Production and spectroscopy of Heavy Flavors at LHCb

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on behalf of the LHCb collaboration

28th Les Rencontres de Physique de la Vallée d'Aoste International Conference on Results and Perspectives in Particle Physics (La Thuile 2014)

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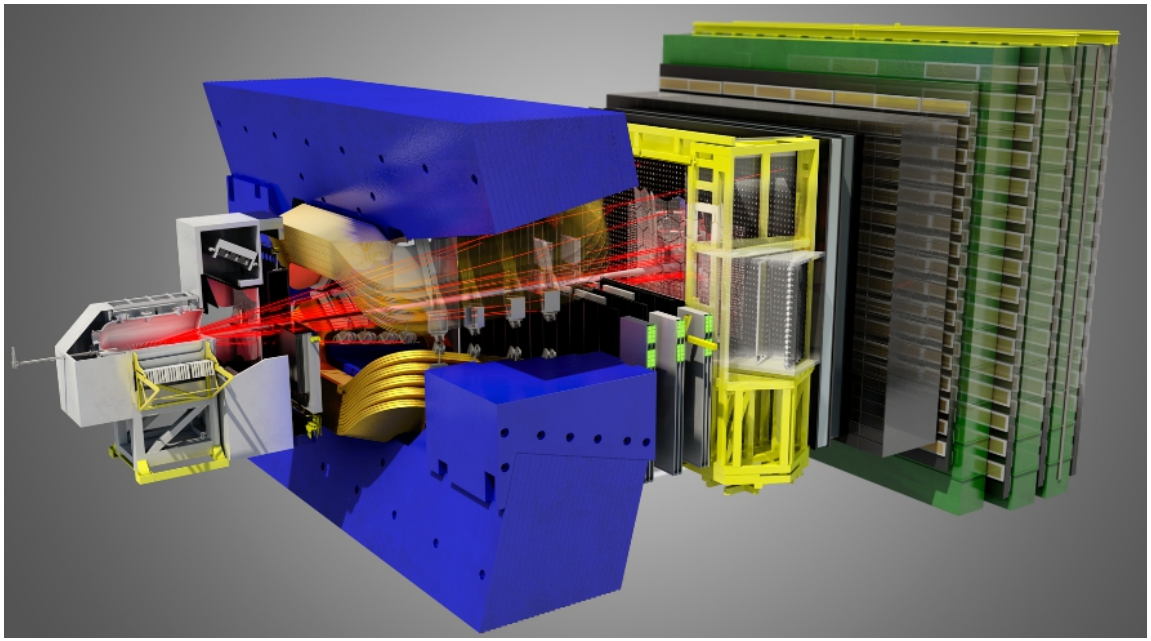
Outline

- *The LHCb experiment*
- *<u>Latest results</u> on Heavy Flavor spectroscopy:*
  - *→ Υ production in pp collisions at 2.76 TeV*
  - *→ ψ(2S) polarisation in pp collisions at 7 TeV*
  - *→ Exclusive J/ψ and ψ(2S) cross-sections*
  - *→ Associative Z+D production*
- *Summary*

The LHCb experiment

- *Forward spectrometer with planar detectors*



- *LHCb uniqueness:*

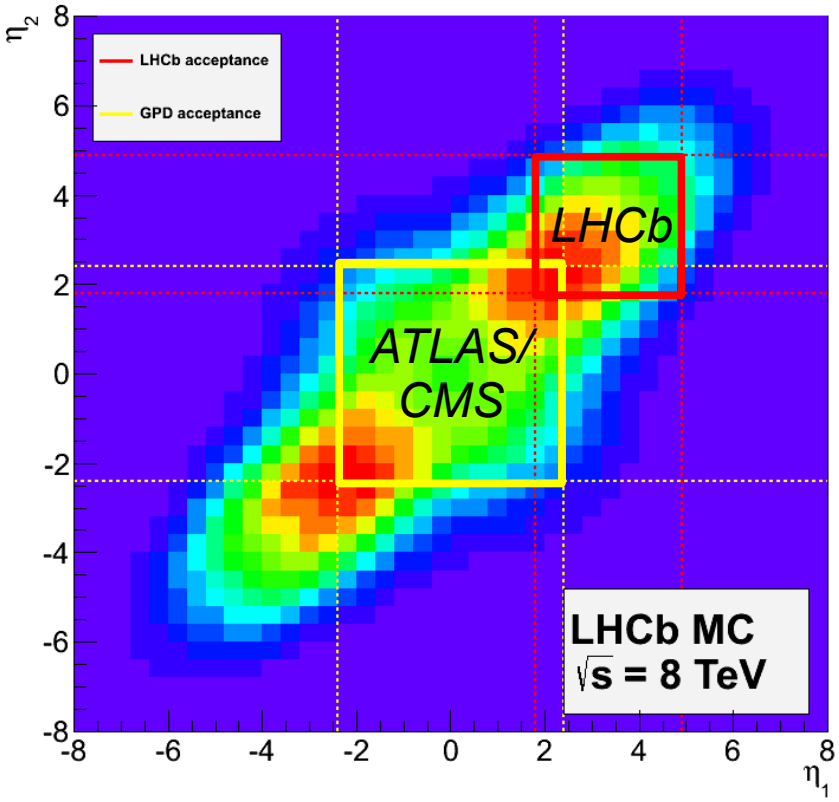
  → *tracking, RICH and calorimeters cover the full detector acceptance (2.0<η<5.0); tracking coverage also in the backward region (-4.0<η<-1.5)*

  → *covers just ~4% of the solid angle but captures ~25% of heavy quark pairs produced at the LHC*

  → *ability to study low-p_T processes at large η*

JINST 3 (2008) S08005

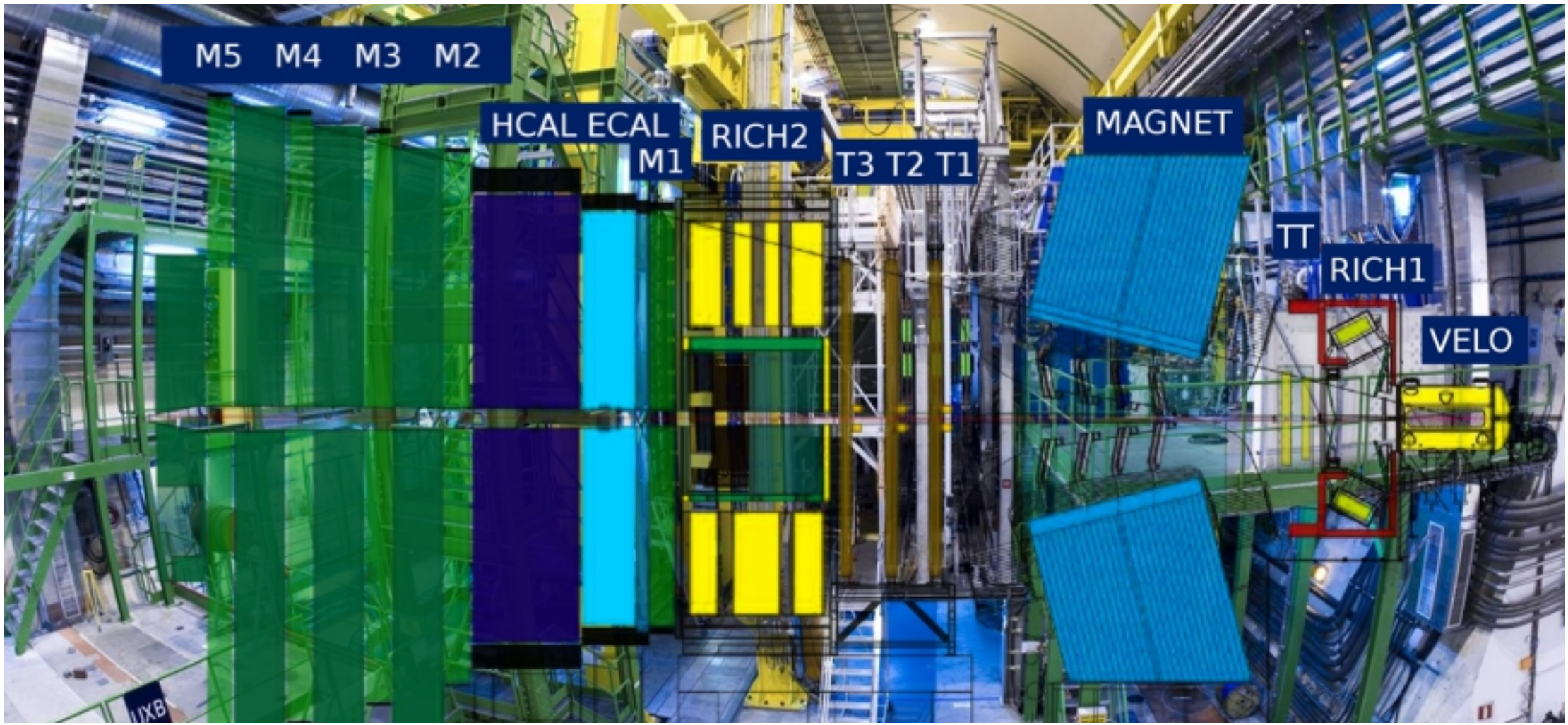
- *heavy quark pair production at the LHC:*



