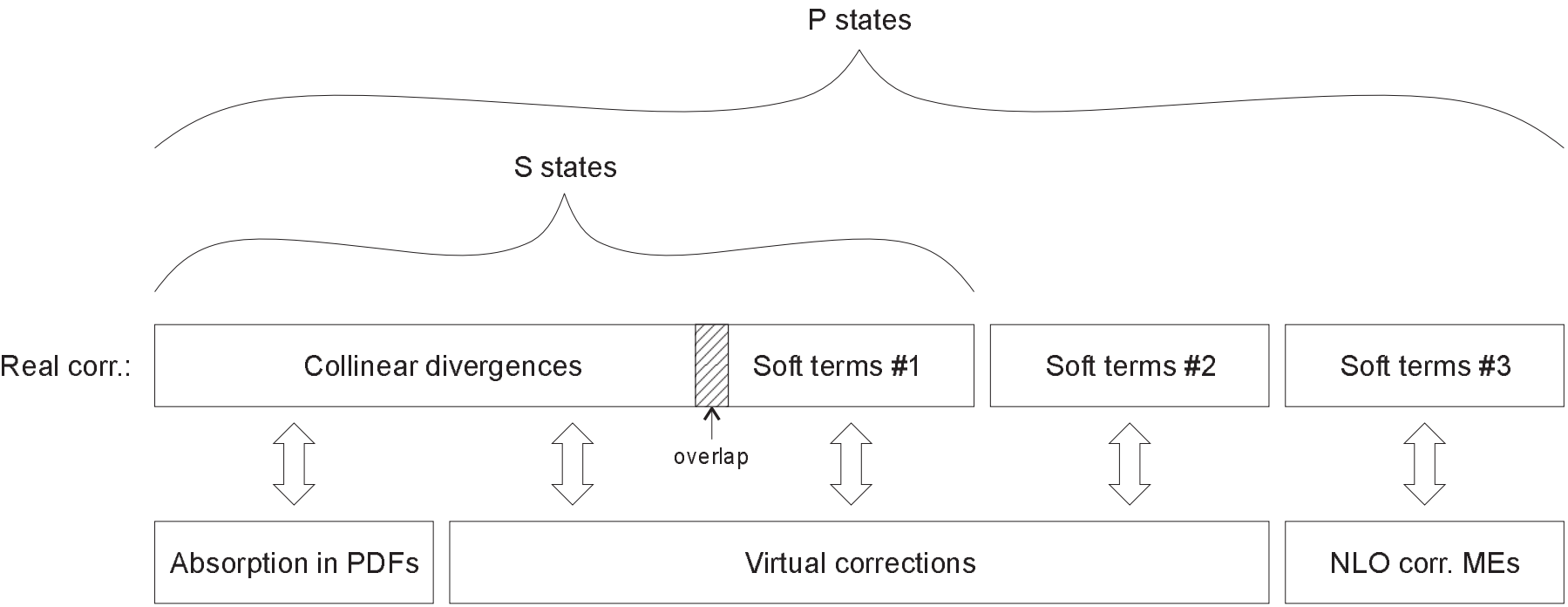
Amplitudes for $c\bar{c}[n]$ production by projector application, e.g.:

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

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

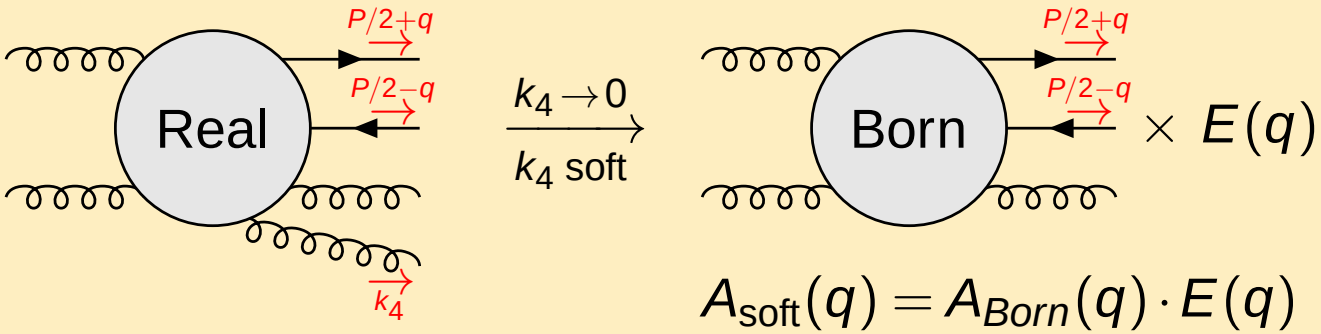
- $A_{c\bar{c}}$: Amputated pQCD amplitude for open $c\bar{c}$ production.
- q: Relative momentum between c and $\bar{c}$.

Overview of IR Singularity Structure



Structure of Soft Singularities

Soft limits of the real corrections:



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

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

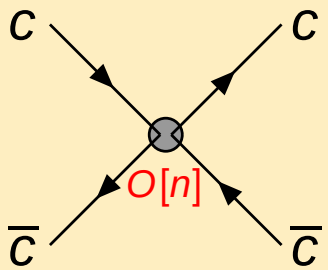
$$A_{\text{soft,s}} = A_{\text{soft}}(0) = A_{\text{Born,s}} \cdot E(0)$$
$$A_{\text{soft,p}} = A'_{\text{soft}}(0) = A_{\text{Born,p}} \cdot E(0) + A_{\text{Born,s}} \cdot E'(0)$$

