IGFAE INSTITUTO GALEGO DE FÍSICA DE ALTAS ENERXÍAS 25 1999 2024

# LHCb Status Report

161st LHCC Open Session - 03/03/2025

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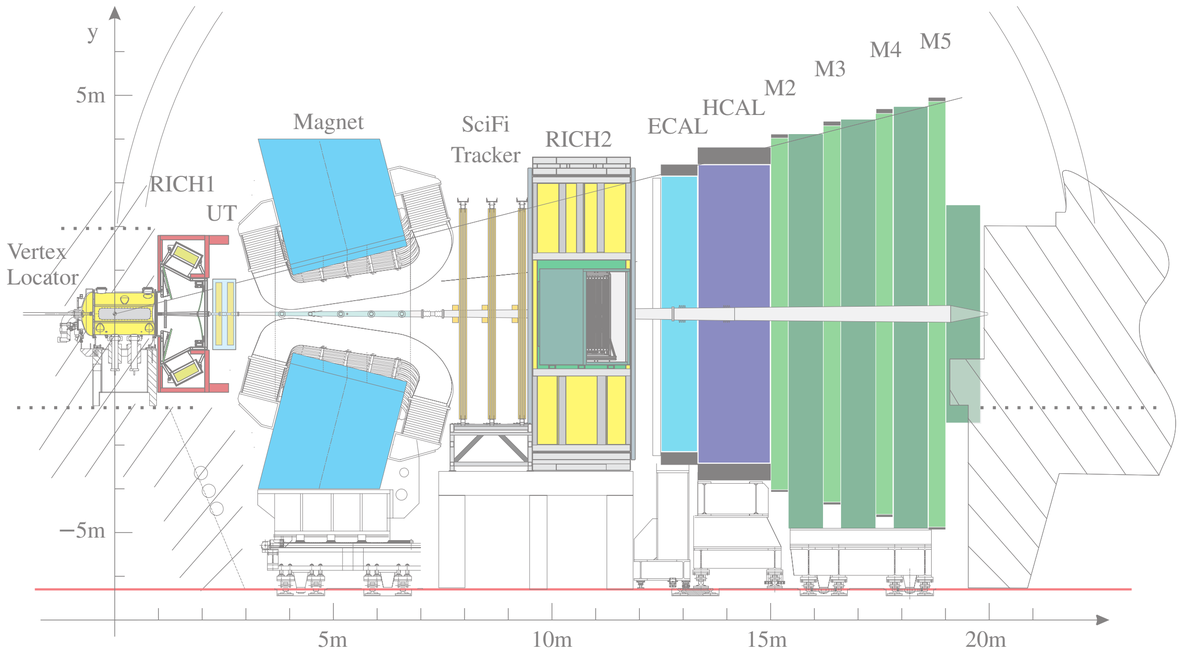
# OUTLINE

1. Most recent physics results
2. Highlights of the 2024 heavy-ion data taking
3. Detector YETS activities
4. Software activities
5. Plans for 2025 data taking
6. Upgrade II status



# RECENT PHYSICS RESULTS

# Summary Analysis

| Paper | Title | Arxiv Number |
|---|---|---|
| **Papers submitted since November LHCC week** | | |
| LHCb-PAPER-2024-031 | First evidence for direct CP violation in beauty to charmonium decays | 2411.12178 |
| LHCb-PAPER-2024-043 | Study of \Lambda^0_b and \Xi^0_b decays to \Lambda h^+ h^'– and evidence for CP violation in \Lambda^0_b \to \Lambda K^+ K^- | 2411.15441 |
| LHCb-PAPER-2024-040 | Observation of the open-charm tetraquark state T^*_{cs0}(2870)^0 in the B^- \to D^- D^0 K^0_S decay | 2411.19781 |
| LHCb-PAPER-2024-047 | Search for D^0 meson decays to \pi^+ \pi^- e^+ e^- and K^+ K^- e^+ e^- final states | 2412.09414 |
| LHCb-PAPER-2024-046 | Test of lepton flavour universality with B^+\to K^+\pi^+\pi^-\ell^+\ell^- decays | 2412.11645 |
| LHCb-PAPER-2024-048 | Measurement of CP asymmetries in \Lambda_b^0\to ph^- decays | 2412.13958 |
| LHCb-PAPER-2024-020 | Measurement of CP asymmetry in B_s^0\to D_s^{\mp} K^{\pm} decays | 2412.14074 |
| LHCb-PAPER-2024-045 | Study of light meson resonances decaying to K^0_S K pi in the B to (K^0_S K pi) K channels | 2501.06483 |
| LHCb-PAPER-2024-044 | Search for charge-parity violation in semileptonically tagged D^0 to K^+pi^- decays | 2501.11635 |
| LHCb-PAPER-2024-038 | Measurement of multiplicity dependence of Upsilon production ratios in pp collisions at \sqrt{s}=13 TeV | 2501.12611 |
| LHCb-PAPER-2024-049 | Observation of the \Lambda_{b}^{0} \to J/\psi\Xi^{-} K^+ and \Xi_{b}^{0} \to J/\psi\Xi^{-} \pi^+ decays | 2501.12779 |
| LHCb-PAPER-2024-037 | Evidence for the B^-\to D^{**0} \tau^- \overline{\nu}_\tau decay | 2501.14943 |
| LHCb-PAPER-2024-051 | Search for resonance-enhanced CP and angular asymmetries in the \Lambda_c^+ \to p \mu^+ \mu^- decay at LHCb | 2502.04013 |
| LHCb-PAPER-2024-022 | Angular analysis of B^0 \to K^{*0} e^+e^- decays | 2502.10291 |
| LHCb-PAPER-2024-055 | Observation of of a new charmed baryon decaying to \Xi_c^+ \pi^+ \pi^- | 2502.18987 |
| **Preliminary results since November LHCC week** | | |
| LHCb-PAPER-2024-056 | Measurement of the branching fraction ratio $R_K$ at large dilepton invariant mass | |

+15

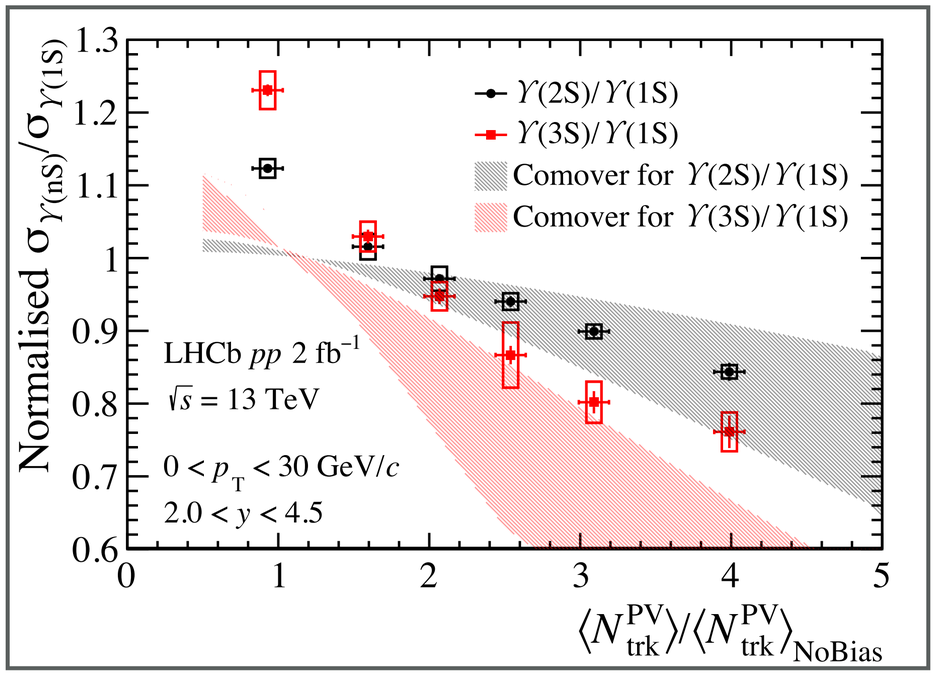
+1

- 765 papers submitted since 2010 (+10 Detector performance)
- 51 papers submitted in 2024 + 8 in 2025
- 15 papers submitted since Nov. LHCC week

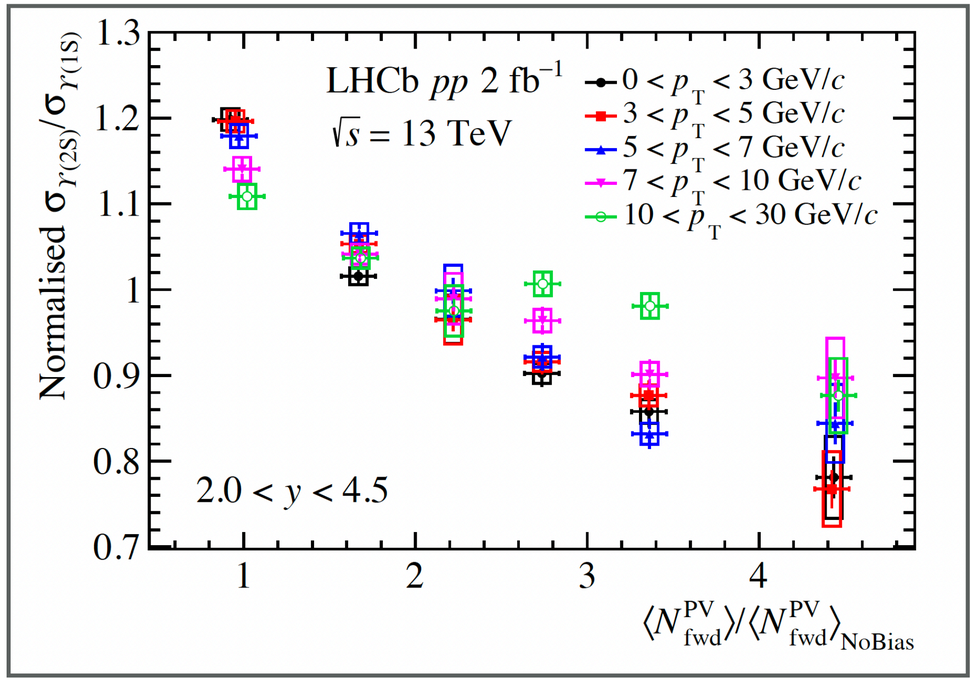
# $\Upsilon(nS)/\Upsilon(1S)$ versus multiplicity in pp collisions

- Does final states effect have an impact on quarkonia production? If yes:
  - Stronger effects in a busy collisions → visible versus multiplicity (here number of tracks used in primary vertex reconstruction)
  - Effect depends on the binding energy of the quarkonia states → ratio measurement between different states
  - Effects due to co-moving particle with similar $p_{\mathrm{T}}$
- We do see a stronger suppression of the $\Upsilon(3S)$ and the effect appears stronger at low $p_{\mathrm{T}}$

Crucial input for QGP studies



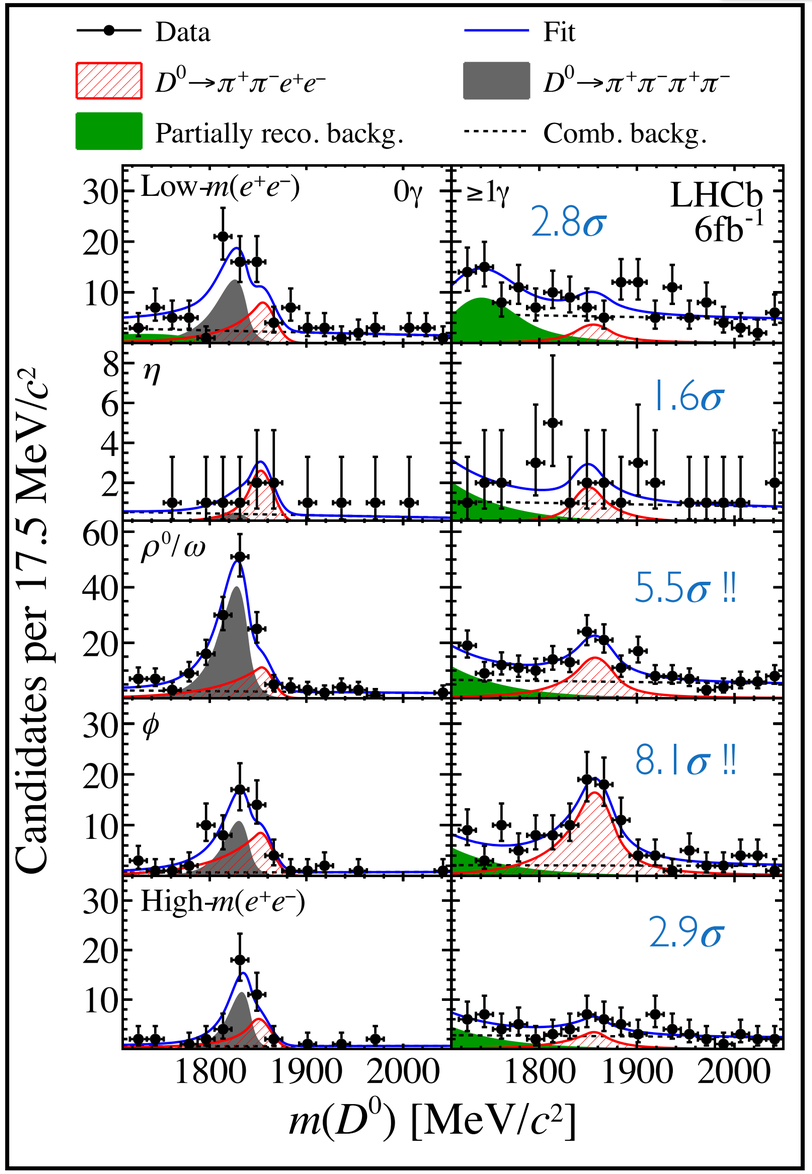

arXiv



# Search for $D^0 \to h^+h^-e^+e^-$

- Short Range decay $D \to Xl^+l^-$ $\mathcal{O}(10^{-9})$
- Long Range decay $D \to XY(\to l^+l^-)$ $\mathcal{O}(10^{-6})$
- Interesting decay for lepton universality testing but only $D^0 \to h^+h^-\mu^+\mu^-$ discovered so far…
- Search through $D^{*+} \to D^0\pi^+$
- Observation of the decay $D^0 \to \pi^+\pi^-e^+e^-$ !!
- BR measured through $D^0 \to K^-\pi^+e^+e^-$:
  $\mathcal{B}(D^0 \to \pi^+\pi^-[e^+e^-]_{m(e^+e^-)>2m_\mu} = (13.3 \pm 1.1 \pm 1.7 \pm 1.8) \times 10^{-7})$