→ *fraction of $\bar{b}b$ pairs in the acceptance:*

c.o.m energy	*ATLAS/CMS*	*LHCb*
8 TeV	*44%*	*25%*
14 TeV	*41%*	*24%*

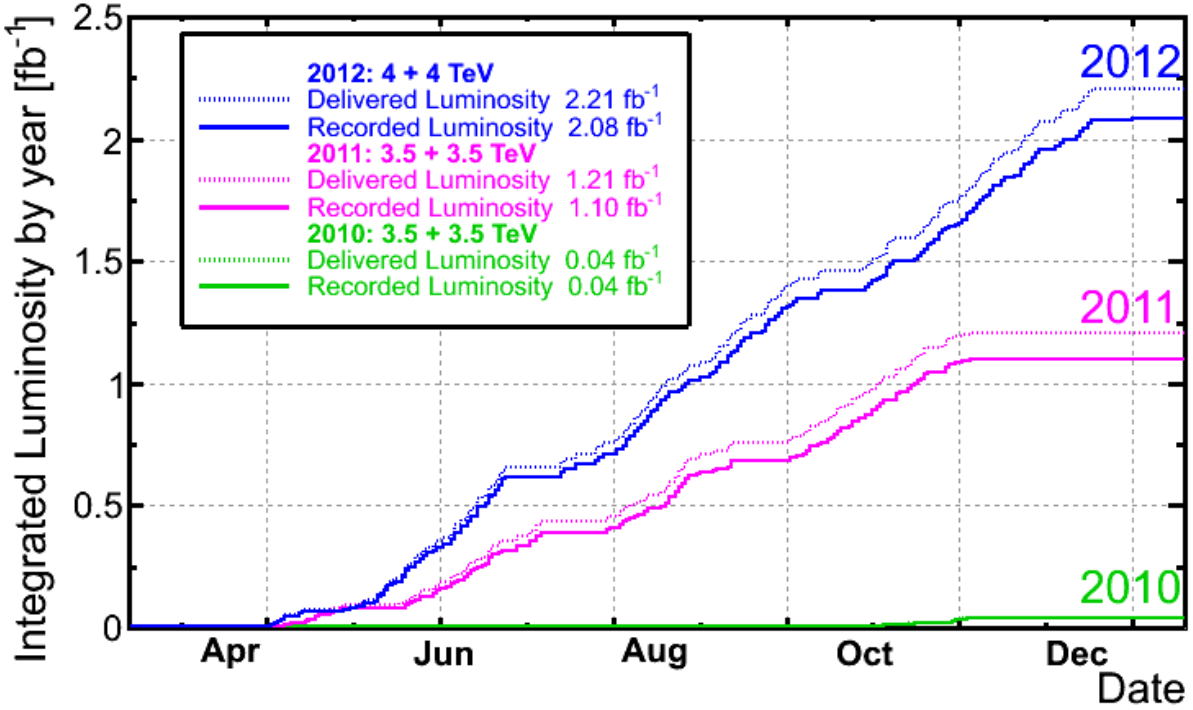
The LHCb experiment



- *Excellent tracking performance: $\delta p/p$~ 0.4–0.6% for tracks traversing full tracking setup*
- *High quality particle identification: robust hadron ID + γ/lepton/hadron separation*
- *Selective and flexible trigger system*

JINST 3 (2008) S08005

The LHCb experiment



- *In the years 2010-2012:*

  → *2 × 10^{14} visible pp interactions*

  → *6 × 10^{12} visible $\bar{c}\,c$ quark pairs*

  → *3 × 10^{11} visible $\bar{b}\,b$ quark pairs*

were produced in the LHCb acceptance

- *~93 % data taking efficiency*
- *~99% r/o channels operational*
- *~99% of accumulated data are useful for physics analyses*
- *Luminosity leveling: constant and moderate interaction rate throughout the data taking periods*
- *Smooth data taking in 2011-2012 regardless high luminosity running*

Ability to perform different measurements with pp collisions at 2.76 TeV, 7 TeV and 8 TeV and with pPb collisions at 5 TeV

Latest LHCb results on Heavy Flavors

- *Measurement of Υ production in pp collisions at 2.76 TeV*
  → arXiv:1402.2539 [hep-ex]; CERN-PH-EP-2014-016;
  submitted to EPJ C

- *Measurement of $\psi(2S)$ polarisation in pp collisions at 7 TeV*
  → LHCb-PAPER-2013-067 (to be submitted to EPJ C)

- *Updated measurements of exclusive J/ψ and $\psi(2S)$ production cross-sections in pp collisions at 7 TeV*
  → arXiv:1401.3288 [hep-ex]; CERN-PH-EP-2013-233;
  submitted to Journal of Physics G

- *Observation of associated production of a Z boson with a D meson in the forward region*
  → arXiv:1401.3245 [hep-ex]; CERN-PH-EP-2013-235;
  submitted to JHEP

Further exploration of heavy quarkonia properties and studies of associated particle production to probe double-parton scattering at the LHC

