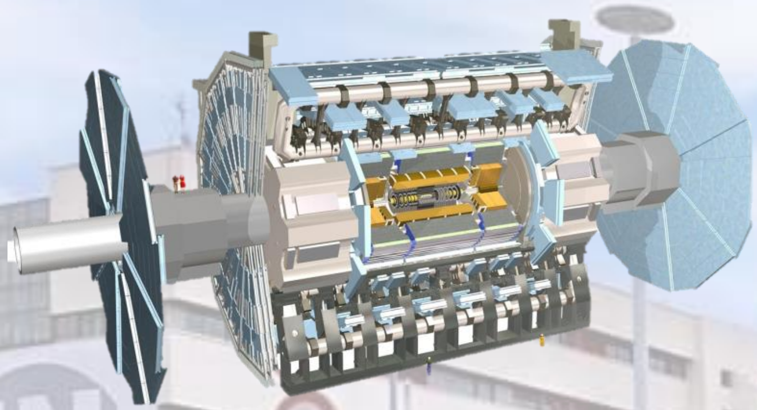
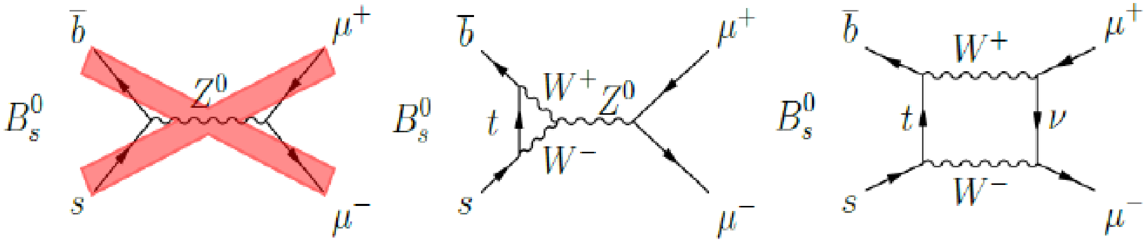


Report sull'attività di analisi nella fisica del flavour

Fabiola Raffaeli, Umberto De Sanctis

Theoretical overview: B^0 and B_s^0 Branching Ratios

- The b quark belongs to the quarks' third generation: the $b \to t$ transition is kinematically forbidden, so the b quark decays in a quark of different generation via FC processes through the CKM matrix.
- In SM B^0 and B_s^0 Branching Ratios are precisely predicted $\mathcal{B}(B_s^0 \to \mu^+\mu^-)_{SM} = (3.66 \pm 0.14) \times 10^{-9}$, $\mathcal{B}(B^0 \to \mu^+\mu^-)_{SM} = (1.03 \pm 0.05) \times 10^{-9}$ [Phys. Rev. Lett. **112** (2014) 101801]
  - Small but precisely known → can have significant contributions from new physics scenarios.
- In the SM the branching fraction of the decays $B_s^0 \to \mu^+\mu^-$ is very small, due to three main reasons
  1. FCNC suppression;
  2. Helicity suppression;
  3. CKM suppression (V_{td} and V_{ts}).



Dominant Feynman diagrams for $B_0^s \to \mu^+\mu^-$.

Lifetime measurement

*related to a specific decay and CP-state (in SM) instead to the admixture of the two eigenstates (heavy and light)

- In addition to the BR measurement, also the $B_s^0 \rightarrow \mu^+ \mu^-$ effective* lifetime is sensitive to New Physics in a complementary way
  - It allows to disentangle the contributions from the two states of the $B_s^0 - \overline{B_s^0}$ system;
  - Open to different CP structure with respect to the SM → in SM only CP-odd (heavy state) can decay to di-muon pair.

- The effective lifetime measurement is sensitive to New Physics contributions and it's a complementary probe to the BR measurement

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

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

Proper-decay time

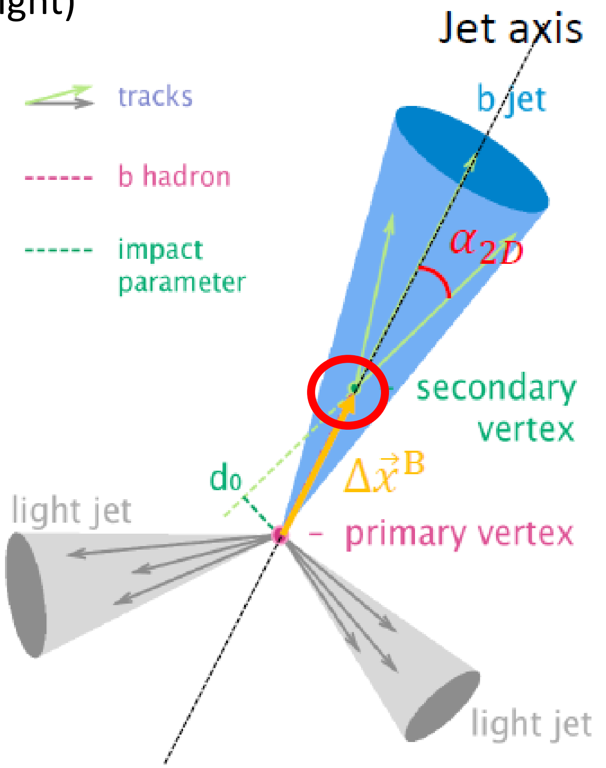
holds, where

a) $\tau_{B_s^0} = 1.510 \pm 0.005\ ps$ is the B_s^0 mean lifetime;

b) $y_s = \frac{\tau_{B_s^0}\Delta\Gamma}{2}$;

c) $\Delta\Gamma$ is the difference between light and heavy mass eigenstates decay width.

d) $A \in [-1;1]$ →in SM only $A = +1$ (CP-odd) → $\tau_{\mu\mu}^{SM} = (1.624 \pm 0.009)\text{ps}$ [Phys. Rev. D **107** (2023) 052008]



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

BR and lifetime analysis

- **Analysis strategy:** Two muons with p_T above 4 and 6 GeV (di-muon trigger with these thresholds);

