Lifetime Measurements from ATLAS

Dr Andy Wharton – On Behalf of the ATLAS Collaboration.

LHCP 2024 – Northeastern University, Boston: 4th June, 2024

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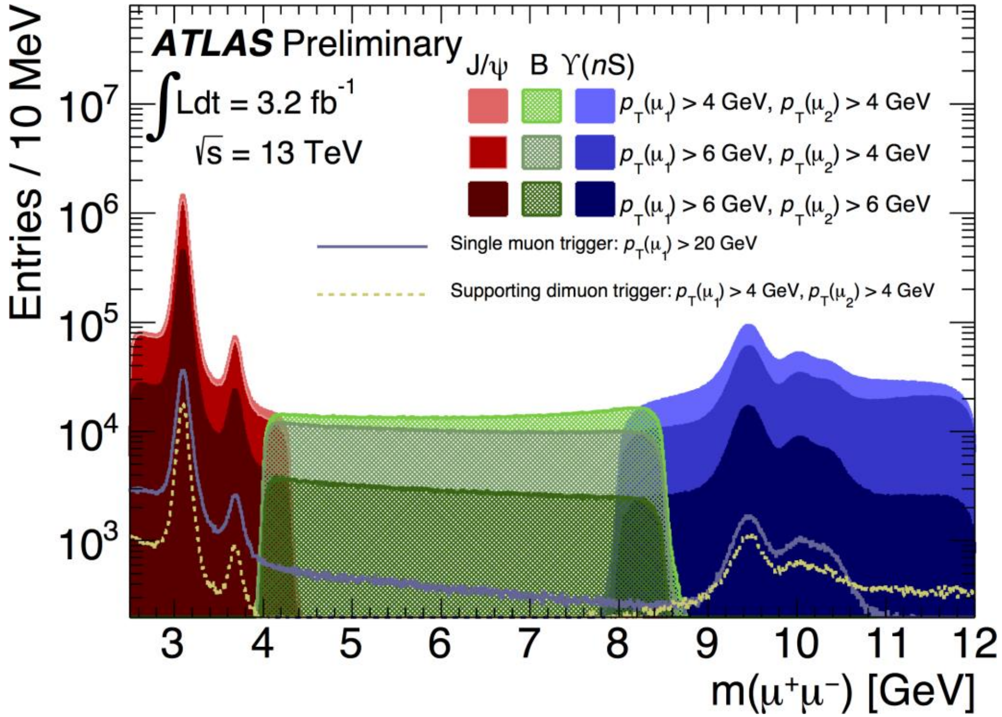
Introduction

- ATLAS has a rich and diverse physics program.
  - Active b-physics and light states community.
- Focus today on a recent b-physics result and future BLS prospects:
  - $B_s \to \mu^+\mu^-$ effective lifetime measurement, $\tau_{\mu\mu}$, in 2015 – 2016 data.
  - JHEP09(2023)199 (also JHEP04(2019)098)
- Other public results from the BLS group can be found here…
- …and at other talks at LHCP 2024!

b-Physics at ATLAS

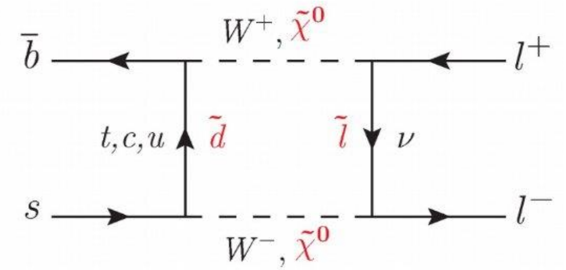
- 139 fb^{-1} of pp collisions collected during the LHC’s Run2.
  - 26.9 fb^{-1} in Run1, 300 fb^{-1} for Run3.
  - > 2 million $b\bar{b}$ pairs a second.
- b-Physics studies focus mainly on:
  - Muonic triggers/final states.
  - Full-reconstruction.
- Low-pT (di-)muon triggers:
  - Vertex + mass cuts for J/ψ triggers.
  - Tracks + cuts for +2/+3/+4 track signals.

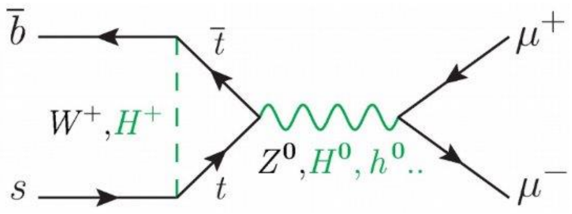


$B_s \rightarrow \mu^+ \mu^-$

Introduction - 1

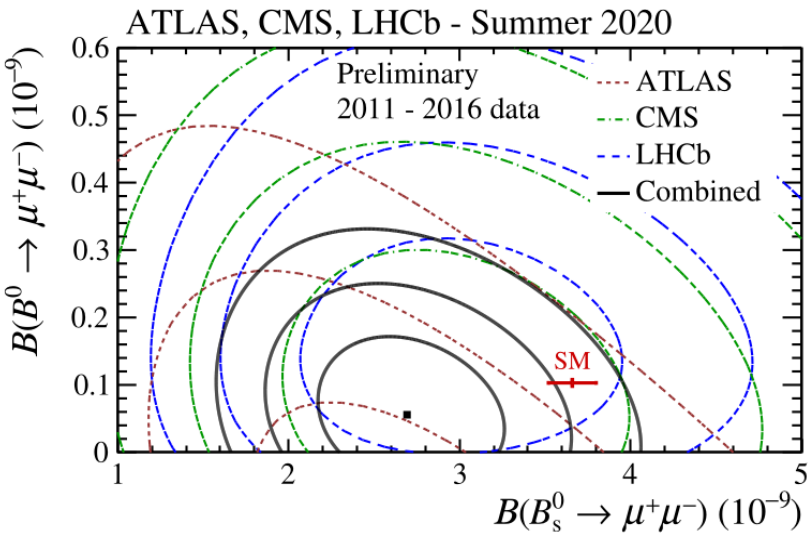
- FCNC decays are heavily suppressed in the SM.
  - Loop and/or box diagrams, $B_s \to \mu^+\mu^-$ also helicity suppressed.
  - In the SM:
    - $Br \sim 10^{-9}$
    - Only the CP-odd/heavy eigenstate will decay into $\mu^+\mu^-$.
- However…
  - Significant differences to SM predictions with NP.
    - For example, JHEP05(2017)076.
  - CP-even/light eigenstate may contribute to $\mu^+\mu^-$ with NP.
  - NP may introduce one without the other, need to check both.

