B-Physics in ATLAS and CMS

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for the ATLAS and CMS Collaborations

OUTLINE

Motivations of heavy quark measurements:

- Precision studies of non-perturbative phenomena
  - Decay rates, angular correlations etc.
- Measurements of rare effects that could be influenced by new physics
  - For example decay rates of $B_{s/d}$ ➔ $\mu^+\mu^-$

In this talk:

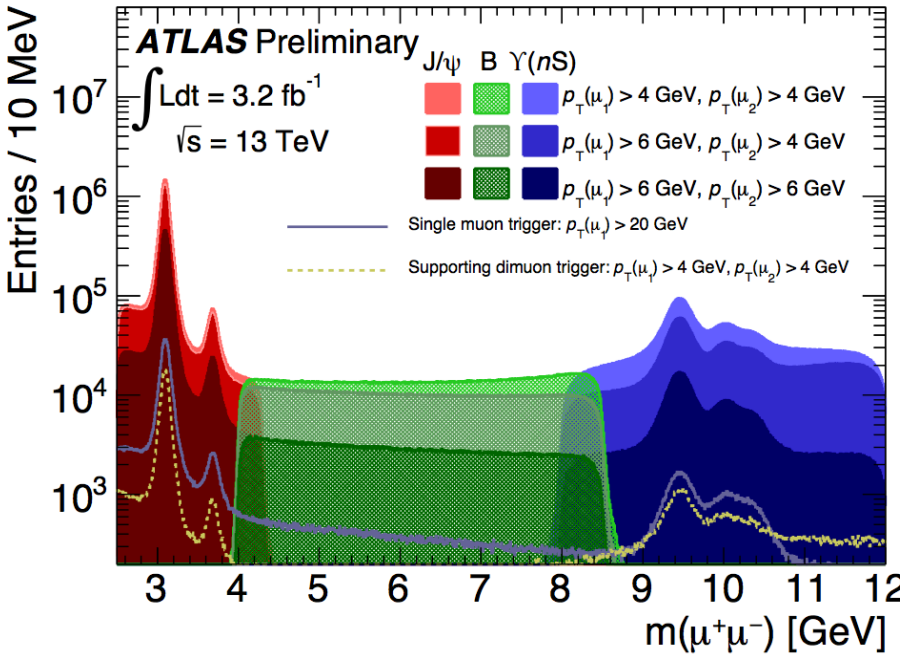
- Charmonium production and properties
- Beauty production, decays and properties

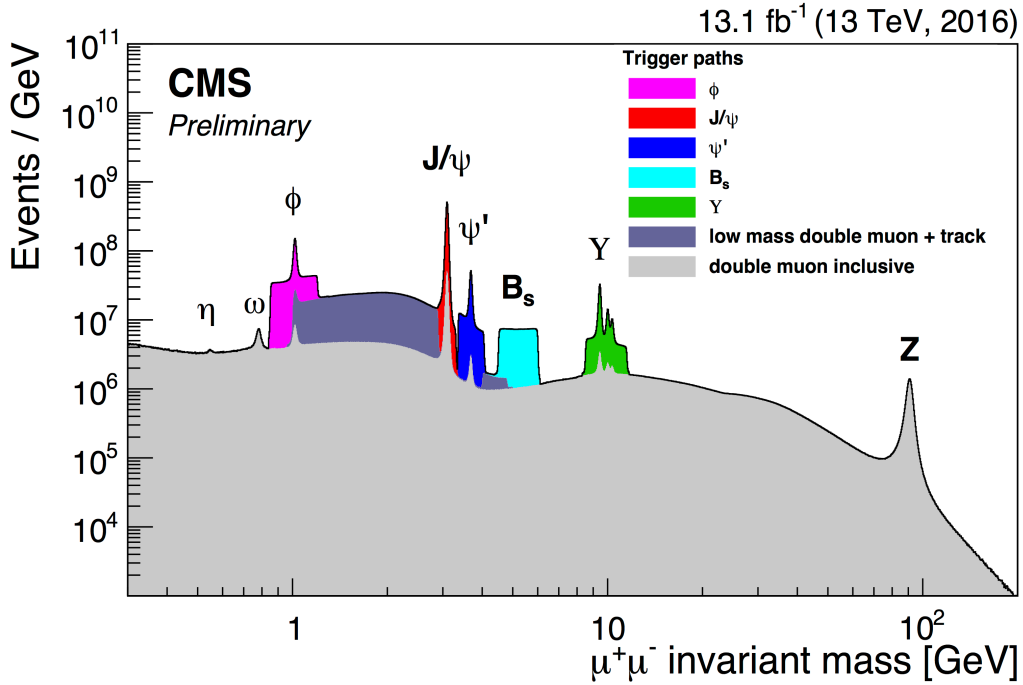
Di-Muon Spectrum at 13 TeV

ATLAS and CMS use specific di-muon triggers to improve physics reach in beauty and charm sector w.r.t. to single muon or di-muon triggers

Trigger selection principle:

- A pair of trigger muons with opposite charge and momentum requirements
- vertex quality requests on the di-muon pair + optional decay length cuts
- **different cuts on the di-muon invariant mass, depending on the state to be selected**





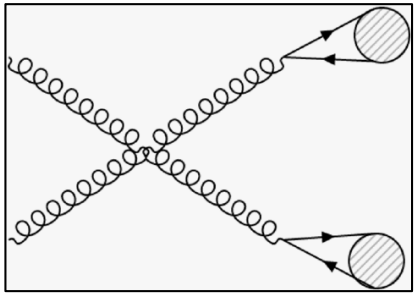
Successfully used in Run-1, re-optimized for Run-2: many results in the following

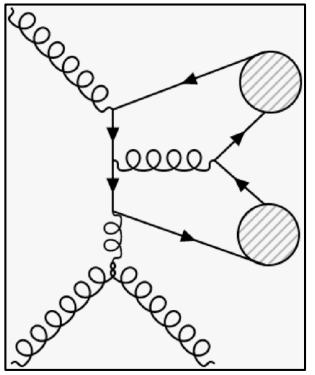
Minor differences between ATLAS and CMS (e.g. on minimum p_T and rapidity requests)

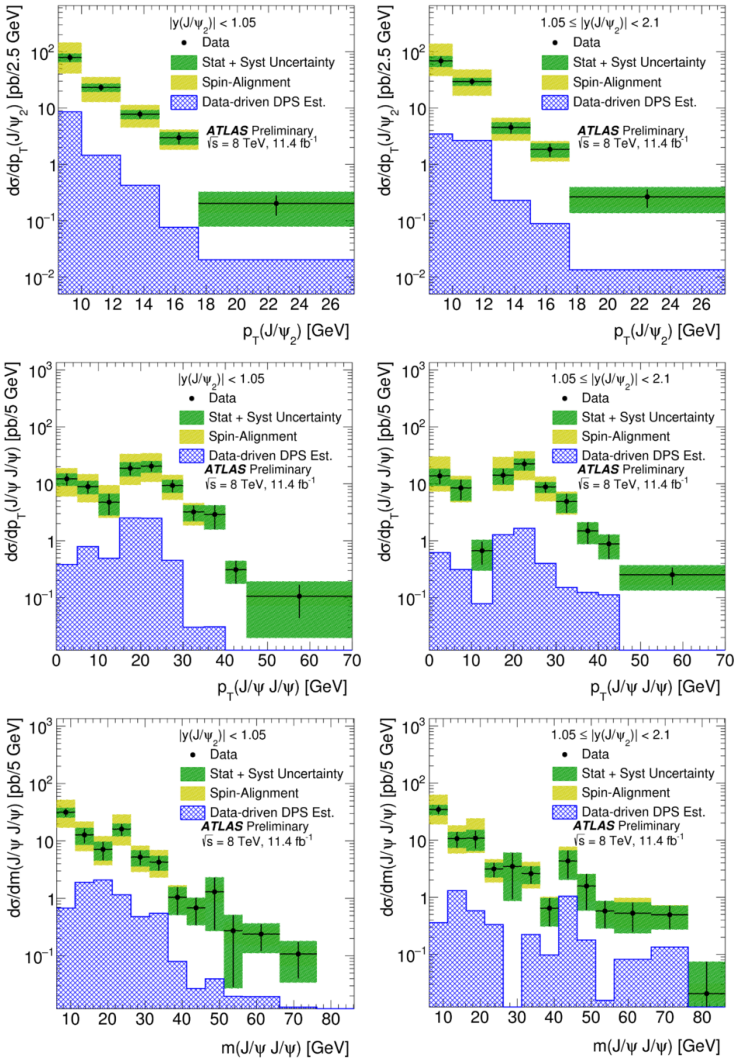
Prompt J/ψ pair production cross-section

Two production mechanisms for prompt J/ψ pairs:

- leading order
- next-to-leading order







Consider carefully all systematics:

- trigger muon overlaps
- fit models
- pile-up effects
- spin alignment
- double parton scattering (data-driven measurement)

ATLAS-CONF-2016-047

Results:

- $\sigma_{total}(J/\psi J/\psi + X) = 160.39 \pm 12.40_{stat} \pm 13.57_{syst} \pm 3.24_{BF} \pm 4.49_{lumi}$ pb
- Differential cross-sections vs $p_T(J/\psi_2)$, $p_T(J/\psi J/\psi)$ and $m(J/\psi J/\psi)$ for low and high J/ψ_2 rapidity in the figures
- effective cross-section of double parton scattering:

$\sigma_{eff} = 8.7 \pm 1.1_{stat} \pm 1.4_{syst} \pm 0.1_{BF} \pm 0.3_{lumi}$ mb

