LHCb RICH Reconstruction

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(on behalf of LHCb RICH Collab.)

Introduction

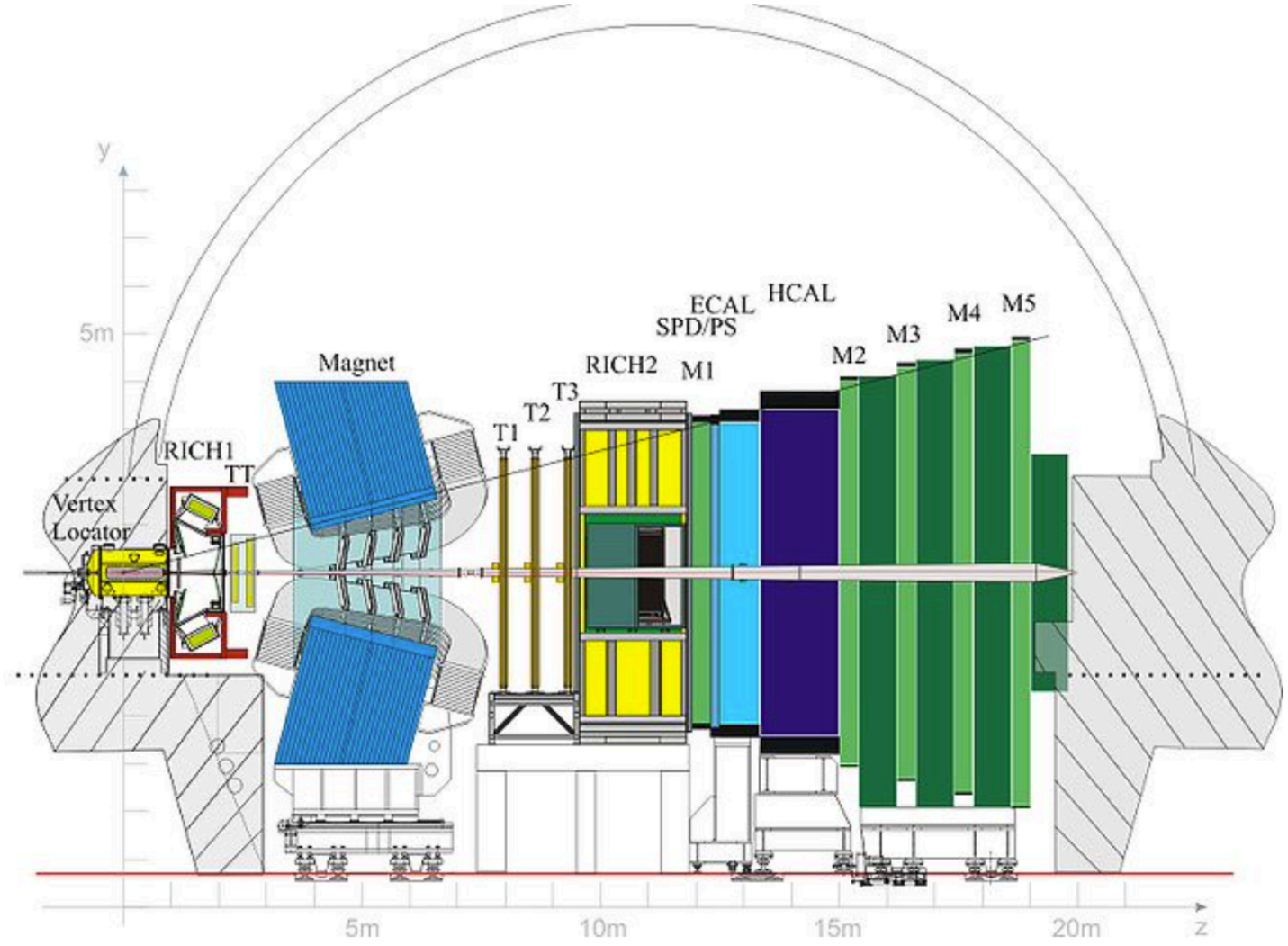
- LHCb and its RICH Detectors
- Principles of Reconstruction and PID
- Run II Operational Aspects
- Run II Performance
- Changes for Run III (and beyond..).

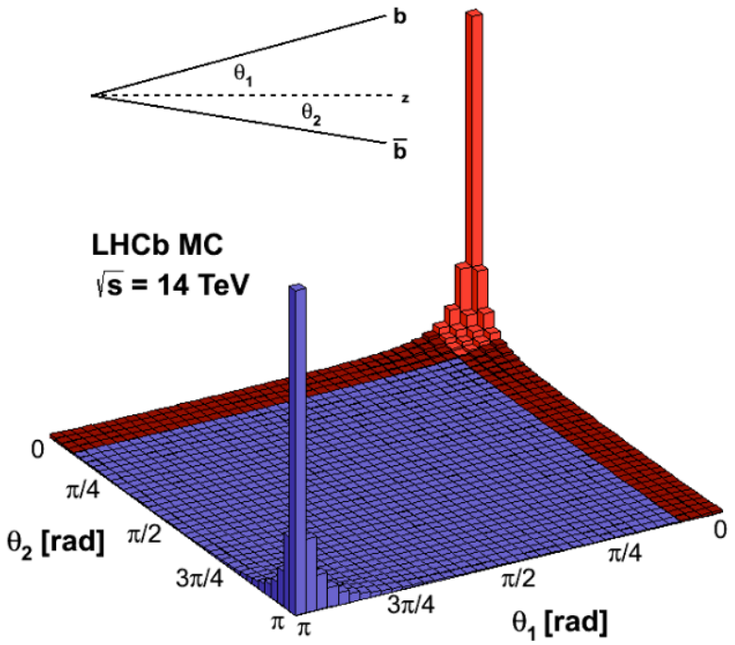
- Thanks various sources of information, in particular :-
  - Antonis Papanestis (RICH Edinburgh 2022),
  - Giovanni Cavallero (CEPC Beijing 2022)

The LHCb detector during Run 1 and 2

[JINST 3 (2008) S08005]

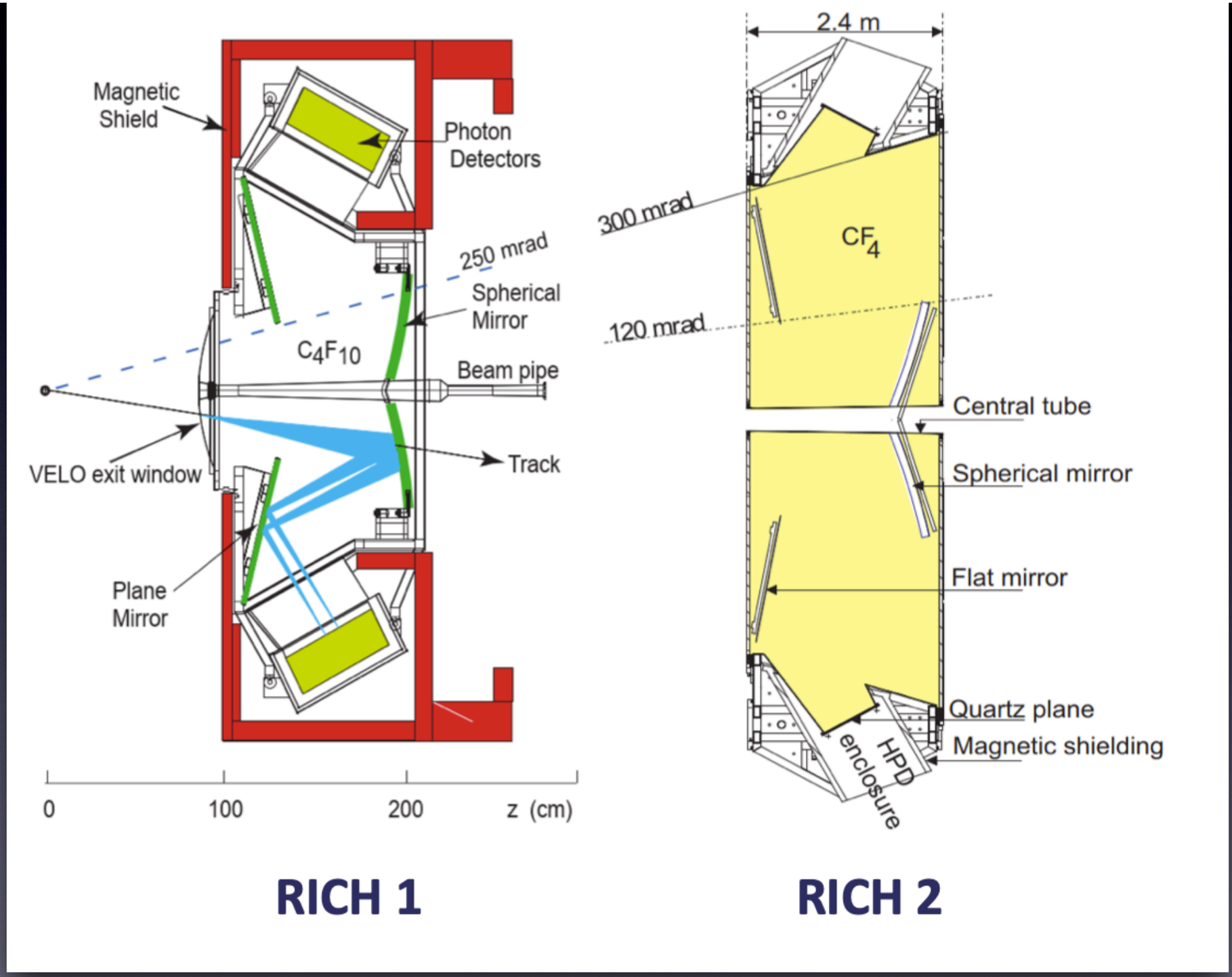
- the LHCb detector covers the forward region in the $2 < \eta < 5$ range
- $\sim 25\%$ of the $b\bar{b}$ pairs are produced inside the LHCb acceptance
- LHCb ran with an instantaneuos luminosity of $\mathcal{L} = 2 - 4 \times 10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- CPV, rare b-hadron decays, spectroscopy, EW, pQCD, heavy ions





