ALICE 3

Lecture I

1st ALICE experiment and heavy-ion workshop

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2025-11-09

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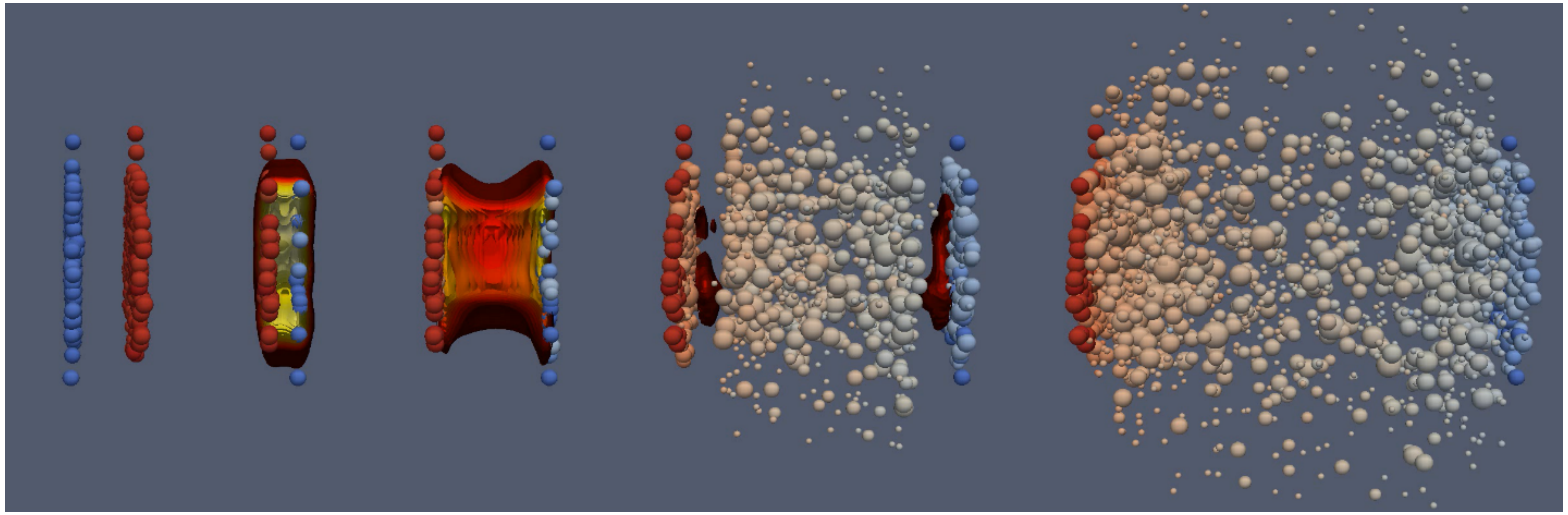
Frustration

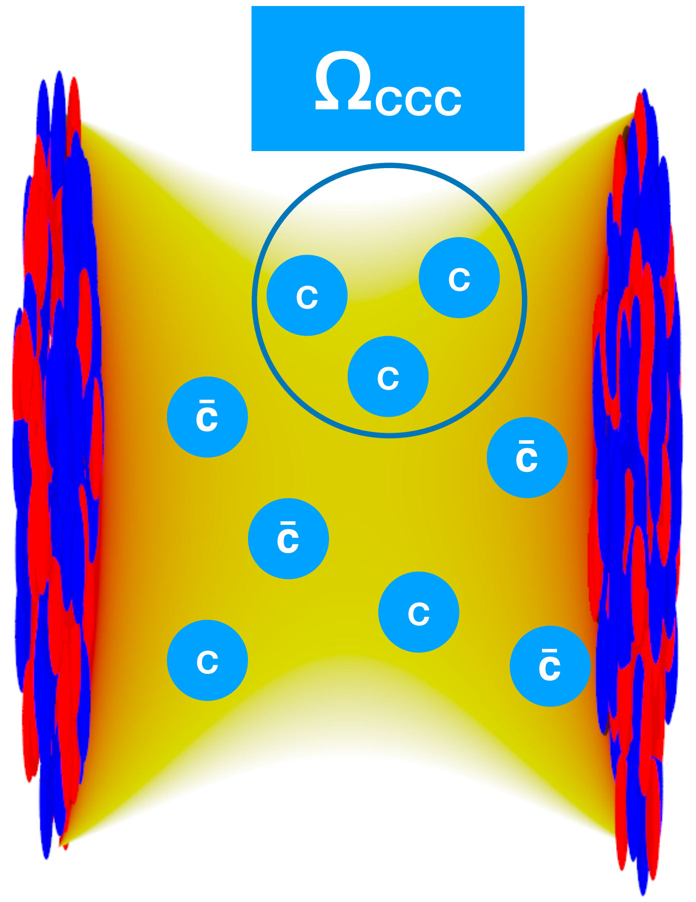
- Many reasons to believe in formation of **deconfined state of matter** in ultra-relativistic heavy-ion collisions, **BUT:**
  - no single measurement to unequivocally demonstrate deconfinement
  - no direct measurement of the initial conditions, e.g. temperature
  - no direct demonstration of phase transition
  - missing handles on interaction potentials and nature of bound states



[MADAI collaboration]

Deconfinement

- **What do we need to demonstrate deconfinement?**
  - traceable probe embedded in quark-gluon plasma
    → light quarks and gluons produced thermally ➟ not traceable 👎
    → heavy quarks only produced initially ➟ traceable 👍
    → charm quarks equilibrate ➟ embedded in QGP 👍
  - proof of free motion within quark-gluon plasma
    → charm quarks produced independently and well separated
    → combination of multiple charm quarks demonstrates motion 👍
  - exclusion of other production mechanisms
    → formation of multi-charm states from fragmentation strongly suppressed 👍

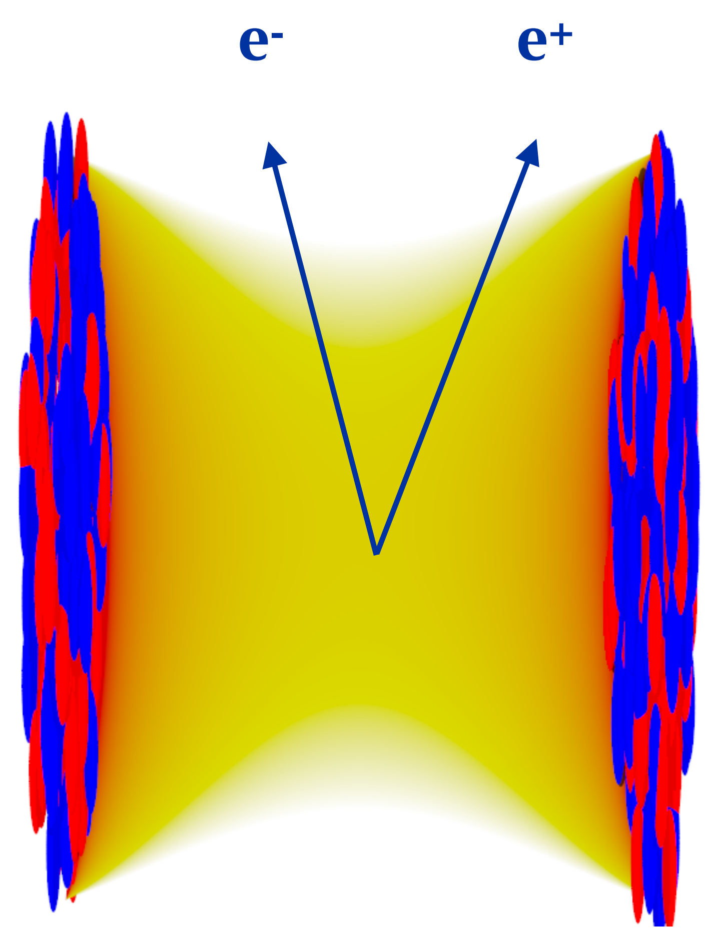


- **Multi-charm hadrons are ideal probe**
  to unequivocally demonstrate equilibration and deconfinement

unique chance at LHC, but not possible yet

Initial conditions

- **What do we need to measure initial temperature?**
  - hadrons produced at freeze-out temperature
    → information about initial state mostly lost 👎
  - electromagnetic probes produced throughout the evolution
    → no strong interaction → escape from quark-gluon plasma 👍
  - photons suffer from blue shift 👎
  - di-leptons escape and invariant mass is unaffected by blue shift 👍

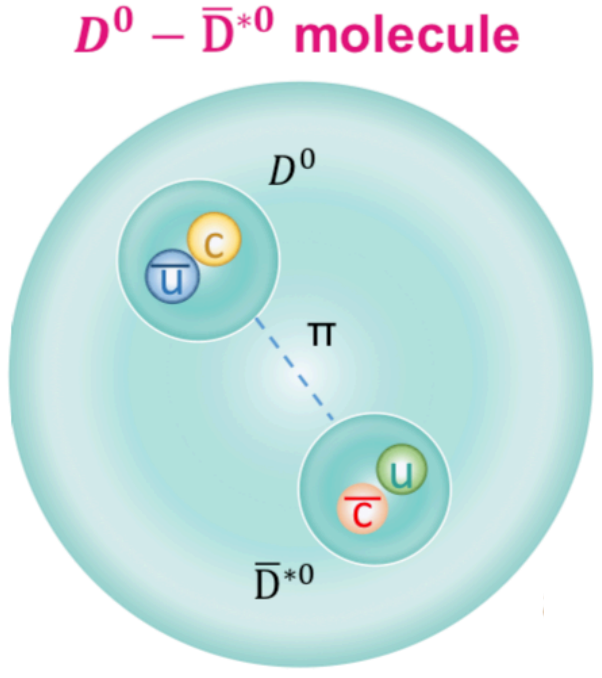


- **Di-leptons are ideal probes**
  to measure properties of the early phases

needs to be done at LHC but not possible yet

Interaction potentials

- **What do we need to understand interaction potentials and the nature of bound states?**
  - production yields only give indirect insights 👎
  - correlations of compounds carry information on interaction potentials and possible bound states 👍



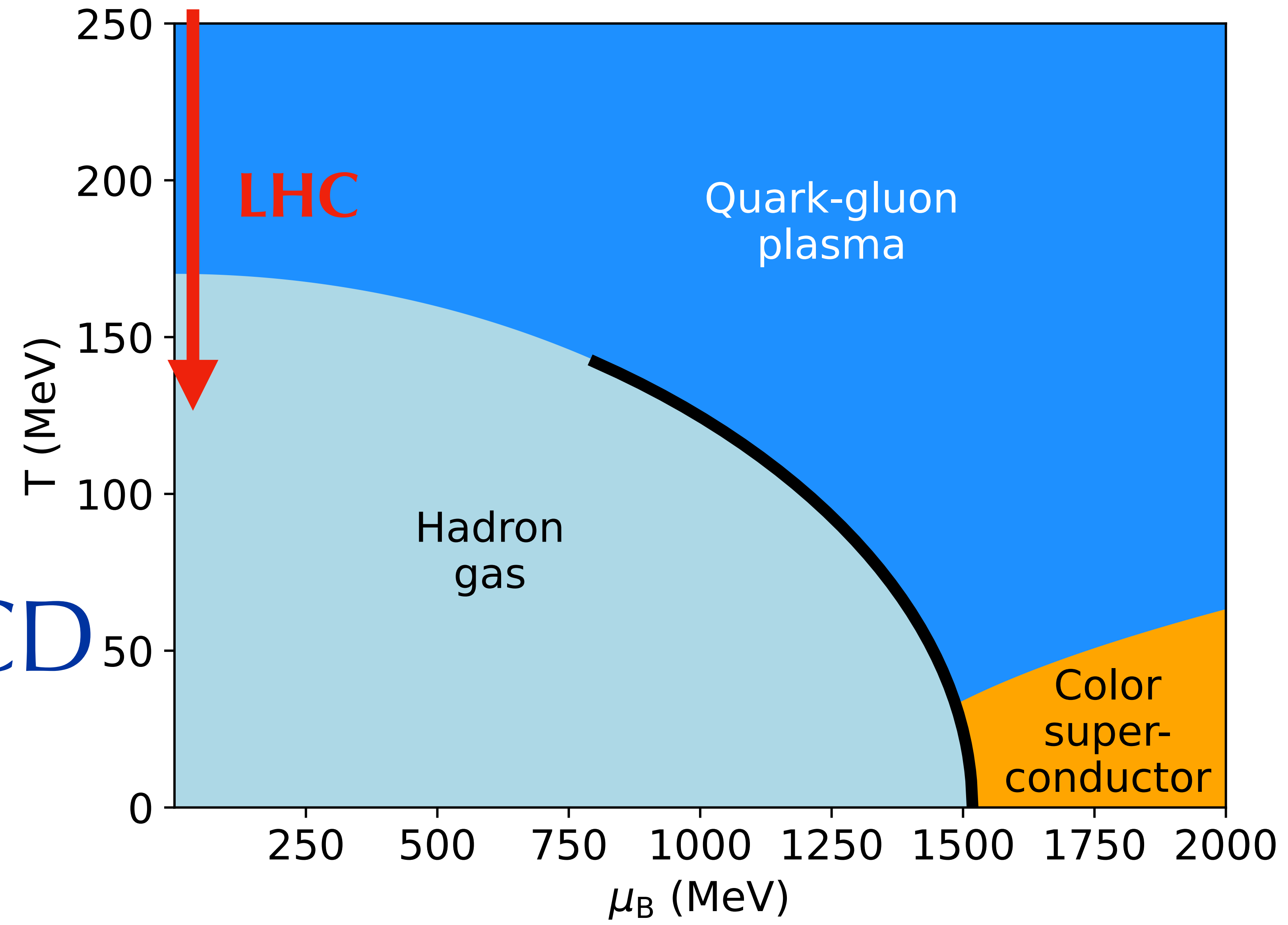
$r_{molecule}$
as large as 5 fm

- **Momentum correlations are ideal probes** to unravel interaction potentials between hadrons and nature of bound states

unique chance at LHC, but not possible yet

Phase transition

- **What do we need to detect and characterise the phase transition of QCD?**
  - phase transition characterised by critical fluctuations
    → cumulants of conserved quantities
    → net-baryon cumulants can be measured
    → can be confronted with predictions from lattice QCD

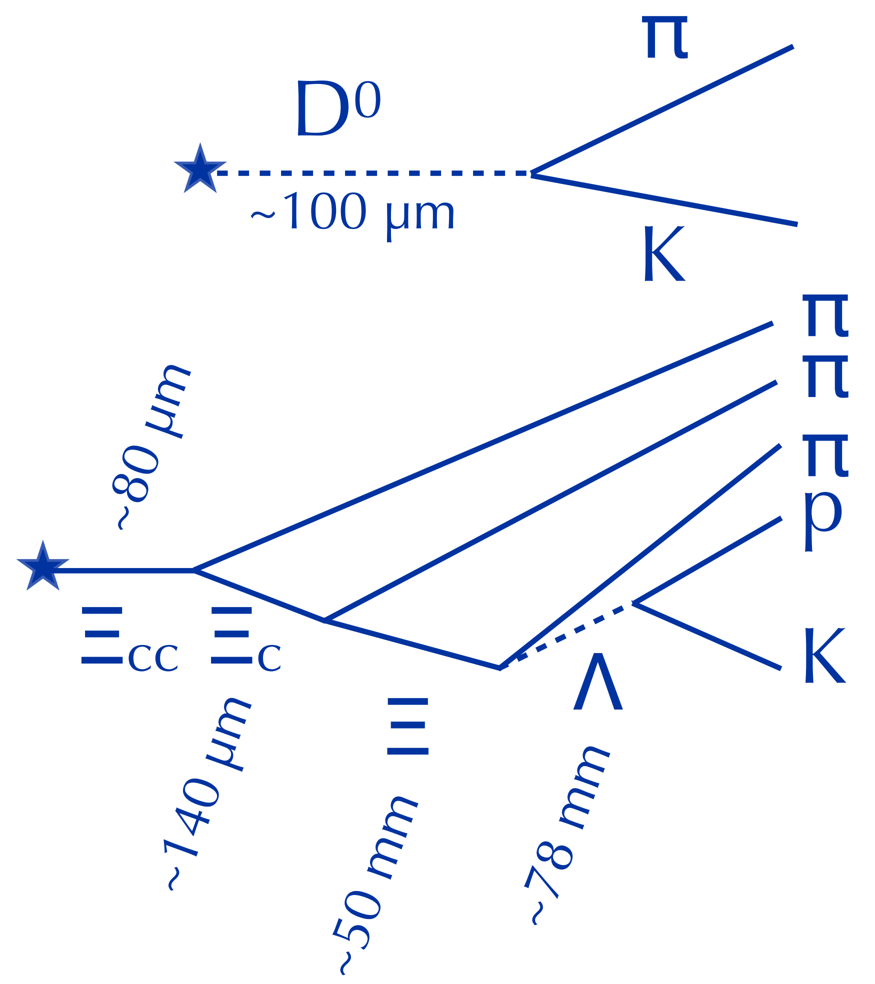


- **Net-baryon fluctuations are ideal probes** to probe the nature of the phase transition

unique chance at LHC, but not possible yet

Key measurements

- **(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



electron identification

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

Experimental requirements

- 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

Detector concepts

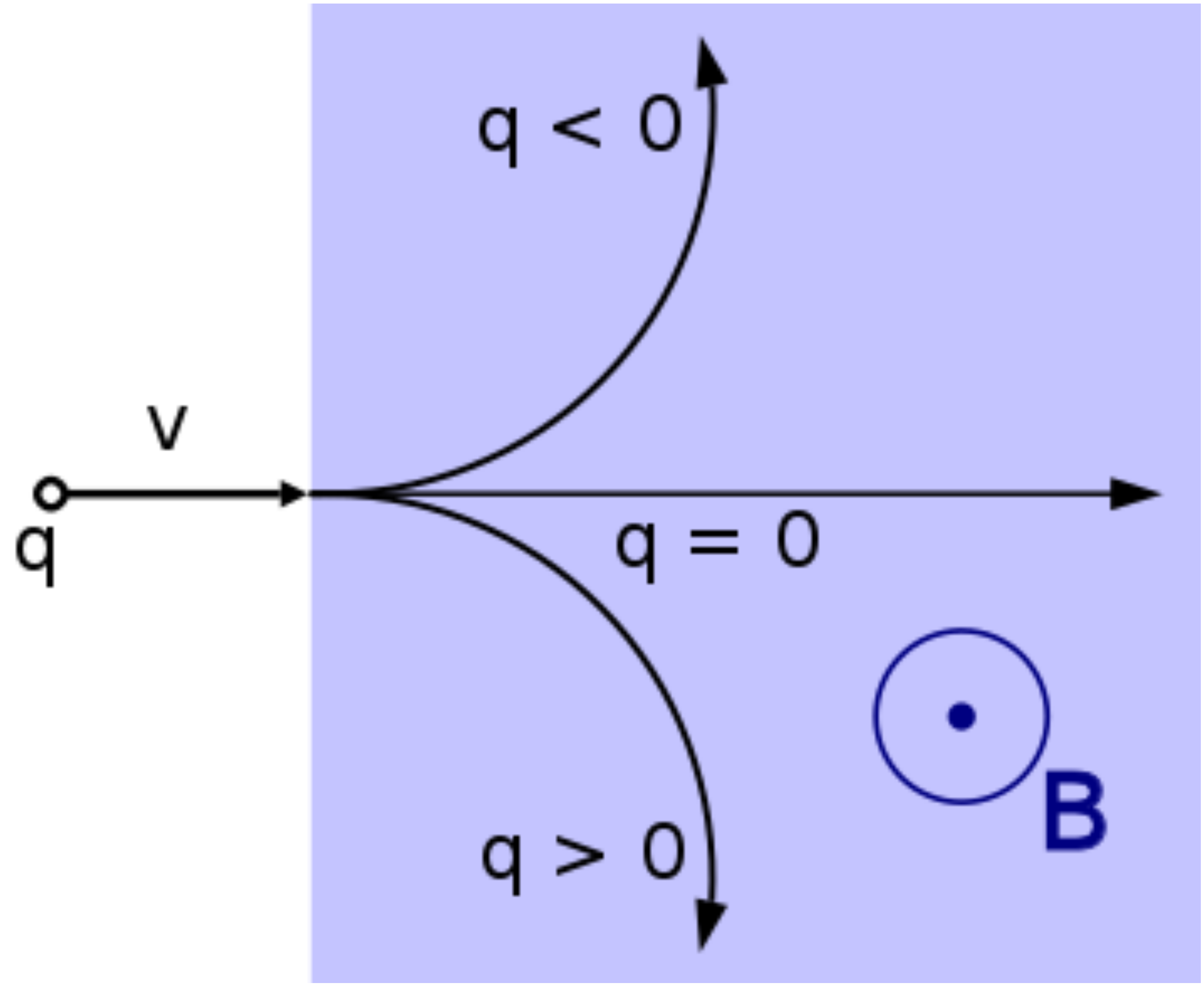
How do we optimise a detector for this programme?

Motion of charged particles

- Motion of charged particle in a magnetic field determined by **Lorentz force**

$$\vec{F} = q\left(\vec{v} \times \vec{B}\right) \;\Rightarrow\; \dot{\vec{v}} = \frac{q}{\gamma m}\left(\vec{v} \times \vec{B}\right)$$

  - force perpendicular to direction of motion
    ➟ in magnetic field **only change of direction**
    ➟ no change of energy ➟ γ constant
  - **valid even relativistically**
    (despite non-covariant formulation)



Helix motion in homogeneous field

- Charged particle in homogeneous magnetic field
  → **helix motion** coaxial with magnetic field (in *z* direction)

$$x = \frac{v_\mathrm{T}}{\eta\omega_B}\sin(\eta\omega_B t + \psi_0) + x_0 \qquad y = \frac{v_\mathrm{T}}{\eta\omega_B}\cos(\eta\omega_B t + \psi_0) + y_0 \qquad z = v_3 t + z_0$$

with cyclotron frequency $\omega_B = \dfrac{|q|B}{\gamma m}$ and $\eta = q/|q|$

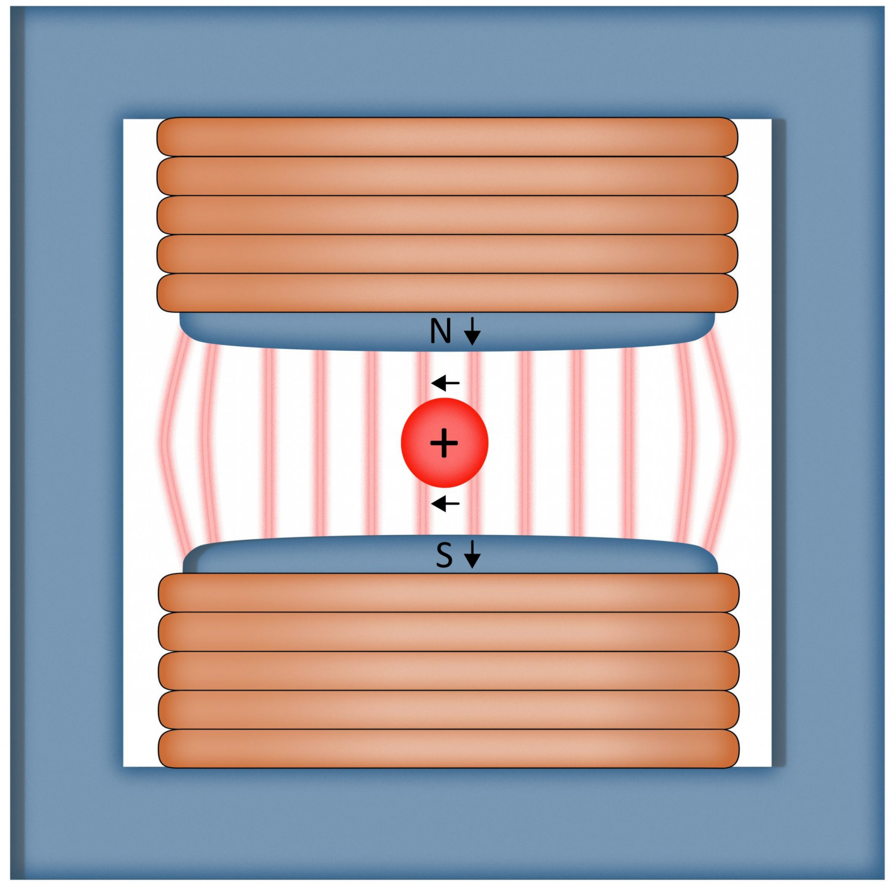
- **radius of curvature** given by $p_\perp = |q|\,B\,R$,
  when using standard units (GeV/*c*, T, m) ➟ $p_\perp = 0.3\,B\,R$

1 GeV/c particle in 1 T field
→ ~3 m radius

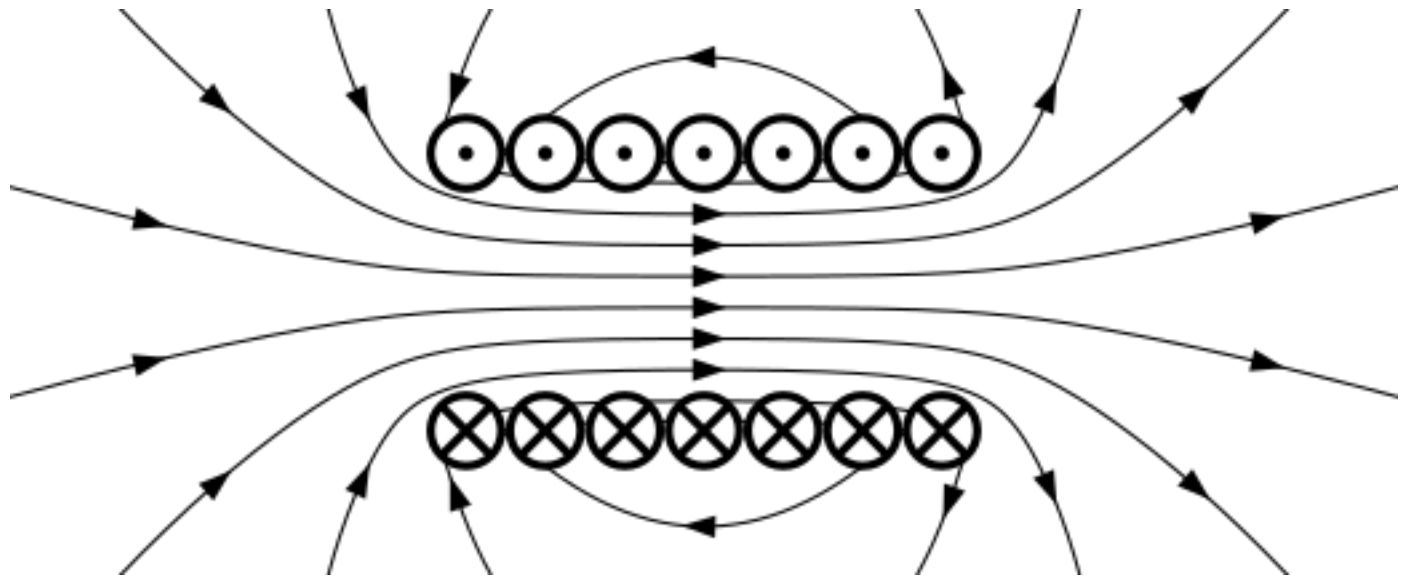
curvature in magnetic field
directly linked to (transverse) momentum

Magnetic field configurations

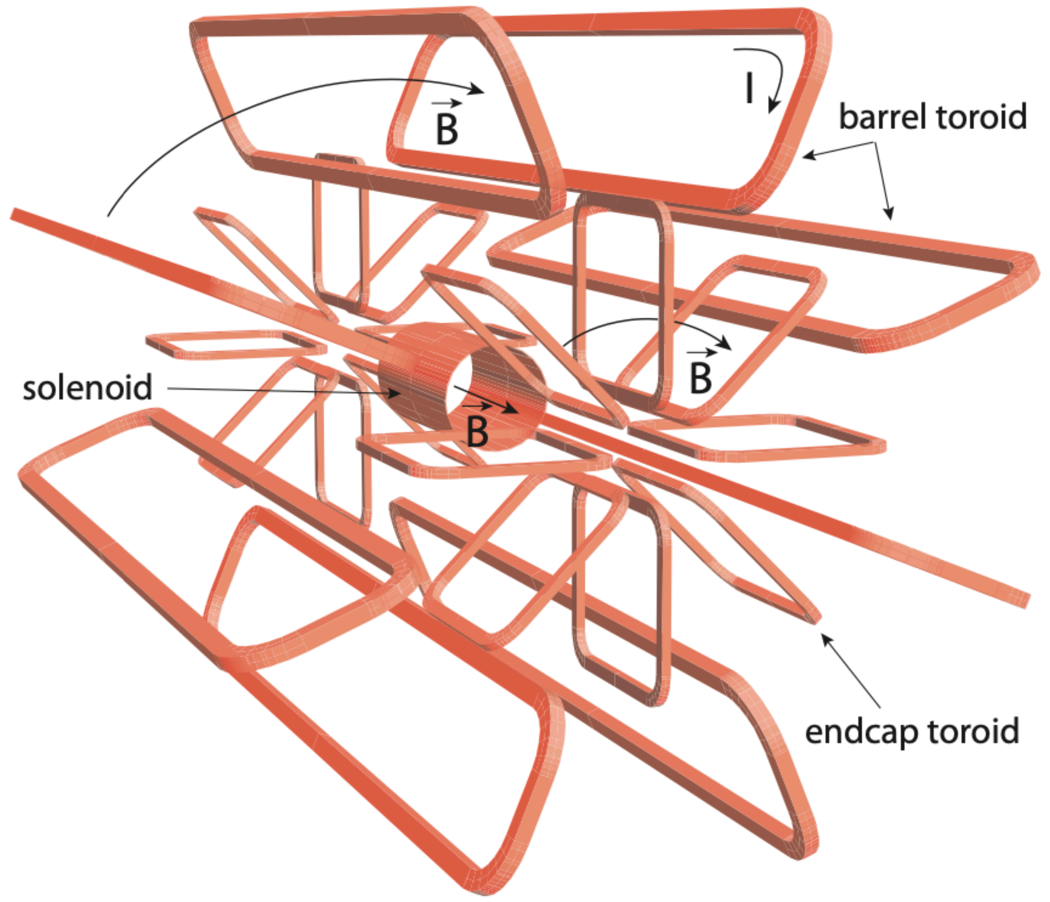
- **Dipole** fields
  - often used in fixed-target experiments or forward part of collider experiments



- **Solenoidal** fields
  - often used in collider experiments (rotationally symmetric)



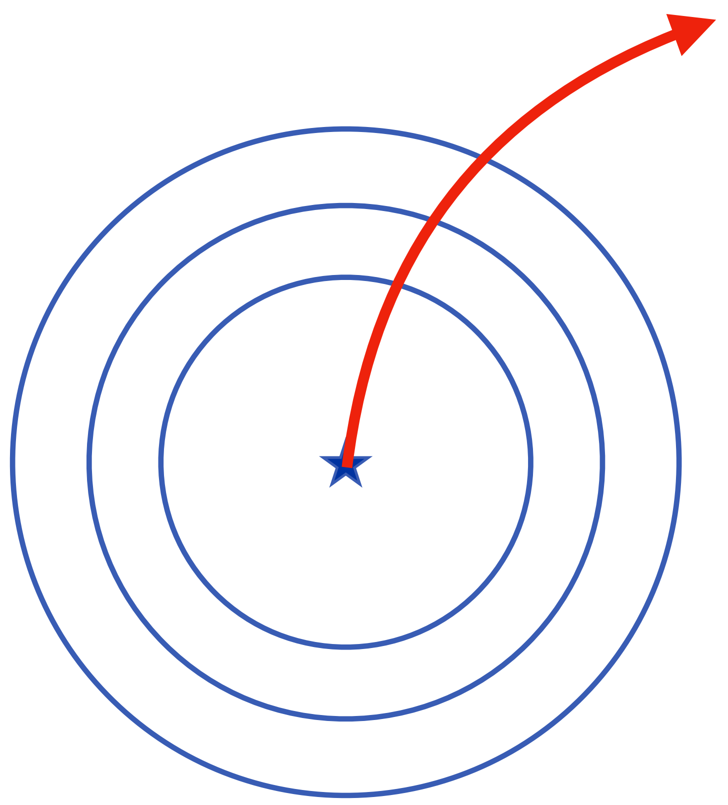
- **Toroidal** fields
  - often used as extension of solenoidal fields (perpendicular, rotationally symmetric)



Deflection depends on motion perpendicular to magnetic fields

Tracking

- **Reconstruction of trajectory** of a particle through the detector with the goal of determining properties of the particle, in particular momentum
  - connection of hits in one or more detectors (originating from the same particle)
    ➠ **track finding**
  - fitting of track parameters from hits (taking into account interaction with material and magnetic fields)
    ➠ **track fitting**
- **Requirements for tracking detectors**
  - 3 space points fully describe trajectory (under ideal conditions)
  - additional measurements can reduce uncertainties
  - need for redundancy and suppression of fake tracks (occupancy)



Trajectory through cylindrical layers

Criteria for tracking performance

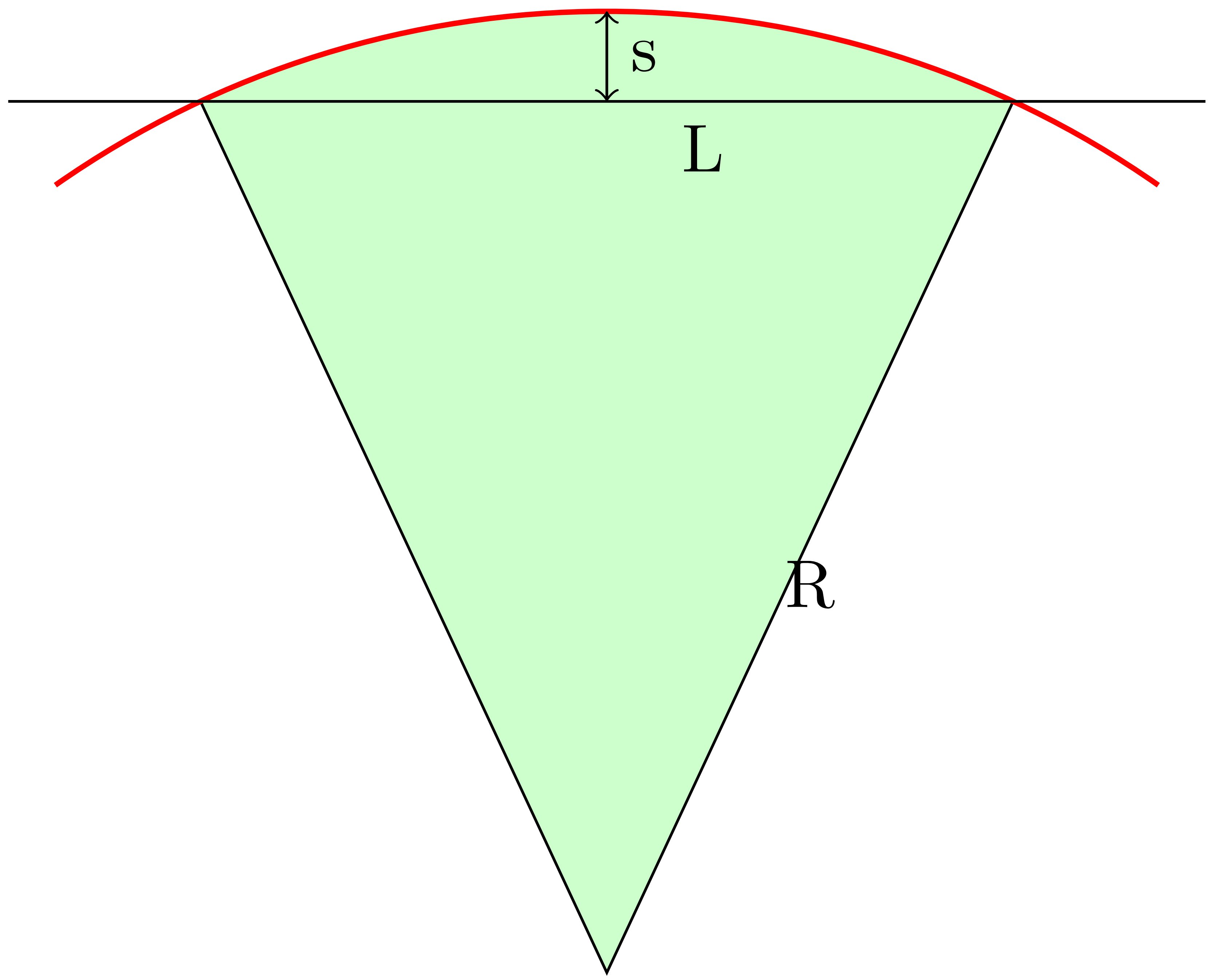
- **Ideal reconstruction**
  - **assignment of all hits to correct track**
    → all tracks are reconstructed, no impact from wrongly assigned hits
  - **precise estimation of track parameters**
    → unbiased, minimal uncertainties

- **Figures of merit**
  - acceptance → fraction of area covered by detector
  - efficiency → fraction of reconstructed tracks
  - fake hit probability → probability of assigning hits from other particles
  - extrapolation uncertainties → propagation beyond volume covered by tracker
  - momentum resolution

Sagitta

- Momentum measurements boils down to **measurement of curvature** in magnetic field
  → extraction from bubble chamber images

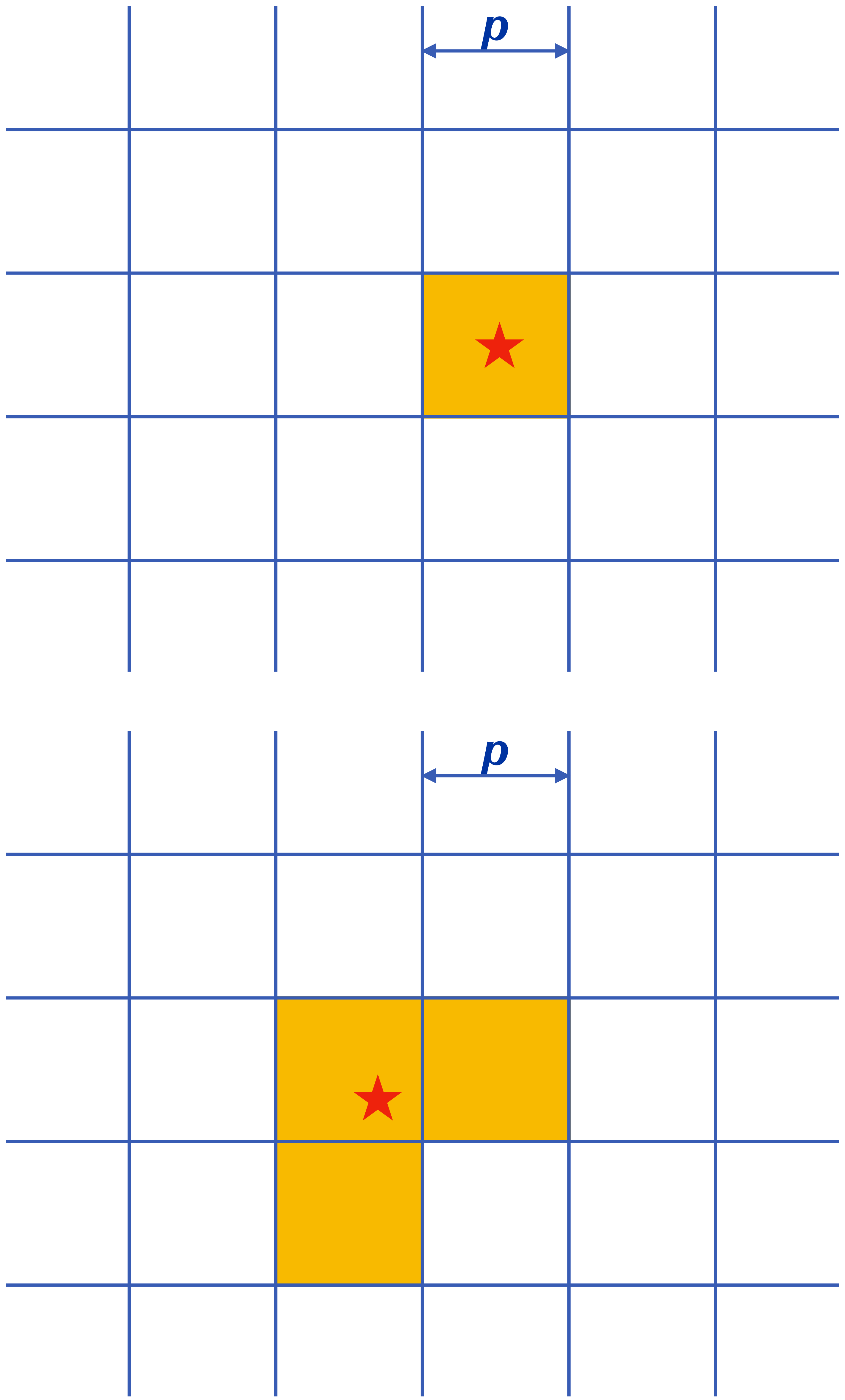
- **Sagitta** → maximum deviation
  from line between endpoints of track segment
  $$s = R - R\cos\frac{\vartheta}{2} = 2R\sin^2\frac{\vartheta}{4} \approx \frac{R\vartheta^2}{8} \approx \frac{L^2}{8R} = \frac{qBL^2}{8p_\perp}$$
  - **quadratic dependence on lever arm**
  - relative uncertainty of momentum proportional to relative uncertainty of sagitta



geometric approach, next consider measurement of points along trajectory

Position resolution

- Measurement of hit position
  limited by detector resolution
  - uncertainty for rectangular structure with **binary readout pitch p**
    $$\sigma^2_{\mathrm{pos}} = \int_{-p/2}^{p/2} \mathrm{d}x\, x^2 \frac{1}{p} = \frac{p^2}{12} \Rightarrow \sigma_{\mathrm{pos}} = \frac{p}{\sqrt{12}}$$
  - uncertainty reduced when signal spreads across multiple bins (**charge sharing**), possibly with information on charge per bin
  - gas detectors typically $\mathcal{O}(100\ \mu\mathrm{m})$,
    semiconductor detectors typically $\mathcal{O}(10\ \mu\mathrm{m})$



Multiple scattering

- Material (incl. sensitive volume!) leads to multiple scattering
  → **random change of direction** on top of curvature in magnetic field
  - width of distribution

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

    - **inversely proportional to momentum**
    - **scales with square root of material thickness**

- Multiple scattering poses **fundamental limit on measurement precision**
  → cannot be mitigated by improved position resolution
  - angular effect, i.e. $\sigma_x \propto \sigma_\alpha \cdot \Delta x$

[R.L. Workman et al. (Particle Data Group), Prog. Theor. Exp. Phys. 2022, 083C01 (2022)]

Track fit

- **Global χ^2 minimisation** of parameterised function f(x) for measured points (x_i, y_i)
  - assume linear dependency on parameters, e.g.
    - straight line
      → $y_i = f(x_i) = a_0 + a_1 x_i$
    - parabola (as approximation to circular shape)
      → $y_i = f(x_i) = a_0 + a_1 x_i + a_2 x_i^2/2$ $(a_2 = 1/R)$
  - **find parameters *a* to minimise**
    $\chi^2 = (y - Ga)^T W (y - Ga)$ with $G := x_i^j$ and weights W
    (W is identity matrix for equal weights)
  - minimum achieved for **solution of normal equation**
    $G^T W G a = G^T W y$
    solvable by matrix inversion or as system of linear equations (numerically more stable)

Tracking uncertainties

- Uncertainties of measurements described by **covariance matrix**
  $C_y = E((y - Ey)(y - Ey)^T)$

- **Propagation of uncertainties** to parameters a
  $C_a = BC_yB^T$ with $B = (G^TWG)^{-1}G^TW$ (from previous slide)

- **Optimal choice of W**
  to achieve unbiased parameter estimation with minimal uncertainties
  $W = C_y^{-1}$

- **Uncertainties for ideal weights** are
  $C_a = (G^TC_y^{-1}G)^{-1}$

Momentum resolution

- Transverse momentum extracted from **curvature in magnetic field**: $p_\perp = |q|\,B\,R$
  - approximated circle by parabola $f(x_i) = a_0 + a_1 x_i + a_2 x_i^2/2$ with $a_2 = 1/R$
  - momentum resolution proportional to uncertainty of curvature:
    ➟ $\dfrac{\Delta p_\mathrm{T}}{p_T} = \dfrac{\Delta R}{R} = \dfrac{\Delta a_2}{a_2} = \dfrac{p_\mathrm{T}}{|q|B}\Delta a_2$
- **Position resolution** of N+1 equidistant layers leads to uncertainty
  $$\frac{\Delta p_\mathrm{T}}{p_\mathrm{T}} = \frac{\sigma\, p_\mathrm{T}}{|q|BL^2}\sqrt{\frac{720N^3}{(N-1)(N+1)(N+2)(N+3)}} \approx \frac{\sigma\, p_\mathrm{T}}{|q|BL^2}\sqrt{\frac{720}{N+4}}$$
  (Glückstern formula, NIM 24 (1963) 381)
- **Multiple scattering** in N+1 equidistant layers leads to uncertainty
  $$\frac{\Delta p_\mathrm{T}}{p_\mathrm{T}} = \frac{N}{\sqrt{(N+1)(N-1)}}\frac{p\sigma_\alpha\sqrt{N+1}}{BL} = \frac{N}{\sqrt{(N+1)(N-1)}}\frac{0.0136\,\mathrm{GeV}/c\,\sqrt{d_\mathrm{tot}/X_0}}{\beta BL}$$

[NIM 24 (1963) 381; NIM A 910 (2018), 127-132]

Considerations for detector layout

- **Multiple scattering** contributes

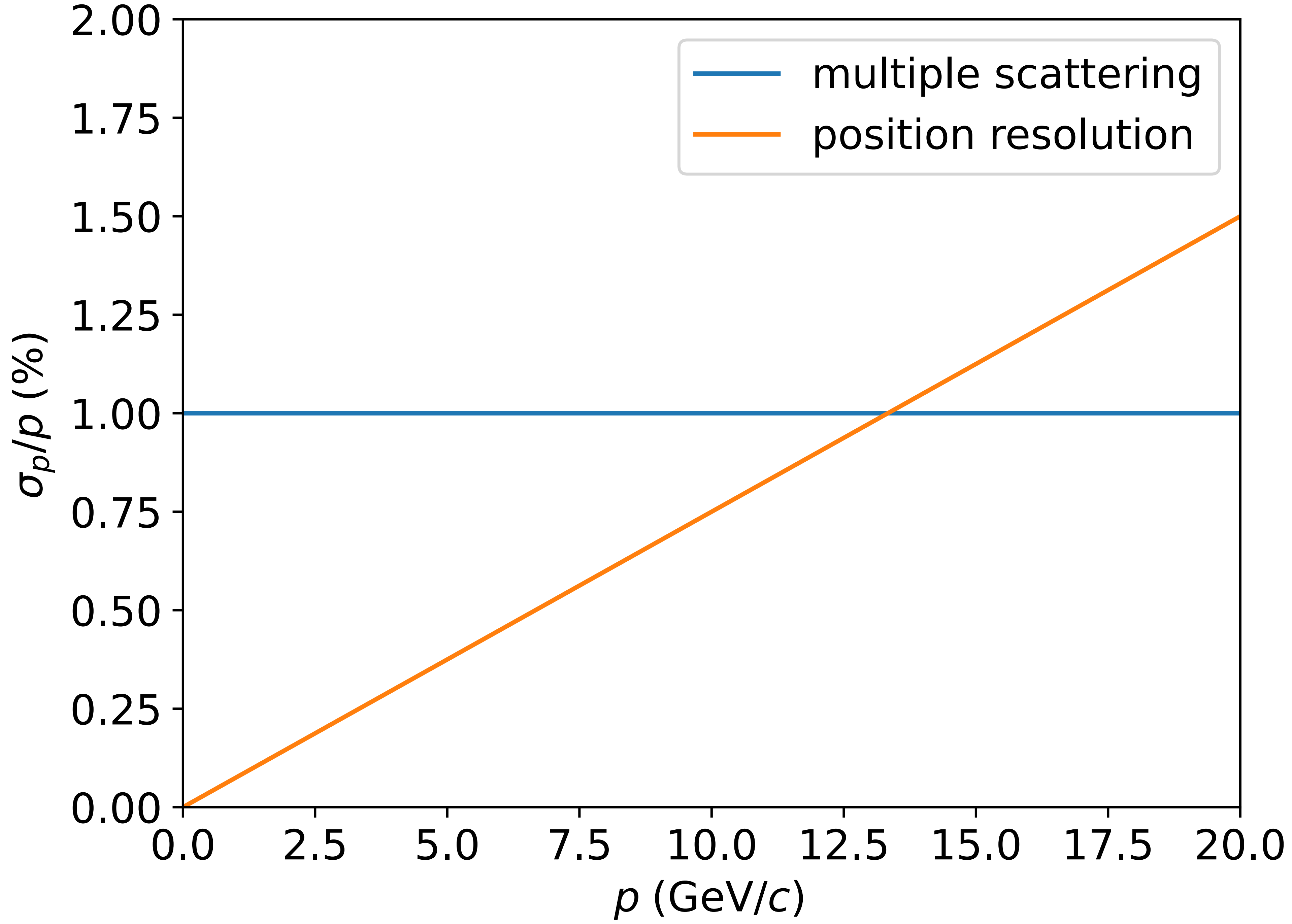
  $$\propto \frac{\sqrt{d_{\mathrm{tot}}/X_0 \cosh\eta}}{\beta B L}$$

  - independent of momentum (for $\beta \approx 1$)
  - linear dependence on lever arm
  - scales with square root of material

- **Position resolution** contributes

  $$\propto \frac{\sigma p_{\mathrm{T}}}{B L^2}$$

  - linear rise with momentum
  - quadratic dependence on lever arm



**m.s. sets irreducible limit,
p.r. takes over at large momenta**

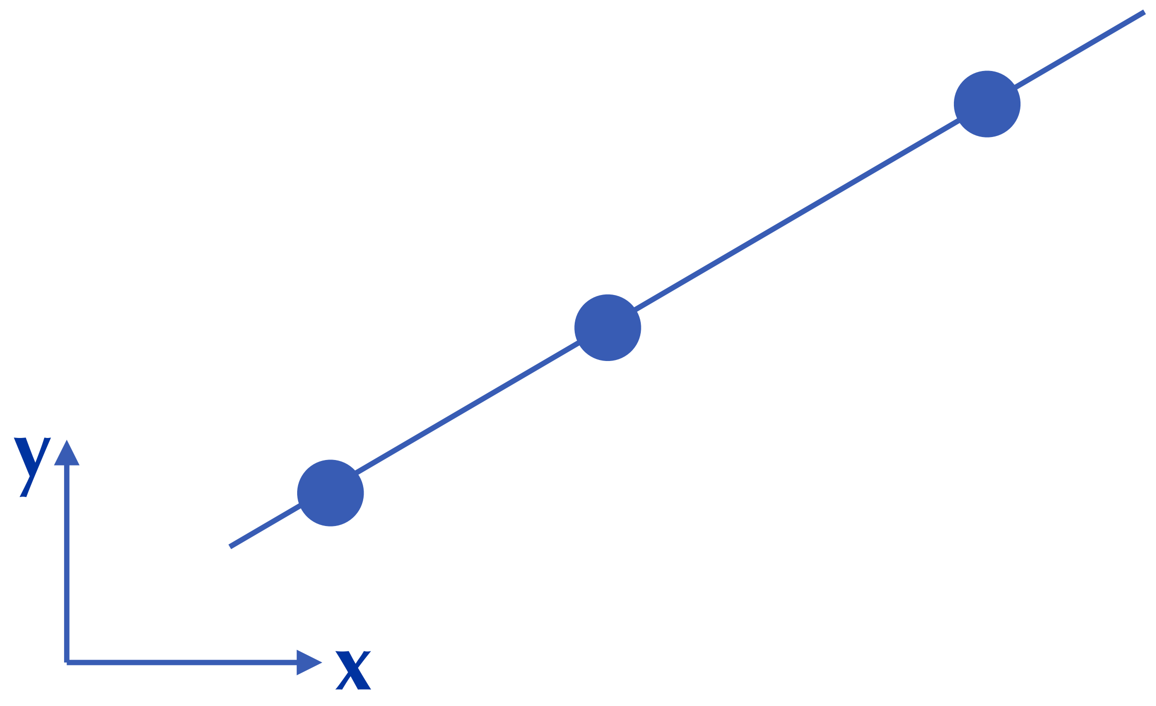
Track finding

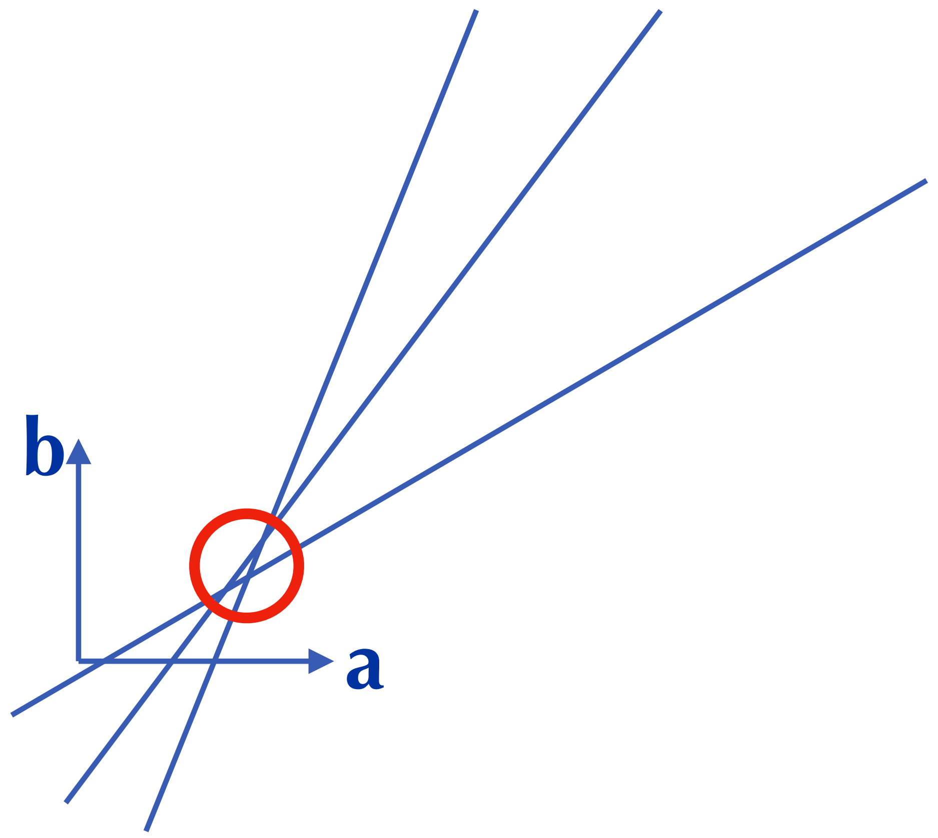
- So far track fit assuming knowledge of contributing hits
  → in reality need to **identify hit-to-track association from data**
  → task of **pattern recognition**

- **Variety of methods available** (and used),
  usability often determined by computational effort
  - fit all combinations (and reject based on χ^2)
  - Hough transformation
  - cellular automaton
  - Kalman filter
  - machine learning

Hough transformation

- Idea: **transformation from space coordinates to parameter coordinates**,
  e.g. describing a straight line y = ax + b
  - every hit (x, y) transforms into a **line in the parameter space**
  - **parameter lines intersect** in a single point (ideal case) or cluster around a value (with uncertainties)
  - **accumulation point** in the parameter space transforms into a line in real space
- Can be generalised to more complex parameterisations





