

Heavy flavour and quarkonium results in pp

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1st SaporeGravis day meeting @ IPN (Orsay), 23/11/2012

1 Introduction

2 Quarkonium production

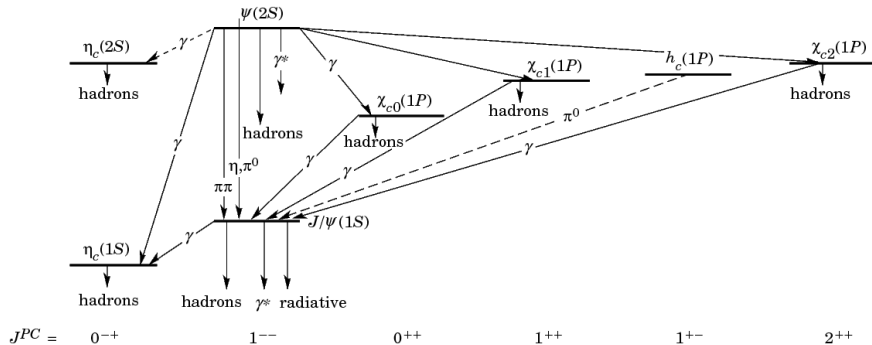
- Charmonium production
- Bottomonium production
- Polarization

3 Heavy flavour production

4 Summary

- Measurements of heavy quark and quarkonium production provide important tests of QCD
 - ▶ Parton distribution function
 - ▶ Hard parton scattering
 - ▶ Fragmentation
 - ▶ ...
- Quarkonium production
 - ▶ Colour singlet model (CSM)
 - ▶ NRQCD
 - ▶ ...

Charmonium



J/ψ production

- Sources of J/ψ

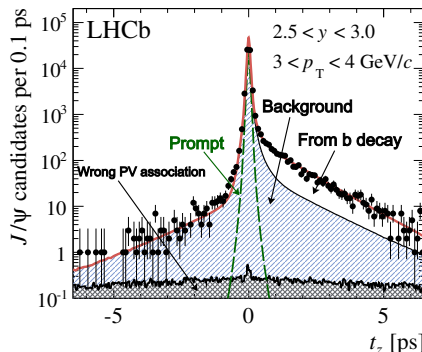
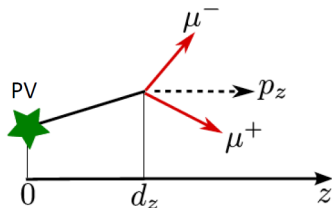
- ▶ Prompt J/ψ

- ★ Directly produced J/ψ

- ★ J/ψ from feed-down of $\chi_c, \psi(2S)$, experimentally challenging to separate

- ▶ J/ψ from b decays, background for quarkonium, while it provides access to b production, can be separated using lifetime information

[LHCb, EPJC 71 (2011) 1645]

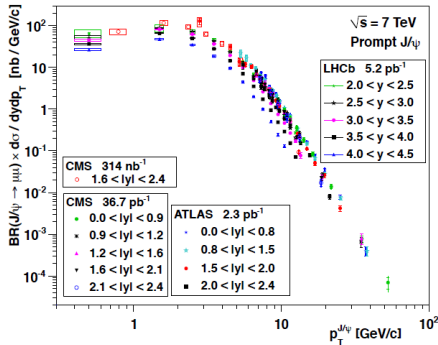
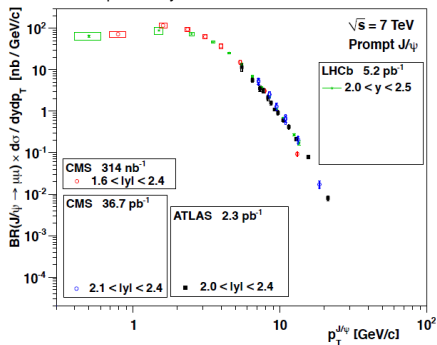


Prompt J/ψ differential cross-section

[ATLAS, NPB 850 (2012) 387] [CMS, JHEP 02 (2012) 011] [LHCb, EPJC 71 (2011) 1645]

