Analysis of $B^0_{(s)} \to \mu^+\mu^-$ Decays as a Tool for LHCb - Run 3 Data Validation

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Motivation

- The precision of many measurements by the LHCb experiment are limited by statistics [1]
- For Run 3 the LHCb detector has been upgraded [2] in order to collect data at $\mathcal{L}_{\text{Run 3}} = 2 \times 10^{33}\,\text{cm}^{-2}\text{s}^{-1} \approx 5 \times \mathcal{L}_{\text{Run 1 + Run 2}}$
- This included
  - the revision of the tracking system
  - the transition to a full software trigger
  - the adaption of the data processing procedure
- All future analyses require an excellent understanding of the new detector

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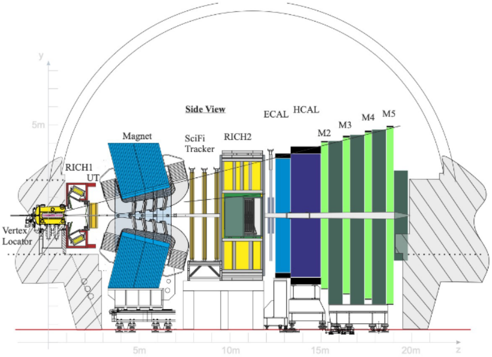
[1]R. Aaij et al. (LHCb), Int. J. Mod. Phys. A **30**, 1530022 (2015)
[2]R. Aaij et al. (LHCb), JINST **19**, P05065 (2024)

The Run 3 LHCb detector layout



- → The Upstream Tracker (UT) replaced the Tracker Turicensis (TT) [3]
- → The Scintillating Fibre (SciFi) Tracker replaced the Inner- and Outer tracker (T1 - T3) [3]

[3]R. Aaij et al. (LHCb), JINST **19**, P05065 (2024)

Goals of the thesis

- → 2024 marks the first year of successful Run 3 data taking with the LHCb detector
- → So far $L = 4.9\,\mathrm{fb}^{-1}$ of data have been collected
- → The presented thesis is aiming for
  - → general data validation →are we understanding measurements with the upgraded LHCb detector?
  - → the implementation and interpretation of studies on the performance of the LHCb detector
  - → providing a first step towards the offline selection of the Run 3 $B^0_{(s)} \to \mu^+\mu^-$ analysis

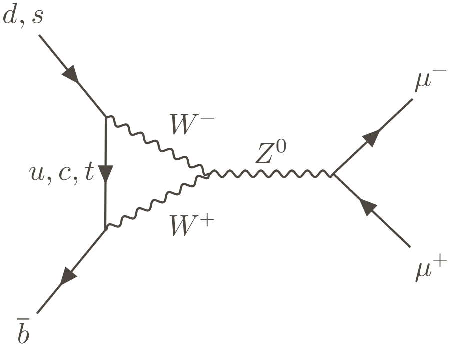
Analysis strategy

- Studies are performed on central non-rare decays in the former $B^0_{(s)} \to \mu^+\mu^-$ analysis [4]
  - e.g. the normalization channel: $B^+ \to J/\psi(\mu^+\mu^-)K^+$
- The measurement qualities give an idea on the quality of the Run 3 analysis
- Similar topological characteristics give hints for the performance of a $B^0_{(s)} \to \mu^+\mu^-$ search
- The full analysis is performed on subsets, because of different data taking conditions

[4]R. Aaij et al. (LHCb), Phys. Rev. D **105**, 012010 (2022)

Why are we looking for $B^0_{(s)} \to \mu^+\mu^-$ decays?

- Determining $\mathrm{BR}(B^0_s \to \mu^+\mu^-)$ is one of the LHCb key measurements [5]
- The decays $B^0_{(s)} \to \mu^+\mu^-$
  - offer a promising opportunity for the search of physics beyond the Standard Model (BSM)
  - can be detected by the LHCb detector with high reliability
- Latest LHCb results [6]:



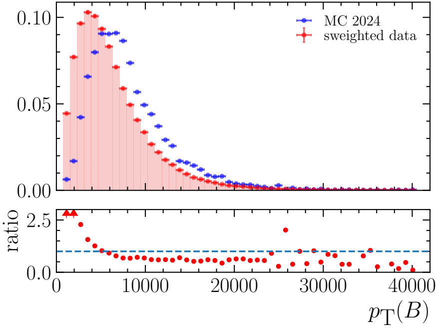
$$\mathrm{BR}(B^0_s \to \mu^+\mu^-) = [3.09^{+0.46}_{-0.44}(\text{stat.})^{+0.14}_{-0.10}(\text{syst.})] \cdot 10^{-9}$$

$$\mathrm{BR}(B^0 \to \mu^+\mu^-) < 2.6 \cdot 10^{-10} \text{ at 95\% CL}$$

[5]B. Adeva et al. (LHCb), *Roadmap for selected key measurements of LHCb*, (Dec. 2009)
[6]R. Aaij et al. (LHCb), Phys. Rev. D **105**, 012010 (2022)

1. Data-simulation comparison

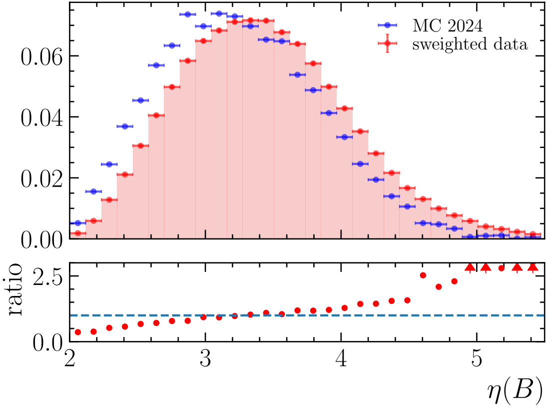
- → Compare normalized distributions of truth-matched simulation and sWeighted data
  - → Truth-matching →ensures to have clean simulation including only signal events
  - → sWeighting →a technique to produce signal event histograms from a polluted datasets [7] [8]
- → Distributions are shown for $B^+ \to J/\psi(\mu^+\mu^-)K^+$



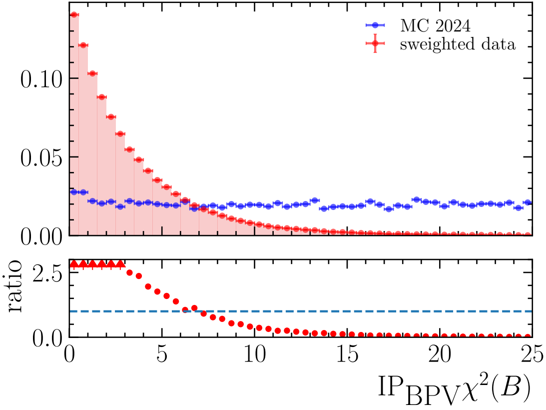
[7]M. Pivk and F. R. Le Diberder, Nucl. Instrum. Meth. A **555**, 356 (2005)
[8]H. Dembinski et al., Nucl. Instrum. Meth. A **1040**, 167270 (2022)

1. Data-simulation comparison

Most of the time:
Small deviations are observed
→expected

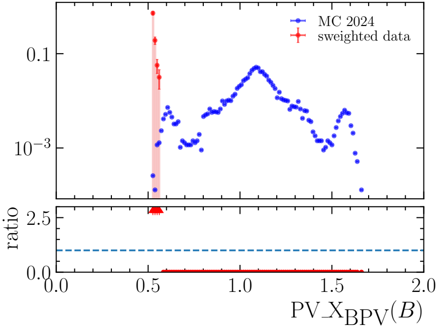


For a few variables:
Significant differences are observed
→problematic



1. Data-simulation comparison

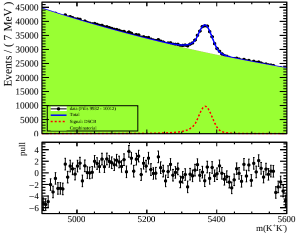
- Comparison performed for ~ 50 variables and multiple channels
  - Good agreement in most cases
  - Strong disagreements are traced back to primary vertex simulation
    - the origin of this problem is found
    - fixed simulation will arrive soon
- Conclusion: A good understanding of the detector has been reached



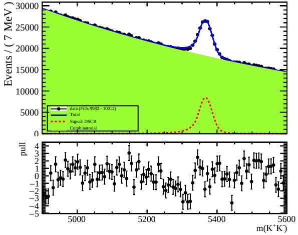
2. Mass calibration: mean mass of $B^0_{(s)}$