Υ production at 2.76 TeV

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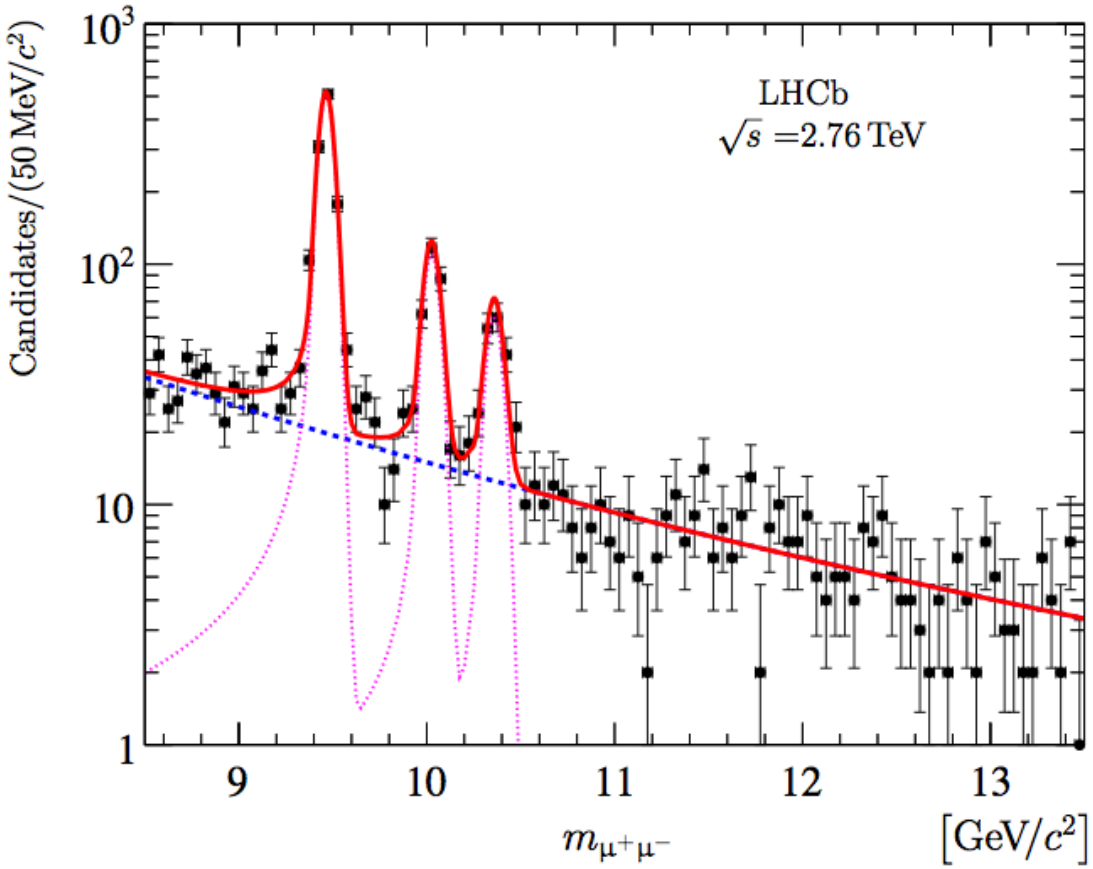
arXiv:1402.2539 [hep-ex]

- *Complementary analysis to those performed at 7 and 8 TeV:*
  - → *Eur. Phys. J. C72 (2012) 2025 , JHEP06 (2013) 064*
  - → *allows studies of bottomonium hadroproduction as a function of collision energy in the forward region: unique input to theory*
- *Performed with 3.3 pb^{-1} of 2013 2.76 TeV pp data:*
  - → *measurement of single differential production cross-sections as functions of p_T and y for $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$*
  - → *total uncertainties dominated by statistical effects*
  - → *$\Upsilon(2S)/\Upsilon(1S)$ and $\Upsilon(3S)/\Upsilon(1S)$ are measured too*
  - → *kinematic range: p_T < 15 GeV and 2.0<y<4.5 (the same as in the previous studies)*



Υ production at 2.76 TeV

- *Measurements are well described by the NLO NRQCD predictions (yellow band) at large p_T, while these underestimate the data at low p_T*
  → Phys. Rev. Lett. 112, 032001 (2014)

- *Total cross-sections for p_T < 15 GeV and 2.0<y<4.5:*

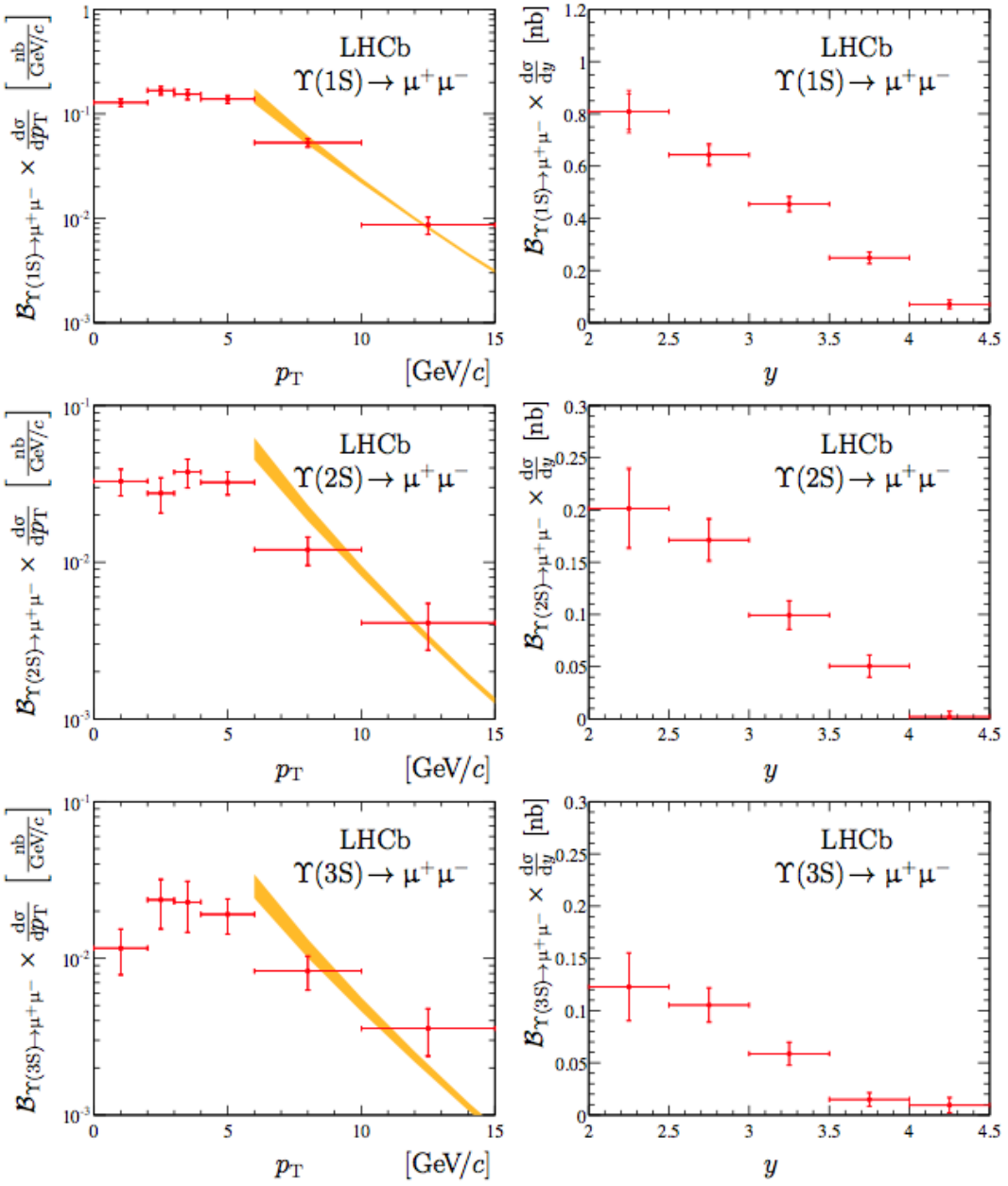
$$\sigma(pp \to \Upsilon(1S)X) \times \mathcal{B}(\Upsilon(1S) \to \mu^+\mu^-) = 1.111 \pm 0.043 \pm 0.044\,\text{nb}$$
$$\sigma(pp \to \Upsilon(2S)X) \times \mathcal{B}(\Upsilon(2S) \to \mu^+\mu^-) = 0.264 \pm 0.023 \pm 0.011\,\text{nb}$$
$$\sigma(pp \to \Upsilon(3S)X) \times \mathcal{B}(\Upsilon(3S) \to \mu^+\mu^-) = 0.159 \pm 0.020 \pm 0.007\,\text{nb}$$

