

# HEAVY QUARKONIUM PHYSICS



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# Quarkonium Production

## QWG Summary

Andreas B. Meyer

LHC-HERA Meeting 22/3/05

# Physics Goals



- [ To achieve a better understanding of the dynamics of the strong interaction
- [ To gain detailed knowledge of the physics of confinement/deconfinement
- [ Improve the determination of the fundamental parameters of the Standard Model
- [ Identify missing experimental information and theoretical questions

# Communicative Goals



- [ To guarantee an efficient communication between experimentalists and theorists within the broad quarkonium physics community
- [ Jointly overcome “dispersion of the research in this field” and study the different approaches and techniques

# 3 Meetings and 1 School



[ CERN, Nov 2002 (3 days)

[ Fermilab, Sept 2003 (3 days)

[ IHEP Beijing, Oct 2004 (3 days, preceded by 1 week of school)

[ 1 meeting/year over 2 years

[ Most of the report was written in spring 2004

[ Report published in dec 2004 [hep-ph/0412158](https://arxiv.org/abs/hep-ph/0412158)

521 pages, 260 figures,  
to appear as CERN Yellow Report

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## 1st International Workshop on Heavy Quarkonium

CERN, November 8-10, 2002

<http://www.qwg.to.infn.it/WS-nov02/index.html>

*Organizing Committee:* A. Böhrer, N. Brambilla, O. Iouchtchenko, M. Kienzle, M. Krämer, C. Lourenço, M. L. Mangano, R. Mussa, T. Teubner, A. Vairo

*Speakers:* G. Bali, E. L. Berger, G. Bodwin, A. Böhrer, E. Braaten, N. Brambilla, H. Castilia-Valdez, C. Davies, A. Deandrea, E. Eichten, S. Eidelman, R. Faustov, T. Ferguson, M. Graham, S. Godfrey, F. Harris, A. Hoang, O. Iouchtchenko, F. Karsch, V. V. Kiselev, B. Kniehl, M. Krämer, M.-P. Lombardo, C. Lourenço, J. P. Ma, M. L. Mangano, A. Meyer, R. Mussa, S. Necco, V. Papadimitriou, A. Penin, K. Peters, P. Petreczky, A. Pich, A. Pineda, A. Polleri, M. Rosati, M. A. Sanchis-Lozano, H. Satz, J. Simone, G. Stancari, I. W. Stewart, Y. Sumino, T. Teubner, J. Tseng, A. Vairo, R. Waldi, B. Yabsley

*Supported by the CERN TH Division*

Agenda and slides available at <http://www.qwg.to.infn.it/WS-nov02/WSagenda.html>

List of participants available on website.

## 2nd International Workshop on Heavy Quarkonium

Fermilab, September 20-22, 2003

<http://www.qwg.to.infn.it/WS-sep03/index.html>

*Organizing Committee:* G. Bodwin, A. Böhrer, N. Brambilla, E. Eichten, V. Jain, M. Krämer, R. Mussa, V. Papadimitriou, S. Pordes, A. Vairo

*Speakers:* J. Appel, G. Bali, G. Bauer, D. Bettoni, E. Braaten, N. Brambilla, K. T. Chao, P. Cooper, A. Deandrea, E. Eichten, A. El-Khadra, J. Erler, R. Faustov, T. Ferguson, S. Fleming, R. Galik, S. Godfrey, Y. Gotra, Z. J. Guo, F. Harris, T. Hatsuda, A. Hoang, J. Huang, U. Husemann, V. Jain, M. Jamin, S. Kelly, D. Kharzeev, S. R. Klein, J. Lee, A. Leibovich, P. Mackenzie, A. B. Meyer, C. Morningstar, H. Muramatsu, R. Mussa, A. Nairz, J. Napolitano, V. Papadimitriou, C. Patrignani, J. C. Peng, P. Petreczky, S. Pordes, J. W. Qiu, R. Rapp, S. Ricciardi, J.-M. Richard, E. Robutti, M. Rosati, M. A. Sanchis-Lozano, H. Sato, X. Shen, J. Simone, R. Spighi, L. Stanco, R. Thews, T. Umeda, A. Vairo, R. Vogt, M. Voloshin, C. Y. Wong, W. Xie, B. Yabsley, C. Z. Yuan, G. Zanderighi, Z.G. Zhao

*Supported by Fermilab*

Agenda and slides available at <http://www.qwg.to.infn.it/WS-sep03/WSagenda.html>

List of participants available on website.

## 3rd International Workshop on Heavy Quarkonium

IHEP Beijing, October 12-15, 2004

<http://www.qwg.to.infn.it/WS-oct04/index.html>

*Organizing Committee:* N. Brambilla, K. T. Chao, A. Deandrea, M. Krämer, Y. P. Kuang, W. G. Li, J. P. Ma, R. Mussa, V. Papadimitriou, C. F. Qiao, X. Y. Shen, A. Vairo, C. Z. Yuan

*Speakers:* G. Bali, S. Baranov, D. Bernard, G. Bodwin, E. Braaten, N. Brambilla, R. Brugnera, C.-H. Chang, K.-T. Chao, H.-S. Chen, Y.-Q. Chen, C.-H. Ching, A. Deandrea, E. Eichten, G. Feild, C. Gao, M. Garcia-Perez, Z. Guo, L. Han, B. Heltsley, P. Ko, J. Lee, T. Lee, Z. Liu, J.-P. Ma, T. Mehen, R. Mussa, S. L. Olsen, C. Patrignani, K. Peters, P. Petreczky, O. Philipsen, A. Pineda, C.-F. Qiao, M. Rosati,

# Authors: topic convenors & contributors – speakers separately listed

# 7 Subgroups



— [ Spectroscopy

— [ Decay

— [ **Production**

— [ Standard Model Parameters

— [ Quarkonia in Media

— [ Beyond the Standard Model

— [ **Future Opportunities**

# Results Overview



## Experiment:

- Essentially all experiments

- dedicated exps: BES, CLEO(-c), KEDR, BaBar, Belle, E835(ppbar)

- multipurpose: LEP, Tevatron, HERA, Fixed Target ...

## Theory:

- HQET, NRQCD, Lattice ...

# Production Chapter



- [ Formalism for inclusive quarkonium production:  
NRQCD, Color-singlet (CS), Color-evaporation (CEM)

