Quarkonium production at LHCb

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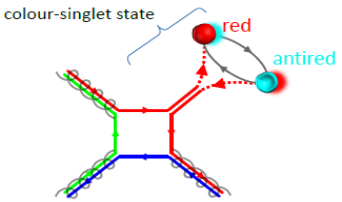
on behalf on the LHCb collaboration

Introduction

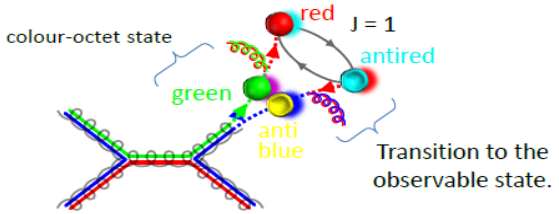
- Quarkonia production provides a test of QCD
- Quarkonia production mechanism is still not well understood

- Inclusive production ($J/\psi, \Upsilon, \chi_{b,c}, \eta_c$):
  - Test of Higher Order corrections
  - Relative importance of color singlet and color octet contributions
  - Tuning of MC

  $\Rightarrow$ understanding of the background for searches for new physics



- Exclusive production of charmonium
  - Pomeron exchange
  - Proble gluon PDF at low x

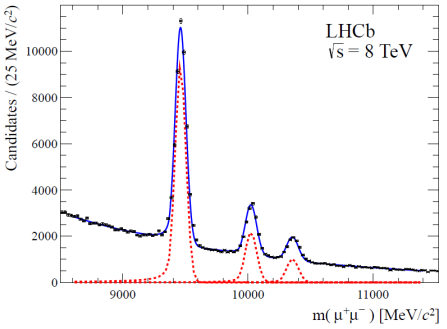


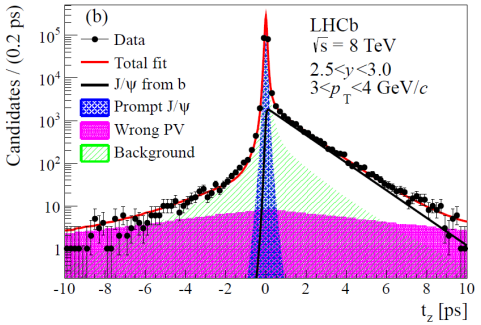
Outline

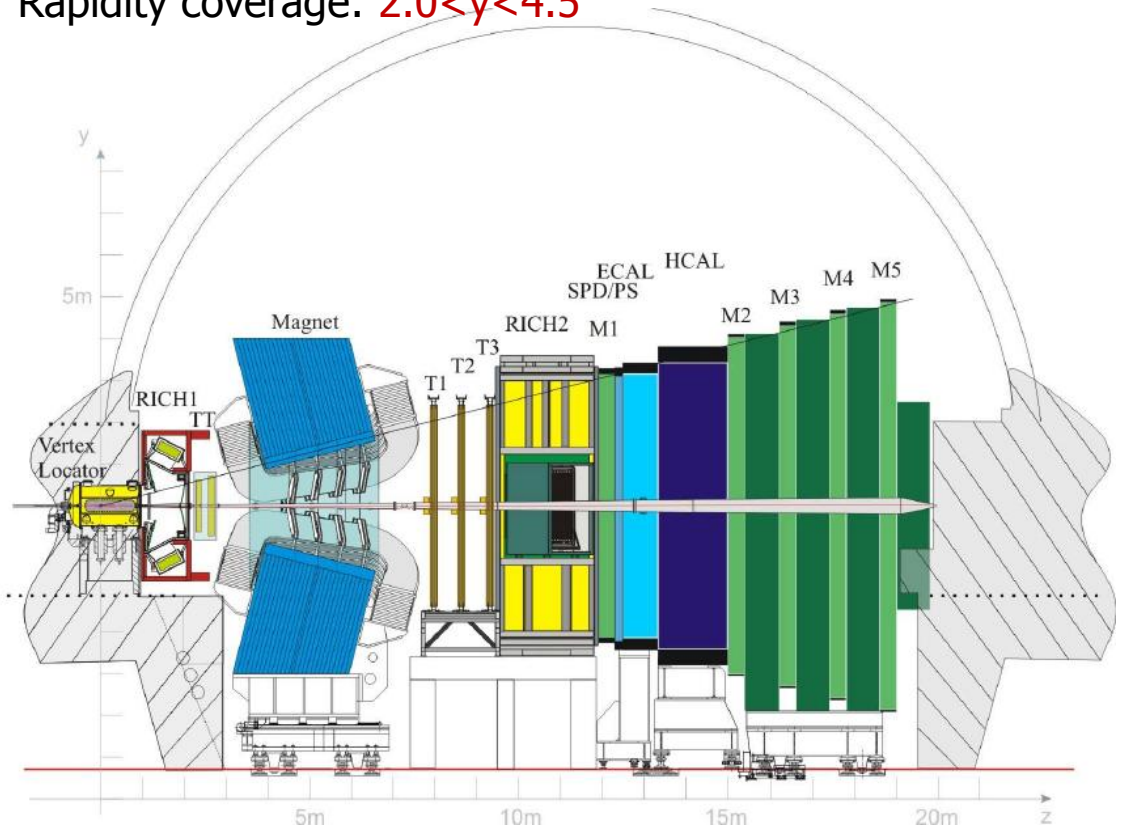
- The LHCb detector and quarkonia
- J/ψ and Υ production
- Feeddown from χ_b to Υ's
- χ_b production
- η_c production
- Exclusive production of charmonium

The LHCb detector and quarkonia

- Efficient muon trigger: $P_T(\mu_1) \times P_T(\mu_2) > 1.68\ (GeV/c)^2$
- Very good momentum resolution (0.5%) : $\sigma = 13\ MeV/c^2$ on J/ψ
- Impact parameter resolution: $\sigma = 20\mu m$ => prompt/secondary
- Very good muon identification: $\varepsilon \sim 97\%$ for $\sim 1\%\ \pi \to \mu$ misid
- Backward coverage of the VELO: important for exclusive production
- Rapidity coverage: $2.0 < y < 4.5$





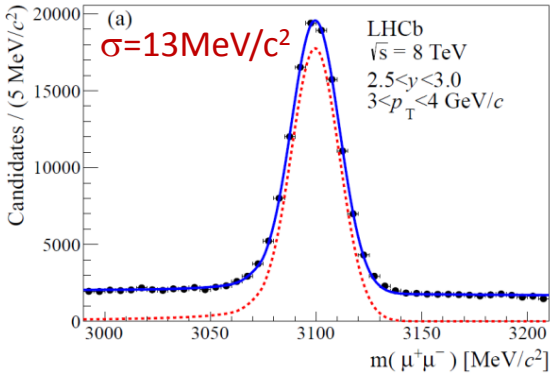


Results based on:

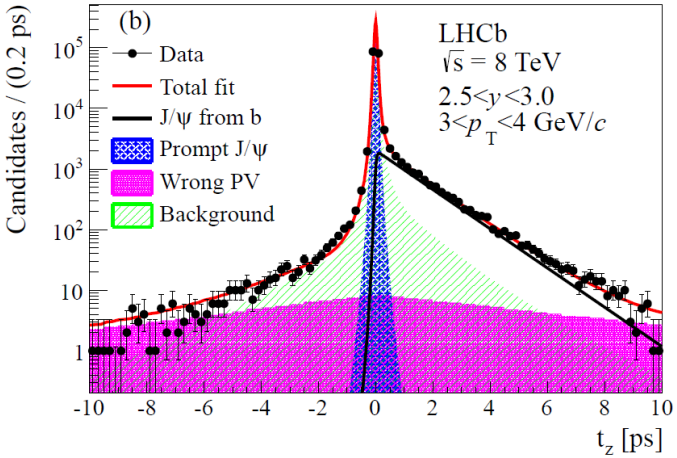
- $1fb^{-1}$ at 7TeV (2011 data)
- $2fb^{-1}$ at 8TeV (2012 data)

