Tracking and PID performance with the upgraded LHCb detector

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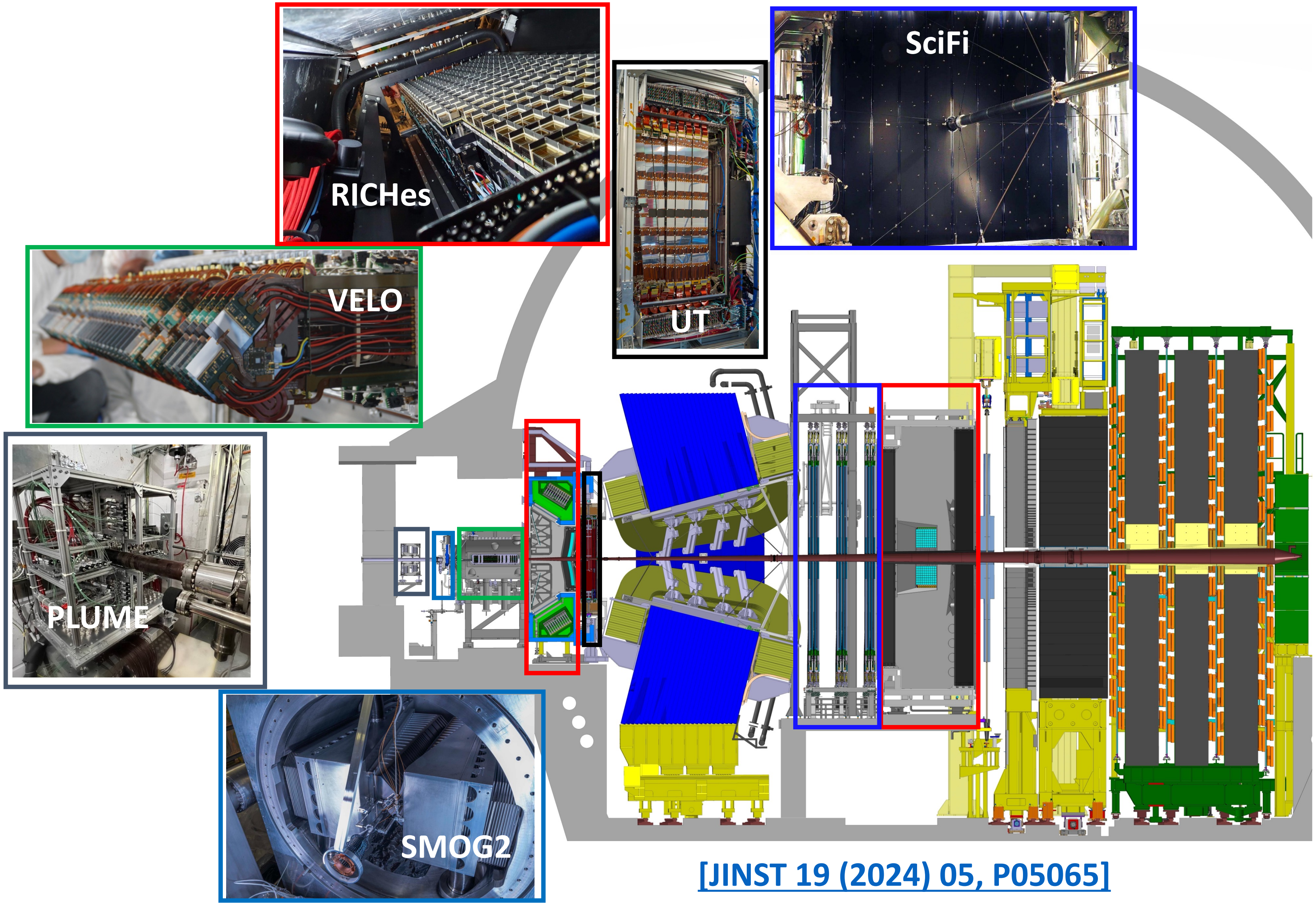
Outline

- Overview of operations in 2024
- Performance of LHCb subdetectors
  - Several numbers shown in these slides rely on alignment and calibration procedure described in Miguel's talk
- Tracking, PID and global LHCb performance in 2024
  - Most of the performance figures of merit shown in this talk refer to nominal Run 3 luminosity of $\mathcal{L} = 2 \cdot 10^{33}\ cm^{-2}\ s^{-1}$ in pp collisions

The upgraded LHCb detector

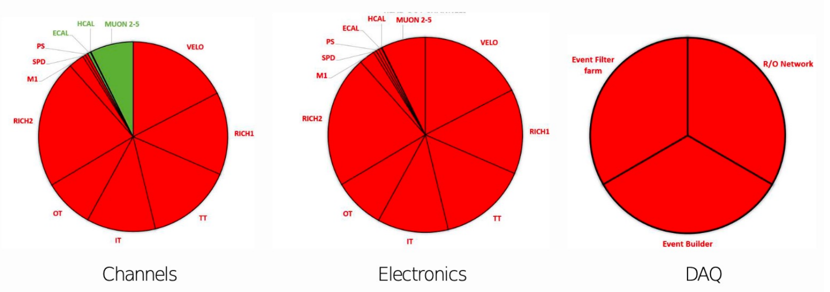


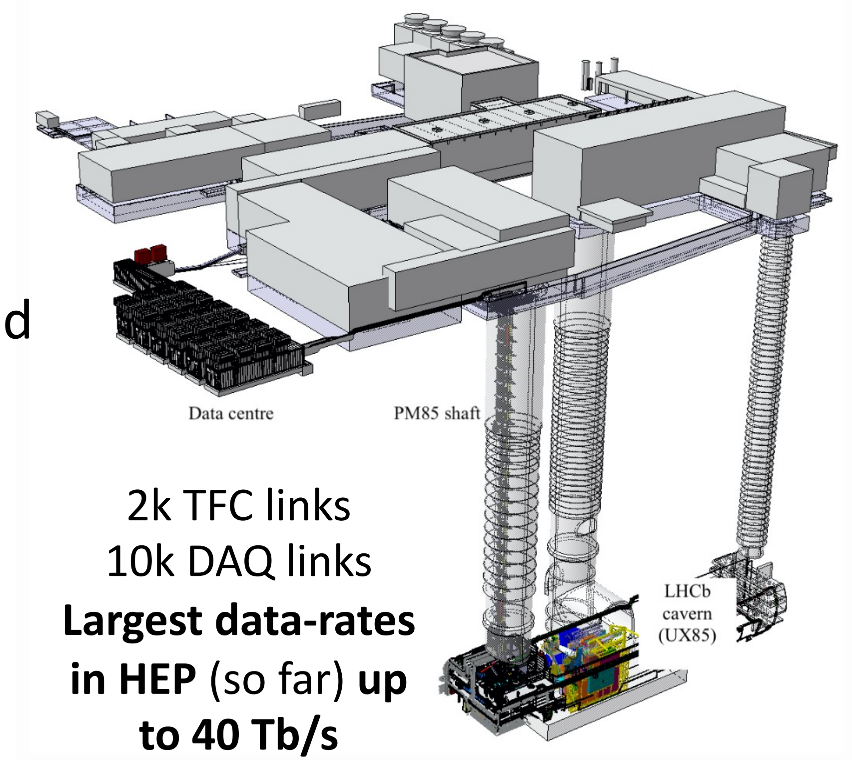
- Tracking system (VELO, UT, SciFi) newly constructed
- Hadron identification (RICHes): new photon-detection chain and RICH1 optics/mechanics
- New luminometer (PLUME) and gas injection system (SMOG2)
- Frontend and backend electronics upgraded for all systems (including CALO and MUON)

[JINST 19 (2024) 05, P05065]

The upgraded LHCb experiment

- Make effective the 5x increase in the instantaneous luminosity by removing the hardware level trigger
  - Avoid saturation in fully hadronic channels: expect 2x gain in trigger efficiency
- Key concept: **triggerless readout of all subdetectors at the 40 MHz LHC bunch crossing rate**
  - new subsystem specific ASICs as frontend electronics compliant with GBT architecture
  - new TFC (deterministic and fixed phase clock at $\sigma \sim 200\ ps$) and DAQ systems implemented on FPGAs installed on PCIe40 cards
  - new Event Builder (EB) farm with 163 servers
- Enables the implementation of a full-software trigger in heterogenous architecture: GPU (HLT1) + CPU (HLT2)
  - Initially 2 GPUs/EB server (+1 GPU/EB server during 2024)
  - See [Dorothea's talk]for more details on the trigger system





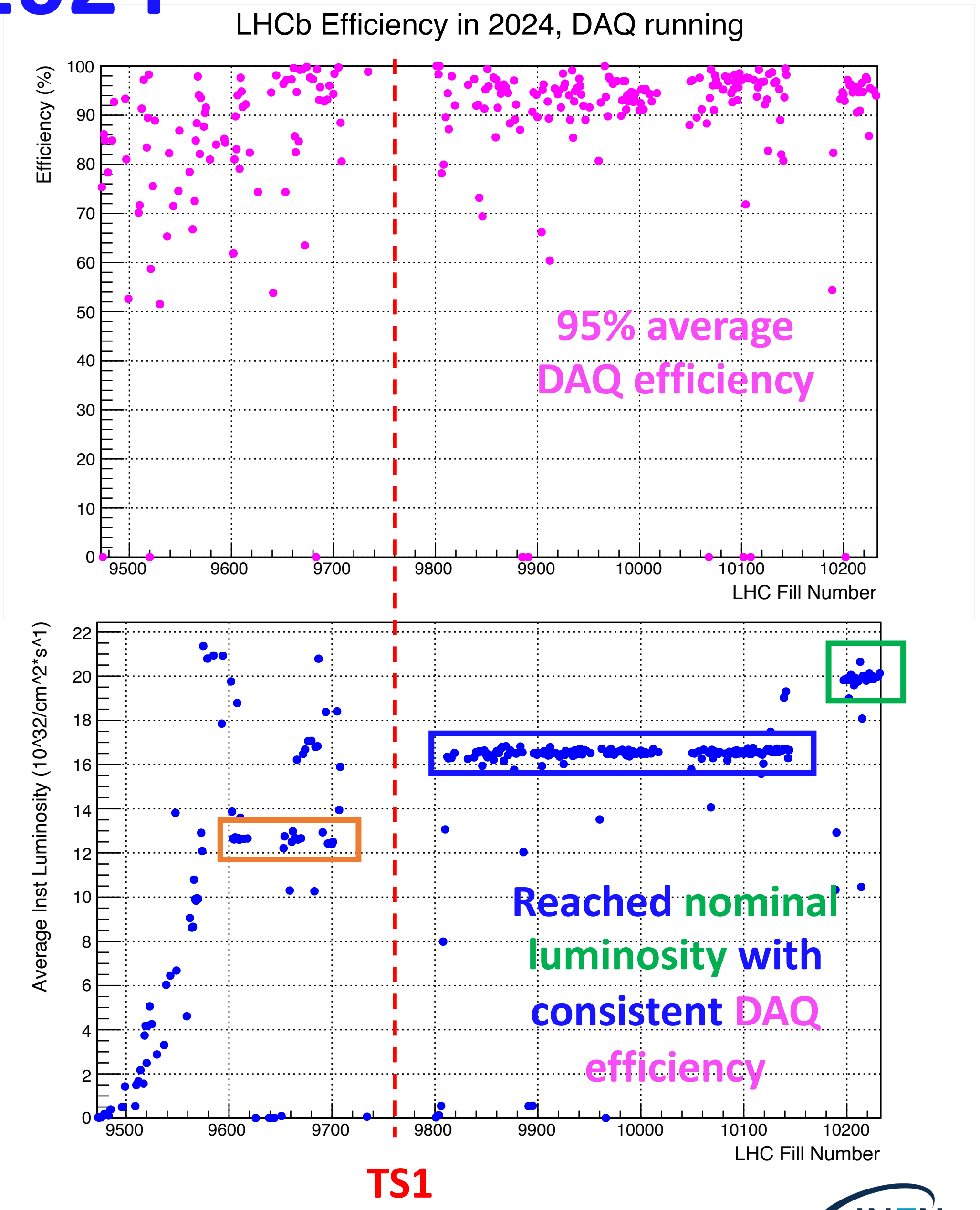
2k TFC links
10k DAQ links
Largest data-rates in HEP (so far) **up to 40 Tb/s**

