

# Quarkonium production in the LHC era: QCD corrections and new observables

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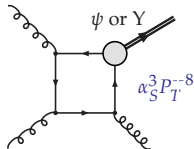
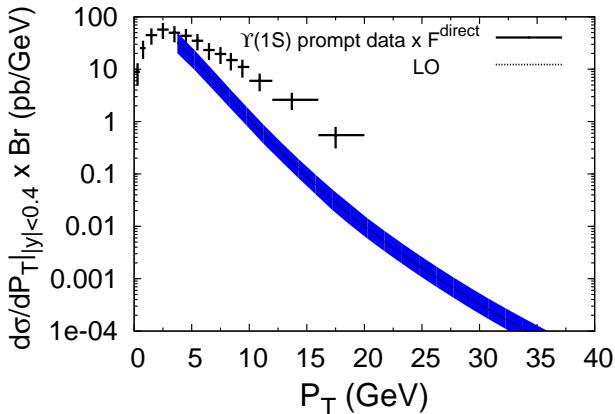
# Part I

## QCD corrections in the CSM and the $P_T$ spectrum

## Reminder: QCD corrections for $Y$ at the Tevatron

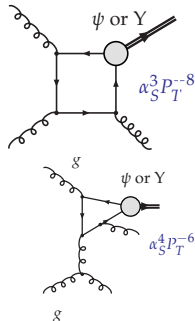
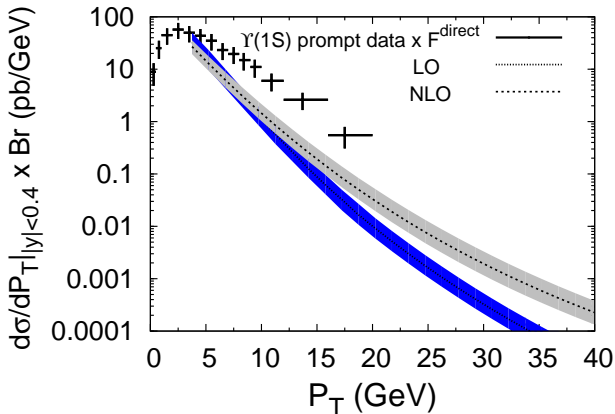
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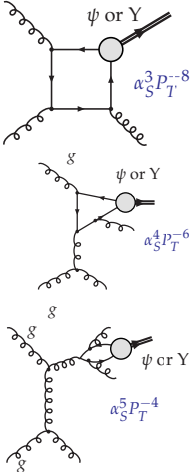
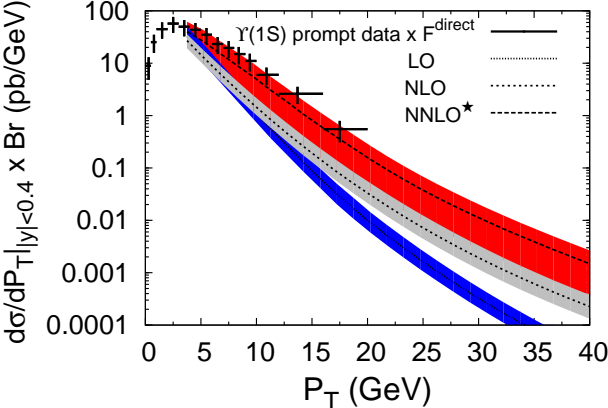
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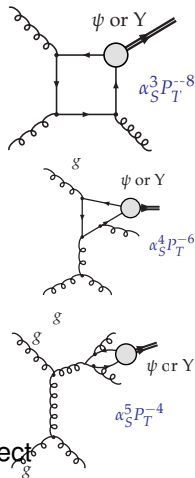
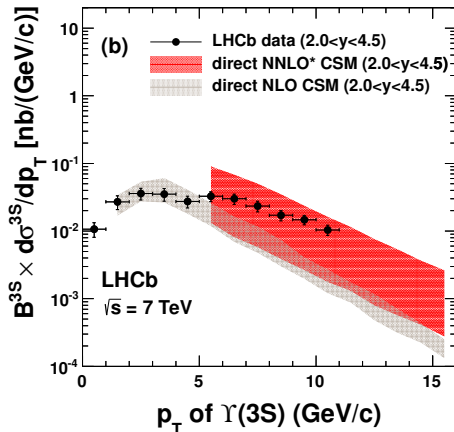
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+ double  $t$ -channel gluon exchange at  $\alpha_S^5$   
 Attention: the NNLO\* is not a complete NNLO

