Measurement of Beauty Baryon Decays at the LHCb Experiment

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LHCb Upgrade I

LHC Run 2
2015 - 2018

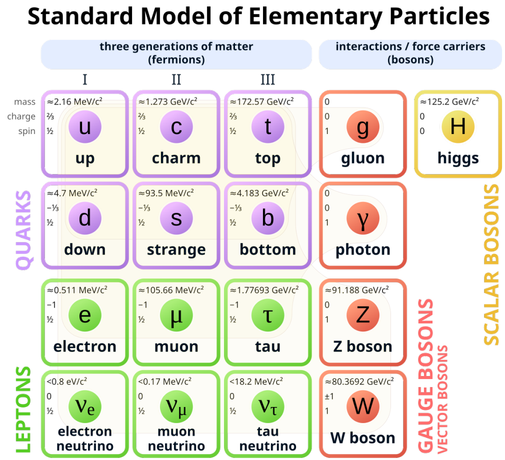
LHC Run 3
2022 - 2026

How does the first study of the decay $\Lambda_b^0 \to \Lambda^0 \mu^+ \mu^-$ with 2024 Run 3 LHCb data compare to the corresponding Run 2 study?

The Standard Model of Particle Physics (SM)

- Describes all known elementary particles and three fundamental interactions
- Predictions are confirmed by many experiments
- Some phenomena are not described by the SM (e.g. dark matter [1])

→ Search for New Physics (NP) beyond the SM

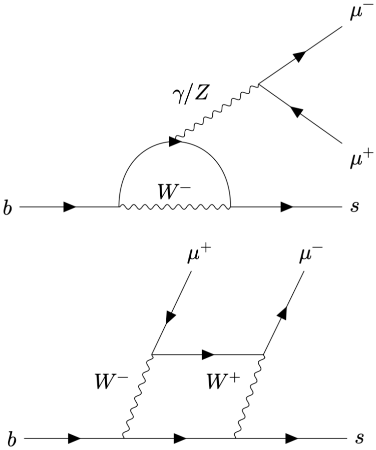


Source: Wikimedia Commons, MissMJ (CC BY 3.0), Link, accessed 19 Sep 2025

[1] V. C. Rubin and W. K. Ford Jr., *Rotation of the Andromeda Nebula from a Spectroscopic Survey of Emission Regions*, Astrophys. J. **159** (1970) 379, doi

The Decay $\Lambda_b^0 \to \Lambda^0 \mu^+ \mu^-$

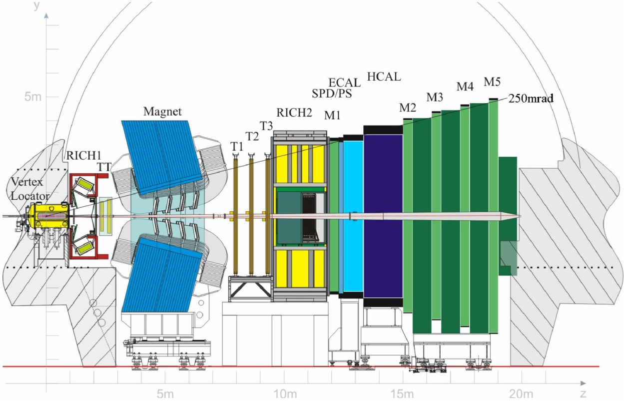
- Quark-level transition: $b \to s\,\mu^+\mu^-$
- Flavor Changing Neutral Current (FCNC)
- SM: Forbidden at tree level → loop processes
- → Rare, sensitive to NP contributions
- → Indirect search for NP
- → Complementary insights to the mesonic sector in the investigation of B-anomalies [1]



[1] J.-T. Wei et al., *Measurement of the Differential Branching Fraction and Forward-Backward Asymmetry for $B \to K^{(*)}\ell^+\ell^-$*, Phys. Rev. Lett. **103** (2009) 171801, doi
R. Aaij et al., *Erratum to: Differential branching fraction and angular analysis of $\Lambda_b^0 \to \Lambda\mu^+\mu^-$ decays*, J. High Energ. Phys. 2018 (2018) 145, doi

The LHCb Experiment in Run 2

- One of the four main experiments at the LHC
- Single-arm forward spectrometer
- → Ideal for studying *b*-hadrons: predominantly produced in the forward and backward direction
- Two systems: Tracking & Particle Identification (PID)
- Trigger: Hardware L0 and software HLT1, HLT2

