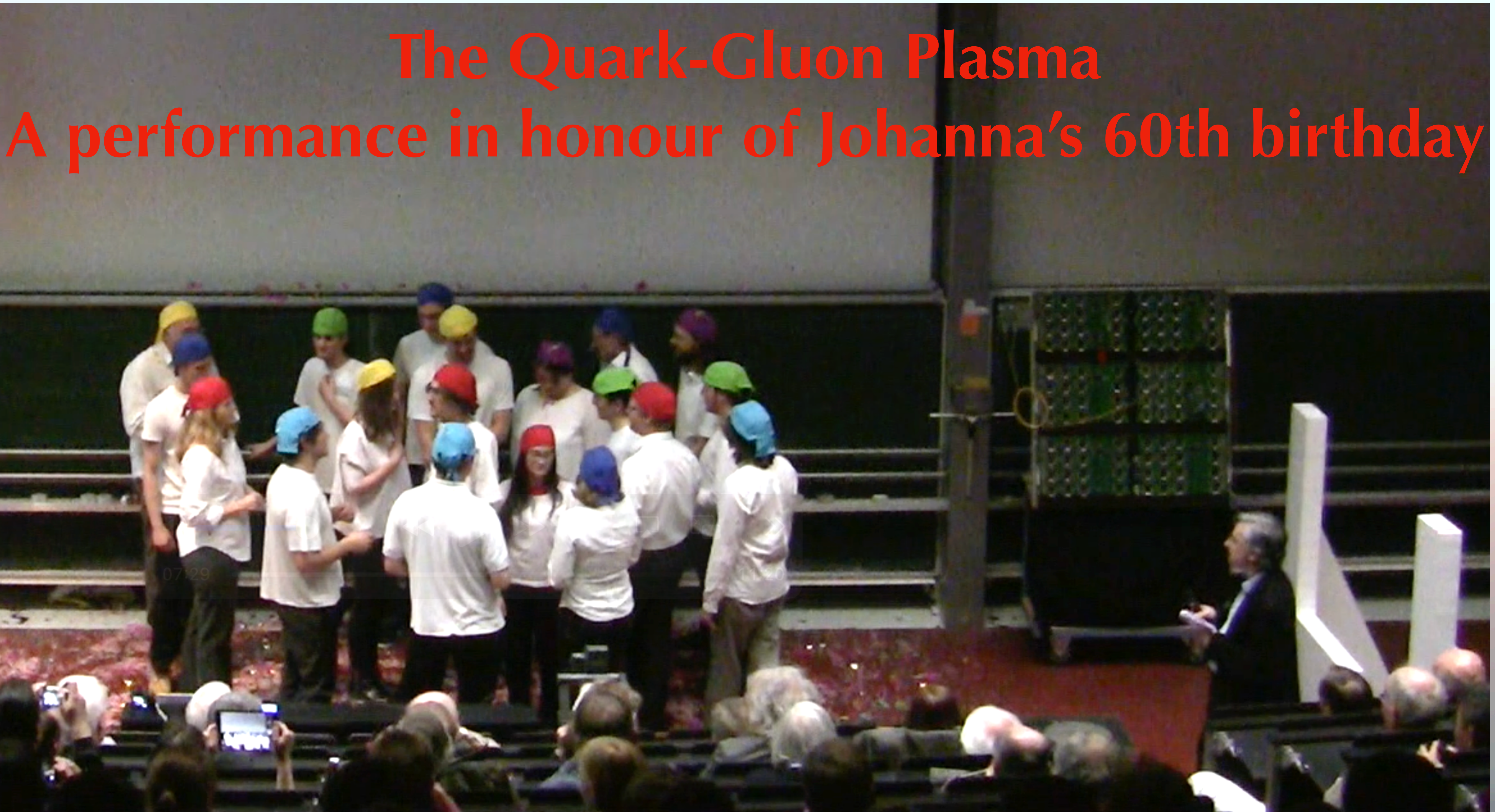
# Pushing the frontiers of heavy-ion physics with ALICE 1, 2 and 3




**Jochen Klein (CERN)**

February 11, 2025

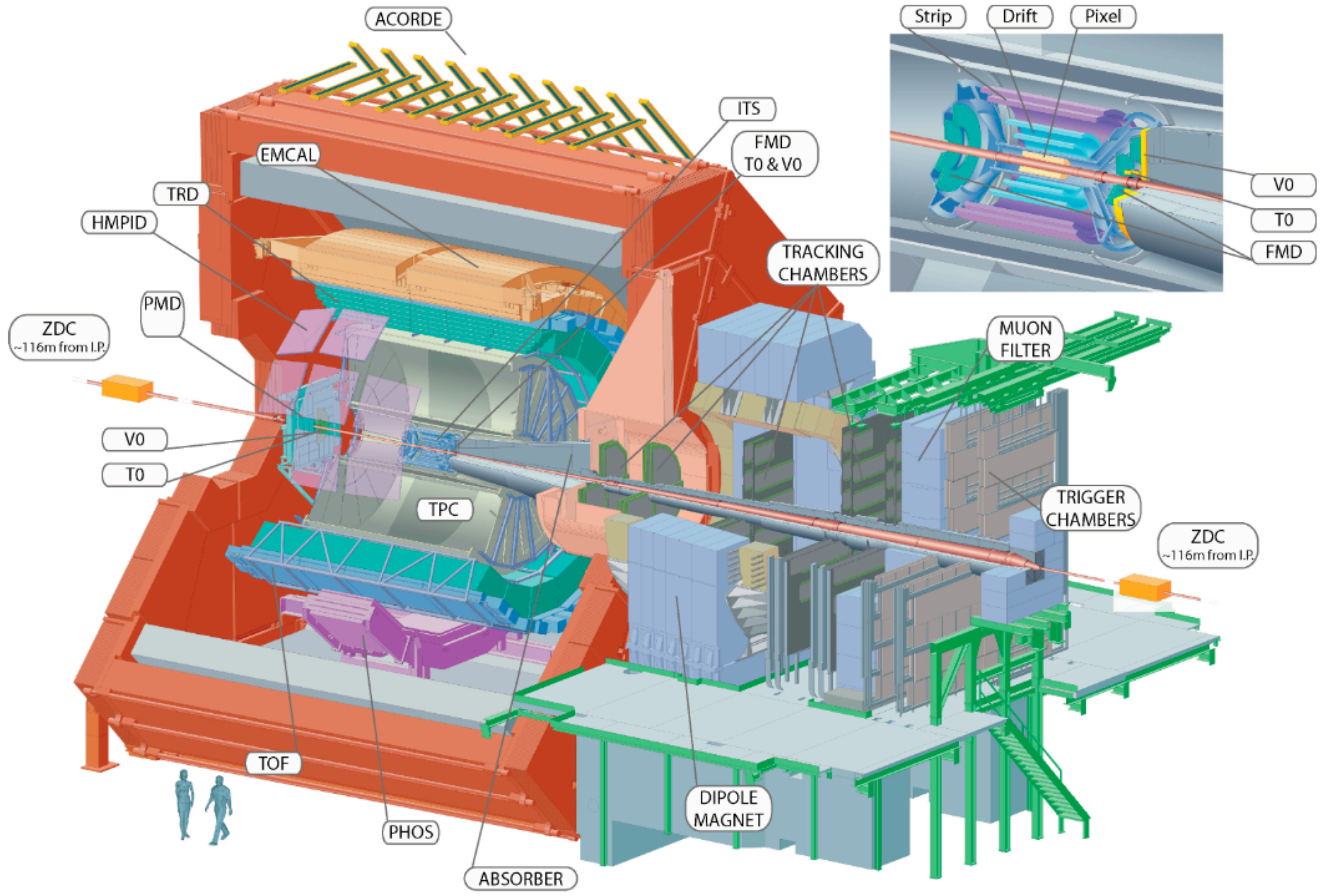
Never at Rest:
A Lifetime Inquiry of QGP

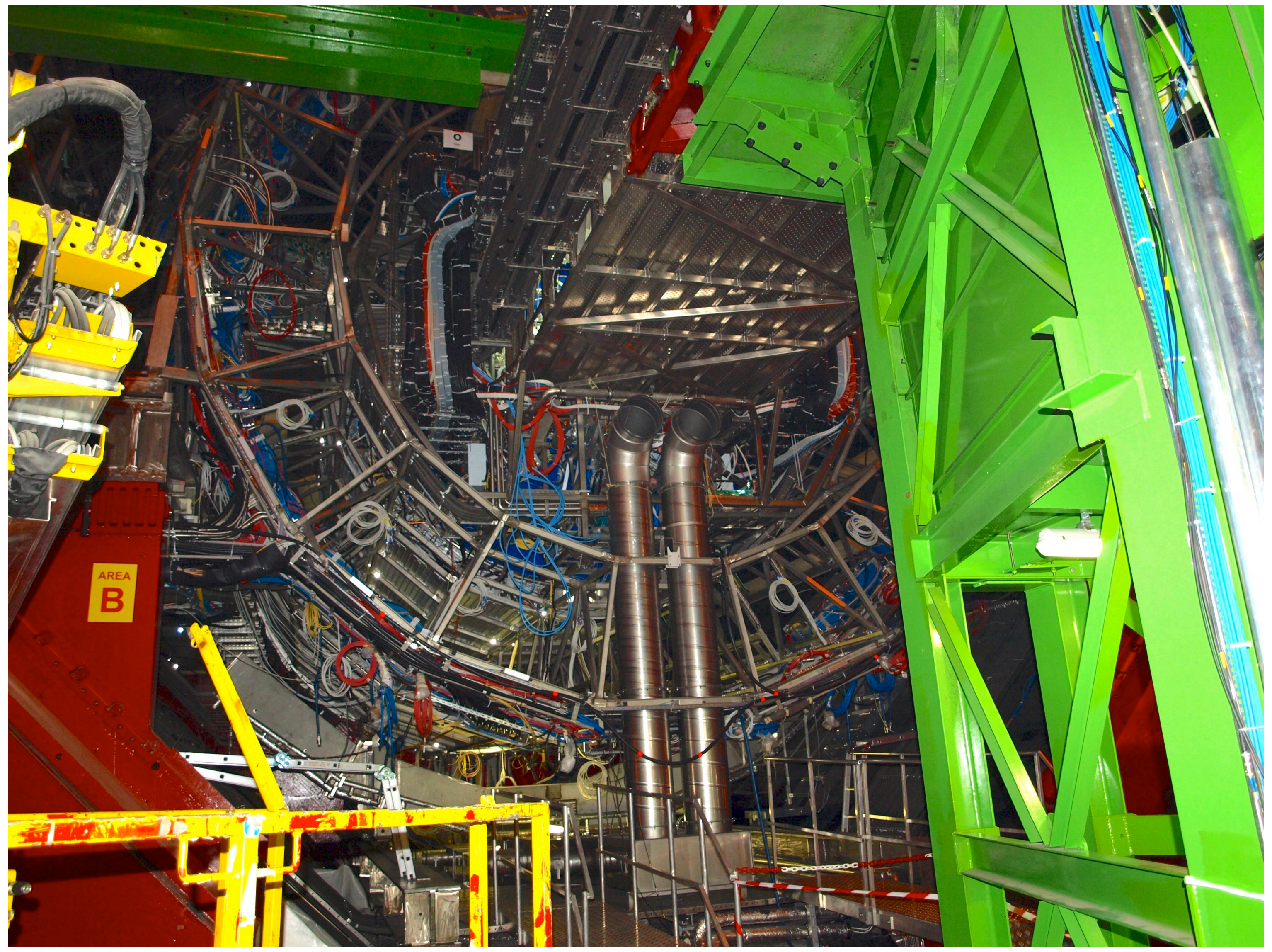
# My way to ALICE

- **Move from Kaiserslautern to Heidelberg** autumn 2006
  - **meeting Johanna** in lecture on "Standard Model" (jointly with Otto Nachtmann)
  - **CERN summer student**
    → ALICE offline group
  - wish to get more involved in detector aspects
    → **ALICE TRD**

- **Extended stays at CERN** since 2007
  - experiment in **installation and commissioning phase**, perfect moment to get in-depth views of full detector
  - going to CERN always felt like coming back to CERN

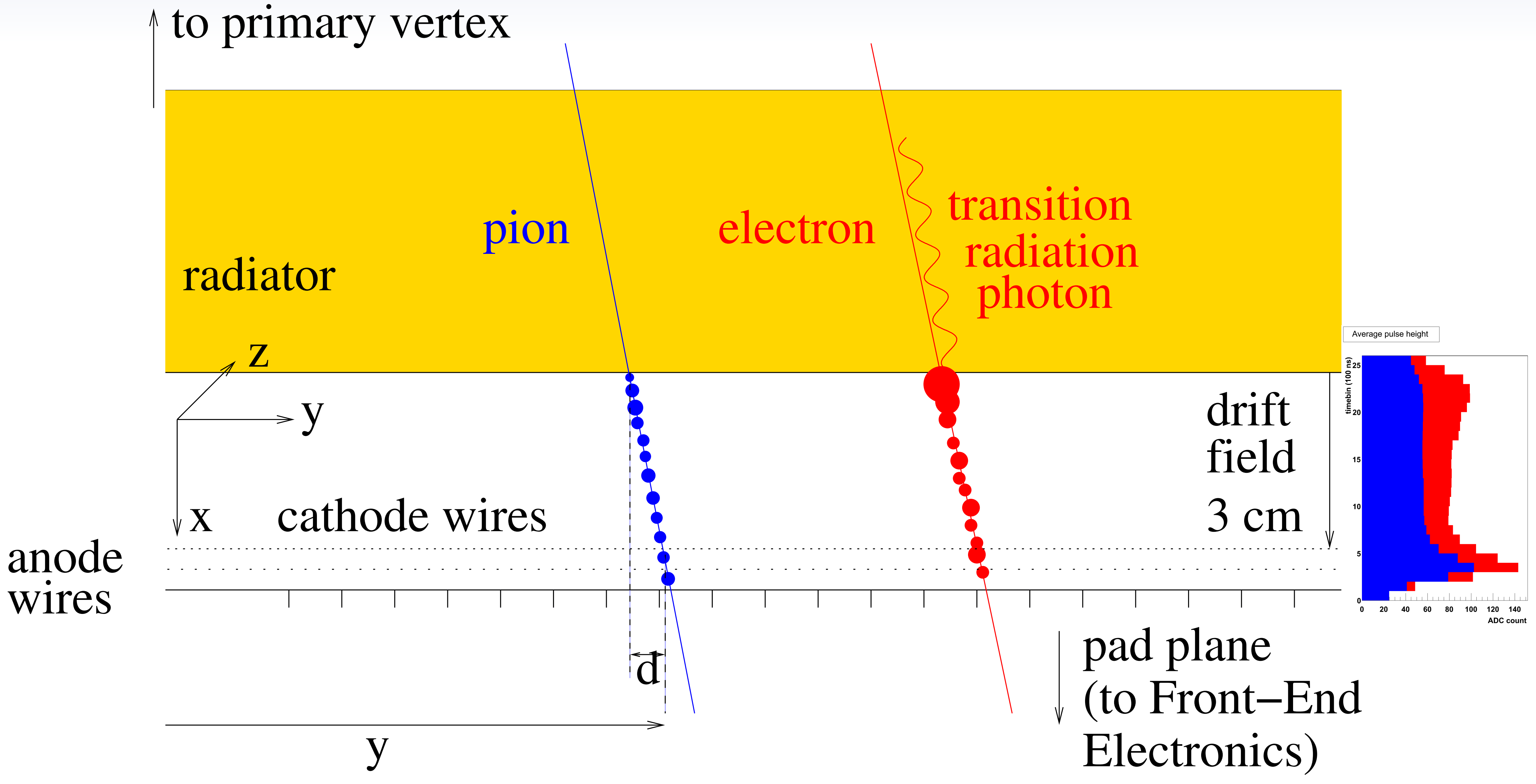
**ALICE 1**



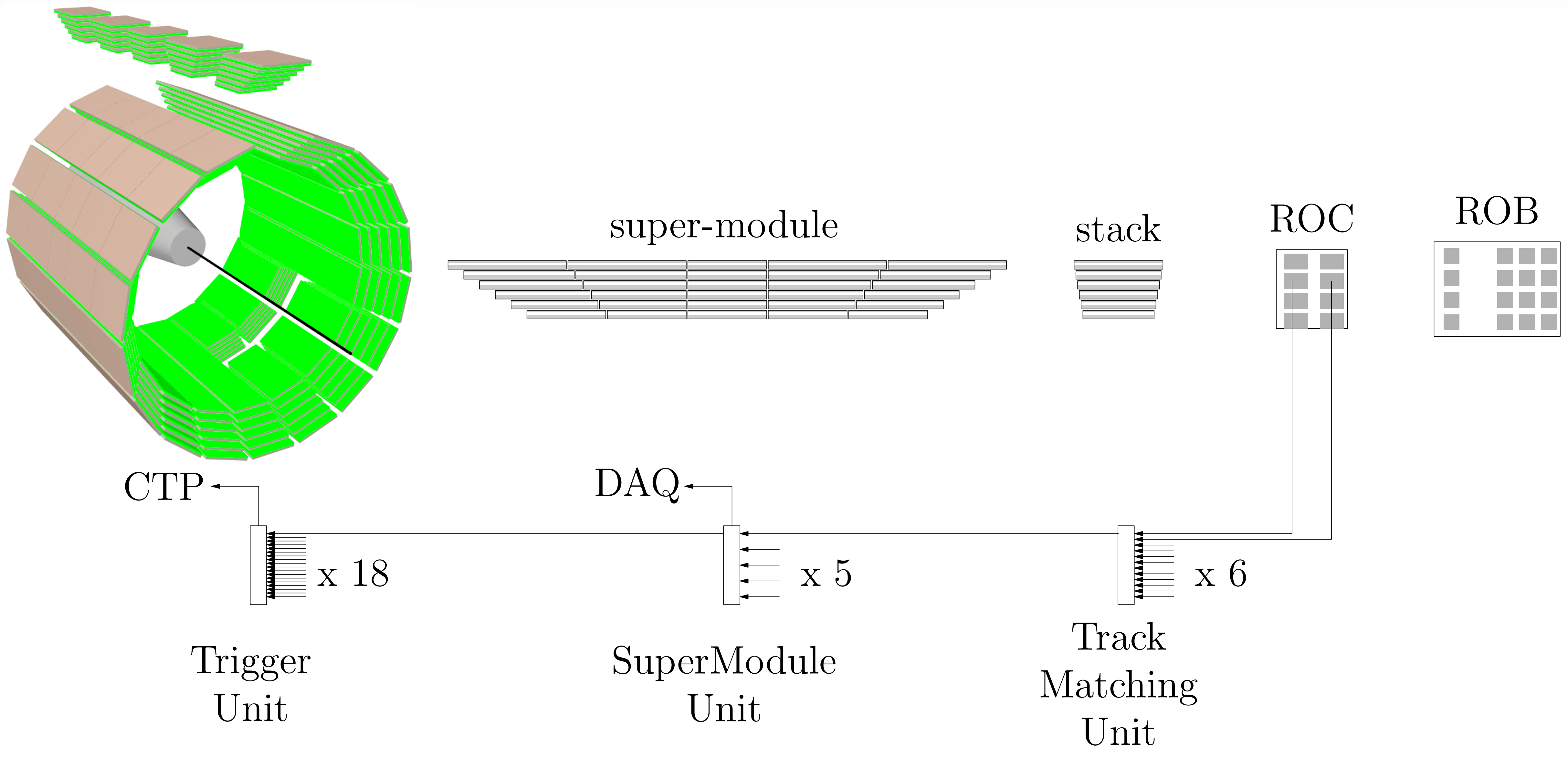



**ALICE during installation**

# ALICE TRD



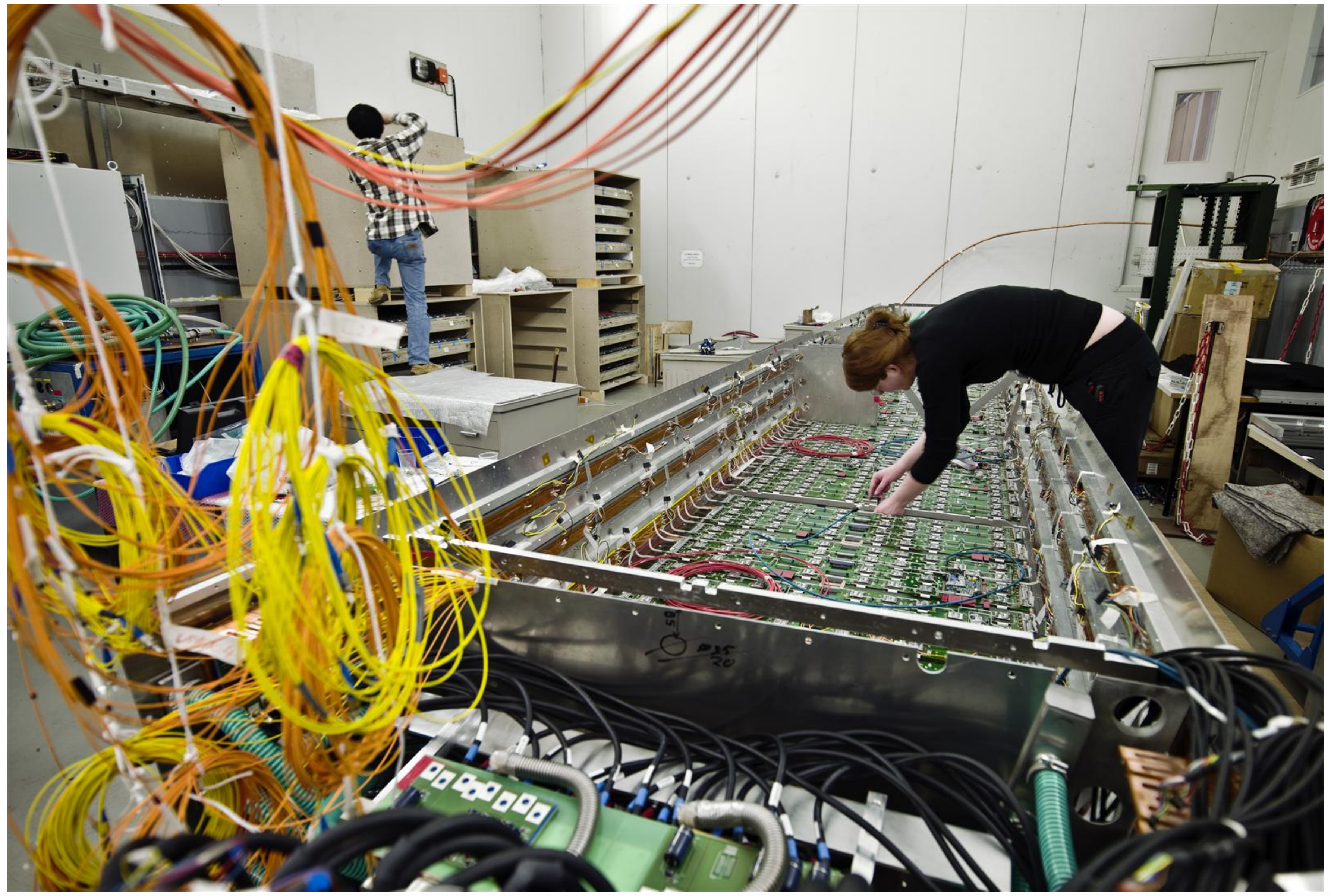

2007




- Extend particle identification capability of ALICE to electrons, incl. triggering

  ➡ **Transition Radiation Detector**
  **with extensive online processing capabilities**

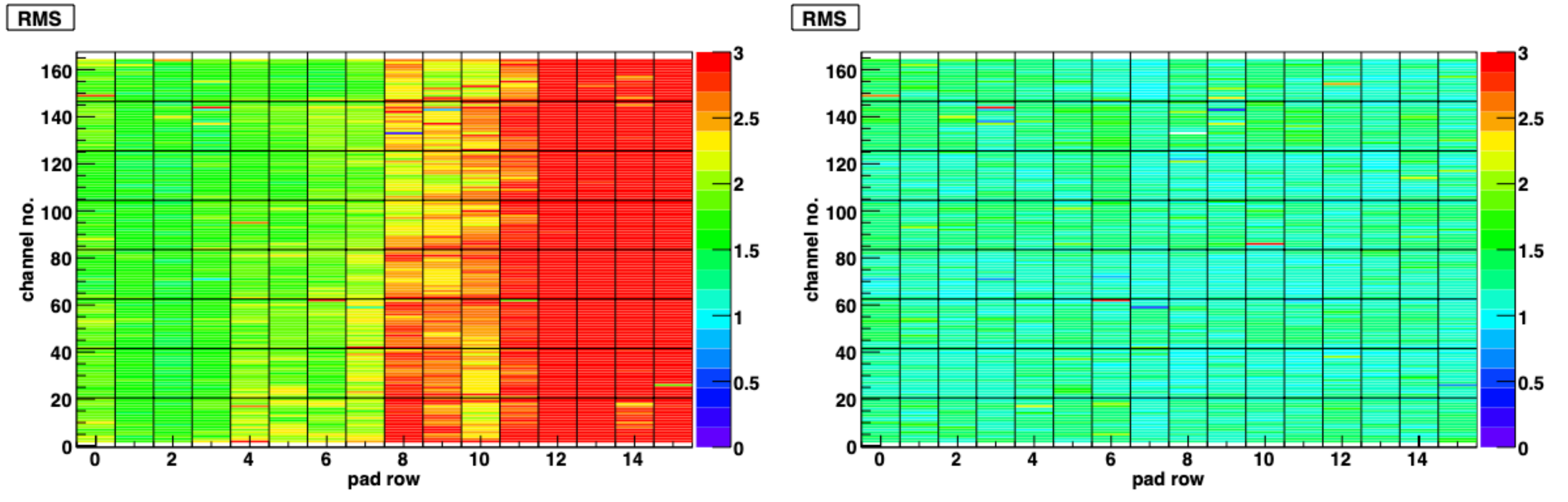
- **Rework campaign in cleanroom**
  following observation of gas leaks
  during test of full super-module at PS beam line



