The upgraded LHCb detector at the start of Run 3: from commissioning to physics production

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TU Dortmund Particle Physics Seminar

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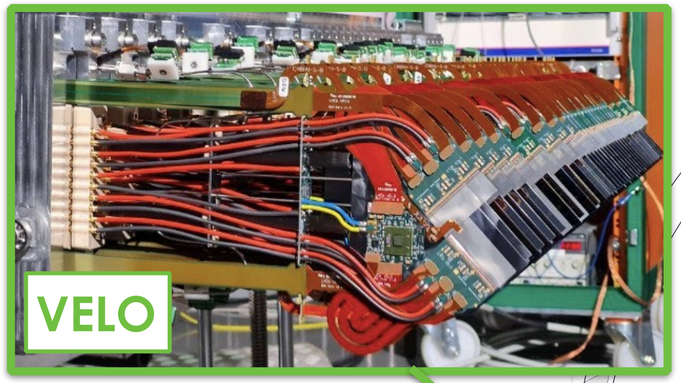
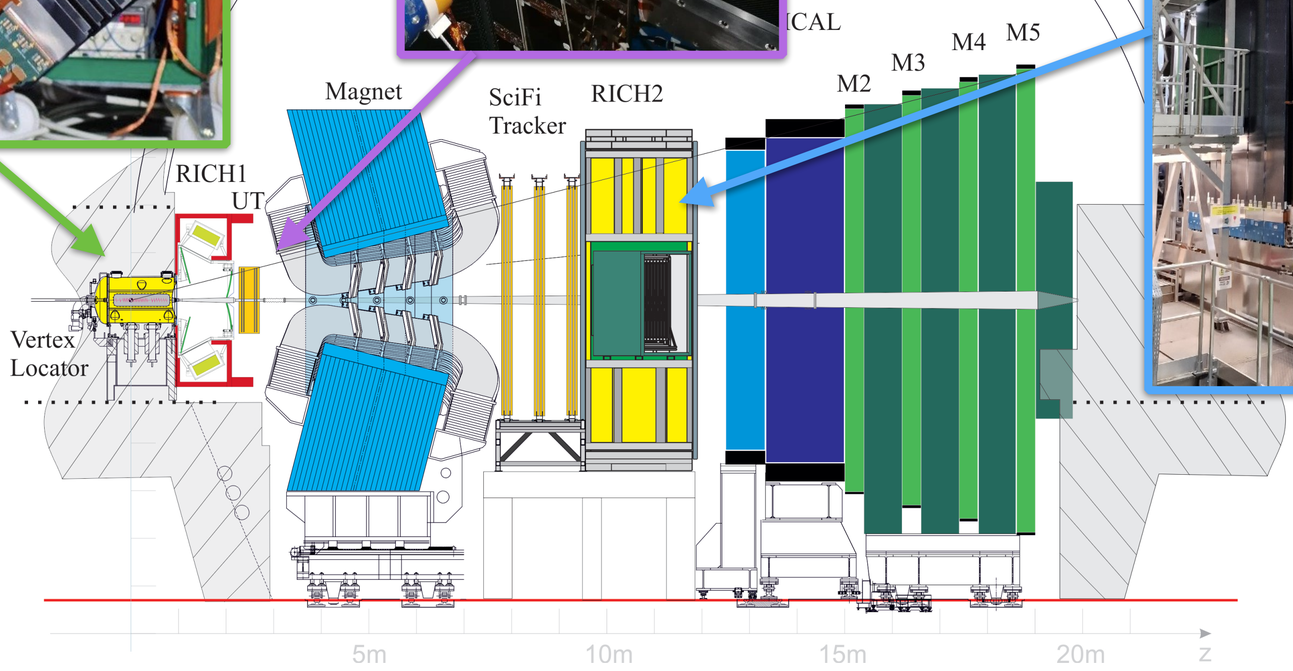
LHCb Upgrade at a glance

Brand new detector!

- 5x instantaneous lumi from $4x10^{32}$ cm^{-2} s^{-1} to $2x10^{32}$ cm^{-2} s^{-1}
- average number of visible pp collisions $\mu = 5.5$

tracking system completely replaced





- LHCb Upgrade at a glance
  - tracking system
  - PID system
  - luminosity and beam background
  - DAQ and trigger
- How is it going so far?
  - Vacuum incident
- LHC in 2024
- LHCb in 2024
  - VELO closure
  - VdM
  - Alignment & Calibration
  - UT integration
  - HLT1 track reconstruction
  - HLT1 & HLT2
  - Gas injection
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- Performance
  - Detectors
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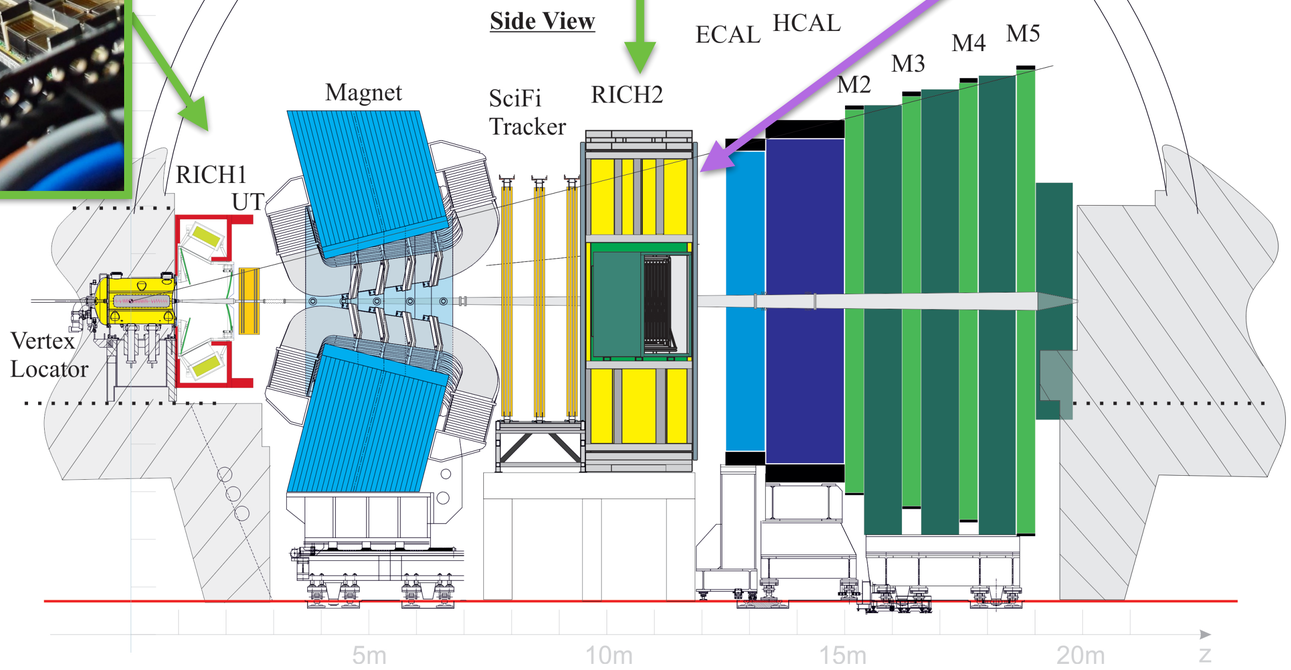
new photo-detectors + new optics

removed first muon station, preshower and scintillating pad detectors + new neutron shielding



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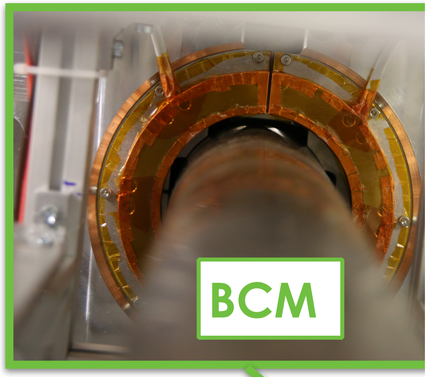
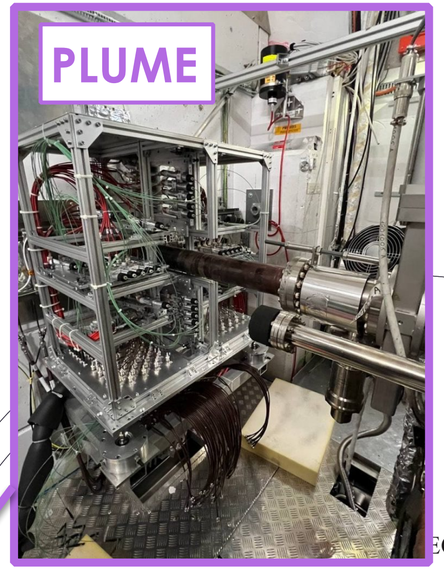
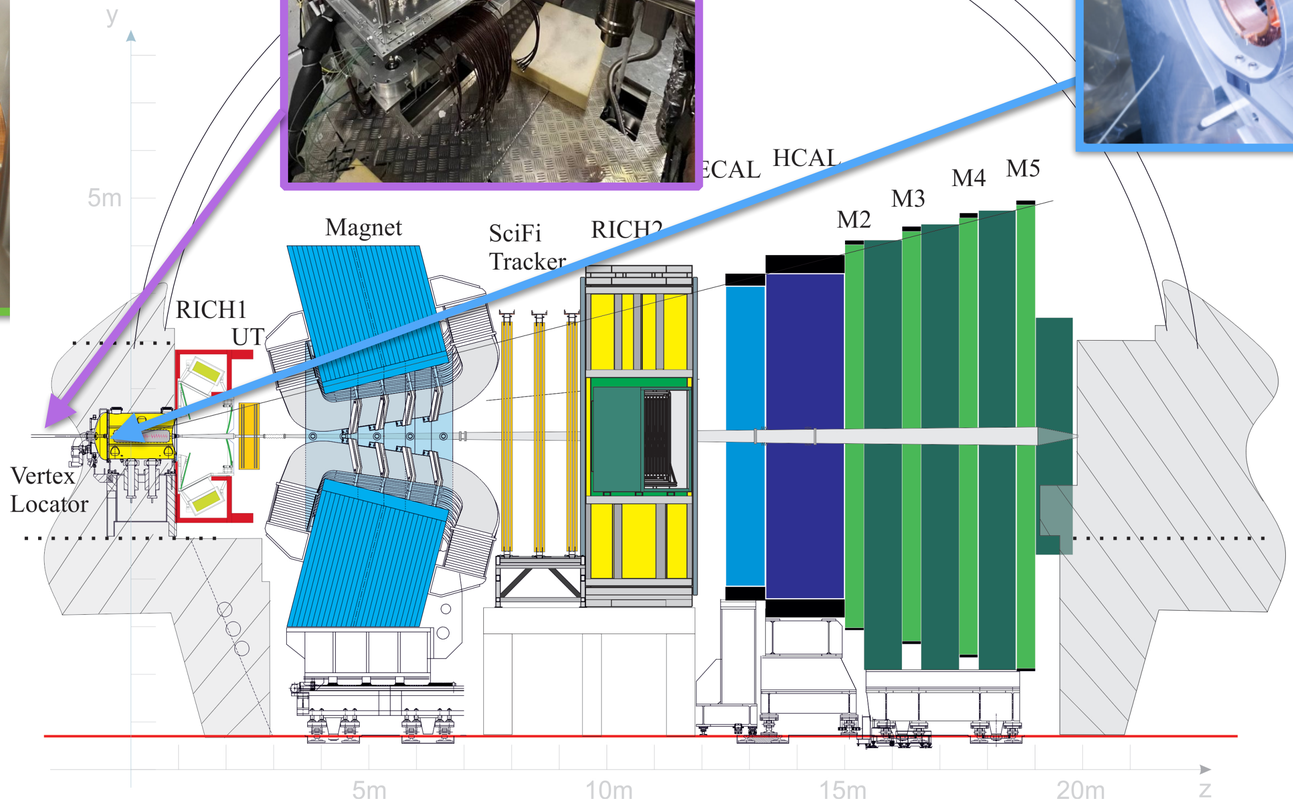


refurbished Beam Conditions Monitor



new luminometer

new gas cell



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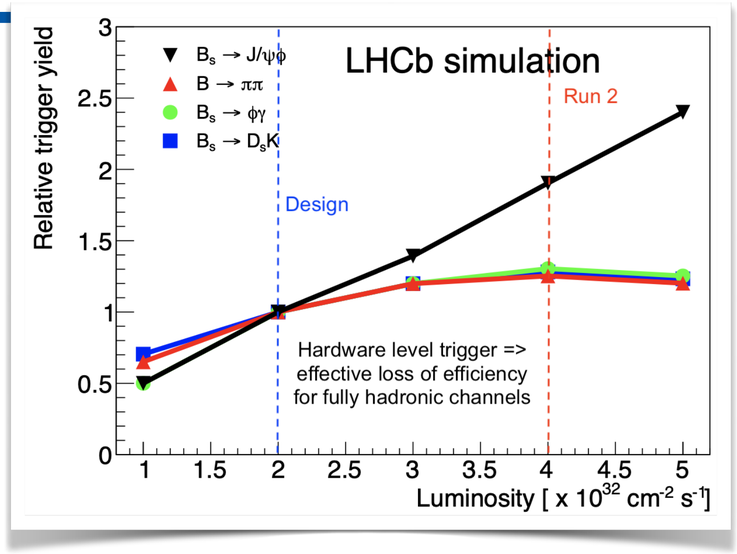
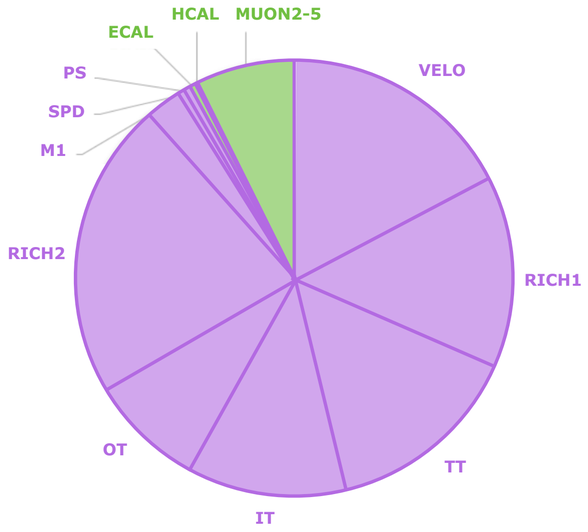
LHCb Upgrade at a glance

readout at 40 MHz

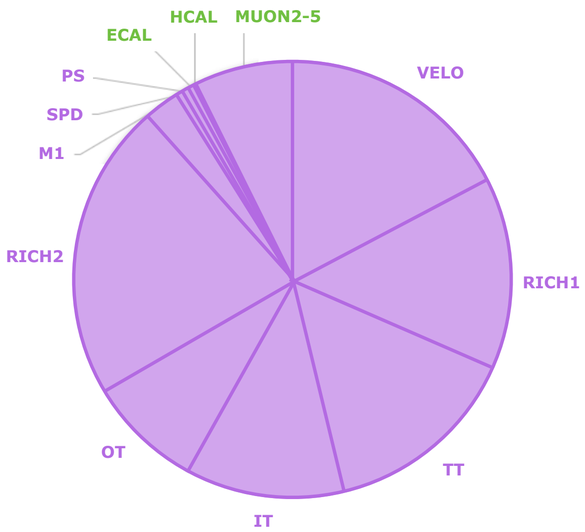
- all electronics and DAQ upgraded
- new timing and fast control distribution
- full software trigger architecture



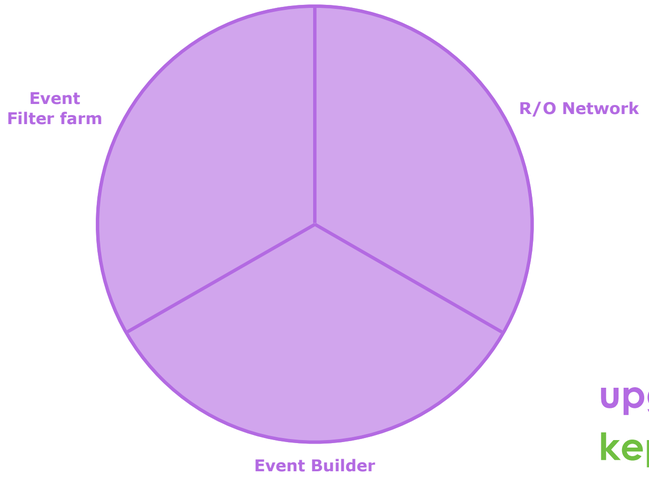
detector channels



R/O electronics



DAQ



upgraded

kept

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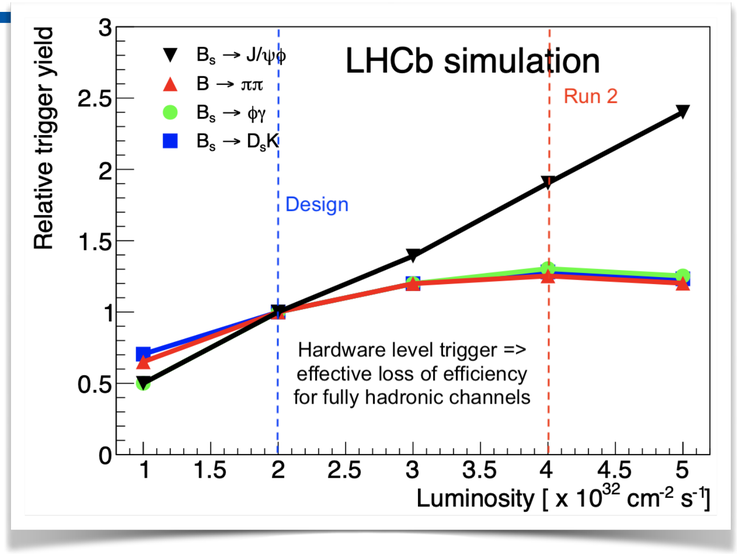

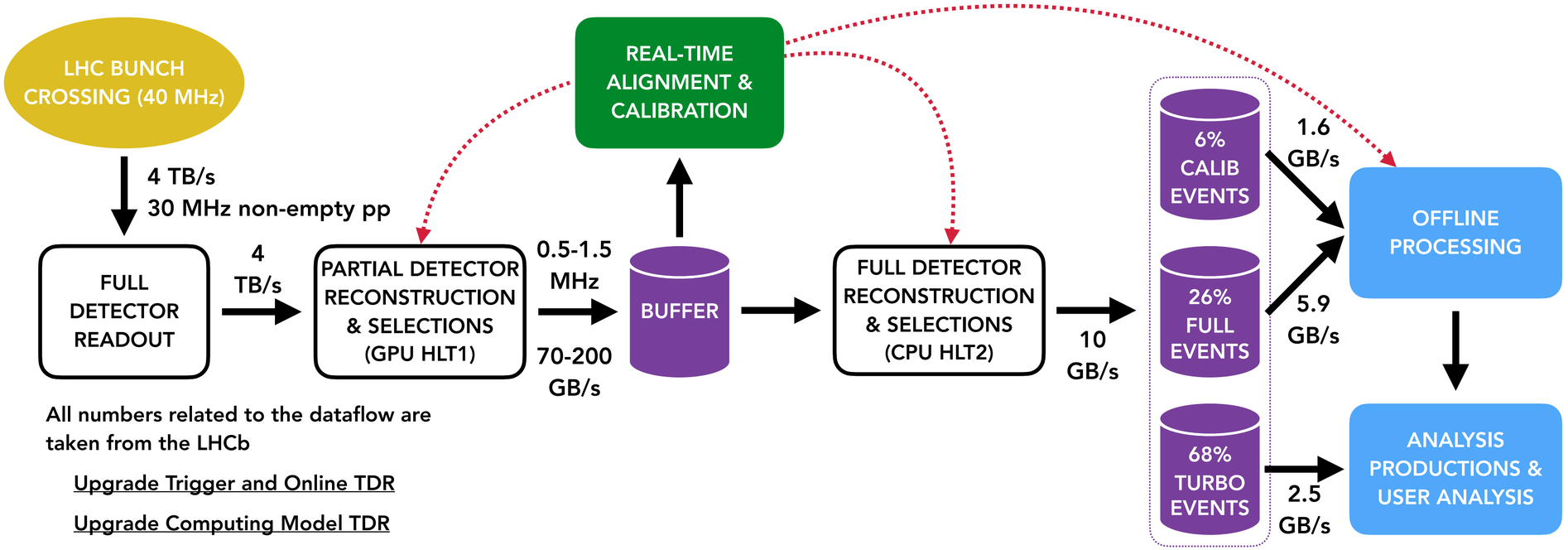

All numbers related to the dataflow are taken from the LHCb

Upgrade Trigger and Online TDR

Upgrade Computing Model TDR

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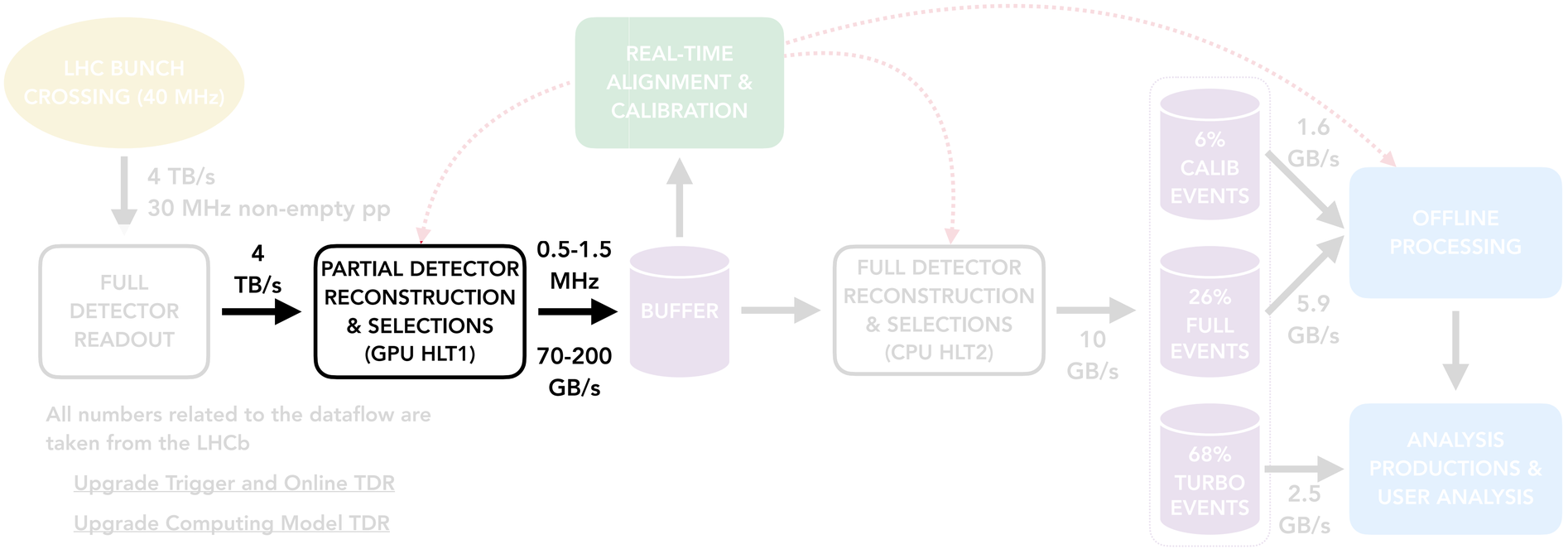
LHCb Upgrade at a glance

HLT1

- mostly track based trigger
- input rate ~26 MHz (all colliding bunches)
- ~50 selection lines (physics + technical)



