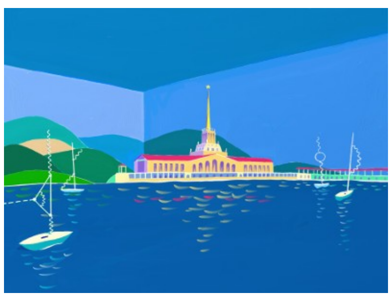
Heavy quark physics at ATLAS and CMS (excluding top)

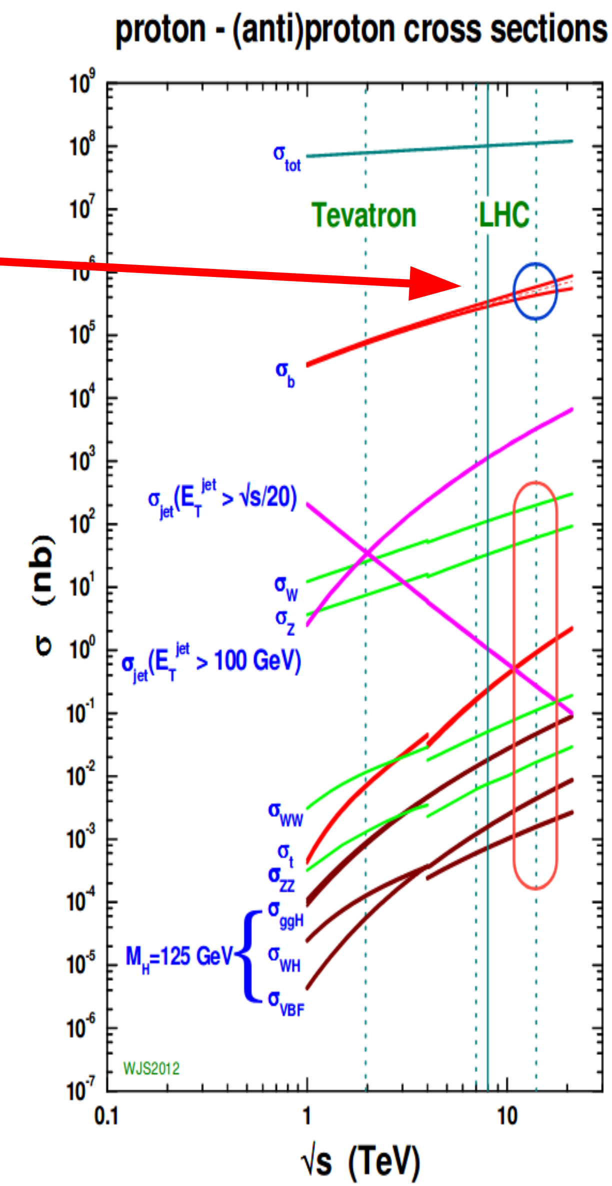


Oleg Meshkov (MSU & Lebedev PI)
The XXIV International Workshop
High Energy Physics and Quantum Field Theory
September 22 – 29, 2019
Sochi, Russia

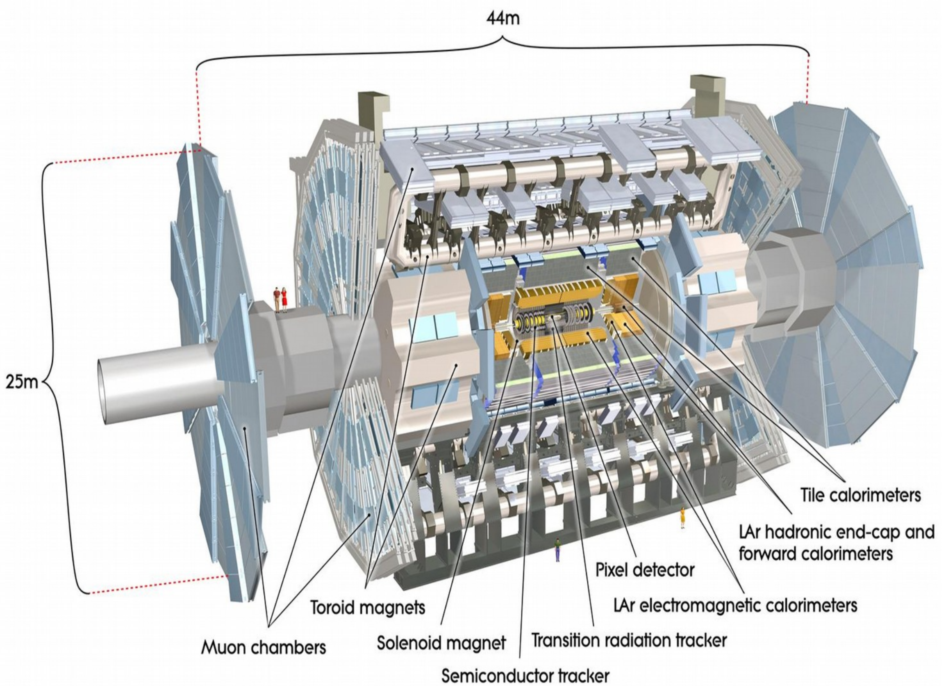
On behalf of the ATLAS and CMS Collaborations

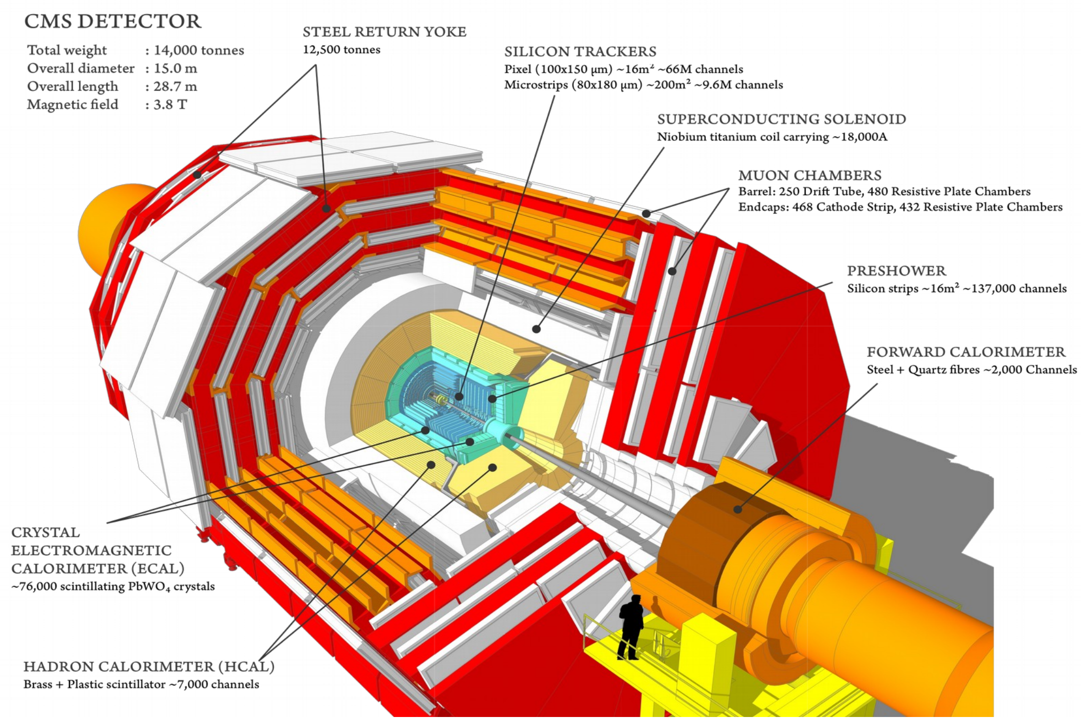
b hadron production at the LHC

- b hadrons (and anti-hadrons) are dominantly produced through strong interaction in pp collisions at the LHC
  - *Large inclusive bb cross-section (~ 0.1 mb)*
  - *All b hadron types including Λ_b , B_c and B_s are produced*
- Unfortunately, it's hard to efficiently trigger on b hadron decays at the LHC
  - *b decay products have relatively low pT, predominantly produced in forward direction*
- Exceptions
  - *Dedicated displaced vertex triggers (for example, LHCb)*
  - *Specific final states, e.g. including di-muons*



The ATLAS and CMS detectors

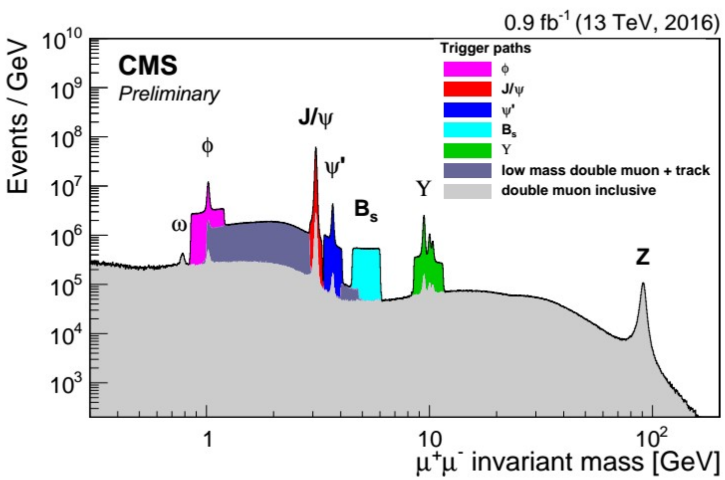


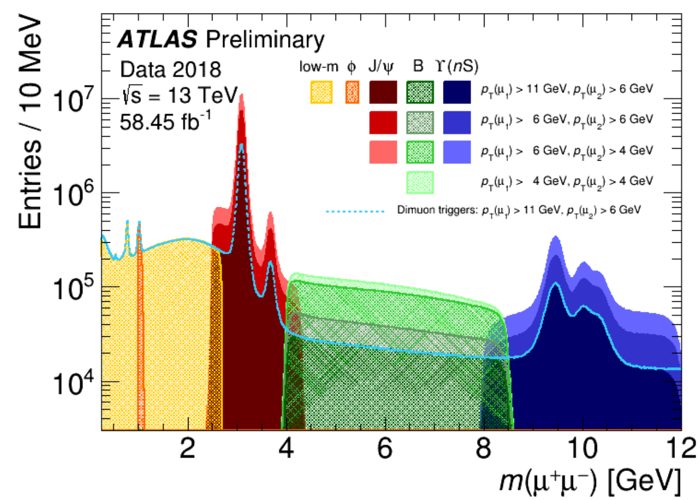


- Multipurpose detectors with similar performance designed to study pp collisions at 14 TeV
  - → Track momentum resolution and therefore b hadron mass resolution depends critically on magnetic field strength
    - ATLAS: 2T; CMS: 4T
  - → Fake muon rejection critical for background suppression
    - CMS: π (0.05-0.13)%, K (0.08-0.22)%, p (0.04-0.15)%
    - ATLAS: π (0.04-0.13)%, K (0.07-0.1)%, p 10^{-5}

B-physics trigger

- 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





B-physics program

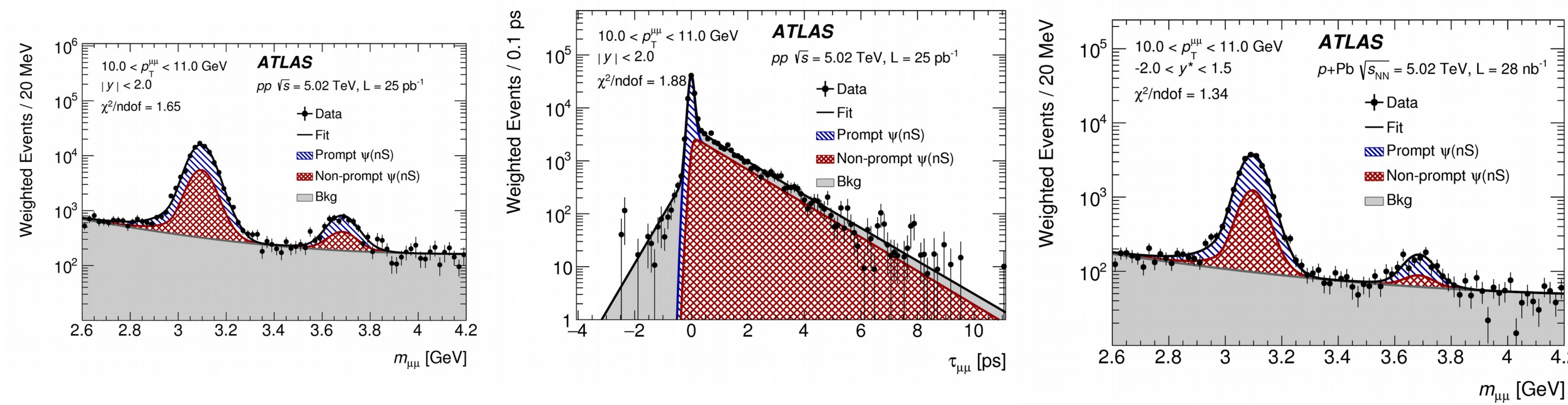
- B-physics (and light states) :
  - Test of QCD-based prediction: cross section,spectroscopy, etc.
    - Quarkonia production and decay
    - J/ψ+J/ψ, $J/\psi W$, J/ψ Z associated production (double parton scattering)
    - Spectroscopy (χ_{b3P} , X_c, X_b searches, B_c excited states), new states
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

