

# Global analysis of yield and polarization of the $J/\psi$ at Tevatron and LHC

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PRL **104** (2010) 072001

PRL **106** (2011) 022003

PRD **84** (2011) 051501 (Rapid Communications)

PRL **107** (2011) 232001

PRL **108** (2012) 172002

MPLA **28** (2013) 1350027 (Brief Reviews)

Introduction



Technology



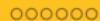
Global fit



Further tests



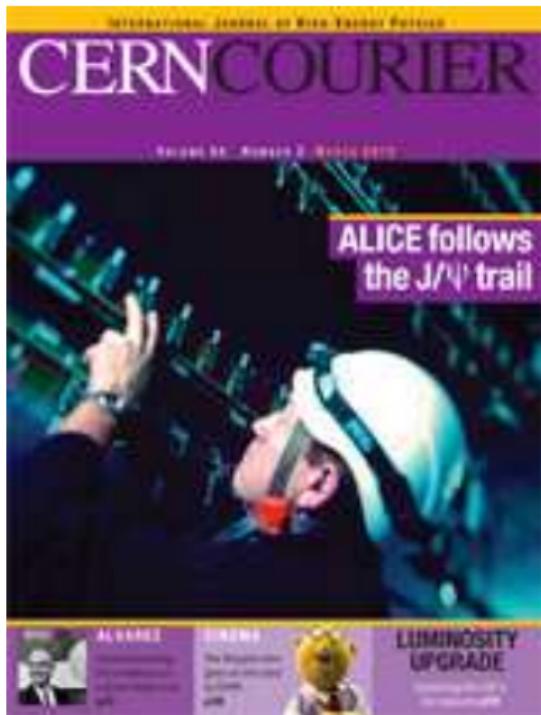
Polarization



Summary



# CERN Courier, Volume 52, Issues 1 and 2



# Outline

- 1 **Introduction:** CSM vs. NRQCD factorization
- 2 **NLO NRQCD:** General concept, singularities
- 3 **Global fit:** Unpolarized  $J/\psi$  yield
- 4 **Further tests:** ATLAS, FTPS, ZEUS
- 5 **Polarization:** HERA, Tevatron, LHC
- 6 **Summary:** NRQCD at the crossroads

# Introduction: CSM 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  $J/\psi$ .
- Nonperturbative information in  $J/\psi$  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 95]

- 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 Magnea<sup>2</sup> Nakhleh Hornbostel 92]

LDMEs scale with relative velocity  $v$  ( $v^2 \approx 0.2$ ).

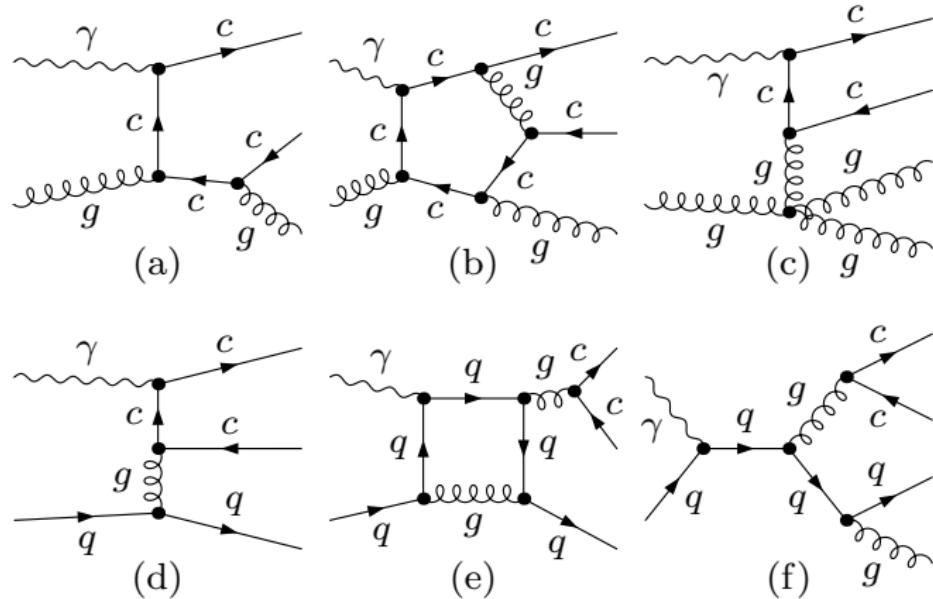
scaling	$v^3$ (CS state)	$v^7$ (CO states)	$v^{11}$
$n$	${}^3S_1^{[1]}$	${}^1S_0^{[8]}, {}^3S_1^{[8]}, {}^3P_{0/1/2}^{[8]}$	$\dots$

- Double expansion in  $v$  and  $\alpha_s$ .
- 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:  
 $\gamma p$  and  $\gamma\gamma$  (resolved photons)  $\rightsquigarrow$  global fit of CO LDMEs
- Butenschön BK 11:  
Polarization in photoproduction
- Butenschön BK 12, Chao Ma K. Wang Y.-J. Zhang 12, Gong, Wan, J.-X. Wang, H.-F. Zhang 12:  
Polarization in hadroprduction

# Sample diagrams for $J/\psi$ 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
- $\varepsilon$ : polarization vectors and tensors

