Heavy Flavour Production and Properties

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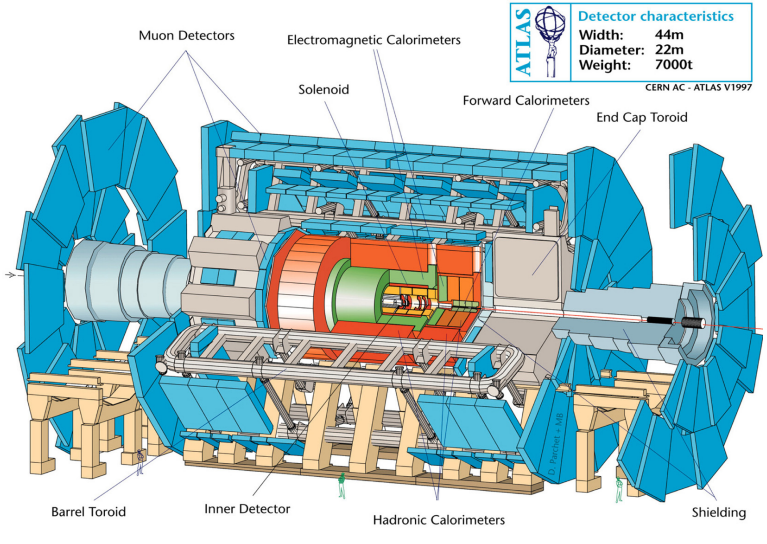
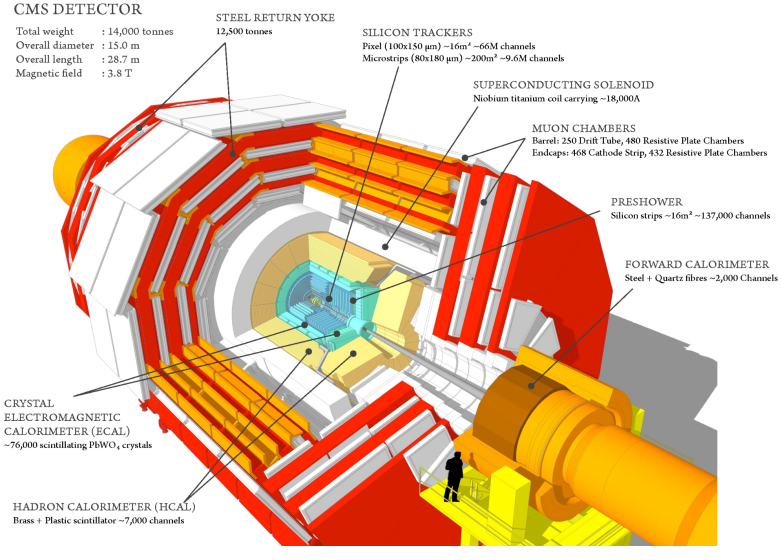
29th Rencontres de Blois
Particle Physics and
Cosmology

Introduction

- Production of c- and b-quarks is an excellent test of our understanding of QCD.
- Heavy flavour production has an important role in the determination of PDFs and composes much of the background to many searches.
- There are many results in this presentation, so they are presented as light summaries. References are given to find the result in either journals or the experiment's public result page.

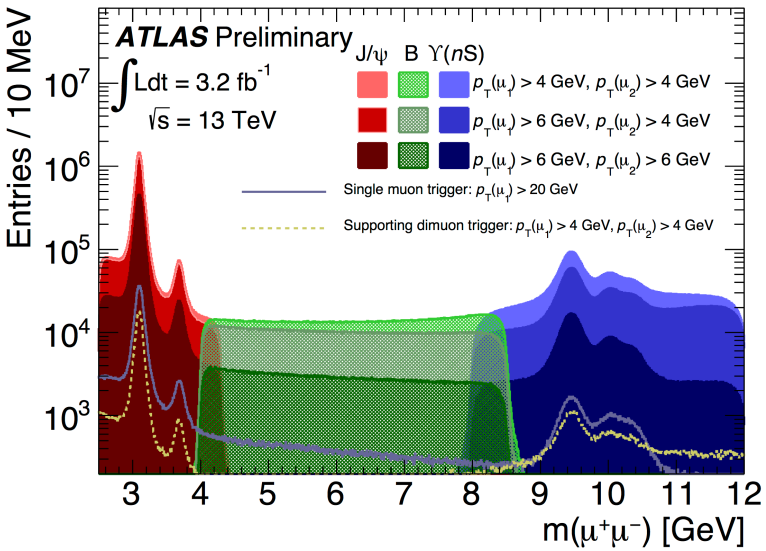


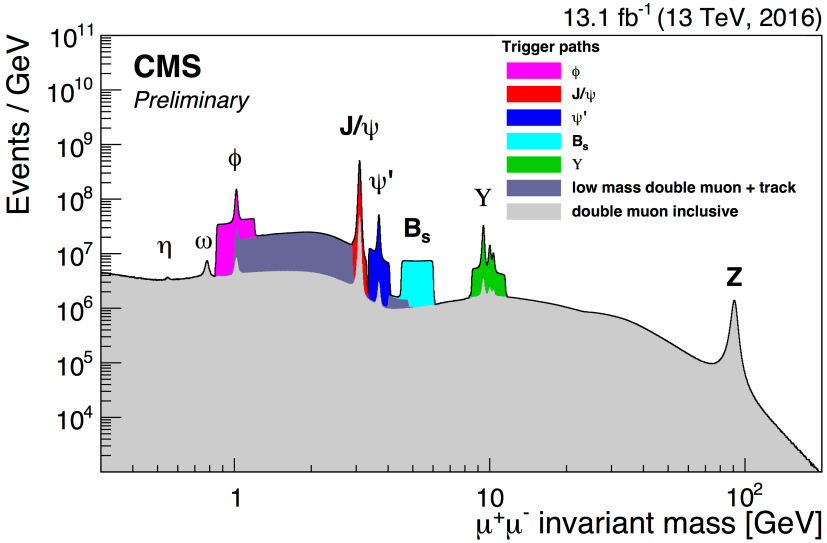


Di-Muon Spectrum at 13TeV

Most heavy flavour physics events at ATLAS and CMS is selected using single and di-muon triggers.

- Di muons select opposite charged tracks that exceed a momentum threshold.
- A vertex quality cut is applied and in some cases a decay length cut.
- The cuts are adjusted in triggers dedicated to the various analyses under consideration.



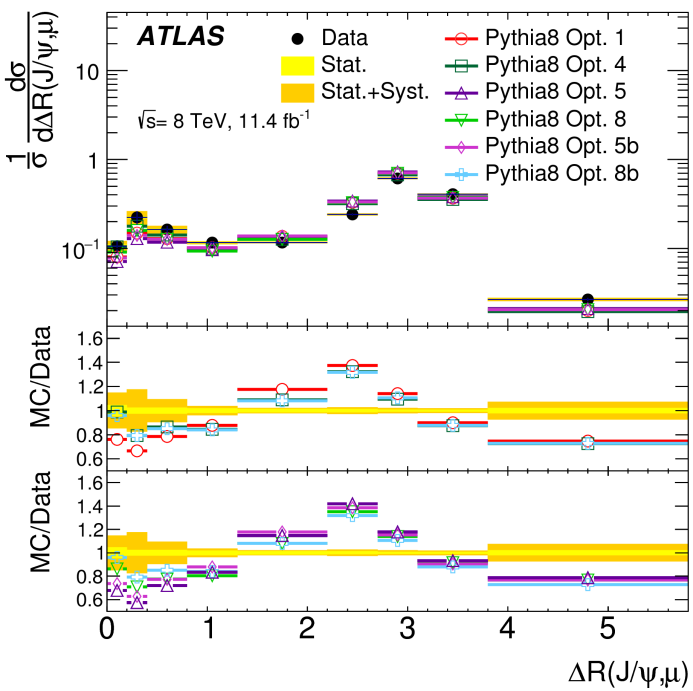


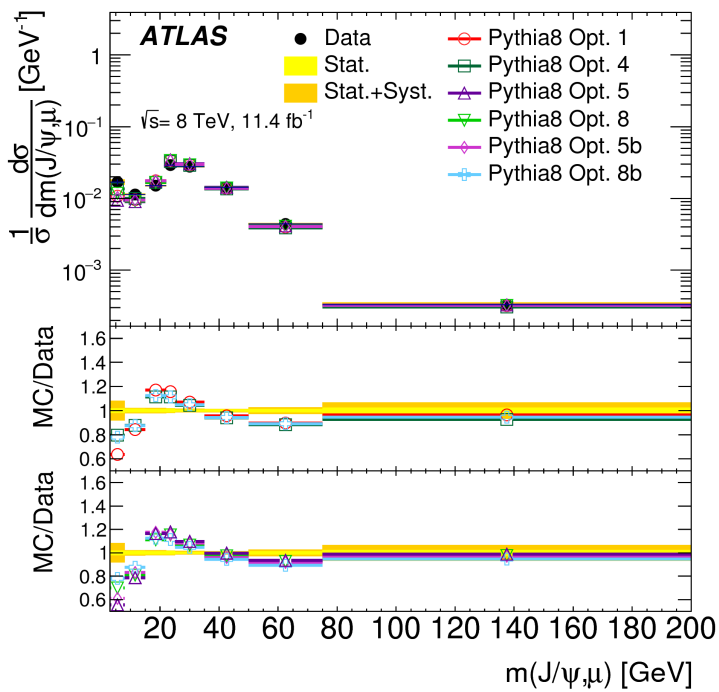
Successfully used in Run-1, re-calibrated for higher luminosity in Run-2

Measurement of b-hadron pair production

arXiv:1705.03374

- Hybrid of methods: look for events with non-prompt J/ψ → μμ on one side and a semi-muonic B-decay on the other.
- Total fiducial cross section: σ [(B → J/ψ(μμ)X)·(B → μX)] = 17.7 ± 0.1 (stat.) ± 2.0 (syst) nb.
- Comparisons of the differential cross sections with various predictions are reported w.r.t various variables

