Quarkonium Production at LHCb

Monica Pepe Altarelli, CERN

On behalf of the LHCb collaboration

LHCP2013, Barcelona

Motivation

- Heavy quarkonium states are particularly interesting systems to test our understanding of strong interactions, both at perturbative and non-perturbative level
- Many papers about theory and experiments
  - LHCb paper on J/ψ production at 7 TeV is one of the most cited ones, just behind searches for $B_s \rightarrow \mu\mu$ and CPV in charm!

Models for heavy-quarkonium production

- Colour Singlet (CS) Model
  - Quarkonia are produced as observable colour-neutral $Q\bar{Q}$ pairs
  - Poor description of production rates at high p_T (LO predicts too fast a decrease in p_T: $\approx p_T^{-8}$)
  - Very large corrections at NLO and NNLO* (subset of NNLO) raise substantially the cross-sections at large p_T ($\approx p_T^{-6}, p_T^{-4}$) bringing them closer to the data
- NRQCD (non relativistic QCD) formalism
  - Factorizes the short distance coefficients (calculated perturbatively as expansions in α_S) from long-distance matrix elements (assumed to be process independent) to be extracted from data → predictive power
  - Includes CS and Colour Octet (CO) amplitudes
  - Good description of data on cross-sections, while description of data on polarisation is still confused
- FONLL (Fixed Order Next to Leading Log) formalism
  - Describes quarkonium production from *b*-hadron decays
  - Combines Fixed Order Calculation (FO) with all order resummation of Leading and NL Logs (NLL)

Selected LHCb experimental results

- Production of
  - J/ψ and $\Upsilon(nS)$
  - $\psi(2s)$
  - Double J/ψ
  - Exclusive J/ψ, $\psi(2s)$
  - J/ψ in pA/Ap collisions

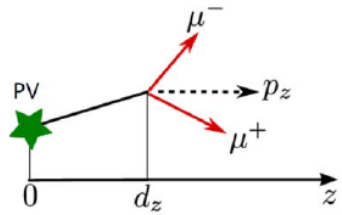
arXiv:1304.6988

J/ψ and ϒ(nS) production at √s=8 TeV

- Double differential in p_T and y

$$\frac{d^2\sigma}{dydp_T}(pp \to VX) = \frac{N(V \to \mu^+\mu^-)}{L \times \varepsilon \times BR(V \to \mu^+\mu^-) \times \Delta y \times \Delta p_T}$$

- In the range
  - $0<p_T<14$ GeV/c for the J/ψ, $2.0<y<4.5$
  - $0<p_T<15$ GeV/c for the ϒ(nS), $2.0<y<4.5$



- Prompt J/ψ and J/ψ from *b* separated by

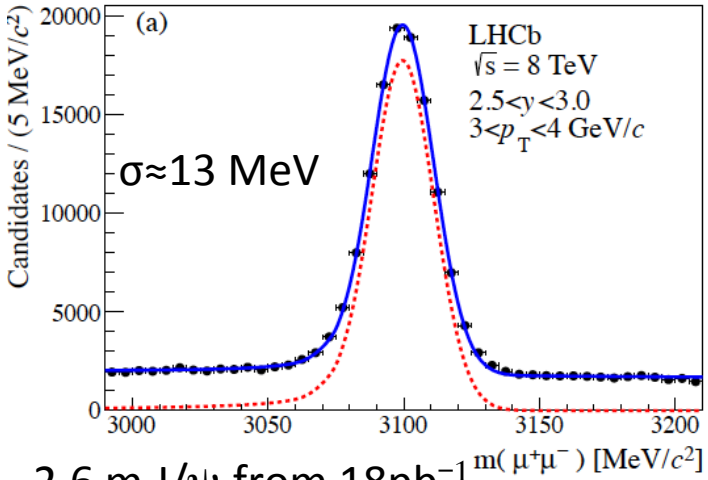
$$t_Z = \frac{(z_{J/\Psi} - z_{PV}) \times M_{J/\Psi}}{p_z}$$

- Signal extraction
  - J/ψ: two-dimensional fit to $m_{\mu\mu}$ and t_Z in each (p_T,y) bin
  - ϒ(nS): fit to $m_{\mu\mu}$ in each (p_T,y) bin

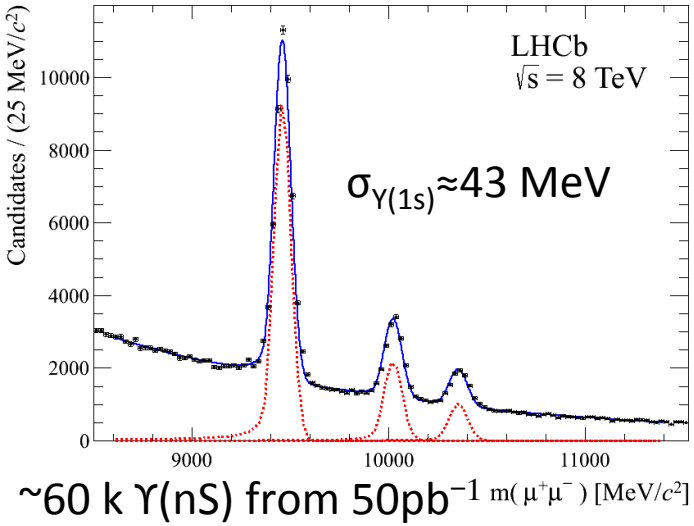
- Results shown under assumption of zero polarisation