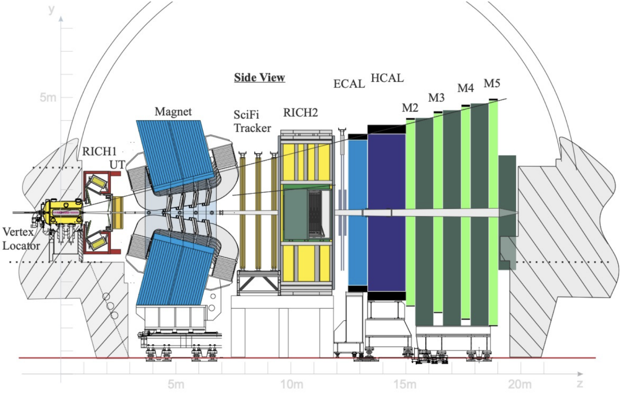


The LHCb detector during Run 2

Source: R. Calabrese et al., *Performance of the LHCb RICH detectors during LHC Run 2*, J. Instrum. 17.07 (2022) P07013, doi

The LHCb Experiment in Run 3

- **Upgrade I:**
  - New fully software-based trigger system
  - Detector fully upgraded
- → 5x instantaneous luminosity
- Challenges:
  - Understanding the new detector and trigger system
  - Commissioning of subdetectors during data taking
  - Simulation needs to be adapted



The LHCb detector during Run 3
Source: LHCb Collaboration, *The LHCb Upgrade I*, J. Instrum. 19.05 (2024) P05065, doi

dortmund university

Analysis Strategy

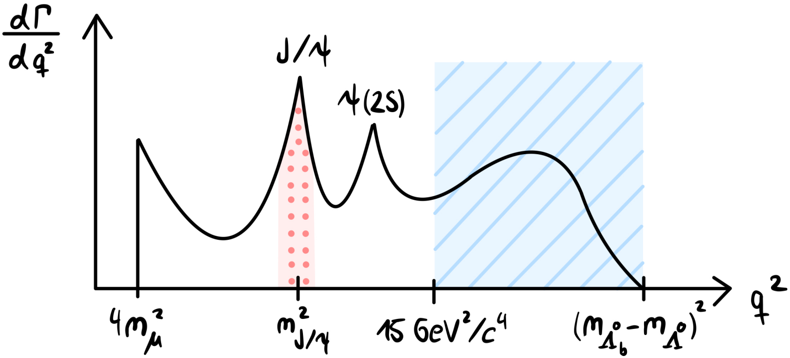
- Measure the signal yield N in both runs

$$N = L\,\epsilon \cdot 2\sigma_{b\bar{b}}\, f_{\Lambda_b^0}\, B(\Lambda_b^0 \to \Lambda^0 \mu^+ \mu^-)\, B(\Lambda^0 \to p\pi^-)$$

- What differs between both runs?
  - Integrated luminosity L
  - Total efficiency ϵ due to the Detector and trigger upgrades
  - → Signal yield comparison: Insights into ϵ

Analysis Strategy

- Decays studied:
  $\Lambda_b^0 \to \Lambda^0 \mu^+ \mu^-$ and
  $\Lambda_b^0 \to \Lambda^0 J/\psi(\to \mu^+ \mu^-)$
- $q^2 = m^2(\mu^+ \mu^-)$
- J/ψ resonance:
  $|m(J/\psi) - m_{\text{PDG}}[1]| < 100\ \frac{\text{MeV}}{c^2}$
- Rare mode: $q^2 > 15\ \frac{\text{GeV}^2}{c^4}$



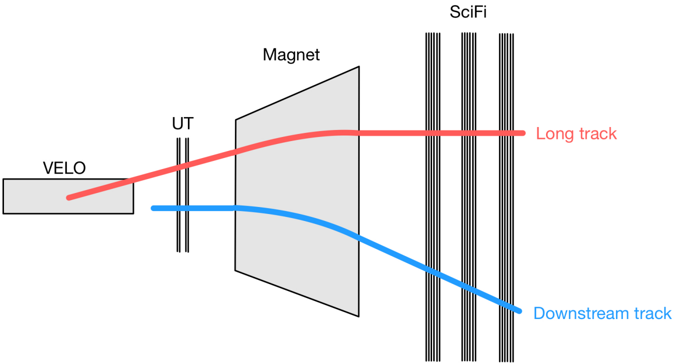
Schematic q^2 spectrum of the $b \to s \mu^+ \mu^-$ transition

[1] S. Navas et al., *Review of Particle Physics*, Phys. Rev. D **110** (2024) 030001, doi.

