QCD at high energy density, heavy-ion physics, and the ALICE experiment

Lecture 1/2

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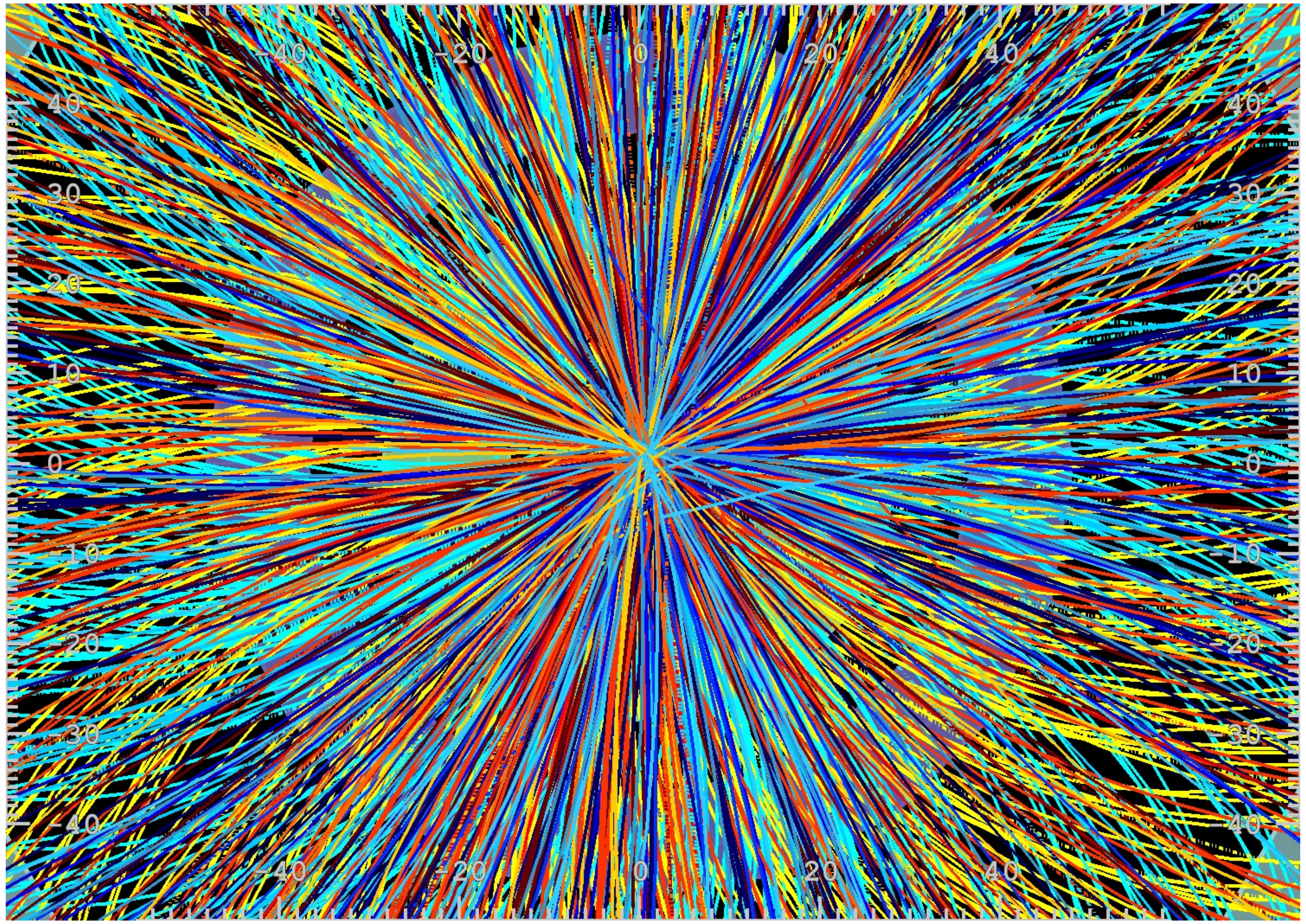
Durham STFC Nuclear Physics Summer School
22/08/2024

Overview

- **ALICE** (**A** **L**arge **I**on **C**ollider **E**xperiment) is the experiment at the LHC dedicated to studying the deconfined state of QCD known as the Quark-Gluon Plasma (QGP)

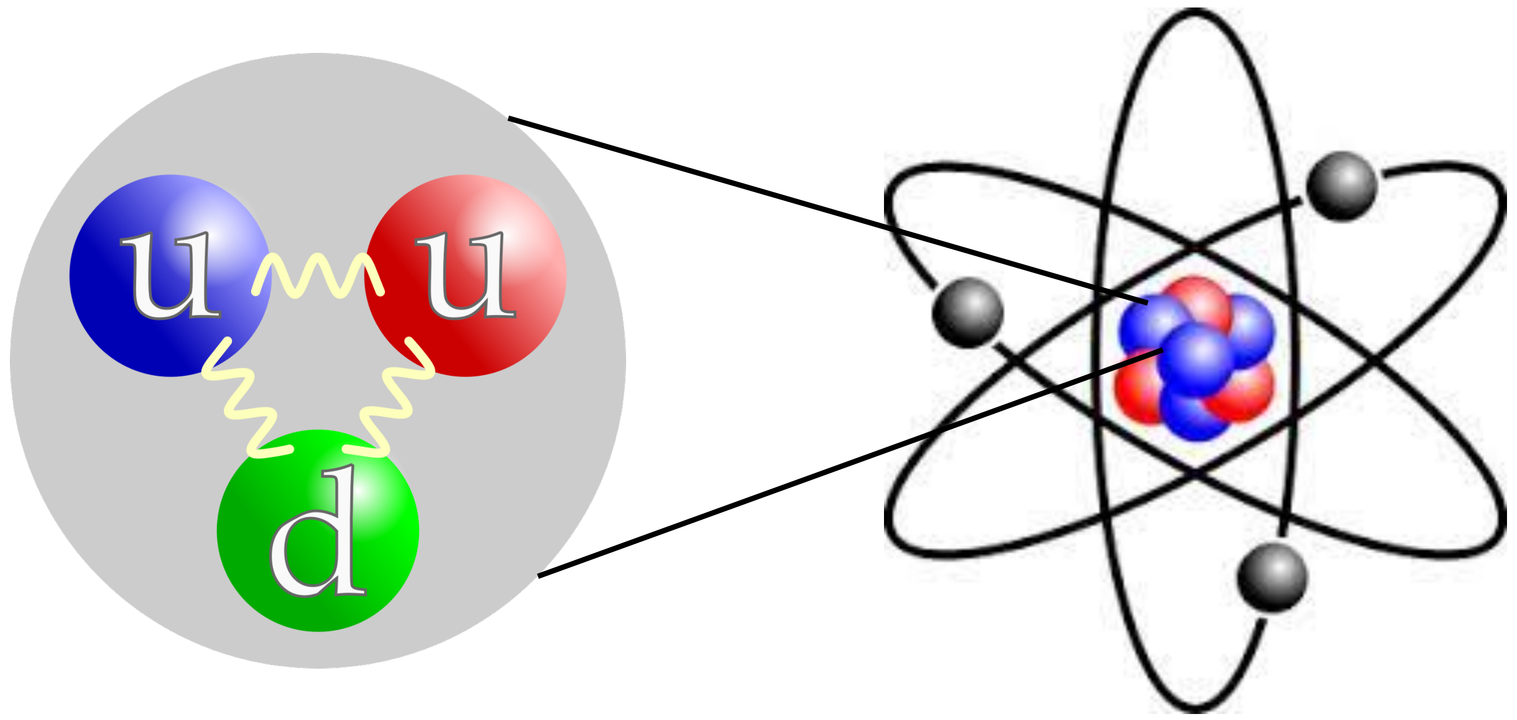
- In these lectures I will give an overview of heavy-ion physics
  - Basic concepts of QCD, the QGP and heavy-ion physics (including collider physics)
  - The ALICE experiment
  - How do we probe the QGP? What have we discovered?
  - Future plans of heavy-ion physics



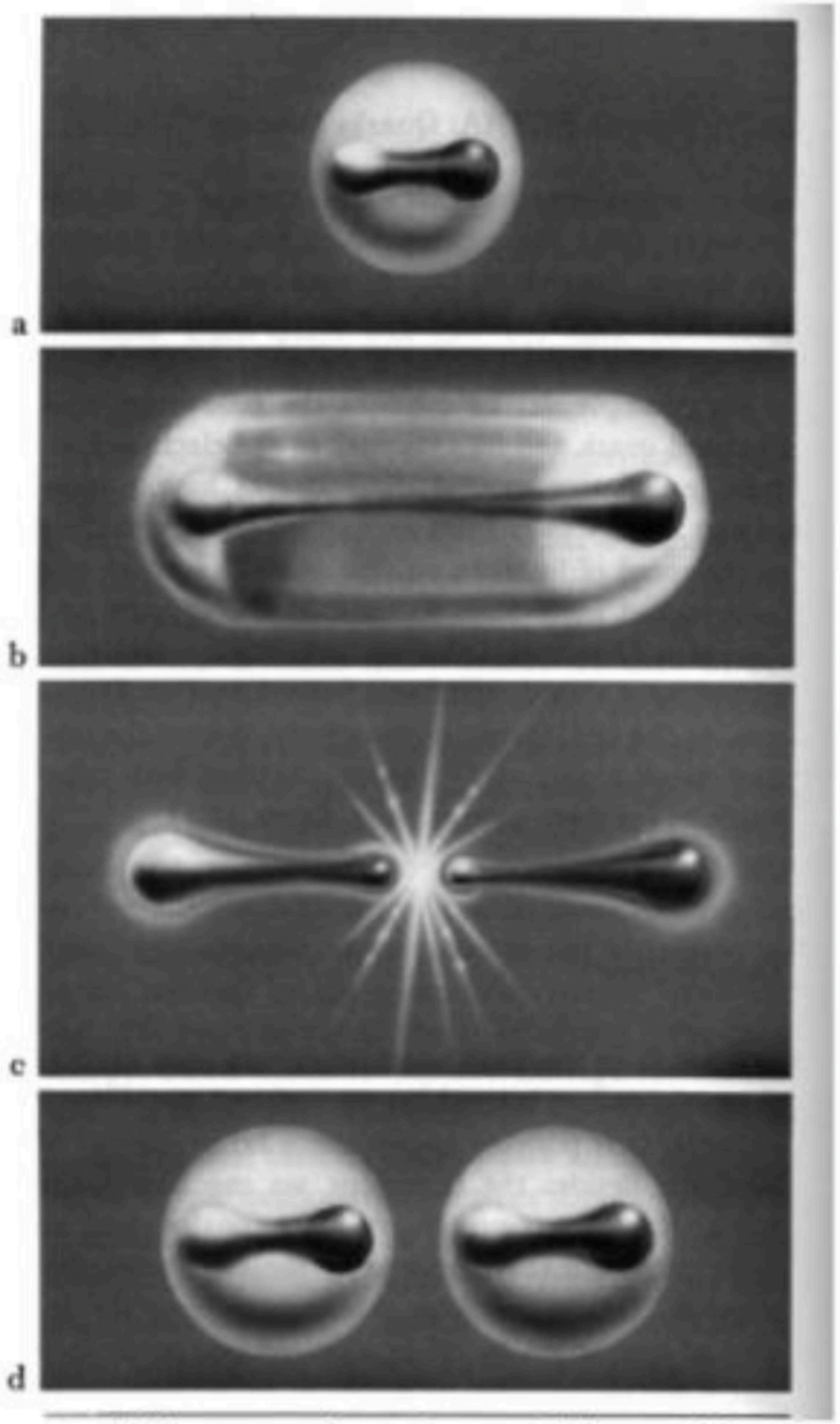
(an experimentalists perspective!)

Confinement in QCD

The fundamental 'quanta' of QCD are quarks and gluons

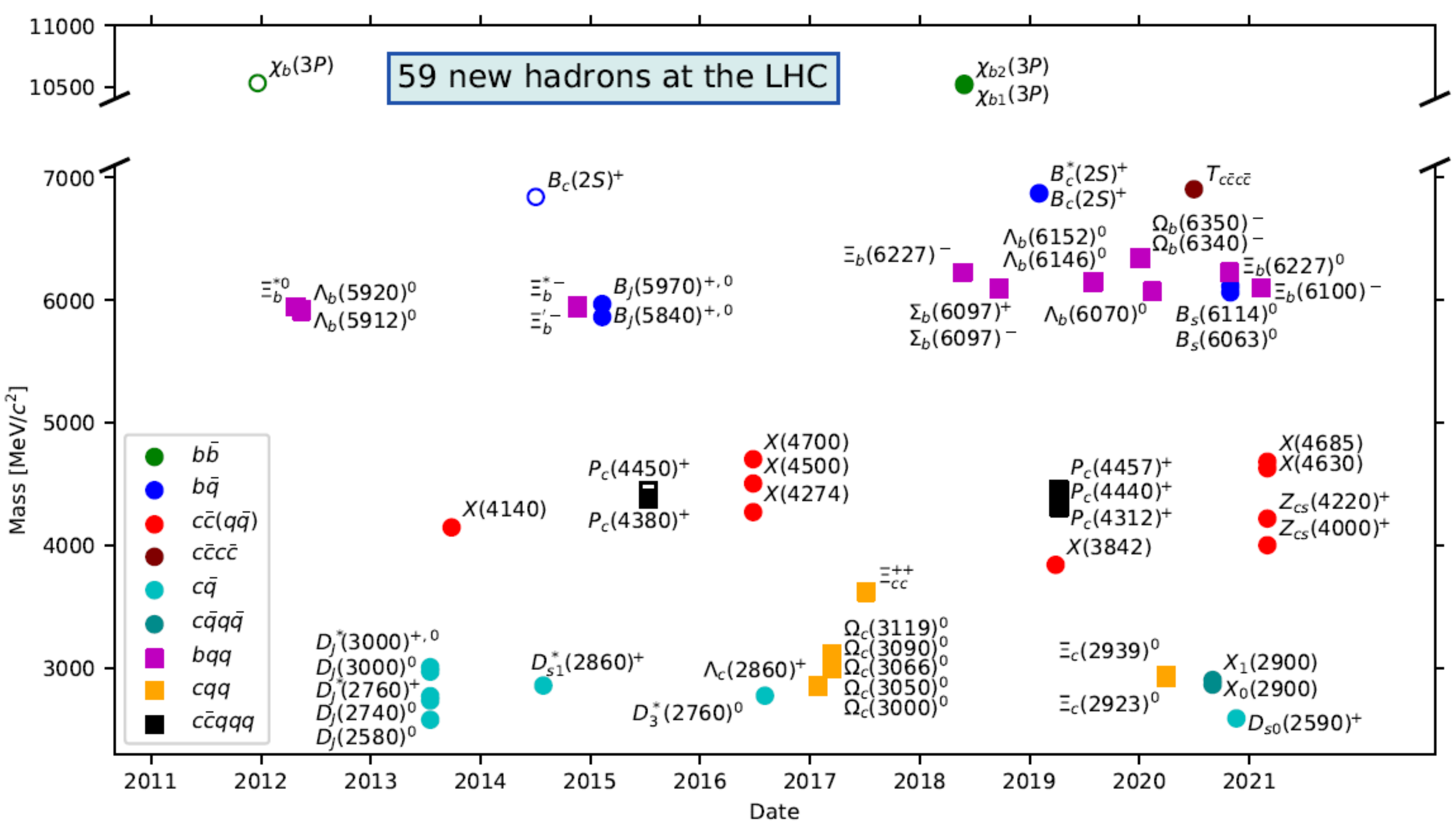


- In QCD vacuum, gluons are self-interacting
  - Potential grows linearly with distance, creating a sort of 'string tension'
- When pulled apart, the energy in the string increases, until it is energetically more favourable to create new $q\bar{q}$ pair
  $\rightarrow$ **quarks not observed free but 'confined within hadrons**



