



ALICE 3

Lecture I

1st ALICE experiment and heavy-ion workshop

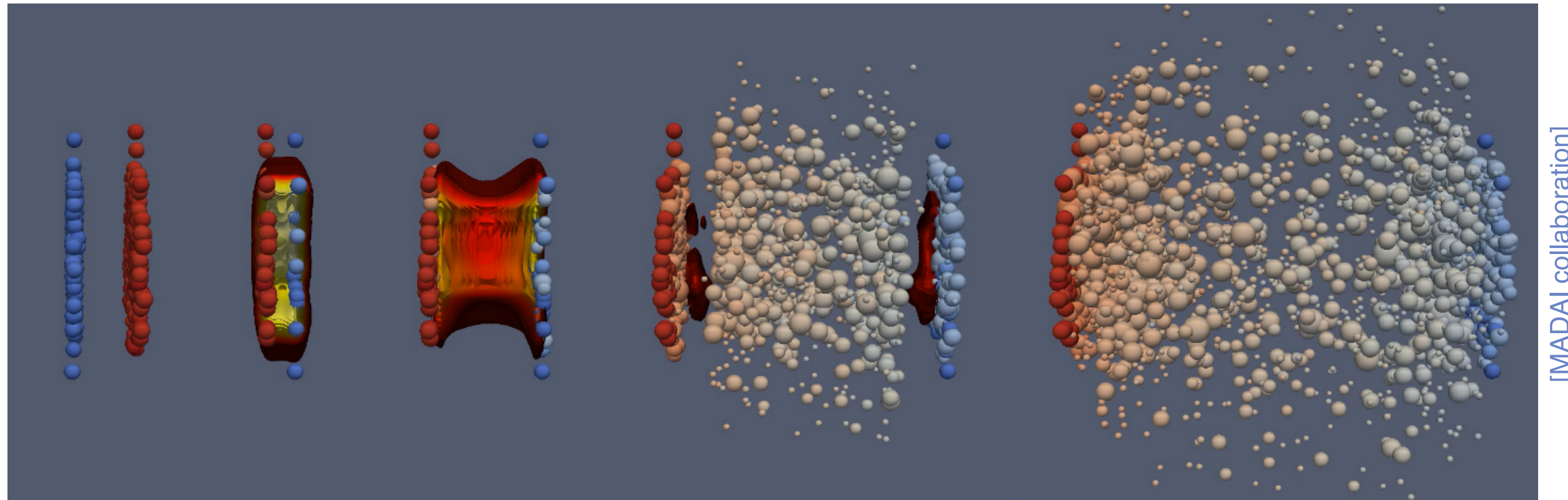
复旦大学（上海，中国）

2025-11-09

Jochen Klein (CERN)

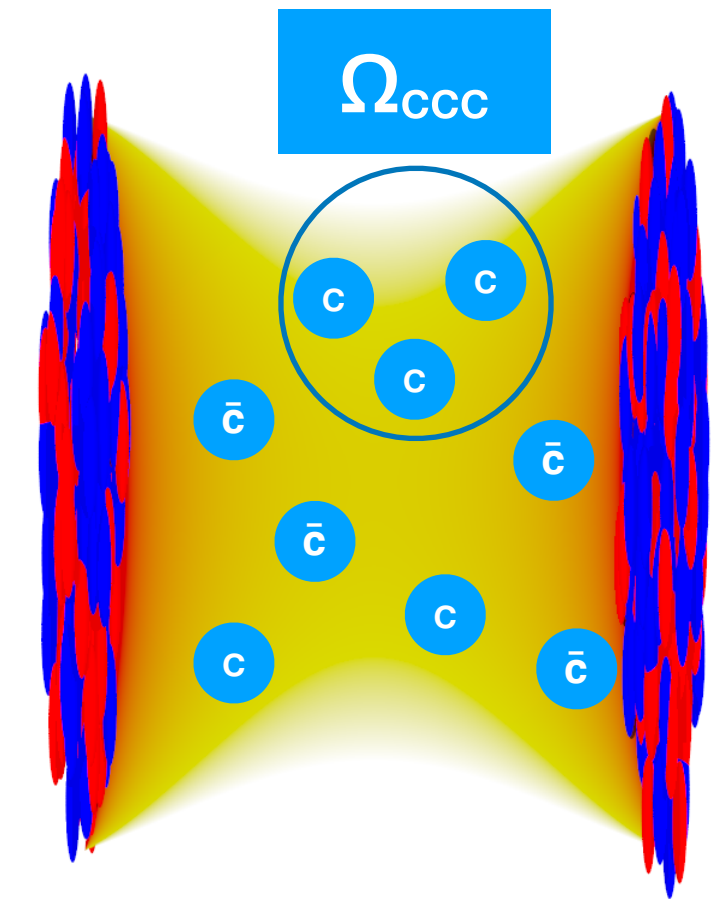
Frustration

- 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



Deconfinement

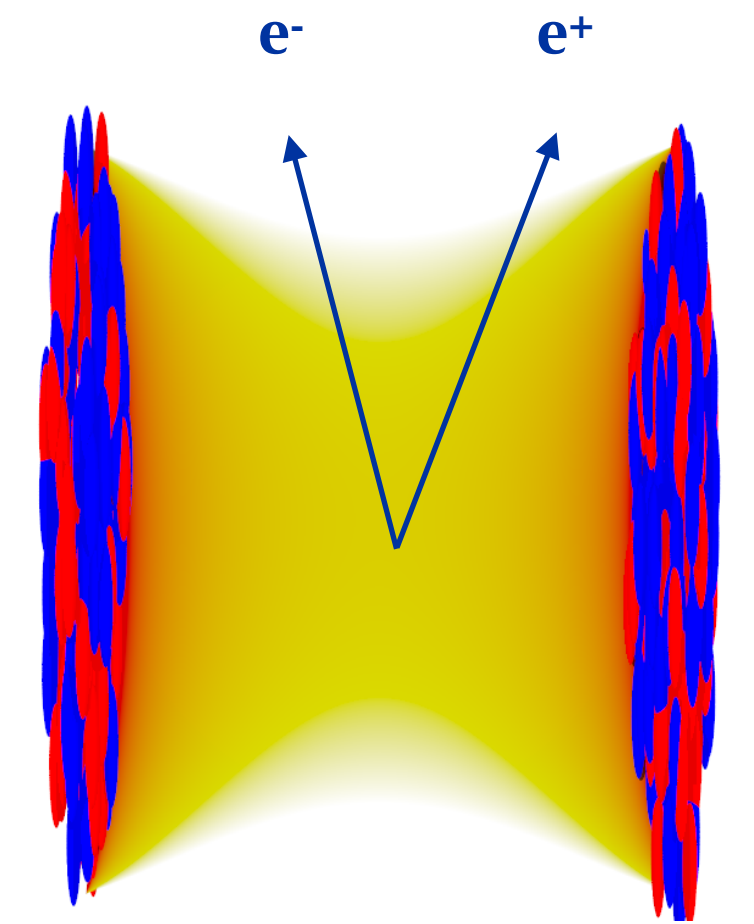
- **What do we need to demonstrate deconfinement?**
 - traceable probe embedded in quark-gluon plasma
 - light quarks and gluons produced thermally $\Rightarrow$ not traceable 🙅
 - heavy quarks only produced initially $\Rightarrow$ traceable 👍
 - charm quarks equilibrate $\Rightarrow$ embedded in QGP 👍
 - 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

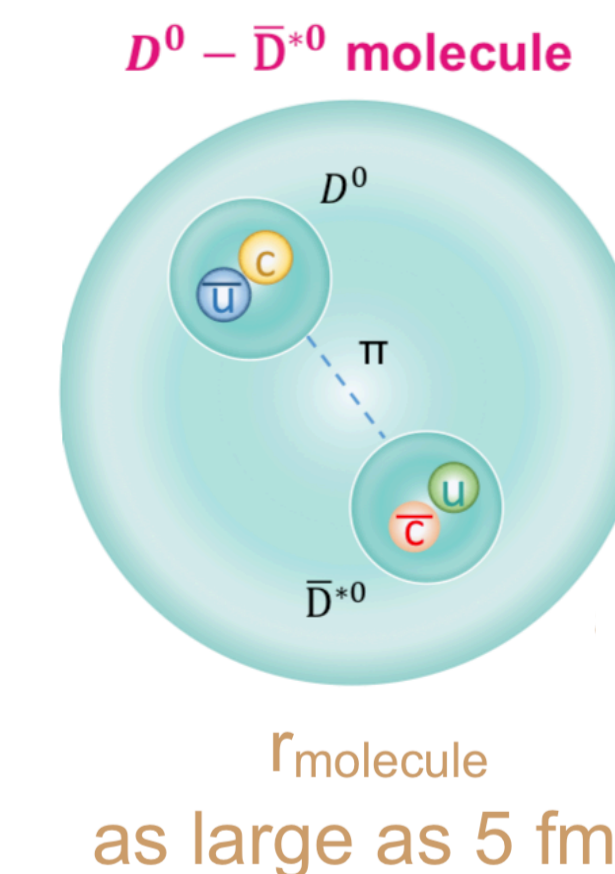
- **What do we need to measure initial temperature?**
 - hadrons produced at freeze-out temperature
→ information about initial state mostly lost 🙅
 - electromagnetic probes produced throughout the evolution
→ no strong interaction → escape from quark-gluon plasma 👍
 - photons suffer from blue shift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

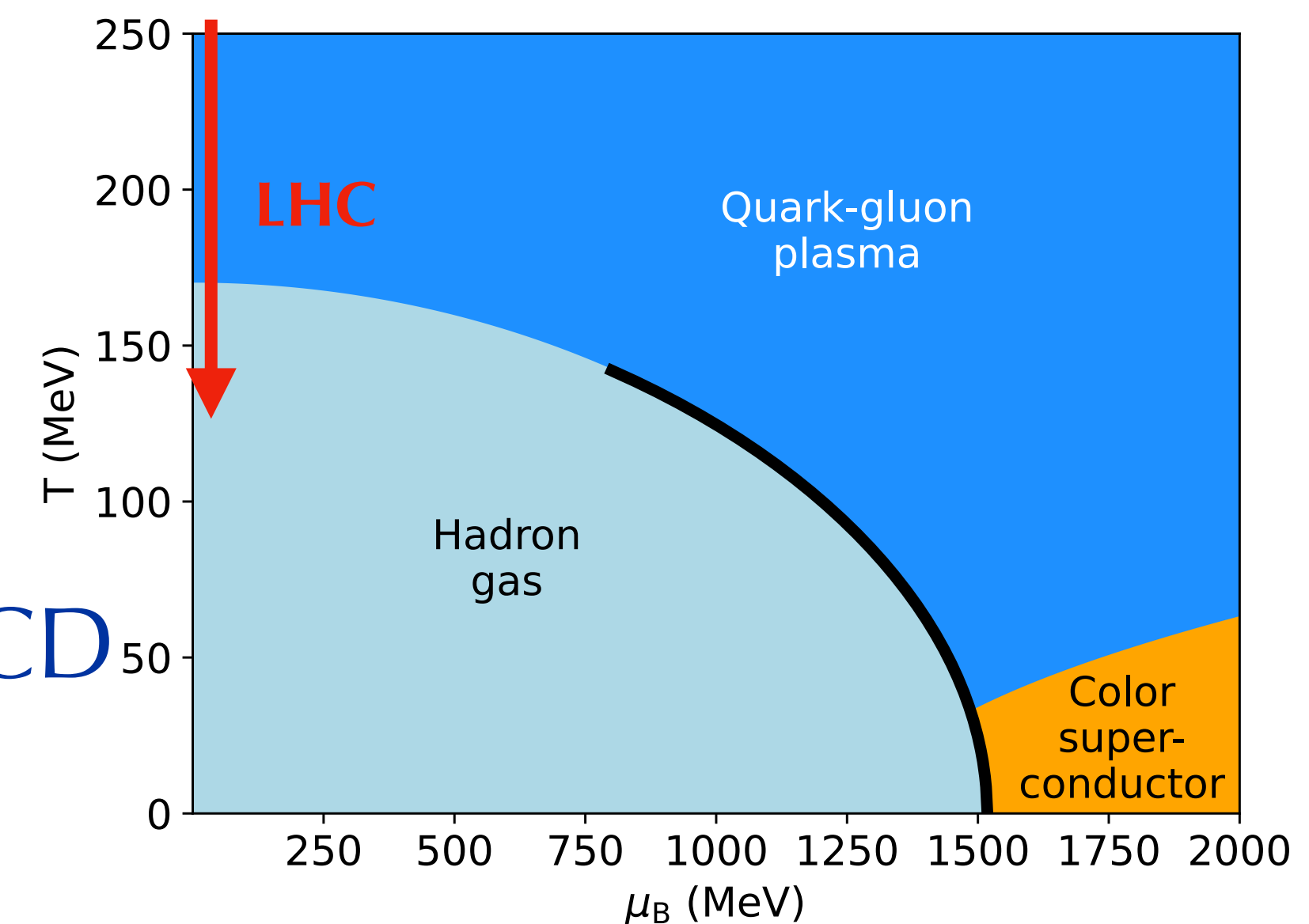
- **What do we need to understand interaction potentials and the nature of bound states?**
 - production yields only give indirect insights 🙄
 - correlations of compounds carry information on interaction potentials and possible bound states 👍
- **Momentum correlations are ideal probes**
to unravel interaction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

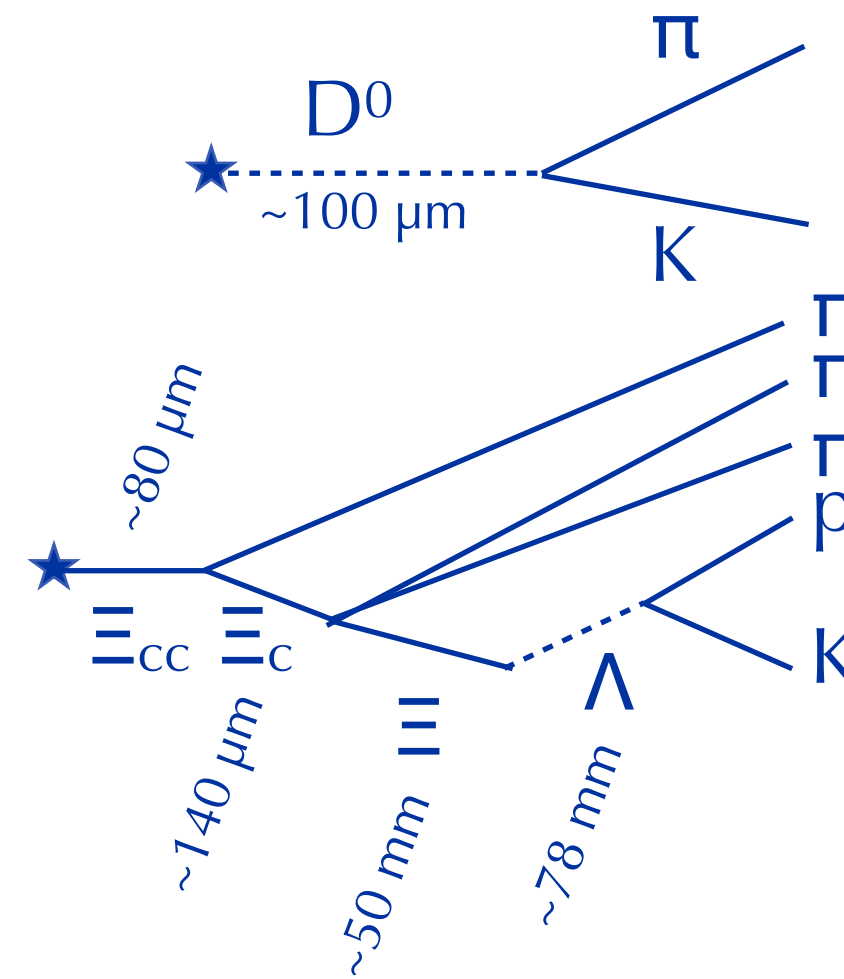
- ➡ modified parton shower
- ➡ transport properties
- ➡ hadronisation