Only recently results are presented

Quarkonia production and decay

Quarkonia production in pp and p-Pb collisions at 5 TeV *ATLAS*

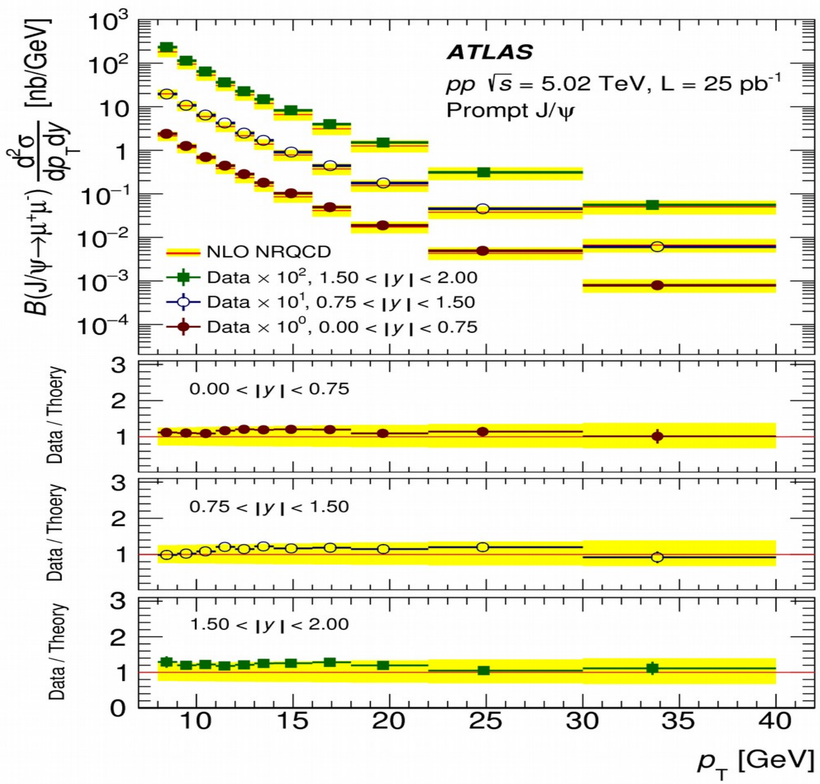
Eur. Phys. J. C 78 (2018) 171

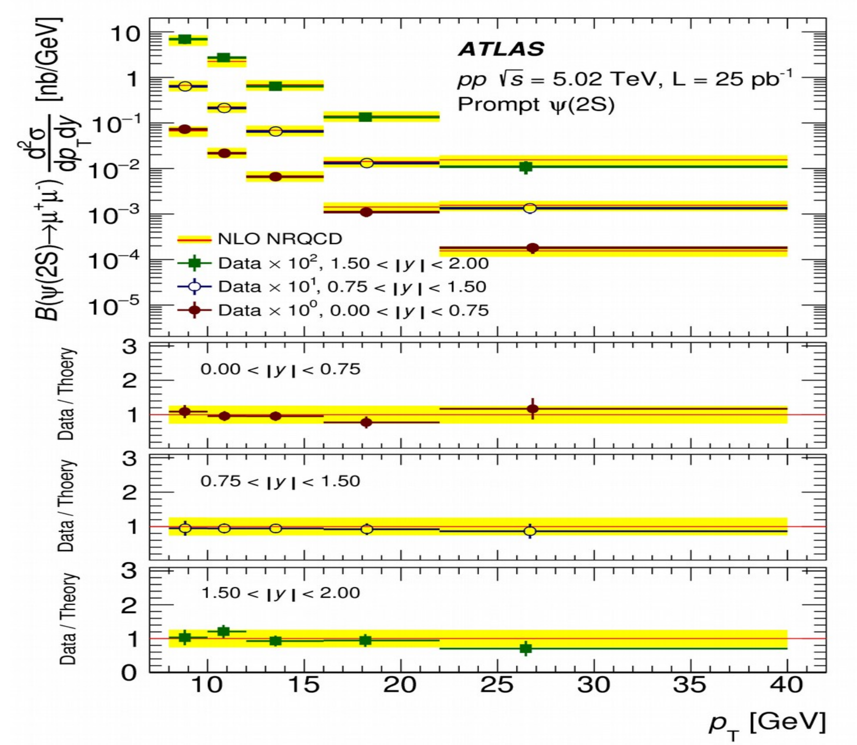


- Prompt(not from B-decays) and non-prompt(from B-decays) J/ψ and ψ(2S) reconstruction
- Simultaneous fit in mass and pseudo-proper lifetime $\tau_{\mu\mu}$
- Fit data in bins of P_T, y and centrality using p.d.f. for $m_{\mu\mu}$ and $\tau_{\mu\mu}$

Charmonia cross-sections in pp collisions at 5 TeV

ATLAS [Eur. Phys. J. C 78 (2018) 171]



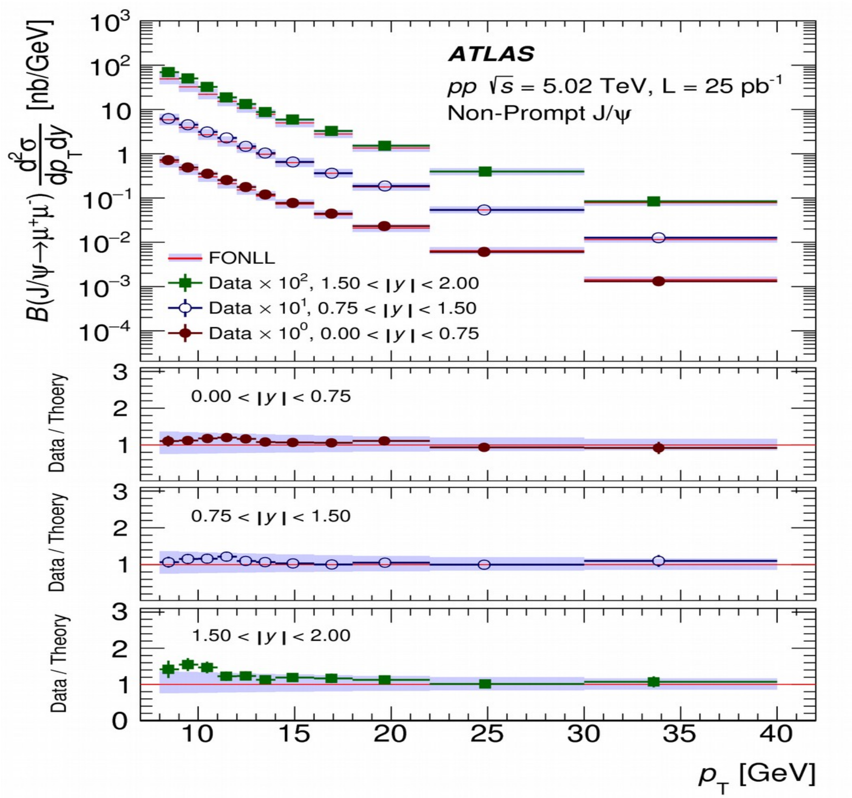


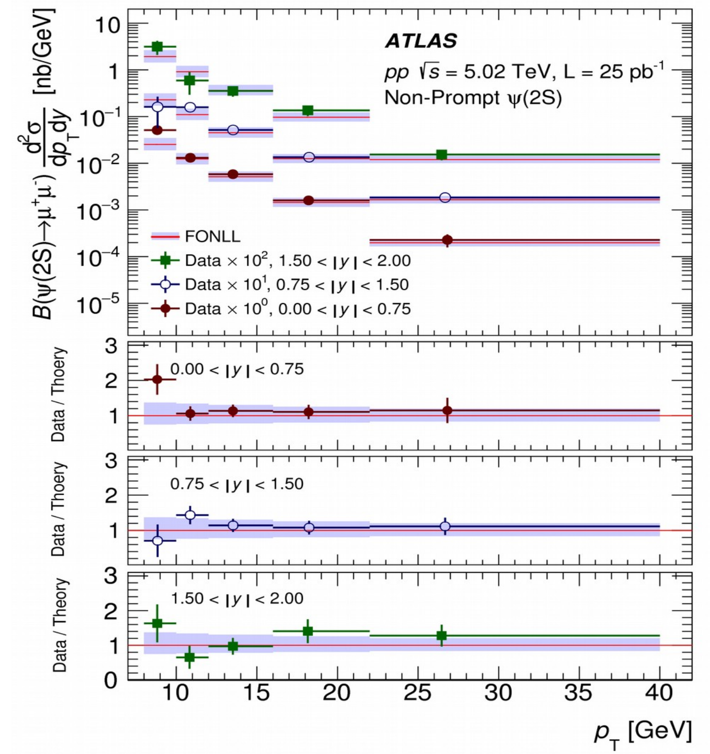
- Prompt charmonia J/ψ and ψ(2S) cross-sections extracted
- Compared with NRQCD predictions
  - Overall good agreement

Charmonia cross-sections in pp collisions at 5 TeV

ATLAS

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

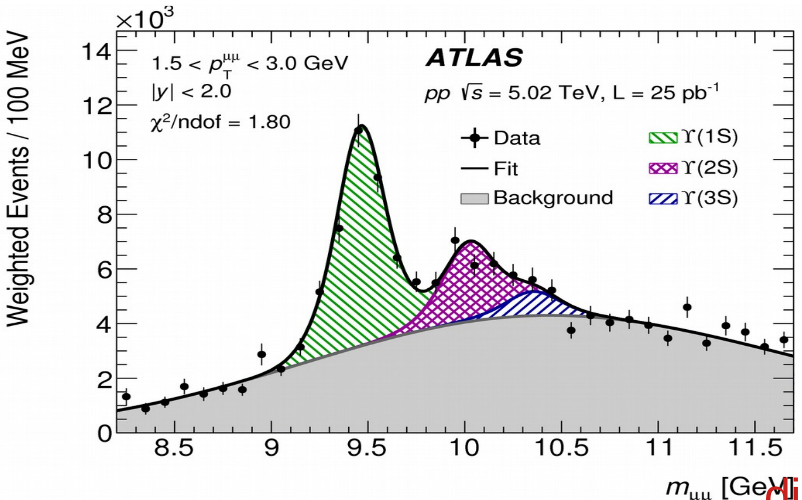




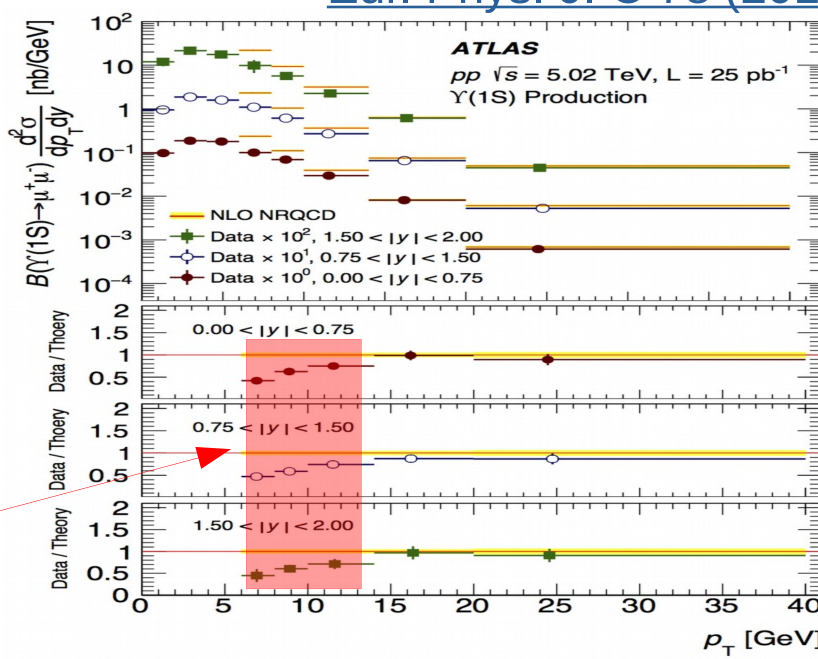
- Non-prompt charmonia J/ψ and ψ(2S) cross-sections extracted
- Compared with FONLL predictions
  - Overall good agreement

