Heavy-ion physics with ALICE at the LHC

CERN-Korean summer student program

CERN
June 28th, 2023

Jochen Klein (CERN)

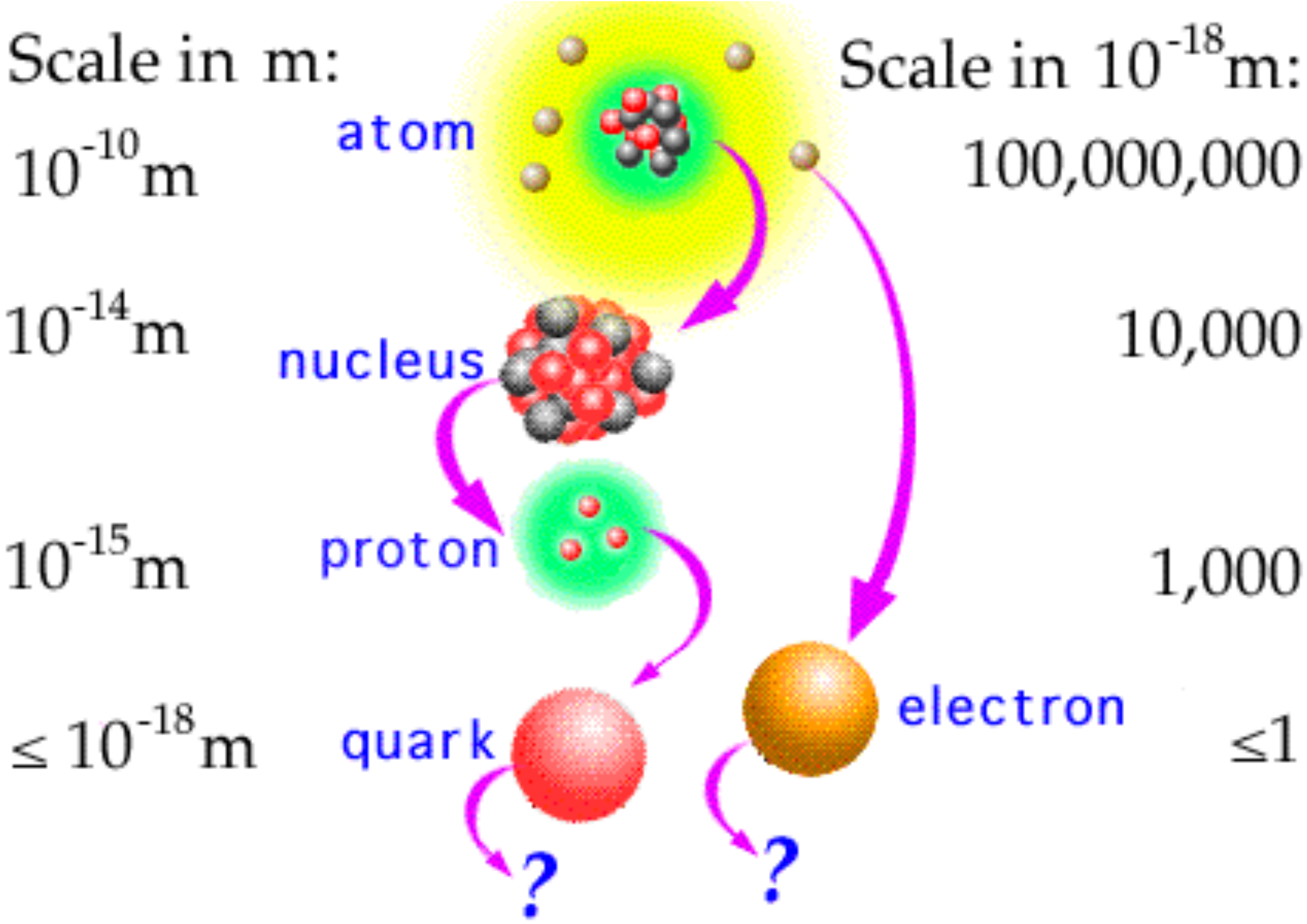
Outline

- **Matter and interactions**
  - role of strong interaction
- **Heavy-ion collisions**
  - observables and results
- **Experimental approach**
  - LHC programme
  - ALICE status and upgrades
- **Prospects**
  - questions and expected results

In this presentation:
concepts and connections,
no rigorous derivations

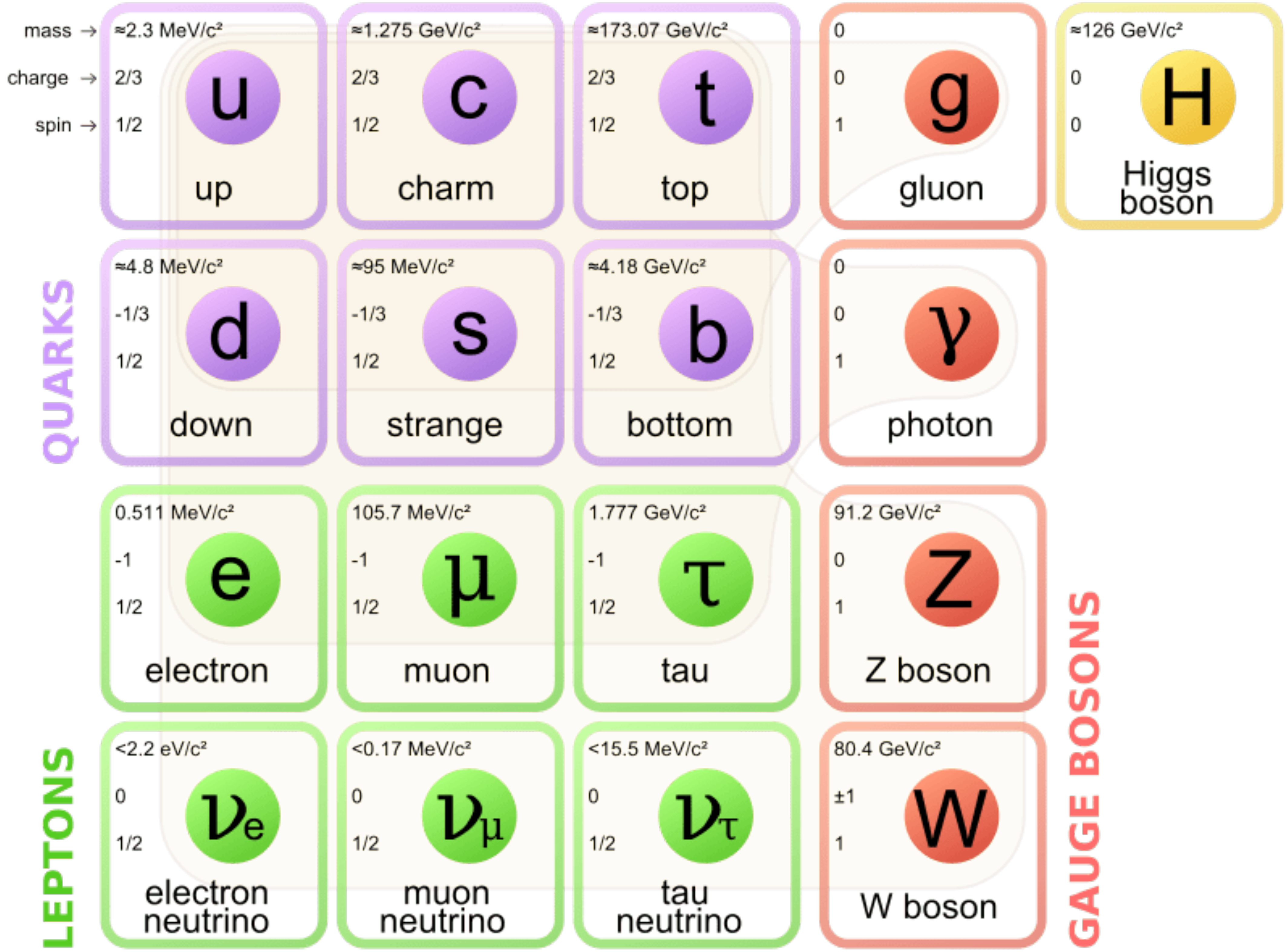
Composition of matter

- Discovery of electrons
  → electromagnetic interaction
- Discovery of nuclei
  → electromagnetic interaction
- Discovery of nucleons
  → strong interaction
- **Quarks, gluons and electrons as fundamental building blocks**
- Discovery of many more (unstable) particles



Fundamental particles and interactions

- **Standard Model of particle physics** summarises our understanding
  - 3 families of quarks
  - 3 families of leptons
  - gauge bosons as carriers of interactions
    - photon → electromagnetic interaction
    - gluon → strong interaction
    - W,Z → weak interaction
  - Higgs boson
    → mass of gauge bosons



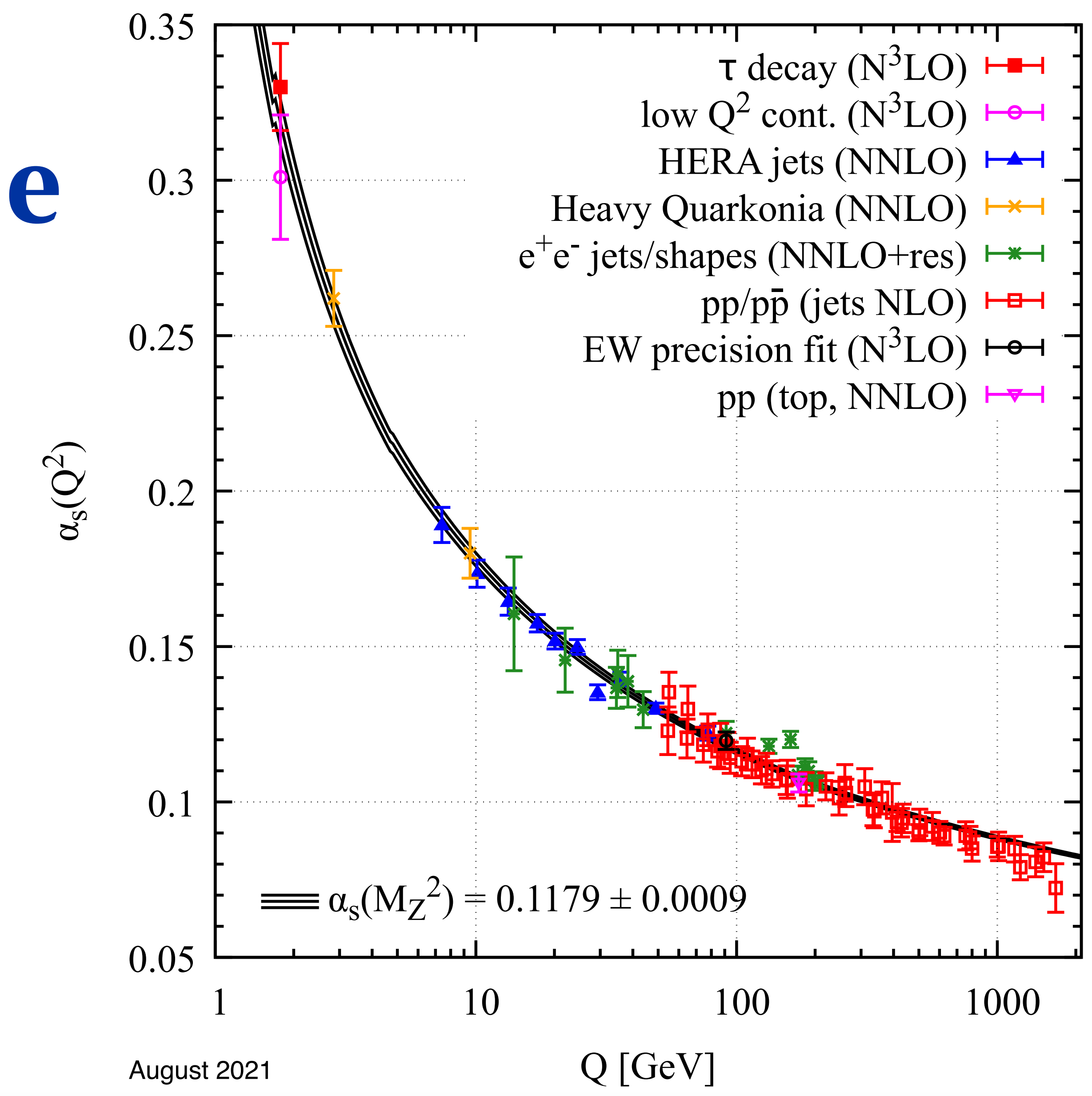
NB: gravity is not included here

Strong interaction

Description in terms of Quantum Field Theory → **Quantum Chromodynamics**

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

- **Running coupling**
- **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

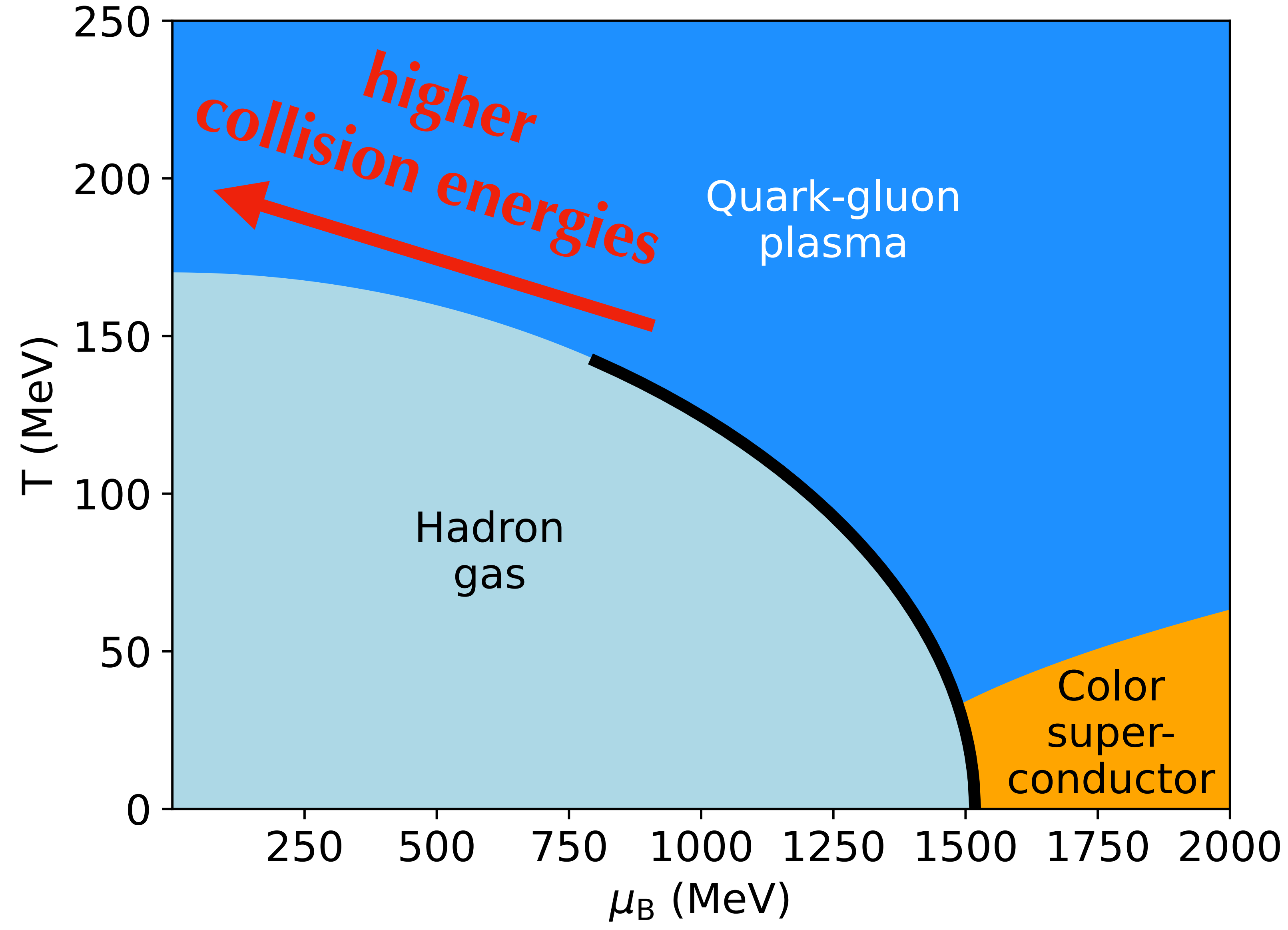


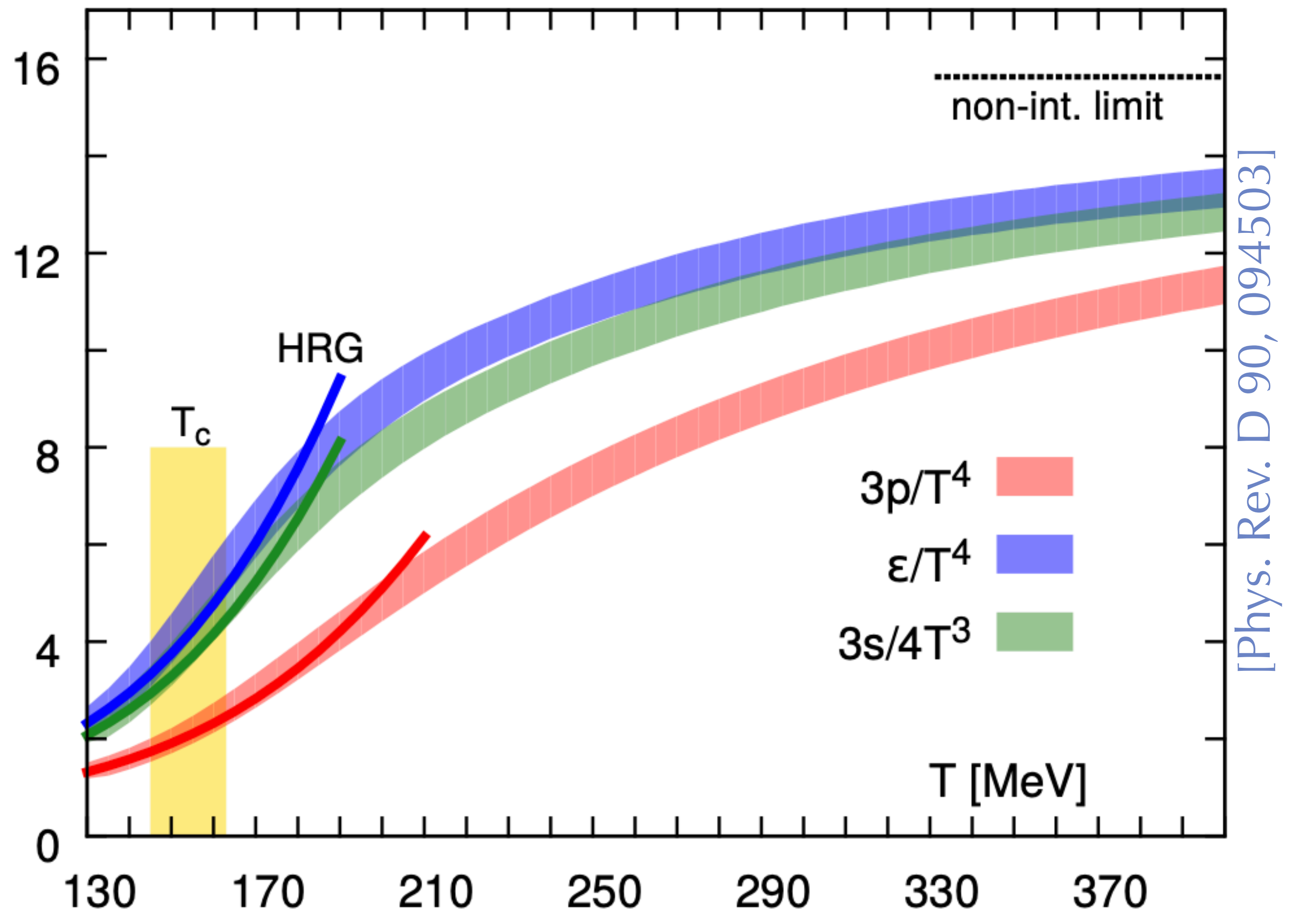
[R.L. Workman et al. (Particle Data Group), Prog. Theor. Exp. Phys. 2022, 083C01 (2022)]

QCD matter

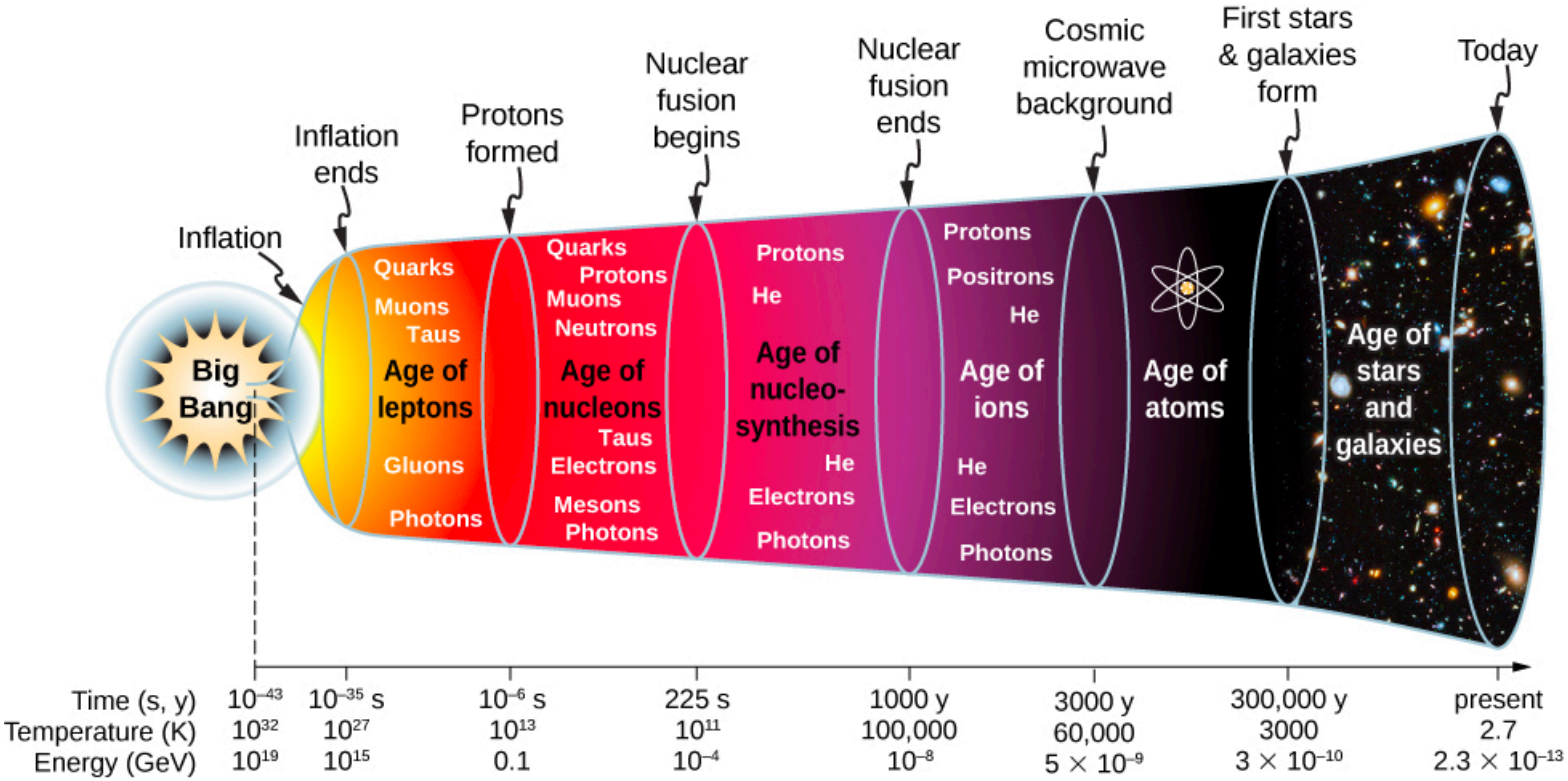
- **Nuclear matter** → QCD matter at ambient conditions
- **QCD matter at different temperatures (T) and densities (μ_B)**
  - asymptotic freedom of QCD
    → **deconfinement** for T → ∞, μ_B → ∞
  - **chiral symmetry restoration**
  - **superconductivity**
- Numerical calculations of **QCD on a discretised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