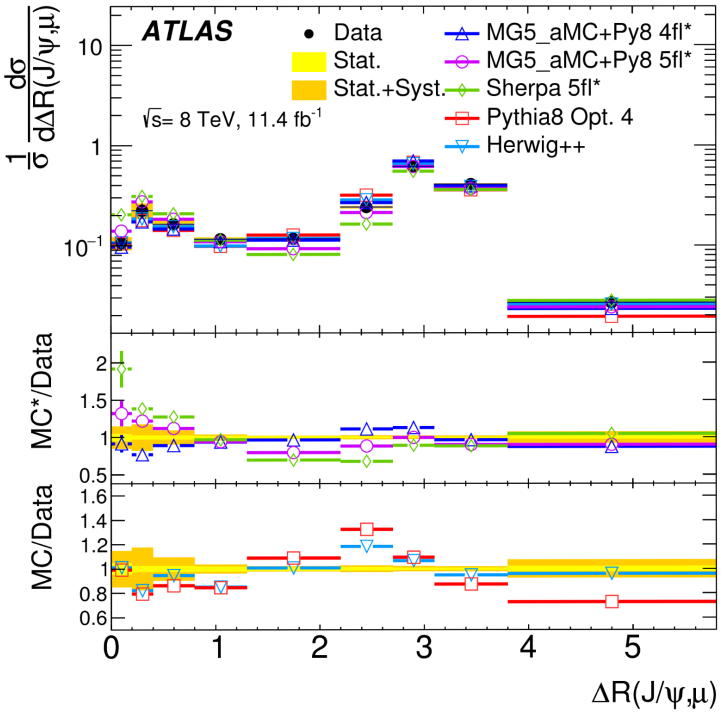




Pythia8 doesn't reproduce the shapes of the angular distributions very well

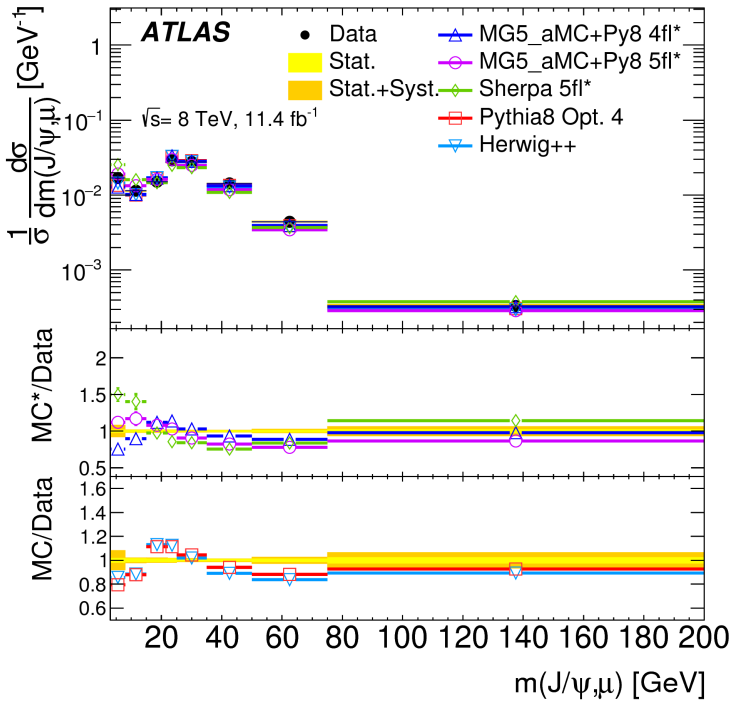
pT-based splitting kernels give a better description at low ΔR (options 1,4)

Measurement of b-hadron pair production



Herwig++ generally better than Pythia8

MG5_aMC 4 flavour and 5 flavour sit on either side of the data, 4 flavour closer in shape to the data



Low m(J/ψ,μ) discriminates between 4 and 5 flavour calculations

arXiv:1705.03374

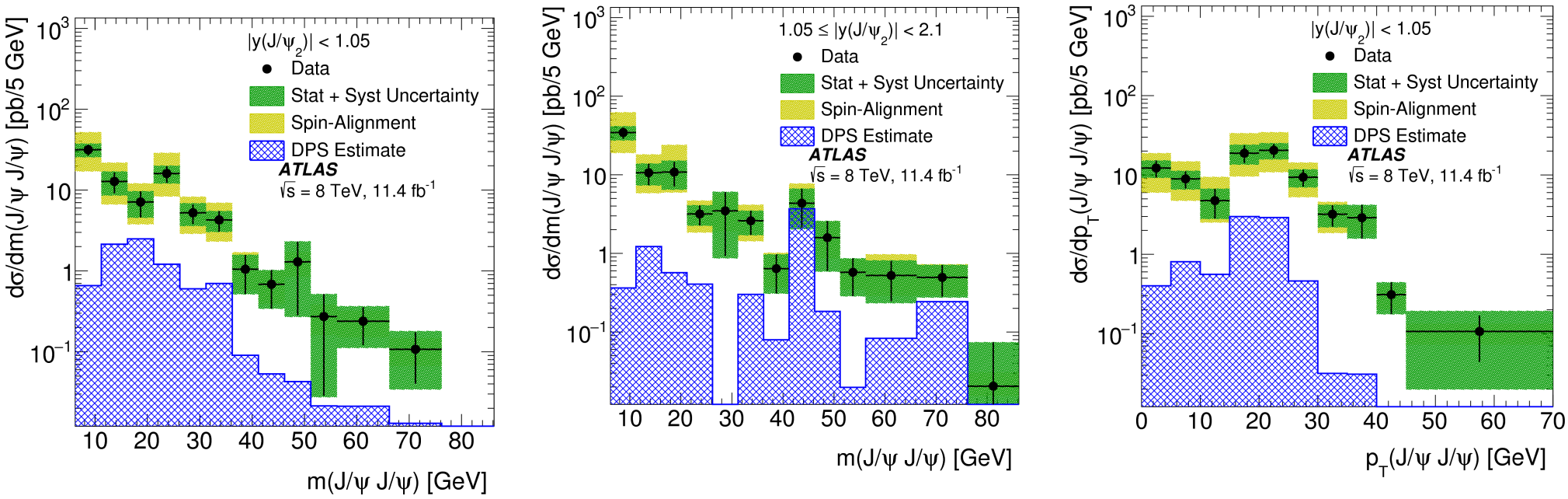
Observations:
Pythia8: pT-based splitting kernel gives the best results

Four flavour MadGraph5_aMC@NLO+Py8 gives the best overall performance

Measurement of the prompt J/ψ pair production cross-section in pp collisions

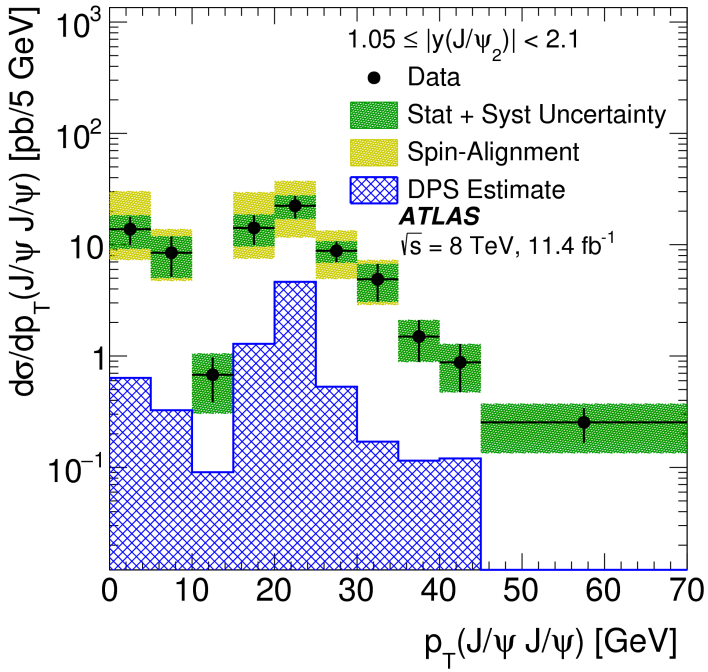
Eur. Phys. J. C77 (2017) 76

- Single-Parton Scattering (SPS) – sensitive to NLO and higher order corrections.
  - Opportunity to learn about J/ψ production models.
- Double-Parton Scattering (DPS) – Likely to play a larger role at higher energies, especially in *cccc* production.
  - Background to Higgs, SUSY and exotic searches.
  - Effective cross-section measured for multiple final states: γ+3-jets, 4-jets, W+2-jets, Z+J/ψ, etc.



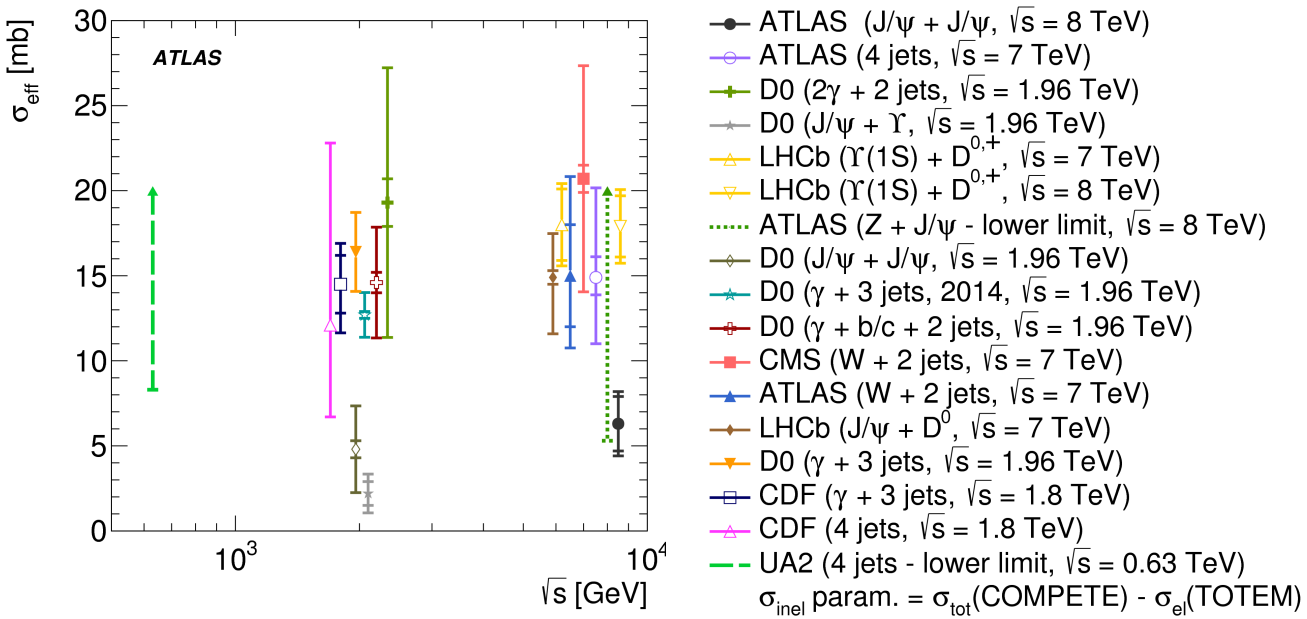
Measurement of the prompt J/ψ pair production cross-section in pp collisions

Eur. Phys. J. C77 (2017) 76



The ATLAS and D0 di-J/ψ analyses provide a hint that the effective cross-section measured from this final state could be lower than that measured for the other final states. A low value of the effective cross-section for gluon dominated processes could indicate a smaller transverse distance between gluons in the nucleon according to the pion cloud model.