Hadronisation probabilities

$$\mathcal{B}(B^0_{(s)} \to \mu^+\mu^-) = N(B^0_{(s)} \to \mu^+\mu^-) \times [\mathcal{B}(B^+ \to J/\psi K^+) \times \mathcal{B}(J/\psi \to \mu^+\mu^-)] \times \frac{f_u}{f_{s/d}} \times \frac{1}{\mathcal{D}_{\text{norm}}}$$

$$\mathcal{D}_{\text{norm}} = \sum_k N^k_{J/\psi K^\pm} \alpha_k \left(\frac{\varepsilon_{\mu^+\mu^-}}{\varepsilon_{J/\psi K^\pm}} \right)_k$$

Number of Bs/Bd events from an unbinned ML fit to m(μμ) distribution

Trigger categories and luminosity prescales*

Reference channel: $B^\pm \to J/\psi K^\pm$
Extracted from an unbinned ML fit to m(μμ$K^\pm$) distribution

Acceptance and efficiencies from simulation

B^0 and B_s^0 Branching Ratios: experimental results

1) ATLAS $\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.69^{+0.37}_{-0.35}) \times 10^{-9}$ $\mathcal{B}(B^0 \to \mu^+\mu^-) < 1.9 \times 10^{-10}$ at 95% CL;

- $\mathcal{L}$(7 TeV)=5fb^{-1}, $\mathcal{L}$(8 TeV)=20fb^{-1}, $\mathcal{L}$(13 TeV)=26.6fb^{-1};

2)CMS $\mathcal{B}(B_s^0 \to \mu^+\mu^-) = [2.9^{+0.7}_{-0.6}$ (exp) $\pm$ 0.2 (frag)] $\times 10^{-9}$ $\mathcal{B}(B^0 \to \mu^+\mu^-) < 3.6 \times 10^{-10}$ at 95% CL

- $\mathcal{L}$(7 TeV)=5fb^{-1}, $\mathcal{L}$(8 TeV)=20fb^{-1}, $\mathcal{L}$(13 TeV)=36fb^{-1};

3)LHCb $\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9}$ $\mathcal{B}(B^0 \to \mu^+\mu^-) < 3.4 \times 10^{-10}$ at 95% CL

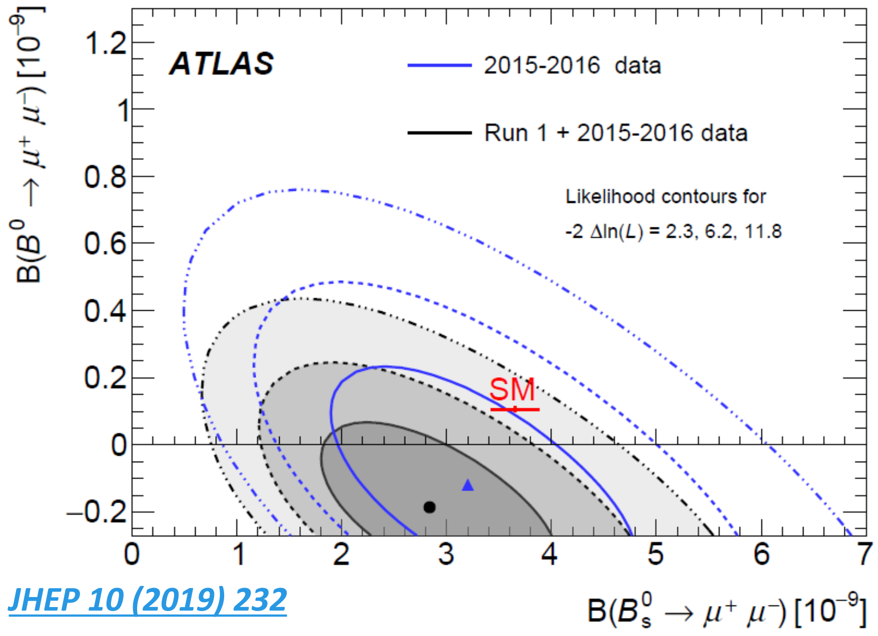
- $\mathcal{L}$=4.4fb^{-1} .

The combination of results from the three experiments using 2011-2016 data gives

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.69^{+0.37}_{-0.35}) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 1.6(1.9) \times 10^{-10} \text{ at } 90\%(95\%) \text{ CL}$$

ATL-CONF-2020-049

~ 2σ «tension» with the SM



JHEP 10 (2019) 232

$B_s^0 \rightarrow \mu^+\mu^-$ lifetime: BDT cut optimisation and event selection

JHEP 04 (2019) 098

JHEP09(2023)199

- Event selection:
  - Two muons with p_T above 4 and 6 GeV (di-muon trigger with these thresholds);
  - $m_{J/\psi} = [2915{,}3275]\text{MeV}\ (B^{\pm}\ analysis), p_T^B > 8.0\ \text{GeV};$
  - Reconstructed B^+ mass in range [4930,5630]MeV;
  - Reconstructed B_s^0 mass in range [4766,5966] MeV.