arXiv:1304.6988

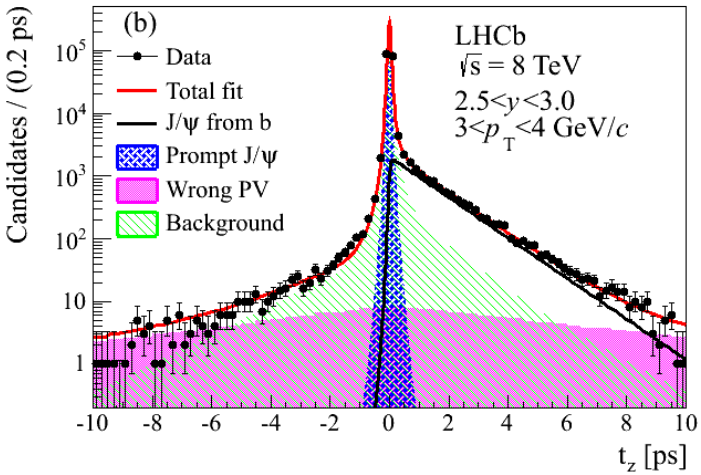
J/ψ and ϒ(nS) production at √s=8 TeV

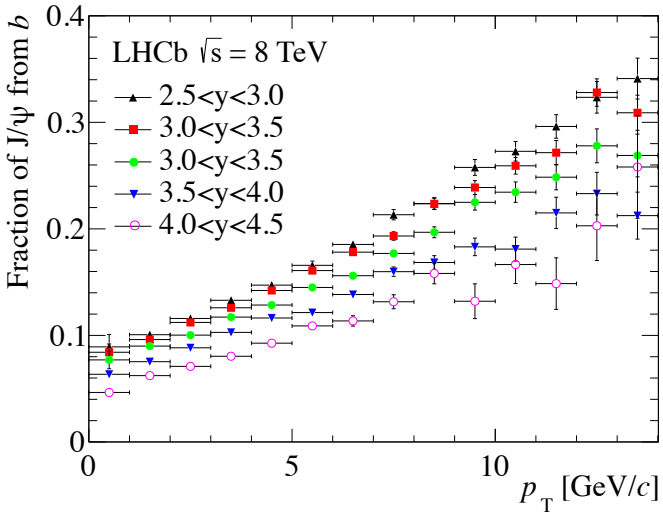


2.6 m J/ψ from 18pb^{-1}



~60 k ϒ(nS) from 50pb^{-1}





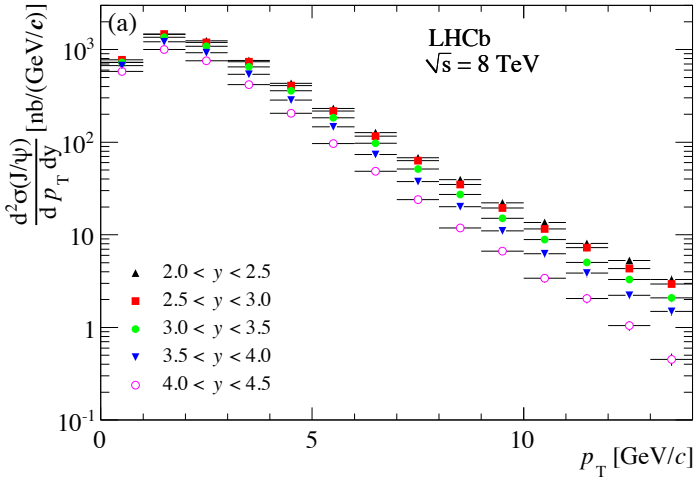
Smaller b fraction at low p_T, and for forward data