J/ψ production at 8 TeV

- J/ψ production measurement in LHCb:
  - Use J/ψ→μμ decay
  - Low pT muon trigger: 2 muons p_T > ~0.5 GeV/c
  - π→μ misid ~0.7%



  - prompt and from-b yields from 2D fit of m(μμ) and t_z
  - J/ψ is assumed to be produced unpolarized as suported by LHCb EPJ.C73(2013)2631, and ALICE PRL108(2012)082001 measurements
  - Efficiencies (trigger, μ id, reconstruction) validated using data-driven techniques
  - April 2012 (small) data sample used: 18.4±0.9 pb^{-1}

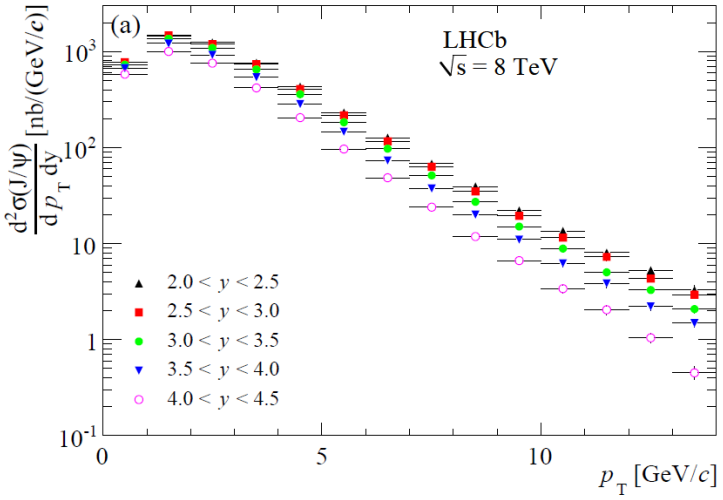


JHEP06(2013)064

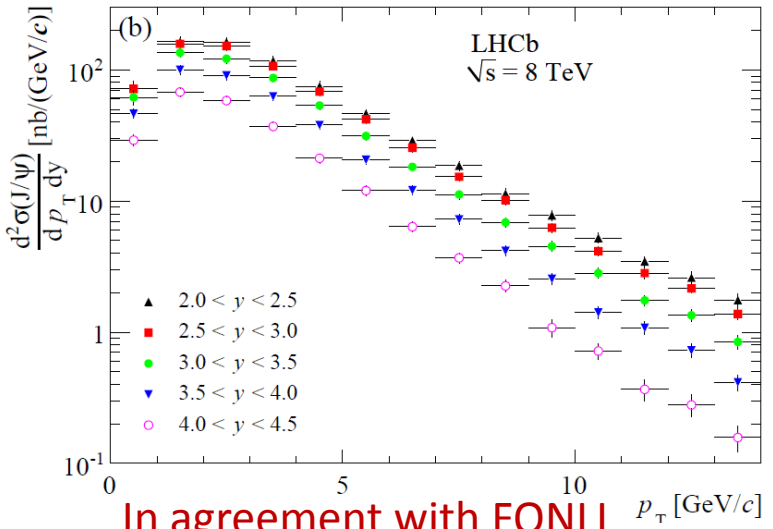
J/ψ production at 8 TeV

- Double differential cross-section for pT<15GeV/c and 2.0<y<4.5

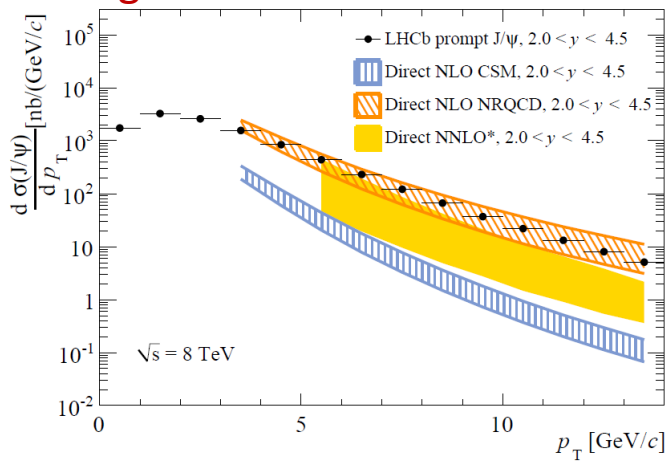
Prompt J/ψ



J/ψ from-b

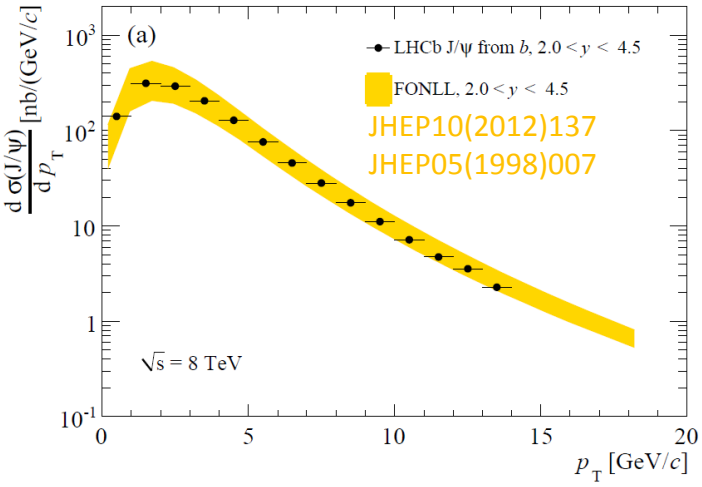


In agreement with NLO NRQCD



PRL98(2007)252002
PRL106(2011)022003
EPJC61(2009)693