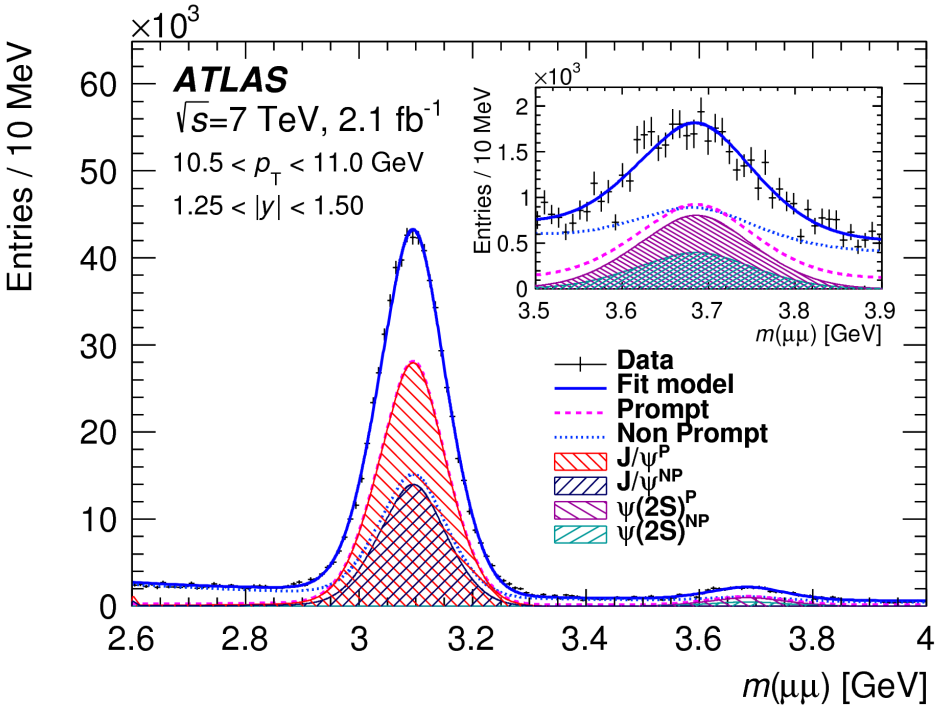
Prompt and Non-Prompt J/ψ and ψ(2S)

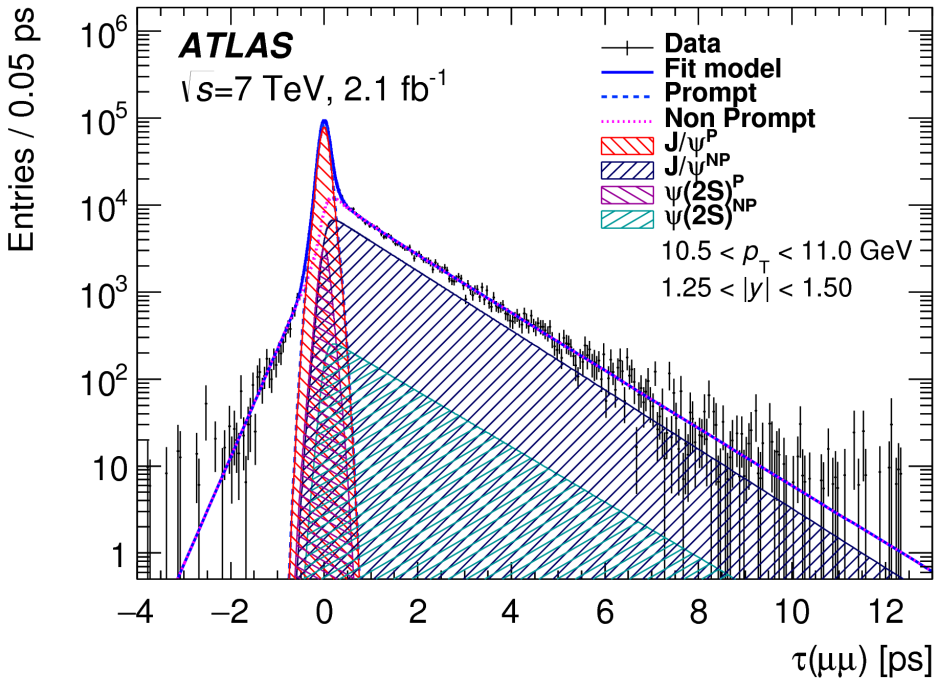
Two different charmonium production mechanisms expected at the LHC:
prompt: direct production from primary interaction or feed-down from heavier states
non-prompt: production from b-hadrons decays

arXiv: 1512.03657

Experimental procedure:

- candidates reconstructed in the di-muon decay channel
- corrections applied for various efficiencies and acceptance
- significant lifetime of b-hadrons exploited to separate prompt and non-prompt candidates
- **ratio measured from unbinned 2D fit of di-muon mass and pseudo-proper time**





Prompt and Non-Prompt J/ψ and ψ(2S)

Powerful tool to validate theoretical models of prompt and non-prompt production:

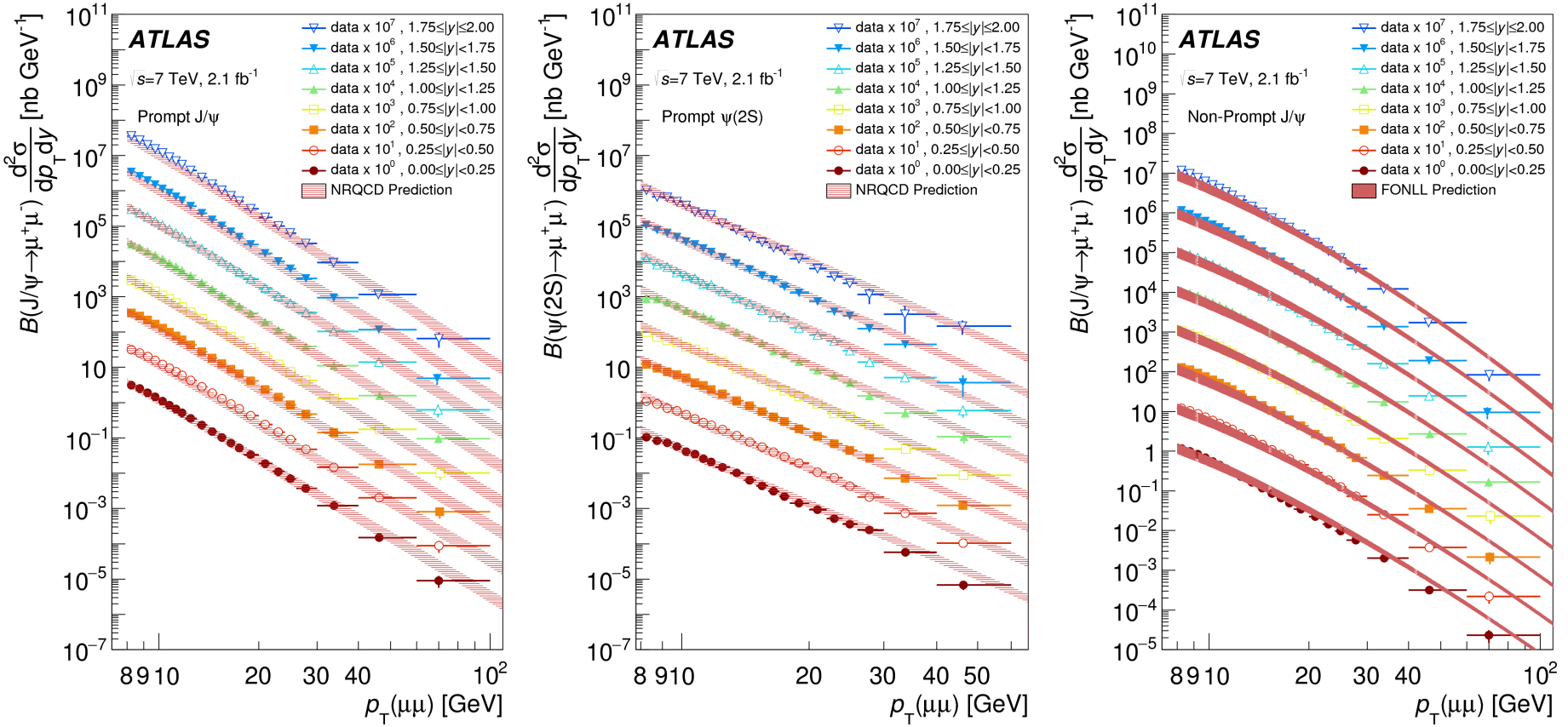
prompt: compared to non-relativistic QCD (NRQCD)

arXiv: 1512.03657

- perturbative QCD for cc-bar pair prod / data for evolution into quarkonium state
- **describes data well, with some discrepancy at higher p_T, especially for ψ(2S)**

non-prompt: compared to Fixed Order Next-to-Leading Logarithm (FONLL)

- perturbative description for bb-bar prod / data for fragmentation and b-hadron decay
- **describes data well, but predicts a p_T spectrum harder than the observed one**
- effect consistent with B→ψ(2S)+X, B→X_c and B± [arXiv:1407.5532/1407.5532/1307.0126]

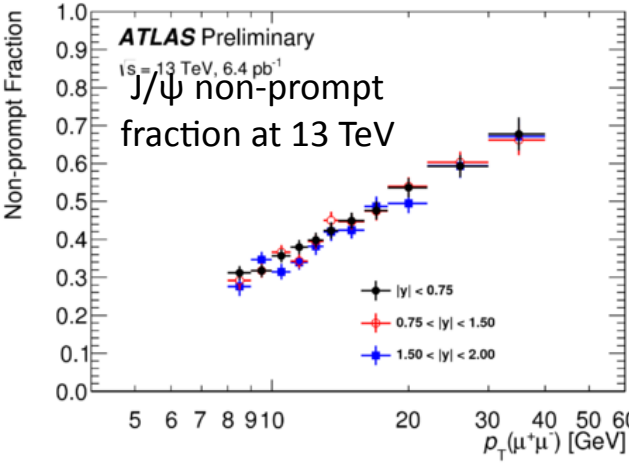


Prompt and Non-Prompt J/ψ at 13 TeV

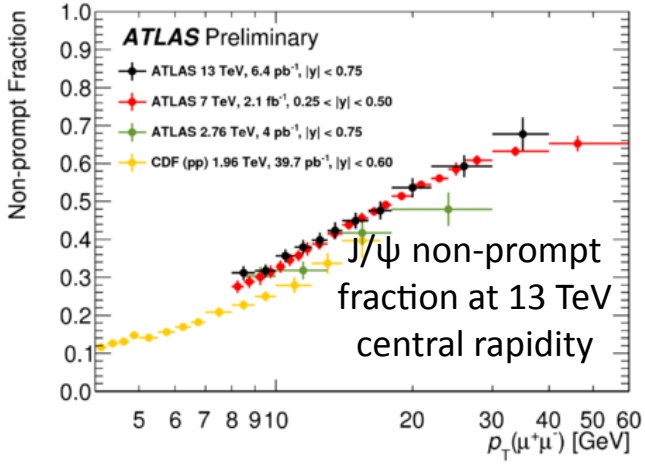
Study repeated as first ATLAS quarkonium production measurement at 13 TeV