- [ Quarkonium production

  - at the Tevatron

  - at fixed target experiments

  - at HERA

  - at LEP

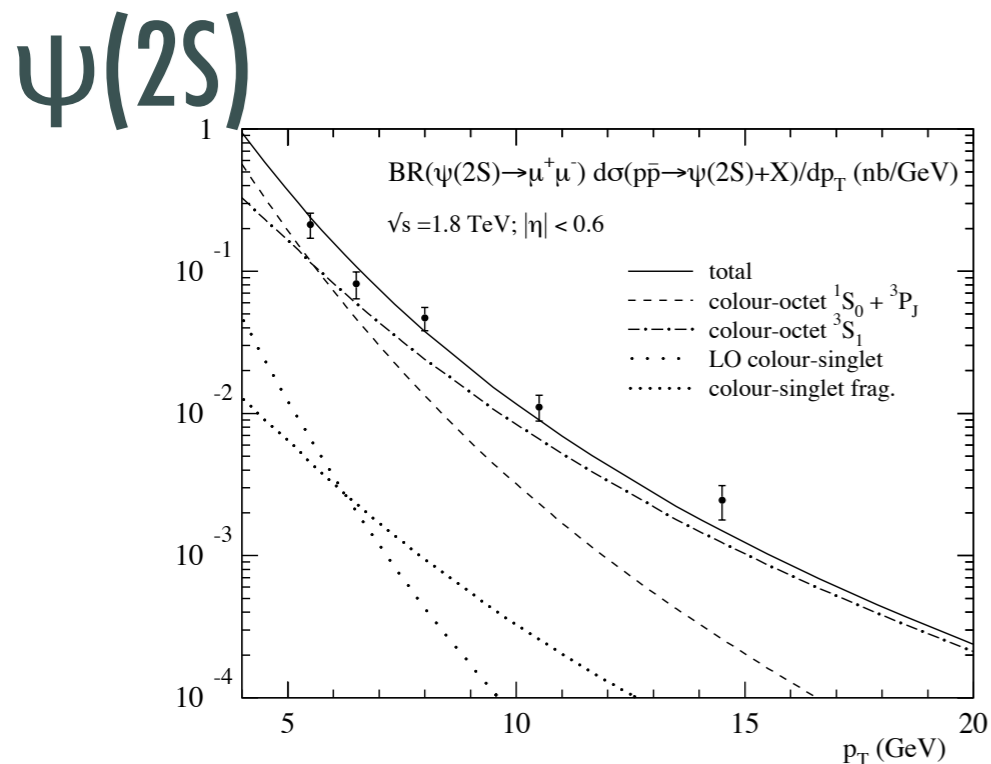
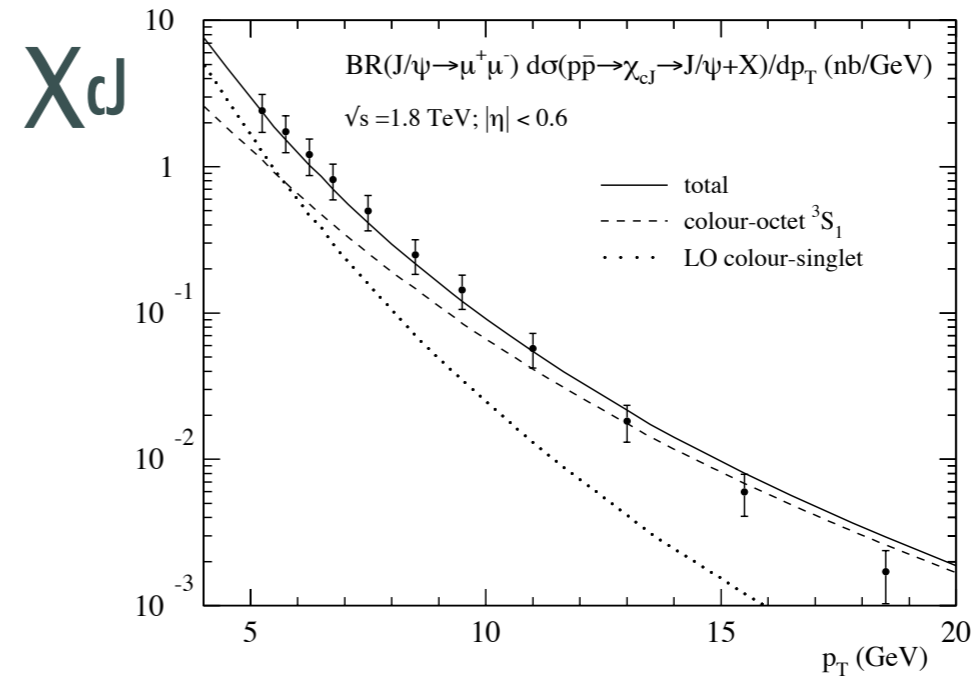
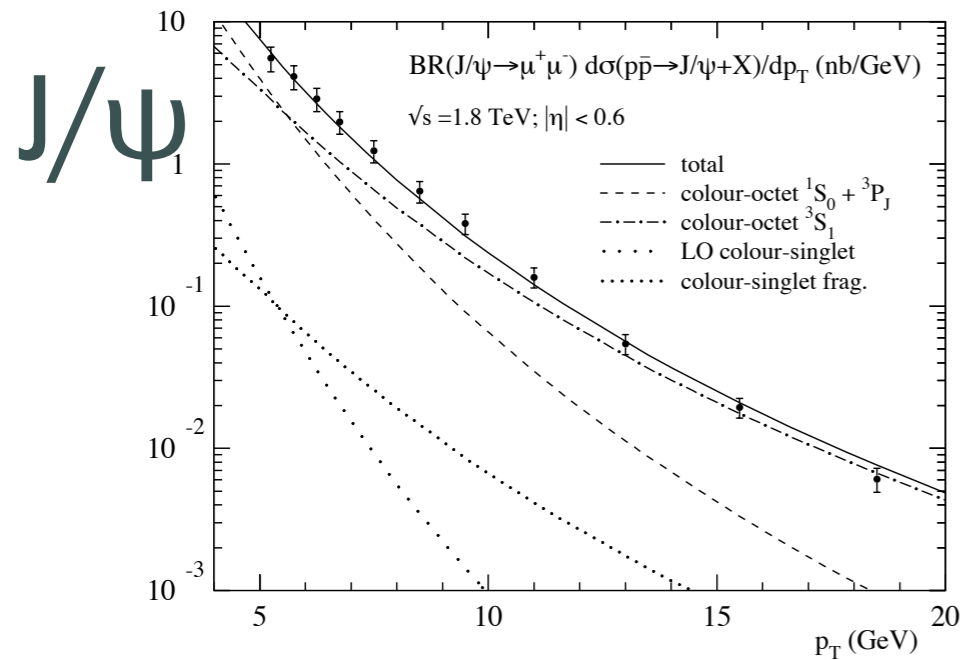
  - in  $e^+e^-$  at 10.6 GeV (Belle)

  - in B-Meson decays

- [  $B_c$  Production



# Tevatron



## NRQCD (at LO) → LDME

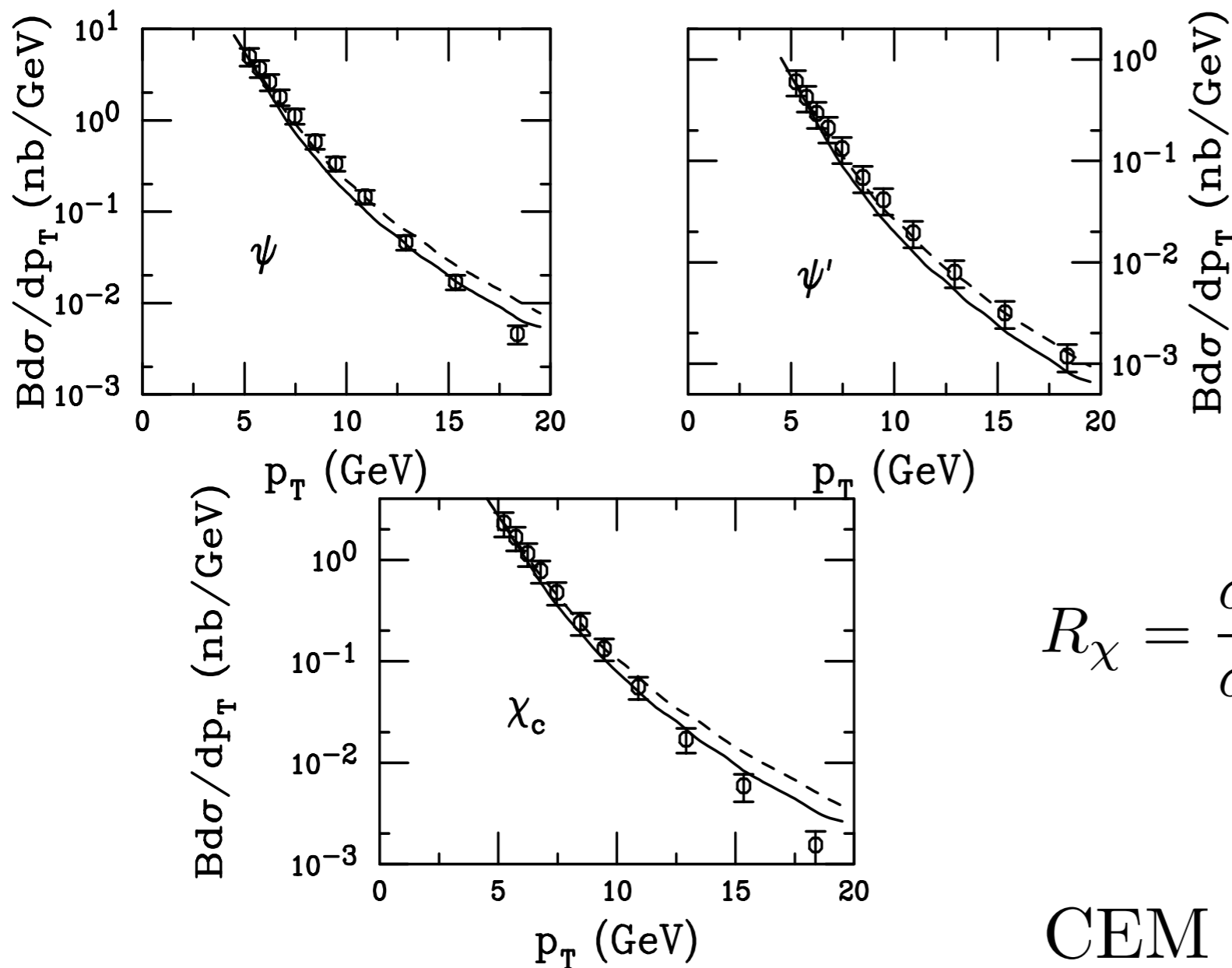
$H$	$\langle \mathcal{O}_1^H \rangle$	$\langle \mathcal{O}_8^H(^3S_1) \rangle$	$M_{3.5}^H$
$J/\psi$	$1.16 \text{ GeV}^3$	$(1.19 \pm 0.14) \times 10^{-2} \text{ GeV}^3$	$(4.54 \pm 1.11) \times 10^{-2} \text{ GeV}^3$
$\psi(2S)$	$0.76 \text{ GeV}^3$	$(0.50 \pm 0.06) \times 10^{-2} \text{ GeV}^3$	$(1.89 \pm 0.46) \times 10^{-2} \text{ GeV}^3$
$\chi_{c0}$	$0.11 \text{ GeV}^5$	$(0.31 \pm 0.04) \times 10^{-2} \text{ GeV}^3$	

## Universal parameters

# Tevatron



## CEM calculations in NLO



Good description of shape  
( $k_t$  smearing applied)

R.Vogt

Also measured (CDF):

$$R_\chi = \frac{\sigma(\chi_{c2})}{\sigma(\chi_{c1})} = 1.04 \pm 0.29 \pm 0.12$$

Predicted:

CEM : 3/5 NRQCD :  $0.9 \pm 0.2$

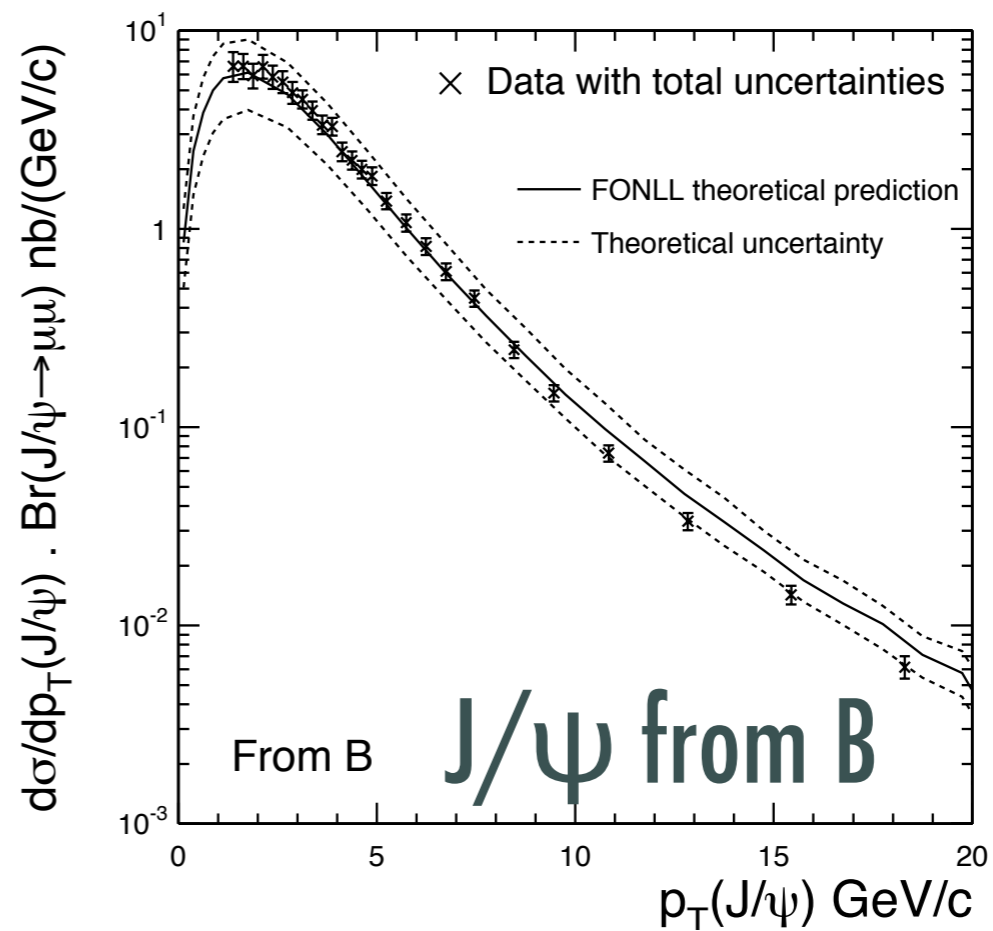
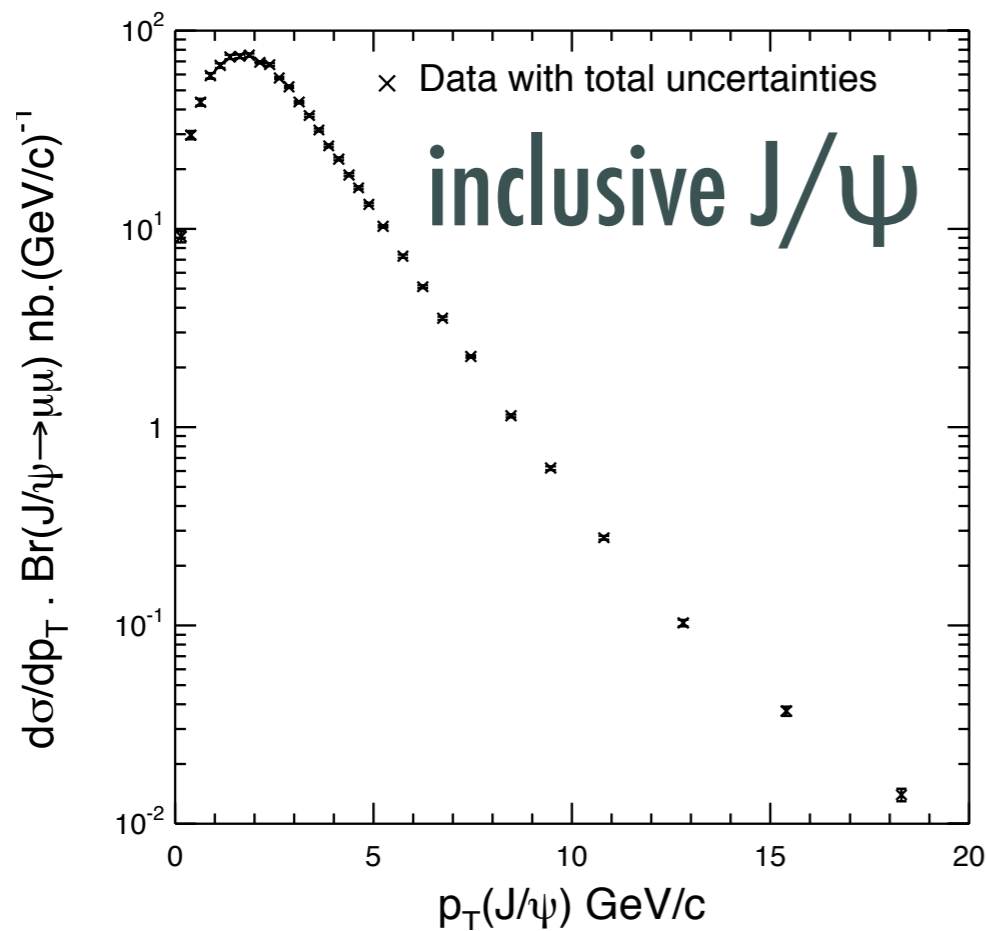
F.Maltoni

# Tevatron



Run-II data

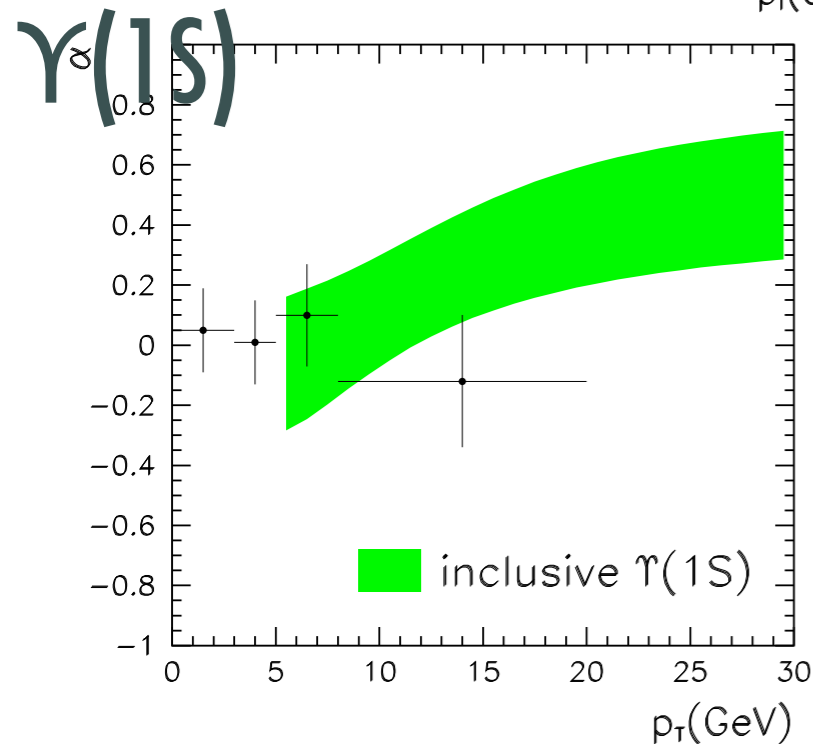
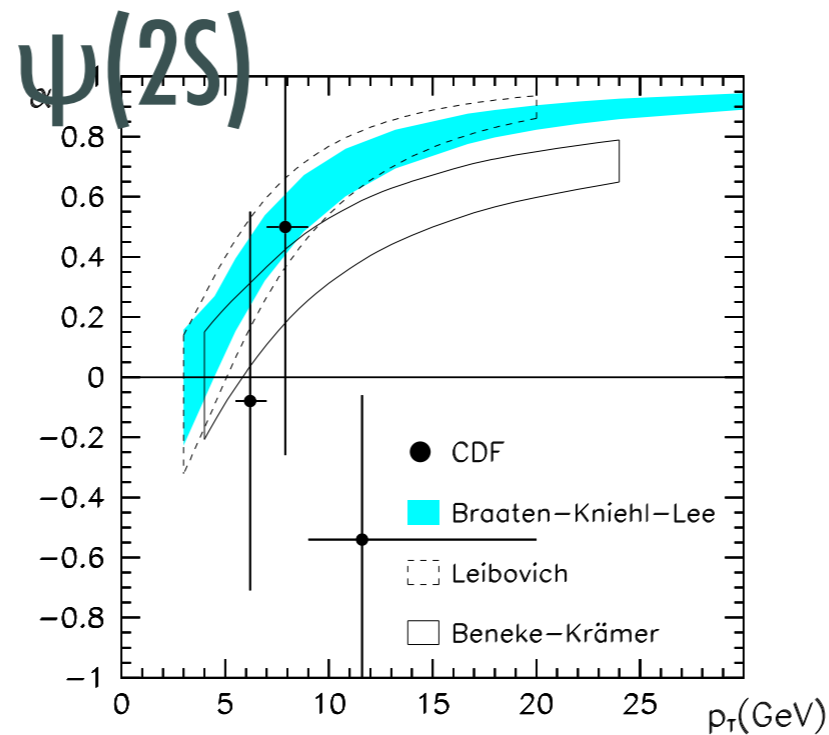
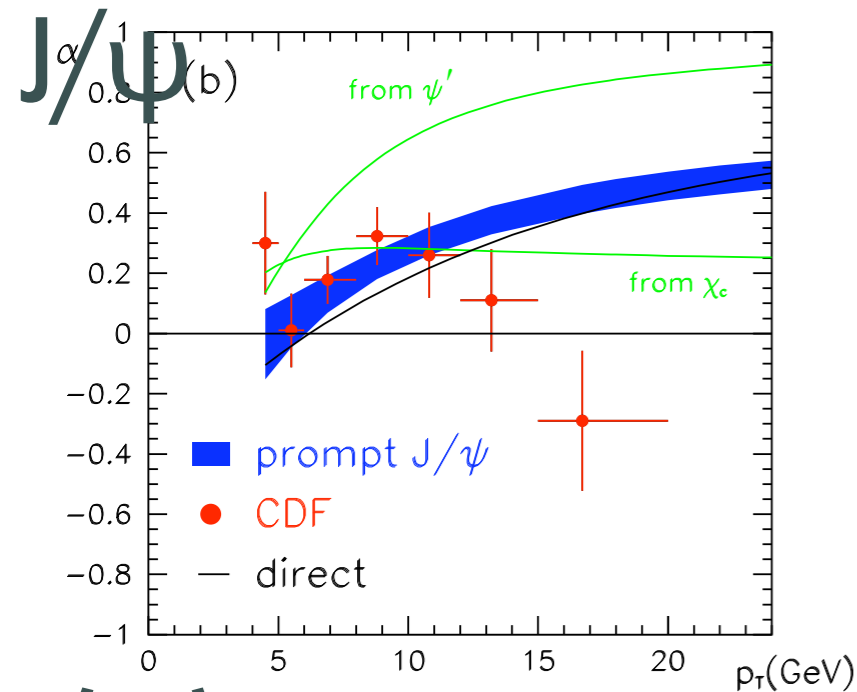
differential inclusive  $J/\psi$  data down to  $p_T = 0$ , huge statistics



