LHCb Performance Highlights

Mark Tobin
Institute of High Energy Physics
Chinese Academy of Sciences
On behalf of the LHCb collaboration

See also Matteo Palutan (opening plenary, 16/5)
+22 other speakers from LHCb!

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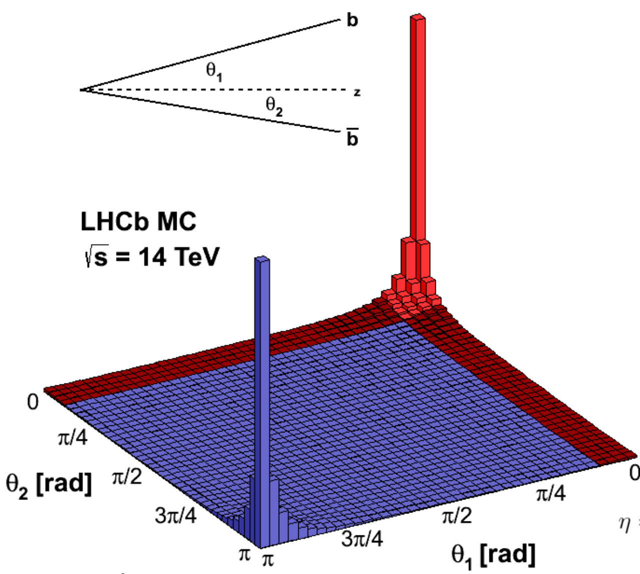
Why LHCb?

- Dedicated heavy flavour experiment at LHC.
  - Measure CP-violation in *b*-sector.
  - Study rare *b*- and *c*- hadron decays.
  - Exploit forward production of *b*-pairs with low angle.

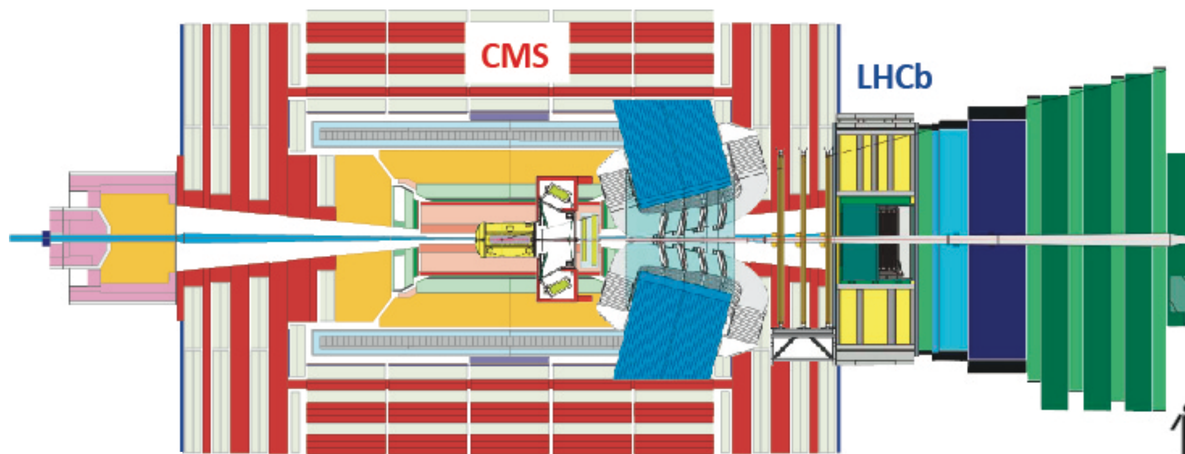
✧ ***Indirect searches for New Physics.***

- Physics program in Runs 1&2 was much much more.
  - Electroweak, QCD, direct searches, heavy ions.

✧ ***General Purpose Detector in forward region.***



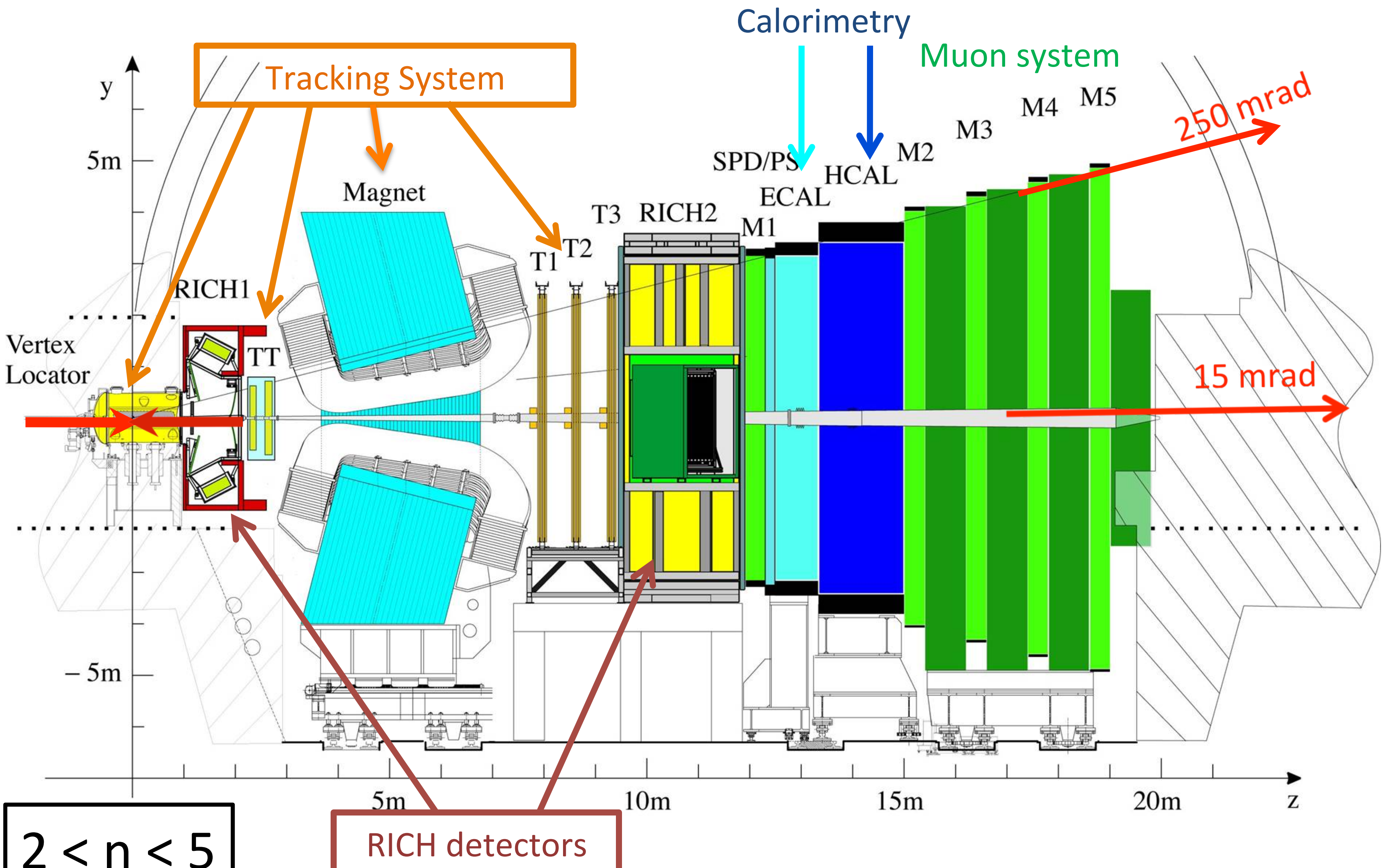
$$\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$



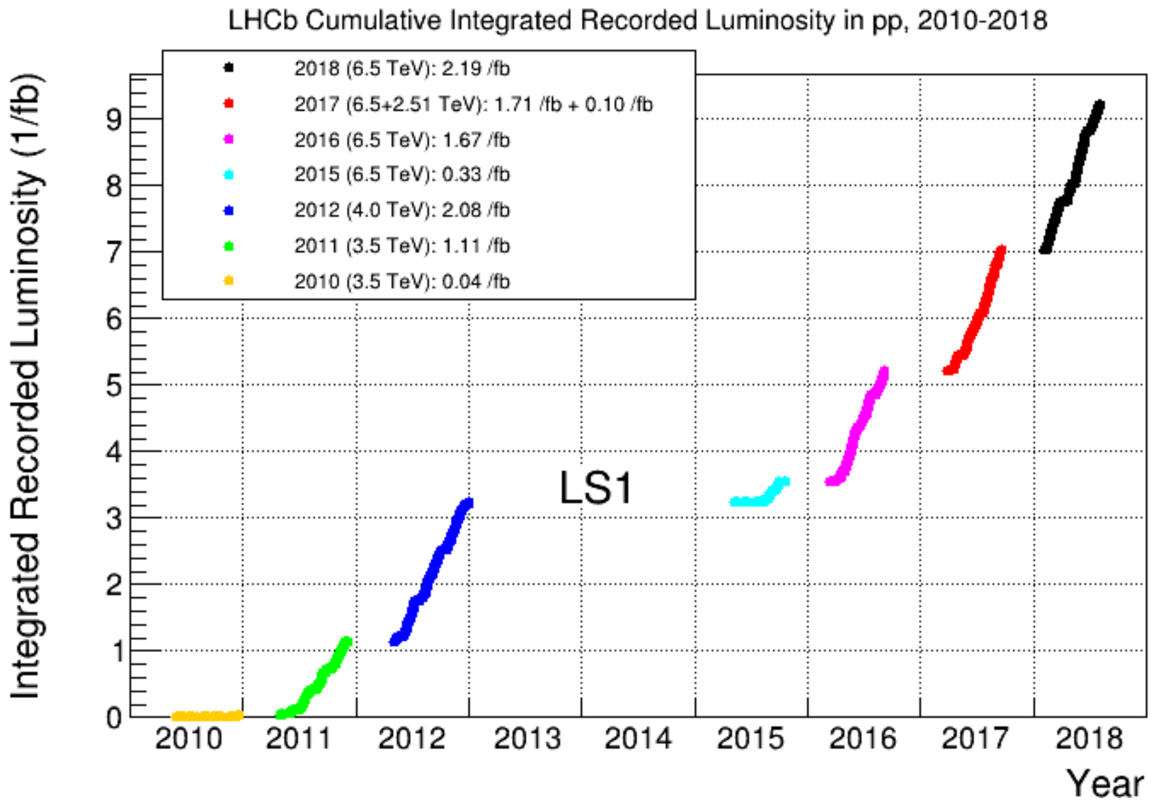
$2 < \eta < 5$

2008 JINST 3 S08005

LHCb detector



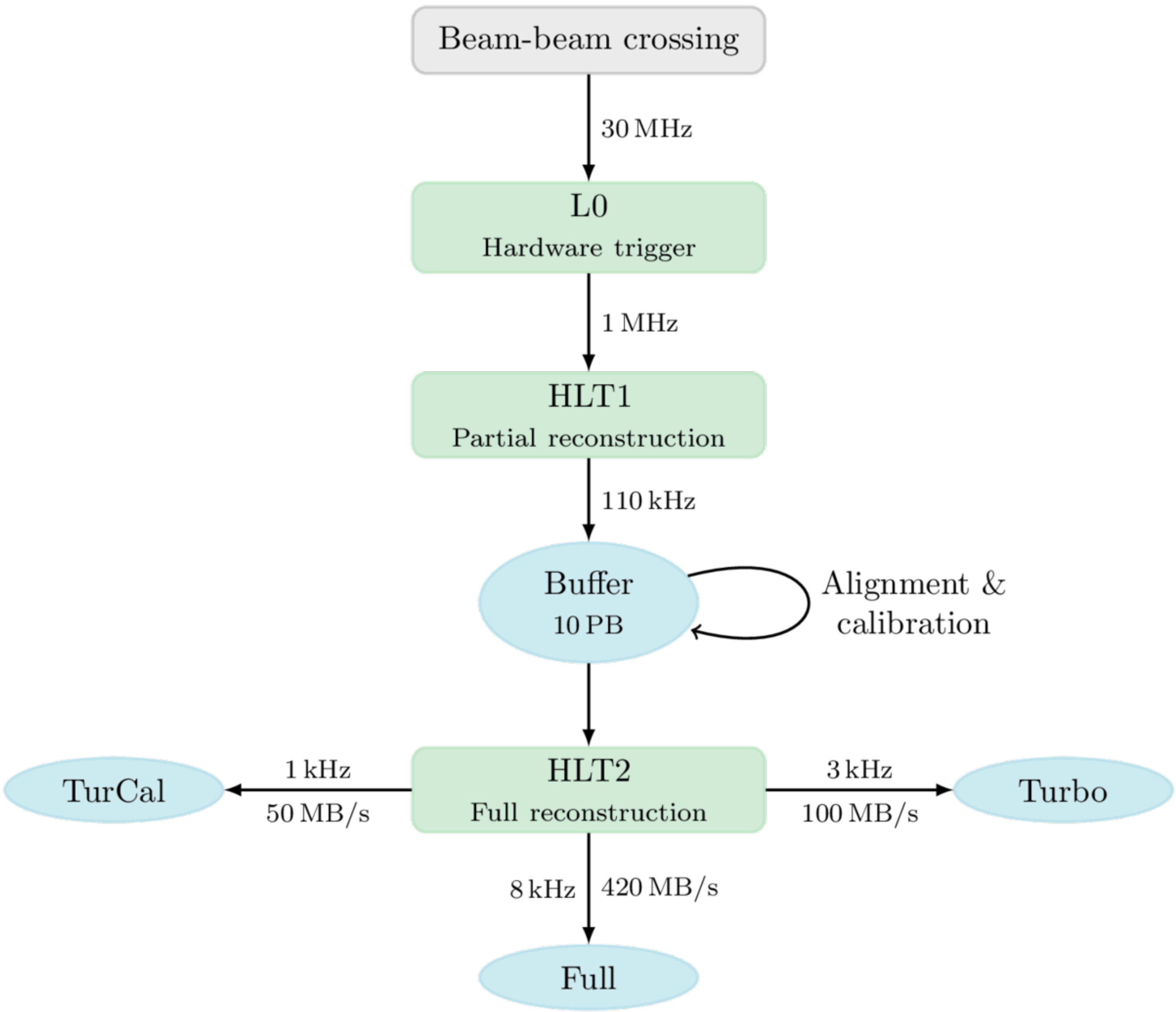
$2 < \eta < 5$


LHCb Cumulative Integrated Recorded Luminosity in pp, 2010-2018
2018 (6.5 TeV): 2.19 /fb
2017 (6.5+2.51 TeV): 1.71 /fb + 0.10 /fb
2016 (6.5 TeV): 1.67 /fb
2015 (6.5 TeV): 0.33 /fb
2012 (4.0 TeV): 2.08 /fb
2011 (3.5 TeV): 1.11 /fb
2010 (3.5 TeV): 0.04 /fb
LS1
Integrated Recorded Luminosity (1/fb)
0
1
2
3
4
5
6
7
8
9
2010
2011
2012
2013
2014
2015
2016
2017
2018
Year

RUN 1 & 2

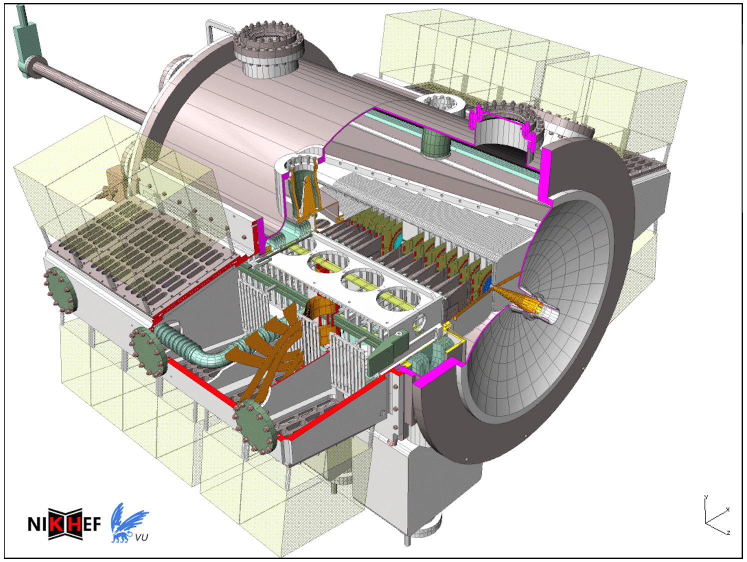
2019 JINST 14 P04006

LHCb Trigger (Run 2)