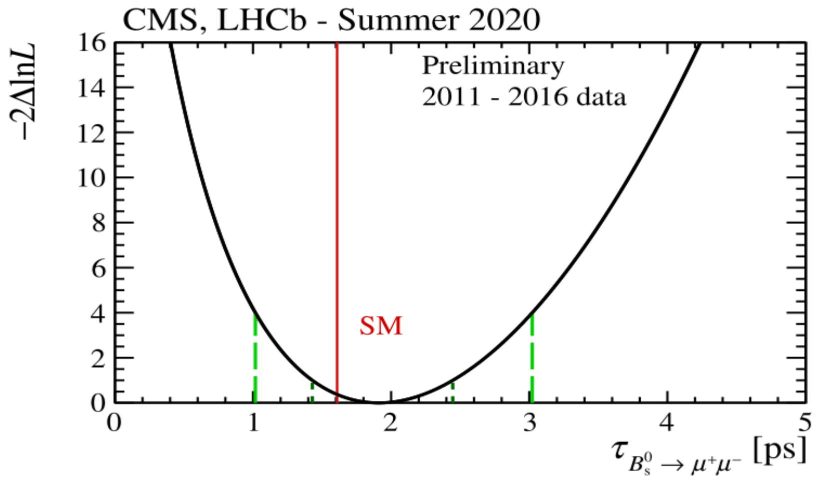




Introduction - 1

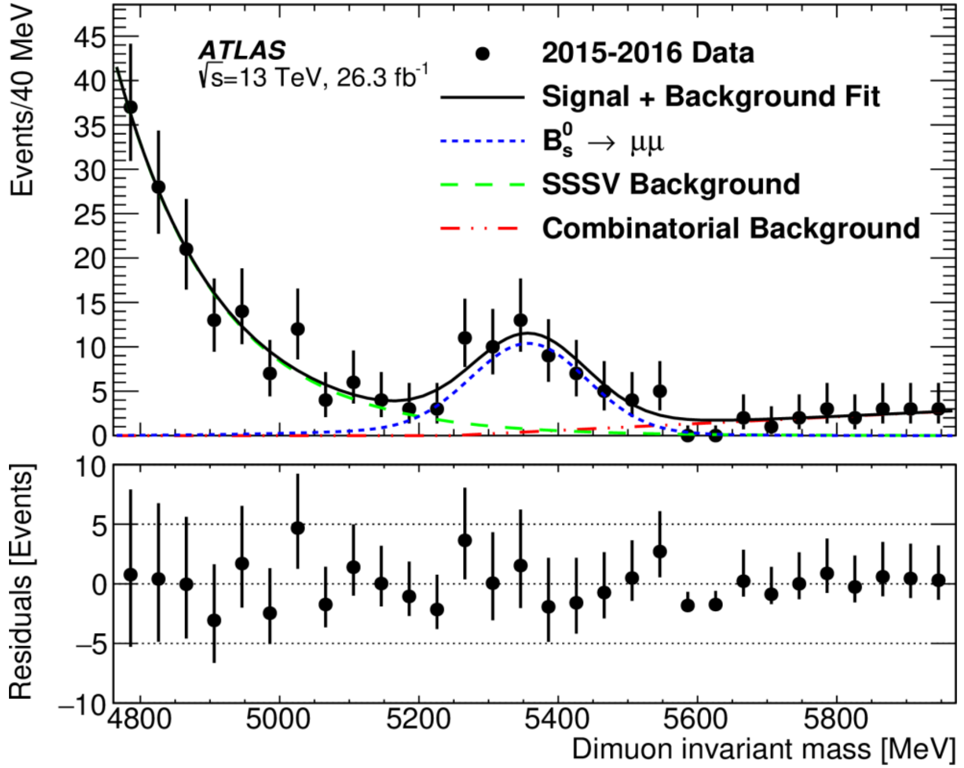
- $\Delta\tau_H$ and τ_H well measured experimentally:
  - $\Delta\tau_H$ = 0.193 ps.
  - τ_H = 1.624 ± 0.009 ps.
    - From the HFLAV and PDG overviews.
- Recent results from:
  - CMS.
  - LHCb.
  - Combinations.





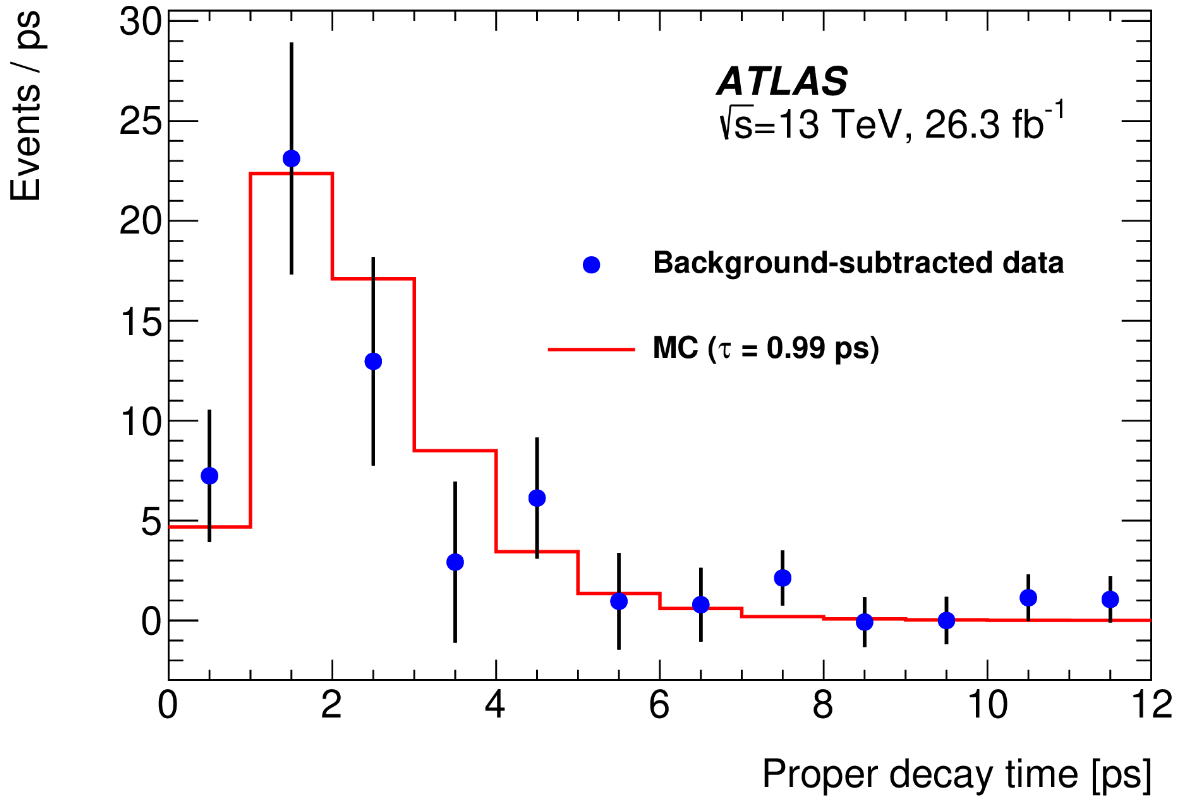
Analysis Strategy - 1

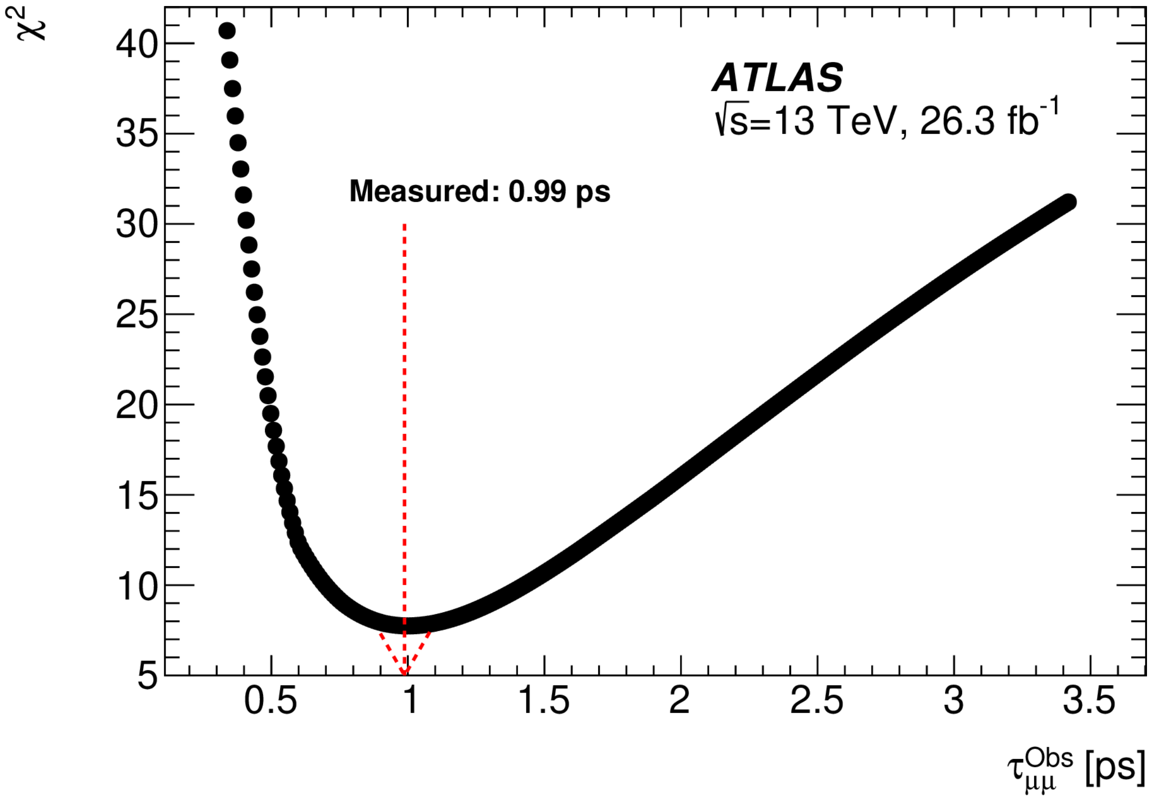
- Event selection based on JHEP04(2019)098.
  - BDT updates:
    - BDT windows.
    - Di-muon and partial B decays.
    - Simple accept/reject.
- Unbinned ML fit of $m(\mu^+\mu^-)$.
  - Signal PDF: Double Gaussian.
  - SSSV Background: Exponential.
    - SS, Same-Side: $b \rightarrow c \rightarrow s$ + 2 muonic $W^\pm$
    - SV, Same-Vertex: $B \rightarrow J/\psi\ \mu\ X$
  - Combinatorial: Linear.



Analysis Strategy - 2

- sPlot to extract signal lifetime → template fits against MC.