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

Radiative Corrections to Long Distance MEs

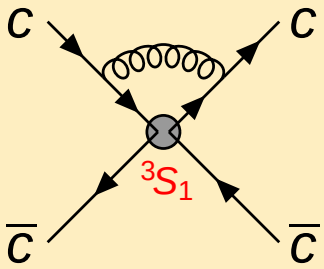
In NRQCD: Long distance MEs = $c\bar{c}$ scattering amplitudes:

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

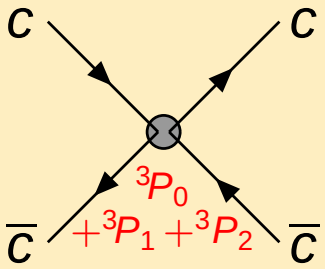


$O[n]$ = 4-fermion operators
$(n = {}^3S_1^{[1]}, {}^1S_0^{[8]}, {}^3S_1^{[8]}, {}^3P_{0/1/2}^{[8]}, \ldots)$

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



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



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

Global fit at NLO in NRQCD

Fit CO LDMEs to all available world data on J/ψ inclusive production:

type	$\sqrt{s}$	collider	collaboration	reference
pp	200 GeV	RHIC	PHENIX	PRD82(2010)012001
$p\bar{p}$	1.8 TeV	Tevatron I	CDF	PRL97(1997)572; 578
$p\bar{p}$	1.96 TeV	Tevatron II	CDF	PRD71(2005)032001
pp	7 TeV	LHC	ALICE, ATLAS, CMS, LHCb	talks; arXiv:1011.4193
γp	300 GeV	HERA I	H1, ZEUS	EPJ25(2002)25; 27(2003)173
γp	319 GeV	HERA II	H1	EPJ68(2010)401
$\gamma\gamma$	197 GeV	LEP II	DELPHI	PLB565(2003)76
e^+e^-	10.6 GeV	KEKB	BELLE	PRD79(2009)071101

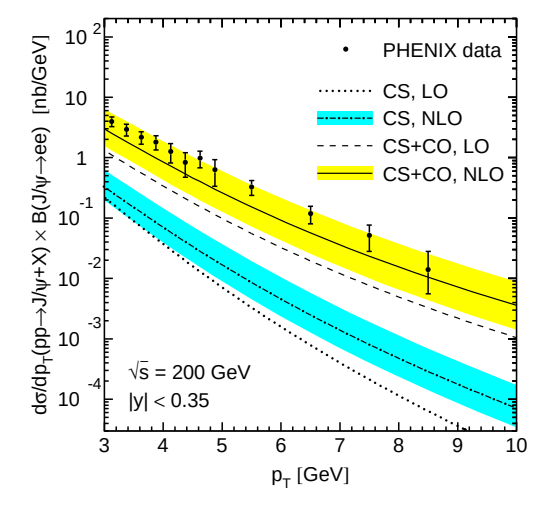
- Best fit values:

10^{-2} GeV^{3+2L}	PRL106(2011)022003	new
$\langle\mathscr{O}(^1S_0^{[8]})\rangle$	4.50 ± 0.72	4.97 ± 0.44
$\langle\mathscr{O}(^3S_1^{[8]})\rangle$	0.312 ± 0.093	0.224 ± 0.059
$\langle\mathscr{O}(^3P_0^{[8]})\rangle$	-1.21 ± 0.35	-1.61 ± 0.20

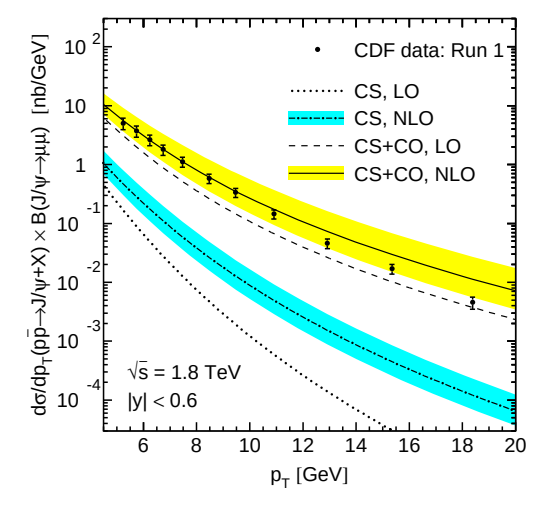
- $\chi^2/\text{d.o.f.} = 857/194 = 4.42$ for default prediction
- $\propto v^4 \langle O_1(^3S_1)\rangle \rightsquigarrow$ NRQCD velocity scaling rules $\surd$