[JINST 19 (2024) 05, P05065]

Overview of 2024 operations

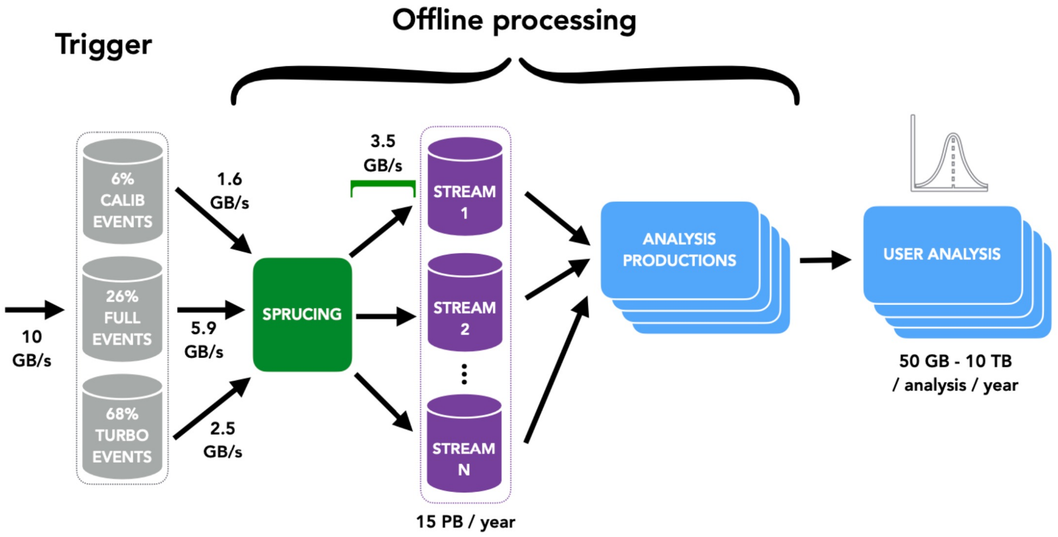
Data-taking in 2024

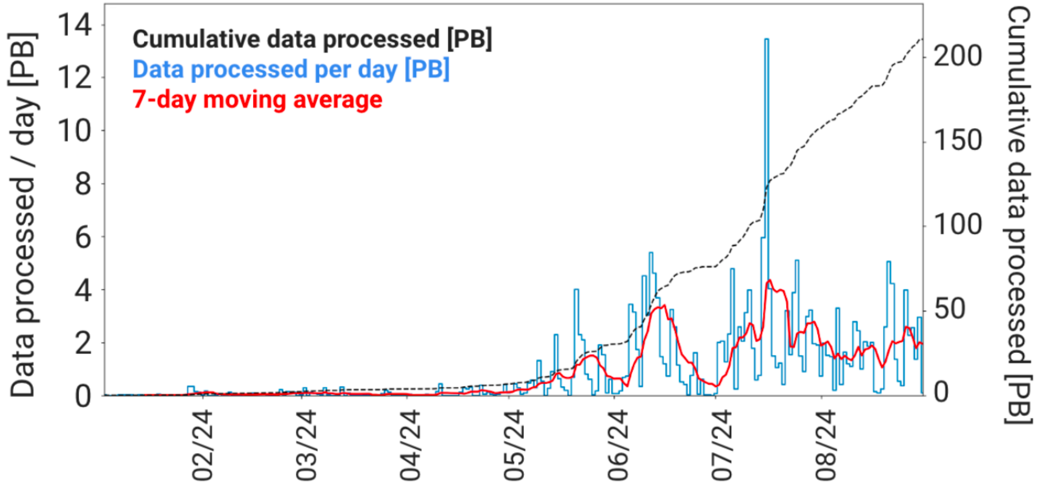
- Data-taking before first LHC Technical Stop (TS1) partially dedicated to
  - recover from 2023 LHC vacuum incident in the VELO volume, gradually include the UT in the global data taking and fix residual frontend instabilities
  - commission final HLT1, HLT2, alignment and calibration configurations
  - physics data-taking at $\mathcal{L} = 1.3 \cdot 10^{33}\ cm^{-2}\ s^{-1}$
- Most of post-TS1 luminosity collected at $\mathcal{L} = 1.7 \cdot 10^{33}\ cm^{-2}\ s^{-1}$
  - moved to nominal $\mathcal{L} = 2.0 \cdot 10^{33}\ cm^{-2}\ s^{-1}$ during the last weeks of pp-physics
- Incremental improvements during the year in track reconstruction and alignment quality



Dataflow and offline data processing

- Factor 30 increase in data rate (5x luminosity, 3x event size, 2x trigger efficiency)
- Sprucing performs data skimming, slimming and streaming to allow write to disk
- TURCAL stream contains selection lines for physics channels used for detector calibration and to assess performance
  - Factor 8 reduction by Sprucing
  - Line by line customisation of persisted reconstructed objects and detector raw banks
- Concurrent Sprucing and centralised Analysis Productions allowing analysts to begin analysing data with only 2-3 days of latency

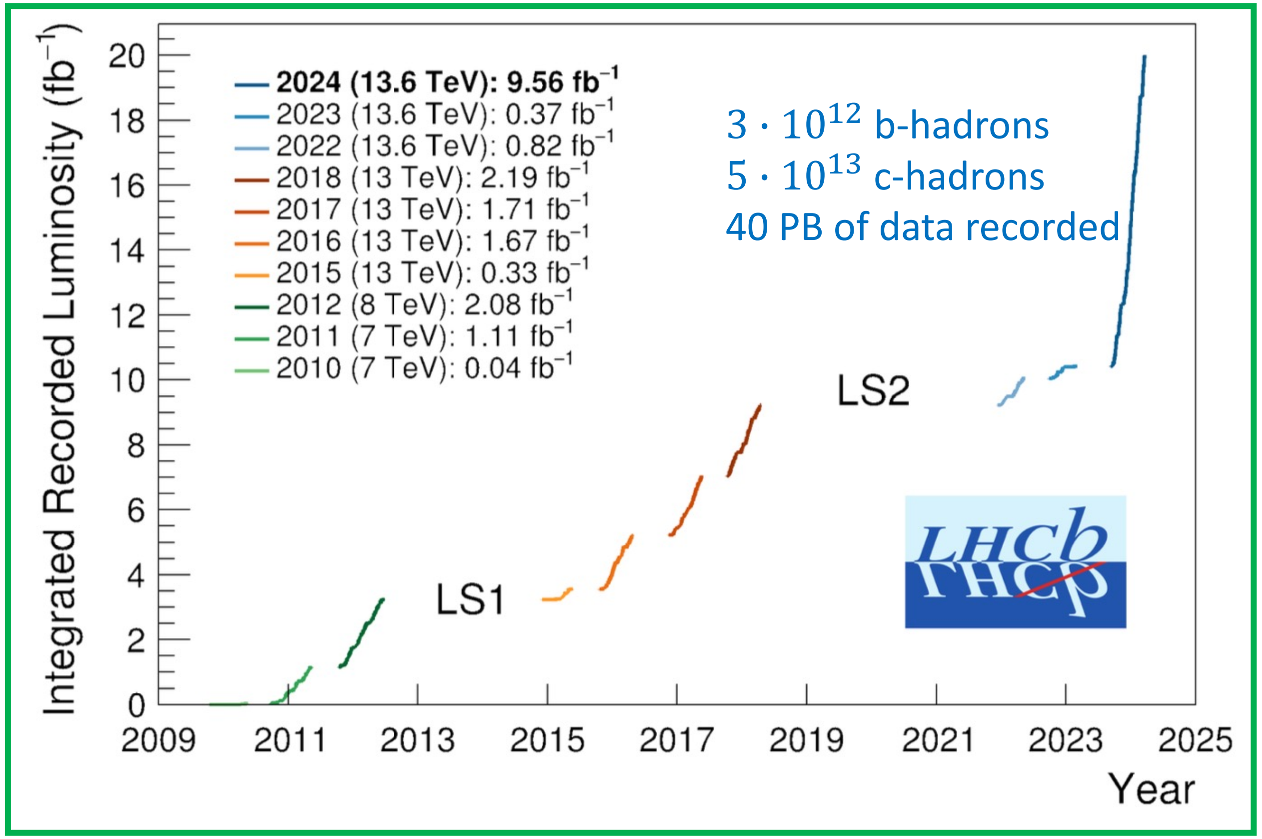


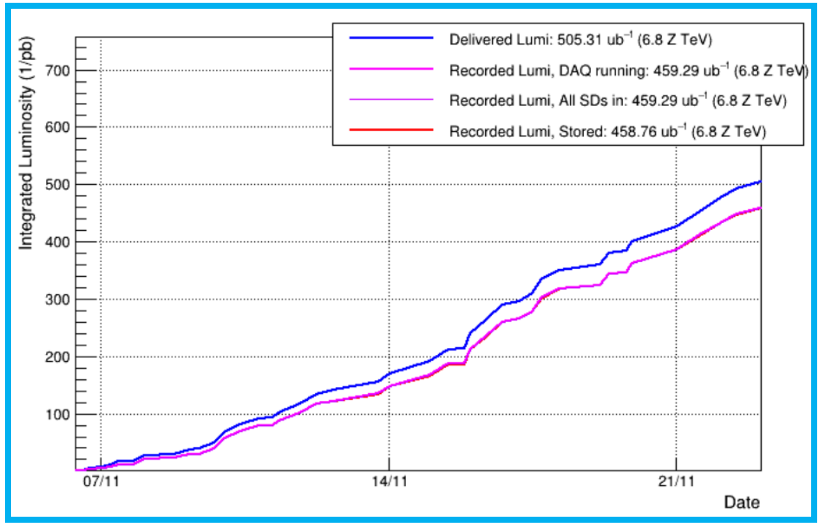


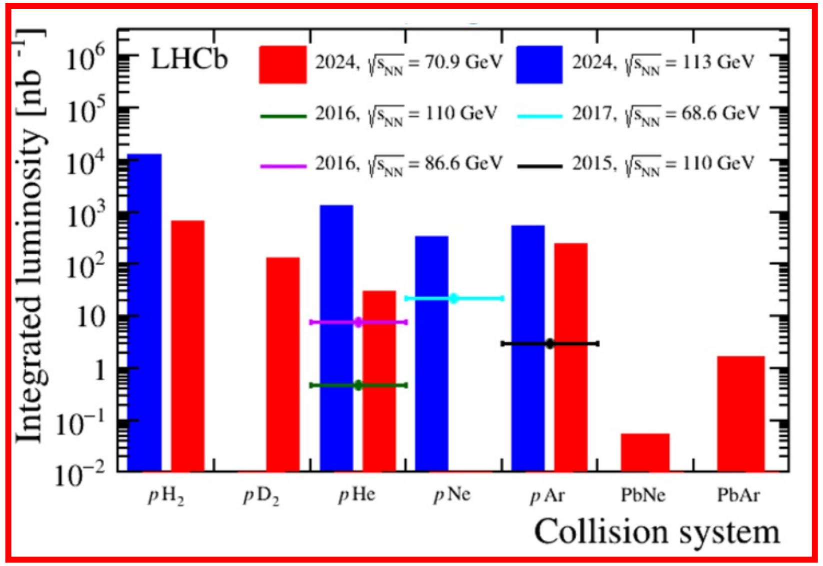
[arXiv:2506.20309]

