$B^0_{(s)} \to \mu^+\mu^-$ in Run 3 at the LHCb Experiment

Studies and Preparations

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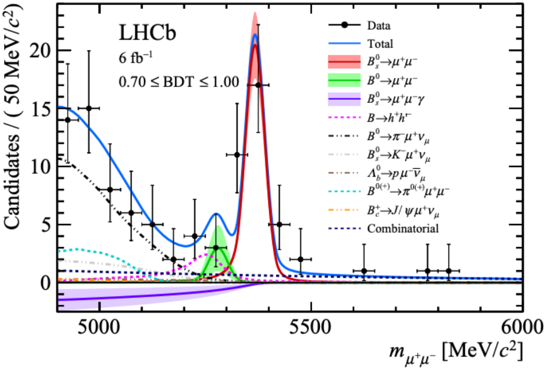
Motivation

- $\mathcal{B}(B^0_{(s)} \to \mu^+\mu^-)$ are key measurements of the LHCb experiment [1]
- In 2024 the LHCb experiment recorded already an integrated luminosity of more than $8.3\,\text{fb}^{-1}$ at $\sqrt{s} = 13.6\,\text{TeV}$
- Throughout the year data and simulation conditions varied significantly
- Studies on control and normalisation channels of the $B^0_{(s)} \to \mu^+\mu^-$ measurements help to verify performance of the detector



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

Menu of Today

- *Detector performance* studies comparing on 2018 and 2024 data:
  - Trigger studies on $B^+ \to K^+ J/\psi(\to \mu^+\mu^-)$ and $B^0 \to K^{*0}(\to K^+\pi^-) J/\psi(\to \mu^+\mu^-)$
  - Yield per luminosity measurements on $B^+ \to K^+ J/\psi(\to \mu^+\mu^-)$ and $B^0 \to K^{*0}(\to K^+\pi^-) J/\psi(\to \mu^+\mu^-)$
- *Detector performance* studies throughout 2024 data:
  - $B^0_s \to K^+K^-$ mass value for varying PID
  - Dimuon mass resolution with J/ψ, $\psi(2S)$, $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$ decays
- *Absolute branching fraction* measurements of $B^0_{(s)} \to h^+h'^-$ modes

Trigger Studies - The TISTOS Method

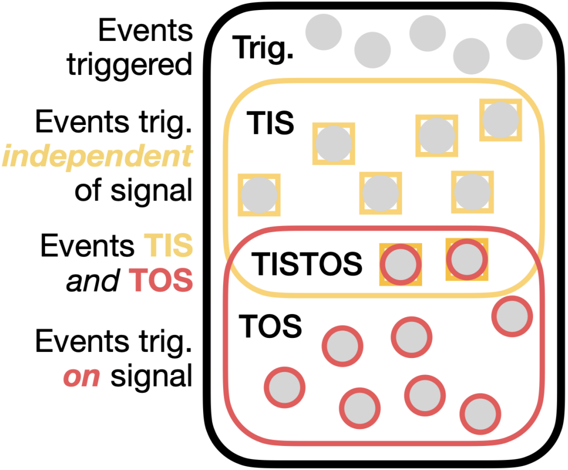
→ Trigger efficiency is in general

$$\varepsilon^{\text{True}}_{\text{Trig.}} = \frac{N_{\text{Trig.}}}{N_{\text{All}}}$$

→ On data N_{All} is not known, `TOS` efficiency can therefore be found with

$$\varepsilon^{\text{approx.}}_{\text{Trig.}} \approx \varepsilon_{\texttt{TOS|TIS}} = \frac{N_{\texttt{TISTOS}}}{N_{\texttt{TIS}}}$$

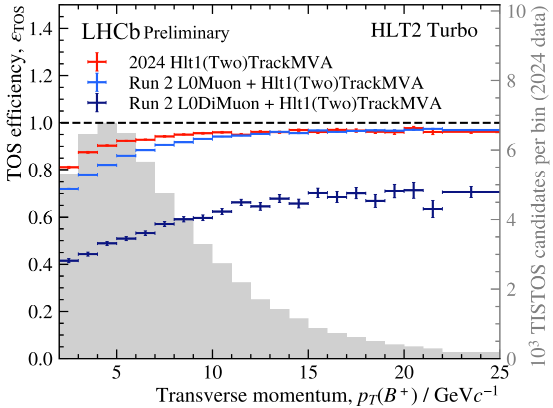
→ Measurements are performed with new `TriggerCalib` tool [1], more details on method in Ref. [2]