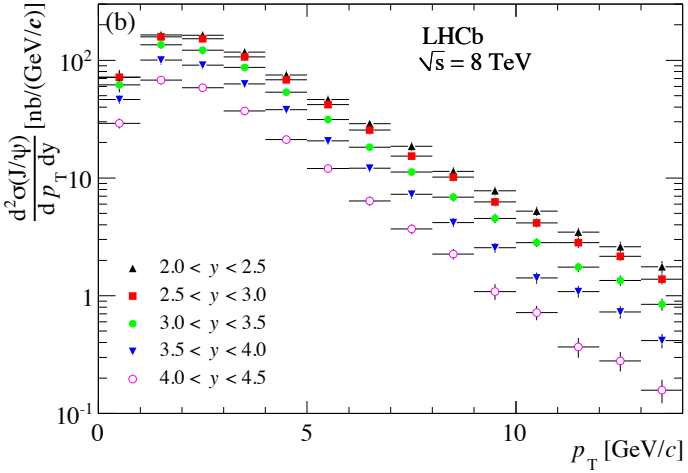
Results: J/ψ cross-section

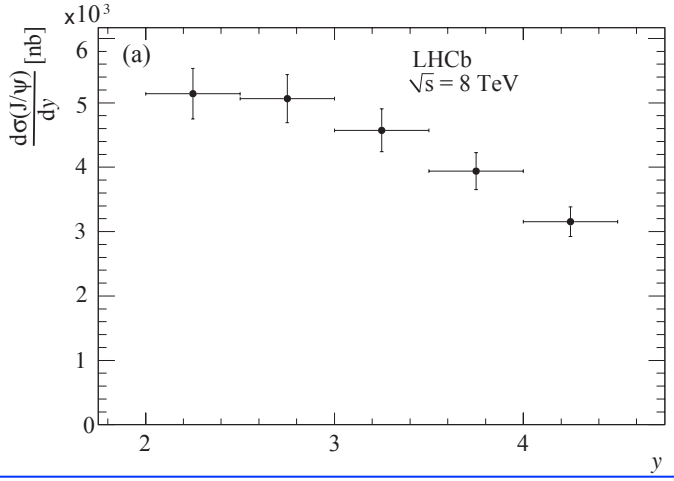
arXiv:1304.6988

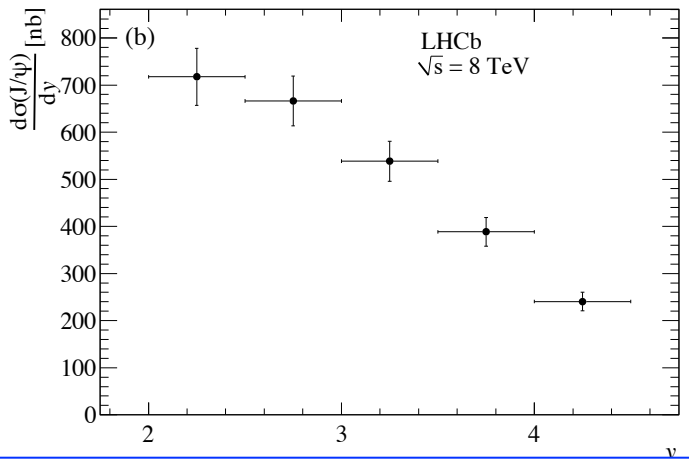
Prompt J/ψ

From b







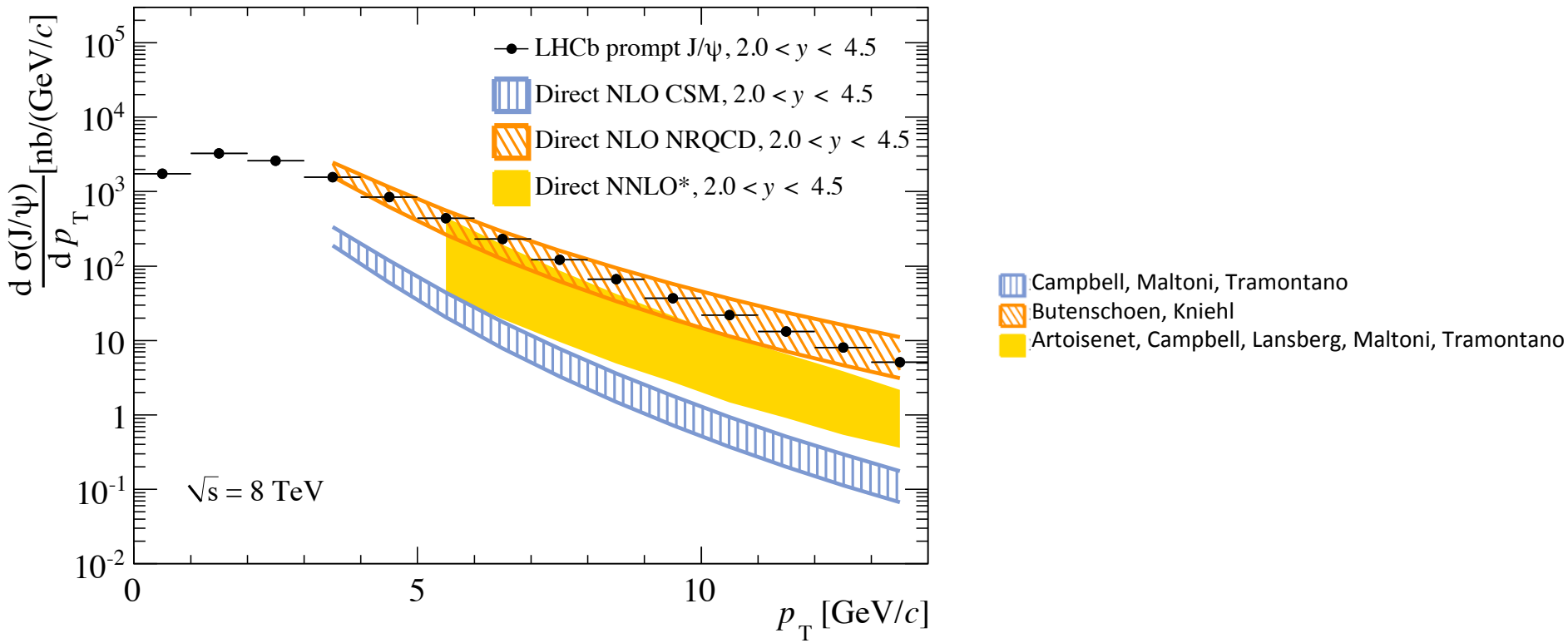


σ (prompt J/ψ, $p_T < 14$ GeV/c, $2.0 < y < 4.5$) $= 10.94 \pm 0.02 \pm 0.79$ μb

σ (J/ψ from b, $p_T < 14$ GeV/c, $2.0 < y < 4.5$) $= 1.28 \pm 0.01 \pm 0.11$ μb

arXiv:1304.6988

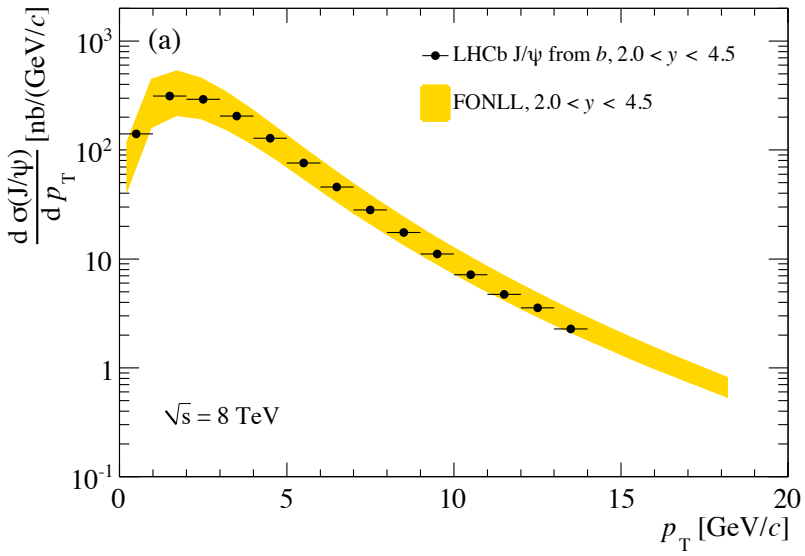
Comparison with theory, prompt J/ψ



- Prompt: J/ψ produced at the interaction point plus feed-down from heavier charmonium (e.g. ~20% from $X_C \rightarrow J/\psi\gamma$ and ~8% from $\psi(2s) \rightarrow J/\psi\pi\pi$)
- Feed-down not included in theory (Direct)
- Allowing for this, both NNLO* CSM and NRQCD provide reasonable description of the experimental data

