Analysis of $B^0_{(s)} \to \mu^+\mu^-$ decays with Run 3 data at the LHCb experiment

57. Herbstschule HEP

Lukas Bertsch

September 10, 2026

TU Dortmund University

Proponents of the analysis*:

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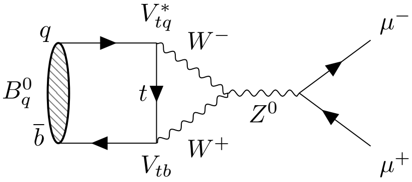
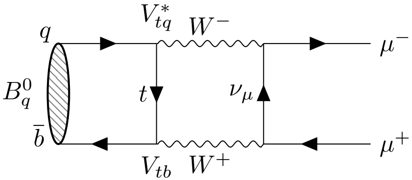
*Not co-authors of the talk

$B^0_{(s)} \to \mu^+\mu^-$ decays

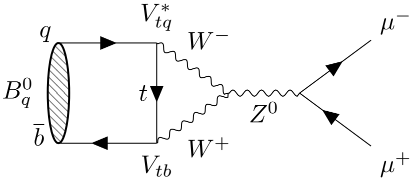
- **Very rare processes**
  - $\rightarrow$ Flavour Changing Neutral Current
    - $\rightarrow$ No tree-level diagram in the Standard Model (SM)
  - $\rightarrow$ Loop-, CKM- & helicity suppression

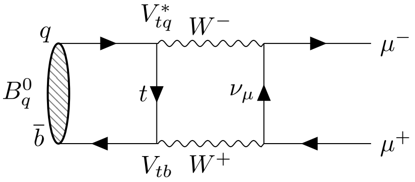




$B^0_{(s)} \to \mu^+\mu^-$ decays

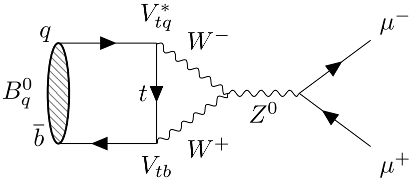
- Very rare processes
- **Precise theory predictions** [JHEP 10 (2019), 232] (purely leptonic final state)
  - → $\mathcal{B}(B^0_s \to \mu^+\mu^-)_{\text{SM}} = (3.66 \pm 0.14) \times 10^{-9}$
  - → $\mathcal{B}(B^0 \to \mu^+\mu^-)_{\text{SM}} = (1.03 \pm 0.05) \times 10^{-10}$

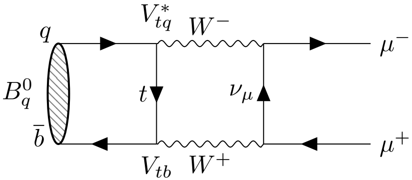




$B^0_{(s)} \to \mu^+\mu^-$ decays

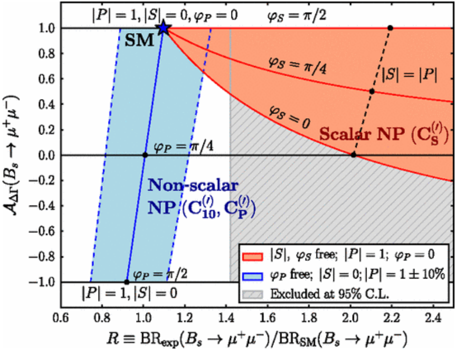
- Very rare processes
- Precise theory predictions
- **Clean experimental signature**