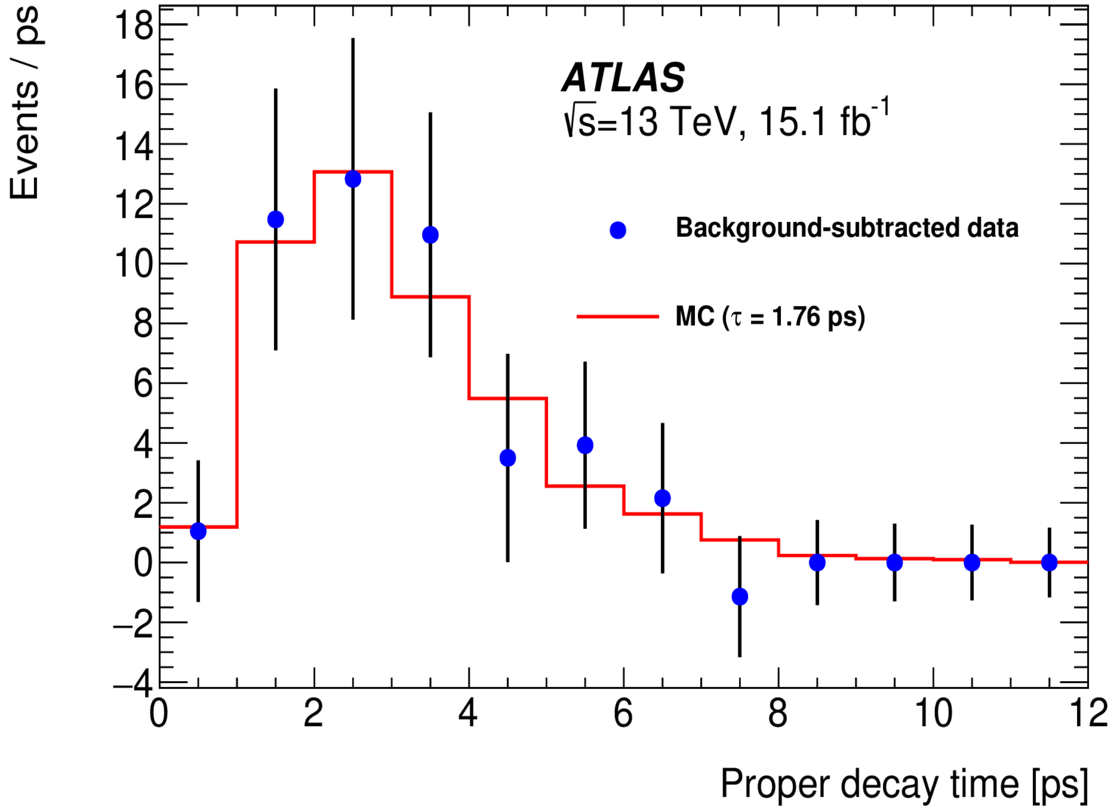




Analysis Strategy - 3

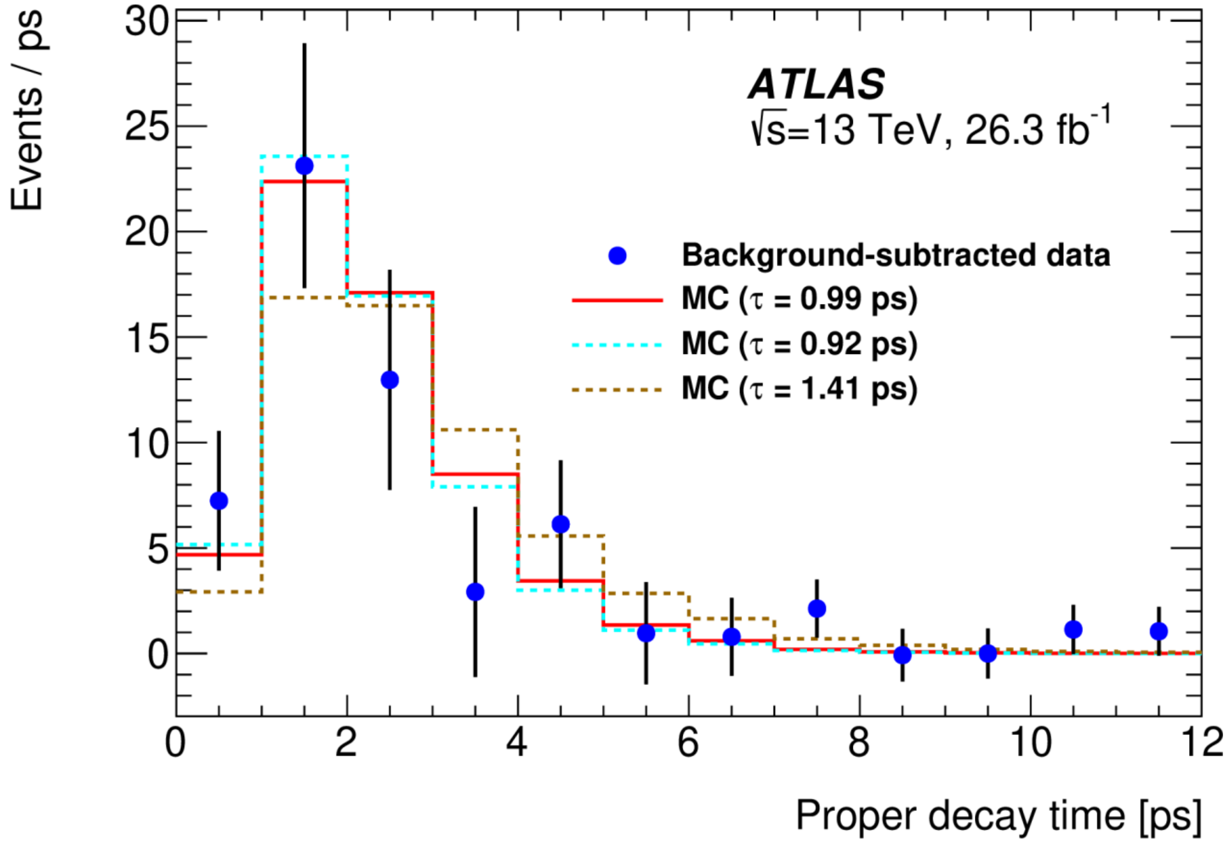
- Duplicate analysis with $B^{\pm} \rightarrow J/\psi\ K^{\pm}$
- Validate method, study systematics.
  - Different triggers/rescales.

- Fitted lifetime, $\tau_{B^{\pm}}$ = 1.76 ps.
  - World average, 1.641 ps.



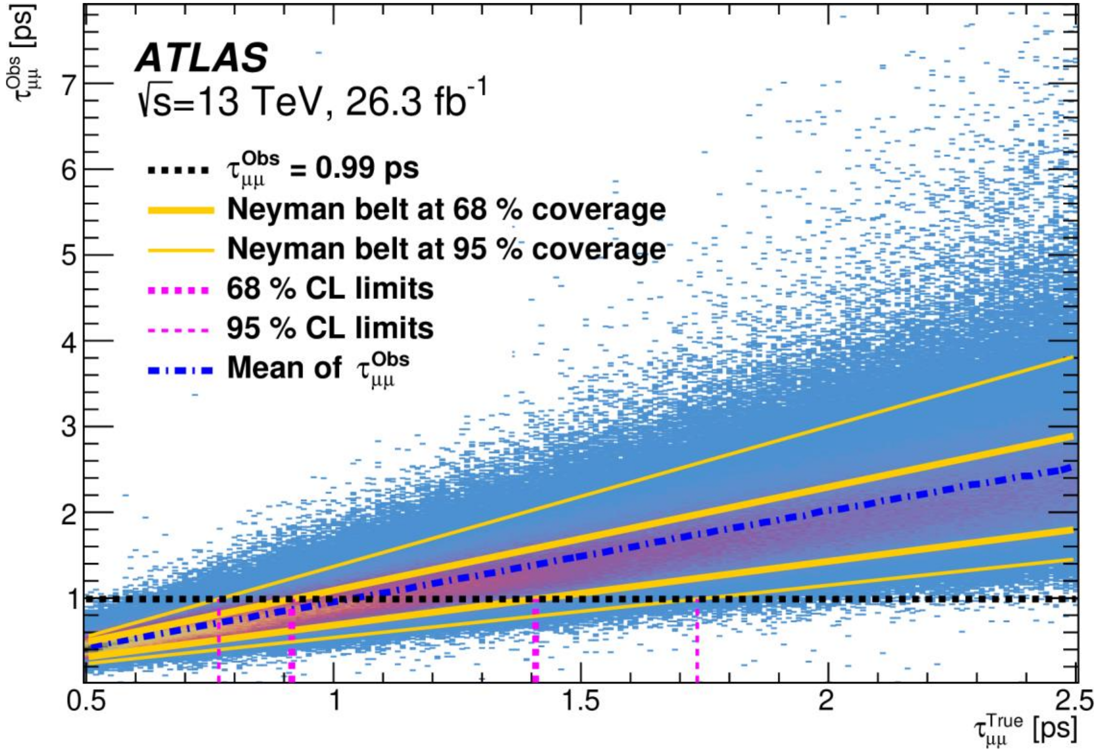
Estimating Statistical Errors - 1

- Constant width bins.
  - Optimised for statistical error.
- Observed bias in fits, (82 ± 4) fs.
  - Subtracted from best-fit value.
- Errors determined from toy MC.
  - Almost entirely.



Estimating Statistical Errors - 2

- χ^2 distribution from fit is non-Gaussian.



Estimating Systematic Errors - 1

- Three types of systematics considered:
  - Fit assumptions.
    - Background shapes.
    - sPlot.
  - MC mis-modelling.
    - Reconstruction effects - underestimated in MC.
    - Differences between signal/background/reference channels.
  - Neglected backgrounds.
    - Assumes only heavy eigenstate contributes.