The effective cross-section of double parton scattering as a function of the centre-of-mass energy

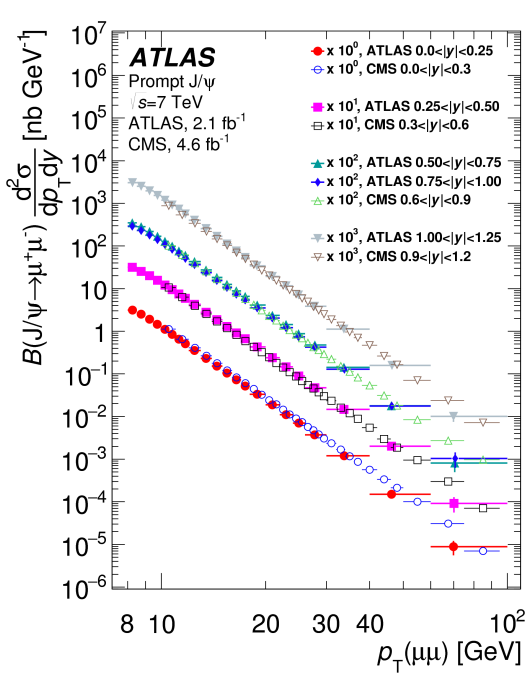


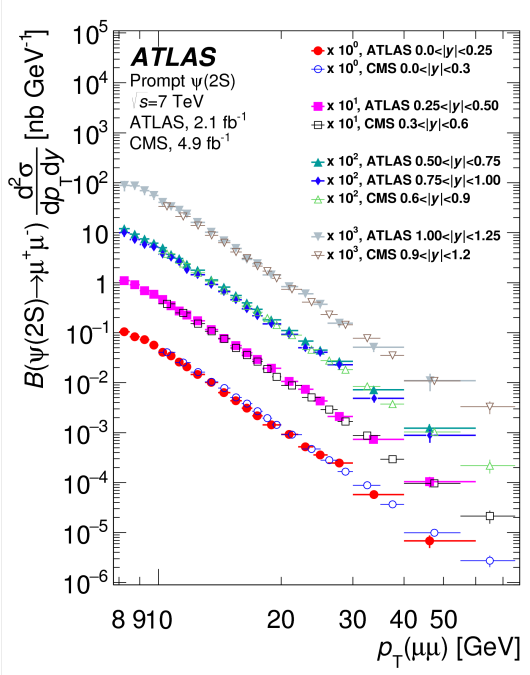
LHCb (arXiv:1612.07451): $\sigma_{eff} = 14.5 \pm 1.7 + 1.7 - 2.3$ mb

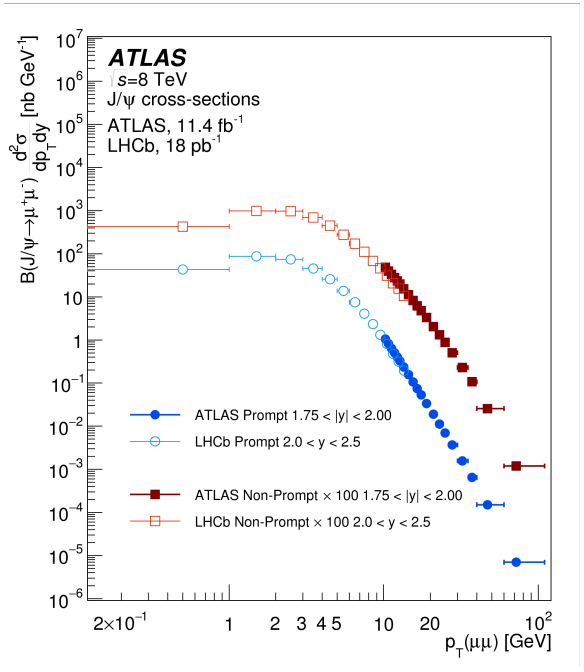
Prompt and Non-Prompt J/ψ and ψ(2S)

Eur. Phys. J. C 76(5), 1-47, (2016)

- Two charmonium production mechanisms:
  - Prompt – produced from primary interaction or from heavier states.
  - Non-prompt – production from b-hadron decays.
- Candidates reconstructed in di-muon channel:
  - Corrections applied for efficiencies and acceptance.
  - The longer lifetimes of b-hadrons distinguishes the production mechanisms.
  - Ratio is extracted using unbinned 2D fit of mass and lifetimes.



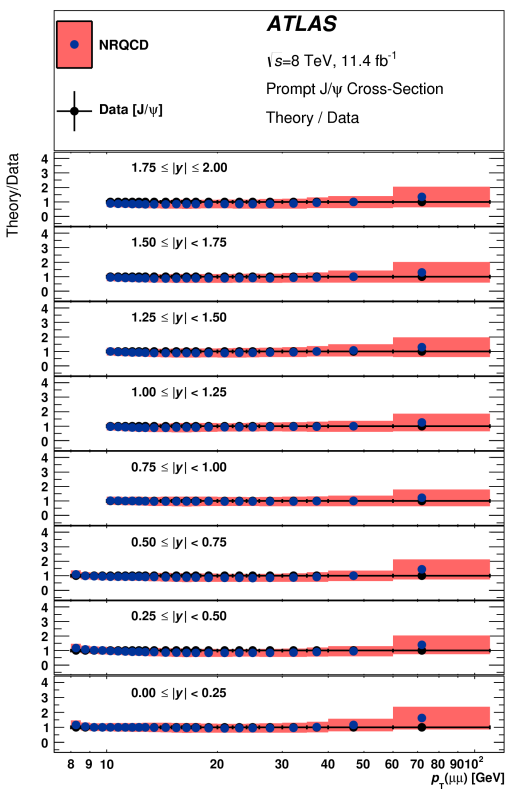


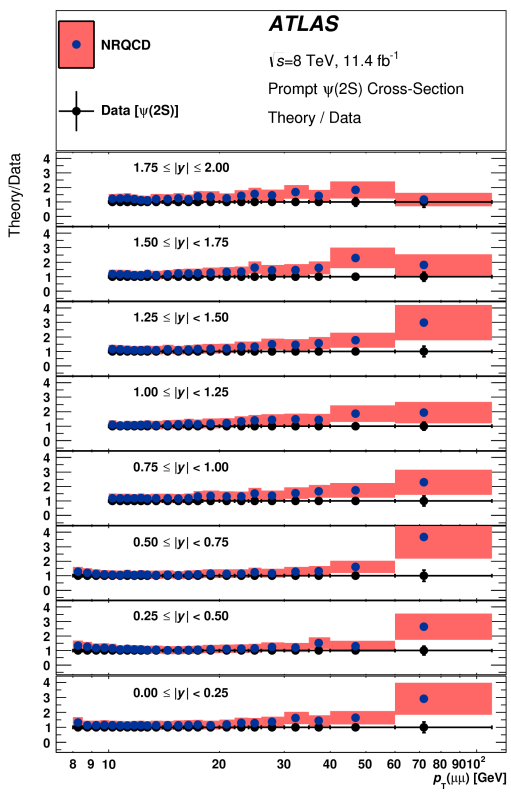


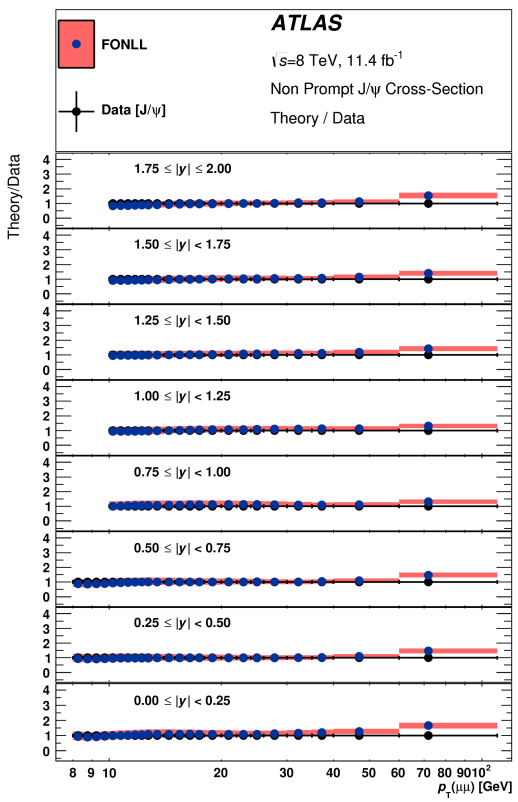
Prompt and Non-Prompt J/ψ and ψ(2S)

Eur.Phys.J. C76 (2016) 5, 283

- The paper makes comparisons to theoretical models:
  - Prompt: compared to non-relativistic QCD (NRQCD)
    - Agrees well with data, with some discrepancy at higher pT.
  - Non-prompt: compared to Fixed Order Next-to-Leading Logarithm (FONLL)
    - Perturbative description for bb-bar prod/data for fragmentation and b-hadron decay.



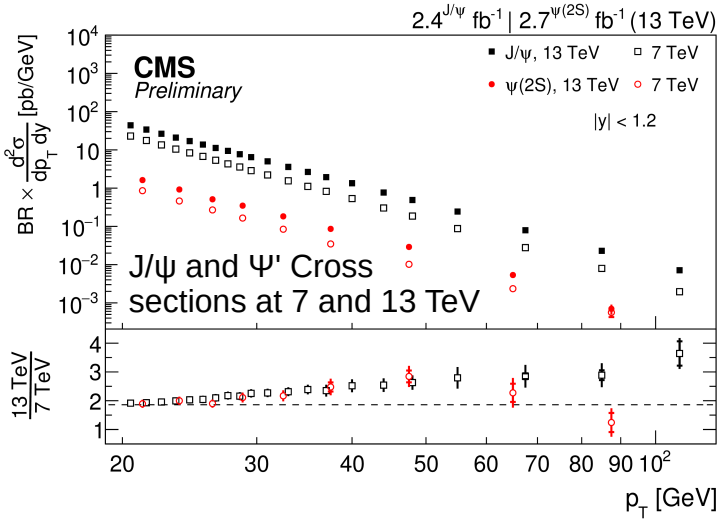


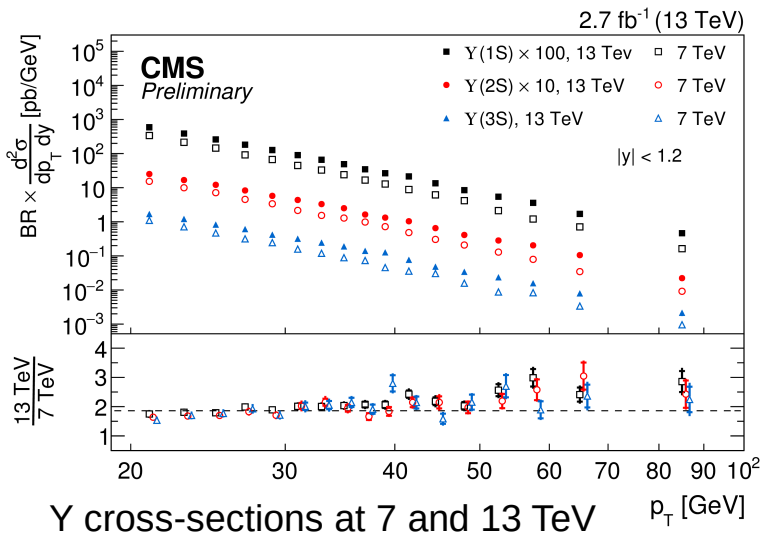


Quarkonia at 13 TeV: J/ψ, ψ(2S), Υ(nS)