Experimental data crucial to understand QCD matter



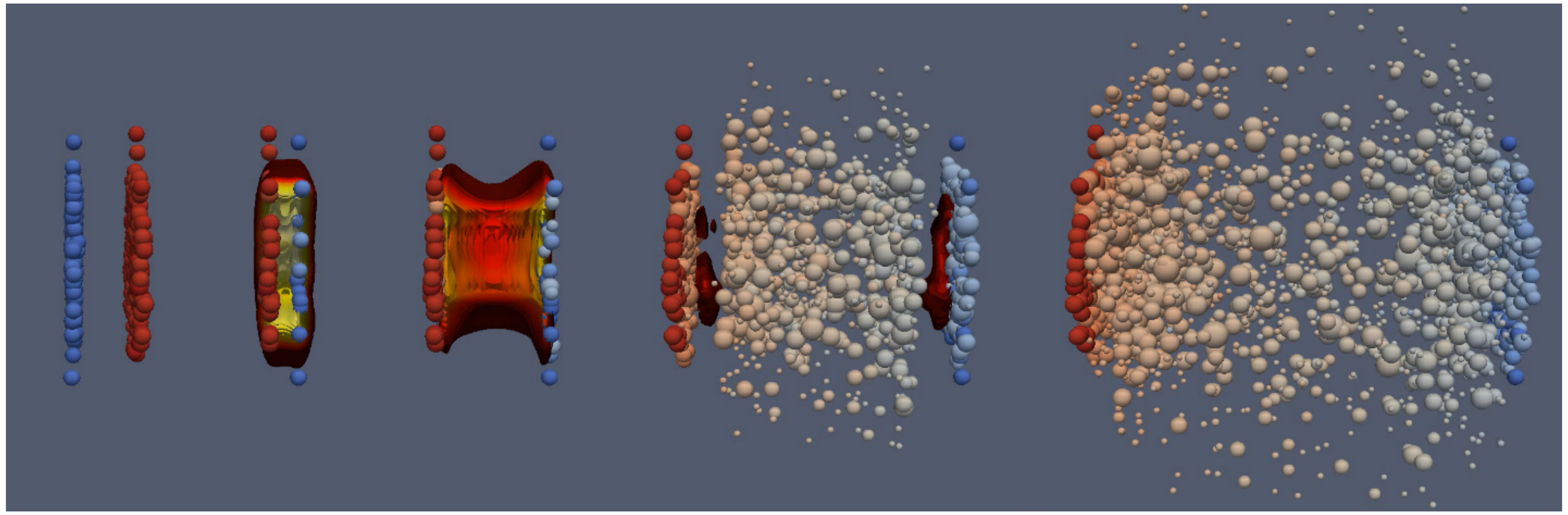


Early universe



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

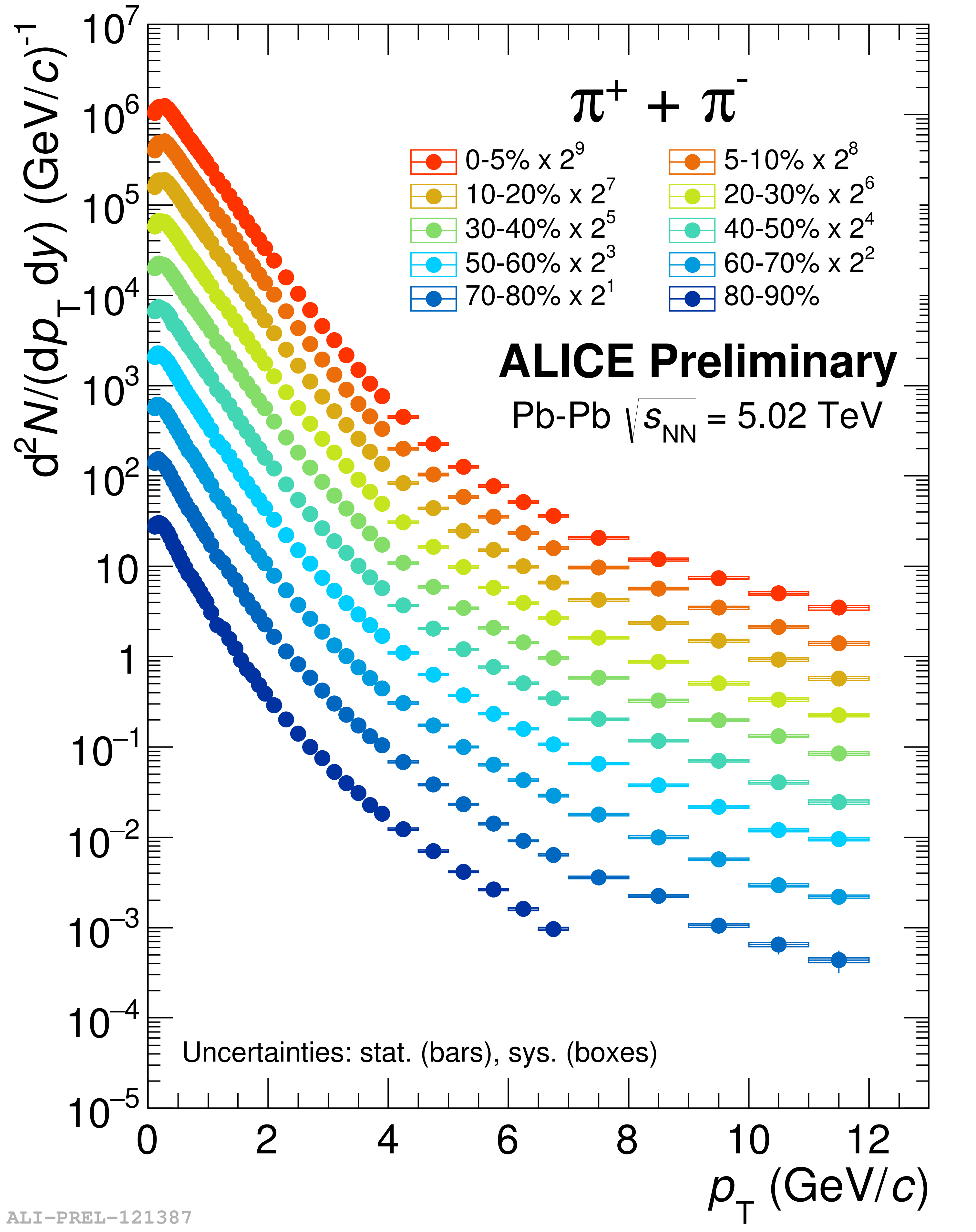
Hadron momentum distributions, azimuthal anisotropy

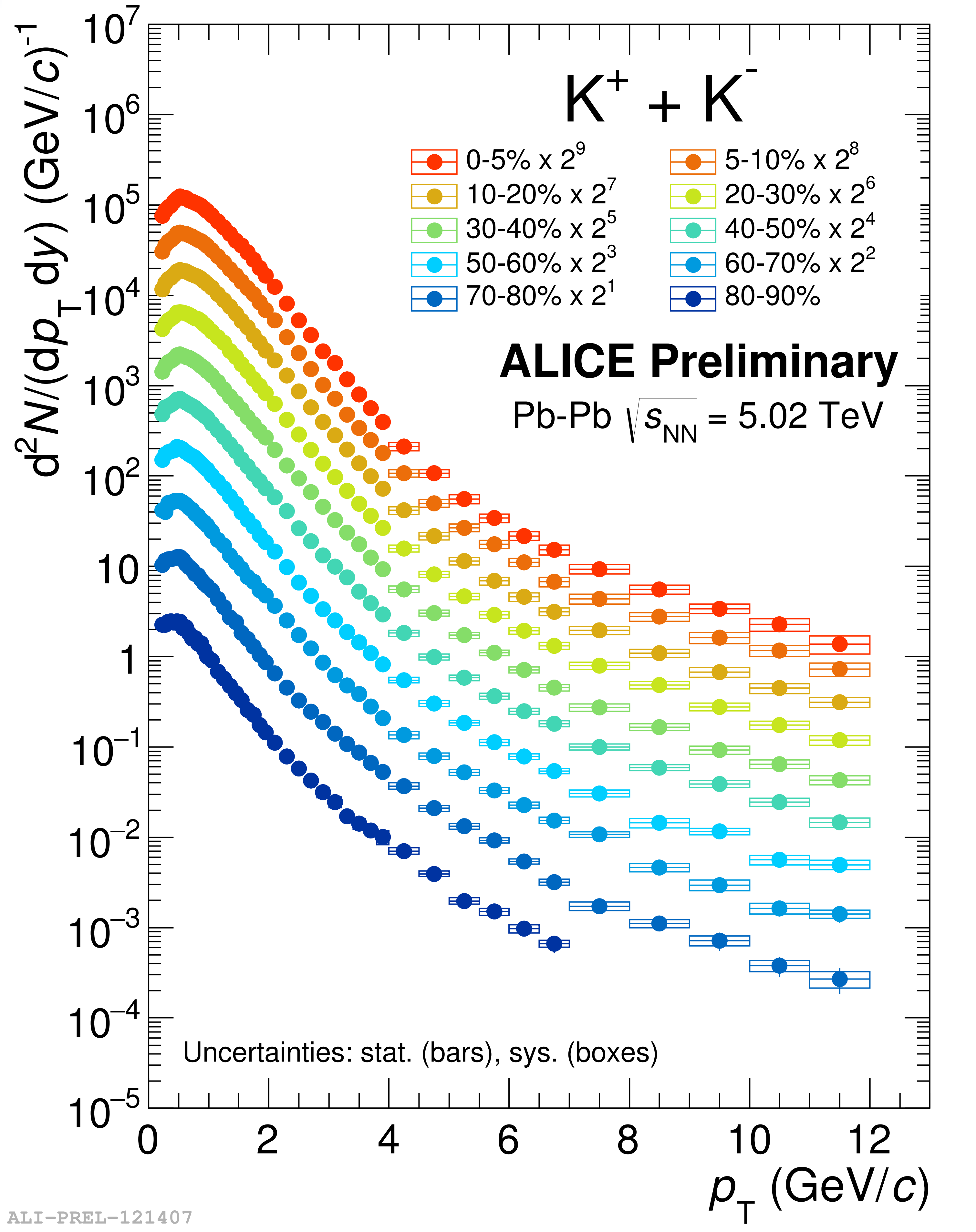
Hadron abundances 'hadrochemistry'

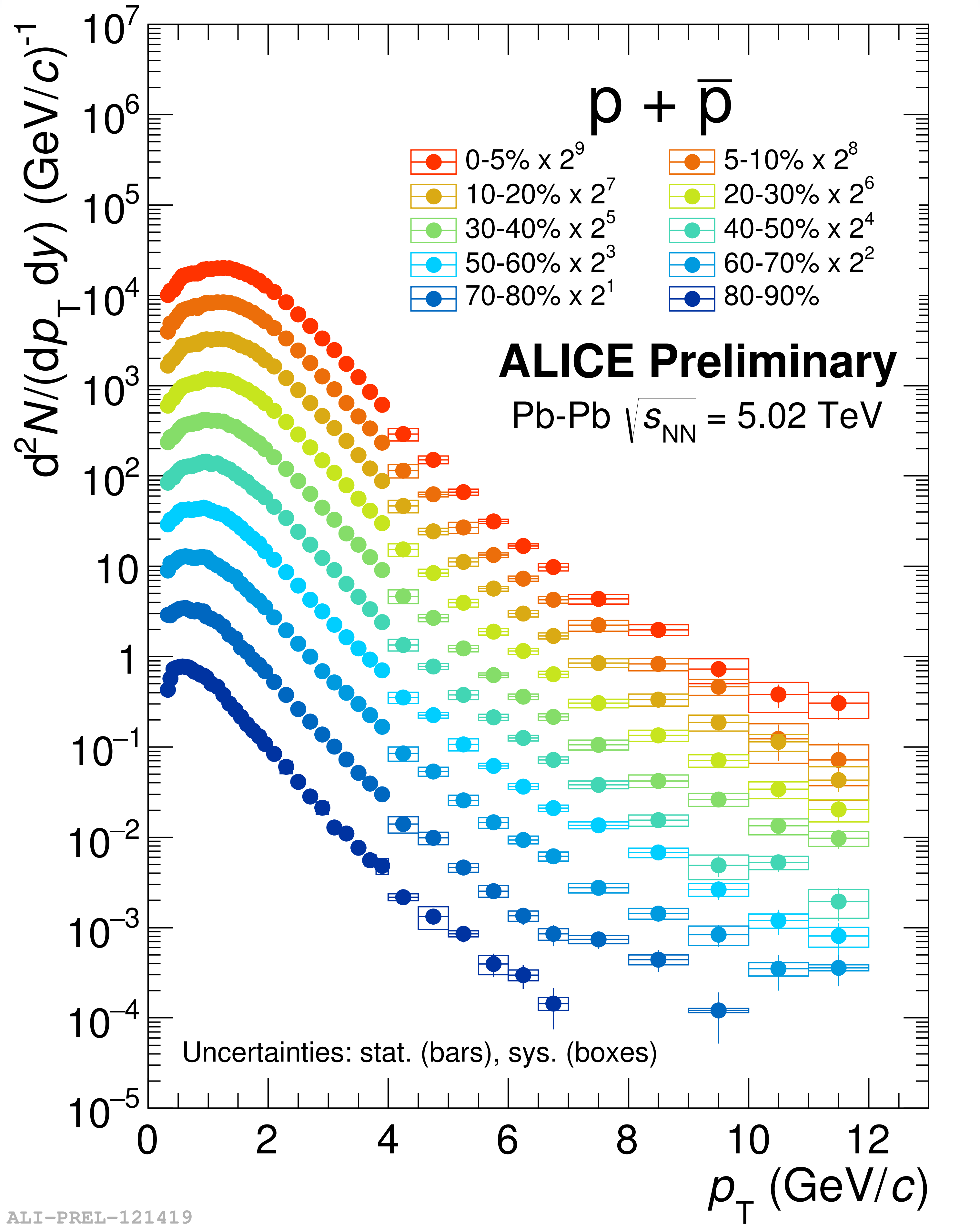
Hadron correlations, fluctuations

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

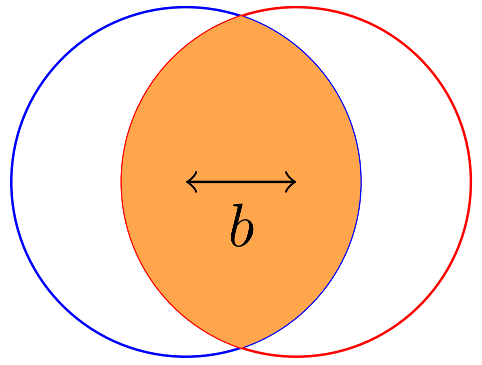
Particle spectra



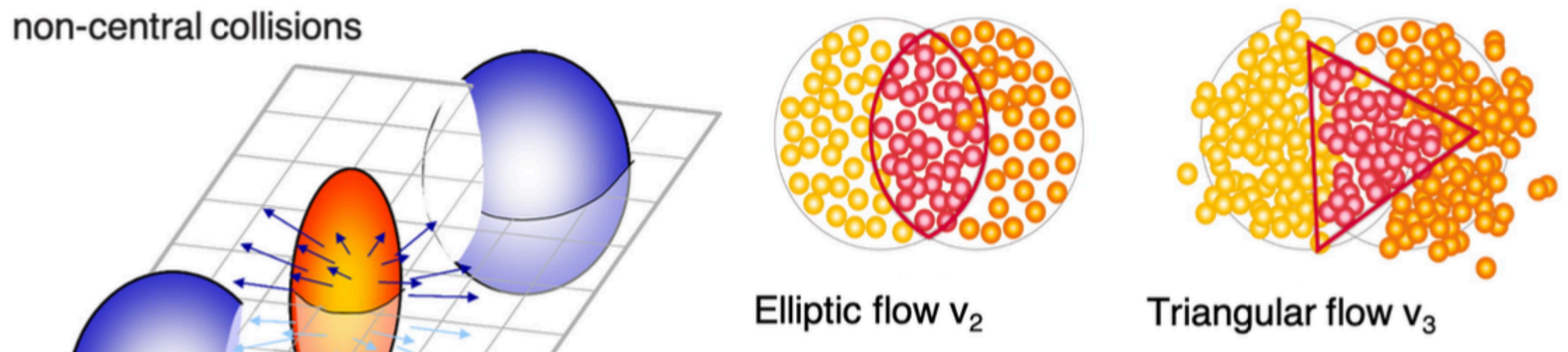




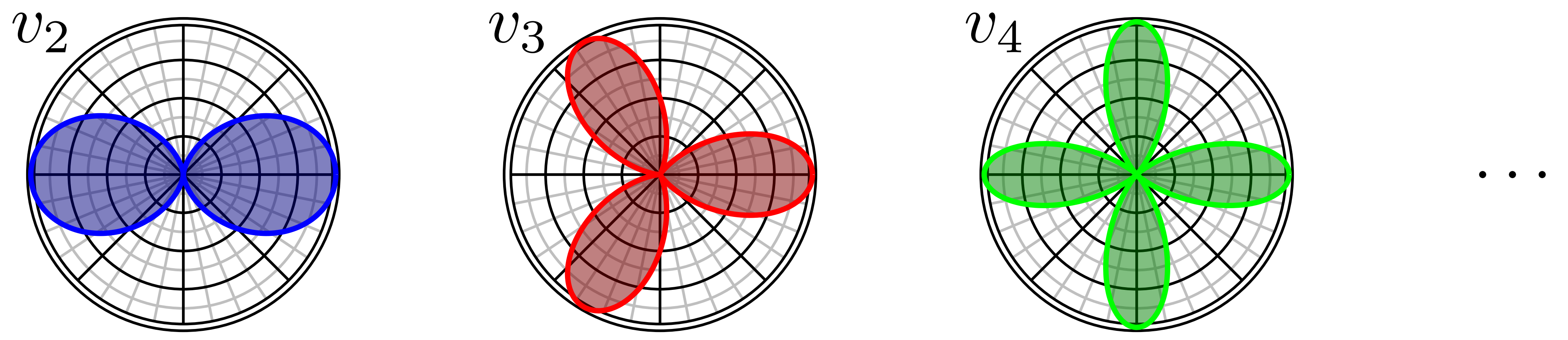
- **precision measurements of identified particles**
  - exponential spectrum → thermal production
  - velocity as common parameter → radial expansion