- **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

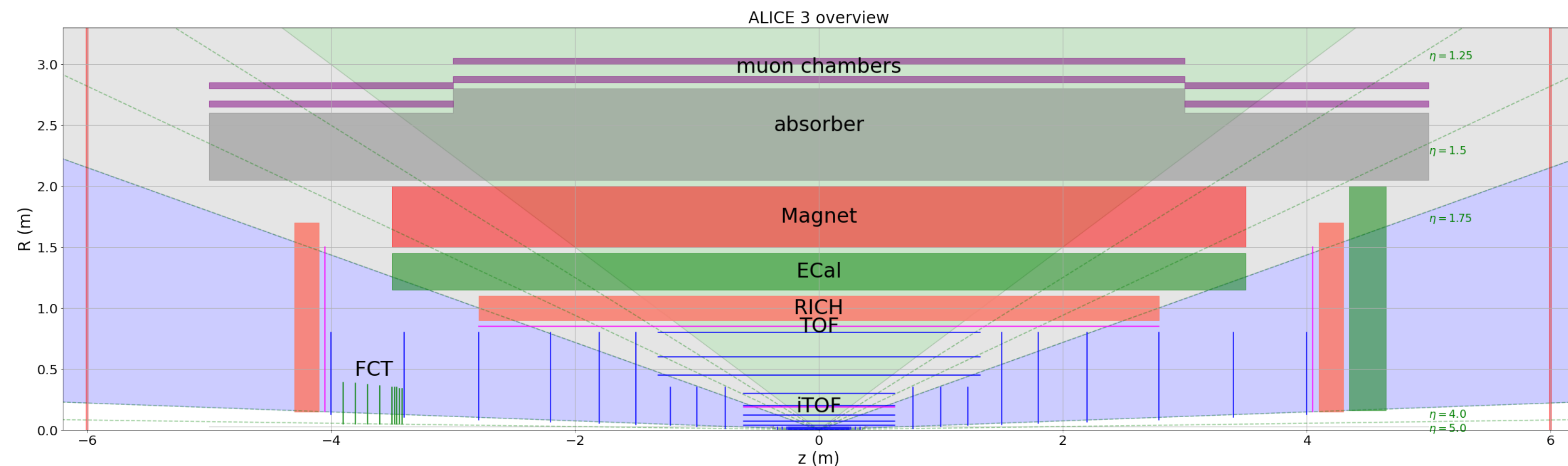
**Progress relies on
detector performance and statistics**

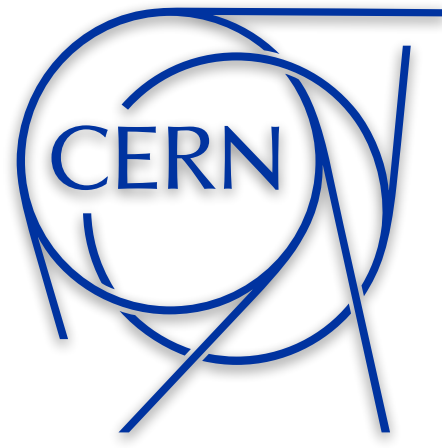
Observables

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

Key requirements

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





Detector concepts

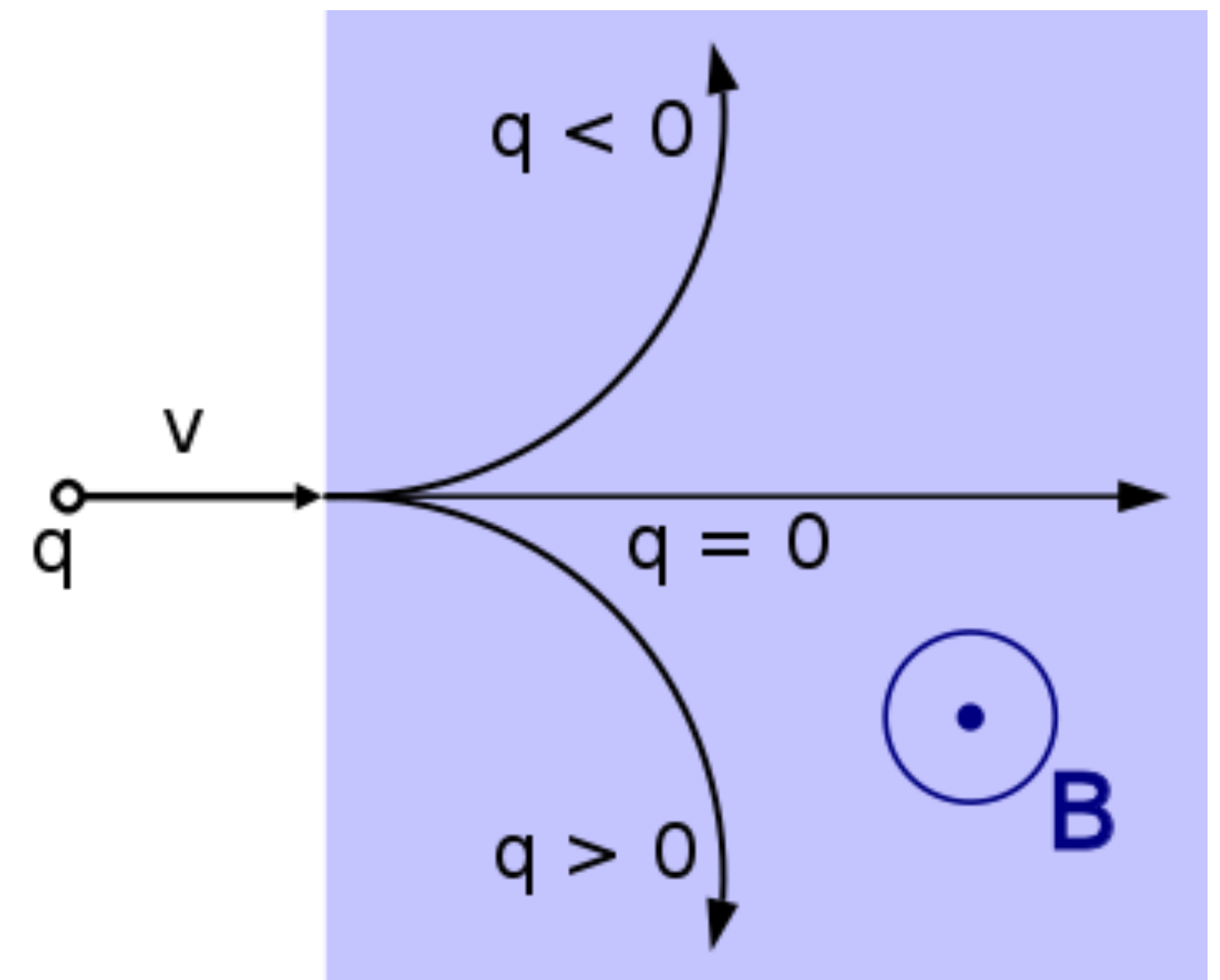
How do we optimise a detector for this programme?

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)

$$x = \frac{v_T}{\eta\omega_B} \sin(\eta\omega_B t + \psi_0) + x_0 \quad y = \frac{v_T}{\eta\omega_B} \cos(\eta\omega_B t + \psi_0) + y_0 \quad z = v_3 t + z_0$$

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

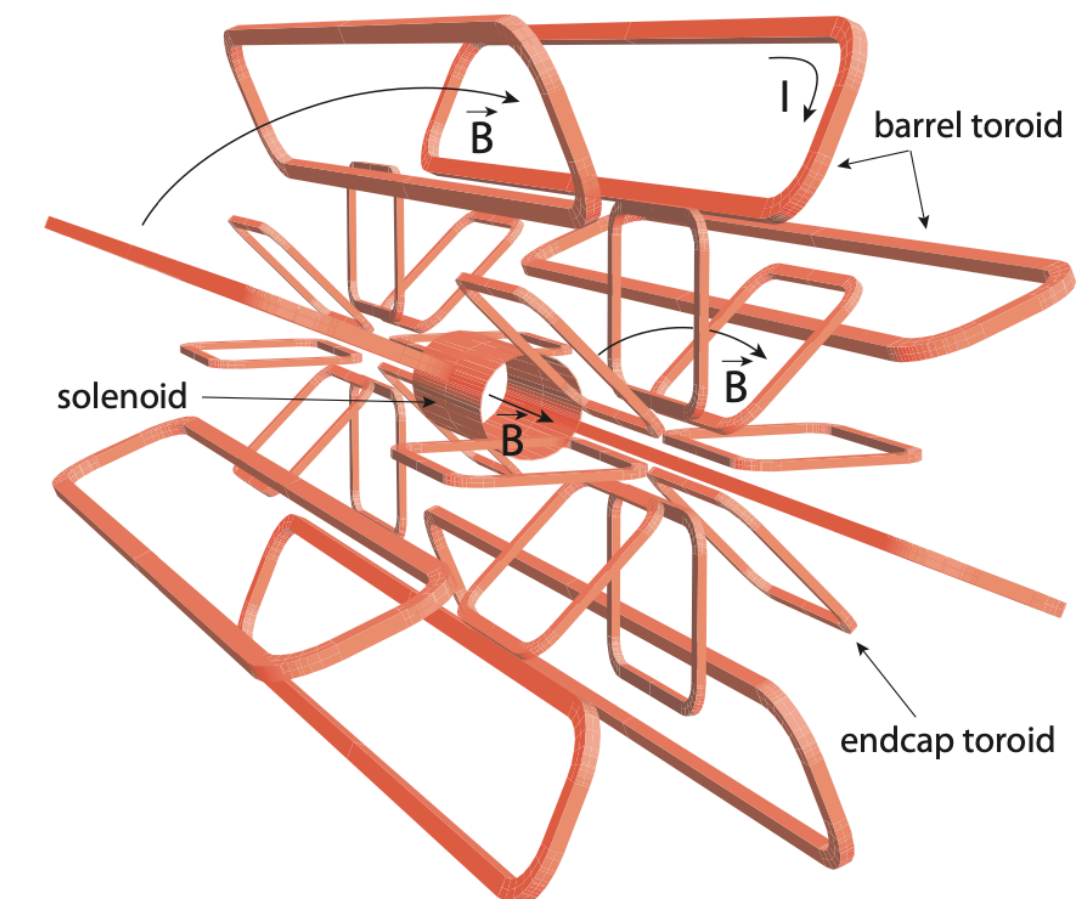
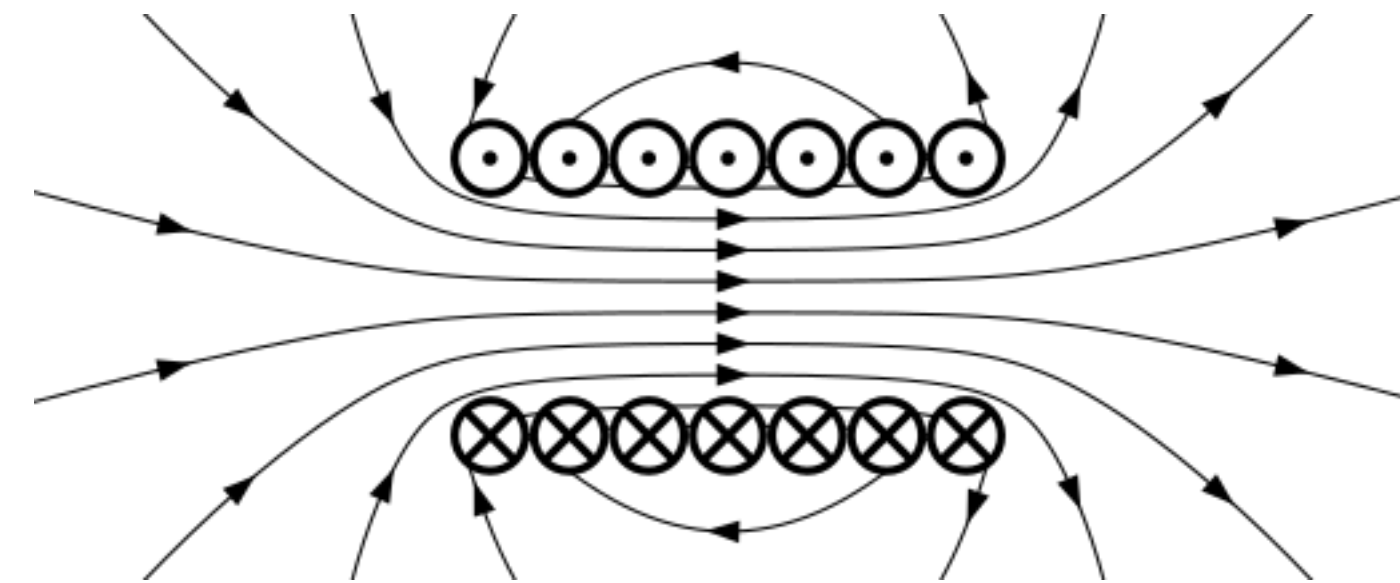
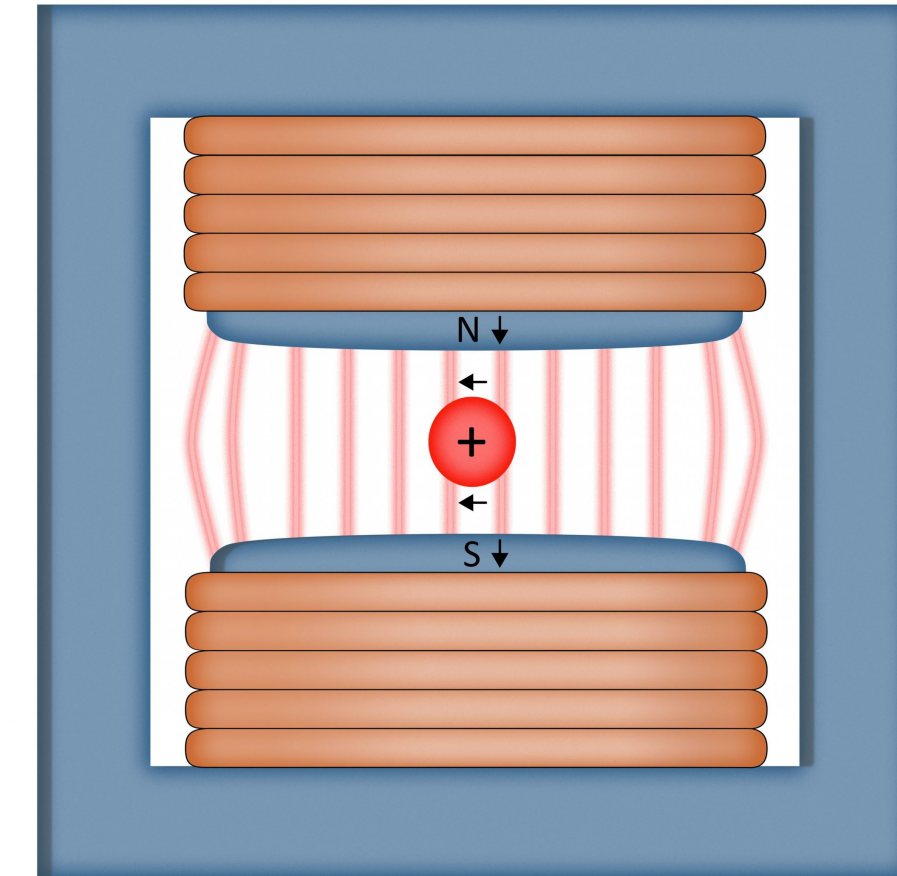
- **radius of curvature** given by $p_\perp = |q| B R$,
when using standard units (GeV/c, T, m) $\Rightarrow p_\perp = 0.3 B R$

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

curvature in magnetic field
directly linked to (transverse) momentum

Magnetic field configurations

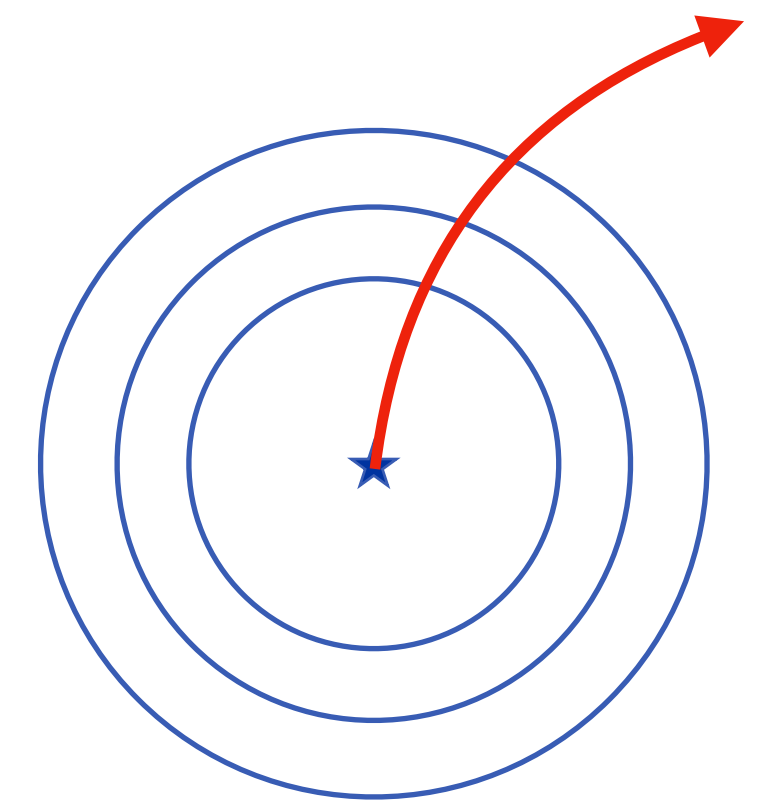
- **Dipole** fields
 - often used in fixed-target experiments or forward part of collider experiments
- **Solenoidal** fields
 - often used in collider experiments (rotationally symmetric)
- **Toroidal** fields
 - often used as extension of solenoidal fields (perpendicular, rotationally symmetric)