$\sim 60k\ b\bar{b}/s$ and $\sim 1M\ c\bar{c}/s$ in acceptance at 13 TeV

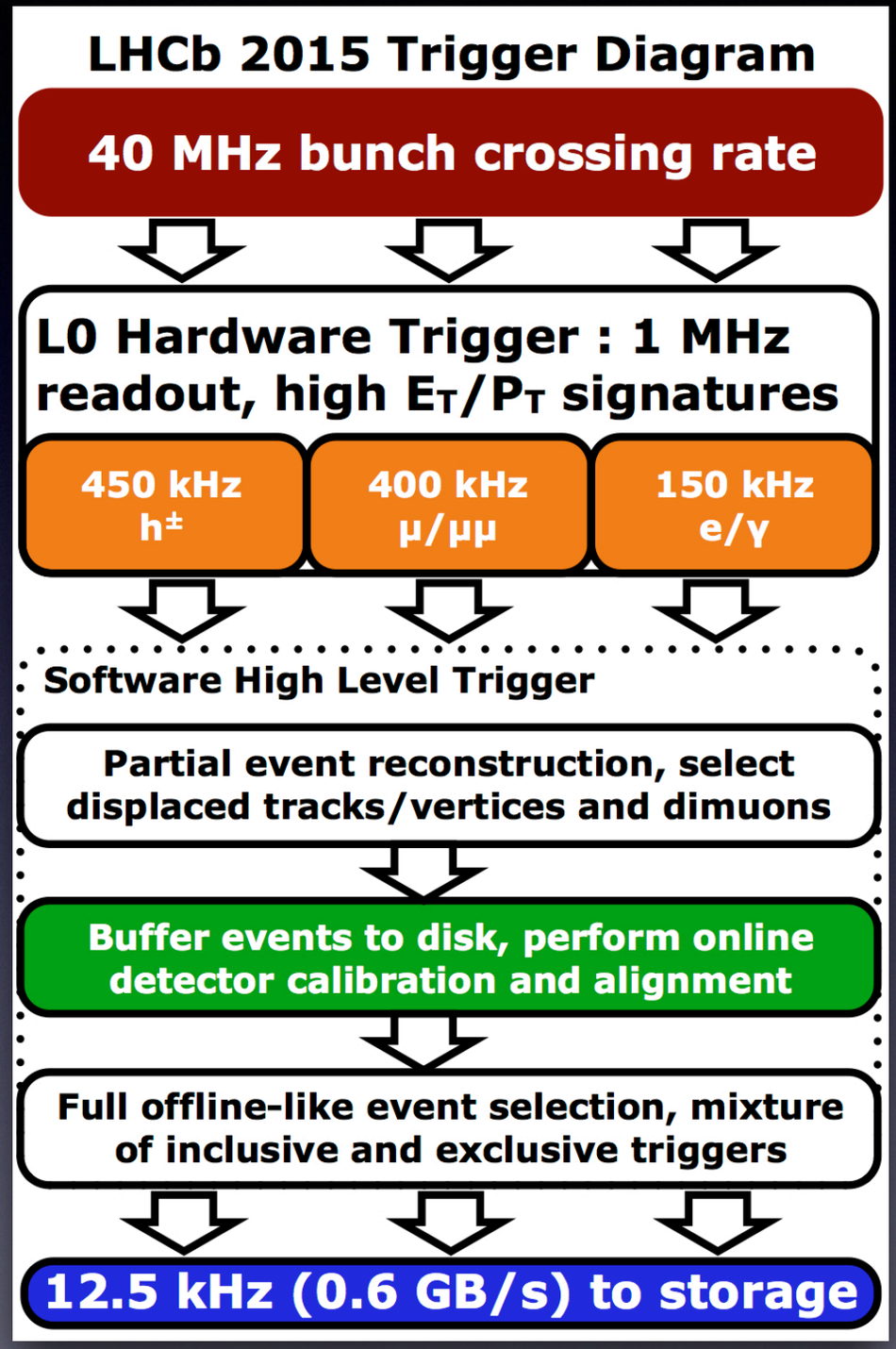
- RICH1 (C_4F_{10}): 3 GeV–40 GeV, 25–300 mrad, $2 \times 3 \times 1\,\mathrm{m}^3$
- RICH2 (CF_4): 30 GeV–100 GeV, 15–120 mrad, $100\,\mathrm{m}^3$



LHCb Trigger

- Originally, at start of Run1 software reconstruction in the trigger was distinct (much simpler) to that deployed ‘offline’.

- Trigger strategy evolved for Run 2 to allow complete offline-quality reconstruction to be performed during the second (deferred) stage of the trigger (HLT2).



Principle Reconstruction Steps

- Decode RICH data, forming 3D **hit detection points** in the LHCb global reference frame.

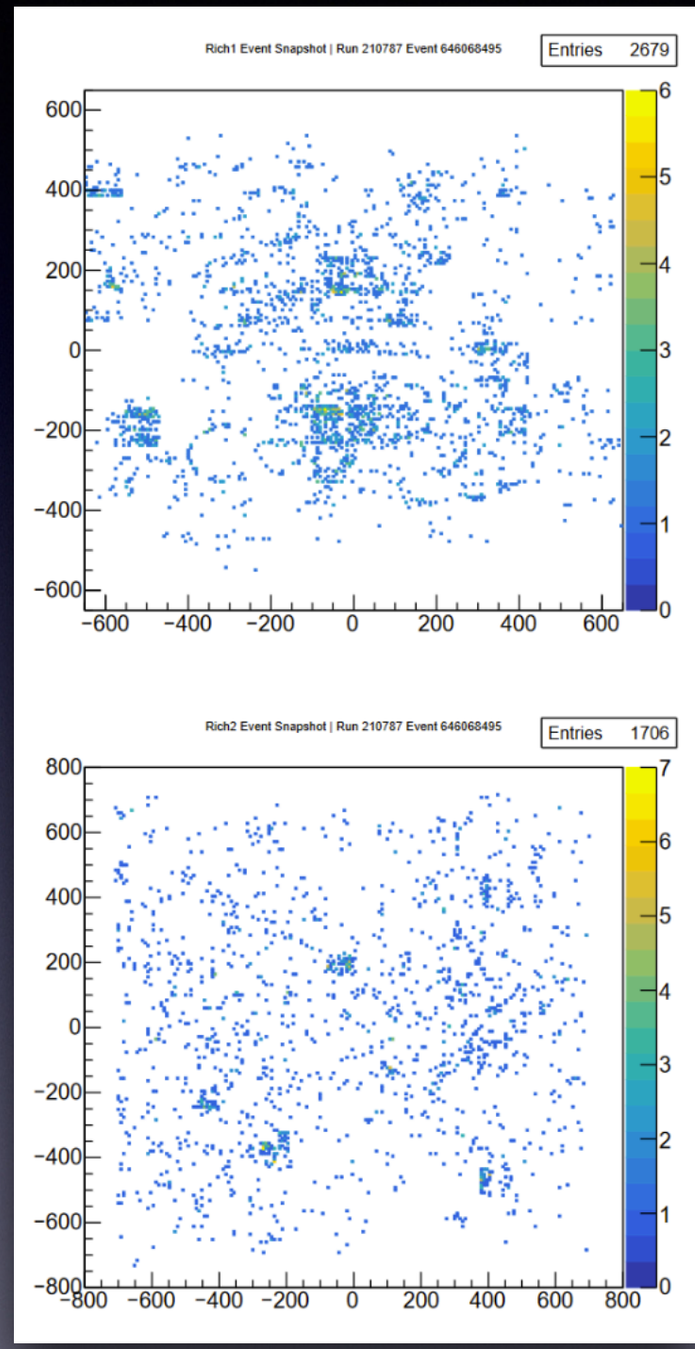
- Take reconstructed track objects and determine their trajectories through the RICH radiator volumes. Primarily for assumed **photon emission point,** but also provides path-length and **impact point on photon detector plane** (raytracing track as if it where a photon).

- Determine, for each Track and mass hypothesis the **expected Cherenkov theta values and resolutions**.

- Reconstruction **candidate Cherenkov photons** (i.e. Theta/Phi angles) by combining the hit detection points with the assumed emission points, with the knowledge of the RICH mirror optics.

- For each reconstructed photon candidate, determine for each mass hypothesis the **expected observable pixel signal yield**.

- Perform a **global event likelihood maximisation**, that iteratively changes the mass hypothesis of each track to find the overall set for the event that is the most likely. Provides the final track mass hypothesis PID information.