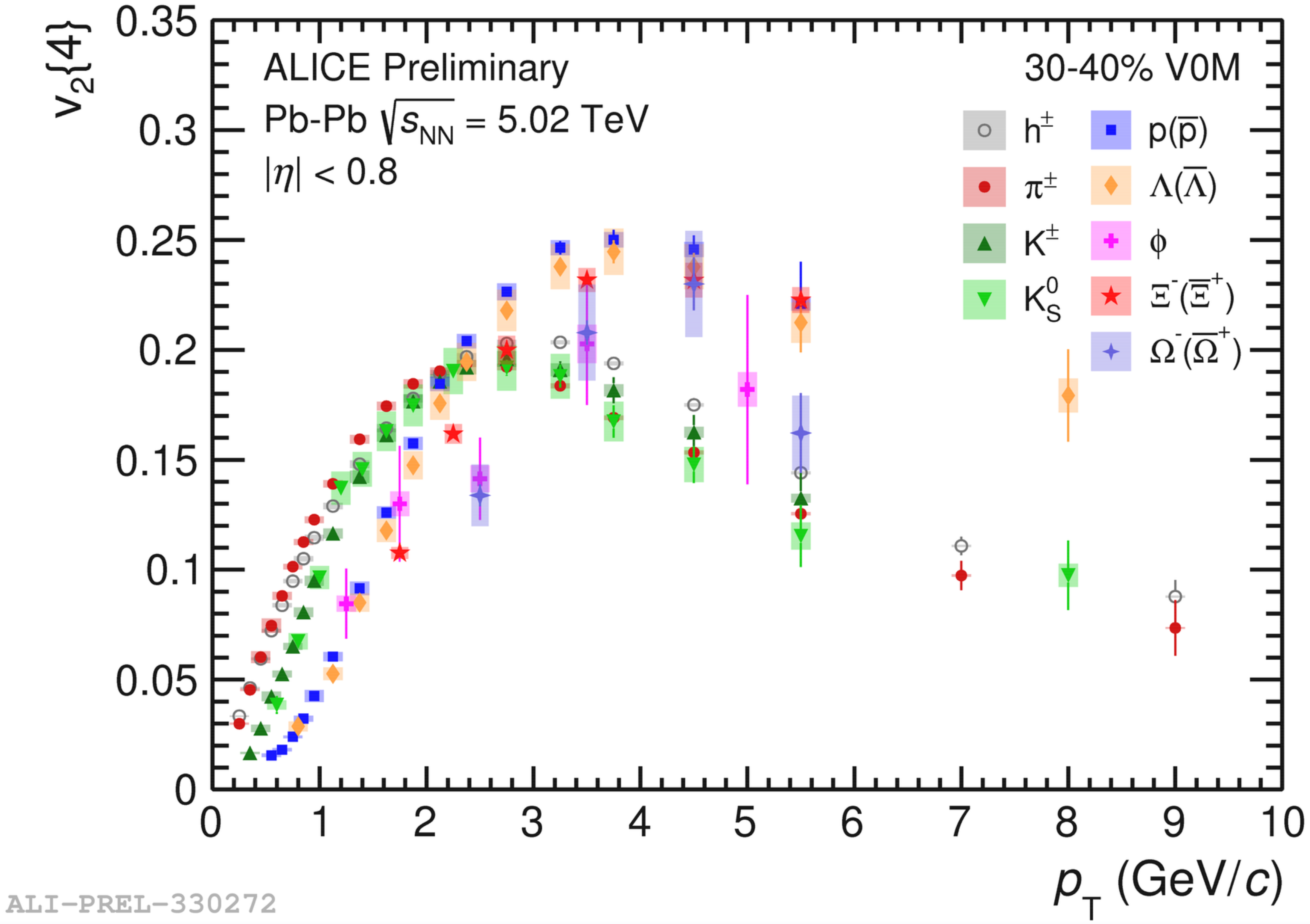
Azimuthal anisotropies



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

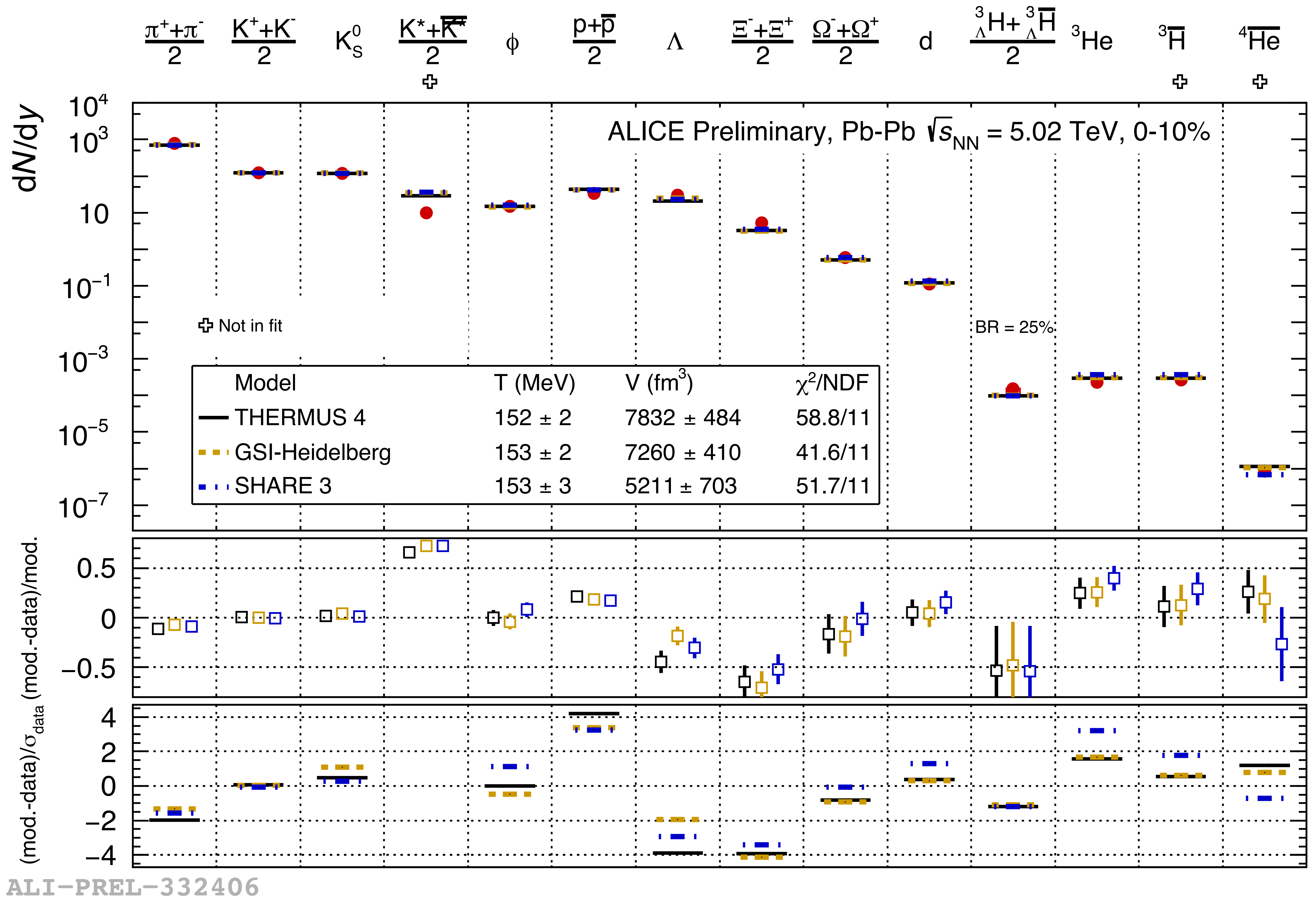


- quantify azimuthal anisotropy by Fourier coefficients v_n
  - v_2 mostly driven by overlap geometry
  - higher orders mostly by fluctuations (no odd harmonics in average geometry)
- **observations consistent with expansion following relativistic hydrodynamics**



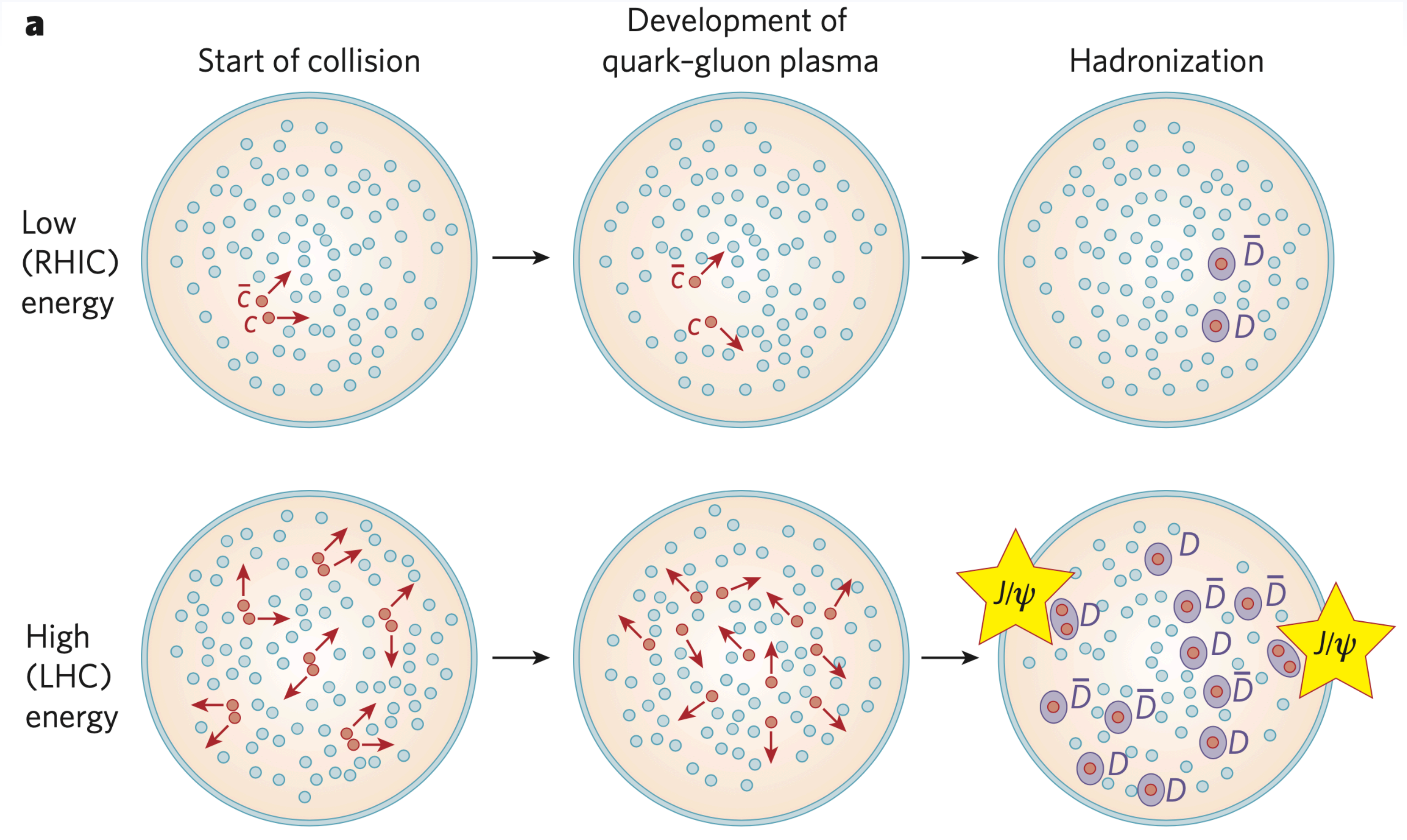
Statistical hadronisation

- thermal models describe hadron yields based on few parameters:
  - temperature
  - baryochemical potential
  - volume
- work well for hadrons from thermally produced quarks (u, d, s)
  → **hadronic states populated according to thermal distribution**
- what about heavy-flavour quarks produced in initial scatterings

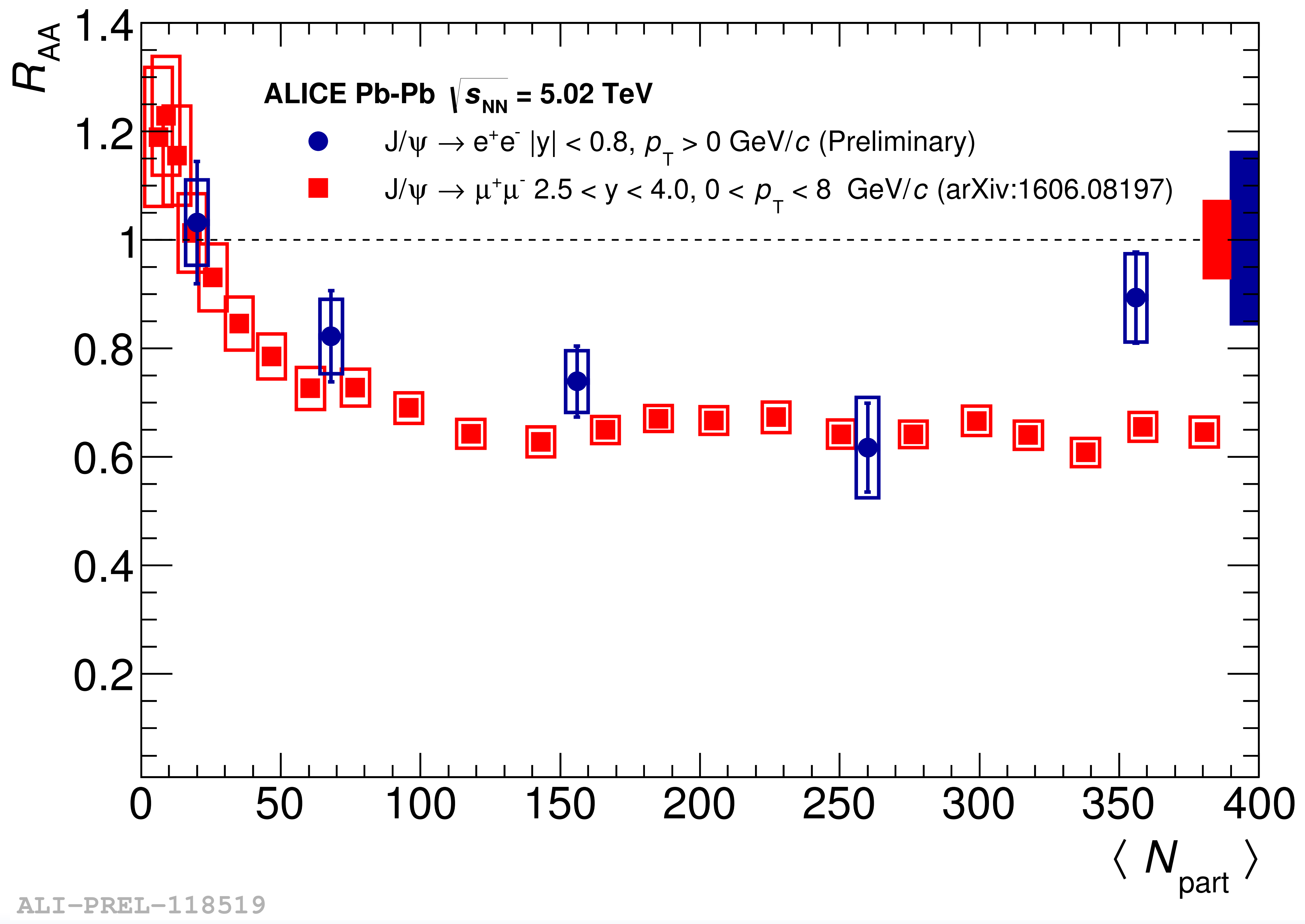


Melting and recombination

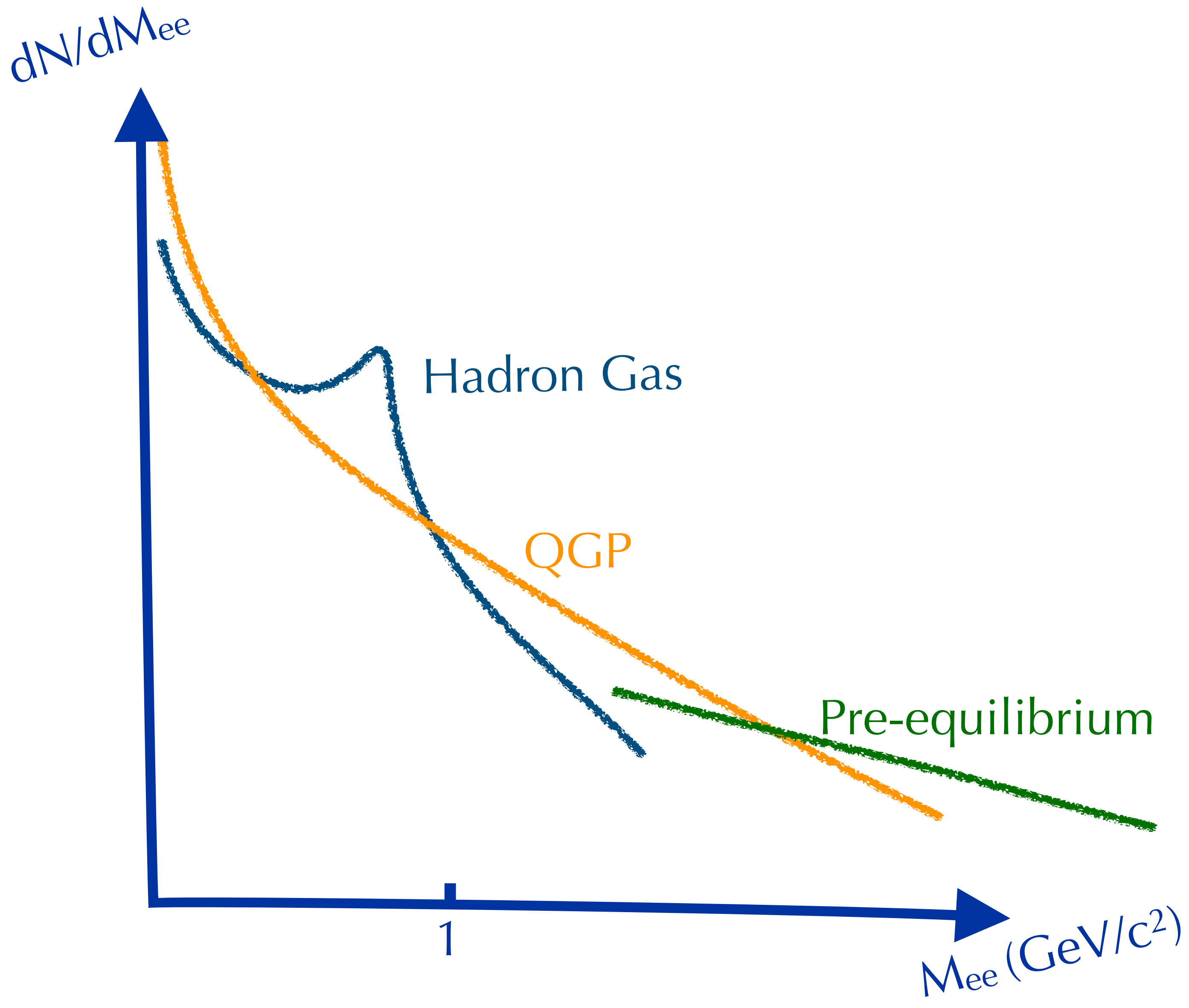
- production of $c\bar{c}$ pairs
- charmonium states (J/ψ, ψ(2S), …) take double role
  - dissociation (melting)
  - recombination
- **suppression of J/ψ from dissociation counteracted by recombination**

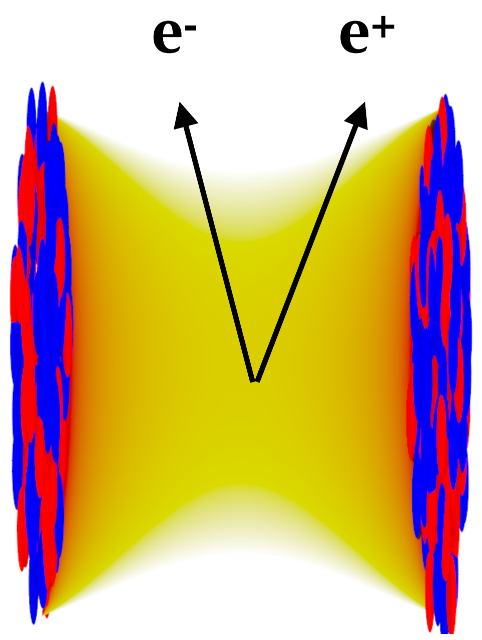


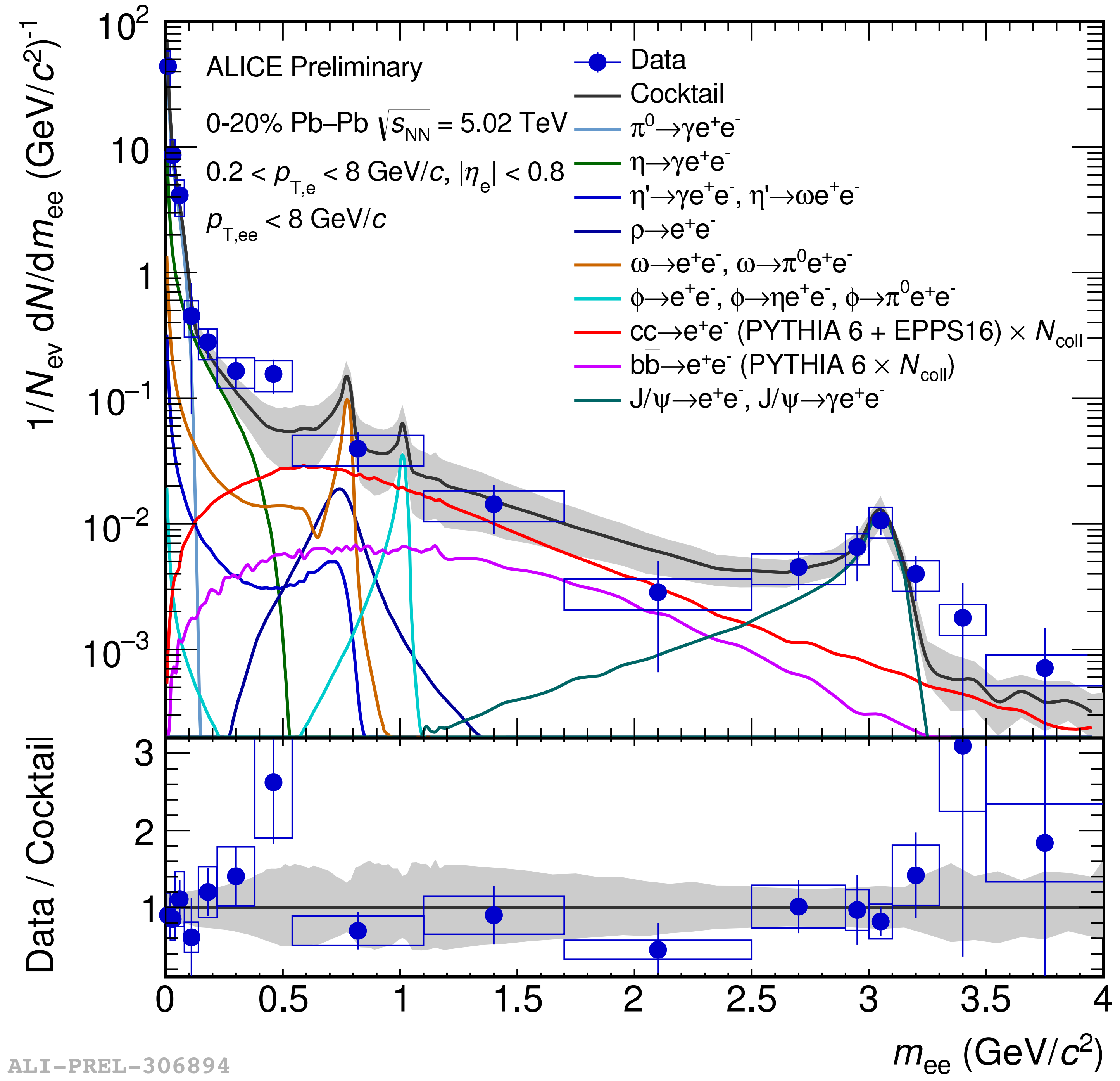
Cartoon from Nature 448, 302–309(2007)



