Tracking and Vertexing

and the impact on detector design

part 2

XXXIV International School
“Francesco Romano”

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Jochen Klein (CERN)

Recap and outlook today

- **Recap**
  - tracking and vertexing
    → **track finding and fitting** from hits along particle trajectory, often in magnetic field to extract curvature and, thus, momentum
  - performance determined by
    position resolution, multiple scattering, magnetic field, lever arm
  - scalings with momentum and pseudo-rapidity
- **Today**
  - particle identification and combination with tracking detectors
  - detector design, using LHC upgrade projects as examples

Integration of other detectors with tracking

particle identification and more

Particle identification

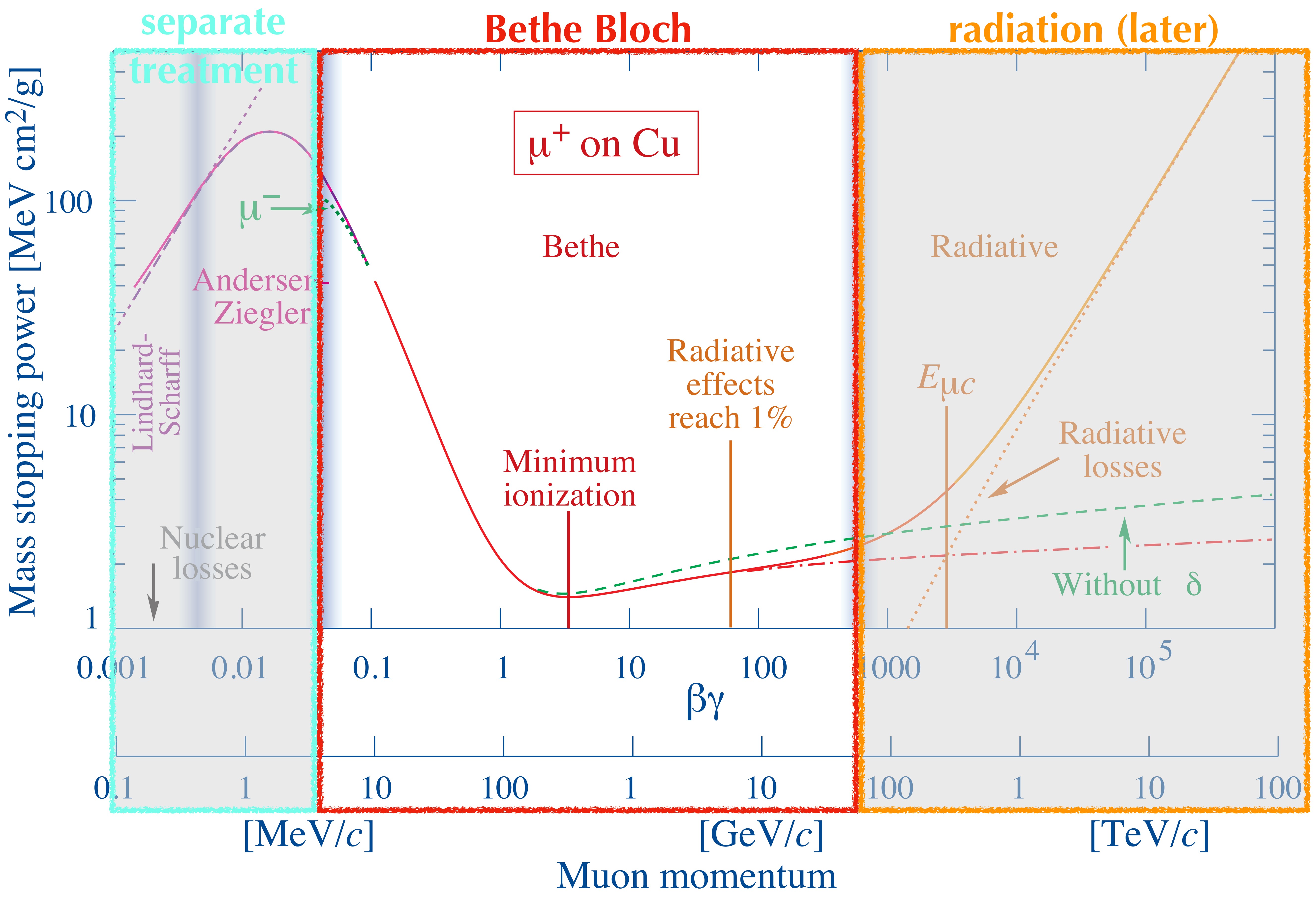
- Idea: **extract mass from combination of momentum and**
  - specific energy loss
  - time of flight
  - Cherenkov radiation
  - transition radiation
  - electromagnetic showering
  - hadron absorption

Combination of techniques
to achieve PID goals

Bethe-Bloch equation

$$-\frac{\mathrm{d}E}{\mathrm{d}x} = Kz^2\frac{Z}{A}\rho\frac{1}{\beta^2}\left[\frac{1}{2}\log\frac{2m_ec^2\beta^2\gamma^2T_{\max}}{I^2} - \beta^2 - \frac{\delta}{2}\right]$$

- Calculation of specific energy loss by Bethe and Bloch
  - $T_{\max}$: max. energy transfer (in single collision)
  - I: ionisation potential (~(10 ± 1) Z eV for elements beyond O)
  - δ/2: density correction (Lorentz contraction + polarisability of material)

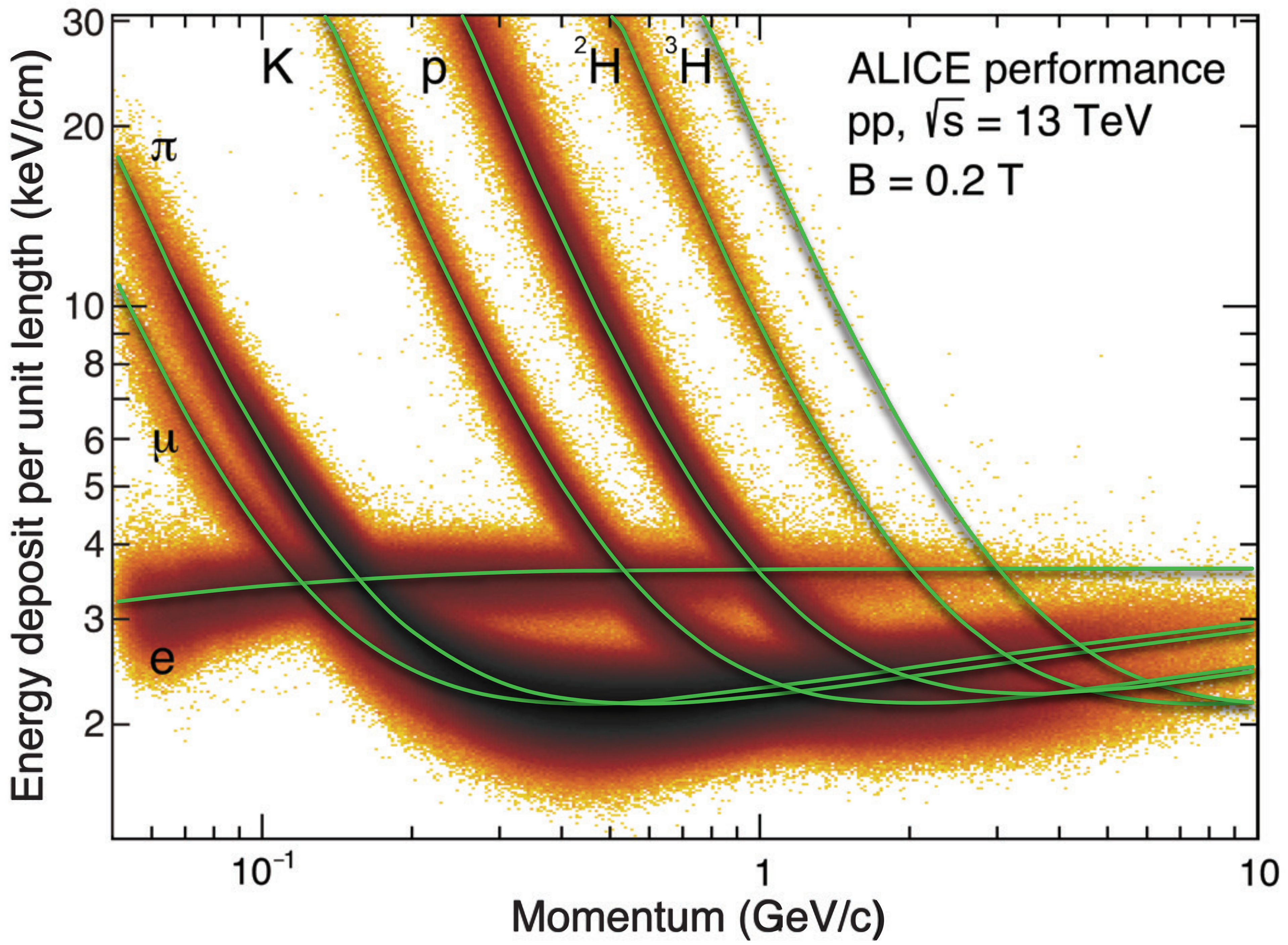


[H. Bethe, Ann. d. Physik 5 (1930) 325; F. Bloch, Ann. d. Physik 16 (1933) 285]

Specific energy loss

- Deposited energy in any detector is function of $\beta\gamma = p/m$
  - for given momentum → function of mass
  - ambiguities at line crossings
- Requires **combined measurement** of
  - curvature → momentum
  - deposited energy → dE/dx
- **Well suited for integration in tracker** with readout of deposited energy

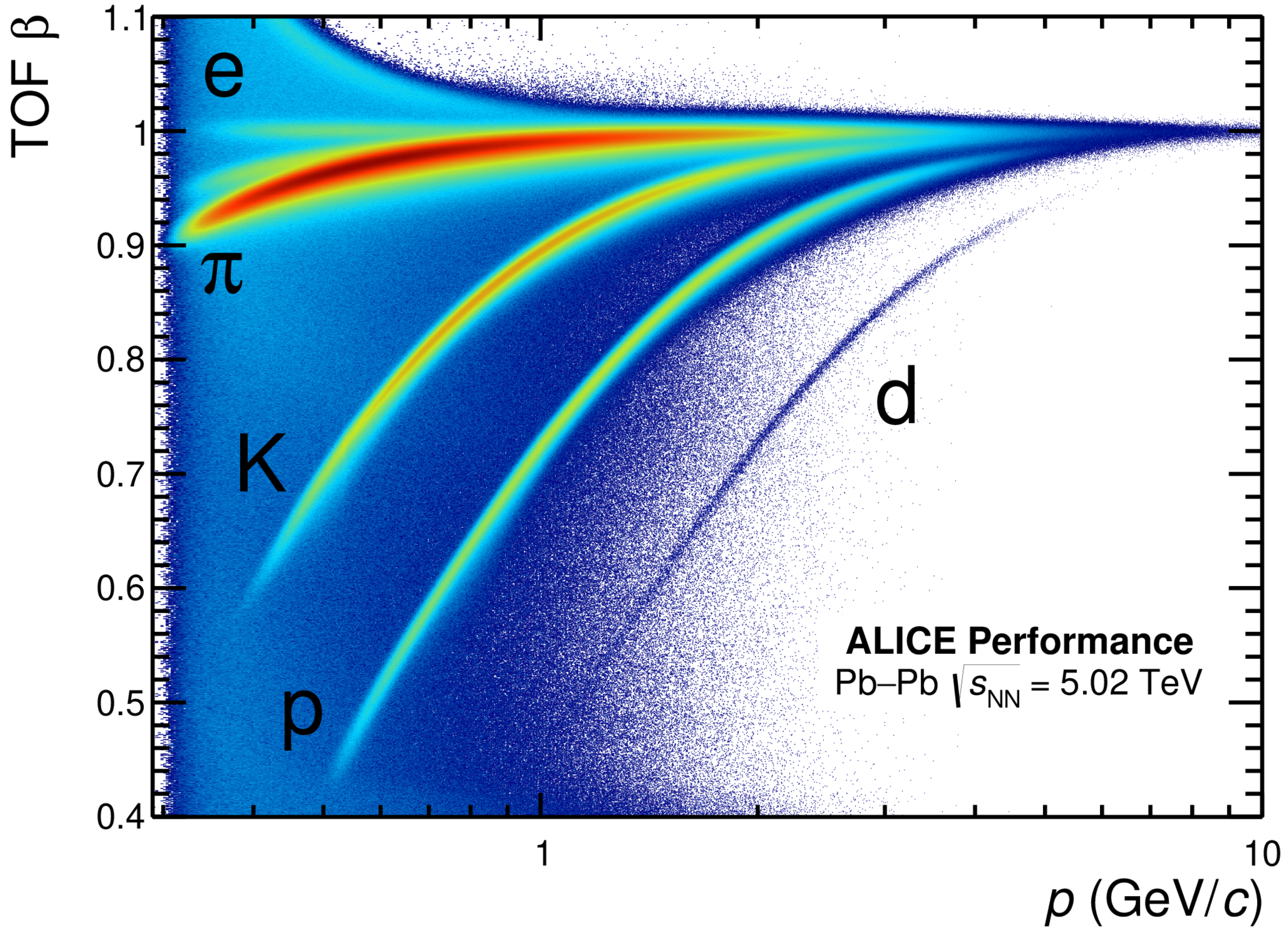
ALICE TPC



Time of flight

- Velocity of particle (at given momentum) depends on mass
  → different time of flight for different mass hypotheses:
  $$\Delta t = \frac{L}{c}\left(\frac{1}{\beta_1} - \frac{1}{\beta_2}\right) \approx \frac{Lc}{2p^2}(m_1^2 - m_2^2)$$
- **Separation power** $N_\sigma = \dfrac{|m_1^2 - m_2^2| L}{2p^2\sigma_t c}$

  improves with
  - path length
  - time resolution → need for fast detectors,
    e.g. scintillators, Cherenkov, MRPCs, LGADs
  - momentum resolution



ALI-PERF-106336

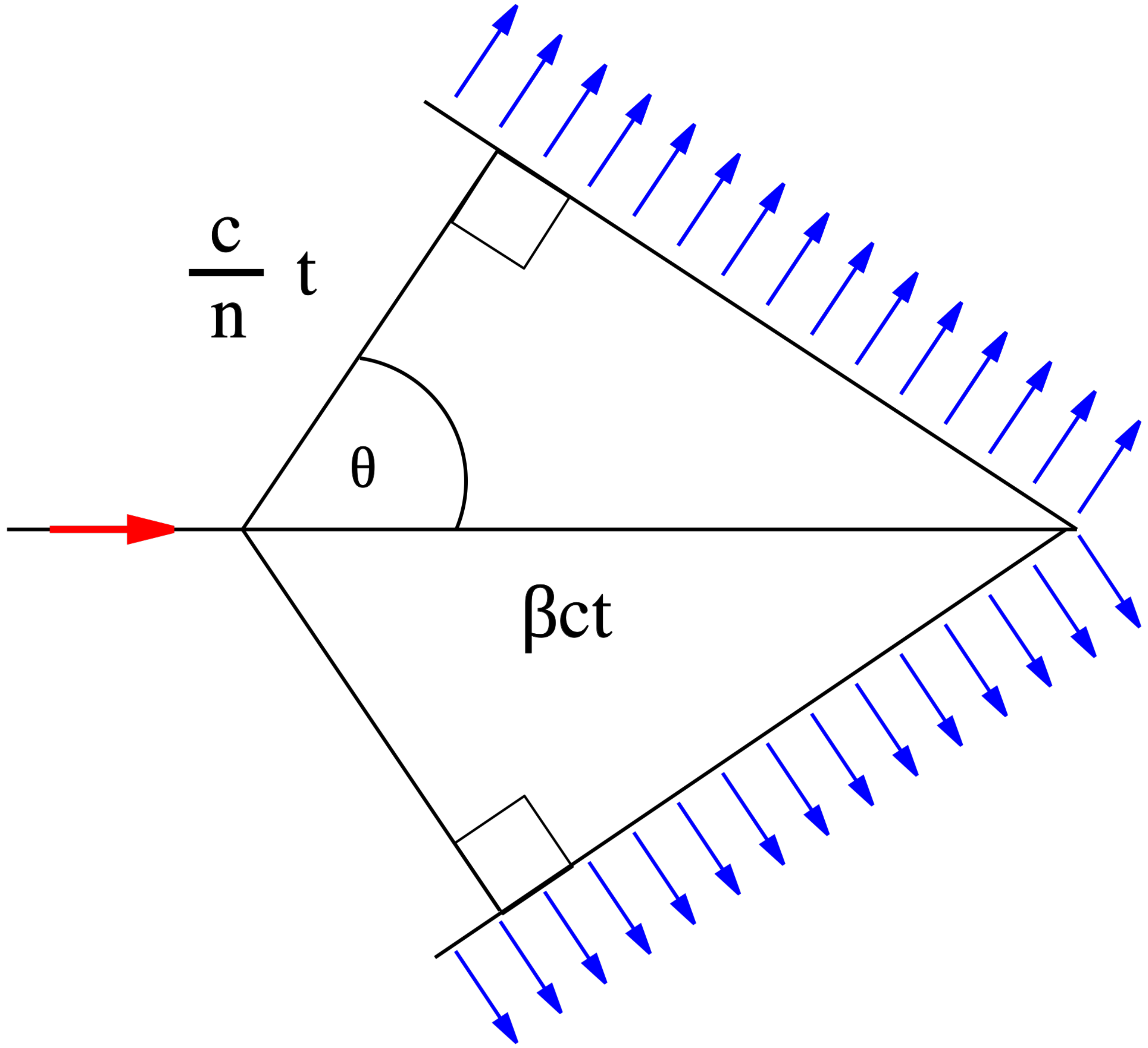
- Often realised as **combination of fast detector outside of tracker**
  → no impact on tracking performance, large path length

4d tracking

- Time information can be used as **additional coordinate in track finding and fitting**
  - reduce mismatch probability in high occupancy environment, e.g. from pile-up, i.e. multiple collisions in short sequence
  - required time resolution depends on nature of pile-up
  - integration of time measurement in
    - every tracking layer
      → so far only feasible with moderate time resolution (material)
    - dedicated timing layers
      → reduce tracks to be considered for each collision

Cherenkov detectors

- Cherenkov effect
  → **emission of light by particles above speed of light**
  - presence of radiation → threshold Cherenkov
  - emission angle function of β = p/E
    → combination of β and p give access to mass
- **Measurement of Cherenkov angle requires**
  - sufficient production of light
    → minimum amount of material
  - focusing onto (single-)photon-sensitive sensors
    → expansion gap or optics
- Typically realised as additional detector outside of tracker (need for space and material)



Calorimetry

- **Detection of total energy based on complete conversion** into secondary particles
  - ECal: pair production and bremsstrahlung
  - HCal: nuclear reactions producing pions, …
- **Calorimeters are destructive detectors** → placed outside of trackers
- **Propagation of (charged particle) tracks to calorimeters** can be required for additional information, e.g. avoidance of double counting

Muon identification

- **Exploit unique signature of muons**
  - energy loss through ionisation/excitation (minimum ionising particle, Bethe Bloch)
  - no electromagnetic shower (too heavy)
  - no hadronic shower (no strong interaction)

- **Absorber** can be used to **block anything but muons**
  → outermost part of a detector

- Tracking can be needed for
  - matching to tracks before absorber
  - propagation of tracks through absorber

Detector design and layout

LHC upgrades used as examples

NB: in reality always an iterative process
with performance studies and detector optimisations

Some (unpleasant) realities

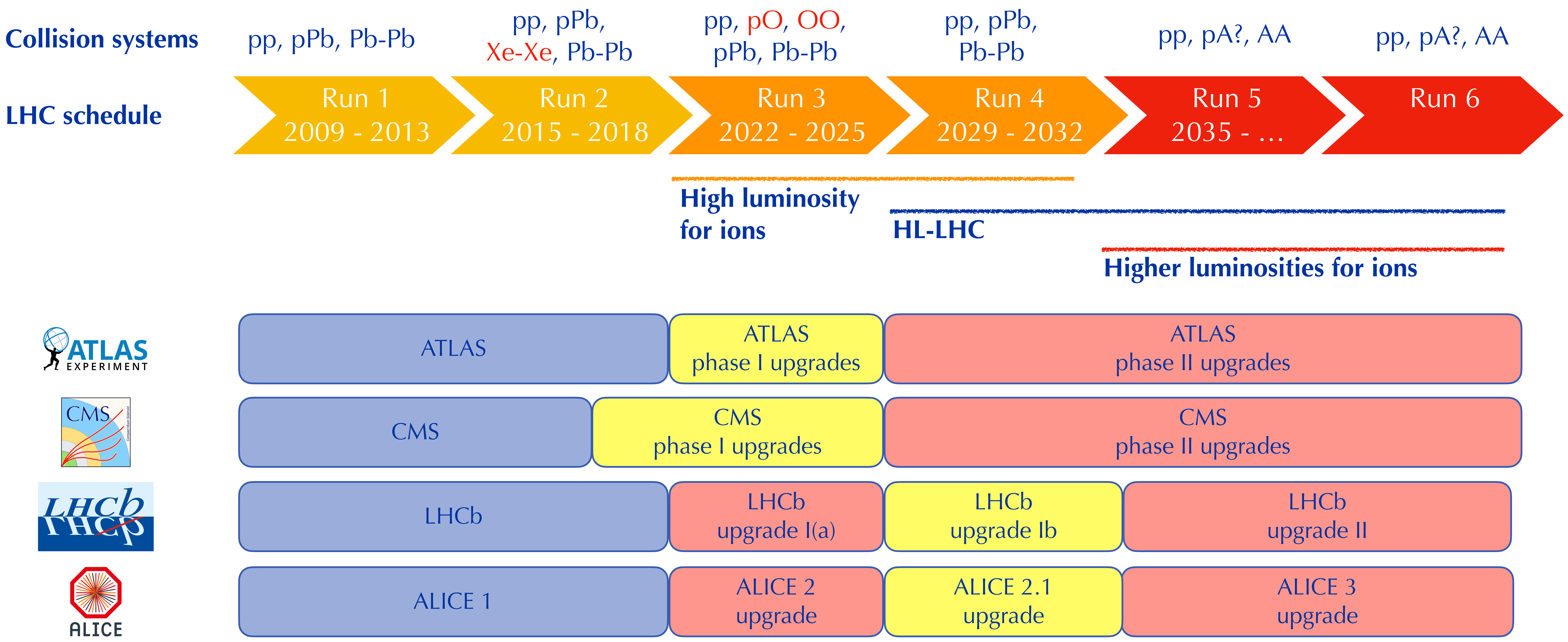
- **Better position resolution**, i.e. higher granularity, and **better time resolution** require **more power**
  - more material for feeding power and for cooling (!)
    → increase in multiple scattering deteriorates performance

