

Associated-quarkonium production

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thanks to W. den Dunnen, C. Lorcé, C. Pisano, M. Schlegel, H.S. Shao

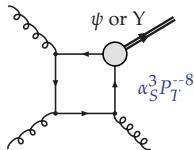
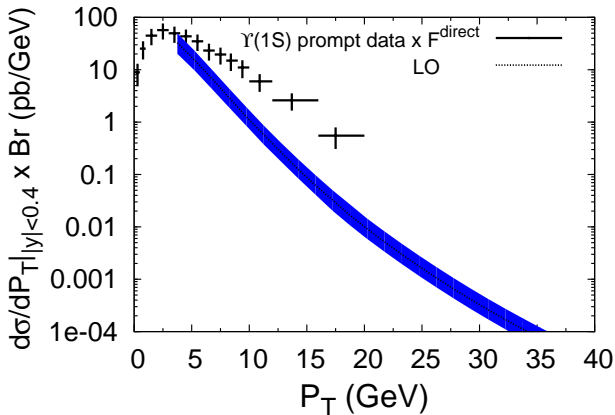
Part I

Quarkonium hadroproduction: where do we stand ?

Reminder: QCD corrections for Υ at the Tevatron

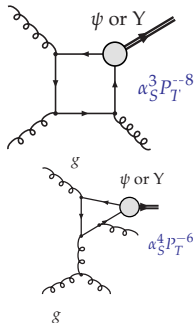
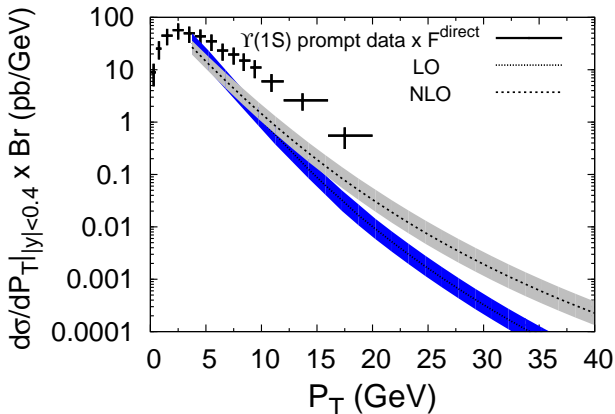
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 CDF PRL 88 (2002) 161802;PRD 87, 052004 (2013)



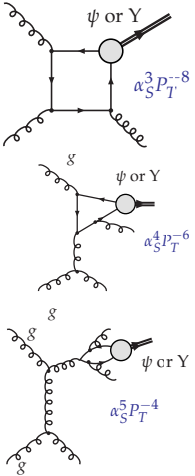
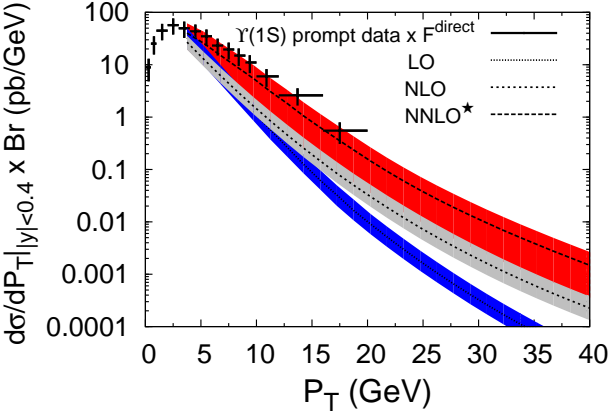
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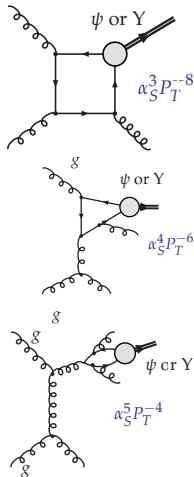
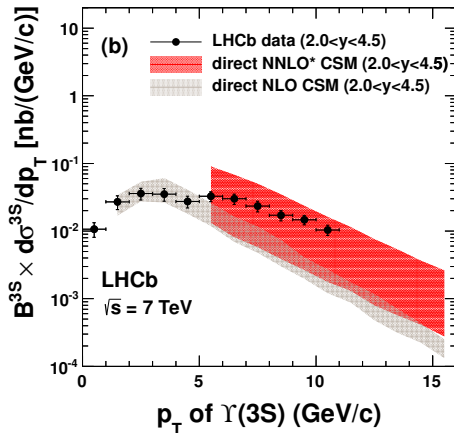
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 Attention: the NNLO* is not a complete NNLO

QCD corrections for Υ at the Tevatron & the LHC

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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); NPA 910-911 (2013) 470

→ The yield vs. \sqrt{s} , y

(here only LO curves*)

*NLO not stable at large \sqrt{s} (small x) and small P_T



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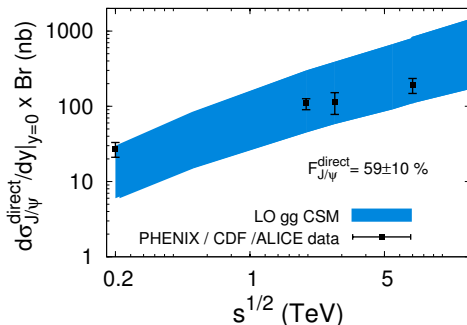
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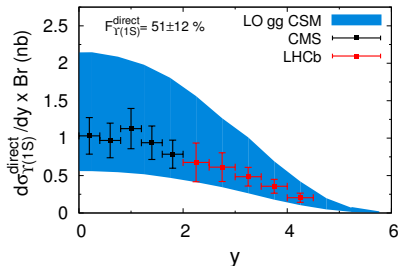
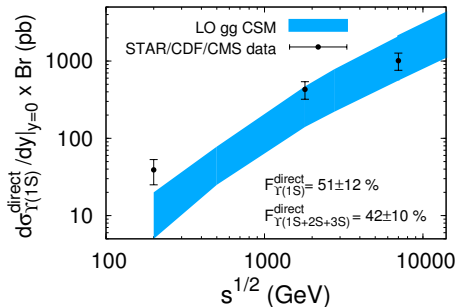
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STAR PRD 82 (2010) 012004 ; CDF PRL 88 (2002) 161802; CMS PRD 83 (2011) 112004; LHCb arXiv:1202.6579 [hep-ex]

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- **All this motivates the study of new observables
which can be more discriminant for specific effects**

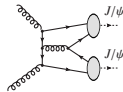
Part II

Quarkonium + Quarkonium

$J/\psi + J/\psi$ & $J/\psi + \eta_c$

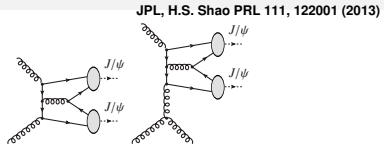
- LO to $J/\psi + J/\psi$ at α_S^4

JPL, H.S. Shao PRL 111, 122001 (2013)