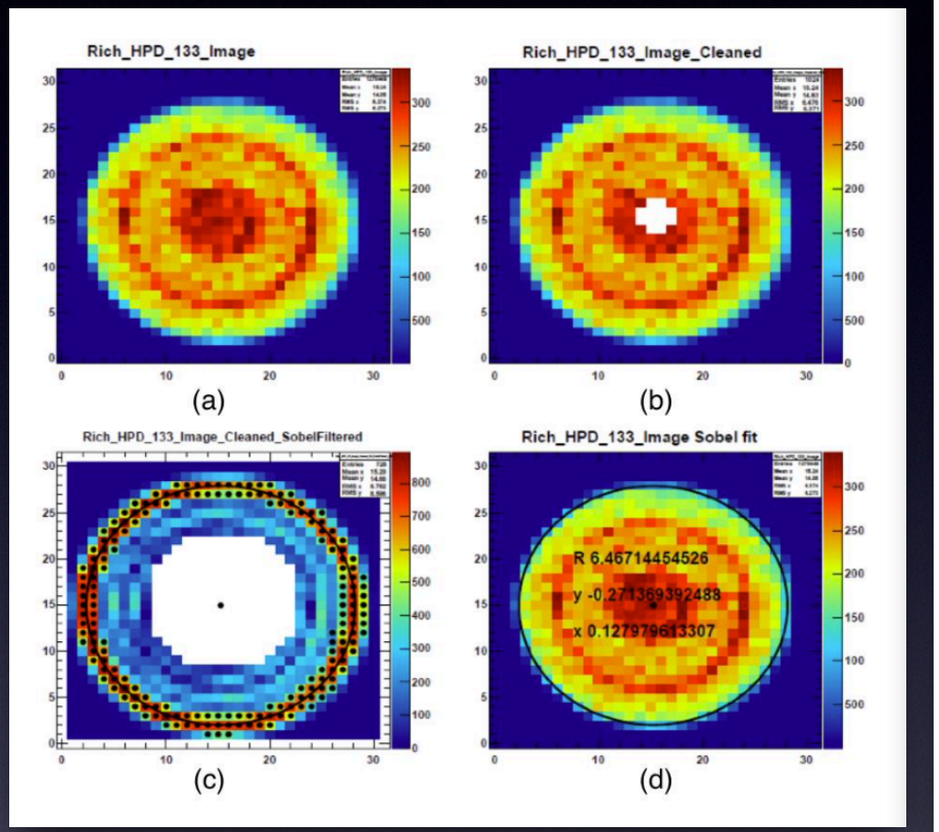
RICH Hit Detection Points

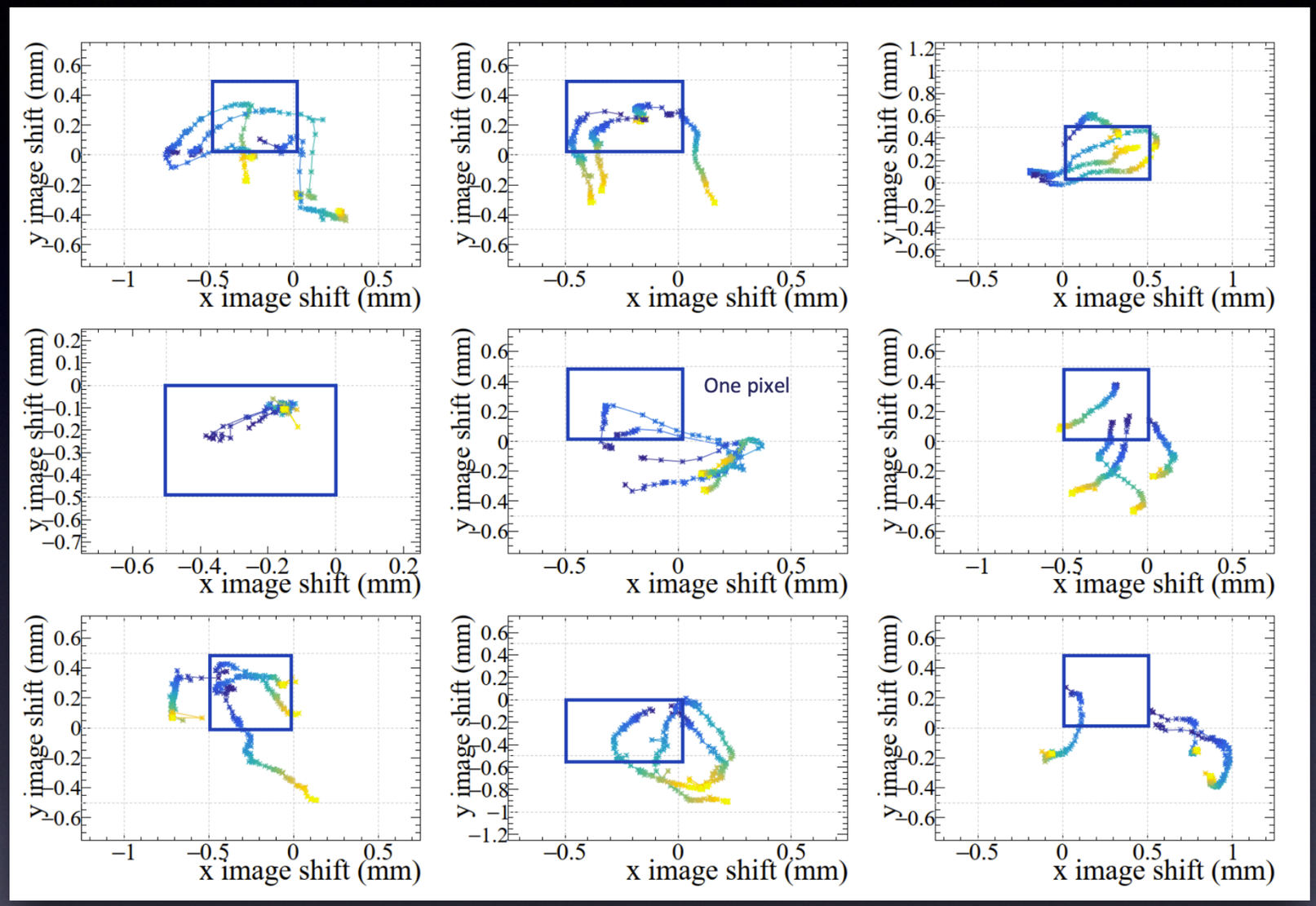
HPD panel position

- Photon detectors in Run{1,2} where HPDs,
    - Cherenkov photons impact cathode (entrance window), create a photo-electron which is accelerated to anode (pixel array) where it is detected.

- Observed during Run1 and Run2 (semi-random) movements of the HPD photocathode image on the detector place over time.
    - Reason attributed due to electrostatic changes over time, building up in tubes affecting the focusing.
- Movements significant enough to require calibration in order to avoid impacting Cherenkov resolution performance.

HPD cathode position calibration

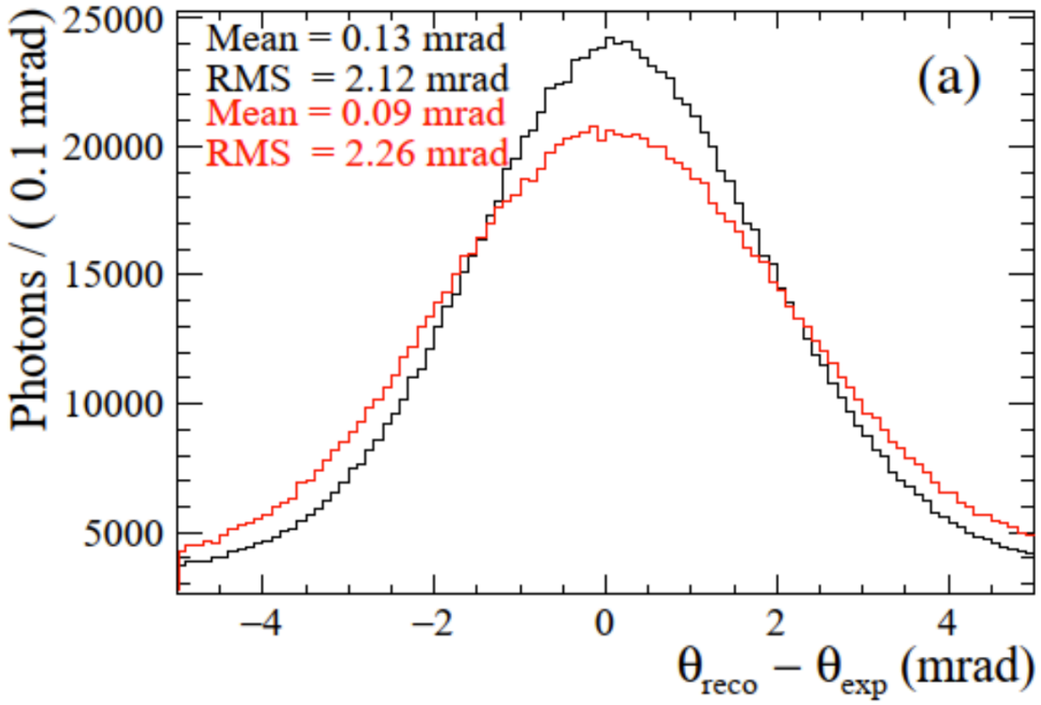


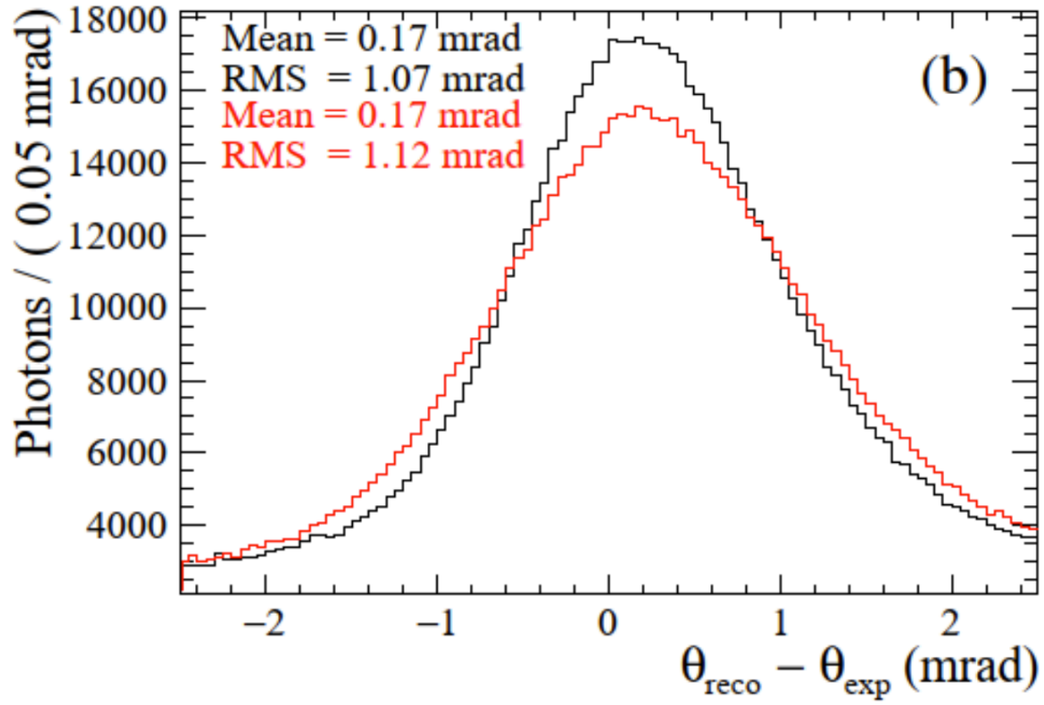


- Calibration performed online for each run (maximum 1 hour of data).
- Made available for subsequent HLT2 processing.

