B-physics in ATLAS and CMS

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on behalf of the ATLAS & CMS Collaborations

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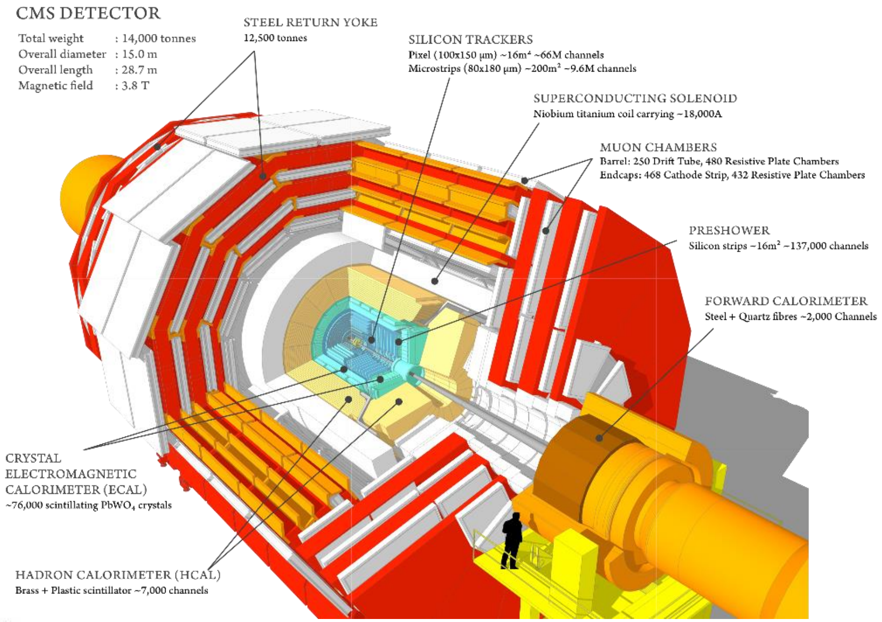
ILHC 2019, ICTP

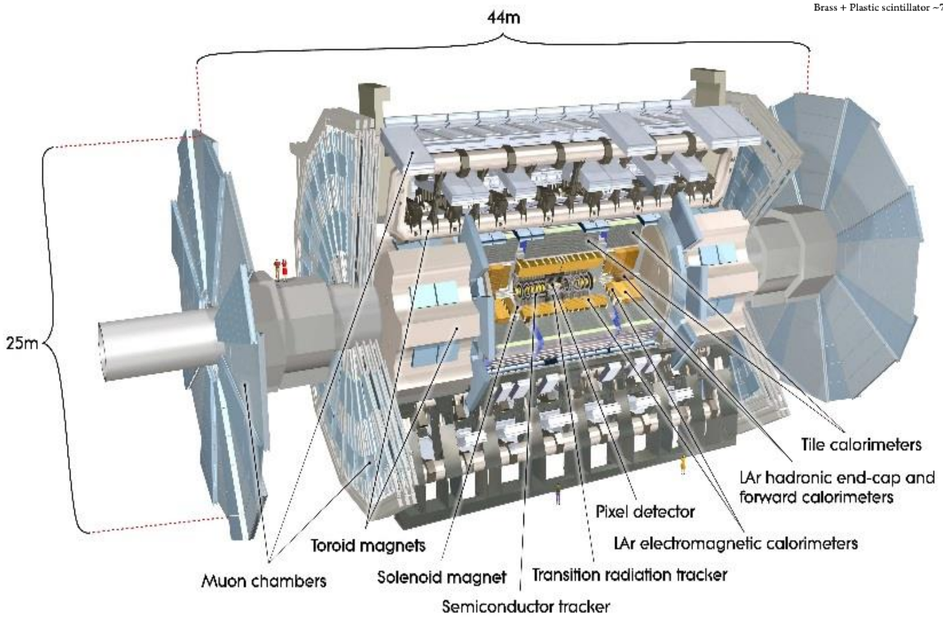
What does B-physics cover?

- B-physics (and *light states*) scope:
  - Test of QCD-based prediction: cross section, spectroscopy, etc.
    - **Quarkonia production and decay**
    - J/ψ+J/ψ, J/ψ + W, J/ψ + Z associated production (double parton scattering)
    - **Spectroscopy (**χ_{b3P}, X_c, X_b searches, **B_c excited states**)
    - Exotic hadrons: Tetraquark ($B_S\pi$), pentaquark (J/ψp) searches
    - Polarisation, decays asymmetries studies (Λ_b, Λ, ***$b\bar{b}$* correlations**)
  - Test of EW physics, or search for new physics is areas where the SM predicts rare processes or small effects
    - **Rare decay of Bs,d → μμ,**
    - **ϕ_S in $B_S \to J/\psi\phi$**
    - Flavour anomalies (angular correlation in $B_d \to K^*\mu\mu$, R(K*))
    - **τ → 3μ**

ATLAS & CMS detectors

- Multi-purpose detectors
- Similar design:
  - Inner Tracking system
  - Calorimeters
  - Muon system





- Different sub-detectors technologies
- Stronger solenoidal magnetic field in CMS
- Wider area covered by ATLAS muon system

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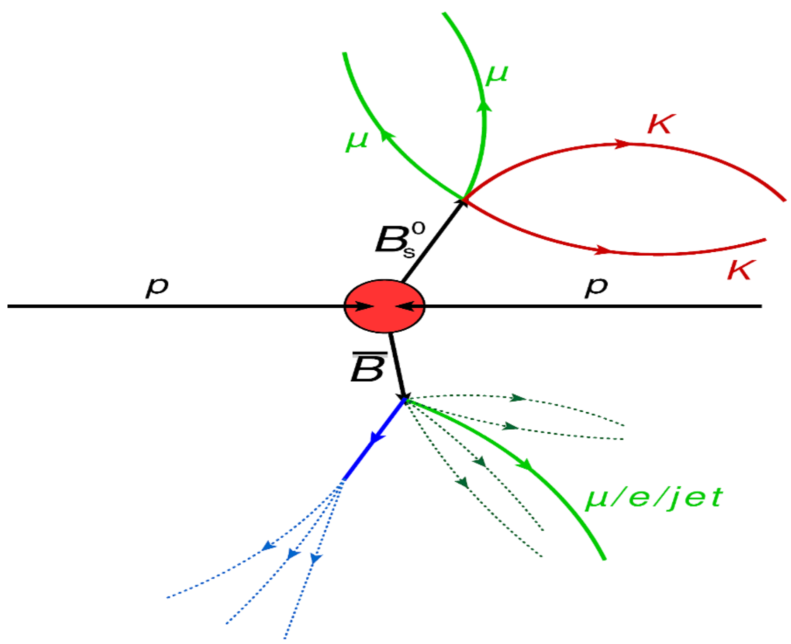
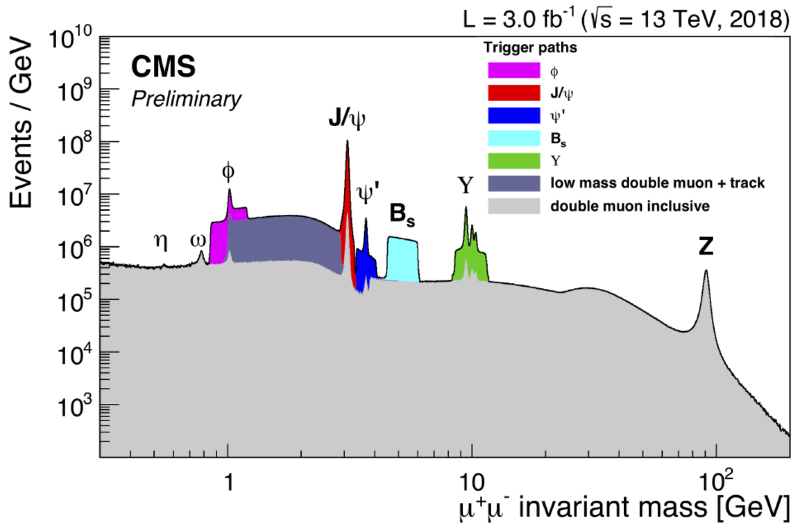
B-physics signatures

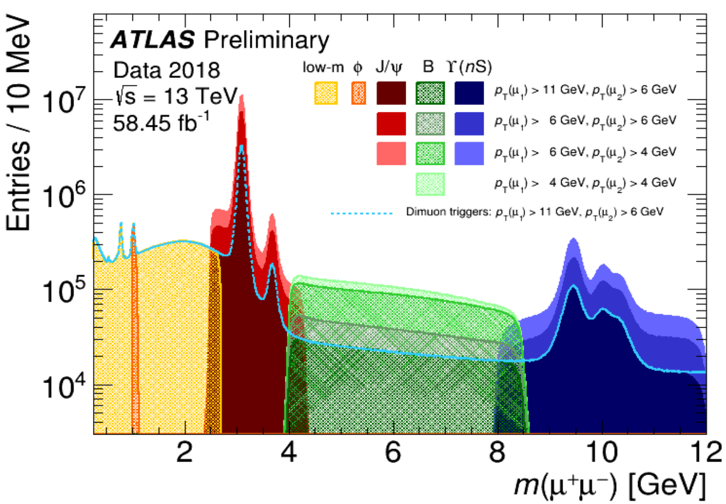
- B-physics signatures at hadron colliders are mainly made by:
  - Low transverse momentum (P_T) muons → Tracking system + muon system
  - Tracks in the Inner detector → Tracking system
  - Reconstruction of secondary vertices → Tracking system
  - Rarely photons/electrons → Electromagnetic calorimeter



Triggering B-physics…

- Both experiments have multi-level triggers
  - Level-1 → hardware muon identification
  - High- level → Complete event reconstruction using also ID information
- Trigger is complicated due to low thresholds in muon P_T → Incompatible with bandwidth constraints at high luminosity
- CMS can go lower in muon P_T for the stronger magnetic field
- ATLAS can use topological information (m(μμ), ΔR(μμ)) to reduce the bandwidth acting on kinematic of the di-muon system





Quarkonia and heavy-flavor production measurements

ATLAS

Eur. Phys. J. C 78 (2018) 171

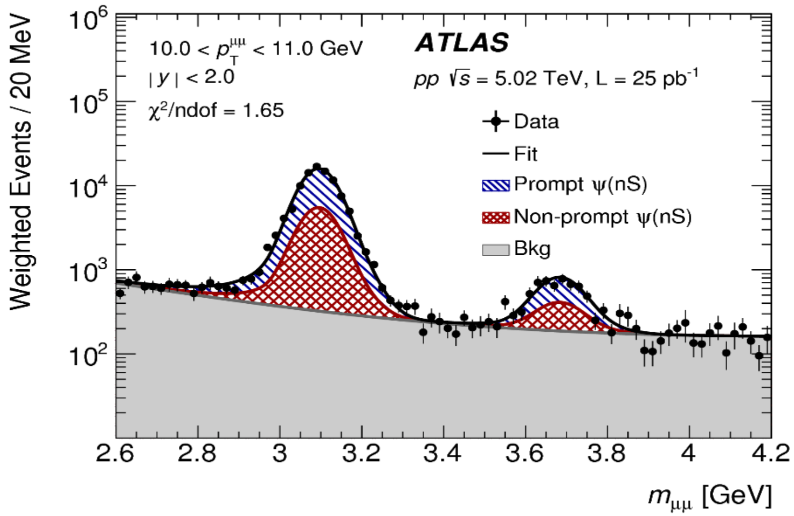
- Production of J/ψ, ψ(2S), and Υ(nS) [n = 1,2,3] in p-Pb collisions is compared to production in p-p collisions
- Intent: better understanding of the impact of normal (cold) nuclear matter on suppression of quarkonium production in an environment where quark-gluon-plasma (QGP) is not expected.
- Measurements with 25 pb^{-1} (28 pb^{-1}) $\sqrt{s}$=5.02 TeV per nucleon in pp (p-Pb) collisions
- Selection: ≥ 1 primary vertex with ≥ 4 tracks, at least 2 muons with a common vertex
- Muons within pseudorapidity $|\eta| \leq 2.4$
- Two muons with opposite charge are quarkonium candidates

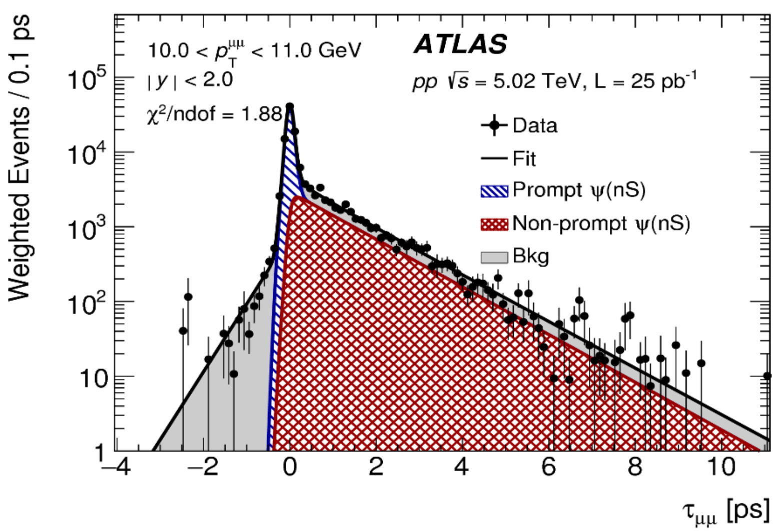
$$\frac{d^2\sigma_{O(nS)}}{dp_T dy^*} \times B(O(nS) \rightarrow \mu^+\mu^-) = \frac{N_{O(nS)}}{\Delta p_T \times \Delta y \times L \times \varepsilon}$$