Estimating Systematic Errors - 2

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- Conservatively symmetrised.
  - Added in quadrature.

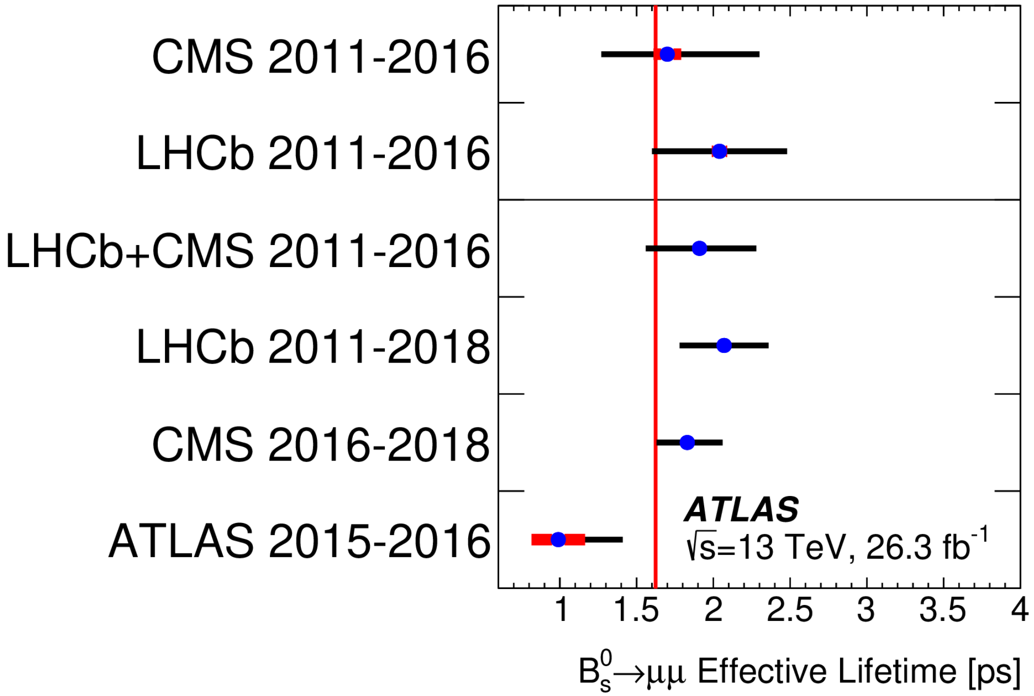
Uncertainty source	$\Delta\tau_{\mu\mu}^{\mathbf{Obs}}$ [fs]
Data - MC discrepancies	134
SSSV lifetime model	60
Combinatorial lifetime model	56
B kinematic reweighting	55
B isolation reweighting	32
SSSV mass model	22
B_d background	16
Fit bias lifetime dependency and B_s^0 eigenstates admixture	15
Combinatorial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

Results

- $\tau_{\mu\mu} = (0.99^{+0.42}_{-0.07}$ (stat.) ± 0.17 (syst.)) ps.
  - SM prediction: 1.624 ± 0.009 ps.

- Consistent with other LHC measurements.

- No evidence of NP.



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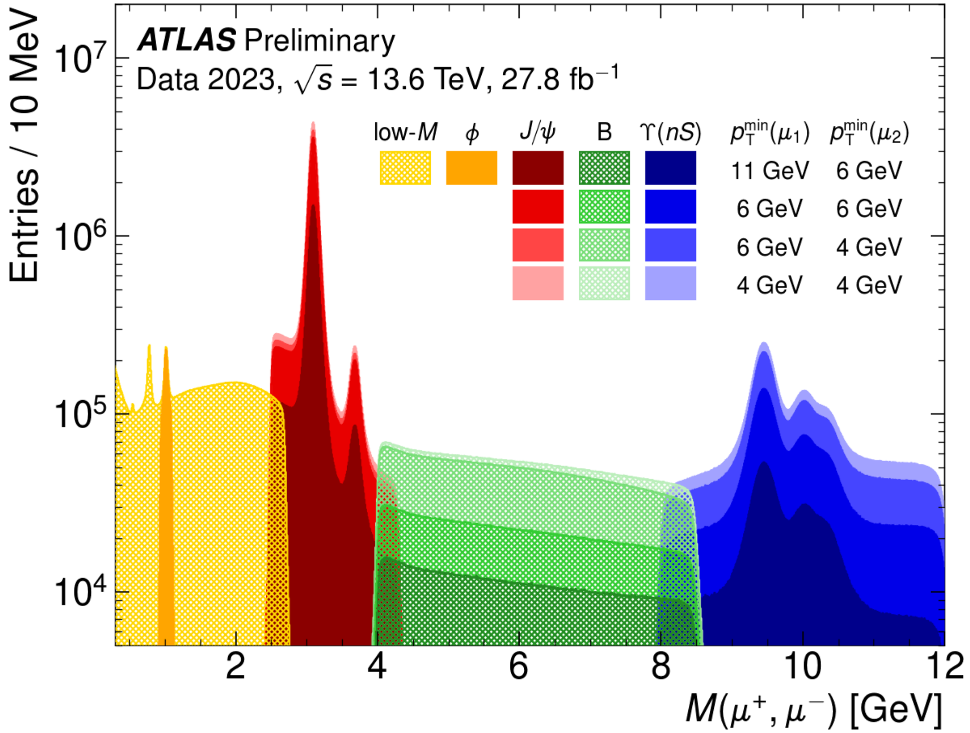
Future Prospects and Summary

Future Prospects

- Full Run2 analysis underway.
  - And many, many more!

- Better...
  - Alignment.
  - MC – Data Reco agreement.

- It's the ~~economy~~ triggers, stupid...
  - Improved L1Topo triggers.
    - Geometric/Kinematic relationships.
  - Still running with no d_0 cuts!