- **Instrumented area costs money**
  - optimisation of coverage with minimal instrumented area, e.g. larger magnetic field

- **Magnet cost scales with stored energy** (to first order) → $\propto B^2 \cdot V$

- **Radiation damage**
  - particle flux scales with R^2 (neglecting secondary particles)
  - usage of sensors limited by radiation tolerance
    → not all technologies can be used everywhere

LHC upgrades



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 - 2025

Run 4 2029 - 2032

Run 5 2035 - …

Run 6

High luminosity for ions

HL-LHC

Higher luminosities for ions

ATLAS | ATLAS phase I upgrades | ATLAS phase II upgrades

CMS | CMS phase I upgrades | CMS phase II upgrades

LHCb | LHCb upgrade I(a) | LHCb upgrade Ib | LHCb upgrade II

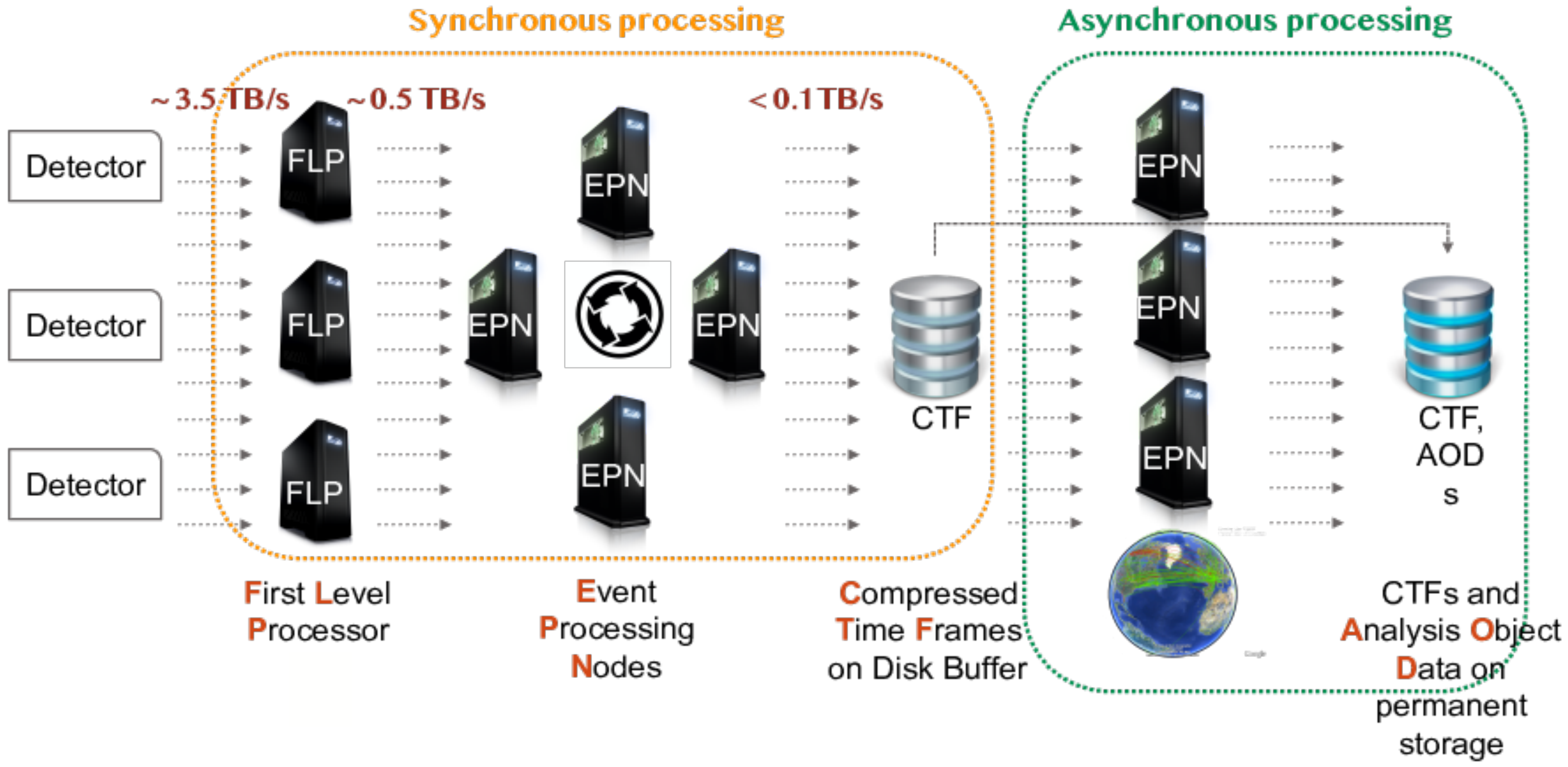
ALICE 1 | ALICE 2 upgrade | ALICE 2.1 upgrade | ALICE 3 upgrade

Focus on phase II (b) upgrades
(with a little more detail on ALICE)

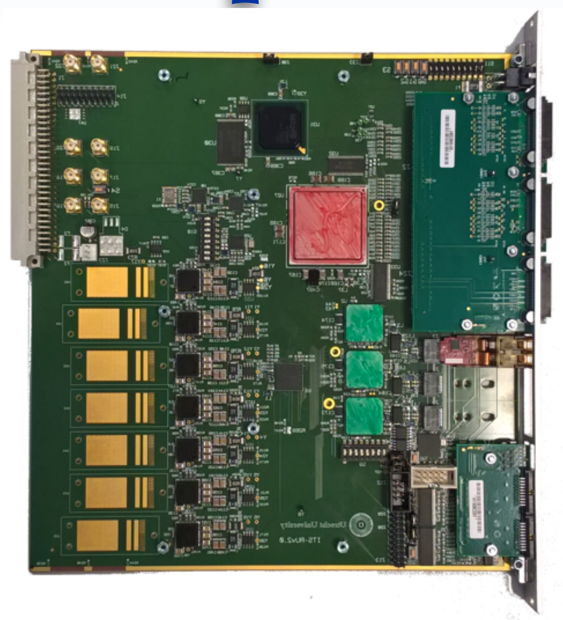
🟨 intermediate upgrade

🟥 major upgrade

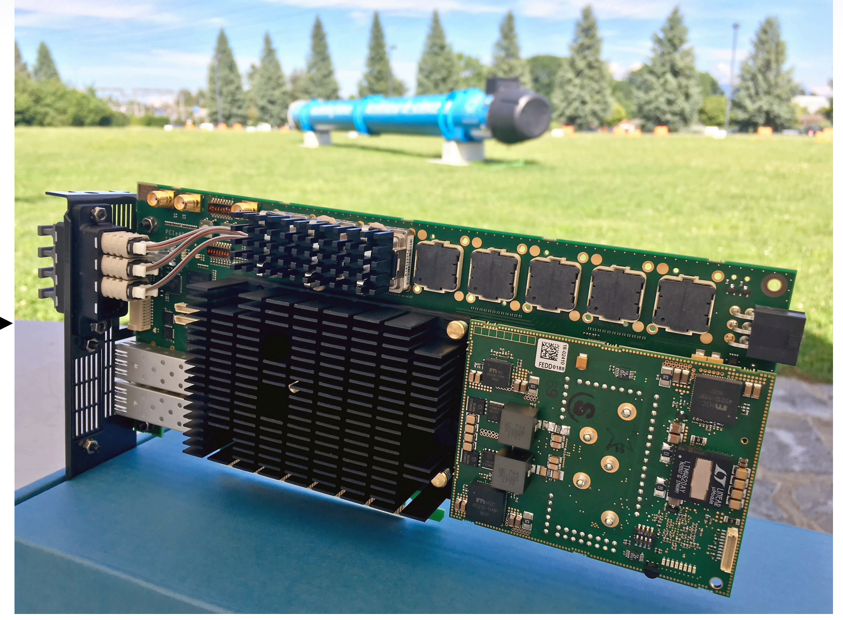
ALICE online-offline processing



- **Zero suppression** and **event building** in First Level Processors
- **Synchronous reconstruction** in Event Processing Nodes
  - 2000 GPUs in 250 EPNs
- **Asynchronous reconstruction** on EPNs and WLCG (improved calibration)



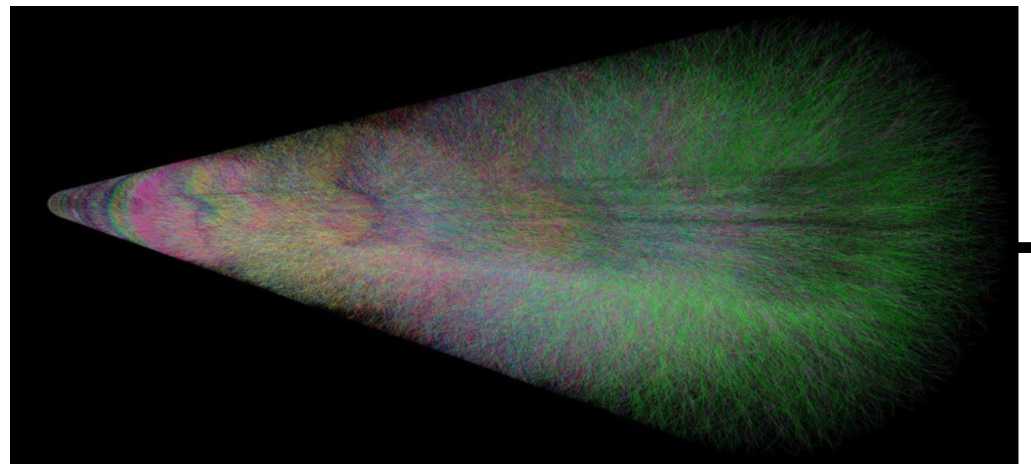
Detector, e.g. RU



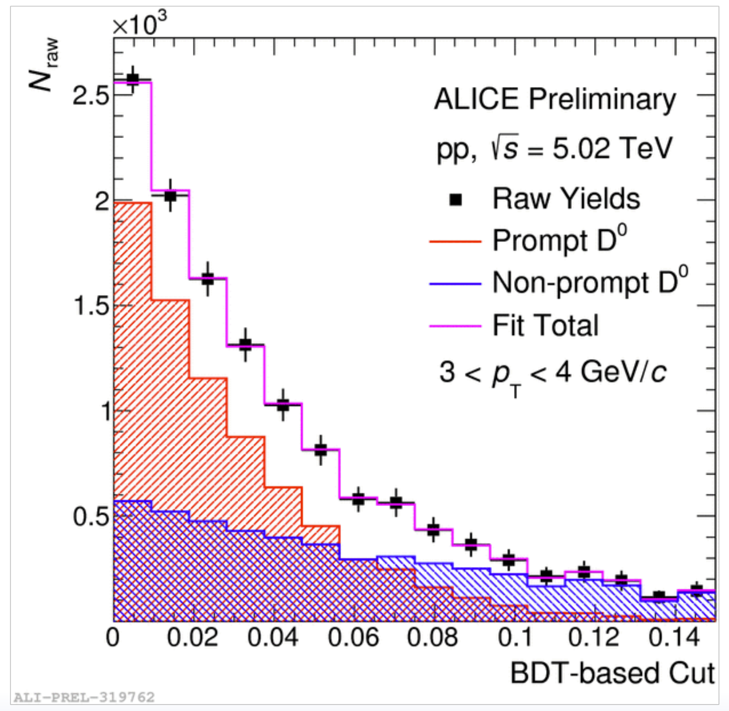
Common Readout Unit

First Level Processors

Event Processing Nodes



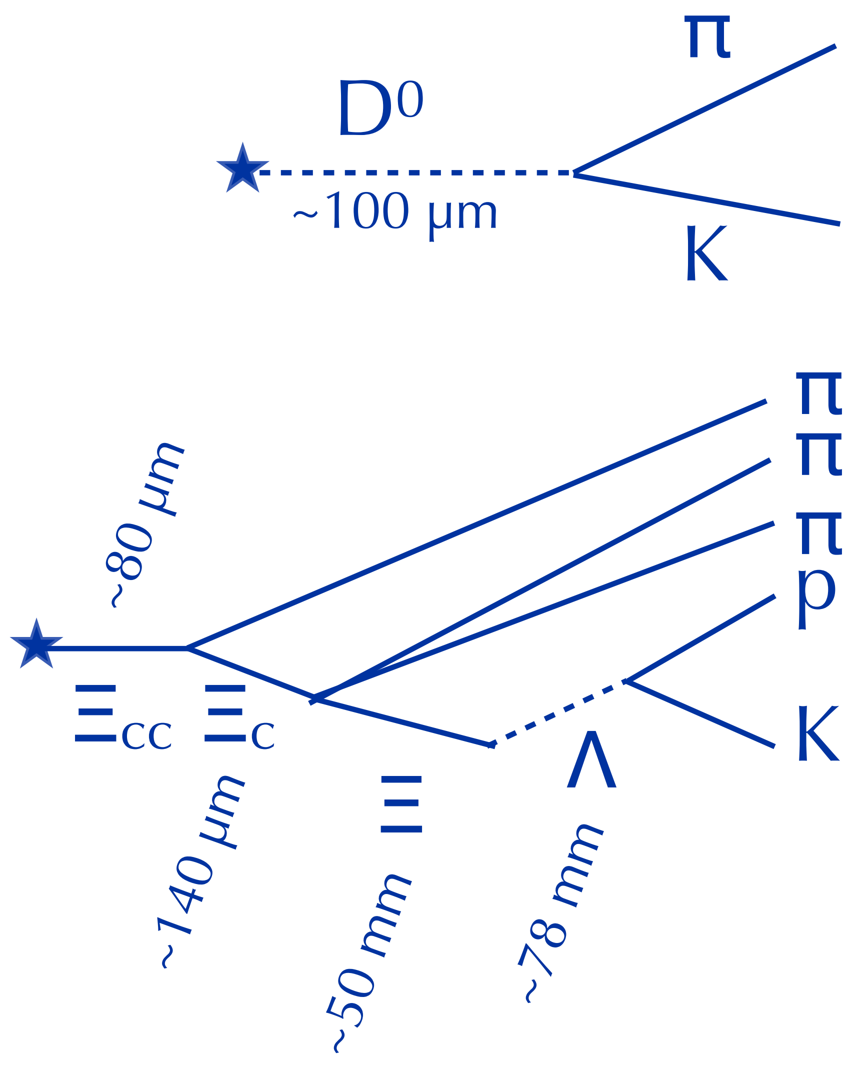
Events from continuous read-out



Data analysis

ALICE 3 requirements

- **(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



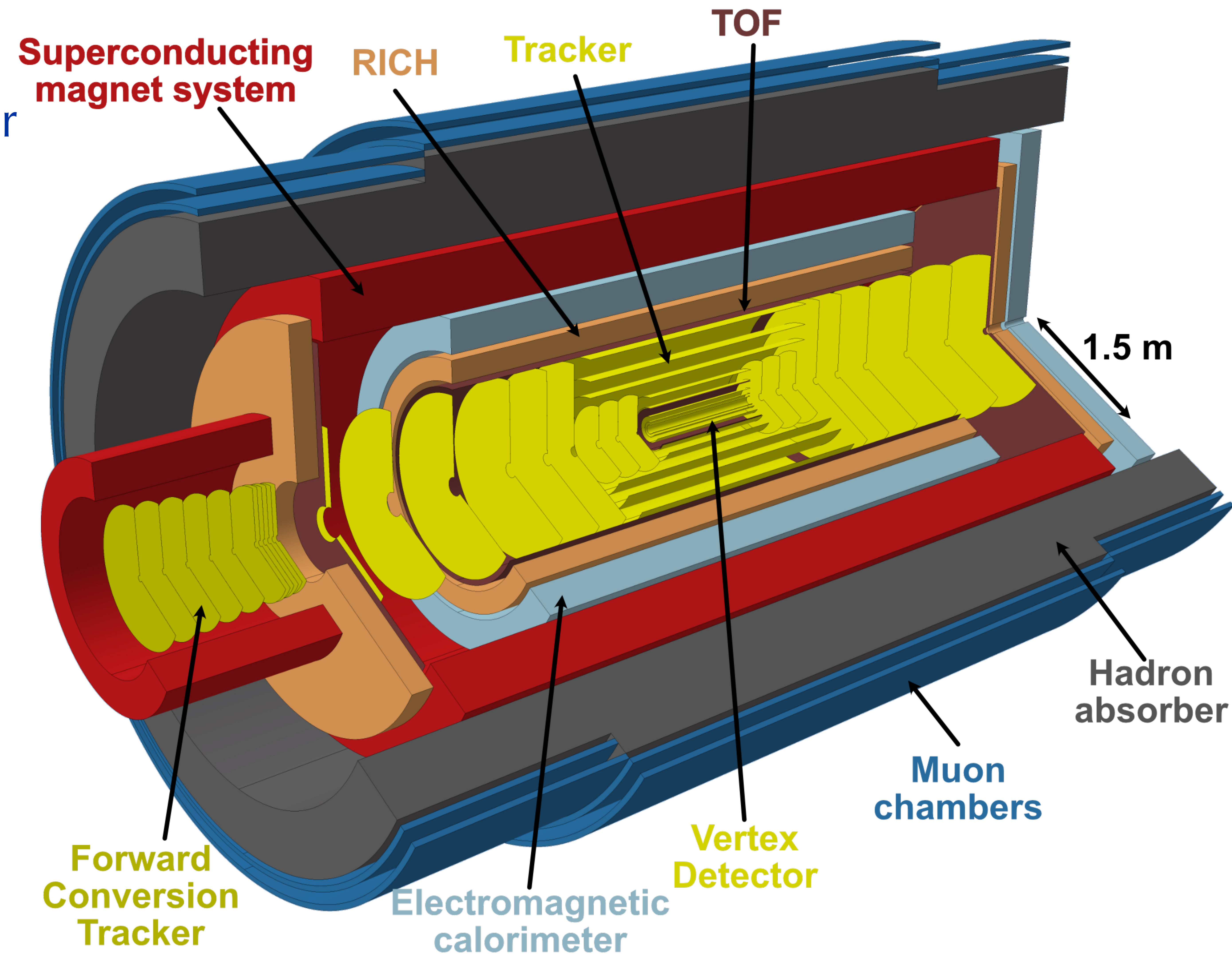
Background from heavy-flavour decays $c\bar{c} \to D\bar{D} \to e^+ e^-$ …