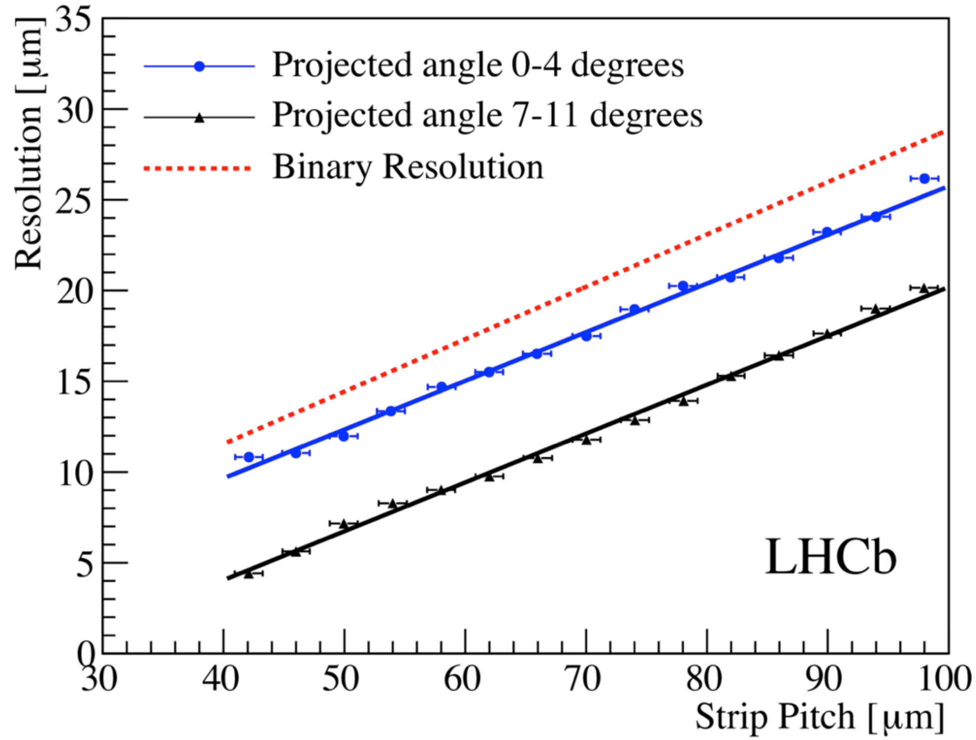


Int. J. Mod. Phys. A 30, 1530022 (2015)
2014 JINST 9 P09007

VErtex LOcator (VELO)



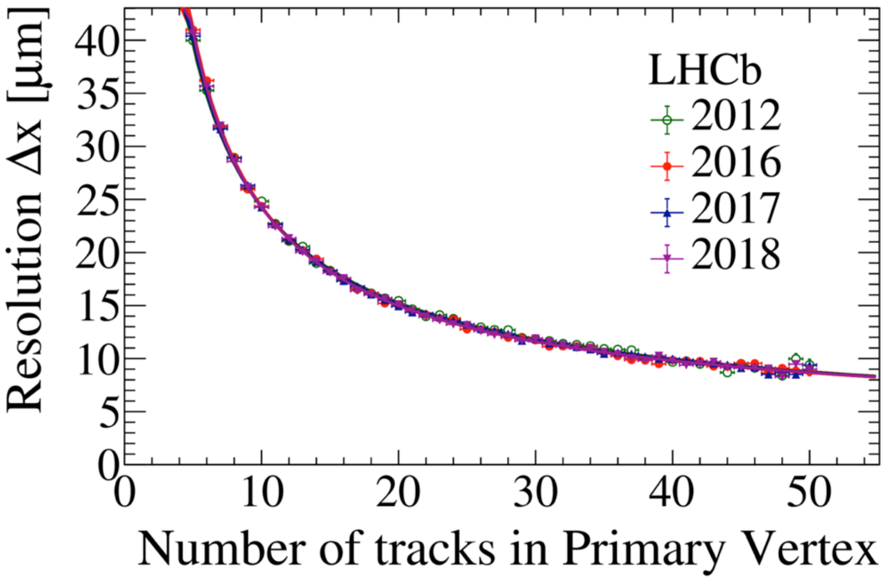
- Two retractable halves
  - 5 mm from beam when closed.
  - 30 mm during injection.
  - First measurement at 8.13 mm.
- Operated in secondary vacuum.
  - 300 μm aluminium foils separates detector from beam vacuum.
- 21 R-Φ modules per half.
  - Silicon microstrip sensors.
  - Pitch: 38 – 101 μm.

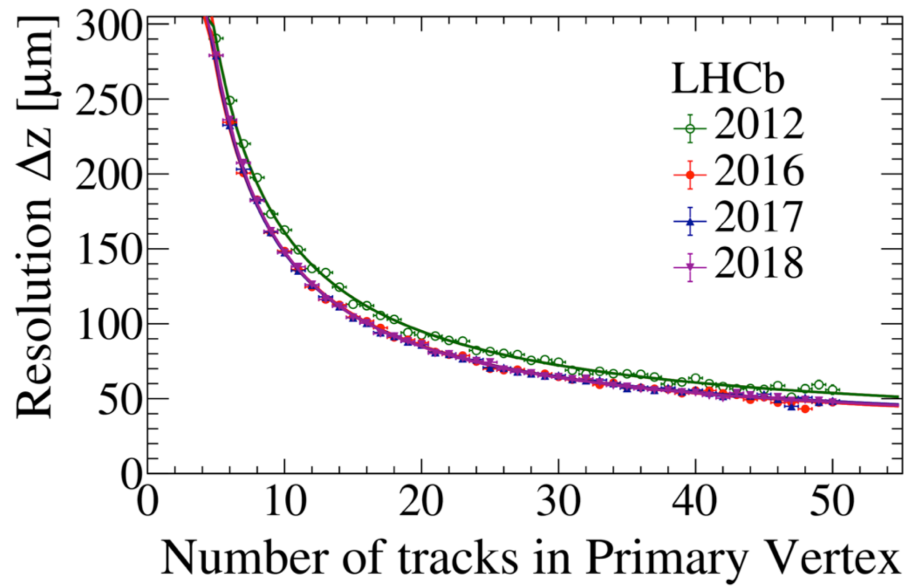


- Hit resolution measured from unbiased residuals of cluster to track.
- Projected angle is the angle between track and strip in plane perpendicular to the track.
- Best resolution: 4 μm!

2019 JINST 14 P04013

Primary Vertex Resolution

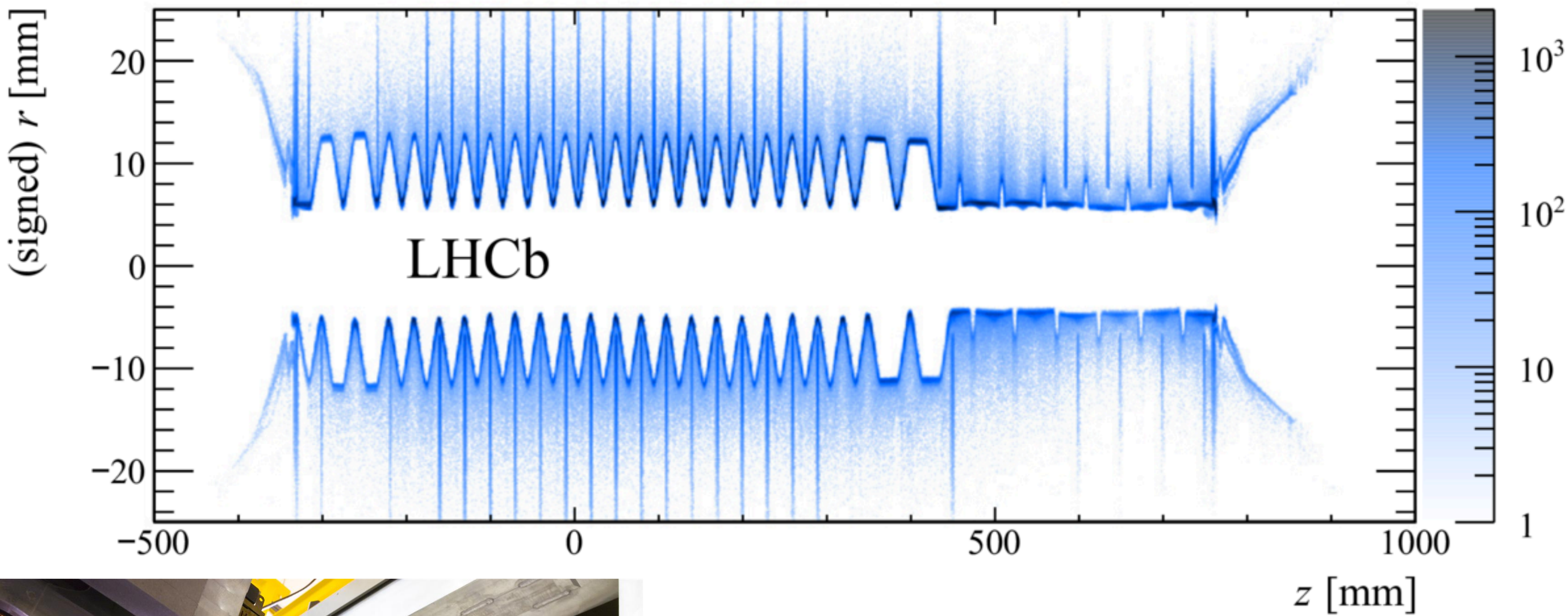


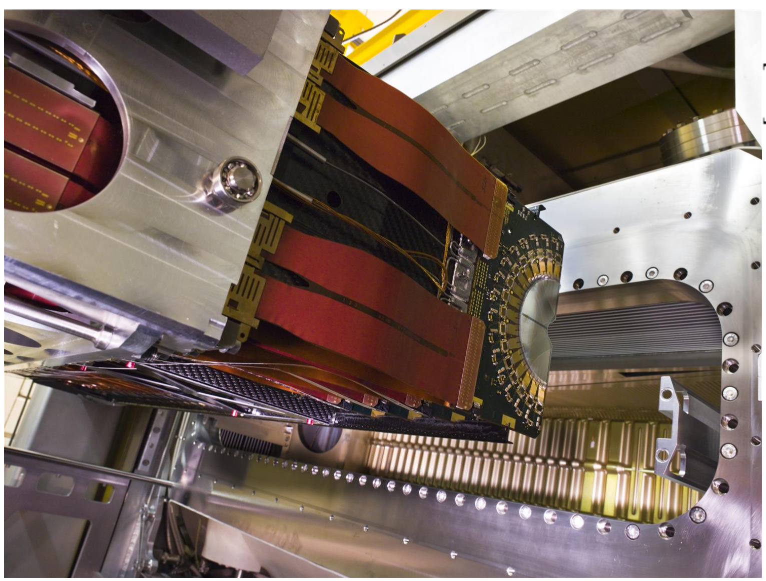


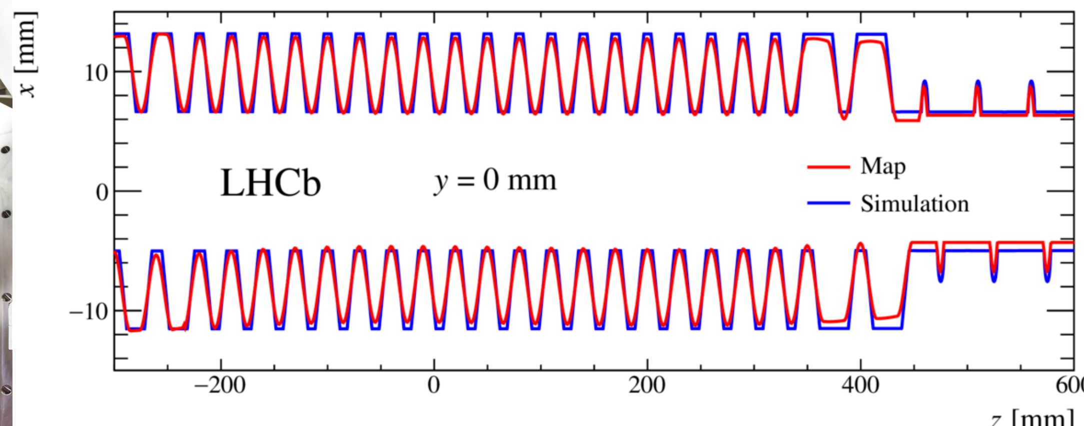
- Randomly split input VELO tracks into two subsets.
- Reconstruct primary vertex with each sample.
- Resolution given by width of distribution of difference of PV positions in each dimension.
- Improved resolution in z-coordinate by ~ 10% in Run 2.

Material Scan

2018 JINST 13 P06008

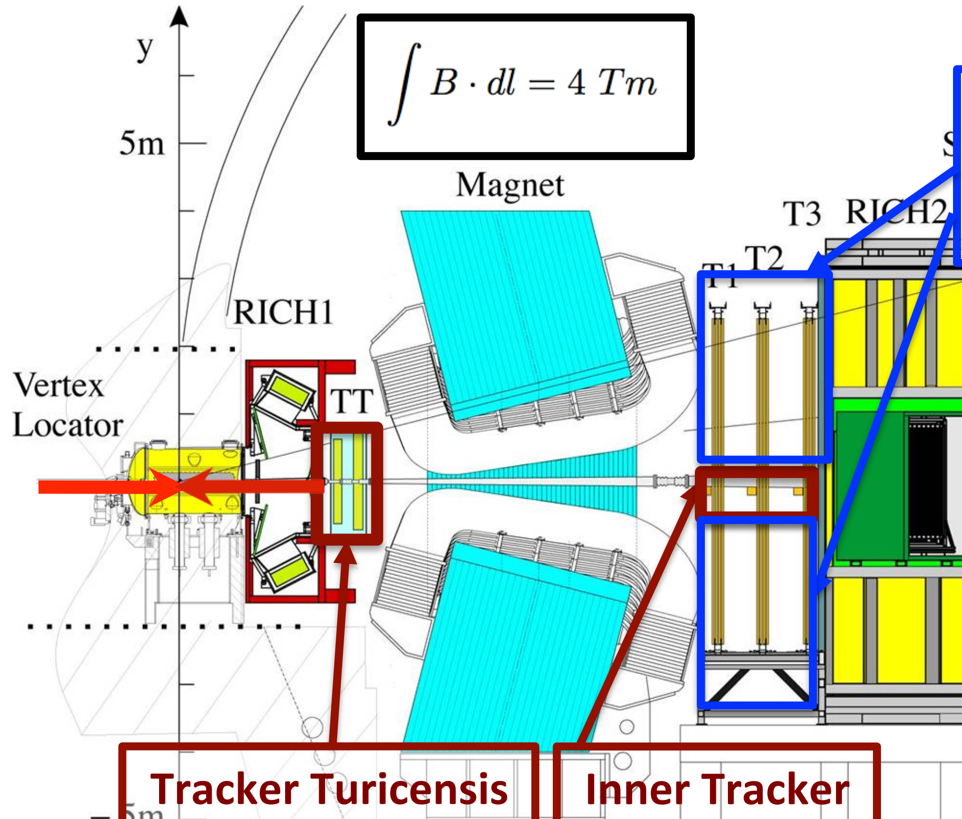




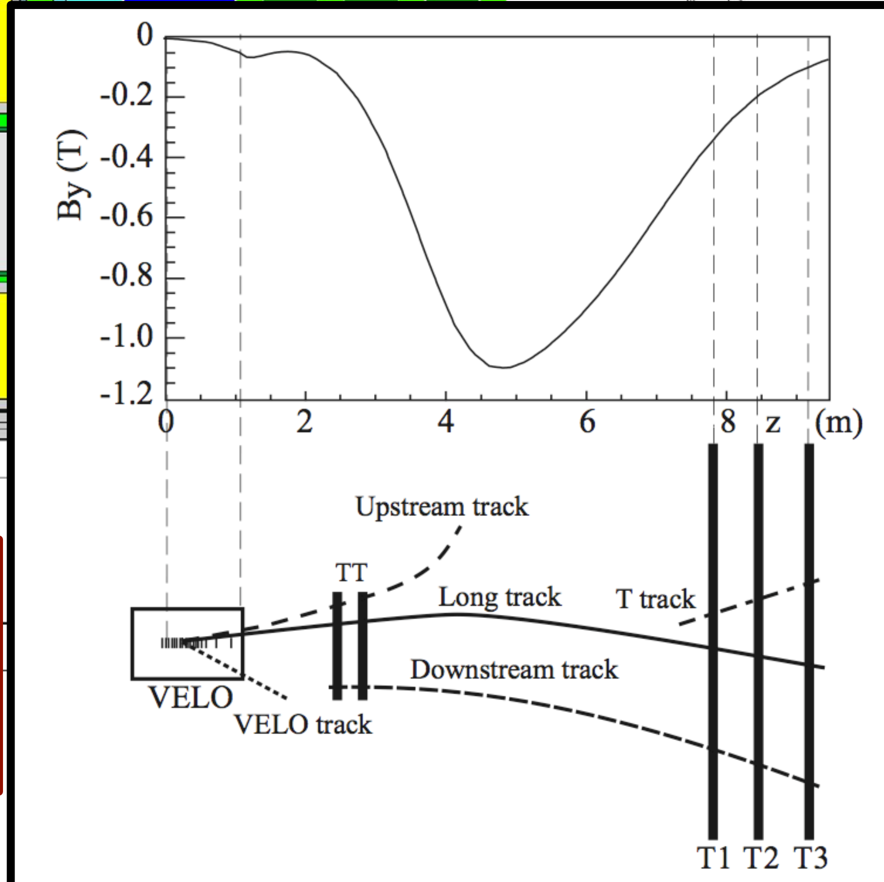


- Reconstruct vertices from hadronic interactions.
- Use to validate material description in simulation.

LHCb Tracker



Outer Tracker:
- Straw tubes covering rest of acceptance.
- Resolution ≈ 200 μm.