$B^0_{(s)} \to \mu^+\mu^-$ decays

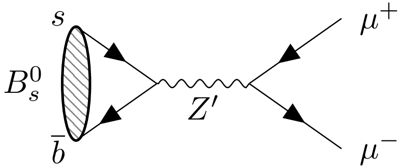
- Very rare processes
- Precise theory predictions
- Clean experimental signature
- **Observables with complementary sensitivity to New Physics (NP)**
  - $\rightarrow$ $\mathcal{B}(B^0_{(s)} \to \mu^+\mu^-)$: $\mathcal{C}_{10}^{(\prime)}$, $\mathcal{C}_S^{(\prime)}$, $\mathcal{C}_P^{(\prime)}$
  - $\rightarrow$ Effective lifetime $\tau_{\mu^+\mu^-}$
    - $\rightarrow$ Mass-eigenstate rate-asymmetry $\mathcal{A}_{\Delta\Gamma}$
  - $\rightarrow$ Time dependent *CP*-asymmetry $S_{\mu\mu}$ (tagged measurement)



[Phys. Rev. Lett. 109 (2012), 041801]

$B^0_{(s)} \to \mu^+\mu^-$ decays

- Very rare processes
- Precise theory predictions
- Clean experimental signature
- Observables with complementary sensitivity to New Physics (NP)
- **Sensitive to different NP contributions from...**
  - → Leptoquarks [JHEP 05 (2017), 076]
  - → Z' bosons [JHEP 02 (2013), 116]
  - → Extended Higgs sector [Phys. B 586 (2000) 39]



$B^0_{(s)} \to \mu^+\mu^-$ decays

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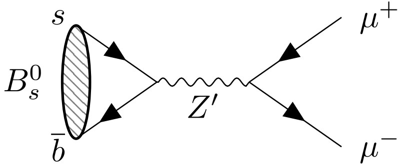
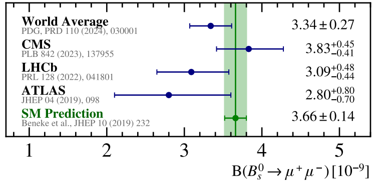
- Precise theory predictions
- Clean experimental signature
- Observables with complementary sensitivity to New Physics (NP)
- Sensitive to different NP contributions

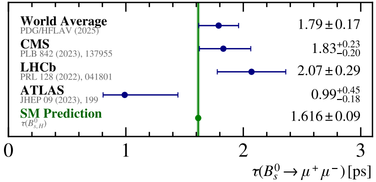


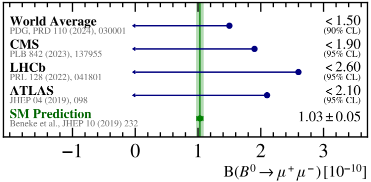
→ Great mode to test the SM and search for NP

State-of-the-art

- Long history of measurements
- A lot of competition in the field!
- First observation of $B_s^0 \to \mu^+\mu^-$ in 2014
  [Nature **522** (2015), 68]
  → More precise measurements followed







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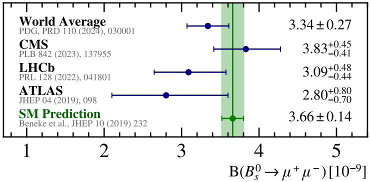
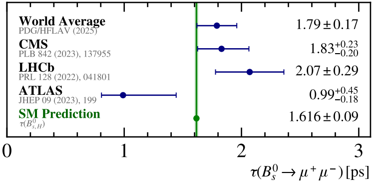
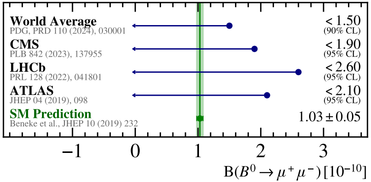
- No evidence for $B^0 \to \mu^+\mu^-$ until now







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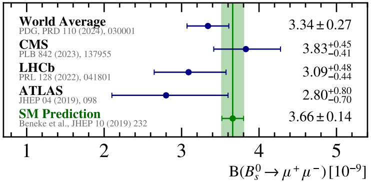
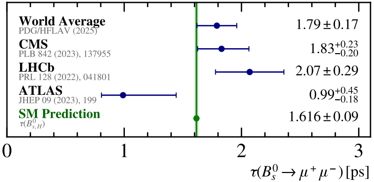
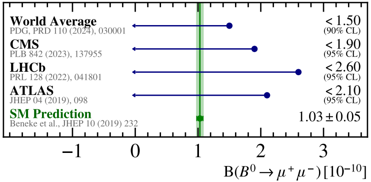
- Goals of this analysis:
  - $\to$ Increase precision on $B_s^0 \to \mu^+\mu^-$
  - $\to$ Evidence for $B^0 \to \mu^+\mu^-$