In agreement with FONLL



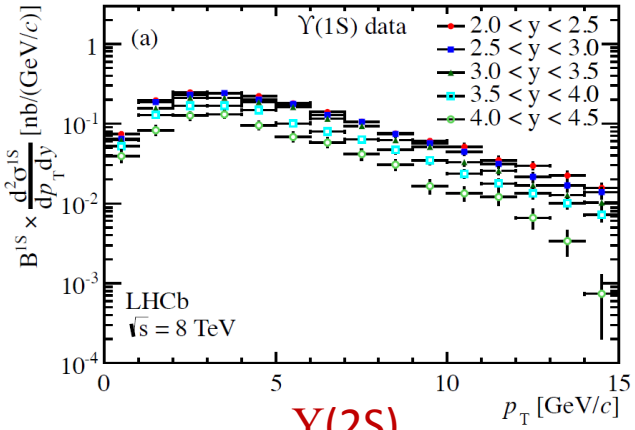
JHEP10(2012)137
JHEP05(1998)007

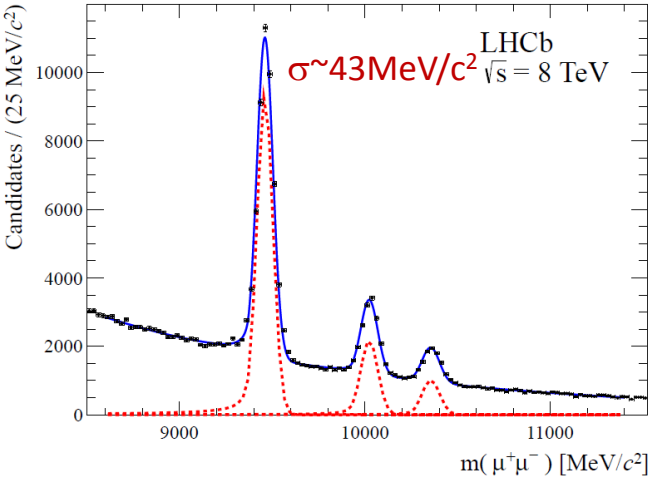
JHEP06(2013)064

Υ Production at 8 TeV

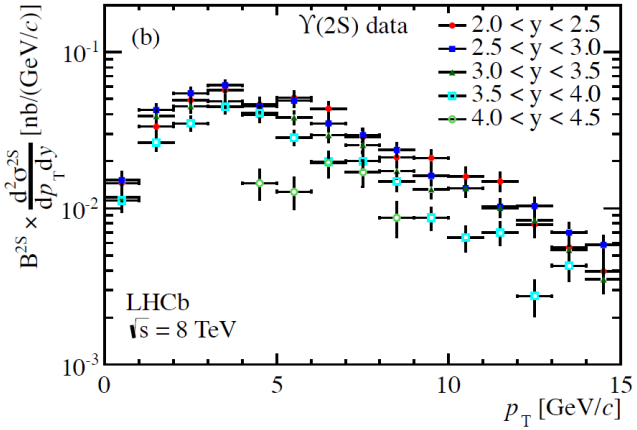
- Same analysis as for J/ψ (except no from-b)
- Assumption: Υ not polarized as suported by CMS measurement (PRL110(2013)081802)
- April 2012 (small) data sample used: 50.6±2.5 pb^{-1}

Υ(1S)

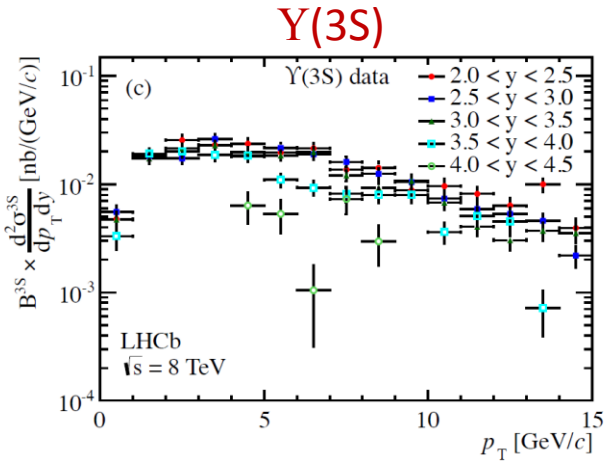




Υ(2S)



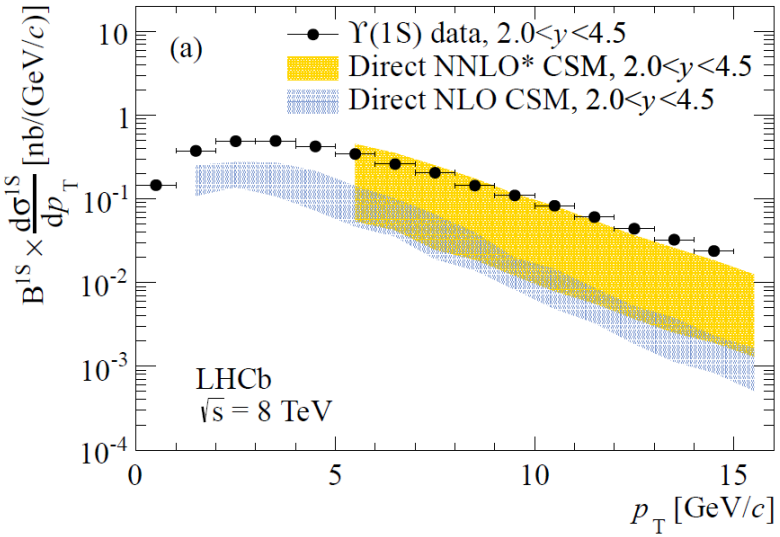
Υ(3S)



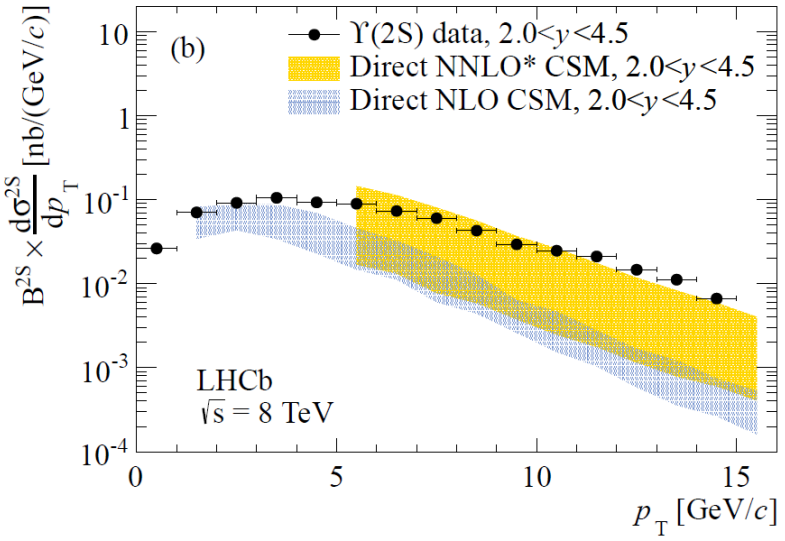
JHEP06(2013)064

Υ Production at 8 TeV

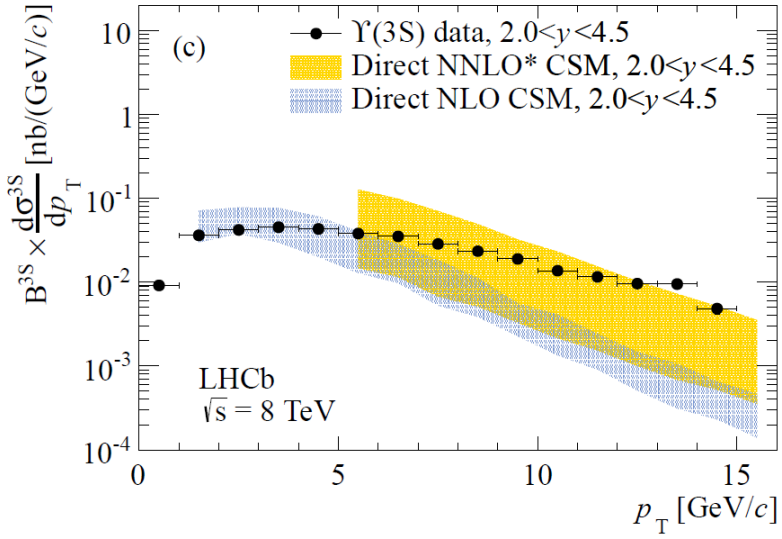
Υ(1S)



Υ(2S)

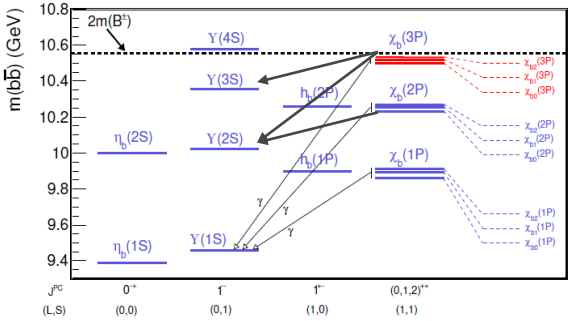


Υ(3S)



- Comparison to theory:
  - CSM NLO PRL98(2007)252002 underestimates production
  - agreement with CSM NNLO* PRL101(2008)152001

!! Measurement includes feedown – not theory !!