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

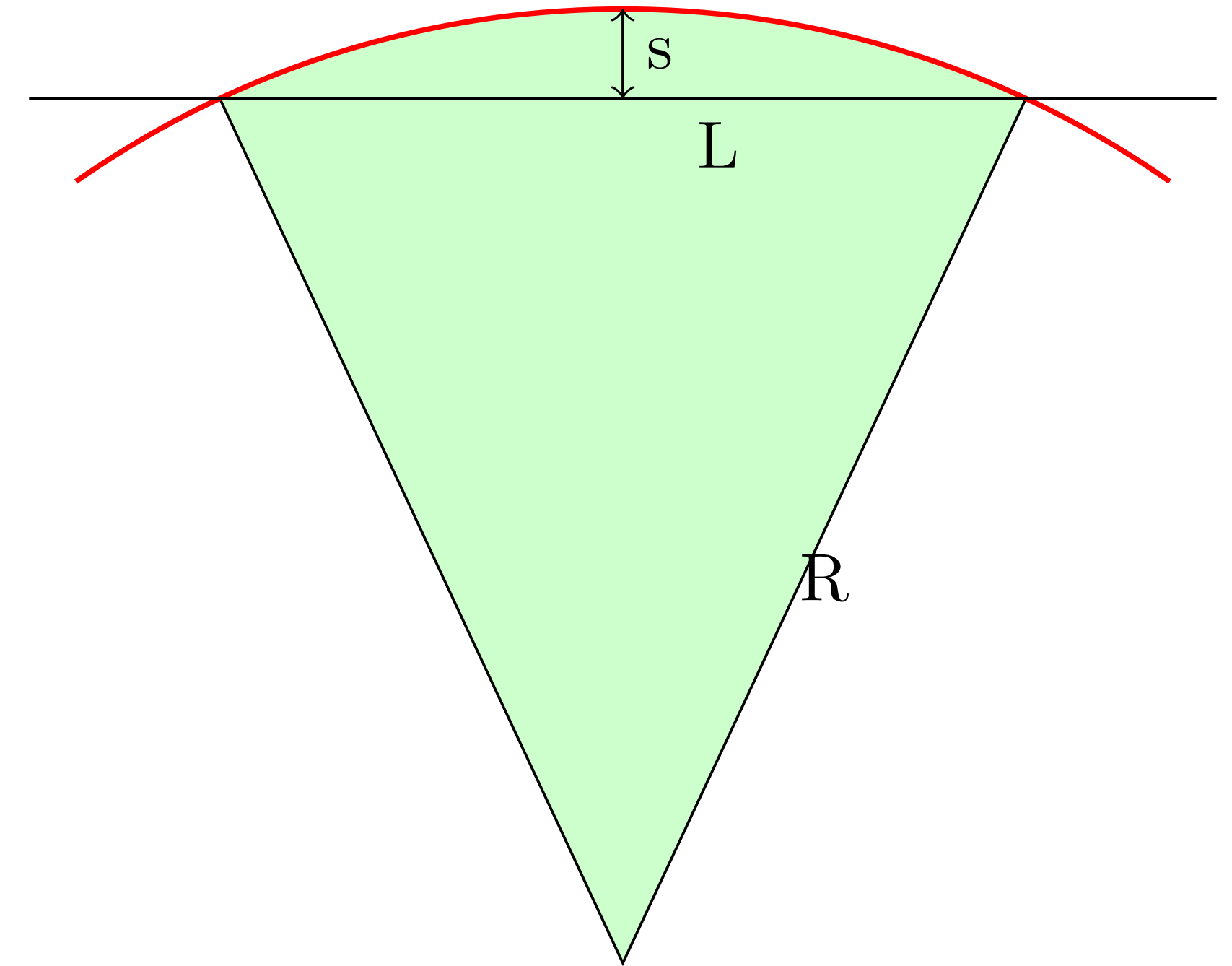
Sagitta

- 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

$$s = R - R \cos \frac{\vartheta}{2} = 2R \sin^2 \frac{\vartheta}{4} \approx \frac{R\vartheta^2}{8} \approx \frac{L^2}{8R} = \frac{qBL^2}{8p_{\perp}}$$

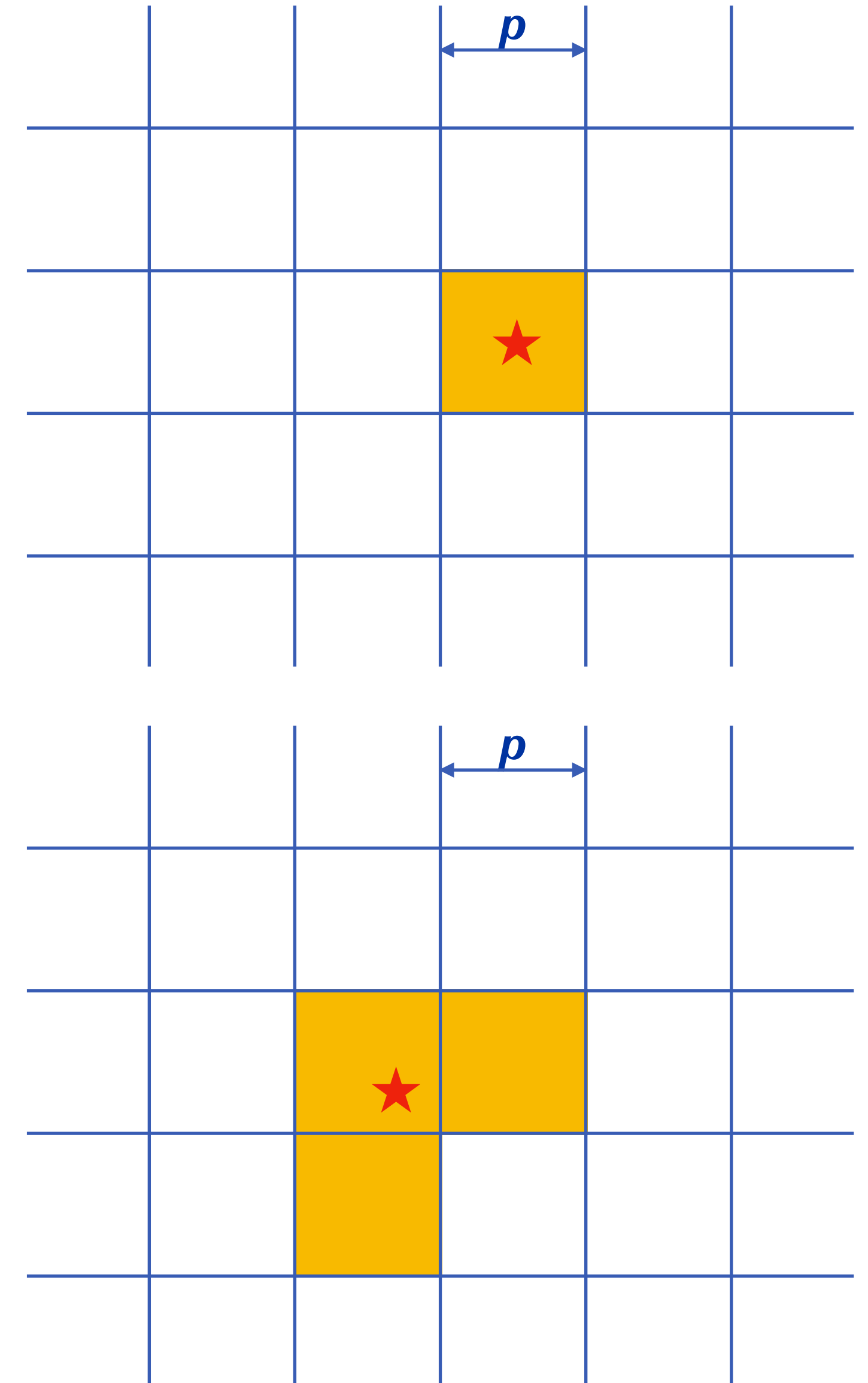
- **quadratic dependence on lever arm**
- relative uncertainty of momentum proportional to relative uncertainty of sagitta



**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**
$$\sigma_{\text{pos}}^2 = \int_{-p/2}^{p/2} dx x^2 \frac{1}{p} = \frac{p^2}{12} \Rightarrow \sigma_{\text{pos}} = \frac{p}{\sqrt{12}}$$
- uncertainty reduced when signal spreads across multiple bins (**charge sharing**), possibly with information on charge per bin
- gas detectors typically $\mathcal{O}(100 \text{ } \mu\text{m})$, semiconductor detectors typically $\mathcal{O}(10 \text{ } \mu\text{m})$



Multiple scattering

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

- width of distribution

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

- **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. $\sigma_x \propto \sigma_{\alpha} \cdot \Delta x$

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
 $\rightarrow y_i = f(x_i) = a_0 + a_1 x_i$
 - parabola (as approximation to circular shape)
 $\rightarrow y_i = f(x_i) = a_0 + a_1 x_i + a_2 x_i^2/2$ ($a_2 = 1/R$)
 - **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:

$$\Rightarrow \frac{\Delta p_T}{p_T} = \frac{\Delta R}{R} = \frac{\Delta a_2}{a_2} = \frac{p_T}{|q| B} \Delta a_2$$

- **Position resolution** of N+1 equidistant layers leads to uncertainty

$$\frac{\Delta p_T}{p_T} = \frac{\sigma p_T}{|q| B L^2} \sqrt{\frac{720 N^3}{(N-1)(N+1)(N+2)(N+3)}} \approx \frac{\sigma p_T}{|q| B L^2} \sqrt{\frac{720}{N+4}}$$

(Glückstern formula, NIM 24 (1963) 381)

- **Multiple scattering** in N+1 equidistant layers leads to uncertainty

$$\frac{\Delta p_T}{p_T} = \frac{N}{\sqrt{(N+1)(N-1)}} \frac{p \sigma_{\alpha} \sqrt{N+1}}{B L} = \frac{N}{\sqrt{(N+1)(N-1)}} \frac{0.0136 \text{ GeV}/c \sqrt{d_{\text{tot}}/X_0}}{\beta B L}$$

Considerations for detector layout

- **Multiple scattering** contributes

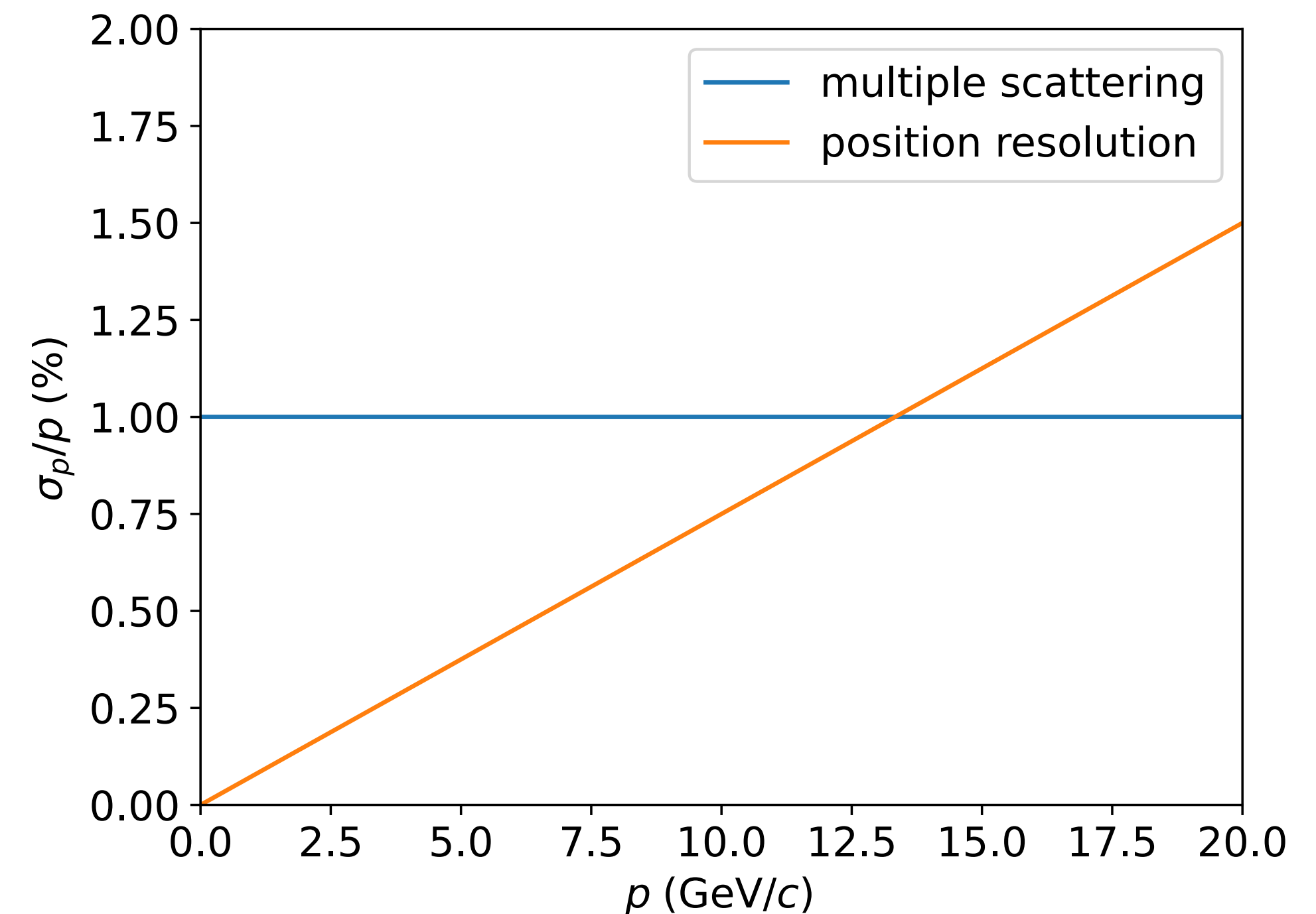
$$\propto \frac{\sqrt{d_{\text{tot}}/X_0} \cosh \eta}{\beta BL}$$