Measurement strategy

- Analysis steps:
  1. **Selection**

     → Two-stage Boosted Decision Tree (BDT) selection
  2. **Corrections** of simulation/data differences
  3. **Efficiency** calculation
  4. **Mass fit** (in bins of the BDT output)

  → **Branching Fraction (BF)** extraction

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Absolute BF measurement

$$\boxed{\mathcal{B}_{\text{sig}} = \frac{N_{\text{sig}}}{2\, f_q\, \mathcal{L}_{\text{int}}\, \sigma_{pp\to b\bar{b}}\, \varepsilon_{\text{sig}}}}$$

- N: # signal candidates (fit)
- ε : efficiency
- $\mathcal{L}_{\text{int}}$: integrated luminosity
- $\sigma_{pp\to b\bar{b}}$: $pp \to b\bar{b}$ cross section
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  $\rightarrow$ Large uncertainties

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Normalised BF measurement

$$\mathcal{B}_{\text{sig}} = \overbrace{\underbrace{\frac{\mathcal{B}_{\text{norm}}}{N_{\text{norm}}} \times \frac{\varepsilon_{\text{norm}}}{\varepsilon_{\text{sig}}}}_{:=\alpha_d(B^0\to\mu^+\mu^-)} \times \frac{f_d}{f_s}}^{:=\alpha_s(B_s^0\to\mu^+\mu^-)} \times N_{\text{sig}}$$

- Normalisation channel: $B^0 \to K^+\pi^-$

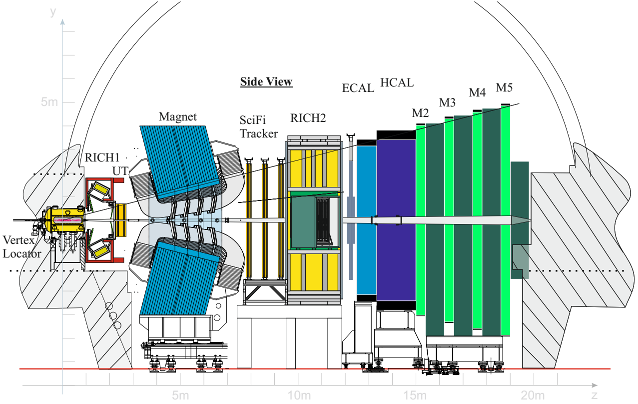
  $\rightarrow$ Similar topology

  $\rightarrow$ Well-measured BF
- Use $B^+ \to J/\psi(\to \mu^+\mu^-)K^+$ for validation/cross-check

The LHCb detector

The LHCb Upgrade 1 detector

- One of four large experiments at the LHC (CERN)
- Single-arm forward spectrometer
  - → Coverage only in the forward region (and one direction)
  - → Design choice motivated by b production in pp collisions

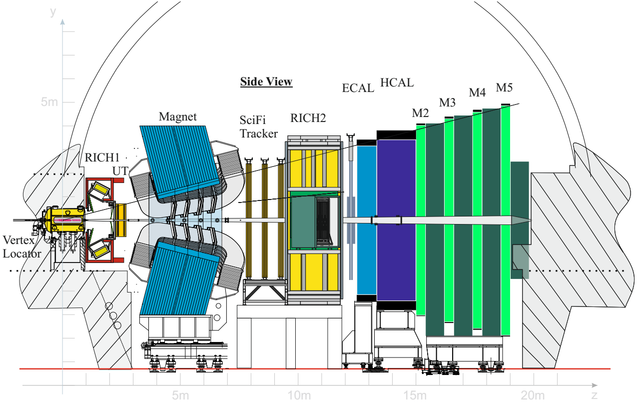


[JINST 19 (2024), P05065]