Experimental requirements

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

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

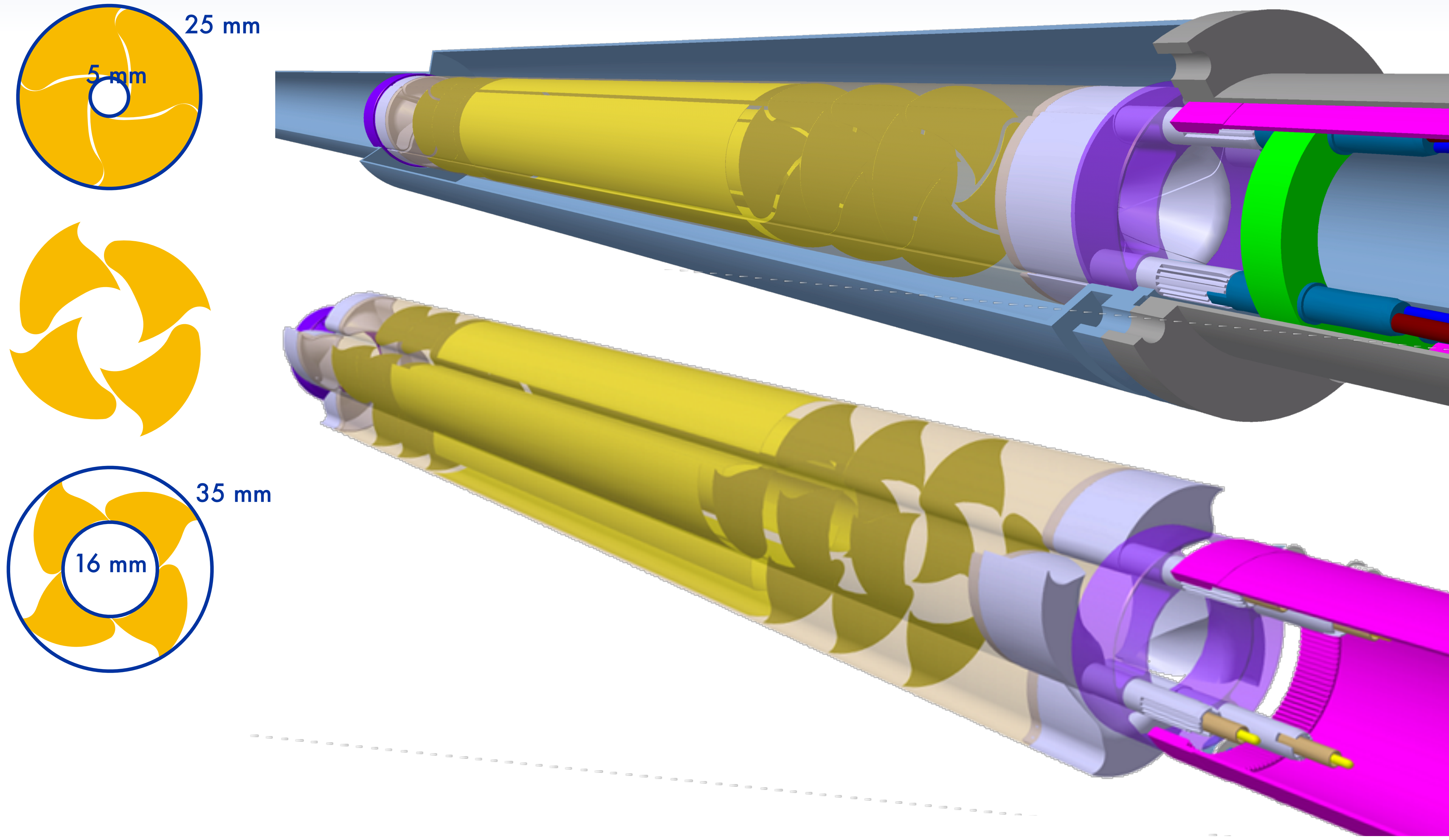


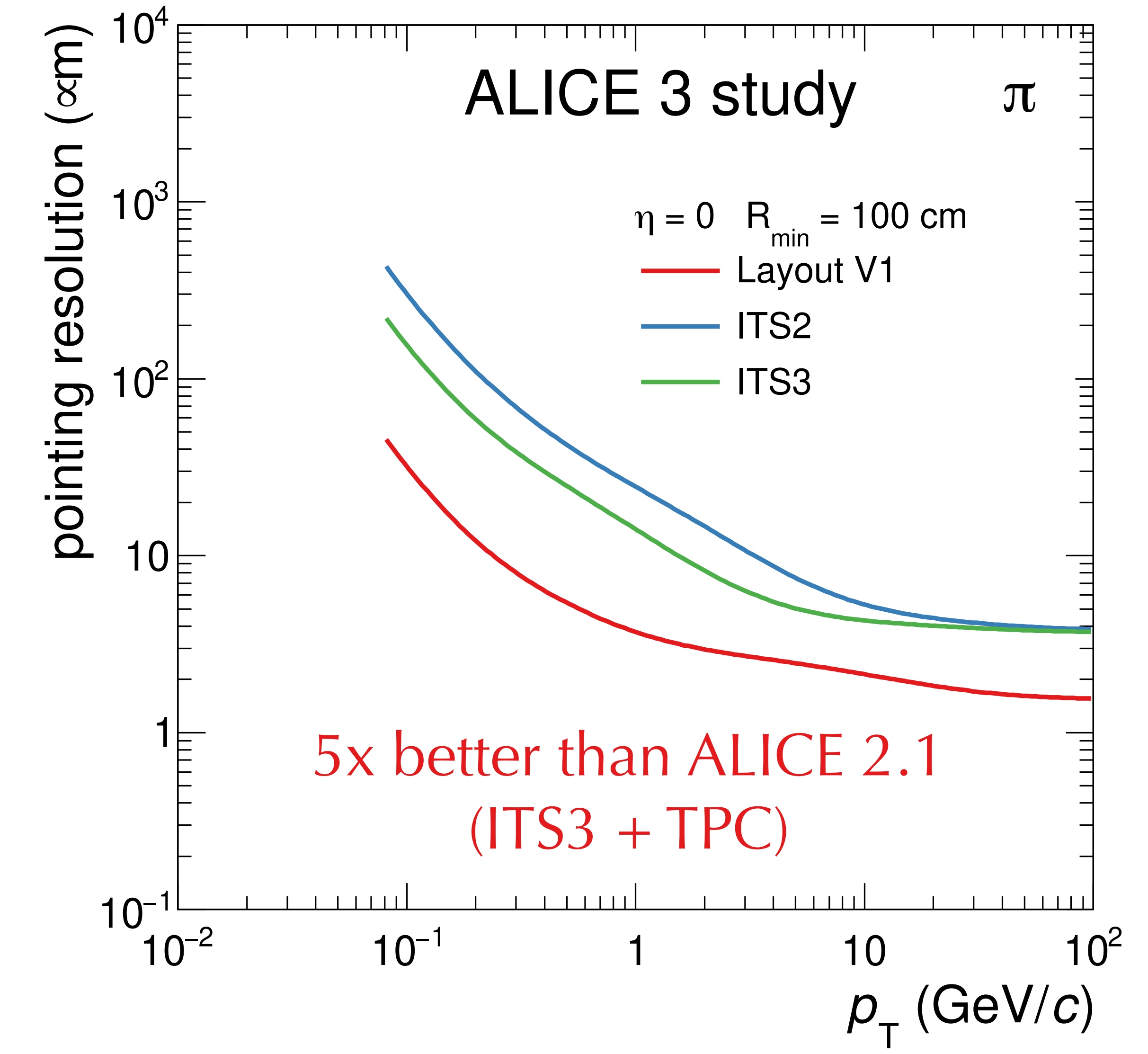
ALICE 3 vertex detector

- **3 retractable layers inside beam pipe**
  at radii of 5 - 25 mm (in secondary vacuum)
  - complex mechanics and LHC interface
  - conceptual study of IRIS tracker

- **Bent monolithic active pixel sensors**
  (pioneered with ITS3 R&D)
  - 0.1 % X_0 per layer → very thin sensors
  - σ_{pos} ~2.5 µm

Ultimate pointing resolution at the LHC





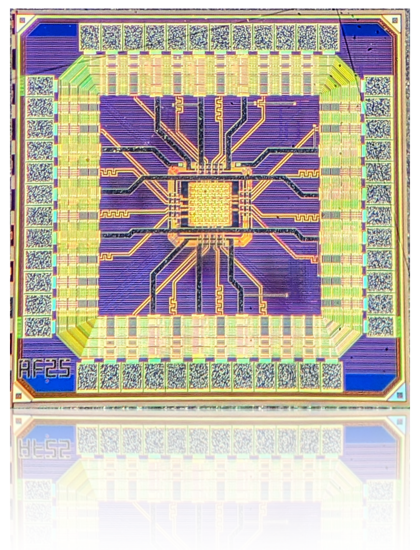
5x better than ALICE 2.1 (ITS3 + TPC)

ALI-SIMUL-491785

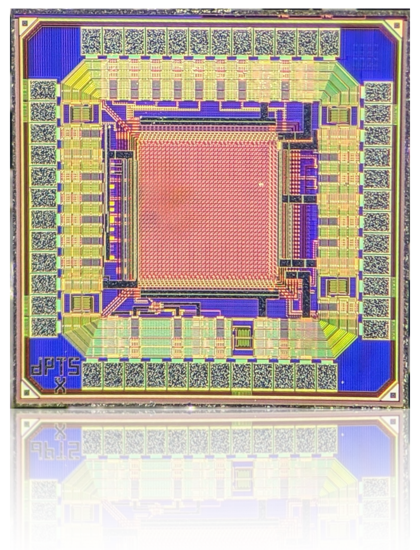
Silicon pixel R&D

- **Established TPSCo 65 nm process for pixel sensors** (extensive R&D run with 55 different prototypes)
  - excellent performance, also after irradiation

APTS

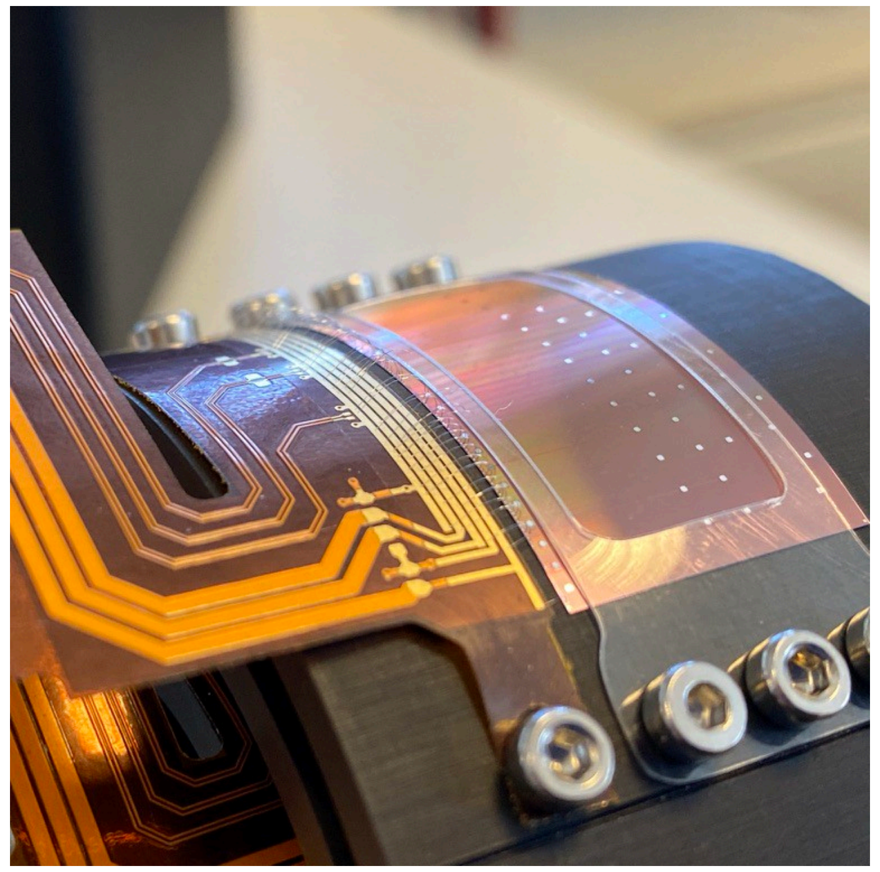


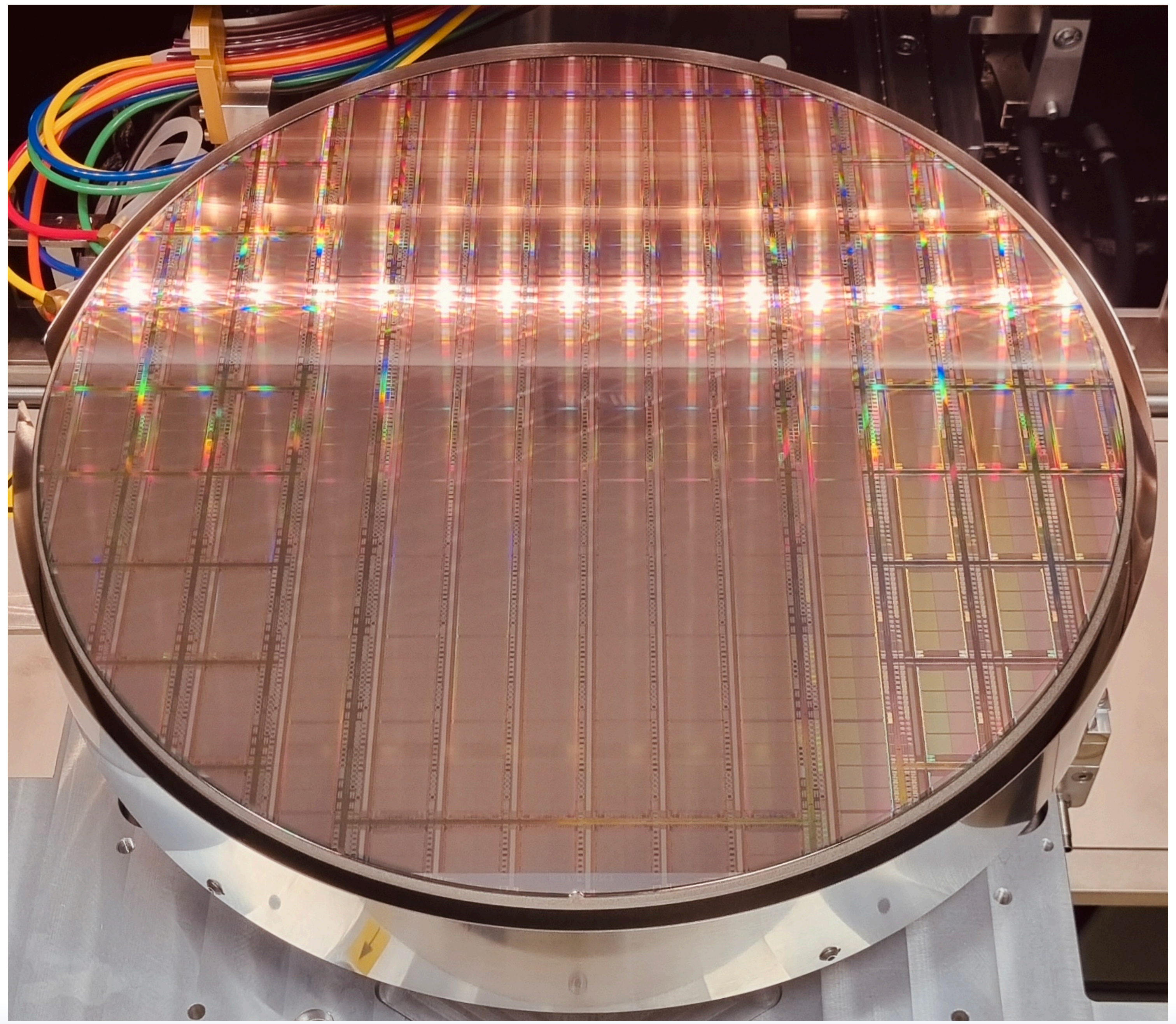
DPTS



- **Established bending of silicon sensors**
  - performance of ALPIDEs not affected at radii down to 1.8 cm
  - prototypes with wafer-scale silicon
- **Developing wafer-scale sensors**
  - stitching of repeated sensor unit
  - first wafers from engineering run received

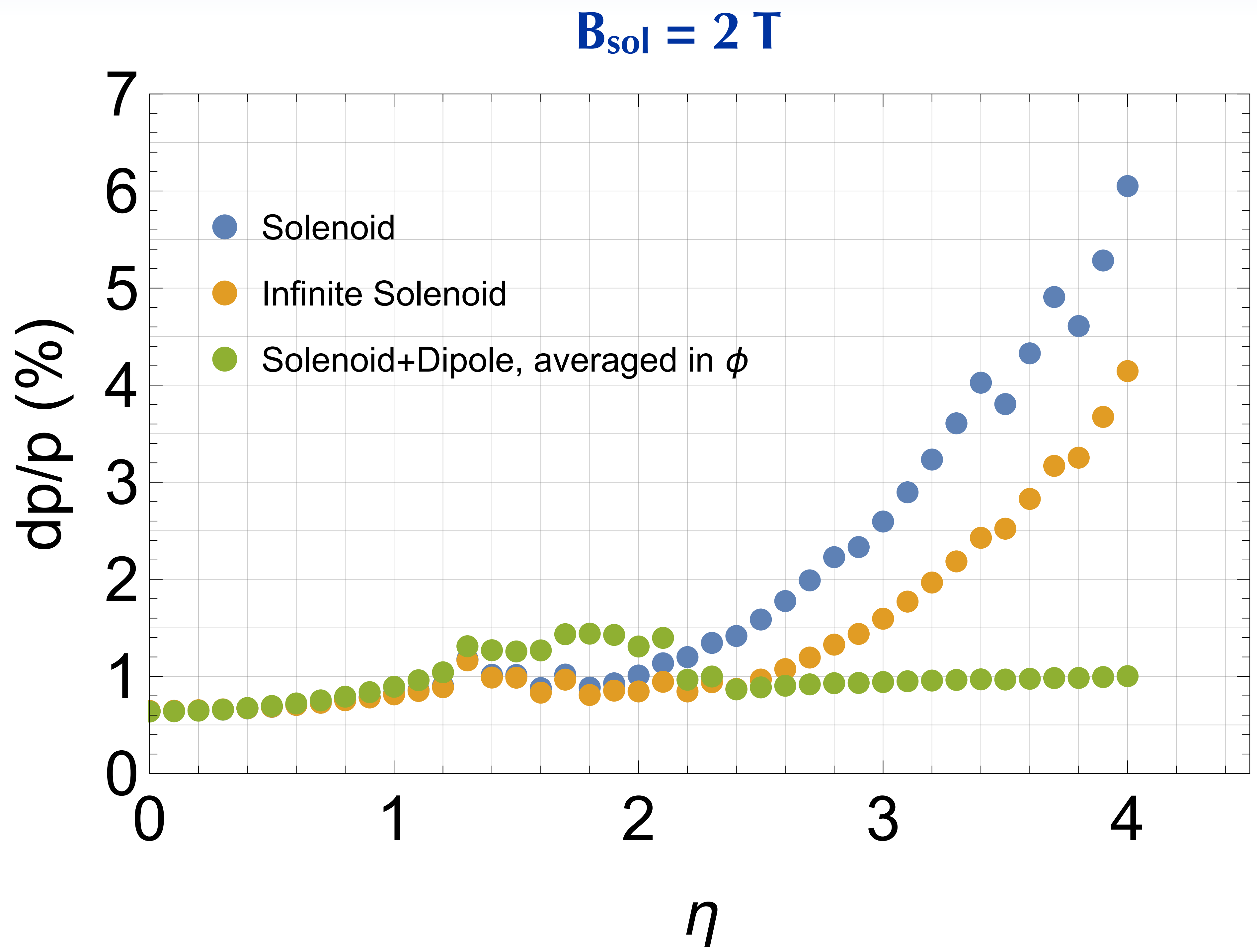
Part of ITS3 R&D
→ D. Bortoletto

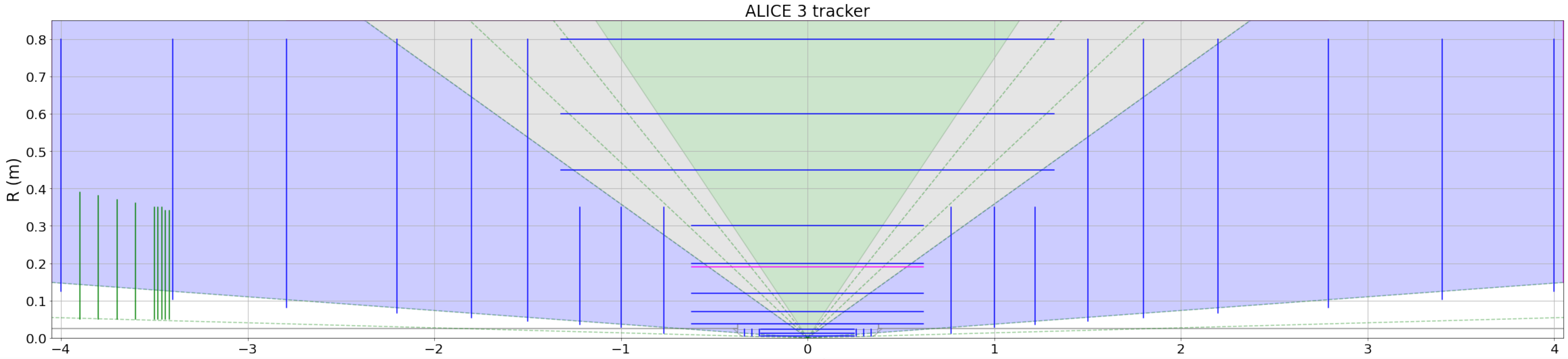




ALICE 3 tracker

- **~11 tracking layers (barrel + disks)**
  - Monolithic Active Pixel Sensors
  - $\sigma_{pos} \approx 10\ \mu m$
  - $R_{out} \approx 80$ cm and $L \approx 8$ m (field integral ~1 Tm)
  - control mismatch probability $\sigma_t \approx 100$ ns
  - ~1 % X_0 / layer → overall $X / X_0 \approx 10$ %