# Cancellation of divergences

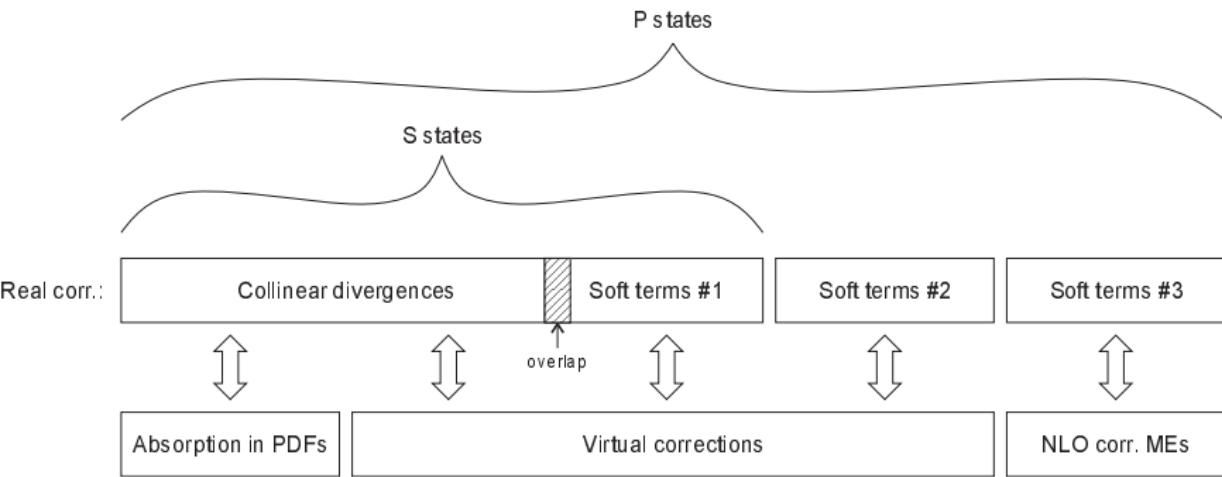
**UV divergences:** Cancellation within virtual corrections:

- 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

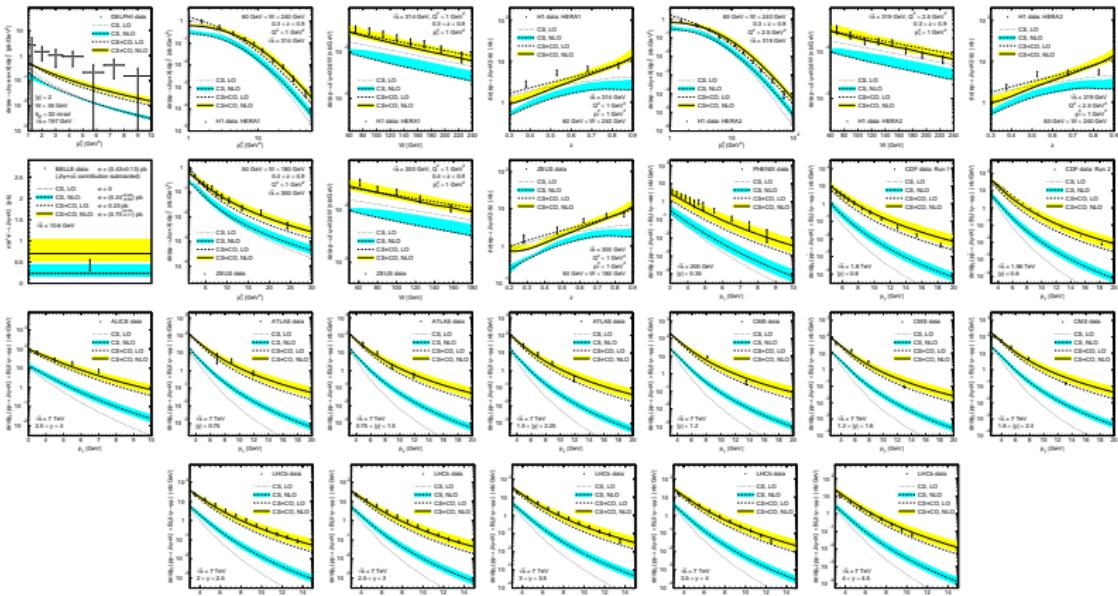
Fit type	CO type	LDMEs to $\sqrt{s}$	all available collider	world collaboration	on $J/\psi$ inclusive production reference
$pp$		200 GeV	RHIC	PHENIX	PRD82(2010)012001
$p\bar{p}$		1.8 TeV	Tevatron I	CDF	PRL97(1997)572; 578
$p\bar{p}$		1.96 TeV	Tevatron II	CDF	PRD71(2005)032001
$pp$		7 TeV	LHC	ALICE ATLAS CMS LHCb	NPB(PS)214(2011)56 PoS(ICHEP 2010)013 EPJC71(2011)1575 EPJC71(2011)1645
$\gamma p$		300 GeV	HERA I	H1, ZEUS	EPJ25(2002)25; 27(2003)173
$\gamma p$		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
$\langle \mathcal{O}[{}^1S_0^{[8]}] \rangle$	$4.97 \pm 0.44$	$3.04 \pm 0.35$
$\langle \mathcal{O}[{}^3S_1^{[8]}] \rangle$	$0.224 \pm 0.059$	$0.168 \pm 0.046$
$\langle \mathcal{O}[{}^3P_0^{[8]}] \rangle$	$-1.61 \pm 0.20$	$-0.908 \pm 0.161$
$\chi^2/\text{d.o.f.}$	$857/194 = 4.42$	$725/194 = 3.74$

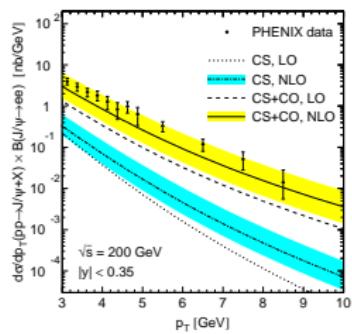
Note: CO LDMEs  $\propto v^4 \times \langle \mathcal{O}[{}^3S_1^{[1]}] \rangle \rightsquigarrow$  NRQCD velocity scaling rules ✓