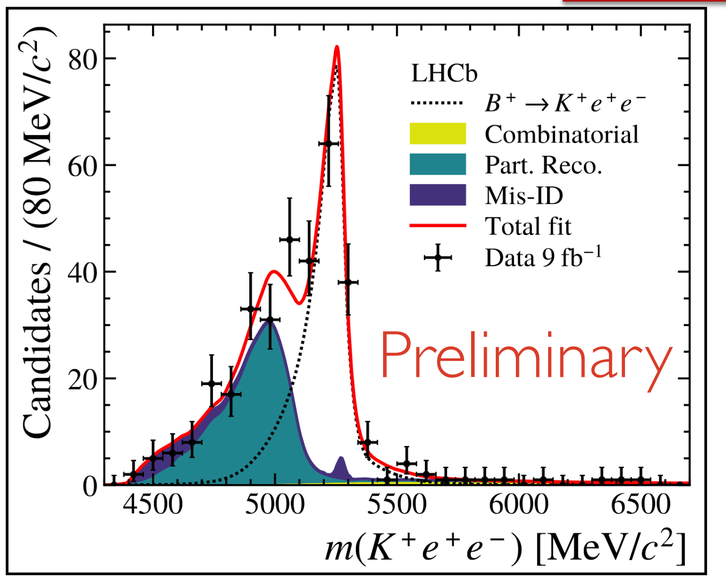
BR compatible with $D^0 \to \pi^+\pi^-\mu^+\mu^-$, consistent with lepton universality at current precision

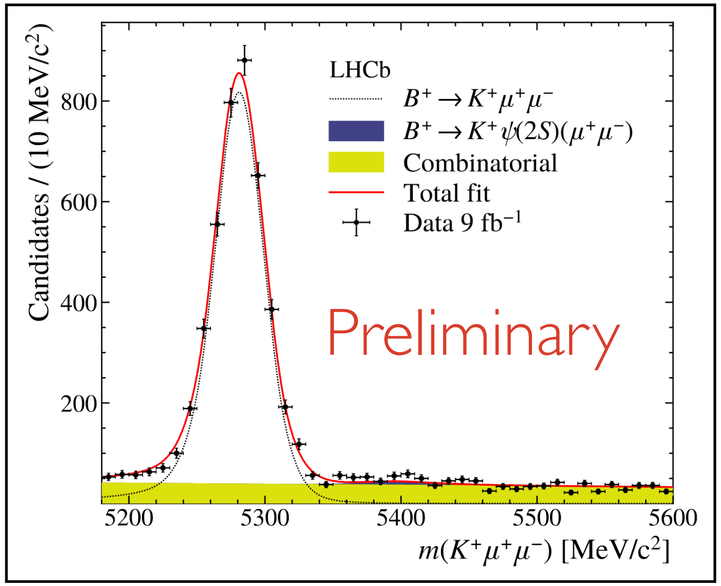



arXiv

# $R_K$ measurement at large $q^2$

- Test lepton universality through $R_K = \dfrac{B^+ \to K^+\mu^+\mu^-}{B^+ \to K^+e^+e^-}$
- High-$q^2$ region not explored before due to:
  - Challenging bremsstrahlung effect, giving high contamination from $B^+ \to K^+\psi(2S)(\to e^+e^-)$. → Selection of $q^2$ only made with information from tracking, loss of signal but better control on background.
  - More challenging combinatorial background → Improved BDT with a complex mix of training samples
  - Important dilepton background from open charms → Mixing event method



# $R_K$ measurement at large $q^2$

First measurement at high-$q^2$ in hadron collider!

- Test lepton universality through $R_K = \dfrac{B^+ \to K^+\mu^+\mu^-}{B^+ \to K^+e^+e^-}$
- High-$q^2$ region not explored before due to:
  - Challenging bremsstrahlung effect, giving high contamination from $B^+ \to K^+\psi(2S)(\to e^+e^-)$. → Selection of $q^2$ only made with information from tracking, loss of signal but better control on background.
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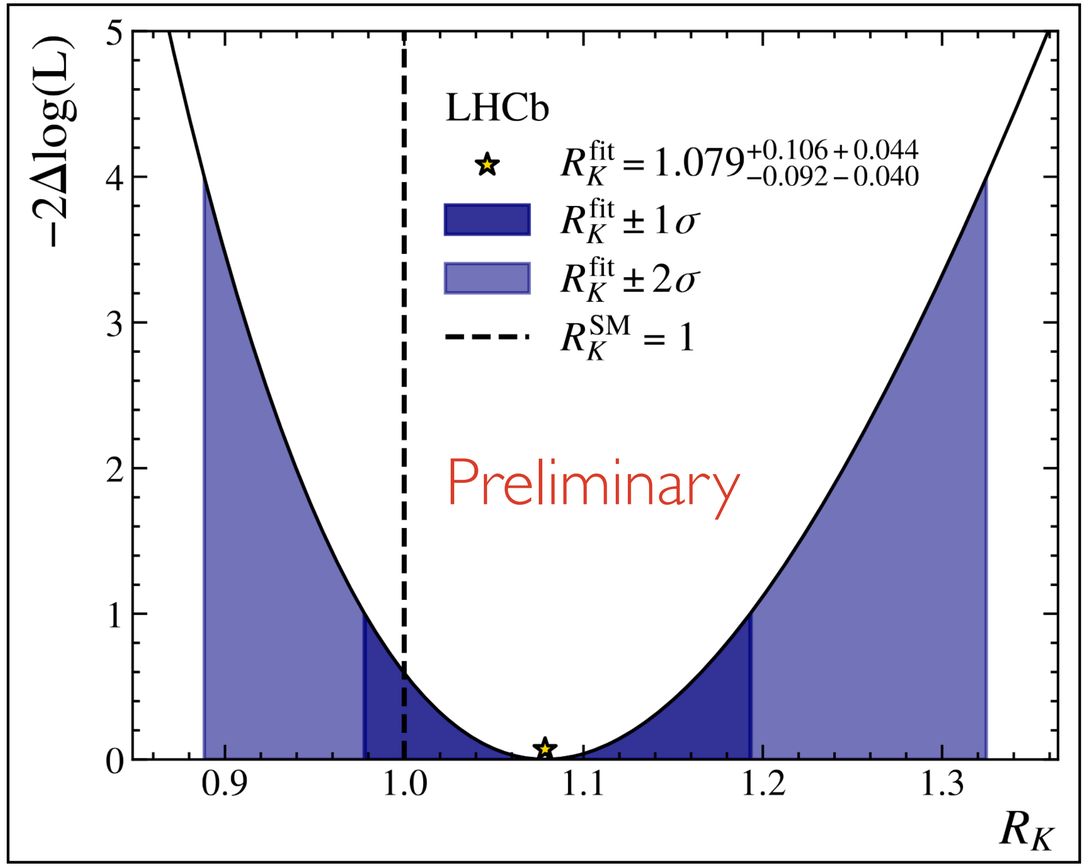


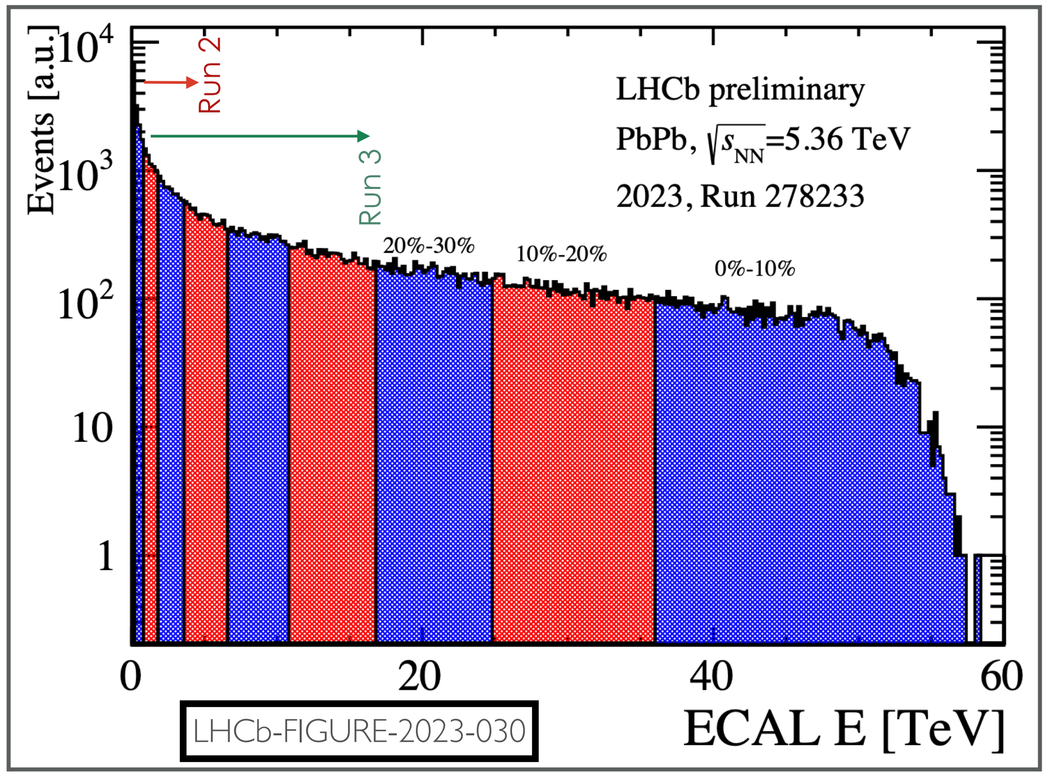

Compatible with SM value and with previous measurements

# HEAVY-ION 2024 OPERATIONS

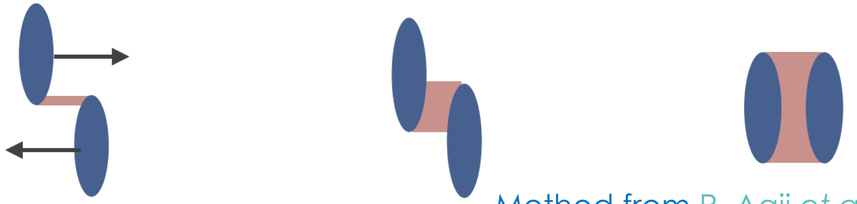
# Why crucial data taking?

- In run 2, tracking working down to 60% centrality, almost not sensitive to QGP formation.
- In run 3, thanks to the upgrade of the tracking, down to 30% centrality, sensitive to QGP formation!
- LHCb can bring many unique results especially thanks to its precise vertexing, hadron identification and forward geometry.
- Injection of gas in the SMOG2 system, simultaneous collider and fixed-target data-taking.

Formation probability/size of QGP




Total energy deposit in ECAL

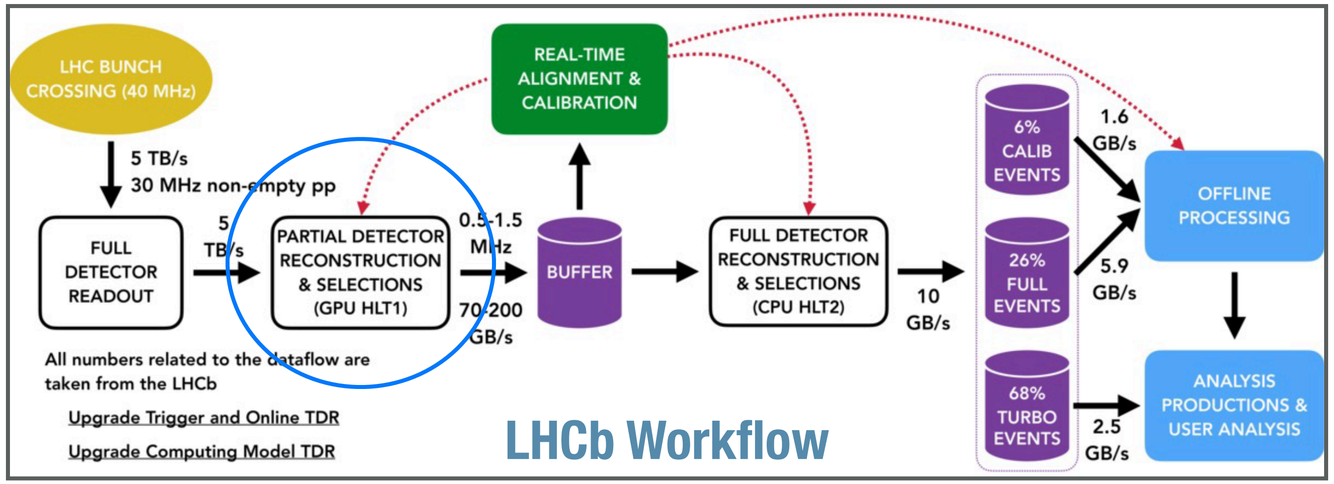




Method from R. Aaij *et al* 2022 *JINST* **17** P05009

# Ion operations (HLT1)

- HLT1 used to:
  - Discriminate collider from fixed-target collisions with PV position
  - Sort events based on SciFi tracker clusters and calorimeter energy




## HLT1 lines in a nutshell

### Physics lines (GEC)

- Selection based on
  - Calorimeter energy.
  - Primary vertex position.

### Calibration/Alignment lines (GEC)

- VELO, RICH, Muon calibration.
- Technical line
- SMOG monitoring.

### Monitoring lines

- Invariant mass histograms.
- Track and PV distributions.
- …

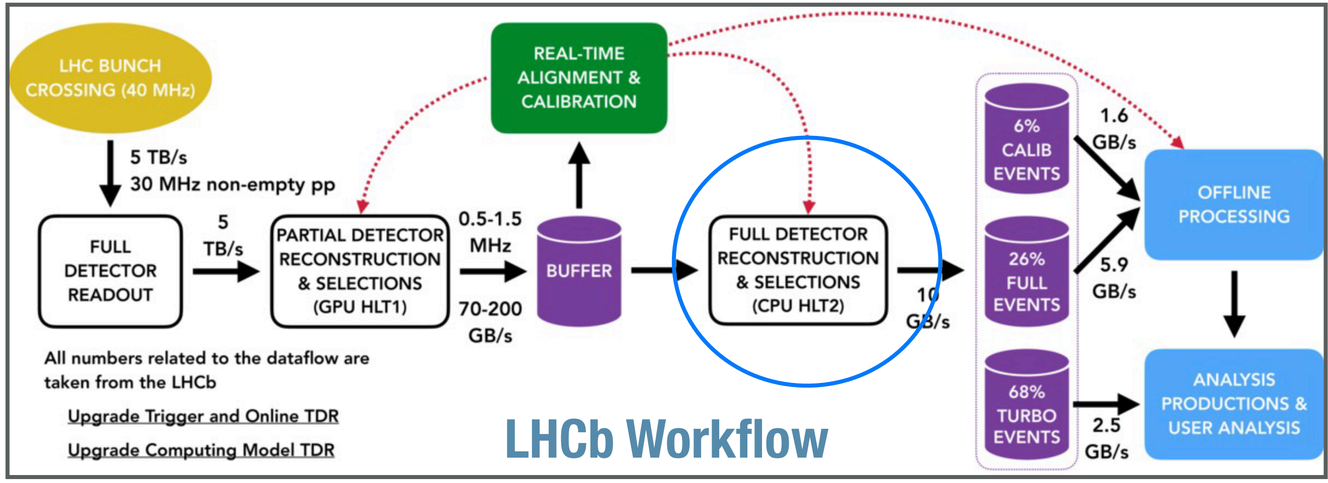
### Luminosity lines

- All luminosity counters.
- Will be used for centrality studies.