Plasma temperature







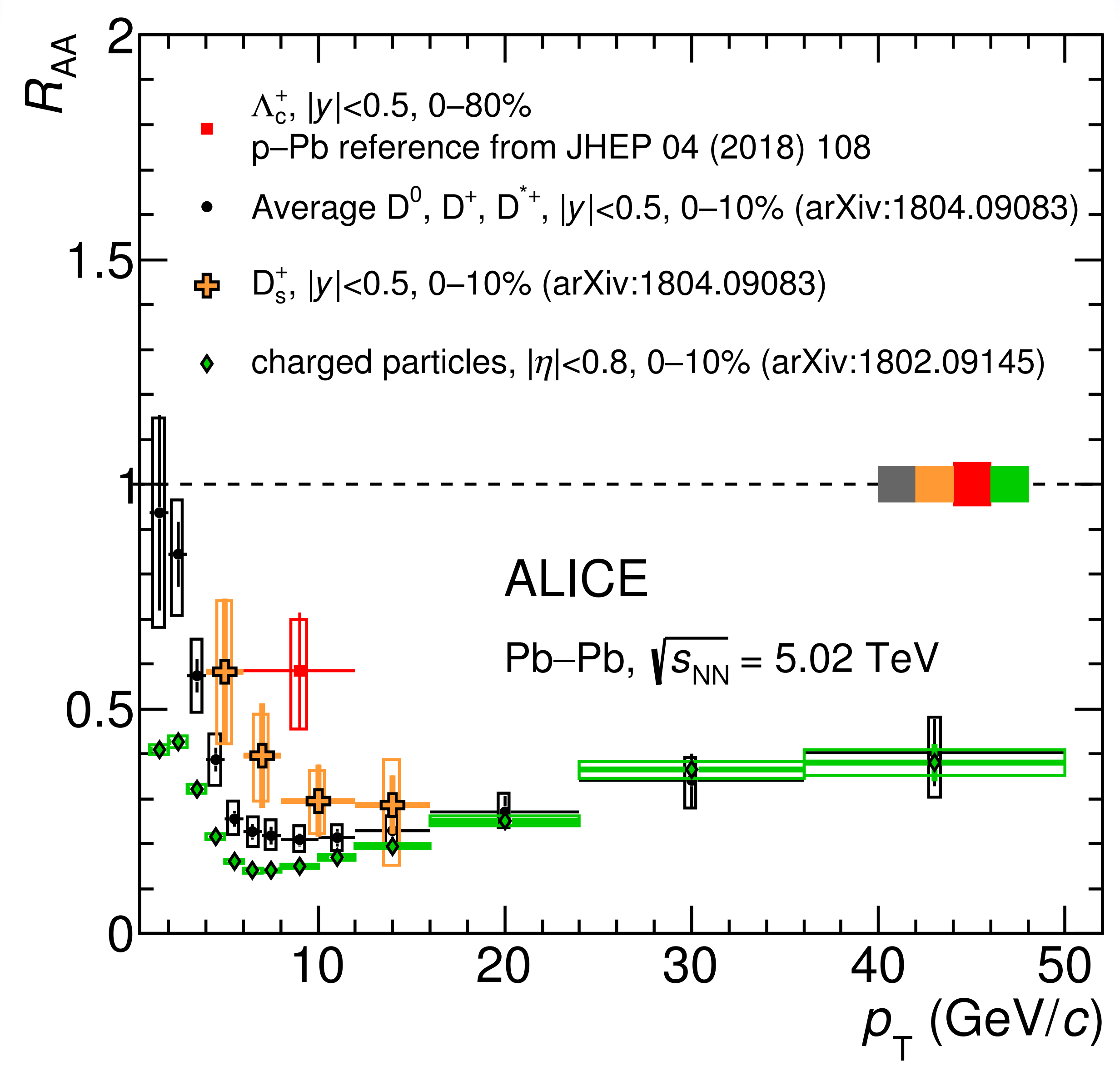
- Use electromagnetic probes to look behind the curtain of hadronisation
  - dielectrons are produced thermally throughout the evolution of the system → carries information on temperature
  - large backgrounds from heavy-flavour decays

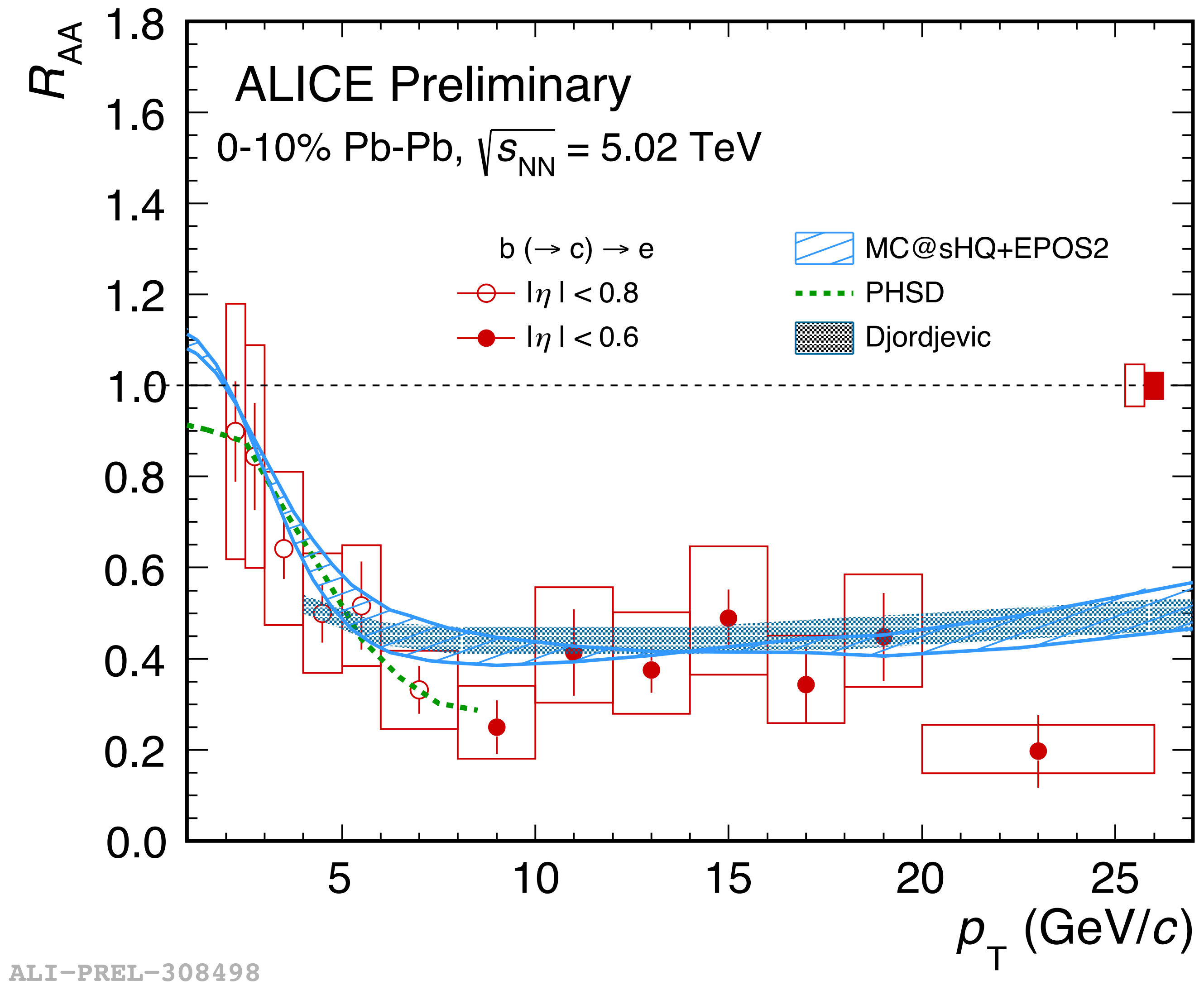
Quenching

- compare Pb-Pb collision with incoherent superposition of pp collisions:

$$R_{AA} = \frac{\mathrm{d}N^{AA}/\mathrm{d}p_T}{\langle N_{coll} \rangle \, \mathrm{d}N^{pp}/\mathrm{d}p_T}$$

- significant suppression in Pb-Pb w.r.t. pp, hint of ordering:
  - charged hadrons
  - D mesons
  - Ds
  - b (→ c) → e
  - Λ_c





LHC programme

	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6
Collision systems	pp, pPb, Pb-Pb	pp, pPb, Xe-Xe, Pb-Pb	pp, pO, OO, pPb, Pb-Pb	pp, pPb, Pb-Pb	pp, pA?, AA	pp, pA?, AA
LHC schedule	2009 - 2013	2015 - 2018	2022 - 2025	2029 - 2032		

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

Run 5 → higher luminosities for ions

Run 4 → HL-LHC (higher pp luminosities)

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

Various collision systems at the LHC
provide highest energies and **ideal and unique environment**

- highest energy density (> 12 GeV/fm^3) and temperature (≳ 300 MeV)
- longest lifetime (≳ 10 fm/c)
- largest heavy-flavour yields (~200 c/$\bar{c}$ in central Pb-Pb collision)
- vanishing net-baryon density ($\mu_B \approx 0$)

LHC experiments

	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6
Collision systems	pp, pPb, Pb-Pb	pp, pPb, Xe-Xe, Pb-Pb	pp, pO, OO, pPb, Pb-Pb	pp, pPb, Pb-Pb	pp, pA?, AA	pp, pA?, AA
LHC schedule	2009 - 2013	2015 - 2018	2022 - 2025	2029 - 2032		

High luminosity for ions

HL-LHC

Higher luminosities for ions

Experiment				
ATLAS	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

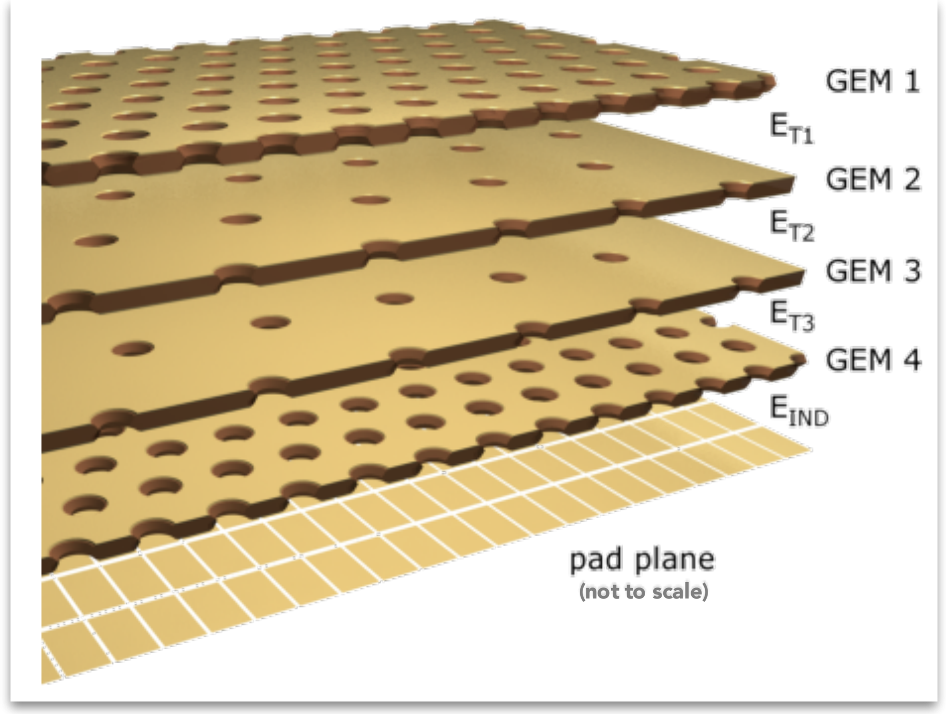
→ **Upgrades of all LHC experiments scheduled according to priorities**

intermediate upgrade | major upgrade

ALICE 2

Time Projection Chamber

- new readout chambers: MWPC → GEM



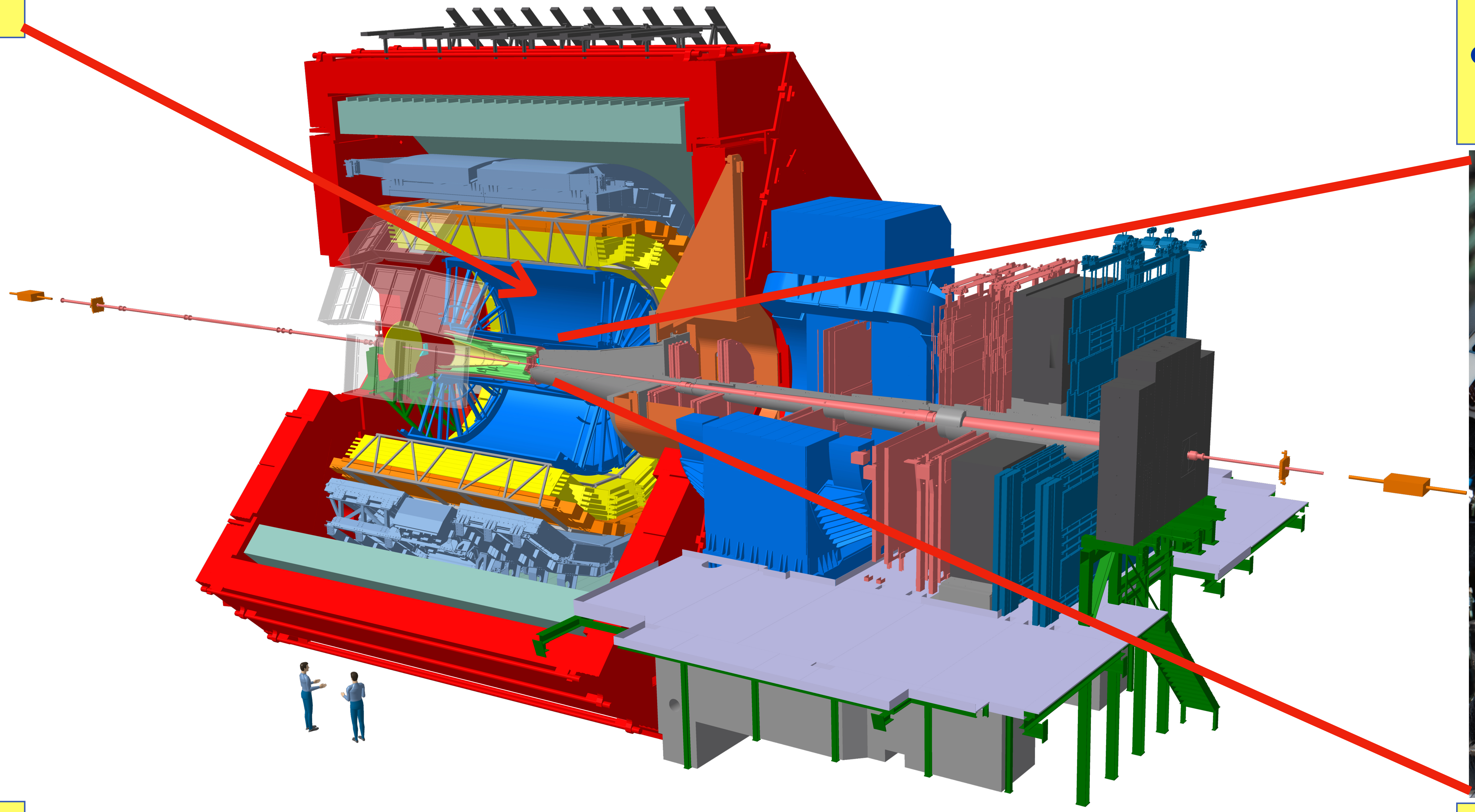
Integrated on-/off-line system

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

Consolidation and readout upgrade of all subsystems

Fast Interaction Trigger

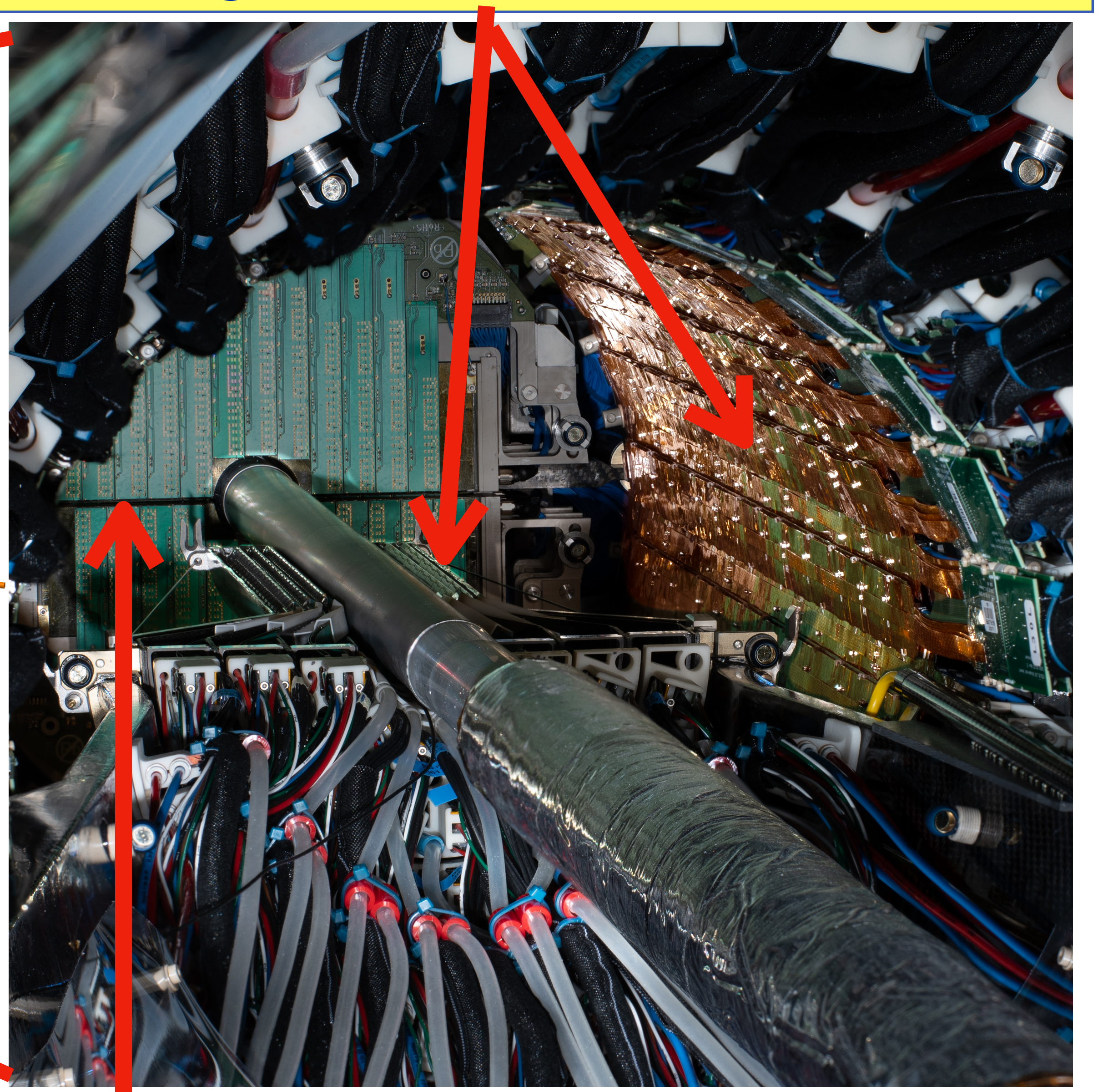
- new detectors



Major upgrade completed
→ continuous readout with improved vertexing
(publication in special issue of JINST)

Inner Tracking System

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



Muon Forward Tracker

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

[arXiv:2302.01238]

ALICE 2.1

Time Projection Chamber

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

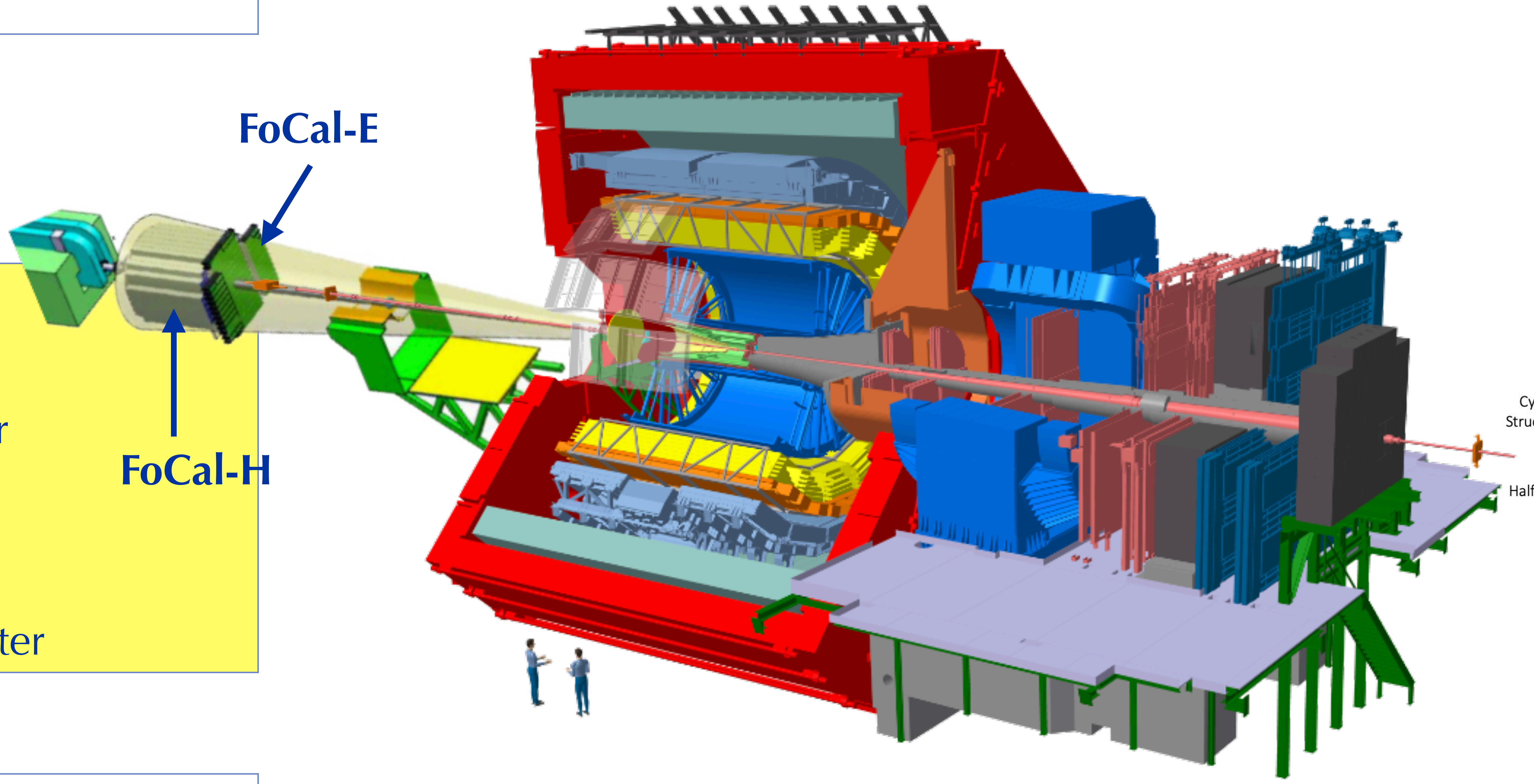
Consolidation and readout upgrade of all subsystems

