

Heavy-quarkonium theory in the LHC era

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In collaboration with Mathias Butenschön

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Introduction



Technology



Global fit



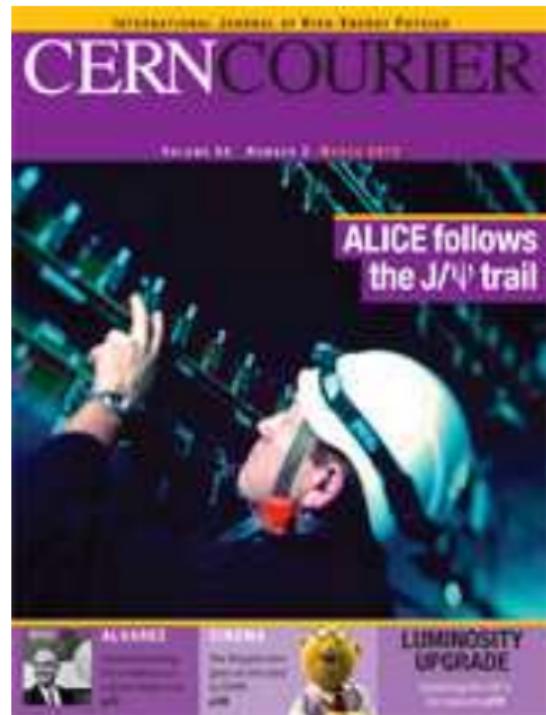
Further tests



Summary



CERN Courier, Volume 52, Issues 1 and 2



Outline

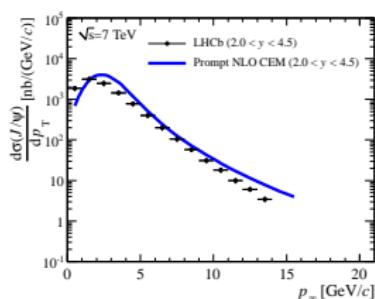
- 1 **Introduction:** CEM, CSM, NRQCD factorization
- 2 **NLO NRQCD:** General concept, singularities
- 3 **Global fit:** Unpolarized J/ψ yield
- 4 **Further tests:** ATLAS, FTPS, ZEUS
- 5 **Summary:** NRQCD at the crossroads

Introduction: CEM, CSM, NRQCD factorization

Color evaporation model [Fritzsch 77; Halzen 77; Glück Owens Reya 78]

$$\sigma_{J/\psi} \approx \frac{1}{9} \rho_{J/\psi} \int_{2m_c}^{2m_D} ds_{c\bar{c}} \frac{d\sigma_{c\bar{c}}}{ds_{c\bar{c}}}$$

- $1/9$: statistical probability that $3 \times \overline{3}$ $c\bar{c}$ pair is asymptotically in color-single state
- $\rho_{J/\psi}$: fraction of charmonia that materialize as J/ψ
- Based local parton-hadron duality
- Assumes soft-gluon exchange with underlying event
- $2s+1 L_J^{[c]}$ quantum numbers do not enter
- Useful qualitative picture, rather than rigorous theory



[Schuler Vogt 96; Vogt 99; Frawley Ullrich Vogt 08]

Color-singlet model vs. NRQCD factorization

Color-singlet model [Berger Jones 81; Baier Rückl 81]

- $c\bar{c}$ pair in physical color-singlet state, e.g. $c\bar{c}[{}^3S_1^{[1]}]$ for J/ψ .
- Nonperturbative information in J/ψ wave function at origin.
- Leftover IR divergences for P-wave quarkonia \leadsto inconsistent!
- Predicted cross section factor 10^1 – 10^2 below Tevatron data.

NRQCD factorization [Bodwin Braaten Lepage 1995]

- Rigorous effective field theory
- Based on factorization of soft and hard scales
(Scale hierarchy: $Mv^2, Mv \ll \Lambda_{\text{QCD}} \ll M$)
- Theoretically consistent: no leftover singularities.
- NNLO proof of factorization [Nayak Qiu Sterman 05]
- Can explain hadroproduction at Tevatron.

NRQCD factorization in a nutshell

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

- 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), nonperturbative, extracted from experiment, universal?

Scaling rules [Lepage Magnea² Nakhleh Hornbostel 92]
 LDMEs scale with relative velocity v ($v^2 \approx 0.2$).