# Ion operations (HLT2)

- PbPb, low hadronic rate but high occupancy
  - HLT2 acts as passthrough (only reconstruction without candidates selections), raw detector information are kept for precise performance studies
- PbAr, high rate, moderate occupancy
  - HLT2 used as in pp conditions, physics line with candidates selection
- PbNe, low rate, « low occupancy »
  - HLT2 acts as a passthrough

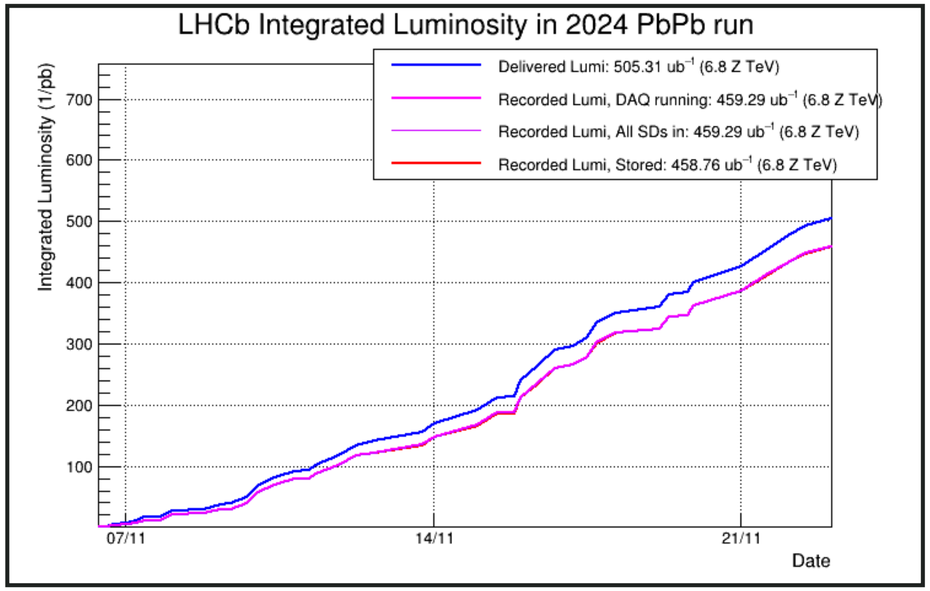
One data taking, three samples!

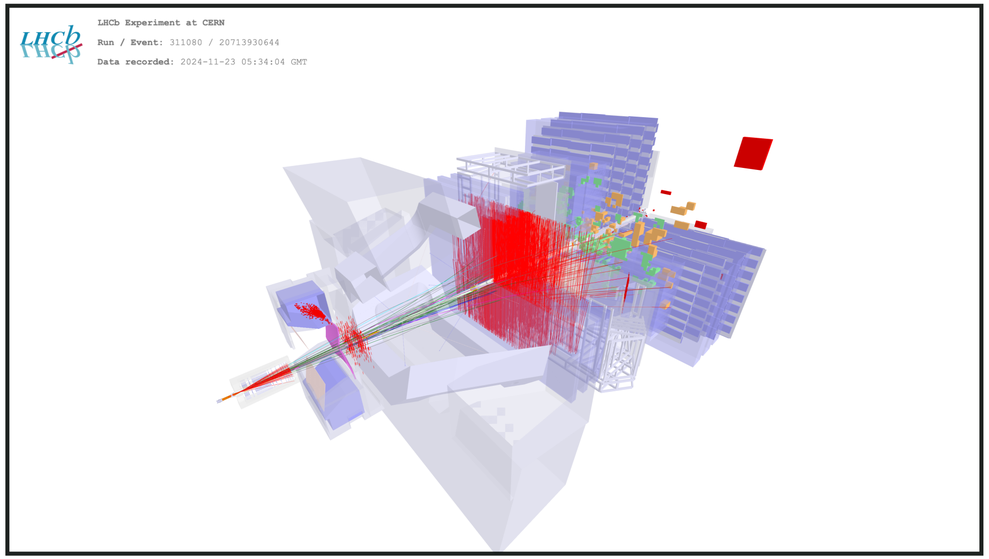


# LHCb luminosity performance

- Optimized LHCb total PbPb luminosity
  - Original luminosity goal ~0.20$nb^{-1}$
  - +20% thanks to a magnet polarity flip
  - +40% alternative filling scheme, thank you to the other experiments for agreeing on this!
  - Target 0.32$nb^{-1}$, reached 0.43$nb^{-1}$!

All sub-detectors working in nominal state



# DATA SETS

- Largest PbPb @ 5.36TeV per nucleon sample in LHCb so far: ~430$\mu b^{-1}$ .
- Twice the luminosity of 2018, but better efficiency and centrality reach, so much higher statistics.

- Largest PbAr SMOG2 sample @ 70.9GeV per nucleon of ~1.5$nb^{-1}$
  - Much more than the PbNe sample from 2018 (~0.3$nb^{-1}$)

- A smaller full minimum bias PbNe sample @ 70.9GeV per nucleon of ~0.05$nb^{-1}$

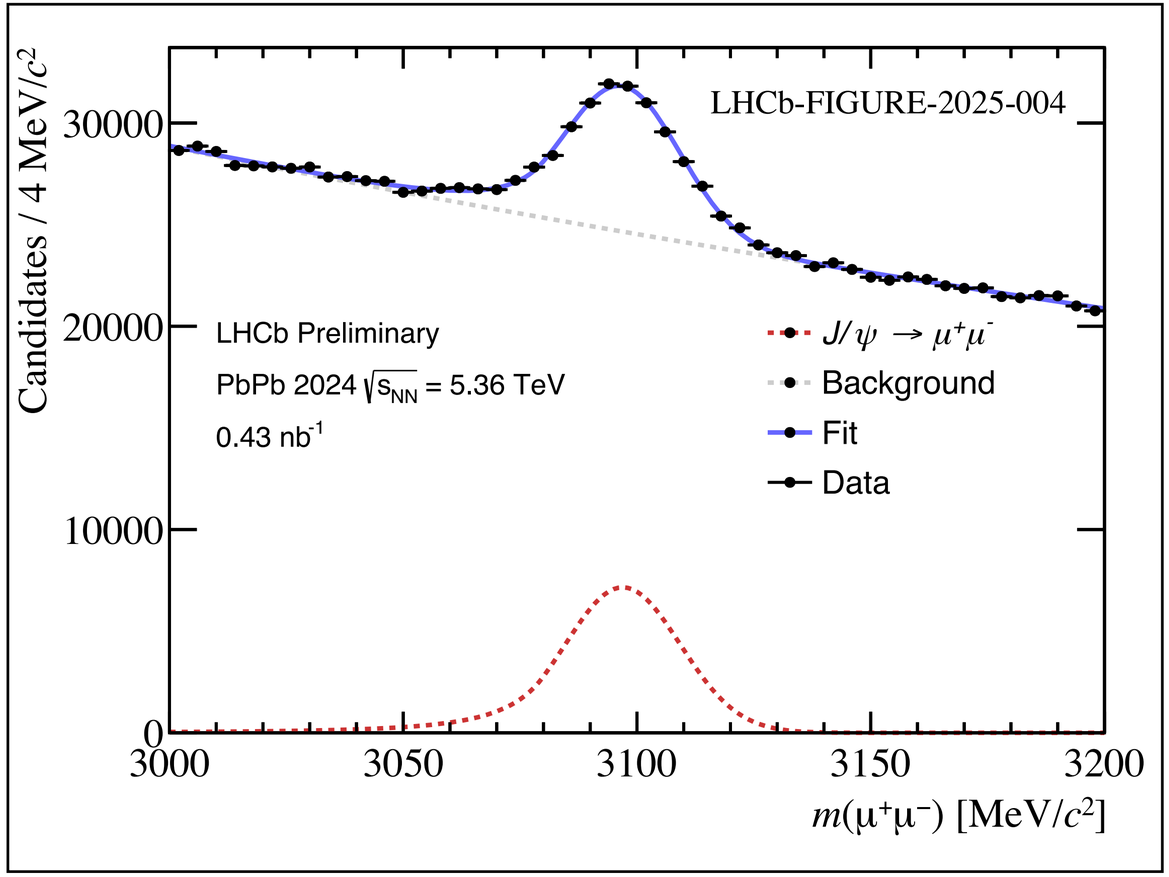
- Both the fixed target samples have full centrality reach!!

In the following, the data presented correspond to events within the ~100-30% centrality range

# First look at PbPb data: $J/\psi$

NEW 2024 PbPb

- Dimuon invariant mass spectrum
- Clear $J/\psi$ signal with excellent resolution
- Precise vertex capabilities allows to retrieve the non-prompt fraction and indirectly measure *b* quark production



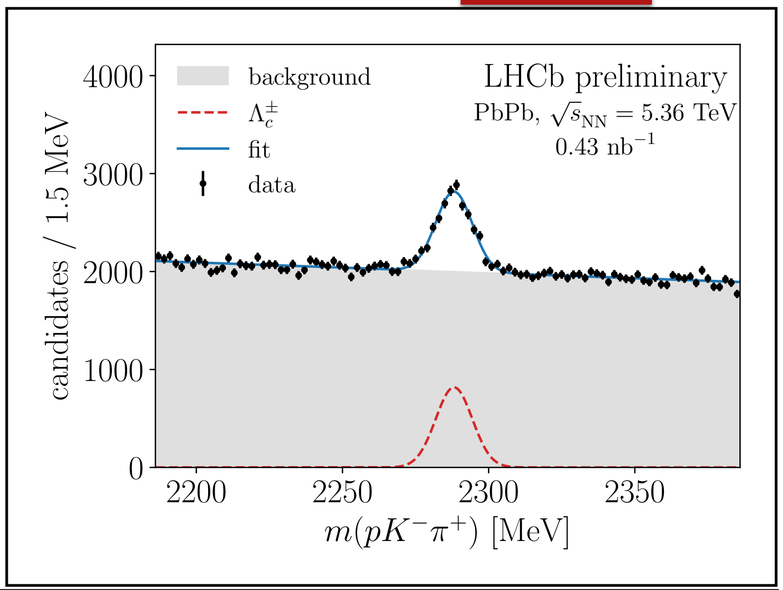

*Events below 30k SciFi clusters, corresponding to ~100-30% centrality

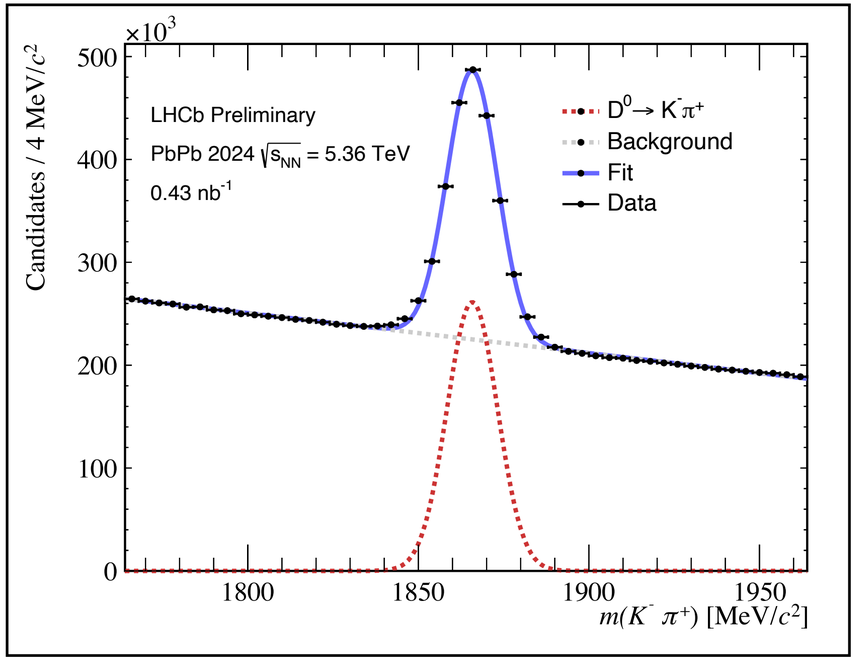
# First look at PbPb data: Open-charm

NEW 2024 PbPb

- Invariant mass spectrum for open-charm hadronic decays $D^0$, $\Lambda_c$, $D^{\pm}$, $D_s^{\pm}$
- Excellent capabilities for hadronic decays also in PbPb collisions!

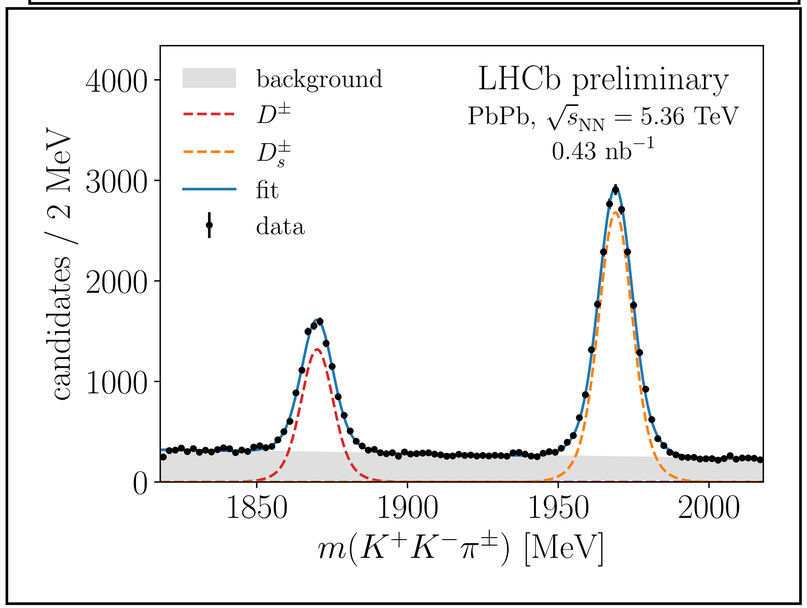
LHCb-FIGURE-2025-004




Large sample of $D^0$!