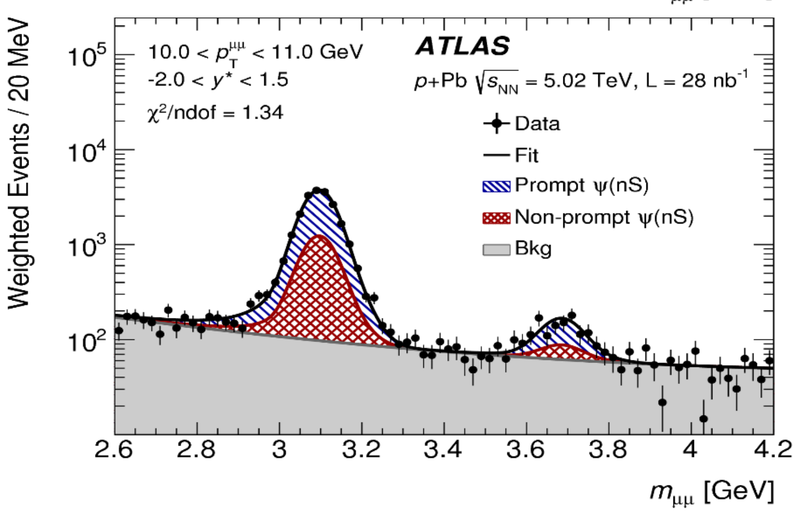
(where y* is shifted by 0.465 wrt laboratory frame in p-Pb collisions)

ATLAS

- Prompt and non-prompt J/ψ and ψ(2S) reconstruction
  - Simultaneous fit in mass and pseudo-proper lifetime $\tau_{\mu\mu}$



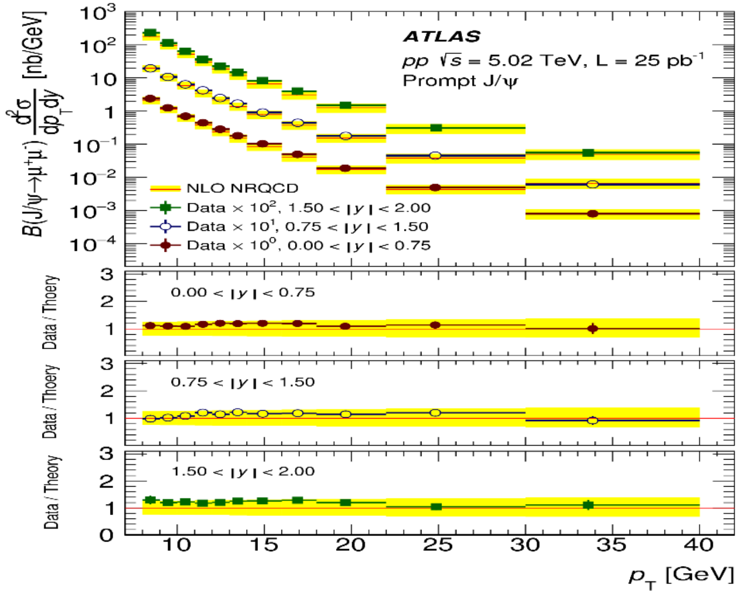


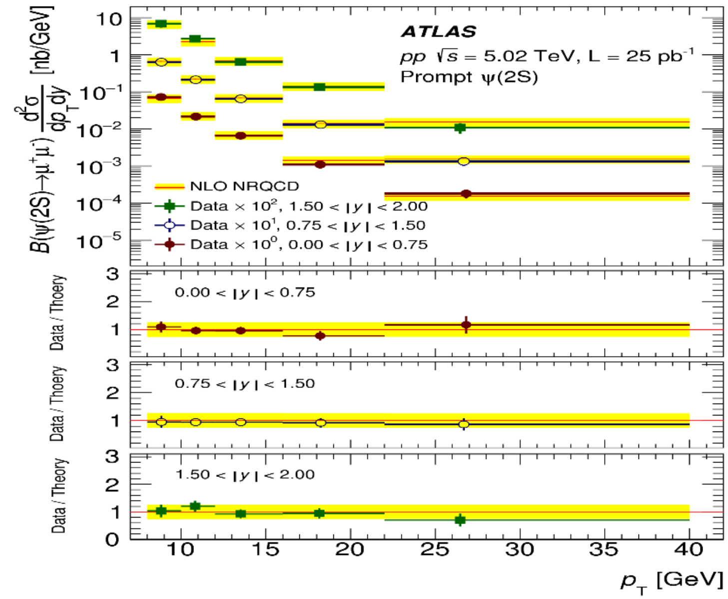


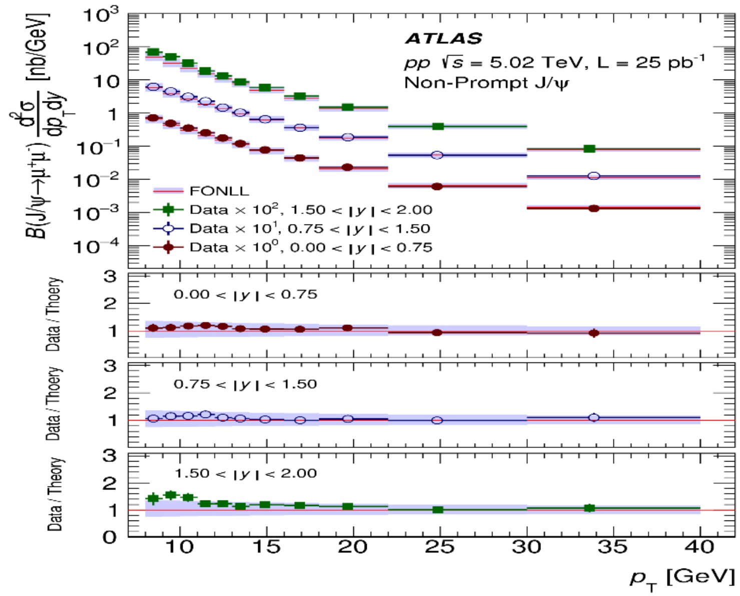
- Fit data in bins of P_T, y and centrality using pd.f. for $m_{\mu\mu}$ and $\tau_{\mu\mu}$
- Significant J/ψ and ψ(2S) suppression for p-Pb collisions
- Higher suppression for ψ(2S)

Charmonia x-sec in pp collisions

ATLAS





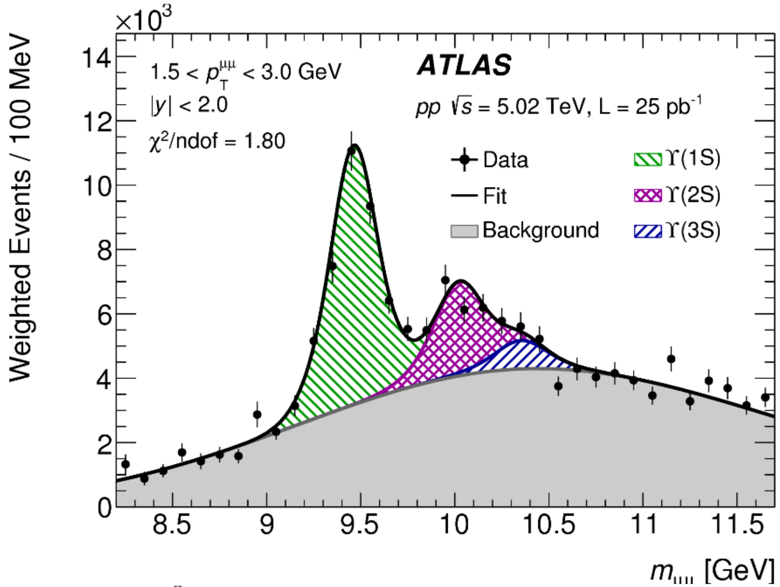


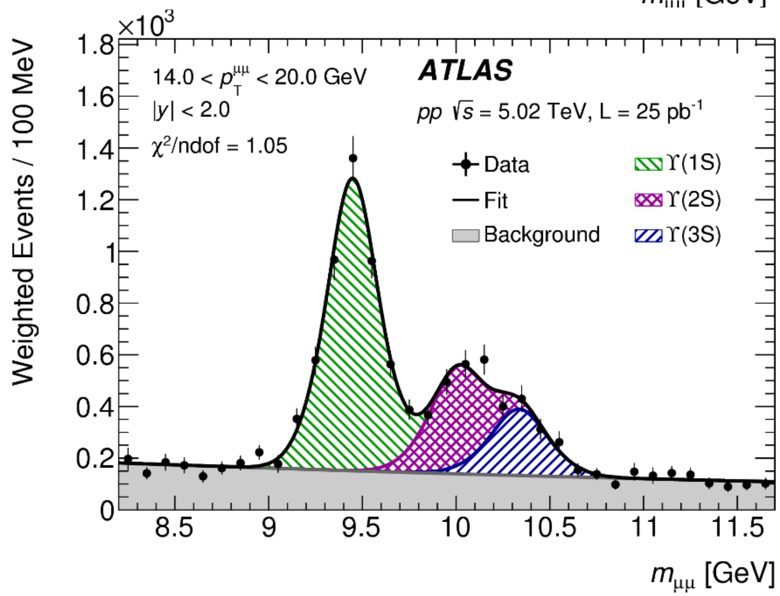
- Prompt and non-prompt charmonia cross-sections extracted
- Compared with FONLL and NRQCD predictions
  - Overall good agreement

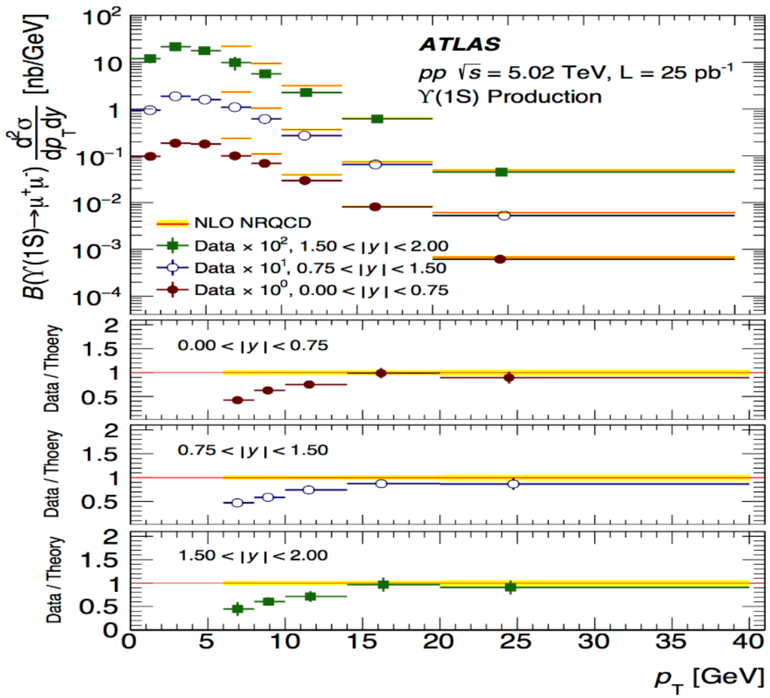
Υ(nS) production in pp collisions

- Similar analysis for bottomonia Υ(nS) (only in $m_{\mu\mu}$)

ATLAS







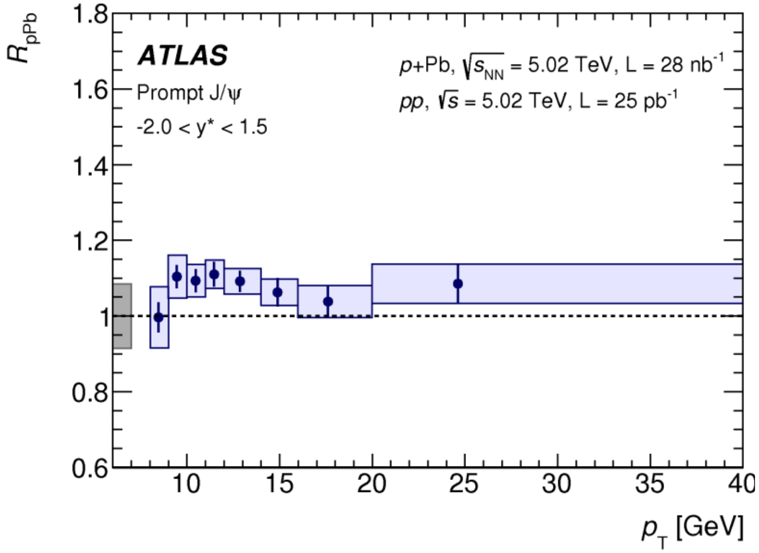
- Fit data in bins of P_T, and y in $m_{\mu\mu}$
- Compared with NRQCD predictions
  - Significant disagreement in the lower part of the P_T spectrum

