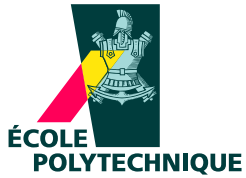

Quarkonium production at the LHC

J.P. Lansberg
Ecole Polytechnique – CPHT

ReteQuarkonii Thematic Day
Université Paris Sud, Orsay – IPNO
February 9, 2010

Outline

Part 1: History

1. Basic pQCD approach in pp: Colour Singlet Model
2. Why does the CSM fail ?
3. Review of some models in pp

Part 2: Present

4. Describing the mid- and high-P_T region: QCD corrections

Part 3: Perspectives for the future

5. Need for more observables !

Conclusions and Outlooks

Part I

History

Basic pQCD approach: the Colour Singlet Model (CSM)

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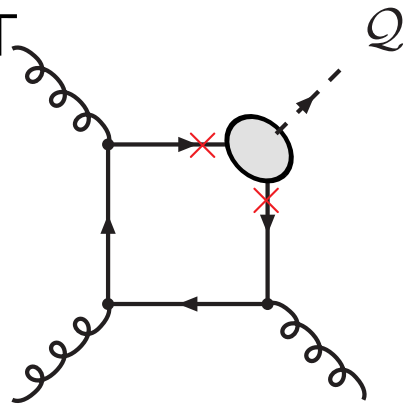

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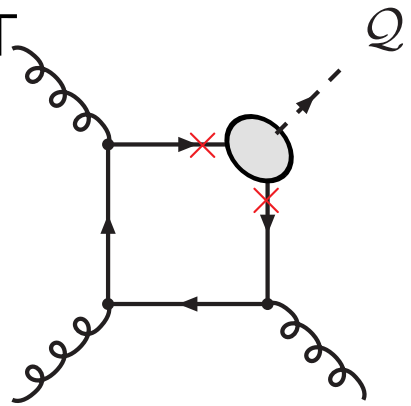

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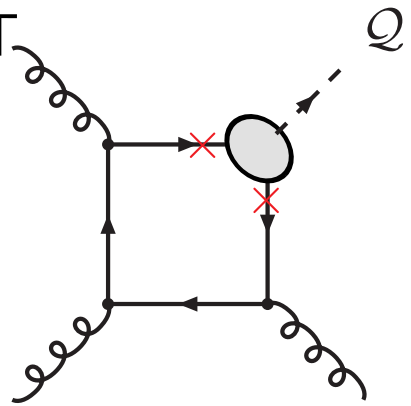

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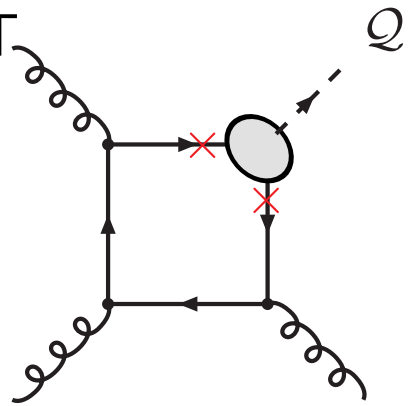

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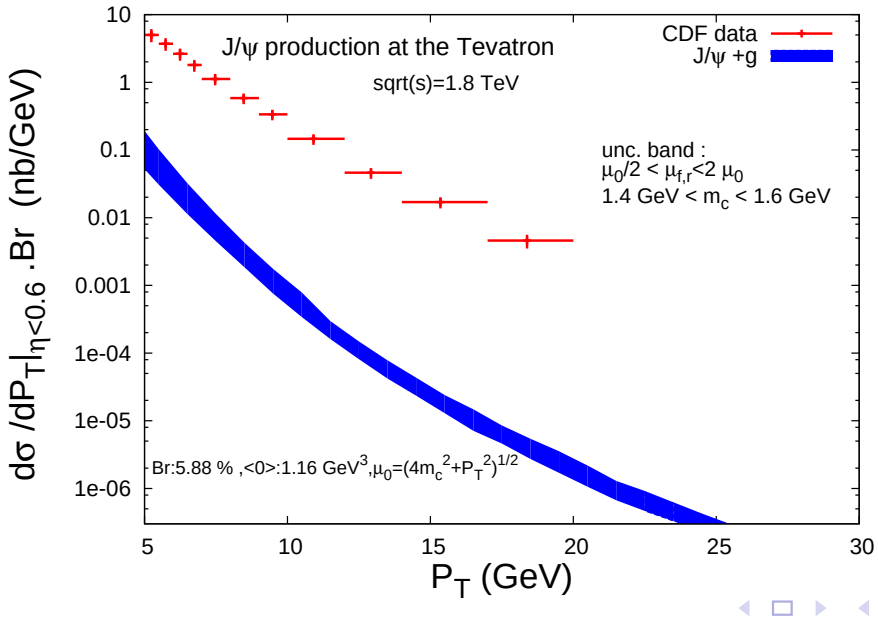

CDF, PRL 79:572 & 578,1997

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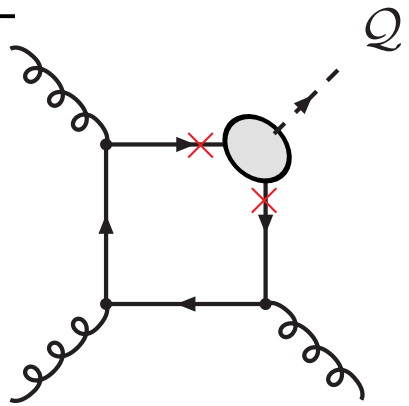

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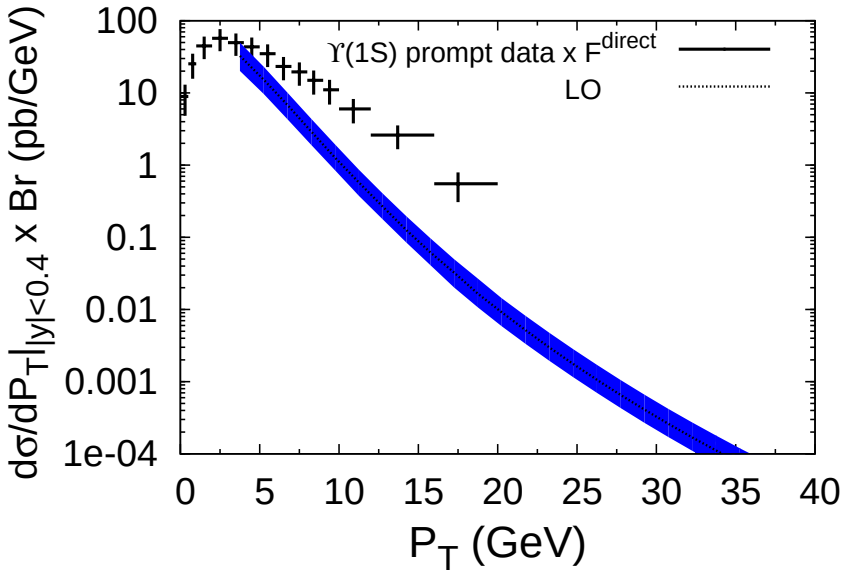

CDF, PRL 88:161802,2002

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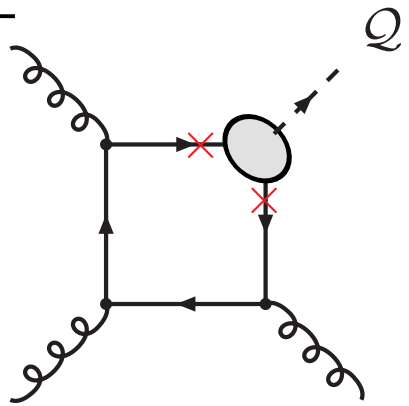

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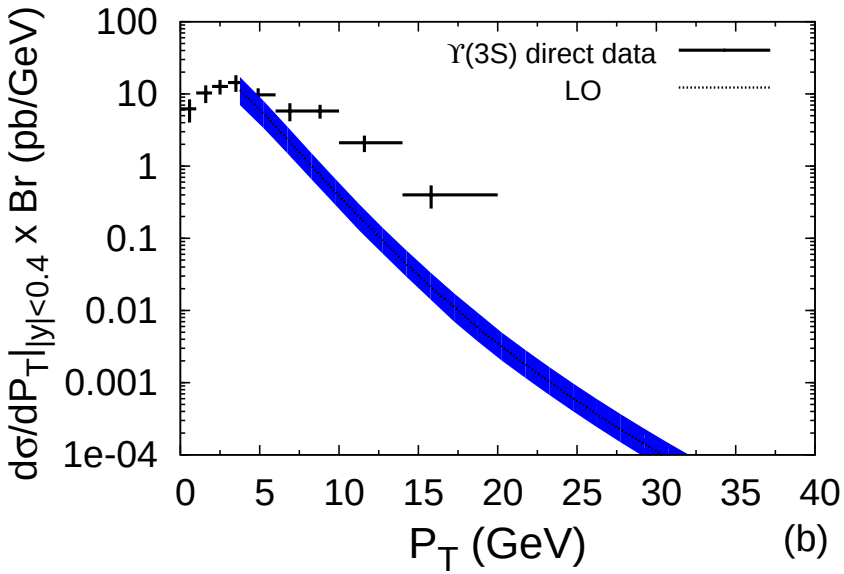

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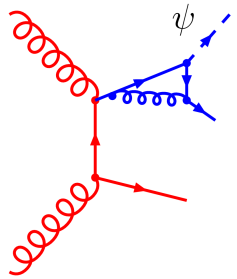

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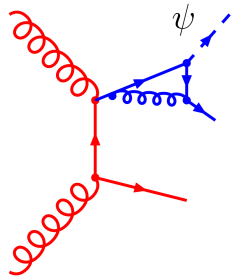

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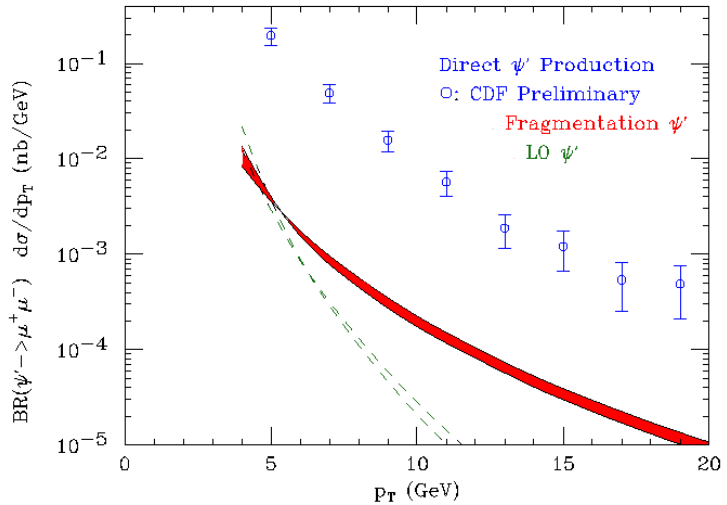
→ Illustration for the ψ'

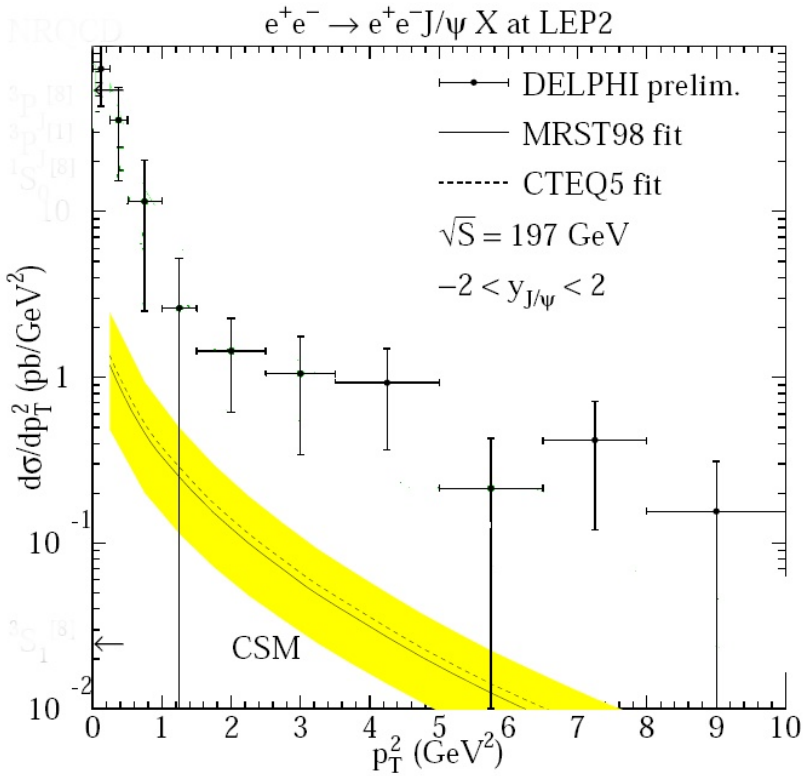


× Off by factor 30-100 for J/ψ and ψ'

× Off by factor 10 for Υ's

J/ψ production in $\gamma\gamma$ collisions at LEP II

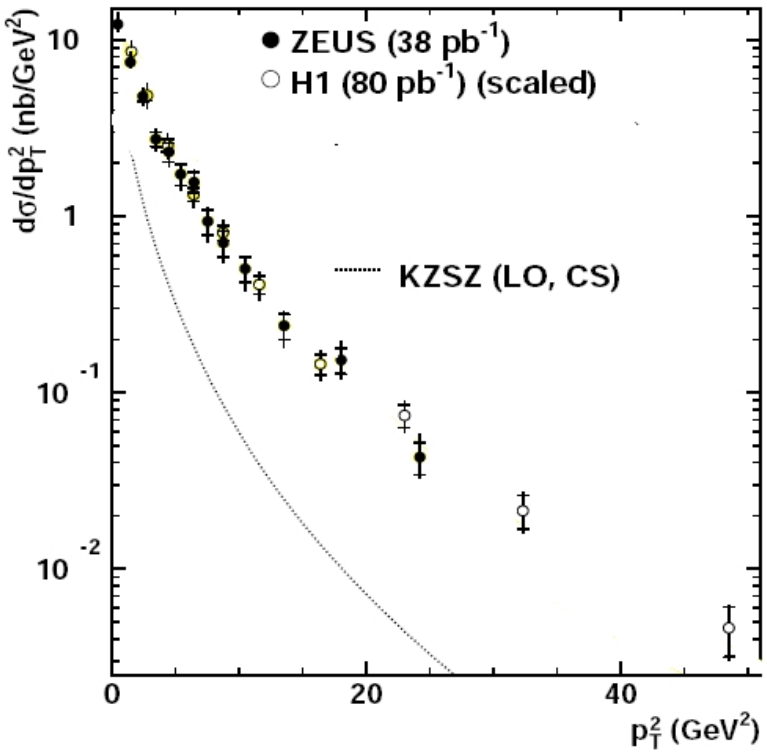
DELPHI, PLB 565 76, 2003



J/ψ photoproduction at HERA

M.Kramer Nucl.Phys.B459:3 1996
H1,EPJC 25, 2,2002; ZEUS, EPJC 27, 173, 2003

LO CSM also fails in photoproduction at HERA...



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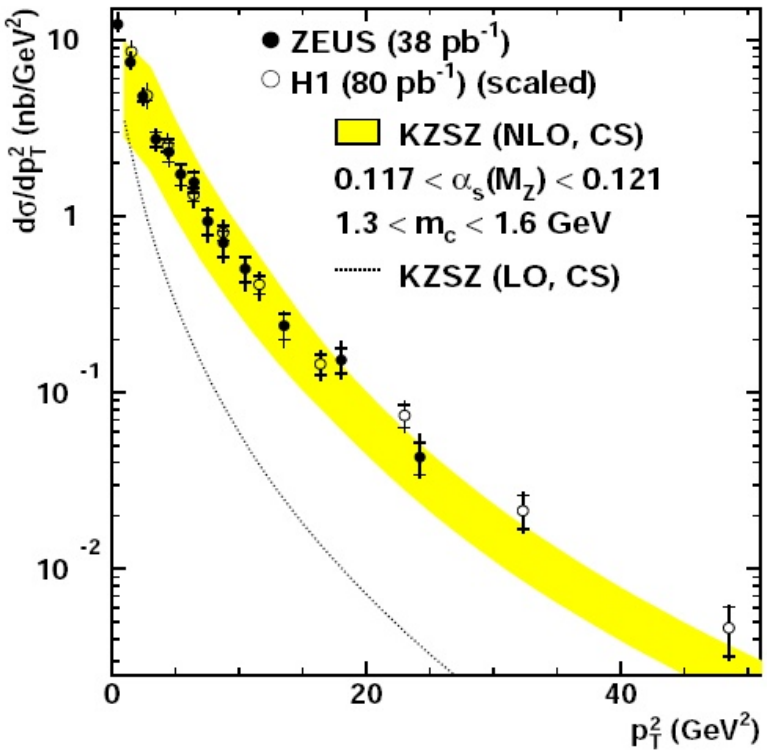
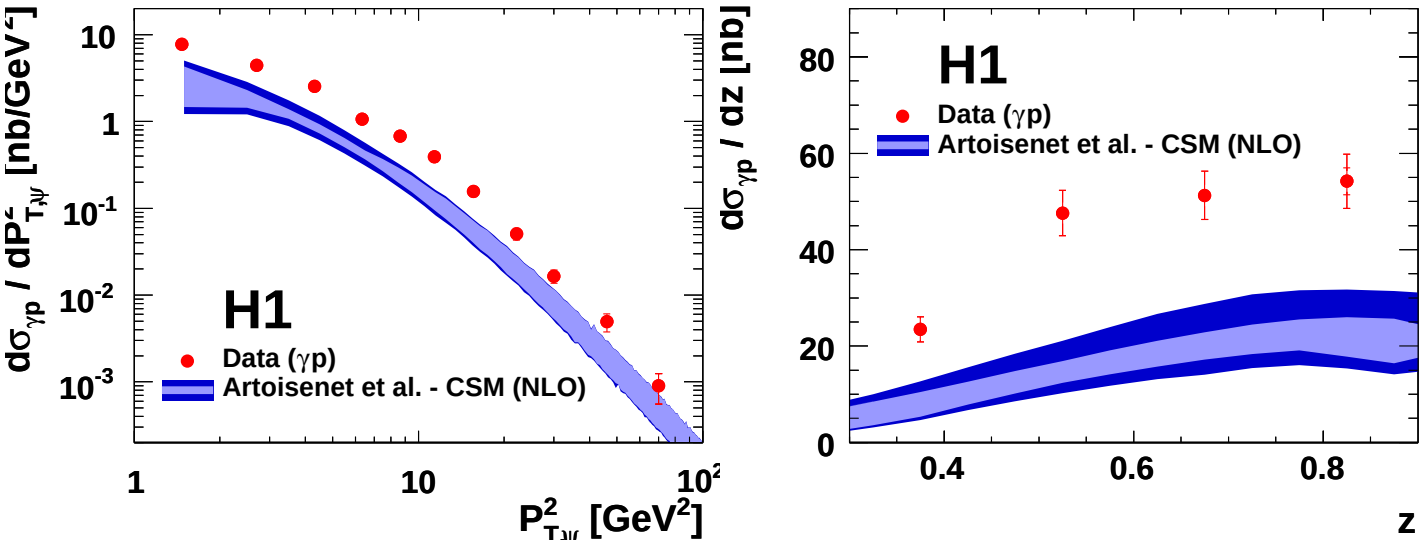


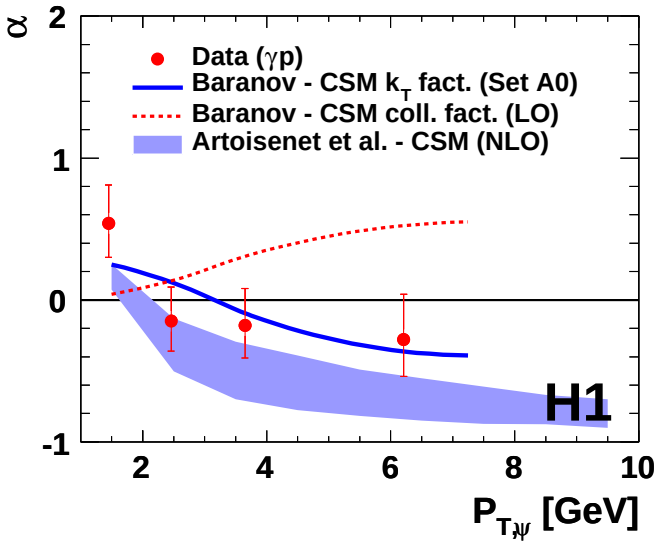
BUT NLO CSM is in better agreement with the data !

see however Phys. Rev. Lett. 102, 142001 (2009) and arXiv:0901.4749 [hep-ph]

J/ψ photoproduction at HERA

P. Artoisenet *et al.*Phys. Rev. Lett. 102, 142001 (2009)
e.g. H1,arXiv:1002.0234

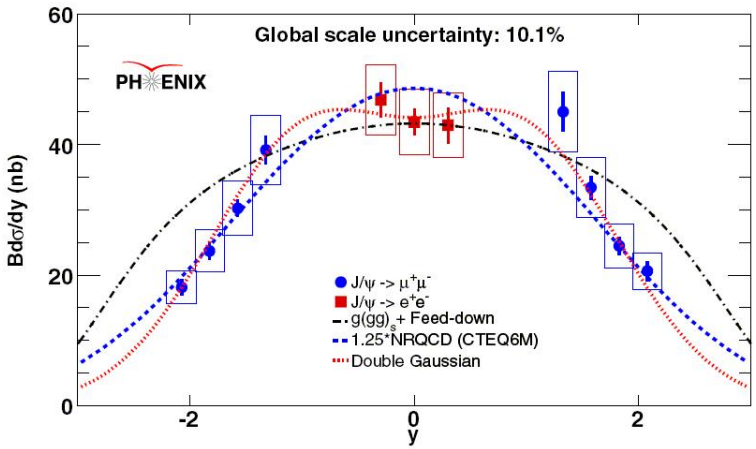




What about the CSM predictions for the total yield & $\frac{d\sigma}{dy}$?