- The idea: Determine the masses of $B^0_{(s)}$ from $B^0 \to K^+\pi^-$ and $B^0_s \to K^+K^-$
- Use data from $B \to HH$ measurements
- apply hadron classification:
  - K : H_PID_K $> \epsilon$
  - π : H_PID_K $< -\epsilon$

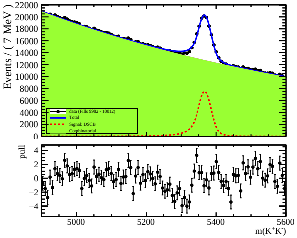
$\epsilon = 5$



$\epsilon = 10$



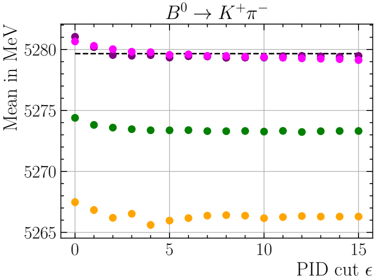
$\epsilon = 15$

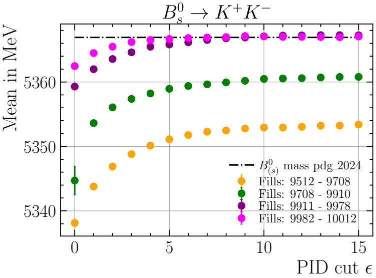


2. Mass calibration: mean mass of $B^0_{(s)}$

→ First measurements show mass shifts of 13 MeV compared to PDG values [9]

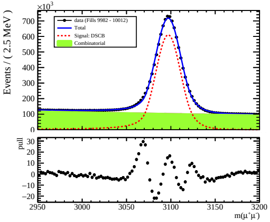
→ Latest measurements are compatible with PDG values [9]

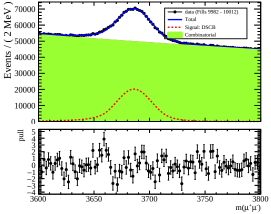


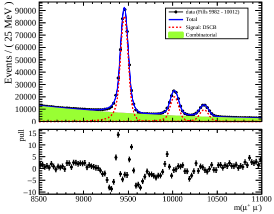


[9]S. Navas et al. (Particle Data Group), Phys. Rev. D **110**, 030001 (2024)

- The idea: Obtain an expected mass resolution for $B^0_{(s)} \to \mu^+\mu^-$ by extrapolation
- Consider the mean and width from mass fits of
  - $J/\psi \to \mu^+\mu^-$
  - $\psi(2S) \to \mu^+\mu^-$
  - $\Upsilon(1S, 2S, 3S) \to \mu^+\mu^-$







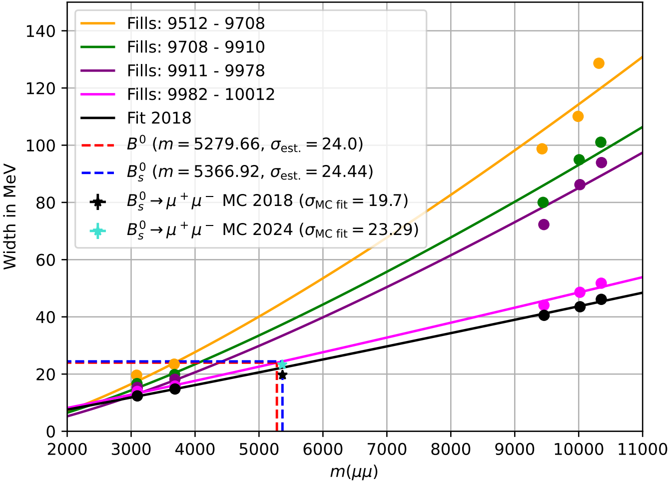
2. Mass calibration: mass resolution around $B^0_{(s)}$ mass

Approach:

- → Fit σ_{fit} vs. $m(\mu\mu)$ with $\sigma_{\mu\mu}(m_{\mu\mu}) = a \cdot m_{\mu\mu} + b \cdot m_{\mu\mu}^{\gamma}$
- → Estimate mass resolution at $m(B^0)$ and $m(B^0_s)$

Result:

- → First measurements →estimated mass resolution around 44 MeV
- → Latests measurements estimate mass resolution very close to expectations from simulation