# Comparison with world data

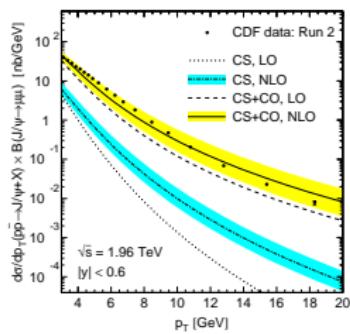


# Comparison with RHIC and Tevatron

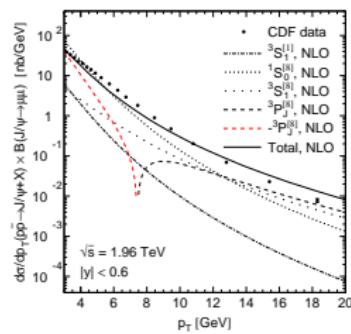
RHIC  
PHENIX



Tevatron II  
CDF

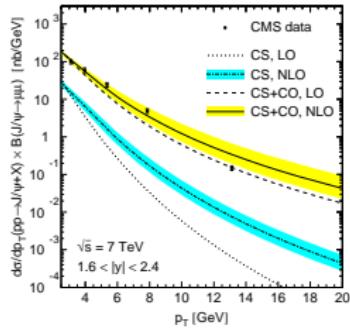
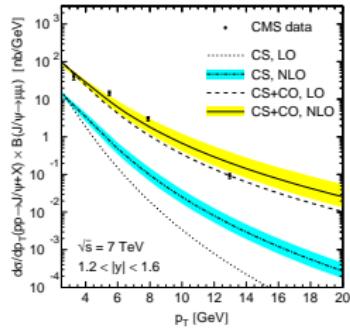
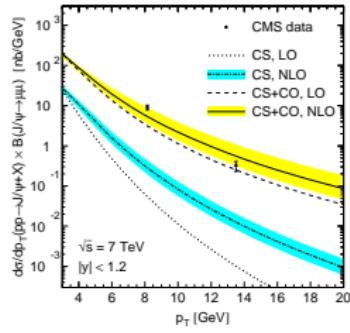
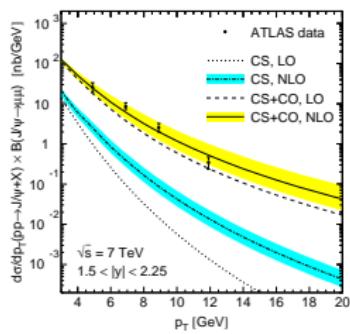
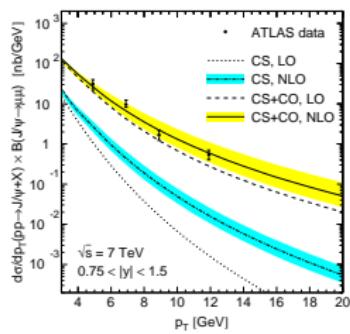
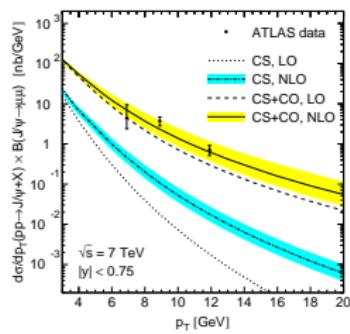


Decomposition of  
NLO NRQCD

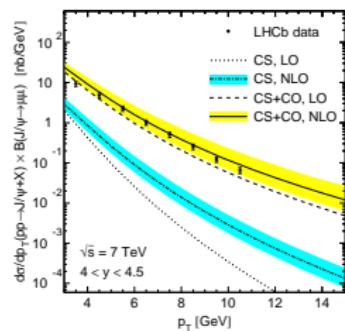
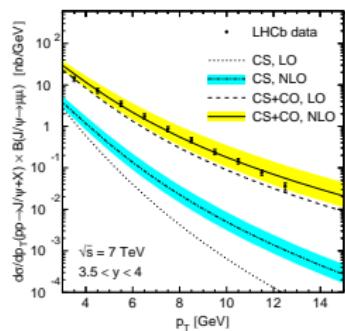
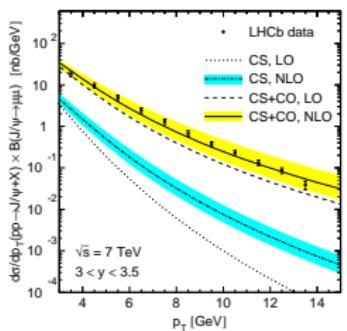
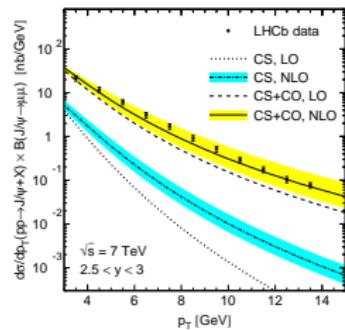
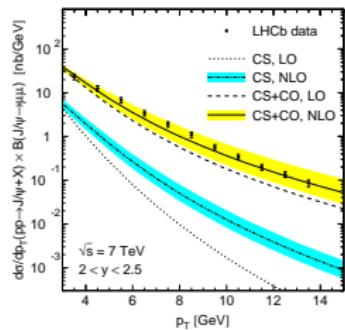
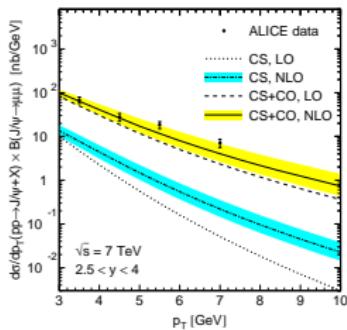


- Data **well described** by CS+CO at NLO.
- CS orders of magnitudes **below** data.
- **Sizeable NLO corrections**, especially in the  ${}^3P_J^{[8]}$  channels.