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

- **Position resolution** contributes

$$\propto \frac{\sigma p_T}{BL^2}$$

- linear rise with momentum
- quadratic dependence on lever arm



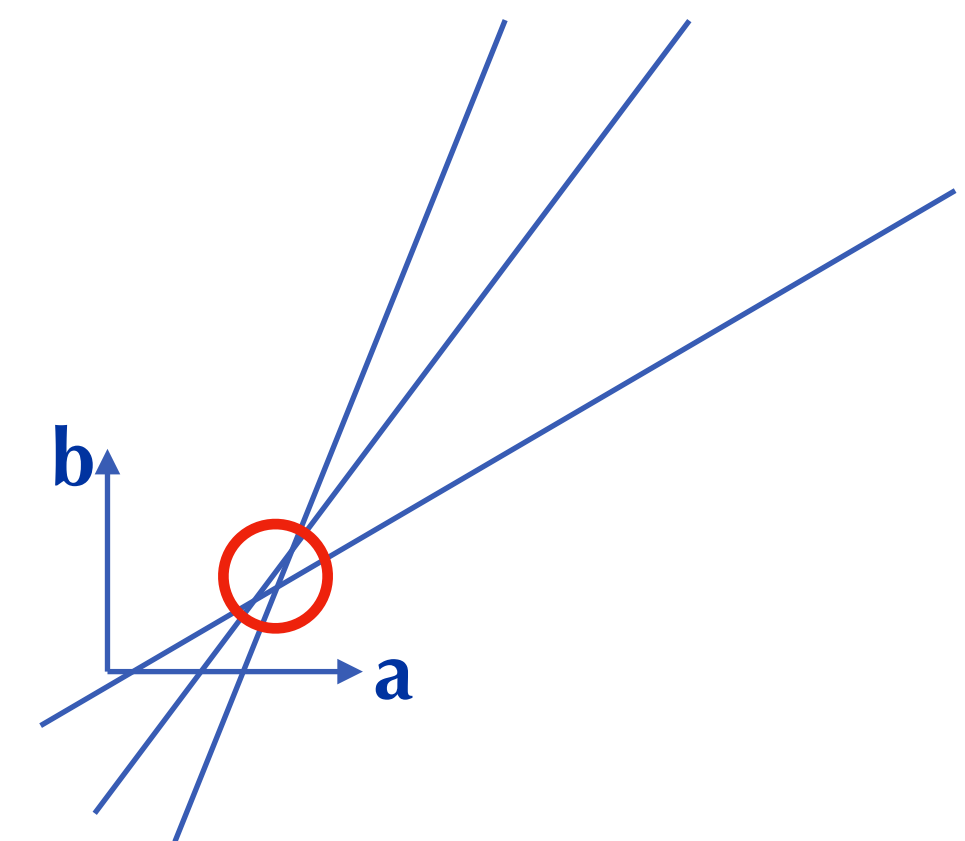
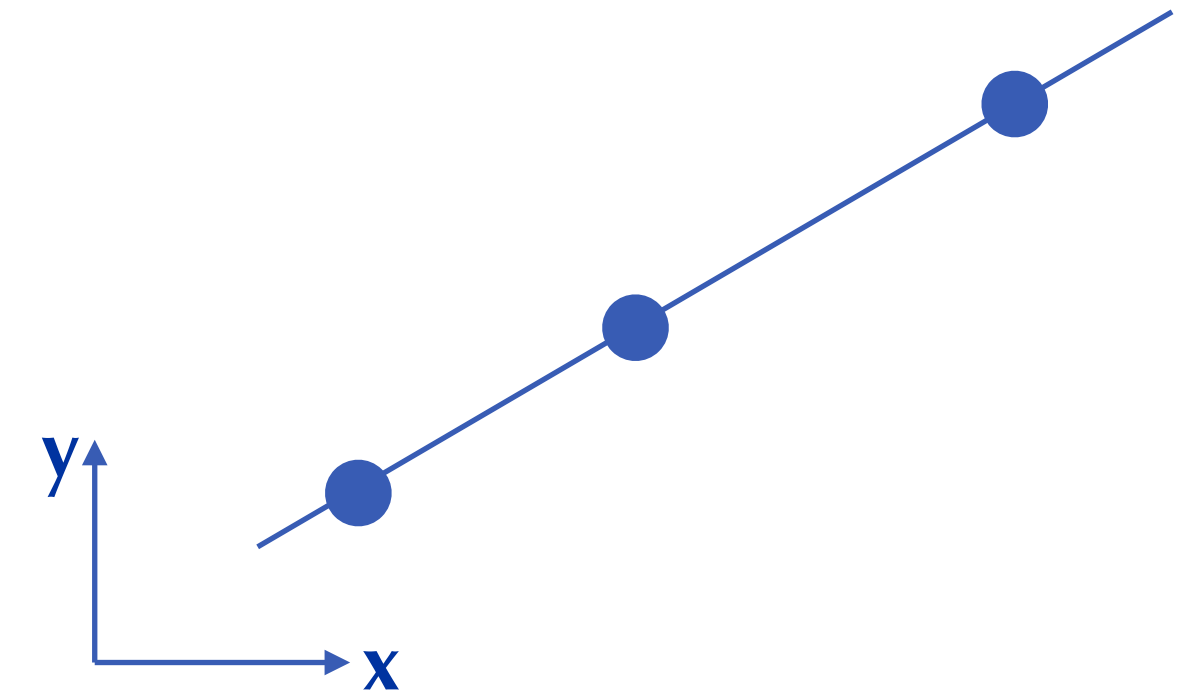
**m.s. sets irreducible limit,
p.r. takes over at large momenta**

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

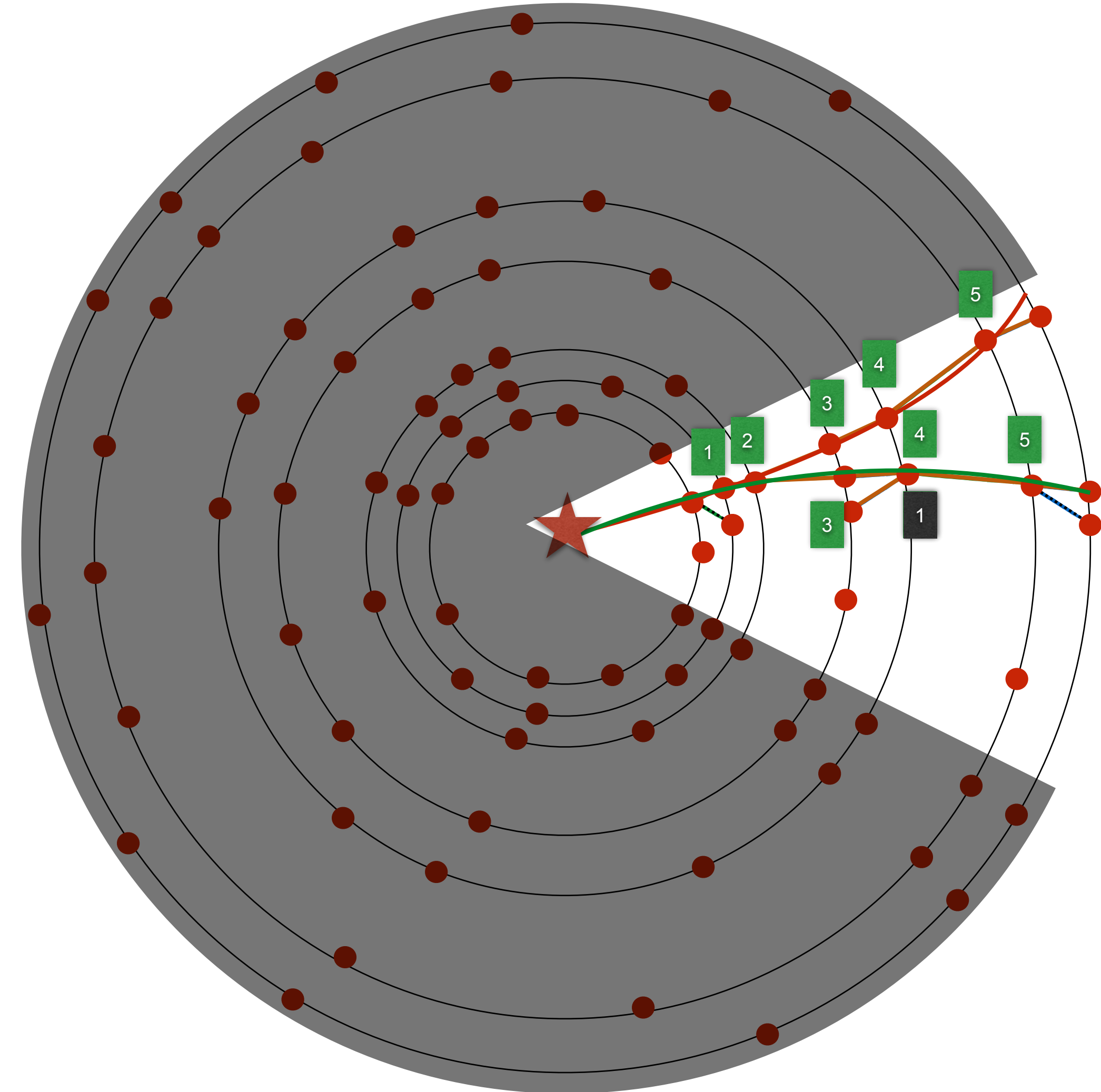
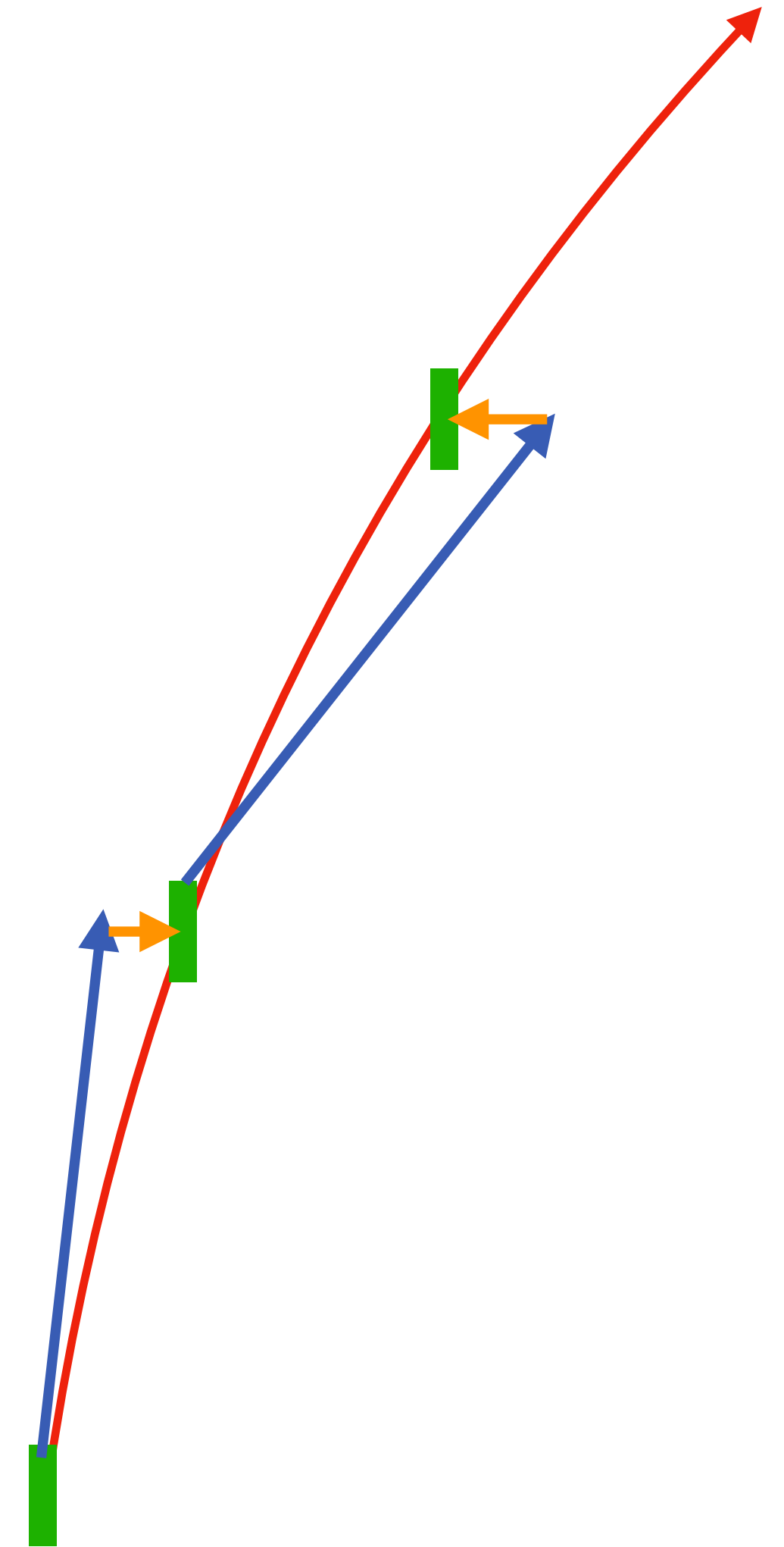


Figure by M. Puccio

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

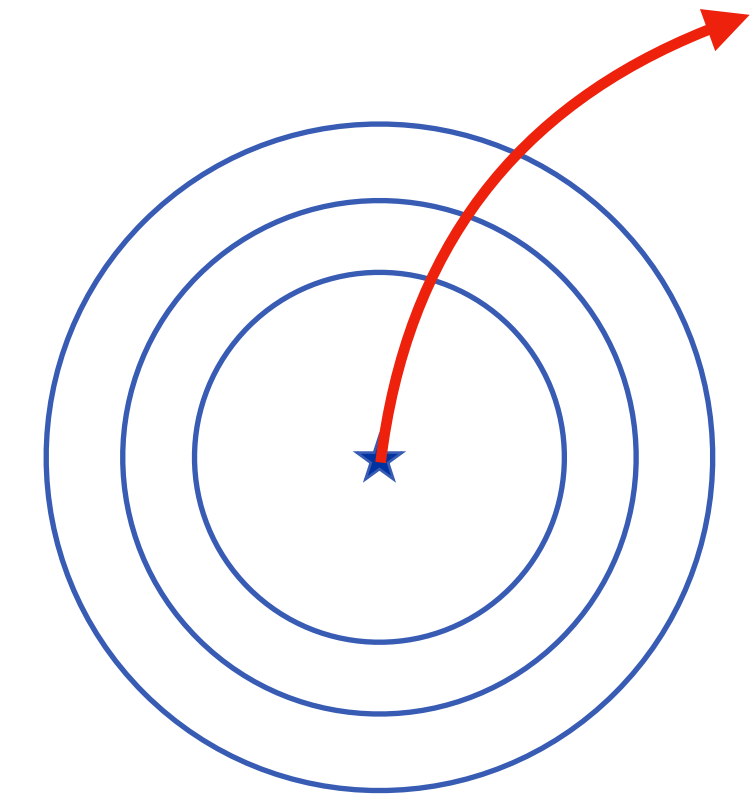
Momentum resolution

- Consider **momentum resolution in solenoidal field**

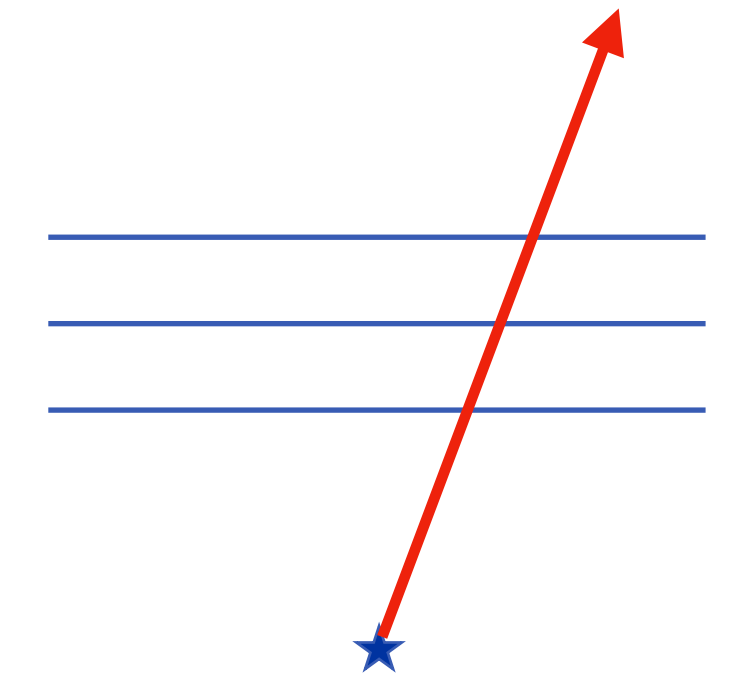
- $\propto \frac{\sqrt{d_{\text{tot}}/X_0 \cosh \eta}}{\beta BL}$ for multiple scattering
- $\propto \frac{\sigma p_T}{BL^2}$ for position resolution