# TRD commissioning

2007-11

- **Connection and control of first installed super-modules**
  - from connection to powering on
- **Control and readout of detector in the cavern**
  - first readout with full DAQ chain
- **Noise measurements**
  - verification of modified power supplies




(a) Unmodified Wiener PL 512 (b) Ferrite modified PL 512

**TRD and TPC stations**

**Main control room**

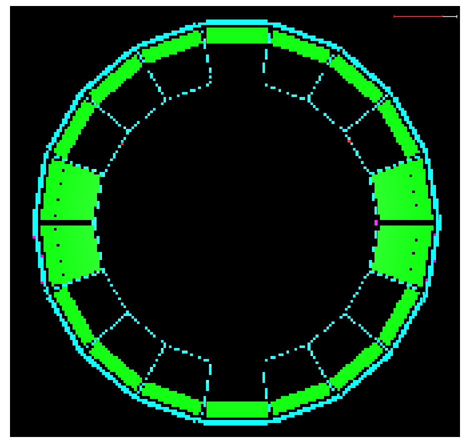
# Cosmic trigger

2008-07-23

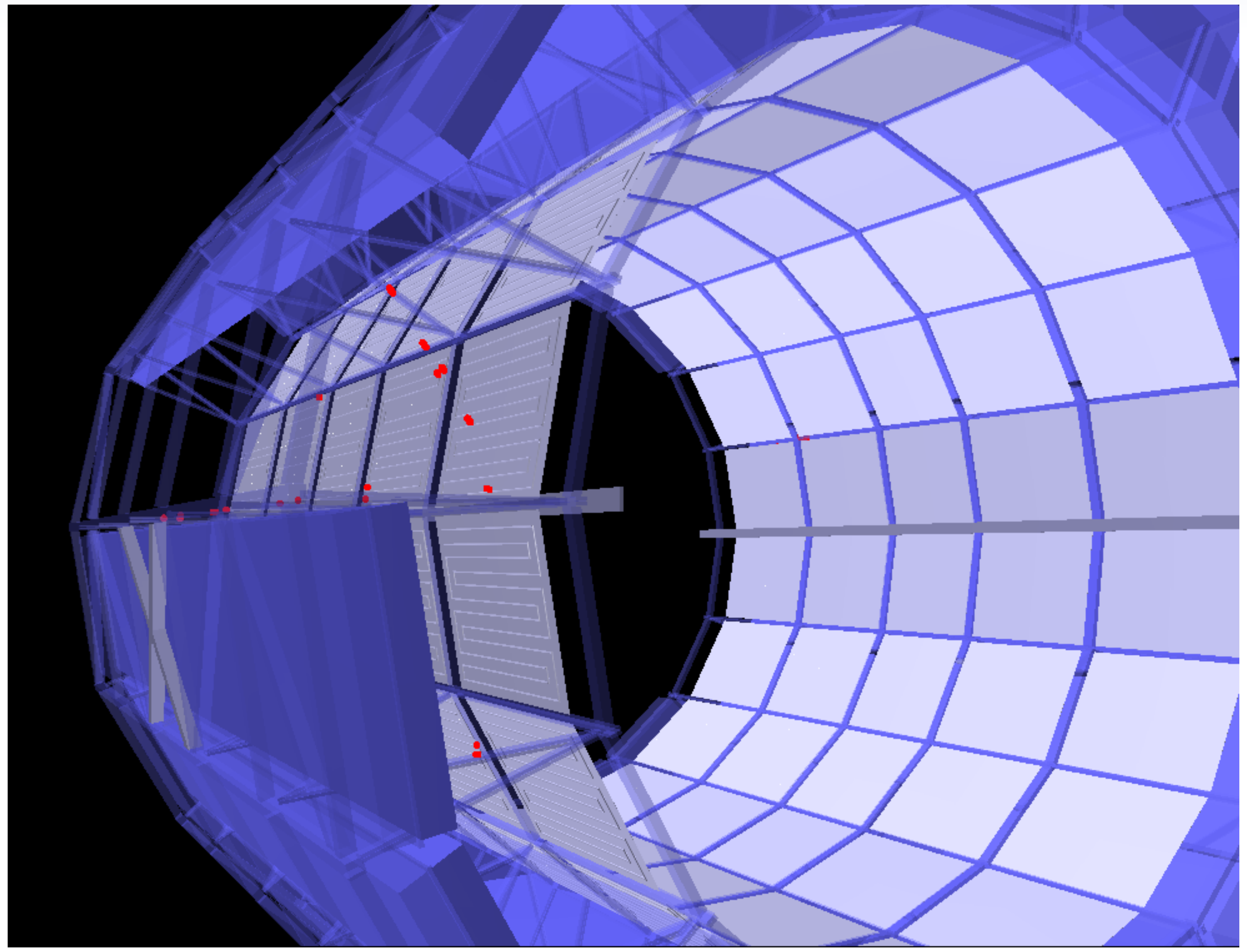
- Remember: LHC not yet running
  ➠ **cosmic rays only source of tracks**
  for calibration and reconstruction

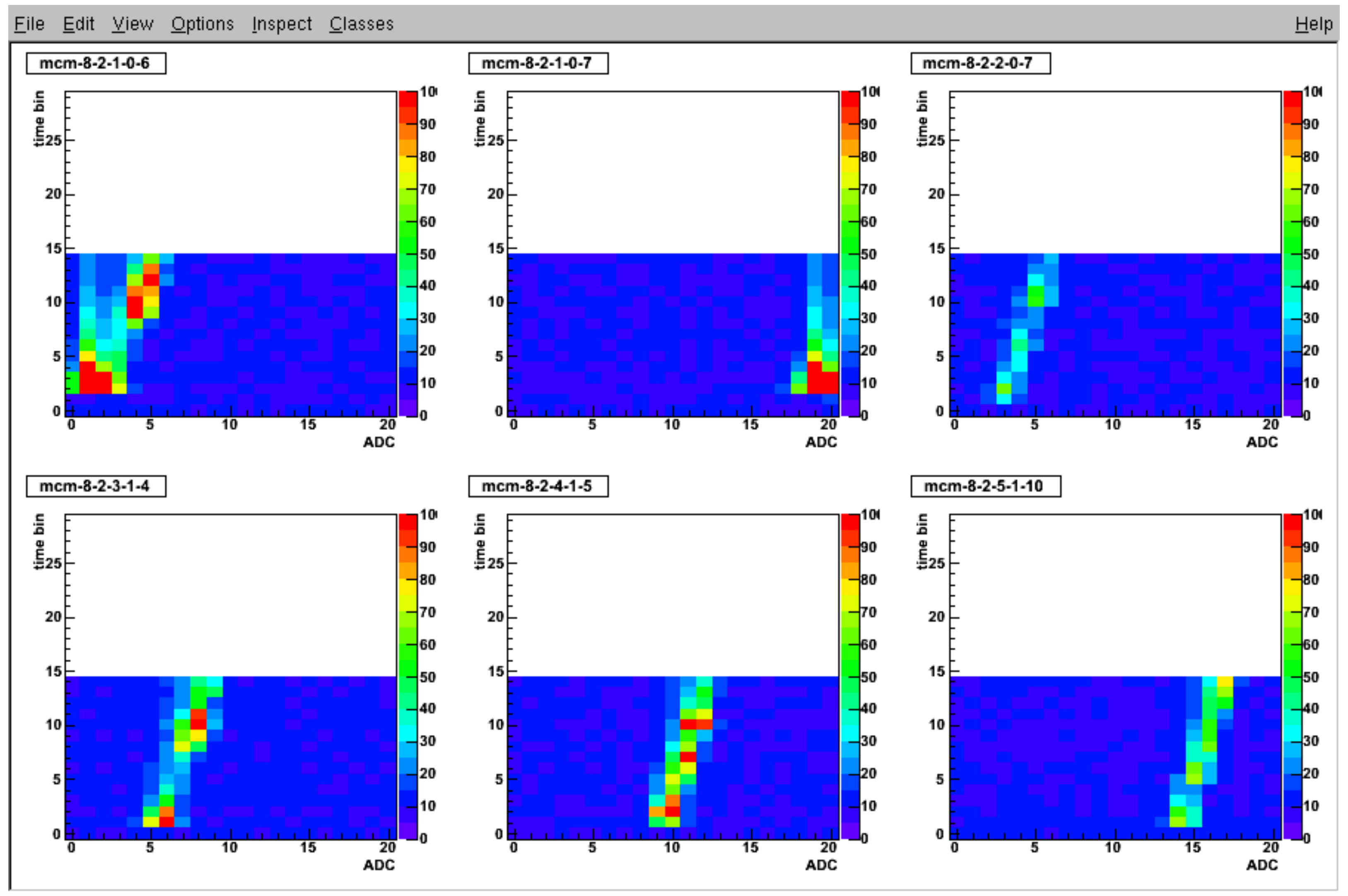
- **4 super-modules in horizontal configuration**
  ➠ very low rate for cosmic rays

- **TRD cosmic trigger** to provide clean sample
  - random pre-selection, later from TOF trigger
  - TRD chamber: charge above threshold
  - TRD stack: threshold exceeded ≥ 4 layers
  - TRD global: back-to-back configuration



Events from first night of triggering

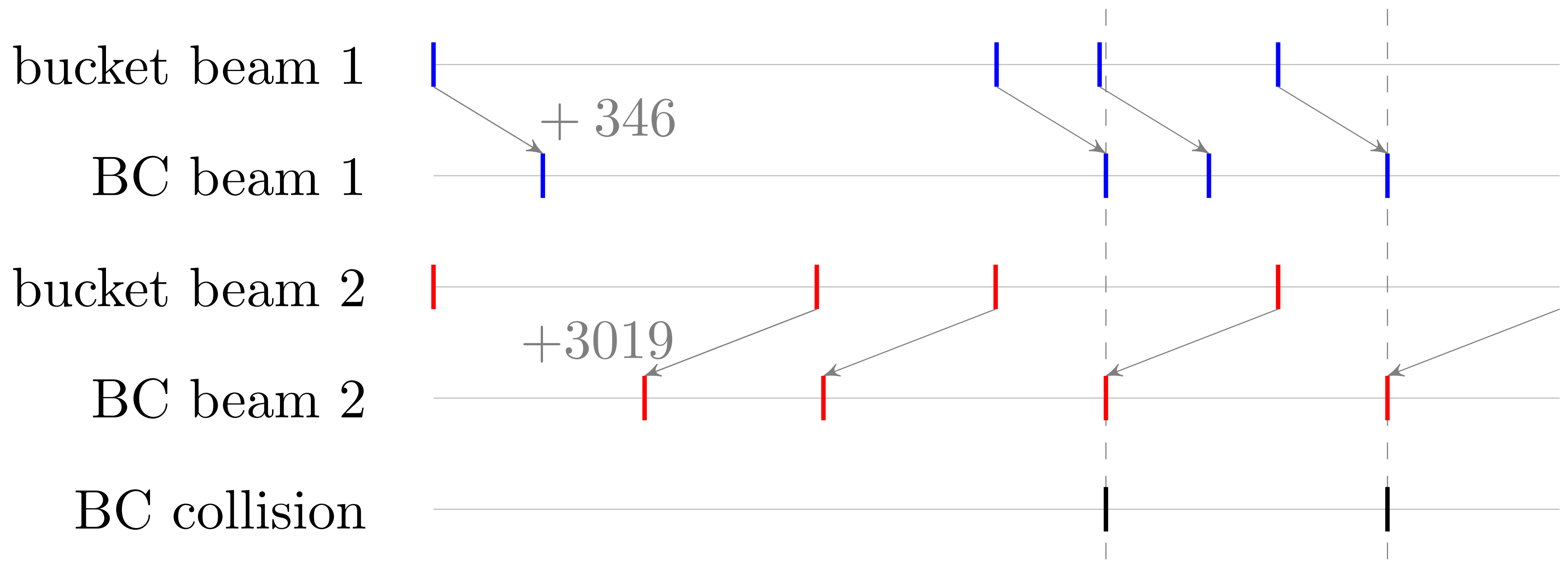




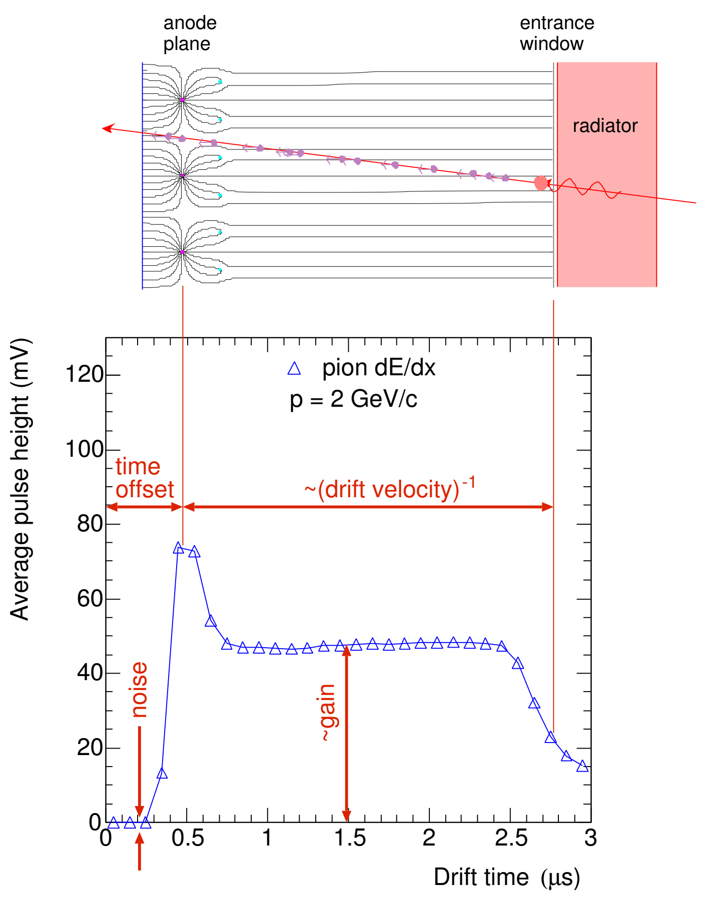
# First collisions

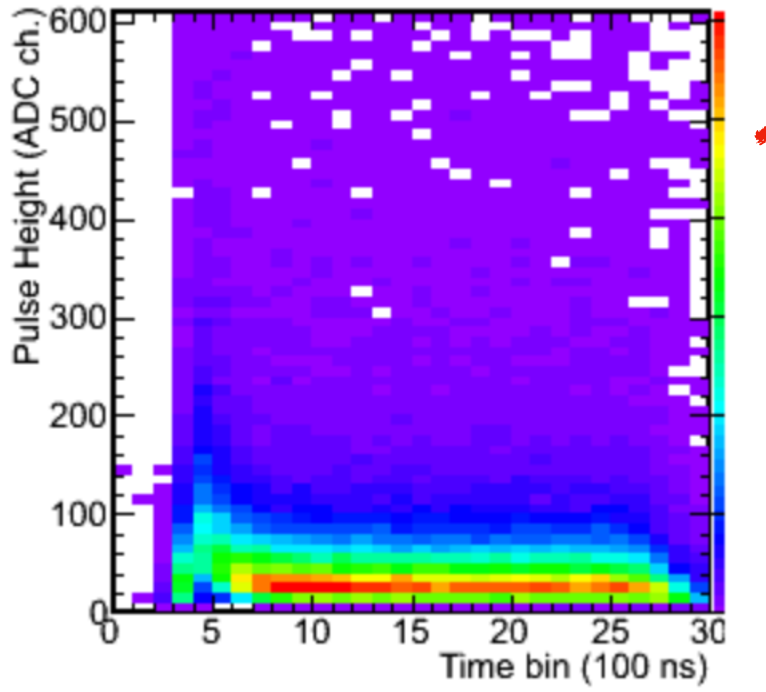
**2009-12-06**

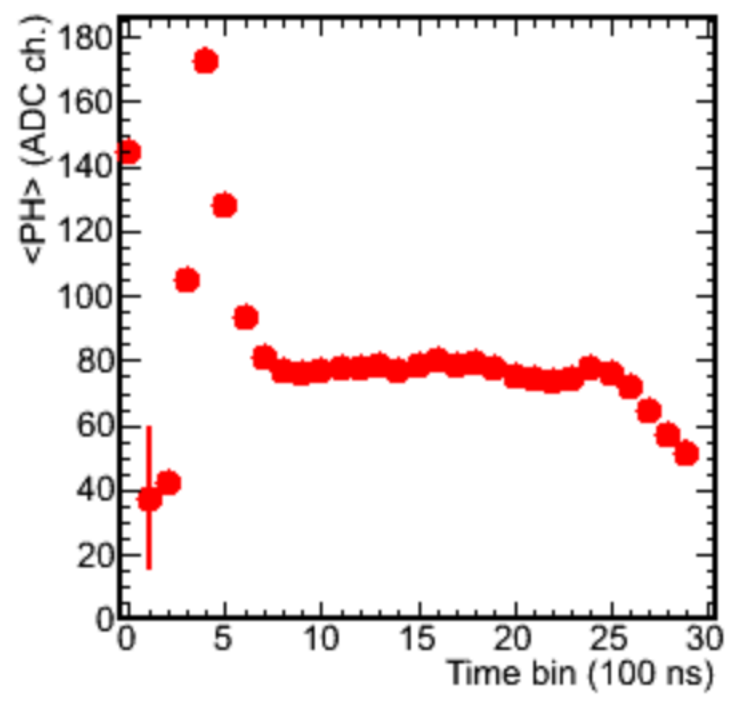
- **First stable beams in the LHC**
  ➟ first data taking with TRD
- **Dedicated pre-trigger**
  to wake up electronics
  based on LHC filling scheme

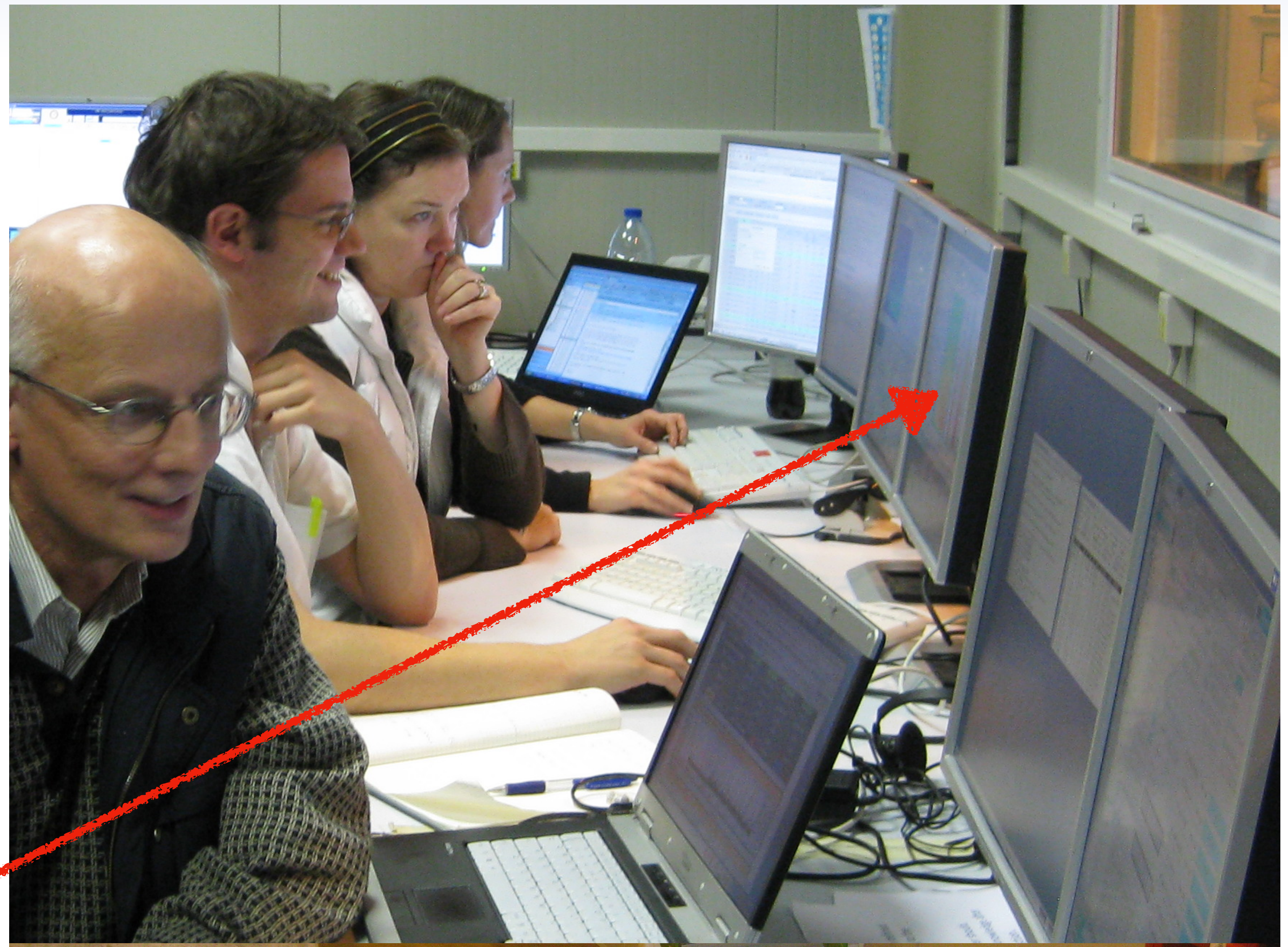



- **Confirmation of signals and timing**
  from pulse height plot
  (amplification peak)