- *Total cross-sections for p_T < 15 GeV and 2.5<y<4.0:*

$$\sigma(pp \to \Upsilon(1S)X) \times \mathcal{B}(\Upsilon(1S) \to \mu^+\mu^-) = 0.670 \pm 0.025 \pm 0.026\,\text{nb}$$
$$\sigma(pp \to \Upsilon(2S)X) \times \mathcal{B}(\Upsilon(2S) \to \mu^+\mu^-) = 0.159 \pm 0.013 \pm 0.007\,\text{nb}$$
$$\sigma(pp \to \Upsilon(3S)X) \times \mathcal{B}(\Upsilon(3S) \to \mu^+\mu^-) = 0.089 \pm 0.010 \pm 0.004\,\text{nb}$$

→ reduced kinematic range: reference measurement for the analysis with pPb data at 5 TeV

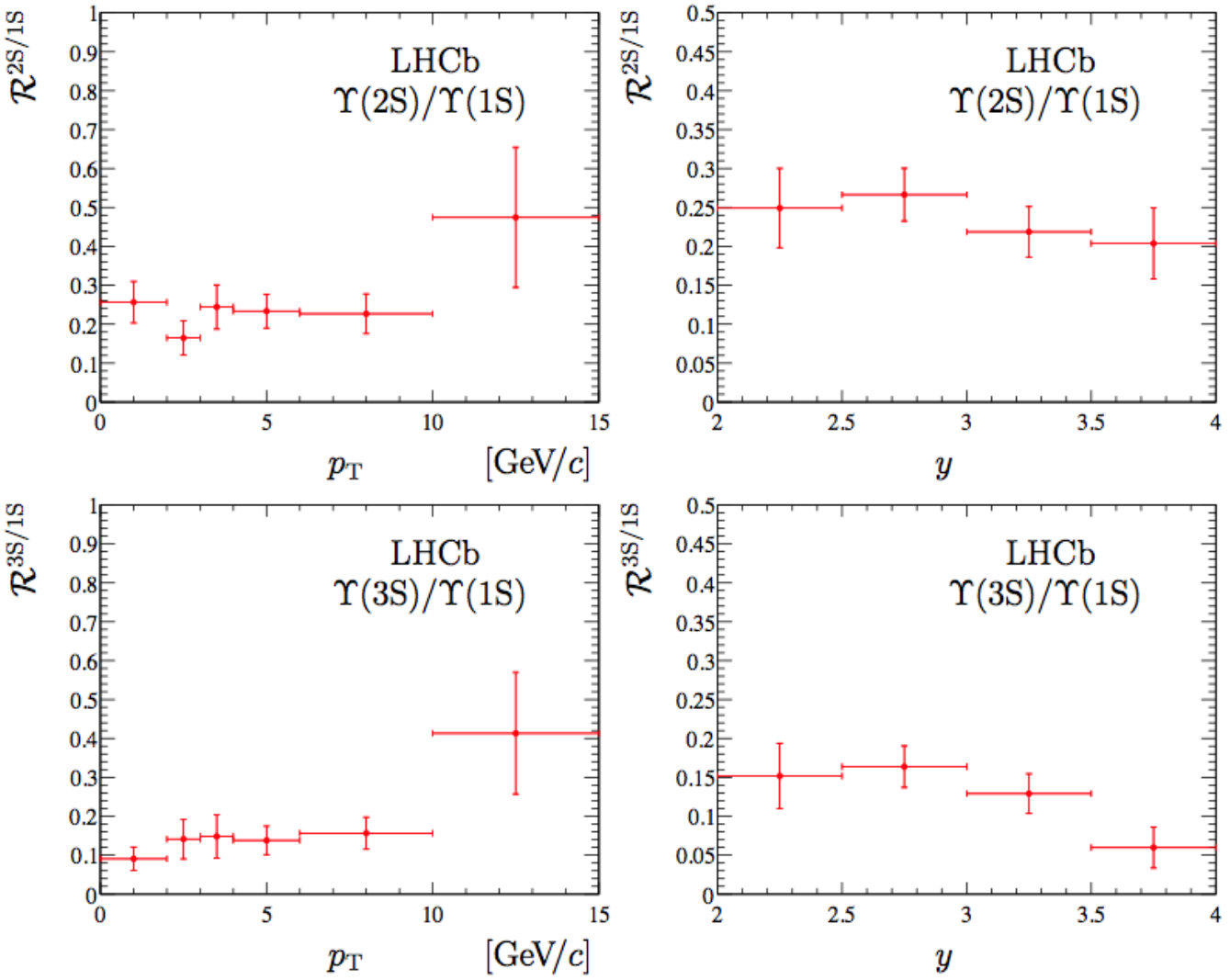
arXiv:1402.2539 [hep-ex]



Υ production at 2.76 TeV

- *Ratios of $\Upsilon(2S)/\Upsilon(1S)$ and $\Upsilon(3S)/\Upsilon(1S)$ as functions of p_T and y:*

arXiv:1402.2539 [hep-ex]



→ *consistency with the corresponding results obtained at higher collision energies*

$\psi(2S)$ polarisation at 7 TeV

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LHCb-PAPER-2013-067

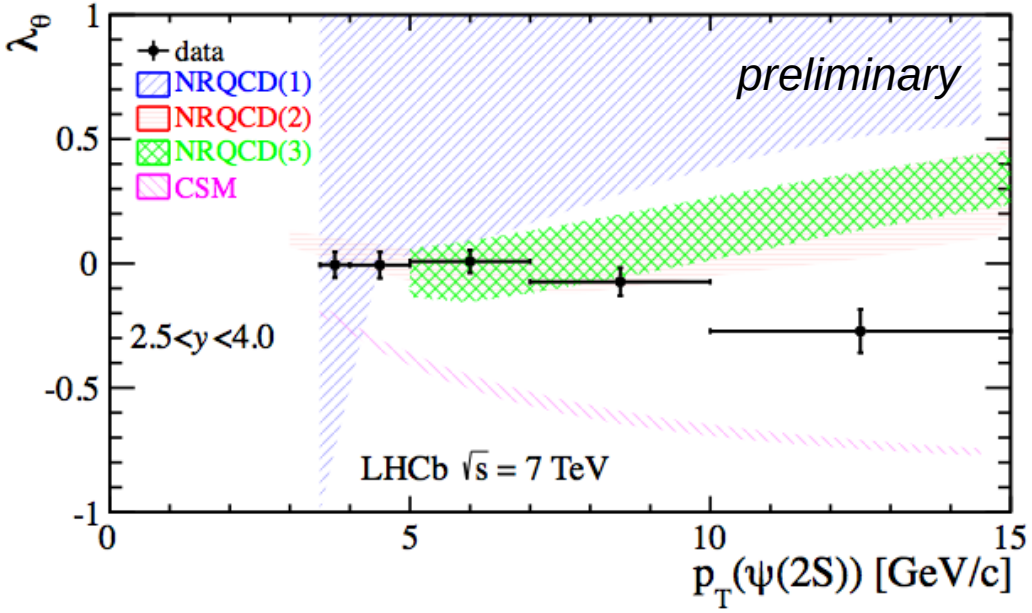
- *Performed with 1 fb^{-1} of 7 TeV pp collision data:*