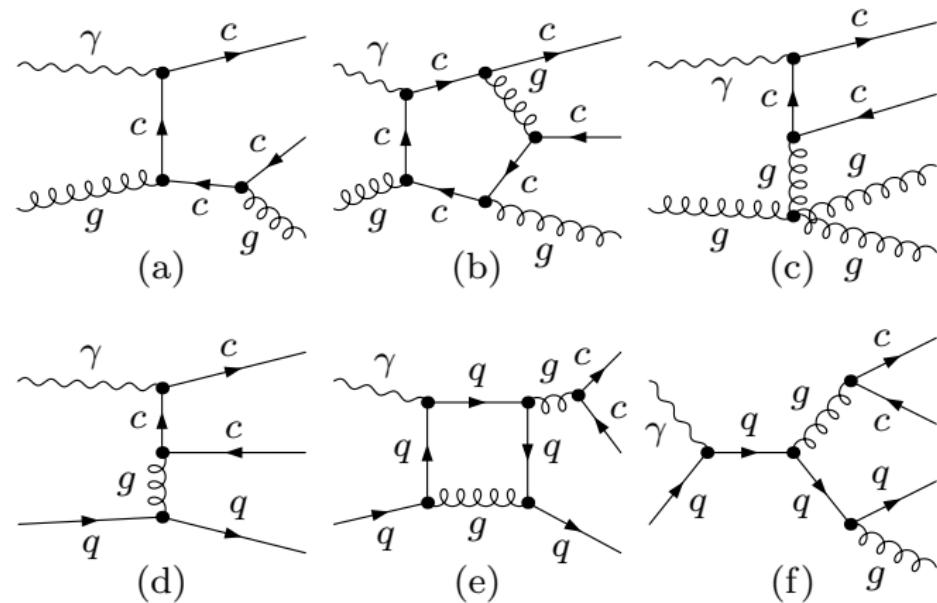
scaling	v^3 (CS state)	v^7 (CO states)	v^{11}
n	${}^3S_1^{[1]}$	${}^1S_0^{[8]}, {}^3S_1^{[8]}, {}^3P_{0/1/2}^{[8]}$	\dots

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

NLO NRQCD calculations

- Petrelli Cacciari Greco Maltoni Mangano 98:
Photo- and hadroproduction (only $2 \rightarrow 1$ processes)
- Klasen BK Mihaila Steinhauser 05:
Two-photon scattering (w/o resolved photons)
- Butenschön BK 09:
Photoproduction (w/o resolved photons)
- Zhang Ma Wang Chao 10:
 $e^+ e^-$ annihilation
- Ma Wang Chao 10, Butenschön BK 10:
Hadroprduction
- Butenschön BK 11:
 γp and $\gamma\gamma$ (resolved photons) \rightsquigarrow global fit of CO LDMEs
- Butenschön BK 11:
Polarization in photoproduction \rightsquigarrow talk by M. Butenschön
- Butenschön BK 12, Chao Ma K. Wang Y.-J. Zhang 12, Gong, Wan, J.-X. Wang, H.-F. Zhang 12:
Polarization in hadroprduction \rightsquigarrow talk by M. Butenschön

Sample diagrams for J/ψ photoproduction in NRQCD



Color and spin projection

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

$$A_{c\bar{c}[^1S_0^{[8]}]} = \text{Tr} [C_8 \Pi_0 A_{c\bar{c}}] |_{q=0}$$

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

$$A_{c\bar{c}[^3P_J^{[8]}]} = \varepsilon_{\alpha\beta} \frac{d}{dq_\beta} \text{Tr} [C_8 \Pi^\alpha A_{c\bar{c}}] |_{q=0}$$

- $A_{c\bar{c}}$: amputated pQCD amplitude for open $c\bar{c}$ production.
- q : relative momentum between c and \bar{c} .
- $C_{1/8}$: color projectors
- $\Pi_{0/1}$: spin projectors
- ε : polarization vectors and tensors

Cancellation of divergences

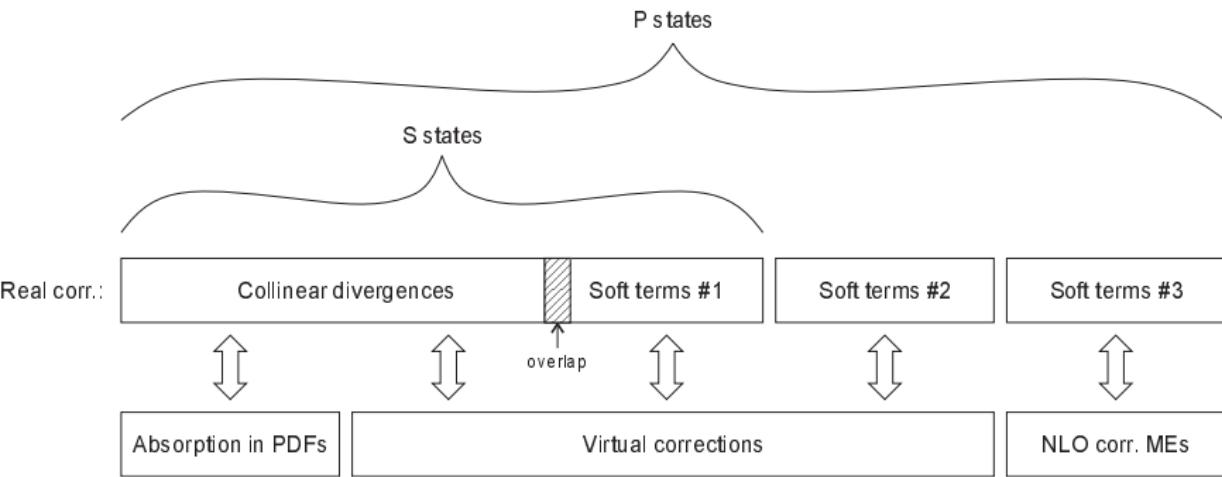
UV divergences: Cancellation within virtual corrections:

- 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



Global fit at NLO in NRQCD

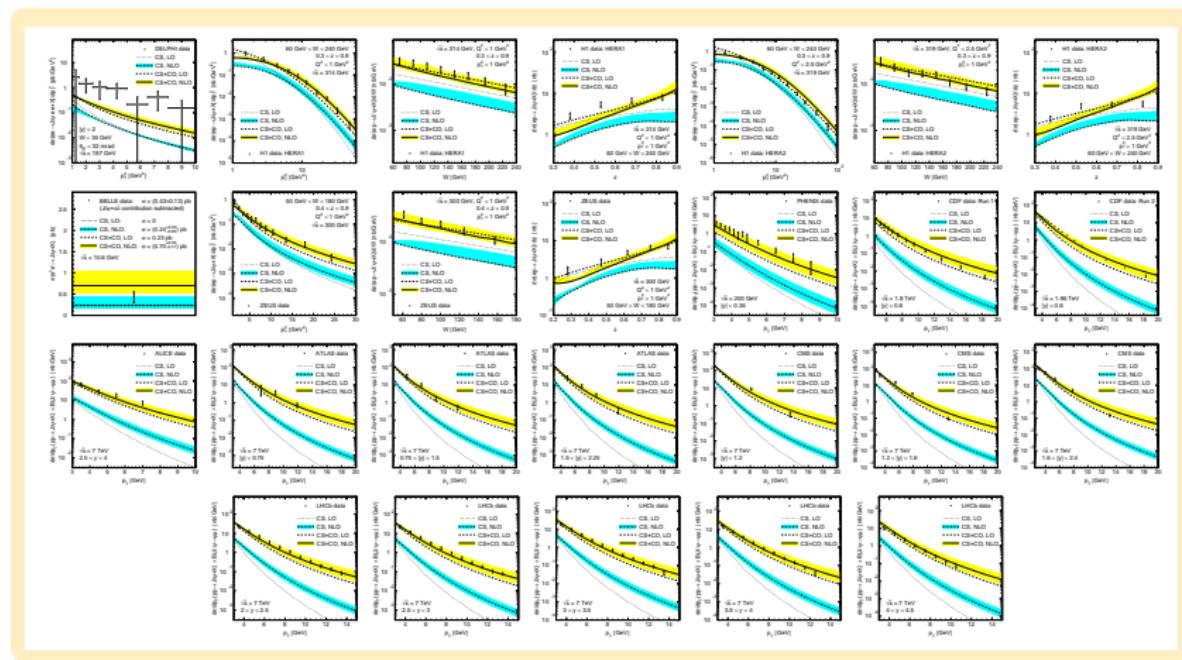
Fit type	CO	LDMEs to all available collider	world data collaboration	on J/ψ inclusive production reference
pp	200 GeV	RHIC	PHENIX	PRD82(2010)012001
$p\bar{p}$	1.8 TeV	Tevatron I	CDF	PRL97(1997)572; 578
$p\bar{p}$	1.96 TeV	Tevatron II	CDF	PRD71(2005)032001
pp	7 TeV	LHC	ALICE ATLAS CMS LHCb	NPB(PS)214(2011)56 PoS(ICHEP 2010)013 EPJC71(2011)1575 EPJC71(2011)1645
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

Fit values for CO LDMEs:

$10^{-2} \text{ GeV}^{3+2L}$	feed-down included	feed-down subtracted
$\langle \mathcal{O}[{}^1S_0^{[8]}] \rangle$	4.97 ± 0.44	3.04 ± 0.35
$\langle \mathcal{O}[{}^3S_1^{[8]}] \rangle$	0.224 ± 0.059	0.168 ± 0.046
$\langle \mathcal{O}[{}^3P_0^{[8]}] \rangle$	-1.61 ± 0.20	-0.908 ± 0.161
$\chi^2/\text{d.o.f.}$	$857/194 = 4.42$	$725/194 = 3.74$

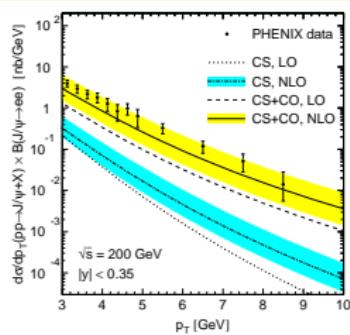
Note: CO LDMEs $\propto v^4 \times \langle \mathcal{O}[{}^3S_1^{[1]}] \rangle \rightsquigarrow$ NRQCD velocity scaling rules ✓