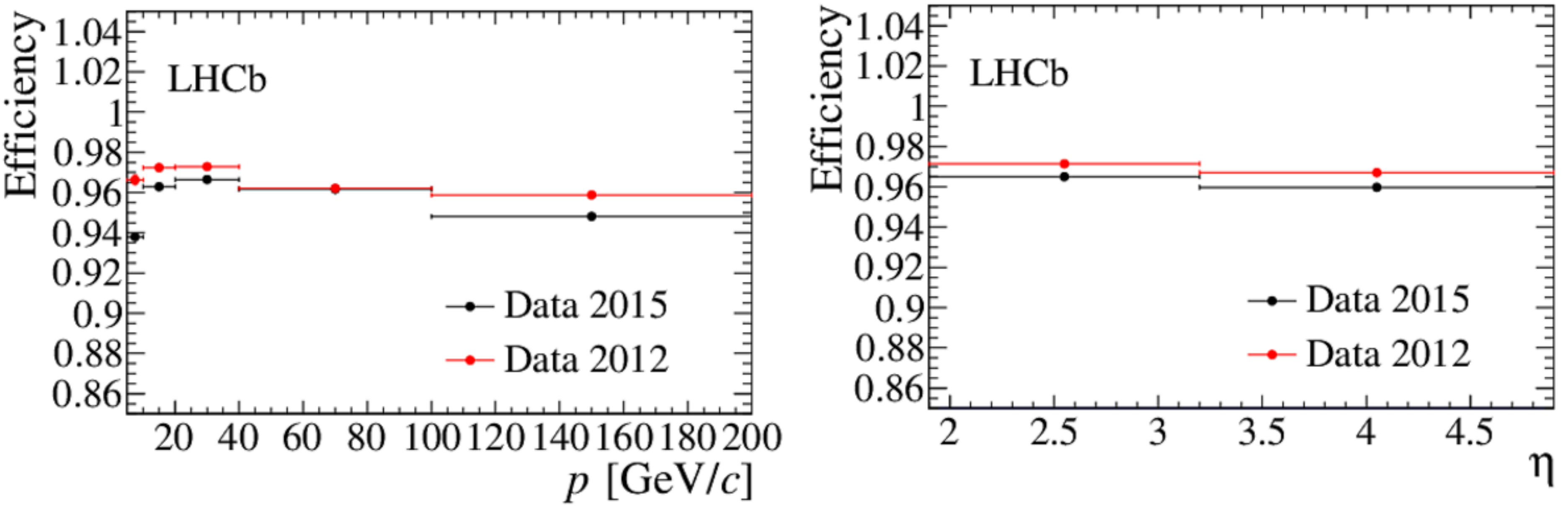


Tracker Turicensis | **Inner Tracker**

Silicon Tracker:
- Silicon micro-strip detectors covering areas closest to the beam pipe.
- Resolution ≈ 50 μm.

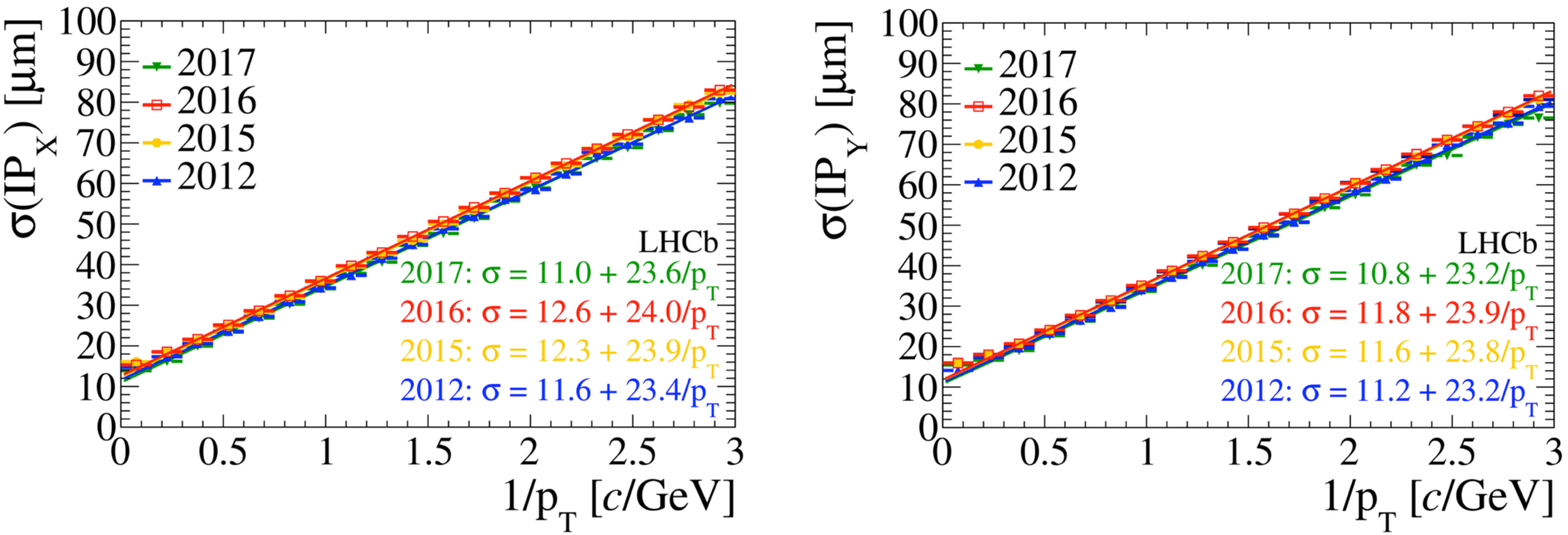
2019 JINST 14 P04013
2015 JINST 10 P02007

Tracking efficiency



- Efficiency determined using tag-and-probe method.
  - Uses $J/\psi \rightarrow \mu^+\mu^-$ from decays of b-hadrons.
  - One muon reconstructed using full reconstruction.
  - Reconstruct second muon using sub-set of tracking stations.
- Lower track reconstruction efficiency in Run 2.
  - Bunch spacing changed from 50ns to 25ns.
  - Read-out window in Outer Tracker > 25ns → spillover.

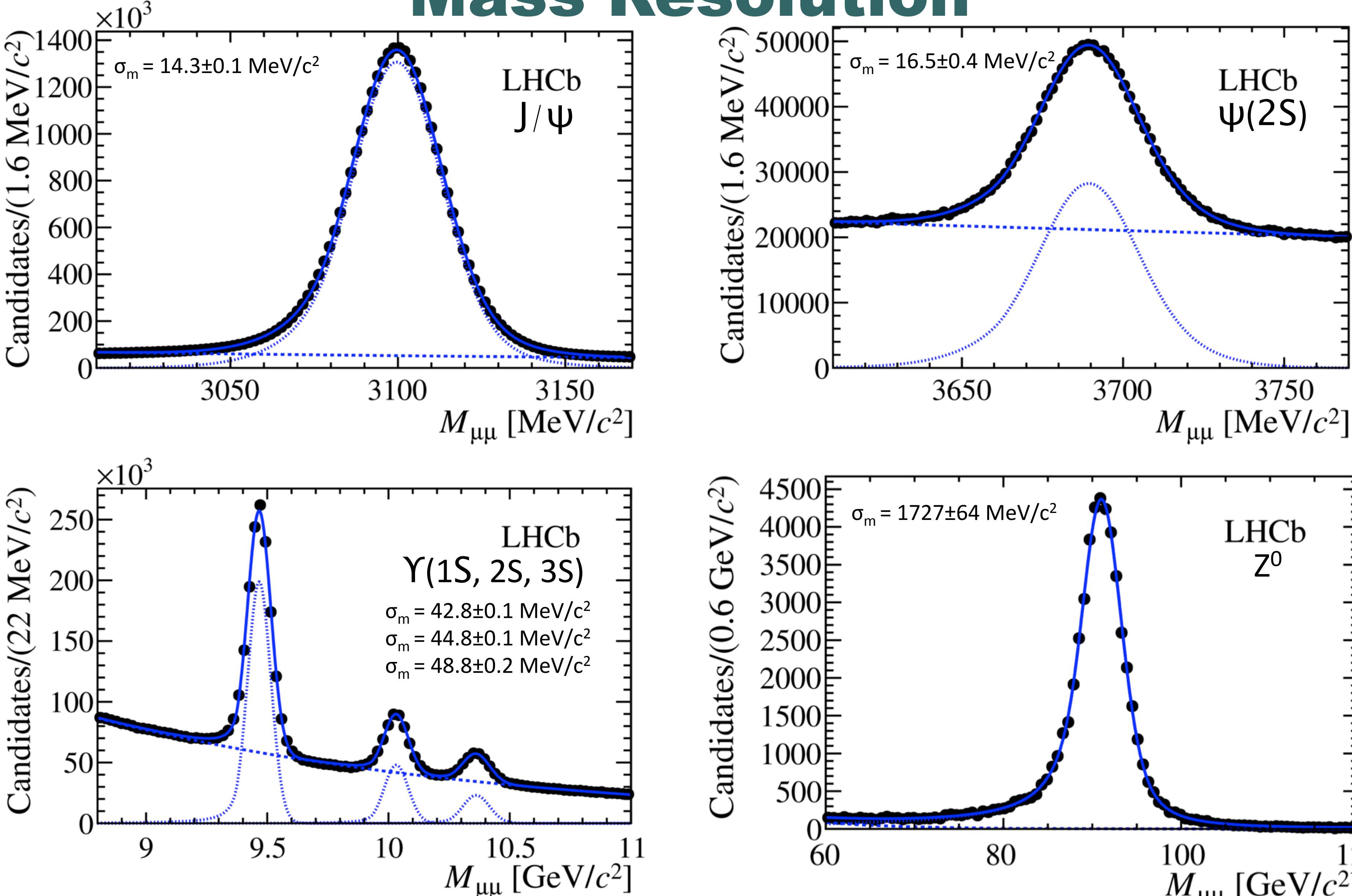
Impact Parameter Resolution



- IP is distance of closest approach of track to PV.
  - Useful variable for selecting B meson decays.
- Depends mainly on 3 factors:
  - Multiple scattering in detector material.
  - Hit resolution.
  - Distance between PV and first measurement.
- No difference between Run 1 and Run 2.
  - Offline quality reconstruction running online!

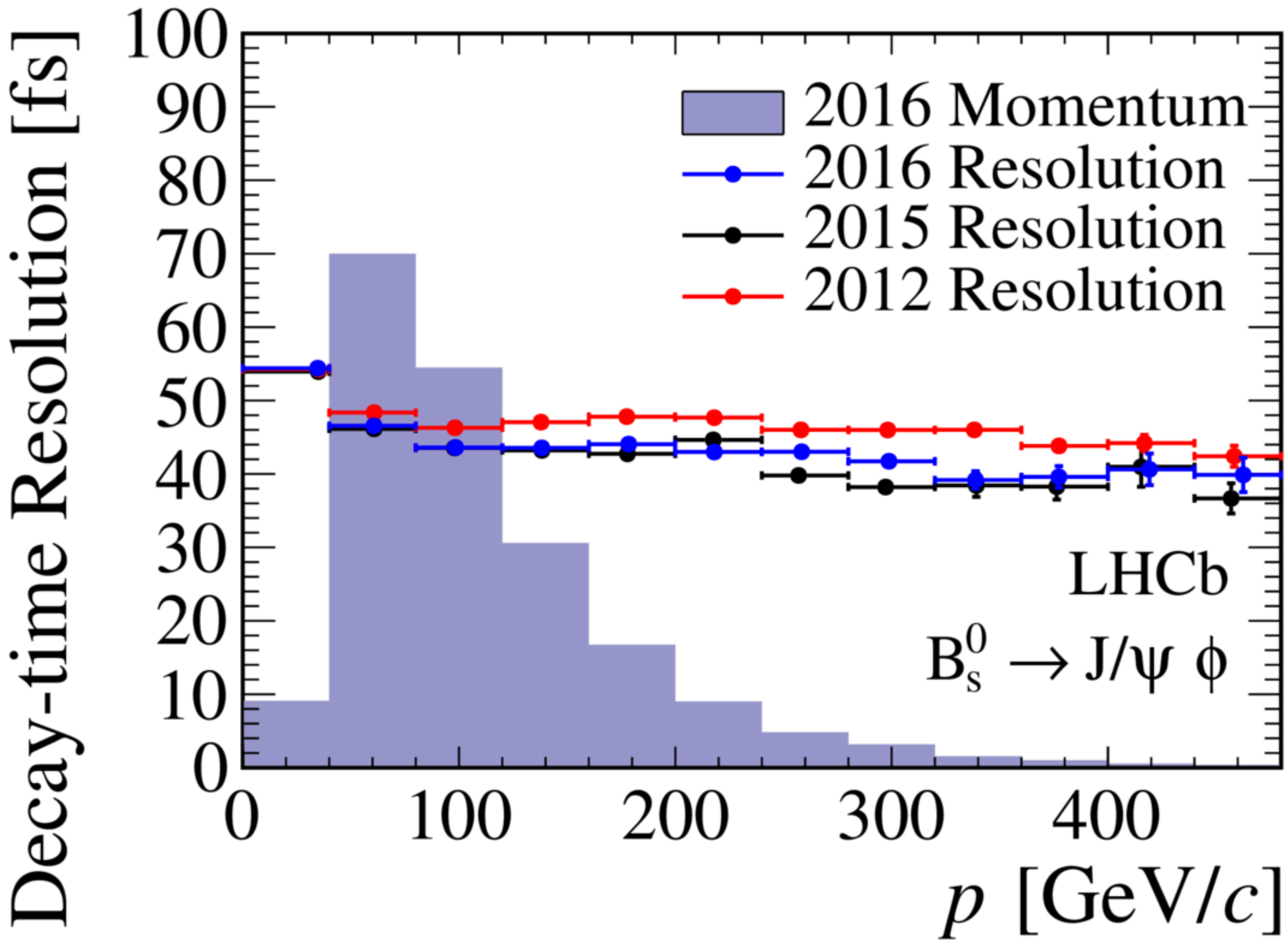
Int. J. Mod. Phys. A 30, 1530022 (2015)

Mass Resolution



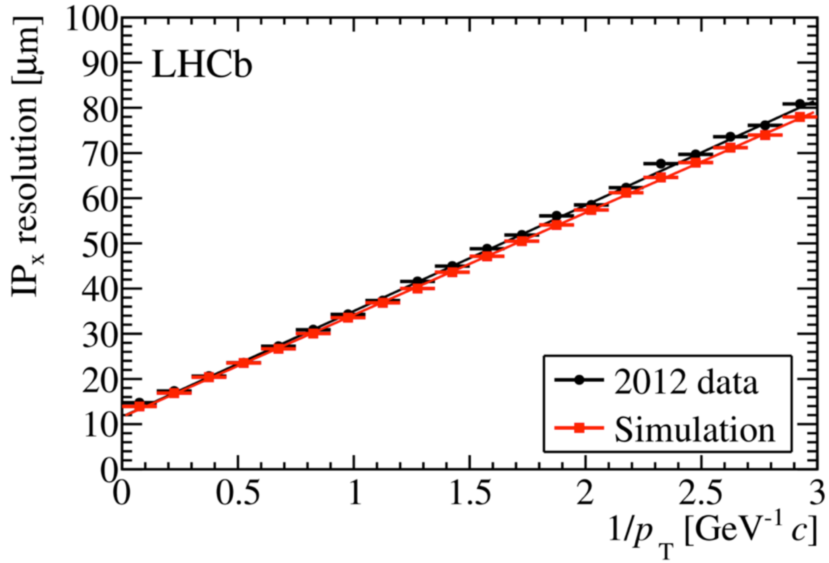
2019 JINST 14 P04013

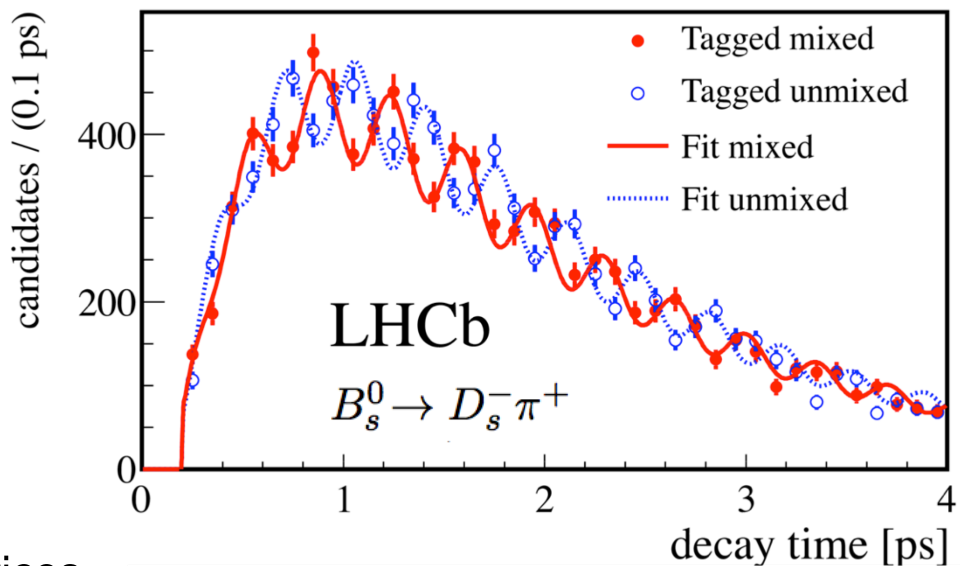
Decay time resolution



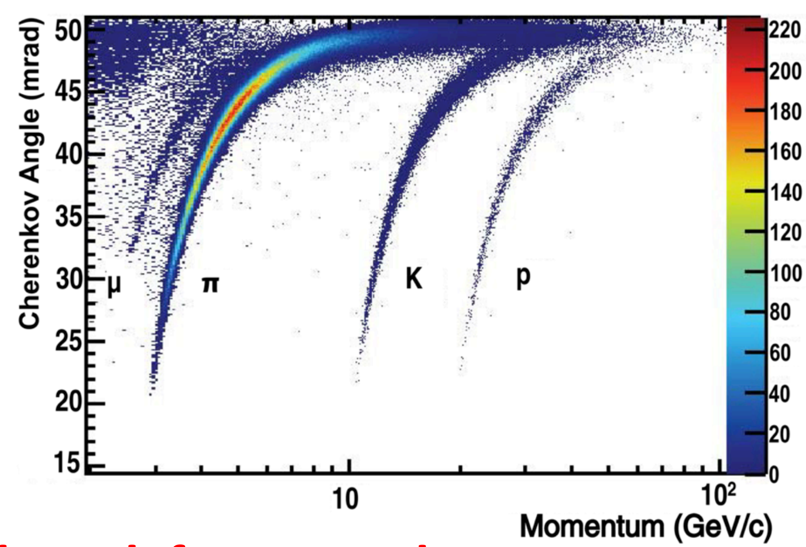
Int. J. Mod. Phys. A 30, 1530022 (2015)