The LHCb Upgrade 1 detector

Upgrade 1

- Detector received a major upgrade after Run 2
- 5x larger instantaneous luminosity
- Renewed most detector parts
- Full detector readout thanks to full software trigger



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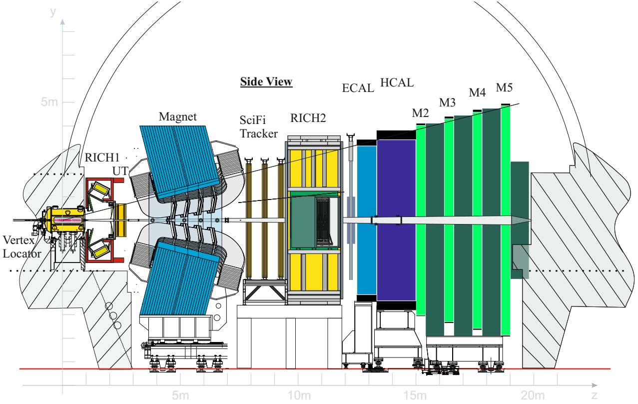
→ **Huge opportunity but also many new challenges**



[JINST 19 (2024), P05065]

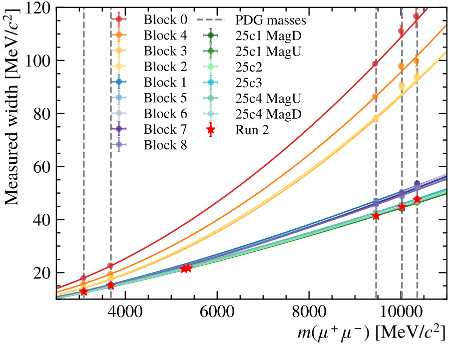
Analysis

Dataset

- Dataset collected in 2024 & 2025 at $\sqrt{s} = 13.6\,\text{TeV}/c^2$
- Only "good" quality data used
- 2024 Split in "blocks" with different conditions
- Total luminosity $\approx 18\,\text{fb}^{-1}$

- Suboptimal alignment in early 2024
  - → Offline calibrations performed
  - → Mass resolution similar to previous detector

- Mass resolution from $\mu\mu$ resonances



Before calibration/refitting

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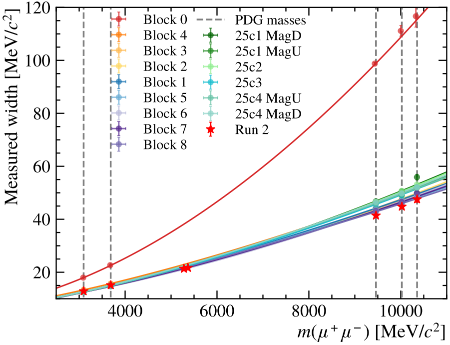
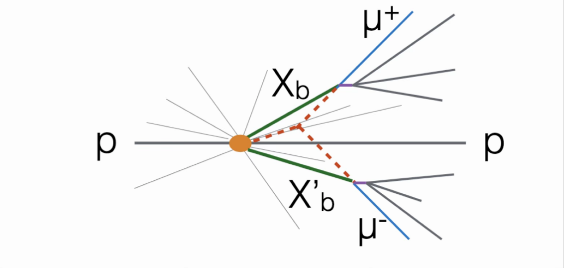
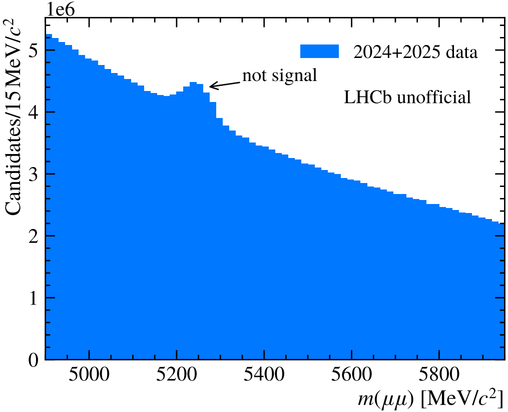


