Exotic hadron spectroscopy & B_s^0 lifetime measurement at ATLAS

FPCP 2024

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27-31 May

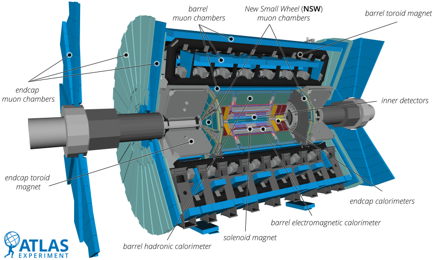
In This Talk...

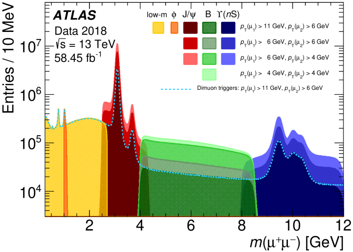
1. Overview
2. Exotic Hadron Spectroscopy
   - Di-charmonium $\rightarrow 4\mu$ search - PhysRevLett.131.151902
   - $\Upsilon(1S) + \mu^{+}\mu^{-} \rightarrow 4\mu$ search - ATLAS-CONF-2023-041
3. $B_s^0 \rightarrow \mu\mu$ effective lifetime measurement - JHEP 09 (2023) 199
4. Summary

Other ATLAS talks in parallel session 6 today –talks from Marek and Qipeng

Overview

- ATLAS has a wide flavour physics programme including:
  - Rare decays, CP/LFU violations, other decay precision measurements
  - Hadron spectroscopy (including exotics)
  - Heavy flavour production measurements
- Generally competitive with other flavour physics experiments, due to high statistics, good muon performance and kinematic coverage
  - Muon reconstruction from $p_T > 2.5$ GeV
  - Track reconstruction covering $|\eta| < 2.5, p_T > 0.5$ GeV





arXiv:2004.13447v2

Structures in di-charmomium mass spectrum

- Motivation
  - Exotic hadron states, such as $qq\bar{q}\bar{q}$ and $qqqq\bar{q}$, allowed in SM. New resonances also predicted by various BSM models
  - LHCb observed (arXiv:2006.16957v2) a structure $X(6900)$, in the di-$J/\psi \to 4\mu$ mass spectrum at $> 5\,\sigma$
    - Consistent with a fully-charmed tetraquark $T_{cc\bar{c}\bar{c}}$
    - Other interpretations possible
  - Excess corroborated by ATLAS and CMS (arXiv:2306.07164v2)
- Additionally, the ATLAS analysis considers both the di-$J/\psi \to 4\mu$ and $J/\psi + \psi(2S) \to 4\mu$ decays
  - Possible 6.9 GeV structure above the $J/\psi + \psi(2S)$ mass threshold

Analysis Strategy

- Combination of di- and tri-muon triggers used to select for events
- Additional selection (based on muon and track fit quality, kinematic and isolation variables) used to define signal, control, and background regions.

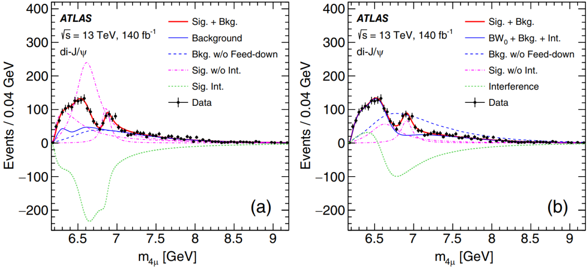
TABLE I. Summary of event selection requirements for different regions.