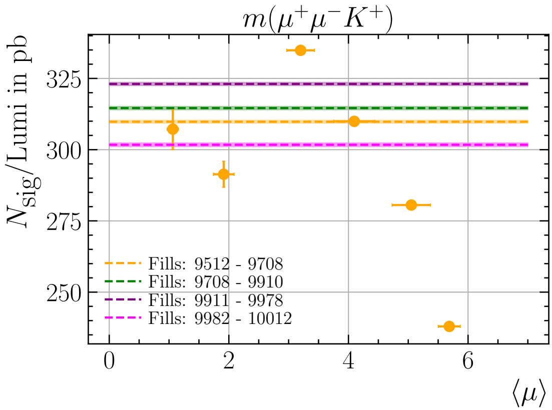


3. Signal yields: the general idea

- → Signal yield $\widehat{=}\ {}^{N_{\text{sig}}}/_{L}$
- → Very important quantity for an analysis
- → In RUN 1 and RUN2 LHCb was limited to one observed interactions per bunch-crossing, $\langle\mu\rangle \approx 1$ (pile-up) [10]
- → Due to the LHCb detector upgrade μ can be increased
- → Interesting questions: How do signal yields change for different μ?
- → Expected behaviors →all observables should be independent of μ

[10]*LHCb technical design report: Reoptimized detector design and performance*, (Sept. 2003)

- Early measurements enabled for $\langle\mu\rangle$-binned studies
  - Strong fluctuations
  - Decreasing for higher $\langle\mu\rangle$, cause could be identified and was fixed
- Intermediate fills show increasing yields
- Latest results show a decrease compared to all former results
- The same decrease is observed in $B_s^0 \to J/\psi\phi$, $J/\psi \to \mu^+\mu^-$, $\psi(2S) \to \mu^+\mu^-$

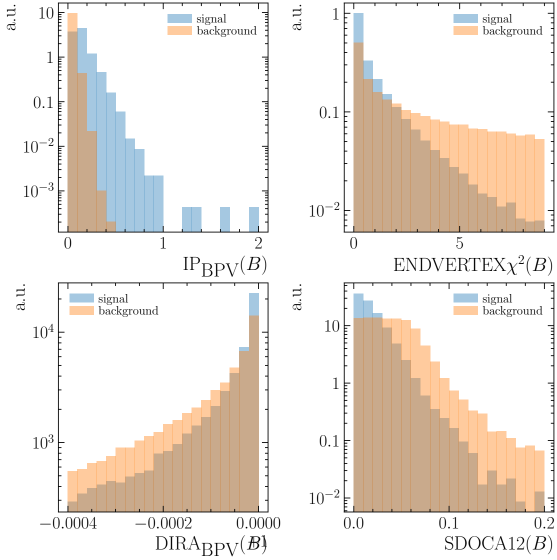


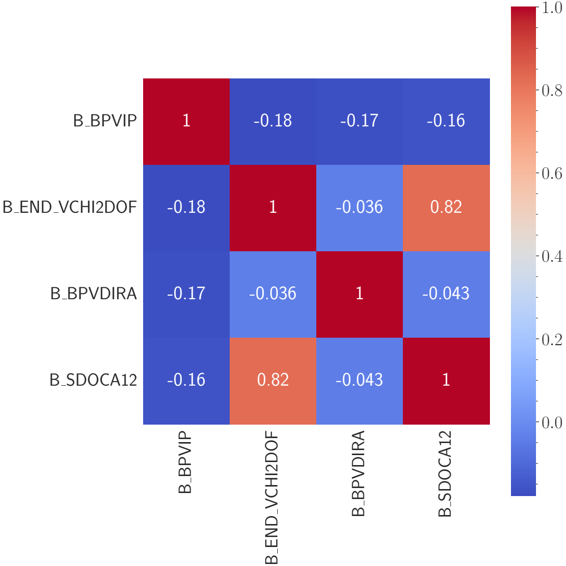
4. Towards a Run 3 offline selection...

- → Train a multivariate classifier to reduce background at the offline selection
  - → Goal: Maximal background reduction while keeping almost all signal events
  - → Model: A Boosted Decision Tree (BDT) based on the XGBoost library [11] [12]
- → signal sample: $B_s^0 \to \mu^+\mu^-$ MC
- → background sample: sidebands from $B \to \mu^+\mu^-$ data
- → Input variables orientated on the classifier trained for former analyses [13]
  - → not all previously used variables are available yet

[11]xgboost developers, *Documentation: XGBoost: a scalable tree boosting system*, version 2.0.3, Sept. 4, 2024
[12]T. Chen and C. Guestrin, `10.1145/2939672.2939785` (2016)
[13]C. Adrover et al., *Search for the rare decays $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ with 1.02 fb $^{-1}$*, (2012)

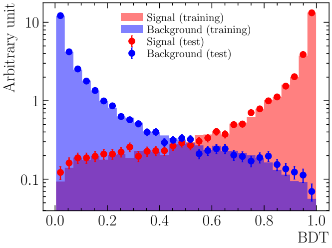
4. Towards a Run 3 offline selection...