Fast Interaction Trigger

- new detectors

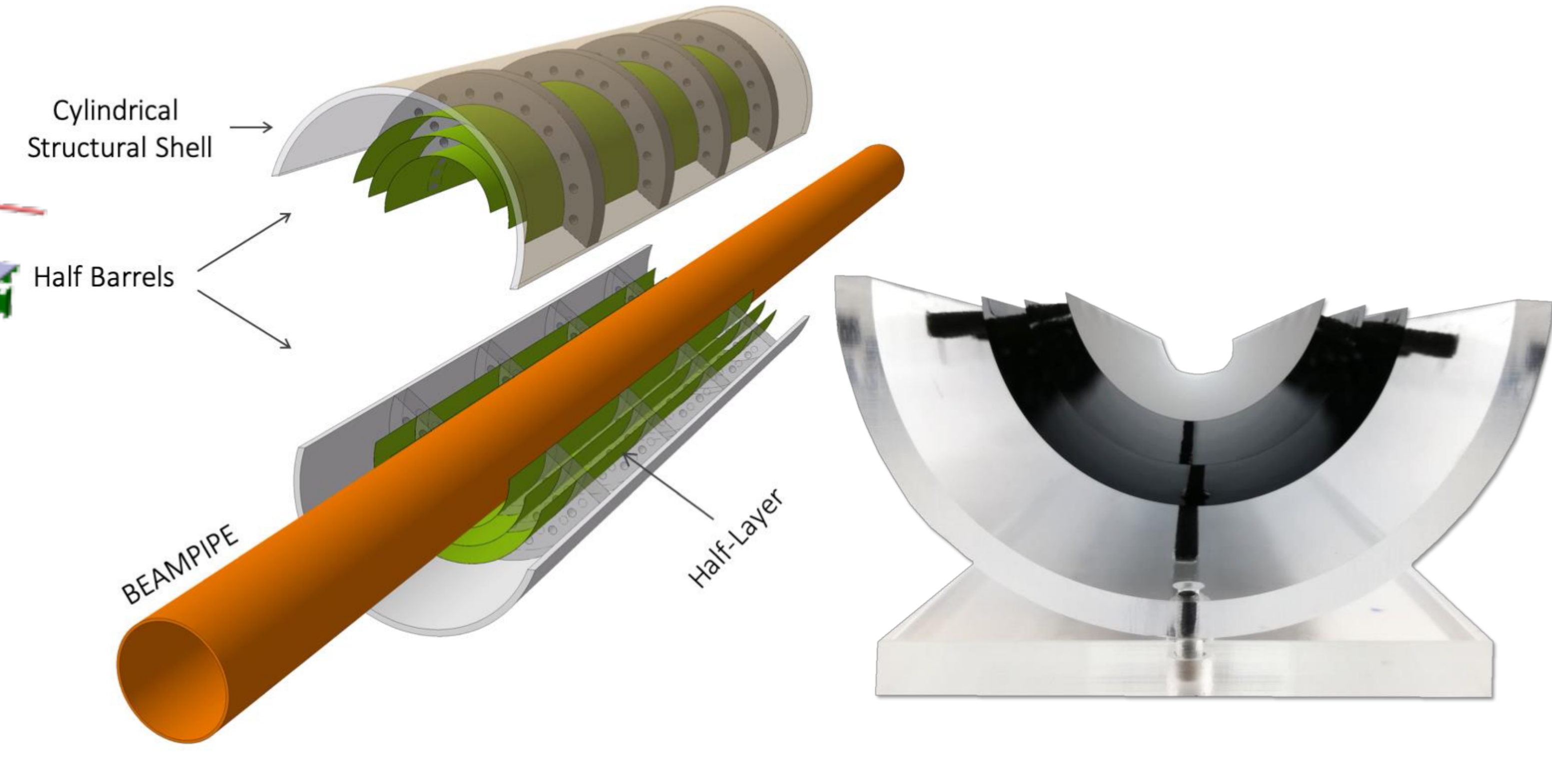
Inner Tracking System

- **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

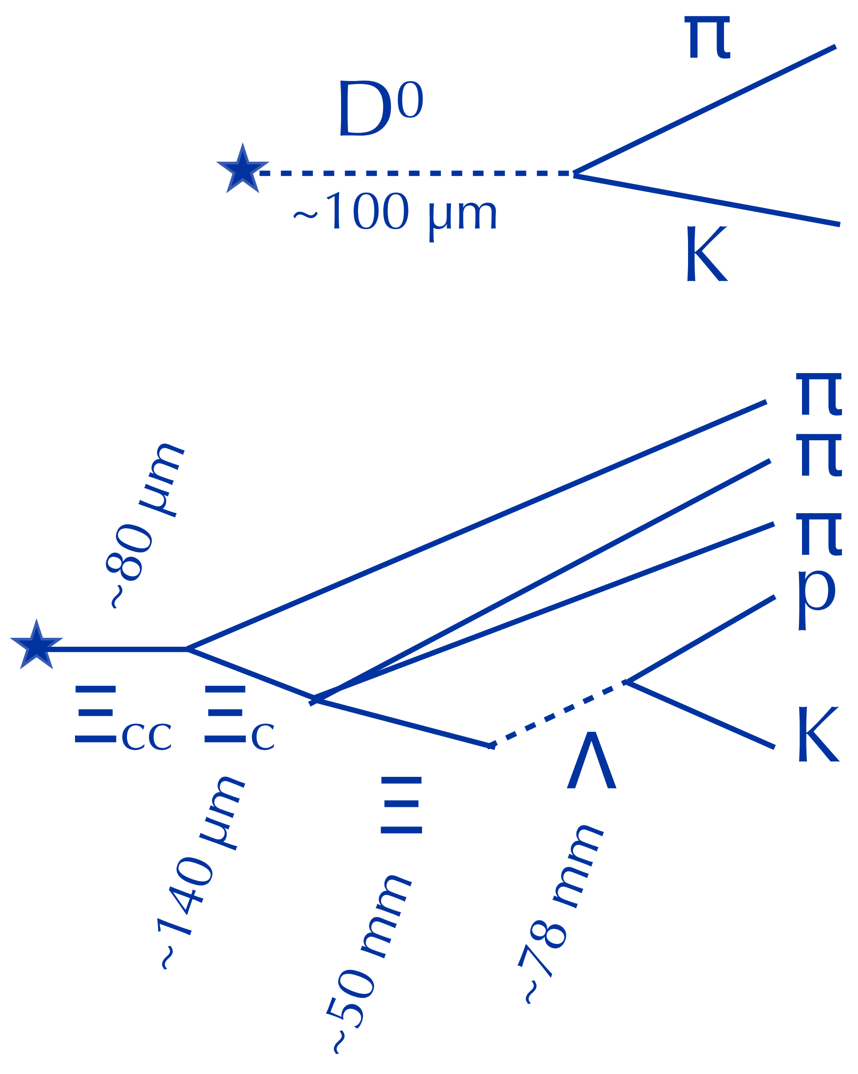
FoCal + ITS3
→ better vertexing, isolated photons

Muon Forward Tracker

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

Towards ALICE 3

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



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

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

Vertex reconstruction

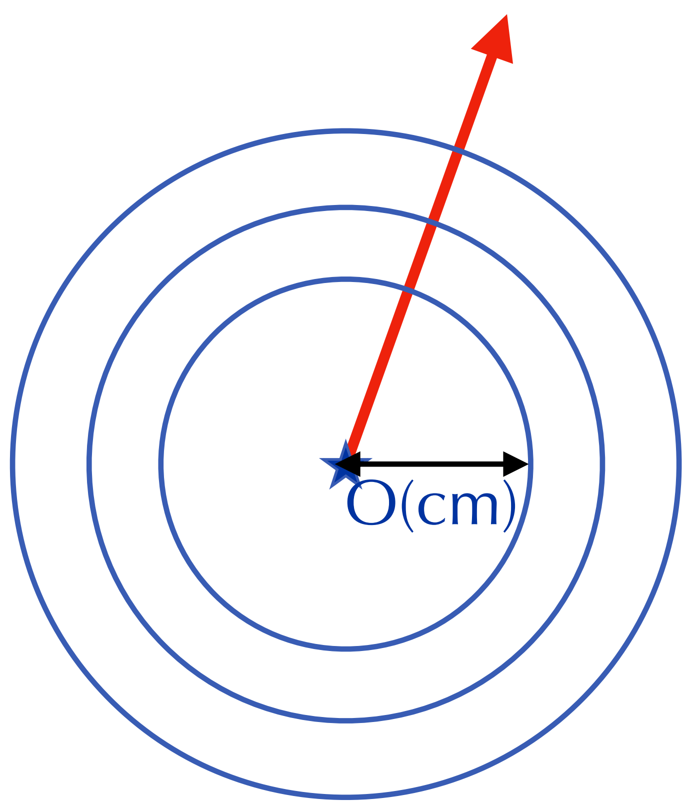
- **Primary and decay vertices** reconstructed through pointing of tracks
  ➟ 2 - 3 detection layers
  - pointing resolution fundamentally limited by multiple scattering:

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

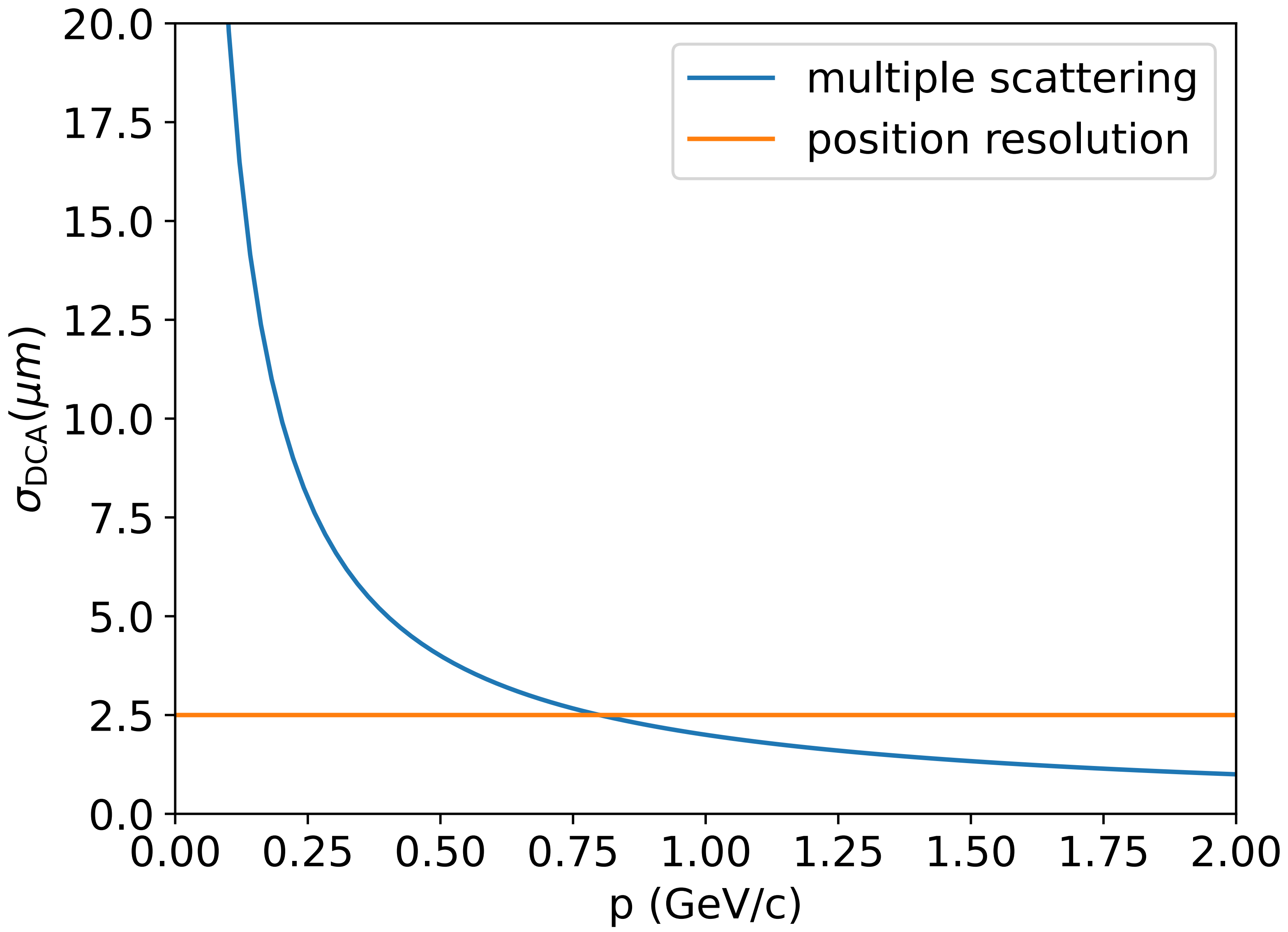
    ➟ **minimal radius** of innermost layer
    ➟ **minimal material** before first layer
  - constant contribution from position resolution
    ➟ stay below limit from multiple scattering

- minimal radius given by required beam aperture:
  R ≈ 5 mm at top energy, R ≈ 15 mm at injection energy

→ Retractable vertex detector



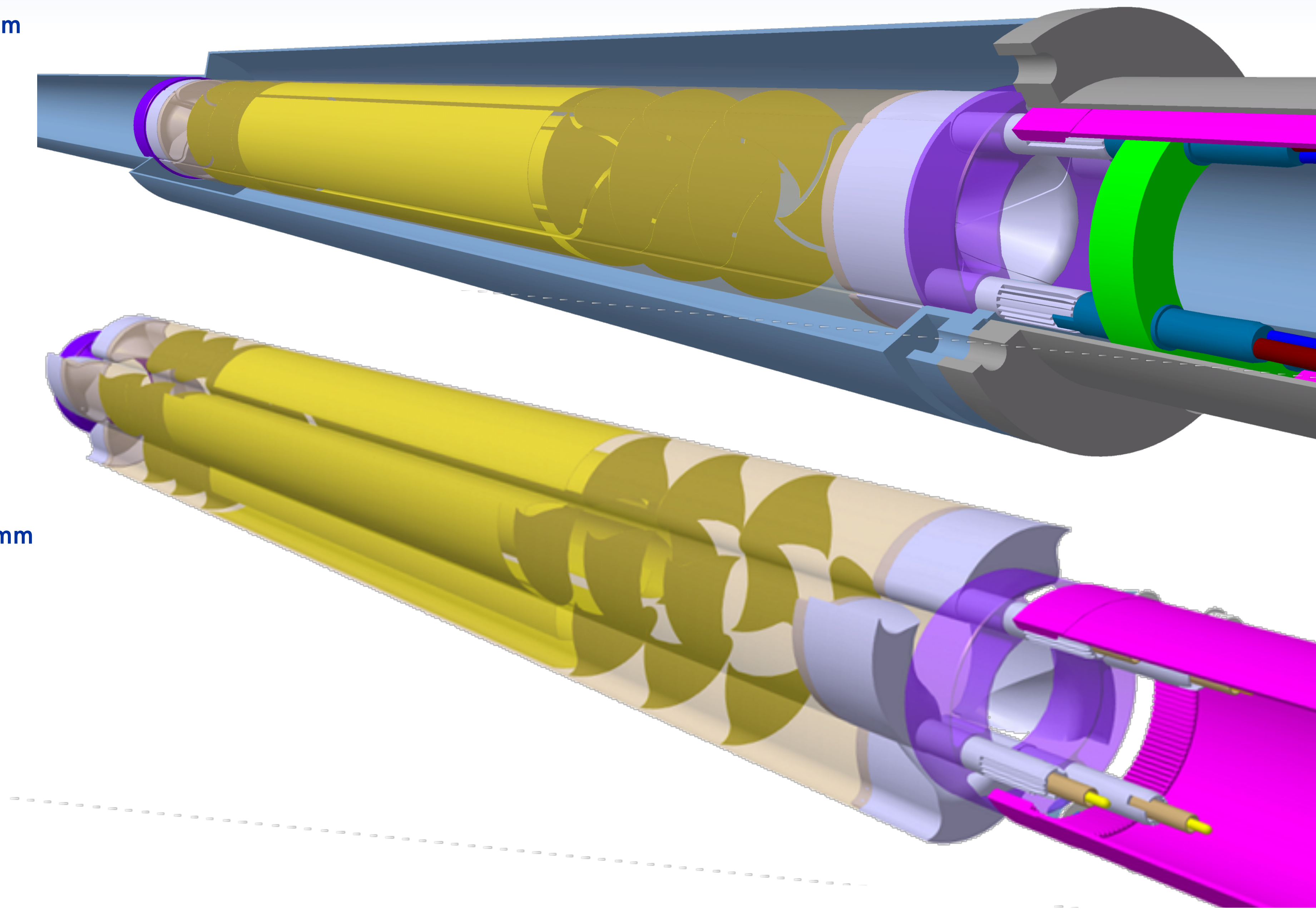
decays with cτ < 100 μm

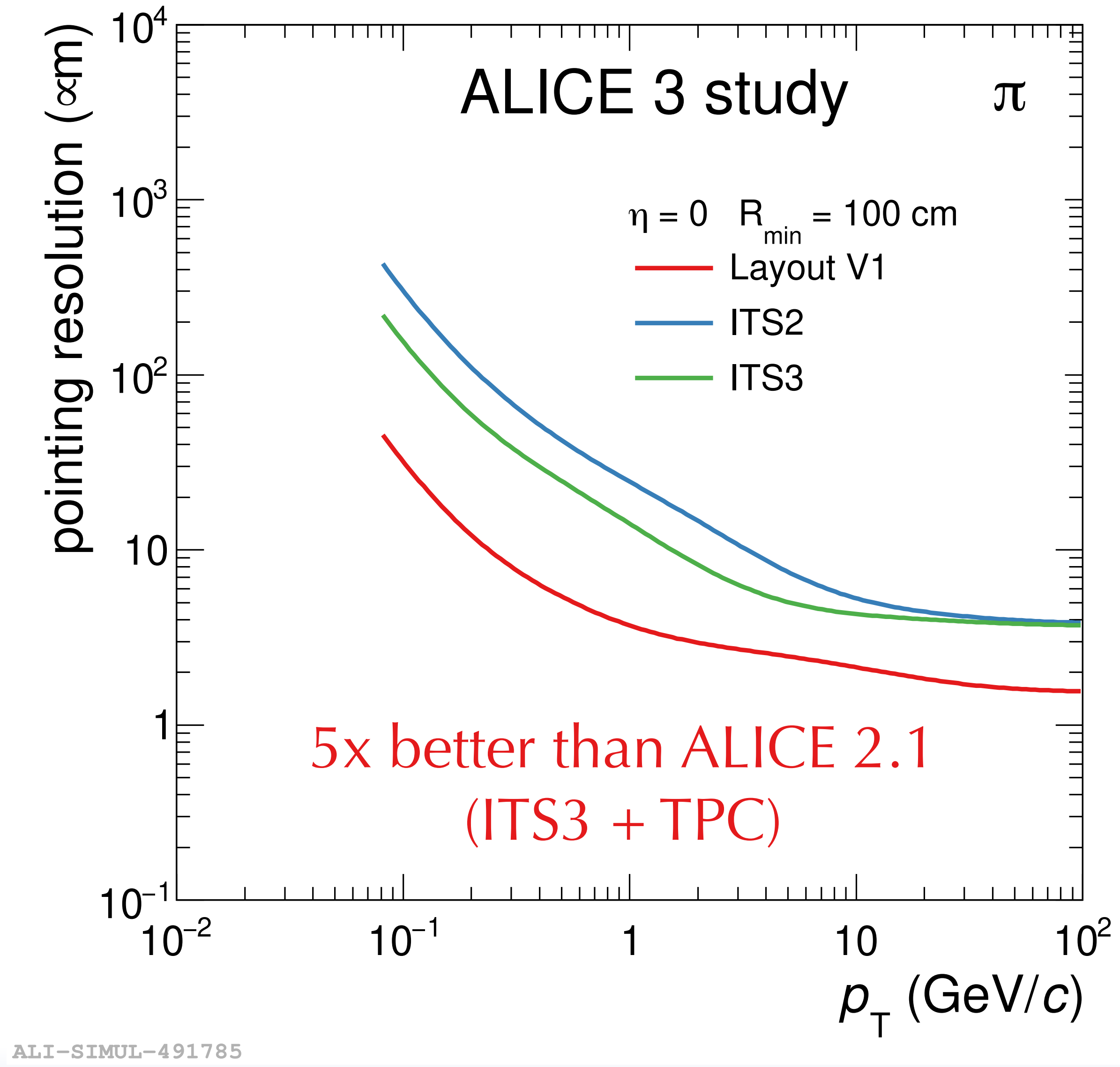


Vertex detector

- **3 retractable layers inside beam pipe** at radii of 5 - 25 mm (in secondary vacuum)
  - complex mechanics and LHC interface
  - conceptual study of IRIS tracker
- **Bent monolithic active pixel sensors** (pioneered with ITS3 R&D)
  - 0.1 % X_0 per layer → very thin sensors
  - σ_{pos} ~2.5 µm