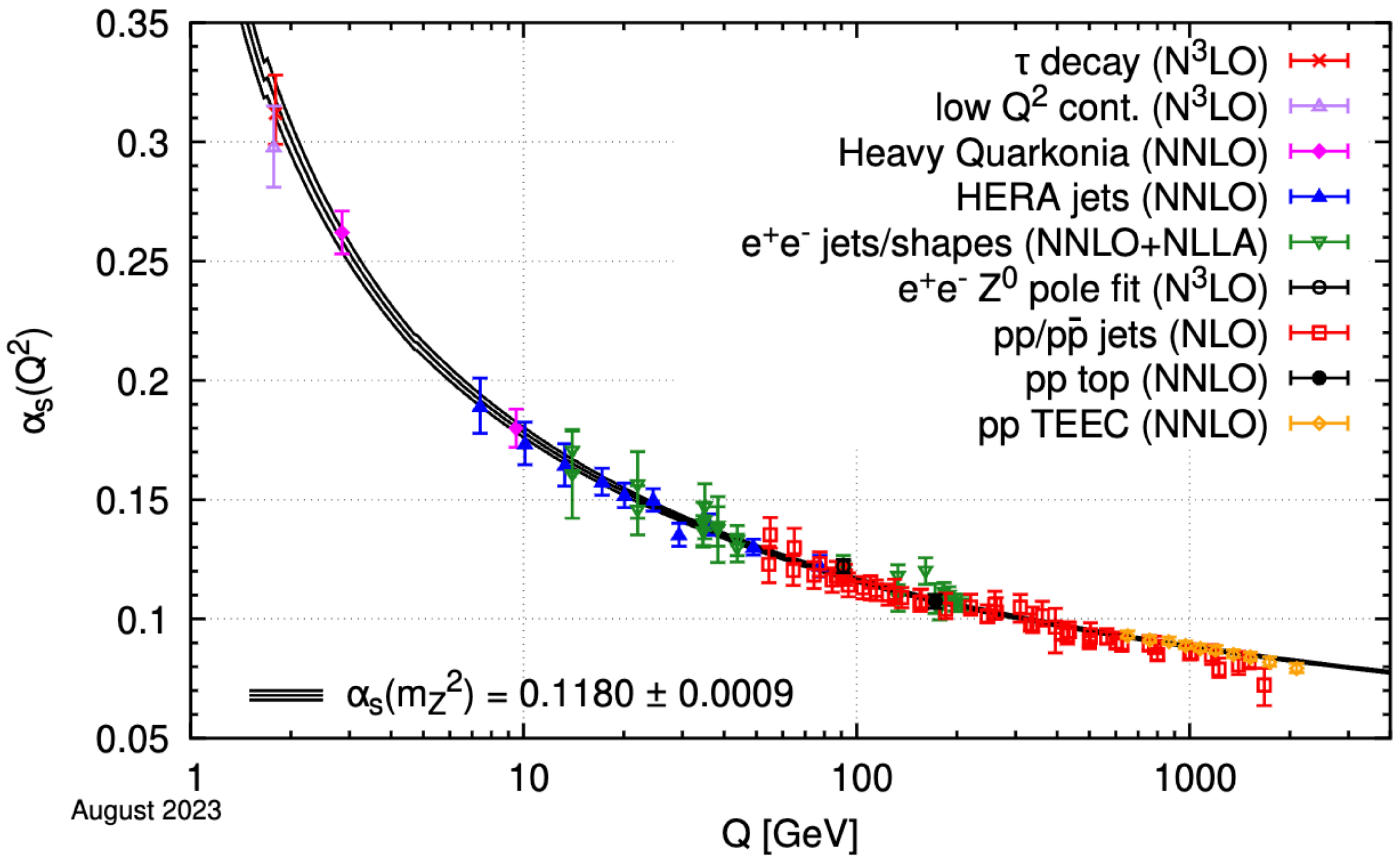
[illustration from Fritzsch]

Confinement in QCD



- Structure of QCD leads to rich ‘zoo’ of hadronic states
  - Thousands of hadrons/resonances discovered
  - many new hadrons discovered at the LHC alone!

Asymptotic freedom



- QCD coupling constant α_s weakens with increasing momentum transfer Q / decreasing distance scale
  → **asymptotic freedom**
  - High Q → calculation possible using perturbative techniques
  - Low Q → non-perturbative approaches required (e.g. Lattice QCD)
    - Boundary between regimes occurs at energy scale Λ_{QCD} ~ 150 MeV

Discovery 1973
Nobel Prize 2004

What is the structure of QCD matter over a range of energies/densities?

D. J. Gross and F. Wilczek, "Ultraviolet Behavior of Non-Abelian Gauge Theories", Phys. Rev. Letters 30 1343 (1973),
H. D. Politzer, "Reliable Perturbative Results for Strong Interactions", Phys. Rev. Letters 30 1346 (1973)

Thermodynamic limit of hadronic matter - early work

- Thermodynamics of hadronic matter and its ‘limit’ was studied before quarks and asymptotic freedom were discovered
  - Rolf Hagedorn, 1965:

In this statistical-thermodynamical approach to strong interactions at high energies it is assumed that higher and higher resonances of strongly interacting particles occur and take part in the thermodynamics as if they were particles. For $m \to \infty$ these objects are themselves very similar to those which shall be described by this thermodynamics. Expressed in a slogan: "We describe by thermodynamics fire-balls which consist of fire-balls, which consist of fire-balls, which ...". This principle, which could be called "asymptotic bootstrap",leads to a self-consistency requirement for the asymptotic form of the mass spectrum. The equation following from this requirement has only a solution if the mass spectrum grows exponentially:

$$\rho(m) \xrightarrow[m \to \infty]{} \text{const.}\, m^{-5/2} \exp\left(\frac{m}{T_o}\right).$$

T_o is a remarkable quantity: the partition function corresponding to the above $\rho(m)$ diverges for $T \to T_o$. T_o is therefore the highest possible temperature for strong interactions. It should - via a Maxwell-Boltzmann law - govern the transversal momentum distribution in all high energy collisions of hadrons (including e.m. form factors, etc.). There is experimental evidence for that, and then T_o is about 158 MeV ($\approx 10^{12}$ °K). With this value of T_o the asymptotic mass spectrum of our theory has a good chance to be the correct extrapolation of the experimentally known spectrum.

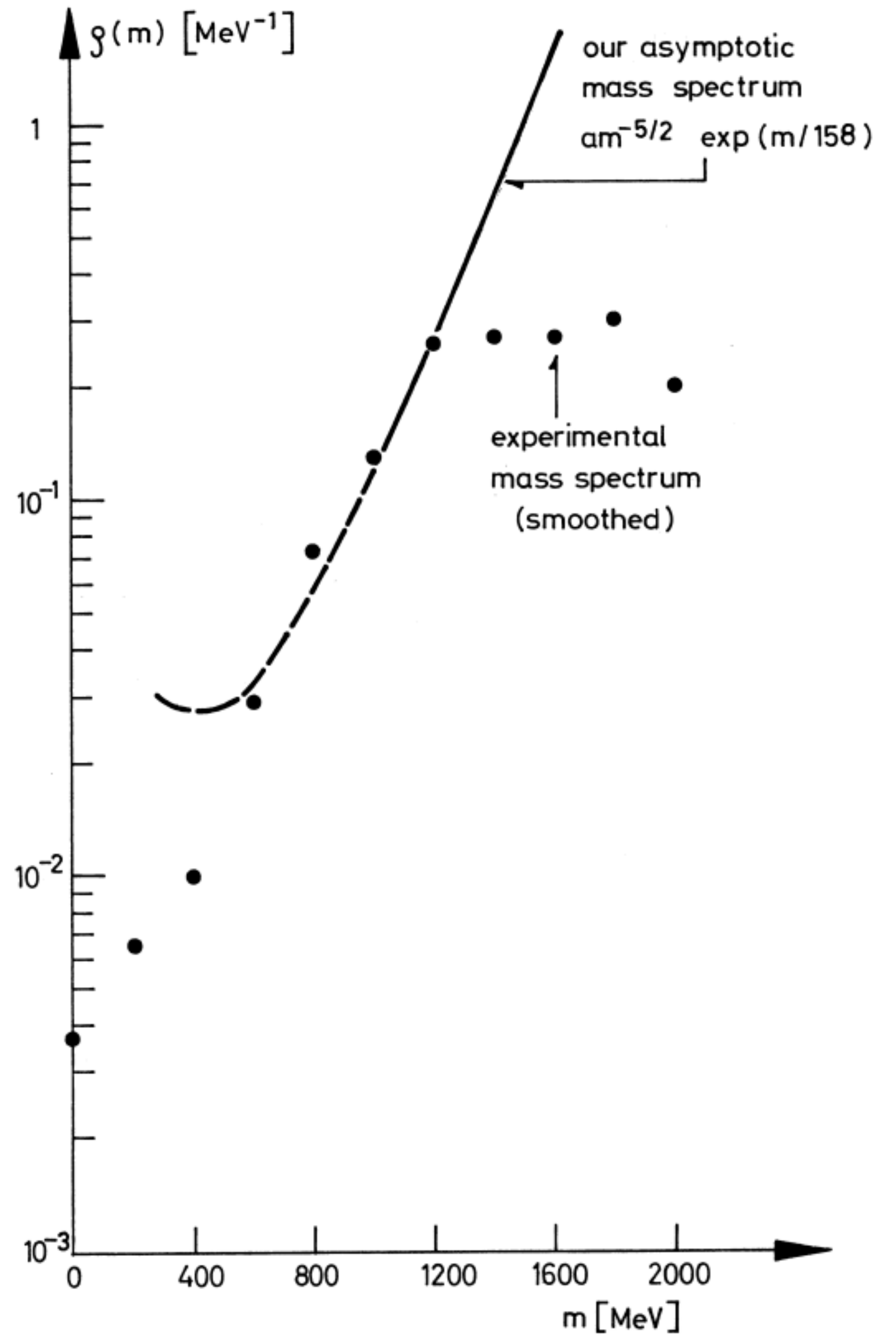


FIG.2 The experimental mass spectrum[10] (smoothed) compared to our asymptotic $\varrho(m)$; one-parameter fit with $a \approx 6.5 \times 10^3$ [$\text{MeV}^{3/2}$]

- Particle production theorised to radiate from small volume ‘fireball’
- If number of particles of a given mass increases exponentially with mass, temperature of fireball has limiting value:

$T_0 \sim 160$ MeV
- Hagedorn temperature

R. Hagedorn, *Nuovo Cim.Suppl.* 3 (1965) 147-186, CERN-TH-520

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https://cerncourier.com/a/the-tale-of-the-hagedorn-temperature/

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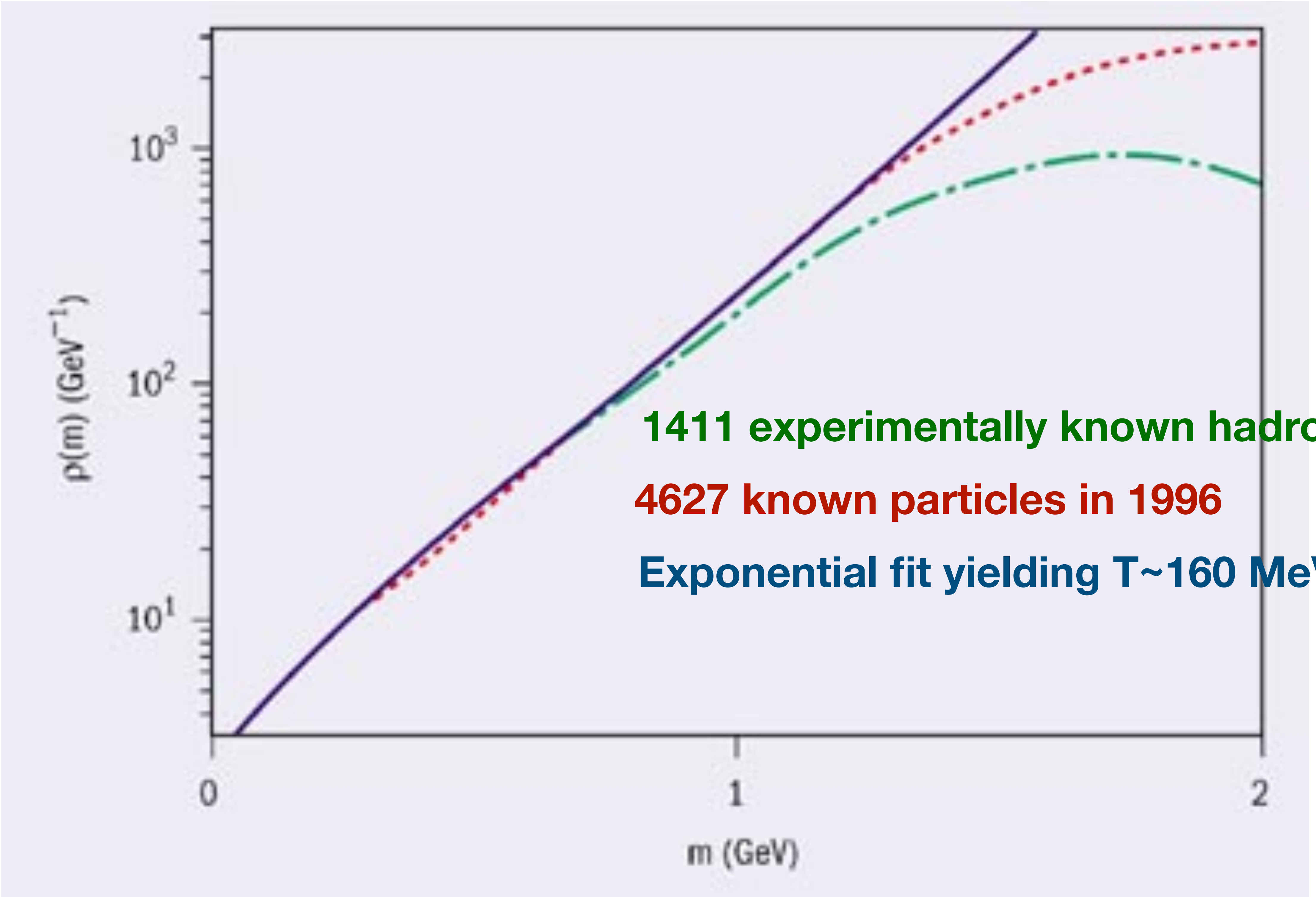