As we have seen:

- ⇨ $\frac{d\sigma}{dP_T}$ cannot be reproduced by the LO CSM
- ⇨ What about the yield and the rapidity distribution ?
- ⇨ PHENIX data ($\sqrt{s} = 200$ GeV) cover a broad range of y, down to small P_T



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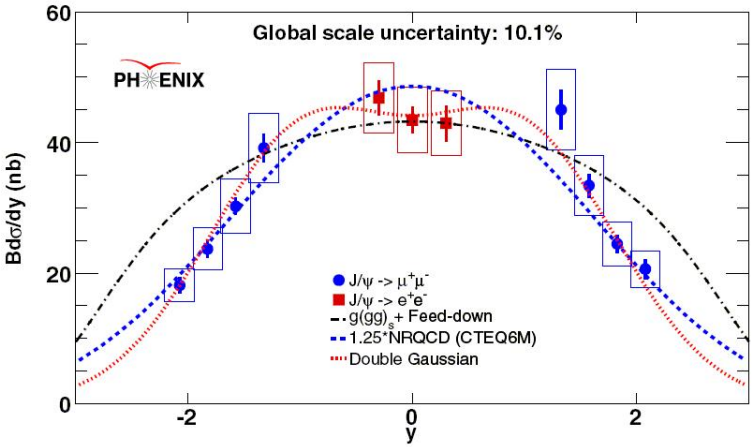

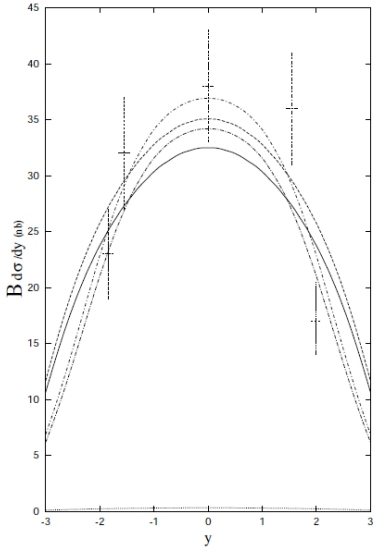

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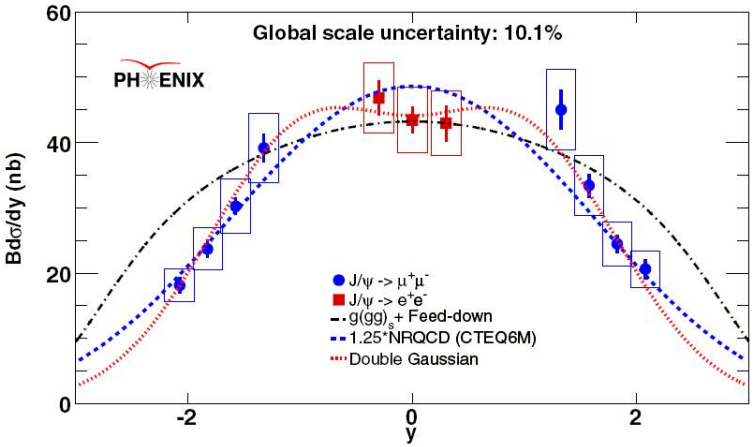

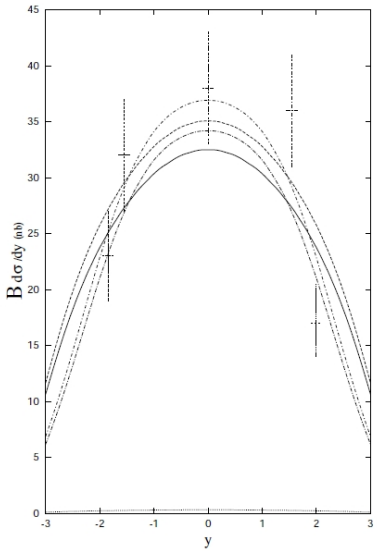

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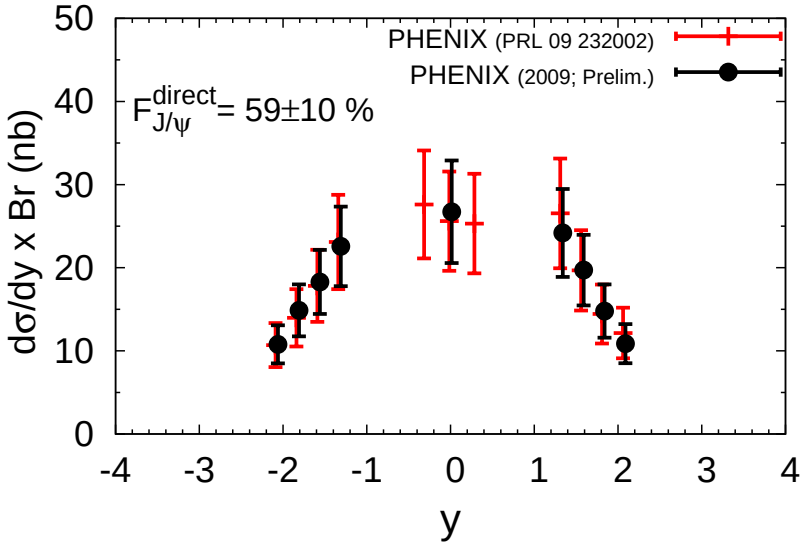
section in the singlet and octet channel. In the color singlet channel, the J/ψ production cross section at α_s^2 order is given by:

$$\sigma_1^{pp\to J/\psi}(s) = \sigma_1^{pp\to\chi_0}(s)BR_{\chi_0}, \quad +\sigma_1^{pp\to\chi_2}(s)BR_{\chi_2}. \quad (9)$$

What about the CSM predictions for $\frac{d\sigma}{dy}$?

S. J. Brodsky and J. P. Lansberg, arXiv:0908.0754 [hep-ph].



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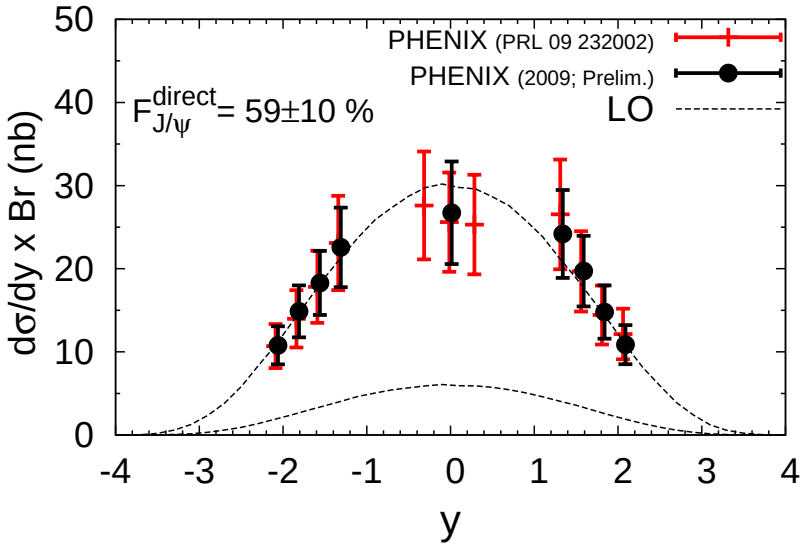

LO: $gg \to J/\psi g$ (see slide 1, nothing new !)

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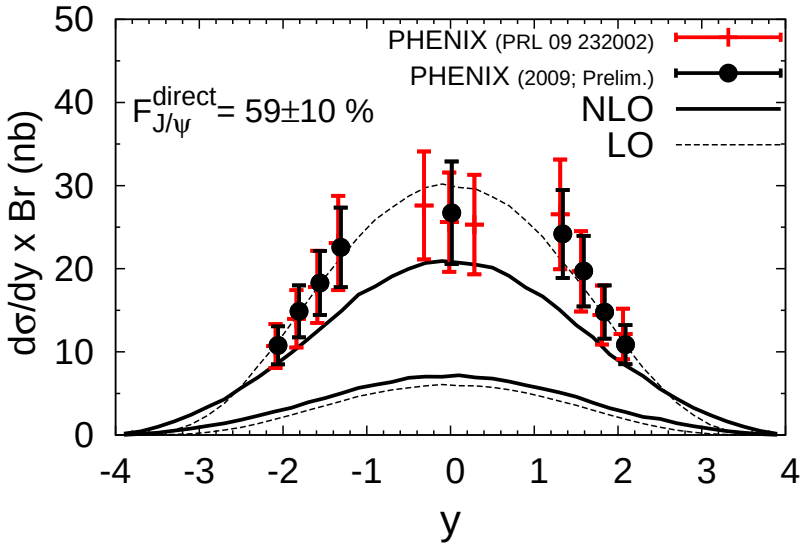

NLO: $gg \to J/\psi, gg\ gq \to J/\psi gq$, ...

using the matrix elements from J.Campbell, F. Maltoni, F. Tramontano, PRL 98:252002,2007

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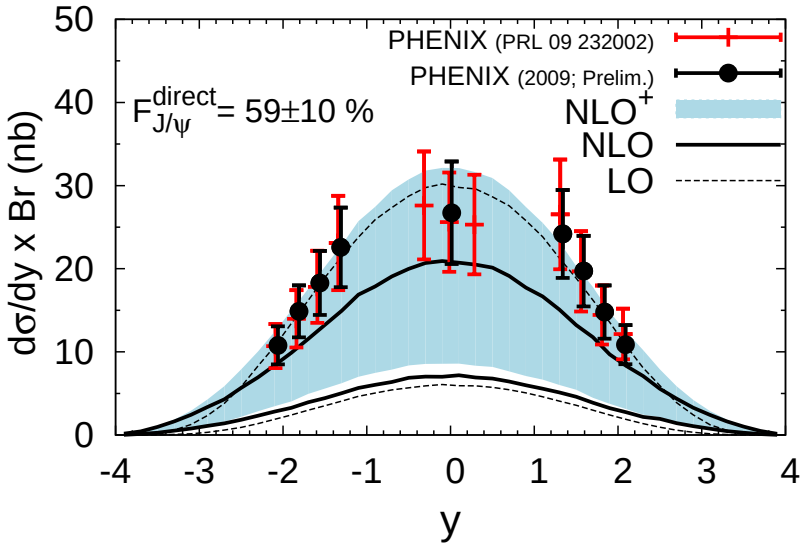

NLO$^+$: adding one new contribution at LO $cg \to J/\psi c$

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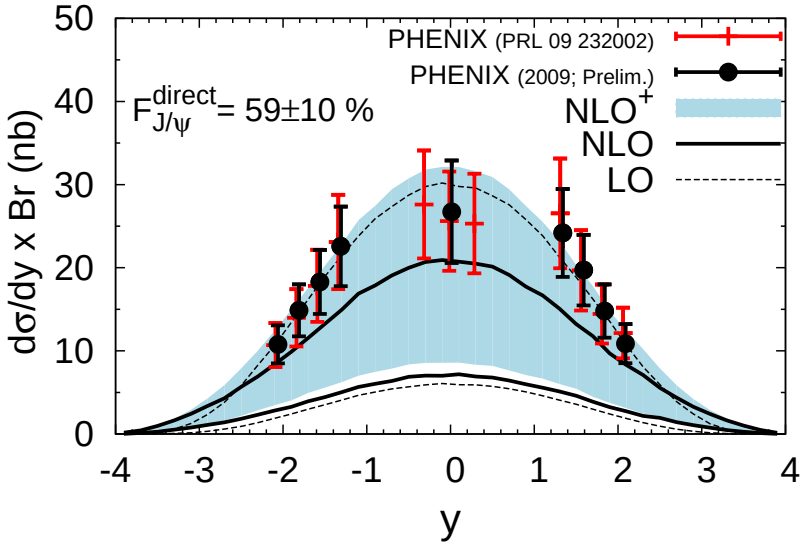

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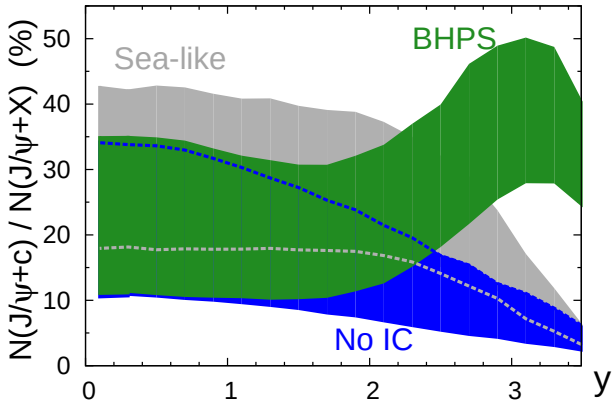

Could be studied via azimuthal correlation $J/\psi + e, \mu$; 10-40% of the direct signal

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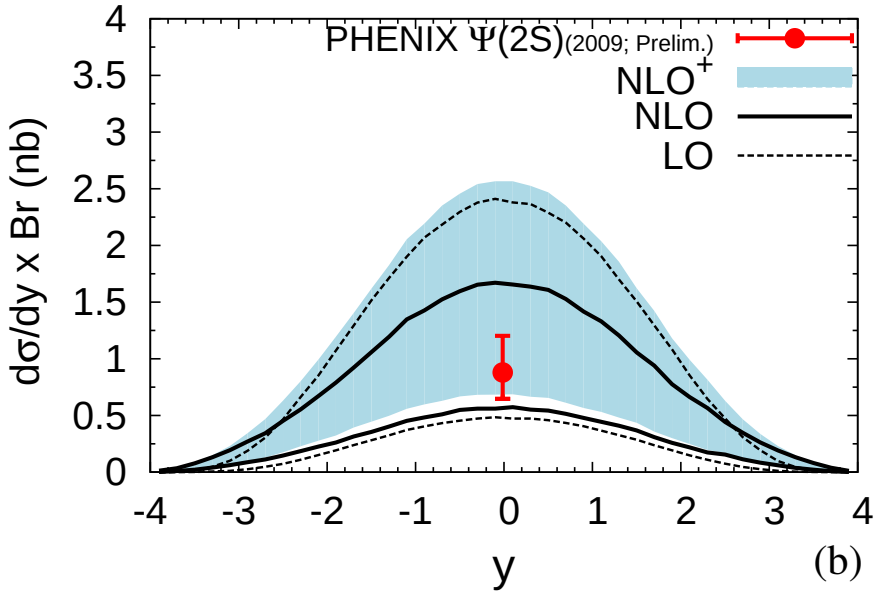

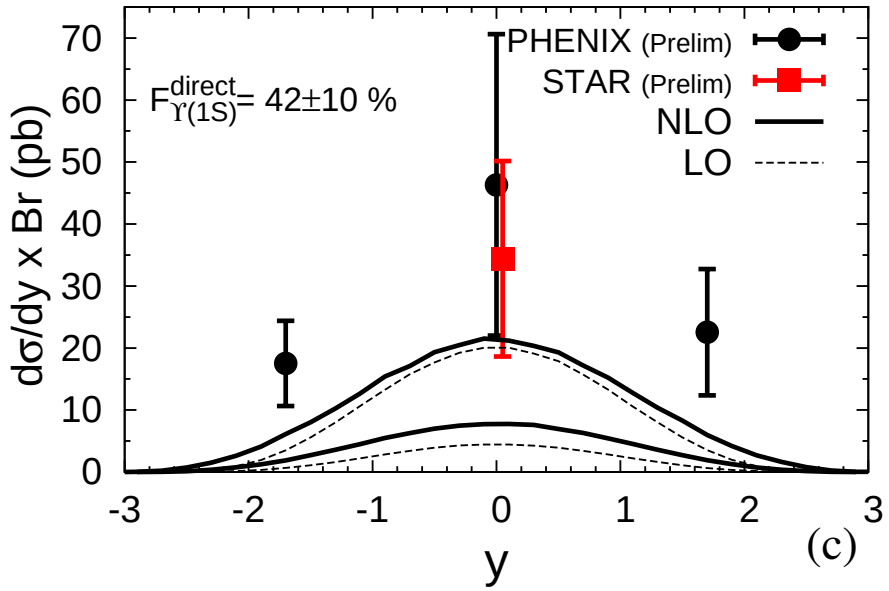

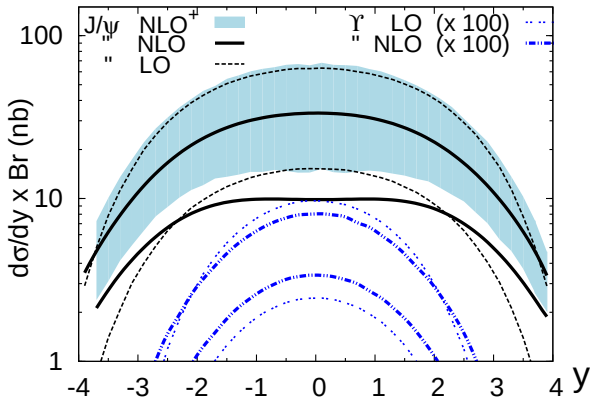

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→ Can't the quarks be produced off-shell ? with relative momentum $\neq 0$?

s-channel cut contribution

Review of some models in *pp* I

for a review, see *e.g* JPL IJMPA 21 3857-3915 (2006)

➪ Colour Evaporation Model (CEM): Halzen *et al*.