Signal region	Control region	Nonprompt region
Dimuon or trimuon 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 $\chi^2_{4\mu}/N > 6$, or $\lvert L^{\text{di-}\mu}_{xy}\rvert > 0.4$ mm
$\Delta R < 0.25$ between charmonia	$\Delta R \geq 0.25$ between charmonia	

- Backgrounds include: SPS, DPS, prompt and non-prompt J/ψ production, and non-resonant $\mu\mu$ production
  - Modelled using MC and background regions in data, with control regions allowing for MC reweighting
  - Feed-down from higher mass channel also contributes

di-$J/\psi \to 4\mu$

- The analysis uses 2 fit models, comparable to those used by LHCb:
  1. Model (a): 3 BW resonance model
     $\rightarrow$ here self-interfering, other models consider but excluded
  2. Model (b): 2 BW resonance model, lower resonance interferes with the SPS background

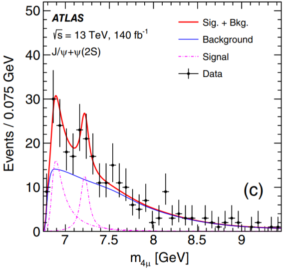


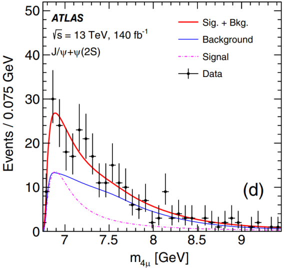
Fit Parameters:

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	$6.63 \pm 0.05^{+0.08}_{-0.01}$	$\cdots$
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	$0.11 \pm 0.05^{+0.02}_{-0.01}$	$0.15 \pm 0.03 \pm 0.01$
$\Delta s/s$	$\pm 5.1\%^{+8.1\%}_{-8.9\%}$	$\cdots$

$J/\psi + \psi(2S) \to 4\mu$

- Two fit models also considered:
  1. Model (c/α): Same 3 interfering BW resonances as in (a), with an additional standalone BW resonance.
  2. Model (d/β): Single BW resonance
- Where the same resonance is considered, the parameters are fixed from the di-J/ψ fit
- Fit results here used to fix feed-down background in di-J/ψ





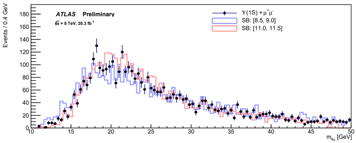
Fit Parameters:

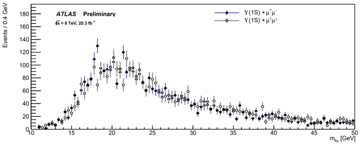
$J/\psi + \psi(2S)$	Model α	Model β
m_3	$7.22 \pm 0.03^{+0.01}_{-0.04}$	$6.96 \pm 0.05 \pm 0.03$
Γ_3	$0.09 \pm 0.06^{+0.06}_{-0.05}$	$0.51 \pm 0.17^{+0.11}_{-0.10}$
$\Delta s/s$	$\pm 21\%^{+25\%}_{-15\%}$	$\pm 20\% \pm 12\%$

Summary

- Up to four resonances observed, with X(6900) being all but confirmed $\rightarrow$ consistent parameters and observation between experiments (LHCb, CMS).
- Significances of $> 5\,\sigma$ for observations in the di-J/ψ channel, and of 4-5 σ in the $J/\psi + \psi(2S)$ channel
- Evidence for possible resonance at ~ 7.2 GeV of 3.0 σ —hinted at by LHCb and CMS di-J/ψ analyses, via higher mass resonance models
- Full characterisation of excess requires further study/more statistics

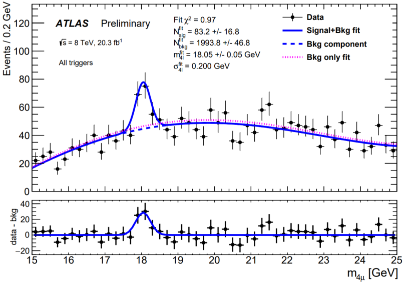
- Motivation
  - Bump hump analysis in the $\Upsilon(1S)(\to \mu^+\mu^-) + \mu^+\mu^-$ mass spectrum
  - Process gives a wide low mass range to search for new fundamental scalars or doubly-hidden b tetraquarks
- Analysis strategy
  - $\Upsilon(1S)$ candidate, with corresponding low-p_T di-μ pair selected
  - Di- and tri-muon triggers used in Run 1, with only tri-muon triggers from Run 2, and tighter trigger reqs. in 2018 data.
  - Analysis performed unblinded, however, excess survives variation in selection and extensive validation
    $\to$ same sign di-lepton analysis shows no excess, non-physical resolutions removed, ...