Cellular automaton

- **Connect hits from adjacent layers** within a search window
  → tree of connections
  - combine track segments
  - longest paths are candidates
  - select candidates based on track fit
- **Advantages**
  - local matching of hits
    → contain computational effort

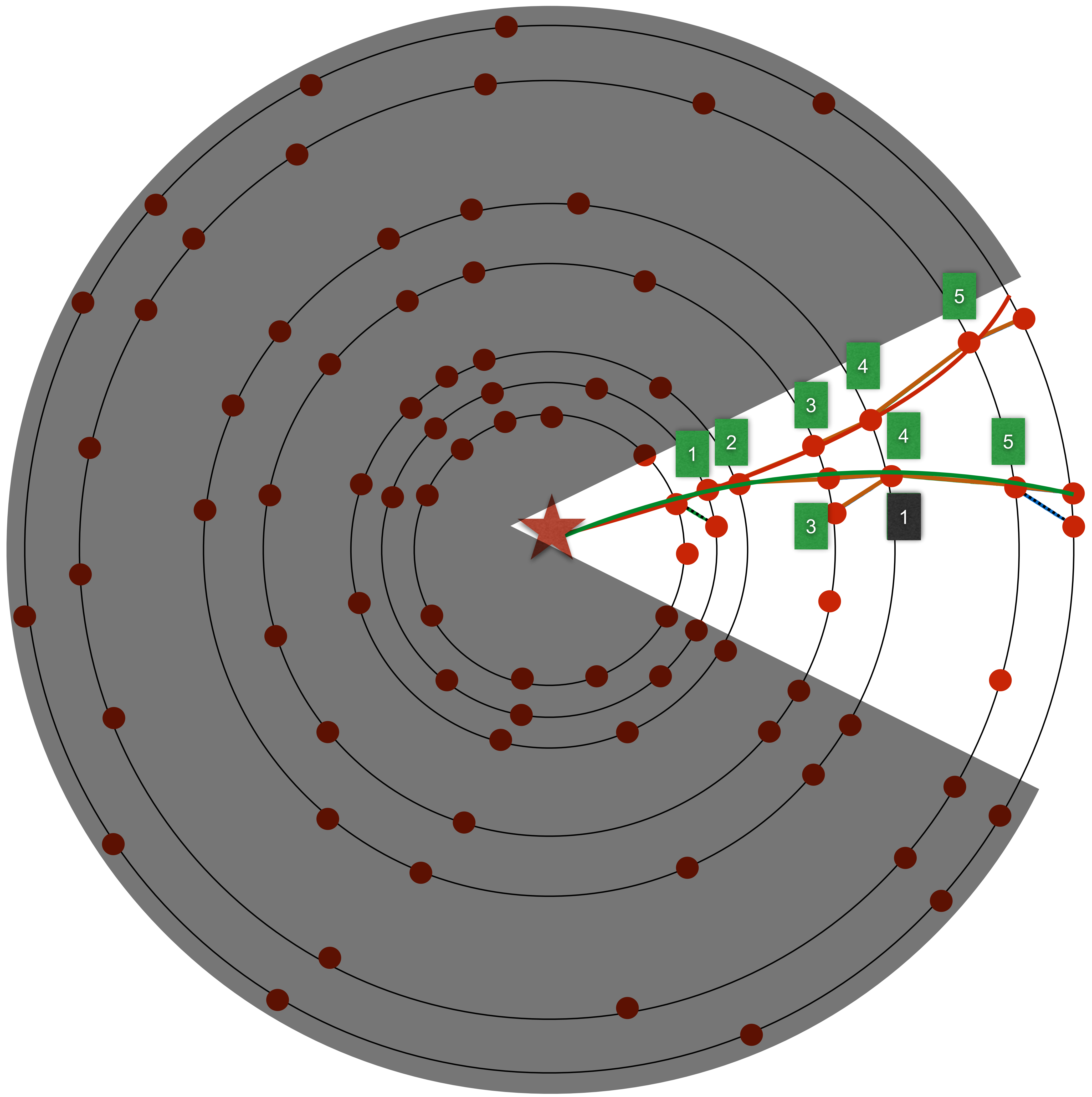
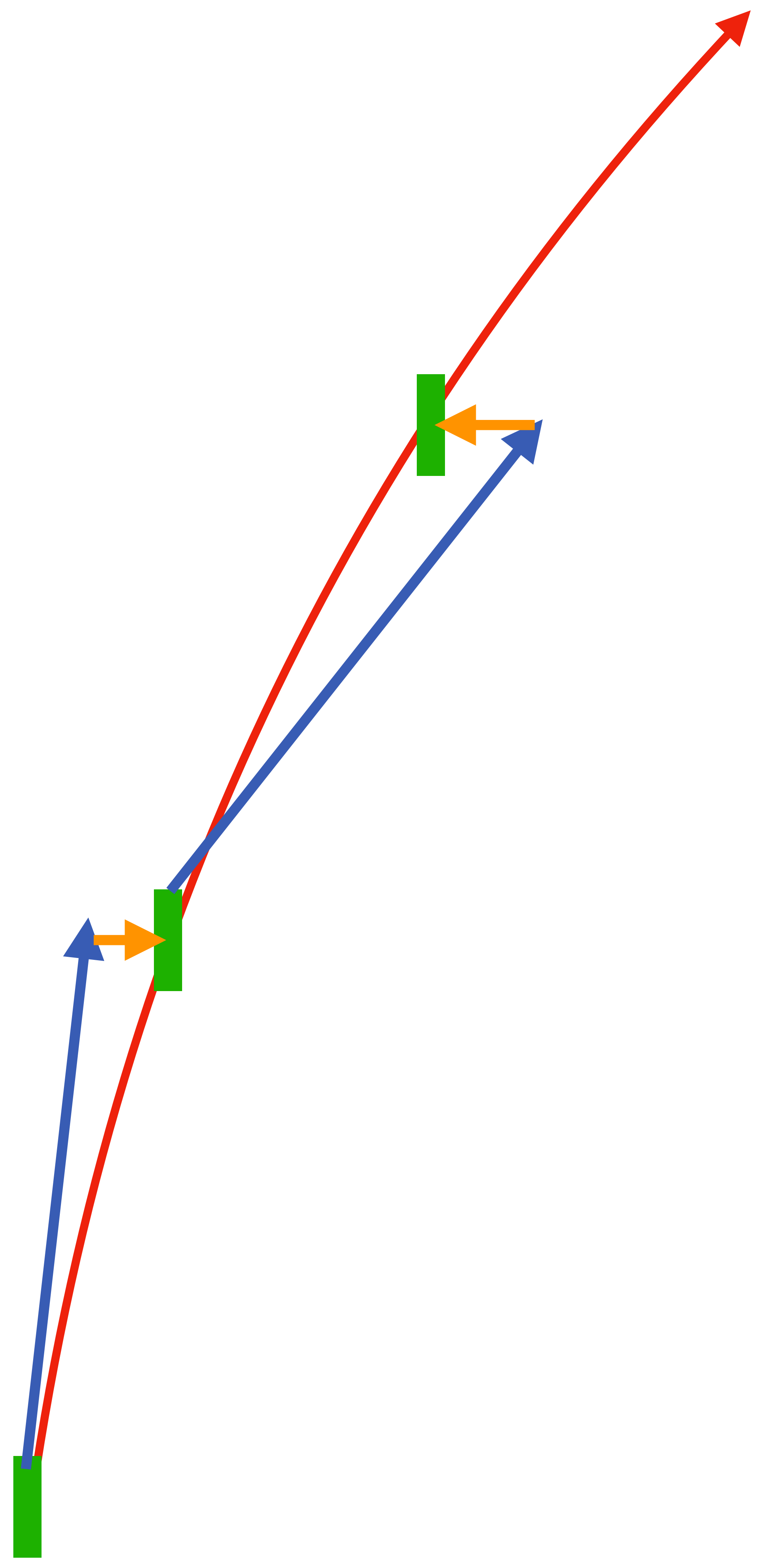


Figure by M. Puccio

Kalman filter

- Idea: propagate track through detector and update parameters
  → combination of track finding and fitting steps
  - Define parametrisation of track at given point together with propagator to next layer
    - propagator can take into account effects such as energy loss in material
  - Find a seed, i.e. rough track parametrisation from a single hit or track segment
  - Iterate over layers
    - propagate track to next layer
    - update parameterisation based on hit in this layer
- Algorithm can be repeated in opposite direction for refined fit and smoothing

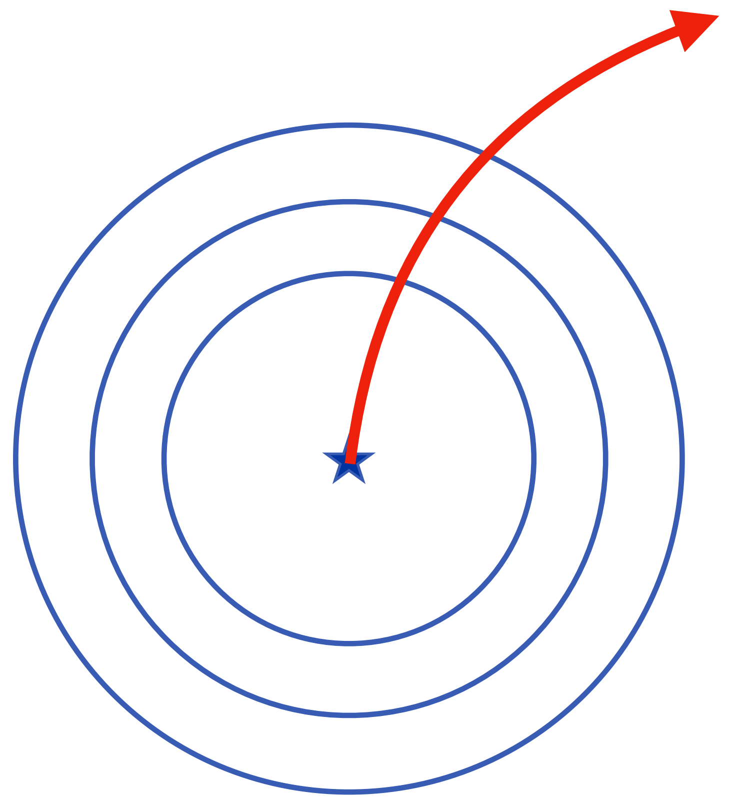


Detector optimisation

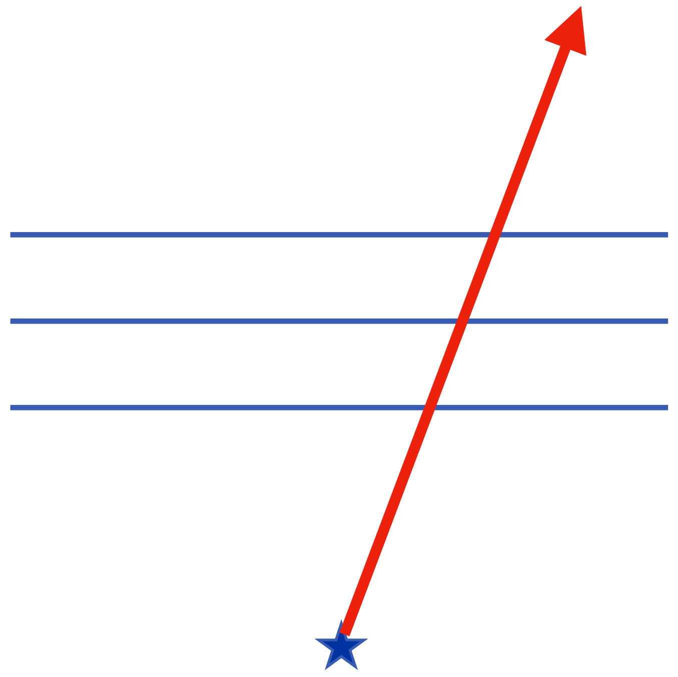
- Impact of **number of layers** on
  - track finding
  - track fitting
- Impact of **placement of layers** on
  - track finding
  - track fitting
- Impact of **lever arm and magnetic field** on
  - momentum resolution
- Impact of **dead zone and inefficiencies** on
  - corrections for analysis

Momentum resolution

- Consider **momentum resolution in solenoidal field**
  - $\propto \dfrac{\sqrt{d_{\text{tot}}/X_0 \cosh\eta}}{\beta B L}$ for multiple scattering
  - $\propto \dfrac{\sigma p_{\text{T}}}{BL^2}$ for position resolution
- **Objectives**
  - choose **lever arm L** required for momentum resolution:
    area (and cost) scales quadratically with L (for fixed η coverage)
  - choose **magnetic field**:
    higher field improves mom. resolution, limits acceptance,
    increases magnet cost
  - optimise **number of layers**:
    more layers add material, help with track finding, increase cost
  - minimise **material per layer**:
    challenge on power consumption, cooling, mechanics



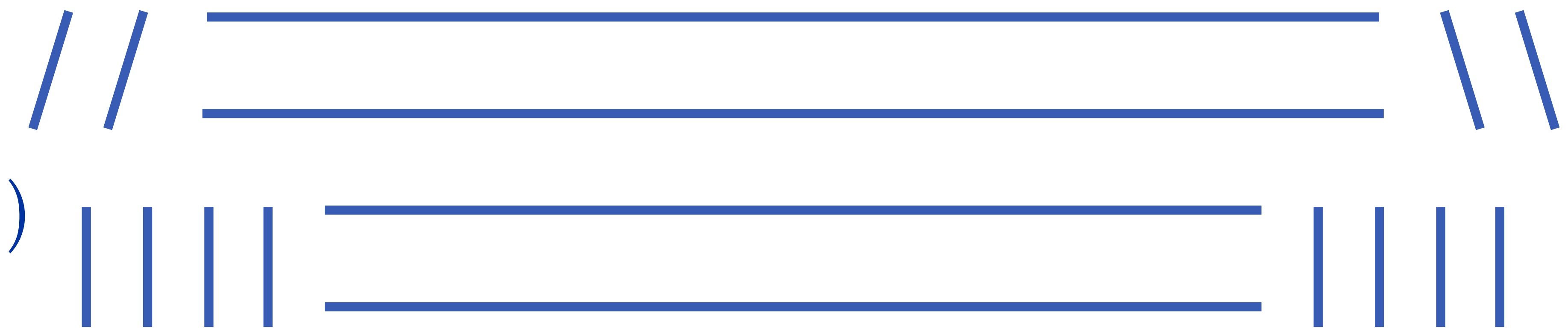
Trajectory through cylindrical layers



forward coverage with barrel layers
- **large areas → expensive**
- **deterioration of performance**

Tracker layout

- **Objectives**
  - optimise momentum resolution
  - reduce instrumented area
  - minimise path length in material (avoid shallow angles)
- Considerations
  - **Barrel layers** well suited to cover central region (up to $\eta \approx 1.5$)
  - **Disks** well suited to cover forward region (beyond $\eta \approx 1.5$)
  - **Inclined layers** can be used for transition region



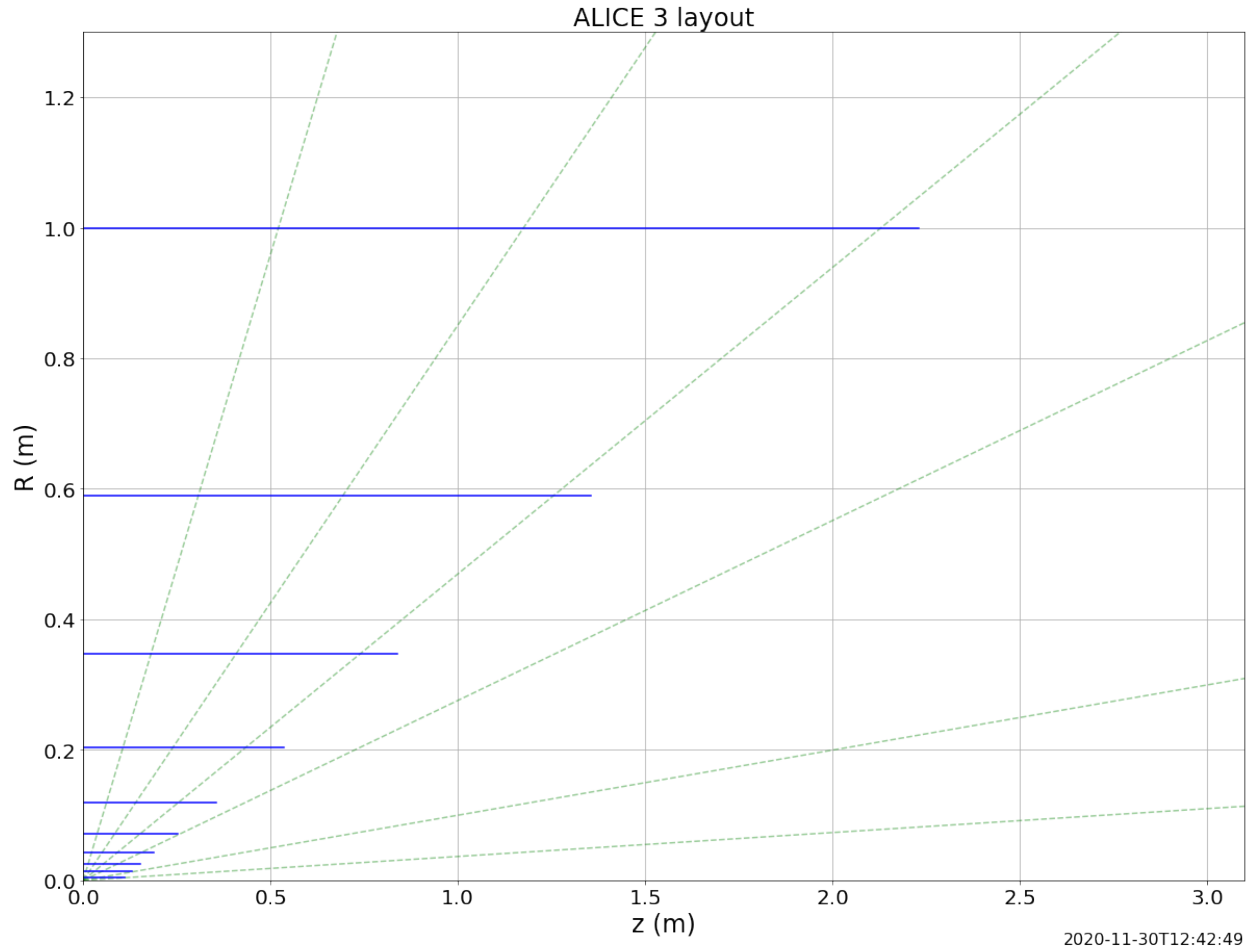
- **Ideal layout** depends on relative contributions of
  - multiple scattering
  - position resolution
  - track finding (pattern recognition)

Mismatch probability

- **Objective**
  - minimise assignment of hits not originating from a given track

- **A conceptual approach**
  - probability of wrong assignment
    scales with number of hits in vicinity
    $$P \propto \frac{\Delta R^2}{R^2} \cdot x/X_0$$
    here: assuming quadratic decay of particle flux
  - distance from preceding layer to achieve constant probability
    $$\Delta R \propto \sqrt{\frac{P}{x/X_0}} \cdot R$$

- **Inefficiencies and dead areas**
  can lead to significant deterioration of matching
  - layers often arranged in pairs to avoid lack of position information

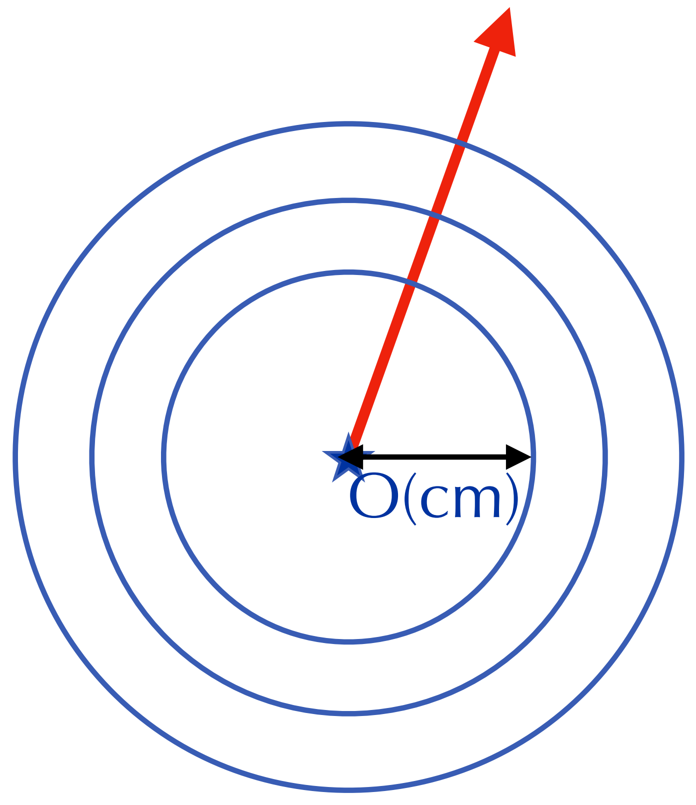


Additional considerations

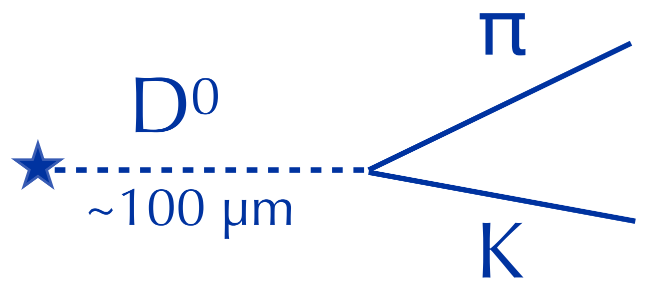
- **Momentum range**
  - limited by particles not reaching outer layers
  - limited by momentum resolution
- **Propagation to other detectors**
  - limited by pointing resolution towards other (outer) detectors
- **Track length determination**
  - limited by precision of propagation inside tracker
- **Reconstruction of secondary particles**
  - limited by number of hits
    for particles produced at a distance from the primary vertex

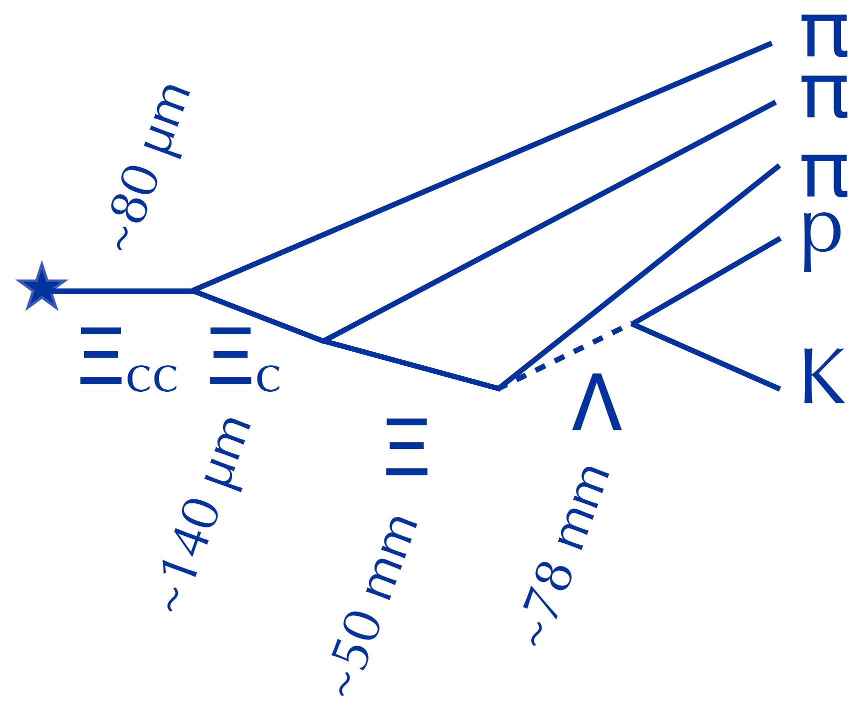
Vertices

- Reconstruction of **primary vertex**, i.e. point of underlying interaction, from emerging tracks
  - need to distinguish primary vertices
  - assignment of tracks to interactions
- Reconstruction of **decay vertices**
  - distinction of prompt and non-prompt particles
  - reconstruction of decay vertices and decay chains
- Need for pointing resolutions well below 100 μm



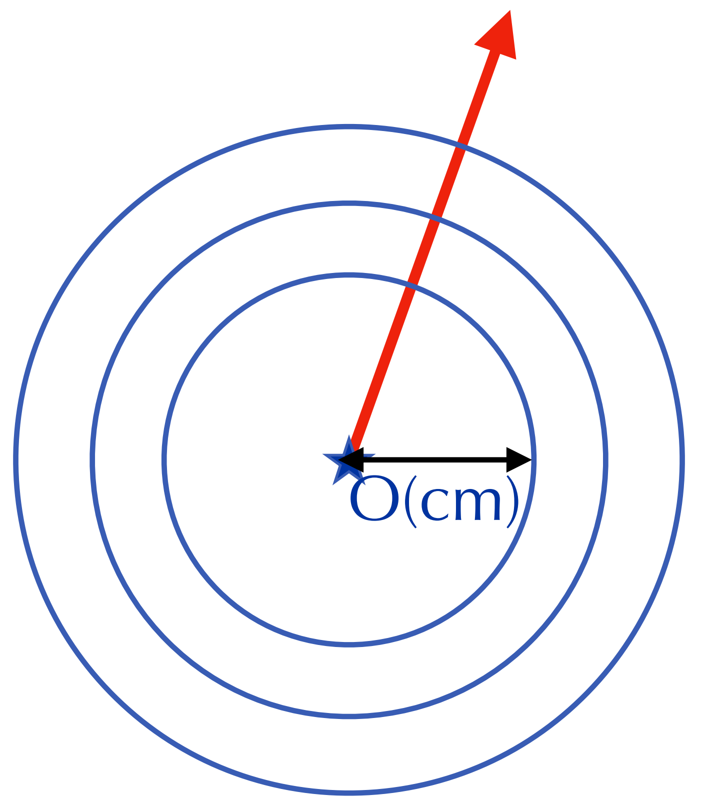
decays with cτ < 100 μm





Track propagation

- **Track finding** like for tracking
- Track and propagation defined by **straight line through 2 hits**
  - magnetic field can often be neglected because of short distances
  - typically vertex detectors feature at least three layers for track finding
- **Extrapolation limited** by
  - position resolution
  - multiple scattering



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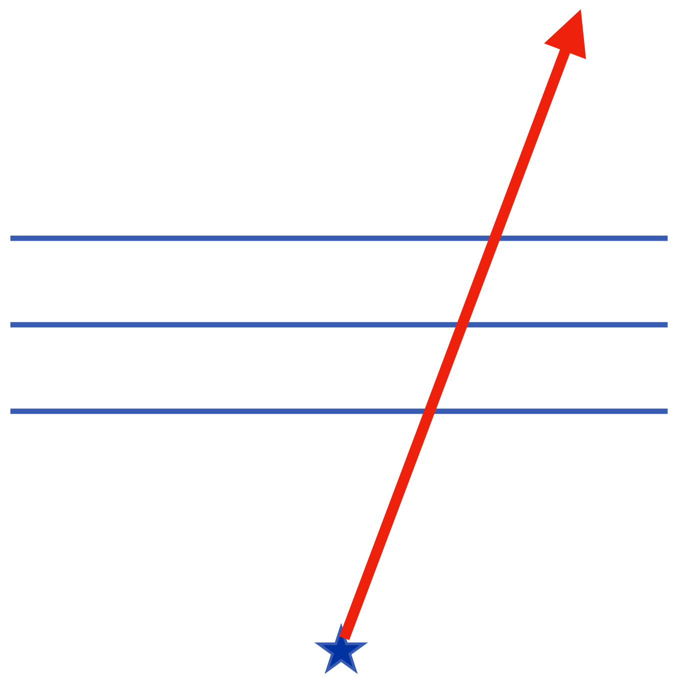
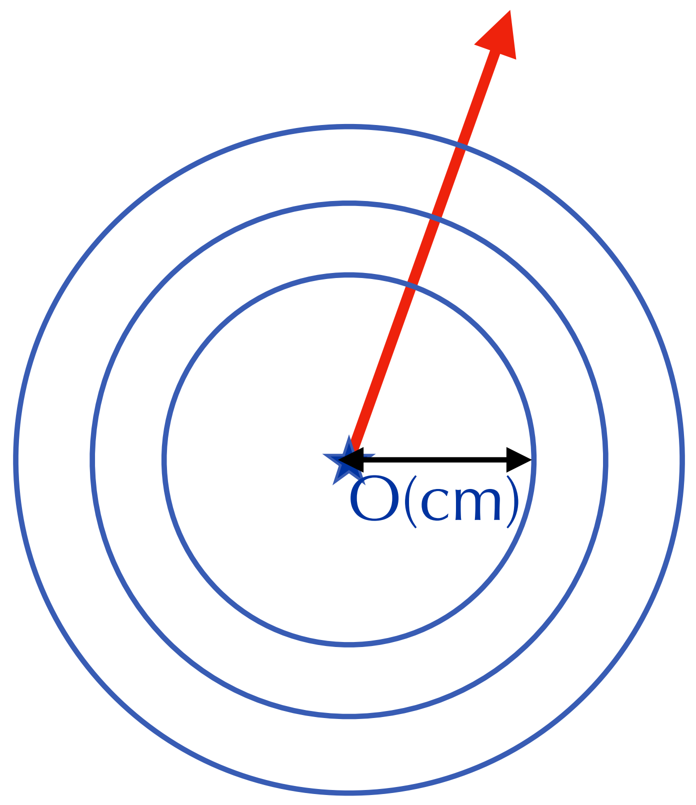


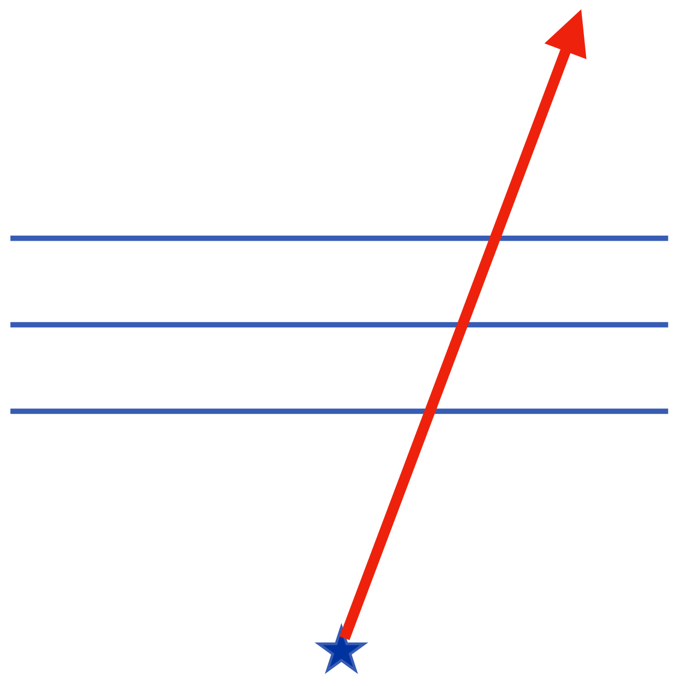
Position resolution

- Impact parameter obtained from **track extrapolation**
  - approximation by straight line
    $$f(x_i) = a_0 + a_1\, x_i$$
  - with first layer at radius r_0, uncertainty given by
    $$\sigma_{xy} = \sigma_{a_1} \cdot r_0$$
    $$\sigma_z = \sigma_{a_1} \cdot r_0 \cdot \cosh \eta$$



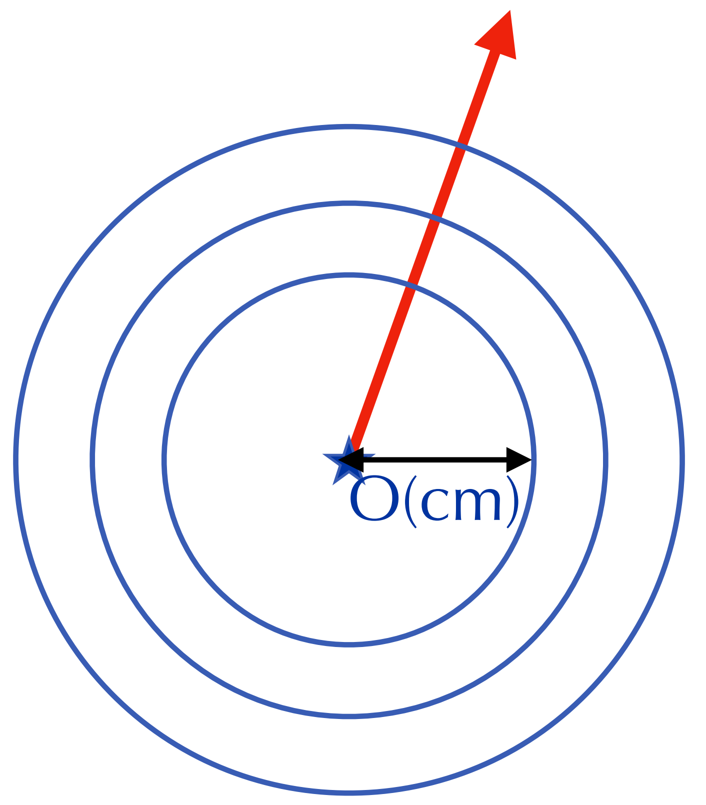
decays with $c\tau$ < 100 μm

- **Position resolution** of N+1 equidistant layers leads to
  - $\sigma_{d_{xy}} \propto \sigma_{r\varphi}$ (transverse impact parameter)
  - $\sigma_{d_z} \propto \sigma_z$ (longitudinal impact parameter)



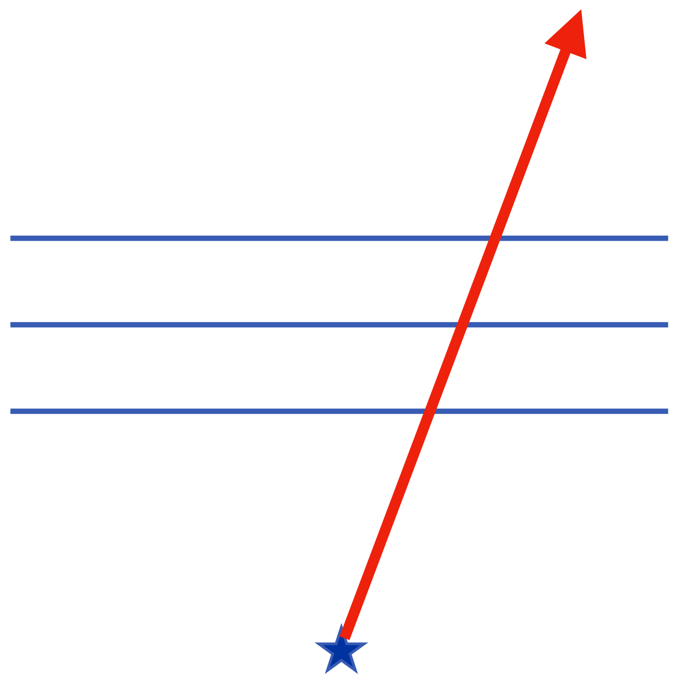
Multiple scattering

- **Multiple scattering in N+1 equidistant layers** leads to
  - $\sigma_{\varphi} \propto \frac{\sqrt{d/X_0 \cosh\eta}}{\beta p_{\mathrm{T}}}$
  - $\sigma_{\vartheta} \propto \frac{\sqrt{d/X_0 \cosh\eta}}{\beta p} \propto \frac{\sqrt{d/X_0}}{\beta p_{\mathrm{T}}\sqrt{\cosh\eta}}$



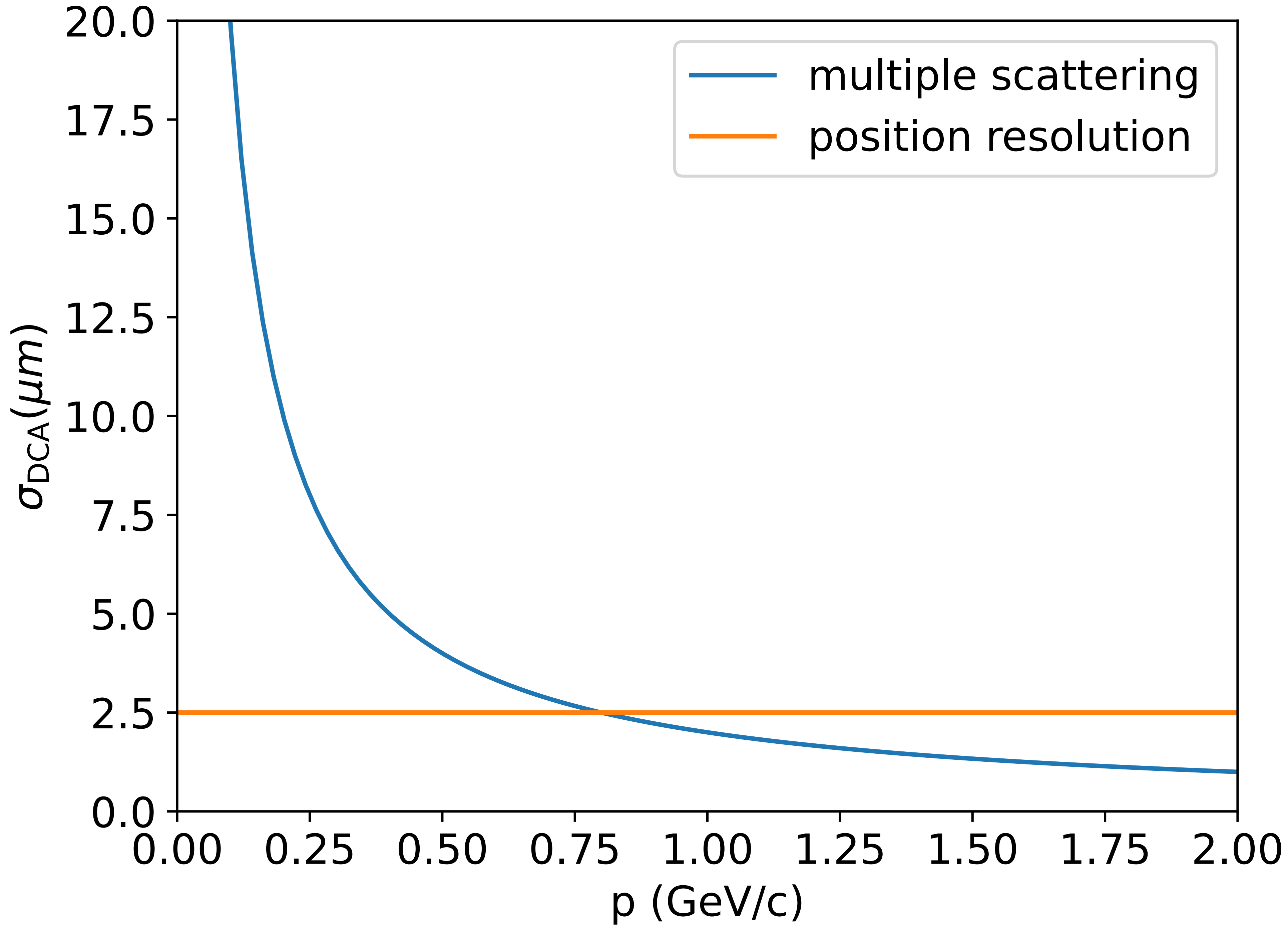
decays with cτ < 100 µm

- **Propagation towards interaction point** leads to
  - $\sigma_{d_{xy}} \propto \sigma_{\varphi} \cdot r_0 \propto \frac{\sqrt{d/X_0 \cosh\eta}}{\beta p_{\mathrm{T}}} r_0$ (transverse)
  - $\sigma_{d_z} \propto \sigma_{\vartheta} \cdot r_0 \cdot \cosh^2\eta \propto \frac{\sqrt{d/X_0}}{\beta p_{\mathrm{T}}} \cdot r_0 \cdot \sqrt{\cosh\eta}^3$ (longitudinal)



Considerations for detector layout

- **Pointing resolution scales**
  - with distance of closest layer
    → priority to be as close as possible
  - with square root of material (m.s. ∝ 1/p)
    → minimise material
  - with position resolution
    → keep sub-dominant (within range)
- **More layers do not improve precision**
  but can be needed for track finding



Scaling of resolutions

(for cylindrical layers)

	position resolution	multiple scattering
momentum	$\propto \frac{\sigma p_\mathrm{T}}{BL^2}$	$\propto \sqrt{d_\mathrm{tot}/X_0}\,\frac{\sqrt{\cosh\eta}}{\beta BL}$
transverse DCA	$\propto \sigma_{xy}$	$\propto r_0\sqrt{d/X_0}\,\frac{\sqrt{\cosh\eta}}{\beta p_\mathrm{T}}$
longitudinal DCA	$\propto \sigma_z$	$\propto r_0\sqrt{d/X_0}\,\frac{\sqrt{\cosh\eta}^{\,3}}{\beta p_\mathrm{T}}$

Particle identification

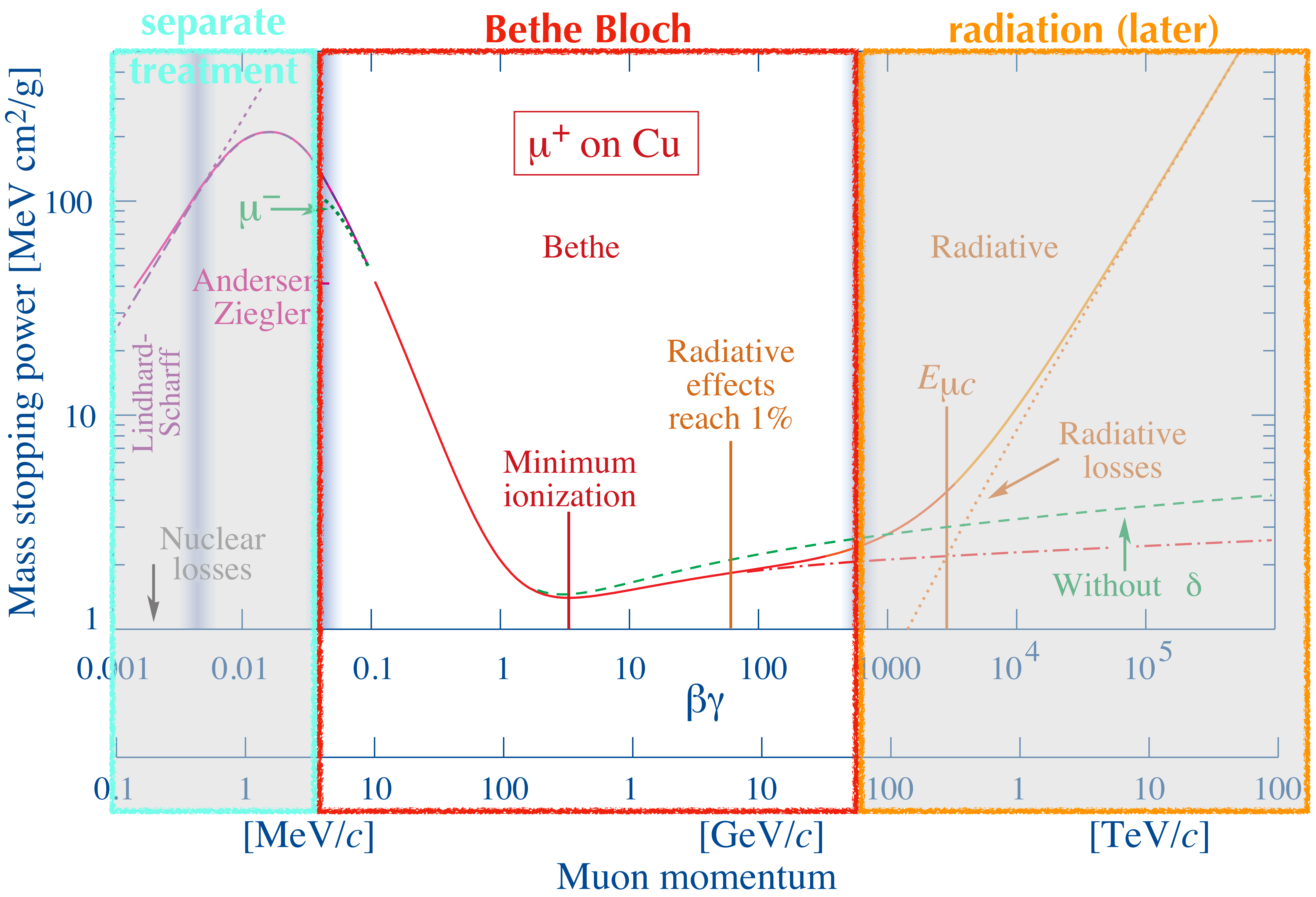
- **Mass measurement** from combination of tracking and additional measurements
  - **Specific energy loss**
    ➟ deposited charge (time over threshold)
  - **Time of flight** separation $\propto L / \sigma_{\mathrm{tof}}$
    ➟ large path length with fast time resolution
  - **Cherenkov** radiation with angle $\cos\vartheta = 1 / n\beta$
    ➟ refractive index to optimise coverage
    ➟ angular resolution
  - **Electromagnetic shower** to identify electrons
  - **Absorption** to identify muons

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)

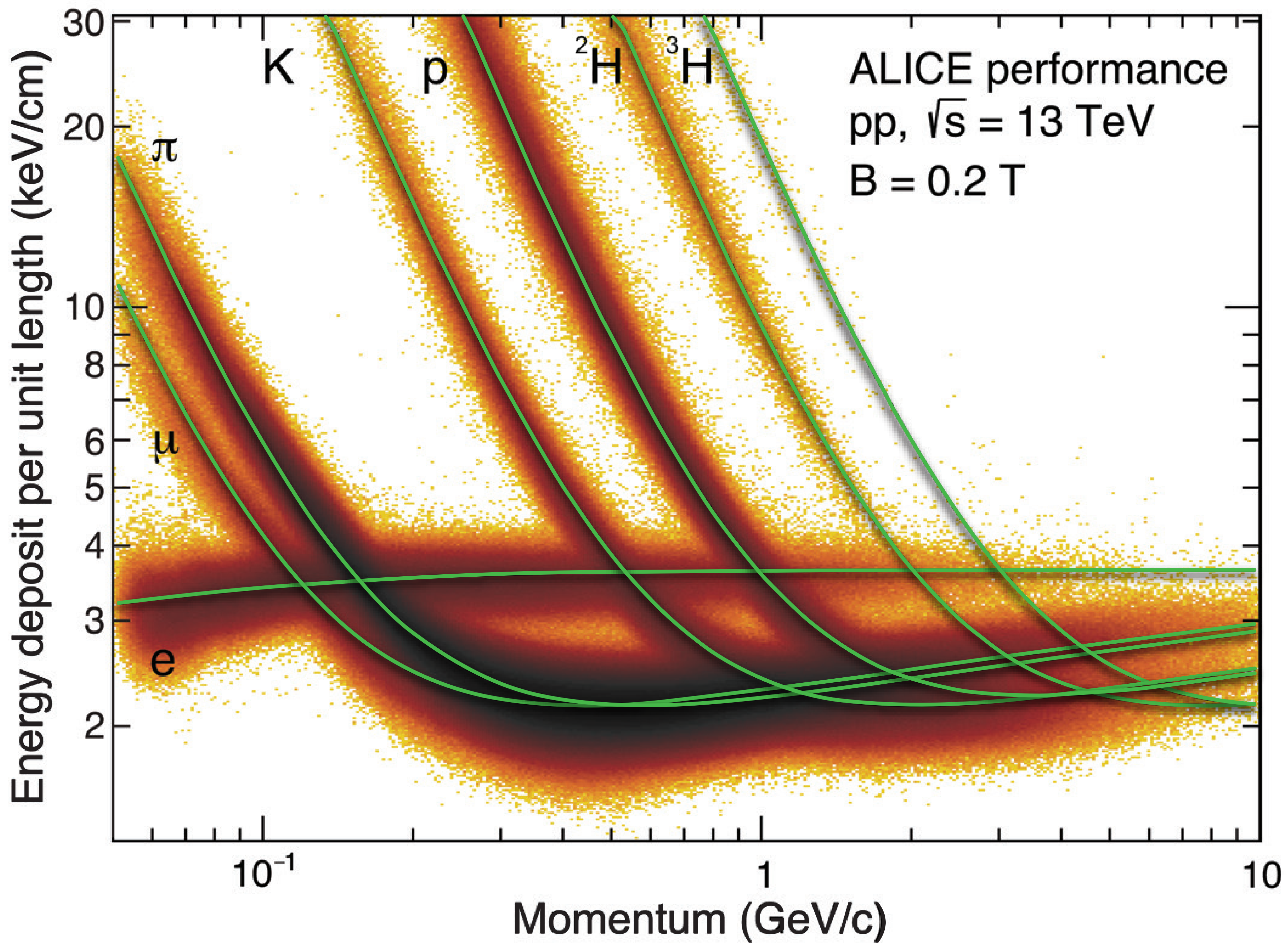


[H. Bethe, Ann. d. Physik 5 (1930) 325; F. Bloch, Ann. d. Physik 16 (1933) 285]

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

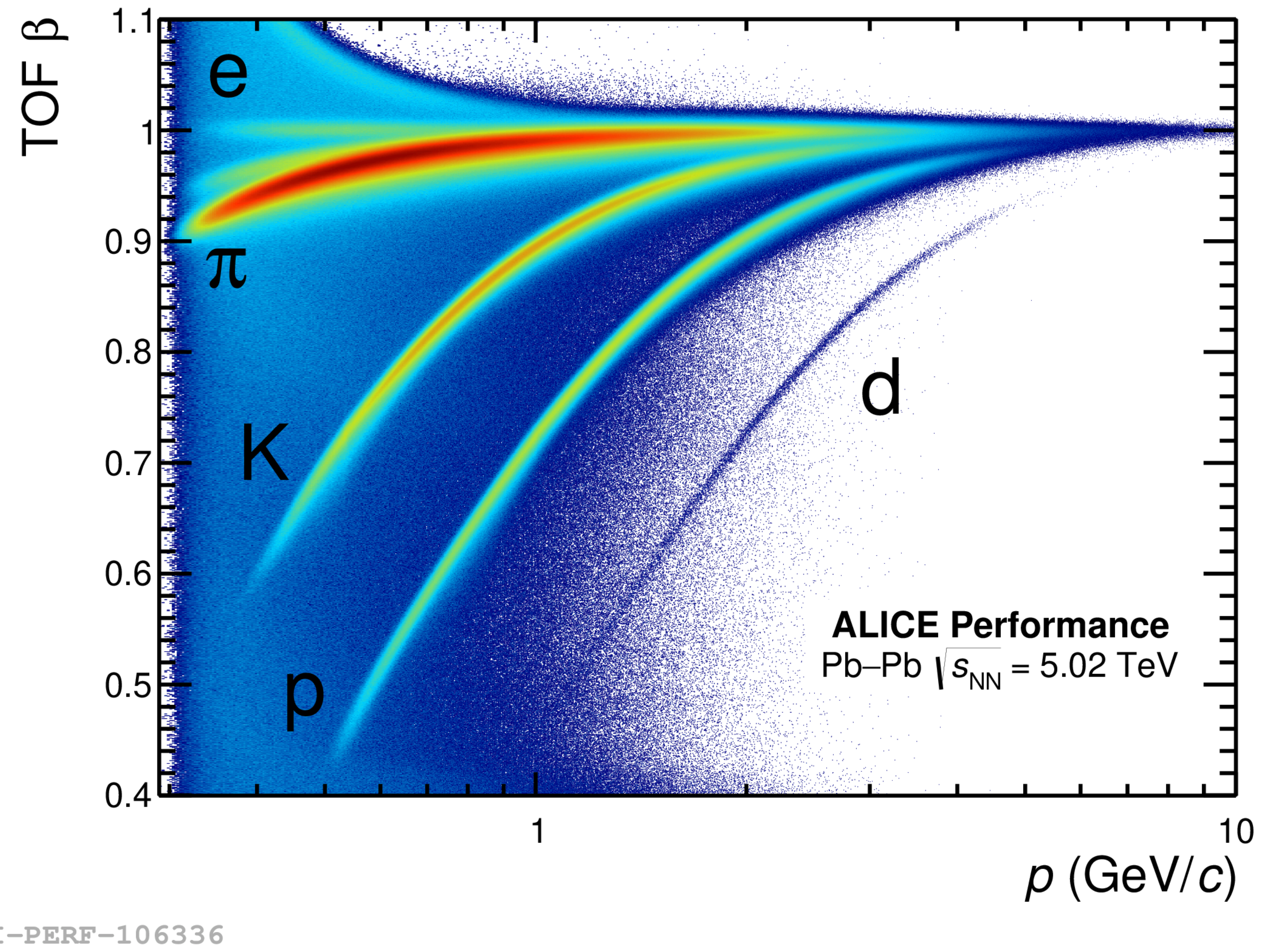
ALICE TPC



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** $N_\sigma = \frac{|m_1^2 - m_2^2| L}{2p^2 \sigma_t c}$

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



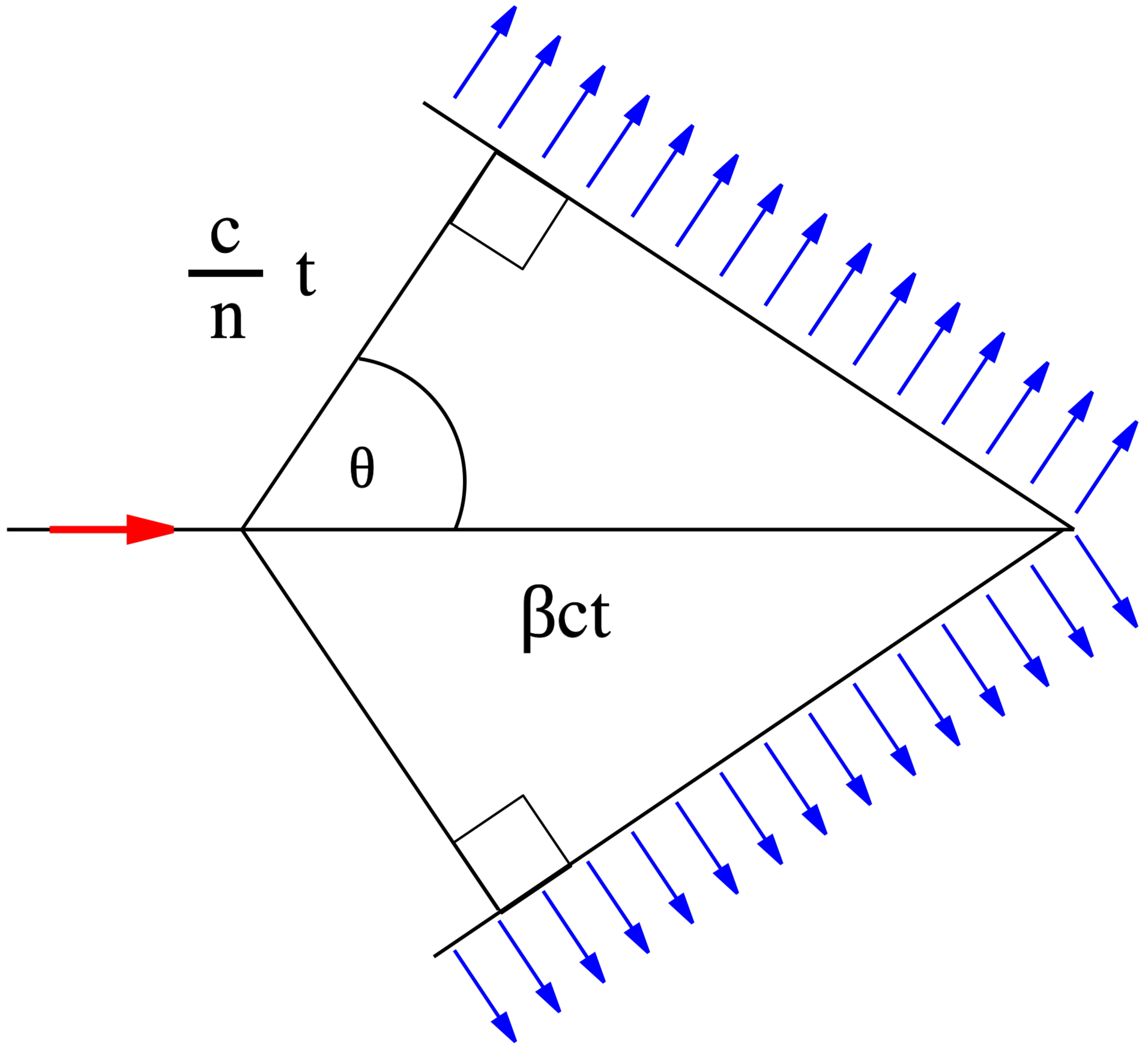
- Often realised as **combination of fast detector outside of tracker**
  → no impact on tracking performance, large path length