- ➞ Numerous soft-gluon emissions from the $Q\bar{Q}$ pair change its quantum state
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✗ Parameters to be fit and may vary from one process to another

✗ Systematic improvement of the model ?

✗ Polarisation ?

Review of some models in pp II

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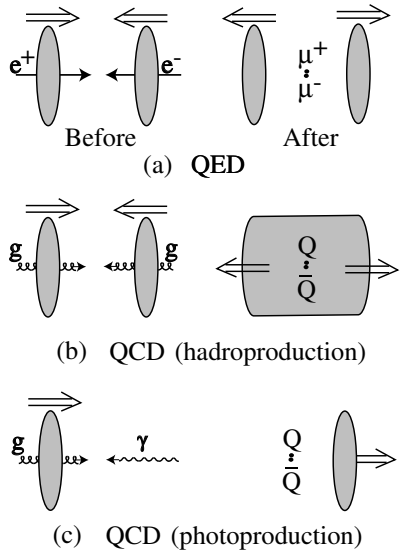

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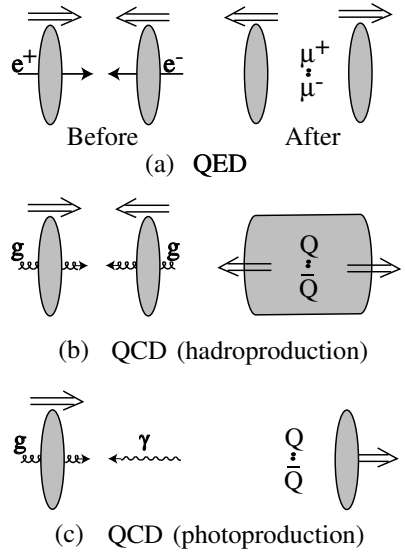

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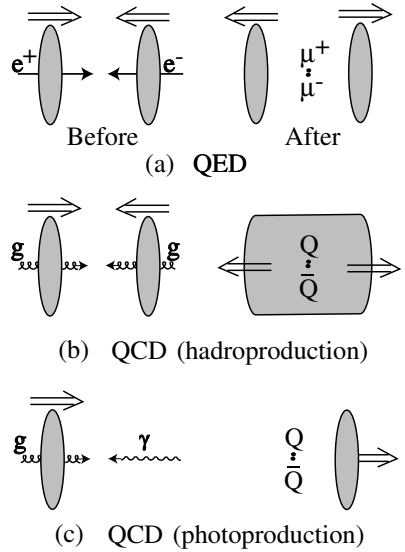

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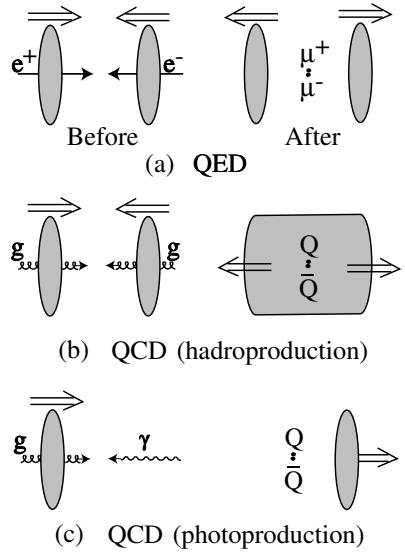

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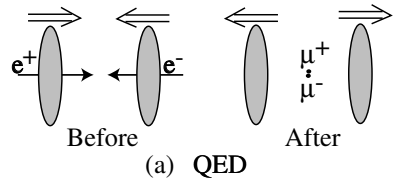

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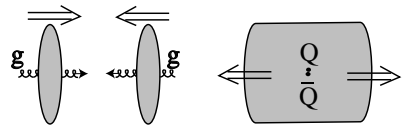

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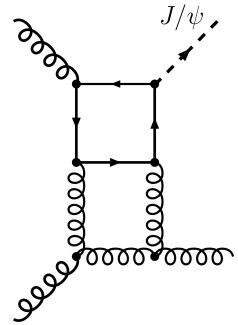

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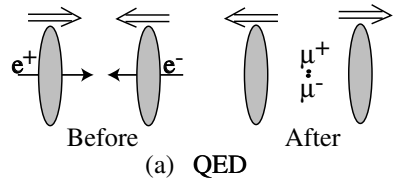

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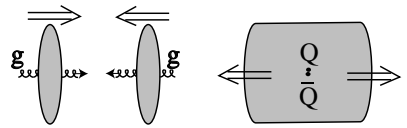

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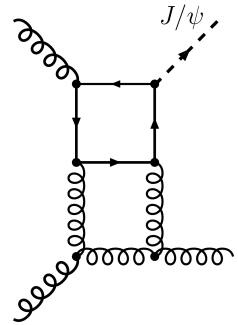

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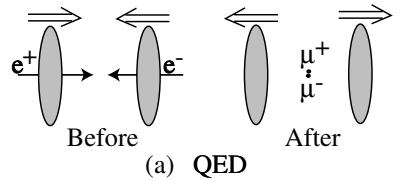

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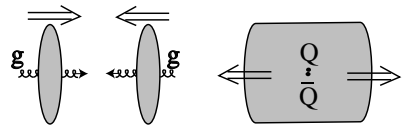

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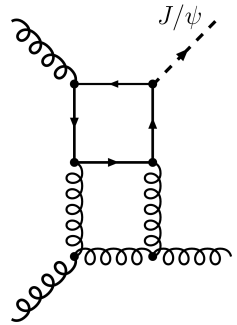

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✗ Only total cross-section prediction

✗ Correct p_T slope from an input

Review of some models in *pp* III

Color Octet Mechanism: physical states can be produced by coloured pairs

Bodwin, Braaten, Lepage, Cho, Leibovich,...

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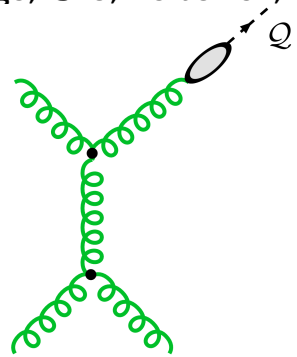

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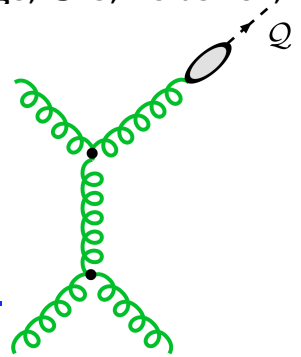

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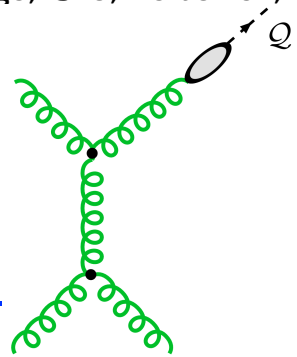

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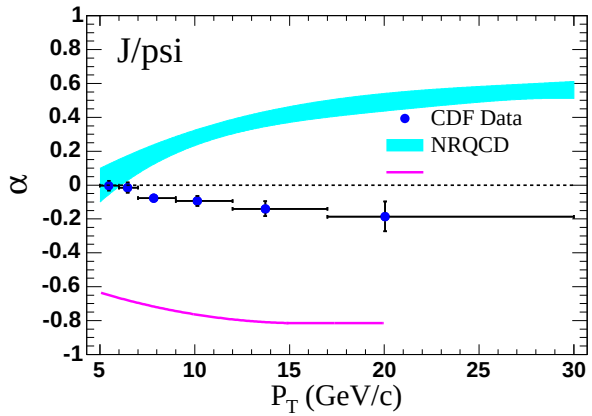
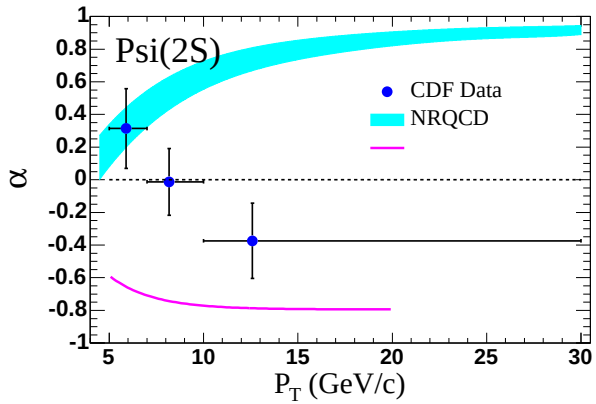
✗ Experimentally, **this is clearly contradicted !**

$\alpha = +1 \Leftrightarrow$ Transverse $\alpha = 0 \Leftrightarrow$ Unpolarised $\alpha = -1 \Leftrightarrow$ Longitudinal





CDF, PRL 99: 132001, 2007

For completeness

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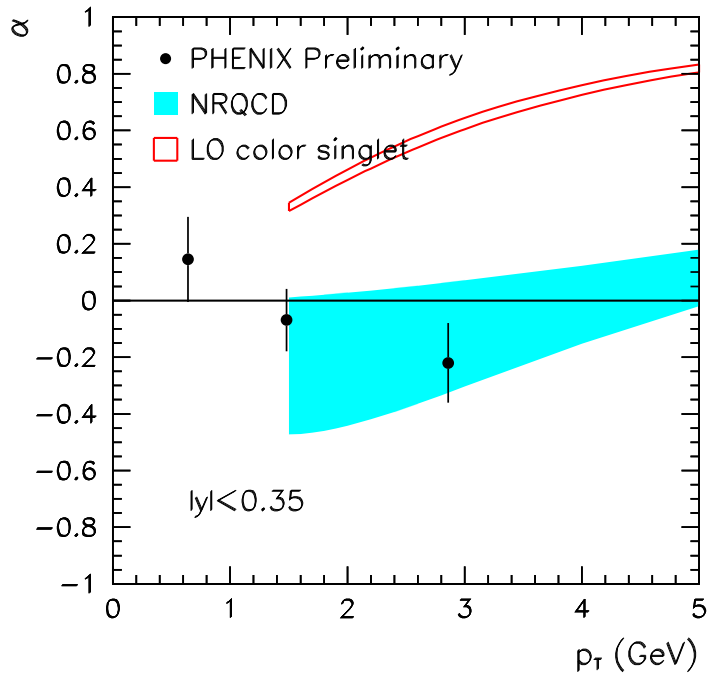

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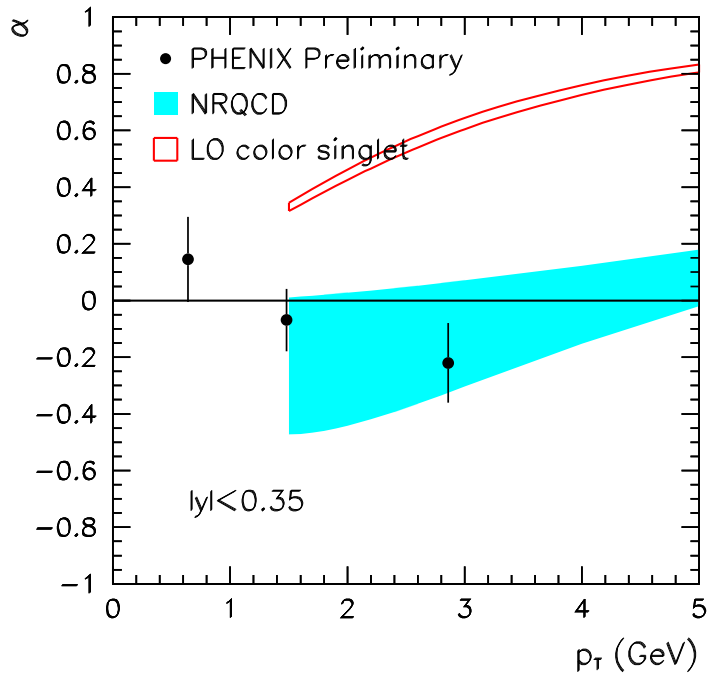

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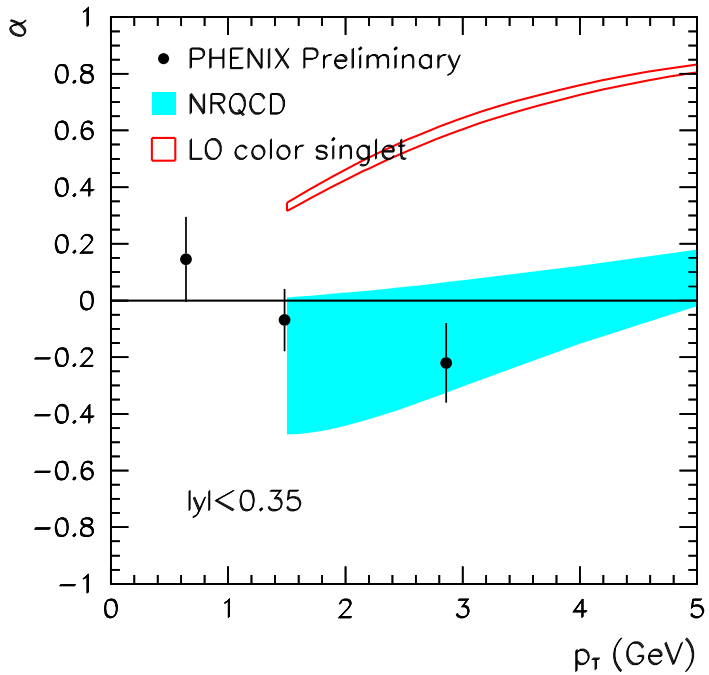

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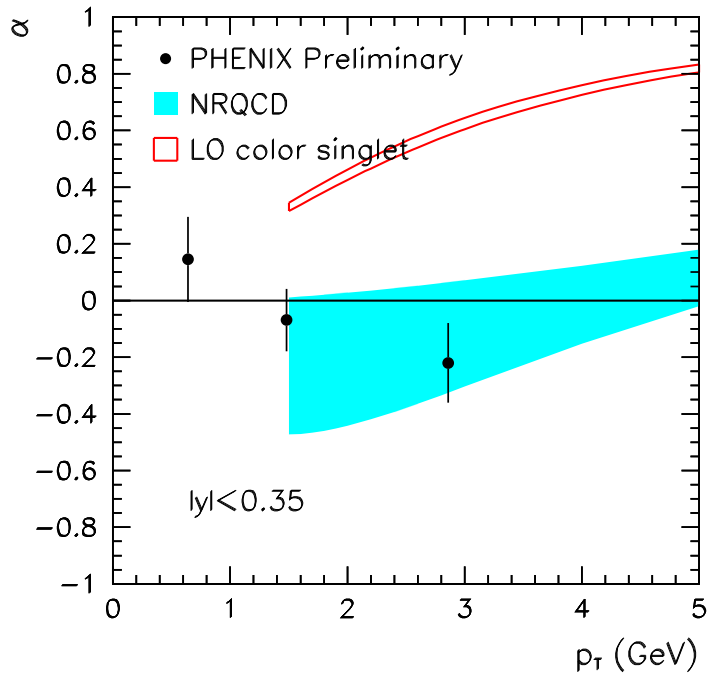

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- As soon as P_T increases, ${}^3S_1^{[8]}$ transitions dominate and CO polarisation becomes transverse

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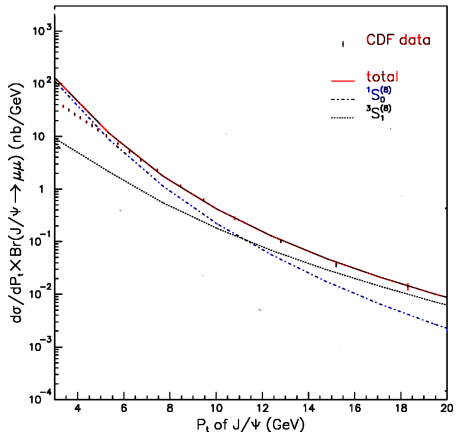

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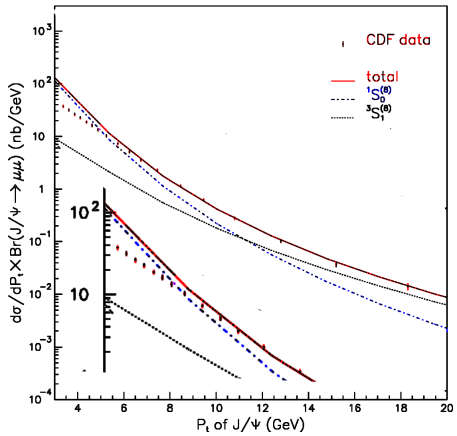

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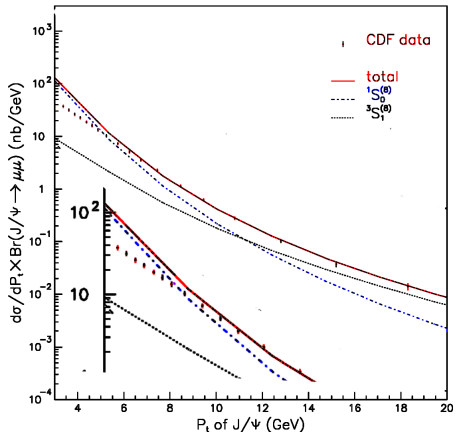

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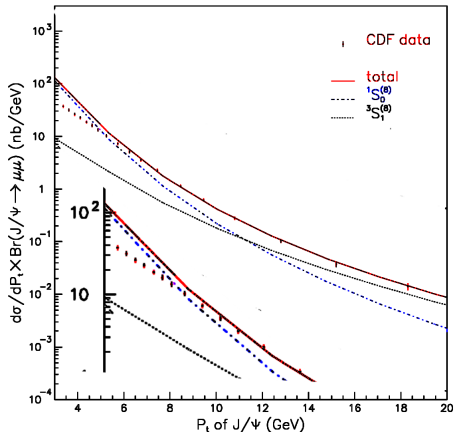

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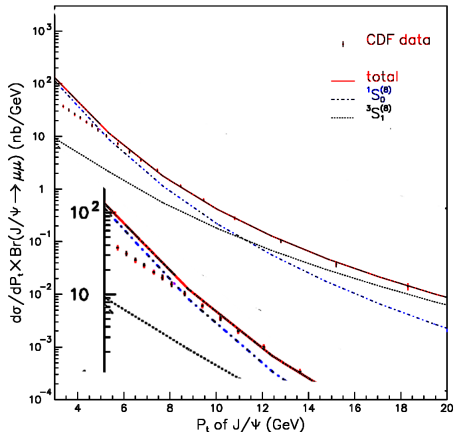

