# Heavy Flavor production@CMS

**N. Leonardo, LIP**

nuno@cern.ch

XXXIX International Conference on High Energy Physics

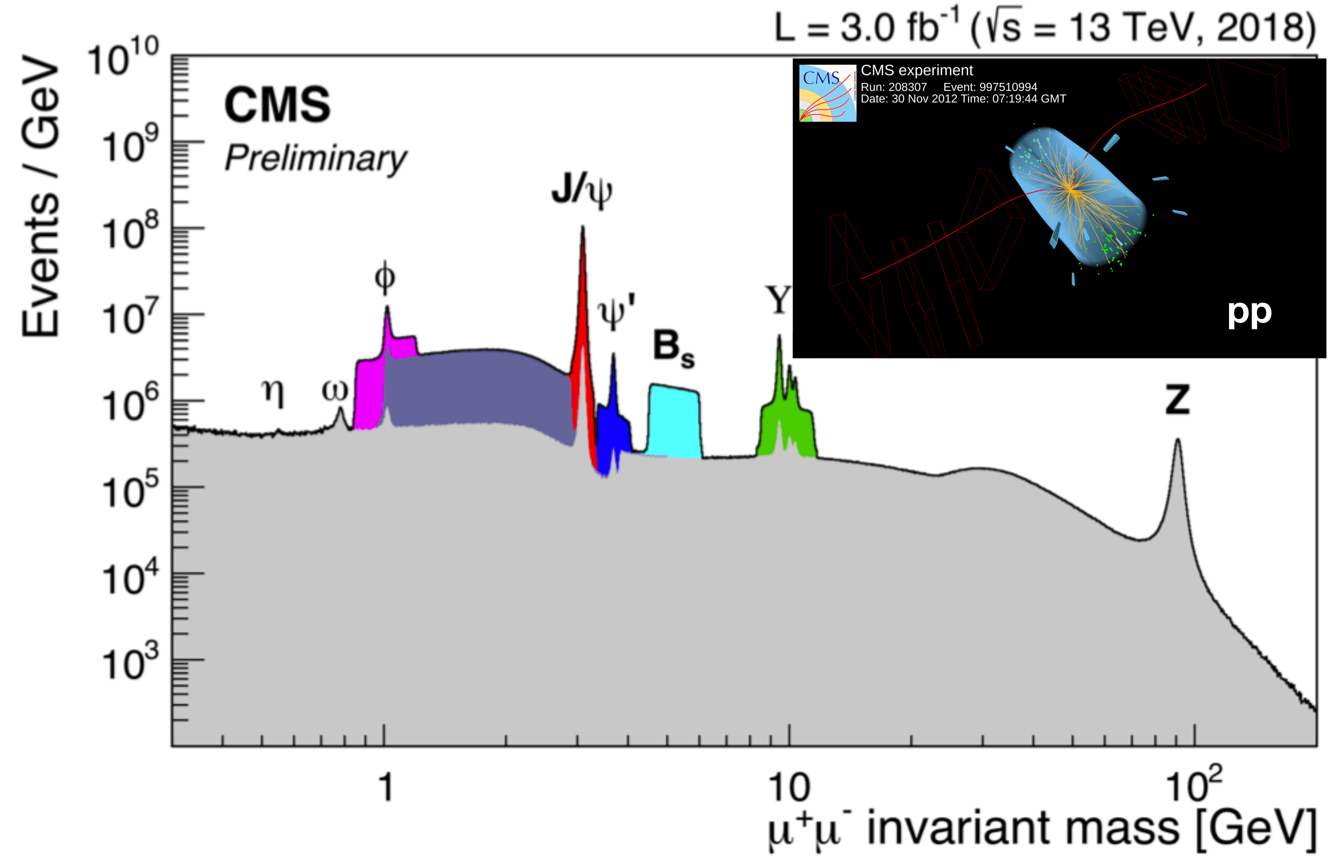
July 4-11, 2018, Seoul, Korea

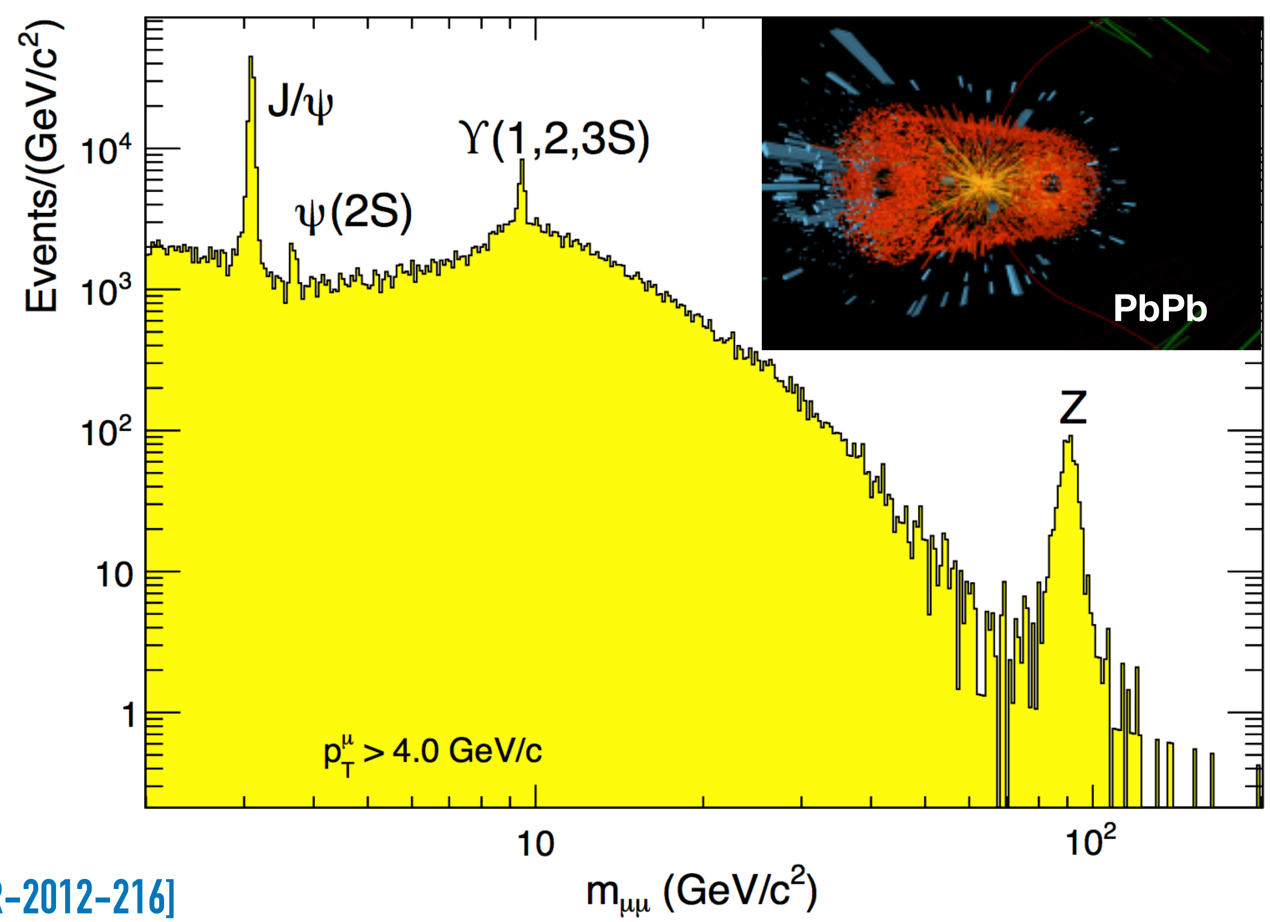
# Heavy quark production

- Measurements and observations provide important tests of QCD and give insight into particle production at colliders
- Hadronization challenging to understand, measurements needed
- Few puzzles: e.g. conciliate cross-section and polarisation results, color singlet vs color octet contributions, single vs multiple particle interaction contributions
- LHC provides access to wide kinematic range, from low to high $p_T$, different collision energies (2.76, 5, 7, 8, 13 TeV) and environments (pp, pA, AA) — all of which are explored by CMS
- Form baseline or background for other physics studies at the LHC
- Topics discussed: production of open and hidden beauty and charm

# dimuons

- provide robust and clean experimental signature (baseline final states)
  - HF→μμX
- flexible trigger
  - muon pairs selected at hardware level, further requirements added at HLT, to allow low $p_T$ thresholds
- good muon identification
  - fakes at permil level
- precise track/vertex reco
  - mass resolution & displaced vertices



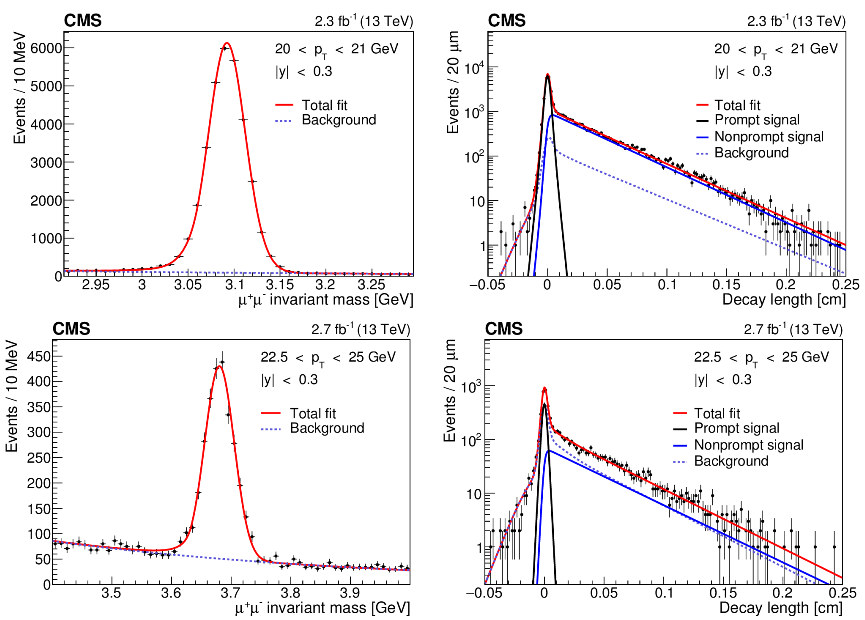




[CMS DP-2018/036], [CMS-CR-2012-216]

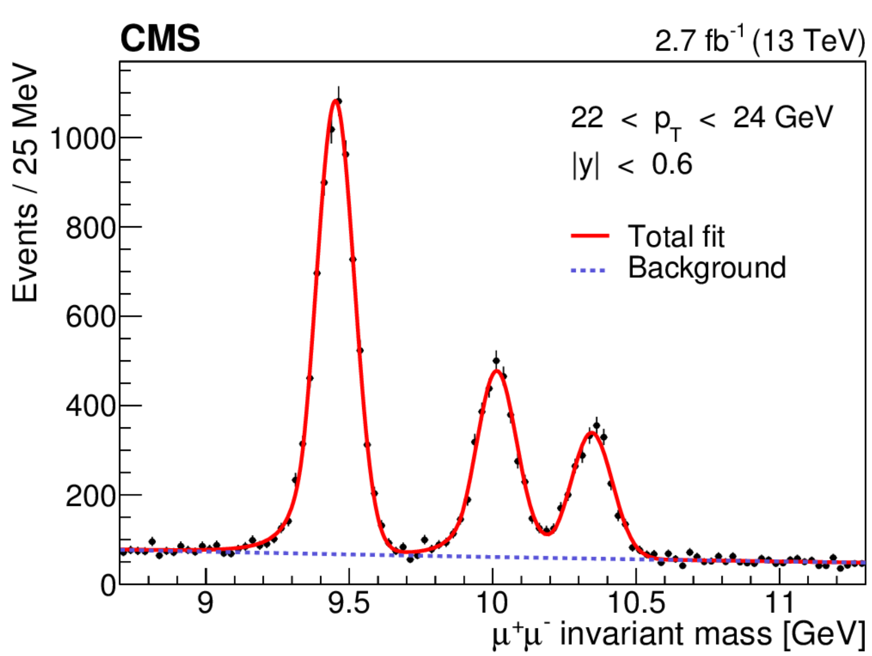
# quarkonium production

[PLB 780 (2018) 251]