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 $\beta = p/E$
    → 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

Summary part 1

- Fundamental physics questions remain open
  - can be addressed at the LHC, but not with existing experiments
- Key measurements need to drive optimisation of detector
  - tracking
  - vertexing
  - particle identification

Time for discussion 😊

ALICE 3

Lecture II

1st ALICE experiment and heavy-ion workshop

复旦大学 （上海，中国）

2025-11-09

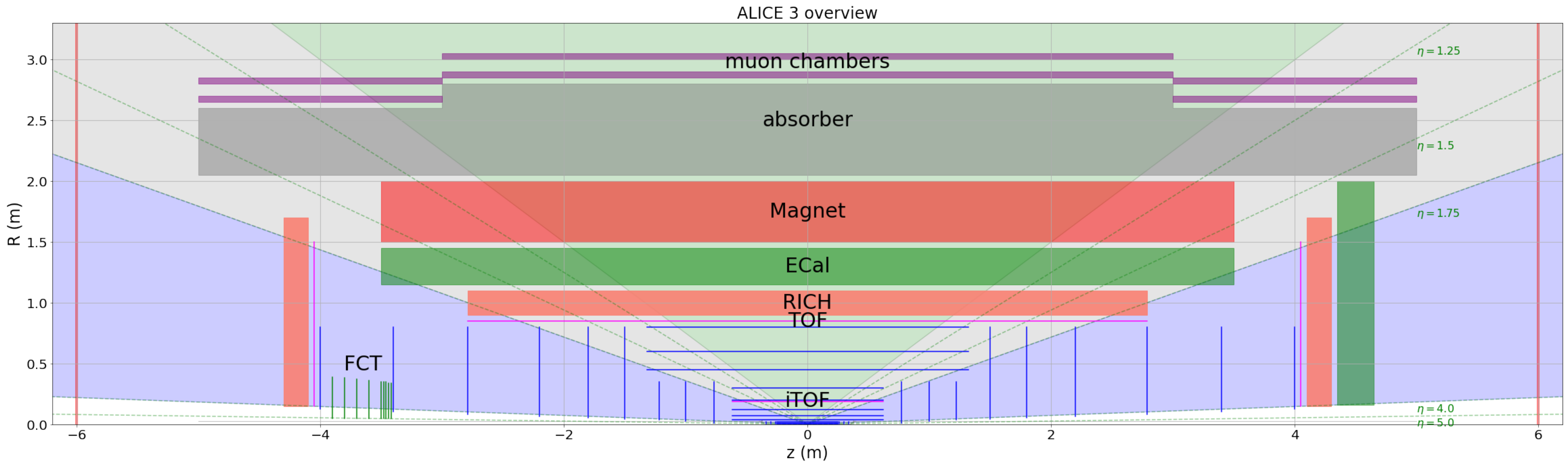
Jochen Klein (CERN)

Observables (recap)

- **Heavy-flavour hadrons** ($p_T \rightarrow 0$, $|\eta| < 4$)
  - vertexing (decay chain)
  - tracking (inv. mass resolution)
  - hadron ID (background suppression)
- **Dielectrons** (p_T ~0.1 - 3 GeV/c, M_{ee} ~0.1 - 4 GeV/c^2)
  - vertexing (HF background suppression)
  - tracking (inv. mass resolution)
  - electron ID
- **Photons** (100 MeV/c - 50 GeV/c, wide η range)
  - electromagnetic calorimetry
- **Quarkonia and Exotica** ($p_T \rightarrow 0$)
  - muon ID
- **Ultrasoft photons** (p_T = 1 - 50 MeV/c)
  - dedicated forward detector
- **Nuclei**
  - identification of $z > 1$ particles

Key requirements

- Tracking over large rapidity range
- Excellent vertexing
- Excellent particle identification
- High rate



Detector requirements

Component	Observables	$\lvert\eta\rvert < 1.75$ (barrel)	$1.75 < \lvert\eta\rvert < 4$ (forward)	Detectors
Vertexing	Multi-charm baryons, dielectrons	**Best possible DCA resolution, $\sigma_{DCA} \approx 10$ μm at 200 MeV/*c***	**Best possible DCA resolution, $\sigma_{DCA} \approx 30$ μm at 200 MeV/*c***	Retractable silicon pixel tracker: $\sigma_{pos} \approx 2.5$ μm, $R_{in} \approx 5$ mm, $X/X_0 \approx 0.1$ % for first layer
Tracking	Multi-charm baryons, dielectrons	**σ_{p_T} / p_T ~1-2 %**		Silicon pixel tracker: $\sigma_{pos} \approx 10$ μm, $R_{out} \approx 80$ cm, $X/X_0 \approx 1$ % / layer
Hadron ID	Multi-charm baryons	**π/K/p separation up to a few GeV/*c***		Time of flight: $\sigma_{tof} \approx 20$ ps RICH: aerogel, $\sigma_\theta \approx 1.5$ mrad
Electron ID	Dielectrons, quarkonia, $\chi_{c1}(3872)$	pion rejection by 1000x up to ~2 - 3 GeV/*c*		Time of flight: $\sigma_{tof} \approx 20$ ps RICH: aerogel, $\sigma_\theta \approx 1.5$ mrad
Muon ID	Quarkonia, $\chi_{c1}(3872)$	reconstruction of J/Ψ at rest, i.e. muons from 1.5 GeV/*c*		steel absorber: L ≈ 70 cm muon detectors
Electromagnetic calorimetry	Photons, jets	large acceptance		Pb-Sci calorimeter
	χ_c	high-resolution segment		$PbWO_4$ calorimeter
Ultrasoft photon detection	Ultra-soft photons		measurement of photons in p_T range 1 - 50 MeV/*c*	Forward Conversion Tracker based on silicon pixel sensors

Detector implementation

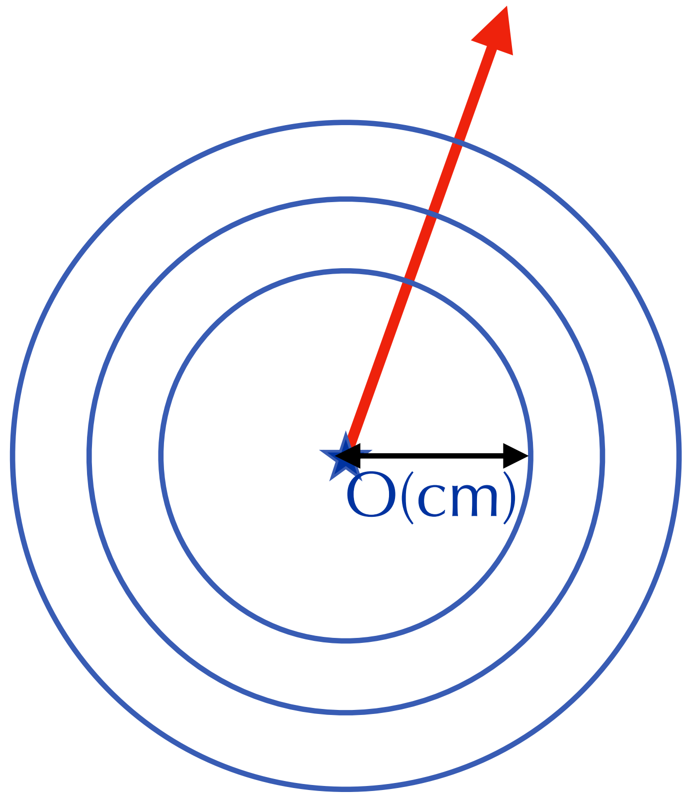
How can we build such a detector?

Vertex reconstruction

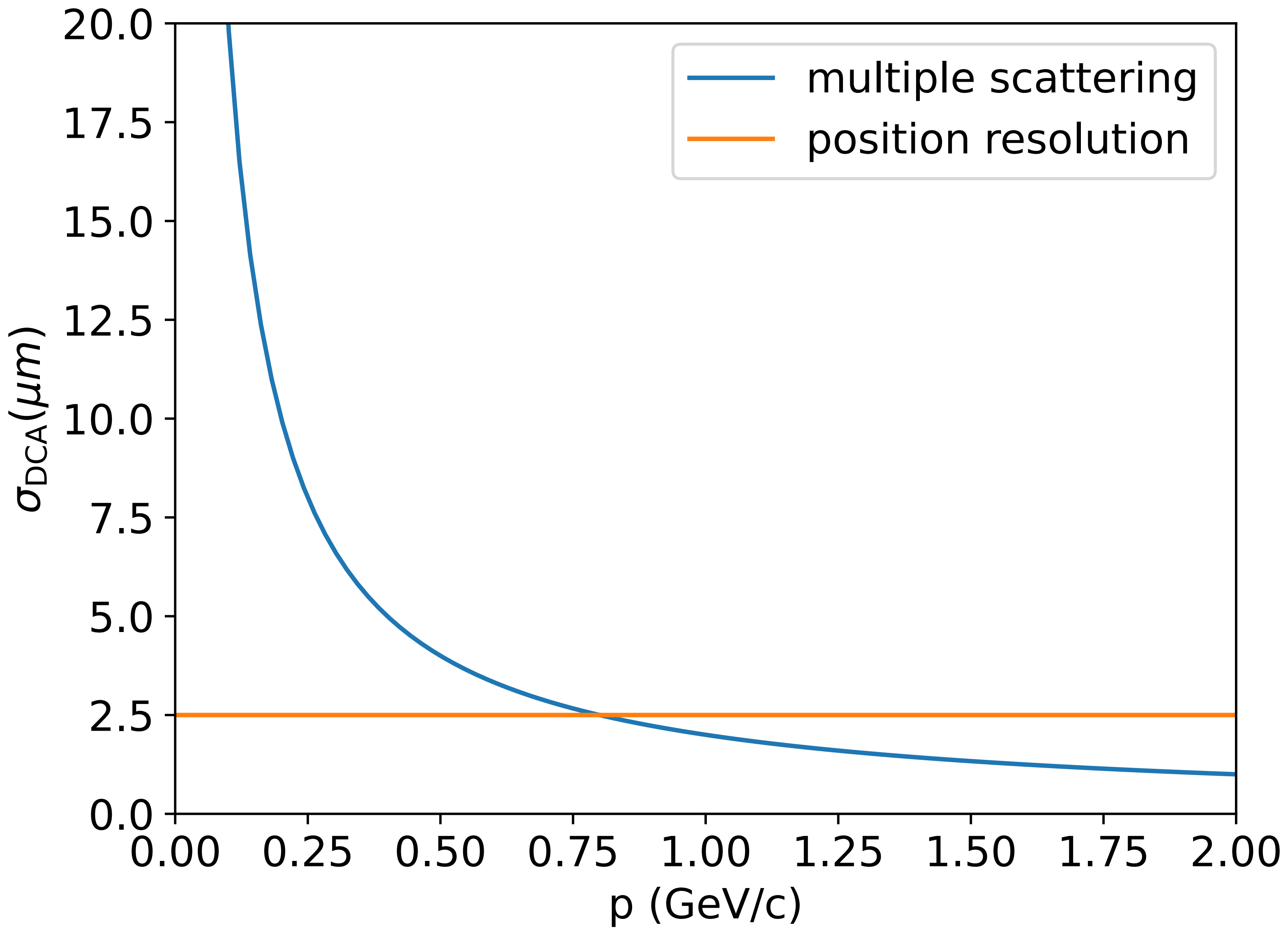
- **Primary and decay vertices** reconstructed through pointing of tracks
  ➠ 2 - 3 detection layers
  - pointing resolution fundamentally limited by multiple scattering:

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

    ➠ **minimal radius** of innermost layer
    ➠ **minimal material** before first layer
  - constant contribution from position resolution
    ➠ stay below limit from multiple scattering



decays with cτ < 100 μm



Beam aperture

- **Minimal radius** given by required beam aperture
  - R ≈ 15 mm at injection energy
  - R ≈ 5 mm at top energy
    (beam emittance shrinks with acceleration)
- Exploitation of ultimate radius requires **retractable detector**
  → moveable device within the beampipe!!!

Challenges of vertex detector

- **Optimisation of pointing resolution** requires
  - minimisation of extrapolation uncertaincty
    → minimal radius of first layer ~5 mm
  - minimisation of multiple scattering
    → low material ~0.1 % X_0
  - sub-dominant contribution of position resolution
    → spatial resolution ~2.5 μm
- **Operational conditions**
  - very high particle fluences
    → radiation tolerance > 10^{15} 1-MeV n_{eq}
  - very large number of hits
    → readout speed to handle 10^8 hits / cm^2 / s
- **Choice of technology**
  - monolithic silicon pixel sensors are well suited

Tracking

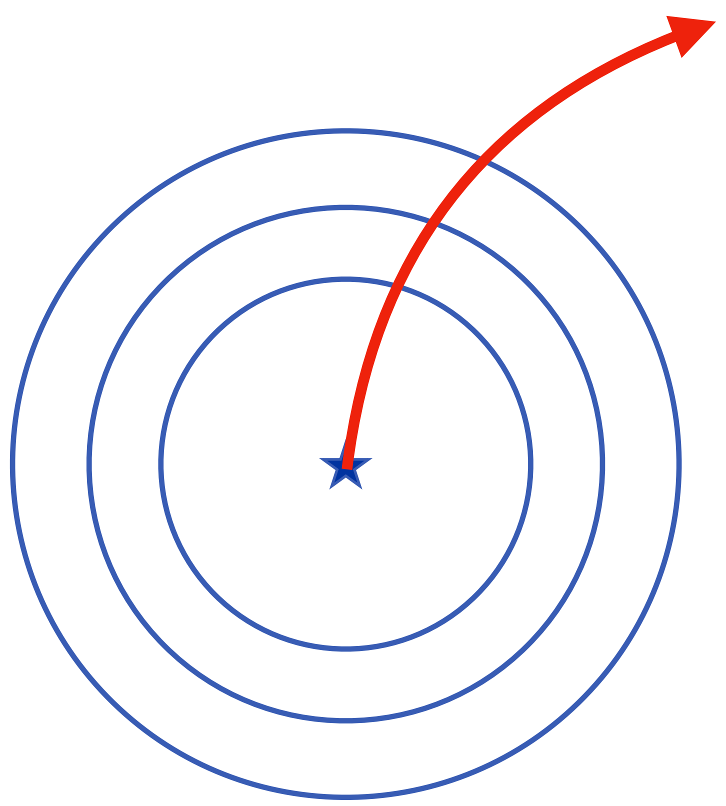
- **Track finding** and **momentum** measurement
  ➟ 3 - N space points in magnetic field
  - momentum resolution limited by **multiple scattering** and lever arm

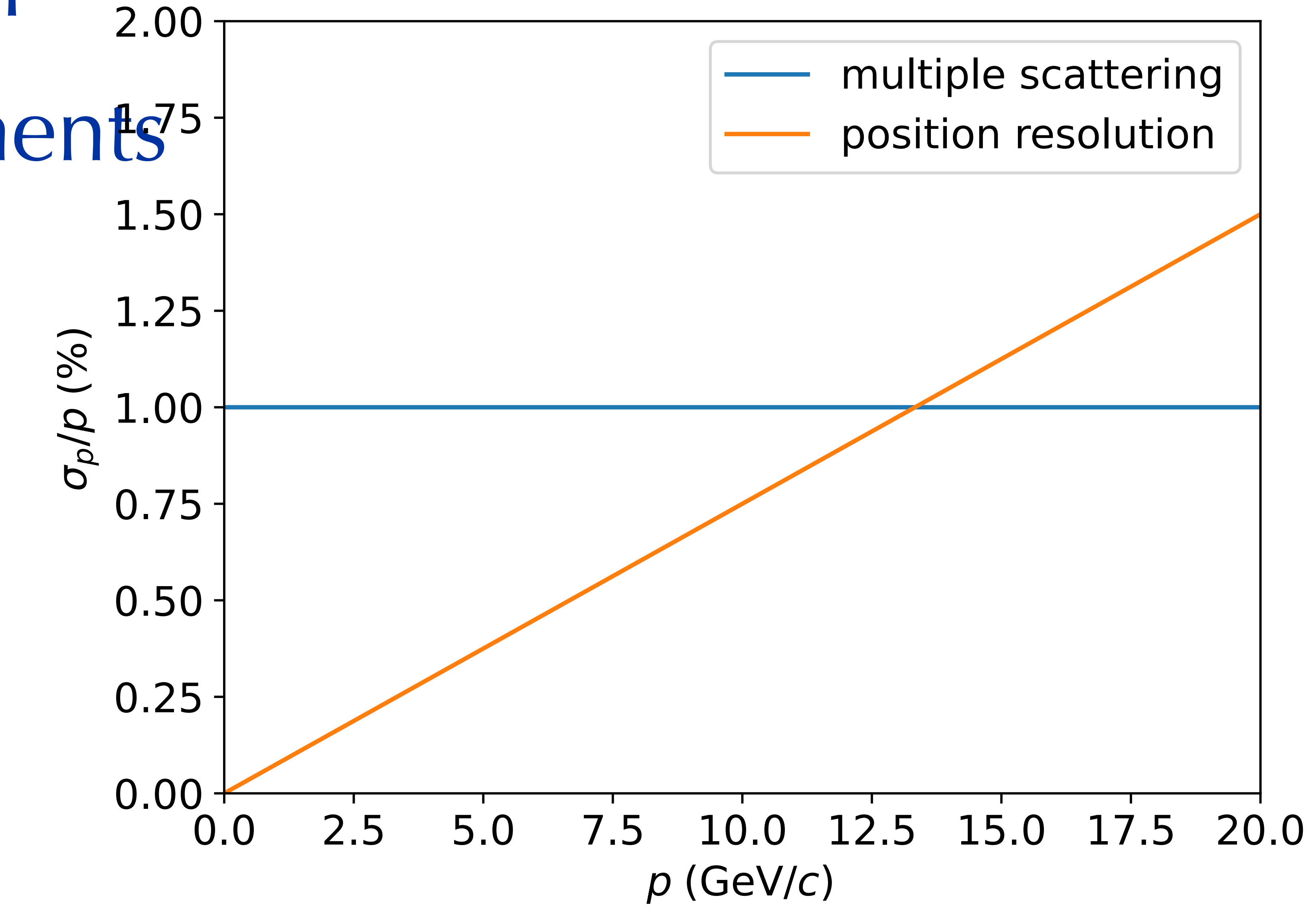
$$\sigma_p/p \propto \frac{\sqrt{x/X_0}}{B \cdot L}$$

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

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

    ➟ should be sub-dominant in region of interest





- Additional considerations
  - high rate → occupancy → fake hit assignments
  - acceptance and cost (area)

Challenges of tracker

- **Optimisation of momentum resolution**
  - minimisation of multiple scattering
    → low material ~0.1 % X_0
  - sub-dominant contribution of position resolution
    → spatial resolution ~2.5 μm
- **Operational conditions**
  - large area to cover acceptance
  - very high particle fluences
    → radiation tolerance > 10^{15} 1-MeV n_{eq}
  - very large number of hits
    → readout speed to handle 10^5 hits / cm^2 / s
- **Choice of technology**
  - monolithic silicon pixel sensors are well suited

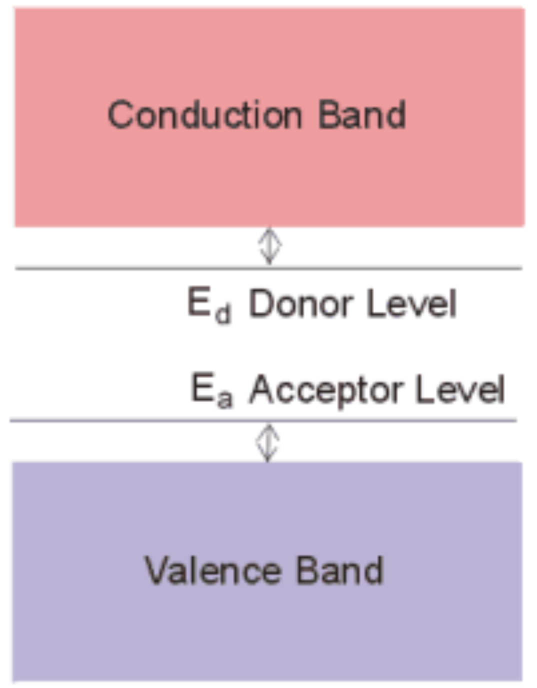
Silicon pixel detectors

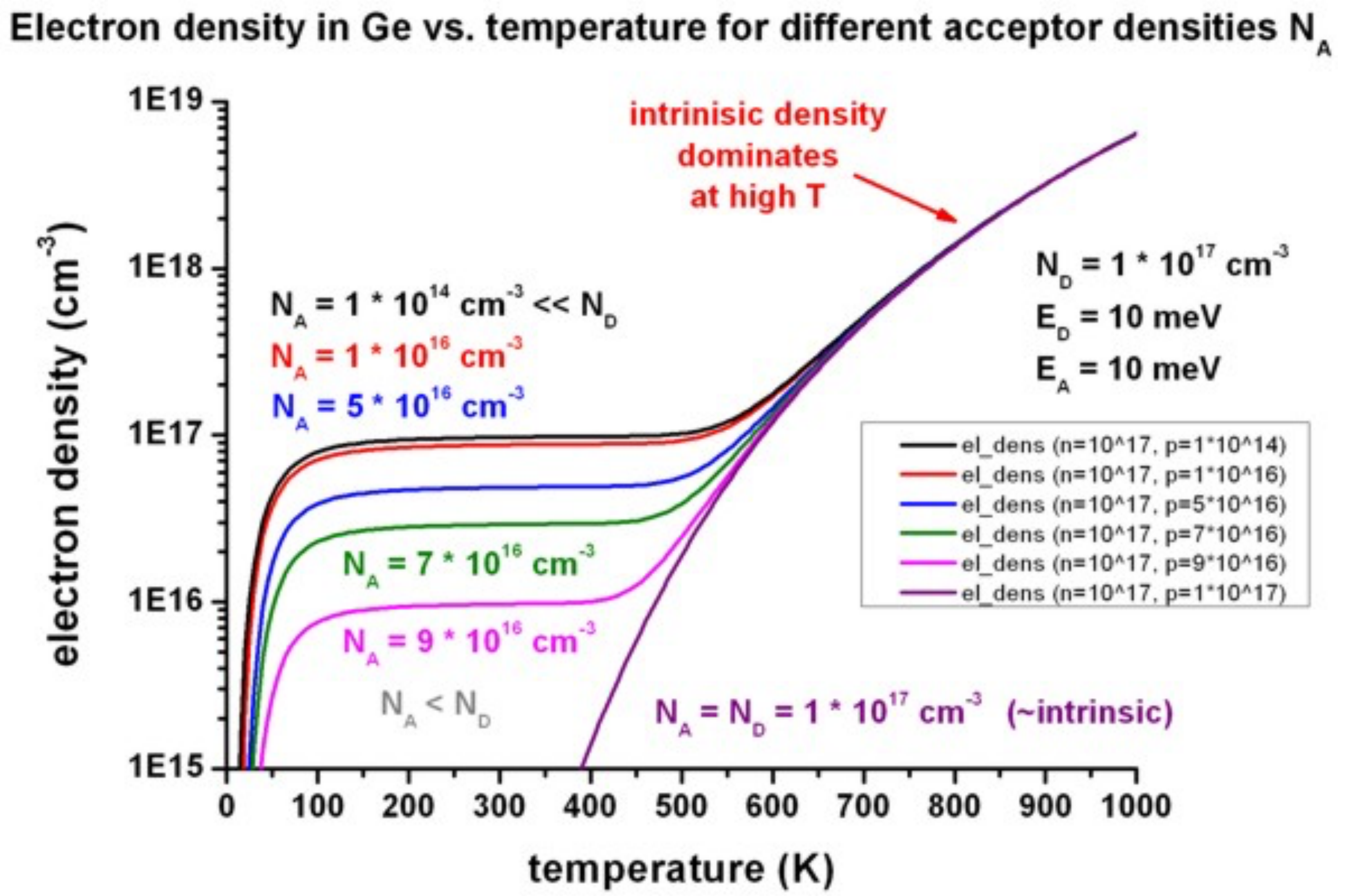
How do we optimise silicon pixel sensors
for the application in the vertex detector and tracker?

Charge carriers in semi-conductors

- Electrons and holes as **charge carriers**
  - **intrinsic semiconductors**:
    thermal excitation across band gap
  - **extrinsic semiconductors (doping)**:
    excitation from/to donor/acceptor levels
    → saturation

- **Drift of charge carriers** similar to gases $\mathcal{O}$(cm/μs),
  slower for holes $v_{\mathrm{h}} \approx 0.3 - 0.5 v_{\mathrm{e}}$





pn junction

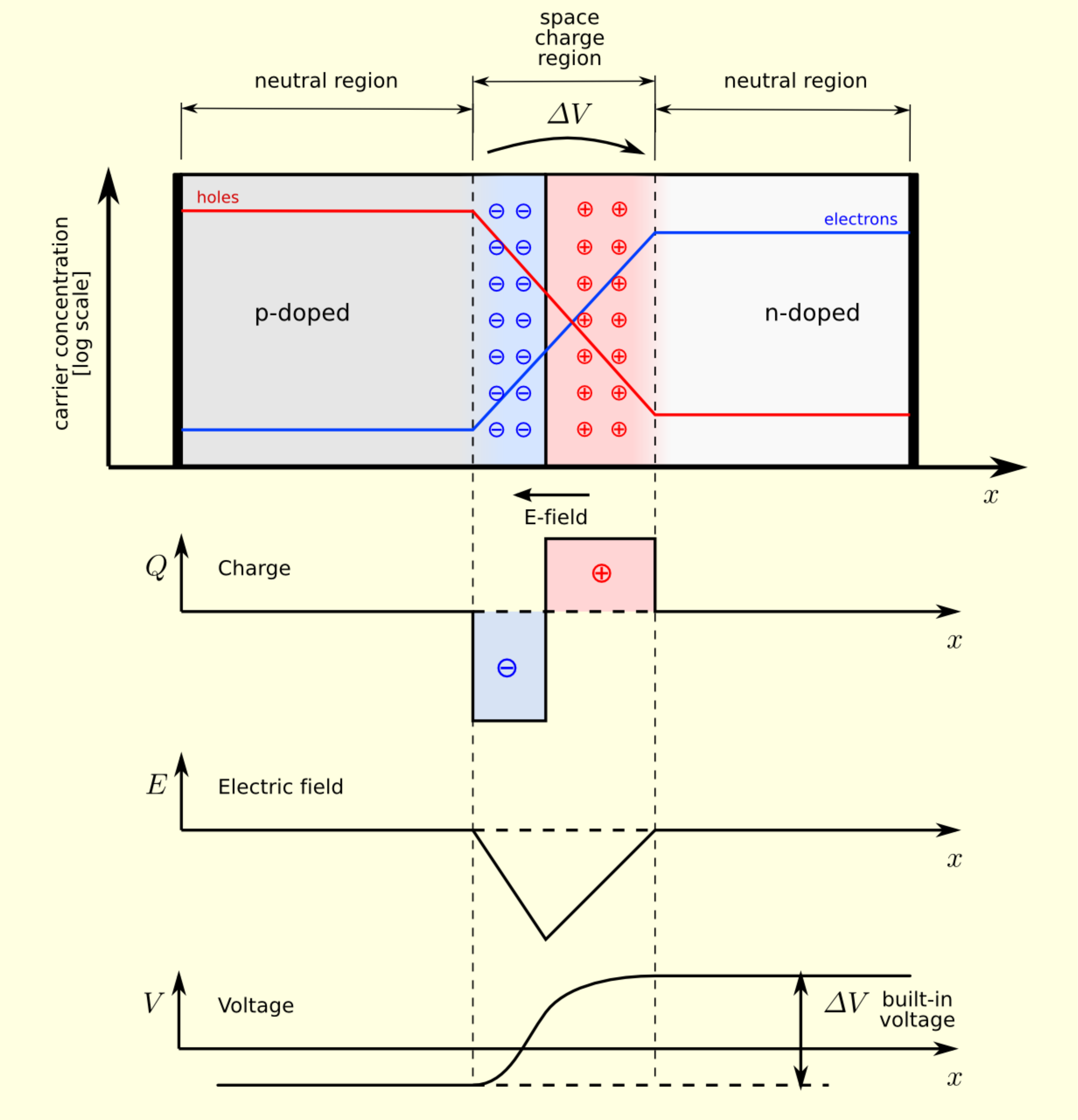
- Contact between p- and n-doped regions
  → **depletion zone**
  - depletion of charge carriers
  - net charge
  - electric field

- **Schottky model**
  - sharp edges of regions
  - thickness of depletion zone

$$d_n = \sqrt{\frac{2\epsilon\epsilon_0 V_D}{e} \frac{N_A/N_D}{N_A + N_D}}$$

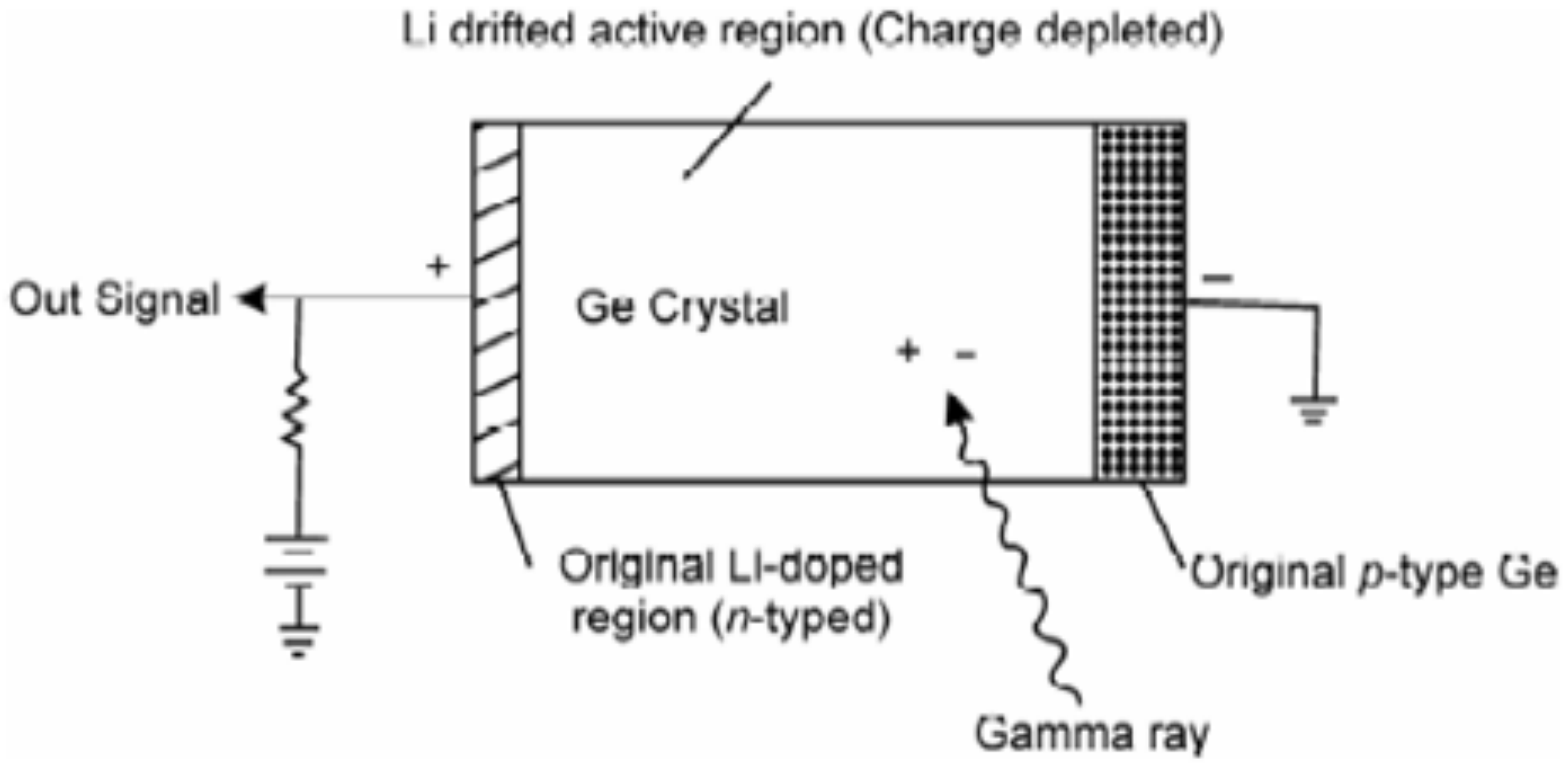
$$d_p = \sqrt{\frac{2\epsilon\epsilon_0 V_D}{e} \frac{N_D/N_A}{N_A + N_D}}$$

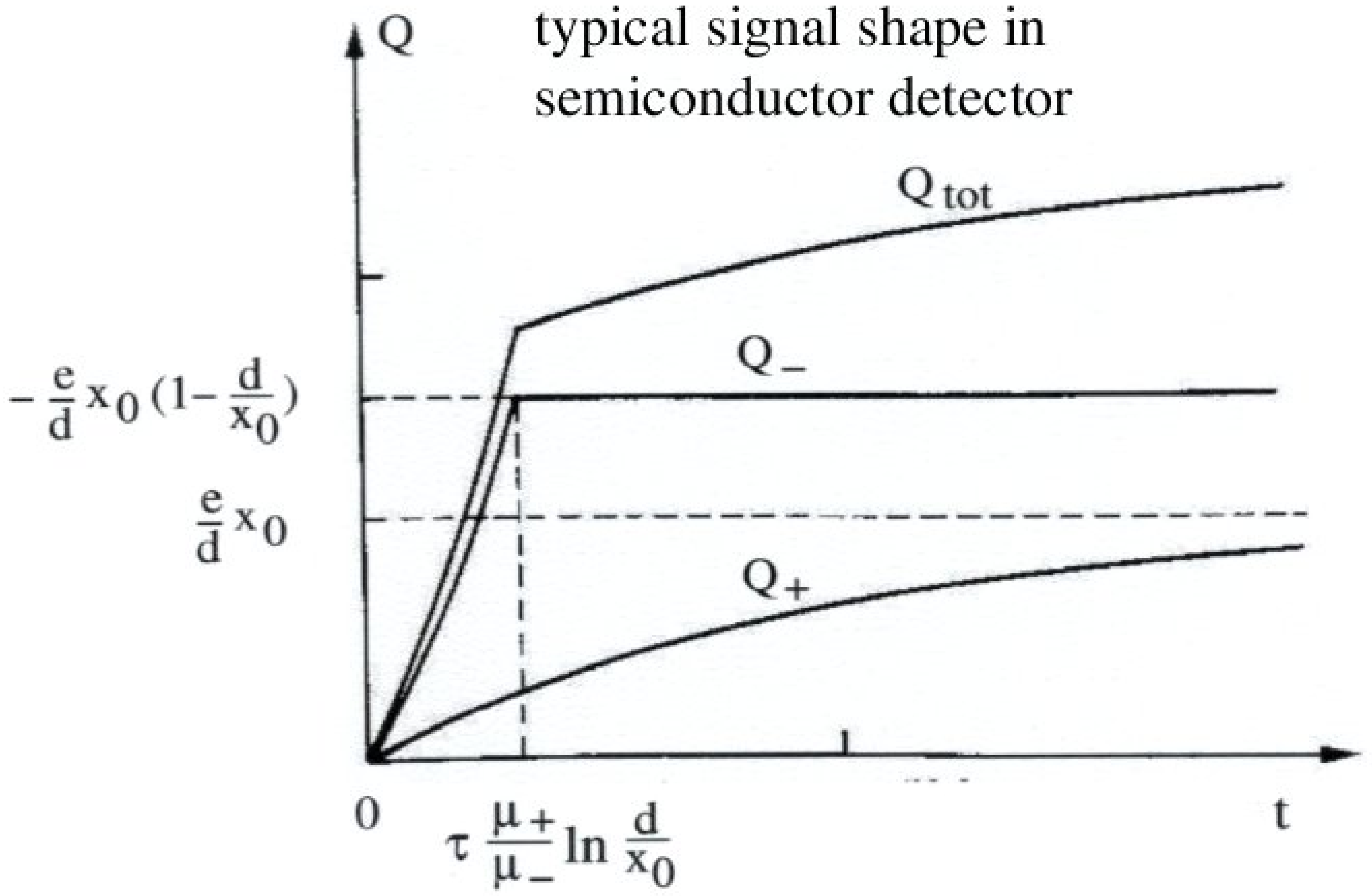
  - large depletion zone achievable
    with highly asymmetric doping and/or bias voltage



Semiconductor sensor

- Ionisation leads to creation of **electrons and holes** (also phonon excitation) in depletion region (used as active volume)
  - electric field leads to drift
    (with similar drift velocities for electrons and holes)





semiconductor analogue of ionisation chamber

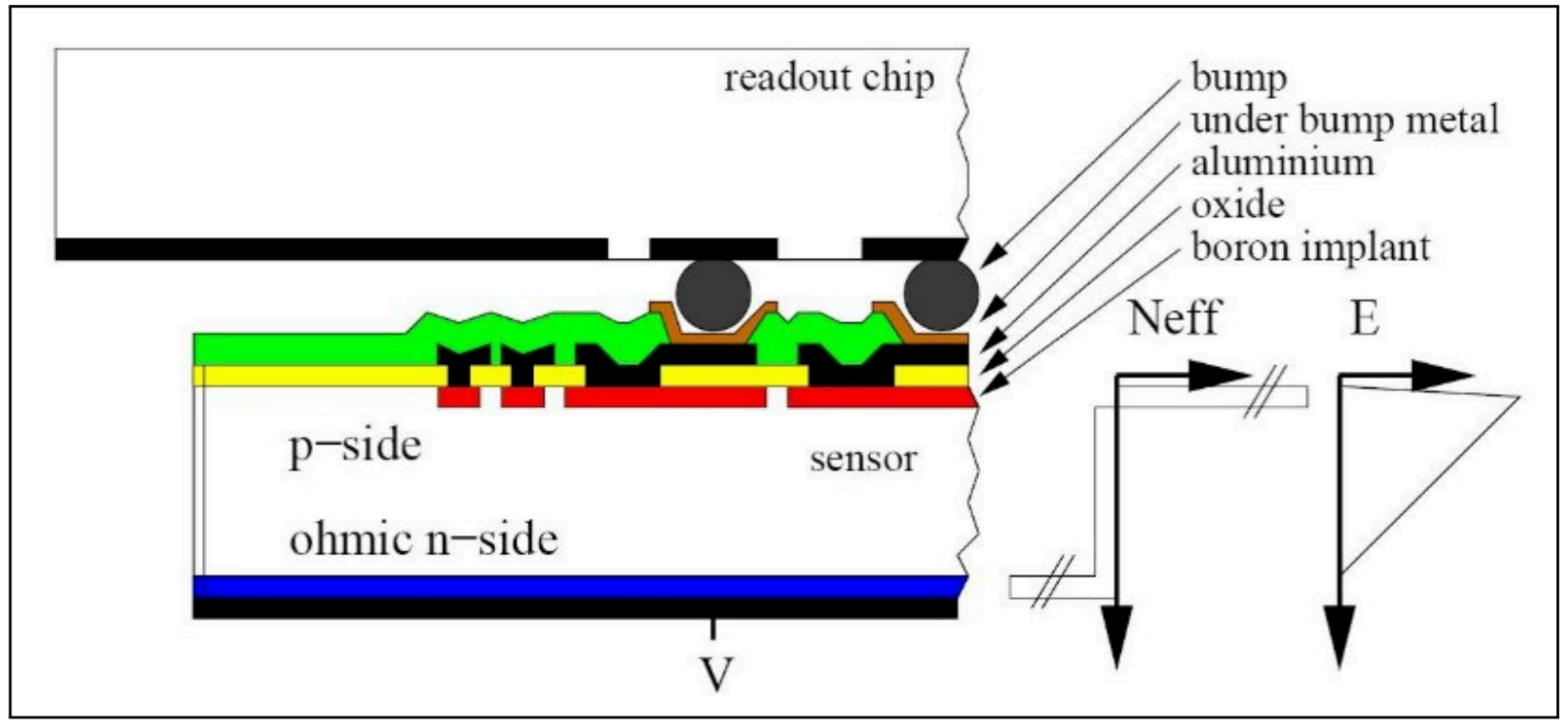
Hybrid vs monolithic

- **Hybrid sensors**
  → separate chips for sensor and readout
  - can be produced in different processes
  - requires bonding
    e.g. bump bonding, wafer to wafer

Examples

- ATLAS Itk
- CMS tracker

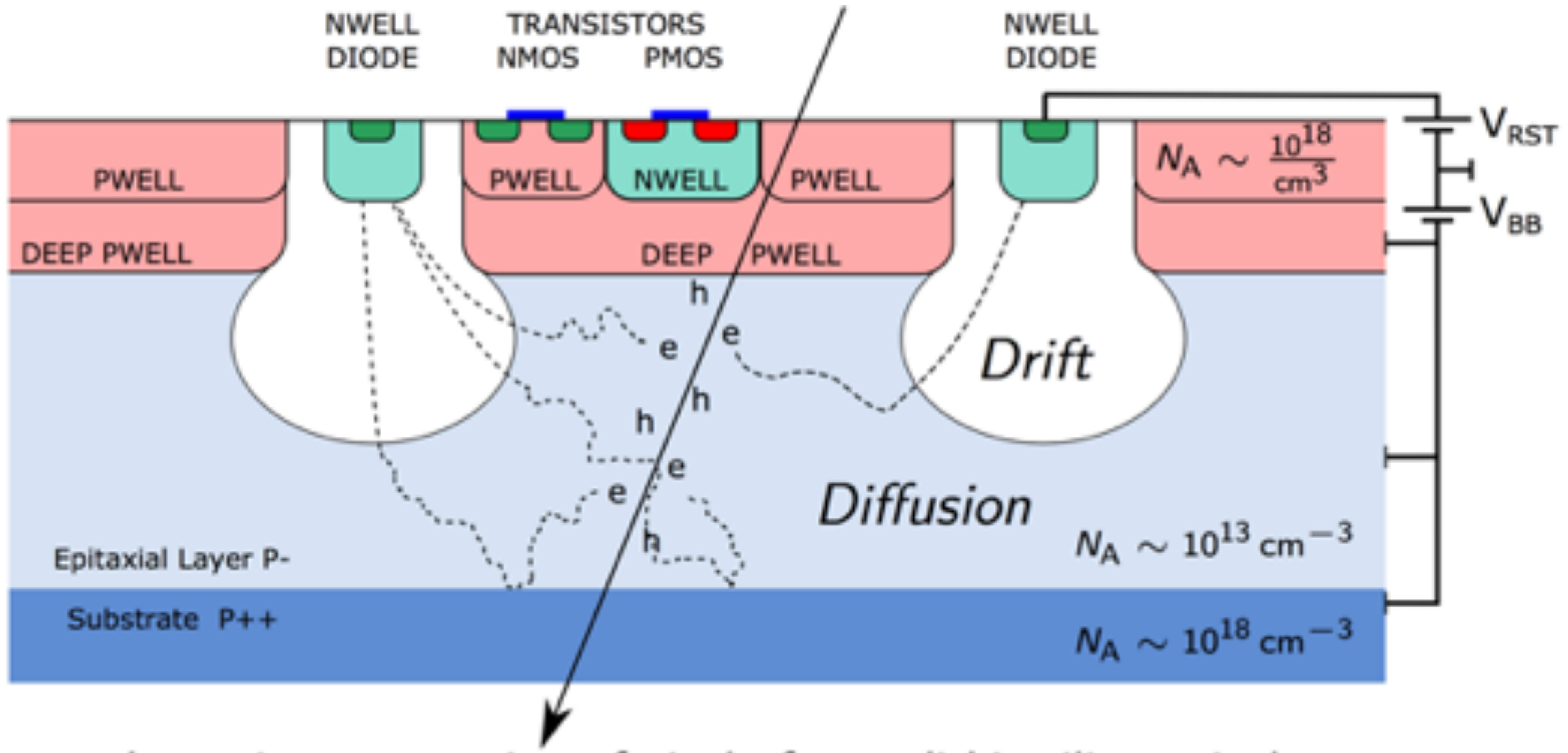
Bump bonding



- **Monolithic sensors**
  → readout circuitry integrated with sensor
  - produced in a single process,
    e.g. CMOS imaging
  - avoids cost and complexity
    of multiple chips and interconnects

Examples

- STAR @ RHIC
- ALICE ITS @ LHC

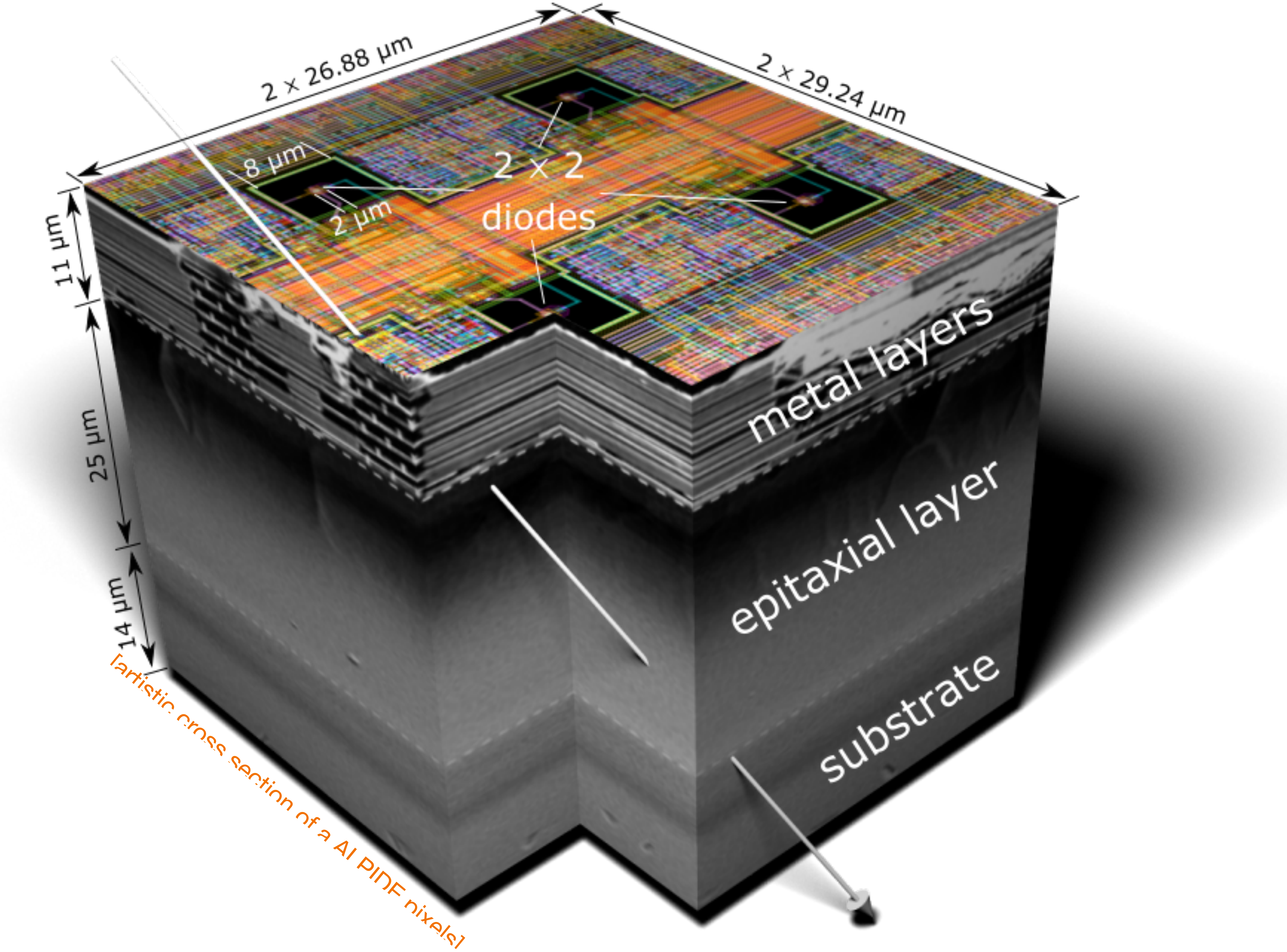


schematic cross section of pixel of monolithic silicon pixel sensor

ALPIDE

- **pixel matrix + readout circuity**
  → 180nm TowerJazz process
  - p-doped wafer
  - epitaxial layer
  - n-doped collection electrode
  - CMOS circuitry

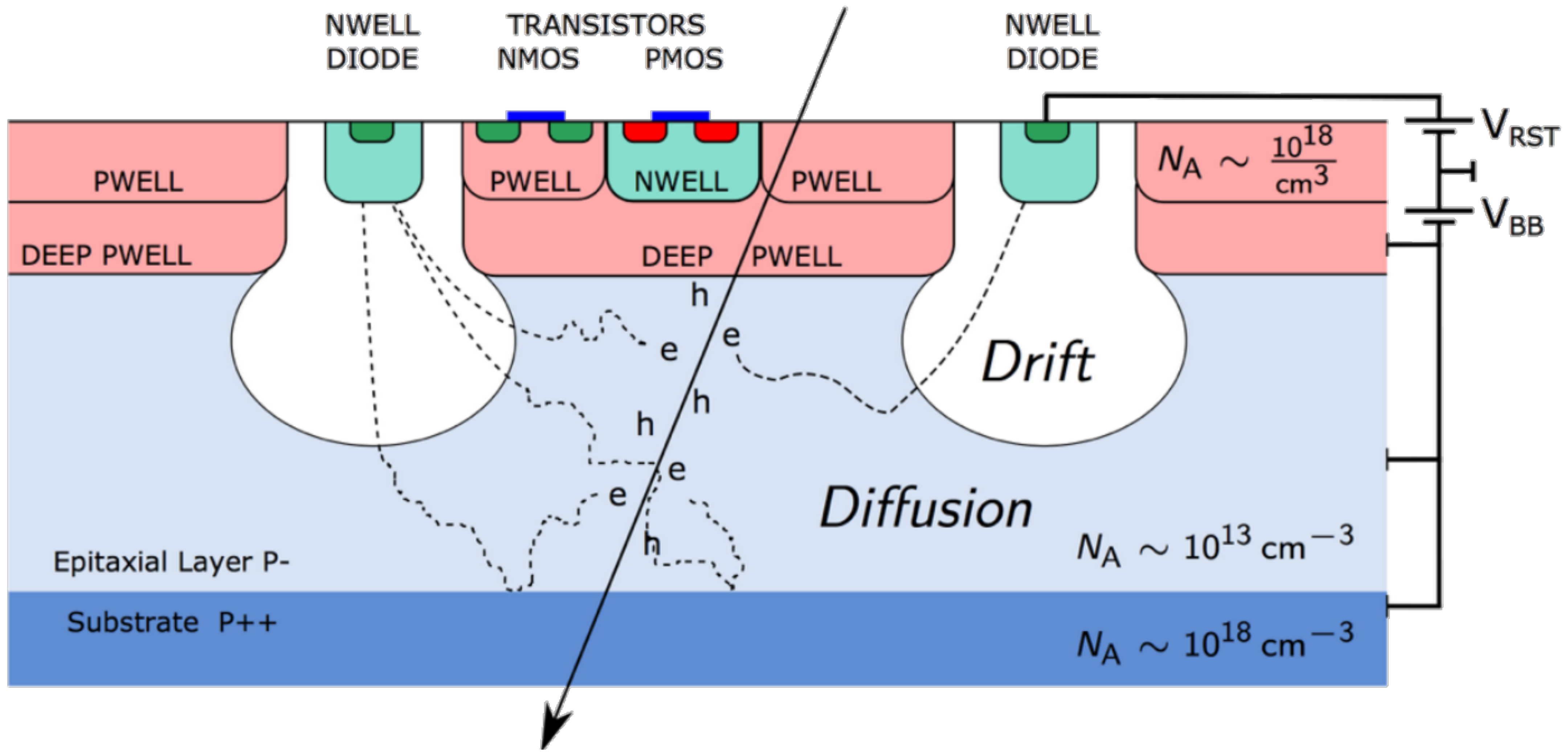
- **Thinning of wafers**
  - 50 µm for innermost layers
  - 100 µm for other layers



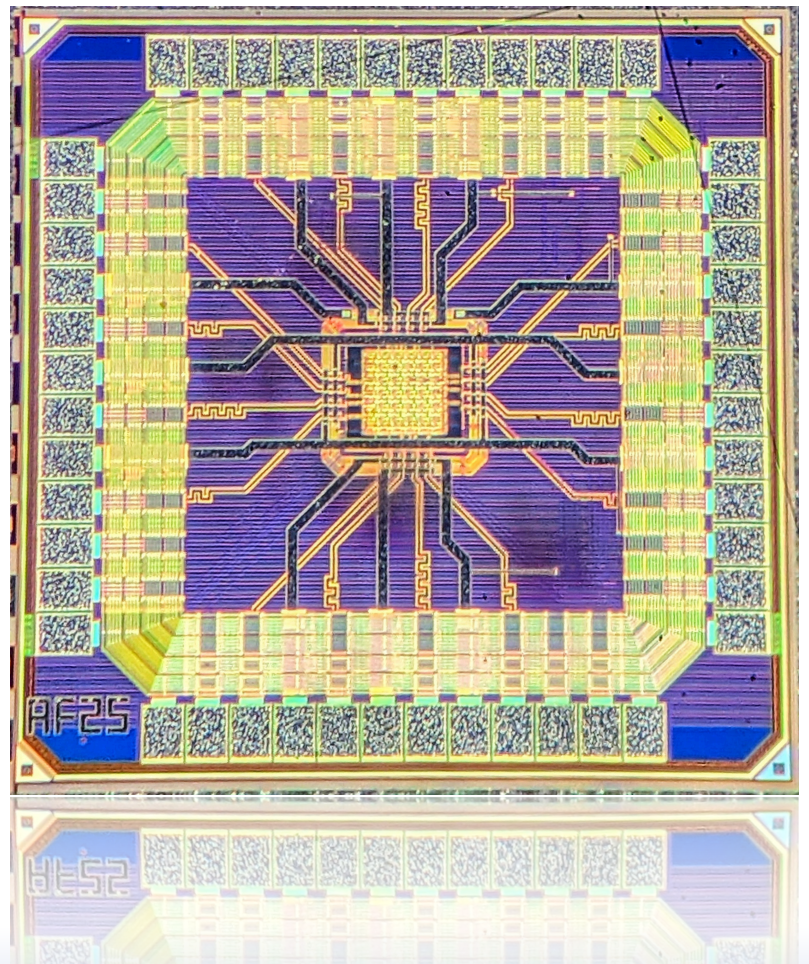
Monolithic pixel sensors

- **Extensive R&D to move from 180 nm to 65 nm TPSCo CMOS imaging process**
  - full functionality of digital front-end verified: 100% detection efficiency
  - 99% detection efficiency retained after irradiation 10^{15} 1 MeV n_{eq}/cm^2 (NIEL), even at room temperature

