Experimental results in heavy flavour and onia production.

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On behalf of the LHC Collaborations

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Outline

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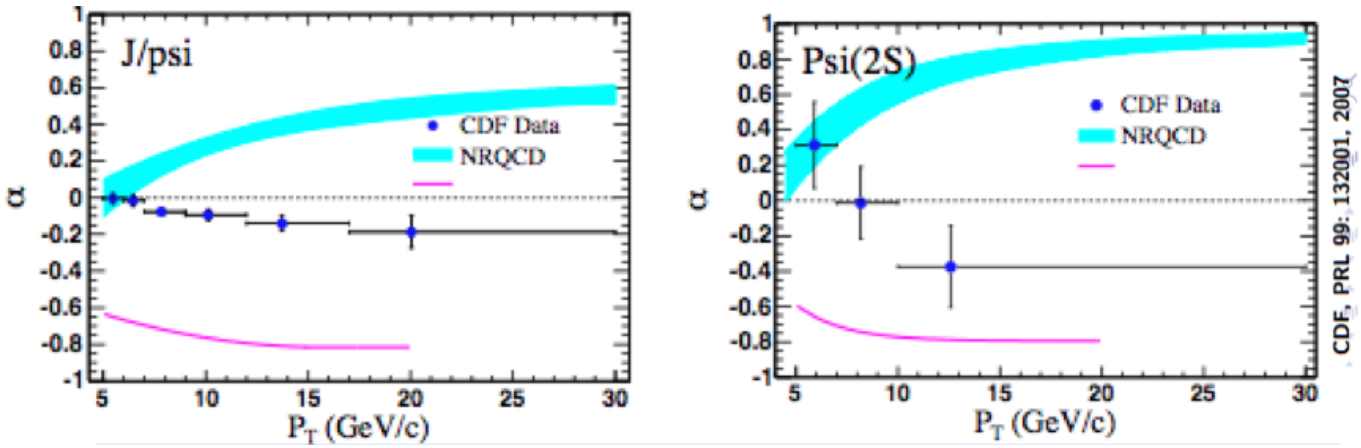
Why production studies?

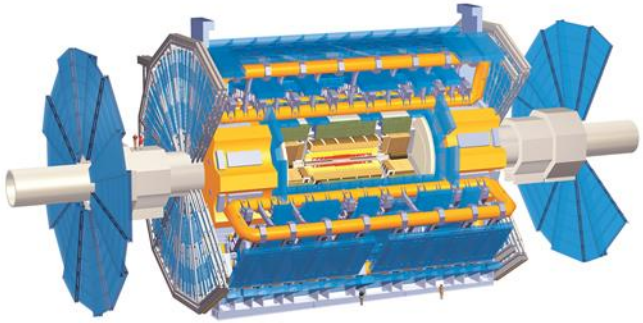
- Quarkonium production at hadron colliders has represented a tough challenge since its first evidence. A combination of Color Octect and Color Singlet mechanisms describe the p_T spectrum and cross-sections measured at Tevatron, but the polarization remains elusive.



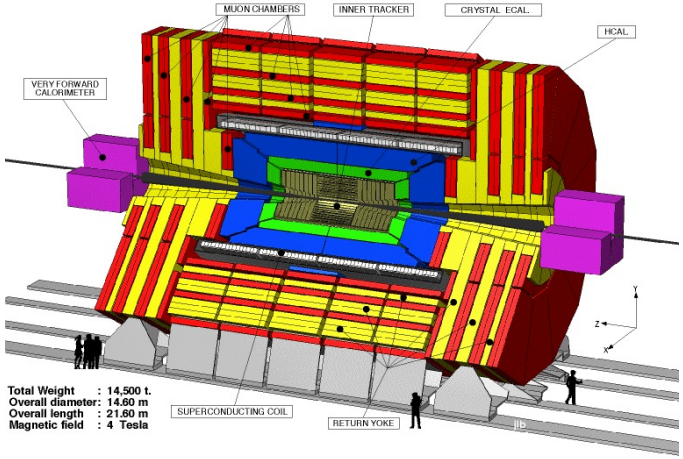
- Other observables, double-charm production, production in p-Pb interactions etc.., have been proposed to solve the puzzle.
- The production cross-section and possibly the polarization of states such as χ_c, χ_b might also become available.
- More in general the study of heavy flavour production processes:
  - provides excellent test of p-QCD and MC generators at new energies;
  - improves the understanding of heavy flavour background in many searches;
  - is an important test of the understanding of the detector.