- Results of three experiments agree well

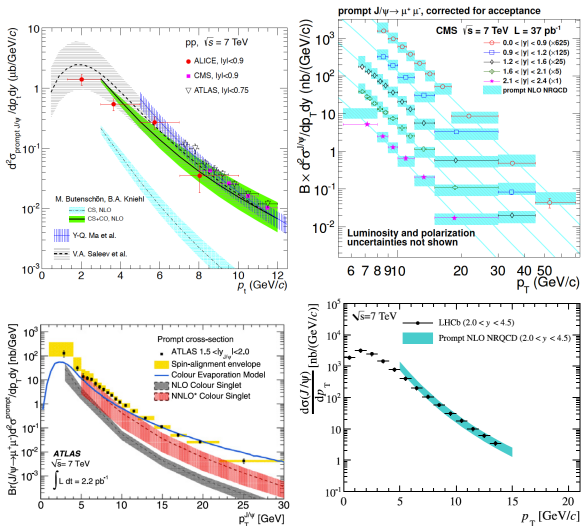
Compilation by H.K. Wöhri



Prompt J/ψ , compare with theo.

[ALICE, arXiv:1205.5880] [ATLAS, NPB 850 (2012) 387] [CMS, JHEP 02 (2012) 011] [LHCb, EPJC 71 (2011) 1645]

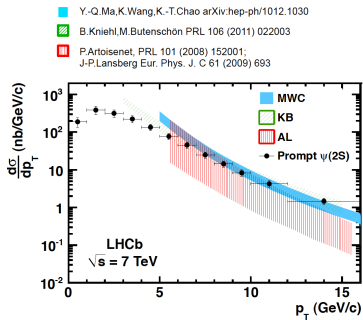
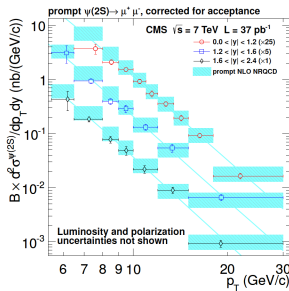
• Theo. predictions in agreement with data



$\psi(2S)$ production

[CMS, JHEP 02 (2012) 011] [LHCb, EPJC 72 (2012) 2100]

- $\psi(2S)$, free from prompt feed-down, more convenient to compare with theoretical prediction

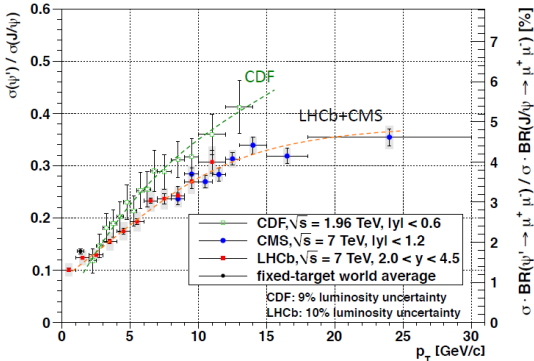


Ratio of prompt $\psi(2S)$ to J/ψ

[CDF, PRD 80 (2009) 031103] [CMS, JHEP 02 (2012) 011] [LHCb, EPJC 72 (2012) 2100] [JHEP10 (2008) 004]

- Ratio in the central region agree with that in the forward region, no strong dependence on rapidity?
- Stronger p_T dependence at CDF than at LHC

Compilation by H.K. Wöhri

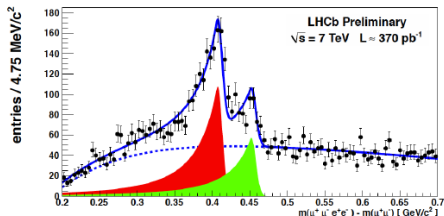
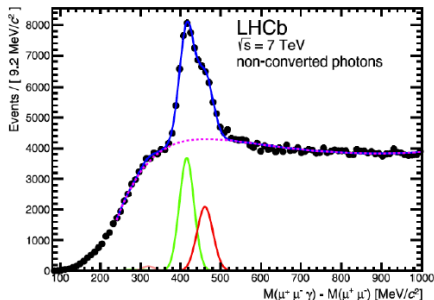
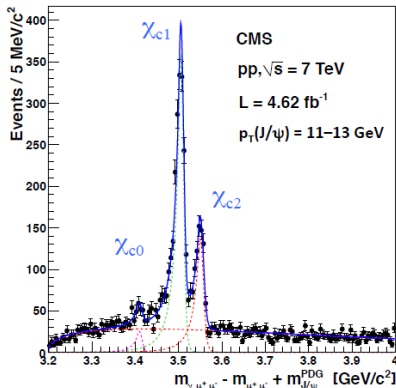