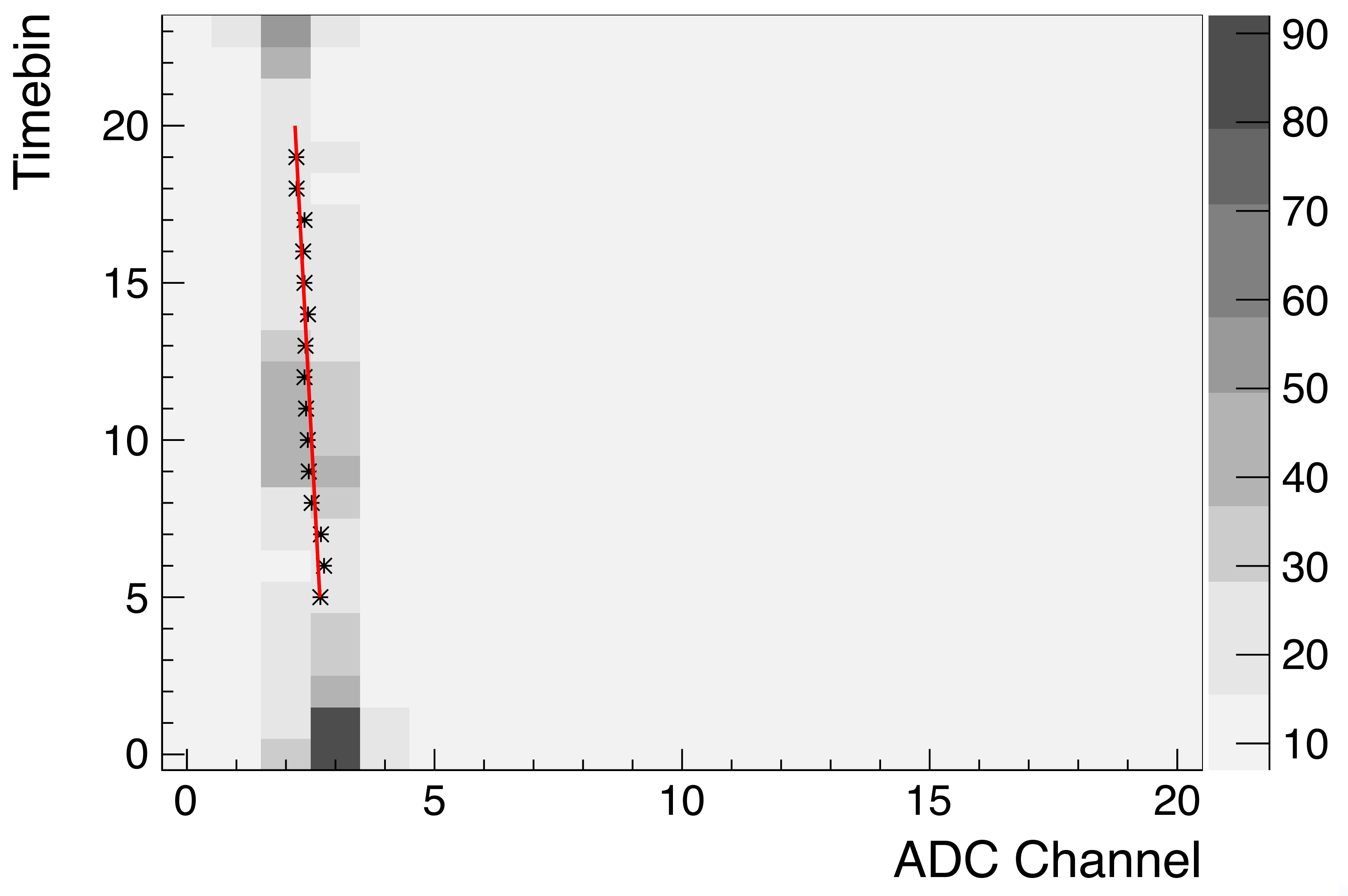



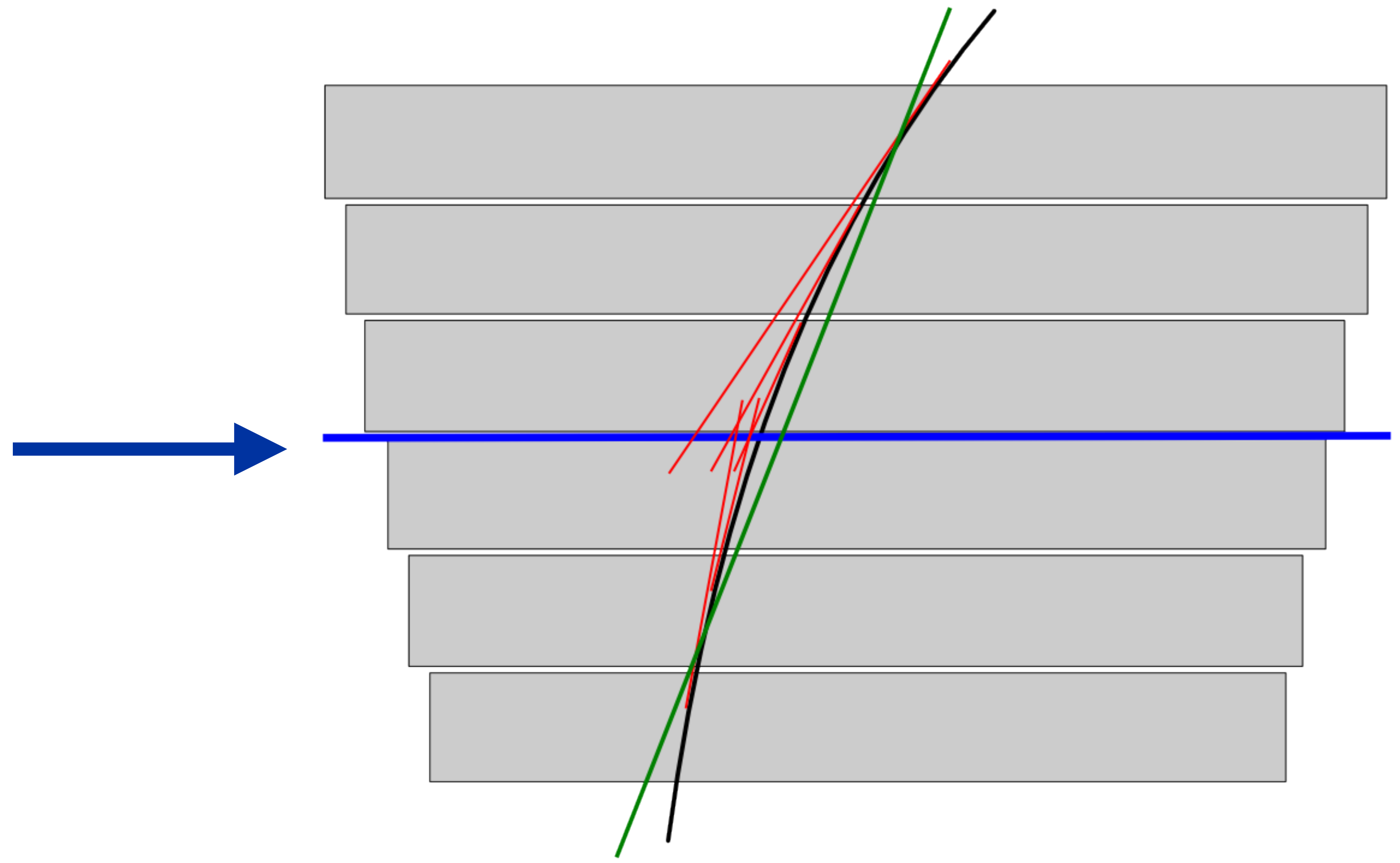
# Online tracking

- **Multi-stage approach to tracking** fully realised in hardware
  - chamber-wise reconstruction of **tracklets** (75k MCMs, 250k CPUs)
  - stack-wise reconstruction of **tracks** (90 FPGAs)
- **Hardware-based reconstruction** of track parameters
  - position
  - transverse momentum (incl. sign)
  - electron likelihood

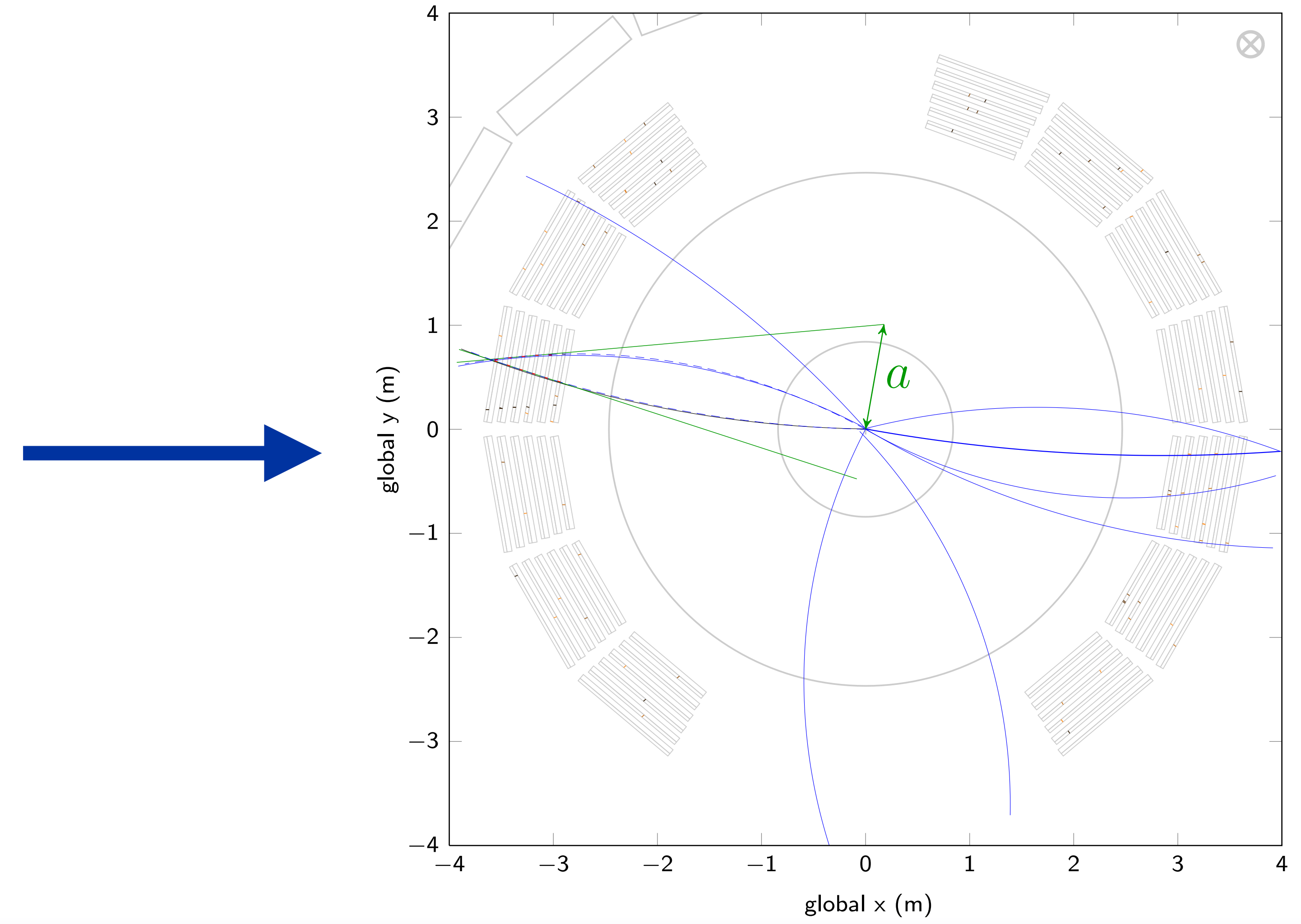
**Tracklets**




**Tracks**

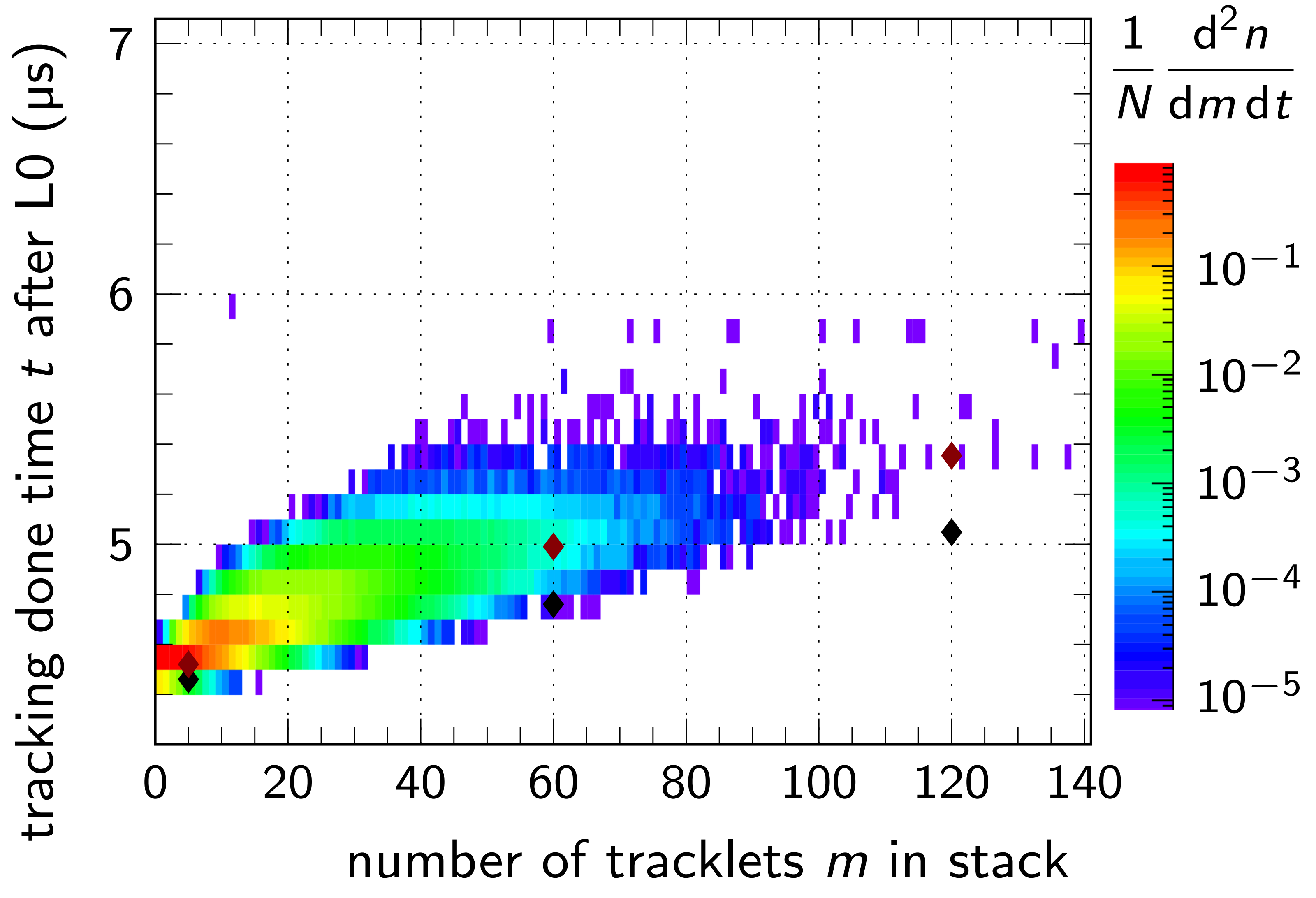


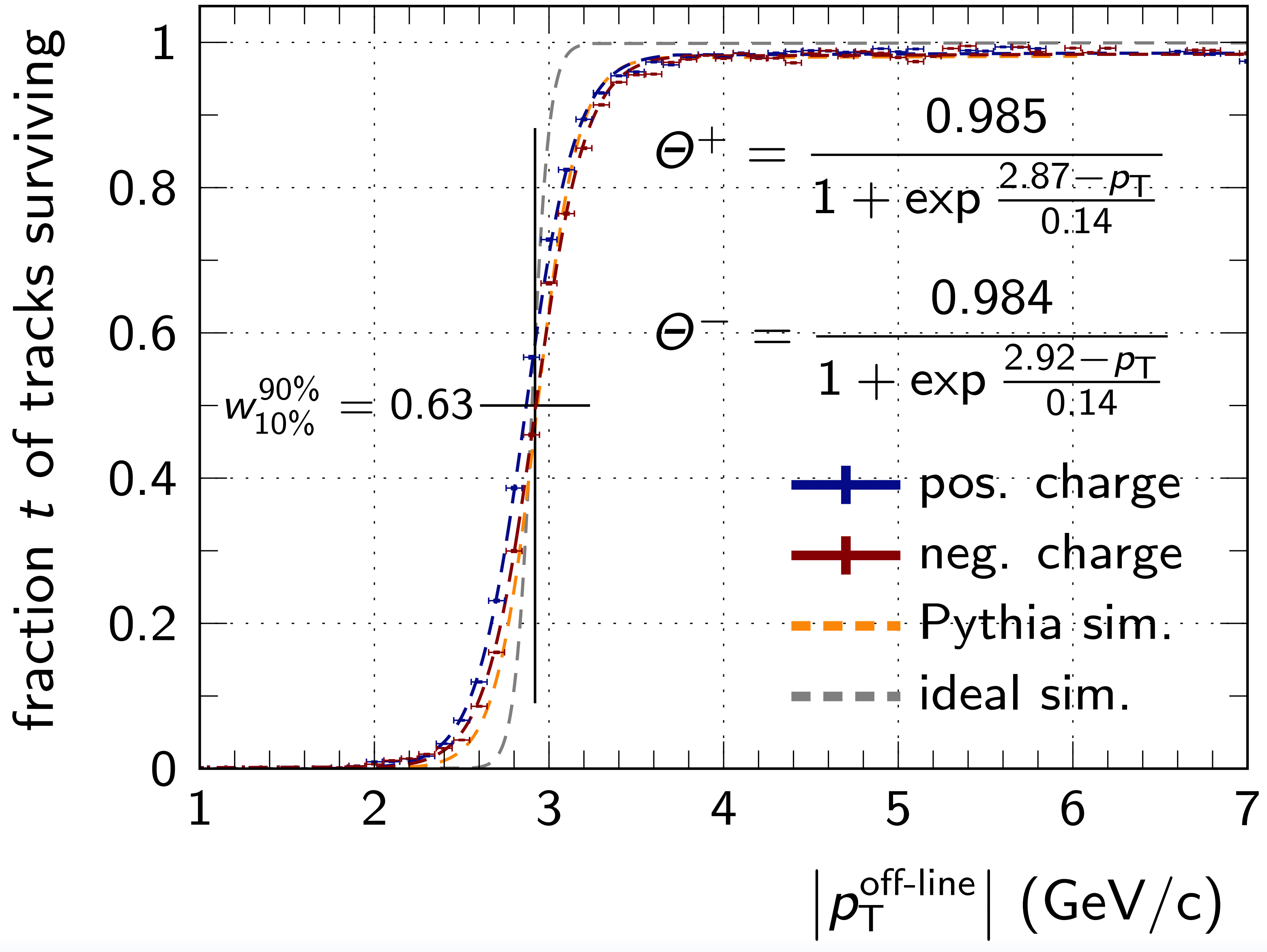
**Global view**



# Track-based triggers

- **Online tracking complete within ~6 μs** (latency!) up to large multiplicities
- **Fast $p_T$ reconstruction sufficiently precise** for $p_T$ thresholds at trigger level
- **Level-1 triggers based track parameters** fully reconstructed in hardware
  - (local) multiplicity
  - transverse momentum
  - charge sign
  - electron likelihood