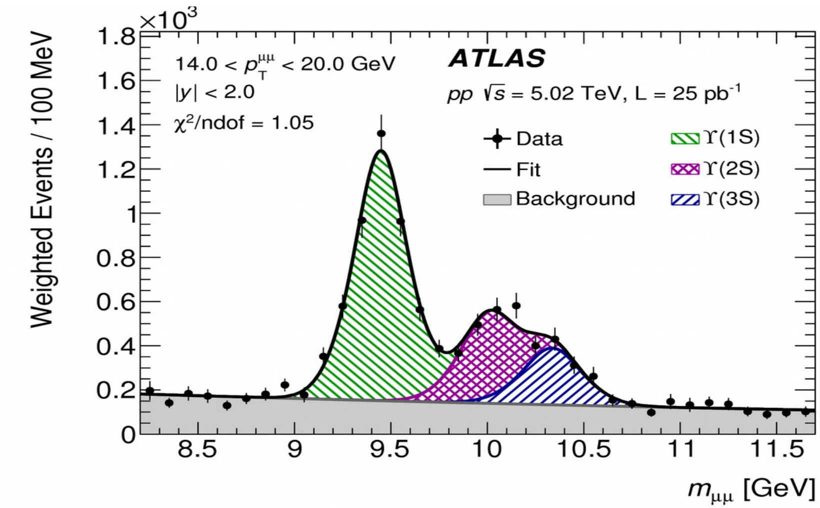
Y(nS) production in pp collisions at 5 TeV *ATLAS*

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



disagreement



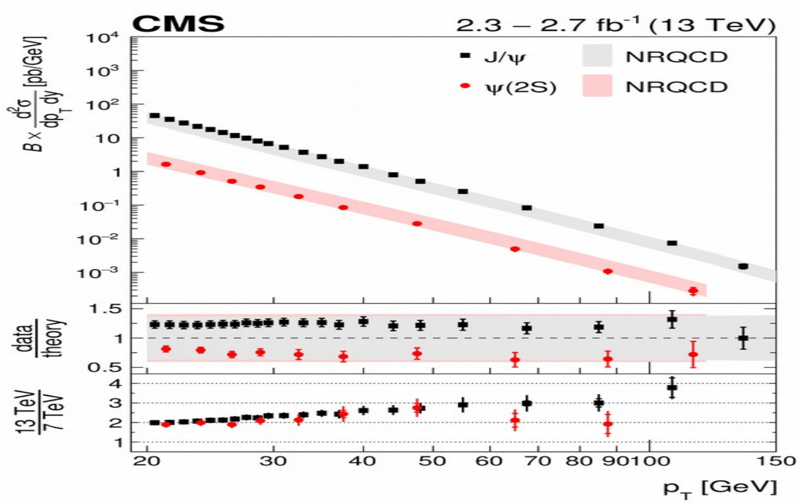


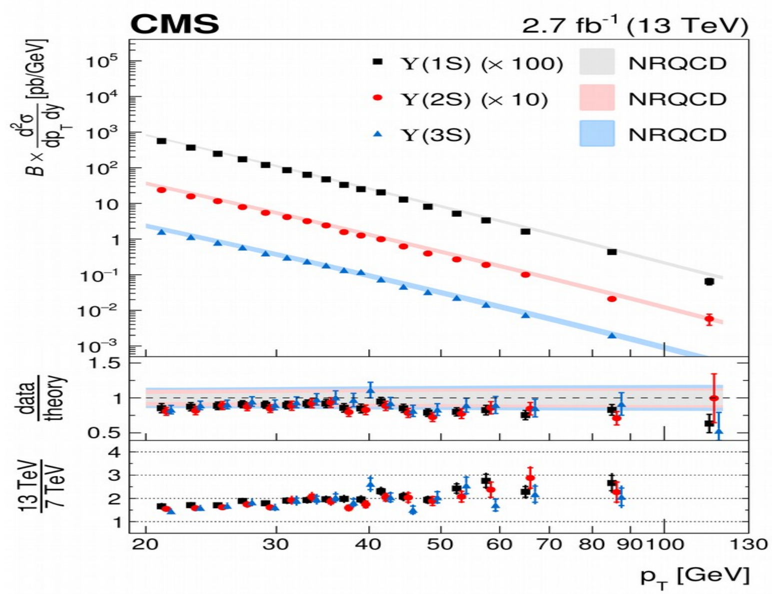
- Similar analysis for bottomonia Y(nS) (only in $m_{\mu\mu}$)
- Fit data in bins of P_T, and y in $m_{\mu\mu}$
- Compared with NRQCD predictions
  - Significant disagreement in the lower part of the PT spectrum

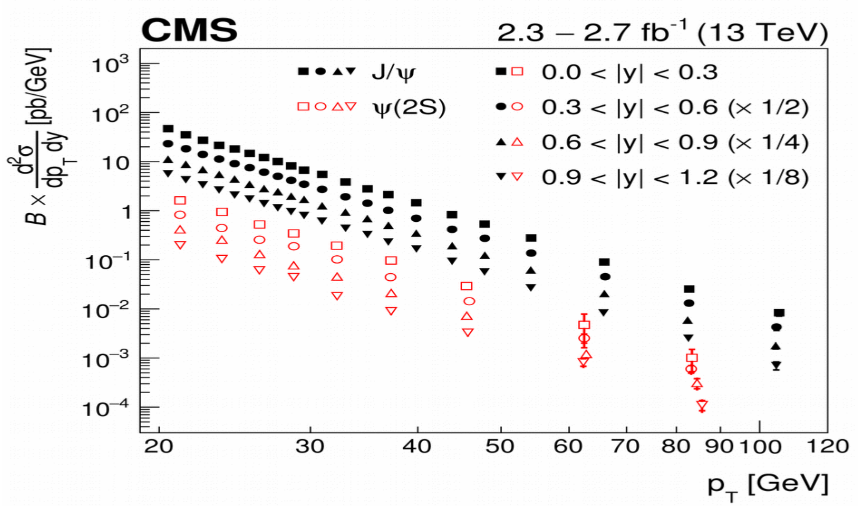
Quarkonia cross-sections in pp collisions at 13 TeV

CMS

Phys. Lett. B 780 (2018) 251







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

J/ψ production in jets at 8 TeV *CMS*

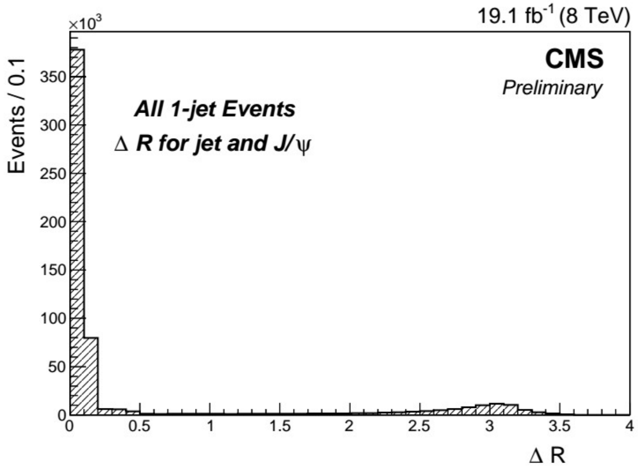
CMS-PAS-BPH-15-003

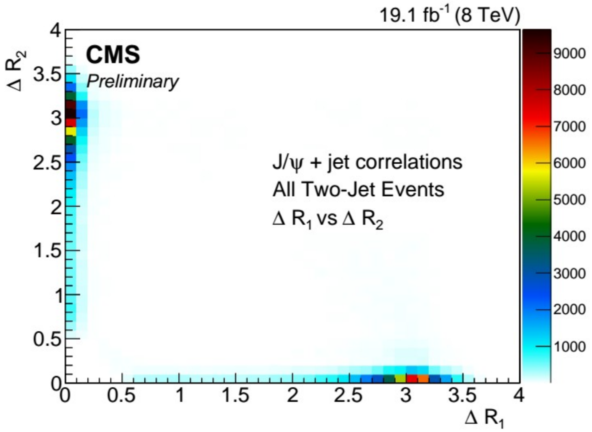
- Measurement of J/ψ–jet Association is a test of the role of jet fragmentation in quarkonium production with Run1 data (19.1 fb^{-1}, $\sqrt{s} = 8$ TeV)
- Theoretically described in Fragmenting-Jet Function(FJF) approach.
- Crucial variables to describe J/ψ kinematics are: E_{jet} and $z = E_{J/\psi}/E_{jet}$
- 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 E_{jet} to disentagle the various LDME contribution

J/ψ production in jets at 8 TeV *CMS*

CMS-PAS-BPH-15-003

- $E(J/\psi) > 15$ 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



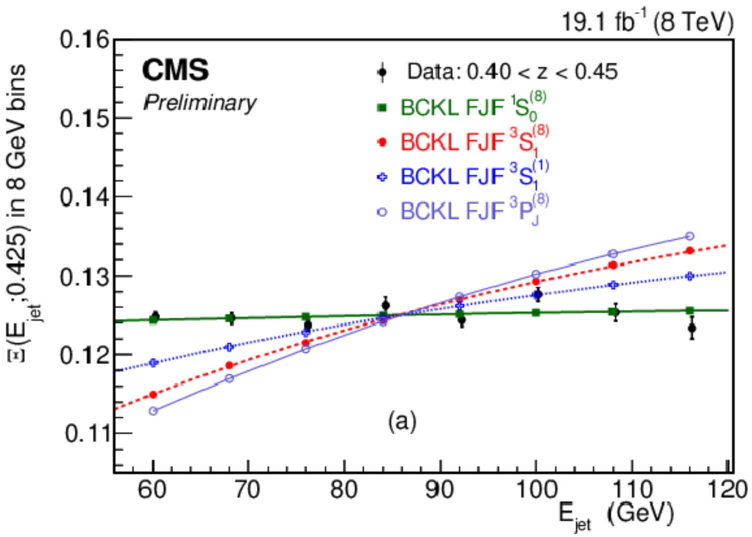


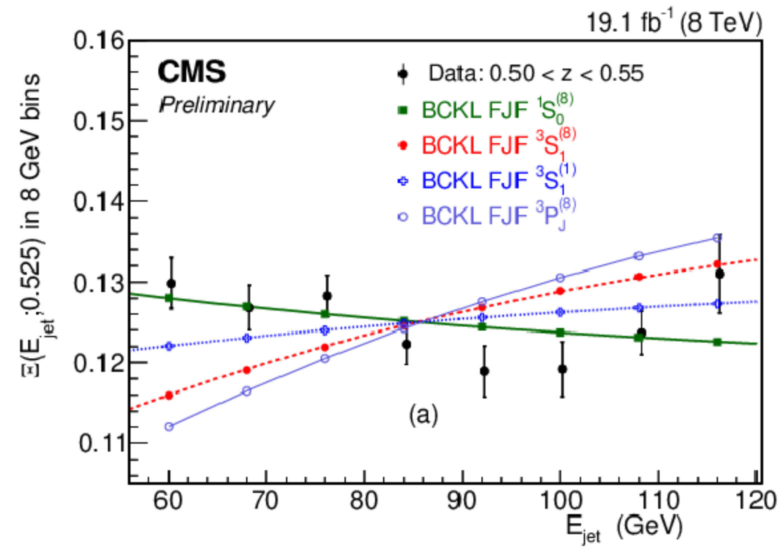
Once J/ψ - jet association is made, compute this:

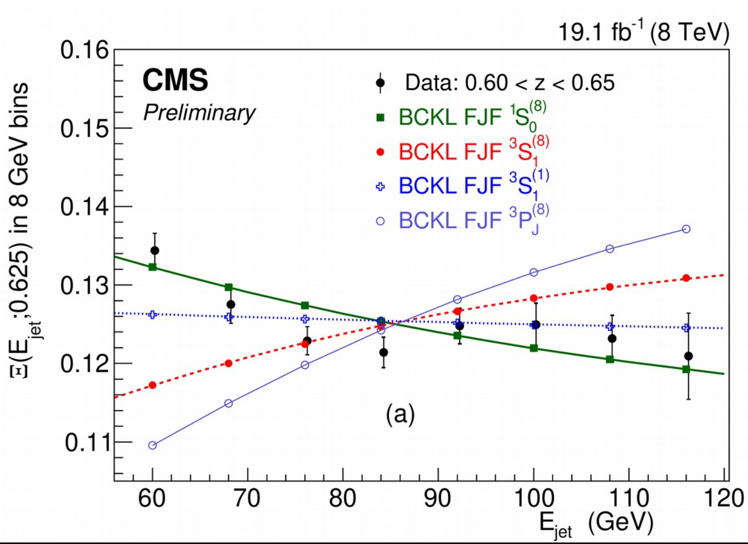
$$\Xi(E,z)=\frac{1}{N(z)}\frac{N(E,Z)}{\int_{0.3}^{0.8} N(E,\acute{z})\,d\acute{z}}$$