Note: the lines do not represent any theoretical model;
they are added to help guiding the eye through the points

χ_c production

[CMS, arXiv:1210.0875] [LHCb, PLB 714 (2012) 215, CONF-2011-062]

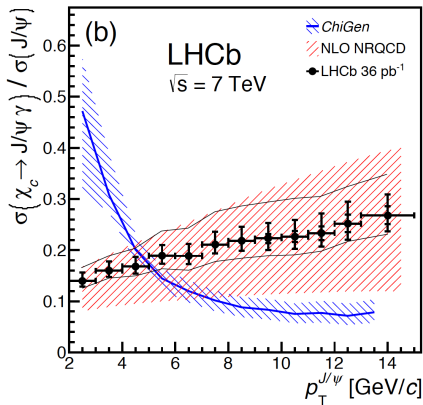
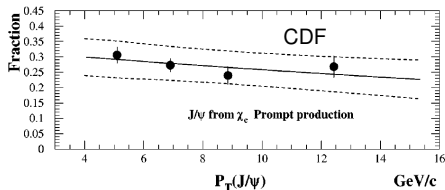
- Using $\chi_c \rightarrow J/\psi \gamma$, converted photon gives much better resolution and separates χ_{c1} , χ_{c2} peaks



Ratio of χ_c to J/ψ

[CDF, PRL79 (1997) 578] [LHCb, arXiv:1204.1462]

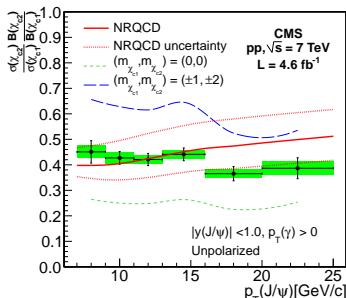
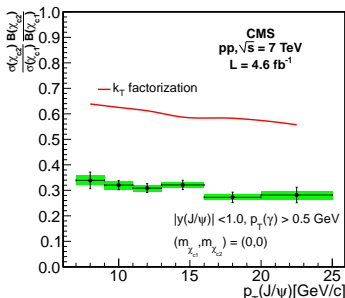
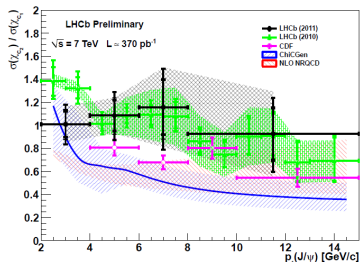
- Most of prompt feed-down are from χ_c



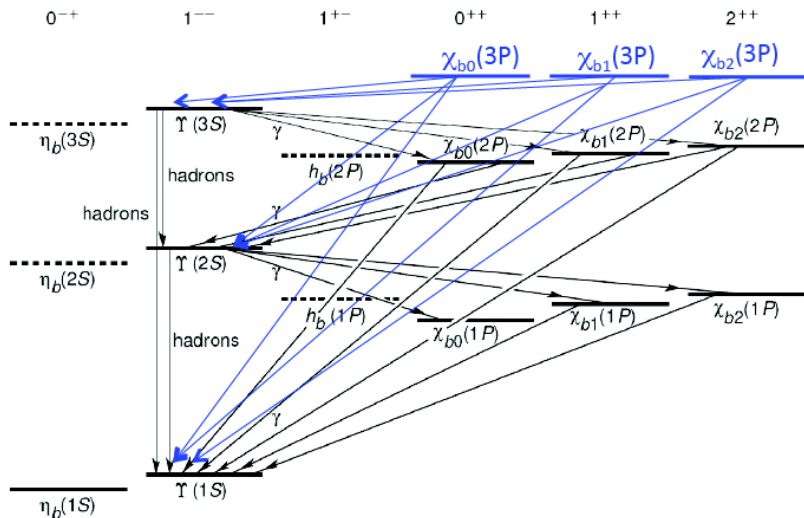
Ratio of χ_{c2} to χ_{c1}

[CMS, arXiv:1210.0875] [LHCb, PLB 714 (2012) 215, CONF-2011-062]