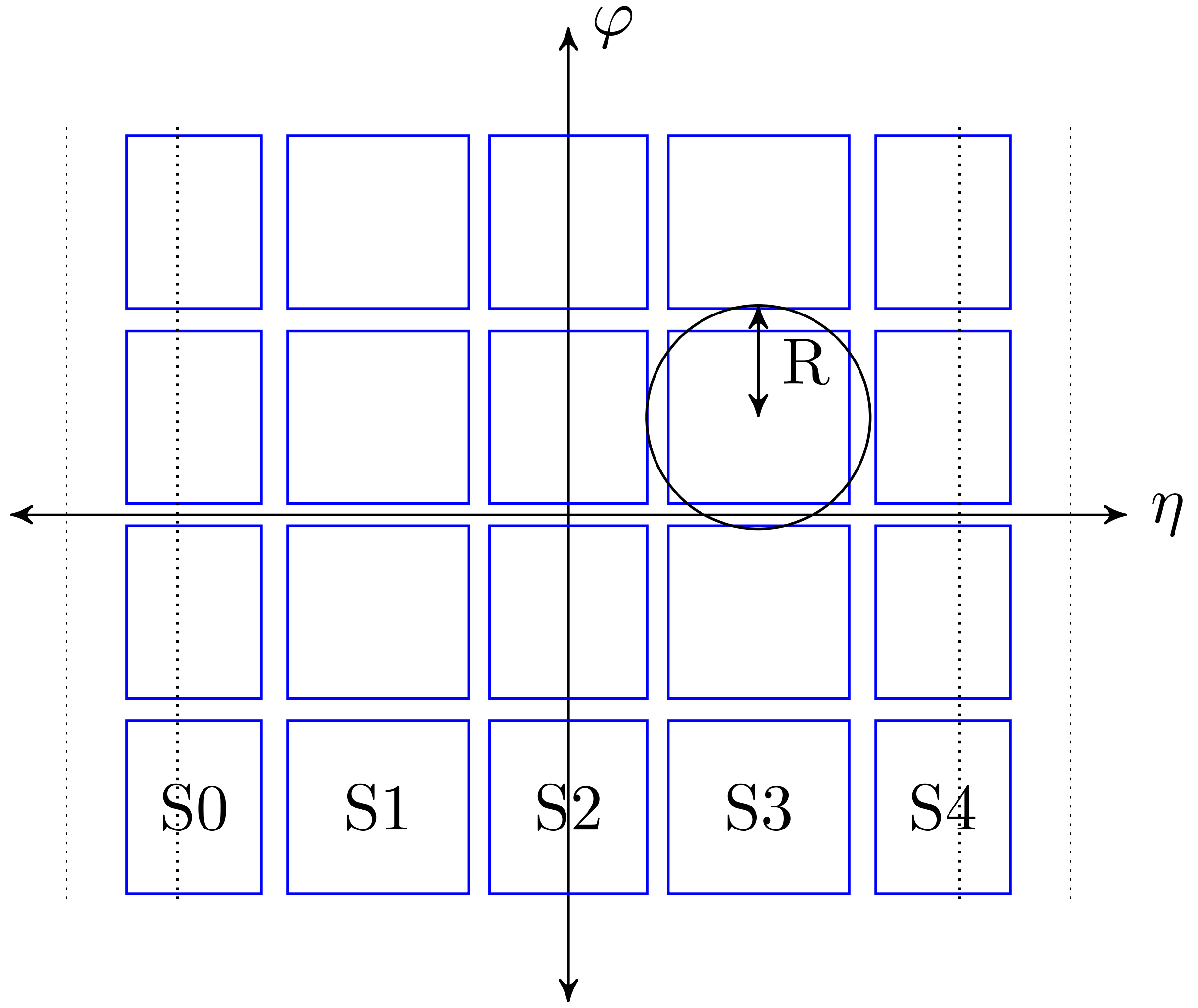



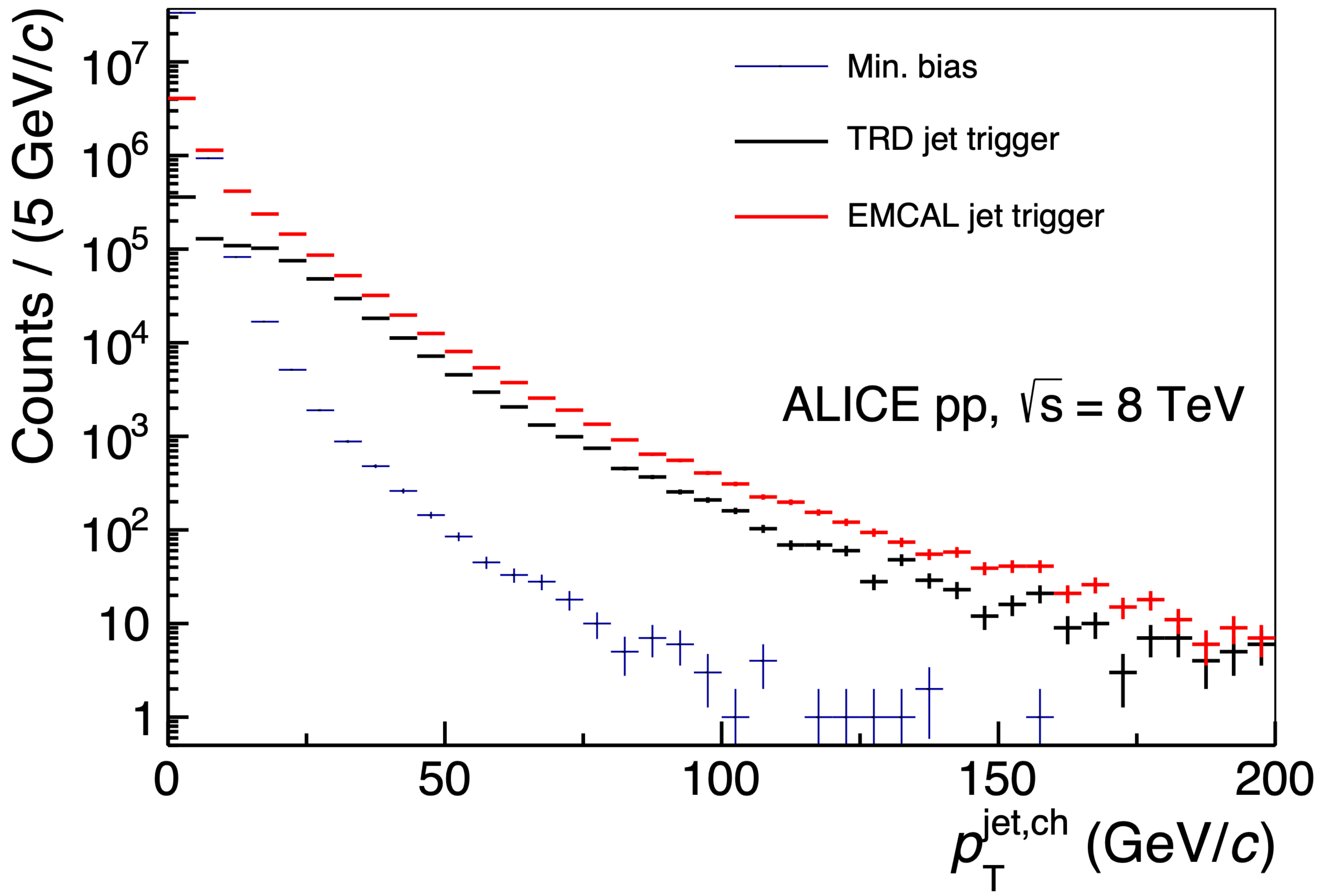
# Jet trigger

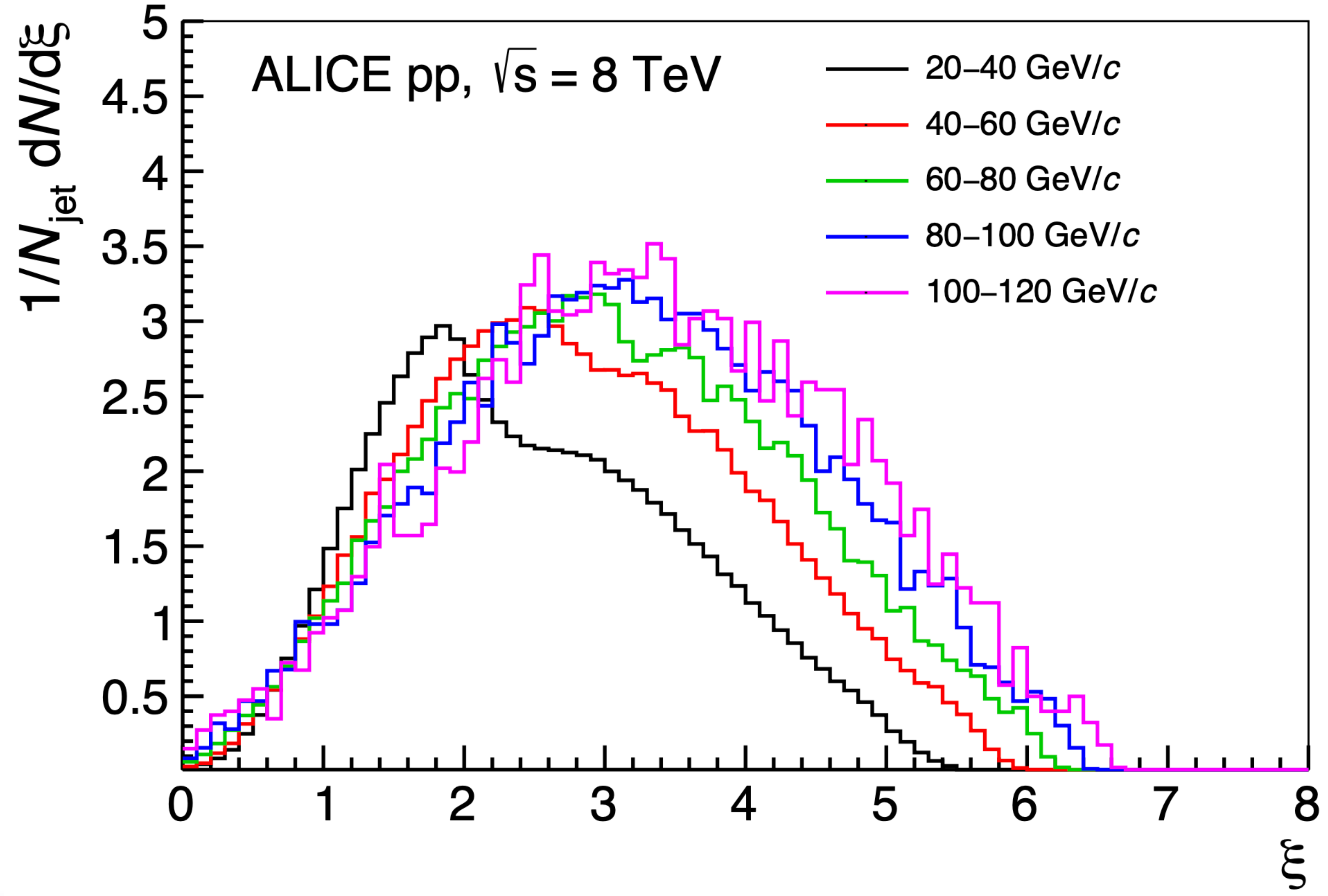
**2012**

- Consider $\eta$-$\varphi$ region of TRD stack
  → **area of typical jet cone** (R ≈ 0.4)
- Minimum number of tracks above $p_T$ threshold
  → **jet trigger**
  - enhancement of data sample
  - limited bias on fragmentation

**TRD geometry in $\eta$-$\varphi$ plane**



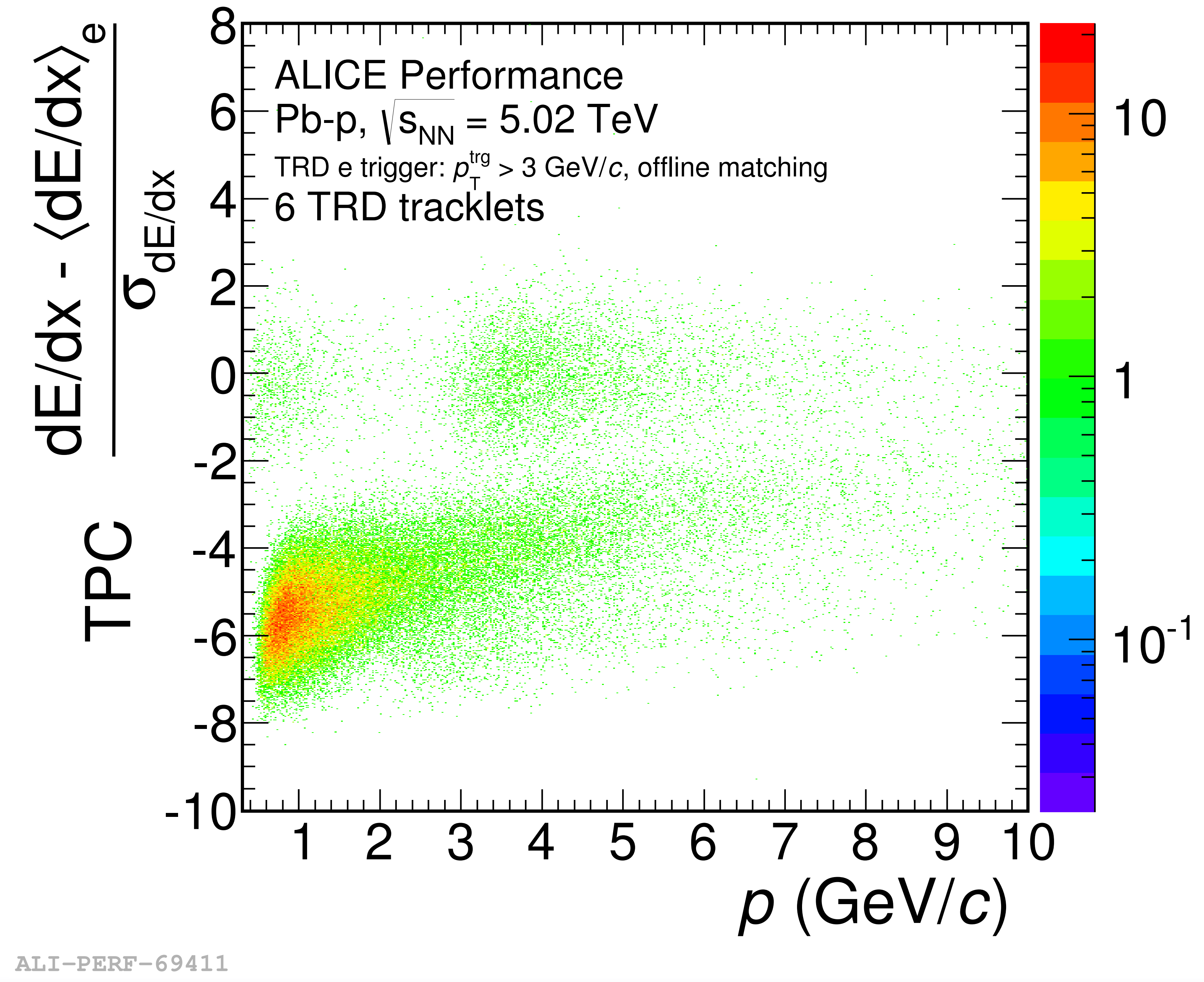



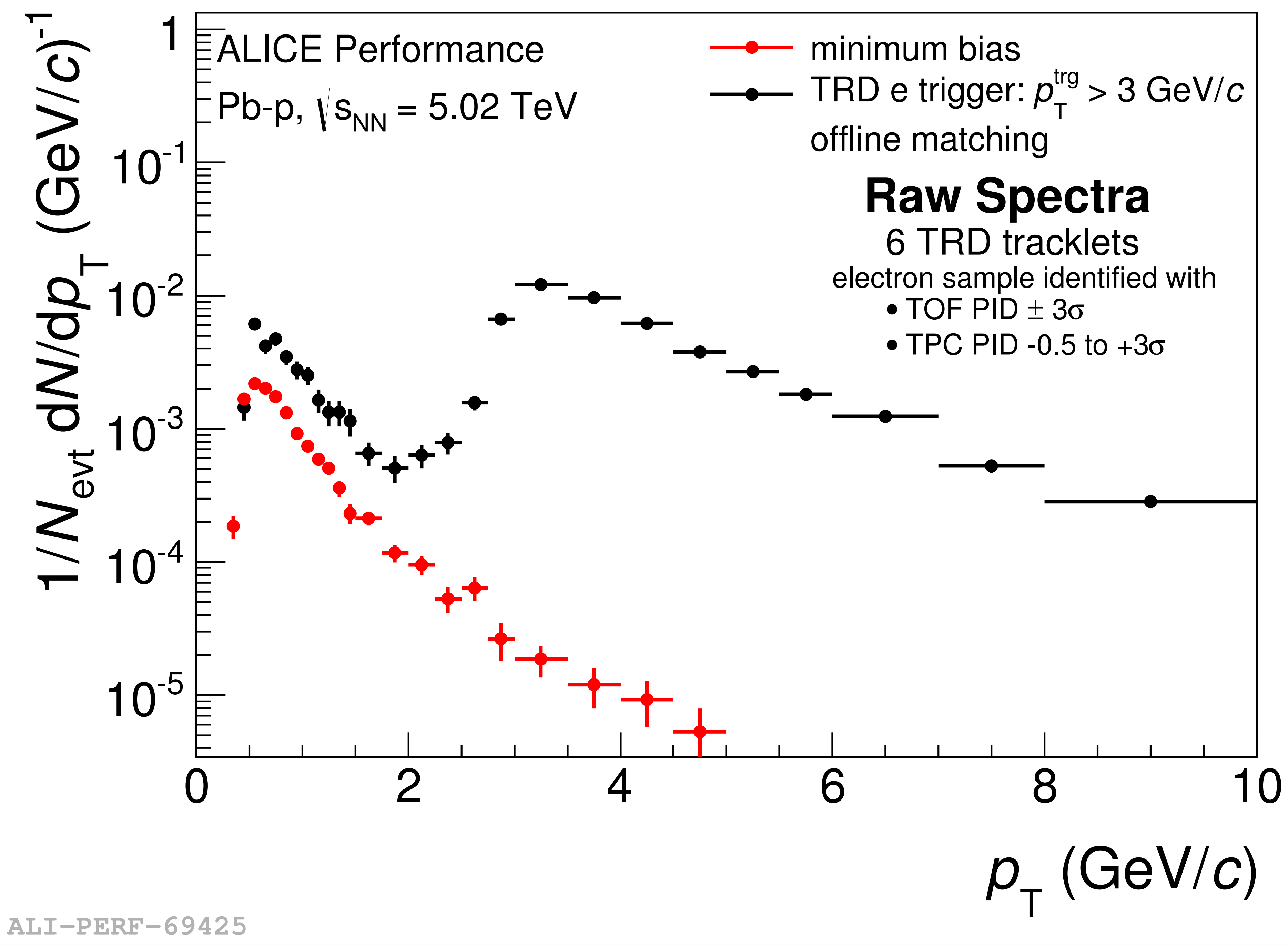
# Electron trigger

2012

- **Heavy-flavour hadrons, incl. J/ψ**, decay into electrons

- Selection of tracks with minimum $p_T$ and electron likelihood
  → **(di-)electron trigger**
  - separate optimisations for electrons from **semi-leptonic heavy-flavour** and **J/ψ** decays

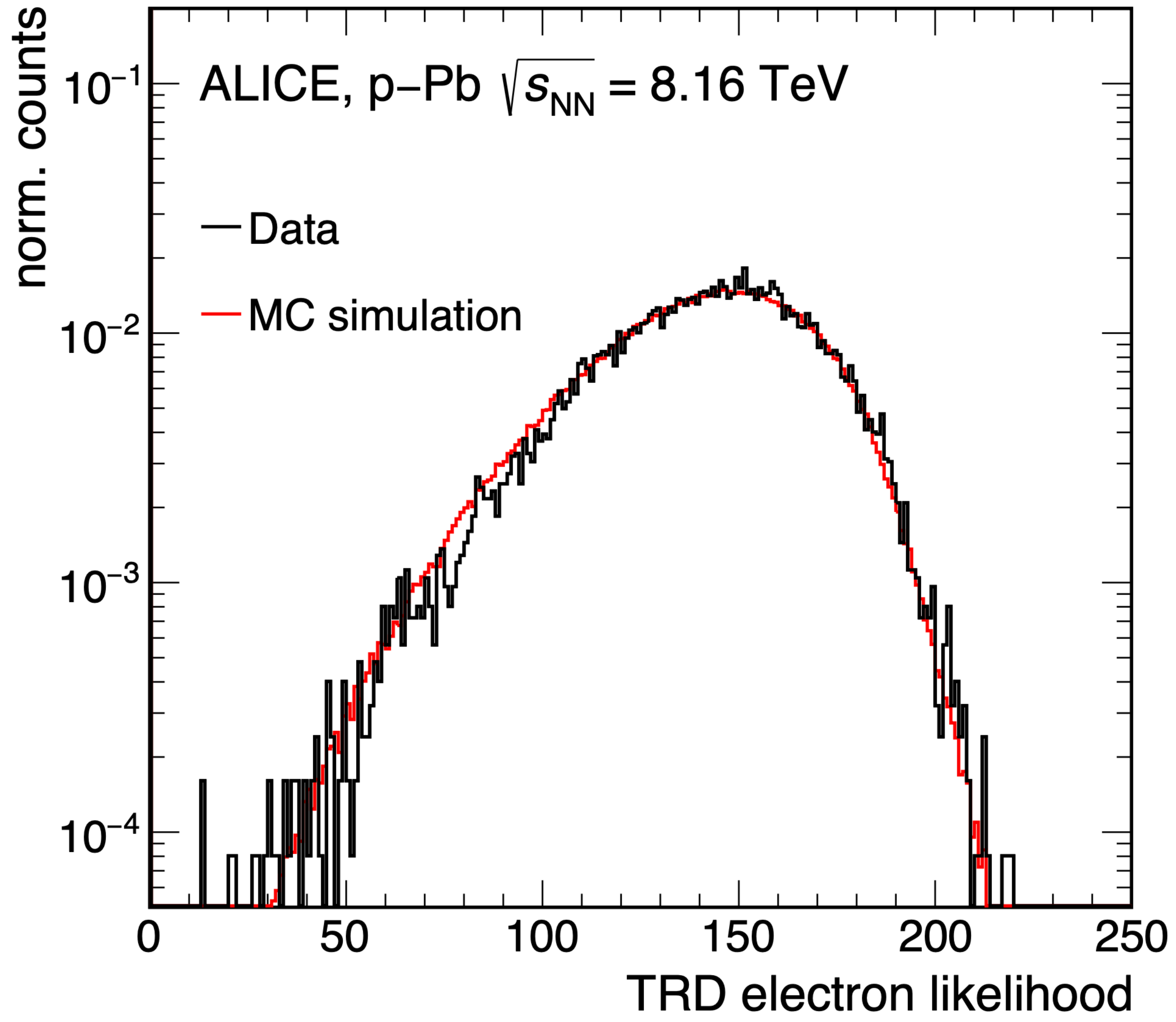


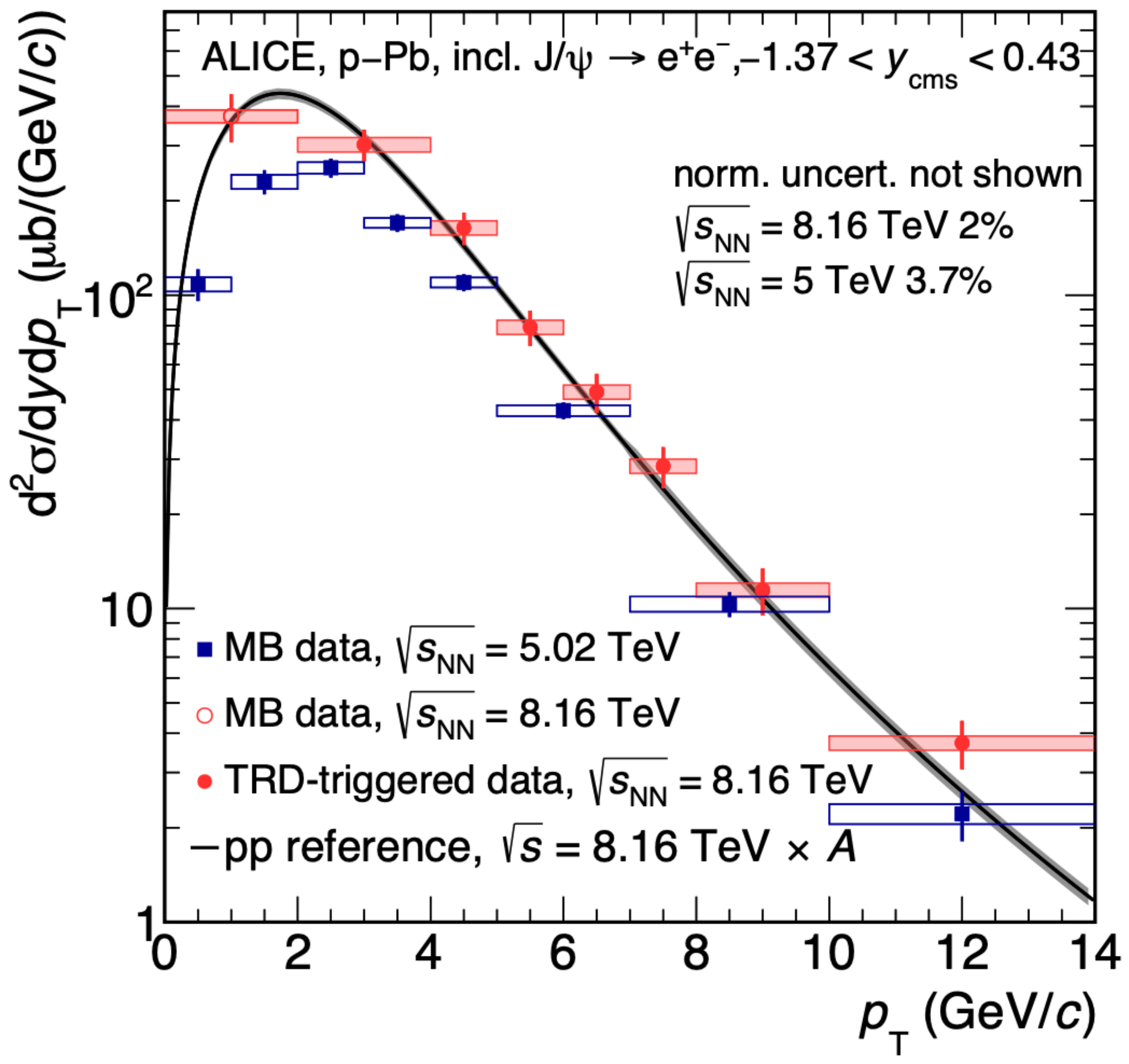



# J/ψ with TRD trigger

**2016**

- **TRD electron trigger enabled measured of J/ψ production** in p-Pb collisions at $\sqrt{s_N N} = 8.16$ TeV
  - little bandwidth allocated to min. bias sample
  - exploited precise (bit-equivalent) simulation of trigger chain for corrections



# Drop read-out of ADC data

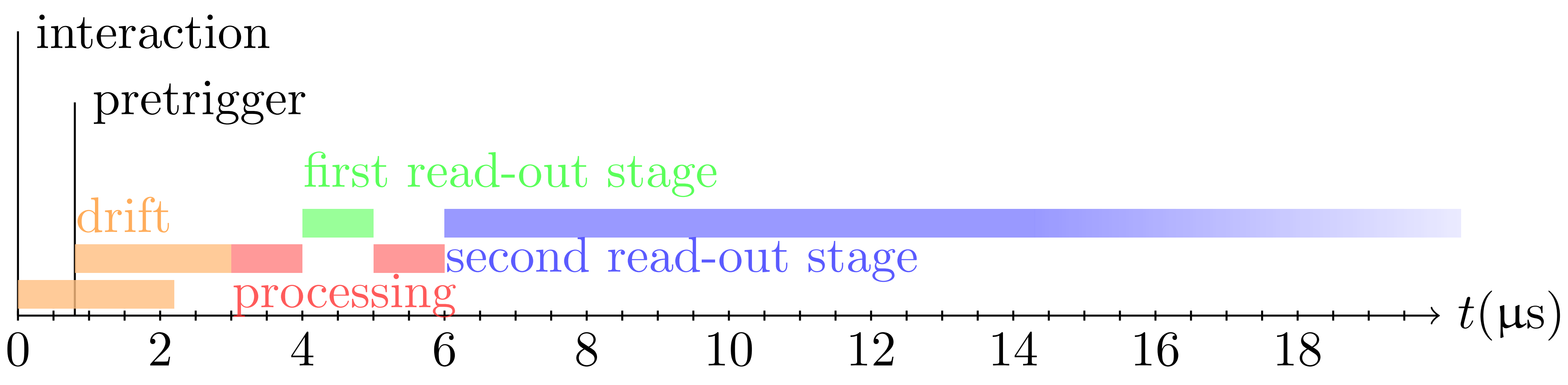
**2014 (default mode in Run 3)**

- **TRD read-out separated in two phases**
  - fast read-out of trigger data (tracklets)
    → ~6 μs
  - slow read-out of raw data (zero-suppressed ADC data)
    → ~8 μs hand-shaking + data transmission

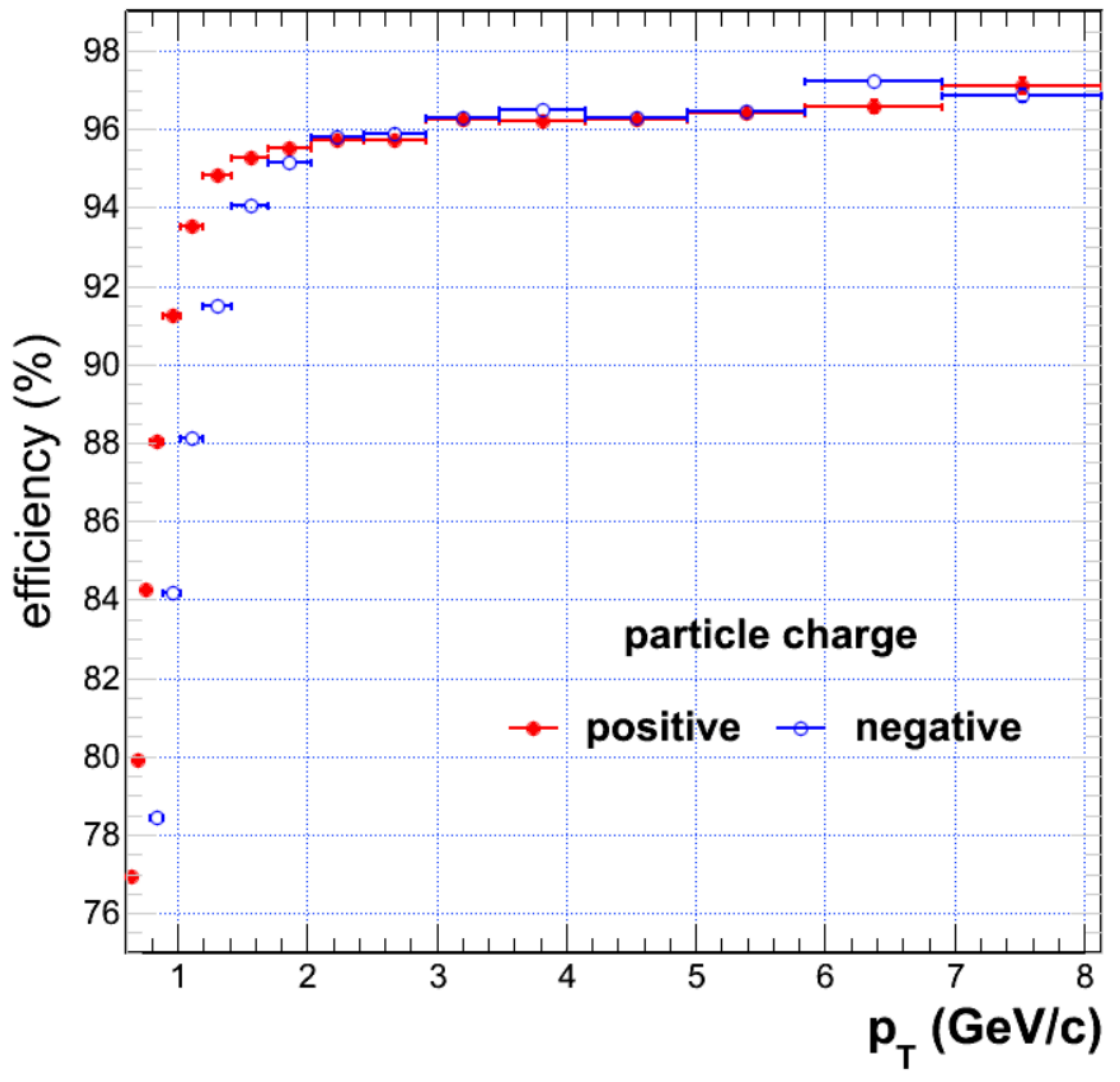
- **Operation beyond few kHz** relies on
  ➟ avoiding read-out raw data
  ➟ limiting data volume
  ➟ **reading out tracklets only**