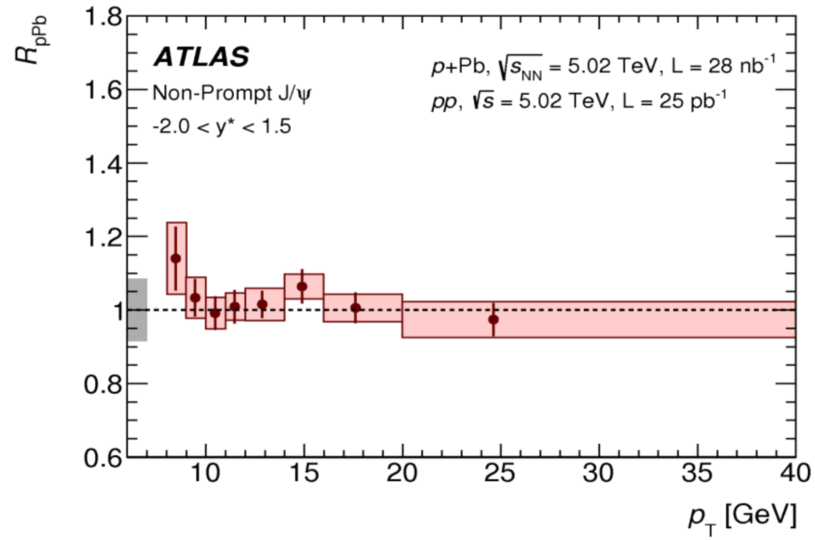
Nuclear modification factors R

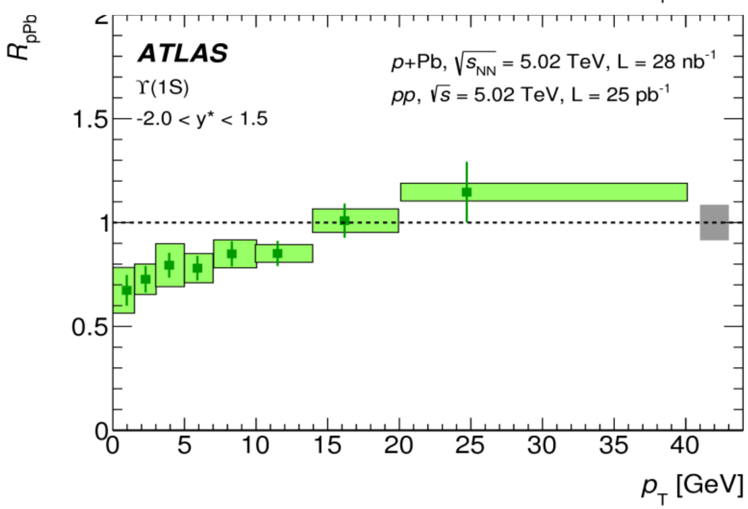
- Nuclear modification factors R_{pPb}

$$R_{pPb} = \frac{1}{208} \frac{\sigma^{O(nS)}_{p+Pb}}{\sigma^{O(nS)}_{p+p}}$$

ATLAS

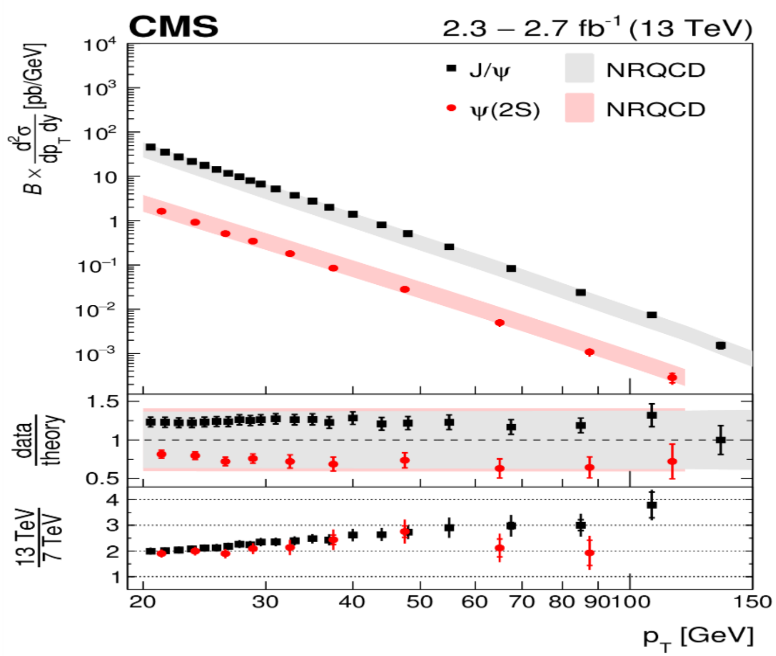


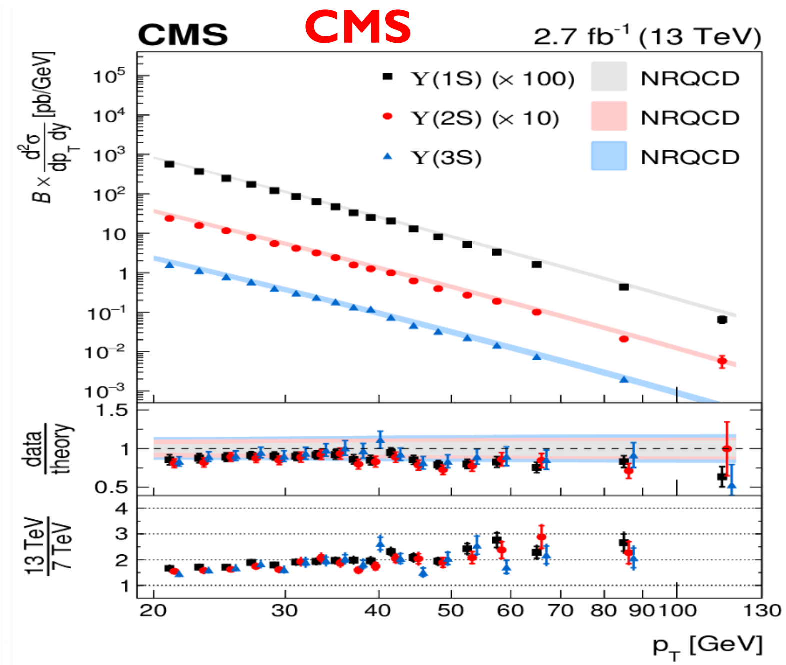


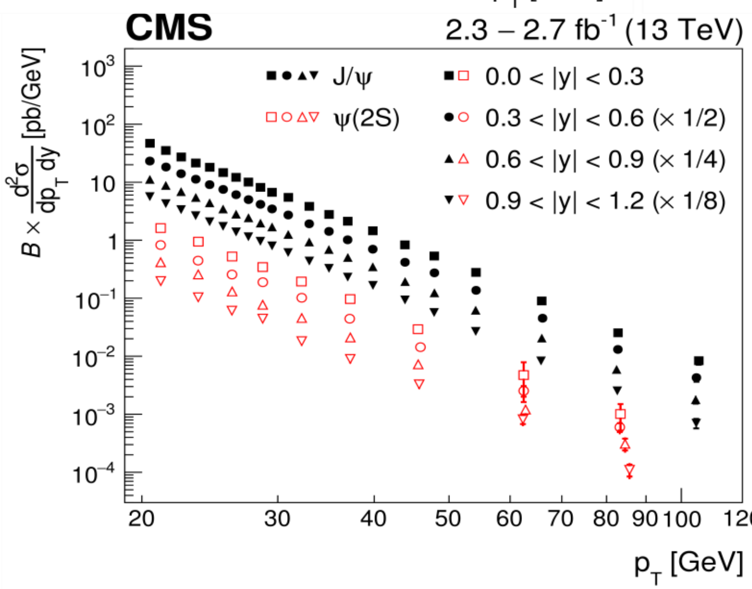


- R_{pPb} basically consistent with unity for both prompt and non-prompt charmonia
- Significant disagreement in the lower part of the Y(nS) P_T spectrum

Quarkonia x-sec in pp collisions







- Prompt and non-prompt charmonia and Υ(nS) cross-sections extracted
- Compared with FONLL and NRQCD predictions
  - Overall good agreement
  - In low-PT Υ(nS) region data below NRQCD prediction (but compatible)

J/ψ production in jets

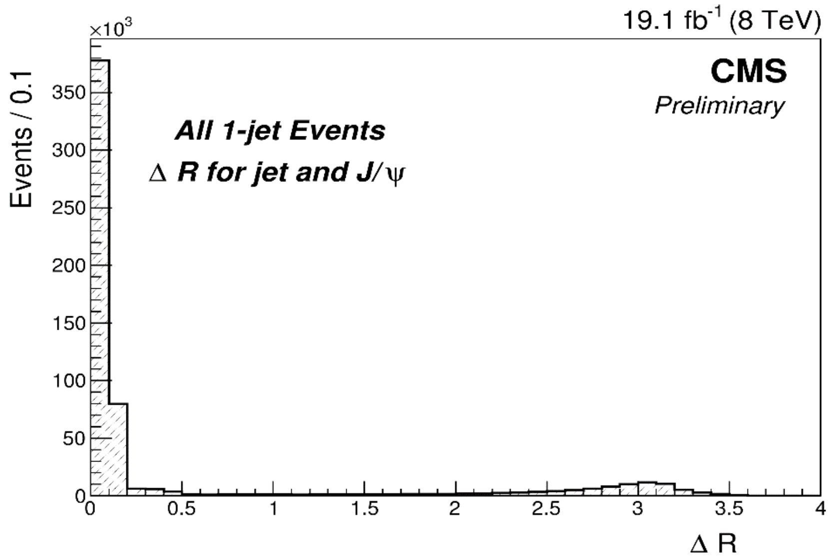
CMS CMS-PAS-BPH-15-003

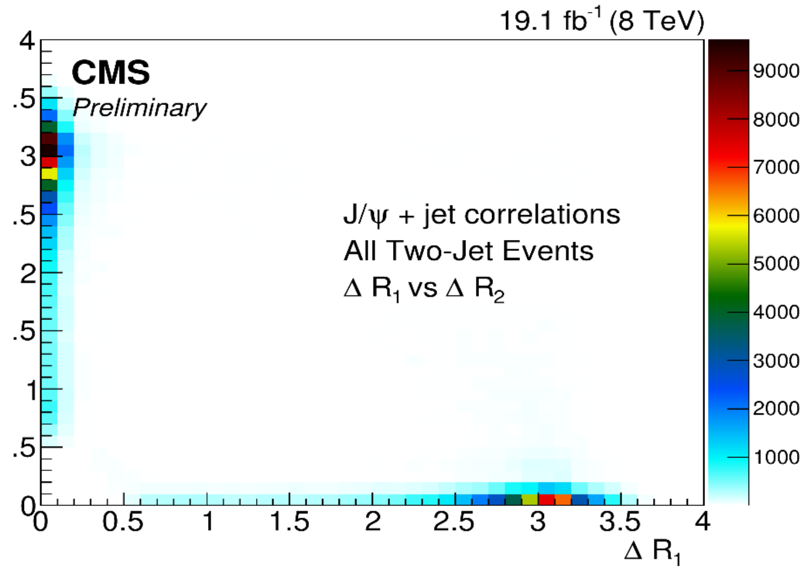
- Measurement of J/ψ–jet association is a test of the role of jet fragmentation in quarkonium production with Run1 data (19.1 fb-1, $\sqrt{s}$ = 8 TeV)
- Theoretically described in Fragmenting-Jet Function(FJF) approach.
- Crucial variables to describe J/ψ kinematics are: $\mathbf{E_{jet}}$ and $\mathbf{z = E_{J/\psi}/E_{jet}}$
- Using NRQCD, the theoretical predictions are based on LDMEs with different amplitudes that dominate depending on jet rapidity regions
  - At large rapidities charm fragmentation more prominent
  - At small rapidities gluon fragmentation dominant
- Goal is to measure the double differential cross-section as a function of **z** and $\mathbf{E_{jet}}$ to disentagle the various LDME contributions

J/ψ production in jets

CMS

- $E(J/\psi) > 15$ GeV, $|y| < 1$.
- Anti-kT jets with R=0.5 and $P_T > 25$ GeV, $|\eta| < 1$
- J/ψ associated to a given jet if $\Delta R < 0.5$
- Investigated region: **$0.3 < z < 0.8$** where FJF predictions available
- Event with one or two jets are considered





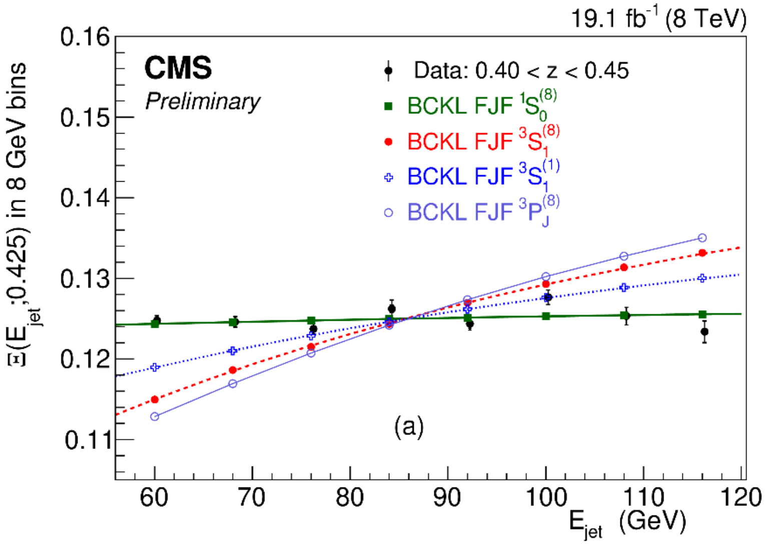
- Once J/ψ - jet association is made, compute this:

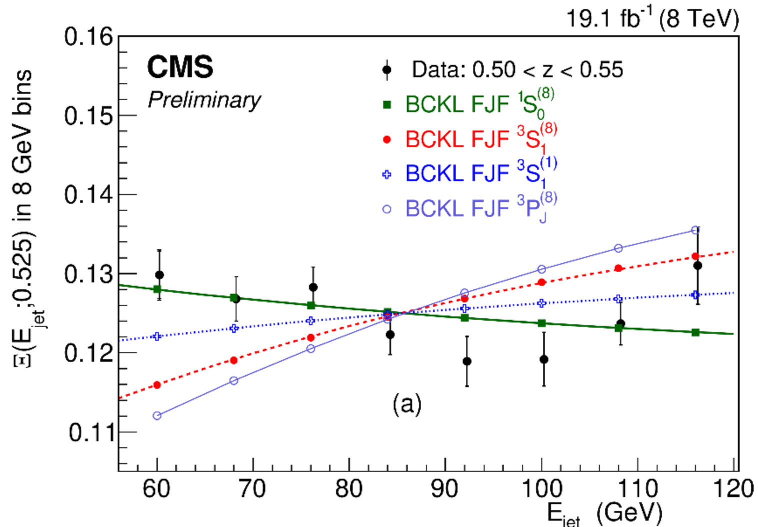
$$\Xi(E,z) = \frac{1}{N(z)} \frac{N(E,z)}{\int_{0.3}^{0.8} N(E,z')dz'}$$