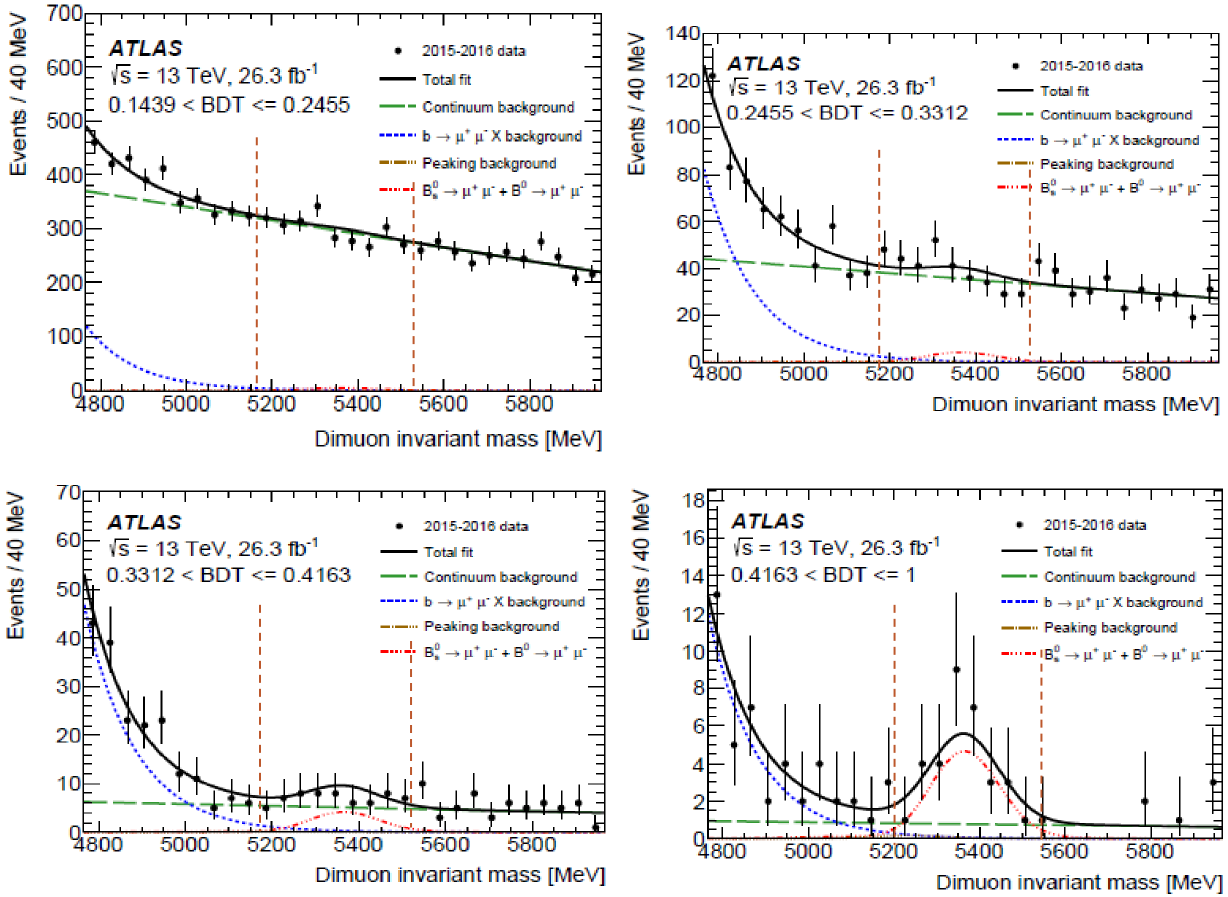
- Small S/B ratio → BDT cut applied;
  - A Boosted Decision Tree is a binary decision tool. It combines information from 15 physical input variables to obtain the signal-to-background discriminator
    - B meson variables;
    - Muons variables;
    - Variables related to the rest of the event.

BDT optimisation for lifetime analysis

JHEP04(2019)098

- The **goal of this optimisation** is to find the best S/B configuration to measure the lifetime → the optimal BDT cut has been searched to discriminate signal with respect to the continuum background.
- The **significance** has been defined as A=S/√(S+B), where S and B are the numbers of MC signal and MC background events.
- The **max A value** has been searched in different S and B configurations.
- Sidebands data have been used to normalize the MC background into the signal region.
- The signal MC normalization obtained in the signal region 5166-5526 MeV, using the expected number of B_s^0 events, assuming the SM BR.

Best BDT cut found at 0.3650 → $\boldsymbol{S}$=49, $\boldsymbol{B}$=27 expected in the signal region.

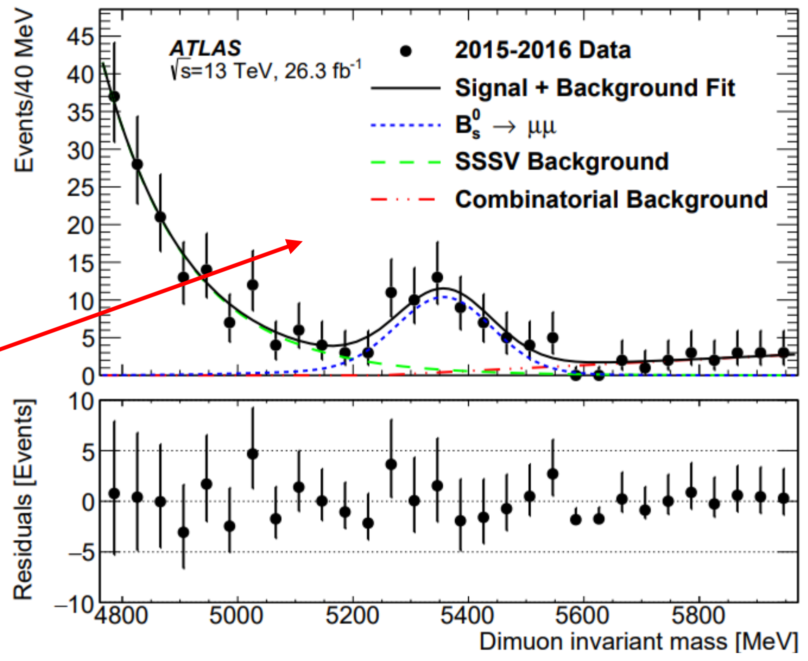


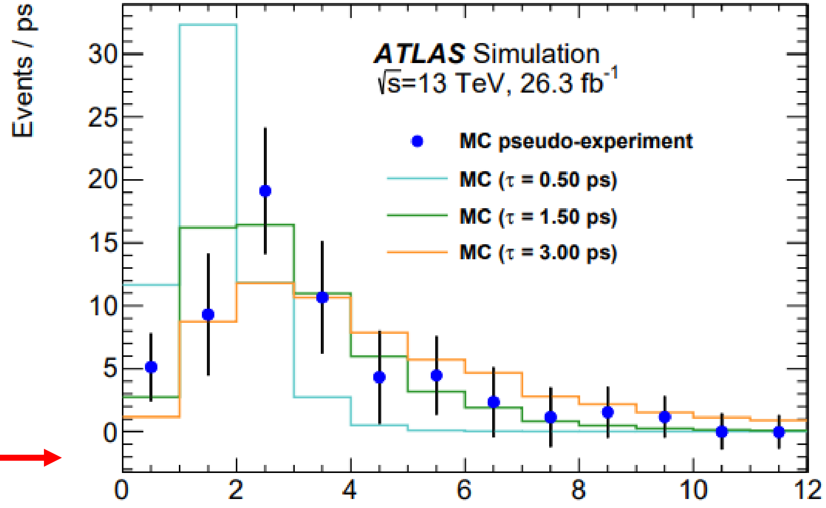
Functions for background interpolation: Chebychev + exponential.

