Istituto Nazionale di Fisica Nucleare

Università di Roma Tor Vergata

Recent Heavy Flavour results from ATLAS

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(INFN & Università Roma Tor Vergata)
on behalf of the ATLAS Collaboration

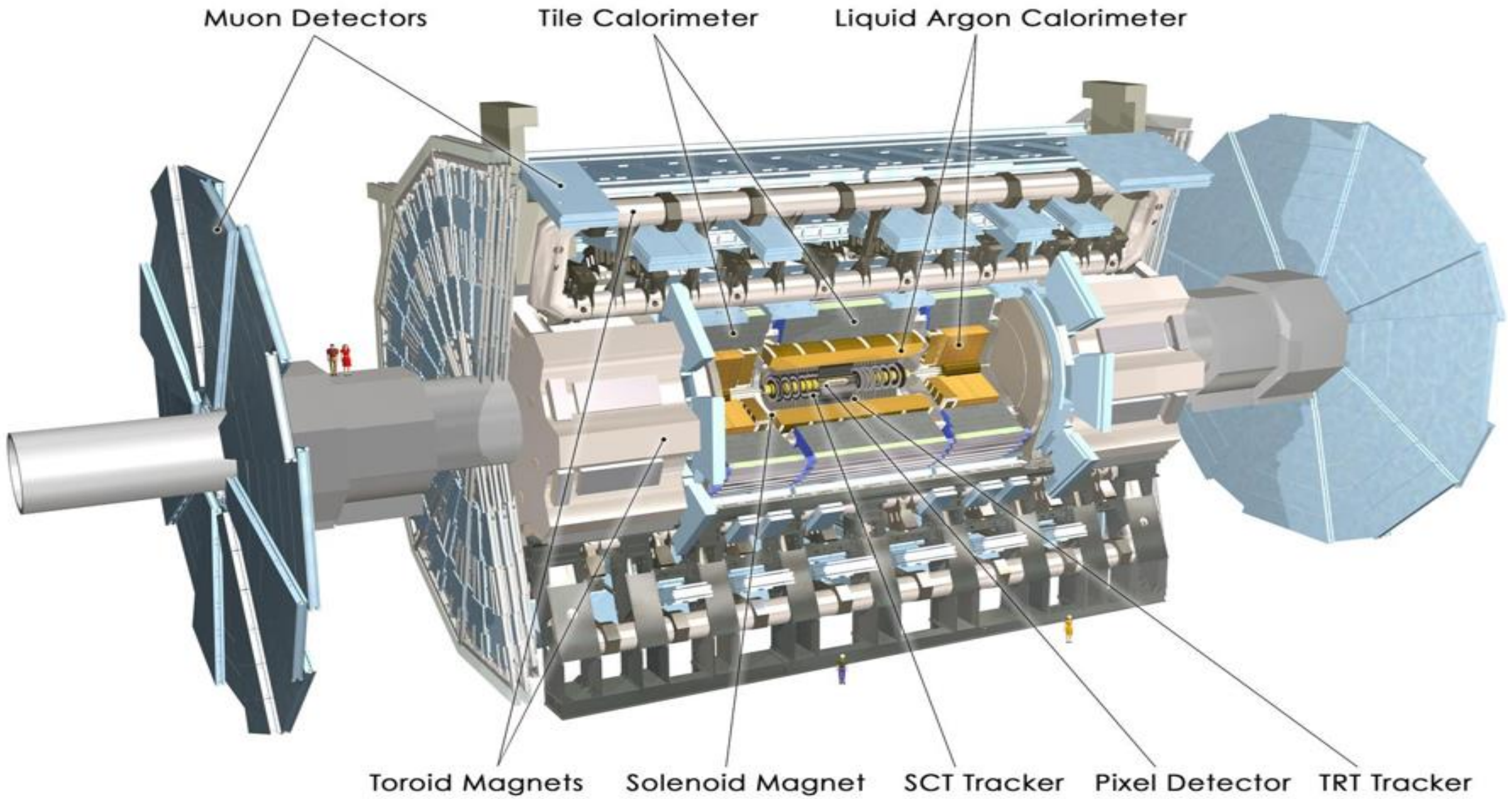
ICFNP, 08/09/2022

Outline

- LHC & the ATLAS Detector
- How ATLAS triggers Heavy Flavour events
- Recent Heavy Flavour ATLAS results
  - Search for Exotic states (see talk "ATLAS results on exotic hadronic resonances" by Ivan Yeletskikh's talk on Saturday)
  - Bc meson properties
  - CP-violation measurements
  - Rare decays and New Physics contributions (e.g. B- anomalies)

The ATLAS Experiment

- ATLAS (**A** **T**oroidal **L**HC **A**pparatu**S**)
  - "The Physics Giant"
  - 44x25 m, 7000 t
  - A multipurpose detector to find new particles and measure the properties of well-known particles



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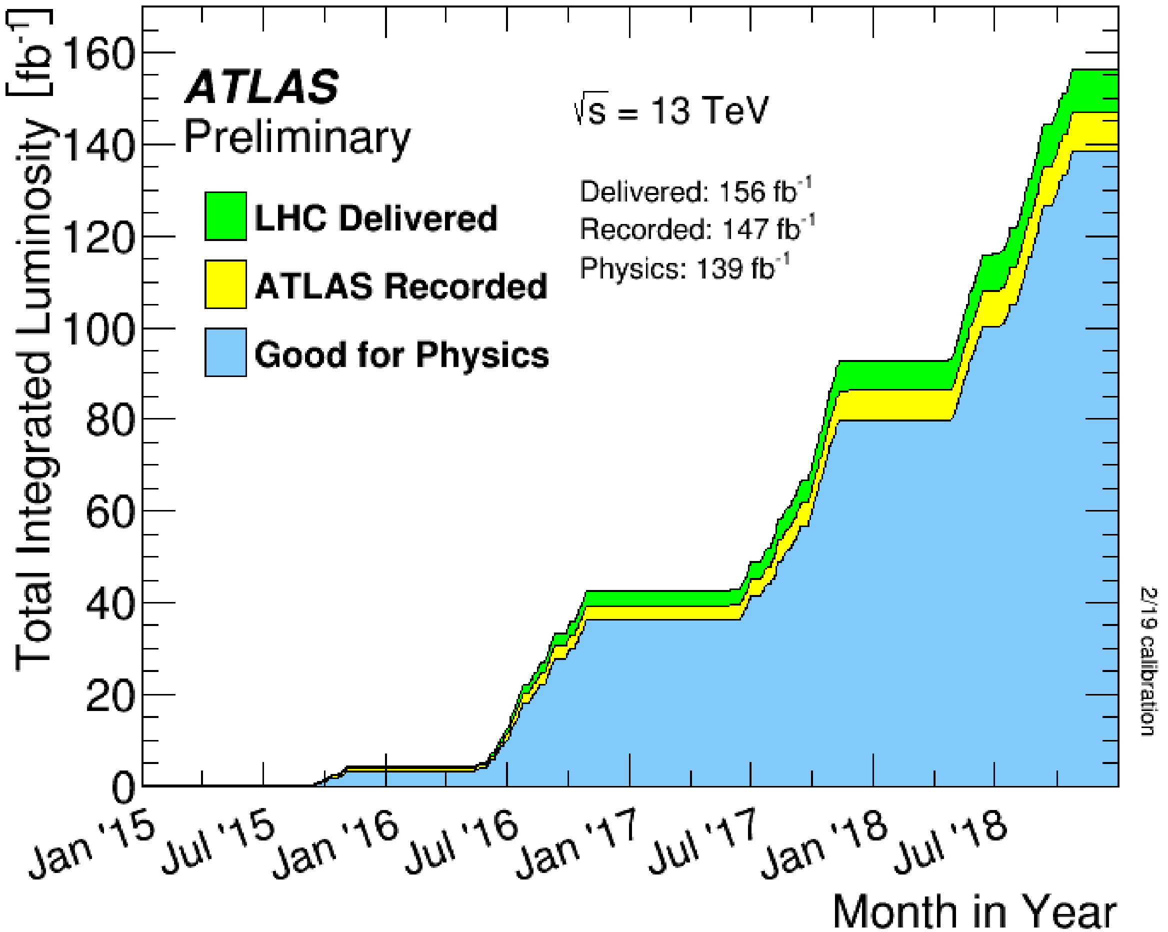
Integrated luminosities

- ATLAS collected data from 2010 to 2018 at a centre-of-mass energy $\sqrt{s}$ = 7, 8 and 13 TeV
  - Run 1 (2010-2013) → 4.9 fb^{-1} @ 7 TeV + 20.3 fb^{-1} @ 8 TeV
  - Run 2 (2015-2018) → 139 fb^{-1} @ 13 TeV