FONLL calculations of B-production describe data

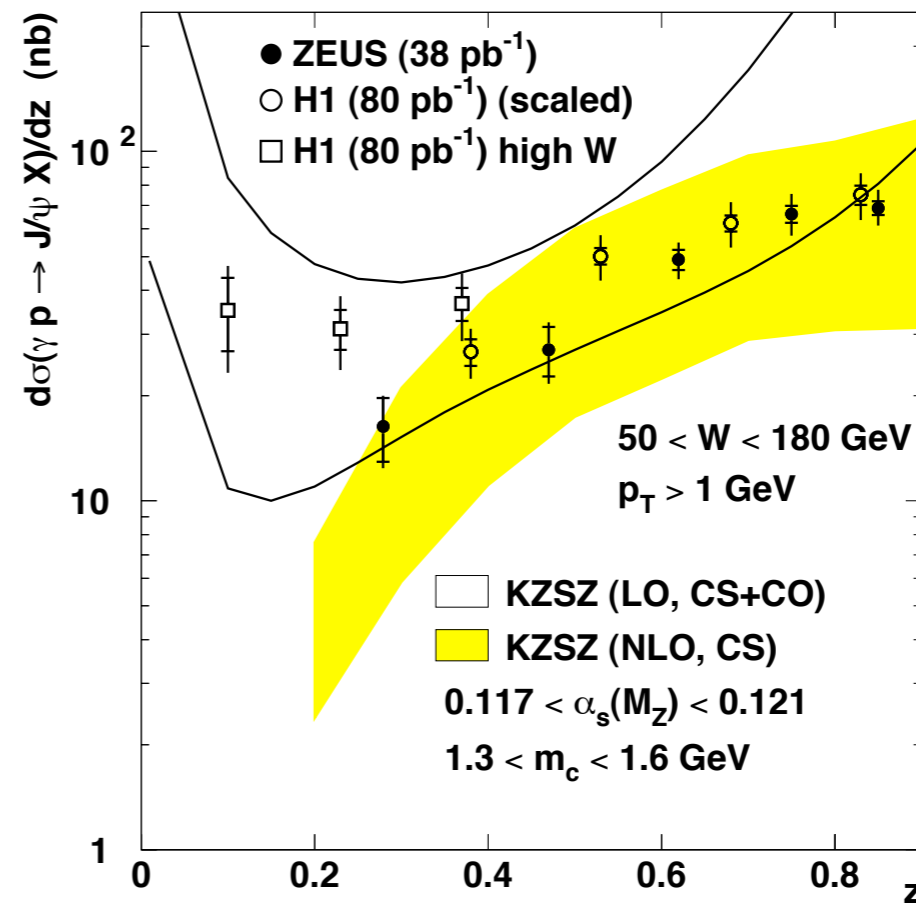
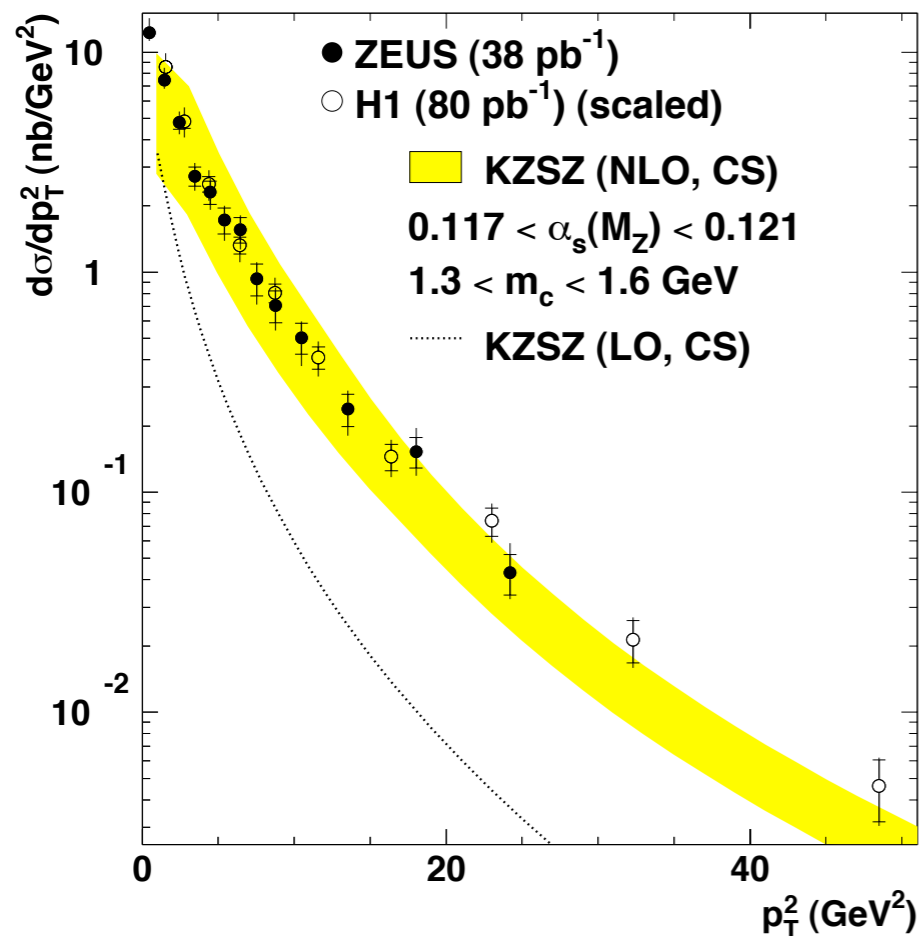
M.Cacciari et al

# Polarization



Firm NRQCD prediction: E.Braaten, B.A.Kniehl, J.Lee  
 Polarization of VM at large  $p_T$   
 dominated by gluon splitting  $\rightarrow$  increase