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Part II

Present: QCD corrections

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$J/\psi + c\bar{c}$: **P.Artoisenet, J.P.L, F.Maltoni, PLB 653:60,2007**
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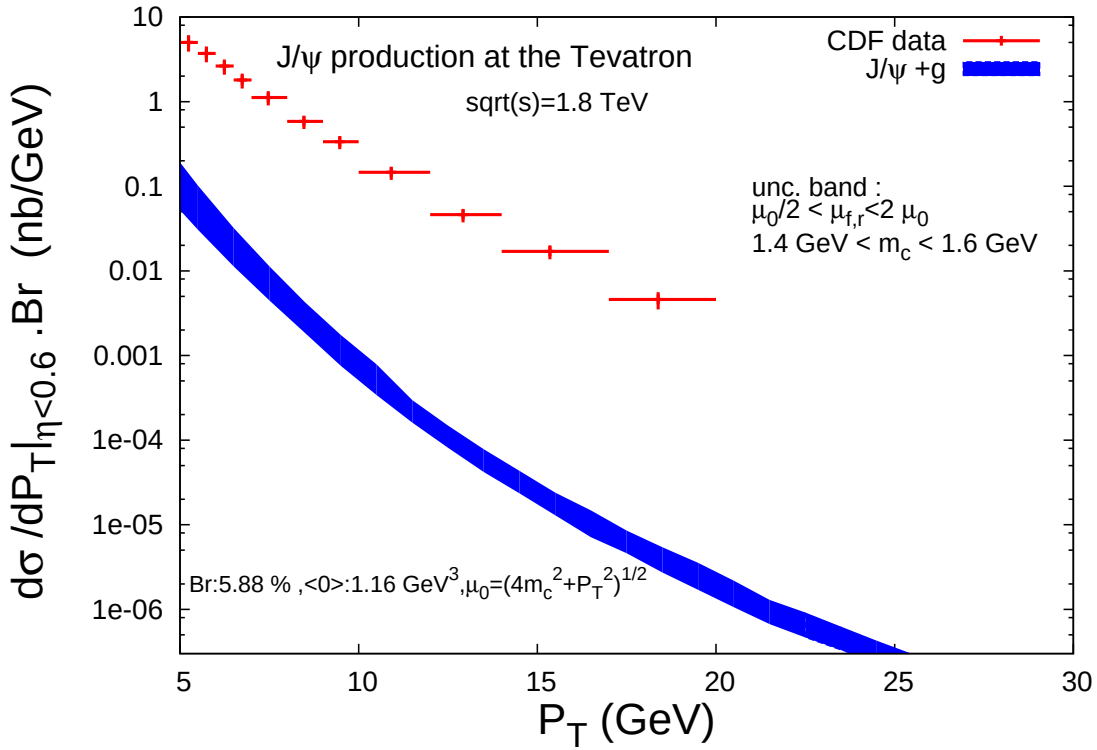

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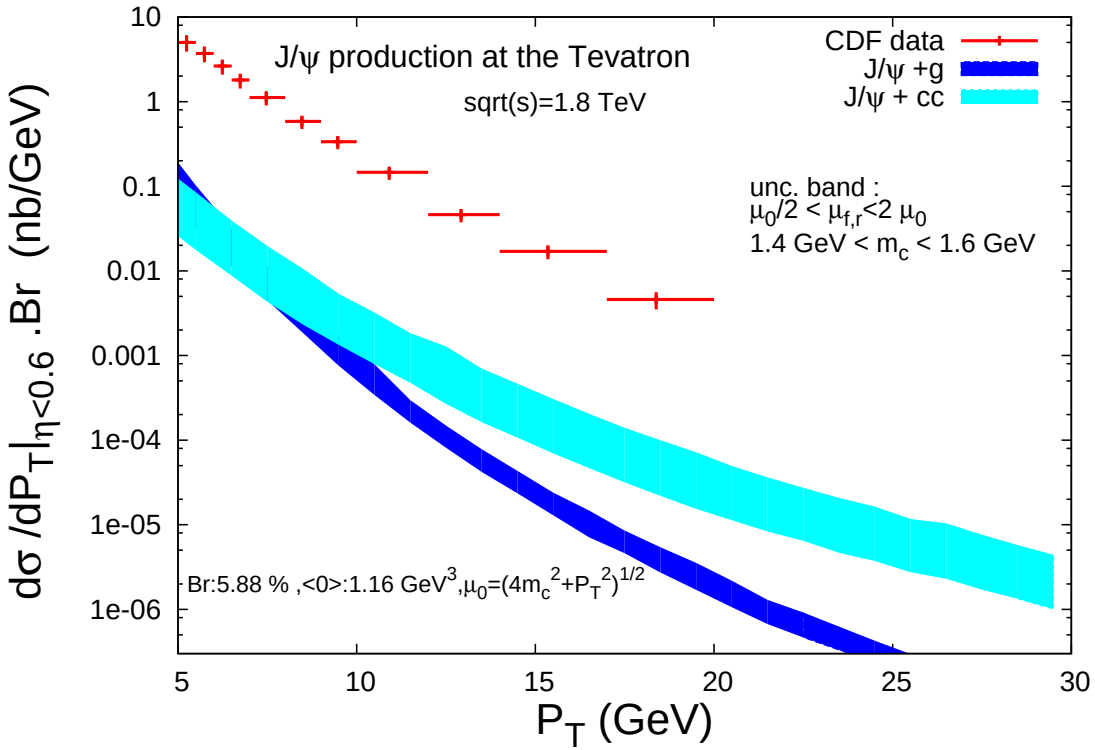

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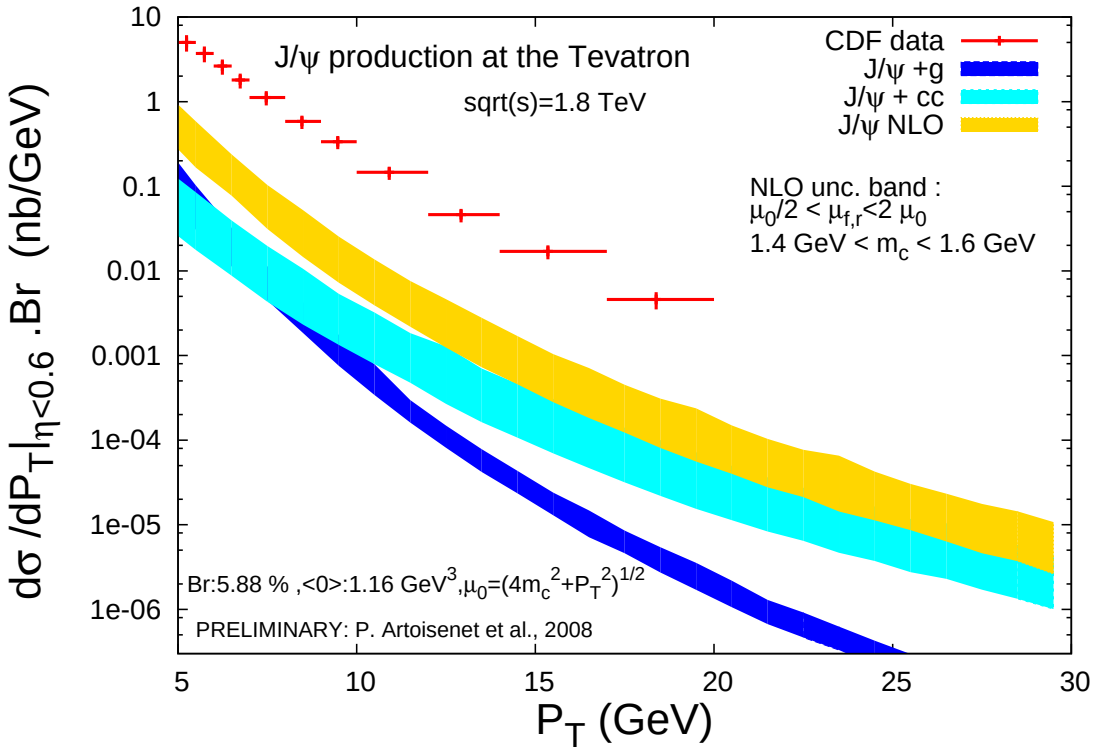
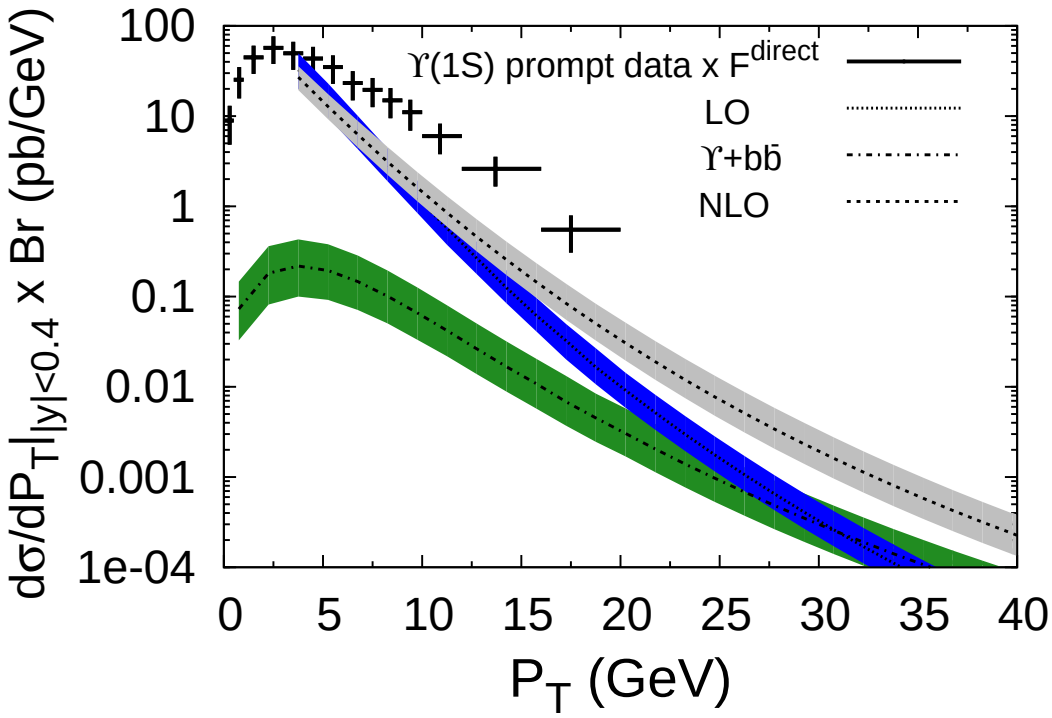


- Significant improvement, but we need something more...
- Confirmed by B. Gong and J.X. Wang who computed the polarisation as well
  Phys. Rev. Lett. 100, 232001 (2008)

What about for the Υ ?

QCD corrections: α_S^4 (NLO) for Υ

$\Upsilon + c\bar{c}$: **P.Artoisenet, J.P.L, F.Maltoni, PLB 653:60,2007**
NLO (e.g.$\Upsilon + gg$)**: J.Campbell, F. Maltoni, F. Tramontano, Phys.Rev.Lett. 98:252002,2007**



Close to an agreement with data

Can we do better ?

NLO QCD corrections to the Colour Octet Mechanism

B. Gong, X. Q. Li, J.-X. Wang, PLB 673:197,2009.

- NLO corrections to COM channels have tiny effects on $d\sigma/dP_t$ at large P_T and α

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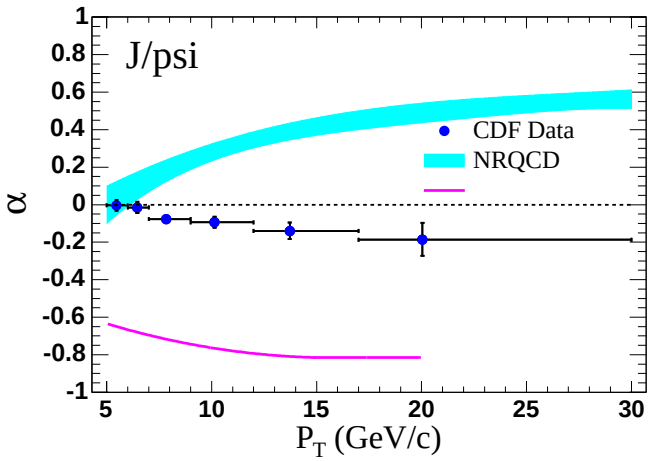

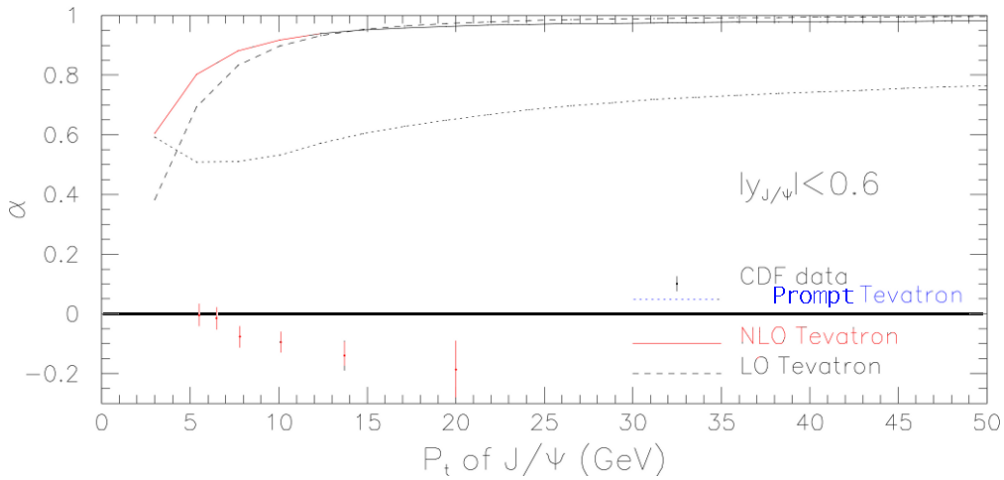

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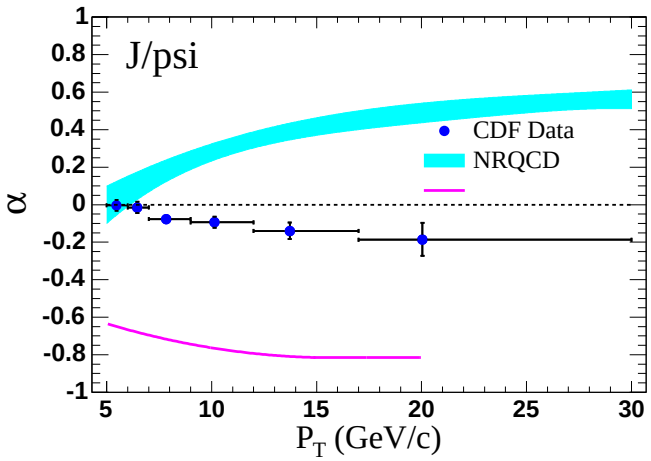

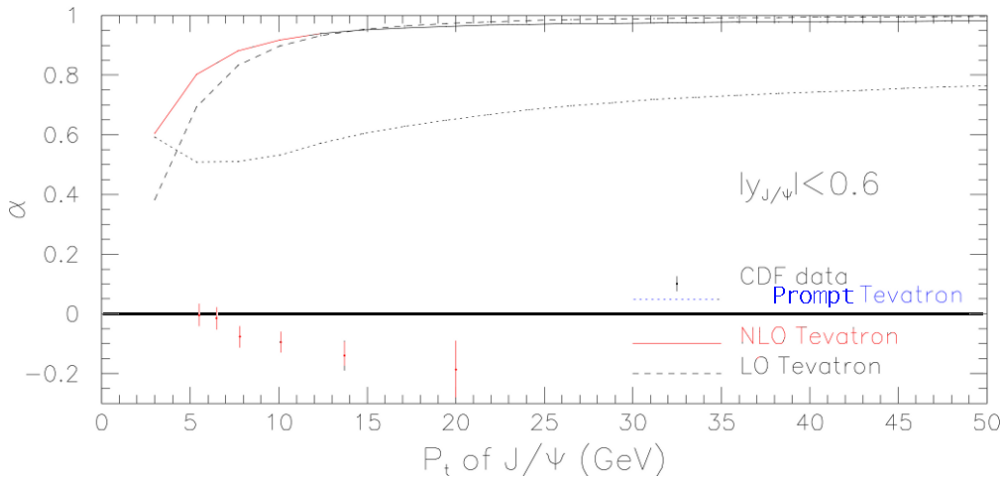

- Confirmation that COM cannot describe the polarisation
- We definitely need something else !

α_s^5 corrections contributions: NNLO*

MadOnia (based on Madgraph): P.Artoisenet, F. Maltoni, T. Stelzer, JHEP 0802:102,2008.

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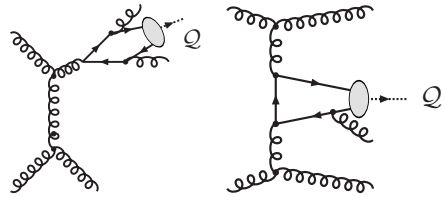

Let's see ...

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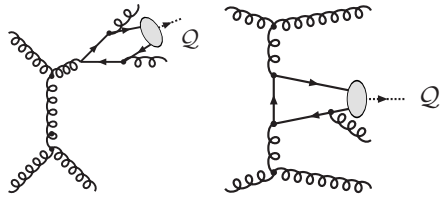

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*MadOnia: Automatic generation of tree-level quarkonium amplitudes

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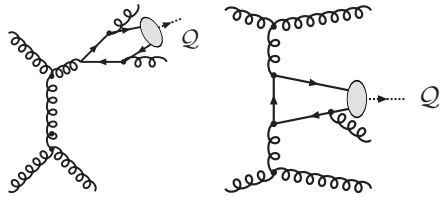

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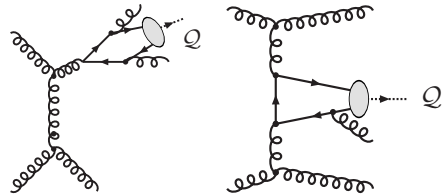

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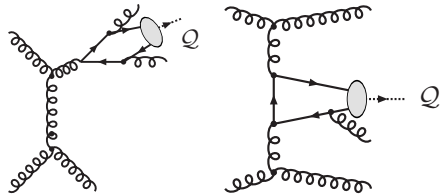

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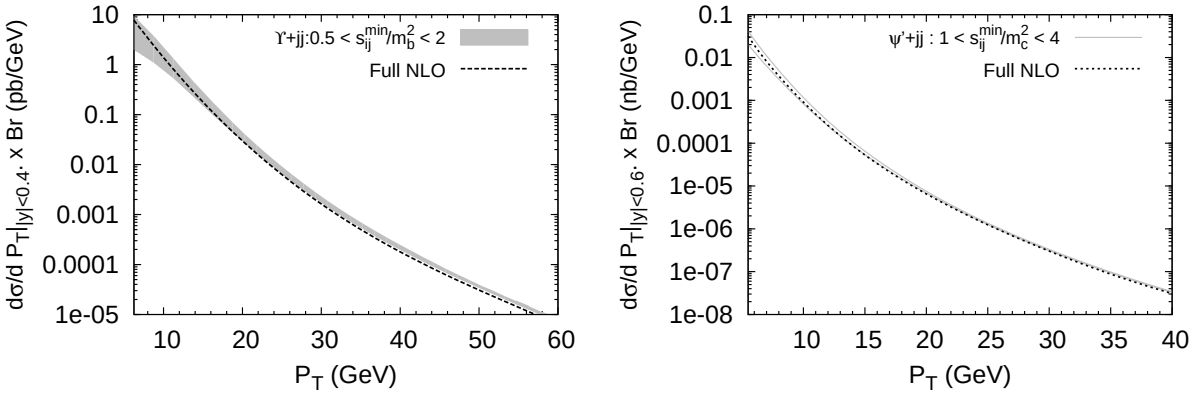