Operations in 2024

- Collected more than Run 1+2 pp-physics in a single year
- Record PbPb and proton-gas integrated luminosities
- >92% of 2024 data flagged OK for data analysis
  - >99% towards the end of the year





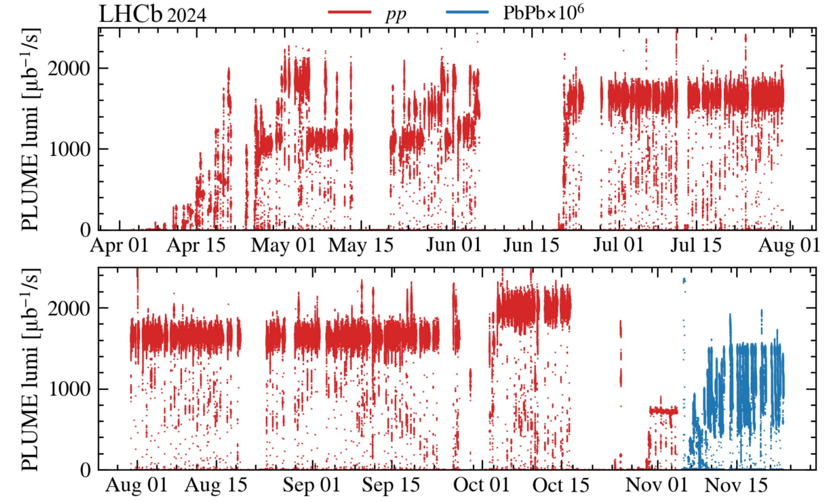


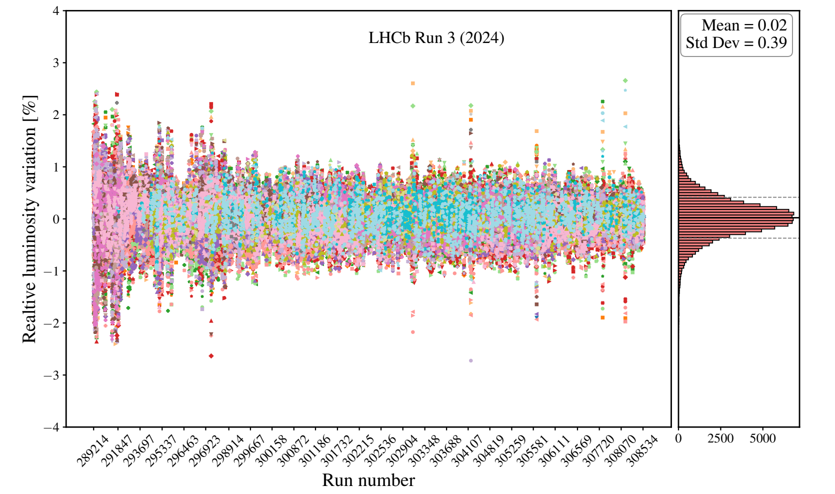
Performance of subdetectors

Luminometers

[LHCB-TDR-022]

- New dedicated luminometer (PLUME) to provide online feedback to the LHC on LHCb instantaneous luminosity => crucial for levelling procedure with a tolerance of $\pm 5\%$
- Beam-background measurements provided by custom BCM and RMS subsystems
- About 350 luminosity counters to assess the integrated offline luminosity of a dataset
  - Information attached to each stream by the Sprucing
  - Nice agreement between counters after preliminary van der Meer scan analysis
- More details in Fabio’s talk



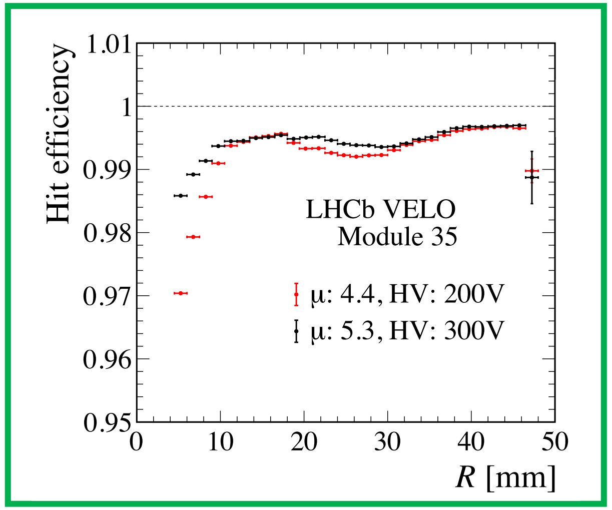


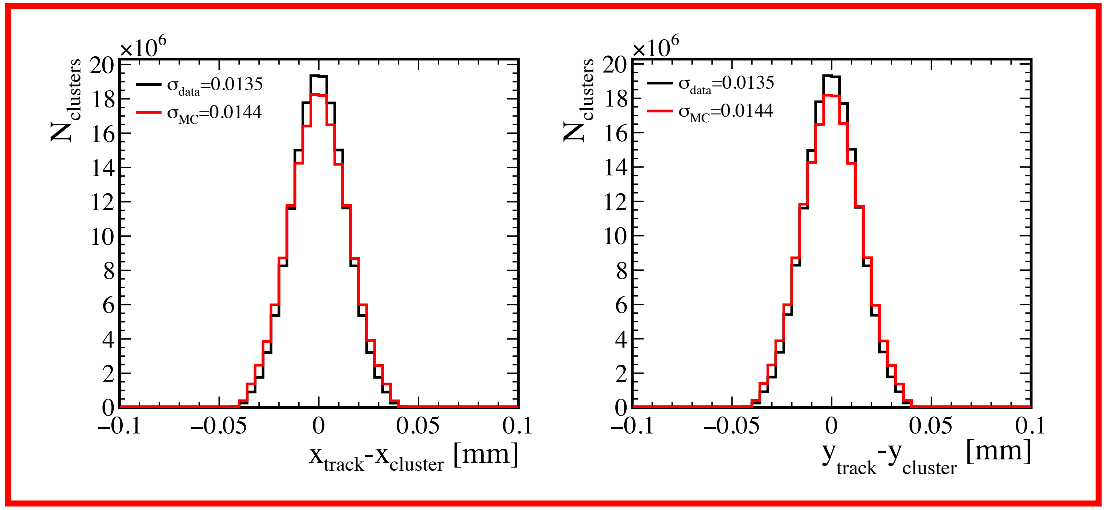
VELO

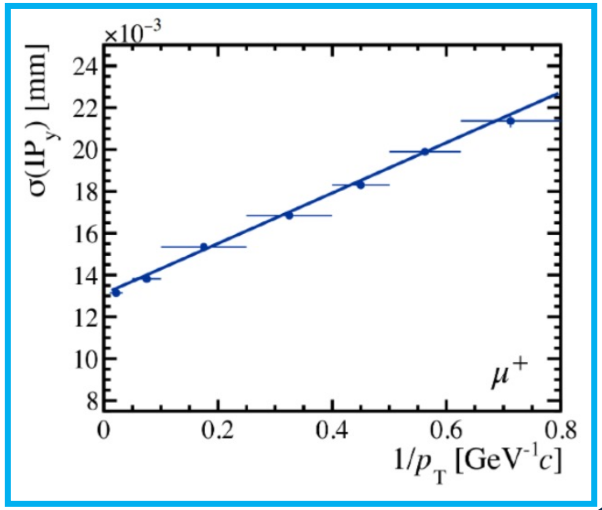
- 52 modules for a total of 41M 55 $\mu m \times 55\ \mu m$ silicon pixels whose signal is readout by the custom VeloPix ASIC
  - First sensitive pixel position at 5.1 mm from the beamline

[LHCB-TDR-013]

- Combined sensor and ASIC clustering efficiency above 99% in average
  - Consistent performance at $\mu = 4.4$ ($\mathcal{L} = 1.7 * 10^{33}\ cm^{-2}\ s^{-1}$) and $\mu = 5.3$ ($\mathcal{L} = 2.0 * 10^{33}\ cm^{-2}\ s^{-1}$)
- Average residual between a track intercept and the cluster position consistent with expected hit resolution of $\sim 13\ \mu m$
- Vertexing capabilities assessed through the impact parameter (IP) of Drell-Yan muons