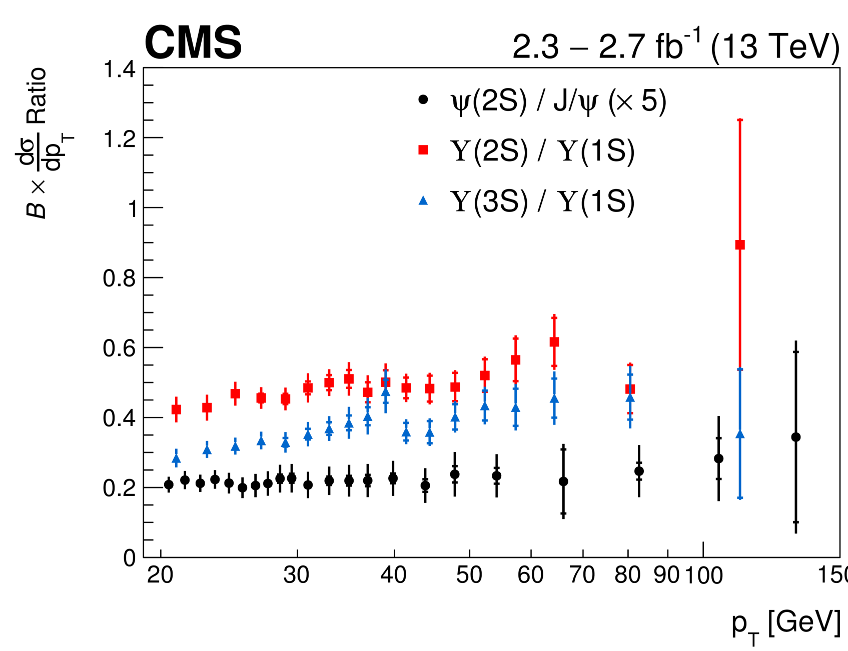
## Charmonia

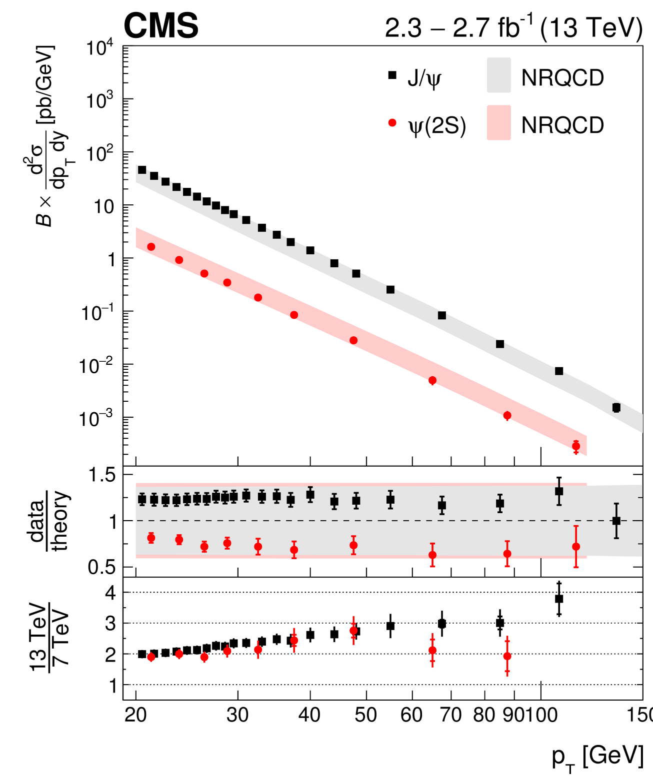


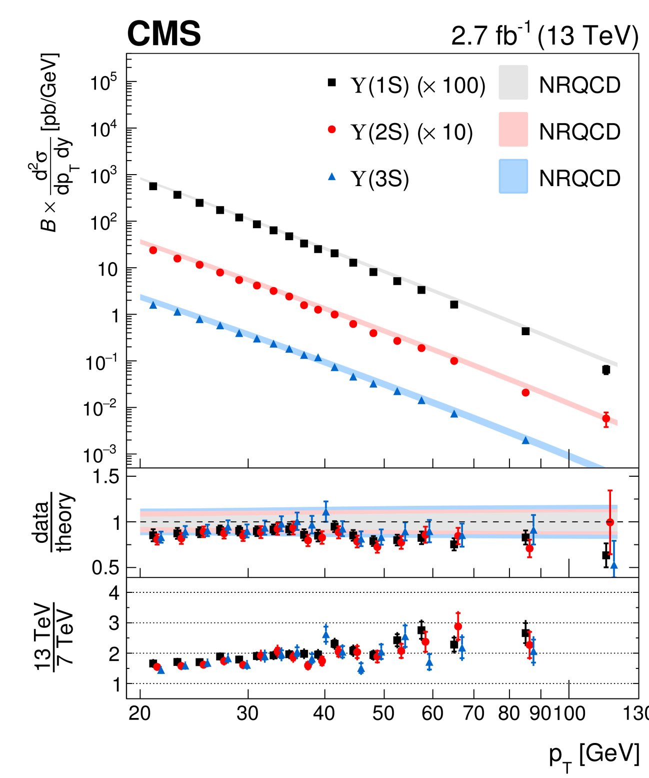

## Bottomonia




- differential cross sections of all 5 S-wave states measured at 13 TeV
  - 2-3 times larger than a 7TeV, slowly increasing with $p_T$
- $p_T$ dependencies of the x-sections well described by NRQCD
  - high $p_T$ reach, beyond 100GeV
- Υ(nS) ratios increase with $p_T$
- results contribute to consolidate underlying hypothesis of QCD and constrain theory parameters

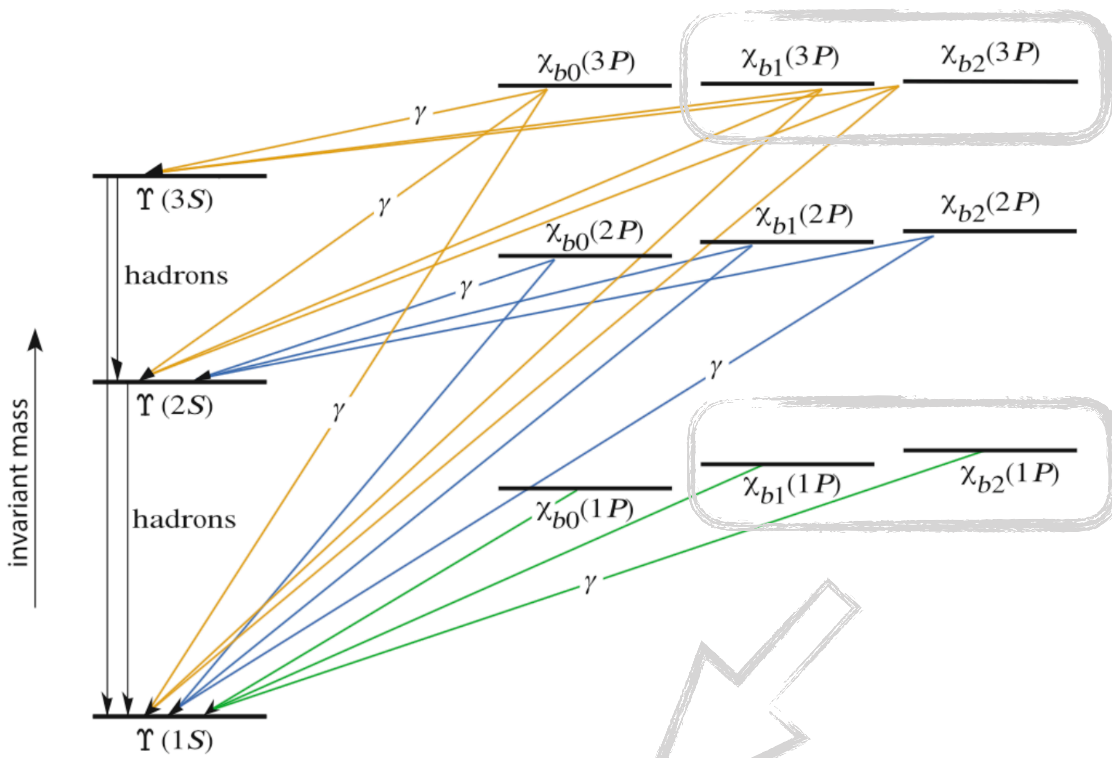


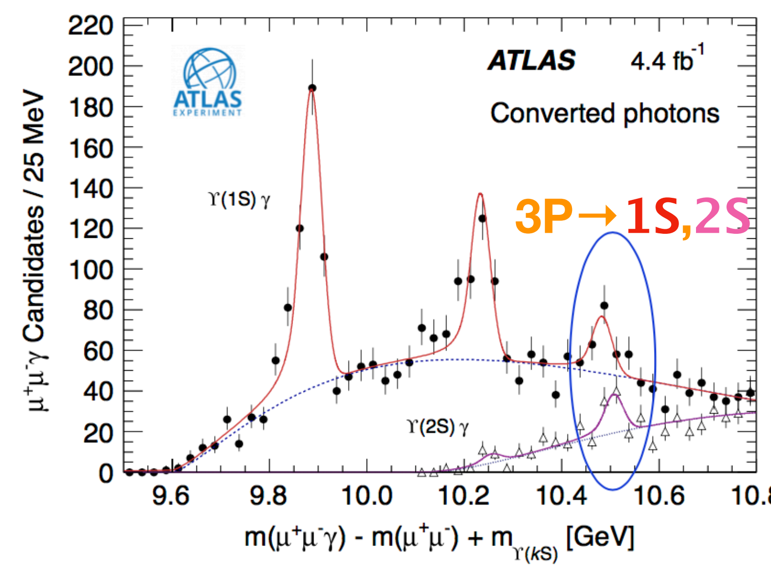
# p-wave bottomonia

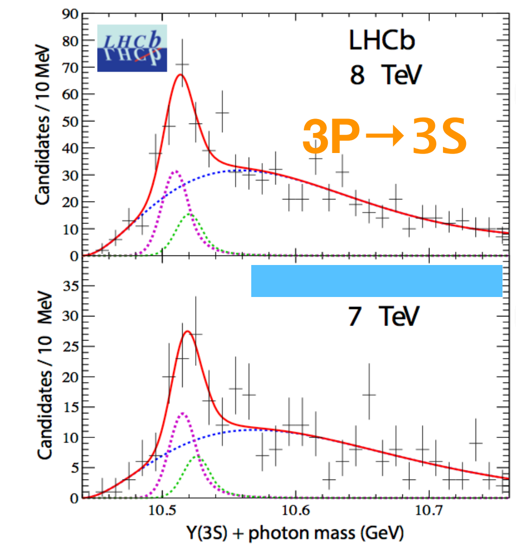
$\chi_b(nP) \to \Upsilon(mS)\,\gamma$




The $\chi_b$(3P) was the first new state found at the LHC

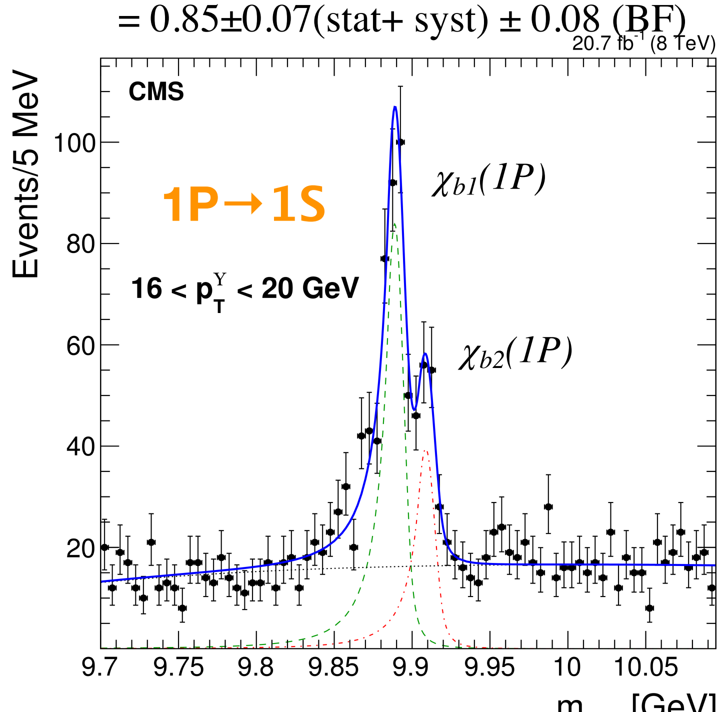
Test effects of open-beauty states on bottomonium spectrum