Photon Reconstruction - Cherenkov Resolutions

HPD cathode position calibration





RICH 1

Before corrections

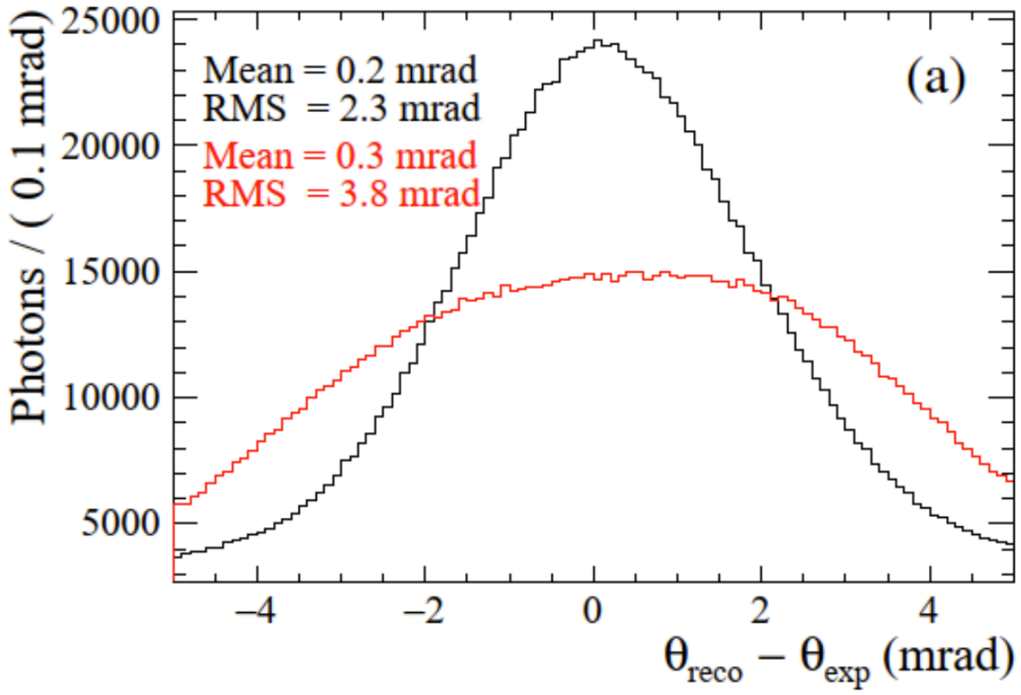
After corrections

RICH 2

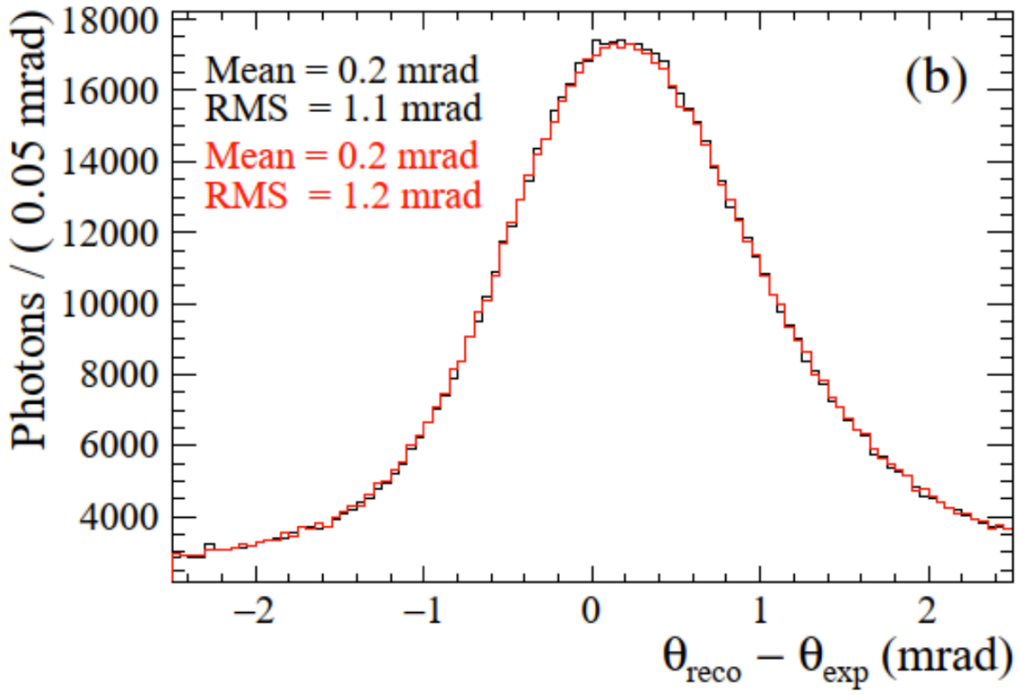
Science and Technology Facilities Council

Magnetic Field Distortions

- HPDs, as electrostatic devices, are effected by magnetic fields.
  - HPDs in RICH2 experience minimal residual field from the LHCb solenoid. RICH1 though much more significant.
  - Dedicated hardware system and data analysis to map and correct for the distortions.



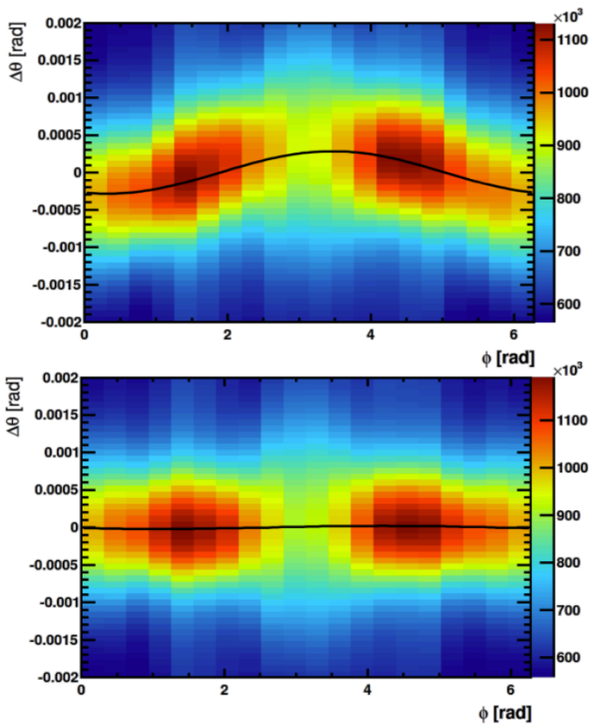
A Borgia *et al*, NIM A 735 (2014) 44-52

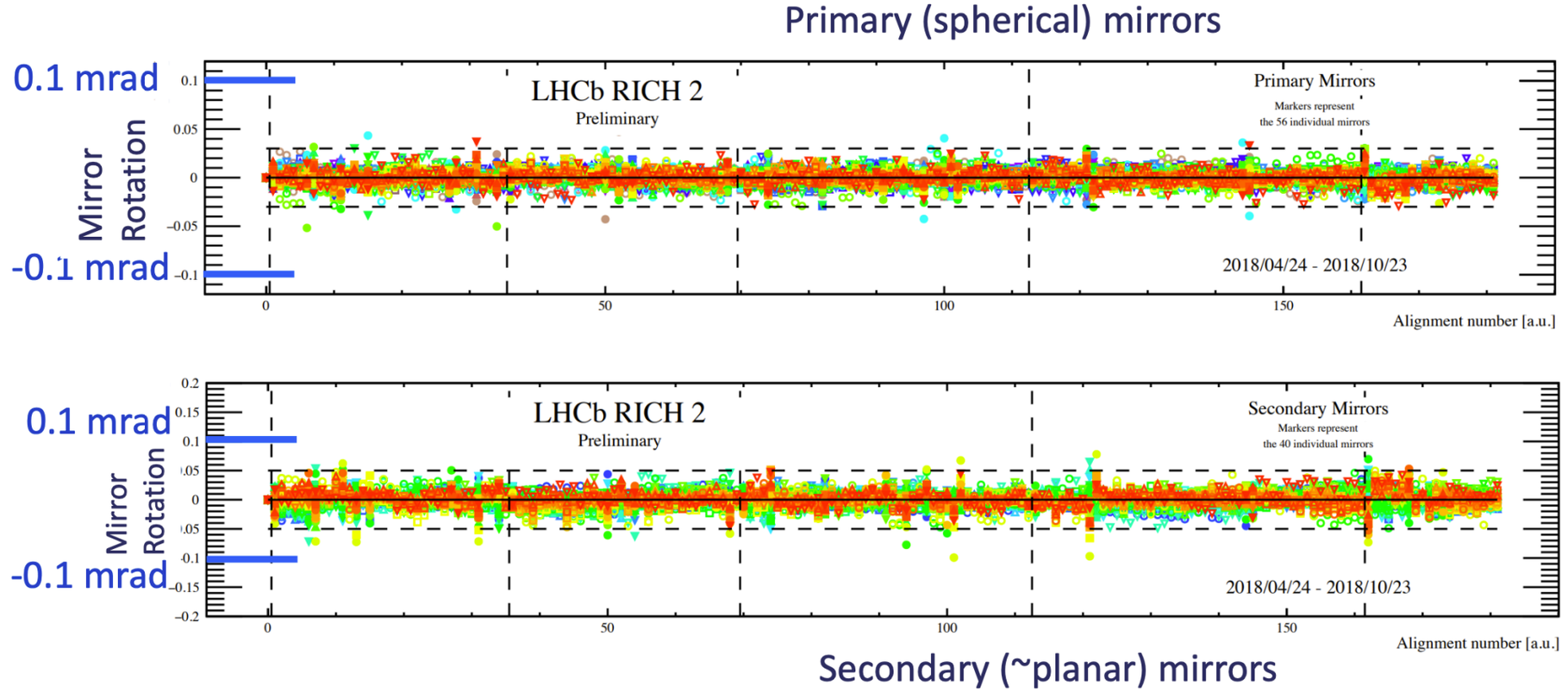


R Cardinale *et al,* 2011 *JINST* **6** P06010

Mirror Segment Alignment

- Mirror alignment refers to the process by which we determine the precise placement of the primary and secondary mirrors in each RICH.
- Critical process in order to achieve our optimal resolutions.
- Alignment performed online automatically each fill, updated if required.