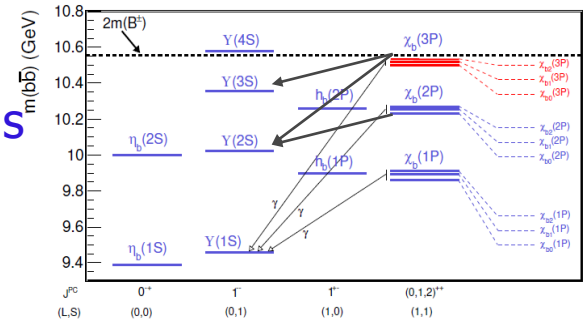


arXiv:1407.7734

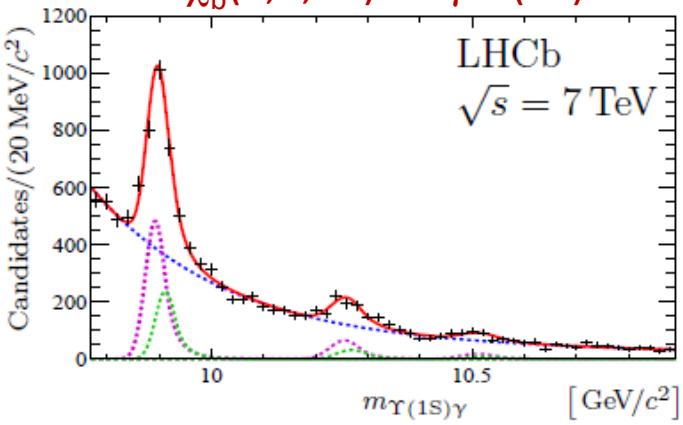
Υ feed-down from χ_b

- Add a photon to the Υ candidates to study the transitions

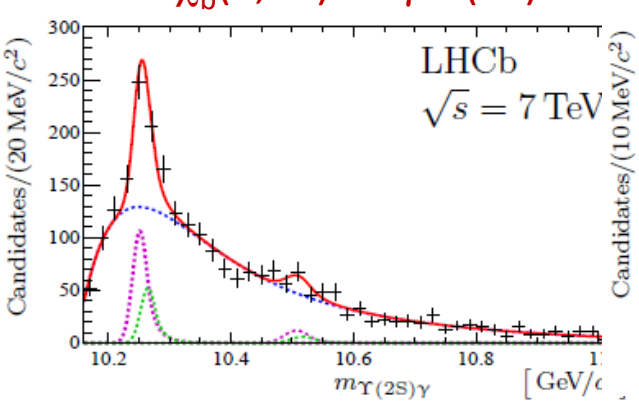
  $\chi_b(mP) \rightarrow \gamma\Upsilon(nS)$ (pT(γ)>600 MeV/c)



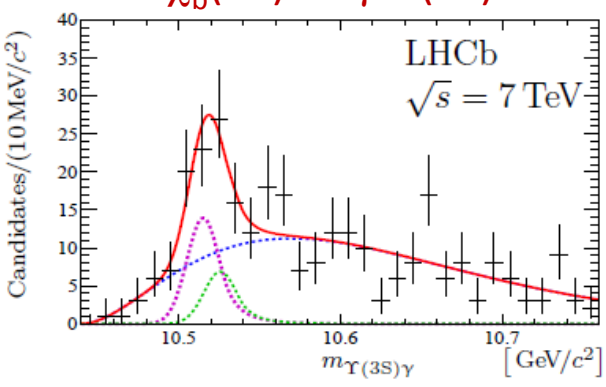
$\chi_b(1,2,3P) \rightarrow \gamma\Upsilon(1S)$



$\chi_b(2,3P) \rightarrow \gamma\Upsilon(2S)$



$\chi_b(3P) \rightarrow \gamma\Upsilon(3S)$



$m(\chi_b)=m(\mu\mu\gamma) - m(\mu\mu)+m_{PDG}(\Upsilon)$: cancellation of the detector resolution on Υ invariant mass

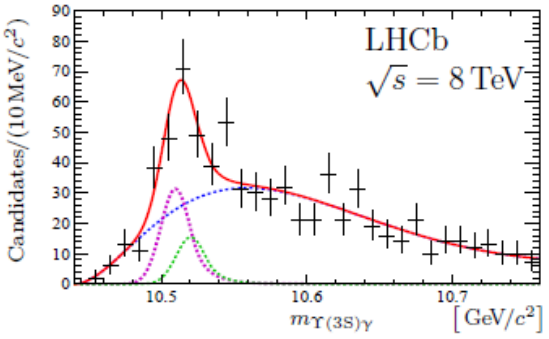
$\Rightarrow$First observation of $\chi_b(3P) \rightarrow \gamma\Upsilon(3S)$!

arXiv:1407.7734

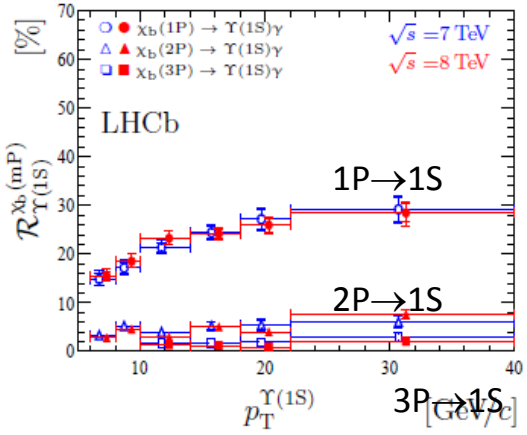
Υ feed-down from χ_b

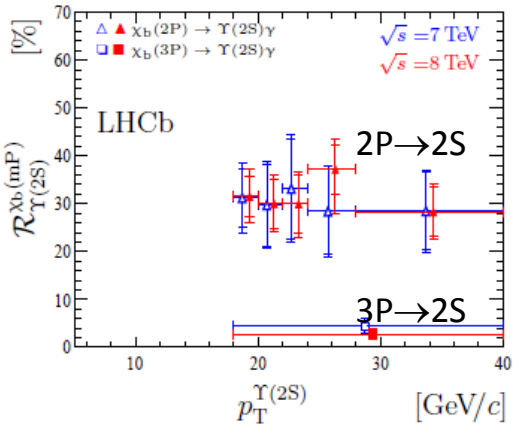
- Feedown derived from:

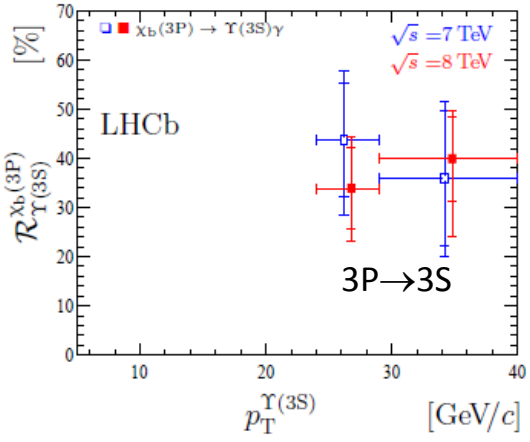
$$R_{\Upsilon}^{\chi_b} = \frac{N_{\chi_b}}{N_{\Upsilon}} \times \frac{\varepsilon_{\Upsilon}}{\varepsilon_{\chi_b}}$$