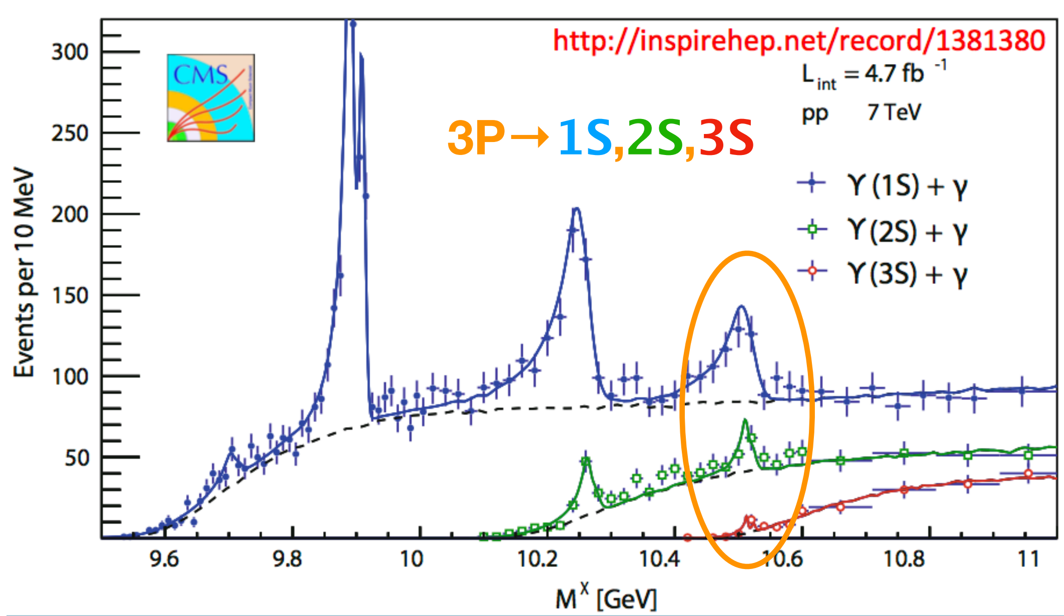


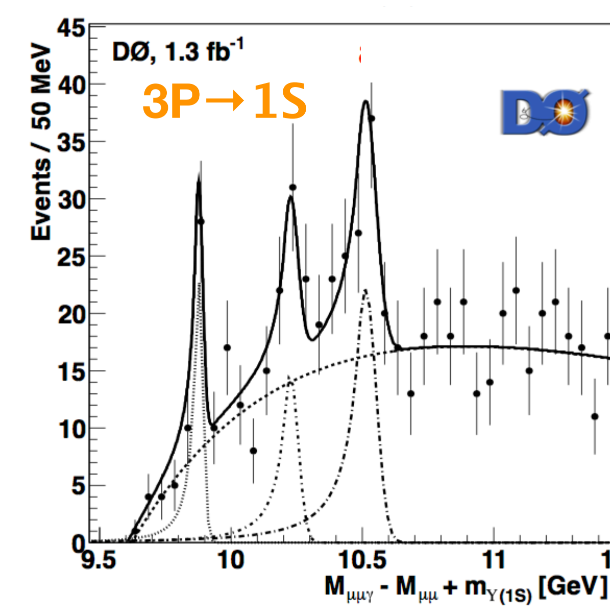




**σ(χb2(1P))/σ(χb1(1P))**

= 0.85±0.07(stat+ syst) ± 0.08 (BF)



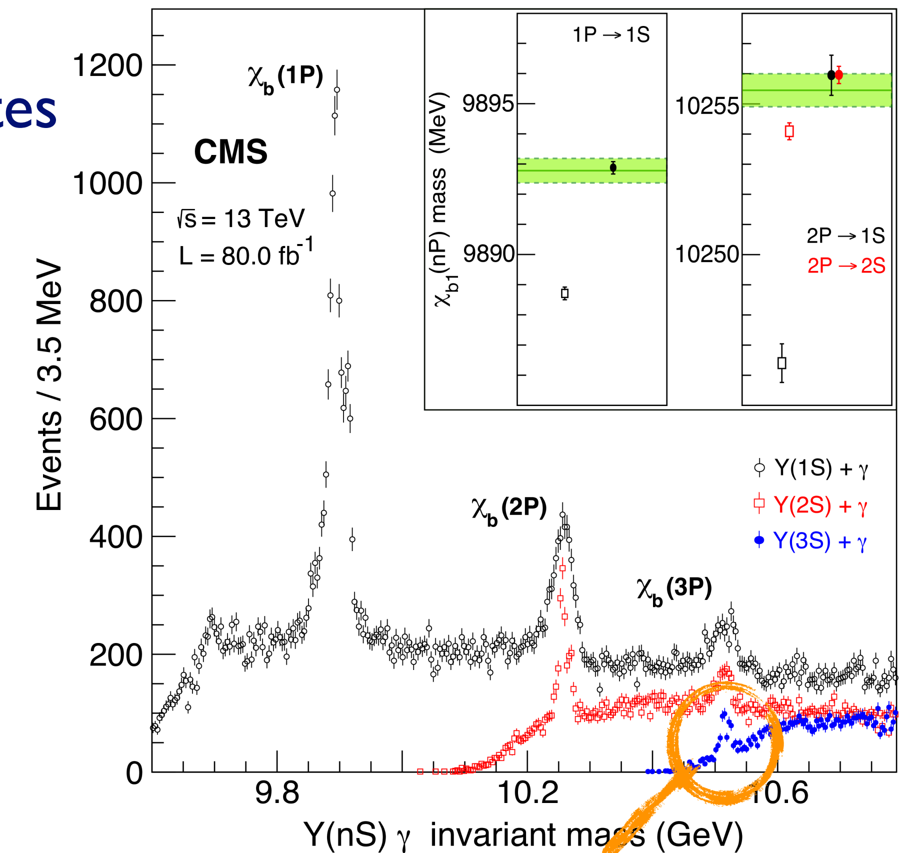

[PLB 743 (2015) 383], [PRL 108 (2012) 152001], [EPJC 74 (2014) 3092], [PRD 86 (2012) 031103]

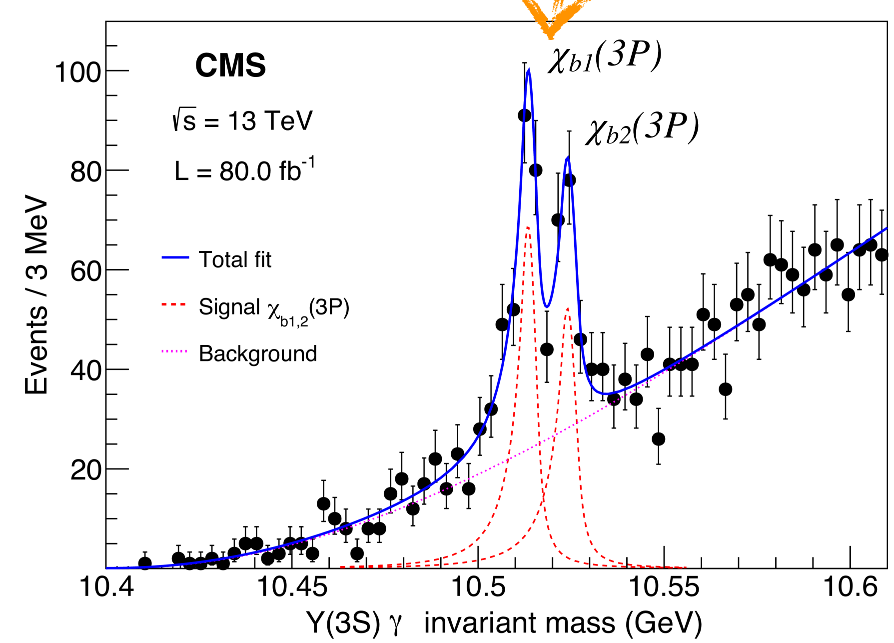
# observation of the $\chi_{b1}(3P)$ and $\chi_{b2}(3P)$ states

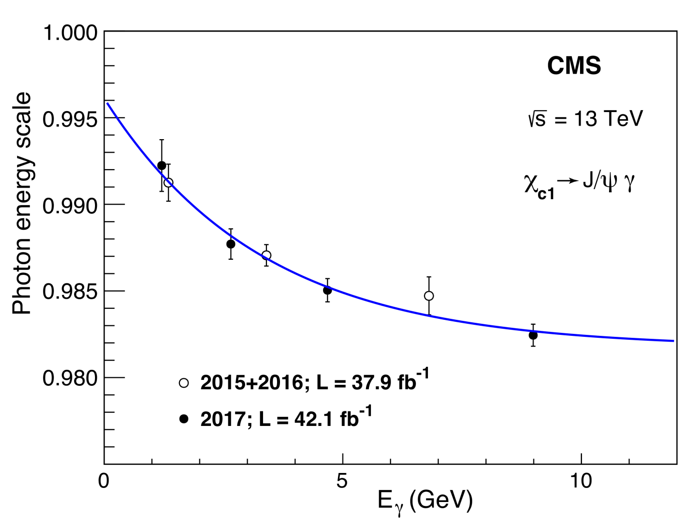
- the first observation of resolved $\chi_{b1}(3P)$ and $\chi_{b2}$ (3P) states
- used pp data at 13TeV collected in 2015 + 2016 + 2017
  - totalling 80 $fb^{-1}$ (2.7 + 35.2 + 42.1 $fb^{-1}$ )
- the photon is reconstructed via pair conversion in tracker
  - the reduced $\gamma \rightarrow e^+e^-$ reconstruction efficiency (<1%) required the large dataset
- measured mass difference between the J=1 and J=2 states
  - $M[\chi_{b2}(3P)] - M[\chi_{b1}(3P)] = 10.60 \pm 0.64$ (stat) $\pm 0.17$ (syst) MeV

$M(\chi_{b1}(3P)) = 10\,513.42 \pm 0.41\ (\text{stat}) \pm 0.18\ (\text{syst})$ MeV

$M(\chi_{b2}(3P)) = 10\,524.02 \pm 0.57\ (\text{stat}) \pm 0.18\ (\text{syst})$ MeV




- photon energy scale calibrated through a $\chi_{c1} \rightarrow J/\psi\gamma$ sample
- tested with $\chi_b$(1P,2P) states

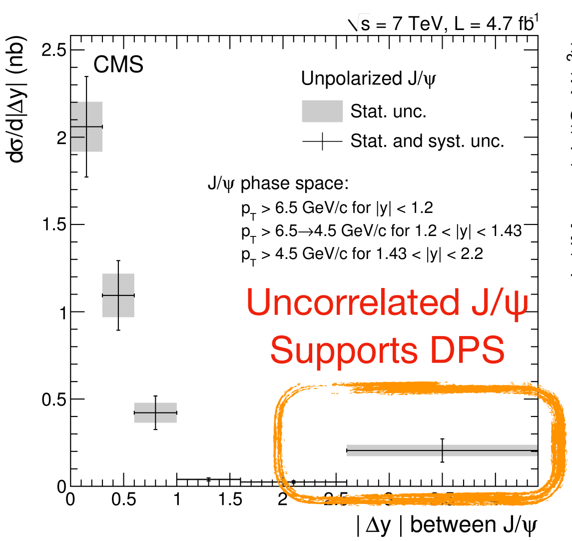
[arXiv:1805.11192]

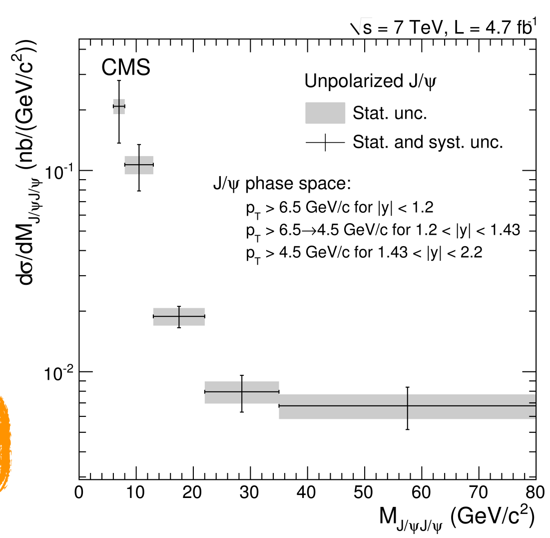
# associated production: double quarkonia

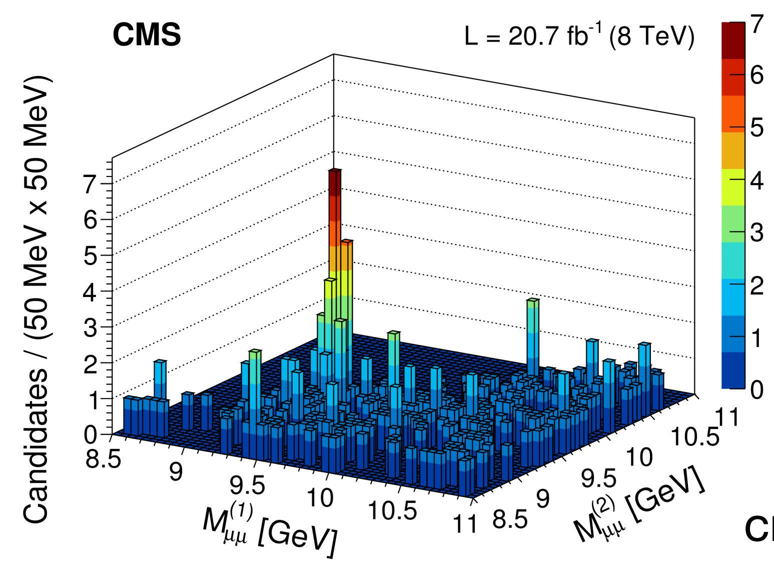
- measurements of associated production give further insight into hadroproduction mechanisms
- allow to study contributions from multi-particle interactions and search for new resonances