$B_s^0 \to \mu^+\mu^-$ lifetime: general strategy

1. **Di-muon invariant mass fit on data**, with models from BR analysis, to extract the number of candidates.
   1. Continuum background (uncorrelated hadrons decays);
   2. Partially reconstructed decays (one or more final state particles are missing);
   3. **Peaking background** ($\sim 4\%$ under the mass peak, both final state hadrons misidentified as muons)
2. Use **sPlot** [sPlot: a statistical tool to unfold data distributions] to extract signal proper decay 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 pseudo proper time $t = (L_{xy} m_B^{PDG})/|\overrightarrow{p_B}|$ → minimal correlation between mass and proper time.
3. Compare the signal proper time distribution with the MC templates to extract the lifetime.
   - χ^2 minimization used to find the best template.

[JHEP09(2023)199]



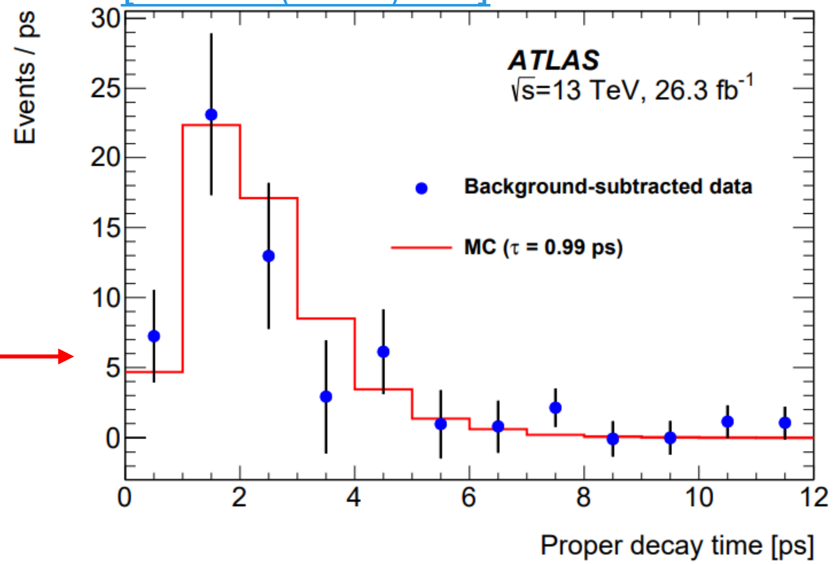


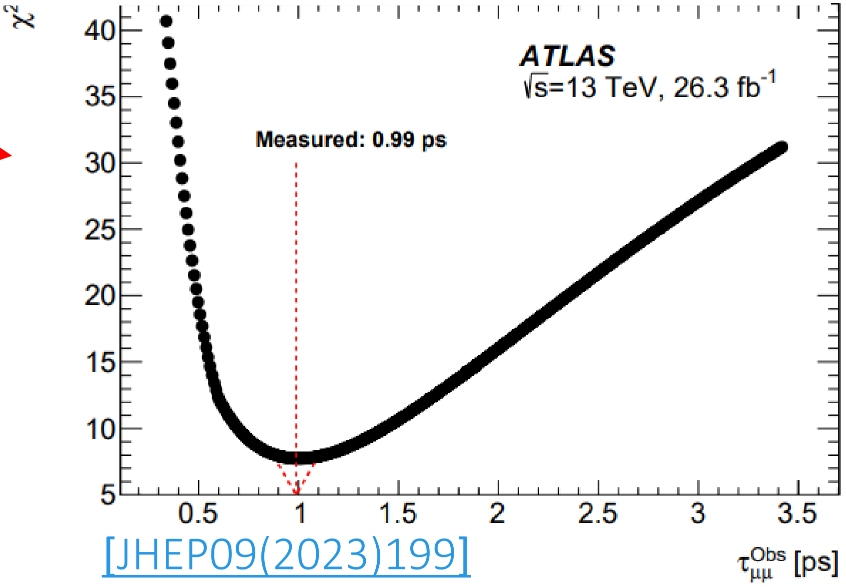
[JHEP09(2023)199]

$B_s^0 \to \mu^+\mu^-$ lifetime: Results

- The proper decay time distribution in data is background-subtracted using per-event weights calculated with sPlot technique
  - Signal and background weights are evaluated from the mass fit result
- The best template is the one that minimises the χ^2 computed
  - Minimum found with an asymmetric parabolic fit
- A closure test is performed applying analysis procedure on generated MC pseudo-experiment with $\tau_{\mu\mu}^{Gen} = \tau_{\mu\mu}^{SM}$
  - Found a bias on $\tau_{\mu\mu}^{Obs}$ of 82 ± 4 fs due to low-statistic regime of the fit
  - $\tau_{\mu\mu}^{Obs}$ redefined as $\tau_{\mu\mu}^{Obs} - 82\text{fs} \to \tau_{\mu\mu}^{Obs} = 0.99\text{ps}$ and taken as central value of the measurement

[JHEP09(2023)199]