$D^{\pm} \to K\pi\pi$ also available with much more statistics



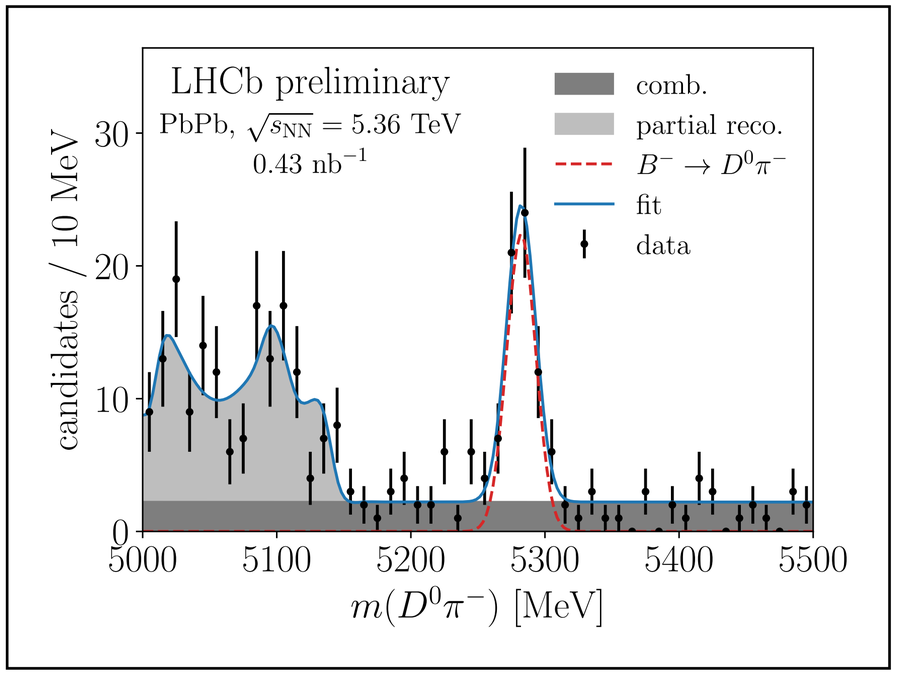

*Events below 30k SciFi clusters, corresponding to ~100-30% centrality

# First look at PbPb data: Open-Beauty

NEW 2024 PbPb

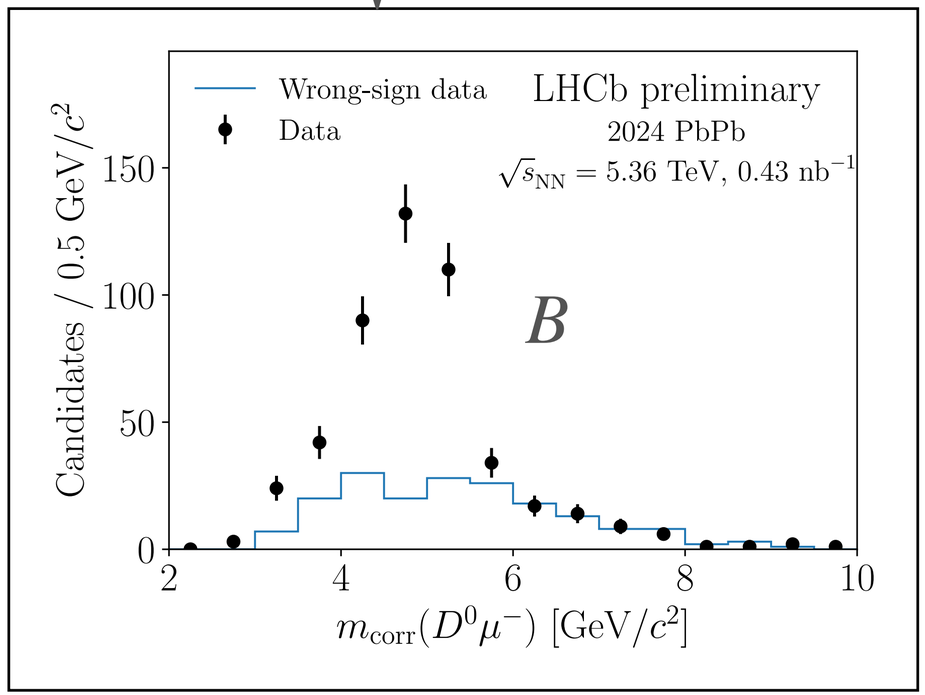
- Invariant mass spectrum for the $B^{\pm}$ with hadronic and semileptonic decay

- Clean signal for $B$ physics even in PbPb collisions!




LHCb-FIGURE-2025-004

$$m_{corr} = \sqrt{m^2 + p_\perp^2} + p_\perp$$





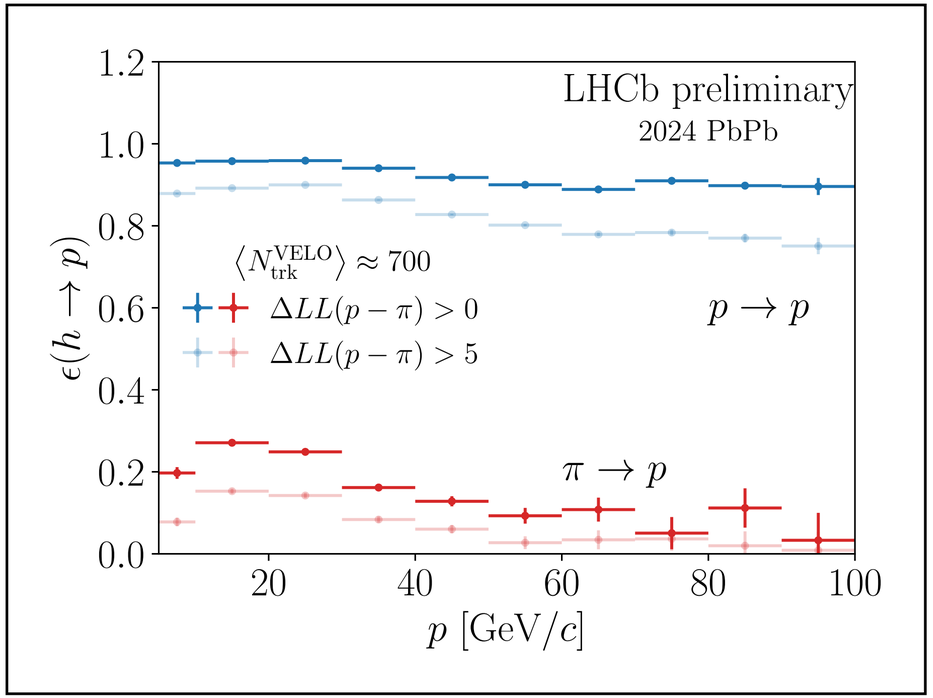

*Events below 30k SciFi clusters, corresponding to ~100-30% centrality

# First look at PbPb data: PID performances

NEW 2024 PbPb

- The PID selection is done using log-likelihood difference ($\Delta LL$) between two particle hypotheses based on information from the RICH.
- The efficiency is calculated for two conditions of $\Delta LL(X-Y)$, a soft and tighter selection.
- Both the identification and mis-identification performances are studied using PbPb data-driven method.
- Excellent performances are found, integrated in rapidity and centrality.

LHCb-FIGURE-2025-005

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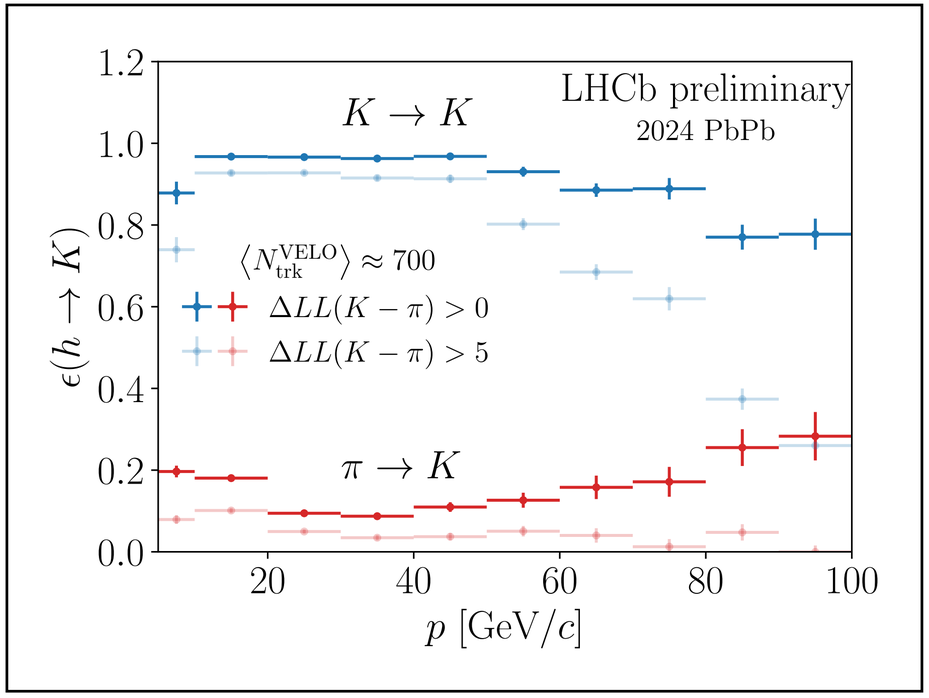
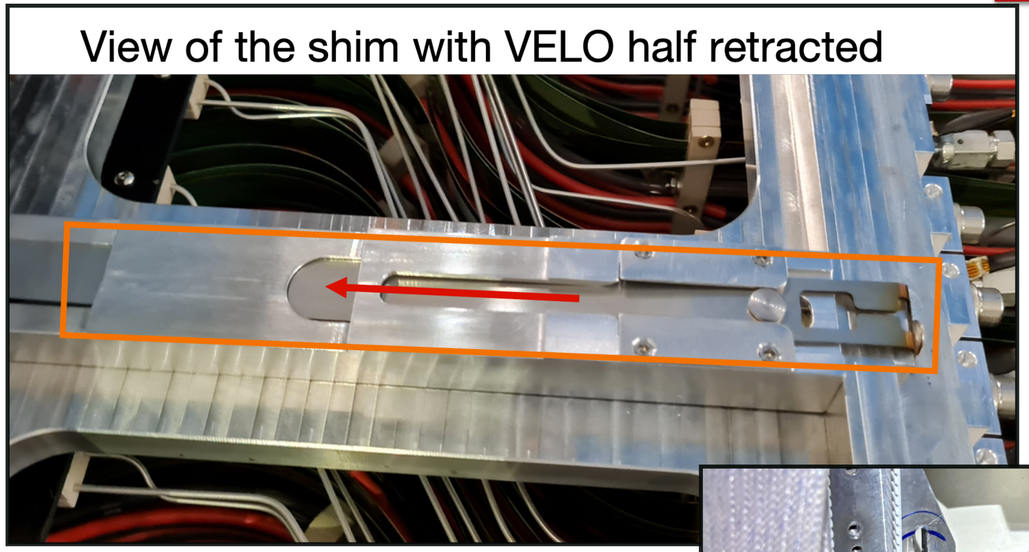
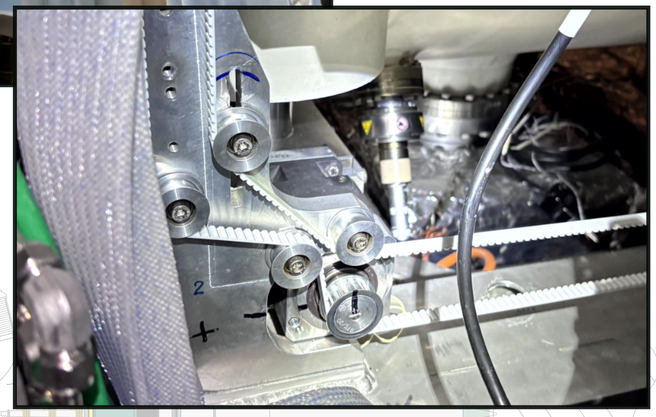


# DETECTOR YETS ACTIVITIES

# VELO - SMOG2

- VELO:
  - Installation of a new belt
  - Change of the O-ring to fix minor leak of the secondary vacuum detected in 2024.
  - Removal of shims allows the VELO sensors to move 0.5mm closer to the beam line. Expecting an improvement in IP resolution of around 10%!
- SMOG2:
  - Change reservoir from 1.5 to 200 bar, enough for full data-taking and faster injection.
  - Consolidation of the SMOG2 gas feeding system



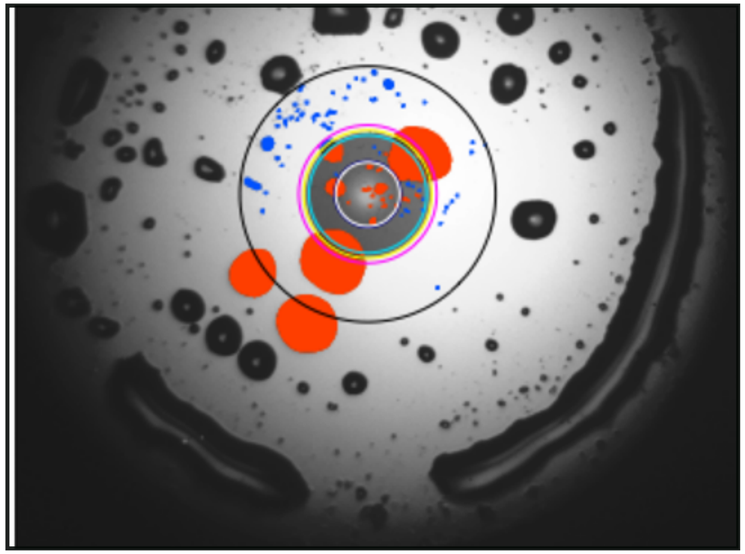



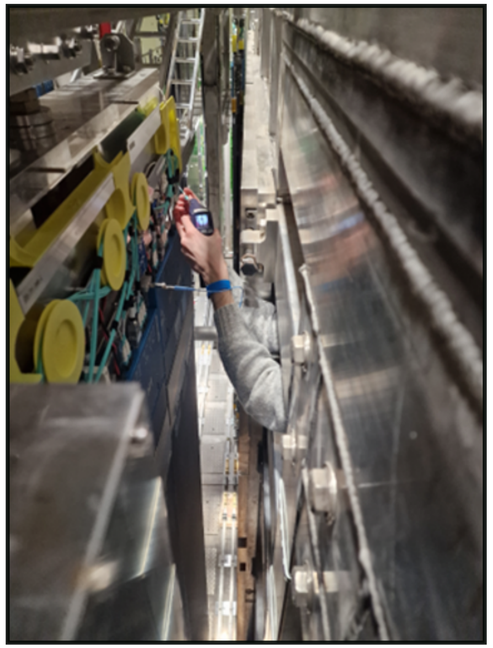



VELO and SMOG2 ready for 2025!