- Systematic uncertainties:
  - photon efficiency: 3%
  - Unknown polarisation: 1-9%
  - Modeling of the 2 χ_b spin states (relative rate and mass spliting): up to 20%

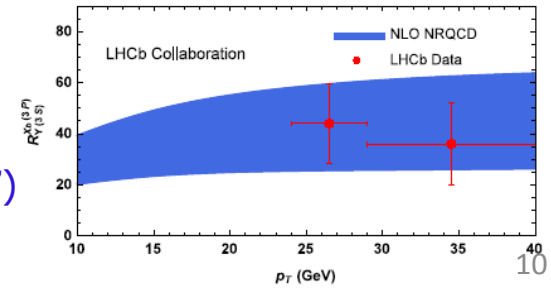






⇒ Feeddown ~ 30% for all Υ's !

In agreement with prediction from NLO NRQCD (arxiv:1410.8537)

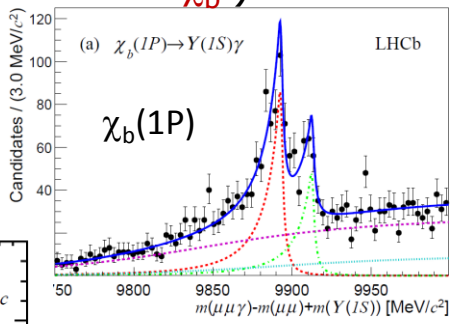


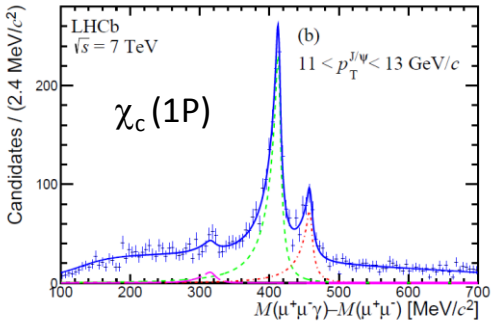
JHEP10(2014)088
JHEP10(2013)115

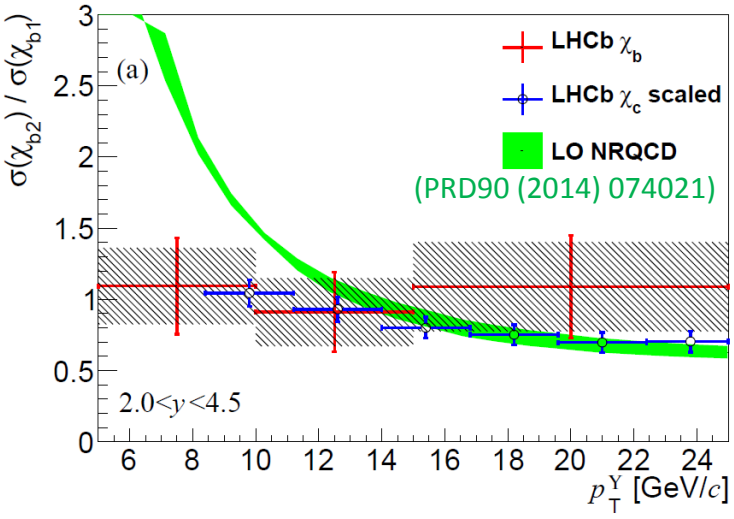
Relative production of $\chi_{b,c}$ spin states

- Study the relative production of the 2 spin states $\chi_{b(c)2}(1P)$ and $\chi_{b(c)1}(1P)$
  ⇒ test color octet and color singlet relative contributions
- Use converted photons in order to separate the 2 states (σ=1.2 MeV for χ_b)
  - Drawback: low efficiency

⇒ χ_b and χ_c results in agreement
⇒ Ratio of cross-section ~ flat with pT
⇒ Increase predicted by LO NRQCD at low pT seems softer

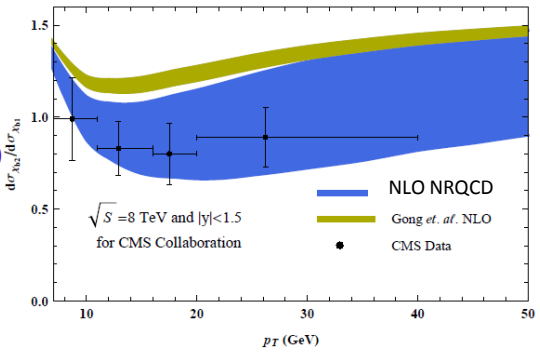






⇒ better agreement with prediction from NLO NRQCD (arxiv:1410:8537)

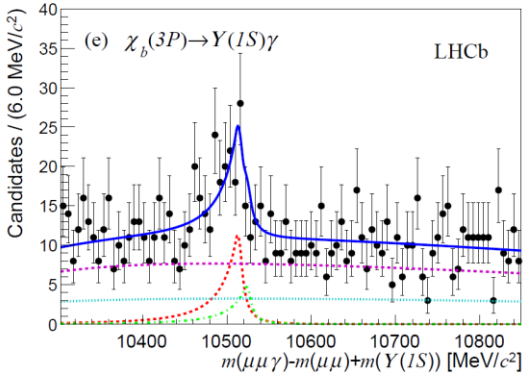
arxiv:1410:8537



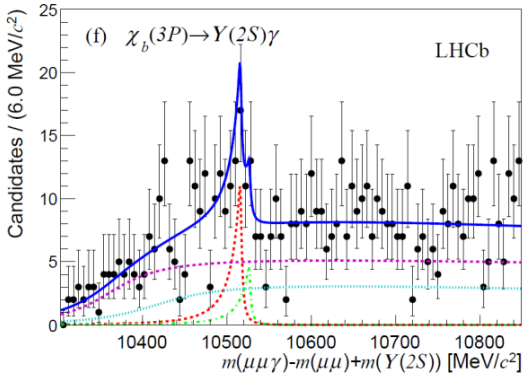
$\chi_b(3P)$ mass

- Using all radiative transitions $\chi_b(3P) \to \gamma\ \Upsilon(1,2,3S)$ with converted and non-converted photons

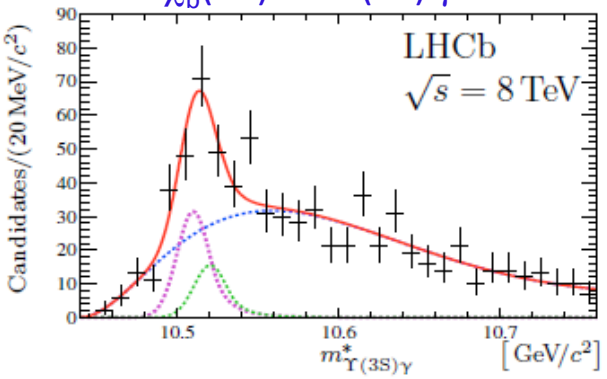
$\chi_b(3P) \to \Upsilon(1S)\ \gamma(\to ee)$



$\chi_b(3P) \to \Upsilon(2S)\ \gamma(\to ee)$



$\chi_b(3P) \to \Upsilon(3S)\ \gamma$



arxiv:1409.1408

arxiv:1407.7734

$\Rightarrow$ m ($\chi_{b1}(3P)$)= $10512.1 \pm 2.1_{exp} \pm 0.9_{model}$ MeV/c^2