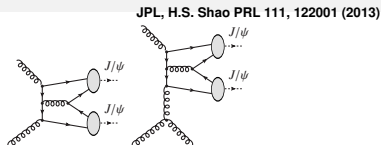
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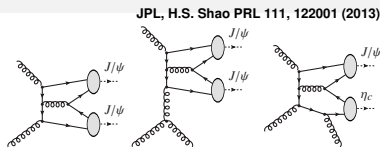


[nicely confirmed by a full NLO]

L.P. Sun *et al.* arXiv:1404.4042 [hep-ph]

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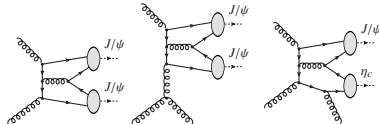
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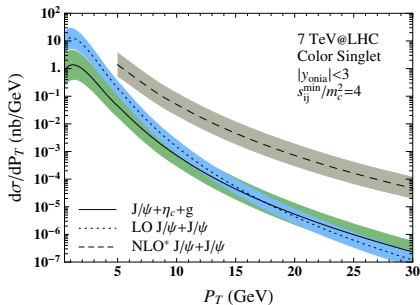
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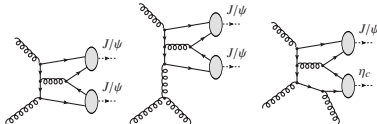
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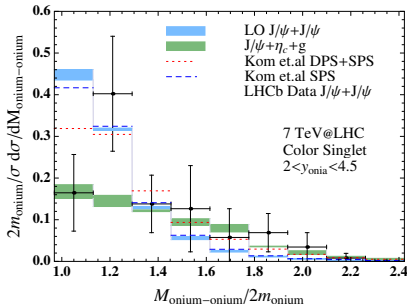
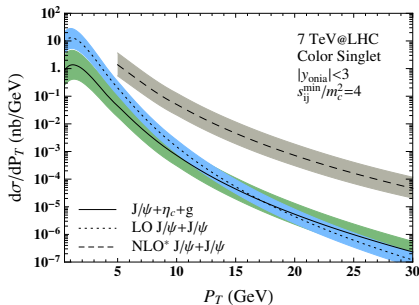
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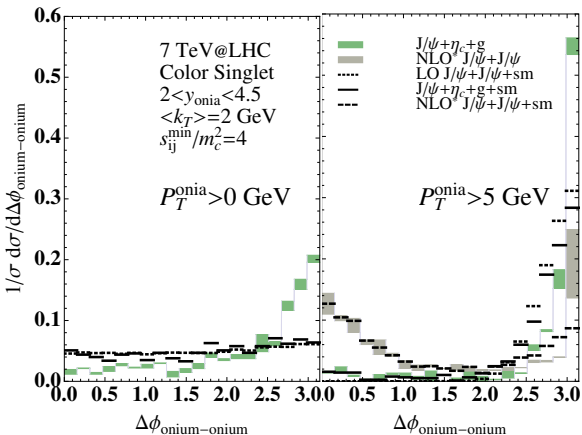


- Different P_T spectrum & different ΔM distribution

k_T smearing and azimuthal distributions

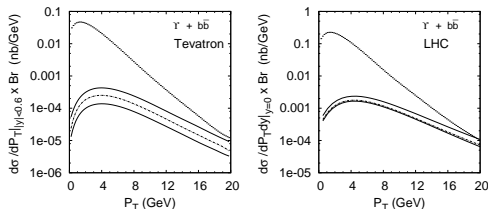
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- The k_T smearing completely flattens the $\Delta\phi$ distribution
Implication for the DPS “extraction” ?????



$Y + b$ -tagged jet (or $Y +$ non-prompt J/ψ)

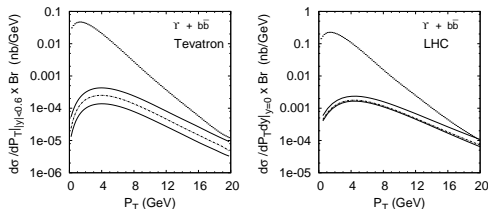
P.Artoisenet, JPL, F.Maltoni, PLB 653:60,2007



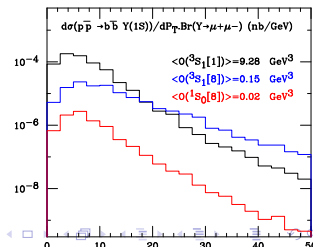
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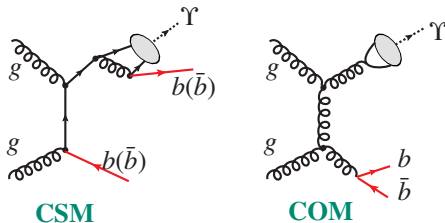


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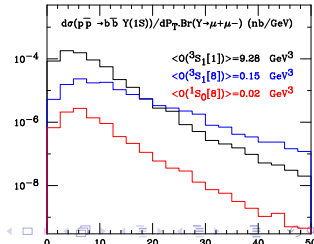


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- **Different topologies/correlation:**
 - **CSM**: 1 b away, 1 b near(er)
 - **COM**: 2 b 's away (from a recoiling gluon)



Part III

Quarkonium + photon

$Q + \text{isolated } \gamma$

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

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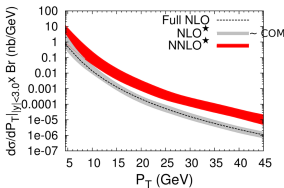
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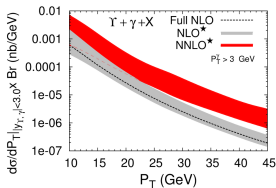
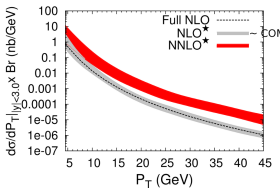


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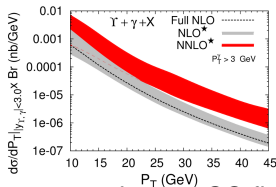
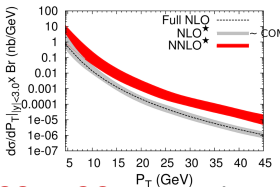
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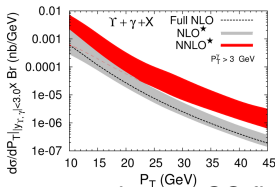
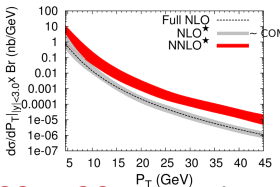
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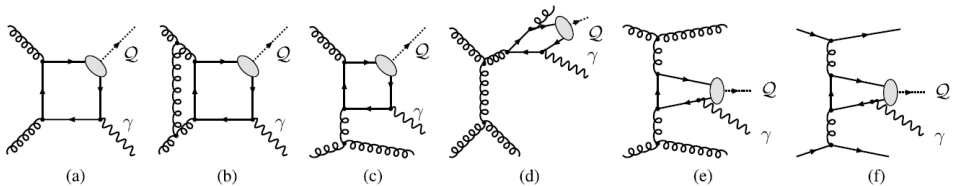
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- Possible at LHC: cf. $(c, b) - jet + \gamma$ studies by D0 up to $P_T^{\gamma} \simeq 150 \text{ GeV}$:

D0, PRL102 (2009) 192002.