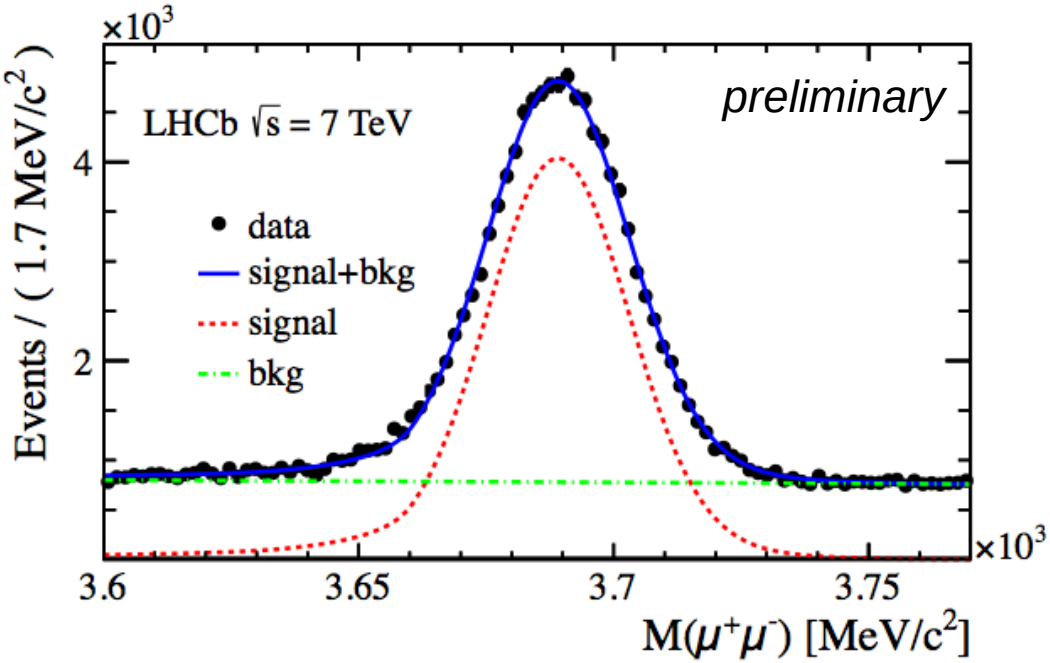
→ *angular analysis of $\psi(2S) \to \mu^+\mu^-$ decay*

→ *angular observables measured as functions of p_T and y in the helicity and Collins-Soper frames by studying the angular distributions of muons*

→ *kinematic range: $3.5 < p_T < 15$ GeV and $2.0<y<4.5$*

→ *data disagrees with NLO CSM, while NLO non-relativistic QCD models provide good description at low p_T*





- *$\psi(2S)$ meson exhibits neither large transverse nor longitudinal polarisation*

Exclusive J/ψ and $\psi(2S)$ at 7 TeV

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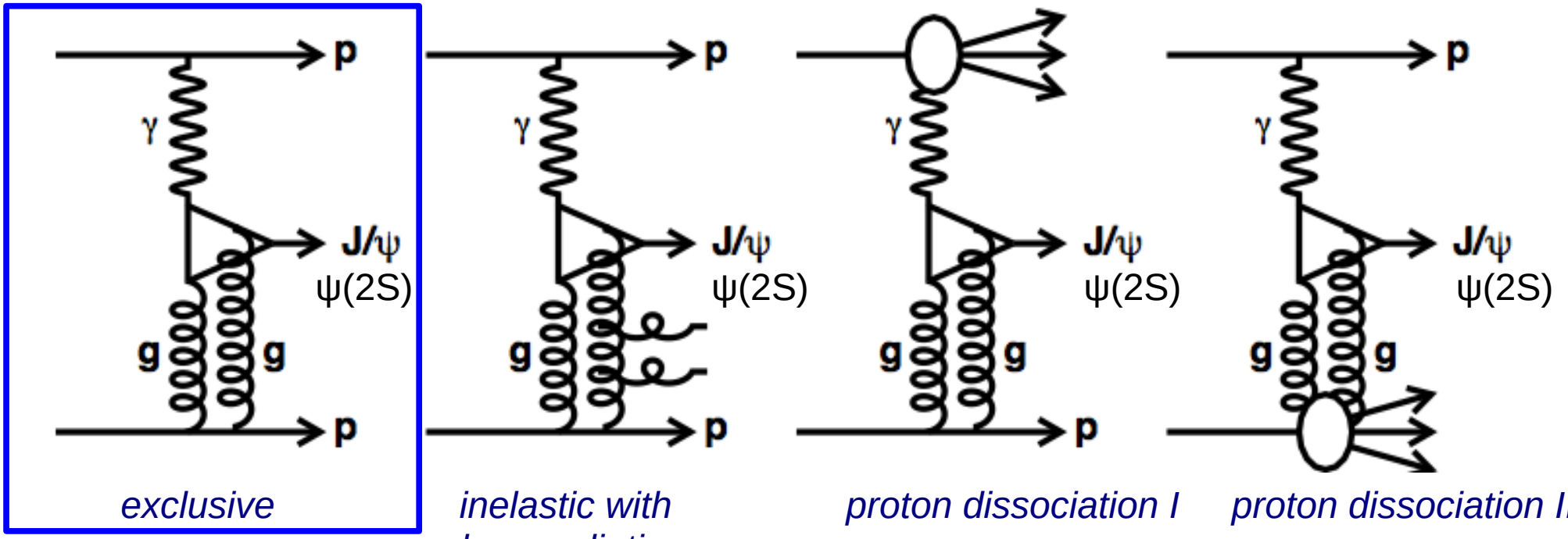
- *Pomeron/photon exchange diffractive processes calculable with pQCD:*

arXiv:1401.3288 [hep-ex]



- *Sensitivity to saturation effects: probing Bjorken-x down to ~5 $\times 10^{-6}$*