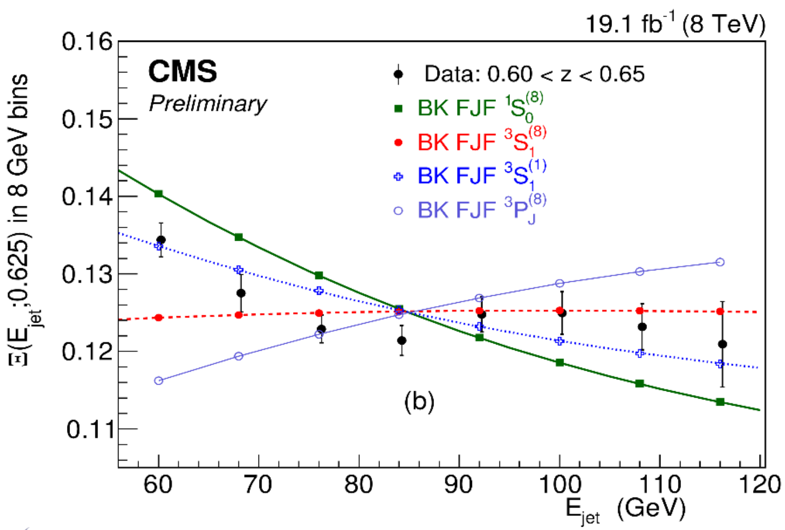
J/ψ production in jets

CMS

- Results in slices of **z** and **E_{jet}** after Bayesian iterative unfolding to correct for jet energy resolution effects







- FJF predictions for gluon jet fragmentation in the central region describe well data
- Only one LDME term $^1S_0^{(8)}$ using BCKL parameters describes the data for the three **z** range considered
- Jet fragmentation can account for > 80% of J/ψ production

$b\bar{b}$ production measurement: why?

ATLAS

JHEP 11 (2017) 62

- Factorization of QCD calculations into parton distribution functions, hard matrix elements, and soft parton shower components depend on the heavy (b) quark mass
  - Several schemes are possible for inclusion of the heavy quark masses
  - Previous analyses of heavy flavor production highlighted disagreements *among* theoretical predictions and *between* predictions and data.
- The region of small-angle production is especially sensitive to details of the calculations but has previously been only loosely constrained by data.
- Searches for Higgs produced in association with a vector boson (VH) and decaying to $b\bar{b}$ rely on the modeling of the V+$b\bar{b}$ background

INFN

$b\bar{b}$ production measurement: strategy

ATLAS

- $b\bar{b}$ events are reconstructed using $b \rightarrow J/\psi + X$ and $\bar{b} \rightarrow \mu + X$ (and charge conjugate)
- 3 muons final state with a pair of them to form a J/ψ
  - Pseudo-proper decay time cut $\tau_{\mu\mu} > 0.25$ to select J/ψ only from B-hadron decays
  - Simultaneous ML fit to the distributions of dimuon mass and $\tau_{\mu\mu}$ → Extract non-prompt J/ψ fraction
- $b \rightarrow \mu + X$ events selected with a simultaneous 2D fit on d_0 significance and BDT output (kinematic variables related to track deflection significance, momentum balance, and |η|)
- Irredducible backgrounds (fitted):
  - $B_c \rightarrow J/\psi \mu \nu$ (very small, taken from simulation)
  - Semileptonic decays of c-hadrons not resulting from b-hadron feed-down
  - Muons from charged π/K decays in flight → Mimic a muon and taken from simulation

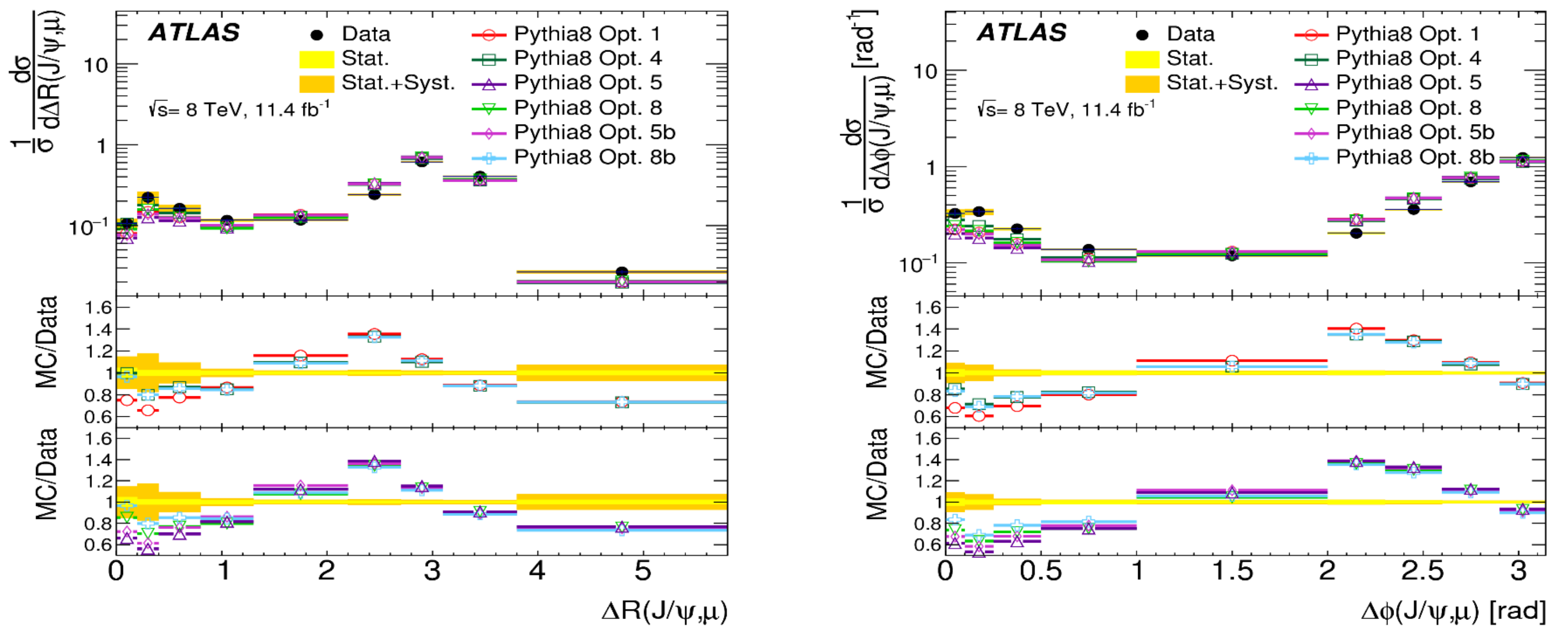
$b\bar{b}$ production measurements: results

ATLAS

- Inclusive cross-section extracted:

$$\sigma\Big(B\big(\to J/\psi\left[\to \mu^+\mu^-\right]+X\big)B\big(\to \mu+X\big)\Big)=17.7\pm0.1(\mathrm{stat})\pm2.0(\mathrm{syst})\ \mathrm{nb.}$$

- Differential cross-section extracted as a function of 8 kinematic variables describing the J/ψμ or the μμμ systems

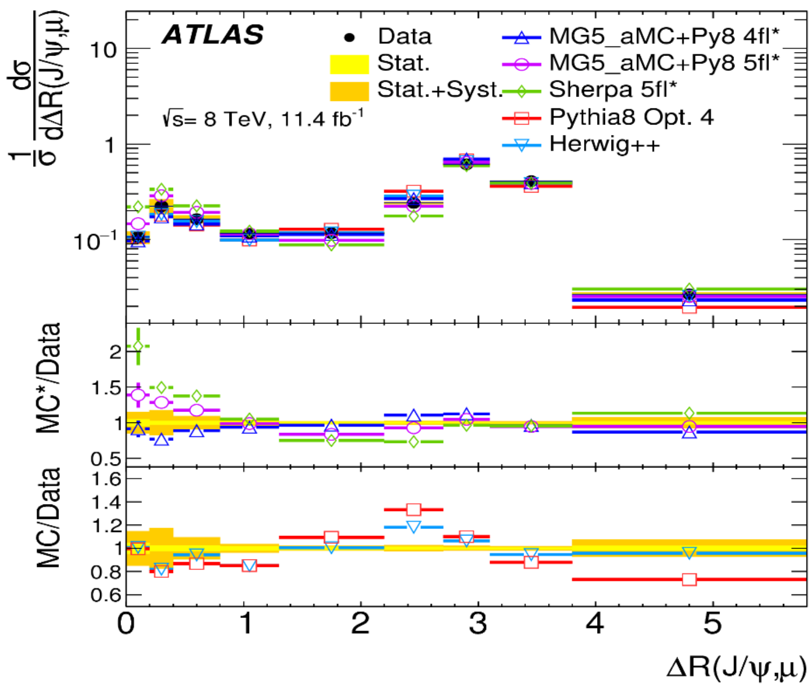


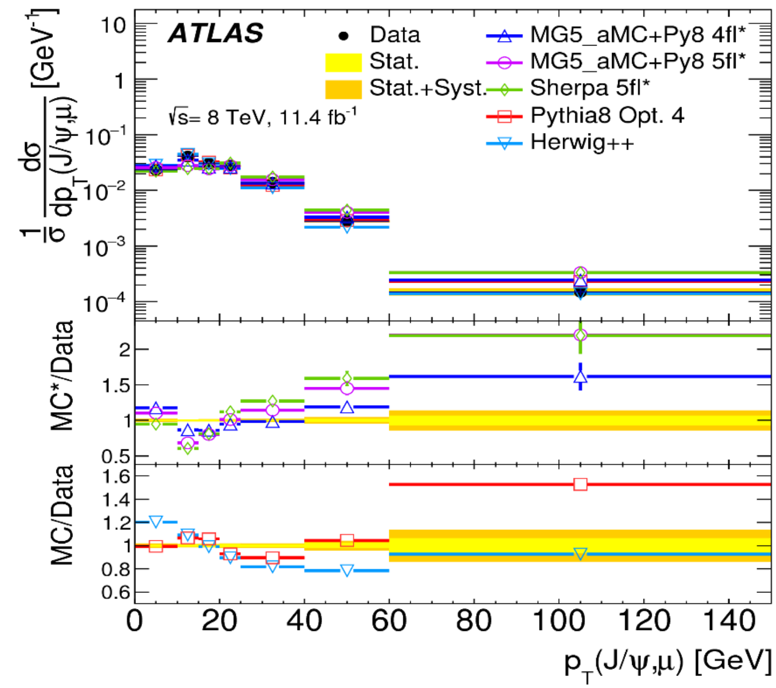
None of Pythia8 tunes describe the angular distances ΔR and ΔΦ

$b\bar{b}$ production measurements: results

ATLAS

- Comparison with different generators and flavor-schemes





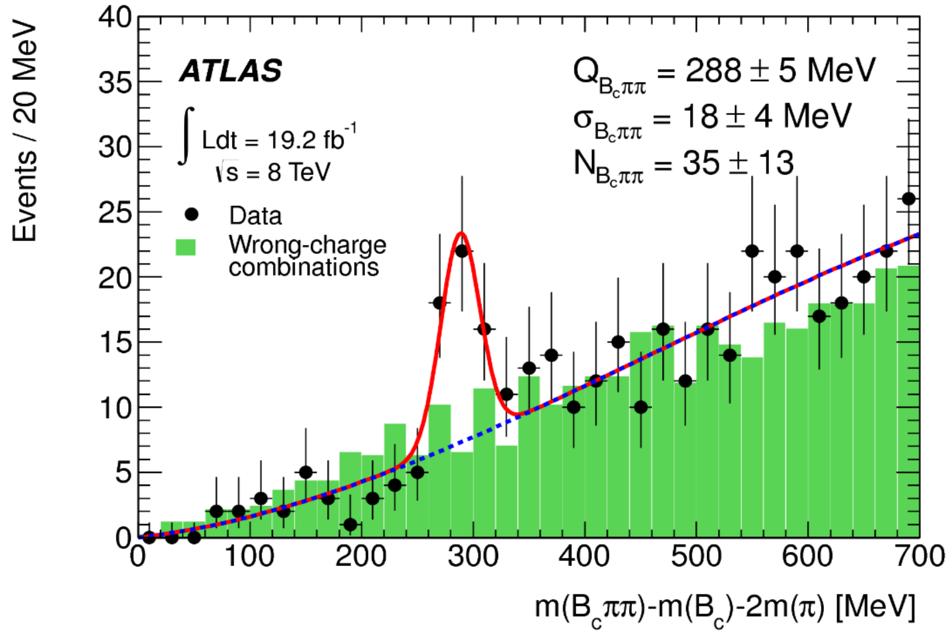
- HERWIG++ reproduces the ΔR and $\Delta\varphi$ distributions best.
- Δy spectrum is well modeled by MadGraph and SHERPA
- Considering all distributions, the 4-massless flavor prediction from MadGraph5_AMC@NLO+PYTHIA8 best describes the data.
- Predictions of PYTHIA8 and HERWIG++ are comparable.
- Among PYTHIA8 options studied, the pT-based splitting kernel is best.