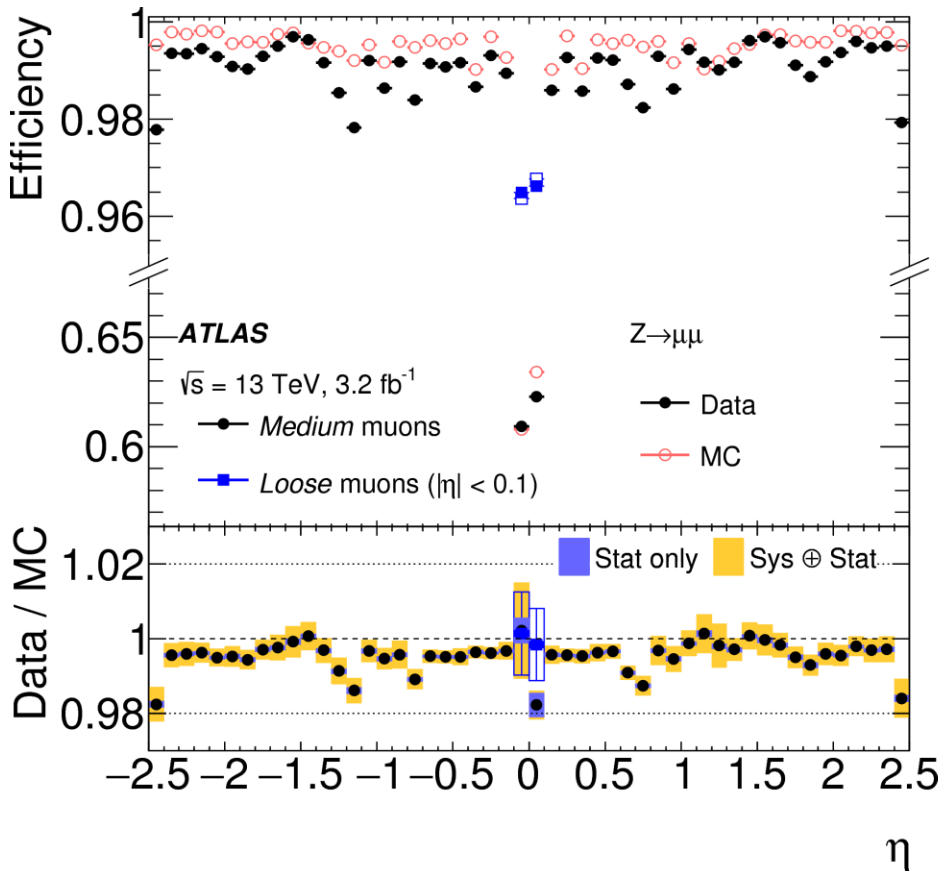
Summary

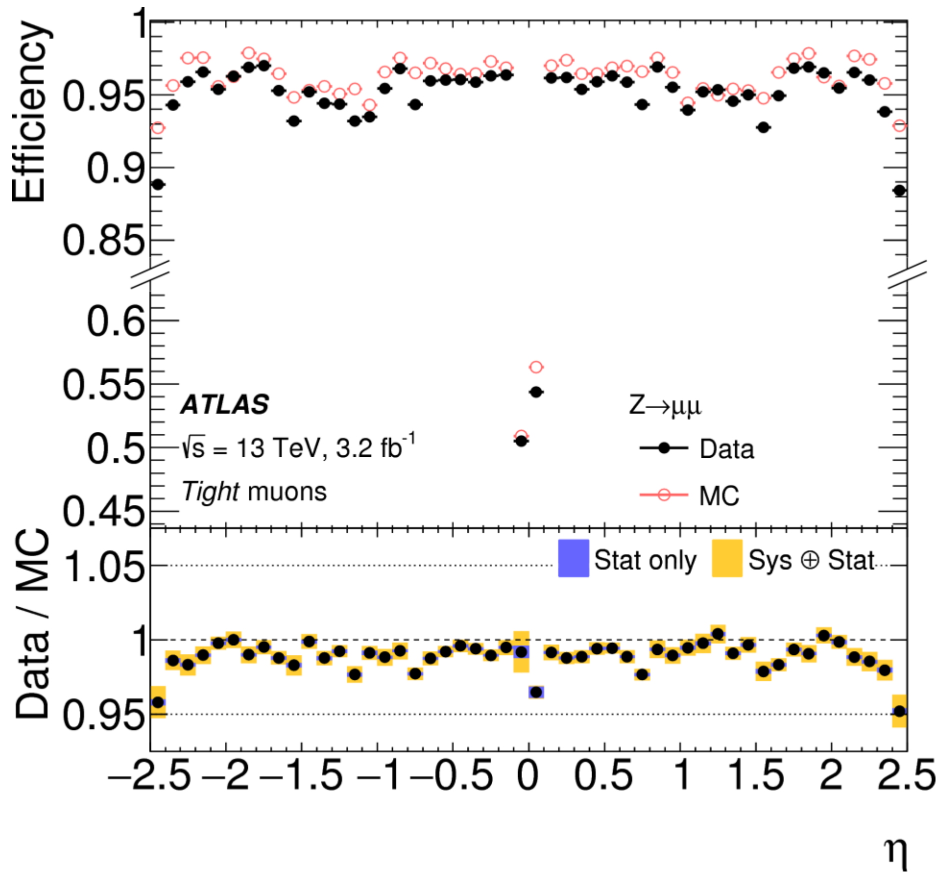
- ATLAS is producing competitive results.
  - And actively collaborating with our LHC partners!
- ATLAS' $B_s \rightarrow \mu^+\mu^-$ results are broadly consistent with SM predictions.
  - But no NP… ☹
- All of these analyses are currently working toward full Run2 results.
- We are well prepared for Run3 data.