Comparison with RHIC and Tevatron

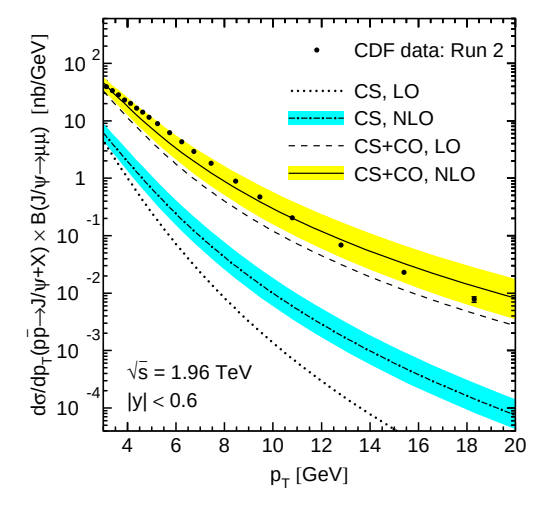
RHIC PHENIX



Tevatron I CDF



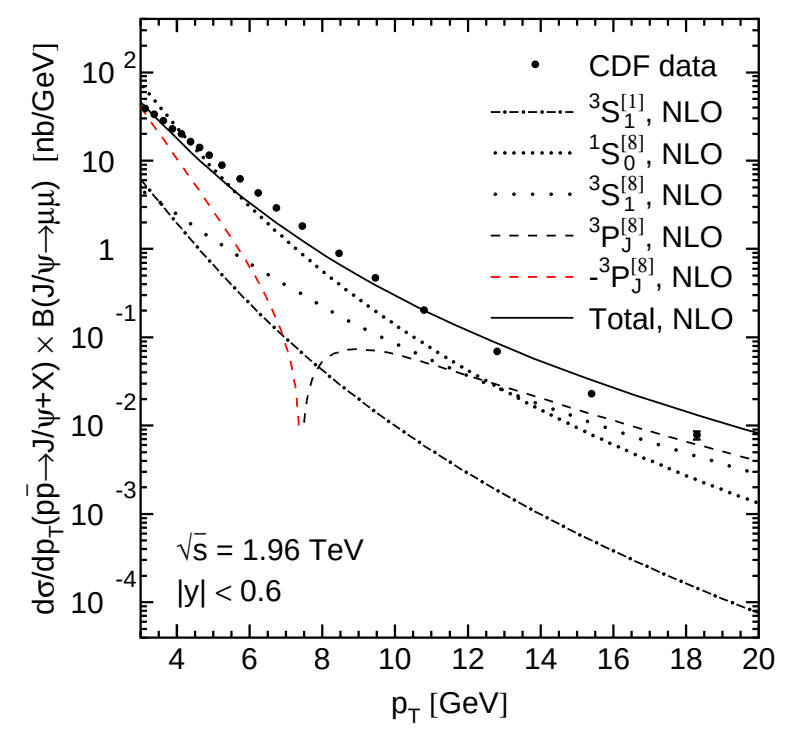
Tevatron II CDF



- Data well described by CS+CO at NLO.
- CS orders of magnitudes below data.

Comparison with Tevatron (cont.)

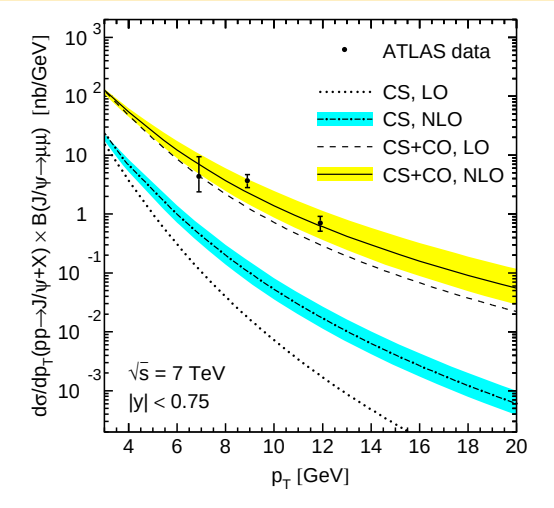
Relative importance of CO processes:



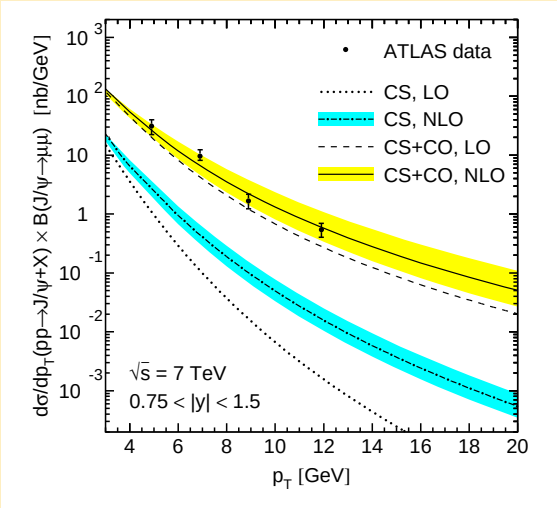
- Short-distance $\sigma(c\bar{c}[^3P_J^{[8]}]) < 0$ for $p_T \gtrsim 7$ GeV.
- But: Short-distance cross sections and LDMEs unphysical (NRQCD scale and scheme dependence) $\rightsquigarrow$ No problem!