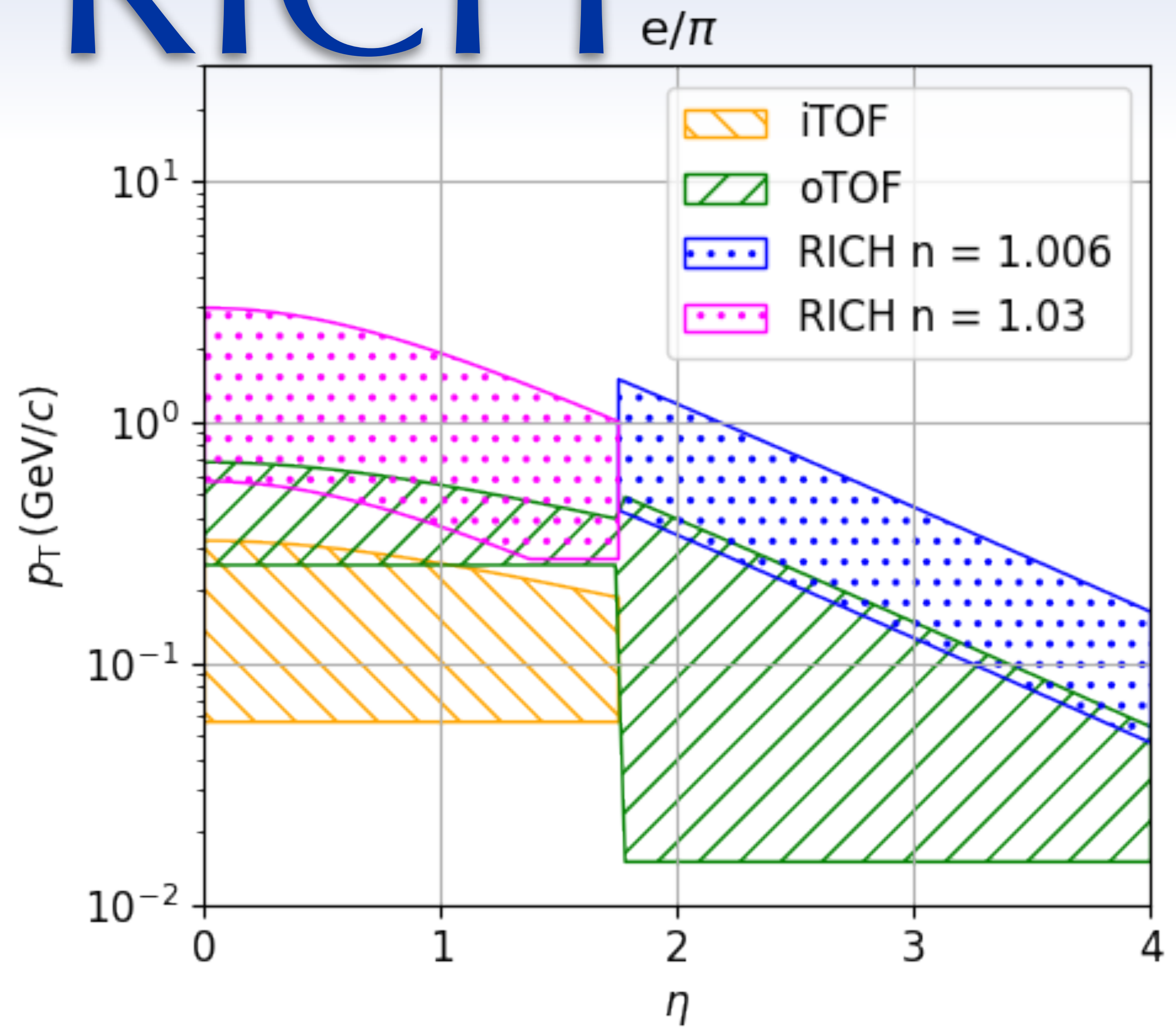


Large-scale tracker
$A \approx 60$ m²

ALICE 3 - TOF and RICH

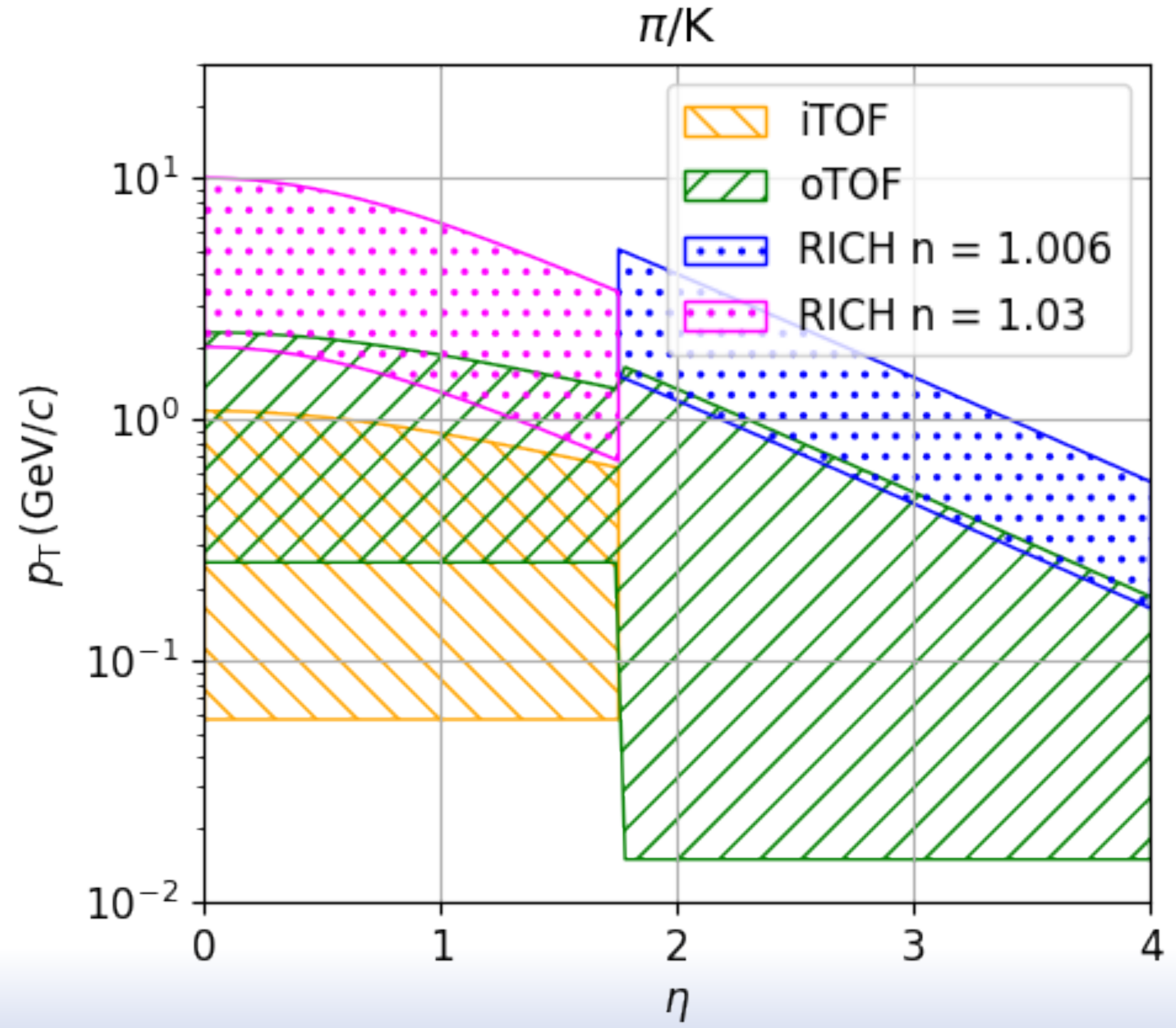
- **Time-of-flight detector**
  → thin layers integrated with tracker
  - 2 barrel + 1 forward layers:
    R ≈ 85 cm, R ≈ 19 cm, z ≈ 405 cm
  - monolithic timing sensors with **σ_{TOF} ≈ 20 ps**
    (CMOS with gain)

Instrumented area ~45 m²



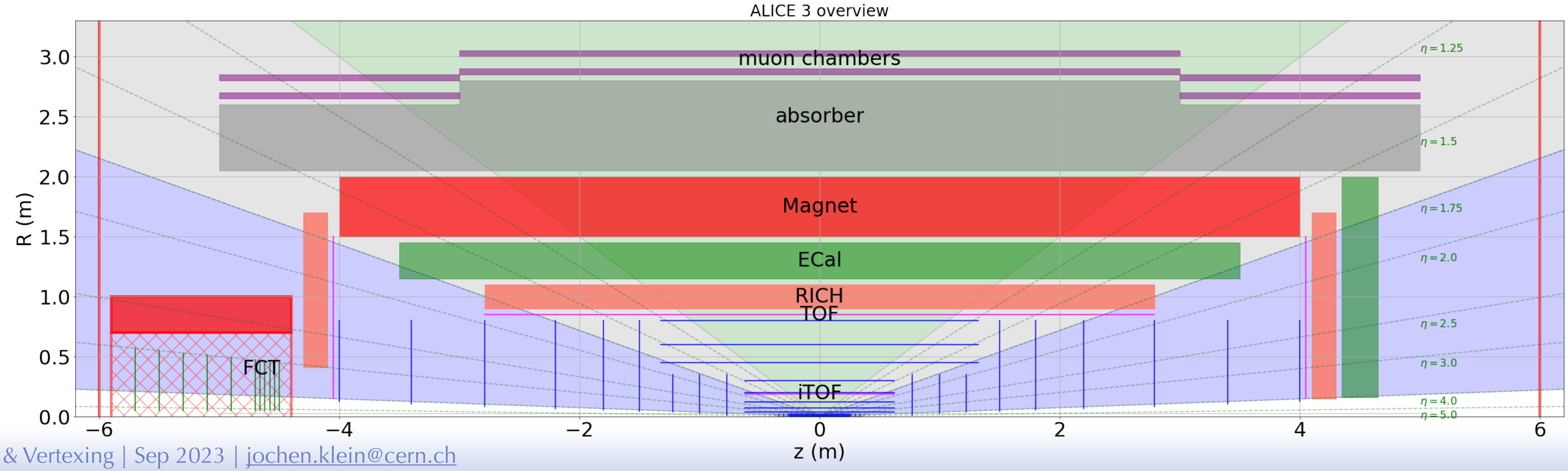
- **Ring Imaging Cherenkov Detector**
  → outside of time-of-flight detector
  - aerogel radiator
    → refractive index n = 1.03 (barrel)
    → refractive index n = 1.006 (forward)
  - silicon photon sensors
    ➡ (monolithic SiPMs)

Instrumented area ~60 m²



Probes and detector

- **Heavy-flavour hadrons** ($p_T \to 0$, wide η range)
  - ➡ vertexing, tracking, hadron ID
- **Dileptons** (p_T ~0.1 - 3 GeV/c, M_{ee} ~0.1 - 4 GeV/c^2)
  - ➡ vertexing, tracking, lepton ID
- **Photons (100 MeV/c - 50 GeV/c, wide η range)**
  - ➡ electromagnetic calorimetry
- **Quarkonia and Exotica ($p_T \to 0$)**
  - ➡ muon ID
- **Jets**
  - ➡ tracking and calorimetry, hadron ID
- **Ultrasoft photons (p_T = 1 - 50 MeV/c)**
  - ➡ dedicated forward detector
- **Nuclei**
  - ➡ identification of $z > 1$ particles



[CERN-LHCC-2021-012]

LHCC review of Framework TDR completed in March 2022

LHCb Upgrade II

RICH

- RICH1 and RICH2
- precision timing

TORCH

- Time-of-flight wall
- precision timing

Run 5 infrastructure

- engineering, mechanical support, shielding

Muon stations

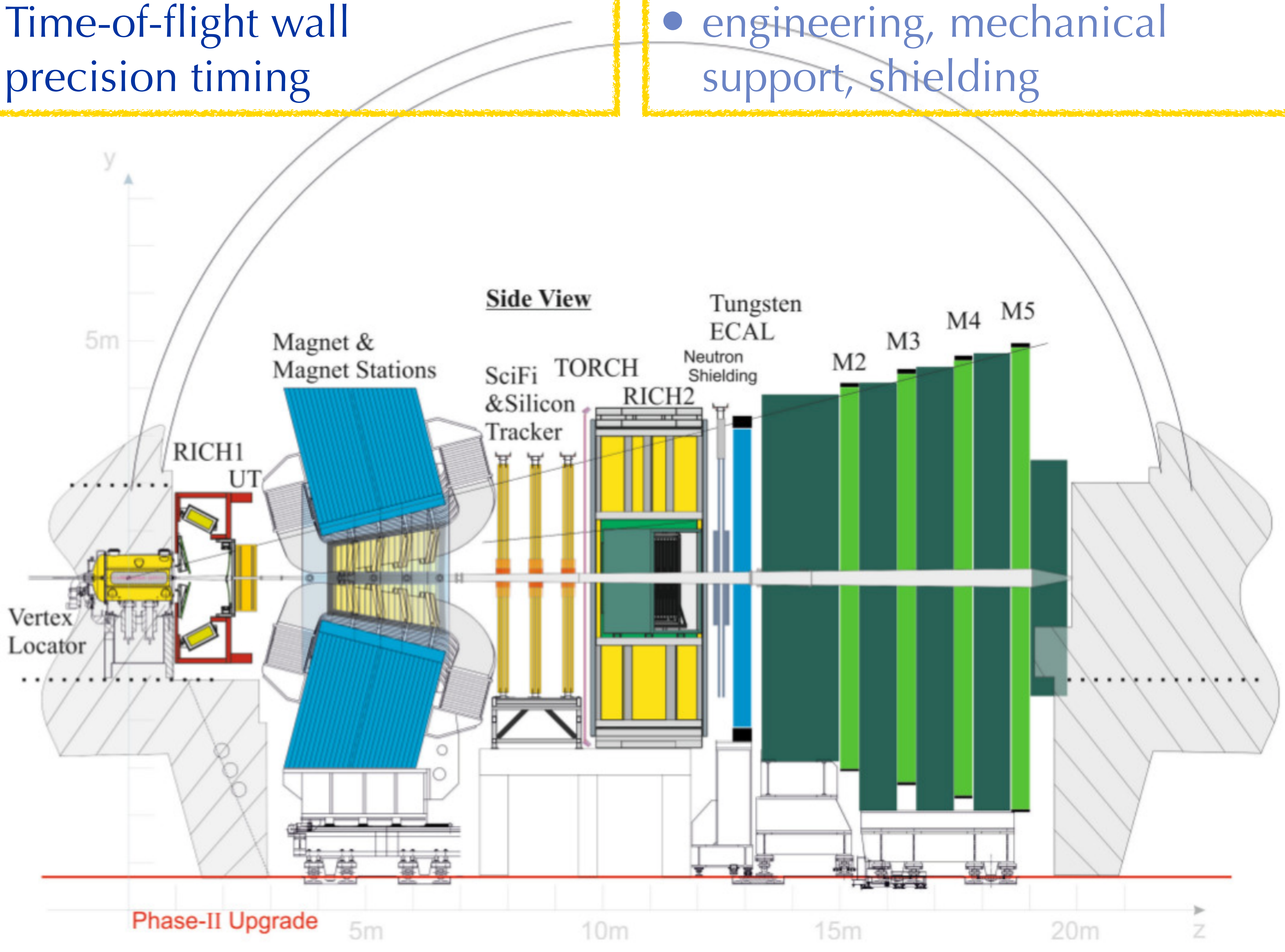
- M2 - M5
- additional shielding (instead of HCal)

Vertex Locator

- new VELO
- precision timing

Tracking

- new Upstream Tracker (timing)
- Mighty Tracker (SciFi + silicon)
- Magnet stations (possibly)
  → p_T below 5 GeV/c