# QCD corrections for $\Upsilon$ at the Tevatron & the LHC

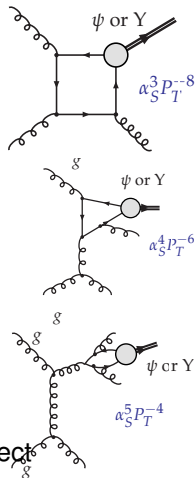
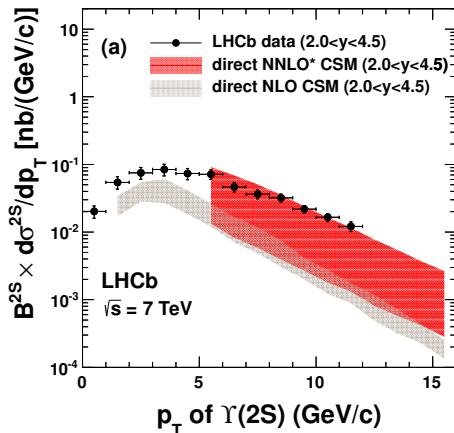
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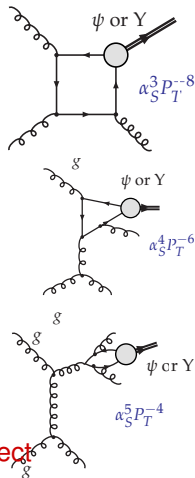
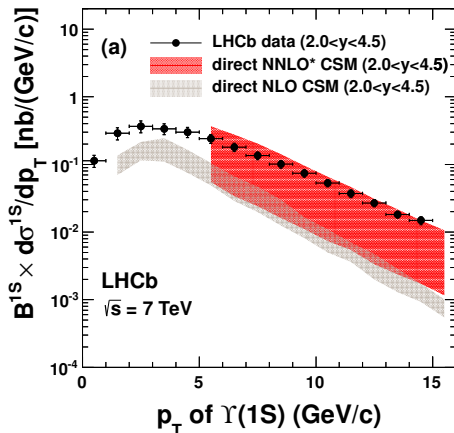
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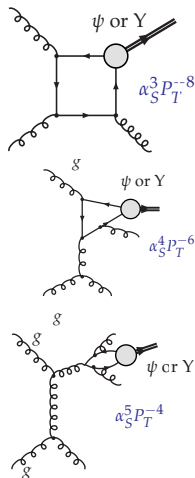
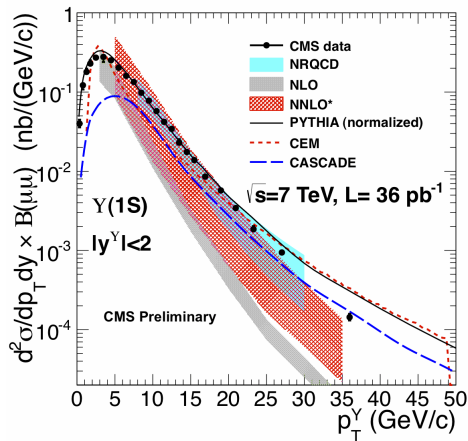
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 CMS, Talk by K.Yi/K.Ulmer on Thursday, CMS-BPH11001



CSM theory curve extrapolated to prompt:  $\times 2$

## Part II

### $P_T$ integrated yields

# CSM predictions account for the $P_T$ -integrated yield

S. J. Brodsky and JPL, PRD 81 051502 (R), 2010; JPL, PoS(ICHEP 2010), 206 (2010)

→ The **yield vs.  $\sqrt{s}$ ,  $y$**

(here only LO curves<sup>1</sup>)