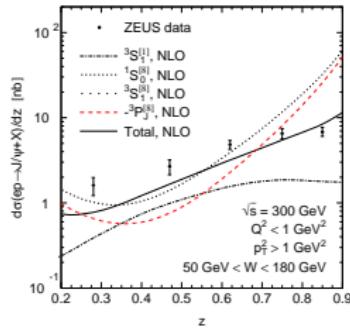
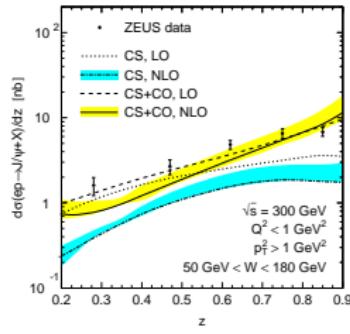
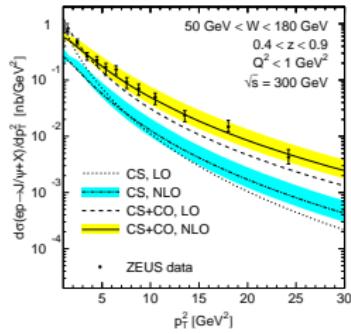
# Comparison with ATLAS and CMS at LHC



# Comparison with ALICE and LHBb at LHC

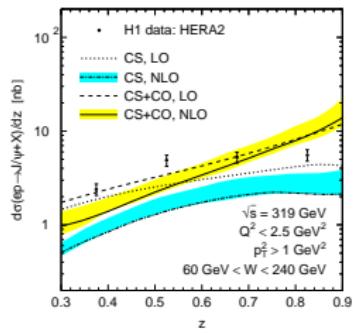
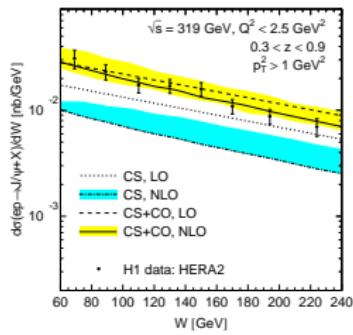
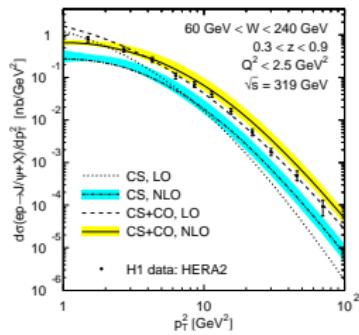
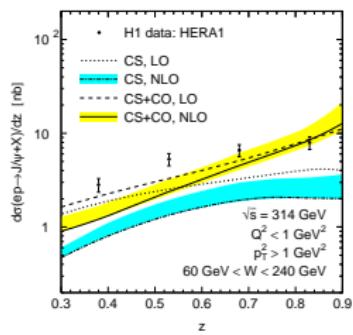
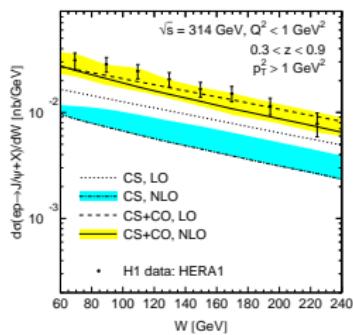
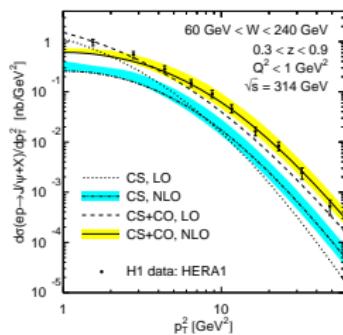


# Comparison with ZEUS at HERA I

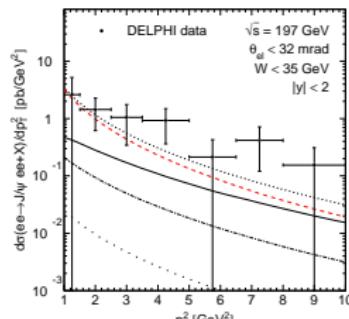
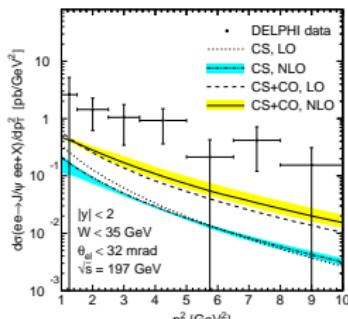
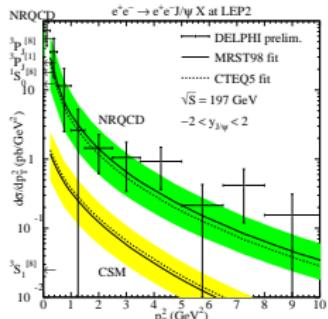


- $W = \gamma p$  CM energy.
- $z =$  fraction of  $\gamma$  energy going to  $J/\psi$  in  $p$  rest frame.
- Compensation of  $^1S_0^{[8]}$  vs.  $^3P_J^{[8]}$   $\rightsquigarrow$  regular  $z \rightarrow 1$  behavior.
- Data **well described** by CS+CO at NLO.
- CS factor of 3–5 **below** the data.