Analysis Strategy

- Classification: **Long–Long (LL)** or **Downstream–Downstream (DD)**
- $\Lambda^0 \rightarrow p\,\pi^-$
- Relatively long lifetime → Two track types

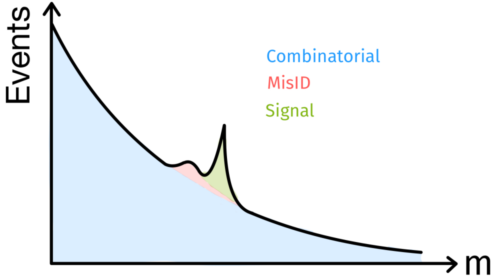
→ Separate treatment in the analysis



Run 2 Study

Run 2 Study

- Analysis is based on an existing angular analysis [1]
- Dataset: $L = 6\,\mathrm{fb}^{-1}$ of pp collisions at $\sqrt{s} = 13\,\mathrm{TeV}$
- Combinatorial background
- MisID background (J/ψ channel)
  - The misID channel is $B^0 \to K^0_S(\to \pi^+\pi^-)J/\psi$.
  - π^+ misidentified as p
  - Mimics $\Lambda^0 \to p\pi^-$



[1] J. Nicolini, *Study of rare beauty baryon decays with the LHCb detector*, PhD thesis, TU Dortmund / Laboratoire de Physique des 2 Infinis Irène Joliot-Curie, France (May 2024), doi

Online Selection

- Online selection: LHCb trigger system reduces the amount of data being recorded
- L0 hardware trigger selects high-p_{T} muons
- HLT1 and HLT2 select high-quality tracks and decay topologies characteristic of the rare decay
- Centrally in the LHCb data flow: Stripping
    - `Bu2LLK_mmLine` → dimuon + hadron selection

Offline Selection

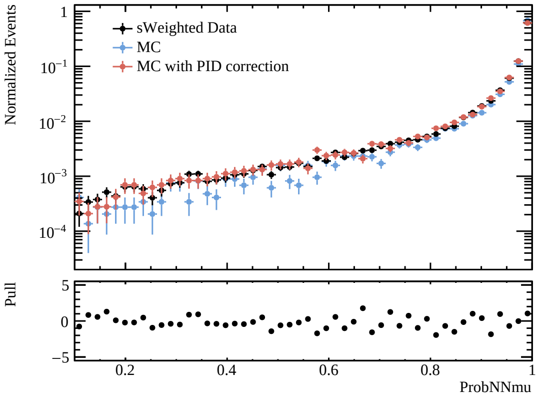
- Fiducial cuts
- Robust muon identification
- Λ^0 properties

Particle	Cuts
μ^+, μ^-	`hasMuon`, `hasRich`, `inAccMuon` $p_T > 800\,\mathrm{MeV}/c$, $p > 3000\,\mathrm{MeV}/c$ `ProbNNMu` > 0.1
Λ^0	$\lvert m - m_{\mathrm{PDG}} \rvert < 8\,\mathrm{MeV}/c^2$, $0 < \tau < 2\,\mathrm{ps}$ $\Theta_{\mathrm{DIRA}} > 0$, $\chi^2_{\mathrm{FD}} > 0$ $0 < z_{\mathrm{EV}} < 2320\,\mathrm{mm}$
Λ_b^0	$\chi^2_{\mathrm{DTF}}/\mathrm{ndof} > 0$

Simulation

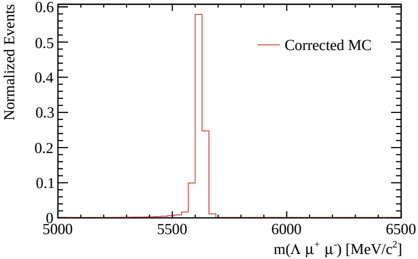
- Needed for multivariate analysis & mass fits
- Exact reproduction of data is not feasible
  - Resources
  - Physics modeling
  - Detector response
- Correct known data–simulation differences:
  - Trigger efficiencies
  - Λ_b^0 lifetime and kinematics
  - PID (`ProbNNMu`)
- Signal proxy is needed

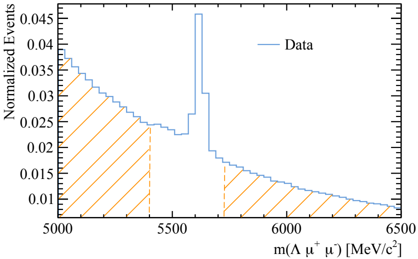
→ J/ψ channel & sWeights from Λ_b^0 mass fit



Multivariate Analysis

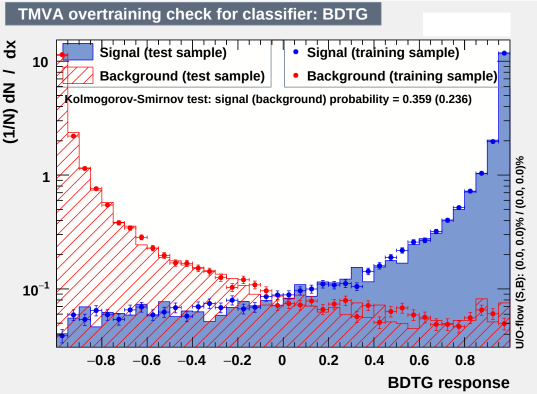
- Combinatorial background suppression with Boosted Decision Trees (BDT)
- Separate BDTs for LL and DD events
- Signal proxy: Rare mode simulation
- Background proxy: Data sidebands
  5000 MeV < $m(\Lambda_b^0)$ < 5400 MeV and
  5720 MeV < $m(\Lambda_b^0)$ < 6500 MeV