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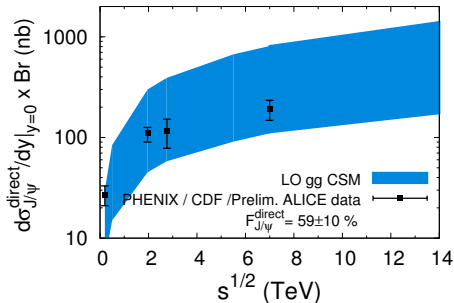
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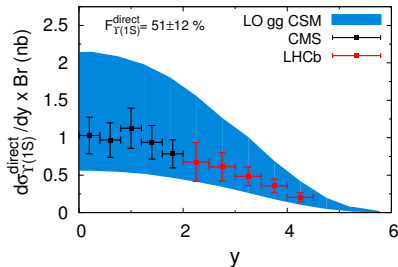
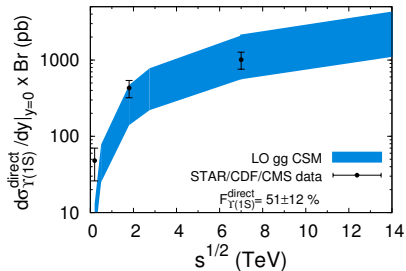
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STAR PRD 82 (2010) 012004 ; CDF PRL 88 (2002) 161802; CMS PRD 83 (2011) 112004; LHCb arXiv:1202.6579 [hep-ex]

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  - Harmless if  $\frac{d\sigma}{dP_T} \propto P_T^{-n}$  with  $n$  fixed, **not** if  $n$  changes, esp. true **at low  $P_T$**

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Y.Q.Ma,*et al.*, PRL102 (2009)162002; B.Gong, J.X.Wang, PRL102 (2009) 162003; Z.G. He,*et al.*, PRD81 (2010) 054036

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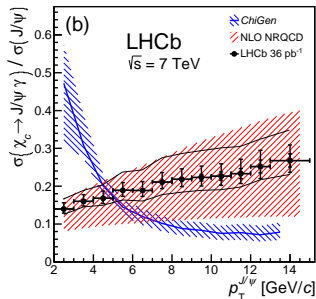
- $e^+e^- \rightarrow J/\psi gg$  **CO** at NLO: 0.9-1.0 pb using universality with Tevatron

**IF one ignores the CSM:** upper bound on CO

Y. Zhang,*et al.*, PRD81:034015,2010.

$$\langle 0 | \mathcal{O}^{J/\psi} [^1S_0^{(8)}] | 0 \rangle + 4.0 \langle 0 | \mathcal{O}^{J/\psi} [^3P_0^{(8)}] | 0 \rangle / m_c^2 \leq (2.0 \pm 0.6) \times 10^{-2} \text{ GeV}^3$$

# Impact of $\chi_c$ 's and $\chi_b$ 's



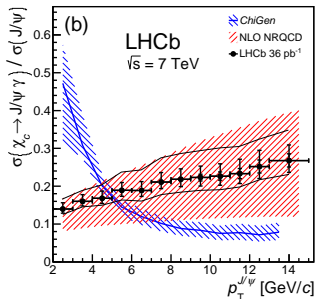
ChiGen: L. A. Harland-Lang and W. J. Stirling, <http://projects.hepforge.org/superchic/chigen.html>

NLO NRQCD: Y.-Q. Ma, K. Wang, K.-T. Chao, Phys. Rev. D83 (2011) 111503 (R)

**The most important and overlooked theory paper on quarkonium physics in 2010 !**

LHCb, arXiv:1204.1462

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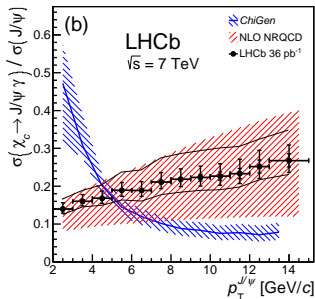
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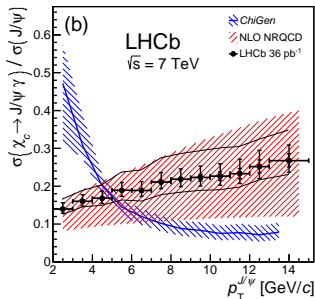
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## Part III

# QCD corrections and polarisation

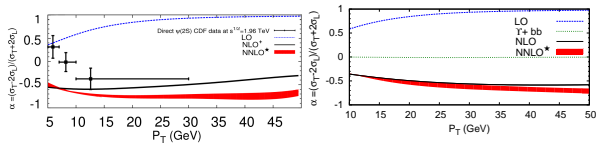
# QCD corrections, feed-down and polarisation