ALPIDE-like sensors

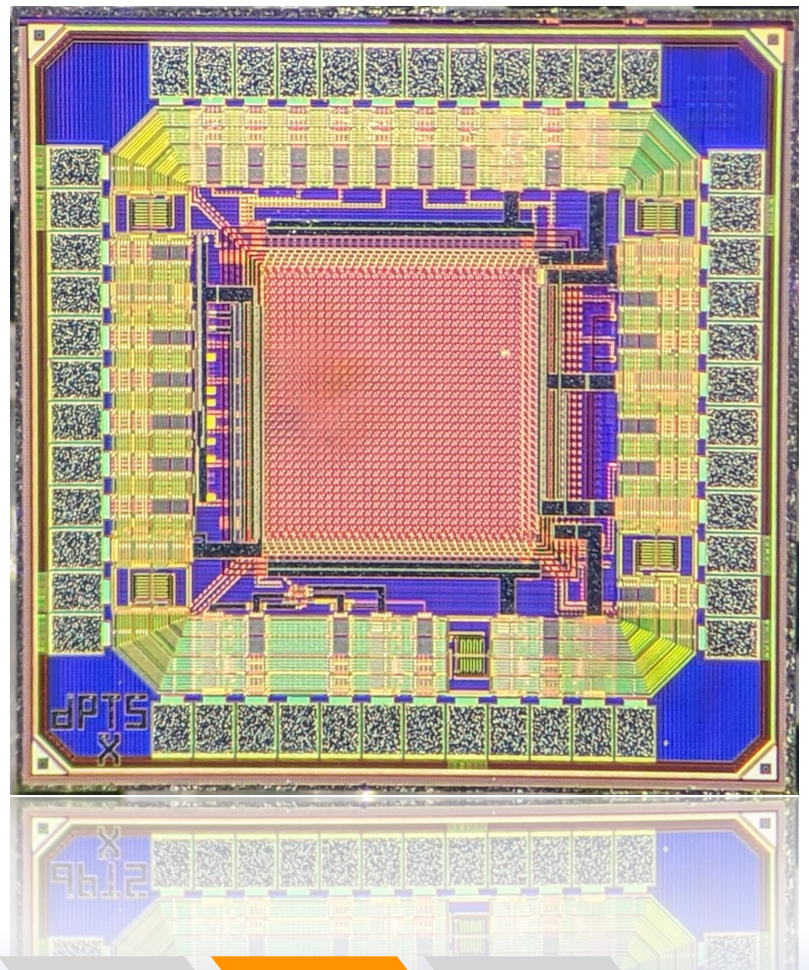


APTS



- **matrix:** 6x6 pixels
- **readout:** direct analog readout of central 4x4
- **pitch:** 10, 15, 20, 25 µm

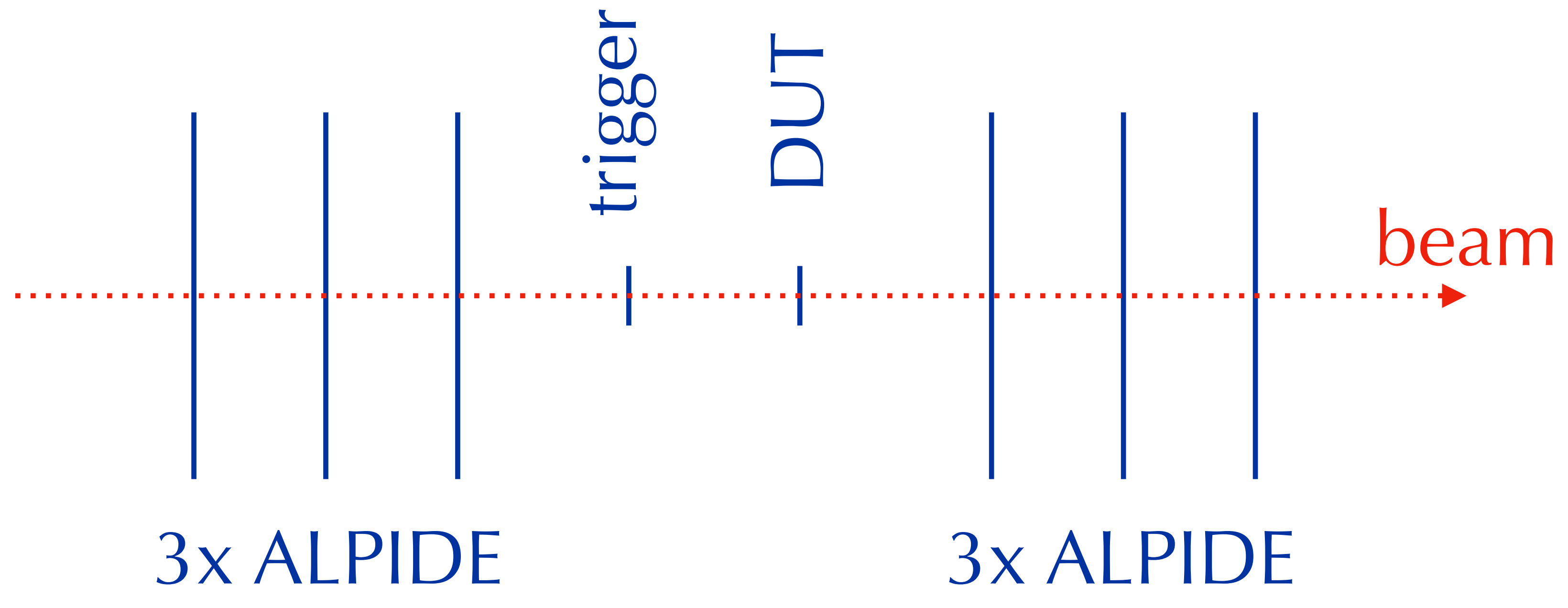
DPTS

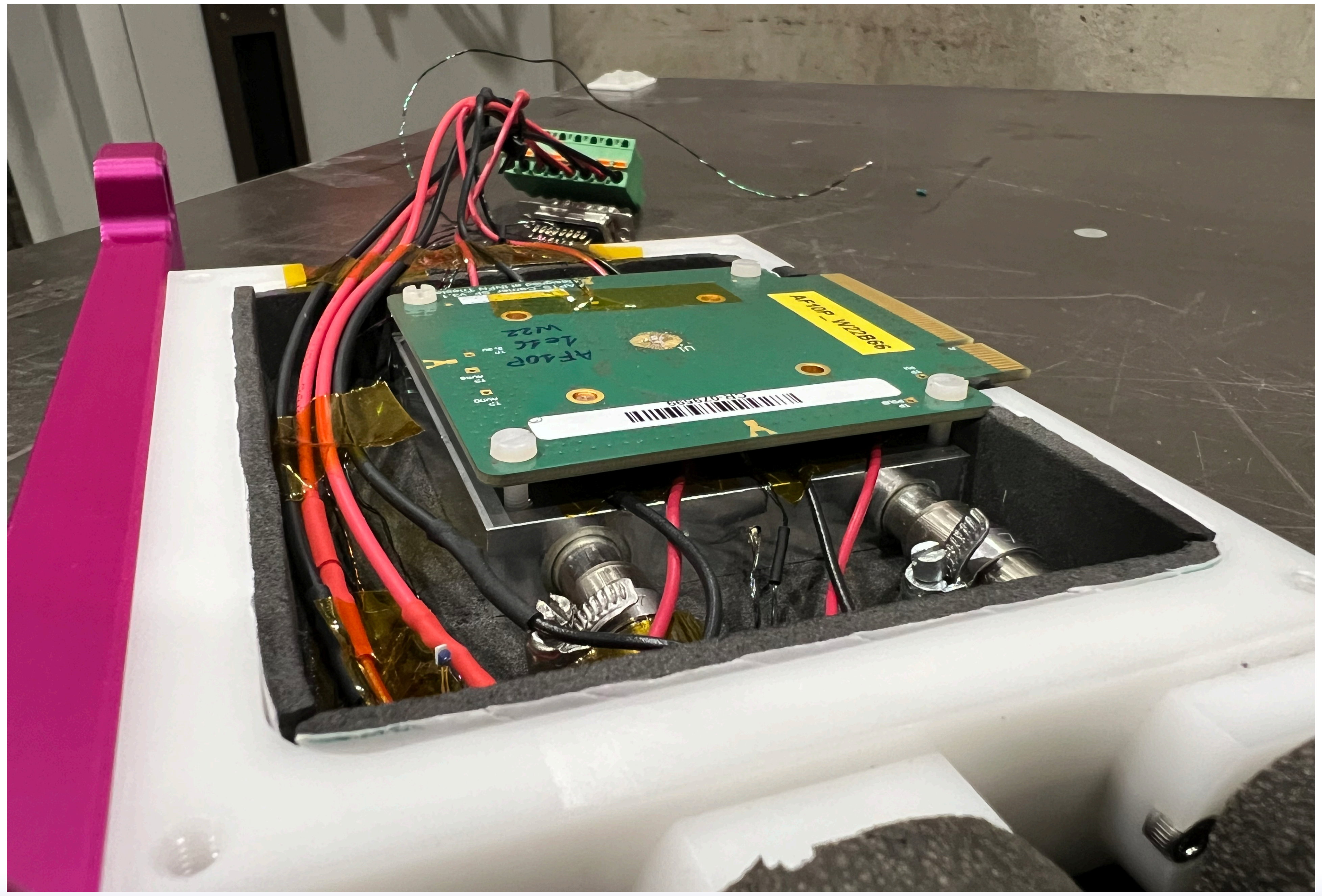


- **matrix:** 32x32 pixels
- **readout:** async. digital with ToT
- **pitch:** 15 µm

Characterisation

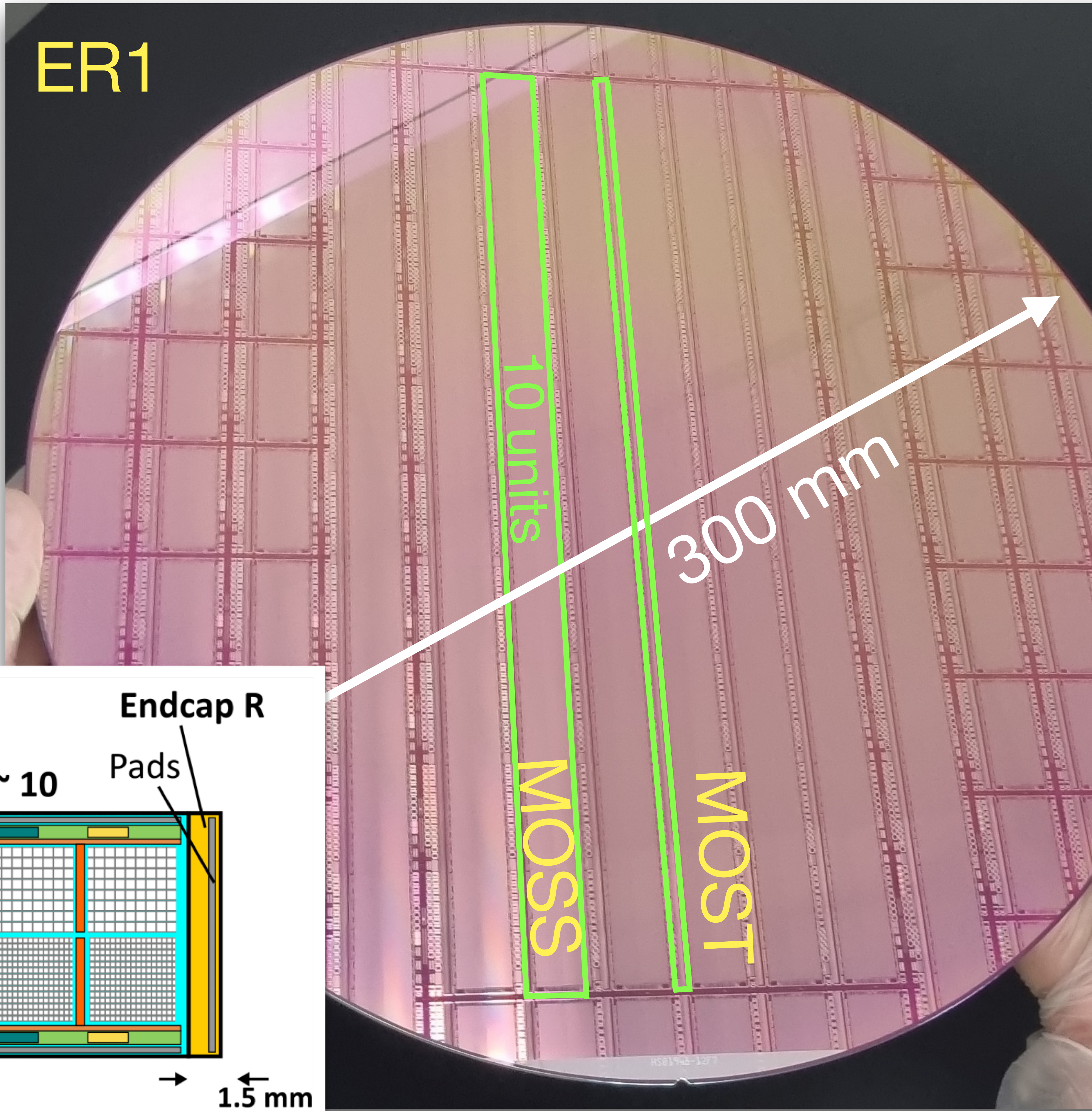
- Current efforts on **operation at cold temperature**
  → mitigation of radiation damage
  - liquid cooling + Peltier elements
  - hadron beam at 120 GeV/c

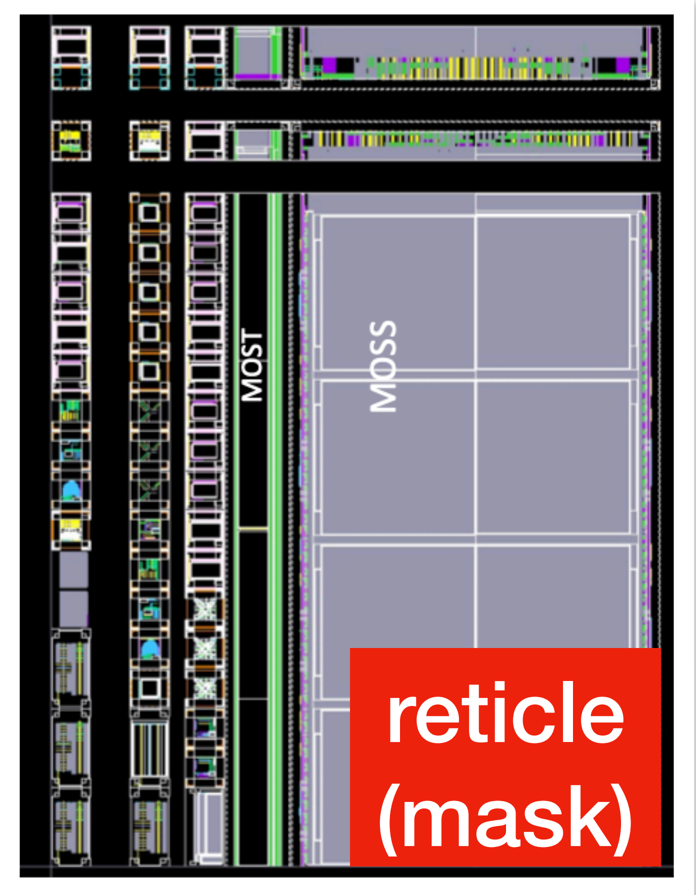


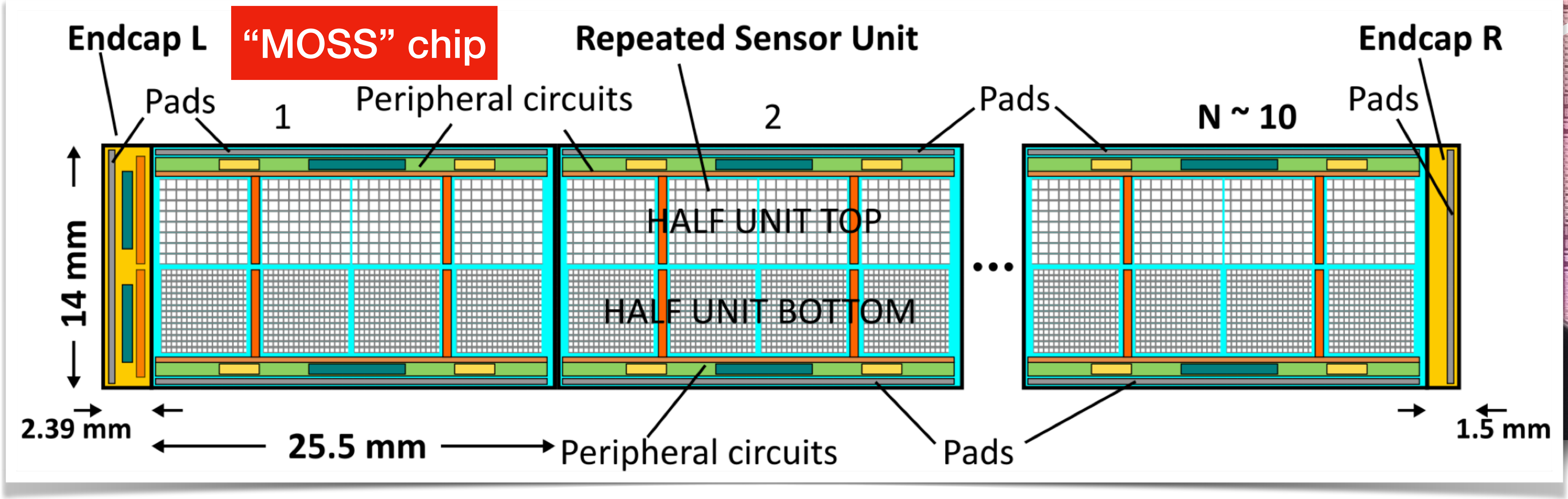


Wafer-scale sensors

- Circumvent limitation to reticle size by **stitching** → successful engineering run
  - **repeated sensor unit** along a stripe, readout circuitry in the endcaps
  - final ITS3 prototype in production → MOSAIX

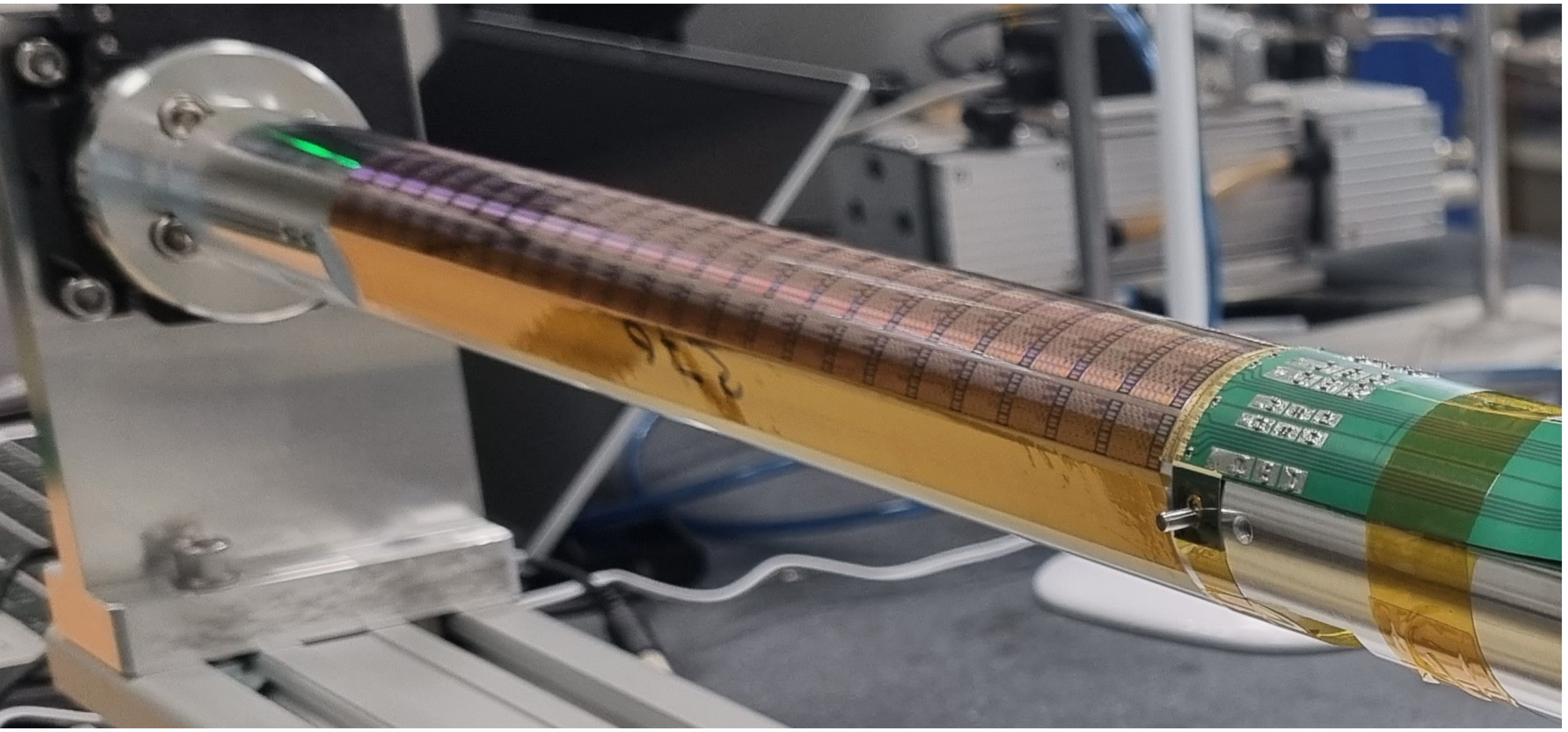


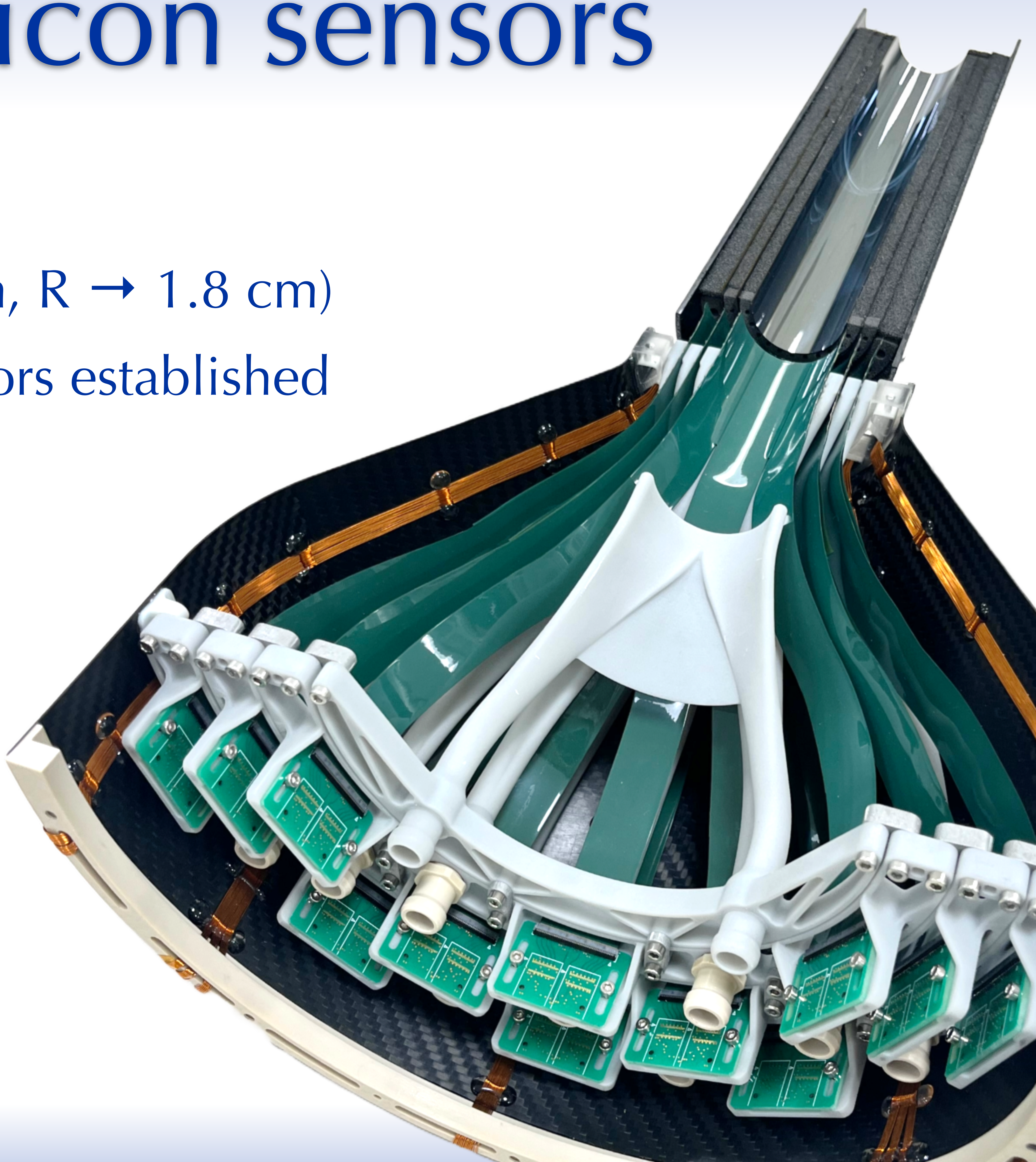




Bending of silicon sensors

- Functionality of bent sensors confirmed in various test beams with ALPIDEs (50 µm, R → 1.8 cm)
- Handling and bending of wafer-scale sensors established
- Mechanics and air cooling demonstrated

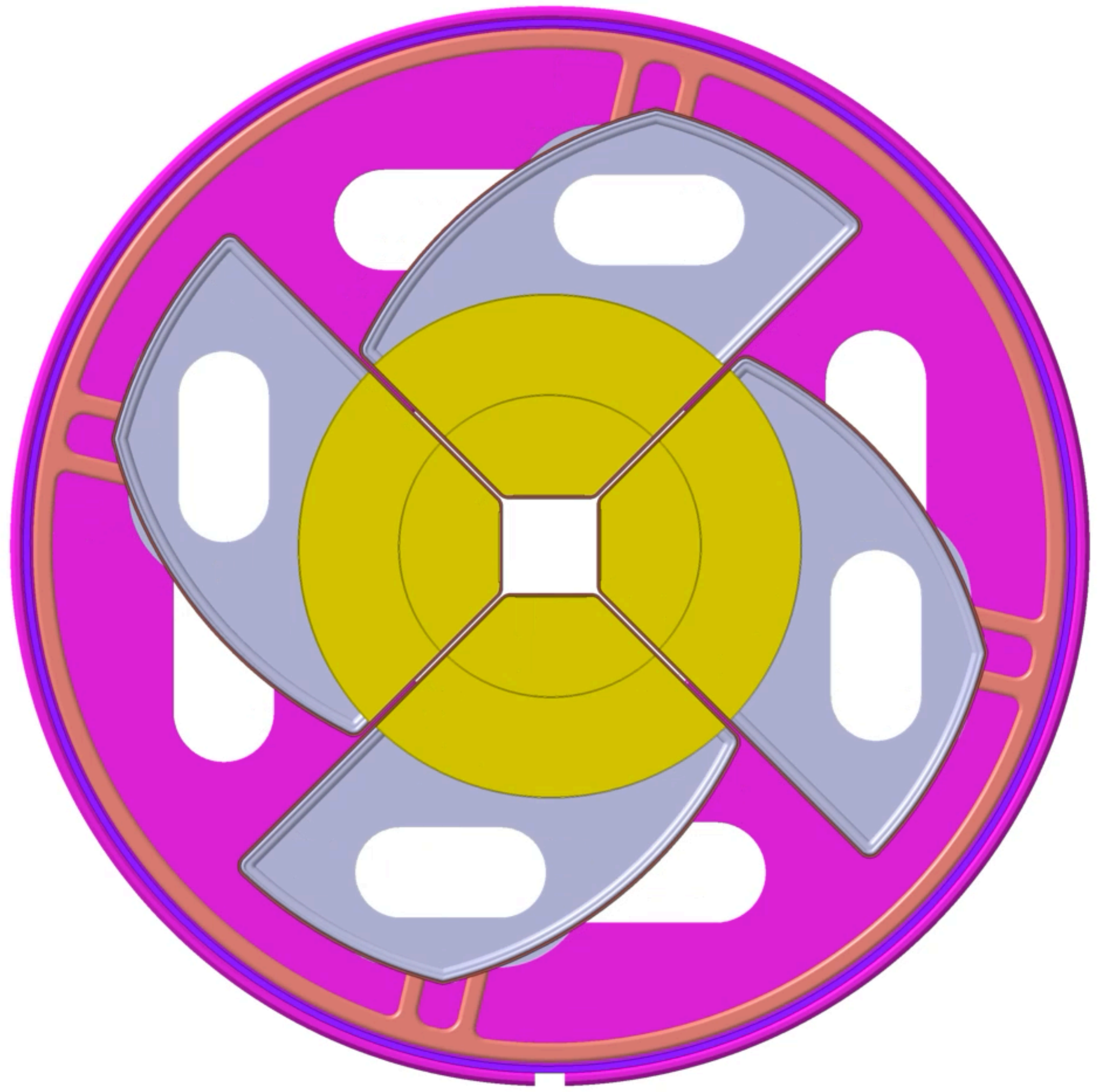


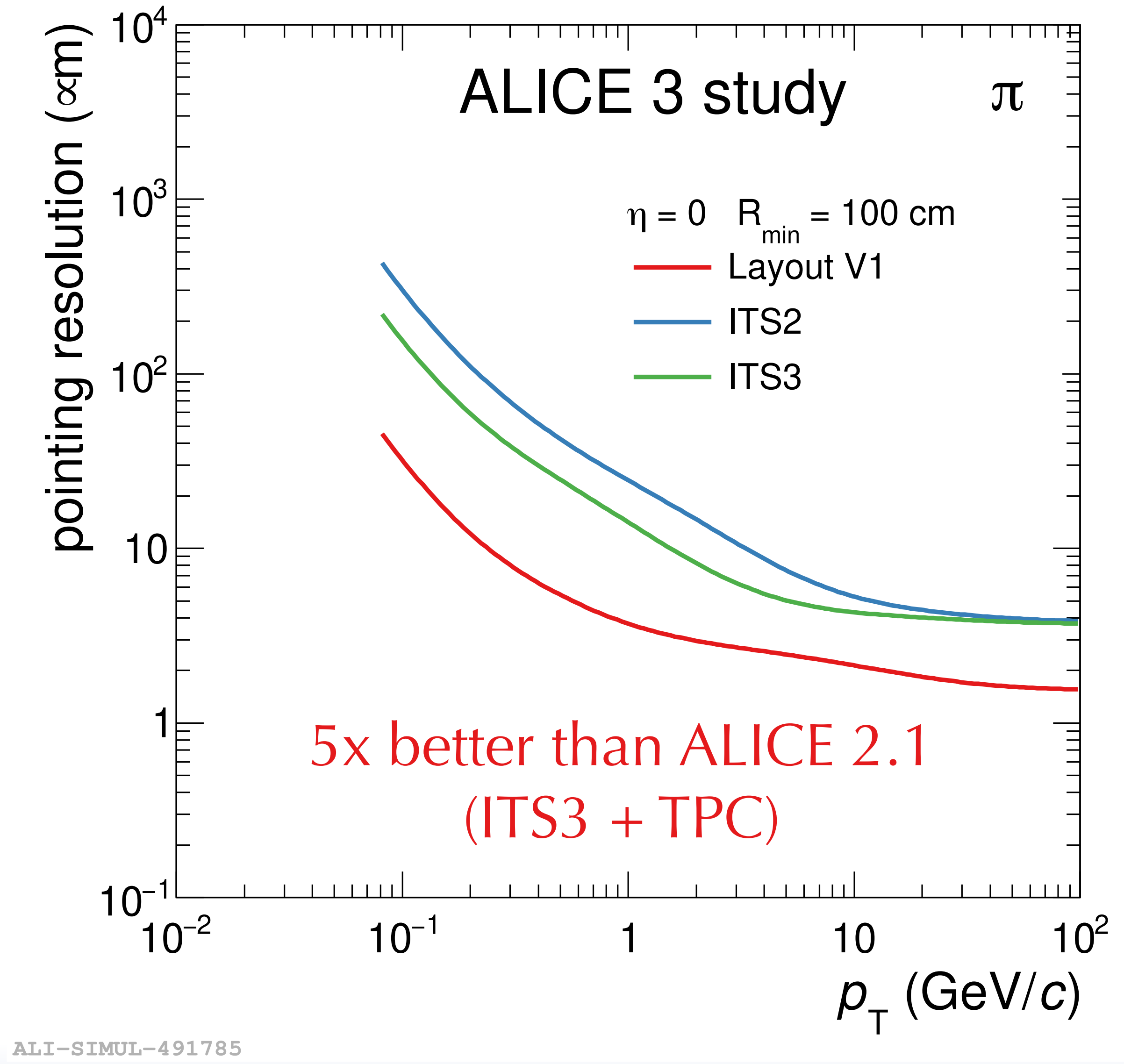


Vertex detector integration

- **3 retractable layers inside beam pipe**
  at radii of 5 - 25 mm (in secondary vacuum)
  - complex mechanics and LHC interface
  - geometry being optimised
- **Bent monolithic active pixel sensors**
  - 0.1 % X_0 per layer → very thin sensors
  - σ_{pos} ~2.5 µm

Ultimate pointing resolution at the LHC

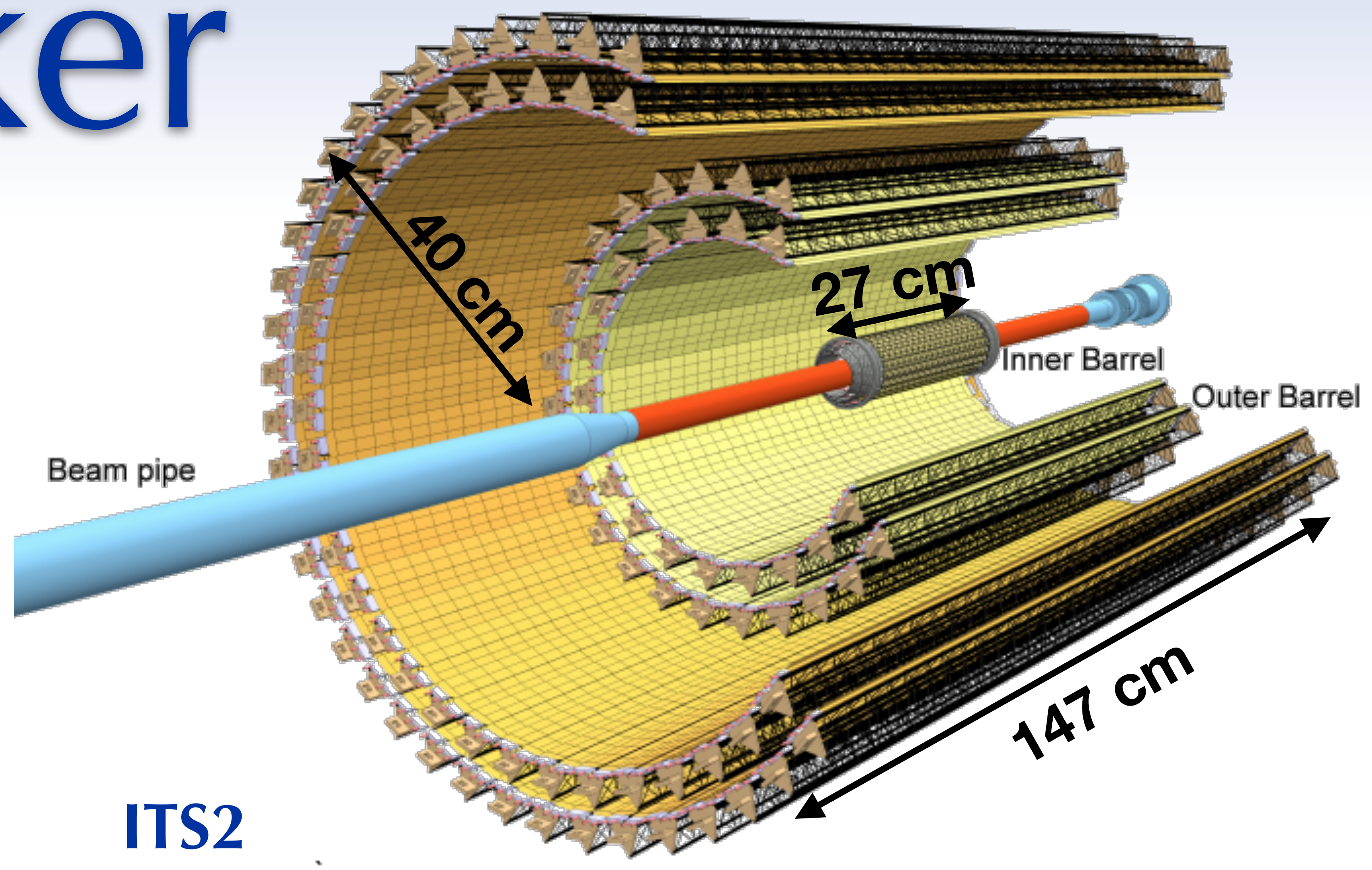




ALICE 3 tracker

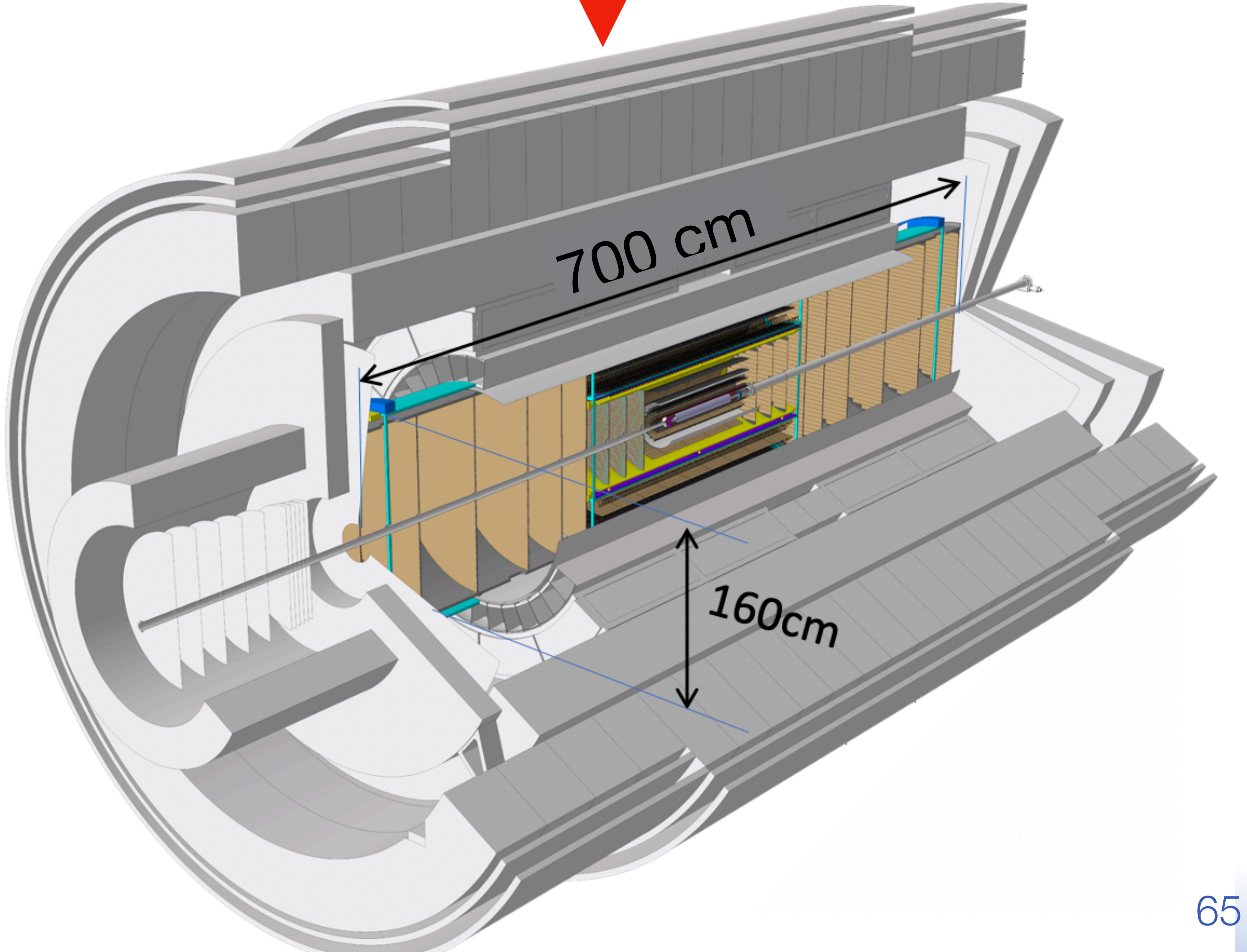
- **Significant step in instrumented surface (10 → 60 m²)**
  - sensor design & production (yield, cost, synergies)
  - modularisation (yield, industrialisation)
  - fault tolerance (redundancy)
- **Challenging for integration and maintainability**
  - mechanical concept with minimal material
  - maintainable integration
- **New concepts for power distribution**
  - serial powering
  - granularity
  - failure handling

Next-generation detector



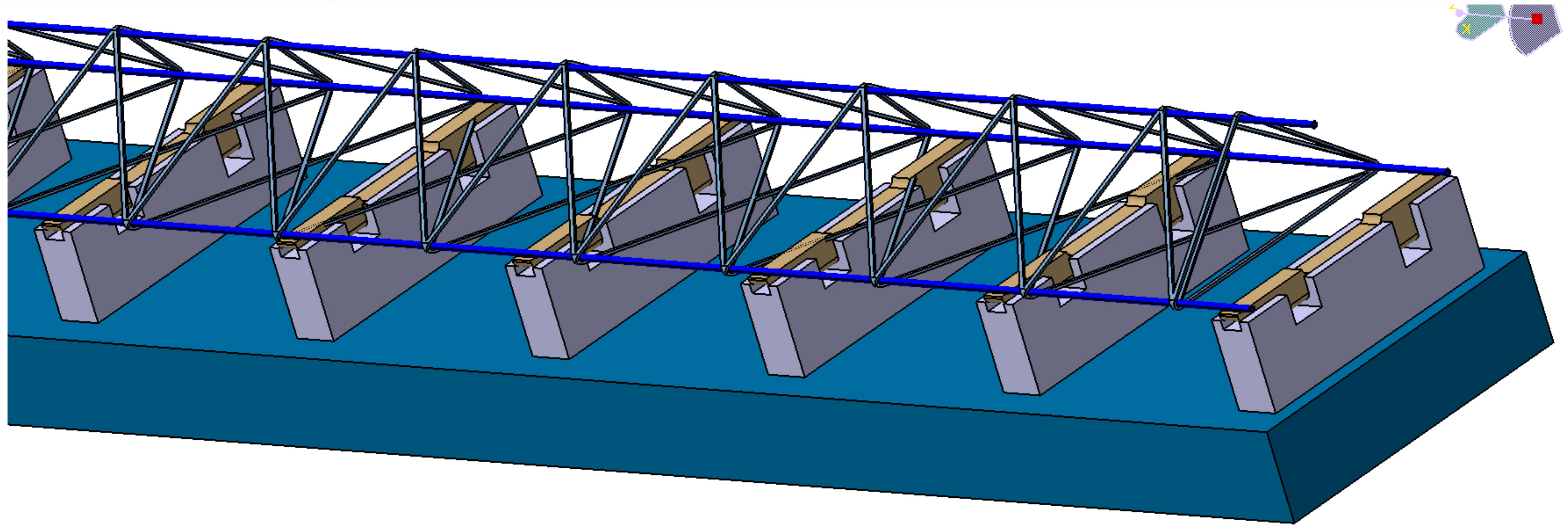
ITS2
(ALPIDE sensors)

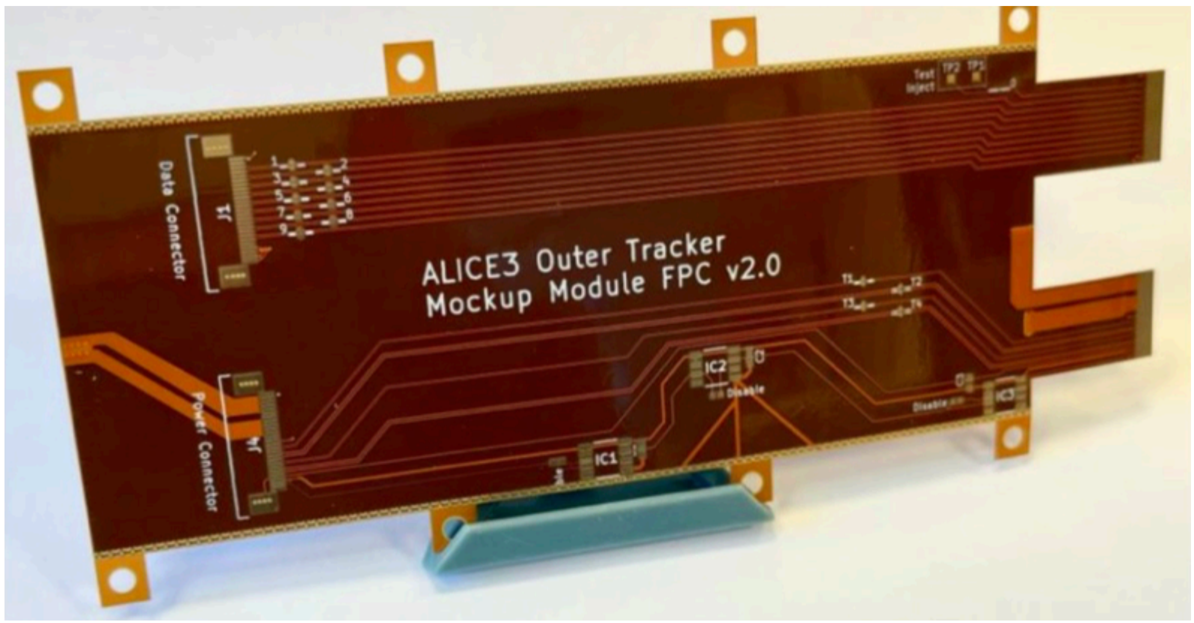
10 m² → 60 m²

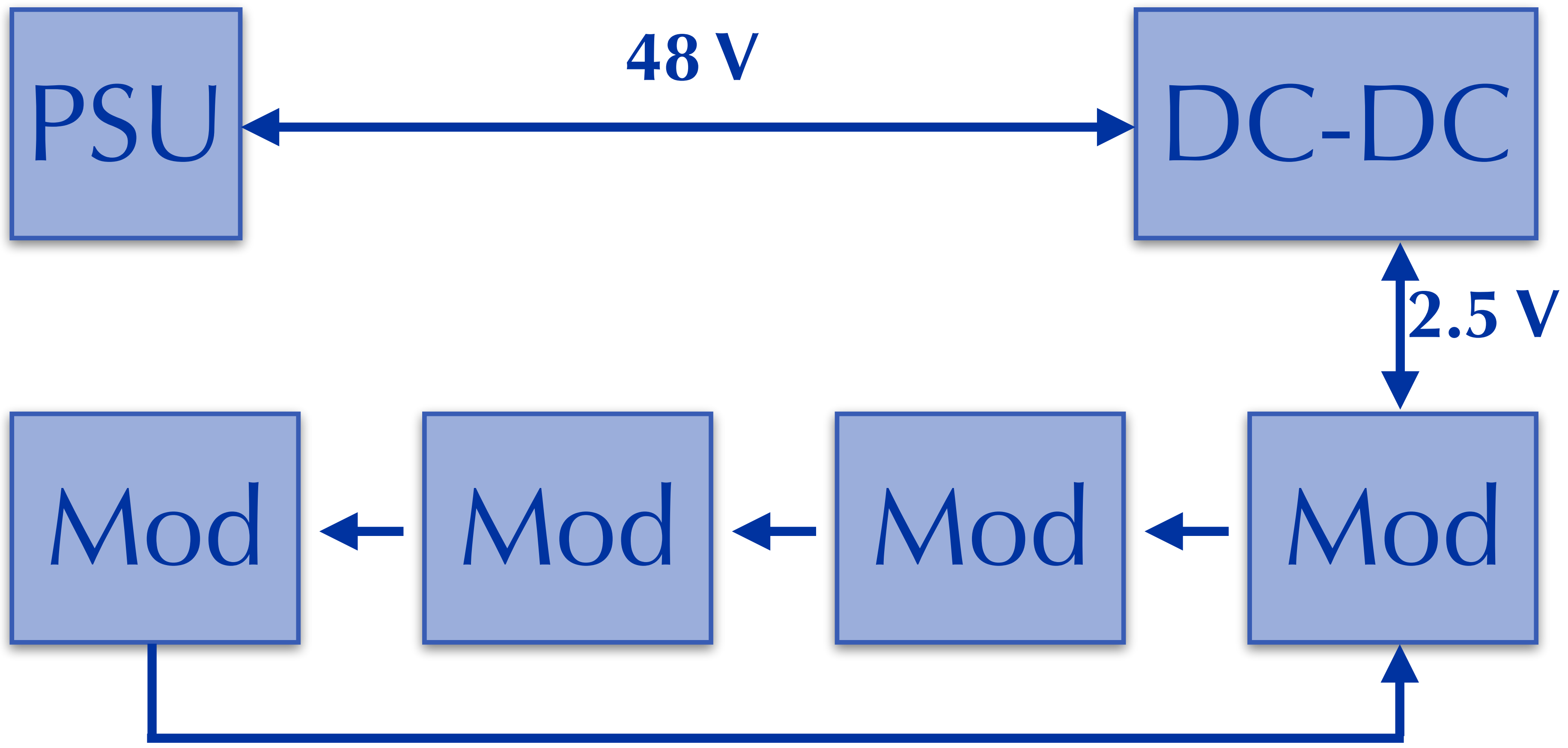


ALICE 3 tracker integration

- **Modular staves**
  - carbon-fibre structures with cold plates
- **Highly-integrated modules:** sensor + readout + power chips
  - industrialised production
  - bonding options: wires, flip-chip, wafer-to-wafer
- **Cooling**
  - air (ITS3), water (ALICE 3), CO_2 (ATLAS, CMS)
- **DC-DC conversion** → reduce current, i.e. material
  - rad. hard buck converters (bPOL…) available
  - ongoing R&D for higher currents (50 A), new processes
- **Serial powering** → reduce material
  - requires shunt regulators in readout chips