Comparison with ATLAS at LHC

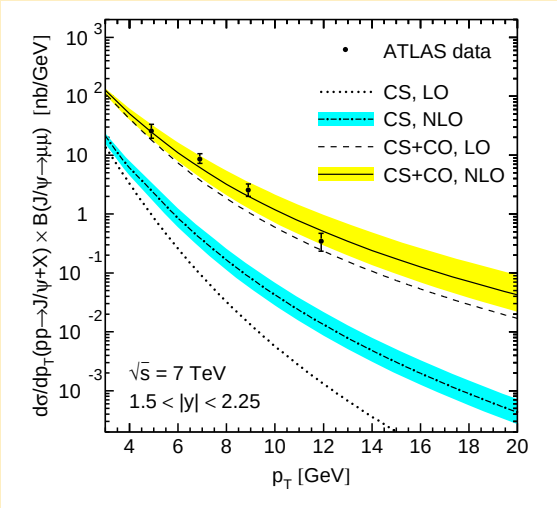
ATLAS $|y| < 0.75$



ATLAS $0.75 < |y| < 1.5$



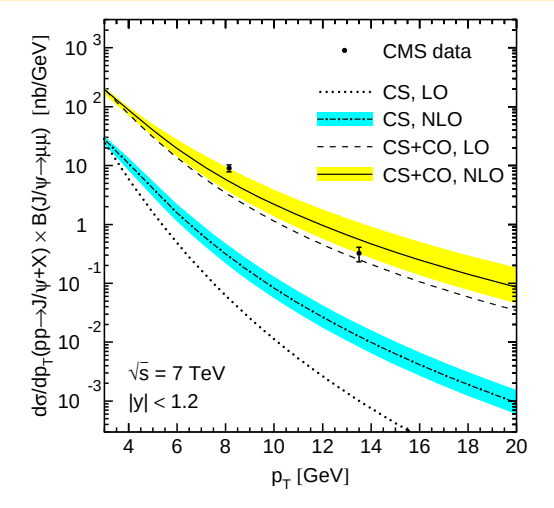
ATLAS $1.5 < |y| < 2.25$



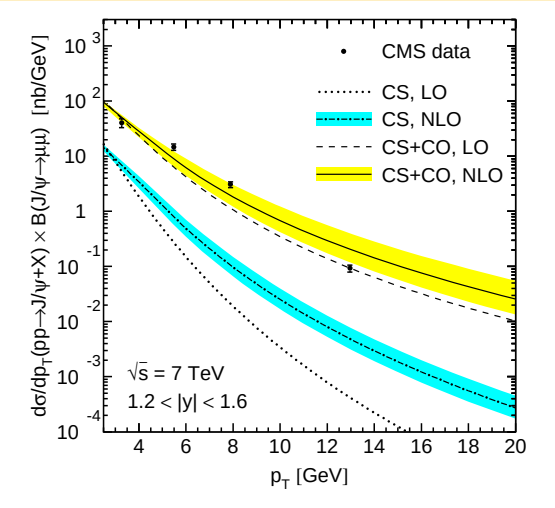
- Data well described by CS+CO at NLO.
- CS orders of magnitudes below data.

Comparison with CMS at LHC

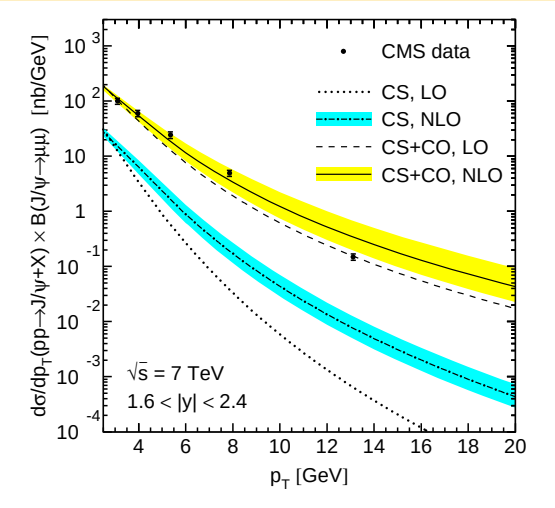
CMS $|y| < 1.2$



CMS $1.2 < |y| < 1.6$



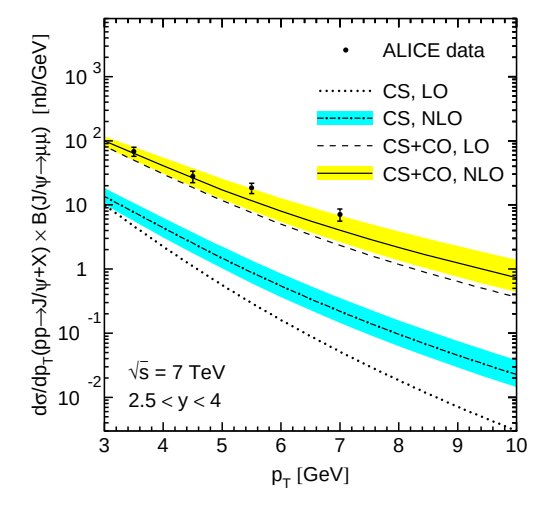
CMS $1.6 < |y| < 2.4$



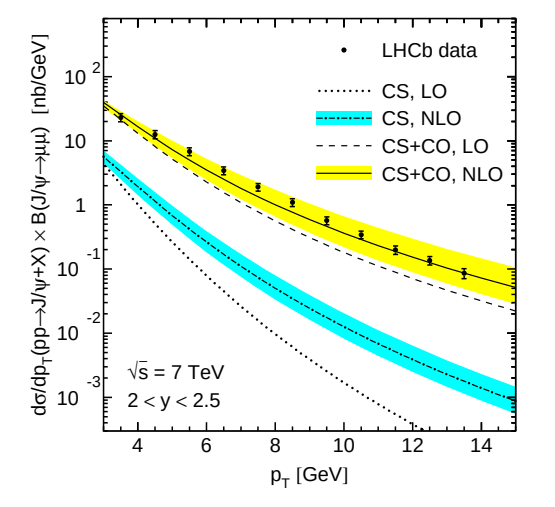
- Data well described by CS+CO at NLO.
- CS orders of magnitudes below data.