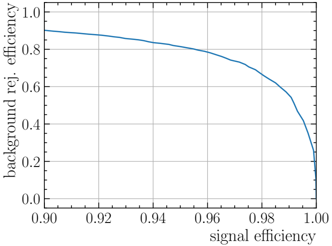




4. Towards a Run 3 offline selection...

- Signal and background events appear to be well separable
- With current performance
  - background events can be reduced by 80%
  - while keeping 95% of signal events
  - corresponding BDT cut: BDT > 0.27
- Small signs of overtraining are visible





Conclusion:

As a part of my thesis

- I set up an analysis pipeline performing
  - comparisons between truth-matched simulation and sWeighted data
  - mass calibration steps including mass and mass resolution determination
  - general and pile-up considering signal yield studies
  - the training of a multivariate classifier for the Run 3 analysis of $B^0_{(s)} \to \mu^+\mu^-$
- I provided critical feedback to the collaboration which
  - helped to improve the online data-taking
  - laid the ground for a high quality measurement of $B^0_{(s)} \to \mu^+\mu^-$

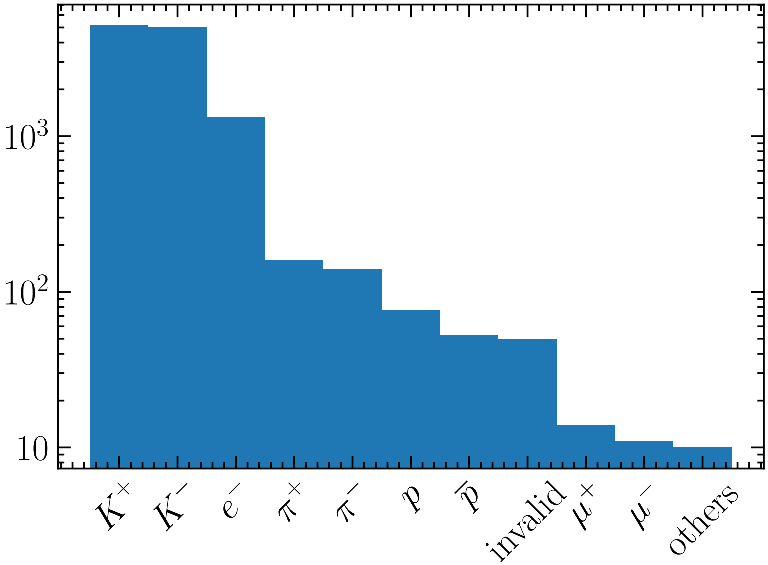
List of applied cuts

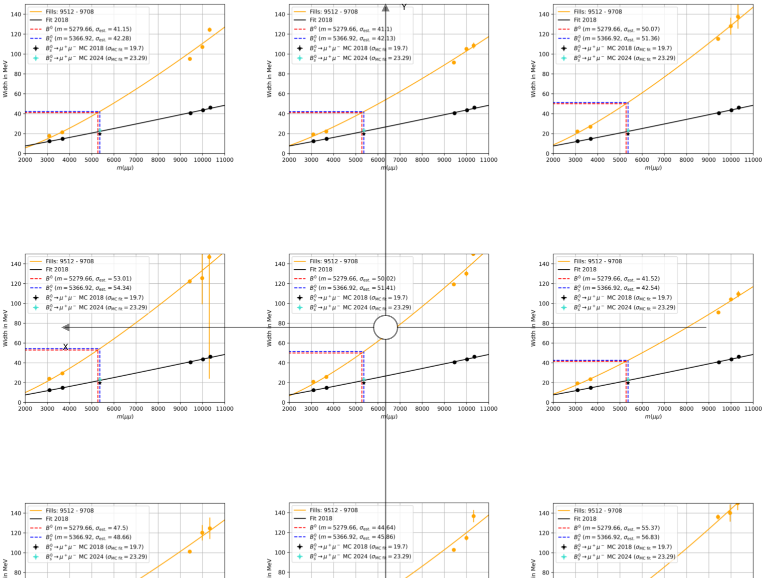
variable	applied to	requirements	
		$B^0_{(s)} \to \mu^+\mu^-$ and $B^0_{(s)} \to H^+H^{(\prime)-}$	$B^+ \to J/\psi(\to \mu\mu)K^+$
trackχ^2/ndof	μ/H	< 3	< 3
ghost prob.		< 0.3	< 0.3
DOCA		$< 0.3\,\mathrm{mm}$	
χ^2_{IP}		> 25	> 25