In agreement with ATLAS measurement: m($\chi_b(3P)$)= $10530 \pm 5 \pm 9$ MeV/c^2 PRL108(2012)152001

and theoretical prediction: m($\chi_{b1}(3P)$)~10516 MeV/c^2 PRD38(1988)279

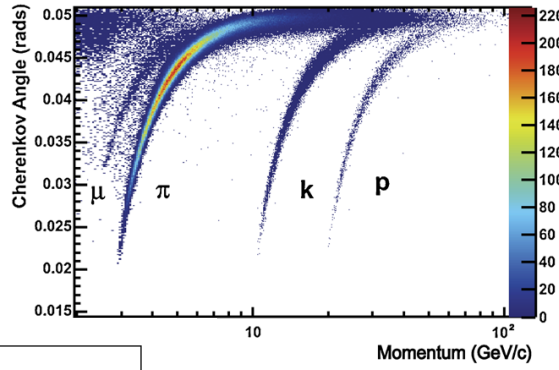
arXiv:1409:3612

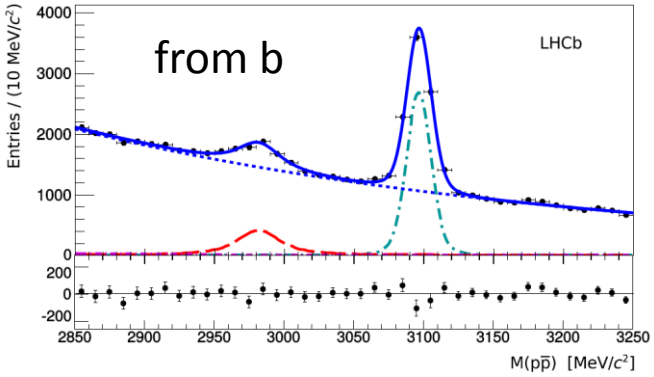
η_c production

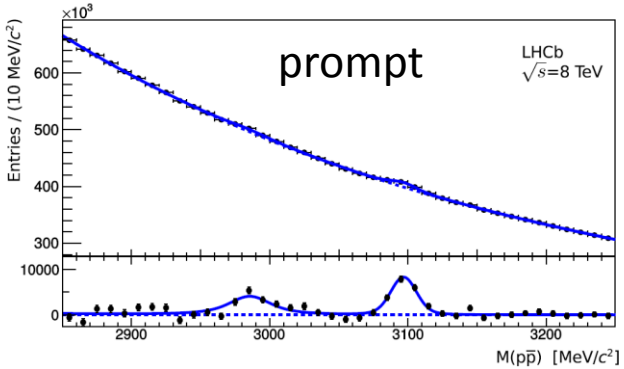
- Theory: NRQCD predicts different pT dependance for η_c and J/ψ production (due to spin difference)

- LHCb analysis:
  - Use common decay of η_c and J/ψ to $p\bar{p}$ and good LHCb particle ID for protons
  - pT($p\bar{p}$)>6.5GeV/c
  - Clear signal in from-b sample (t_z>80fs) used for parametrizing the prompt signal shapes (t_z<80fs)

  + measurement of η_c natural width and η_c-J/ψ mass difference



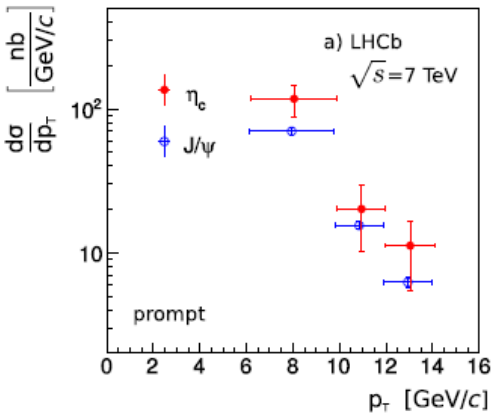




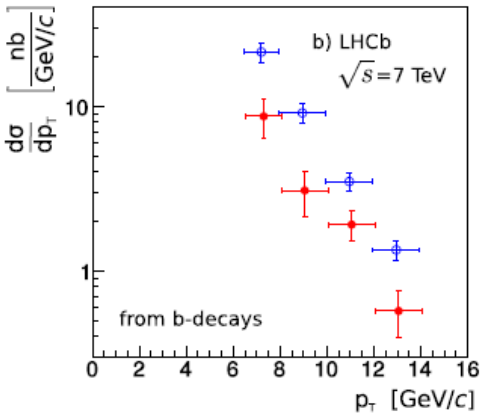
η_c production

- Normalize η_c to J/ψ using J/ψ absolute cross-section measurement

prompt



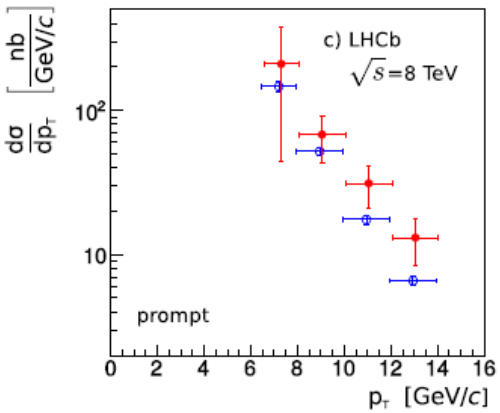
from-b

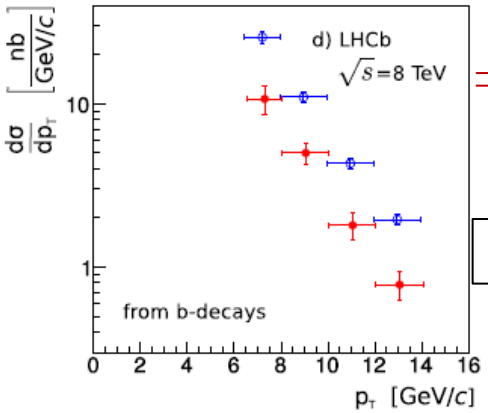


$\Rightarrow \eta_c$ production cross sections for 2<y<4.5 and p_T > 6.5 GeV/c:

$$\left(\sigma_{\eta_c(1S)}\right)_{\sqrt{s}=7\,\mathrm{TeV}} = 0.52 \pm 0.09 \pm 0.08 \pm 0.06_{\sigma_{J/\psi},\mathcal{B}}\ \mu\mathrm{b},$$
$$\left(\sigma_{\eta_c(1S)}\right)_{\sqrt{s}=8\,\mathrm{TeV}} = 0.59 \pm 0.11 \pm 0.09 \pm 0.08_{\sigma_{J/\psi},\mathcal{B}}\ \mu\mathrm{b},$$

$\Rightarrow$Input to theory for estimate of CS/CO contributions (arXiv: 1411.1247)





$\Rightarrow$inclusive branching fraction of b-hadrons to η_c

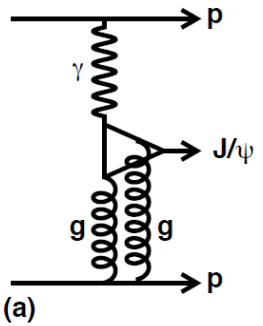
$$\mathcal{B}(b \to \eta_c(1S)X) = (4.88 \pm 0.64 \pm 0.25 \pm 0.67_{\mathcal{B}}) \times 10^{-3}$$