[JHEP 05 (2017) 013]

pp→J/ψ J/ψ



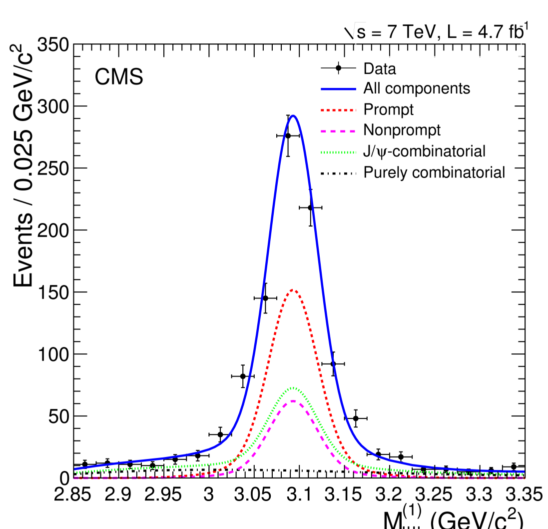




pp→Υ(1S)Υ(1S)

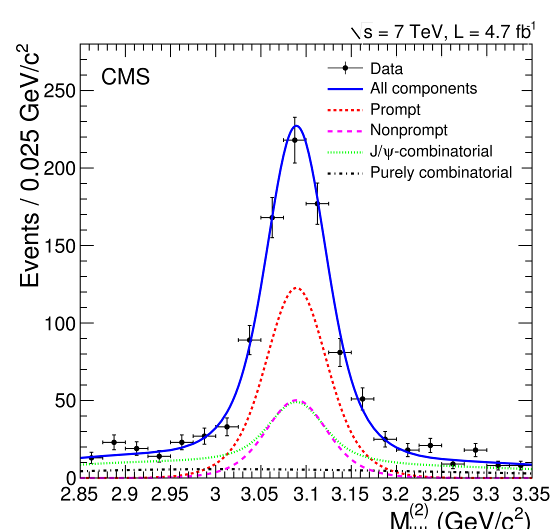
first observation of this process

cross-section measurement:

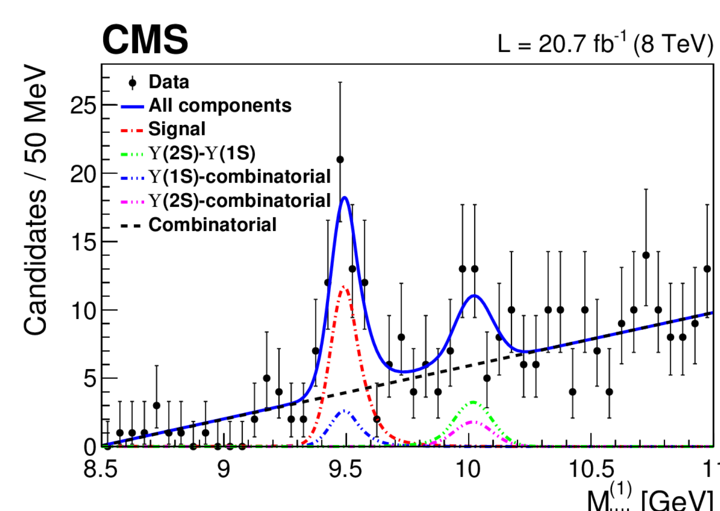
$$\sigma\ (pp\rightarrow \Upsilon\Upsilon) = 68.8 \pm 12.7_{\ stat} \pm 7.4_{\ syst} \pm 2.8_{\ BR}\ pb$$



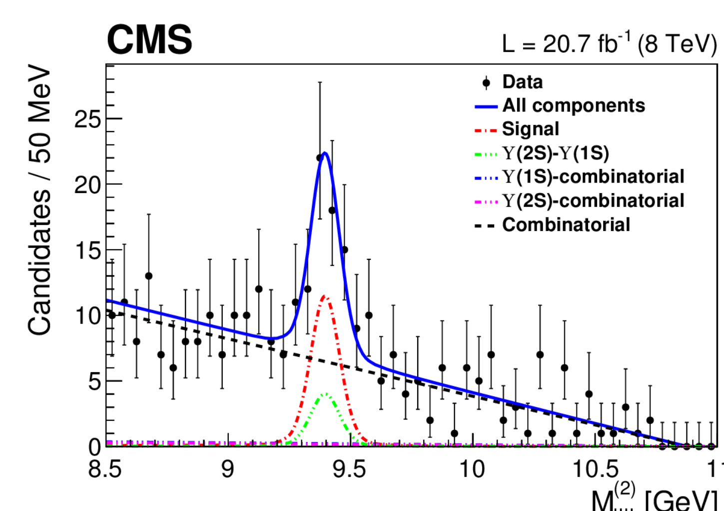

ψ1




ψ2



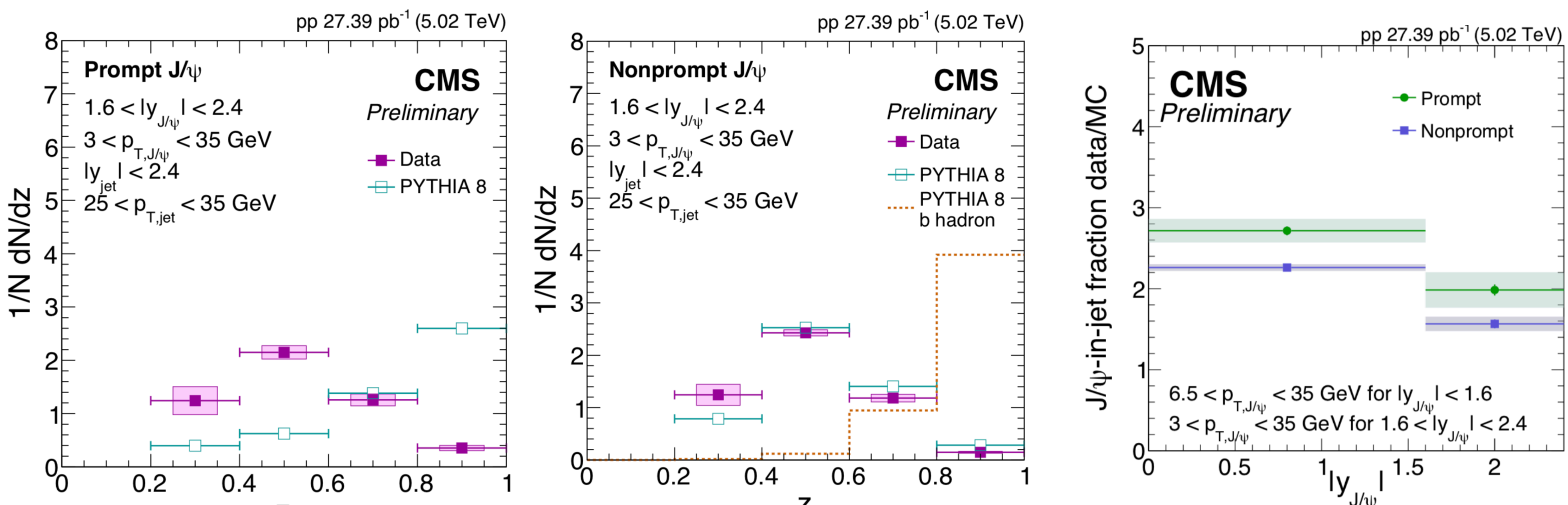

Υ1




Υ2

# associated production: quarkonia in jets

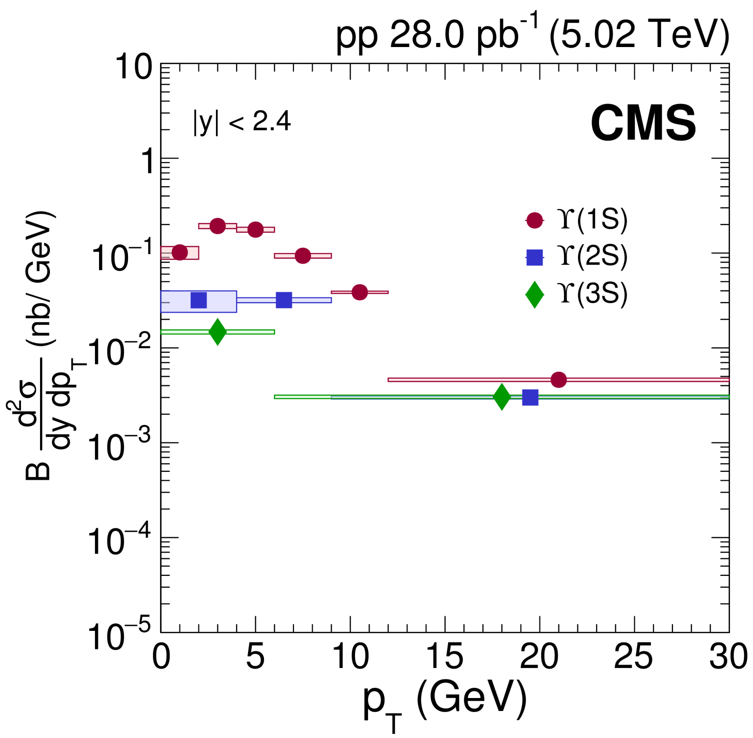
- measure fraction of jet momentum taken by J/ψ, $z \equiv p_{\mathrm{T,J}/\psi} / p_{\mathrm{T,jet}}$
  - for prompt and non-prompt components, extracted with 2D (m,t) fit
- but jet activity accompanying prompt J/ψ is found to be much underestimated in simulation
  - indicating they are less isolated than suggested by production models
- fraction of J/ψ produced in jets is also under-predicted
- these results may shed also light into the polarisation puzzle

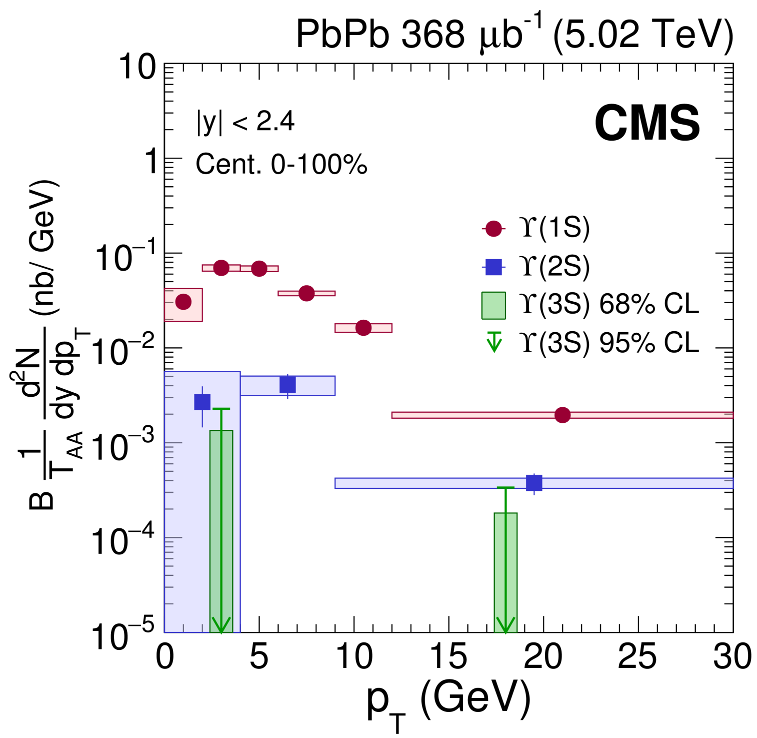


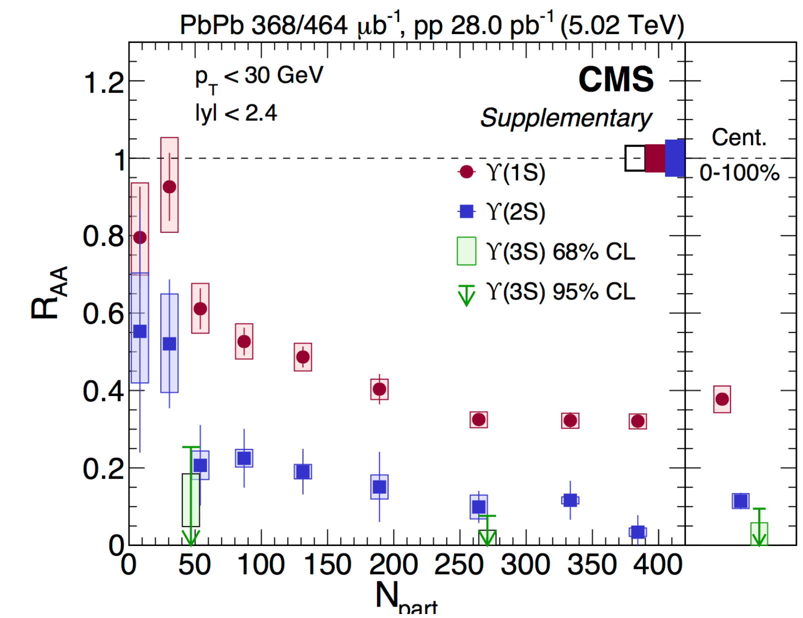

[CMS PAS HIN-18-012]    see aslo: D mesons in jets [arXiv:1803.00042], W+D [CMS-PAS-SMP-17-014]