Original deviation at high m likely due to undiscovered states

R. Hagedorn, *Nuovo Cim.Suppl.* 3 (1965) 147-186, CERN-TH-520

Thermodynamic limit of hadronic matter - phase transition

- Suggested after discovery of quarks that this limiting temperature represents **the existence of a phase boundary**

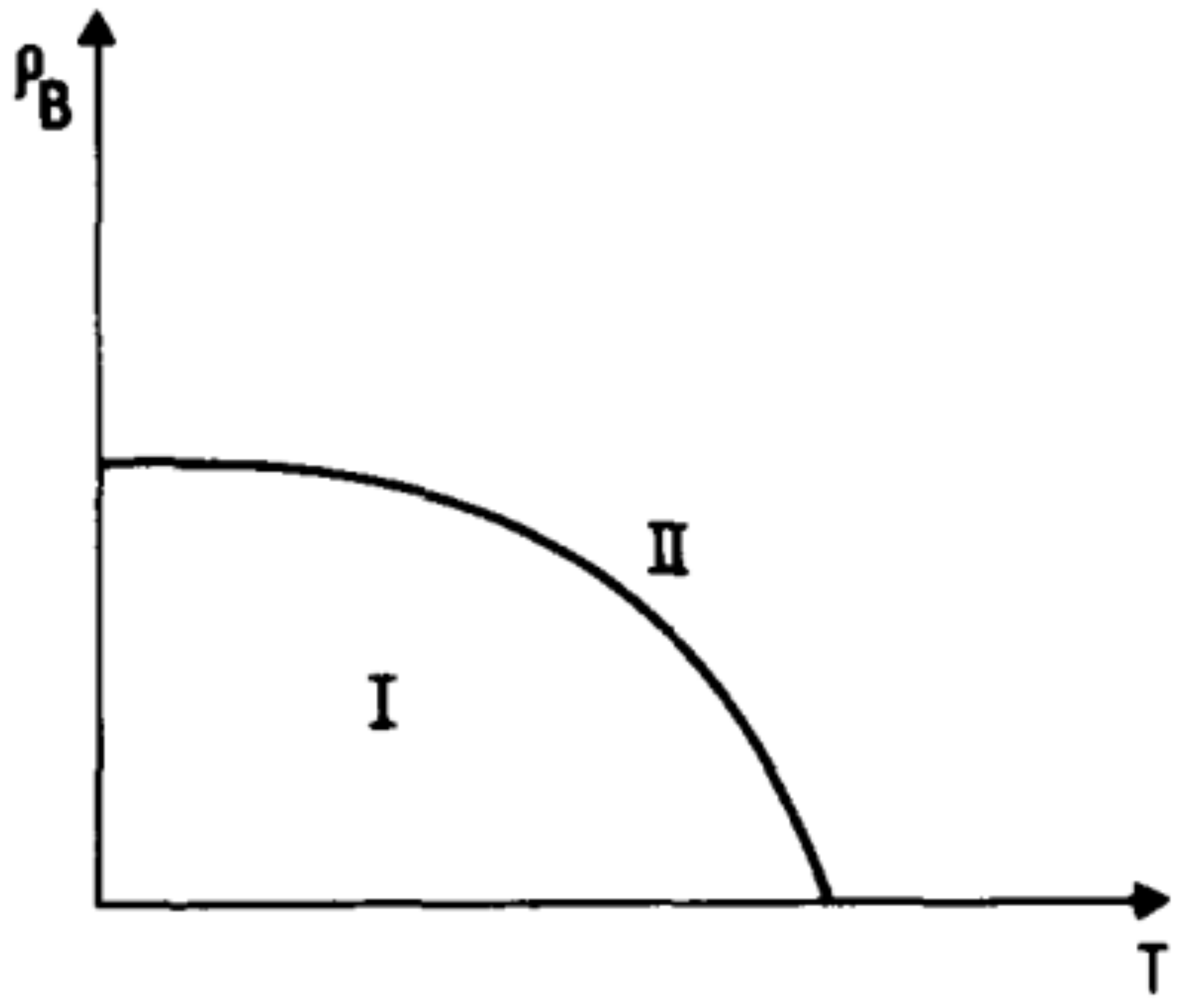
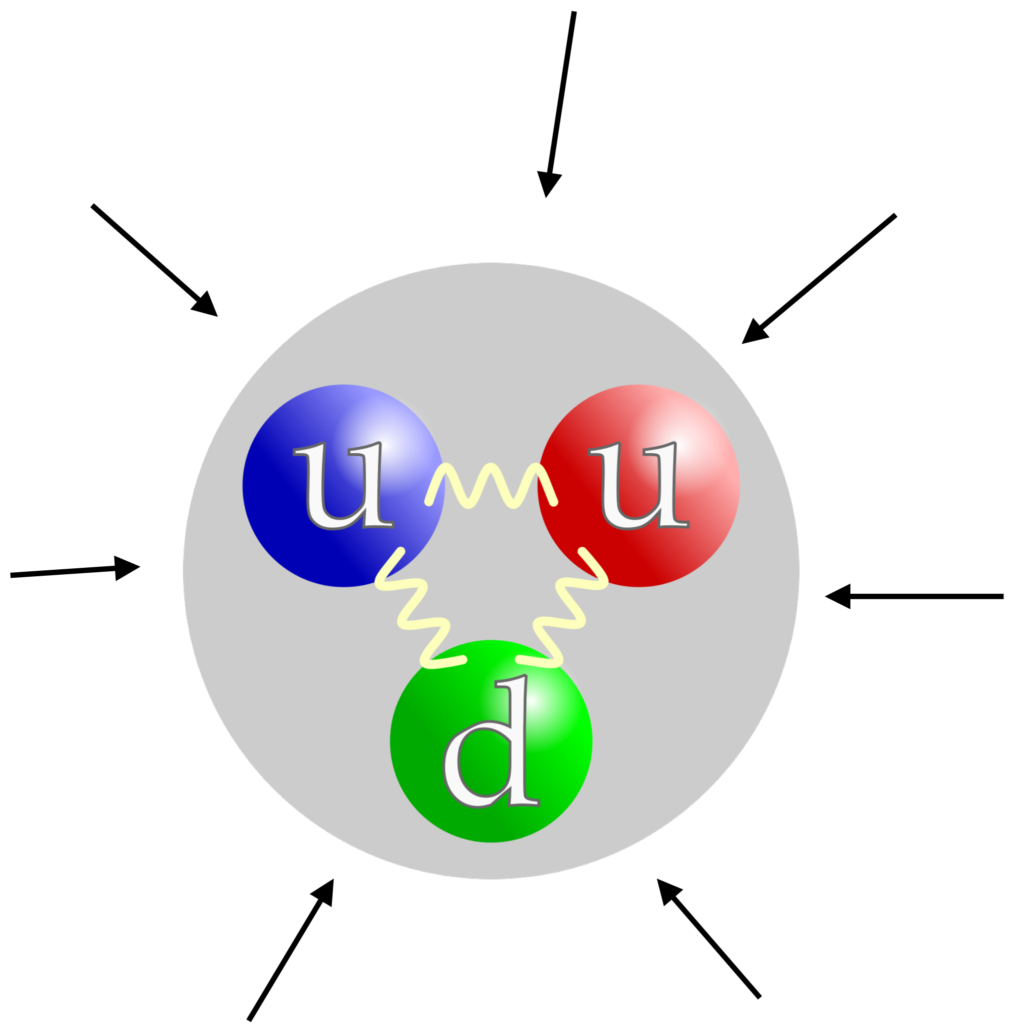
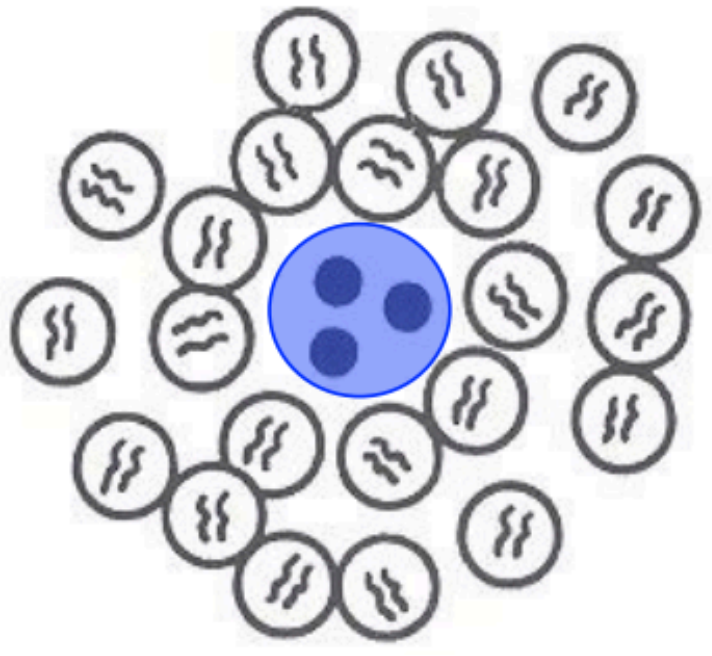


Fig. 1. Schematic phase diagram of hadronic matter. ρ_B is the density of baryonic number. Quarks are confined in phase I and unconfined in phase II.

‘We suggest that the “observed” exponential spectrum ((of Hagedorn)) is connected to the existence of a different phase of the vacuum in which quarks are not confined.’

N. Cabibbo, G. Parisi, Phys. Lett. B59 (1975) 67–69.





MIT bag model of quarks
Hadron = bag of quarks with potential energy B
Vacuum = exerts pressure on bag
Quark matter - one big bag with pressure reduced by B

A. Chodos et al, Phys. Rev. D 9 (Jun, 1974) 3471–3495
T. DeGrand et al, Phys. Rev. D12 (1975) 2060

In this model, critical temperature T_c where pressure on hadrons is overcome:

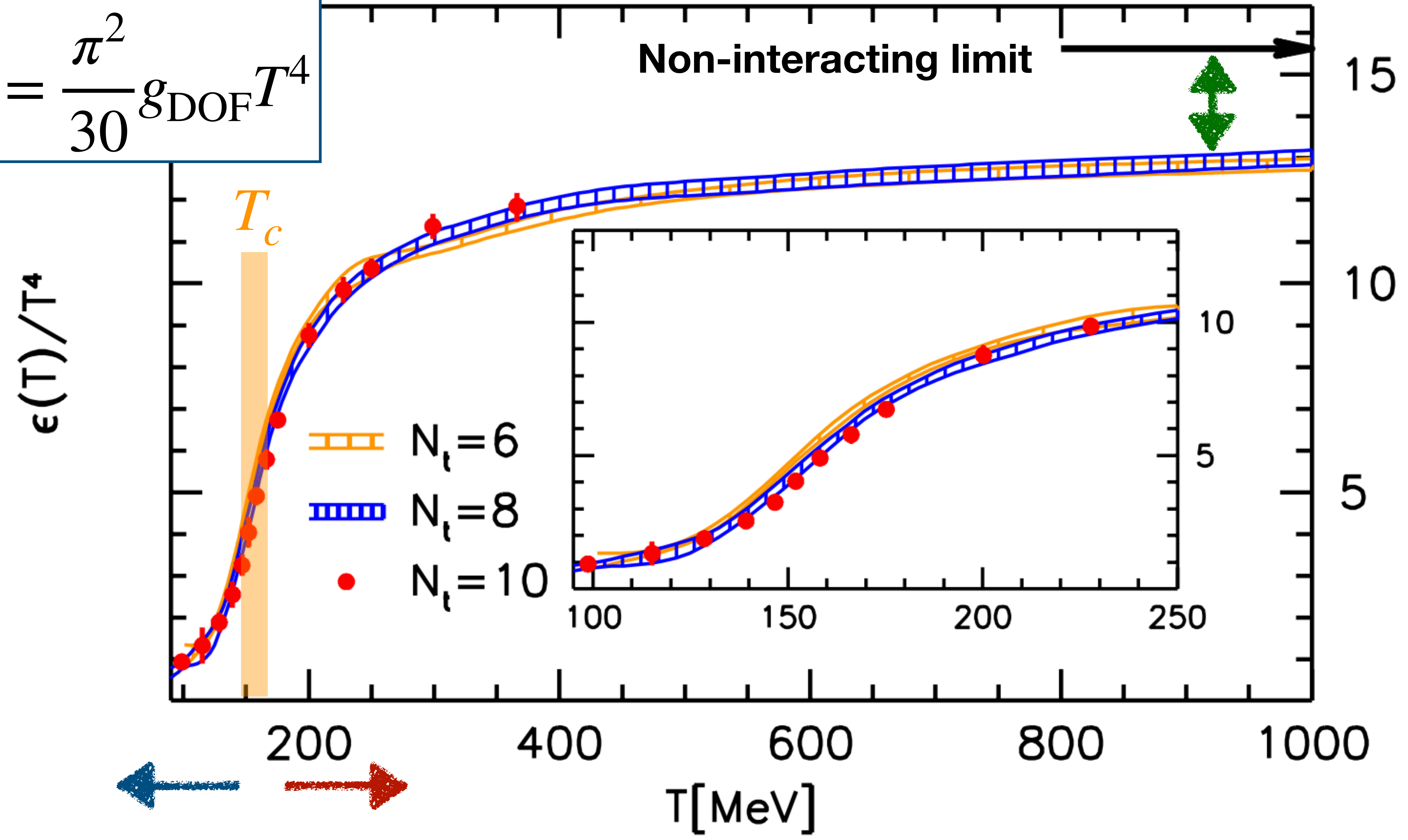
$T_c \sim 140$ MeV

Modern picture of QCD thermodynamics at high temperature

Lattice QCD today used to study QCD equation of state and phase transitions
(where α_s is large and thus perturbative techniques can't be applied)