After calibration/refitting

Backgrounds

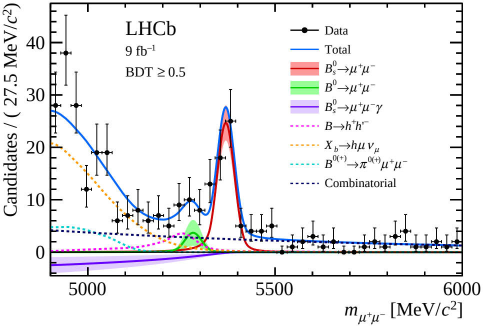
- Dataset dominated by random combination of tracks ("combinatorial")





Backgrounds

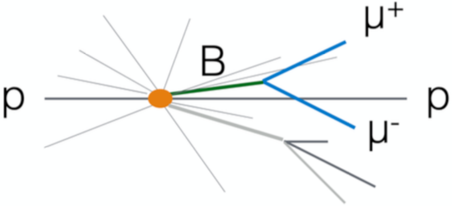
- Dataset dominated by random combination of tracks (“combinatorial”)
- Physical backgrounds:
  - Semi leptonic X_b decays with misidentified hadron h
  - Partially reconstructed decays
  - Double-misidentified $B^0_{(s)} \to h^+ h'^-$ decays



Run 2 fit [Phys. Rev. Lett. 128 (2022), 041801]

Selection

1. Trigger selection not relying on muonic trigger
   → Good alignment between $B^0_{(s)} \to \mu^+\mu^-$ signal and $B^0_{(s)} \to h^+h'^-$
2. Cut-based selection
   → Displacement from primary vertex, good vertex/track reconstruction, ...
3. BDT selection
   → Multiple BDTs employed
4. Particle IDentification (PID)
   → Different PID depending on final state

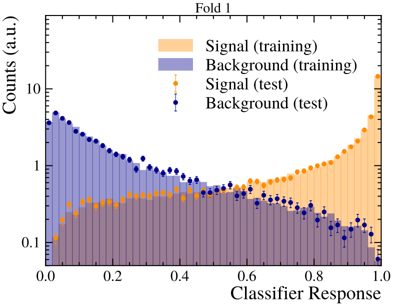


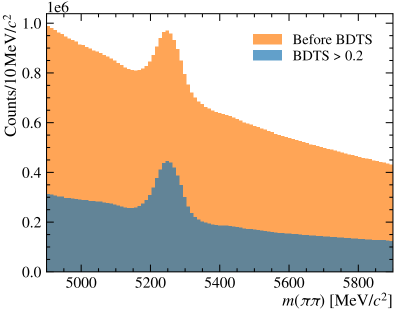
- Selection aligned between signal and normalisation/control modes as much as possible

BDT selection and track isolation 1/2

First BDT “BDTS”:

- Based on candidate-level information
- Loose selection for initial suppression of combinatorial background





BDT selection and track isolation 1/2

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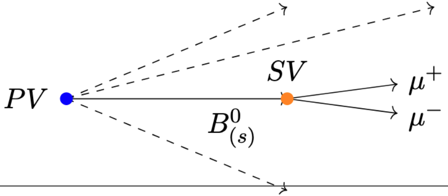
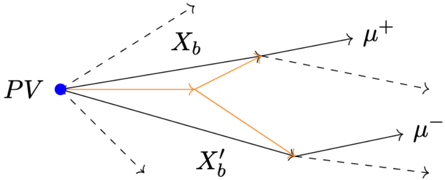
Track isolation BDTS:

- Exploiting full event information
- Quantify isolation of signal w.r.t other tracks
- Derive candidate-level features from this