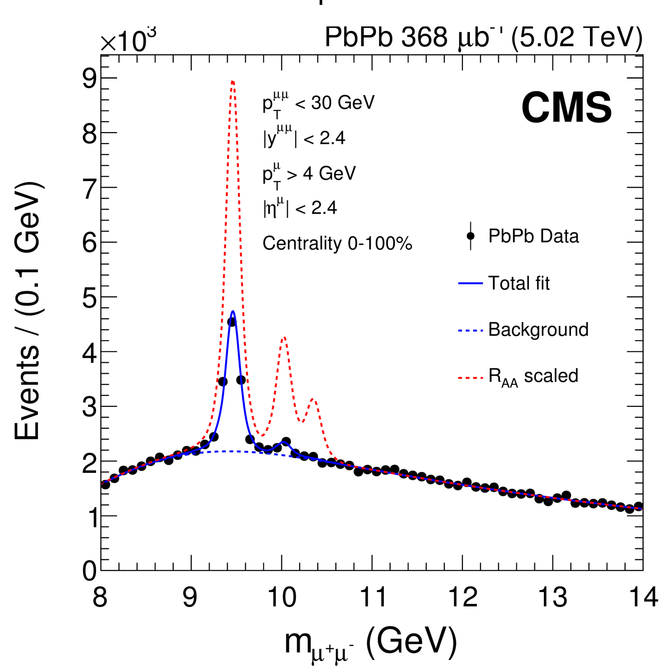
# quarkonium production at 5TeV

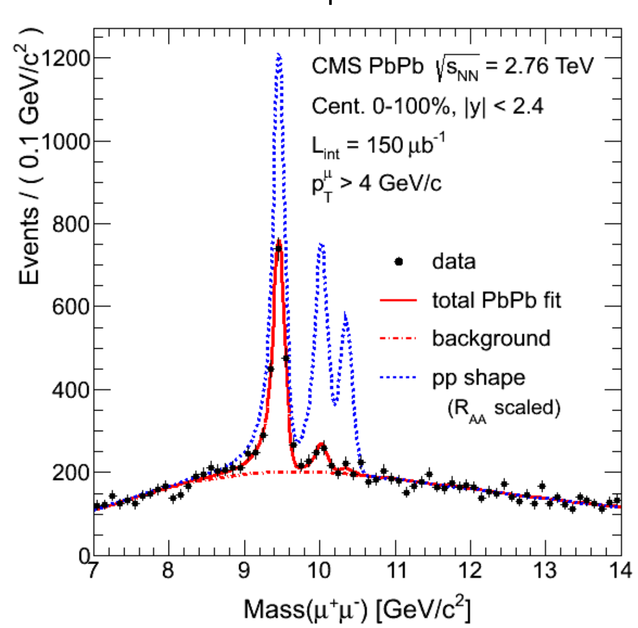
$$R_{AA} = \frac{1}{T_{AA}} \frac{dN_{PbPb}}{dp_T} \bigg/ \frac{d\sigma_{pp}}{dp_T}$$

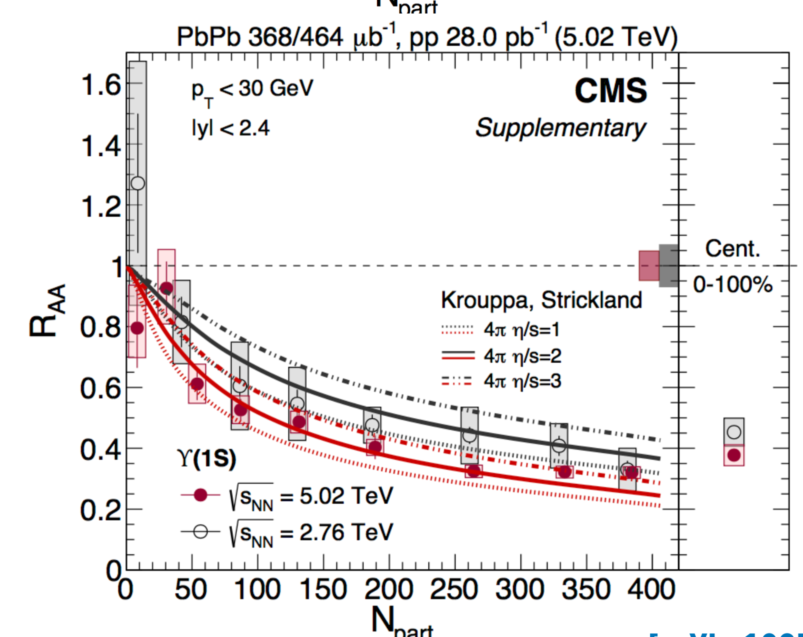


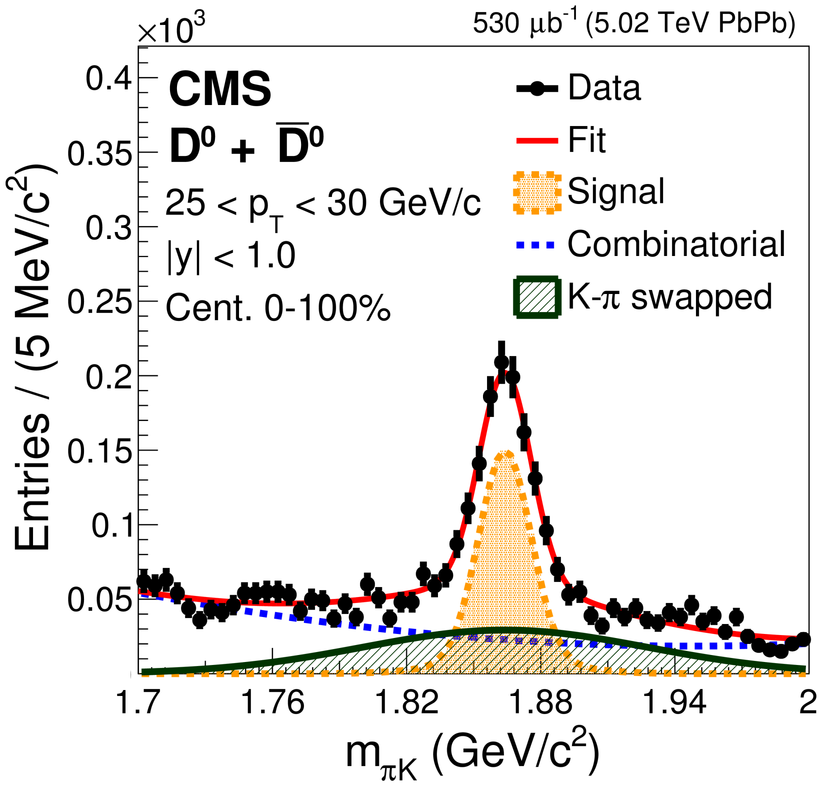



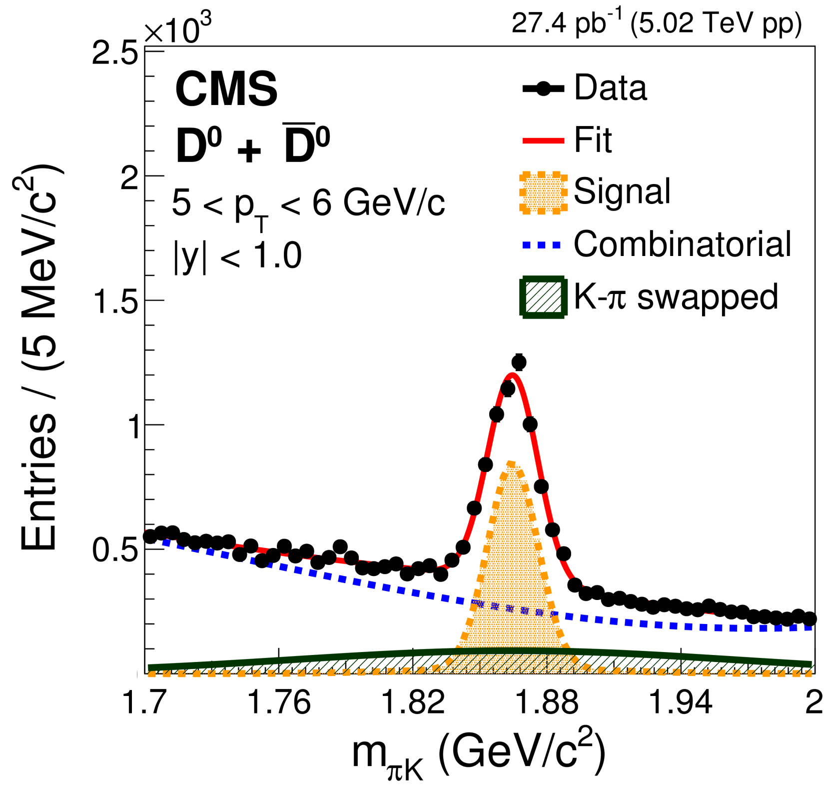

[arXiv:1805.09215]

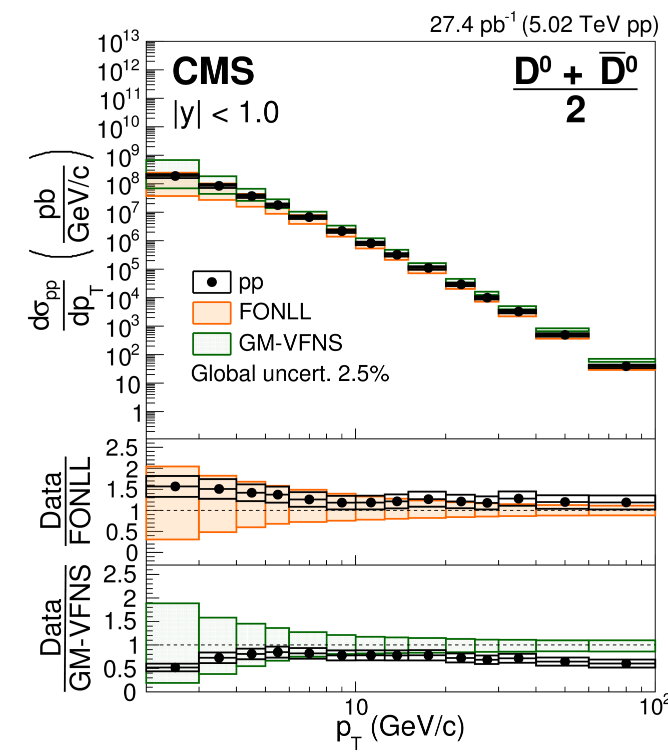
- sequential state suppression in ion collisions: 1S > 2S > 3S

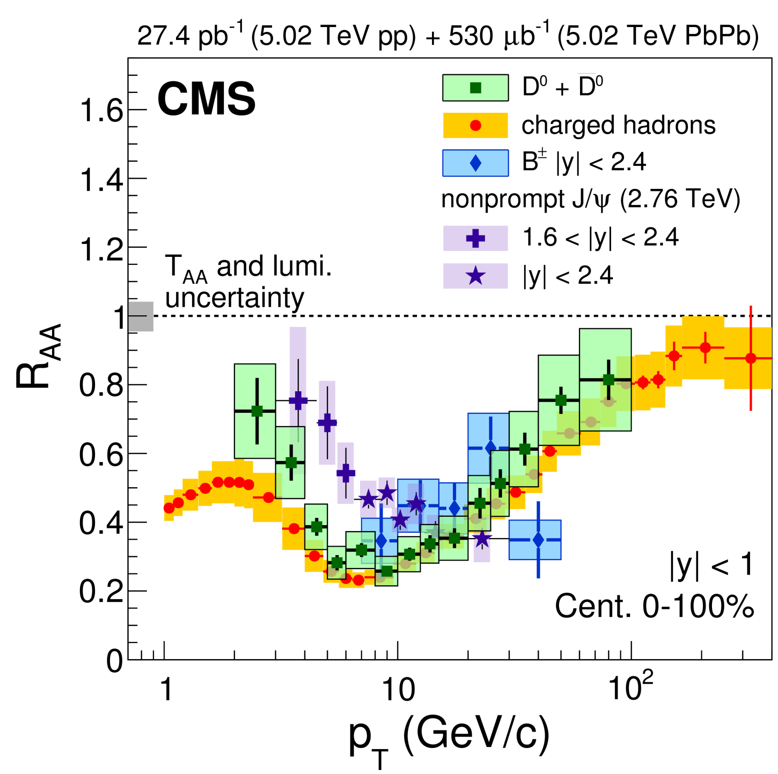
# open charm production

[arXiv:1708.04962]