- **Readout upgrade for LHC Run 3**
  - new tracklet format optimised for reconstruction
  - transition to common read-out card
    (instead of global tracking unit used for triggering)

**Read-out timing**




**Tracking efficiency (online / offline)**



# ALICE 2 (current)

- High interaction rate:
  50 kHz Pb-Pb, 1 MHz pp
  → **limit ion backflow in TPC without gating!**

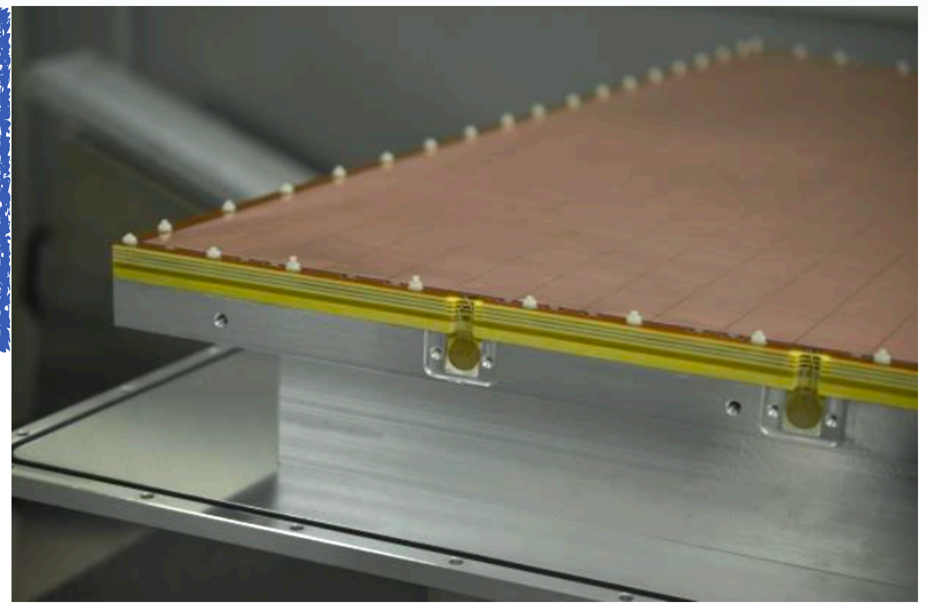
- Reconstruction of
  heavy-flavour decay vertices
  → **improve pointing resolution**

- Large statistics of untriggerable probes
  → **continuous readout**

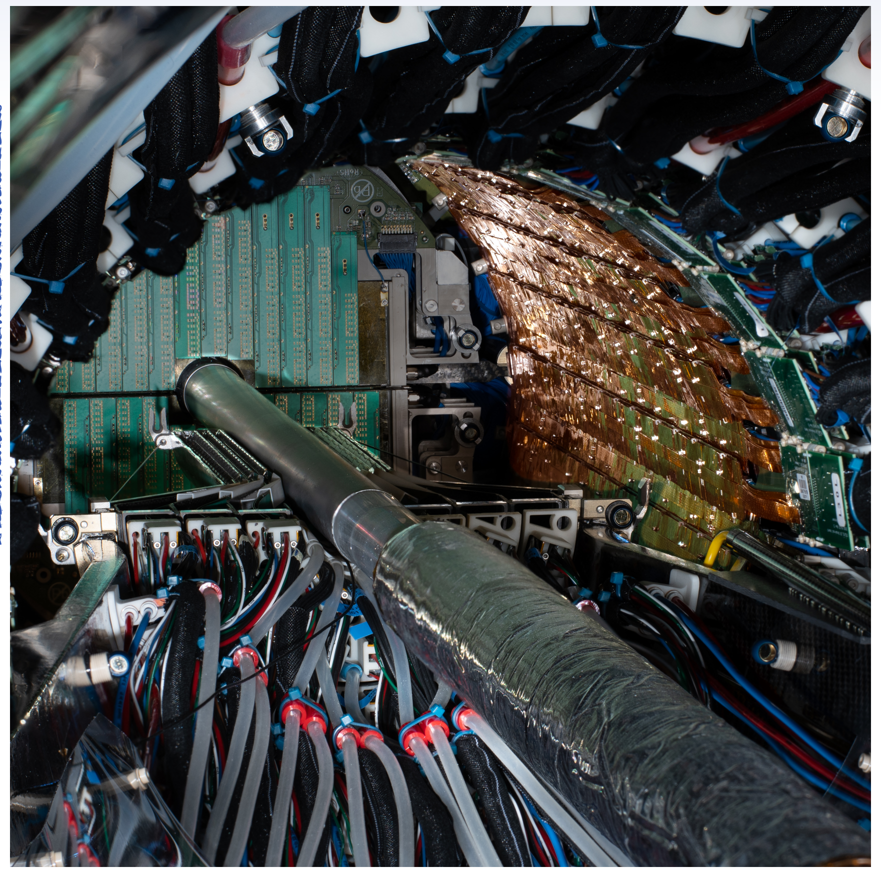
- Data reduction based on tracking
  → **online reconstruction**

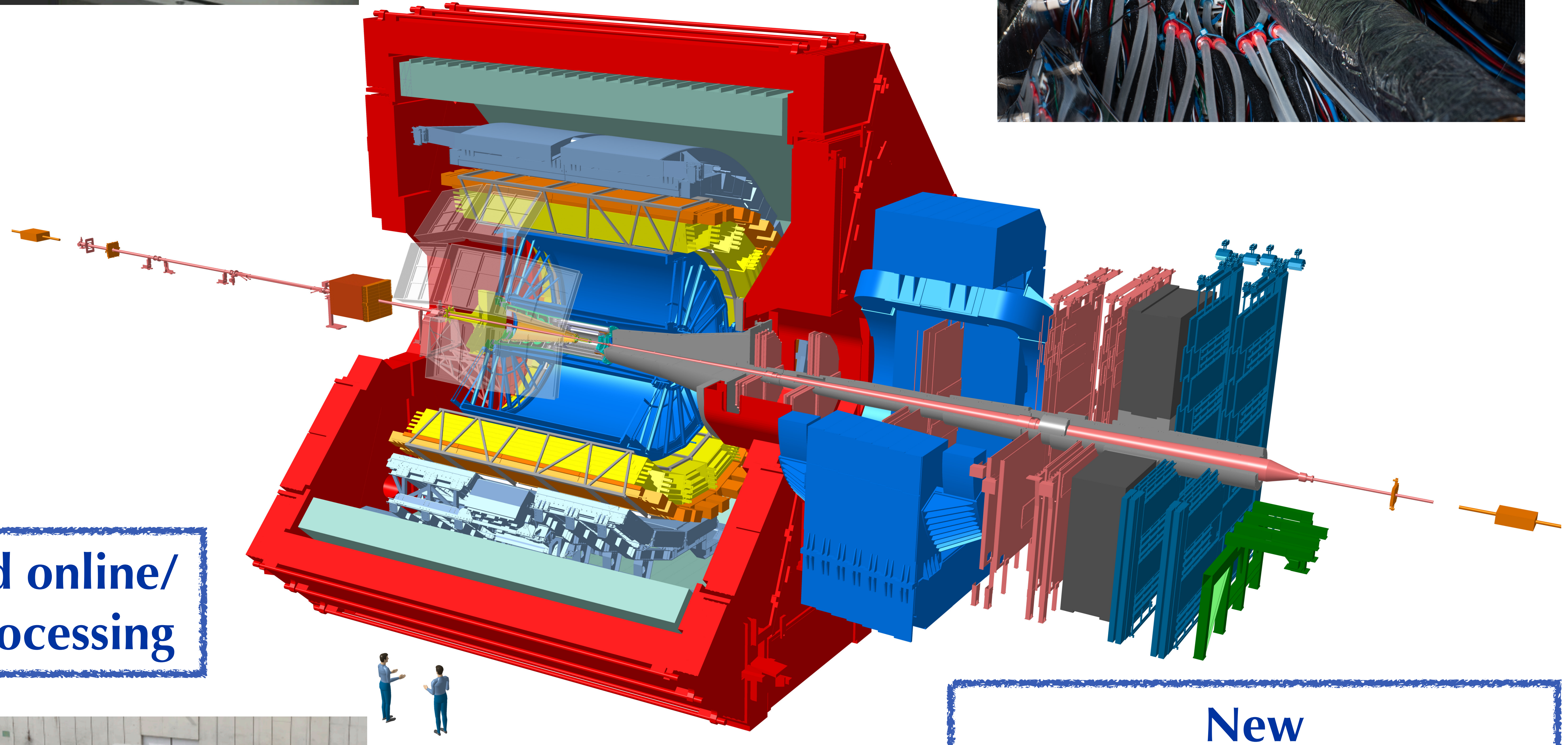
**Consolidation and readout upgrade of all subsystems**

**GEM-based Time Projection Chamber**



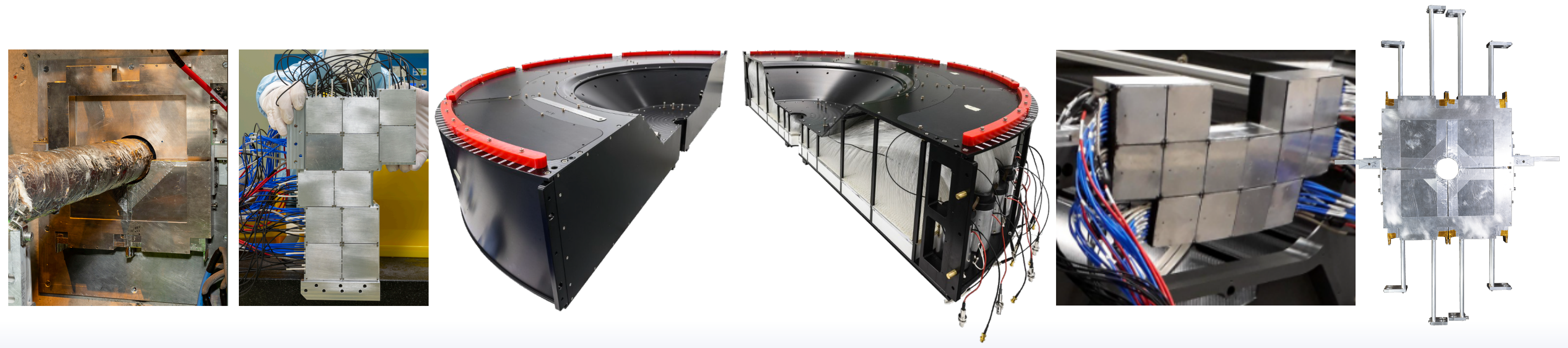
**MAPS-based Inner Tracking System and Muon Forward Tracker**





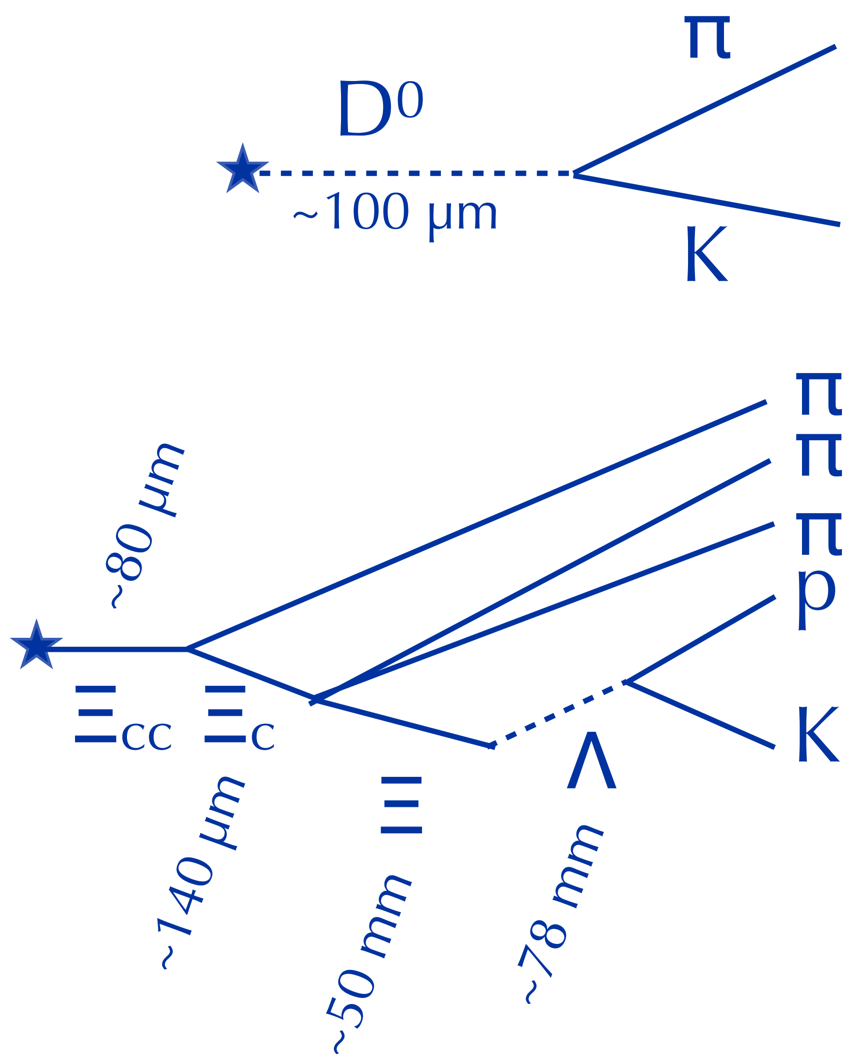
**Integrated online/ offline processing**

**New Fast Interaction Trigger**



# Pushing beyond ALICE 2

- **(Multi-)heavy-flavoured probes**
  - ➡ modified parton shower
  - ➡ transport properties
  - ➡ hadronisation
- **Dielectrons down to low mass**
  - ➡ temperature and early stage
  - ➡ chiral symmetry restoration
- **Correlations and fluctuations**
  - ➡ net-baryon fluctuations
  - ➡ transport properties
  - ➡ strong interaction potentials




Background from heavy-flavour decays
$c\bar{c} \rightarrow D\bar{D} \rightarrow e^+ e^- \ldots$

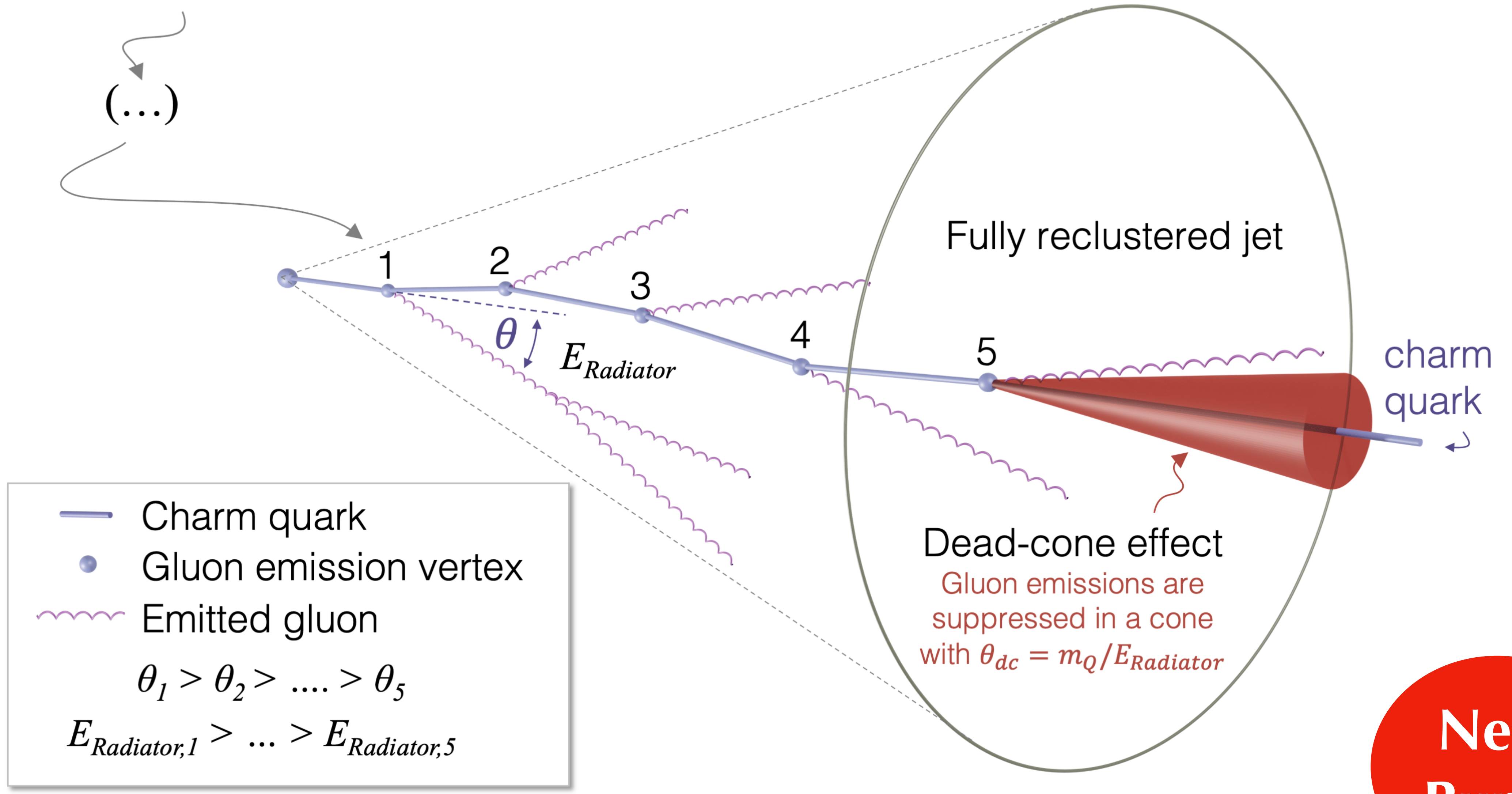
**Key ingredients**

- Excellent pointing resolution
- Tracking down to $p_T \approx 0$
- Excellent particle identification
- Large acceptance
- High rates for large data samples

**Progress relies on detector performance and statistics**

# Heavy-flavour jets

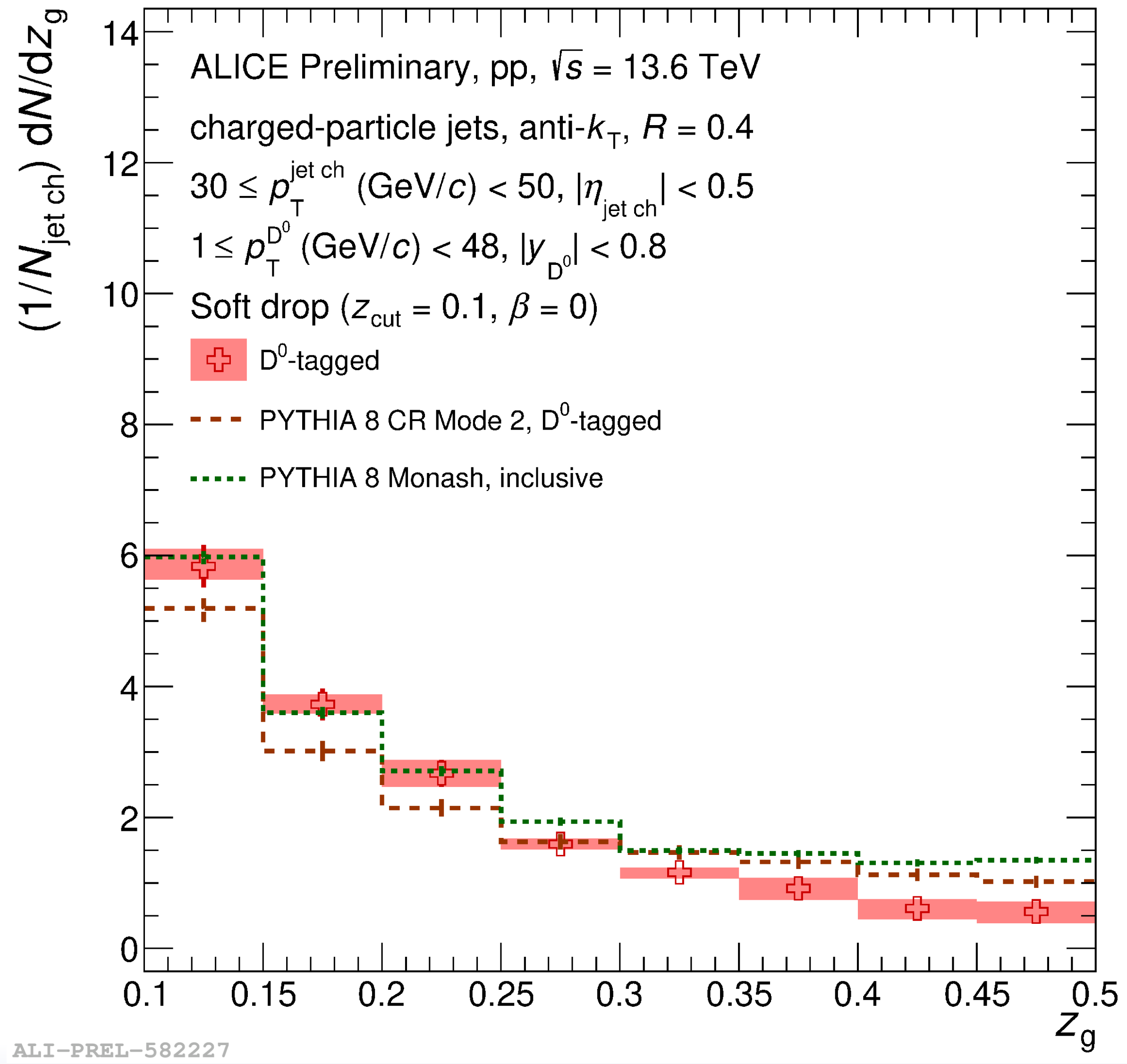
- **Evolution of high-energy partons** described by **QCD parton shower** → radiation/splittings depend on
  - colour factors (gluon vs quark)
  - mass (charm and beauty)
  - interactions with QGP



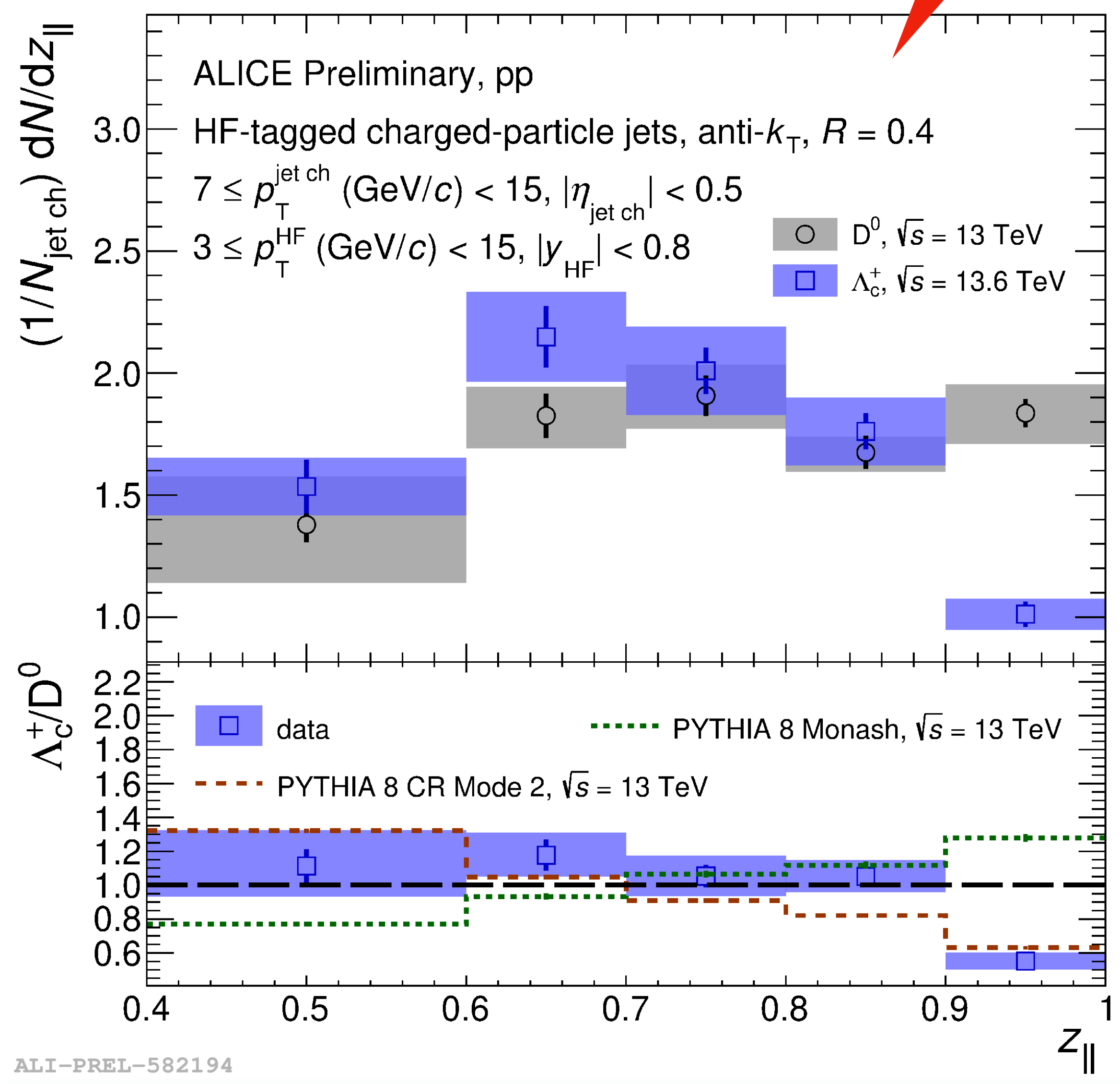

[Nature 605 (2022) 7910, 440-446]