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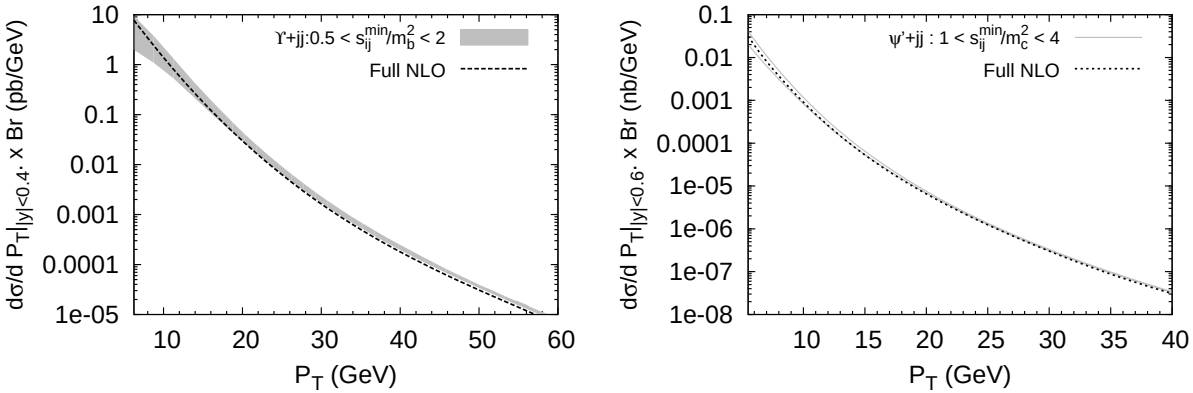

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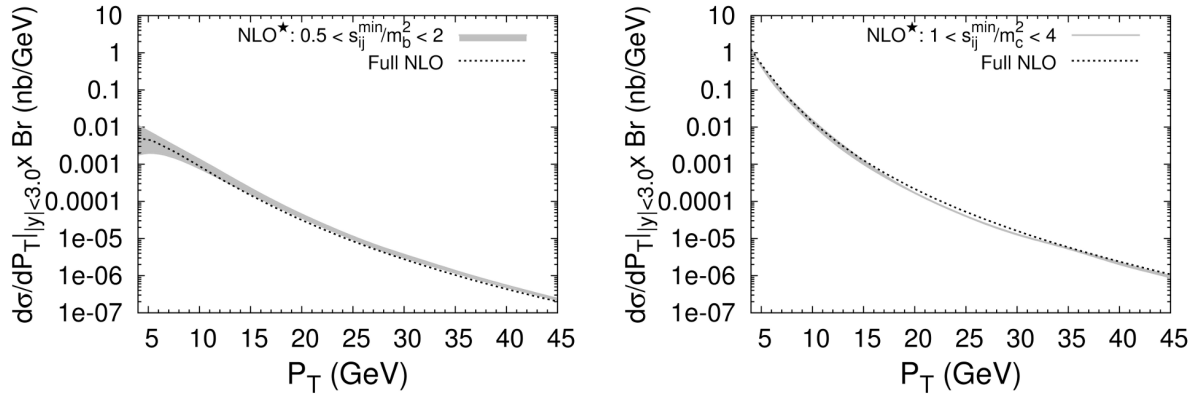

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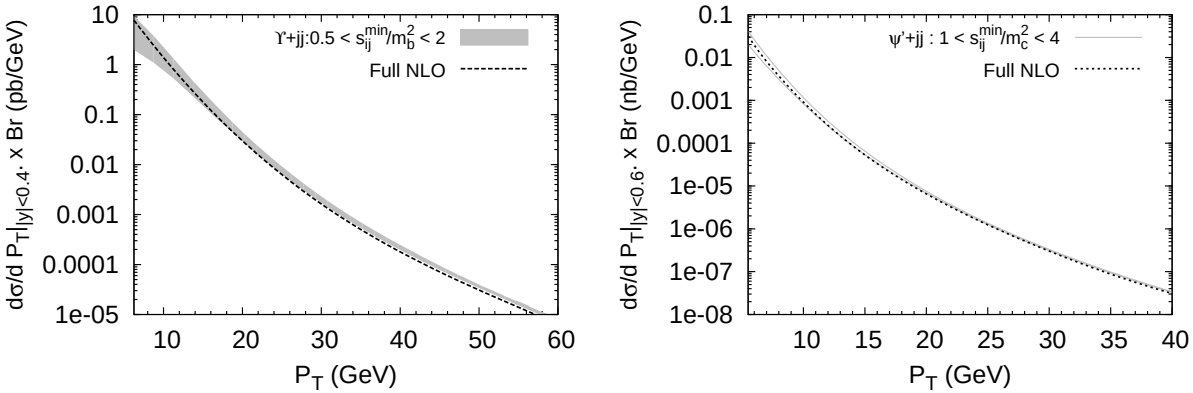

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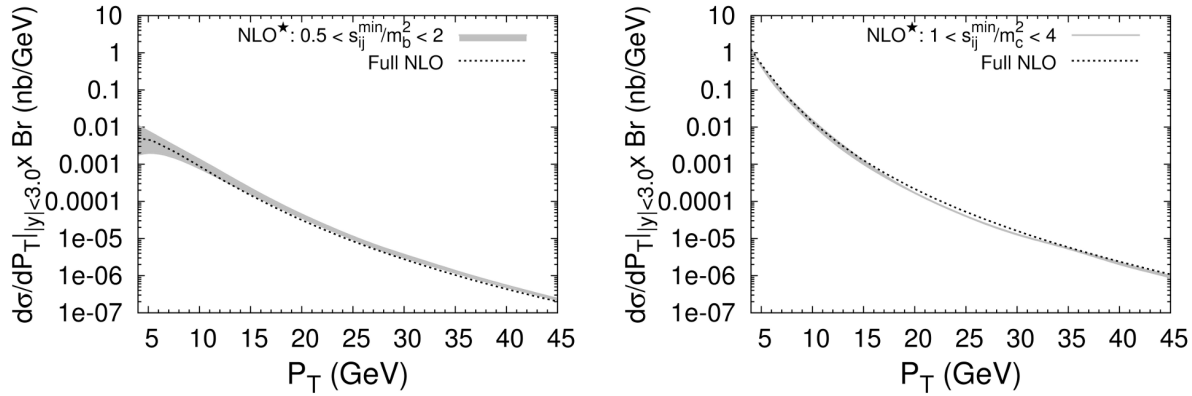

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➞ $p\bar{p} \to \mathcal{Q}jjj$ $(j = g, u, d, s, c)$ with cuts:

first estimate of the impact of NNLO contributions (α_s^5)

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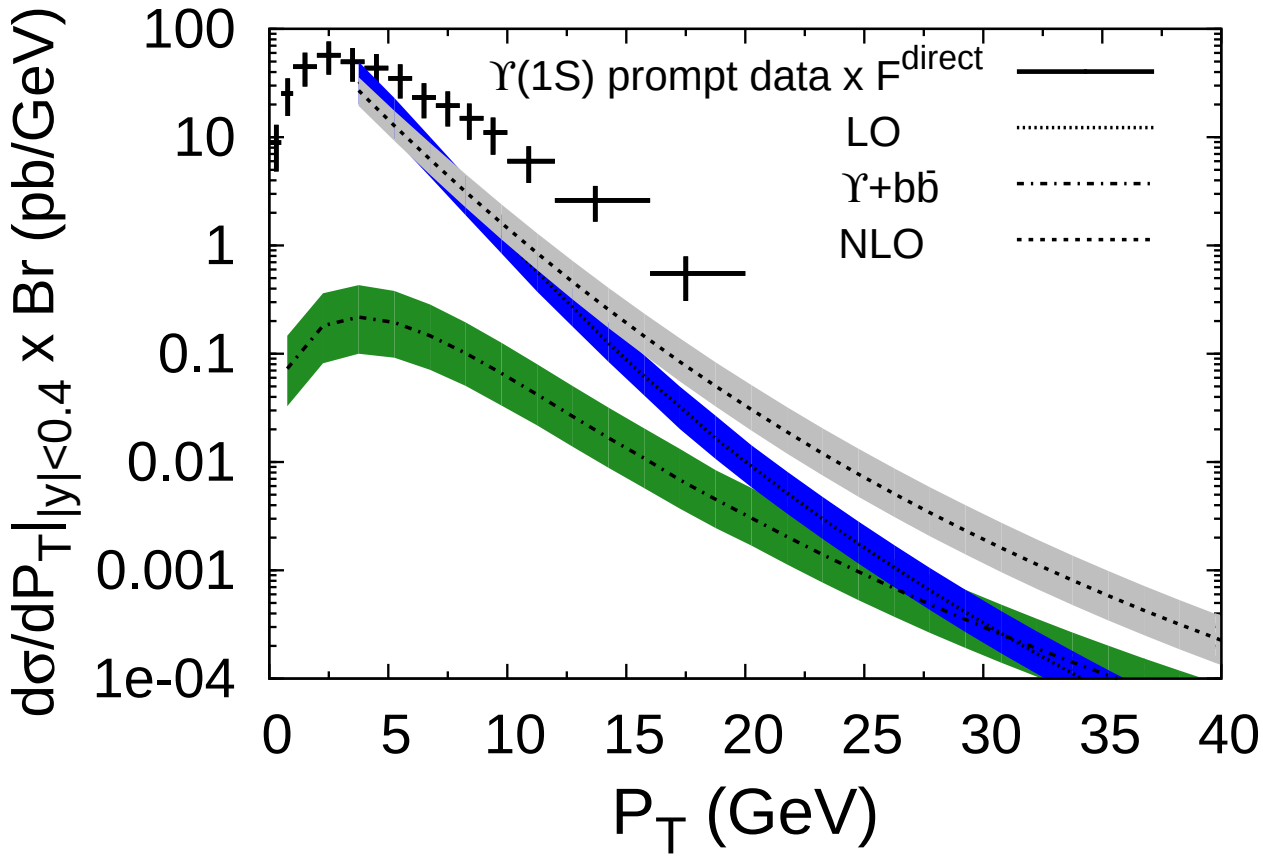

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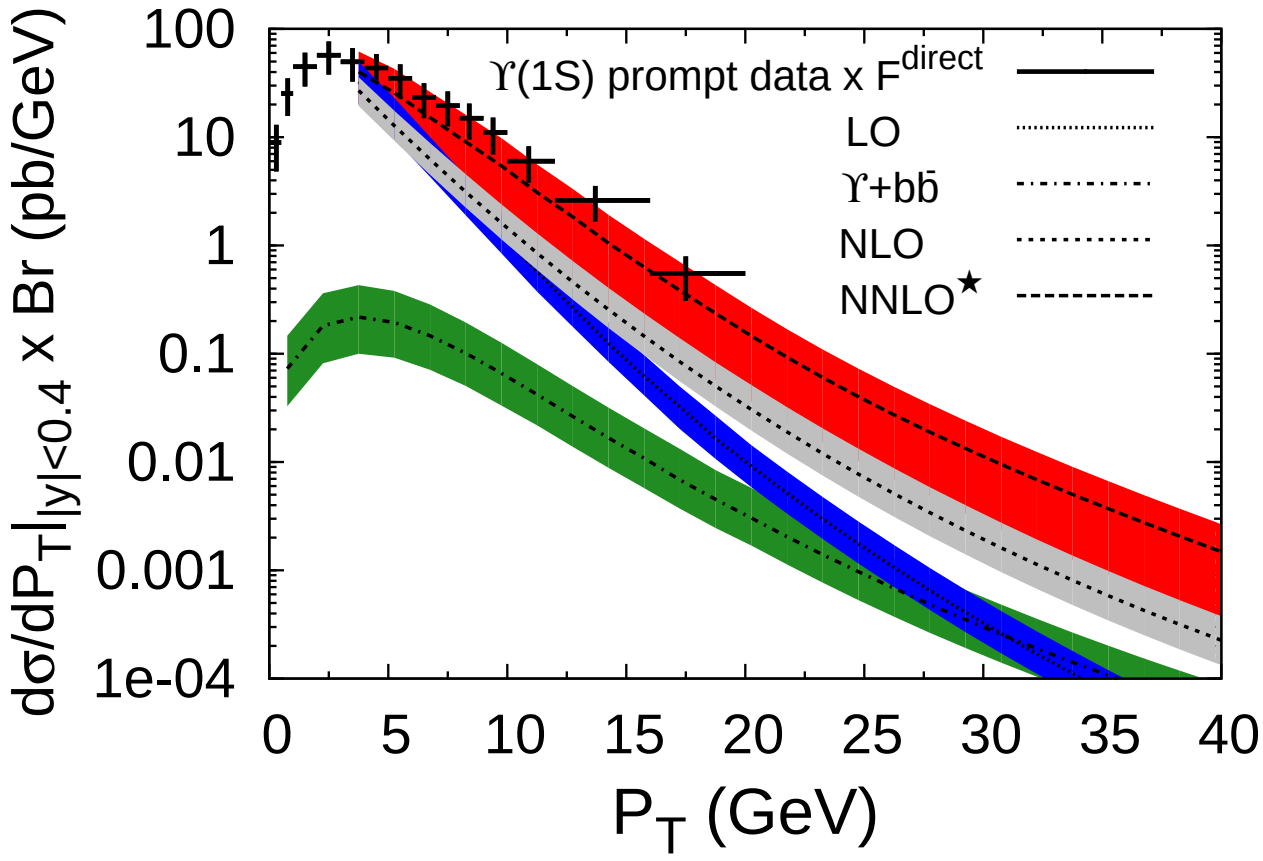

✔ Exactly what is needed in normalisation and shape !

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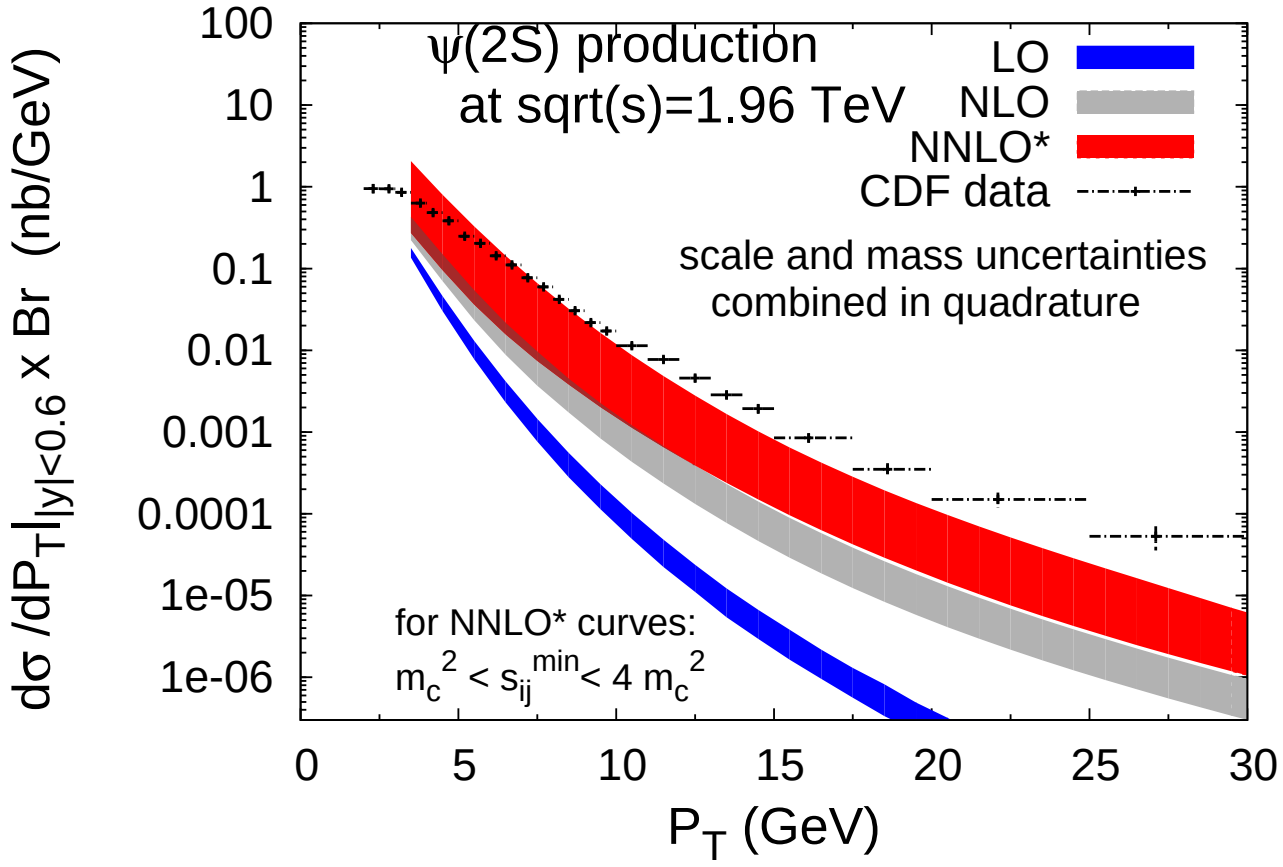
JPL, EPJC 61:693,2009.