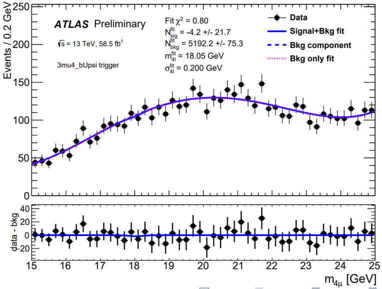




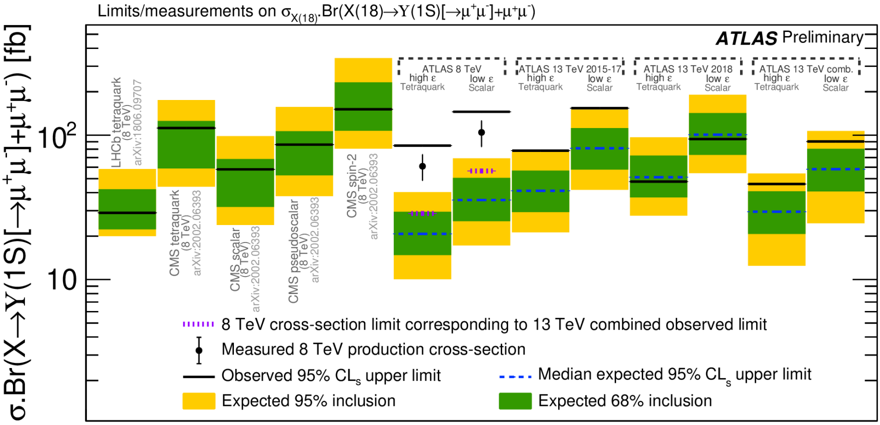
Results

- Excess of events at 18 GeV in Run 1, local significance of 3.6-6.3 σ $\rightarrow$ corresponding to a global significance of 1.9-5.4 σ depending on the selection choice.
- Reduction/absence of excess seen in Run 2, consistent with MC and data-driven studies on reduced sensitivity from tighter trigger reqs.
- 13 TeV result in tension with 8 TeV at 2.7 σ for MC models.
- Needs further study





Results



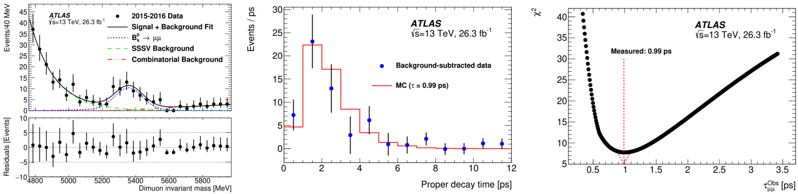
Limits/measurements on σX(18).Br(X(18)→Υ(1S)[→μ+μ-]+μ+μ-)
ATLAS Preliminary
σ.Br(X→Υ(1S)[→μ+μ-]+μ+μ-) [fb]
10
10^2
LHCb tetraquark (8 TeV) arXiv:1806.09707
CMS tetraquark (8 TeV) arXiv:2002.06393
CMS scalar (8 TeV) arXiv:2002.06393
CMS pseudoscalar (8 TeV) arXiv:2002.06393
CMS spin-2 (8 TeV) arXiv:2002.06393
ATLAS 8 TeV
ATLAS 13 TeV 2015-17
ATLAS 13 TeV 2018
ATLAS 13 TeV comb.
high ε Tetraquark
low ε Scalar
8 TeV cross-section limit corresponding to 13 TeV combined observed limit
Measured 8 TeV production cross-section
Observed 95% CLs upper limit
Median expected 95% CLs upper limit
Expected 95% inclusion
Expected 68% inclusion