Detector Performance





- Separation of primary and secondary vertices.
  - Impact parameter resolution: (15 +29/p_T[GeV]) μm.
- Proper time resolution.
  - Decay time resolution: ~45 fs ($B_s \to J/\psi\phi$ & $B_s \to D_s\pi$).
- Excellent momentum resolution:
  - Δp / p = 0.5% (<20 GeV) to 1.0% (200 GeV).
- Particle Identification:
  - Separation between γ, e$^{\pm}$, mu$^{\pm}$, π, K, p.
- Trigger Selection:
  - Efficient trigger for leptonic and hadronic final states.
  - Fast reconstruction of primary and secondary vertices



Run 1&2 performance is benchmark for Upgrades

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1. CERN-LHCC-2008-007
2. CERN-LHCC-2011-001
3. CERN-LHCC-2012-007
4. CERN-LHCC-2013-021
5. CERN-LHCC-2013-022
6. CERN-LHCC-2014-001
7. CERN-LHCC-2014-016
8. CERN-LHCC-2018-007
9. CERN-LHCC-2018-014
10. CERN-LHCC-2019-005
11. CERN-LHCC-2020-006
12. CERN-LHCC-2021-002

RUN 3

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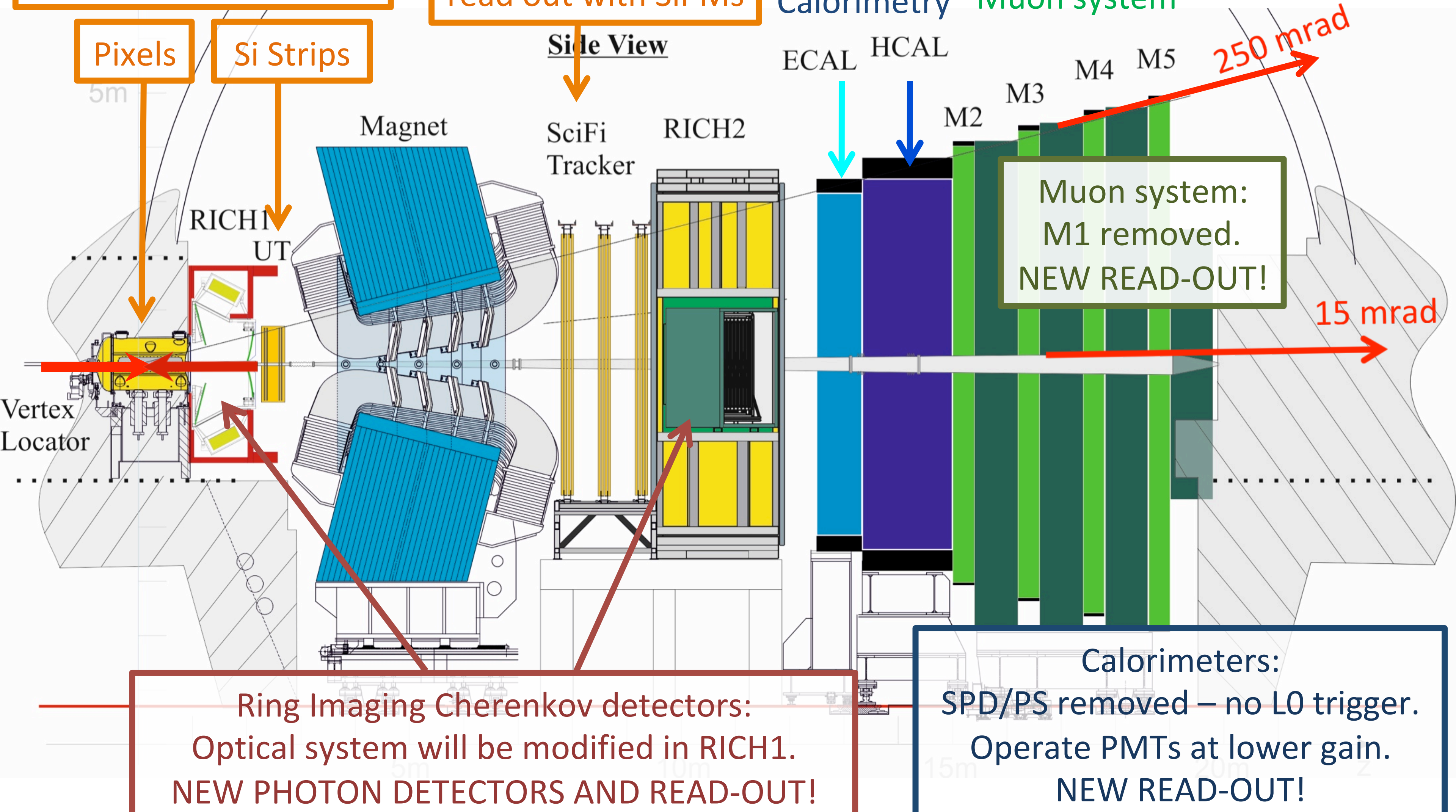
LHCb Upgrade I

See also Paula Collins (plenary VIII, 20/5)

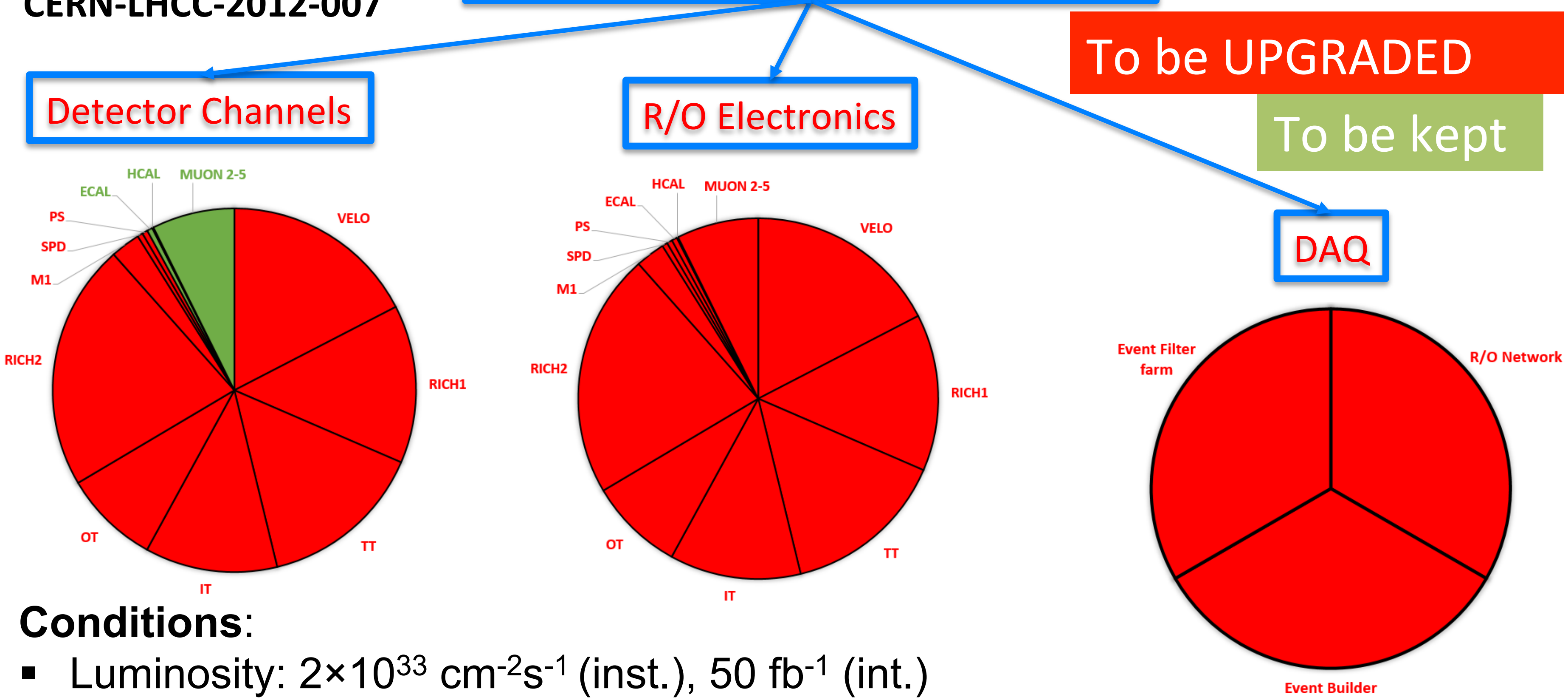
Tracking System: NEW DETECTORS!

Scintillating fibres read out with SiPMs



CERN-LHCC-2012-007

Upgraded LHCb Detector



Conditions:

- Luminosity: 2×10^{33} cm^{-2}s^{-1} (inst.), 50 fb^{-1} (int.)
- 5.2 visible interactions / crossing.

Challenge:

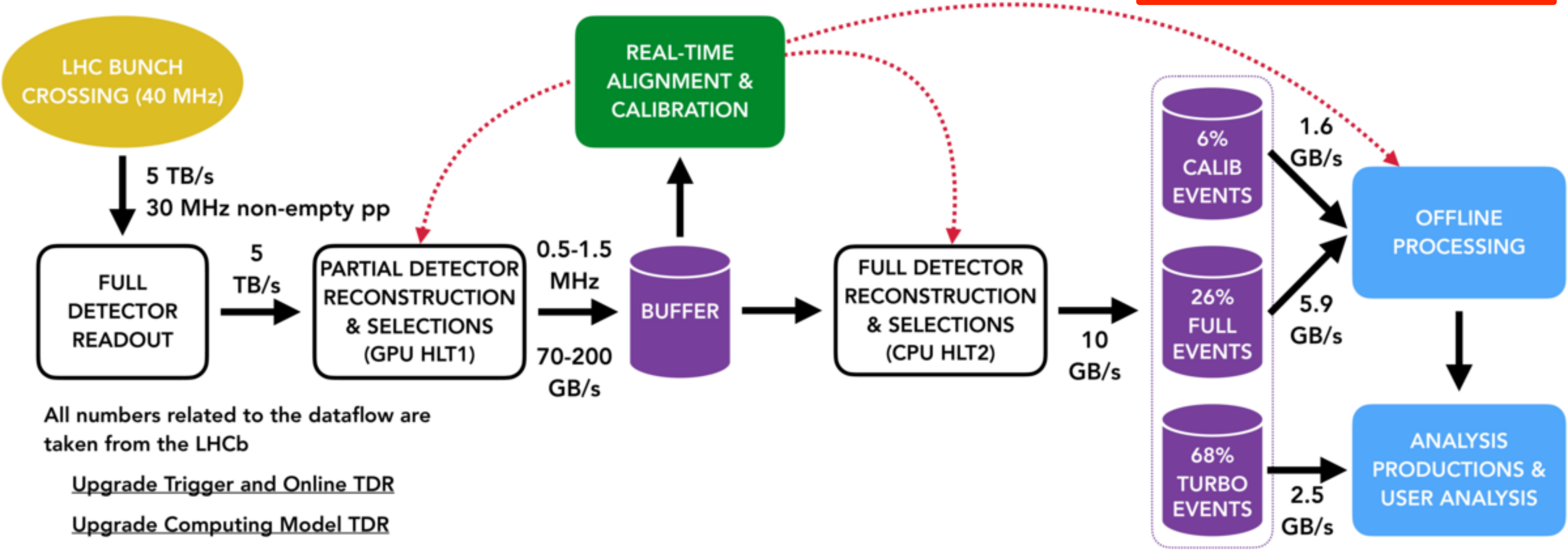
- Install and commission a brand new detector & read-out during LS2!
- Maintain current reconstruction performance in harsher environment.
- Read out the complete detector at 40 MHz → full software trigger.
- Run HLT1 reconstruction on GPUs in event builder servers.

Comput. Phys. Commun. **208** 35-42
Run 2: 2019 *JINST* **14** P04013
GPU: Comput Softw Big Sci 4, 7 (2020)
TURBO: 2019 *JINST* **14** P04006

Data Processing

LHCb-FIGURE-2020-016

See also Maarten Van Veghel (Performance & Tools, 16/5)



- RTA is integral part of DAQ chain in upgrade data processing.
  - Offline reconstruction in HLT2 à la Run 2.
- TURBO model for exclusive selections.
  - High-level physics objects directly from the HLT → fraction of raw event size.
- HLT1 reconstruction will run on GPUs.

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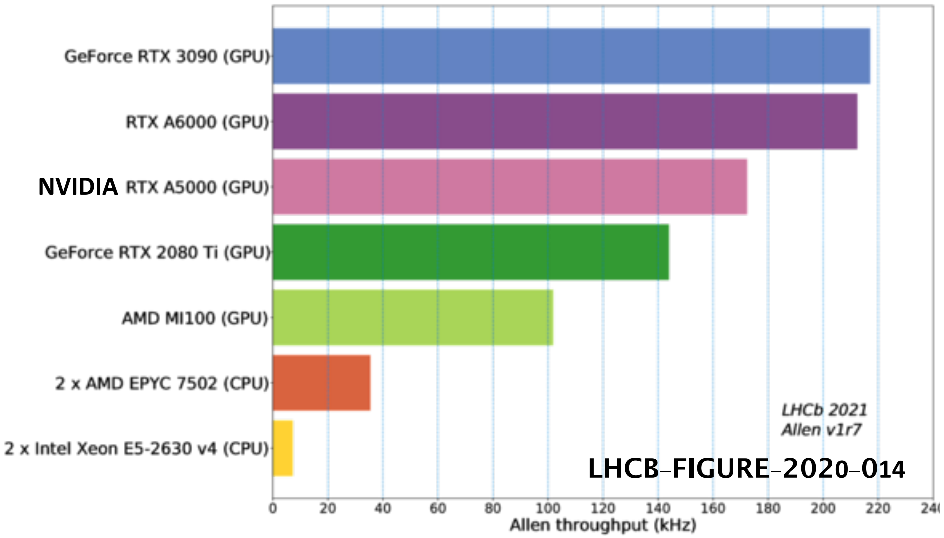
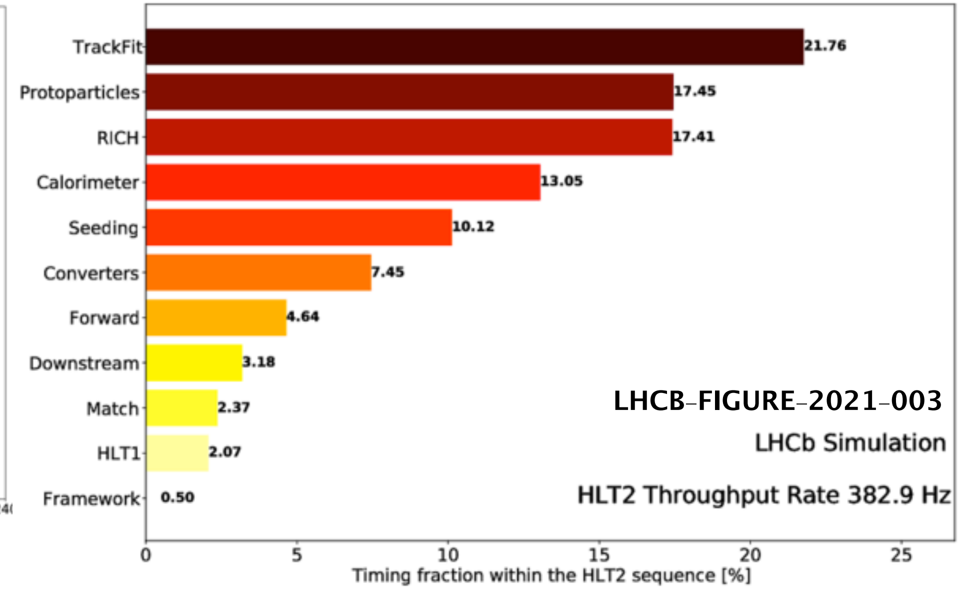
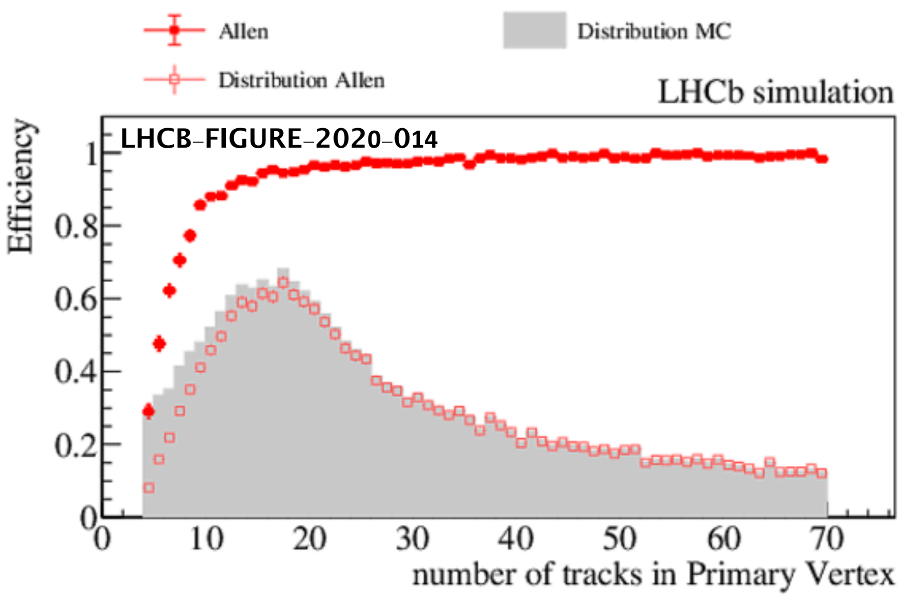
HLT 1 & 2