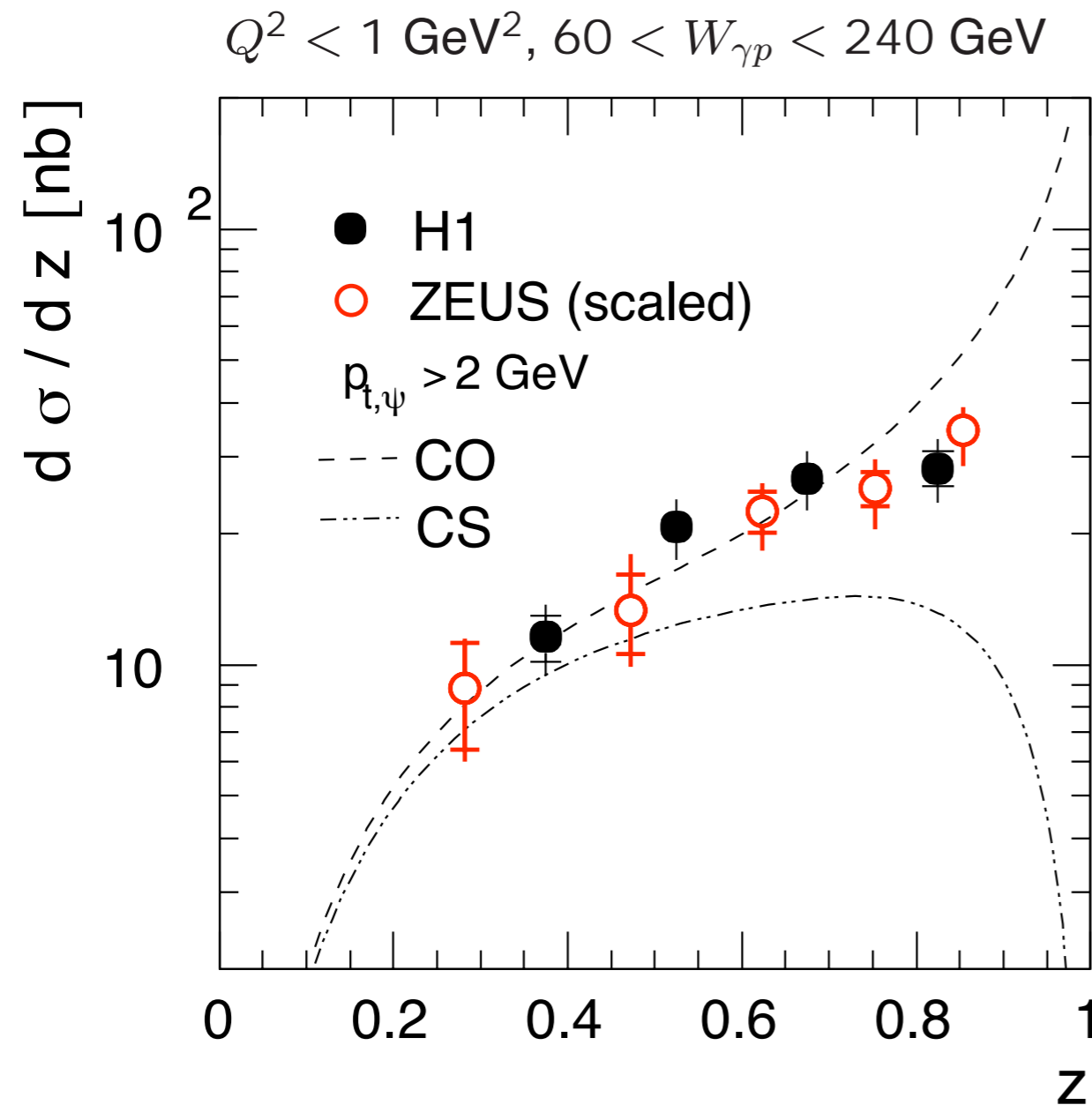
Run-II precision measurements awaited



Perfect description of  $\gamma p \rightarrow J/\psi X$   
by Color-singlet contribution at NLO

Uncertainties from  
 $\alpha_s$ ,  $m_c$  and LDME

# HERA



**LO Color octet:**

→ no hard gluon

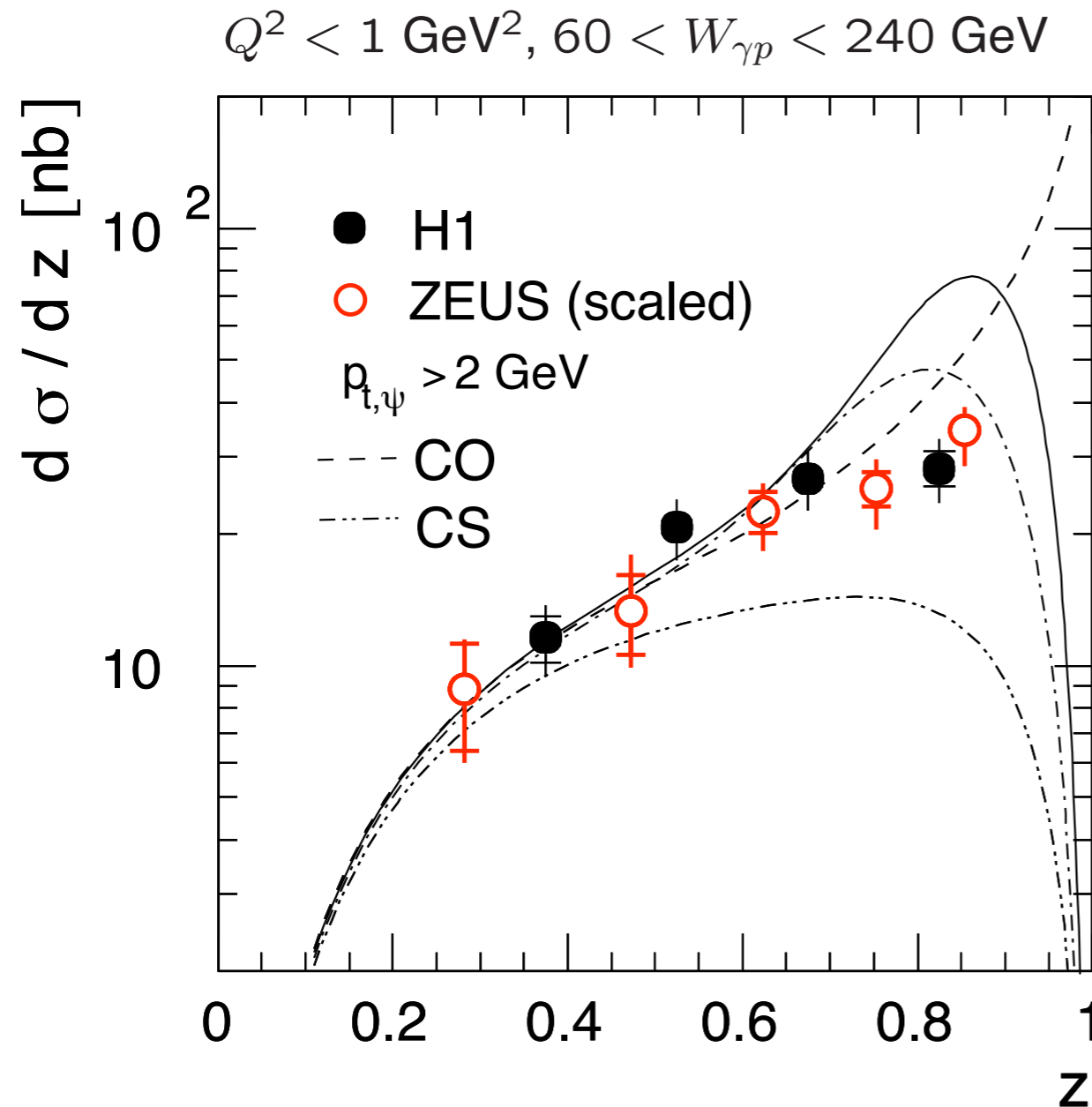
→ rises to large z

**CS contribution:**

→ hard gluon

→ falling off at large z

# HERA



**LO Color octet:**

→ no hard gluon

→ rises to large  $z$

**CS contribution:**

→ hard gluon

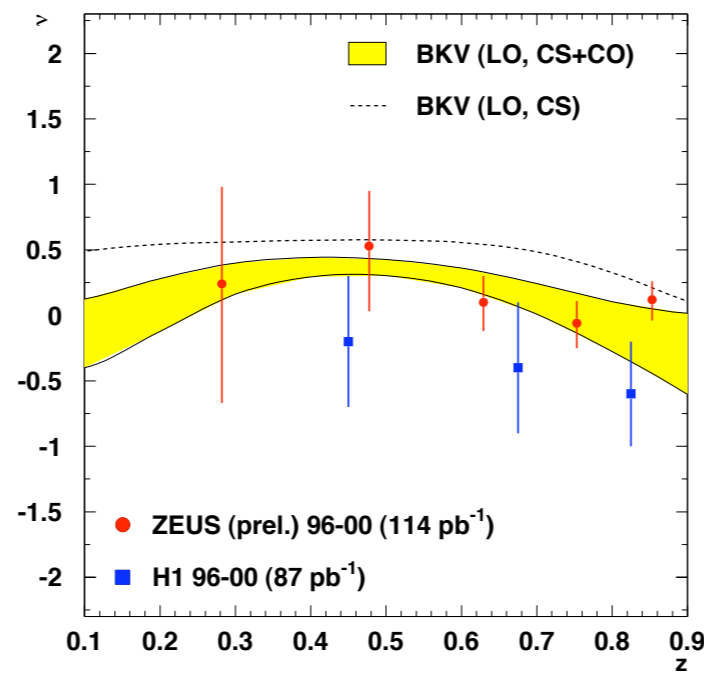
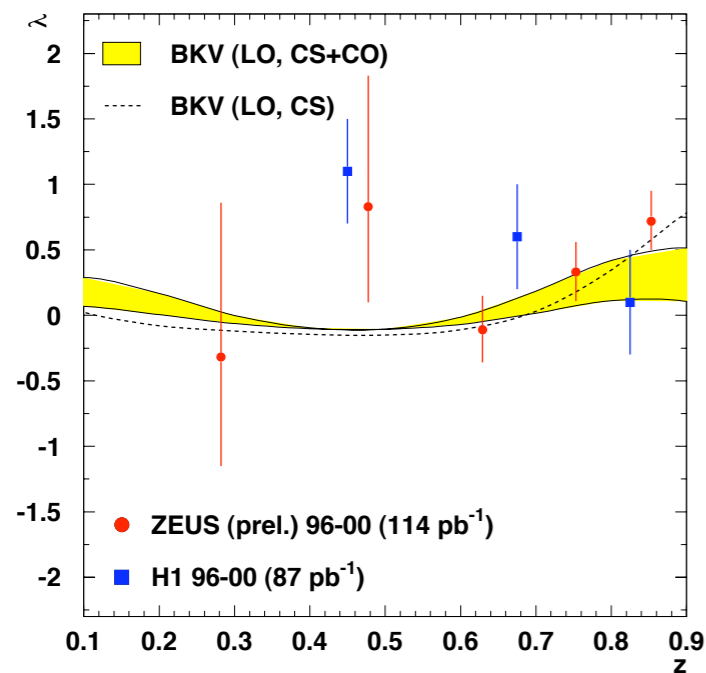
→ falling off at large  $z$