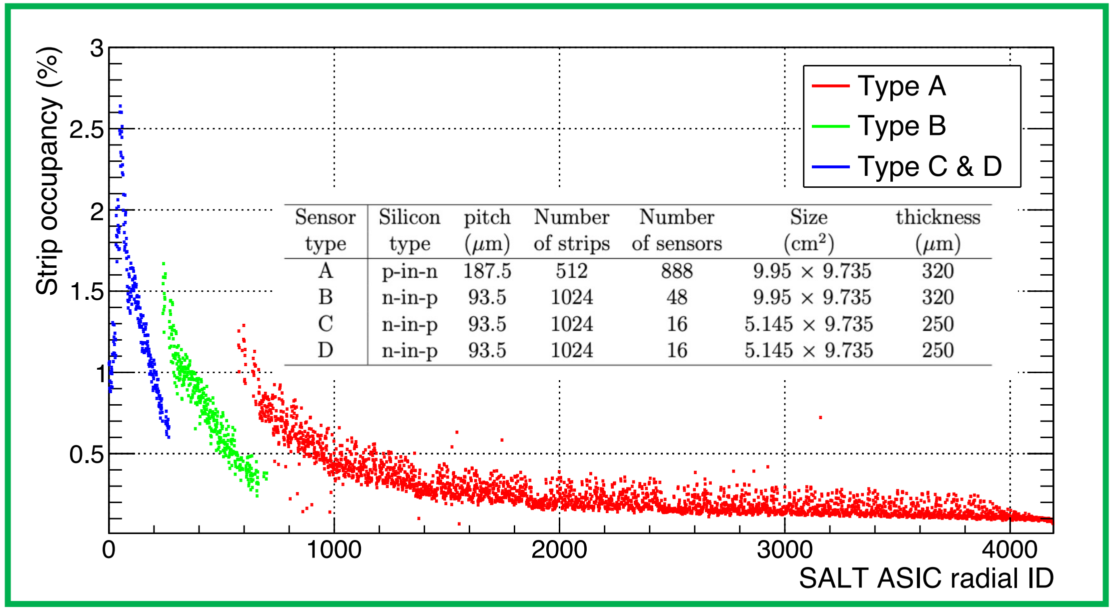




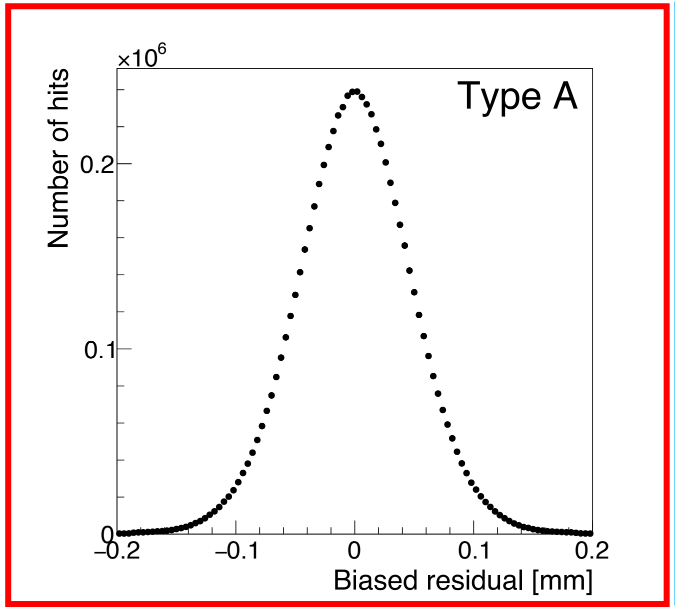


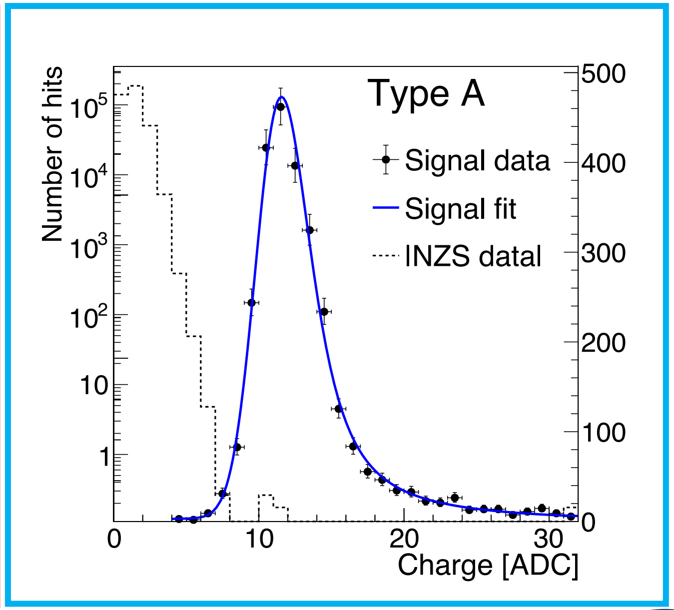
UT

- 4 planes of silicon-strip detectors each containing 4 types of sensors to match detector occupancy and readout by the custom SALT ASIC [LHCB-TDR-015]
- Biased residual distribution showing a hit resolution of $\sim 50\ \mu m$
- Signal well separated from noise
  - Zero-Suppression (ZS) threshold at ≥ 4 ADC counts
- UT helps in reducing “ghost” tracks: more details in Wojciech’s talk



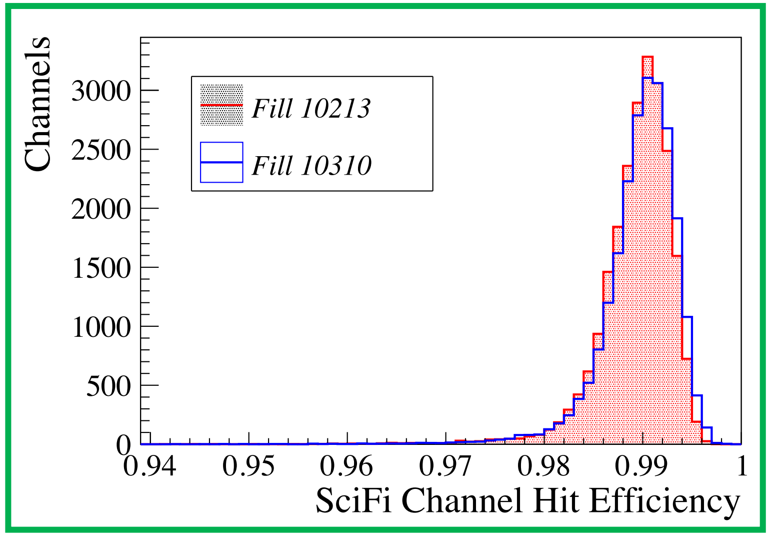
Sensor type	Silicon type	pitch (μm)	Number of strips	Number of sensors	Size (cm^2)	thickness (μm)
A	p-in-n	187.5	512	888	9.95 × 9.735	320
B	n-in-p	93.5	1024	48	9.95 × 9.735	320
C	n-in-p	93.5	1024	16	5.145 × 9.735	250
D	n-in-p	93.5	1024	16	5.145 × 9.735	250

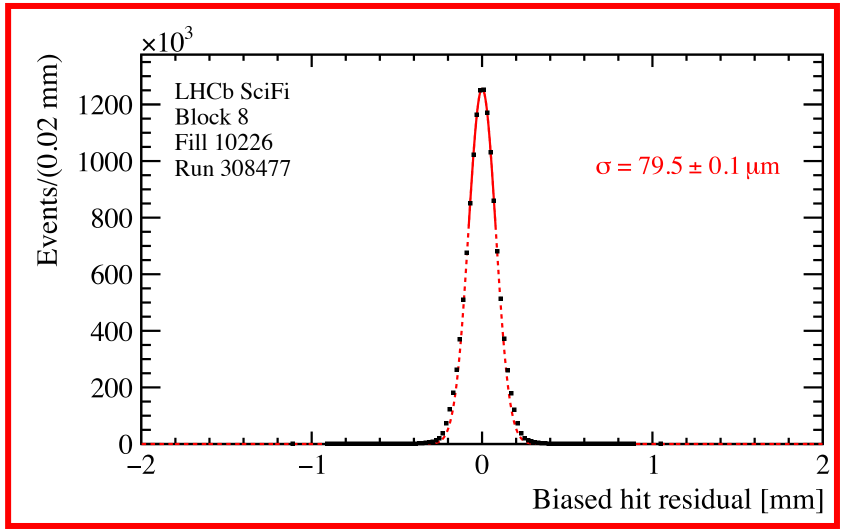


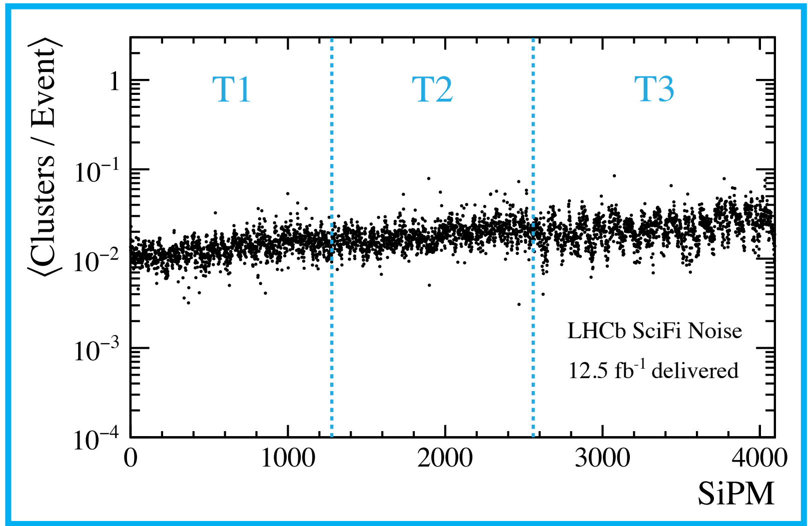


SciFi

- Three stations (T1, T2 and T3) each containing four layers of scintillating fibres mats: over 10^4 km of $250\ \mu m$ diameter scintillating fibres whose light is readout by SiPM + custom PACIFIC ASIC [LHCB-TDR-015]
- Hit efficiency for non-edge channels of the innermost modules is ~99%
- Biased residual distribution showing a hit resolution of $\sim 80\ \mu m$
- SiPM dark count rate kept under control by cooling at $-50\ °C$