- Assume χ_c are unpolarized
- Big uncertainty due to unknown polarization
- Ratio not consistent with simple spin counting, 5/3



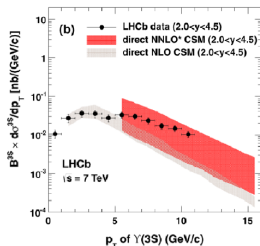
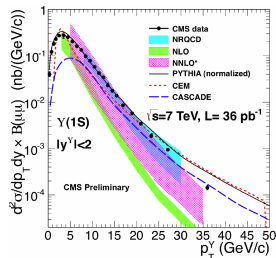
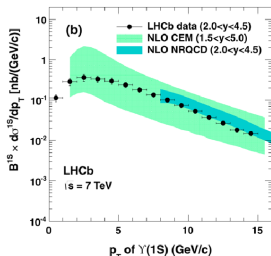
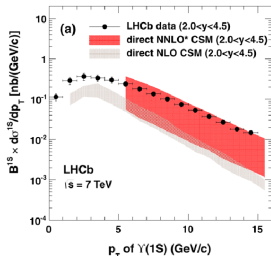
Bottomonium



Υ production

[CMS, BPH-11-001] [LHCb, EPJC 72 (2012) 12]

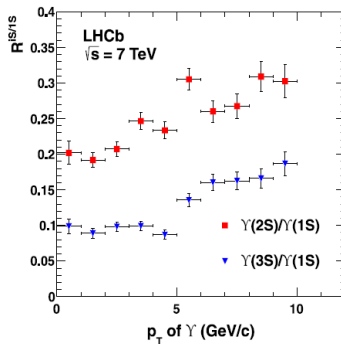
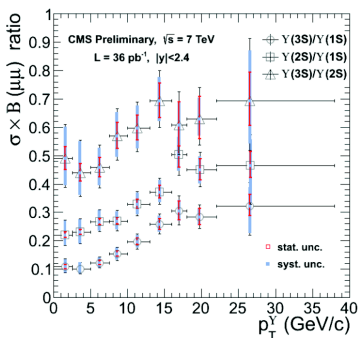
- Good agreement between data and theoretical prediction



Ratio of Υ s cross section

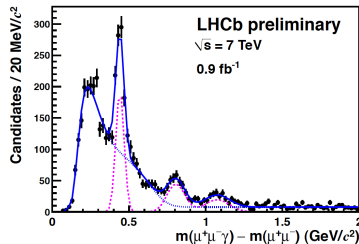
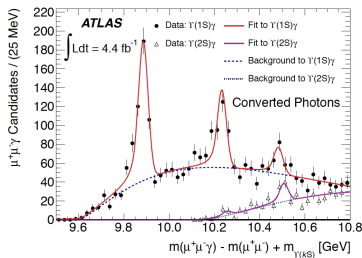
[CMS, BPH-11-001] [LHCb, EPJC 72 (2012) 12]

- Clear dependence on p_T , due to feed-down?