J/ψ production in jets at 8 TeV *CMS*

CMS-PAS-BPH-15-003







- FJF predictions for gluon jet fragmentation in the central region describe well data
- Jet fragmentation can account for > 80% of J/ψ production

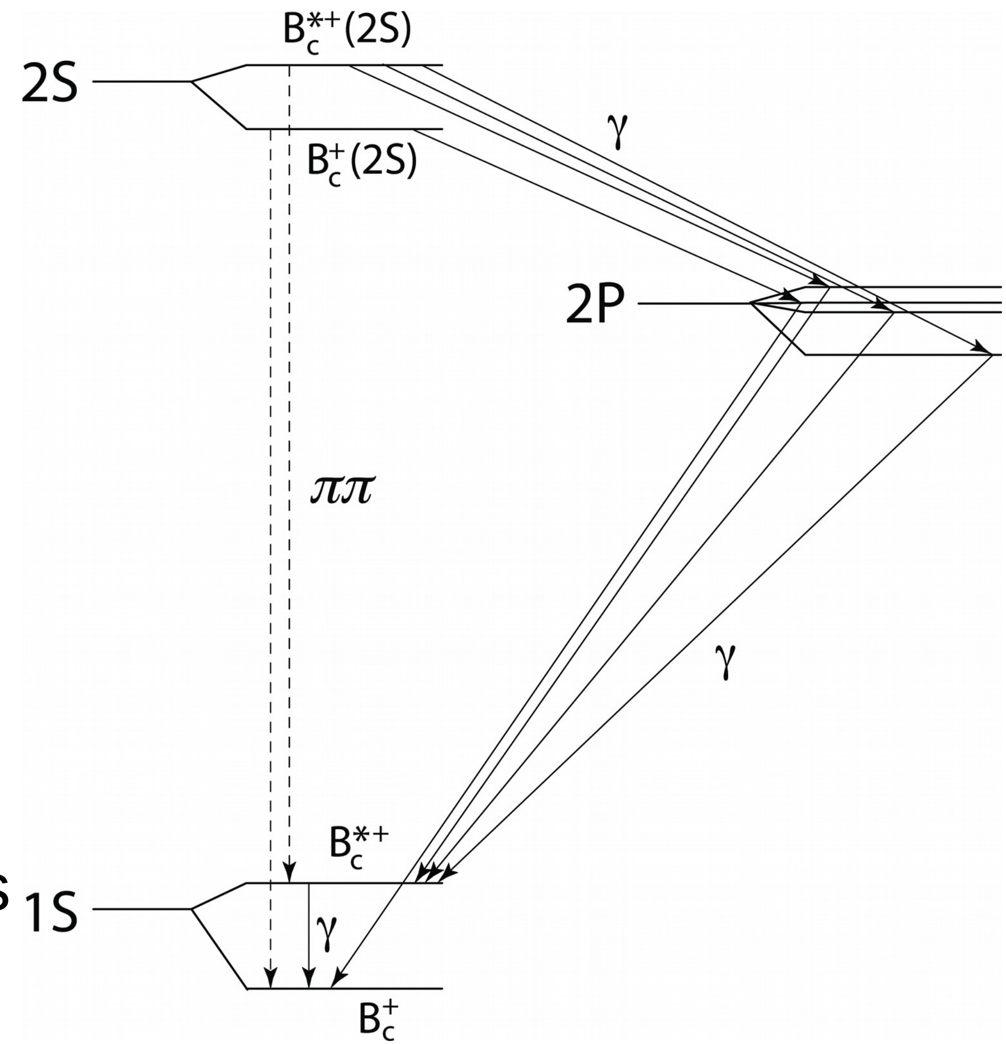
Spectroscopy
New states

$B_c(2s)$ excited state

CMS

- CMS measured it with full Run2 data: 143 fb^{-1}
- 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

Phys. Rev. Lett. 122 (2019) 132001

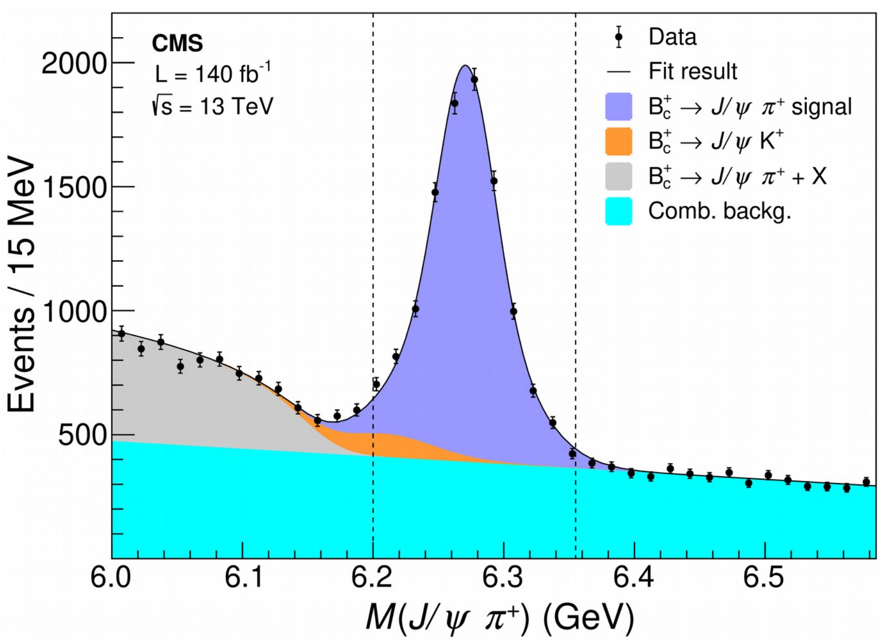


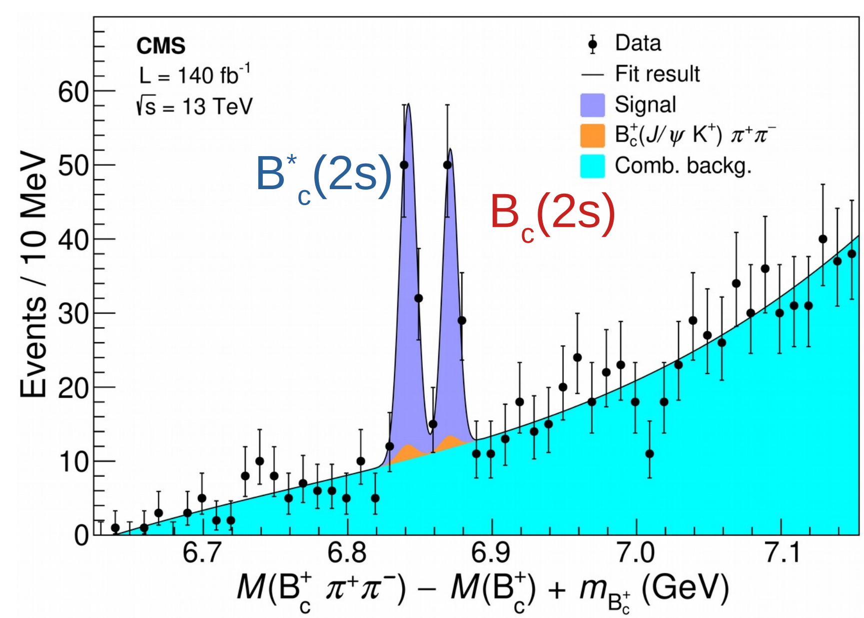
B_c(2s) excited state

CMS

Phys. Rev. Lett. 122 (2019) 132001

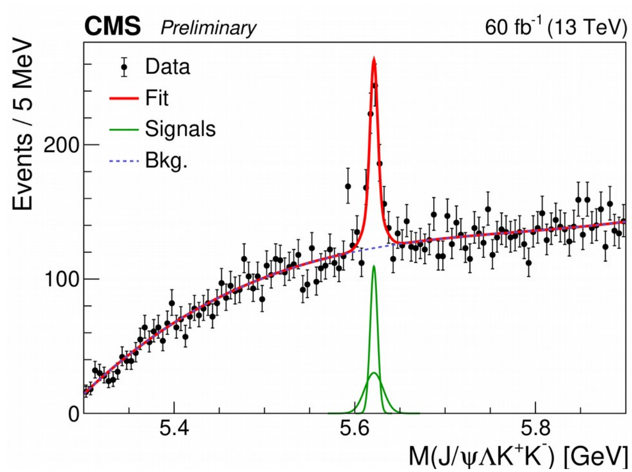
- Higher $P_T(B^+_c)$ threshold at 15 GeV
- ~ 7600 candidates
- Resolution allows to separate both peaks
- Δm_{exp} = 29 ± 1.5 ± 0.7 MeV
- $M(B^+_c(2s))$ = 6871.0 ± 1.2 (stat.)±1.1 (syst) MeV
- Two states recently seen also by LHCb
  - Compatible masses and Δm with CMS

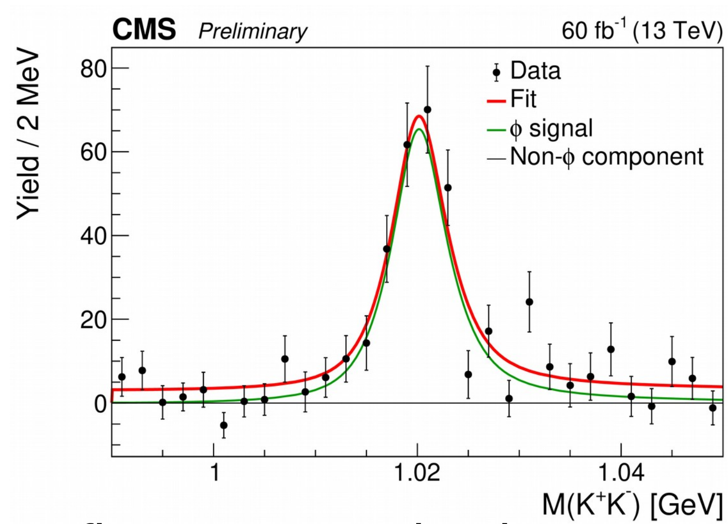


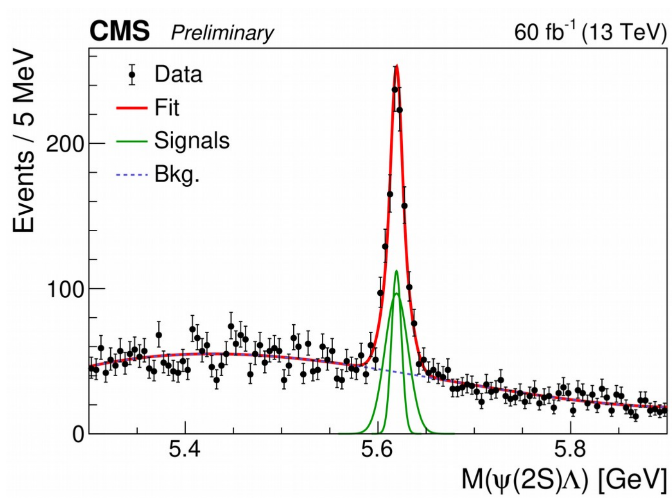


First observation of the $\Lambda_b \to J/\psi\Lambda\phi$ *CMS*

CMS-PAS-BPH-19-002







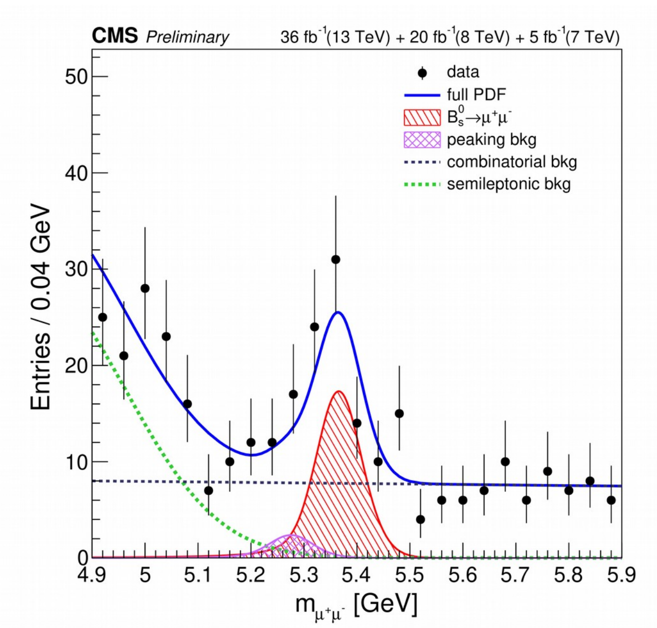
- 60 fb^{-1} at 13 TeV by the CMS
- $Br(\Lambda_b \to J/\psi\Lambda\varphi)/Br(\Lambda_b \to \psi(2S)\Lambda) = (8.26 \pm 0.90\,(stat) \pm 0.68\,(syst) \pm 0.11(Br)) \times 10-2$
- Calculated by callibration to $Br(\Lambda_b \to \psi(2S)\Lambda)$