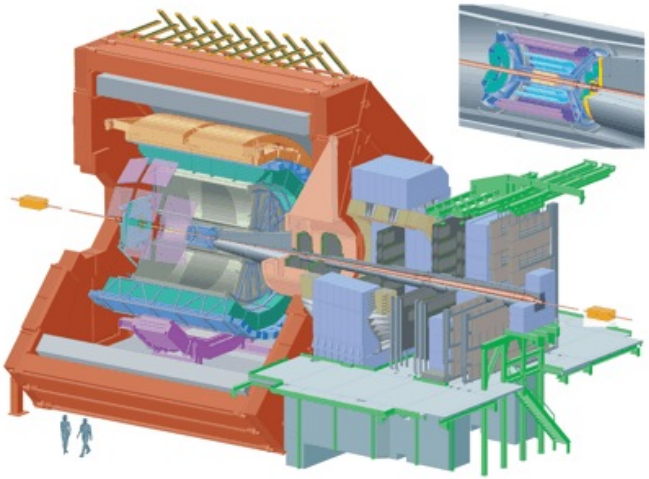
The LHC detectors

ATLAS

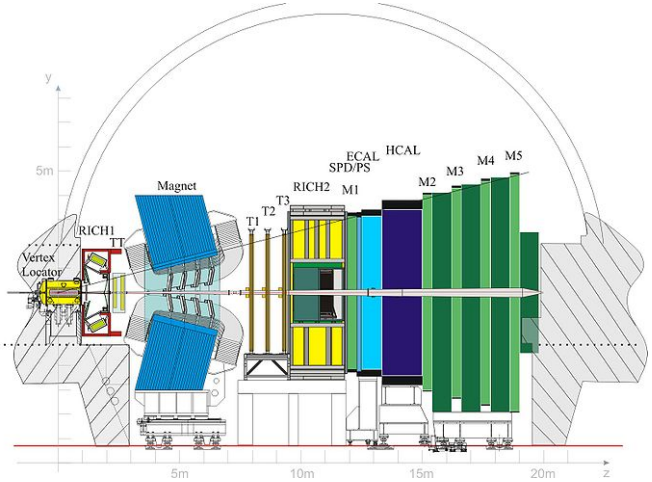


CMS



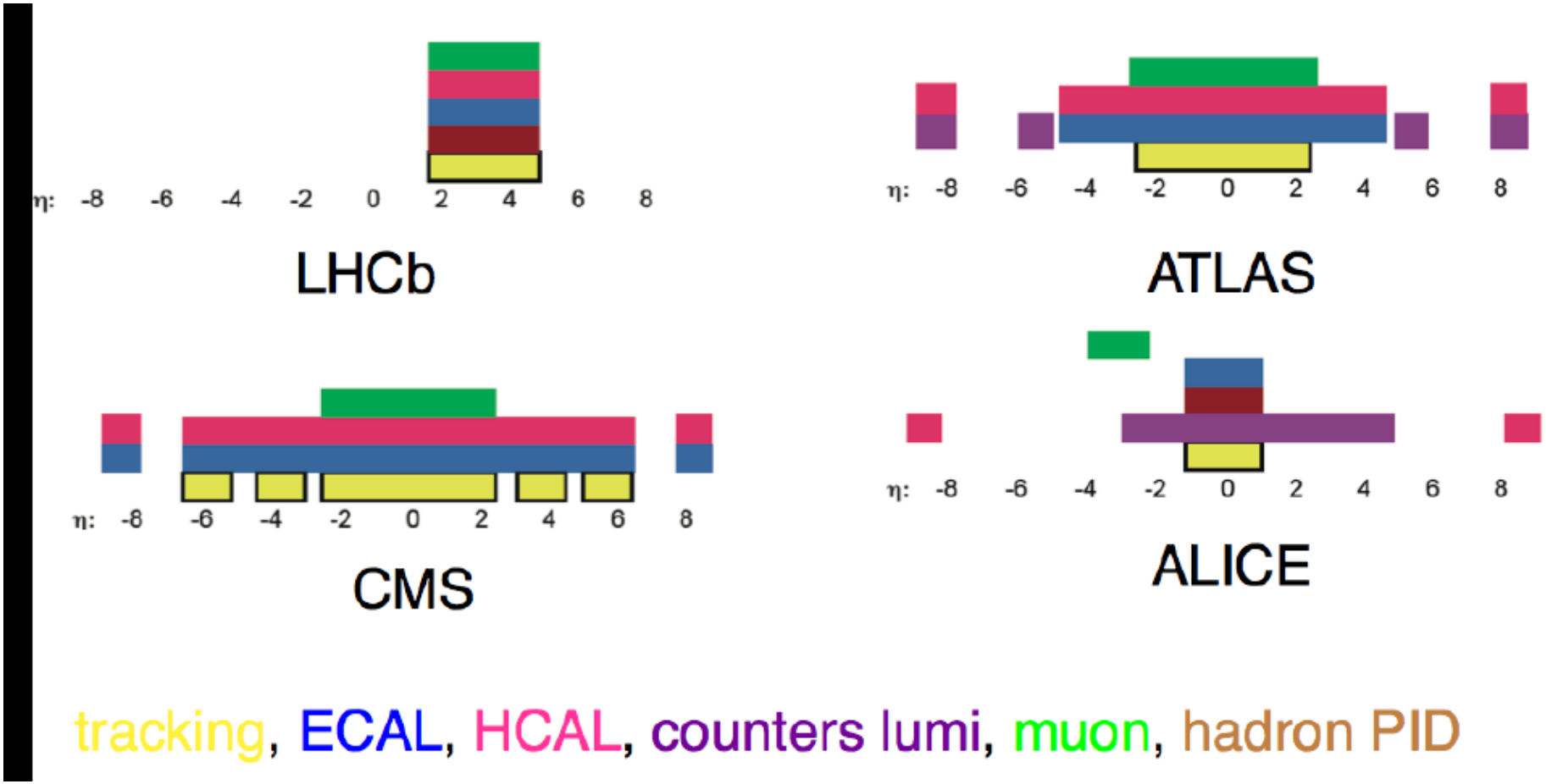


ALICE



LHCb

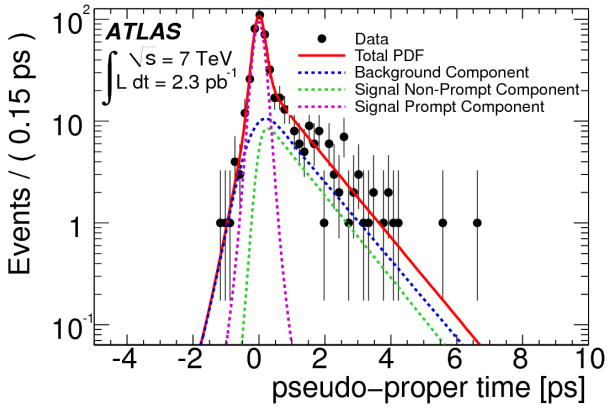
Rapidity range

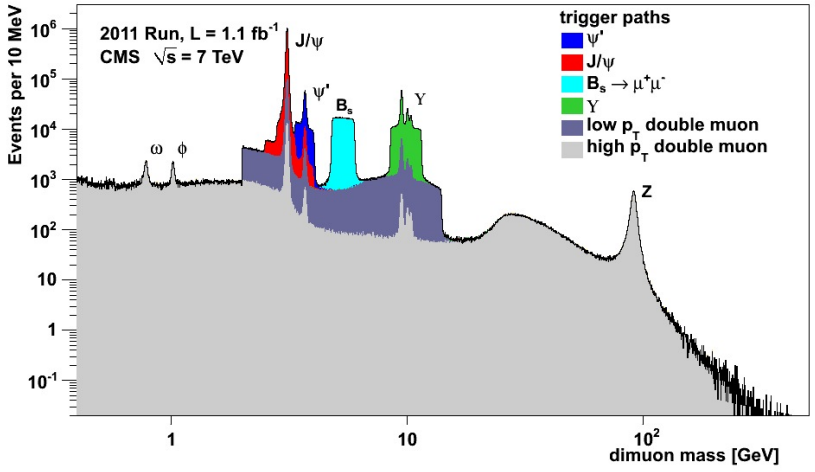


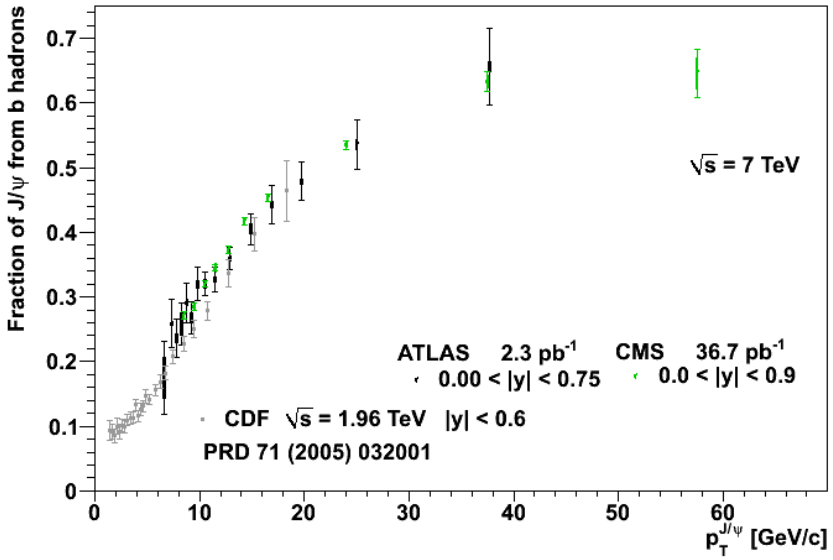
Outline

J/ψ production 101

- J/ψ produced in different ways:
  - Prompt production;
  - Feed down from heavier states: χ_c, $\Psi(2S)$;
  - Secondary production from b-hadrons decays.
- Separation of the feed down component, $\sim$ 30-40%, not trivial





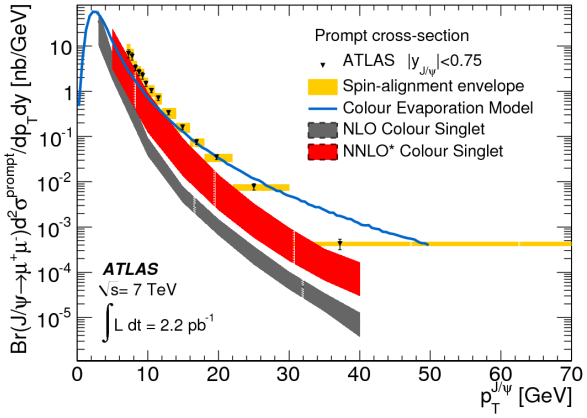


b component separated exploiting the long lifetime of the b-hadrons, selecting on J/ψ proper time.

J/ψ production cross-section

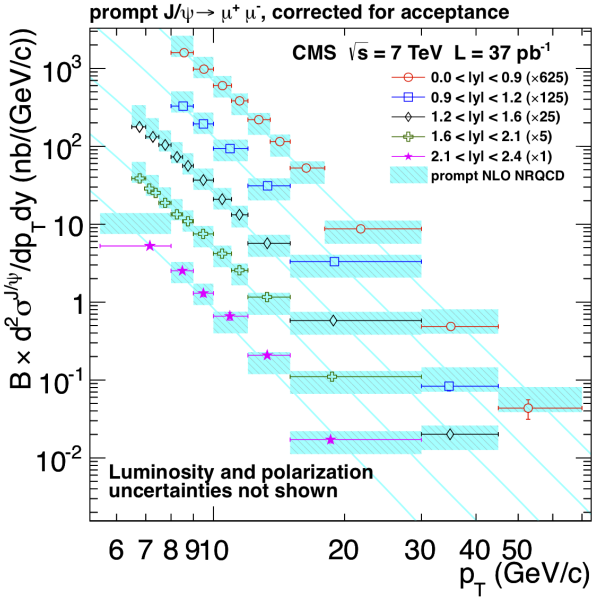
- A wealth of results already available
- All results in good agreement with NRQCD calculations.

ATLAS data vs. CS



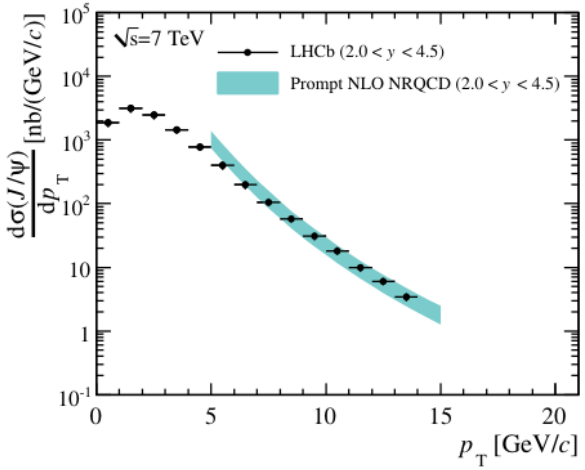
Nucl. Phys. B 850 (2011) 387-444

CMS data vs. CS+CO



JHEP 02 (2012) 011

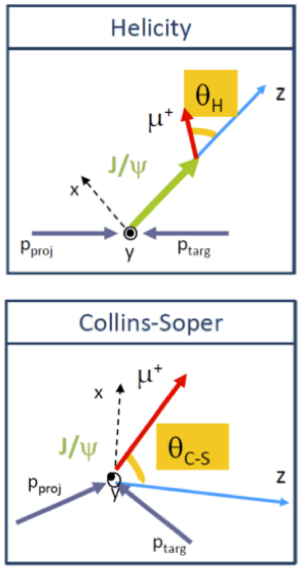
LHCb data (5.2 pb^{-1}) vs. CS+CO

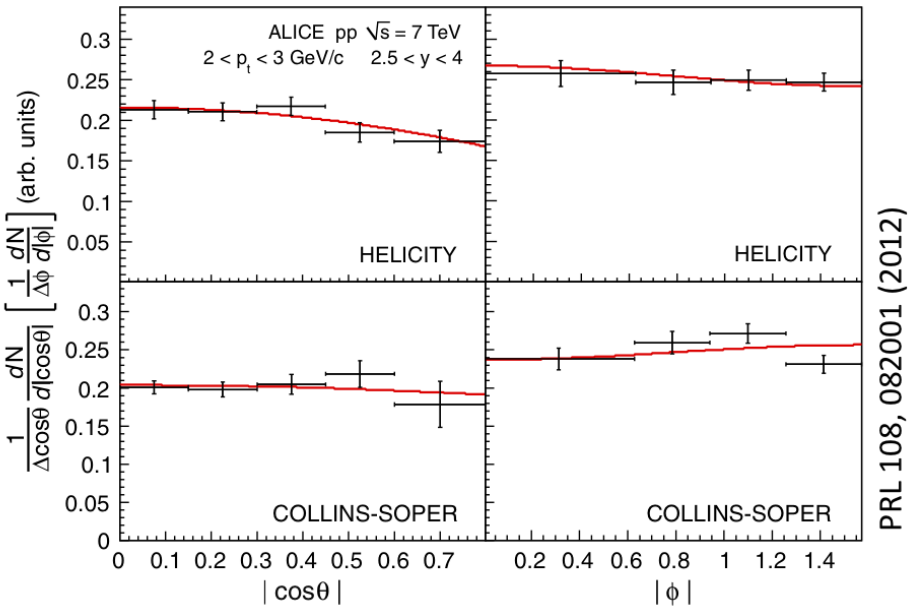


EPJC 71(2011)1645

- The dominant error is the uncertainty on the J/ψ polarization.