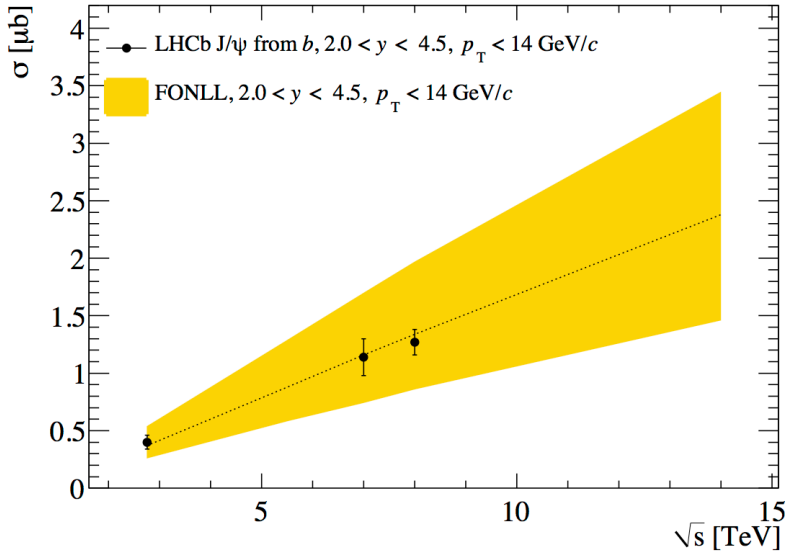
arXiv:1304.6988

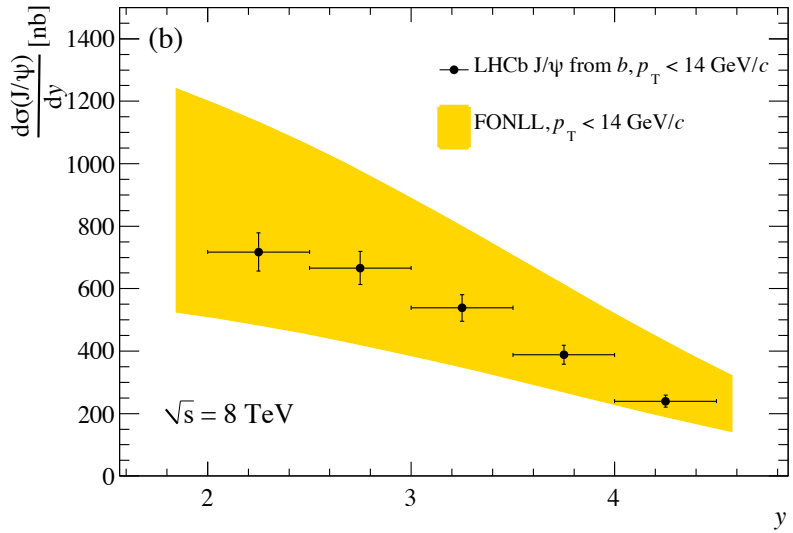
Comparison with theory, J/ψ from *b*



$$\sigma(pp \to b\bar{b}X)_{8TeV} = \alpha_{4\pi} \frac{\sigma(J/\Psi \text{ from } b,\ p_T < 14GeV,\ 2.0 < y < 4.5)}{2B(b \to J/\Psi X)} = 298 \pm 2 \pm 36 \mu b$$

$$\alpha_{4\pi} = 5.4$$





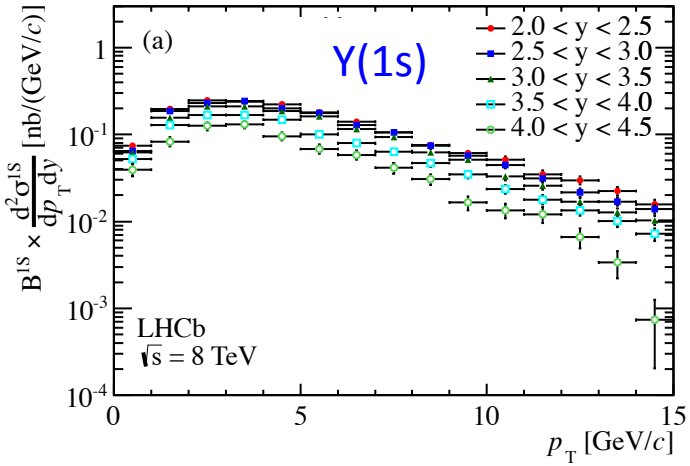
FONLL: Cacciari et al, Cacciari, Greco & Nason

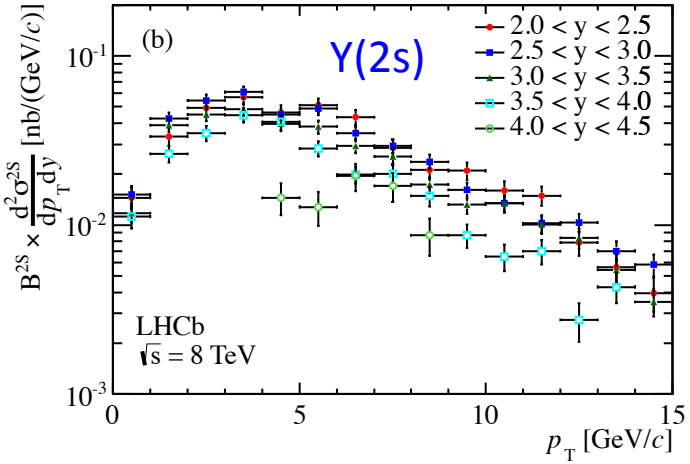
Very good description of the data, including behaviour as a function of √s