- *Possibility to constrain gluon PDF: theoretical predictions depend on it*

Exclusive J/ψ and $\psi(2S)$ at 7 TeV

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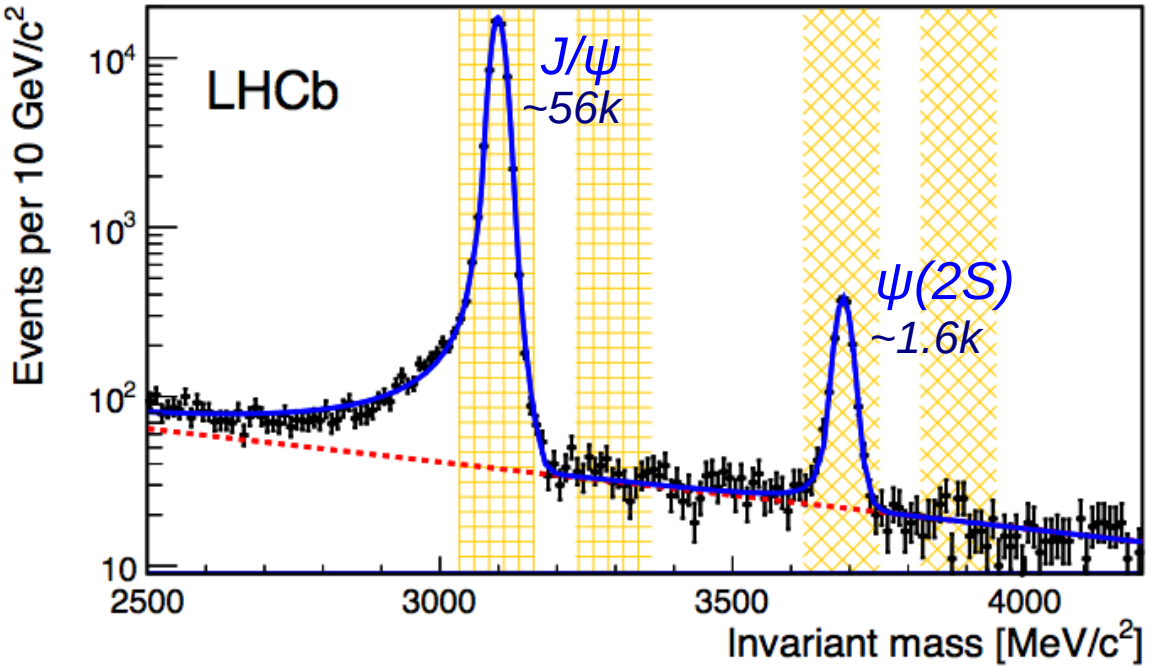
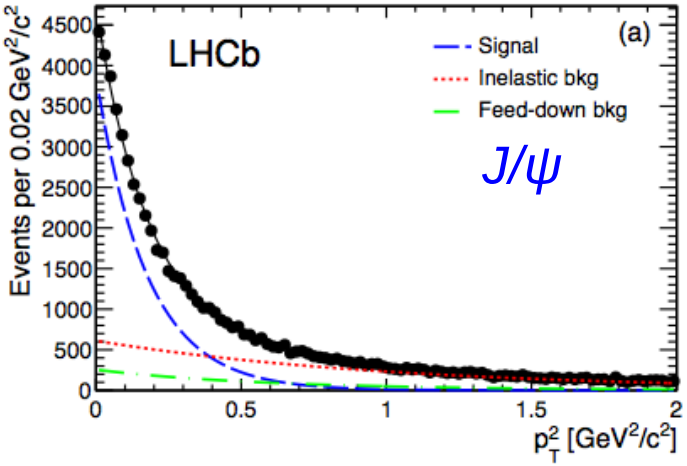
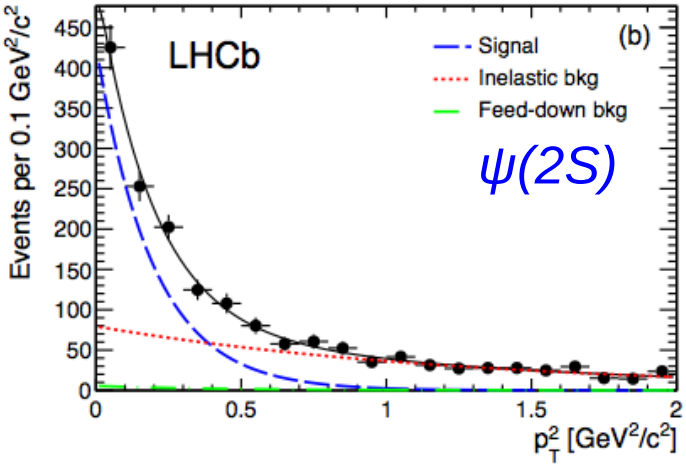
arXiv:1401.3288 [hep-ex]

- *Performed with 0.93 fb^{-1} of 7 TeV pp collision data:*
  - → *supersedes previous study: J. Phys. G40 (2013) 045001*
  - → *J/ψ / $\psi(2S) \to \mu^+\mu^-$ decay modes*
  - → *kinematic range: $2.0 < \eta(\mu) < 4.5$*
- *Clean experimental signature: empty event except for two muon tracks*
  - → *large rapidity gap over the backward region*
  - → *feed-down contributions estimated from simulation and normalised using the data*
  - → *inelastic background determined from p^2_T distributions*



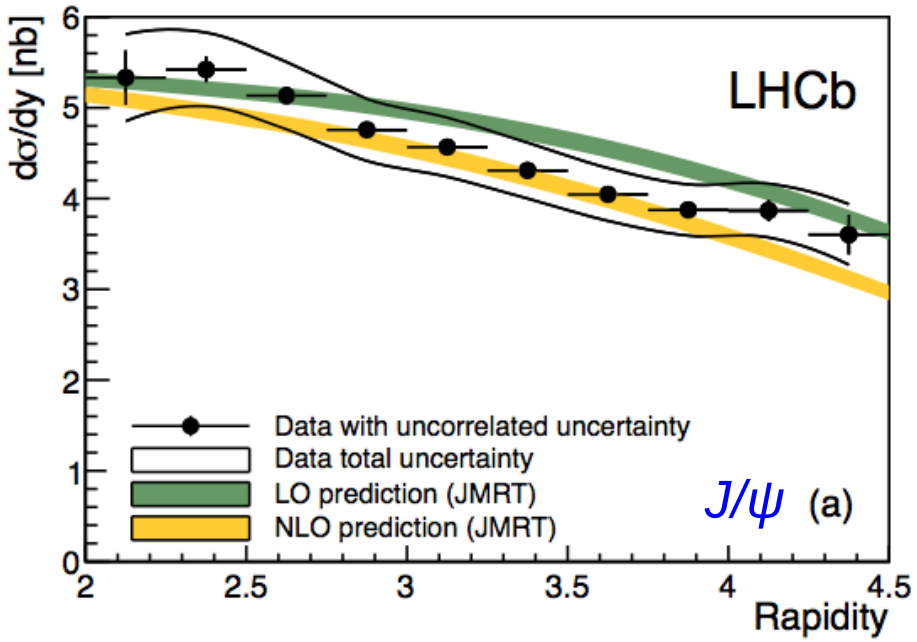


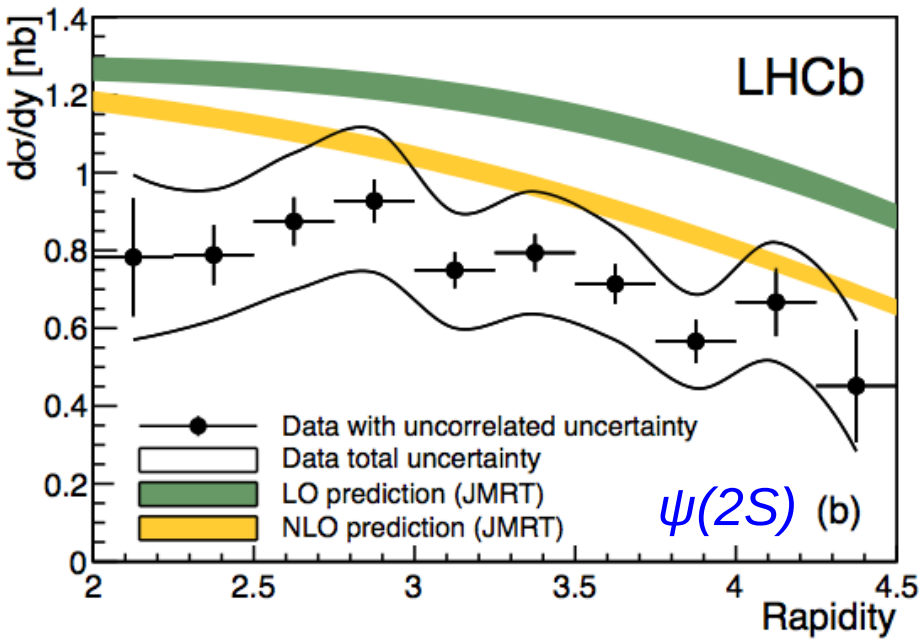


Exclusive J/ψ and $\psi(2S)$ at 7 TeV

- *Single differential cross-sections as a function of rapidity:*

arXiv:1401.3288 [hep-ex]