Comparison with ALICE and LHBb at LHC

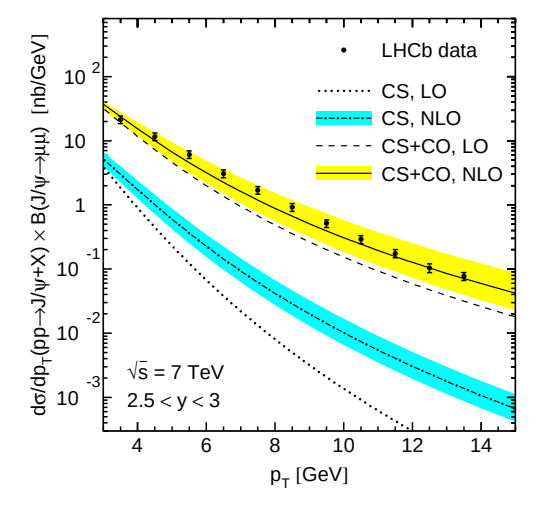
ALICE $2.5 < y < 4.0$



LHCb $2.0 < y < 2.5$



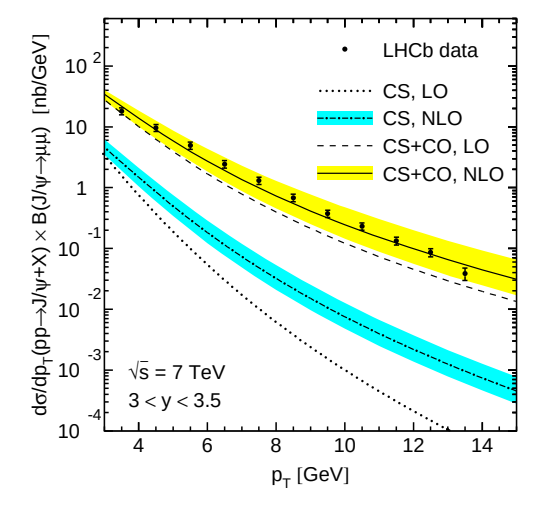
LHCb $2.5 < y < 3.0$



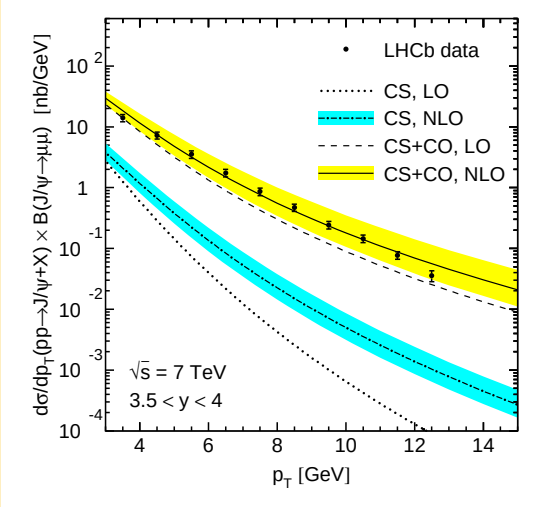
- Data well described by CS+CO at NLO.
- CS orders of magnitudes below data.

Comparison with LHBb at LHC (cont.)