Backup

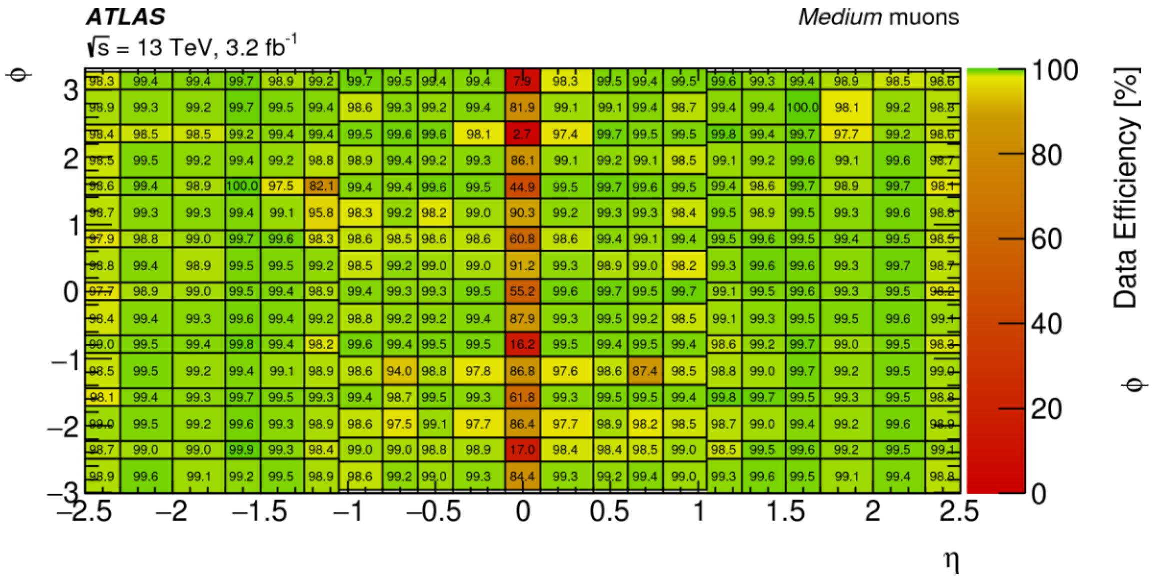
ATLAS

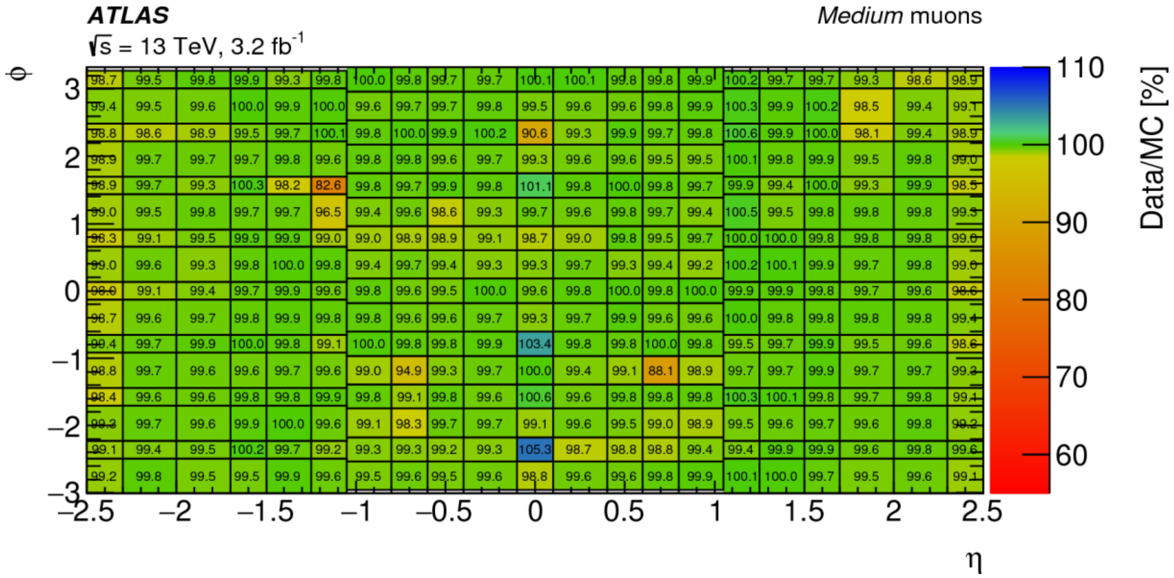
Muon Spectrometer Performance - 1





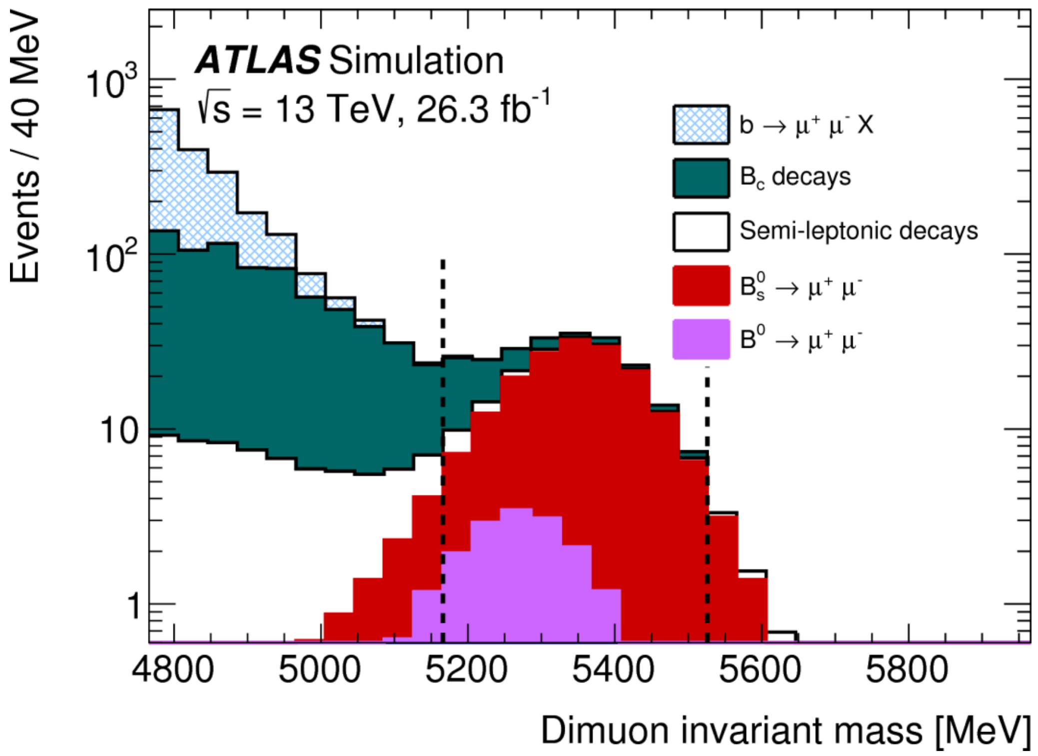
Muon Spectrometer Performance - 2



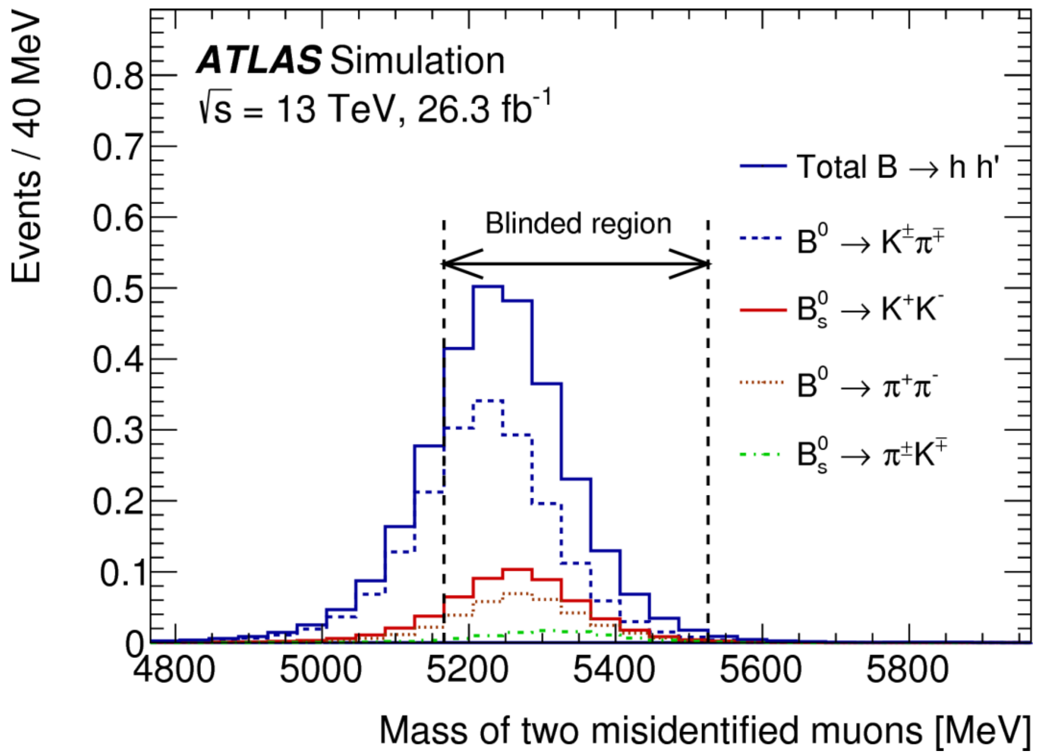


$B_s \rightarrow \mu^+ \mu^-$ Branching Ratio

Mass PDFs



ATLAS Simulation
√s = 13 TeV, 26.3 fb-1
b → μ+ μ- X
Bc decays
Semi-leptonic decays
Bs0 → μ+ μ-
B0 → μ+ μ-
Events / 40 MeV
Dimuon invariant mass [MeV]

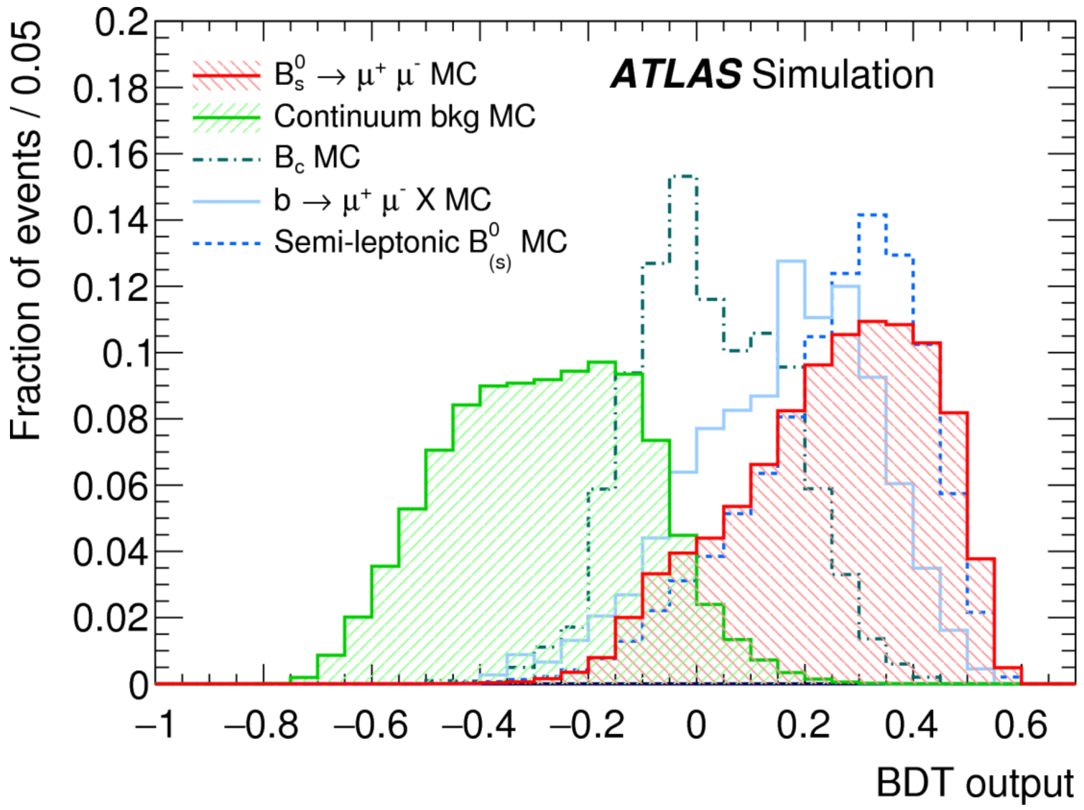


ATLAS Simulation
√s = 13 TeV, 26.3 fb-1
Total B → h h'
Blinded region
B0 → K±π∓
Bs0 → K+K-
B0 → π+π-
Bs0 → π±K∓
Events / 40 MeV
Mass of two misidentified muons [MeV]