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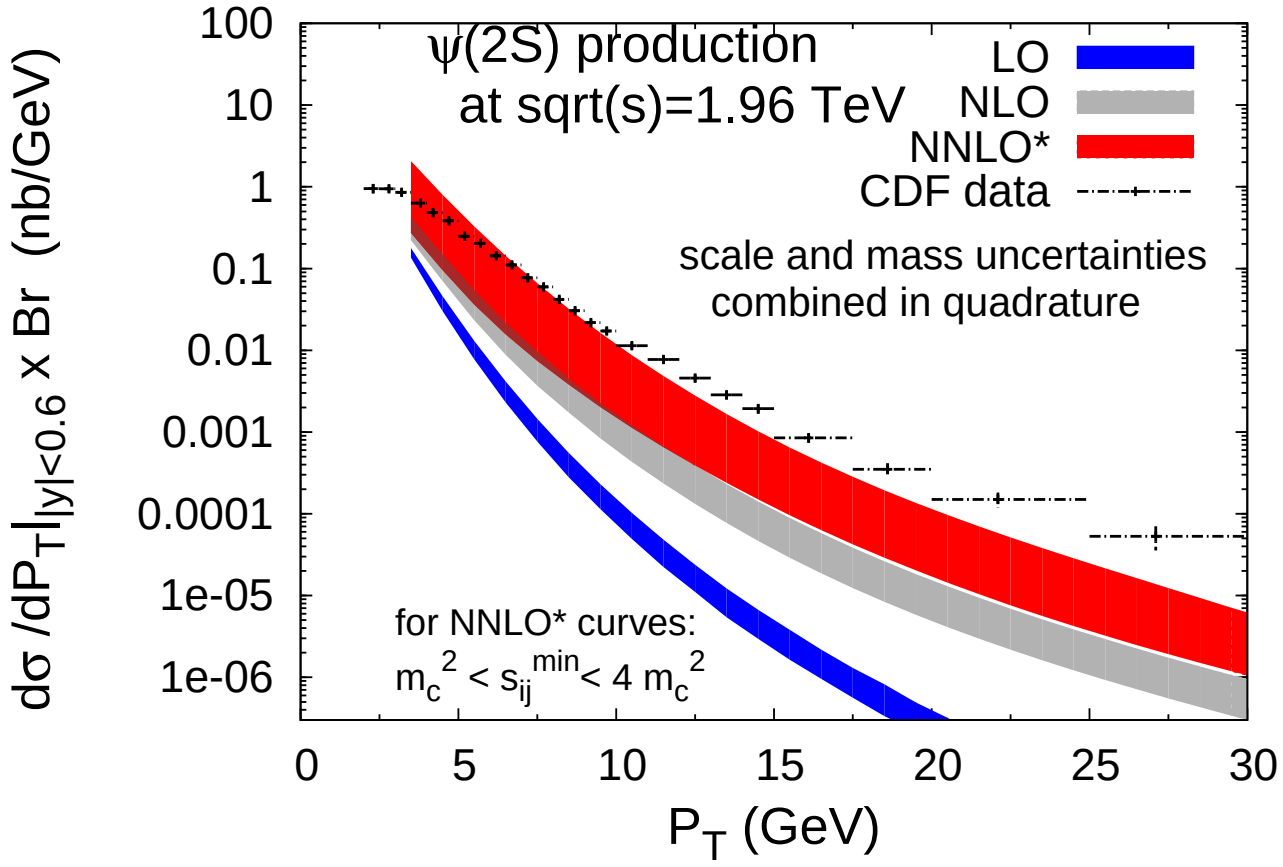

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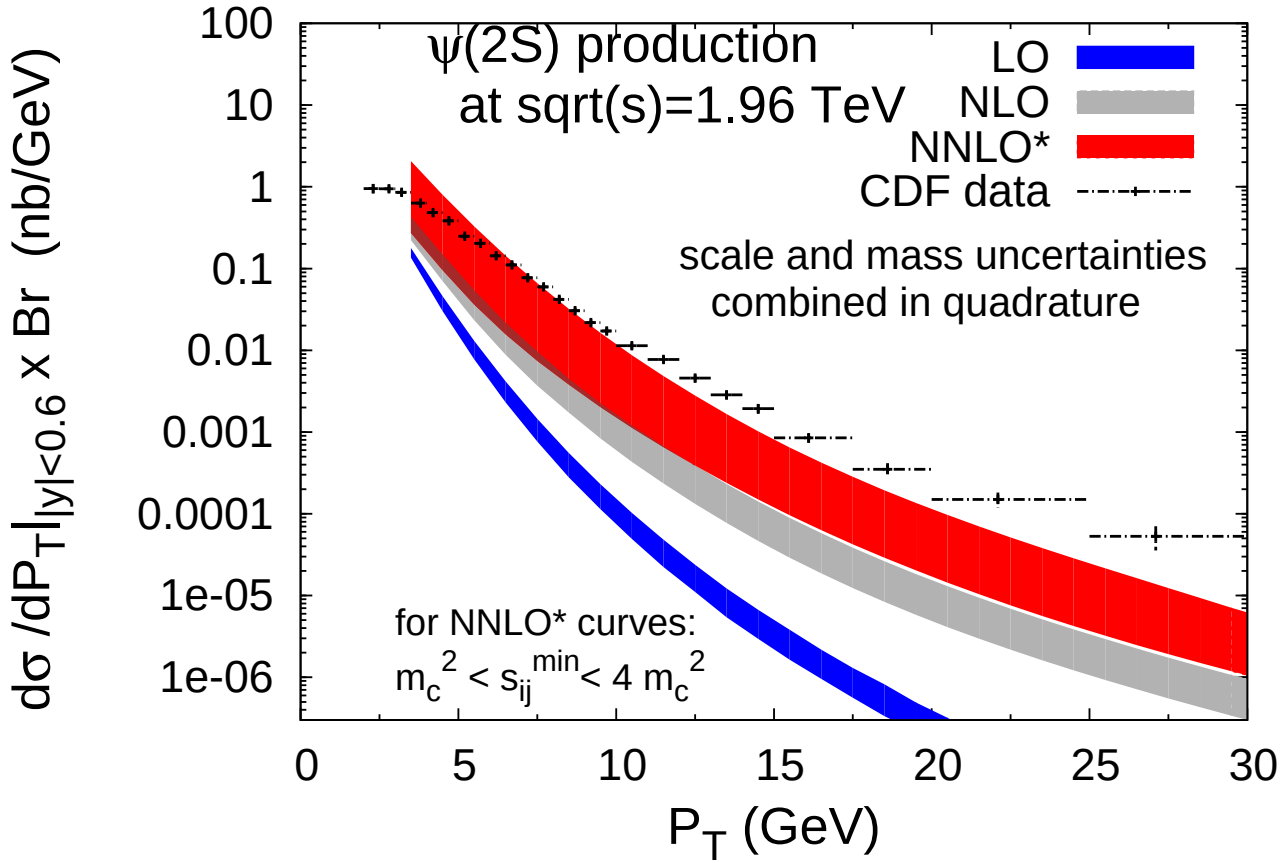

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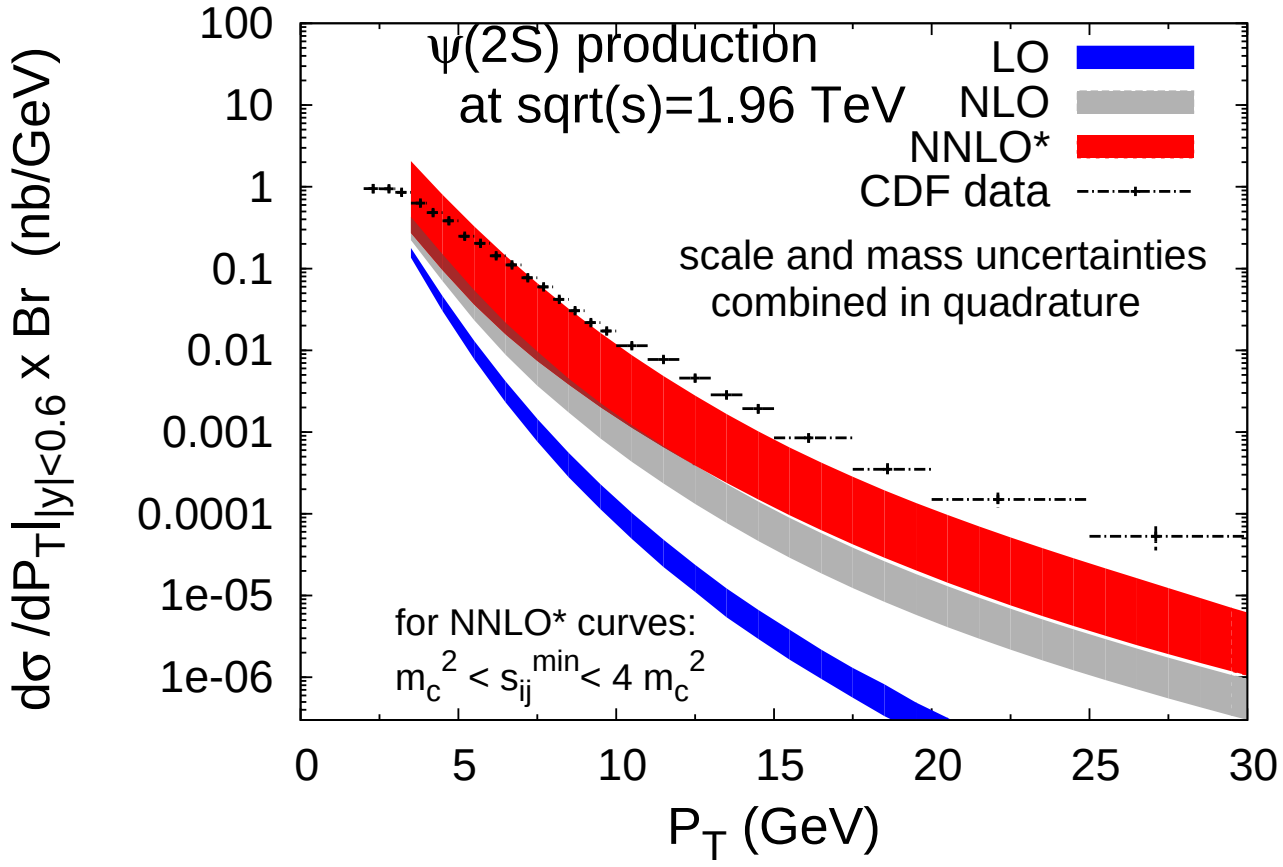

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✗ Very large uncertainty attached to the choice of μ_r

Υ and J/ψ polarisation in hadroproduction at $\mathcal{O}(\alpha_S^5)$

P.Artoisenet, J.Campbell, JPL, F.Maltoni, F. Tramontano, Phys. Rev. Lett. 101, 152001 (2008)
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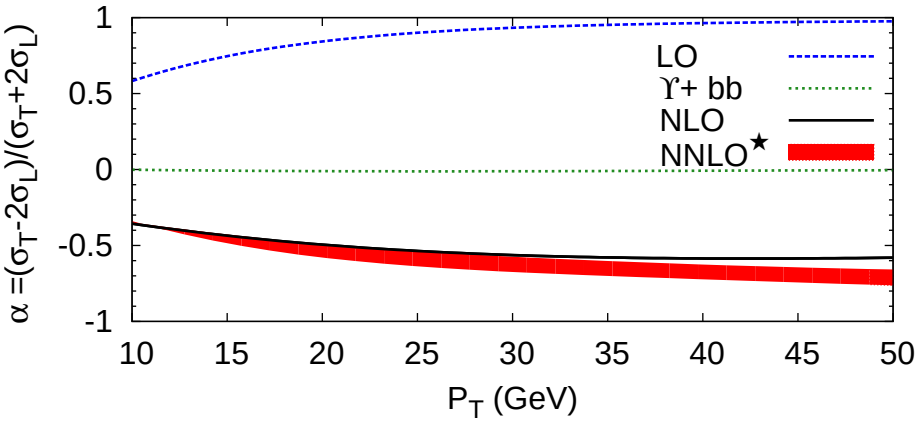

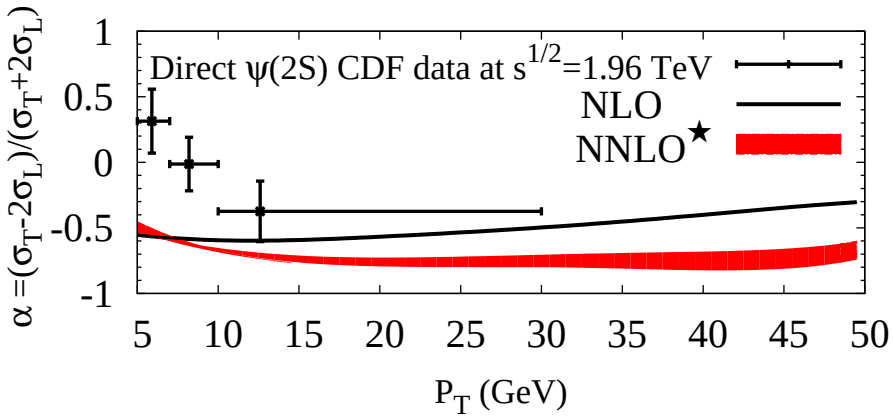

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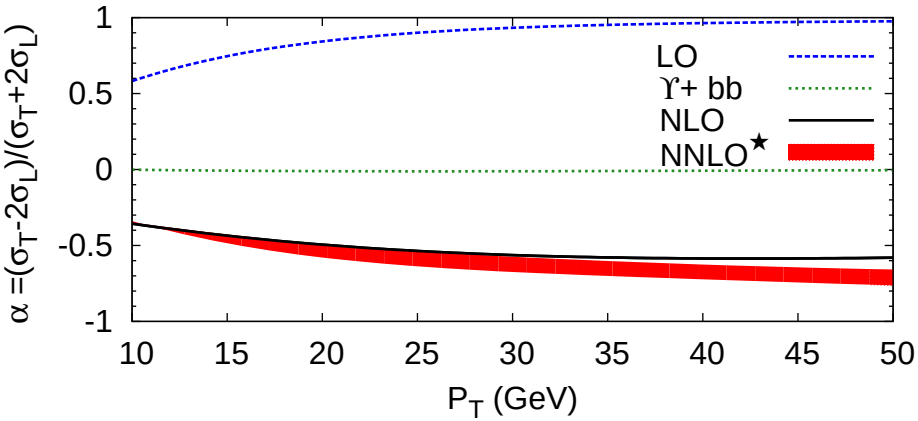

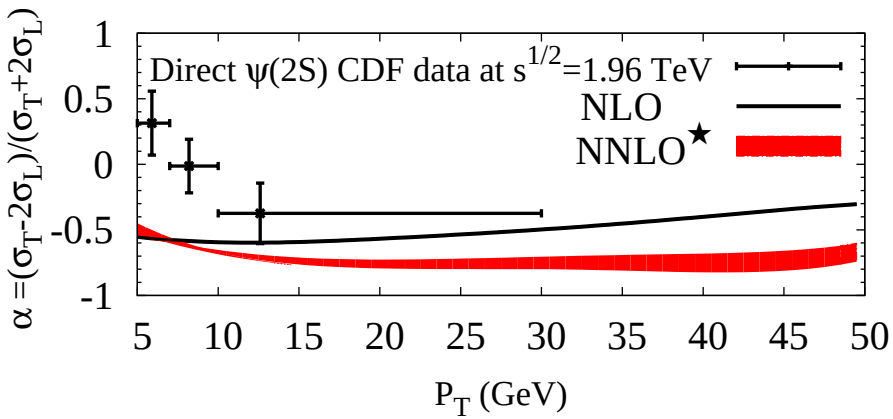

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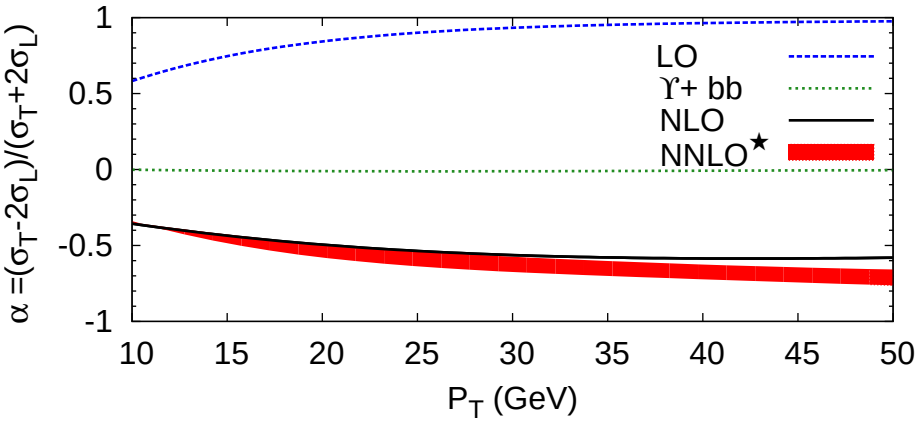

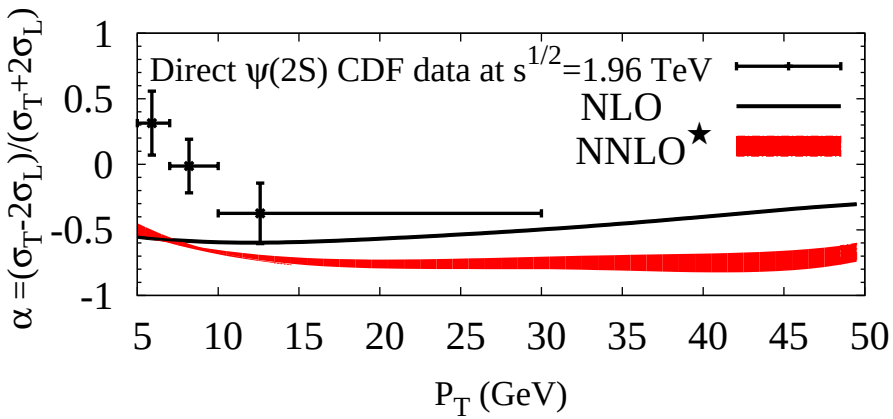

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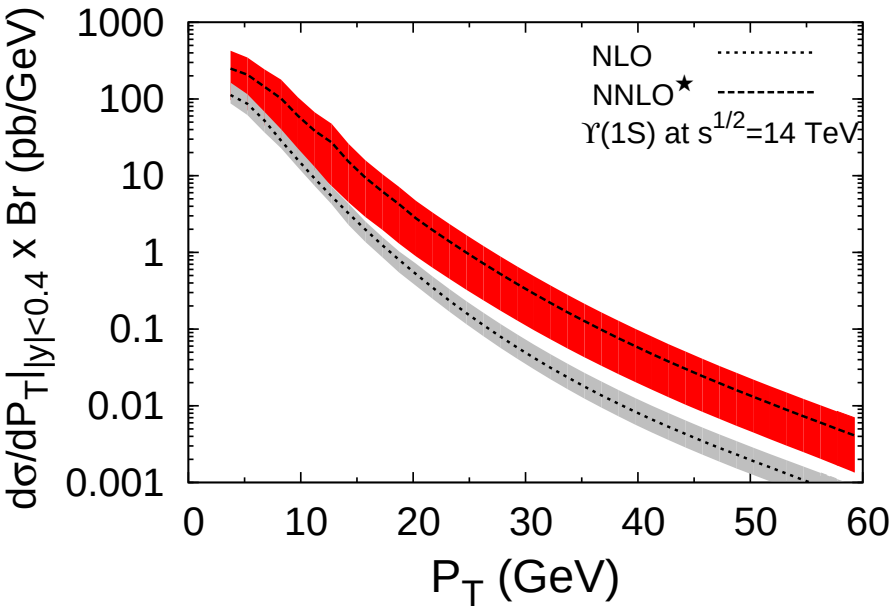