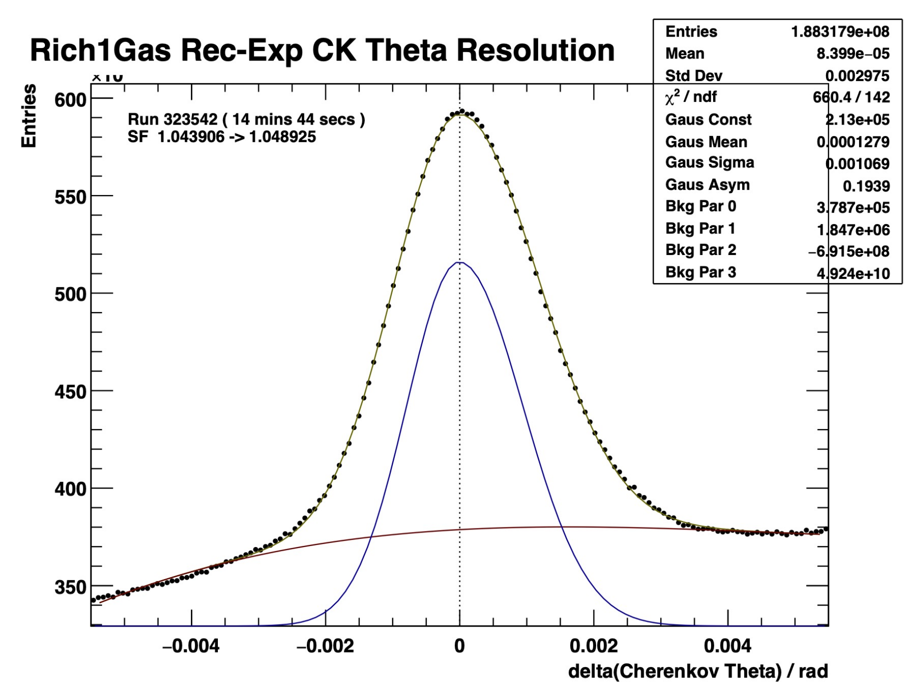


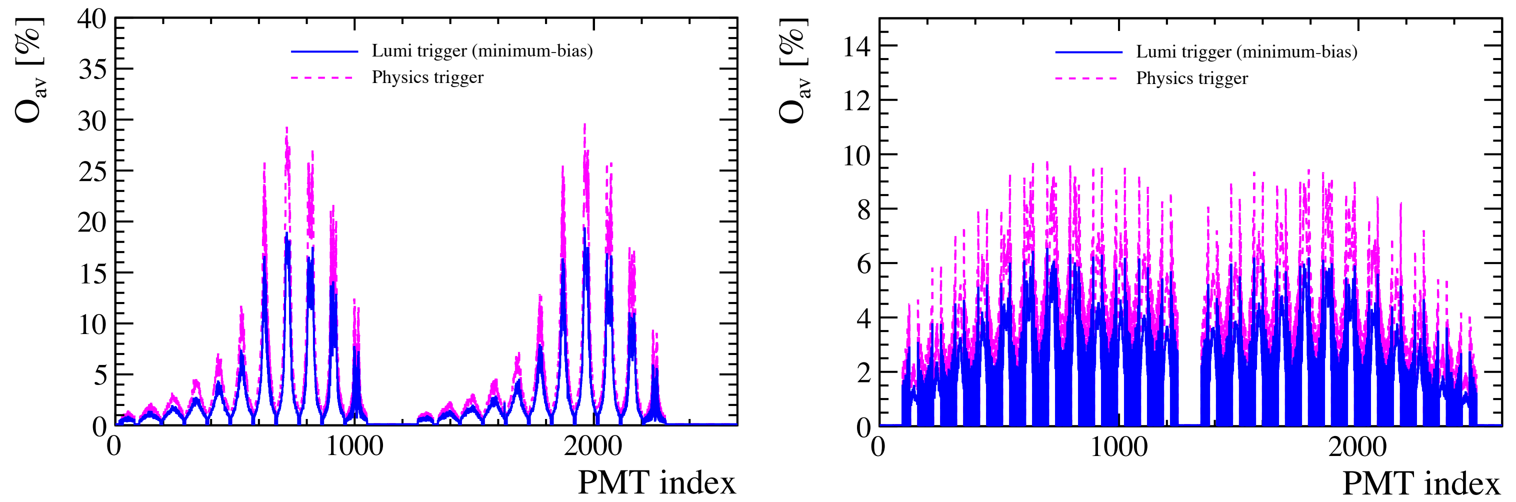




RICHes

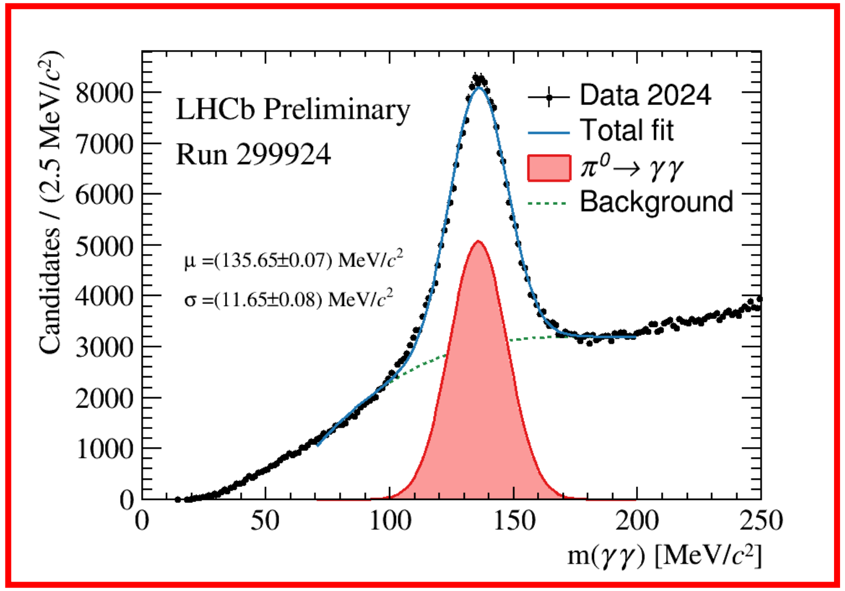
- Two Ring Imaging Cherenkov detectors equipped with 64 channels Multi-Anode Photo-Multiplier Tubes readout by the CLARO ASIC [LHCB-TDR-014]
- Unbiased detected peak occupancy of 20% at the 30 MHz colliding bunch rate
- Single photon resolution of $\sim 1.1\,mrad$ (RICH1) and $\sim 0.6\,mrad$ (RICH2)
- More details in Federica's talk

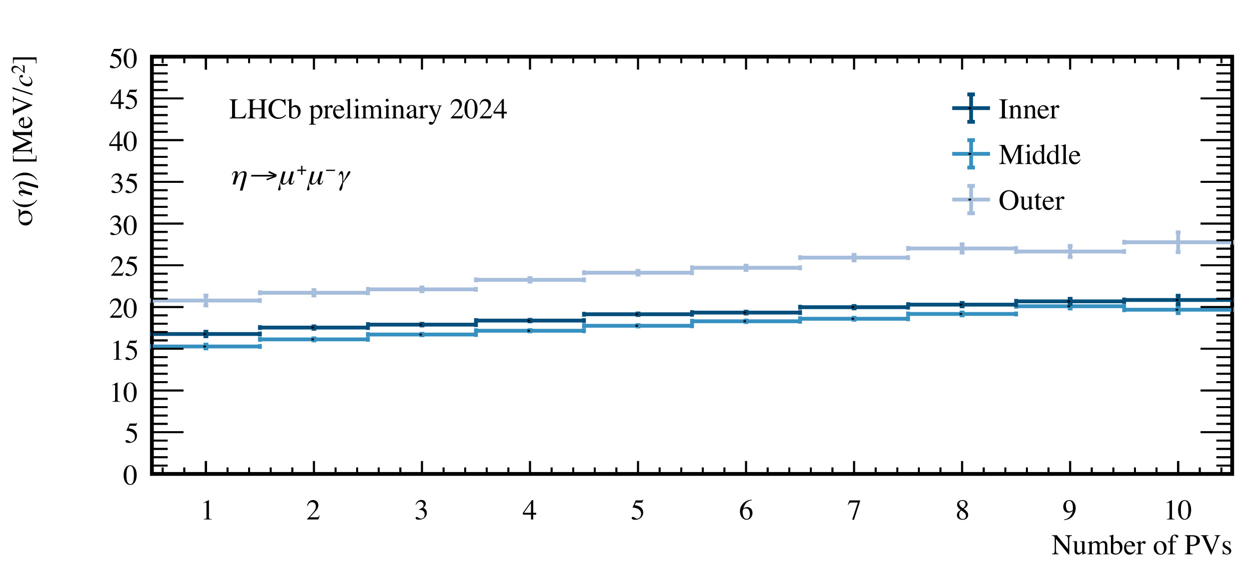




CALO

- Shashlik calorimeters with PMT readout kept from Run 1 and 2 [LHCB-TDR-014]
- Calibration performed using dedicated LED and low-multiplicity data-taking to scale the energy calibration on the known π^0 mass by adjusting high-voltage settings
- Performance (resolution) affected by pile-up interactions according to expectations

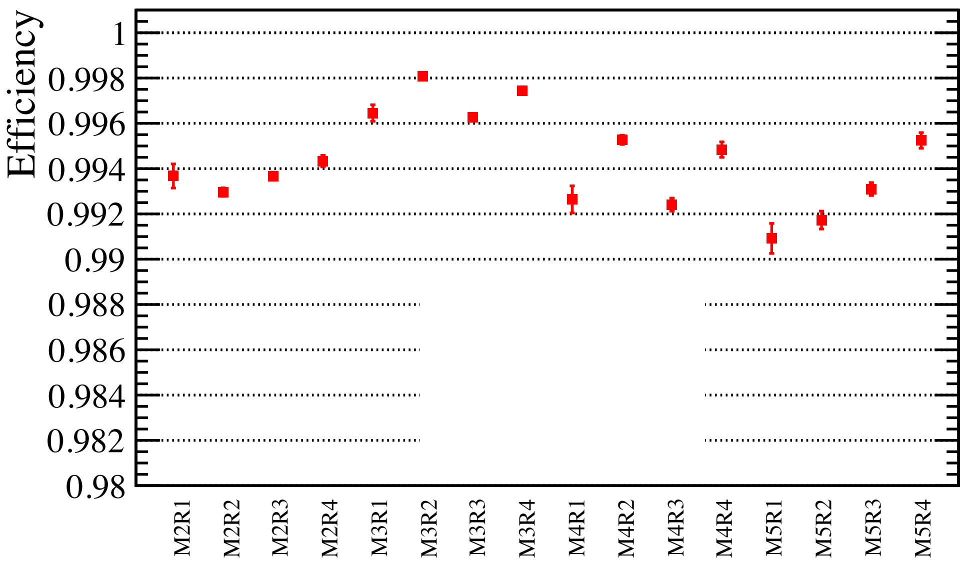


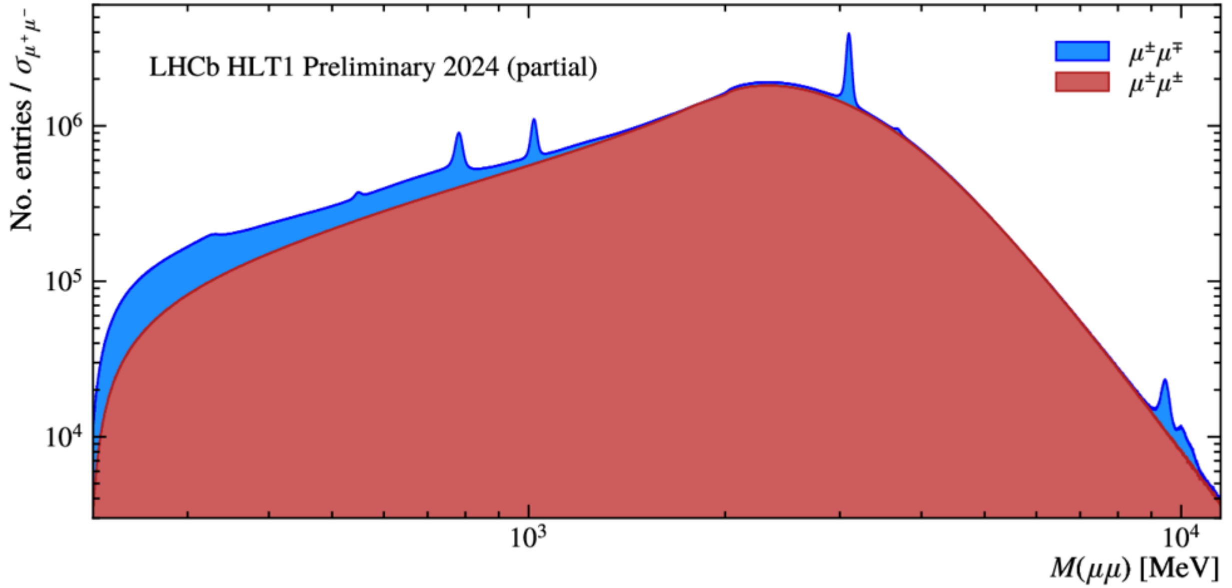


MUON

- Four stations (M2,M3,M4,M5) each segmented in four regions (R1,R2,R3,R4) of decreasing readout granularity from the beam-pipe [LHCB-TDR-014]
  - Four-gap MWPC with Ar: CO_2: CF_4 mixture (38:57:5) kept from Run 1 and 2 but from increased readout granularity of the inner region
- $\geq$ 99% hit efficiency achieved allowing efficient muon identification based on coincidence requirement

[LHCB-FIGURE-2024-029]