- 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

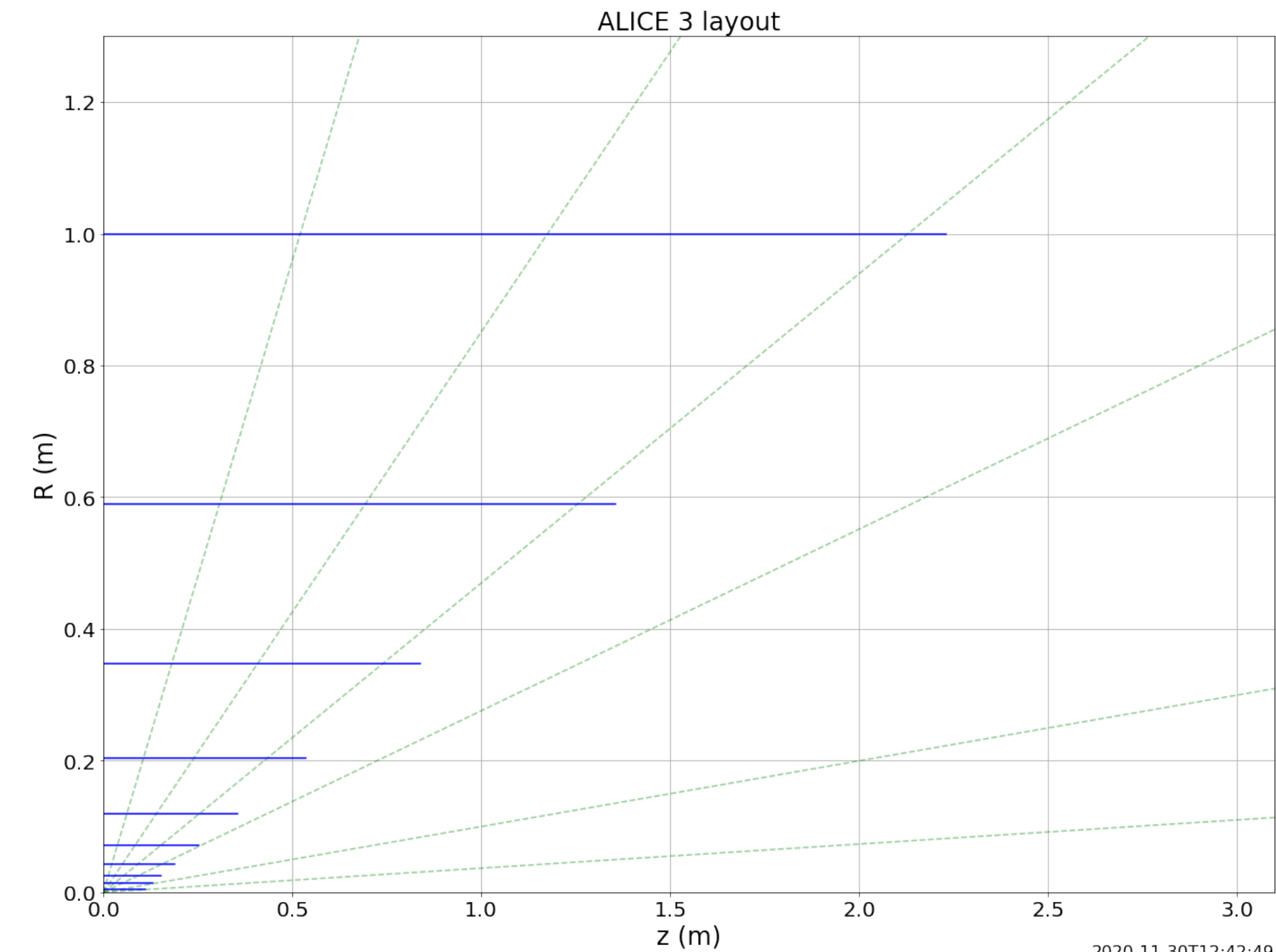
- distance from preceding layer to achieve constant probability

$$\Delta R \propto \sqrt{\frac{P}{x/X_0}} \cdot R$$

- **Inefficiencies and dead areas**

can lead to significant deterioration of matching

- layers often arranged in pairs to avoid lack of position information

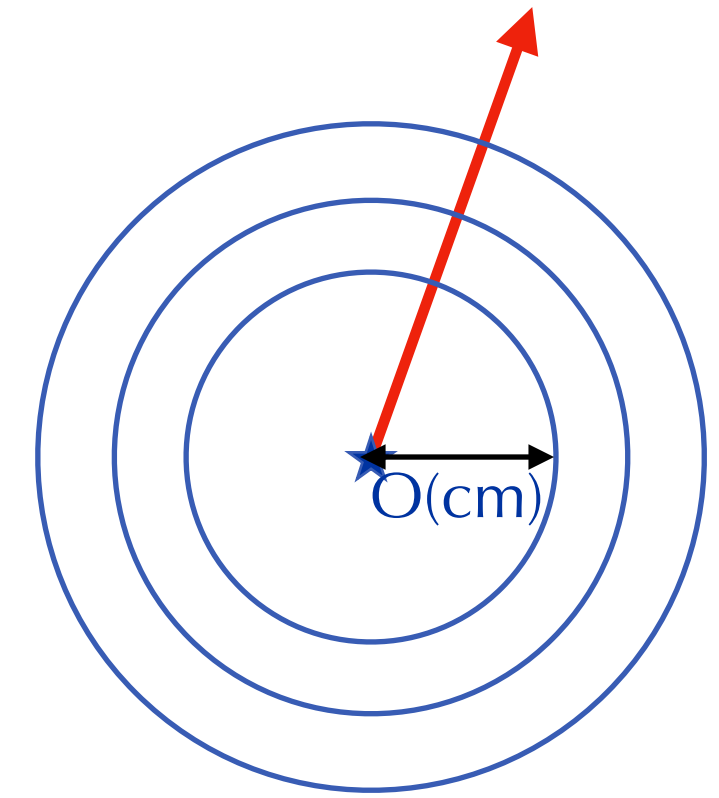


Additional considerations

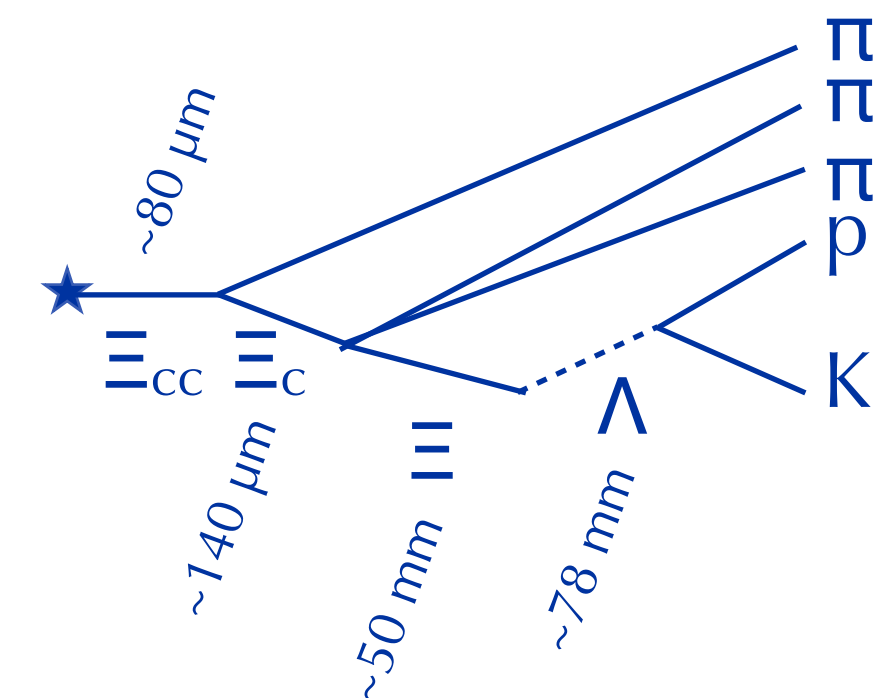
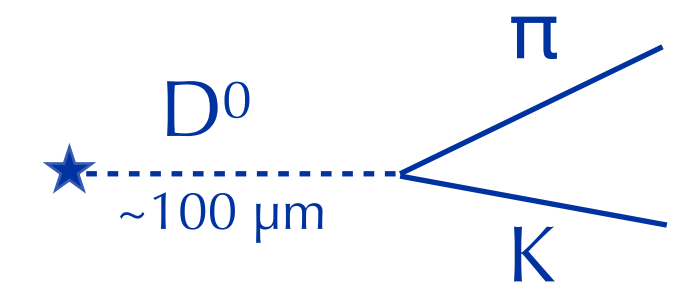
- **Momentum range**
 - limited by particles not reaching outer layers
 - limited by momentum resolution
- **Propagation to other detectors**
 - limited by pointing resolution towards other (outer) detectors
- **Track length determination**
 - limited by precision of propagation inside tracker
- **Reconstruction 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 $100\ \mu\text{m}$

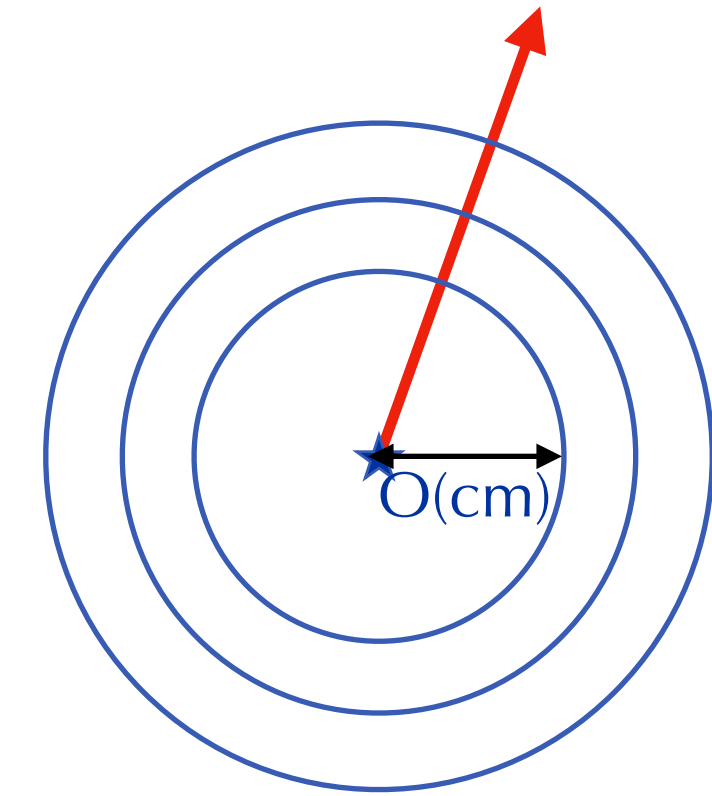


decays with $c\tau < 100\ \mu\text{m}$

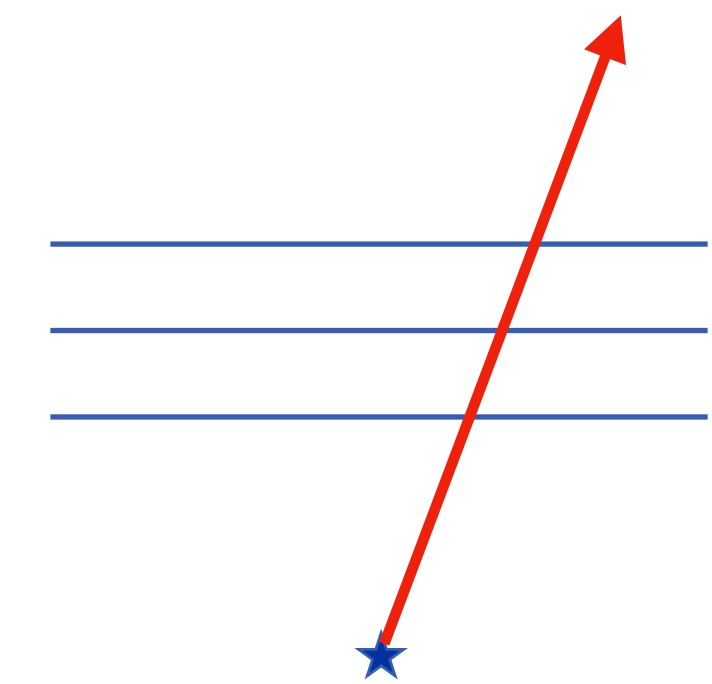


Track propagation

- **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



decays with $c\tau < 100 \mu\text{m}$



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

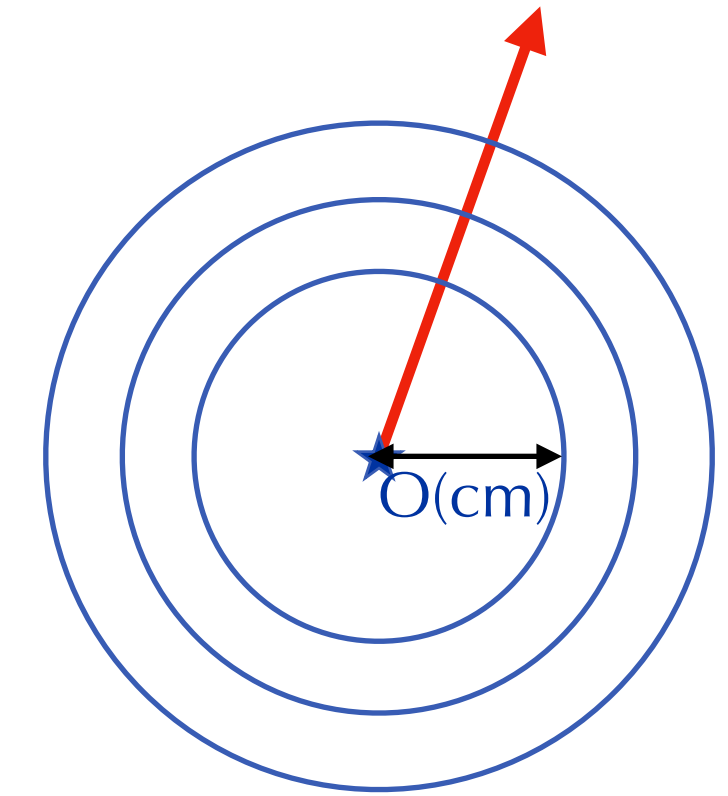
$$\sigma_{xy} = \sigma_{a_1} \cdot r_0$$

$$\sigma_z = \sigma_{a_1} \cdot r_0 \cdot \cosh \eta$$

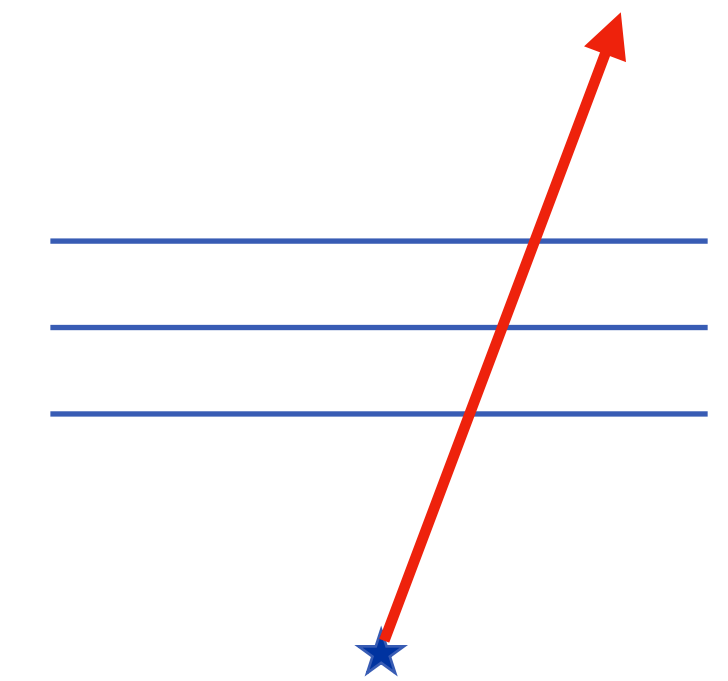
- **Position resolution** of $N+1$ equidistant layers leads to

- $\sigma_{d_{xy}} \propto \sigma_{r\varphi}$ (transverse impact parameter)

- $\sigma_{d_z} \propto \sigma_z$ (longitudinal impact parameter)



decays with $c\tau < 100 \mu\text{m}$



Multiple scattering

- **Multiple scattering in N+1 equidistant layers leads to**

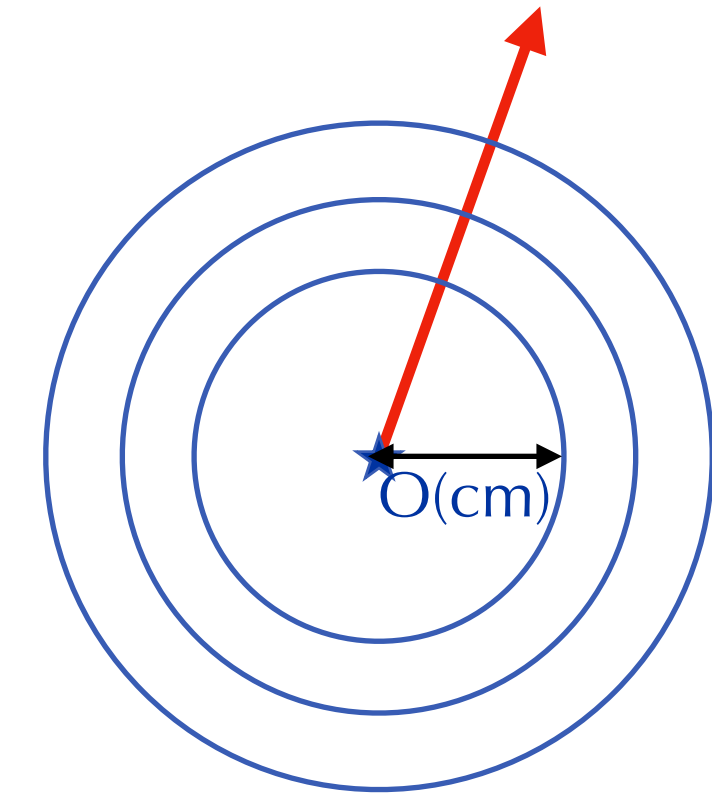
- $\sigma_\varphi \propto \frac{\sqrt{d/X_0 \cosh \eta}}{\beta p_T}$