Uncertainty from Br($\eta \to p\bar{p}$), Br(J/$\psi \to p\bar{p}$) and Br(b $\to$J/ψX)

$\Rightarrow$ Similar p_T dependance

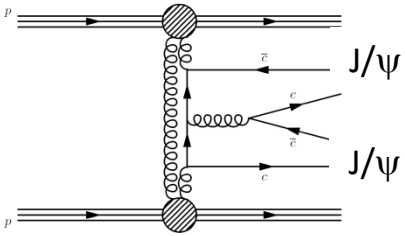
Exclusive charmonium production

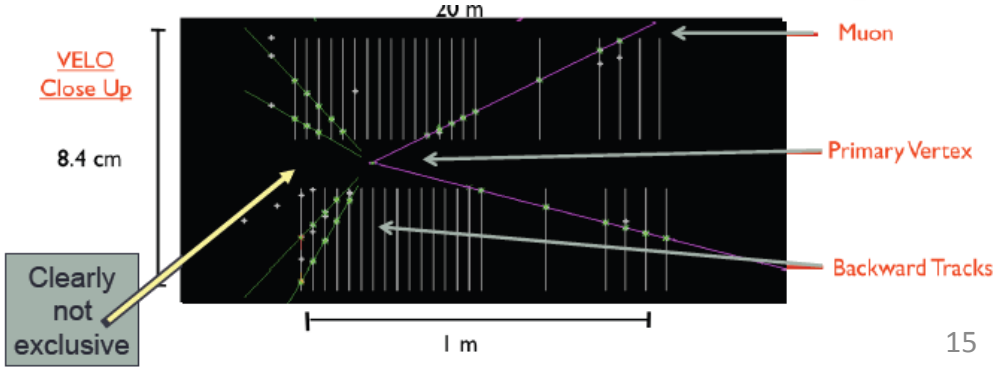
- Exclusive J/ψ, ψ(2S) and χ_c production:
  - test of QCD and pomeron exchange
  - sensitive to gluon-saturation effects
  - provides constraints on gluon PDF at small x (5×10^{-6})



- LHCb analysis:
  - single J/ψ, ψ(2S) exclusive production J. Phys. G: Nucl. Part. Phys. 41 (2014) 055002
  - double charmonium exclusive production: J/ψ, ψ(2S) and χ_c J. Phys. G: 41 (2014) 115002

⇒ select events with
  - exclusively 2 or 4 tracks identified as μ (no other activity)
    - Use backward extension of the vertex detector
  - no photons or 1 for $\chi_c \to J/\psi\gamma$
  - low pT (>400MeV/c)





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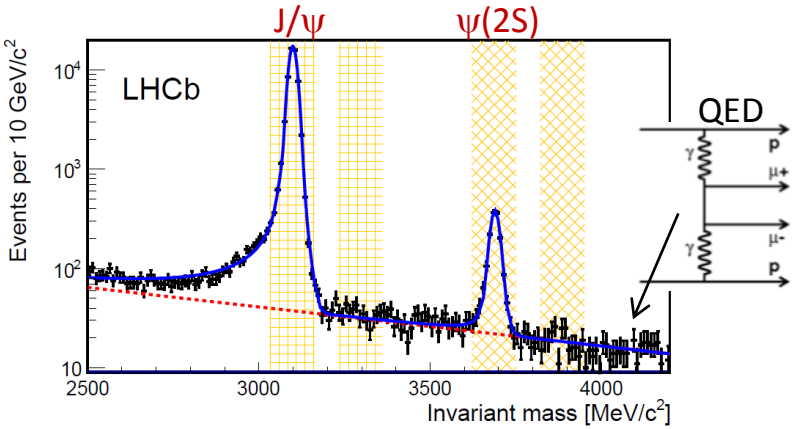
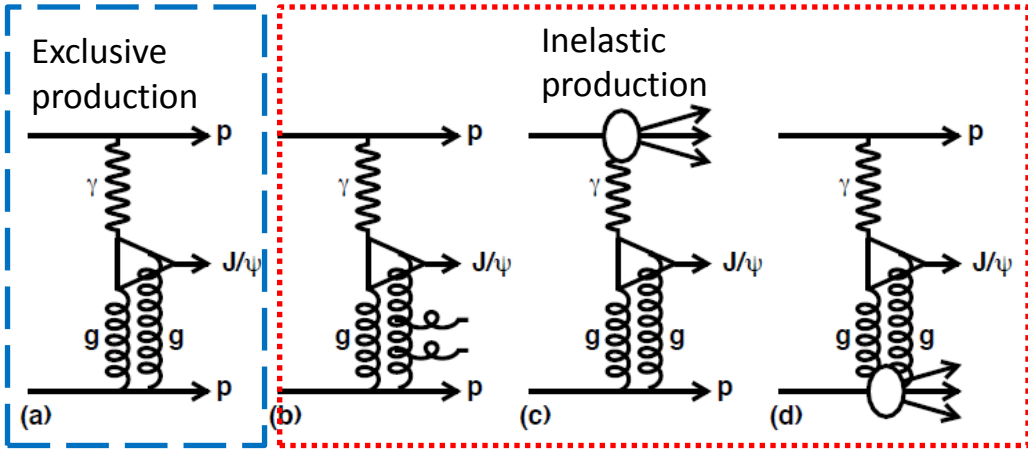
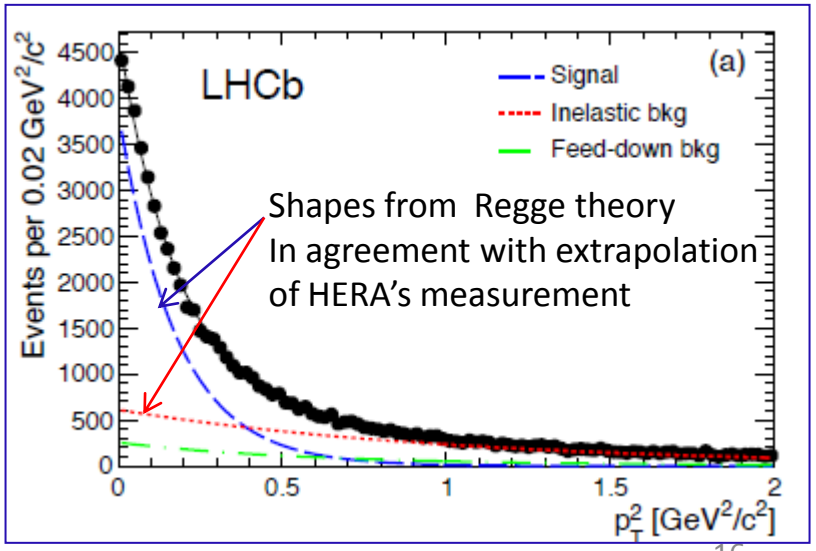
Exclusive J/ψ and ψ(2S) production

- Backgrounds:
  - Non resonant (QED)
  - Feeddown (χ_c)
  - Inelastic





- Signal and inelastic background shapes:
  - Regge theory: $\exp(-bp_T^2)$
  - b parameters fitted to data in agreement with extrapolation from HERA's data