Energy density

$$\epsilon = \frac{\pi^2}{30} g_{\mathrm{DOF}} T^4$$

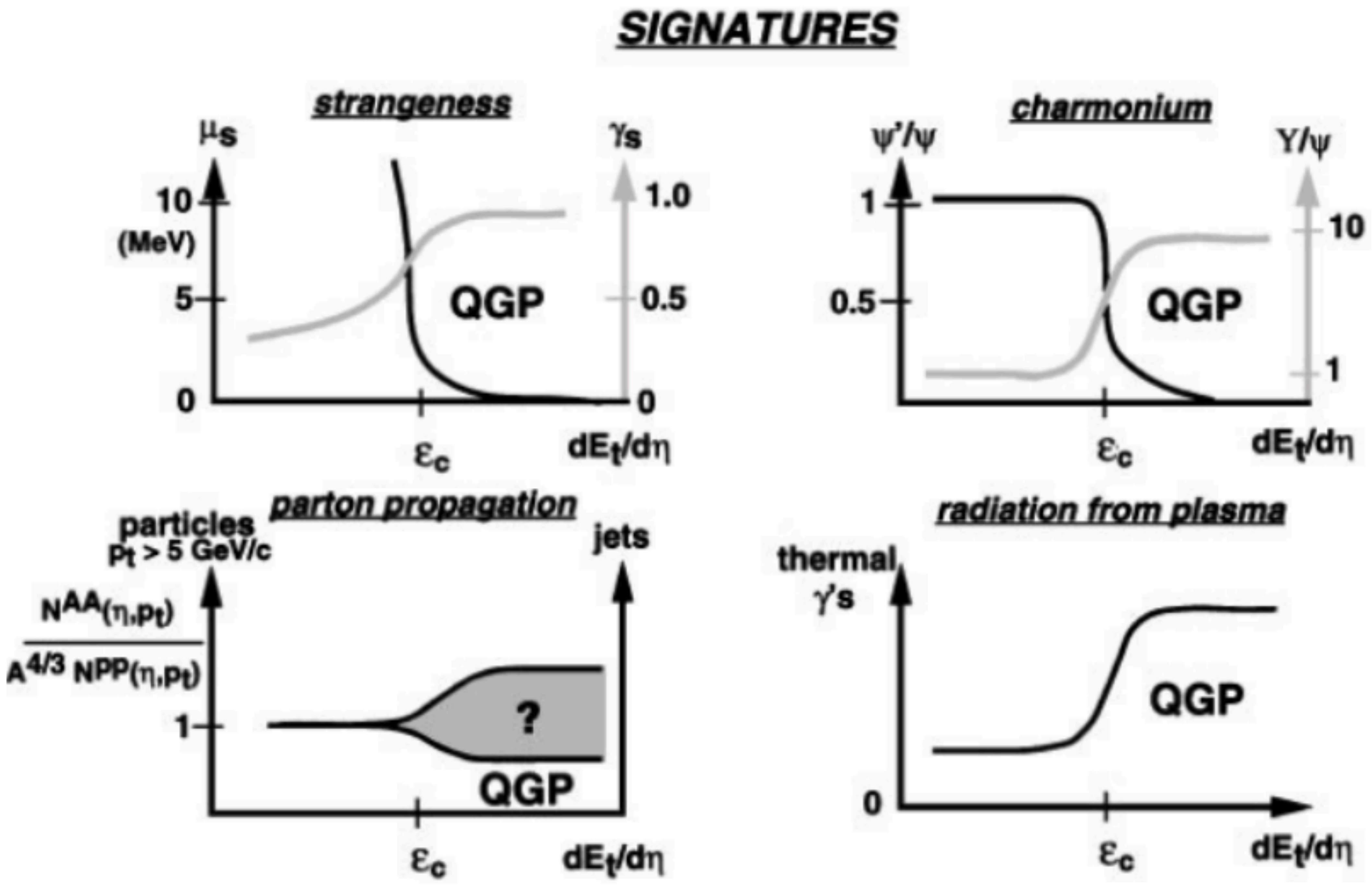


Confinement **Deconfinement**

S.Borsanyiet al., JHEP 1011, 077 (2010)

- **Key points looking at temperature vs energy density:**
  - **Smooth crossover at T_c~155 MeV**
  - Liberation of many new degrees of freedom → **sharp increase in energy density**
  - Gradually approaches non-interacting limit, but ~20% lower in experimentally accessible region - **strongly coupled**

Experimental evidence of a deconfined phase



B. Mueller, J. Harris,
'The Search for the QGP', arxiv:2308.05743
QGP signatures revisited, arxiv:2308.05743

- A number of experimental observables proposed by theorists during late ~70s-80s (quarkonia melting, strangeness enhancement, jet modification/suppression..)
- First "compelling" evidence of QGP at SPS (late 90s-2000)

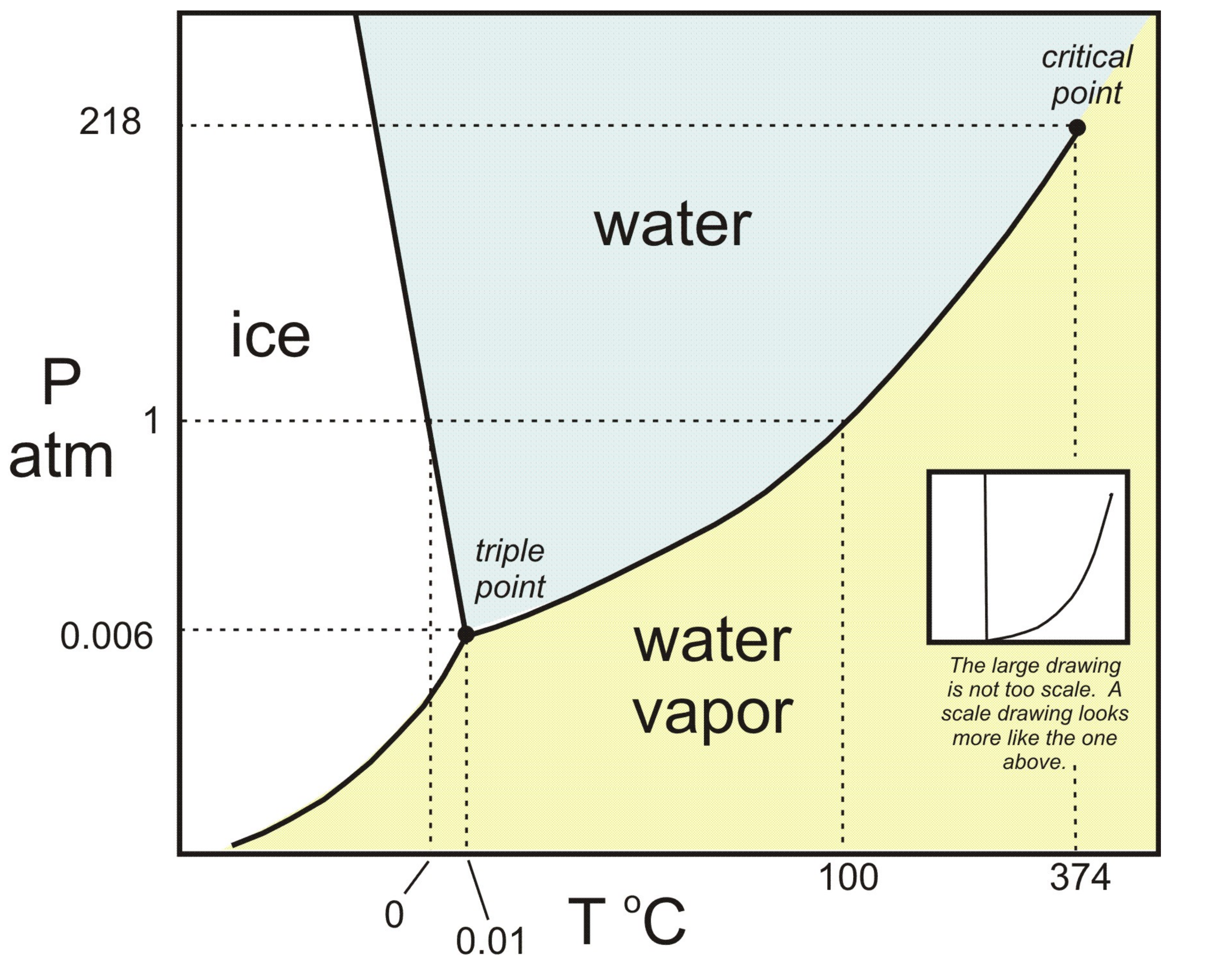
See U. Heinz, M. Jacob, https://arxiv.org/abs/nucl-th/0002042

- "Discovery" of deconfined state of matter confirmed at RHIC (2005)

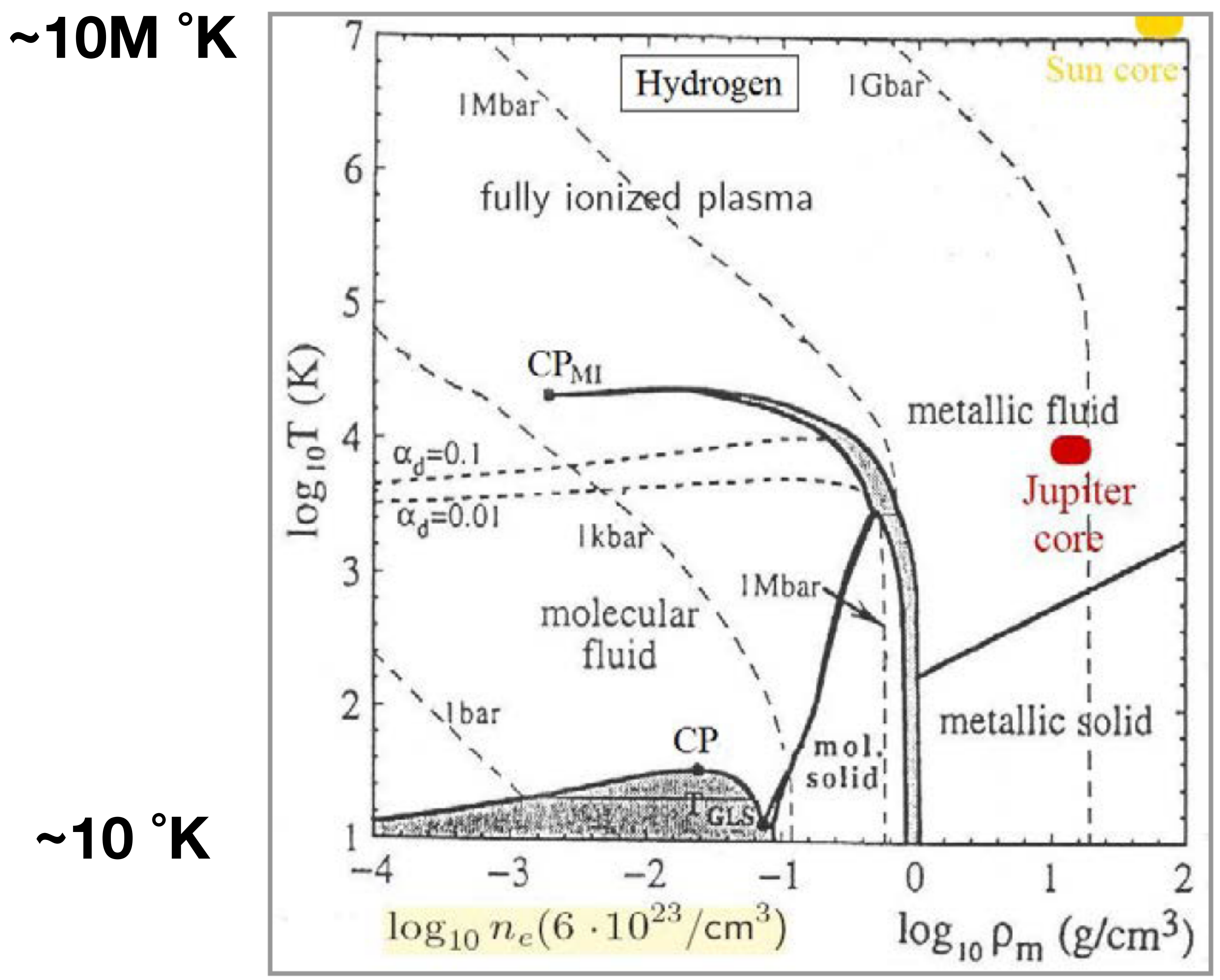
https://www.bnl.gov/newsroom/news.php?a=110303
BRAHMS: Nucl.Phys. A757 (2005) 1-27
PHENIX: Nucl.Phys. A757 (2005) 184-283
PHOBOS: Nucl.Phys. A757 (2005) 28-101
STAR: Nucl.Phys. A757 (2005) 102-183

Phase transitions for 'cold' nuclear/hadronic matter

Gas, liquid and solid phase transitions in H20



Gas, liquid and plasma phase transitions in hydrogen



- Phase transition - change from one physical state to another
  → solid ↔ liquid ↔ gas ↔ plasma… (e.g. ice ↔ water ↔ vapour)
  → critical point - where order of phase transition changes