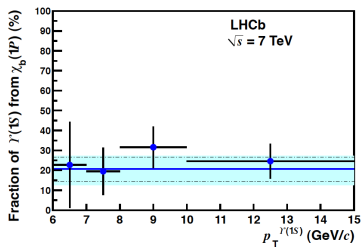


- Observation of $\chi_b(3P)$ states

[ATLAS, PRL 108 (2012) 152001] [LHCb, CONF-2012-020]



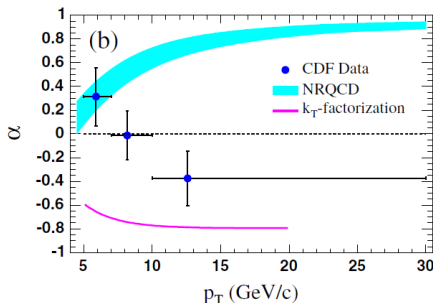
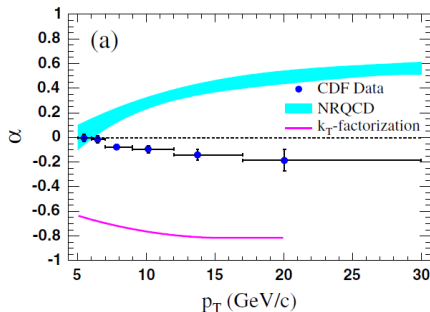
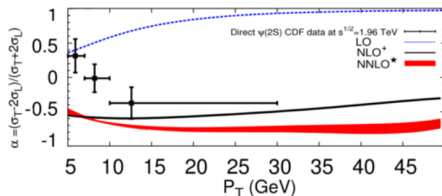
- LHCb also measured fraction of $\Upsilon(1S)$ from $\chi_b(1P)$



The ψ polarization puzzle

- NRQCD [Braaten, Kniehl & Lee, PRD 62, 094005 (2000)]
- CSM [Gong & Wang, PRL 100,232001 (2008)]
[Artoisenet et al., PRL 101, 152001 (2008)]
- k_T fact. [Baranov, Phys. Rev. D 66, 114003 (2002)]

[CDF, PRL 99 (2007) 132001]

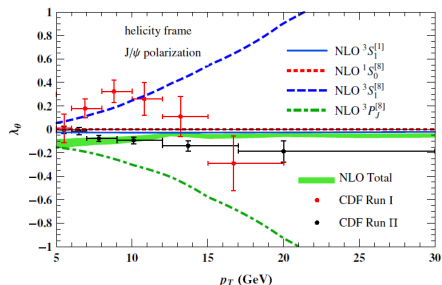
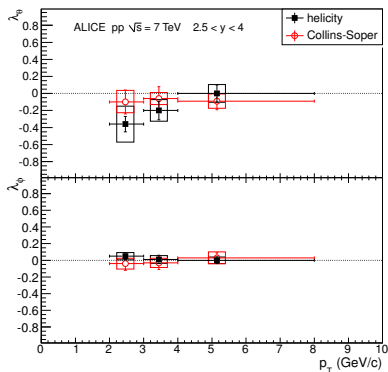


J/ψ polarization, recent results

[ALICE, PRL 108 (2012) 082001]

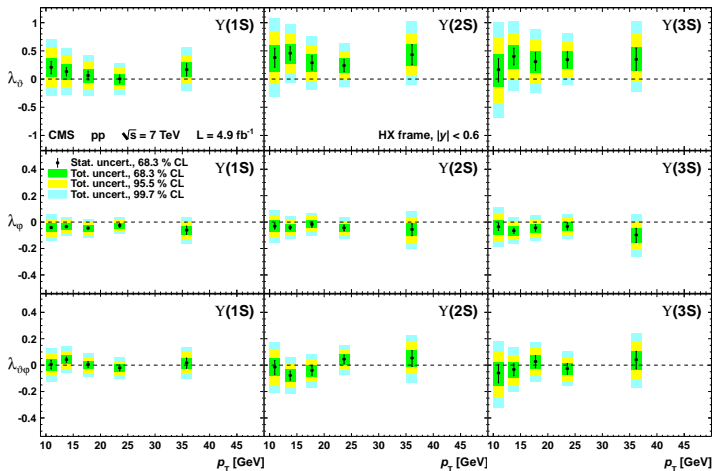
- ALICE has not seen significant polarization in inclusive J/ψ sample
- The puzzle may be understood as the transverse components canceling between $^3S_1^{[8]}$ and $^3P_J^{[8]}$ with NLO NRQCD calculation

[Chao et al, PRL 108 (2012) 242004]