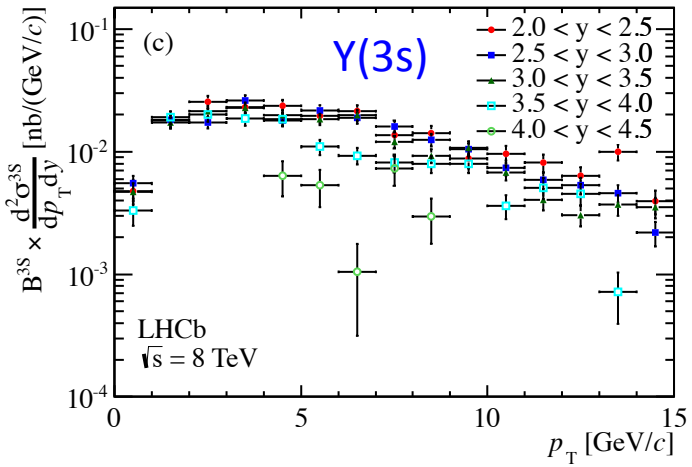
Theory of σ_{bb} BR(b→J/ψ) is simpler

arXiv:1304.6988

Results: Υ(ns) cross-sections



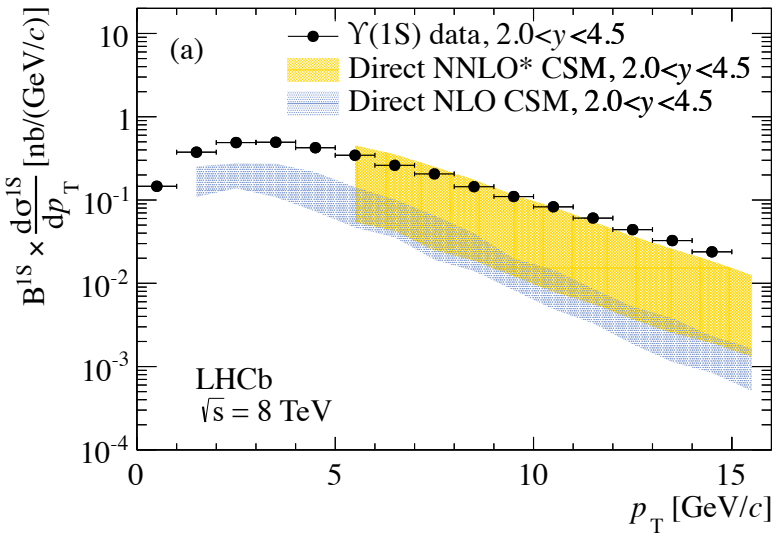


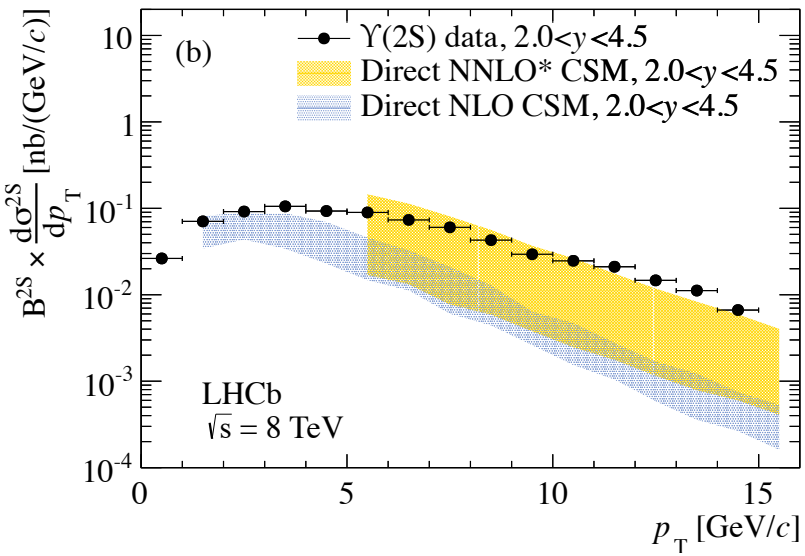


$$\sigma(pp \to \Upsilon(1S)X) \times B^{1S} = 3.241 \pm 0.018 \pm 0.231\,\text{nb},$$
$$\sigma(pp \to \Upsilon(2S)X) \times B^{2S} = 0.761 \pm 0.008 \pm 0.055\,\text{nb},$$
$$\sigma(pp \to \Upsilon(3S)X) \times B^{3S} = 0.369 \pm 0.005 \pm 0.027\,\text{nb},$$

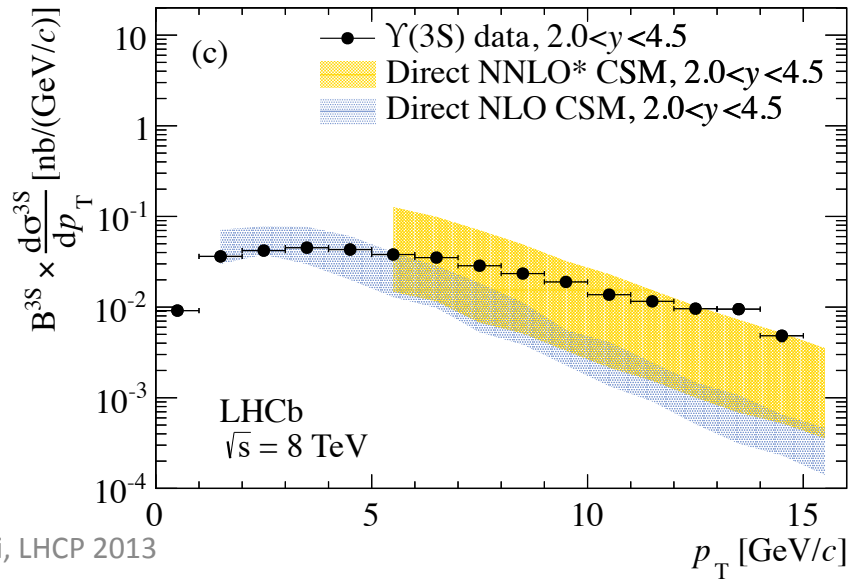
arXiv:1304.6988

Comparison with theory





NNLO* CSM Artoisenet, Campbell, Lansberg, Maltoni, Tramontano
NLO CSM Campbell, Maltoni, Tramontano