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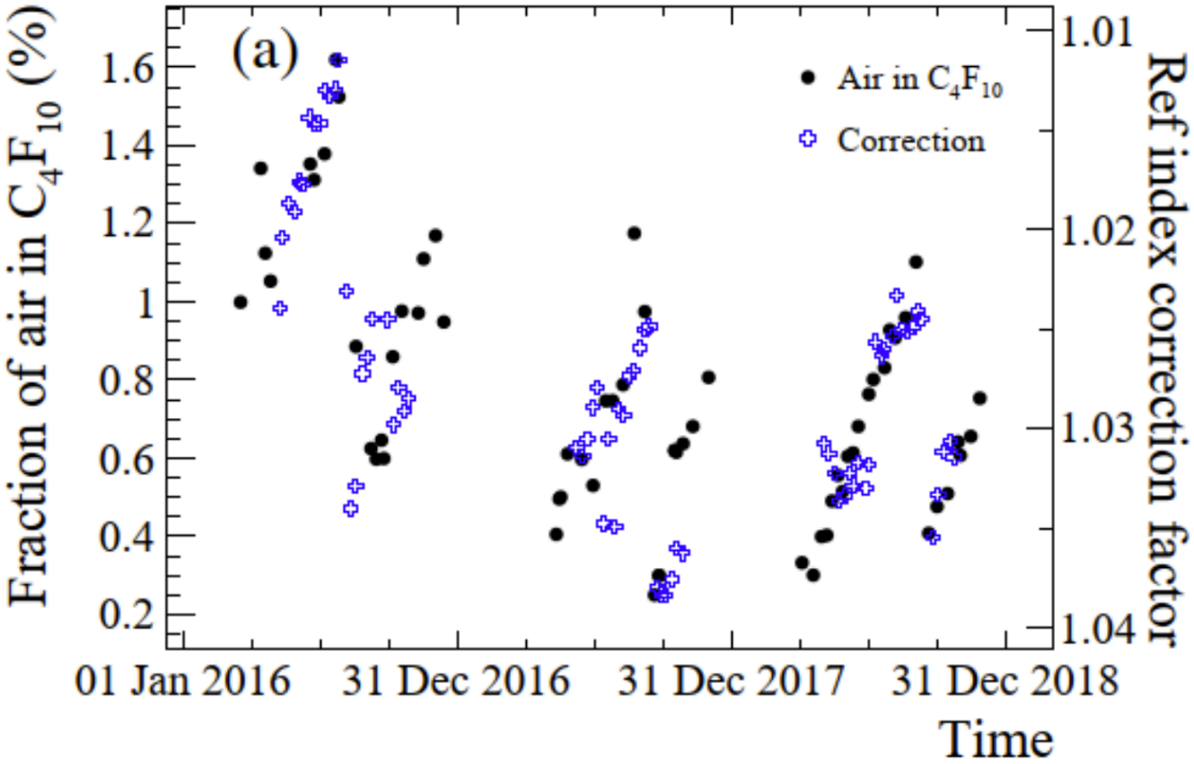
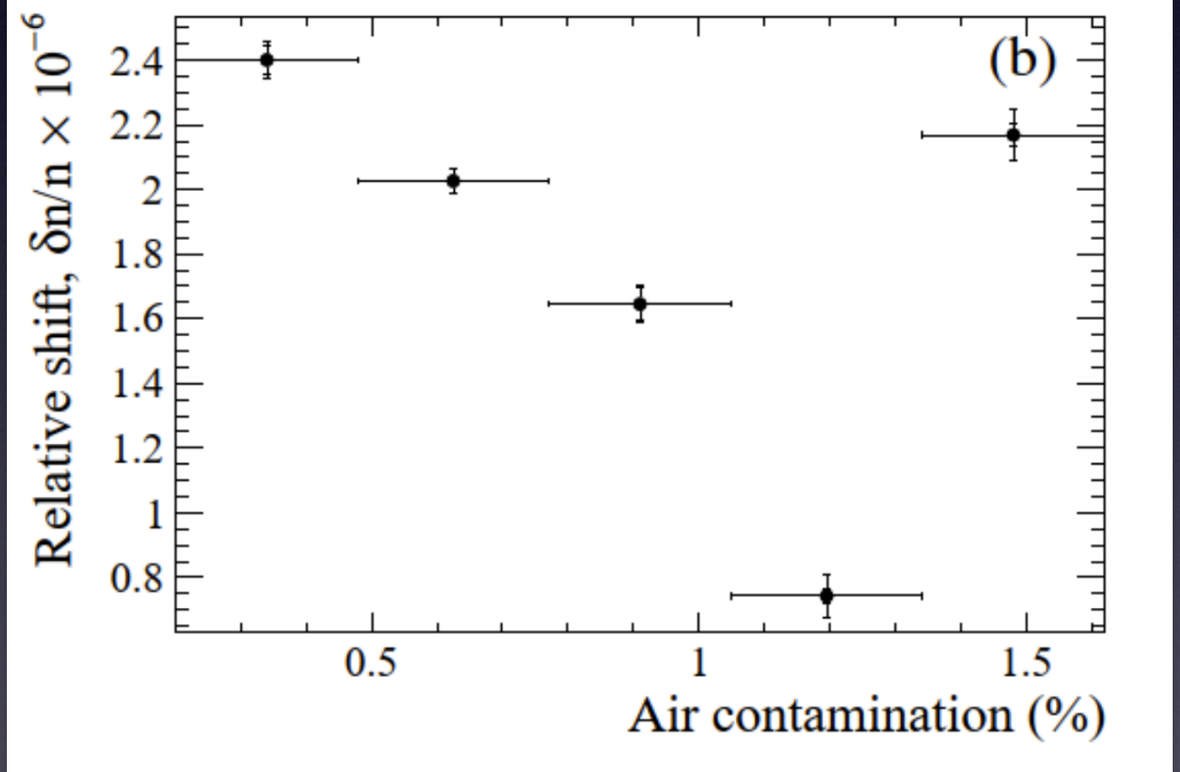
Refractive Index Calibration

- Corrections necessary to for small variations in the gas radiator refractive indices.
  - Ambient pressure, temperature. Small amounts of air contamination.
- Calibration performed in realtime and again made available to HLT2 reconstruction.