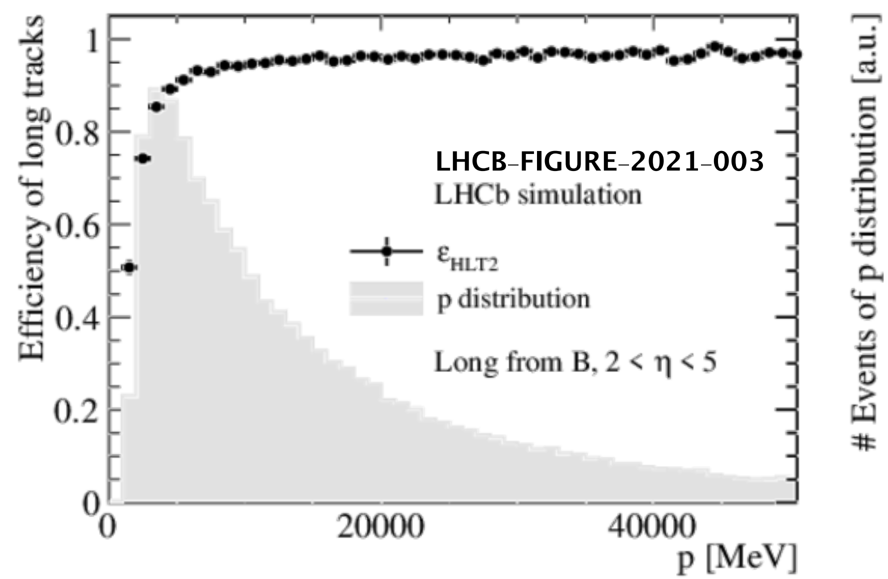
HLT1



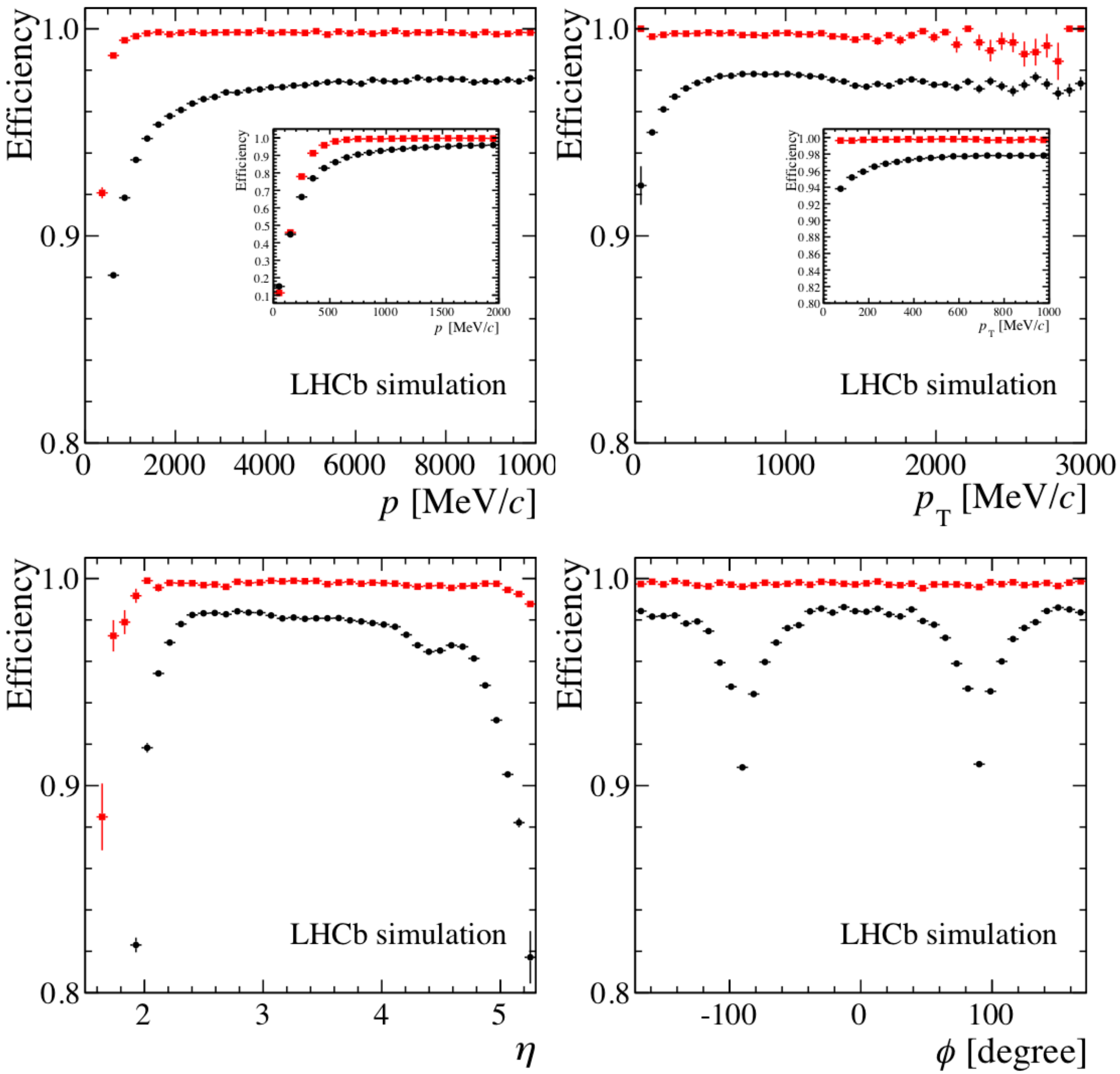
HLT2

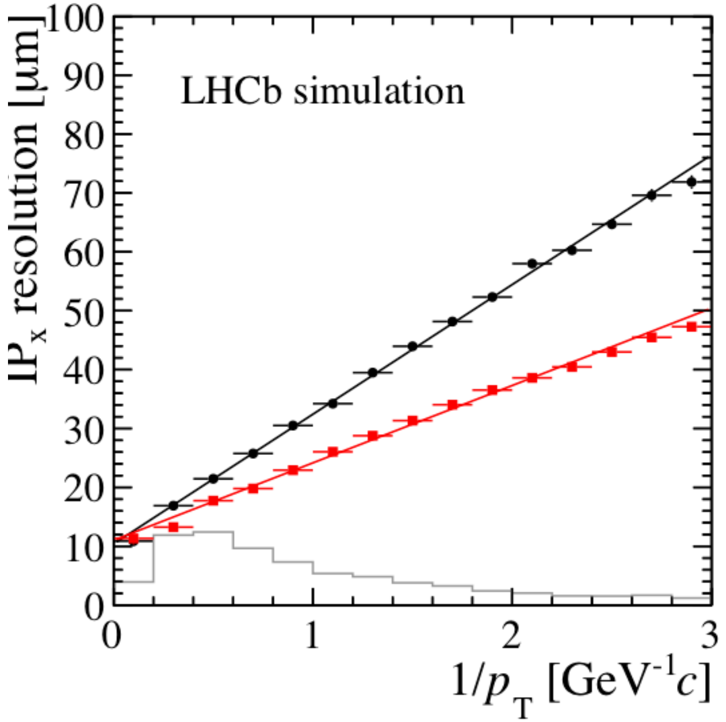






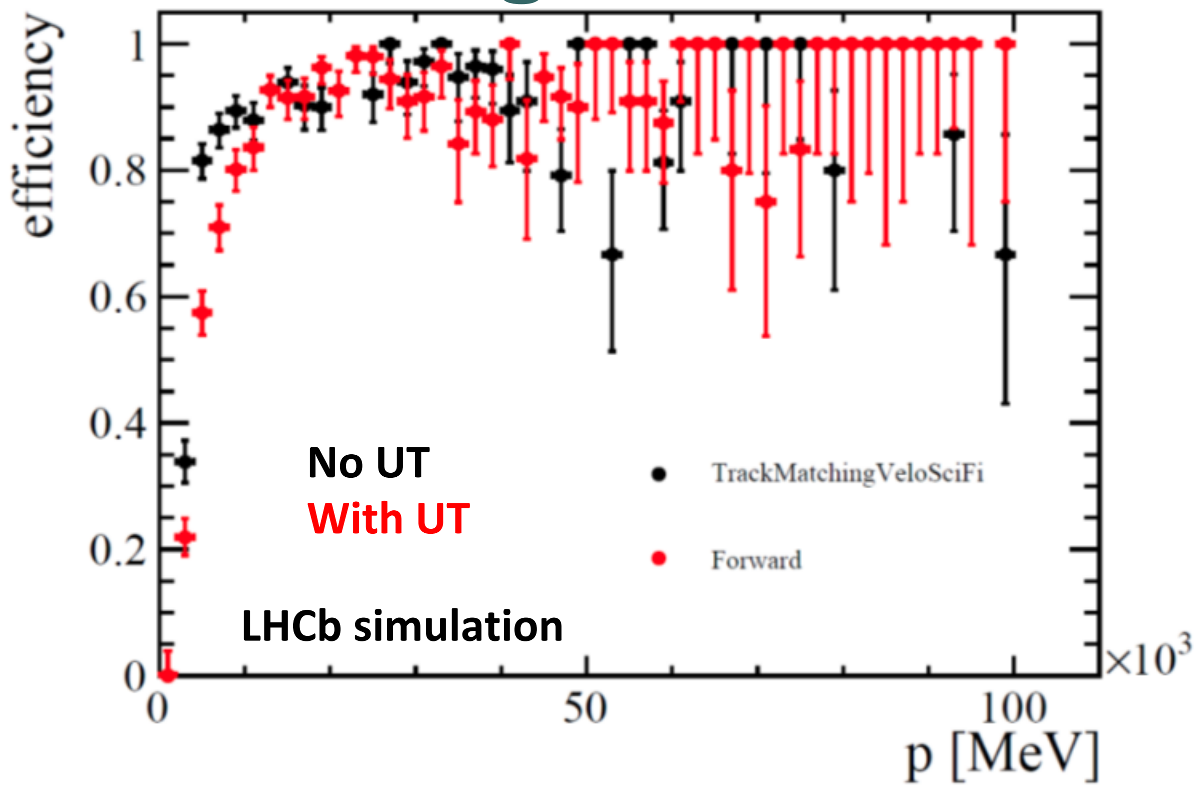
Expected Performance





- Original VELO (strips)
- New VELO (pixels)

Tracking without UT



	Bs -> ϕϕ	Min Bias	Bs -> ϕϕ	Min Bias
Hl1TrackMVA	21 %	3.8 %	21 %	1.8 %
Hlt1TwoTrackMVA	32 %	2.1 %	31 %	1.5 %

- HLT tracking studies without UT.
- Slightly improved efficiency but higher ghost rates.

Summary

CONCLUSIONS

Summary

LHCb version 1 (1995 – 2018):

- Excellent performance in Run 1 & 2.
- Many interesting physics results made possible.

LHCb version 2 (2008 – 2022+):

- We are (almost) up and running with a completely new detector!
- Sub-detector commissioning on-going.
  - Much less time to prepare w.r.t. Run 1.
- Many data-driven tools from Run 1&2 can re-used.
  - e.g. Tag-and-probe methods for tracking efficiency.
- Waiting for first Run 3 collision data!

2022 LHCP TAIPEI Online

The 10th Annual
Large Hadron Collider Physics Conference
May 16-20, 2022

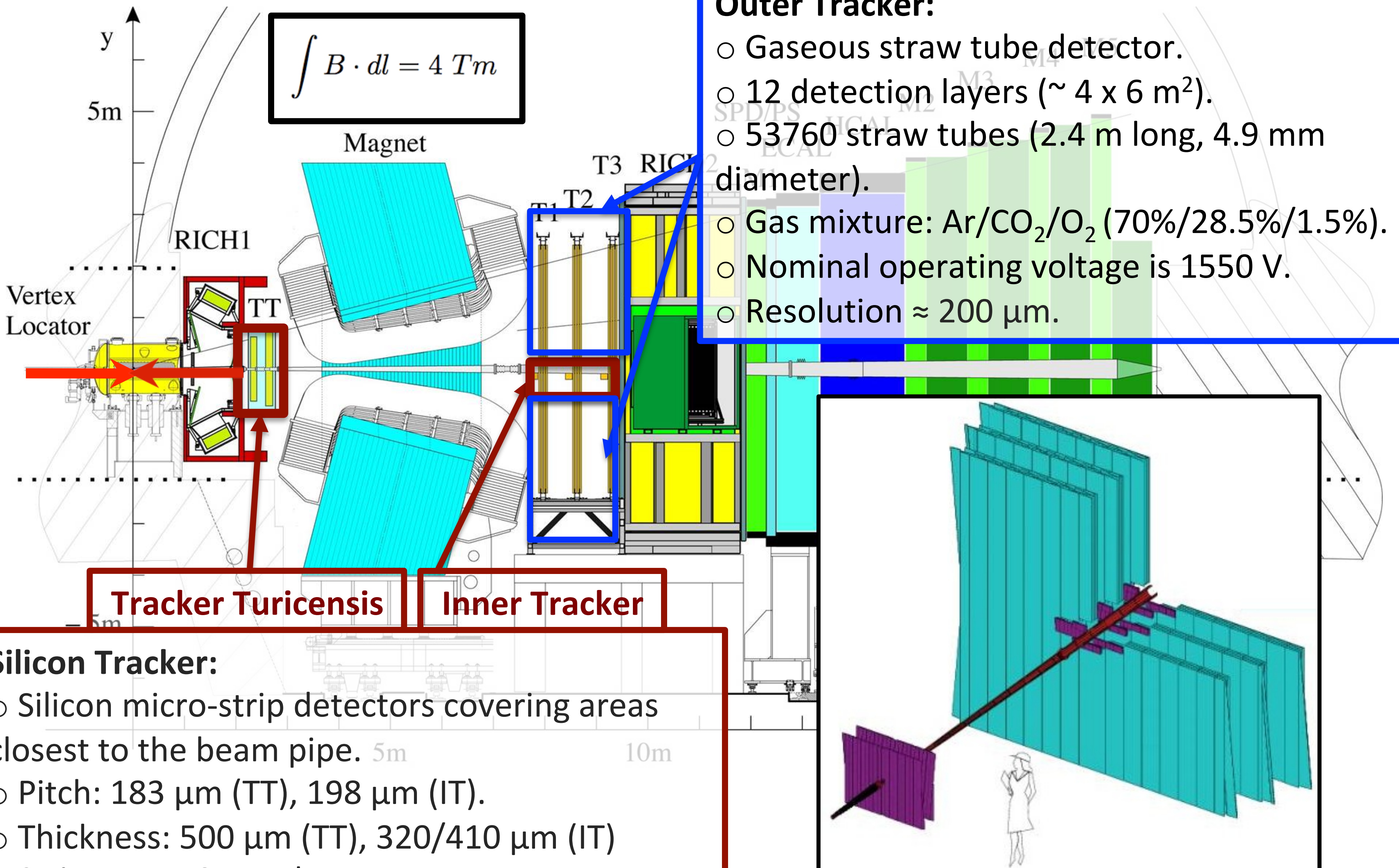
谢谢

MORE?