- BDT features: Decay topology & ability to discriminate signal from background
- Features with high correlation and low importance are removed iteratively
- BDT cut: Maximize the Punzi Figure of Merit

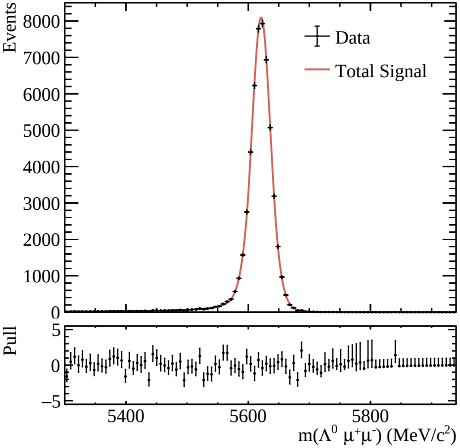
$$\mathrm{FOM}_{\mathrm{Punzi}} = \frac{\epsilon_{\mathrm{signal}}}{\frac{5}{2} + \sqrt{B}}$$



LL BDT

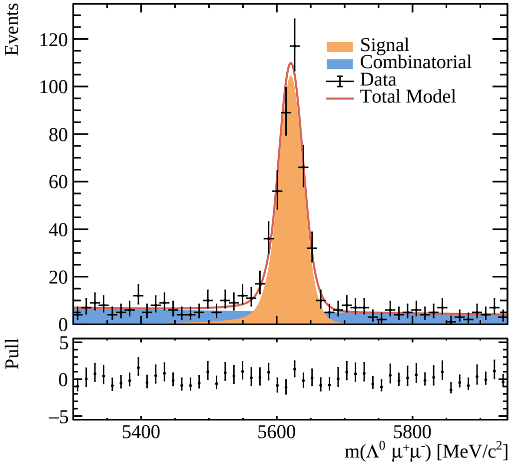
Mass Fits

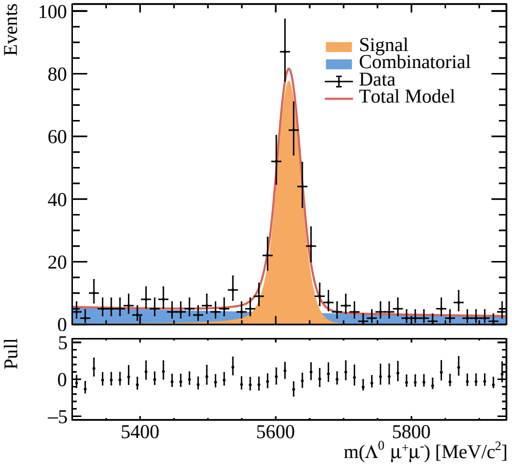
- 1D maximum likelihood fits
  - MisID: Double-sided Crystal Ball function (DSCB)
  - Signal: Linear sum of two DSCB functions with common mean
  - Combinatorial: Exponential function
- Signal & misID shape determined on simulation