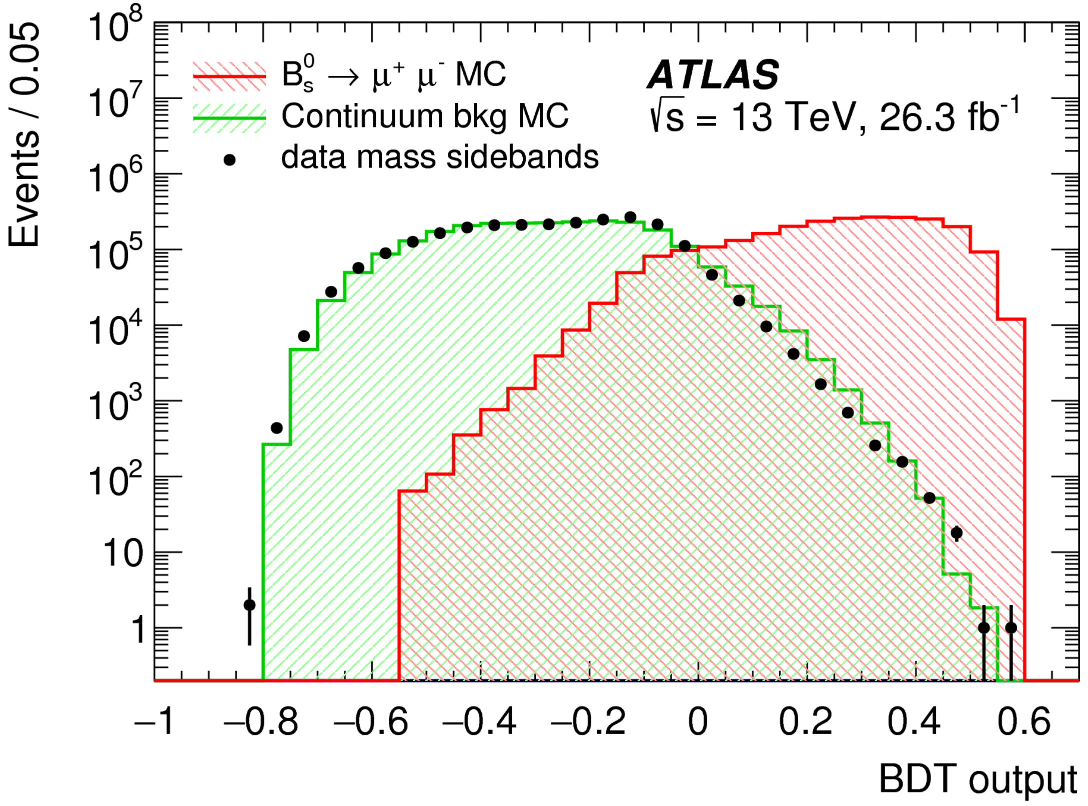
BDT Inputs

Variable	Description
p_{T}^{B}	Magnitude of the B candidate transverse momentum $\overrightarrow{p_{\mathrm{T}}}^{B}$.
$\chi^2_{\mathrm{PV,DV}\ xy}$	Compatibility of the separation $\overrightarrow{\Delta x}$ between production (i.e. associated PV) and decay (DV) vertices in the transverse projection: $\overrightarrow{\Delta x}_{\mathrm{T}} \cdot \Sigma^{-1}_{\overrightarrow{\Delta x}_{\mathrm{T}}} \cdot \overrightarrow{\Delta x}_{\mathrm{T}}$, where $\Sigma_{\overrightarrow{\Delta x}_{\mathrm{T}}}$ is the covariance matrix.
$\Delta R_{\mathrm{flight}}$	Three-dimensional angular distance between $\overrightarrow{p}^{B}$ and $\overrightarrow{\Delta x}$: $\sqrt{\alpha_{2\mathrm{D}}{}^2 + (\Delta\eta)^2}$
$\lvert\alpha_{2\mathrm{D}}\rvert$	Absolute value of the angle in the transverse plane between $\overrightarrow{p_{\mathrm{T}}}^{B}$ and $\overrightarrow{\Delta x}_{\mathrm{T}}$.
L_{xy}	Projection of $\overrightarrow{\Delta x}_{\mathrm{T}}$ along the direction of $\overrightarrow{p}_{\mathrm{T}}^{B}$: $(\overrightarrow{\Delta x}_{\mathrm{T}} \cdot \overrightarrow{p_{\mathrm{T}}}^{B}) / \lvert\overrightarrow{p_{\mathrm{T}}}^{B}\rvert$.
$\mathrm{IP}_{B}^{3\mathrm{D}}$	Three-dimensional impact parameter of the B candidate to the associated PV.
$\mathrm{DOCA}_{\mu\mu}$	Distance of closest approach (DOCA) of the two tracks forming the B candidate (three-dimensional).
$\Delta\phi_{\mu\mu}$	Azimuthal angle between the momenta of the two tracks forming the B candidate.
$\lvert d_0\rvert^{\mathrm{max}}$-sig.	Significance of the larger absolute value of the impact parameters to the PV of the tracks forming the B candidate, in the transverse plane.
$\lvert d_0\rvert^{\mathrm{min}}$-sig.	Significance of the smaller absolute value of the impact parameters to the PV of the tracks forming the B candidate, in the transverse plane.
$P_{\mathrm{L}}^{\mathrm{min}}$	The smaller of the projected values of the muon momenta along $\overrightarrow{p_{\mathrm{T}}}^{B}$.
$I_{0.7}$	Isolation variable defined as ratio of $\lvert\overrightarrow{p_{\mathrm{T}}}^{B}\rvert$ to the sum of $\lvert\overrightarrow{p_{\mathrm{T}}}^{B}\rvert$ and the transverse momenta of all additional tracks contained within a cone of size $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} = 0.7$ around the B direction. Only tracks matched to the same PV as the B candidate are included in the sum.
$\mathrm{DOCA}_{\mathrm{xtrk}}$	DOCA of the closest additional track to the decay vertex of the B candidate. Only tracks matched to the same PV as the B candidate are considered.
$N_{\mathrm{xtrk}}^{\mathrm{close}}$	Number of additional tracks compatible with the decay vertex (DV) of the B candidate with $\ln(\chi^2_{\mathrm{xtrk,DV}}) < 1$. Only tracks matched to the same PV as the B candidate are considered.
$\chi^2_{\mu,\mathrm{xPV}}$	Minimum χ^2 for the compatibility of a muon in the B candidate with any PV reconstructed in the event.

BDT Outputs

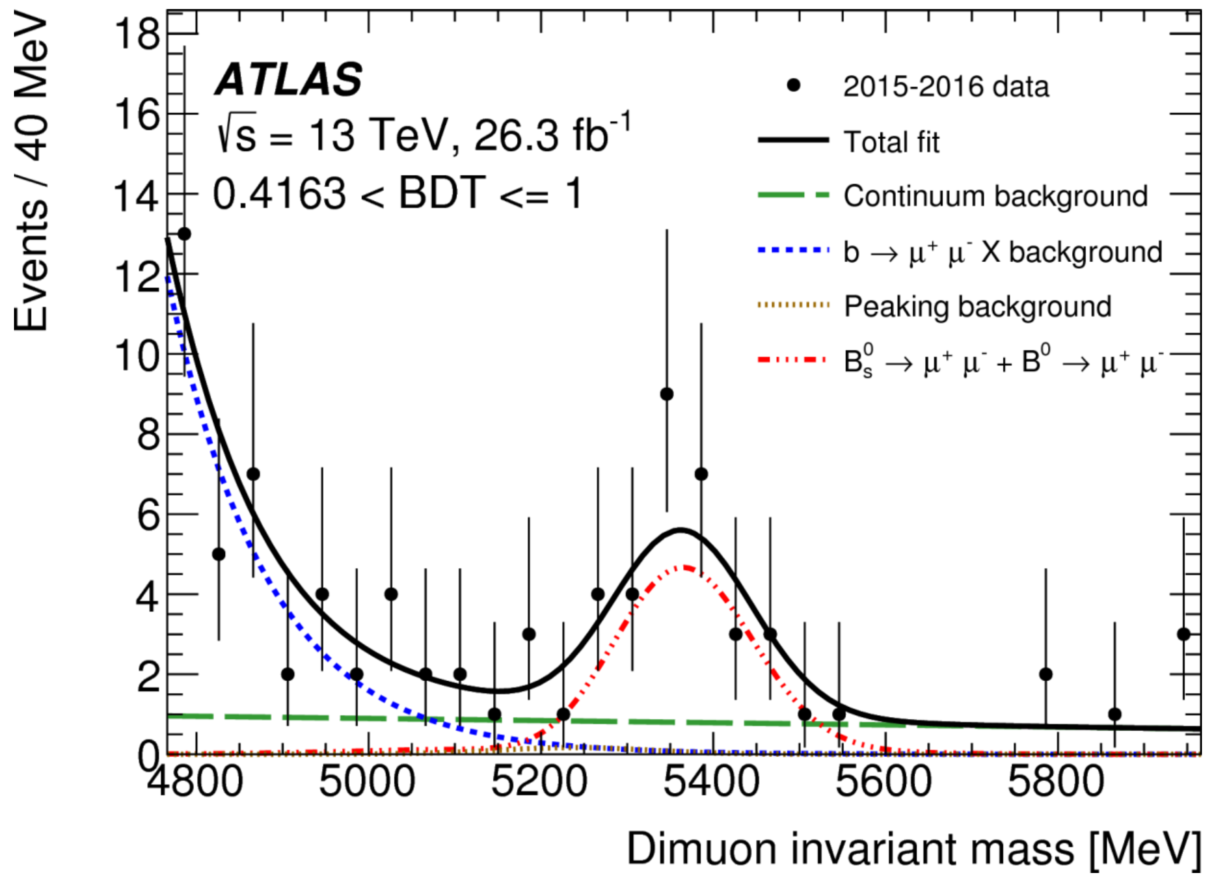


ATLAS Simulation
$B_s^0 \to \mu^+ \mu^-$ MC
Continuum bkg MC
B_c MC
$b \to \mu^+ \mu^- X$ MC
Semi-leptonic $B^0_{(s)}$ MC
Fraction of events / 0.05
BDT output
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
–1
–0.8
–0.6
–0.4
–0.2
0
0.2
0.4
0.6