Comparison with world data

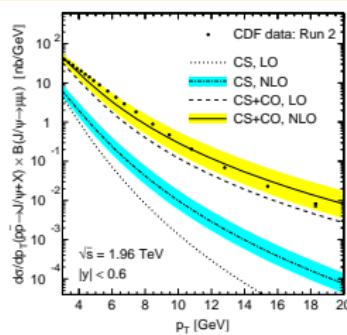


Comparison with RHIC and Tevatron

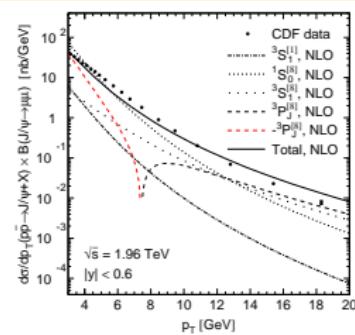
RHIC
PHENIX



Tevatron II
CDF

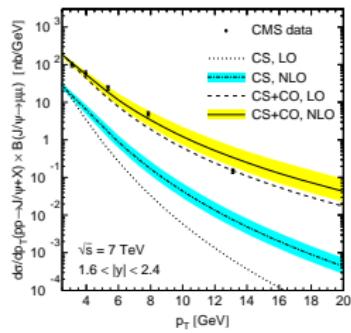
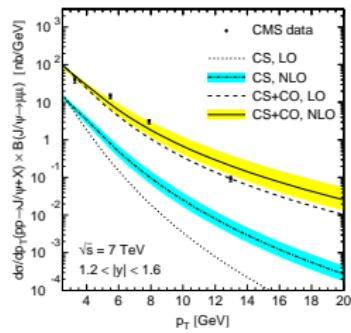
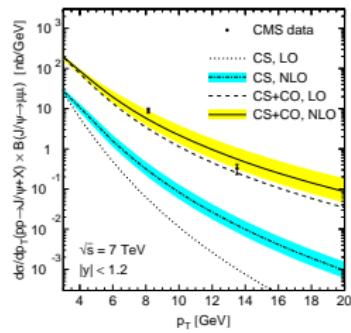
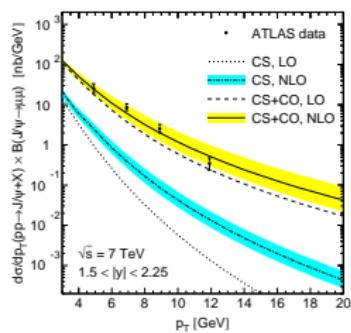
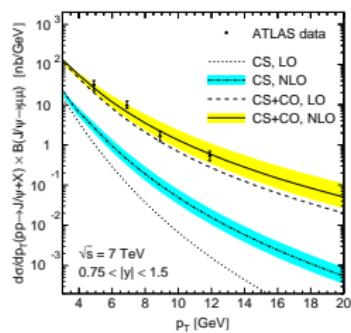
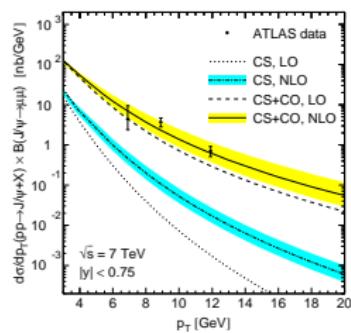


Decomposition of
NLO NRQCD

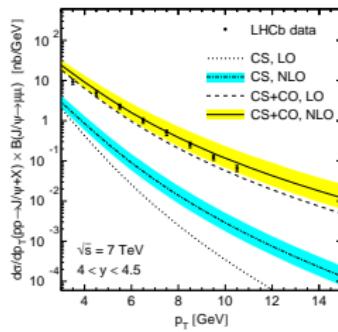
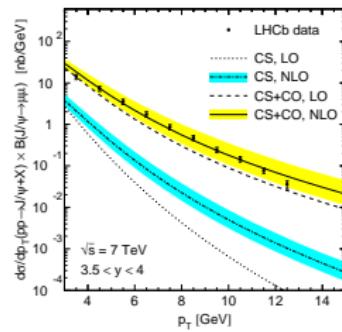
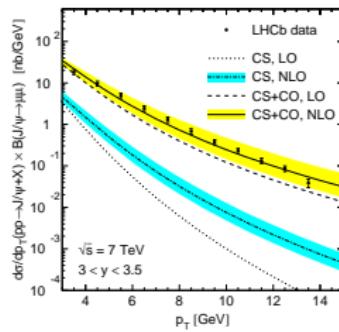
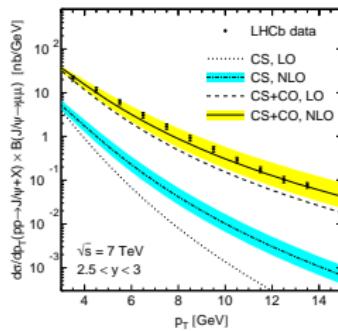
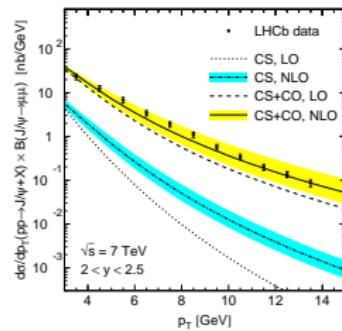
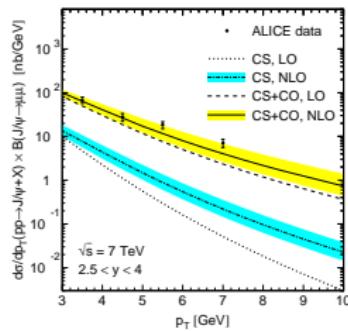


- Data **well described** by CS+CO at NLO.
- CS orders of magnitudes **below** data.
- **Sizeable NLO corrections**, especially in the $3P_J^{[8]}$ channels.

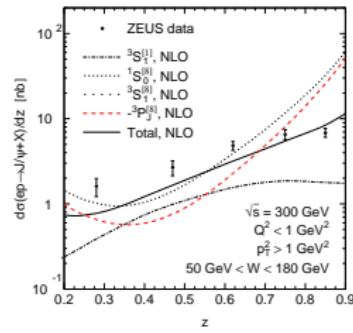
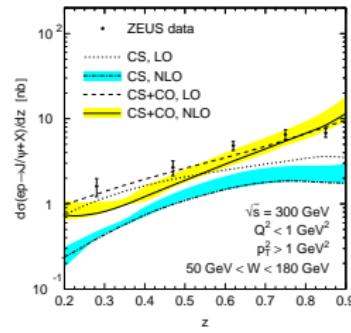
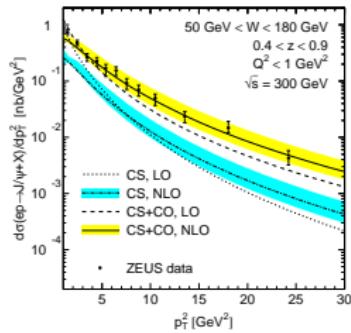
Comparison with ATLAS and CMS at LHC