J/ψ polarization

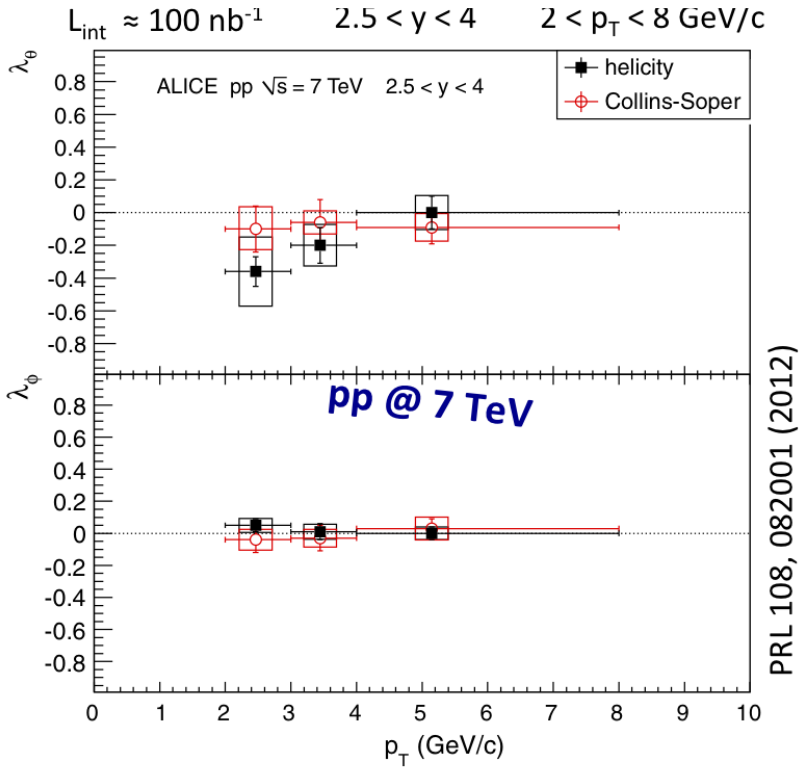




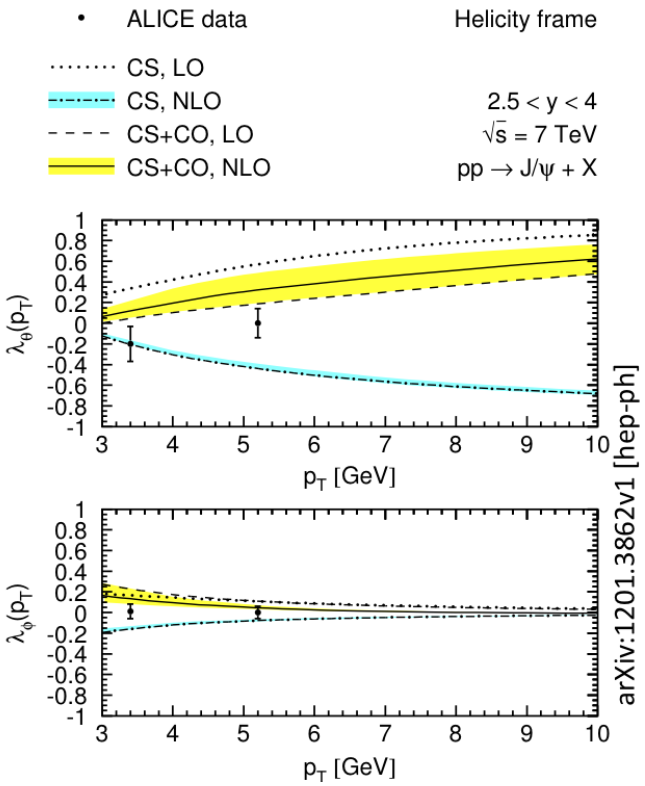
- ALICE has measured the J/ψ polarization by means of an angular analysis of the muon decay polar and azymuthal angle distribution.
- The analysis is carried out both in the Helicity and Collins-Soper frames.

$$W(\cos\theta) \propto \frac{1}{3+\lambda_\theta}(\lambda_\theta \cos^2\theta) \qquad W(\Phi) \propto 1 + \frac{2\lambda_\Phi}{3+\lambda_\theta}\cos 2\Phi$$

J/ψ polarization at ALICE



PRL 108, 082001 (2012)

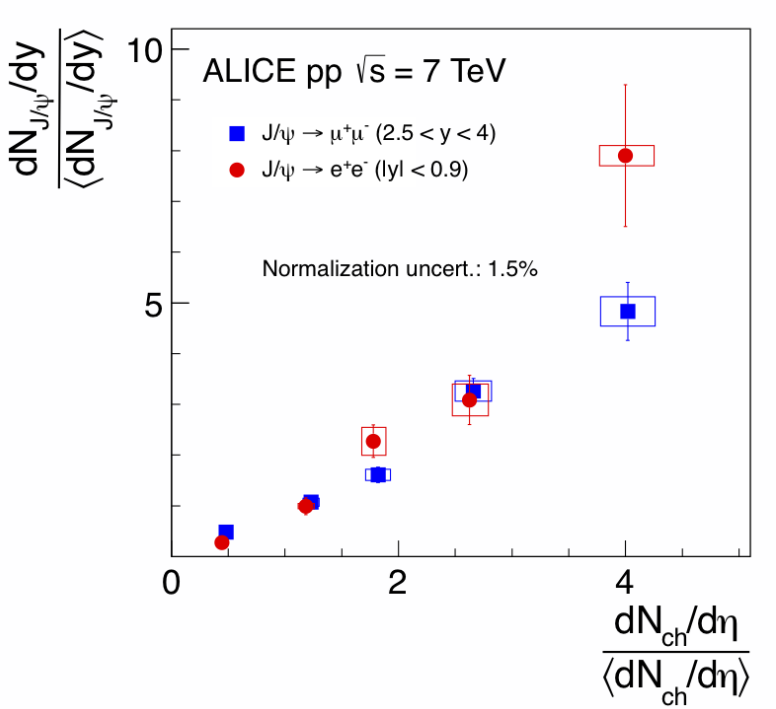


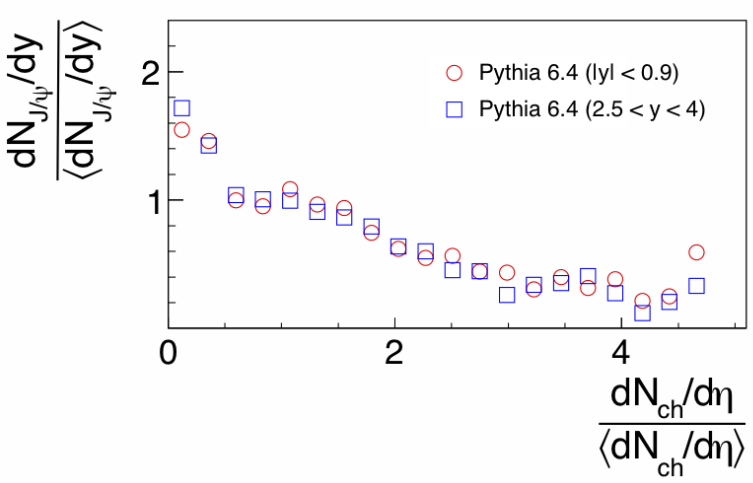
arXiv:1201.3862v1 [hep-ph]

- Almost no polarization for inclusive J/ψ
- The λ_θ difference between prompt and inclusive J/ψ polarization estimated to be less than 0.05.