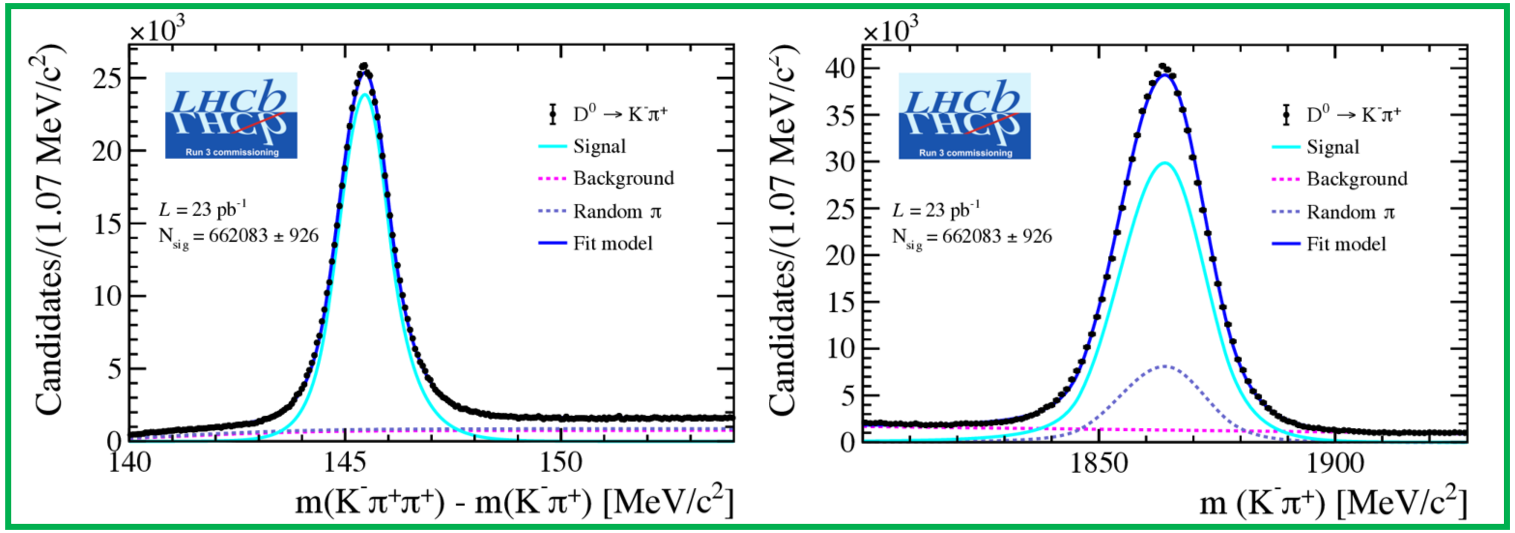


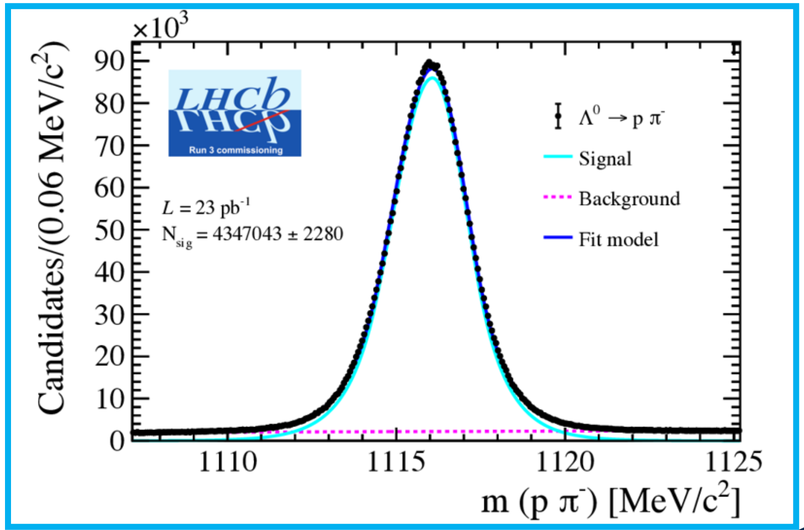
Global performance

Global performance assessment

- Global performance figures of merit are determined through data-driven methods using the dataset available in the TURCAL stream
  - tag-and-probe method employing $J/\psi \to l^+ l^-$ detached (from-b) decays used to determine tracking efficiency, momentum resolution for long tracks and lepton identification performance
  - charged hadron performance assessed by using decays that can be selected by purely kinematic means, e.g. $D^{*+} \to D^0(\to K^-\pi^+)\pi^+$ and $\Lambda \to p\pi^-$

[LHCB-FIGURE-2023-019]



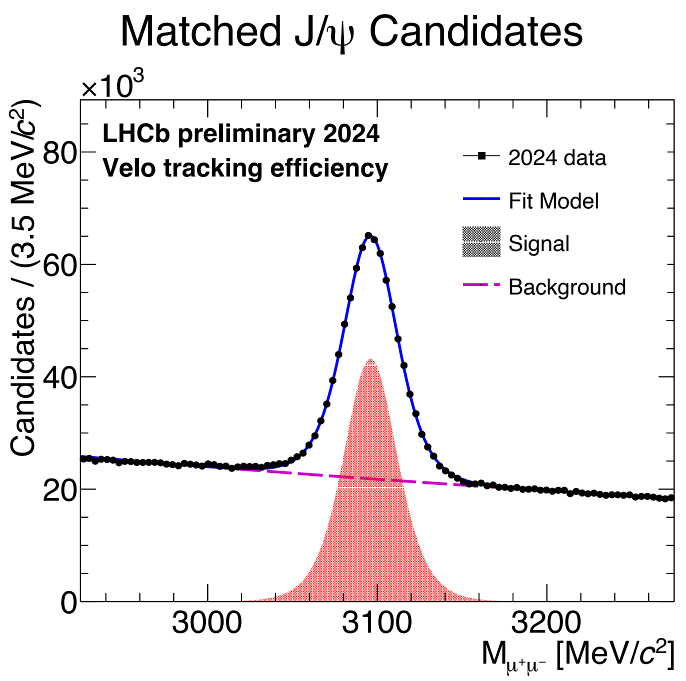


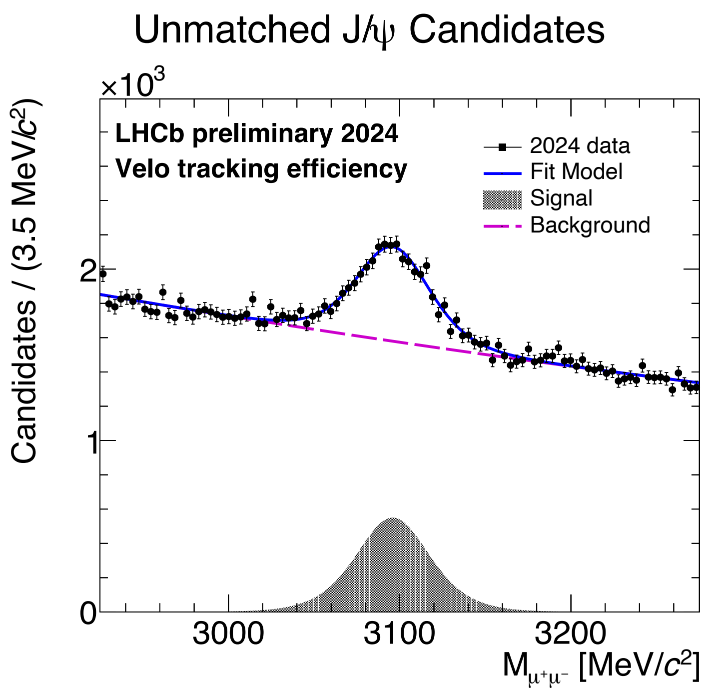
Tracking performance: efficiency

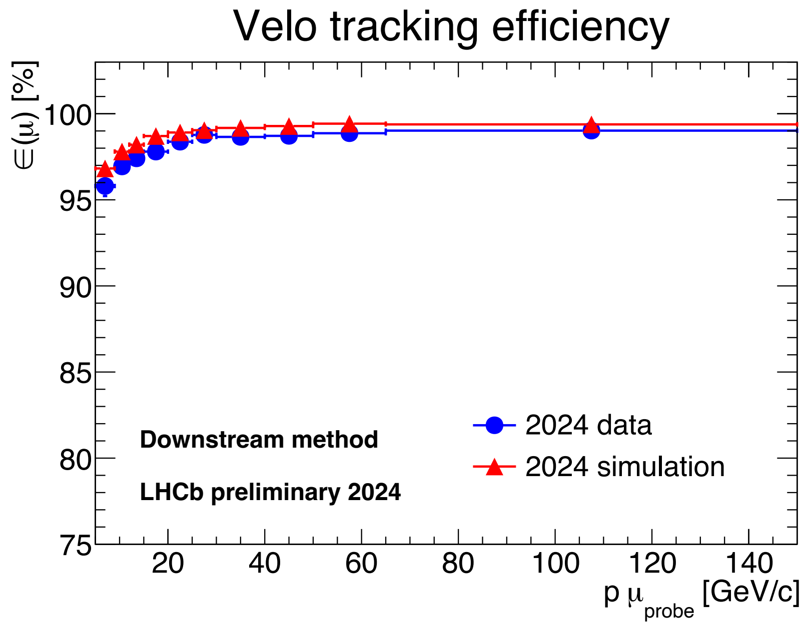
- **VELO tracking efficiency**: use the information from the UT, SciFi and MUON stations (probe) and match to a fully reconstructed long track (tag)

$$\epsilon_{track} = \frac{N_{matched}}{N_{matched} + N_{unmatched}}$$

[LHCB-FIGURE-2024-032]