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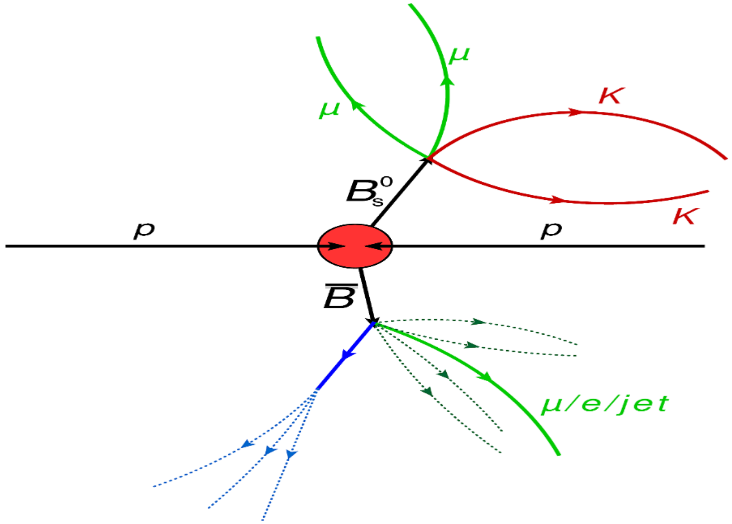
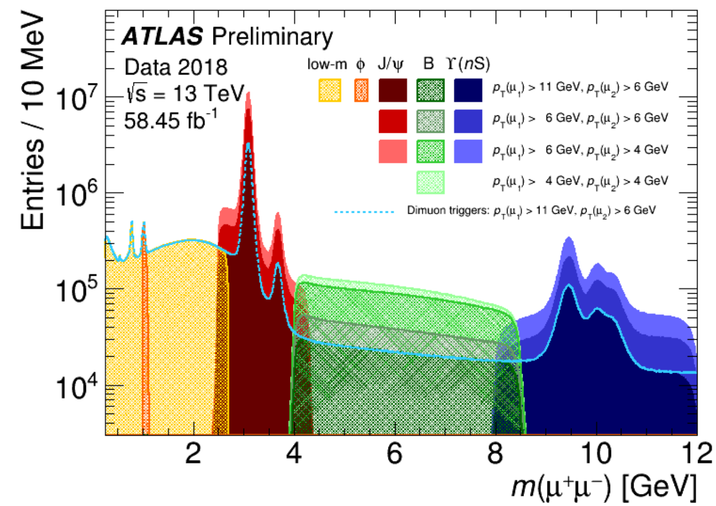
Typical B-physics signatures

- 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
  - Rarely photons/electrons → Electromagnetic calorimeter
- Trigger these events is complicated due to low thresholds in muon P_T → Incompatible with bandwidth constraints at high lumin.
- In addition ATLAS (and CMS) does not have specific detectors for particle identification → Kaons, pions, protons are all "just" tracks

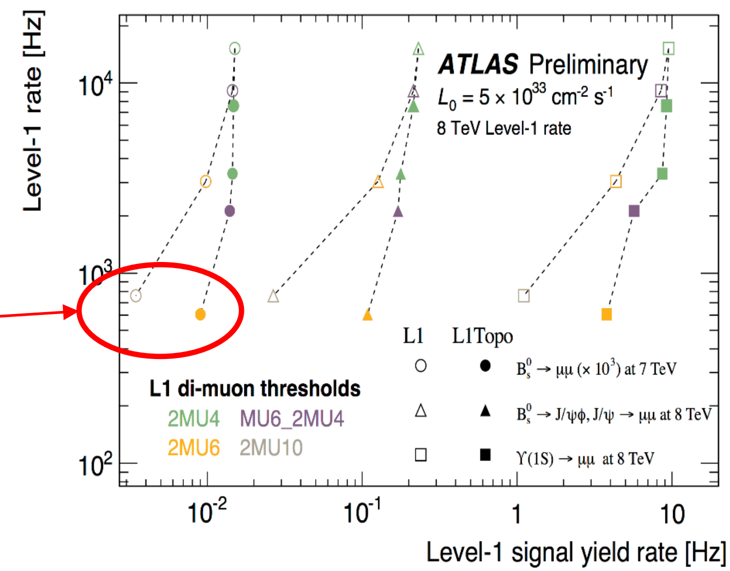


Triggering events in Run 1 and Run 2

- Regional readout → Define a Region of Interest (RoI) around the L1 muons
  - Lower rate but less efficient for low-P_T
  - Primary trigger in most of Run1



- Run2 : Topological trigger!
- Use info on PT, η and φ of the muon ROIs to build topological di-muon quantities (inv.mass or ΔR):
  - Efficient way to reduce bandwidth usage keeping the signal efficiency high
  - Gain up to a **factor of 3** in di-muon background rejection!
  - Baseline for 2017 data (with MU4_MU6 and 2MU6 thresholds



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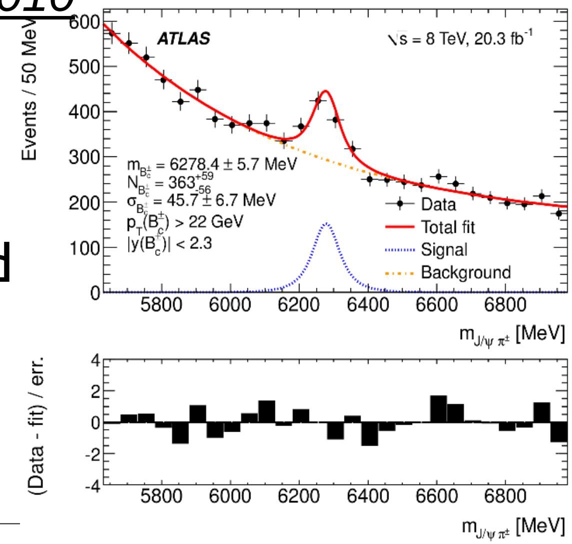
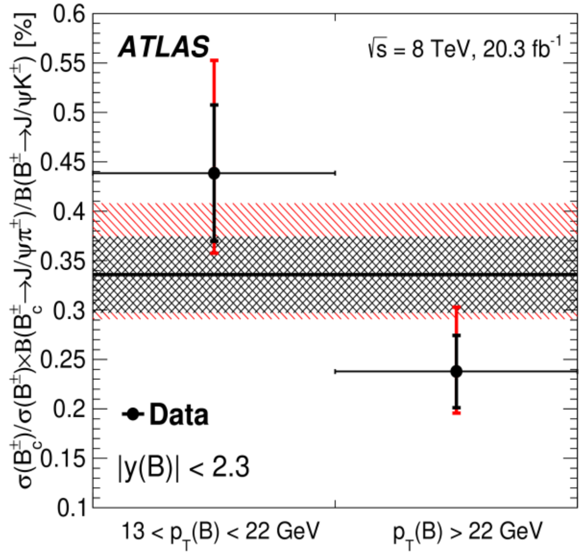
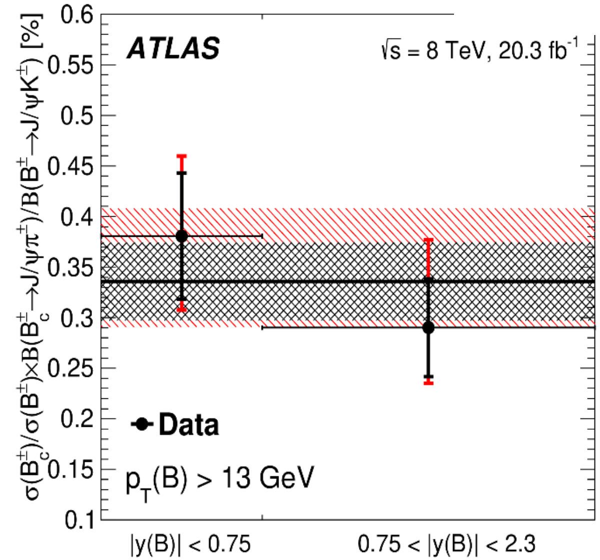
Bc/B+ production cross-section

Phys. Rev. D 104 (2021) 012010



- ➢Bc meson is the heaviest known meson
- ➢Its dynamics are still under investigation
  - ➢ No data from B-factories
- ➢ This measurement compares its total and differential production cross-section w.r.t. the $B^\pm$
  - ➢Bc → $J/\Psi\pi^\pm$ vs $B^\pm$ → $J/\Psi K^\pm$



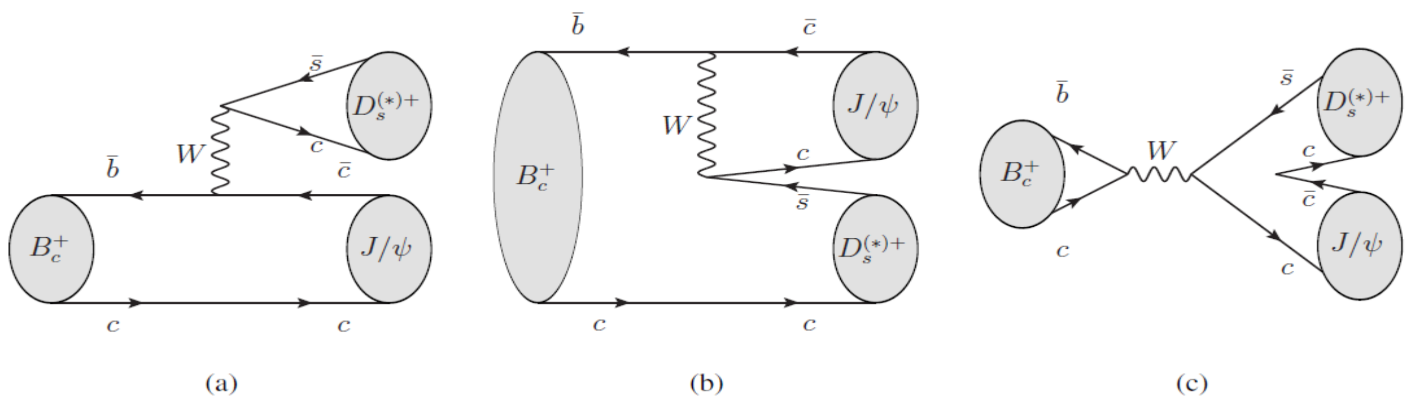


- First hint of a dependence from PT of the Bc cross-section w.r.t. the $B^\pm$ one

- LHCb measured the ratio in the forward region → Higher ratio
- CMS measured the inclusive ratio at 7 TeV in the same kinematical region → 30% higher value but still compatible with ATLAS

$B^+c \to J/\Psi\ D^{(*)}s$

- The analysis focuses on the B^+c decay to $J/\Psi \to \mu\mu$ and $D^+s \to \Phi\pi^+$ or $D^{*+}s \to D^+s\ \gamma/\pi^0$ where γ/π^0 are too soft and not reconstructed → But a separation in the $J/\Psi\ D^+s$ invariant mass still possible!
- Goals are:
  - Measure the decay widths w.r.t. a reference channel: $B^+c \to J/\Psi\pi^+$
  - The decay in $J/\Psi D^{*+}s$ is described by three helicity amplitudes → measure their relative contribution and the $J/\Psi D^{*+}s / J/\Psi D^+s$ ratio
  - Compare with theoretical models available



JHEP 08 (2022) 087

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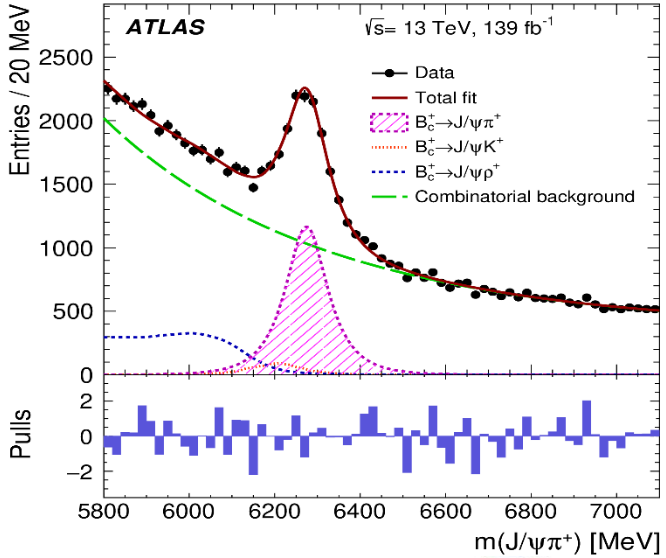
Bc → J/Ψ D(*)s

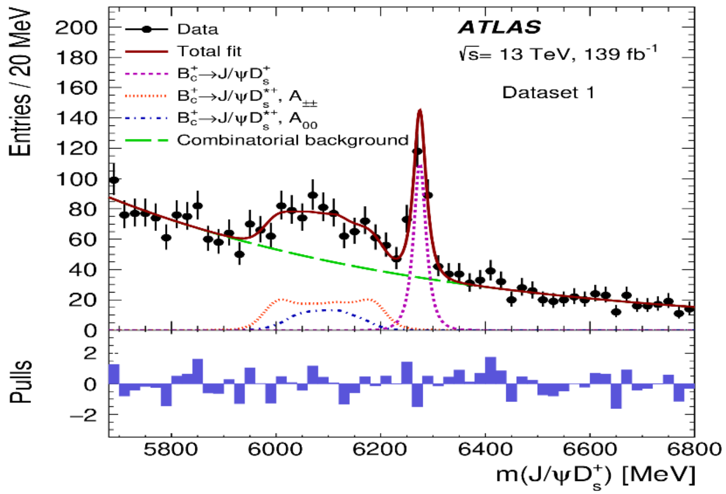
- Triggers used:
  - Di-muon/tri-muon triggers → Used to measure the ratios w.r.t. the ground state
  - Trigger based on the Bs → μμΦ topology → Used to measure the amplitudes ratio and the J/ΨD*+s /J/ΨD+s ratio
- Muon PT threshold: 4,6 GeV; $P_T(B^+c)$ > 15 GeV && $|\eta(B^+c)|$ < 2.0
- To suppress the backgrounds:
  - Cuts on Lxy and longitudinal/transverse impact parameters
  - Removal of the Bs→J/ΨΦ contribution
  - BDT against the combinatorial background
  - «Cascade» fit for the J/ΨD+s decay (tertiary vertices)

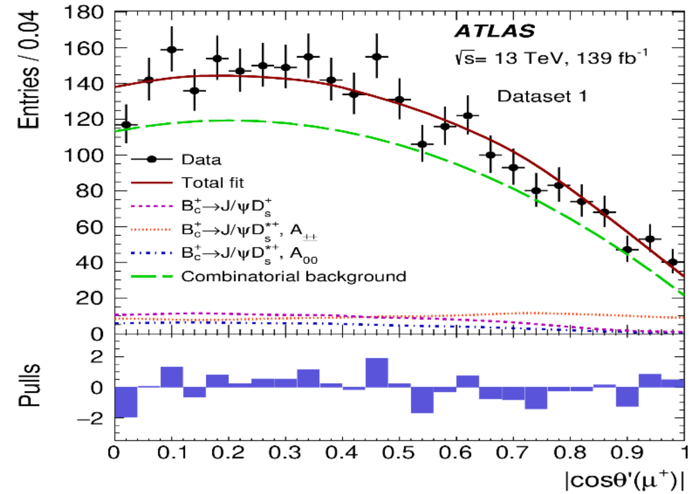
- The ground state B^+c → $J/\Psi\pi^+$ reconstructed with the same cuts on muons and B^+c and $P_T(\pi^+)$ > 3.5 GeV.
- Signal events ~ 8500

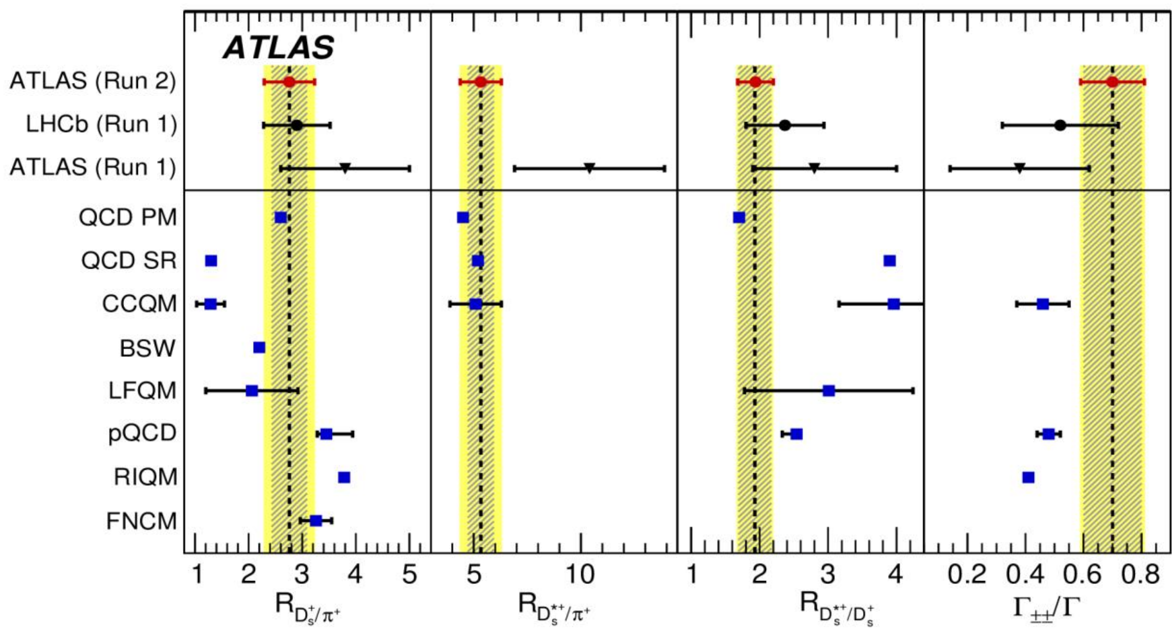


Bc → J/Ψ D(*)s

- 2D fit on m(J/ΨDs) and the J/Ψ helicity angle cos(θ*) to extract the signal parameters and the relative helicity amplitudes



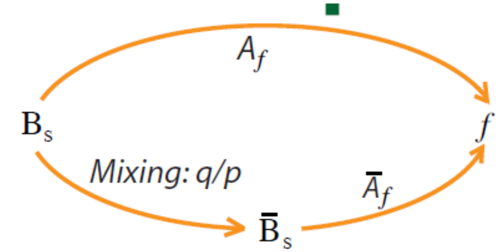


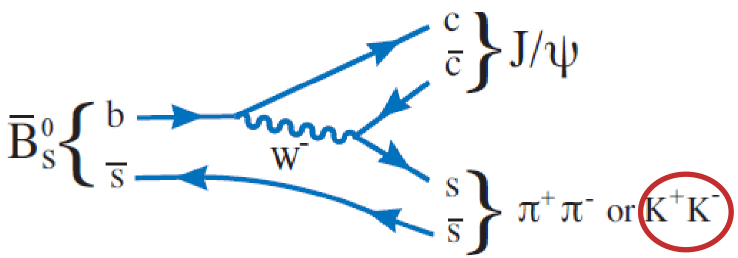


- Comparison with several models on the market and with previous results by ATLAS and LHCb
- QCD PM model seems to better describe all ratios

CPV in Bs → J/ΨΦ

➢Interference between mixing and decay



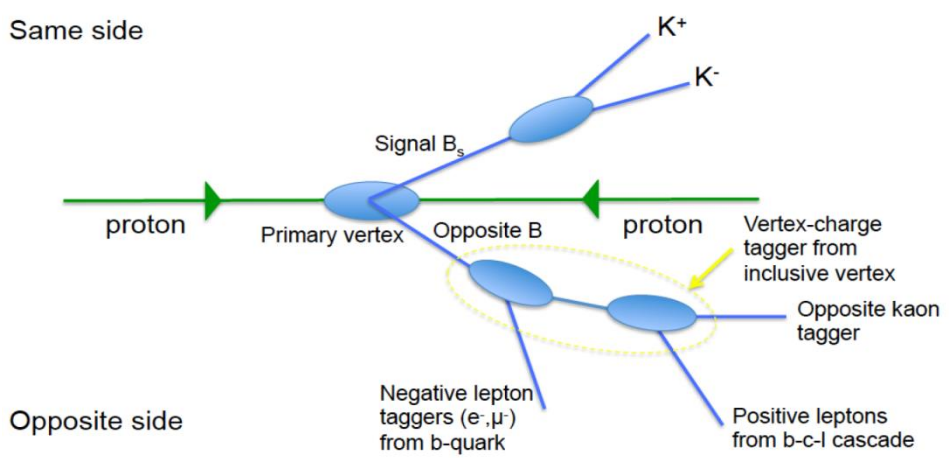


$$\varphi_s^{SM} \equiv -2\beta_s = -2\arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right) = -0.04 \text{ rad}$$

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

➢Essential ingredients at hadron colliders:

- ➢ Good time (spatial) resolution to measure the oscillation accurately
- ➢ Flavour tagging (i.e. distinguish the "Bs side" of the event)



Muons, electrons and jets used as taggers

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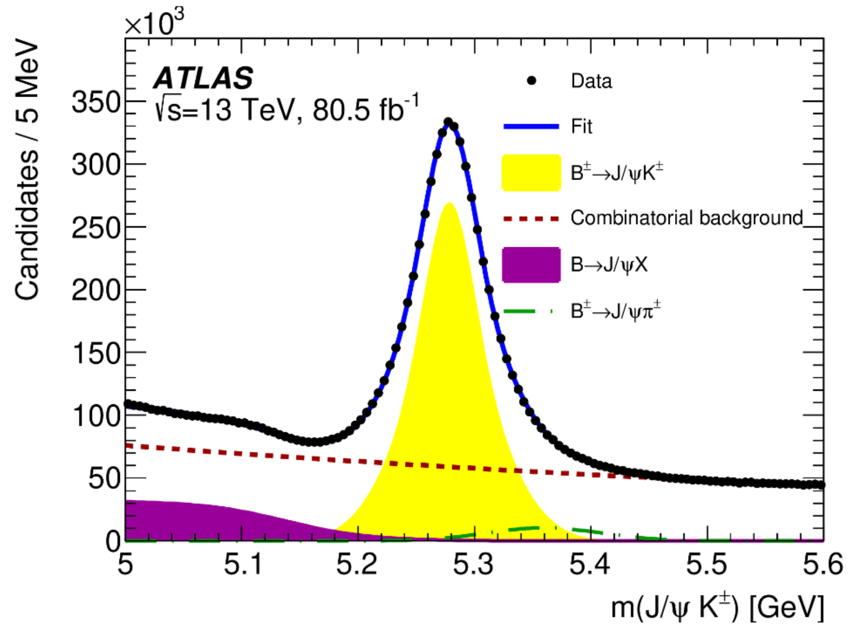
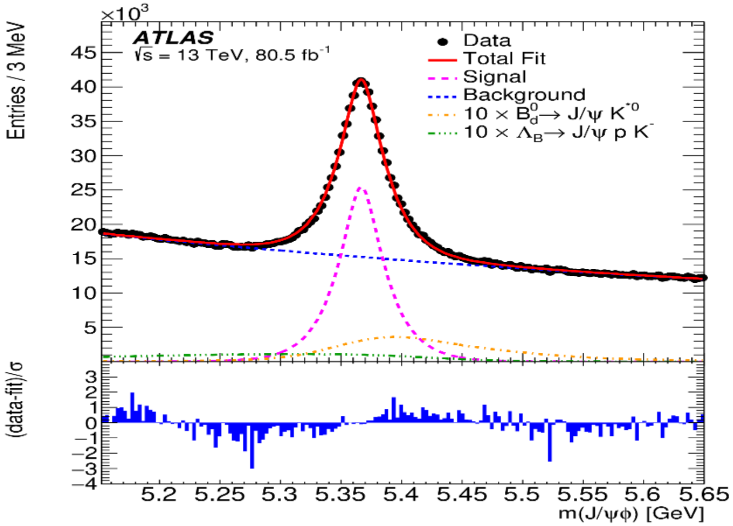
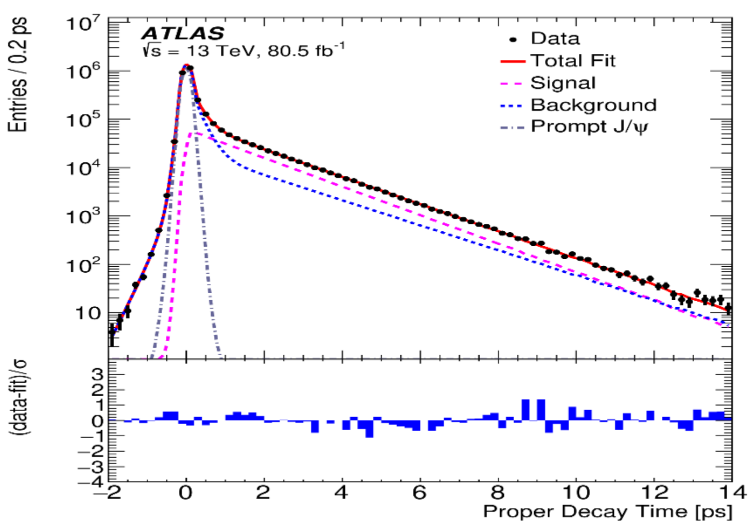
Bs → J/ΨΦ measurement

Eur. Phys. J. C 81 (2021) 342

- Flavour tagging calibration done using **$B^{\pm}$ → J/ΨK$^{\pm}$**
- Information on $B^{\pm}$ flavour extracted from the kaon charge
- Flavour tagging probability affect significantly the precision on the extraction of the parameters
- Total tagging power: 1.75%
- Angular analysis with 10 amplitude functions is done (J/ΨΦ is not a CP eigenstate!!)







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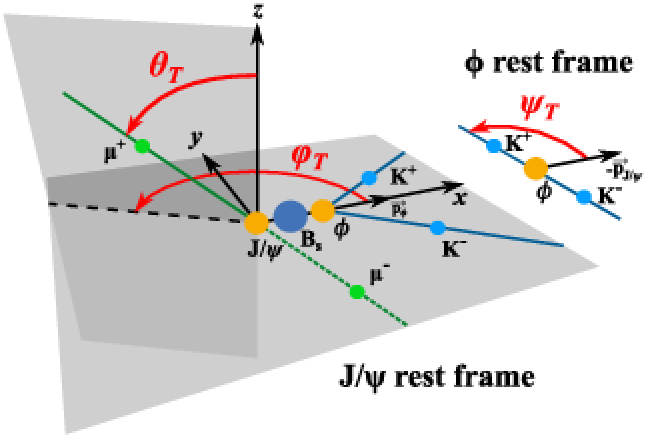
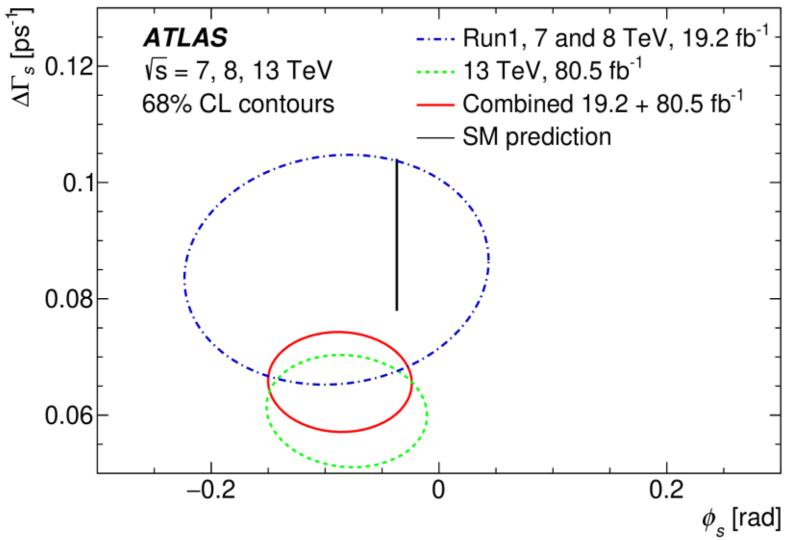
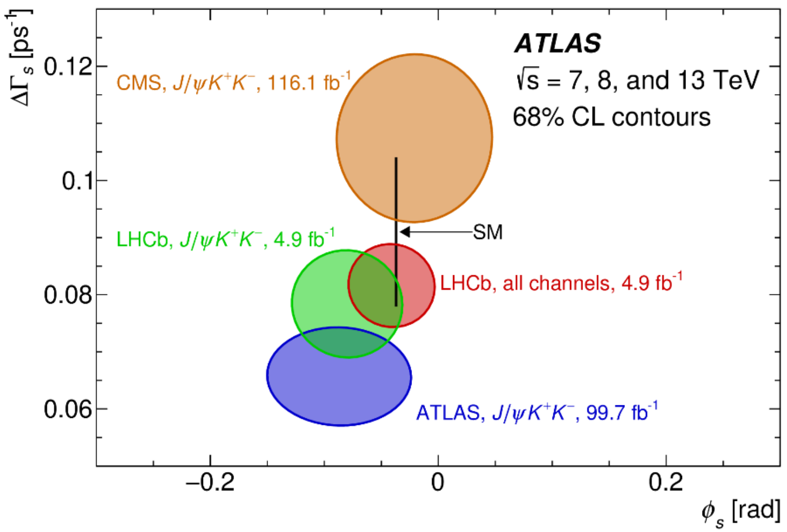
Bs → J/ΨΦ measurement

- Extract the 10 parameters from a global simultaneous fit to the various distributions (mass, angles, etc)
- Focus on three parameters:
  - Γ_s (decay width)
  - $\Delta\Gamma_s$ (difference of the widths)
  - Φ_s (the CPV weak-phase)







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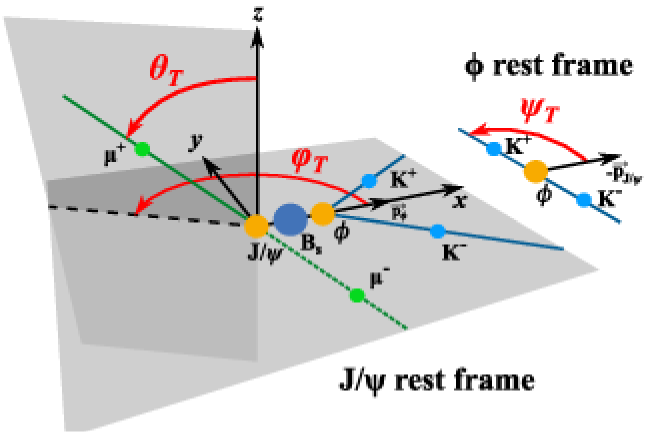

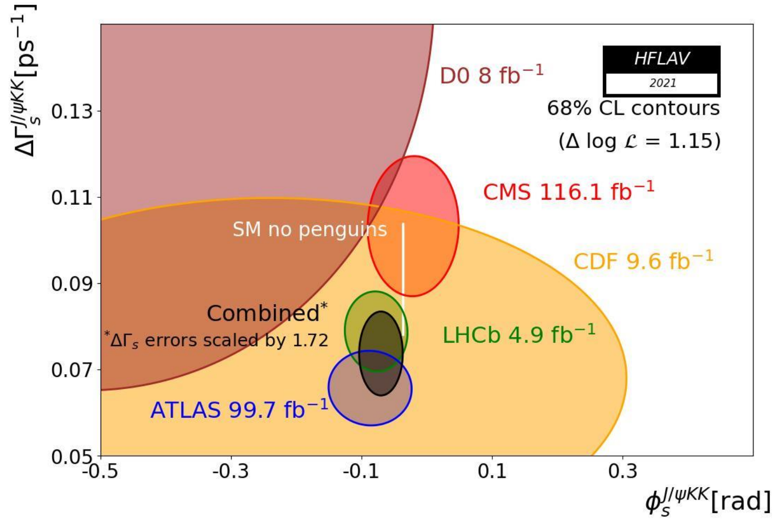

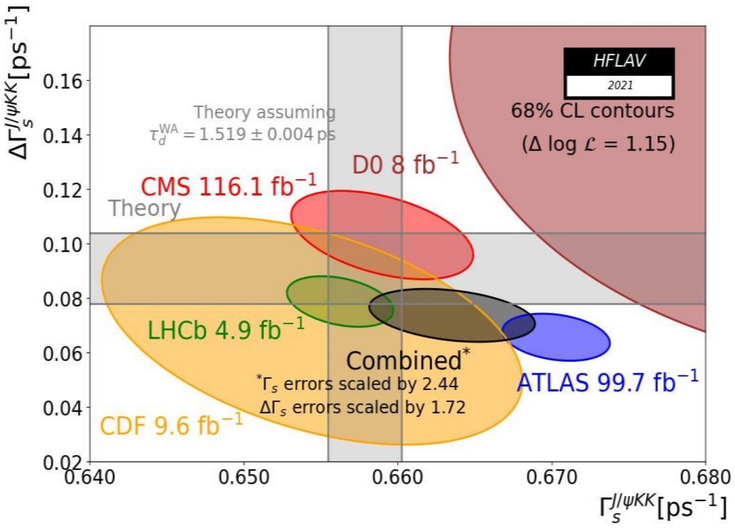

Γ_s in tension with LHCb and CMS measurements

Bs,d→μμ BR measurement

- **Rare but clean** decay suppressed by FCNC in the SM
  - BR(Bs→μμ) = (3.66 ± 0.14) x10^{-9}
  - BR(Bd→μμ) = (1.03 ± 0.05) x10^{-10}

  JHEP 10 (2019) 232
- **Three suppression factors:**
  - FCNC processes forbidden at tree-level
  - CKM elements (V_{ts} , V_{td})
  - Helicity suppression (0^- state going into two fermions)
- **Sensitive to New Physics** contributions through loops
- 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: $B^\pm \to J/\psi K^\pm$ Extracted from an unbinned ML fit to m(μμ$K^\pm$) distribution

Trigger categories and luminosity prescales*

Acceptance and efficiencies from simulation

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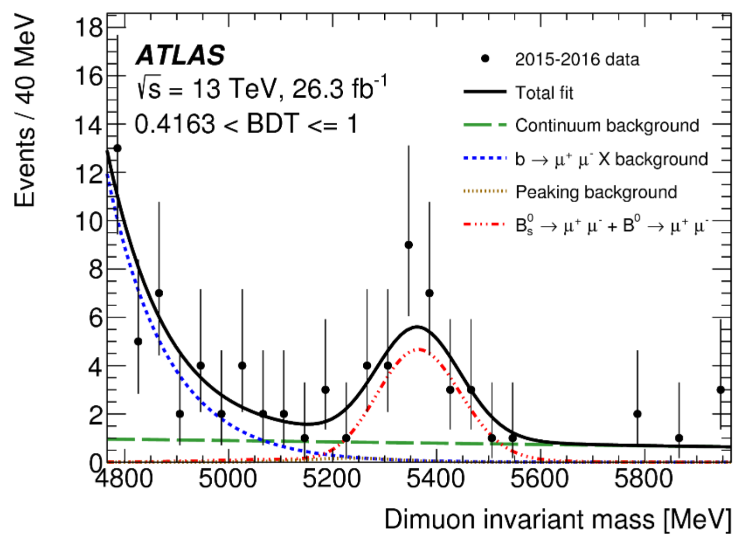
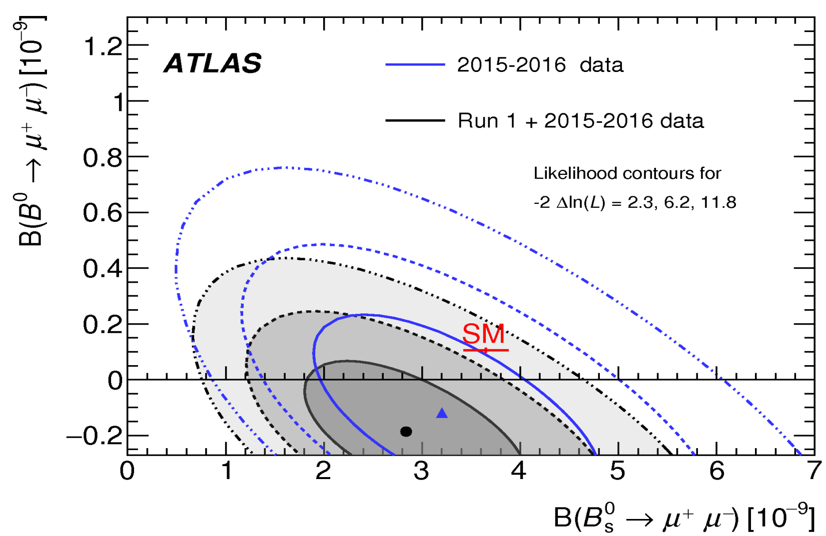
$B_{s,d} \rightarrow \mu\mu$ BR measurement

- BR extracted w.r.t to a well know high statistics reference channel ($B^{\pm} \rightarrow J/\psi K^{\pm}$) → reduce systematics
- Blind analysis
- High reduction and control of the backgrounds (both from fake muons and combinatorial)
- Simultaneous fit for the two channels in the di-muon invariant mass in 4 BDT regions (with different S/B ratio)

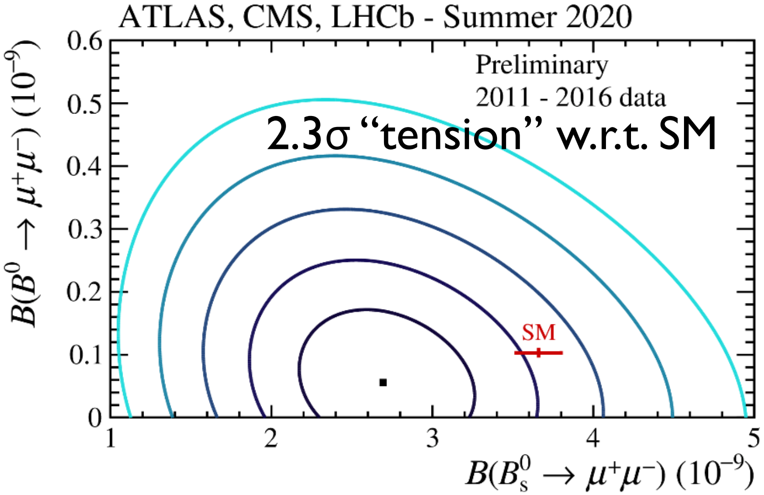


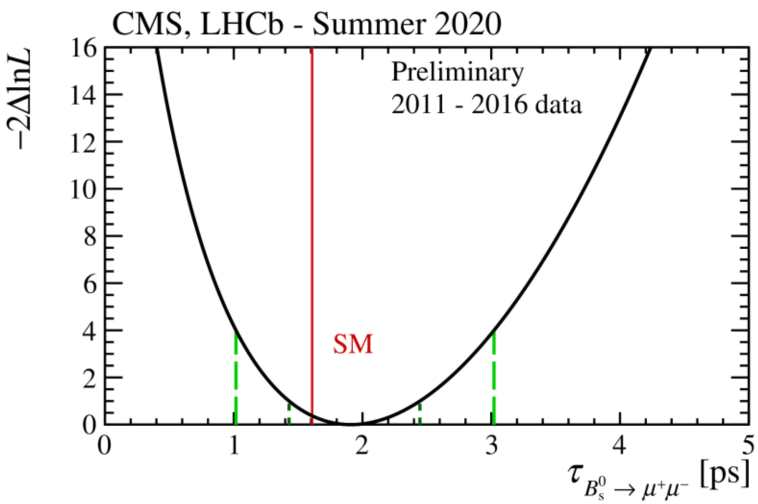


BR(Bs) = $2.8^{+0.8}_{-0.7}$ x10^{-9} (stat. ± syst.) **BR(Bd) < 2.1x10^{-10} (95% CL)**

ATLAS+CMS+LHCb combination

- Effort to combine the three measurements — ATL-CONF-2020-049
  - First ATLAS+CMS+LHCb combination!
  - Effective $B_s \rightarrow \mu\mu$ lifetime CMS+LHCB combination included
  - Done with the 2015+2016 dataset
- Combination of the three likelihoods
  - Measurements dominated by the statistical uncertainty





- Recent measurements on the full Run 2 dataset more compatible with SM:

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left[3.83^{+0.38}_{-0.36}\,(\text{stat})\,^{+0.19}_{-0.16}\,(\text{syst})\,^{+0.14}_{-0.13}\,(f_s/f_u)\right] \times 10^{-9},$$

CMS-PAS-BPH-21-006

$$\mathcal{B}(B^0 \to \mu^+\mu^-) = \left[0.37^{+0.75}_{-0.67}\,(\text{stat})\,^{+0.08}_{-0.09}\,(\text{syst})\right] \times 10^{-10}.$$

$BR(B_s \rightarrow \mu\mu) = (3.09^{+0.46+0.15}_{-0.43-0.11}) \times 10^{-9}$ (LHCb)
$BR(B_d \rightarrow \mu\mu) = (< 2.6) \times 10^{-10}$ (LHCb)

Phys. Rev. Lett. 128, (2022) 041801

Conclusions & outlooks

- Recent highlights in heavy flavour physics by ATLAS with Run 2 data have been shown

- The ATLAS programme in flavour physics is quite rich and cover a good portion of the most interesting topics in the domain

- ATLAS is competitive with LHCb (despite the different performance and environment) in few channels. Among them:
  - Search for some exotic state
  - Bc meson physics
  - CPV with the analysis of the Bs → J/ΨΦ decay
  - Measurement of the BR($B_{s,d} \to \mu\mu$) rare decay

- New measurements using the full Run1+Run2 statistics are ongoing: stay tuned!

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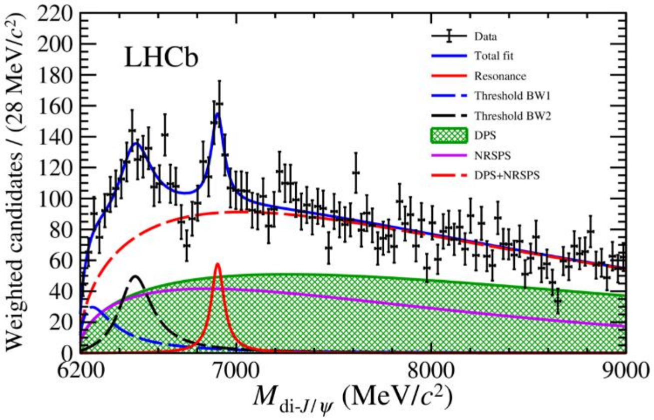
BACKUP

Di-charmonium events

Science Bulletin 65 (2020) 1983

- Search for tetraquarks Tc made of only charm quarks
- In 2020 LHCb found:
  - A narrow structure X(6900) in the di-J/Ψ channel
  - A broad structure just above twice the J/Ψ mass



- Look for confirmation in the di-J/Ψ spectrum and for structures also above the J/ΨΨ(2S) threshold
- Analysis uses full Run 2 statistics (i.e. 140 fb-1)
- Di-muon or 3 muons triggers (with J/Ψ mass requirements)
- Offline muon P_T thresholds: 4, 4, 3, 3 GeV
- Signal region:
  - m(4μ) < 7.5 GeV && Lxy < 0.2/0.3 && ΔR < 0.25 between the two charmonium pairs
- Control regions:
  - SPS → 7.5 < m(4μ) < 12 GeV
  - DPS → 14 < m(4μ) < 25 GeV
  - Non-prompt di-J/Ψ → Poor quality 4μ vertex + Lxy > 0.4

Di-charmonium events

- Unbinned ML fit to the 4μ mass distribution with m(4μ) < 11 GeV and ΔR < 0.25 (SR)/ ΔR > 0.25 (CR)
- Fit model: several interfering Breit-Wigner functions convoluted with Mass Resolution functions

di-J/Ψ model

$$f_s(x) = \left|\sum_{i=0}^{2} \frac{z_i}{x^2 - m_i^2 + i m_i \Gamma_i}\right|^2 \sqrt{1 - \frac{4m_{J/\psi}^2}{x^2}} \otimes R(\alpha)$$

- z_i complex numbers representing the amplitudes
- No interference with NRSPS (as in LCHb model)

J/Ψ+Ψ(2S) models:

Model A

$$f_s(x) = \left(\left|\sum_{i=0}^{2} \frac{z_i}{x^2 - m_i^2 + i m_i \Gamma_i}\right|^2 + \left|\frac{z_3}{x^2 - m_3^2 + i m_3 \Gamma_3}\right|^2\right) \sqrt{1 - \left(\frac{m_{J/\psi} + m_{\psi(2S)}}{x}\right)^2} \otimes R(\alpha)$$

Parameters of the first three resonances are fixed to those extracted in the di-J/Ψ fit

Model B single resonance

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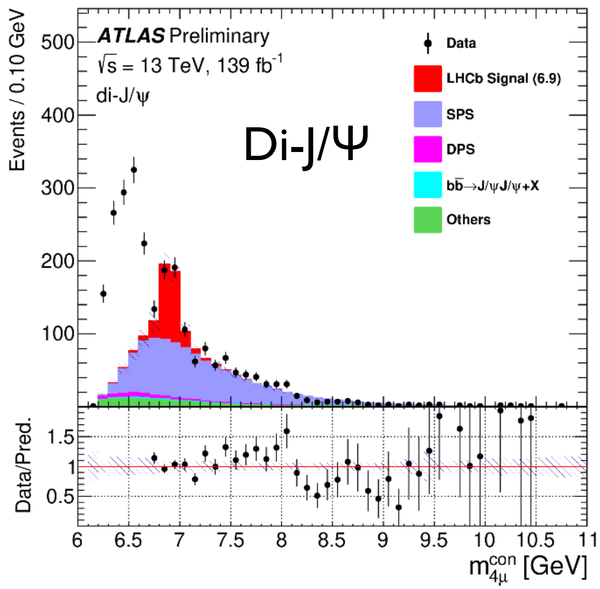
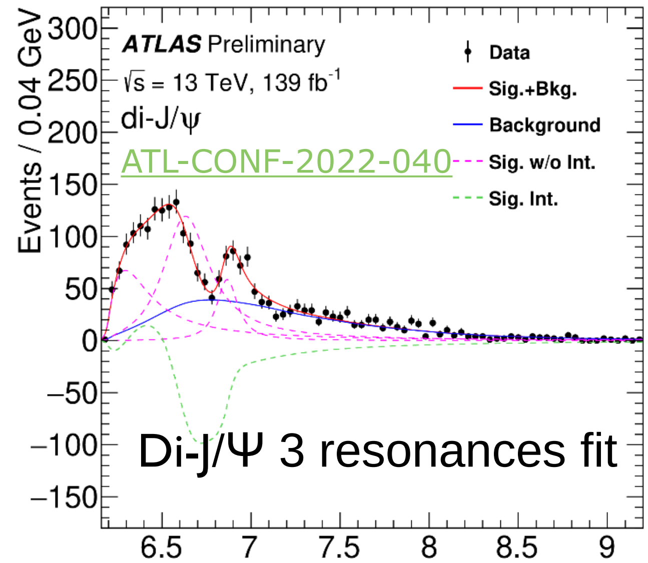
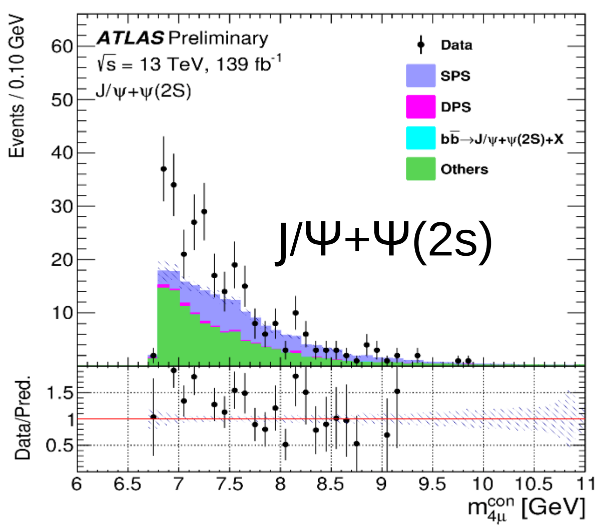
Di-charmonium events

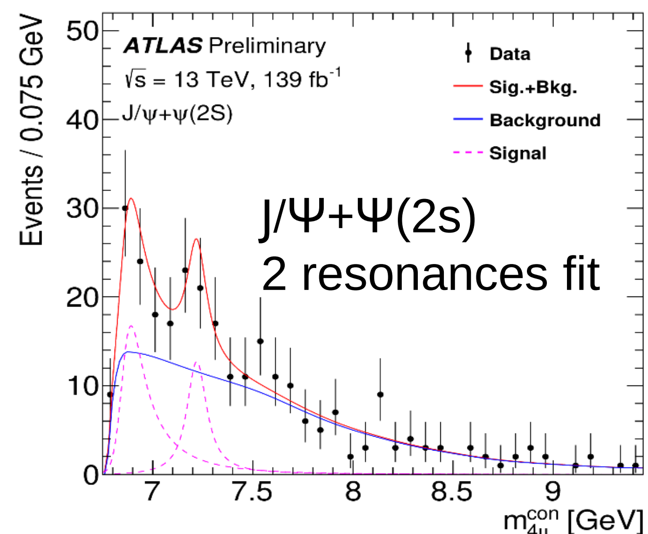




Best fit:

- 3 resonances model
- Resonance at 6900 MeV compatible with LHCb
- Broad res. might be due to other effects





Best fit:

- 2 resonances model slighlty preferred with one resonance at 6900 MeV
- Stat. Significance 4.6σ
- Hint for a resonance at 7.2 GeV (need confirmation)

CMS confirmed a resonance around 6900 MeV + 2 other resonances → Need to unifiy the model description among the 3 experiments!

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Mass/widths for the di-J/Ψ resonances

Table 3: The fitted masses and natural widths (in GeV) of the interfering resonances in the di-J/ψ and J/ψ+$\psi(2S)$ channels. The results of both model A and B are given for J/ψ+$\psi(2S)$. The first errors in each value are statistical while the second ones are systematic.

(GeV)				
di-J/ψ	m_0	Γ_0	m_1	Γ_1
	$6.22 \pm 0.05^{+0.04}_{-0.05}$	$0.31 \pm 0.12^{+0.07}_{-0.08}$	$6.62 \pm 0.03^{+0.02}_{-0.01}$	$0.31 \pm 0.09^{+0.06}_{-0.11}$
	m_2	Γ_2	—	
	$6.87 \pm 0.03^{+0.06}_{-0.01}$	$0.12 \pm 0.04^{+0.03}_{-0.01}$	—	
(GeV)		m_3	Γ_3	
J/ψ+$\psi(2S)$	model A	$7.22 \pm 0.03^{+0.02}_{-0.03}$	$0.10^{+0.13+0.06}_{-0.07-0.05}$	—
	model B	$6.78 \pm 0.36^{+0.35}_{-0.54}$	$0.39 \pm 0.11^{+0.11}_{-0.07}$	—

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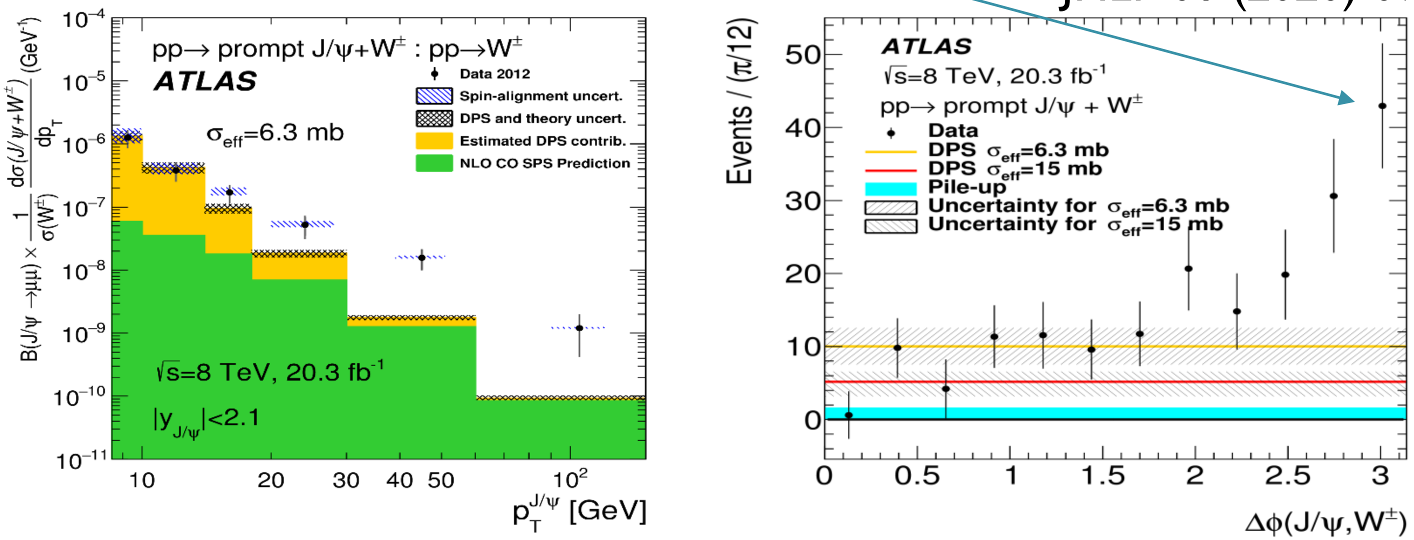
W+J/Ψ associated production

- Interesting to study the QCD at the border between perturbative and non-perturbative regimes.
- W+J/Ψ can be produced via two mechanisms:
  - SPS (Single Parton Scattering)
  - DPS (Double Parton Scattering)
- The J/Ψ is reconstructed in the di-muon decay while the W in its leptonic decay (electron/muon)
- SPS contribution extracted from data after subtracting the DPS (uncorrelated) component

JHEP 01 (2020) 095



NLO CO model does not describe well data at high PT(J/Ψ)

Charmonium differential cross-section

- I^{st} full Run2 analysis: measurement of the J/ψ and ψ(2s) x-sec
  - Differential in P_T and y; focus on high-P_T region: > 60 GeV
  - Single muon trigger: HLT_mu50
  - Pseudo proper lifetime fit to separate prompt component

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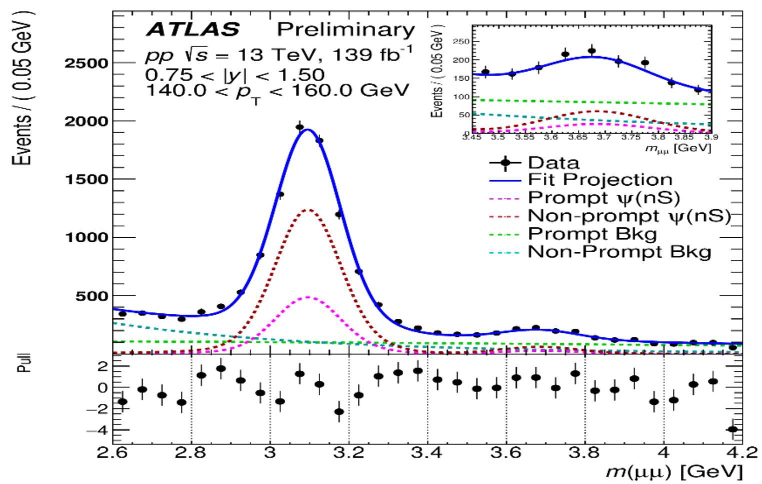
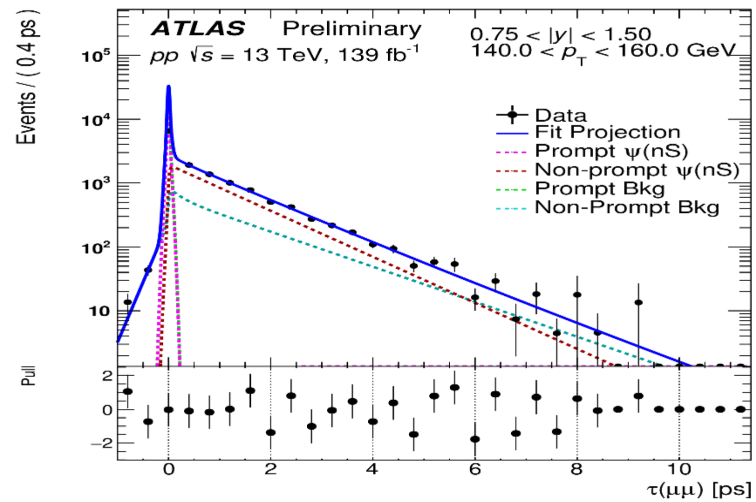
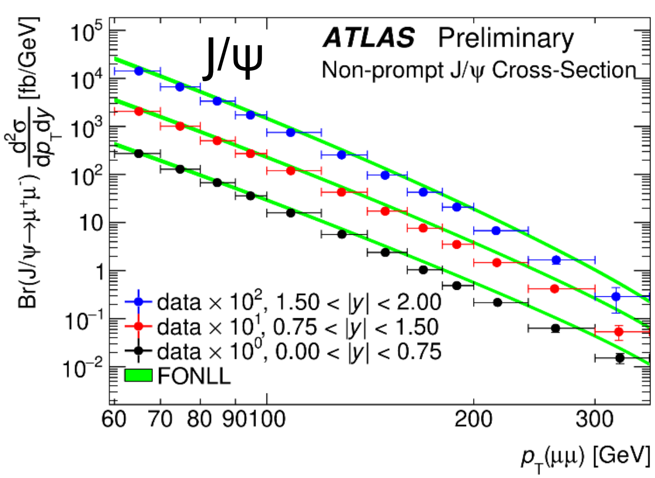
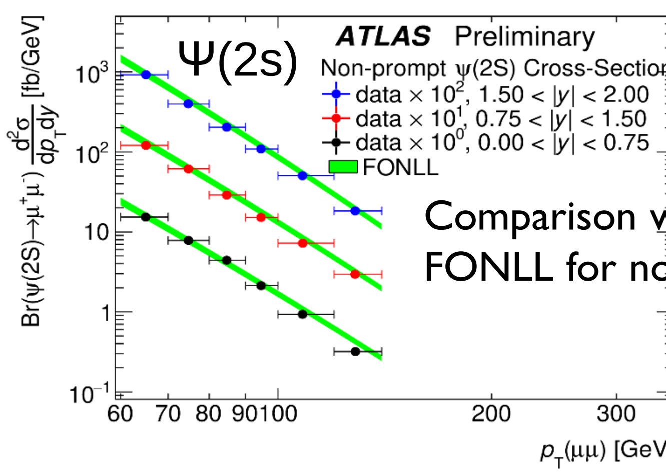




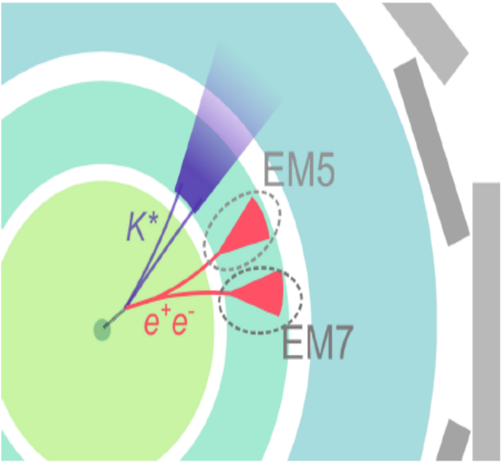


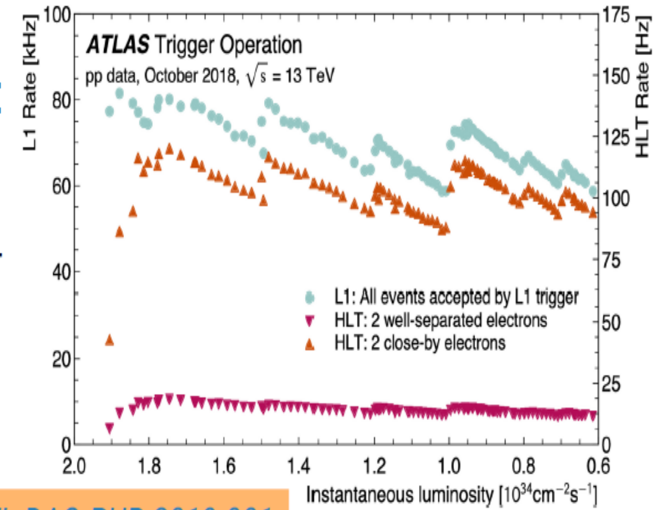


Comparison with FONLL for non-prompt

R(K*) in ATLAS ??

- Target $B \to K^{(*)}ee$
- L1 triggers: new topological triggers which look for a pair of soft electrons with low mass, or a soft "jet" near an electron (the jet assumed to combine two electrons)
  - to reduce rates also require additional muons from other B hadrons in event
- Software HLT dielectron low-mass triggers:
  - some seeded by the L1 topological triggers
  - also triggers that look at **all** events accepted by the L1 – very powerful
- Deployed mid-2018, ran for ~ 40 fb^{-1}





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