J/ψ vs. multiplicity

- Recent result from ALICE: arXiv 1202.2816

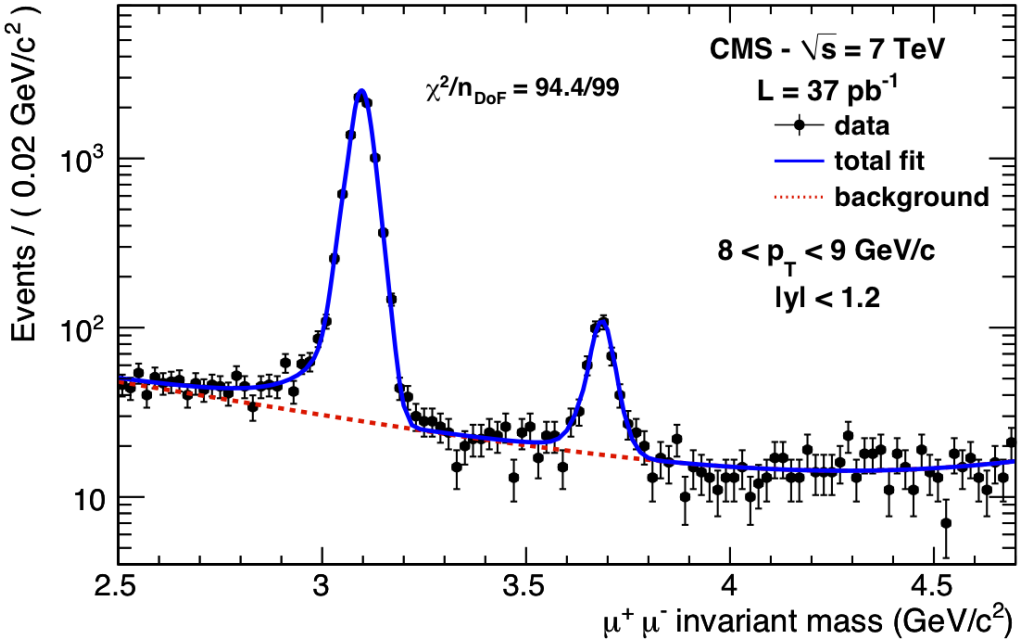


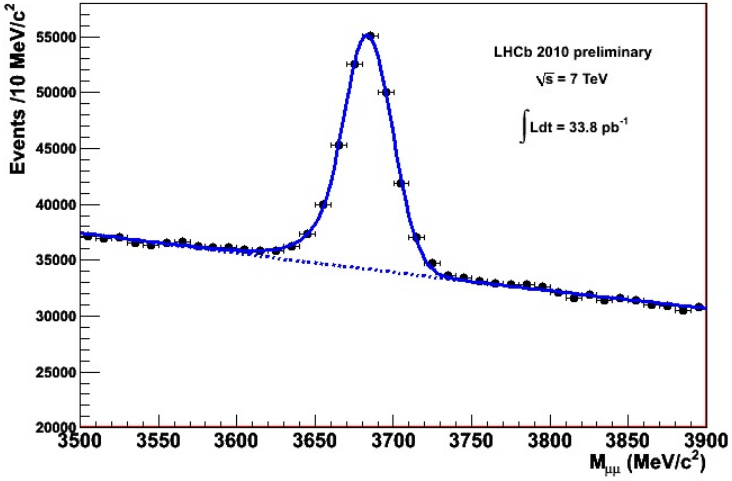


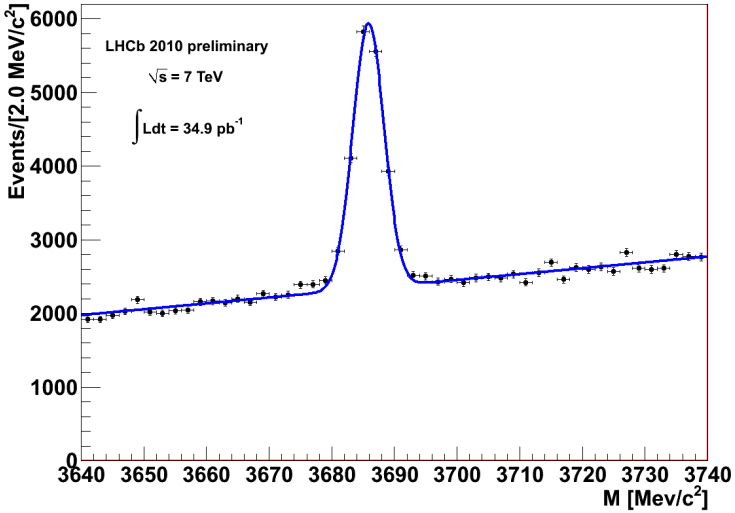
- The J/ψ yields appear to increase linearly as function of charged particles multiplicity.
- Simulation carried out with PYTHIA 6.4.25 and Perugia 2011 tunes does not reproduce the results.

$\Psi(2S)$ production

- $\Psi(2S)$ does not suffer from feed-down from higher mass states, all prompt is direct.
- Reconstructed by LHCb (arXiv:1204.1258) and CMS (JHEP 02 (2012) 011) as:
  - $\Psi(2S) \to \mu^+\mu^-$
  - $\Psi(2S) \to J/\psi\,\pi^+\pi^-$



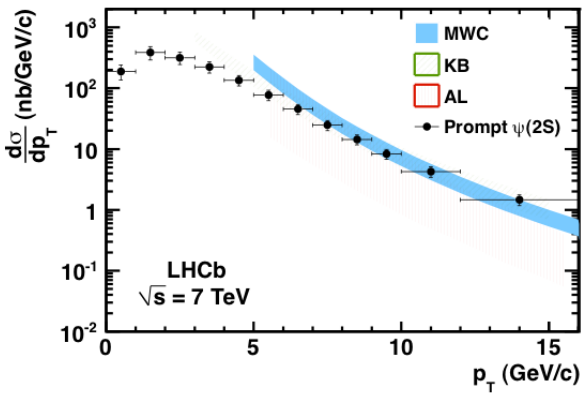




Ψ(2S) production cross-section

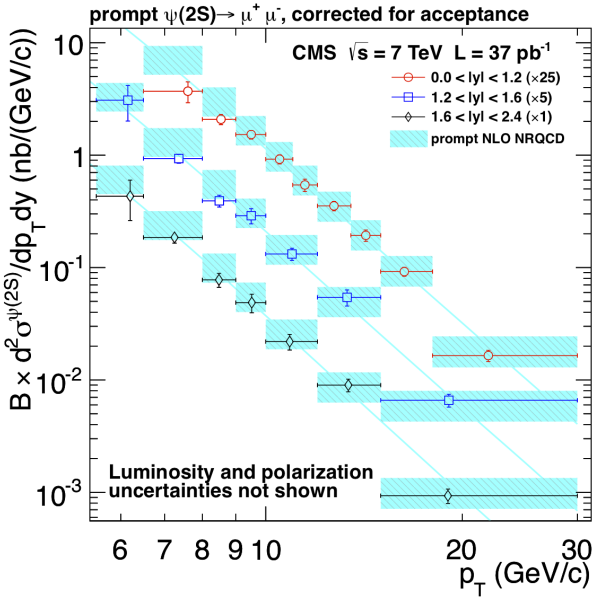
- The Ψ(2S) cross-section has been measured both at LHC and Tevatron.

LHCb data (36 pb^{-1})



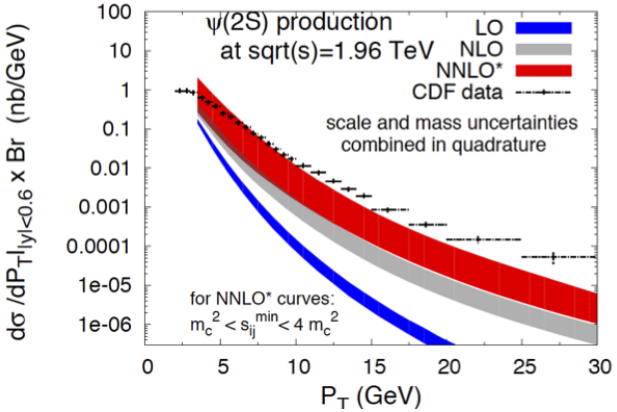
arXiv:1012.1030
PRL 106 (2011) 022003
PRL 101 (2008) 152001
EPJC 61 (2009) 693

CMS data vs. CS+CO



JHEP 02 (2012) 011

CDF data vs. CS

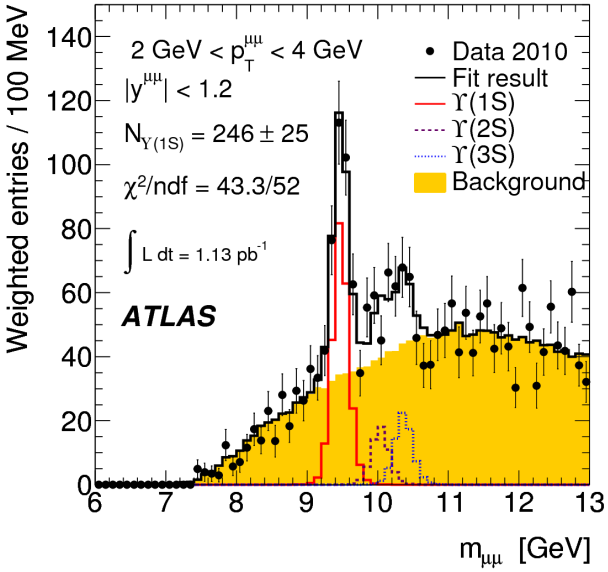


PRD 80 (2009) 031103

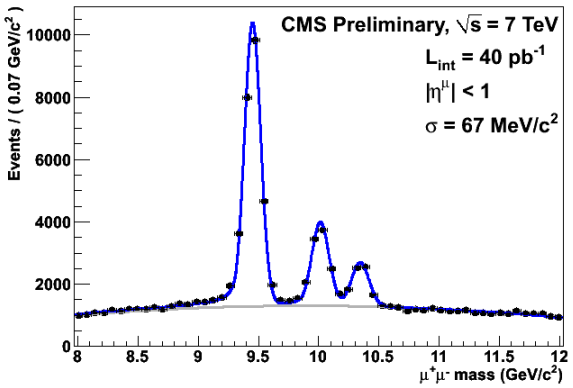
- Reasonable agreement between data and theory predictions.

Outline

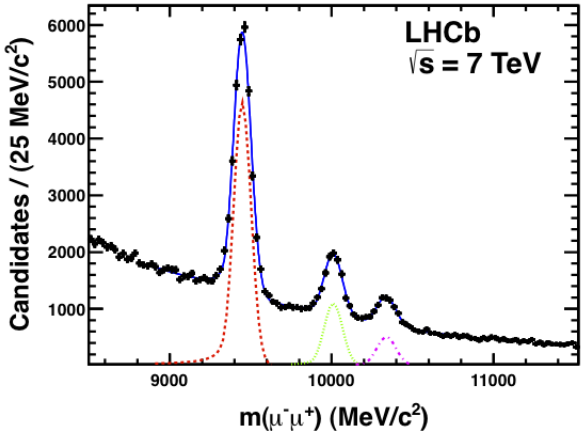
Υ(nS) production



PLB 705 (2011) 9-27



PRD 83 112004 (2011)