The phase diagram of QCD matter

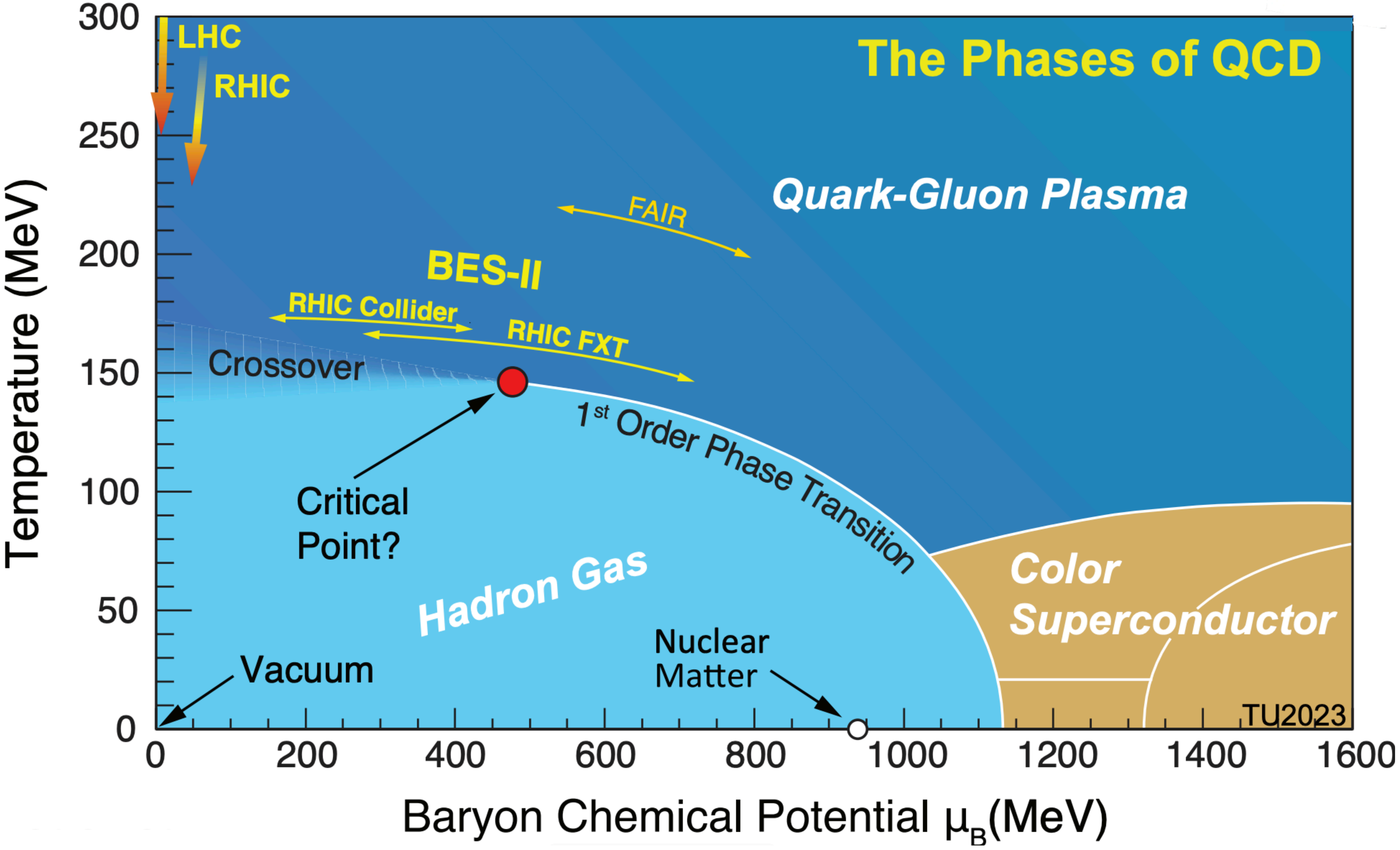


fig. H. Caines

- Phase transition at low baryochemical potential (~density) around ~2 trillion ˚K (150 MeV) is 100,000 times hotter than the centre of the sun
  - Smooth crossover, with 1st order phase transition at higher μ_B
- Deconfined phase thought to also exist at small temperatures/ high density (neutron stars?)

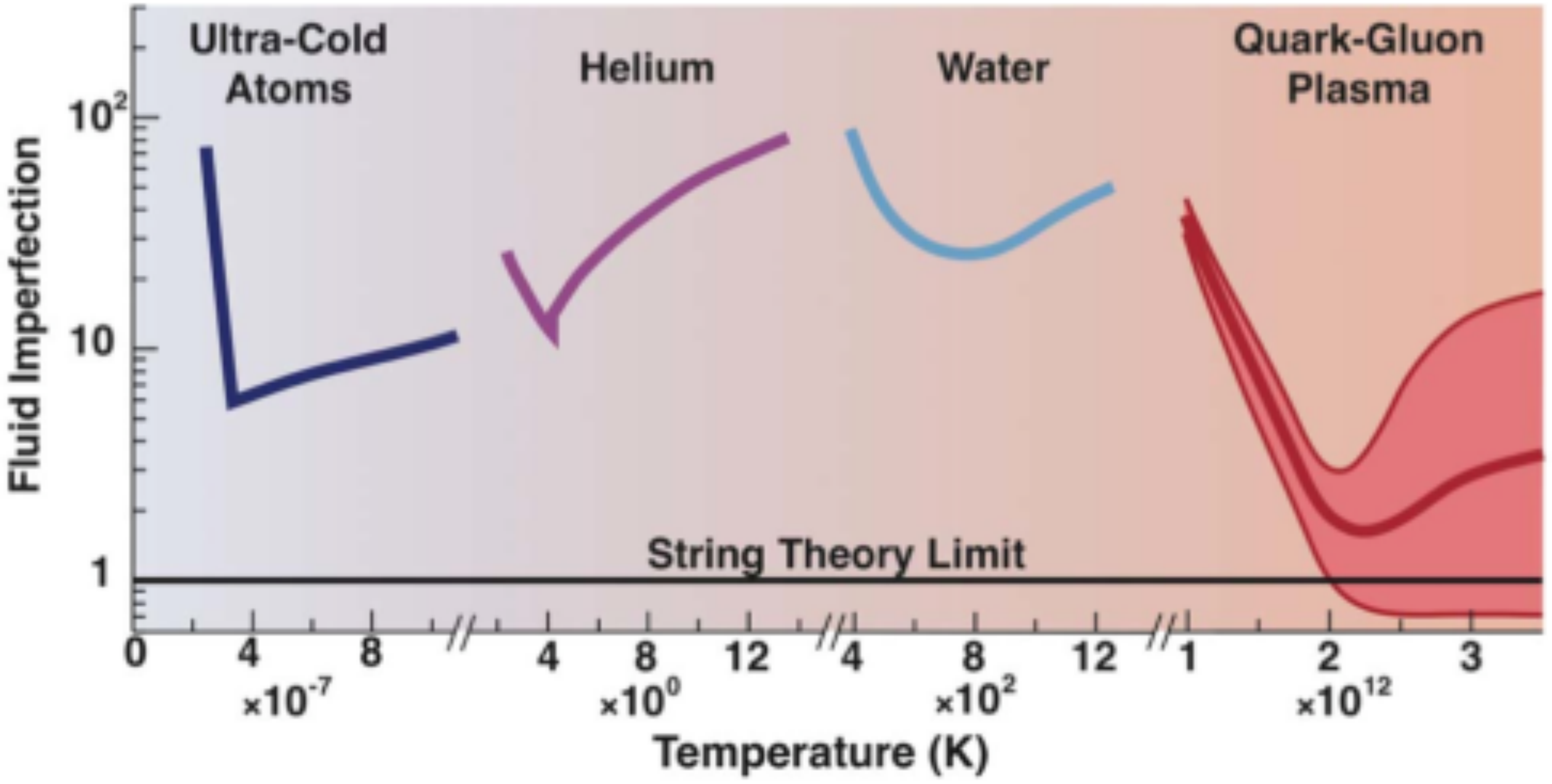
Why study the deconfined phase of QCD? 1)

- **It allows to study the bulk and thermodynamic properties of a fundamental field theory**
  - QCD is the only non-abelian field theory whose bulk, high-temperature properties can be studied experimentally.
  - Emergent properties of QCD under high-temperature *just as fundamental* as confinement/asymptotic freedom

Example

- Discovery by RHIC ~2005 that QGP as created in a lab is a strongly-interacting ***liquid*** with very low viscosity
- Profound and fundamental connections with string theory, holographic theories of black holes - pushes theoretical tools to study QCD

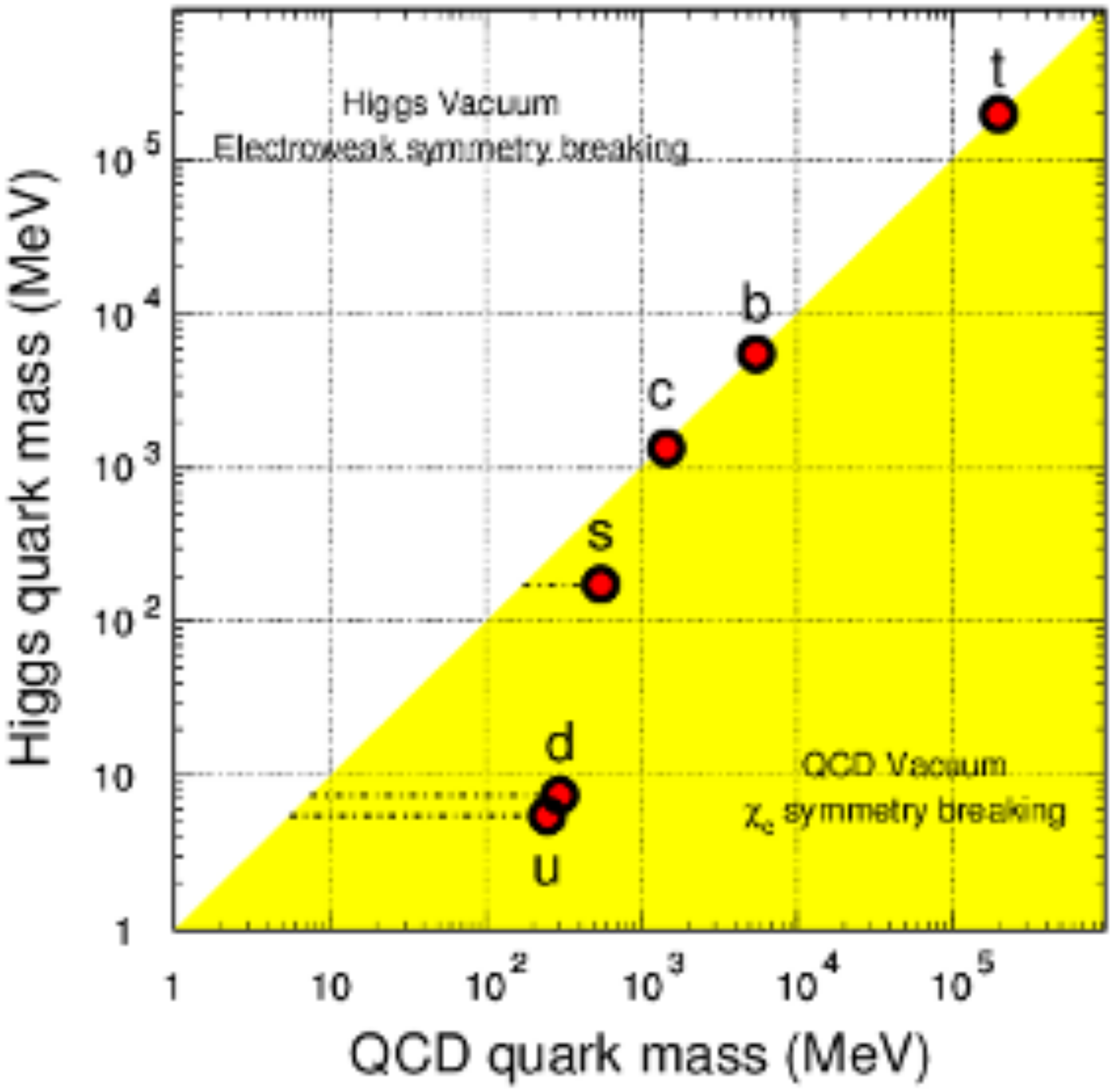
Fluid imperfection ∝ shear viscosity



C. Shen, U. Heinz, Nucl.Phys.News 25 (2015) 2, 6-11

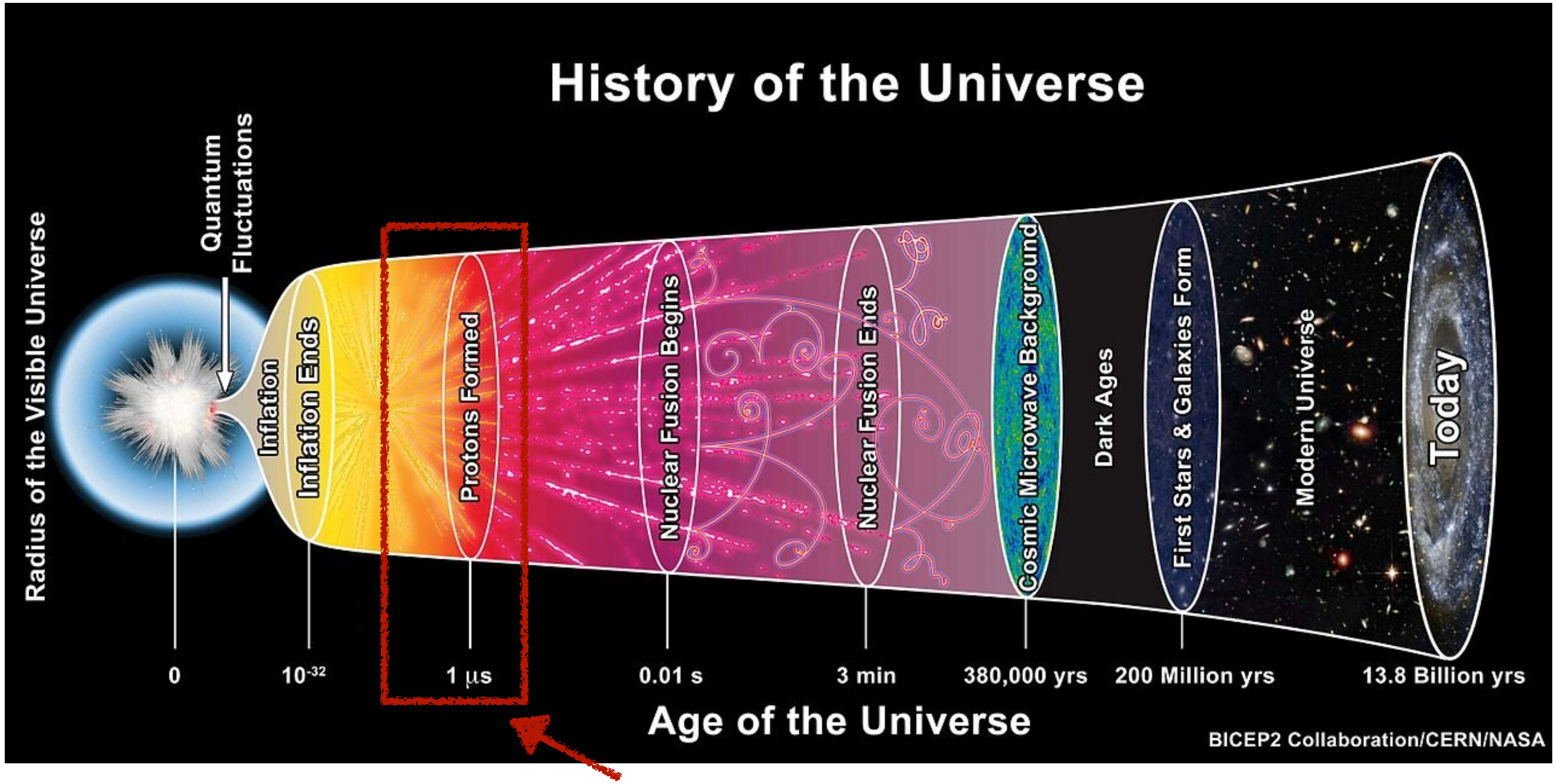
Why study the deconfined phase of QCD? 2)

- **By probing deconfined QCD matter, we can study quarks and gluons in their bare state**
  - Higgs mechanism only accounts for 1% of mass of ordinary matter
  - The dynamical generation of mass through confinement accounts for ~99% of the total mass of ordinary matter
  - Study of QCD (de)confinement helps us understand the origin of mass



Why study the deconfined phase of QCD? 3)

- **It helps us understand the early universe and how it evolved**
  - The universe was in a QGP-state up to $\sim 10^{-6}$ s after the Big Bang
    - Thought to also exist in neutron stars (gravitational waves?)