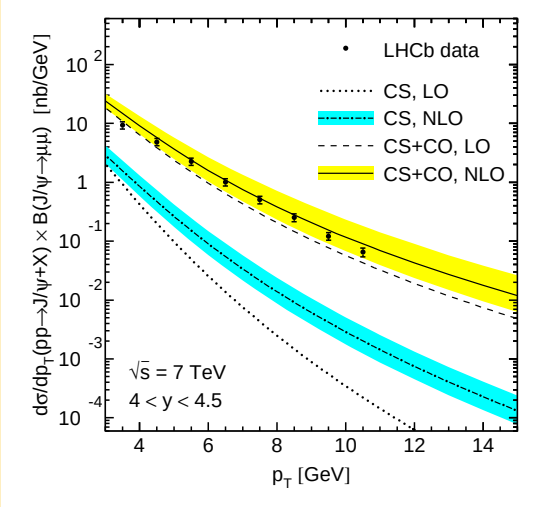
LHCb $3.0 < y < 3.5$



LHCb $3.5 < y < 4.0$

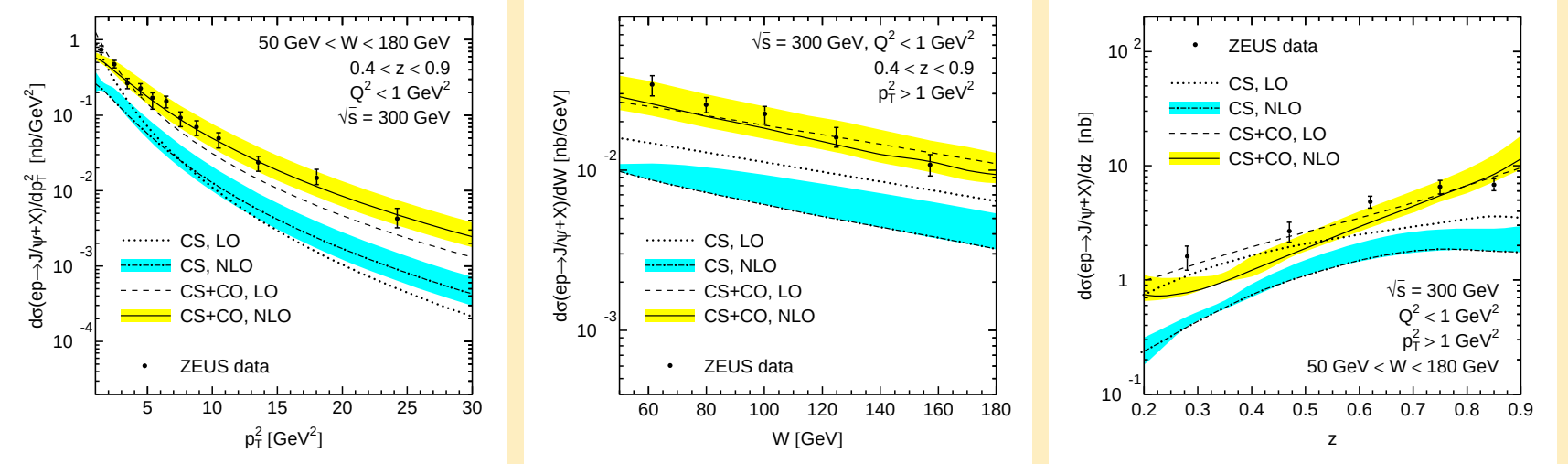


LHCb $4.0 < y < 4.5$



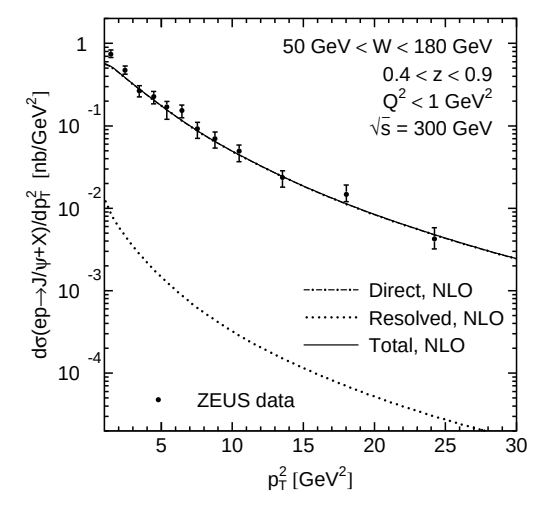
- Data well described by CS+CO at NLO.
- CS orders of magnitudes below data.

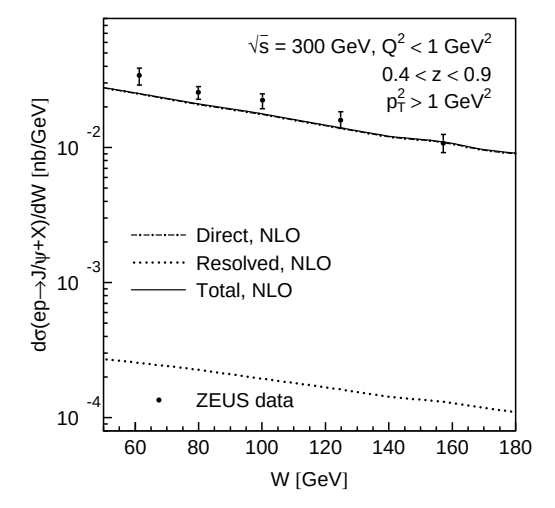
Comparison with ZEUS at HERA I (1)

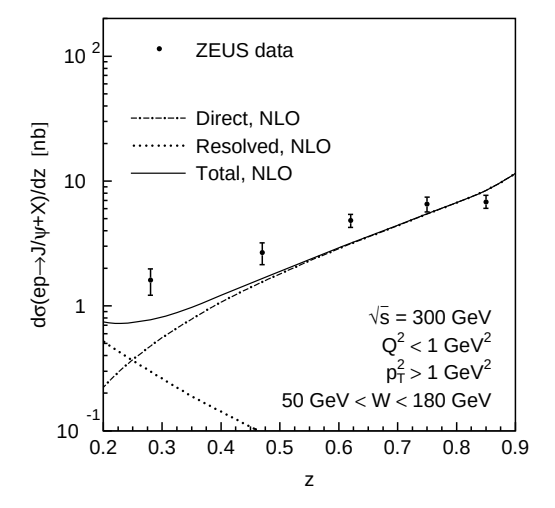


- $W =$ γp CM energy.
- $z =$ fraction of γ energy going to J/ψ in p rest frame.
- Singularity for $z \to 1$ eliminated by shape function in SCET.
- Data well described by CS+CO at NLO.
- CS factor of 3–5 below the data.

Comparison with ZEUS at HERA I (2)

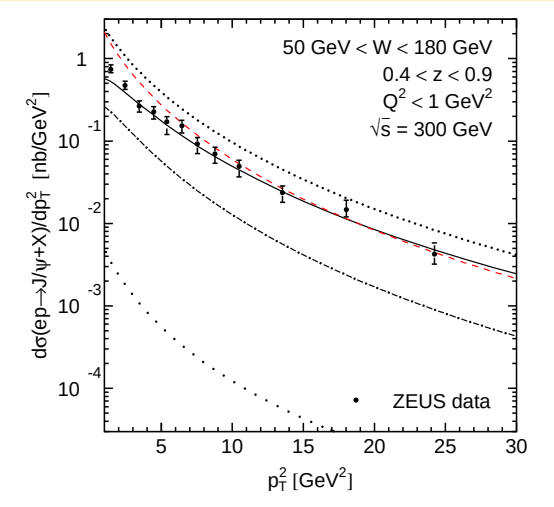


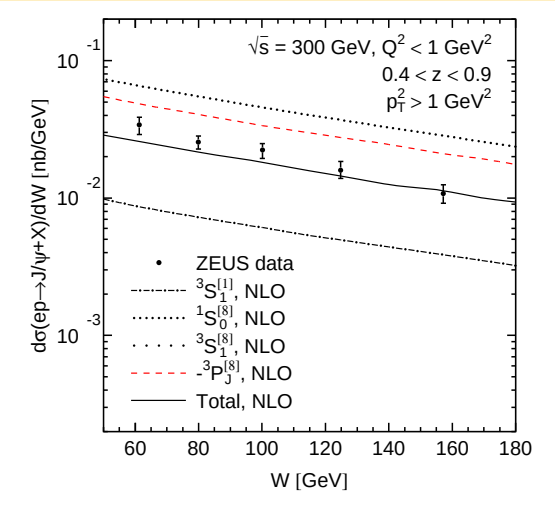


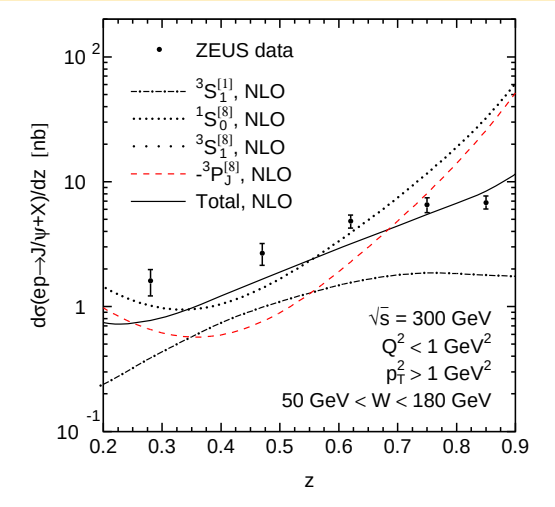


- Data for $0.4 < z < 0.9$ exhausted by direct photoproduction.
- Resolved photoproduction only relevant for $z \lesssim 0.4$.