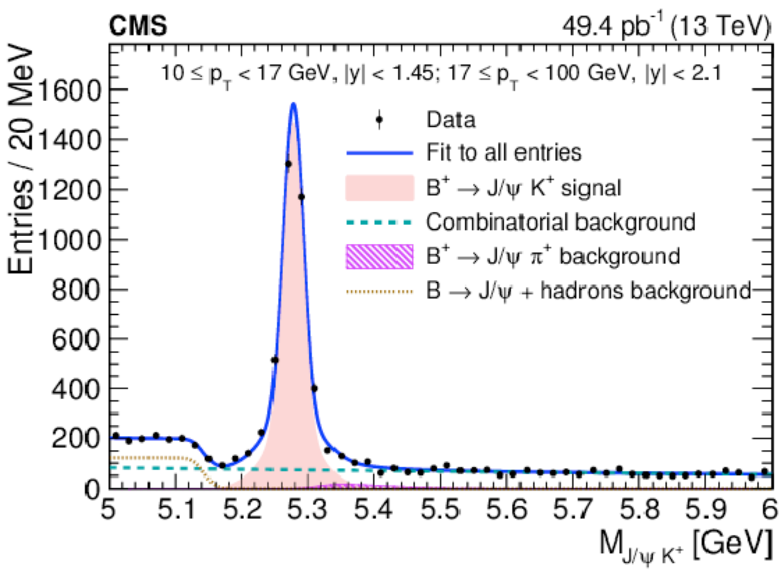

- the differential cross section in pp collisions, measured from 0 to 100GeV, lie in agreement with theory prediction

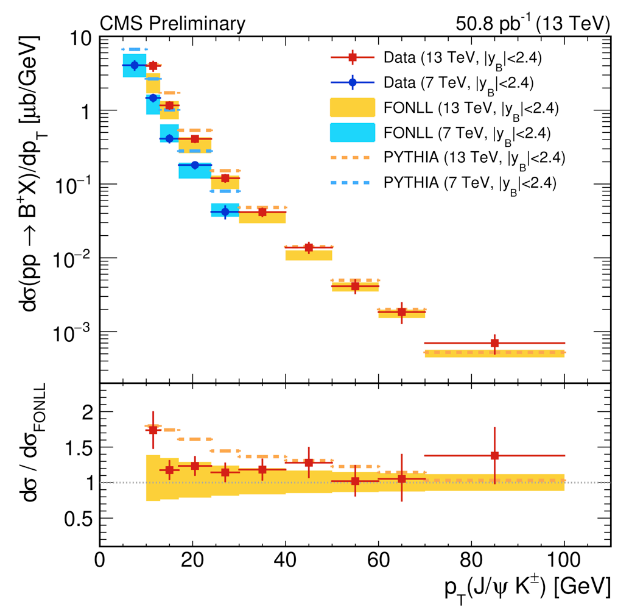
- D mesons are suppressed in PbPb collisions relative to pp collisions. The suppression factor displays a $p_T$ dependence. At intermediate $p_T$ open charm appears to be less suppressed than light hadrons, and more suppressed than B hadrons (accessed via displaced J/ψ)

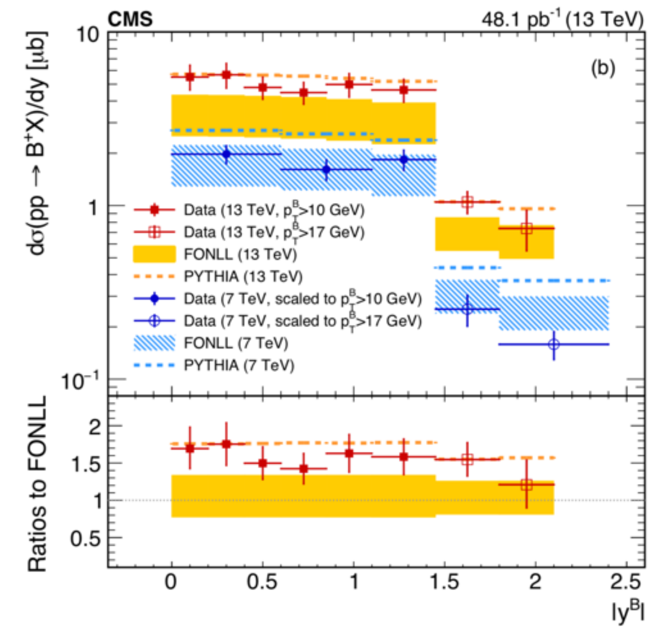
# open beauty production

- b-hadron cross sections measured at different pp collision energies [PLB 711 (2017) 435] [CMS-PAS-BPH-13-002]

13TeV

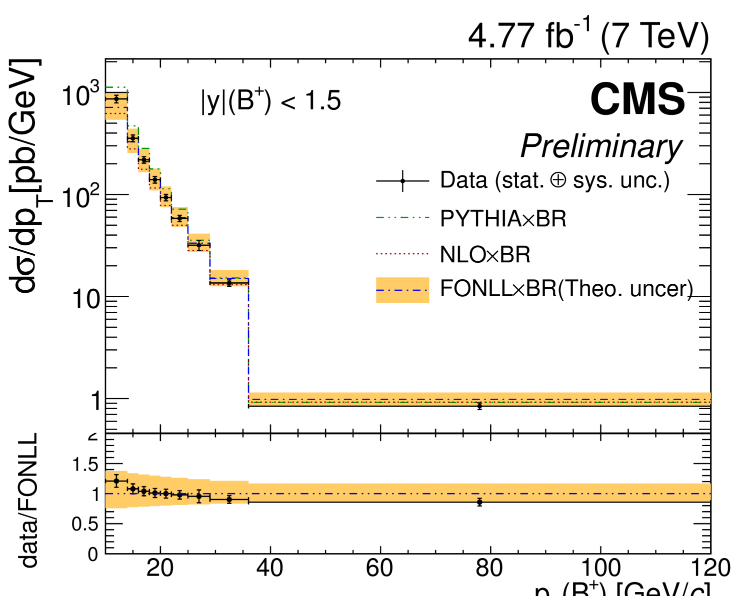


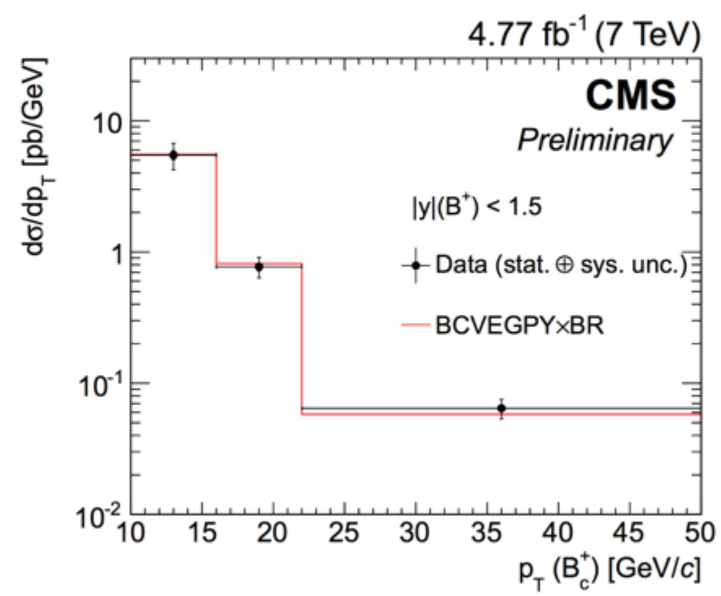



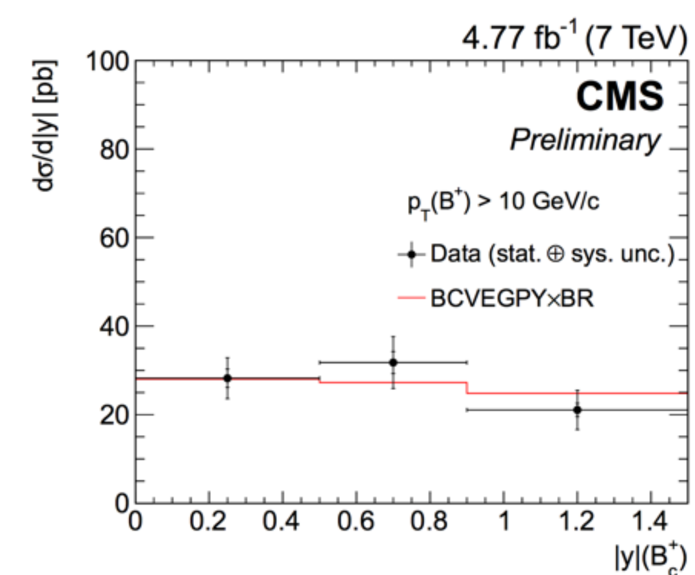




- $B^+$ cross sections in good agreement with FONNL prediction, although discrepancies at low $p_T$

7TeV



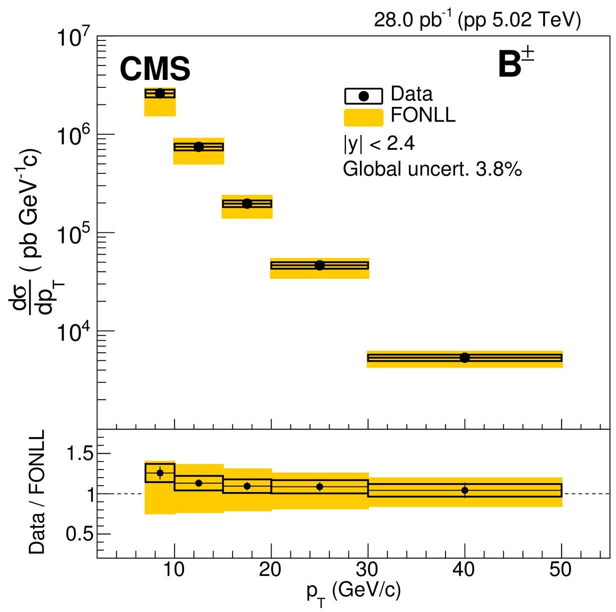



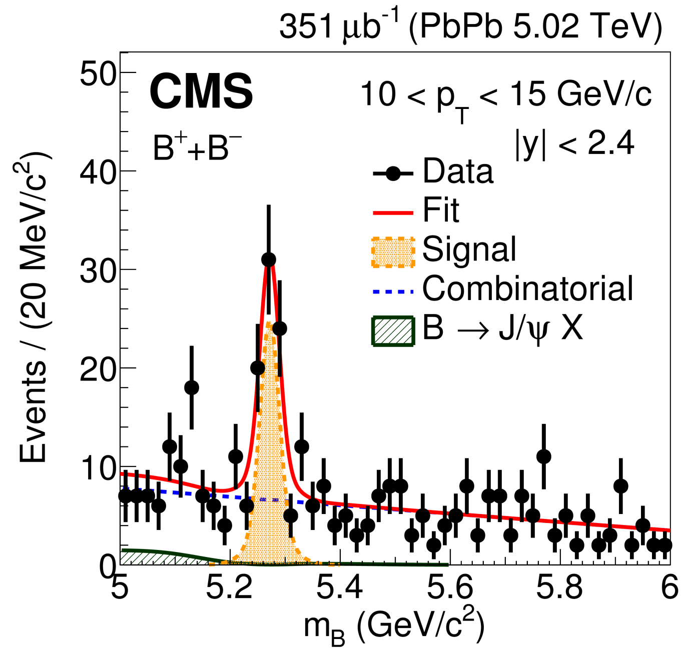

- $B_c$ cross sections shape in good agreement with prediction, normalisation is off by a factor ~3