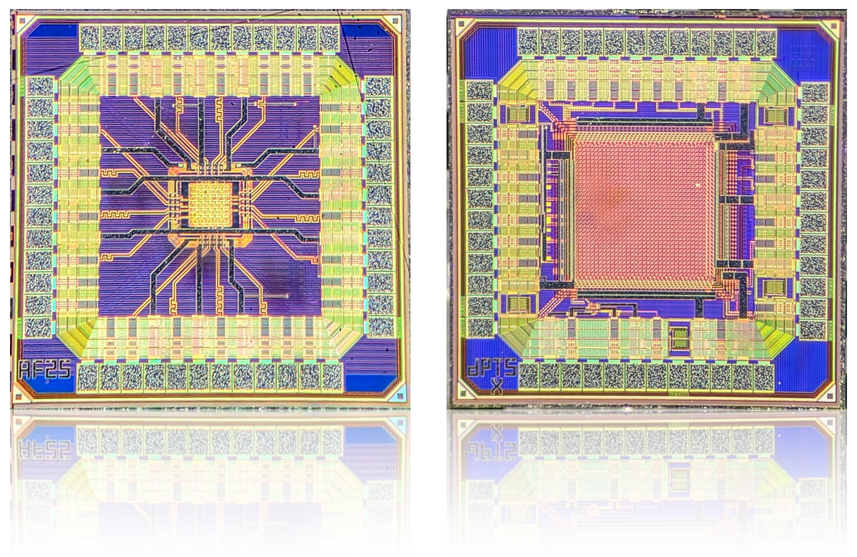
Ultimate pointing resolution at the LHC



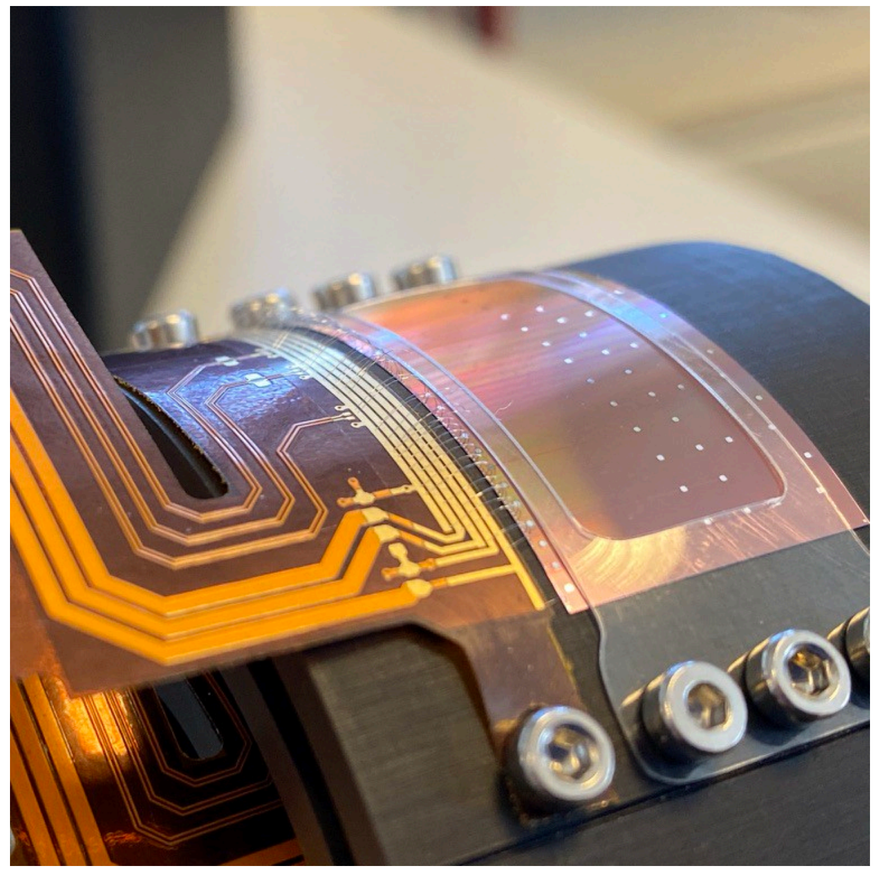


Silicon pixel sensors

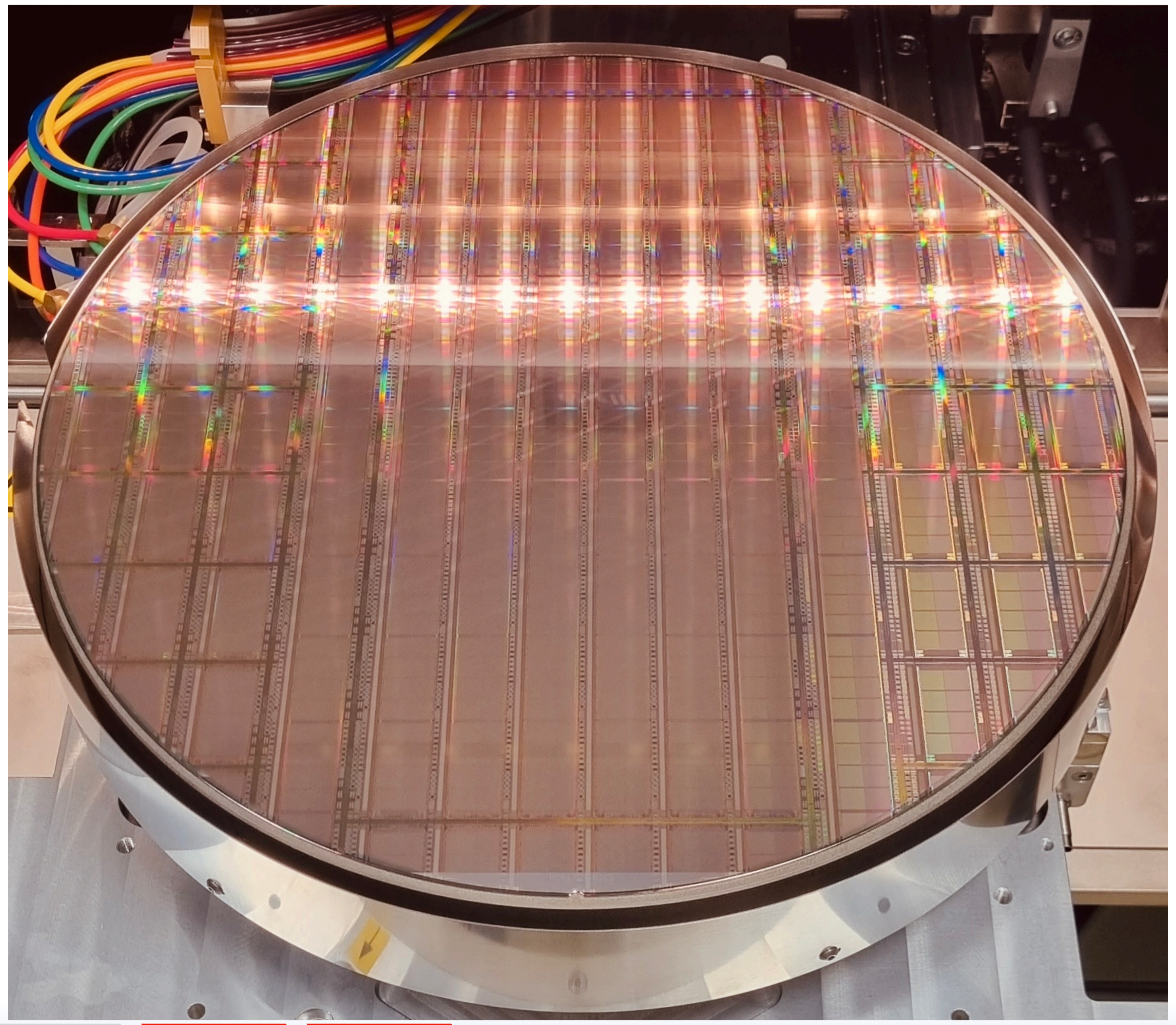
- **Established TPSCo 65 nm process for pixel sensors** (extensive R&D run with 55 different prototypes)
  - excellent performance, also after irradiation



- **Established bending of silicon sensors**
  - performance of ALPIDEs not affected at radii down to 1.8 cm
  - prototypes with wafer-scale silicon



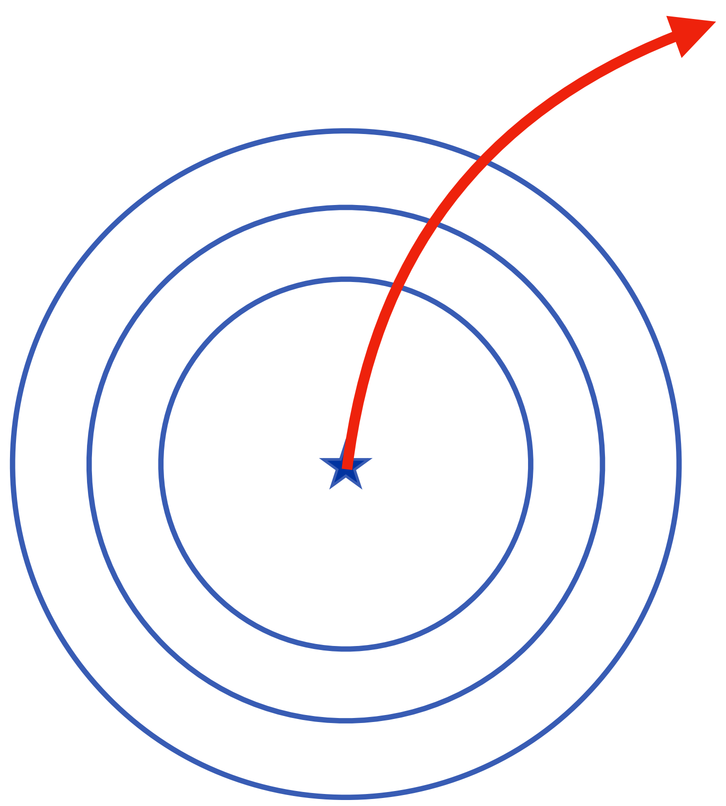
- **Developing wafer-scale sensors**
  - stitching of repeated sensor unit
  - first wafers from engineering run received

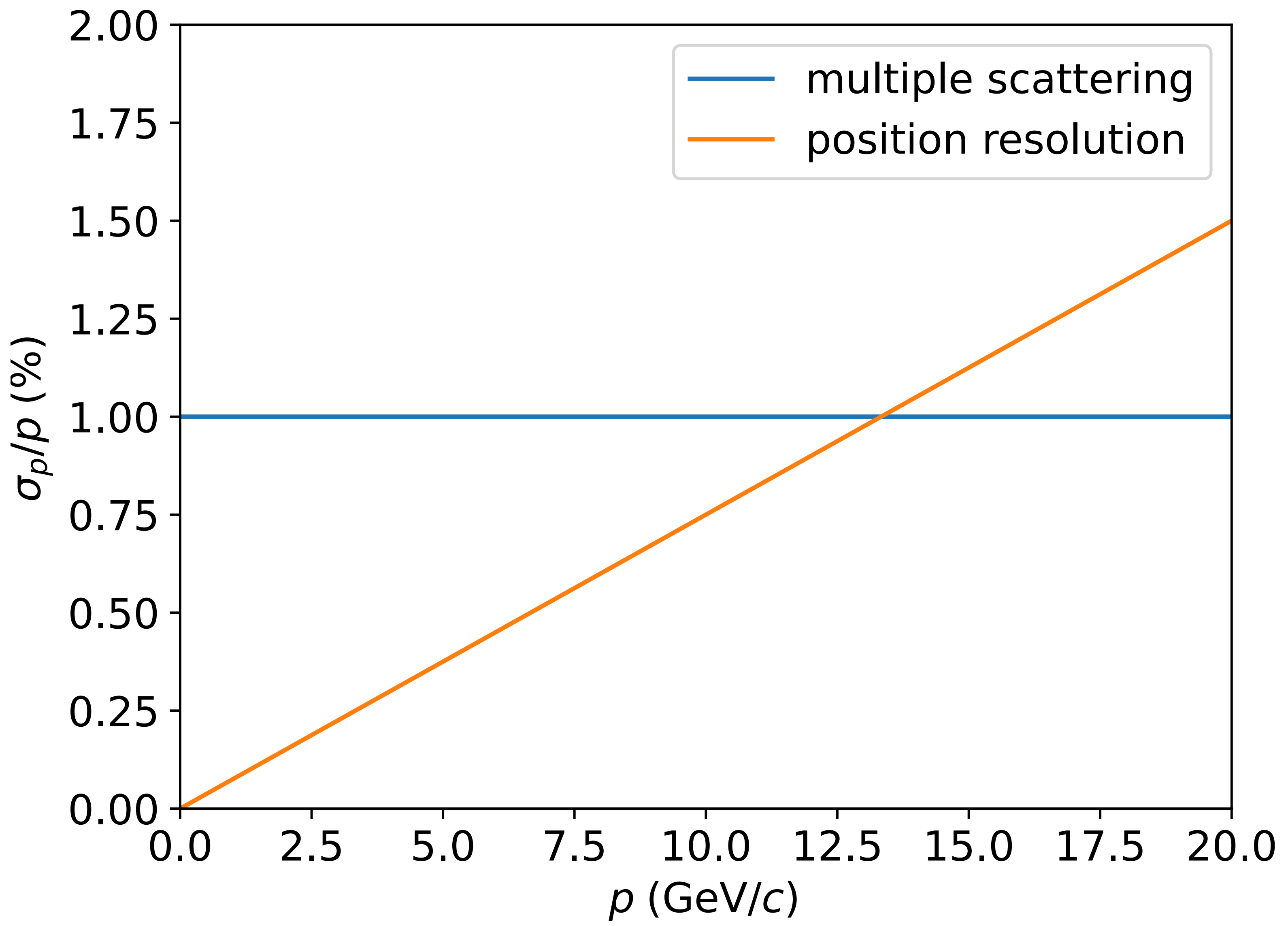


Excellent progress with ITS3 R&D
paving the way for ALICE 3

Tracking

- Tracking and momentum measurement
  ➟ 3 - N space points in magnetic field
  - momentum resolution limited by multiple scattering and lever arm
    $$\sigma_p/p \propto \frac{\sqrt{x/X_0}}{B \cdot L}$$
    ➟ maximise lever arm and magnetic field, minimise material
  - linear contribution from position resolution of hit measurements
    $$\sigma_p/p \propto \frac{\sqrt{x/X_0}}{B \cdot L^2} \cdot p$$
    ➟ should be sub-dominant in region of interest





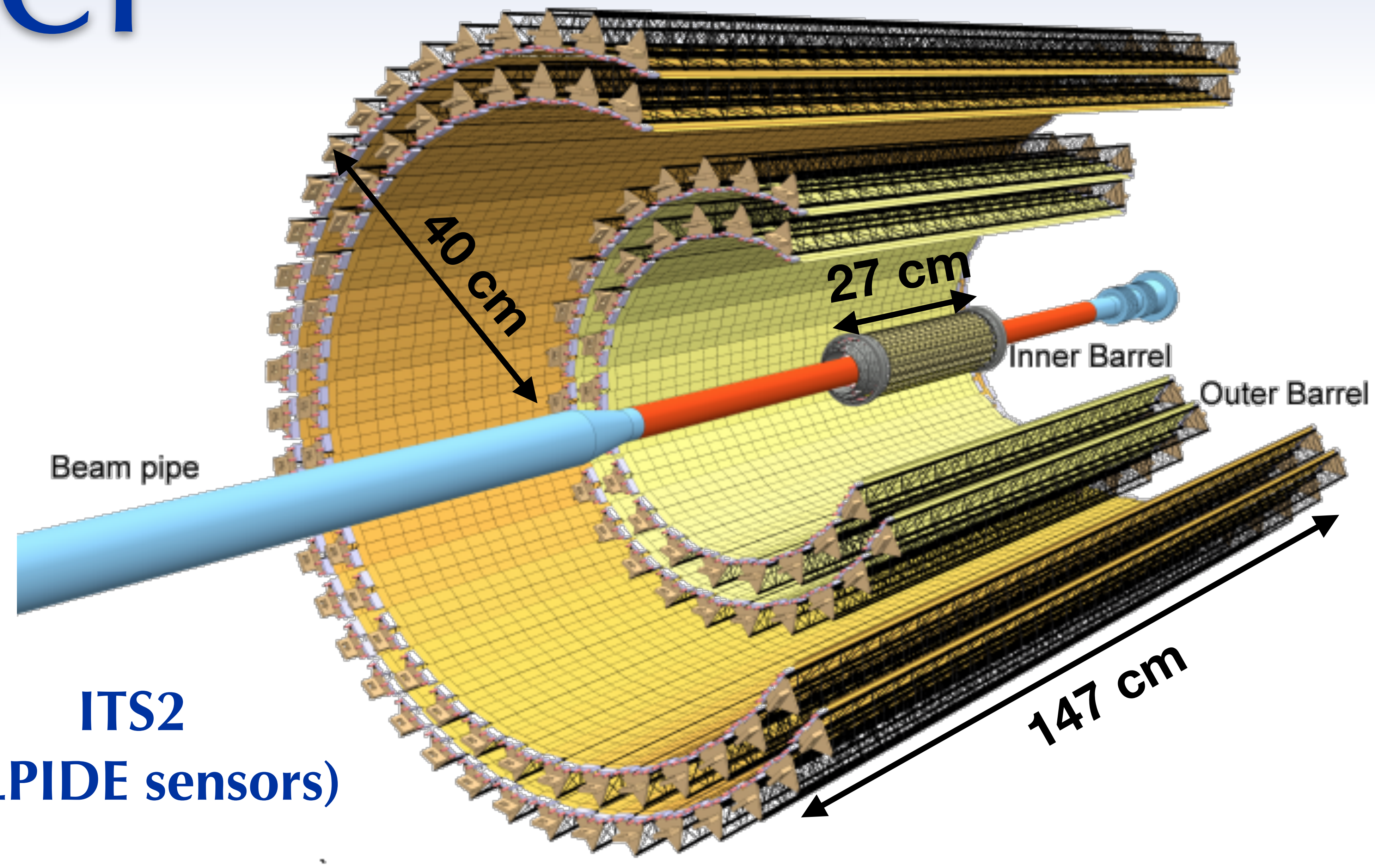
- Additional considerations
  - high rate → occupancy → combinatorics
  - acceptance and cost (area)

→ compact all-silicon tracker

Outer tracker

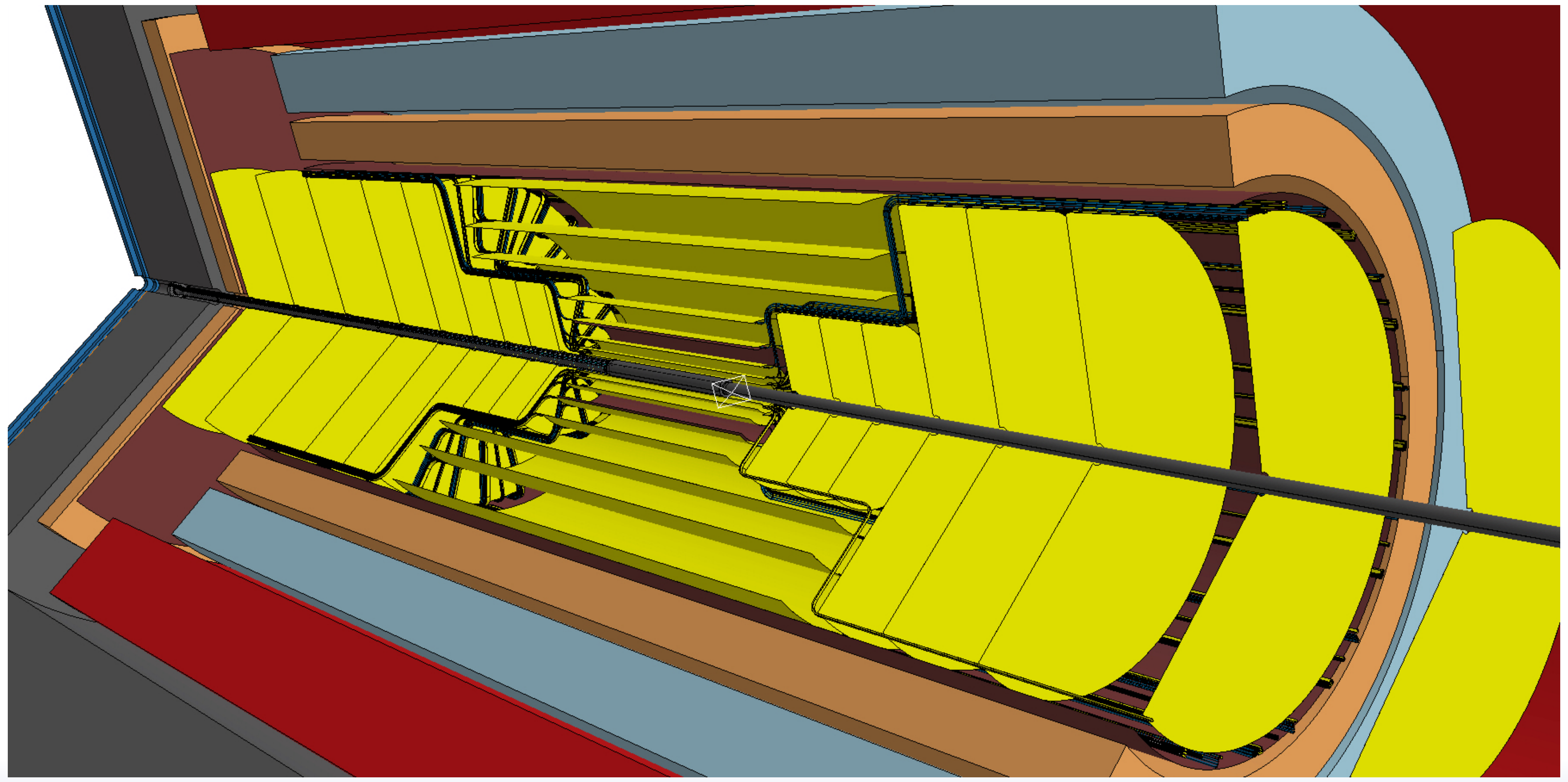
- **~11 tracking layers (barrel + disks)**
  - Monolithic Active Pixel Sensors
  - σ_{pos} ~10 µm
  - $R_{out} \approx$ 80 cm and L ≈ 8 m
    → magnetic field integral ~1 Tm
  - control mismatch probability
    → timing resolution ~100 ns
  - ~1 % X_0 / layer → overall X / X_0 = ~10 %
- **Significant step in instrumented surface (10 → 60 m²)**
- **Challenging for integration and maintainability**
- **New concepts for power distribution**

Next-generation detector
going beyond scaling of current ITS2



ITS2
(ALPIDE sensors)