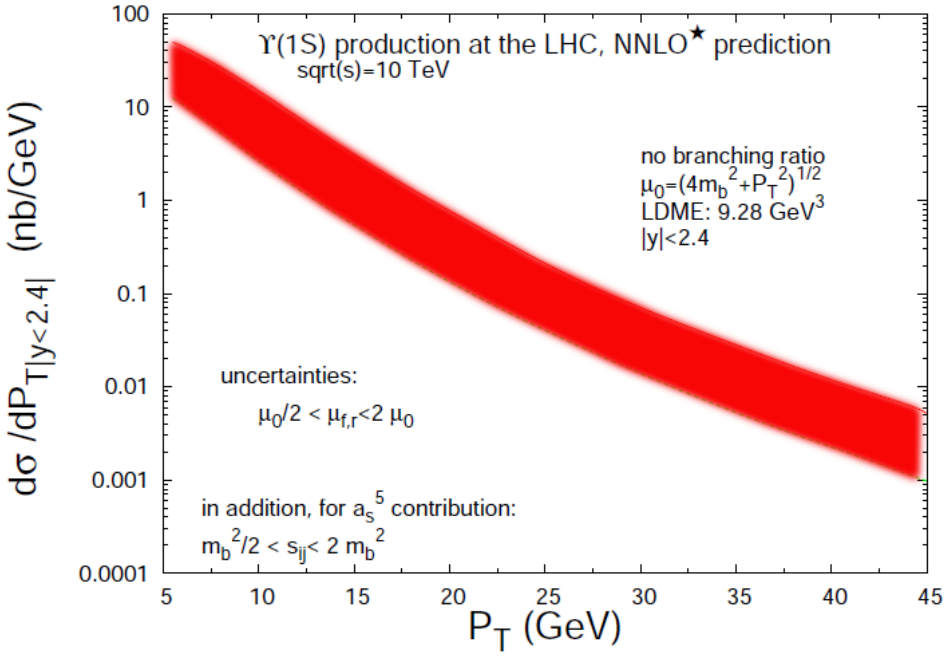

J/ψ cross section at the LHC

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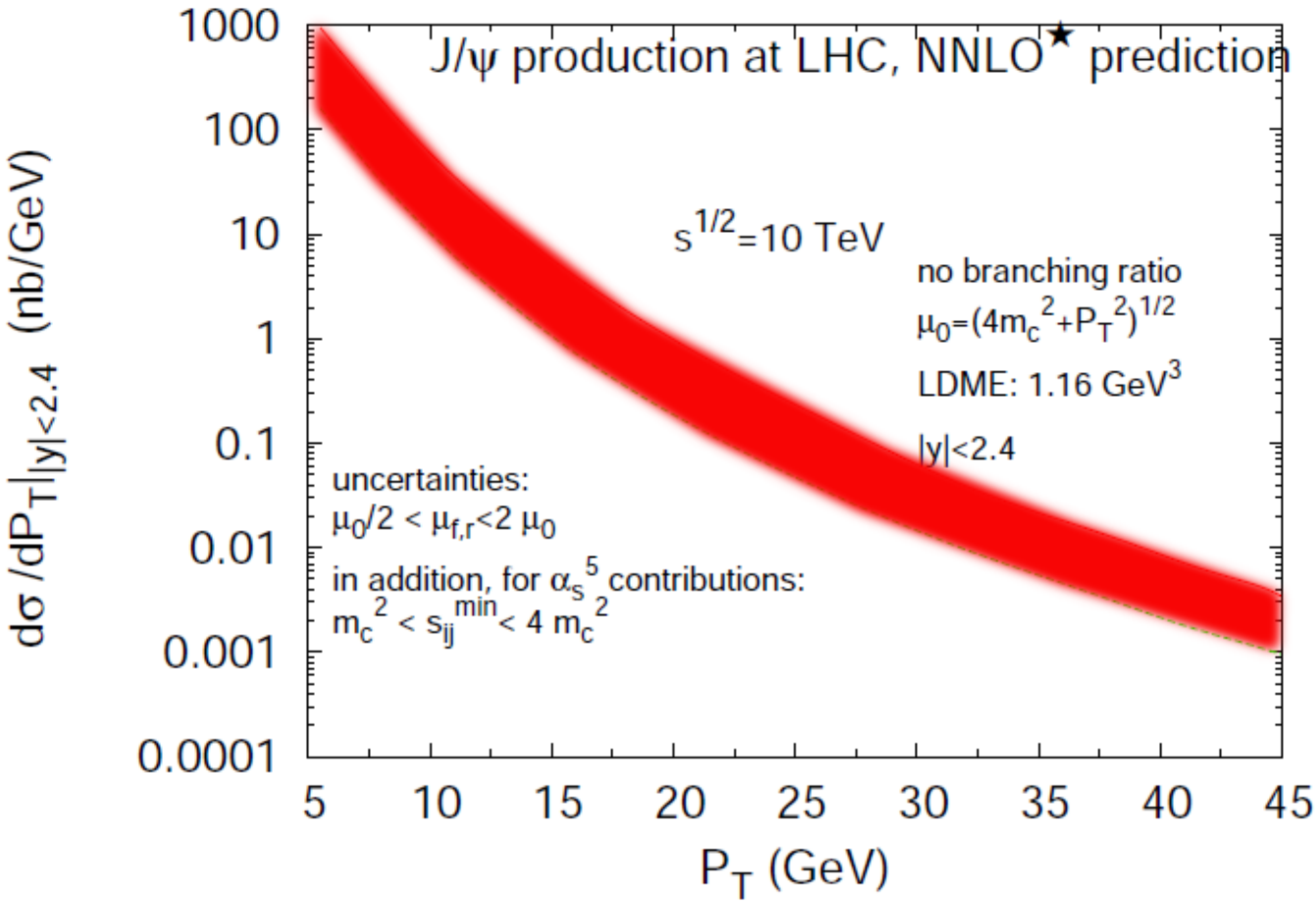

Part III

Perspectives for the future

New observable: $\mathcal{Q} + Q\bar{Q}$

➥ Double charm/beauty HADRO-production should show large rates
let us see how it can be a new valuable observable

P.Artoisenet, J.P.L, F.Maltoni, PLB 653:60,2007; S.P. Baranov PRD73:074021,2006.

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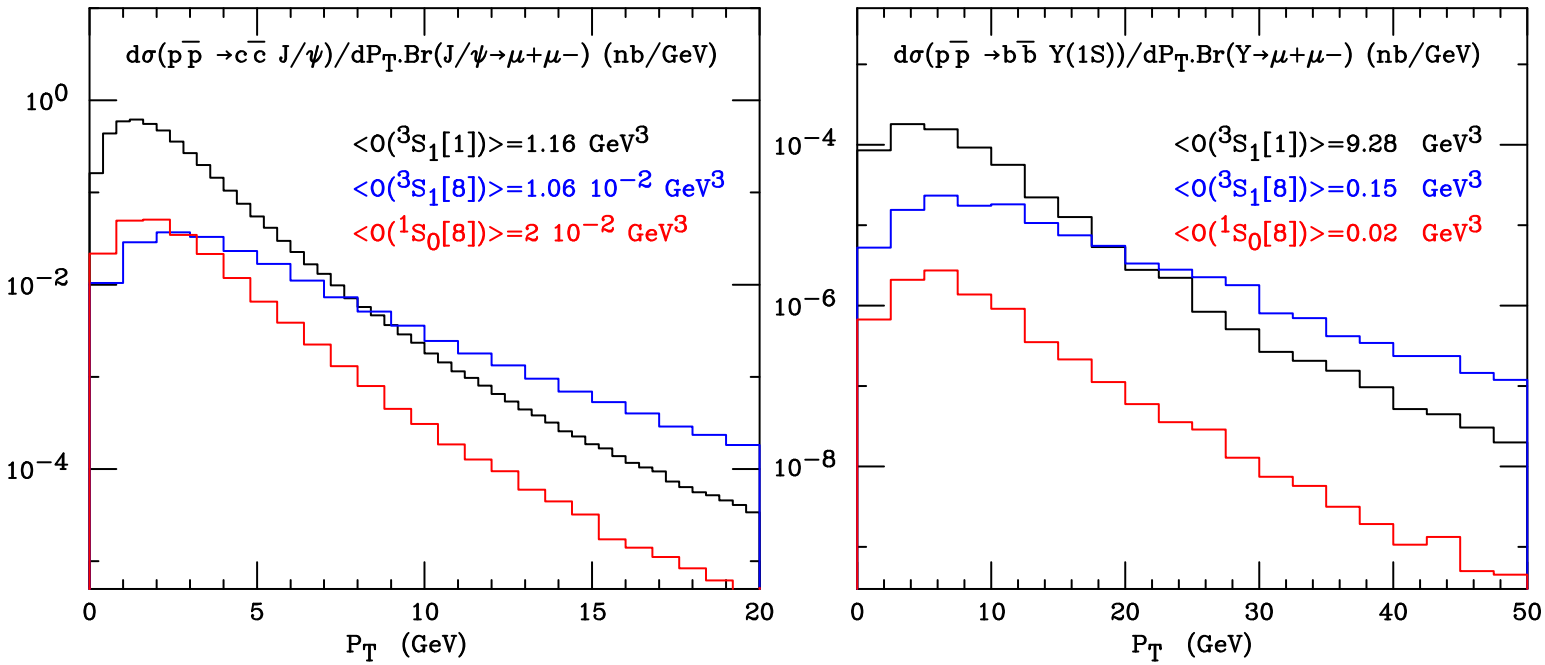
- ➞ NRQCD factorisation ? Colour transfer mechanism ?

G.Nayak, J.W Qiu, G.Sterman,PRL99:212001,2007, PRD 77:034022,2008.

$\mathcal{Q} + Q\bar{Q}$: CSM vs. COM (at the LHC)

P.Artoisenet, J.P.L, F.Maltoni, PLB 653:60,2007; P.Artoisenet, arXiv:0804.2975

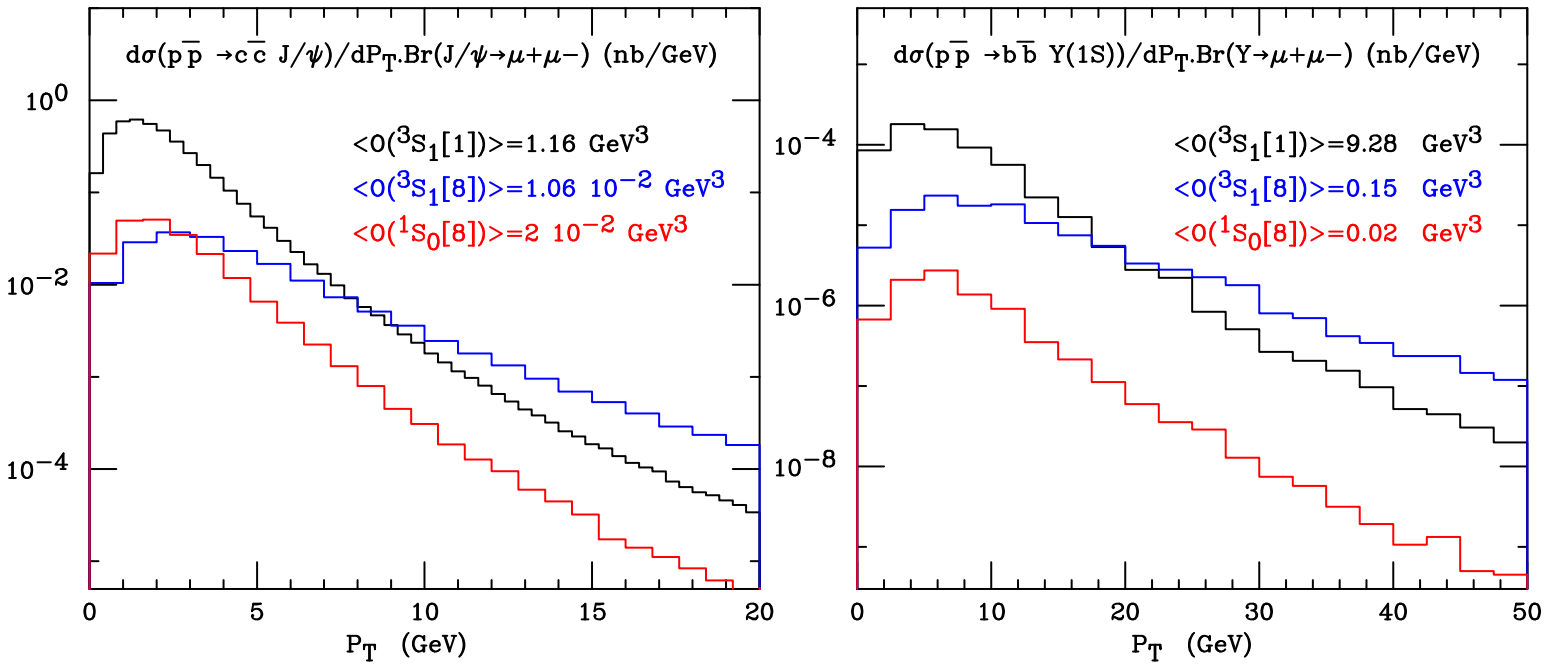


If we ignore changes in the fits of COM matrix elements due to QCD corrections:

- CSM contributions dominate at low P_T
- COM contributions (may) dominate from $P_T \geq 15$ GeV

$\mathcal{Q} + Q\bar{Q}$: CSM vs. COM (at the LHC)

P.Artoisenet, J.P.L, F.Maltoni, PLB 653:60,2007; P.Artoisenet, arXiv:0804.2975

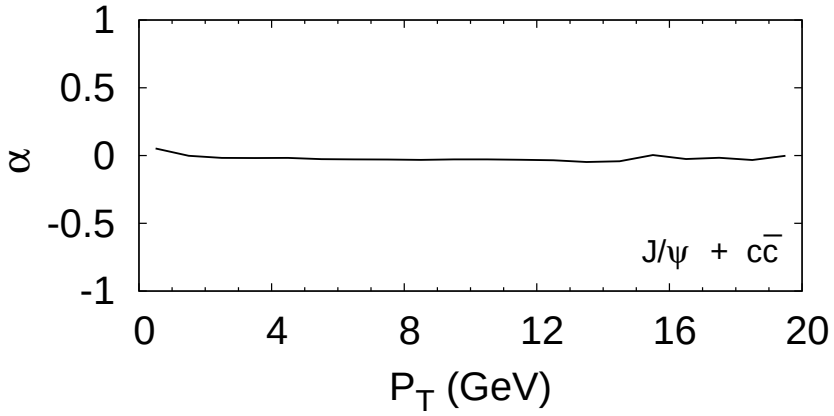


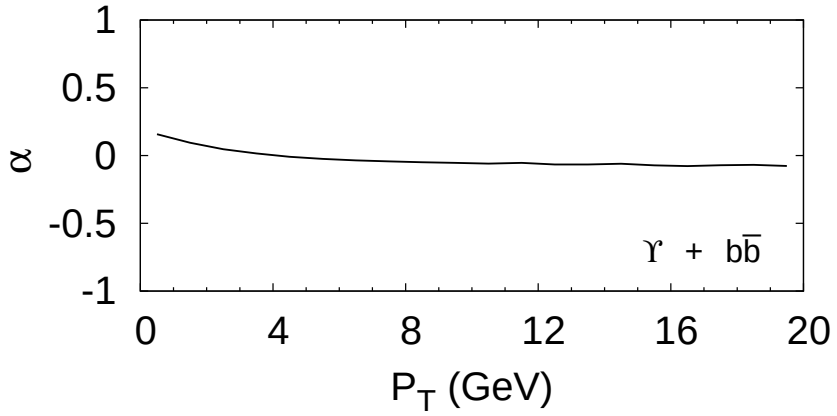
If we ignore changes in the fits of COM matrix elements due to QCD corrections:

- CSM contributions dominate at low P_T
- COM contributions (may) dominate from $P_T \geq 15$ GeV
- Integrated cross section largely dominated by CSM contributions
- Can rely on CSM predictions for α for $P_T \leq 15$ GeV

$\mathcal{Q} + Q\bar{Q}$: polarisation

P.Artoisenet, J.P.L, F.Maltoni, PLB 653:60,2007





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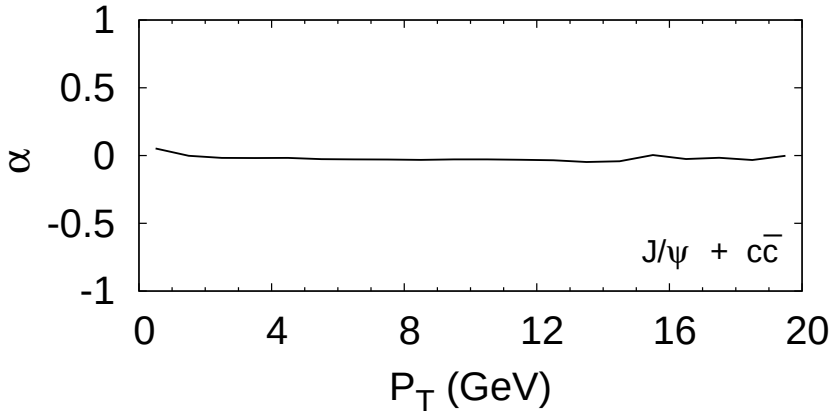
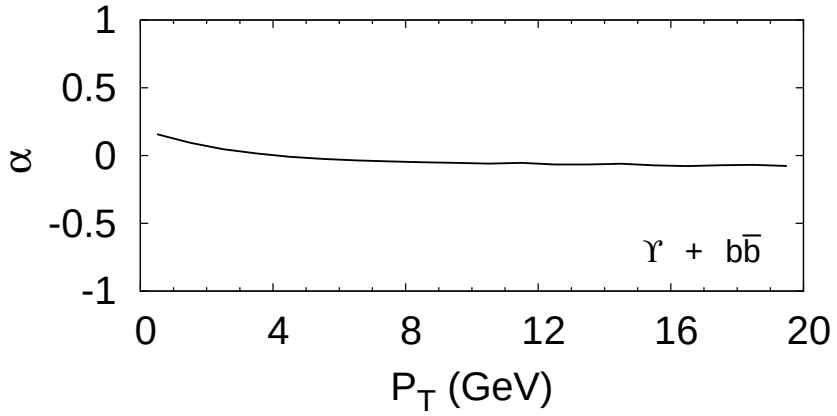
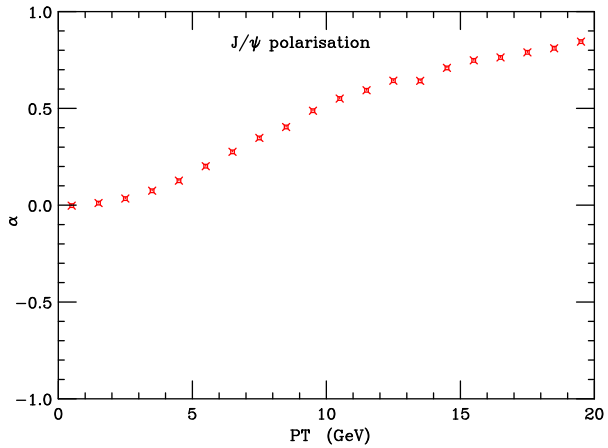




➯ $J/\psi + c\bar{c}$: polarisation with COM ("old" CO matrix elements)

P.Artoisenet, private communication



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

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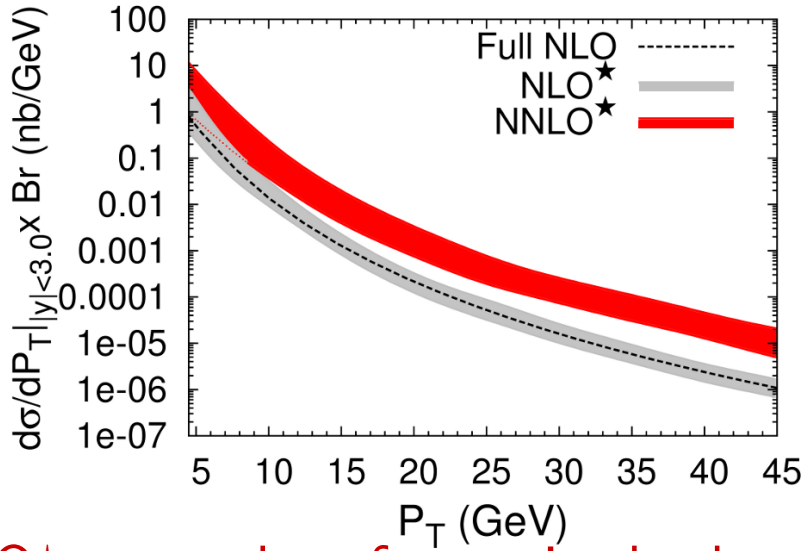
R.Li and J.X. Wang, PLB 672:51,2009

➪ But...



JPL, PLB 679:340,2009.

NNLO* one order of magnitude than NLO

↓

The yield will be dominated by the Color singlet transitions !

Once more, no kinematical enhancements for CO

Part IV

Conclusions and Outlooks

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- Yet, the LO (and NLO) CSM reproduces the yield:
  relevant for heavy-ion studies !
- No totally satisfactory solution for $d\sigma/dP_T$
- Colour Octet Mechanism
  - (although) less predictive
  - contradicted by polarisation measurements at the Tevatron
  - Nearly no room for CO in $\gamma p \to J/\psi X$ and $e^+e^- \to J/\psi X$
  - NRQCD may be ok, but the dominance of COM seems not
- Off-shell effects via the s-channel cut may matter at small P_T
  needs to be updated . . .

Conclusions and Outlooks II

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  - Other proposals are welcome !