# Comparison with H1 at HERA I and II



# Comparison with DELPHI at LEP II



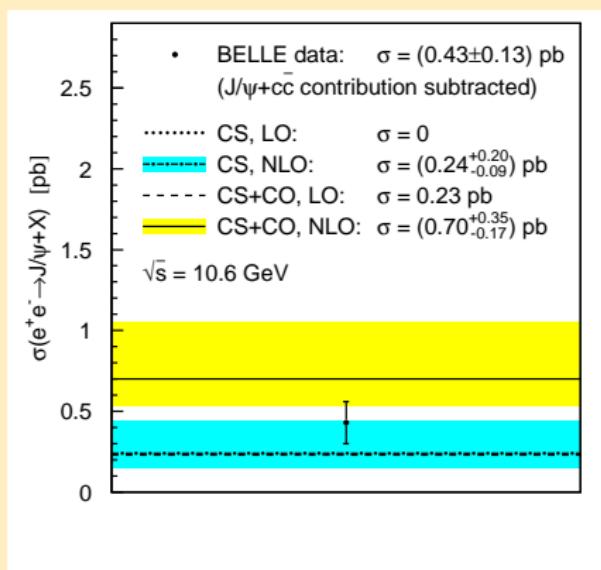
[Klasen BK Mihaila  
 Steinhauser 02]

## NLO NRQCD

## Decomposition of NLO NRQCD

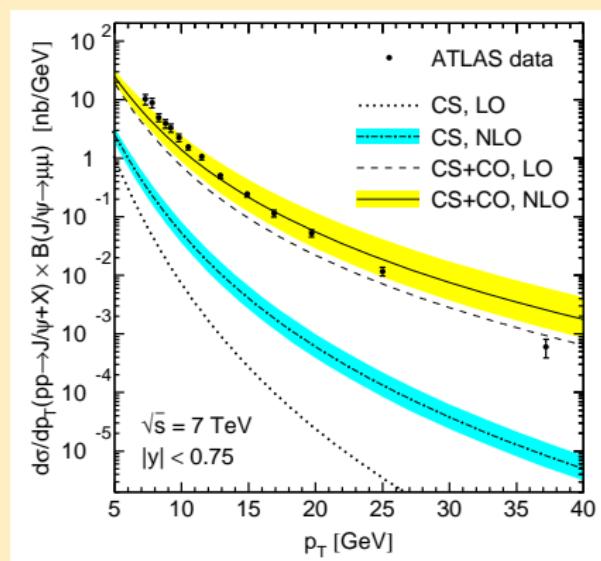
- Agreement with NRQCD at NLO worse than in 2002 at LO.
- Just 16 DELPHI events with  $p_T > 1$  GeV.
- No results from ALEPH, L3, OPAL.
- Data exhausted by single-resolved contribution.

# Comparison with Belle at KEKB



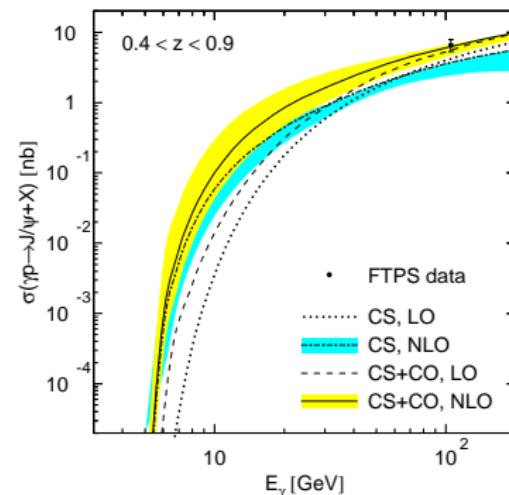
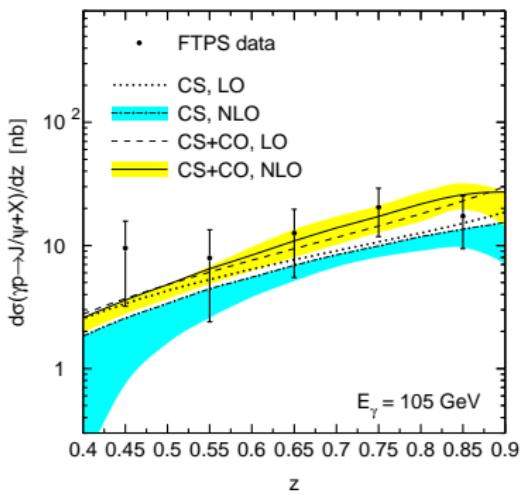
- At NLO, both CSM and NRQCD agree with data.
- # of charged tracks  $> 4$ , missing events **not corrected** for.  
 ↵ Belle point likely **higher**.

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



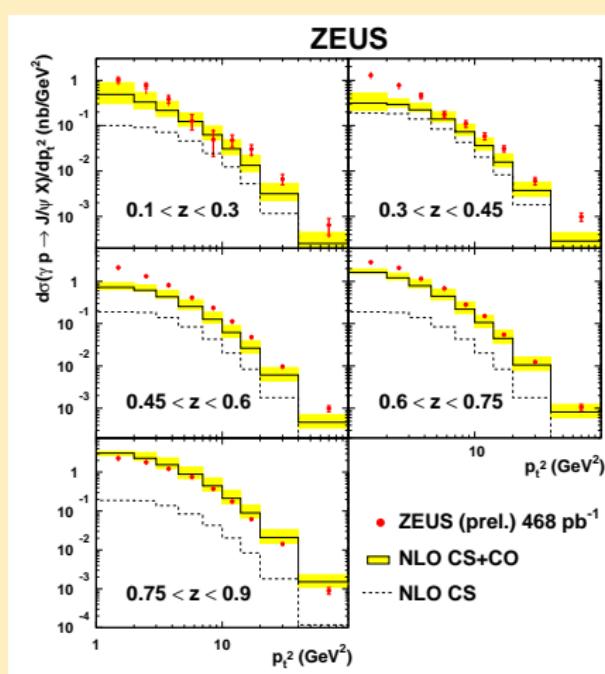
- Resummation of large logs  $\ln(p_T^2/M^2)$  necessary at large  $p_T$ .
- New formalism to include non-leading powers in  $p_T^2/M^2$  [Kang Qiu Sterman 2012].