LL Rare Mode Simulation

Rare Mode Fits

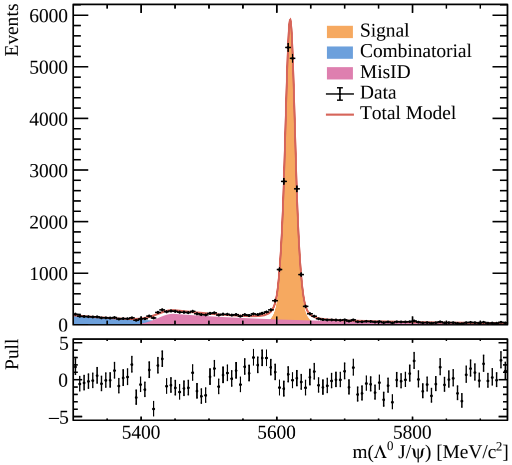


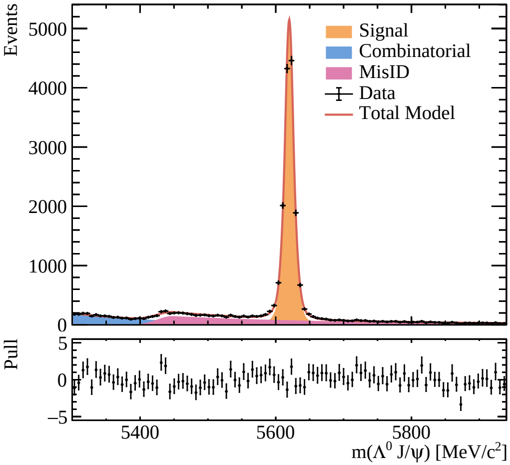


Downstream–Downstream: $N = 409 \pm 23$

Long–Long: $N = 297 \pm 19$

J/ψ Mode Fits





Downstream–Downstream: $N = 18\,475 \pm 143$

Long–Long: $N = 14\,341 \pm 126$

Run 3 Study

Run 3 Study

- 2022: Hardware commissioning
- 2023: VELO incident & data without UT
- This thesis: Last weeks of 2024 data taking (Blocks 5-8)
- $L = 3.33\,\mathrm{fb}^{-1}$ of pp collisions at $\sqrt{s} = 13.6\,\mathrm{TeV}$
- Analysis strategy adapted from Run 2 study
- No simulation correction

Online and Offline Selection

- Upgrade I: New fully software-based trigger system

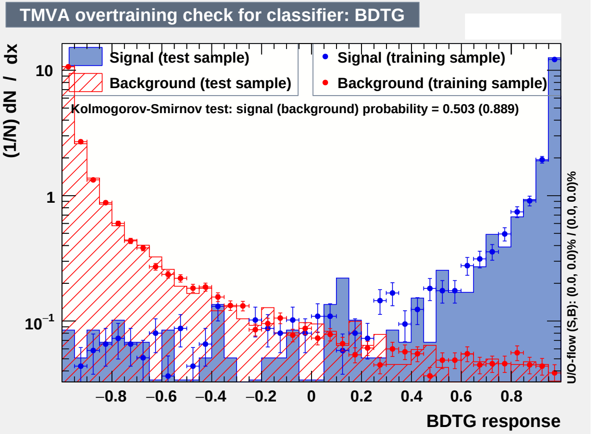
→ L0 triggers removed

- HLT1 adapted from Run 2
- Dedicated HLT2 lines for LL and DD events:
  - `Hlt2RD_LbToMuMu_LL`
  - `Hlt2RD_LbToMuMu_DD`
  - Replaced stripping
- Offline selection adapted from Run 2, except χ^2_{FD} cut (not available in the simulation)

→ The preselection can be optimized in the future

Multivariate Analysis

- New BDTs for Run 3
- Same strategy as in Run 2
- However: No simulation calibration
- → Room for improvement

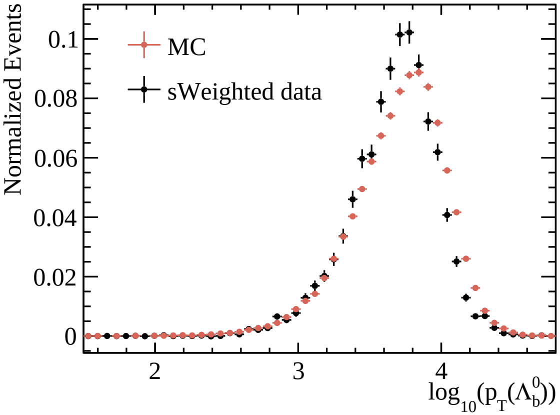


LL BDT

Proof of Need for Simulation Correction

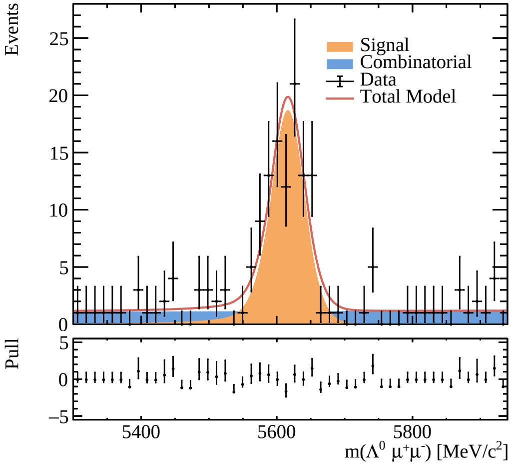
- $p_T(\Lambda_b^0)$ is known to be mismodeled in the Run 2 simulation

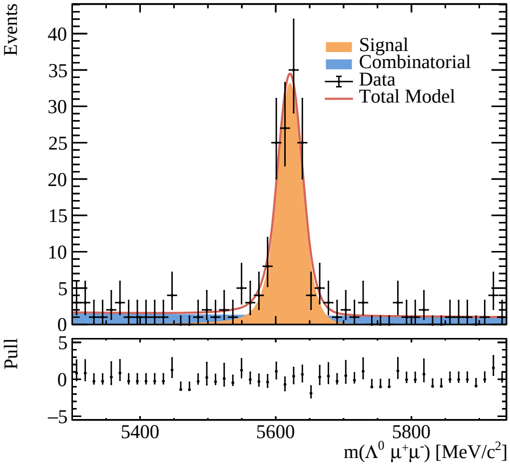
→ How does the Run 3 simulation compare?