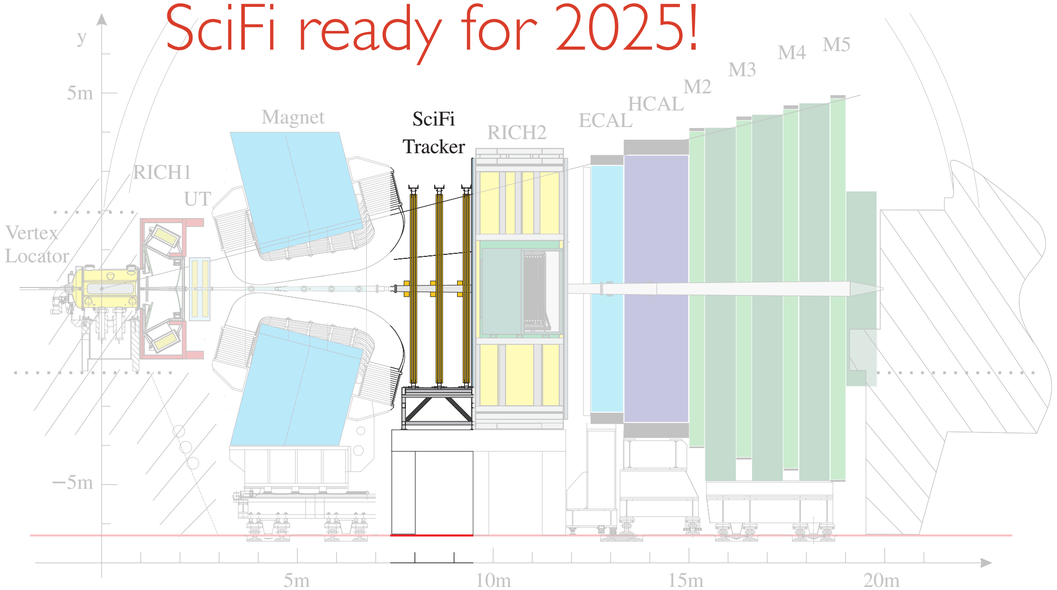
# SciFi Tracker

- Upgrade of the Condensation Prevention System (CPS) (heating wires).
- Changing the SiPM cooling liquid. From $C_6F_{14}$ to NOVEC 7100, 30 times lower greenhouse warming potential.
- A few optical fibers had performance affected by VTRx outgassing: Huge campaign to clean fibres for the unbaked VTRx in the majority of the detector



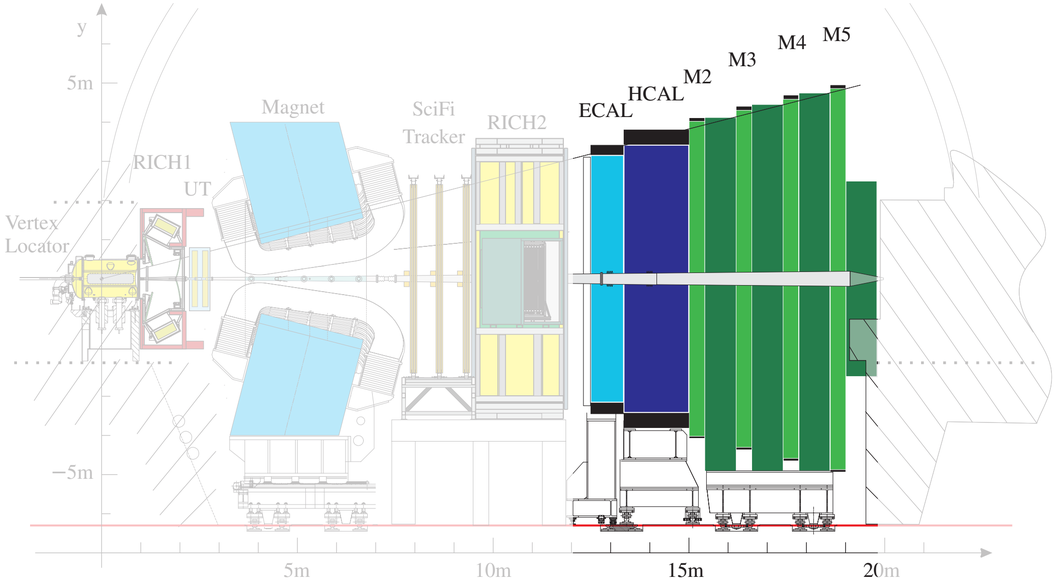


SciFi ready for 2025!



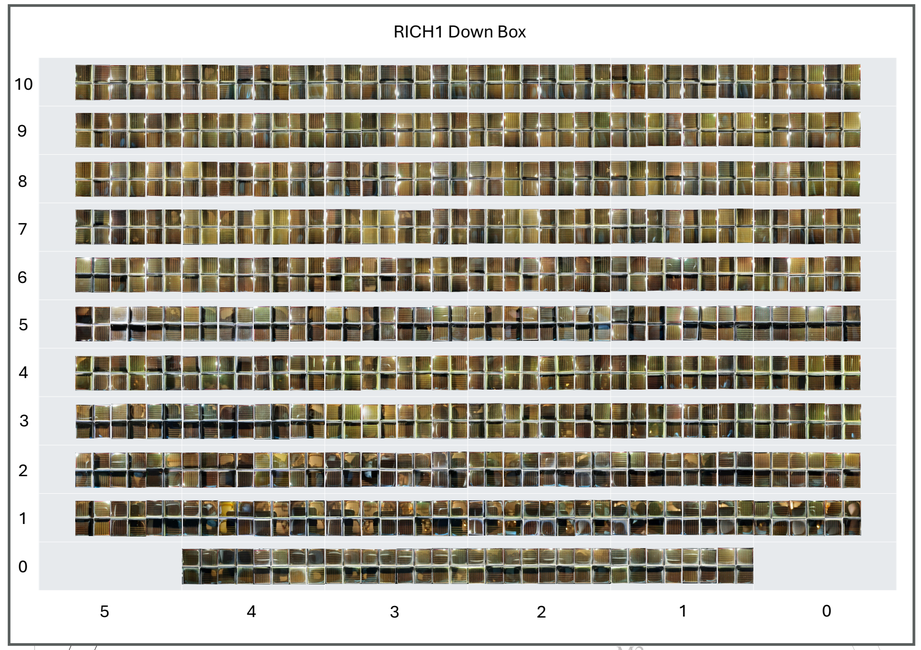
# Calorimeters and Muon stations

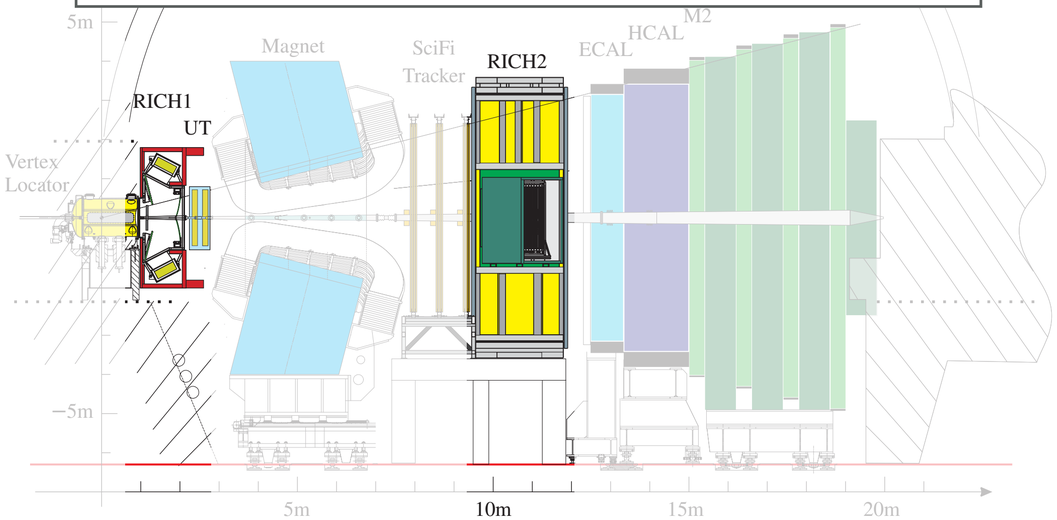
- ECAL
  - 201 power boards for the PMTs at the the centre of ECAL were changed as expected to reach 10kGy in 2025
- HCAL
  - Replaced 21 degraded PMTs in HCAL (high dark current)
- Muon stations
  - A few front end boards and muon chambers were replaced
  - Shielding test for Upgrade II
- The three detectors are ready for 2025 operations



# UT and RICH

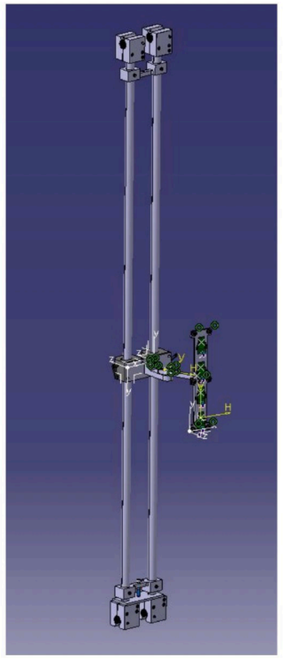
- UT
  - Maintenance and replacement of hardware components
  - Specific test on temperature operations for performance optimization. CO2 cooling is lowered from −10°C to −15°C
  - Major improvements in the UT firmware with upcoming tests on hardware.
  - Overall UT efficiency expected to increase!
- RICH
  - Inspection and cleaning of RICH1's MaPMTs
  - Some outgassing in optical fibers due to VTRx → inspection and cleaning
- RICH and UT are ready for 2025 data taking!



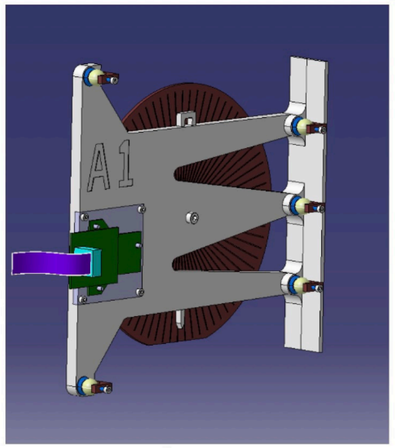



# MAGNET

- Improve magnetic field map
- Some material in the cavern not included in the field map simulation
- Would reduce the dependence on the momentum scaling by having a more accurate field map



-> UT Rail Frame (upstream plane)

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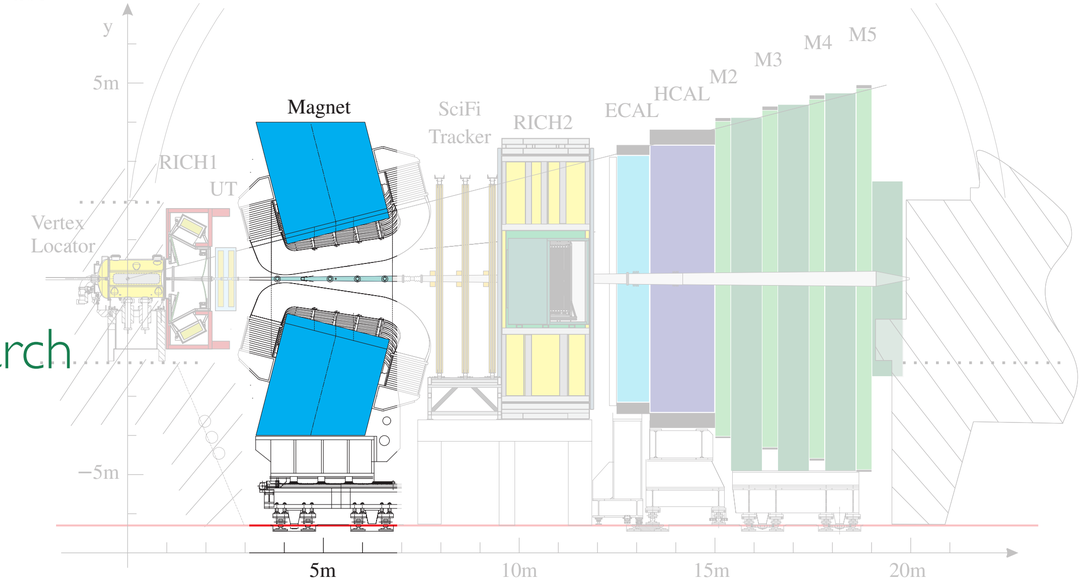
SciFi Stick on Fixture
(downstream plane)

Rail to be installed near UT and SciFi to fix sensors

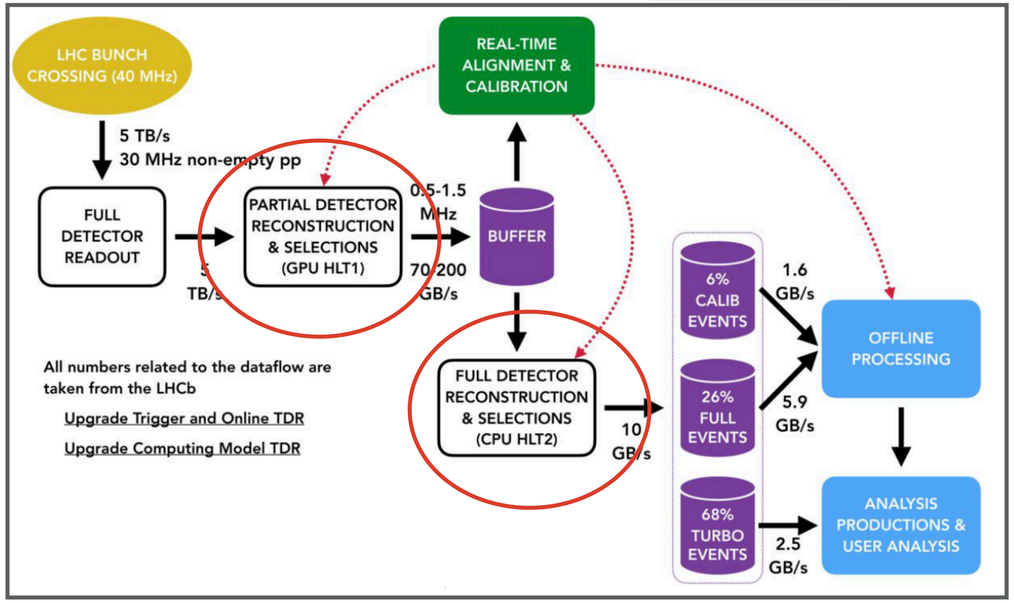
Operation planned in March

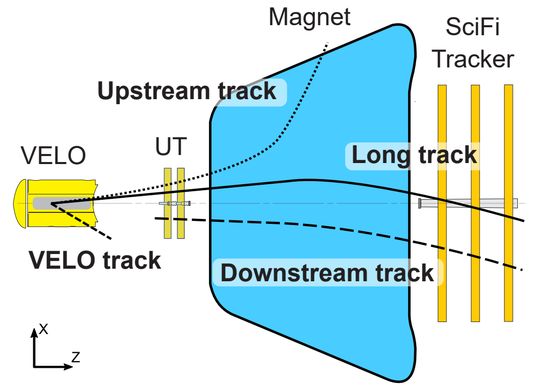


# SOFTWARE OPERATIONS

# RTA - HLT1 and HLT2

- Many developments to improve both HLT1 and HLT2 reconstruction, especially on the UT tracking, and low momentum charged particles.
- Aging of the calorimeter affects the photon detection, plan to fully automatize calorimeter calibration.
- Final bandwidth has to be re-assessed with new detector conditions and optimization of HLT1 and HLT2 selections ongoing by the different physics working groups.