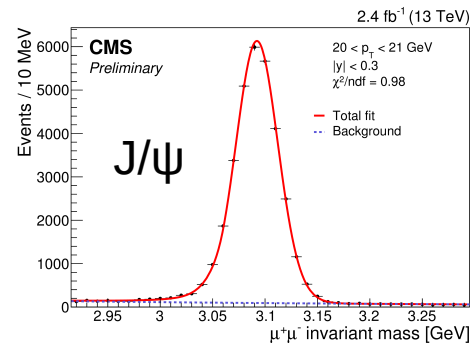
CMS-PAS-BPH-15-005

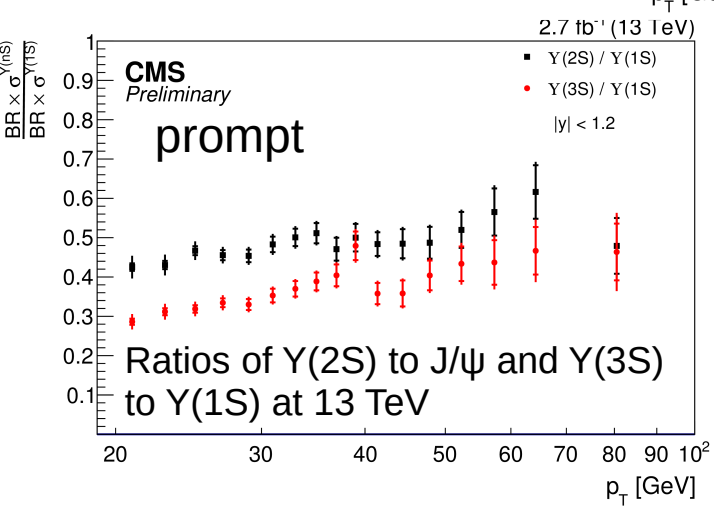
- CMS has preliminary results of Quarkonia at 13 TeV.
- 2015 data sample of 2.7 fb-1 (2.4 fb-1 for J/ψ), candidates triggered by opposite-sign muons.
- In the charmonium case, the prompt and non-prompt fractions are separated by a 2D mass, pseudo proper decay length fit.

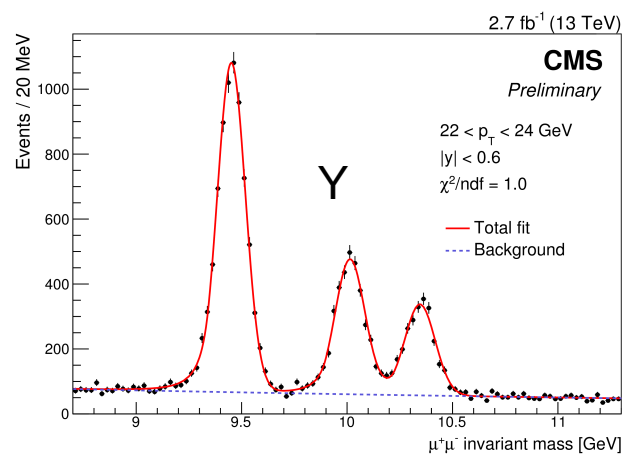


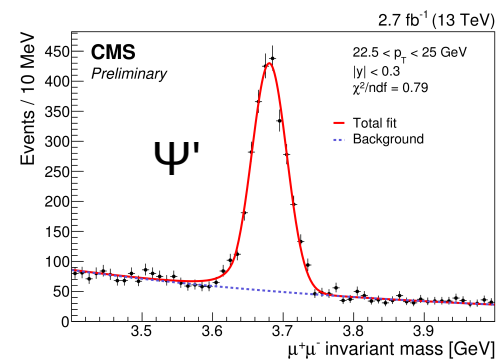


Υ cross-sections at 7 and 13 TeV





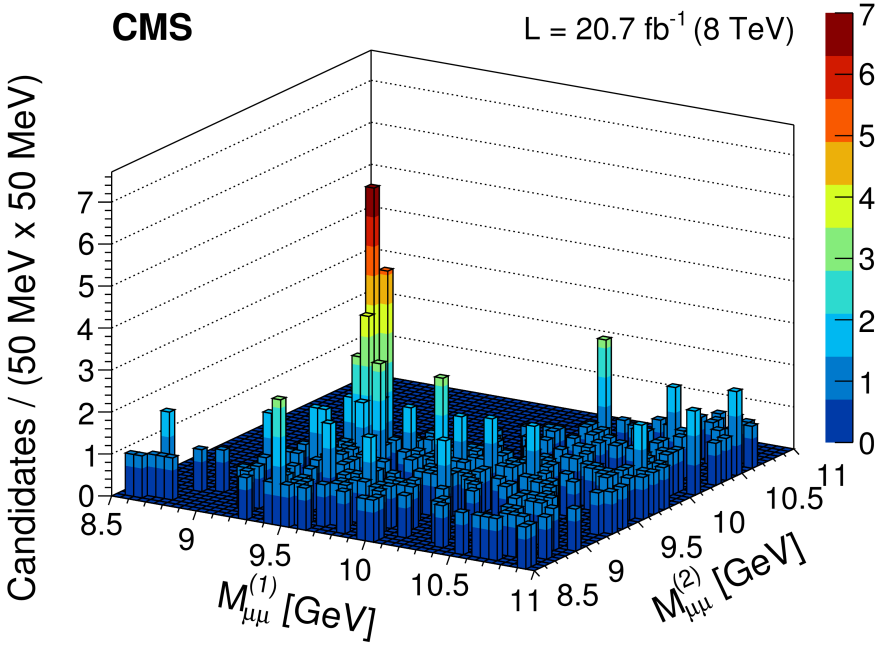


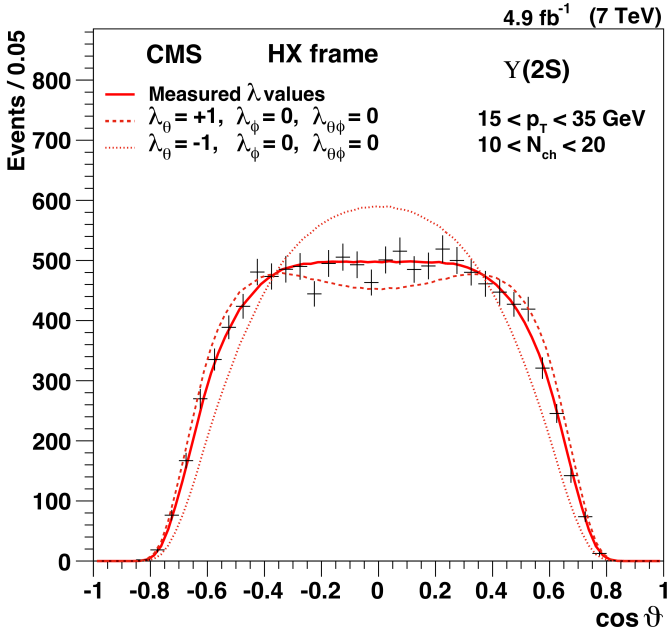


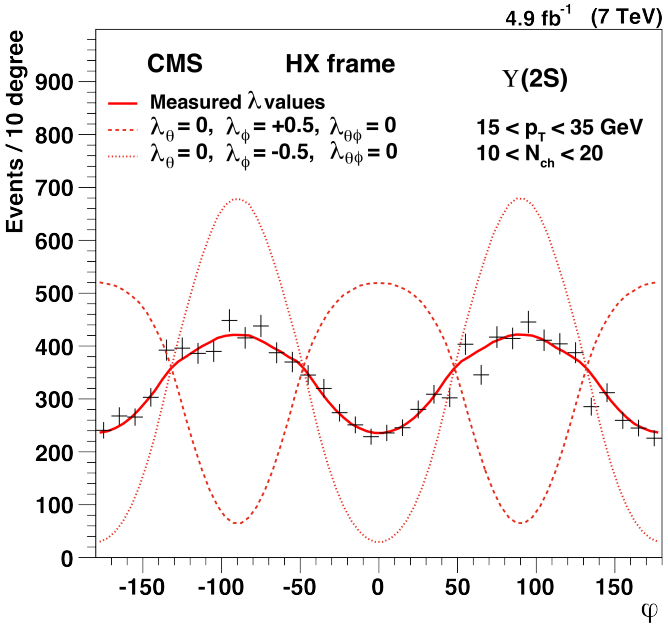
Observations of Υ(1S) pair production and Υ(nS) polarization versus particle multiplicity

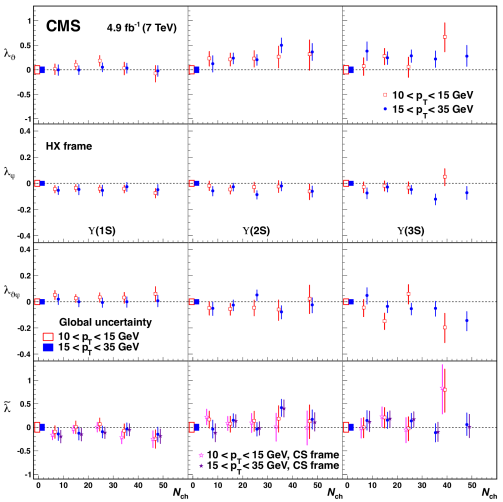
CMS-PAS-BPH-14-008

- CMS measured the associated production of two Υ(1S) in the same event at √s=8 TeV.
- The cross section (pT(Υ)<50 GeV and |y(Υ)|<2) is 68.8±12.7(stat)±7.4(syst)±2.8(BR) pb.
- The polarizations of the Υ(nS) mesons products in pp collisions at √s=7 TeV as functions of the charged particle multiplicity of the event in two Υ(nS) pT ranges.
- No significant dependence on event multiplicity is visible.