Fixed target

- possible extension with polarised gas target, solid target

Calorimeters

- SPACAL or Shashlik
- precision timing

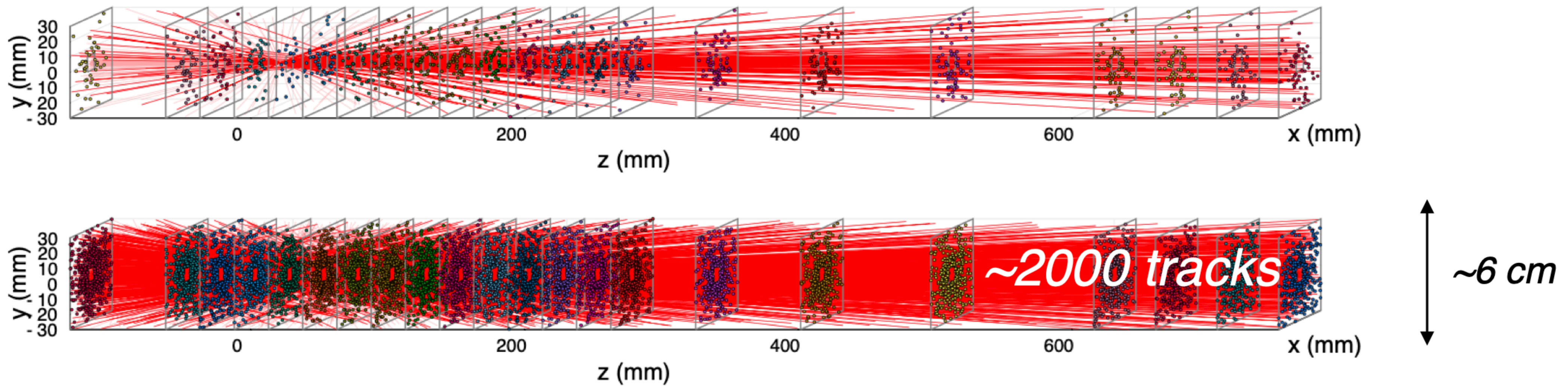
➡ **Higher rates and occupancies**

➡ **Excellent vertexing capabilities**

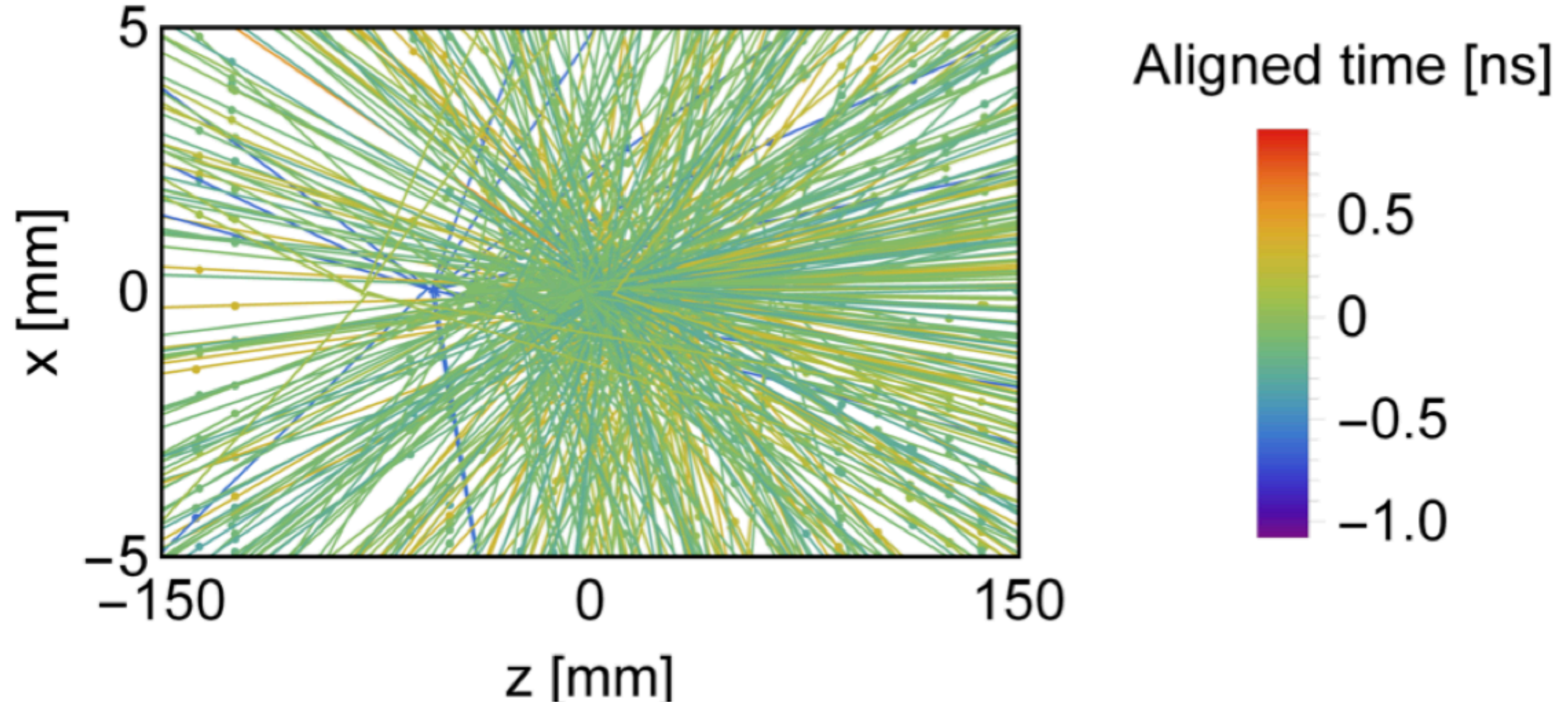
LHCb VELO

Run 3: pile-up ~6

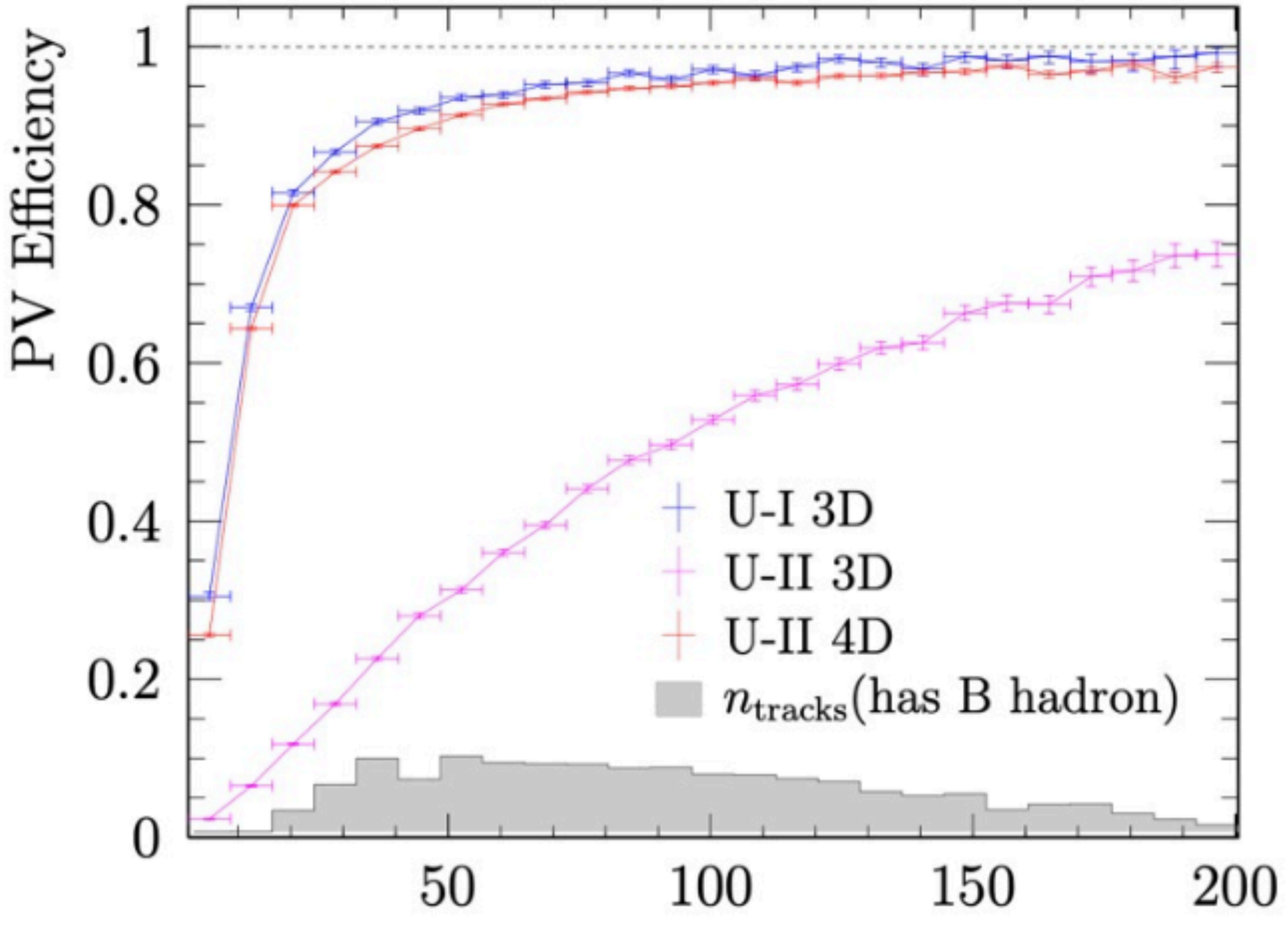
Upgrade II: pile-up ~40



track density with ~40 interactions

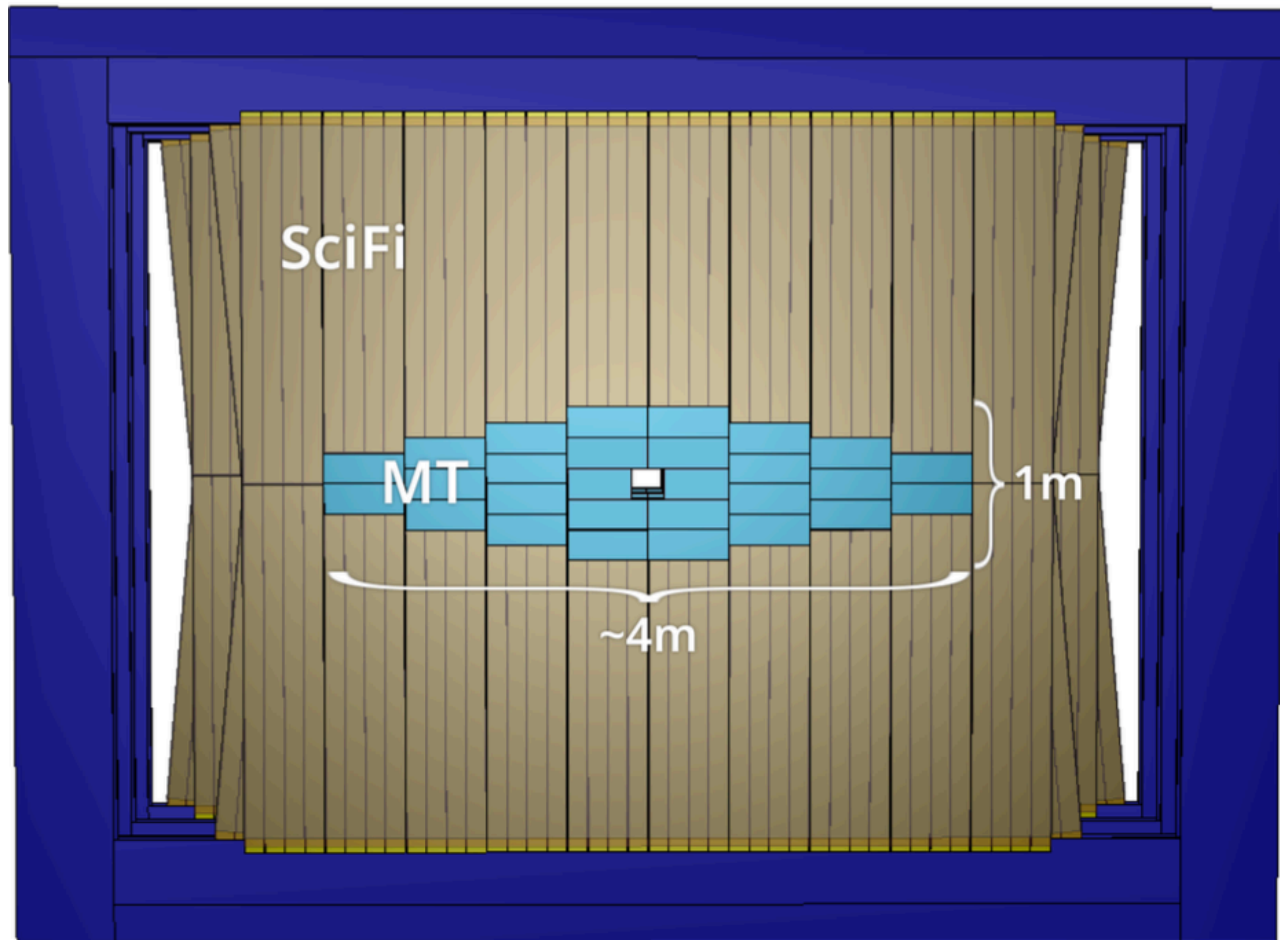


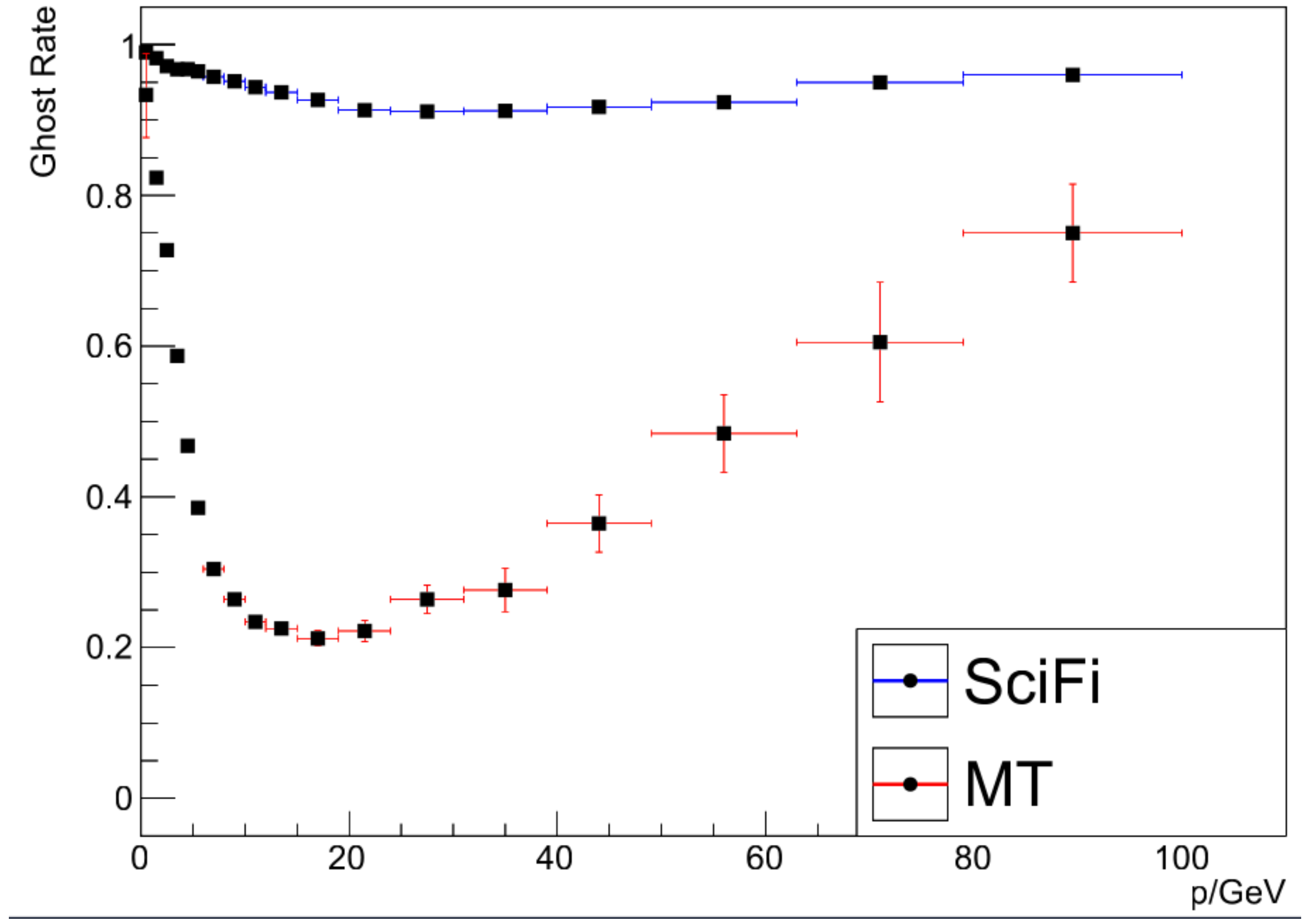
- **Retractable detector close to interaction point**
  → active R&D on sensors
  - addition of precision timing (tens of ps)
  - excellent position resolution (< 10 μm)
  - radiation hard ($6 \cdot 10^{16}$ n_{eq}/cm^2)
- **4d tracking to exploit precision timing**
  → upgrade I performance despite high luminosity



LHCb mighty tracker

- **Forward tracking**
  with dipole field ∫B dl = 4 Tm
- **Monolithic Active Pixel Sensors** (inner region)
  - low-cost, commercial process
  - pixel size to be optimised (100x300, 50x150 μm²)
  - up to $3 \cdot 10^{15}$ n_{eq}/cm^2
- **Scintillating fibres** (outer region)
  - radiation-hard fibres
  - micro-lens enhanced SiPMs
  - 250 μm diameter → ~100 μm resolution





ATLAS phase II upgrades

LAr calorimeter

- **Segmented super-cells:** shower-shape discrimination at trigger level

Trigger and DAQ

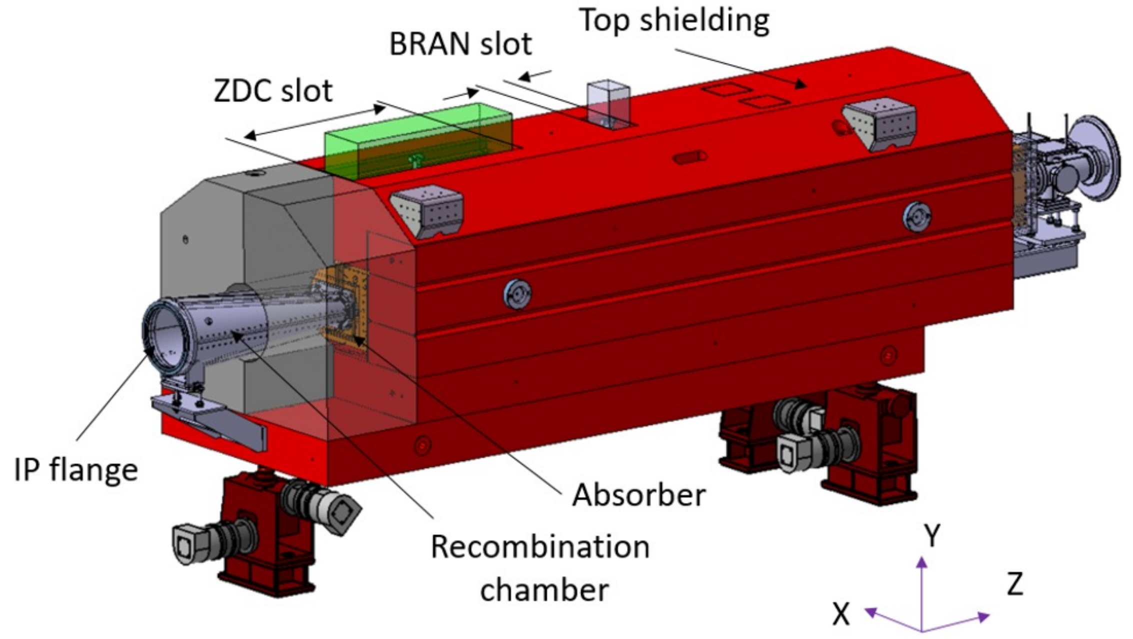
- L1 and HLT improvements
- Further upgrades

Electronics upgrades

Luminosity detectors

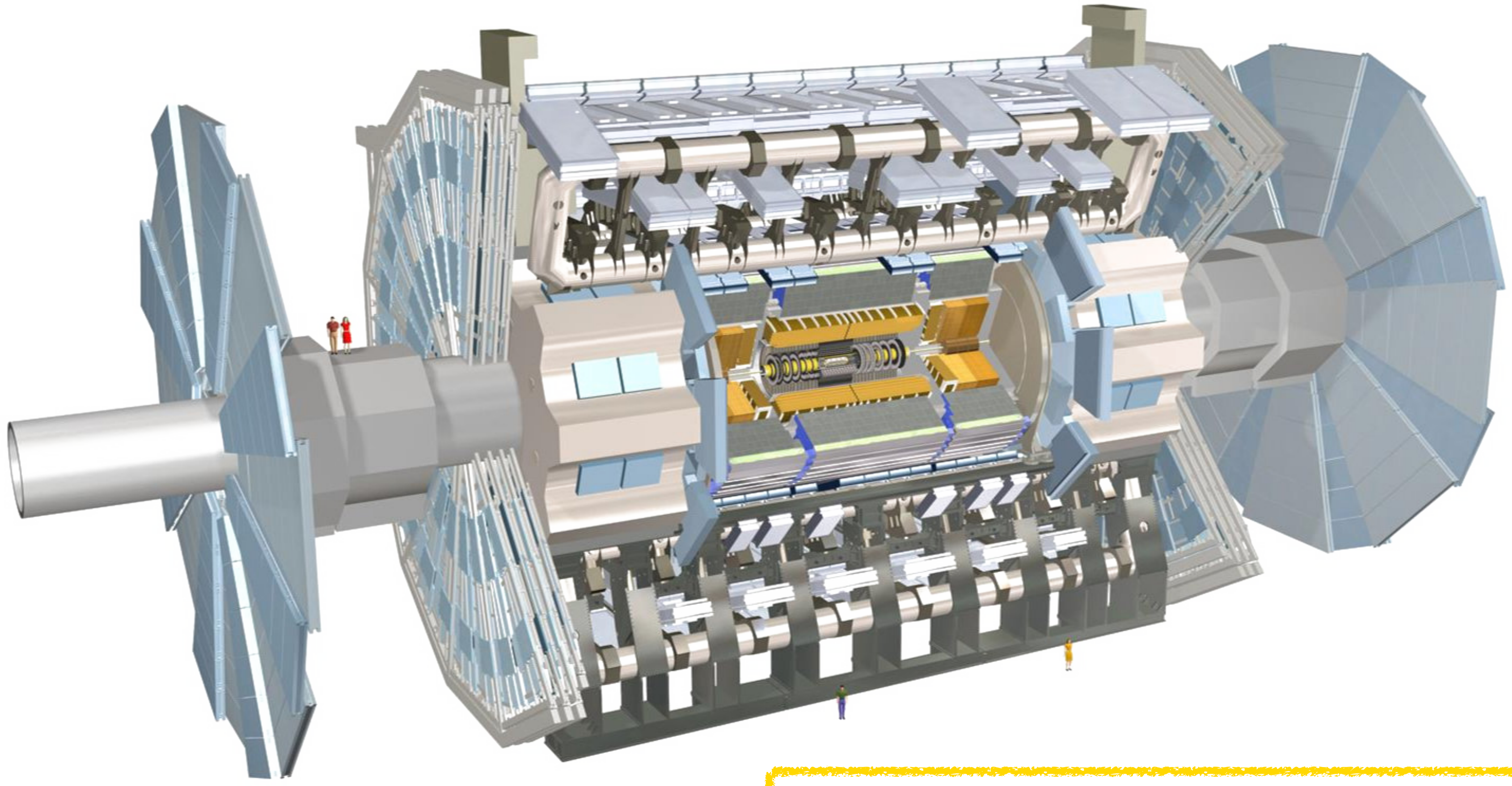
HL-ZDC

- JZCaP (jointly with CMS)
- adapt to new optics
- increase radiation hardness
- Reaction plane detector



High-granularity timing detector

- Based on LGADs
- treatment of pile-up
- PID with $\sigma_{TOF} \approx 35$ ps
- Baseline trigger for HI

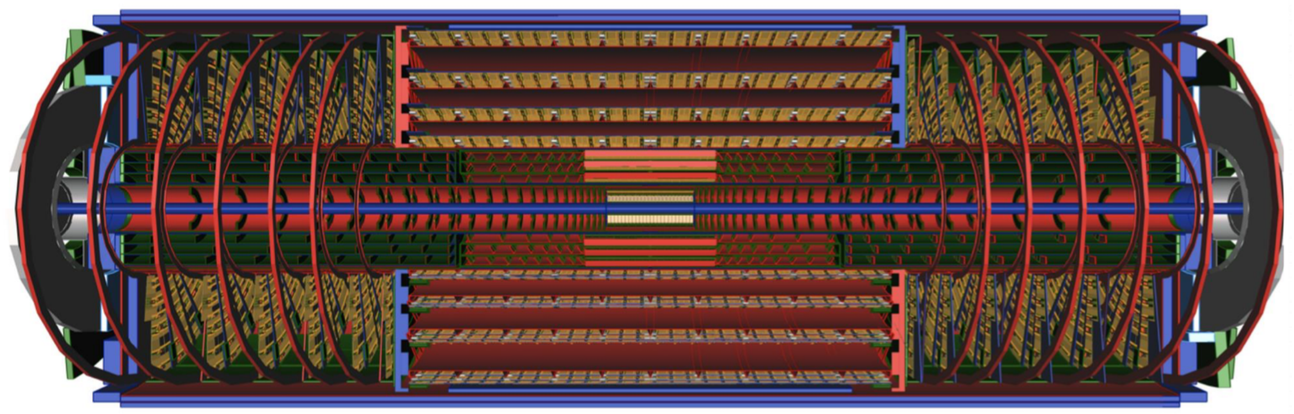


Endcap calorimeters

- higher granularity

New Inner Tracker (ITk)

- hybrid silicon pixel and strip sensors
- coverage up to $|\eta| < 4$



Muon system

- **New Small Wheels** installed
  → sTGC + MicroMegas
- **New muon chambers**

➠ **Extend tracker acceptance to $|\eta| < 4$**

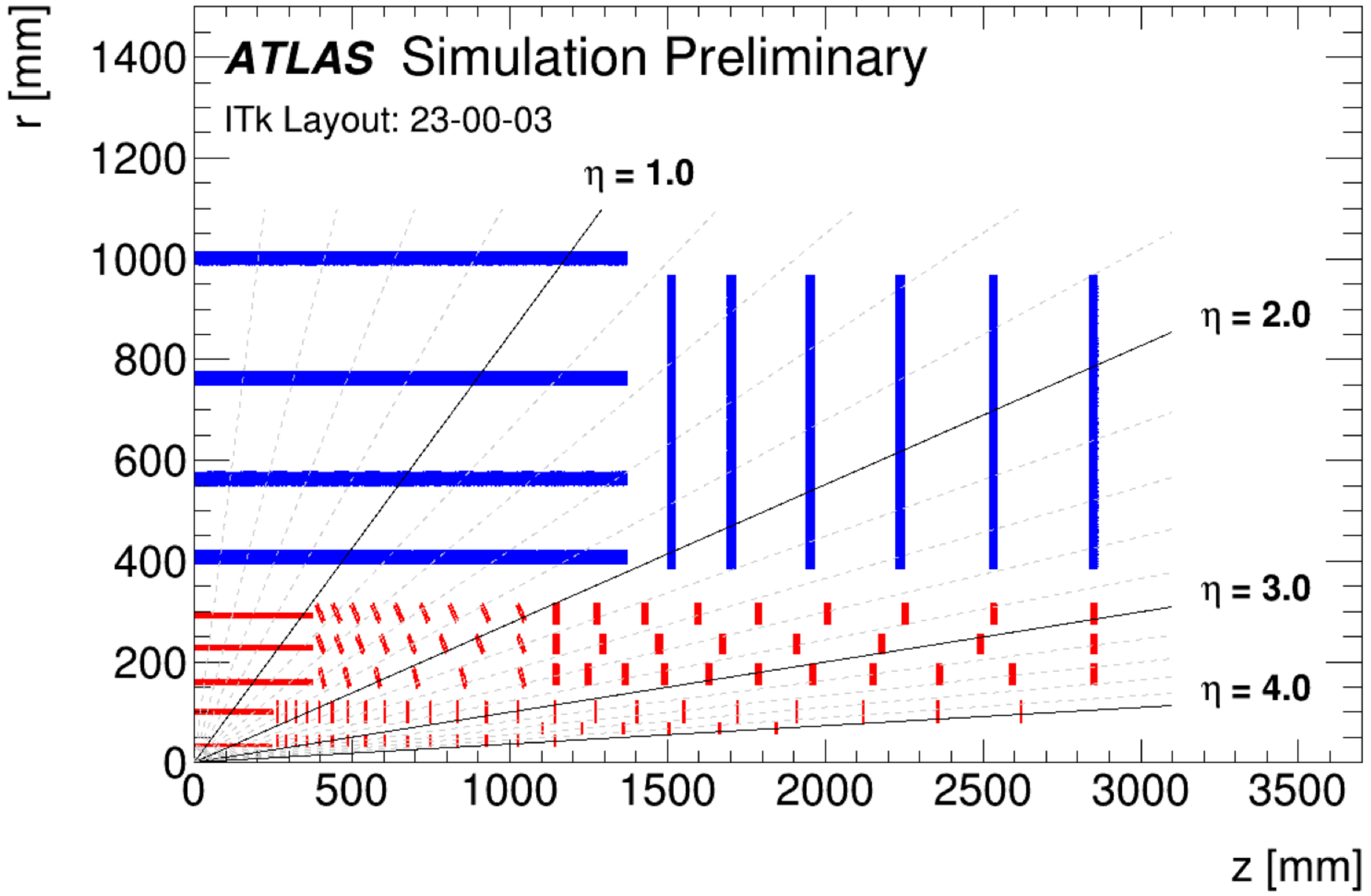
➠ **Time-of-flight PID $2.5 < |\eta| < 4$**