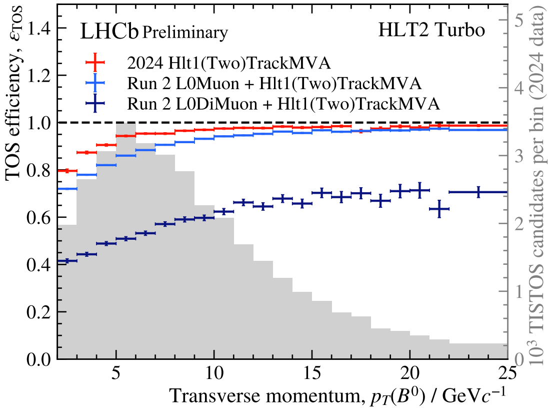


[1]triggercalib.docs.cern.ch
[2]LHCb-PUB-2014-039

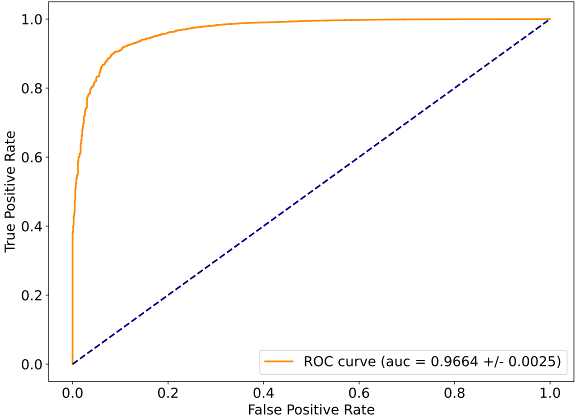
Trigger Studies

- → $B^+ \to K^+ J/\psi(\to \mu^+\mu^-)$ (left) and $B^0 \to K^{*0}(\to K^+\pi^-) J/\psi(\to \mu^+\mu^-)$ (right) channel
- → 2024 `HLT1(Two)TrackMVA` compared to Run 2 `L0(Di)Muon + HLT1(Two)TrackMVA`
- → $\varepsilon_{\mathtt{TOS}}$ in 2024 data consistently above Run 2 efficiencies





- Following results from Ref. [1]
- HLT1 Trigger:
  - `Hlt1(Two)TrackMVA_TOS`
  - `Hlt1TrackMuonMVA_TOS`
- Clone cut removal: $\theta_{t_1,t_2} > 1\,\text{mrad}$
- Two $q^2 = m(\mu^+\mu^-)$ regions:
  - $q^2 \in (1.1, 6)\,\text{GeV}^2$
  - $\left|\sqrt{q^2} - 3096.9\right| < 100\,\text{MeV}^2$
- Additional BDT:
  - $B^+ \to K^+\mu^+\mu^-$ cut: 0.91
  - $B^0 \to K^{*0}\mu^+\mu^-$ cut: 0.43

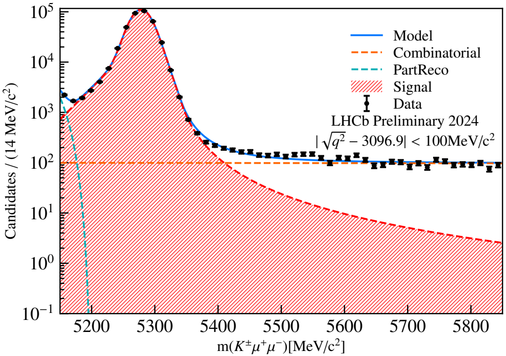


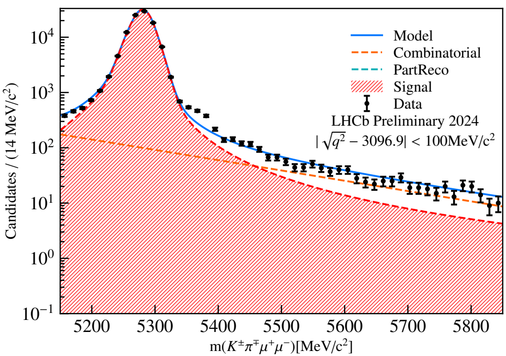
[1] LHCB-FIGURE-2024-022

Yields/Luminosity Studies

→ Invariant mass fits in the region $\left|\sqrt{q^2} - 3096.9\right| < 100\,\text{MeV}^2$

$B^+ \to K^+ J/\psi(\to \mu^+\mu^-)$	$B^0 \to K^{*0}(\to K^+\pi^-) J/\psi(\to \mu^+\mu^-)$
$382\,821 \pm 640$	$104\,729 \pm 340$