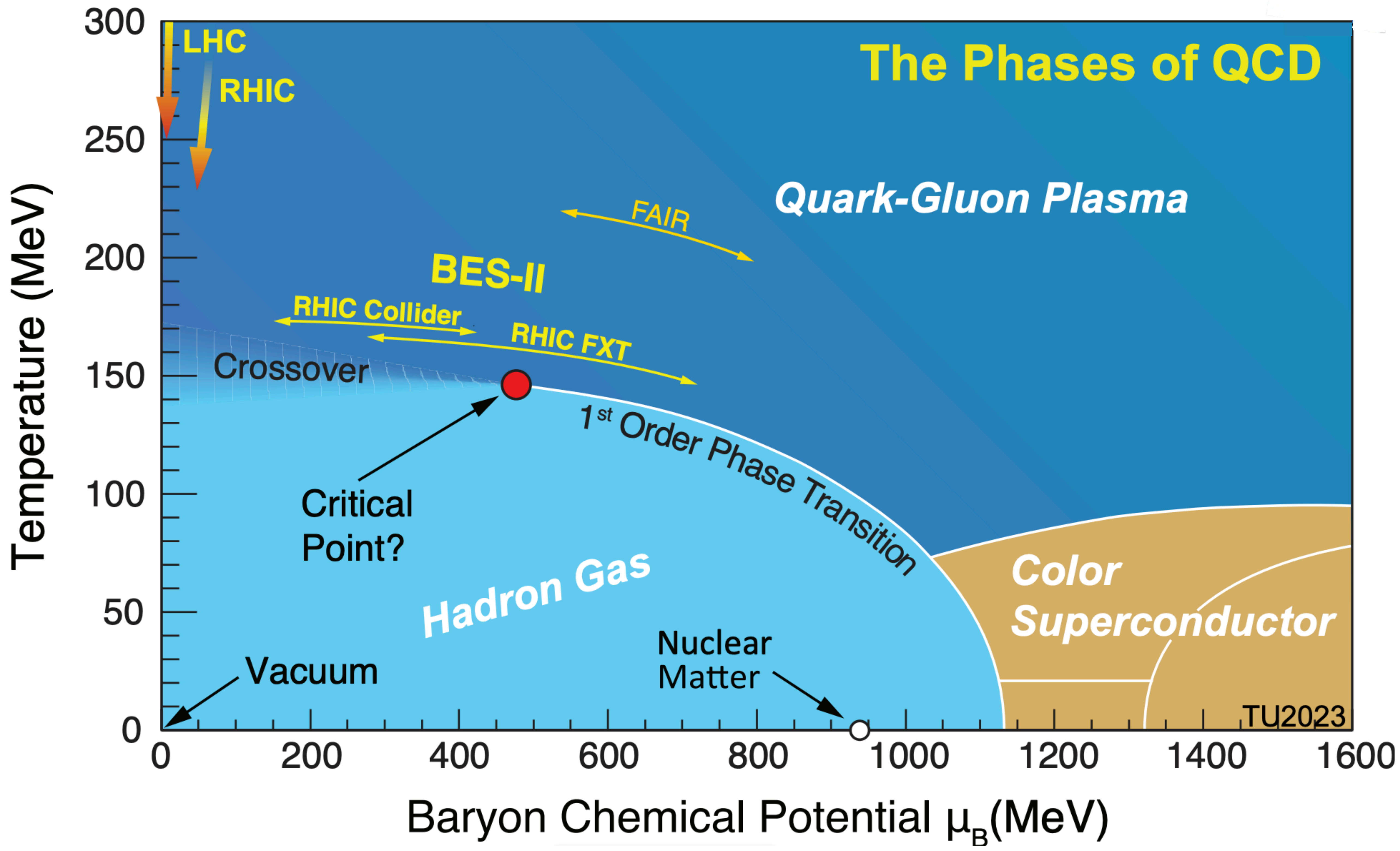


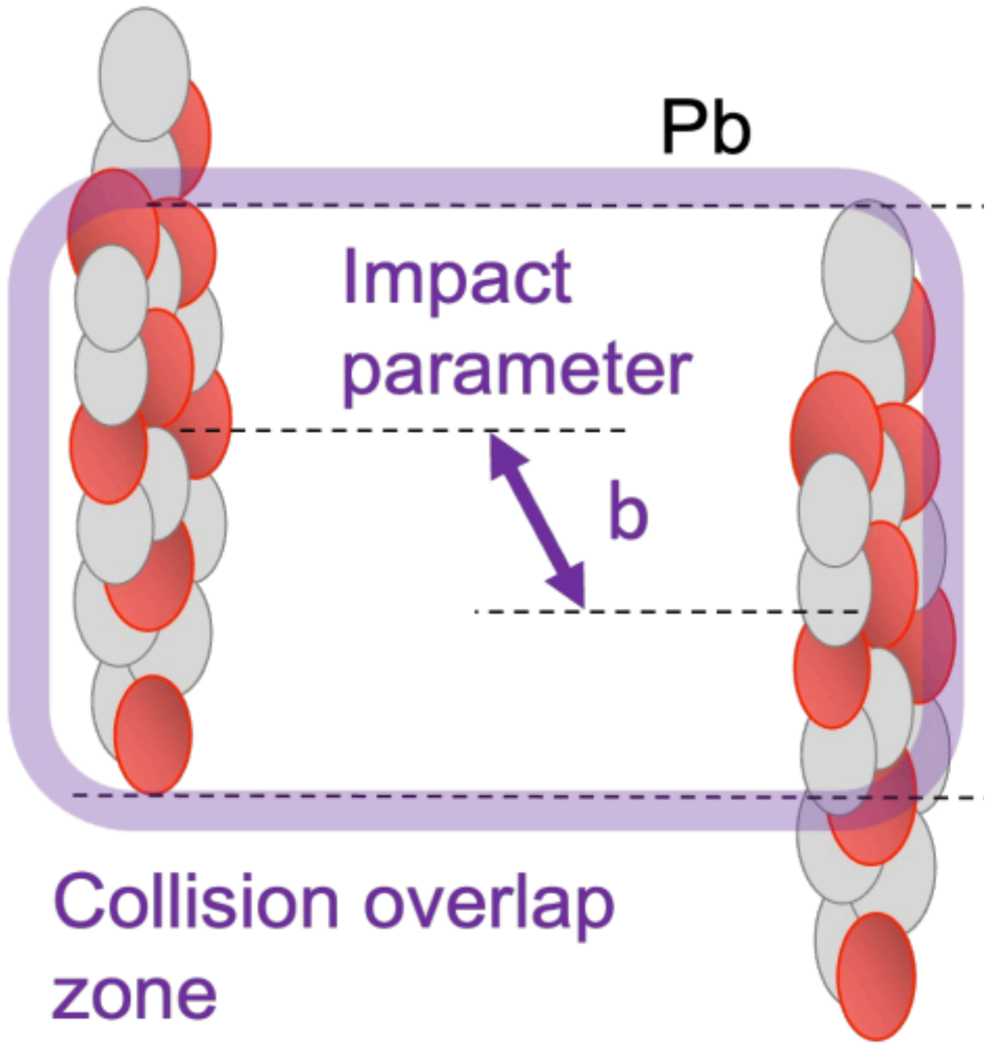
'Primordial Matter', the first material ever created

How can we make a QGP?

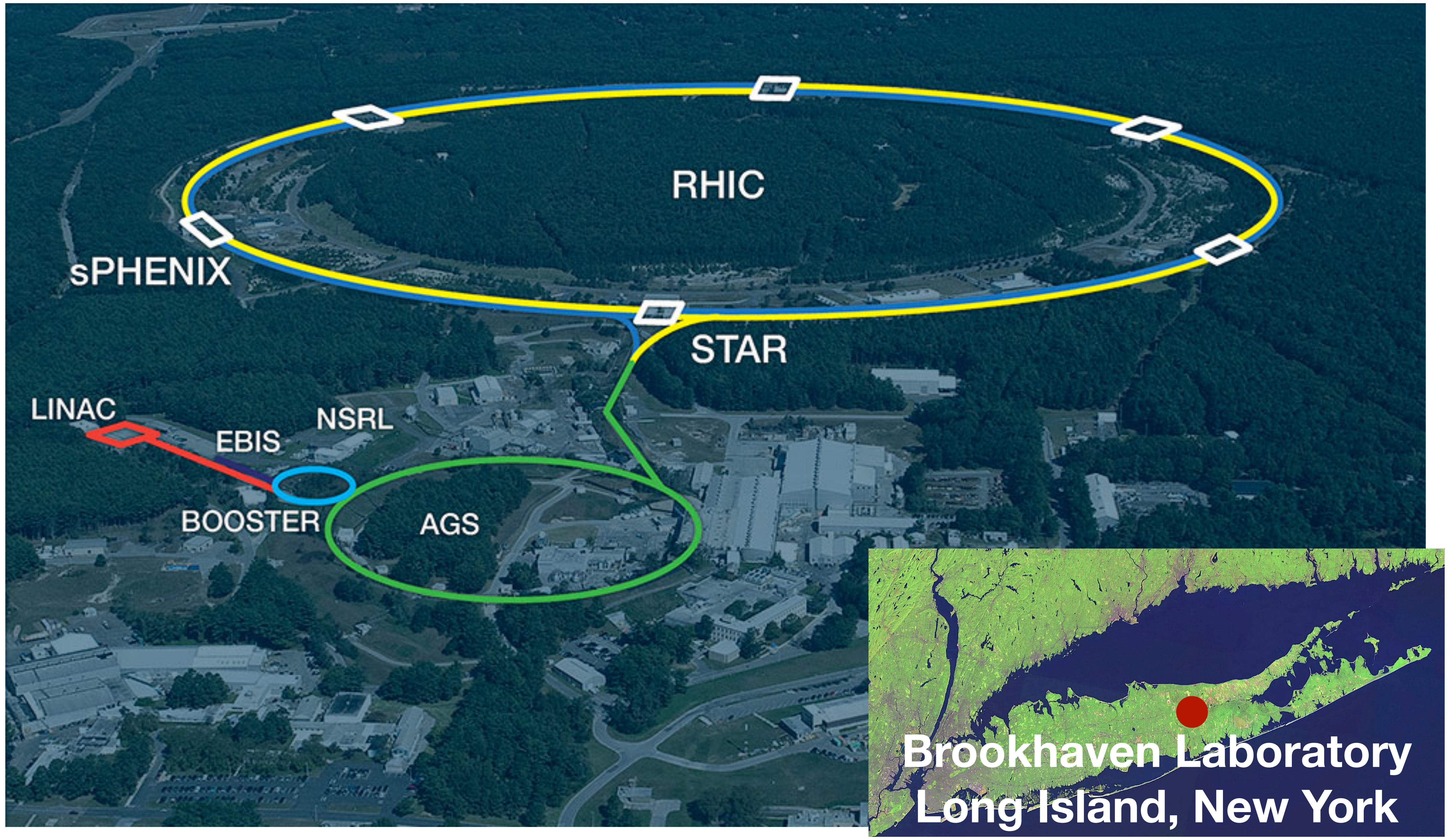
- A QGP can be formed by compressing large amount of energy into a small volume
  → **collide heavy nuclei**

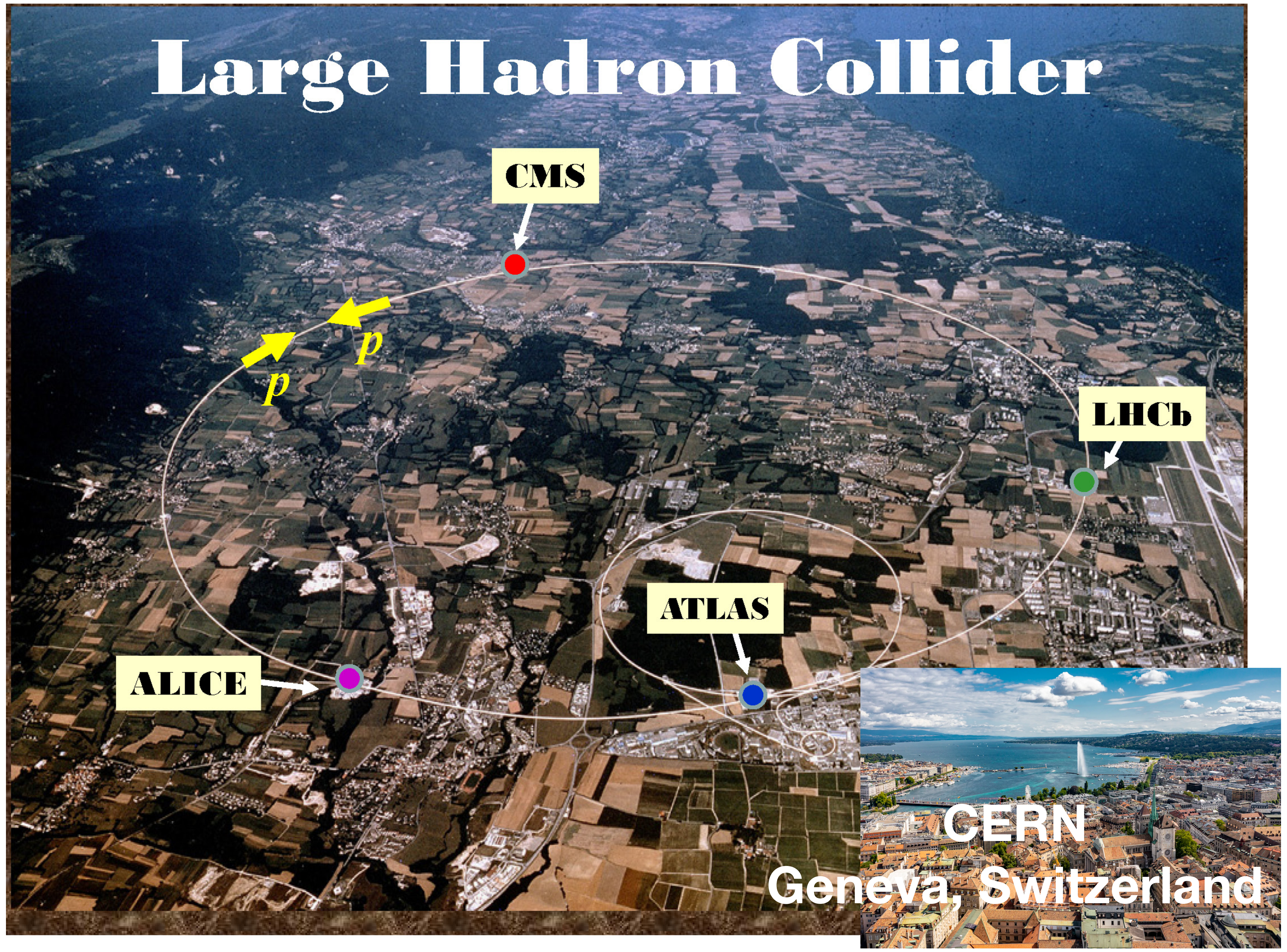
- Control energy deposited to explore different regions of QCD phase diagram
  → **vary collision system, ion species, impact parameter b (centrality) of collision …**





Where can we make a QGP?