Experimental procedure to extract fraction of non-prompt J/ψ is almost identical to Run 1:

- analyzed a partial data sample of 6.4 pb^{-1}, recorded by di-muon and high-p_T muon triggers
- non-prompt J/ψ fraction determined with unbinned 2D fit to mass and pseudo-proper decay time
- measuring a fraction means simplified systematics, as efficiencies cancel to very good approximation in the ratio (3% syst effect)



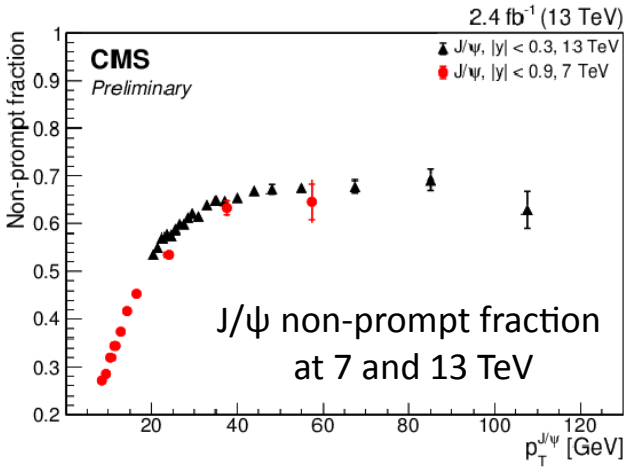
J/ψ non-prompt fraction at 13 TeV



J/ψ non-prompt fraction at 13 TeV central rapidity

ATLAS-CONF-2015-030

CMS-PAS-BPH-15-005



J/ψ non-prompt fraction at 7 and 13 TeV

Minimal dependence on rapidity interval, as seen in Run 1

New 13 TeV results almost identical to 7 TeV ones

Larger differences had been already observed w.r.t. lower energies

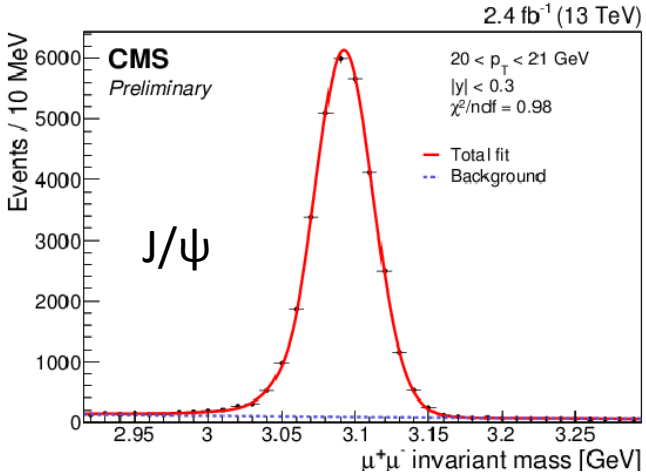
Quarkonia at 13 TeV: J/ψ, ψ(2S), Υ(nS)

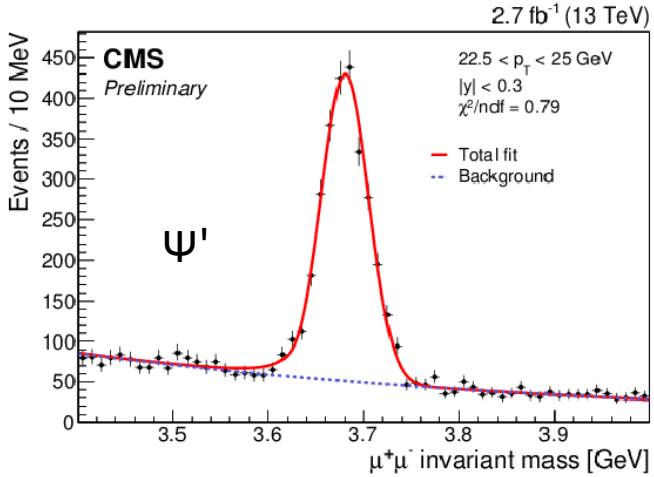
CMS recently measured the double-differential production cross section of prompt J/ψ and ψ(2S), and the production cross section of Υ(nS), n=1,2,3, at 13 TeV

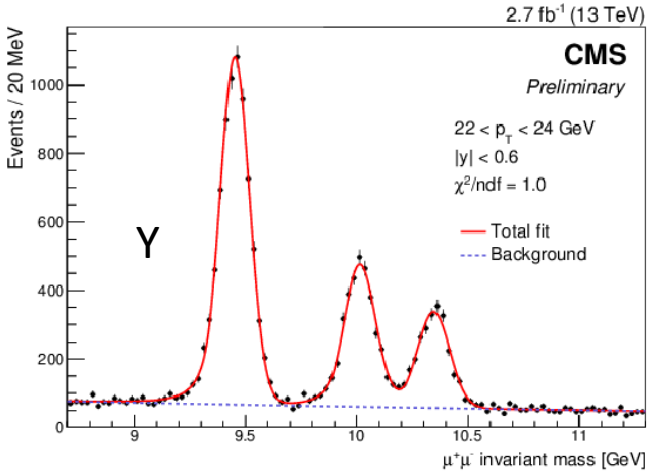
CMS-PAS-BPH-15-005

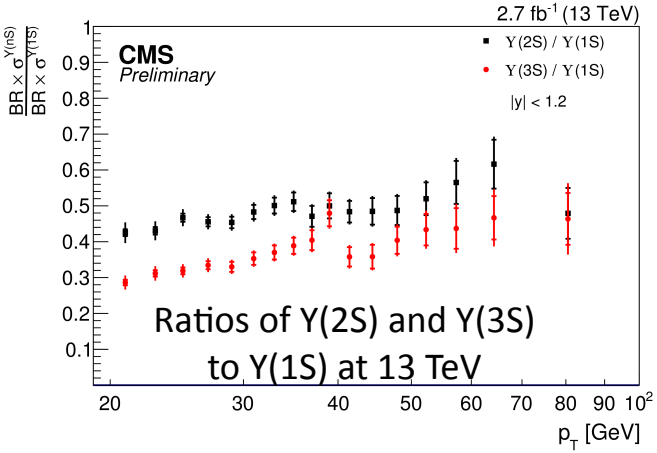
Experimental procedure:

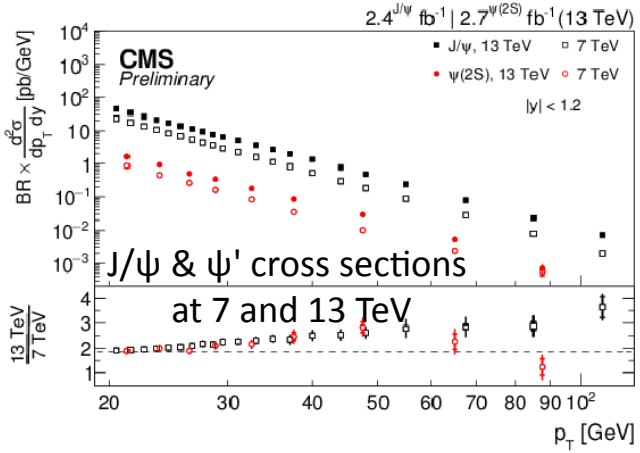
- 2015 data sample of 2.7 fb^{-1}, triggered by opposite-sign muons
- kinematical range: pT > 20 GeV, |y| < 1.2
- for charmonium, 2D fit to mass and pseudo-proper decay length separates prompt component

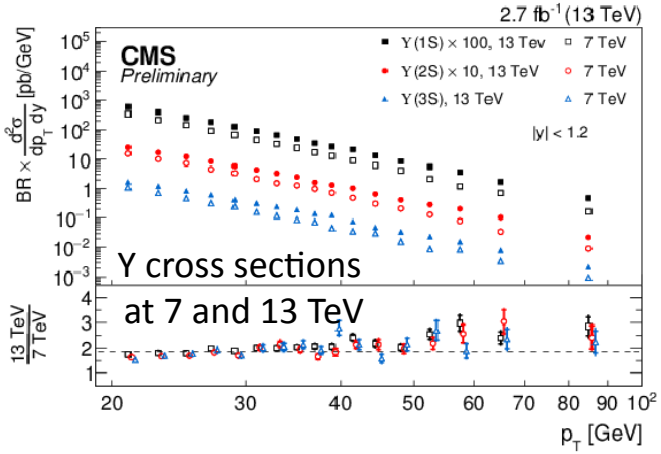












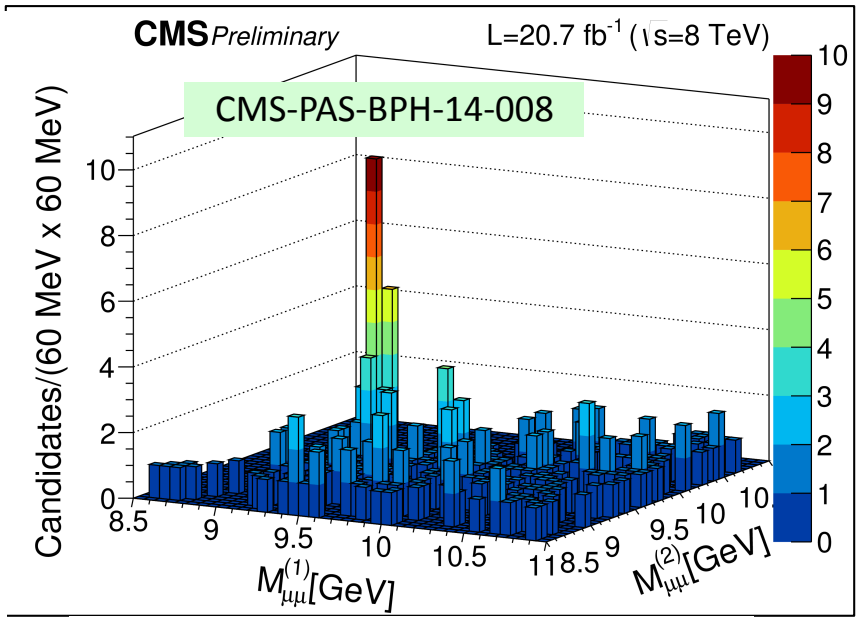
Observation of Υ(1S) pair production and Υ(nS) polarizations versus particle multiplicity