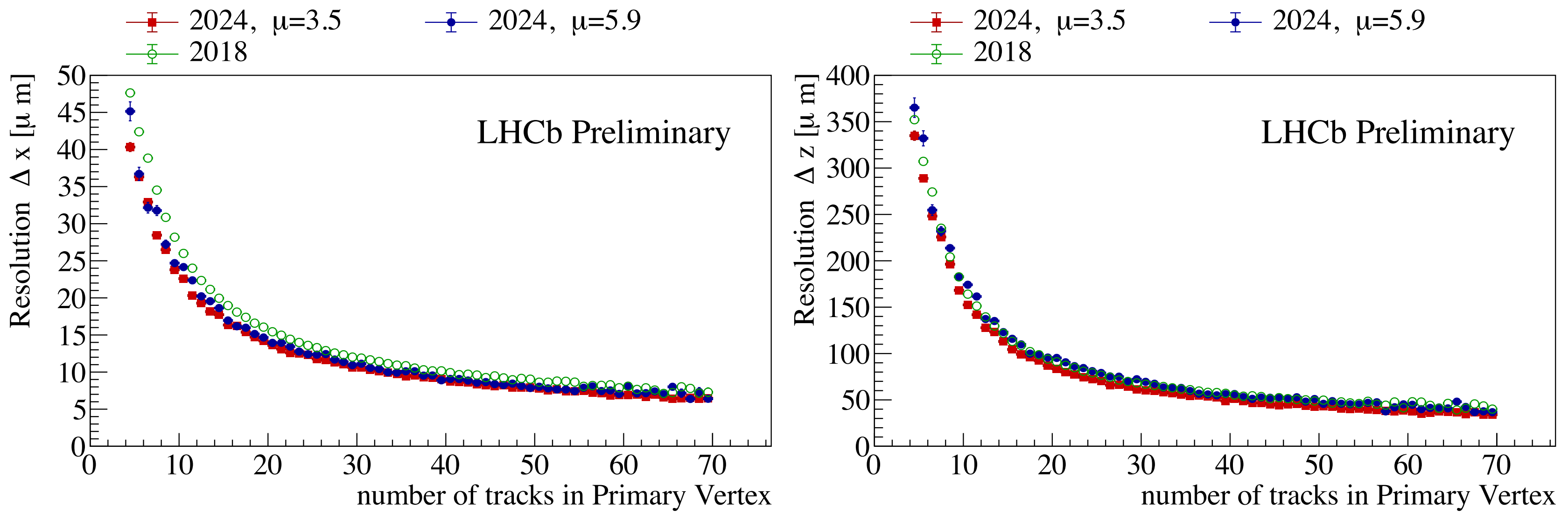




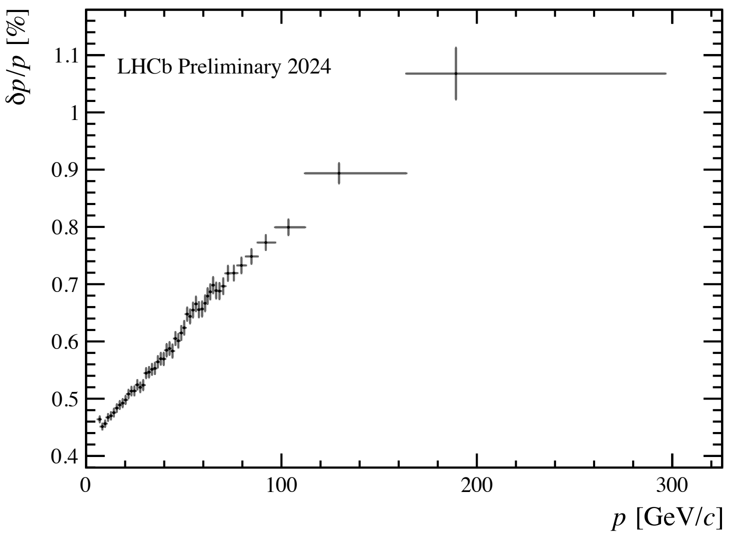
Tracking performance: resolutions

- PV resolution better than Run 2
- Momentum resolution determined fitting the $J/\psi \to \mu^+ \mu^-$ invariant mass in bins of momentum: between 0.4% and 1.1%

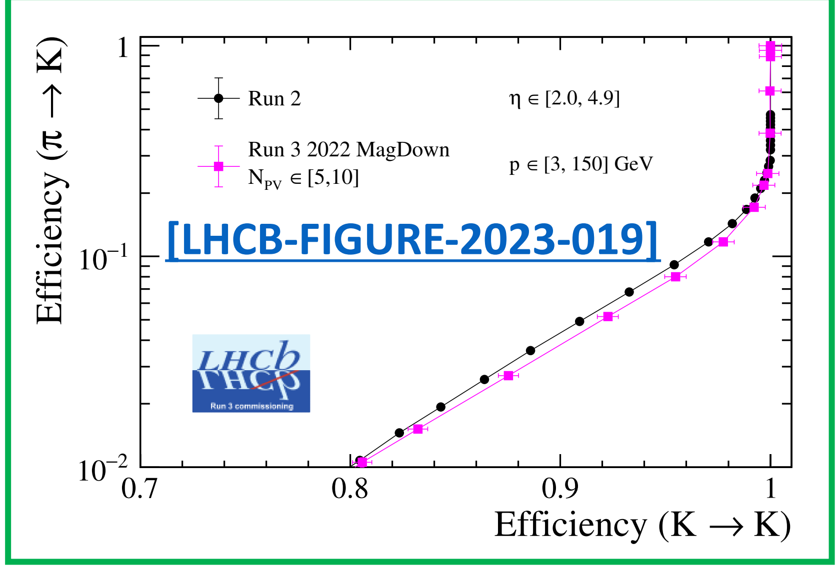
[LHCB-FIGURE-2024-011]



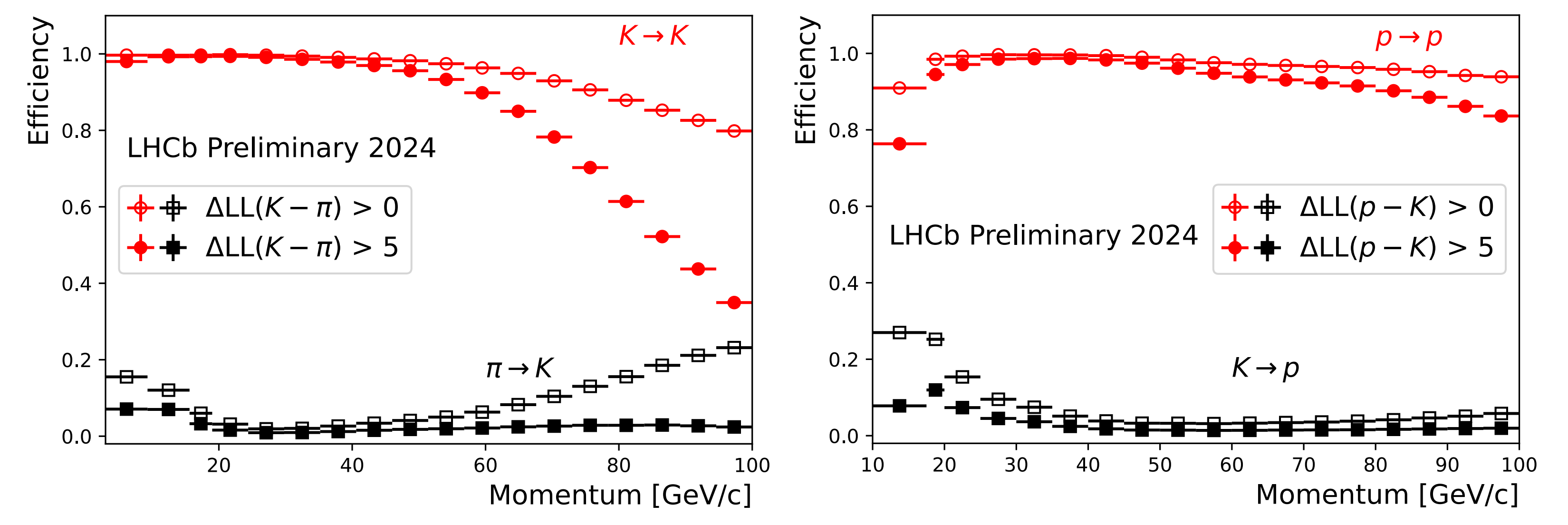
[LHCB-FIGURE-2024-040]



Hadron identification performance

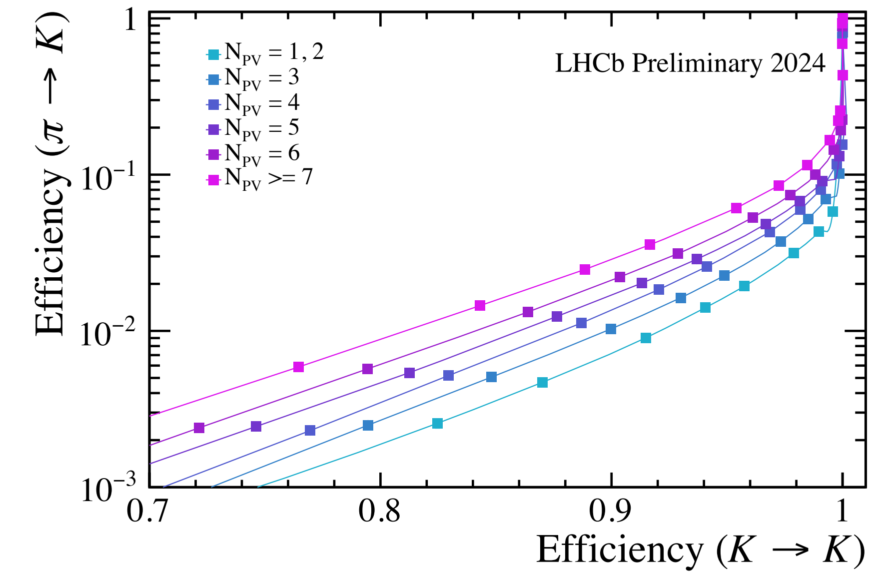


[LHCB-FIGURE-2023-019]



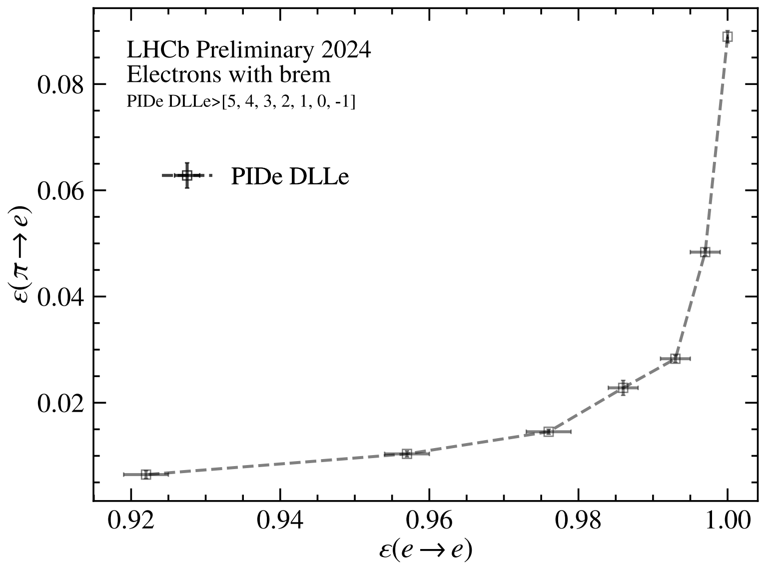
- Better RICH performance at typical Run 3 event multiplicity than in Run 2 already obtained in 2022
- Excellent hadron identification in the full range of momentum
- Expected degradation with increased event multiplicity kept under control

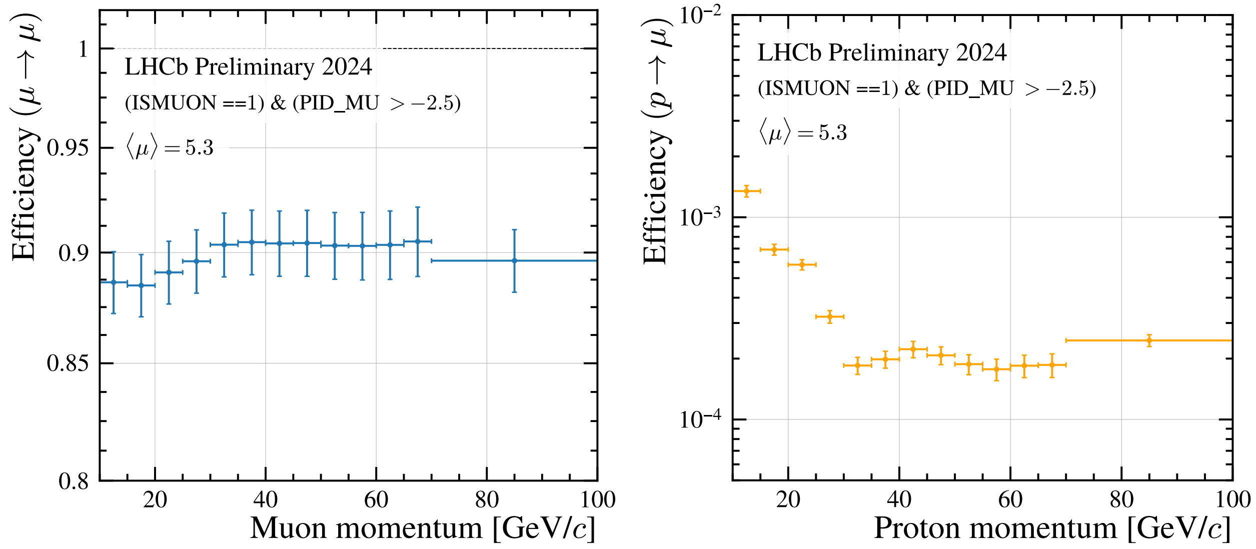
[LHCB-FIGURE-2024-031]