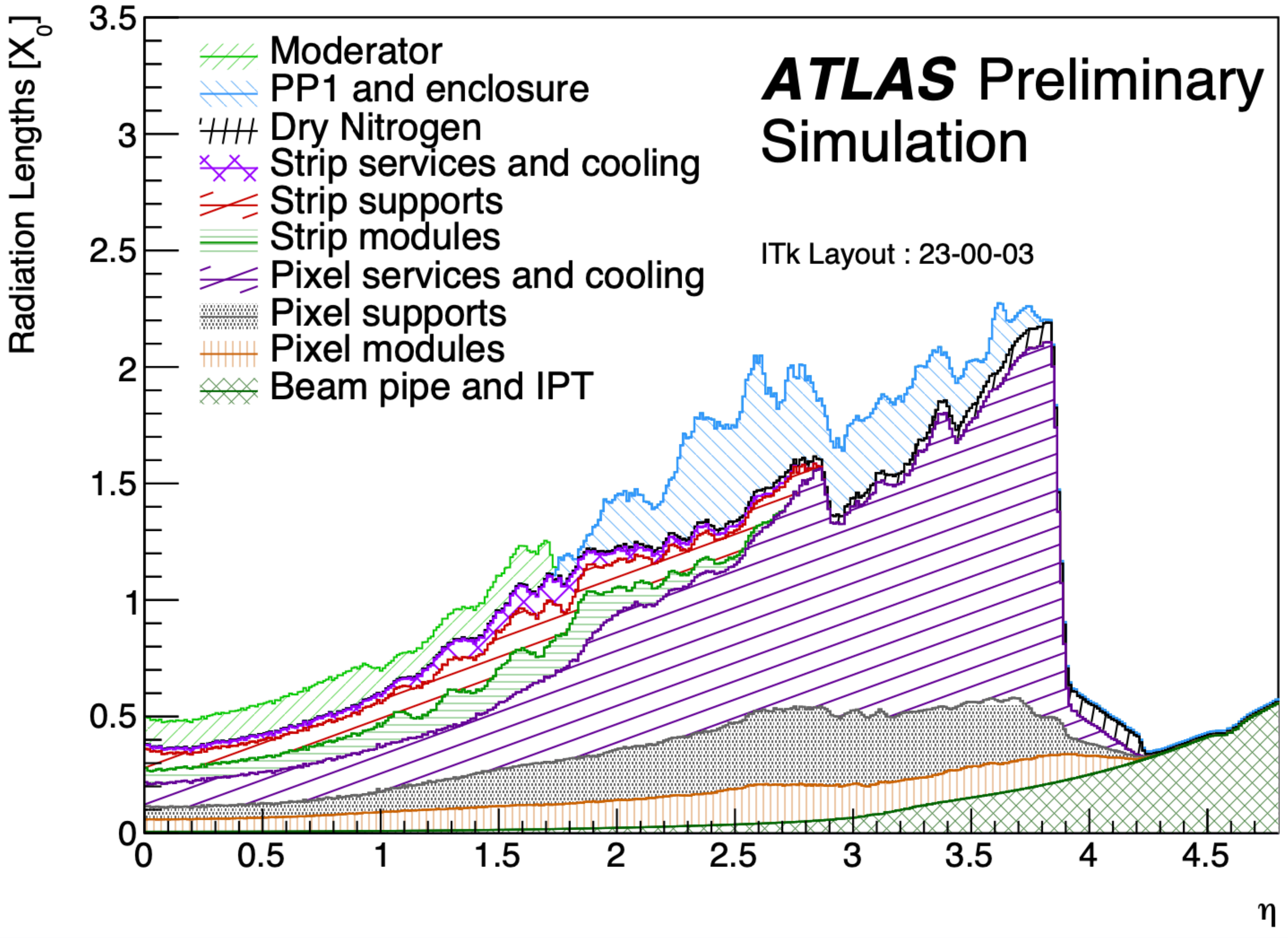
➠ **Endcap calorimeters with higher granularity**

Run 1 Run 2 Run 3 Run 4 Run 5 Run 6

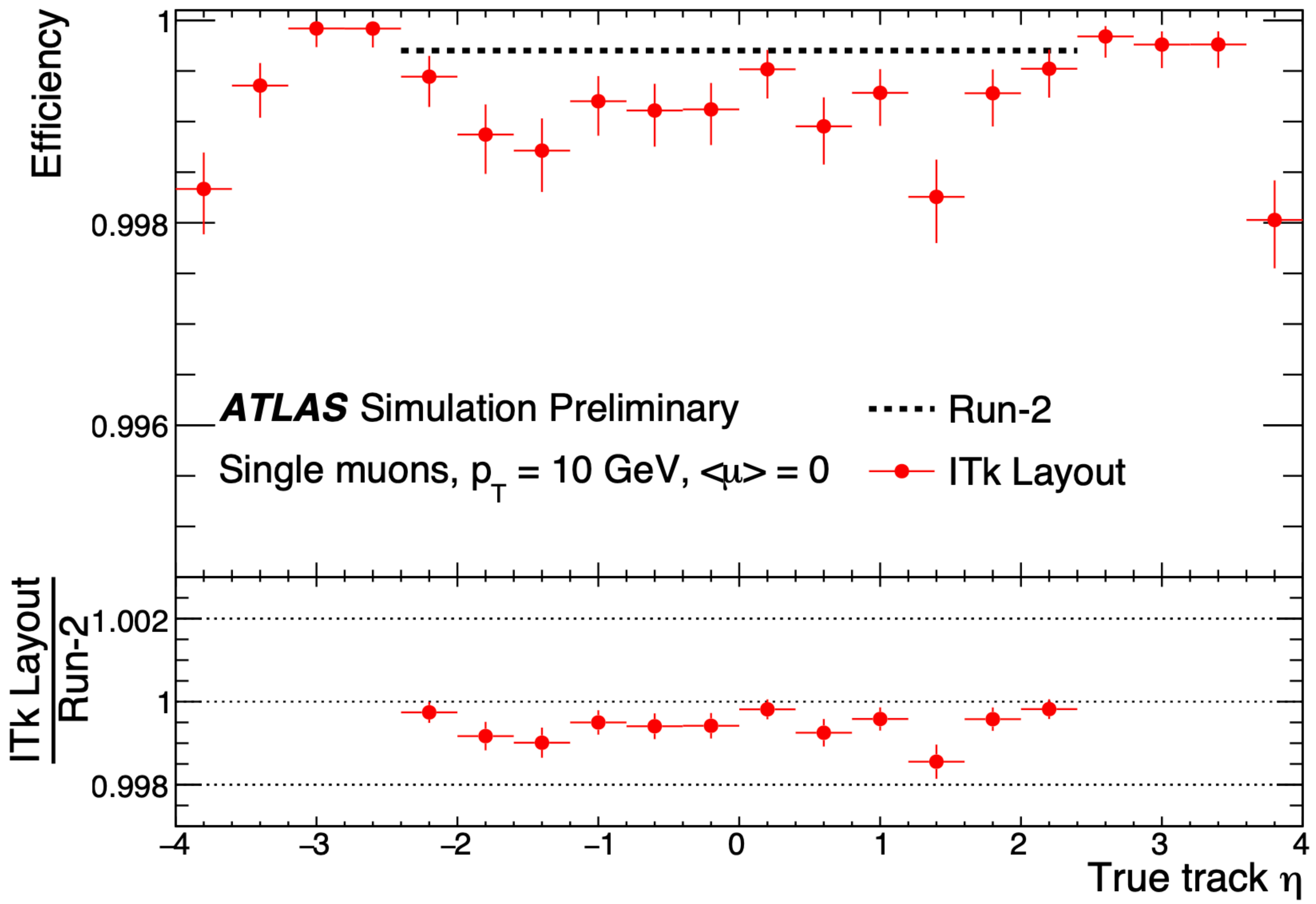
ATLAS ITk

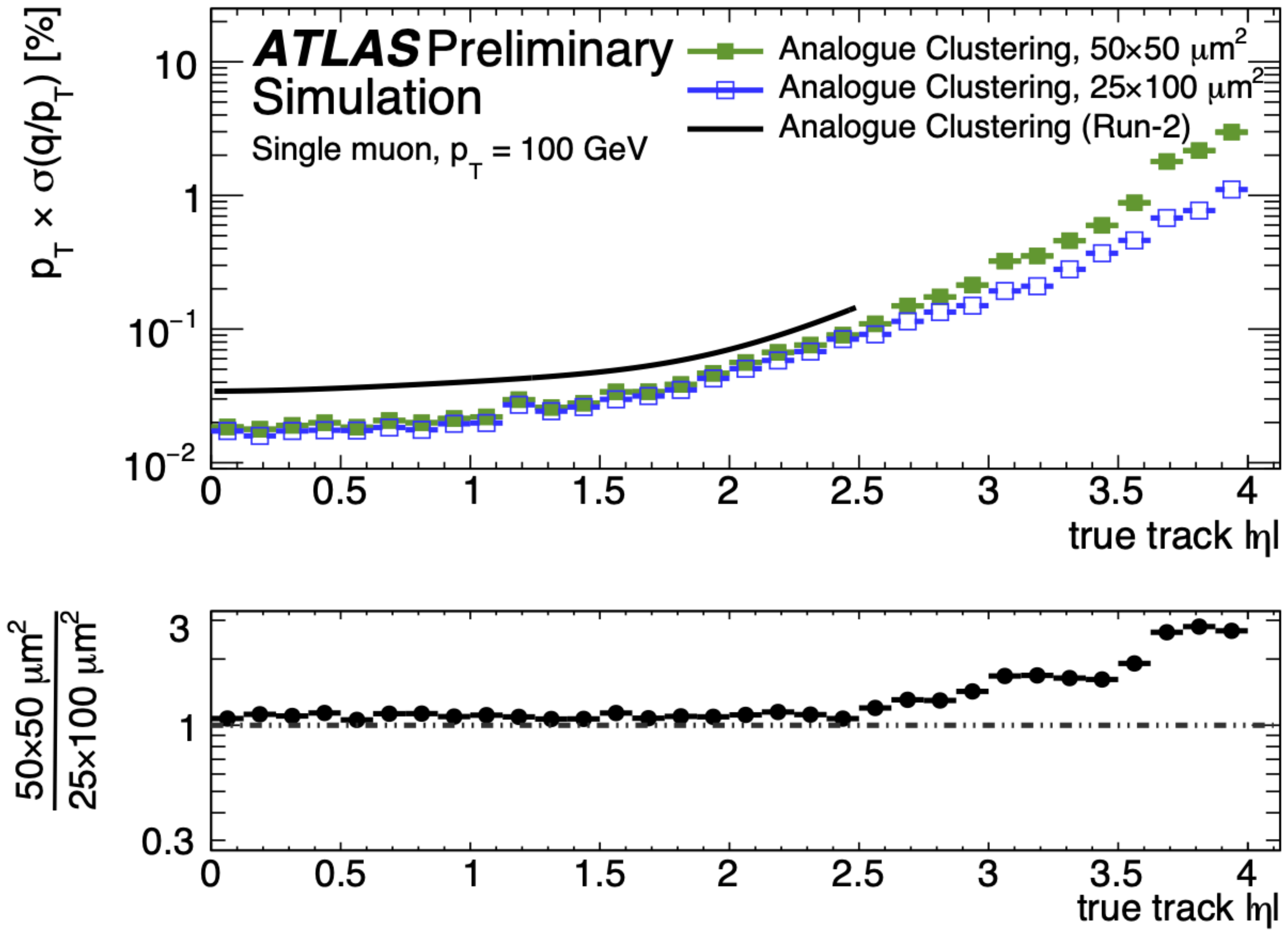
- **2 T solenoidal magnet**
- **Large coverage up to |η| = 4**
  - barrel for central part
  - inclined layers in intermediate region
  - endcaps in forward region
- **Combination of technologies**
  - hybrid Si pixel sensors for inner layers: 1.4 Gp, $A \approx 13\ \mathrm{m}^2$, $r_0 \approx 34$ mm, ~0.7 X_0, 25x100 / 50 x 50 $\mu\mathrm{m}^2$
  - Si strip detectors for outer layers: $A \approx 165\ \mathrm{m}^2$, ~0.6 $X_{0,}$ $p \approx 70\ \mu\mathrm{m}$





ATLAS ITk performance





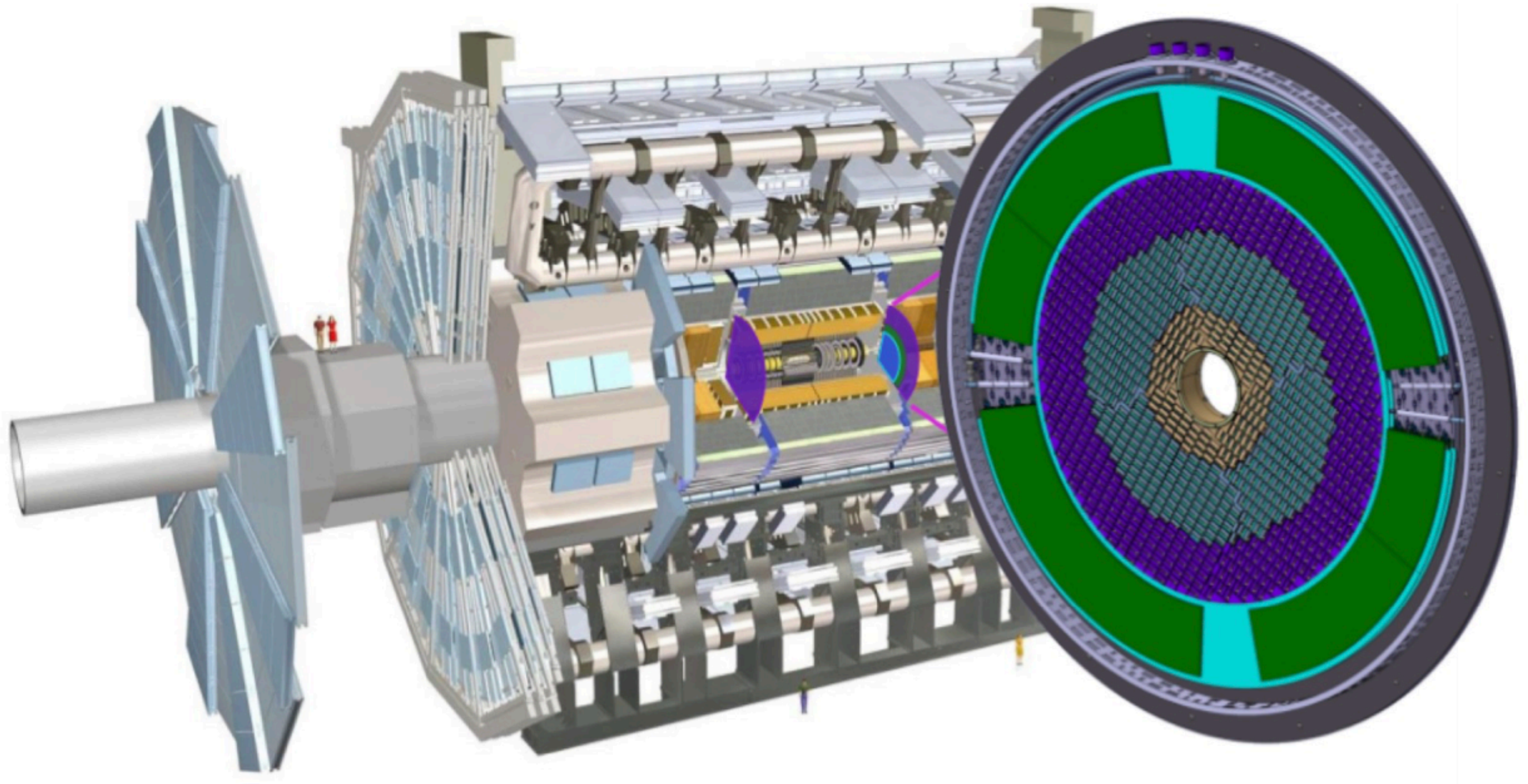
- Good efficiency over full η range

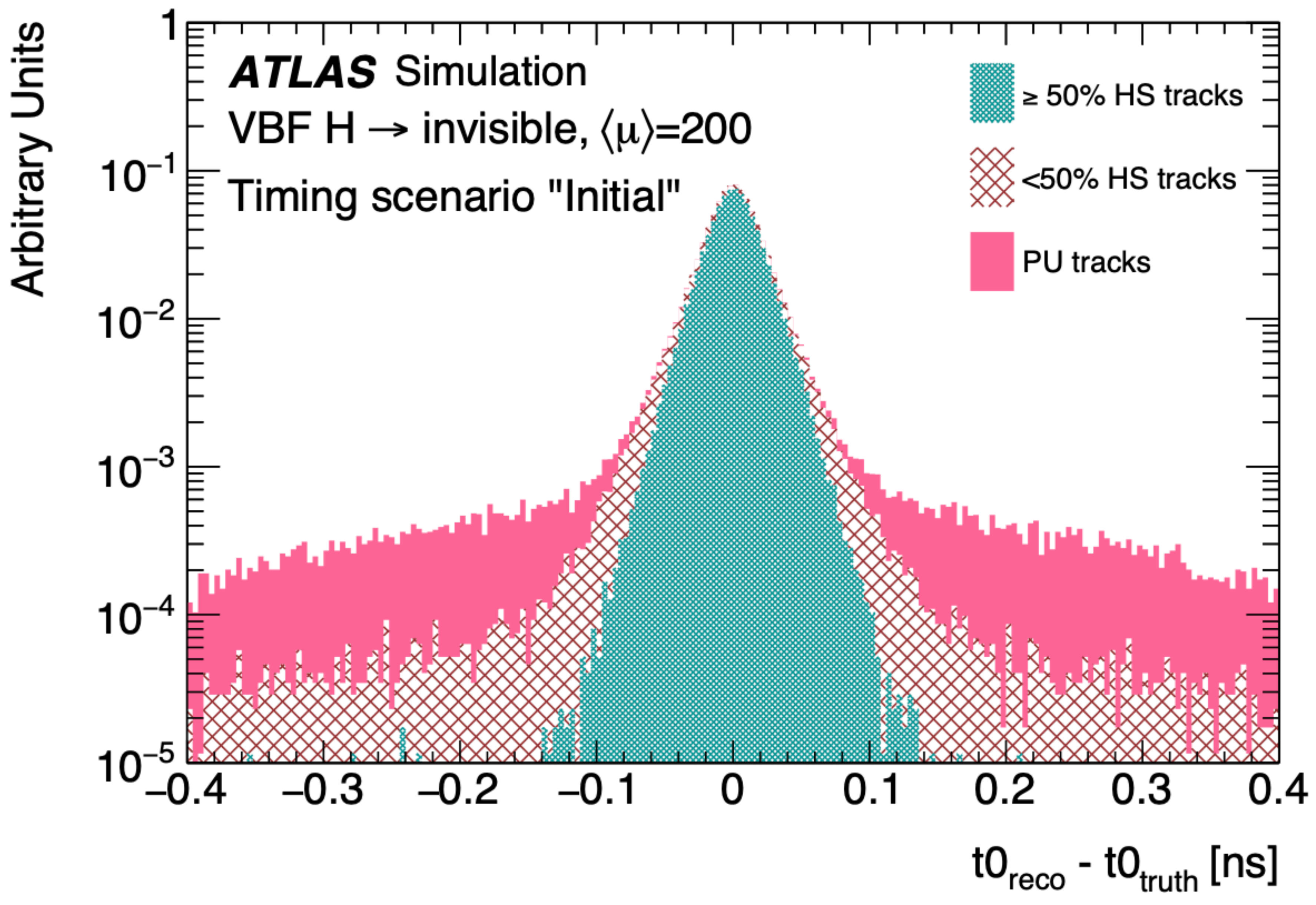
- p_T resolution increases towards larger η as expected from material

[ATL-PHYS-PUB-2019-014]

ATLAS High Granularity Timing Detector

- Precision time reconstruction (30 ps) using Low-Gain Avalanche Detectors (LGAD)
- Time slicing to maintain primary vertex reconstruction performance as now despite higher luminosity
- Measurement of bunch-by-bunch luminosity