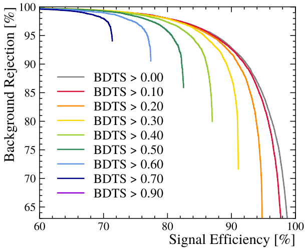


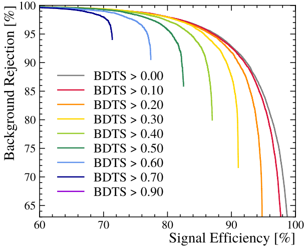


BDT selection and track isolation 2/2

Second BDT "Global BDT":

- Uses track isolation as input
- Optimised in dependence on BDTS
- Output transformed to be uniform for signal
  - $\rightarrow$ Final fit in bins of this output





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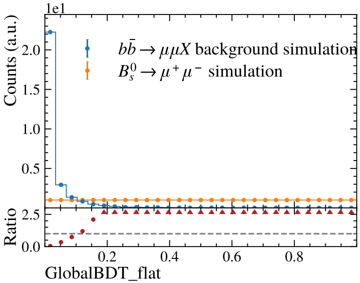
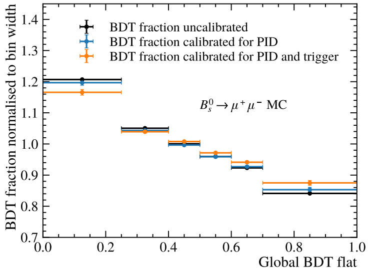


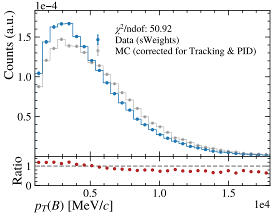


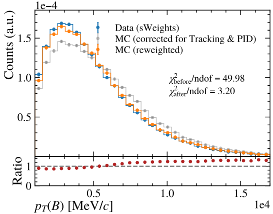
Simulation corrections

- Simulation is imperfect due to
  → Complex detector response, time dependent effects, limited precision ...
- Have to correct/calibrate these effects

Corrections:

1. Decay kinematics and multiplicity
   → Correct using **G**radient**B**oosted**R**eweighters (GBRs)
   → Train GBRs to reweight simulation to match sWeighted control-mode data





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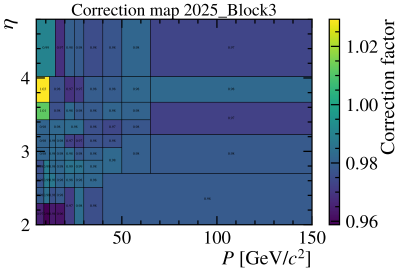
Corrections:

1. Decay kinematics and multiplicity
2. Tracking efficiency and hadronic interaction corrections
   → Apply data/simulation correction maps calibrated from different decay channels



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   $\rightarrow$ Calibrate trigger efficiency on data

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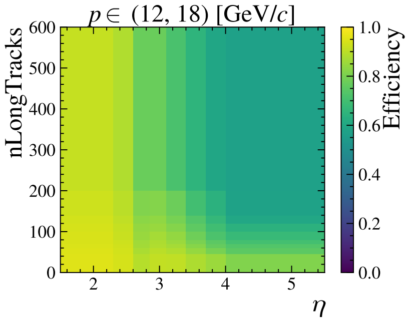
3. Trigger efficiency
   - → Calibrate trigger efficiency on data
4. PID efficiency
   - → Apply per-event PID efficiencies from data