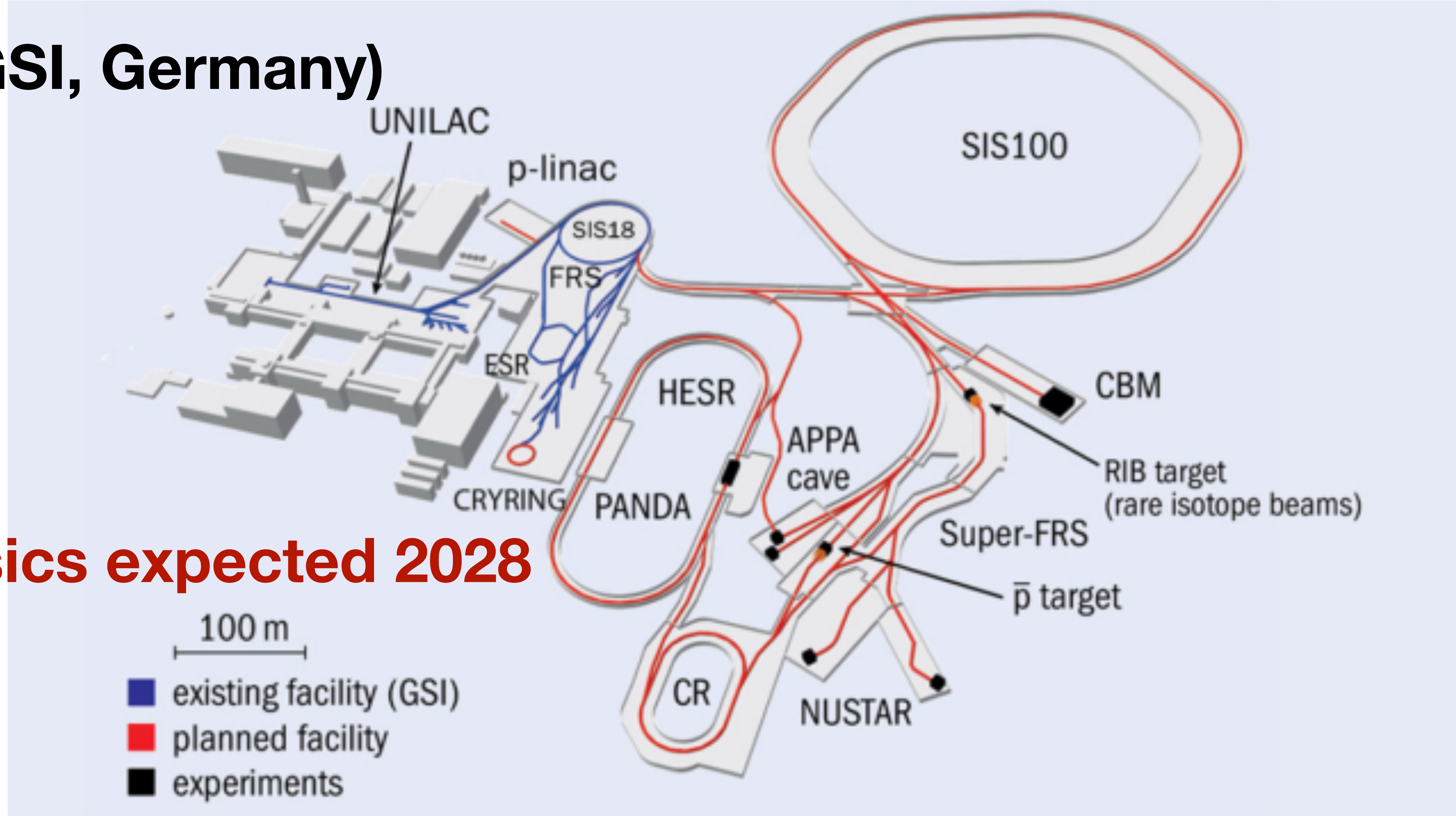


- Collisions of protons (pp), gold-ions (Au-Au), plus many other ions (Al, Cu, Zr, U…)
- Centre-of-mass energy per nucleon-nucleon collision up to $\sqrt{s_{NN}}$ = 200 GeV (Au-Au)

- In addition to collisions of protons (pp), for one month a year collide lead-ions (Pb-Pb) and proton-lead (p-Pb) (plus Xe-Xe, in future O-O?)
- Centre-of-mass energy per nucleon-nucleon collision up to $\sqrt{s_{NN}}$ = 5.36 TeV (Pb-Pb), $\sqrt{s}$ = 13.6 TeV (pp)

Lower-energy facilities

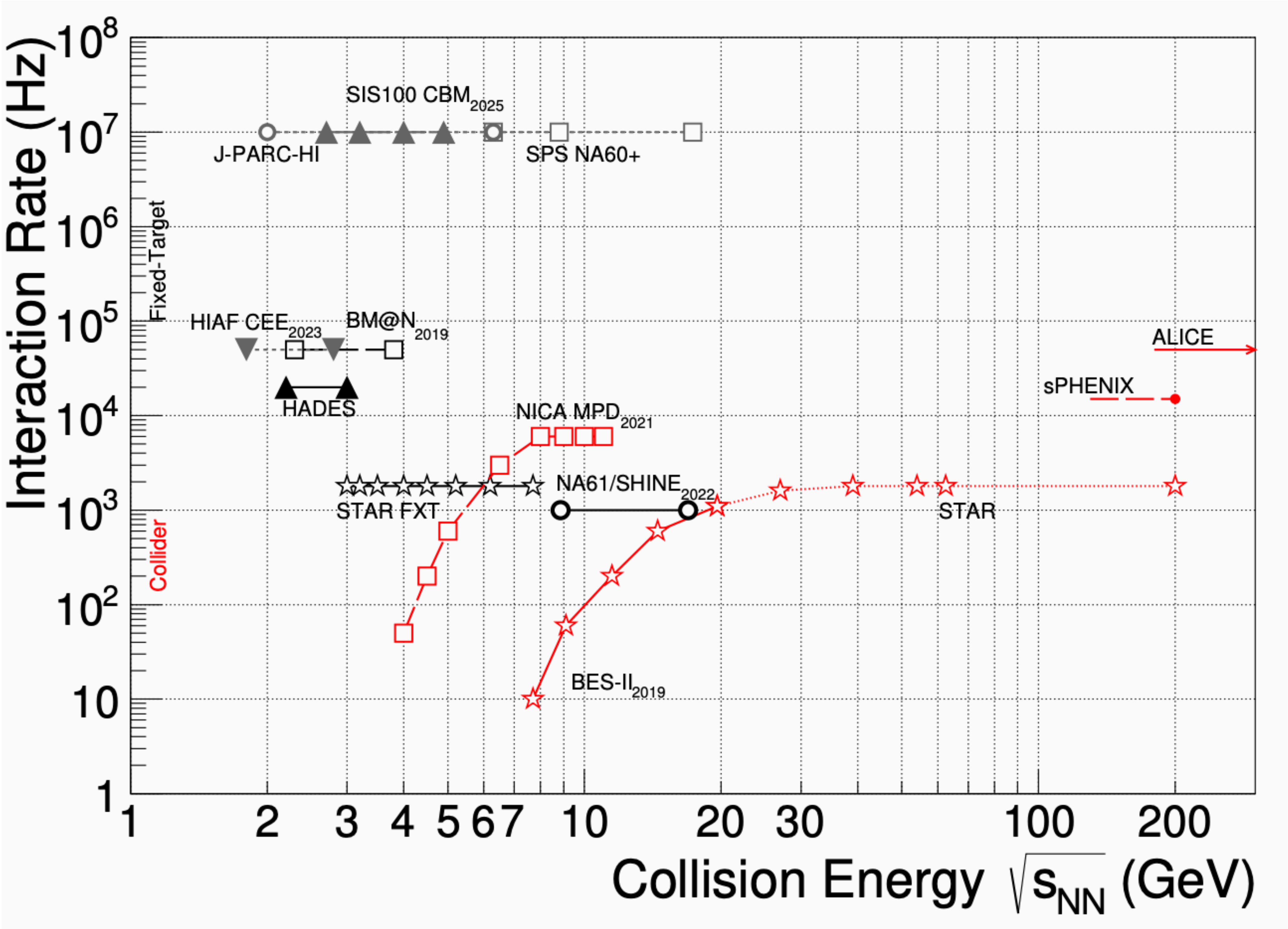
FAIR (GSI, Germany)



First physics expected 2028

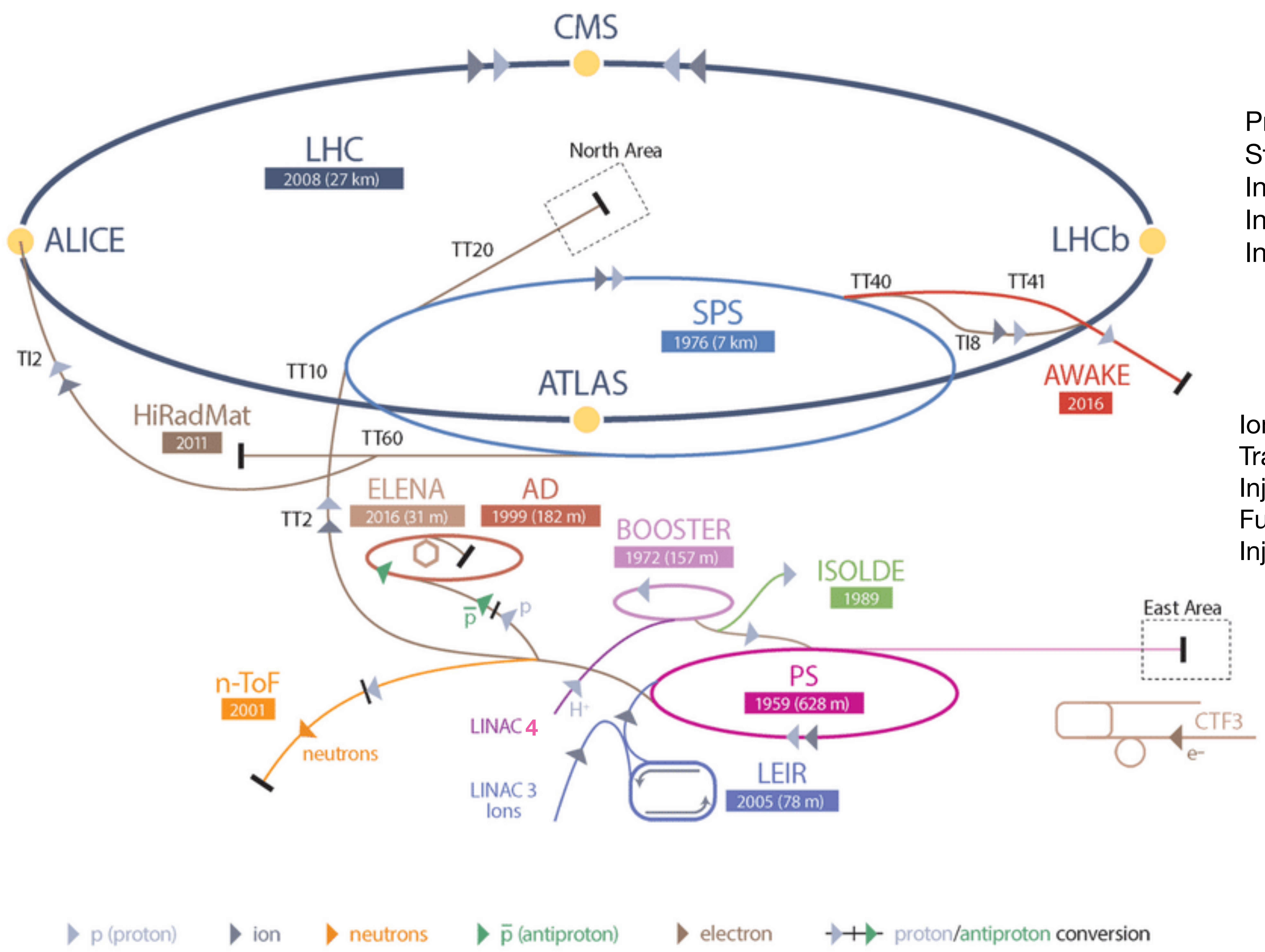
+ new facilities at JPARC, JINR, SPS and Beam energy scan at RHIC

T. Galatyuk, Nucl.Phys.A 982 (2019) 163-169



Different facilities aimed at probing different regions of QCD phase diagram (lower energies probe larger μ_B)

A closer look at the LHC



Protons: accelerated beam of H- from LINAC4 (160 MeV)
Stripped of electrons and injected into Booster (2 GeV)
Injected into PS and accelerated (25 GeV)
Injected into SPS and accelerated (450 GeV)
Injected into LHC and accelerated (up to 6.8 TeV)

Ions: Ionised (Pb 54+) and accelerated by LINAC3 (4.2 MeV/u)
Transformed into bunches and accelerated by LEIR (72 MeV/u)
Injected into PS and accelerated (4.3 GeV/u)
Fully ionised (Pb 82+), injected into SPS and accelerated (177 GeV/u)
Injected into LHC and accelerated (up to 2.68 TeV/u)

→ **collision energy up to 5.36 TeV / nucleon-nucleon collision**

Physics since 2010

Run 3 started in 2022 and is ongoing..!