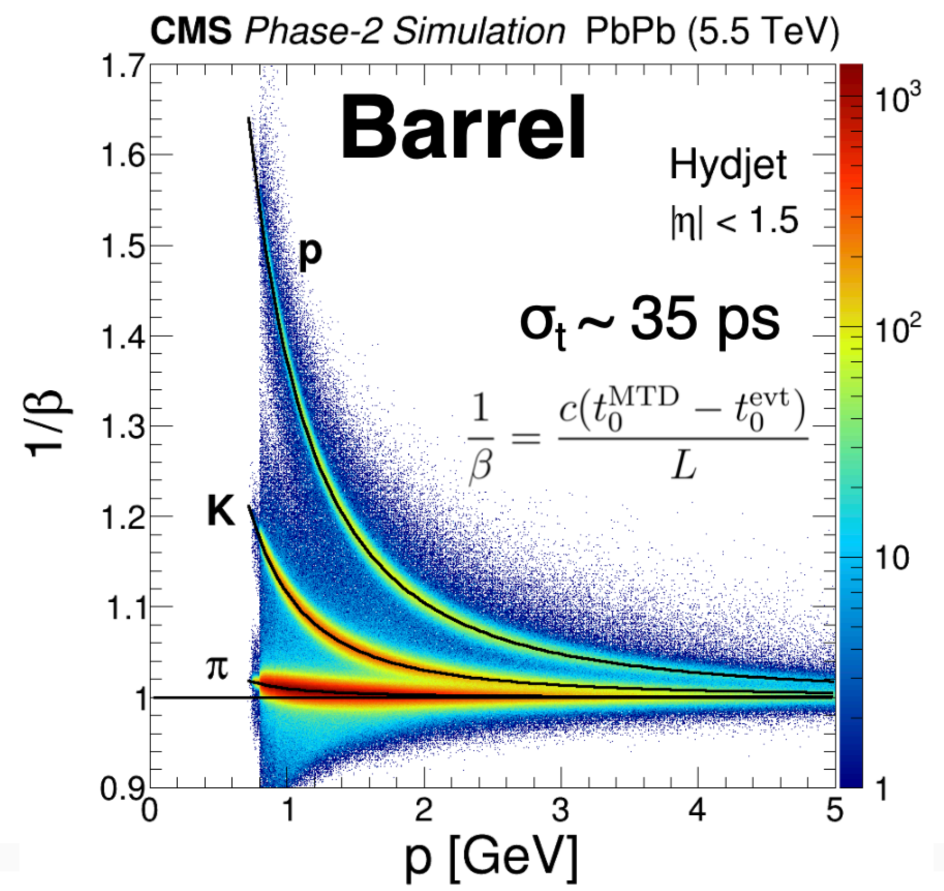




CMS phase II upgrades

MIP timing detector

- barrel: LYSO + SiPMs
- endcaps: LGADs
- $\sigma_{TOF} \approx 30$ ps



Tracker

- inner: hybrid silicon pixels
- outer: hybrid silicon pixels + strips

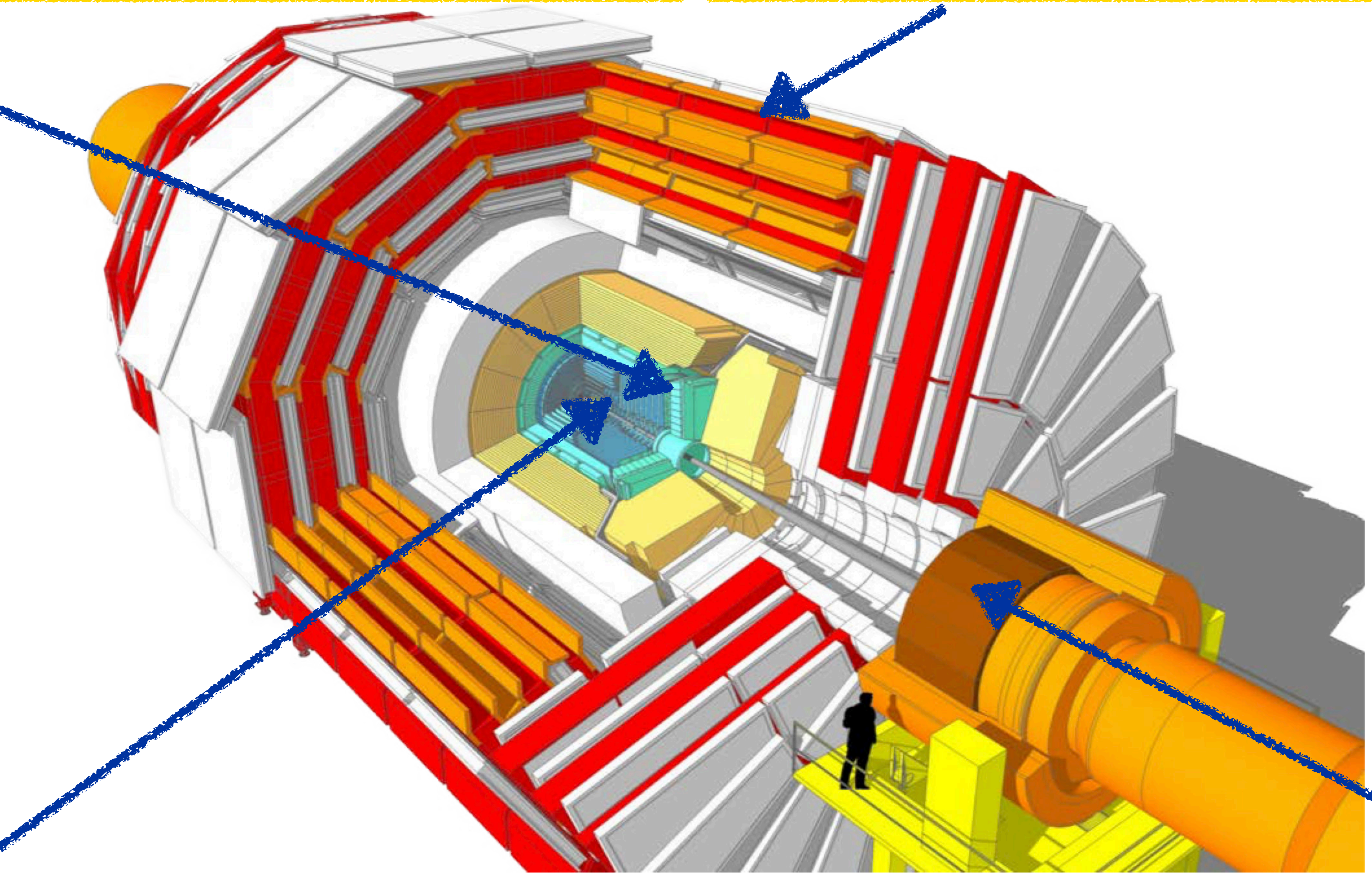
HCal

- HPD → SiPMs

L1 trigger, HLT, DAQ

Luminosity detectors

New readout for muon system



➡ **Charged particle tracking up to |η| < 4, muons up to |η| < 3**

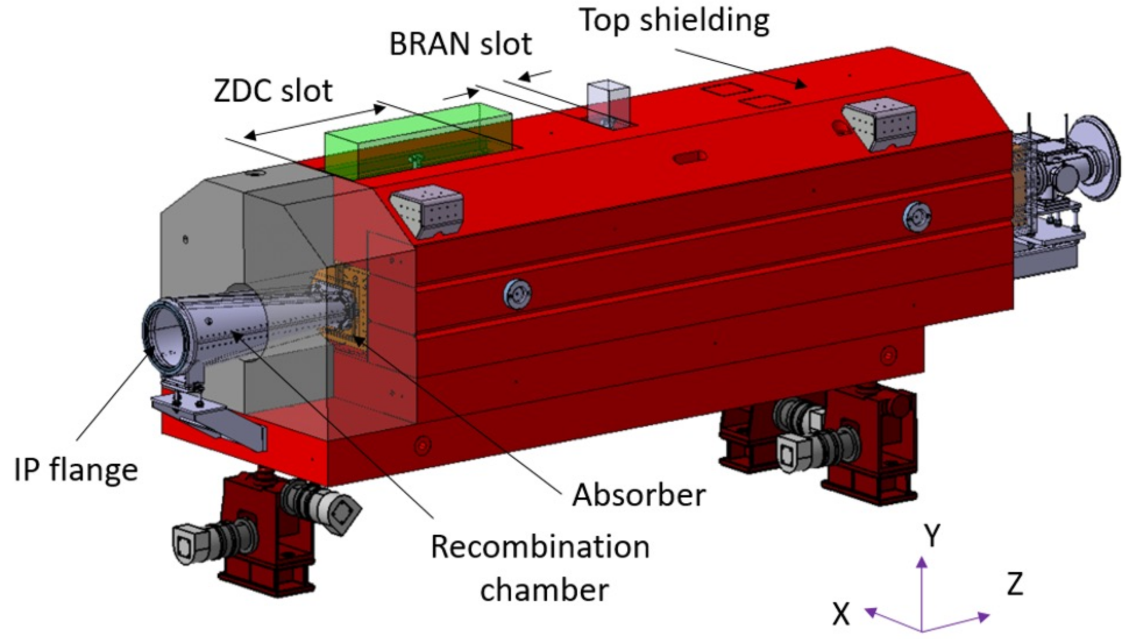
➡ **Time-of-flight PID up to |η| < 3**

➡ **High-precision vertexing**

➡ **Wide coverage calorimetry**

HL-ZDC

- JZCaP (jointly with CMS)
- adapt to new optics
- increase radiation hardness
- Reaction plane detector



Endcap calorimeter

- **High-granular ECal + HCal → 4d showers ($\sigma_t \approx 20$ ps)**

Forward muon system

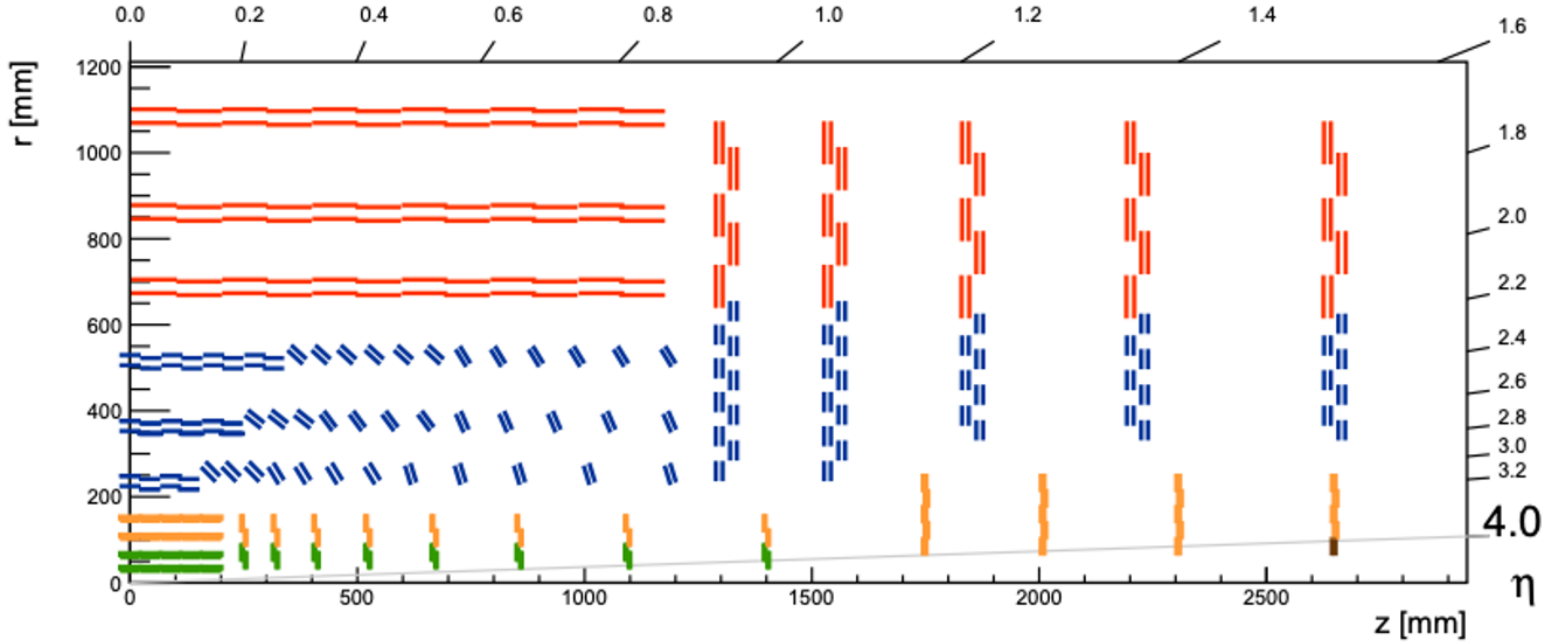
- All GEM chambers
- new frontend electronics for CSC endcaps

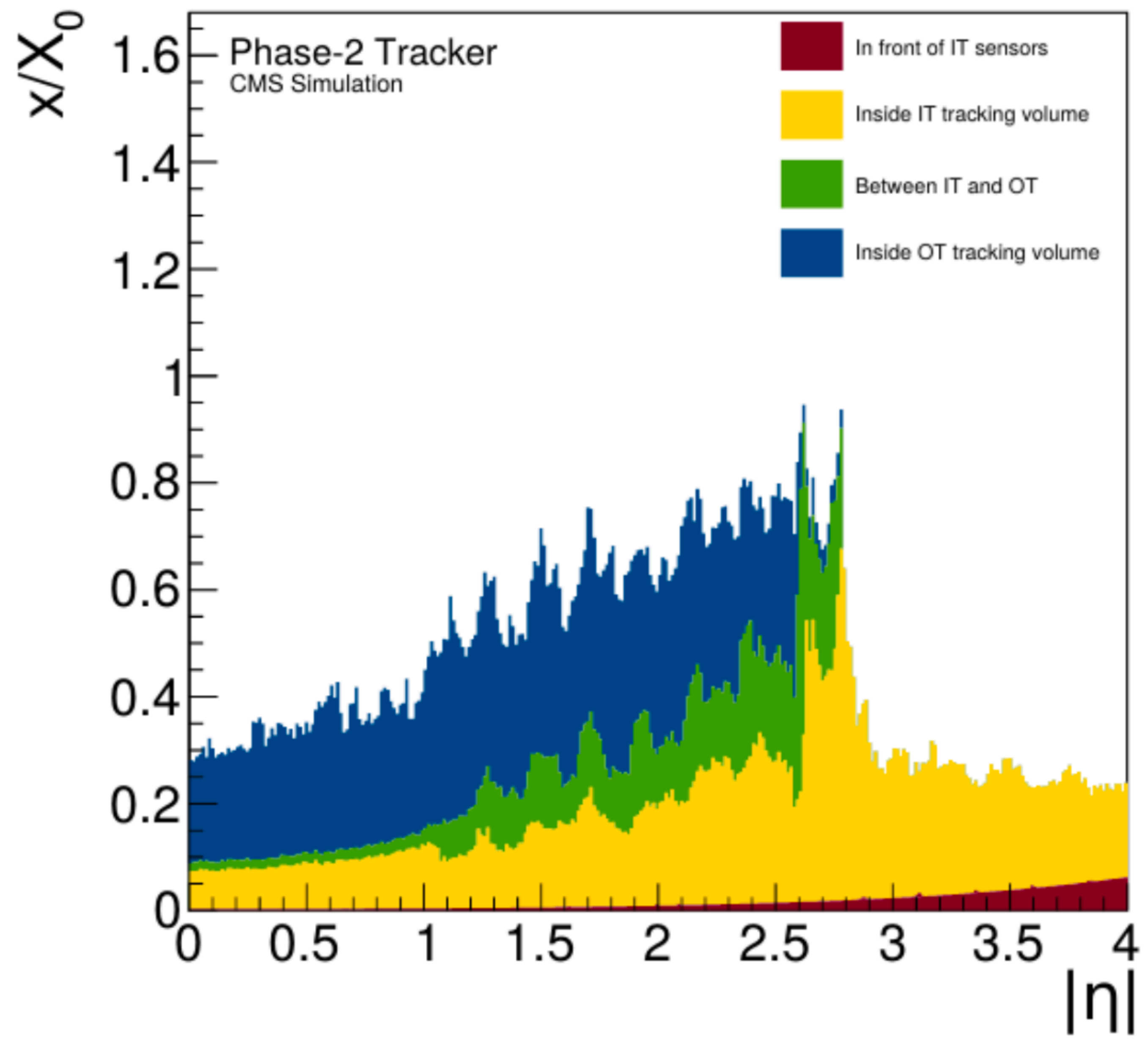
CMS tracker

- **3.8 T magnet**

- **Large coverage up to |η| = 4**
  - barrel for central part
  - inclined layers in intermediate region
  - endcaps in forward region

- **Combination of technologies** (A ≈ 200 m^2)
  - Si pixel layers for inner layers:
    1.4 Gp, p = 100 µm, $r_0 \approx 29$ mm
  - Si strip detectors for outer layers
    (pixel-strip and strip-strip modules)

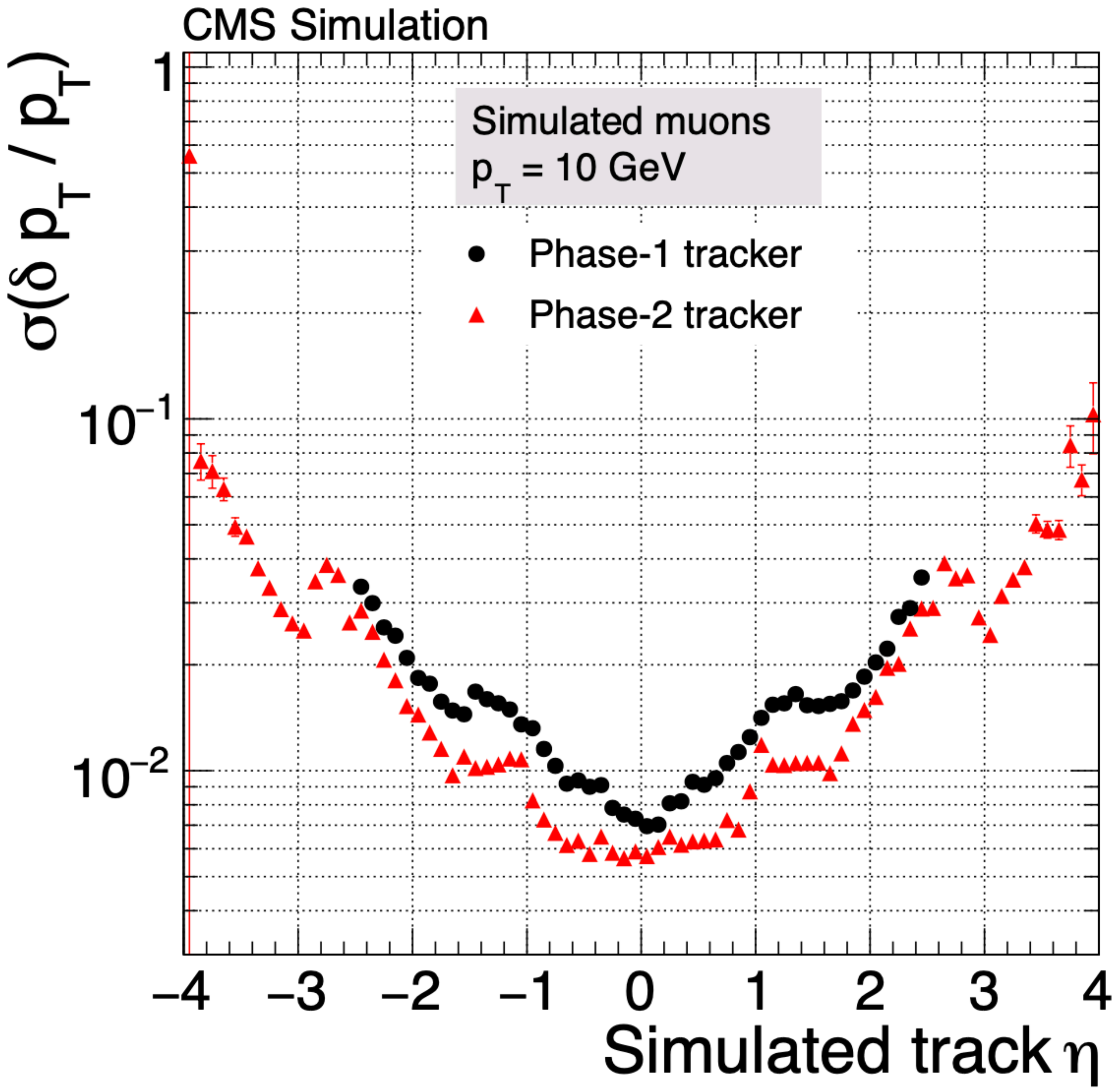


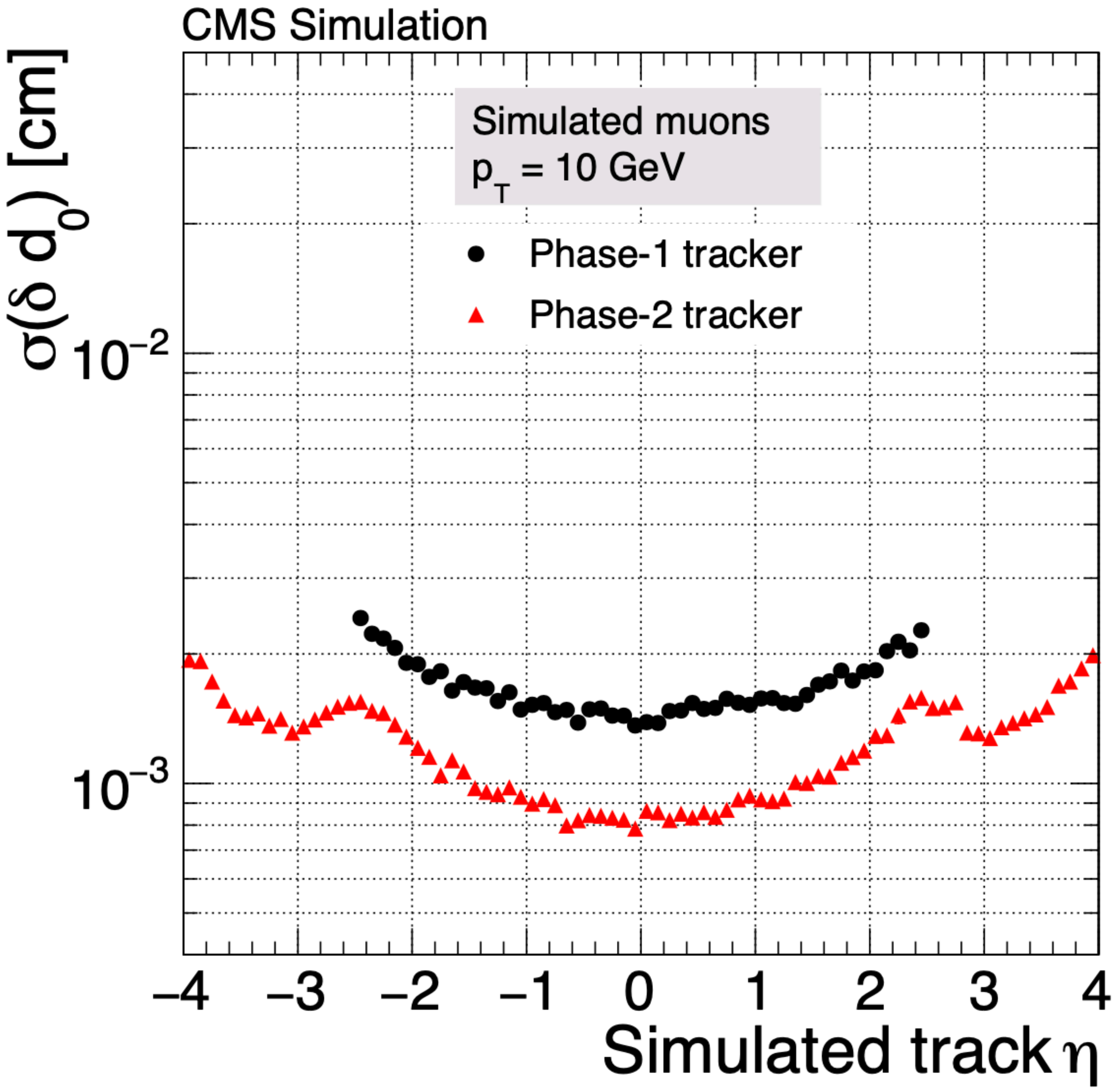


[CERN-LHCC-2017-009]