- $\sigma_\vartheta \propto \frac{\sqrt{d/X_0 \cosh \eta}}{\beta p} \propto \frac{\sqrt{d/X_0}}{\beta p_T \sqrt{\cosh \eta}}$

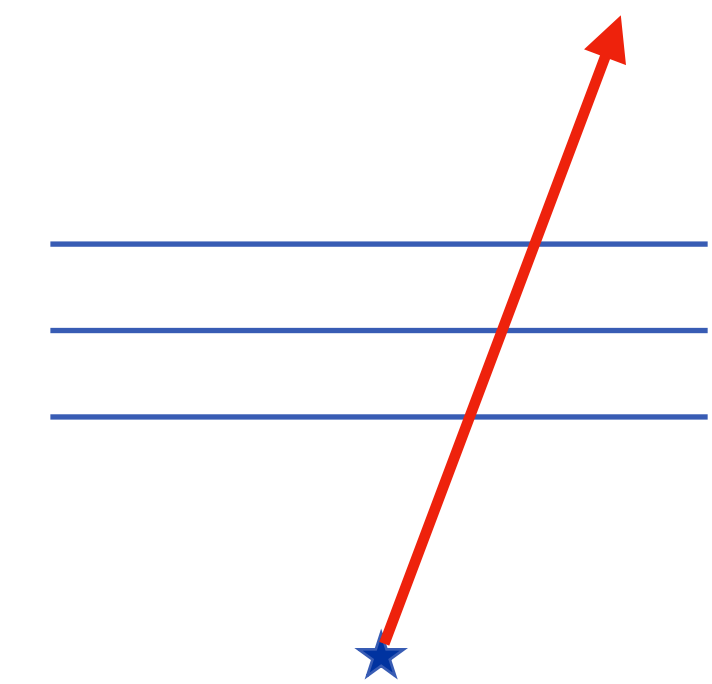
- **Propagation towards interaction point leads to**

- $\sigma_{d_{xy}} \propto \sigma_\varphi \cdot r_0 \propto \frac{\sqrt{d/X_0 \cosh \eta}}{\beta p_T} r_0$ (transverse)

- $\sigma_{d_z} \propto \sigma_\vartheta \cdot r_0 \cdot \cosh^2 \eta \propto \frac{\sqrt{d/X_0}}{\beta p_T} \cdot r_0 \cdot \sqrt{\cosh \eta}^3$ (longitudinal)

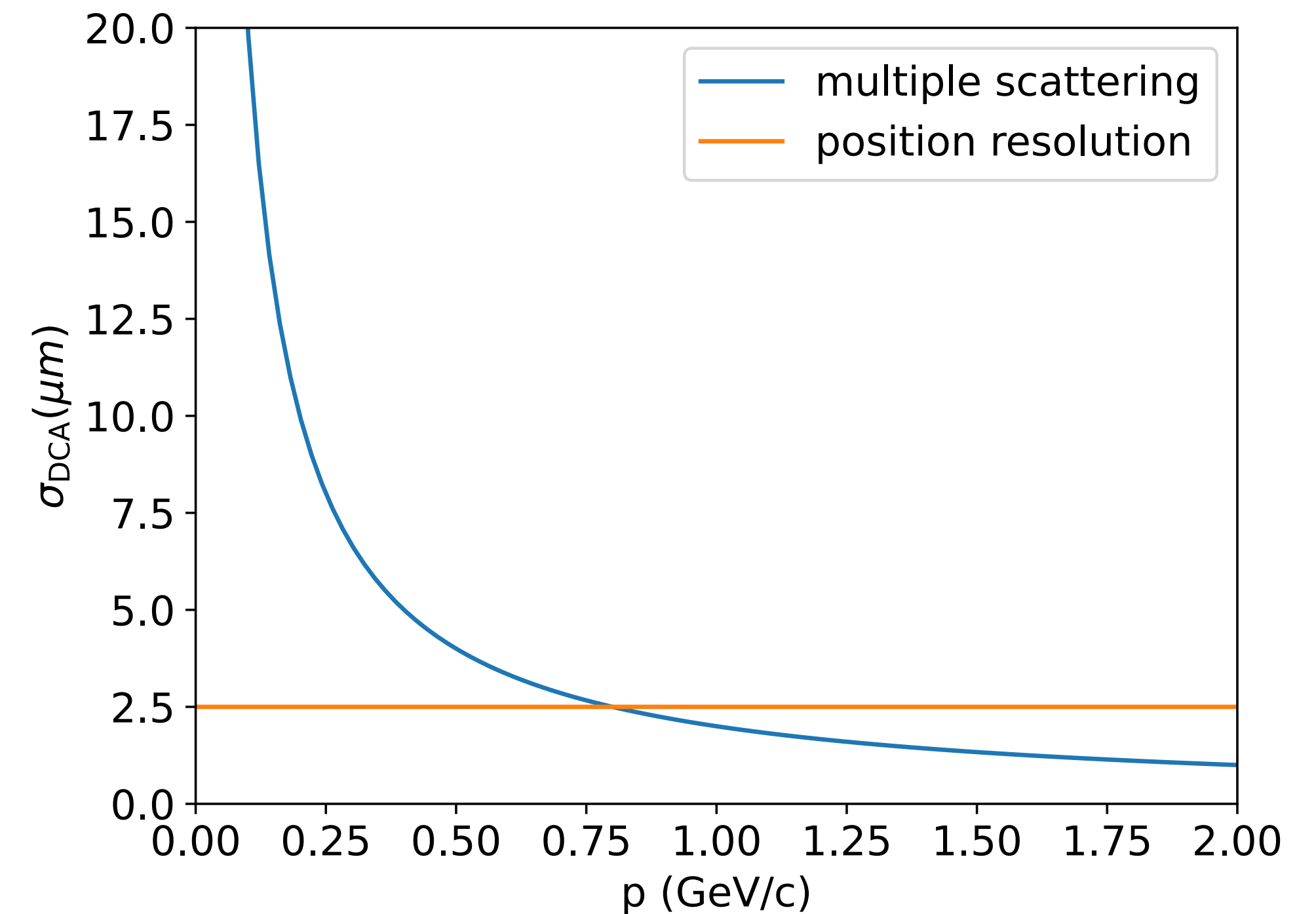


decays with $c\tau < 100 \mu\text{m}$



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. $\propto 1/p$)
→ 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

$$\propto \frac{\sigma p_T}{BL^2}$$

$$\propto \sqrt{d_{\text{tot}}/X_0} \frac{\sqrt{\cosh \eta}}{\beta BL}$$

transverse DCA

$$\propto \sigma_{xy}$$

$$\propto r_0 \sqrt{d/X_0} \frac{\sqrt{\cosh \eta}}{\beta p_T}$$

longitudinal DCA

$$\propto \sigma_z$$

$$\propto r_0 \sqrt{d/X_0} \frac{\sqrt{\cosh \eta}^3}{\beta p_T}$$

Particle identification

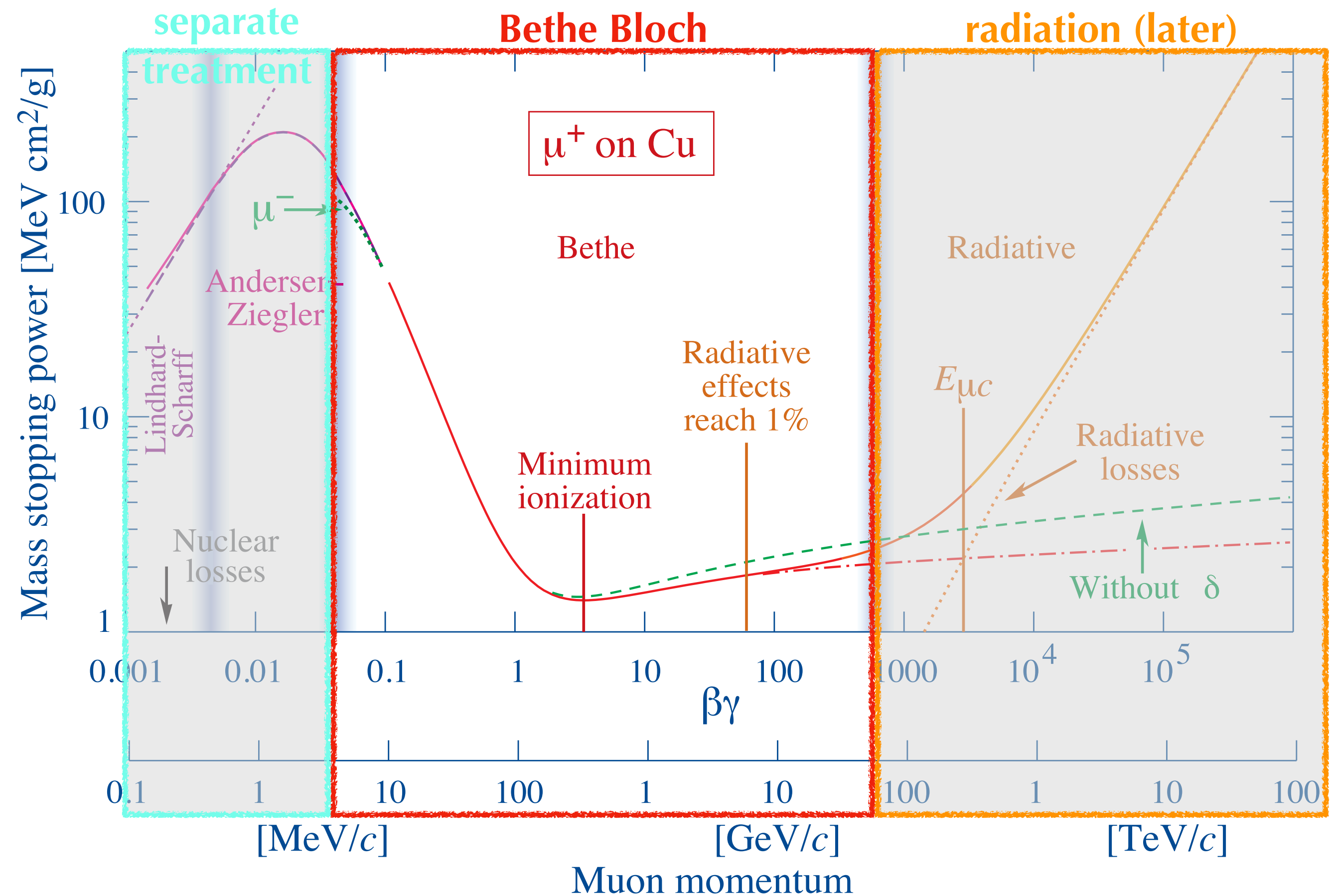
- **Mass measurement** from combination of tracking and additional measurements
 - **Specific energy loss**
 - ⇒ deposited charge (time over threshold)
 - **Time of flight** separation $\propto L / \sigma_{\text{tof}}$
 - ⇒ large path length with fast time resolution
 - **Cherenkov** radiation with angle $\cos \vartheta = 1 / n\beta$
 - ⇒ 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

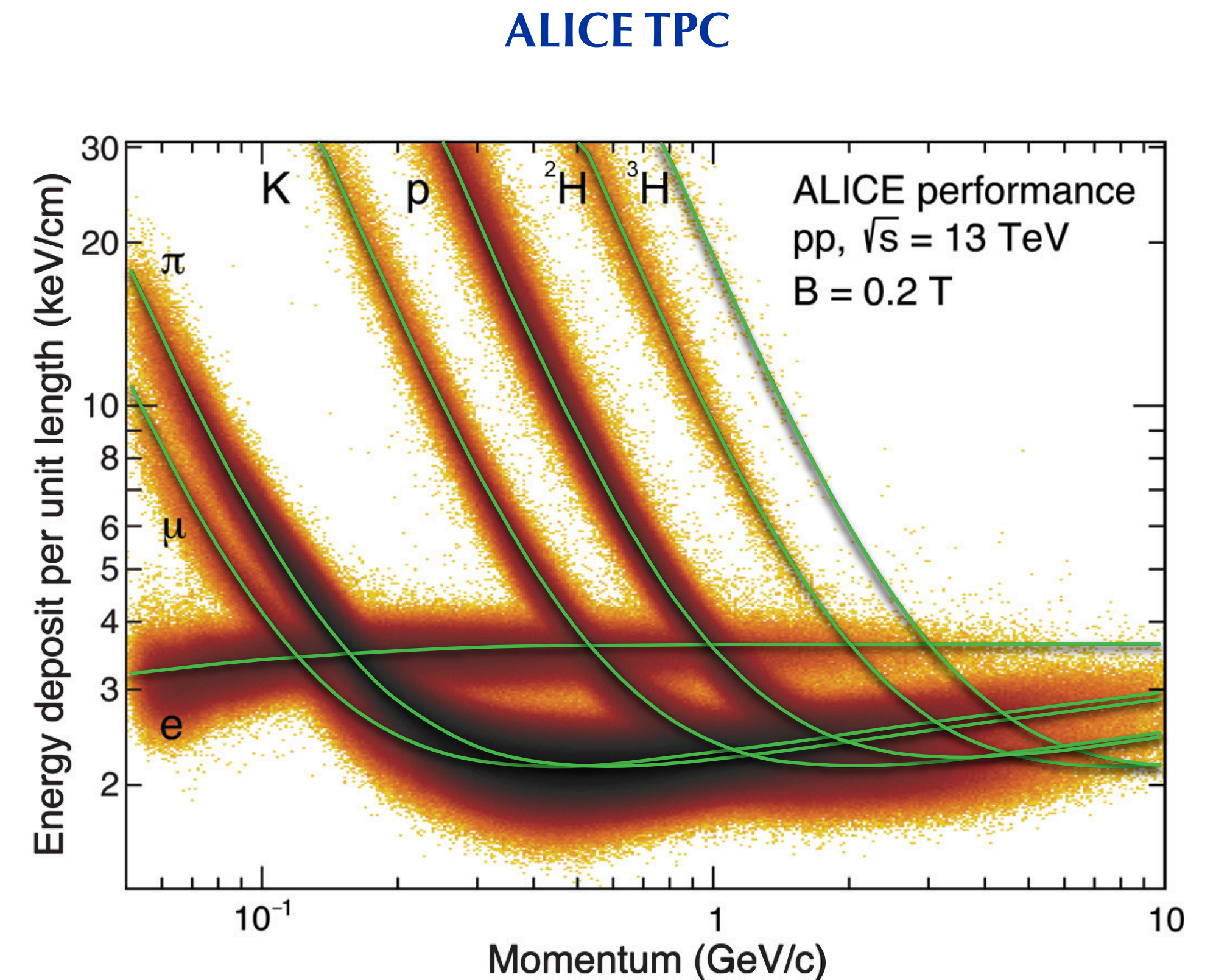
$$-\frac{dE}{dx} = Kz^2 \frac{Z}{A} \rho \frac{1}{\beta^2} \left[\frac{1}{2} \log \frac{2m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta}{2} \right]$$