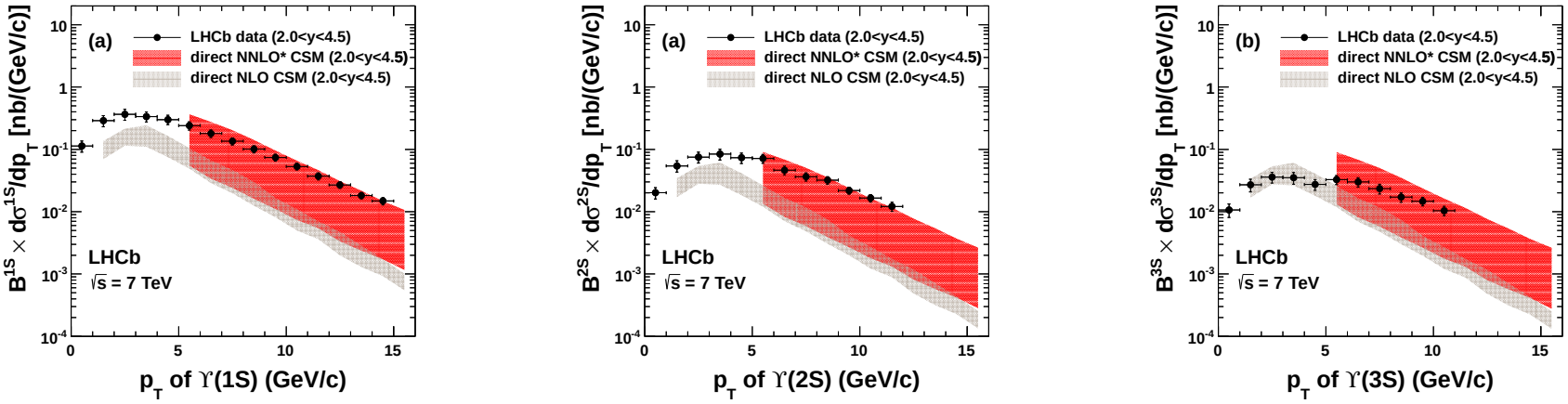


(25 pb^{-1}) arXiv:1202.6579

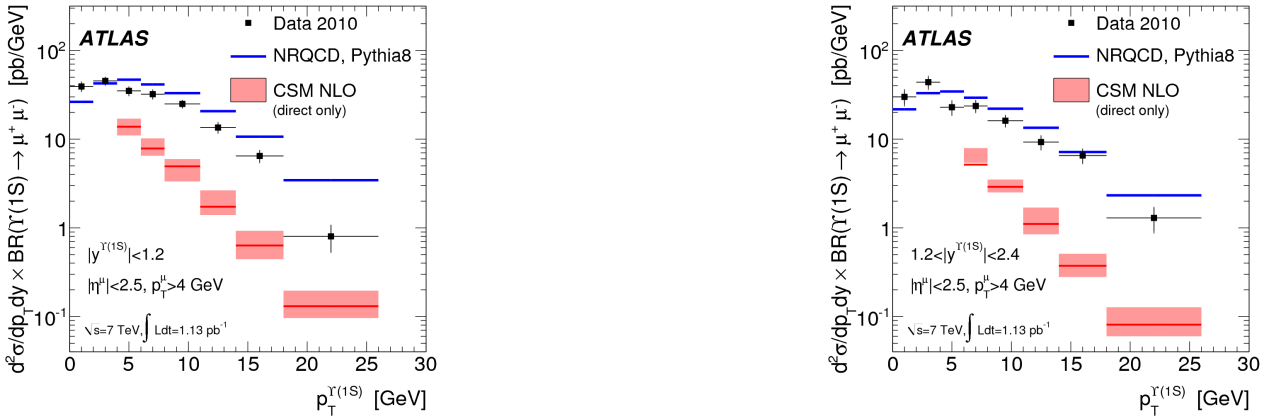
- Three states Υ(1S), Υ(2S) and Υ(3S) decay to $\mu^+\mu^-$ pairs.
- Υ(1S) and Υ(2S) also produced through feed-down from higher mass states.

Υ(nS) cross-section

Reasonable agreement with theory found at LHCB for the 3 Υ states.

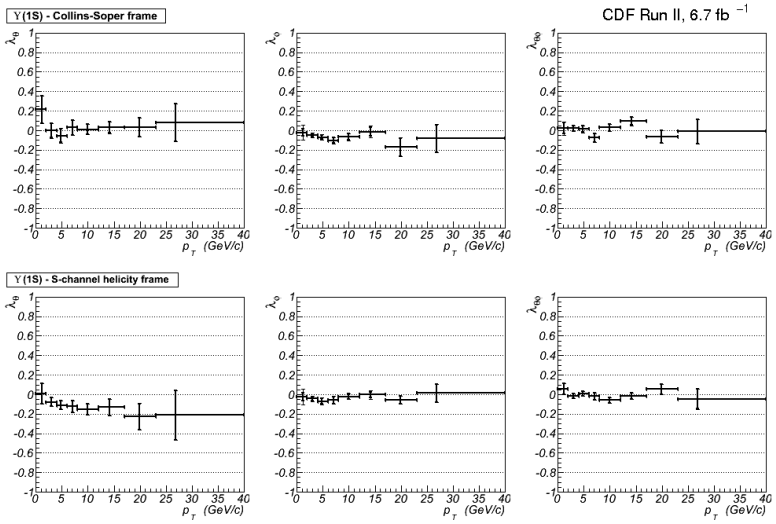


ATLAS measures the production of Υ(1S) in different *y* regions.

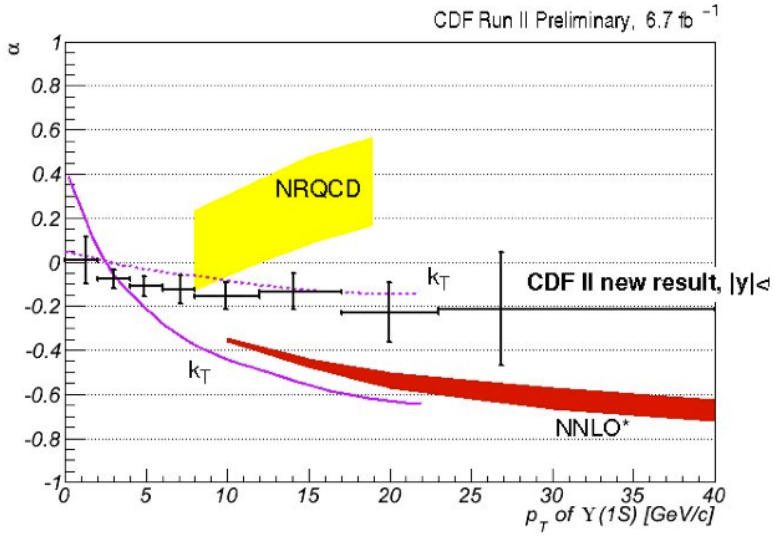


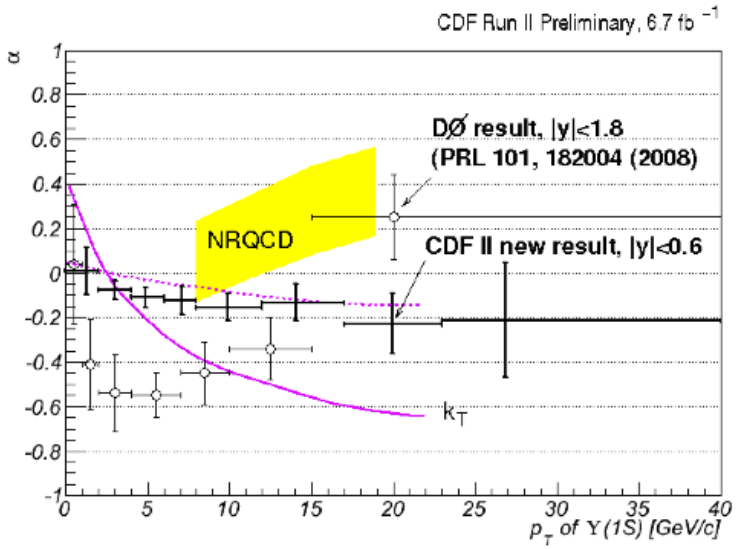
Υ polarization

- First measurement for $\Upsilon(3S)$.
- Full angular analysis recently performed at CDF, PRL 108 151802 (2012)), in both Helicity and Collins-Soper frame.
- No strong longitudinal or transverse polarization in any state.



PRD 63 071501(R) (2001)
PRD 81 111502(R) (2010)



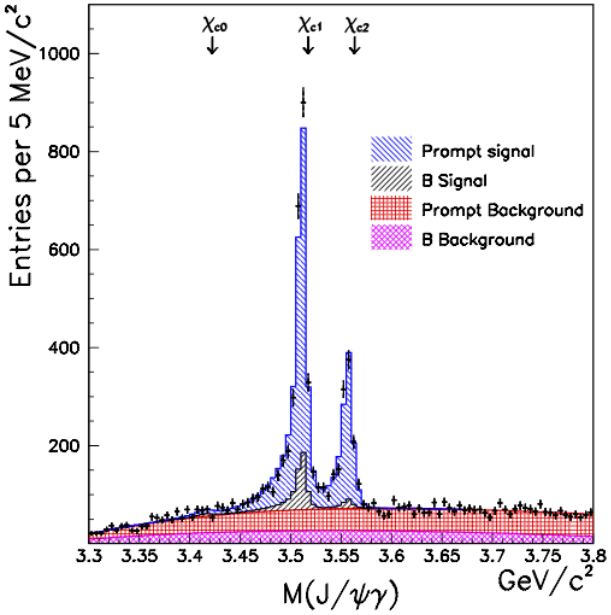


4.5 σ disrepancy with D0 results

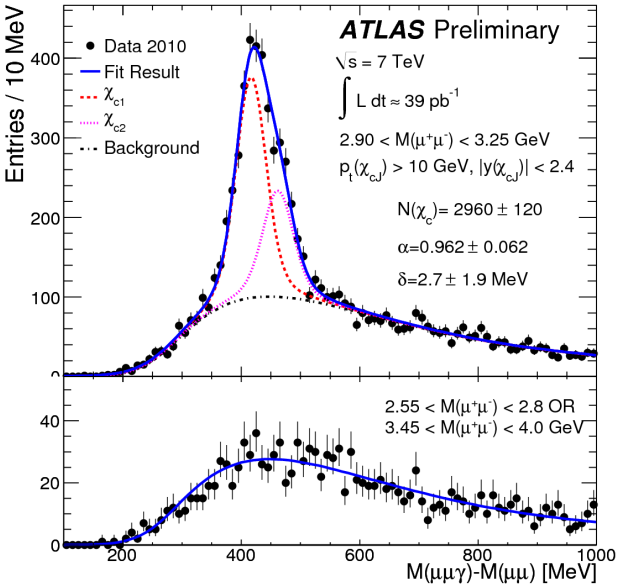
Outline

Production of χ_c

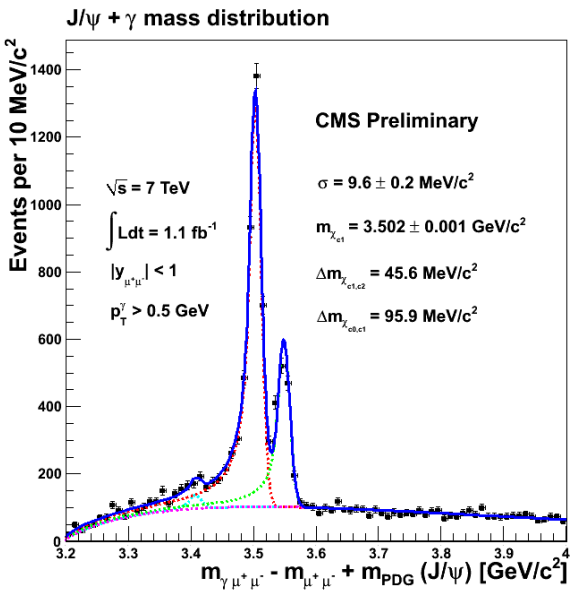
- Detected as $\chi_c \to J/\psi\,\gamma$
- Energy resolution crucial to resolve the χ_{c1} and χ_{c2} states.