**soft CO gluons resummed:**

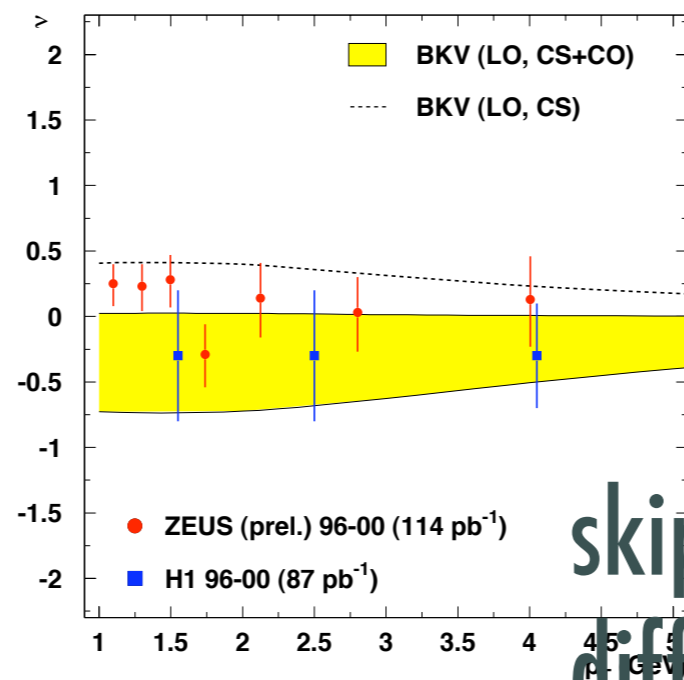
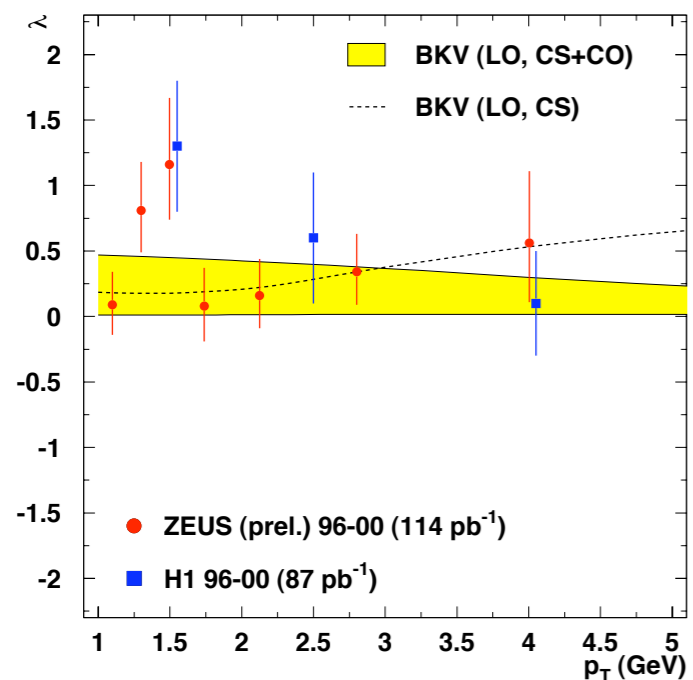
→ good description

M.Beneke, G.A. Schuler, S.Wolf

# Polarization



$p_T$ -range at HERA:  
too low for gluon splitting



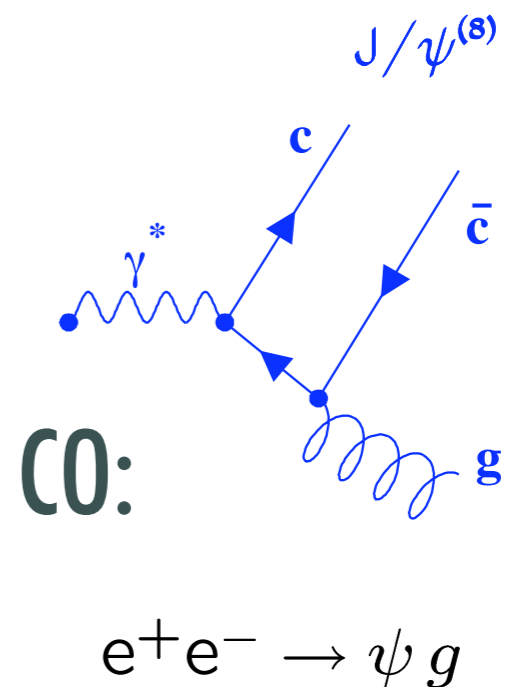
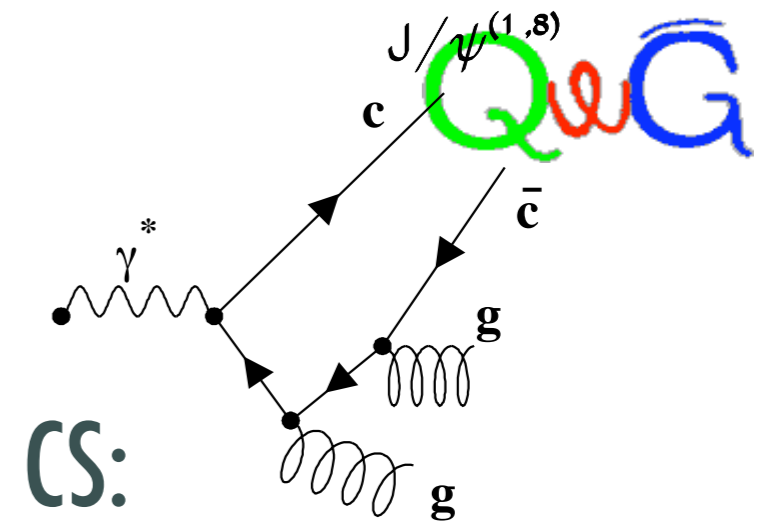
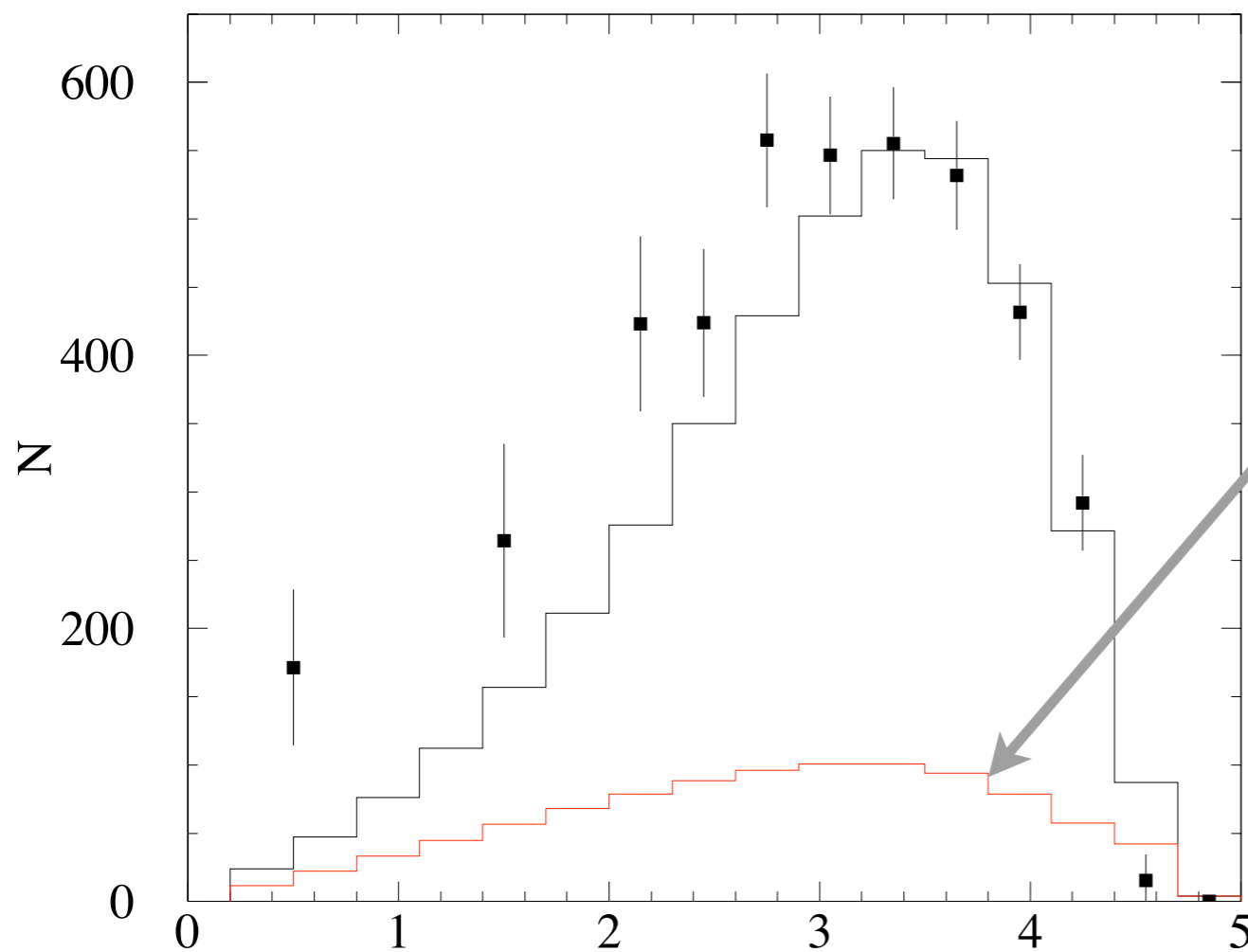
Results not conclusive yet:  
→ much more stats. needed

skipping electroproduction &  
diffractive production channel...