→ *NLO describes data better than LO based predictions*

→ *better description for J/ψ than for $\psi(2S)$*

→ *uncertainties are highly correlated between the bins*

Exclusive J/ψ and $\psi(2S)$ at 7 TeV

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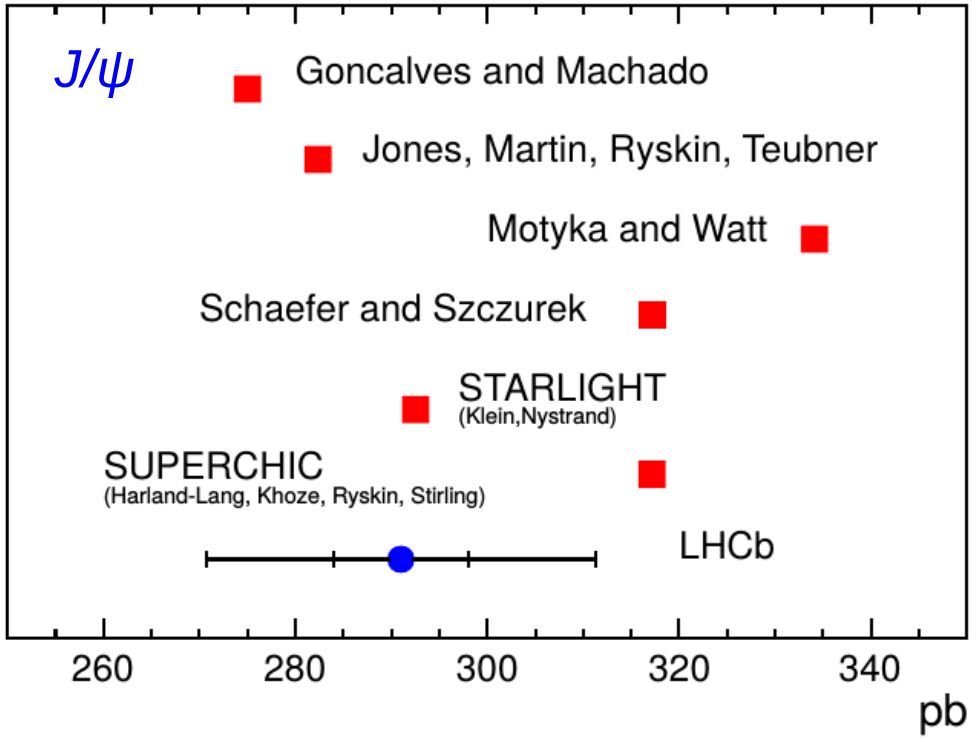
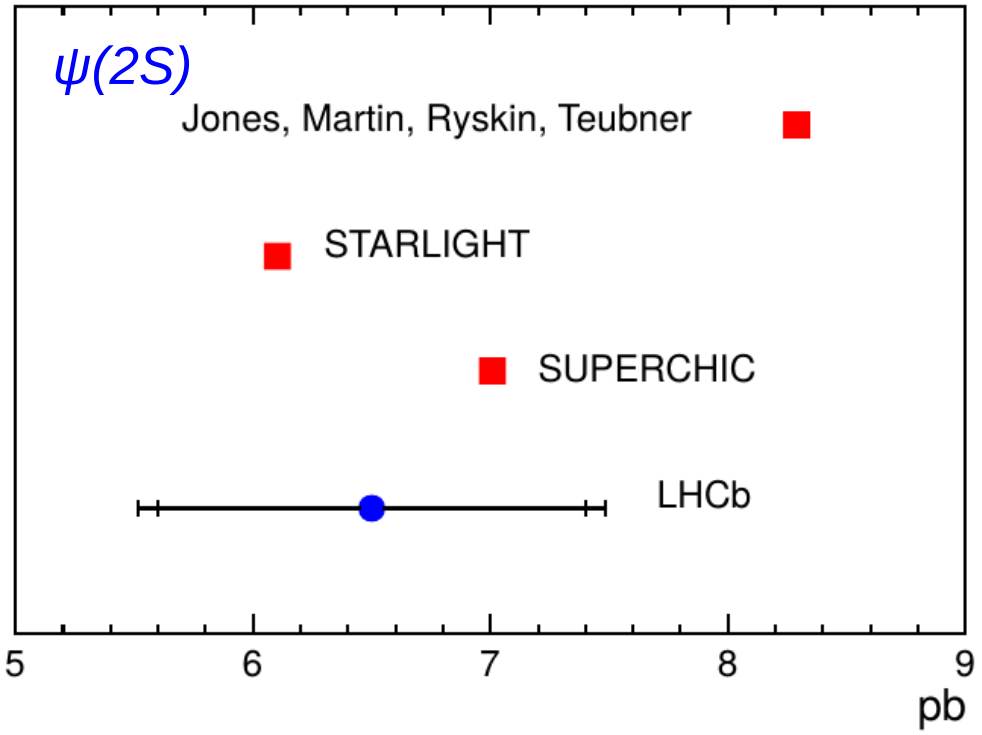
arXiv:1401.3288 [hep-ex]

- *Total cross-sections: data vs theory*
  - → *scaled with the dimuon branching fractions*
  - → *kinematic range: 2.0 < η(μ) < 4.5*





→ *good agreement with theoretical predictions*

Phys. Rev. C84 (2011) 011902
JHEP 1311 (2013) 085
Phys. Rev. D78 (2008) 014023
Phys. Rev. D76 (2007) 094014
Phys. Rev. Lett. 92 (2004) 142003
Eur. Phys. J. C65 (2010) 433

Z+D observation at 7 TeV

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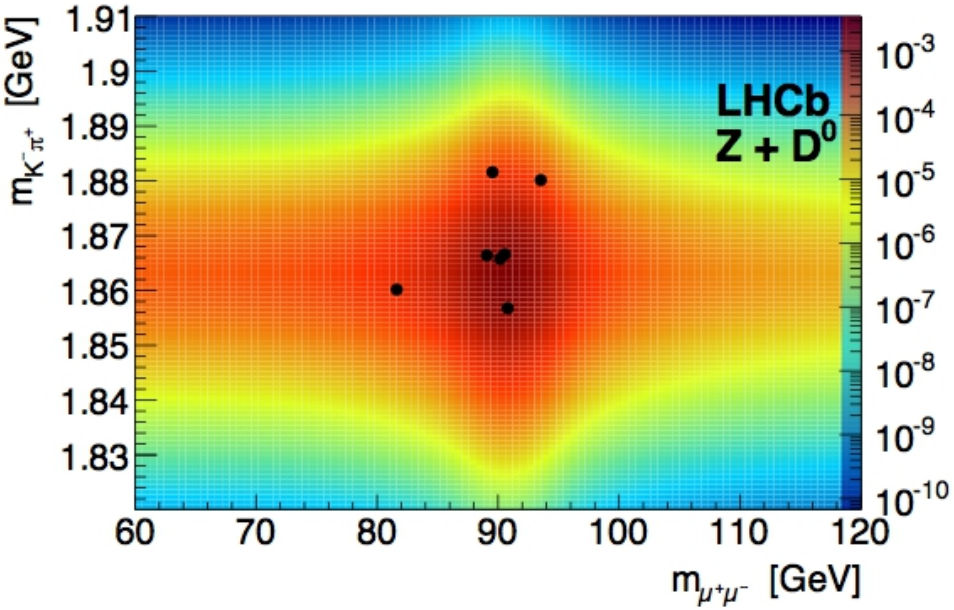
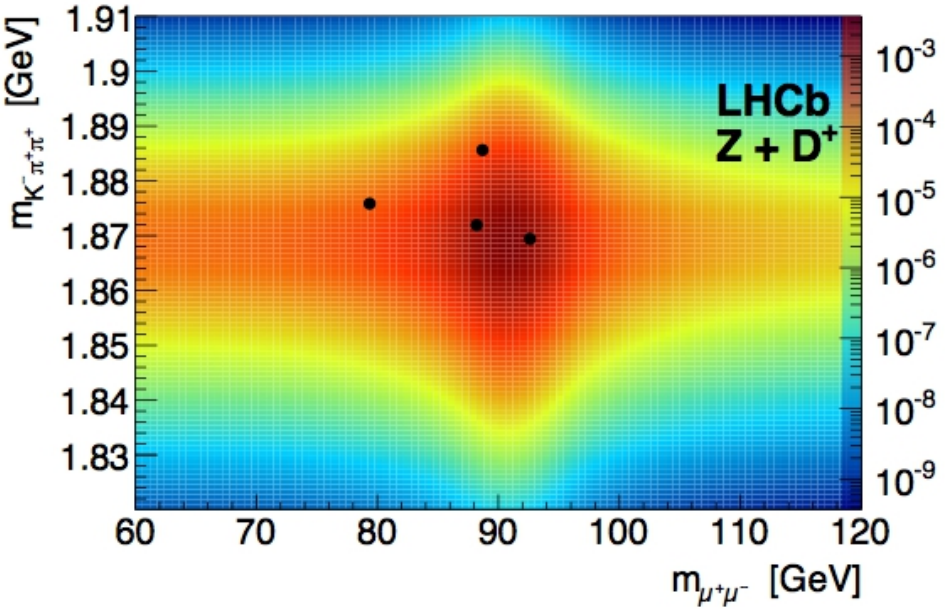
arXiv:1401.3245 [hep-ex]