Spectroscopy

Bc(2s) excited state: 1st evidence

ATLAS

- First B^+_c meson excited state seen by ATLAS in Run I
  - Excited state $B^+_c(2s) \rightarrow B^+_c\,\pi\pi$ where $B^+_c \rightarrow J/\psi\pi$
  - Peak in the $Q = M(B^+_c\,\pi\,\pi) - M(B^+_c) - 2m(\pi)$
    - 5.2 σ evidence
    - Mass: 6842 ± 4 ± 5 MeV
  - Actually… a superposition of two excited states:
    - $B^+_c(2s)$ and $B^*c(2s) \rightarrow B^+_c(2s)\,\gamma$
    - No attempt to distinguish them



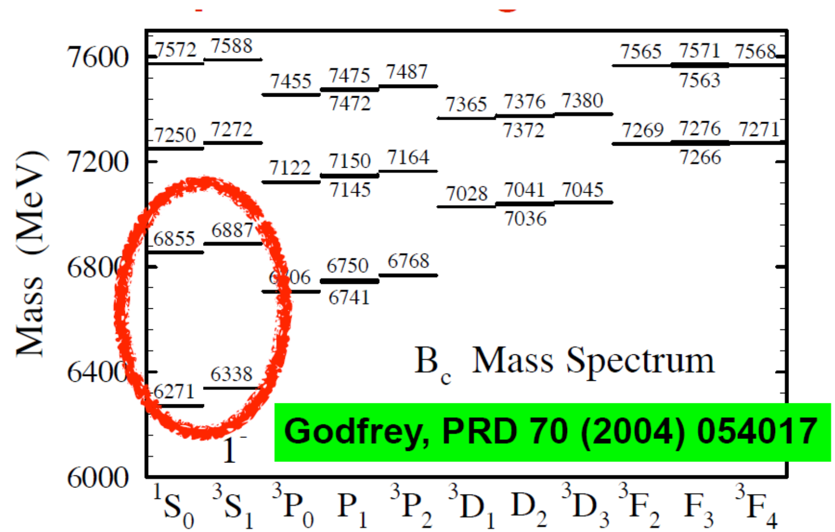
Phys. Rev. Lett. 113, 212004 (2014)

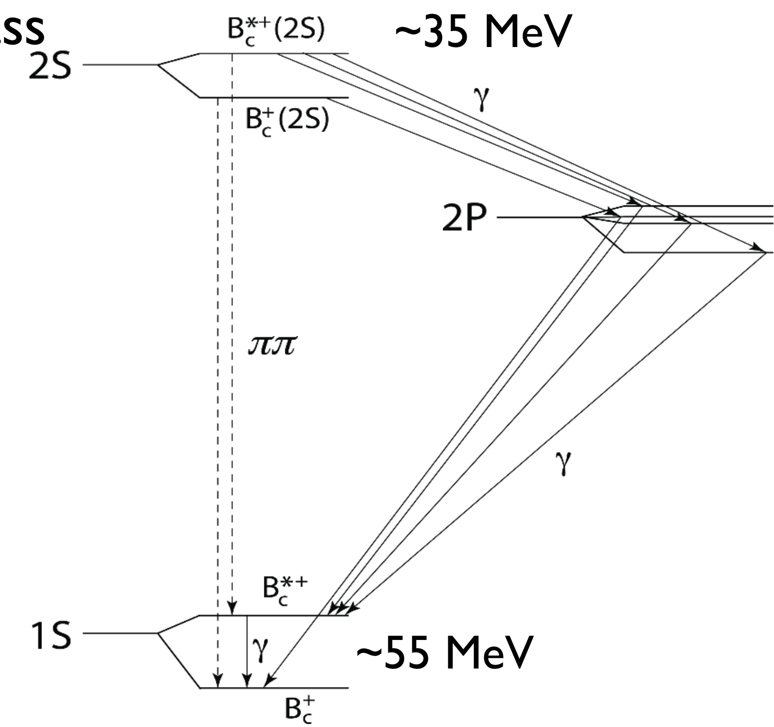
Bc(2s) excited state: new result!

CMS

PRL122 (2019) 132001

- CMS measured it with full Run2 data → 143 fb^{-1}
  - Same final states:
    - $B^+_c(2s) \to B^+_c\,\pi\pi$ where $B^+_c \to J/\psi\pi$
    - $B^{+\,*}_c(2s) \to B^+_c(2s)\,\gamma \to B^+_c\,\pi\pi$ where $B^+_c \to J/\psi\pi$
  - Sensitive to both transition despite the lost soft-photon
    - Theory predicts smaller mass gap w.r.t. $B^{+\,*}_c$ and B^+_c

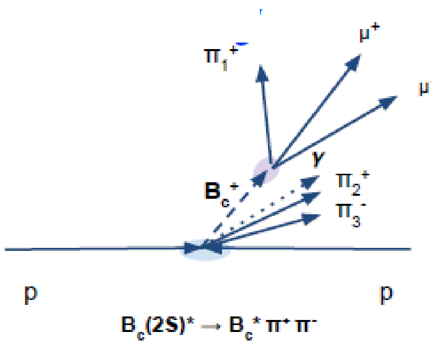


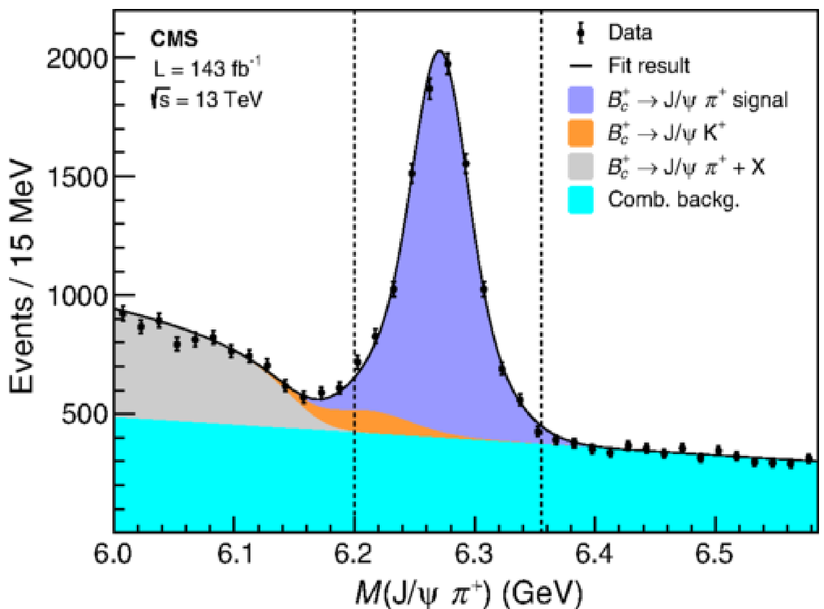


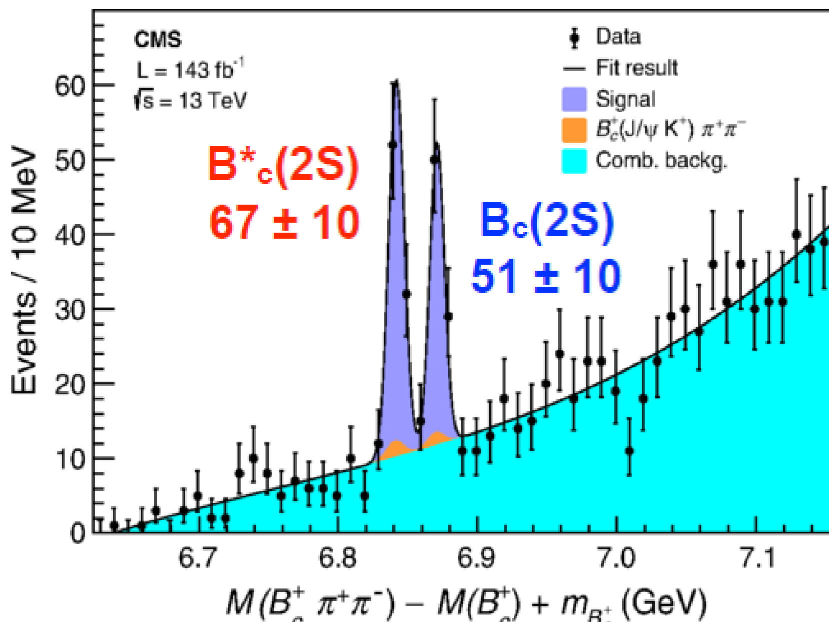
Bc(2s) excited state: new result!

CMS

- Higher $P_T(B^+_c)$ threshold at 15 GeV
- ~ 7600 candidates
- Resolution allows to separate both peaks
- Δm_{exp} = 29.1 ± 1.5 ± 0.7 MeV
- $M(B^+_c(2s))$ = 6871.0 ± 1.2 (stat.) ± 1.1 (syst)
- Two states recently seen also by LHCb (Daria Savrina's talk)
  - Compatible masses and Δm w.r.t. CMS



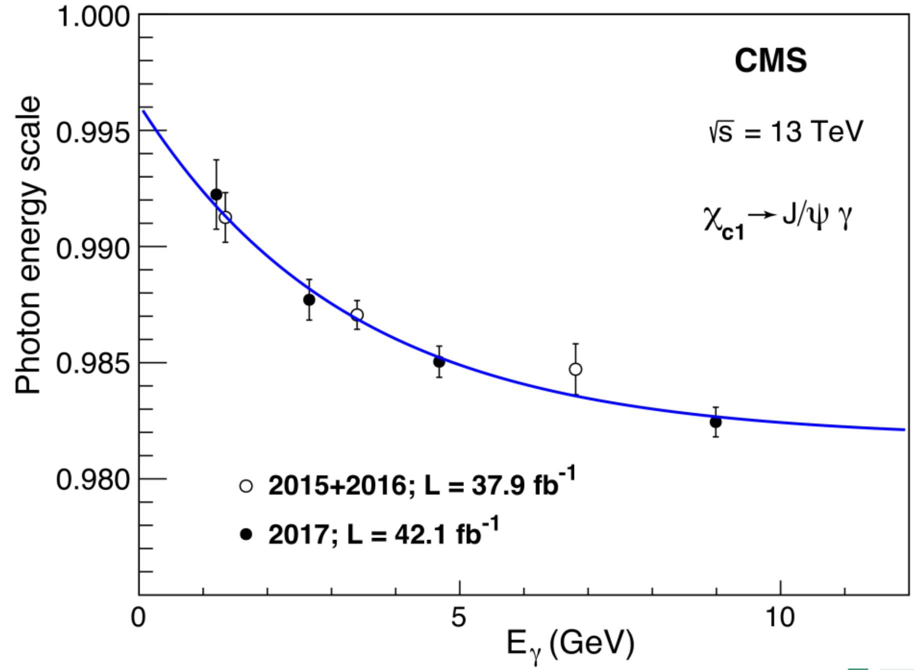




χ_b excited states

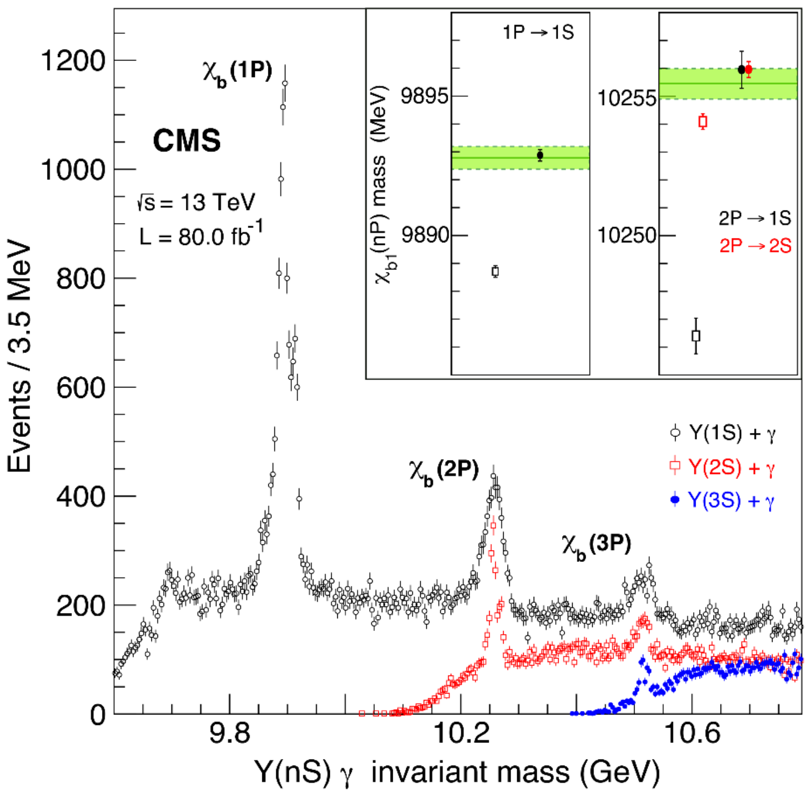
CMS — Phys. Rev. Lett. 121 (2018) 092002

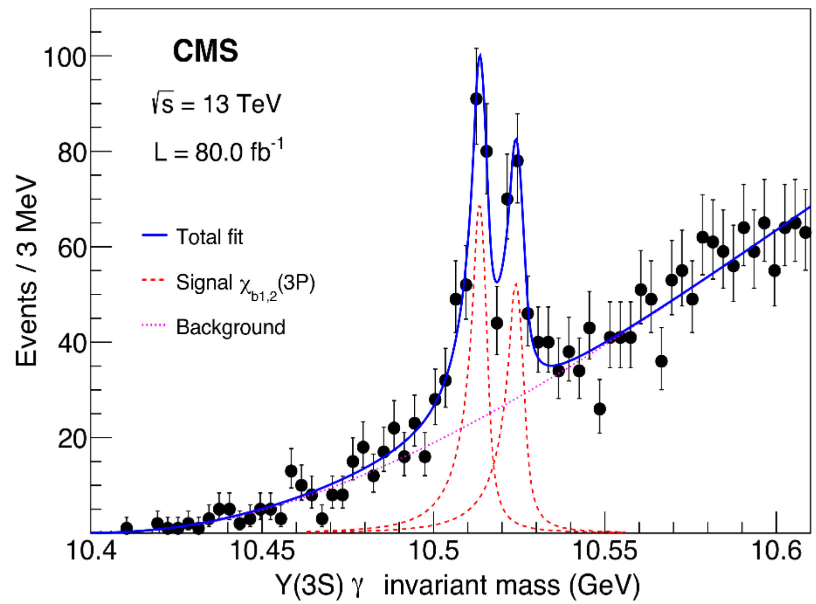
- χ_b (3P) state first discovered by ATLAS, (PRL 102 (2012) 1528001)
  - Also seen by D0 and LHCb
- Analyzing Run 2 dataset (13 TeV, 80 fb-1), CMS has observed for the first time the split in the $\chi_{b,1}$(3P) – χ_{b2} (3P) doublet and measured the masses of the two states
- χ_b(3P) is reconstructed in Υ(3S) + γ mode.
  - The low energy γ is detected through γ → e+e- conversion inside the silicon tracker
  - Photon energy scale is calibrated using high yield $\chi_{c,1}$ → J/ψ + γ samples for high accuracy mass measurements
  - Tested with χ_b(1P, 2P) states