CDF PRL 98 (2007) 232001

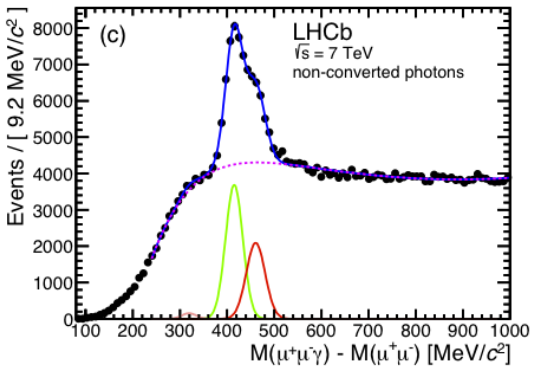


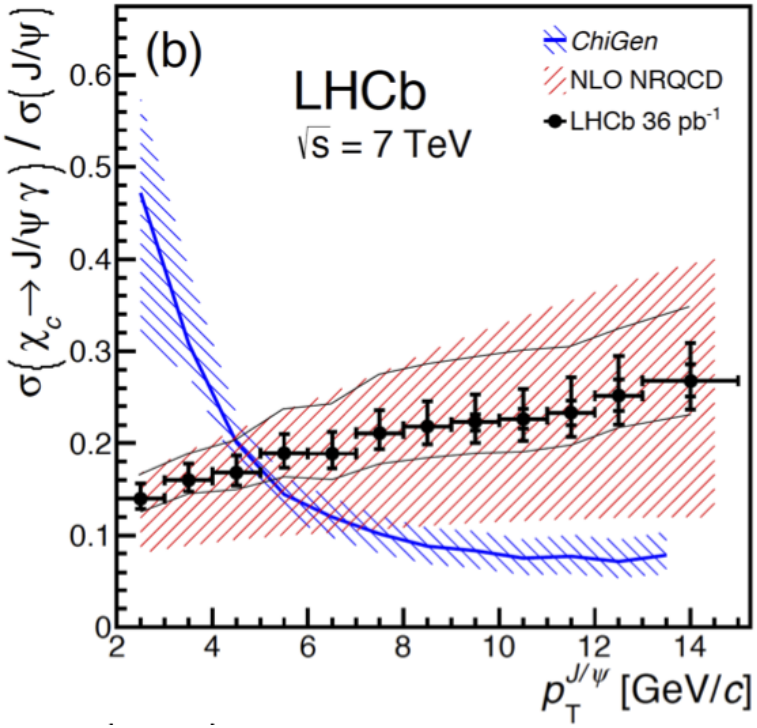
ATLAS-CONF-2012-136



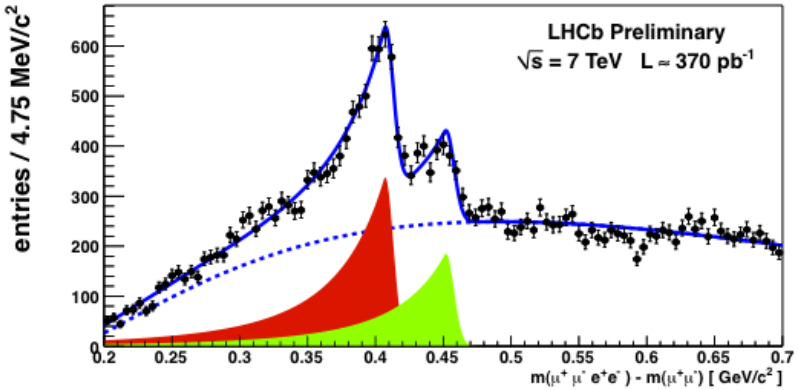
CMS-DP-2011-006

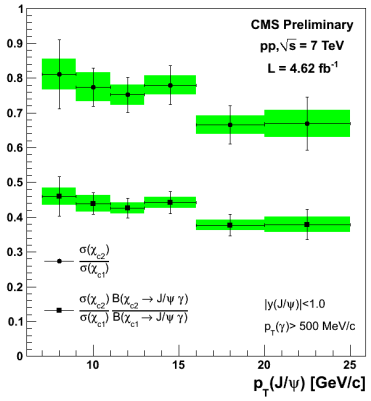
χ_c cross-section





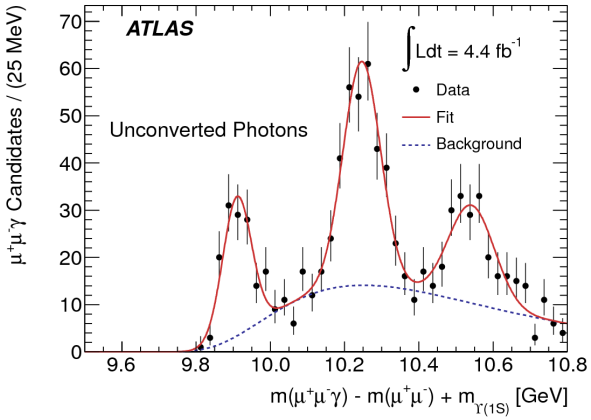
- $\sigma(\chi_c \to J/\psi\gamma)/\sigma(J/\psi)$ arXiv:1202.1462
- $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ measured at LHCb arXiv:1202.1080
- Photons observed in the ECAL or as two converted electrons.
- Results in agreement with NLO CO+CS.
- **NEW** CMS results presented last week at Blois (PAS-BPH-11-010)

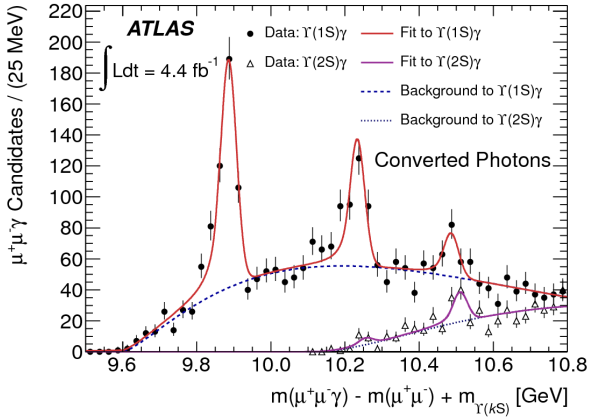


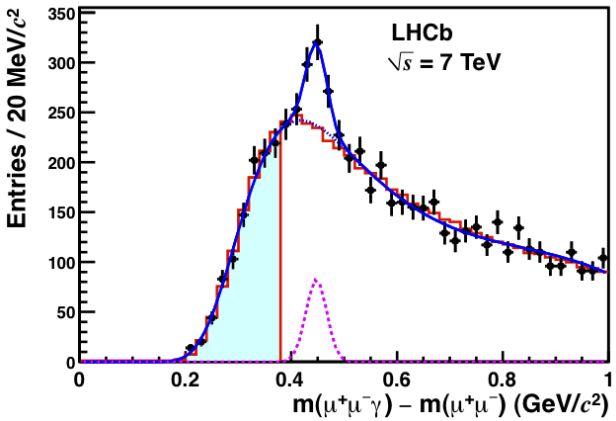


χ_b production

- Observed by ATLAS, PRL 108 (2012) 152001, as $\chi_b \to \Upsilon(nS) + \gamma$
- First observation of the $\chi_b(3P)$ state.
- Photons reconstructed from calorimeter and from conversions.



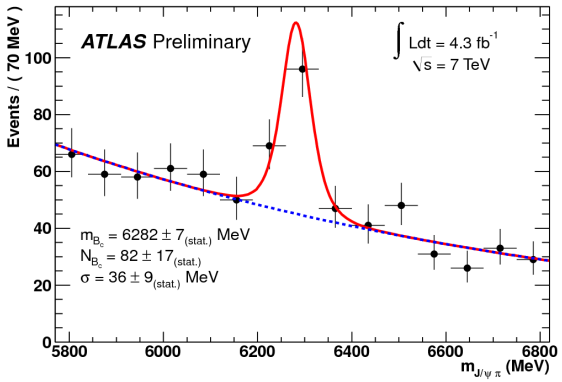




- Observed by LHCb in the 2010 data.
- Only using non converted photons.
- Measurement with converted photons and χ_b ratios coming shortly.

Outline

B_c^+

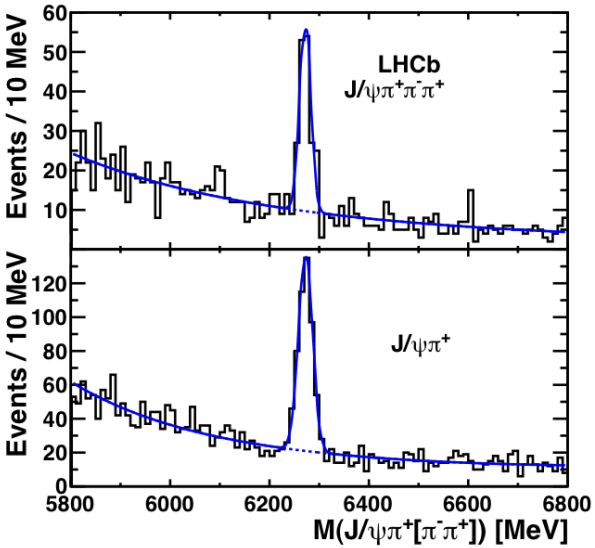


- First observation by CDF in the mode $B_c^+ \to J/\psi\, l^+ \nu$
- Observed in the $B_c^+ \to J/\psi\, \pi^+$ mode by LHCb (LHCB-CONF-2011-027) and ATLAS (ATLAS-CONF-2012-028)
- In this mode LHCb measures its mass as $M(B_c^+) = 6268.0 \pm 4.0 \pm 0.6\,\mathrm{MeV}/c^2$

- LHCb also observes the mode $B_c^+ \to J/\psi\, \pi^+\, \pi^-\, \pi^+$ (LHCB-PAPER-2011-044)
- The relative branching ratio is measured:

$$\frac{\mathcal{B}(B_c^+ \to J/\psi\, \pi^+\, \pi^-\, \pi^+)}{\mathcal{B}(B_c^+ \to J/\psi\, \pi^+)} = 2.41 \pm 0.30 \pm 0.33$$

consistent with theoretical predictions.