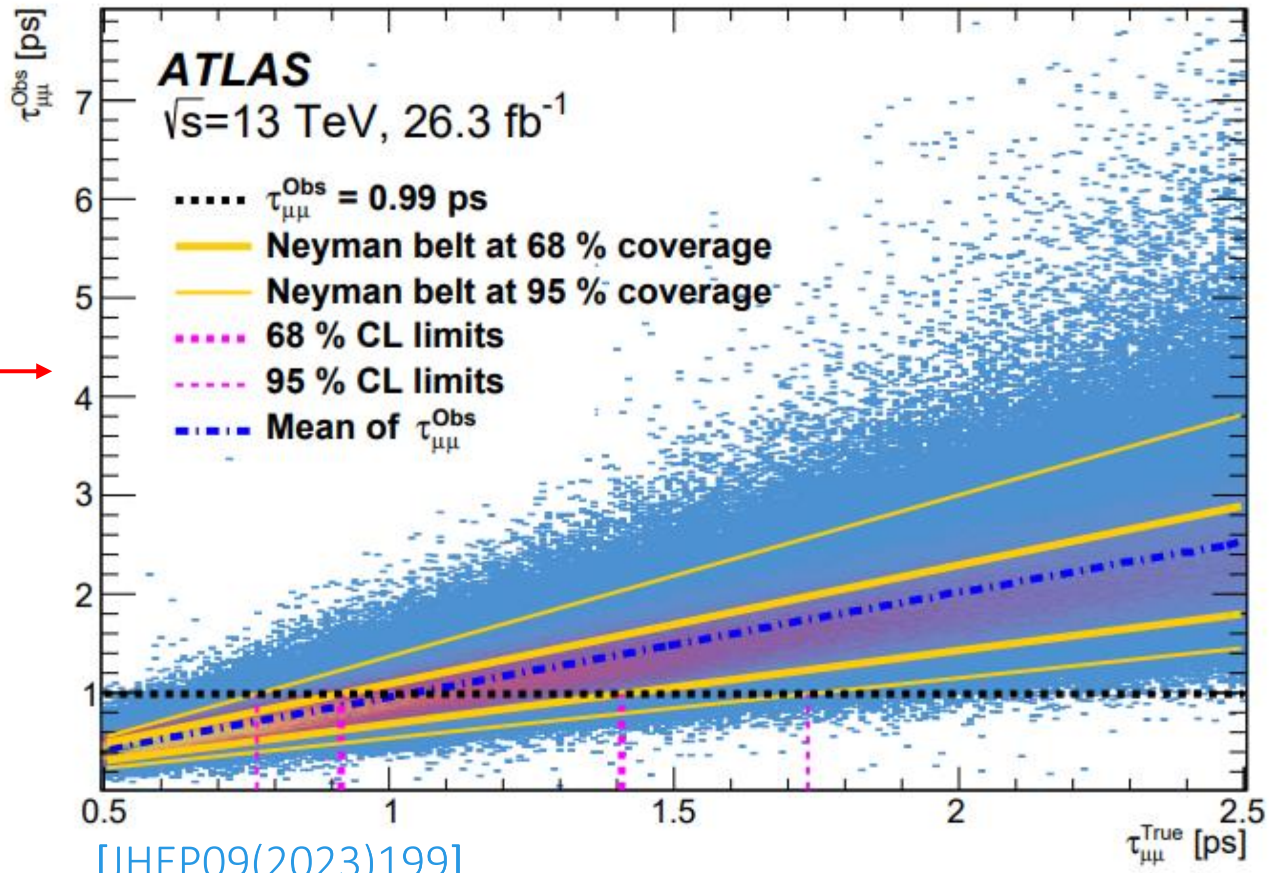


[JHEP09(2023)199]

$B_s^0 \to \mu^+\mu^-$ lifetime: Results

- Neyman construction (based on MC toys) to estimate the statistical uncertainty
  - $\Delta\chi^2 = 1$ not usable due to the non-Gaussian regime (asymmetric χ^2 distribution)
  - The χ^2 minimum and the Neyman belt construction yield

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



[JHEP09(2023)199]

$B_s^0 \to \mu^+\mu^-$ lifetime: Systematic uncertainties

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

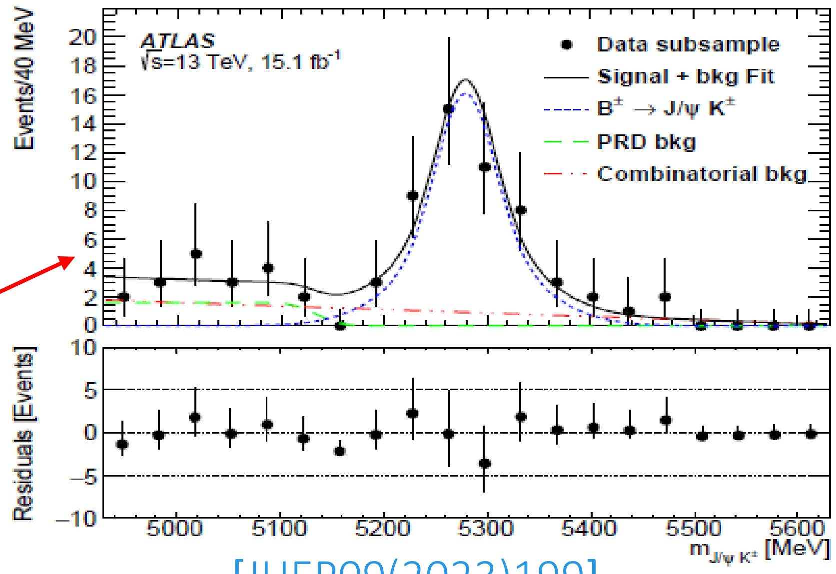
Systematic uncertainties studies:

- Fit procedure related
  - Includes intrinsic fit bias and signal/background modelization
- Signal modeling
  - Data/MC discrepancies estimated using data-driven approach using $B^\pm \to J/\psi K^\pm$ control channel→ is used to test the fitter procedure and the lifetime extraction with respect to a well known channel
- Background contributions
  - Add/remove neglected components

$Total\ systematic\ uncertainty\ \mathbf{0.17\ ps}$

Detector modelization $B^{\pm} \rightarrow J/\psi K^{\pm}$

- For this measurement, an important role is played by the vertex position resolution
  - A good proxy is given by $\sigma_{L_{xy}}$, i.e. the resolution on L_{xy} →Idea is to check its modelling using data from the control channel