# Belle

## J/ψ momentum spectrum



described after resummation of soft-gluon radiation

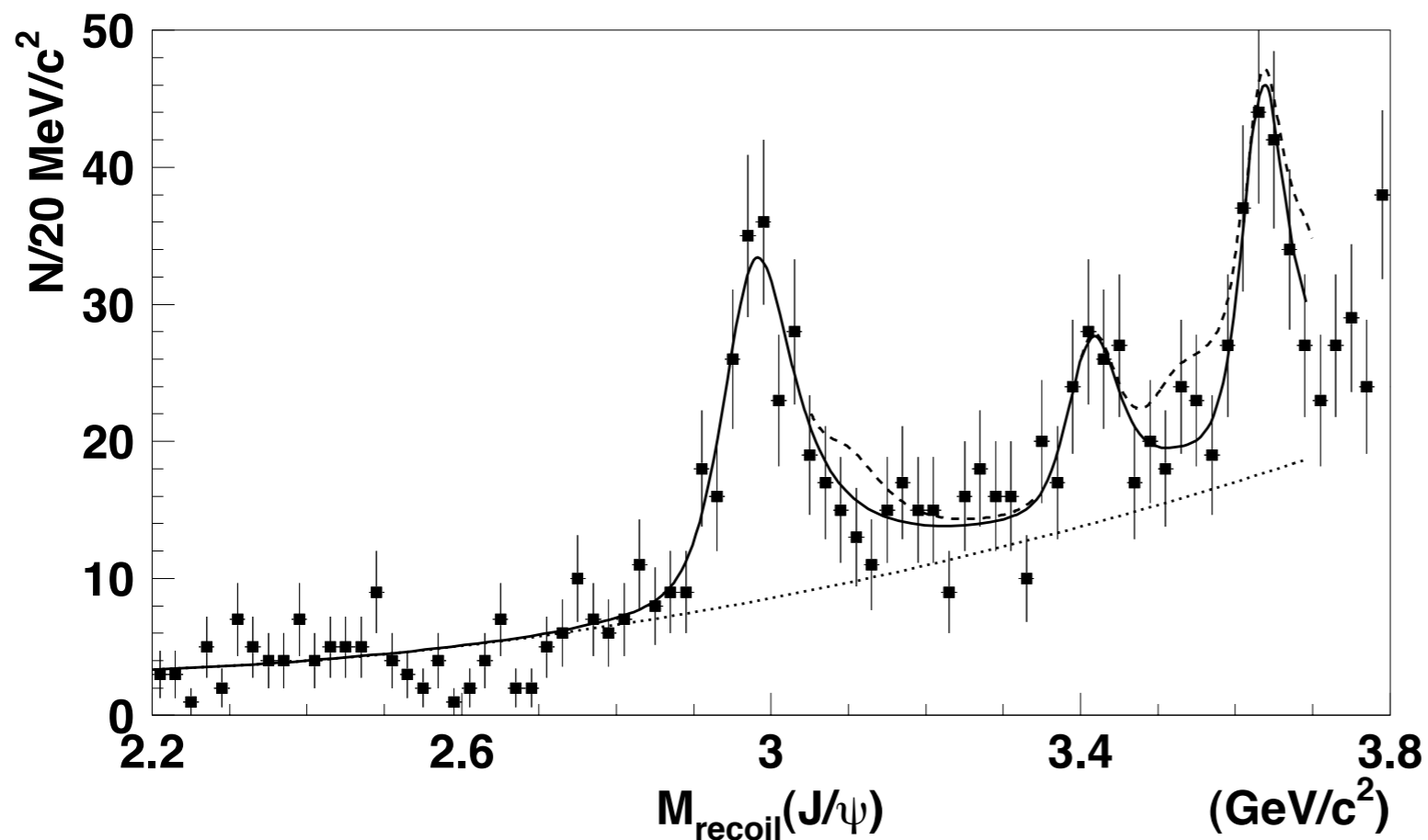
S.Fleming, A.K. Leibovich, T.Mehen

→ test this shape function with HERA data

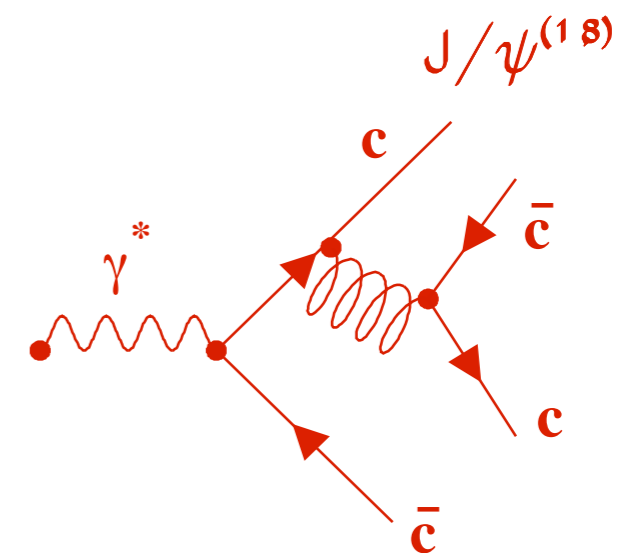
# Belle



## Double- $c\bar{c}$ production



>60% of  $J/\psi$  have another charm pair in the event



$$e^+e^- \rightarrow \psi c\bar{c}$$

as yet unexplained

$$M_{\text{recoil}} = \sqrt{(\sqrt{s} - E_{\psi}^*)^2 - (p_{\psi}^*)^2}$$

→ search  $c\bar{c}c\bar{c}$  in HERA data

# Production Summary



## Tevatron:

- NRQCD (leading order) CO contributions to describe data
- Polarization: stringent test of NRQCD — large stats. will decide

## HERA:

- Color Singlet at NLO: good description w/o CO contributions
- CS+CO at LO: also ok, large effects from resummation of gluons
- Polarization: need more stats. at larger  $p_{\perp}$