χ_b excited states

CMS





M_1 = 10513.42 ± 0.41(stat) ± 0.18(syst) MeV
M_2 = 10524.02 ± 0.57(stat) ± 0.18(syst) MeV
Mass split: ΔM = 10.60 ± 0.64(stat) ± 0.17(syst) MeV

- J=1 and J=2 states resolved for the first time
- Valuable input to constraint theoretical predictions for quarkonia just below the $Q\overline{Q}$ threshold

Rare decays

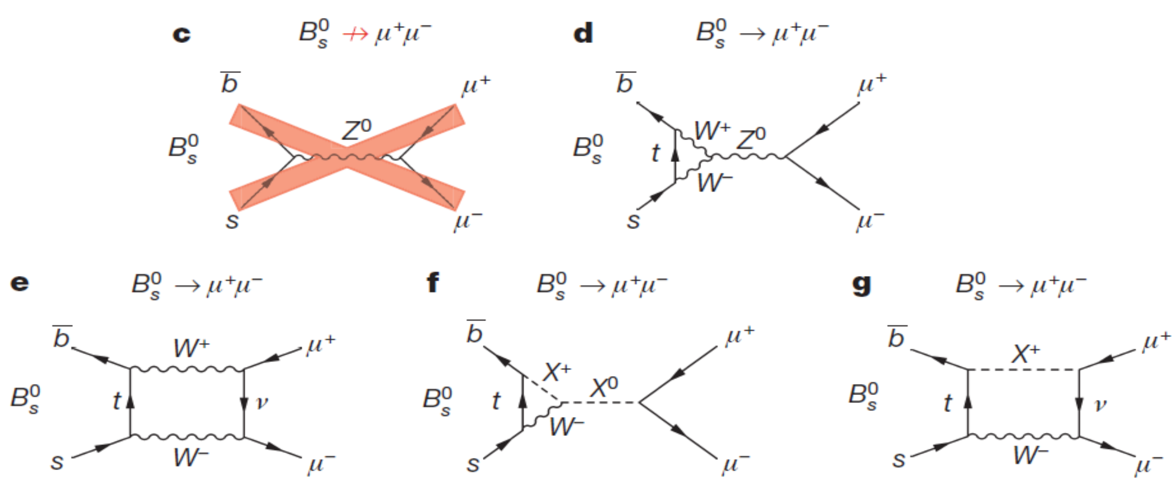
Bs,d→μμ BR measurement

- Rare but clean decay suppressed by FCNC in the SM
  - BR(Bs→μμ) = $(3.65 \pm 0.23)\times10^{-9}$
  - BR(Bd→μμ) = $(1.06 \pm 0.09)\times10^{-10}$
- Sensitive to New Physics contributions through loops
- Measurements by CMS and LHCb (combined):

BR(Bs→μμ) = $(2.8^{+0.7}_{-0.6})\times10^{-9}$ $\quad 3.0^{+0.7}_{-0.6}\times10^{-9}$

BR(Bd→μμ) = $(3.9^{+1.6}_{-1.4})\times10^{-10}$ $\quad < 3.4\times10^{-10}$

LHCb-only (Run2)



Bs,d→μμ BR measurement

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  - BR(Bd→μμ) = (1.06 ± 0.09) x10^{-10}
- Sensitive to New Physics contributions through loops
- Measurements by CMS and LHCb: Nature 522 (2015) 68

BR(Bs→μμ) = ($2.8^{+0.7}_{-0.6}$) x10^{-9} (combined) $3.0^{+0.7}_{-0.6}$x10^{-9} LHCb (Run2)

BR(Bd→μμ) = ($3.9^{+1.6}_{-1.4}$) x10^{-10} $< 3.4 \times 10^{-10}$ Phys. Rev. Lett. 118 (2017) 191801

- Analysis strategy:

Hadronisation probabilities

$$\mathcal{B}(B^0_{(s)} \to \mu^+\mu^-) = N(B^0_{(s)} \to \mu^+\mu^-) \times [\mathcal{B}(B^+ \to J/\psi K^+) \times \mathcal{B}(J/\psi \to \mu^+\mu^-)] \times \frac{f_u}{f_{s/d}} \times \frac{1}{\mathcal{D}_{\rm norm}}$$

$$\mathcal{D}_{\rm norm} = \sum_k N^k_{J/\psi K^\pm} \alpha_k \left(\frac{\varepsilon_{\mu^+\mu^-}}{\varepsilon_{J/\psi K^\pm}}\right)_k$$

Number of Bs/Bd events from an unbinned ML fit to m(μμ) distribution

Reference channel: B$^\pm$→J/ψK$^\pm$ Extracted from an unbinned ML fit to m(μμK$^\pm$) distribution

Trigger categories and luminosity prescales*

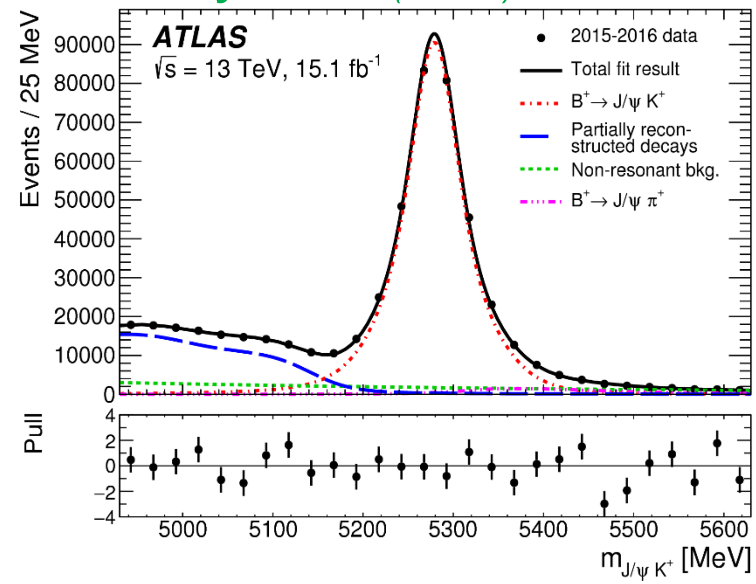
Acceptance and efficiencies from simulation

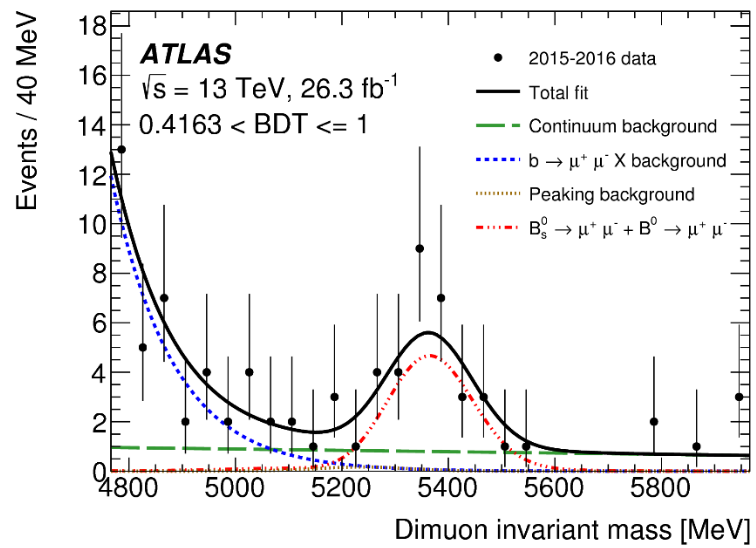
Bs,d→μμ BR measurement

ATLAS

JHEP 04 (2019) 098

- Use high statistics reference channel ($B^{\pm} \rightarrow J/\psi K^{\pm}$) → reduce systematics
- Blind analysis (e.g. the event selection and all the analysis is frozen before looking at data)
- Di-muon low-P_T triggers
- High reduction and control of the backgrounds (BDT for combinatorial)
- Main backgrounds:
  - Combinatorial (i.e. 2 "random" muons forming a common vertex
  - Semi-leptonic decays
    - e.g. b → cμν → s(d)μμνν
  - Hadrons identified as muons
    - K/π decays in flight

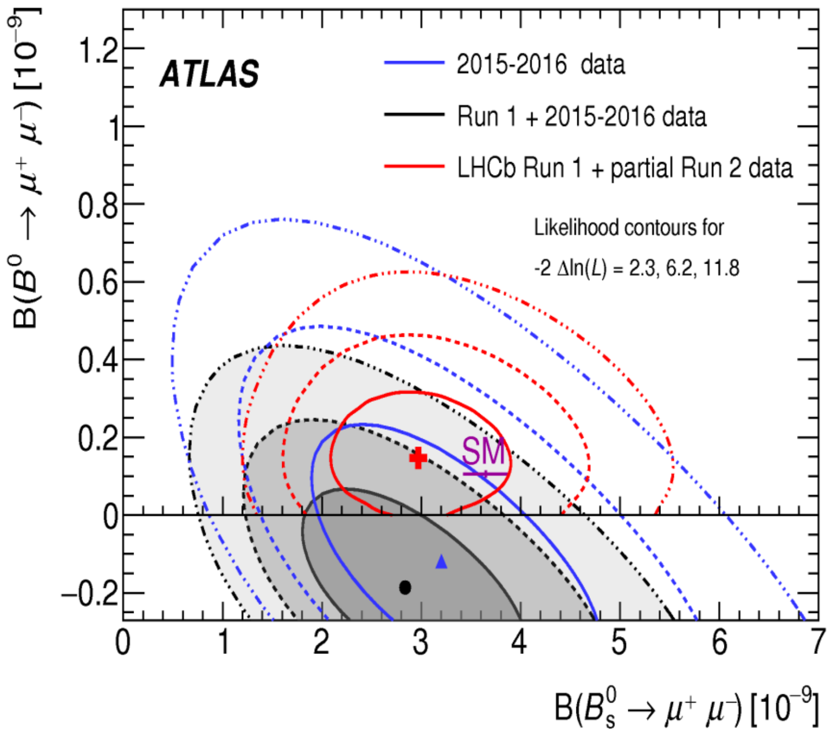




Bs,d→μμ BR measurement

ATLAS

- Results for full Run1+Partial Run2 dataset (25+26 fb^{-1})
- Simultaneous BR(Bs →μμ, Bd→μμ) extraction
- Comparable precision w.r.t. CMS and LHCb despite their better m(μμ) resolution



- BR(Bs) = $2.8^{+0.8}_{-0.7}$ x10^{-9} (stat. ± syst.)
  - Evidence at 4.6σ
- Upper limit on BR(Bd) placed at 2.1x10^{-10} (95% CL)
  - Currently the most stringent limit

$\tau \rightarrow \mu\mu\mu$ BR measurement

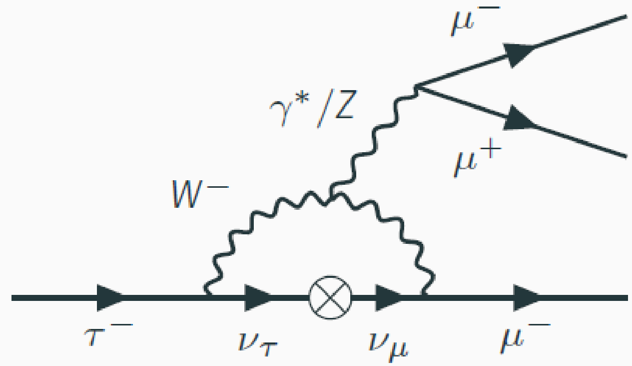
Physics motivations

- Charged Lepton Flavour Violation decay allowed by neutrino oscillation
- Predicted branching fraction smaller than experimentally accessible values [1]
- Many New–Physics scenarios predict branching ratio enhancement [2]

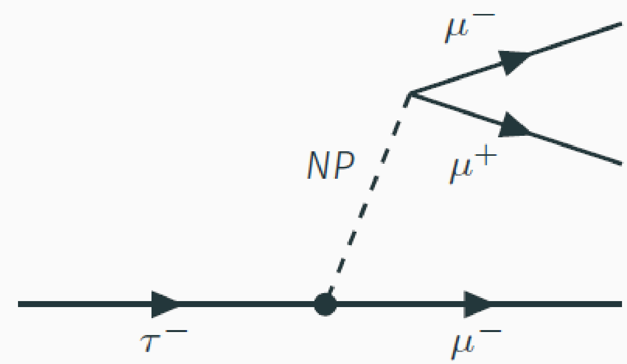
Experimental state of the art

- Experimentally clean three–muon final state
- No signal observed by Belle [3], BaBar [4], LHCb [5] and ATLAS [6]
- ATLAS limit: 3.76×10^{-7} (Run1 using τ from W)
- Most stringent limit (Belle): $BF < 2.1 \; 10^{-8}$ (90% CL)
- Recent new CMS analysis (CMS-PAS-BPH-17-004)

Standard Model ($BF \sim 10^{-14}$)