- Programme
  - **characterisation of jet radiation**, e.g. dead cone effect (charm & beauty)
  - **modification of jet substructure**

**Excellent prospects already with Run 3 and 4**




**New Run 3**



# Strangeness tracking

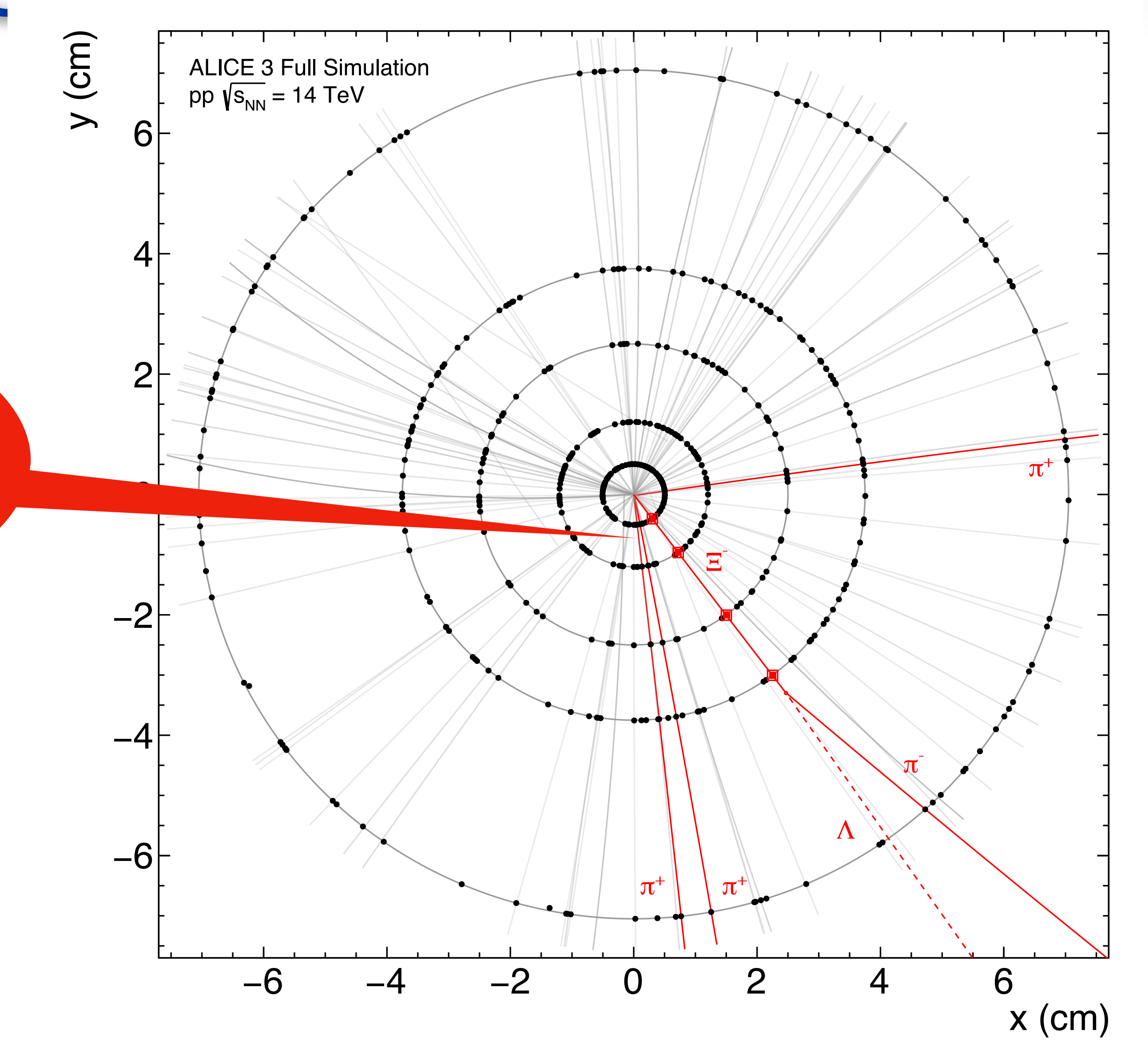
- **Challenging probes with strange decays**
  - rare with large background
  - limited pointing resolution for vertexing

- **Strangeness tracking** before decay
  → improved pointing resolution

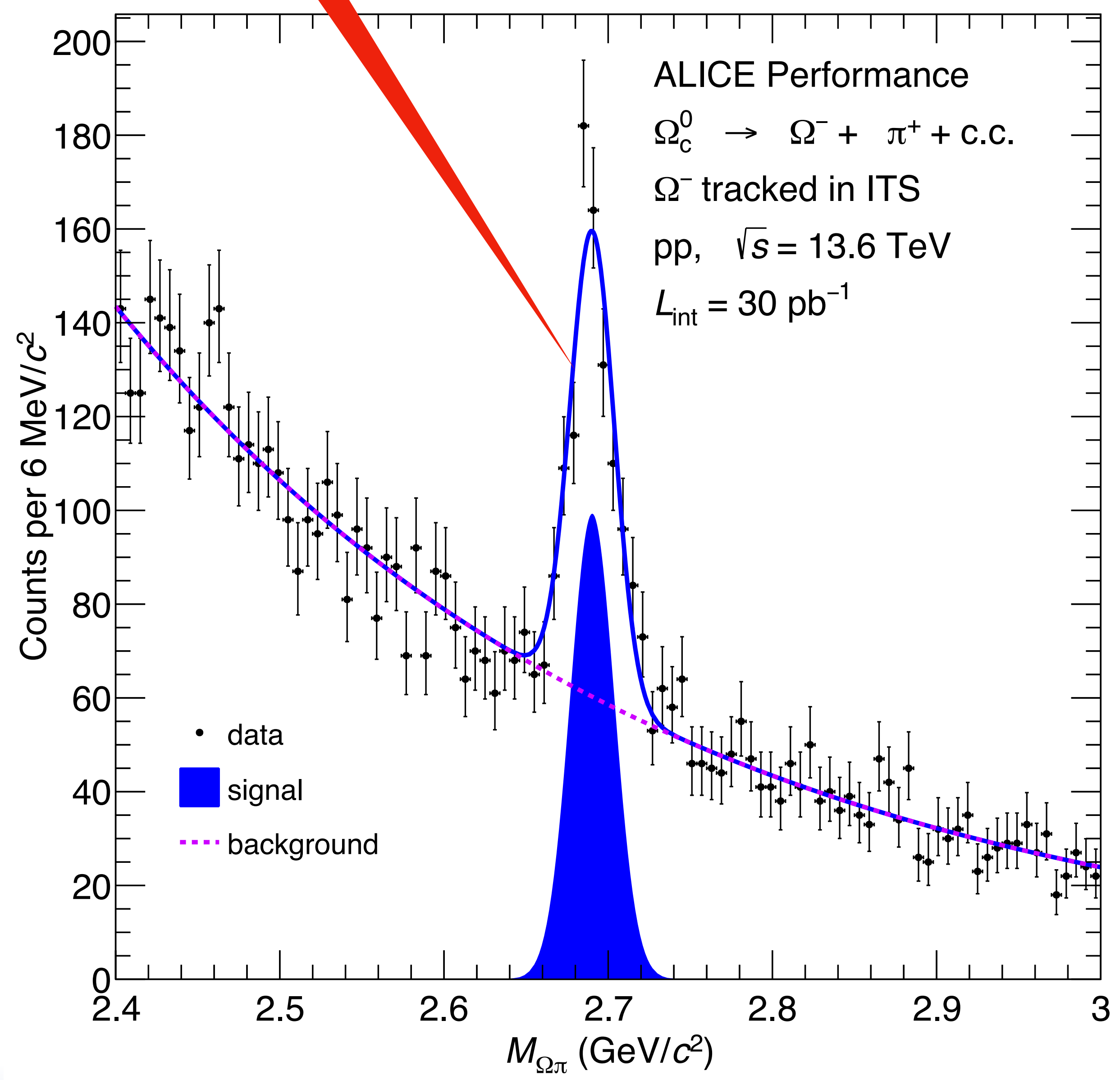
- Programme
  - $\Omega_c \rightarrow \Omega$, hypertriton (Run 3 & 4)
  - $\Xi_{cc}$, $\Omega_{cc}$, $\Omega_{ccc}$ (Run 5 & 6)

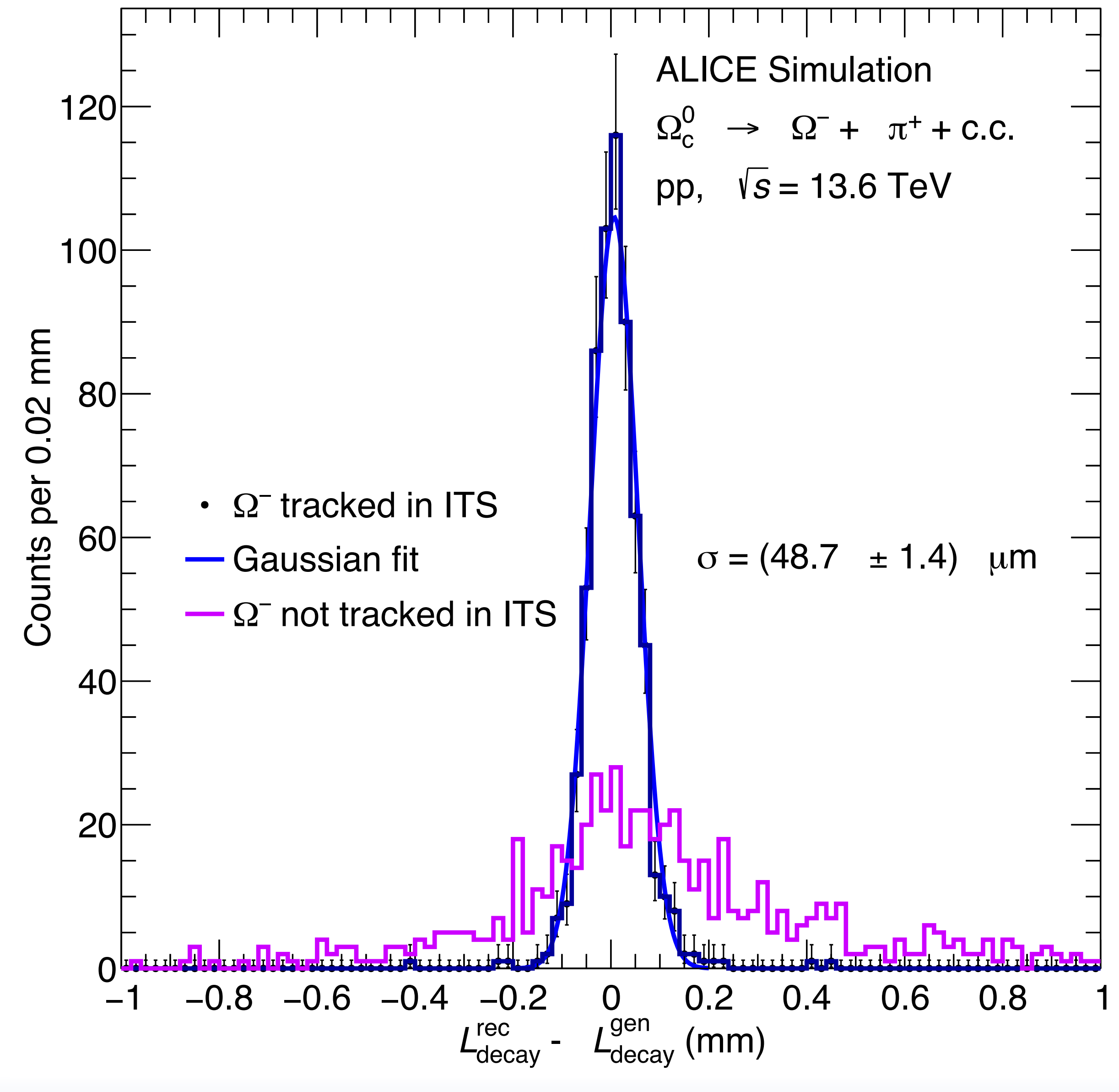
**Novel technique for Run 3 and beyond**

**Only possible in Run 3 with ITS2!**




**~600 $\Omega_c$**



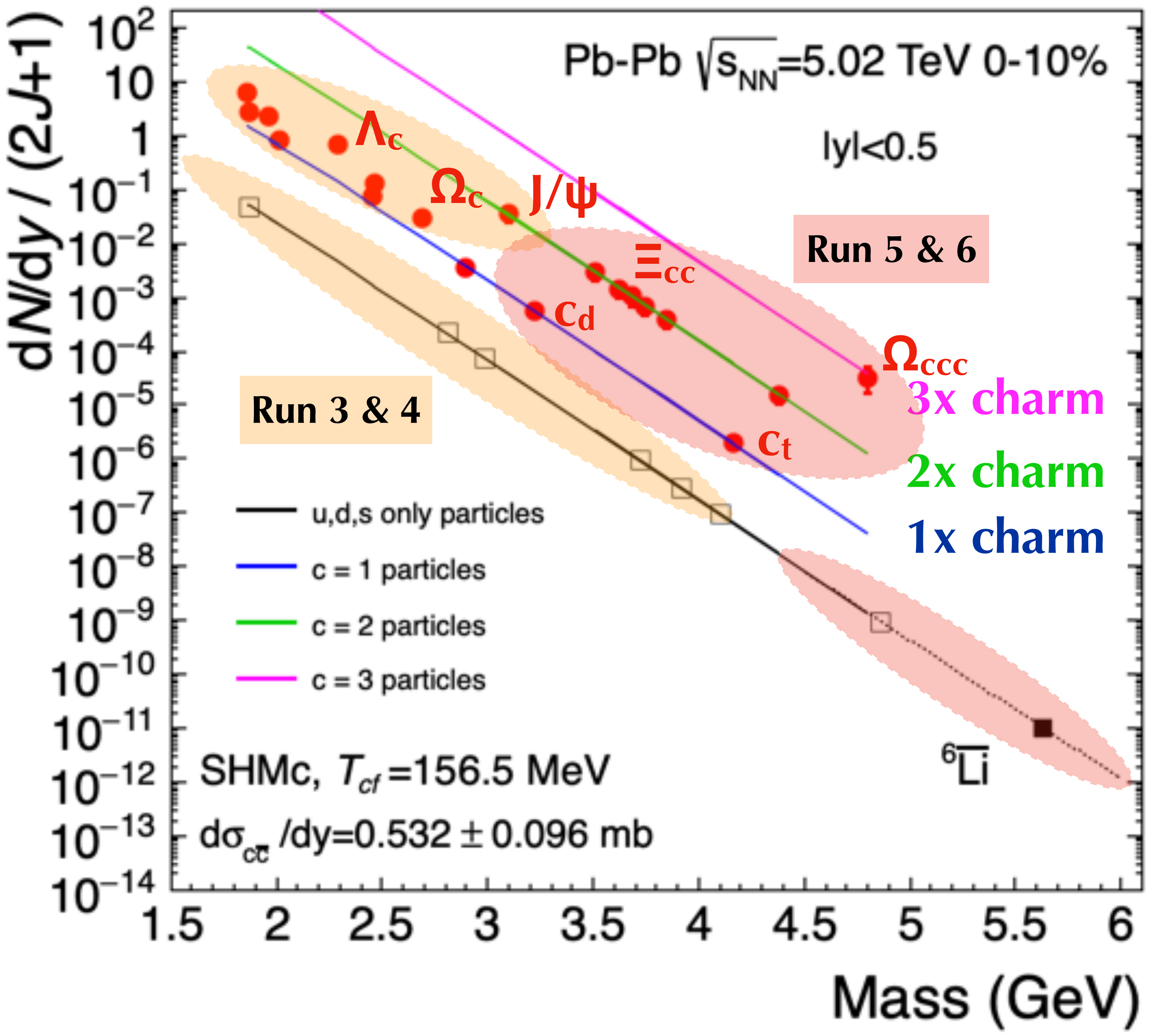
# Multi-charm baryons

- Large heavy-flavour yields
  - combination of independently produced charm quarks
    → **strong enhancement of multi-charm states**

- Programme
  - **multi-charm hadrons**
  - **(anti-)nuclei**

**Extreme sensitivity to equilibration and hadronisation in Run 5 & 6**

Hadron yields in statistical hadronisation model



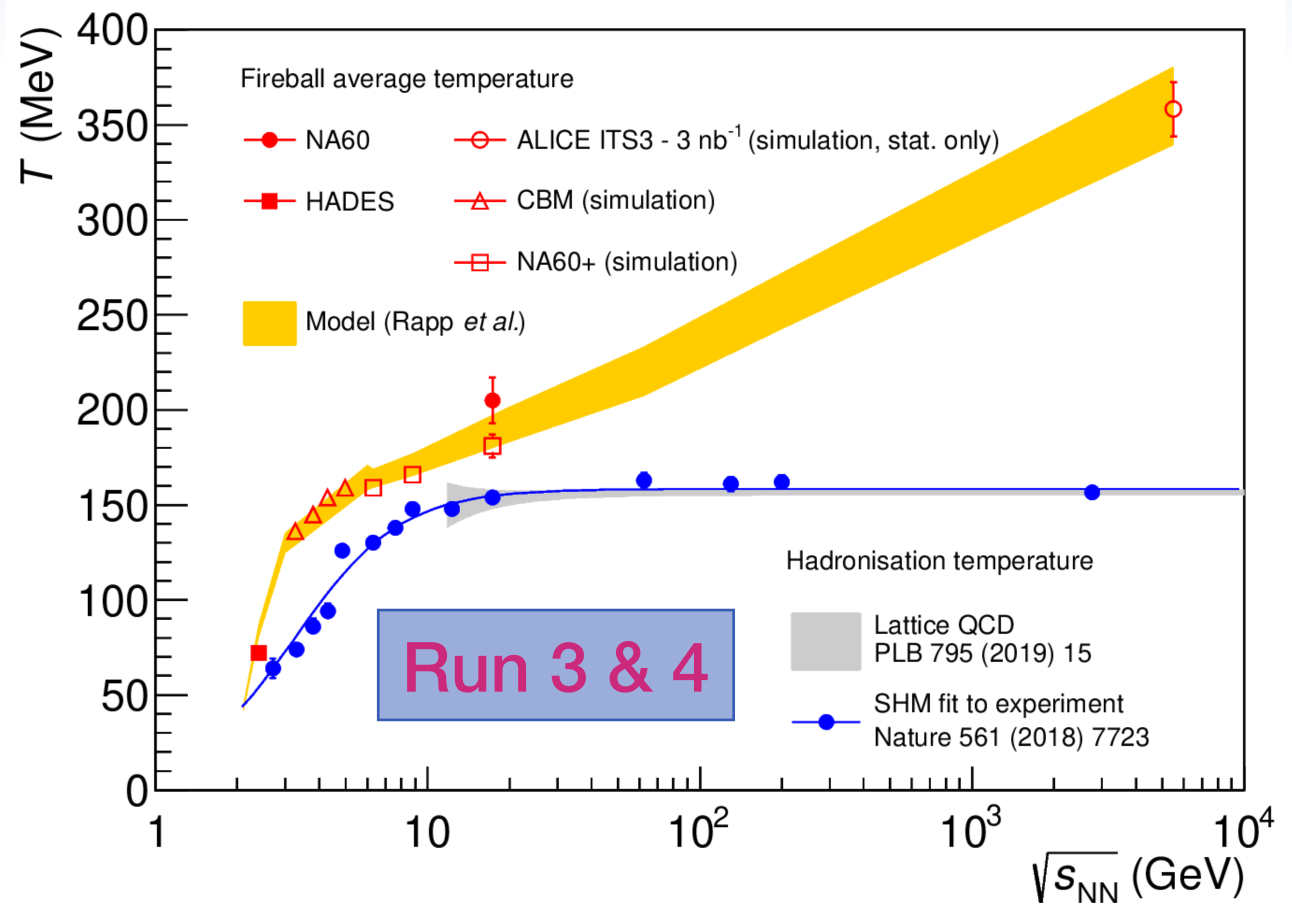

[A. Andronic et al, JHEP 07 (2021) 035]

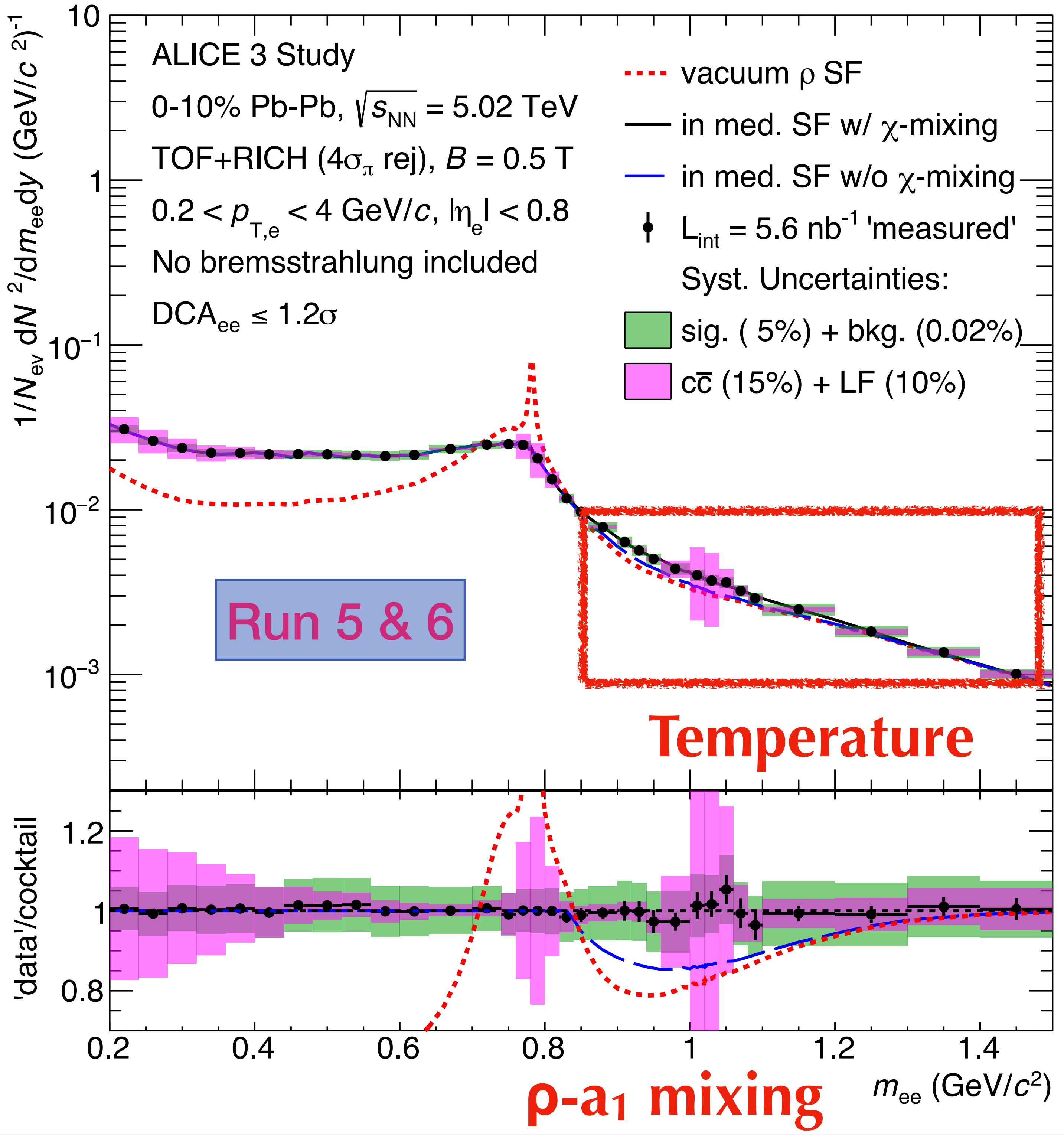
# Thermal radiation

- Hot QCD matter emits **thermal radiation**
  - **invariant mass of dileptons**
    not affected by blueshift from expansion
  - **emission throughout the entire evolution**