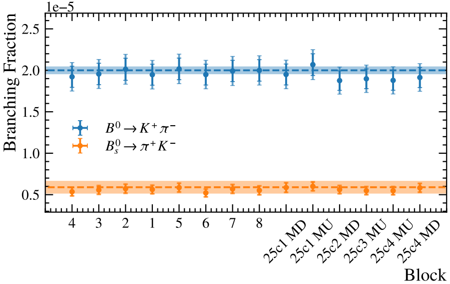


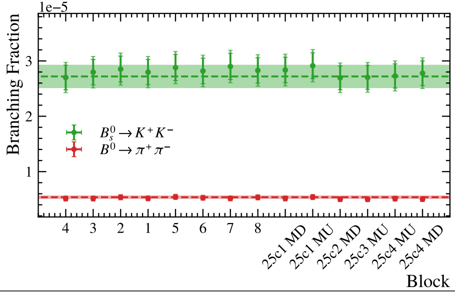
Cross checks

- Cross-checks required to validate the method and exclude potential errors

1. Absolute and normalised branching fraction measurements on $B^0_{(s)} \to h^+h'^-$

Absolute Branching Fractions





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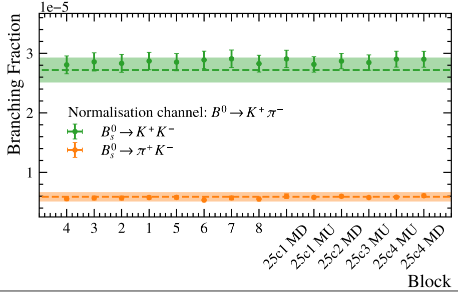
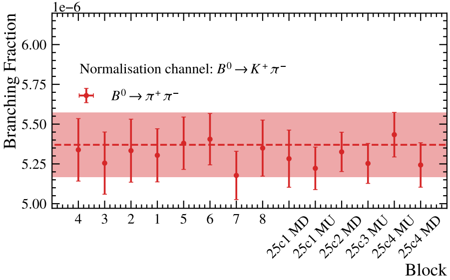
Normalised Branching Fractions





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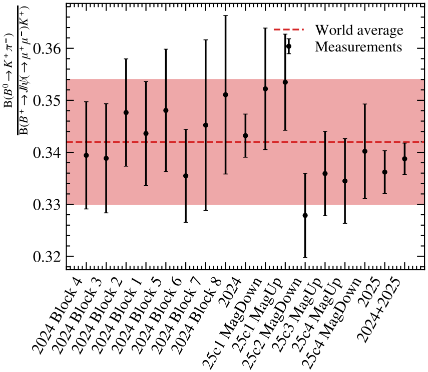
- Cross-checks required to validate the method and exclude potential errors

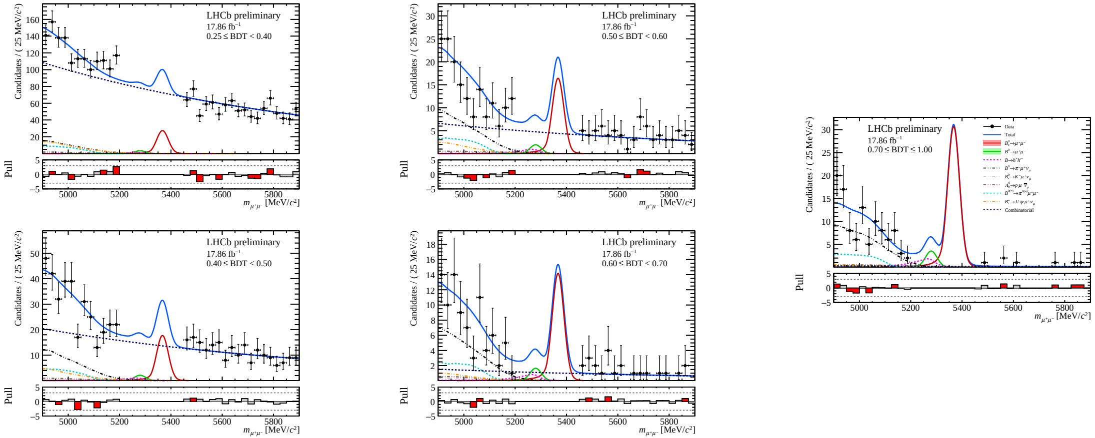
1. Absolute and normalised branching fraction measurements on $B^0_{(s)} \to h^+h'^-$
2. Ratio of $B^0 \to K^+\pi^-$ over $B^+ \to J/\psi K^+$