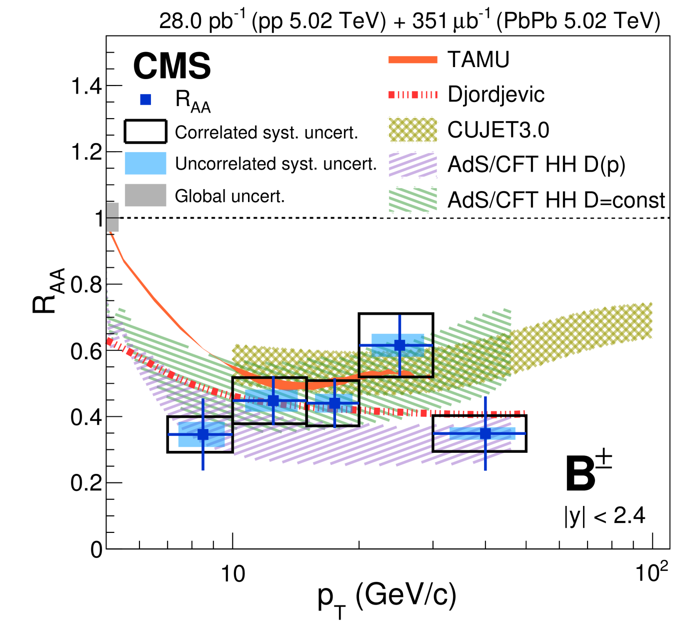
# B production in AA collisions

- First direct reconstruction of B mesons in heavy ion collisions

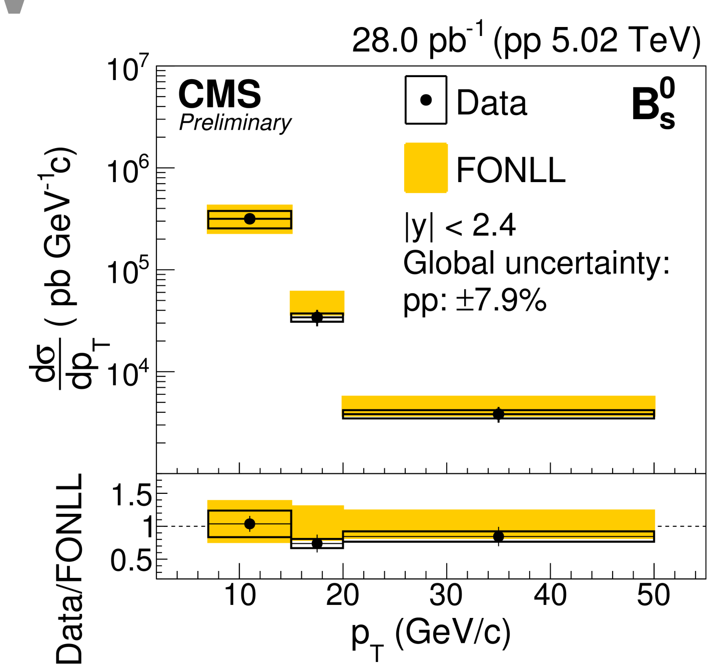
[PRL 119 (2017) 152301] [CMS-PAS-HIN-17-008]

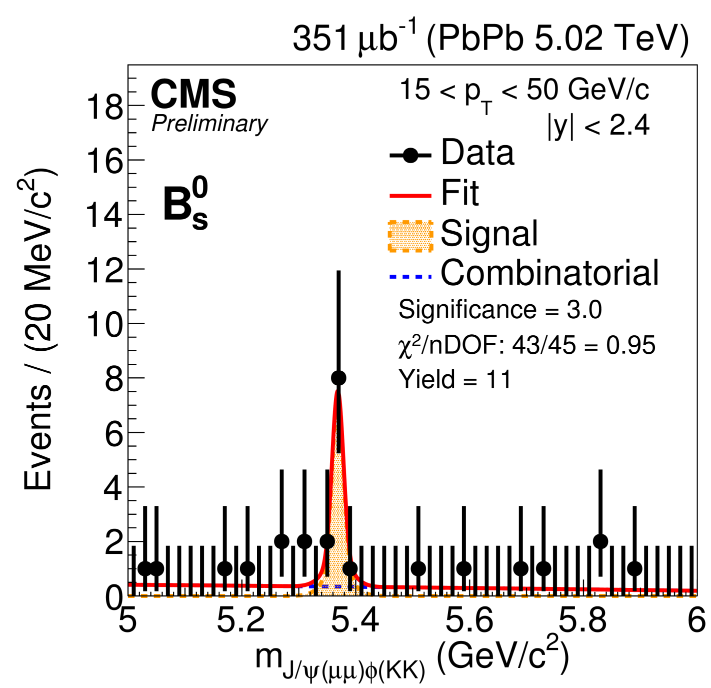


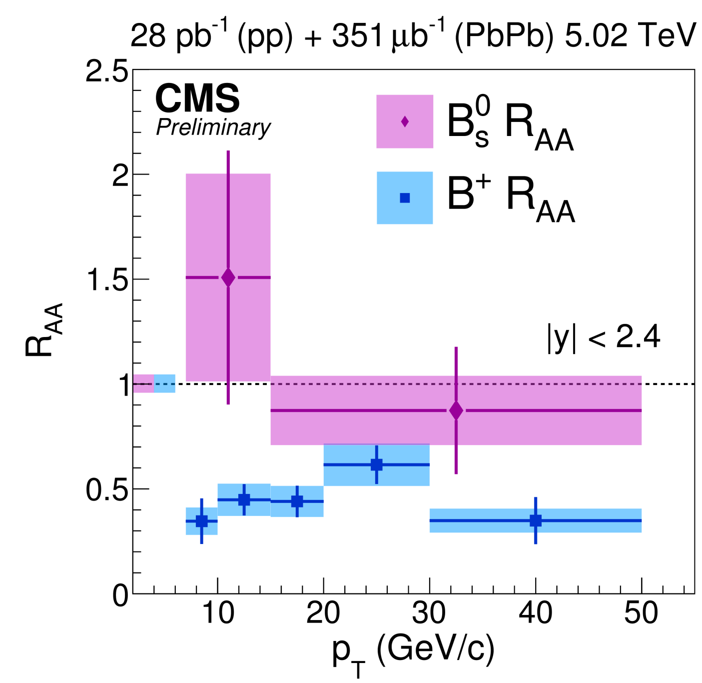




5TeV



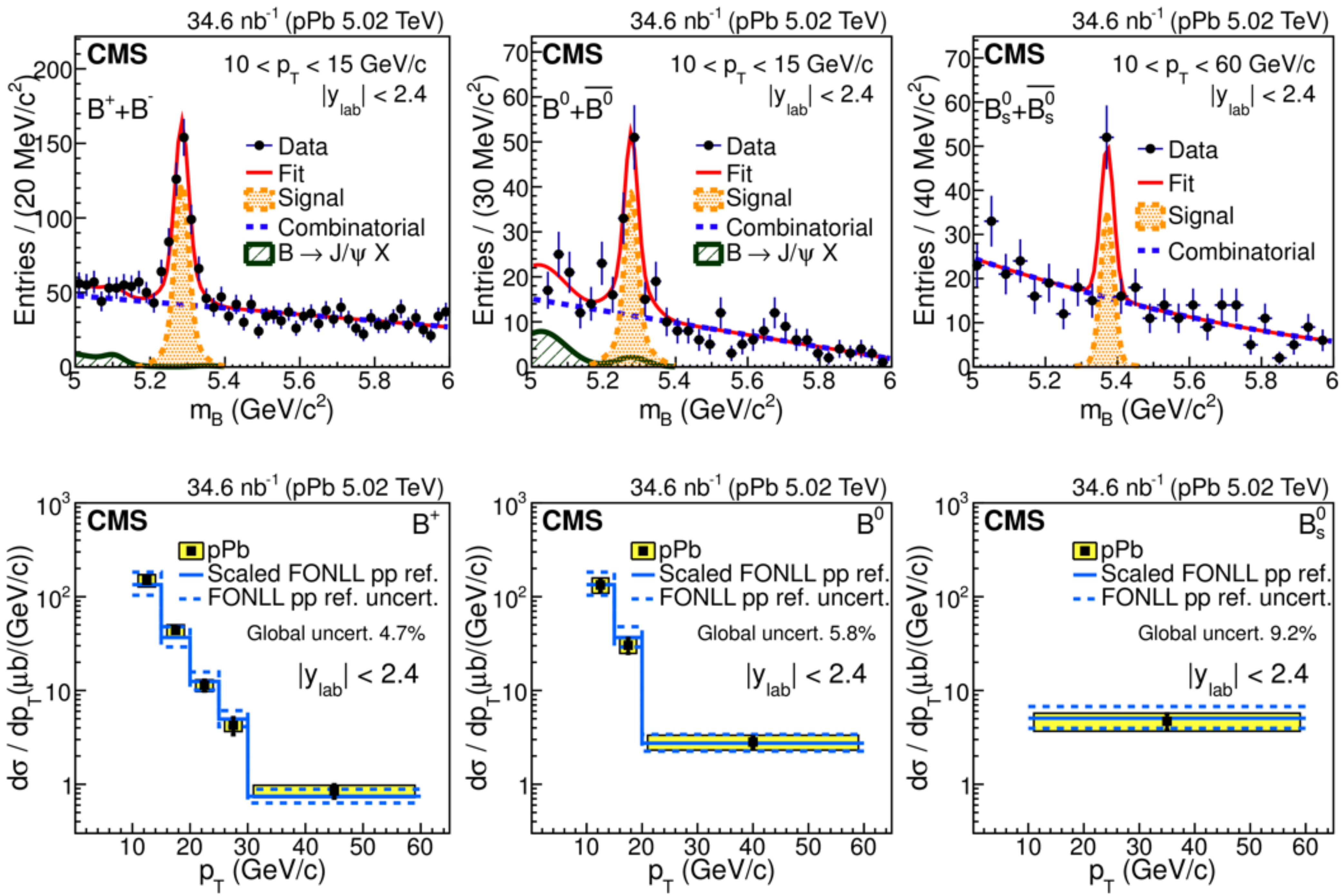




- Significant suppression of B yields in PbPb compared to pp
- Hint of smaller $B_s$ suppression relative to $B^+$, consistent with strangeness enhancement
- (indications of strangeness enhancement have been reported by ALICE in the charm sector)

# … and in pA collisions

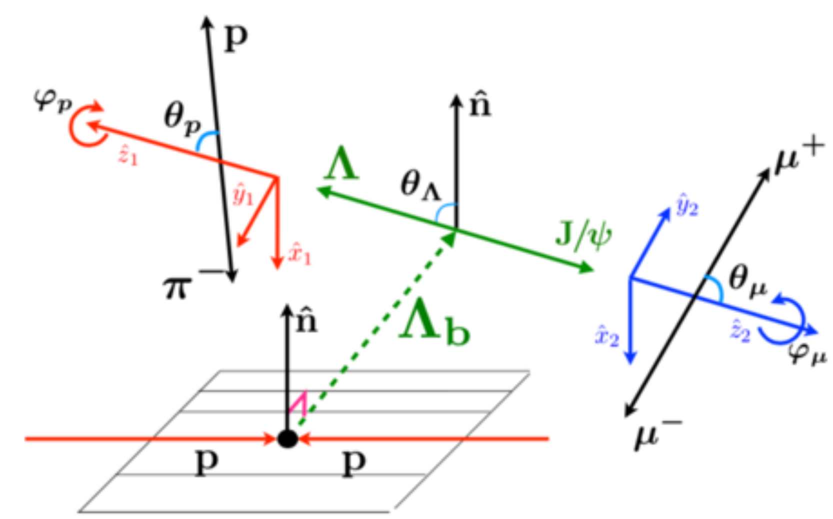
[PRL 116 (2016) 032301]