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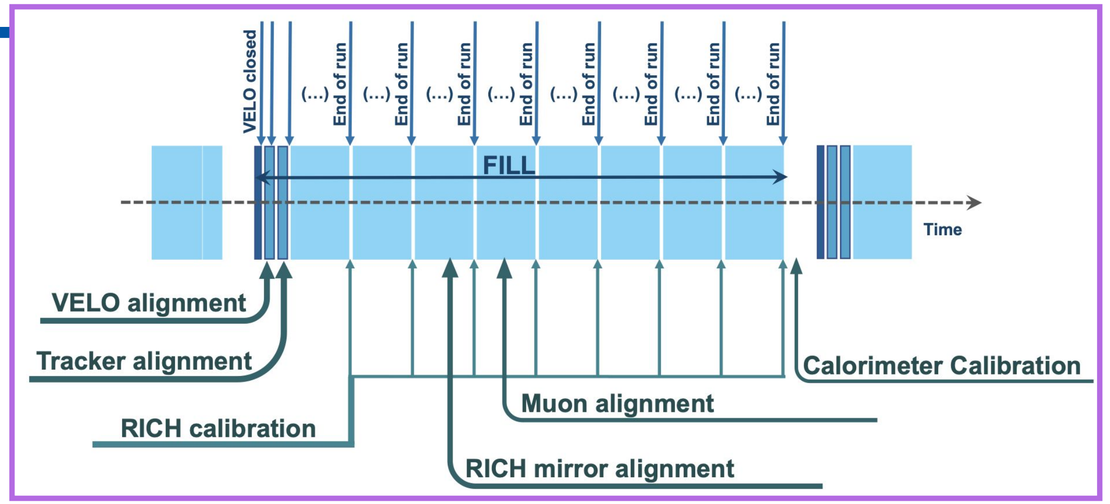
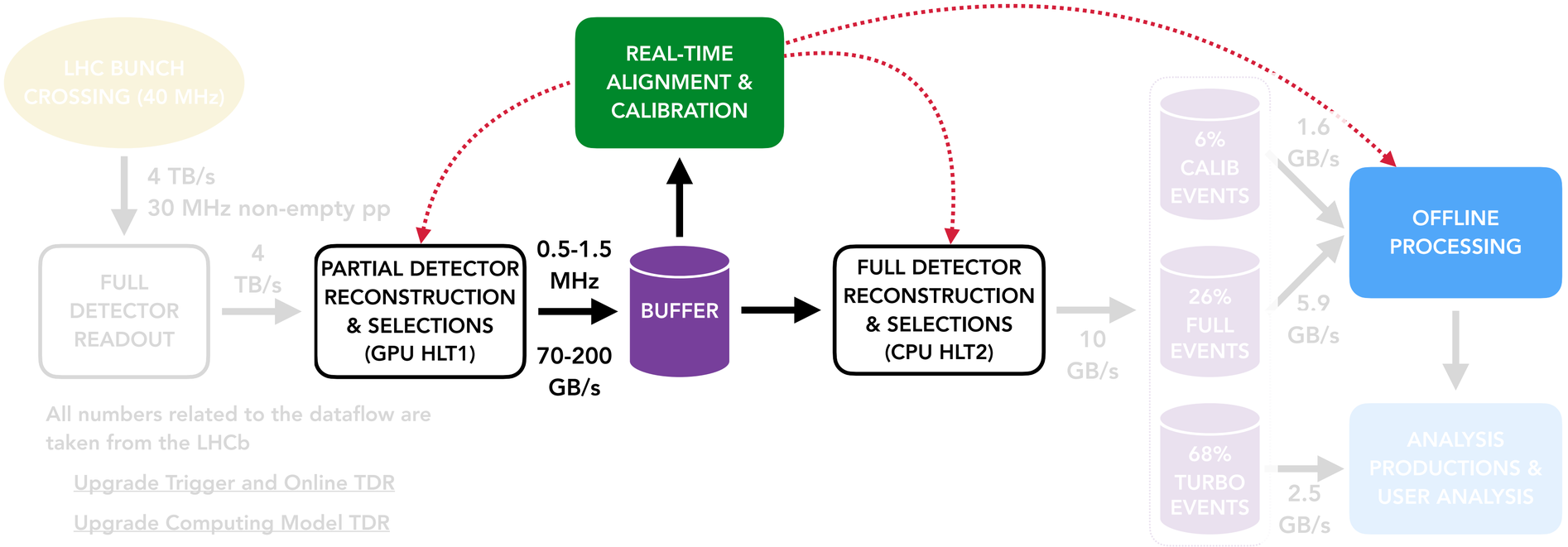
LHCb Upgrade at a glance

A. Scarabotto, CHEP 2024



alignment & calibration

- critical to ensure offline-like quality of HLT2 reconstruction



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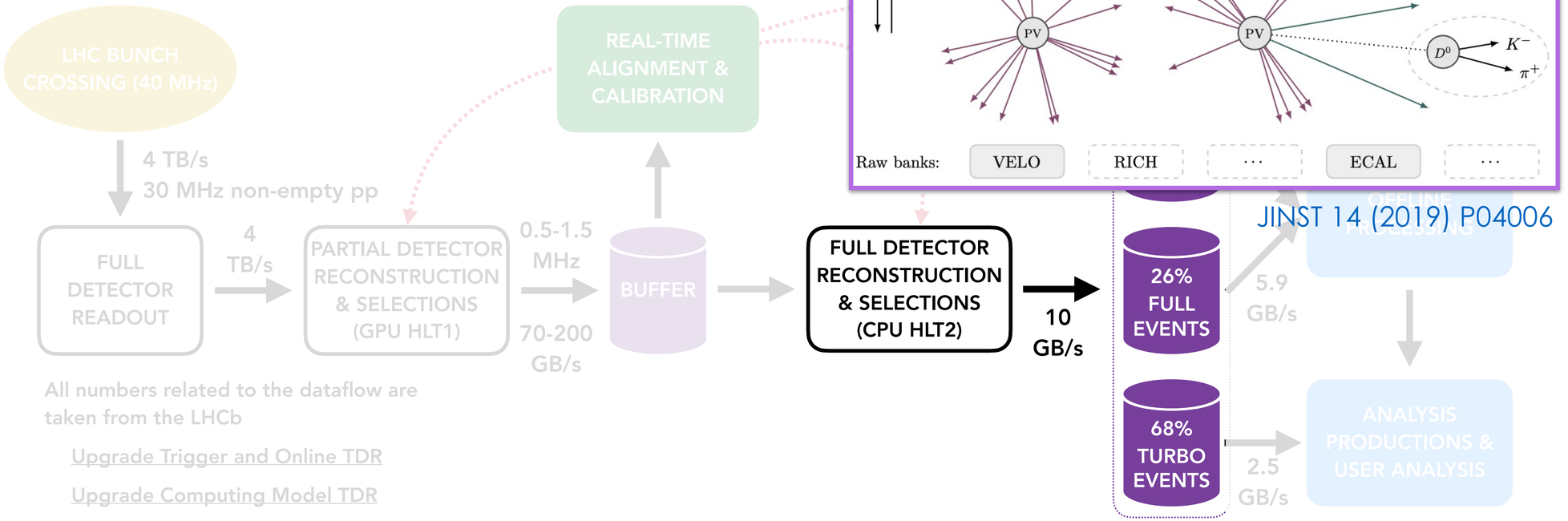
LHCb Upgrade at a glance

HLT2

- runs asynchronously after alignment is performed
- different level of persistency depending on the selection
- ~3000 lines (mostly exclusive)



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How is it going so far?

2022

LHC off
LHC commissioning
pp physics
ion physics
special runs

LHC

unscheduled stop:
RF recovery

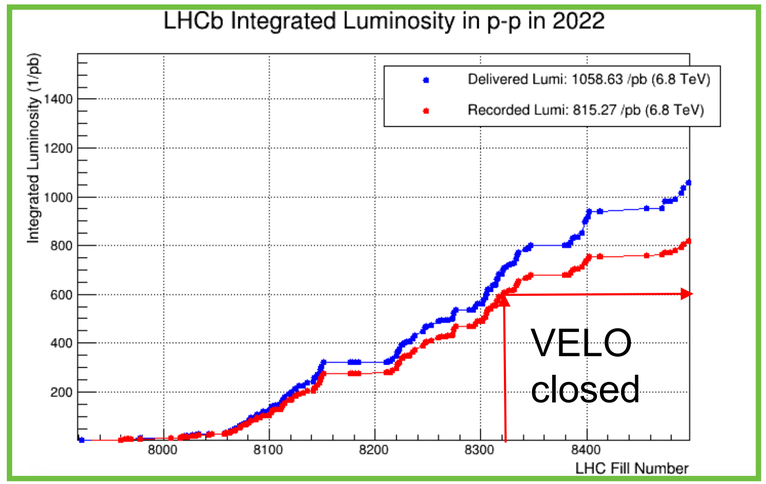
unscheduled stop:
RF cryo incident,
repair and recovery

01/01 LS2 01/08 01/10 EYETS 31/12

commissioning of subdetectors, when stable beams during intensity ramp up (<4w)

commissioning of subdetectors, trigger and alignment

LHCb



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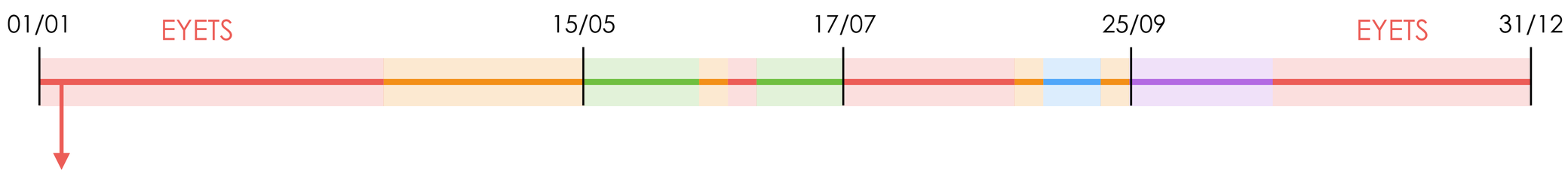
How is it going so far?

2023

LHC



LHC vacuum incident in the VELO

LHCb

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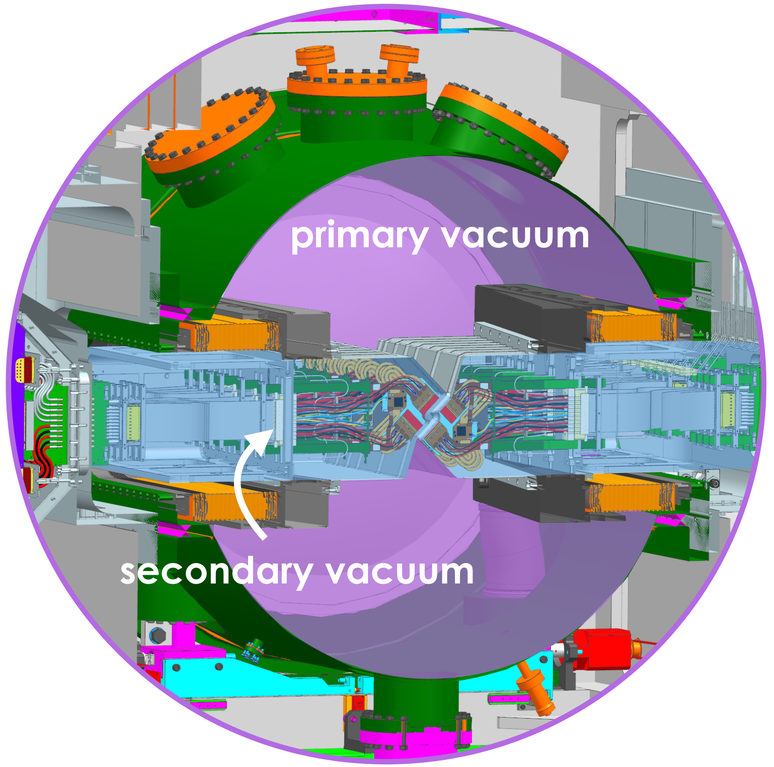
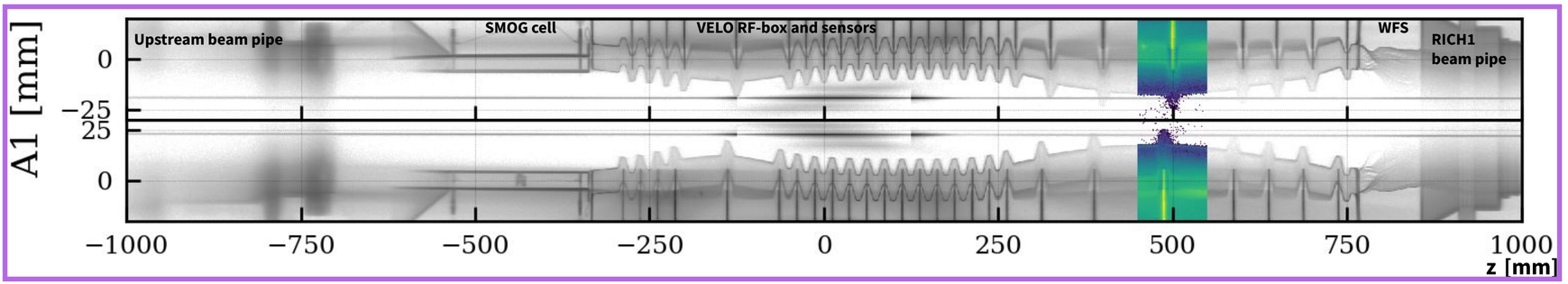
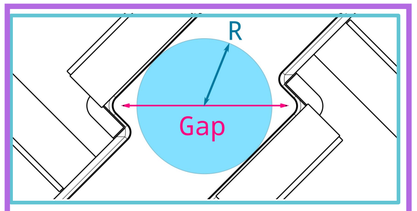
Vacuum incident

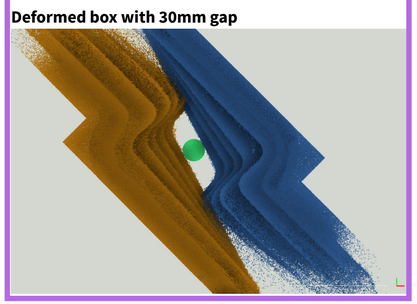


- LHC vacuum incident in the VELO volume led to over pressurisation of the detector volume and deformation of the RF foil
- leading factors to velo position in 2023:
  - deformation of the foil allowing for max 30 mm gap
  - damaged coupling piece in the motion system
- decided not to move the VELO halves at every fill, but keep them fixed to the smallest aperture that allows beam injection
- RF foil replacement in the EYETS23/24

VELO 2023 gap = 49 mm







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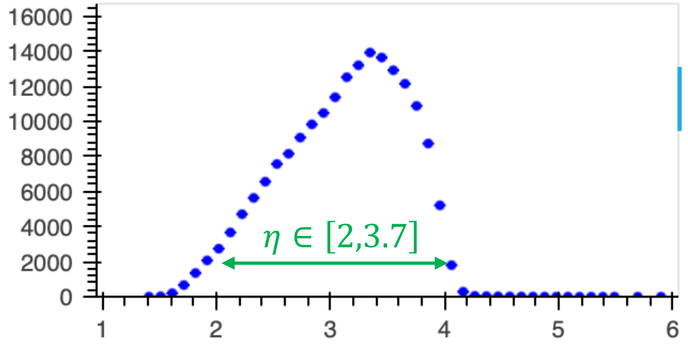
Vacuum incident

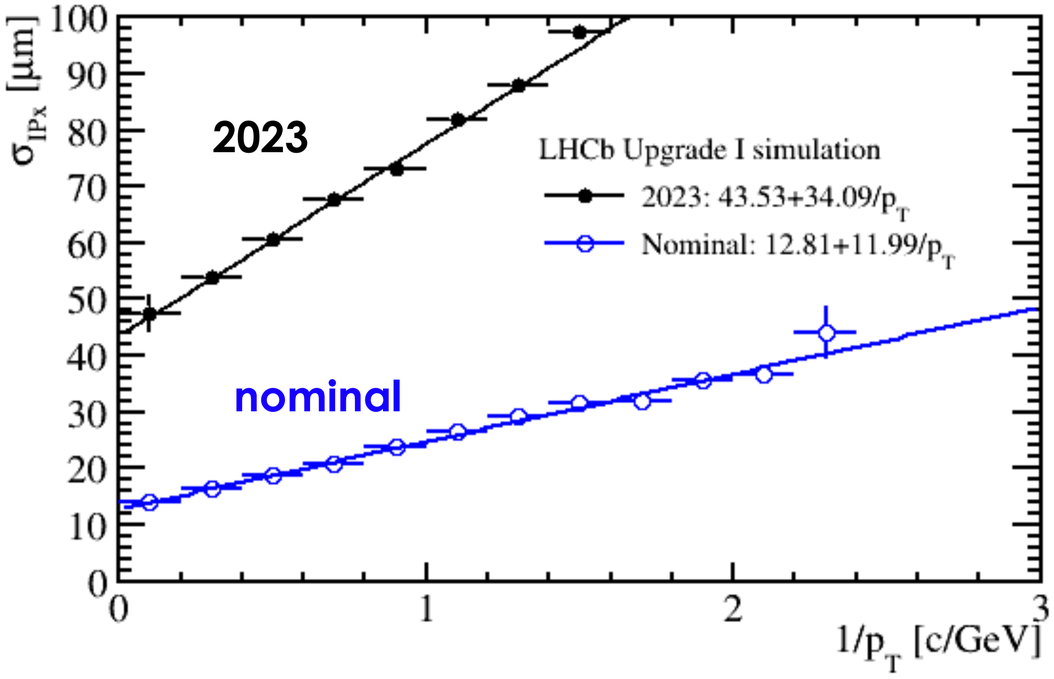
Impact of VELO gap = 49 mm

- acceptance reduced: from η [2,5] to η [2, 3.7]
- impact parameter (IP) resolution degraded

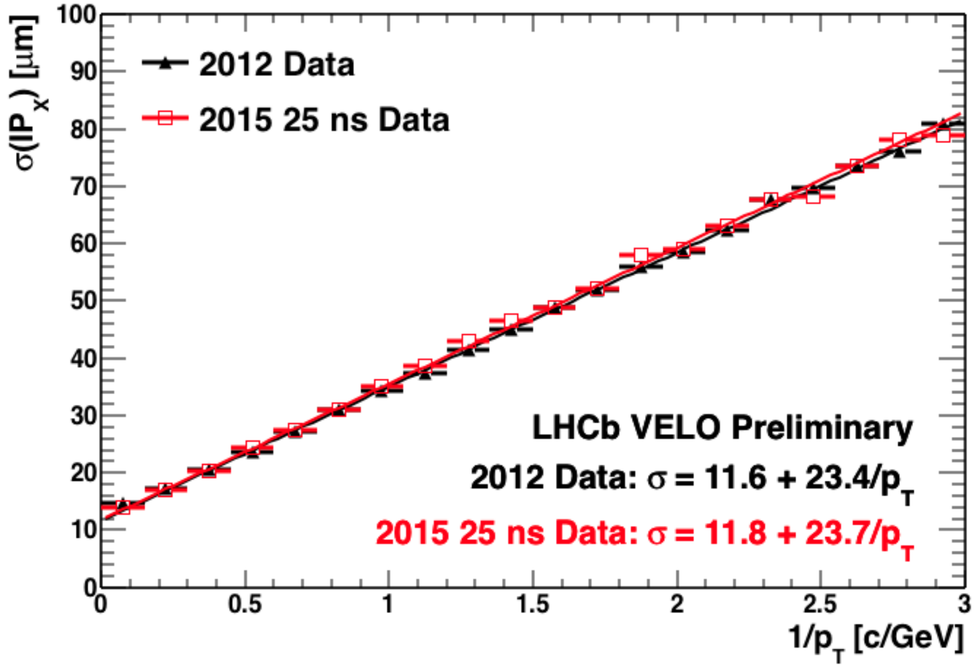
long tracks (up to the last tracking station)



IP resolution from simulation



IP resolution in Run 2



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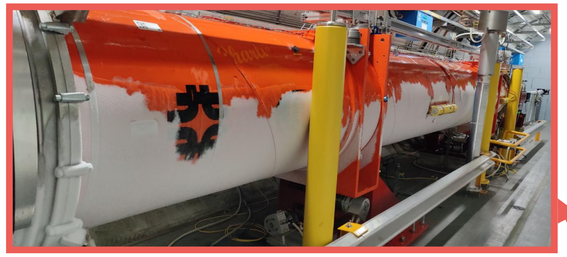
How is it going so far?

2023

LHC off
LHC commissioning
pp physics
ion physics
special runs

unscheduled stop:
cold mass - insulation vacuum leak repair



LHC

01/01 EYETS 15/05 17/07 25/09 EYETS 31/12

no pp reference run because of
leaks in machine protection device

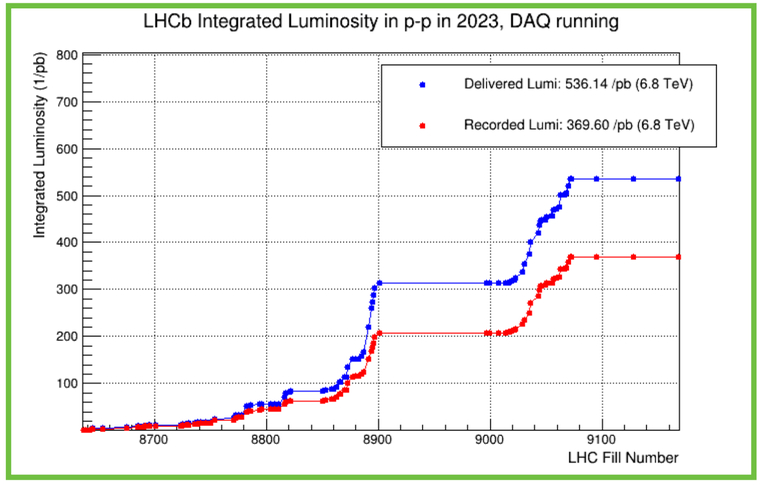
LHC vacuum
incident in the VELO

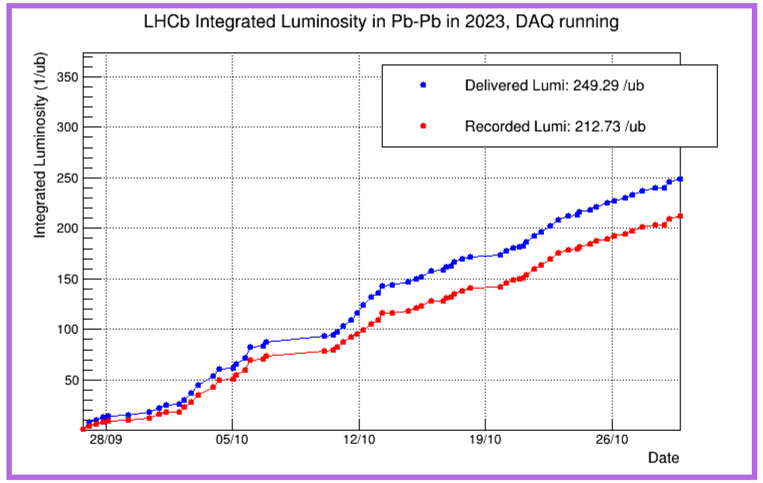
UT completed
installation

complete commissioning
+ data taking

data taking + UT
commissioning continues

LHCb





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Setting the scene…

prior to 2024 never run at nominal luminosity, with the VELO closed and UT included in global data taking

goals for 2024

- integrated luminosity of 7 fb^{-1} of pp collisions
- collect a significant sample of PbPb data with UT
- achieve 90-95% efficiency at high pile up, with UT

critical activities in early 2024:

- re-qualification of the VELO motion system and automatisation of the procedure
- operations at nominal luminosity of the full system, with particular eye on trigger and online alignment and calibration
- integration of UT in global data taking

2024 schedule

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LHC in 2024

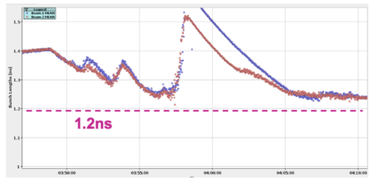
LHCC accelerator status report

Great performance of the LHC!