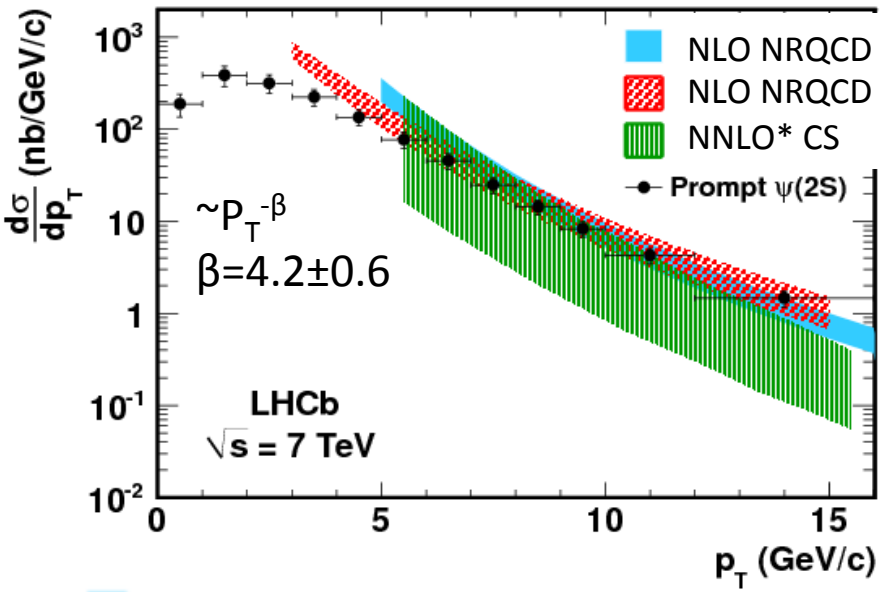


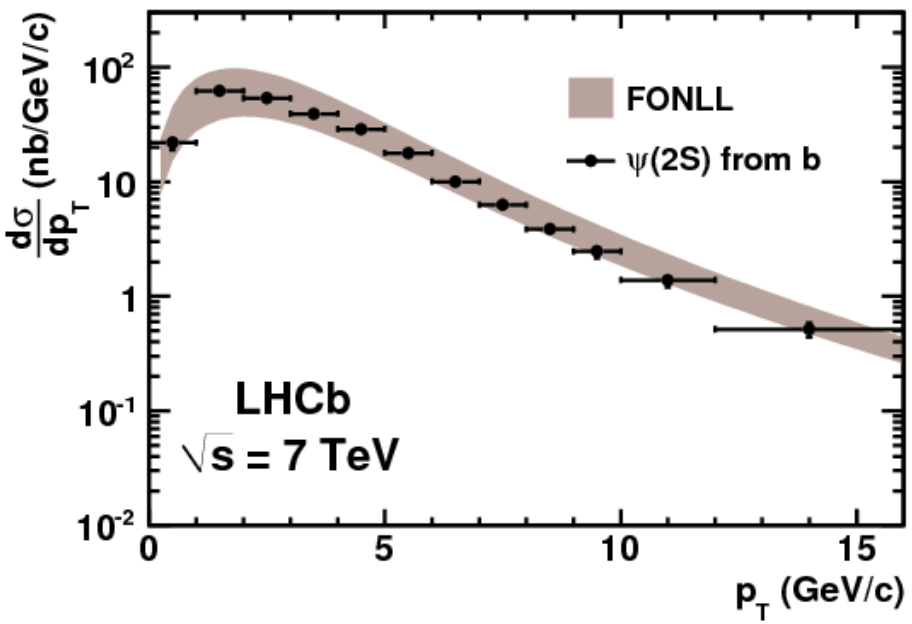
- e.g. ~20% feed-down from $X_b(1P) \rightarrow \Upsilon(1S)\gamma$ not included in the theory
- NNLO* calculations provide a reasonable description of the data

Eur.Phys.J.C (2012) 72:2100

ψ(2S) production at 7 TeV

- $\psi(2s) \rightarrow \mu^+\mu^-$, $\psi(2s) \rightarrow J/\psi\pi^+\pi^-$ - results are combined
- Prompt ψ(2s) and ψ(2s) from *b*
- No significant feed-down from excited charmonium states → simpler comparison with models



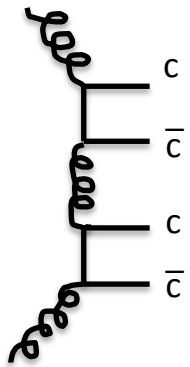


Ma, Wang, Chao
Kniehl, Butenschoen
Artoisenet et al

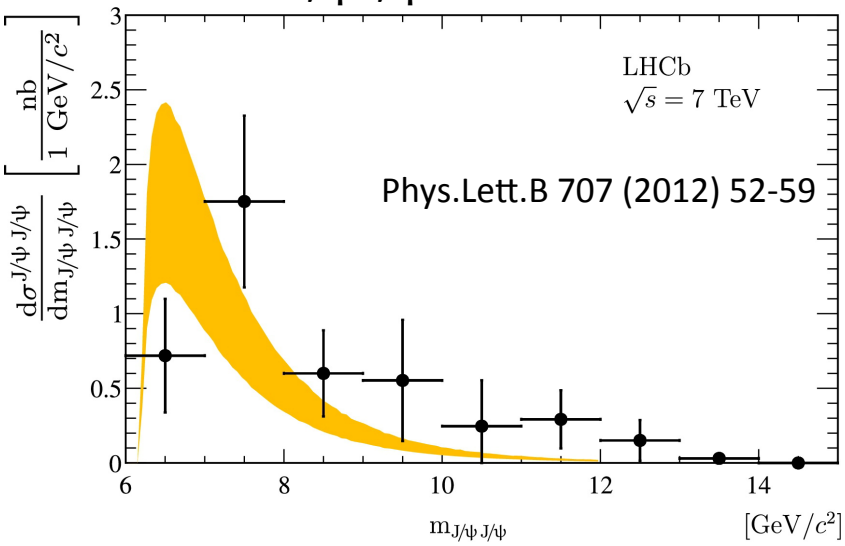
FONLL Cacciari et al, Cacciari, Greco & Nason

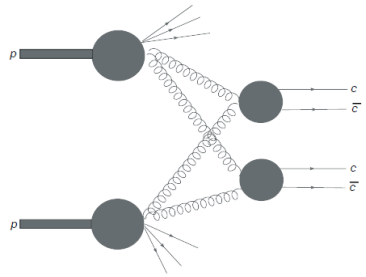
Double J/ψ production at 7 TeV

- As charmonium production cross-sections are large, the question of multiple production naturally arises
- How to get double J/ψ production?
  - gg→J/ψ J/ψ LO α_S^4 PQCD → ~4 nb in LHCb acceptance
- LHCb result $\sigma_{J/\psi\ J/\psi}$=5.1±1.0±1.1 nb