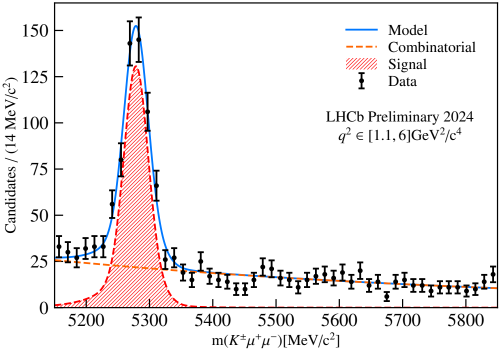


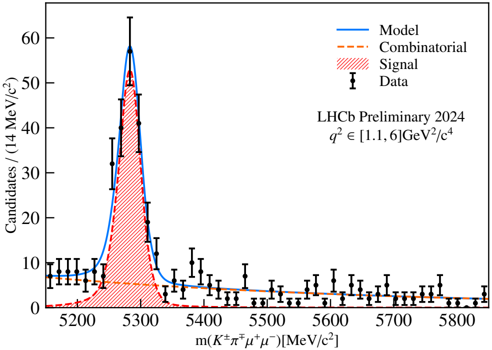


Yields/Luminosity Studies

→ Invariant mass fits in the region $q^2 \in (1.1, 6)$ GeV^2

$B^+ \to K^+\mu^+\mu^-$	$B^0 \to K^{*0}(\to K^+\pi^-)\mu^+\mu^-$
523 ± 31	157 ± 18





Yields/Luminosity Studies

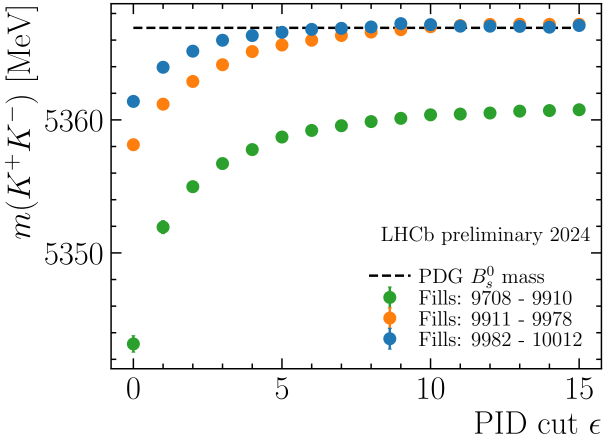
- Comparison with results from R_X Analysis [1]
- No attempt to align the results have been made, purity is qualitatively similar
- 2024 results provide a lower bound, not all data has been processed for these results

Region	2024 Yield/fb^{-1}		2018 Yield/fb^{-1}	
	$B^+ \to K^+\mu^+\mu^-$	$B^0 \to K^{*0}\mu^+\mu^-$	$B^+ \to K^+\mu^+\mu^-$	$B^0 \to K^{*0}\mu^+\mu^-$
central-q^2	0.57 ± 0.04	0.27 ± 0.03	0.59 ± 0.01	0.23 ± 0.01
J/ψ-q^2	471 ± 1	181.1 ± 0.6	377.3 ± 0.3	125.2 ± 0.2

[1]R. Aaij et al. (LHCb), Phys. Rev. D **108**, 032002 (2023), LHCb-ANA-2020-069

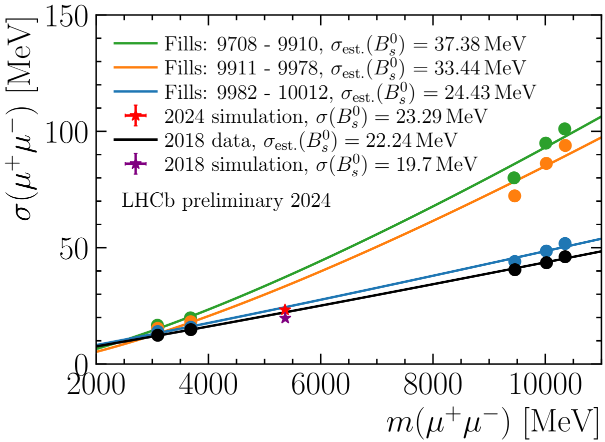
2024 Data - Mean of Mass vs. PID

- Mean of $B_s^0 \to K^+K^-$ mass peak for different values of ϵ_{PID} with $\text{PID\_}K > \epsilon_{\text{PID}}$
- Huge improvements of B_s^0 mass mean between different fill ranges in 2024 data
- Good agreement with PDG values in latest fills