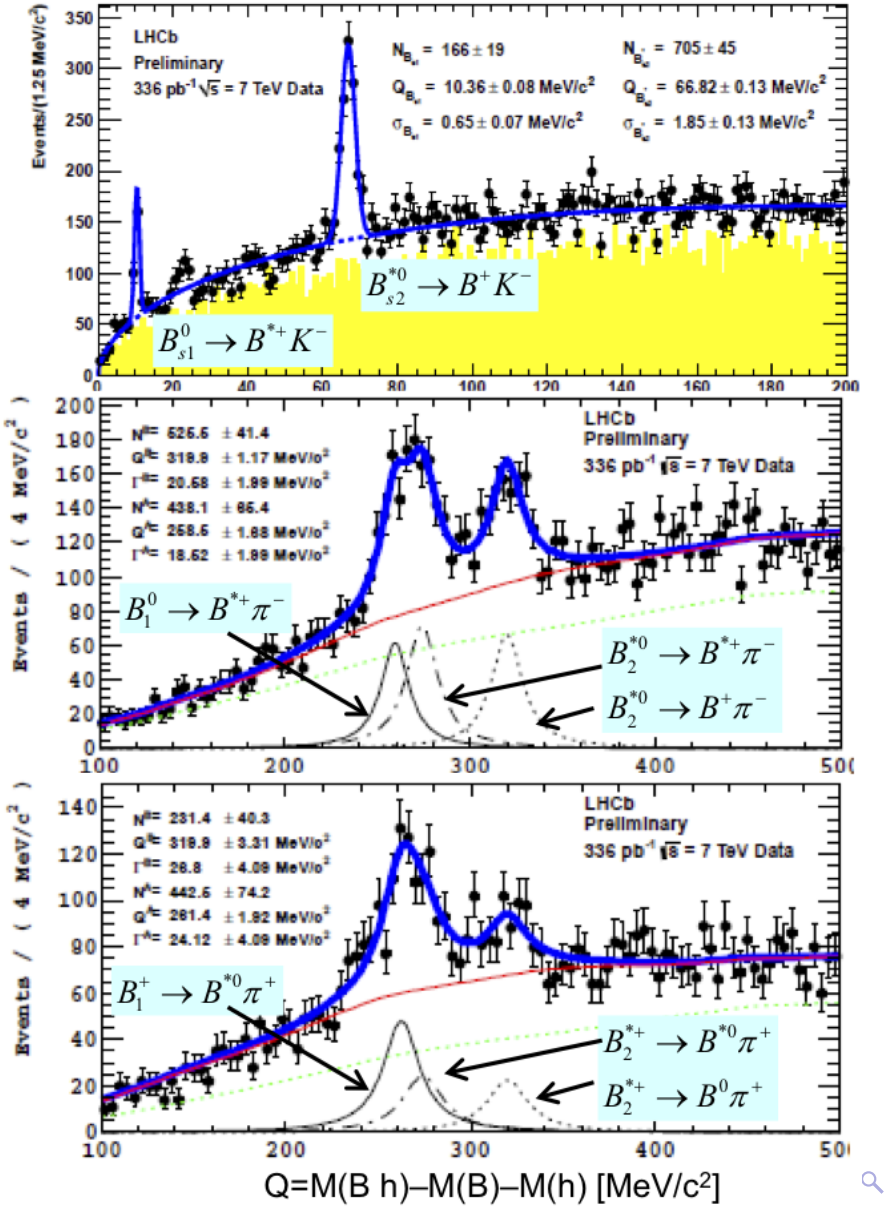


Observation of $B^{**}_{(s)}$ mesons

- Observed by LHCb (LHCB-CONF-2011-053)
- Searched in the $B^+\pi^-$, B^+K^- and $B^0\pi^-$ channels.
- The photon from the $B^* \to B\gamma$ is not reconstructed.
- First direct observation of the B_1^+ and B_2^{*+} states.

$$
\begin{aligned}
M_{B^0_{s1}} &= (5828.99 \pm 0.08_{\rm stat} \pm 0.13_{\rm syst} \pm 0.45^{B\,\rm mass}_{\rm syst})\ \ {\rm MeV}/c^2\,,\\
M_{B^{*0}_{s2}} &= (5839.67 \pm 0.13_{\rm stat} \pm 0.17_{\rm syst} \pm 0.29^{B\,\rm mass}_{\rm syst})\ \ {\rm MeV}/c^2\,,\\
M_{B^0_1} &= (5724.1 \pm 1.7_{\rm stat} \pm 2.0_{\rm syst} \pm 0.5^{B\,\rm mass}_{\rm syst})\ \ {\rm MeV}/c^2\,,\\
M_{B^+_1} &= (5726.3 \pm 1.9_{\rm stat} \pm 3.0_{\rm syst} \pm 0.5^{B\,\rm mass}_{\rm syst})\ \ {\rm MeV}/c^2\,,\\
M_{B^{*0}_2} &= (5738.6 \pm 1.2_{\rm stat} \pm 1.2_{\rm syst} \pm 0.3^{B\,\rm mass}_{\rm syst})\ \ {\rm MeV}/c^2\,,\\
M_{B^{*+}_2} &= (5739.0 \pm 3.3_{\rm stat} \pm 1.6_{\rm syst} \pm 0.3^{B\,\rm mass}_{\rm syst})\ \ {\rm MeV}/c^2\,,
\end{aligned}
$$

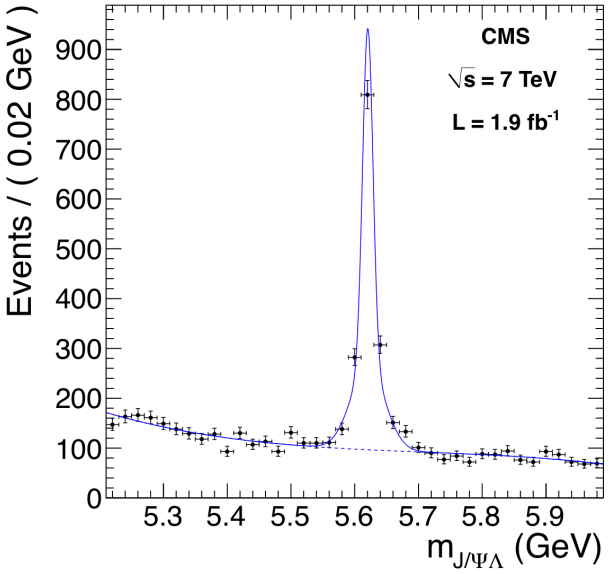
preliminary

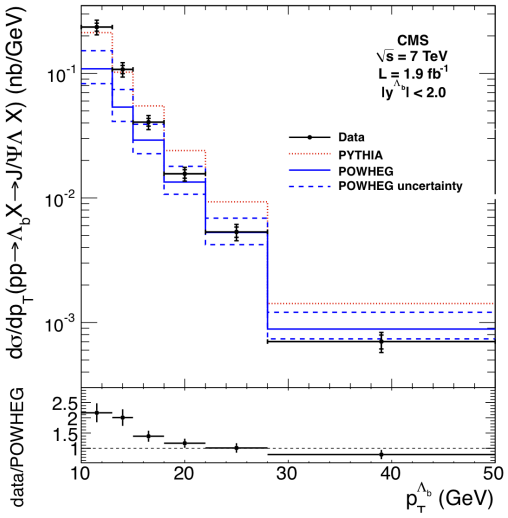


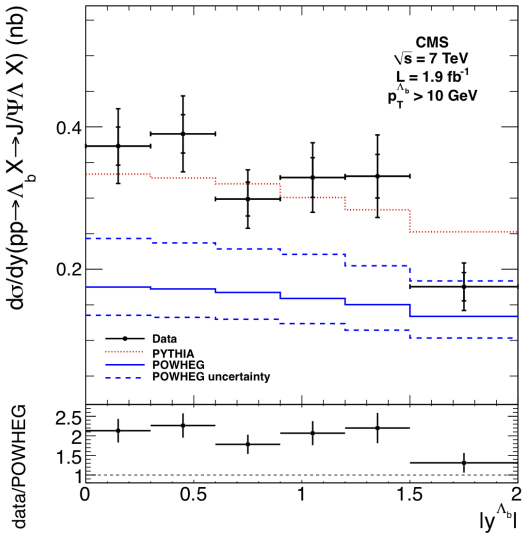
Outline

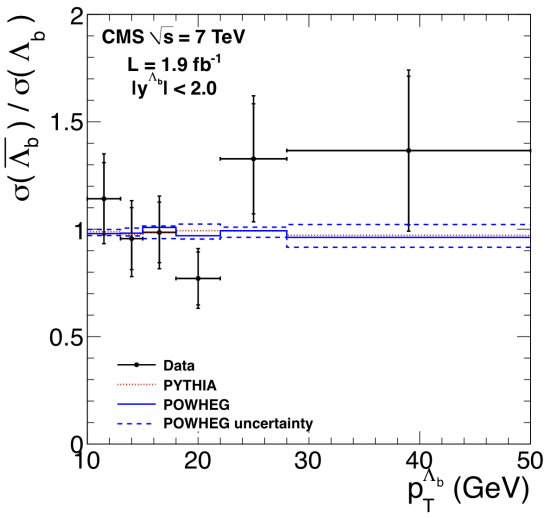
Λ_b cross-section

- Λ_b differential cross-section $\sigma(pp \to \Lambda_b)BR(\Lambda_b \to J/\psi\, \Lambda^0)$ recently measured by CMS (arXiv:1205.0594)
- Dependance on p_T and y studied, as well as the $\bar{\Lambda}_b/\Lambda_b$ ratio









Λ_b^{0*} observation

- Two narrow states observed at LHCb in the $\Lambda_b\,\pi^+\,\pi^-$ spectrum (arXiv:1205.3452).
- Λ_b reconstructed as $\Lambda_c^+\,\pi^-$
- Masses:

$$M_{\Lambda_b^{0*}(5912)} = 5911.05 \pm 0.12 \pm 0.03 \pm 0.66\,\mathrm{MeV}/c^2$$