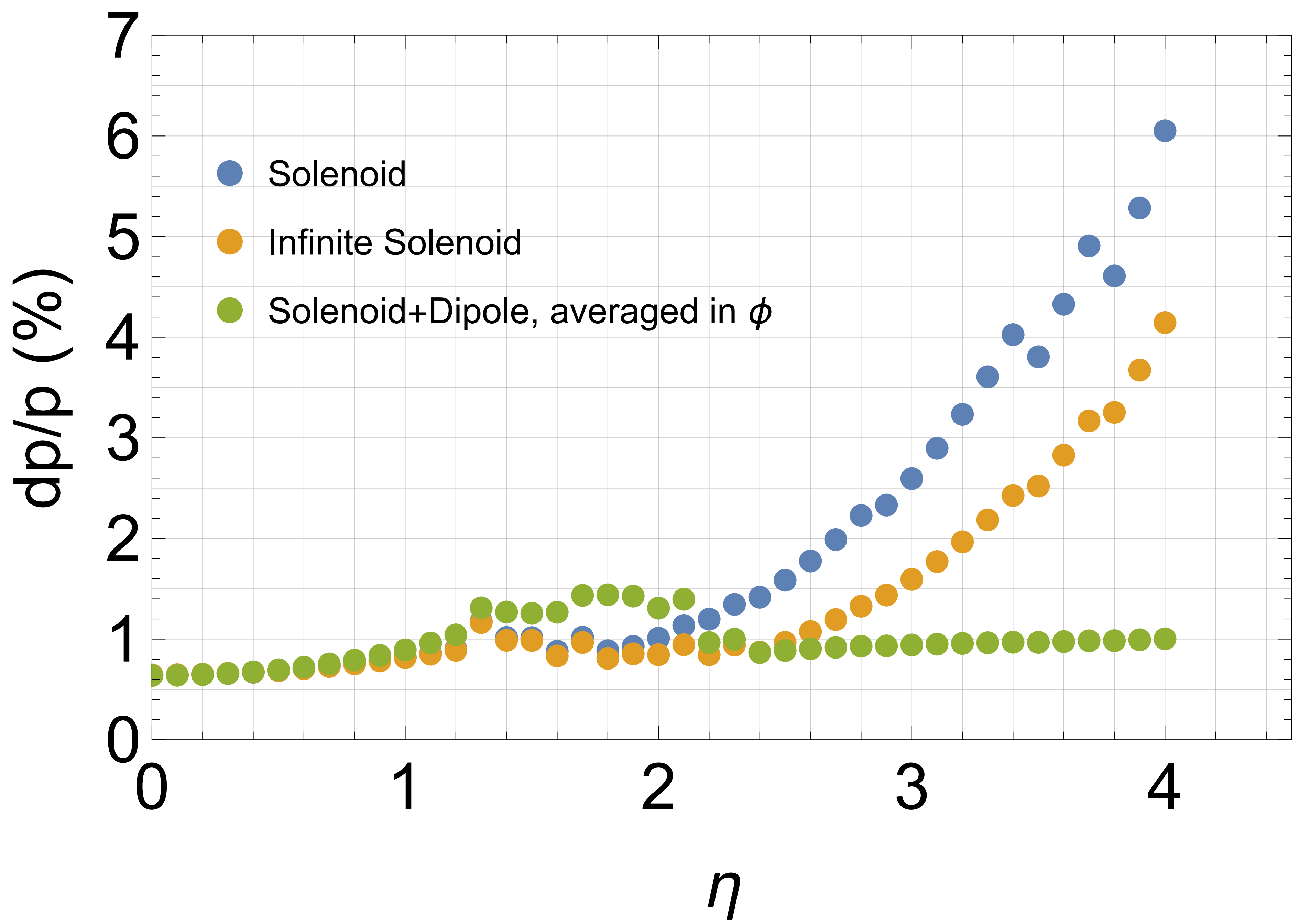


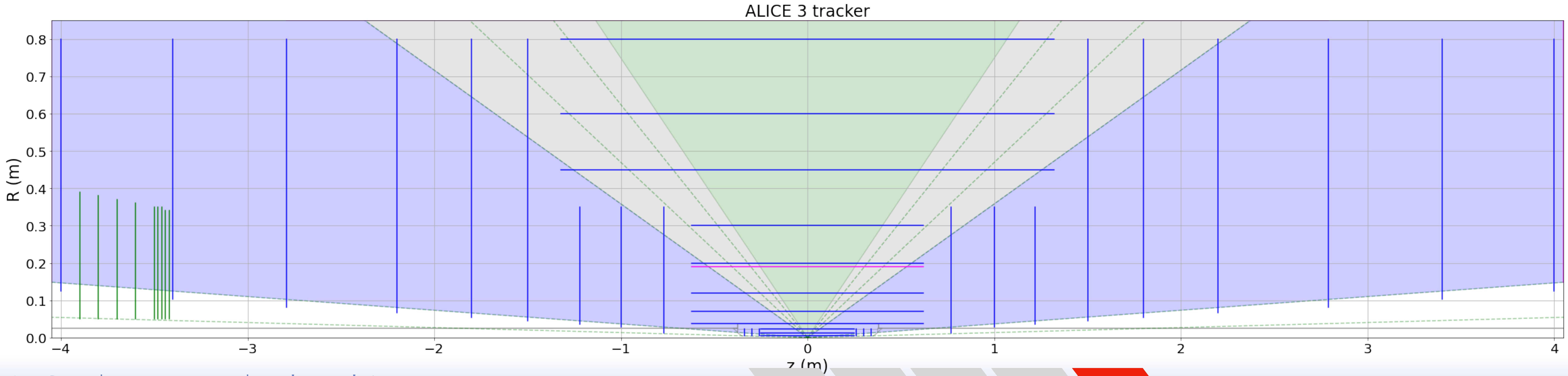


Simplified powering scheme

ALICE 3 tracking

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





Large-scale tracker
$A \approx 60$ m²

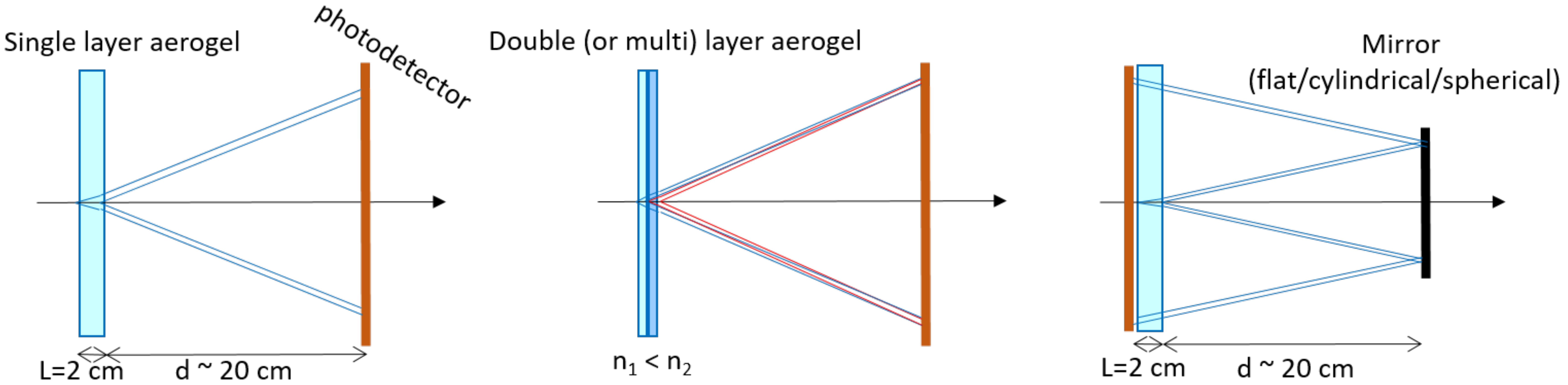
Time of flight

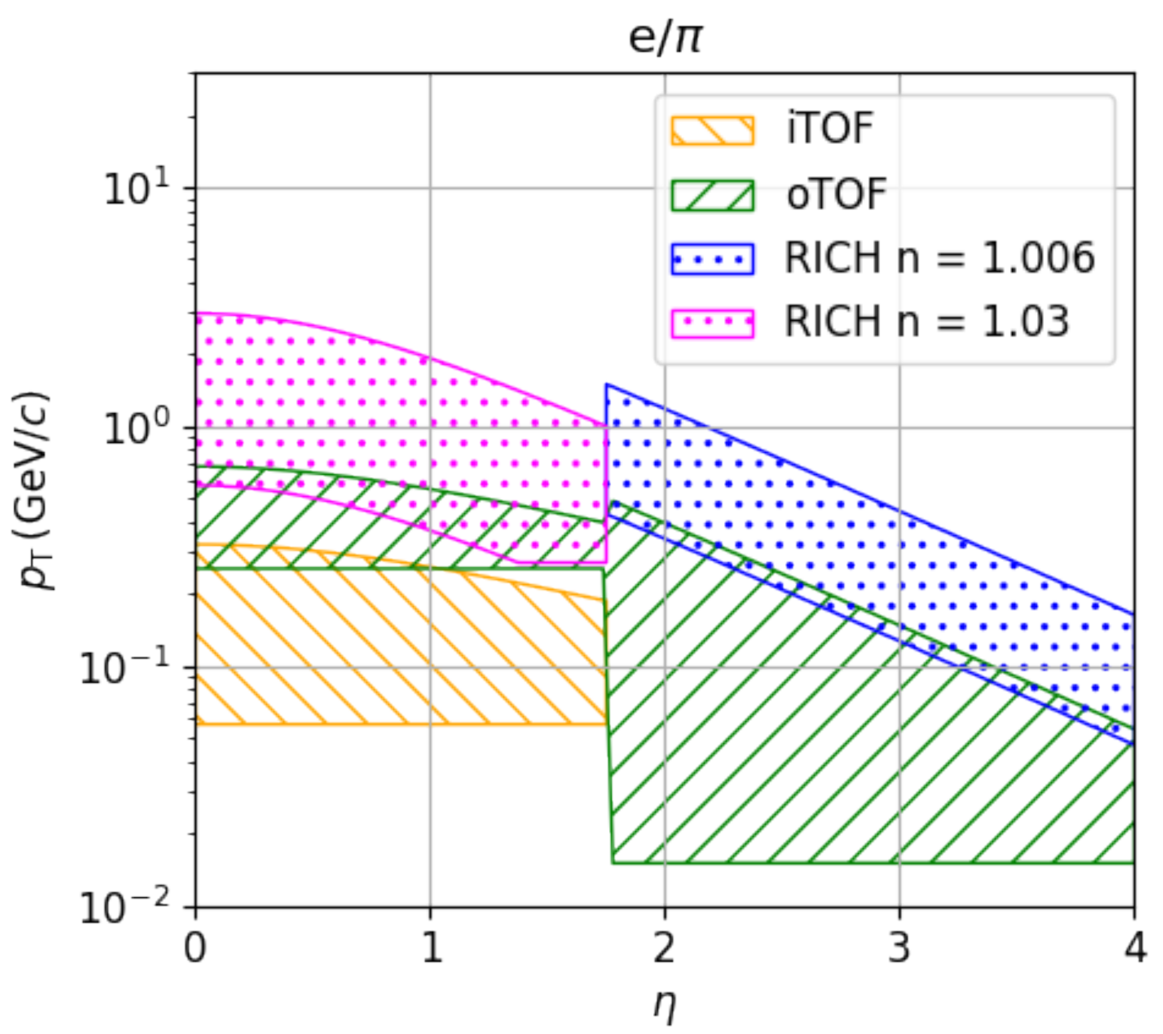
- Velocity of particle (at given momentum) depends on mass
  → different time of flight for different mass hypotheses:
  $$\Delta t = \frac{L}{c}\left(\frac{1}{\beta_1} - \frac{1}{\beta_2}\right) \approx \frac{Lc}{2p^2}(m_1^2 - m_2^2)$$
  - separation requires

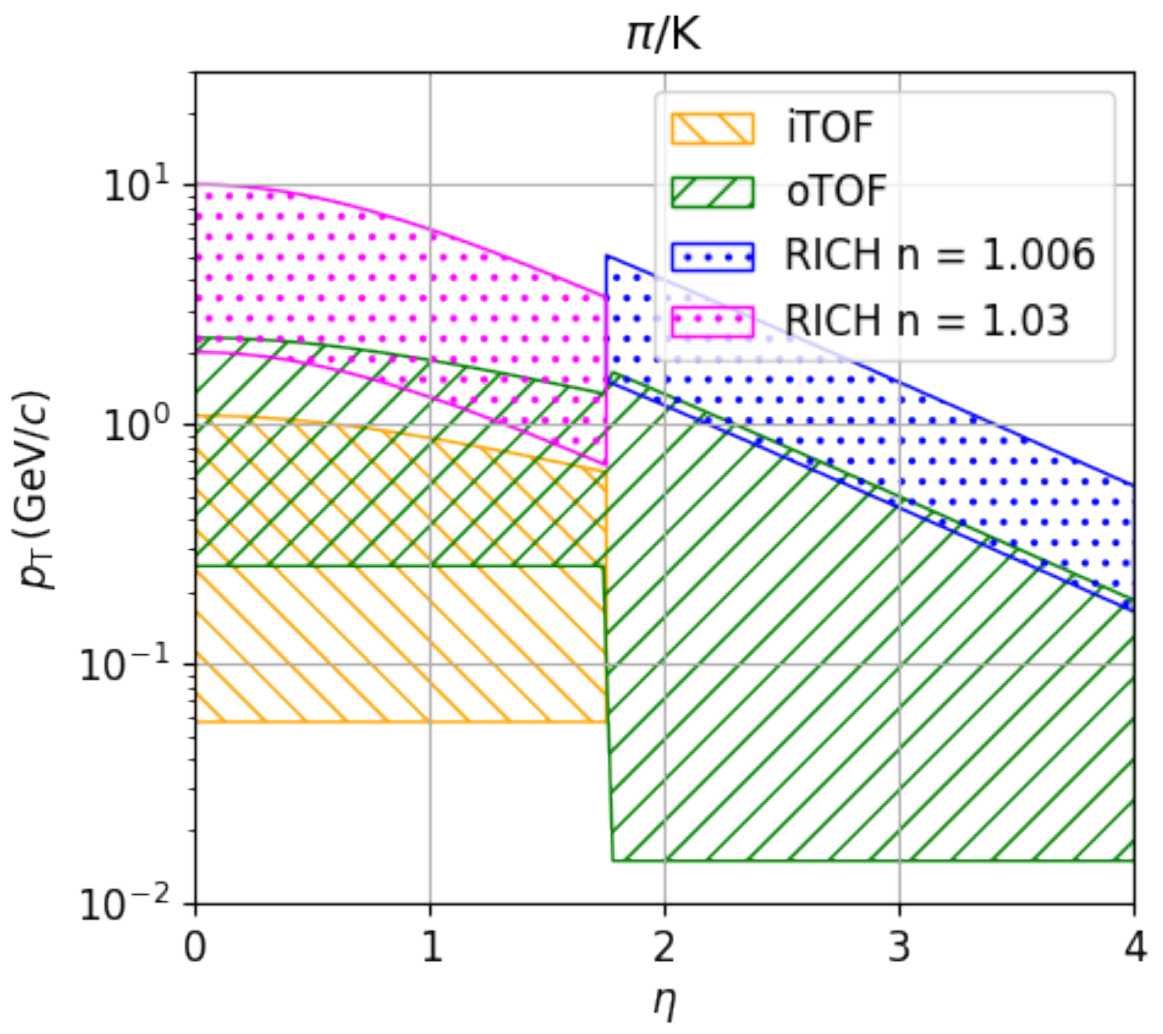
- Requires **fast detectors** with time resolutions on the order of **50 ps**
  - Scintillators + PMT
  - MRPCs
  - LGADs (already discussed in context of charge amplification)
  - Cherenkov counters

Ring-imaging Cherenkov

- **Extend PID reach of outer TOF to higher p_T**
  ➟ Cherenkov
  - ensure continuous coverage from TOF
    → refractive index n = 1.03 (barrel)
    → refractive index n = 1.006 (forward)
  - aerogel radiator + SiPM readout



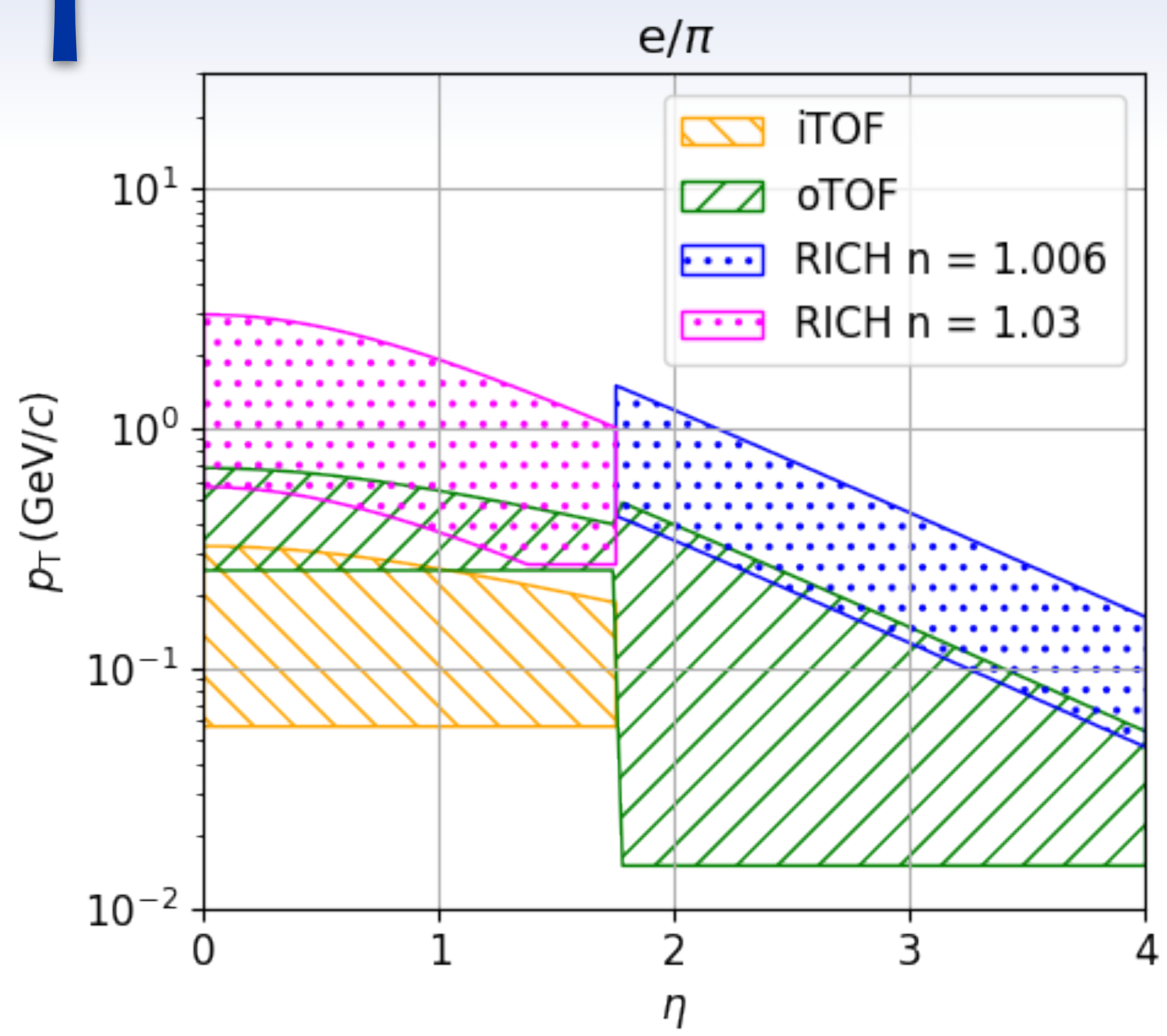




TOF and RICH

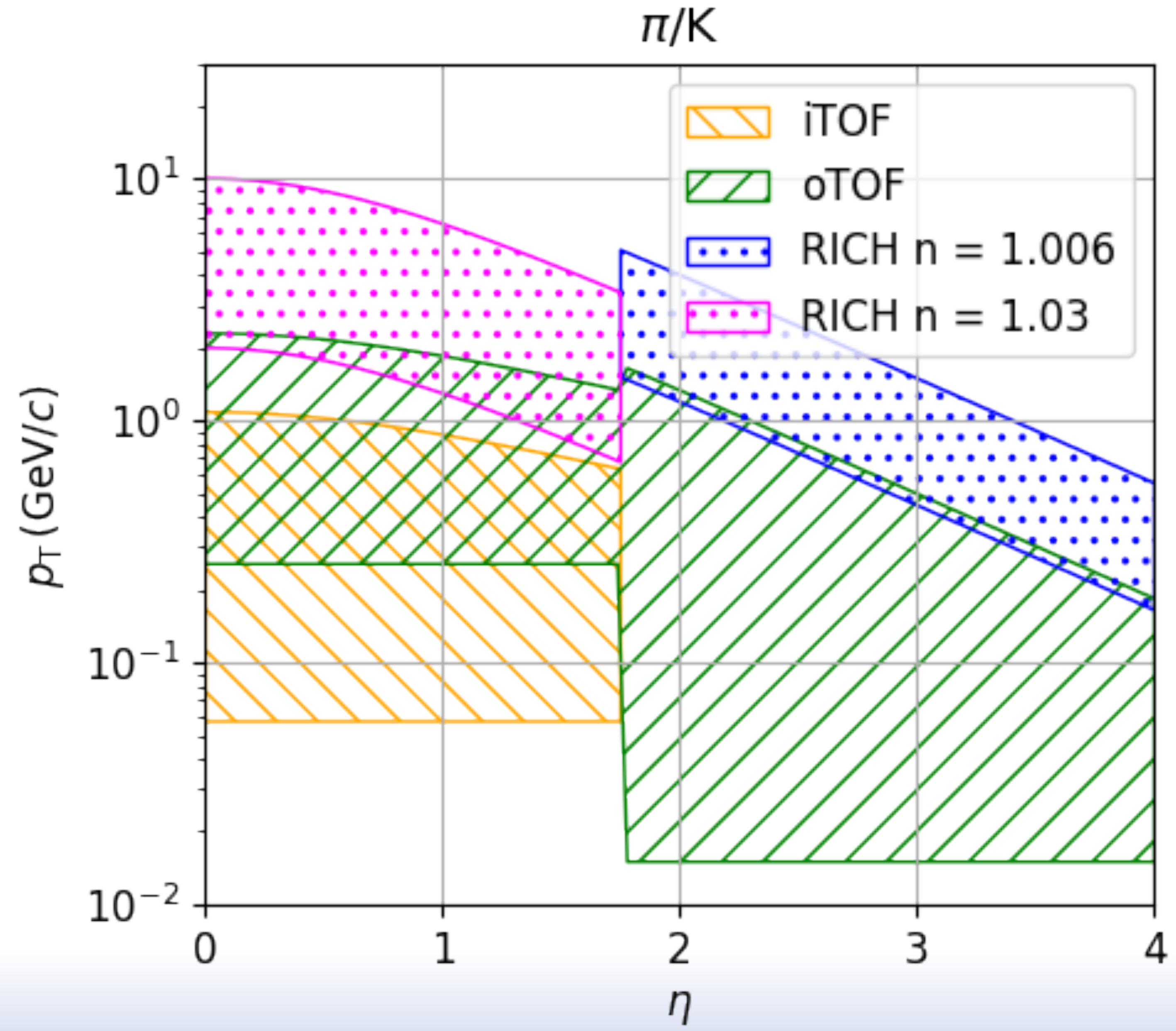
- **Time-of-flight detector**
  - 2 barrel + 1 forward layers:
    R ≈ 85 cm, R ≈ 19 cm, z ≈ 405 cm
  - silicon timing sensors with $\boldsymbol{\sigma_{TOF}} \approx$ **20 ps**
    ➟ monolithic CMOS sensors with gain

Instrumented area ~45 m²



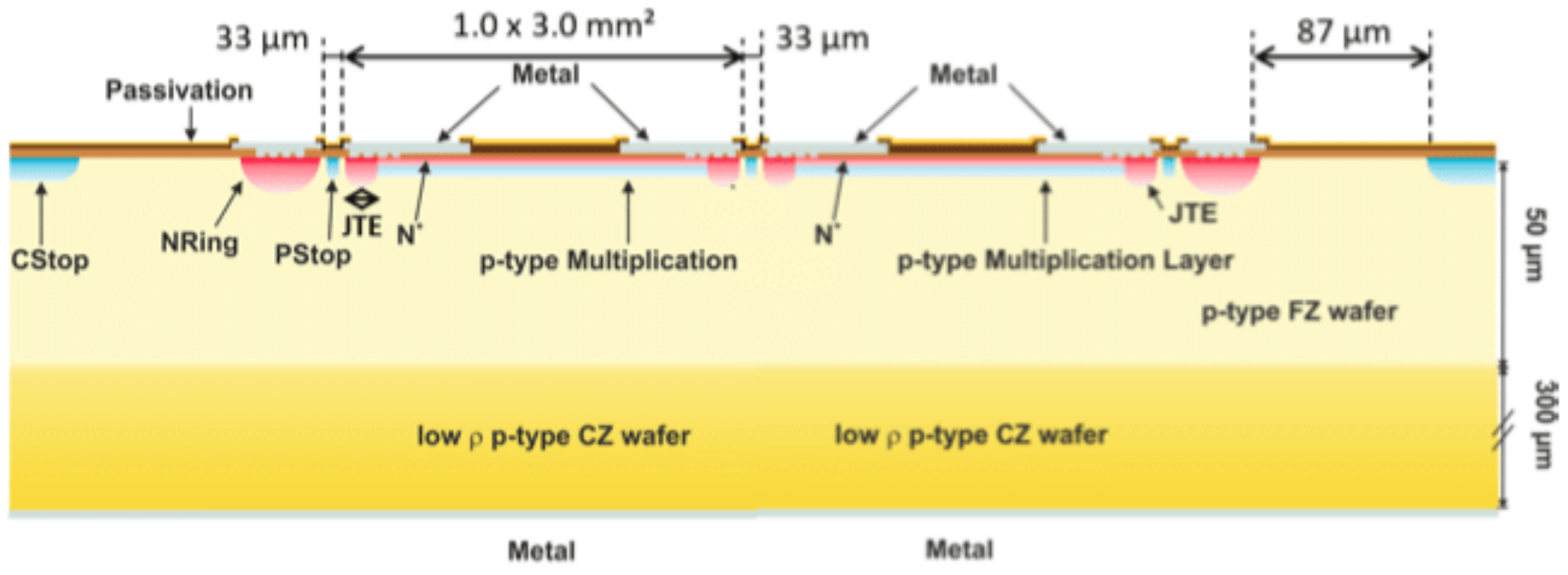
- **Ring Imaging Cherenkov Detector**
  - aerogel radiator
    → refractive index n = 1.03 (barrel)
    → refractive index n = 1.006 (forward)
  - silicon photon sensors
    ➟ R&D on monolithic SiPMs

Instrumented area ~60 m²



Charge amplification in semiconductors

- **Amplification also possible in semiconductors**
  - addition of doped layer
    → strong electric field
    → amplification



- **Advantages**
  - larger signal
  - faster charge collection

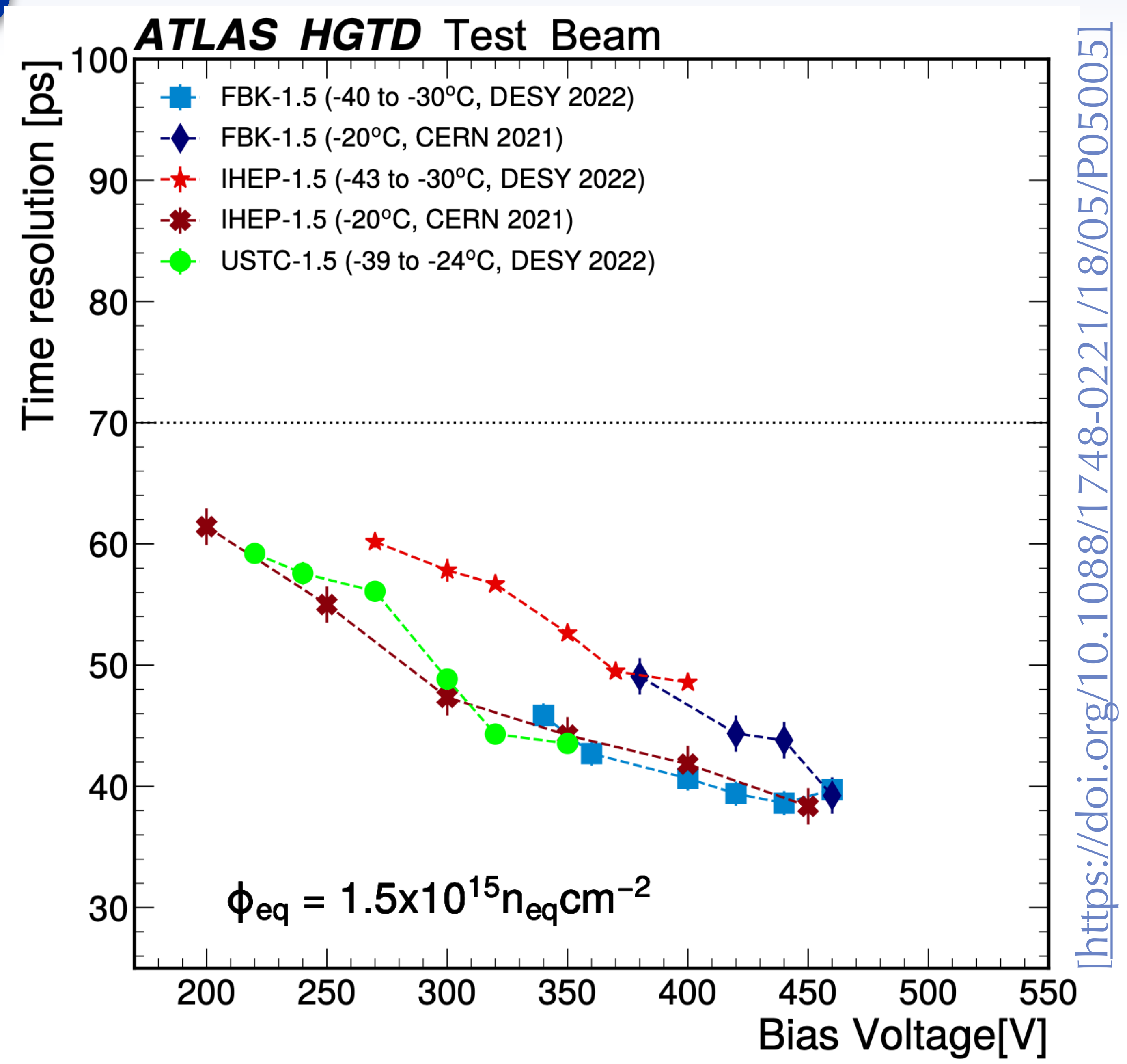
Examples

- ATLAS/CMS timing

- **Applications**
  - Avalanche Photo Diode (APD, gain 100-1000) → photon detection
  - Single Photon Avalanche Diode (SPAD, breakdown) → single photon detection
  - Low-Gain Avalanche Diode (LGAD, gain 10-100) → timing detectors

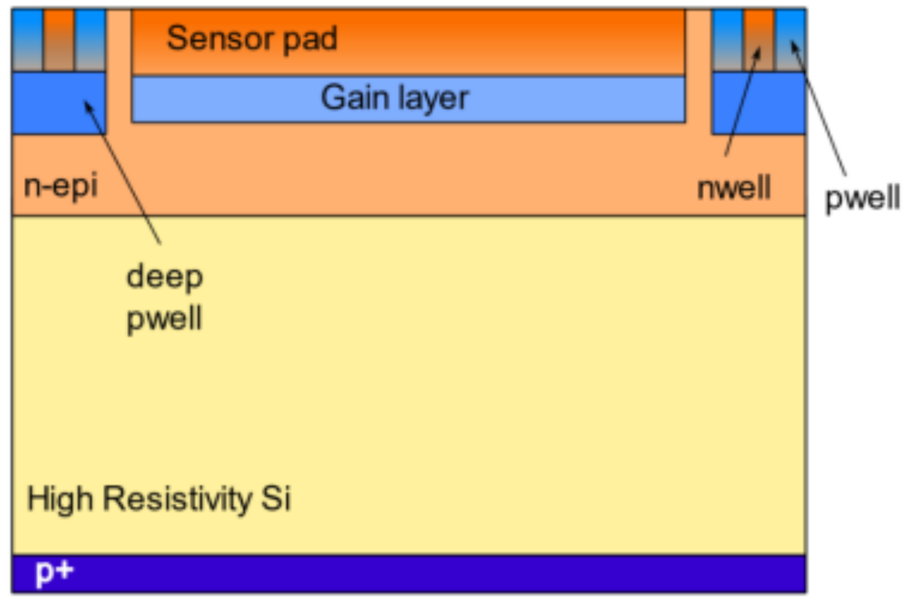
Silicon sensors with gain

- Additional layer to **amplify primary ionisation signal**
  → fast response (from charged particle or photon)
- **Low-Gain Avalanche Diode** (LGAD)
  → limited gain to mitigate large dark count rates
  - timing endcaps for ATLAS/CMS
- **Single-Photon Avalanche Diode** (SPAD, array → SiPM)
  → large gain + quenching to achieve single photon efficiency
  - considered also for charged particle detection
- **Monolithic sensors with gain**
  → CMOS process with additional gain layer
  - promising results with LFoundry 110 nm (ALICE 3)

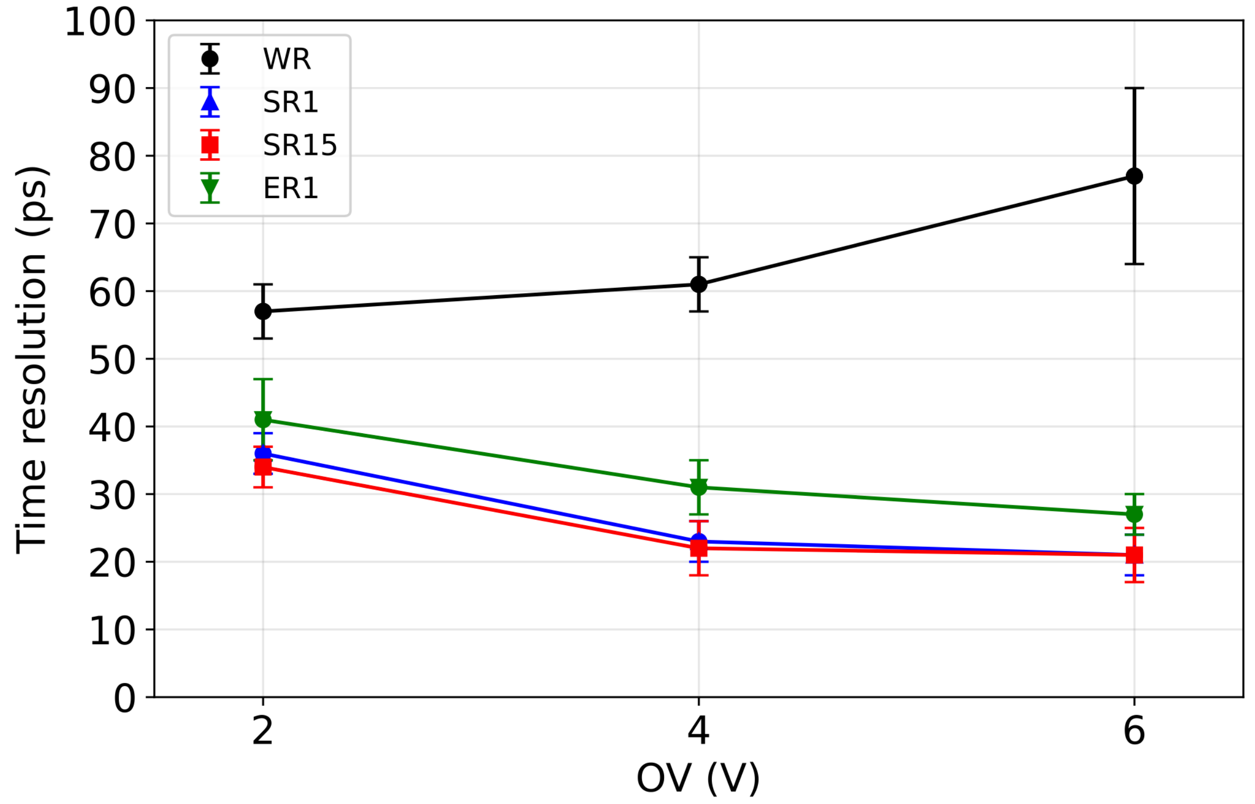


[https://doi.org/10.1088/1748-0221/18/05/P05005]

ATLAS HGTD



Gain layer in CMOS

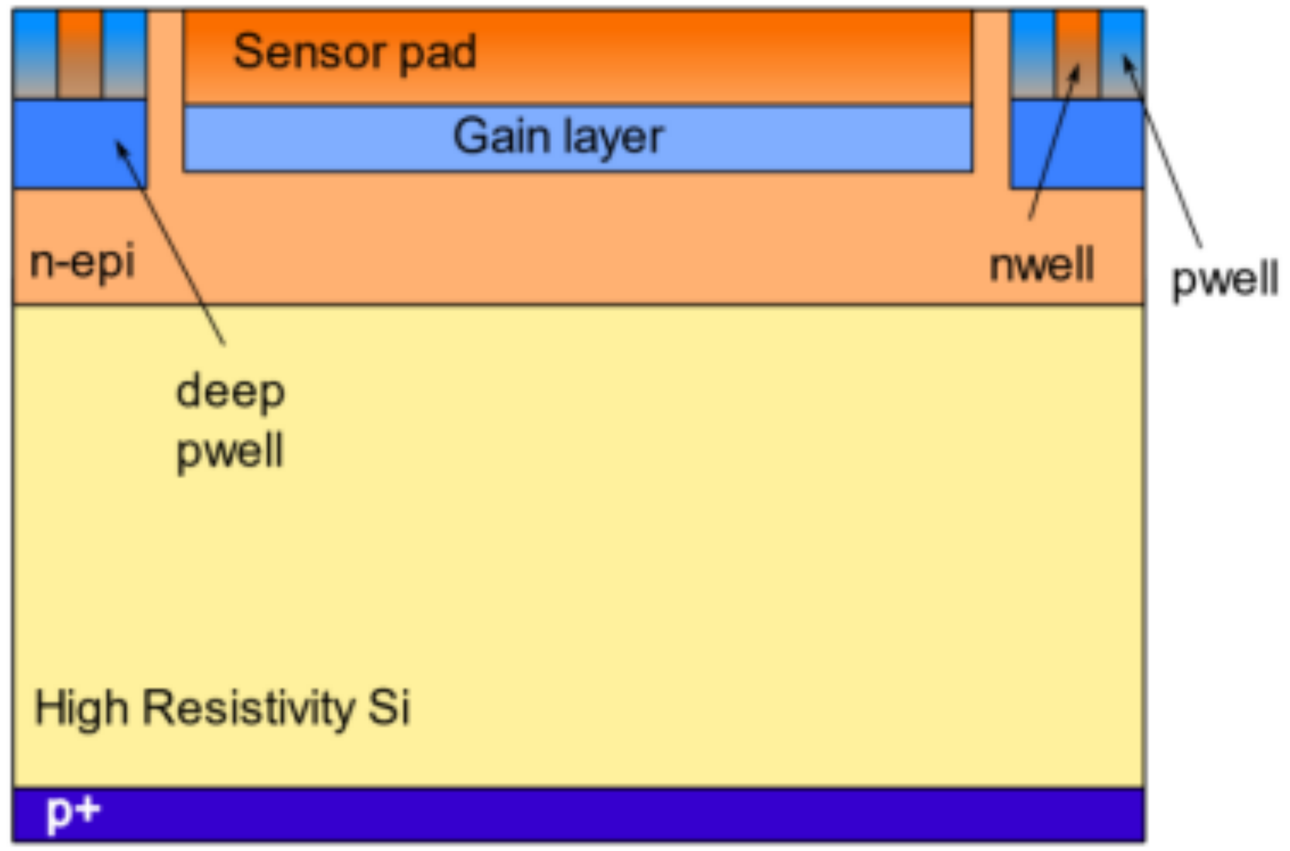


[arXiv:2305.17762]

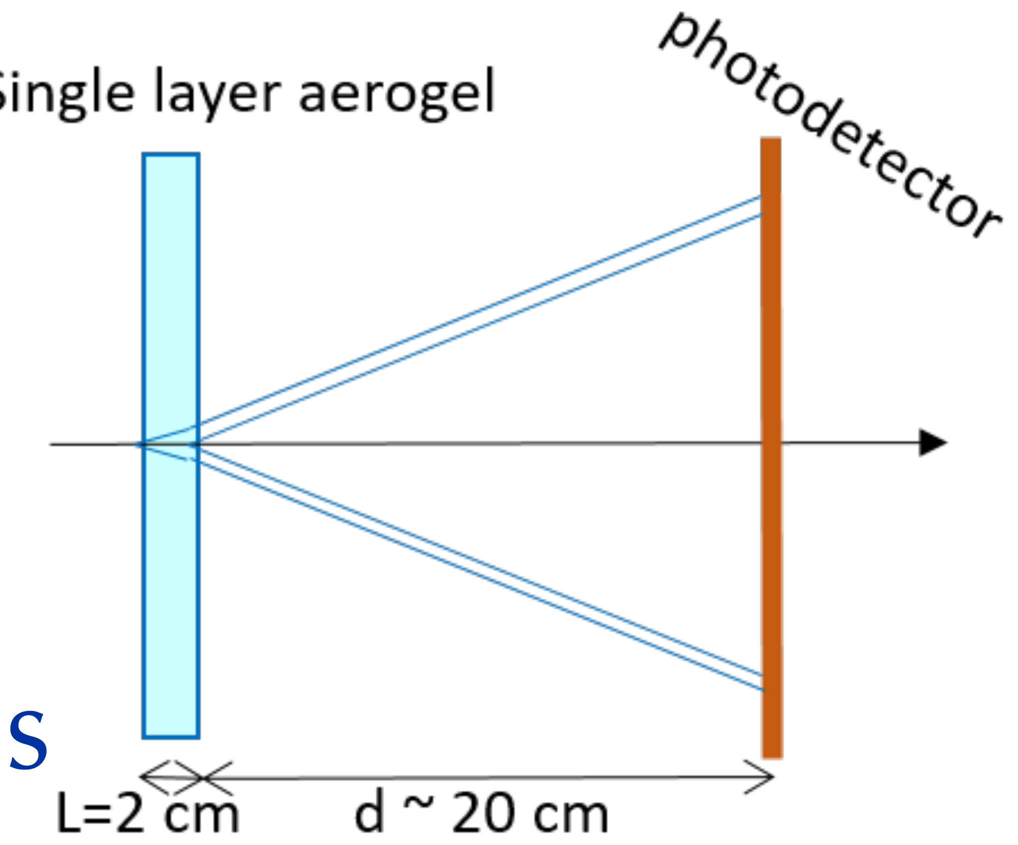
SPADs w/ and w/o resin layers

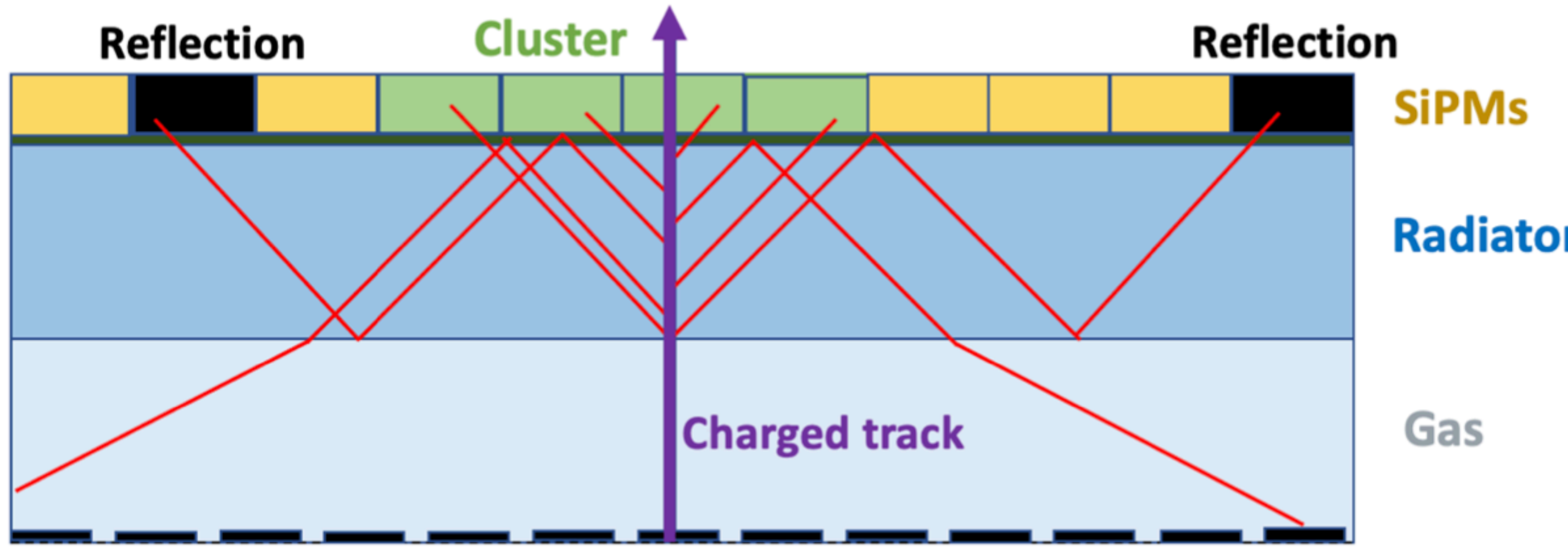
Developments for TOF & RICH

- **Monolithic timing sensor**
  - test gain layer in L-foundry process
- **Low-gain avalanche diodes (LGADs)**
  - characterisation in beam tests
- **SiPMs for charged particle detection**
  - multiple Cherenkov photons in cover → improved time resolution
- **Combination of RICH & TOF**
  - combination of gas and aerogel
  - time-of-flight from Cherenkov photons



CMOS sensor with gain

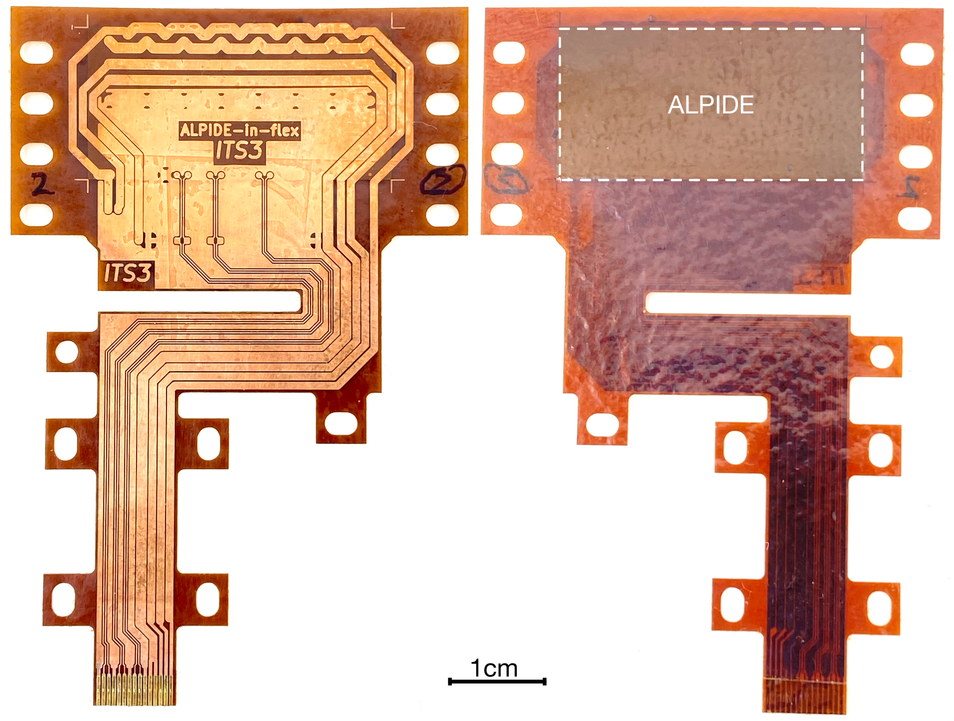


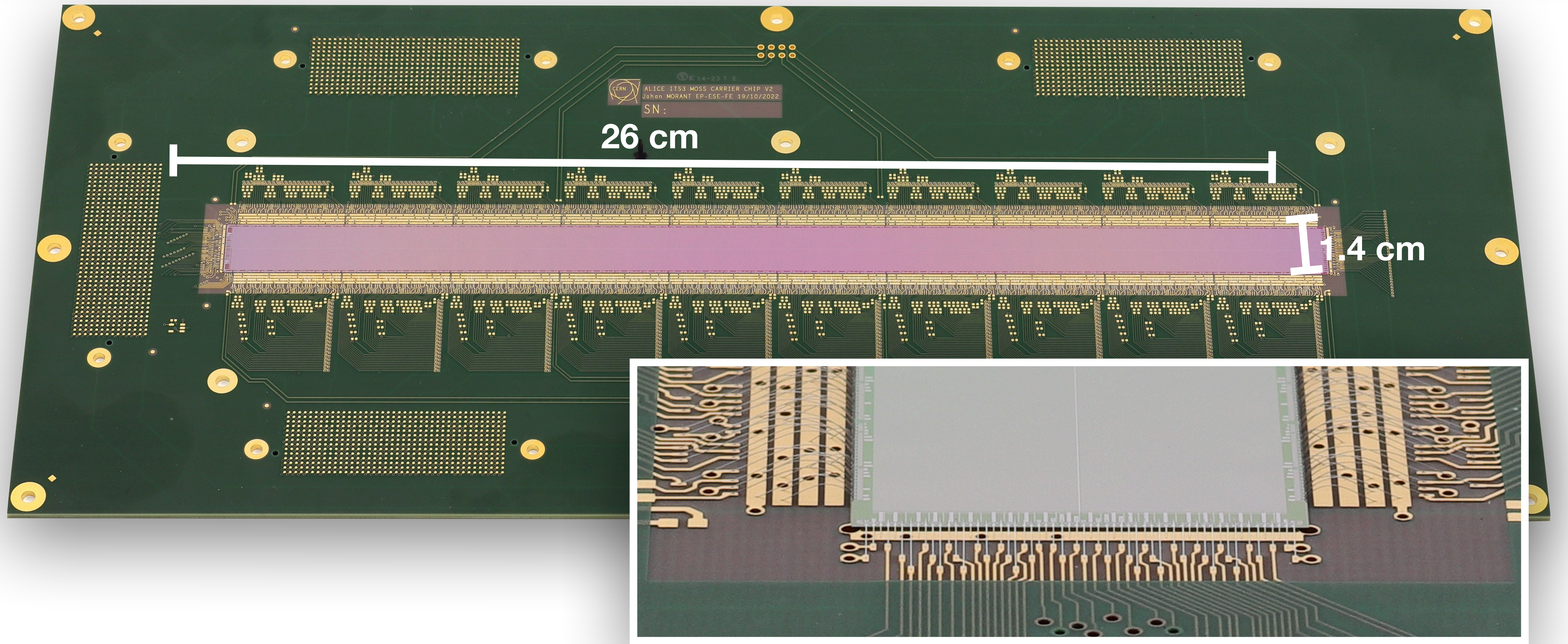


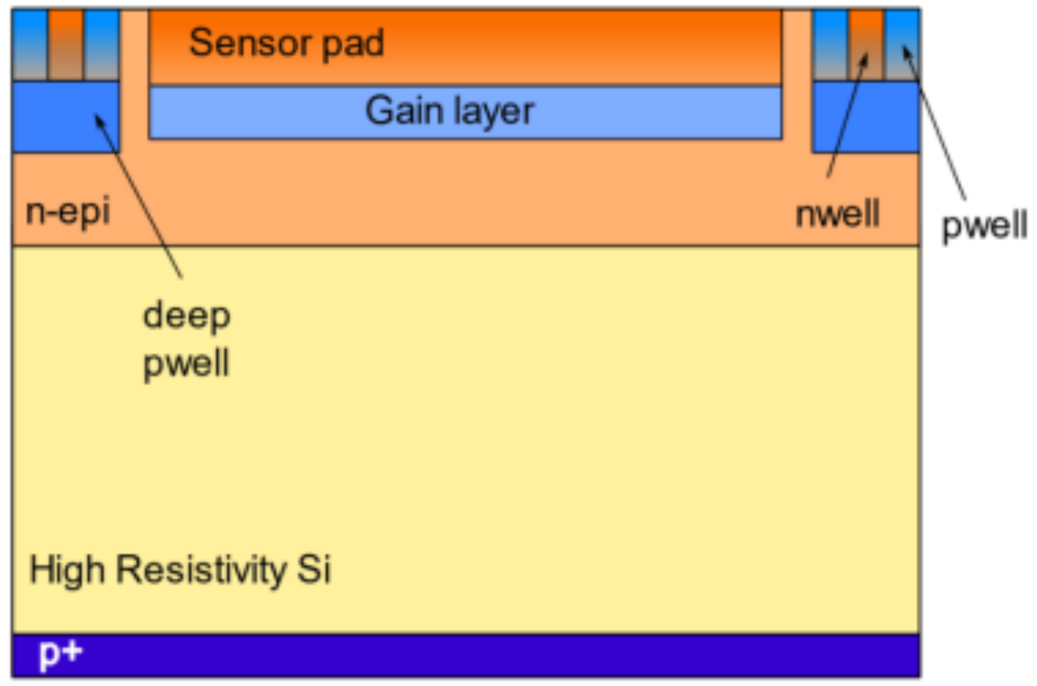
Extended RICH

Exciting R&D in strategic areas

- **Silicon pixel sensors**
  - thinning and bending of silicon sensors
    → expand on experience with ITS3
  - exploration of new CMOS processes
    → expand on 65 nm technology
  - modularisation and industrialisation
    → new concepts for large-scale production
- **Silicon timing sensors**
  - monolithic timing sensors
    → implement gain layer
  - study of thinned LGADs and SPADs/SiPMs
    → characterisation in beam tests
- **Photon sensors**
  - monolithic SiPMs
    → integrate read-out
- **Detector mechanics and cooling**
  - mechanics for low-material, large acceptance tracker
    → new concepts for
  - mechanics for operation in beam pipe
    → establish compatible with LHC beam
  - minimisation of material in the active volume
    → micro-channel cooling







Innovative and relevant technologies

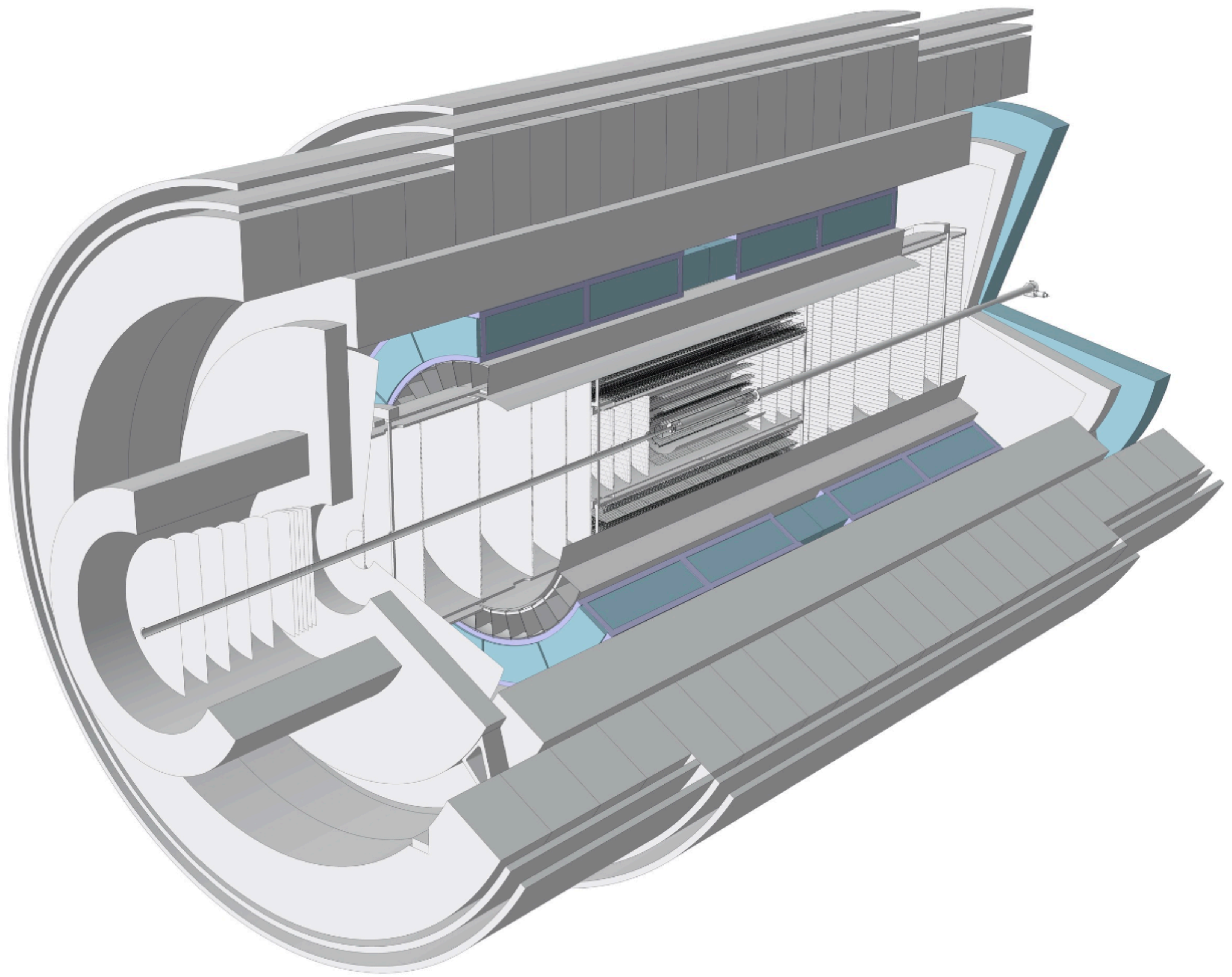
→ Synergies with LHC, FAIR, EIC, …

Electromagnetic calorimeter

- **Large acceptance calorimeter**
  → sampling calorimeter (à la EMCal/DCal):
  e.g. O(100) layers (1 mm Pb + 1.5 mm plastic scintillator)