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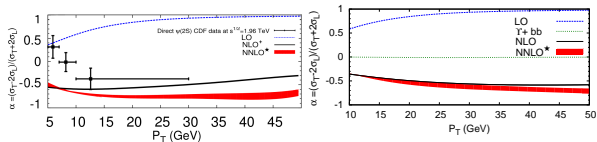
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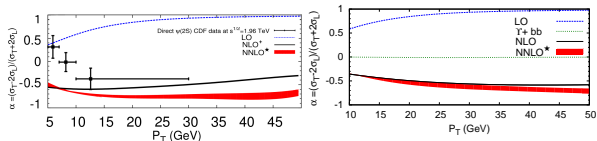


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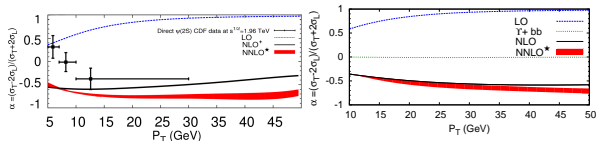
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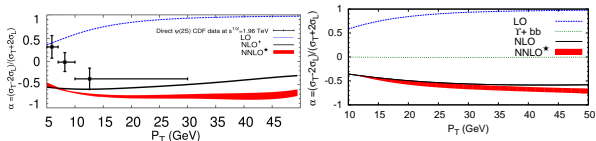
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JPL J. Phys. G 38 (2011) 124110

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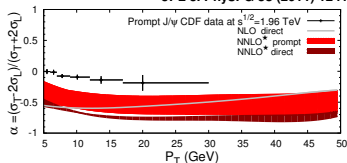
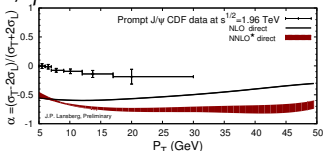
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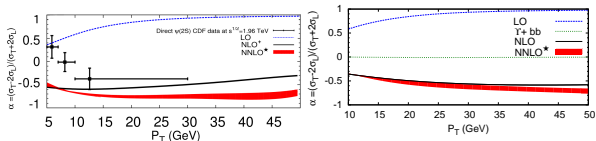
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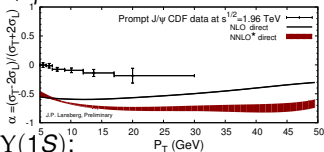
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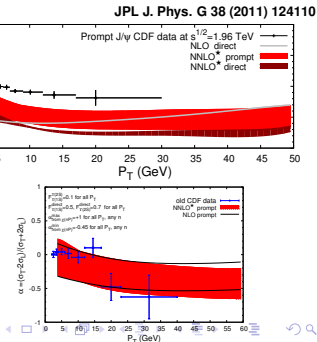
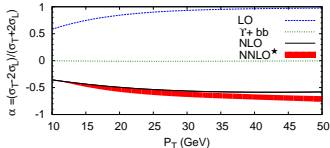


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PRL 108:172002, 2012

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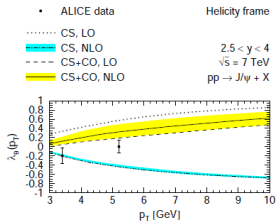
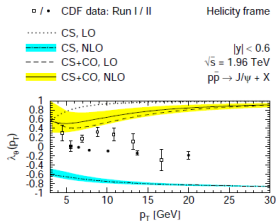
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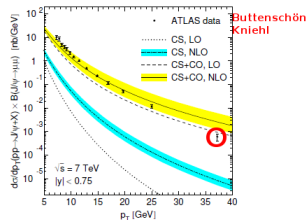
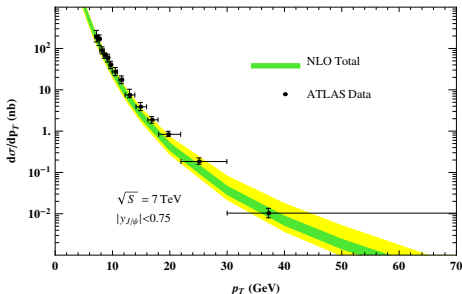


Figure 4: Predictions for the ATLAS measurement [29]. Note that these data are not part of our global fit, since they became public after our global fit was finished. The bands are again constructed by variation of the renormalization, factorization and NRQCD scales. At very high  $p_T$ , it will be necessary to resum large logarithms  $\log(p_T^2/m_{J/\psi}^2)$ . For instance, at  $p_T = 40$  GeV,  $\alpha_s \log(p_T^2/m_{J/\psi}^2) \approx 0.7$ .