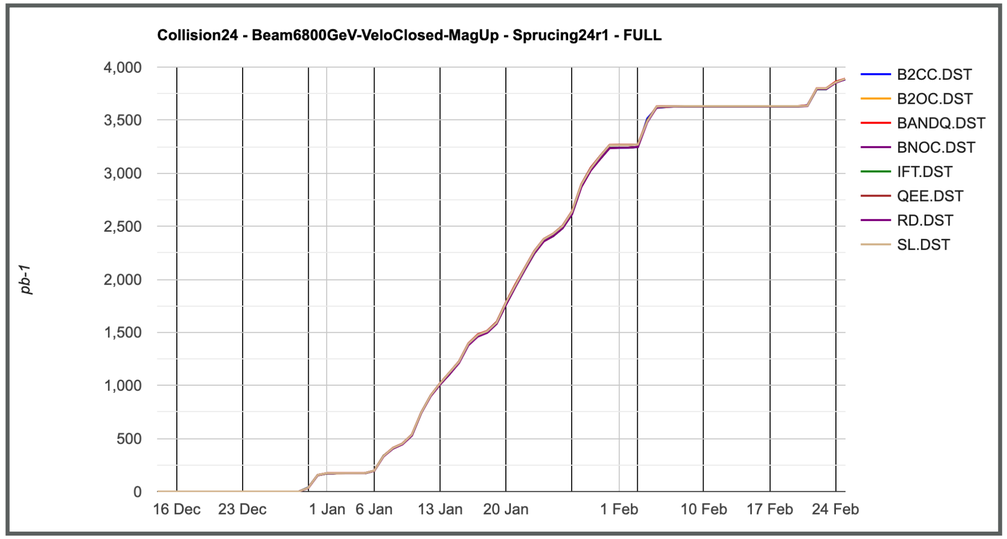


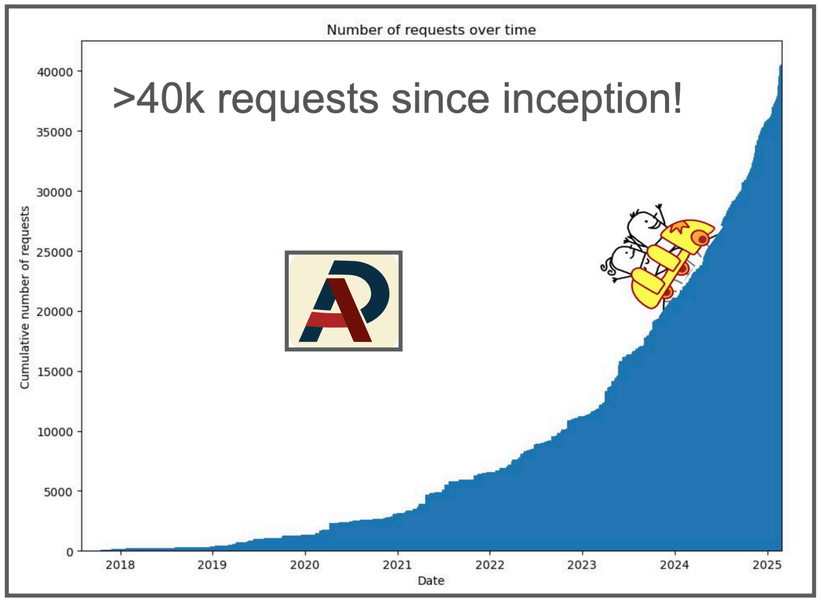




Work very advanced for 2025 data taking

# DPA: Data Processing & Analysis

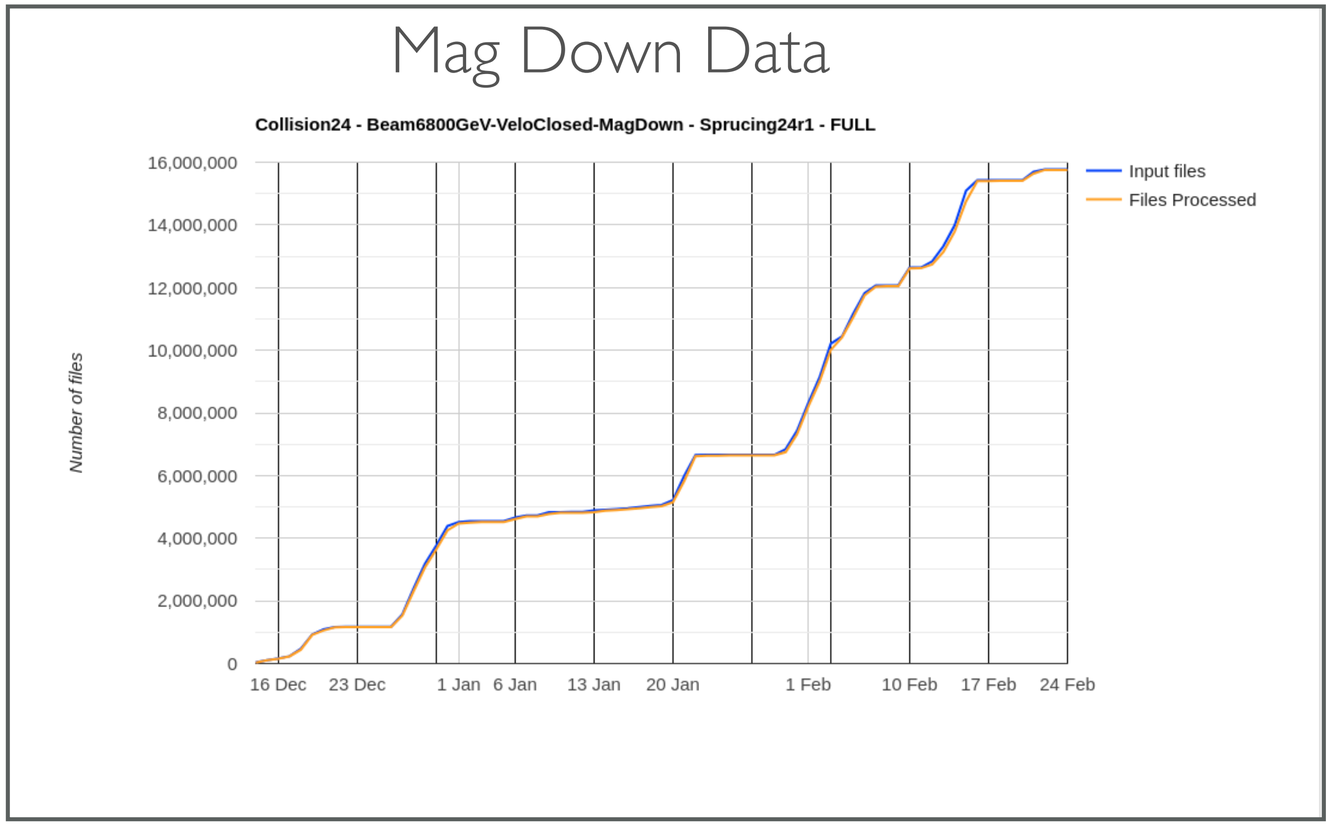
- Sprucing - central offline skimming and slimming
  - 2024 pp resprucing allows recover 9PB disk
  - November ION spruced - analysis already starting!
- Analysis Production - declarative tupling using centralised productions on WLCG
  - New development to better monitor storage
- The LHCb ntupling service for open data accessibility is now in public Beta



# Computing status

- Ongoing (re)processing of data from 2024 (new selections) and some run 2 fixed target.
- Smooth running of LHCb Grid is critical for these campaigns
- NIKHEF and Lanzhou are now T2D providing additional disk capacity
- Sufficient Grid capacity for 2025 data taking
  - Thanks to funding agencies!



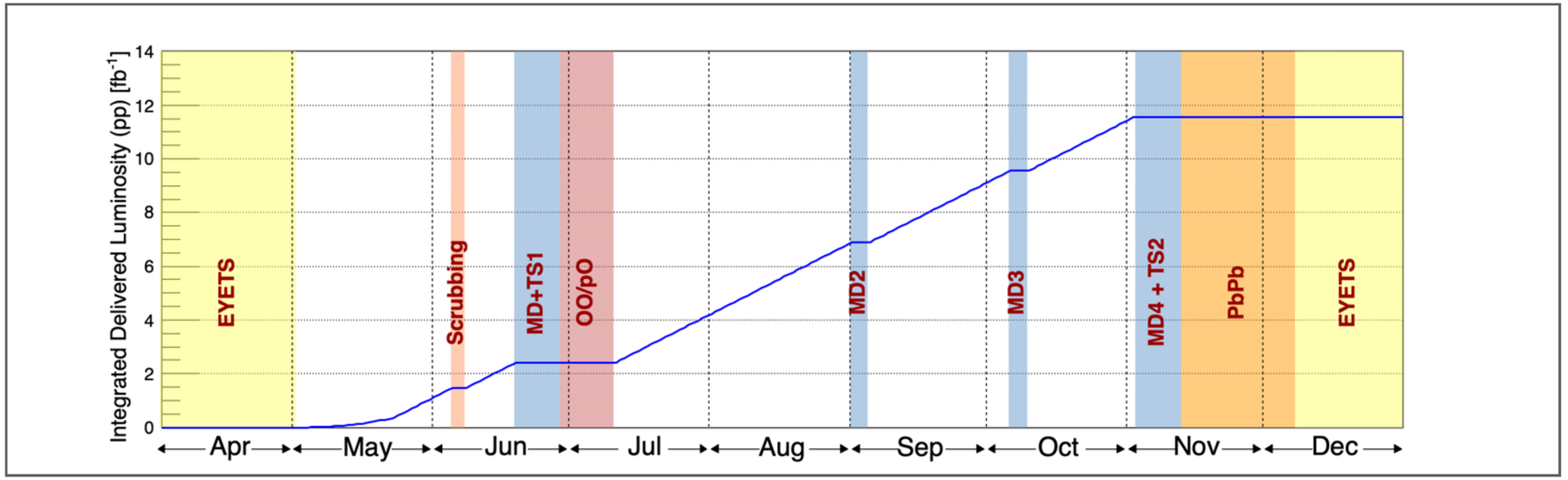
# Simulation

- Made good use of the online farm for simulation production during YETS
- Production ongoing for the corresponding 2024 data samples (pp, PbPb, fixed-target)
- Development to further improve detector description
- Fast simulation development
  - Point library method under review (more here)
  - Machine learning approach under review (more here)
- Progress for Upgrade II – All the tracking detector are now integrated

# Data taking plan for 2025

- Top priority: accumulating large pp sample in stable conditions
  - Target for 2025 12 $\mathrm{fb}^{-1}$ delivered luminosity
  - Target for PbPb 0.7-0.8 $\mathrm{nb}^{-1}$ delivered luminosity (target for entire run 3 is 2 $\mathrm{nb}^{-1}$)
  - Expected pPb/Pbp (run 3+4) 300 $\mathrm{nb}^{-1}$ delivered luminosity for each configuration

And all the different fixed target samples!

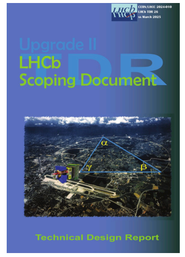



- Specials runs 2025 OO - pO
  - pO target 2 $\mathrm{nb}^{-1}$ delivered luminosity
    - Crucial for nPDFs determination at low Bjorken-x, important for extrapolation between p and heavier nuclei (Pb/Au)
  - OO target 0.5 $\mathrm{nb}^{-1}$ delivered luminosity
    - Unique conditions to detect QGP effects with no detector saturation

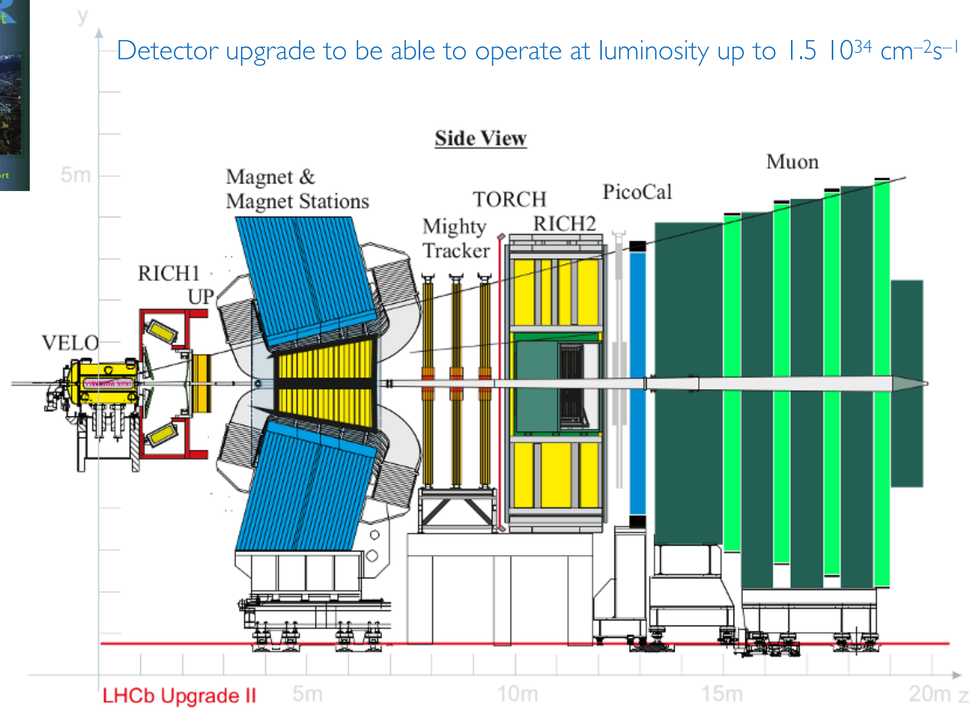
# LHCB UPGRADE II

# LHCb Upgrade II

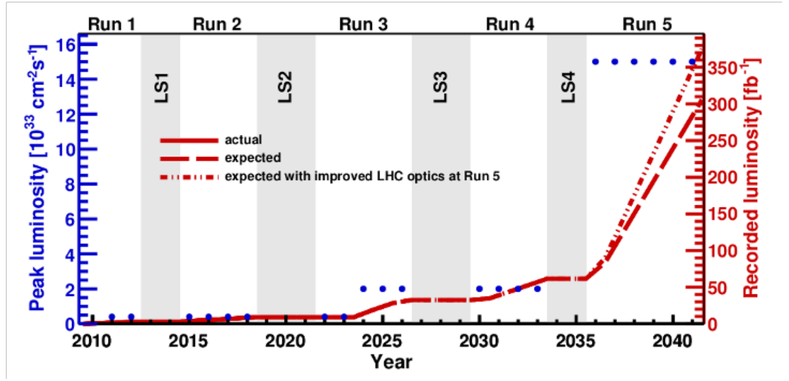
- Final recommendation by LHCC referees this week
- Heidelberg Upgrade II workshop in March to move towards a TDR in 2026
- Preparing documents for ESPPU:
  - Discovery potential of LHCb Upgrade II (LHCb-PUB-2025-001)
  - Technology developments for LHCb Upgrade II (LHCb-PUB-2025-002)
  - Heavy ion physics with LHCb Upgrade II (LHCb-PUB-2025-003)
  - Computing and software for LHCb Upgrade II (LHCb-PUB-2025-004)
  - Projections for Key Measurements in Heavy Flavour Physics – with ATLAS, CMS and Belle II




Detector upgrade to be able to operate at luminosity up to 1.5 $10^{34}$ $cm^{-2}s^{-1}$