10 m² → 60 m²



Particle identification

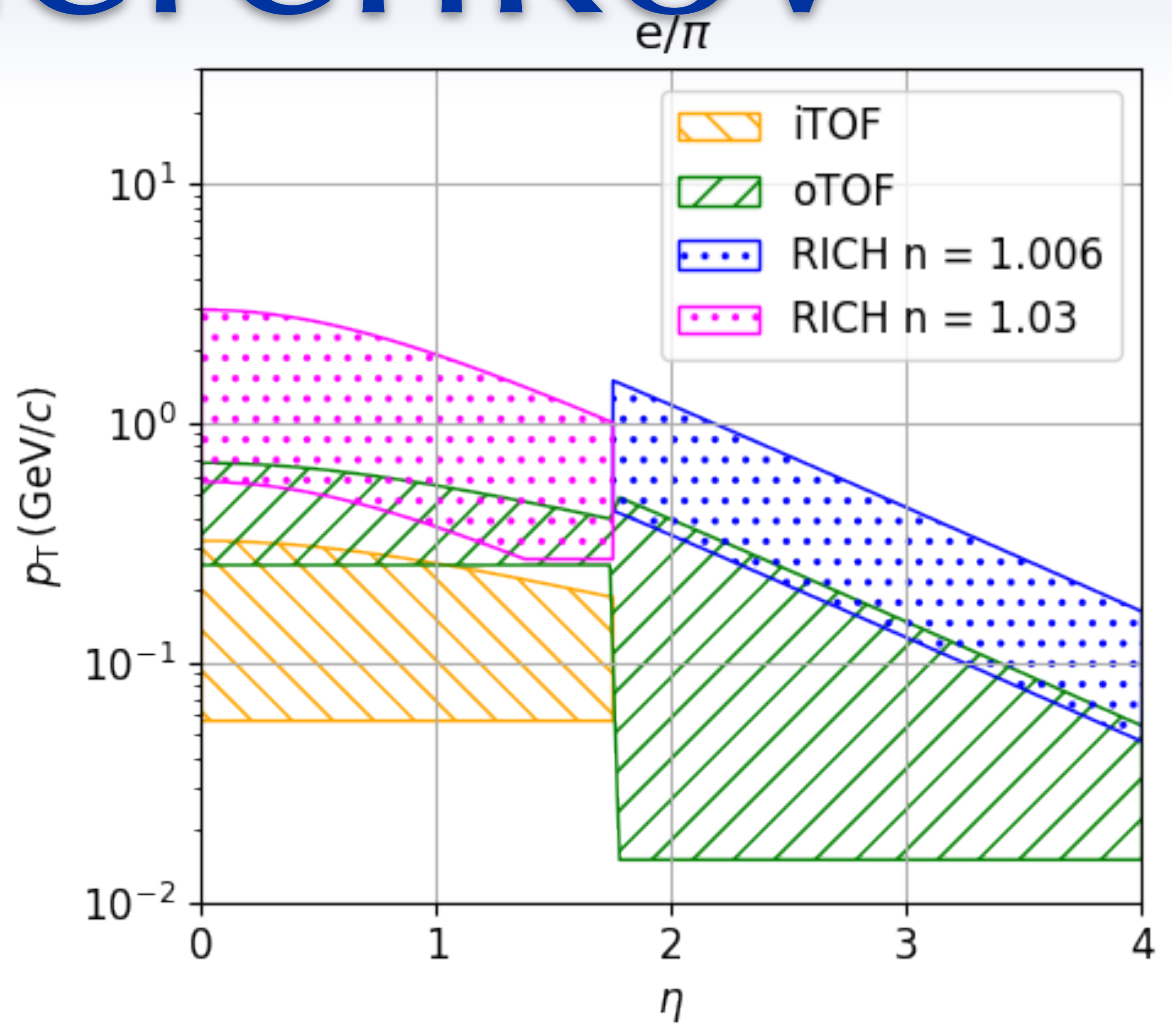
- Exploit mass measurement from tracking and additional measurements
  - **Time of flight** separation $\propto L / \sigma_{\mathrm{tof}}$
    ➟ large path length with fast time resolution
  - **Cherenkov** radiation with angle $\cos \vartheta = 1 / n\beta$
    ➟ refractive index to optimise coverage
    ➟ angular resolution
  - **Electromagnetic shower** to identify electrons
  - **Absorption** to identify muons

Combination of techniques
to achieve PID goals

Time-of-flight and Cherenkov

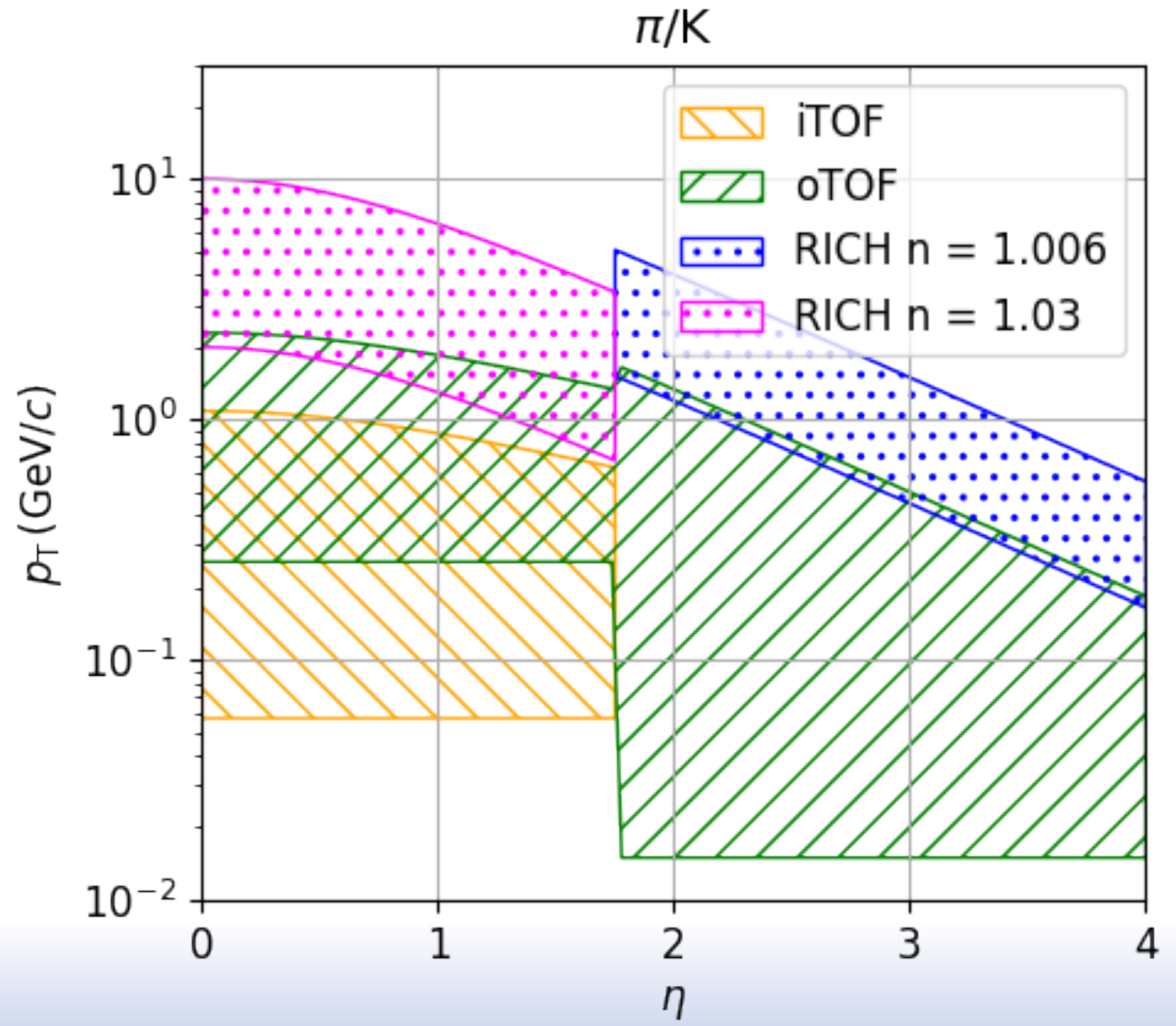
- **Time-of-flight detector**
  - 2 barrel + 1 forward layers:
    R ≈ 85 cm, R ≈ 19 cm, z ≈ 405 cm
  - silicon timing sensors with $\boldsymbol{\sigma_{TOF} \approx 20}$ **ps**
    ➠ monolithic CMOS sensors with gain

Instrumented area ~45 m²



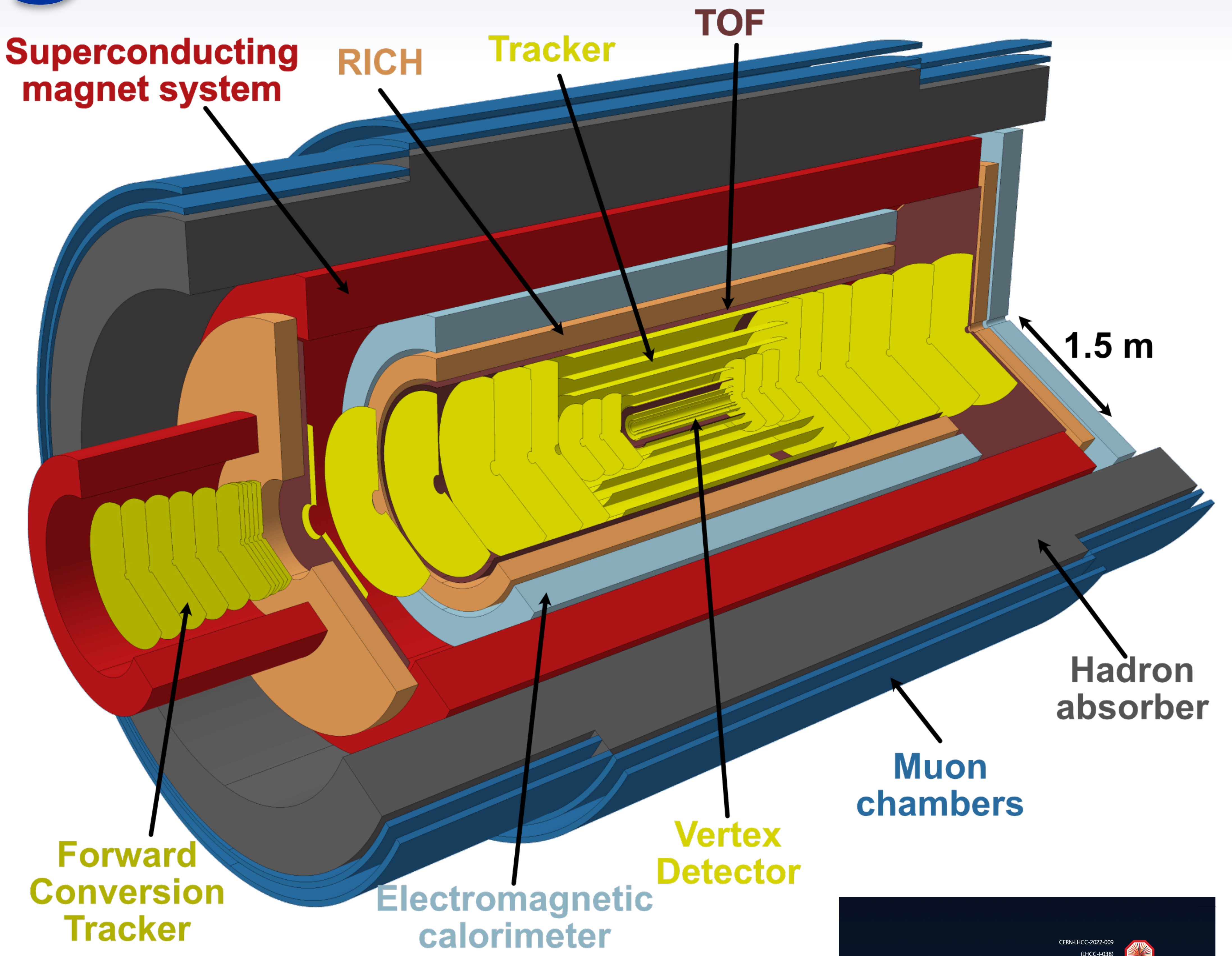
- **Ring Imaging Cherenkov Detector**
  - aerogel radiator
    → refractive index n = 1.03 (barrel)
    → refractive index n = 1.006 (forward)
  - silicon photon sensors
    ➠ R&D on monolithic SiPMs

Instrumented area ~60 m²



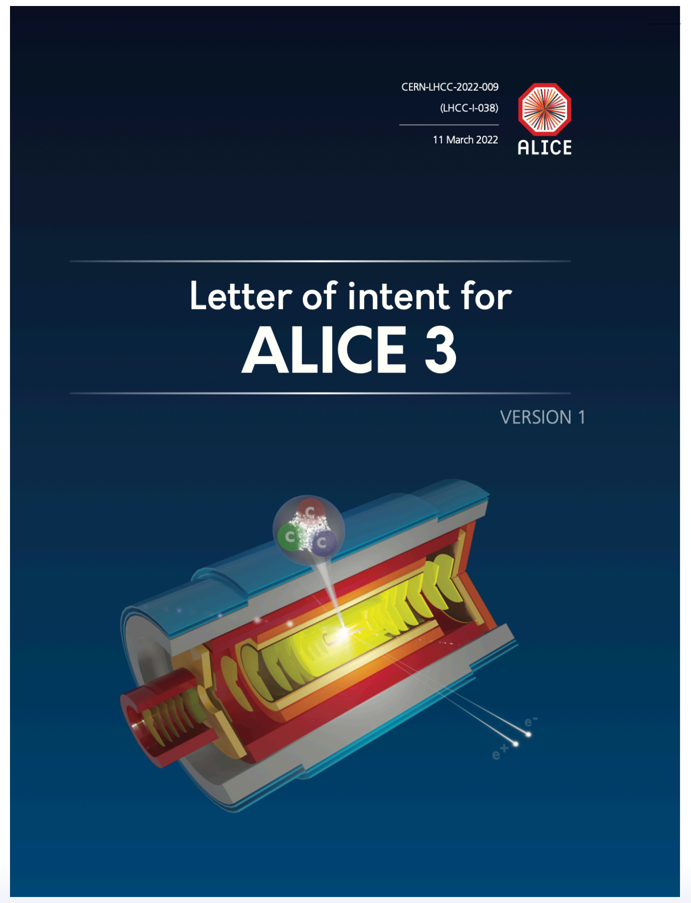
ALICE 3

- **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

➡ **Positive evaluation of Letter of Intent (March 2022)**
➡ **Scoping document in preparation (aligned with LHCb)**



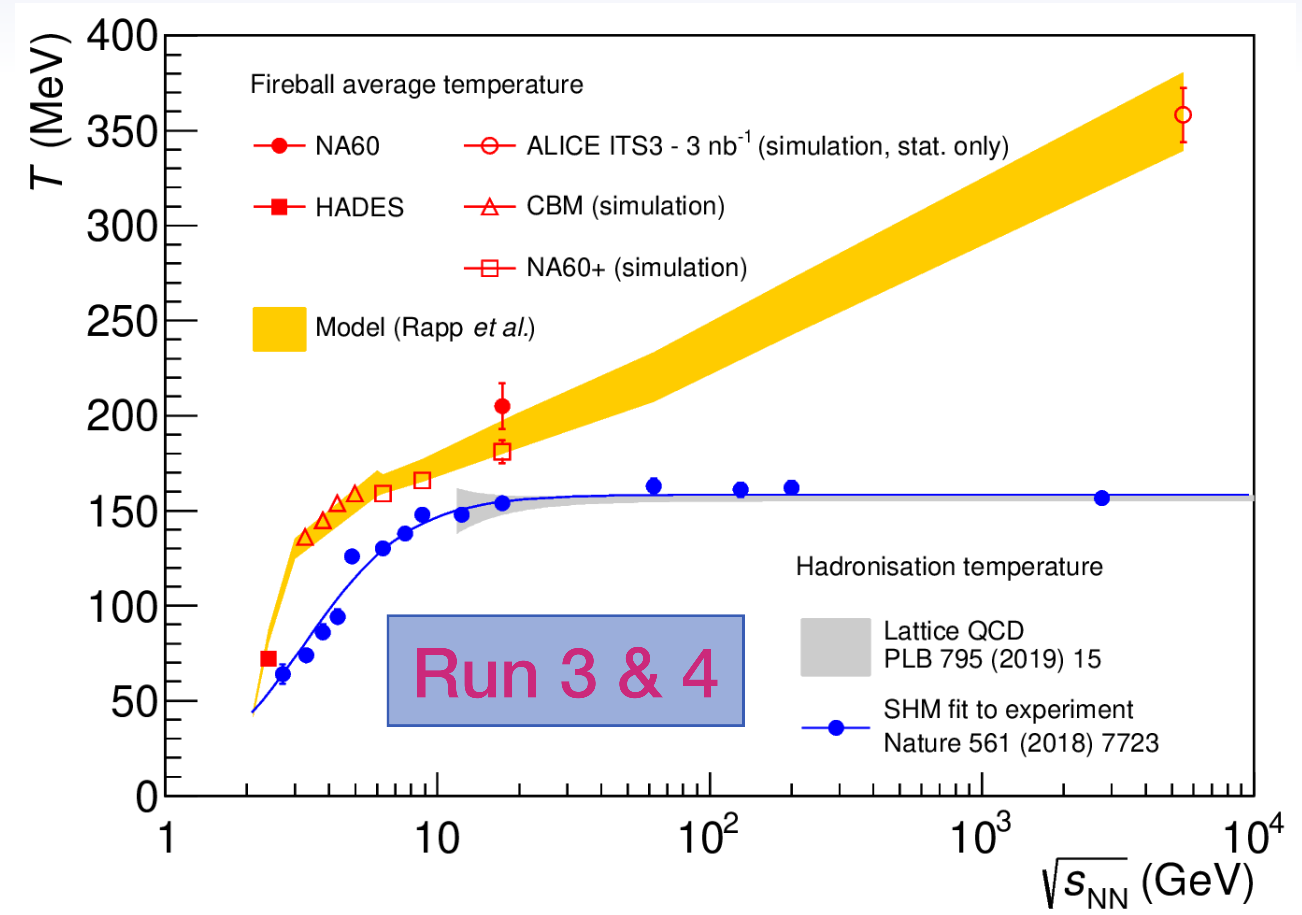
Thermal radiation

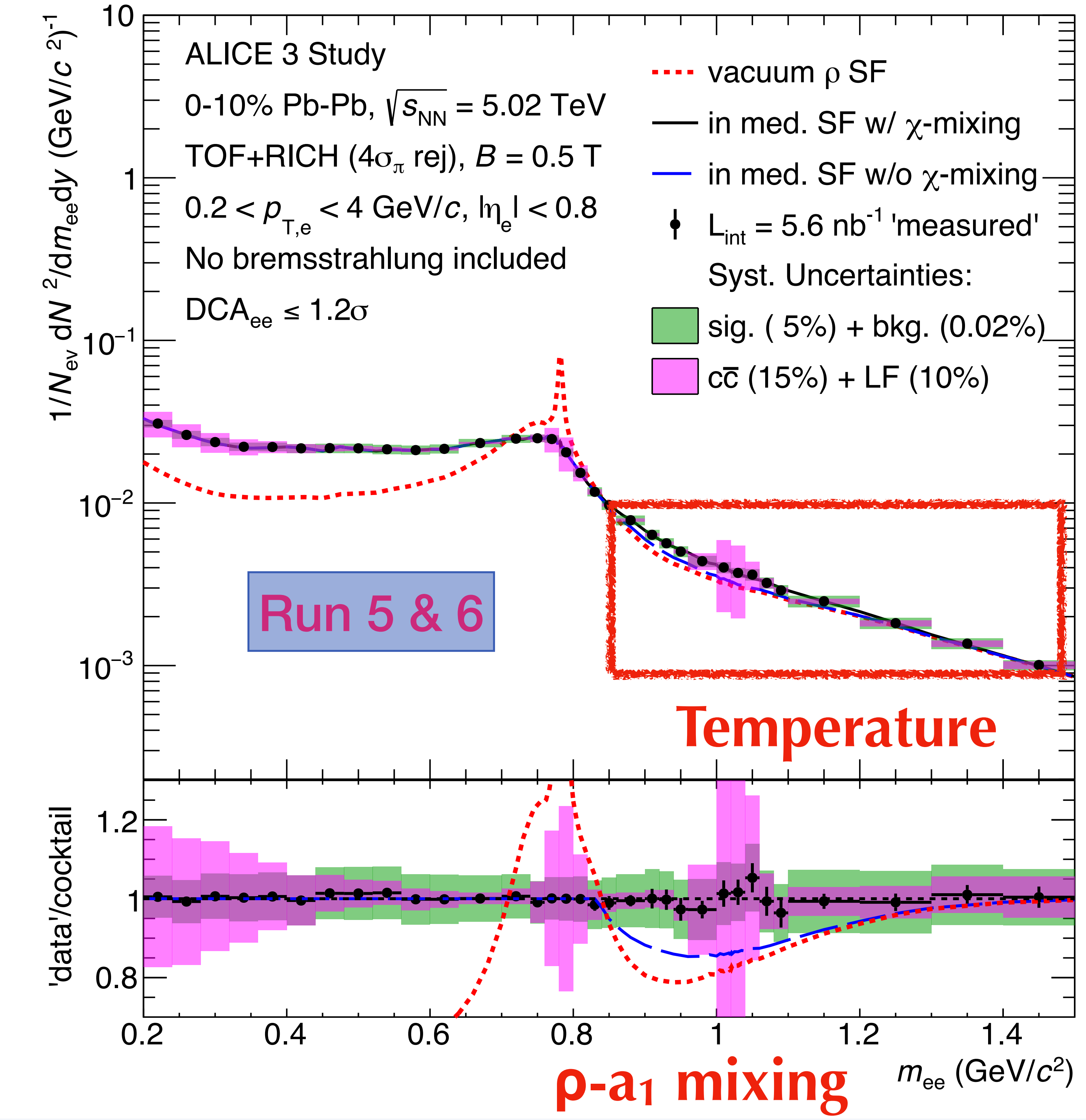
- Hot QCD matter emits **thermal radiation**
  - **invariant mass of dileptons**
    not affected by blueshift from expansion
  - **emission throughout the entire evolution**

Also pursued with LHCb

- 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)

First measurements in Run 3 & 4, ultimate precision only in Run 5 & 6





[CERN-LHCC-2022-009]