Run 3 J/ψ mode DD data and sWeighted simulation

Rare Mode Fits

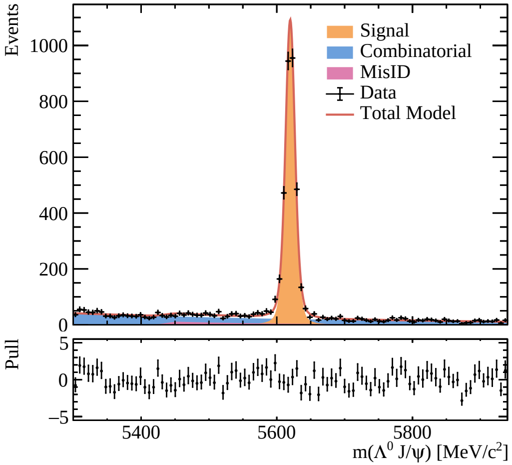




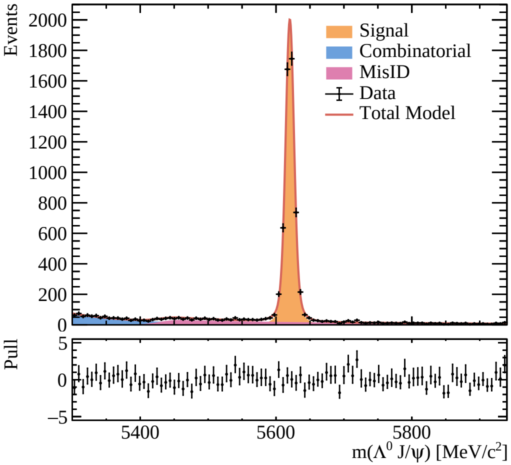
Downstream–Downstream: $N = 99 \pm 11$

Long–Long: $N = 132 \pm 13$

J/ψ Mode Fits



Downstream–Downstream: $N = 3212 \pm 60$



Long–Long: $N = 14\,341 \pm 126$

Signal Yield Comparison

- **Signal yield decrease in Run 3**
- Particularly pronounced in the DD category
- Selection not aligned
- Caveats: No simulation correction, non-optimized selection
- **UT: Commissioning**
- Crucial role in DD reconstruction
- → Reduced DD yields
- LL events have VELO hits → less affected

Yield	LL	DD
$N_{\text{Run 3}}$	132 ± 13	99 ± 11
$N_{\text{Run 2}} \cdot \frac{L_{\text{Run 3}}}{L_{\text{Run 2}}}$	165 ± 10	227 ± 13

Cross-Check with J/ψ Mode

- LL-to-DD Ratio is compared between both runs
- Same observation: Relative decrease in DD events

→ Supports the hypothesis of the UT affecting the DD yield

$\frac{N_{\mathrm{LL}}}{N_{\mathrm{DD}}}$	Run 2	Run 3
Rare Mode	0.73 ± 0.06	1.33 ± 0.20
J/ψ Mode	0.776 ± 0.009	1.65 ± 0.04

Summary & Outlook

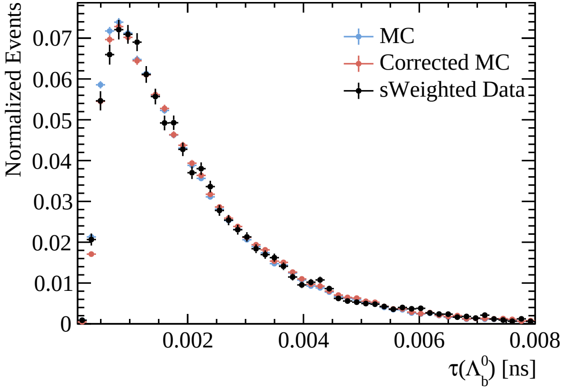
- Signal yield decrease in Run 3, especially DD
- Caveats: no simulation correction, non-optimized preselection, selection not aligned
- Hypothesis: UT in commissioning → reduced DD yields
- Ongoing Run 3 + stable UT → increased statistics:
    - reduces uncertainties & fluctuations
    - improves mass fit precision & signal yield accuracy
    - HLT1 downstream track reconstruction (since 2025) → signal selection improvement
    - Compare DD vs. LL event trends vs. 2024