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



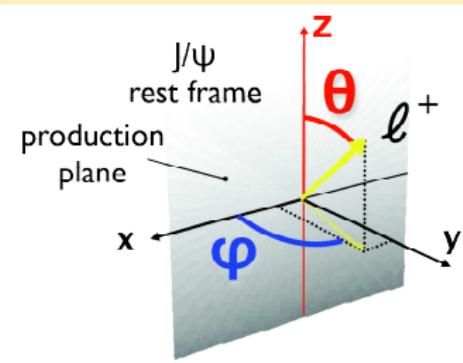
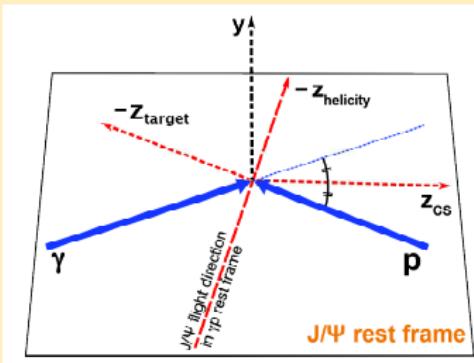
- Inelastic scattering of 105 GeV photons on hydrogen target.
- Data **remarkably well described** by CS+CO at NLO.

# Comparison with ZEUS (after fit) [JHEP1302(2013)071]



- Notorious NRQCD overshoot at large  $z$  overcome.

# Polarized $J/\psi$ photo- and hadroproduction



Decay angular distribution:

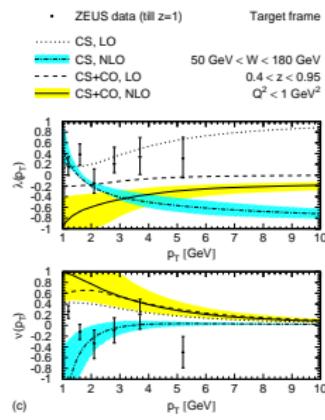
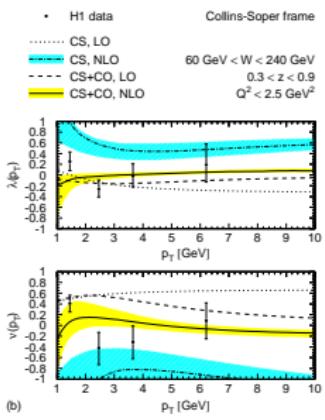
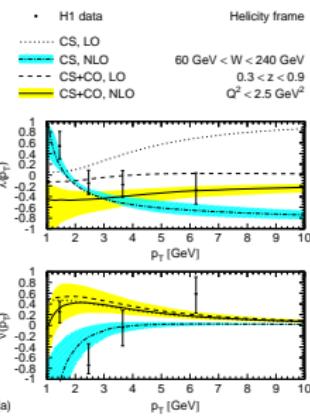
$$\frac{d\Gamma(J/\psi \rightarrow l^+ l^-)}{d\cos\theta d\phi} \propto 1 + \lambda_\theta \cos^2\theta + \lambda_\phi \sin^2\theta \cos(2\phi) + \lambda_{\theta\phi} \sin(2\theta) \cos\phi$$

Polarization observables in spin density matrix formalism:

$$\lambda_\theta = \frac{d\sigma_{11} - d\sigma_{00}}{d\sigma_{11} + d\sigma_{00}}, \quad \lambda_\phi = \frac{d\sigma_{1,-1}}{d\sigma_{11} + d\sigma_{00}}, \quad \lambda_{\theta\phi} = \frac{\sqrt{2}\operatorname{Re} d\sigma_{10}}{d\sigma_{11} + d\sigma_{00}}$$

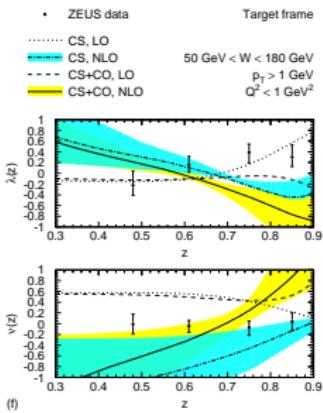
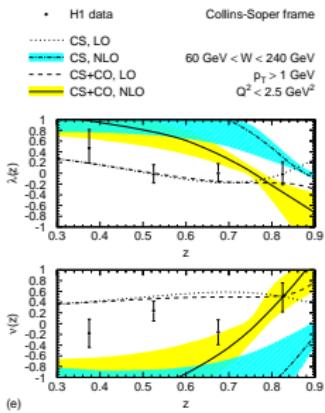
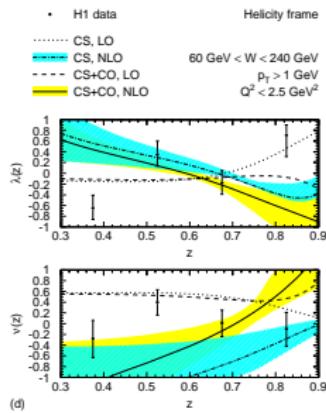
$\lambda = 0, +1, -1$ : unpolarized, transversely and longitudinally polarized.

# Comparison with H1 and ZEUS



- No  $z$  cut on ZEUS data  $\rightsquigarrow$  diffractive production included.
- Perturbative stability in NRQCD higher than in CSM.
- $J/\psi$  preferably unpolarized at large  $p_T$ .