- *Associated production of Z+D mesons - unique insight into:*
  - → *double parton scattering (DPS)*
  - → *charm production mechanism and charm parton distribution inside the proton*
- *Performed with 1 fb^{-1} of 7 TeV pp data:*
  - → *kinematic range: $60<M(\mu^+\mu^-)<120$ GeV; $p_T(\mu)>20$ GeV; $2.0<\eta(\mu)<4.5$; $2<p_T(D)<12$ GeV; $2.0<y(D)<4.0$*
  - → *$Z\to\mu^+\mu^-$; $D^0\to\pi^+K^-$; $D^+\to\pi^+\pi^+K^-$ decay modes*
  - → *$Z+D^0$: 7 reconstructed candidates ; $Z+D^+$: 4 reconstructed candidates*
  - → *5.1σ combined significance: first observation*
  - → *background contamination mainly due to Z+b(D) feed down contribution - included in the systematics*





→ *color scale shows the PDF value at any given point*

Z+D observation at 7 TeV

arXiv:1401.3245 [hep-ex]

- *Cross-section (in pb): data vs theory*
  - → *contribution from SPS and DPS production mechanisms*
  - → *SPS: NLO parton-level integrator, MCFM*
  - → *DPS: factorisation approximation* $\sigma^{DPS}_{Z\to\mu^+\mu^-,D} = \frac{\sigma_{Z\to\mu^+\mu^-}\,\sigma_D}{\sigma_{eff}}$

Nucl. Phys.Proc. Suppl. 205-206 (2010) 10

	measured	MCFM massless	MCFM massive	DPS
$Z + D^0$	$2.50 \pm 1.12 \pm 0.22$	$0.85^{+0.12}_{-0.07}\,{}^{+0.11}_{-0.17} \pm 0.05$	$0.64^{+0.01}_{-0.01}\,{}^{+0.08}_{-0.13} \pm 0.04$	$3.28^{+0.68}_{-0.58}$
$Z + D^+$	$0.44 \pm 0.23 \pm 0.03$	$0.37^{+0.05}_{-0.03}\,{}^{+0.05}_{-0.07} \pm 0.03$	$0.28^{+0.01}_{-0.01}\,{}^{+0.04}_{-0.06} \pm 0.02$	$1.29^{+0.27}_{-0.23}$

→ *MCFM underestimates $Z(\mu^+\mu^-)+D^0$ and provides good description for $Z(\mu^+\mu^-)+D^+$*

→ *DPS provides reasonable description for $Z(\mu^+\mu^-)+D^0$ and overestimates $Z(\mu^+\mu^-)+D^+$ production*

Summary

- *LHCb provides a great possibility to study different aspects of heavy flavor spectroscopy at different collision energies in a unique, previously unexplored kinematic range - important input to theory !*

- *First 2014 LHCb results on heavy flavor spectroscopy are highly exciting:*
  - *→ Υ production at 2.76 TeV is measured for the first time*
  - *→ $\psi(2S)$ polarisation at 7 TeV is studied for the first time at forward rapidities*
  - *→ associative Z+D production is measured for the first time*
  - *→ exclusive J/ψ and $\psi(2S)$ cross-section measurements are updated*

- *Existing theoretical models cannot describe all aspects of heavy flavor spectroscopy: LHCb data are helpful to improve things :-)*

Stay tuned for further results !

Backup: exclusive J/ψ and $\psi(2S)$

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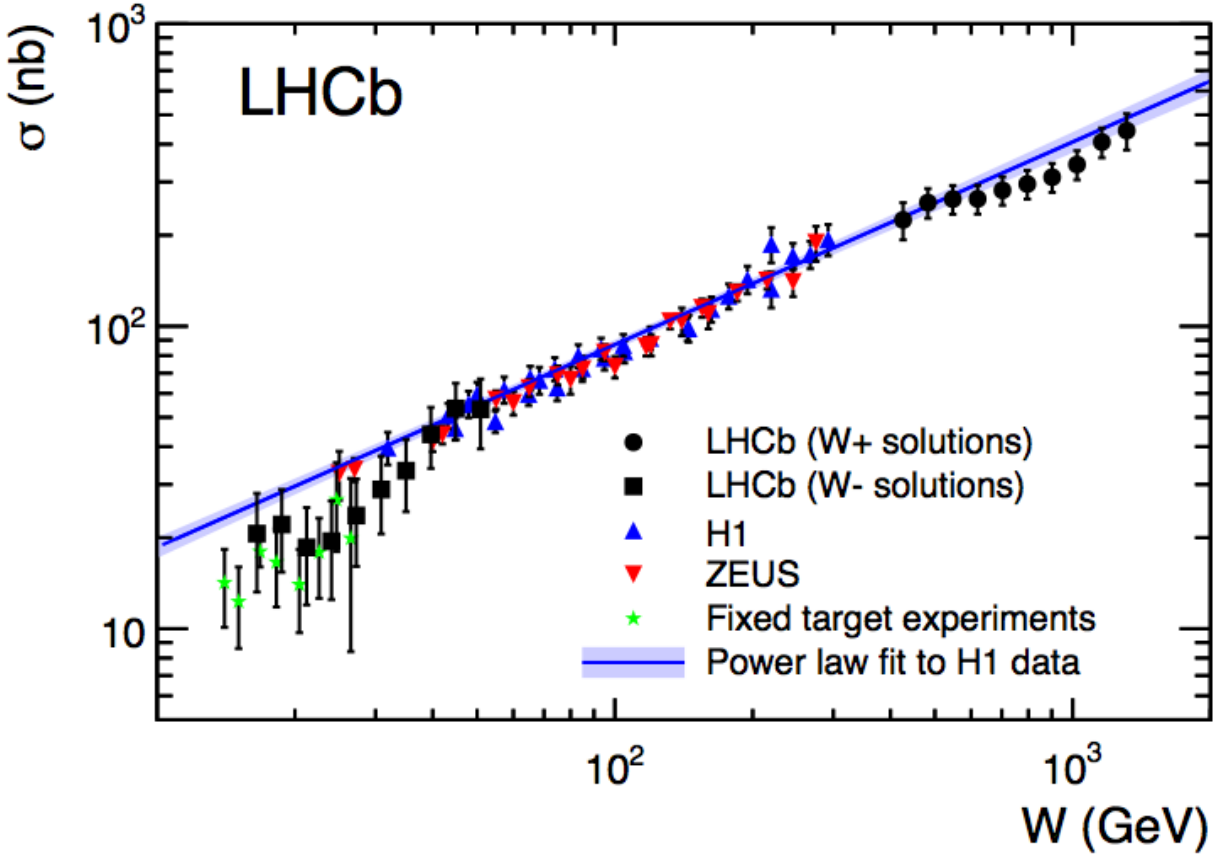
- *Photoproduction cross-section as a function of the c.o.m. photon-proton system*
  → *H1 power law fit results are superimposed*



arXiv:1401.3288 [hep-ex]