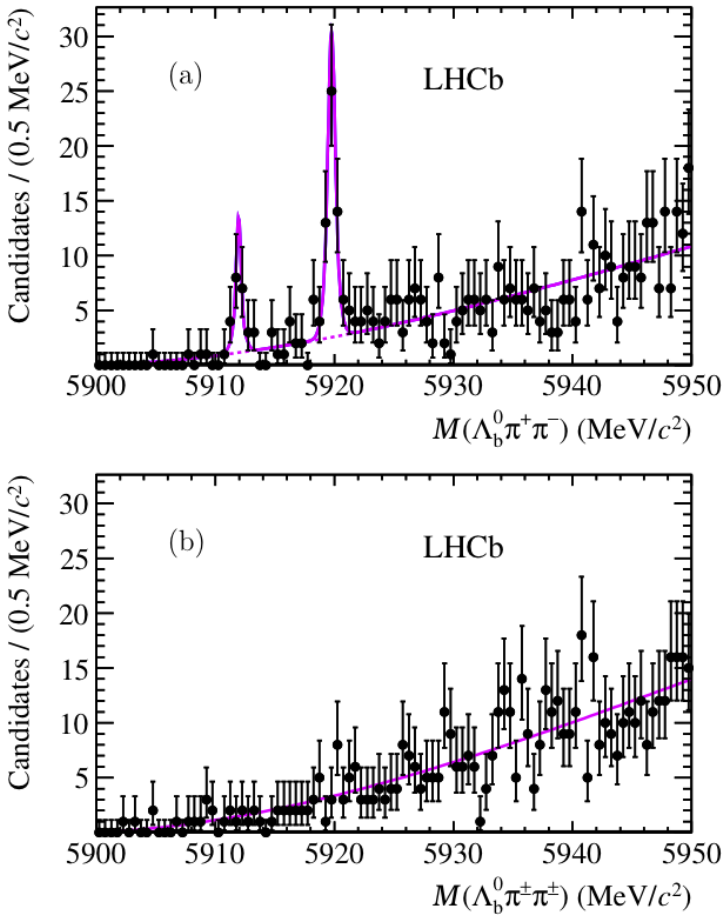
$$M_{\Lambda_b^{0*}(5920)} = 5919.76 \pm 0.07 \pm 0.02 \pm 0.66\,\mathrm{MeV}/c^2$$

- Width limits at 95% CL:

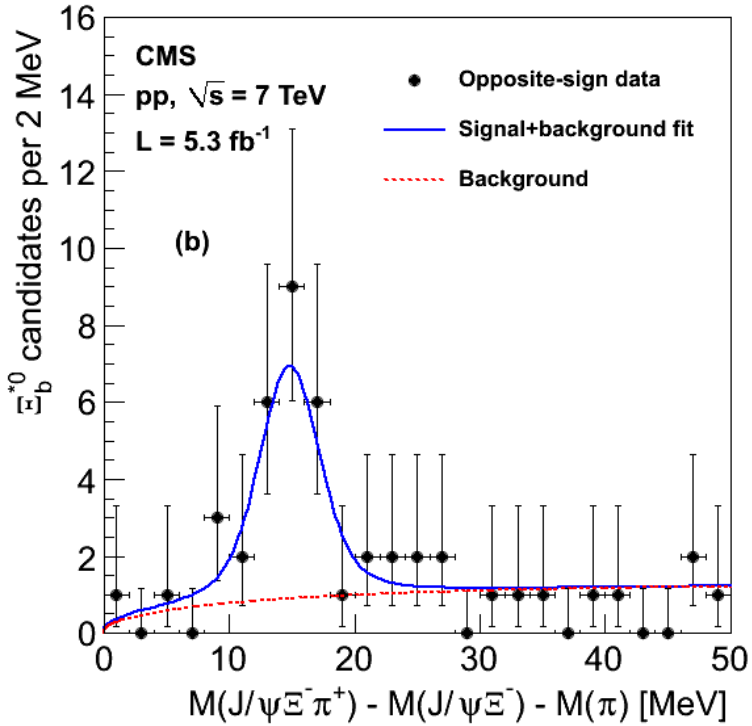
$$\Gamma_{\Lambda_b^{0*}(5912)} < 0.82\,\mathrm{MeV}$$

$$\Gamma_{\Lambda_b^{0*}(5920)} < 0.71\,\mathrm{MeV}$$

- Expected to be $J^P = 1/2^-$ and $3/2^-$ states.



Ξ_b^{*+} observation



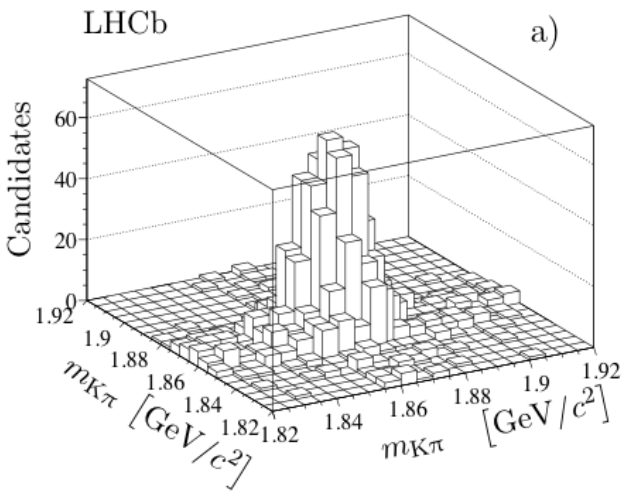
- Recently observed at CMS (arXiv:1204.5955)
- First observation of the $\Xi_b^{*+} \to \Xi_b\,\pi^+$ decay.
- $M(\Xi_b^{*+}) - M(\Xi_b\,\pi) = 14.84 \pm 0.74 \pm 0.26\,\mathrm{MeV}$
- Consistent with the theoretical prediction for Ξ_b^{*+} and expected to have $J^P = 3/2^+$

Outline

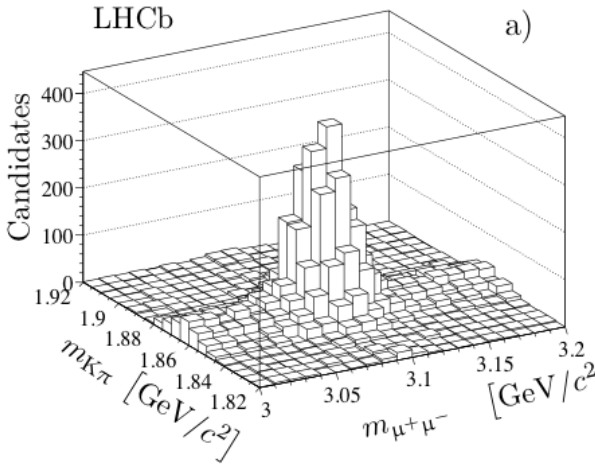
Double charm observation

Mode	yield
$J/\psi D^0$	4875 ± 86
$J/\psi D^+$	3323 ± 71
$J/\psi D_s^+$	328 ± 22
$J/\psi \Lambda_c^+$	116 ± 14
$D^0 D^0$	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

- J/ψ + C and CC production studied at LHCb in 16 channels (arXiv:1205.0975)

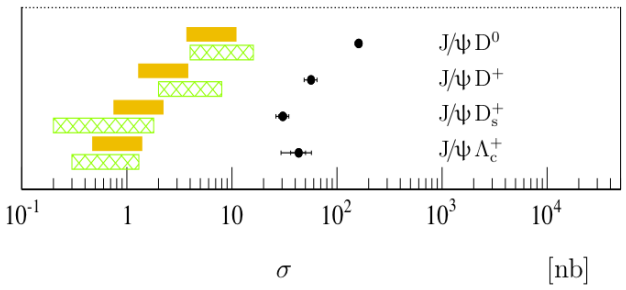


$D^0 D^0$



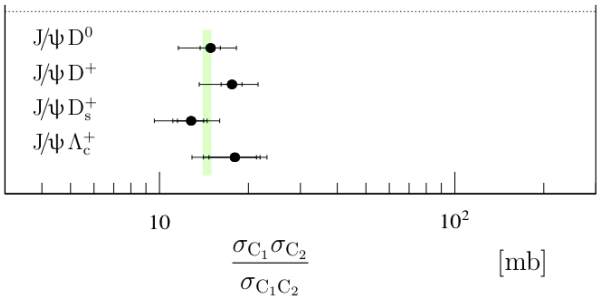
$J/\psi\ D^0$

Double charm production



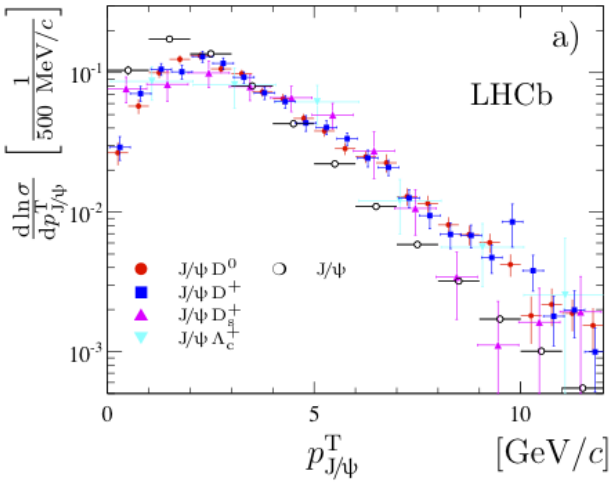
Compared to $gg \longrightarrow J/\psi c\bar{c}$ computations

PRD 57 (1998) 4385
PRD 73 (2006) 074021



Compared to Double Parton Scattering computations

arXiv:1105.4105



- The J/ψ p_T distribution appears to be the same for all species of open charm hadrons.
- Analogously the p_T distribution of the open charm appear to be the same.
- Fit to the distribution yields results that agree within errors.
- The azymuthal angle and rapidity correlations have been studied too.

Outline

Conclusions and outlook

- Many new results and updates of old results produced since PLHC 2011
- My apologies to all those that did not fit in because of time constraints.
- Several measurements will be repeated at 8 TeV
- Still much to explore:
  - Exotic spectroscopy
  - Polarization measurements
  - B_c physics
  - Double quarkonium
  - Precision measurements
  - ...
- Stay tuned for PLHC 2013