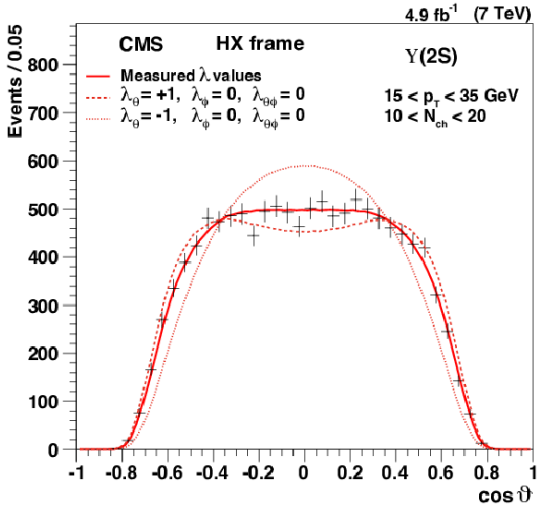
CMS recently measured the associated production of two Υ(1S) in the same event (in the decay mode $\mu^+\mu^-$) at $\sqrt{s}$ = 8 TeV

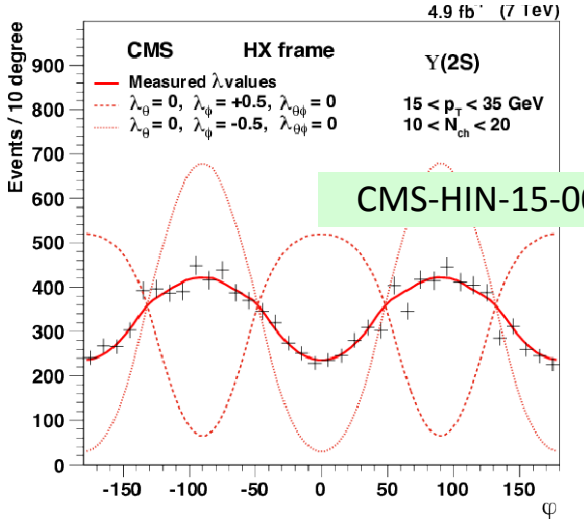
The cross-section within acceptance ($p_T(\Upsilon) < 50$ GeV and $|y(\Upsilon)| < 2$) is 68.8±12.7(stat)±7.4(syst)±2.8 (BR) pb

CMS also measured the polarizations of the Υ(1S), Υ(2S), and Υ(3S) mesons produced in pp collisions at $\sqrt{s}$ = 7 TeV as functions of the charged particle multiplicity of the event in two Υ(nS) p_T ranges

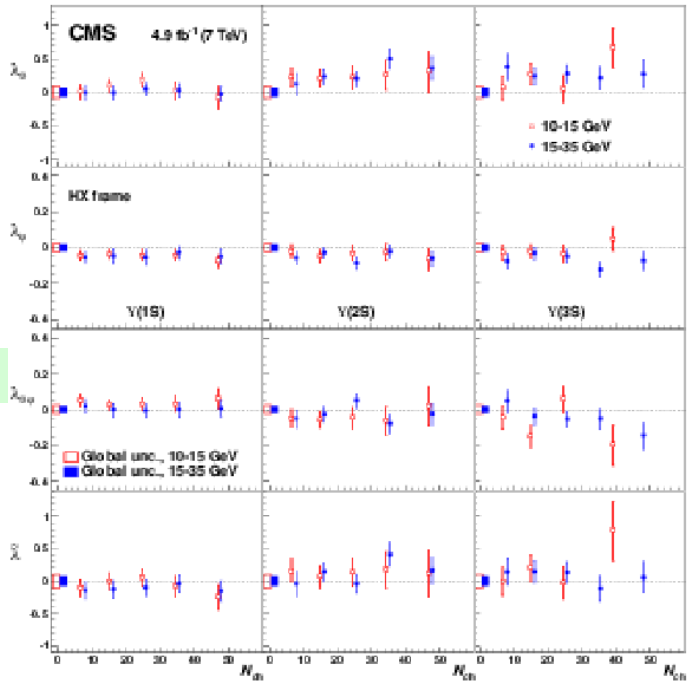
No significant dependence on event multiplicity is visible







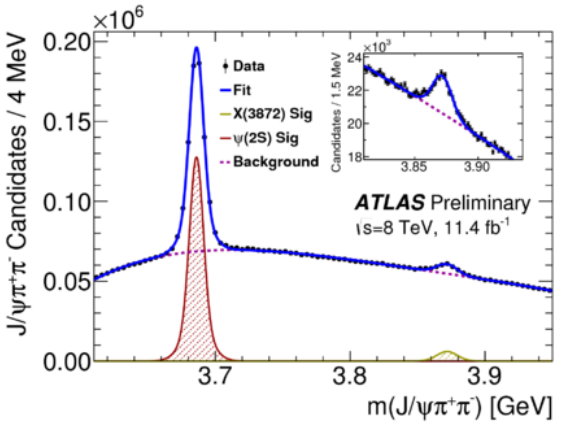
CMS-HIN-15-003



Production of ψ(2S) and X(3872)→J/ψ(→μ⁺μ⁻)π⁺π⁻

ψ(2S) and X(3872) rates extracted from the J/ψ(→μ⁺μ⁻)π⁺π⁻ spectrum

Data binned in p_T and pseudo-proper lifetime τ



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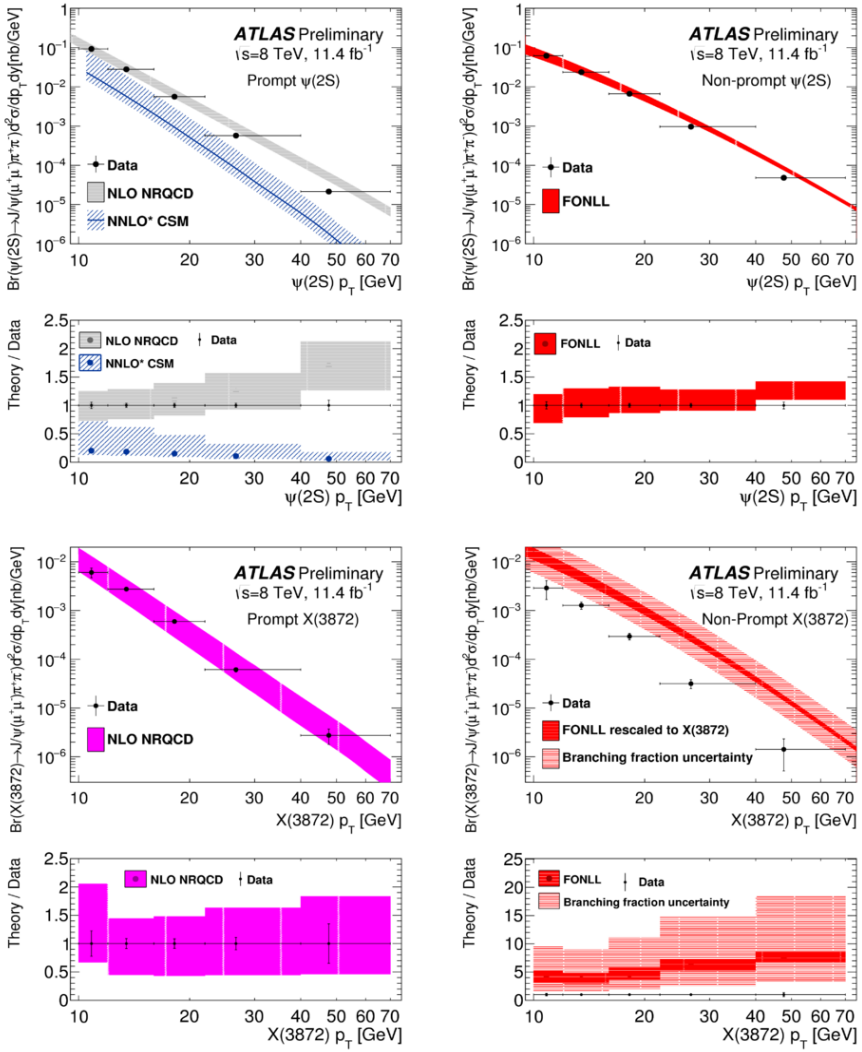
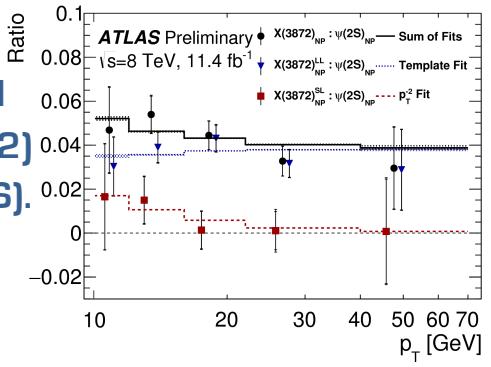


Results:

- The ψ(2S) cross section measurements show good consistency with the theoretical predictions based on NLO NRQCD for prompt and FONLL for non-prompt production
- The prompt X(3872) cross section measurement shows good agreement with theoretical predictions within the NLO NRQCD model, which considers X(3872) to be a mixture of $\chi_{c1}(2P)$ and a $D^0\overline{D}^{*0}$ molecular state, with production dominated by the $\chi_{c1}(2P)$ component
- The FONLL predictions overestimate the non-prompt production of X (3872), especially at large p_T.
- Significant short-lifetime component to non-prompt production that may be attributed to a surprisingly large $B_c \to X(3872)$ decay rate compared to $B_c \to \psi(2S)$.