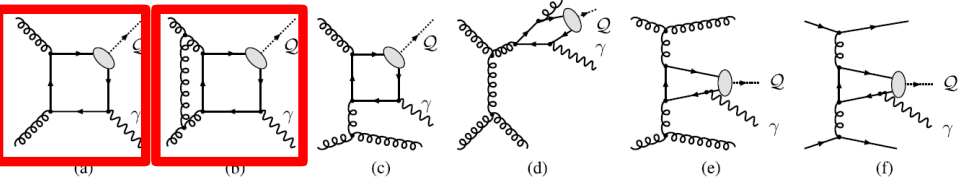
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$Q + \gamma$: **back-to-back** and both isolated



Representative diagrams contributing to the hadroproduction of a Q in association with a photon at orders $\alpha_s^2\alpha$ (a), $\alpha_s^3\alpha$ (b, c), $\alpha_s^4\alpha$ (d, e, f).

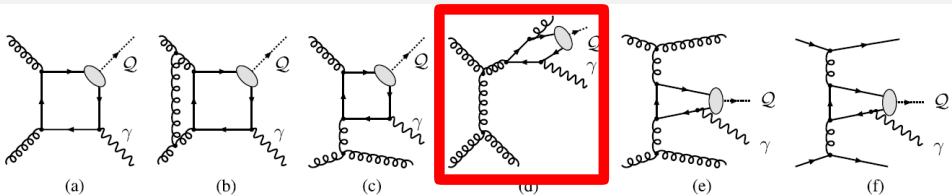
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Representative diagrams contributing to the hadroproduction of a Q in association with a photon at orders $\alpha_s^2\alpha$ (a), $\alpha_s^3\alpha$ (b, c), $\alpha_s^4\alpha$ (d, e, f).

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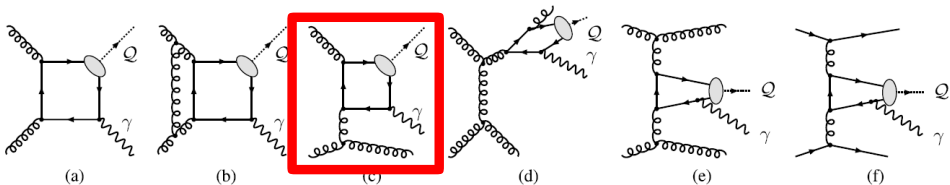
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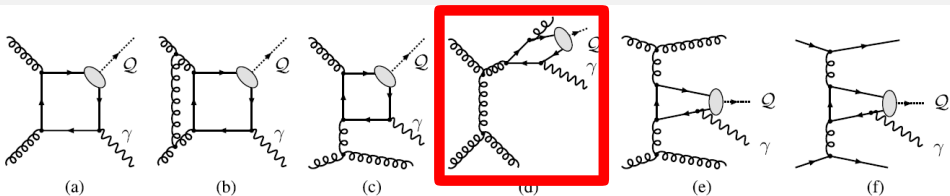
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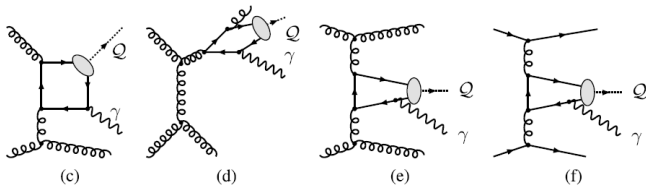
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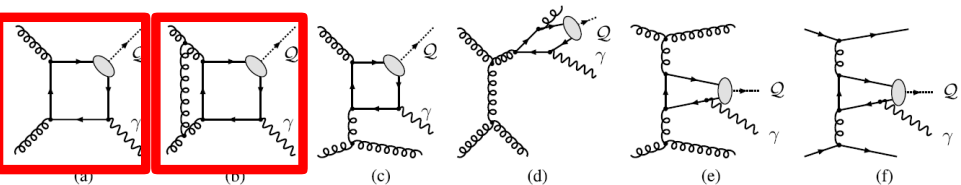
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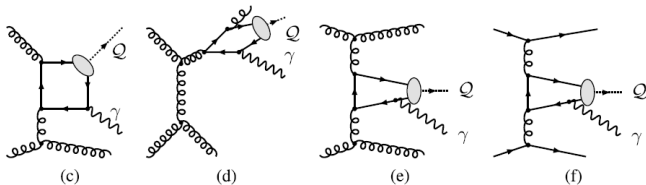
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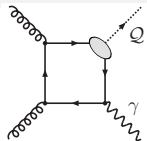


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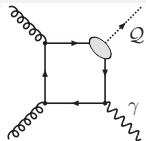
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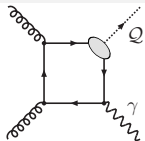
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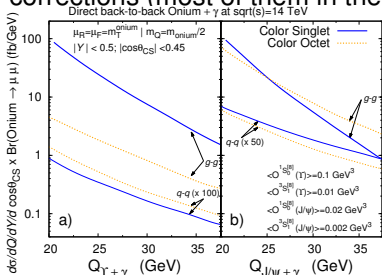
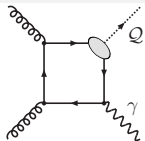
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W. den Dunnen, JPL, C. Pisano, M. Schlegel, arXiv:1401.7611v1 [hep-ph]

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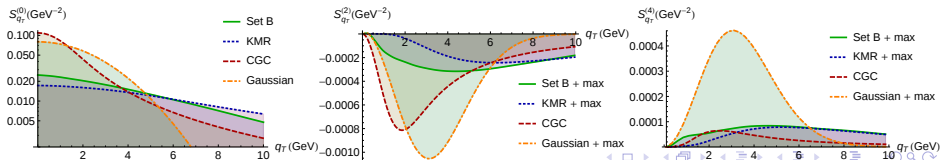
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Part IV