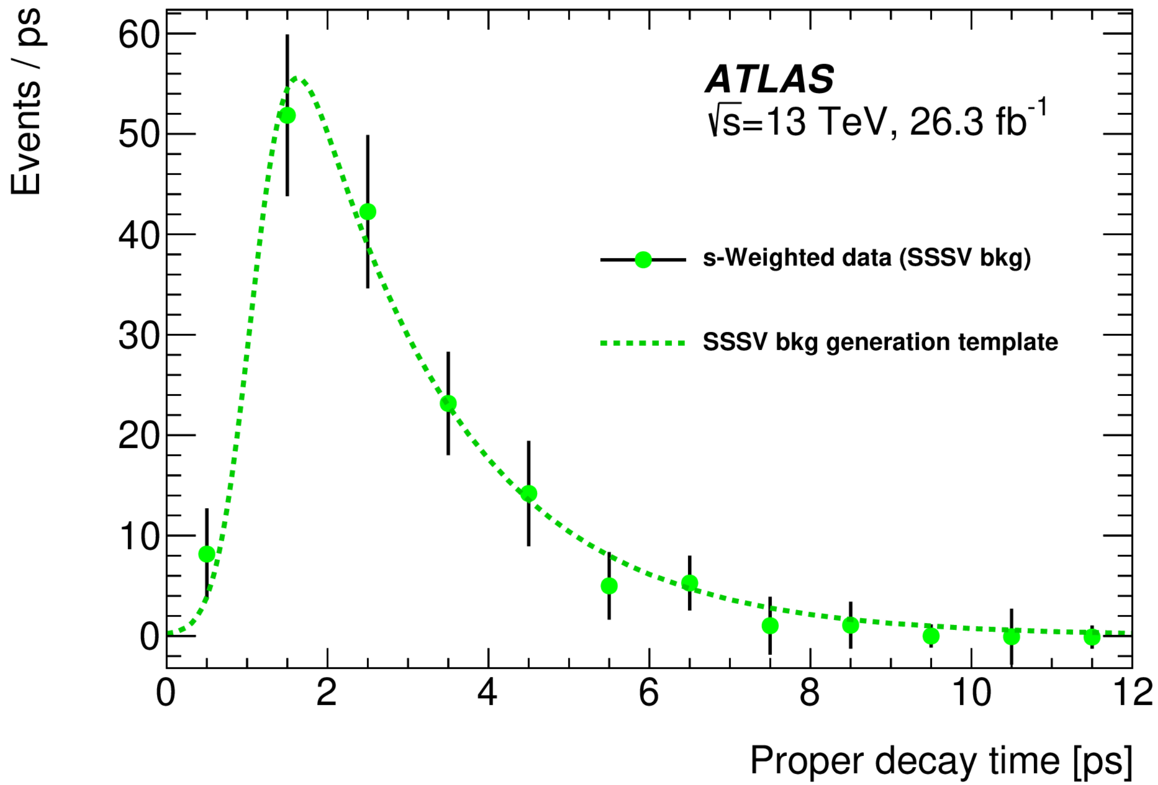
ATLAS
$\sqrt{s}$ = 13 TeV, 26.3 fb^{-1}
$B_s^0 \to \mu^+ \mu^-$ MC
Continuum bkg MC
data mass sidebands
Events / 0.05
BDT output
1
10
10^2
10^3
10^4
10^5
10^6
10^7
10^8
–1
–0.8
–0.6
–0.4
–0.2
0
0.2
0.4
0.6

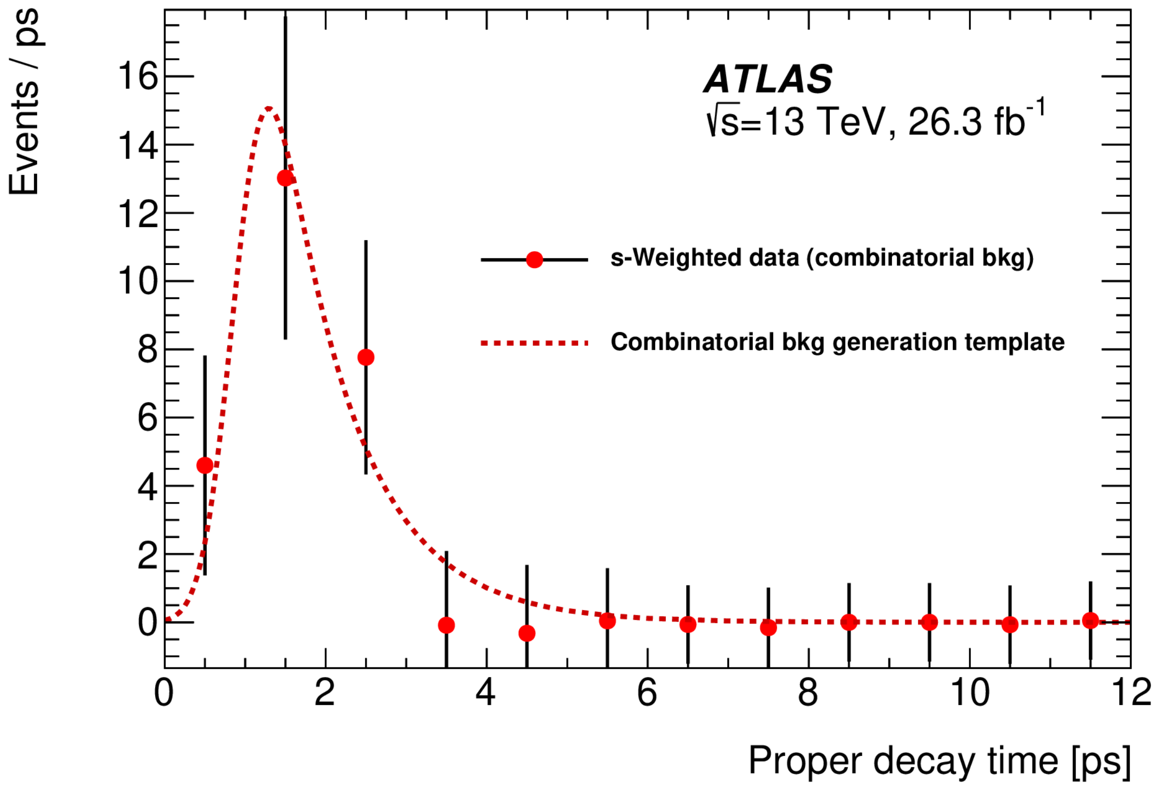
Mass Fits


ATLAS
$\sqrt{s}$ = 13 TeV, 26.3 fb^{-1}
0.4163 < BDT <= 1
2015-2016 data
Total fit
Continuum background
$b \to \mu^+ \mu^- X$ background
Peaking background
$B_s^0 \to \mu^+ \mu^- + B^0 \to \mu^+ \mu^-$
Events / 40 MeV
Dimuon invariant mass [MeV]
0
2
4
6
8
10
12
14
16
18
4800
5000
5200
5400
5600
5800

$B_s \rightarrow \mu^+ \mu^-$ Lifetime

Background Lifetime Fits





Reference Channel Mass Fit

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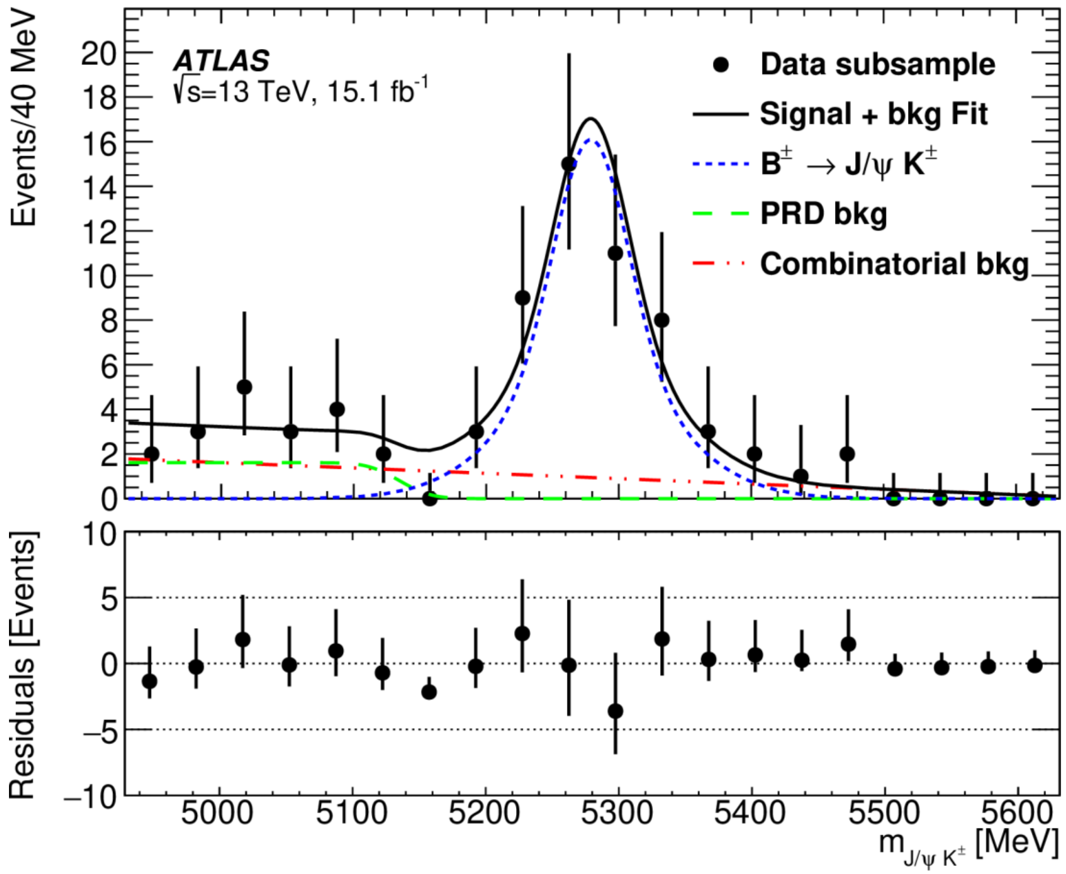

Lifetime Fit Bias