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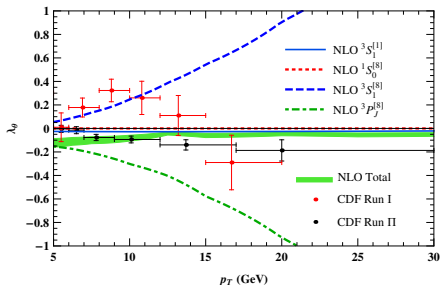
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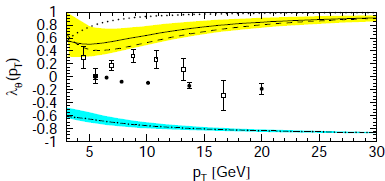
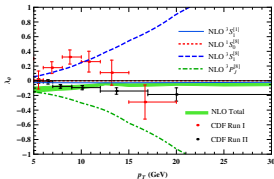
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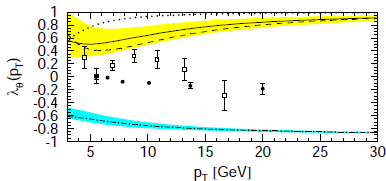
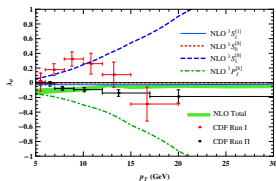
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# Part IV

## New observables

## Double charm: $J/\psi + D$

→  $J/\psi + D$  or  $J/\psi + \text{lepton}$  in the yield integrated over  $P_T$

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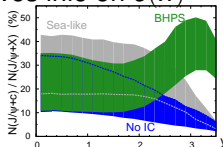
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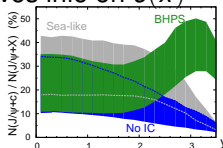
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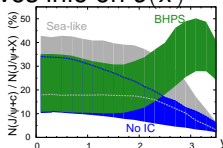
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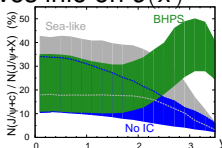
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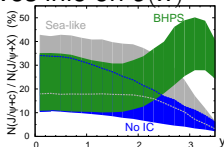
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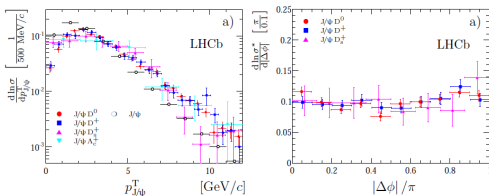


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→ First measurement by LHCb ( $p_T^D \geq 3$  GeV  $\Rightarrow p_T^{\text{charm quark}}$  not small)



LHCb arXiv:1205.0975

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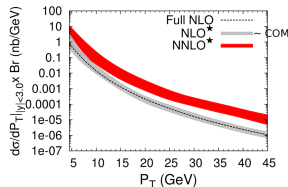
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R.Li and J.X. Wang, PLB 672,51,2009

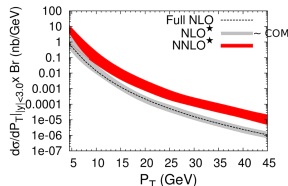


JPL, PLB 679,340,2009.

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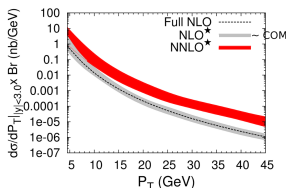
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- Clearly, **new info on CS vs CO w.r.t inclusive case !**
- Possible: see  $(c, b) - jet + \gamma$  studies by D0 up to  $P_T^\gamma \simeq 150 \text{ GeV} !$

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the opportunity of extracting  $g(x)$  with quarkonium
- A Fixed Target Experiment at the LHC (AFTER) can also provide much  
information on quarkonia  
see <http://after.in2p3.fr> and my talk earlier today

# Part V

## Backup

# Quarkonia and the gluon PDF

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PHYSICAL REVIEW D

VOLUME 37, NUMBER 5

1 MARCH 1988

## Structure-function analysis and $\psi$ , jet, $W$ , and $Z$ production: Determining the gluon distribution

A. D. Martin

*Department of Physics, University of Durham, Durham, England*

R. G. Roberts

*Rutherford Appleton Laboratory, Didcot, Oxon, England*

W. J. Stirling

*Department of Physics, University of Durham, Durham, England*

(Received 27 July 1987)