Quarkonium + W/Z boson

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- $Y + W/Z$ boson

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CDF Collaboration, PRL. 90 (2003) 221803

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- $J/\psi + Z$ and $J/\psi + W$ recently computed at NLO in α_S

L.Gang *et al.* PRD83,014001,2011; JHEP02(2011)071

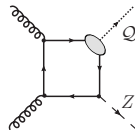
- $J/\psi|Y + Z$ at NLO in α_S + Polarisation

B.Gong *et al.* JHEP 1303 (2013) 115

$Y + Z$ cross sections

B. Gong, J.P. Lansberg, C. Lorcé, J.X. Wang, JHEP 1303 (2013) 115

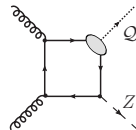
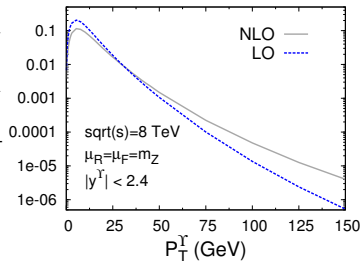
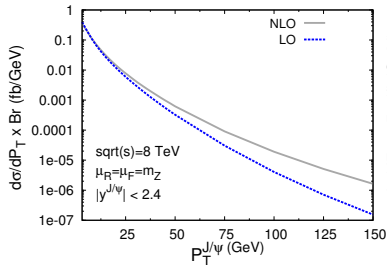
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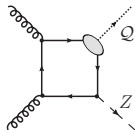
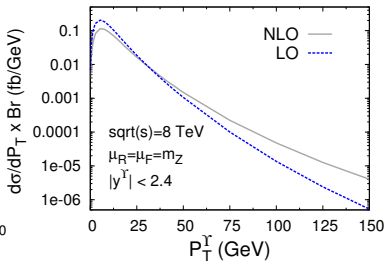
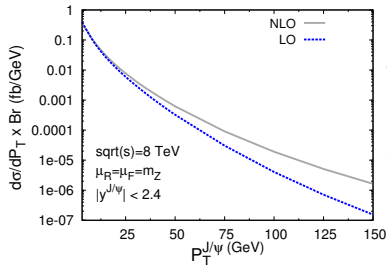
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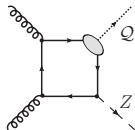
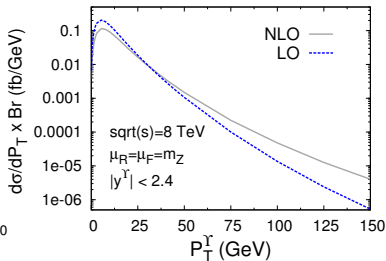
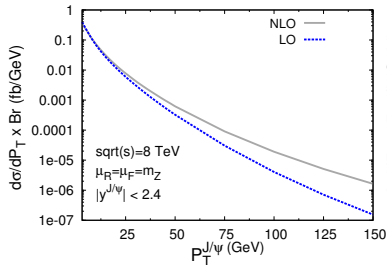


- Mass effects ($m_c \leftrightarrow m_b$ less relevant because of m_Z)
- $|R(0)|^2$ is 10 times larger for Y than for J/ψ
- Branching “only” 2.5 times smaller

Y + Z cross sections

B. Gong, J.P. Lansberg, C. Lorcé, J.X. Wang, JHEP 1303 (2013) 115

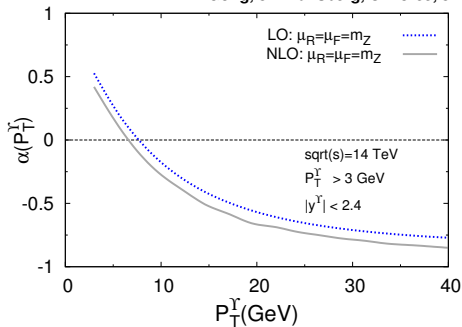
- Rates similar for $Y + Z$ and $J/\psi + Z$ [Same for $Q + \gamma$ for $Q \gtrsim 20$ GeV]



- Mass effects ($m_c \leftrightarrow m_b$ less relevant because of m_Z)
- $|R(0)|^2$ is 10 times larger for Y than for J/ψ
- Branching “only” 2.5 times smaller
- Potential probe of gluon TMDs as well

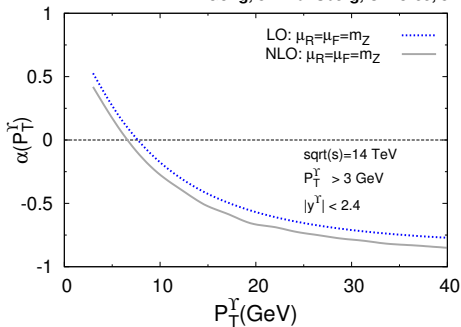
$Y + Z$: Y polarisation

B. Gong, J.P. Lansberg, C. Lorcé, J.X. Wang, JHEP 1303 (2013) 115



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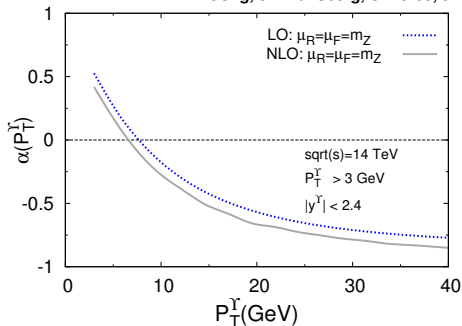
B. Gong, J.P. Lansberg, C. Lorcé, J.X. Wang, JHEP 1303 (2013) 115



- Y polarisation at LO and NLO are **similar**

Y + Z :Y polarisation

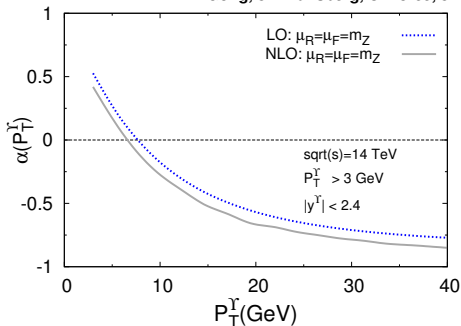
B. Gong, J.P. Lansberg, C. Lorcé, J.X. Wang, JHEP 1303 (2013) 115



- Y polarisation at LO and NLO are **similar**
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Y + Z :Y polarisation

B. Gong, J.P. Lansberg, C. Lorcé, J.X. Wang, JHEP 1303 (2013) 115



- Y polarisation at LO and NLO are **similar**
- unlike the inclusive case
- not clear why: need for further investigation
- **CSM predictions** seem **robust** both for the yield and the polarisation