Comparison with ZEUS at HERA I (3)

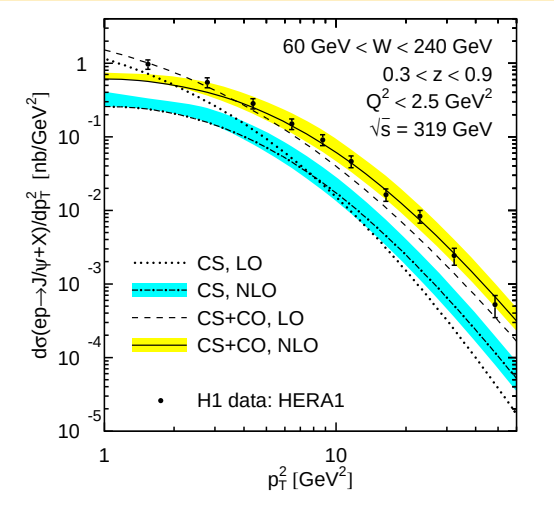


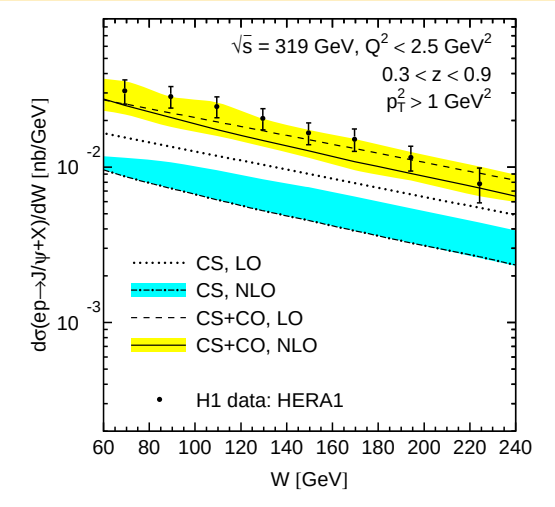


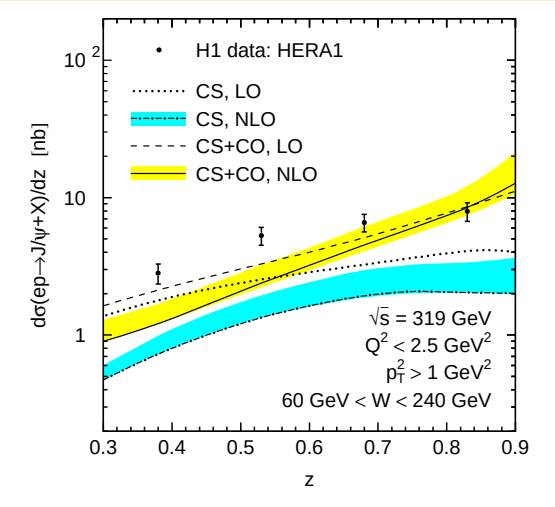


- $\langle \mathscr{O}(^3P_0^{[8]}) \rangle < 0 \rightsquigarrow {}^3P_0^{[8]}$ contribution negative.
- Negative interference with ${}^1S_0^{[8]}$ contribution beneficial.
- ${}^3S_1^{[8]}$ contribution negligible here.