Former CMS result at 7 TeV in JHEP 04 (2013) 154

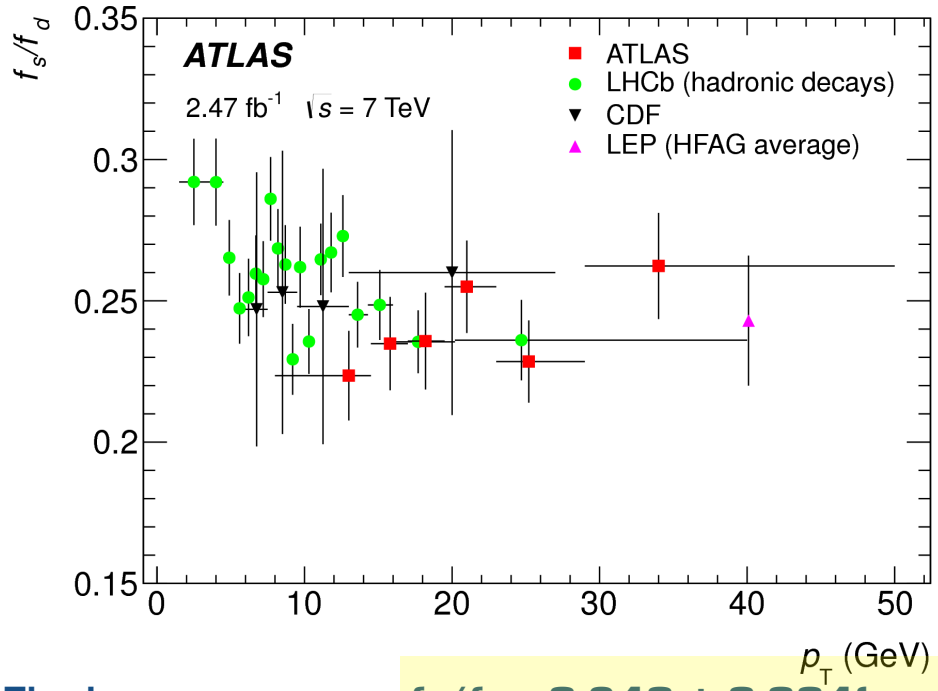
Ratio of b fragmentation fractions f_s/f_d

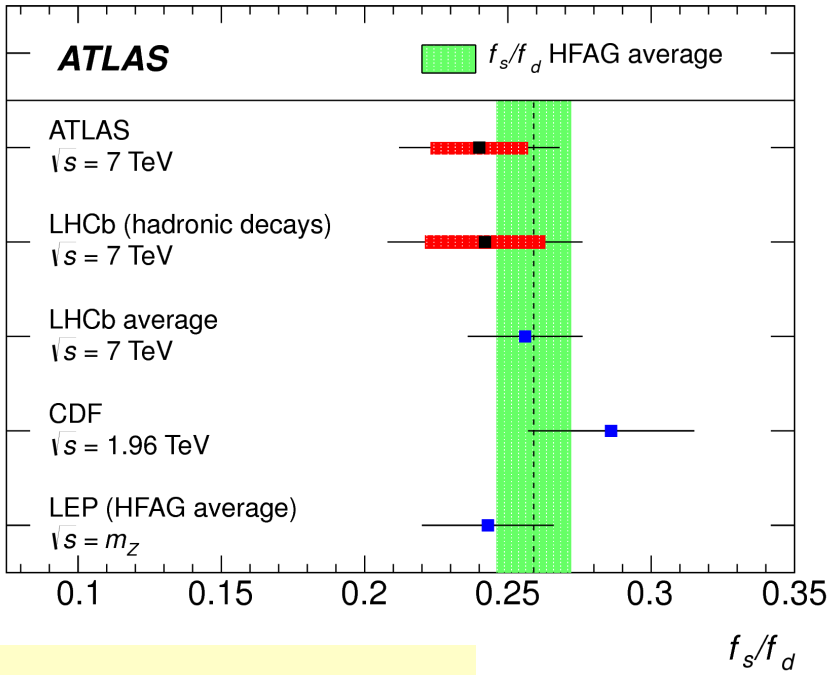
$B^0_s \to J/\psi\phi$ and $B^0_d \to J/\psi K^{*0}$ used to determine ratio of fragmentation fractions f_s/f_d

The ratio is **extracted from the measured signal yields**, converted into B meson yields:

- number of candidates from unbinned maximum likelihood fit to invariant-mass spectra
- correction for acceptance and selection efficiency ratios in the two modes

arXiv: 1507.08925





Final measurement: $f_s/f_d = 0.240 \pm 0.004(\text{stat}) \pm 0.010(\text{sys}) \pm 0.017(\text{th})$

Uses **perturbative QCD calculation of branching fractions ratio** [arXiv:1309.0313]

Measurement repeated in p_T and pseudorapidity intervals: **no visible dependence in the ATLAS range**

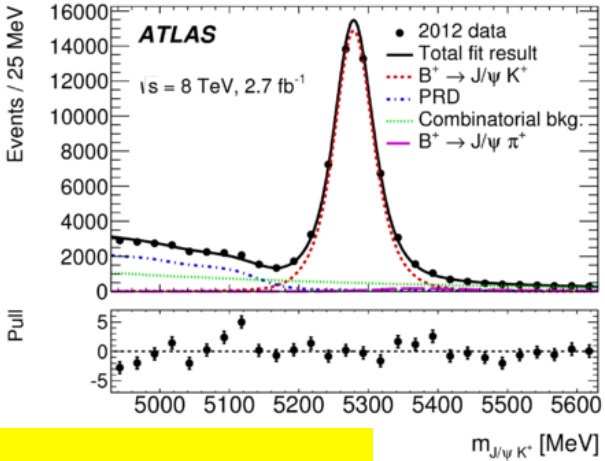
Results compared to previous experimental results (historical tension between LEP/CDF)

Good agreement with recent LHCb results, significantly improving the world average

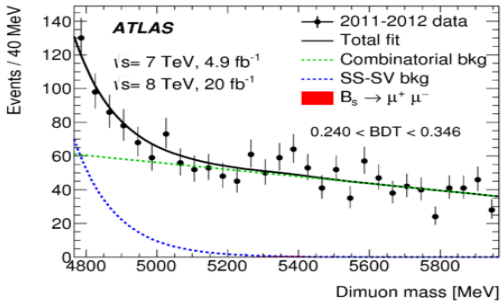
Decays of B^0_s and B^0_d into muon pairs

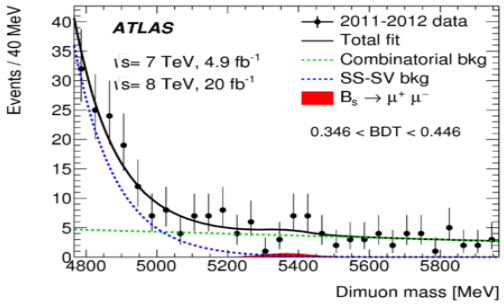
The $B^0_s \to \mu^+\mu^-$ and $B^0_d \to \mu^+\mu^-$ branching fractions are measured relative to the normalisation decay $B^+ \to J/\psi(\to\mu^+\mu^-)K^+$

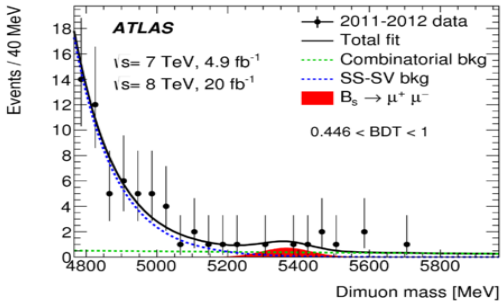
Multivariate analysis used to separate signal from background



arXiv:1604.04263

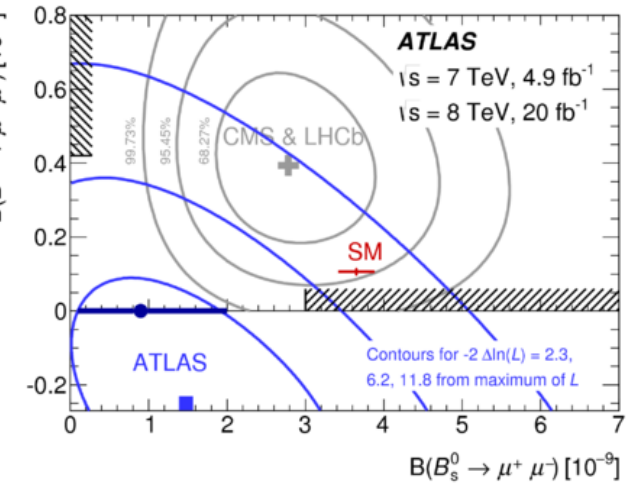






Results:

- For B^0_d an upper limit $B(B^0_d \to \mu^+\mu^-) < 4.2 \times 10^{-10}$ is placed at the 95% confidence level, based on the CLs method. The limit is compatible with the predictions based on the SM and with the combined result of the CMS and LHCb experiments.
- For B^0_s the result is $B(B^0_s \to \mu^+\mu^-) = 0.9^{+1.1}_{-0.8} \times 10^{-9}$, where the errors include both the statistical and systematic uncertainties.
- An upper limit $B(B^0_s \to \mu^+\mu^-) < 3.0 \times 10^{-9}$ at 95% CL is placed, lower than the SM prediction, and in better agreement with the measurement of CMS and LHCb.
- A p-value of 4.8% is found for the compatibility of the results with the SM prediction.