Υ polarization by CMS

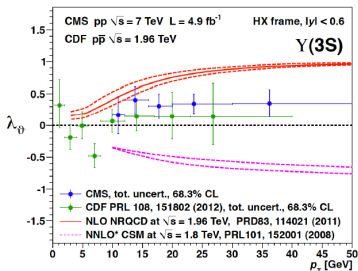
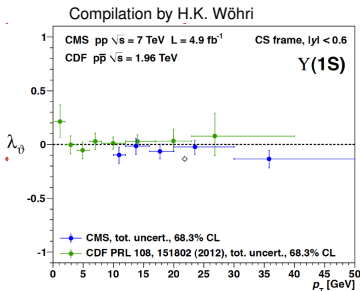
[CMS, arXiv:1209.2922]



Υ polarization, Exp vs. Theo

[CMS, arXiv:1209.2922] [CDF, PRL 108 (2012) 151802]

- Measured polarization weaker than theoretical prediction
- $\Upsilon(3S)$ almost free of feed-down, more convenient to compare to theoretical prediction

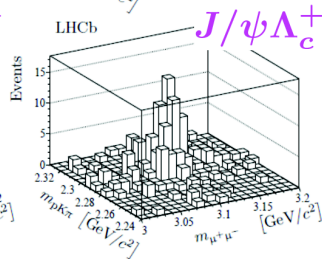
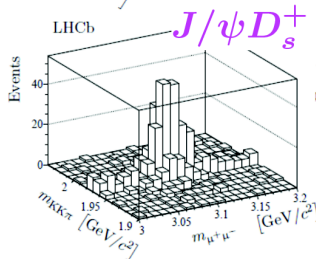
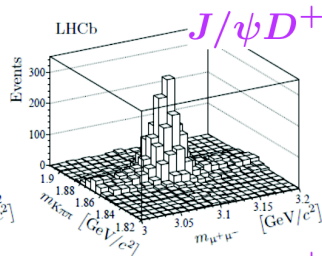
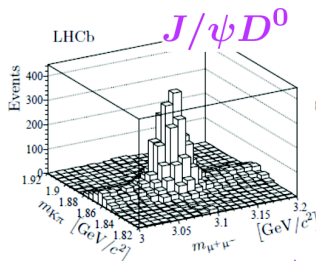


Double charm(onium) production

[LHCb, PLB 707 (2012) 52, JHEP06(2012)141]

- LHCb made the first observation of double J/ψ production at hadron colliders. Many double charm(onium) modes observed!

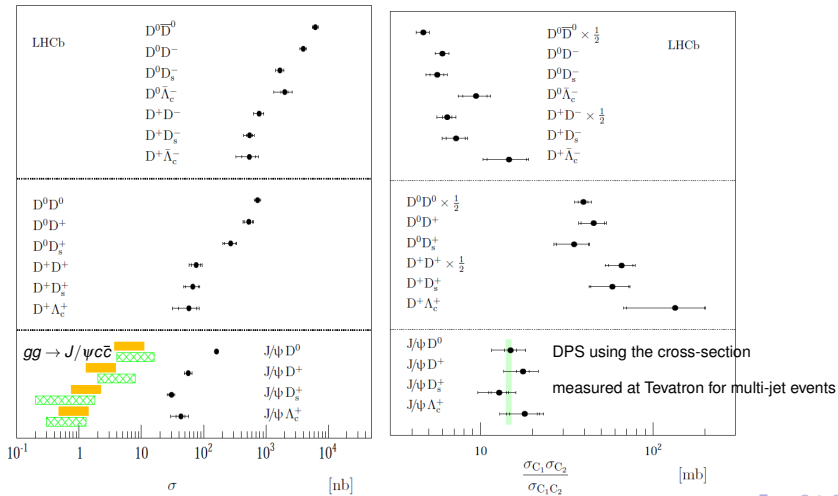
Mode	S
$J/\psi D^0$	4875 ± 86
$J/\psi D^+$	3323 ± 71
$J/\psi D_s^+$	328 ± 22
$J/\psi \Lambda_c^+$	116 ± 14
$D^0 \bar{D}^0$	1087 ± 37
$D^0 \bar{D}^0$	10080 ± 105
$D^0 D^+$	1177 ± 39
$D^0 D^-$	11224 ± 112
$D^0 D_s^+$	111 ± 12
$D^0 D_s^-$	859 ± 31
$D^0 \Lambda_c^+$	41 ± 8
$D^0 \bar{\Lambda}_c^-$	308 ± 19
$D^+ D^+$	249 ± 19
$D^+ D^-$	3236 ± 61
$D^+ D_s^+$	52 ± 9
$D^+ D_s^-$	419 ± 22
$D^+ \Lambda_c^+$	21 ± 5
$D^+ \bar{\Lambda}_c^-$	137 ± 14