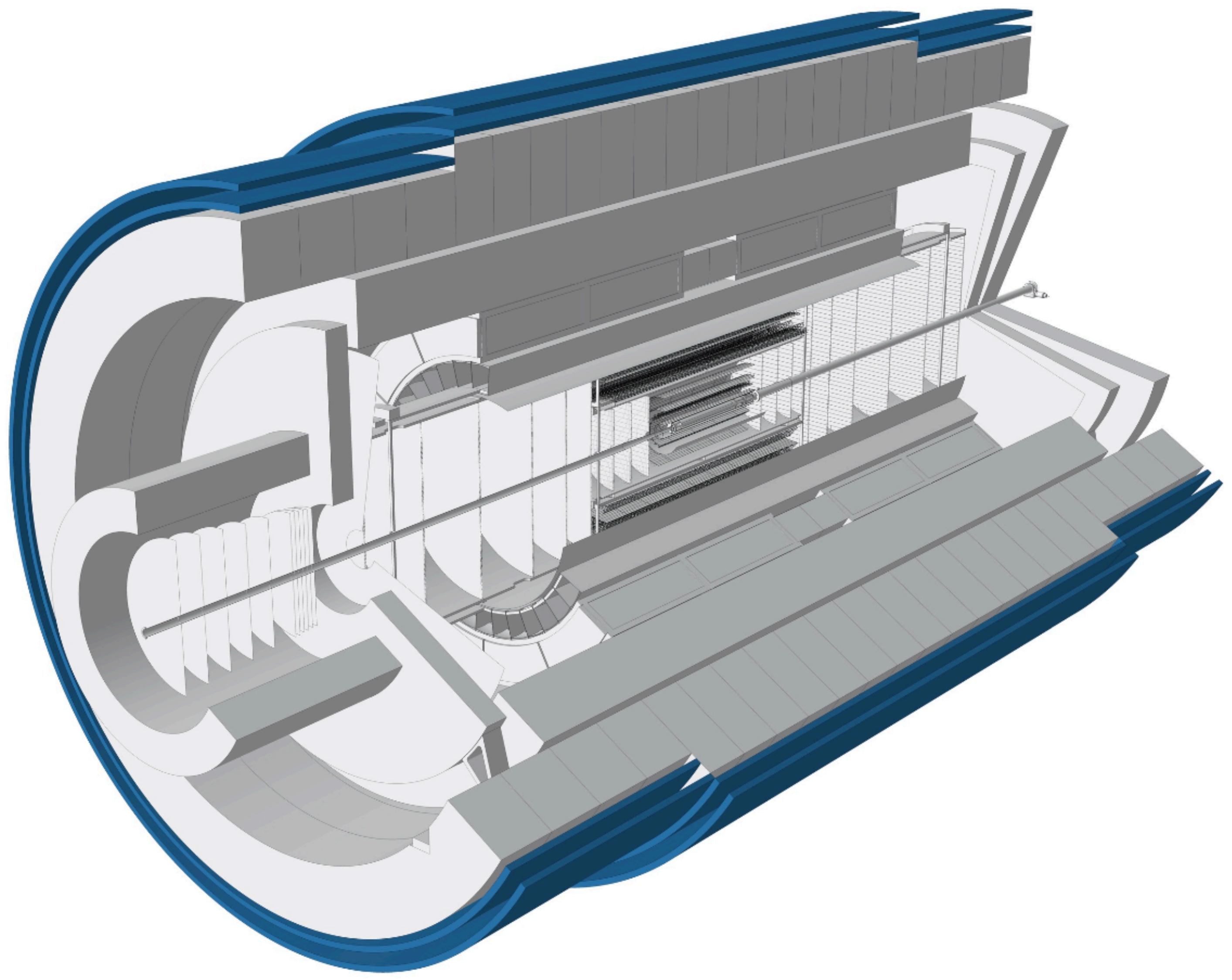
- **Additional high energy resolution segment**
  around midrapidity
  → $PbWO_4$-based

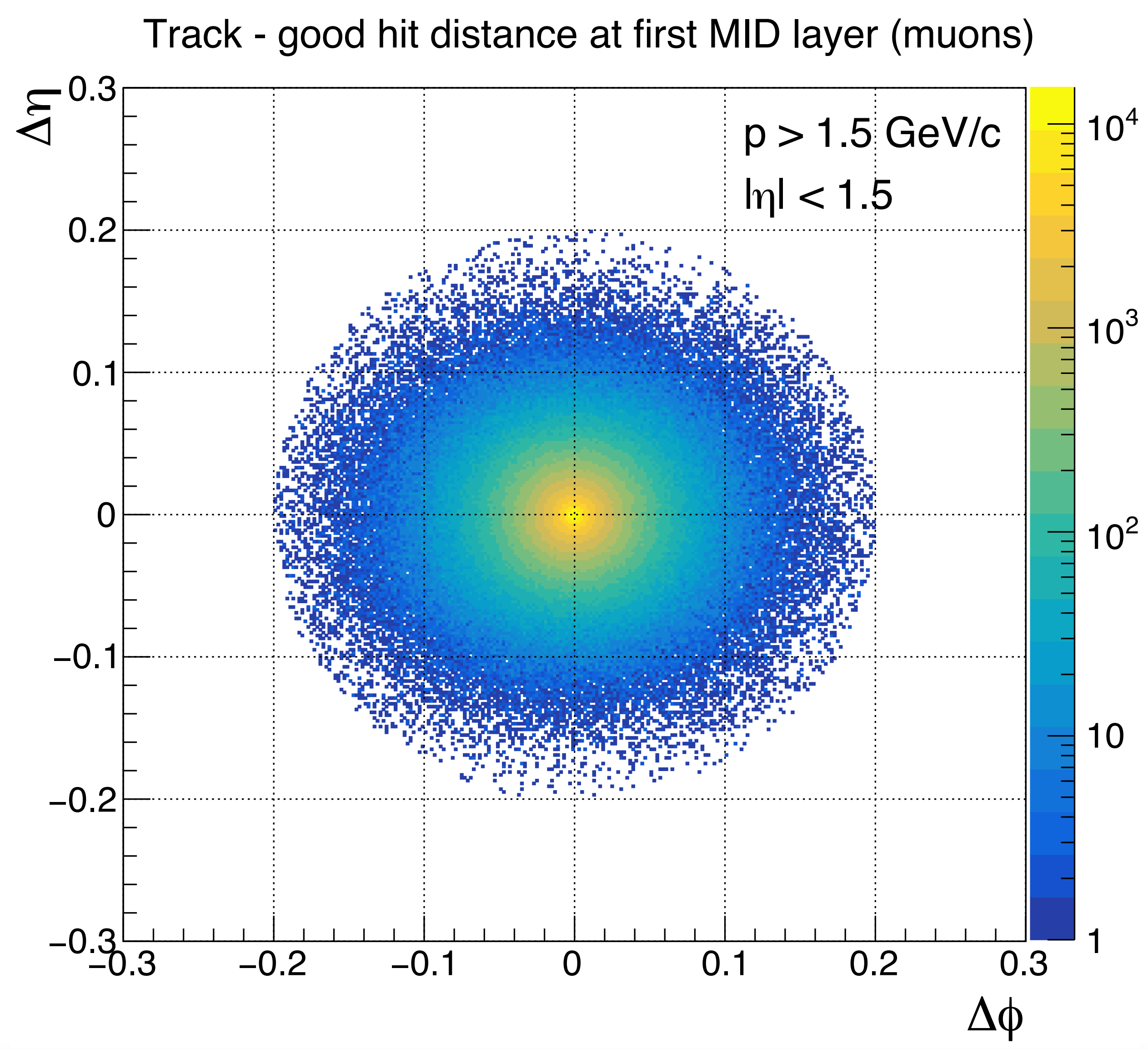
ECal module	Barrel sampling	Endcap sampling	Barrel high-precision
acceptance	$\Delta\varphi = 2\pi$, $\|\eta\| < 1.5$	$\Delta\varphi = 2\pi$, $1.5 < \eta < 4$	$\Delta\varphi = 2\pi$, $\|\eta\| < 0.33$
geometry	$R_{in} = 1.15$ m, $\|z\| < 2.7$ m	$0.16 < R < 1.8$ m, $z = 4.35$ m	$R_{in} = 1.15$ m, $\|z\| < 0.64$ m
technology	sampling Pb + scint.	sampling Pb + scint.	$PbWO_4$ crystals
cell size	30×30 mm^2	40×40 mm^2	22×22 mm^2
no. of channels	30 000	6 000	20 000
energy range	$0.1 < E < 100$ GeV	$0.1 < E < 250$ GeV	$0.01 < E < 100$ GeV



Muon identifier

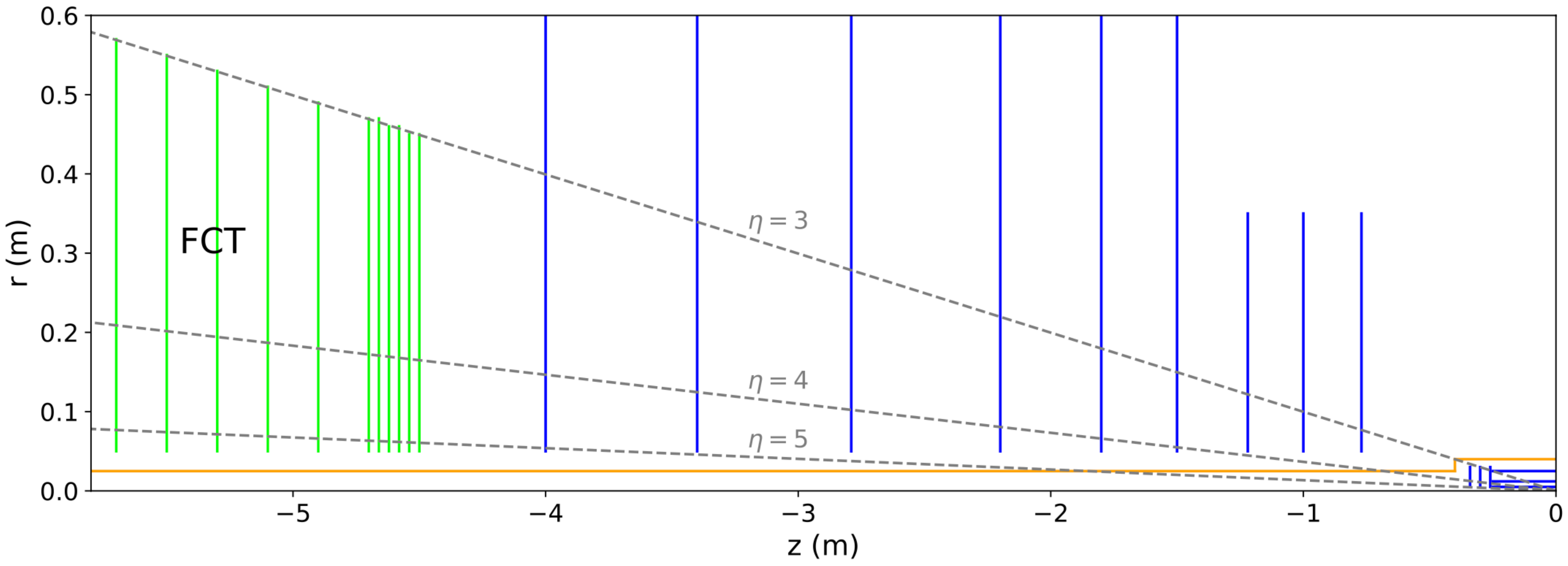
- **Hadron absorber** outside of the magnet
  - ~70 cm non-magnetic steel
- **Muon chambers**
  - search spot for muons ~0.1 x 0.1 (eta x phi)
    → ~5 x 5 cm² cell size
  - matching demonstrated with 2 layers of muon chambers
    - scintillator bars with SiPM read-out
    - resistive plate chambers





Forward conversion tracker

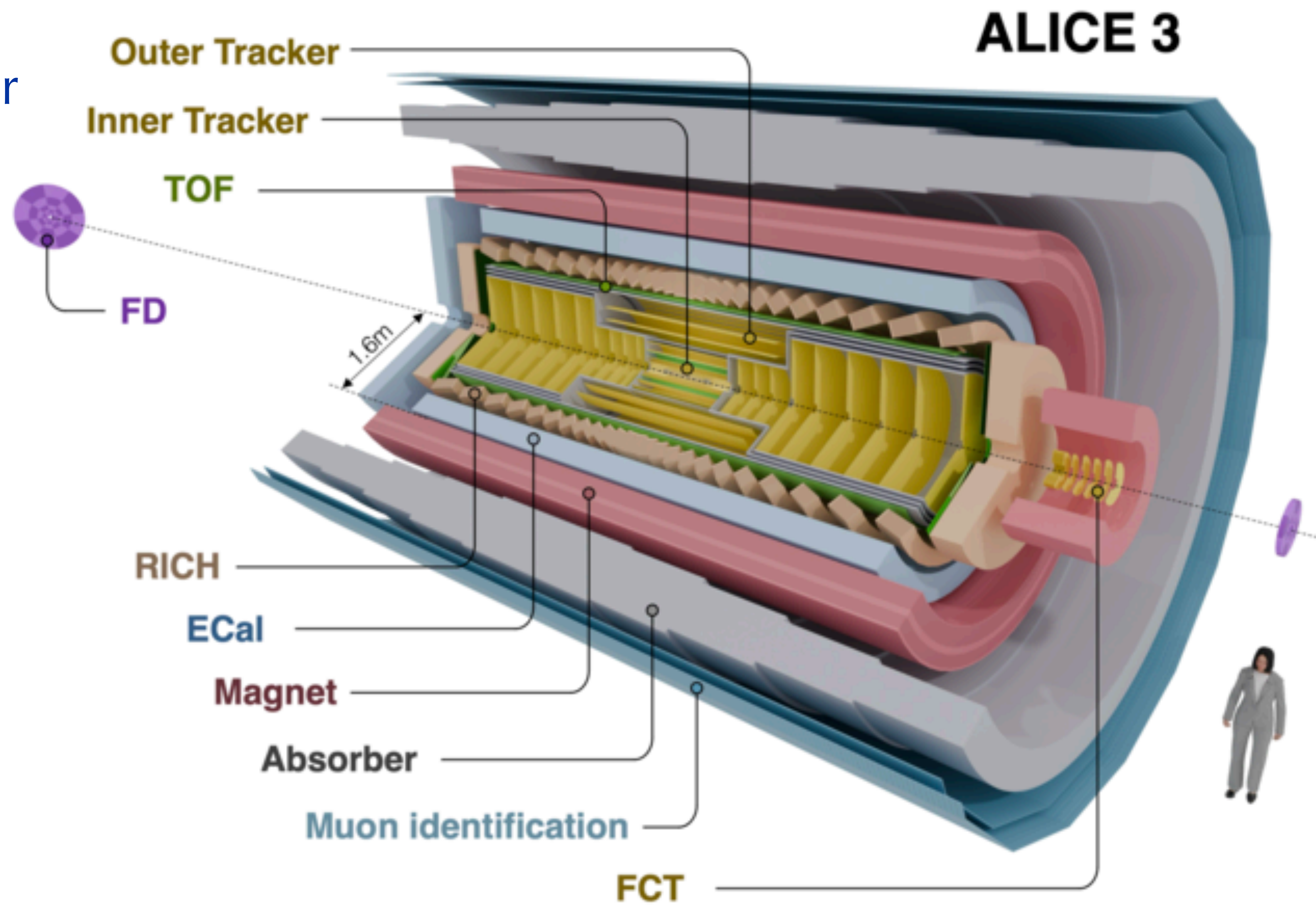
- **Thin tracking disks** to cover $3 < \eta < 5$
  - few ‰ of a radiation length per layer
  - position resolution < 10 μm
- **Research & Development**
  - Large area, thin disks
  - Minimisation of material in front of FCT
  - Operational conditions



Layer	z (m)	r_{min} (m)	r_{max} (m)
0	−4.50	0.05	0.45
1	−4.54	0.05	0.45
2	−4.58	0.05	0.46
3	−4.62	0.05	0.46
4	−4.66	0.05	0.47
5	−4.70	0.05	0.47
6	−4.90	0.05	0.49
7	−5.10	0.05	0.51
8	−5.30	0.05	0.53
9	−5.50	0.05	0.55
10	−5.70	0.05	0.57

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



Physics Performance

What will be able to measure?

ALICE 3 physics programme

- **Susceptibilities**
- **Quarkonia and exotic mesons**
  - dissociation and regeneration
- Structure of **exotic hadrons**
  - Momentum correlations (femtoscopy)
  - Production yields (dissociation in final state scattering)

- **Emergence of collectivity** from small to large systems
- New **nuclear states**
- **Ultra-peripheral collisions**
- **Ultra-soft photons**: experimental test of Low's theorem
- **BSM searches**: ALPs, dark photons

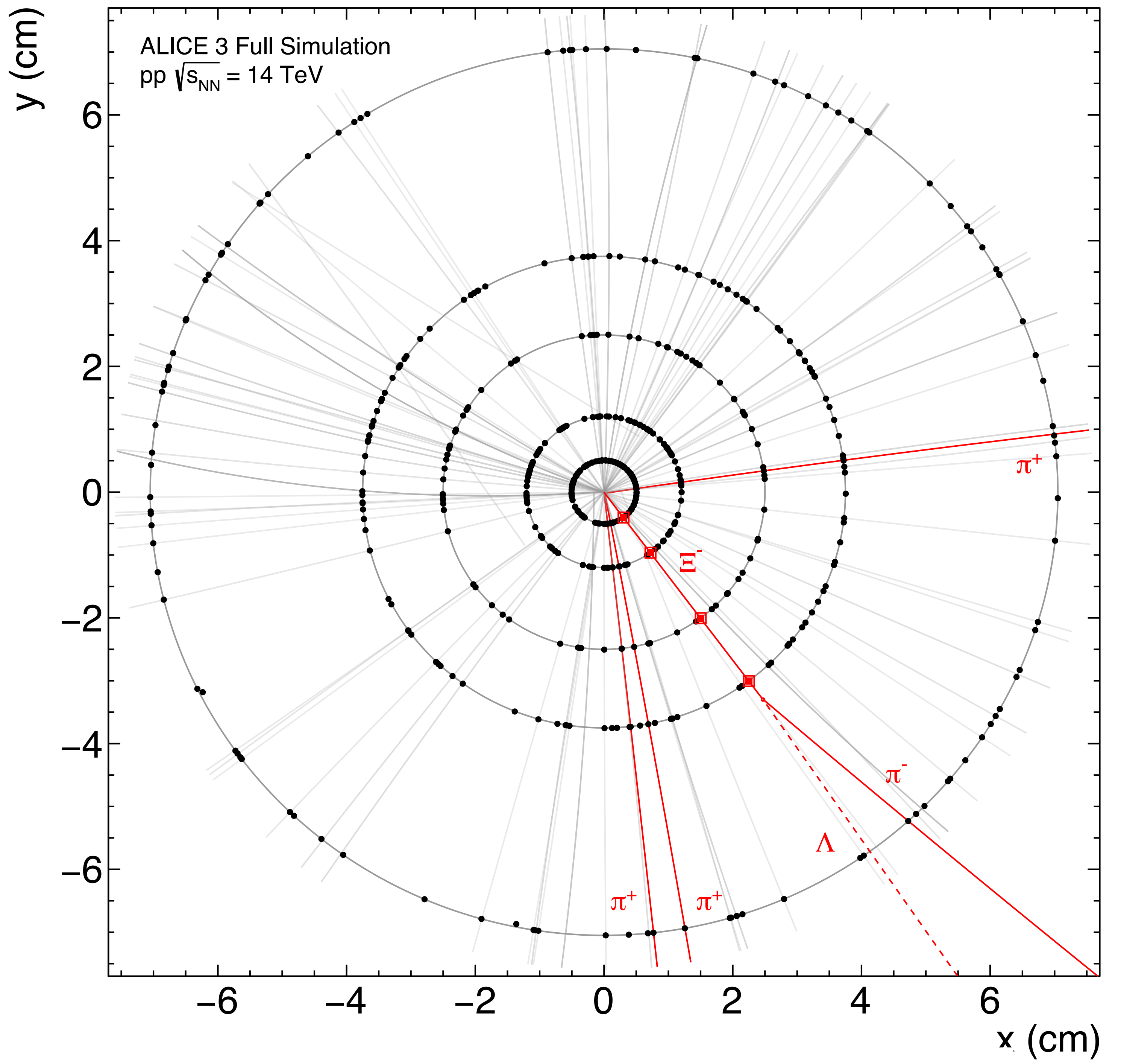
unique instrument with a plethora of new possibilities
➟ ample room for further ideas

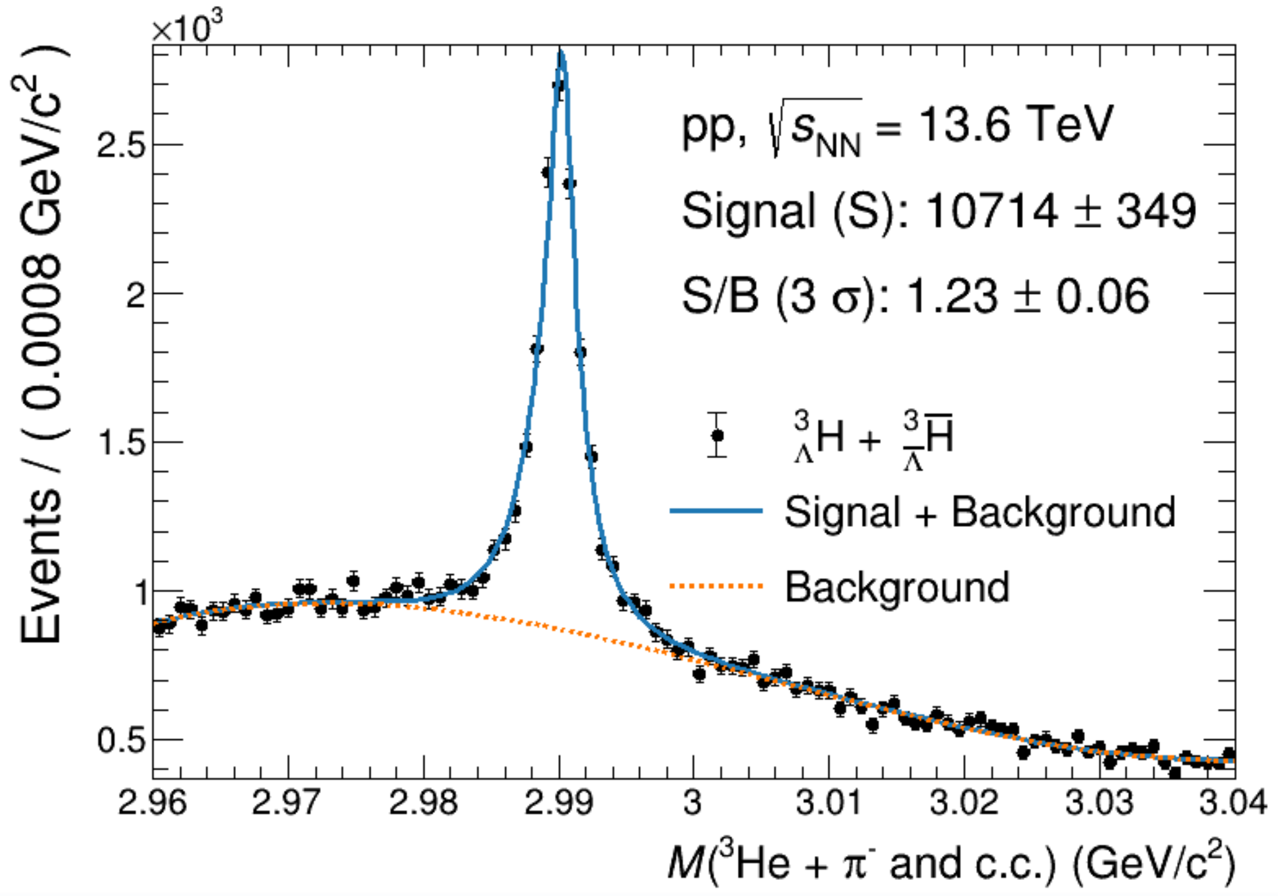
[CERN-LHCC-2022-009]

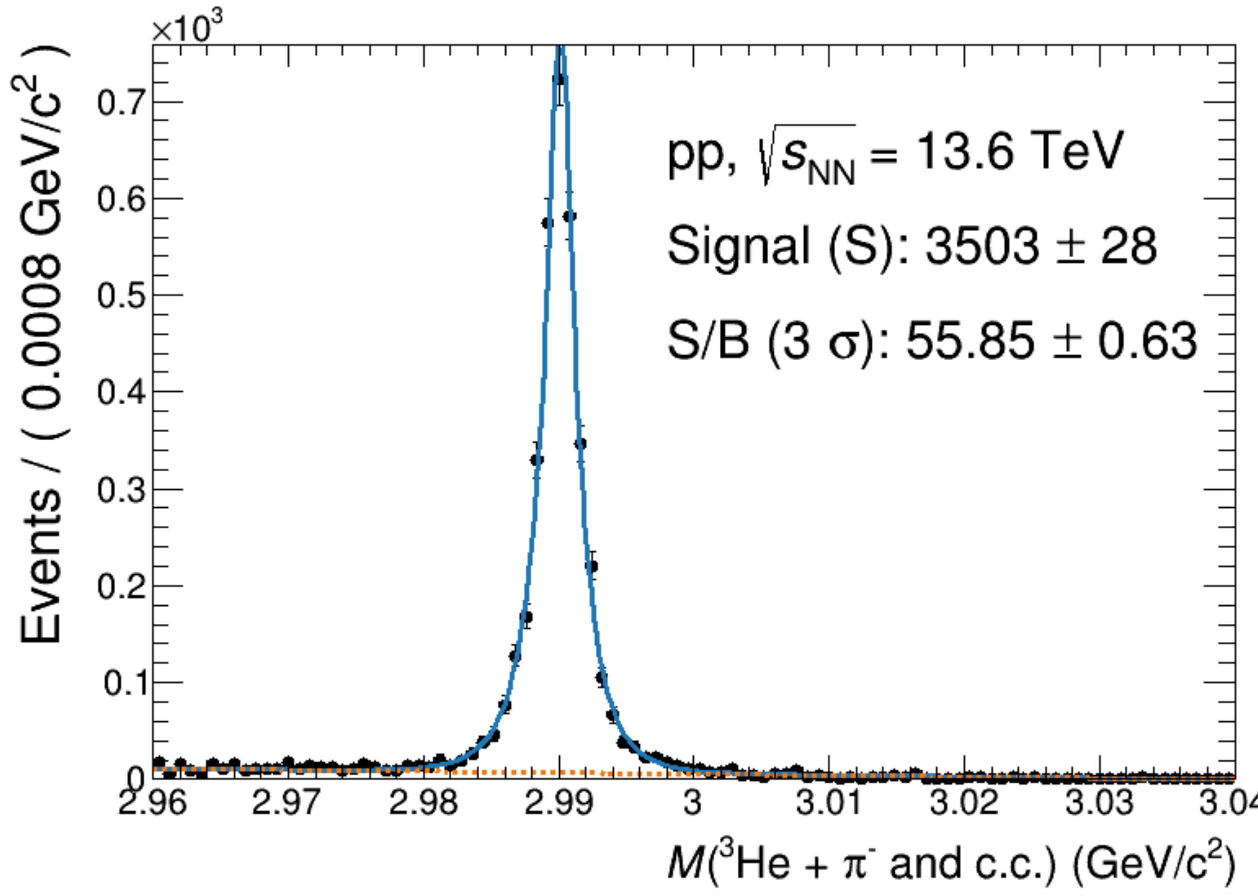
Strangeness tracking

- **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)
  - Ξ_{cc}, Ω_{cc}, Ω_{ccc} (Run 5 & 6)

Novel technique for Run 3 and beyond

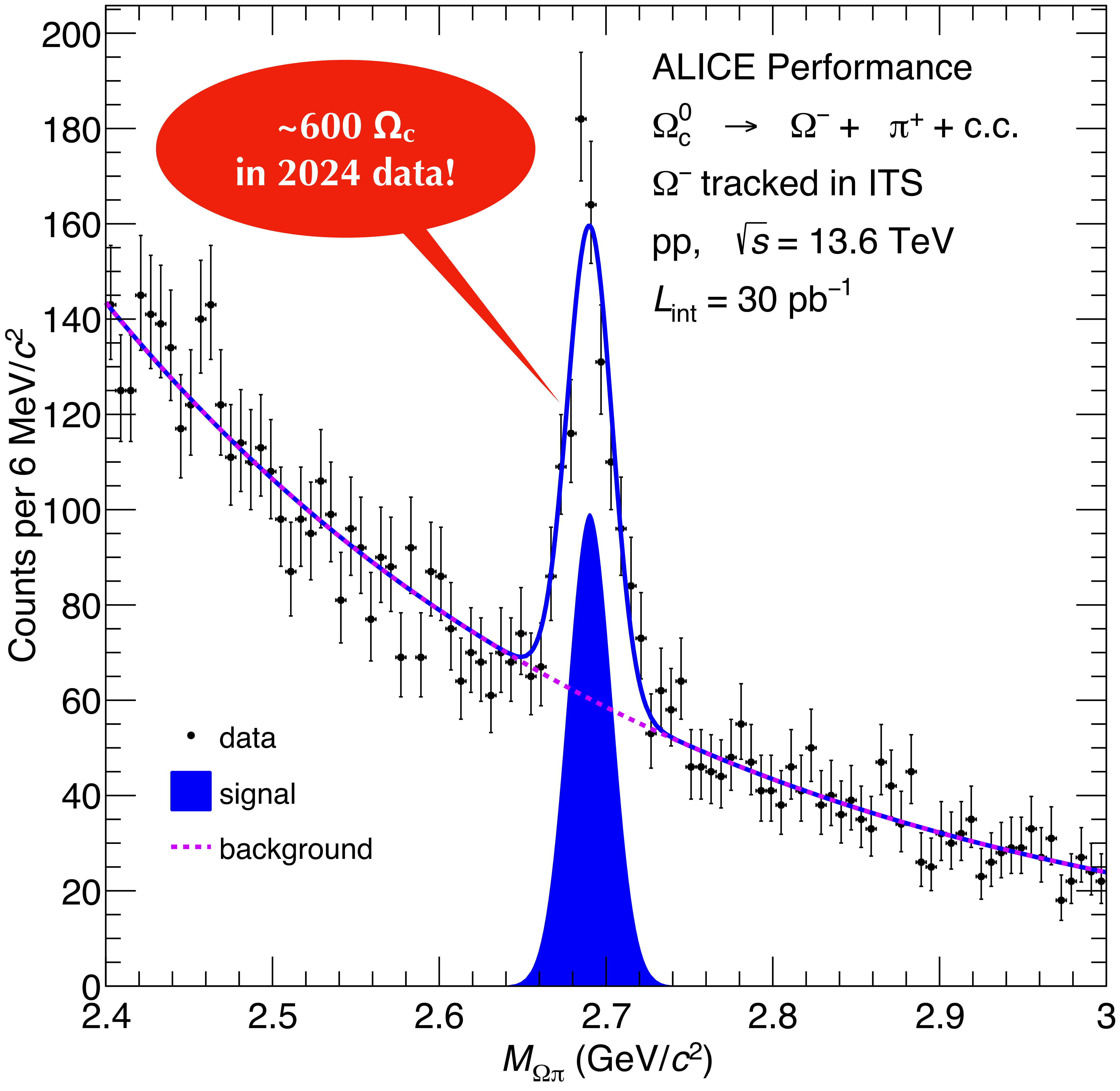


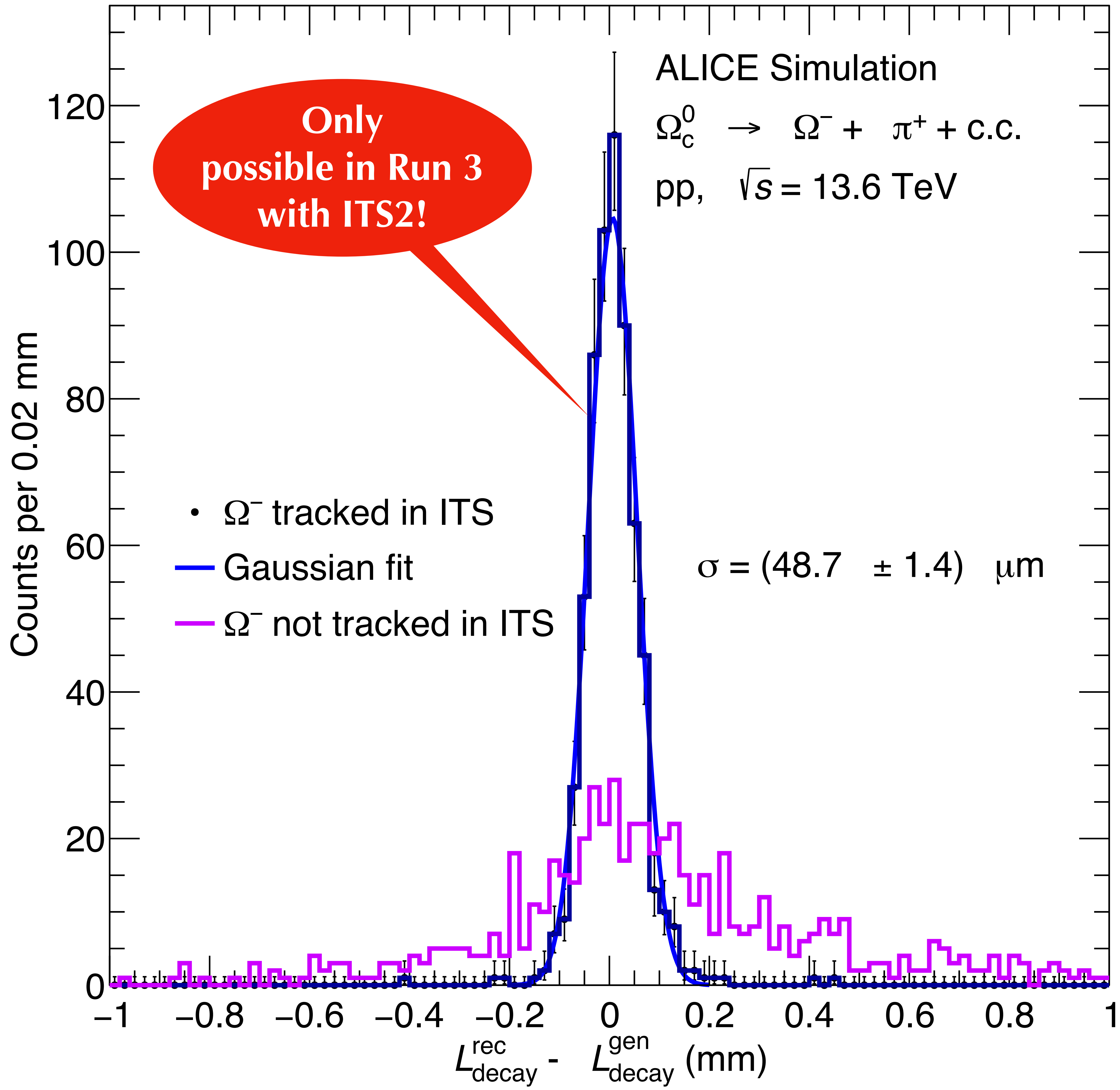




projections for hyper-triton

Run 3 performance



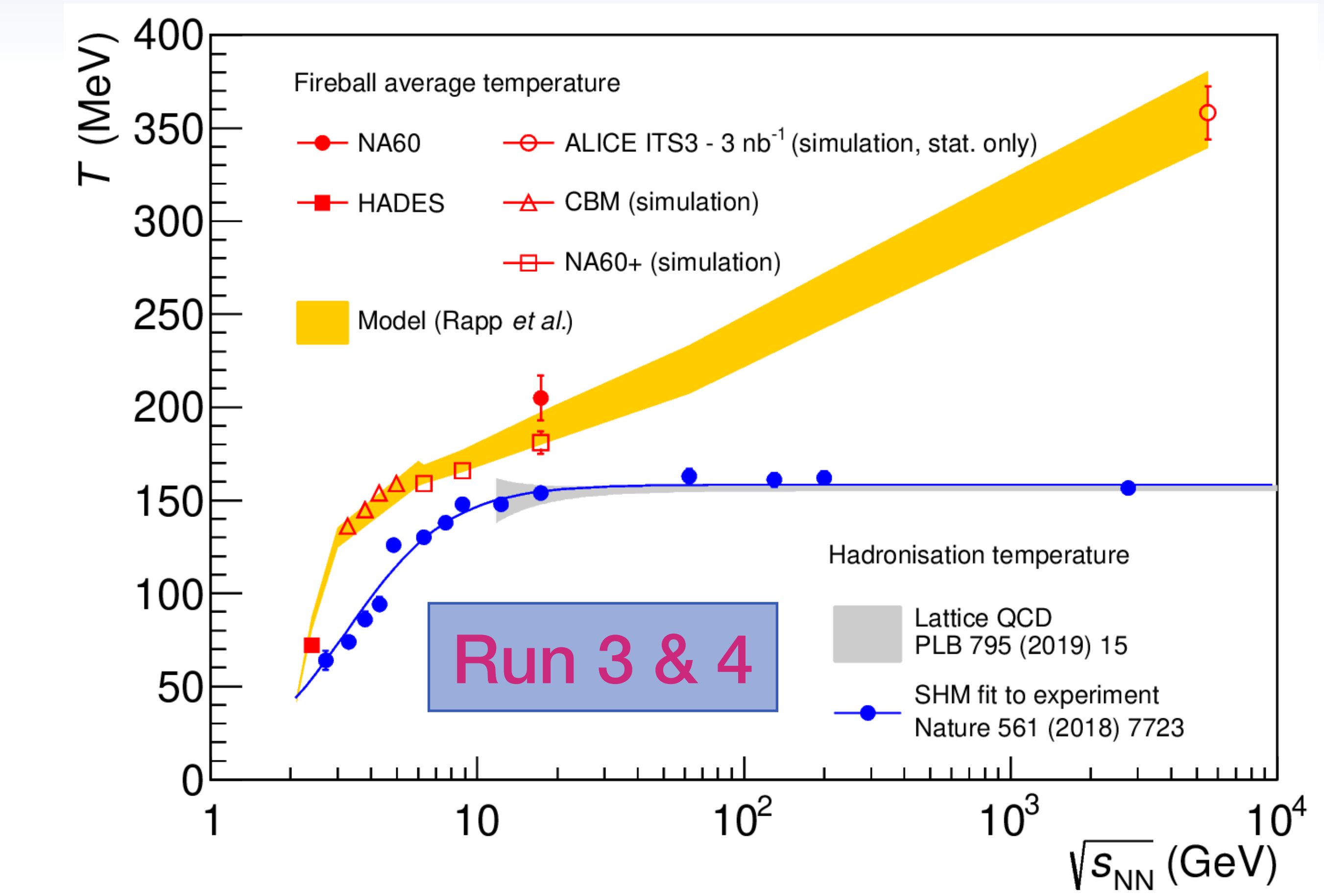


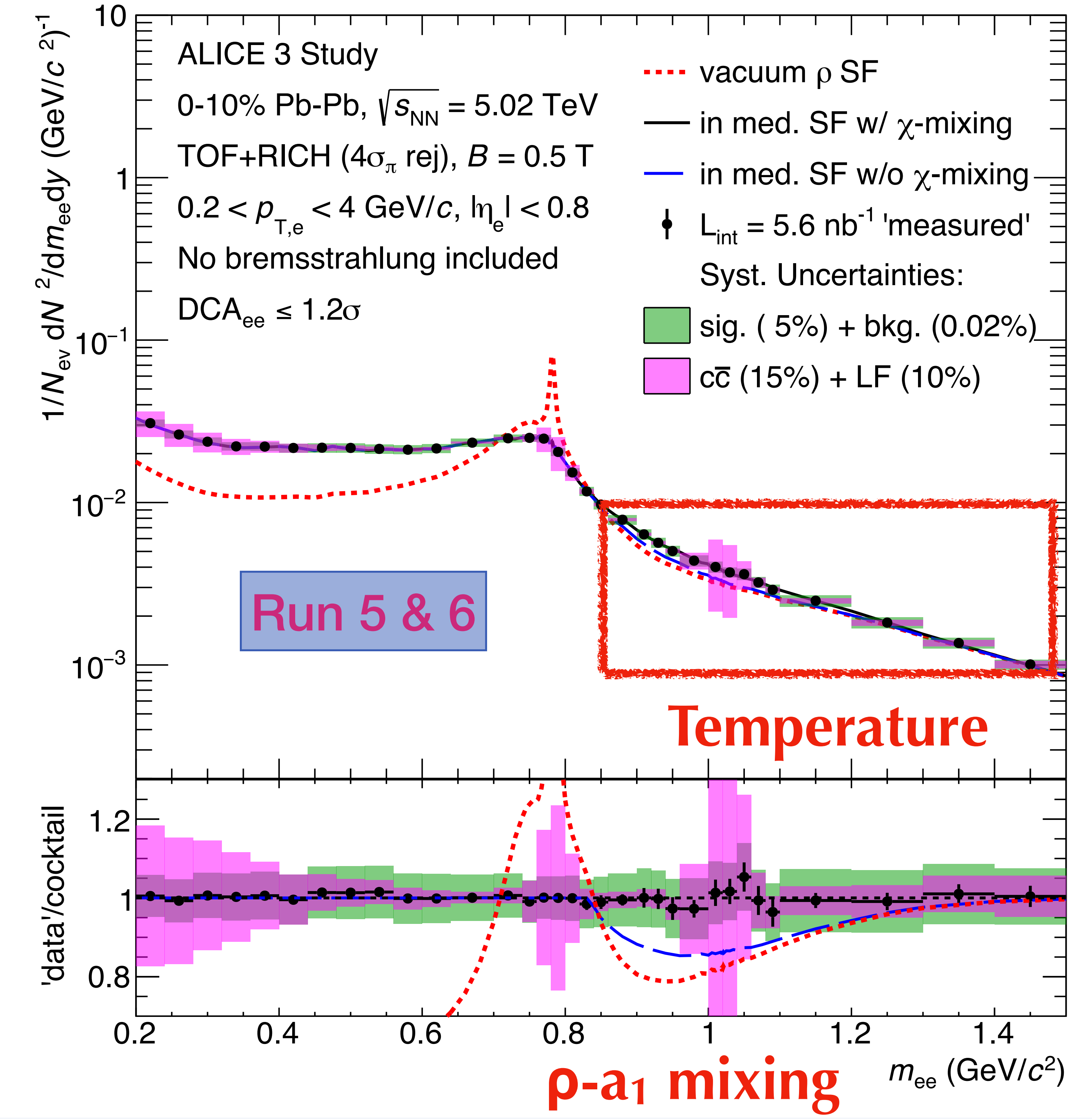
Thermal radiation

- 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



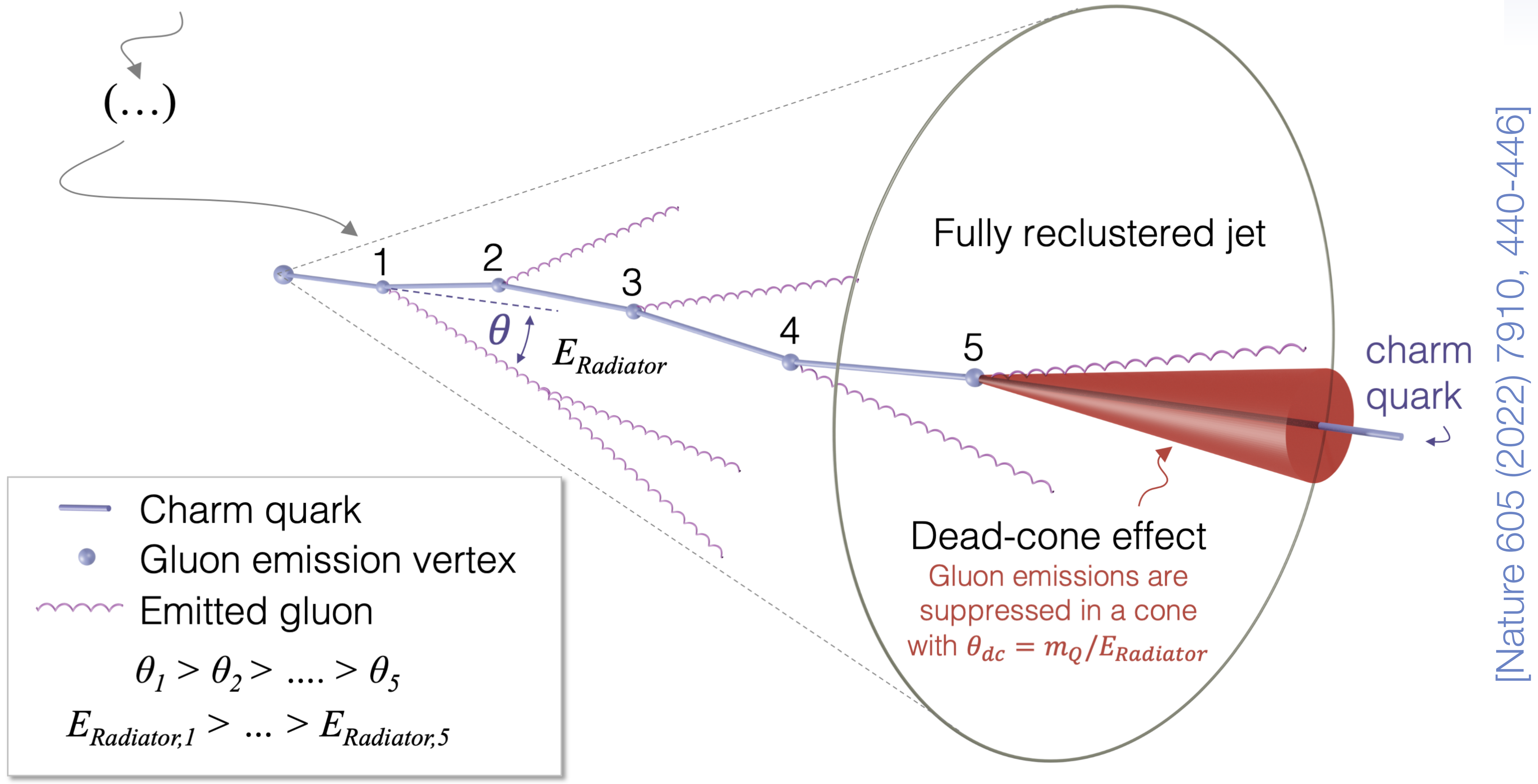


Jets

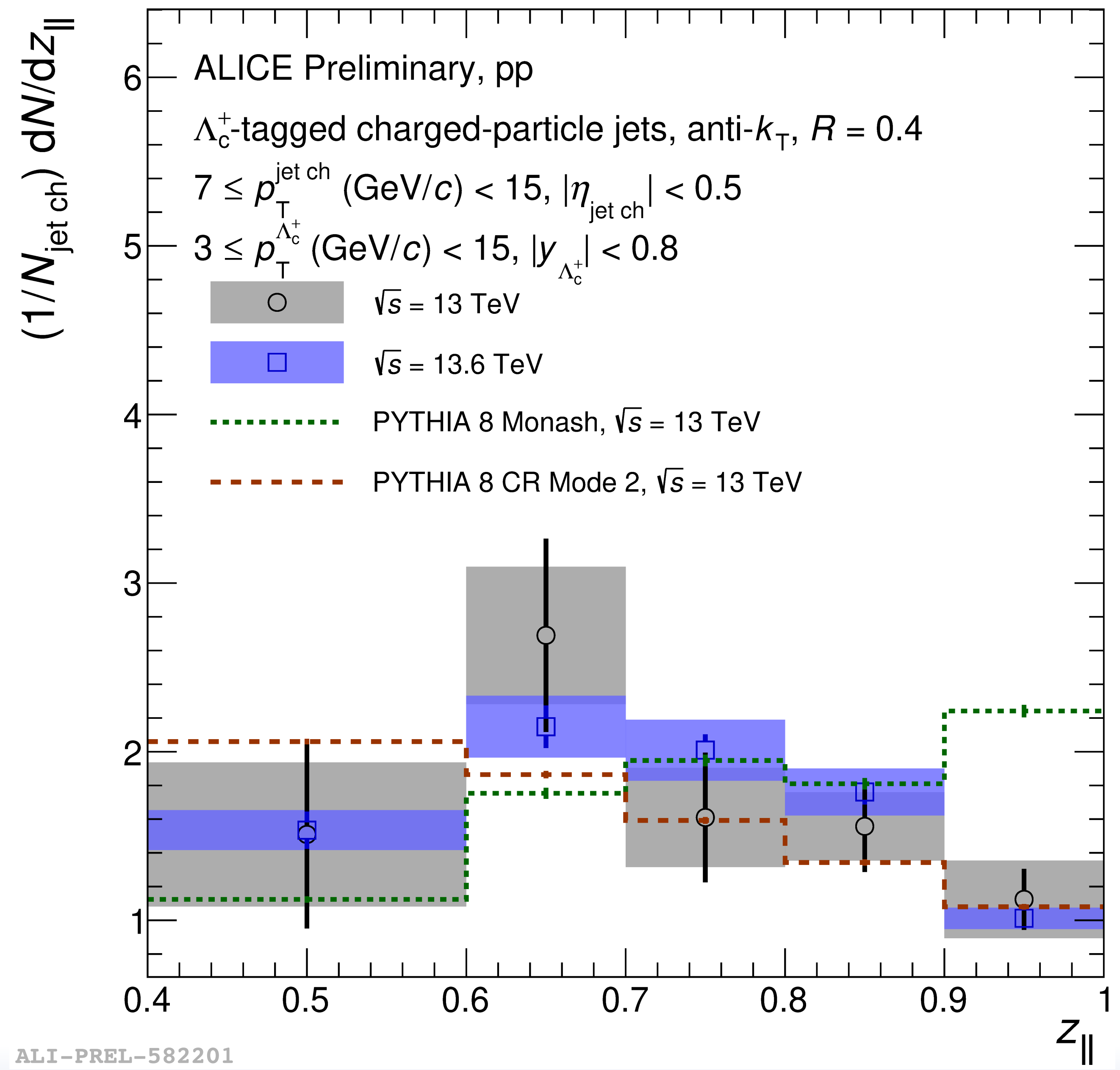
- **Evolution of high-energy partons** described by **QCD parton shower** → radiation/splittings depend on
  - colour factors (gluon vs quark)
  - mass (charm and beauty)
  - interactions with QGP

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

Excellent prospects with Run 3 and 4



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



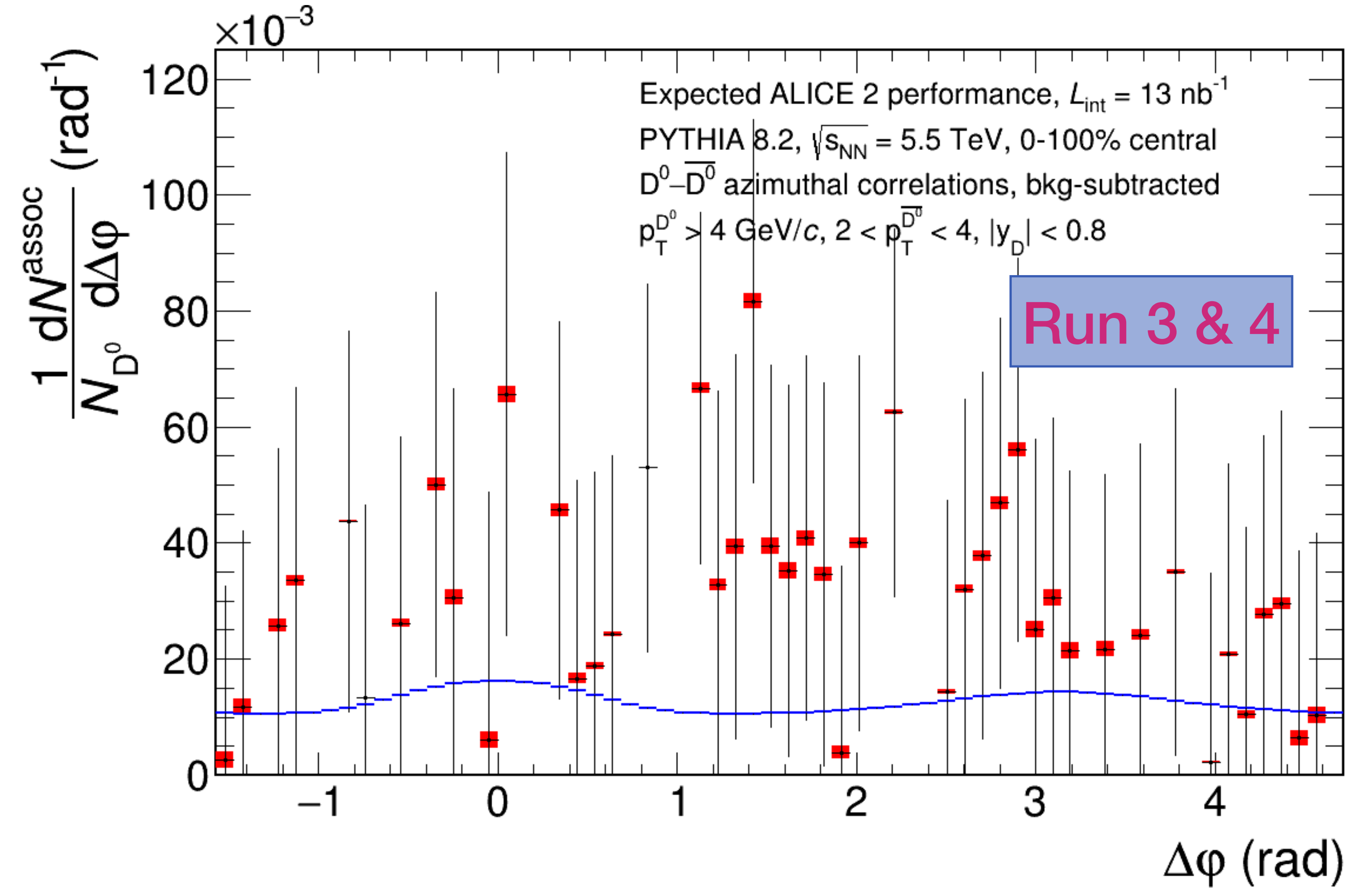
Heavy-flavour transport

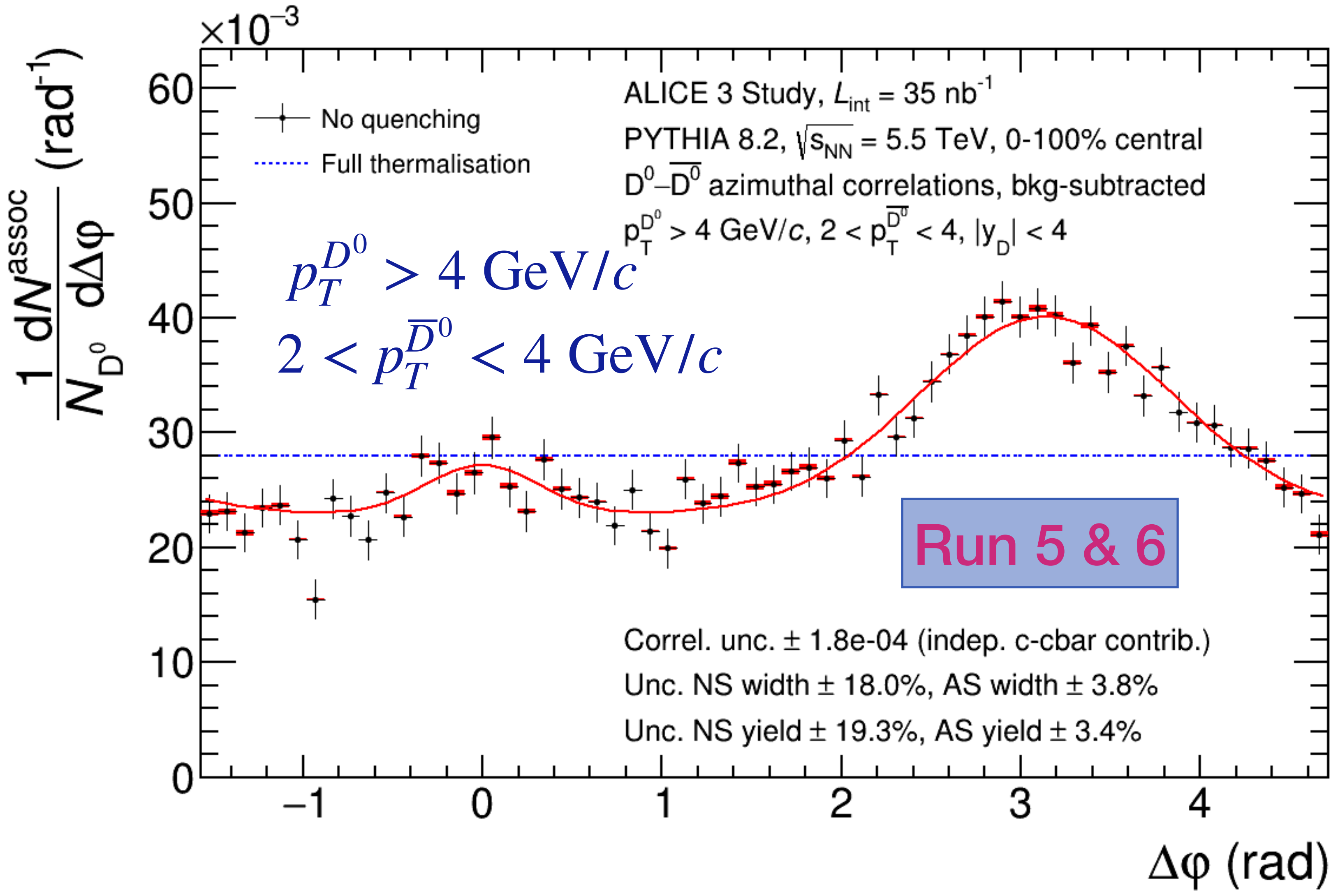
- **Propagation of (traceable) heavy quarks** depends on interaction with QGP
  - diffusion and approach to thermal equilibrium
  - extent of thermalisation depends on mass
    → beauty quarks retain more information