We perform a next-to-leading-order structure-function analysis of deep-inelastic  $\mu N$  and  $\nu N$  scattering data and find acceptable fits for a range of input gluon distributions. We show three equally acceptable sets of parton distributions which correspond to gluon distributions which are (1) “soft,” (2) “hard,” and (3) which behave as  $xG(x) \sim 1/\sqrt{x}$  at small  $x$ .  $J/\psi$  and prompt photon hadroproduction data are used to discriminate between the three sets. Set 1, with the “soft”-gluon distribution, is favored.  $W$ ,  $Z$ , and jet production data from the CERN collider are well described but do not distinguish between the sets of structure functions. The precision of the predictions for  $\sigma_W$  and  $\sigma_Z$  allow the collider measurements to yield information on the number of light neutrinos and the mass of the top quark. Finally we discuss how the gluon distribution at very small  $x$  may be directly measured at DESY HERA.

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Z. Phys. C – Particles and Fields 38, 473–478 (1988)

## $J/\psi$ Production at large transverse momentum at hadron colliders

E.W.N. Glover<sup>1\*</sup>, A.D. Martin<sup>2</sup>, W.J. Stirling<sup>2</sup>

<sup>1</sup> Cavendish Laboratory, University of Cambridge, Cambridge, CB3 0HE, England

<sup>2</sup> Physics Department, University of Durham, Durham, DH1 3LE, England

Received 7 October 1987

**Abstract.** We calculate  $J/\psi$  hadroproduction and emphasize the importance of the  $J/\psi$  signal as a measure of  $b\bar{b}$  production via the decay  $B \rightarrow \psi X$  and of the gluon structure function at low  $x$  via  $\chi$  hadroproduction followed by  $\chi \rightarrow \psi\gamma$  decay. We compare with UA1 data and data at ISR energies and make predictions for  $\psi$  production at TEVATRON energies.

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PHYSICAL REVIEW D

VOLUME 48, NUMBER 11

1 DECEMBER 1993

## $\psi$ production in $\bar{p}N$ and $\pi^-N$ interactions at 125 GeV/c and a determination of the gluon structure functions of the $\bar{p}$ and the $\pi^-$

C. Akerlof,<sup>4</sup> H. Areti,<sup>3,\*</sup> M. Binkley,<sup>2</sup> S. Conetti,<sup>3,†</sup> B. Cox,<sup>2,†</sup> J. Enagonio,<sup>2</sup>  
He Mao,<sup>5</sup> C. Hojvat,<sup>2</sup> D. Judd,<sup>2,†</sup> S. Katsanevas,<sup>1</sup> R. D. Kephart,<sup>2</sup> C. Kourkouvelis,<sup>1</sup> P. Kraushaar,<sup>4,§</sup>  
P. Lebrun,<sup>3,\*</sup> P. K. Malhotra,<sup>2,†</sup> A. Markou,<sup>1</sup> P. O. Mazur,<sup>2</sup> D. Nitz,<sup>4</sup> L. K. Resvanis,<sup>1</sup> D. Ryan,<sup>5</sup>  
T. Ryan,<sup>3,§</sup> W. Schappert,<sup>3,\*\*</sup> D. G. Stairs,<sup>2</sup> R. Thun,<sup>4</sup> F. Turkot,<sup>2</sup> S. Tzamarias,<sup>1,††</sup> G. Voulgaris,<sup>1</sup>  
R. L. Wagner,<sup>2</sup> D. E. Wagoner,<sup>2,†</sup> W. Yang,<sup>2</sup> and Zhang Nai-jian<sup>5</sup>

(E537 Collaboration)

<sup>1</sup>University of Athens, Athens, Greece

<sup>2</sup>Fermi National Accelerator Laboratory, Batavia, Illinois 60510

<sup>3</sup>McGill University, Montreal, Quebec, Canada H3A 2T8

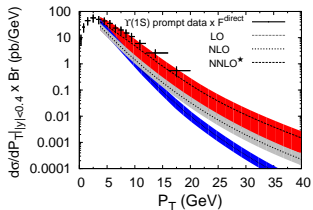
<sup>4</sup>University of Michigan, Ann Arbor, Michigan 48109