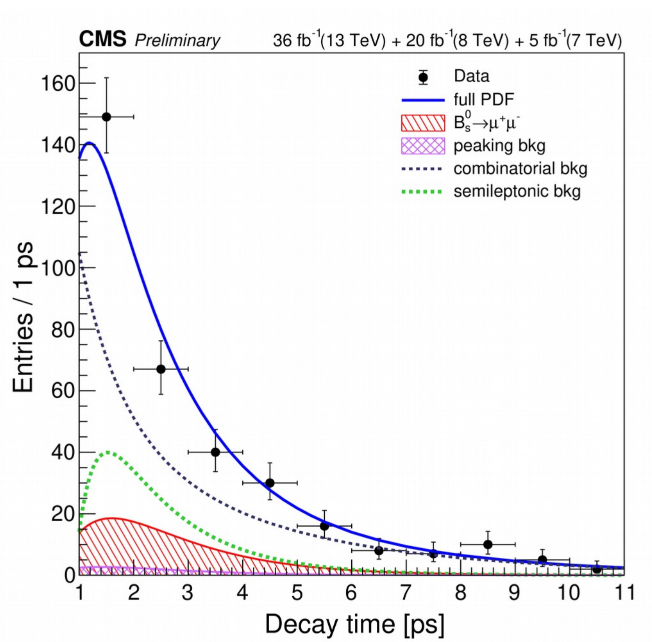
$$\frac{\mathcal{B}(\Lambda_b^0 \to J/\psi\Lambda\phi)}{\mathcal{B}(\Lambda_b^0 \to \psi(2S)\Lambda)} = \frac{N(\Lambda_b^0 \to J/\psi\Lambda\phi)\mathcal{B}(\psi(2S) \to J/\psi\pi^-\pi^+)\epsilon(\Lambda_b^0 \to \psi(2S)\Lambda)}{N(\Lambda_b^0 \to \psi(2S)\Lambda)\epsilon(\Lambda_b^0 \to J/\psi\Lambda\phi)\mathcal{B}(\phi \to K^+K^-)},$$

Rare decays

Measurement of $B^0_s \to \mu\mu$ and search $B_0 \to \mu\mu$

- Leptonic B meson decays offer excellent opportunities to perform precision tests of the SM due to minimal uncertainties
- $B^0_s \to \mu\mu$ was first observed by CMS and LHCb jointly, but $B^0 \to \mu\mu$ is still not observed yet
- Data sets: 5 and 20 fb^{-1} in 2011 and 2012 at 7 TeV and 8 TeV(Run 1), 36 fb^{-1} in 2016 at 13 TeV(Run2)





CMS

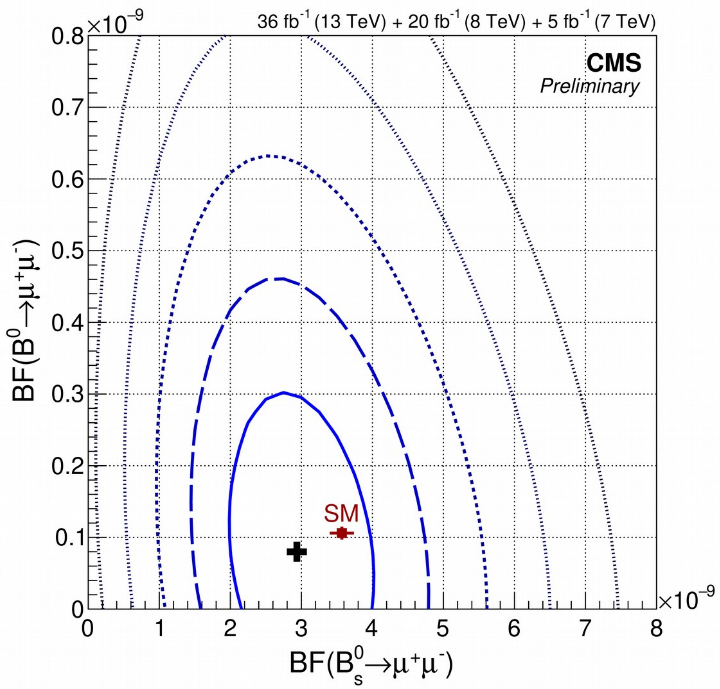
CMS-PAS-BPH-16-004

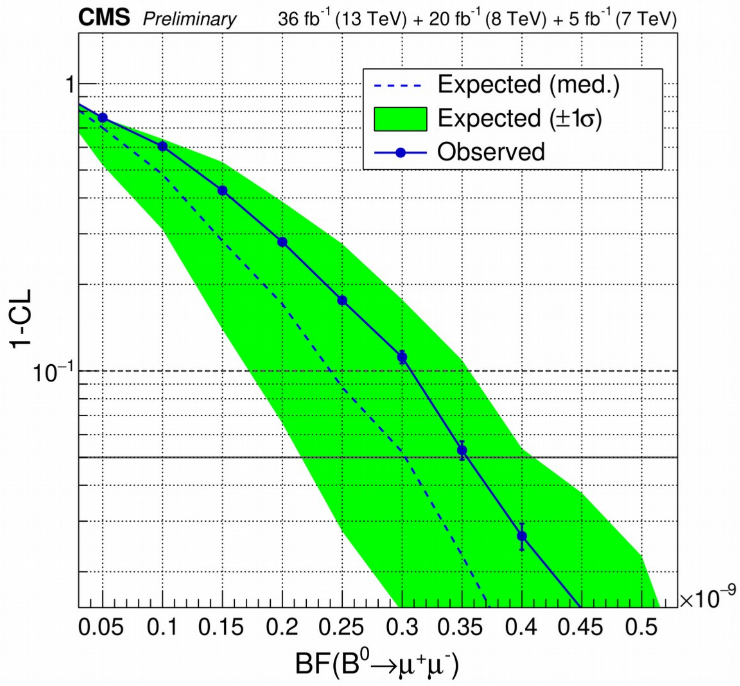
Measurement of $B^0_s \to \mu\mu$ and search $B_0 \to \mu\mu$

CMS-PAS-BPH-16-004

- The $B^0_s \to \mu\mu$ decay is observed (expected) with a significance of 5.6σ (6.5σ) and the time integrated branching fraction is measured to be $B(B^0_s \to \mu\mu) = [2.9\ ^{+0.7}_{-0.6}$ (exp) ± 0.2 (frag)] $\times 10^{-9}$,
- No significant $B^0 \to \mu\mu$ signal is observed and an upper limit $B(B^0 \to \mu\mu) < 3.6 \times 10^{-10}$ is determined at 95% CL
- B^0_s life time is measured $\tau_{\mu\mu} = 1.70\ ^{+0.61}_{-0.44}$ ps

CMS





$B_{s,d} \to \mu\mu$ BR measurement

ATLAS

- Rare but clean decay suppressed by FCNC in the SM
  - $BR(B_s \to \mu\mu) = (3.65 \pm 0.23)\times 10^{-9}$
  - $BR(B_d \to \mu\mu) = (1.06 \pm 0.09)\times 10^{-10}$
- Sensitive to New Physics contributions through loops
- Analysis strategy:

$$B(B_s^0 \to \mu\mu) = N(B_s^0 \to \mu\mu) \times [B(B^+ \to J/\psi K^+)] \times B(J/\psi \to \mu\mu) \times \left(\frac{f_u}{f_{s/d}}\right) \times \left(\frac{1}{D_{norm}}\right)$$

$$D_{norm} = \sum_k N_{J/\psi K}^k \alpha_k \left(\frac{\varepsilon_{\mu\mu}}{\varepsilon_{J/\psi K}}\right)_k$$

Hadronisation probabilities

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

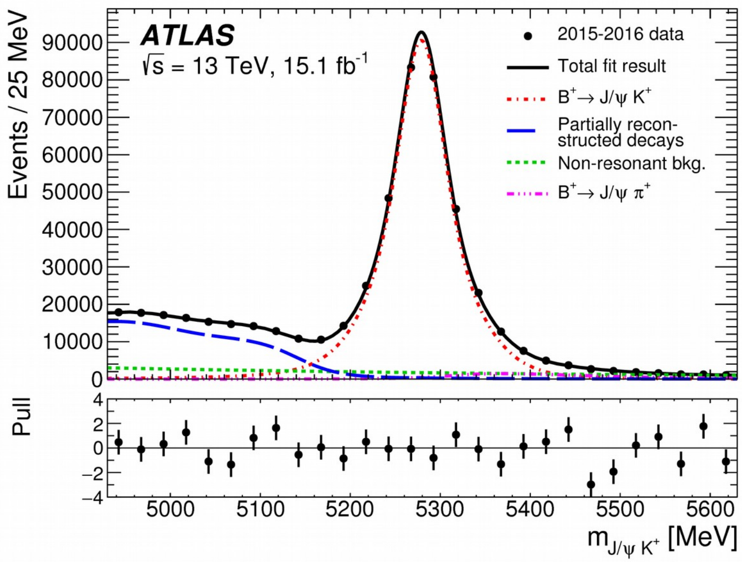
Reference channel: $B^\pm \to J/\psi K^\pm$ Extracted from an unbinned ML fit to $m(\mu\mu K^\pm)$ distribution

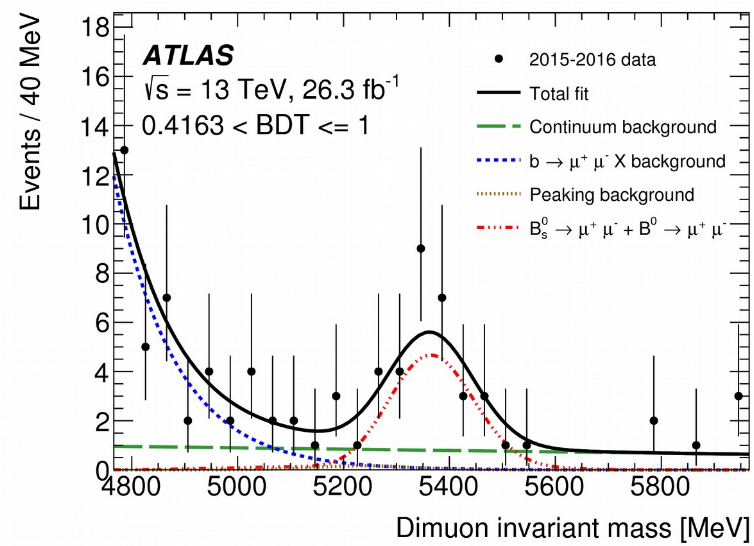
Trigger categories and luminosity prescales

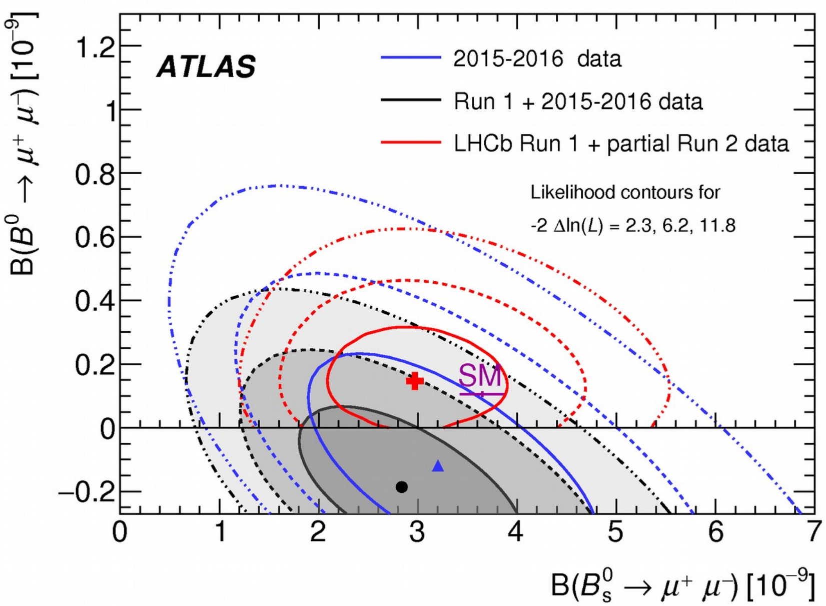
Acceptance and efficiencies from simulation