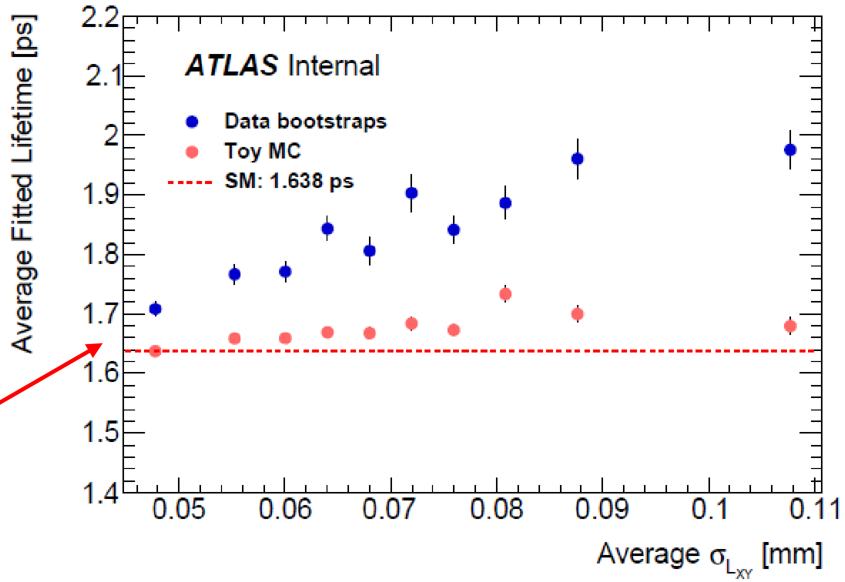


[JHEP09(2023)199]

- The lifetime extraction procedure in $B^{\pm}$ data is made of 5 steps.

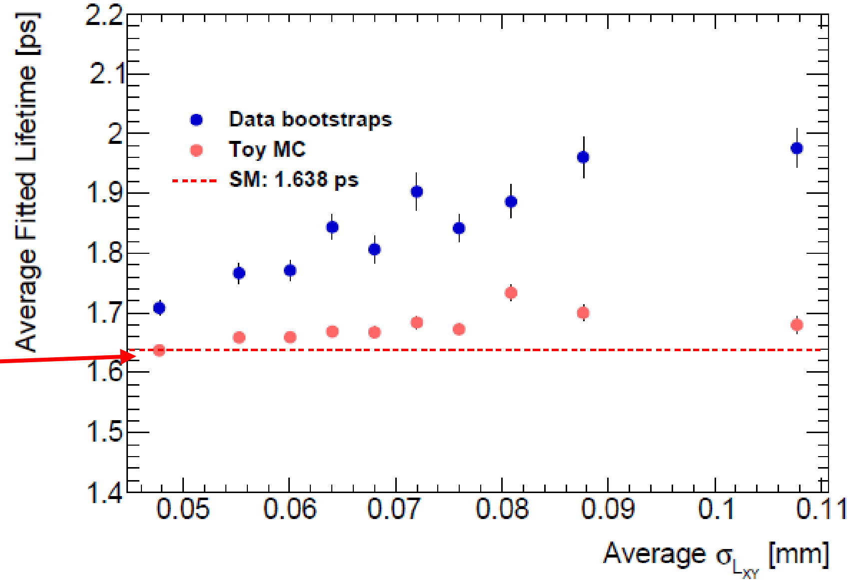
1. In each $\sigma_{L_{xy}}$ bin an UEML fit is performed on the **full statistics**
   - Fit model as in slide 7;
   - sPlot used to extract the signal proper-decay time distribution
   - Fit to proper-decay time distribution to extract shape parameters to be used in the Toy MC generation

2. In each $\sigma_{L_{xy}}$ bin an UEML fit is performed on 200 sub-samples (∼80 events) of independently bootstrapped events
   - Shape parameters taken from the Step 1 act as gaussian constraints
   - Lifetime is extracted for each of the 200 sub-samples using the same strategy as for the B_s signal
   - Average lifetime and its uncertainty reported for each bin (blue points)



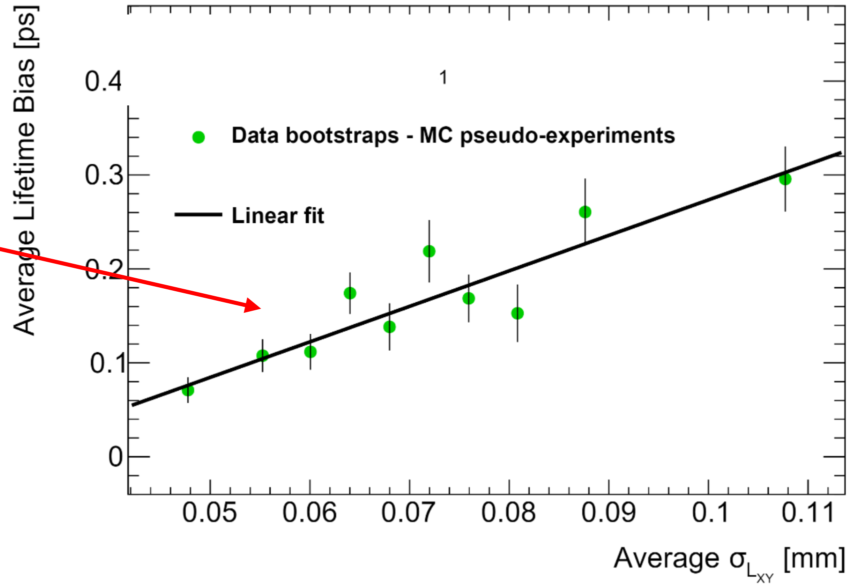
Detector modelization $B^{\pm} \rightarrow J/\psi K^{\pm}$

3. In each $\sigma_{L_{xy}}$ bin an UEML invariant mass fit is performed on 1000 toys MC of ~ 80 events each
   - Correct for the intrinsic bias of the procedure (same as for the Bs case)
   - Same procedure as in Step 2 to extract the average lifetime and its uncert. in each bin (red points)