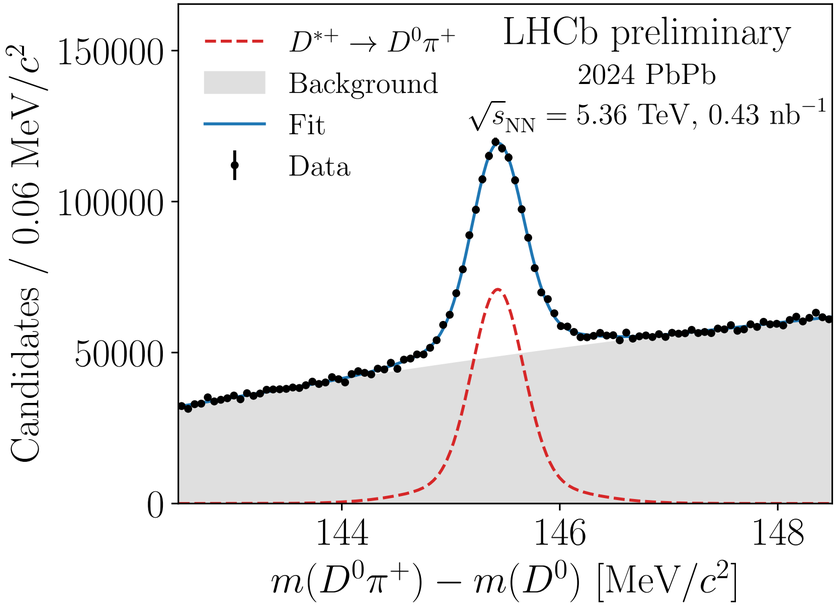

« 4D » reconstruction with timing handling of unprecedented data rates

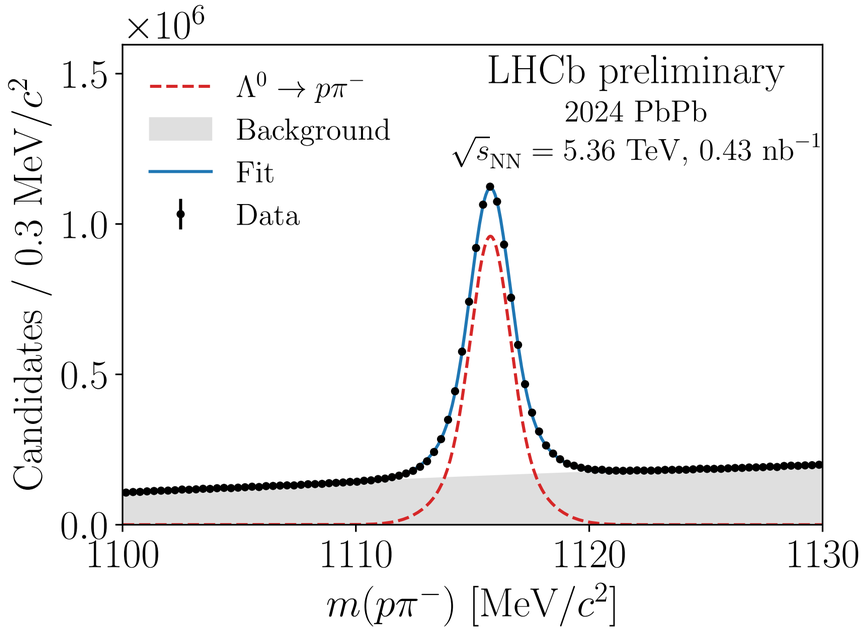


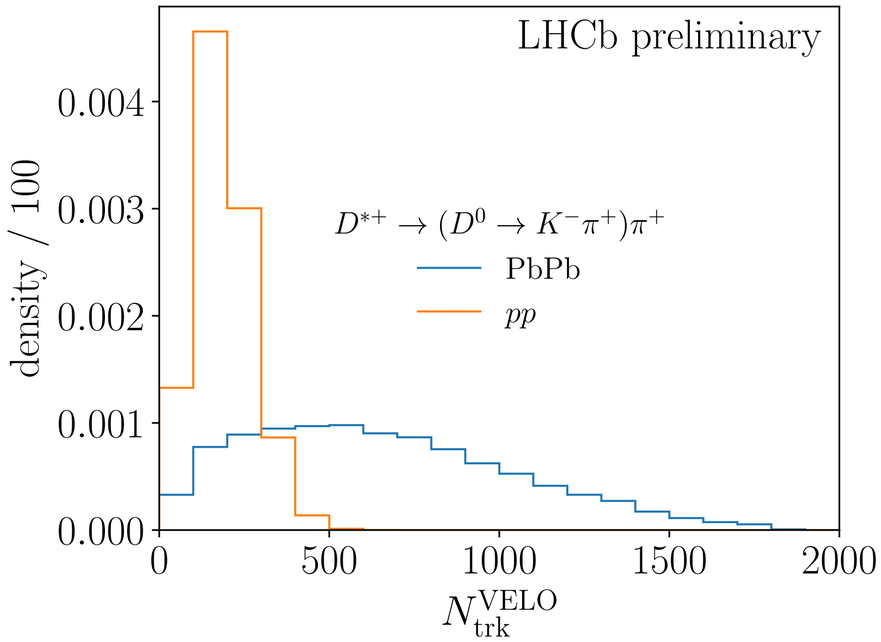

# Conclusion

- First look at data already shows the success of the heavy-ion data taking of 2024:
  - Three samples, one in collider mode (PbPb), and two fixed-target (PbAr and PbNe)
  - Large statistics for open charm signals in PbPb, will allow multi-dimensional analyses down to 30% centrality. LHCb is also entering the era of *b* physics in heavy-ion collisions
- Many YETS interventions done/ongoing
  - Maintenance work, most of detector ready to start 2025 operations
  - Push further LHCb performances (removal of VELO shims, magnetic field measurement, improved reconstruction in HLT1 and HLT2)
- Optimization of data storage size by improving the physics selections thanks to experience gained with 2024 data

# PID


LHCb preliminary
2024 PbPb
$\sqrt{s_{\mathrm{NN}}} = 5.36$ TeV, 0.43 nb$^{-1}$
$D^{*+} \to D^0\pi^+$
Background
Fit
Data
Candidates / 0.06 MeV/$c^2$
150000
100000
50000
0
144
146
148
$m(D^0\pi^+) - m(D^0)$ [MeV/$c^2$]


$\times 10^6$
LHCb preliminary
2024 PbPb
$\sqrt{s_{\mathrm{NN}}} = 5.36$ TeV, 0.43 nb$^{-1}$
$\Lambda^0 \to p\pi^-$
Background
Fit
Data
Candidates / 0.3 MeV/$c^2$
1.5
1.0
0.5
0.0
1100
1110
1120
1130
$m(p\pi^-)$ [MeV/$c^2$]

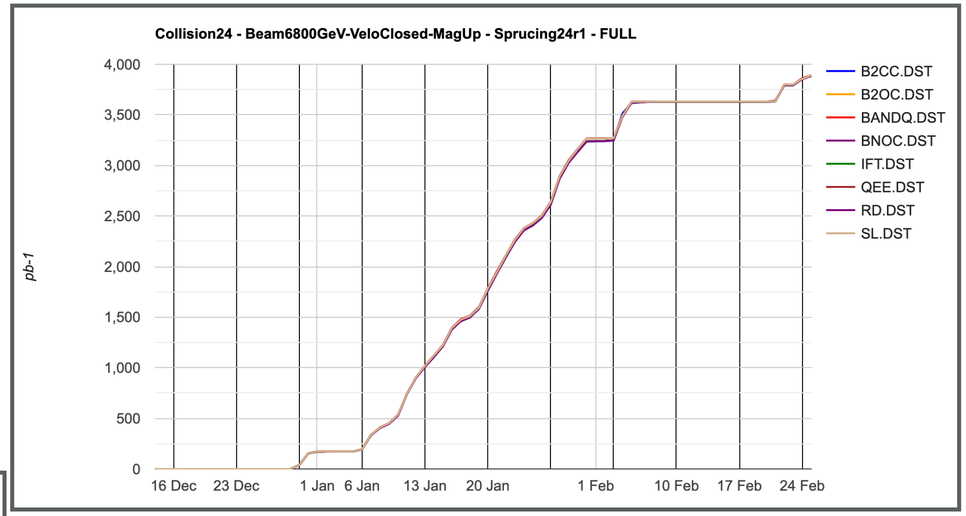

LHCb preliminary
$D^{*+} \to (D^0 \to K^-\pi^+)\pi^+$
PbPb
$pp$
density / 100
0.004
0.003
0.002
0.001
0.000
0
500
1000
1500
2000
$N_{\mathrm{trk}}^{\mathrm{VELO}}$

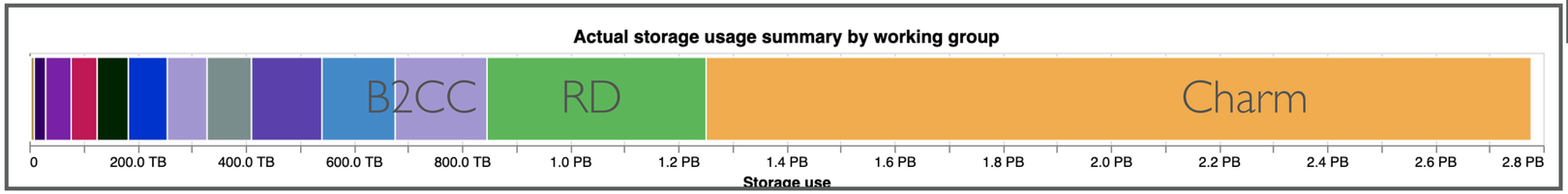
# Civil Engineering work

"UGC1" gallery. The plan is to use this gallery in LS3 as a buffer/storage area for the ECAL modules.

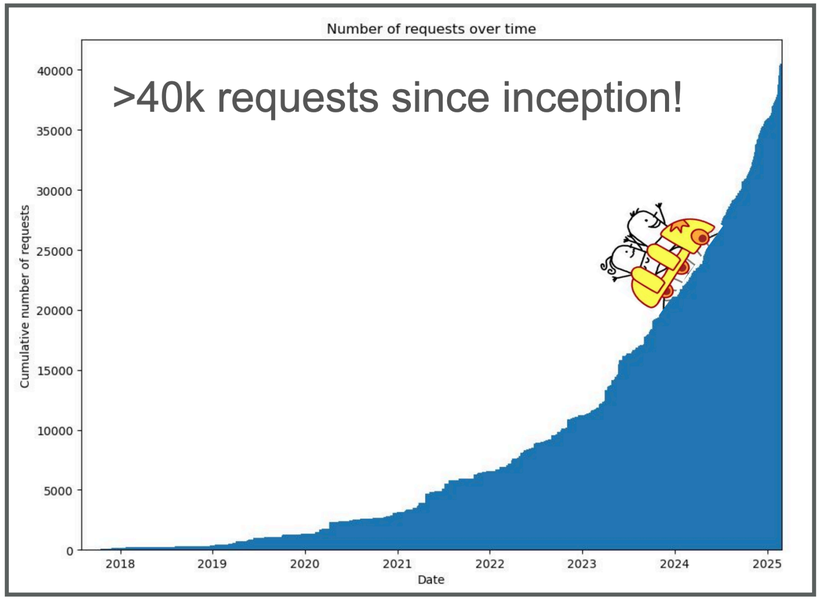
# DPA: Data Processing & Analysis

- Sprucing - central offline skimming and slimming
  - Resprucing full persistency streams to exploit further 2024 pp data
  - By additionally Sprucing the low persistency stream can remove previously inherent data duplication between streams - recover 9PB disk
  - November ION spruced - analysis already starting!
- Analysis Production - declarative tupling using centralised productions on WLCG
  - New development to better monitor storage



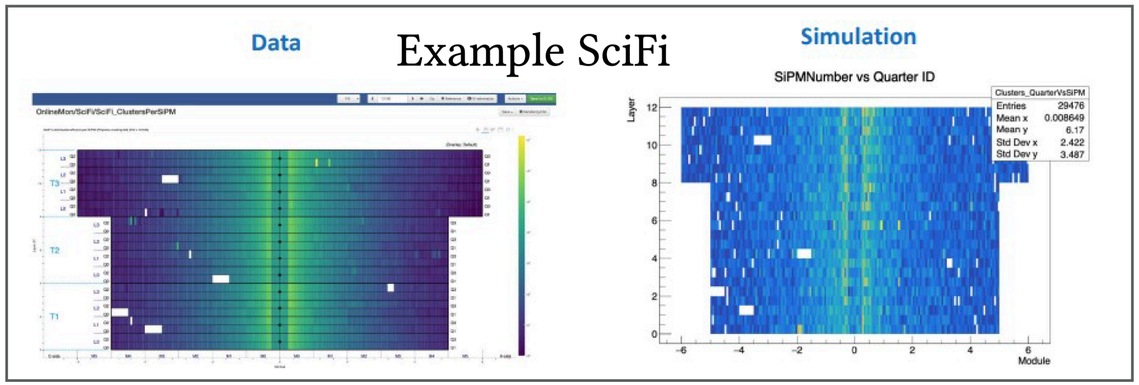




- The LHCb ntupling service for open data accessibility is now in public Beta
  - Run 2 open data release approved by CB in January
  - Hopefully public release later this year
- Run 3 Starterkit "First Analysis Steps" are public!
  - « Second analysis steps » coming soon



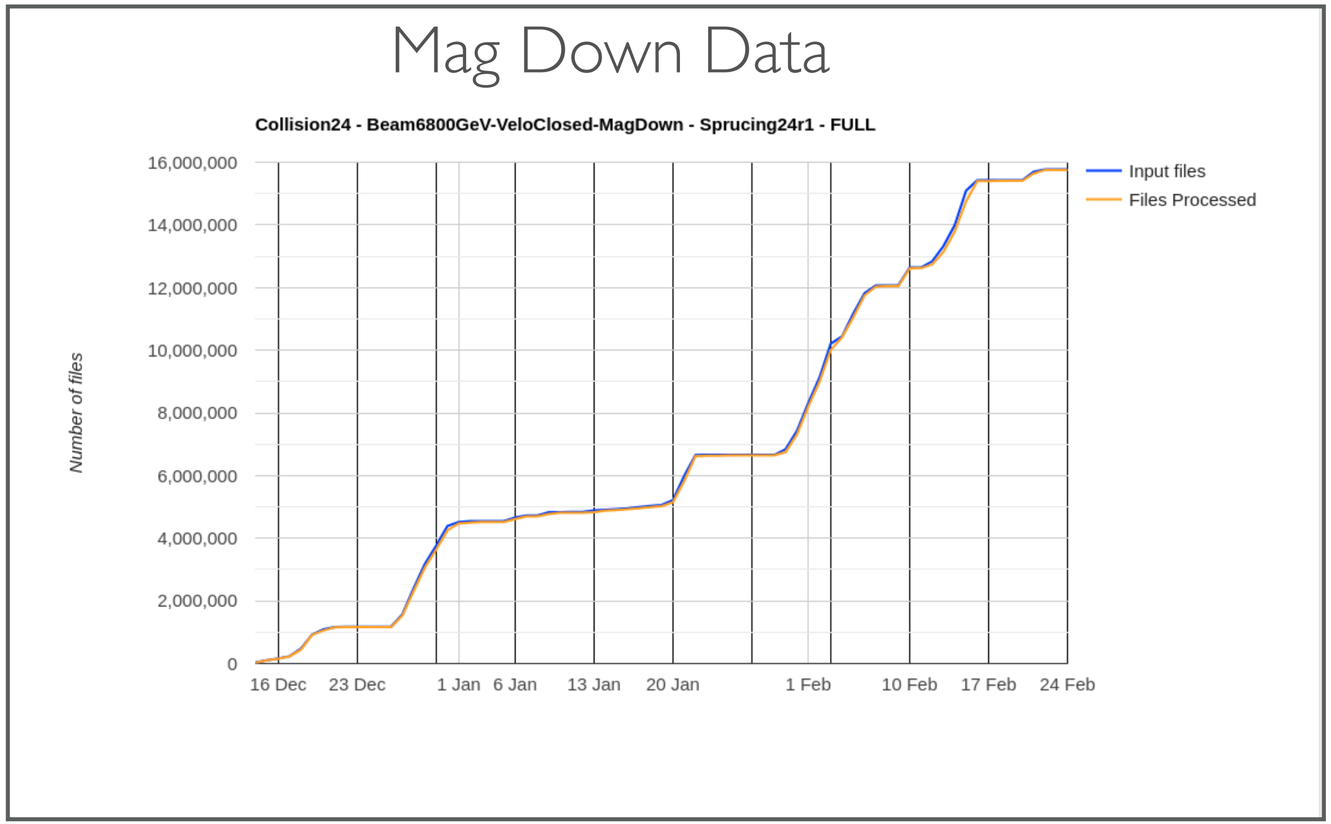
# Simulation

- Made good use of the online farm for simulation production during YETS
- Filtered productions (by HLT1, HLT2 and Sprucing lines) available for 2024 samples
- Sim10e deployed and Sim10f coming very soon
  - Significant sub-detector updates for hit efficiencies and material description
- Working towards new simulation version with DD4hep – Sim11
  - Anticipated to replaced Sim10 later this year for Run 3 productions
- Fast simulation development
  - Progress on fast calorimeter simulation (ECAL takes 50% of the detector simulation time)
  - Point library method under review, targeting Sim10
  - Machine learning approach under review, targeting Sim11
- Progress for Upgrade II – Sim11
  - Tracking system in, with descoped options now also available
  - Magnet stations, TORCH and ECAL making progress
  - Work on pile-up and decaying luminosity modelling underway