New Physics ($BF \sim 10^{-8}$)

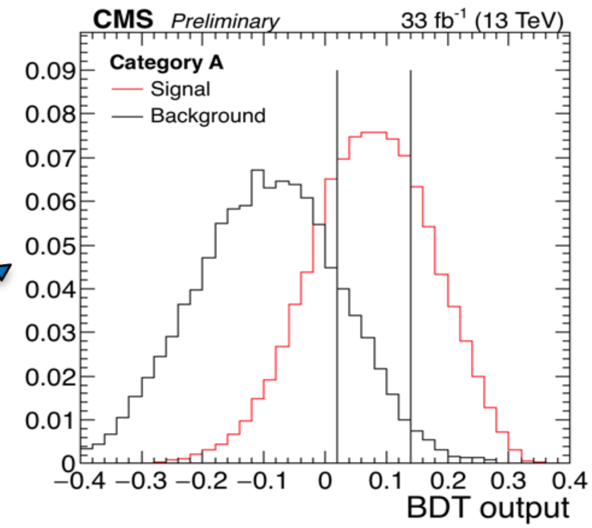


[1] Eur. Phys. J. C 8 (1999) 513–516 [2] Ann. Rev. Nucl. Part. Sci. 58 (2008) 315 [3] Phys. Lett. B687 (2010) 139143 [4] Phys. Rev. D81 (2010) 111101 [5] JHEP 02 (2015) 121 [6] Eur. Phys. J. C (2016) 76:232

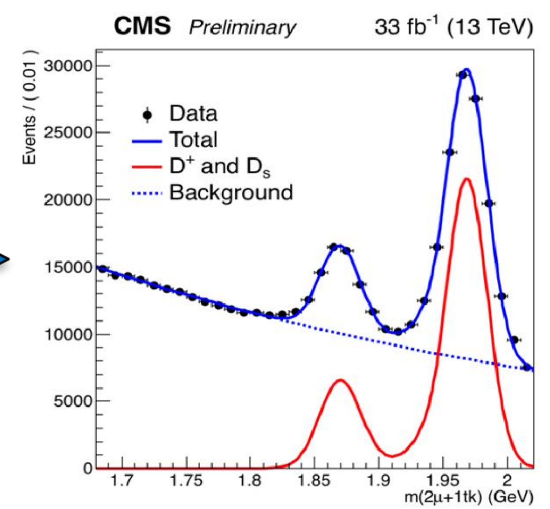
$\tau \rightarrow \mu\mu\mu$ BR measurement

CMS

- τ from Ds and B decays
- 3 muons candidate with
  - PT(1st, 2nd) > 3 GeV, PT(3rd) > 2 GeV;
  - Sum of charge = 1
  - 1.62 < m(3) < 2.00 GeV
  - Displaced vertex (from beam-spot)
  - Trigger: dimuon + 1 track with mass and displacement requirements



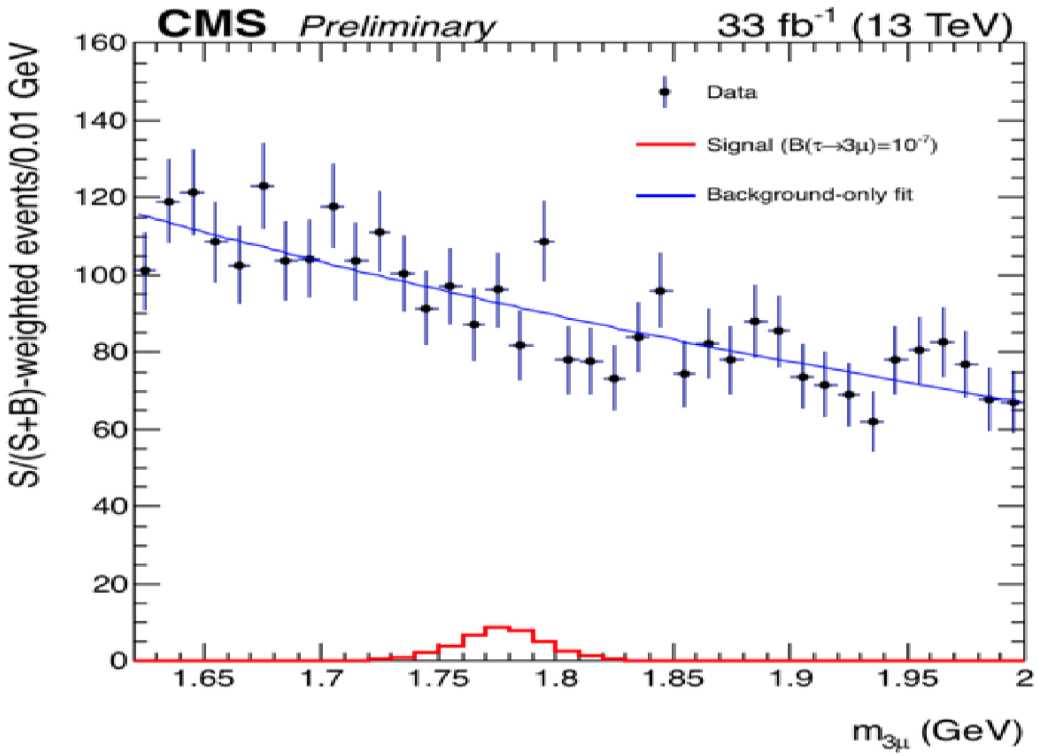
- BDT to separate signal (MC) from background (sidebands)
- Events classified in categories (mass resolution and BDT score)
- Normalisation channel:
  - Ds → Φ(→ μμ) π



$$N_{\text{sig}} = N_{\mu\mu\pi} \frac{\mathcal{B}(D_s \to \tau\nu)}{\mathcal{B}(D_s \to \mu\mu\pi)} \frac{\epsilon(\text{signal})}{\epsilon(\mu\mu\pi)} \mathcal{B}(\tau \to 3\mu)$$

CMS

- Maximum Likelihood fit in m(μμμ) simultaneously for the six categories (3 mass resolution regions X 2 BDT score regions)



- Dominant systematic uncertainty is on the Ds normalization channel

No excess observed

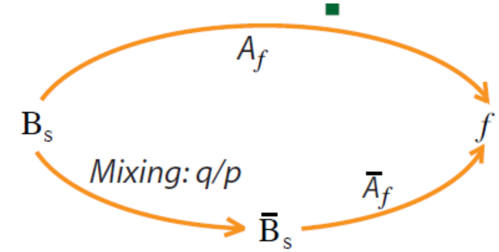
Observed (expected) limits at 90% CL:

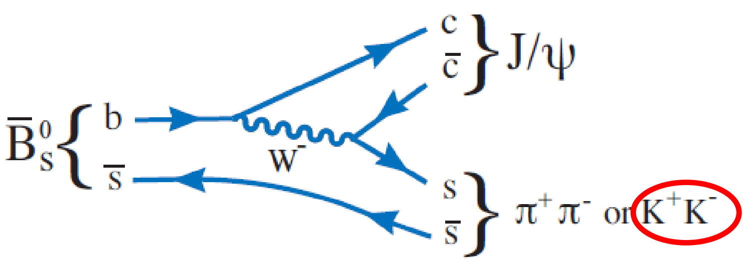
$\mathcal{B}(\tau \to 3\mu) < 8.8(9.9) \cdot 10^{-8}$

CP Violation

CP violation in $B_s \rightarrow J/\psi\phi$

- Interference between mixing and decay

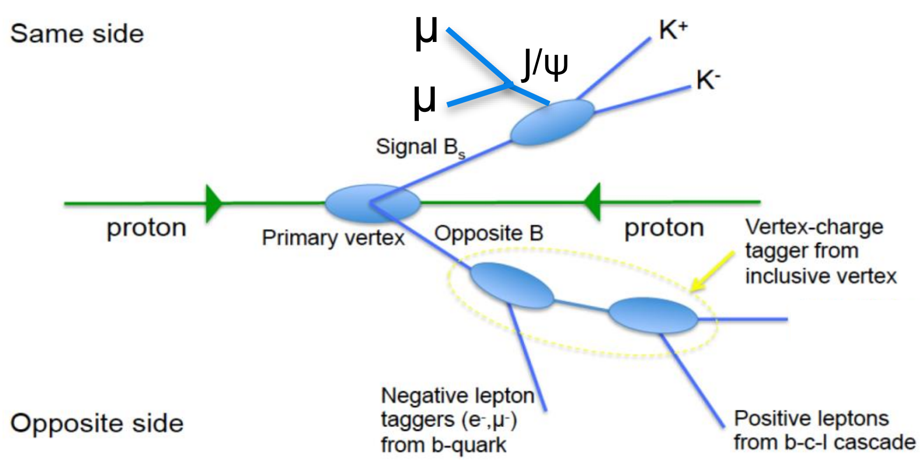




$$\varphi_s^{SM} \equiv -2\beta_s = -2\arg\left(-\frac{V_{ts}V^*_{tb}}{V_{cs}V^*_{cb}}\right) = -0.04 \text{ rad}$$

Small CPV phase in SM → Ideal place for New-Physics!

- Essential ingredients at hadron colliders:
  - Good time resolution to measure the oscillation accurately
  - Flavour tagging (i.e. distinguish the "Bs side" of the event)



CPV in $B_s \rightarrow J/\psi\phi$

- The final state $J/\psi(\rightarrow \mu+\mu-)\ \phi(\rightarrow K+K-)$ is a superposition of CP=+1 and CP=-1 configurations.
- The two components can be distinguished looking at the angular correlations among kaons and muons (slide in backup).

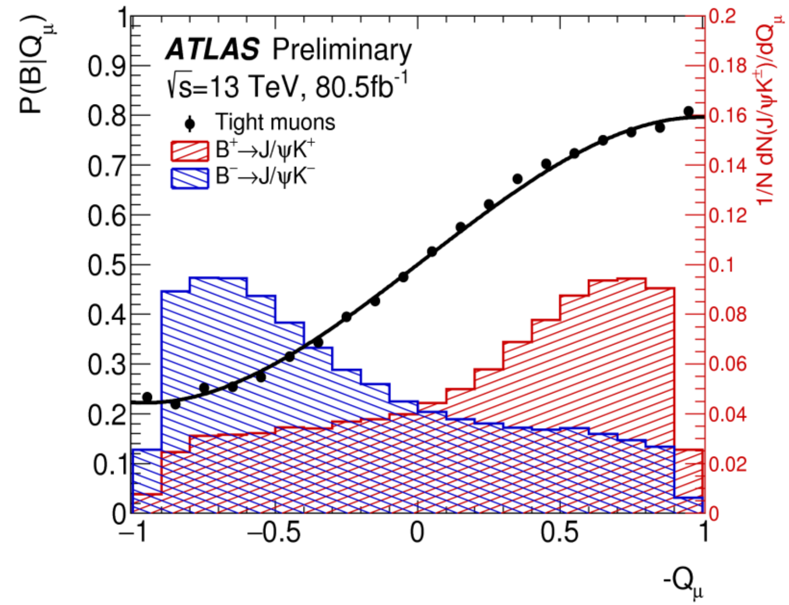
- The distribution of the proper decay time includes contribution from Bs^H ($\tau^H \approx 1.58$ ps) and Bs^L ($\tau^L \approx 1.39$ ps) and of their interference ($\tau^S = 1.48$ ps) → $\mathbf{\Gamma_s}$ and $\mathbf{\Delta\Gamma_s} = \Gamma_L - \Gamma_H$ are extracted
- The phase $\boldsymbol{\varphi_s}$ can be extracted looking at the relative amplitudes on these long time scales

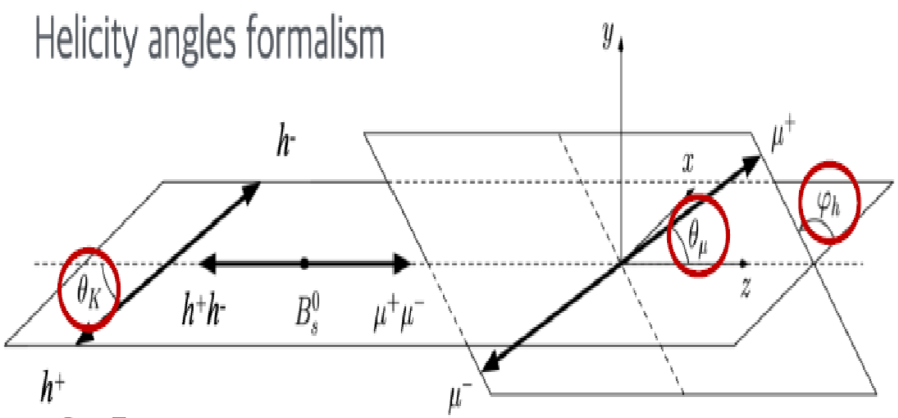
- Or, more accurately, one can tag the initial Bs ad anti-Bs flavor at production, by looking at the decay of the accompanying B/antiB meson. In this way, φ_S is mainly extracted from the fast (and small) oscillations occurring on the time scale of $1/\Delta ms = 0.056$ ps.

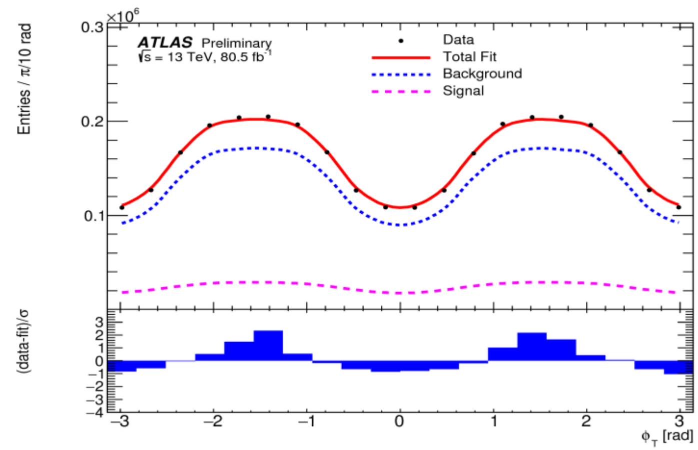
CPV in $B_s \to J/\psi\phi$

ATLAS

- New ATLAS result [ATLAS-CONF-2019-009]
- Opposite-side tagging to determine initial flavour (using e/μ/jet charge from "the other side")
  - $B^{\pm} \to J/\psi K^{\pm}$ calibration sample
- Flavour tagging probability affects significantly the precision on the extraction of the parameters
- Angular analysis with 10 amplitude functions is done (J/ΨΦ is not a CP eigenstate!!)