<sup>5</sup>Shandong University, Jinan, People's Republic of China

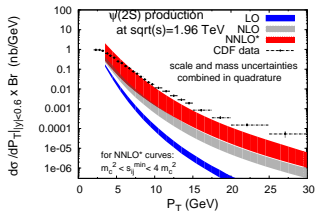
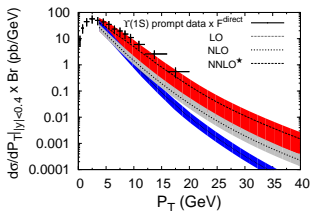
(Received 9 February 1993)

We have measured the cross section for production of  $\psi$  and  $\psi'$  in  $\bar{p}$  and  $\pi^-$  interactions with Be, Cu, and W targets in experiment E537 at Fermilab. The measurements were performed at 125 GeV/c using a forward dimuon spectrometer in a closed geometry configuration. The gluon structure functions of the  $\bar{p}$  and  $\pi^-$  have been extracted from the measured  $d\sigma/dx_F$  spectra of the produced  $\psi$ 's. From the  $\bar{p}$  data we obtain, for  $\bar{p}$ ,  $xG(x) = (2.15 \pm 0.7)[1-x]^{6.83 \pm 0.51} [1 + (5.85 \pm 0.95)x]$ . In the  $\pi^-$  case, we obtain, from the W and the Be data separately,  $xG(x) = (1.49 \pm 0.03)[1-x]^{1.98 \pm 0.06}$  (for  $\pi^-$ -W),  $xG(x) = (1.10 \pm 0.10)[1-x]^{1.29 \pm 0.20}$  (for  $\pi^-$ -Be).

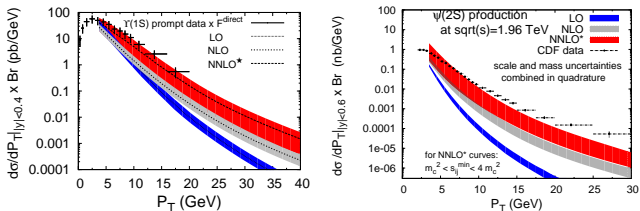
# Impact of QCD corrections to CSM at mid and high $P_T$



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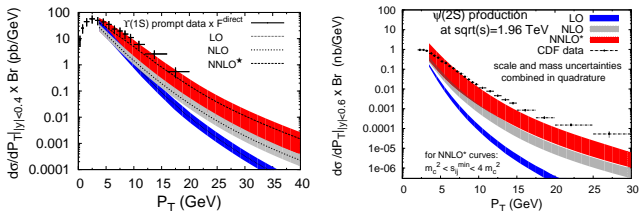