BACK UP

RUN 1 & 2

LHCb Tracker



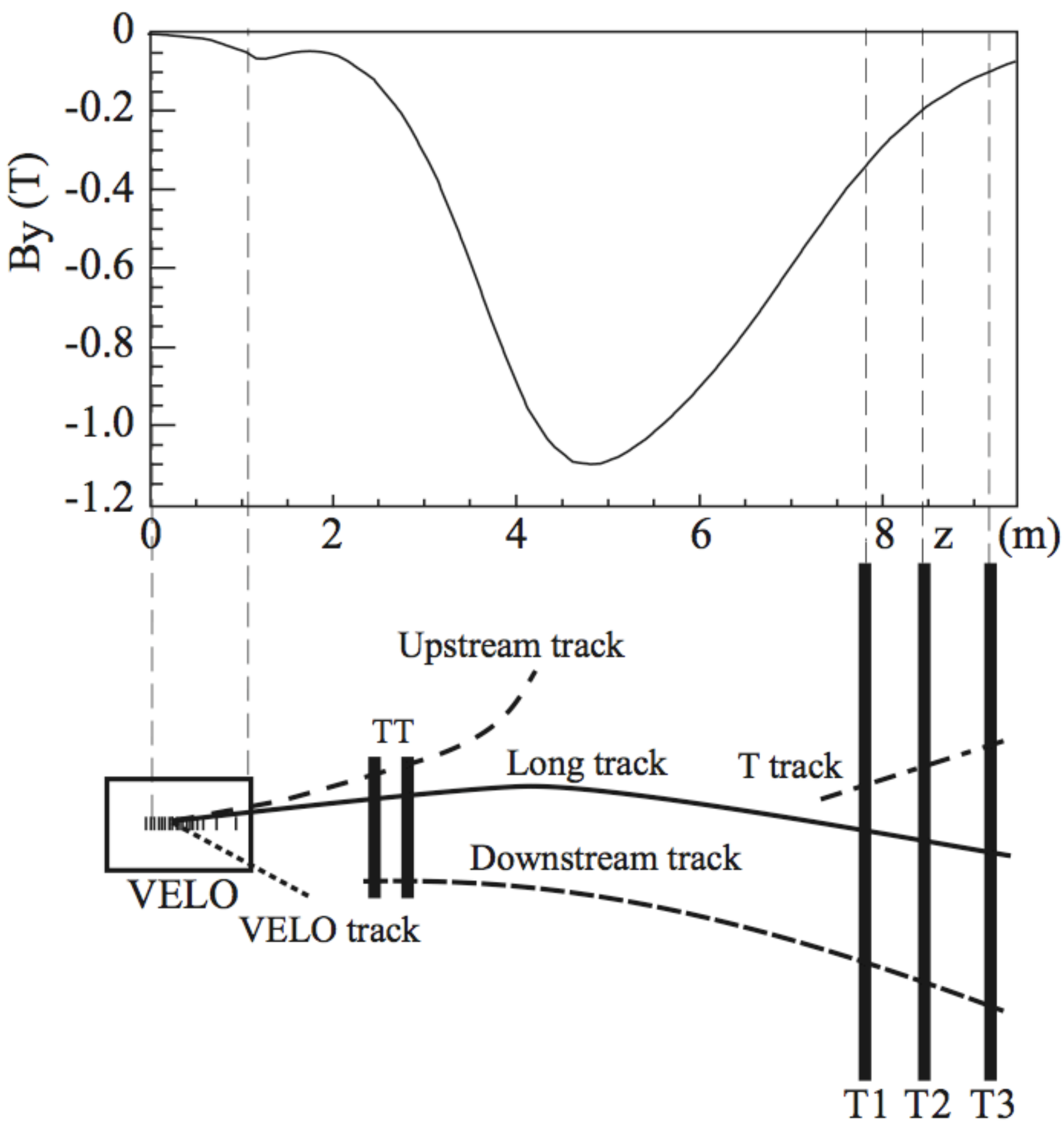
Outer Tracker:

○ Gaseous straw tube detector.
○ 12 detection layers (~ 4 x 6 m^2).
○ 53760 straw tubes (2.4 m long, 4.9 mm diameter).
○ Gas mixture: $Ar/CO_2/O_2$ (70%/28.5%/1.5%).
○ Nominal operating voltage is 1550 V.
○ Resolution ≈ 200 μm.

Silicon Tracker:

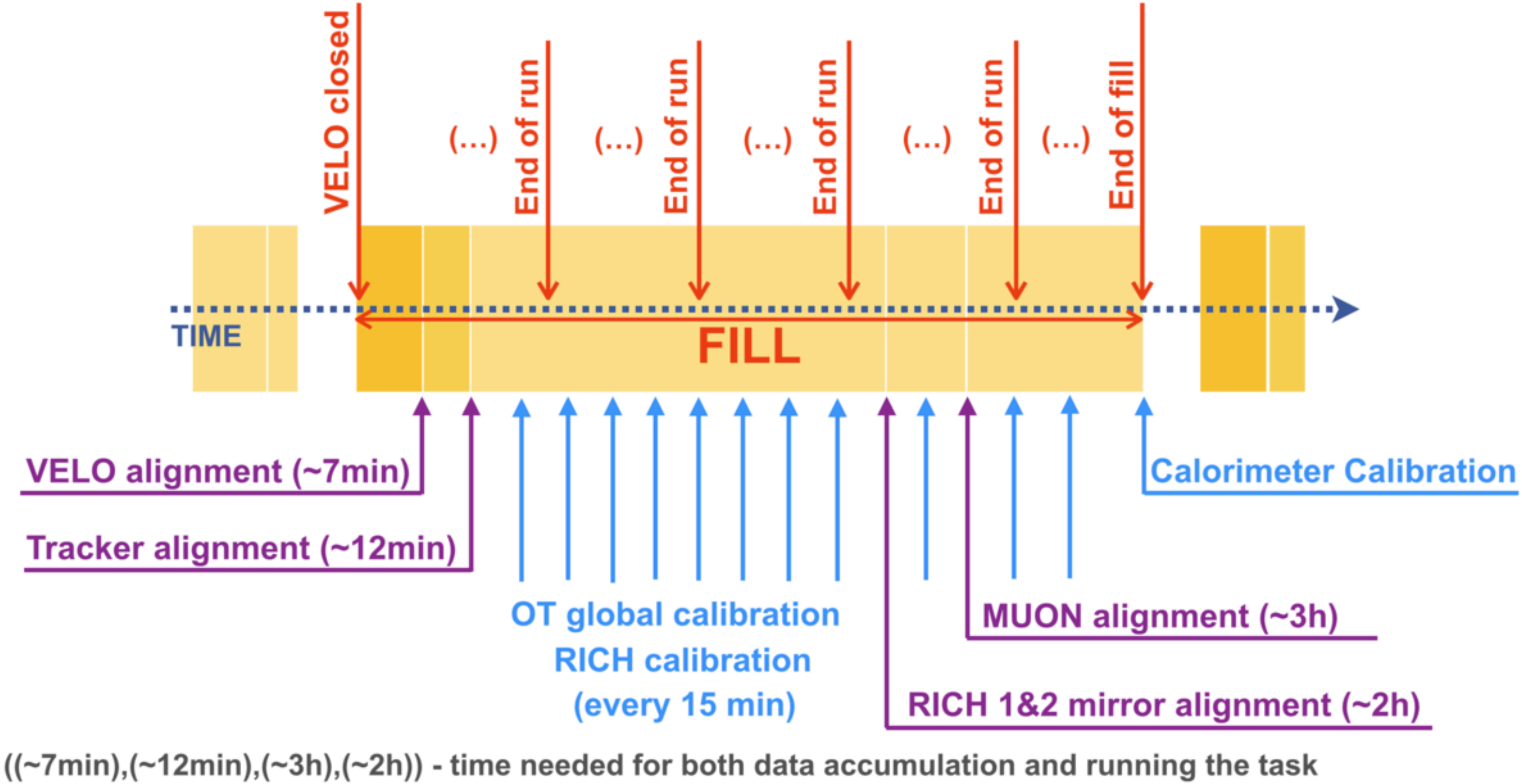
○ Silicon micro-strip detectors covering areas closest to the beam pipe.
○ Pitch: 183 μm (TT), 198 μm (IT).
○ Thickness: 500 μm (TT), 320/410 μm (IT)
○ Strips up to 37 cm long.
○ Resolution ≈ 50 μm.

Track Types


0
-0.2
-0.4
-0.6
-0.8
-1.0
-1.2
By (T)
0
2
4
6
8
z (m)
Upstream track
TT
Long track
T track
Downstream track
VELO
VELO track
T1 T2 T3

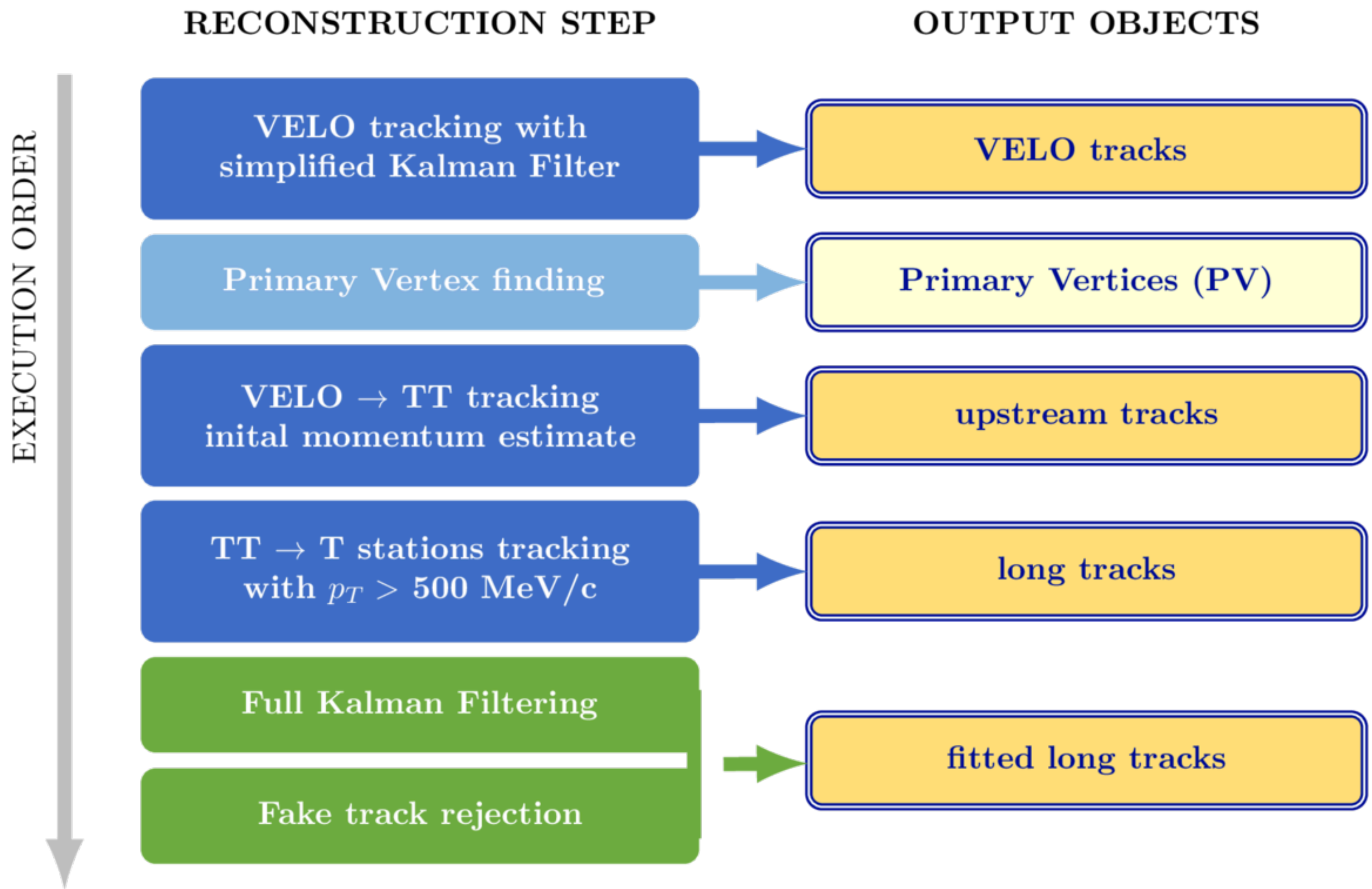
2019 JINST 14 P04013

Alignment & Calibration



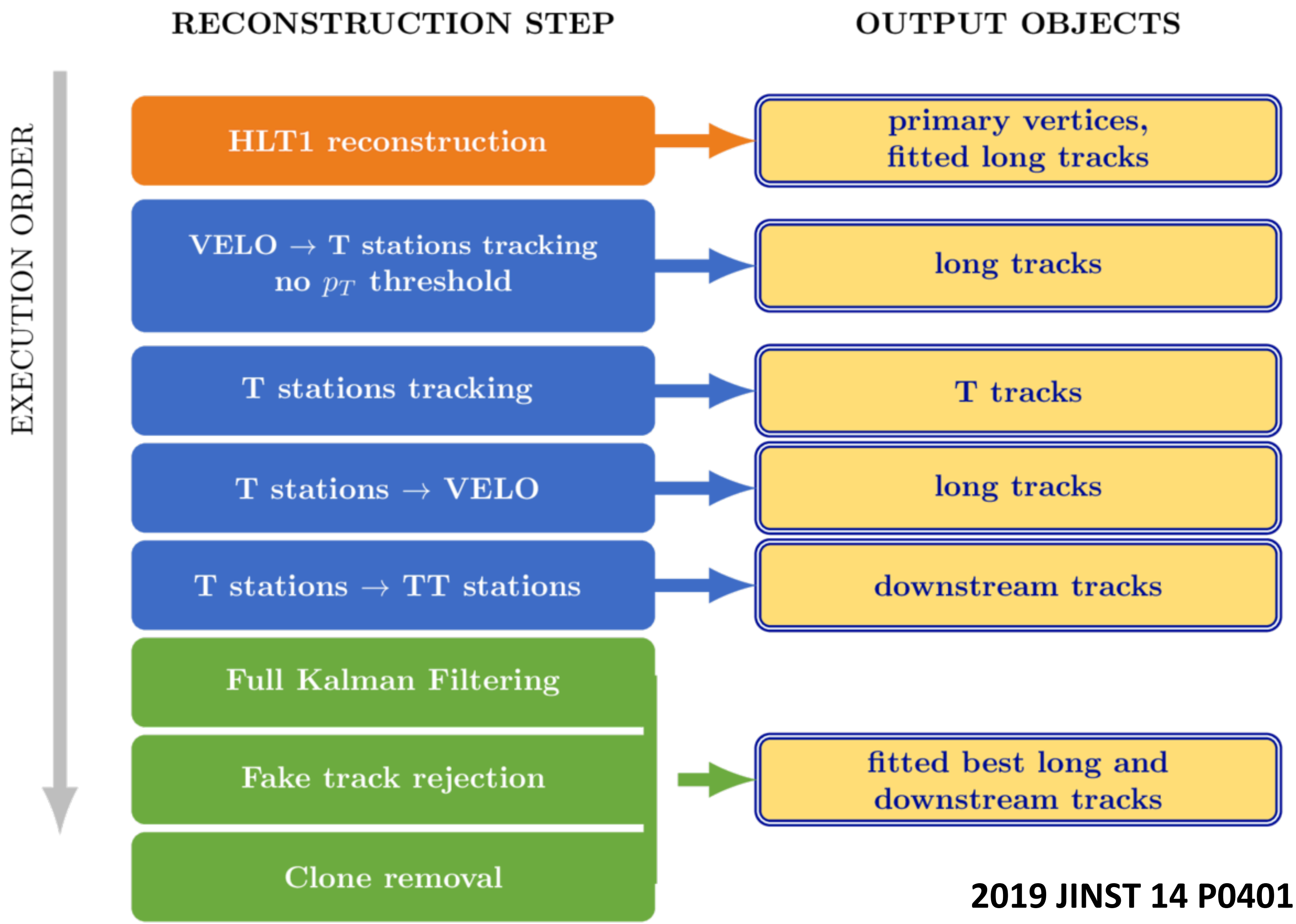
Aim to have offline-quality reconstruction running online.