Double charm production, DPS needed

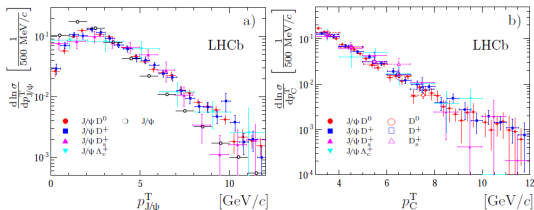
[LHCb, JHEP 06 (2012) 141]

- Measured cross-section suggests Double Parton Scattering (DPS) needed

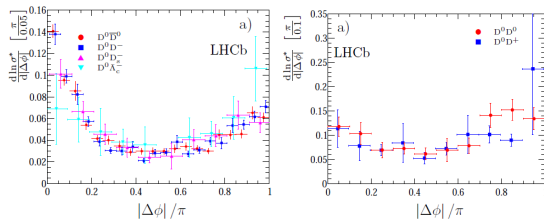


Double charm production, some properties

- $p_T(J/\psi)$ spectra harder than that of prompt J/ψ , seems to be not the case for charm hadron [LHCb, JHEP 06(2012) 141]

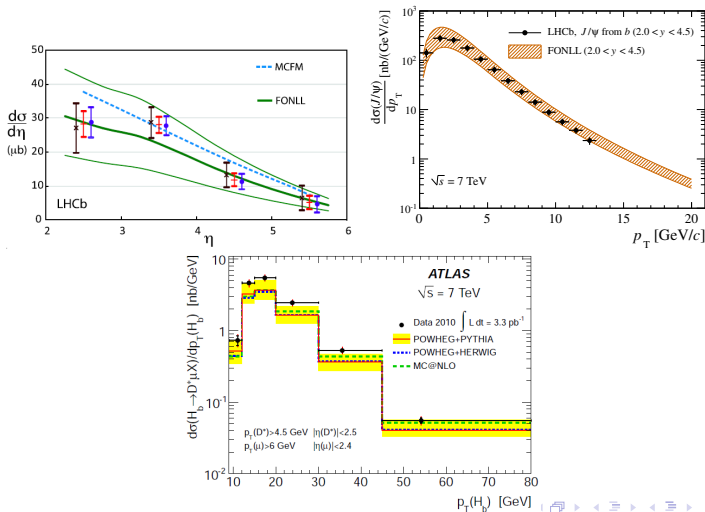


- Opposite sign, $\Delta\phi \rightarrow 0$ peak indicates $g \rightarrow c\bar{c}$ splitting? Same sign, no significant production correlation



b production

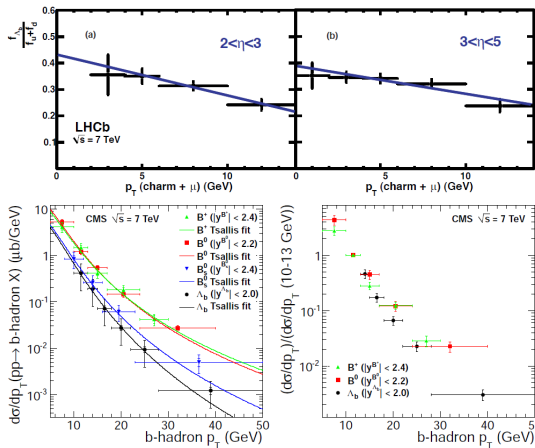
- Measured using $b \rightarrow D^{0(*)} \mu^- X$, and J/ψ from b decays, in good agreement with theoretical predictions [M. Cacciari et al, JHEP 1210 (2012) 137]