Berezhnoy, Likhoded, Luchinsky, Novoselov



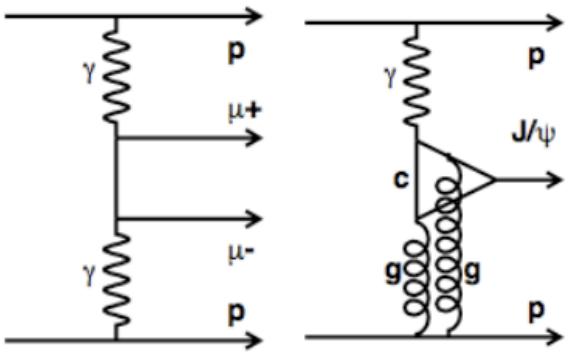


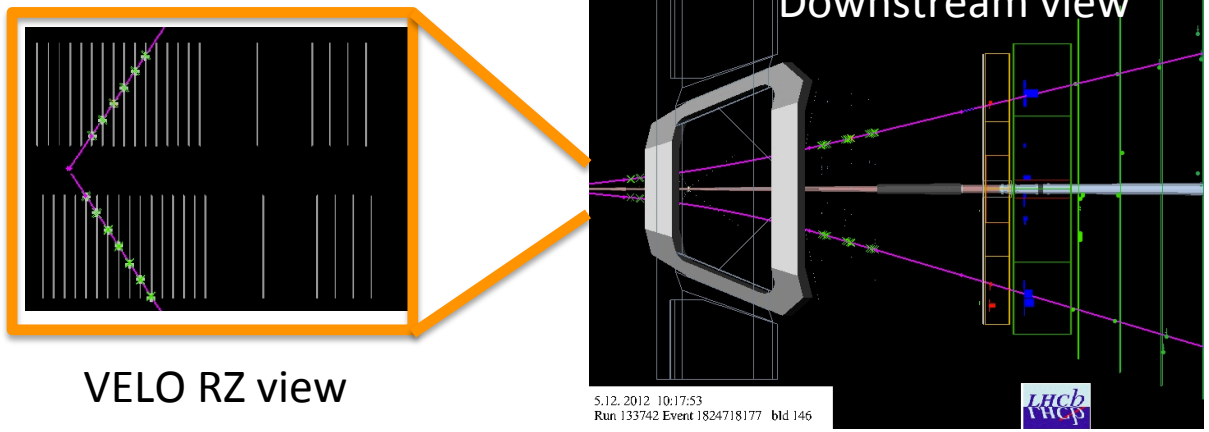
- Double Parton Scattering → ~4 nb in LHCb acceptance
- Also measured $J/\psi D^0$, $J/\psi D^+$, $J/\psi D_S$, $J/\psi \Lambda_C$ .....

JHEP06 (2012) 141

Exclusive J/ψ, ψ(2s) production

- Two muons and nothing else





VELO RZ view

- Cross section x branching ratio (2010 data sample of 36 pb^{-1})

$$\sigma_{pp\to J/\psi(\to\mu^+\mu^-)}(2.0 < \eta_{\mu^\pm} < 4.5) = 307 \pm 21 \pm 36 \text{ pb},$$

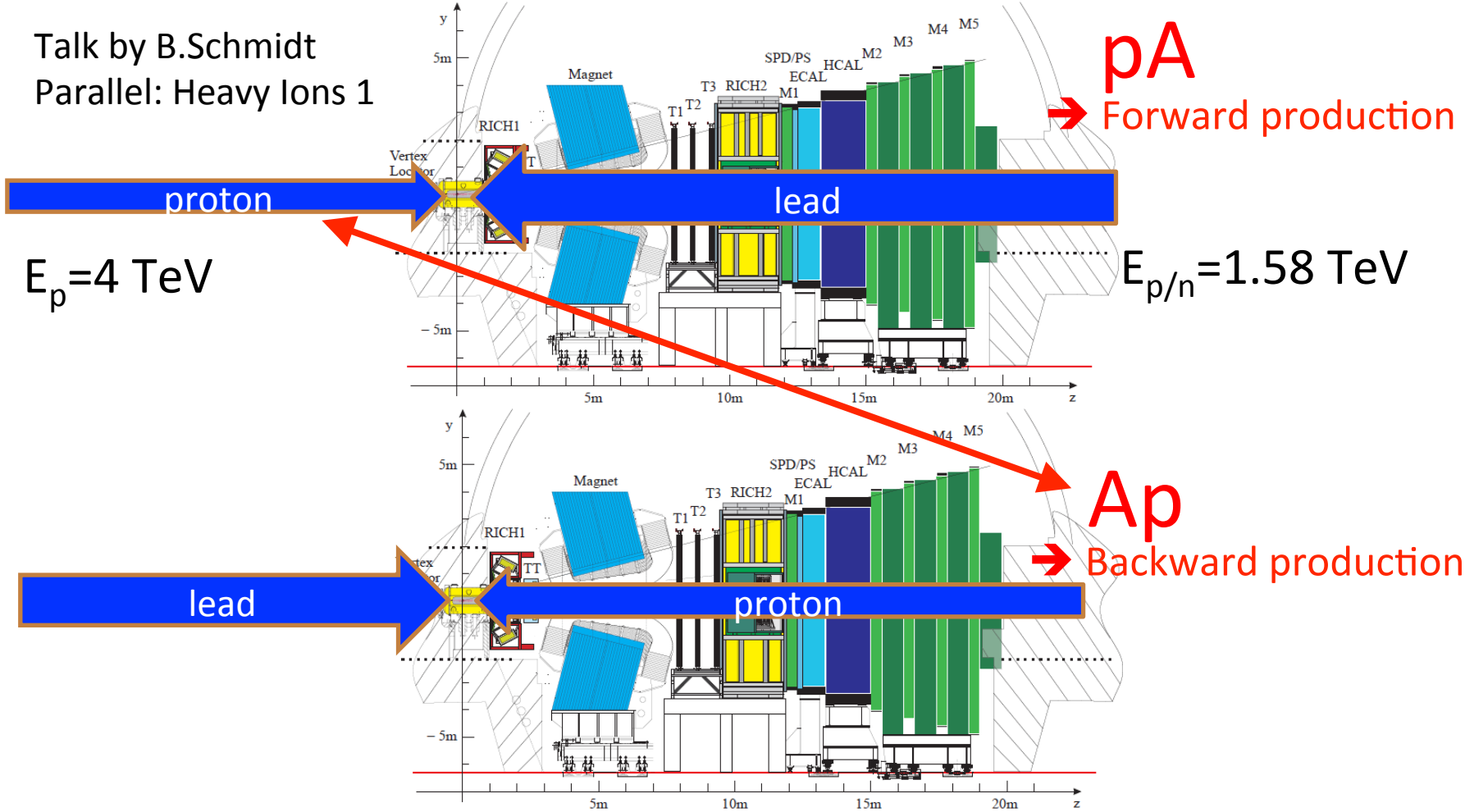
$$\sigma_{pp\to\psi(2S)(\to\mu^+\mu^-)}(2.0 < \eta_{\mu^\pm} < 4.5) = 7.8 \pm 1.3 \pm 1.0 \text{ pb},$$