Comparison with ALICE and LHBb at LHC

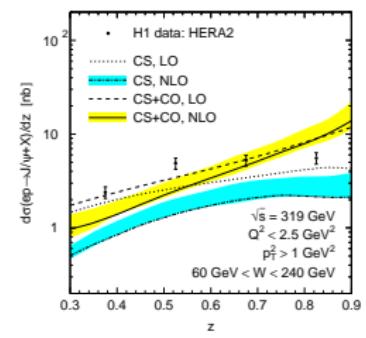
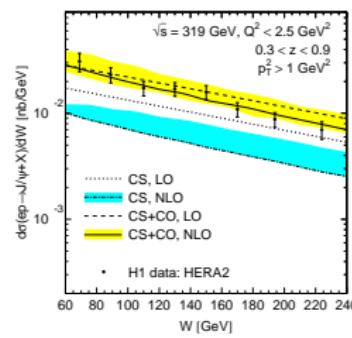
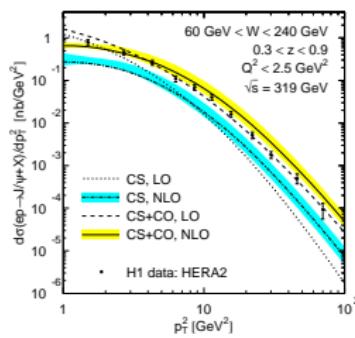
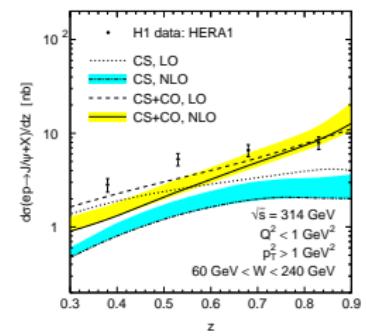
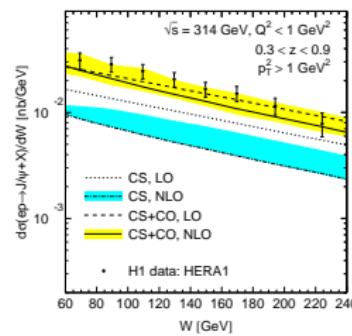
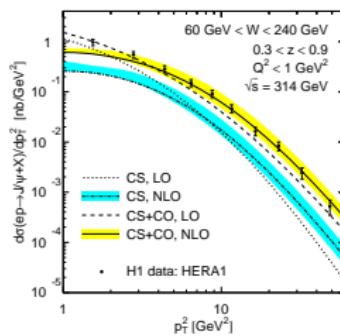


Comparison with ZEUS at HERA I

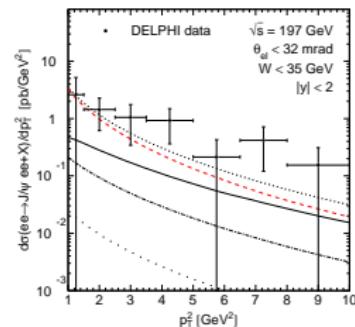
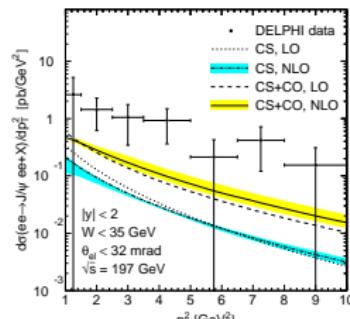
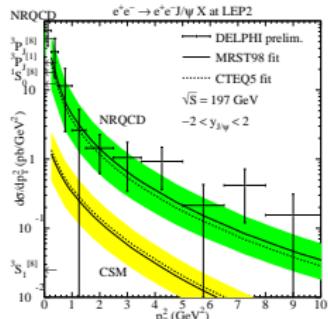


- $W = \gamma p$ CM energy.
- $z =$ fraction of γ energy going to J/ψ in p rest frame.
- Compensation of $^1S_0^{[8]}$ vs. $^3P_J^{[8]}$ \rightsquigarrow regular $z \rightarrow 1$ behavior.
- Data **well described** by CS+CO at NLO.
- CS factor of 3–5 **below** the data.