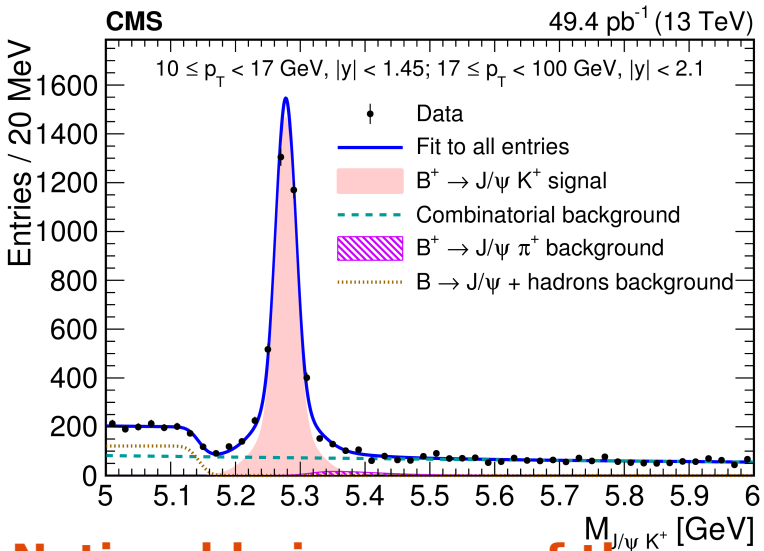


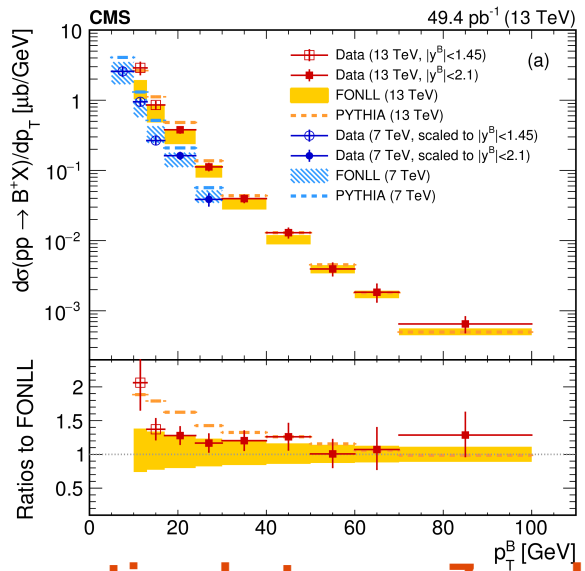
CMS-HIN-15-003

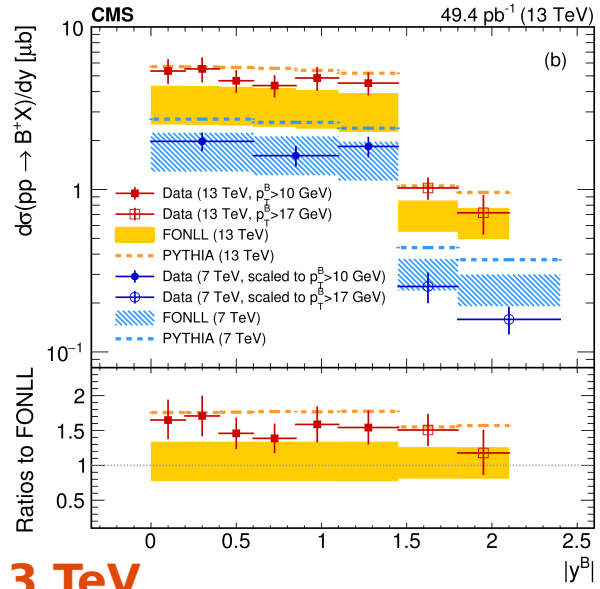
Run 2: Measurement of the total and differential inclusive B^+ hadron cross sections

arXiv:1609.00873

- Reconstructs the exclusive channel $B^+ \rightarrow J/\psi K^+$ where J/ψ decays to muons.
- The total cross section summed over all bins is measured to be 14.9 ± 0.4 (stat) ± 2.0 (syst) ± 0.4 (lumi) μb.
- Measurements are compared with predictions from Fixed-Order plus next to leading log (FONLL) and PYTHIA.
- The measured values show reasonable agreement in terms of shape, as well as normalization.







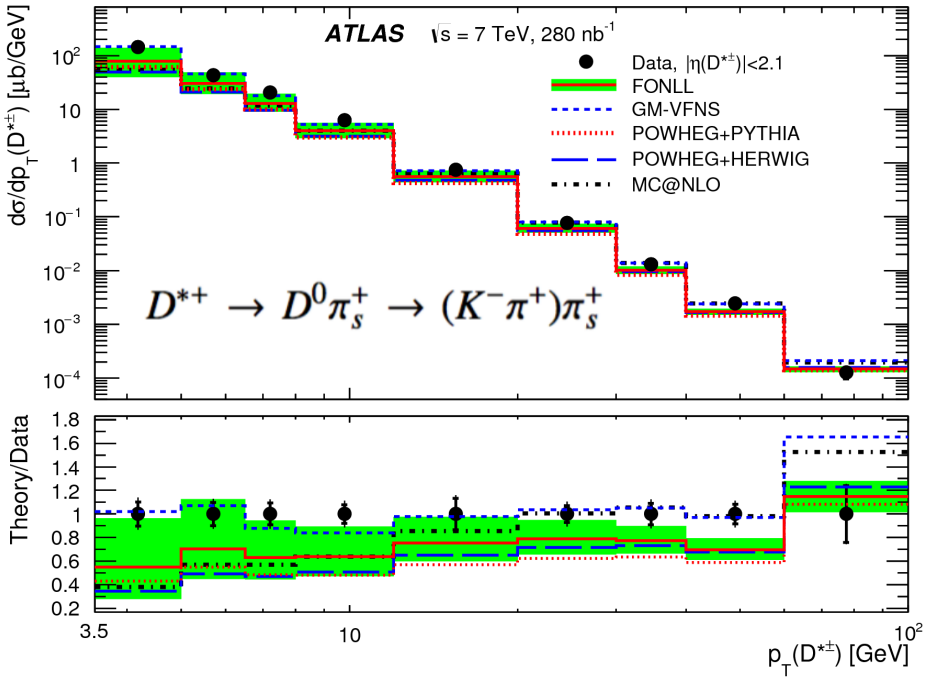
Noticeable increase of the cross-section between 7 and 13 TeV

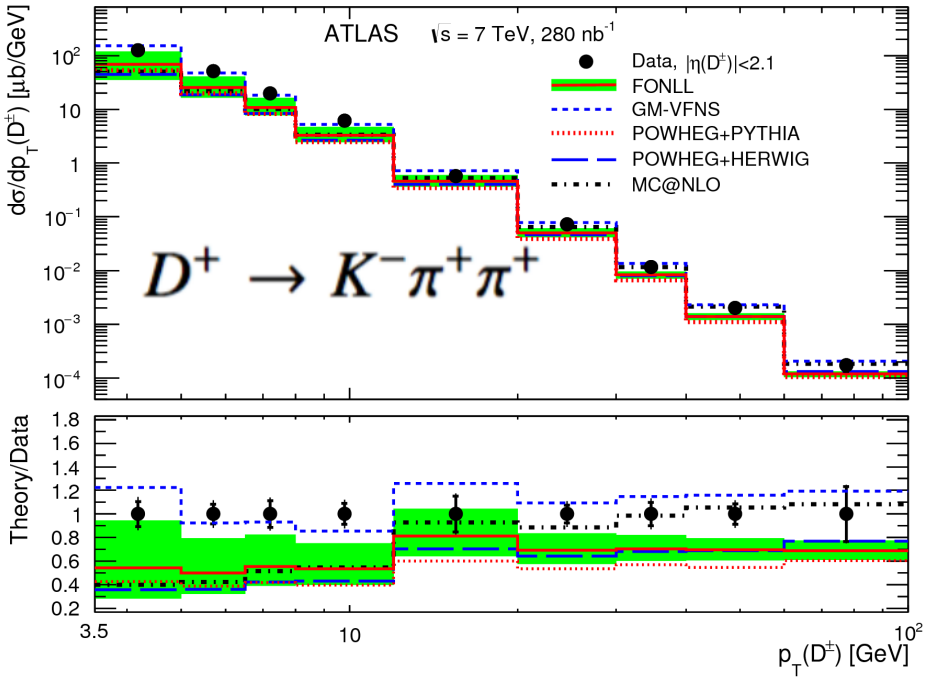
Data in good agreement with both theoretical predictions, FONLL and PYTHIA

Measurement of D meson productions

- Charm production is measured and compared with
  - Fixed-Order Next-to-Leading-Logarithm (FONLL)
  - General-Mass Variable-Flavour-Number scheme (GM-VFNS)
  - NLO QCD calculations matched with leading-logarithm parton-shower MC simulation (NLO-MC)
- Useful for calibrating MC generation.
- Predictions consistent with data in normalization.
- GM-VFNS predictions seem most accurate.

Nucl. Phys. B 907 (2016) 717

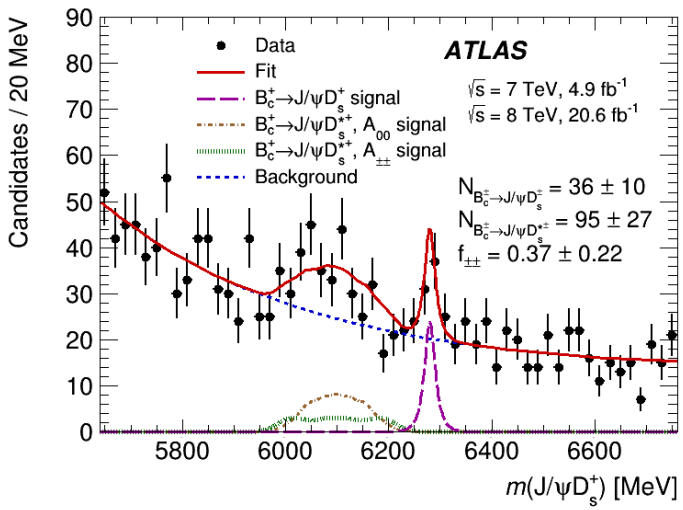


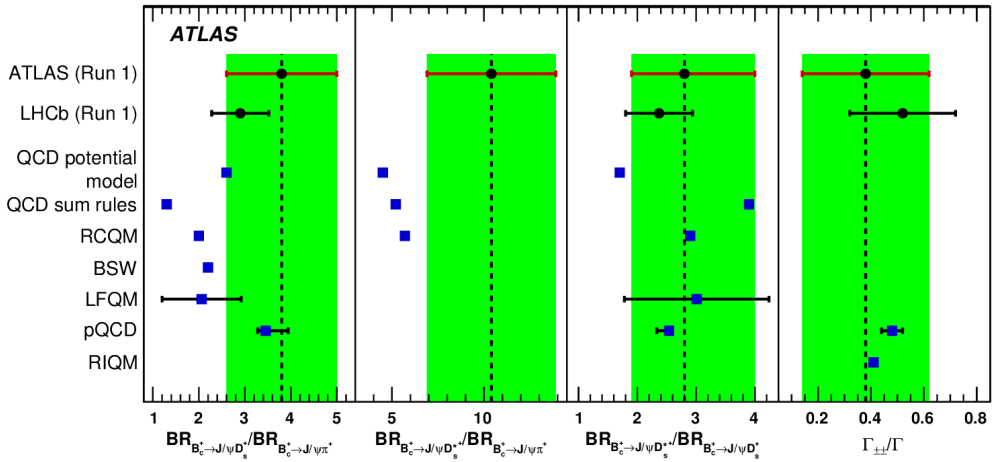


$B^+_c \to J/\psi D^+_s$ and $B^+_c \to J/\psi D^{*+}_s$ decays

Eur. Phys. J. C, 76(1), 1 (2016)

- The D^{*+}_s meson decays into a D^+_s meson and a soft photon or π^0. Since these are hard to detect it is ignored.
- Information about the helicity of the decay is in the distribution of the angle between the μ^+ and the D^+_s candidates in J/ψ rest frame, and from the mass distribution.
- Both are fit in an unbinned maximum-likelihood fit.