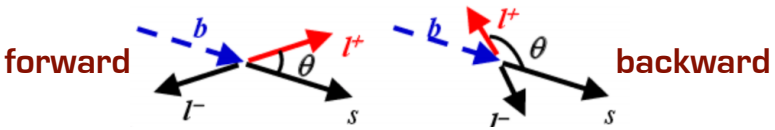
Angular analysis of $B^0 \to K^{*0}\mu^+\mu^-$

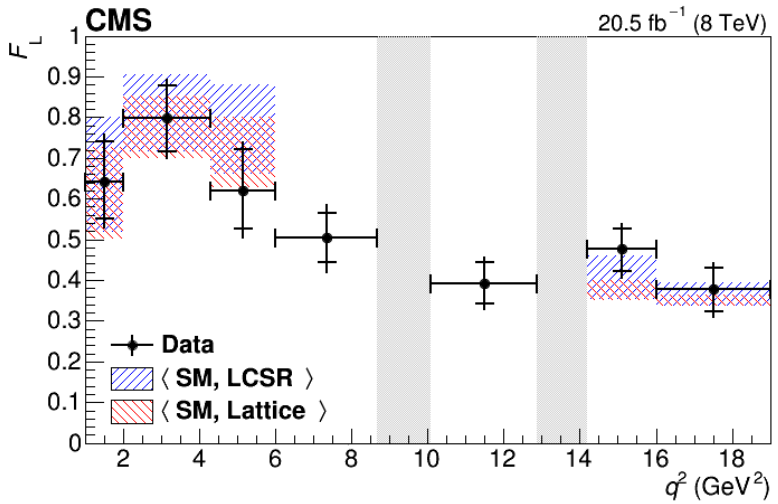
arXiv: 1507.08126

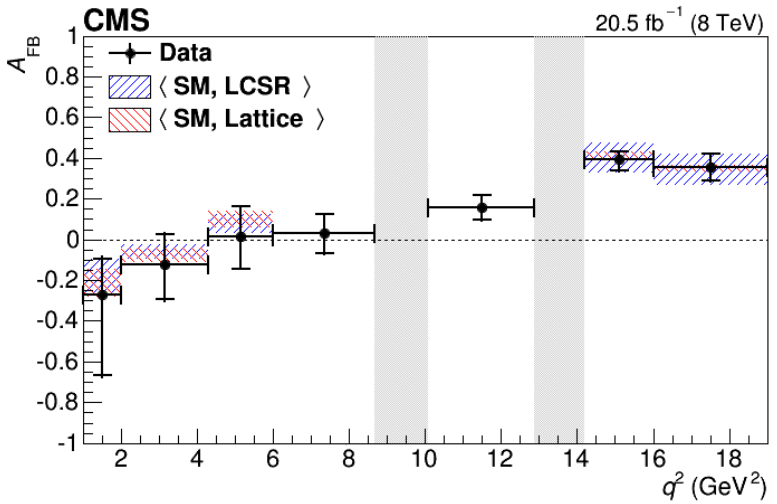
Study of angular distributions and differential branching fractions, with 8 TeV data

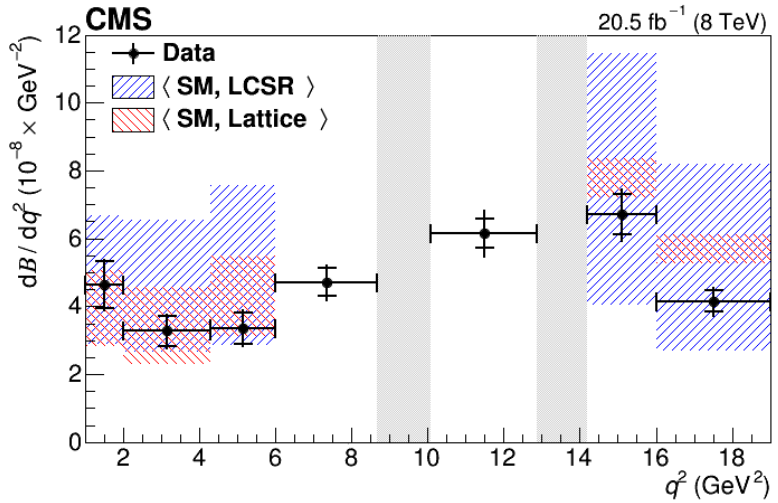
Two angular outputs: **long. polarization fraction of K^{*0}** and **fw-bk asymmetry of muons**

For each q^2 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

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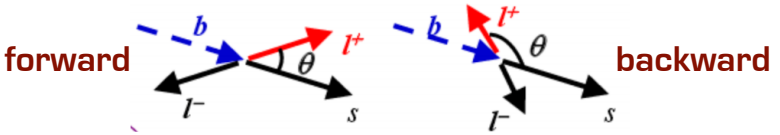

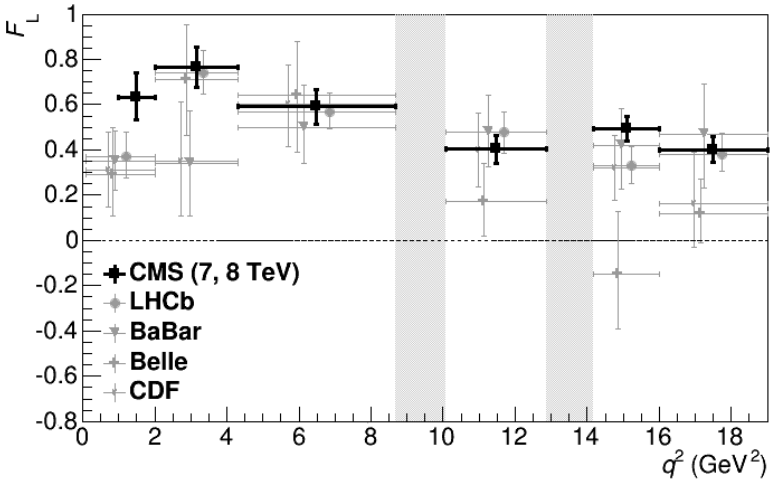

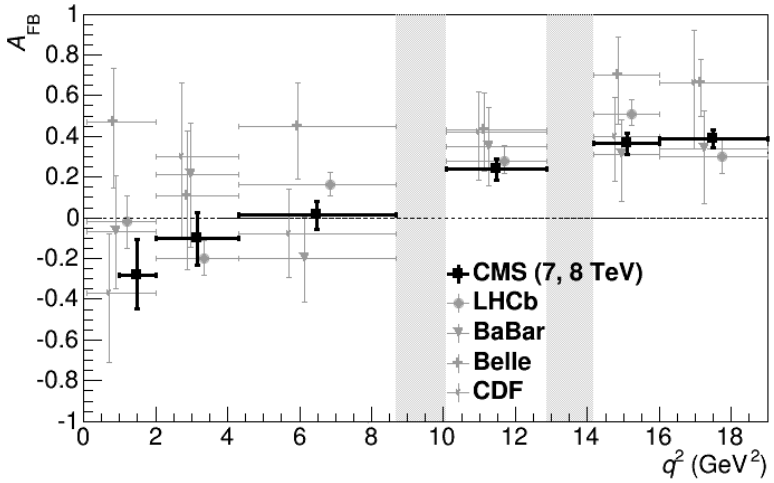

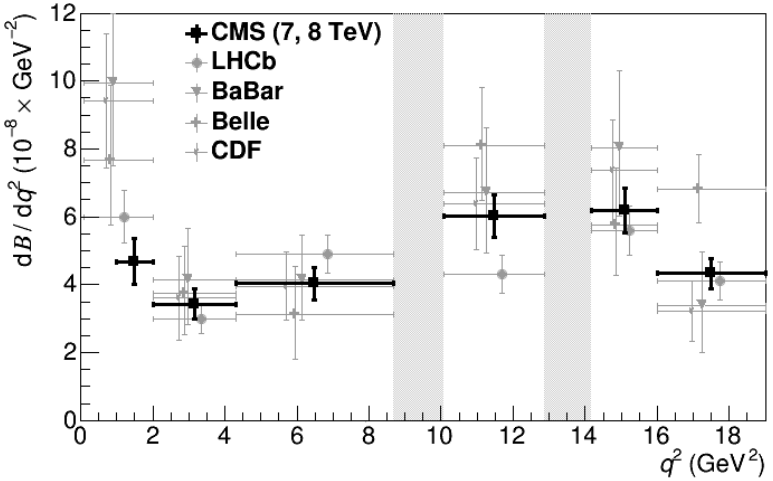

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Analysis combined with previous 7 TeV results: agree with other experiments

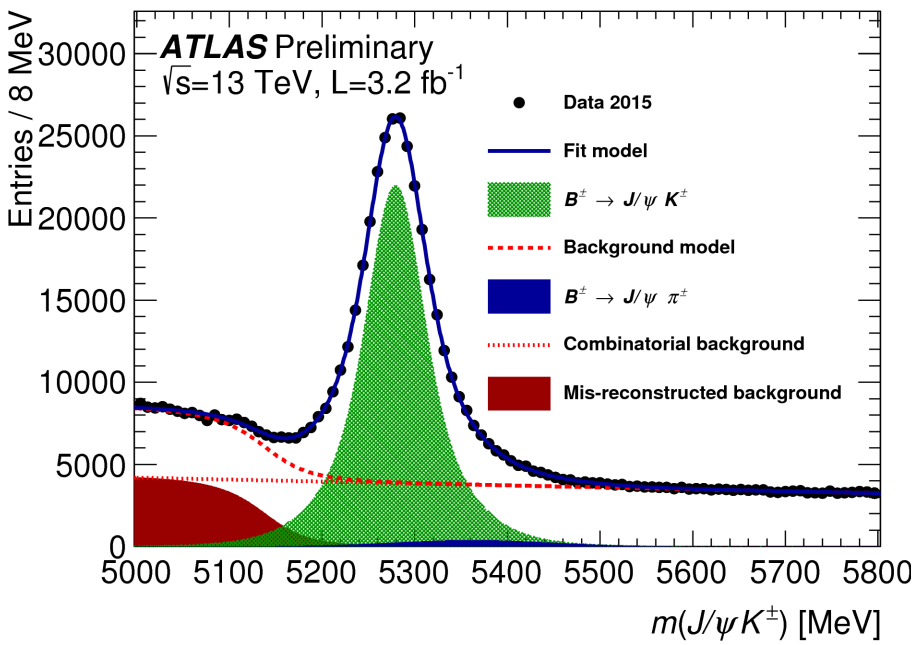
$B^{\pm}$ reconstruction in $B^{\pm} \rightarrow J/\psi K^{\pm}$ decay