2024 Data - Mass Resolution

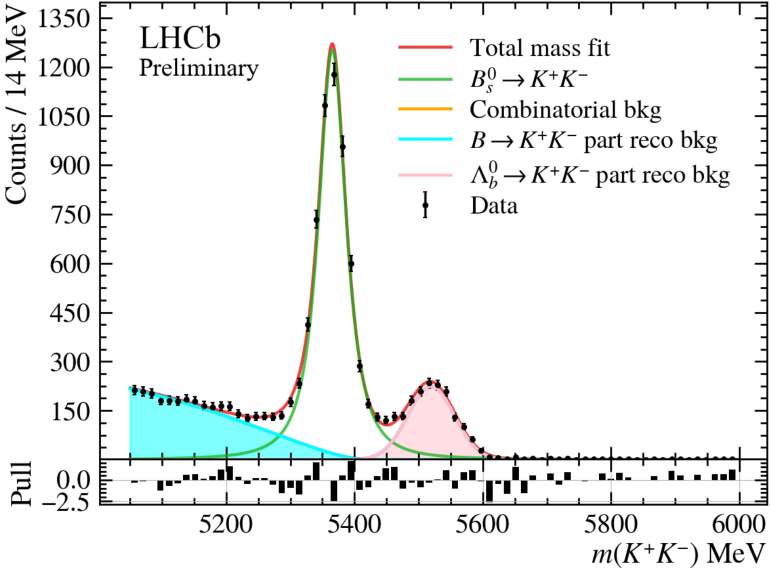
- → Comparison of mass resolution for different 2024 data conditions
- → Comparison with values from 2018 and B_s^0 mass resolution from simulation
- → With latest detector alignment, conditions comparable with 2018 detector were seen



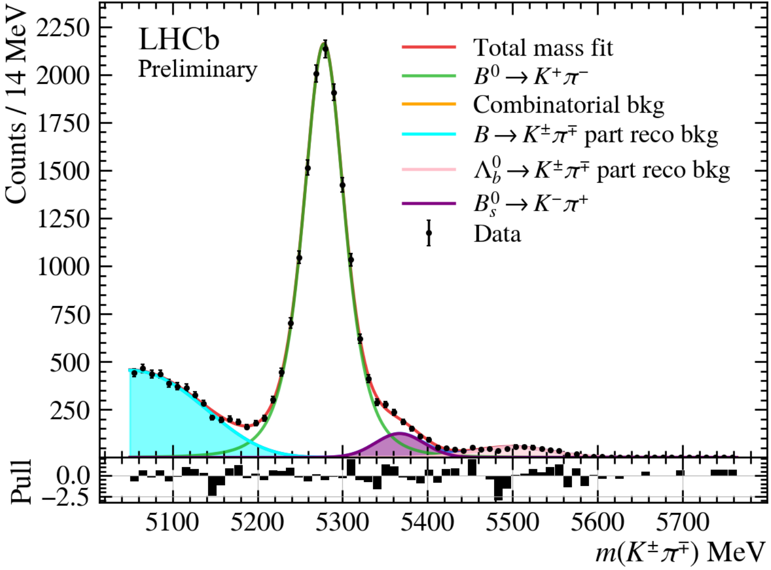
$\mathcal{B}(B \to h^+h^-)$ Strategy

- Analysis strategy:
  - Understand and correct data/simulation discrepancies
  - Kinematic and PID Multivariate Analysis (MVA) to extract signal candidates in data
- $\mathcal{B}(B^0_{(s)} \to h^+h'^-) = \frac{N(B^0_{(s)} \to h^+h'^-)}{2\mathcal{L}_{\text{int}}\sigma_{b\bar{b}} f_{d(s)} \varepsilon_{h^+h'^-}}$
- $N(B^0_{(s)} \to h^+h'^-)$ is the signal yield, measured from invariant mass fits
- $\mathcal{L}_{\text{int}}$ is the integrated Luminosity, calculated from LHCb's Run Database
- $\sigma_{b\bar{b}}$ and $f_{d(s)}$ are the $b\bar{b}$ production cross section and hadronization fraction [1], [2]
- $\varepsilon_{h^+h'^-}$ is the total selection efficiency, estimated on simulation
- $\varepsilon_{h^+h'^-} = \varepsilon_{\text{geo}} \times \varepsilon_{\text{rec,trig|geo}} \times \varepsilon_{\text{loose|rec,trig}} \times \varepsilon_{\text{MVA+PID|loose}}$