Comparison with H1 at HERA I and II



Comparison with DELPHI at LEP II



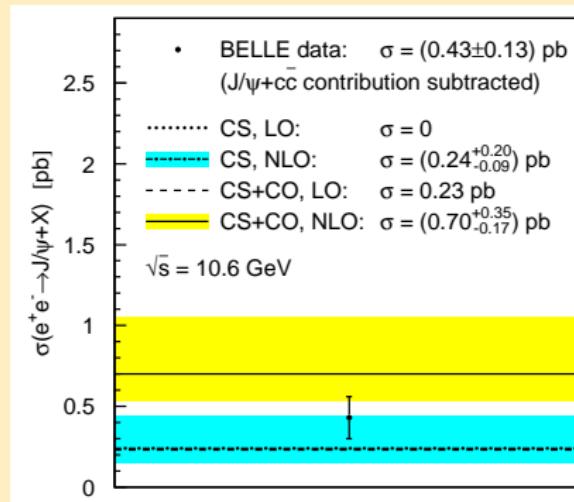
[Klasen BK Mihaila
Steinhauser 02]

NLO NRQCD

Decomposition of NLO NRQCD

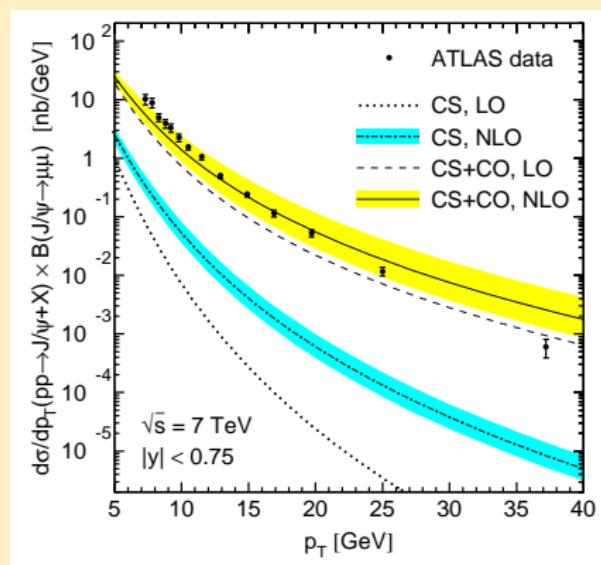
- Agreement with NRQCD at NLO worse than in 2002 at LO.
- Just 16 DELPHI events with $p_T > 1$ GeV.
- No results from ALEPH, L3, OPAL.
- Data exhausted by single-resolved contribution.