$J/\psi + W$

J.P. Lansberg, C. Lorcé, PLB 726 (2013) 218

' $\psi + W$ offers a clean test of the colour octet contributions'

V. D. Barger, S. Fleming and R. J. N. Phillips, PLB 371, 111 (1996)

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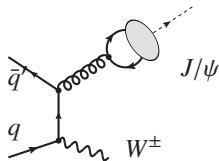
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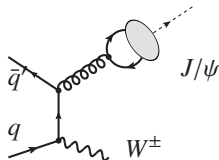
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- The corresponding process suppressed in the CSM by α_s^2
(similarly to the gluon fragmentation in the inclusive case)
- Usual conclusion:
the CSM contribution is strongly suppressed even at rather low P_T



V. D. Barger, S. Fleming and R. J. N. Phillips, Phys. Lett. B 371, 111 (1996)
G. Li, M. Song, R. -Y. Zhang and W. -G. Ma, Phys. Rev. D 83, 014001 (2011).

direct $J/\psi + W$

J.P. Lansberg, C. Lorcé, PLB 726 (2013) 218

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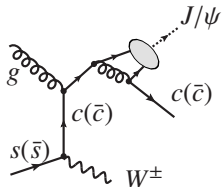
J.P. Lansberg, C. Lorcé, PLB 726 (2013) 218

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J.P. Lansberg, C. Lorcé, PLB 726 (2013) 218

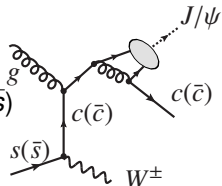
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J.P. Lansberg, C. Lorcé, PLB 726 (2013) 218

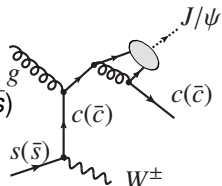
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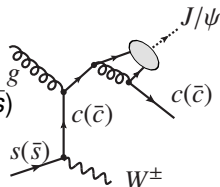
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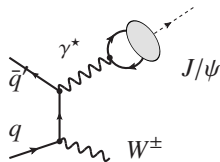
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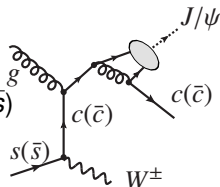
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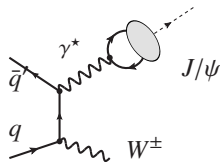
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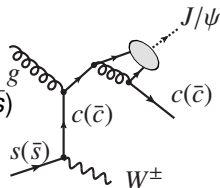
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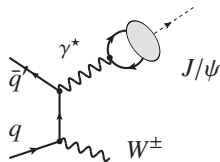
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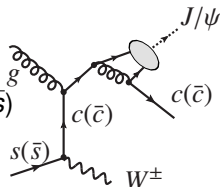
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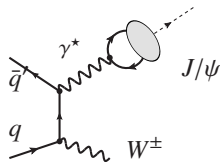
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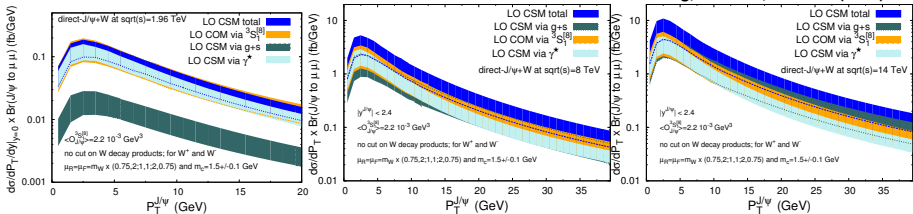


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- $q\bar{q}' \rightarrow \gamma^* W \rightarrow J/\psi W$: negligible since α^3 ?