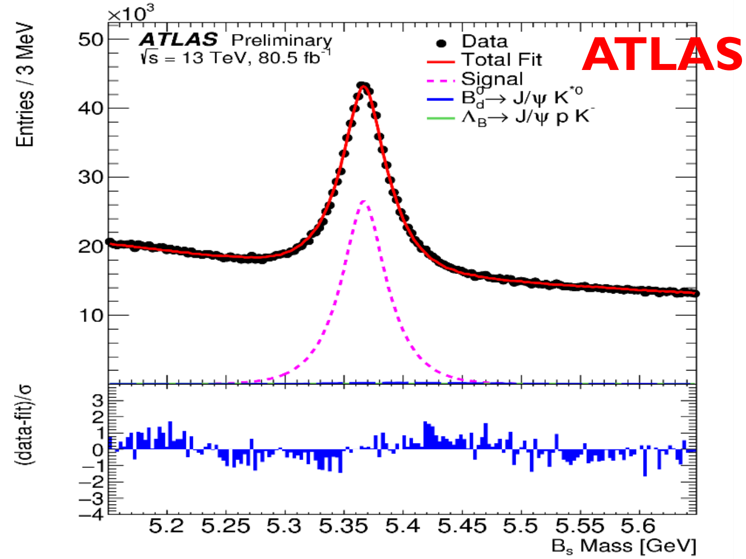


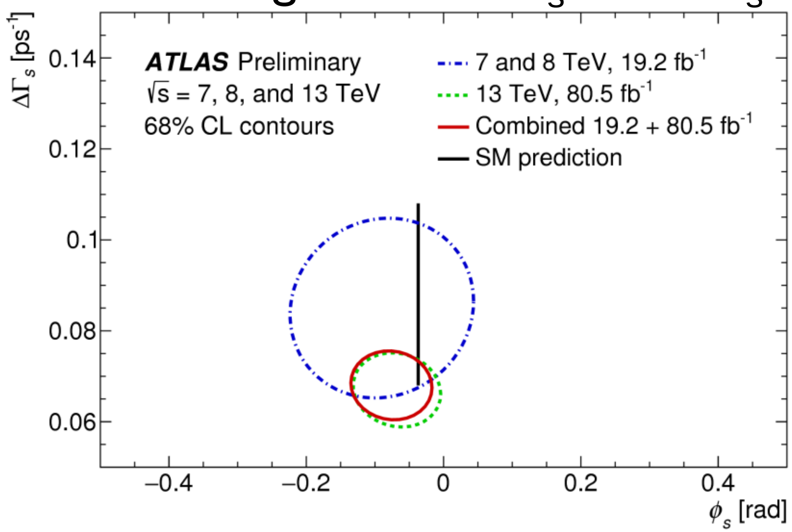


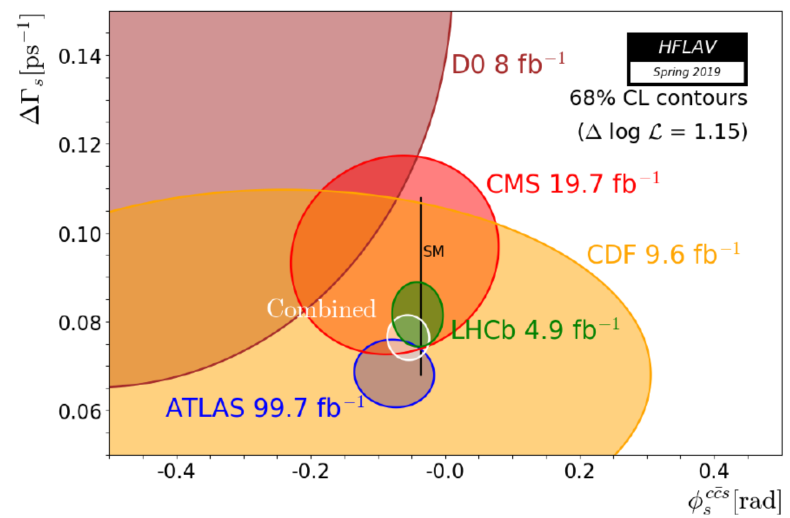


CPV in $B_s \rightarrow J/\psi\phi$ in Run2

- Simultaneous fit in Bs mass, lifetime, and the three angles
- Extraction of the amplitude parameters and phases with correlations
- Main systematics:
  - Tagging for φ_s
  - Fit models for signal and background for Γ_s and $\Delta\Gamma_s$







$$\varphi_s = -0.055 \pm 0.021 \text{ rad}$$
$$\Delta\Gamma_s = 0.0764^{+0.0034}_{-0.0033} \text{ ps}^{-1}$$

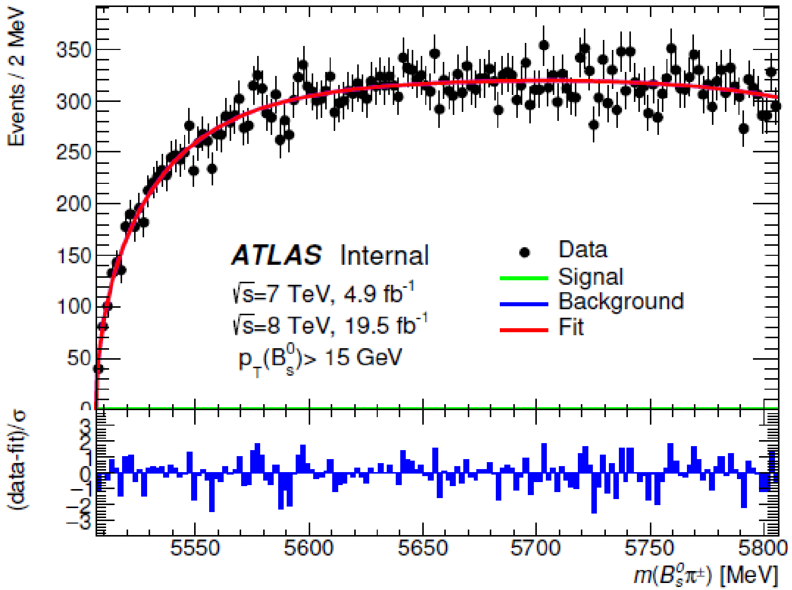
Conclusions

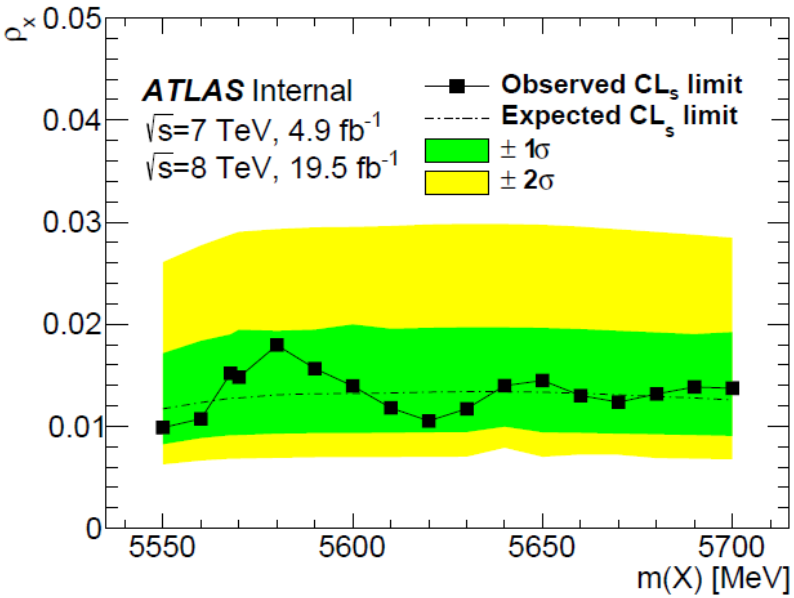
- Several measurements in the B-phyiscs and light states areas have been shown
- Both ATLAS and CMS are able to constrain QCD and EW predictions and to give valuable inputs to theoretical models for spectroscopy and quarkonia
- Both experiments can be competitive with LHCb in few areas
- Both experiments are analysing now the full Run2 dataset → Stay tuned for exciting new results soon!

Backup

Tetraquark searches

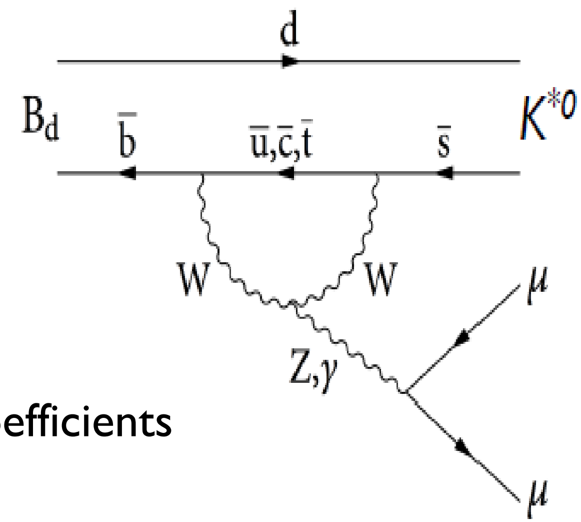
- D0 experiments found an evidence of a four-quarks bound state (u-dbar-s-bbar) in B*s → Bsπ decay not confirmed by any other experiment
- Mass 5568 MeV, Γ≈21.9 MeV
- We performed the search with 7 and 8 TeV data
- No excess found → Upper limit on the production rate ratio w.r.t. Bs+X production and on searches for general resonances X decaying into Bsπ





Rare decays: $B_d \rightarrow K^*\mu\mu$

- $b \rightarrow s\, l+\, l-$ transitions are FCNC processes → Highly suppressed in SM

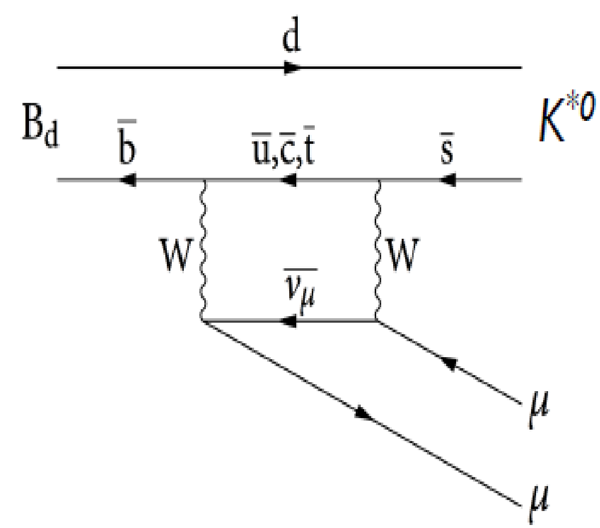


- Sensitive to New Physics (NP) through loop effects → EFT approach

$$L = L_{SM} + \sum_i c_i \frac{O_i}{\Lambda_{NP}^2}$$

Wilson coefficients

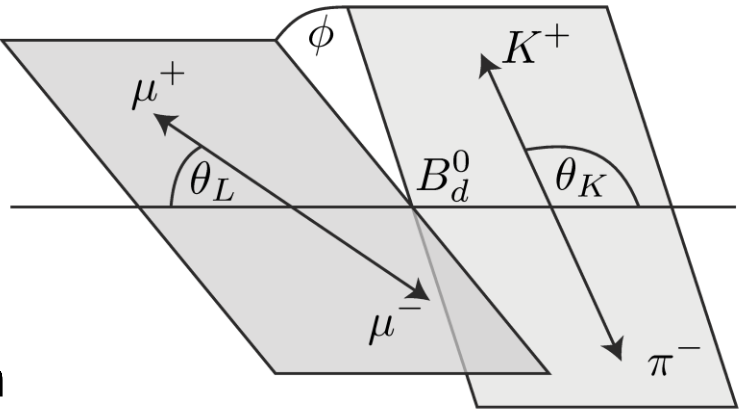
- No helicity suppression → theoretical calculations reasonably clean (charm loop effects in the form-factors though…)



- $BR(B_d \rightarrow K^*\mu\mu) = (1.06 \pm 0.10) \times 10^{-6}$

- Angular variables also sensitive to any NP contributions

Rare decays: $B_d \rightarrow K^*\mu\mu$



- Decay amplitude fully described by the invariant mass q^2 of the di-muon system and three angles: $\theta_{L,}$ θ_K and Φ
- Si and FL are extracted and then translated into Wilson coefficients and/or optimised variables P'i

$$P_1 = \frac{2S_3}{1-F_L}$$

$$P_2 = \frac{2}{3}\frac{A_{FB}}{1-F_L}$$

$$P_3 = -\frac{S_9}{1-F_L}$$

$$P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_L(1-F_L)}}.$$

- P'i less sensitive to form factor uncertainties at leading order.
- LHCb reported a
  - 3.4σ excess in P'_5 parameter
  - Similar excess in Bs $\rightarrow \phi\mu\mu$ vs q^2

R. Aaij et al., JHEP 02 (2016) 104
R. Aaij et al., JHEP 1509 (2015) 179

Rare decays: $B_d \rightarrow K^*\mu\mu$

Measurements statistically limited