Comparison with H1 at HERA I

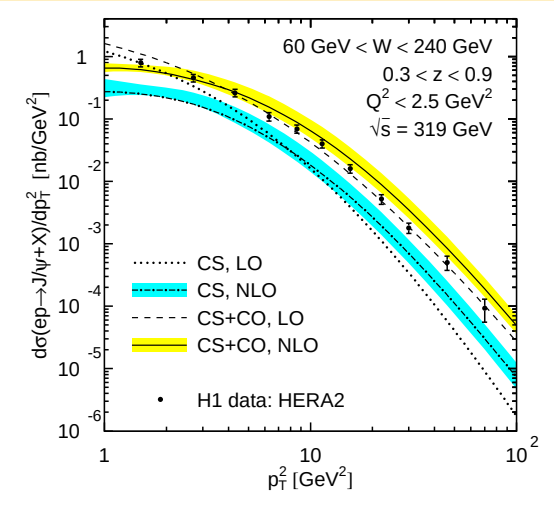


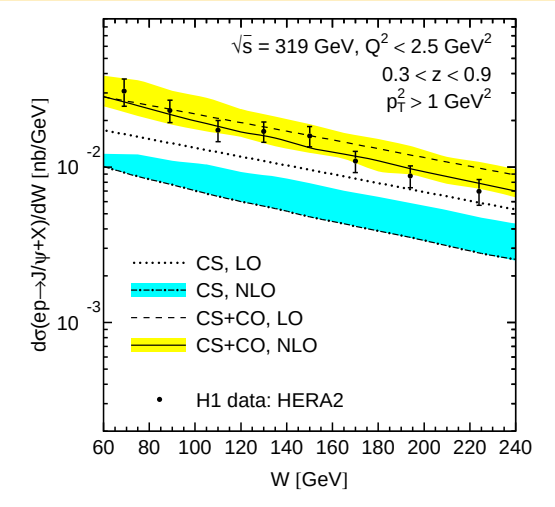


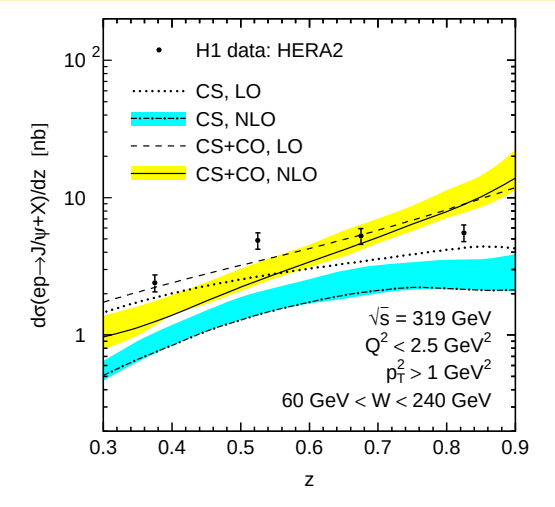


- Data well described by CS+CO at NLO.
- CS factor of 3–5 below data.

Comparison with H1 at HERA II

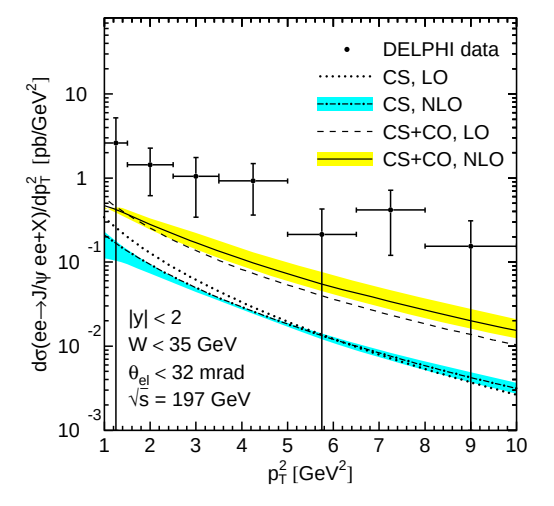


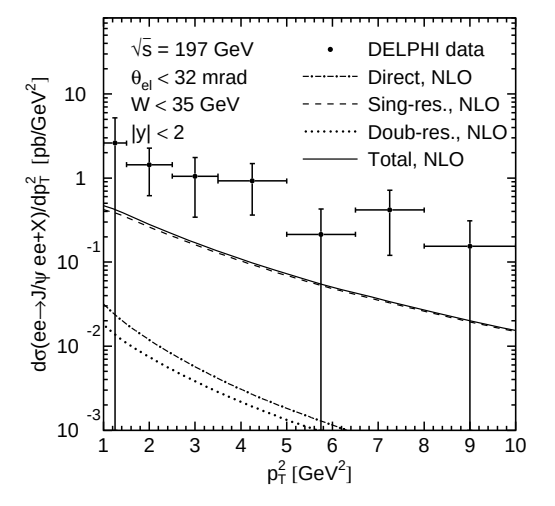


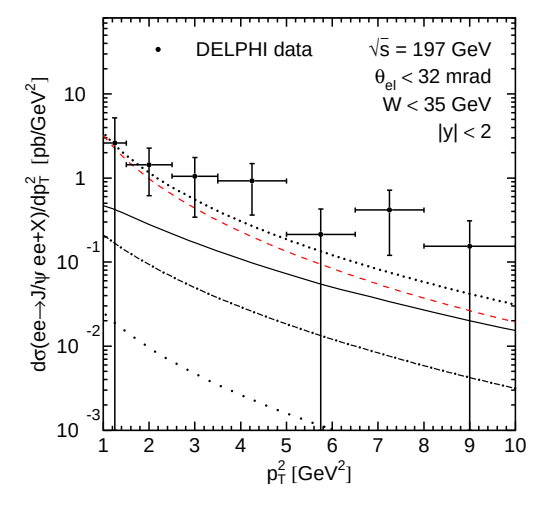


- Data well described by CS+CO at NLO.
- CS factor of 3–5 below the data.

Comparison with DELPHI at LEP II







- Agreement with NRQCD at NLO worse than 2002 with LO.
- Just 16 DELPHI events with $p_T > 1$ GeV.
- No results from ALEPH, L3, OPAL.
- Data exhausted by single-resolved contribution.

Comparison with BELLE at KEKB

Total cross section $\sigma(e^+e^- \to J/\psi + X)$
$\sqrt{s}$ = 10.6 GeV

BELLE data: $\sigma = (0.43 \pm 0.13)$ pb
($J/\psi + c\bar{c}$ contribution subtracted)

CS, LO: $\sigma = 0$
CS, NLO: $\sigma = (0.24^{+0.20}_{-0.09})$ pb
CS+CO, LO: $\sigma = 0.23$ pb
CS+CO, NLO: $\sigma = (0.70^{+0.35}_{-0.17})$ pb

(LO means $e^+e^- \to J/\psi + 1$ jet)

- At NLO, both CSM and NRQCD agree with data.

Summary

- NRQCD provides rigorous factorization theorem for production and decay of heavy quarkonia; predicts:
  - existence of CO states;
  - universality of LDMEs.
- Previous LO tests not conclusive.
- Here: first global analysis of unpolarized-J/ψ world data at NLO.
- Hadro- and photoproduction: striking evidence of NRQCD vs. CSM.
- $\gamma\gamma$ scattering, e^+e^- annihilation: not conclusive yet.
- Contributions from feed-down and B decays throughout small against theoretical uncertainties.
- Hadroproduction data alone cannot reliably fix all 3 CO LDMEs and give misleading results for their linear combinations (cf. arXiv:1009.3655).
- Polarized J/ψ?