- 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**





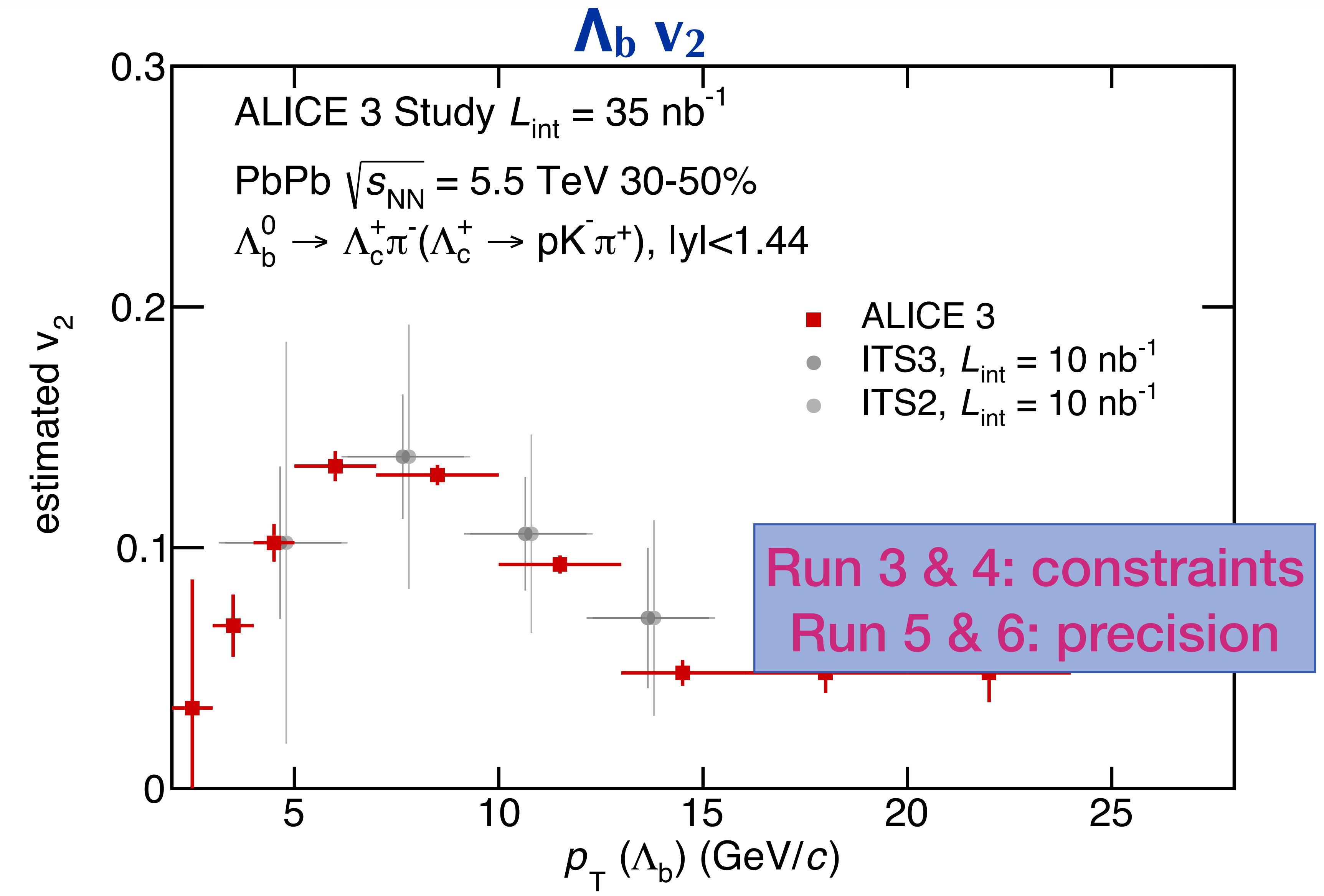
[CERN-LHCC-2022-009]

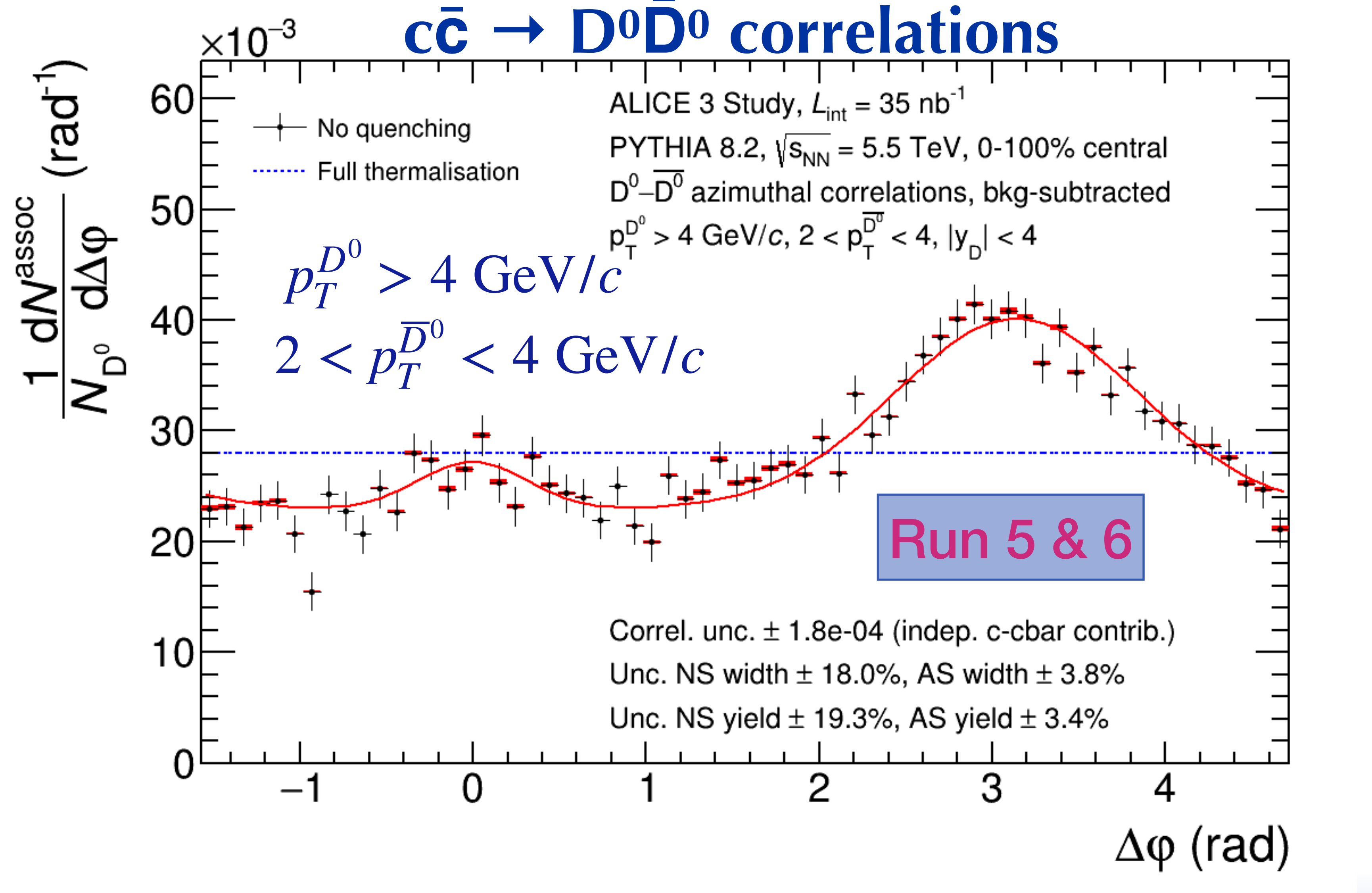
Transport and thermalisation

- **Propagation of (traceable) heavy quarks** depends on interaction with QGP
  - characterised by spatial diffusion coefficient D_s
    $\langle r^2 \rangle = 6\ D_s\ t$
  - determines relaxation time and thermalisation
    $\tau_Q = (m_Q/T)\ D_s$

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

First measurements with Run 3 & 4, ultimate precision requires ALICE 3





[CERN-LHCC-2022-009]

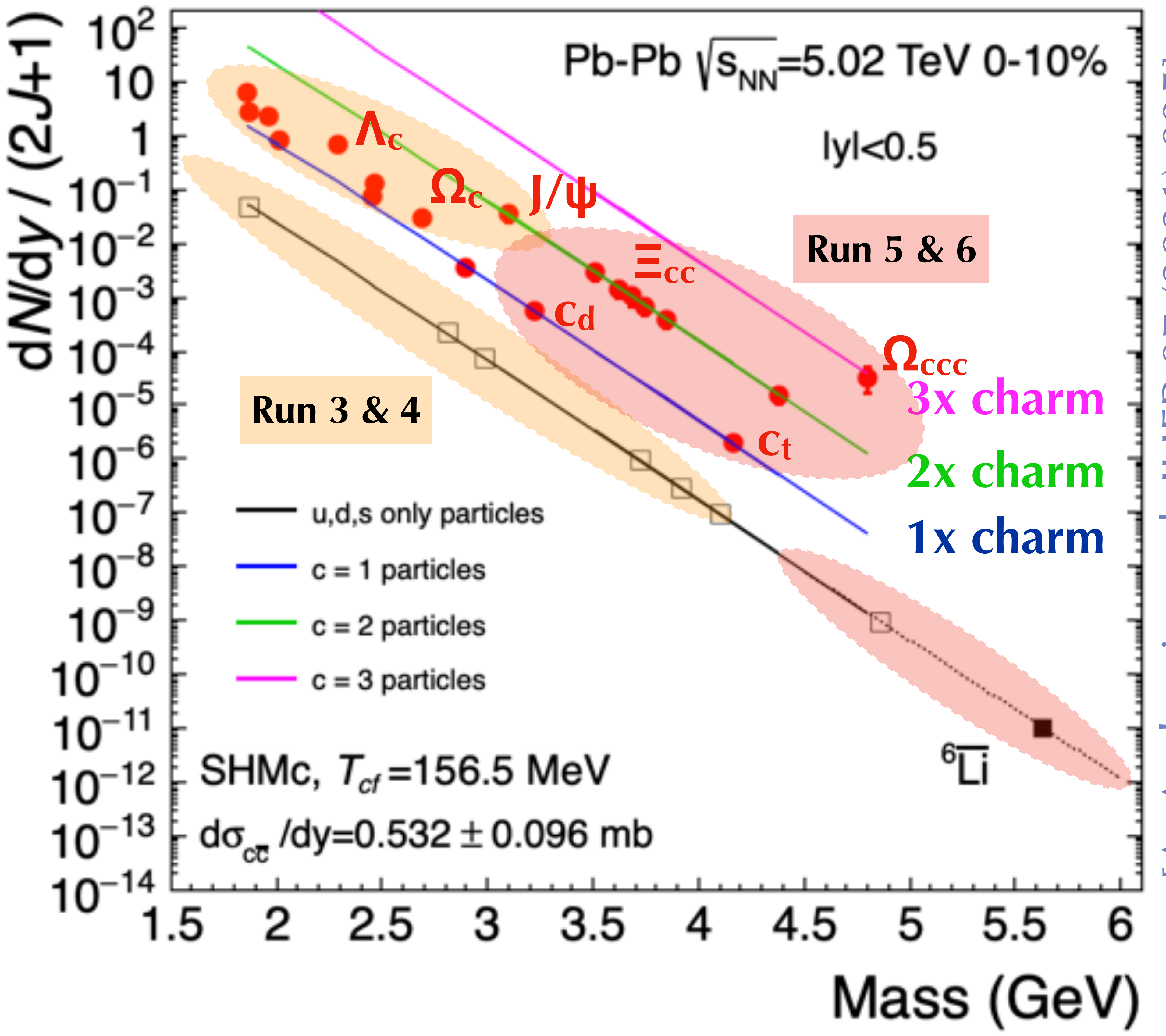
Multi-charm baryons

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

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

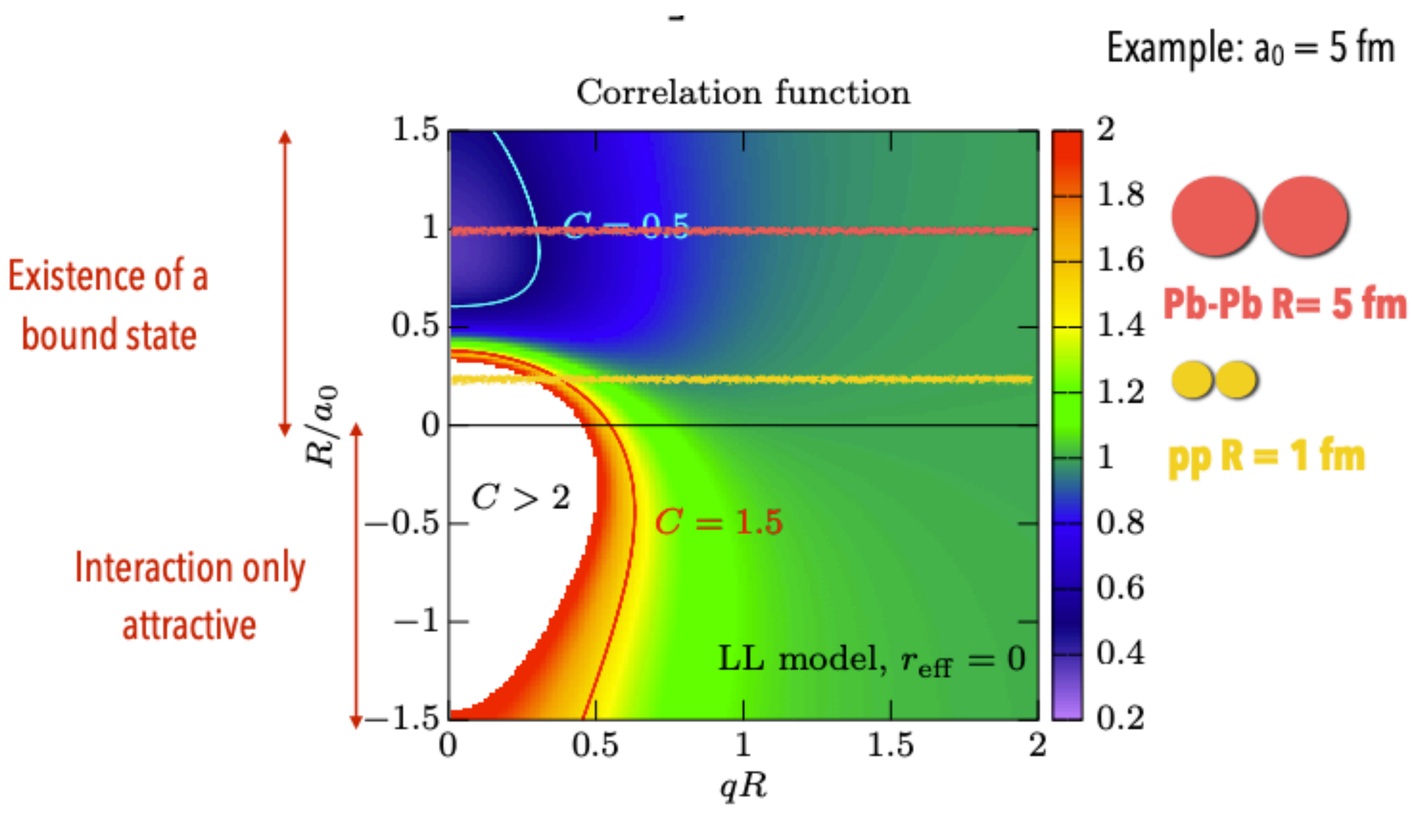
Extreme sensitivity to equilibration and hadronisation in Run 5 & 6

Hadron yields in statistical hadronisation model



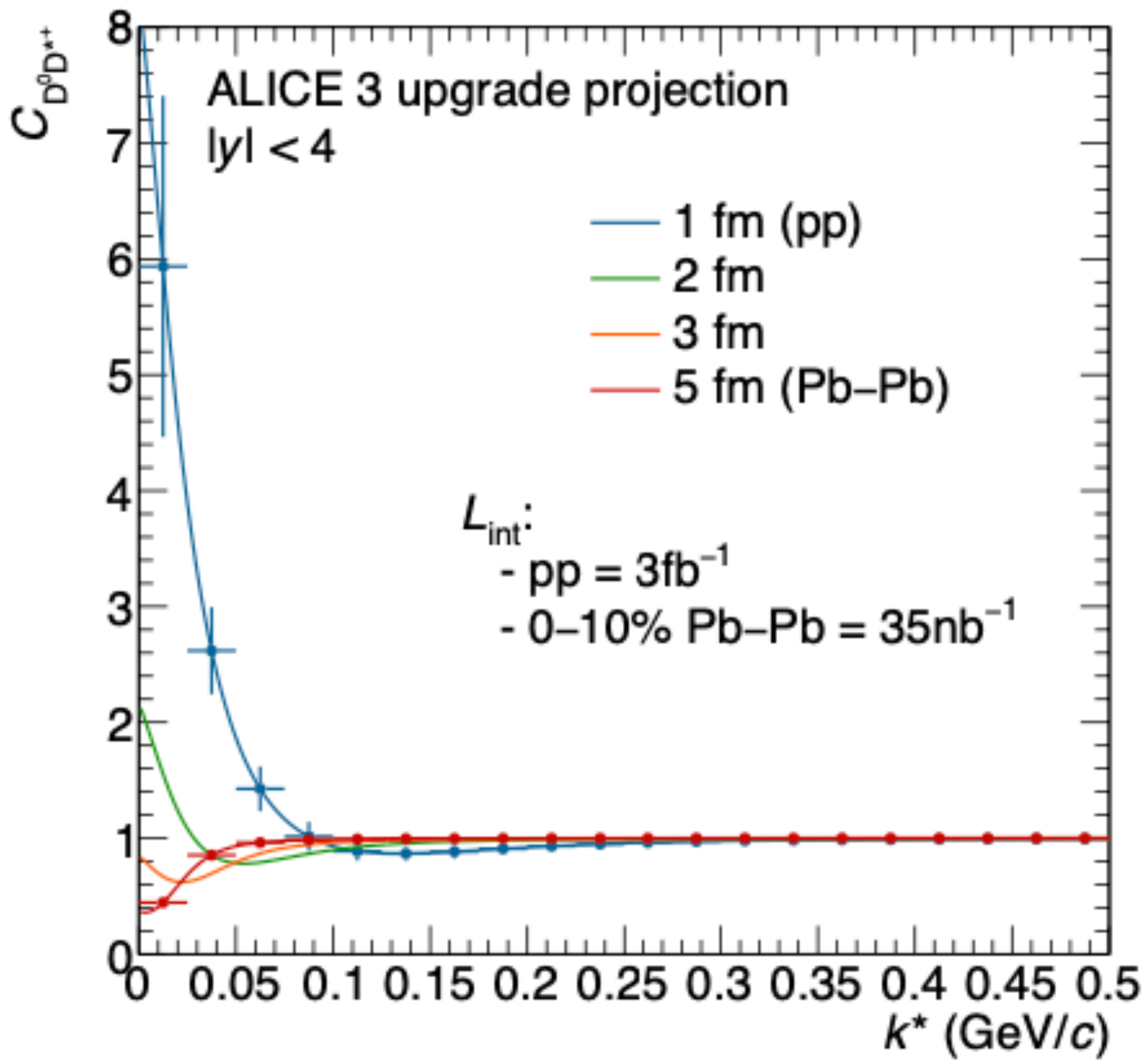
[A. Andronic et al, JHEP 07 (2021) 035]

Nature of exotic states



Y. Kamiya et al. arXiv:2108.09644v1

DD* momentum correlation

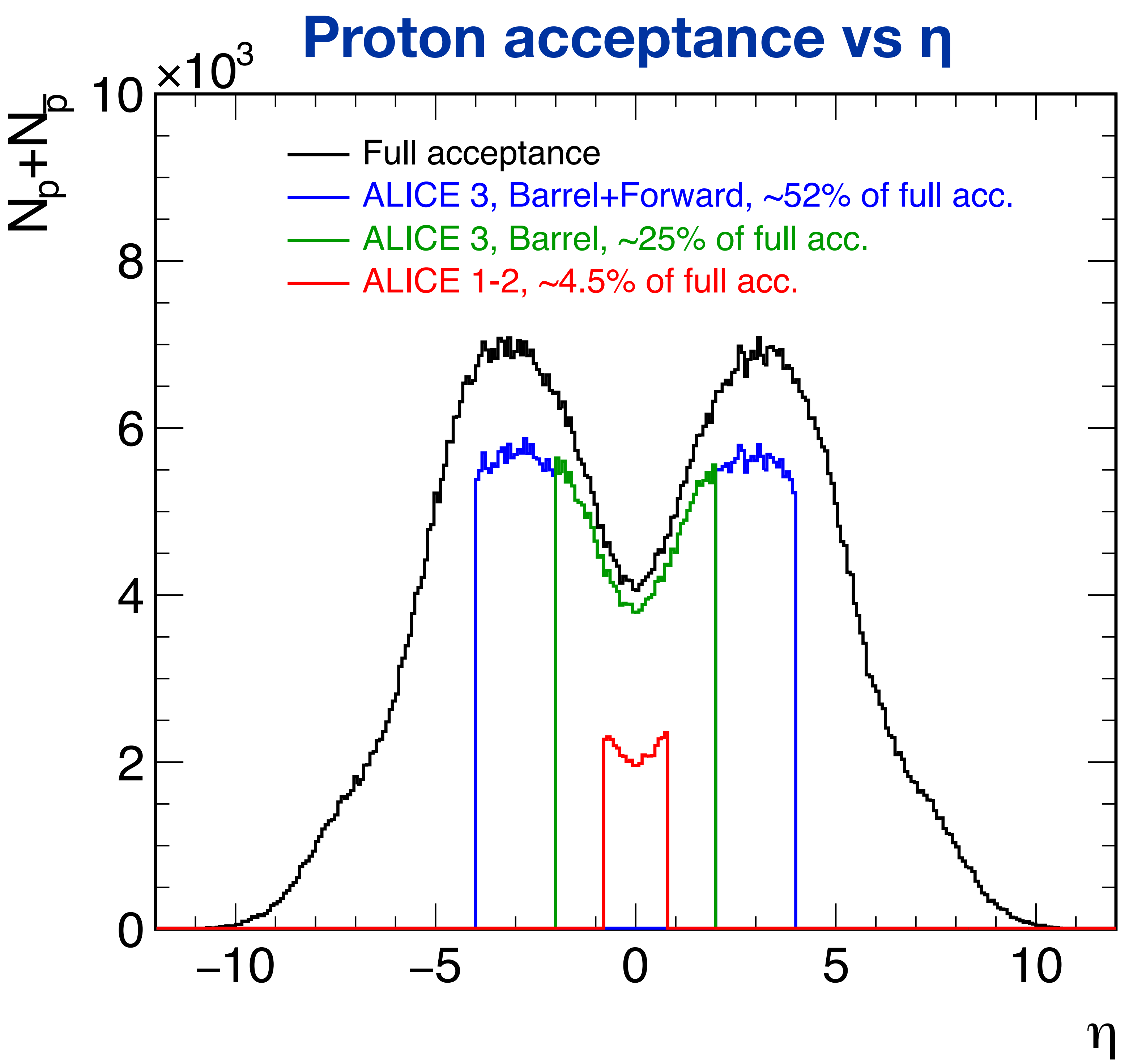


- Study interaction between hadrons trough momentum correlation
- Carries information about existence of bound states

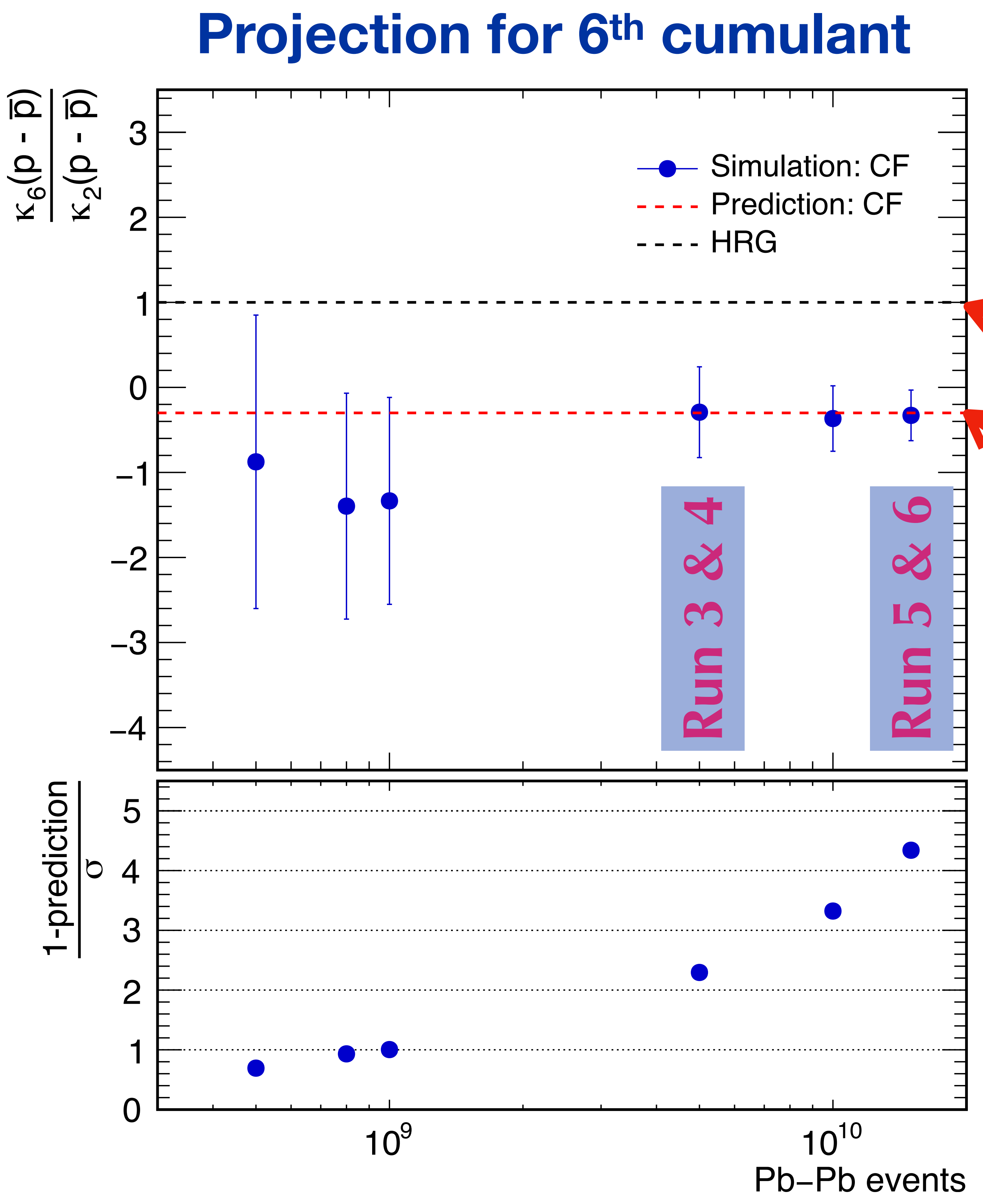
- Characteristic sign-change between pp and Pb-Pb in case of bound T_{cc} state
- Effect clearly visible within experiment precision

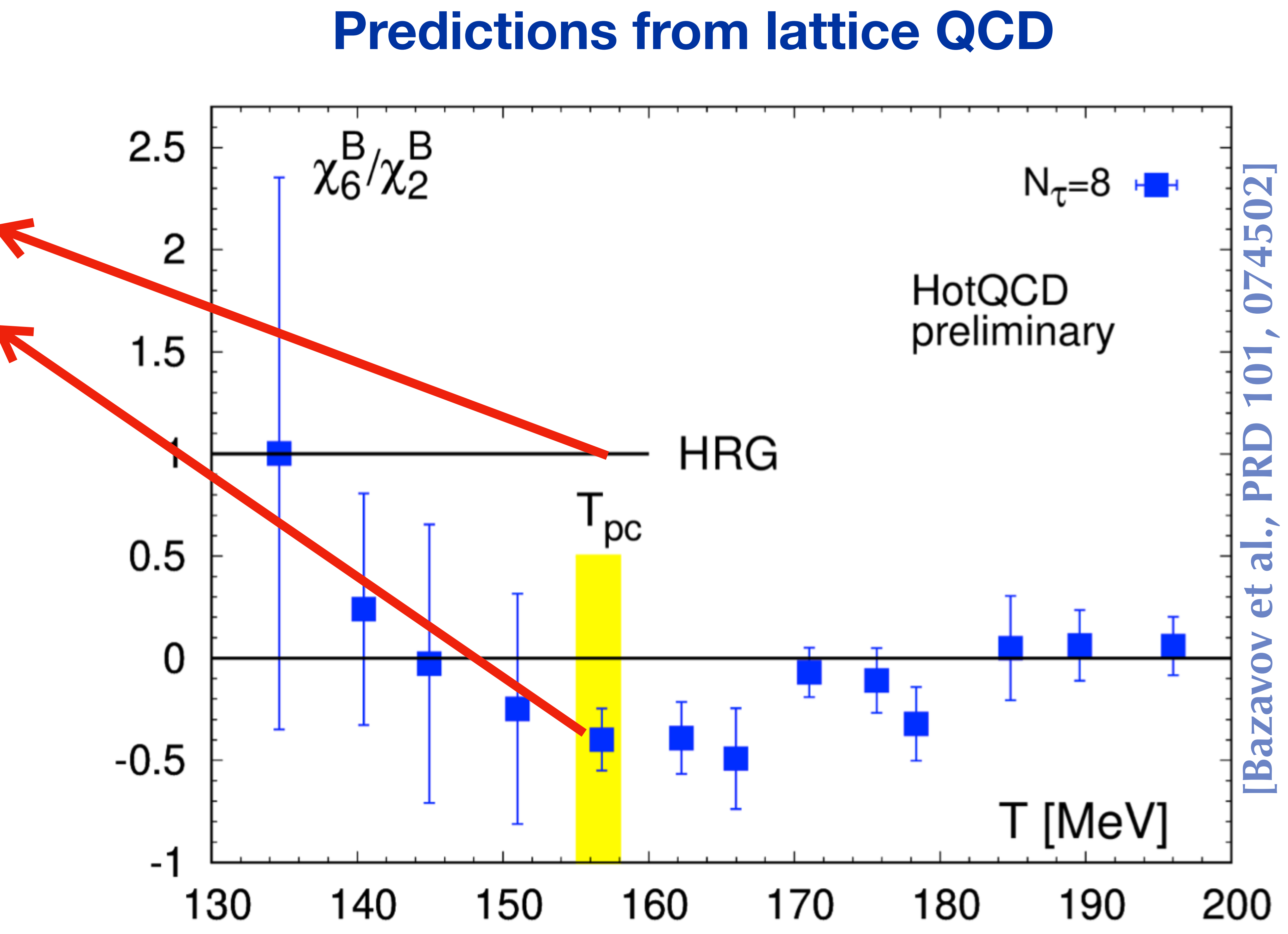
Susceptibilities

- **Comparison of critical behaviour with lattice QCD predictions**
  → measurements of net-baryon fluctuations (cumulants κ_n)
  → excellent particle identification over large acceptance



Run 3 & 4: limited Eff. x Acc.
Run 5 & 6: large Eff. x Acc.





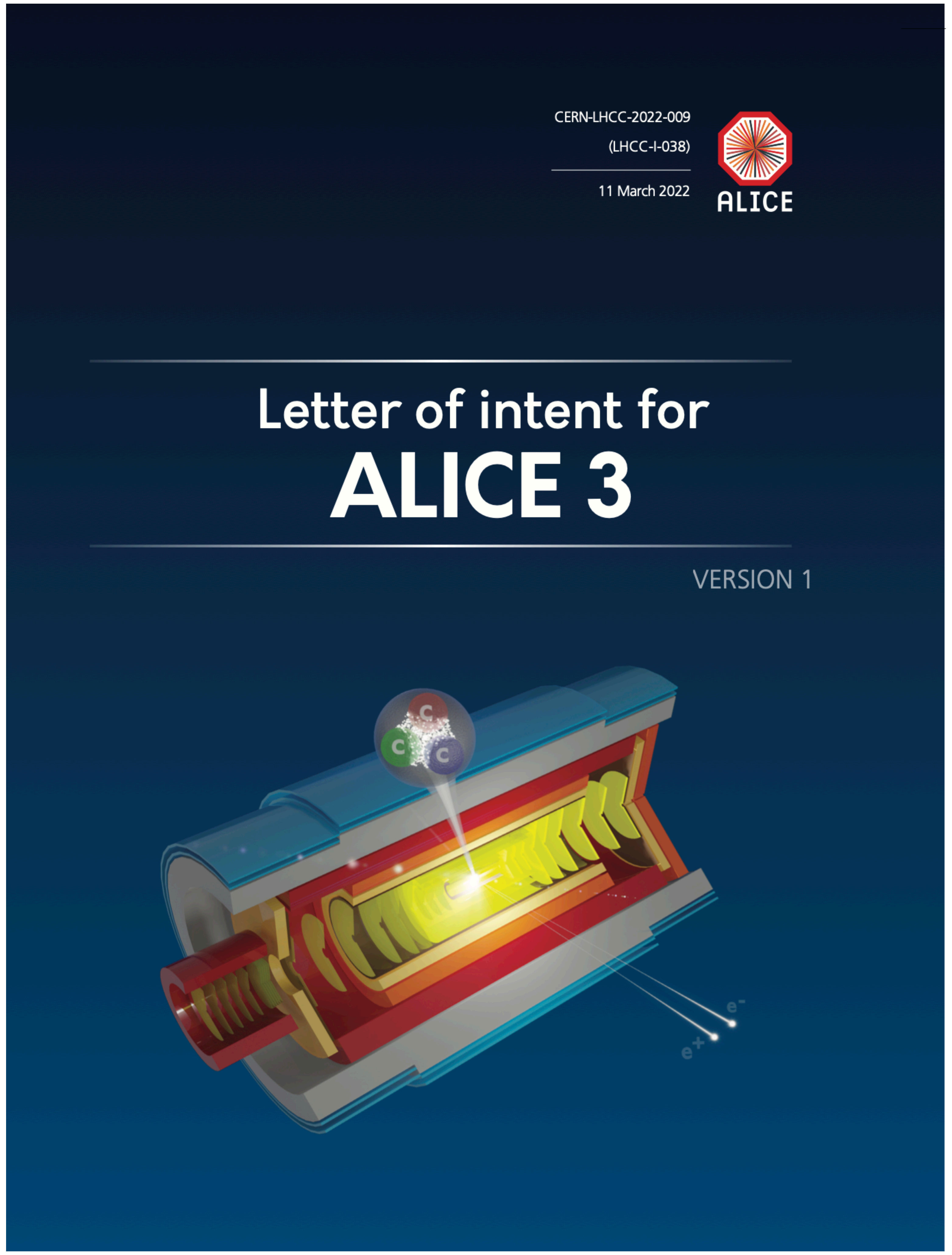
Summary

ALICE 3 status

- Review of **Letter of Intent** concluded in March 2022 with **positive evaluation** [LHCC-149]
  - exciting physics program
  - detector well matched with physics program
  - strategically interesting R&D opportunities

- Review of **scoping document** concluded in March 2025 with positive evaluation

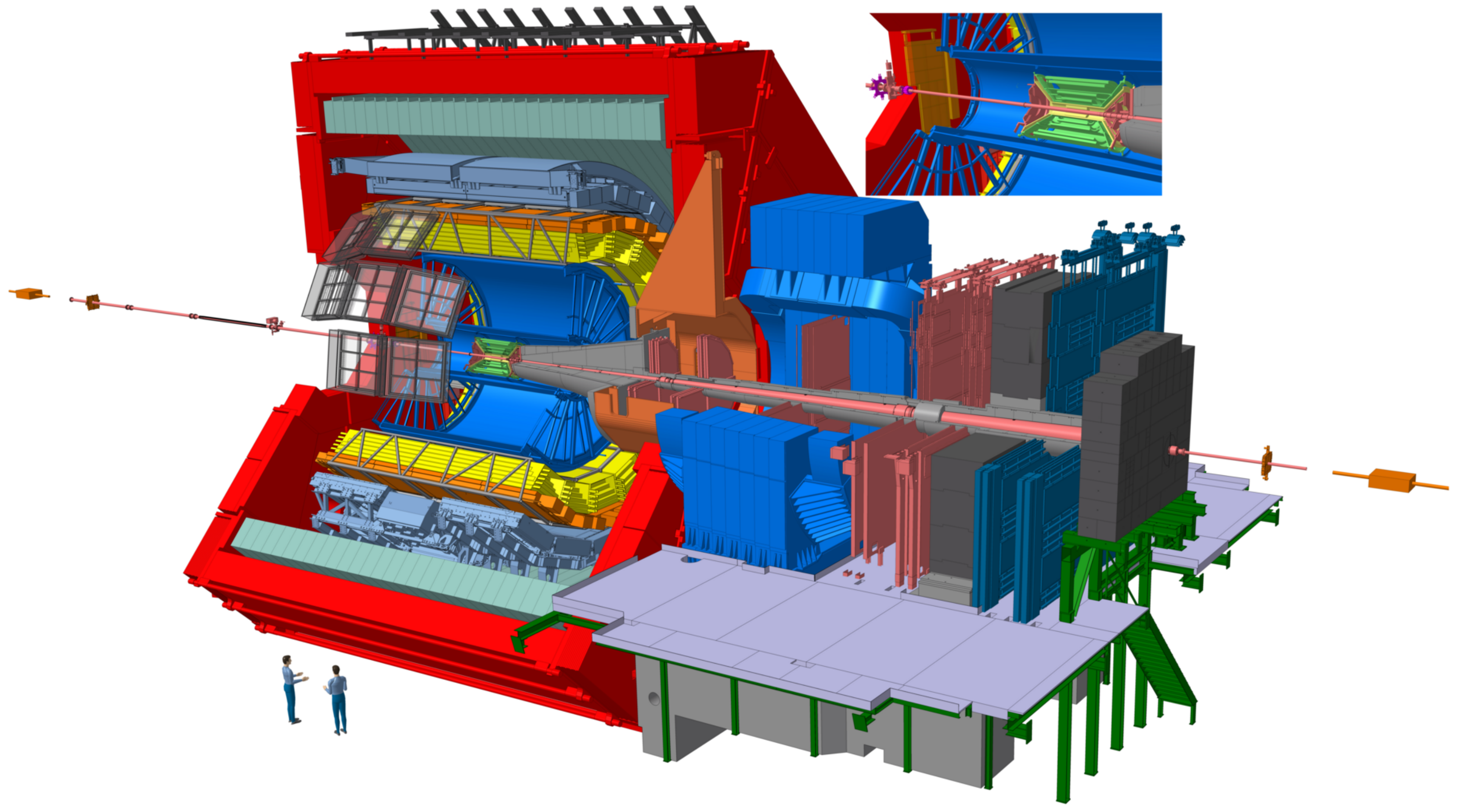
- R&D towards **Technical Design Reports**



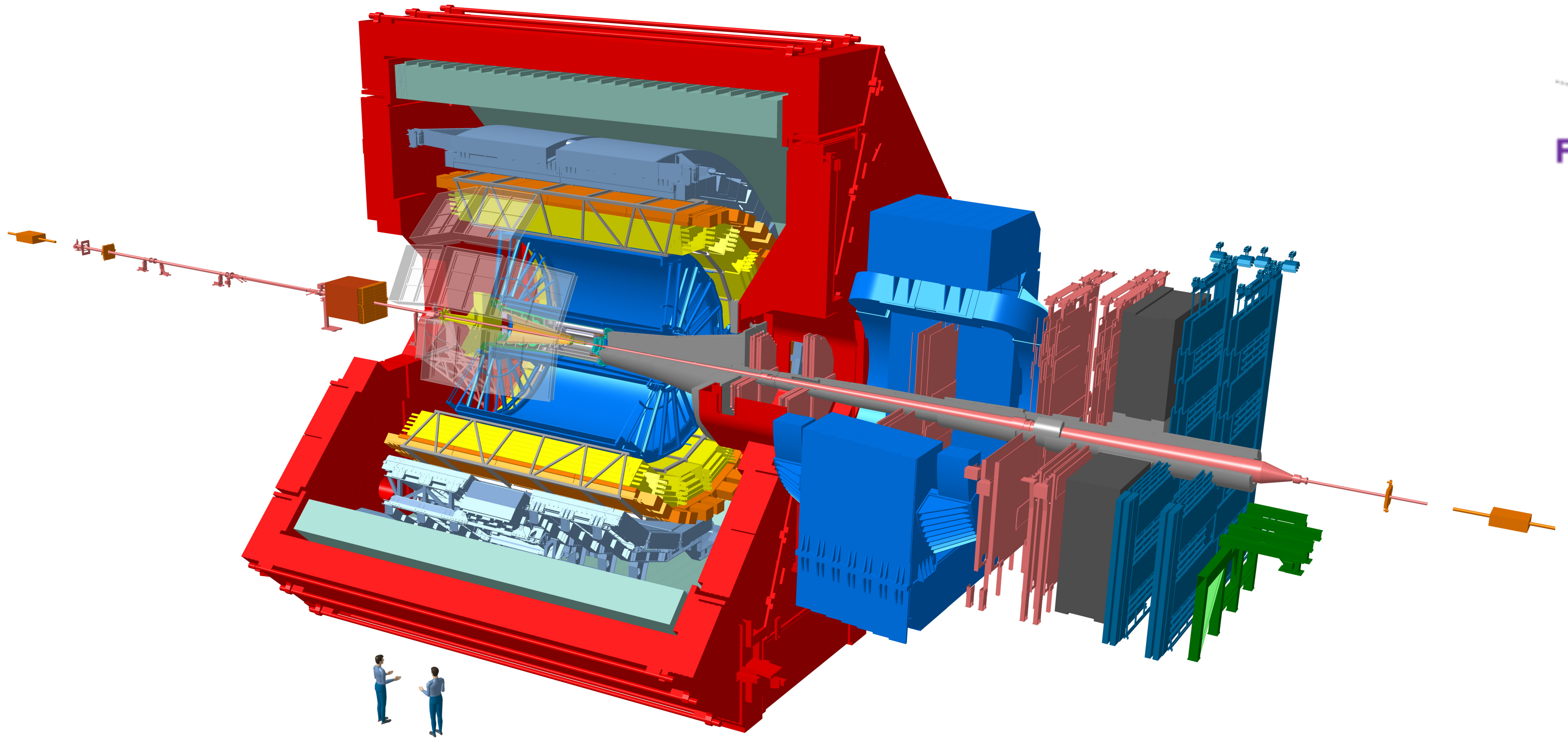
[CERN-LHCC-2022-009]

Timeline

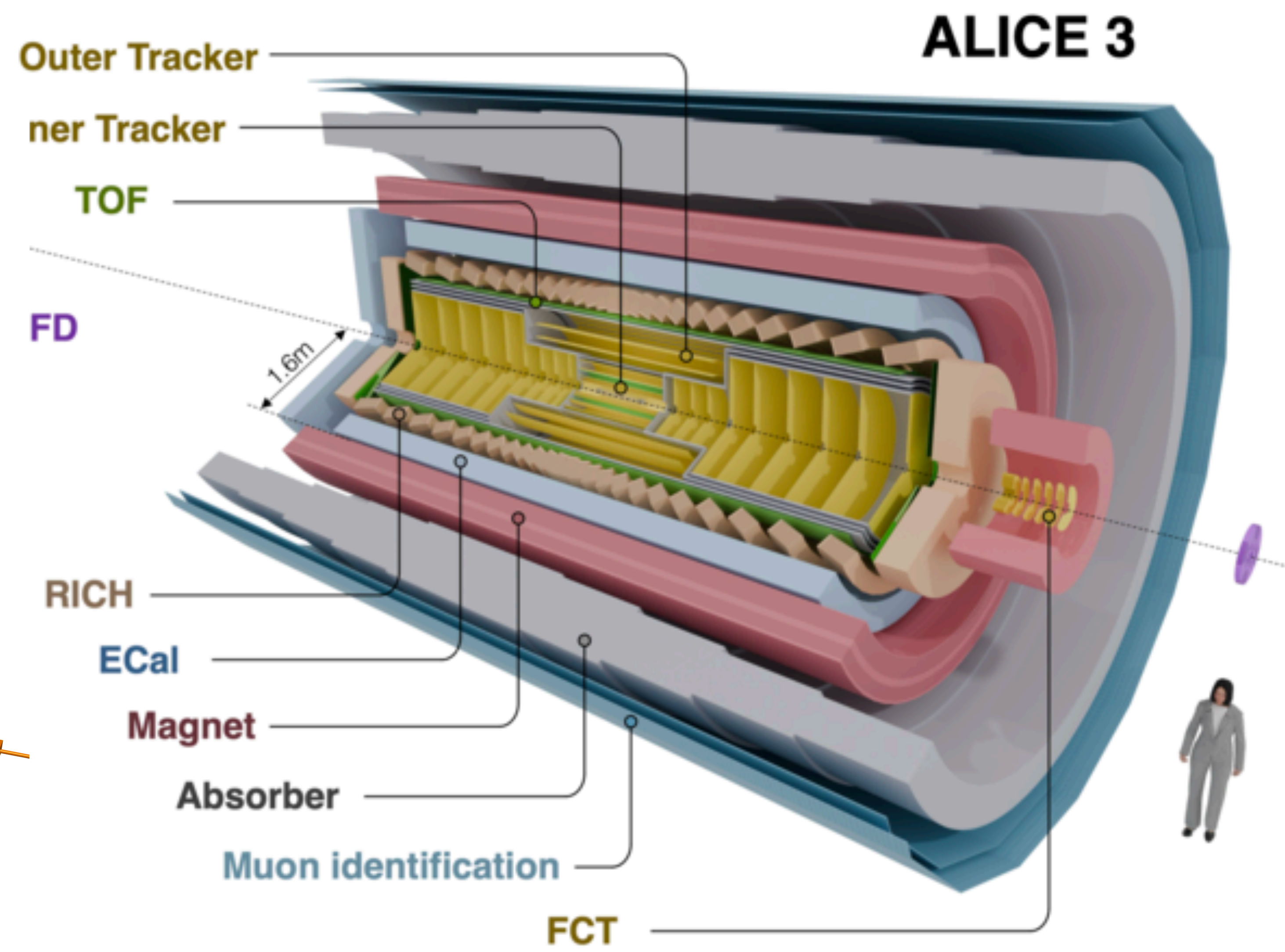
ALICE 1



ALICE 2



ALICE 3



TDRs for ALICE 2 | Construction of ALICE 2 | Installation of ALICE 2 | TDRs for ALICE 3 | Construction of ALICE 3 | Installation of ALICE 3

ALICE 1 | ALICE 2 | ALICE 2.1 | ALICE 3

LHC Run 1 | LHC LS1 | LHC Run 2 | LHC LS2 | LHC Run 3 | LHC LS3 | LHC Run 4 | LHC LS4 | LHC Run 5

2012 2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033 2034 2035 2036 2037 2038

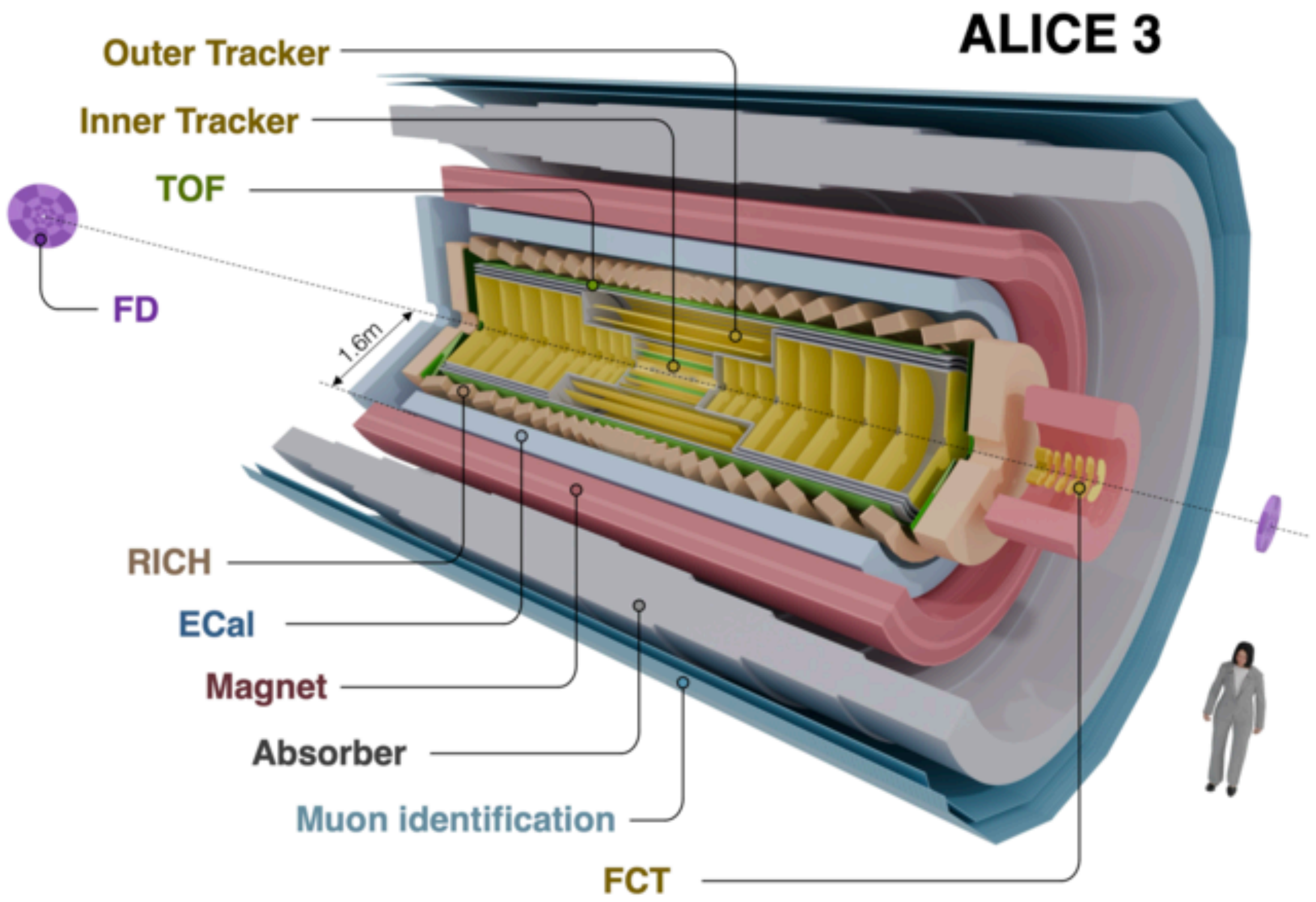
Summary part 2

- **Long-term heavy-ion programme at the LHC** (Run 5)
  → full exploitation of physics potential
- **Novel detector concept with ALICE 3**
  → innovative R&D in strategic areas of general relevance

Time for discussion 😊

Conclusions

- **Exciting physics perspectives with ALICE 2** (Run 3 & 4)
  → high-luminosity era for ions
- **Novel detector concept with ALICE 3**
  → innovative R&D in strategic areas of general relevance
- **Long-term heavy-ion programme at the LHC** (Run 5)
  → full exploitation of physics potential



Thank you
for your attention!