p_{T}		$\in [0.25, 40]\,\mathrm{GeV}$	$\in [0.25, 40]\,\mathrm{GeV}$
p		$< 500\,\mathrm{GeV}$	$< 500\,\mathrm{GeV}$
isMuon	onlyμ	true	true
χ^2_{vertex}	$\mu\mu/HH$	< 9	< 9
χ^2_{FD}		> 225	> 225
$\lvert m(\mu\mu) - m_B \rvert$		$< 1200\,\mathrm{MeV}$	
$\lvert m(HH) - m_B \rvert$		$< 500\,\mathrm{MeV}$	
$\lvert m(\mu\mu) - m_{J/\psi} \rvert$			$< 60\,\mathrm{MeV}$
χ^2_{IP}	B	< 25	< 25
t		$< 9 \cdot \tau(B^0_s)$	$< 9 \cdot \tau(B^0_s)$
p_{T}		$> 500\,\mathrm{MeV}$	$> 500\,\mathrm{MeV}$
$\lvert m(J/\psi K^+) - m_B \rvert$			$< 100\,\mathrm{MeV}$
χ^2_{vertex}			< 45

List of applied cuts

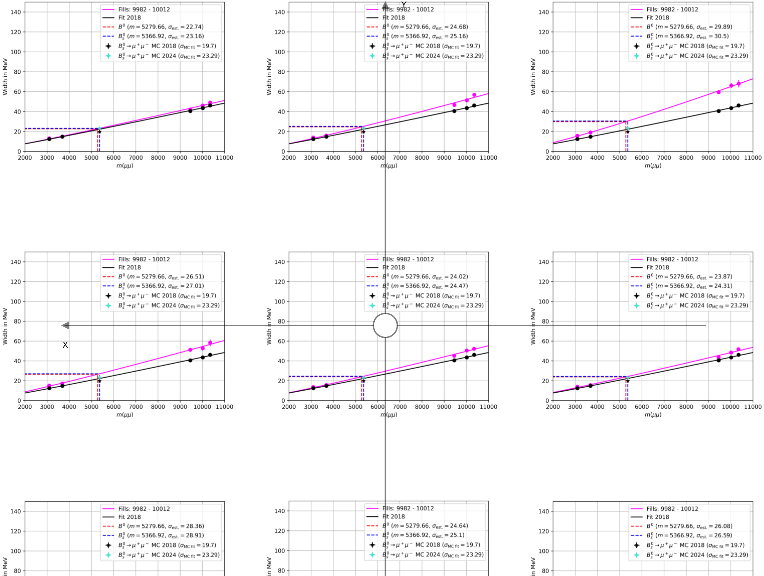
variable	applied to	requirements	
		$B_s^0 \to J/\psi(\to \mu^+\mu^-)\phi(\to K^+K^-)$	$J/\psi, ... \to \mu^+\mu^-$
trackχ^2/ndof	μ/K	< 4	< 3
ghost prob.		< 0.4	< 0.3
χ^2_{IP}		> 25	
p_{T}		$> 250\,\text{GeV}$	$\in [0.25, 40]\,\text{GeV}$
p			$< 500\,\text{GeV}$
isMuon	onlyμ	true	true
χ^2_{vertex}	$\mu\mu$	< 9	< 9
χ^2_{FD}		> 225	
DOCA		$< 0.3\,\text{mm}$	
$\lvert m(\mu\mu) - m_{J/\psi}\rvert$		$< 100\,\text{MeV}$	
χ^2_{IP}	KK	> 25	
$\lvert m(KK) - m_{/\phi}\rvert$		$< 20\,\text{MeV}$	
χ^2_{vertex}	$J/\psi\phi$	< 75	
χ^2_{IP}	B	< 25	
$\lvert m(J/\psi\phi) - m_B\rvert$		$< 500\,\text{MeV}$	
χ^2_{IP}	$J/\psi, ...$		< 12