## Comparison with H1 and ZEUS (cont.)

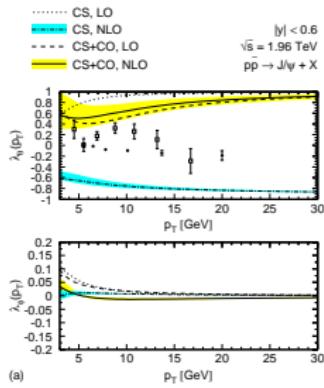


- Large scale uncertainties due to low cut  $p_T > 1$ .
  - Overall  $\chi^2$  w.r.t. default prediction more than halved by going from CSM to NRQCD.

# Comparison with CDF and ALICE

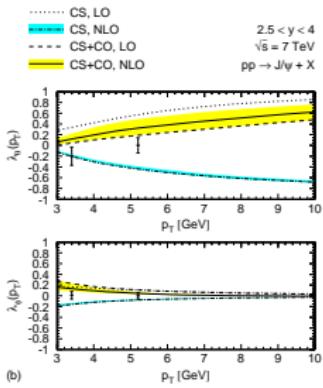
■ / + CDF data: Run I / II

Helicity frame



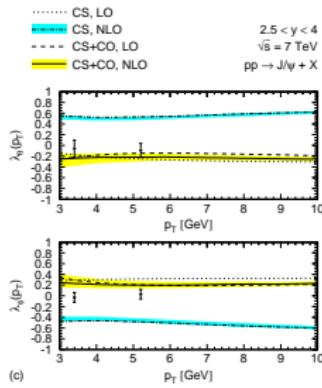
• ALICE data

Helicity frame



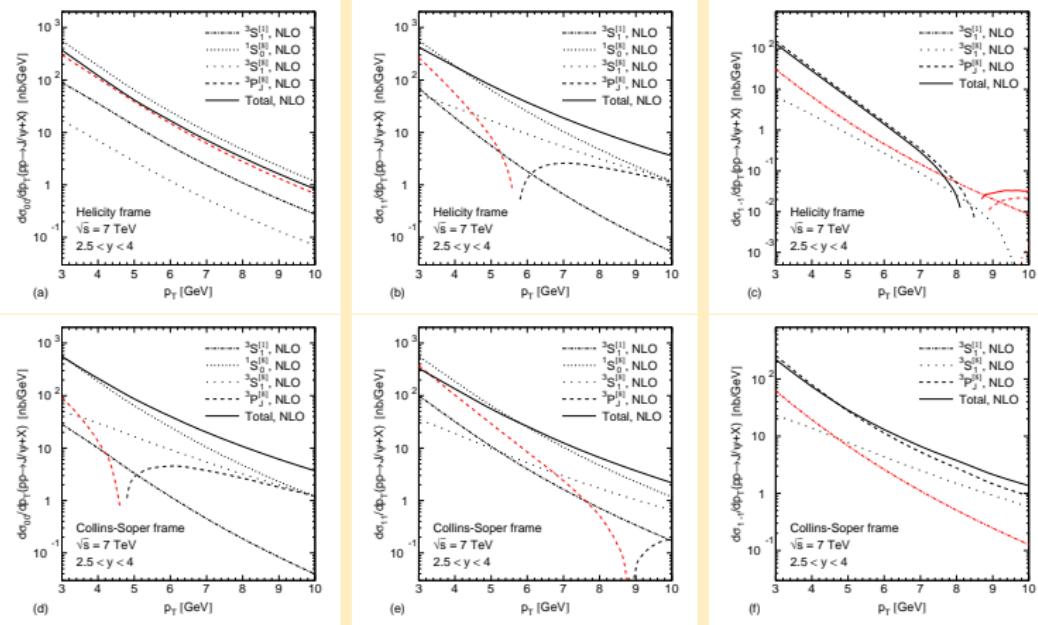
• ALICE data

Collins-Soper frame



- CDF I and II data mutually inconsistent for  $p_T < 12$  GeV.
- CDF  $J/\psi$  polarization anomaly persists at NLO.
- 4/8 ALICE points agree w/ NLO NRQCD within errors, others  $< 2\sigma$  away.

# Decomposition for ALICE



- $d\sigma_{\text{unpol}} = d\sigma_{00} + 2d\sigma_{11}$ ;  $d\sigma_{1,-1}$  auxiliary.
- Previously unknown  $^3P_J^{[8]}$  NLO correction significant.