Backup

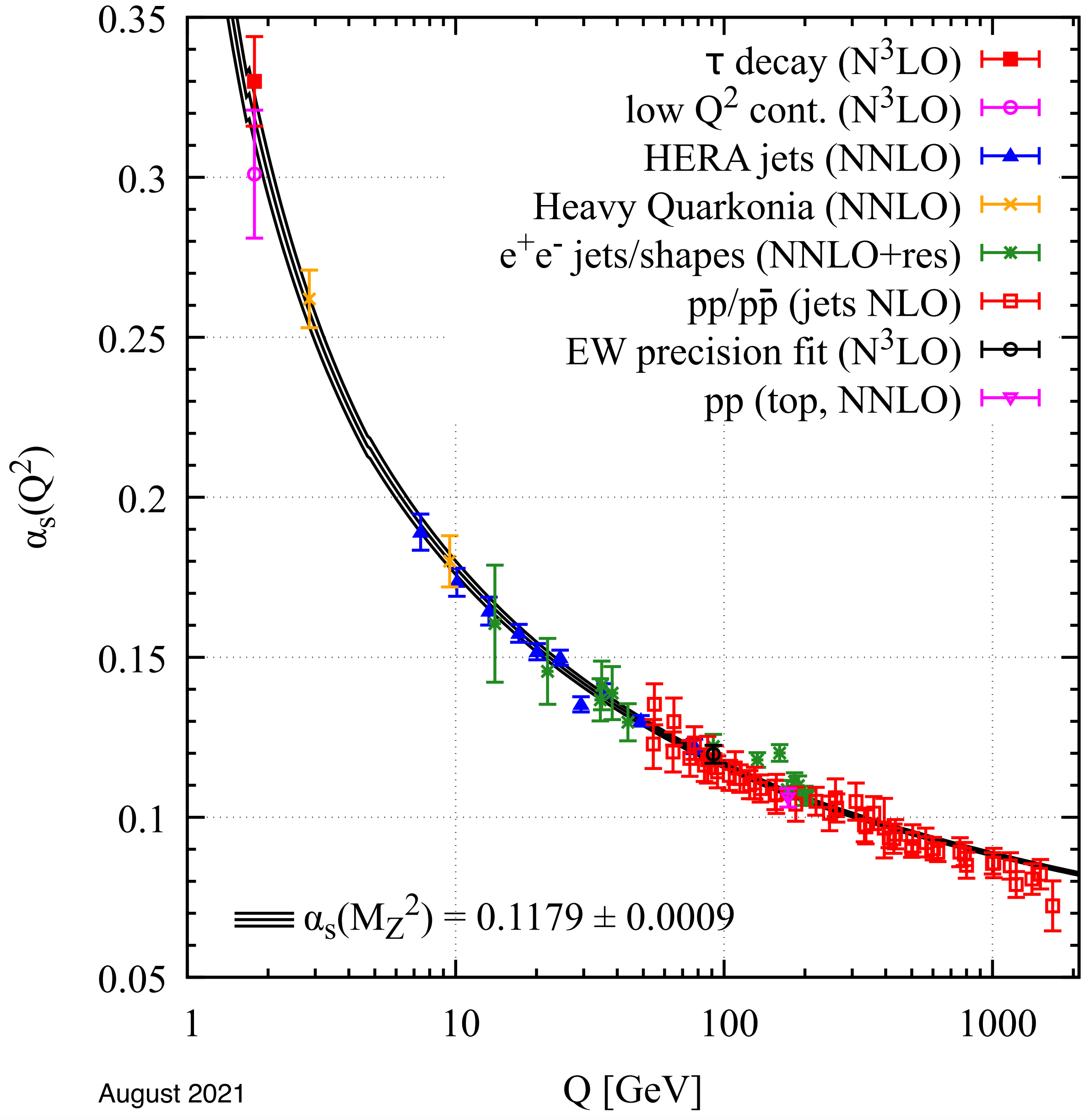
Quantum Chromodynamics

Lagrangian of **Quantum Chromodynamics** → strong interaction

$$\mathscr{L}_{\mathrm{QCD}} = \overline{\psi}_i \left(i\gamma^\mu \left(D_\mu \right)_{ij} - m\delta_{ij} \right) \psi_j - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a$$

- **Interactions with high Q² well described by perturbative calculations**
- **Many non-trivial features of QCD emerge from low-Q² regime**
  - confinement → no free quarks
  - chiral symmetry breaking → nucleon mass
  - fragmentation → formation of hadrons
  - QCD matter → thermodynamic properties

Emerging features of QCD of fundamental interest

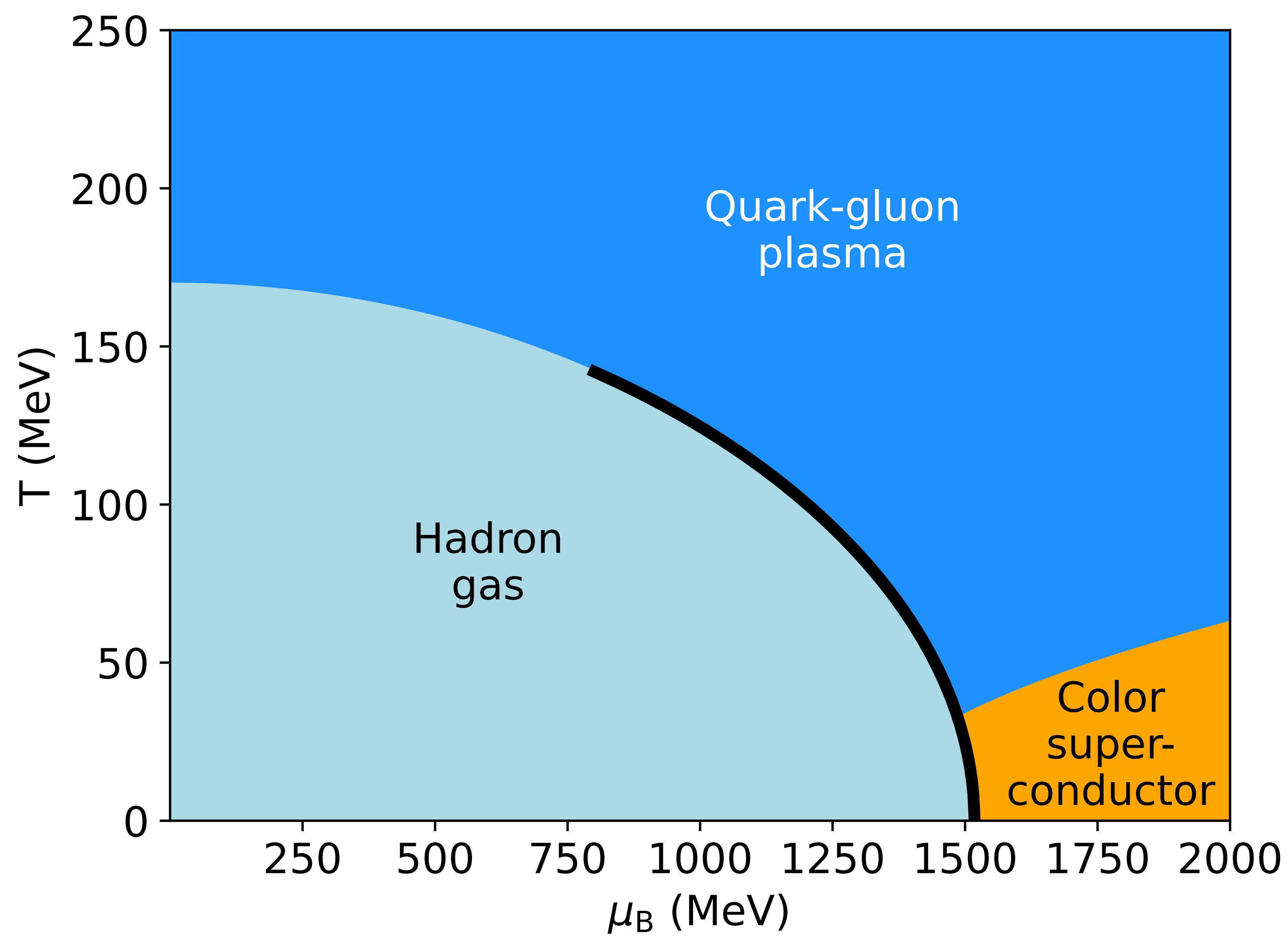


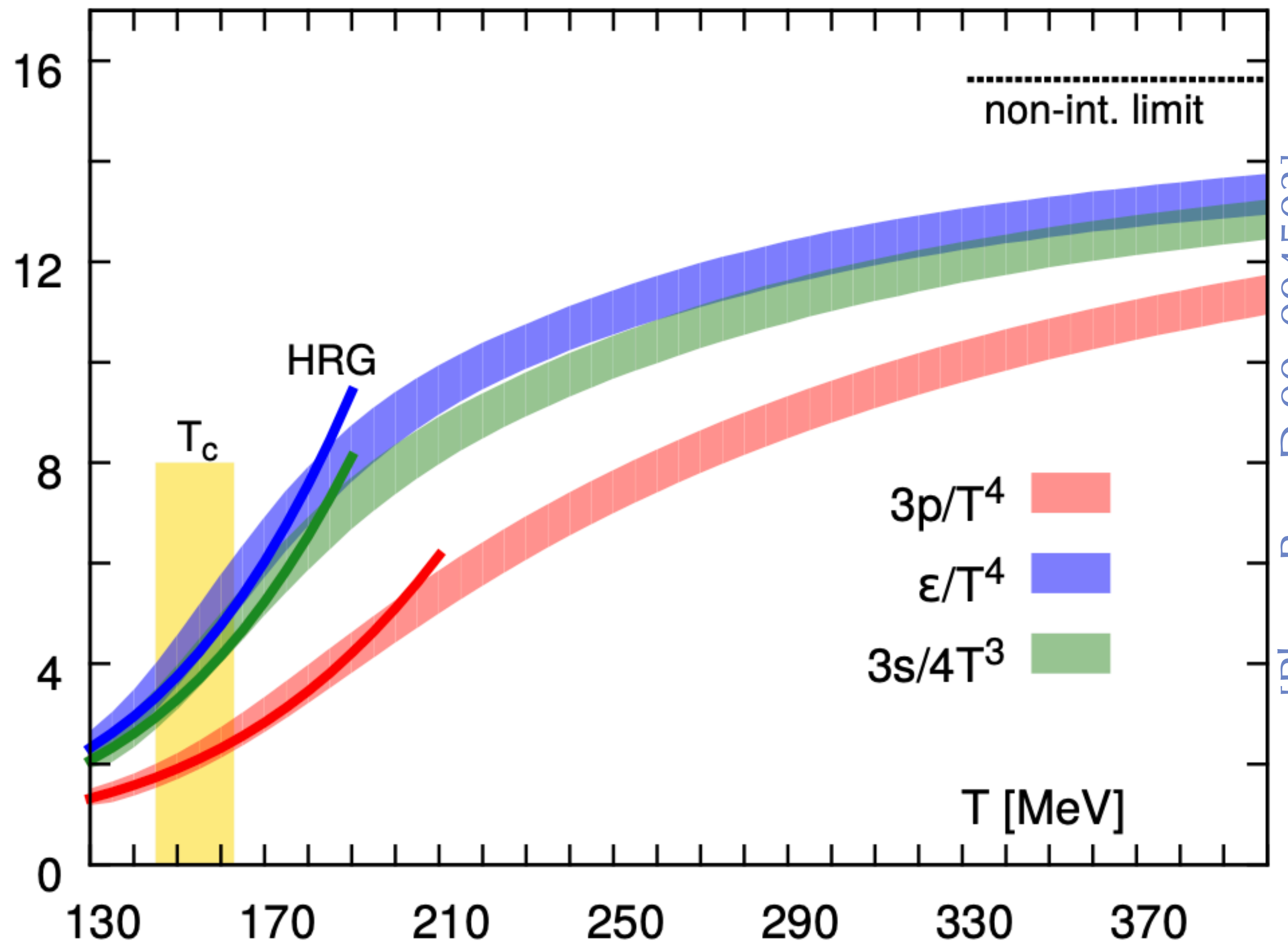
[R.L. Workman et al. (Particle Data Group), Prog. Theor. Exp. Phys. 2022, 083C01 (2022)]

QCD matter

- **Nuclear matter** → QCD matter at ambient conditions
- **QCD matter at different temperatures T and densities μ_B**
  - **deconfinement** for $T \to \infty$, $\mu_B \to \infty$
  - **chiral symmetry restoration**
  - **superconductivity**
- Numerical calculations of **QCD on a discretised lattice**
  - **cross-over** from hadron gas to quark-gluon plasma around pseudo-critical temperature T_{pc}
  - **interactions still relevant for $T \gg T_{pc}$**

Experimental data crucial to understand QCD matter

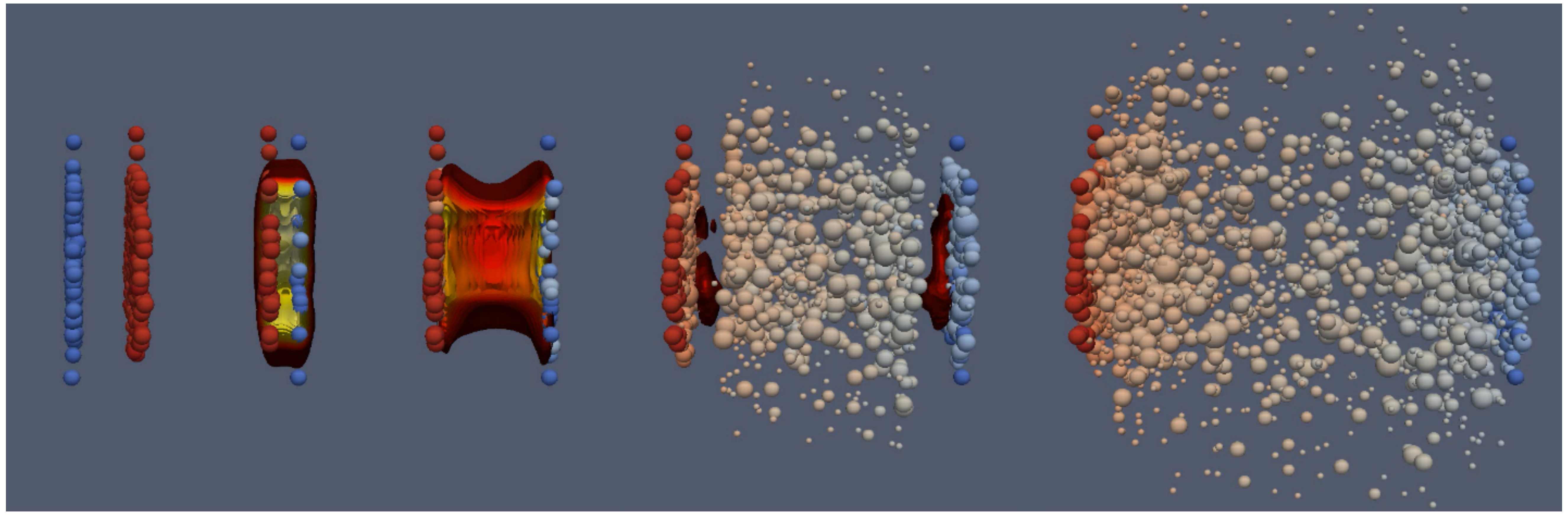




[Phys. Rev. D 90, 094503]

Nuclear collisions

- Ultra-relativistic collisions of nuclei
  → **hot and dense nuclear matter**
  - **deconfinement** of nuclear matter
    to quark-gluon plasma and back
  - **small, short-lived, dynamic system**
  - **self-generated probes**
    from all stages of the evolution
  - conditions controlled through
    collision energy and geometry



[MADAI collaboration]

Electromagnetic radiation ($\propto T^2$)

Hadron momentum distributions, azimuthal anisotropy

Hadron abundances ‘hadrochemistry’

Hadron correlations, fluctuations

Ultra-relativistic heavy-ion collisions
→ **excellent means to study hot QCD matter**

LHC experiments

Collision systems

	Run 1	Run 2	Run 3	Run 4	Run 5
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
LHC schedule	Run 1 2009 - 2013	Run 2 2015 - 2018	Run 3 2022 - 2025	Run 4 2029 - 2032	Run 5 2035 - …

High luminosity for ions

HL-LHC

Higher luminosities for ions

ATLAS EXPERIMENT	ATLAS	ATLAS phase I upgrades	ATLAS phase II upgrades	
CMS	CMS	CMS phase I upgrades	CMS phase II upgrades	
LHCb	LHCb	LHCb upgrade I(a)	LHCb upgrade Ib	LHCb upgrade II
ALICE	ALICE 1	ALICE 2 upgrade	ALICE 2.1 upgrade	ALICE 3 upgrade

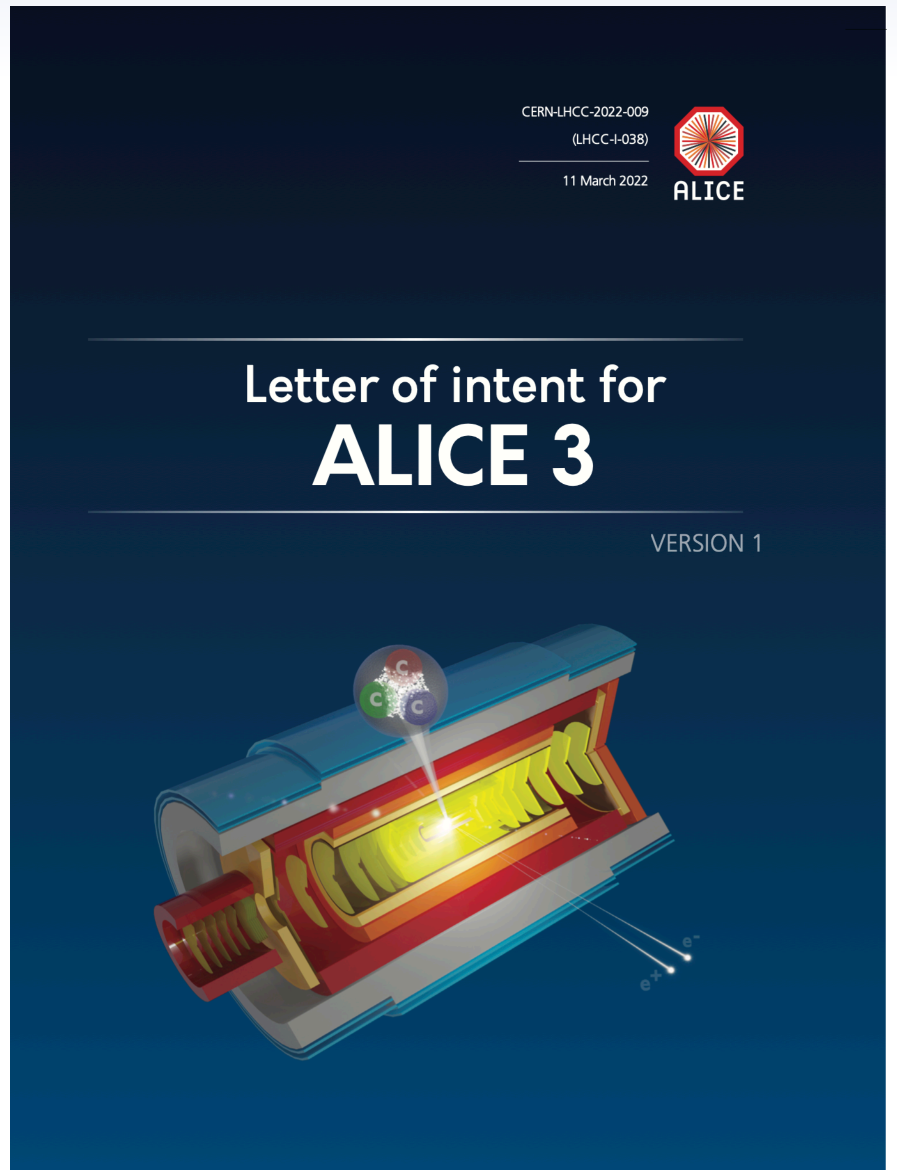
All large LHC experiments have (planned) upgrades improving the performance for heavy-ion collisions

intermediate upgrade

major upgrade

Heavy ions at the LHC

- **Various collision systems at highest energies $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$**
  → QCD matter with
  - highest energy density (> 12 GeV/fm³) and temperature (≳ 300 MeV)
  - longest lifetime (≳ 10 fm/c)
  - largest heavy-flavour yields (~200 c/c̄ in central Pb-Pb collision)
  - vanishing net-baryon density ($\mu_B \approx 0$)



[CERN-LHCC-2022-009]
[arXiv:2211.02491]

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
LHC schedule	Run 1 2009 - 2013	Run 2 2015 - 2018	Run 3 2022 - 2025	Run 4 2029 - 2032	Run 5 2035 - …
ALICE	ALICE 1		ALICE 2	ALICE 2.1	ALICE 3

LHC provides **ideal and unique environment** to study hot QCD matter with heavy ions

intermediate upgrade | major upgrade

ALICE 2

Time Projection Chamber

- new readout chambers: MWPC → GEM

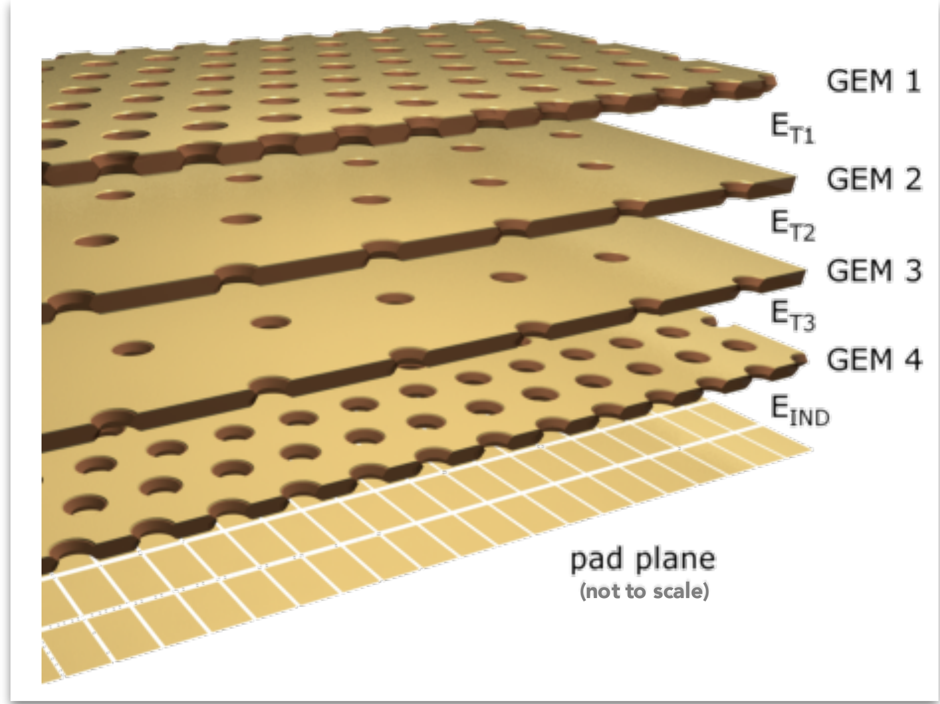
Consolidation and readout upgrade of all subsystems

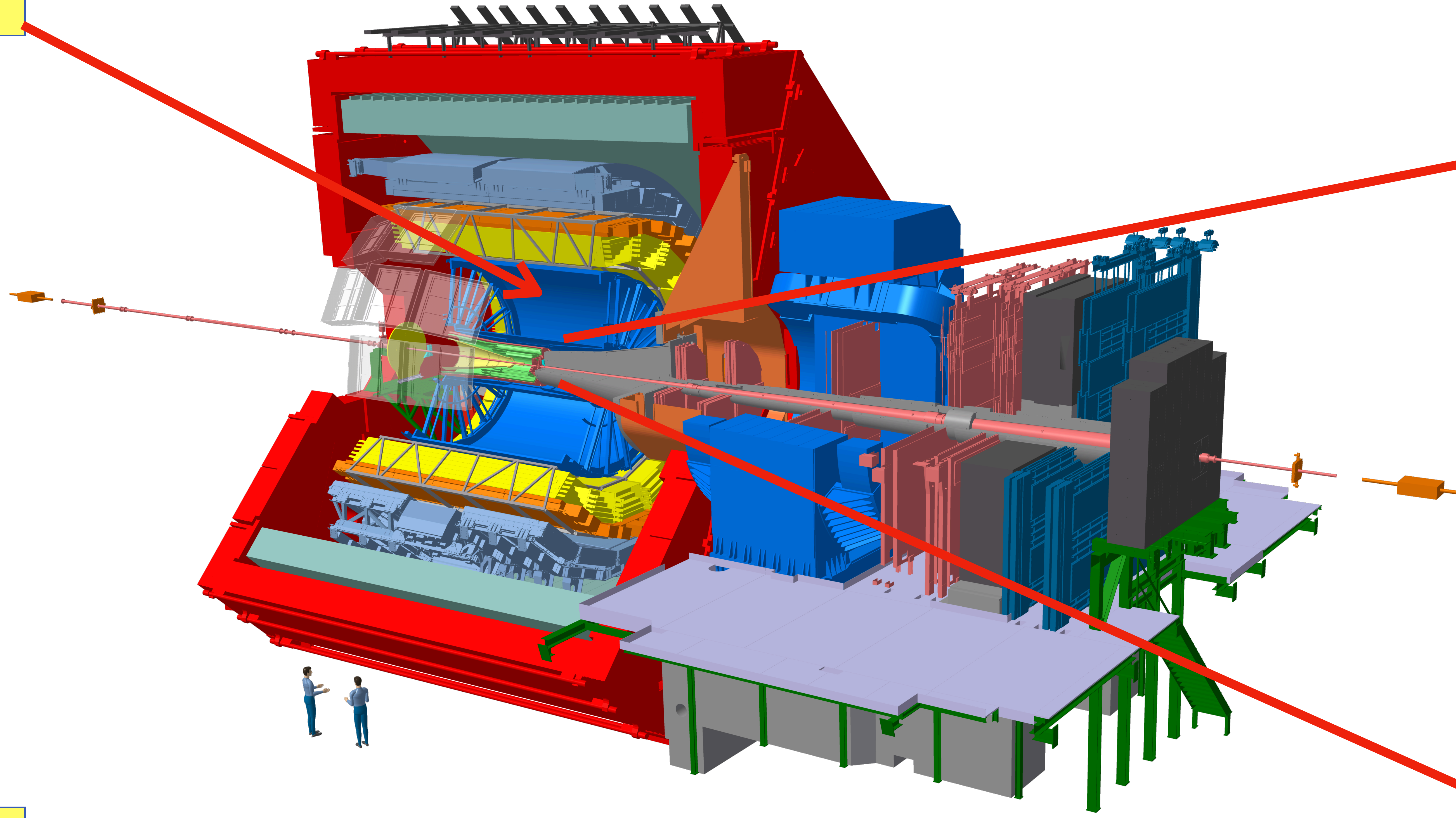
Fast Interaction Trigger

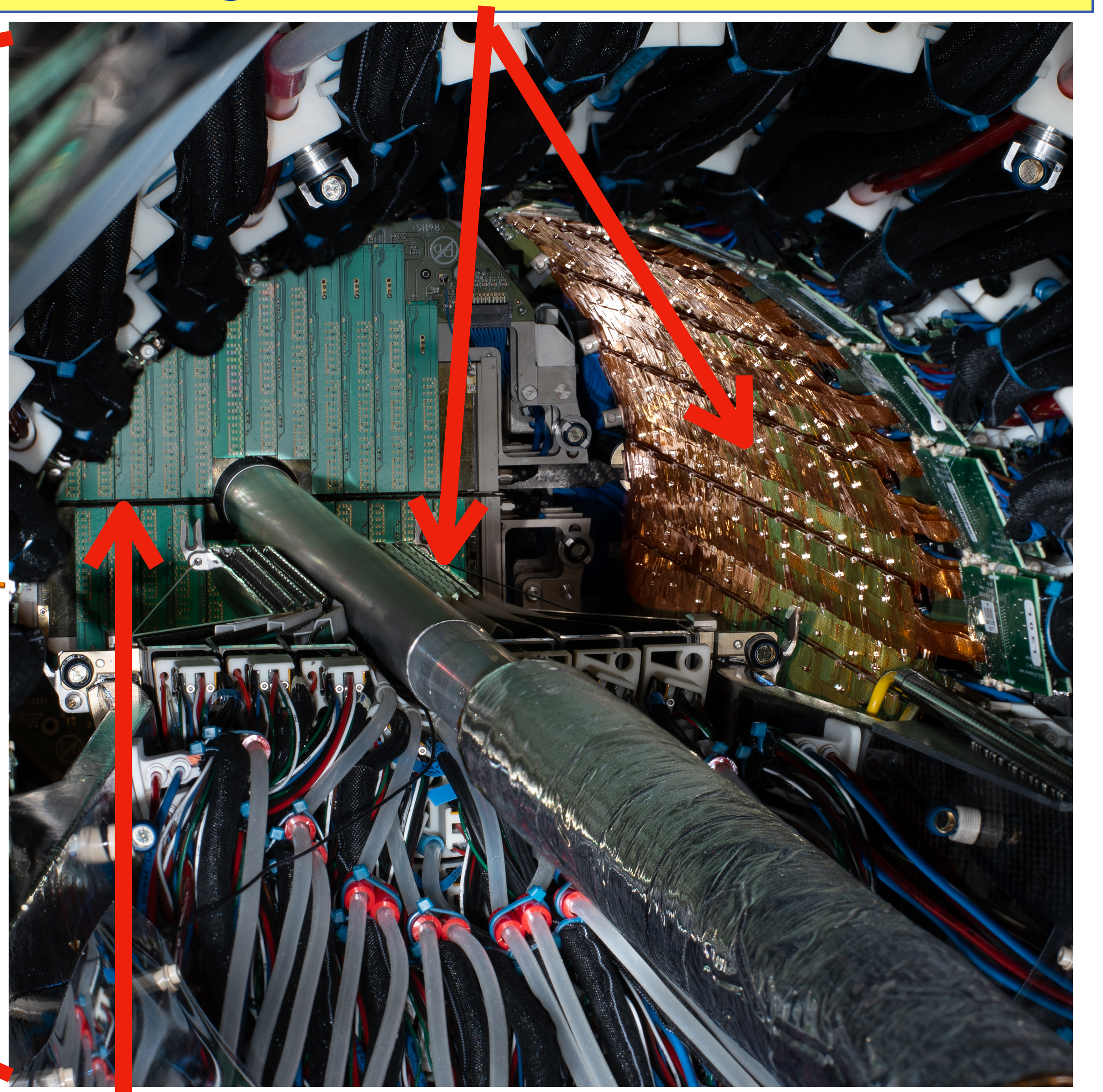
- new detectors

Inner Tracking System

- **3 + 2 + 2 layers of MAPS (~10 m², 12.5 Gpx)**
- improved vertexing at higher rates







Integrated on-/off-line system

- continuous readout
- GPU-based reconstruction parallel with data taking
- online event selection

New possibilities in Run 3
with continuous readout and improved vertexing

Muon Forward Tracker

- MAPS-based tracker installed
- vertexing in forward acceptance (muon arm)

ALICE 2.1

Time Projection Chamber

- new readout chambers: **MWPC → GEM**

Consolidation and readout upgrade of all subsystems

Fast Interaction Trigger

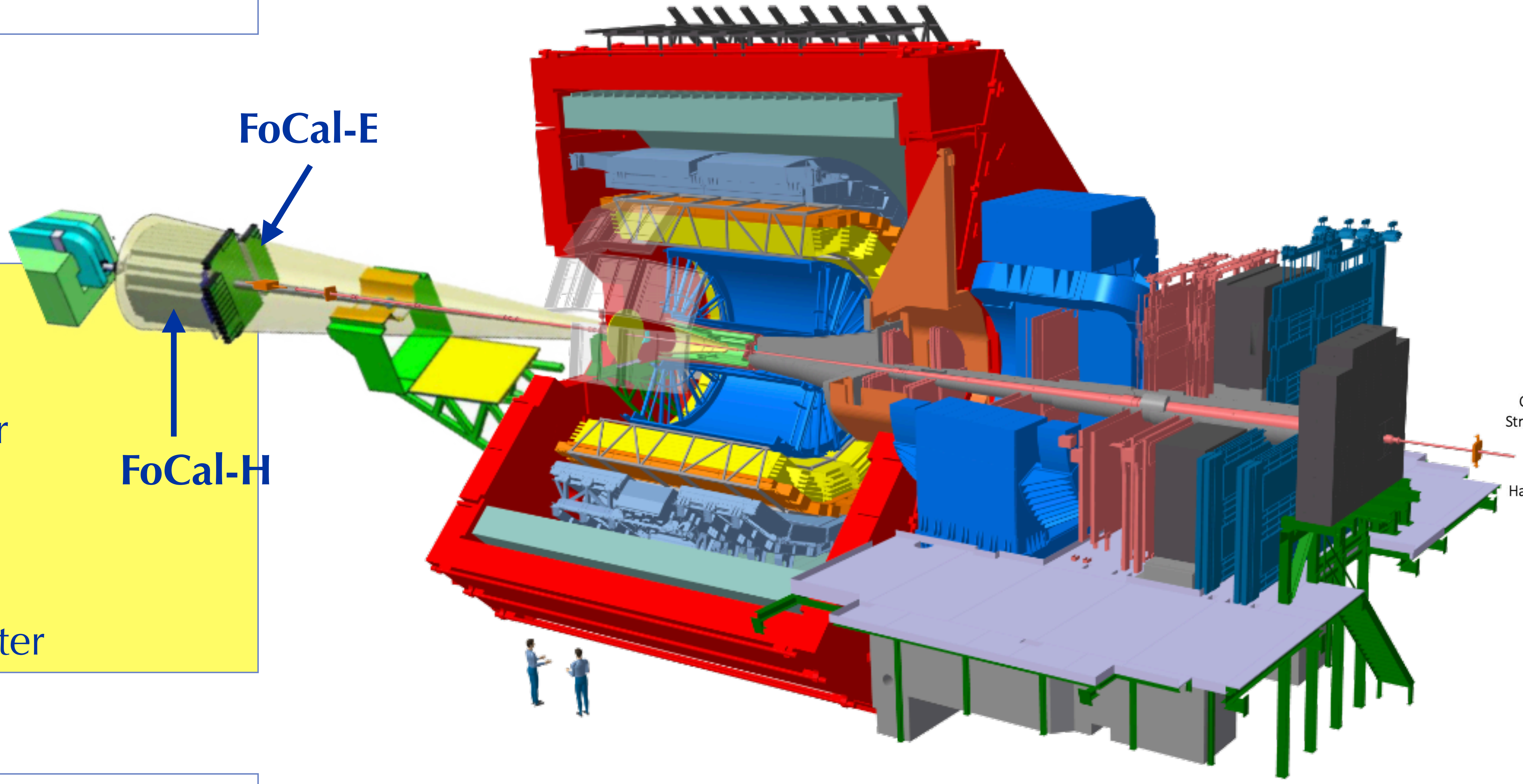
- new detectors

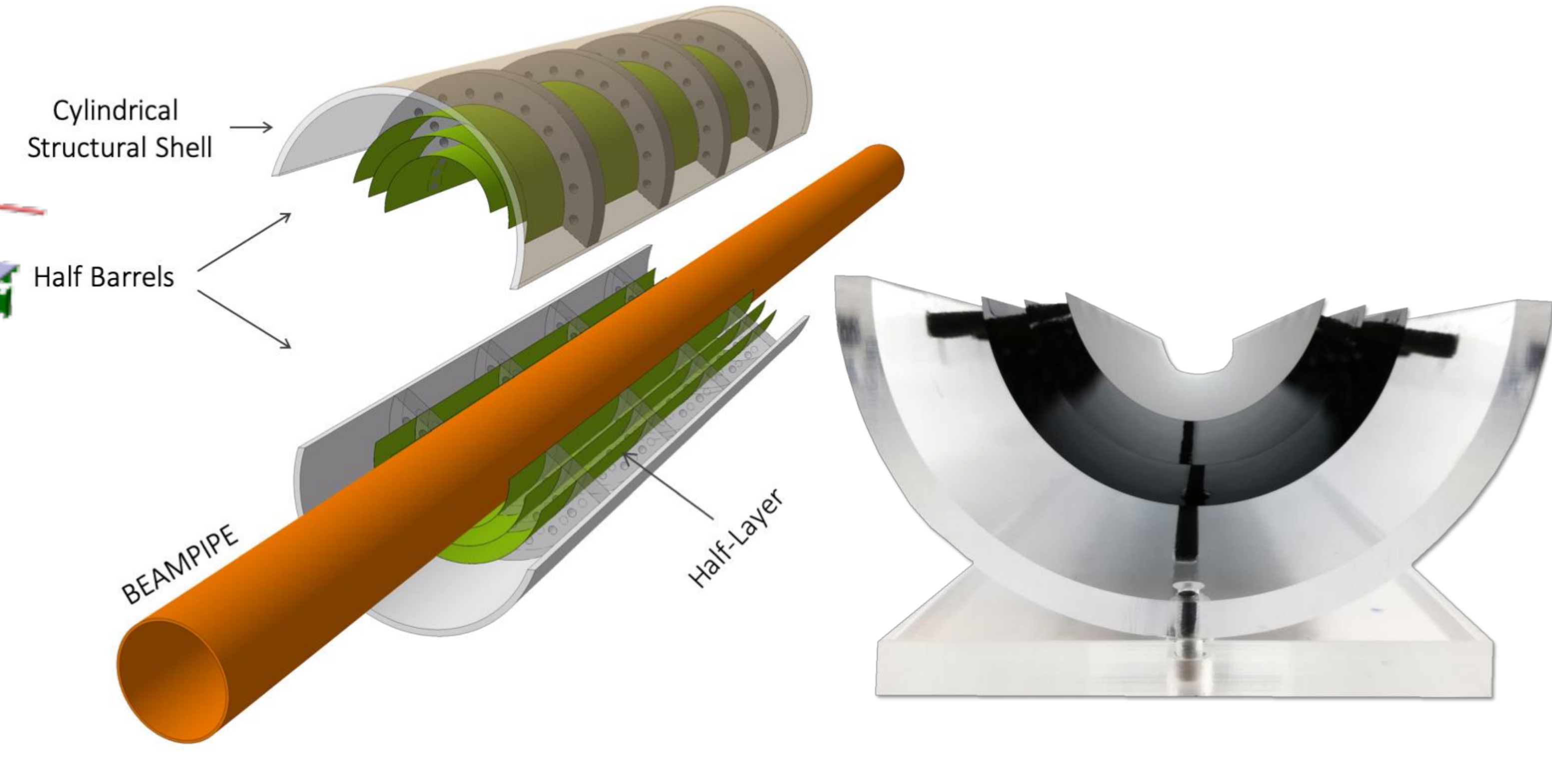
Inner Tracking System

- **3 + 2 + 2 layers of MAPS (~10 m², 12.5 Gpx)**
- improved vertexing at higher rates
- **ITS3 → Bent, wafer-scale monolithic pixel sensors for 3 innermost layers**

FoCal

- **FoCal-E**: Si-W high-granular elm. calorimeter
- **FoCal-H**: Cu-fibre hadronic calorimeter





Integrated on-/off-line system

- **continuous readout**
- **GPU-based reconstruction** parallel with data taking
- online event selection

Excellent R&D progress (towards TDRs)
→ **better vertexing, isolated photons**

Muon Forward Tracker

- **MAPS-based tracker** installed
- vertexing in forward acceptance (muon arm)

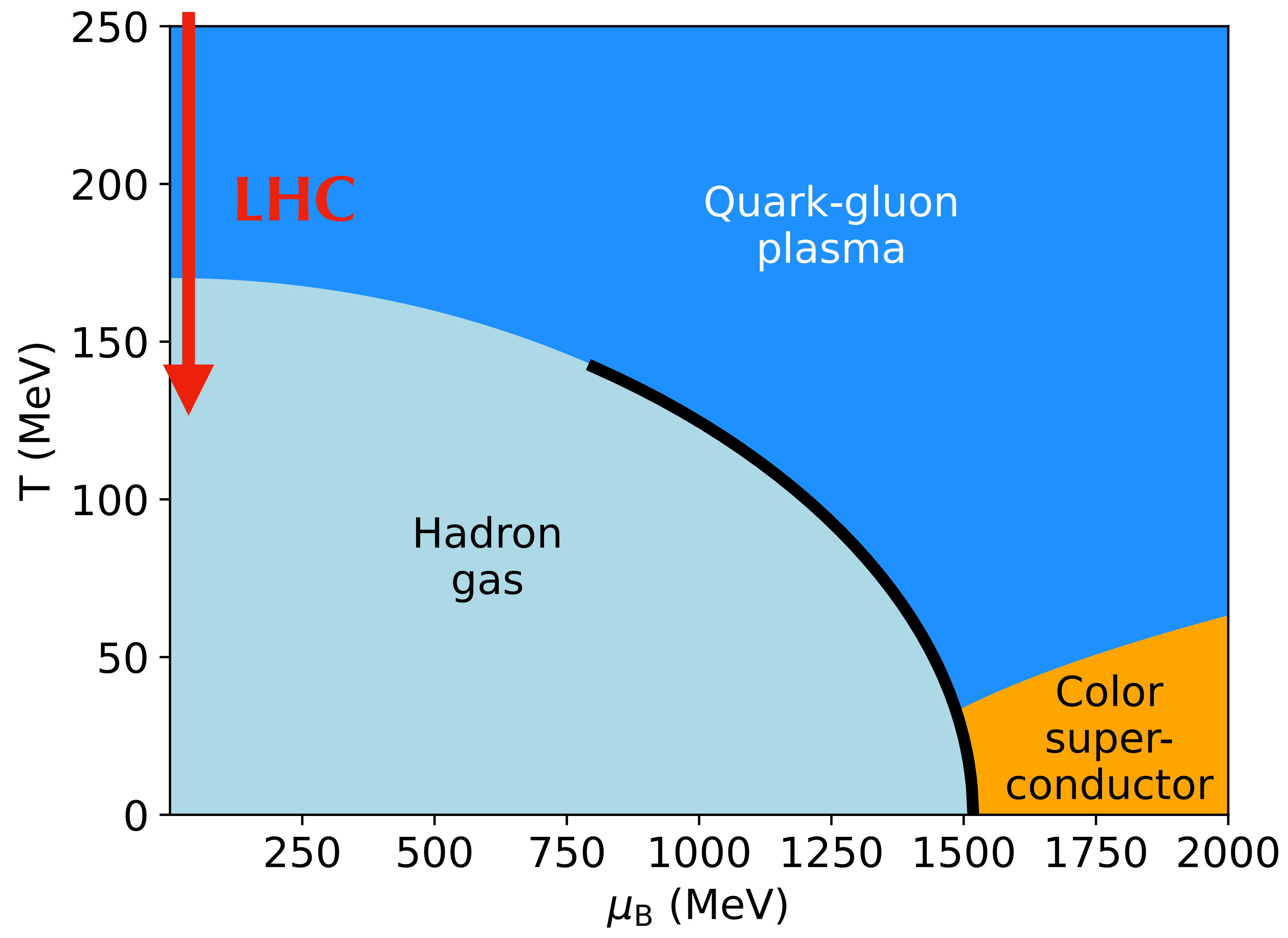
Quark-gluon plasma

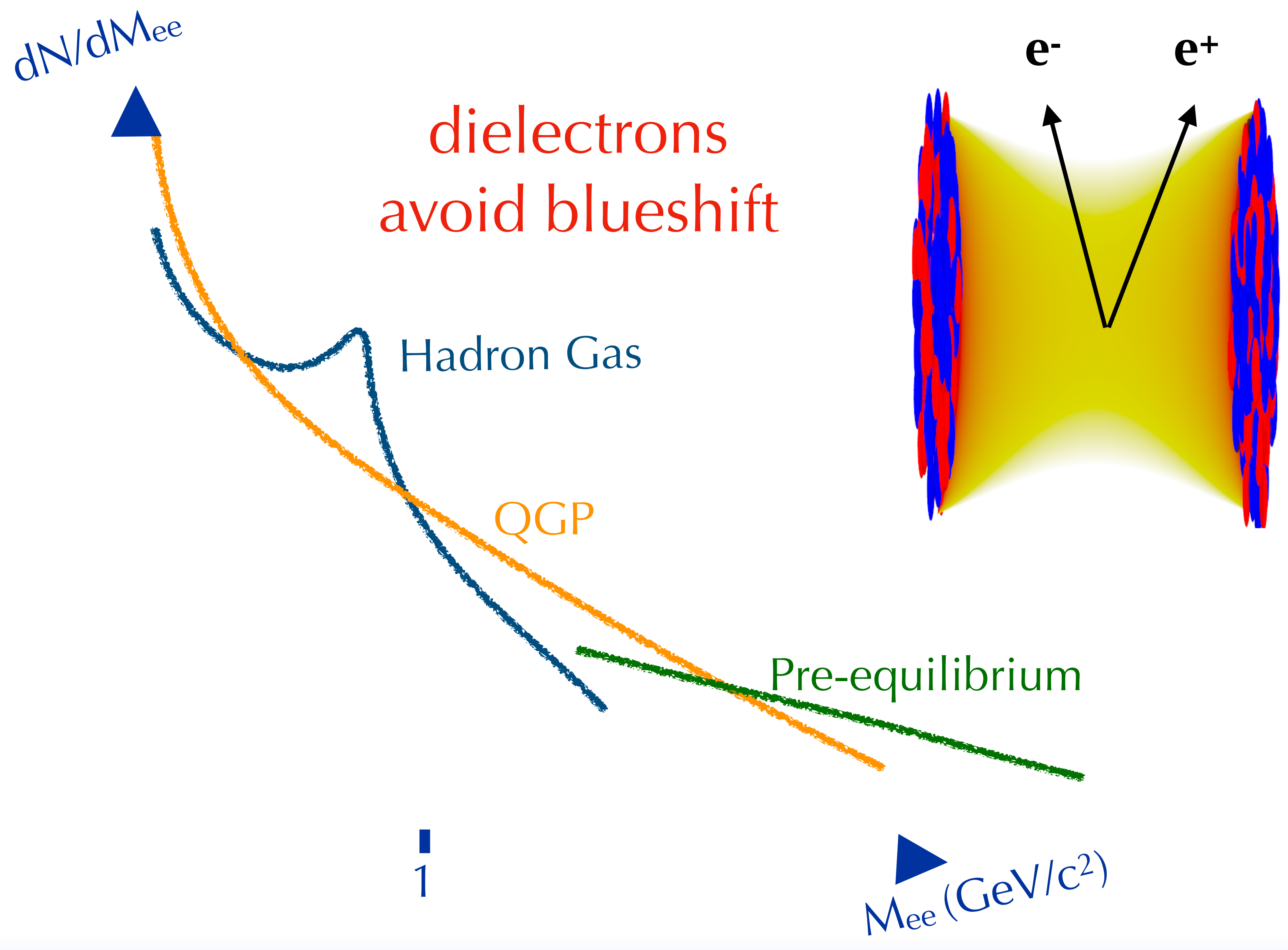
- **Consider QCD matter in heavy-ion collision → path in phase diagram**
  - kinetic energy → creation of quark-gluon plasma
  - expansion and cool down → hadron production

- **What is the initial temperature and how does it evolve?**
  → thermal spectra of photons and dileptons

- **What are the mechanisms for the restoration of chiral symmetry in the quark-gluon plasma?**
  → ρ-a_1 mixing → dileptons

- **What is the nature of the phase transition?**
  → critical behaviour → fluctuations (cf. lattice QCD)

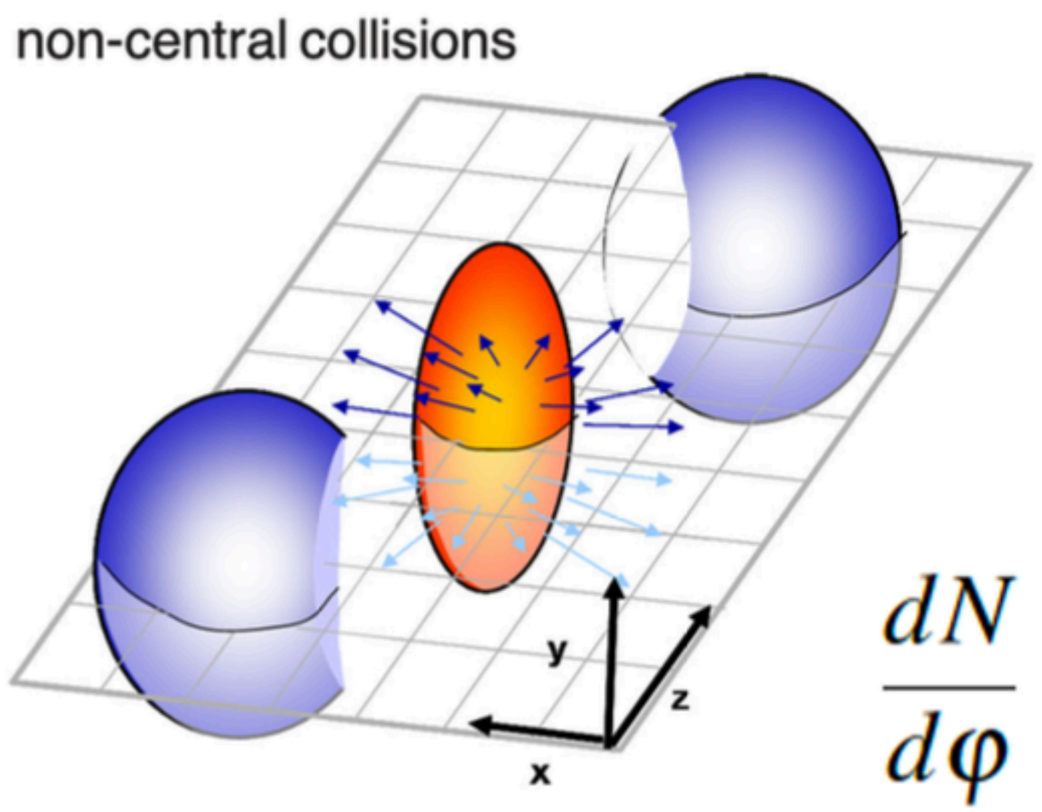


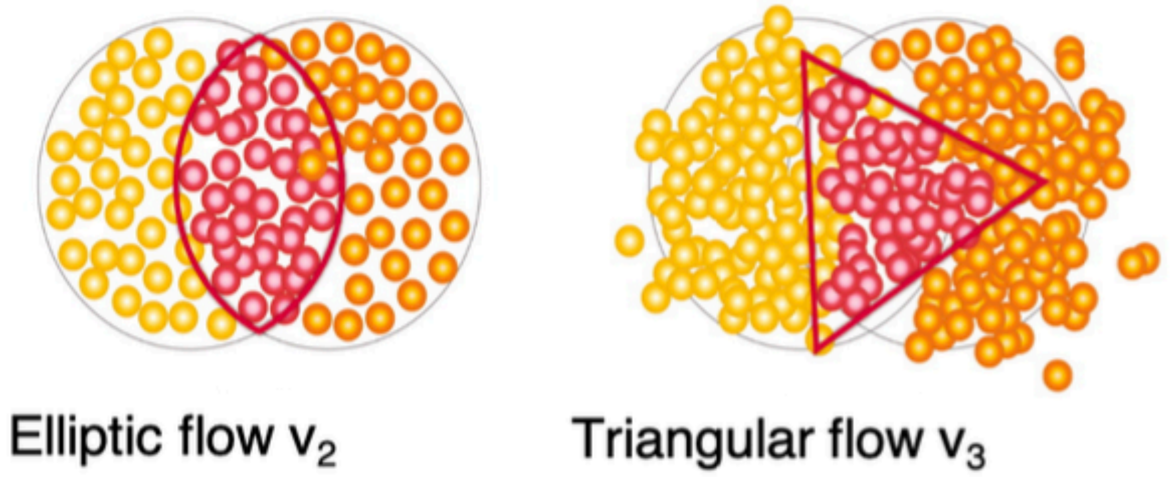


Interactions with QGP

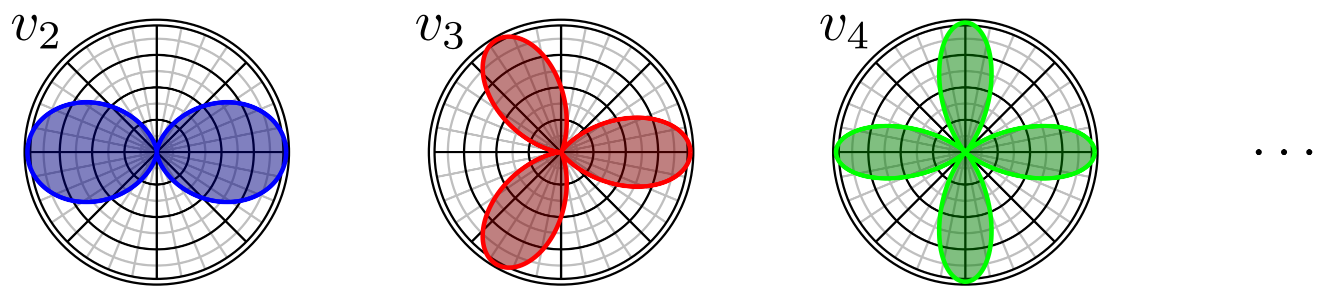
- **Consider QGP phase of a heavy-ion collision**
  - **quarks and gluons interact with the plasma**
  - **pressure-driven expansion**
    → viscous, relativistic hydrodynamics

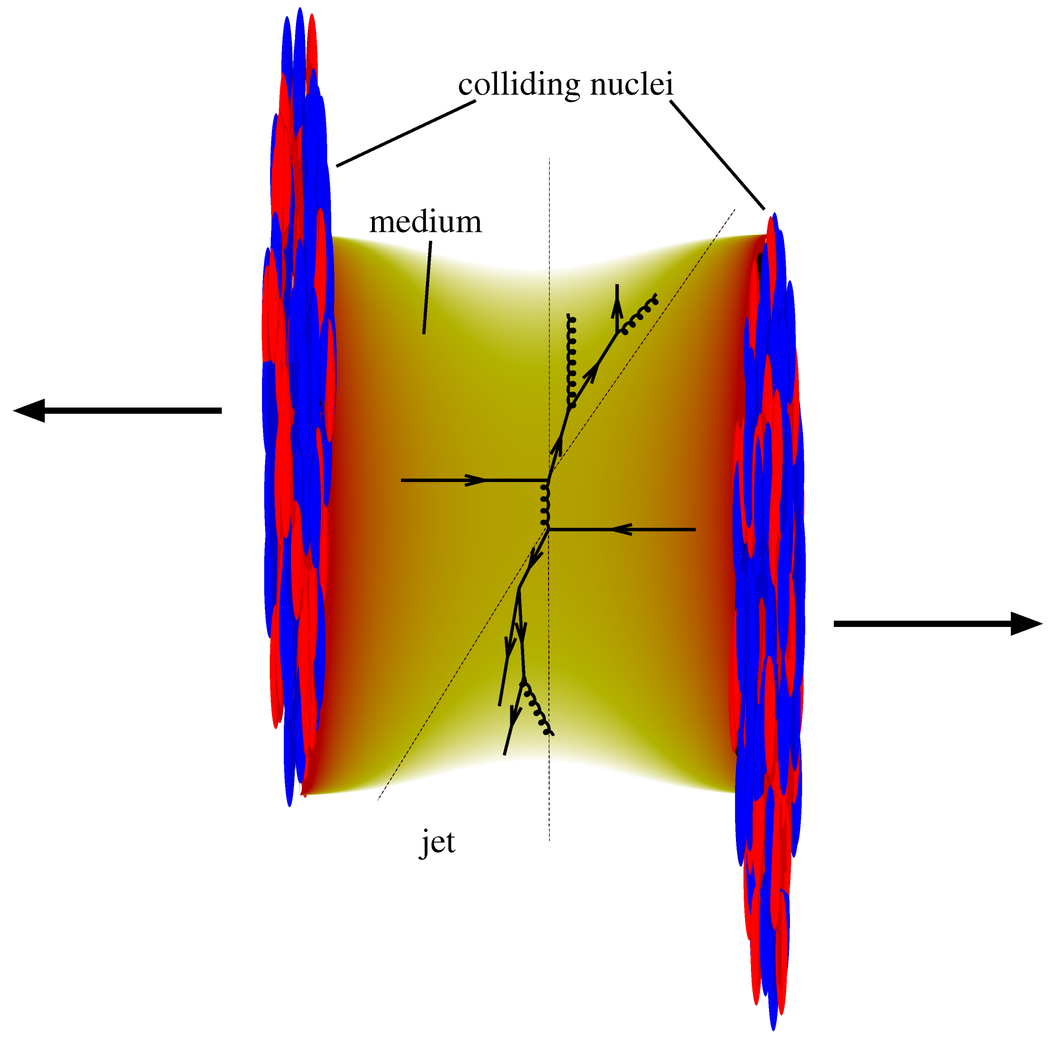
- **What is the nature of interactions between quarks and gluons and the quark-gluon plasma?**
  - mass dependence of medium interaction
    → charm and beauty jets
  - transport coefficients for charm and beauty
    → anisotropy (v_n) and suppression (R_{AA})
  - equilibration of charm and beauty
    → hadron yields and decorrelation

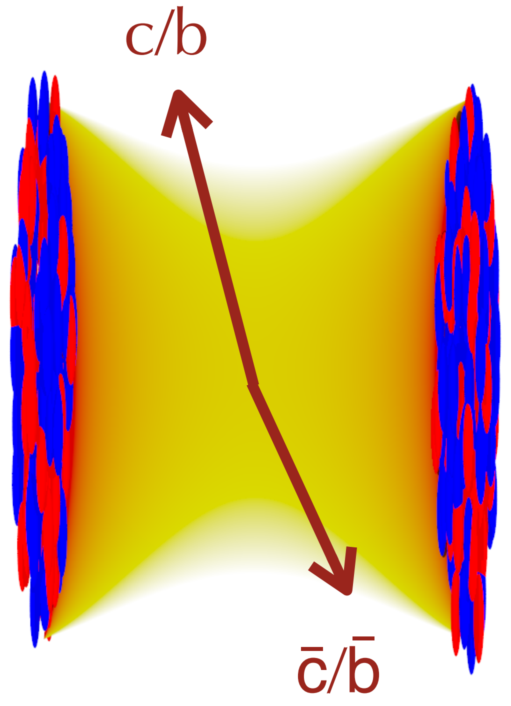




$$\frac{dN}{d\varphi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos[n(\varphi - \Psi_n)]$$







Hadron formation

- **Consider transition from QGP to hadrons**
  - hadron yields described by thermal models with temperature and baryochemical potential
  - light-flavour quarks produced thermally, heavy-flavour quarks only in initial scatterings
- **To what extent do quarks of different mass reach thermal equilibrium?**
  - statistical hadronisation of charm/beauty quarks → yields of heavy-flavour hadrons
- **How do quarks and gluons transition to hadrons as the quark-gluon plasma cools down?**
  - combination of independently produced quarks → multi-heavy-flavour states
  - production of bound states → hyper/charm-nuclei