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



Specific energy loss

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



Time of flight

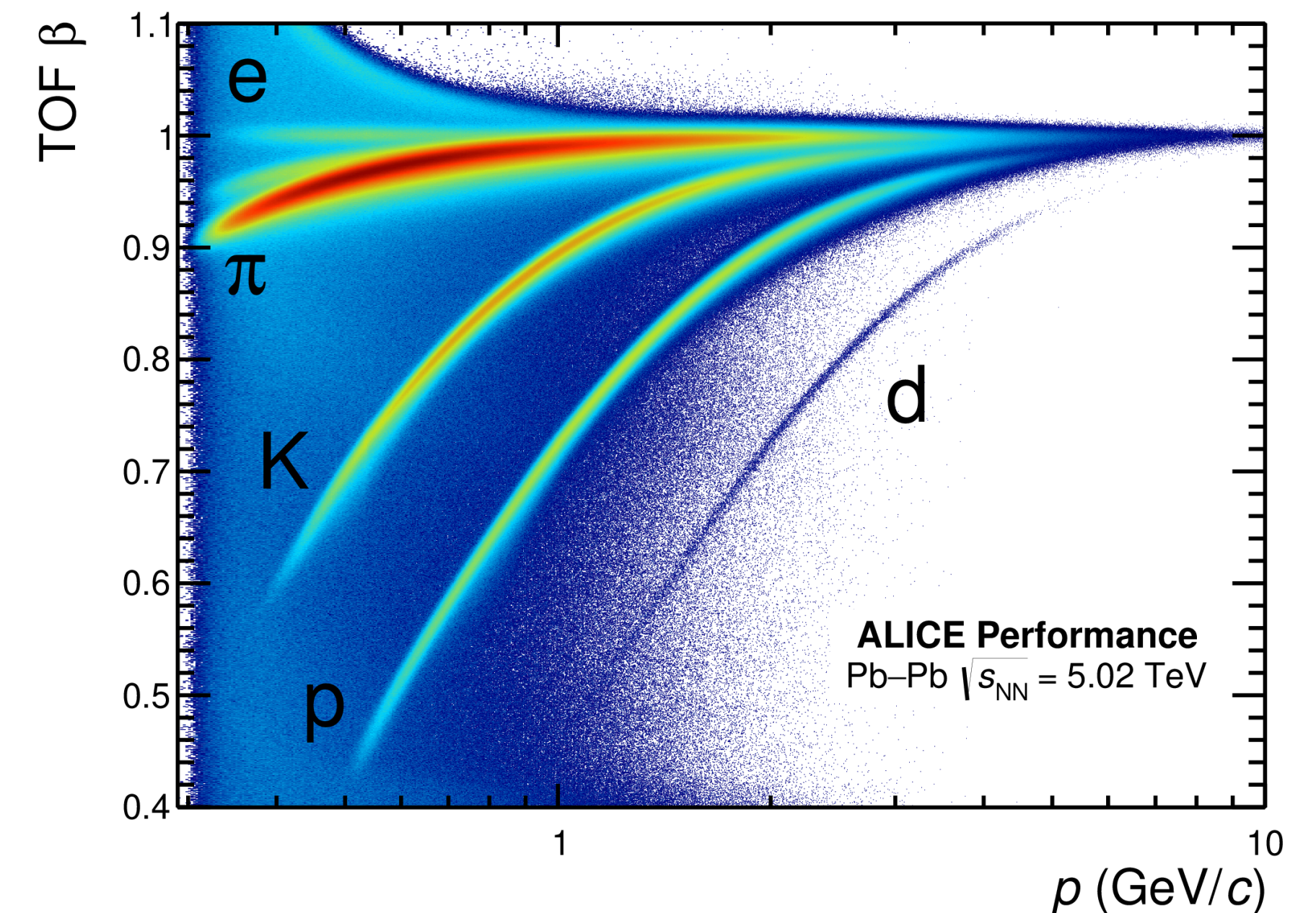
- Velocity of particle (at given momentum) depends on mass
→ different time of flight for different mass hypotheses:

$$\Delta t = \frac{L}{c} \left(\frac{1}{\beta_1} - \frac{1}{\beta_2} \right) \approx \frac{Lc}{2p^2} (m_1^2 - m_2^2)$$

- 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



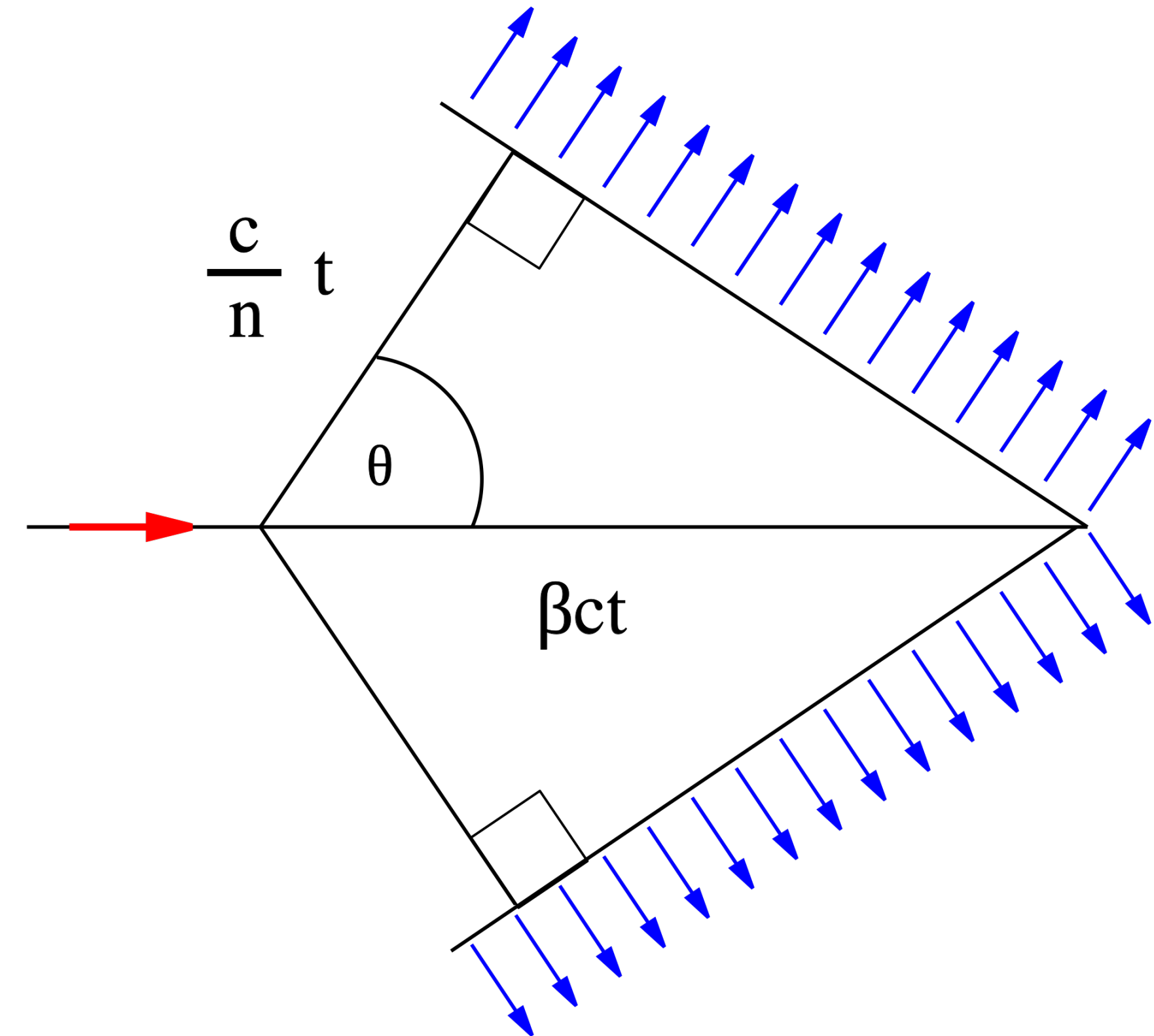
ALI-PERF-106336

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

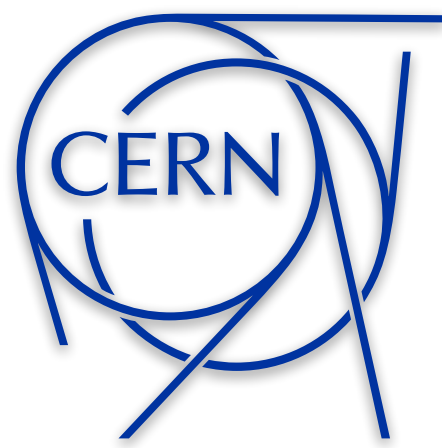
Muon identification

- **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 😊



Backup

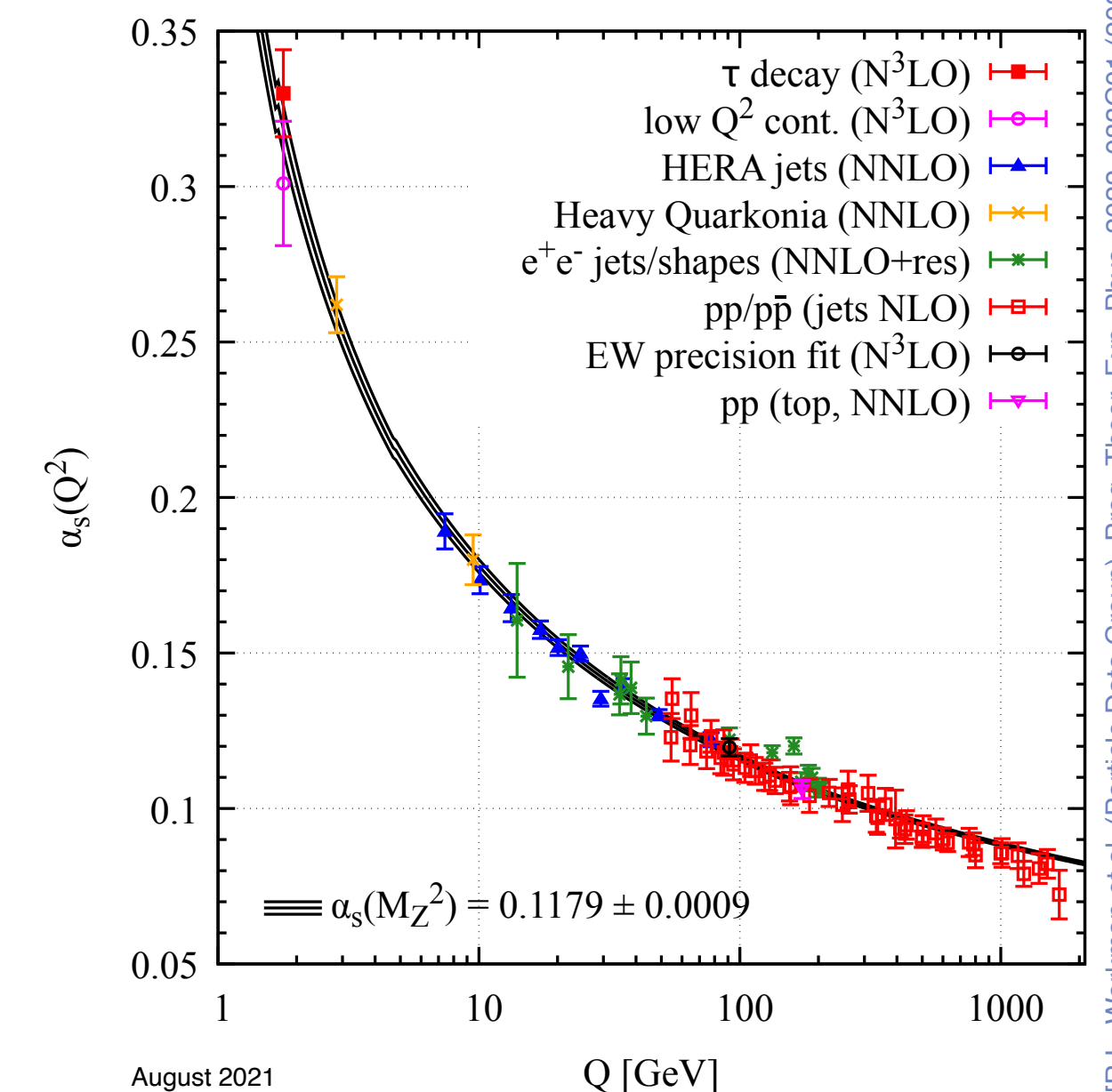
Quantum Chromodynamics

Lagrangian of Quantum Chromodynamics → strong interaction

$$\mathcal{L}_{\text{QCD}} = \bar{\psi}_i \left(i\gamma^\mu \left(D_\mu \right)_{ij} - m\delta_{ij} \right) \psi_j - \frac{1}{4} G_{\mu\nu}^a G_a^{\mu\nu}$$

- Interactions with high Q^2 well described by perturbative calculations
- Many non-trivial features of QCD emerge from low- Q^2 regime
 - confinement → no free quarks
 - chiral symmetry breaking → nucleon mass
 - fragmentation → formation of hadrons
 - QCD matter → thermodynamic properties

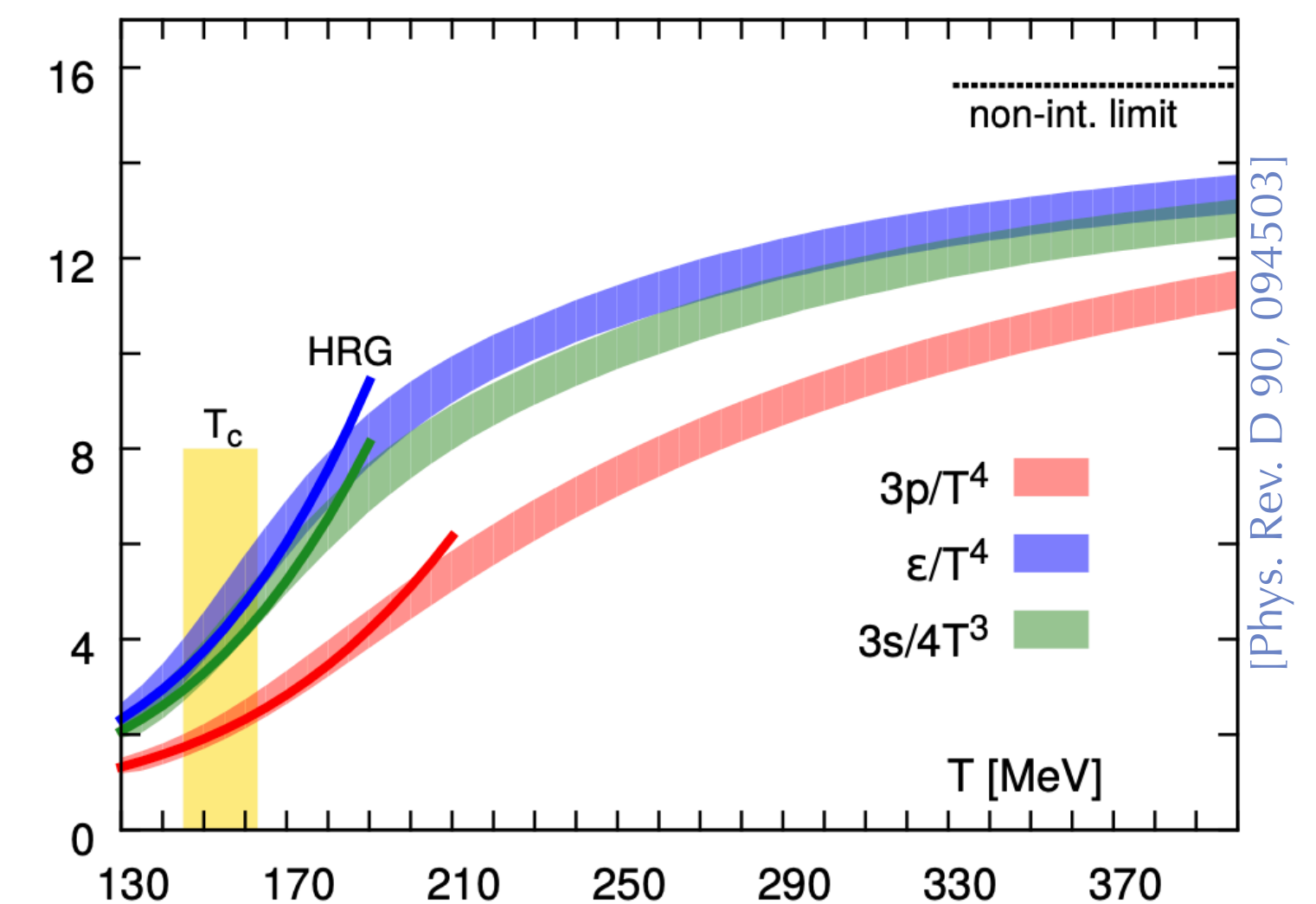
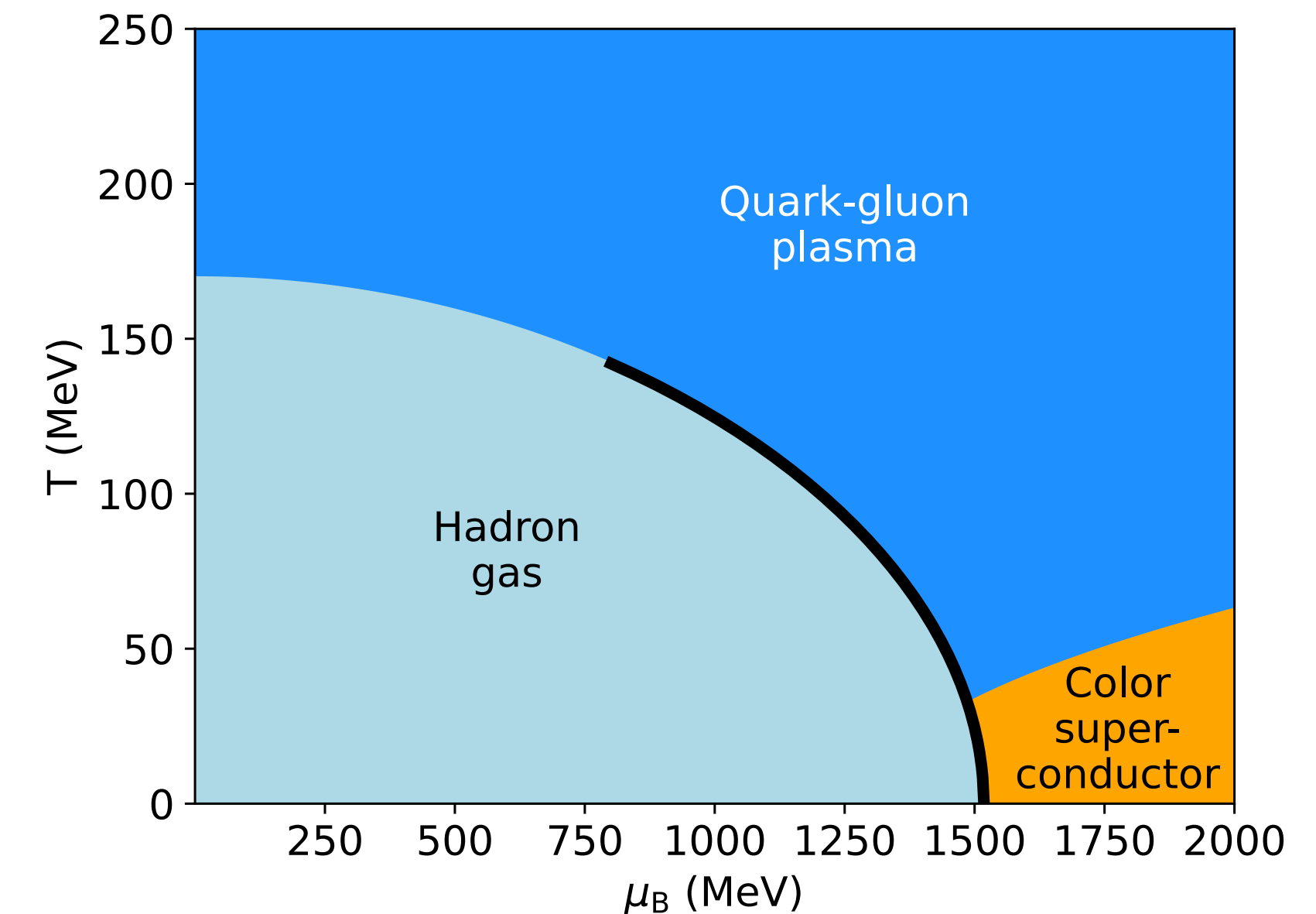
**Emerging features of QCD
of fundamental interest**