- Programme
  - average temperature (Run 3 & 4)
  - temporal evolution (Run 5 & 6)
    → multi-differential measurements ($p_T$, $v_2$)
  - imprints of chiral mixing (Run 5 & 6)

**Particularly interesting with ITS3 and ALICE 3**

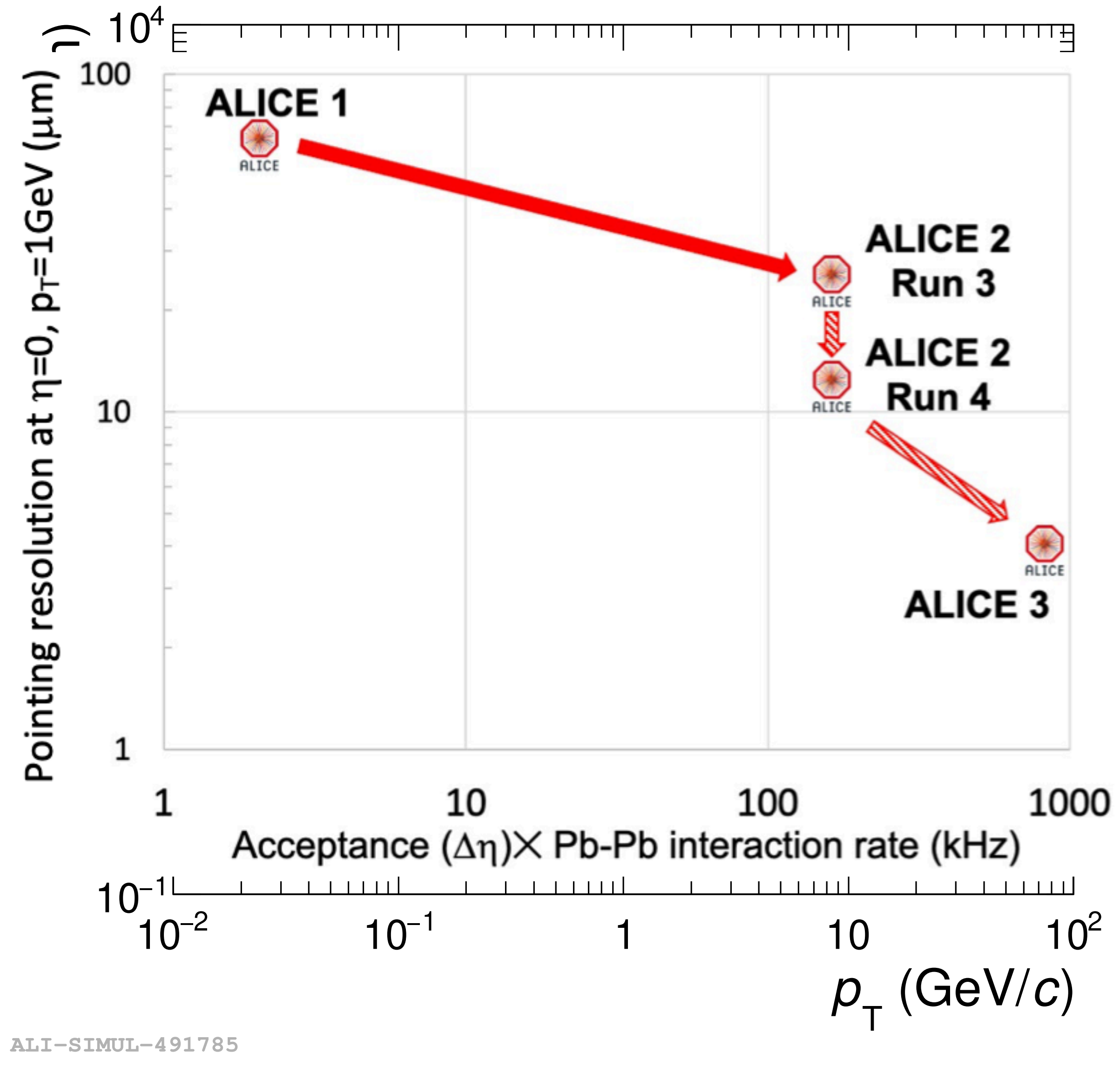


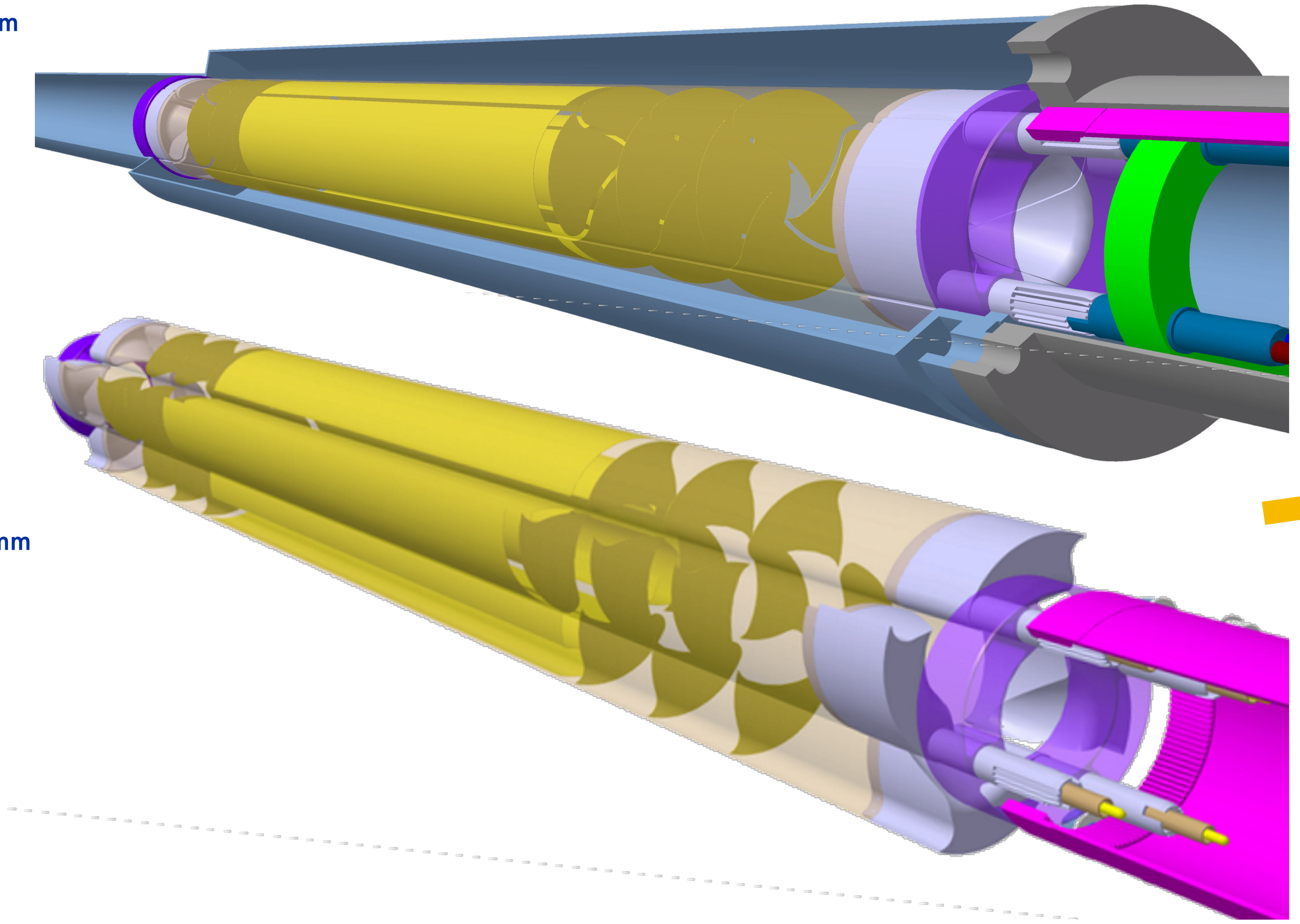
# ALICE 3 tracking and vertexing

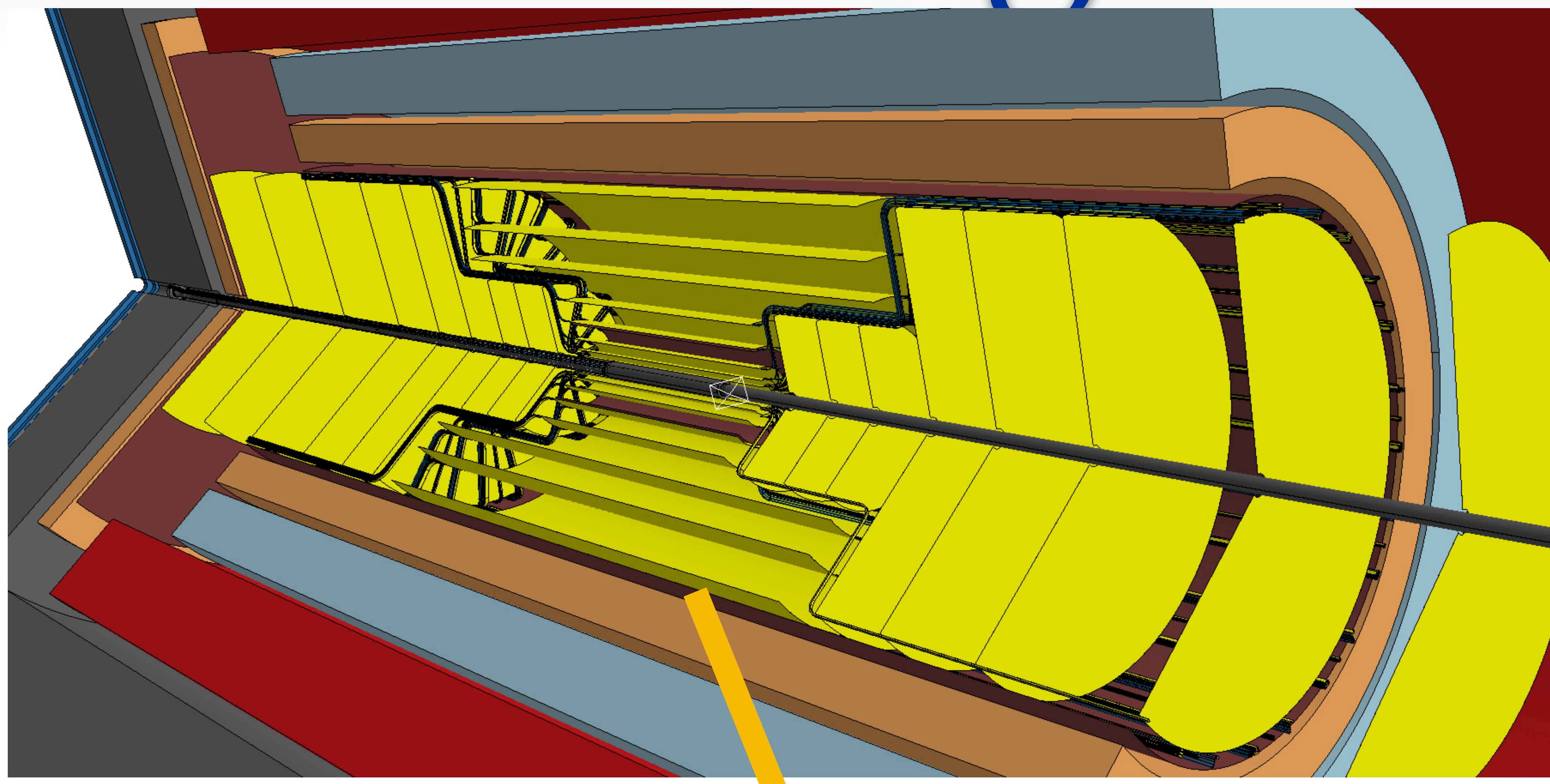
## Observables and tracking needs

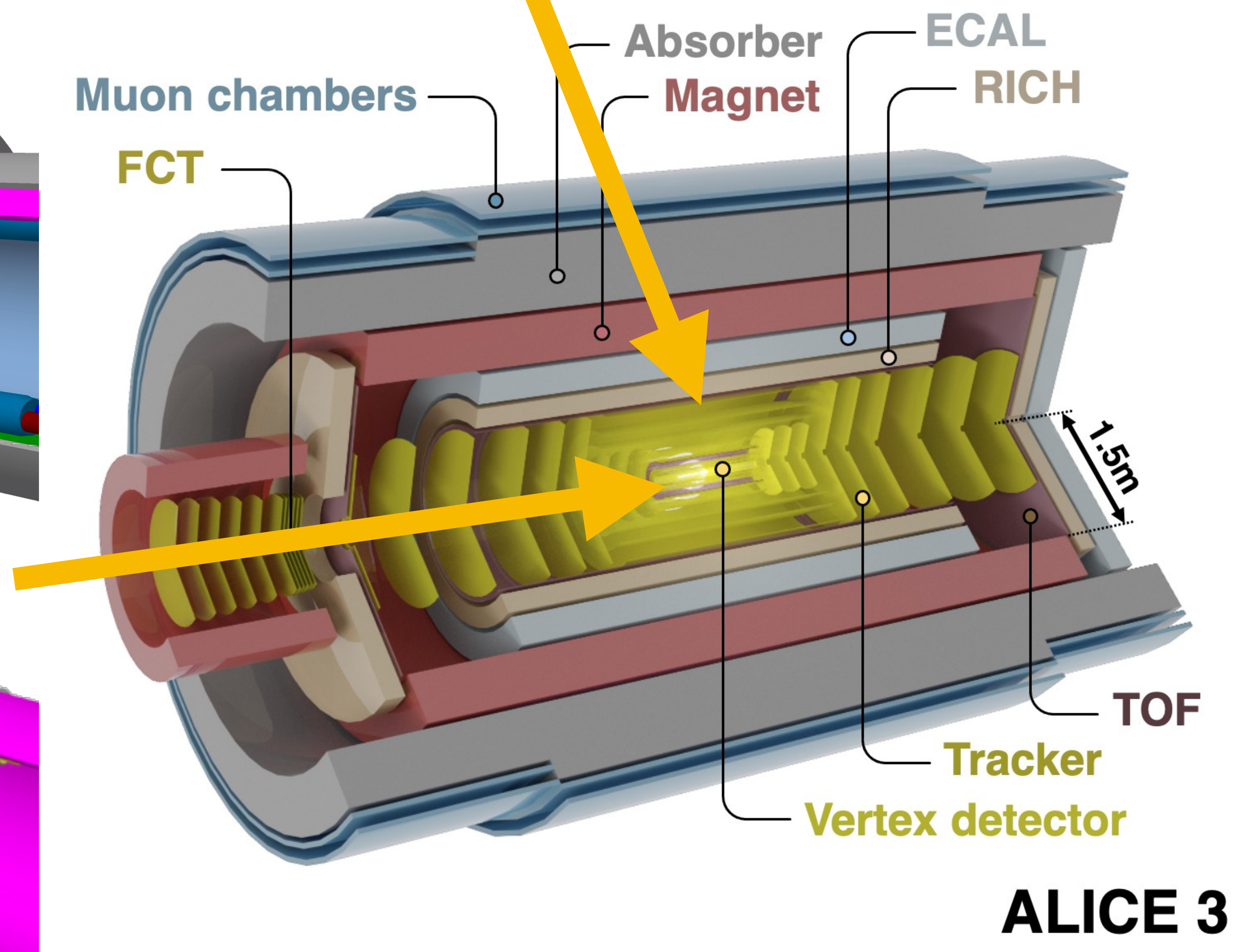
- multi-charm baryons → multi-vertex decay chains
- dielectrons → heavy-flavour rejection
- correlations → large acceptance









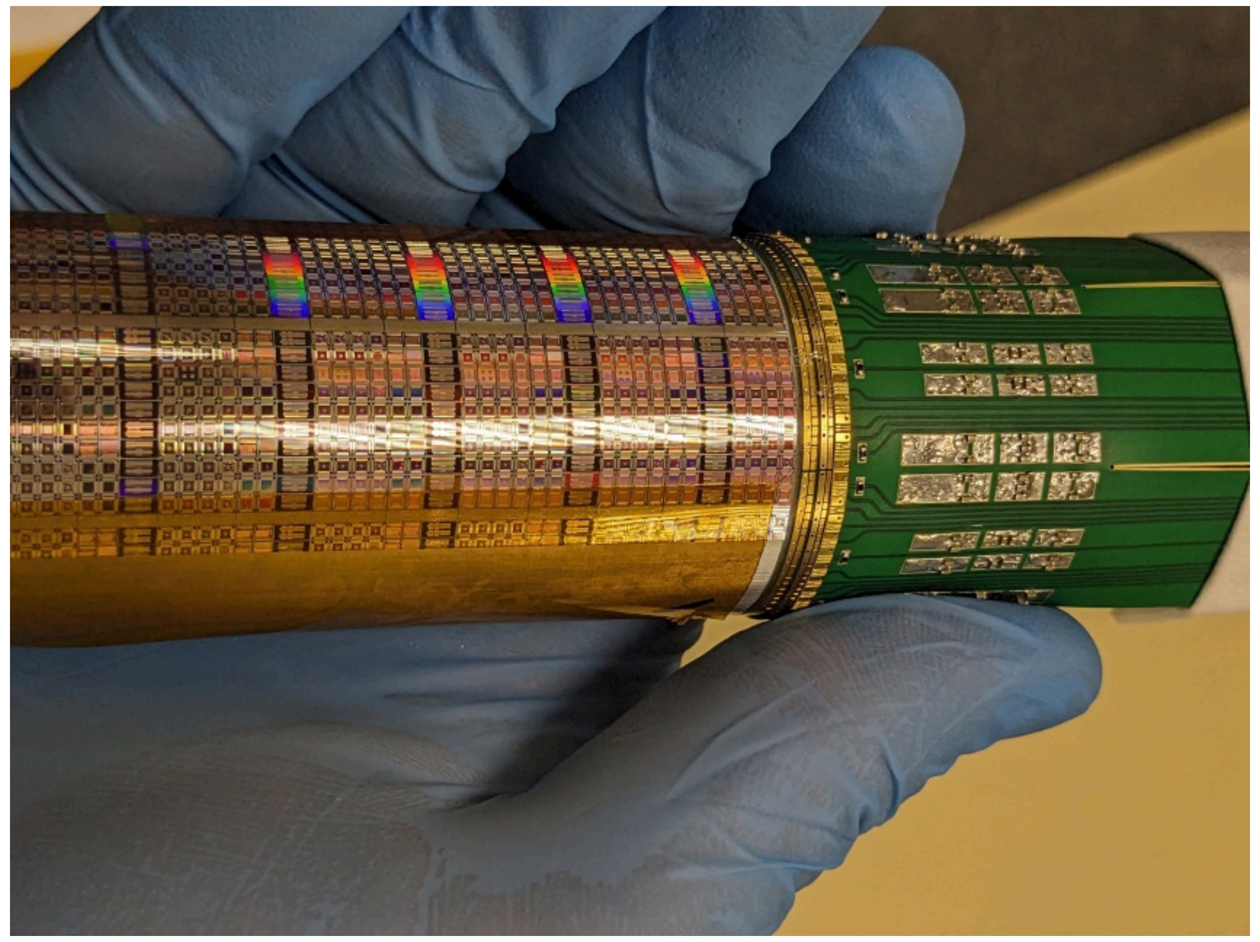



**Retractable vertex detector**

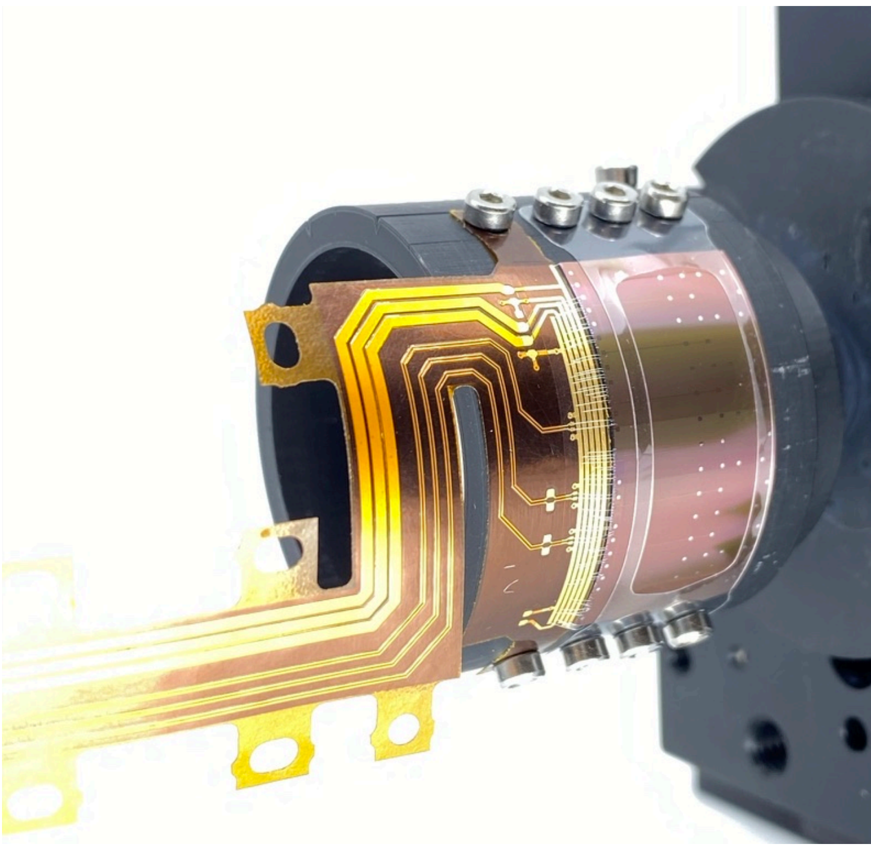
# Bent and stitched MAPS

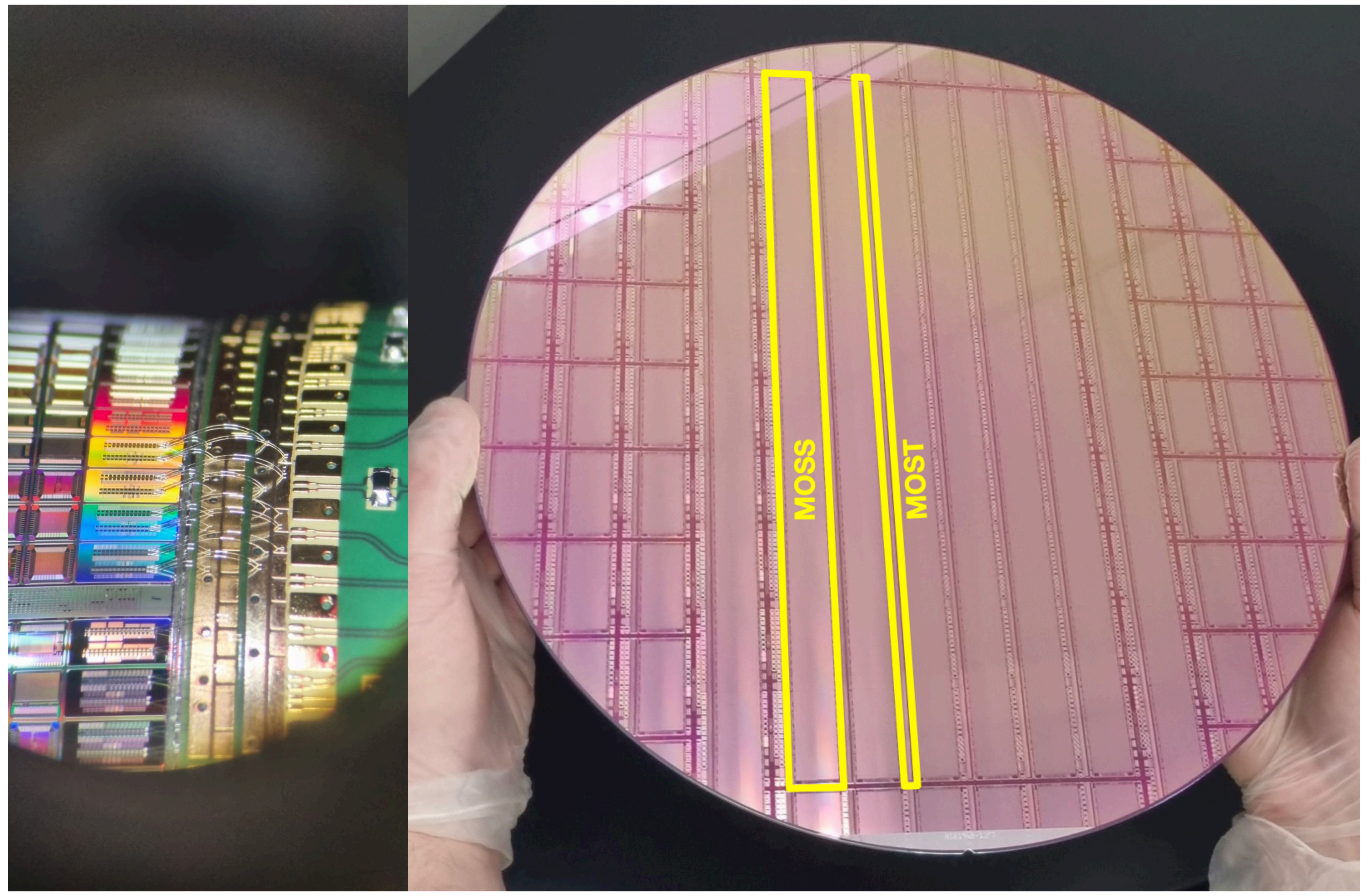
- Exploit flexibility of thin (≤ 50 μm) silicon
  → **truly cylindrical detection layers**
  - bent sensors retain full performance, with bending radii down to cm
  - bending possible with full wafers