$B_{s,d} \rightarrow \mu\mu$ BR measurement

ATLAS [JHEP 04 (2019) 098]







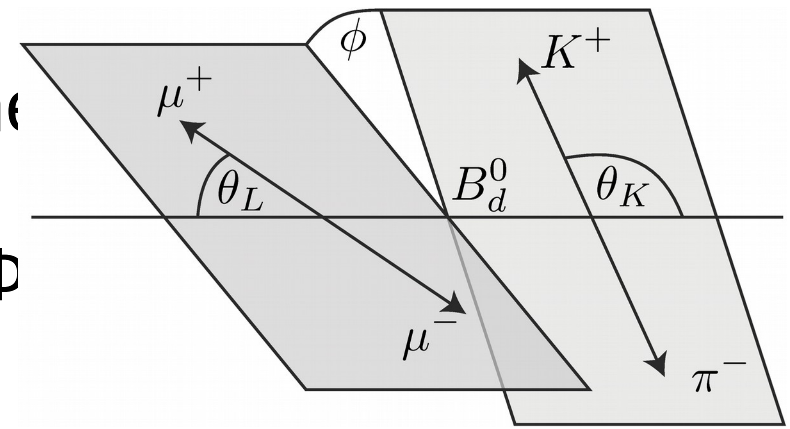
- Results for full Run1+Partial Run2 dataset (25+26 fb^{-1})
- $BR(B_s) = 2.8\ ^{+0.8}_{-0.7} x10^{-9}$ (stat. ± syst.)
  - Evidence at 4.6σ
- Upper limit on $BR(B_d)$ placed at $2.1x10^{-10}$(95% CL)
  - Currently the most stringent limit

Angular analysis of $B_d \rightarrow K^*\mu\mu$

ATLAS

JHEP 10 (2018) 047

- The study is using 20.3 fb^{-1} at 8 TeV
- Decay amplitude fully described by the invariant mass q^2 of the di-muon system and three angles: θ_L, θ_K and Φ
- S_i-angular coefficients, F_L- fraction of longitudinally polarised K*
- 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 q2

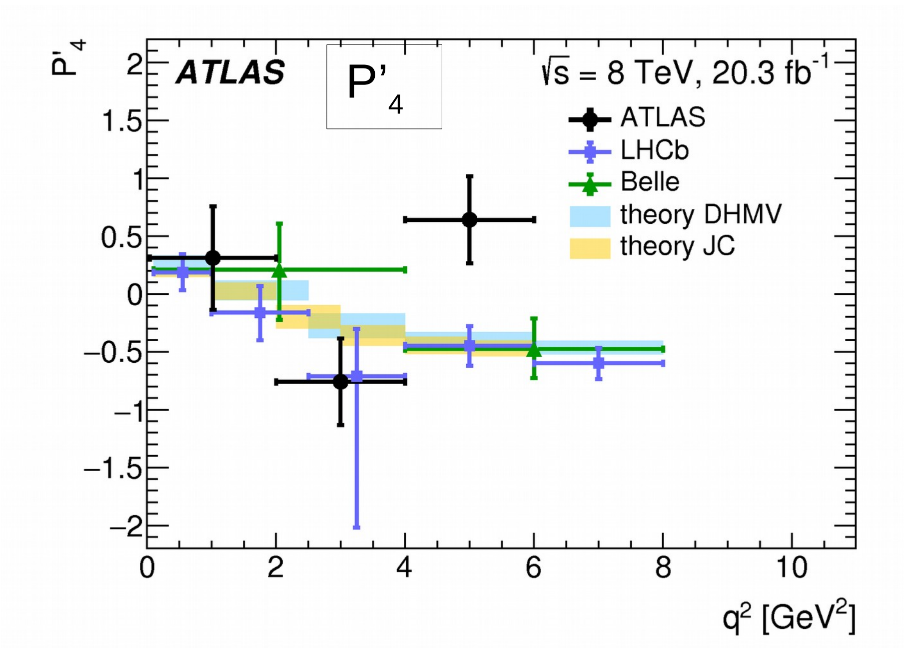


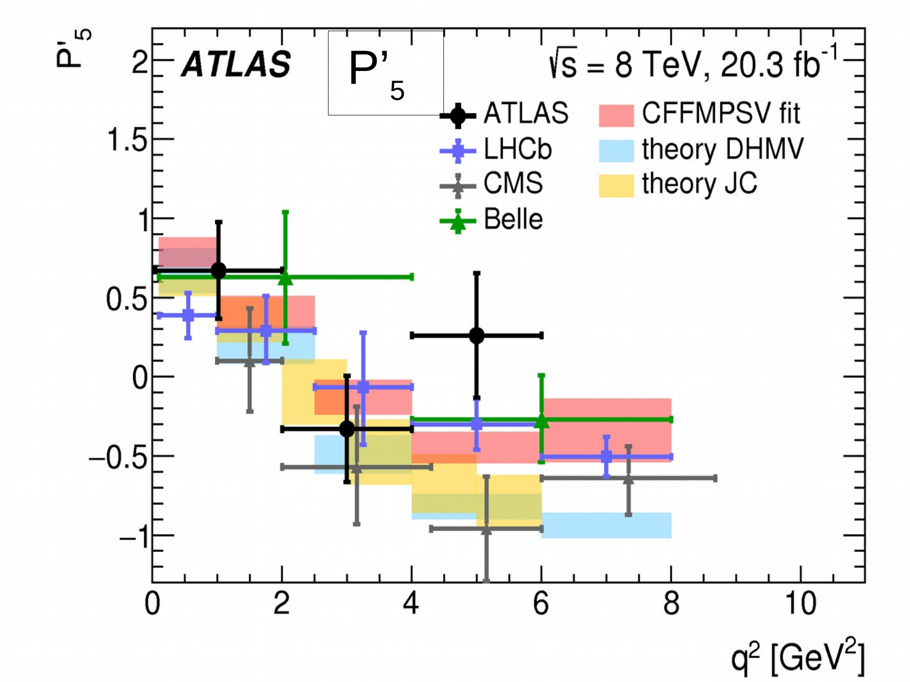
$$
\begin{aligned}
P_1 &= \frac{2S_3}{1-F_L} \\
P_2 &= \frac{2}{3}\frac{A_{FB}}{1-F_L} \\
P_3 &= -\frac{S_9}{1-F_L} \\
P'_{j=4,5,6,8} &= \frac{S_{i=4,5,7,8}}{\sqrt{F_L(1-F_L)}}.
\end{aligned}
$$

$B_d \to K^*\mu\mu$: Results

ATLAS

JHEP 10 (2018) 047





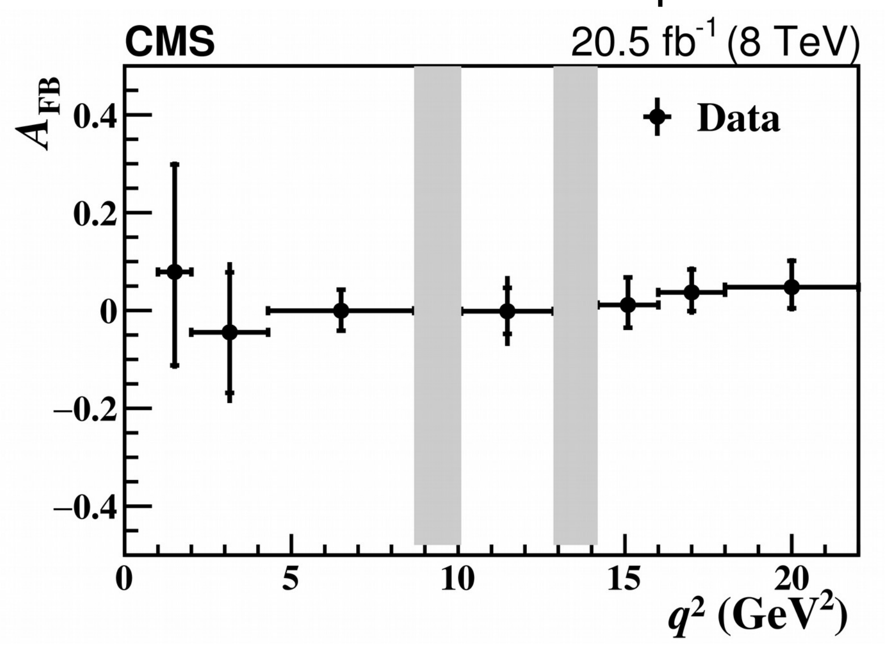
- largest deviation ~2.7σ from theoretical model for in P'_4 and P'_5 in $q^2 \in [4,6]$ GeV^2 bin
- results consistent with other experiments
  - deviation in P'5 coherent with LHCb measurement

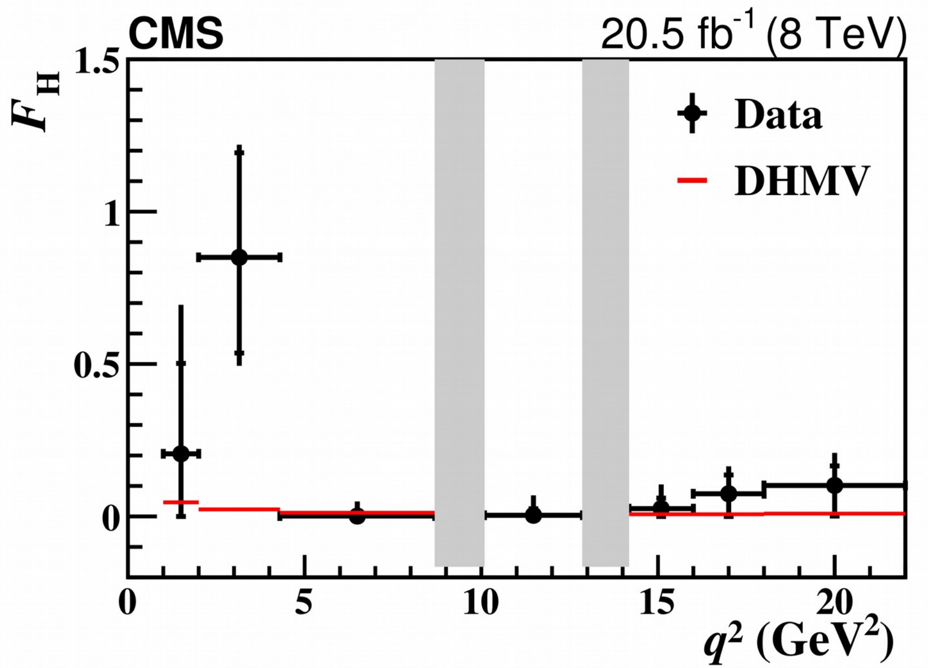
Angular analysis of the decay $B^+ \rightarrow K^+\mu\mu$

CMS

Phys. Rev. D 98 (2018) 112011

- The decay $B^+ \rightarrow K^+\mu\mu$ is a manifestation of a flavor changing neutral current process of the type $b \rightarrow sl^+l^-$
- A_{FB}- forward-backward asymmetry and contribution F_H from the pseudoscalar, scalar, tensor amplitudes to the decay width
- In the SM, A_{FB} is zero up to small corrections, and F_H is also small
- The results are consistent with previous measurements, and are also compatible with different standard model predictions



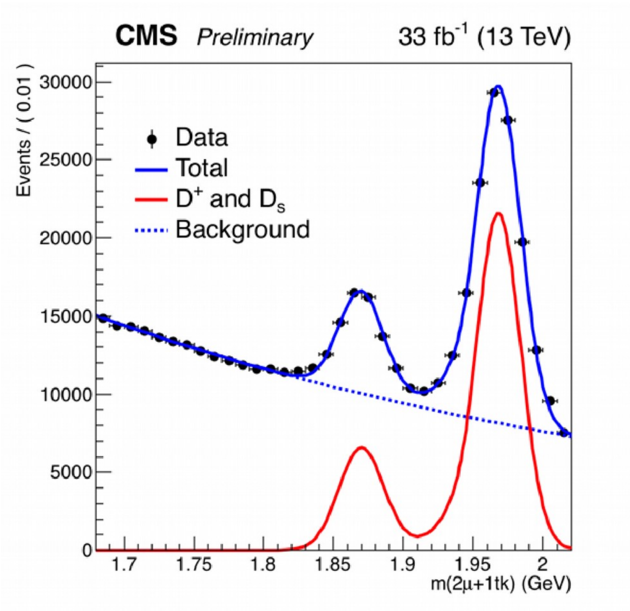


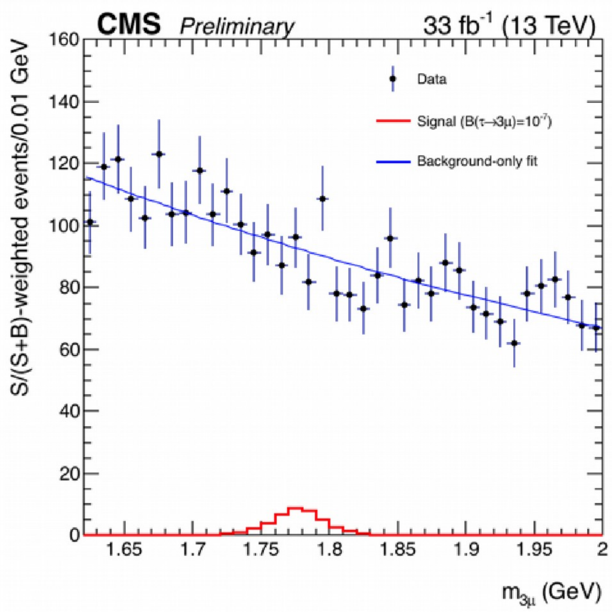
$\tau \rightarrow \mu\mu\mu$ BR measurement

CMS

CMS-PAS-BPH-17-004

- τ from Ds and B decays
- Maximum Likelihood fit in m($\mu\mu\mu$) simultaneously for the six categories (3 mass resolution regions X 2 BDT score regions)
- No excess observed. An upper observed (expected) limit of 8.8(9.9) $\times 10^{-8}$ is set on the branching fraction BR($\tau \rightarrow 3\mu$) at 90% CL



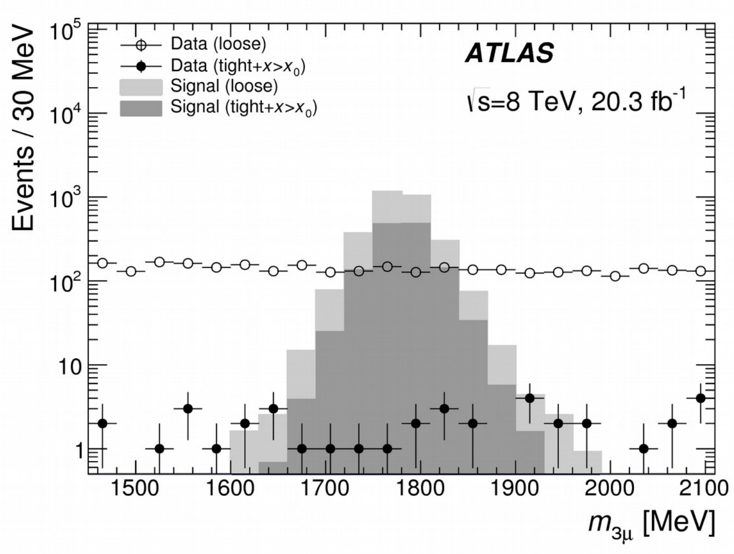


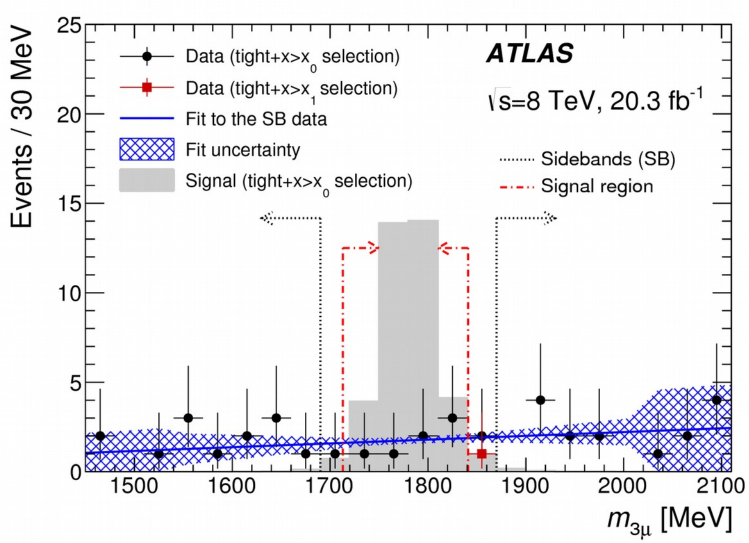
$\tau \to \mu\mu\mu$ BR measurement

ATLAS

Eur. Phys. J. C (2016) 76:232

- τ from $W \to \tau\nu$ decays (20.3 fb^{-1} at 8 TeV)
- $Br(\tau \to 3\mu) = \frac{N_s}{(A_s \times \varepsilon_s) N_{W \to \tau\nu}}$
- $N_{W \to \tau\nu} = (2.41 \pm 0.08) \times 10^8$
- No events are observed in the signal region for the final selection. $Br(\tau \to 3\mu)$ upper limit an observed(expected) $3.76(3.94) \times 10^{-7}$





$\tau \to \mu\mu\mu$ BR measurement

- No signal observed
- $Br(\tau \to 3\mu) < 2.1\times10^{-8}$ Belle
  - (Phys. Lett. B687 (2010) 139143)
- $Br(\tau \to 3\mu) < 8.8\times10^{-8}$ CMS
  - (CMS-PAS-BPH-17-004)
- $Br(\tau \to 3\mu) < 3.76\times10^{-7}$ ATLAS
  - (Eur. Phys. J. C (2016) 76:232)
- $Br(\tau \to 3\mu) < 4.6 \times 10^{-8}$ LHCb
  - (JHEP 02 (2015) 121)

CP Violation

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

ATLAS

- CPV occurs due to interference between a direct decay and a decay with B_s - $\overline{B}_s$ mixing
- 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 "B_s side" of the event)
- The final state $J/\psi(\rightarrow \mu\mu)\ \varphi(\rightarrow KK)$ is a superposition of CP=+1 and CP=-1 configurations

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

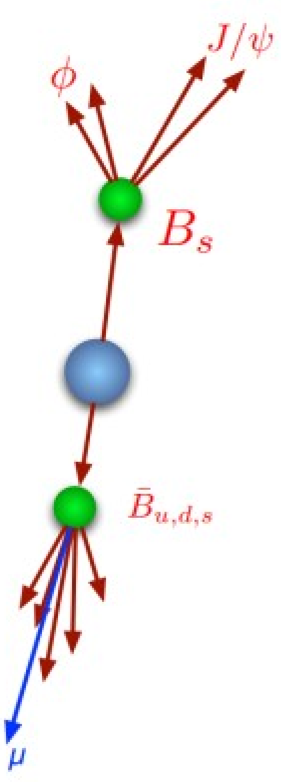
Flavour tagging

ATLAS

Opposite side tagging (to identify the flavour of neutral meson is extracted of the other(or opposite) b-hadron from the pair of b and $\bar{b}$ quarks)

- Use b-$\bar{b}$ correlation to determine initial signal flavour from the other B-meson in the event
- b → l transition are clean tagging method
- b → c → l and neutral B-meson oscillations dilute the tagging
- Provide probability of signal candidate to be B^0_s or $\bar{B}^0_s$
- Tagger types :
  - tight muon, low-p_T muon, electron, b-tagged jet
- Signal flavour probability derived from charge of p_T weighted tracks in a cone around the opposite side primary object (e±, μ±, b-jet)

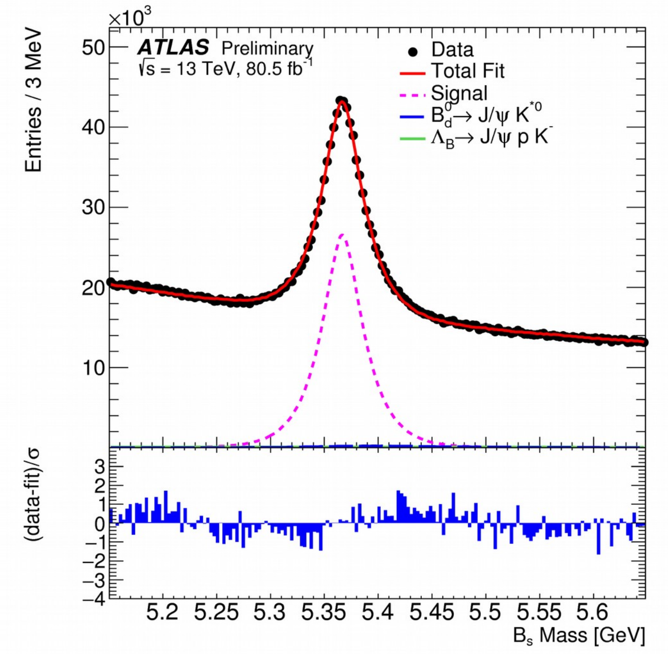
$$Q_x = \frac{\sum_i^{N\ \mathrm{tracks}} q_i \cdot (p_{\mathrm{T}i})^\kappa}{\sum_i^{N\ \mathrm{tracks}} (p_{\mathrm{T}i})^\kappa}$$

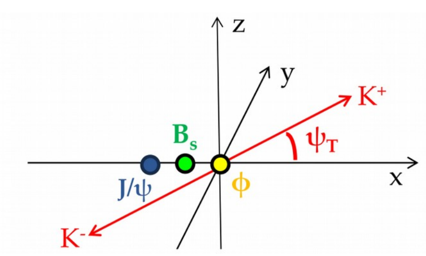


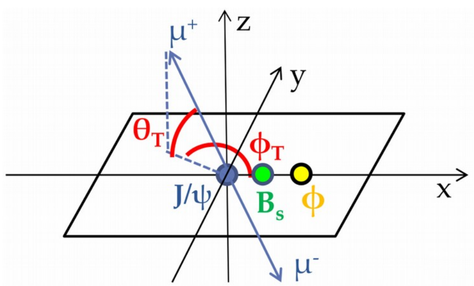
CPV in $B_s \rightarrow J/\psi\phi$

ATLAS

- ATLAS result: [ATLAS-CONF-2019-009]
- Angular analysis with 10 amplitude functions is done
- Simultaneous fit in Bs mass, lifetime, and the three angles
- Extraction of the amplitude parameters and phases with correlations
- Main systematics:
  - Tagging for φs
  - Fit models for signal and background for Γ_s and Δr_s







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

ATLAS

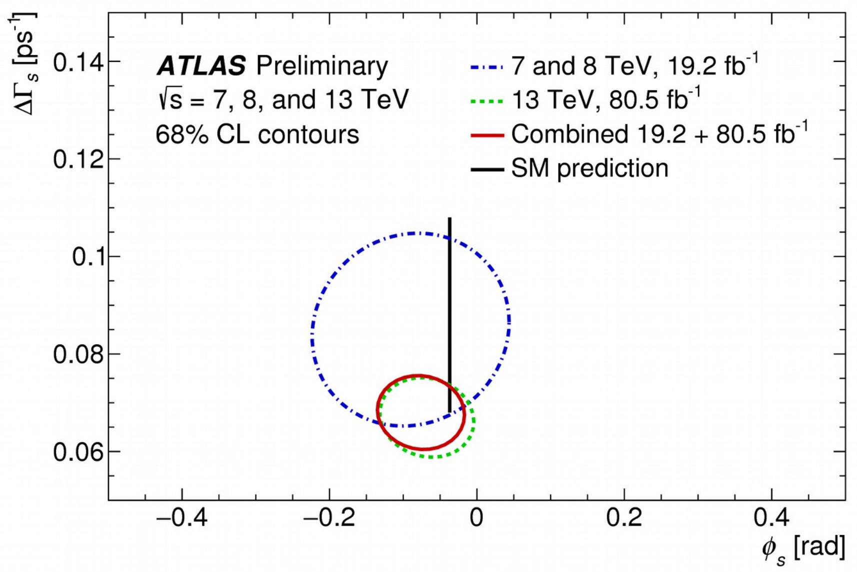
ATLAS-CONF-2019-009

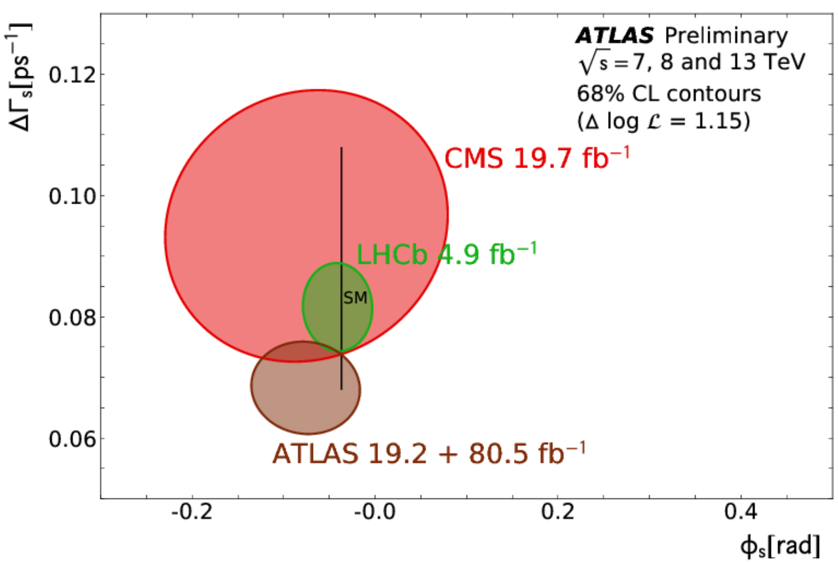
ATLAS results:

- $\varphi_s = -0.076 \pm 0.034$ (stat.) ± 0.019 (syst.) rad
- $\Delta\Gamma_s = 0.068 \pm 0.004$ (stat.) ± 0.003 (syst.) ps^{-1}

φ_s (combined)=-0.055±0.021 rad

Parameter	Value	Statistical uncertainty	Systematic uncertainty
ϕ_s[rad]	−0.076	0.034	0.019
$\Delta\Gamma_s[ps^{-1}]$	0.068	0.004	0.003
$\Gamma_s[ps^{-1}]$	0.669	0.001	0.001
$\lvert A_{\parallel}(0)\rvert^2$	0.220	0.002	0.002
$\lvert A_0(0)\rvert^2$	0.517	0.001	0.004
$\lvert A_S\rvert^2$	0.043	0.004	0.004
$\delta_\perp$ [rad]	3.075	0.096	0.091
$\delta_\parallel$ [rad]	3.295	0.079	0.202
$\delta_\perp - \delta_S$ [rad]	−0.216	0.037	0.010





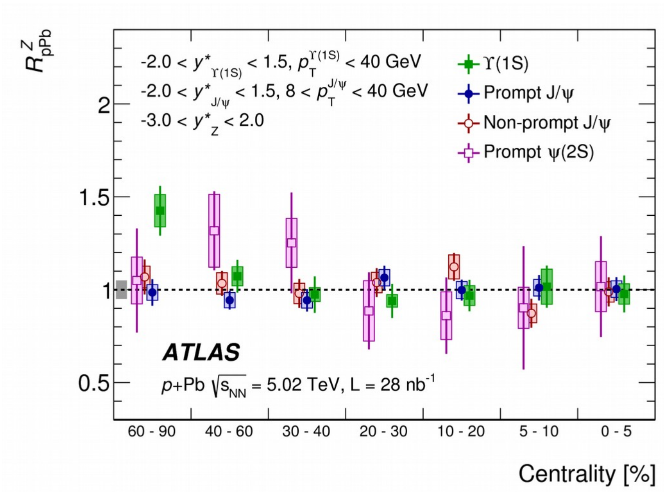
Conclusion

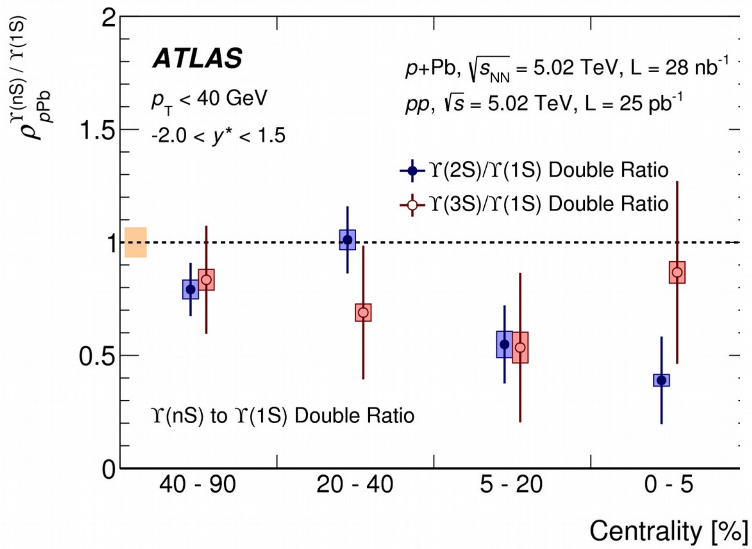
- Several measurements in the B-phyiscs and light states areas have been shown
- Both ATLAS and CMS are able to constrain QCD and EW predictions and to give valuable inputs to theoretical models for spectroscopy and quarkonia
- Both experiments can be competitive with LHCb in few areas
- Both experiments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

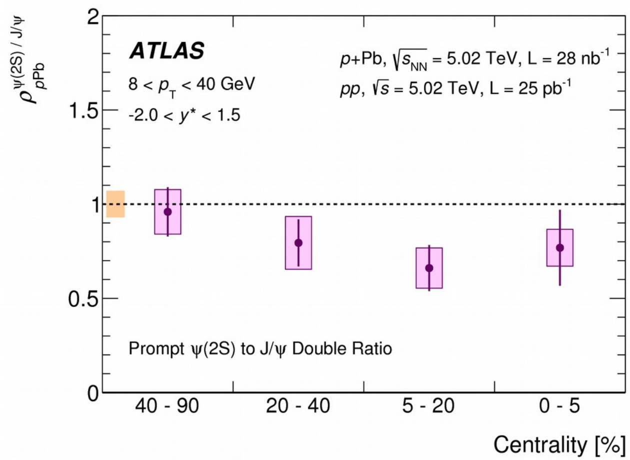
Backup

Nuclear modification factor R

ATLAS







$$R^{Z}_{p\mathrm{Pb}}(O(nS)) = \frac{N^{\mathrm{cent}}_{O(nS)}/N^{\mathrm{cent}}_{Z}}{N^{0-90\%}_{O(nS)}/N^{0-90\%}_{Z}}$$

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

- The behaviour of the ground-state yields as a function of centrality is found to match that of Z bosons, while excited states are relatively suppressed in more central collisions
- A stronger cold nuclear matter effect is observed in excited quarkonium states compared to that in ground states

$B_{s,d} \to \mu\mu$ BR measurement

- Measurement by CMS and LCHb (combined):

  $BR(B_s \to \mu\mu) = 2.8 \cdot 10^{-9}$ $3.0 \cdot 10^{-9}$ LHCb-only(Run2)

  $BR(B_d \to \mu\mu) = 3.9 \cdot 10^{-10}$ $< 3.4 \cdot 10^{-10}$

- CMS last result:

  $BR(B^0_s \to \mu\mu) = 2.9 \cdot 10^{-9}$

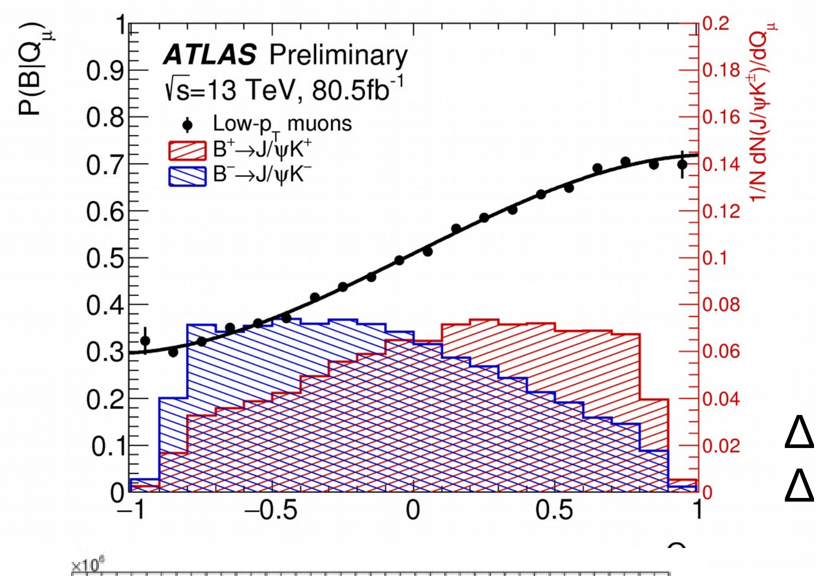
  $BR(B_d \to \mu\mu) < 3.6 \cdot 10^{-10}$

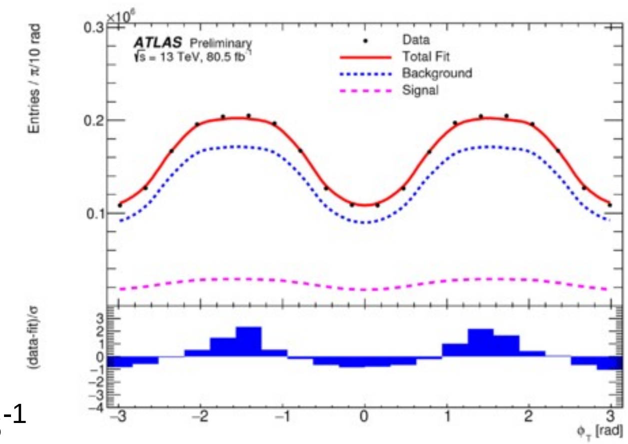
- ATLAS last result:

  $BR(B^0_s \to \mu\mu) = 2.8 \cdot 10^{-9}$

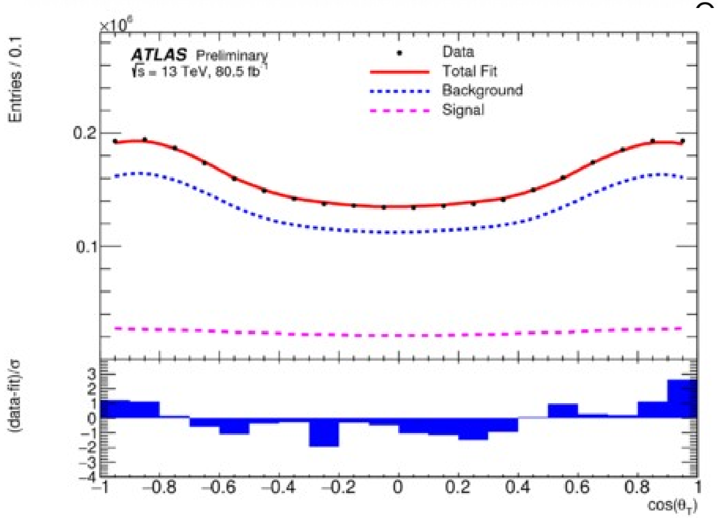
  $BR(B_d \to \mu\mu) < 2.1 \cdot 10^{-10}$

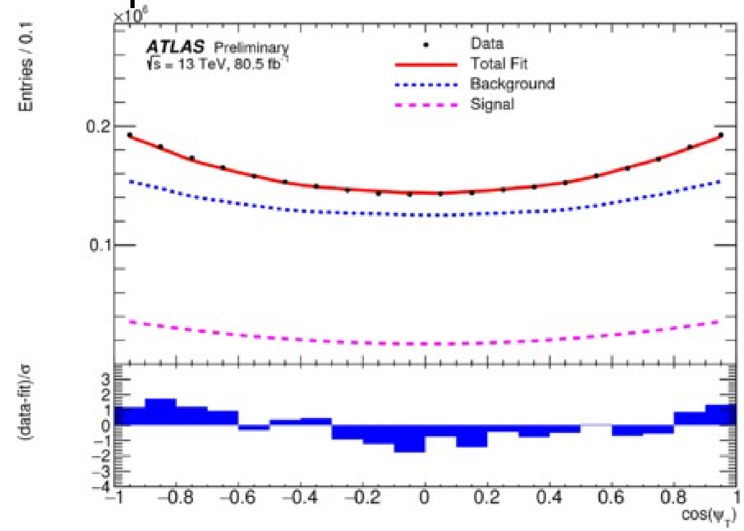
CP violation in $B_s \rightarrow J/\psi\phi$





$\Delta\Gamma s = 0.087 \pm 0.021$ ps^{-1}
$\Delta\Gamma s(\text{comb}) = 0.0764$ ps^{-1}





Search for the X(5568) → $B^0_s \pi^\pm$ in pp collisions at 8 TeV

CMS

[Phys. Rev. Lett. 120 (2018) 202005](#)

- $\rho_X < 1.1\%$ at 95% CL for $p_T(B^0_s) > 10$ GeV
- $\rho_X < 1.0\%$ at 95% CL for $p_T(B^0_s) > 15$ GeV
- $\rho_X^{LHCb} < 2.4\ \%$ at 95% CL