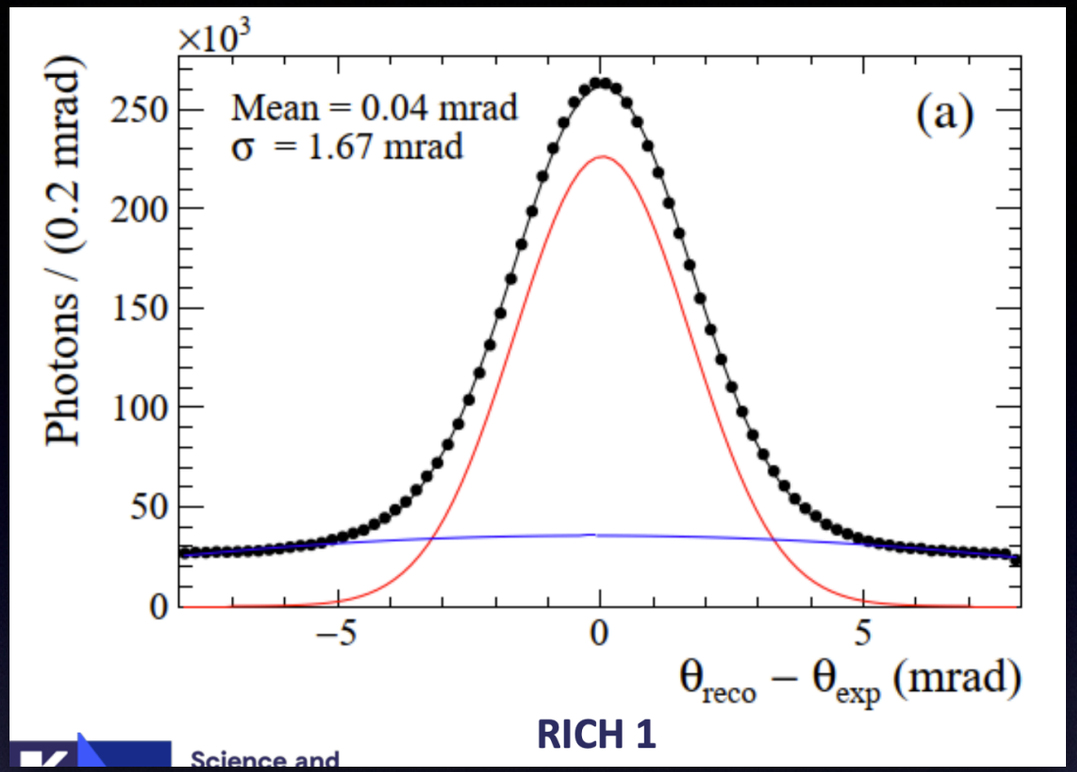


Correction factor and air contamination

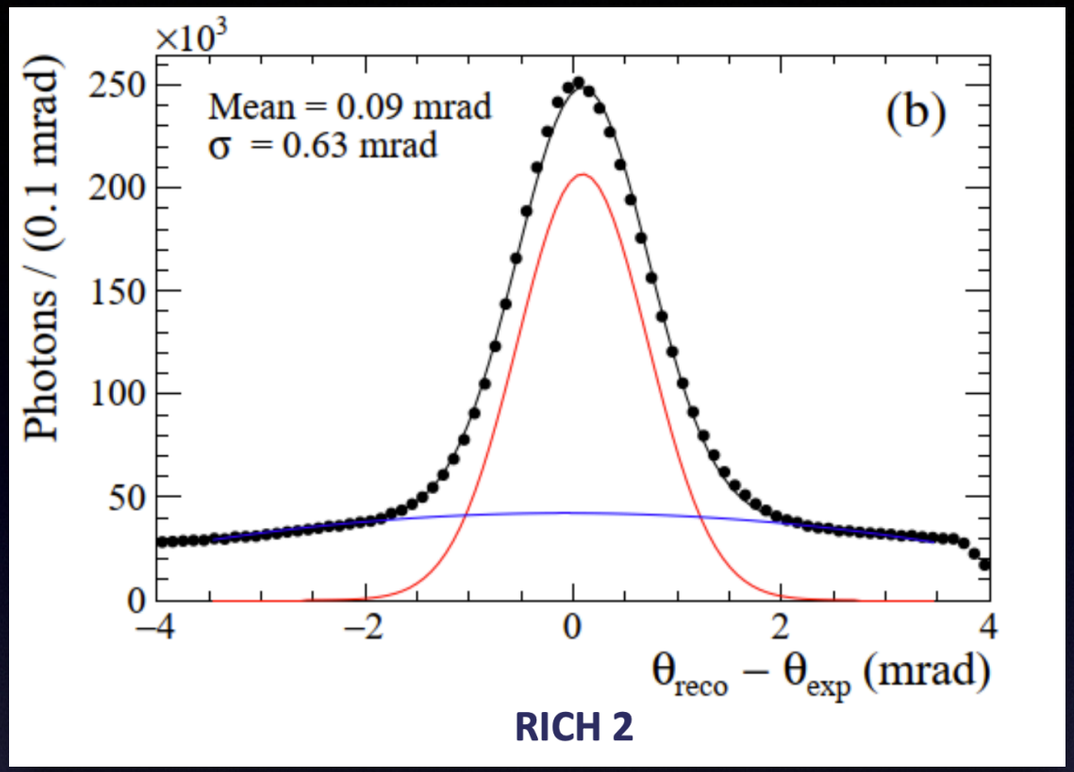


Residual refractive index bias after correction

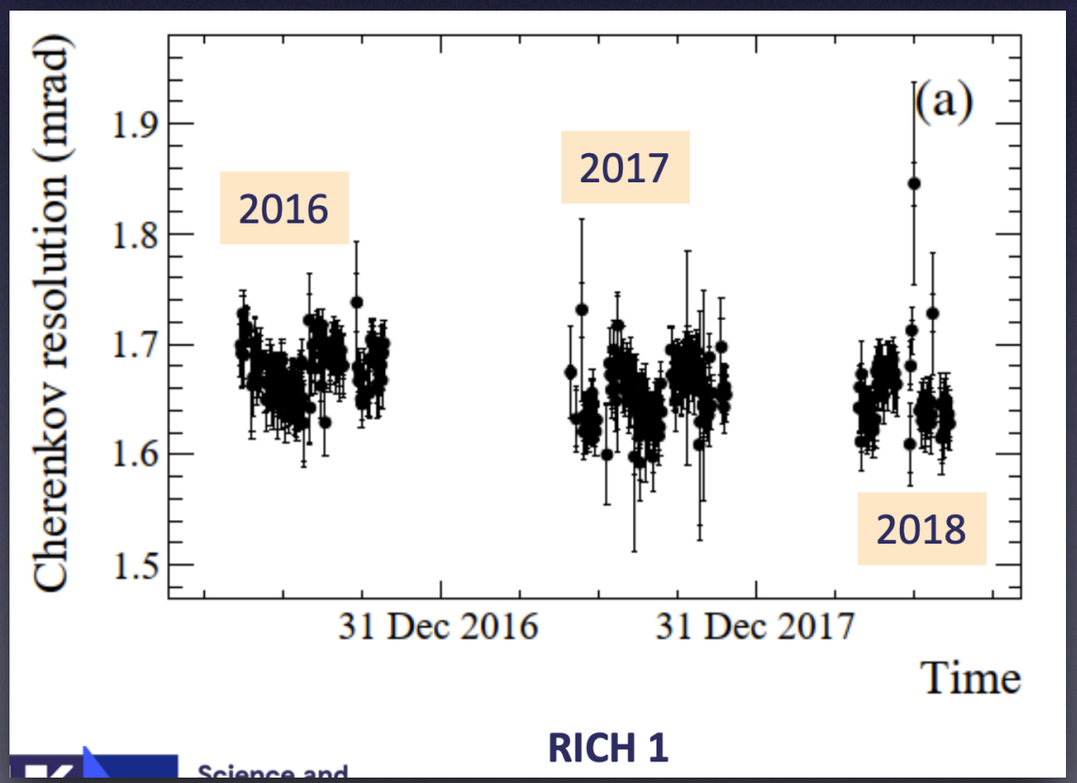
Final Cherenkov Theta Resolutions



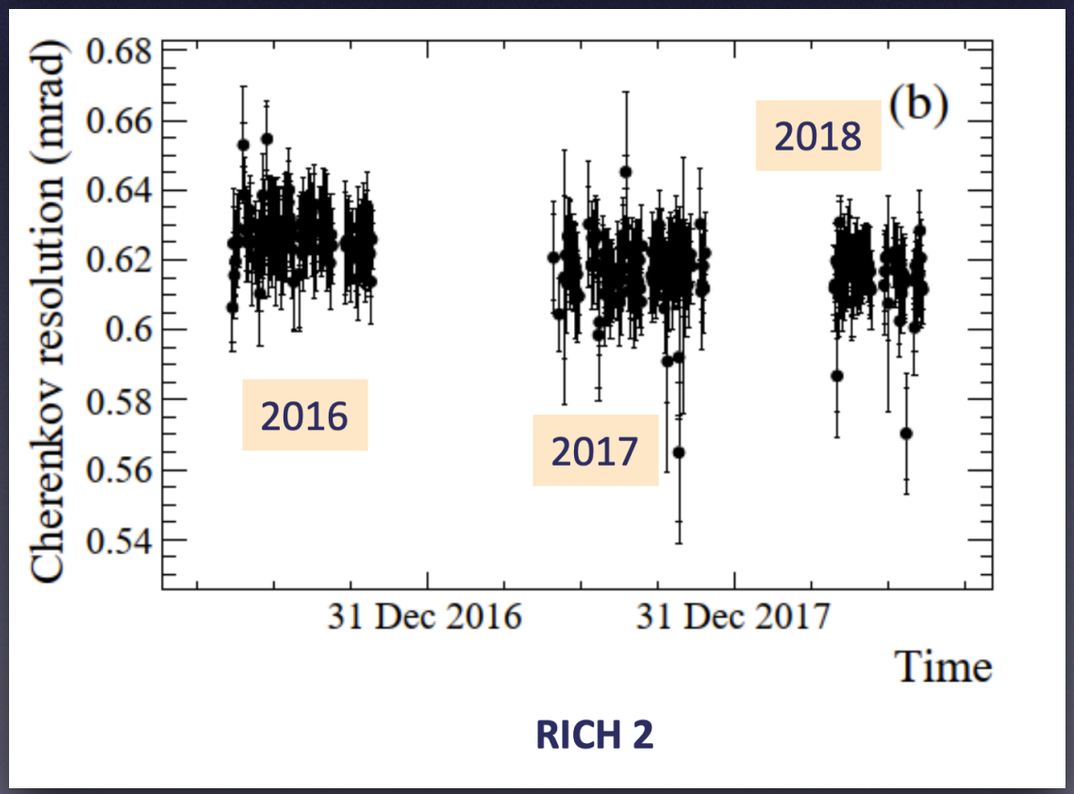
RICH 1



RICH 2

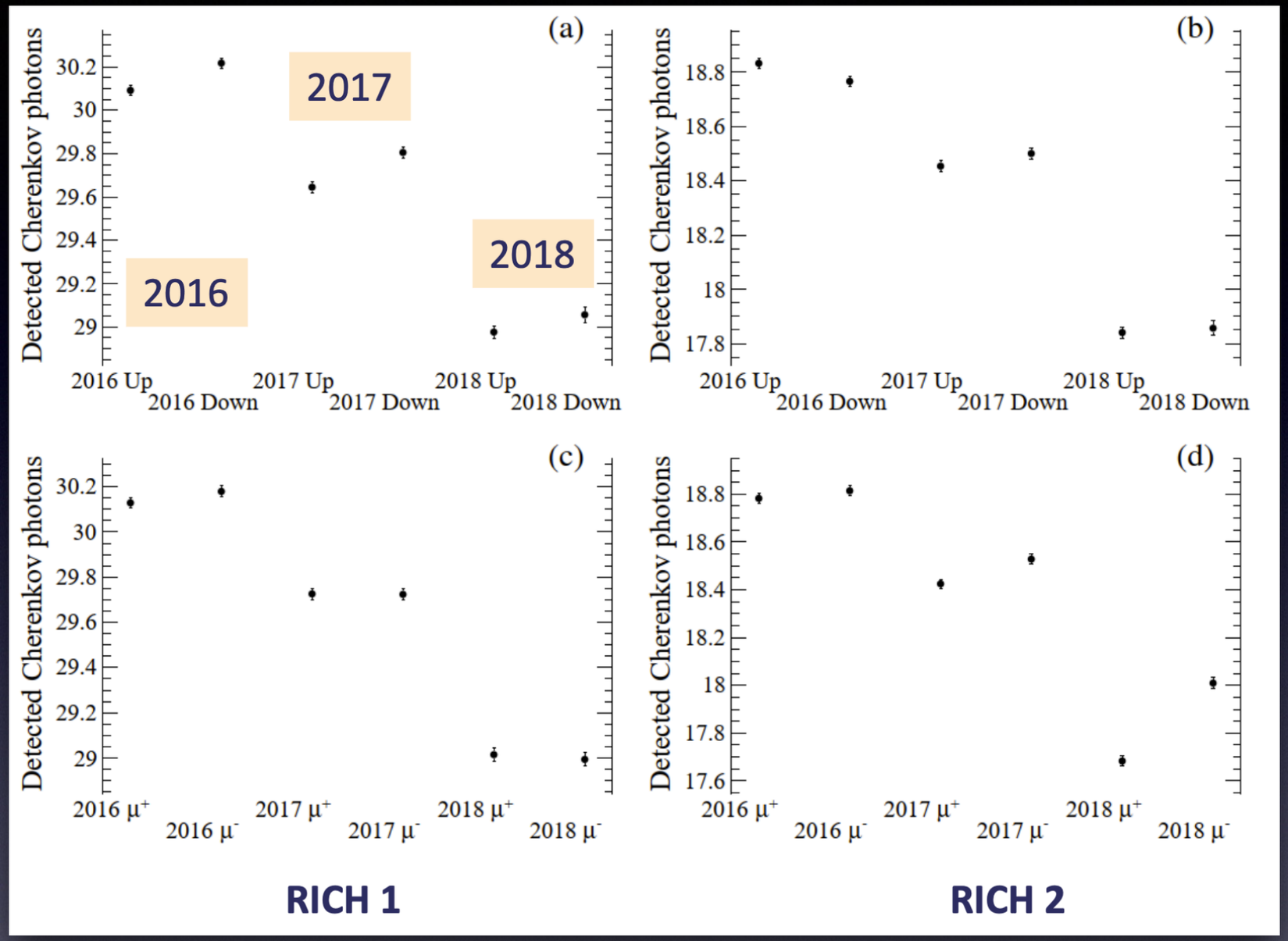


RICH 1



RICH 2

Cherenkov Photon Yield



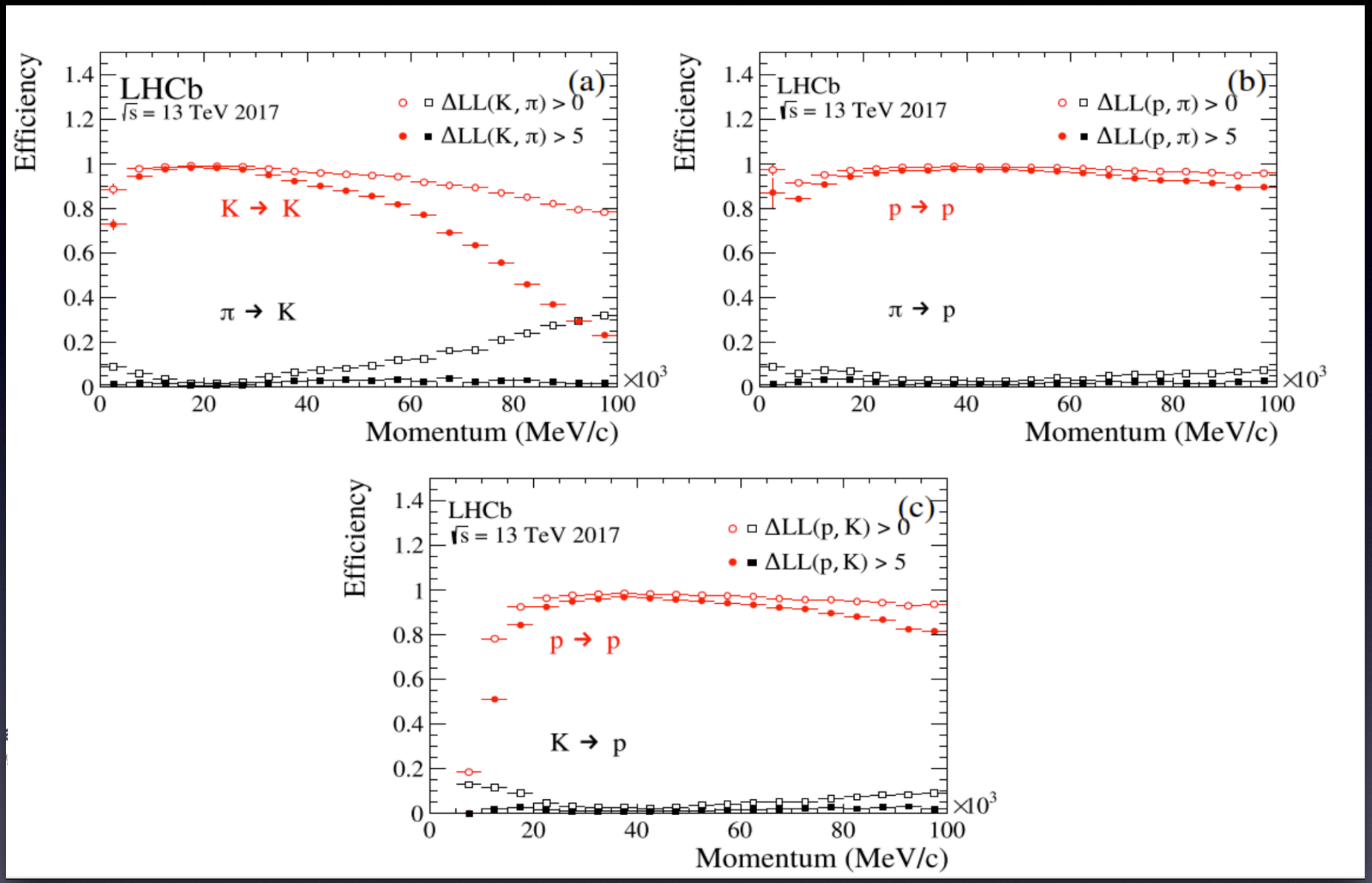
- Estimated per track from resolution plot, incorporating background subtraction.
- Measured in lower occupancy events, where it is easier to handle the backgrounds.
- Two magnet polarities used (Up,Down). Flipped periodically to minimise systematic effects.