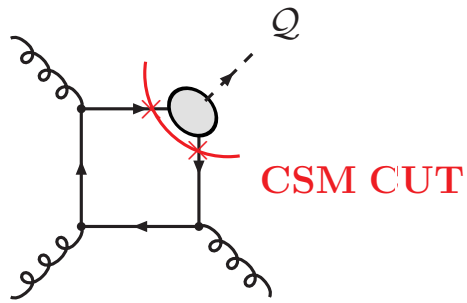
Part V

Backup slides

The s-channel cut contribution

➪ So far, one considered only such configurations

idem for NRQCD



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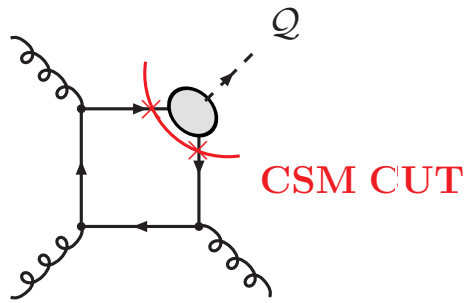

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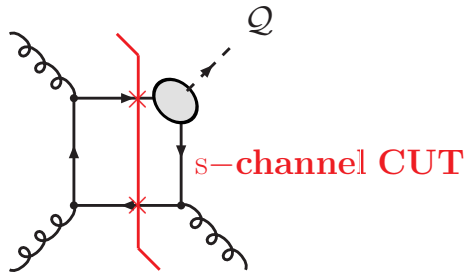
(*i.e.* the usual contributions to $Im(\mathcal{M})$)



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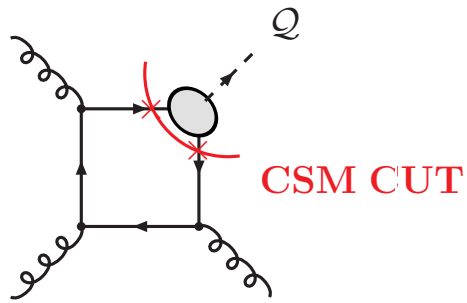

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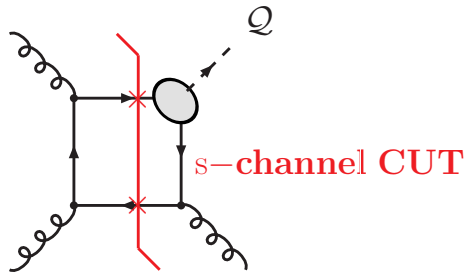

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➪ A bit challenging:

➞ Quark relative momentum not fixed to zero; 2 more integrals

➞ $c - \bar{c} - \mathcal{Q}$ vertex has one leg off-shell

Introduction of a 4-point function – the $c - \bar{c} - \mathcal{Q} - g$ coupling –

to preserve gauge-invariance

The s-channel cut contribution: first evaluation

H. Haberzettl, J.P.L, PRL 100,032006,2008

If the $c - \bar{c} - \mathcal{Q} - g$ coupling is constrained to satisfy:

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→ low energy limit,

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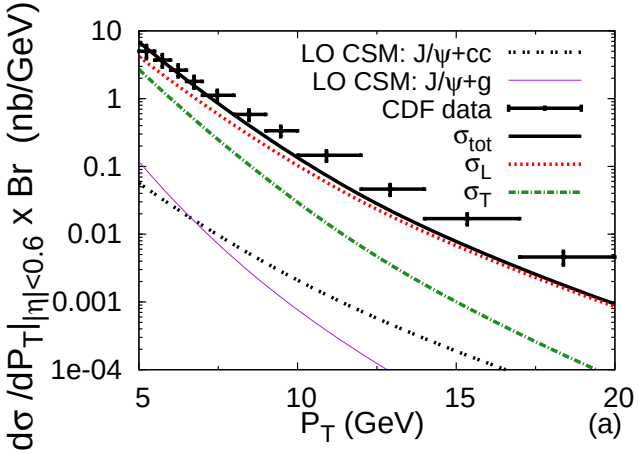

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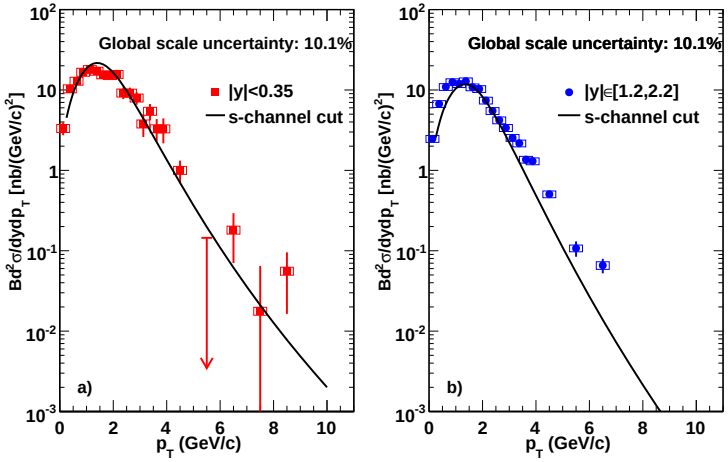

RHIC data are very well described !

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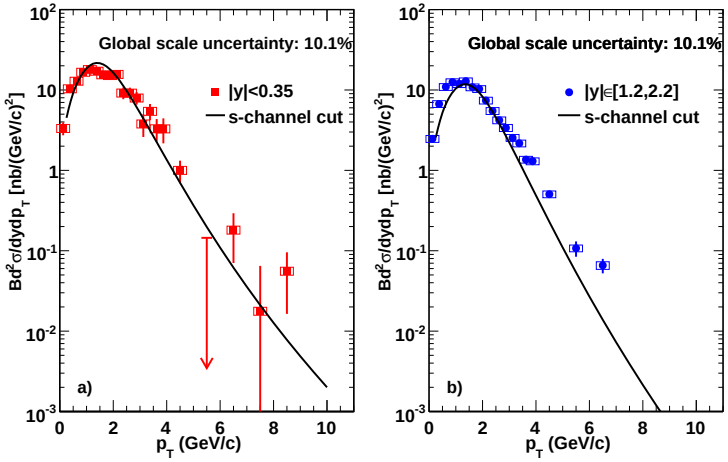

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➞ s-channel cut contribution can be large, specifically at small P_T

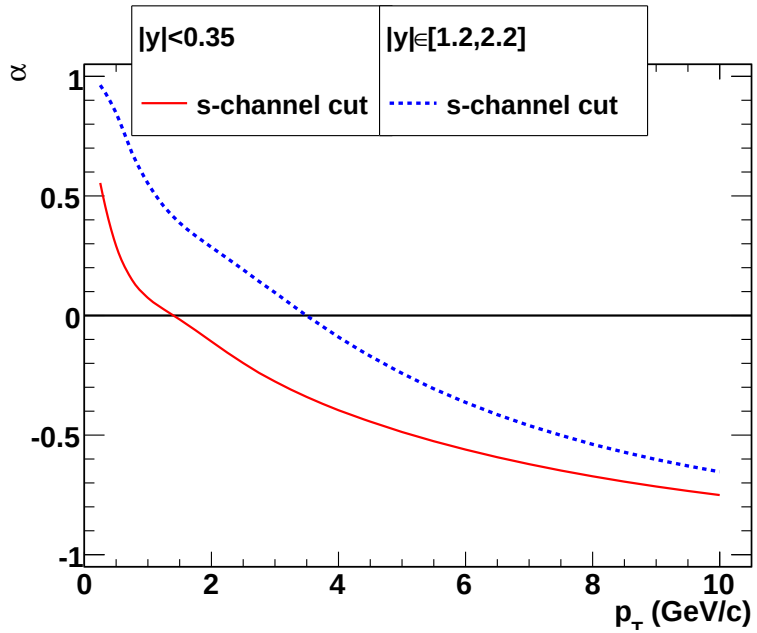
➞ This has to be tested: ep, $\gamma\gamma$ → Need for more observables !

The s-channel cut contribution: polarisation

H. Haberzettl, J.P.L, PRL 100,032006,2008
J.P.L, H. Haberzettl, AIP Proc. Conf. 1038 83, 2008
M. Donadelli, for the PHENIX Collab, talk at PANIC 2008, Nov.2008

J/ψ polarisation in pp at $\sqrt{s} = 200$ GeV measured by PHENIX

(note however that our computation does not include specific effects of χ_c)



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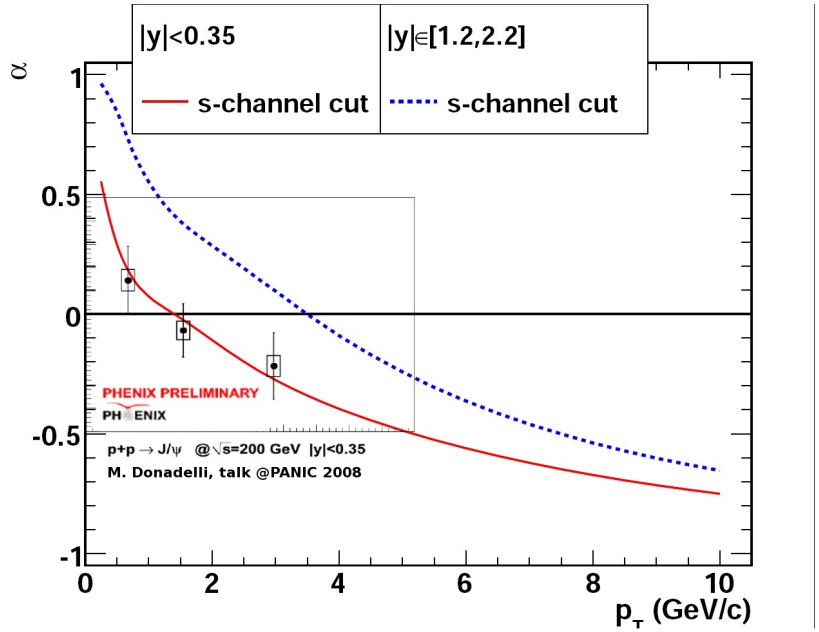

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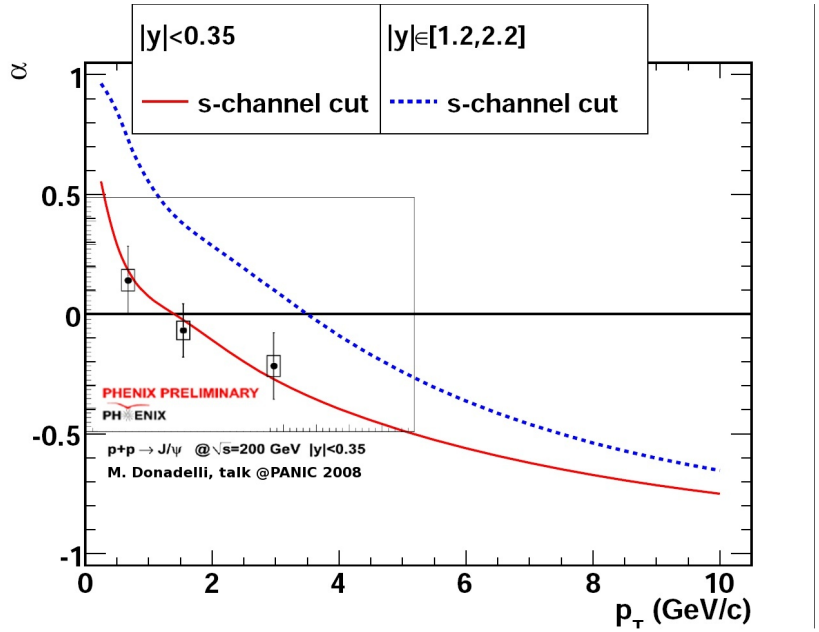
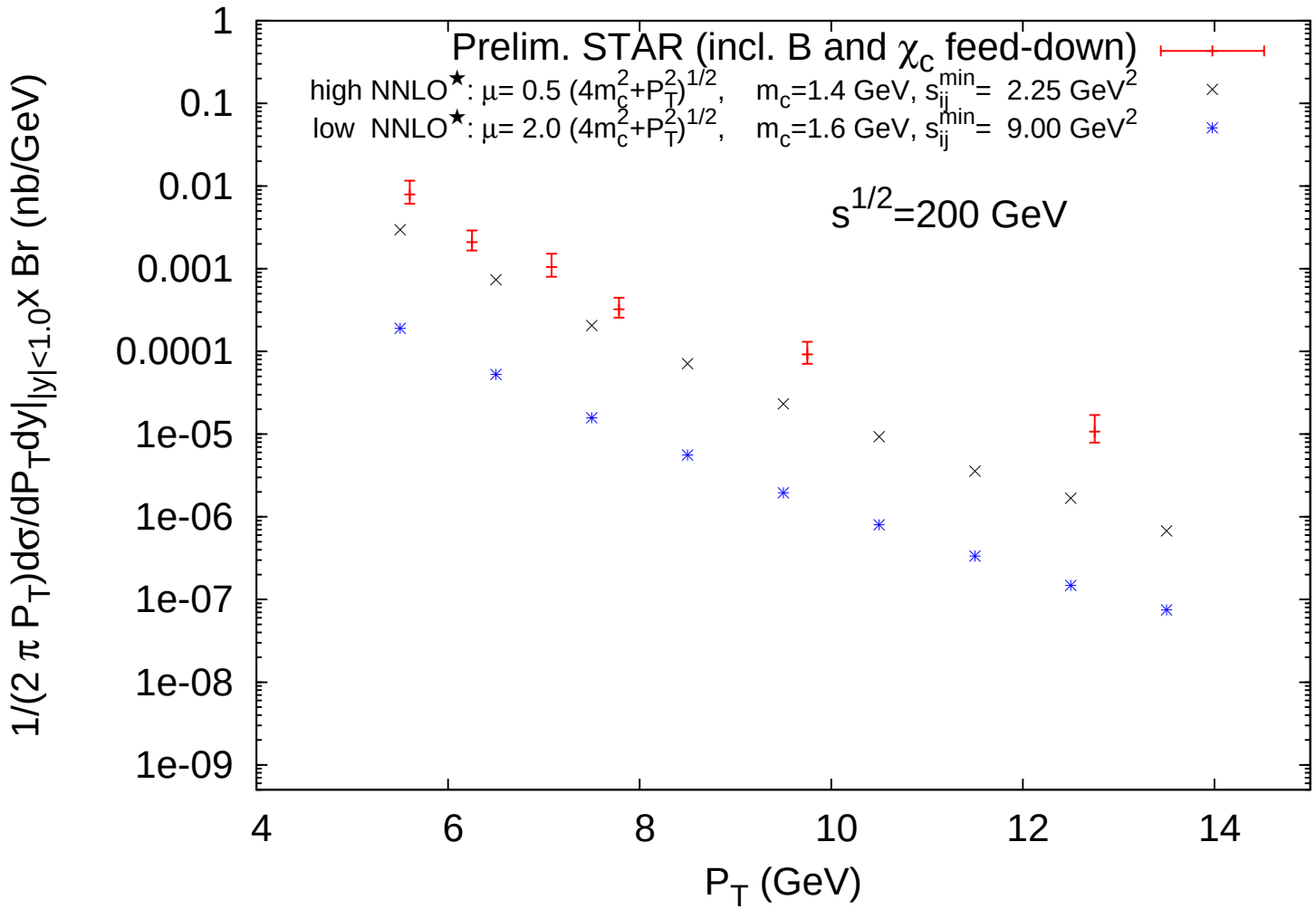


Yet, forward data seems to disagree with this evaluation ...

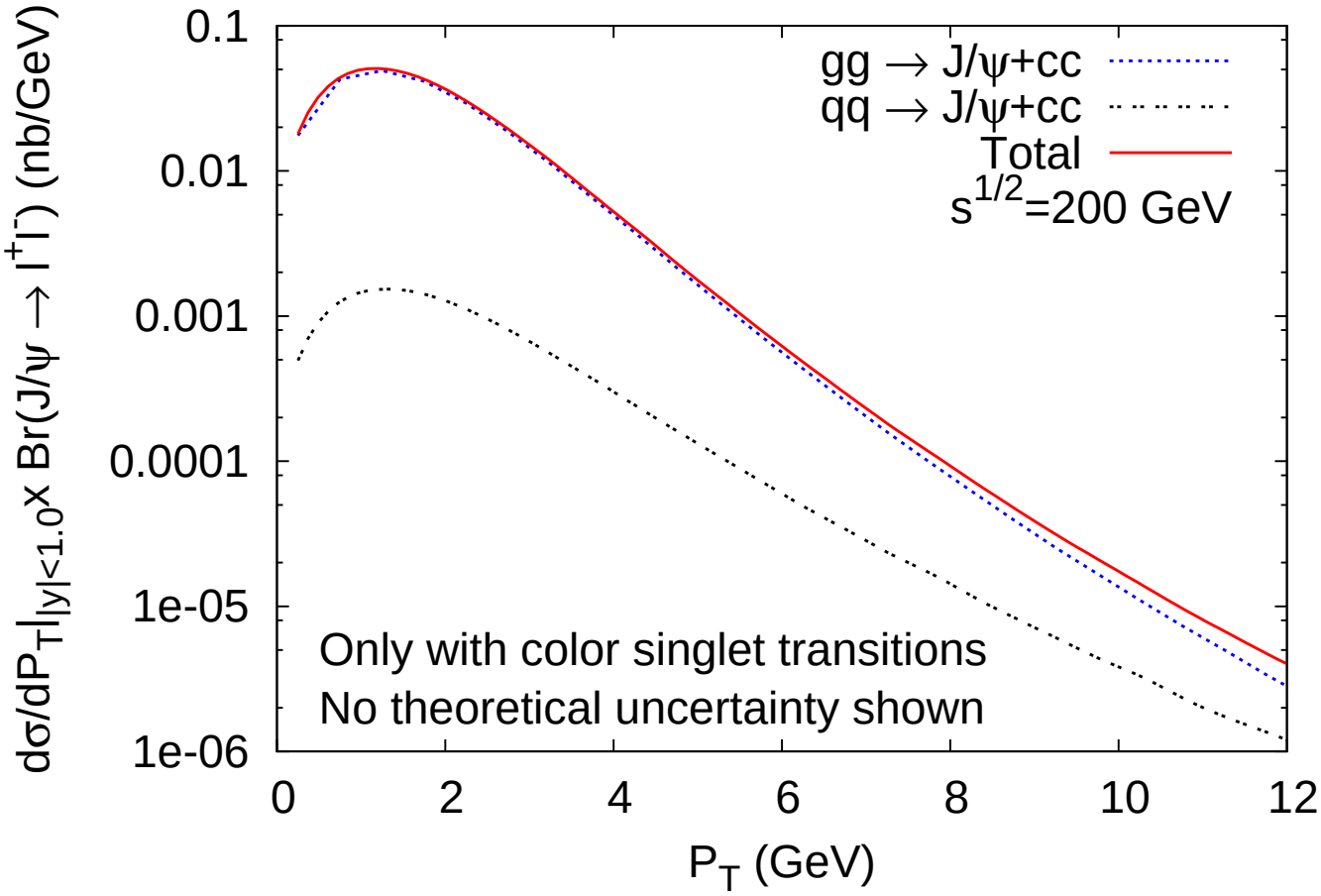
Further drawback: fit done without the CSM which is not small contrarily to what was commonly believed

Inclusive cross section at NNLO* compared to STAR data

STAR Collab., arXiv:0904.0439 [nucl-ex]



New observable: $J/\psi + cc$ (with STAR)



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