- pp nominal energy: target overpassed (best year ever for production with 72% availability and 54% stable beams)
- pp reference energy: excellent machine availability ~90% allowed to reach all targets
- ion run: problems encountered in 2023 mitigated increasing the availability and establishing smooth operating conditions

First injection: 8th March (3 days early)

Bunch length control/target Limit RF module heating risk

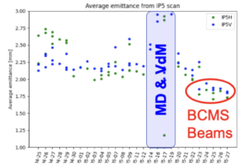


1200 bunches on 14th April (10 days early)

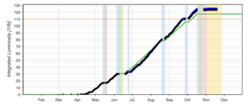
VdM & Calibration Runs, 16 – 20 May

Availability	Stable beams (SB)
85.3%	63.6%

BCMS beams May

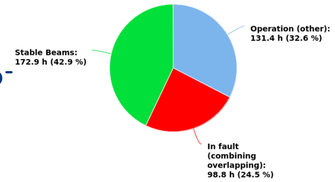


Stable Lumi Production Summer period

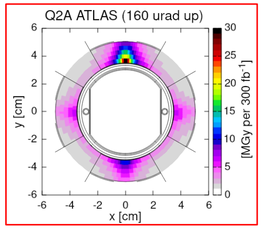


Beyond 110 fb^{-1}

IONS run (YETS starts on 25th November)



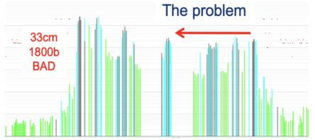
Reverse Polarity optics commissioned (~ +1 week)



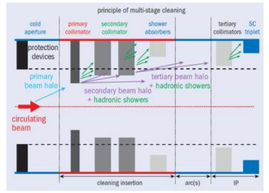
First Stable Beams @6.8 TeV 5th April (3 days early)

LHCb VELO closed for the 1st time

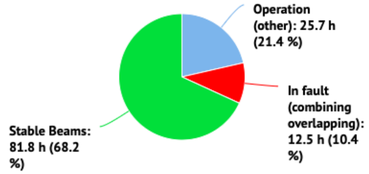
β* limited to 36 cm 17th April



β* back to 30 cm 17th June



pp reference run 28th Oct – 2nd Nov



Availability
89.6%

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  - luminosity and beam background
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  - VdM
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  - UT integration
  - HLT1 track reconstruction
  - HLT1 & HLT2
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  - Hit efficiency
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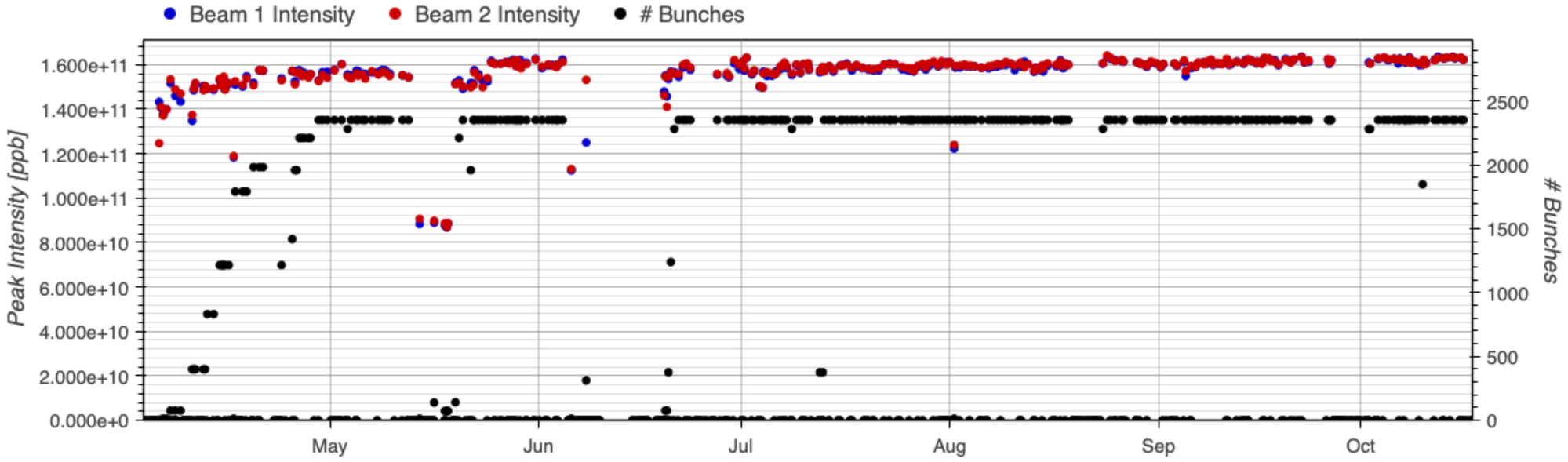
  - PID
  - Trigger efficiency
- In summary…

LHC in 2024

- bunch intensities stable at 1.6e11 ppb at start of stable beams
- 3x36b allowed to reach 2133 colliding bunches in LHCb at full machine
  - nominal luminosity of 2e3 Hz/ub can be reached with a pile-up of ~ 5.3



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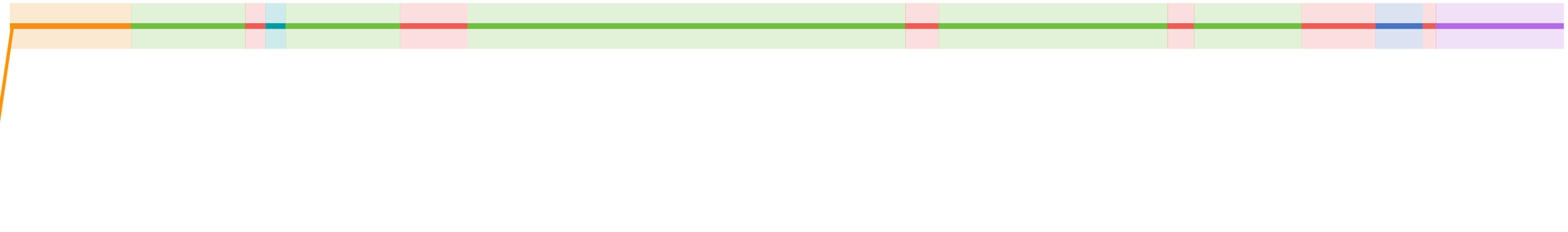
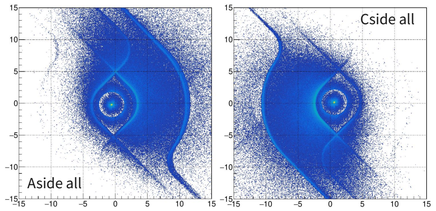
LHCb in 2024

TS/MD/setup
pp intensity ramp up
pp nominal physics
ion physics
pp reference physics
pp vdM



first VELO closure in 4b fill [05/04]



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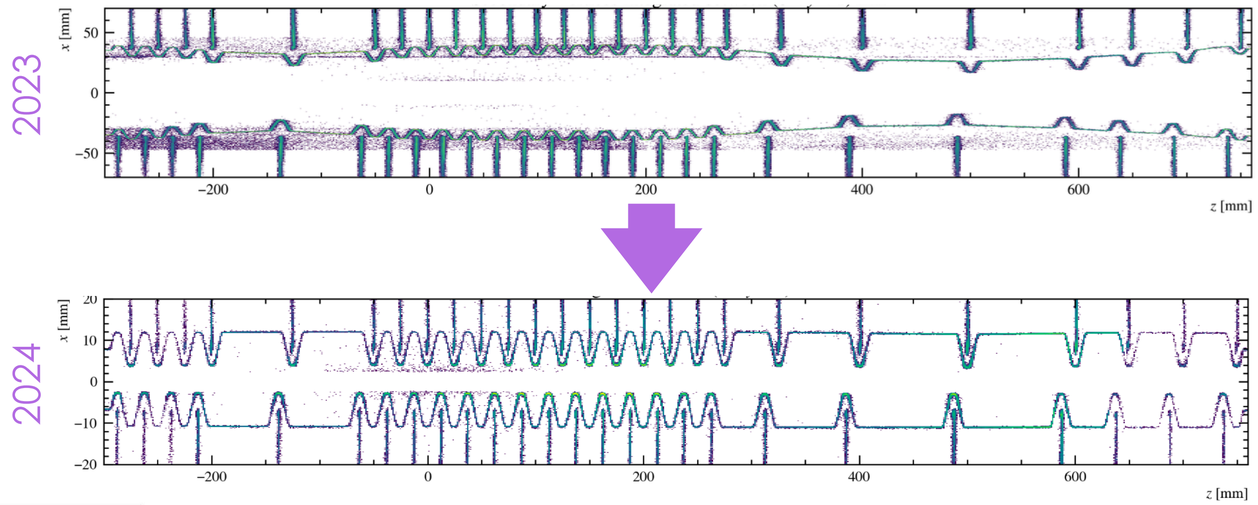
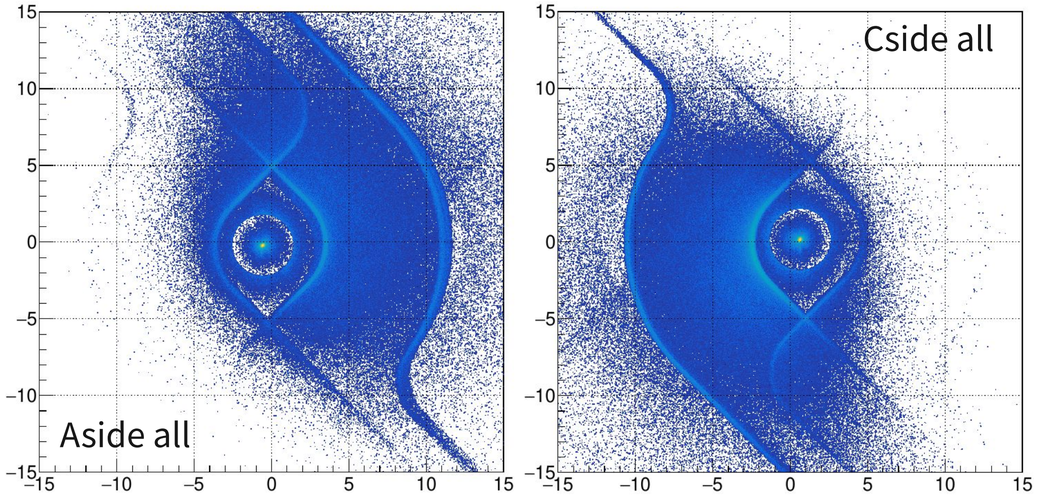
VELO Closure

- first VELO closure performed in steps
- tomography performed at every step with SMOG injected in the VELO vessel

RF-box and VELO modules reconstructed by hadronic interaction vertices



VELO tomography for aperture checks



VELO routinely closed at every fill (gap 0 mm) since the first fill of the intensity ramp up

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LHCb in 2024

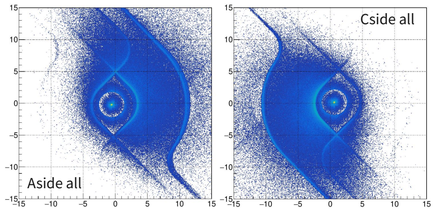
TS/MD/setup
pp intensity ramp up
pp nominal physics
ion physics
pp reference physics
pp vdM

all SDs (but UT) can operate stably at nominal lumi [07/05]

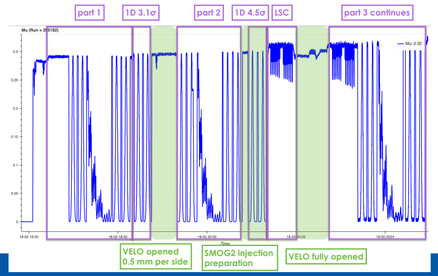
nominal HLT1 bw [10/04]

change of policy: 50% physics 50% optimisation

first VELO closure in 4b fill [05/04]



VdM program [16-18/04]



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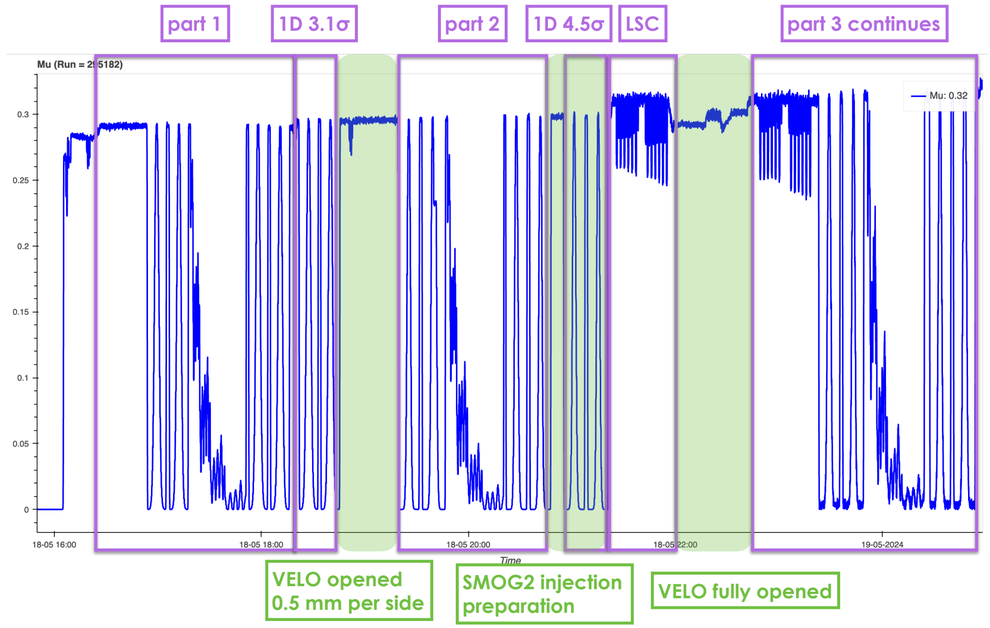
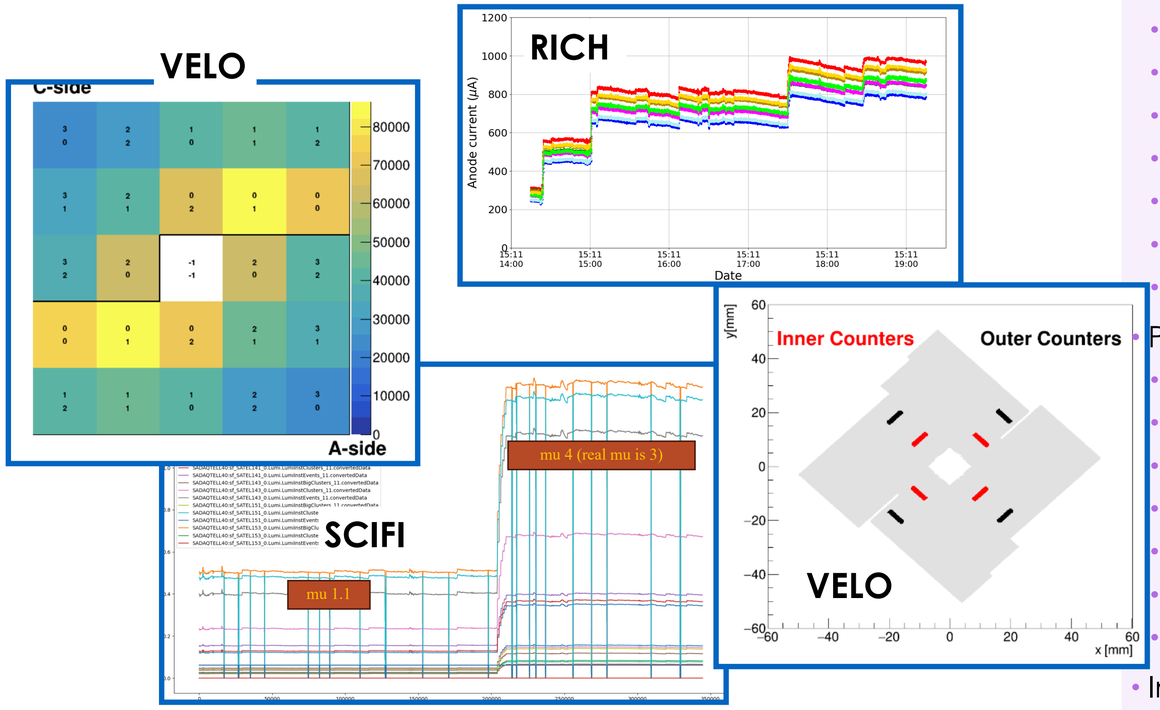
Van der Meer scan

- more than 100 luminosity counters of both high and low level quantities from different subdetectors implemented in HLT1 and in HLT2
- several online luminosity counters as a backup for PLUME (main luminometer)
- absolute luminosity calibration via BGI and vdM scans
  - performed once per year and center of mass energy in dedicated fills with different optics and filling scheme

VdM program 2024



Online counters



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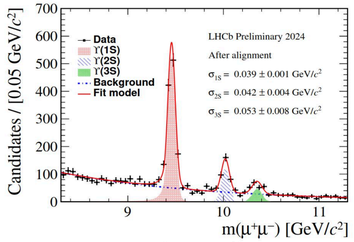
LHCb in 2024

TS/MD/setup
pp intensity ramp up
pp nominal physics
ion physics
pp reference physics
pp vdM



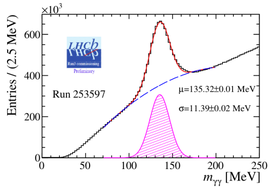
major alignment update [06/08]

all SDs (but UT) can operate stably at nominal lumi [07/05]

change of policy: 50% physics 50% optimisation

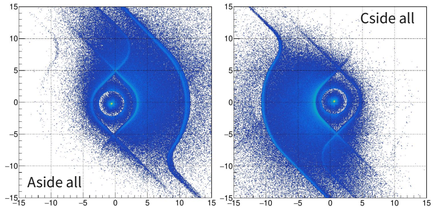
nominal HLT1 bw [10/04]

first online ECAL calibration [03/07]

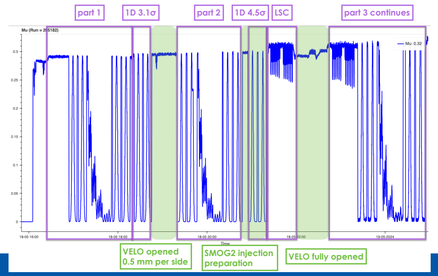


major alignment + magnetic field map update [05/07]

first VELO closure in 4b fill [05/04]



VdM program [16-18/04]



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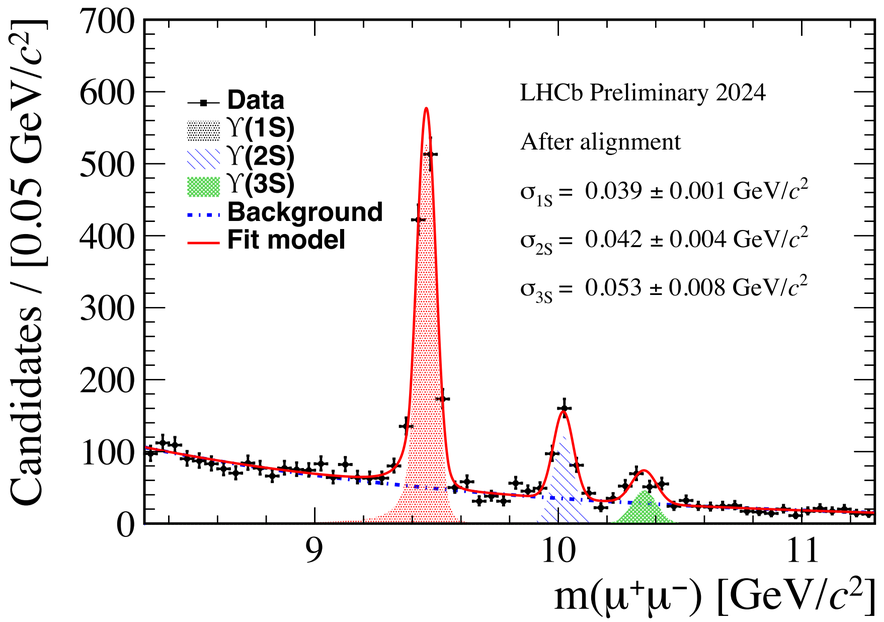
Alignment & Calibration

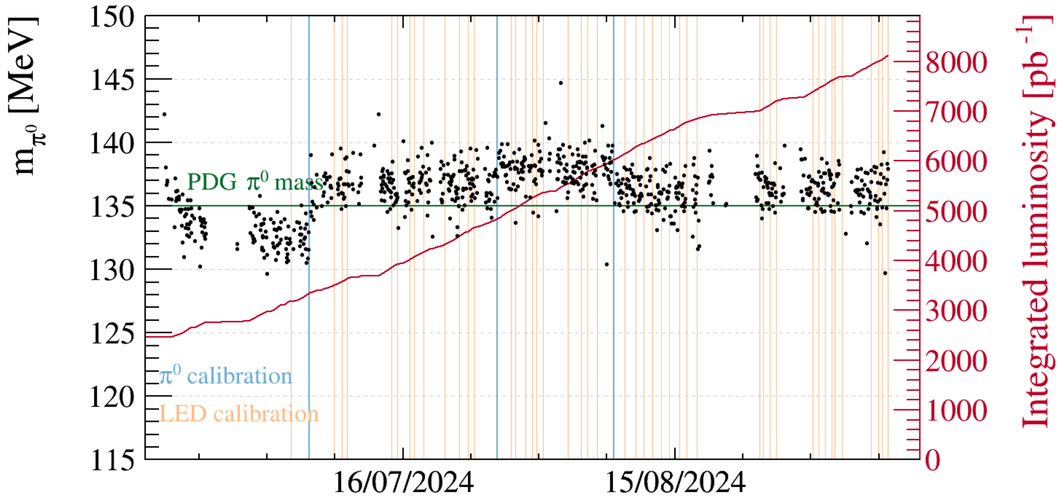
2 major alignment updates throughout the year

- improved mass resolution: approaching Run 2 performance
- all trackers (VELO, UT, SciFI) aligned simultaneously, not individually in sequence
- exploited both magnet off and magnet on data
- greatly benefitted from the update of the magnetic field map from the latest measurements



Calibration of calorimeter system crucial to compensate for ageing

- π^0 based calibration performed on a regular basis (absolute calibration)
- LED based corrections applied after ~each fill (relative calibration)



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LHCb in 2024

TS/MD/setup
pp intensity ramp up
pp nominal physics
ion physics
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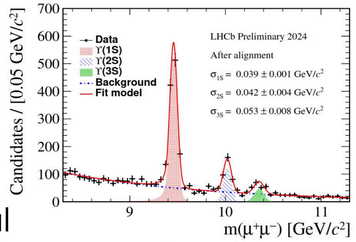
pp vdM

Road to nominal lumi

trigger/reconstruction and UT commissioning proceeding in parallel but at the same time strongly intertwined



nominal HLT1 bw [10/04]

all SDs (but UT) can operate stably at nominal lumi [07/05]

change of policy: 50% physics 50% optimisation

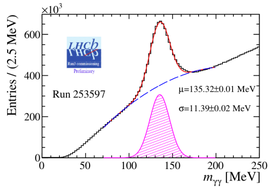
UT in global and in HLT2 [15/06]

major alignment update [06/08]

installation of 3rd GPU [19-23/08]

HLT1 reconstruction update to handle high occupancy [19/04]

first online ECAL calibration [03/07]

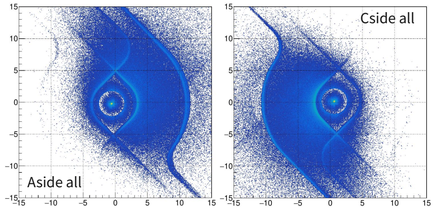


major alignment + magnetic field map update [05/07]

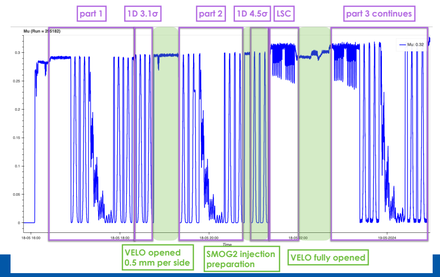
UT in HLT1 (forward+ matching)
UT lower thresholds
SciFi higher thresholds
[26/08]

3rd GPU in production
downstream tracking
HLT1 bw at 5.3
UT tuned settings
line tunings at HLT2
[03/10]

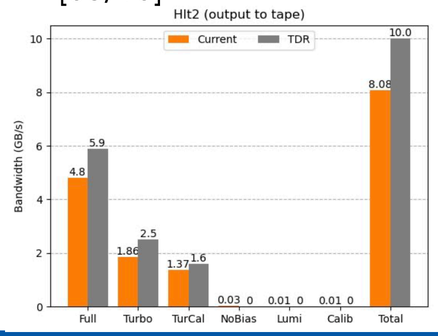
first VELO closure in 4b fill [05/04]



VdM program [16-18/04]



CPU upgrade [summer]