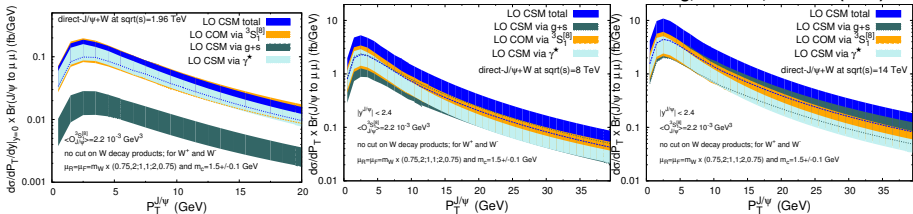
Results

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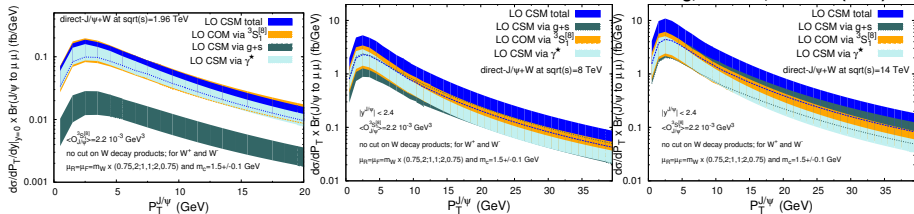
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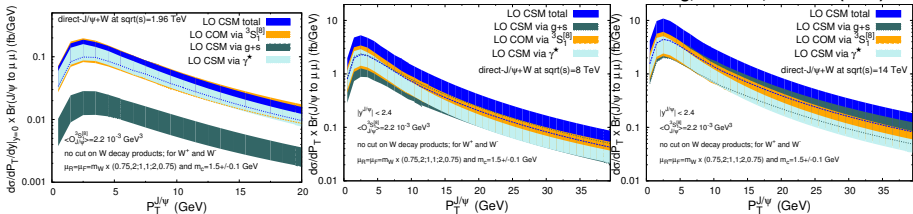
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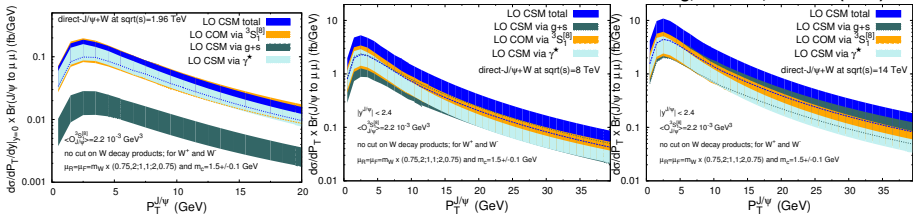
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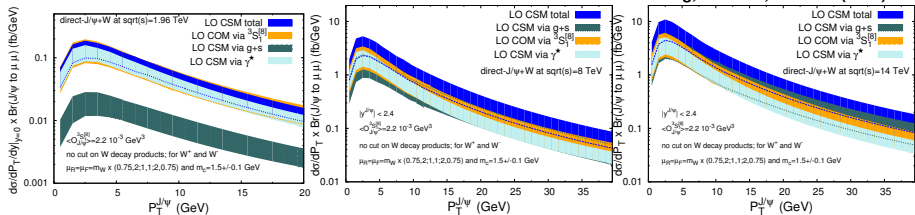
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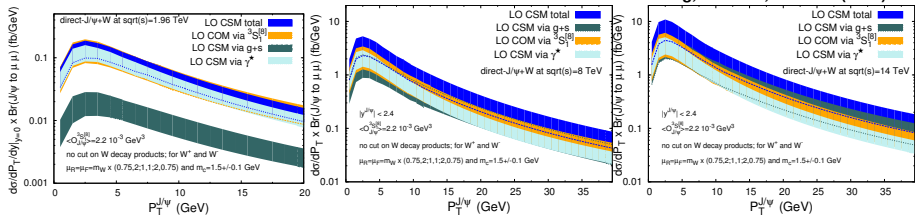
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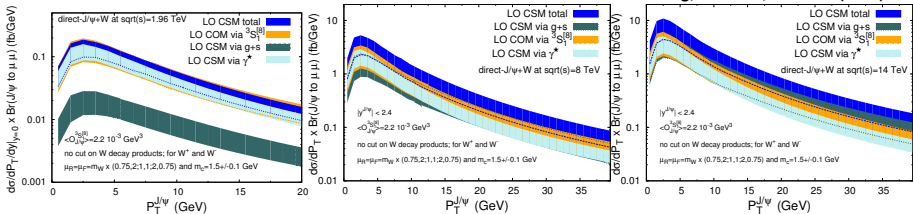
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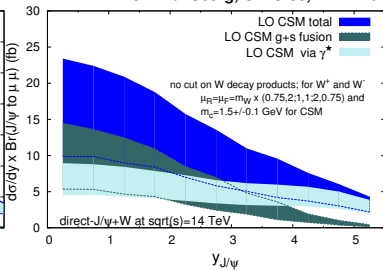
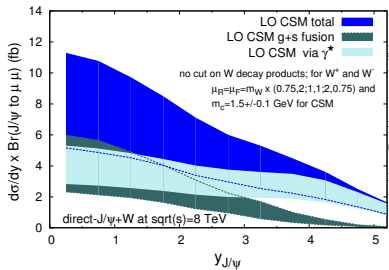


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- Unfortunately, $J/\psi + W$ not a clean test of colour octets

but measured by ATLAS !

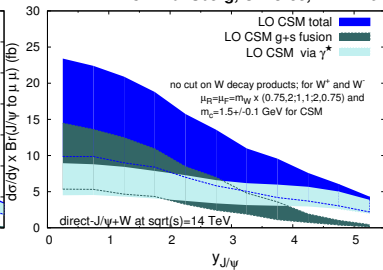
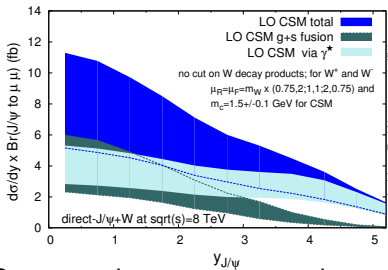
Rapidity distribution – Comparison with ATLAS

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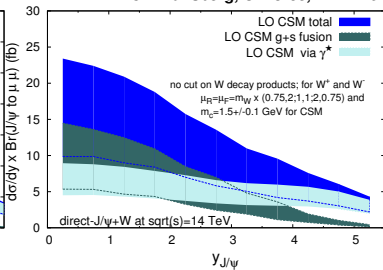
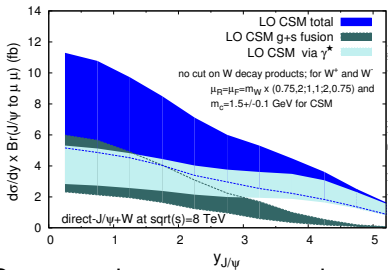
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- Cross sections are not very large

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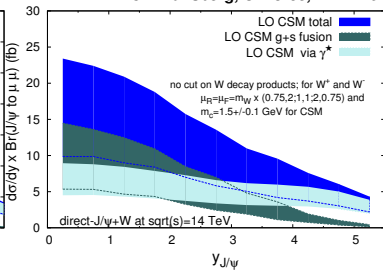
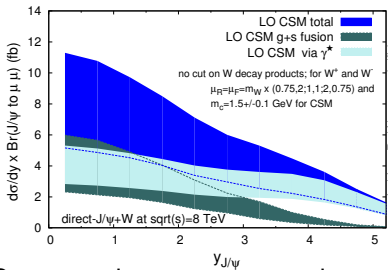


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arXiv:1401.2831 [hep-ex]

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J.P. Lansberg, C. Lorcé, PLB 726 (2013) 218



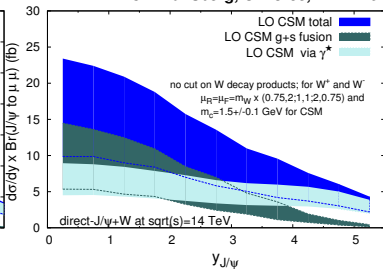
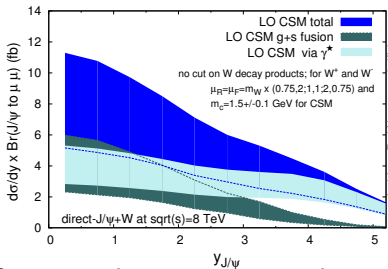
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J.P. Lansberg, C. Lorcé, PLB 726 (2013) 218



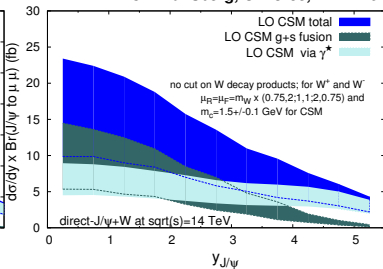
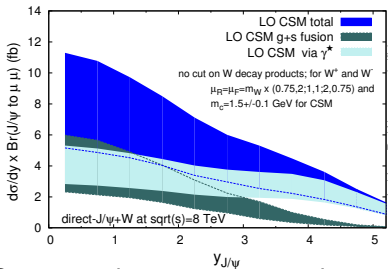
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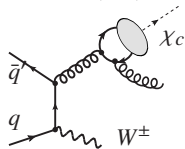