Charged lepton identification performance

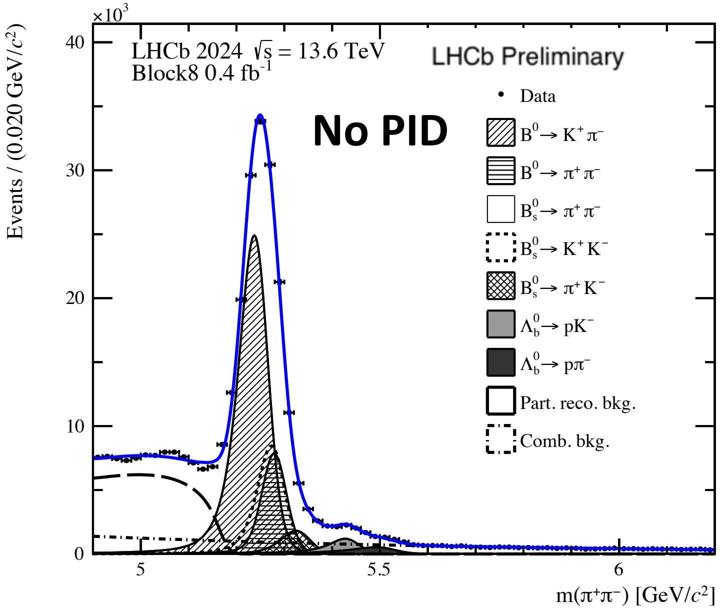
- Global electron identification efficiency as a function of the pion-electron mis-identification probability depends on the electron energy correction for bremsstrahlung losses
- Muon identification: at efficiencies > 90% the proton-muon mis-identification rate is below one per mille
  - Similar mis-identification rates for decays in flight of pions and kaons to muons

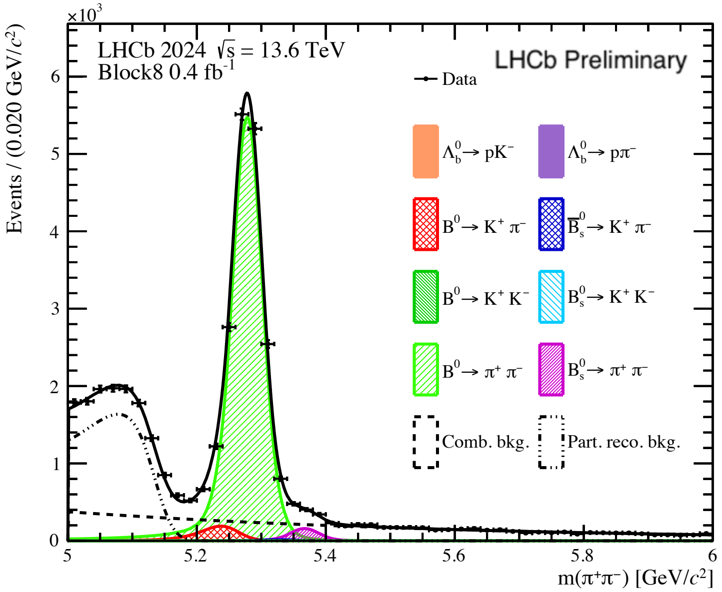


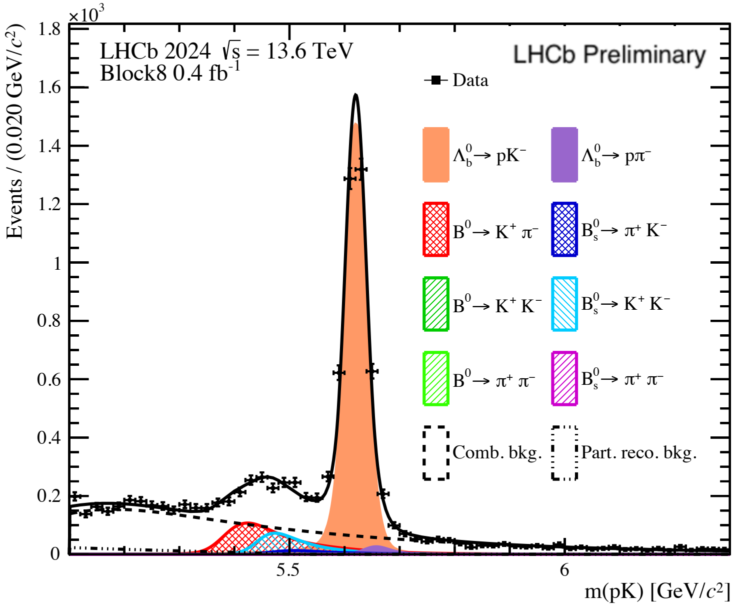


Global performance

- Illustrated by $b \rightarrow h^+h^-$ decays, where the parent particle is B^0, B_s^0 or Λ_b^0 and $h = \pi, K, p$
- Invariant mass of the decays, depending on the mass hypothesis for the final state hadron, shows excellent resolution and particle identification



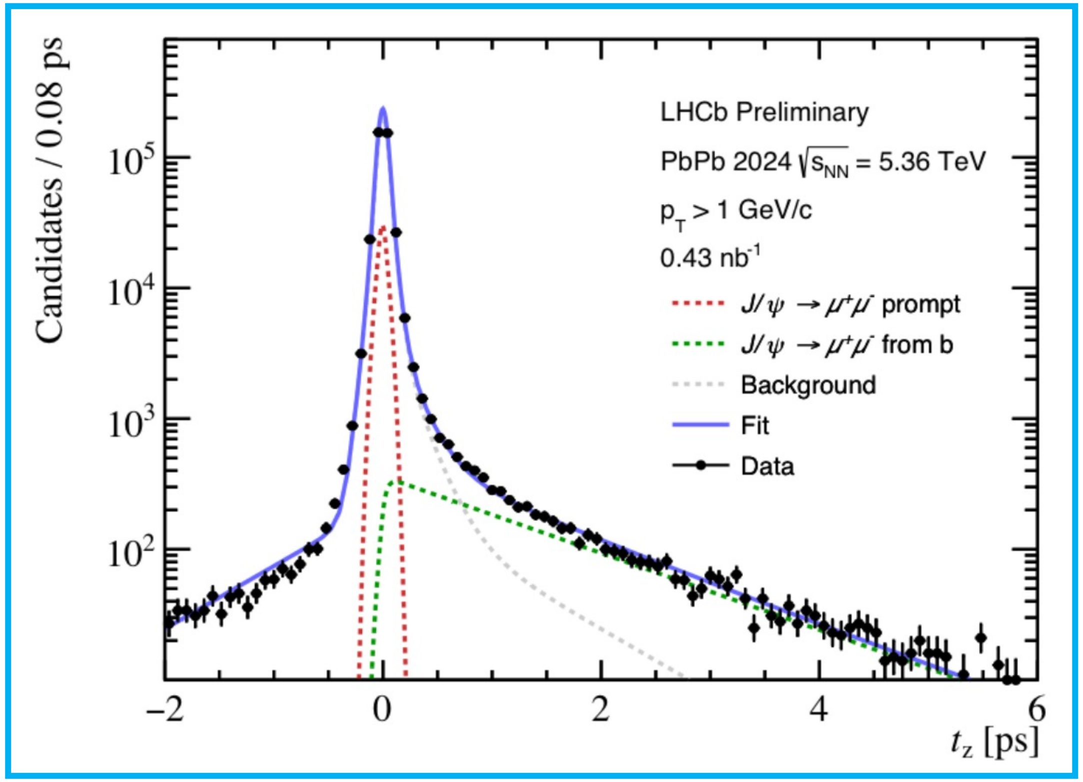




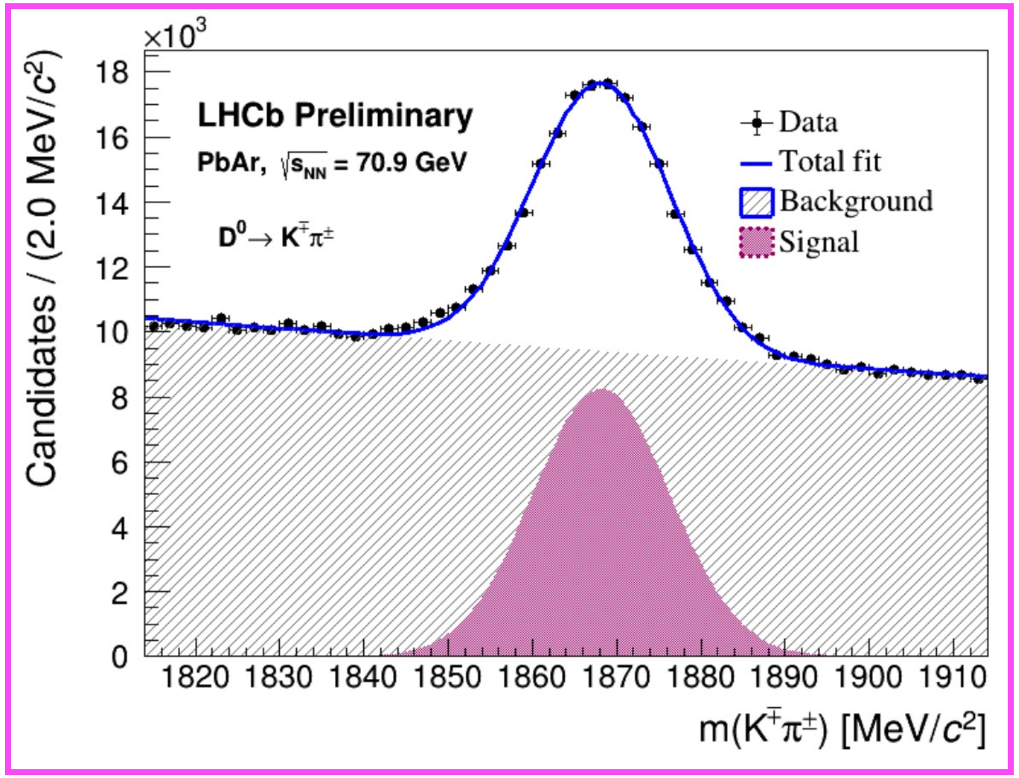
Highlights of performance in other collision systems

- Larger gas pressure thanks to the new SMOG2 cell
  - In 2024 injected hydrogen, deuterium, helium, neon and argon simultaneously to pp data-taking
- Also took PbPb, PbNe and PbAr collisions

[LHCB-FIGURE-2025-012]



[LHCB-FIGURE-2025-014]



Conclusions

- LHCb experiment brought to nominal luminosity operations in 2024
- Thanks to the huge commitment of the whole LHCb community, advanced automation of operations and the excellent LHC performance in 2024, LHCb collected and processed about 10/fb in a single year
- All subdetectors reaching or surpassing the performances of their Run 1 and 2 predecessors in a harsher environment
- Ambitious and challenging triggerless readout at 40 MHz, enabling an innovative fully-software trigger system, together with online alignment and calibration procedures, working in full steam
- **LHCb upgrade concepts fully demonstrated => ready to unleash state-of-the-art flavour physics measurements (and beyond) at the LHC**