HLT1 Reconstruction



2019 JINST 14 P04013

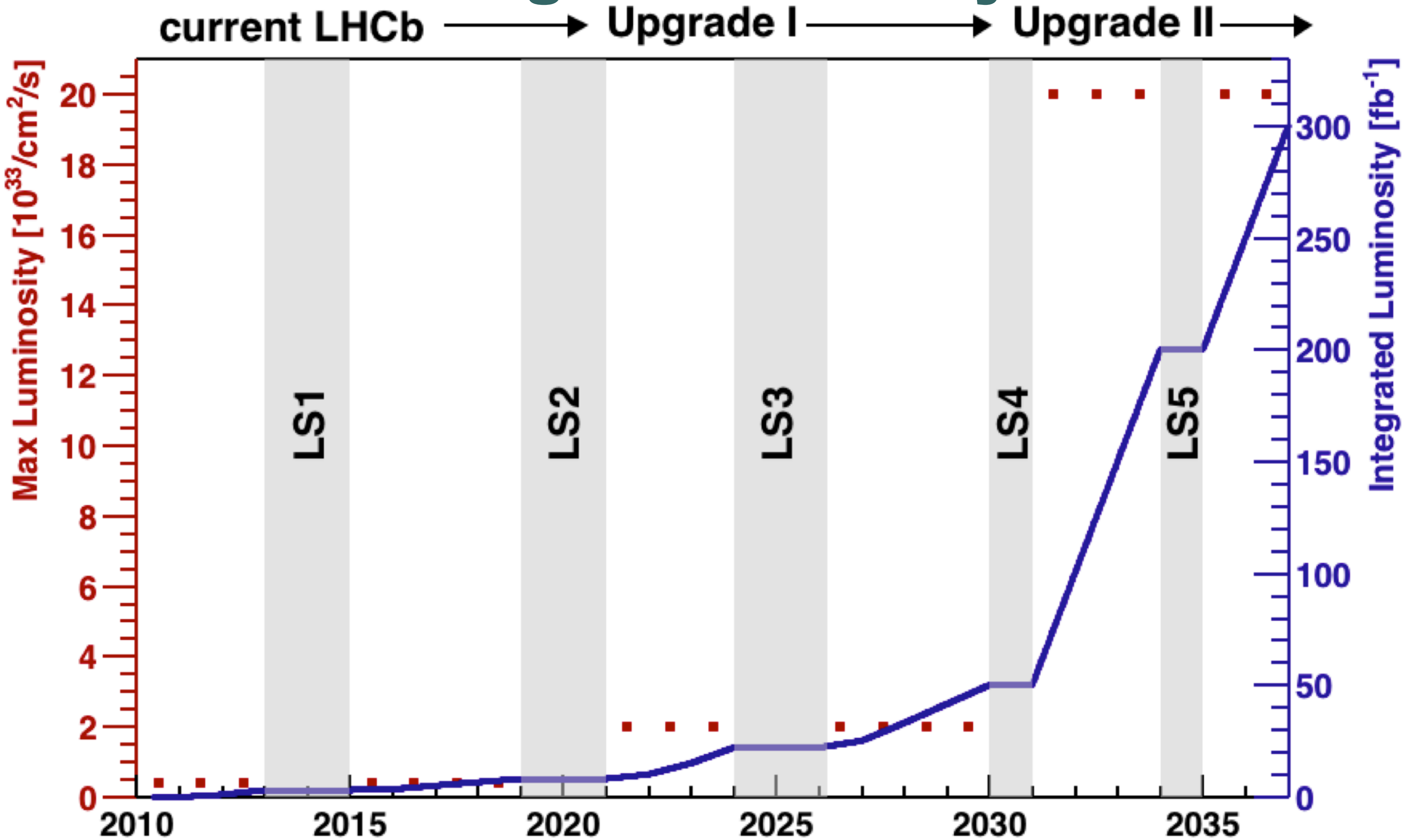
HLT2 Reconstruction



2019 JINST 14 P04013

RUN 3

Target Luminosity

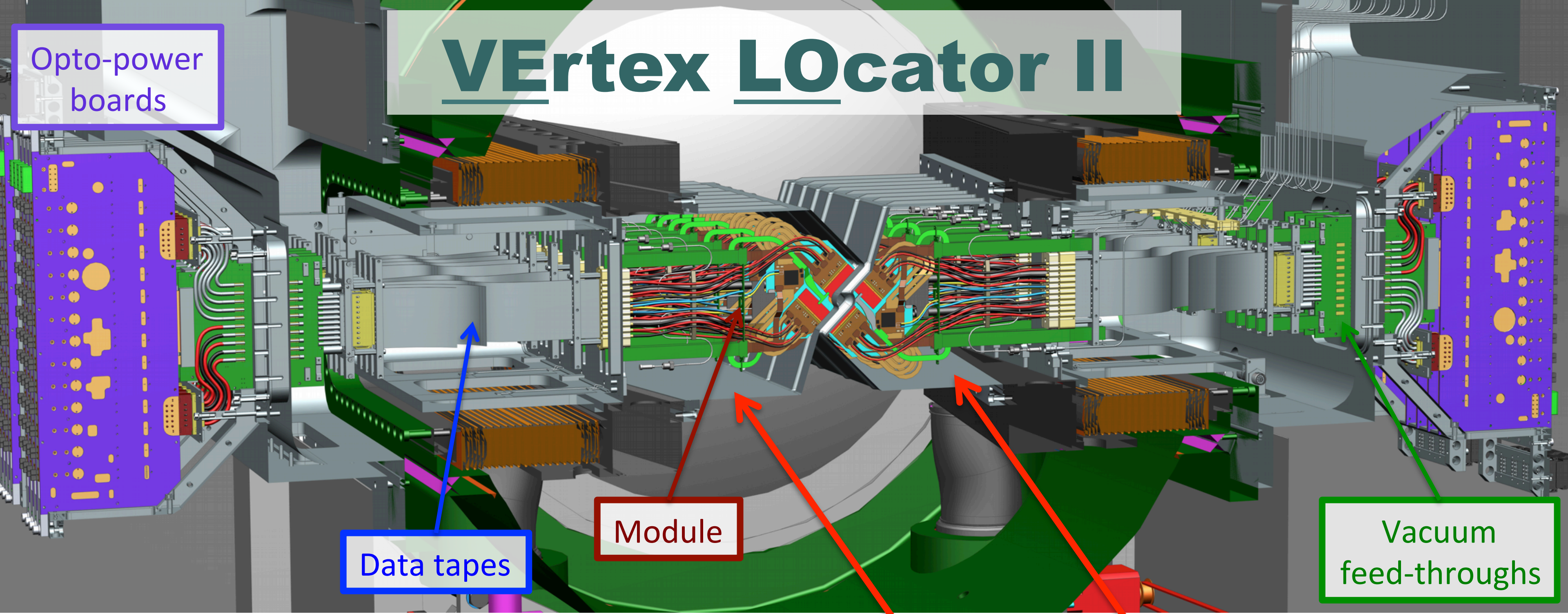


$L_{inst.} = 4 \times 10^{32}$ cm^{-2}s^{-1} → $L_{inst.} = 2 \times 10^{33}$ cm^{-2}s^{-1} → $L_{inst.} = 1 - 2 \times 10^{34}$ cm^{-2}s^{-1}

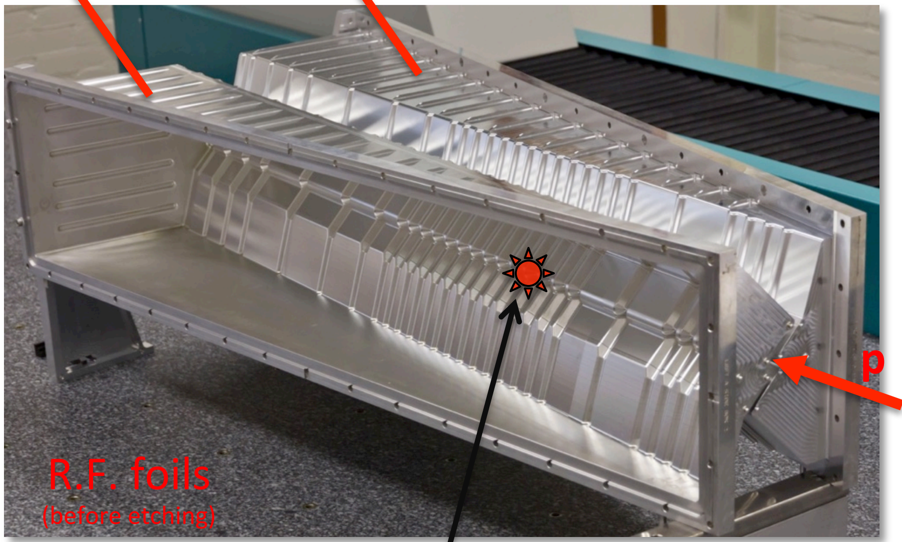
$\mu \approx 1$ → $\mu \approx 5.2$ → $\mu \approx 28 - 55$

* μ is average number of visible *pp* interactions per bunch crossing.

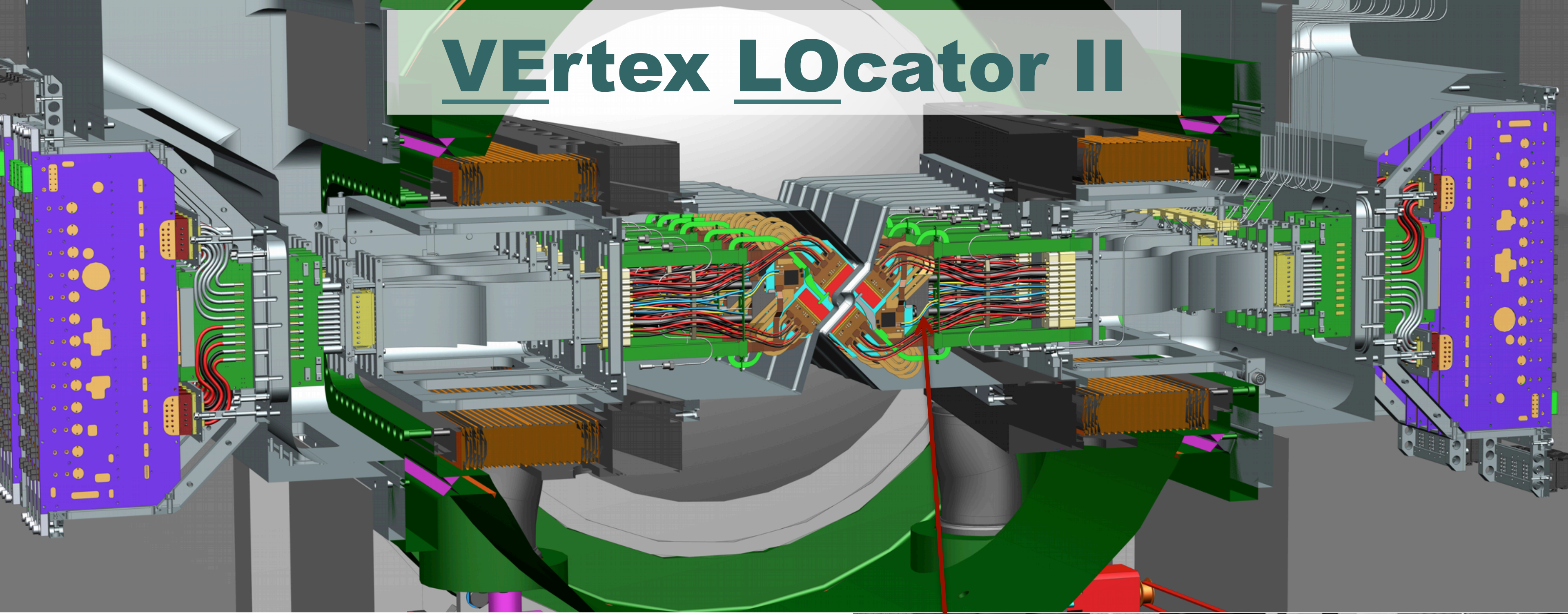
VErtex LOcator II



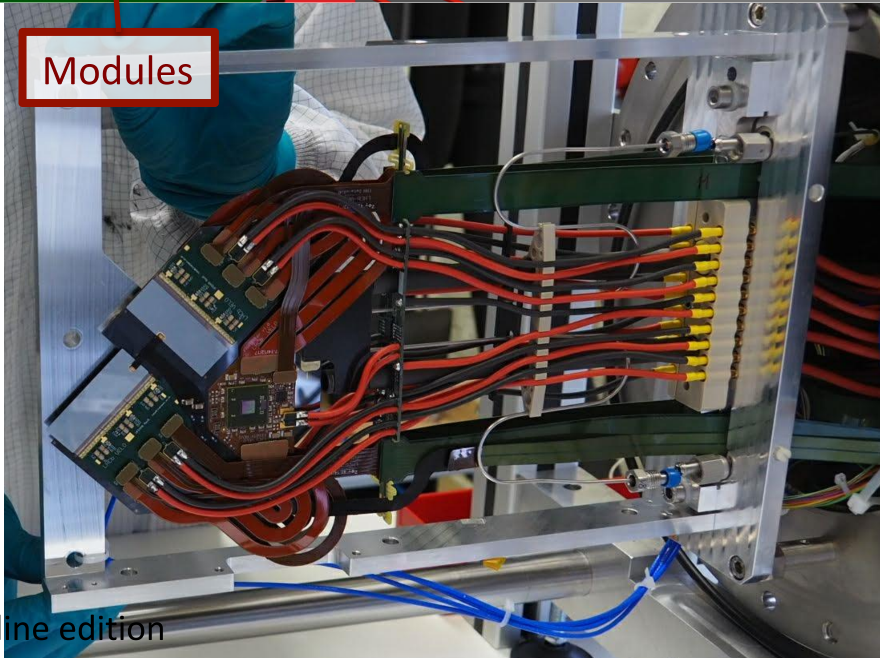
- Two retractable halves
  - 3.5 mm from beam when closed.
  - First measurement at 5.1 mm.
- Operates in secondary vacuum.
  - Aluminium R.F. foils separate detector from beam vacuum.
  - Milled to 250 µm thick then chemically etched to 150 µm.
- 52 hybrid-pixel modules.
  - 41M pixels covering total area ~ 1.2 m^2.



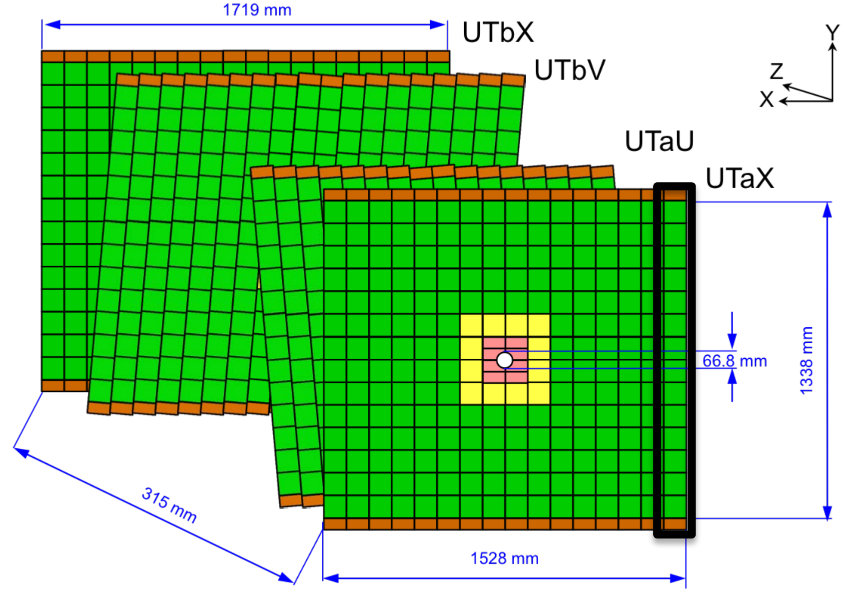
VErtex LOcator II



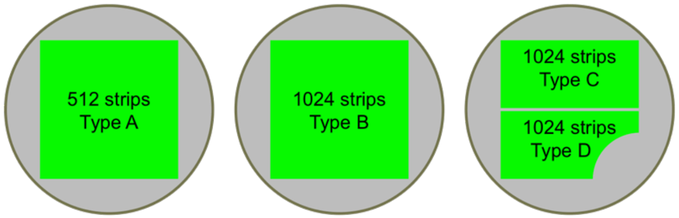
- Hybrid pixel detector.
  - 200 μm n-on-p sensor tiles.
- New read-out ASIC (VeloPix).
  - 256x256 pixel array (55 μm x 55 μm)
  - 12 per module.
- Evaporative CO_2 cooling in silicon micro-channel substrates (T < −20°C).
- High bandwidth:
  - 20 Gbit/s in hottest ASICs with ~ 3 Tbit/s overall.
- Non-uniform irradiation:
  - $8 \times 10^{15}\ n_{eq}\ /\ cm^2$ which falls as ~ $r^{-2.1}$.

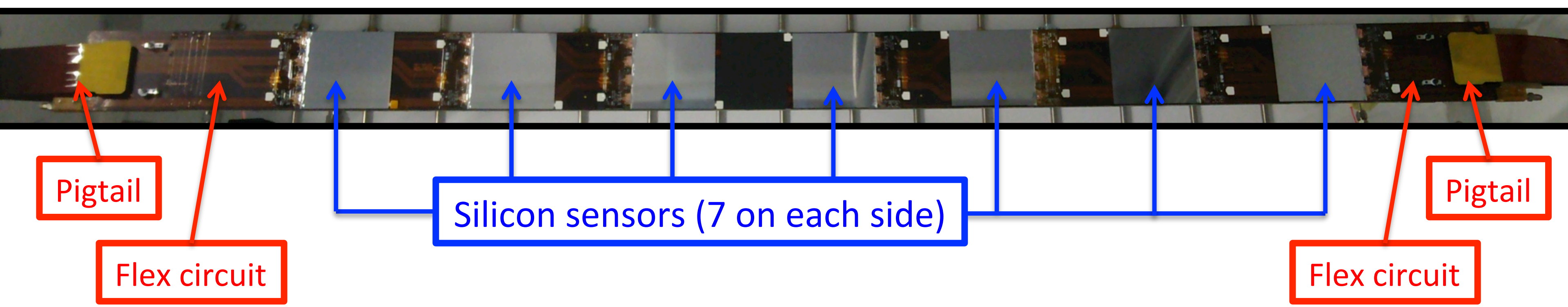


Upstream Tracker



- Silicon micro-strip detector.
  - Four layers (x, u, v, x) upstream of magnet.
  - Finer granularity, closer to beam.
- Four types of sensors.
  - n- and p-type with 512 or 1024 strips.
  - 320/250 µm thick; 190/95 µm pitch.
- Modules mounted on double-sided staves.
  - 68 staves / 968 sensors.
  - Bi-phase CO_2 cooling pipe integrated in stave.
- New read-out ASIC (SALT).
  - 128 channels with 6-bit ADC.
  - Pedestal & common-mode subtraction, zero-suppression.
  - Output up to 6 SLVS e-links per ASIC.
  - 1048 4-asic read-out sectors = 4192 ASICs.
- Read-out electronics mounted on detector frame.