Backup

Lifetime Correction

- Correction applied for difference between simulated and updated Λ_b^0 mean lifetime
- Simulation used $\tau_{\text{old}} = 1.451\,\text{ps}$
- Updated measurement: $\tau_{\text{new}} = 1.468\,\text{ps}$ [1]
- Event weight applied:

$$w_\tau = \frac{\exp(-t/\tau_{\text{new}})}{\exp(-t/\tau_{\text{old}})}$$

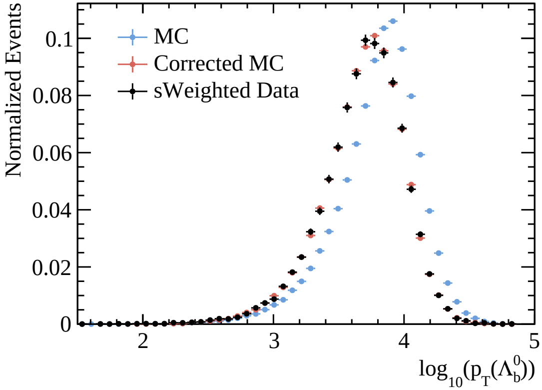


LL

[1] S. Navas et al., *Review of Particle Physics*, Phys. Rev. D **110** (2024) 030001, doi.

Kinematic Correction

- *b*-hadron kinematics are known to be mismodeled in LHCb simulations
- Correction: reweight simulation using a weight map binned in p_T and η
- Weight map computed from J/ψ mode simulation and sWeighted data



DD

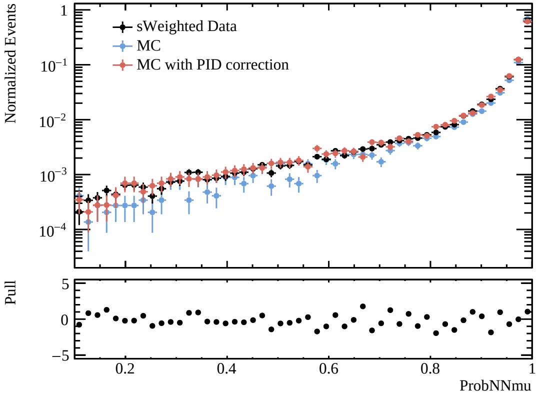
Trigger Efficiency Correction

- L0 trigger efficiency depends on muon kinematics:
  - Transverse momentum (p_T)
  - Pseudorapidity (η)
- Simulation is reweighted to match the L0 efficiency in sWeighted data
- Efficiency maps computed using the TISTOS method on a dedicated $B^+ \to J/\psi K^+$ calibration sample
- Correction applied separately for `Muon` and `DiMuon` trigger decisions
- Final L0 trigger weight:

$$w_{L0} = 1 - (1 - \mathtt{Muon} \cdot w_{\mathtt{Muon}})(1 - \mathtt{DiMuon} \cdot w_{\mathtt{DiMuon}})$$

ProbNNMu Calibration

- `ProbNNMu`: probability of a particle being a muon, used in offline selection
- Not calibrated in previous angular analysis
- PIDGen2 transformation method uses:
  - Transverse momentum (p_T)
  - Pseudorapidity (η)
  - Event multiplicity (`nTracks`)
- `nTracks` mismodeled → corrected by scaling each value by 1.1 to match sWeighted data
- Dedicated $J/\psi \to \mu^+\mu^-$ calibration sample used for each year and magnet polarity