- **MAPS realized in 65 nm technology** (TPSCo imaging process with modification)
  → denser integration, **larger wafers, stitching**
  - power distribution and readout fully integrated
    → **no external components in active area**
  - wafer-sized stitched sensor, $\mathcal{O}(10 \times 10)$ μm² pixels
    → MOSAIX under development for ALICE ITS3



Bent ALPIDE






Stitched sensors

# New adventures ahead of us!

| | | | | | | |
|---|---|---|---|---|---|---|
| **Collision systems** | pp, pPb, Pb-Pb | pp, pPb, Xe-Xe, Pb-Pb | pp, pO, OO, pPb, Pb-Pb | pp, pPb, Pb-Pb | pp, pA?, AA | pp, pA?, AA |
| **LHC schedule** | Run 1 2009 - 2013 | Run 2 2015 - 2018 | Run 3 2022 - 2026 | Run 4 2030 - 2033 | Run 5 2036 - … | Run 6 |
| ALICE | ALICE 1 | | ALICE 2 | ALICE 2.1 | ALICE 3 | |

- **New analyses with Run 3 & 4 data**
- **Innovative and exciting R&D**
- **Construction of new detectors**
- **Preparation for physics with ALICE 3**

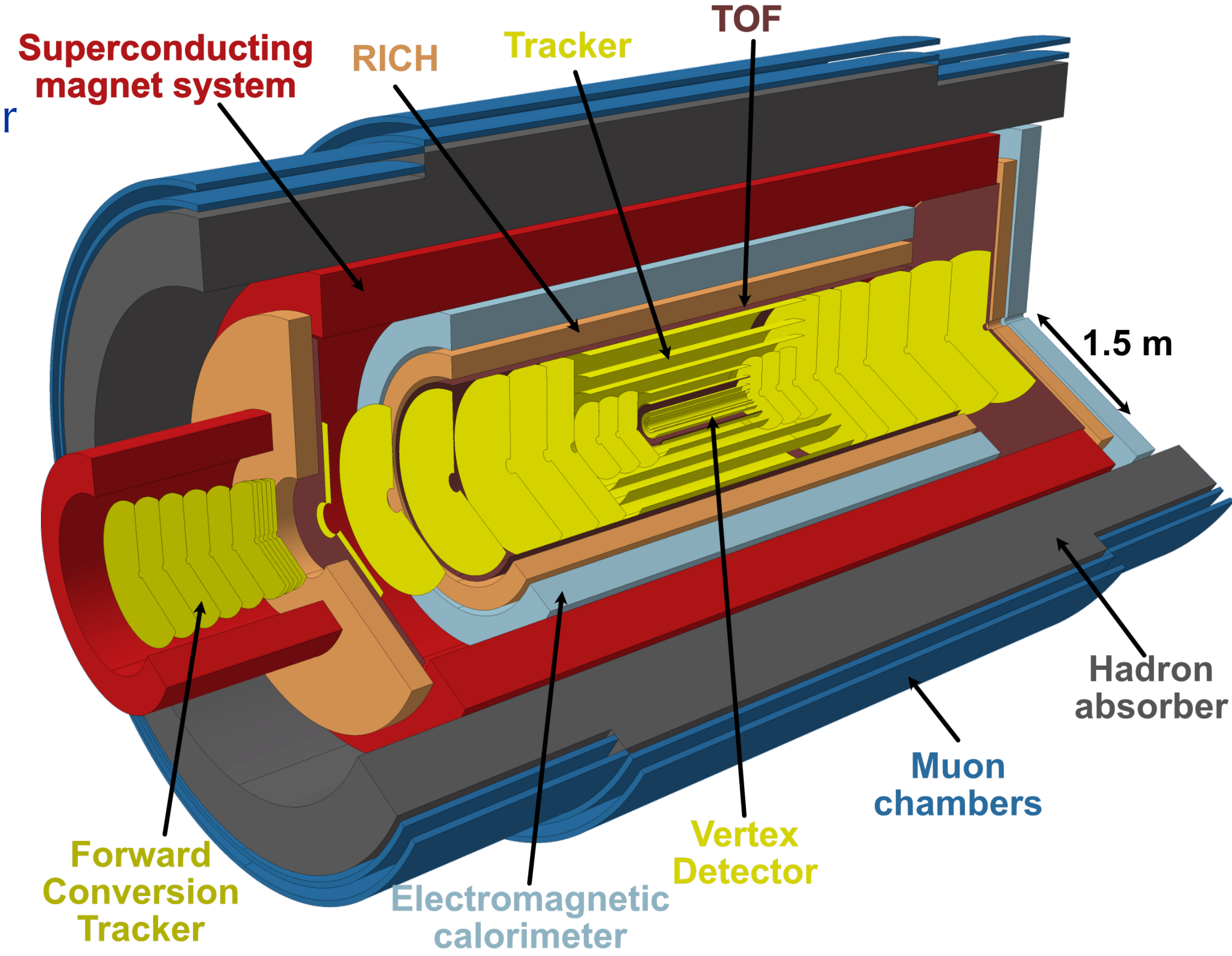
Thank you, Johanna!

# Backup

# ALICE 3

- **Novel and innovative detector concept**
  - compact, lightweight all-silicon tracker
  - retractable vertex detector
  - extensive particle identification
  - large acceptance
  - superconducting magnet system
  - continuous read-out and processing

- **Further detectors**
  - Muon identifier
  - Electromagnetic calorimeter
  - Forward Conversion tracker



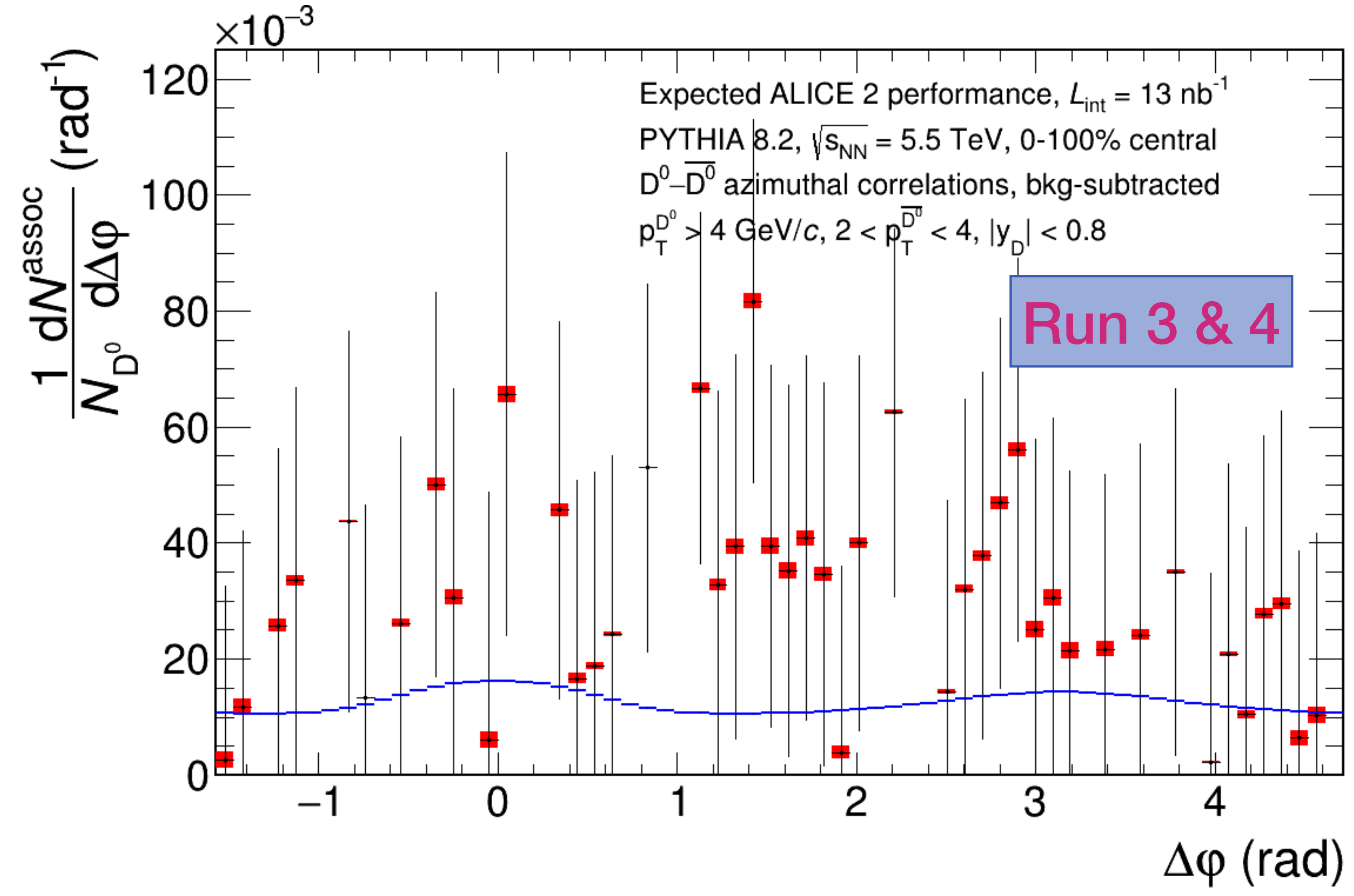
# Heavy-flavour transport

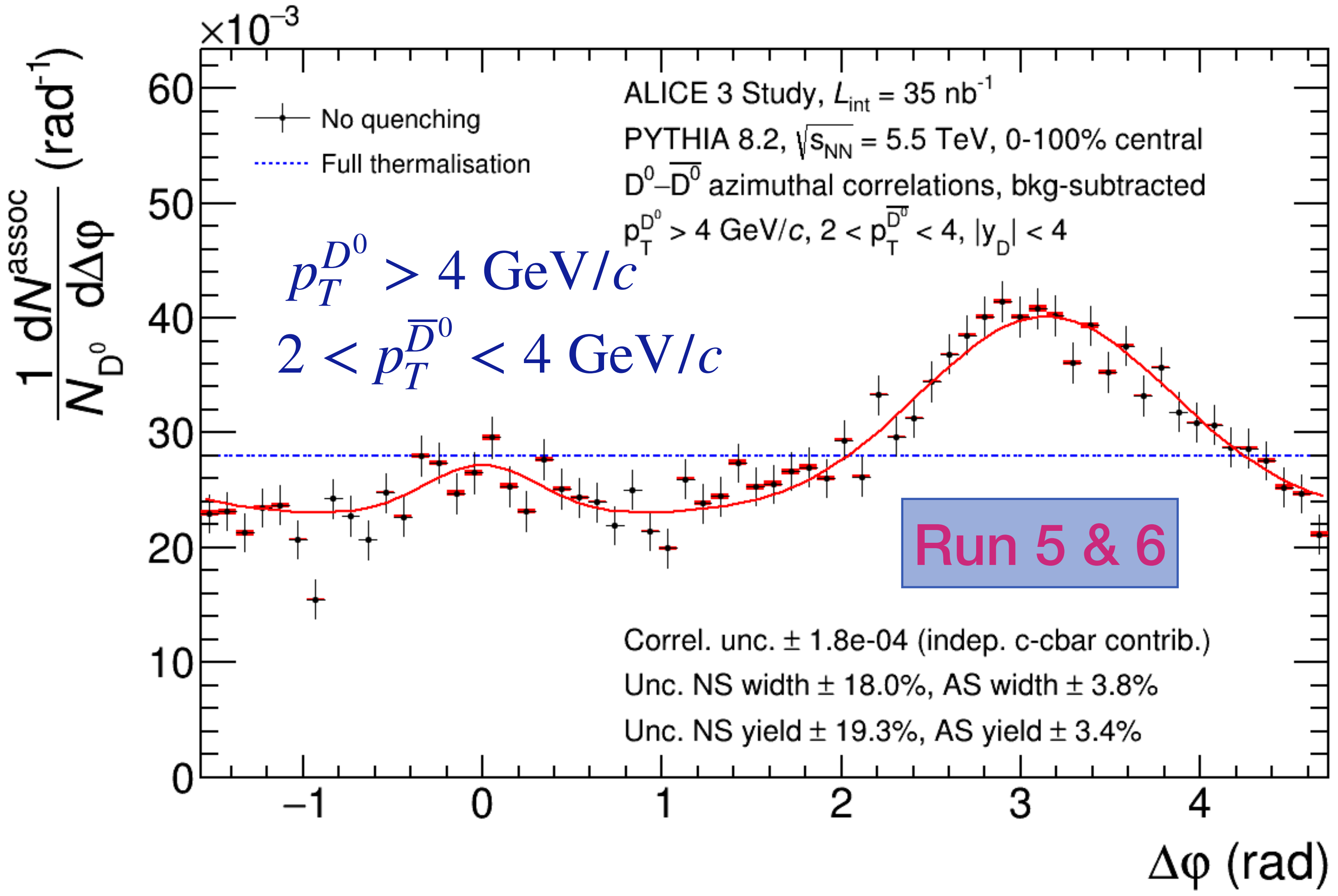
- **Propagation of (traceable) heavy quarks** depends on interaction with QGP
  - diffusion and approach to thermal equilibrium
  - extent of thermalisation depends on mass
    → beauty quarks retain more information

- Programme
  - determine **spatial diffusion coefficient**
    → precise suppression ($R_{AA}$) and anisotropy ($v_2$)
  - directly measure **decorrelation of charm pairs**
    → $D\bar{D}$ correlations

**Required precision only achievable with ALICE 3**

**$c\bar{c} \rightarrow D^0\bar{D}^0$ correlations**



# Momentum resolution

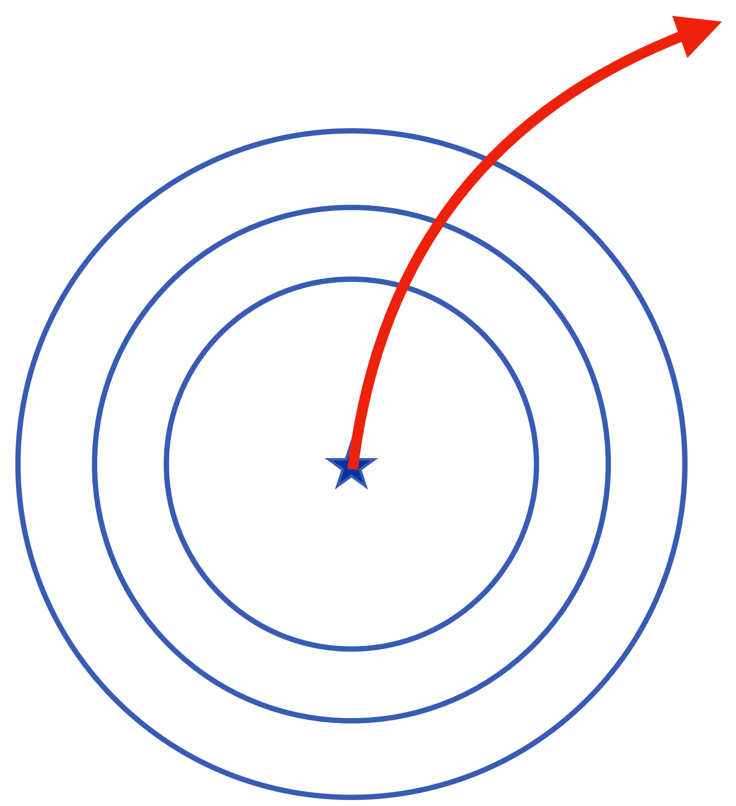
- Tracking and momentum measurement ➟ 3 - $N$ space points in magnetic field
  - momentum resolution limited by multiple scattering and lever arm

    $$\sigma_p/p \propto \frac{\sqrt{x/X_0}}{B \cdot L}$$

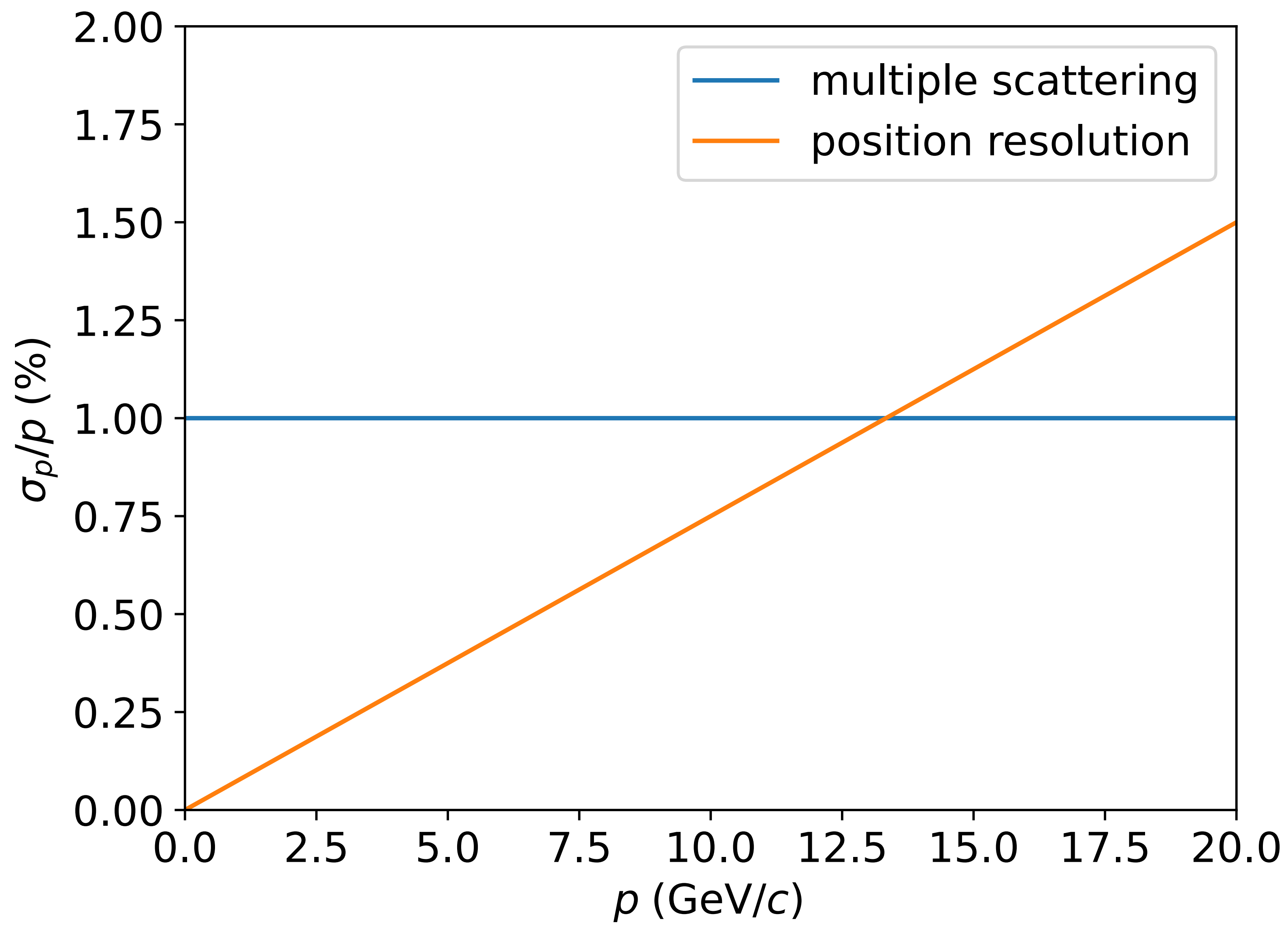
    ➟ **maximise lever arm and magnetic field, minimise material**
  - linear contribution from position resolution of hit measurements

    $$\sigma_p/p \propto \frac{\sqrt{x/X_0}}{B \cdot L^2} \cdot p$$

    ➟ **keep sub-dominant in region of interest**



**Example of cylindrical layers**




- Additional considerations
  - high rate → occupancy → combinatorics
  - acceptance and cost (area)

**→ low material, large field,**
**large lever arm, large-acceptance, high rate**

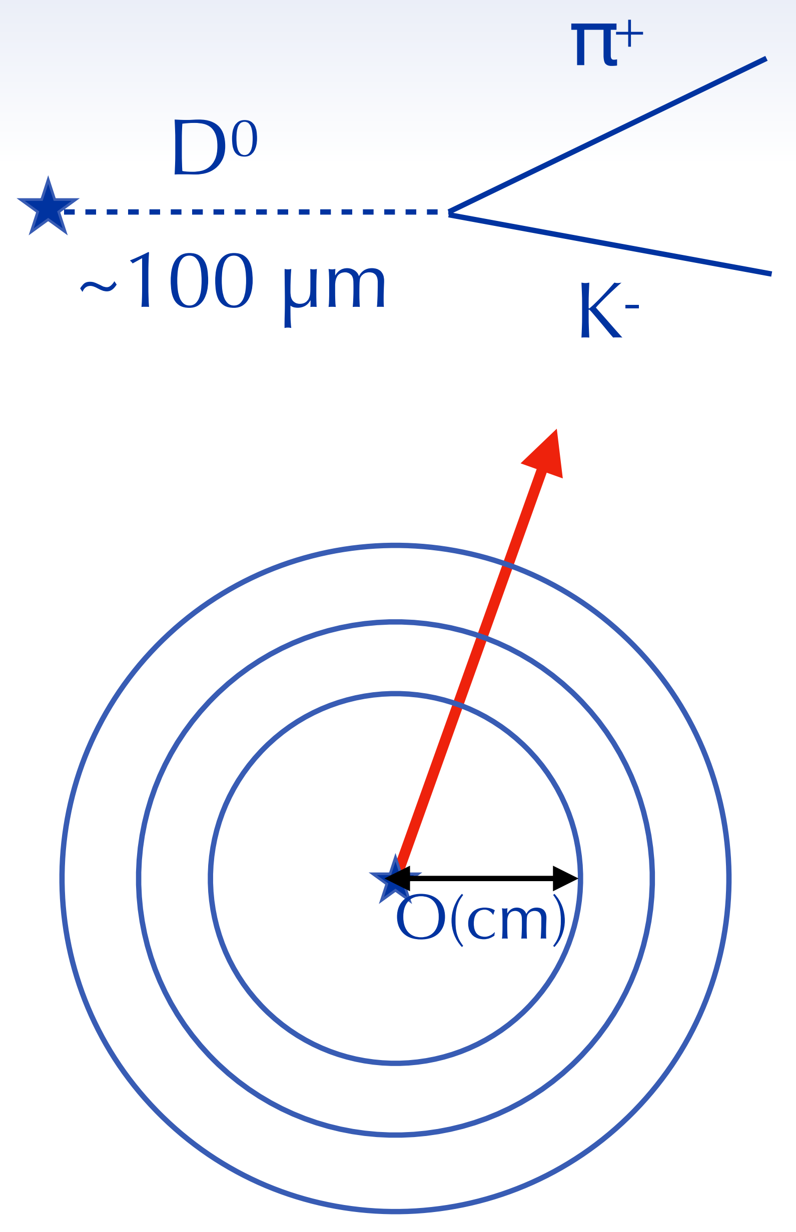
# Vertex resolution

- **Primary and decay vertices** reconstructed through pointing of tracks
  ➟ 2 - 3 detection layers
  - pointing resolution fundamentally limited by multiple scattering:

$$\sigma_\alpha = \frac{0.0136\,\mathrm{GeV}/c}{\beta p}\sqrt{\frac{d}{X_0}}, \quad \sigma_{\mathrm{DCA}} = \sigma_\alpha \cdot r_0$$

    ➟ **minimal radius**
    ➟ **minimal material**
  - constant contribution from position resolution
    ➟ stay below limit from multiple scattering
- boundary conditions on proximity,
  e.g. radiation, beam aperture, …

**→ proximity, low material**




decays with cτ < 100 μm