Λ_b production

[CMS, arXiv:1205.0594] [LHCb, PRD 85 (2012) 032008]

- Measured by semileptonic decay modes, and exclusive decay modes, $f_{\Lambda_b}/(f_u + f_d)$ has significant p_T dependence



B_c production

[ATLAS, CONF-2012-028] [CMS, PAS-BPH-11-003] [LHCb, arXiv: 1209.5634]

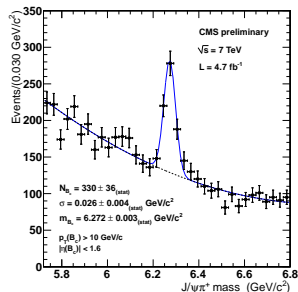
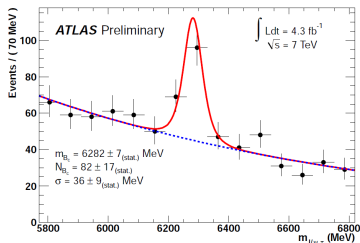
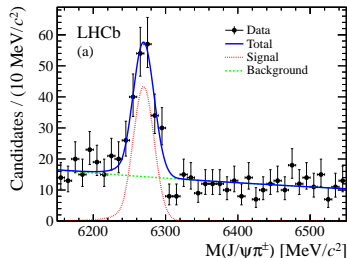
- B_c^+ observed at Tevatron, now also by 3 LHC experiments.

- $\frac{\sigma(B_c^+)^{\text{LHC}}}{\sigma(B_c^+)^{\text{Tevatron}}} \sim O(10)$, to study B_c family systematically

- LHCb measured

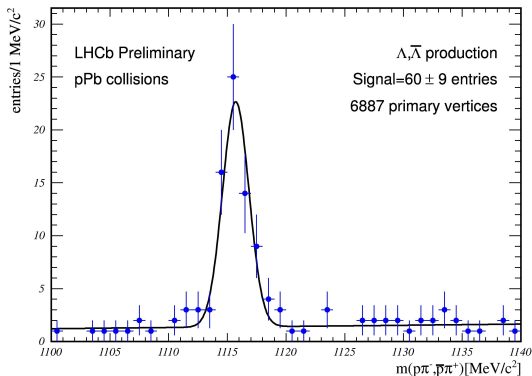
$$\frac{\sigma(B_c^+) \times \mathcal{B}(B_c^+ \rightarrow J/\psi \pi^+)}{\sigma(B^+) \times \mathcal{B}(B^+ \rightarrow J/\psi K^+)} = (0.68 \pm 0.10 (\text{stat.}) \pm 0.06 (\text{syst.})) \%$$

for $p_T(B) > 4 \text{ GeV}/c$, $2.5 < \eta(B) < 4.5$



Prospects of pA physics at LHCb

- LHCb just joined the heavy-ion party
- During the pilot run, LHCb collected a lot of V^0 (K_S^0, Λ)



- Heavy quark and quarkonium production measurements with pA data of 2013 seems to be promising

- Soft QCD
 - ▶ Particle multiplicities and production ratios, correlations
 - ▶ Strangeness production V^0 , ϕ , and Λ polarization
 - ▶ Energy flow and underlying events measurements
- Quarkonium measurements
 - ▶ J/ψ production and polarization
 - ▶ Υ production
- Other topics
 - ▶ Low mass DY..
 - ▶ Inclusive photon production
 - ▶ Open charm, b production
- Your suggestions?

Summary

- A lot of interesting and important results from four experiments at LHC based on the pp data
 - ▶ Production of heavy quark and quarkonium
 - ▶ Some polarization results
 - ▶ Observation of new states, which is relevant for production measurement
- Many more results will come out
 - ▶ Polarization of J/ψ , $\psi(2S)$, $\Upsilon(ns)$, ...
 - ▶ Triple charm, associated production of Υ and open charm, etc
 - ▶ Heavy quark and quarkonium with pA data