4. In each $\sigma_{L_{xy}}$ bin , the average lifetime obtained from MC toys is subtracted from that obtained with bootstraps → linear fit on this distribution

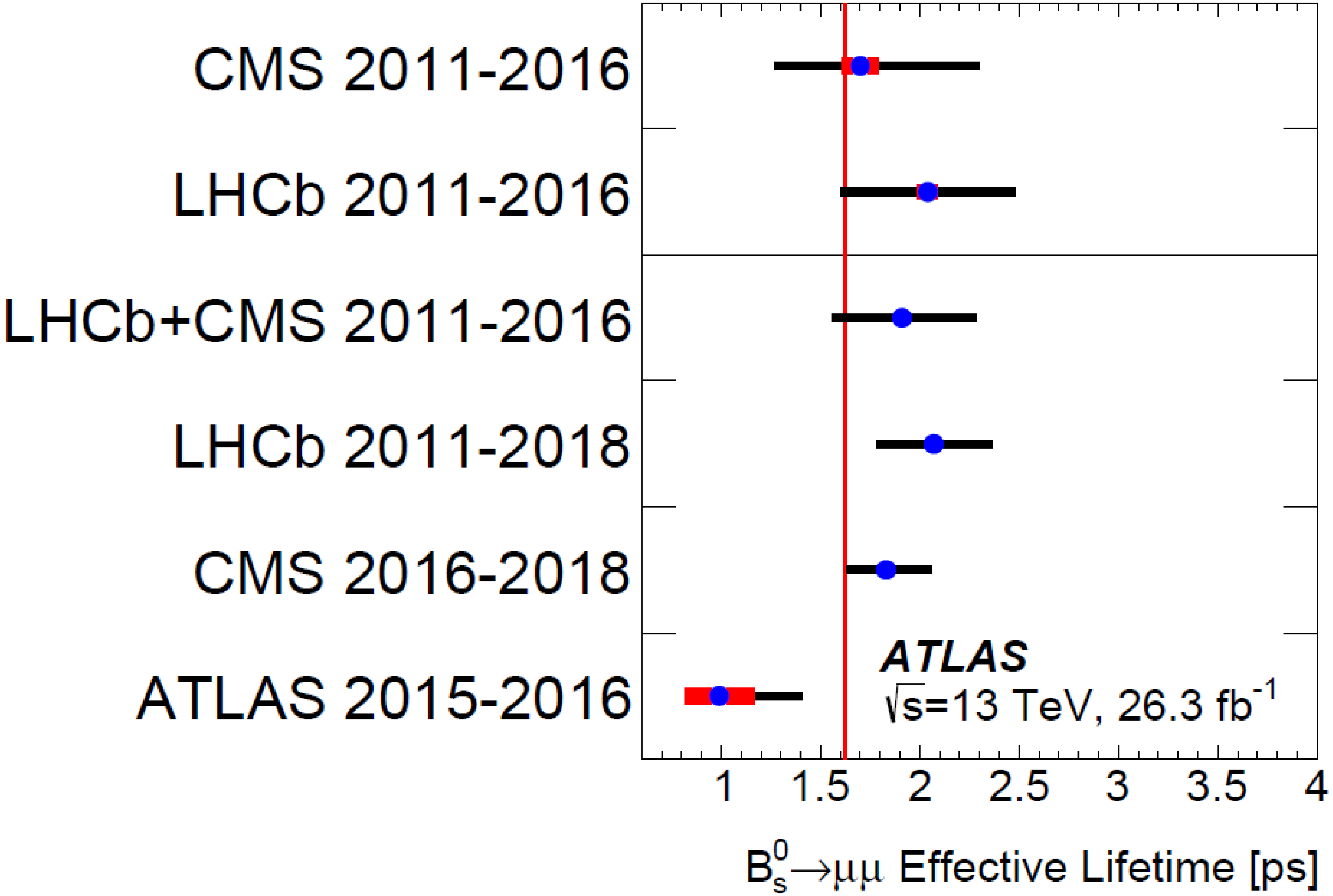
5. Weighted average of the lifetime bias using the $\sigma_{L_{xy}}$ distribution of the B_s channel



$B_s^0 \to \mu^+\mu^-$ lifetime: final result

- Horizontal bars represent the statistical and systematic uncertainties;
- Published combination [ATLAS-CONF-2020-049] on 2011-2016 data by CMS and LHCb collaborations is reported with the total uncertainty;
- The SM prediction and its uncertainty $\tau_{\mu\mu}^{SM} = (1.624 \pm 0.009)\text{ps}$ [Phys. Rev. D **107** (2023) 052008] are represented by the vertical line and its thickness, respectively;
- The result obtained is consistent with the SM prediction as well as other available experimental results.

[JHEP09(2023)199]



Conclusions and outlooks

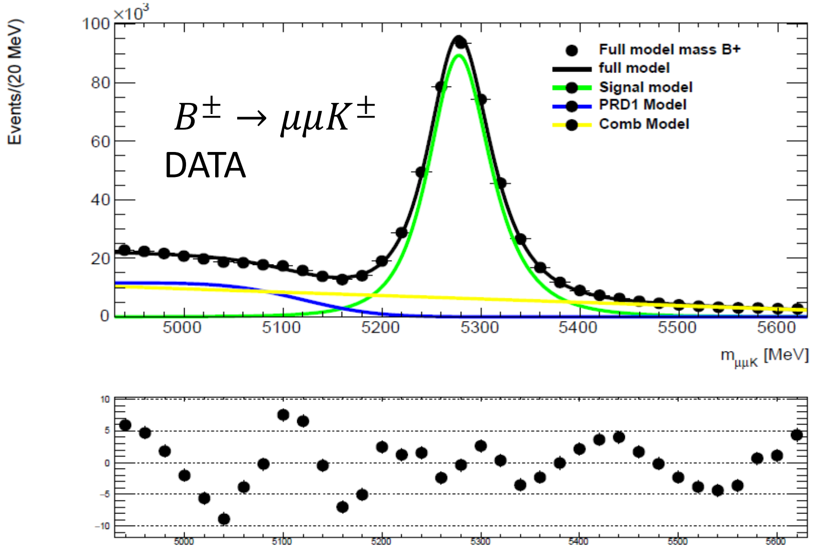
- B_s^0 effective lifetime has been measured for first time in ATLAS using pp data collected in 2015 and 2016
  1. Fit to di-muon invariant mass distribution;
  2. Used sPlot to extract the signal proper time distribution;
  3. Compared the signal proper time distribution with MC templates to extract the $B_s^0 \to \mu^+\mu^-$ effective lifetime.
- The result [JHEP09(2023)199] obtained based on a fraction of Run2 dataset corresponding to 26.3 fb^{-1} of 13 TeV LHC pp collisions is