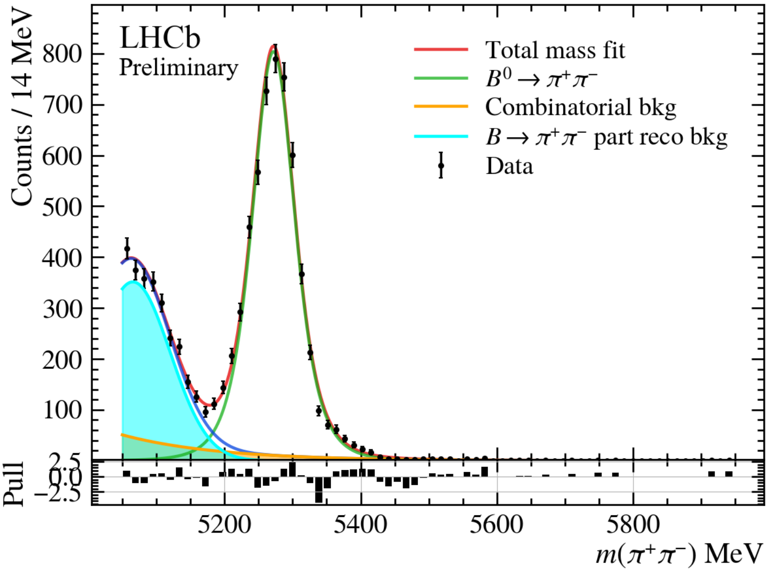
[1]R. Aaij et al. (LHCb), JHEP **10**, [Erratum: JHEP 05, 063 (2017)], 172 (2015)
[2]Y. Amhis et al. (HFLAV), Eur. Phys. J. C **77**, 895 (2017)


LHCb
Preliminary
Total mass fit
$B_s^0 \to K^+K^-$
Combinatorial bkg
$B \to K^+K^-$ part reco bkg
$\Lambda_b^0 \to K^+K^-$ part reco bkg
Data
Counts / 14 MeV
1350
1200
1050
900
750
600
450
300
150
Pull
0.0
−2.5
5200
5400
5600
5800
6000
$m(K^+K^-)$ MeV

Invariant Mass Fits



Invariant Mass Fits

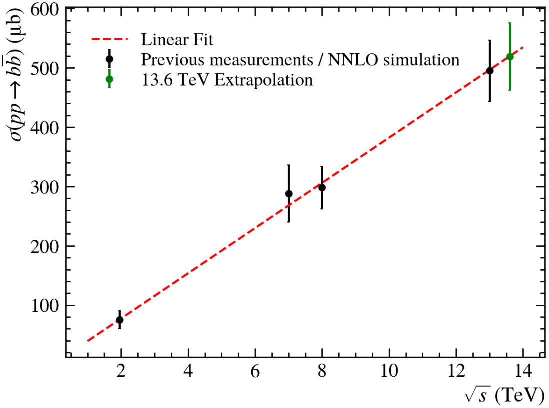


Efficiencies

- $\varepsilon = \frac{N_{\text{passed}}}{N_{\text{total}}}$ or $\varepsilon = \frac{\sum_{\text{passed}} \omega}{\sum_{\text{total}} \omega}$, where ω are the weights of individual events
- $\sigma(\varepsilon) = \sqrt{\frac{\varepsilon \cdot (1-\varepsilon)}{N_{\text{total}}}}$ or $\sigma(\varepsilon) = \sqrt{\frac{\varepsilon \cdot (1-\varepsilon)}{\sum_{\text{total}} \omega}}$
- $\varepsilon_{h^+h'^-} = \varepsilon_{\text{geo}} \times \varepsilon_{\text{rec,trig}|\text{geo}} \times \varepsilon_{\text{loose}|\text{rec,trig}} \times \varepsilon_{\text{MVA+PID}|\text{loose}}$

Decay	**Efficiency (%)**				
	ε_{geo}	$\varepsilon_{\text{rec,trig}\|\text{geo}}$	$\varepsilon_{\text{loose}\|\text{rec,trig}}$	$\varepsilon_{\text{MVA+PID}\|\text{loose}}$	$\varepsilon_{\text{total}}$
$B^0 \to K^+\pi^-$	19.77 ± 0.06	0.921 ± 0.009	67.05 ± 0.58	89.52 ± 0.47	0.109 ± 0.002
$B^0 \to \pi^+\pi^-$	19.50 ± 0.06	0.957 ± 0.009	68.78 ± 0.54	93.48 ± 0.35	0.119 ± 0.002
$B_s^0 \to K^-\pi^+$	19.98 ± 0.06	0.921 ± 0.009	67.56 ± 0.58	87.63 ± 0.49	0.107 ± 0.002
$B_s^0 \to K^+K^-$	19.77 ± 0.06	0.897 ± 0.009	70.35 ± 0.61	94.37 ± 0.36	0.119 ± 0.002