J.Phys.G 40(2013)045001

- Measured cross sections are consistent with theoretical predictions (L. Motyka & G. Watt, W. Shafer & A. Szczurek, SuperChic, Starlight)
- New trigger implemented to increase rate of exclusive events (*e.g.* use of upstream silicon sensors to veto backwards activity, soft p_T cuts for hadronic final states) ~ 1.4 fb^{-1} already collected and being analysed
  - Study charmonium decaying into two and four-body final states (*e.g.* $\chi_{c0}\to K^+K^-, p^+p^-$) to complement di-muon studies
  - Spectroscopy, etc

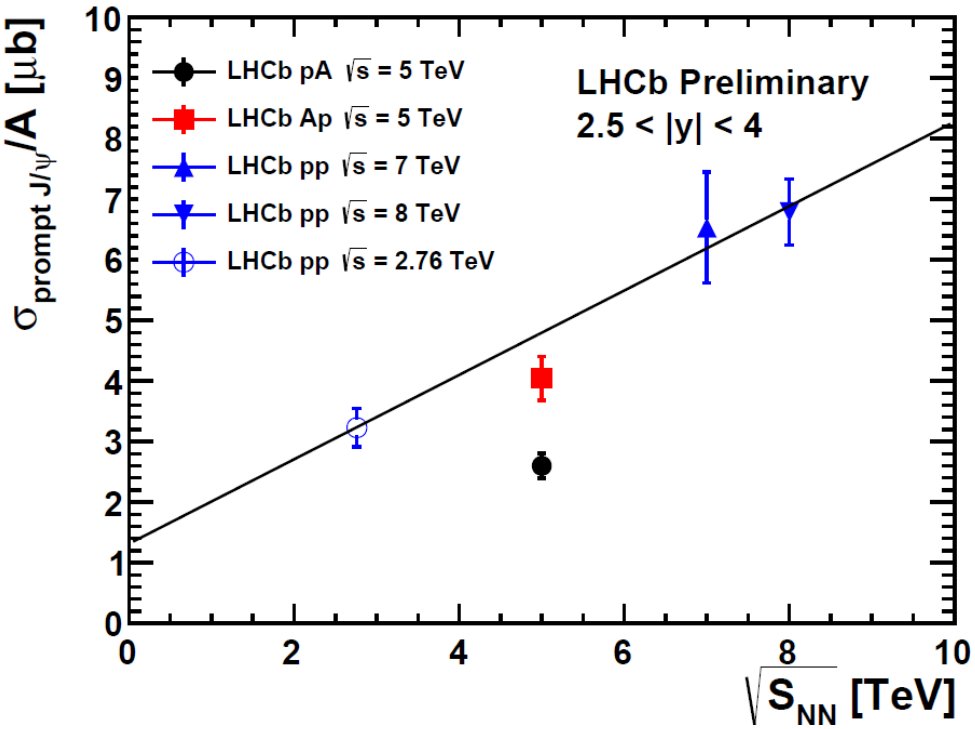
J/ψ production in pA/Ap collisions

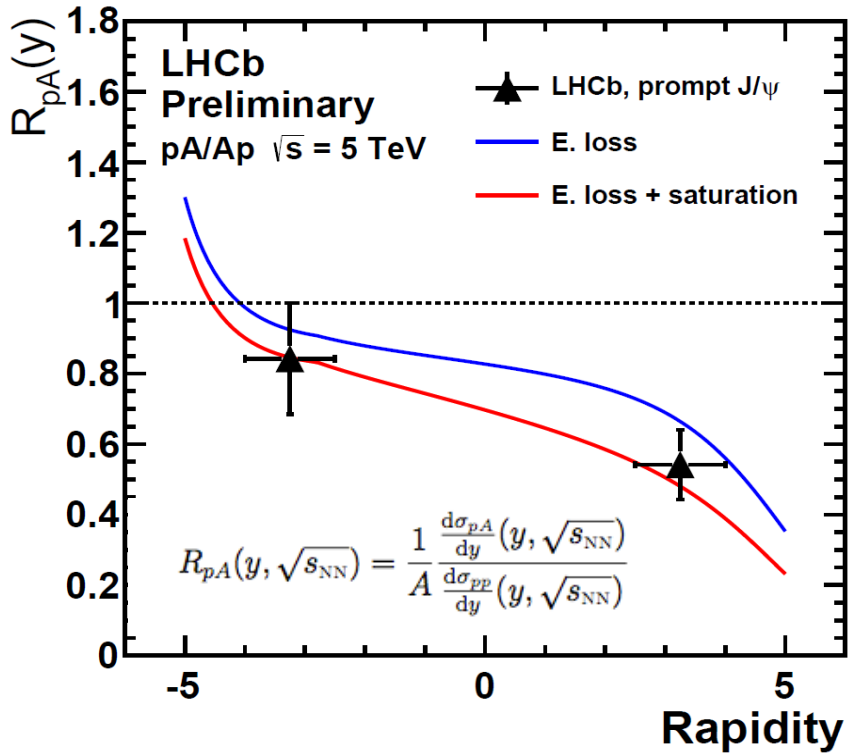
Talk by B.Schmidt
Parallel: Heavy Ions 1



- Centre-of-mass energy of pN system $\sqrt{s_{NN}}$=5 TeV
- Rapidity coverage 1.5<y<4.0 (pA) -5<y<-2.5 (Ap)
- Integrated luminosity ~2/nb

J/ψ production in pA/Ap collisions





Arleo & Peigne

- J/ψ production less suppressed in backward region
- Good agreement with theoretical model

Conclusions

- A wealth of measurements on quarkonium production performed by LHCb (and more coming)
- These results allow an in depth comparison with theoretical models
- A simple CSM is disfavoured by the data, while a combination of CS and CO, as implemented in the NRQCD model, or CS improved by QCD corrections (NNLO*) are more successful
- Many new ongoing studies (*e.g.* exclusive production, double quarkonium production, in p-lead collisions)

Back-up

χ_C production at 7 TeV

- Ratio $\sigma(\chi_{C1})/\sigma(\chi_{C2})$ sensitive to CS vs CO models
- $\chi_{CJ} \rightarrow J/\psi(\mu\mu)\gamma$
  - Photons reconstructed in calorimeters → signal peaks cannot be resolved(ΔM=45 MeV)
  - Photons converted before magnet, use $e^+ e^-$ tracks → gain resolution; χ_{C1}, χ_{C2} can be resolved but efficiency is lower
  - Analysis of full 2011 data sample (1 fb^{-1}) based on converted photons completed and under review (not yet public)

~20% χ_C feed-down contribution to J/ψ production