# Comparison with Gong et al. and Chao et al.

BK, MB

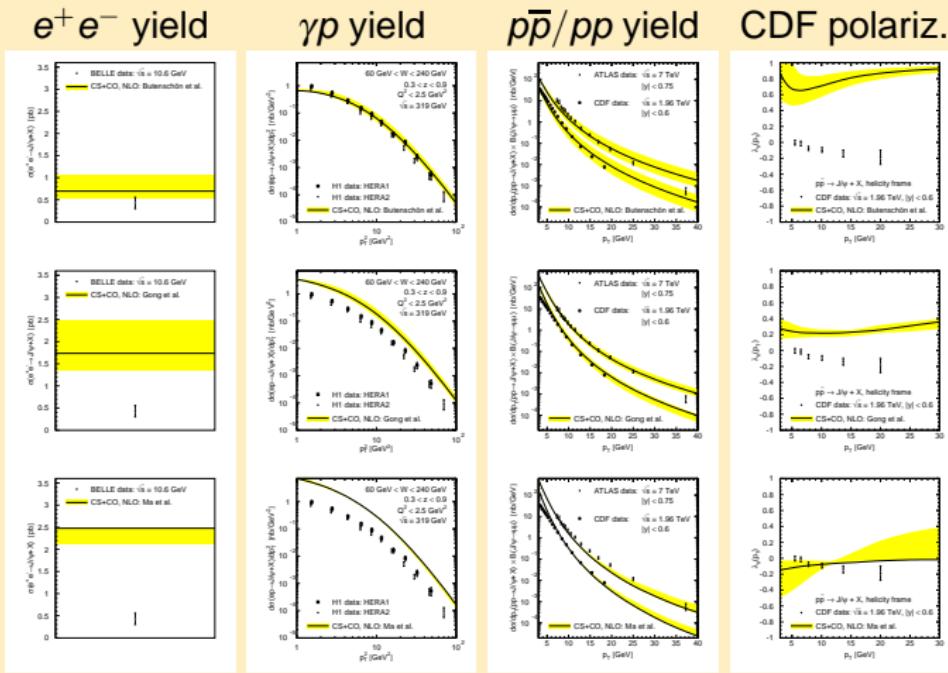
PRL108(2012)172002

Gong et al.

PRL110(2013)042002

Chao et al.

PRL108(2012)242004



# 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](#).

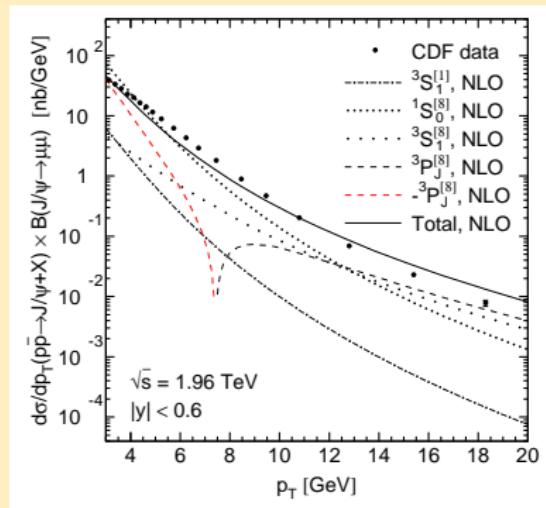
## Summary (cont.)

- Case for NRQCD less strong in polarized  $J/\psi$  photoproduction at HERA.
- Polarized  $J/\psi$  hadroproduction at Tevatron in severe conflict with NLO NRQCD, while first LHC data nicely agree.
- In the absence of new-physics signals, LHC's most tantalizing physics opportunities include verification/falsification of NRQCD factorization in charmonium and bottomonium yield and polarization!
- **Stay tuned!**

# Backup Slides

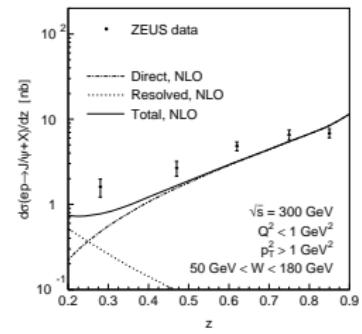
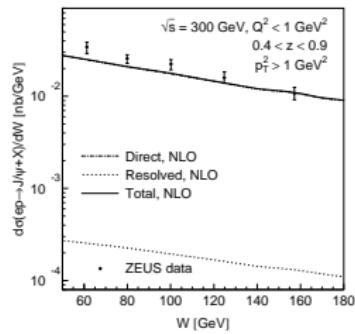
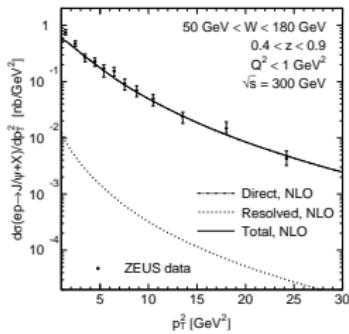
# Comparison with Tevatron (cont.)

## Relative importance of CO processes:



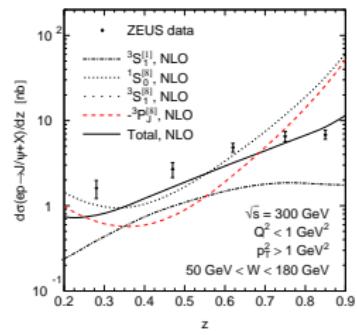
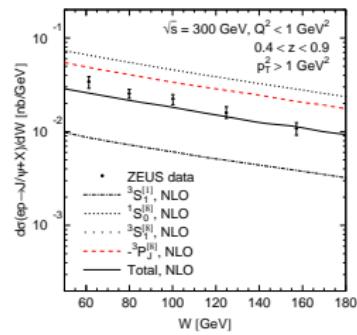
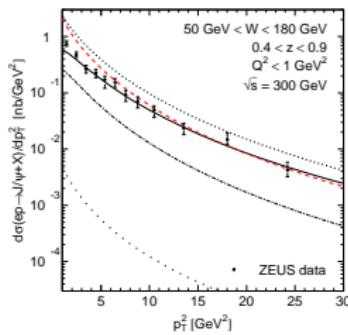
- Short-distance  $\sigma(c\bar{c}[{}^3P_J^{[8]}]) < 0$  for  $p_T \gtrsim 7$  GeV.
- But: Short-distance cross sections and LDMEs **unphysical** (NRQCD scale and scheme dependence)  $\leadsto$  No problem!

# 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 148 points	$p_T > 2$ GeV 134 points	$p_T > 3$ GeV 119 points	$p_T > 5$ GeV 86 points	$p_T > 7$ GeV 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 74 points	$p_T > 2$ GeV 30 points	$p_T > 3$ GeV 15 points	$p_T > 5$ GeV 5 points	$p_T > 7$ GeV 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 148 points	$p_T > 2$ GeV 134 points	$p_T > 3$ GeV 119 points	$p_T > 5$ GeV 86 points	$p_T > 7$ GeV 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):

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

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