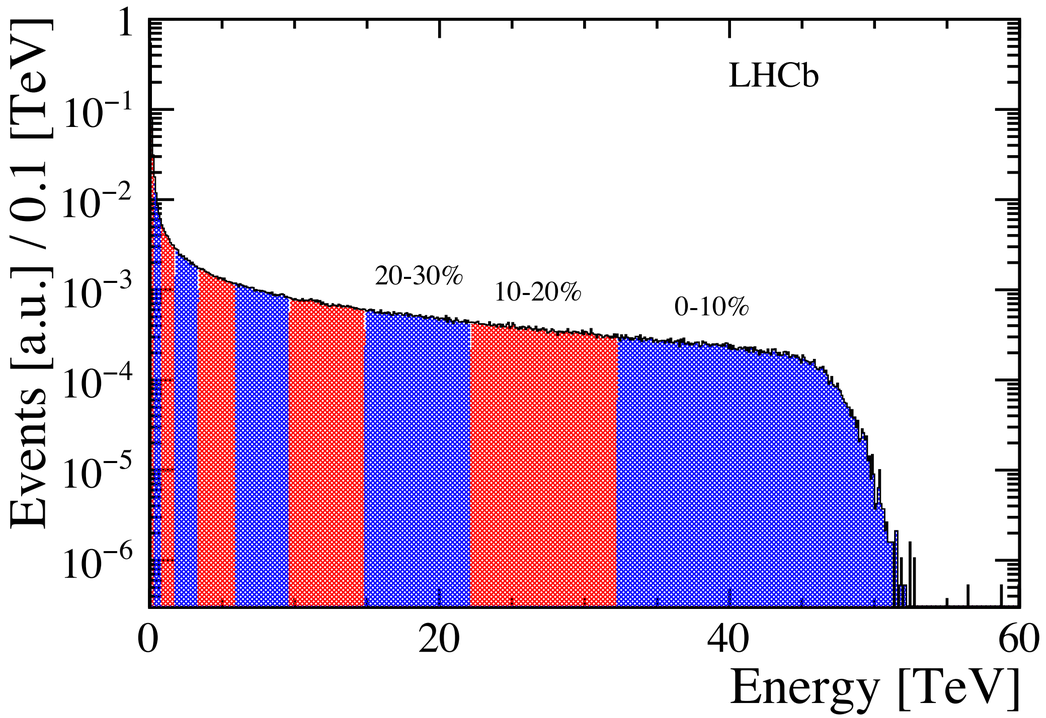
# Computing status

- Ongoing (re)processing of data from 2024 (save space!)
- 2024 Proton data FULL stream re-sprucing
  - Expecting to be completed  by the end February
- 2024 proton-Ion data re-sprucing
  - Processing started, almost done
- Also: Run-2 Proton SMOG data reprocessing
  - Processing starting now
- Smooth running of LHCb Grid is critical for these campaigns
  - Progress on the issues of CNAF Storage system
  - NIKHEF and Lanzhou providing additional disk capacity
- Sufficient Grid capacity for 2025 data taking
  - Thanks to funding agencies!



# Centrality

- In the following slides, we present invariant mass plots in different centralities
- The centrality is not yet measured with the 2024 sample, so we use the results from 2018 as we have the same calorimeter and almost same colliding energy




| Centrality % | E [ GeV ] | $N_{\text{part}}$ | $\sigma_{N_{\text{part}}}$ | $N_{\text{coll}}$ | $\sigma_{N_{\text{coll}}}$ | $b$ | $\sigma_b$ |
|---|---|---|---|---|---|---|---|
| $100-90$ | $0-310$ | 2.9 | 1.2 | 1.8 | 1.2 | 15.4 | 1.0 |
| $90-80$ | $310-800$ | 7.0 | 2.9 | 5.8 | 3.1 | 14.6 | 0.9 |
| $80-70$ | $800-1750$ | 15.9 | 4.8 | 16.4 | 7.0 | 13.6 | 0.7 |
| $70-60$ | $1750-3360$ | 31.3 | 7.1 | 41.3 | 14.7 | 12.6 | 0.6 |
| $60-50$ | $3360-5900$ | 54.7 | 10.0 | 92.6 | 27.7 | 11.6 | 0.5 |
| $50-40$ | $5900-9630$ | 87.5 | 13.3 | 187.5 | 46.7 | 10.5 | 0.5 |
| $40-30$ | $9630-14860$ | 131.2 | 16.9 | 345.5 | 71.6 | 9.2 | 0.5 |
| $30-20$ | $14860-22150$ | 188.0 | 21.5 | 593.9 | 105.2 | 7.8 | 0.6 |
| $20-10$ | $22150-32280$ | 261.8 | 27.1 | 972.5 | 151.9 | 6.0 | 0.7 |
| $10-0$ | $32280-\infty$ | 357.2 | 32.2 | 1570.3 | 236.8 | 3.3 | 1.2 |

Total energy deposit in ECAL



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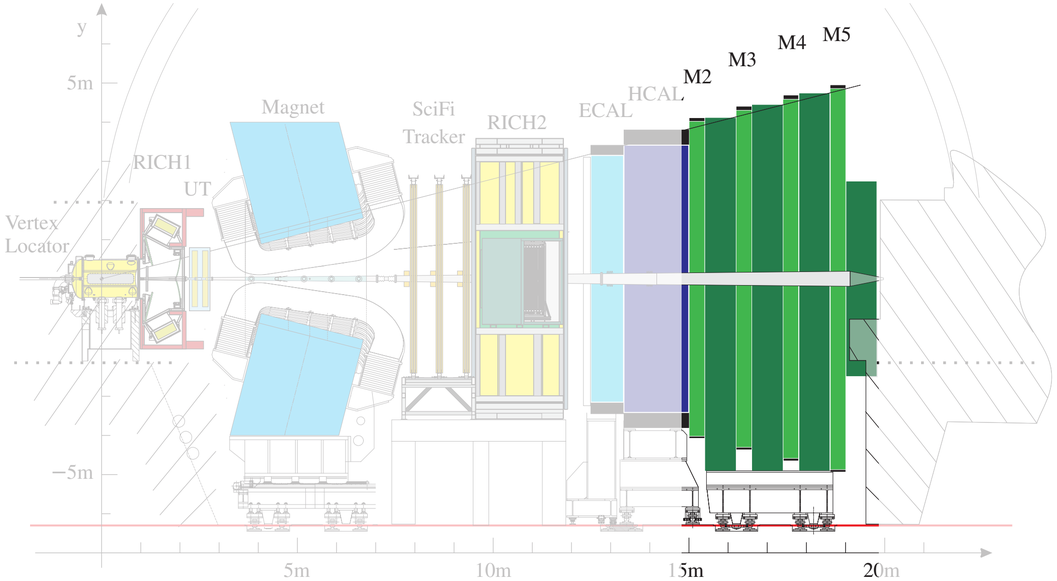
# Muon stations

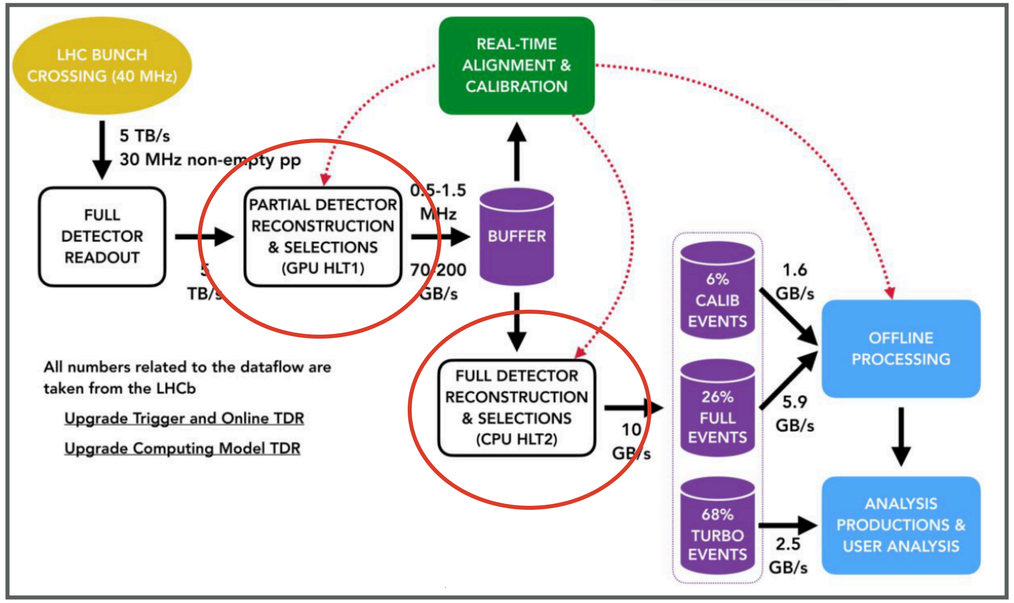
- Some maintenances work for example:
- High Voltage:
  - 4 out of 1368 muon MWPC chambers have been replaced;
  - 5 voltage regulators and one CAEN board have been replaced;
- Low Voltage
  - 5 FEBs have been replaced
- Shielding test for Upgrade II

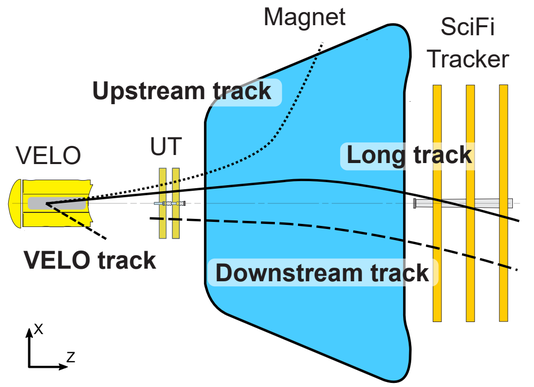
MUON runs in local, no issues.



# RTA - HLT1 and HLT2 Reconstruction

- HLT1 - Trigger based on fast partial reconstruction (GPU)
  - Development to improve performances for 2025 data taking
    - Diverse improvement to the UT tracking, better efficiency to Long and downstream tracks, better throughput…
    - Improve robustness of the VELO in case of missing modules
    - Plan to use a full Kalman Filter, leading to a better mass resolution and better ghost rejection
- HLT2 - Trigger based on full detector reconstruction (CPU)
  - Major update on low momentum tracking (VELO-UT), more than double efficiency increase
  - Effort to assess and improve calo reconstruction → Improved efficiency for high occupancy collisions

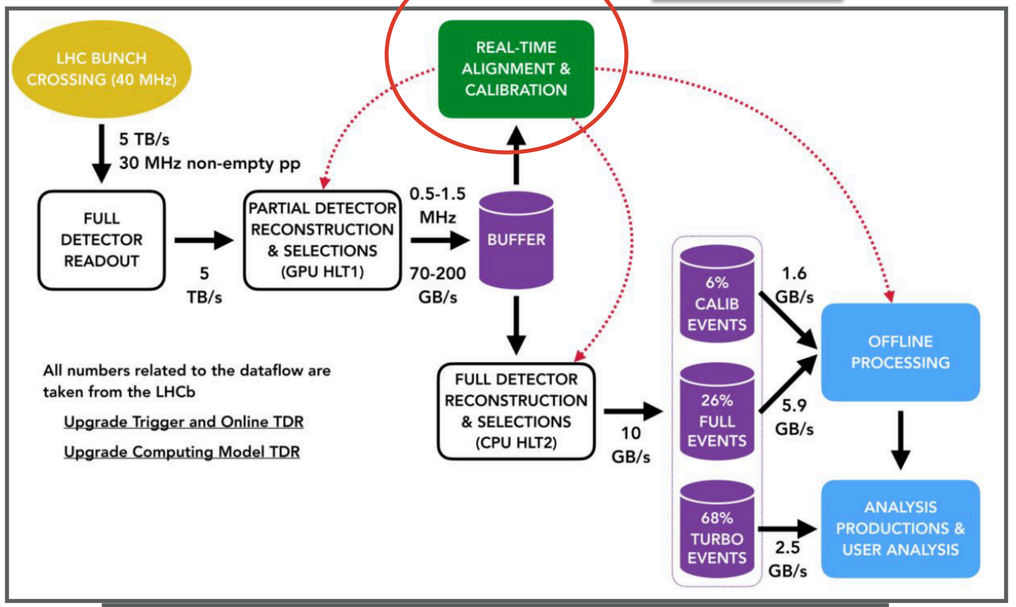



Most of improvements ready for 2025 data taking

# RTA - Calibration and alignment

- Calorimeter energy calibration:
  - Aging of calorimeter affect photon measurement over time
  - Plan to fully automatize calibration based on $\pi^0 \to \gamma\gamma$
- Final bandwidth has to be re-assessed with new detector conditions and optimization of HLT1 and HLT2 selections ongoing by the different physics working groups




- Tracking resolution studies made with $J/\psi \to \mu^+\mu^-$ decays shows a relative momentum resolution of long tracks mostly below 1%! Similar performance expected for 2025