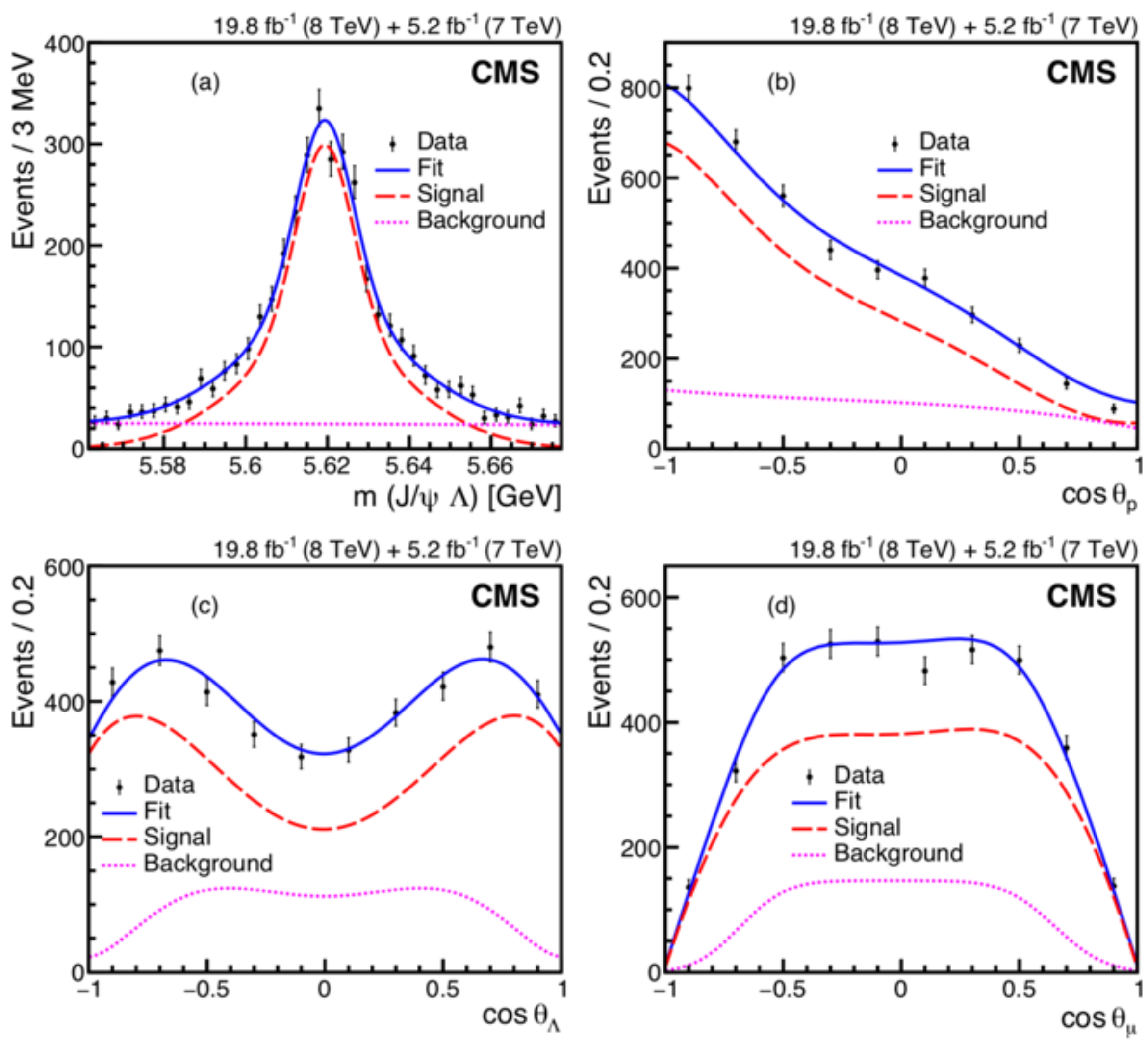



- B mesons as novel probes of the QGP
  - For characterising hot and cold matter effects, and flavor dependence of energy loss in media

# $\Lambda_b$ polarisation

- study the angular distributions in the decay $\Lambda_b \to J/\psi \Lambda \to \mu\mu p\pi$
  - extract the $\Lambda_b$ polarisation and the parity-violating decay asymmetry $\alpha$




$$\frac{d^3\Gamma}{d\cos\theta_\Lambda\, d\cos\theta_p\, d\cos\theta_\mu}(\theta_\Lambda,\theta_p,\theta_\mu) = \int_{-\pi}^{\pi}\int_{-\pi}^{\pi}\frac{d^5\Gamma}{d\cos\theta_\Lambda\, d\Omega_p\, d\Omega_\mu}(\theta_\Lambda,\theta_p,\theta_\mu,\varphi_p,\varphi_\mu)\,d\varphi_p\, d\varphi_\mu$$
$$\sim \sum_{i=1}^{8} u_i\left(|T_{\lambda_1\lambda_2}|^2\right) v_i(P,\alpha_\Lambda) w_i(\theta_\Lambda,\theta_p,\theta_\mu).$$

Based on about 6000 $\Lambda_b$ decays, the polarization parameters are found to be:

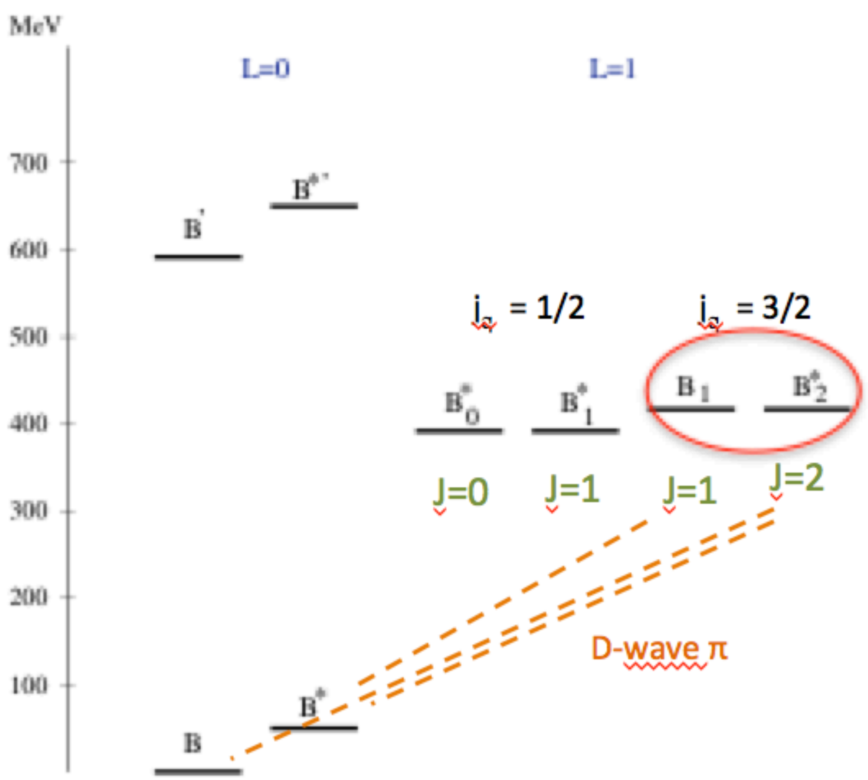
$$P = 0.00 \pm 0.06\,(\text{stat}) \pm 0.06\,(\text{syst})$$
$$\alpha_1 = 0.14 \pm 0.14\,(\text{stat}) \pm 0.10\,(\text{syst})$$

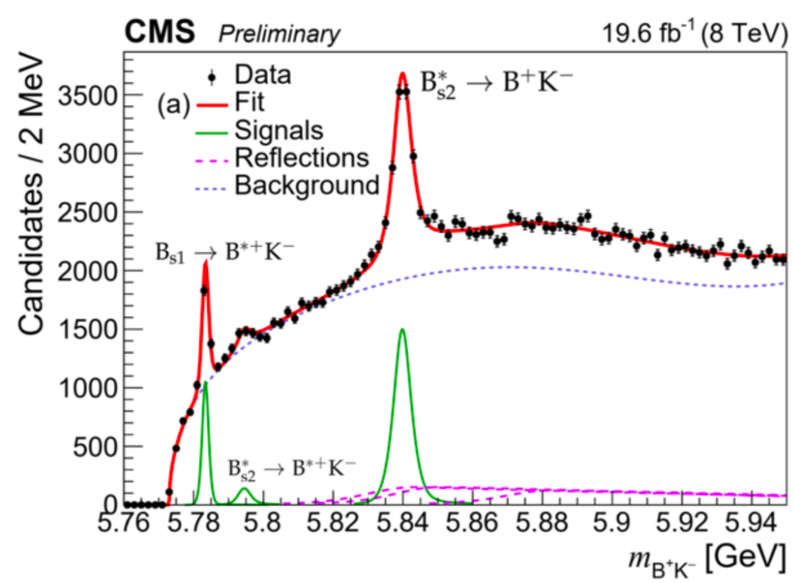
Results are in agreement with LHCb and ATLAS

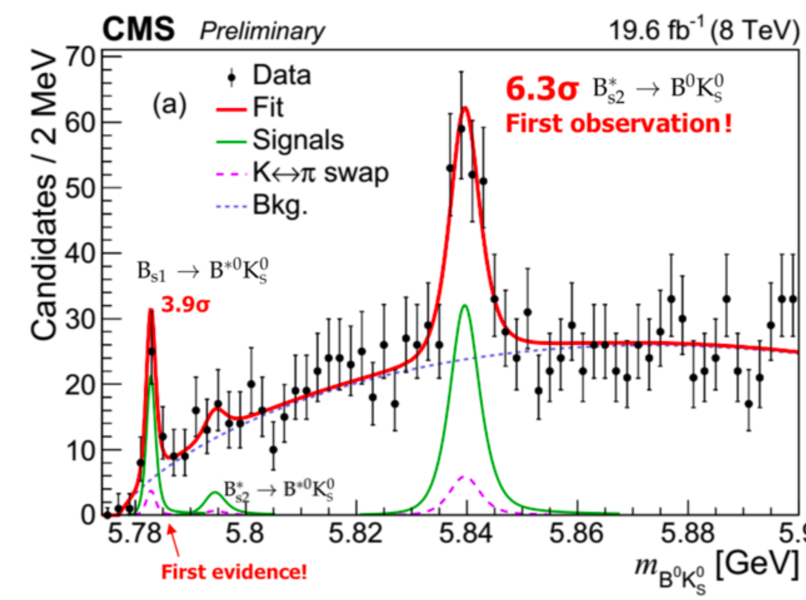
[PRD 97 (2018) 072010]

# study of P-wave $B_s$ mesons

[CMS-PAS-BPH-16-003 ]

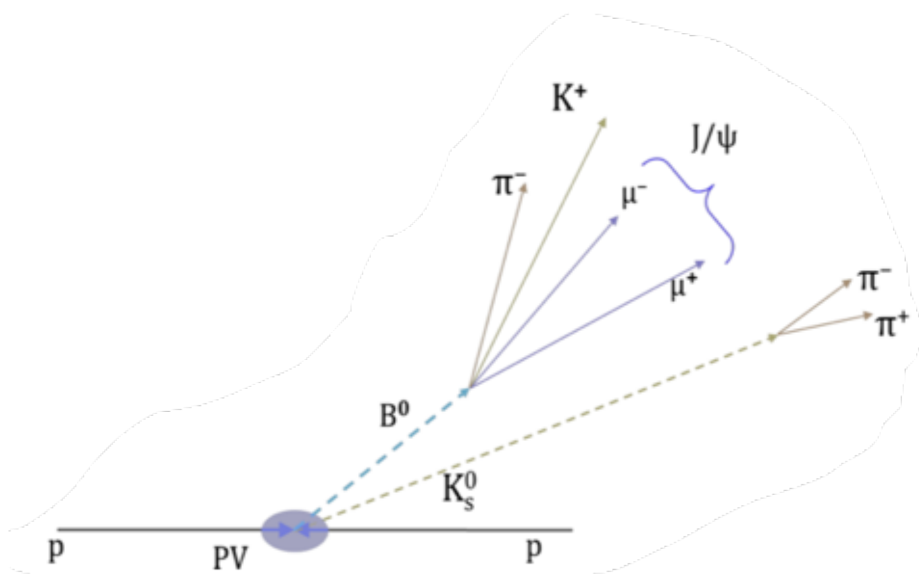



$B^*_{s2} \to B^+K^-$ **$B^*_{s2} \to B^0K^0_S$**

$B_{s1} \to B^+K^-$ **$B_{s1} \to B^{*0}K^0_S$**




- observed the $B^*_{s2} \to B^0K^0_S$ decay
- measured relative branching fractions

$$\frac{\mathcal{B}(B^*_{s2} \to B^0K^0_S)}{\mathcal{B}(B^*_{s2} \to B^+K^-)}, \frac{\mathcal{B}(B_{s1} \to B^{*0}K^0_S)}{\mathcal{B}(B_{s1} \to B^{*+}K^-)}, \frac{\mathcal{B}(B^*_{s2} \to B^{*+}K^-)}{\mathcal{B}(B^*_{s2} \to B^+K^-)}, \frac{\mathcal{B}(B^*_{s2} \to B^{*0}K^0_S)}{\mathcal{B}(B^*_{s2} \to B^0K^0_S)}$$

- measured mass differences M(B*)-M(B)
- measured $B^*_{s2}$ natural width
- precision on pair with LHCb and CDF
- good agreement also with theory predictions

# summary

- while CMS is a multi-purpose detector, not designed for dedicated heavy flavor studies, it delivers complementary and unique results
  - covering central-rapidity, high-$p_T$ kinematic region
- reported measurements of charm and beauty production
  - at different collision energies and collision systems
- these heavy flavour production results aim at facilitating
  - an improved understanding of the QCD hadroproduction mechanisms, through dedicated measurements of cross sections and polarizations
  - an improved understanding of the properties of the media created in ion collisions, through a variety of exclusively reconstructed heavy flavor states, as novel probes of the medium and of the flavor dependence of energy loss
  - the exploration of rarer processes, and the pursuit of new physics effects though heavy flavor decays
- see also CMS reports in tracks: Heavy ions; Quark & lepton flavor physics