- $\sigma(pp \to b\bar{b}) = (519 \pm 57)$ µb
  - Extrapolated at Center of Mass energy $\sqrt{s} = 13.6$ TeV from next-to-next-to leading order (NNLO) quantum chromodynamics (QCD) simulation [1] and previous measurements [2]
- Hadronization fractions $f_{\mathrm{d}} = 0.404 \pm 0.006$ and $f_{\mathrm{s}} = 0.102 \pm 0.005$ [3]
- $\mathcal{L}_{\mathrm{int}} = 2.1\,\mathrm{fb}^{-1}$, calculated from LHCb's Run Database



[1]S. Catani et al., JHEP **03**, 029 (2021)
[2]R. Aaij et al. (LHCb), JHEP **10**, [Erratum: JHEP 05, 063 (2017)], 172 (2015)
[3]Y. Amhis et al. (HFLAV), Eur. Phys. J. C **77**, 895 (2017)

Branching ratio measurements

→ The results were produced in a 2.5 month summer project, many things need to be understood and hard approximations were made, but first results look promising

Branching ratio	Signal yield	Measured Value	PDG value [1]
$\mathcal{B}(B^0 \to K^+\pi^-)$	$15\,515 \pm 264$	$(1.610 \pm 0.182) \cdot 10^{-5}$	$(2.00 \pm 0.04) \cdot 10^{-5}$
$\mathcal{B}(B^0 \to \pi^+\pi^-)$	5661 ± 84	$(5.351 \pm 0.604) \cdot 10^{-6}$	$(5.37 \pm 0.20) \cdot 10^{-6}$
$\mathcal{B}(B_s^0 \to K^-\pi^+)$	1241 ± 51	$(5.194 \pm 0.665) \cdot 10^{-6}$	$(5.90 \pm 0.70) \cdot 10^{-6}$
$\mathcal{B}(B_s^0 \to K^+K^-)$	7100 ± 161	$(2.680 \pm 0.331) \cdot 10^{-5}$	$(2.72 \pm 0.23) \cdot 10^{-5}$

Relative Branching ratio	Measured Value	PDG value
$\frac{\mathcal{B}(B_s^0 \to K^+K^-)}{\mathcal{B}(B^0 \to \pi^+\pi^-)}$	(5.009 ± 0.306)	(5.065 ± 0.485)
$\frac{\mathcal{B}(B^0 \to K^+\pi^-)}{\mathcal{B}(B_s^0 \to K^-\pi^+)}$	(3.099 ± 0.219)	(3.389 ± 0.408)

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

Conclusion and Outlook

- Many studies on the quality of 2024 data were performed from a rare decay perspective
  - Trigger
  - Yields/Luminosity
  - Mass Mean/Resolution
  - Preliminary absolute branching fraction measurements
- LHCb's 2024 data looks very promising showing at least data quality of Run 2 or even beyond
- The $B^0_{(s)} \to \mu^+\mu^-$ group grows steadily in Dortmund and within the LHCb collaboration
- More and even better quality data will follow in 2025 and beyond
- Continuous feedback from rare decays group will enhance data and simulation quality even further
- Keep tuned for more!

Used Data Samples

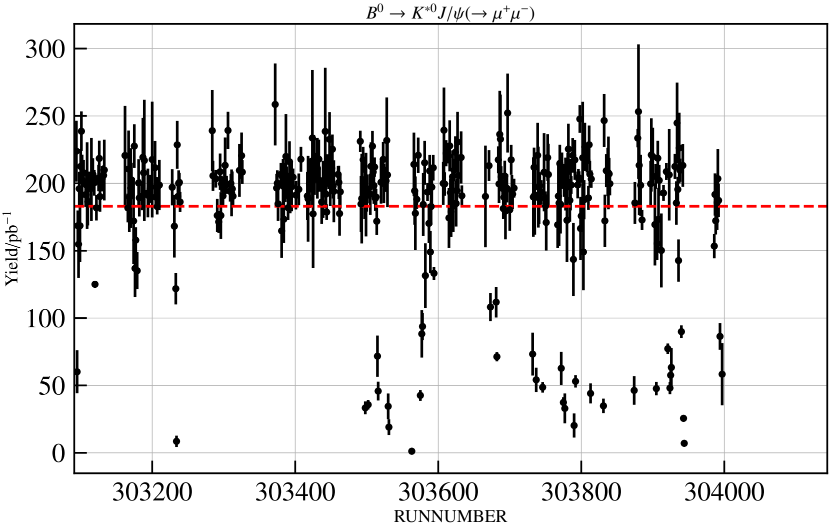
- Reproducible data and simulation samples in LHCb's Rare Decays group with Analysis Production tool
- Trigger studies:
  - Fills: 9982-10056 ($1.2\,\mathrm{fb}^{-1}$)
  - Trigger lines: `HLT1TrackMVA`, `HLT1TwoTrackMVA`
  - Dimuon lines: `Hlt2RD_BuToKpJpsi_JpsiToMuMu`, `Hlt2RD_B0ToKpPimMuMu`
  - Run 2 data: from Ref. [1]
- Yield/Lumi studies:
  - Run numbers: 303091-304144, 303091-303994
  - lines: `Hlt2RD_BuToHpMuMu_Incl`, `Hlt2RD_B0ToKpPimMuMu`