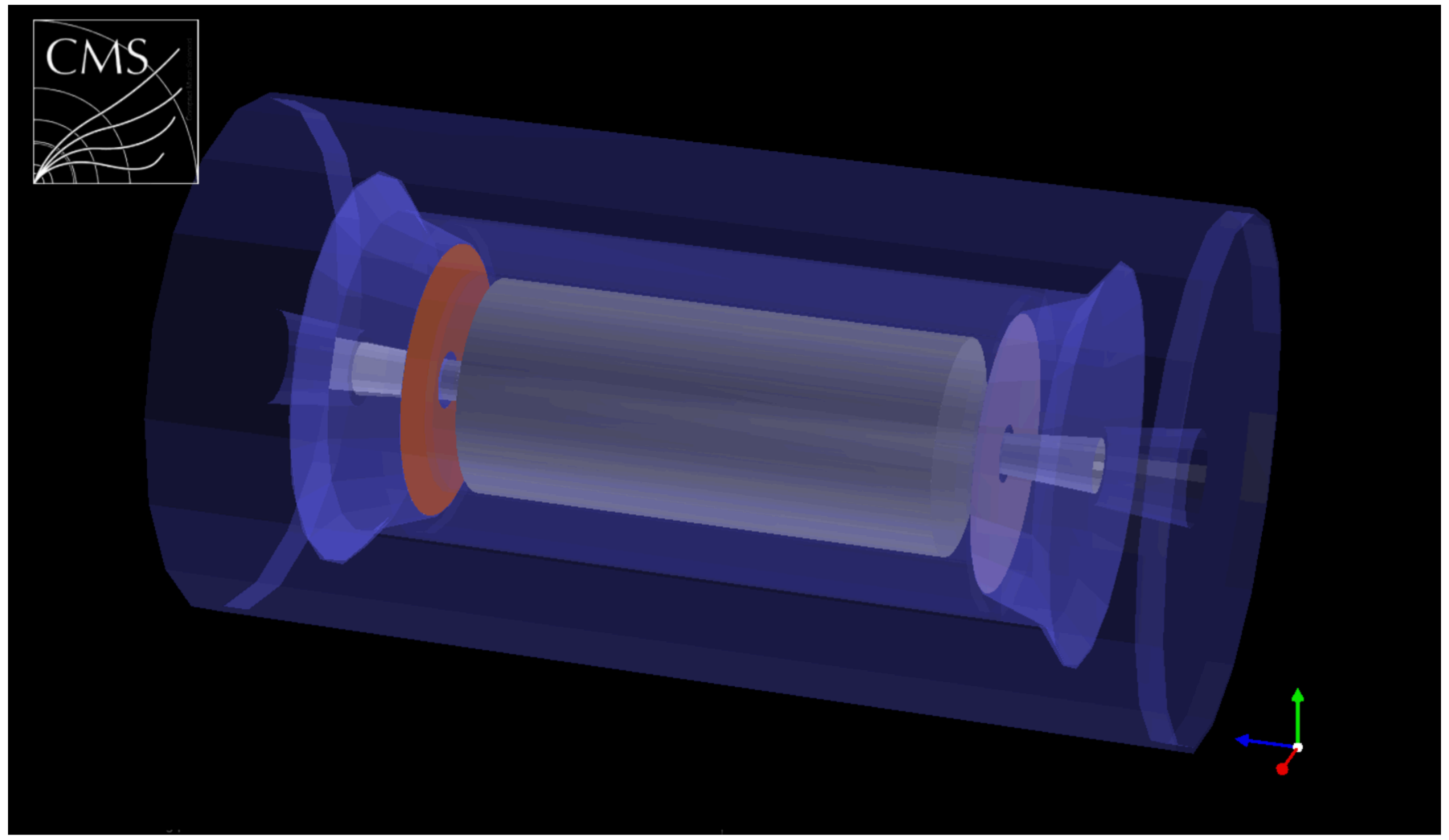
https://cds.cern.ch/record/2703569/plots

CMS tracker performance

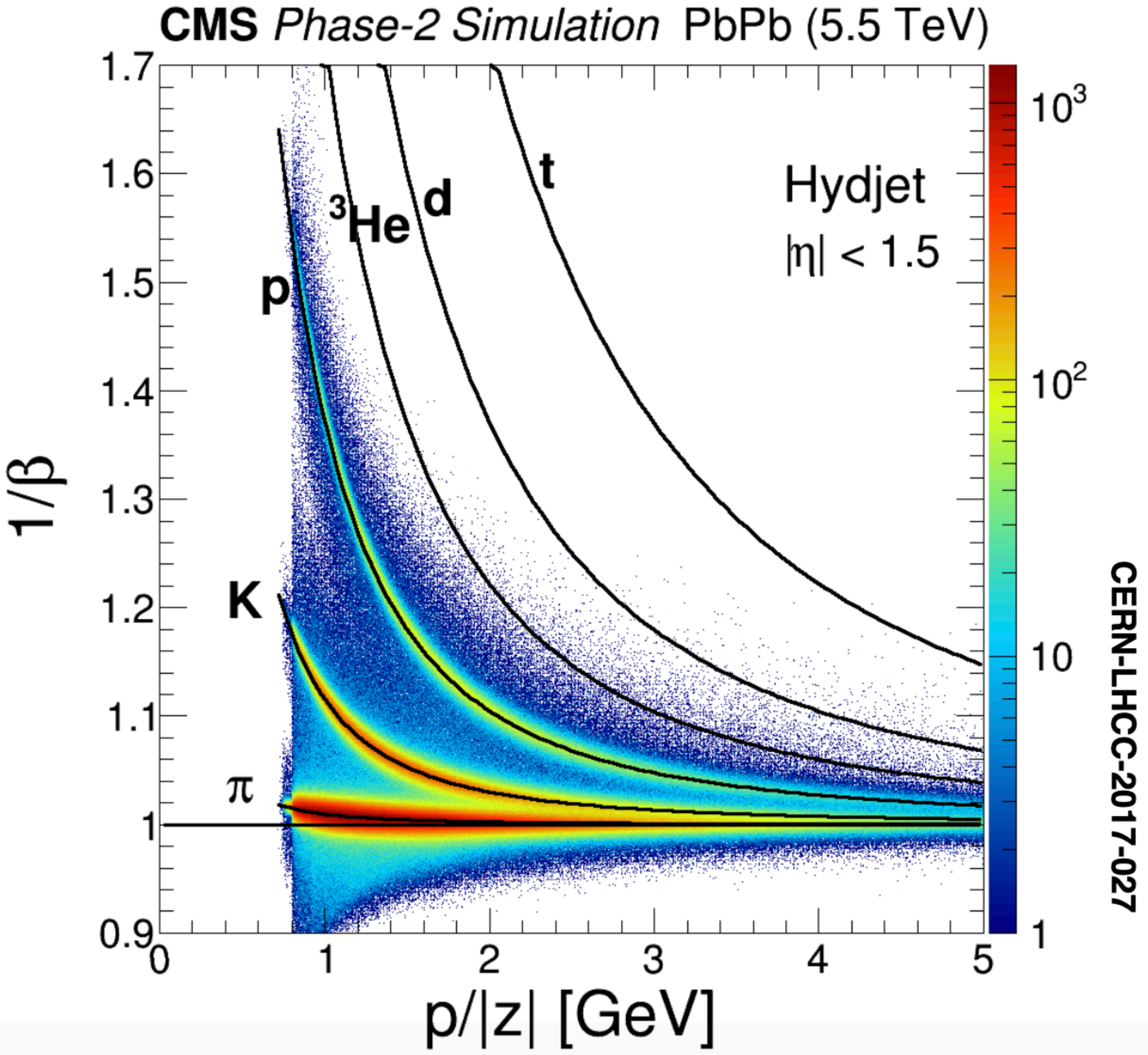




CMS mip timing detector



- **Barrel Timing Layers**
  - LYSO crystals with SiPM readout
- **Endcap Timing Layers**
  - Low-Gain Avalanche Diodes (LGADs)
- Use for **pile-up rejection** and **particle identification**



Summary

- Tracking and vertex **crucial for modern experiments**
  - concepts well established
  - pushing the limits

- Detector technologies achieve **unprecedented precision**
  - very active R&D on low power, low material, high resolution sensors

- High rates and large number of channels pose **computational challenges**
  - usage of new methods and technologies, e.g. GPUs, FPGAs

Time for discussion 😊

Backup

Energy loss of charged particles

- Average energy loss from **integration over relevant range of *b*** (avoiding divergence)
  - $b_{\min}$: localisation limited by uncertainty: $\frac{h}{p} = \frac{h}{\gamma m_e v}$
  - $b_{\max}$: interaction time limited by revolution period of electrons: $t_{\text{int}} < T_e$
- Integration yields

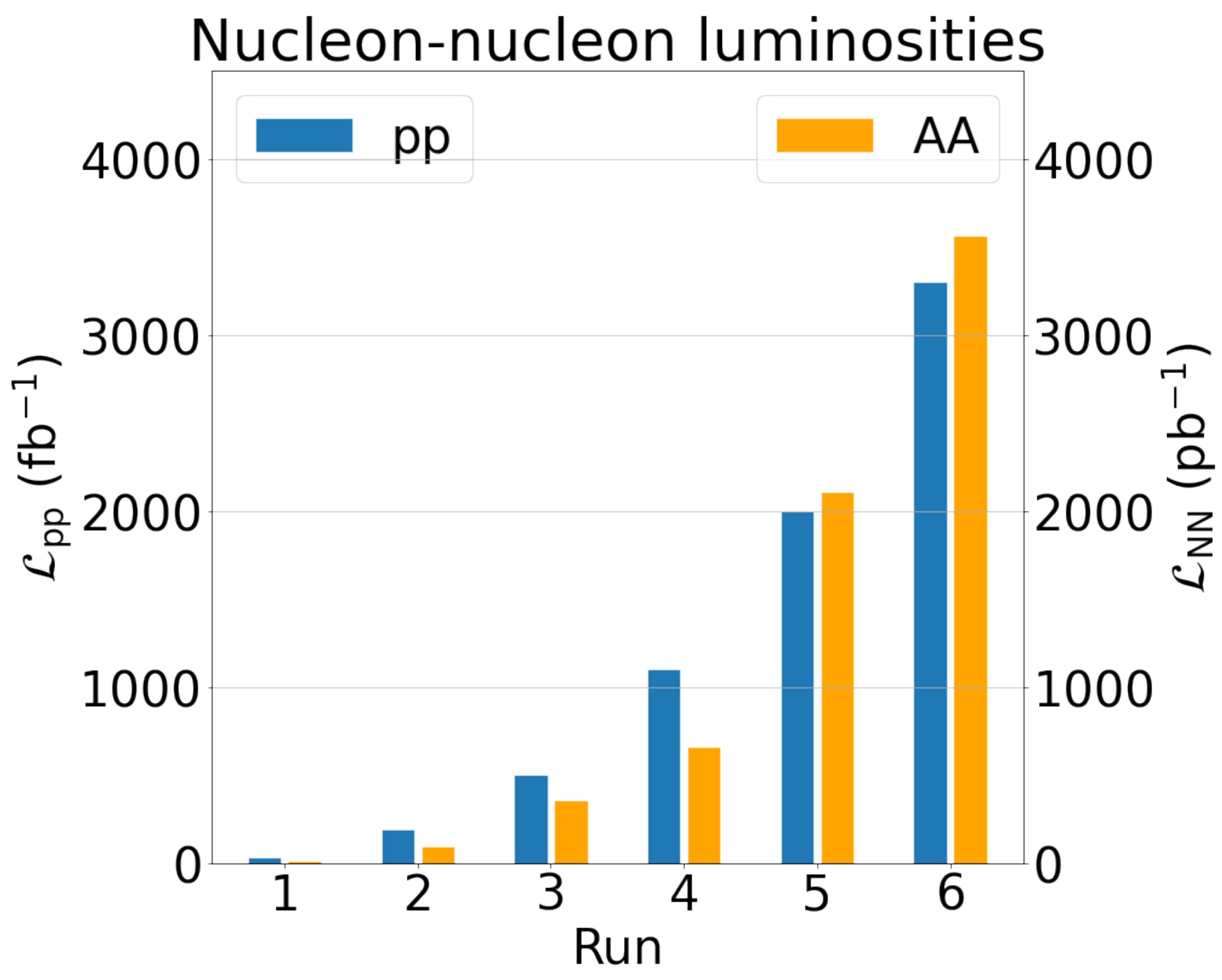
$$-\frac{\mathrm{d}E}{\mathrm{d}x} = \frac{4\pi z^2 e^4}{m_e c^2 \beta^2} n \ln \frac{m_e c^2 \beta^2 \gamma^2}{\hbar \langle \nu \rangle} \text{ with } n = \frac{N_A \rho Z}{A}$$

$\beta = p/E, \gamma = E/m \Rightarrow \beta\gamma = p/m$

LHC programme

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 - 2025	Run 4 2029 - 2032	Run 5	Run 6

Pb-Pb luminosity limited by LHC
~1-2·10^{27} cm^{-2} s^{-1}



Run 5 → higher luminosities for ions

- mitigate space charge effects (SPS & LEIR), e.g. with lighter species

Run 4 → HL-LHC

- push pp luminosity to 4·10^{34} cm^{-2} s^{-1}

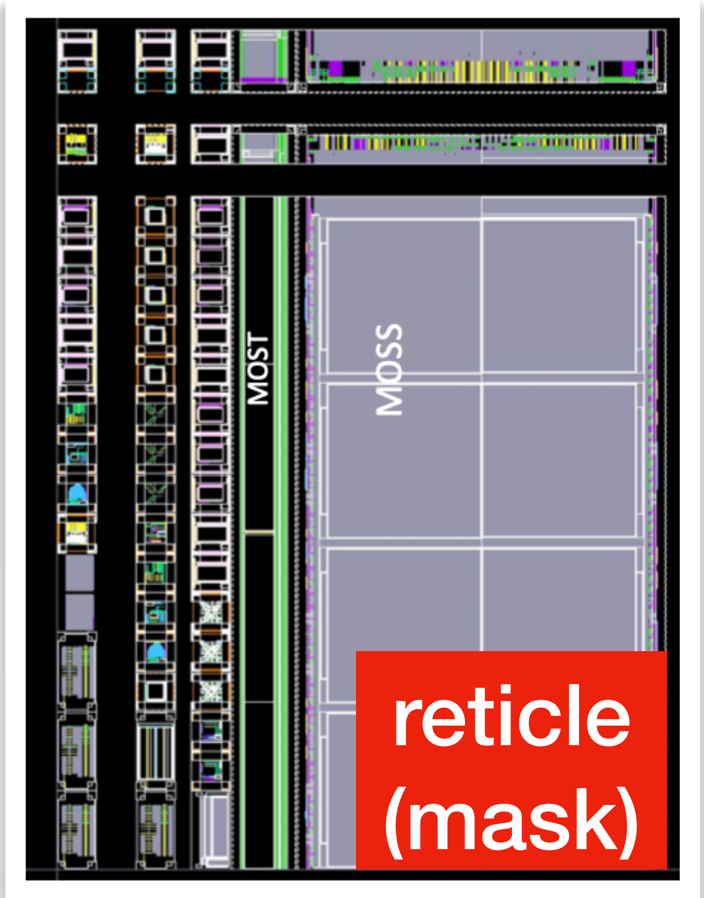
Run 3 → high luminosity for ions (~7·10^{27} cm^{-2} s^{-1}) and **OO**

- improved collimation systems
  - ➟ lifted limitation in the LHC from bound-free pair production
  - ➟ ion luminosities now limited by bunch intensities from injectors

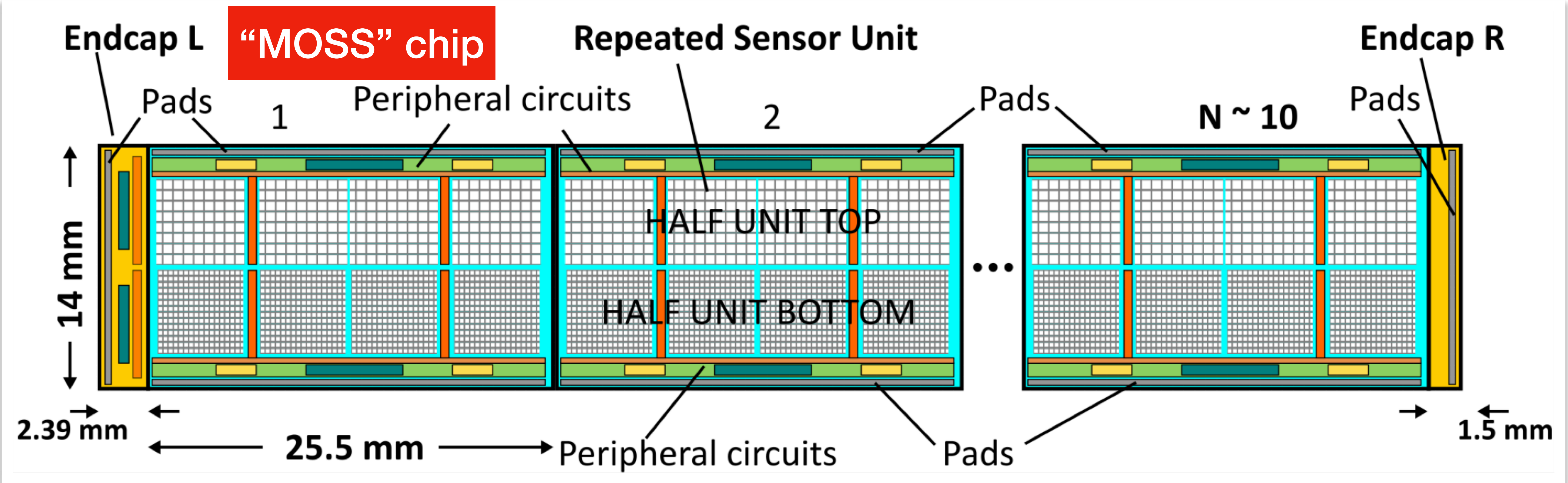
Wafer-scale sensors

ITS3

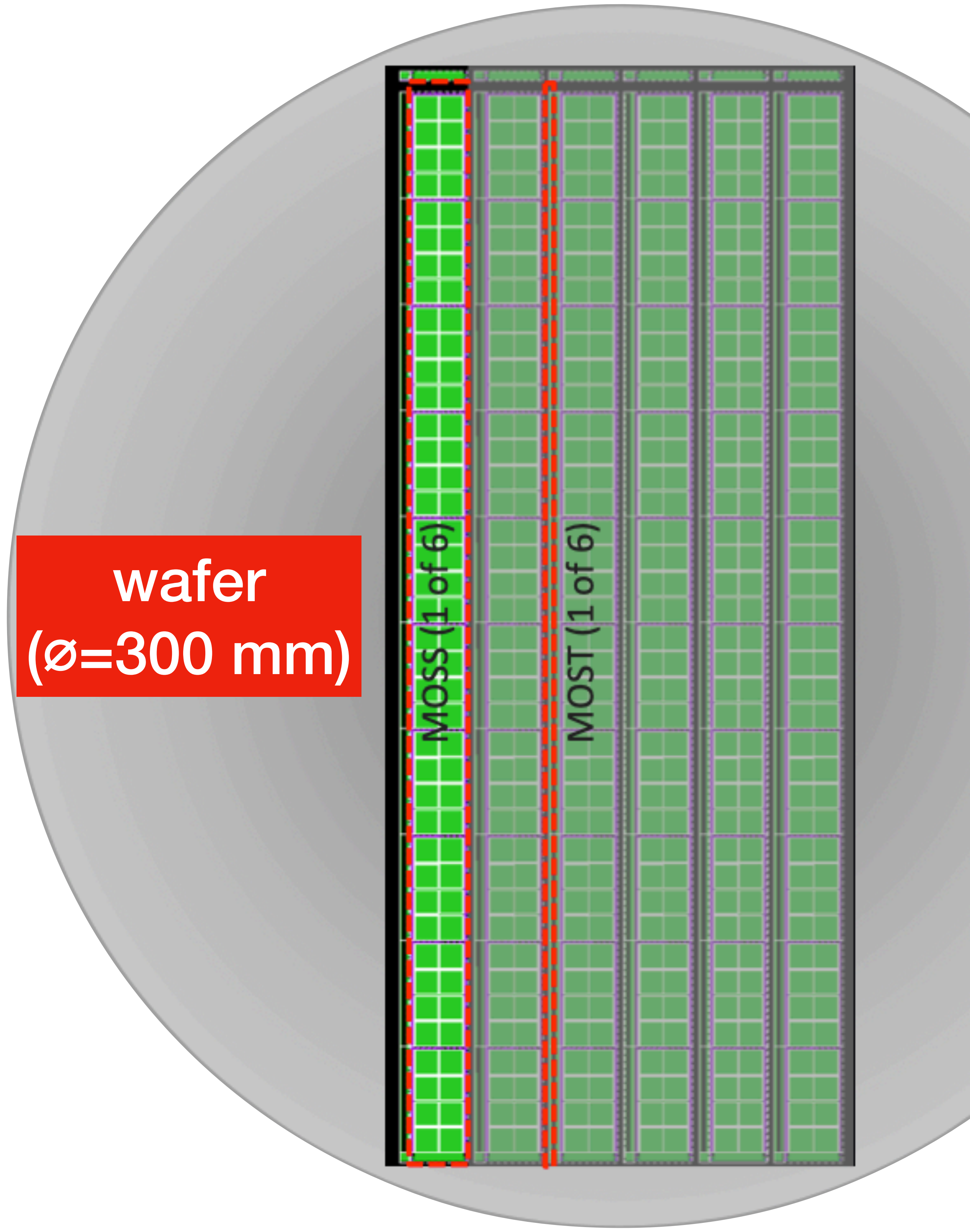
- First engineering run with stitched digital pixels submitted
  - sensor unit repeated along a stripe (stitching), readout circuitry in the endcaps
  - processed wafers expected back mid 2023 (final milestone for TDR)



reticle (mask)



"MOSS" chip



wafer (ø=300 mm)