Global Likelihood PID

Global Likelihood PID

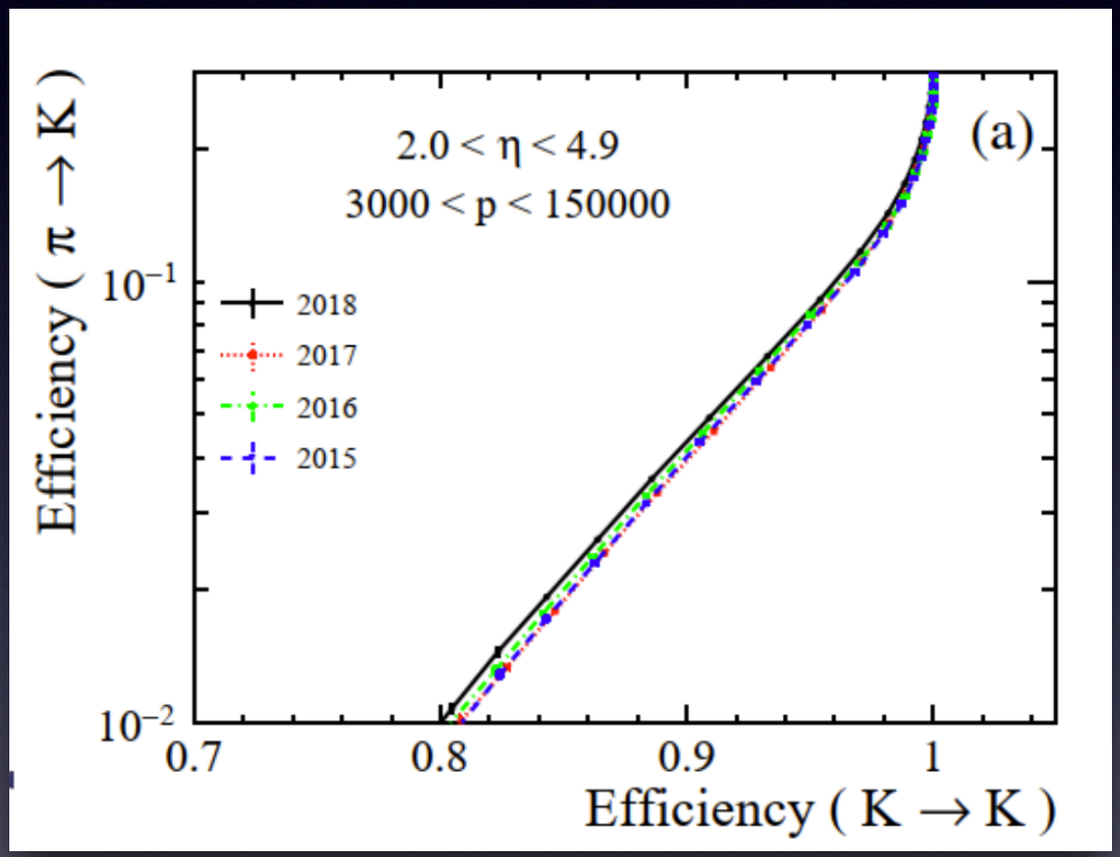
- For each track in the event, and for a given mass hypothesis, create Cherenkov photons and project them to the detector plane using the knowledge of the geometry of the detector and its optical properties.
- Repeat this for all the other tracks.
- From the photon distribution on the detector plane calculate the probability that a signal would be seen in each pixel of the detector from all tracks.
- Compare this with the observed set of photoelectron signal on the pixels, by creating a likelihood.
- Repeat all the above after changing the set of mass hypothesis of the tracks.
- Find the set of mass hypotheses, which maximize the likelihood.
- Provide for each track delta log likelihood values, that give the overall change in event likelihood changing that track to that given type.

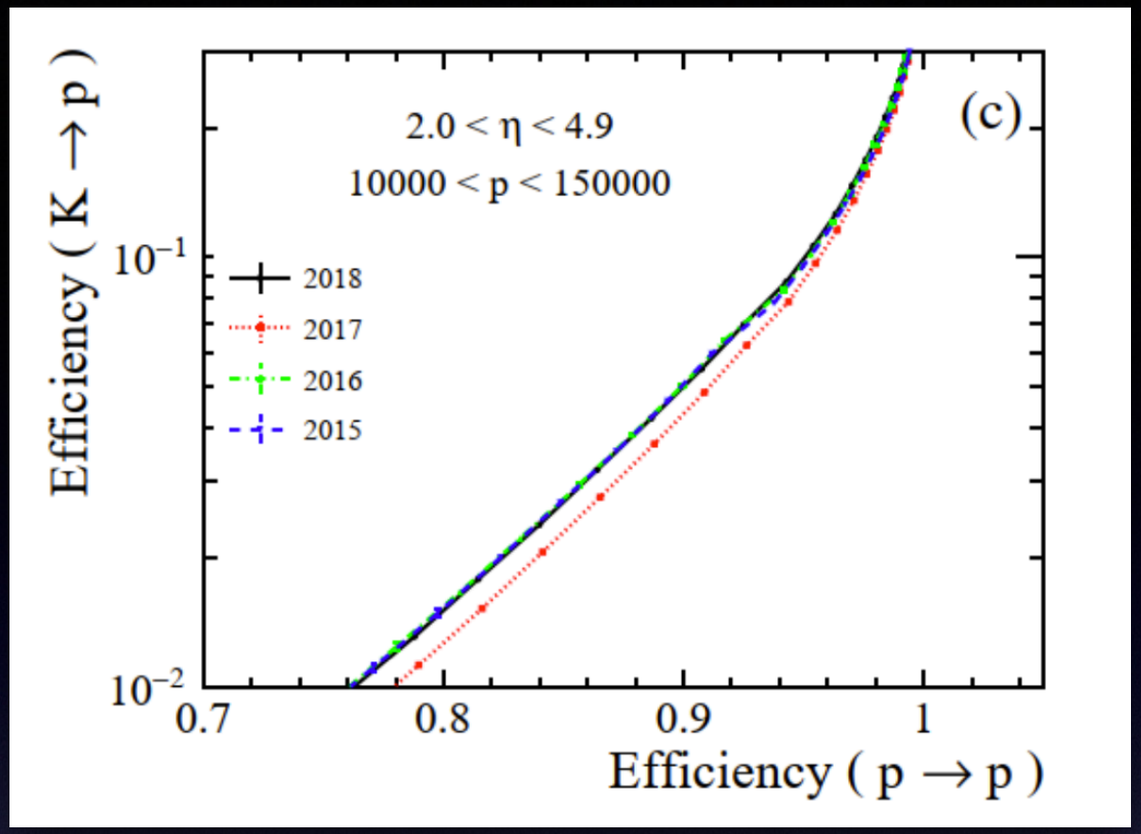
PID Performance

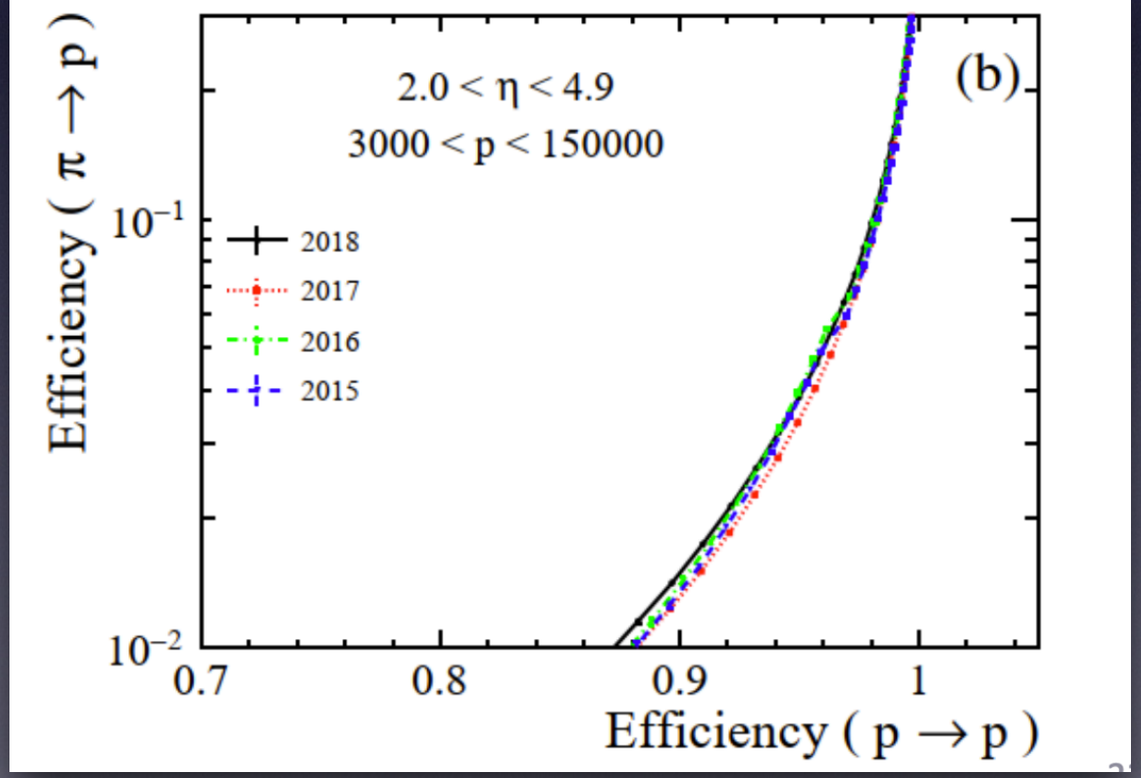


- Determined from data using decay modes where clean samples of particles of known types can be identified.