$B_s^0 \to \mu\mu$ effective lifetime measurement

- Motivation
  - SM: only the CP-odd, heavy eigenstate $B_{s,H}^0$ decays via $B_s^0 \to \mu\mu$, may have BSM contribution
  - Large relative difference ($\Delta\tau_{B_{s,L/H}^0} = 0.193$ ps, $\tau_{B_{s,H}^0} = 1.624$ ps) in lifetime and rarity of decay $\mathcal{B}(B_s^0 \to \mu\mu) \sim \mathcal{O}(10^{-9})$
    $\to$ Sensitive to BSM $B_{s,L}^0$ contribution
  - Is complementary to $\mathcal{B}(B_s^0 \to \mu\mu)$ measurement
    - same data and tools used
    - both give independent tests for New Physics.
- Status
  - BR analysis for Run 1 and partial Run 2 study performed at ATLAS (arXiv:1812.03017v2)
  - First ATLAS measurement for effective lifetime $\tau_{\mu\mu}$, using 2015-2016 data

Analysis Strategy

1. An unbinned ML fit performed on $m(\mu\mu)$ distribution
   - Background consists mainly of continuum di-muons and partially reconstructed B decays
   - Signal shape modelled using double Gaussian
   - BDT trained on dimuon mass sidebands used for background discrimination
2. Signal proper decay time extracted from invariant mass using ${}_s\mathcal{P}$lot technique
3. $\tau_{\mu\mu}$ calculated by comparing proper decay time distribution with MC template that minimises χ^2



Uncertainty Studies

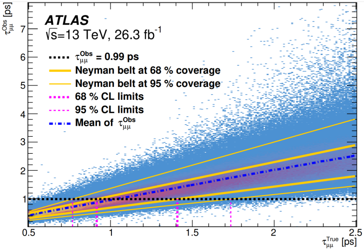
Systematic

- Three categories: Fit-dependent, MC/data discrepancies, neglected backgrounds
- MC/data discrepancies evaluated using $B \to J/\psi K$ reference channel, otherwise toyMC studies used
- Contributions added in quadrature

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

Statistical

- Fit to mass distribution extracts 58 ± 13 events
- Uncertainty evaluated using Neyman construction, using toyMC study
  $\rightarrow$ Generated $\tau_{\mu\mu}^{\mathrm{True}}$ compared to extracted $\tau_{\mu\mu}^{\mathrm{Obs}}$, 68 % and 95 % CLs taken from measured $\tau_{\mu\mu}$



Results

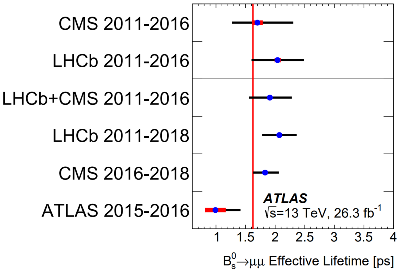
Measured value:

$$\tau_{\mu\mu} = 0.99^{+0.42}_{-0.07}(\text{stat.}) \pm 0.17(\text{syst.})\,\text{ps}$$

- Consistent with SM prediction [1]

$$\tau_{\mu\mu} = 1.624 \pm 0.009\,\text{ps}$$

- Consistent with other measurements at LHC
  - competitive precision for similar sized data set
- Analysis of full Run 2 data set underway
  $\rightarrow$Improvements in BDT and fit model



Summary

- Presented results of three flavour physics analyses at ATLAS
- Further studies for each analysis to come...
  → full Run 2 studies
  → Run 3 data
- Other up-coming B-physics results from ATLAS - keep an eye out:
  https://twiki.cern.ch/twiki/bin/view/AtlasPublic/BPhysPublicResults

References I

[1] Amhis, Y. S. et al. (2023). Averages of b-hadron, c-hadron, and τ-lepton properties as of 2021. *Phys. Rev. D*, 107(5):052008.

Back-up Slides