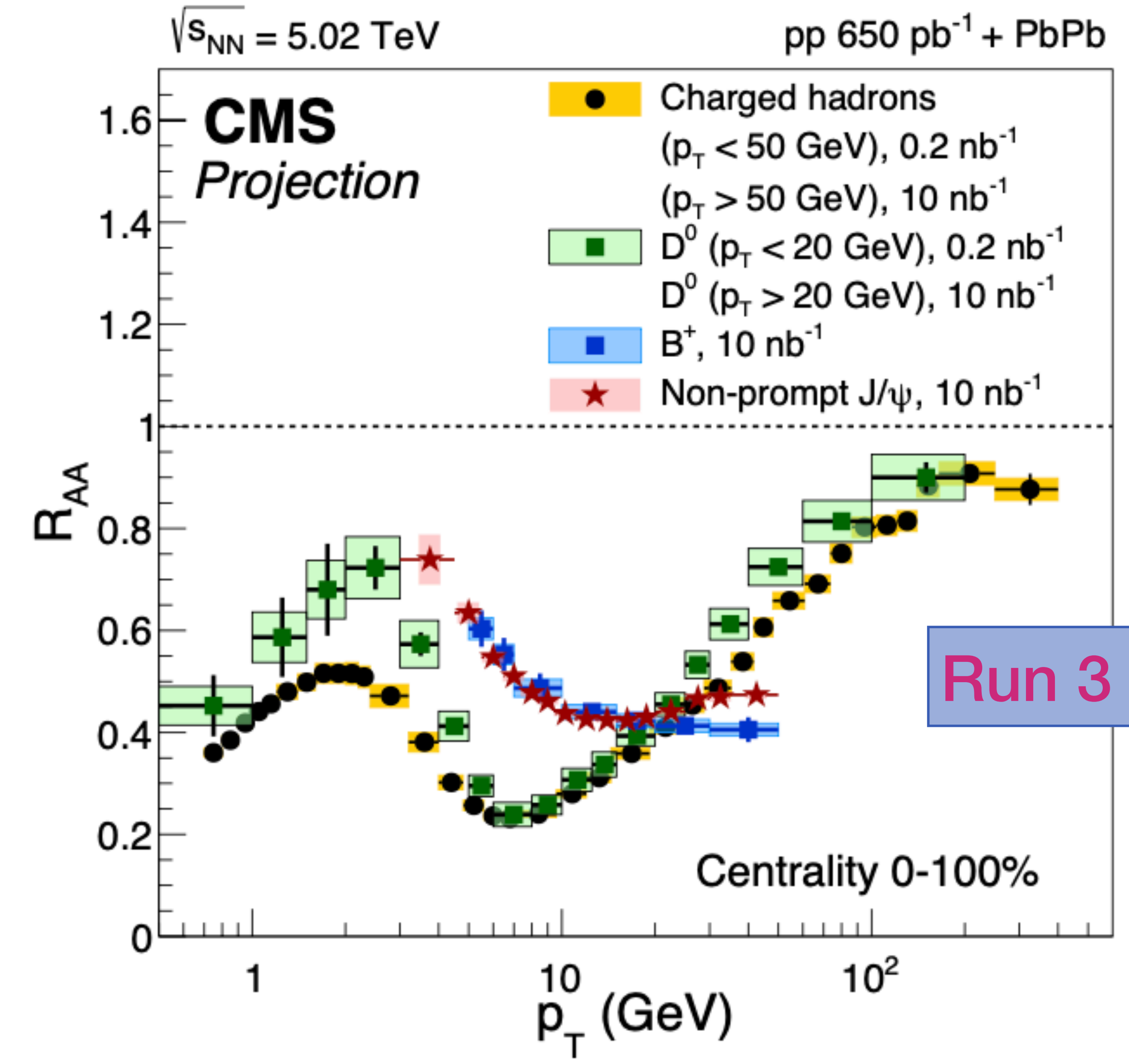
Heavy-flavour transport

- **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

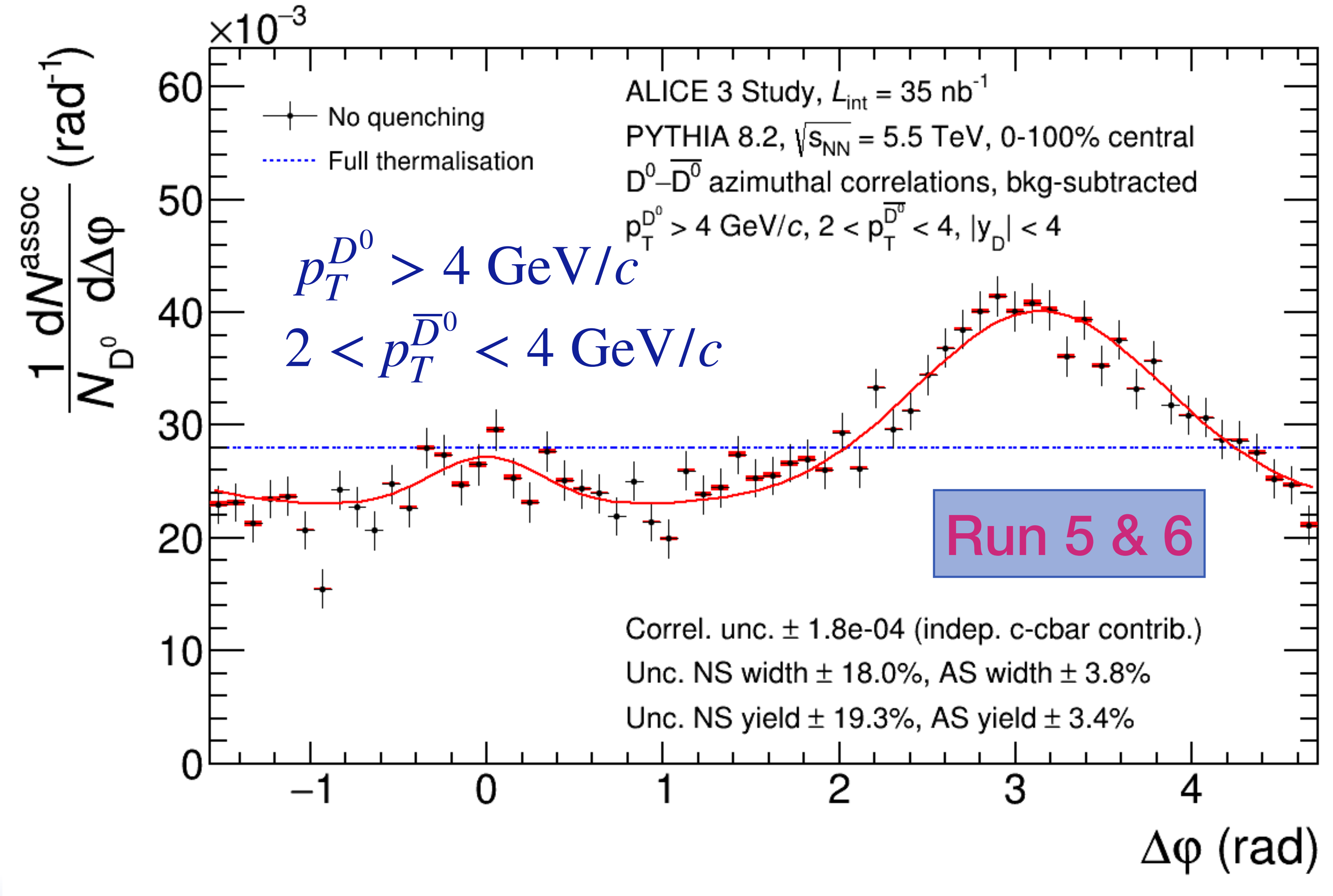
- Programme
  - determine **spatial diffusion coefficient** → precise suppression (R_{AA}) and anisotropy (v_2)
  - directly measure **decorrelation of charm pairs** → $D\bar{D}$ correlations

Indirect constraints in Run 3 & 4, direct measurements only in Run 5 & 6

Precise R_{AA} for c and b mesons



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



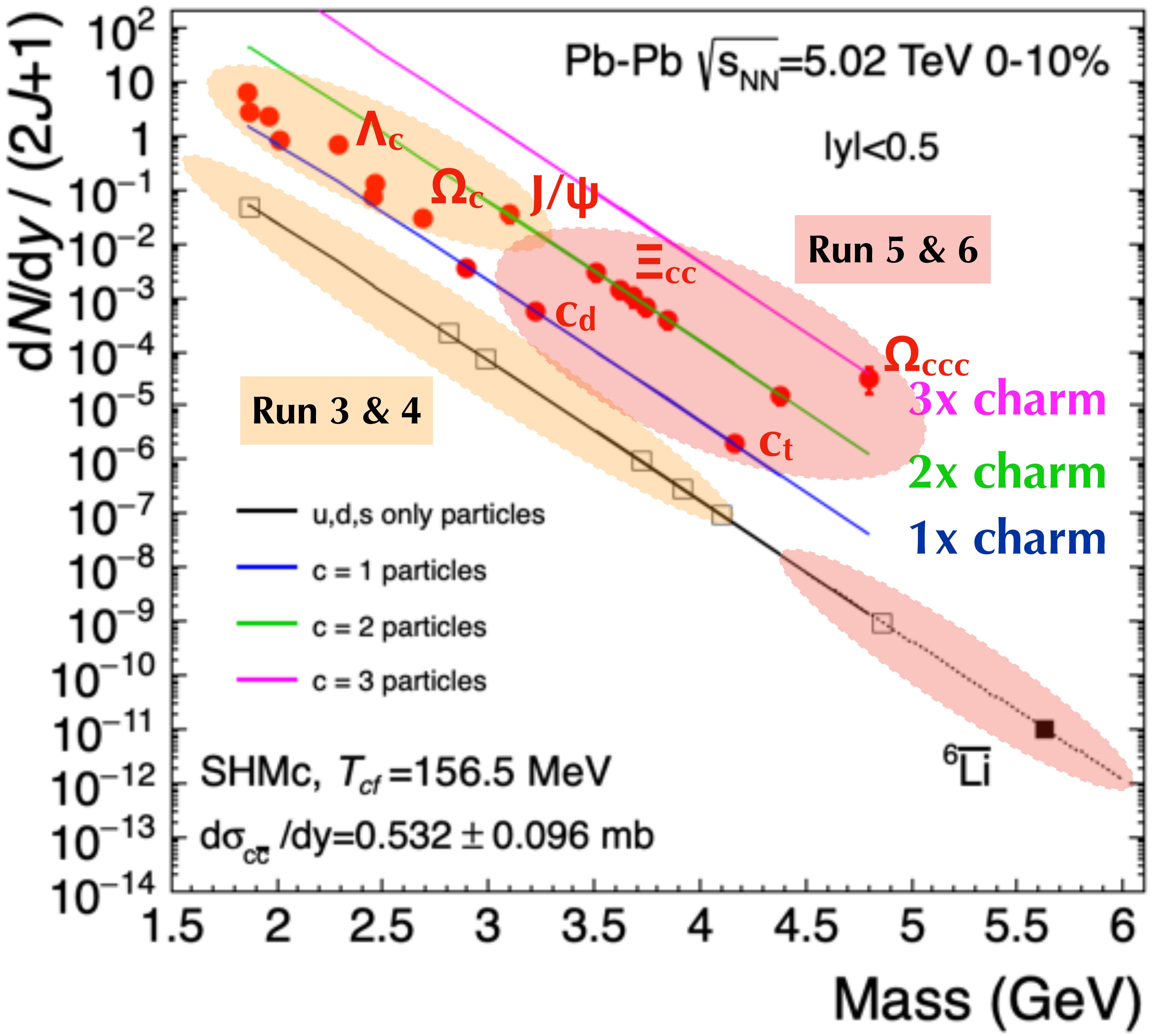
[CERN-LHCC-2022-009]

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



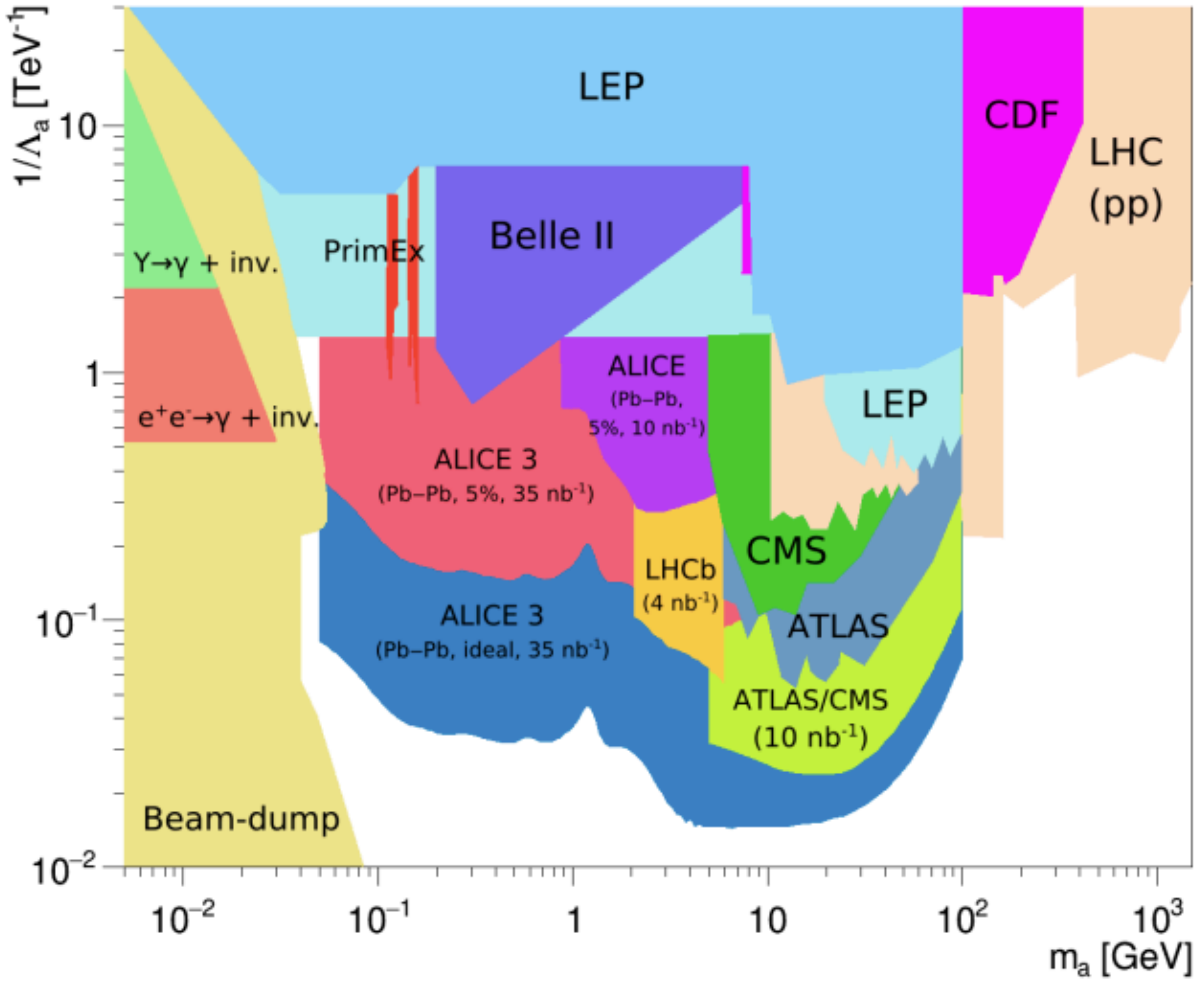
[A. Andronic et al, JHEP 07 (2021) 035]

More physics with AA collisions at LHC

- **Nuclear PDFs**
  → ultra-peripheral collisions, pA
- **Onset of collective behaviour**
  → high-multiplicity pp collisions
  and intermediate systems (pA, OO)
- **Quenching** and **collectivity in small systems**
  → comparison of different collision systems
- **BSM searches**
  → photon flux in ultra-peripheral collisions
- **Strong interaction potentials**
  → correlations
- …

Search for axion-like particles

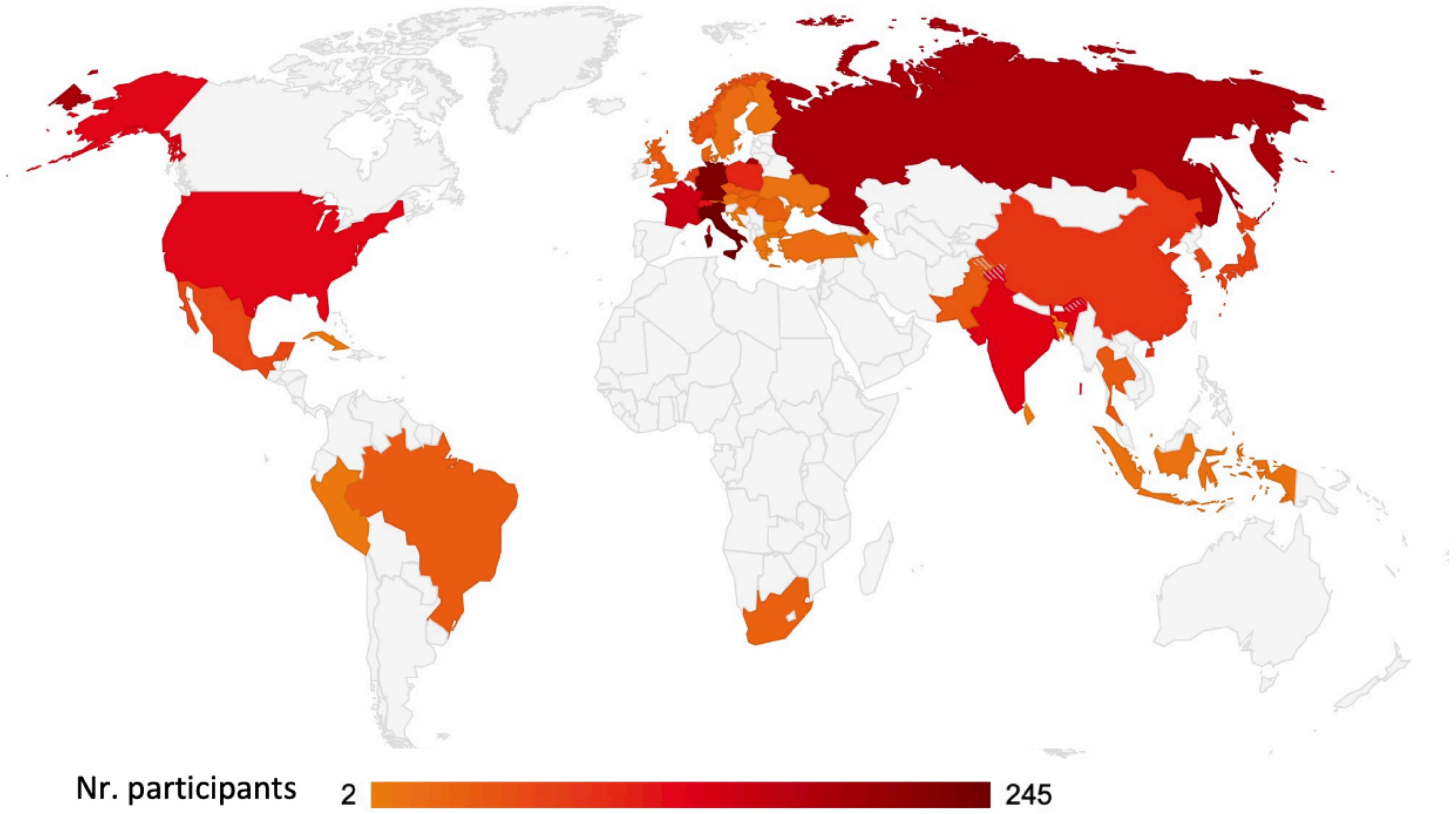
$\gamma\gamma \to a \to \gamma\gamma$

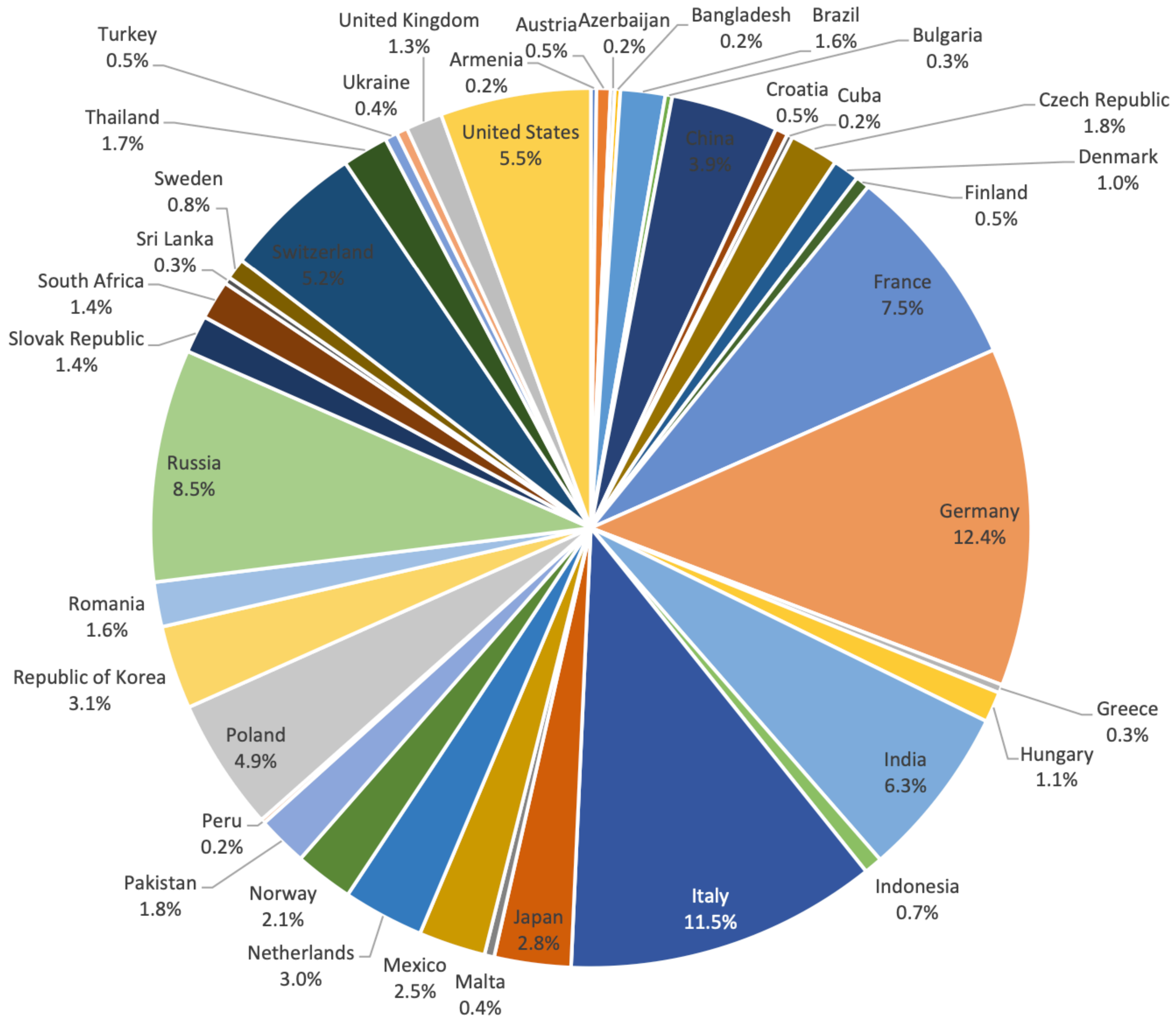


Great laboratory
for a wide range of physics topics

ALICE planning

ALICE collaboration





- collaborators around the world
- ~2000 members, ~1000 scientific authors

ALICE @ CERN

- ALICE CERN team covers central areas of the experiment
  - Technical coordination
  - Data acquisition
  - Detector control
  - Detector development
    → monolithic silicon pixel sensors (F. Reidt)
  - Software development
  - Computing grid
  - Physics and analysis
    → physics studies and upgrade plans (J. Klein)

Large variety of topics and ample opportunity to get involved

Conclusions

- **QCD matter is a hot topic of research**
- **Heavy-ion collisions are ideal probes**
  → high-luminosity era of LHC with ions
- **Rich experimental programmes (not only at LHC)**
  → R&D in strategic areas of general interest
- **Excellent prospects for new results**
  on QCD physics and beyond

Thank you for your attention,
time for discussion!