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

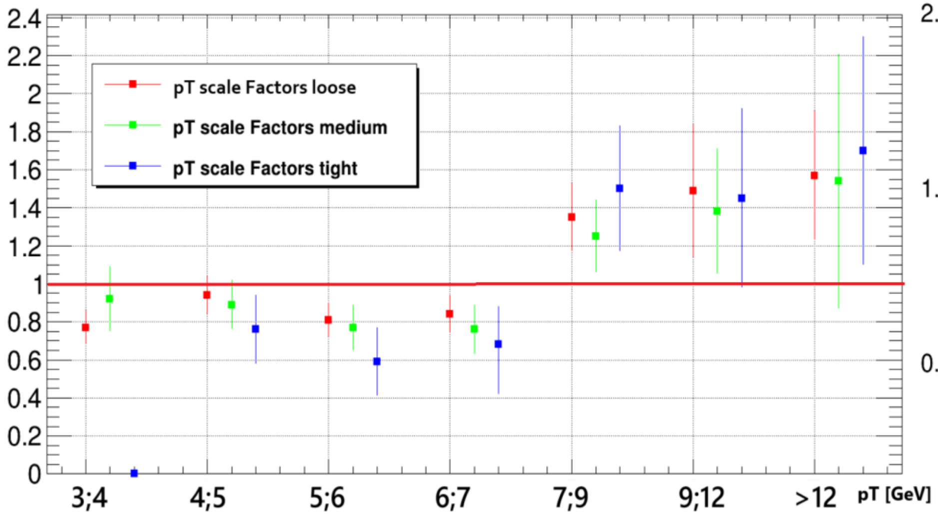
- The value obtained is consistent with the SM prediction $\tau_{\mu\mu}^{SM} = (1.624 \pm 0.009)\mathrm{ps}$ and with other available experimental results.
- We are moving towards complete Run 2 dataset analysis.
  - **Studies on muons fake rates;**
  - Studies on $B^{\pm}$ fit;
  - Studies related to BDT variables.

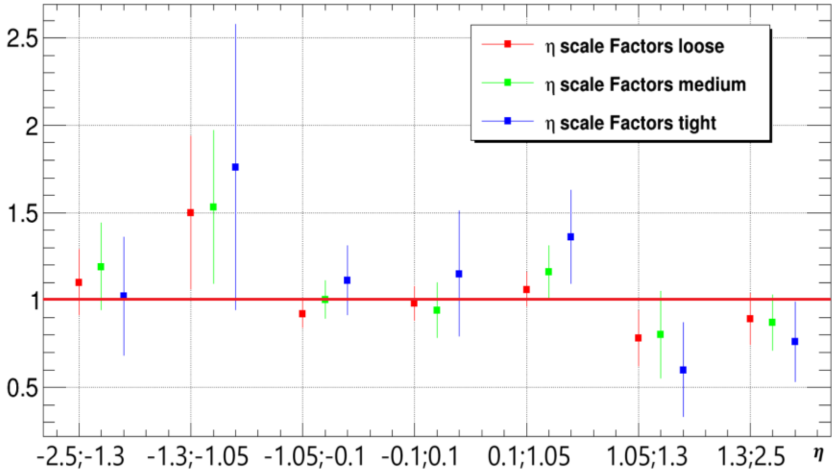
Outlooks: Fake Rates studies

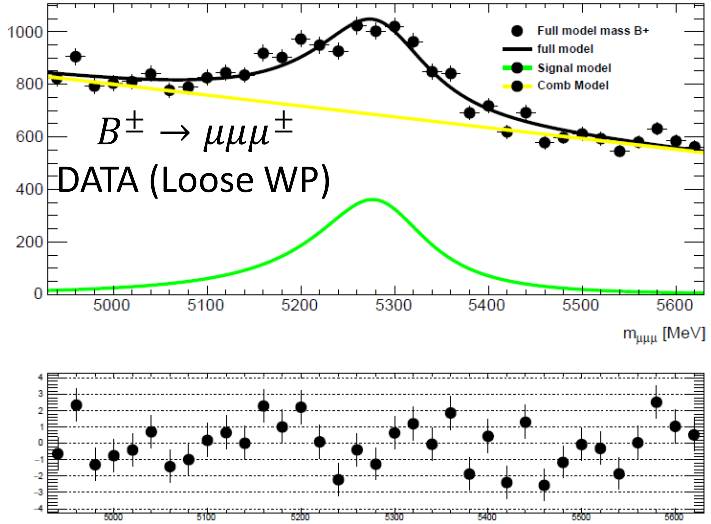
- B^0 and B_s hadrons decaying into a pair of hadrons (essentially kaons and pions).
- The goal is to study **in data** how many kaons have been misidentified as muons and produce Scale Factors in bins of η and p_T of the muon to correct MC.
- $B^\pm \to J/\psi K^\pm$ events have been chosen to study the muons' fake rate.
  1. First, an Unbinned Extended ML fit to $B^\pm$ candidate invariant mass distribution is performed to obtain the number of $B^\pm$ signal events
  2. Fake rates computed as function of p_T and η bins of ID track of the muon matching the kaon in the three Working Points (Loose, Medium and Tight).
- MC simulation looks in agreement with data within the uncertainty of the estimate (i.e. 20-40%)



Bin 3
4 GeV $< p_T \leq$ 5 GeV







Thank you for your attention