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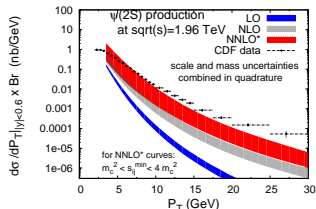
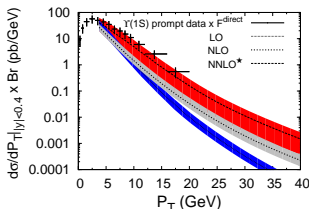
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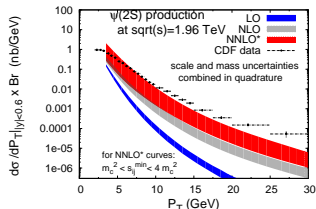
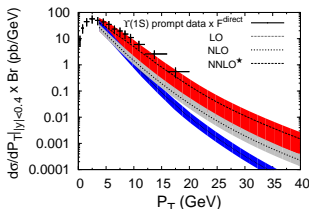
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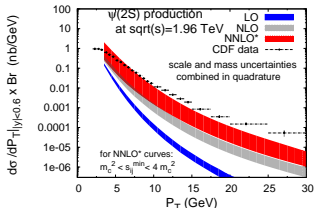
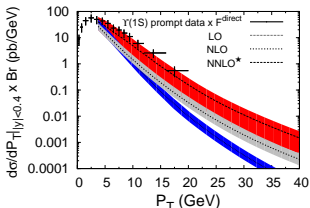
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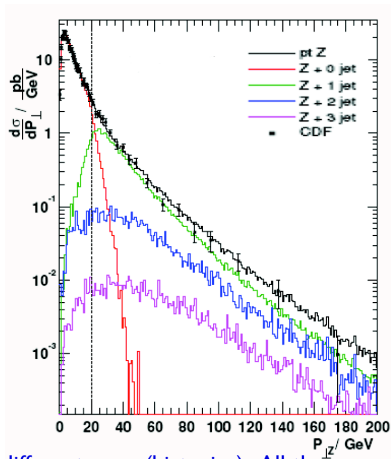
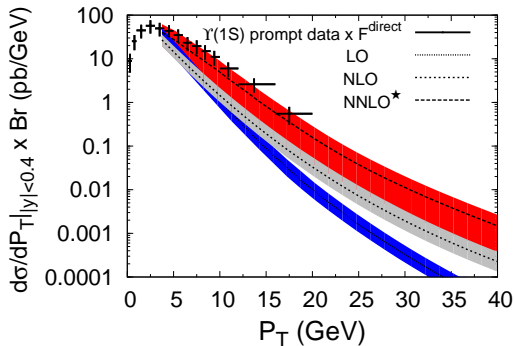
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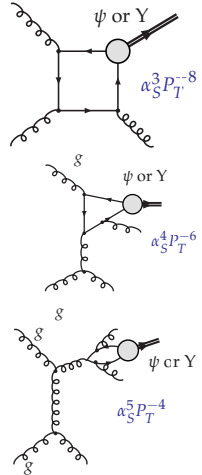
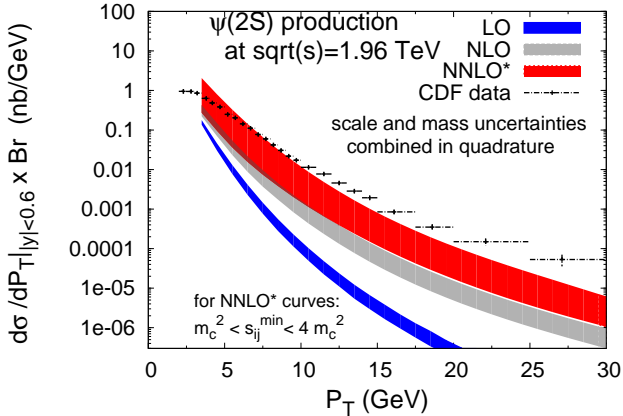
$k_T$  fact.  $\leftrightarrow$  NNLO Collinear fact. ?

# Analogy with the $P_T$ spectrum for the $Z^0$ boson



# QCD corrections for $\psi(2S)$ at the Tevatron

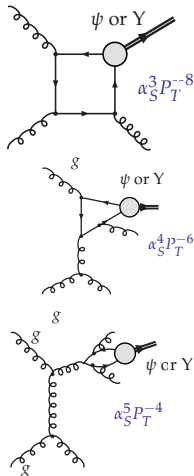
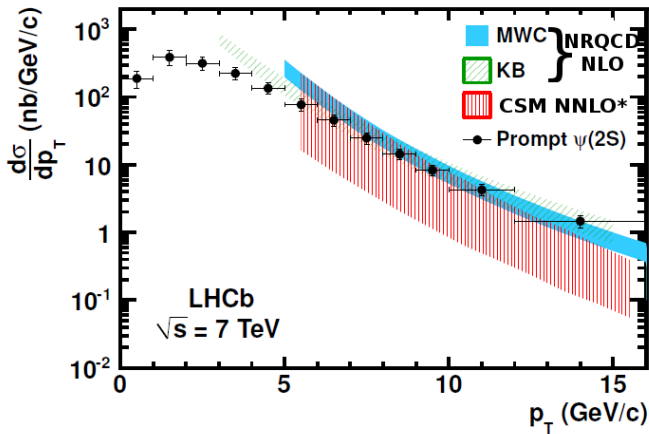
J.Campbell, F. Maltoni, F. Tramontano, Phys.Rev.Lett. 98:252002,2007  
JPL, EPJC 61:693,2009.



**Disclaimer:** comparison to be done with the CMS data:  
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# QCD corrections for $\psi(2S)$ at the Tevatron & the LHC

J.Campbell, F. Maltoni, F. Tramontano, Phys.Rev.Lett. 98:252002,2007  
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