Truth-matching

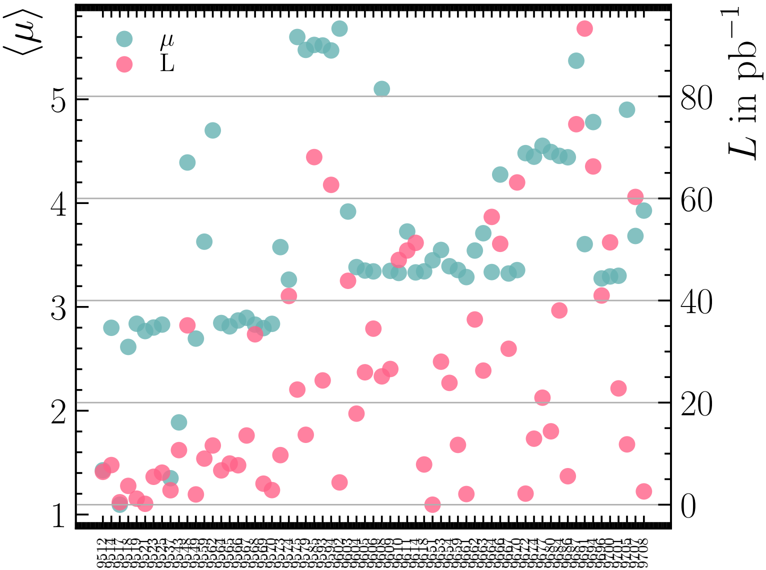



Fills: 9512 - 9708
Fit 2018
B^0 ($m = 5279.66$, $\sigma_{est.} = 41.15$)
B_s^0 ($m = 5366.92$, $\sigma_{est.} = 42.28$)
$B_s^0 \to \mu^+\mu^-$ MC 2018 ($\sigma_{MC\ fit} = 19.7$)
$B_s^0 \to \mu^+\mu^-$ MC 2024 ($\sigma_{MC\ fit} = 23.29$)
B_s^0 ($m = 5366.92$, $\sigma_{est.} = 42.13$)
B^0 ($m = 5279.66$, $\sigma_{est.} = 50.07$)
B_s^0 ($m = 5366.92$, $\sigma_{est.} = 51.36$)
B^0 ($m = 5279.66$, $\sigma_{est.} = 53.01$)
B_s^0 ($m = 5366.92$, $\sigma_{est.} = 54.34$)
B^0 ($m = 5279.66$, $\sigma_{est.} = 50.02$)
B_s^0 ($m = 5366.92$, $\sigma_{est.} = 51.41$)
B^0 ($m = 5279.66$, $\sigma_{est.} = 41.52$)
B_s^0 ($m = 5366.92$, $\sigma_{est.} = 42.54$)
B^0 ($m = 5279.66$, $\sigma_{est.} = 47.5$)
B_s^0 ($m = 5366.92$, $\sigma_{est.} = 48.66$)
B^0 ($m = 5279.66$, $\sigma_{est.} = 44.64$)
B_s^0 ($m = 5366.92$, $\sigma_{est.} = 45.86$)
B^0 ($m = 5279.66$, $\sigma_{est.} = 55.37$)
B_s^0 ($m = 5366.92$, $\sigma_{est.} = 56.83$)
Width in MeV
$m(\mu\mu)$
X
Y