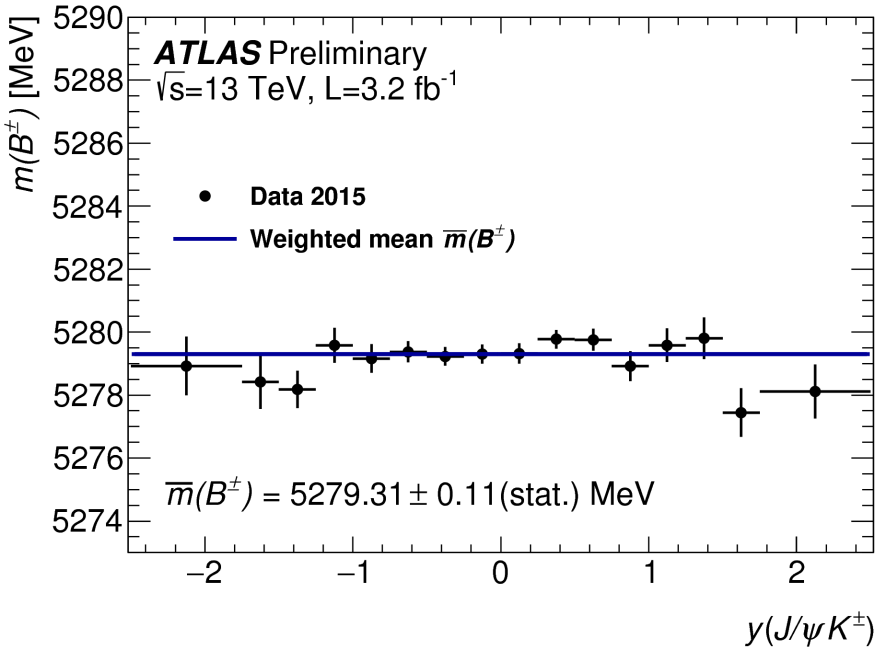
2015 dataset at 13 TeV used to reconstruct mass in rapidity intervals, **testing the momentum calibration of Inner Detector tracking**, prerequisite for Run-2 analyses

Experimental procedure:

ATLAS-CONF-2015-064

- simple track selection, requiring muon and kaon momentum above 4 and 3 GeV
- vertex selection applied to J/ψ (chi2/d.o.f. < 10) and full vertex (chi2/d.o.f. < 3)
- **B mass reconstructed from individual unbinned fits in 16 rapidity intervals**





Overall $B^{\pm}$ mass: 5279.31 ± 0.11 (stat.) ± 0.25 (syst.) MeV

Main systematics from signal model and background parametrization

Measured mass in good agreement with world average and LHCb results

Values in different rapidity bins show uniformity of reconstruction over the entire detector

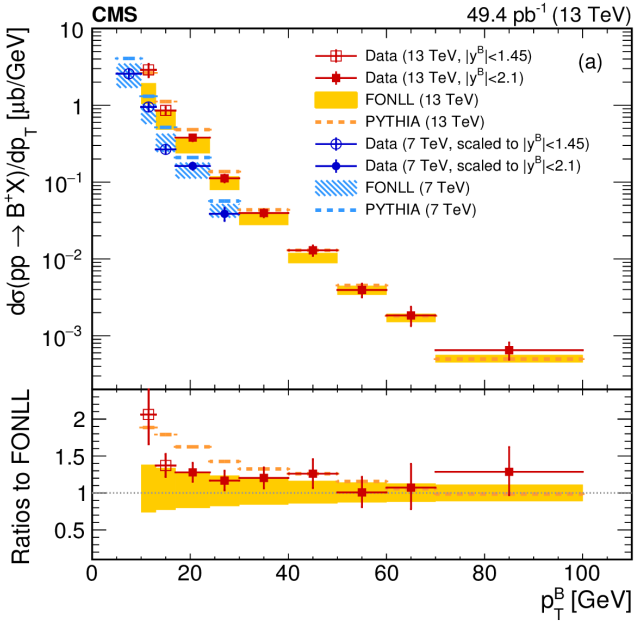
B^+ production cross-section at 13 TeV

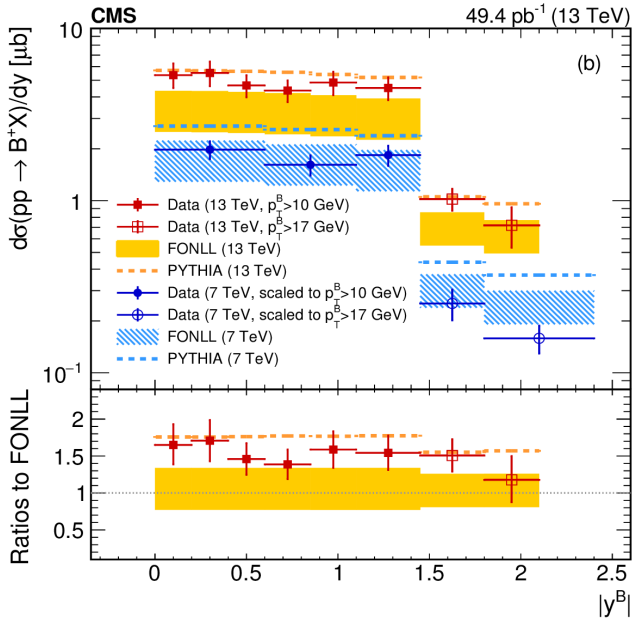
Measurement of exclusive decay $B^+ \to J/\psi K^+$, with $J/\psi \to \mu^+\mu^-$

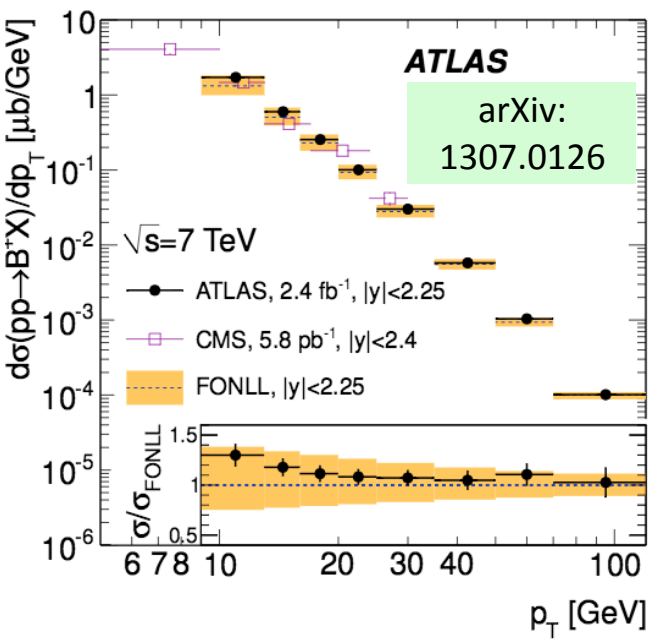
arXiv:1609.00873

Experimental procedure:

- signal yield extracted with extended unbinned maximum likelihood fit to the invariant mass distribution of B^+ candidates, performed in several momentum and rapidity bins
- corrections for acceptance and efficiencies, to extract differential cross sections







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

Results presented along with previous 7 TeV measurement

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

Results at 7 TeV show very good agreement with ATLAS

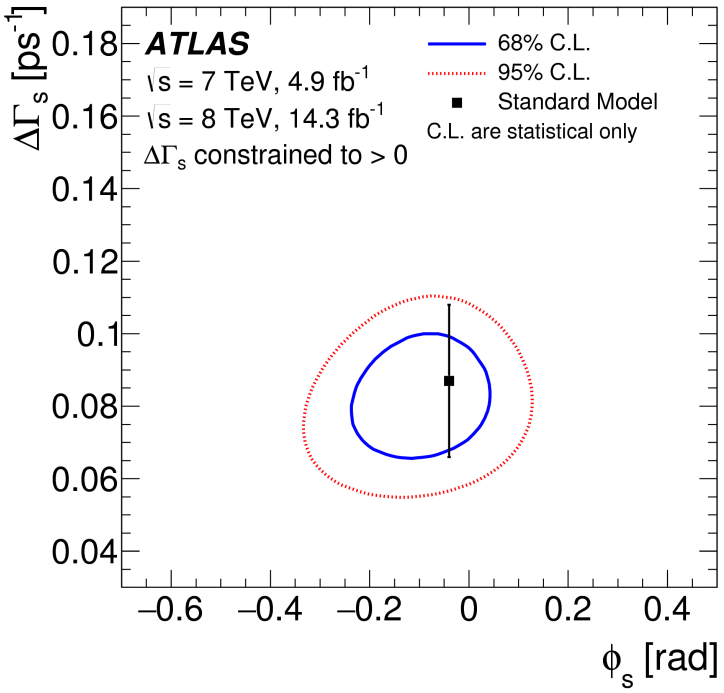
CP violating phase ϕ_s and decay width difference $\Delta\Gamma_s$ in Bs -> J/ψ φ decays

Very complex analyses: just a snapshot here!