[1]R. Aaij et al. (LHCb), JINST **14**, P04013 (2019)

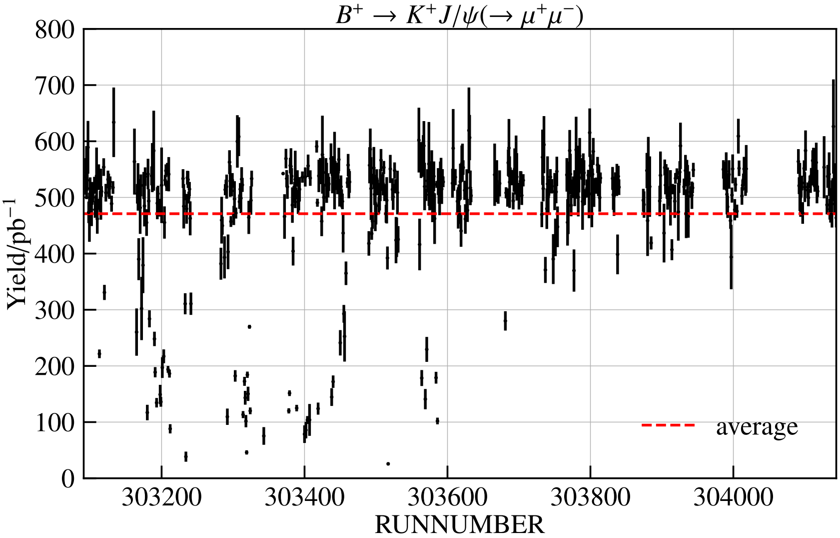
Used Data Samples

- Reproducible data and simulation samples in LHCb's Rare Decays group with Analysis Production tool
- $B^0_{(s)} \to h^+ h'^-$ mass mean vs PID:
  - Fill range: 9708-10012
- Dimuon mass resolution studies:
  - Fill range: 9708-10012
  - Simulation: `2024-expected`
- $B^0_{(s)} \to h^+ h'^-$ branching fraction measurements:
  - Fill range: 9911-10012
  - Simulation: $B^0_{(s)} \to h^+ h'^-$ `2024-expected`, $B^0 \to K^{*0}(\to K^+\pi^-)J/\psi(\to \mu^+\mu^-)$ `expected-2024.Q1.2`