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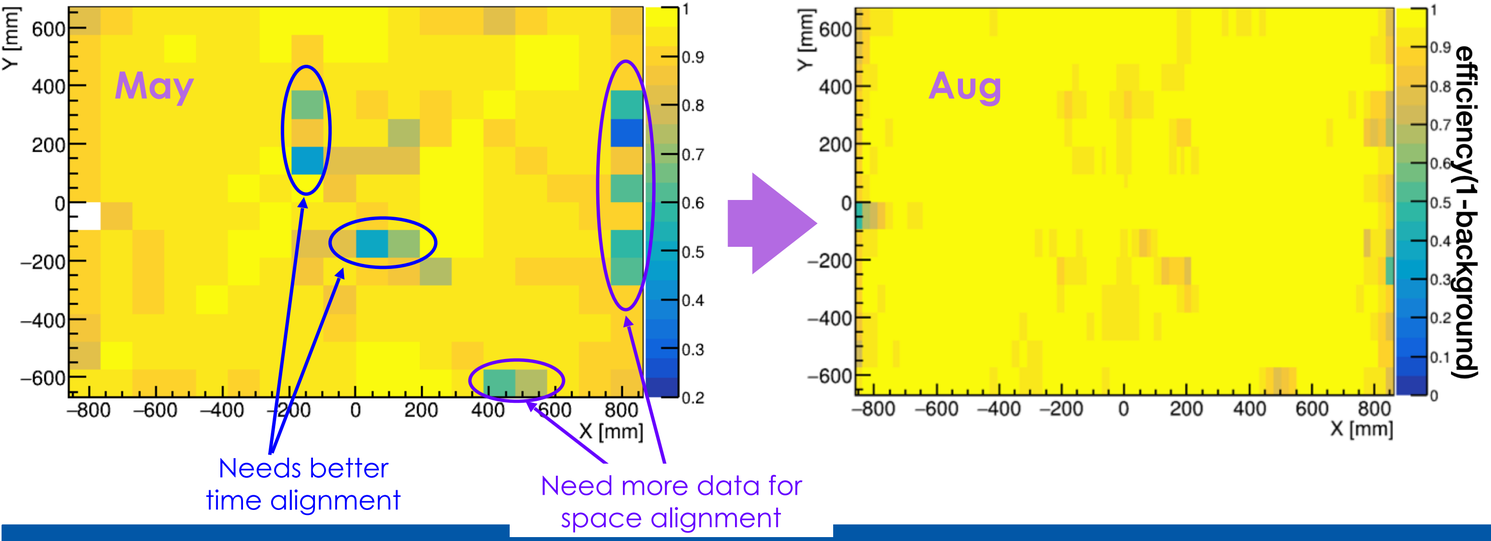
UT integration

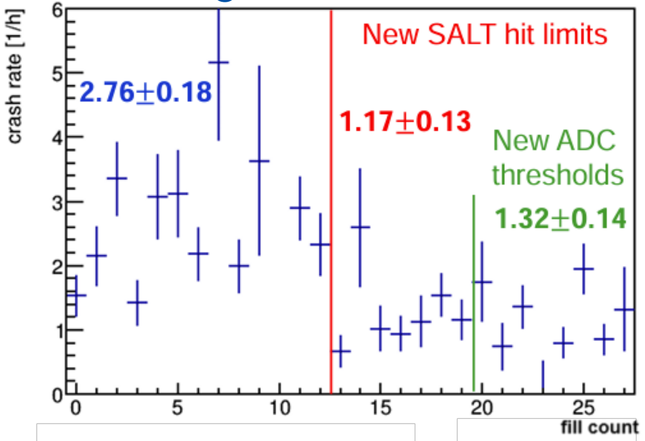
very rapid progress in UT commissioning

- phase 1: UT in local commissioning with dedicated runs in global
  - by TS1 96% efficiency as measured on VELO-SciFi tracks matched to 3-4 UT layers PRE-TS1
- phase 2: UT in global by default with occasional dedicated runs in local
  - tuning of problematic boards throughout data taking
  - tuning of FE settings in parallel to firmware development POST-TS1
- phase 3: UT used in the trigger decision
  1. UT included in HLT2 track reconstruction: POST-TS1
  2. UT included in HLT1 track reconstruction POST-MD3
  3. commission downstream tracking POST-MD4

UT efficiency map as measured on Velo-SciFi tracks



DAQ error rate with different FE settings



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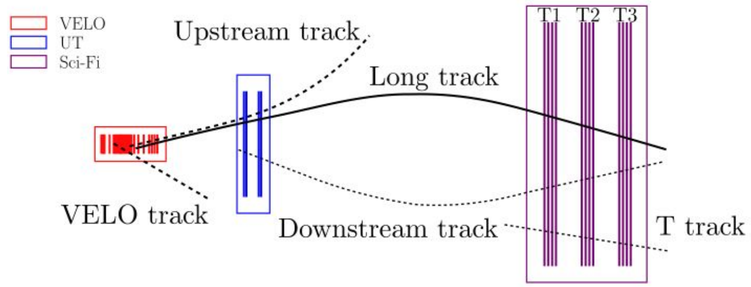
HLT1 track reconstruction

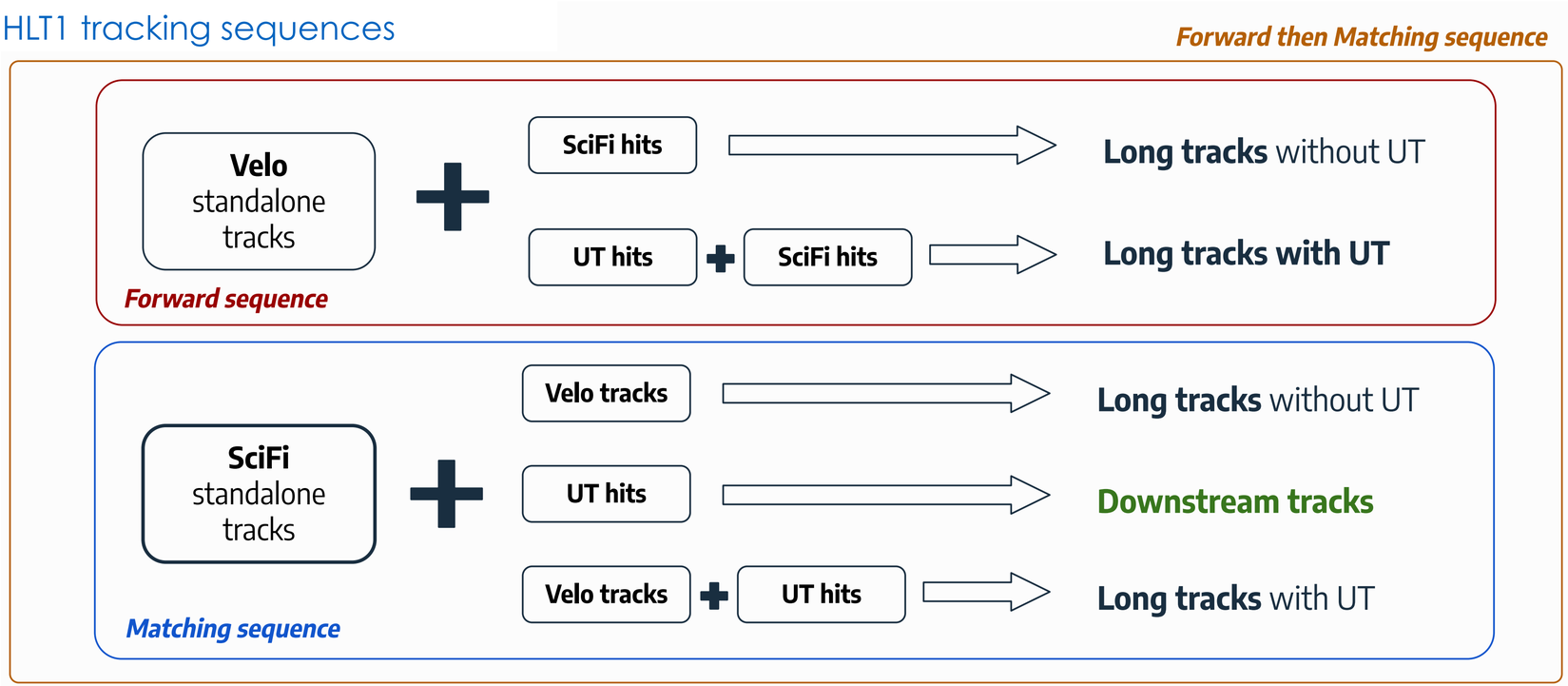
J. Zhuo, CHEP 2024

- run matching sequence only until UT included in HLT1
- forward then matching sequence improves significantly the reconstruction efficiency at high occupancy, but reduces the throughput to a barely acceptable level at nominal lumi

track types at LHCb



HLT1 tracking sequences



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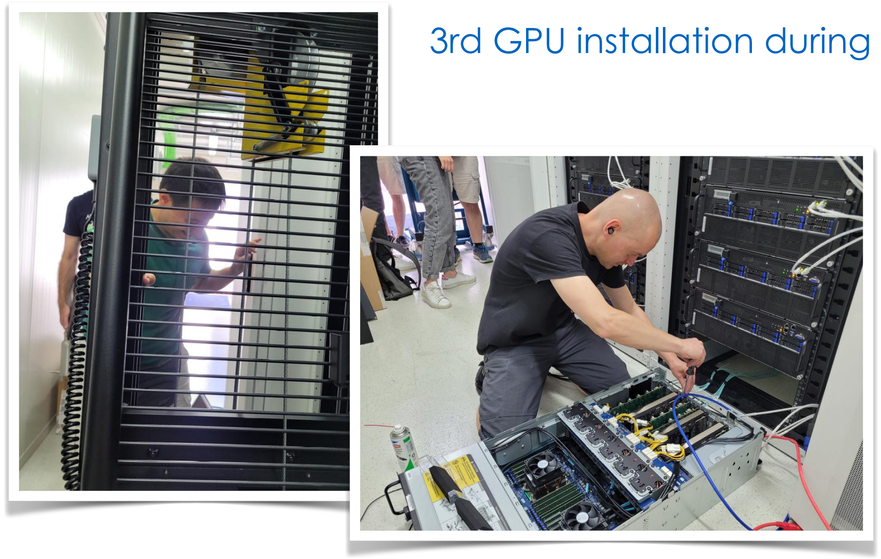
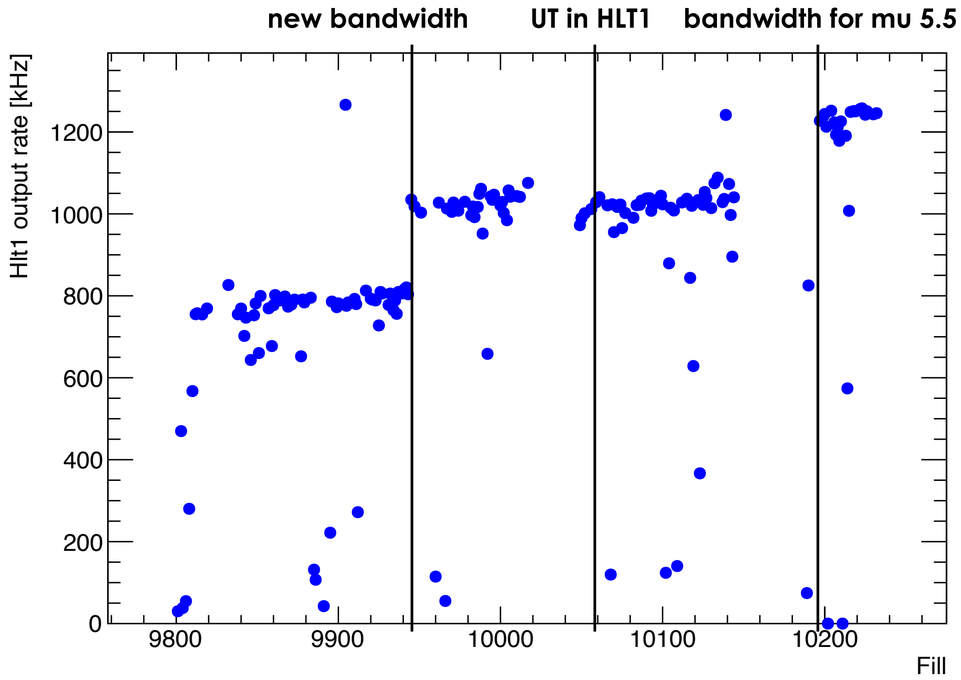
HLT1

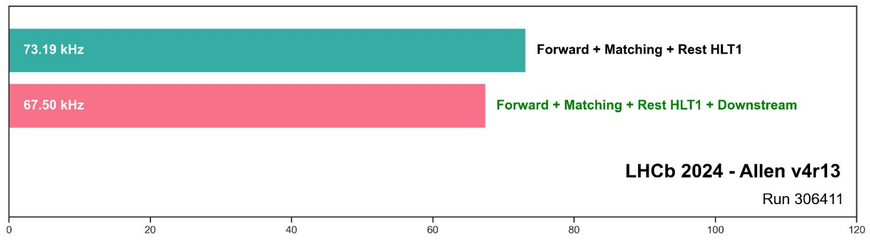
- to accomodate the forward then matching sequence + downstream installed a 3rd GPU per event builder node (163 more GPUs in total)
- several tunings of HLT1 bandwidth division depending on the acceptable output rate and instantaneous luminosity
- acceptable HLT1 output rate gradually increased up to 1.2-1.3 MHz following improvements in HLT2 computing power



3rd GPU installation during MD3



HLT1 throughput per GPU



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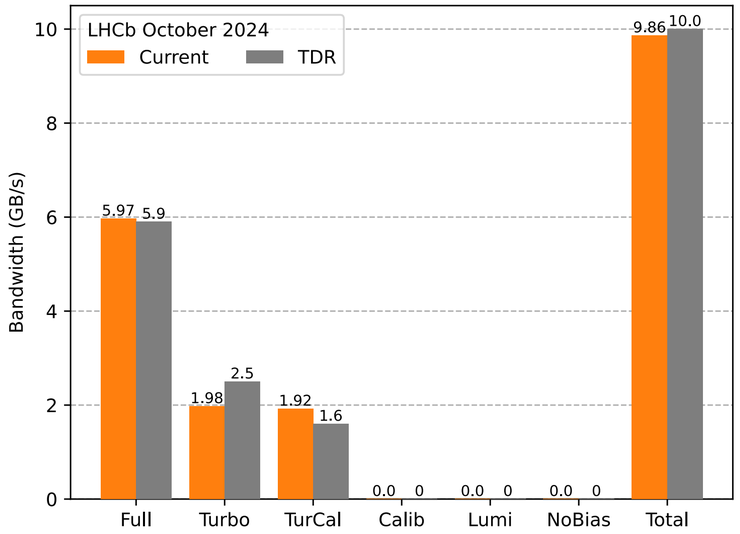
HLT2

- HLT2 needs to process data at rate greater than half of the HLT1 output (1 MHz): minimum 500 kHz
- HLT2 compute power upgrade
  - upgraded older CPUs (8 cores) to more powerful ones (14 cores)
  - 4400 CPUs replaced in two weeks in 2200 servers
  - 204 new HLT2 nodes installed with 128 cores each
- ultimately achieved a HLT2 throughput of 900 kHz!

- several iterations between analysts and trigger experts to tune the exclusive HLT2 lines and keep the output rate under control at nominal luminosity

HLT2 CPU upgrade

HLT2 output to tape



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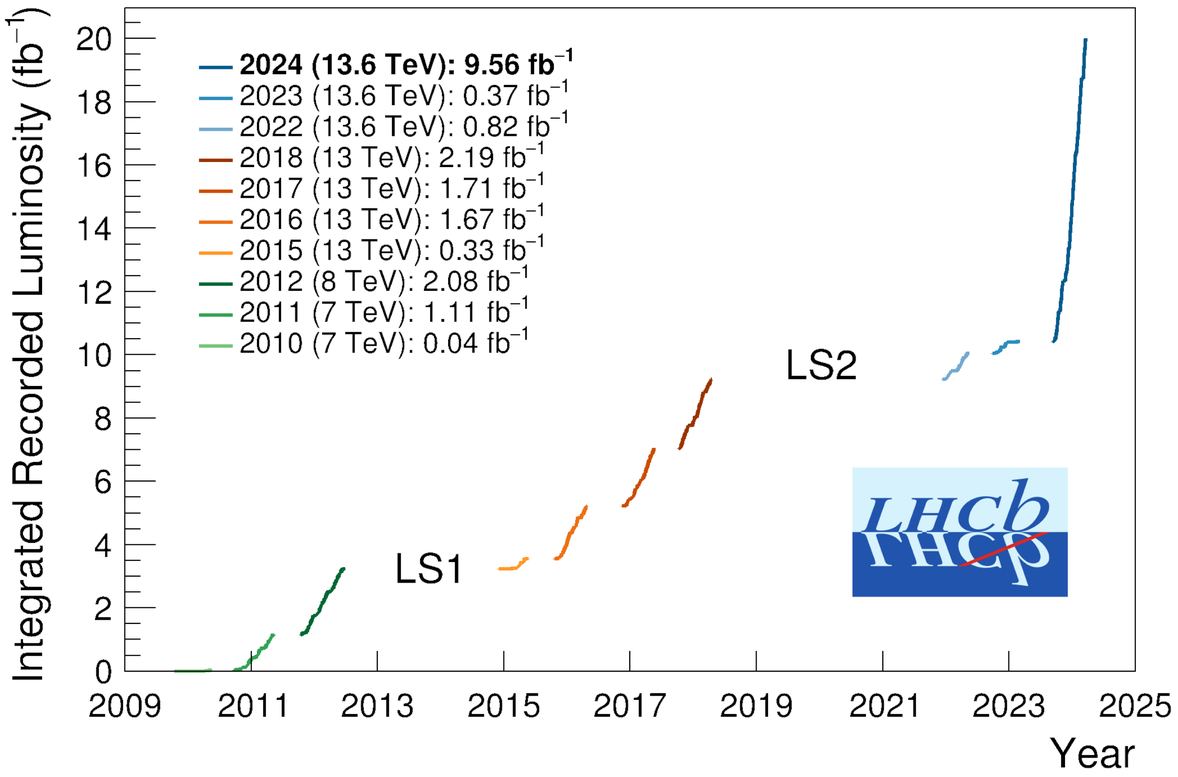
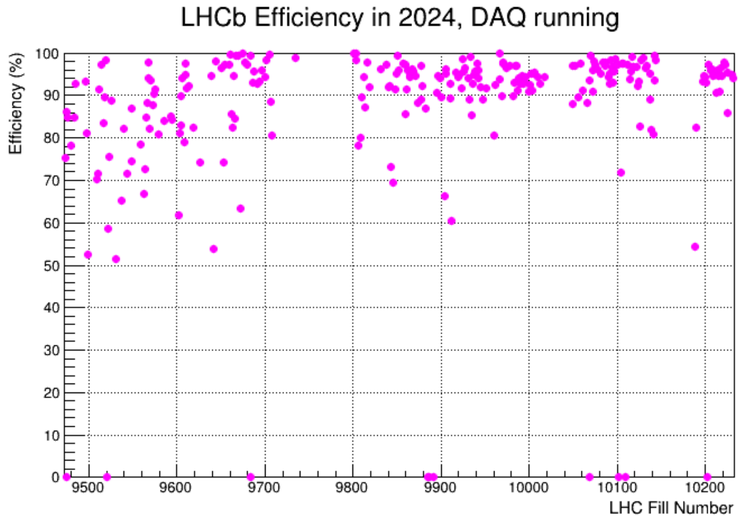
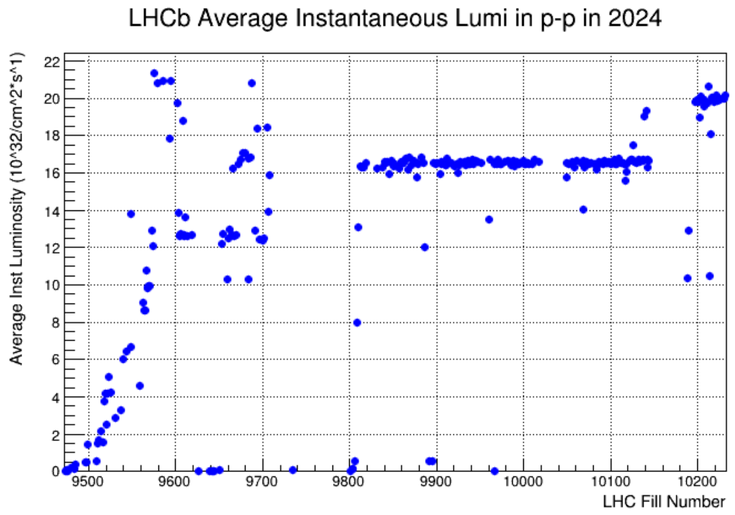
2024 nominal pp run

collected more data in 2024 than in Run 1 + Run 2 combined!







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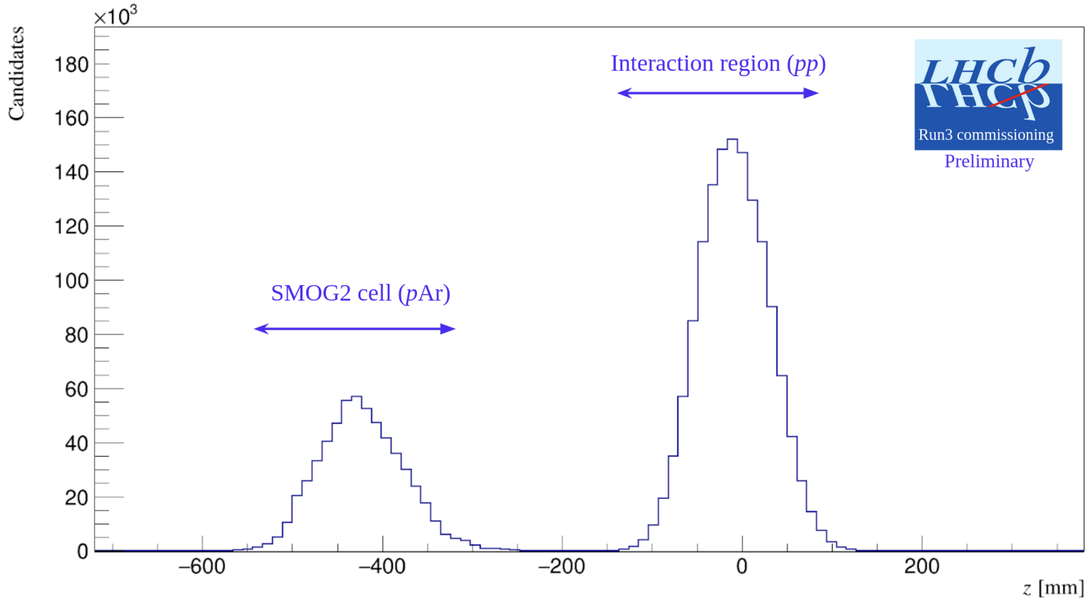
Gas injection

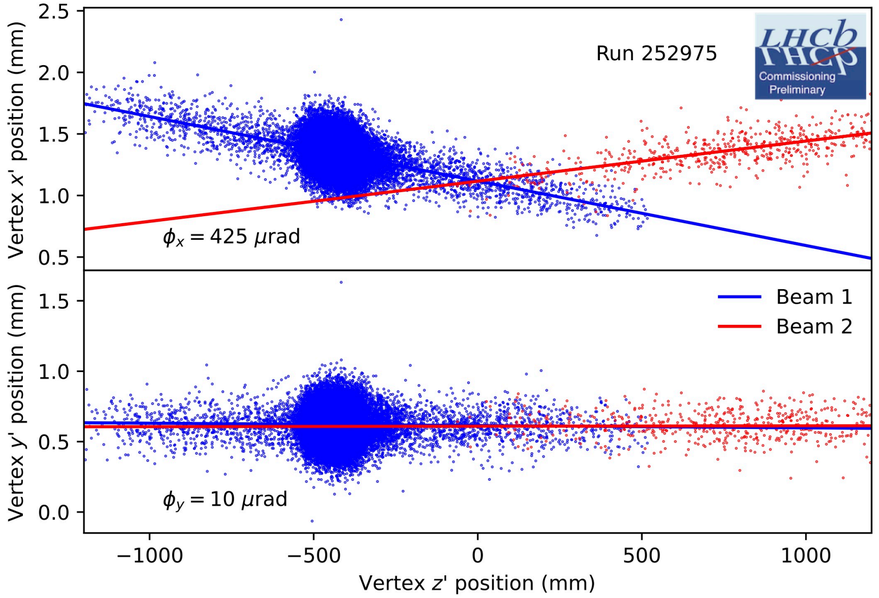
LHCb-FIGURE-2023-001

- unique possibility in LHCb to inject gas with SMOG2 and run the experiment in fixed target mode
- goal is to run both pp/ion-ion and p-gas/ion-gas in parallel throughout data taking
- already operated in 2022 with noble gases (He,Ne,Ar) and H_2
- during the EYETS 23/24 upgraded the gas feed system to inject also D_2,O_2

primary vertices distribution



beam imaging



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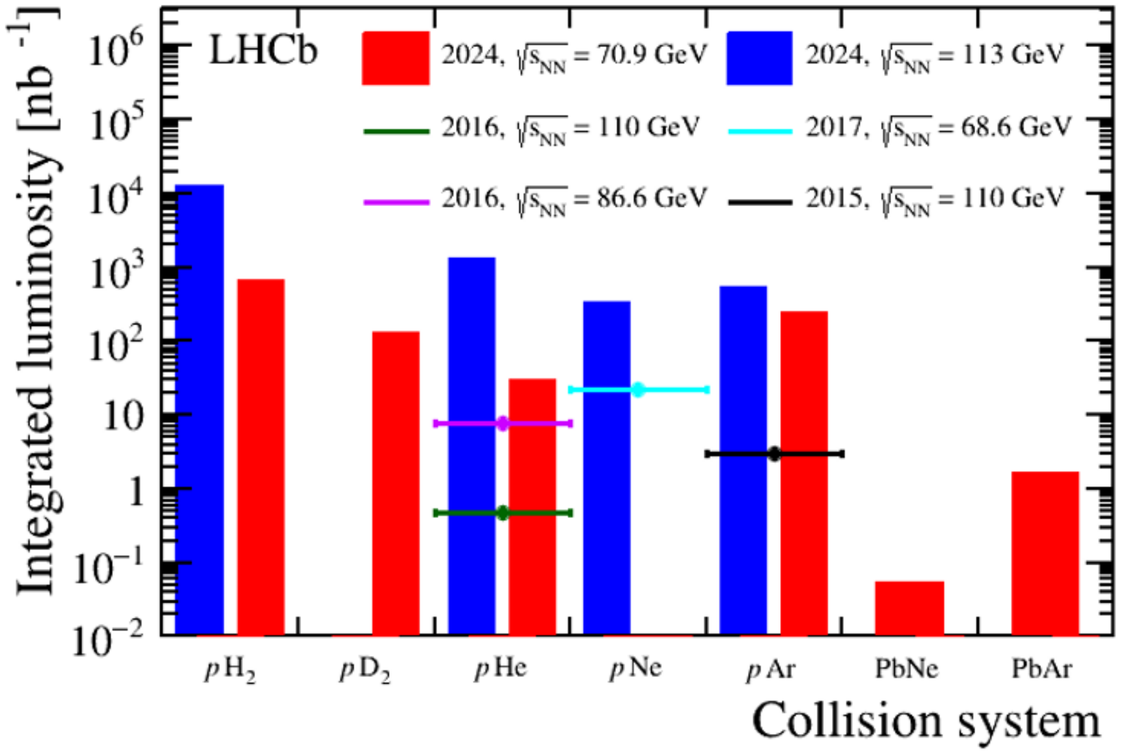
intense SMOG2 program in 2024!