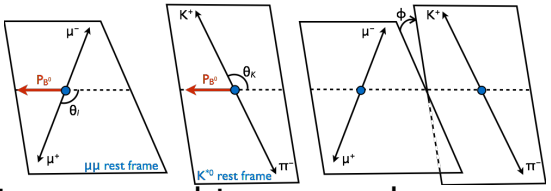
Ratios of branching fractions measured w.r.t $J/\psi\pi^+$ decay and one w.r.t. the other.
The transverse polarization is measured as the $\Gamma_{\pm\pm}/\Gamma$ fraction.
Results compared with LHCb results and various theoretical calculations, showing good agreement with perturbative QCD and discrepancies always below two standard deviations.

Angular analysis of $B^0 \rightarrow K^{*0}\mu^+\mu^-$

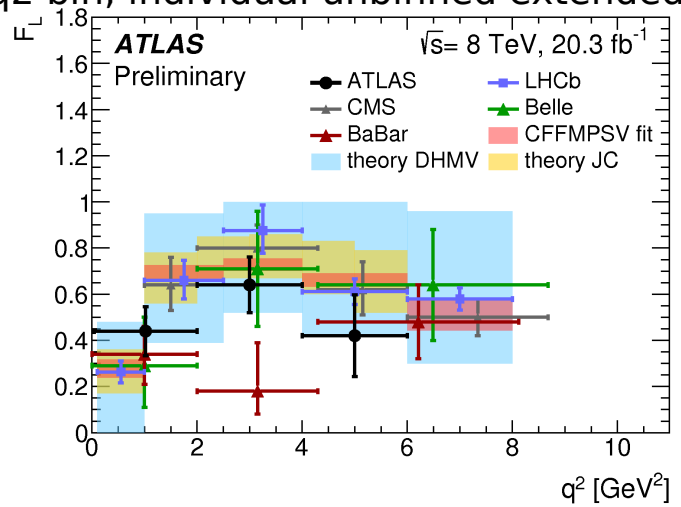
PLB 753 (2016) 424

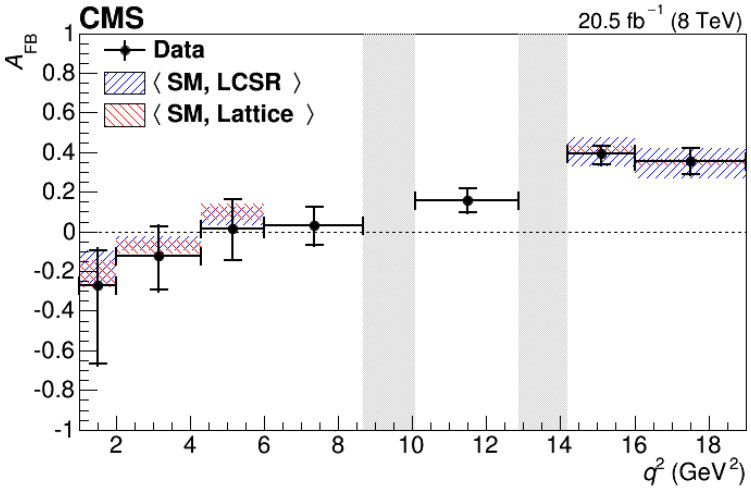
Study of angular distributions and differential branching fractions, with 8 TeV data.

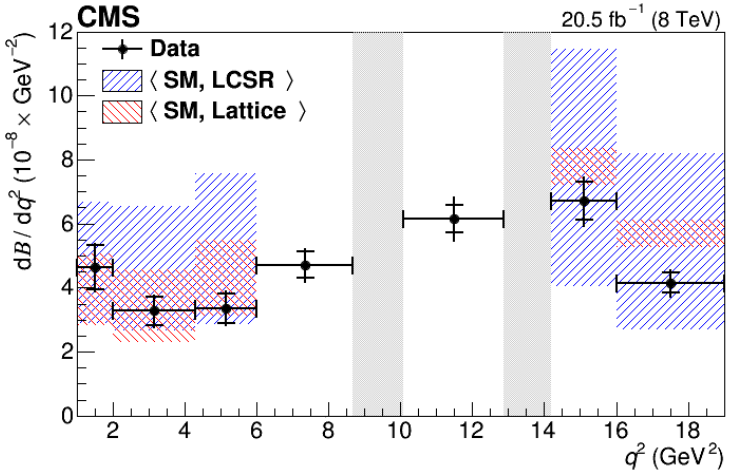
Two angular outputs: longitudinal polarization fraction of K^{*0} and fw-bk asymmetry of muons.



For each q2 bin, individual unbinned extended maximum likelihood fit to invariant mass and two angular variables.







Forbidden at tree level, but allowed via loop.

Sensitive to NP: BSM particles in the loop.

Result consistent with SM prediction.

QCD factorization for low q_2 bins and operator product expansion for high q_2 bins.

Main syst. from fit and background model.

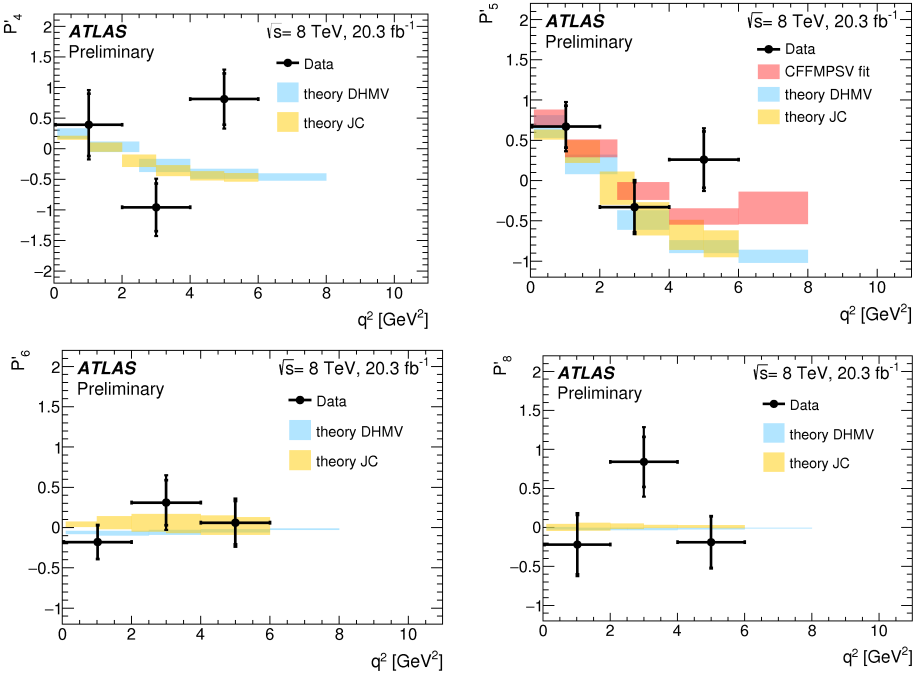
Analysis combined with previous 7 TeV results: agree with other experiments.

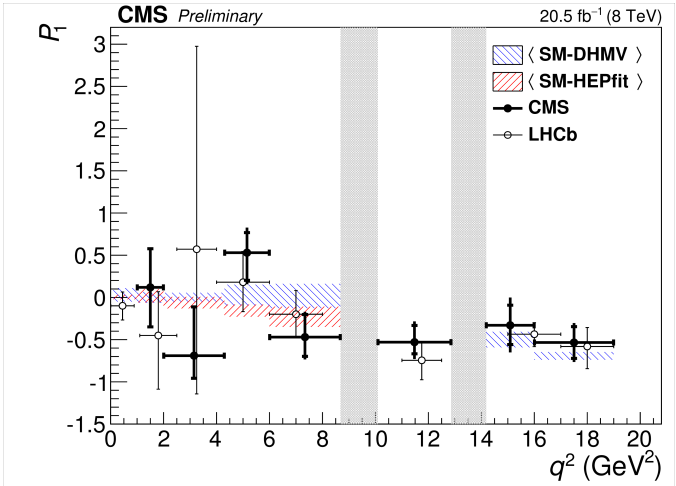
Angular analysis of $B^0 \to K^{*0}\mu^+\mu^-$

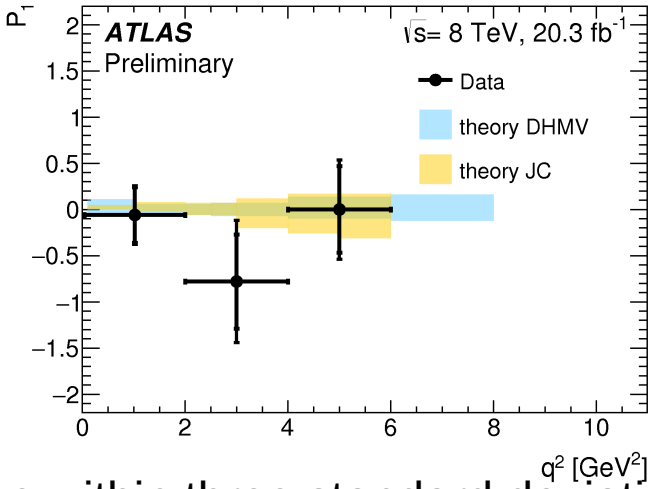
- CMS-PAS-BPH-15-008 20.5fb^{-1}
- ATLAS-CONF-2017-023 20.3fb^{-1}
- CMS PLB 753 (2016) 424 20.5fb^{-1}