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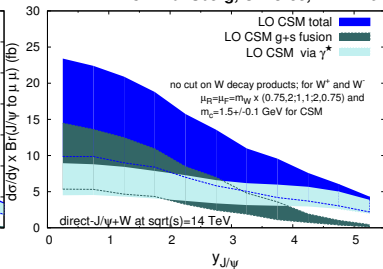
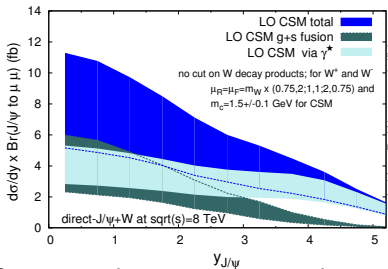
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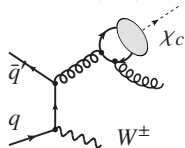
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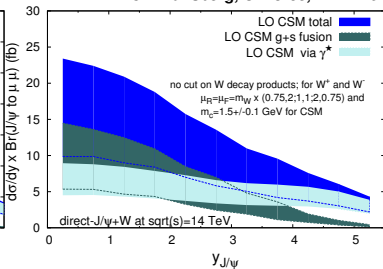
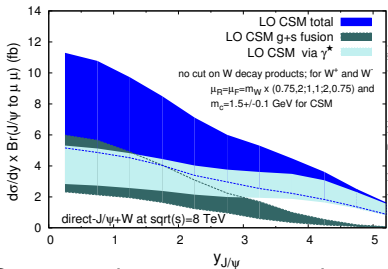
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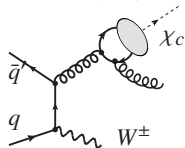
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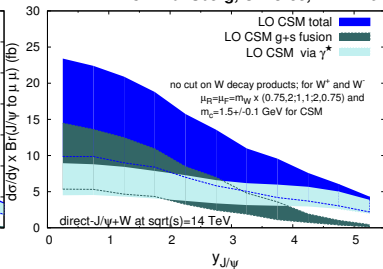
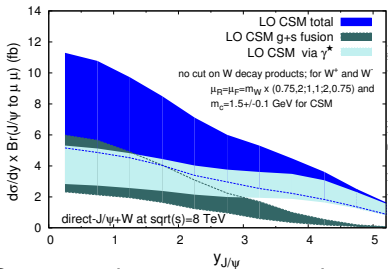
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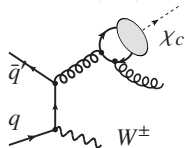
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arXiv:1401.2831 [hep-ex]

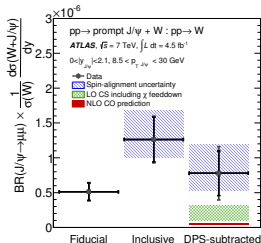
$$\sigma = \sigma(P_T^\psi > 8.5\text{GeV}, |y^\psi| < 2.4)$$



[marginal agreement]

Rapidity distribution – Comparison with ATLAS

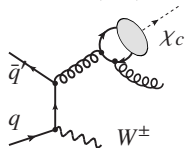
J.P. Lansberg, C. Lorcé, PLB 726 (2013) 218



- Cross sections are not very large
- Comparison with ATLAS
- CSM
 - direct: $0.6 \pm 0.2 \text{ fb}$
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Part V

Quarkonium + hadron

$Q + \text{hadron}$ azimuthal correlations

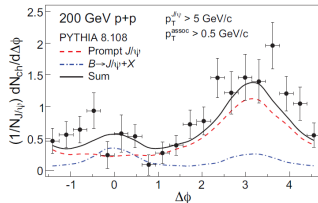
→ $J/\psi + \text{hadron}$ azimuthal correlations

STAR Collab., Phys.Rev.C80:041902 (R),2009.

Q + hadron azimuthal correlations

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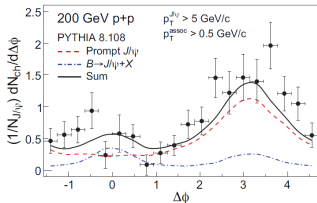
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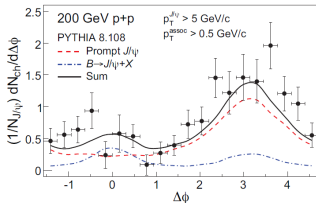


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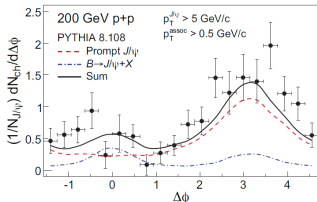


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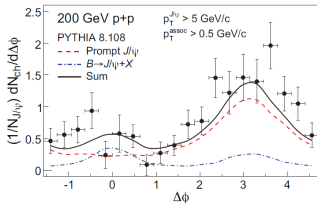


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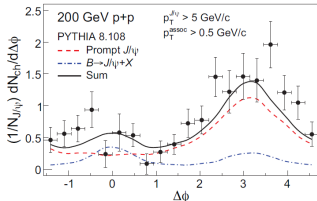


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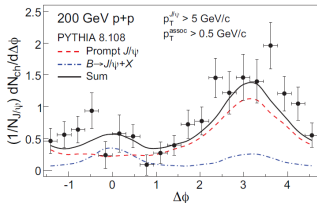


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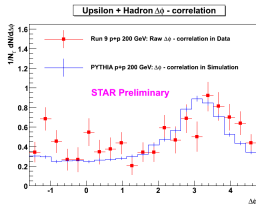
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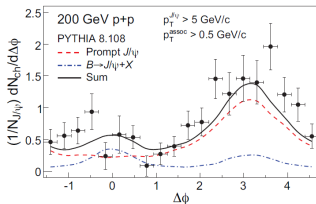
Talk by M. Cervantes (STAR) at WWND 2011



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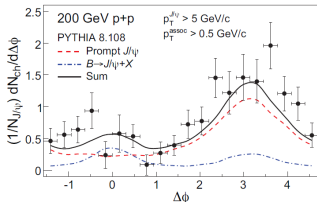
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Could that be used to discriminate octet vs. singlet hadronisation ?