2024 integrated luminosities



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LHCb in 2024

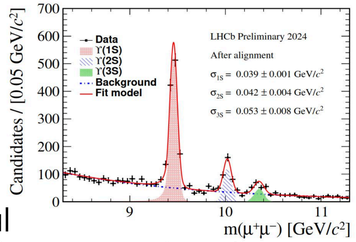
TS/MD/setup
pp intensity ramp up
pp nominal physics
ion physics
pp reference physics
pp vdM

nominal HLT1 bw [10/04]

all SDs (but UT) can operate stably at nominal lumi [07/05]

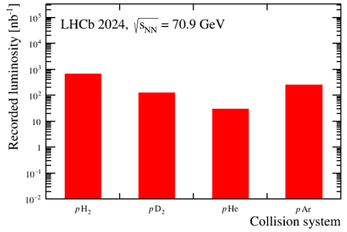
change of policy: 50% physics 50% optimisation

UT in global and in HLT2 [15/06]



major alignment update [06/08]

installation of 3rd GPU [19-23/08]



4 ditterent gases injected in SMOG2 [28/10-3/11]

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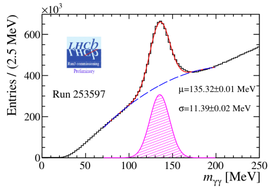

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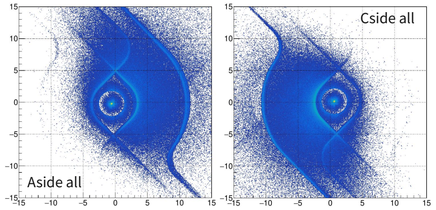

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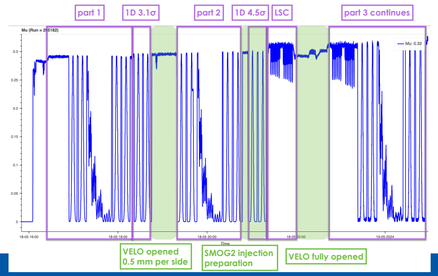

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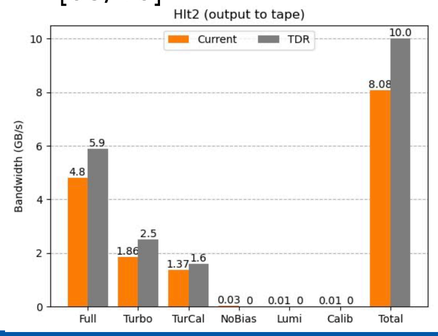

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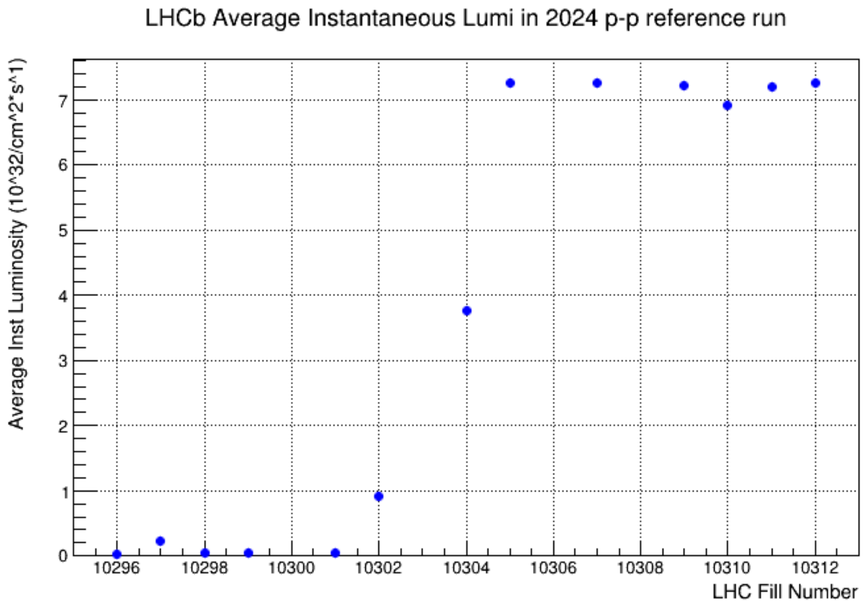
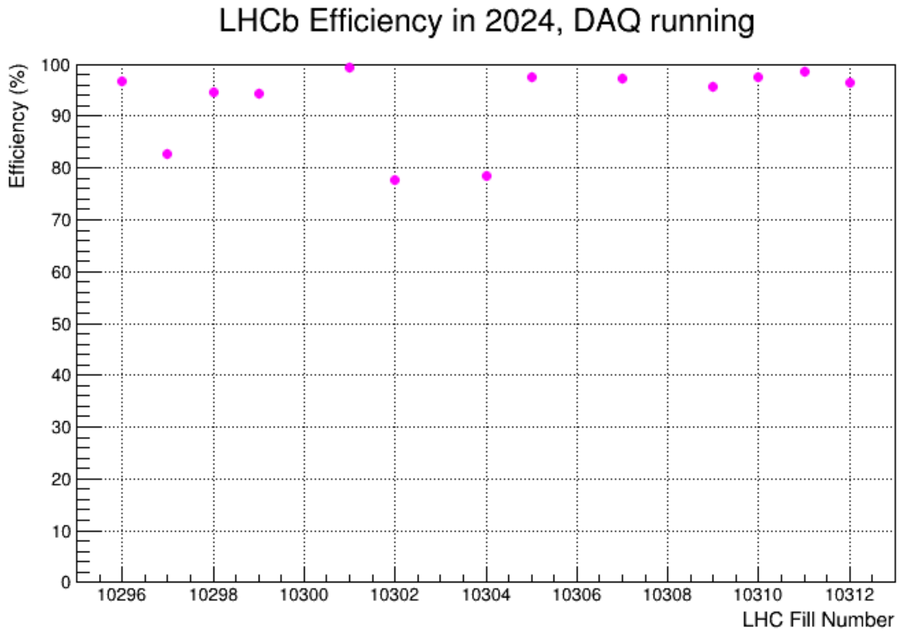
pp reference run

- 7-day run (extended by one day to satisfy ALICE target following Run3 extension)
- took advantage of the intensity ramp up for calibration scans and tests in preparation of PbPb data taking
- levelled for most of the time, beams head-on only in fill 10310
- >95% DAQ efficiency during data taking (excluding tests/calibrations)
- 4 different gases (He, Ar, D2, H2) injected
  - different HLT1 tuning depending on the gas





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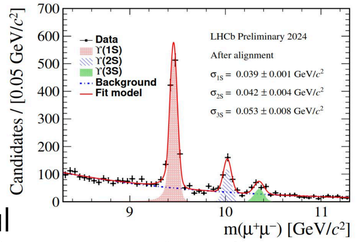

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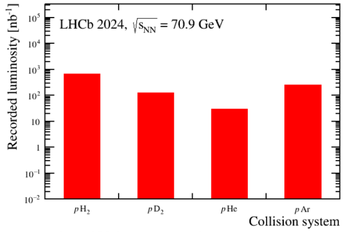

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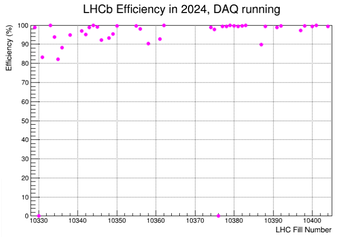
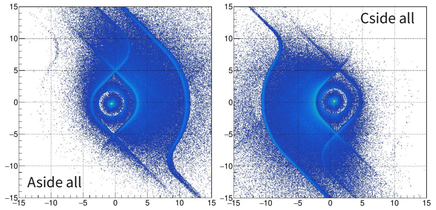


ion run [4-23/11]

first VELO closure in 4b fill [05/04]



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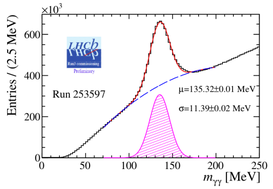

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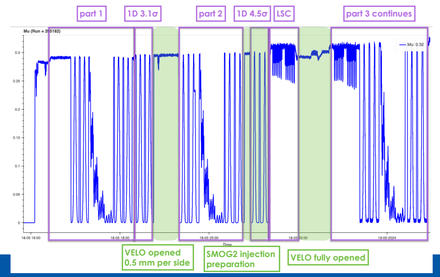

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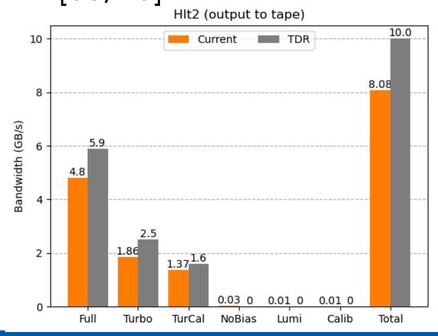

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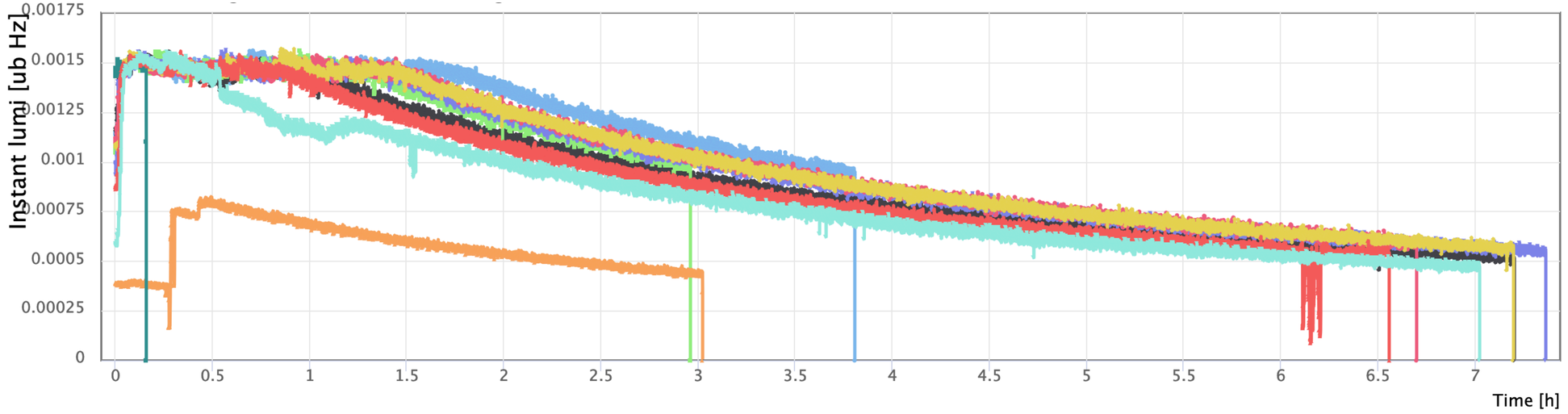
Ion run

- 3.5 days intensity ramp up (-0.5 days wrt plan)
- 12.5 days physics at full machine: 0.036/nb/day for LHCb
- leveling at 1.5e-3 Hz/ub in LHCb (increasing to >1.5h)
- bunch intensity increased up to 2.4e8 Pb/bunch at Stable Beams

Higher instantaneous luminosity wrt 2023

- flip polarity of the magnet from +/DOWN to -/UP:
  - 20% gain in lumi: agreed as default for 2024
- increase number of colliding bunches at IP8
  - +159 bb (40% more) for LHCb
  - -56 bb (5% less) for ATLAS/ALICE/CMS



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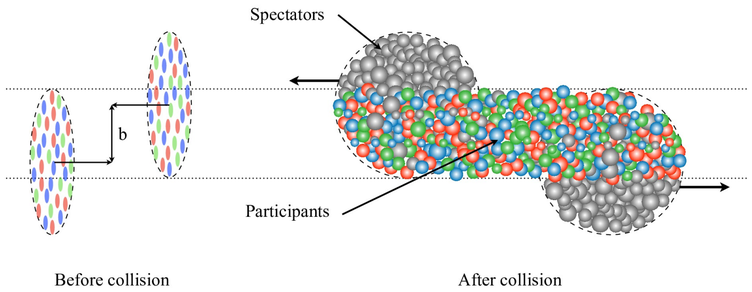
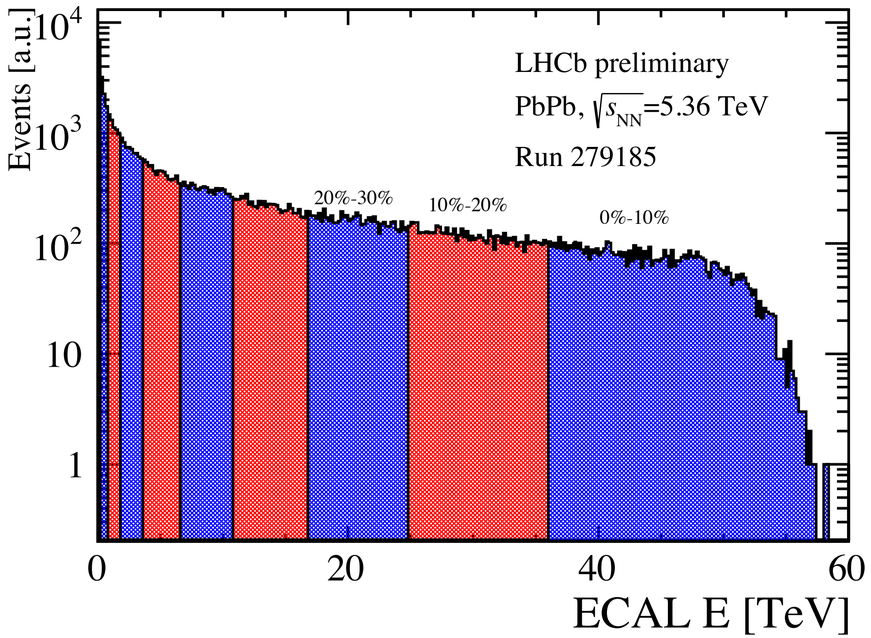
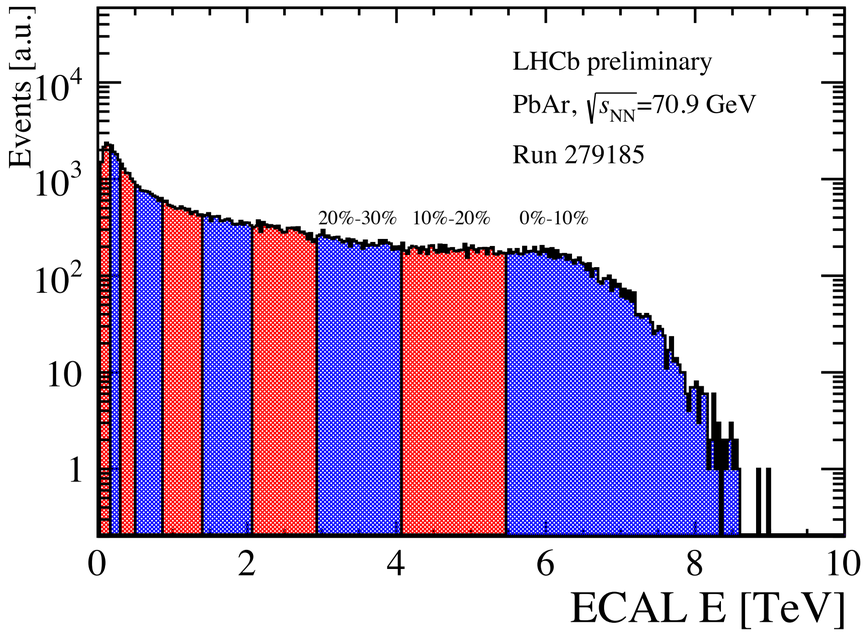
Ion run

- PbPb running conditions challenging for data taking: mu~0.002 with beams head on
- additionally Ar and Ne injection á-la-SMOG for most of the fills

LHCb-FIGURE-2023-030







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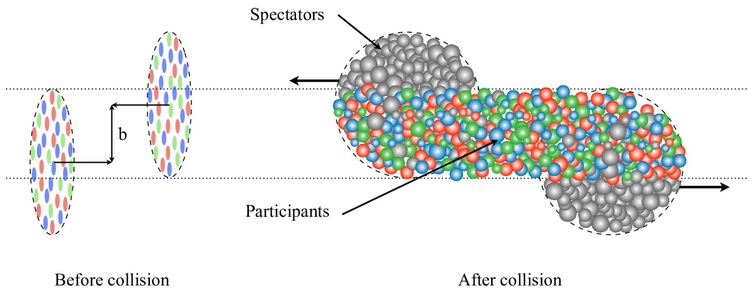
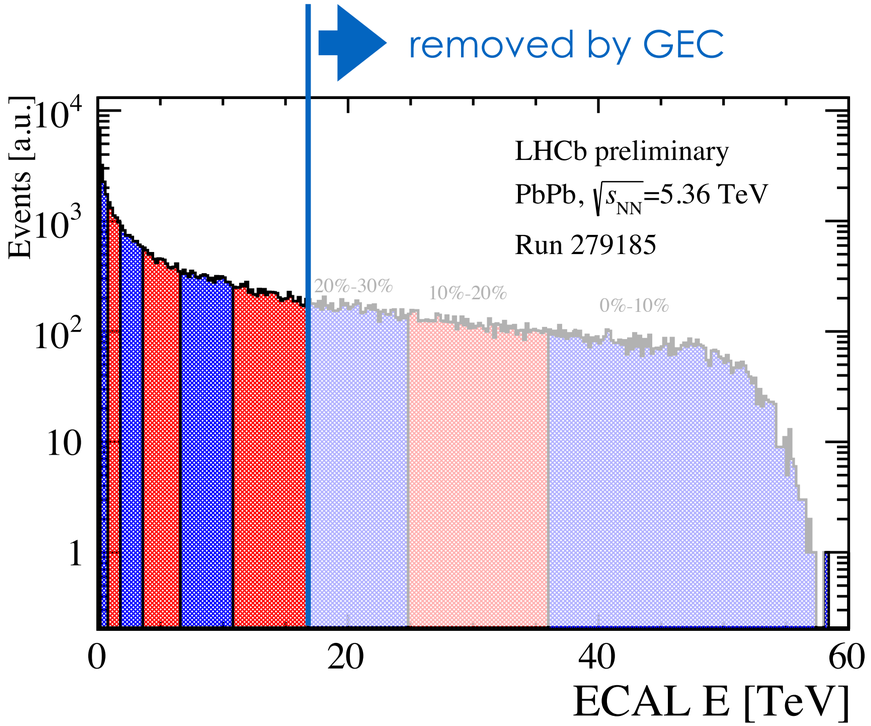
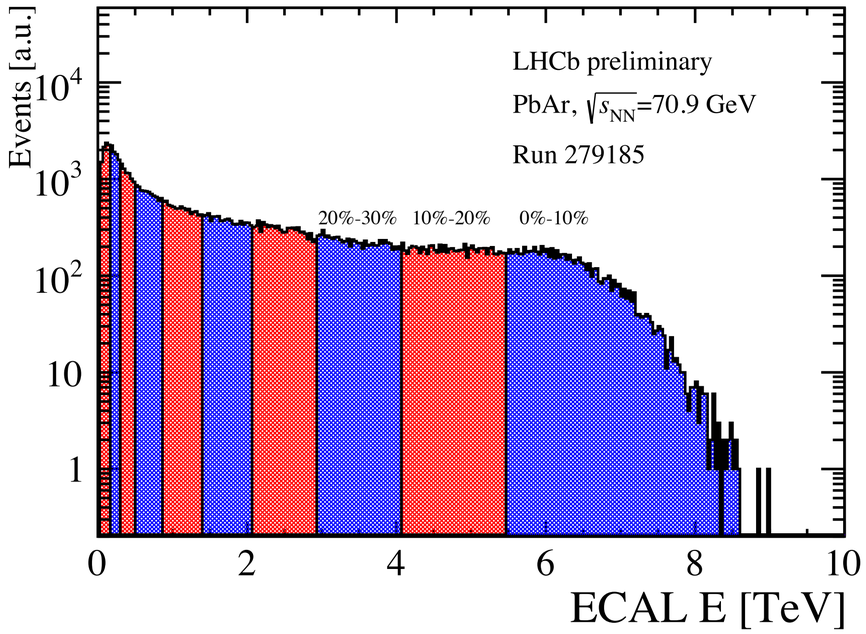
- PbPb running conditions challenging for data taking: mu~0.002 with beams head on
- additionally Ar and Ne injection á-la-SMOG for most of the fills
- trigger mitigation strategy: global event cut (GEC) at 30k SciFi clusters