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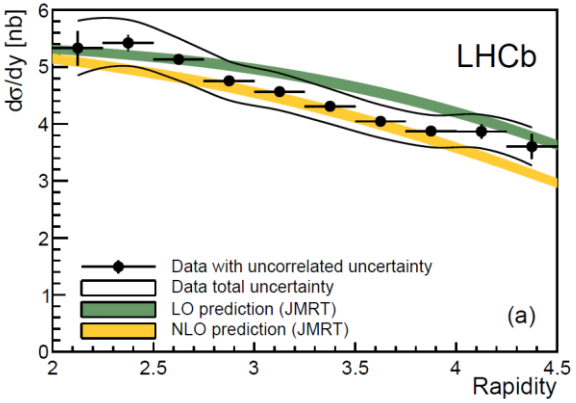
Exclusive J/ψ and ψ(2S) production

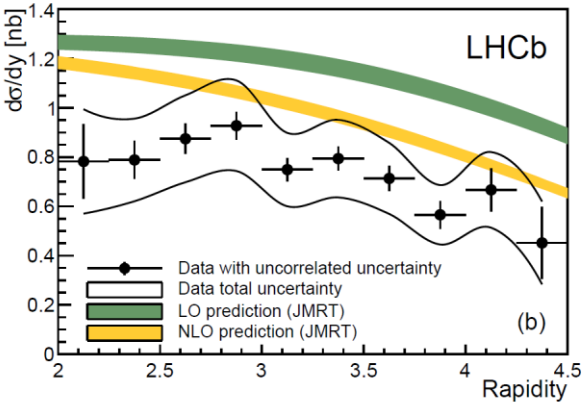
- Differential cross section in agreement with NLO prediction and with saturation models

J/ψ

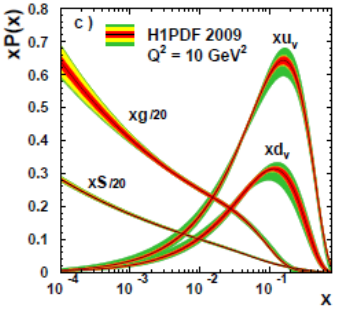
ψ(2S)

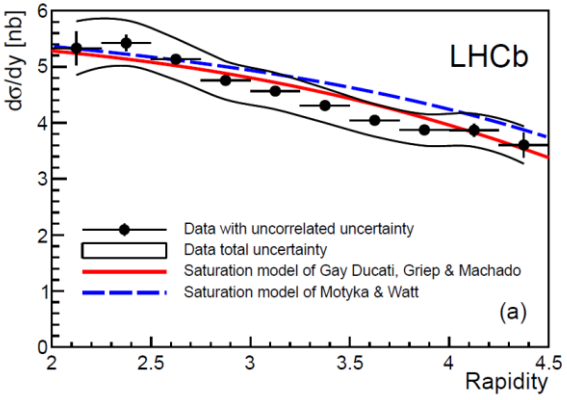
LO and NLO
JHEP1311(2013)085

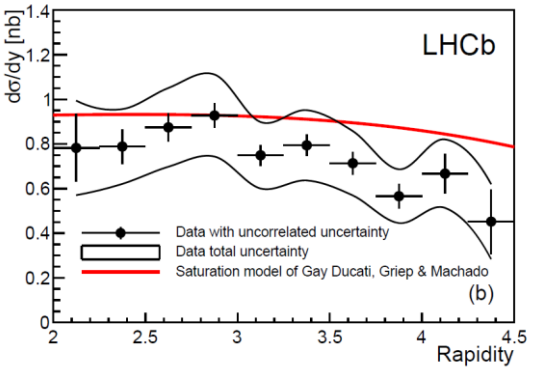




Saturation models
arXiv:1305.4611
PRD78(2008)014023







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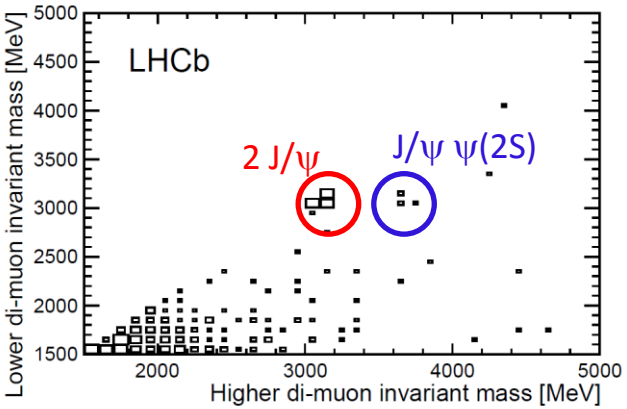
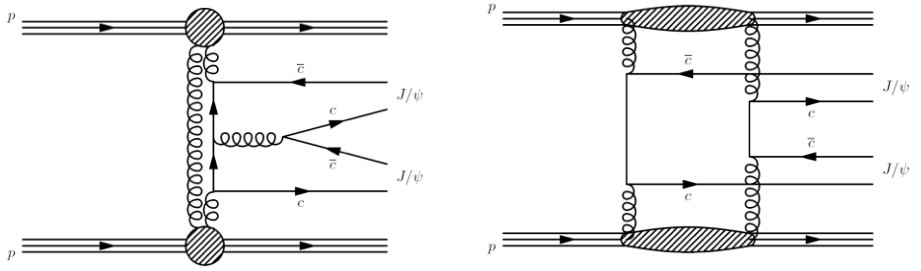
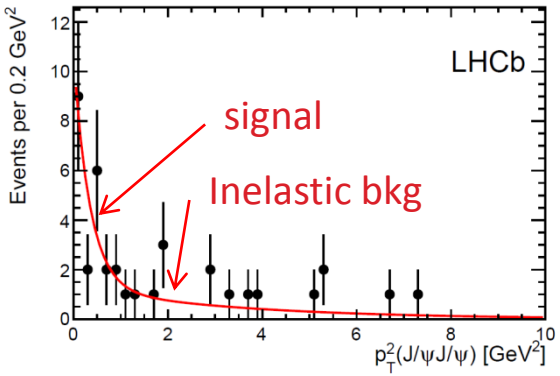
Double charmonium exclusive production

- Similar analysis for double exclusive production of J/ψ, ψ(2S) and χ_c





2 J/ψ candidates



Cross sections in 2.0<y<4.5 (elastic + inelastic):

$$\begin{aligned}
\sigma^{J/\psi\,J/\psi} &= 58 \pm 10(\text{stat}) \pm 6(\text{syst})\,\text{pb}, \\
\sigma^{J/\psi\,\psi(2S)} &= 63^{+27}_{-18}(\text{stat}) \pm 10(\text{syst})\,\text{pb}, \\
\sigma^{\psi(2S)\psi(2S)} &< 237\,\text{pb}, \\
\sigma^{\chi_{c0}\chi_{c0}} &< 69\,\text{nb}, \\
\sigma^{\chi_{c1}\chi_{c1}} &< 45\,\text{pb}, \\
\sigma^{\chi_{c2}\chi_{c2}} &< 141\,\text{pb},
\end{aligned}$$

2 J/ψ production cross section in agreement with theory prediction but large errors on both sides

Shapes in agreement with expectations from single production

Exclusive fraction: 42±13 %

Summary and Prospects

- LHCb is contributing to the progress in understanding quarkonium production:

  Inclusive
  - Differential production cross section (J/ψ, $\psi(2S)$, Υ's, η_c)
  - Including production from b
  - Feeddown of χ_b to Υ's

  Exclusive charmonium
  - Single and double charmonium

  $\Rightarrow$ Constraints on QCD models, PDFs, MC tuning

- Prospects
  - Bottomonium measurements are mostly statistically limited $\Rightarrow$ more to come
  - Υ polarisation
  - Production measurements of J/ψ, Υ ($\psi(2S)$) will be repeated at 13 TeV with early 2015 data