Details on Yield/Lumi Study

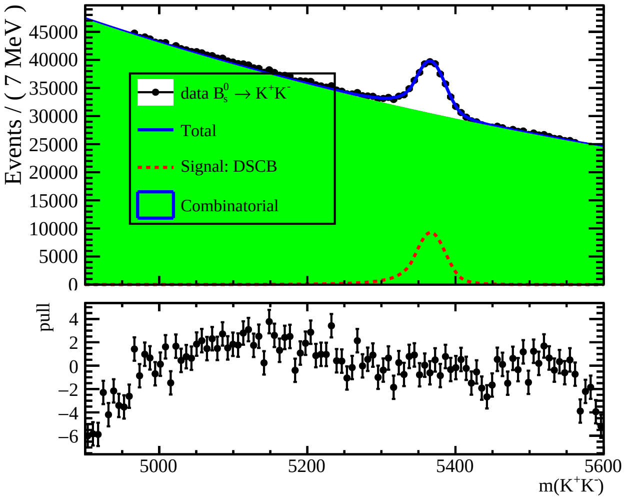


Details on Yield/Lumi Study



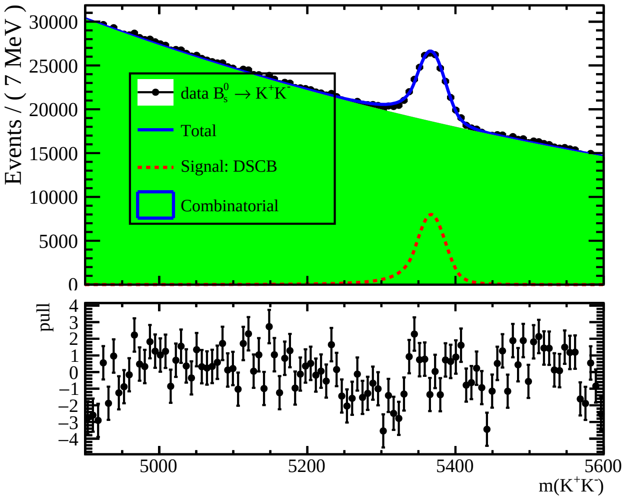
Mean vs PID

→ Invariant Mass Fit of $B_s^0 \to K^+K^-$ at `PID_K` greater 5



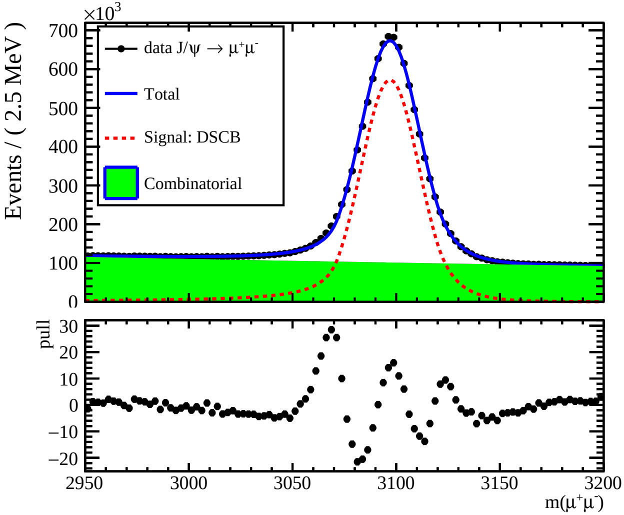
Mean vs PID

→ Invariant Mass Fit of $B_s^0 \to K^+K^-$ at `PID_K` greater 10



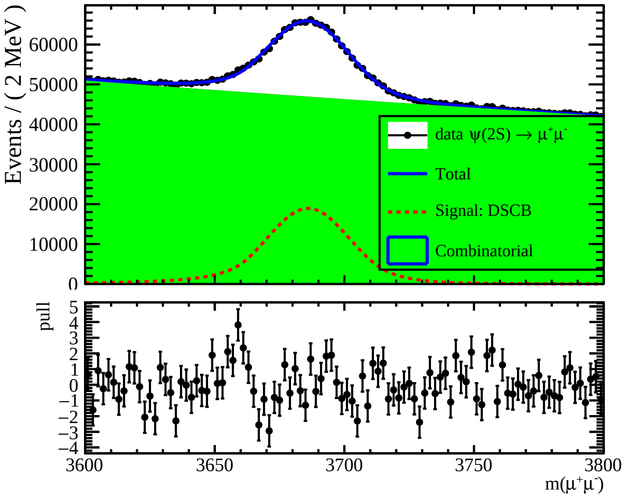
Mass Fits for Dimuon Mass Resolution

→ Invariant mass fit of $J/\psi \to \mu^+\mu^-$



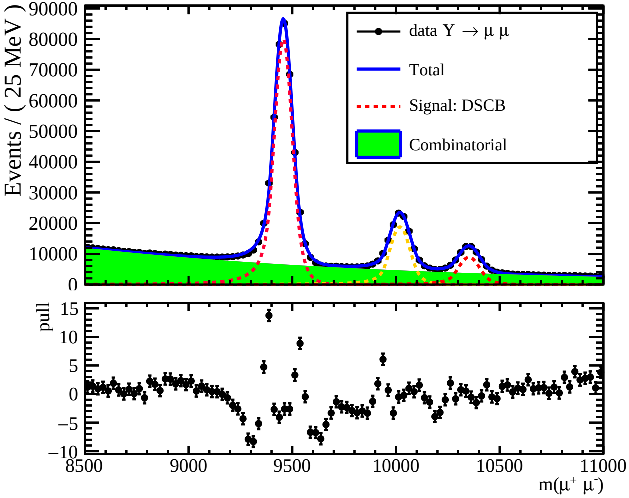
Mass Fits for Dimuon Mass Resolution

→ Invariant mass fit of $\psi(2S) \to \mu^+\mu^-$



Mass Fits for Dimuon Mass Resolution

→ Invariant mass fit of $\Upsilon(1S) \to \mu^+\mu^-$, $\Upsilon(2S) \to \mu^+\mu^-$, $\Upsilon(3S) \to \mu^+\mu^-$



Details on Branching Fraction Measurement

→ See more information in B2MuMu Meeting, September 10 2024

→ See more information in GP Meeting, September 16 2024