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  - pp reference run
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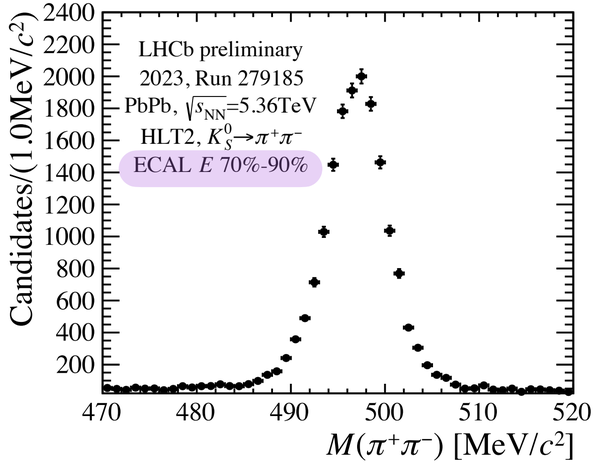
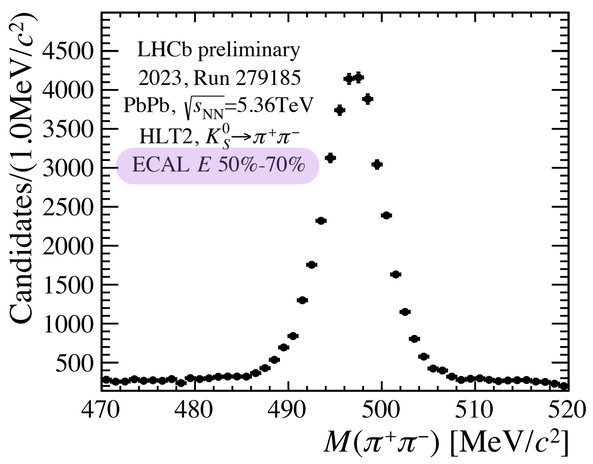
  - PID
  - Trigger efficiency
- In summary…

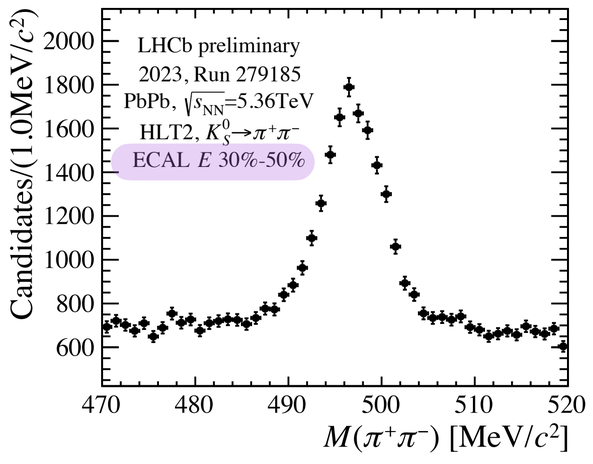
Ions data taking

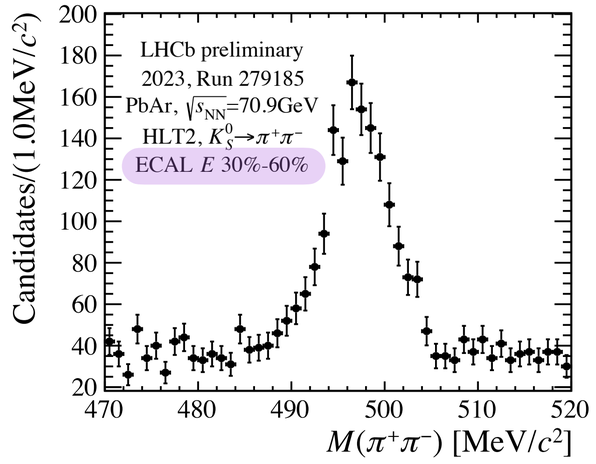
LHCb-FIGURE-2023-030

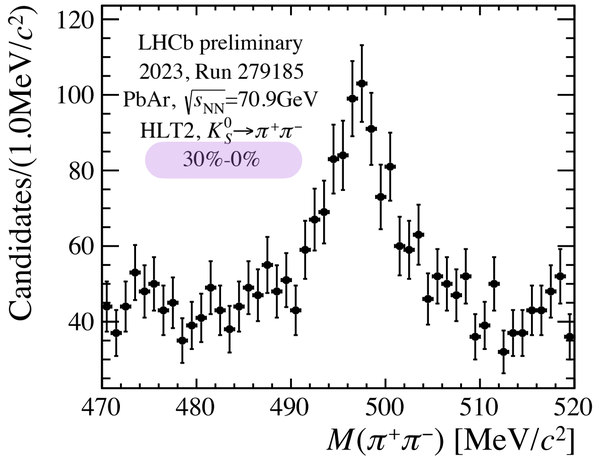
first PbPb data reconstructed down to 30% centrality by LHCb











first PbAr data reconstructed down to full centrality by LHCb

- plots show 2023 data
- in 2024 VELO closed and UT included

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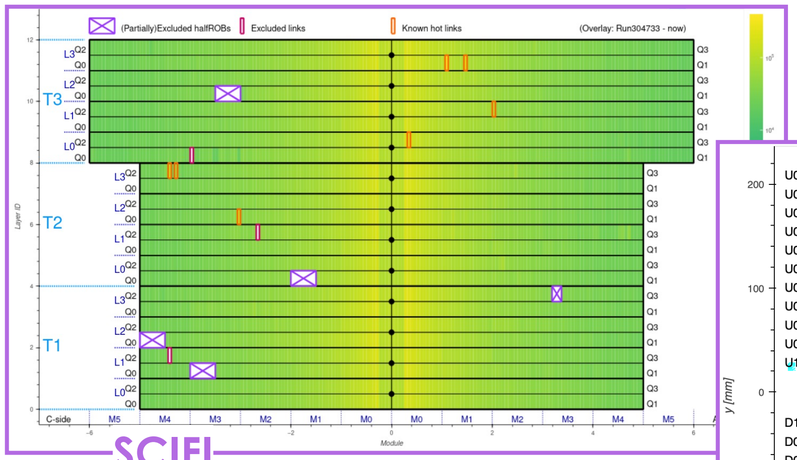
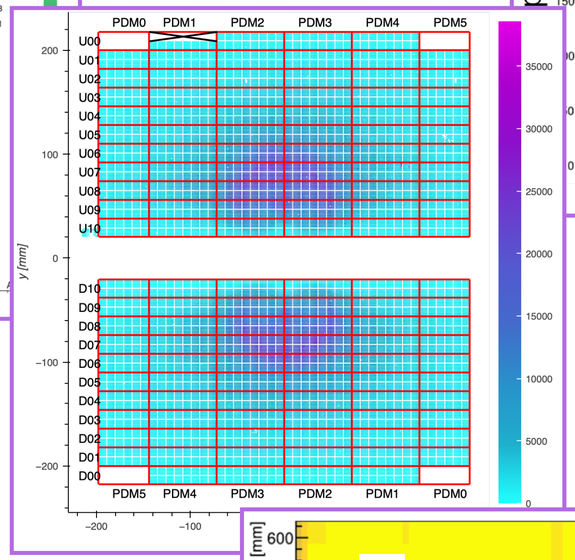
Detectors performance

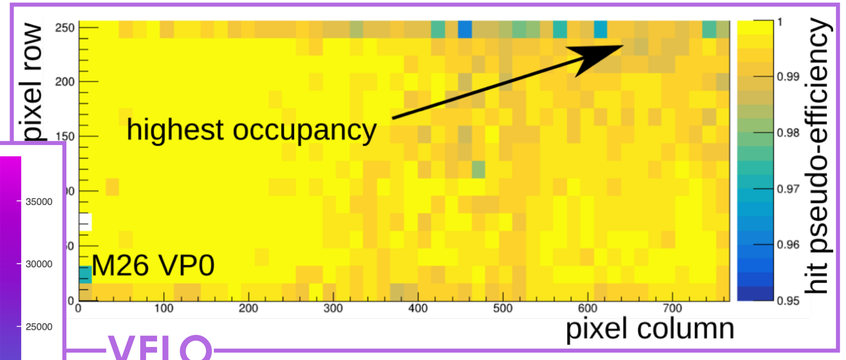
- detectors operating in stable conditions at nominal luminosity
  - focus shifted to performance fine tuning, radiation damage monitoring and simulation improvements
  - hardware-wise standard maintenance: small areas became inactive, but no effect on data quality



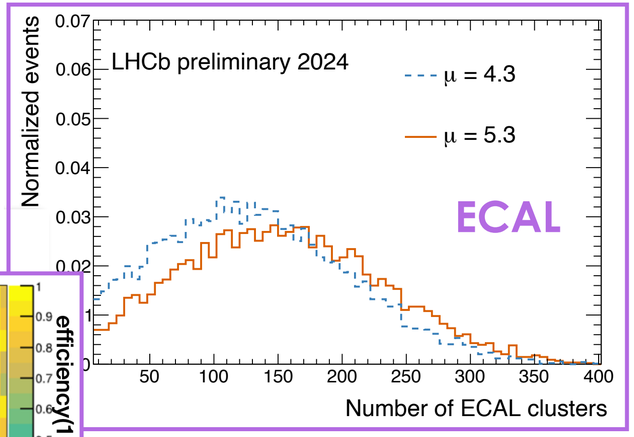
SCIFI



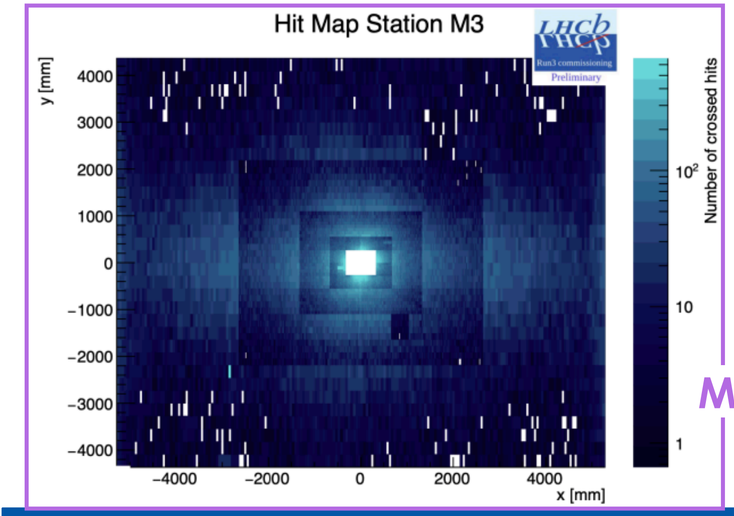
RICH



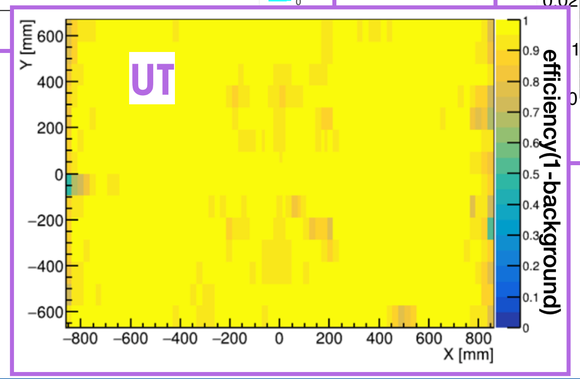
VELO



ECAL



MUON



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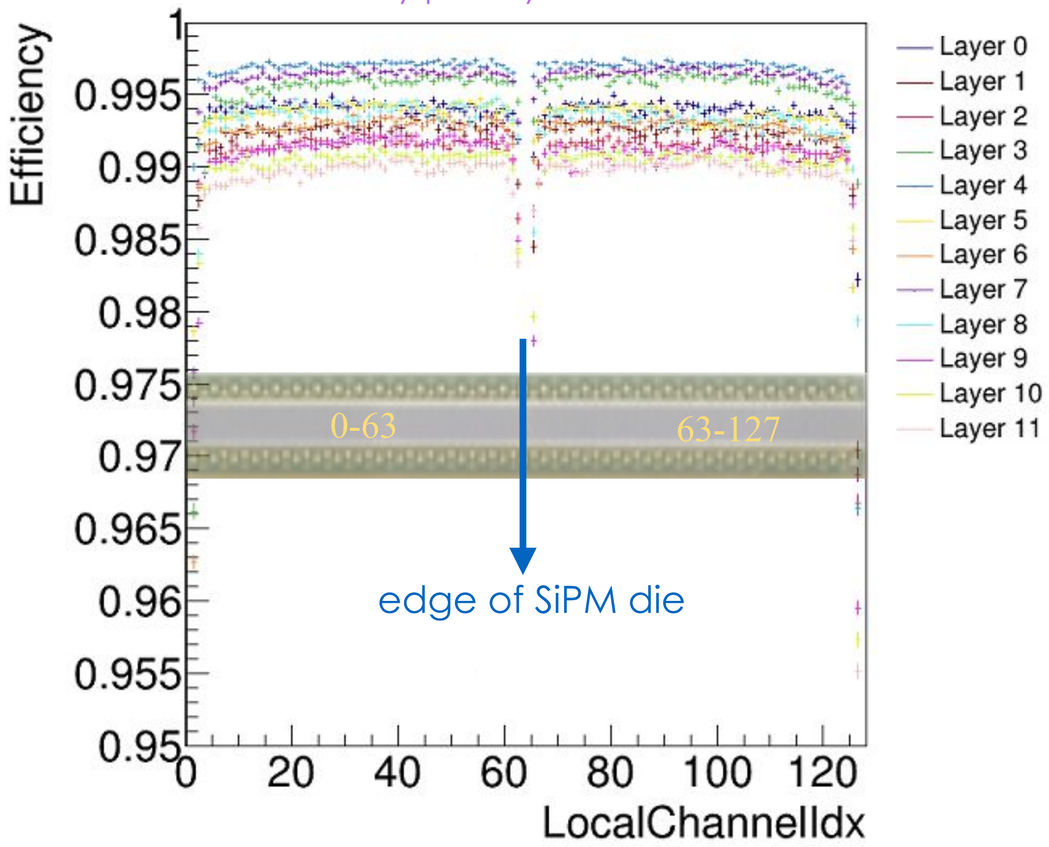
- In summary…

Hit efficiency

hit efficiency for SciFi and VELO approaching design specifications

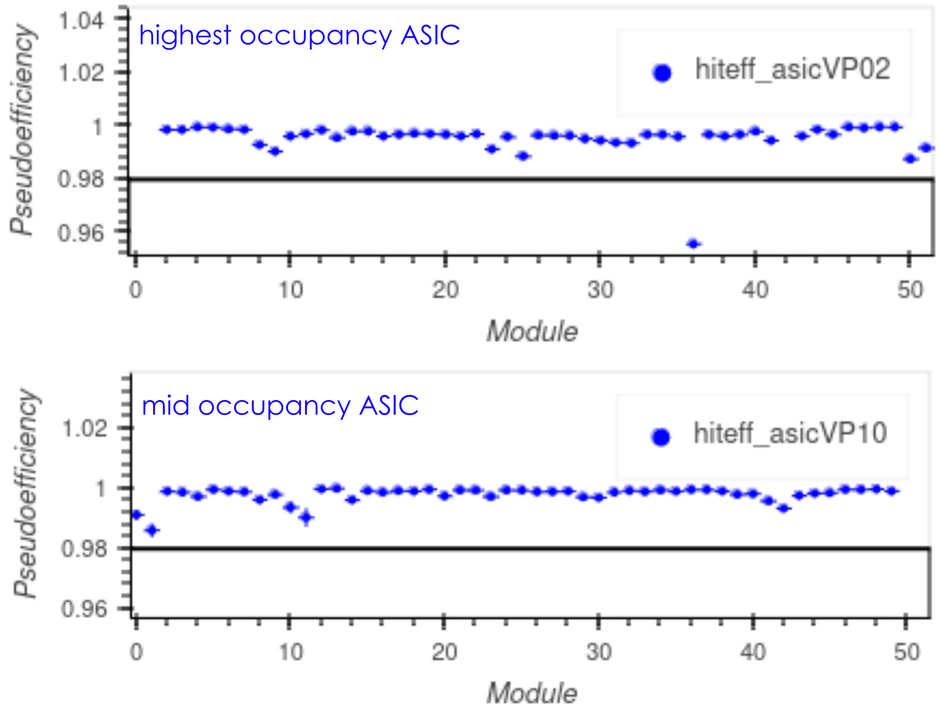
SciFi

hit efficiency per layer



VELO

biased hit efficiency in online monitoring



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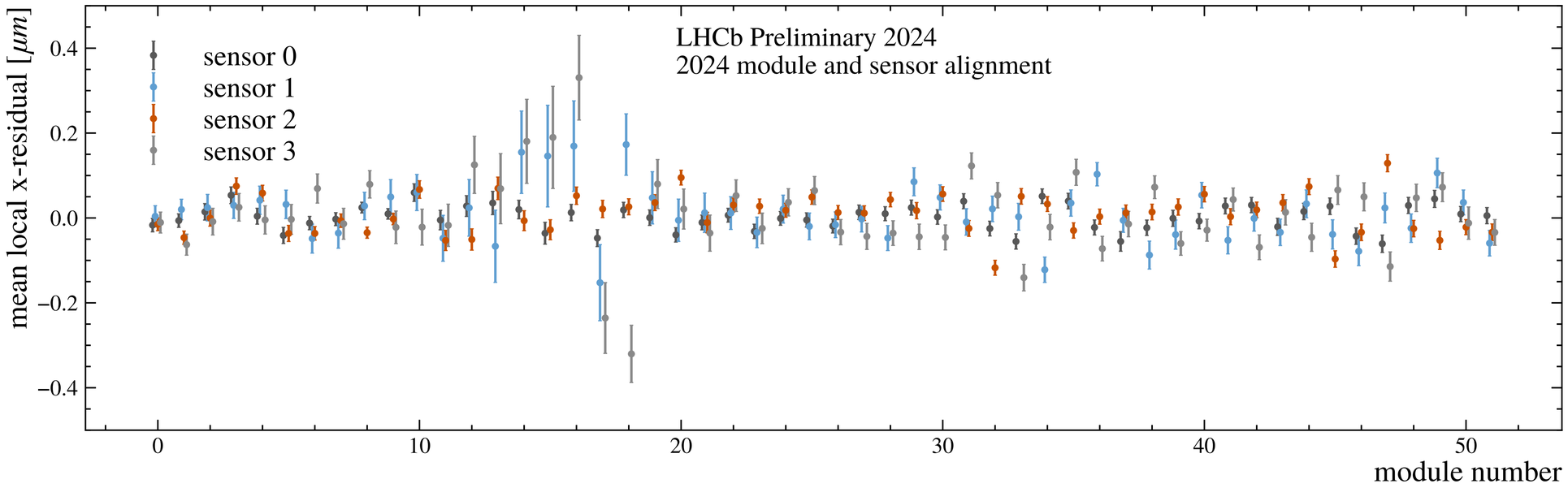
Alignment

LHCb-FIGURE-2024-009

online trackers alignment crucial for a performant track-based trigger

- VELO half alignment automatically evaluated every 10 min, module alignment on demand a few times per year
- SciFi and RICH alignment automatically evaluated and applied on demand
- MUON alignment performed ~once per year

VELO alignment performance



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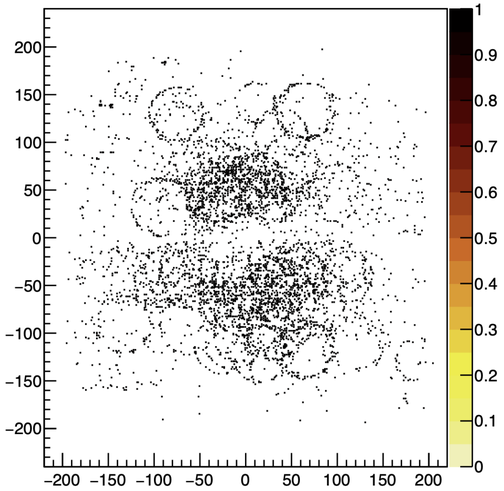
Cherenkov angle resolution

LHCb-FIGURE-2023-007

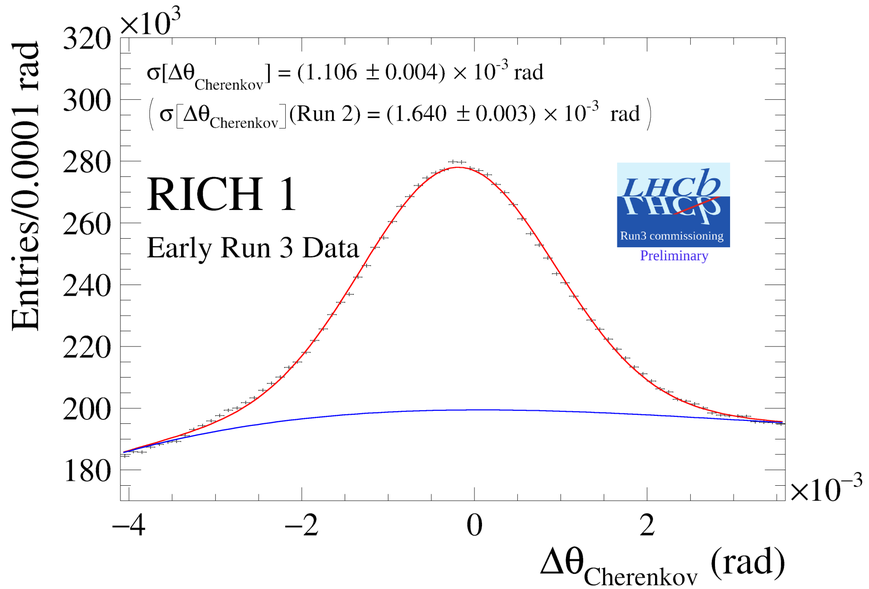
- depends on other subdetectors spatial alignment
- optimisation of operations parameters ongoing based on scans taken recently, further improvements expected

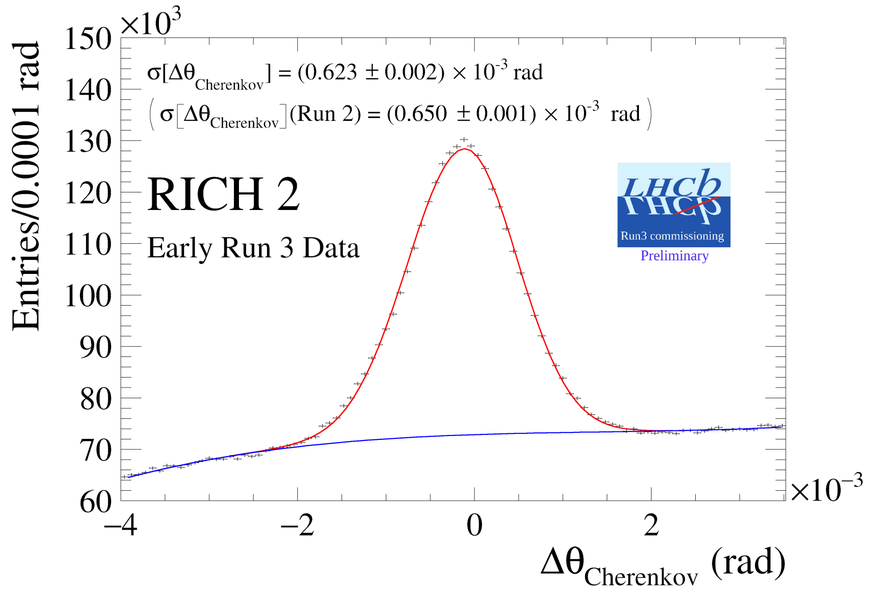
clear improvement from Run 2 to Run 3

RICH 1 at μ=5.5



single photon Cherenkov angle resolution





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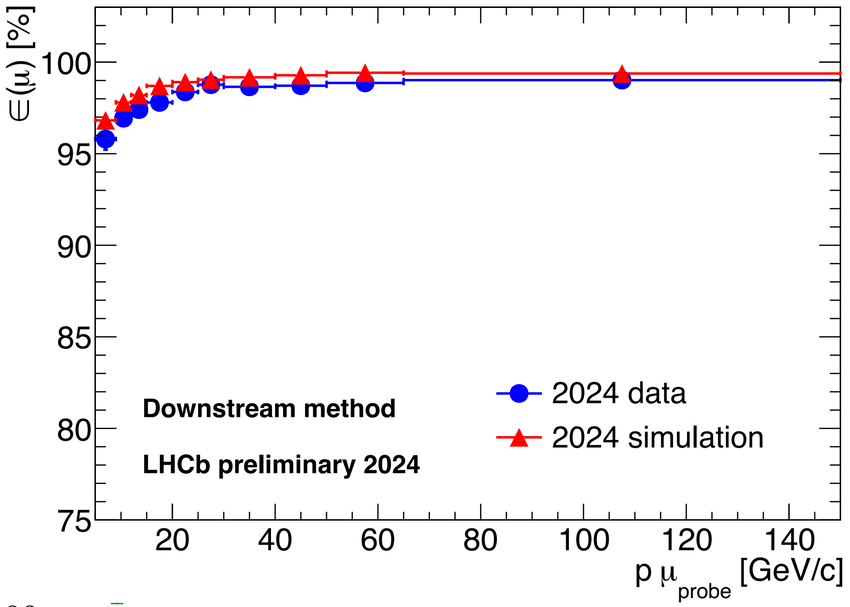
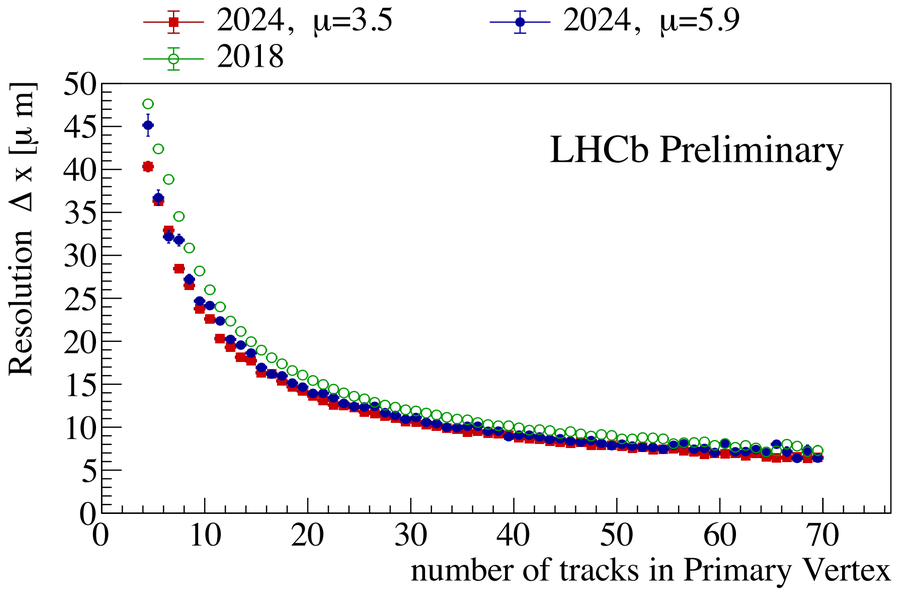
VELO reconstruction