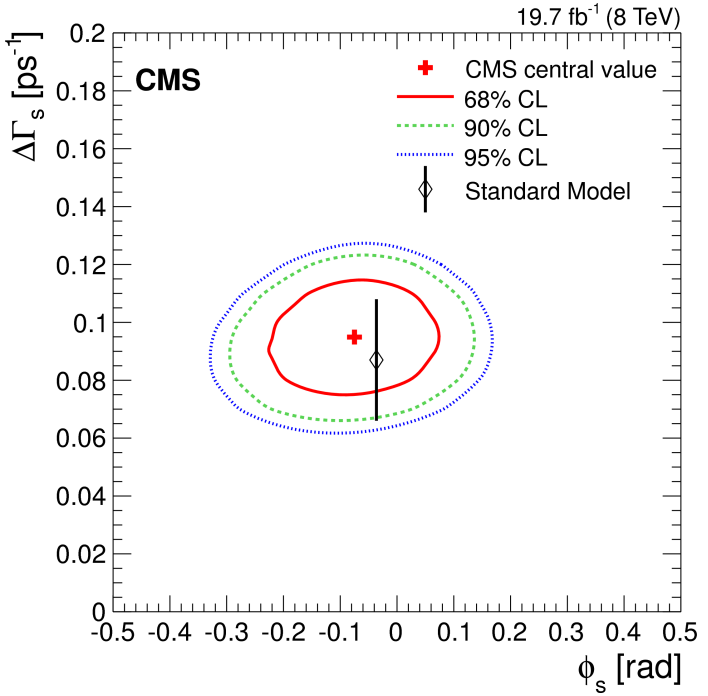
arXiv: 1601.03297
arXiv: 1507.07527

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



$$\phi_s = -0.098 \pm 0.084\,(\text{stat.}) \pm 0.040\,(\text{syst.})\ \text{rad}$$
$$\Delta\Gamma_s = 0.083 \pm 0.011\,(\text{stat.}) \pm 0.007\,(\text{syst.})\ \text{ps}^{-1}$$



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

The two experiments are compatible; similar uncertainties

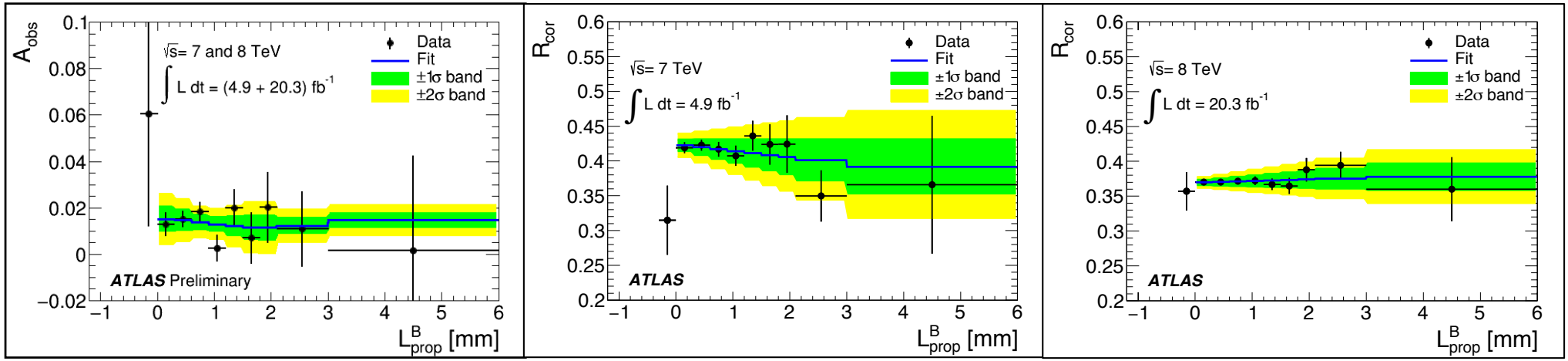
Compatible with SM and LHCb (most accurate single measurement) $\phi_s = -0.010 \pm 0.039\,\text{rad}.$

Measurement of the B_d width difference $\Delta\Gamma_d/\Gamma_d$ using B_d -> J/ψ K_s and B_d -> J/ψ K^{*0} decays

JHEP 06 (2016) 081

Essential ingredients of this measurement:

- Proper decay length (L_{prop}) distributions of $B_d \to J/\psi\, K_s$ and $B_d \to J/\psi\, K^{*0}$ decays
  - Proper decay length is equivalent to proper decay time: $L_{prop} = c\,t$
  - It is a three-dimensional decay length divided by the γ factor of B_d meson
- Production asymmetry of B_d meson
- Ratio of reconstruction efficiencies of $B_d \to J/\psi\, K_s$ and $B_d \to J/\psi\, K^{*0}$ decays



- Result of this analysis:
- The ATLAS result is consistent with other measurements of $\Delta\Gamma_d$:
  - Currently it is the most precise single measurement
- It is consistent with the SM prediction:

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

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

$$\Delta\Gamma_d/\Gamma_d = (+1.7 \pm 1.8 \pm 1.1) \times 10^{-2} \quad \text{(Belle)}$$

$$\Delta\Gamma_d/\Gamma_d = (+0.8 \pm 3.7 \pm 1.8) \times 10^{-2} \quad \text{(Babar)}$$

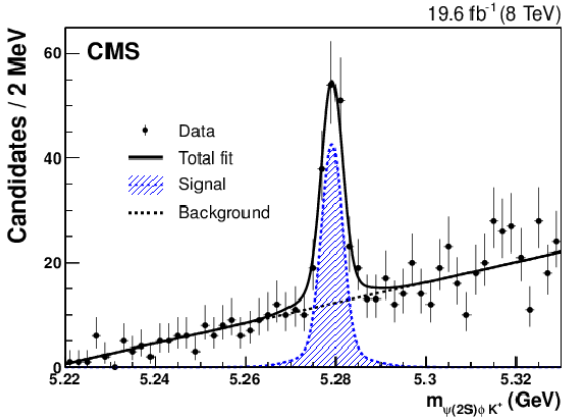
$$\Delta\Gamma_d/\Gamma_d = (0.42 \pm 0.08) \times 10^{-2} \quad \text{(SM)}$$

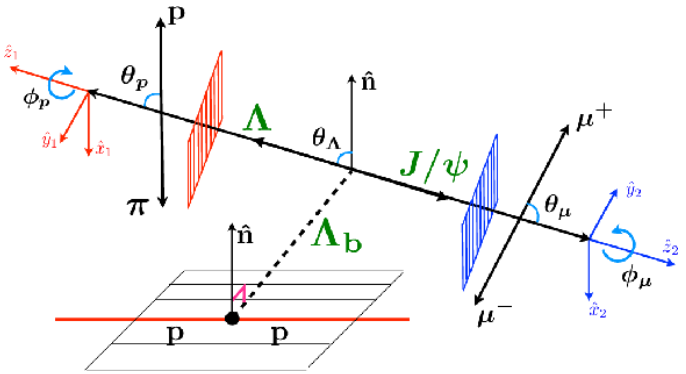
Measurement of the decay $B^+ \to \psi(2S)\phi(1020)K^+$ and of the Λ_b polarization and angular parameters of the decay $\Lambda_b \to J/\psi(\mu^+\mu^-)\Lambda_0(p\pi^-)$

arXiv:1607.02638

CMS recently obserbed the decay $B^+ \to \psi(2S)\phi K^+$ and measured its branching fraction by normalising it to $B^+ \to \psi(2S)K^+$:

$(4.0 \pm 0.4\,(stat) \pm 0.6\,(syst) \pm 0.2\,(B)) \times 10^{-6}$

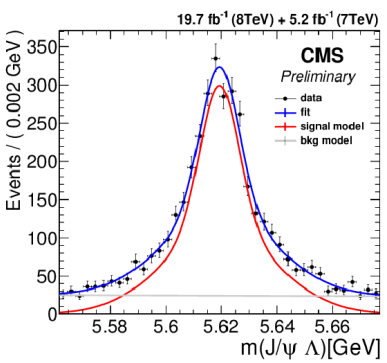


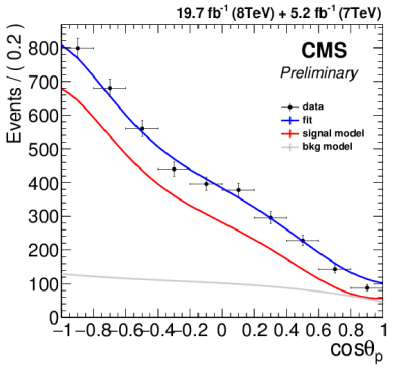


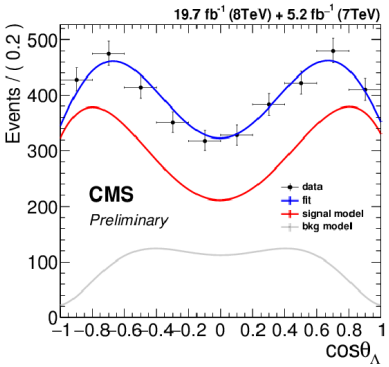
Complete angular analysis of the decay $\Lambda_b \to J/\psi(\mu^+\mu^-)\Lambda_0(p\pi^-)$

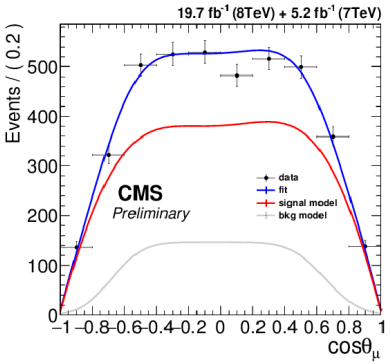
The result of the Λ_b polarization is compatible with predictions from pQCD calculations for a polarization of ~10% at 1.5σ and with earlier ATLAS and LHCb measurements

$$P = 0.00 \pm 0.06(stat) \pm 0.02(syst),$$
$$\alpha_1 = 0.12 \pm 0.13(stat) \pm 0.06(syst),$$
$$\alpha_2 = -0.93 \pm 0.04(stat) \pm 0.04(syst)$$
$$\gamma_0 = -0.46 \pm 0.07(stat) \pm 0.04(syst)$$









CMS-PAS-BPH-15-002

CONCLUSIONS

Many results based on 7 and 8 TeV data finalized by ATLAS and CMS during the long shutdown and 2015

In the meanwhile, LHC operations restarted and first Run 2 results with data recorded at 13 TeV have been presented

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 flavor results useful for combination and comparison with other experiments

Actually much more material than what can fit in this talk!

ATLAS: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/BPhysPublicResults
CMS: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsBPH