Istituto Nazionale di Fisica Nucleare

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Recent Heavy Flavour results from ATLAS

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

ICFNP, 26/08/2024

Outline

- ATLAS HF physics programme covers a wide range of studies:
  - Open heavy-flavour and heavy quarkonium production
  - Spectroscopy (including exotic states)
  - Decays (CPV, rare and semi-rare decays etc.)
- Competitive when (mostly) muon final states are involved and when statistics plays a crucial role
- In today talk:
  - How ATLAS triggers Heavy Flavour events
  - Recent Heavy Flavour ATLAS results covered in this talk:
    - Measurement of the J/Ψ and Ψ(2S) differential cross-sections paper
    - Search for di-charmonium events paper
    - Bs → μμ effective lifetime measurement paper

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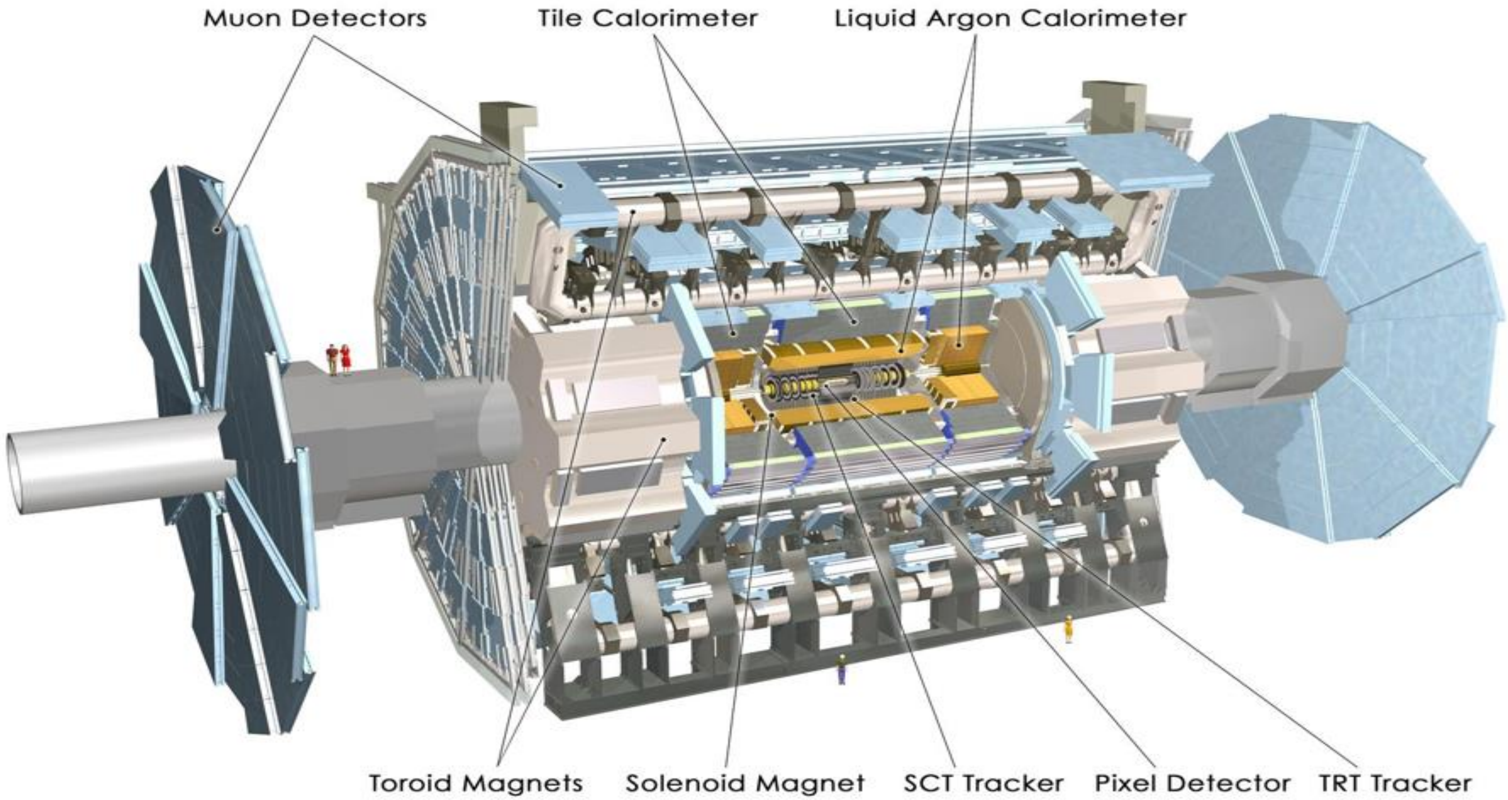
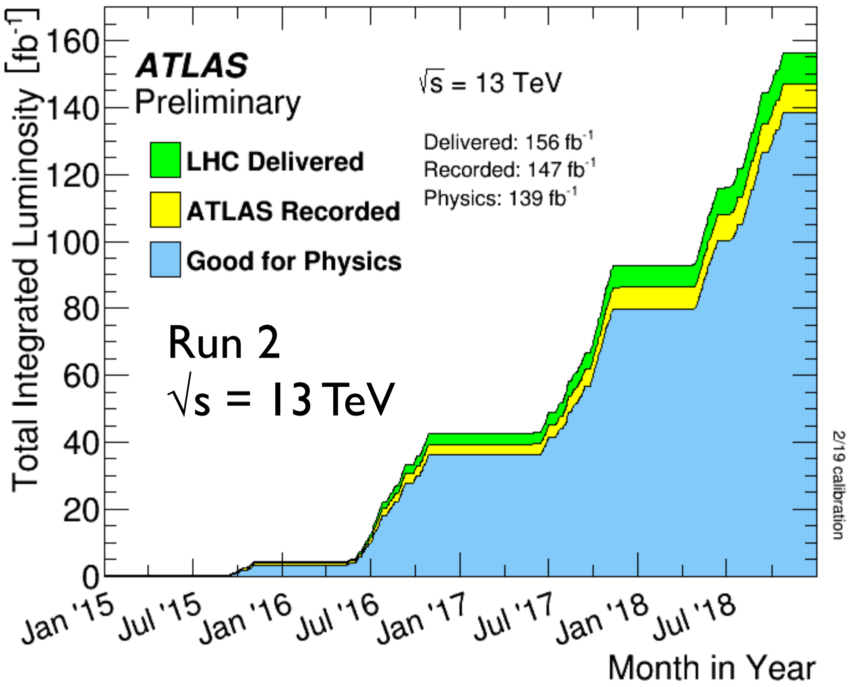
The ATLAS Experiment

- 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



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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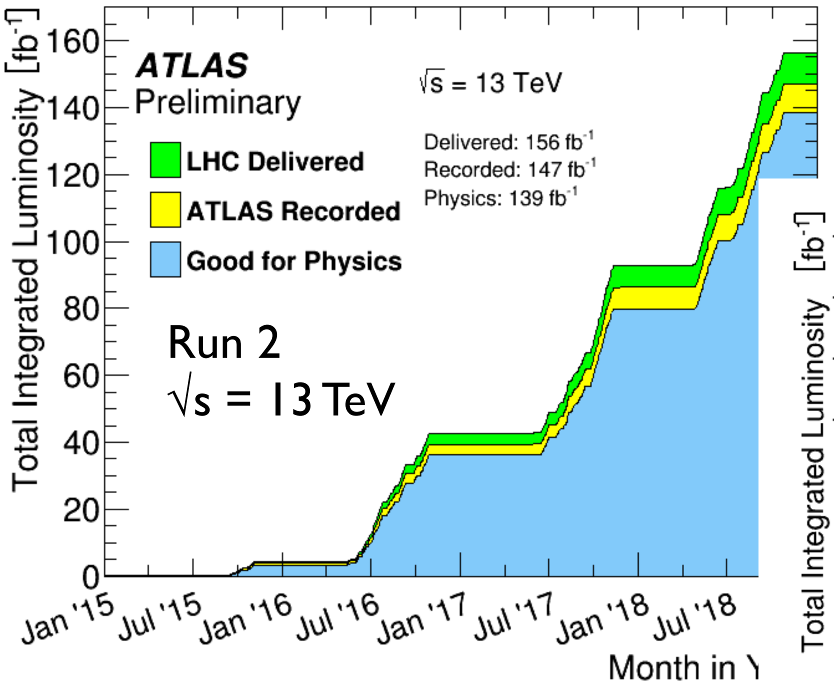

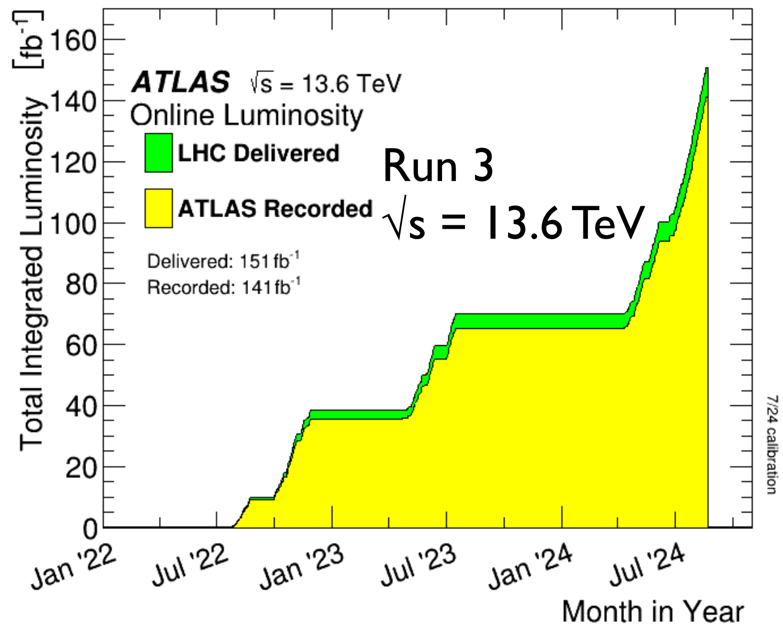

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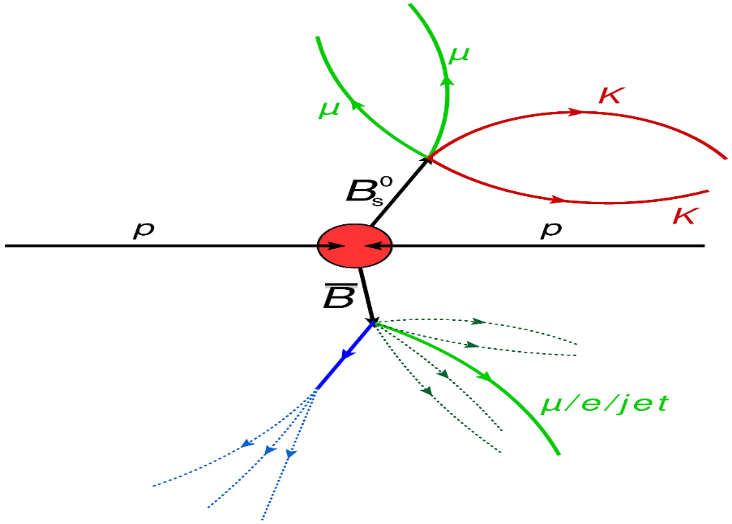
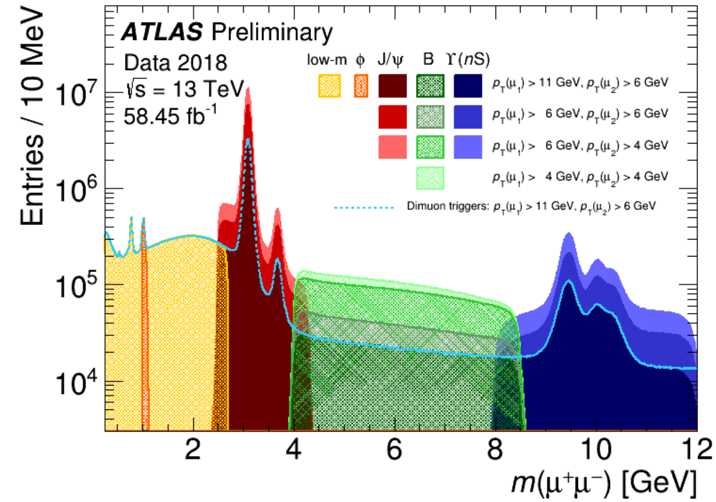
Typical B-physics signatures

- 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

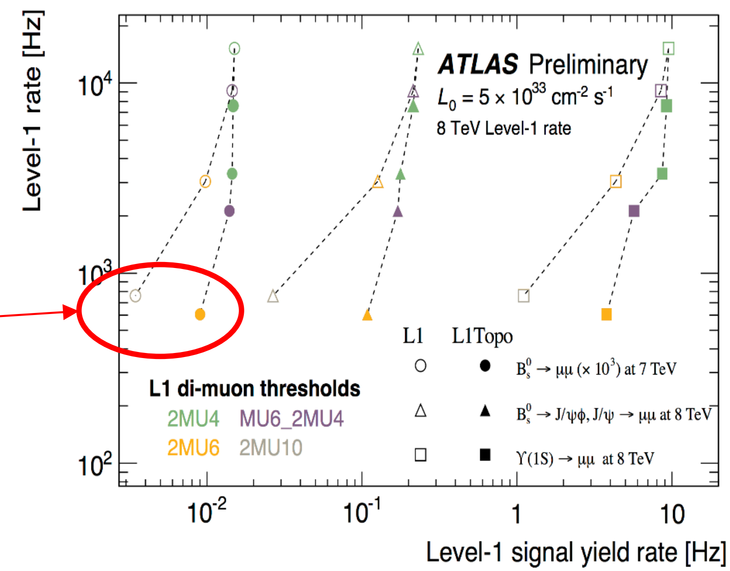


Triggering events in Run 1 and Run 2

- 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 2017-18 data (with MU4_MU6 and 2MU6 thresholds



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J/Ψ & Ψ(2S) cross-section

paper

- Despite its discovery dated almost 50 years, the QCD production mechanisms of charmonia (Ψ = J/Ψ or Ψ(2S)) is still not fully understood
  - Non-prompt production is reasonably well predicted by pQCD
  - Prompt production still to be understood.

- Goal: measure the J/Ψ and Ψ(2S) differential cross-sections in $\mathbf{P_T}$ and **y** separately in prompt and non-prompt production
  - Ψ → μμ
  - Triggers:
    - 2mu4 → 2.6 fb^{-1} to cover the region 8 GeV < PT(Ψ) < 60 GeV
    - Mu50 → 139 fb^{-1} to cover the region PT(Ψ) > 60 GeV
  - Offline cuts on Ψ follow the two trigger regions

- Cross-section computed in the fiducial region (PT cuts as above + |η(μ)| < 2.4) where ATLAS has the highest precision:
  - For the J/Ψ and Ψ(2S) mesons
  - For prompt (P) vs non-prompt (NP)
- Differential cross-section ratio NP/P is also measured

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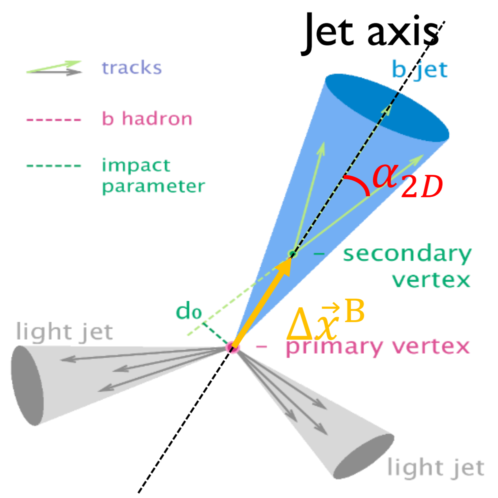
J/Ψ & Ψ(2S) cross-section

paper

- Fit model:
  - 2D unbinned extended ML fit on Ψ mass and proper-time $\tau = \frac{m_{\mu\mu}}{p_T}\frac{L_{xy}}{c}$ to extract the raw yields $N_{\Psi}^{P,NP}$
- Signal:
  - Mass → 2 Gaussians + Crystal-Ball
  - Proper-time:
    - P → Delta with gaussian smearing
    - NP → 2 exponentials
- Backgrounds:
  - Mass → Polynomial or exponential
  - Proper-time:
    - P → Delta with gaussian smearing
    - NP → 2 exponentials



L_{xy} is the projection of $\overrightarrow{\Delta x_B}$ in the transverse plane.

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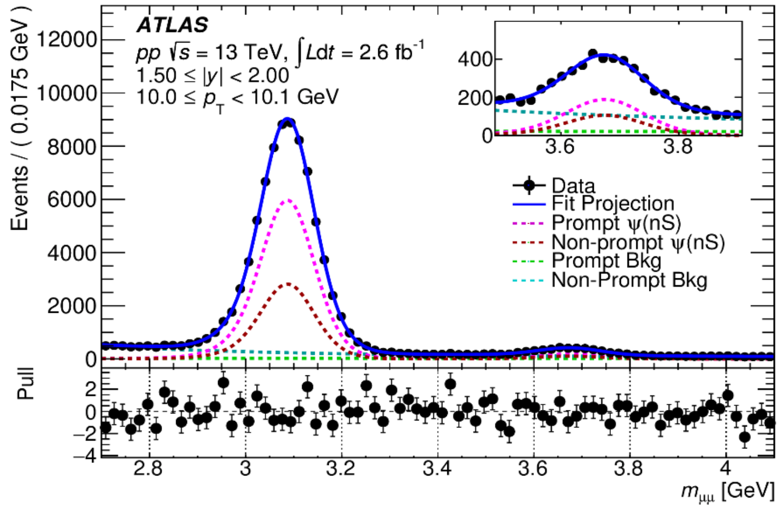
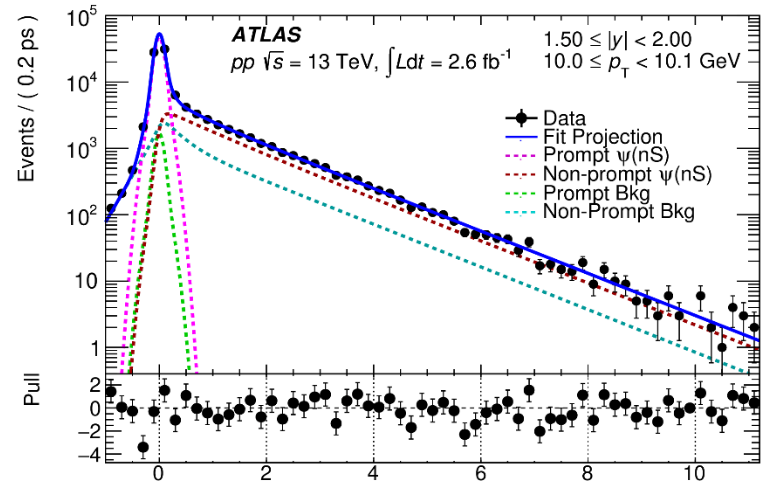
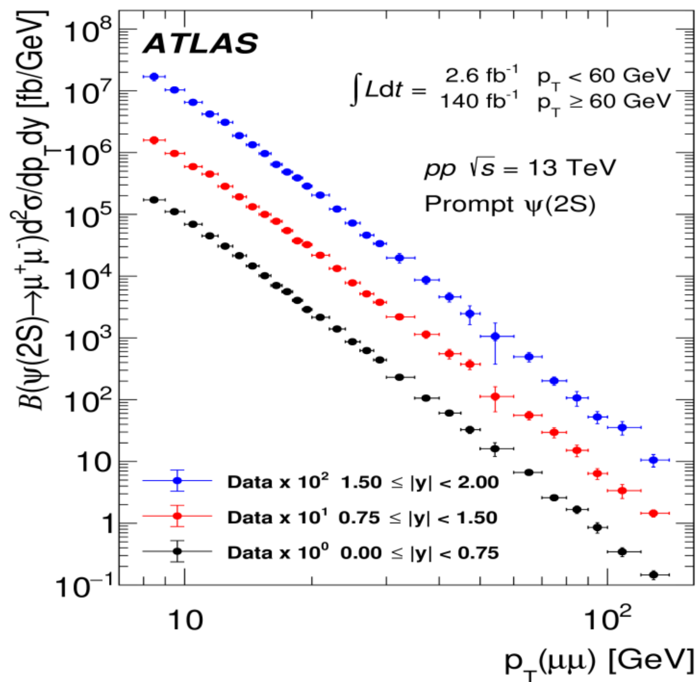
Low-PT region

paper

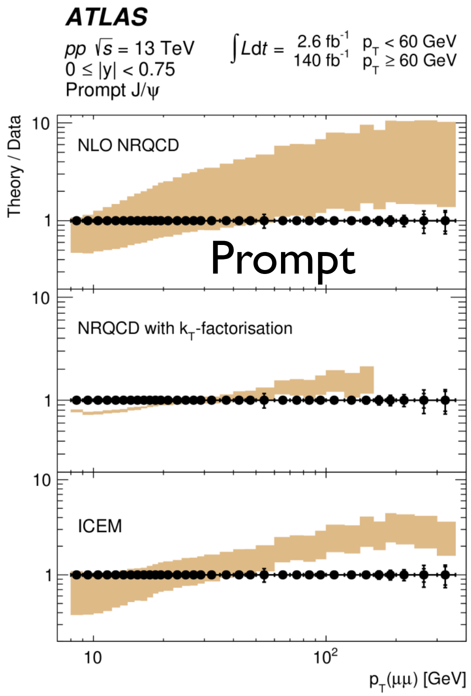


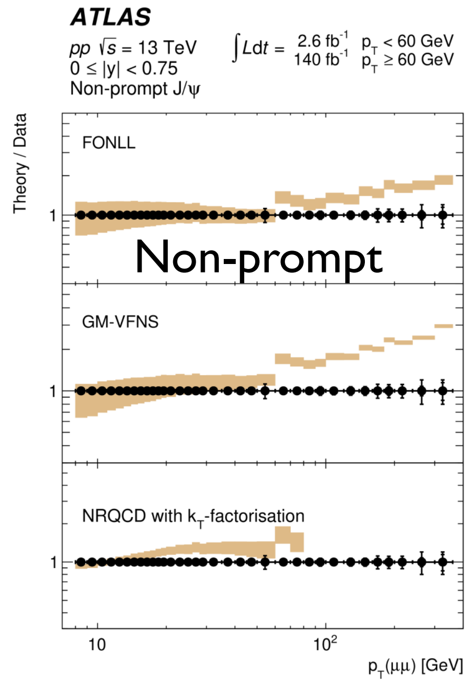


- Main systematic uncertainties:
  - Efficiency (dominant in the low-PT region)
  - Acceptance
  - Fit modelling (dominant in the high-PT region)
  - Spin alignment (main impact up to the transition region)



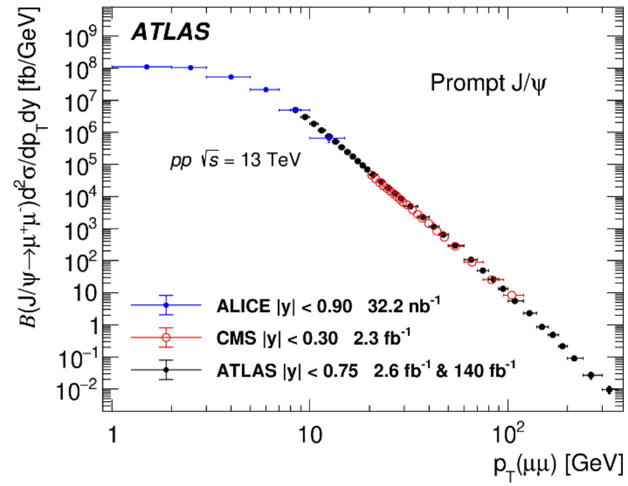
J/Ψ & Ψ(2S) cross-section





paper

Agreement with CMS and ALICE in the overlapping regions



- Conclusions:
  - Ψ differential cross-section measured in P_T and y
  - Range in P_T between 8 and 360 GeV
  - Prompt:
    - Much harder spectra predicted, room for improvement in all models
  - Non-prompt:
    - Generally better description, although still tend to over-estimate high pT

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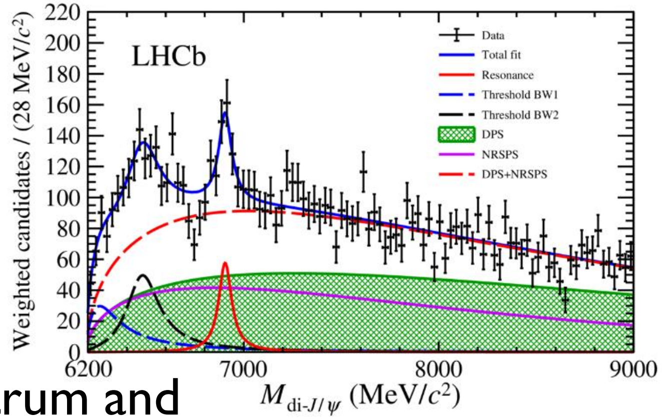
Di-charmonium events

- Search for tetraquarks Tc ($c\bar{c}\ c\bar{c}$)
- 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

Science Bulletin 65 (2020) 1983



- Look for confirmation in the di-J/Ψ spectrum and for structures also above the J/Ψ-Ψ(2S) threshold

Signal region	Control region	Non-prompt region
Di-muon or tri-muon triggers, oppositely charged muons from each charmonium, *loose* muons, $p_T^{1,2,3,4} > 4, 4, 3, 3$ GeV and $\lvert\eta_{1,2,3,4}\rvert < 2.5$ for the four muons, $m_{J/\psi} \in [2.94, 3.25]$ GeV, or $m_{\psi(2S)} \in [3.56, 3.80]$ GeV, Loose vertex requirements $\chi^2_{4\mu}/N < 40$ ($N = 5$) and $\chi^2_{\text{di-}\mu}/N < 100$ ($N = 2$),		
Vertex $\chi^2_{4\mu}/N < 3$, $L^{4\mu}_{xy} < 0.2$ mm, $\lvert L^{\text{di-}\mu}_{xy}\rvert < 0.3$ mm, $m_{4\mu} < 11$ GeV,		Vertex $\chi^2_{4\mu}/N > 6$,
$\Delta R < 0.25$ between charmonia	$\Delta R \geq 0.25$ between charmonia	or $\lvert L^{\text{di-}\mu}_{xy}\rvert > 0.4$ mm

Fit to the 4μ mass distribution with m(4μ) < 11 GeV and ΔR < 0.25 (SR)/ ΔR > 0.25 (CR)

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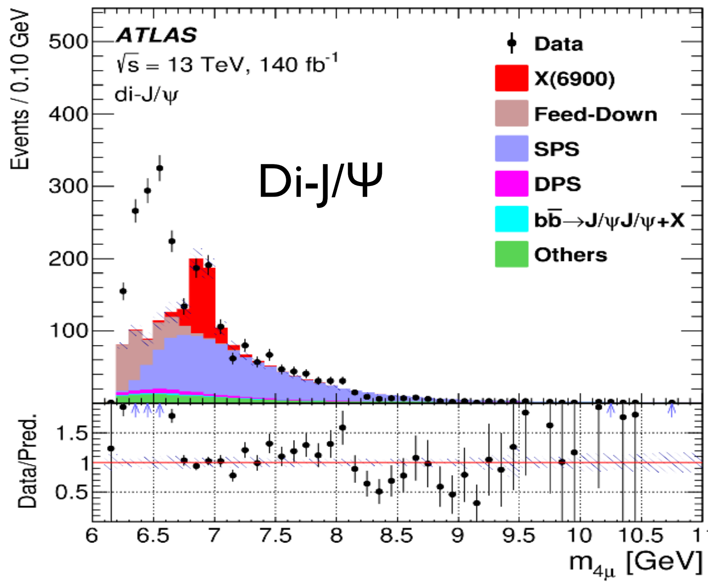
Di-J/Ψ events



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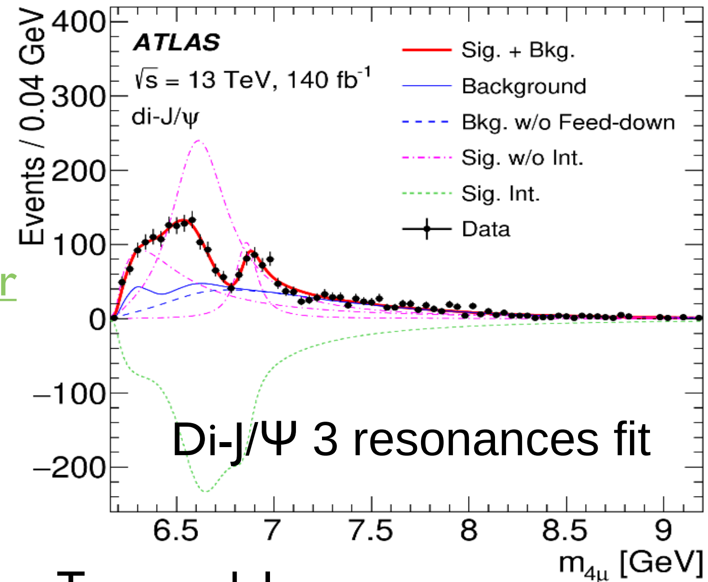

di-J/ψ	model A	model B
m_0	$6.41 \pm 0.08^{+0.08}_{-0.03}$	$6.65 \pm 0.02^{+0.03}_{-0.02}$
Γ_0	$0.59 \pm 0.35^{+0.12}_{-0.20}$	$0.44 \pm 0.05^{+0.06}_{-0.05}$
m_1	$6.63 \pm 0.05^{+0.08}_{-0.01}$	—
Γ_1	$0.35 \pm 0.11^{+0.11}_{-0.04}$	
m_2	$6.86 \pm 0.03^{+0.01}_{-0.02}$	$6.91 \pm 0.01 \pm 0.01$
Γ_2	$0.11 \pm 0.05^{+0.02}_{-0.01}$	$0.15 \pm 0.03 \pm 0.01$
$\Delta s/s$	$\pm 5.1\%^{+8.1\%}_{-8.9\%}$	—

Two models:

- Three interfering BW resonances (model A)
- One BW interfering with SPS + one BW standalone (model B)

Clear resonance at 6900 MeV (far more than 5σ) compatible with LHCb and CMS

- Nature of the broad structure at low mass less certain (feed-down?)

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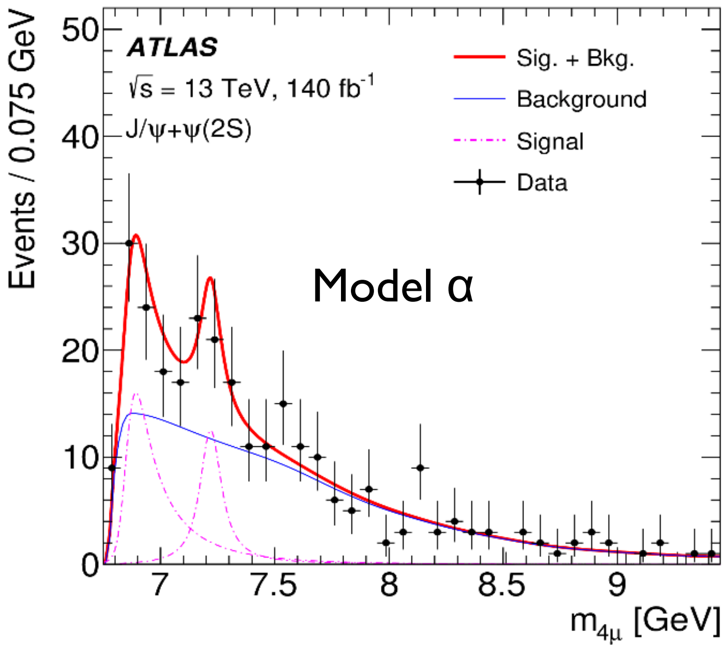
J/Ψ + $\Psi(2S)$ events



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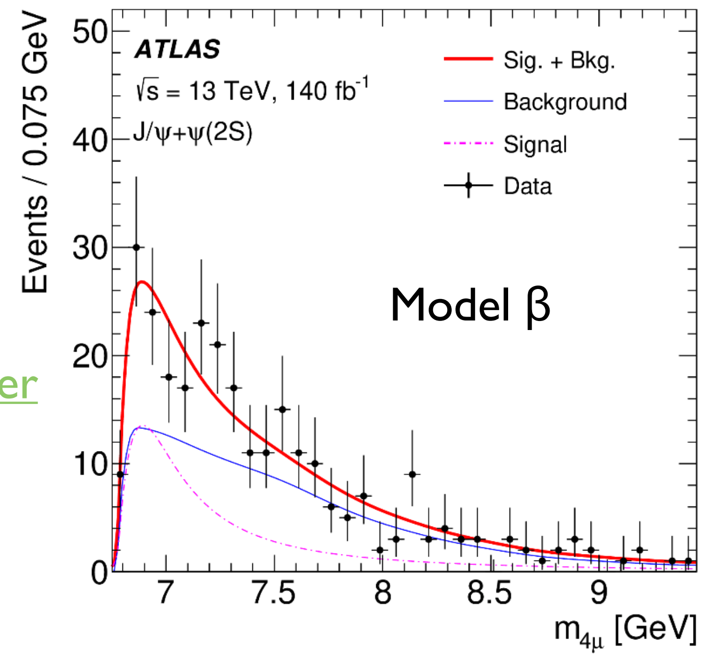

$J/\psi+\psi(2S)$	model α	model β
m_3	$7.22 \pm 0.03^{+0.01}_{-0.04}$	$6.96 \pm 0.05 \pm 0.03$
Γ_3	$0.09 \pm 0.06^{+0.06}_{-0.05}$	$0.51 \pm 0.17^{+0.11}_{-0.10}$
$\Delta s/s$	$\pm 21\%^{+25\%}_{-15\%}$	$\pm 20\% \pm 12\%$

Two models:

- Model α: three interfering BW (as for di-J/Ψ) + one standalone BW
  - Stat. significance 4.7 σ
- Model β: single BW resonance
  - Stat. Significance 4.3σ

3σ significance for a resonance at 7.22 GeV in model α

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Bs → μμ effective lifetime 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}

paper

- 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
- The effective lifetime is a complementary measurement with respect to the BR:
  - Sensitive to the CP structure of potential NP

In the SM $A_{\Delta\Gamma} = +1$ (CP-odd)

$$\tau_{\mu^+\mu^-} = \frac{\tau_{B_s^0}}{1 - y_s^2}\left(\frac{1 + A_{\Delta\Gamma}^{\mu^+\mu^-} y_s + y_s^2}{1 + A_{\Delta\Gamma}^{\mu^+\mu^-} y_s}\right)$$

holds, where

- $\tau_{B_s^0} = 1.510 \pm 0.005\, ps$ is the B_s^0 mean lifetime;
- $y_s = \tau_{B_s^0}\Delta\Gamma/2$;
- $\Delta\Gamma$ is the difference between light and heavy mass eigenstates decay width.

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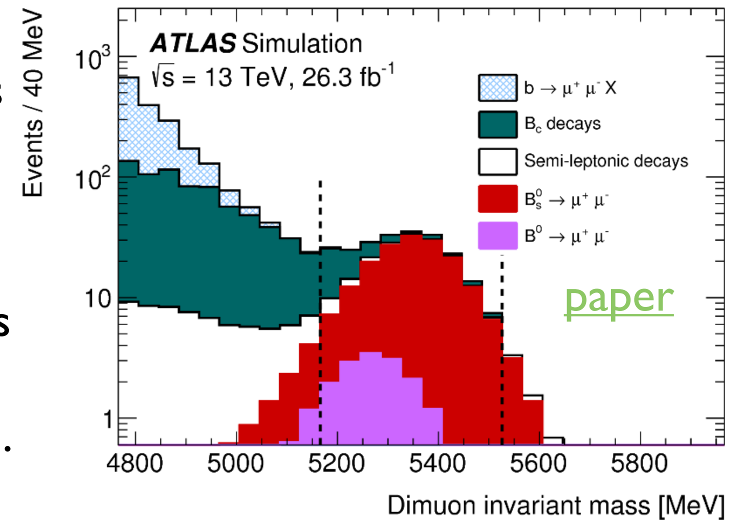
Bs → μμ effective lifetime measurement

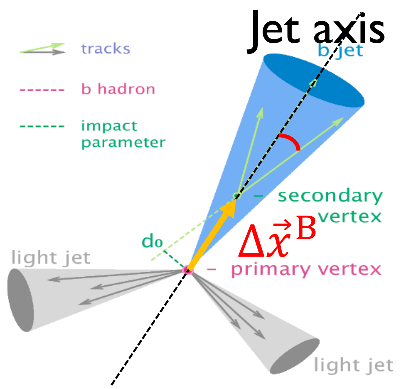
- Same dataset used for the latest BR $(B^0_{(s)} \to \mu^+\mu^-)$ measurement BR paper
- Main backgrounds for the measurement:
  - Combinatorial background: real muons coming from the decay chain of b and $\bar{b}$ initial quarks
  - Partially reconstructed B decays: real muons coming from B → μμ+X decays
  - Any B-hadron decay involving k/π faking a muon (e.g. B→μhX or B→hh').



- The key variable is the proper decay time

$$t = \frac{L_{xy} m_B}{|\vec{p}_T^{\,B}|}$$

- New optimisation of the BDT selection tailored for the effective lifetime measurement
  - One single BDT region > 0.3650



L_{xy} is the projection of $\overrightarrow{\Delta x_B}$ in the transverse plane.

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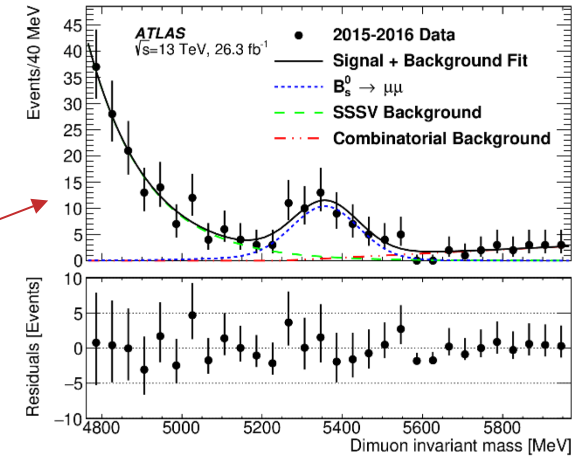
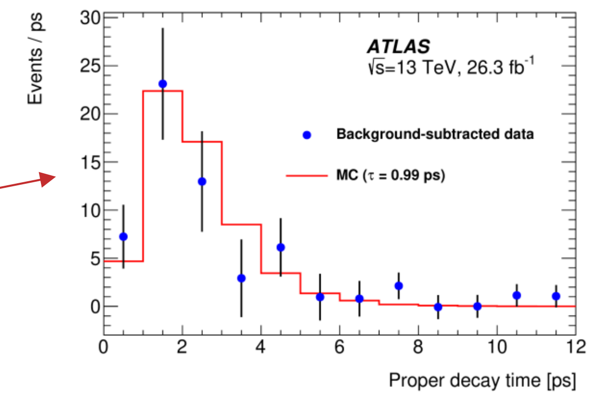
Analysis strategy

paper

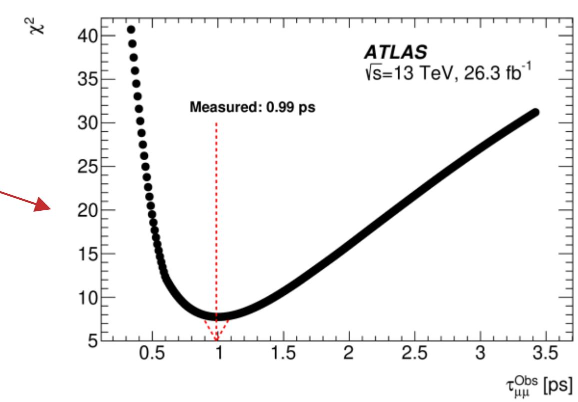
1. UEML fit to the dimuon invariant mass distribution based on 2015-2016 models for signal and background components to extract the number of candidates.
   - Signal modelled with a double Gaussian
   - Continuum background modelled with a 1° order pol.
   - Partially reconstructed decays modelled with an exponential



2. Use sPlot to extract signal proper time distribution from data.
   - The sPlot technique allows to estimate the distribution of a **control variable** using the known distribution of a **discriminating variable**.
   - The proper decay time is the control variable, the mass the discriminating variable → minimal correlation between them.



3. Compare the signal proper time distribution with the MC templates to extract the lifetime.
   - MC templates generated for different lifetimes
   - χ^2 minimization used to find the best template.



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Results

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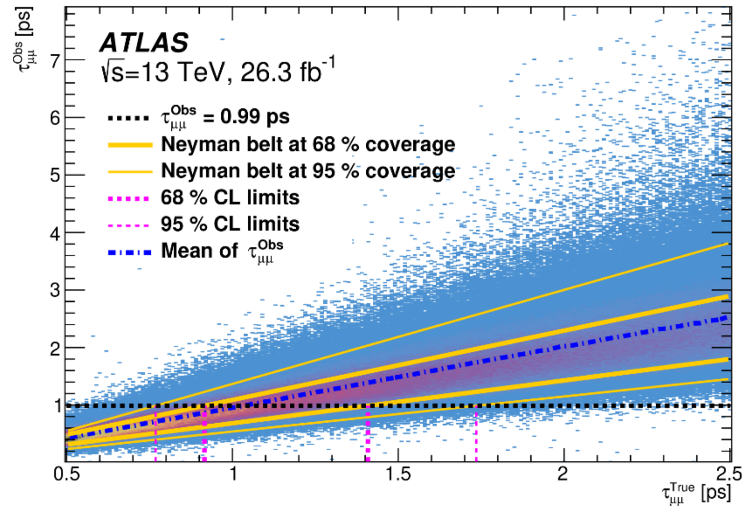
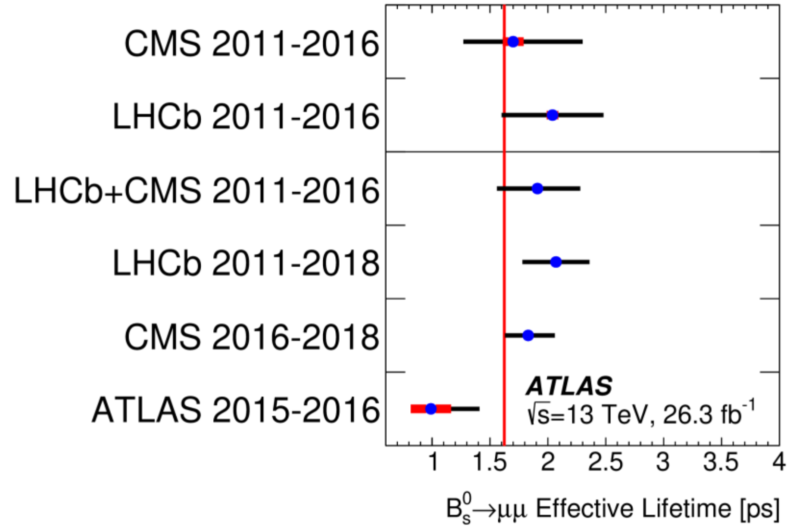
- Measured value:
  $\tau_{\mu\mu} = (0.99)^{+0.42}_{-0.07}(stat.) \pm 0.17(syst)\ ps$
  - Corrected for the fit bias of 82 fs
- Stat. uncertainty is dominant:
  - Estimated with the Neyman belt construction
- Main systematics:
  - Data/MC discrepancies
  - Mass fit modelling
  - Lifetime dependence
- Similar precision as CMS and LHCb with the same dataset (syst. uncert. in red)
  - Compatible with the SM and all other measurements





Conclusions & outlooks

- The ATLAS programme in flavour physics is quite rich and cover a good portion of the most interesting topics in the domain
  - Competitive in final states with muons and when statistics is important

- Recent highlights in heavy flavour physics by ATLAS with Run 2 data have been shown:
  - Measurement of the J/Ψ and Ψ(2S) differential cross-sections
  - Bs → μμ effective lifetime measurement
  - Search for di-charmonium events

- New measurements using the full Run2+ Run3 statistics are ongoing: stay tuned!

BACKUP

J/Ψ & Ψ(2S) cross-section

paper

- Despite its discovery dated almost 50 years, the QCD production mechanisms of charmonia (Ψ = J/Ψ or Ψ(2S)) is still not fully understood
  - Non-prompt production is reasonably well predicted by pQCD
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- Goal: measure the J/Ψ and Ψ(2S) differential cross-sections in $\mathbf{P_T}$ and **y** separately in prompt and non-prompt production
  - Ψ → μμ
  - Triggers:
    - 2mu4 → 2.6 fb^{-1} to cover the region 8 GeV < PT(Ψ) < 60 GeV
    - Mu50 → 139 fb^{-1} to cover the region PT(Ψ) > 60 GeV
  - Offline cuts on Ψ follow the two trigger regions

- Cross-section computed in the two regions as:

P= Prompt
NP = Non-prompt

$$\frac{d^2\sigma^{P,NP}(pp \to \psi)}{dp_T dy} \times \mathcal{B}(\psi \to \mu^+\mu^-) = \frac{1}{\mathcal{A}(\psi)\epsilon_{trig}\epsilon_{trigSF}\epsilon_{reco}\epsilon_{recoSF}} \frac{N_{\psi}^{P,NP}}{\Delta p_T \, \Delta y \, \int \mathcal{L}dt},$$

Acceptance

Efficiencies

Corrections to MC samples

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J/Ψ & $\Psi(2S)$ cross-section

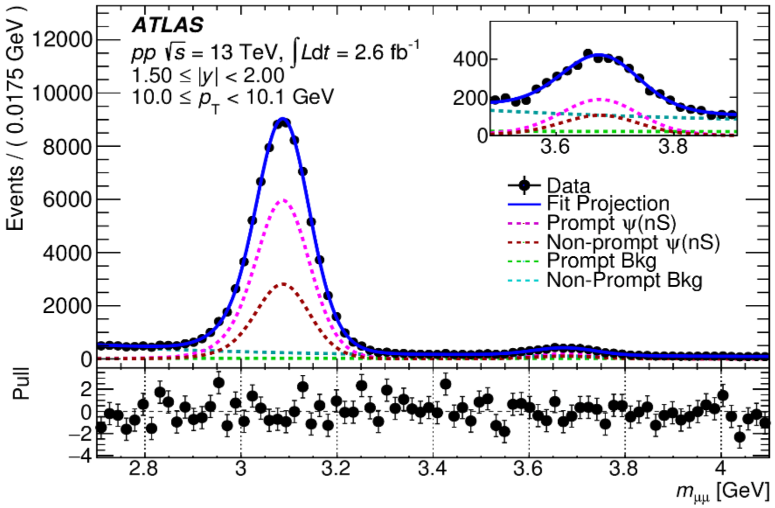
Fit model

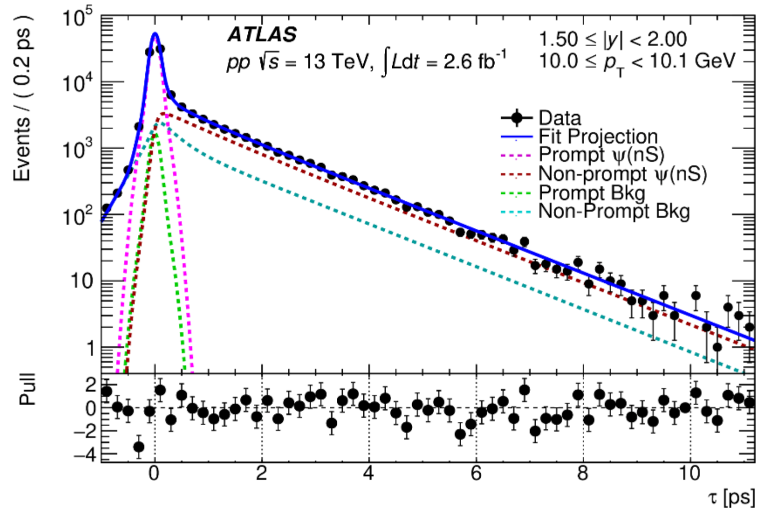
i	Type	P/NP	$f_i(m)$	$h_i(\tau)$
1	J/ψ	P	$\omega_0 G_1(m) + (1-\omega_0)[\omega_1 CB(m) + (1-\omega_1)G_2(m)]$	$\delta(\tau)$
2	J/ψ	NP	$\omega_0 G_1(m) + (1-\omega_0)[\omega_1 CB(m) + (1-\omega_1)G_2(m)]$	$\omega_2 E_1(\tau) + (1-\omega_2)E_1(b\tau)$
3	$\psi(2S)$	P	$\omega_0 G_1(\beta m) + (1-\omega_0)[\omega_1 CB(\beta m) + (1-\omega_1)G_2(\beta m)]$	$\delta(\tau)$
4	$\psi(2S)$	NP	$\omega_0 G_1(\beta m) + (1-\omega_0)[\omega_1 CB(\beta m) + (1-\omega_1)G_2(\beta m)]$	$E_2(\tau)$
5	Bkg	P	P	$\delta(\tau)$
6	Bkg	NP	$E_3(m)$	$E_4(\tau)$
7	Bkg	NP	$E_5(m)$	$E_6(\|\tau\|)$

J/Ψ & Ψ(2S) cross-section

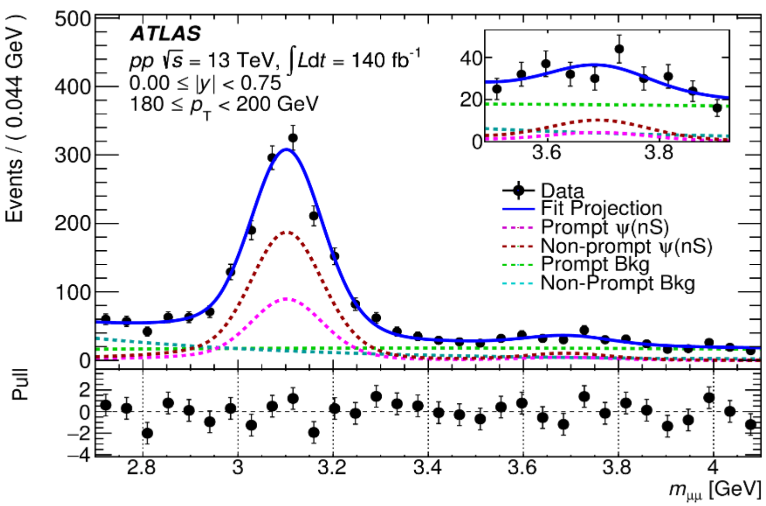
paper

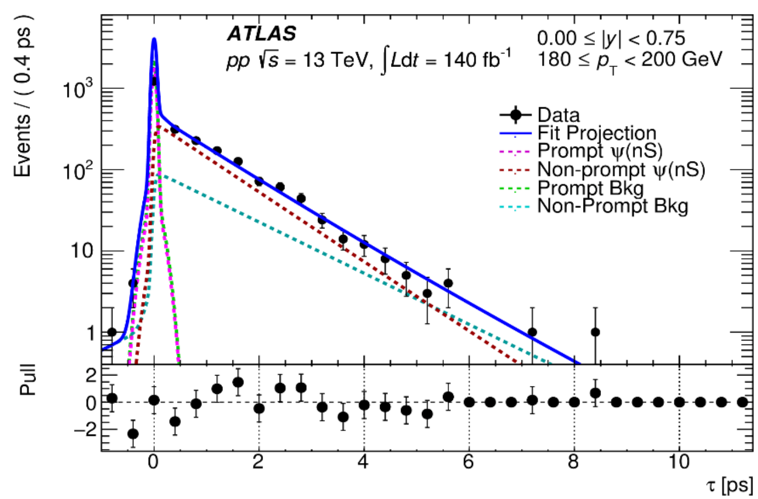
Low-PT region





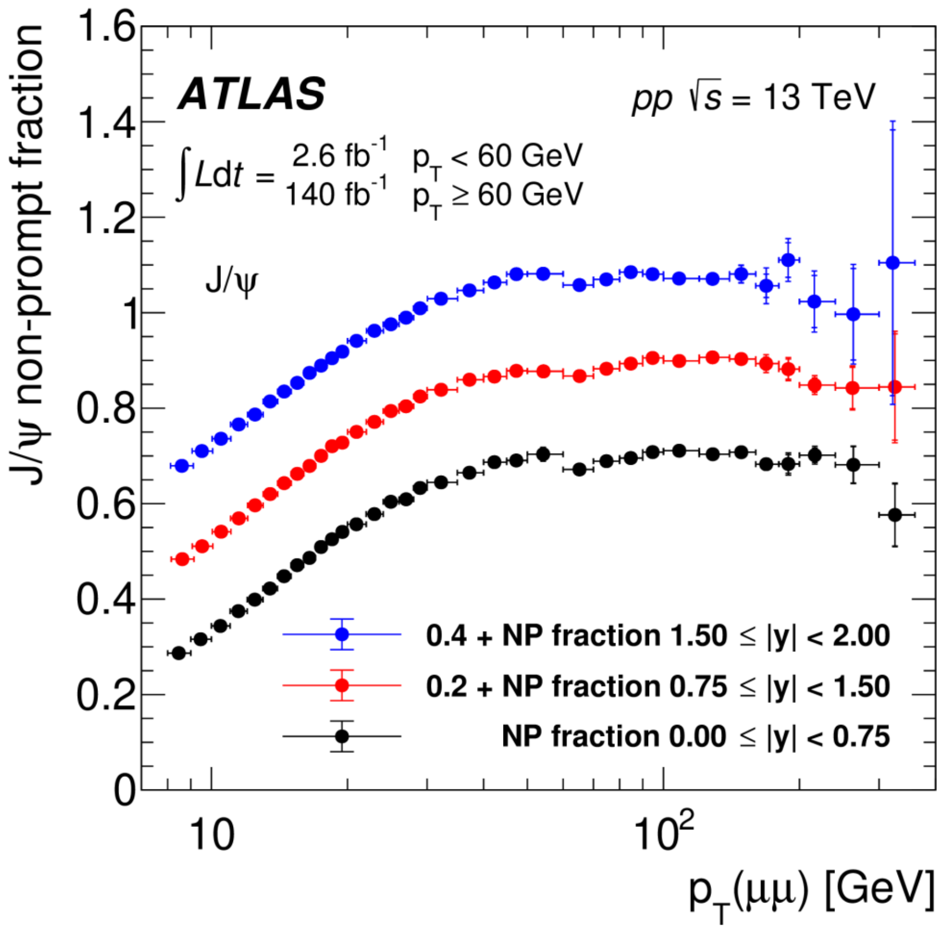
High-PT region





J/Ψ & Ψ(2S) cross-section

Non-prompt fraction



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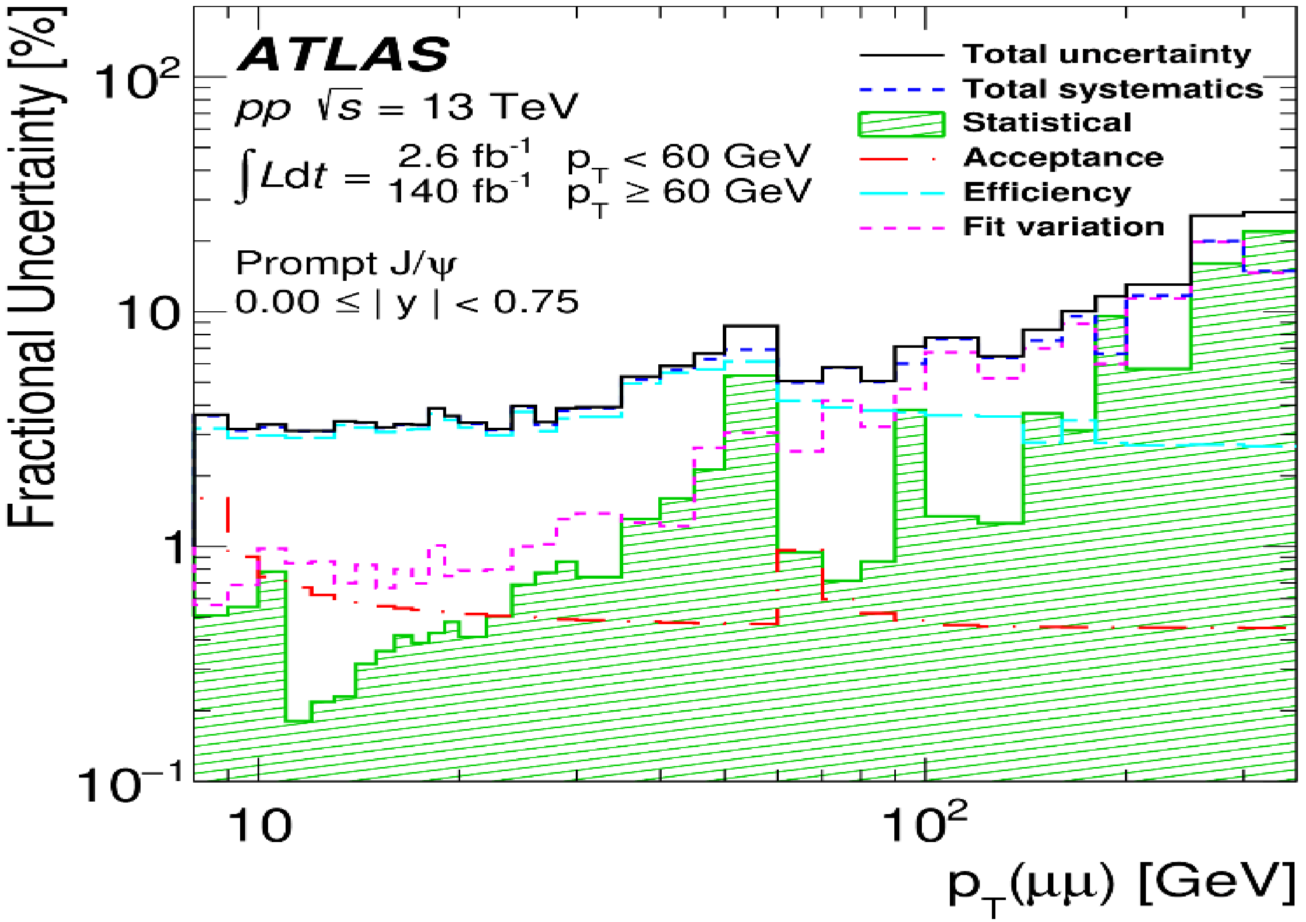
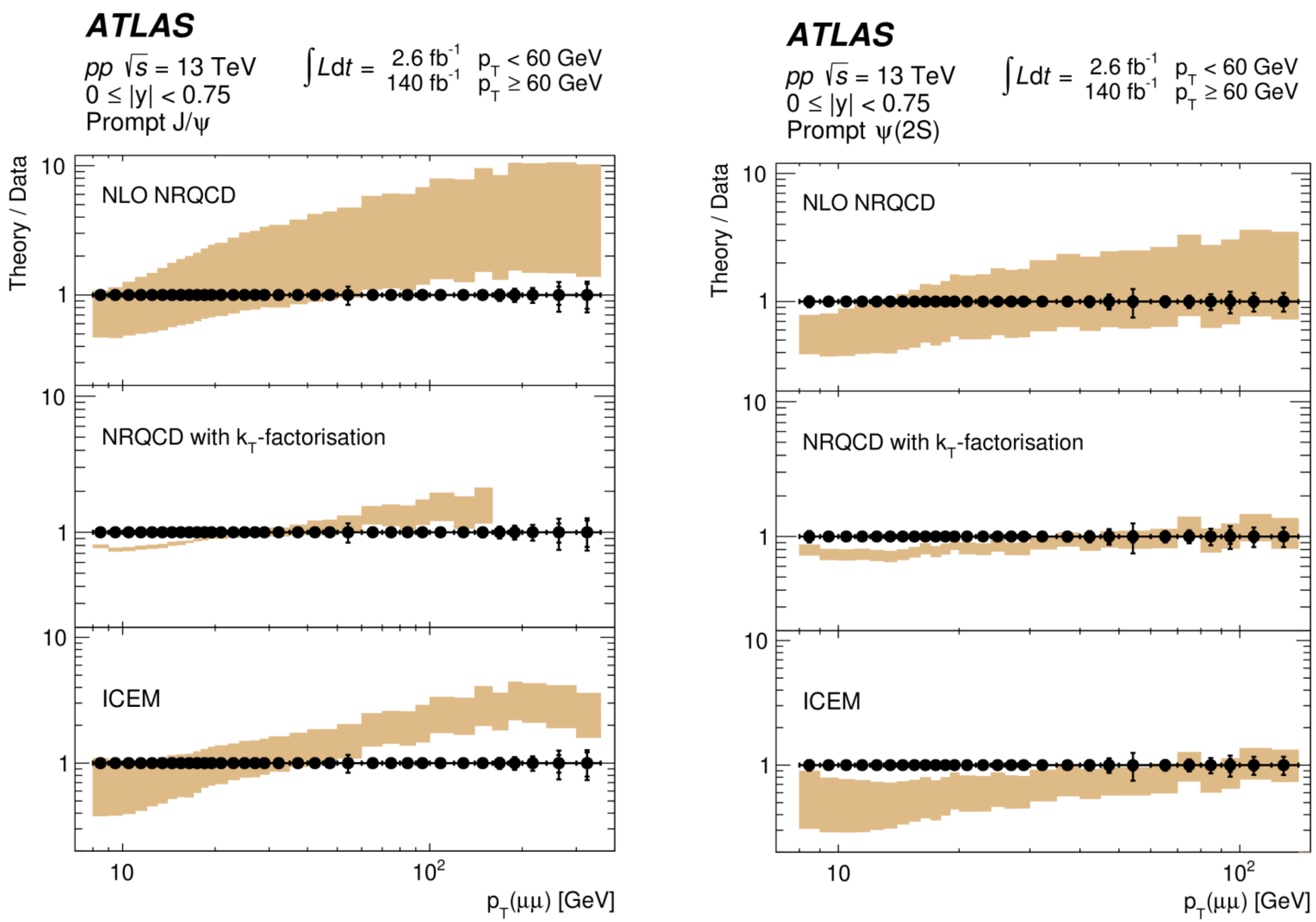
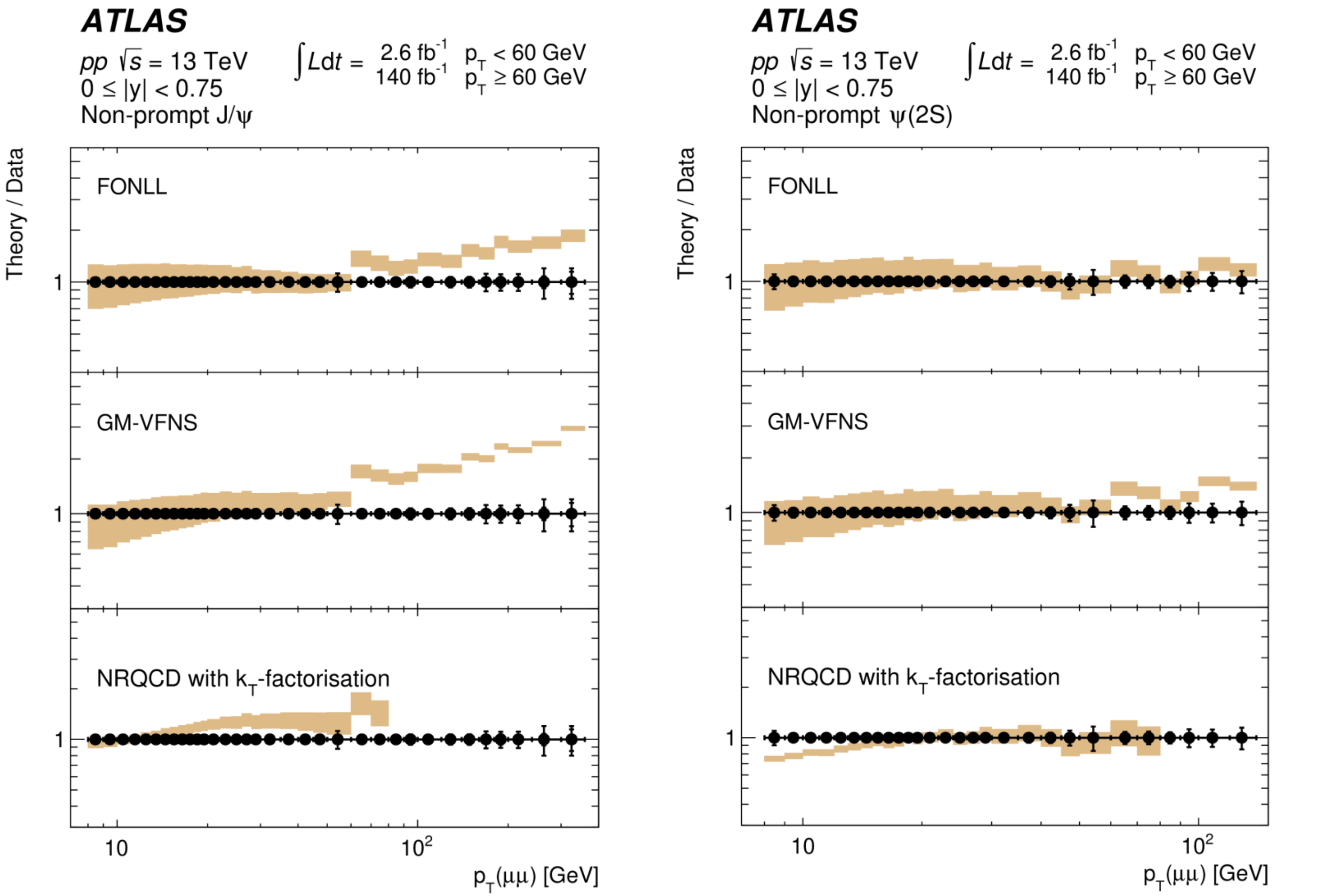
J/Ψ & Ψ(2S) cross-section

Systematic uncertainites budget




ATLAS
pp √s = 13 TeV
0 ≤ |y| < 0.75
Prompt J/ψ
∫Ldt = 2.6 fb-1 pT < 60 GeV
140 fb-1 pT ≥ 60 GeV
Theory / Data
NLO NRQCD
NRQCD with kT-factorisation
ICEM
pT(μμ) [GeV]
ATLAS
pp √s = 13 TeV
0 ≤ |y| < 0.75
Prompt ψ(2S)
∫Ldt = 2.6 fb-1 pT < 60 GeV
140 fb-1 pT ≥ 60 GeV
Theory / Data
NLO NRQCD
NRQCD with kT-factorisation
ICEM
pT(μμ) [GeV]


ATLAS
pp √s = 13 TeV
0 ≤ |y| < 0.75
Non-prompt J/ψ
∫Ldt = 2.6 fb-1 pT < 60 GeV
140 fb-1 pT ≥ 60 GeV
Theory / Data
FONLL
GM-VFNS
NRQCD with kT-factorisation
1
10
10^2
pT(μμ) [GeV]
ATLAS
pp √s = 13 TeV
0 ≤ |y| < 0.75
Non-prompt ψ(2S)
∫Ldt = 2.6 fb-1 pT < 60 GeV
140 fb-1 pT ≥ 60 GeV
Theory / Data
FONLL
GM-VFNS
NRQCD with kT-factorisation
1
10
10^2
pT(μμ) [GeV]

- 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 A

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

- z_i complex numbers representing the amplitudes
- Interference between the 3 resonances

di-J/Ψ model B

$$f(x) = \left(\left|\frac{z_0}{m_0^2 - x^2 - i m_0 \Gamma_0(x)} + A(x)e^{i\phi}\right|^2 + \left|\frac{z_2}{m_2^2 - x^2 - i m_2 \Gamma_2(x)}\right|^2\right) \sqrt{1 - \frac{4m_{J/\psi}^2}{x^2}} \otimes R(\theta),$$

Interfere with SPS

Standalone

J/Ψ+Ψ(2S) model α:

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

J/Ψ+Ψ(2S) model β: as model α with one single resonance

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

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Mass/widths for the di-J/Ψ resonances

Fitted masses and natural widths for the various models

paper

di-J/ψ	model A	model B
m_0	$6.41 \pm 0.08^{+0.08}_{-0.03}$	$6.65 \pm 0.02^{+0.03}_{-0.02}$
Γ_0	$0.59 \pm 0.35^{+0.12}_{-0.20}$	$0.44 \pm 0.05^{+0.06}_{-0.05}$
m_1	$6.63 \pm 0.05^{+0.08}_{-0.01}$	—
Γ_1	$0.35 \pm 0.11^{+0.11}_{-0.04}$	
m_2	$6.86 \pm 0.03^{+0.01}_{-0.02}$	$6.91 \pm 0.01 \pm 0.01$
Γ_2	$0.11 \pm 0.05^{+0.02}_{-0.01}$	$0.15 \pm 0.03 \pm 0.01$
$\Delta s/s$	$\pm 5.1\%^{+8.1\%}_{-8.9\%}$	—
$J/\psi + \psi(2S)$	model α	model β
m_3	$7.22 \pm 0.03^{+0.01}_{-0.04}$	$6.96 \pm 0.05 \pm 0.03$
Γ_3	$0.09 \pm 0.06^{+0.06}_{-0.05}$	$0.51 \pm 0.17^{+0.11}_{-0.10}$
$\Delta s/s$	$\pm 21\%^{+25\%}_{-15\%}$	$\pm 20\% \pm 12\%$

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Bs → μμ effective lifetime measurement

Uncertainty source	$\Delta\tau_{\mu\mu}^{\mathrm{Obs}}$ [fs]
Data - MC discrepancies	134
SSSV lifetime model	60
Combinatorial lifetime model	56
B kinematic reweighting	55
B isolation reweighting	32
SSSV mass model	22
B_d background	16
Fit bias lifetime dependency and B_s^0 eigenstates admixture	15
Combinatorial mass model	14
Pileup reweighting	13
B_c background	10
Muon Δ_η correction	6
$B \to hh'$ background	3
Muon reconstruction SF reweighting	2
Semileptonic background	2
Trigger reweighting	1
Total	174

Bs → μμ effective lifetime measurement

Toy MC example