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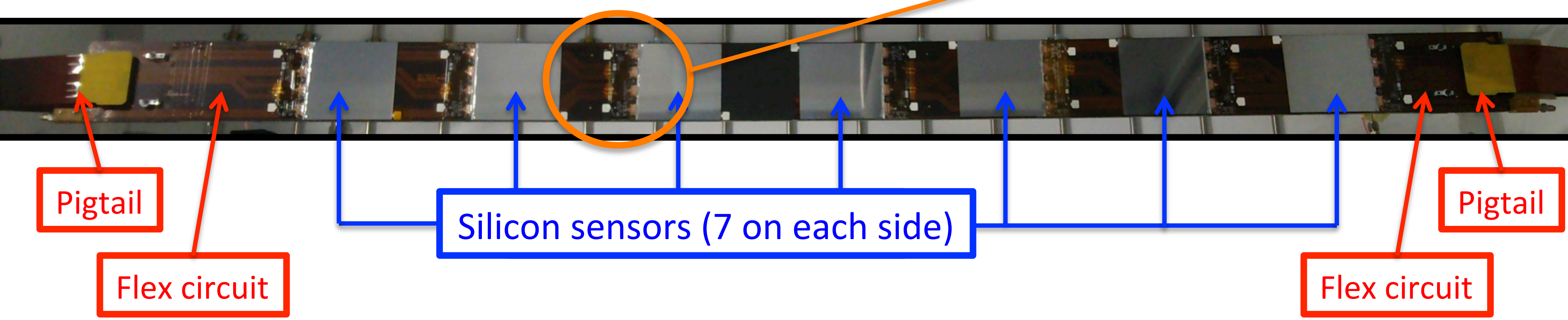
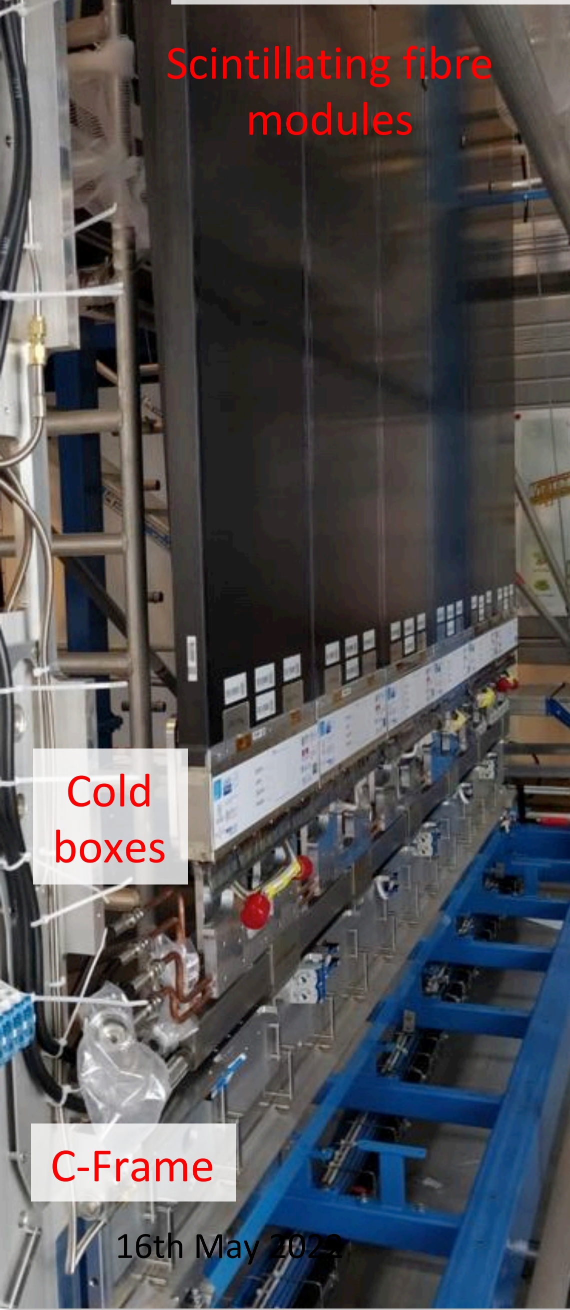
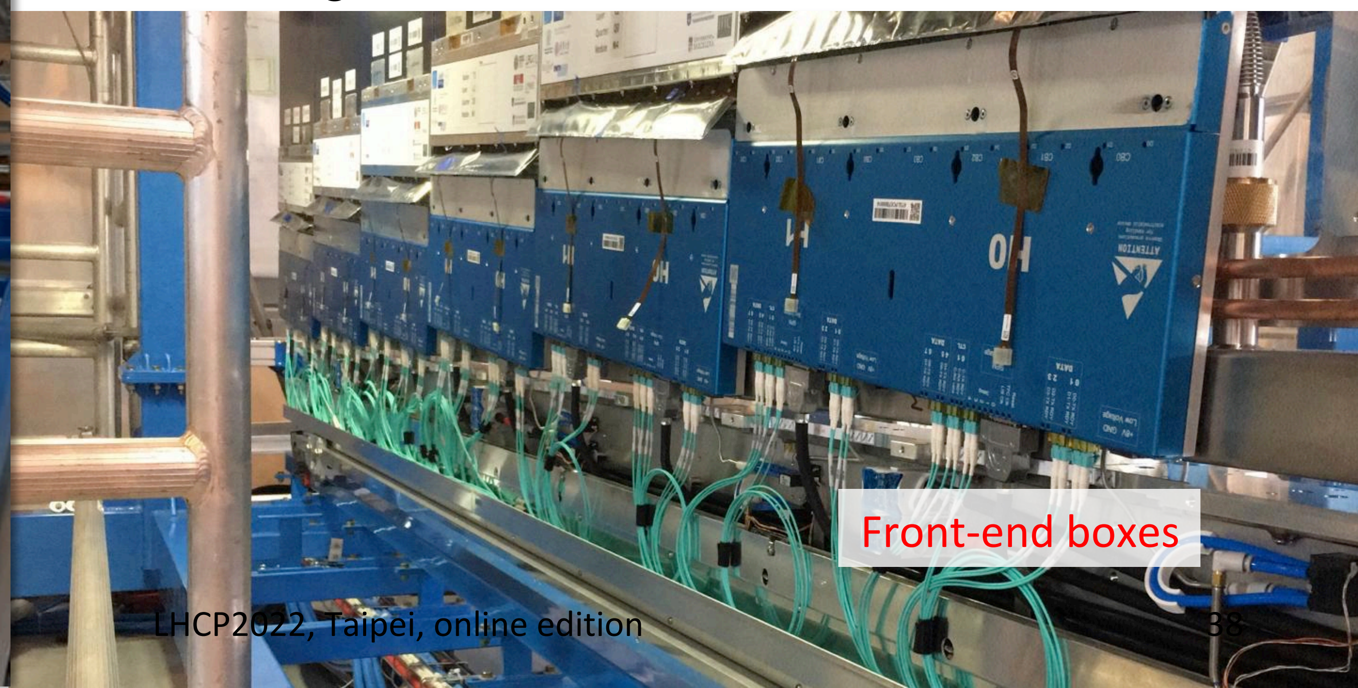
- Read-out electronics mounted on detector frame.



Scintillating Fibre Tracker



- Scintillating fibres read out with SiPMs.
  - 2.4 m long, 250 μm diameter, 6 layers of fibres in module.
  - 12 detection planes − 3 × (x, u, v, x).
- SiPMs outside acceptance.
  - 128 channels with width 250 μm
  - Require cooling to −40°C (neutron radiation).
- New ASIC for read-out (PACIFIC).
  - 64 channels, 130 nm CMOS (TSMC).
  - ADC with three hardware thresholds.
- Clustering on FPGA board in front-end box.



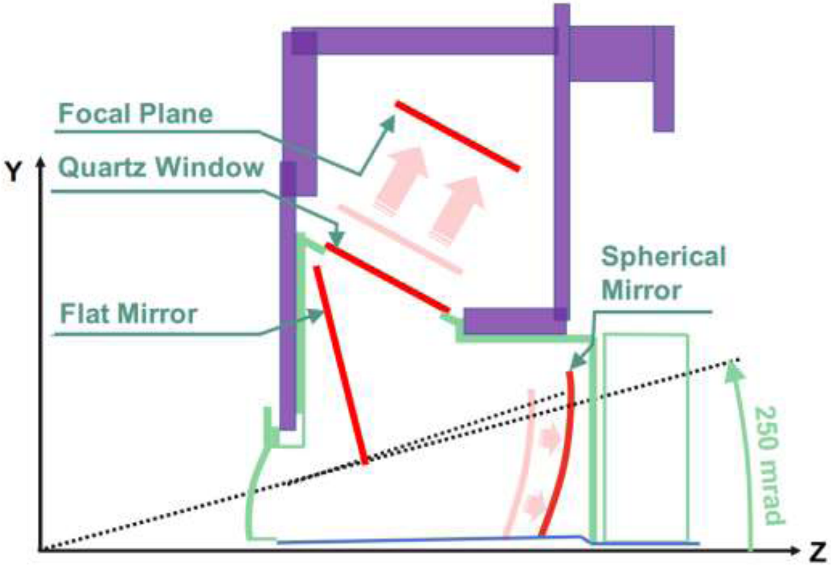
Particle ID

Cherenkov detectors:

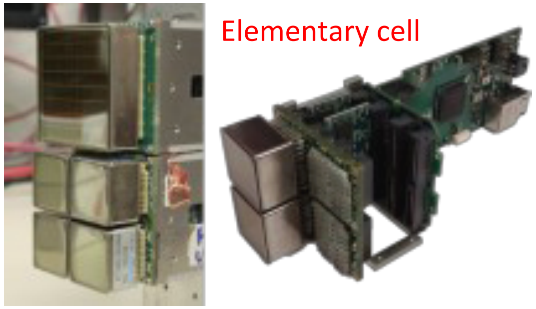
- RICH 1: C_4F_{10} (10 – 65 GeV/*c*).
  - Replace everything (mirrors, gas enclosure, quartz windows).
- RICH 2: CF_4 (15 – 100 GeV/*c*).
- Replace Hybrid Photon Detectors (HPDs) with Multi Anode Photomultiplier Tubes (MaPMTs).
- New 8-channel read-out ASIC (CLARO).

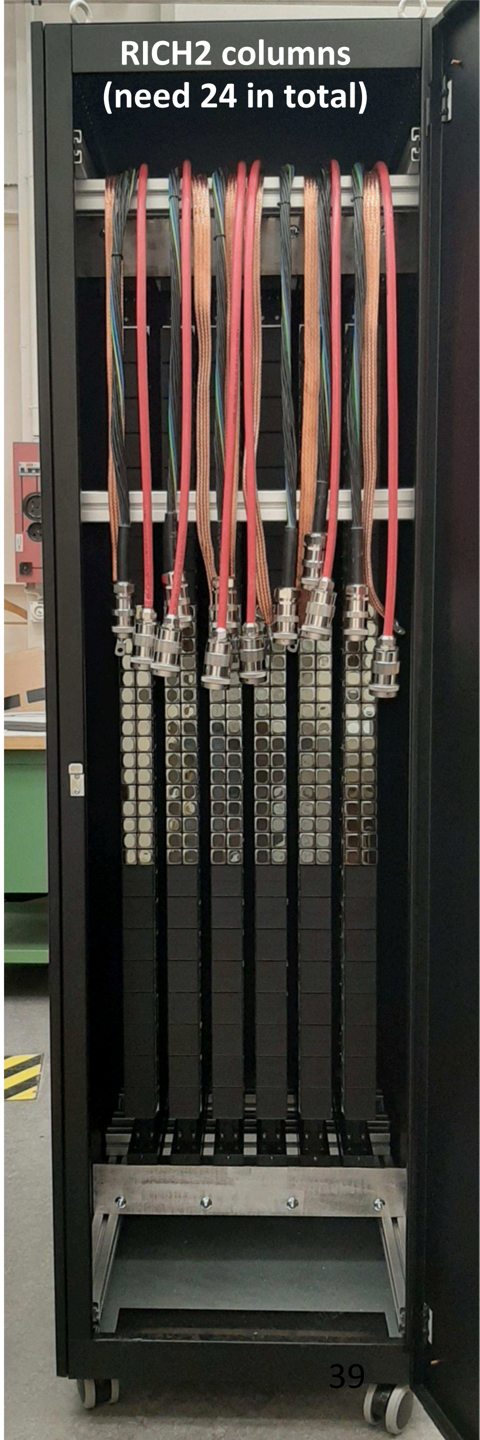
Calorimeters & Muon System

- Remove unnecessary detectors.
- Replace read-out electronics.



MaPMTs (Hamamatsu)





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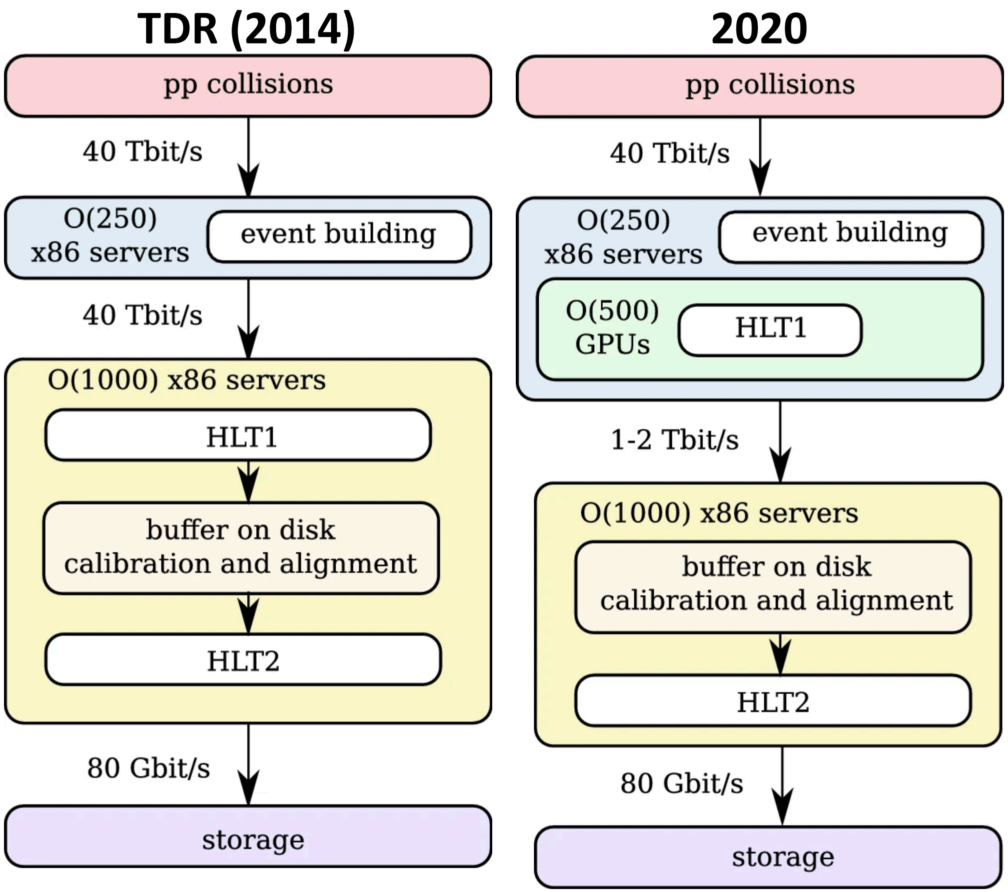
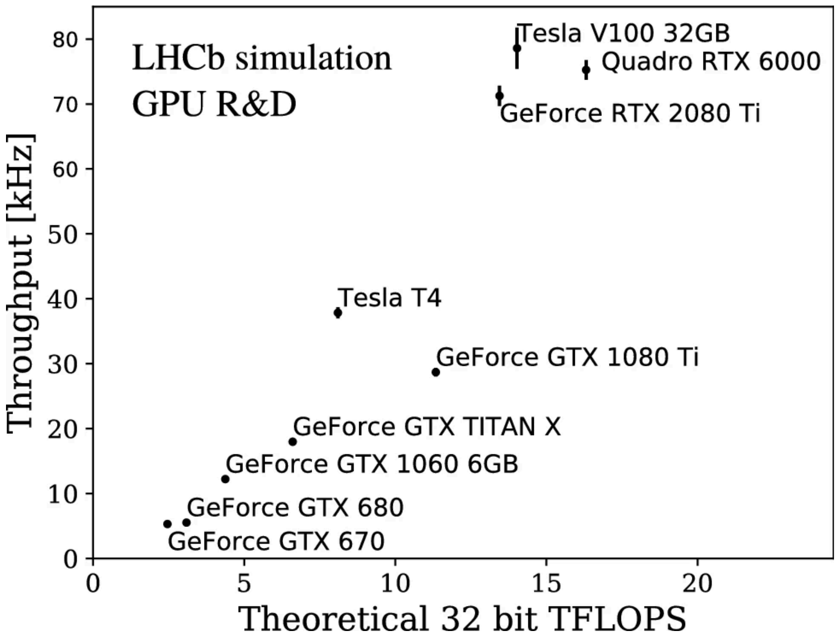
HLT1 on GPUs



Three good GPU candidates



- Each event builder server has two GPU slots = 500 GPUs.
- HLT1 ***must*** run at visible collision rate (30 MHz).
  - Minimum throughput rate per GPU is 60 kHz.