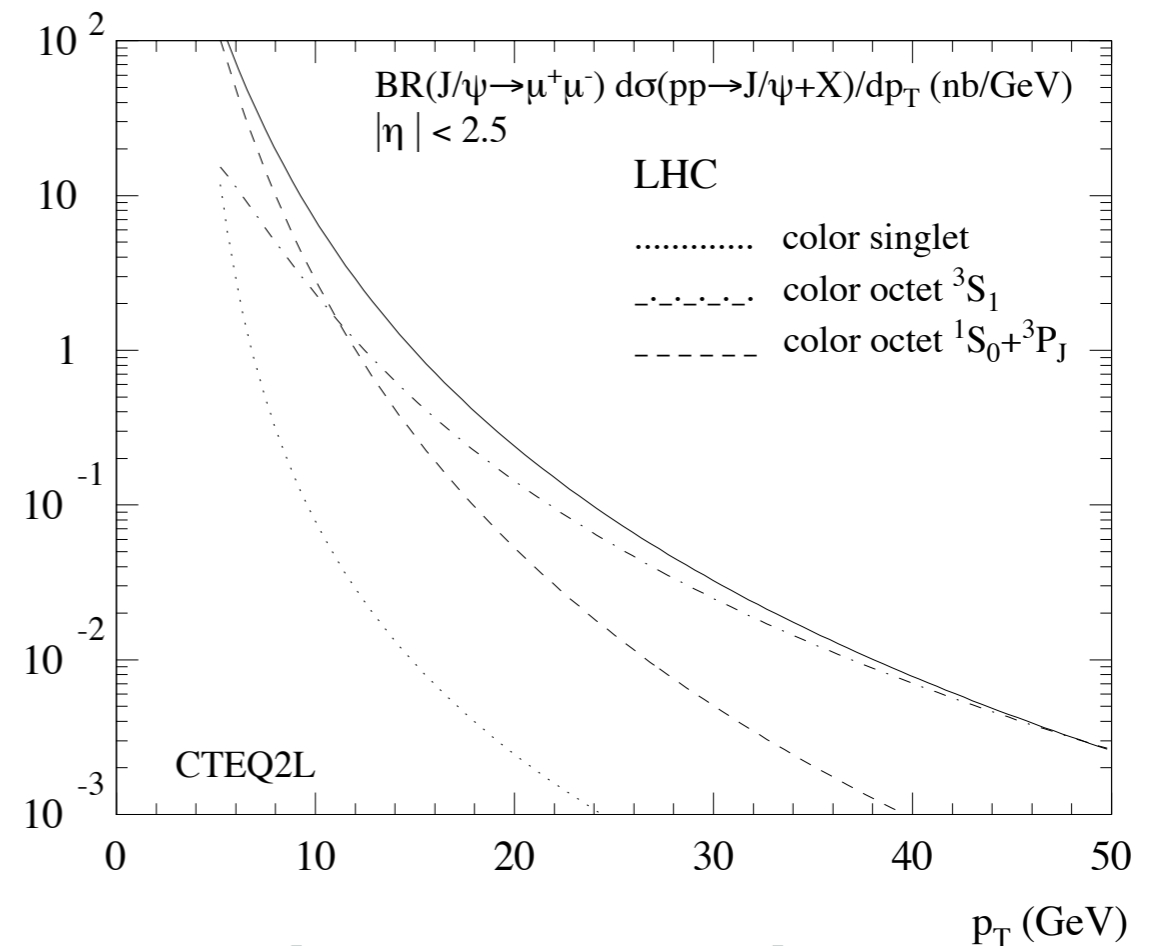
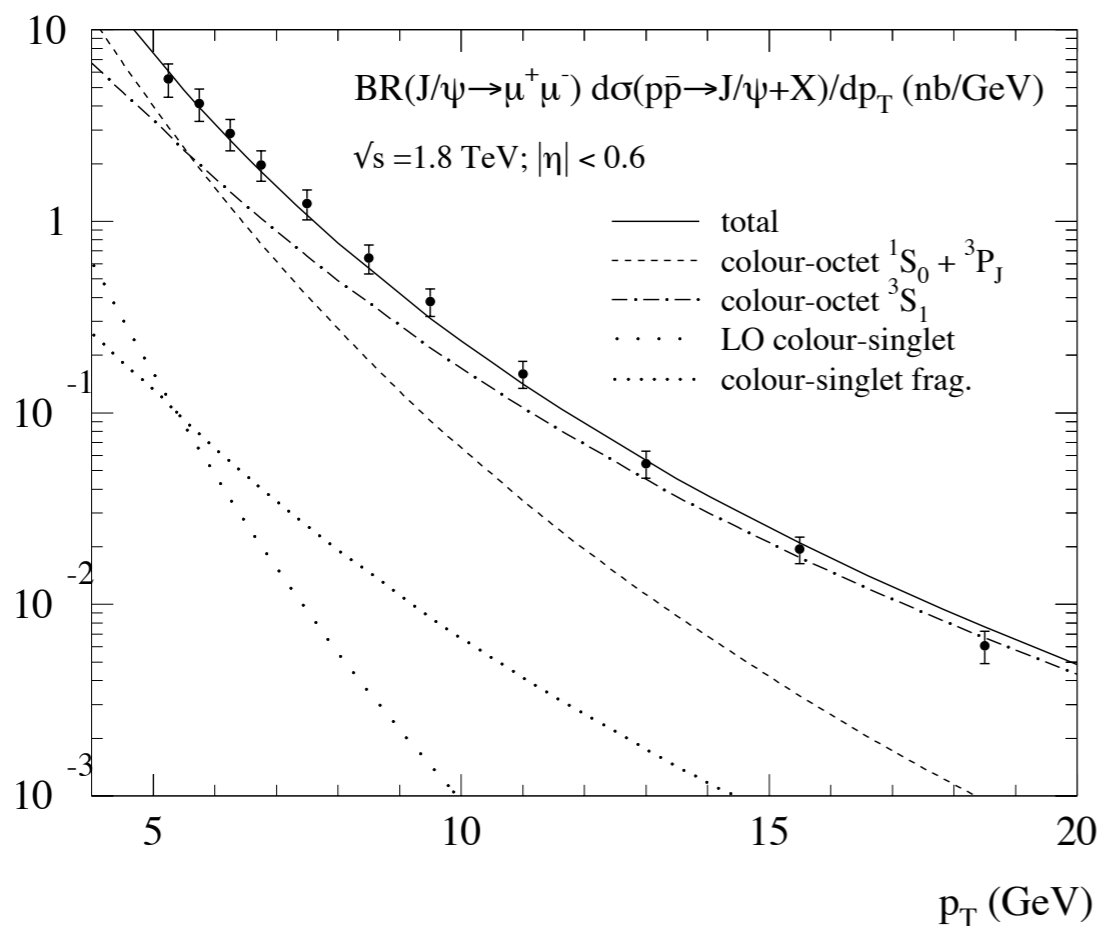
## Belle:

- similar resummation effects in  $p(J/\psi)$ .
- unexplained large fraction of  $c\bar{c}c\bar{c}$

# Future Opportunities (LHC): QwG

Total charm cross section: 7.8mb (beauty: 0.5mb)

1fb<sup>-1</sup> (= 1 week @ 2·10<sup>33</sup>cm<sup>-2</sup>s<sup>-1</sup>) → 7.8·10<sup>12</sup> events



Prediction: Pythia with CO LDME tuned to Tevatron data

M.A.Sanchis-Lozano

# Analysis @ LHC



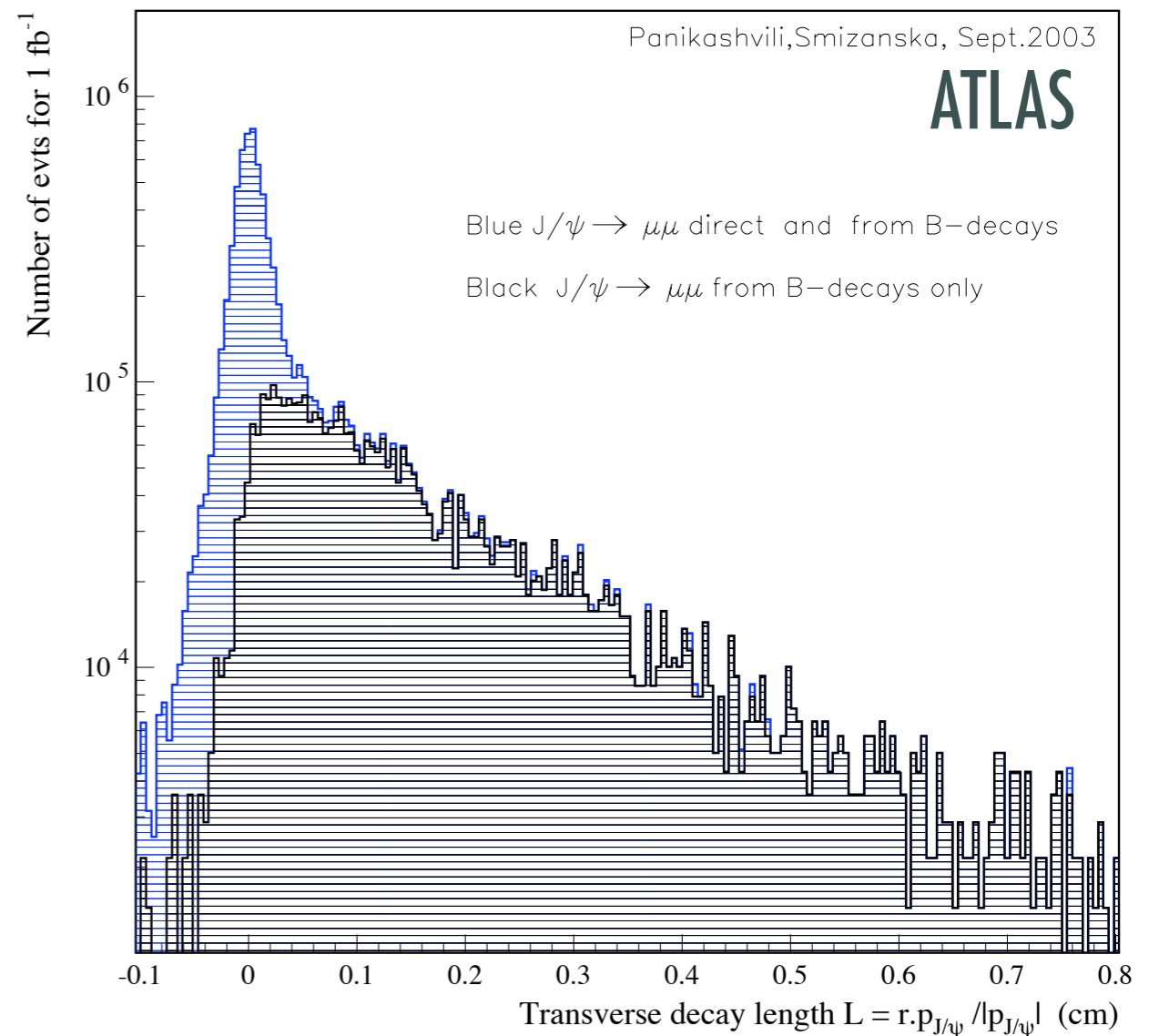
## Separation of prompt $J/\psi$ and from B-decay

ATLAS, CMS:

—  $J/\psi$  cross section:  $\sim 5\text{nb}$

—  $J/\psi \rightarrow \mu\mu$  mass resolution:  $40\text{ MeV}$

—  $B_c \rightarrow J/\psi\pi$  in 1 year: 5600 events



## Measure cross sections, polarization for $\psi(2S)$ , $\chi_c$ and $\Upsilon$

# Conclusions



— [ NRQCD: How large are the LDME really?

— Real test yet to be done at NLO

— Awaiting large statistics polarisation measurements

— [ Quarkonium Production: Mechanism still not resolved

— A lot of experimental and theoretical work ahead

— Will redo all measurements at LHC