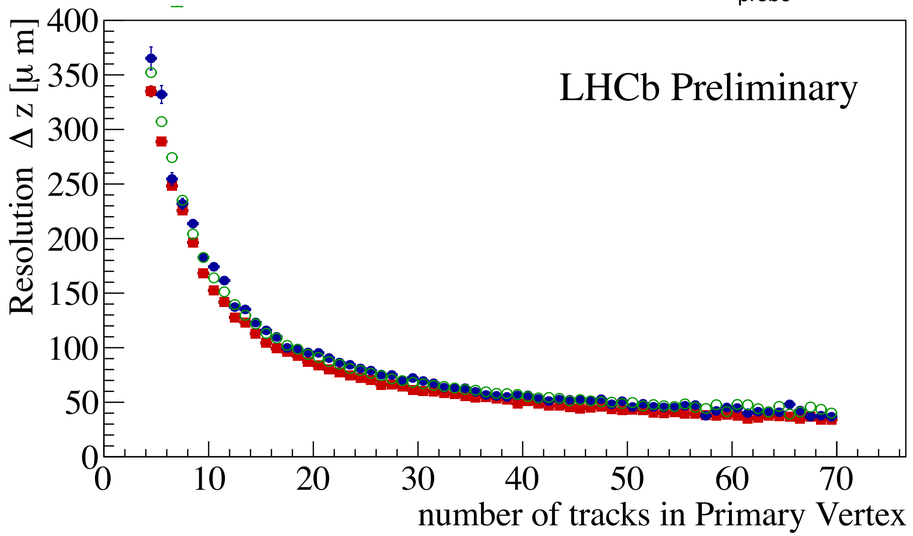
LHCb-FIGURE-2024-011
LHCb-FIGURE-2024-032

- good VELO track reconstruction efficiency, approaching expectations from simulation
- vertex resolution performance comparable to Run 2 while at higher instantaneous luminosity

VELO tracking efficiency







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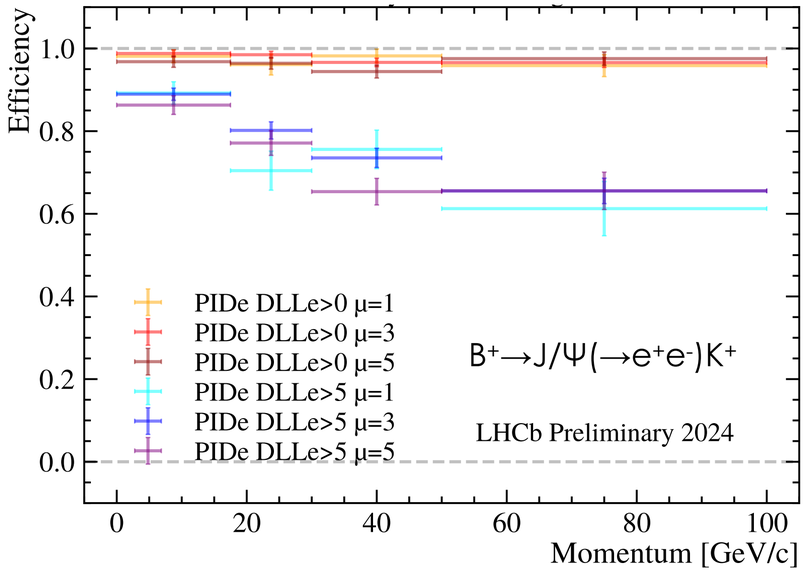
PID: muon & electron

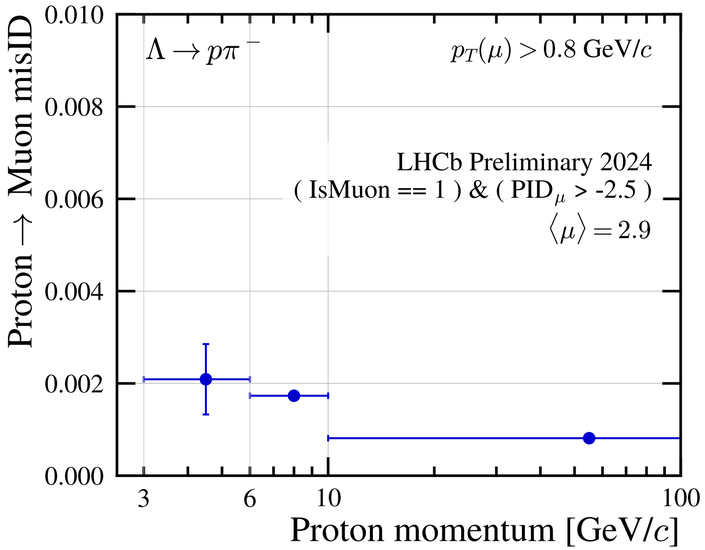
LHCb-FIGURE-2024-010

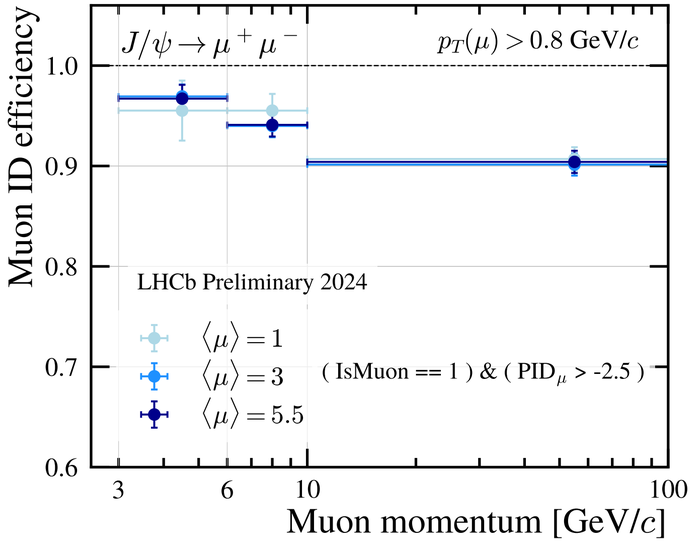
Comparable performance of electron and muon identification wrt Run 2

- no strong dependence observed with instantaneous luminosity

both electrons with brem photon associated







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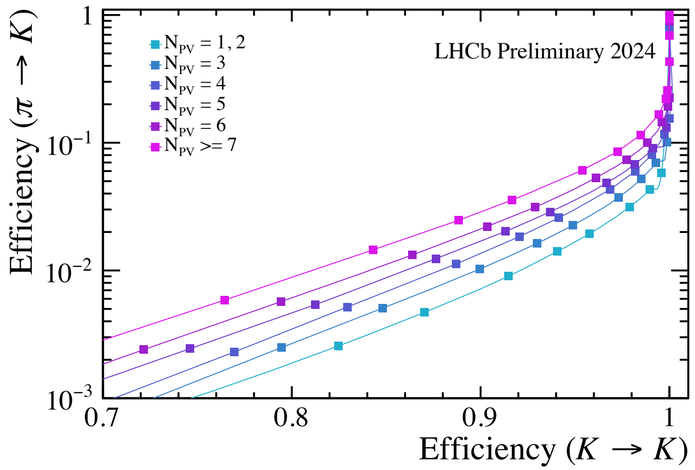
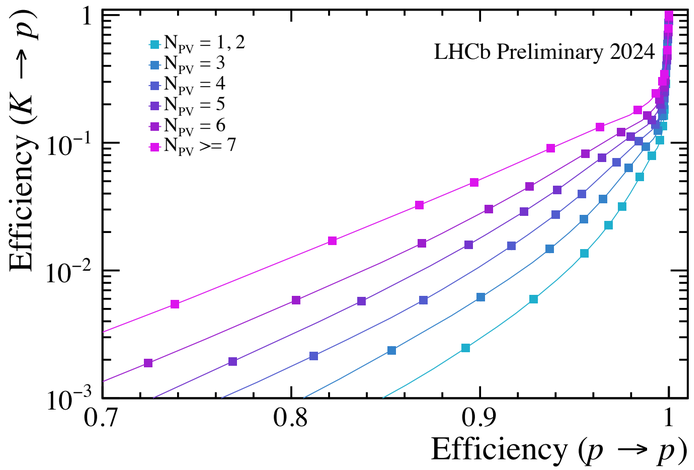
- In summary…

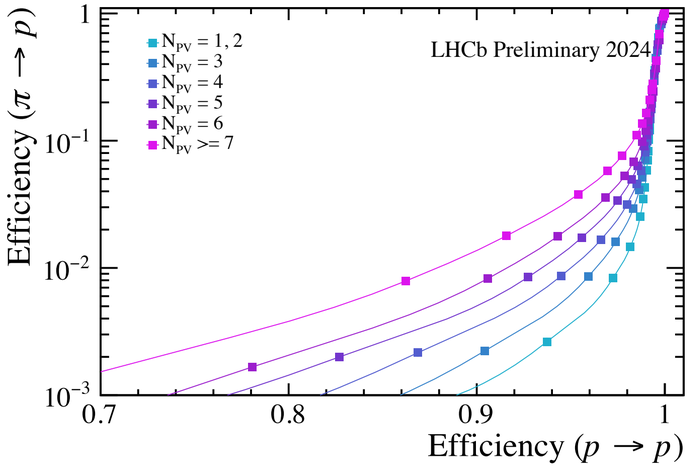
PID: hadrons

LHCb-FIGURE-2023-019
LHCb-FIGURE-2024-031

misidentification vs identification efficiency







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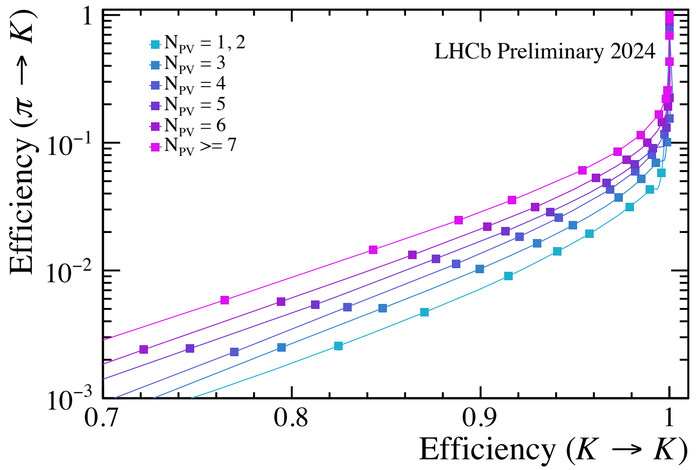
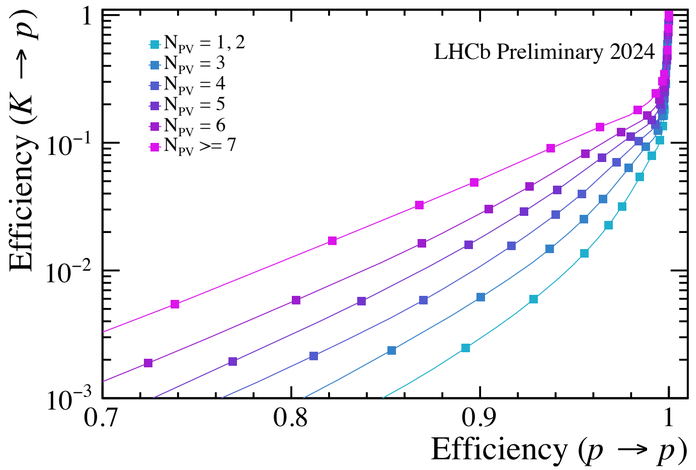
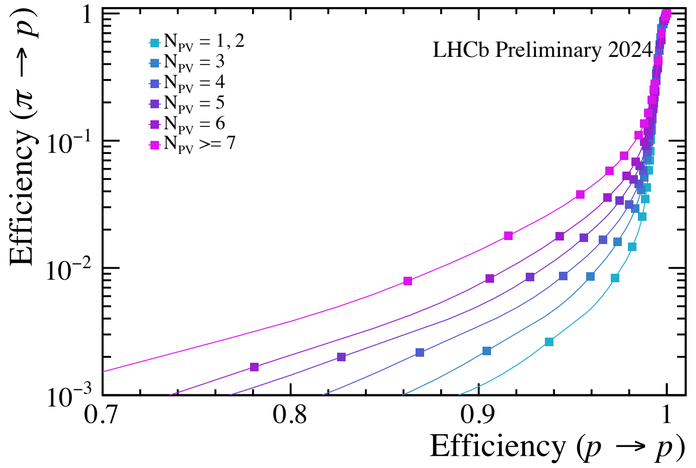
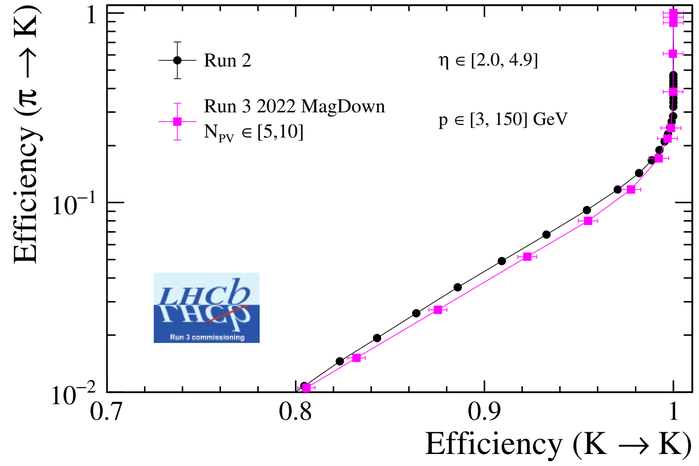
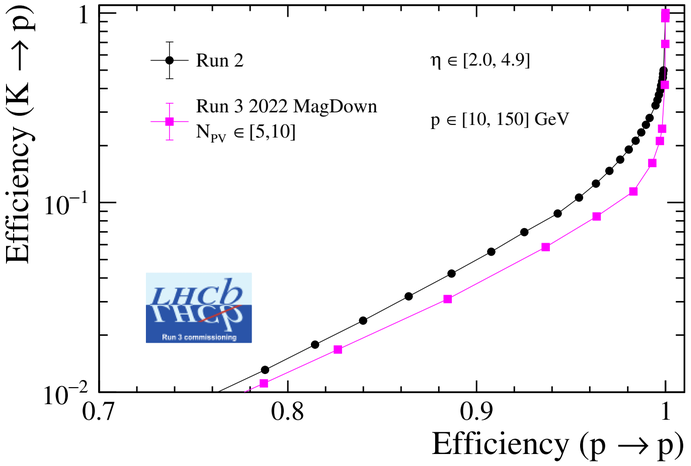
misidentification vs identification efficiency

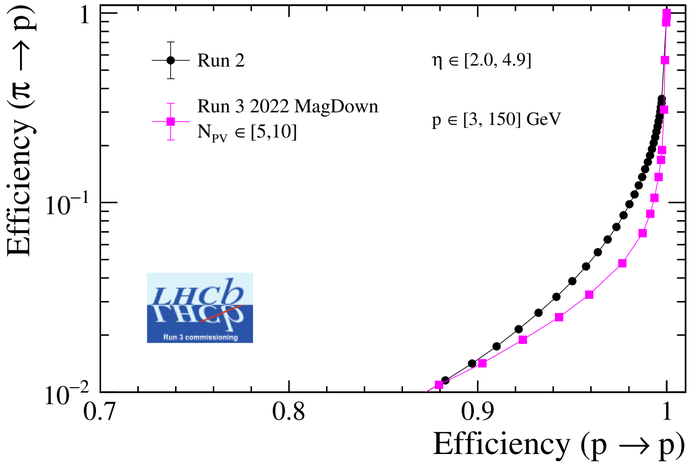












PID as good as Run2 but operating at 5x instantaneous luminosity

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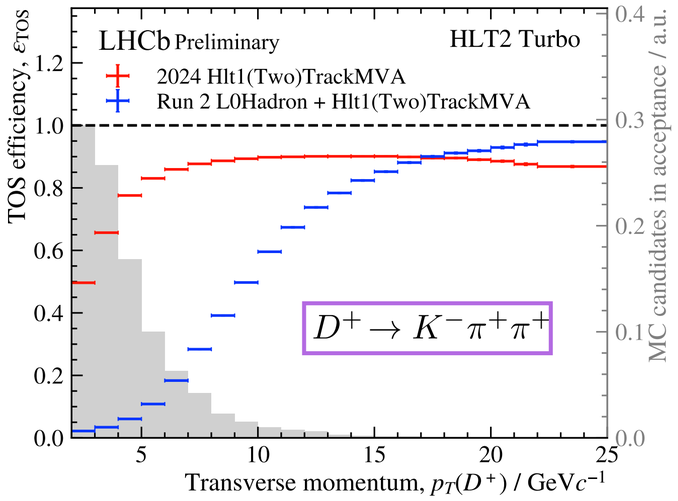
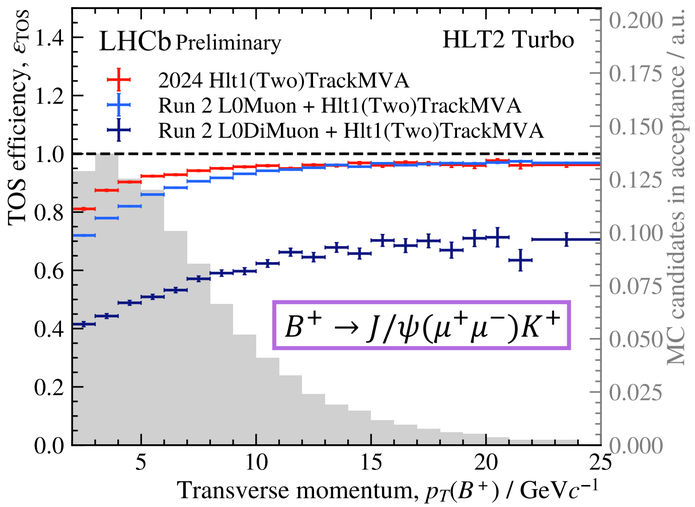
Trigger efficiency

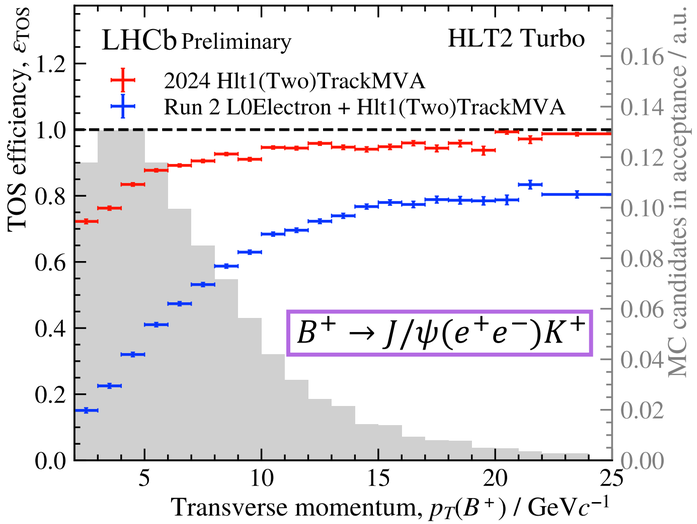
LHCb-FIGURE-2024-030

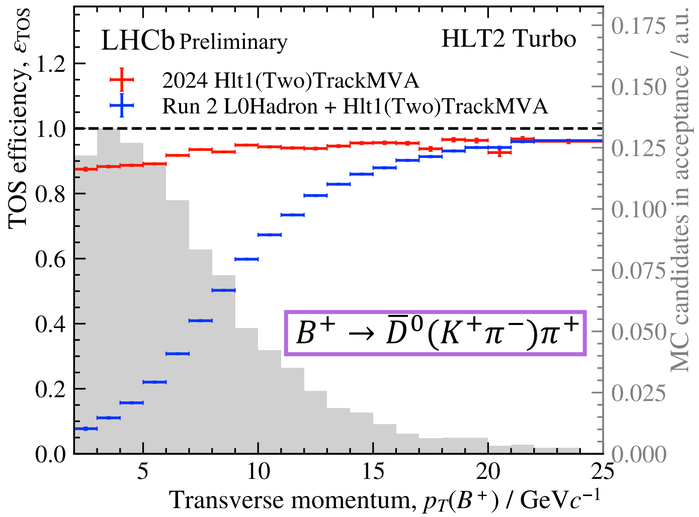
Significant improvements wrt Run 2 in terms of efficiencies at HLT1

- significant gain at low momentum for hadrons and electrons channels
- charm benefits at low Pt where bulk of the signal lies
- comparable performance wrt Run 2 for muon channels









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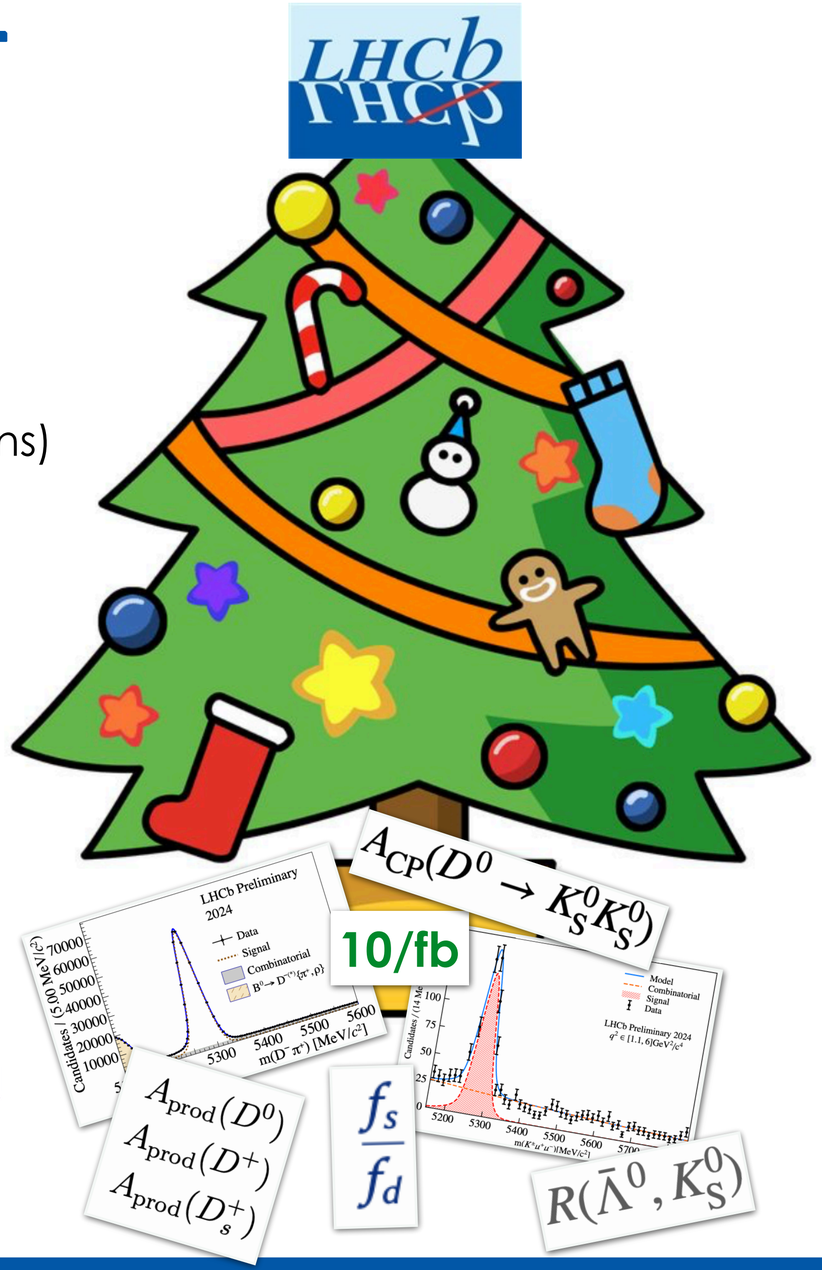
In summary…

very successful year for LHCb!