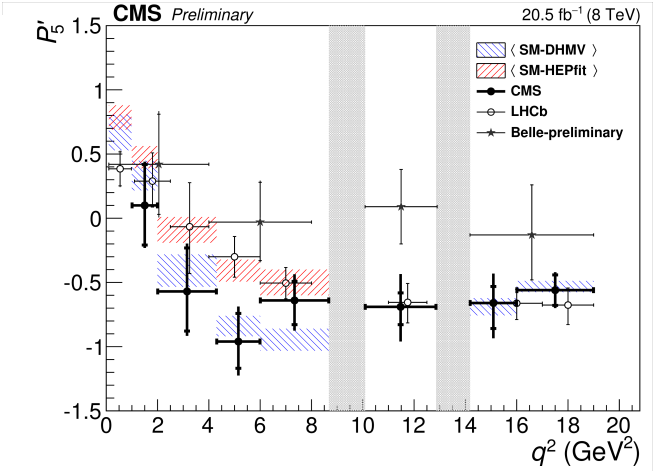
CMS-PAS-BPH-15-008

q^2 (GeV^2)	Signal yield	P_1	P'_5
1.00–2.00	80 ± 12	$+0.12^{+0.46}_{-0.47} \pm 0.06$	$+0.10^{+0.32}_{-0.31} \pm 0.12$
2.00–4.30	145 ± 16	$-0.69^{+0.58}_{-0.27} \pm 0.09$	$-0.57^{+0.34}_{-0.31} \pm 0.15$
4.30–6.00	119 ± 14	$+0.53^{+0.24}_{-0.33} \pm 0.18$	$-0.96^{+0.22}_{-0.21} \pm 0.16$
6.00–8.68	247 ± 21	$-0.47^{+0.27}_{-0.23} \pm 0.13$	$-0.64^{+0.15}_{-0.19} \pm 0.14$
10.09–12.86	354 ± 23	$-0.53^{+0.20}_{-0.14} \pm 0.14$	$-0.69^{+0.11}_{-0.14} \pm 0.23$
14.18–16.00	213 ± 17	$-0.33^{+0.24}_{-0.23} \pm 0.22$	$-0.66^{+0.13}_{-0.20} \pm 0.19$
16.00–19.00	239 ± 19	$-0.53^{+0.19}_{-0.19} \pm 0.13$	$-0.56^{+0.12}_{-0.12} \pm 0.07$







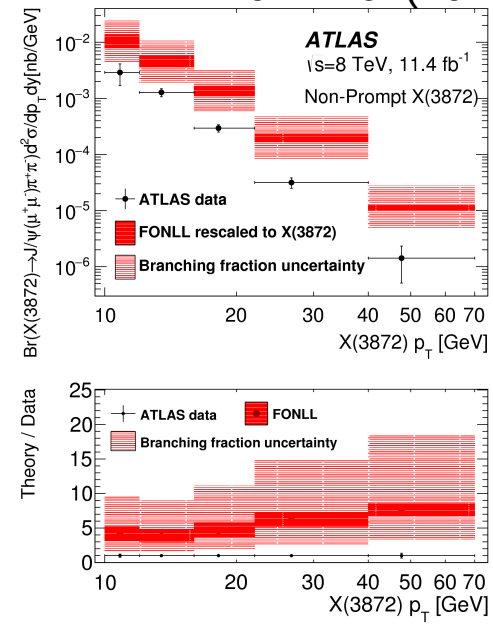


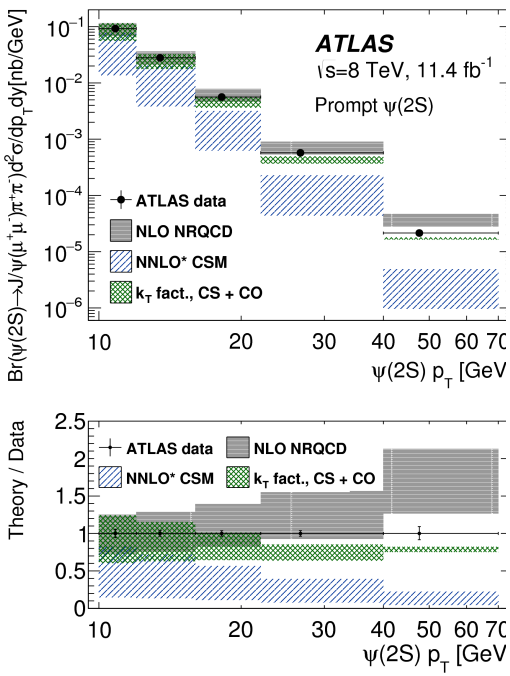
All measurements are found to be within three standard deviations of the range covered by the different predictions. But some tension is found in P'5

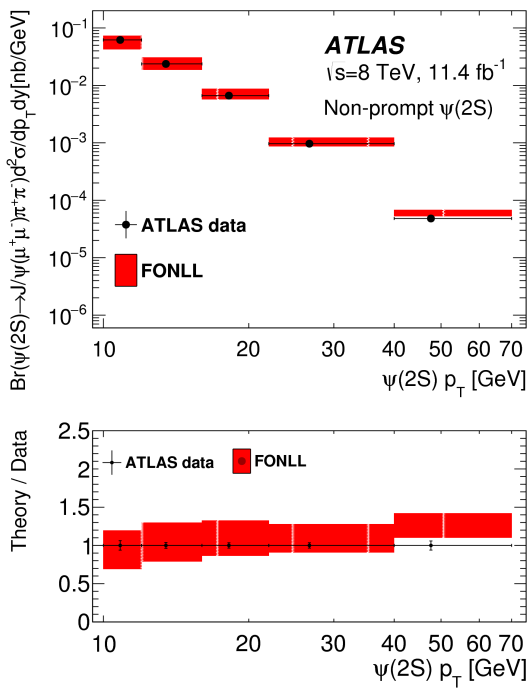
Measurements of ψ(2S) and X(3872) → J/ψπ⁺π⁻ production

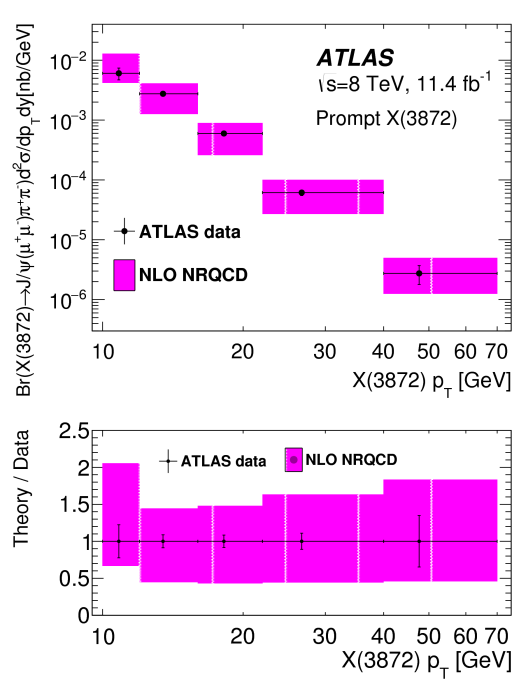
JHEP01(2017)117

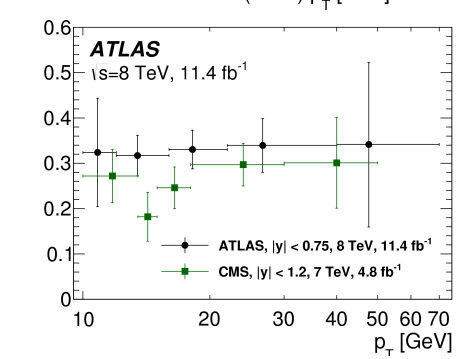
- NLO NRQCD describes X(3872) well but overestimates ψ(2S) at high pT.
- The kT factorisation model, which includes the colour-octet (CO) contributions tuned to 7TeV CMS data describes ψ(2S) with some tension at higher pT.
- NNLO* colour-singlet model calculations underestimate the data especially at high pT.
- X(3872) has good agreement with the CMS measurement (JHEP 04 (2013) 154).
- The FONLL model describes ψ(2S) well but when recalculated to to X(3872) using the branching fraction from Tevatron data it consistently overestimates the ATLAS measurement.
- One of the interesting indications from this analysis is the possible increase of X production from Bc.

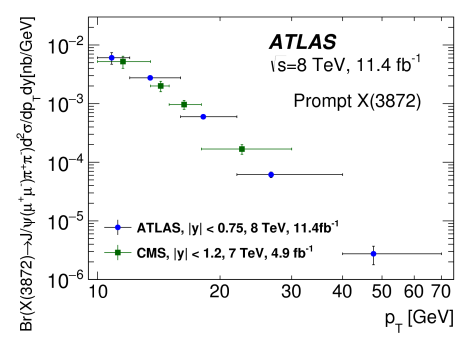








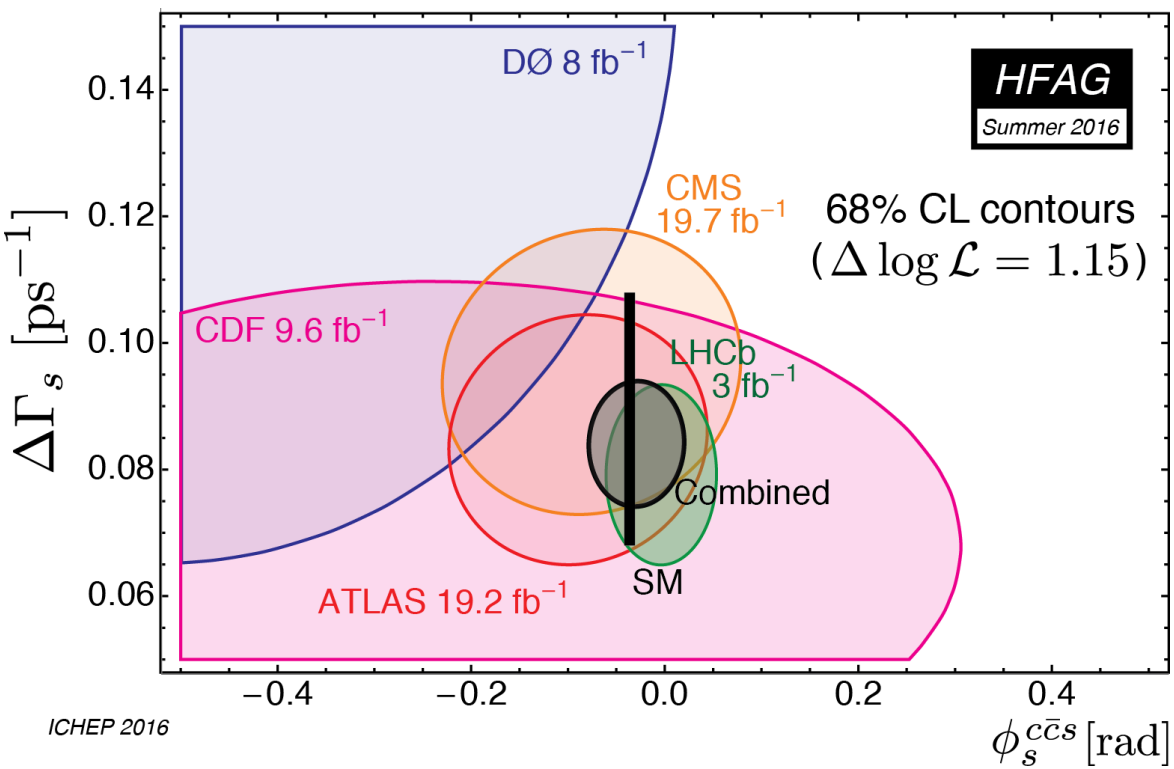




CP violating phase φ_s and decay width difference $\Delta\Gamma_s$ in B_s -> J/ψ φ decays

Similar experimental procedure adopted by ATLAS and CMS experiments:

- use “opposite side tagging” to infer the initial flavor probability of B^0_s candidates.
- likelihood including mass, proper decay time and angular variables of each decay.
- simultaneous fit of φ_s and $\Delta\Gamma_s$ values.