Results

Results

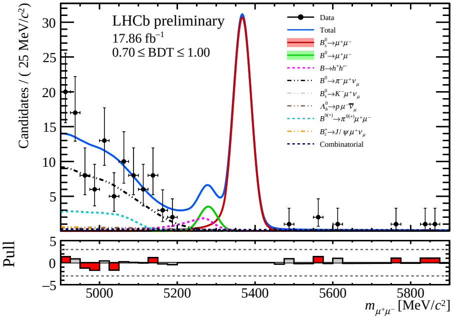
- Perform a blinded fit and overlay expected signal model
- Fit simultaneous in BDT bins



Results

- Perform a blinded fit and overlay expected signal model
- Fit simultaneous in BDT bins

- Blinded fit looks very promising
  → Very low background in highest BDT bins
- Expected precision scales well with the luminosity (compared to previous measurement)
- Sensitivity for $B^0 \to \mu^+\mu^-$ is being studied with pseudo experiments
  → Good chance for evidence
  → Still statistically limited



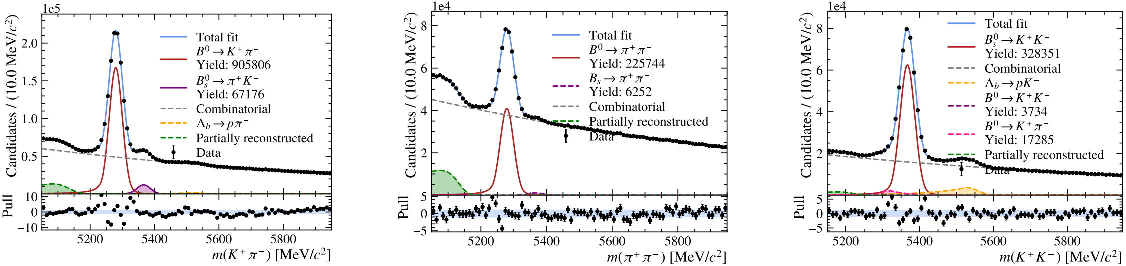
Conclusion

Conclusion

- $B^0_{(s)} \to \mu^+\mu^-$ decays provide sensitive tests of the Standard Model and offer a rich physics programme
- Long history of measurements established these decays as an important probe of the SM
- One of the first major analyses with LHCb Upgrade 1 detector
  - $\to$ With the new dataset we are getting closer to finding evidence for $B^0 \to \mu^+\mu^-$
- Large and complex analysis involving many different aspects and contributions from a large team
  - Only shown a small part today
- Analysis well on track $\to$ working on the last finalisations

Backup

Control mode fits



Observables

- $\mathcal{A}_{\Delta\Gamma}$

$$\mathcal{A}_{\Delta\Gamma} = \frac{1}{y_s} \frac{(1-y_s^2)\tau_{\mu\mu} - (1+y_s^2)\tau_{B_s^0}}{2\tau_{B_s^0} - (1-y_s^2)\tau_{\mu\mu}}, \quad \text{with} \quad y_s = \frac{\Delta\Gamma}{2\Gamma_s}$$

- $S_{\mu\mu}$

$$\frac{\Gamma(B_s^0(t)\to\mu^+\mu^-) - \Gamma(\bar{B}_s^0(t)\to\mu^+\mu^-)}{\Gamma(B_s^0(t)\to\mu^+\mu^-) + \Gamma(\bar{B}_s^0(t)\to\mu^+\mu^-)} = \frac{S_{\mu\mu}\sin(\Delta M t)}{\cosh\left(\frac{y_s t}{\tau_{B_s^0}}\right) + A_{\Delta\Gamma}^{\mu\mu}\sinh\left(\frac{y_s t}{\tau_{B_s^0}}\right)}$$

Mass resolution fits