- finally operating in nominal conditions
  - VELO closed at 0 mm gap
  - achieved DAQ efficiency > 95% in all runs (pp and ions)
  - instantaneous luminosity of 2000 Hz/ub
  - gas almost continuously injected
- lots of data to analyze from 2024 run
  - pp 13.6 TeV: 9.6 /fb
  - pp XXX TeV: 232 /pb
  - PbPb: 450 /ub
- first Run 3 results expected for Moriond 2025

Merry Christmas and wishes for many Run3 physics results!



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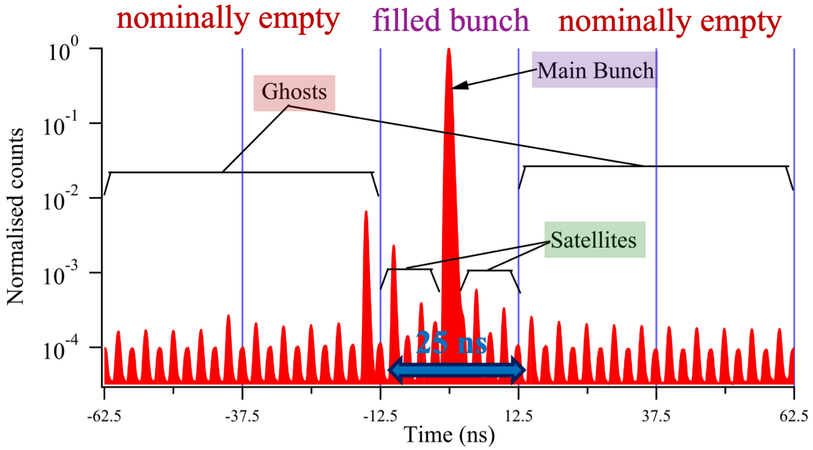
  - UT integration
  - HLT1 track reconstruction
  - HLT1 & HLT2
  - Gas injection
  - pp reference run
  - ion run
- Performance
  - Detectors
  - Hit efficiency
  - Alignment
  - Cherenkov angle
  - VELO reconstruction
  - PID
  - Trigger efficiency
- In summary…

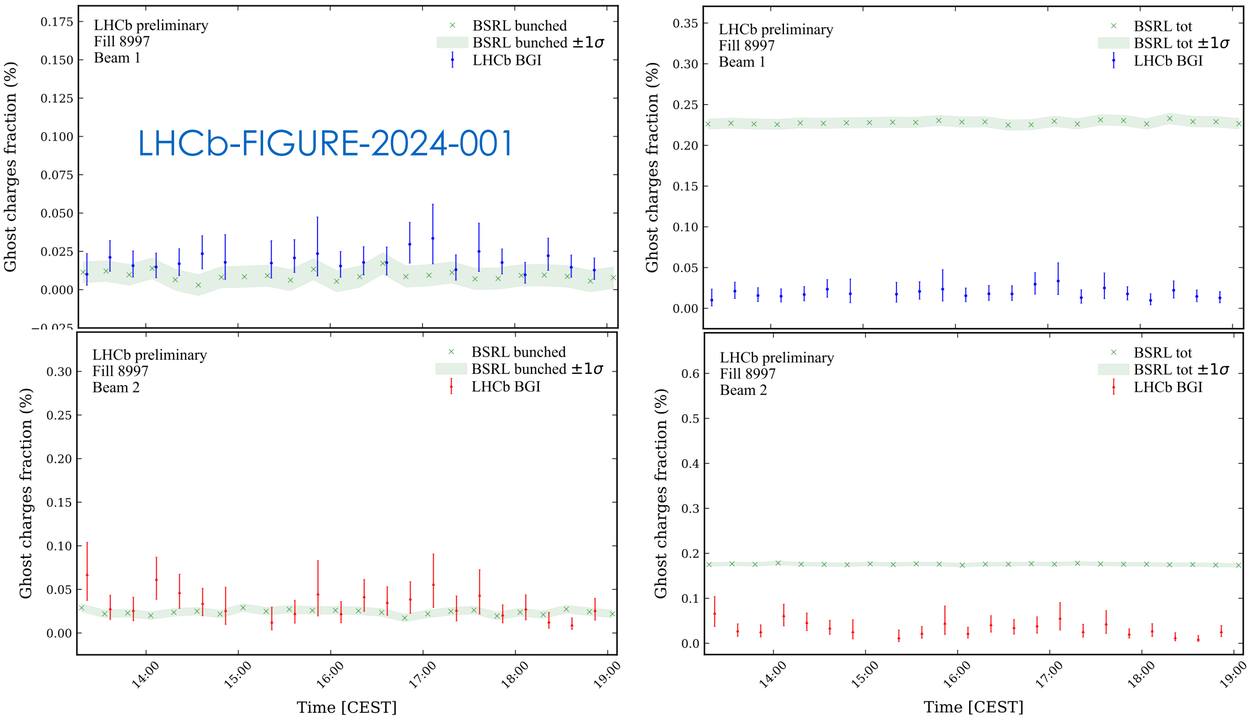
Additional material

Ghost charge measurement

- precise knowledge of ghost charge fraction fundamental for the measurement of luminosity
- Satellite and Ghost charges are measured by Beam Synchrotron Radiation Longitudinal (BSRL):
  - per bunch: baseline subtracted
  - total: no subtraction

CERN-ATS-Note-2012-029





LHCb provides a unique and complementary measurement of ghost charges

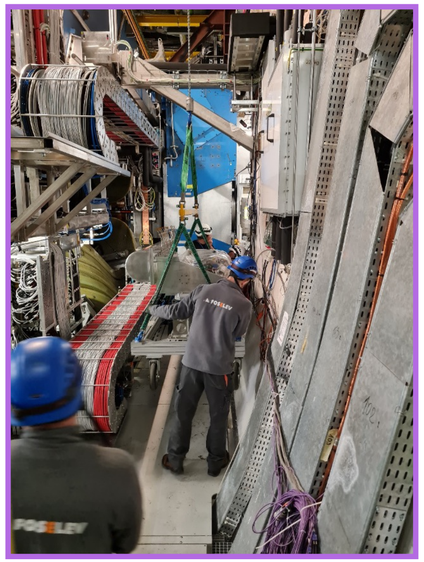
- based on PV reconstructed due to the interaction with gas injected by SMOG
- results in agreement with the BSRL
- fundamental input for the luminosity measurements of ATLAS, CMS and ALICE

VELO

RF foil replacement in EYETS 23/24

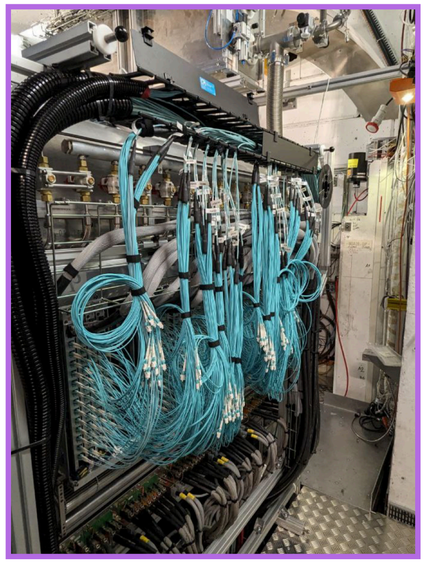
- detector de-installation, RF foil replacement and re-installation went smoothly
  - 0.5 mm shims installed to increase the clearance between modules and foil, to be removed in the first Technical Stop (June) pending tomography
- detector already under vacuum and cooled to -35 deg

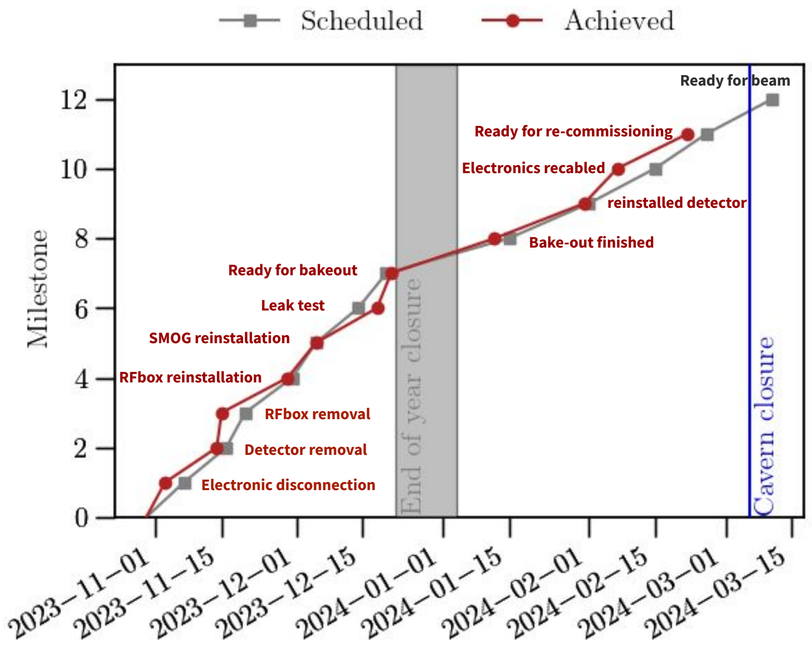
transport to the alcove



half installation

cabling





intense re-commissioning ongoing to be fully ready for the first beam!

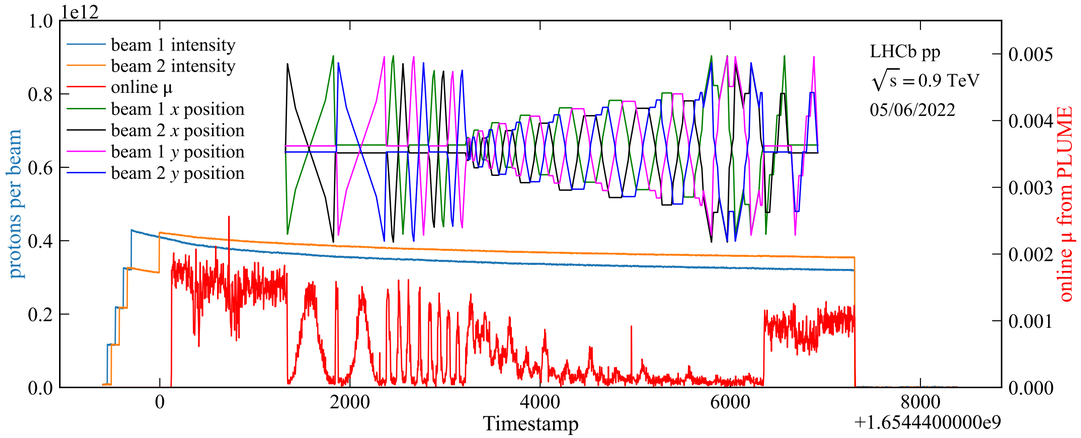
PLUME & BCM

LHCb-FIGURE-2022-012

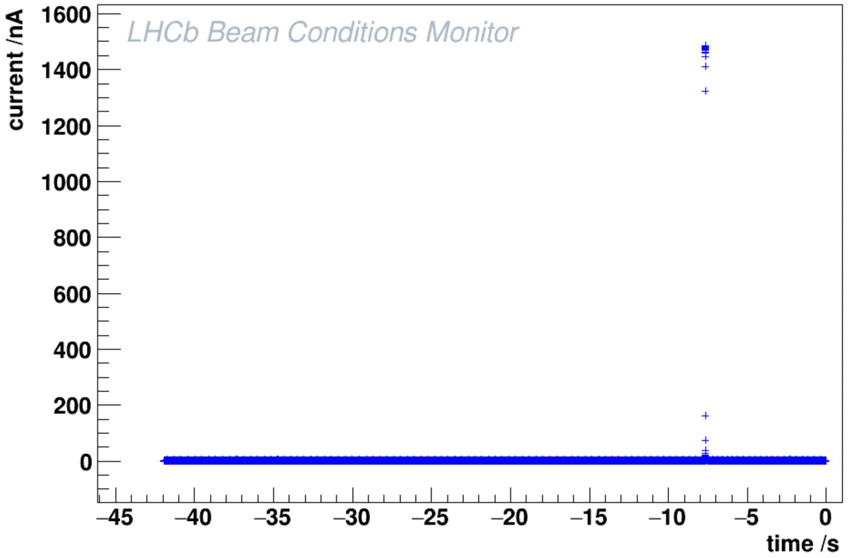
Plume

- per PMT ADC counters used to provide instantaneous luminosity to the LHC every 3s
- additional features developed during the EYETS:
  - luminosity per bunch crossing
  - possibility to run continuously independently of global experiment status

first plume online calibration with van der Meer scan



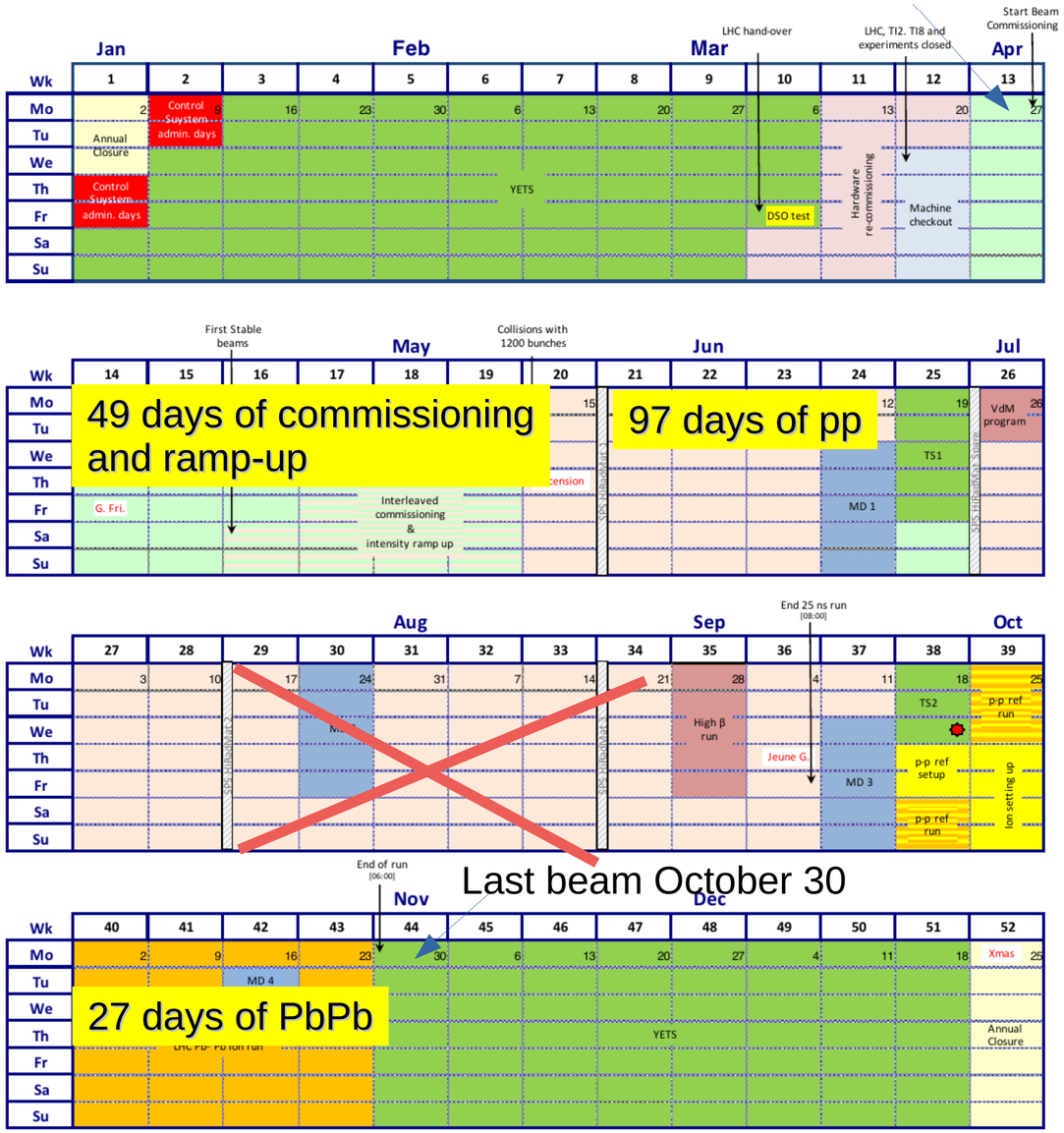
first beam dump with upgraded electronics board



BCM

- fully refurbished during before restart of Run 3 with new DAQ operational since 2023
- beam dump logic + Run 3 updated thresholds validated by dumping the beam as expected during LHC tests

The (evolving) LHC 2023 schedule

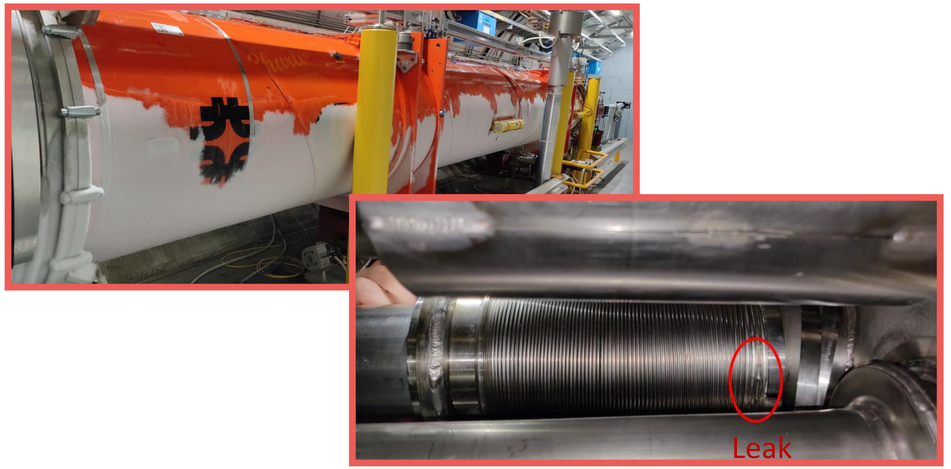


How it started…

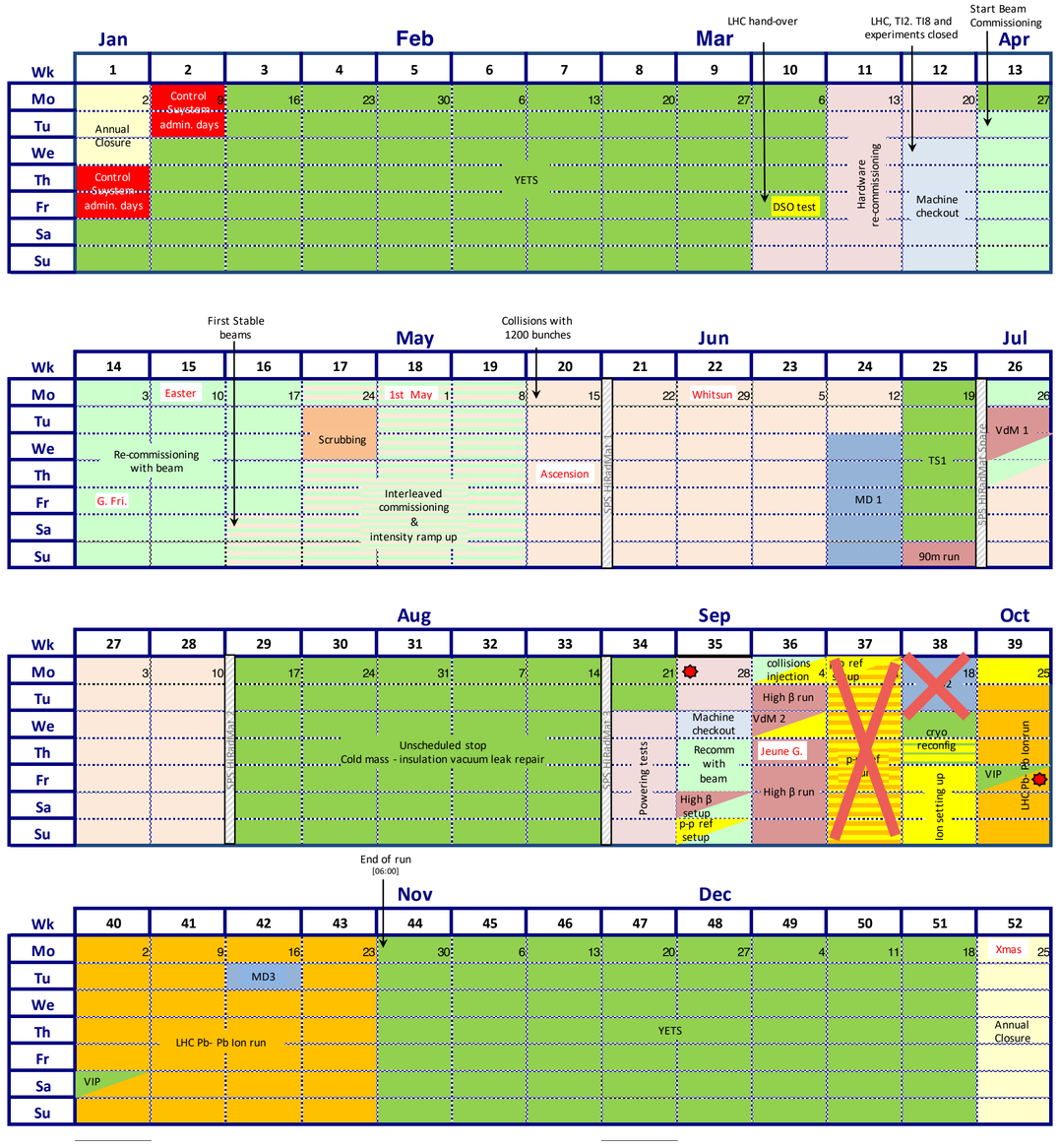
- short pp run: 13.5 weeks
- extended ion run: 4 weeks of ion physics, 1 week of pp reference run

ITL8 incident

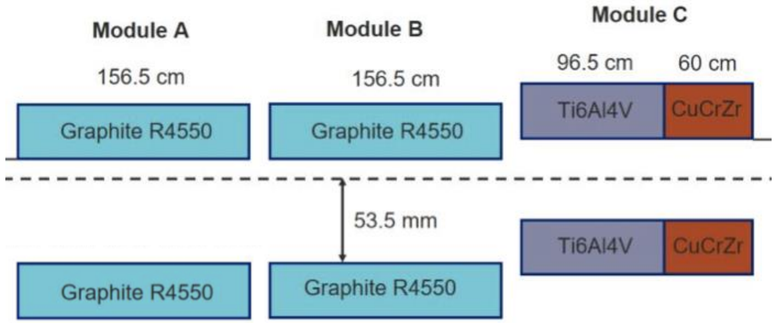
- leak found in a bellow in the triplet left of 8
- replacement done in difficult conditions (arc kept cold-ish) but fully successful



The (evolving) LHC 2023 schedule



…how it evolved…

Leaks in TDIS

- two leaks found in close succession in the same TDIS
- replacement not preferred choice
- running with jaws open, high intensity proton beam not possible in this configuration