Comparison with Belle at KEKB



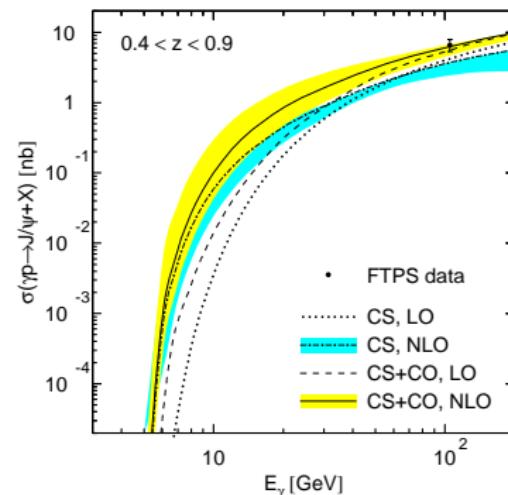
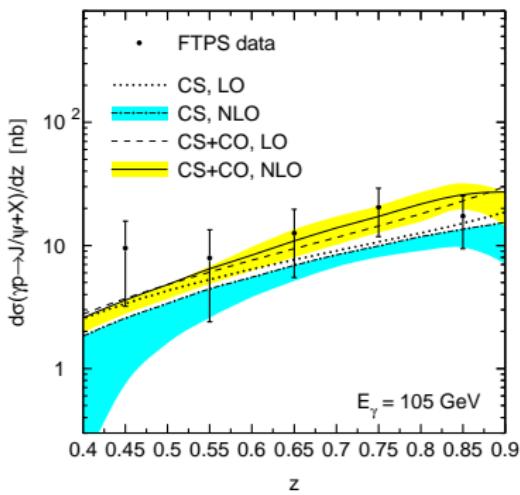
- At NLO, both CSM and NRQCD agree with data.
- # of charged tracks > 4, missing events **not corrected** for.
~~~ Belle point likely **higher**.

# Comparison with ATLAS (after fit) [NPB850(2011)387]



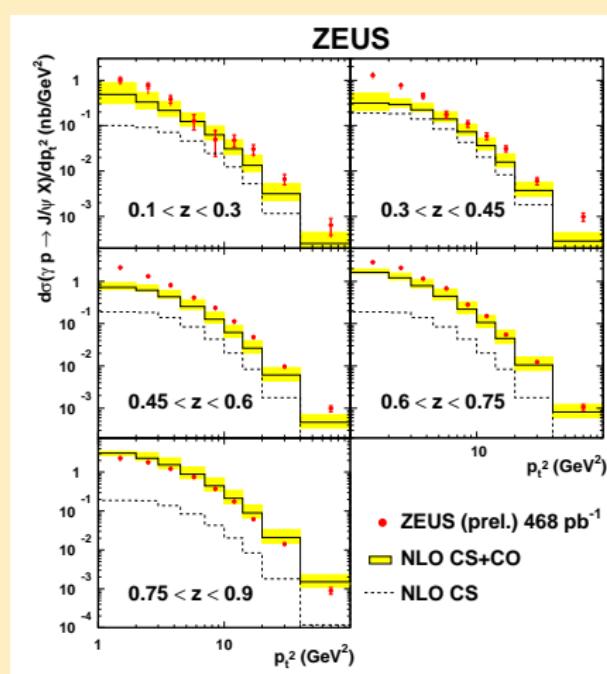
- Resummation of large logs  $\ln(p_T^2/M^2)$  necessary at large  $p_T$ .
- New formalism to include non-leading powers in  $p_T^2/M^2$  [Kang Qiu Sterman 2012].

# Comparison with Fermilab Tagged-Photon Spectrometer data (excluded from fit) [PRL52(1984)795]



- Inelastic scattering of 105 GeV photons on hydrogen target.
- Data **remarkably well described** by CS+CO at NLO.

# Comparison with ZEUS (after fit) [A. Bertolin, QWG 2011]



- Notorious NRQCD overshoot at large  $z$  overcome.

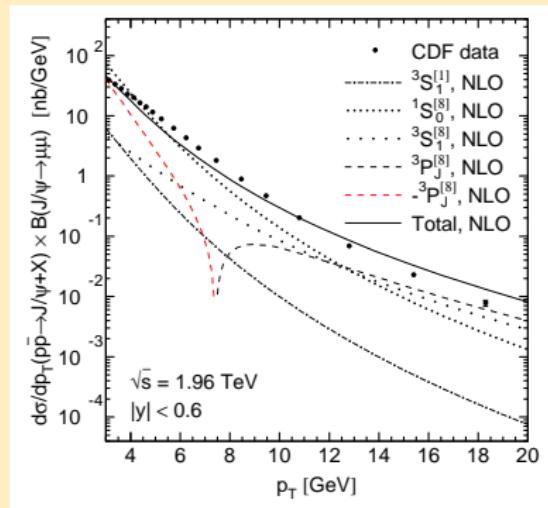
# Summary

- 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  $J/\psi$  world data at NLO.
- Hadro- and photoproduction: striking evidence for NRQCD.
- CSM greatly undershoots data, except for  $e^+e^-$  annihilation.
- $\gamma\gamma$  scattering not conclusive yet.
- Contributions from feed-down and  $B$  decays throughout small against theoretical uncertainties  $\rightsquigarrow$  subtracted in fit.
- Hadroproduction data alone cannot reliably fix all 3 CO LDMEs and give misleading results for their linear combinations; cf.  
[Ma et al. PRL106\(2011\)042002; PRD84\(2011\)114001](#);  
[Butenschön BK AIPConfProc1343\(2011\)409](#).
- $J/\psi$  polarization  $\rightsquigarrow$  talk by M. Butenschön

# Backup Slides

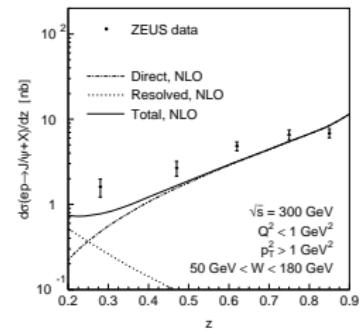
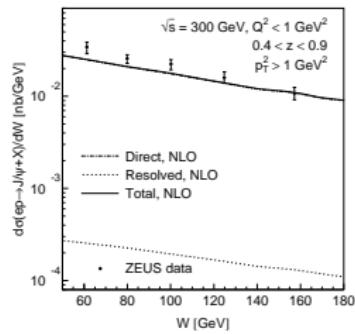
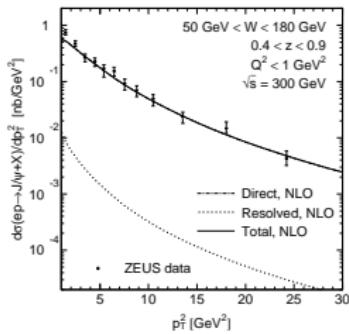
# Comparison with Tevatron (cont.)

## Relative importance of CO processes:



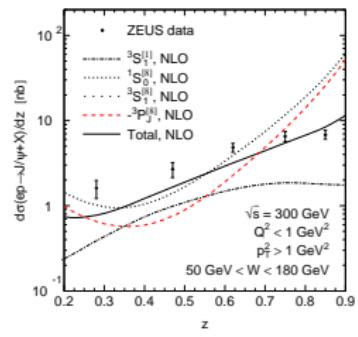
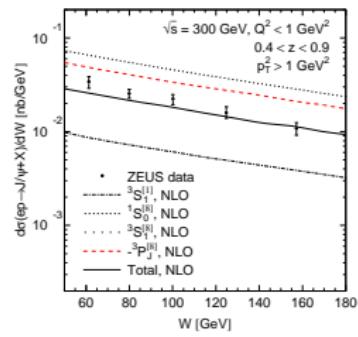
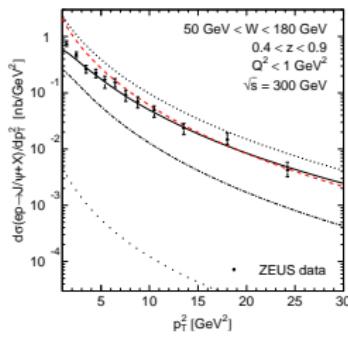
- Short-distance  $\sigma(c\bar{c}[{}^3P_J^{[8]}]) < 0$  for  $p_T \gtrsim 7 \text{ GeV}$ .
- But: Short-distance cross sections and LDMEs **unphysical** (NRQCD scale and scheme dependence)  $\leadsto$  No problem!

# Comparison with ZEUS at HERA I (cont.)



- 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 (cont.)



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

# Dependence on low- $p_T$ cut: Global fit

Vary low- $p_T$  cut on  $pp$  and  $p\bar{p}$  data:

| Data left                                             | $p_T > 1$ GeV<br>148 points | $p_T > 2$ GeV<br>134 points | $p_T > 3$ GeV<br>119 points | $p_T > 5$ GeV<br>86 points | $p_T > 7$ GeV<br>60 points |
|-------------------------------------------------------|-----------------------------|-----------------------------|-----------------------------|----------------------------|----------------------------|
| $\langle \mathcal{O}^{J/\psi}[{}^1S_0^{[8]}] \rangle$ | $5.68 \pm 0.37$             | $4.25 \pm 0.43$             | $4.97 \pm 0.44$             | $4.92 \pm 0.49$            | $3.91 \pm 0.51$            |
| $\langle \mathcal{O}^{J/\psi}[{}^3S_1^{[8]}] \rangle$ | $0.90 \pm 0.50$             | $2.94 \pm 0.58$             | $2.24 \pm 0.59$             | $2.23 \pm 0.62$            | $2.96 \pm 0.64$            |
| $\langle \mathcal{O}^{J/\psi}[{}^3P_0^{[8]}] \rangle$ | $-2.23 \pm 0.17$            | $-1.38 \pm 0.20$            | $-1.61 \pm 0.20$            | $-1.59 \pm 0.22$           | $-1.16 \pm 0.23$           |