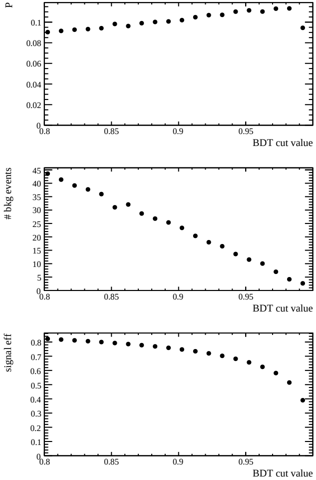


BDT Variables

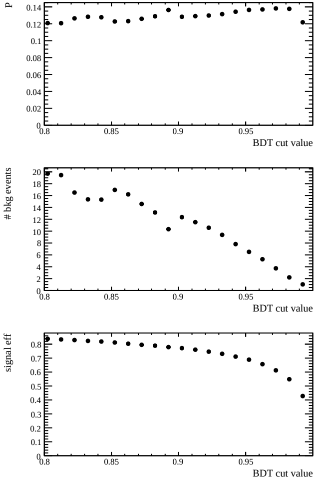
Rank	LL Run 3	DD Run 3
1	$\log_{10}(\Theta_{\text{DIRA}}(\Lambda_b^0))$	$\chi^2_{\text{DTF}}(\Lambda_b^0)/\text{ndof}$
2	$\chi^2_{\text{DTF}}(\Lambda_b^0)/\text{ndof}$	$\log_{10}(\Theta_{\text{DIRA}}(\Lambda_b^0))$
3	$\log_{10}(\chi^2_{\text{IP, min}}(\mu^+,\mu^-))$	$\log_{10}(p_{\text{T}}(\Lambda_b^0))$
4	$\text{FD}(\Lambda^0)$	$\log_{10}(\chi^2_{\text{IP, min}}(\mu^+,\mu^-))$
5	$\chi^2_{IP}(\Lambda^0)$	$\text{FD}(\Lambda^0)$
6	$\log_{10}(p_{\text{T}}(\Lambda_b^0))$	$\log_{10}(p_{\text{T}}(p))$
7	$\log_{10}(\chi^2_{\text{IP, max}}(\mu^+,\mu^-))$	$\tau(\Lambda^0)$
8	$\tau(\Lambda^0)$	$\log_{10}(p_{\text{T}}(\mu))$
9	$\log_{10}(\chi^2_{\text{IP, min}}(\pi,p))$	$\tau(\Lambda_b^0)$
10	$\texttt{ProbNNMu}_{\text{min}}$	$\log_{10}(\chi^2_{\text{IP, max}}(\mu^+,\mu^-))$
11	$\log_{10}(p_{\text{T}}(p))$	$\texttt{ProbNNMu}_{\text{min}}$
12	$\chi^2_{\text{IP}}(\pi)$	$\log_{10}(\chi^2_{\text{IP, min}}(\pi,p))$
13	$\log_{10}(p_{\text{T}}(\mu))$	$\chi^2_{\text{FD}}(\Lambda^0)$
14	$\chi^2_{\text{FD}}(\Lambda^0)$	$\chi^2_{\text{IP}}(\Lambda^0)$
15	$\tau(\Lambda_b^0)$	$\chi^2_{\text{IP}}(\pi)$

Rank	LL Run 2	DD Run 2
1	$\log_{10}(\Theta_{\text{DIRA}}(\Lambda_b^0))$	$\chi^2_{\tau}(\Lambda_b^0)$
2	$\chi^2_{\text{DTF}}(\Lambda_b^0)/\text{ndof}$	$\log_{10}(p_{\text{T}}(\Lambda_b^0))$
3	$\chi^2_{\tau}(\Lambda_b^0)$	$\log_{10}(\Theta_{\text{DIRA}}(\Lambda_b^0))$
4	$\chi^2_{z_{\text{endvertex}}}(\Lambda_b^0)$	$\log_{10}(p_{\text{T}}(p))$
5	$\chi^2_{IP}(\Lambda^0)$	$\chi^2_{\text{m}}(\Lambda_b^0)/\text{ndof}$
6	$\chi^2_{\text{FD}}(\Lambda^0)$	$\tau(\Lambda_b^0)$
7	$\log_{10}(p_{\text{T}}(\Lambda_b^0))$	$\log_{10}(\chi^2_{\text{IP, min}}(\mu^+,\mu^-))$
8	$\tau(\Lambda_b^0)$	$\log_{10}(p_{\text{T}}(\mu))$
9	$\log_{10}(\chi^2_{\text{IP, min}}(\mu^+,\mu^-))$	$\log_{10}(\chi^2_{\text{IP, max}}(\mu^+,\mu^-))$
10	$\log_{10}(\chi^2_{\text{IP, min}}(\pi,p))$	$\texttt{ProbNNMu}_{\text{min}}$
11	$\log_{10}(p_{\text{T}}(p))$	$\text{FD}(\Lambda^0)$
12	$\log_{10}(p_{\text{T}}(\mu))$	$\chi^2_{\text{IP}}(\pi)$
13	$\log_{10}(\chi^2_{\text{IP, max}}(\mu^+,\mu^-))$	$\chi^2_{\text{endvertex}}(\Lambda_b^0)$
14	$\texttt{ProbNNMu}_{\text{min}}$	$\tau(\Lambda^0)$
15	$\text{FD}(\Lambda^0)$	$\texttt{ProbNNMu}_{\text{max}}$
16	$\chi^2_{\tau}(\Lambda^0)$	
17	$\texttt{ProbNNMu}_{\text{max}}$	
18	$\chi^2_{\text{IP}}(\pi)$	

Punzi FOM



Run 2 LL



Run 3 DD

Truth Matching

- Simulation: Only correctly reconstructed events should be considered
- Two methods
    1. Match reconstructed particles to generator-level counterparts
    2. BKGCAT classifies events into signal or several background types.
- Select BKGCATs with a characteristic Λ_b^0 mass signal shape