Part VI

$J/\psi + \text{charm}$

Double charm: $J/\psi + D$

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

S. J. Brodsky and JPL, PRD 81 051502 (R), 2010

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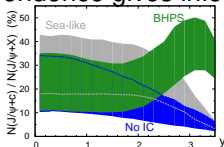
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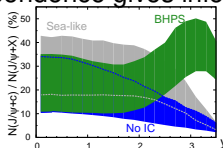
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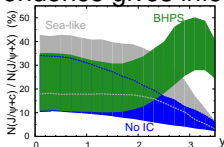
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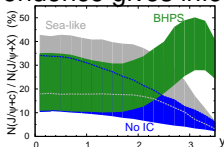
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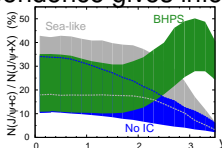
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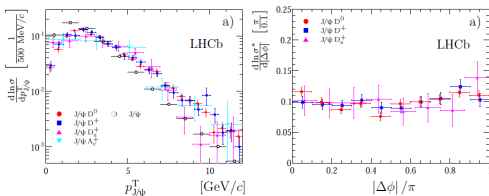


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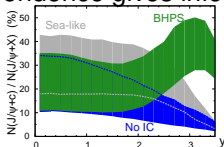
LHCb, JHEP 1206 (2012) 141

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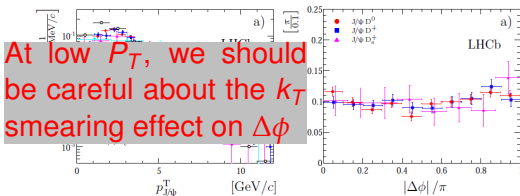


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- and by extension the gluon TMDs (gluon transverse motion)
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Part VII

Backup

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CMS, PRD 83, 112004 (2011)

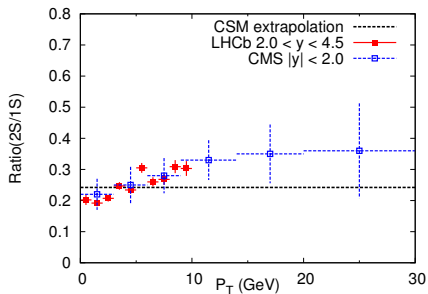
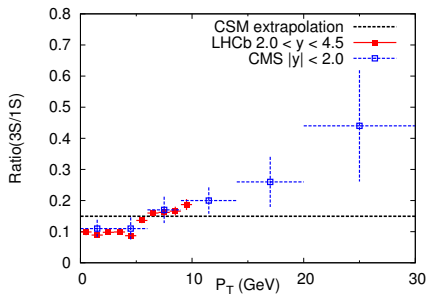
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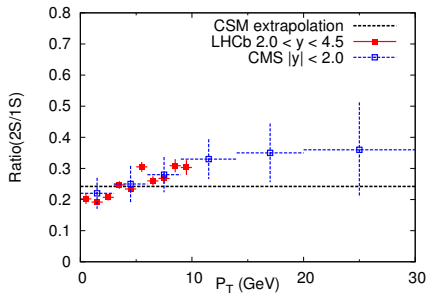
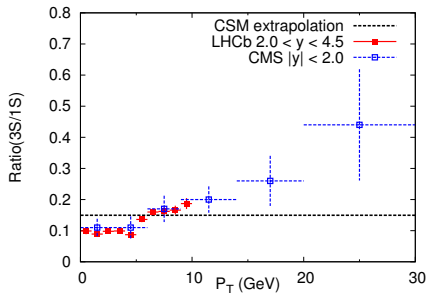
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CMS, PRD 83, 112004 (2011)
- **NEW**: the 3S yield likely not 100% direct
cf. $\chi_b(3P)$ observation by ATLAS PRL, 108, 152001 (2012)

Cross section ratio II

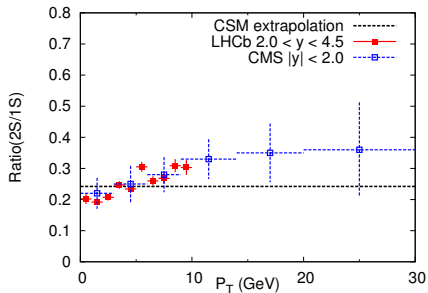
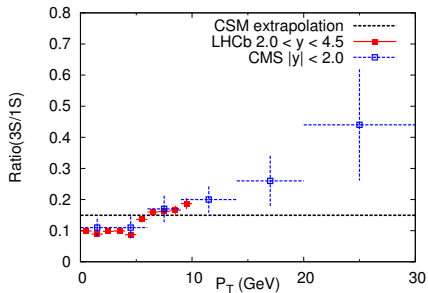


Cross section ratio II



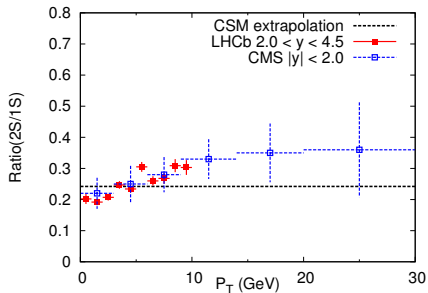
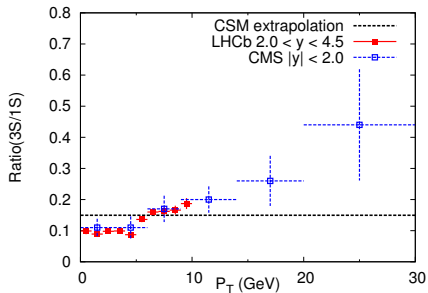
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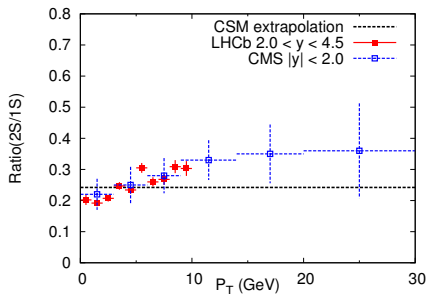
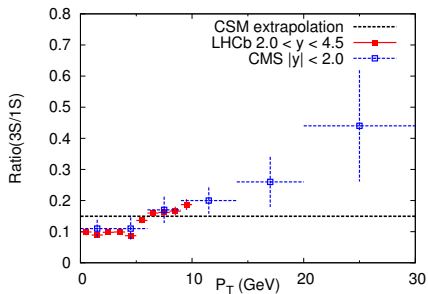
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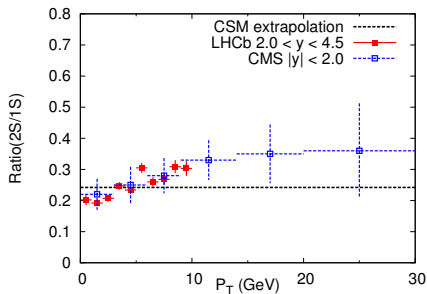
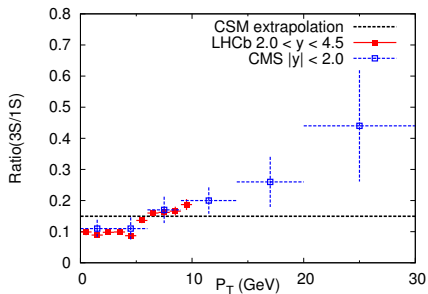
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- General conclusion:

For production processes involving light quarks, the CSM via off-shell photon competes with the COM via off-shell gluon