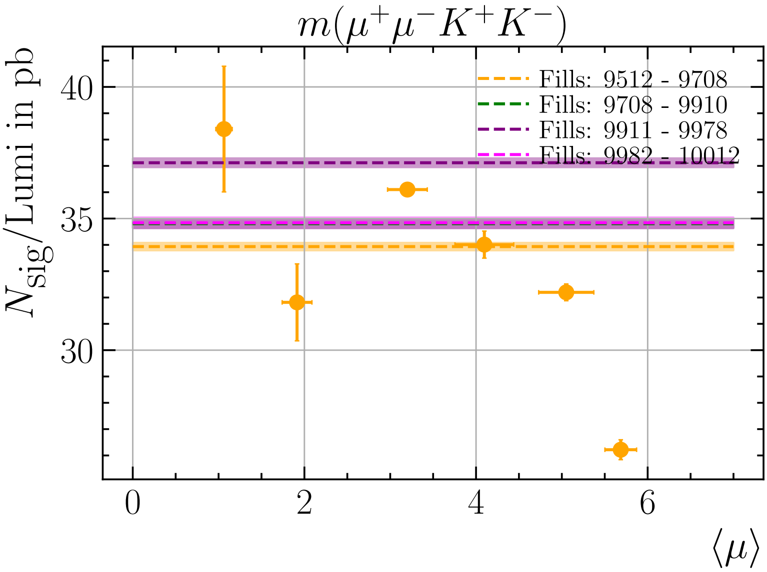
SciFi alignment



Mu and Lumi distribution for early measurements

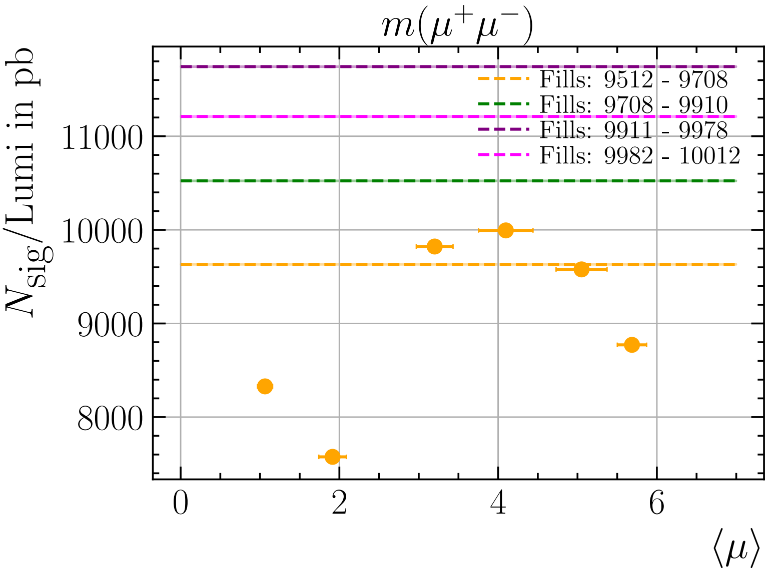


Yields



$m(\mu^+\mu^-K^+K^-)$
N_{sig}/Lumi in pb
40
35
30
0
2
4
6
$\langle\mu\rangle$
Fills: 9512 - 9708
Fills: 9708 - 9910
Fills: 9911 - 9978
Fills: 9982 - 10012

Yields



$m(\mu^+\mu^-)$
N_{sig}/Lumi in pb
11000
10000
9000
8000
0
2
4
6
$\langle\mu\rangle$
Fills: 9512 - 9708
Fills: 9708 - 9910
Fills: 9911 - 9978
Fills: 9982 - 10012

[1] R. Aaij et al. (LHCb), Int. J. Mod. Phys. A **30**, 1530022 (2015).

[2] R. Aaij et al. (LHCb), JINST **19**, P05065 (2024).

[3] R. Aaij et al. (LHCb), Phys. Rev. D **105**, 012010 (2022).

[4] B. Adeva et al. (LHCb), *Roadmap for selected key measurements of LHCb*, (Dec. 2009).

[5] M. Pivk and F. R. Le Diberder, Nucl. Instrum. Meth. A **555**, 356 (2005).

[6] H. Dembinski, M. Kenzie, C. Langenbruch, and M. Schmelling, Nucl. Instrum. Meth. A **1040**, 167270 (2022).

[7] S. Navas et al. (Particle Data Group), Phys. Rev. D **110**, 030001 (2024).

[8] *LHCb technical design report: Reoptimized detector design and performance*, (Sept. 2003).

[9] xgboost developers, *Documentation: XGBoost: a scalable tree boosting system*, version 2.0.3, Sept. 4, 2024.

[10] T. Chen and C. Guestrin, `10.1145/2939672.2939785` (2016).

Yields

[11] C. Adrover, J. Albrecht, F. Archilli, M.-O. Bettler, X. Cid Vidal, F. Dettori, C. Elsasser, J. A. Hernando Morata, G. Lanfranchi, G. Mancinelli, D. Martinez Santos, M. Palutan, M. Perrin-Terrin, N. Sagidova, A. Sarti, B. Sciascia, J. Serrano, F. Soomro, Y. Shcheglov, and O. Steinkamp, *Search for the rare decays $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ with 1.02 fb $^{-1}$*, (2012).