Heavy flavor production and properties in ATLAS and CMS

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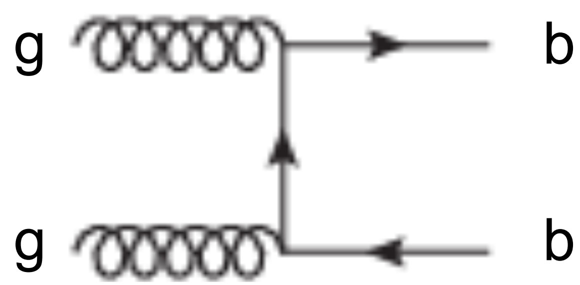
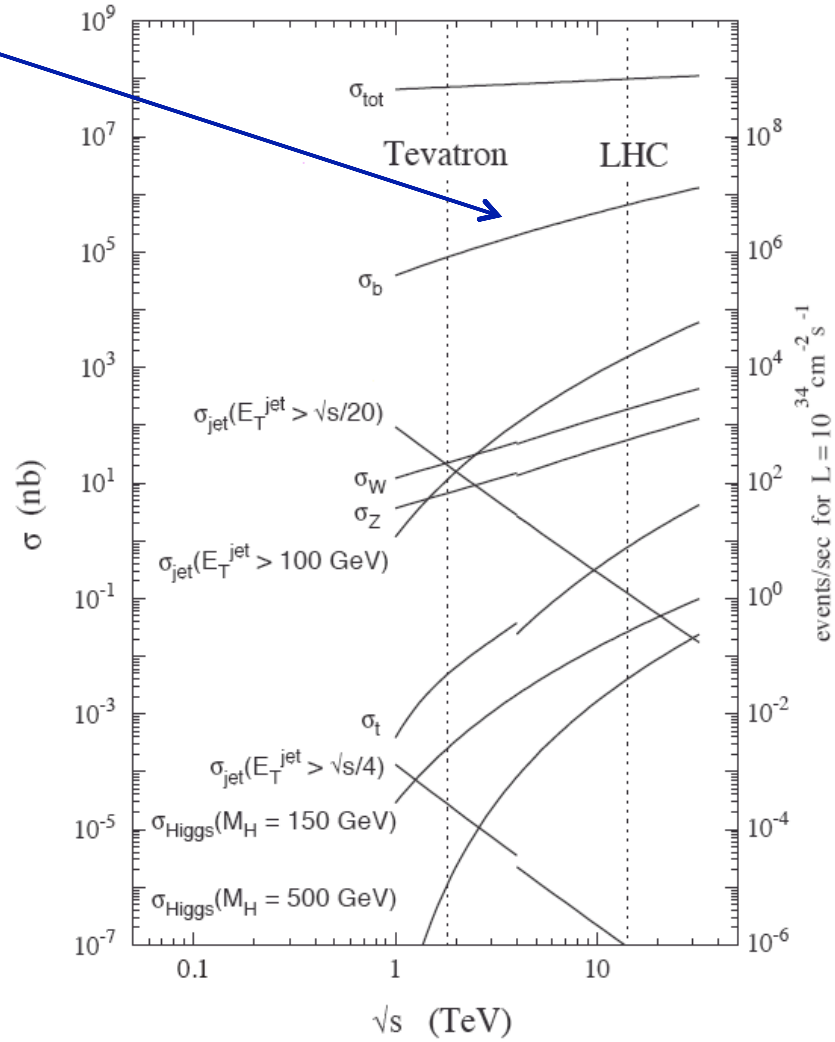
On behalf of the ATLAS and CMS Collaborations

b hadron production at the LHC

- *b hadrons (and anti-hadrons) are dominantly produced through strong interaction in pp collisions at the LHC*
  - *Example: gluon-gluon fusion*
  - *Large inclusive $b\bar{b}$ cross-section (~ 0.1 mb)*
  - *All b hadron types including Λ_b , B_c and B_s are produced*

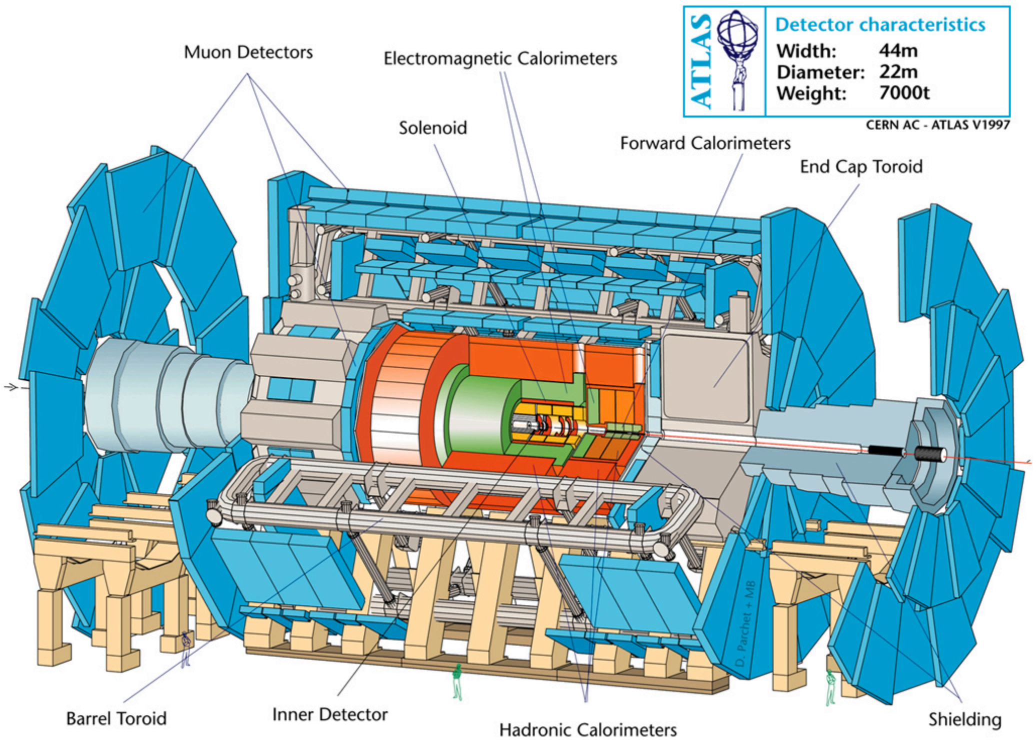


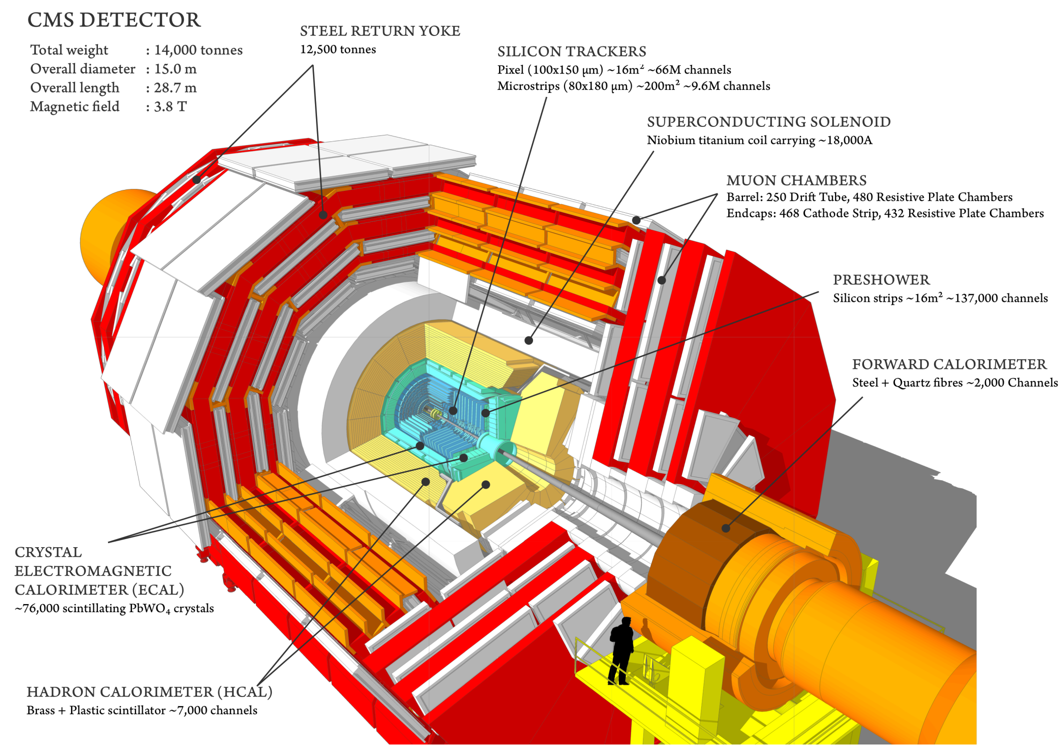


- *Unfortunately, it's hard to efficiently trigger on b hadron decays at the LHC*
  - *b decay products have relatively low p_T, predominantly produced in forward direction*
  - *Rare hadronic final states swamped by light hadron backgrounds*

- *Exceptions*
  - *Dedicated displaced vertex triggers (for example, LHCb)*
  - *Specific final states, e.g. including di-muons*

The ATLAS and CMS detectors

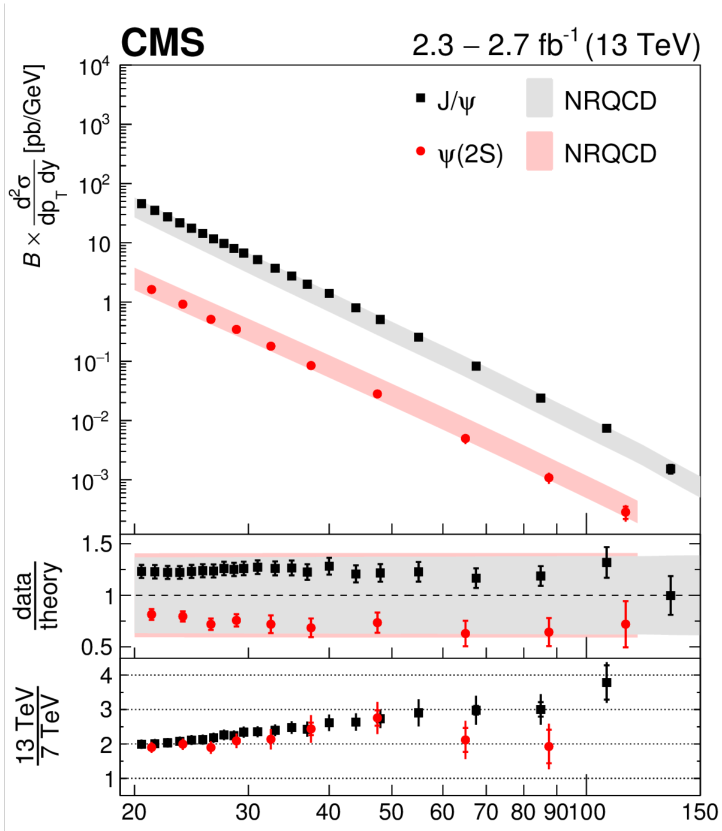


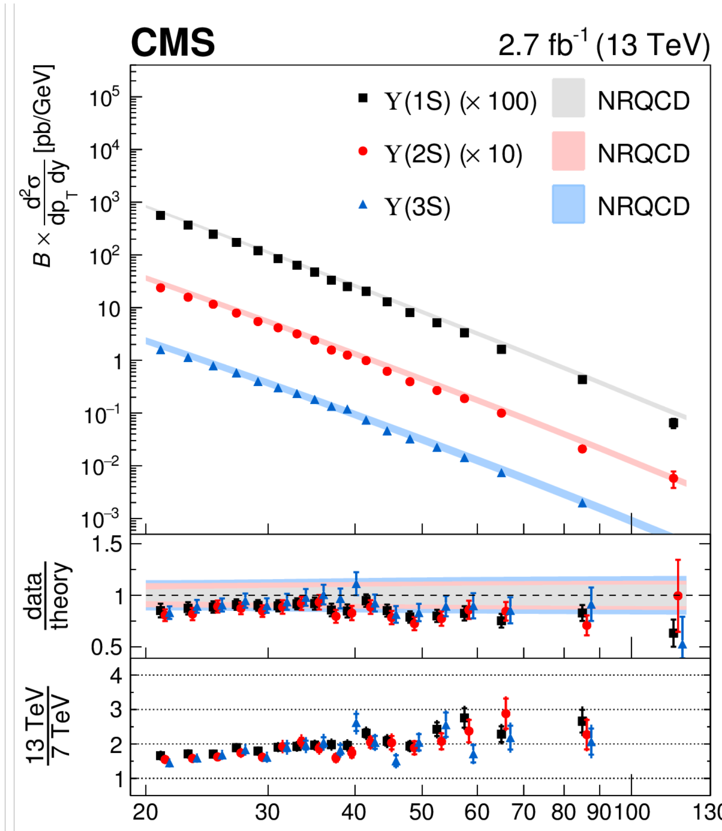


- *Multipurpose detectors with similar performance designed to study pp collisions at 14 TeV*
  - *Track momentum resolution and therefore b hadron mass resolution depends critically on magnetic field strength*
    - *ATLAS: 2T; CMS: 4T*
  - *Fake muon rejection critical for background suppression*
    - *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}*

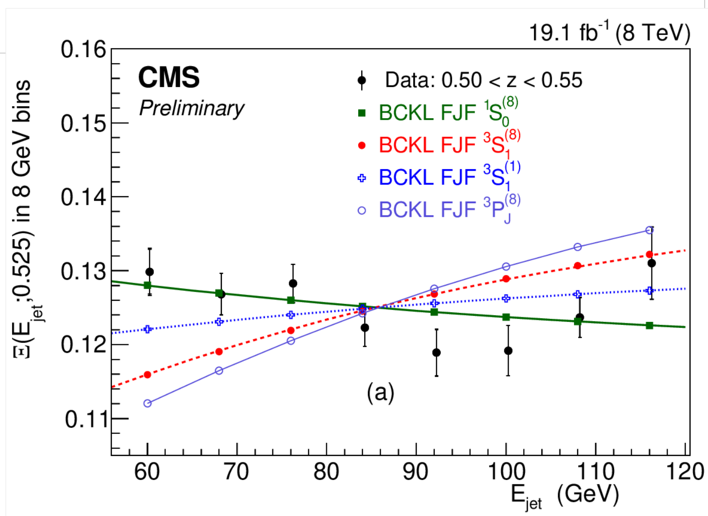
Quarkonium production in pp

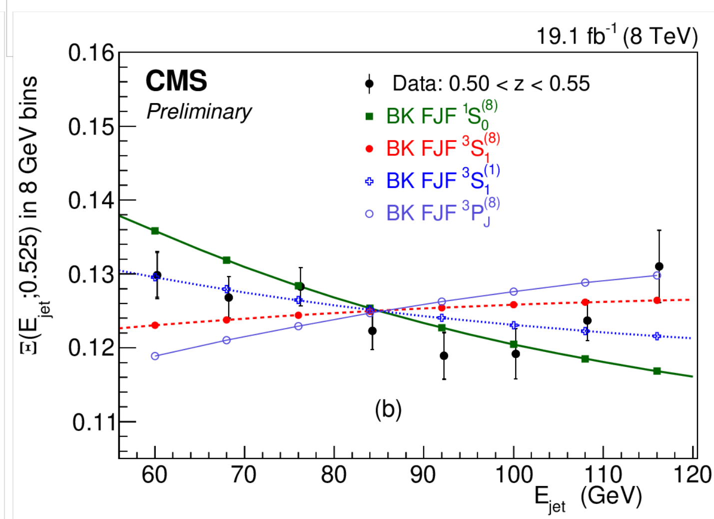
- Production of prompt quarkonium (Q) tests NRQCD framework
  - Factorization hypothesis and LDME universality
- New measurements of double-differential x-sections (p_T, y) agree with NLO NRQCD predictions





- Measurement of J/ψ in conjunction with jets
  - 84% of J/ψ > 15 GeV and |y| <1 are fragments of jet with |η| < 1
  - New way to test NRQCD predictions and to measure LDMEs

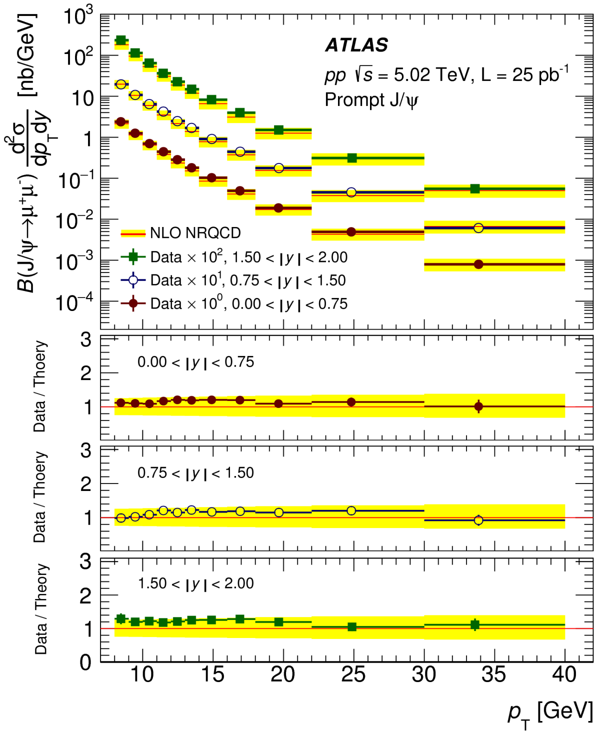


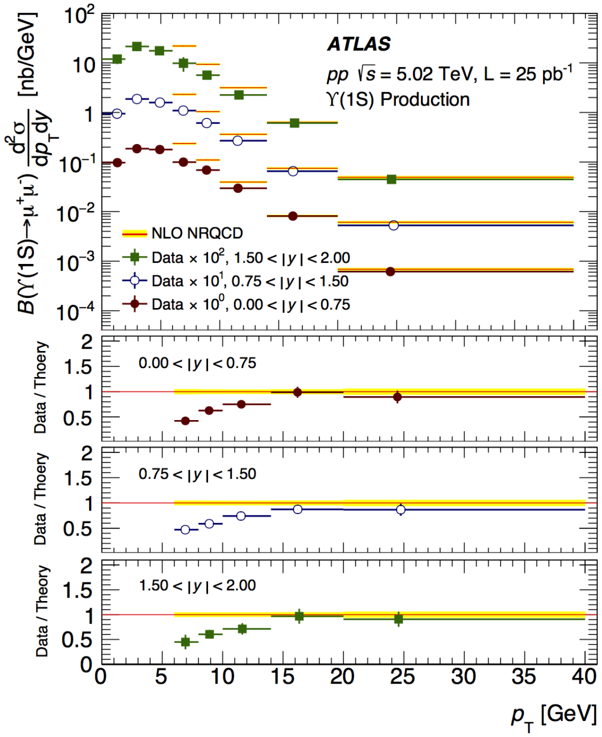


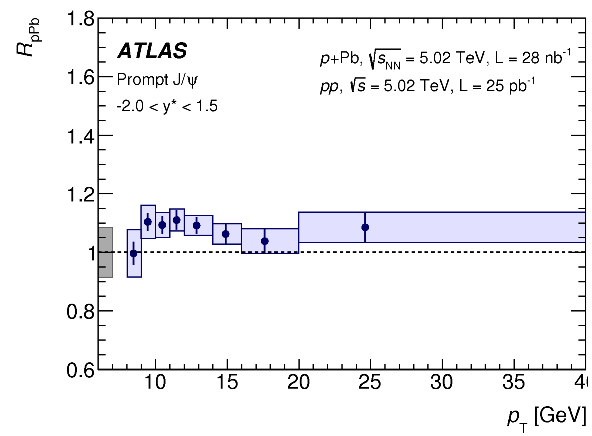
Quarkonium production in pp and pPb

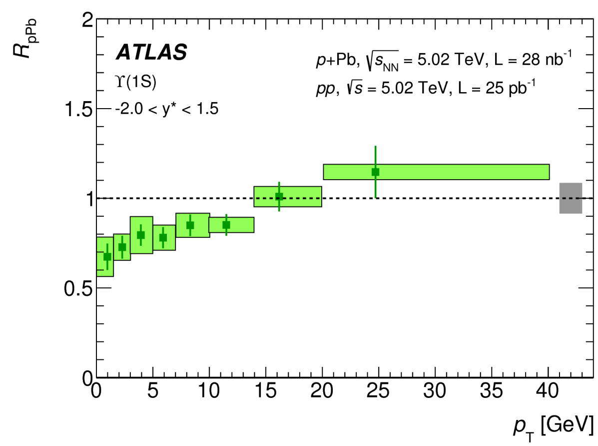
- *Prompt heavy quarkonium (Q) production tests QGP created in ultra-relativistic heavy ion (A+A) collisions*
- *p+A collisions can be used to disentangle effects from interaction of Q with cold nuclear matter (CNM)*
  - *Q suppression in p+A collisions attributed to CNM*
- *ATLAS measure*
  - *Prompt and non-prompt J/ψ and ψ(2S) differential x-sections (p_T,y) and nuclear modification factor R_{pPb}*

    and observe
  - *Weak modification of J/ψ production due to CNM effects at central rapidity and high pT*
  - *Suppression of ϒ(1S) at low pT*









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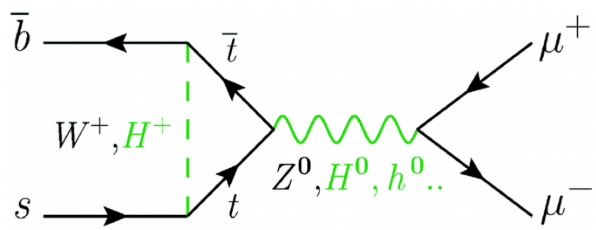
Search for rare decays $B_{s,d} \to \mu\mu$

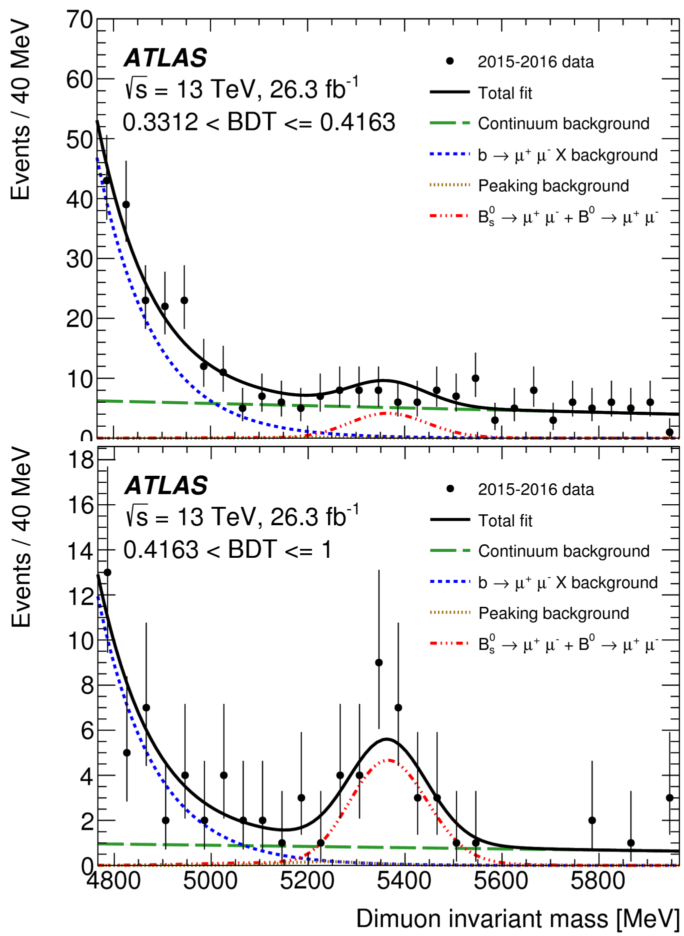
- *FCNC in the SM is forbidden at tree level*
- *BFs could be enhanced significantly by NP particles*



Standard Model predictions
[Bobeth et al., PRL 112 (2014) 101801]

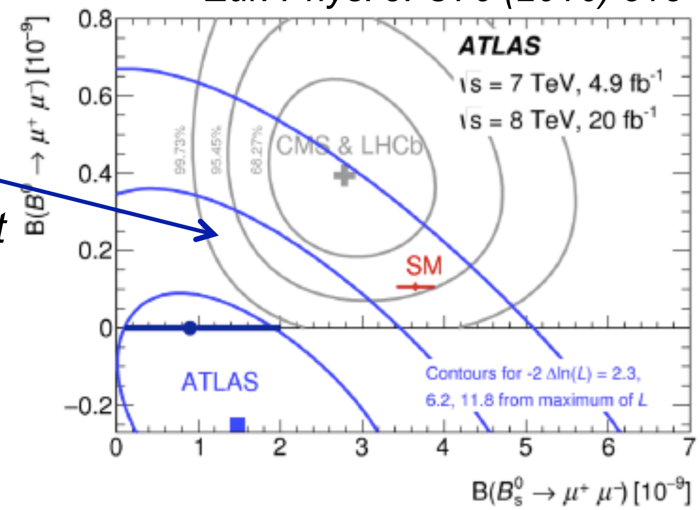
$$BF(B_s \to \mu\mu) = (3.65 \pm 0.23) \times 10^{-9}$$
$$BF(B_d \to \mu\mu) = (1.06 \pm 0.09) \times 10^{-10}$$

Unbinned ML fit to m(μμ) distribution in 4 BDT bins



Some tension between Run 1 measurements

Eur. Phys. J. C76 (2016) 513



LHCb Run 2 measurement reduced tension [PRL 118 (2017) 191801] :

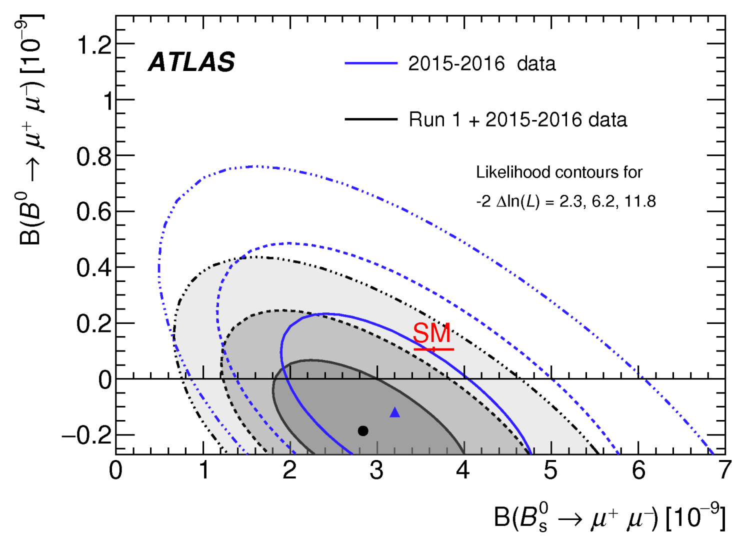
$$B(B^0 \to \mu\mu) < 3.4 \times 10^{-10} \text{ @95\% C.L.}$$

ATLAS Run 2 measurements

$$B(B_s \to \mu\mu) = \left(3.21^{+0.96+0.49}_{-0.91-0.30}\right) \times 10^{-9}$$
$$B(B_d \to \mu\mu) < 4.3 \times 10^{-10}$$

ATLAS Run 1+2 combinations

$$B(B_s \to \mu\mu) = (2.8 \pm 0.7) \times 10^{-9}$$
$$B(B_d \to \mu\mu) = (-1.9 \pm 1.6) \times 10^{-10}$$
$$B(B_d \to \mu\mu) < 2.1 \times 10^{-10}$$

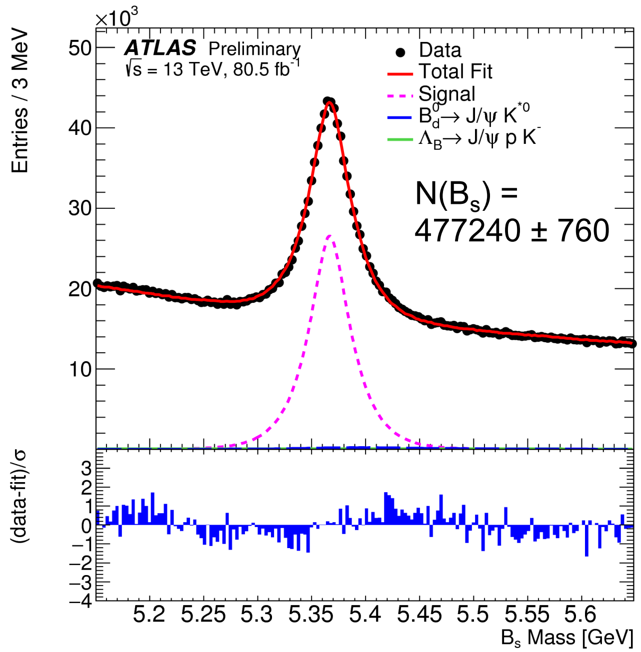


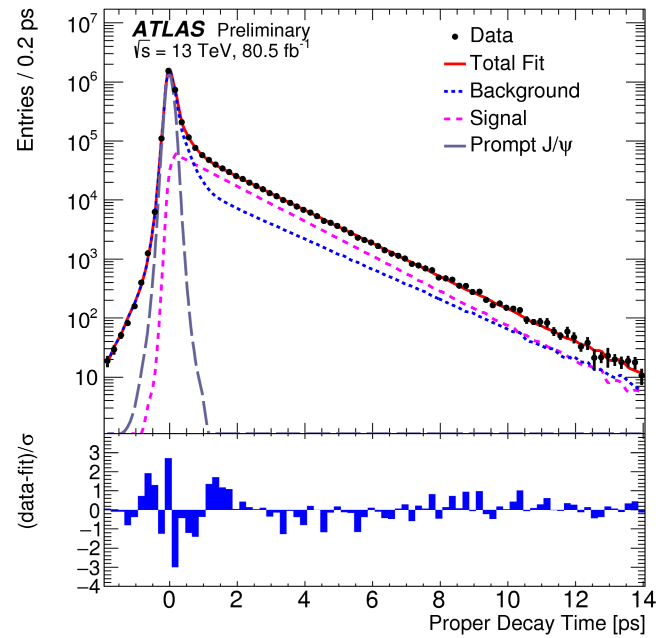
CP Violation in $B_s \to J/\psi\ \phi$

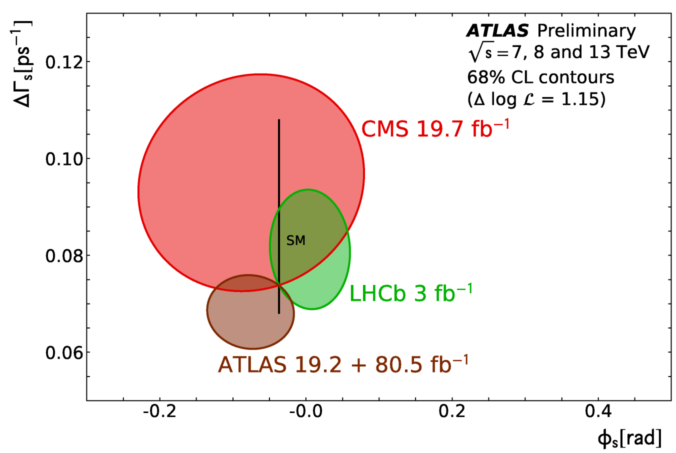
- *Weak phase between B_s direct decay and decay after mixing is sensitive to new physics*
  - *SM: $\phi_s = -0.0363 \pm 0.0016$*
    [Charles et al., PRD 84 (2014) 033005]
- *Decay $B_s \to J/\psi\ \phi\ (K^+K^-)$ has an admixture of CP-odd and CP-even final states*
  - *Separated statistically based on decay angular information*
- *Determine weak phase ϕ_s along with other parameters from simultaneous fit to B_s and B_s decay time and decay angular distributions*

80.5 fb^{-1} ('15-'17) + 19.2 fb^{-1} Run 1

$$\phi_s = -0.076 \pm 0.034 \pm 0.019$$
$$\Delta\Gamma_s = +0.068 \pm 0.004 \pm 0.003$$
$$\Gamma_s = +0.669 \pm 0.001 \pm 0.001$$





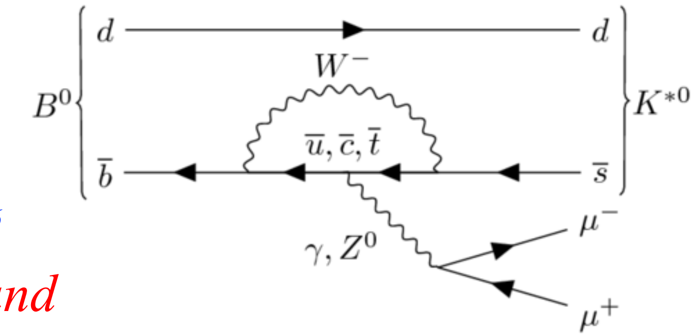


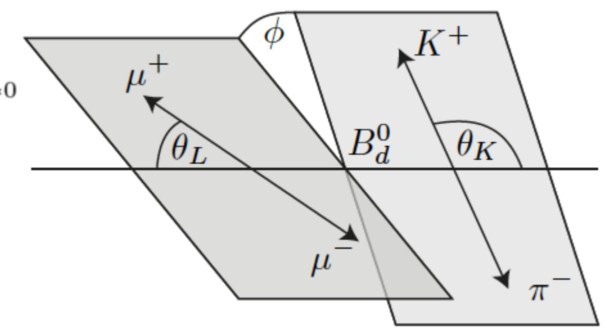
Results based on 80.5 fb^{-1} ('15-'17)

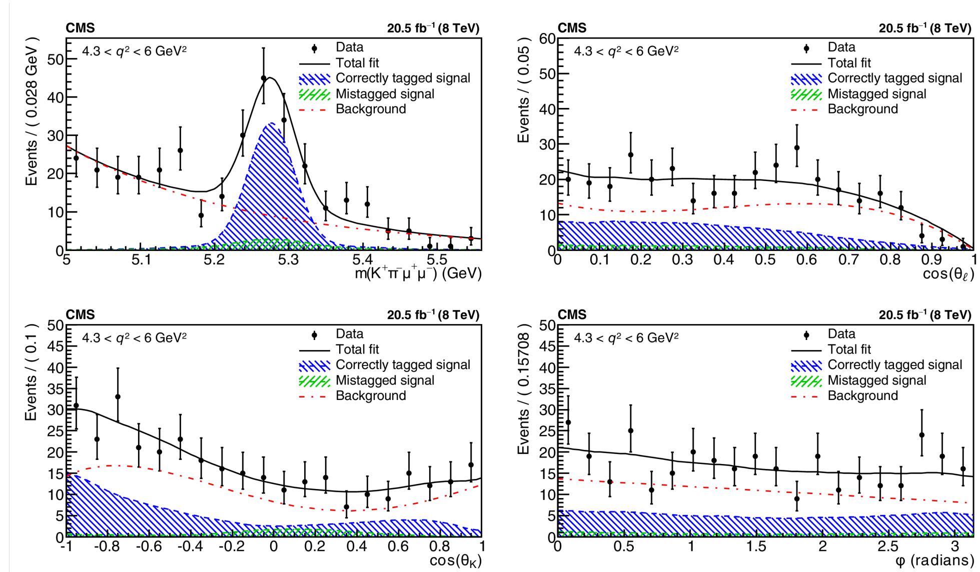
Parameter	Value	Statistical uncertainty	Systematic uncertainty
ϕ_s[rad]	−0.068	0.038	0.018
$\Delta\Gamma_s$[ps^{-1}]	0.067	0.005	0.002
Γ_s[ps^{-1}]	0.669	0.001	0.001
$\lvert A_\parallel(0)\rvert^2$	0.219	0.002	0.002
$\lvert A_0(0)\rvert^2$	0.517	0.001	0.004
$\lvert A_S(0)\rvert^2$	0.046	0.003	0.004
$\delta_\perp$ [rad]	2.946	0.101	0.097
$\delta_\parallel$ [rad]	3.267	0.082	0.201
$\delta_\perp - \delta_S$ [rad]	−0.220	0.037	0.010

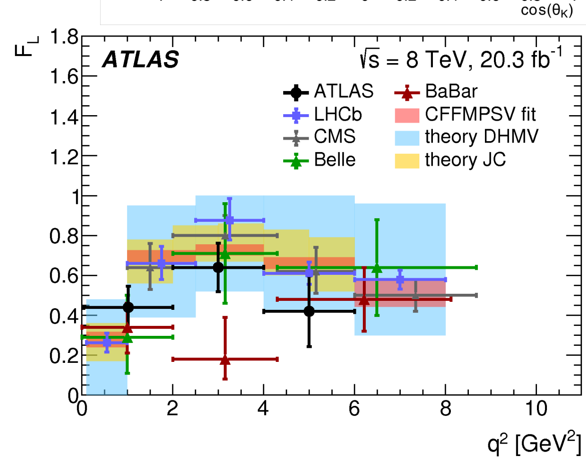
Angular analysis of $B_d \to K^* \mu\,\mu$

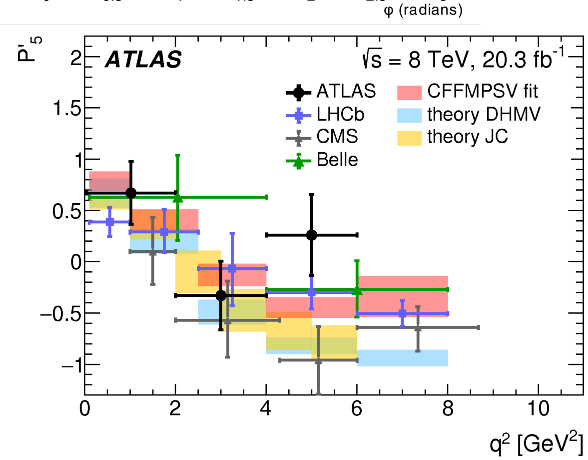
- *Rare flavor-changing neutral current decay sensitive to BSM physics in the box/loop*
  - *$BR(B_d \to K^* \mu\,\mu) = (1.02 \pm 0.09) \times 10^{-6}$*
- *Fit decay angular distributions and compare measured parameters to SM predictions*
- *LHCb and Belle have previously reported 3.4 σ and 2.6 σ deviations from the Standard Model [JHEP 02 (2016) 104, PRL 118 (2017) 111801]*
- *ATLAS data compatible with SM [JHEP 10 (2018) 47]*
  - *Largest deviations ATLAS sees are 2.7 σ wrt DHMV for P'_4, P'_5 in $4 < q^2 < 6$ GeV^2 bin*
  - *All ATLAS measurements are within 3 σ range covered by predictions*
- *Recent CMS measurement also agree with SM [PLB 781 (2018) 517]*





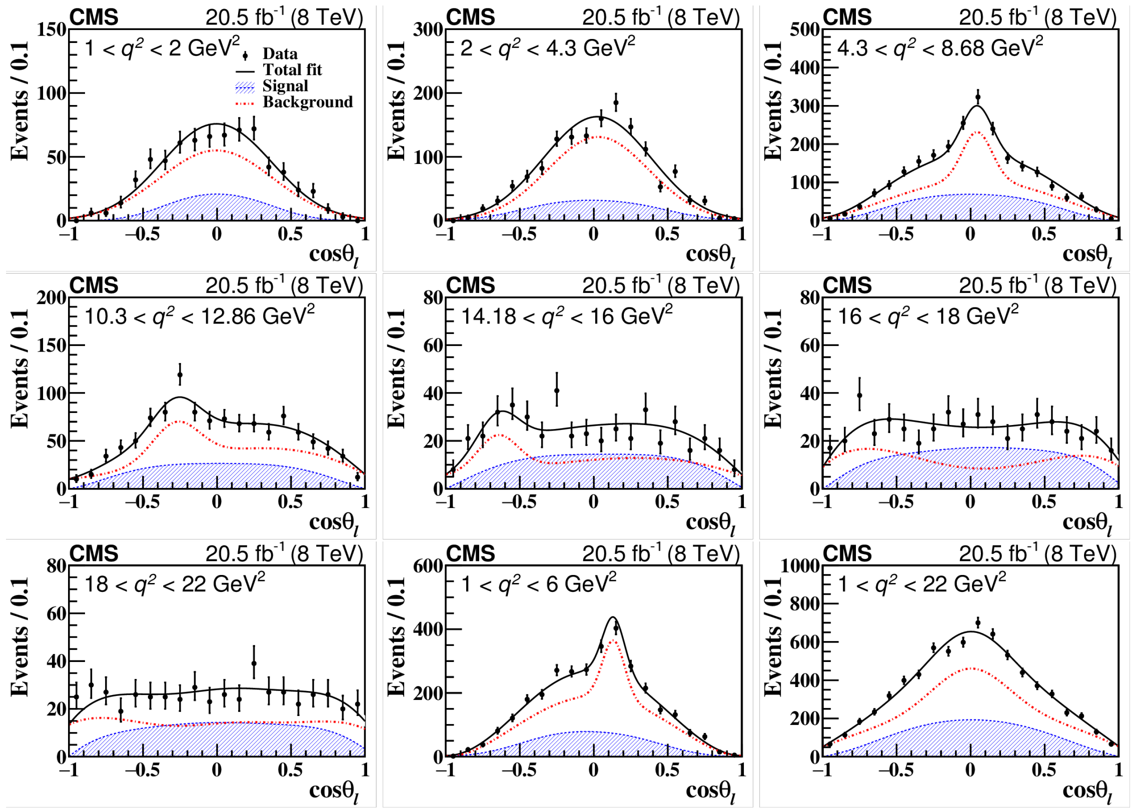


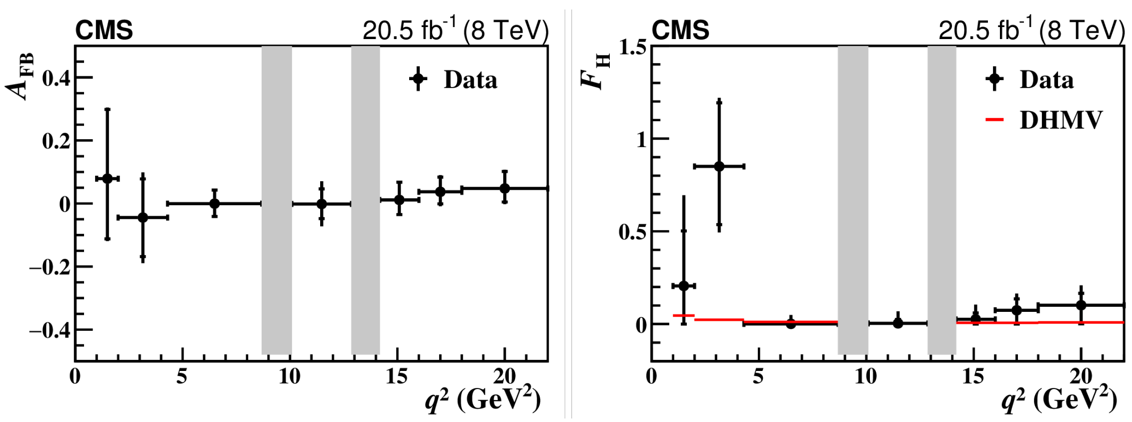




PRD 98 (2018) 112011 *Angular analysis of $B^+ \to K^+ \mu\mu$*

- *Same quark-level diagram and motivation as $B_d \to K^{*0} \mu\mu$*
- *Simpler decay angular distribution than $B_d \to K^* \mu\mu$*
  - *Extract forward-backward asymmetry of muon system A_{FB} and contributions from (pseudo)scalar and tensor amplitudes F_H from fit to decay angular distributions*
- *Previous measurements agree with SM*
  - *BABAR [PRD 73 (2006) 092001]*
    Belle [PRL 103 (2009) 171801]
    CDF [PRL 108 (2012) 081807]
    LHCb [JHEP 02 (2013) 105, JHEP 05 (2014) 82]
- *New CMS measurements of A_{FB} and F_H agree with SM*

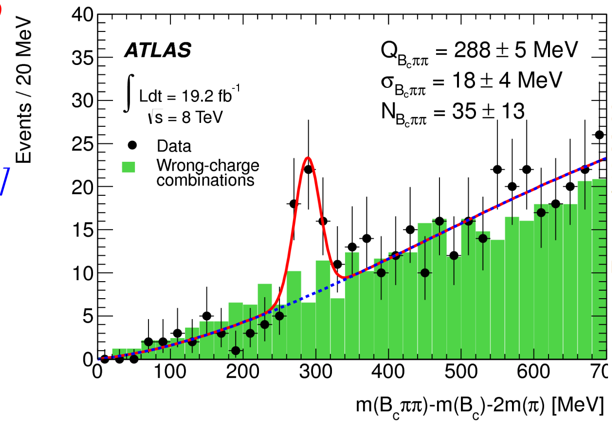




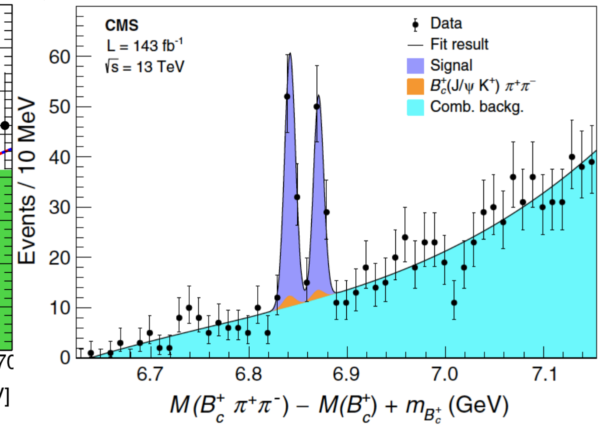
EPJC 78 (2018) 939
PRL 122 (2019) 132001

B_s and B_c states

- *Excited B_c state first seen in decay to $B_c\pi\pi$ ($B_c \to J/\psi\ \pi$) by ATLAS* *[PRL 113 (2014) 212004]*
  - *Not confirmed by LHCb [JHEP 01 (2018)138]*



- *New CMS analysis sees 2 well-resolved peaks, presumably the radially-excited $B_c(2S)$ and $B_c^*(2S)$* *[PRL 122 (2019) 132001]*

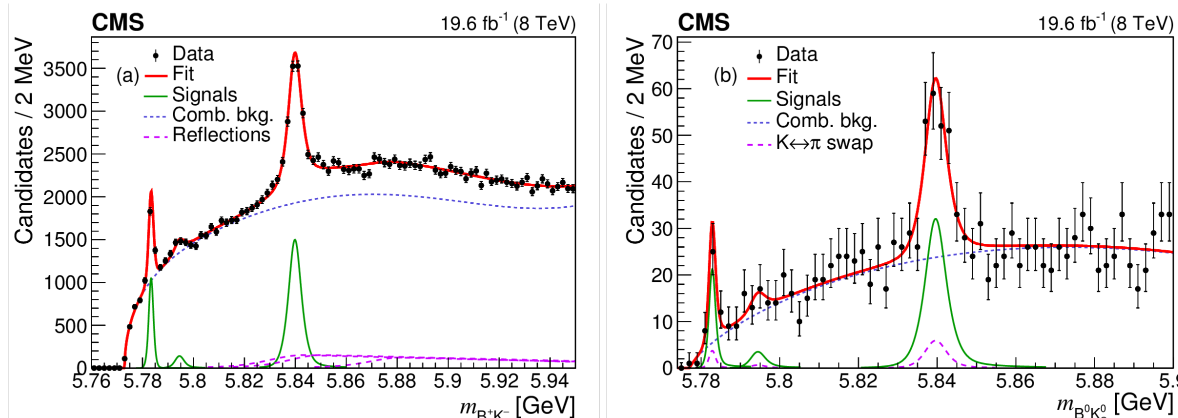


$$M_{B_c(2S)} = 6871.0 \pm 1.2 \pm 0.8 \pm 0.8(B_c^+)\ \mathrm{MeV}$$

$B_c^*(2S) \to B_c^*\pi\pi$ and $B_c^* \to B_c\gamma$. Since the γ is not reconstructed, the $B_c^*(2S)$ mass is not measured.

  - *LHCb now confirms the two states* *[LHCb-PAPER-2019-007]*

- *CMS has studied the orbitally-excited L=1 states $B^*_{s2}(5840)^0$ and $B_{s1}(5830)^0$ decaying to $B^{(*)+}K^-$ and $B^{(*)0}K_S$* *[EPJC 78 (2018) 939]*
  - *First observation of $B^*_{s2}(5840)^0 \to B^0K_S$*

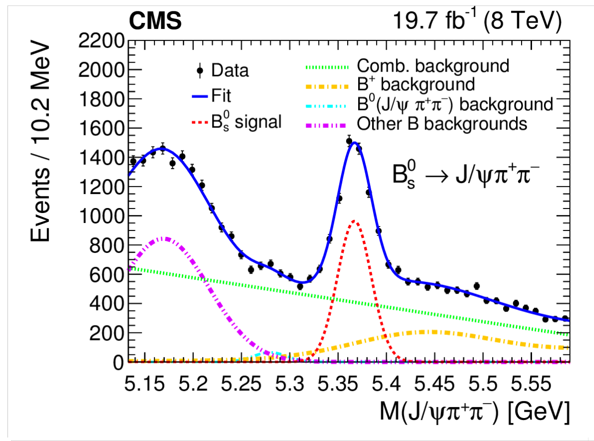


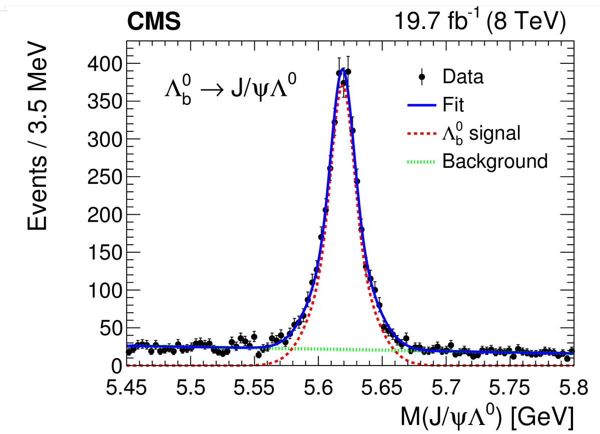
	B^+K^-	$B^0K^0_S$
$N(B^*_{s2} \to BK)$	5424 ± 269	128 ± 22
$N(B^*_{s2} \to B^*K)$	455 ± 119	12 ± 11
$N(B_{s1} \to B^*K)$	1329 ± 83	34.5 ± 8.3
$\Gamma(B^*_{s2})$ [MeV]	1.52 ± 0.34	2.1 ± 1.3
$\Gamma(B_{s1})$ [MeV]	0.10 ± 0.15	0.4 ± 0.4
$M(B^*_{s2}) - M_B^{PDG} - M_K^{PDG}$ [MeV]	66.93 ± 0.09	62.42 ± 0.48
$M(B_{s1}) - M_{B^*}^{PDG} - M_K^{PDG}$ [MeV]	10.50 ± 0.09	5.65 ± 0.23

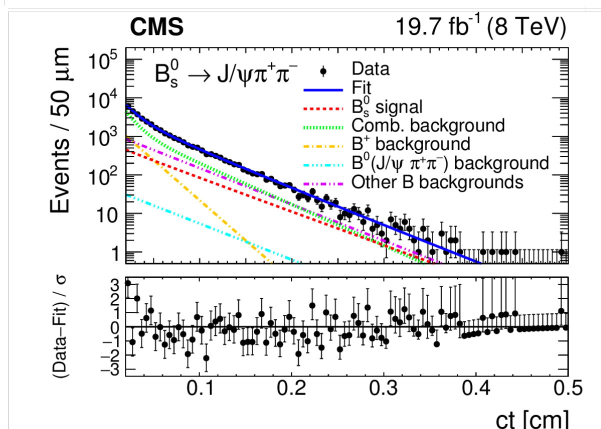
	CDF [?]	D0 [?]	LHCb [?]	CDF [?]
$M(B^*_{s2})$ [MeV]	5839.6 ± 0.7	5839.6 ± 1.3	5839.99 ± 0.21	5839.7 ± 0.2
$M(B_{s1})$ [MeV]	5829.4 ± 0.7	–	5828.40 ± 0.41	5828.3 ± 0.5
$\Delta M^{\pm}_{B_{s1}}$ [MeV]	10.73 ± 0.25	11.5 ± 1.4	10.46 ± 0.06	10.35 ± 0.19
$\Delta M^{\pm}_{B^*_{s2}}$ [MeV]	66.96 ± 0.41	66.7 ± 1.1	67.06 ± 0.12	66.73 ± 0.19
$\Gamma(B^*_{s2})$ [MeV]	—	—	1.56 ± 0.49	1.4 ± 0.4
$\Gamma(B_{s1})$ [MeV]	—	—	—	0.5 ± 0.4

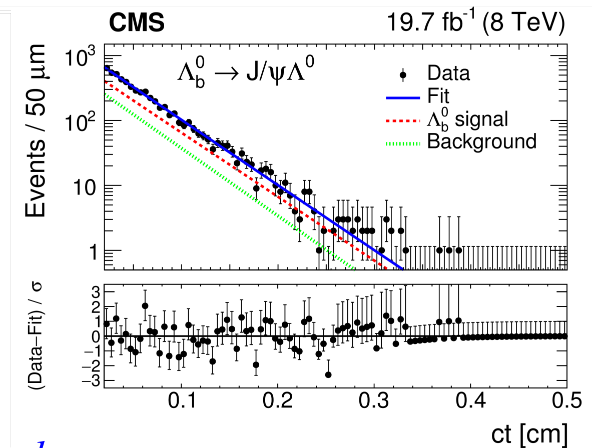
b hadron lifetimes

- *HQ expansion model can predict ratio of lifetimes with for hadrons with same heavy quark*
- *Measurements are based on decay length from primary vertex in J/ψ final states*
  - $B^0 \to J/\psi\, K^*$, $J/\psi\, K_S$, $B_s \to J/\psi\, \pi\pi$, $J/\psi\, \phi$, $\Lambda_b \to J/\psi\, \Lambda$, $B_c \to J/\psi\, \pi$









Lifetimes

$$\left.\begin{aligned} c\tau_{B^0\to J/\psi K^*} &= 453.0 \pm 1.6 \pm 1.8\ \mu m \\ c\tau_{B^0\to J/\psi K_S} &= 457.8 \pm 2.7 \pm 2.8\ \mu m \end{aligned}\right\} \langle c\tau_{B^0}\rangle = 454.1 \pm 1.4 \pm 1.7\ \mu m$$

$$c\tau_{B_s\to J/\psi\pi\pi} = 502.7 \pm 10.2 \pm 3.4\ \mu m$$

$$c\tau_{B_s\to J/\psi\phi} = 443.9 \pm 2.0 \pm 1.5\ \mu m$$

$$c\tau_{\Lambda_b\to J/\psi\Lambda} = 442.9 \pm 8.2 \pm 2.8\ \mu m$$

$$c\tau_{B_c\to J/\psi\pi} = 162.3 \pm 7.8 \pm 4.2\ \mu m$$

- *Extract $B_{s,L}$ lifetime from $B_{s,H}$ lifetime and effective lifetime in $B_s \to J/\psi\, \phi$*

$$c\tau_{B_{s,L}} = 420.4 \pm 6.2\ \mu m$$

- *Extract Γ and ΔΓ between light and heavy mass eigenstates from τ for $B^0 \to J/\psi\, K^*$ and $B^0 \to J/\psi\, K_S$*

$$\Gamma_d = 0.662 \pm 0.003 \pm 0.003\ \text{ps}^{-1}$$

$$\Delta\Gamma_d = 0.023 \pm 0.015 \pm 0.016\ \text{ps}^{-1}$$

$$\frac{\Delta\Gamma_d}{\Gamma_d} = 0.034 \pm 0.023 \pm 0.024$$

- *Previous ATLAS result [JHEP 06 (2016) 81]*

$$\frac{\Delta\Gamma_d}{\Gamma_d} = -0.001 \pm 0.011 \pm 0.009$$

Lifetime ratios

$$\tau_{\Lambda_b} / \tau_{B^0\to J/\psi K^*} = 0.978 \pm 0.018 \pm 0.006$$

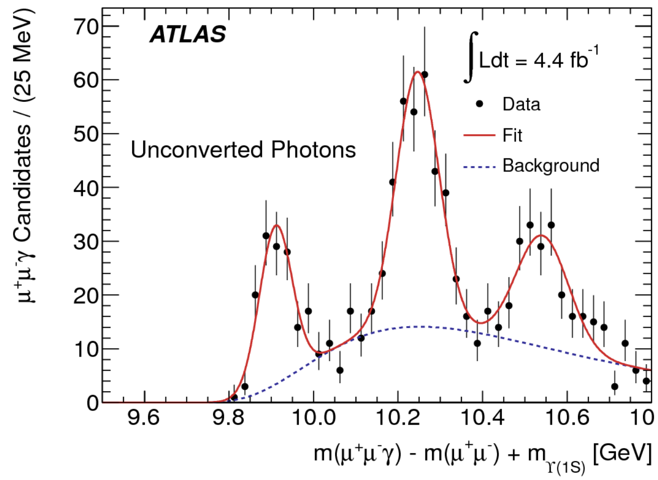
$$\tau_{\Lambda_b} / \tau_{B_s\to J/\psi\phi} = 0.980 \pm 0.006 \pm 0.003$$

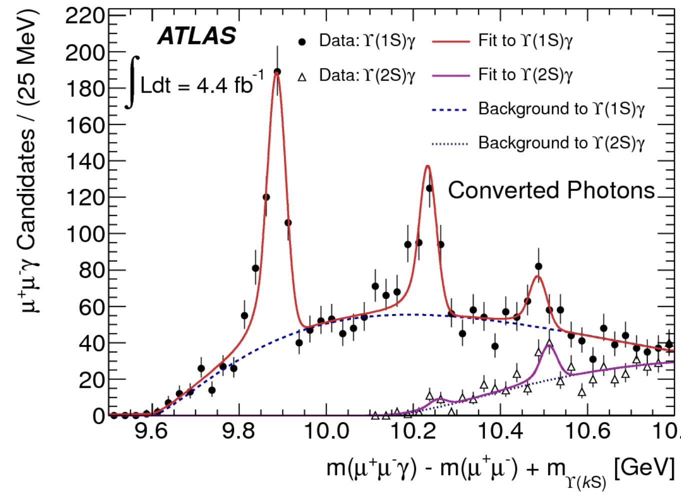
All measurements in agreement with current world averages.

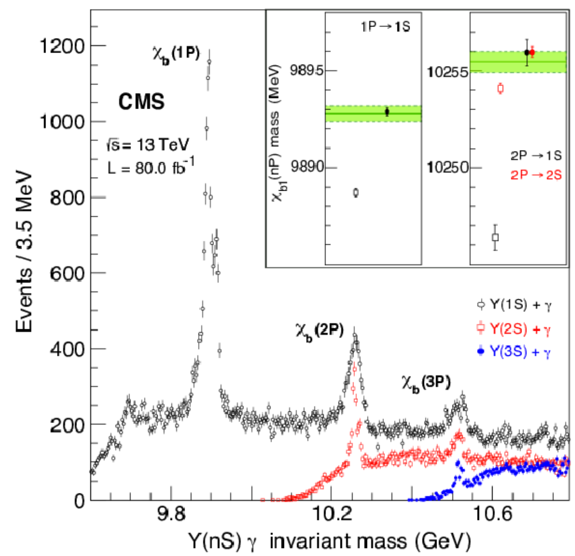
PRL 121 (2018) 092002

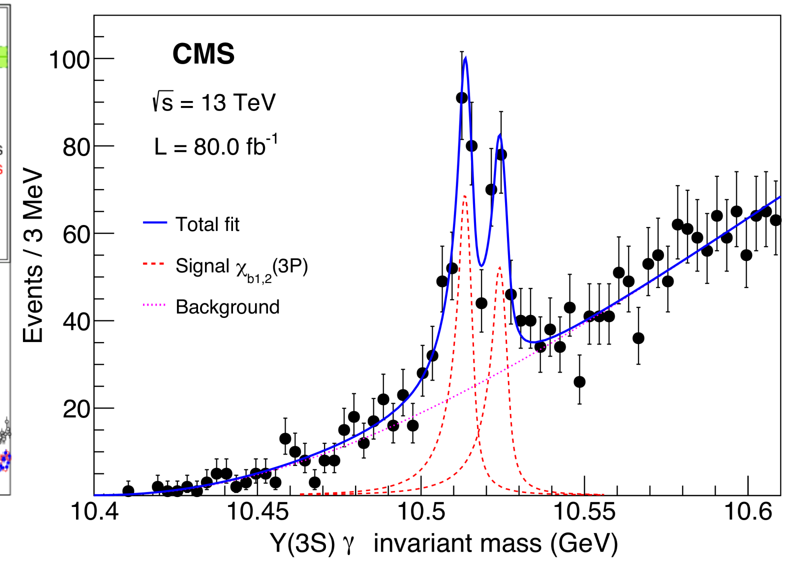
Observation of $\chi_{b1}(3P)$ and $\chi_{b2}(3P)$

- *ATLAS first discovered $\chi_b(3P)$ system in radiative decay to $\Upsilon(1S)$ and $\Upsilon(2S)$* *[PRL 108 (2012) 152001]*
  - *Also seen by D0 and LHCb*
- *CMS recently studied $\Upsilon(3S)\gamma$ mass spectrum*
  - *Better mass resolution (2.2 MeV) due to lower Q value*
  - *First observation of two separate nearby peaks*
  - *Interpret as $\chi_{b1}(3P)$ and $\chi_{b2}(3P)$ [$\chi_{b0}(3P)$ is expected to have neglible radiative decay width]*
- *Mass splitting ΔM is consistent with SM calculations*
  - *Most predictions range from 8-18 MeV*
  - *One prediction of -2 MeV is strongly disfavored*









$$M(\chi_{b1}(3P)) = 10513.42 \pm 0.41 \pm 0.18 \text{ MeV}$$

$$M(\chi_{b2}(3P)) = 10524.02 \pm 0.57 \pm 0.18 \text{ MeV}$$

$$\Delta M \equiv M(\chi_{b2}(3P)) - M(\chi_{b1}(3P)) = 10.60 \pm 0.64 \pm 0.17 \text{ MeV}$$

Search for tetraquark state X(5568)

- *D0 reported a resonance in the $B_s\pi^+$ mass spectrum at 5568 MeV at 5.1σ significance [PRL 117 (2016) 022003]*

$$M_X = 5567.8 \pm 2.9^{+0.9}_{-1.9}\ \text{MeV}$$
$$\Gamma_X = 21.9 \pm 6.4^{+5.0}_{-2.5}\ \text{MeV}$$

$$\rho_X \equiv \frac{\sigma\left(p\bar{p}(pp) \to X + \text{ anything}\right) B\left(X \to B_s\pi\right)}{\sigma\left(p\bar{p}(pp) \to B_s + \text{ anything}\right)}$$

$$\rho_X = (8.6 \pm 2.4)\% \quad \text{for } p_T(B_s) > 10\ \text{GeV}$$

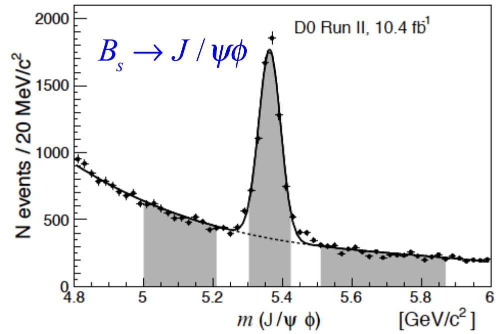
  - *Interpret as bsud four-quark state*
  - *D0 find supporting evidence with semileptonic B_s decays with a combined significance of 6.7σ [PRD 97 (2018) 092004]*

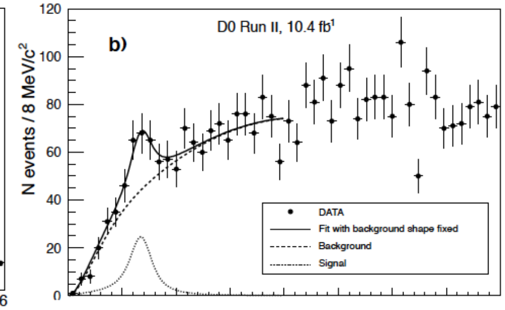
- *LHCb & CDF report negative results*

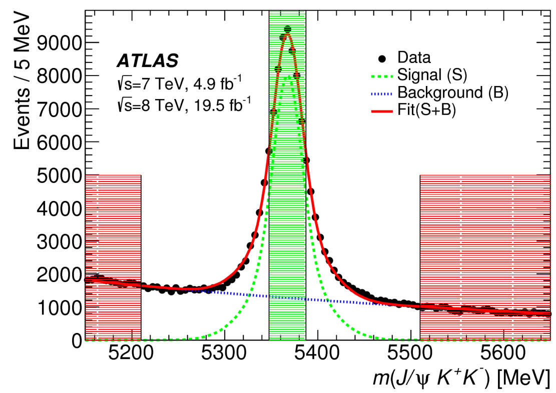
$\rho_X < 2.4\%$ LHCb [PRL 117 (2016) 152003]
$\rho_X < 6.7\%$ CDF [PRL 120 (2018) 202006]

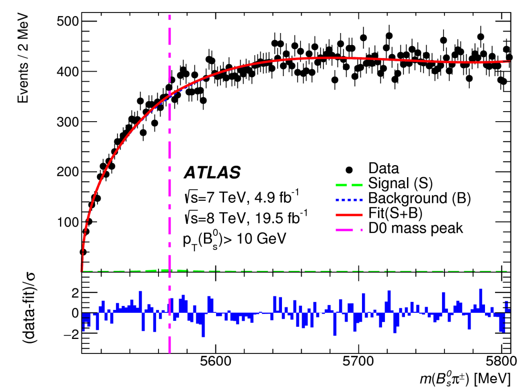
- *ATLAS & CMS report tightest constraints yet*

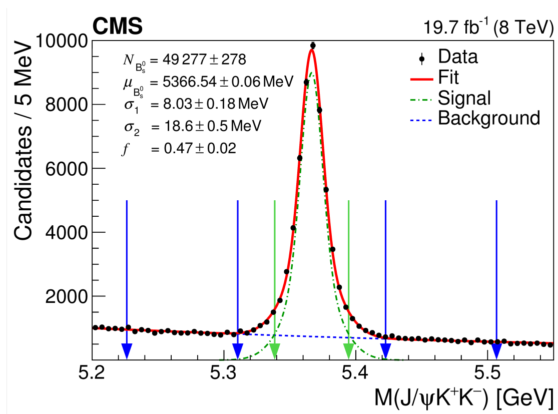
$\rho_X < 1.5\%$ ATLAS [PRL 120 (2018) 202007]
$\rho_X < 1.1\%$ CMS [PRL 120 (2018) 202005]

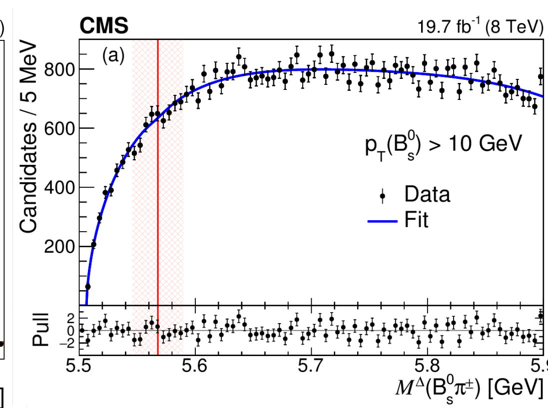












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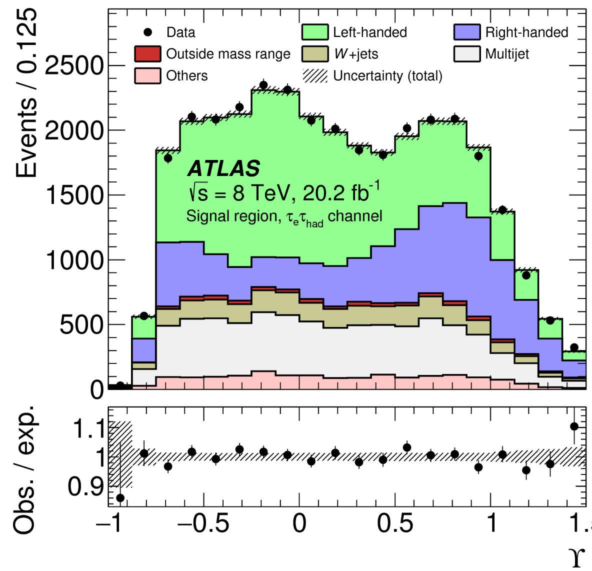
τ polarization and LFV decay to 3μ

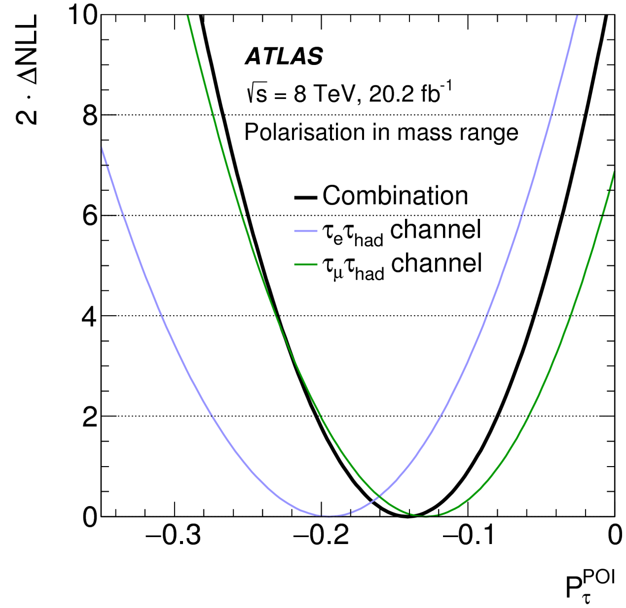
- τ (polarization) plays an important role in physics analyses
  - E.g. in separating Z, H, A bosons
- ATLAS has measured in Z ➛ ττ decays, where one τ decays leptonically and the other hadronically
  - Precise LEP combination of τ production asymmetry
  - ATLAS measurement of τ polarization for 66 < m(Z➛ ττ)<116 GeV agrees with SM prediction

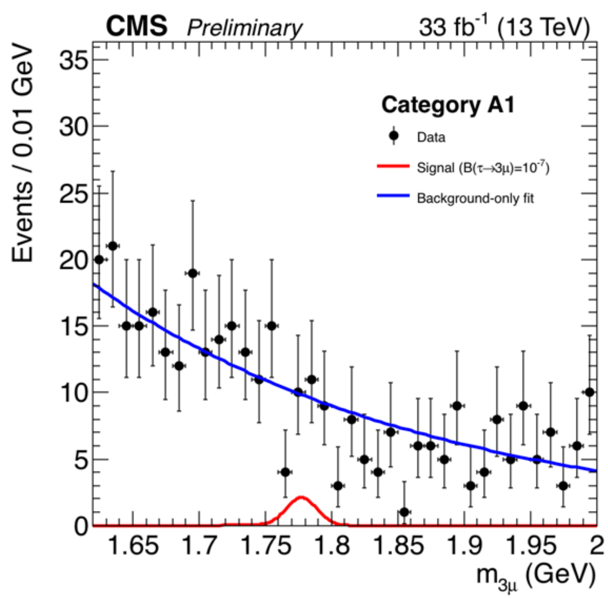
$$P_\tau = -0.14 \pm 0.02 \pm 0.04 \text{ (ATLAS)}$$
$$P_\tau = -0.1517 \pm 0.0019 \text{ (SM)}$$

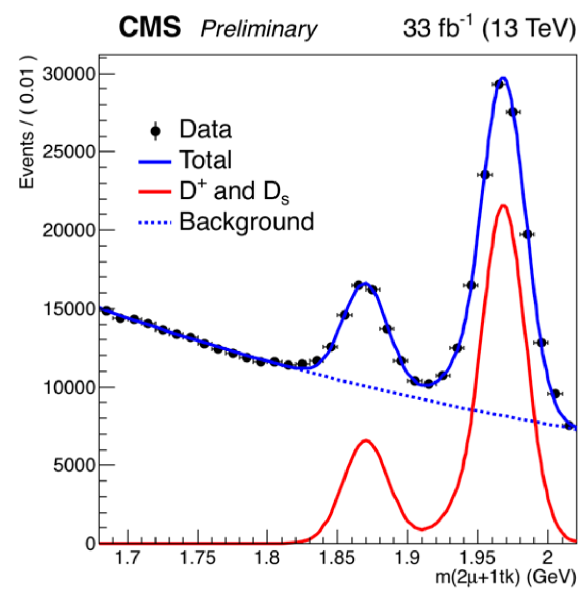
- CMS searches for LFV τ➛3μ decay and sets upper limit

$$B(\tau \to 3\mu) < 8.8 \times 10^{-8} \,@ 90\% \text{ C.L.}$$



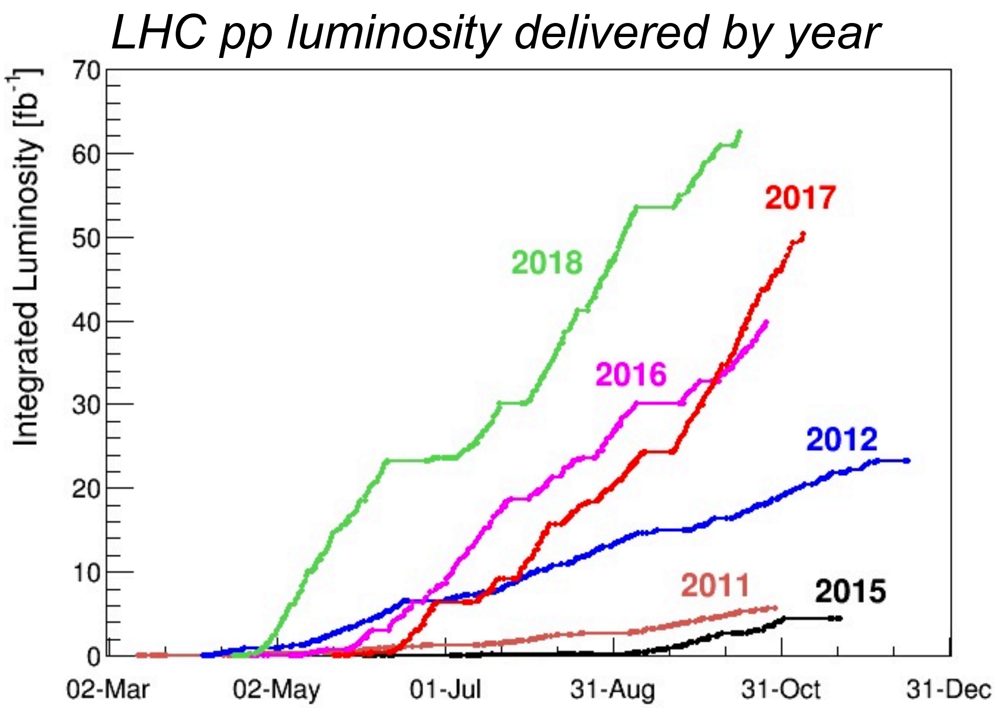






Conclusions

- *Several new results from ATLAS and CMS on heavy flavor production, properties and decay were presented*
  - *Complicated analyses that take time*
  - *Many results still based only on Run 1 data (25 fb^{-1}, 2011+2012)*
  - *Only one result uses full Run 2 data set (140 fb^{-1}, 2015−2018)*



- *Expect many more exciting results to come out over the next few years from ATLAS and CMS exploiting the full Run 1 + 2 data set !!!*