ATLAS JHEP 1608 (2016) 147

$$\phi_s = -0.090 \pm 0.078\,(\text{stat.}) \pm 0.041\,(\text{syst.})\,\text{rad}$$
$$\Delta\Gamma_s = 0.085 \pm 0.011\,(\text{stat.}) \pm 0.007\,(\text{syst.})\,\text{ps}^{-1}$$
$$\Gamma_s = 0.675 \pm 0.003\,(\text{stat.}) \pm 0.003\,(\text{syst.})\,\text{ps}^{-1}.$$

CMS PLB 757 (2016) 97

$$\phi_s = -0.075 \pm 0.097\,(\text{stat}) \pm 0.031\,(\text{syst})\,\text{rad},$$
$$\Delta\Gamma_s = 0.095 \pm 0.013\,(\text{stat}) \pm 0.007\,(\text{syst})\,\text{ps}^{-1}.$$

LHCb

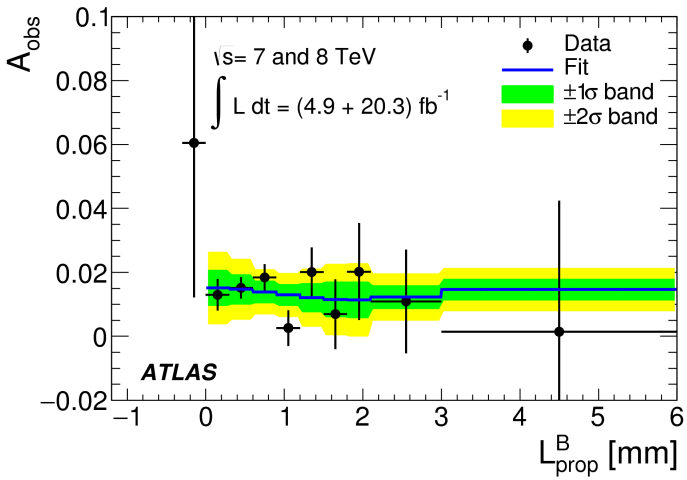
$$\phi_s = -0.010 \pm 0.039\,\text{rad}.$$

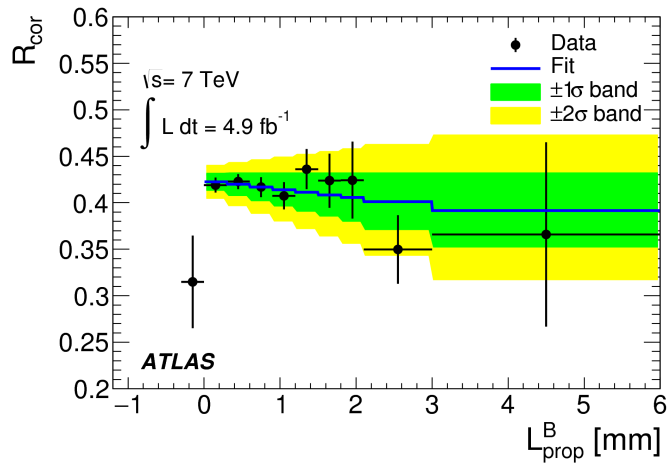
Measurement of the B_d width difference $\Delta\Gamma_d/\Gamma_d$ using $B_d \to J/\psi\, K_s$ and $B_d \to J/\psi\, K^{*0}$ decays

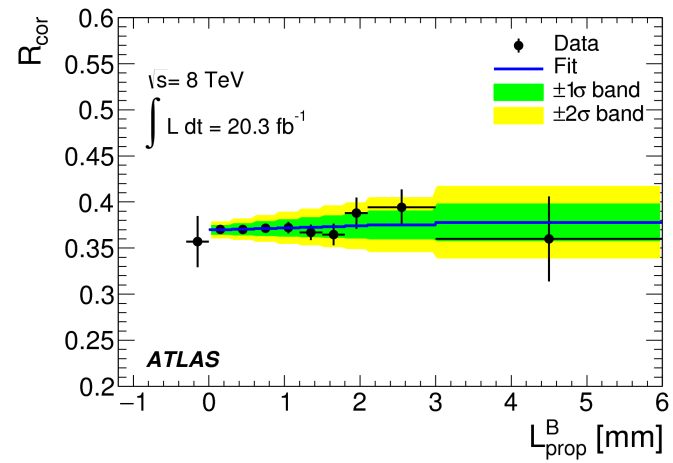
Ingredients:

JHEP06 (2016) 081

- Proper decay length (L_{prop}) distributions of $B_d \to J/\psi\, K_s$ and $B_d \to J/\psi\, K^{*0}$ decays.
- Production asymmetry of B_d meson.
- Ratio of reconstruction efficiencies of $B_d \to J/\psi$ Ks and $B_d \to J/\psi\, K^{*0}$ decays.







The ATLAS result is consistent with other measurements of $\Delta\Gamma_d$ and the SM prediction.

Currently it is the most precise single measurement.

$\Delta\Gamma_d/\Gamma_d = (-0.1 \pm 1.1\ (\text{stat.}) \pm 0.9\ (\text{syst.})) \times 10^{-2}$ (ATLAS)

$\Delta\Gamma_d/\Gamma_d = (-4.4 \pm 2.5 \pm 1.1) \times 10^{-2}$ (LHCb)

$\Delta\Gamma_d/\Gamma_d = (0.42 \pm 0.08) \times 10\ -2$ (SM)

Conclusions

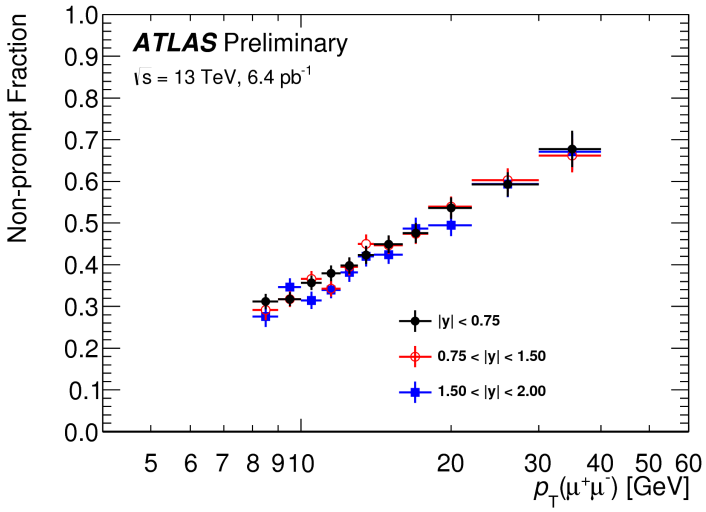
- In the meanwhile, LHC operations have restarted with the first beam splashes recorded on the 29th April and stable beams on 23rd May.
- Both ATLAS and CMS do not depart from their general purpose nature, demonstrating to be able to produce many interesting and stringent QCD tests for theoretical predictions, and heavy flavour results useful for combination and comparison with other experiments.
- This is a brief summary of the analyses, much more material can be found online or in the referenced papers.

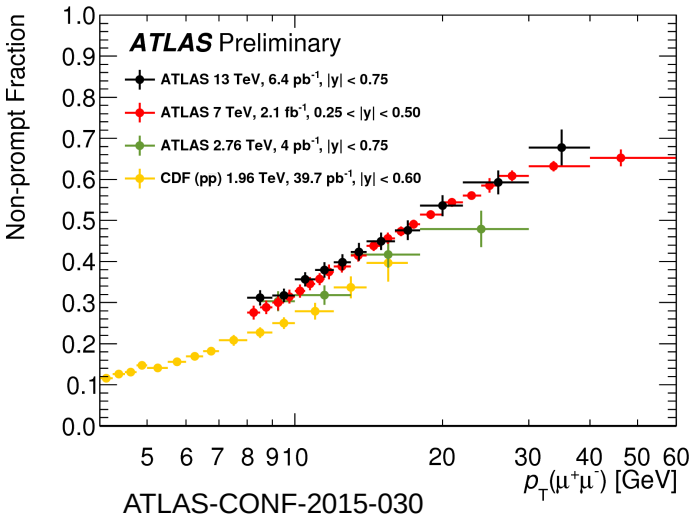
Backup

Prompt and Non-Prompt J/ψ at 13 TeV

Preliminary studies have been made at 13 TeV

- Experimental procedure identical to Run-1:
  - ATLAS' Currently limited to a sample of 6.4 pb^{-1} at 13 TeV.
  - Measurements are presented as a fraction to cancel systematics.





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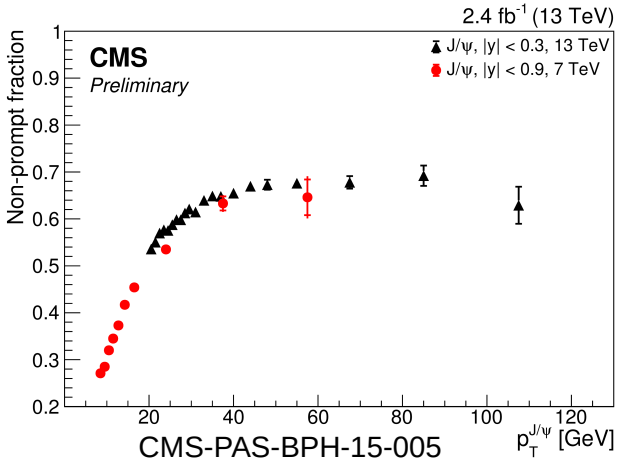

CMS-PAS-BPH-15-005

Minimal dependence on rapidity interval, minimal centre-of-mass energy dependence between 7 and 13 TeV