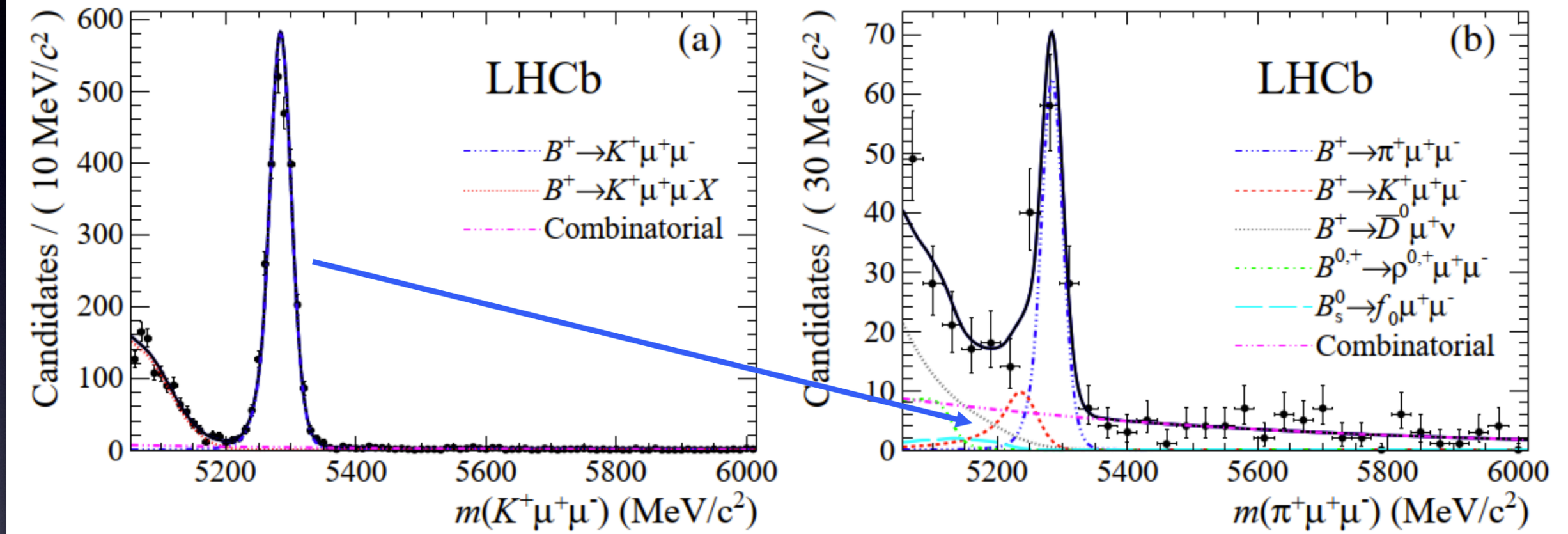
PID Stability







Physics Impact

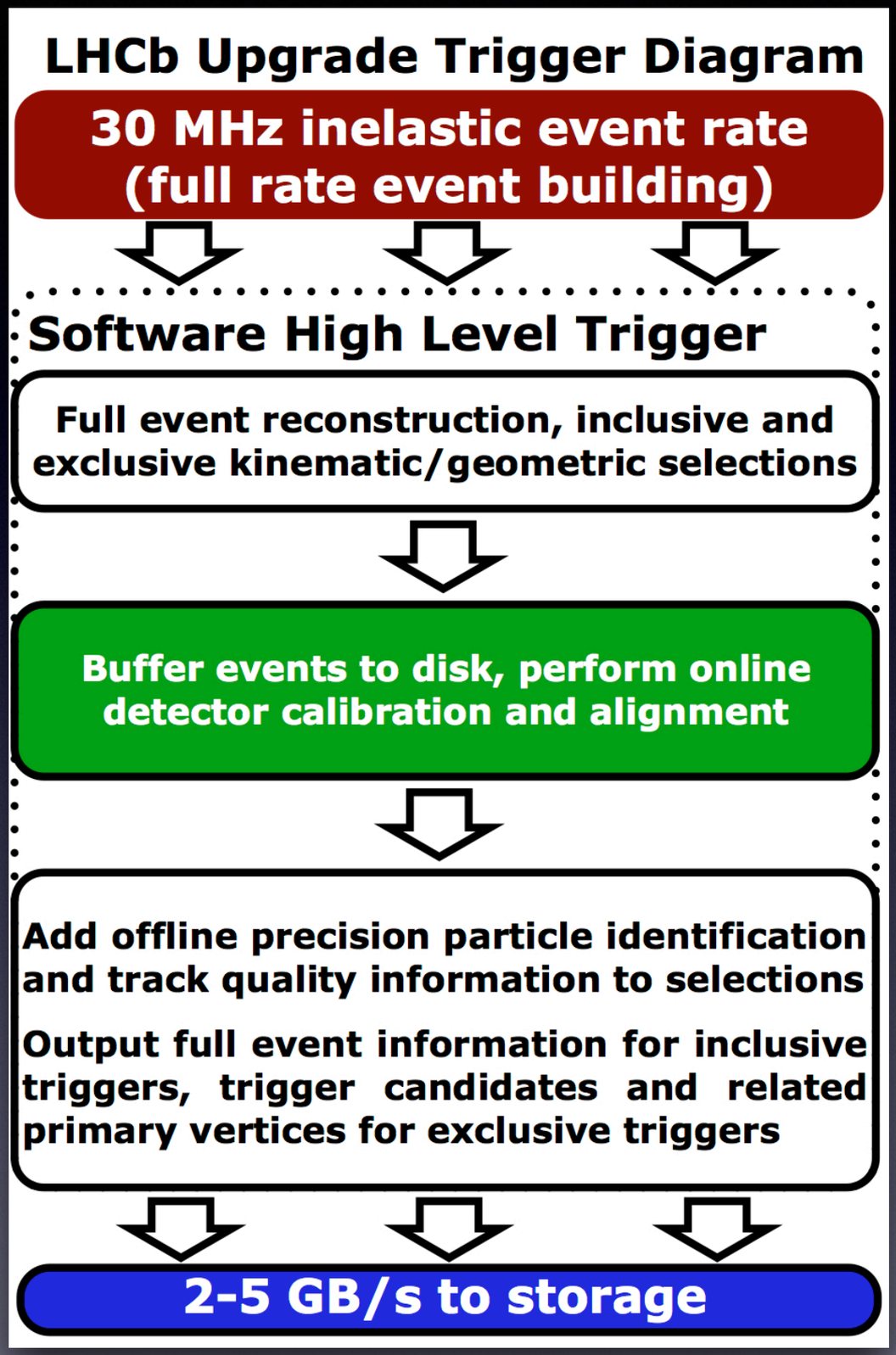


First measurement of the differential branching fraction and CP asymmetry of the $B\pm \to \pi\pm\ \mu+\ \mu-$ decay, JHEP 10 (2015) 034 [arXiv:1509.00414]

Run III

Run III

- Run III started this year. Commissioning with beam still ongoing.
- Primary aim to increase physics output.
  - Remove hardware L0 trigger. Full 30MHz inelastic rate to software trigger.
  - Implies new readout electronics for all subsystems.
- Hardware upgrades to numerous systems. For the RICHes, e.g. :-
  - Switch from HPDs to MaPMTs.
  - Optimise optics in RICH1.

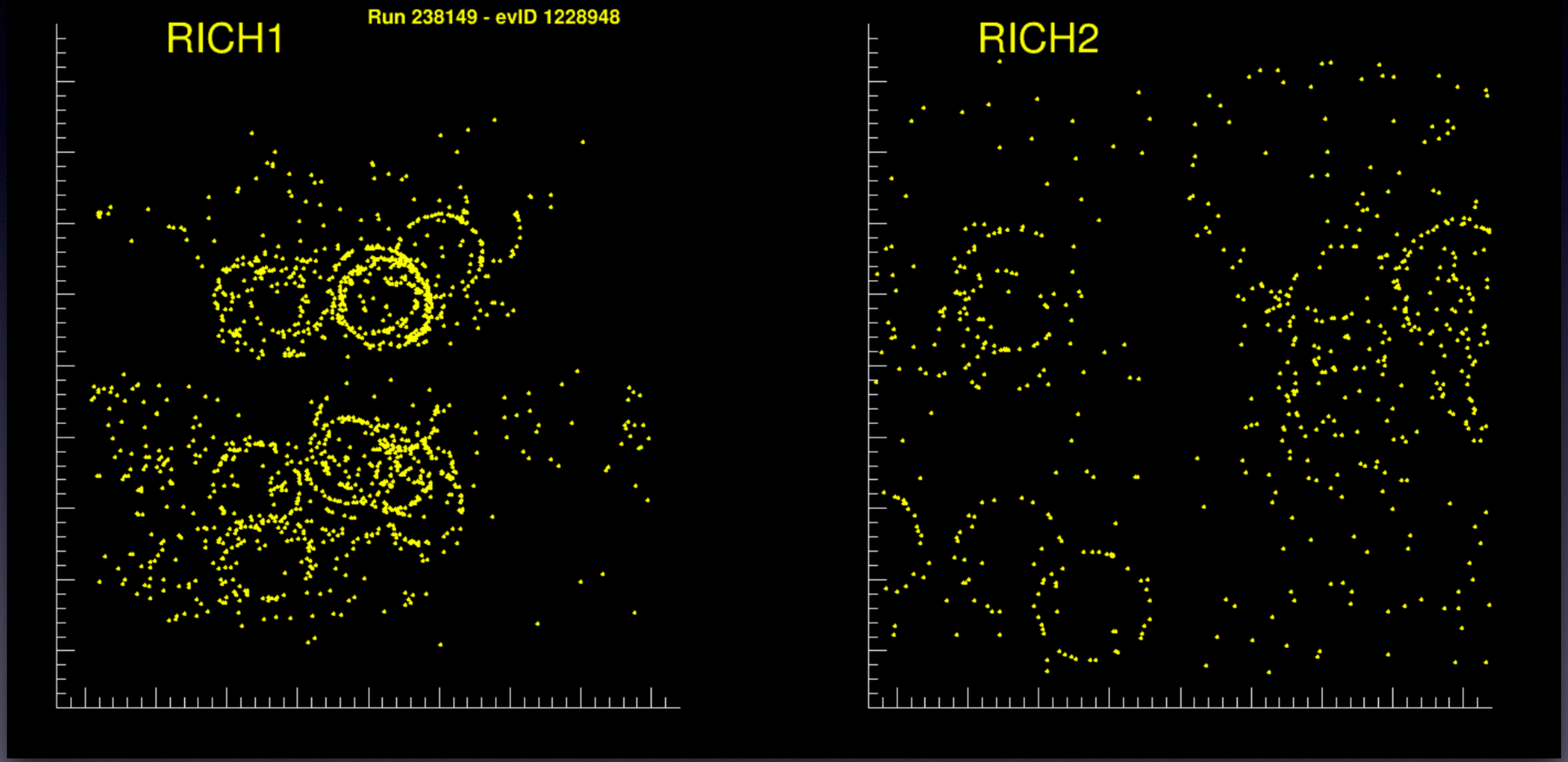


Run III MaPMTs

RICH1

RICH2

First Run III Cherenkov Rings !



Conclusions

- LHC Runs I and II provided a wealth of knowledge on how to operate the LHCb RICH detectors.
- Cutting edge use of online calibration and ‘offline quality’ reconstruction, including the RICH, in its higher level triggers.
- Work ongoing to commission a new set of detectors for Run III.