↝ Global fit insensitive to low- $p_T$  cut on  $pp$  and  $p\bar{p}$  data as long as  $\gamma p$ ,  $\gamma\gamma$  (74 points with  $p_T > 1$  GeV), and  $e^+e^-$  data (1 point) are retained.

Vary low- $p_T$  cut on  $\gamma p$  and  $\gamma\gamma$  data:

| Data left                                             | $p_T > 1$ GeV<br>74 points | $p_T > 2$ GeV<br>30 points | $p_T > 3$ GeV<br>15 points | $p_T > 5$ GeV<br>5 points | $p_T > 7$ GeV<br>1 points |
|-------------------------------------------------------|----------------------------|----------------------------|----------------------------|---------------------------|---------------------------|
| $\langle \mathcal{O}^{J/\psi}[{}^1S_0^{[8]}] \rangle$ | $4.97 \pm 0.44$            | $5.10 \pm 0.92$            | $4.05 \pm 1.17$            | $5.44 \pm 1.27$           | $9.56 \pm 1.59$           |
| $\langle \mathcal{O}^{J/\psi}[{}^3S_1^{[8]}] \rangle$ | $2.24 \pm 0.59$            | $2.11 \pm 1.22$            | $3.52 \pm 1.56$            | $1.73 \pm 1.68$           | $-3.66 \pm 2.09$          |
| $\langle \mathcal{O}^{J/\psi}[{}^3P_0^{[8]}] \rangle$ | $-1.61 \pm 0.20$           | $-1.58 \pm 0.48$           | $-0.97 \pm 0.63$           | $-1.63 \pm 0.68$          | $-3.73 \pm 0.83$          |

↝ Global fit insensitive to **moderate** low- $p_T$  cut on  $\gamma p$  and  $\gamma\gamma$  data as long as  $pp$  and  $p\bar{p}$  data (119 points with  $p_T > 3$  GeV), and  $e^+e^-$  data (1 point) are retained.

# Dependence on low- $p_T$ cut: Fit to $pp$ and $p\bar{p}$ data only

Vary low- $p_T$  cut:

| Data left                                             | $p_T > 1$ GeV<br>148 points | $p_T > 2$ GeV<br>134 points | $p_T > 3$ GeV<br>119 points | $p_T > 5$ GeV<br>86 points | $p_T > 7$ GeV<br>60 points |
|-------------------------------------------------------|-----------------------------|-----------------------------|-----------------------------|----------------------------|----------------------------|
| $\langle \mathcal{O}^{J/\psi}[{}^1S_0^{[8]}] \rangle$ | $8.54 \pm 0.52$             | $16.85 \pm 1.23$            | $11.02 \pm 1.67$            | $1.68 \pm 2.20$            | $2.18 \pm 2.56$            |
| $\langle \mathcal{O}^{J/\psi}[{}^3S_1^{[8]}] \rangle$ | $-2.66 \pm 0.69$            | $-13.36 \pm 1.60$           | $-5.56 \pm 2.19$            | $8.75 \pm 2.98$            | $10.34 \pm 3.55$           |
| $\langle \mathcal{O}^{J/\psi}[{}^3P_0^{[8]}] \rangle$ | $-3.63 \pm 0.23$            | $-7.70 \pm 0.61$            | $-4.46 \pm 0.87$            | $2.20 \pm 1.23$            | $3.50 \pm 1.50$            |
| $M_0$                                                 | $2.25 \pm 0.12$             | $3.51 \pm 0.19$             | $3.29 \pm 0.20$             | $5.50 \pm 0.29$            | $8.24 \pm 0.58$            |
| $M_1$                                                 | $6.37 \pm 0.19$             | $5.80 \pm 0.19$             | $5.54 \pm 0.20$             | $3.27 \pm 0.29$            | $1.63 \pm 0.43$            |

↷ Fit highly sensitive to low- $p_T$  cut.

Comparison with fit to unpolarized, direct CDF II data with  $p_T > 7$  GeV

Y.-Q. Ma, K. Wang, and K.-T. Chao, Phys. Rev. D 84, 114001 (2011):

$$M_0 = (8.54 \pm 1.02) \times 10^{-2} \text{ GeV}^3$$

$$M_1 = (1.67 \pm 1.05) \times 10^{-3} \text{ GeV}^3$$