QCD matter

- Nuclear matter $\rightarrow$ QCD matter at ambient conditions
- QCD matter at different temperatures T and densities μ_B
 - deconfinement for $T \rightarrow \infty, \mu_B \rightarrow \infty$
 - 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 $T \gg T_{pc}$

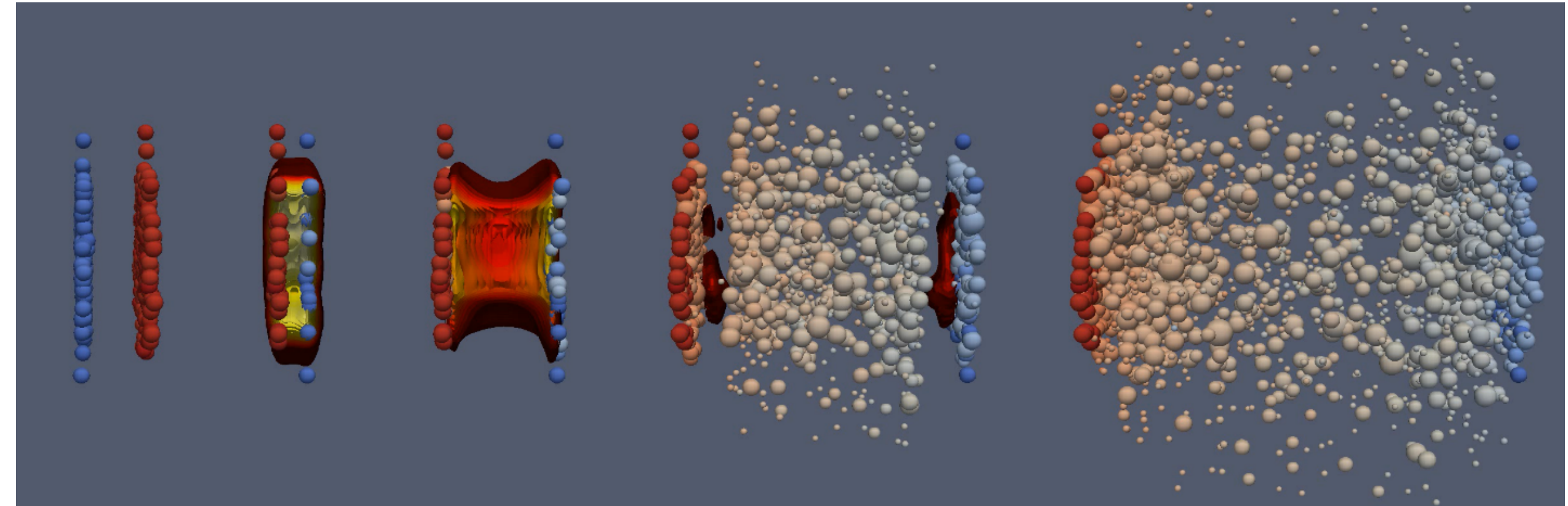
Experimental data crucial to understand QCD matter



[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



Electromagnetic radiation ($\propto T^2$)

Hadron momentum distributions, azimuthal anisotropy

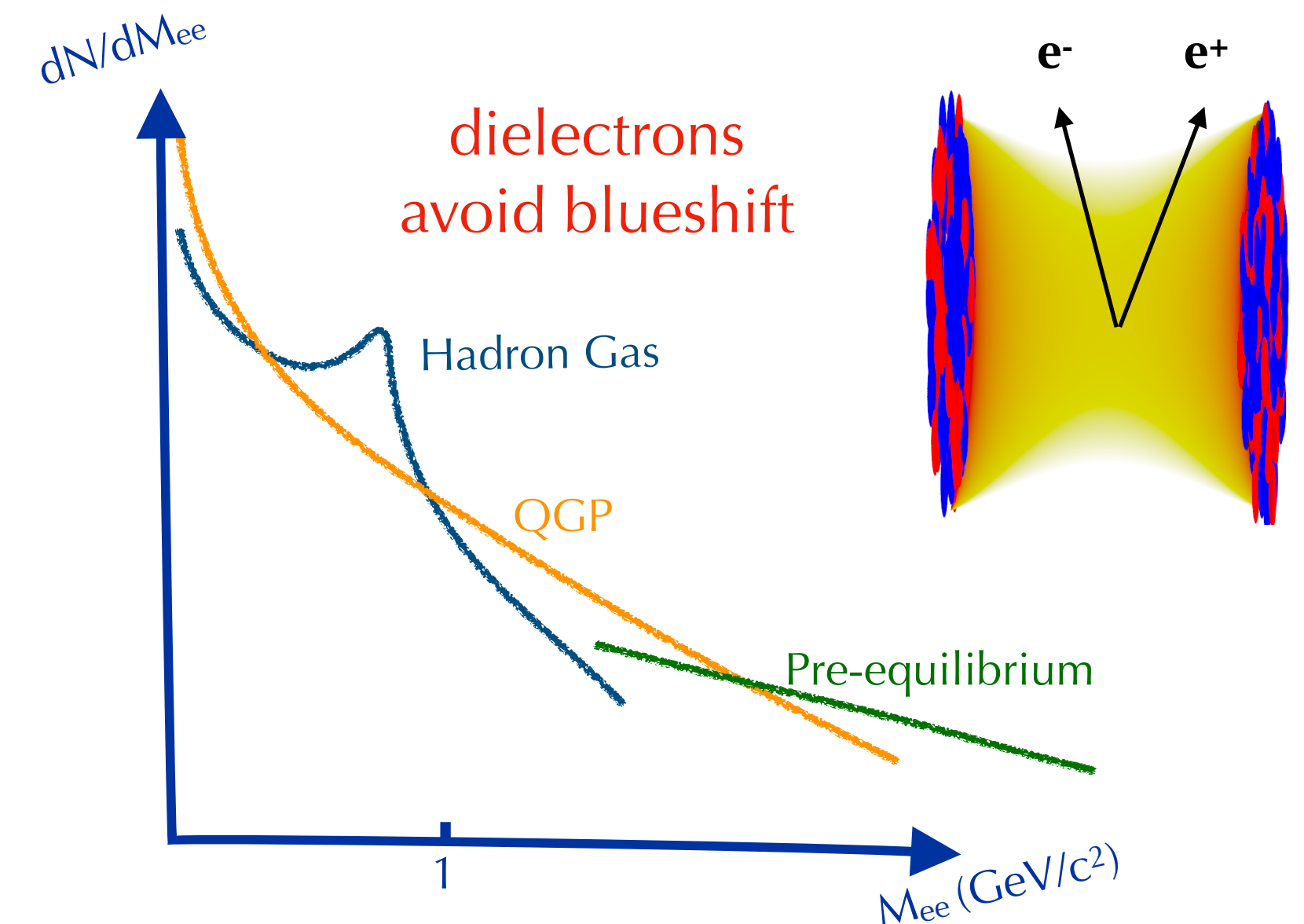
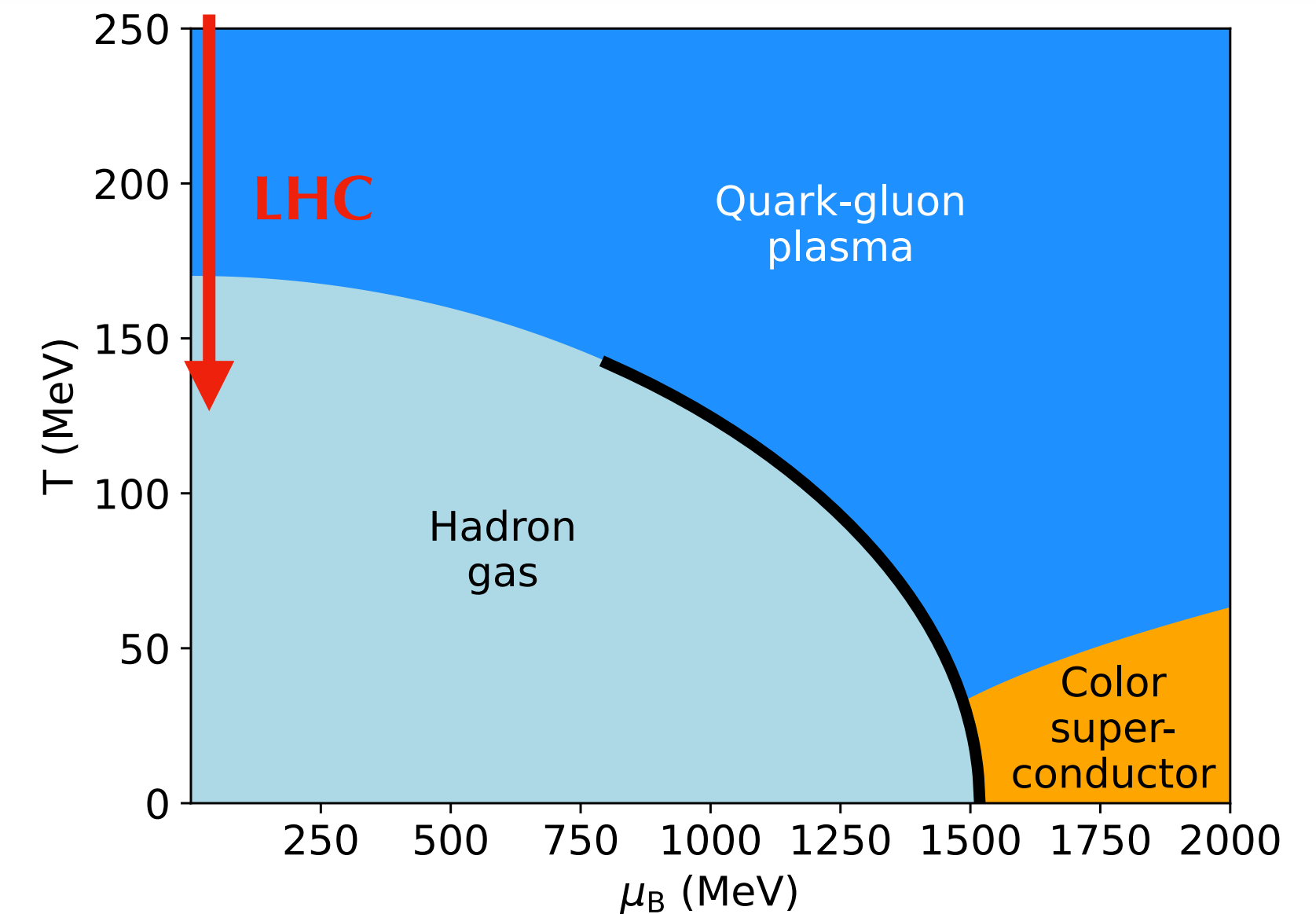
Hadron abundances 'hadrochemistry'

Hadron correlations, fluctuations

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

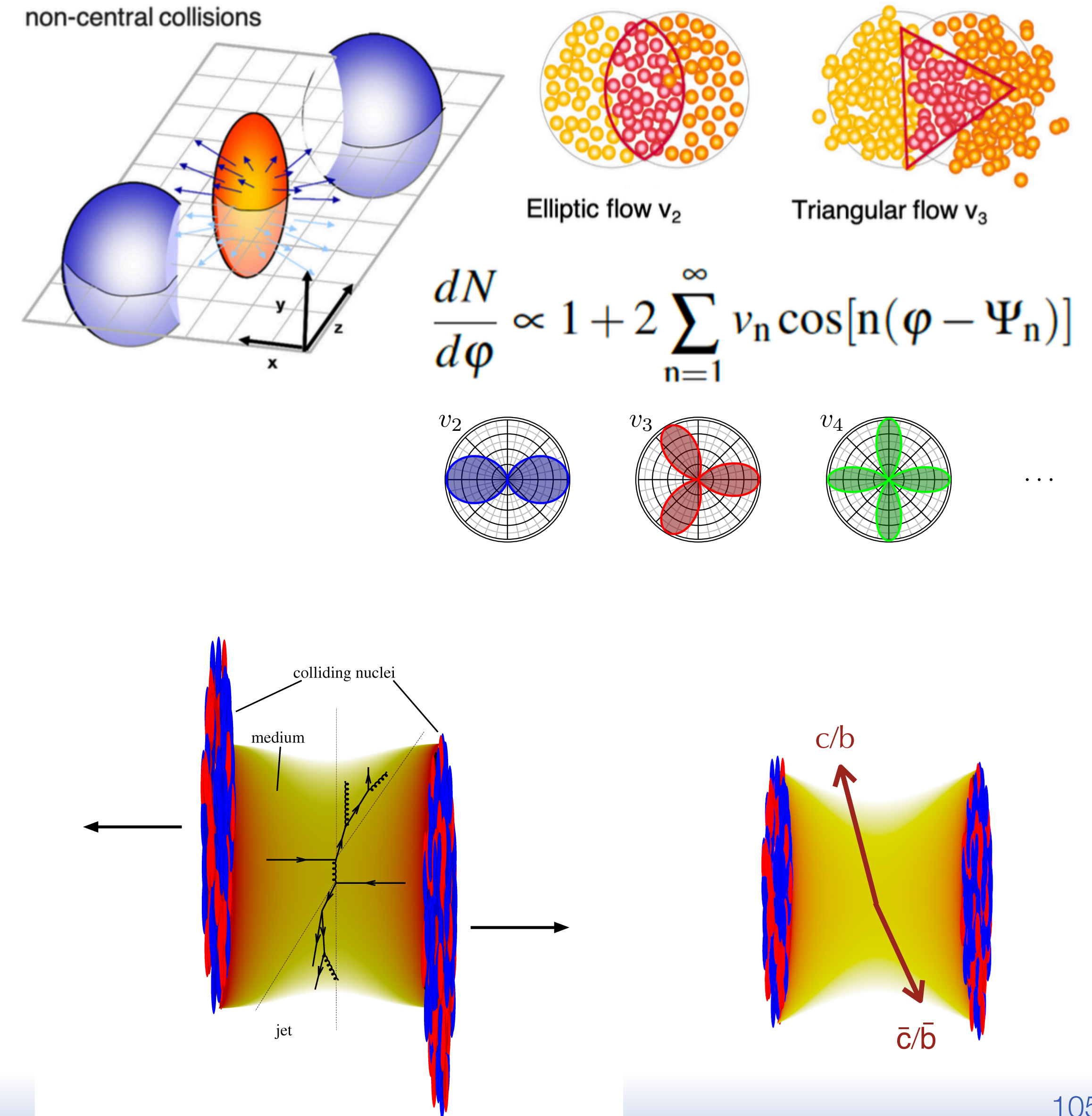
Quark-gluon plasma

- 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



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