A Large Ion Collider Experiment (ALICE) at the LHC

2200 participants from 175 institutes in 41 countries

UK involvement

University of Birmingham	University of Liverpool	University of Derby	Daresbury Lab
Trigger, jets, ultra-peripheral, LF measurements	Building Inner tracker, HF, jet measurements	jet, light flavour measurements	Building inner tracker, jets

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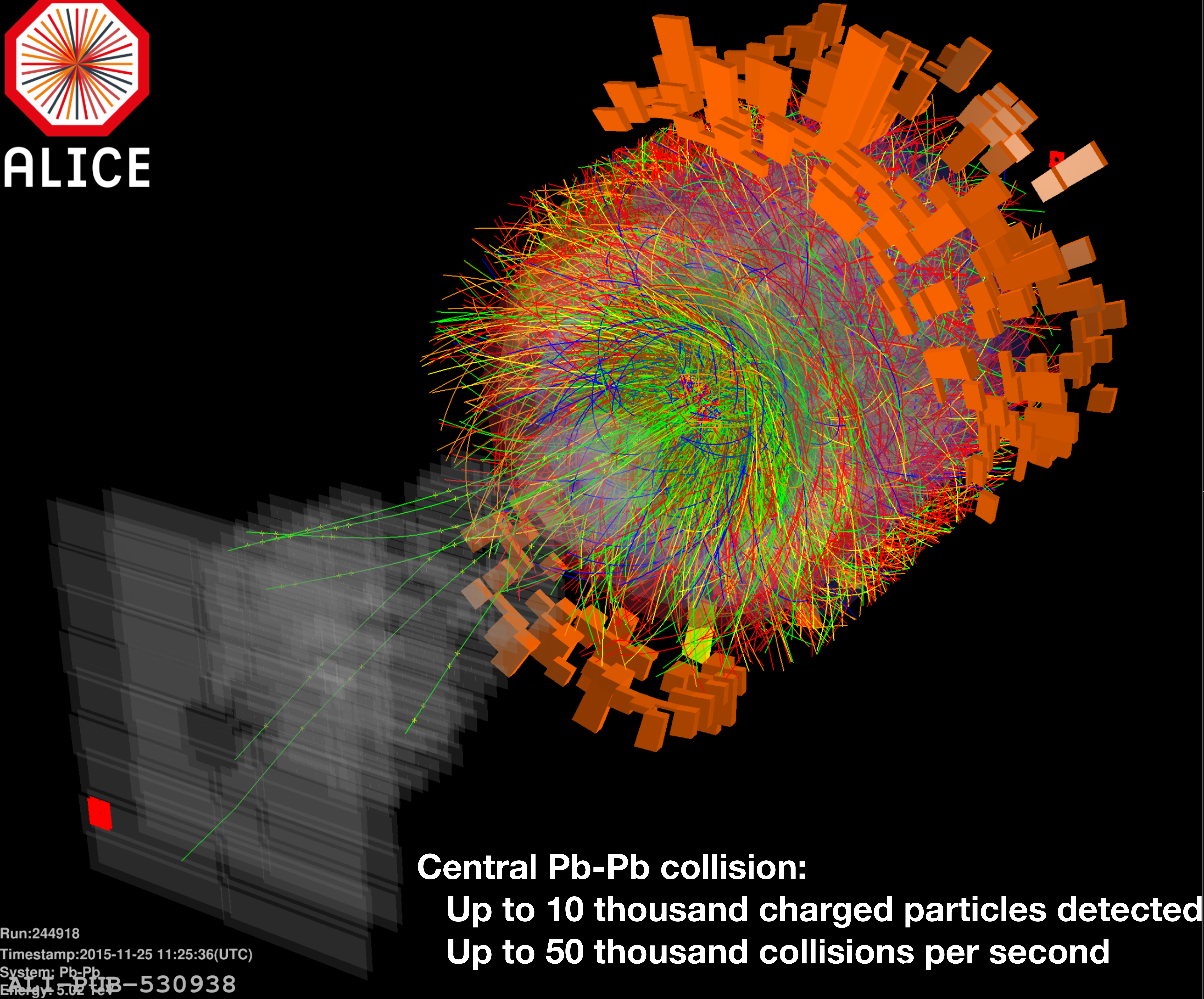
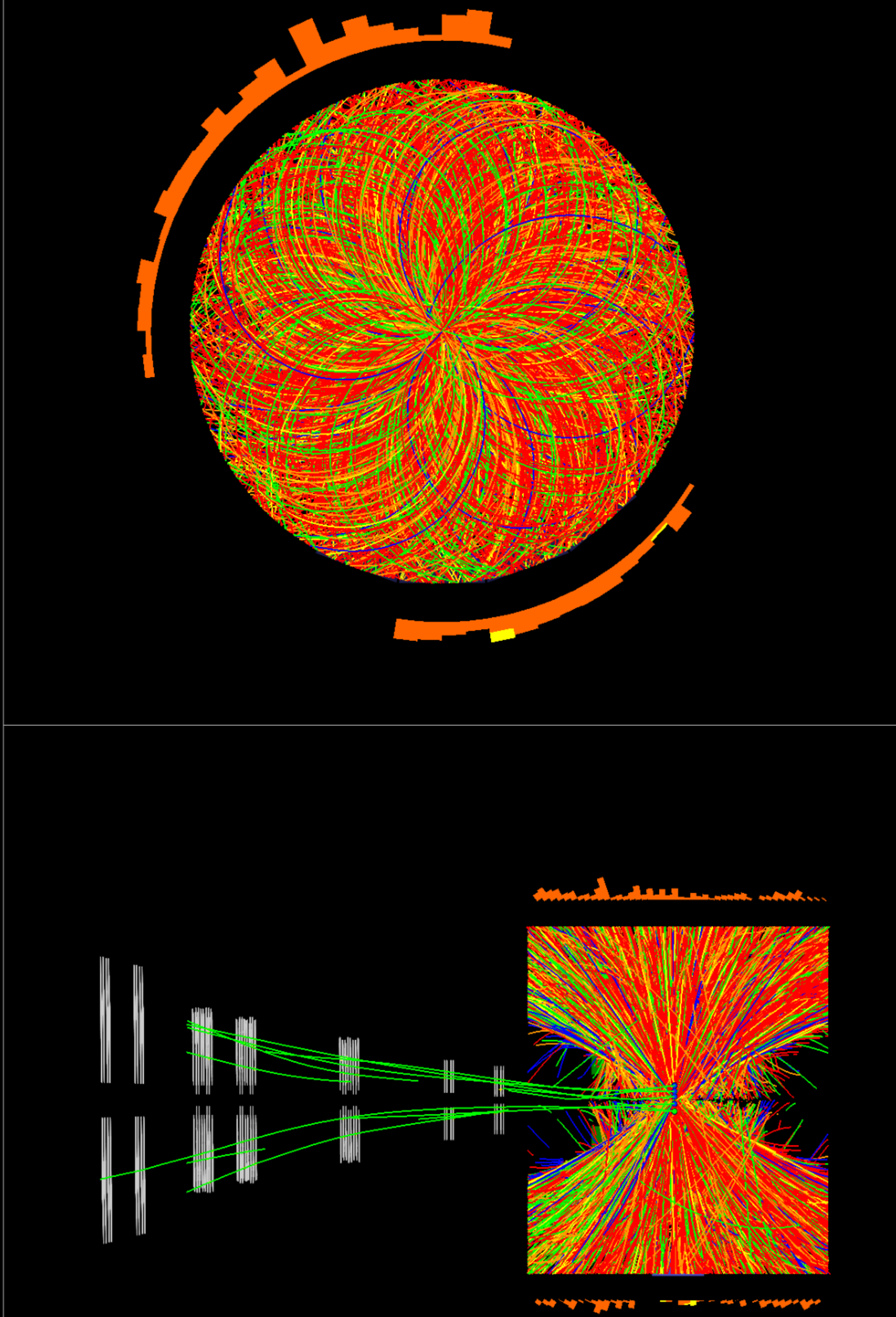
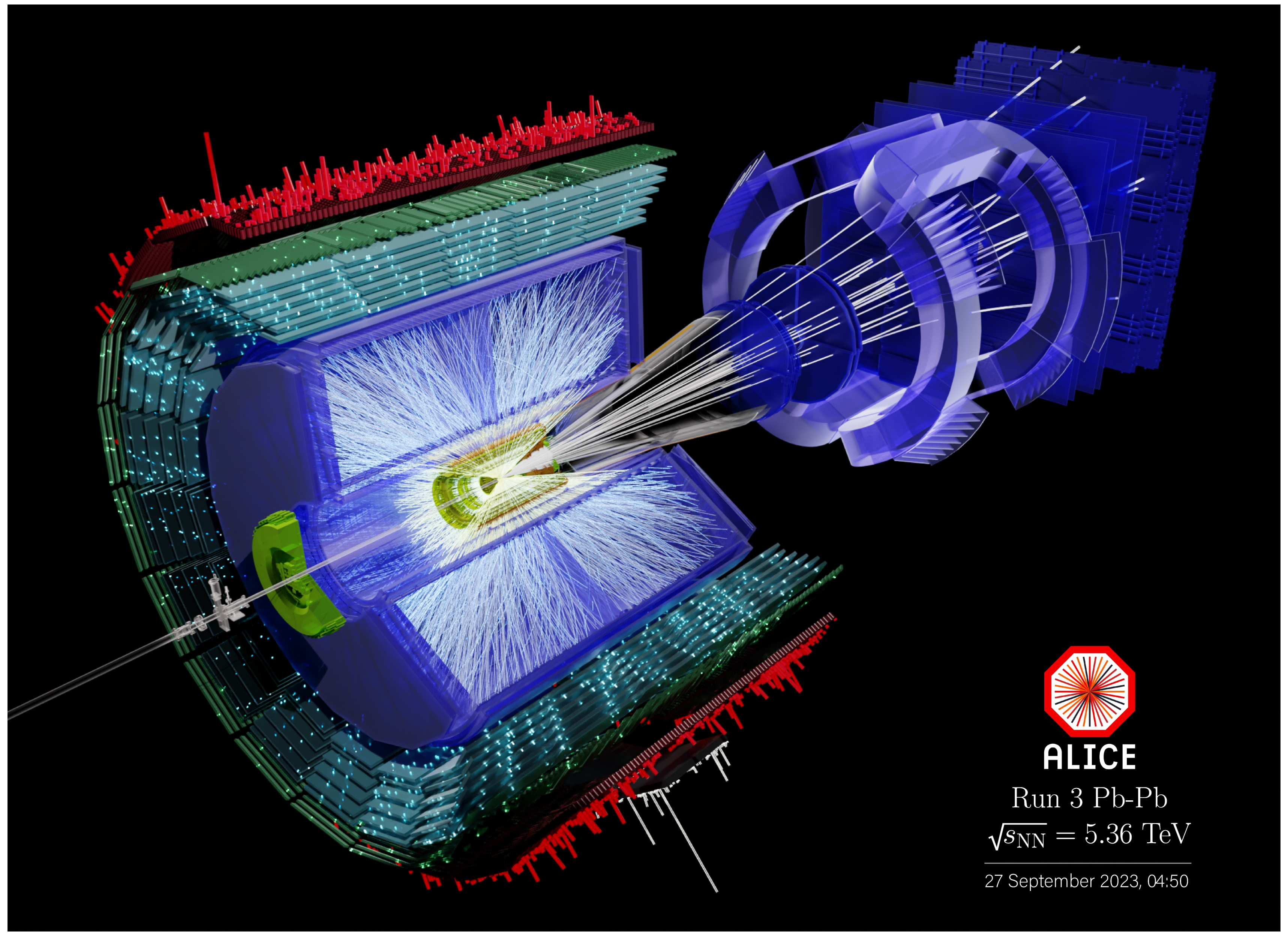
ALICE

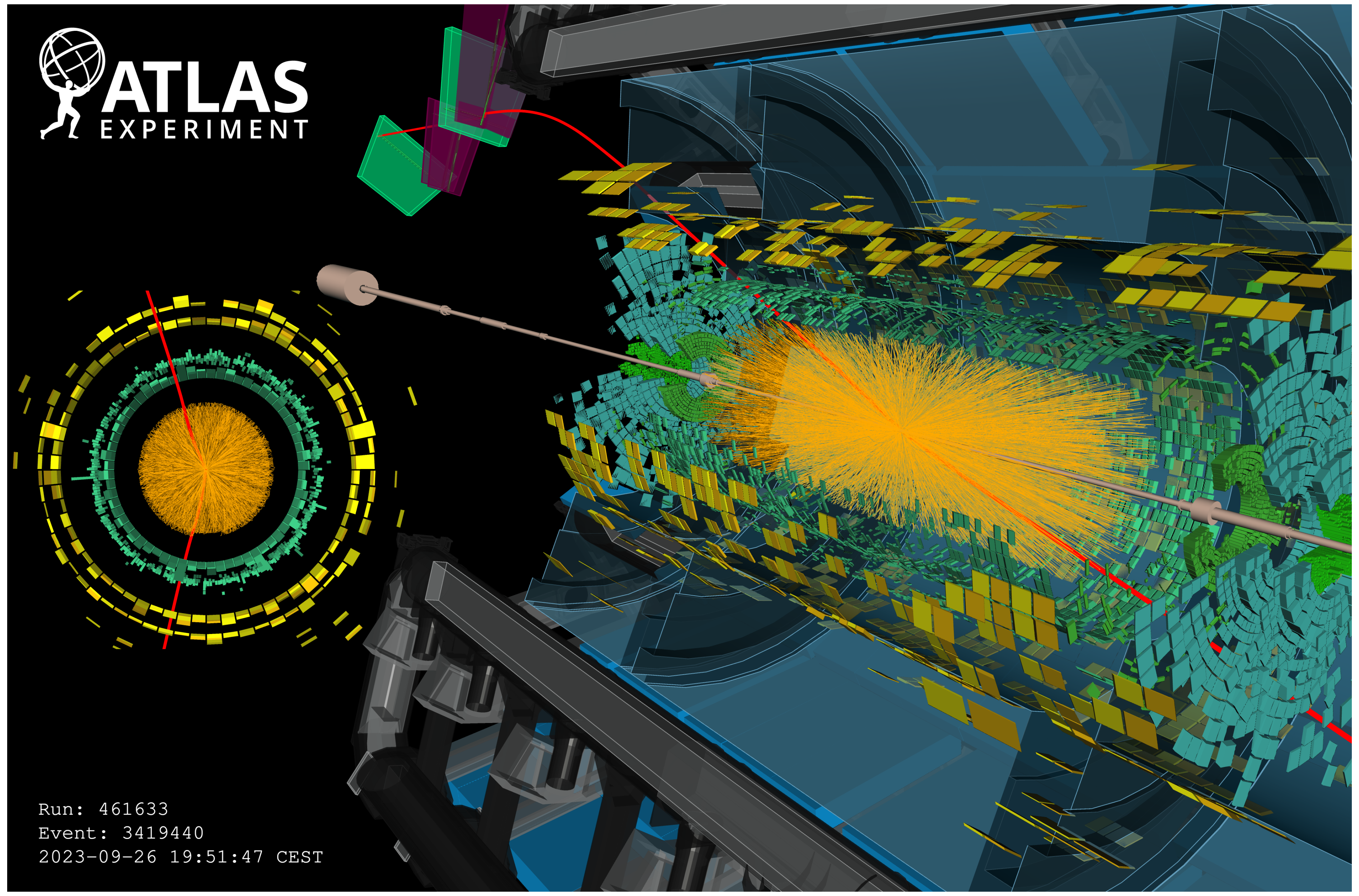


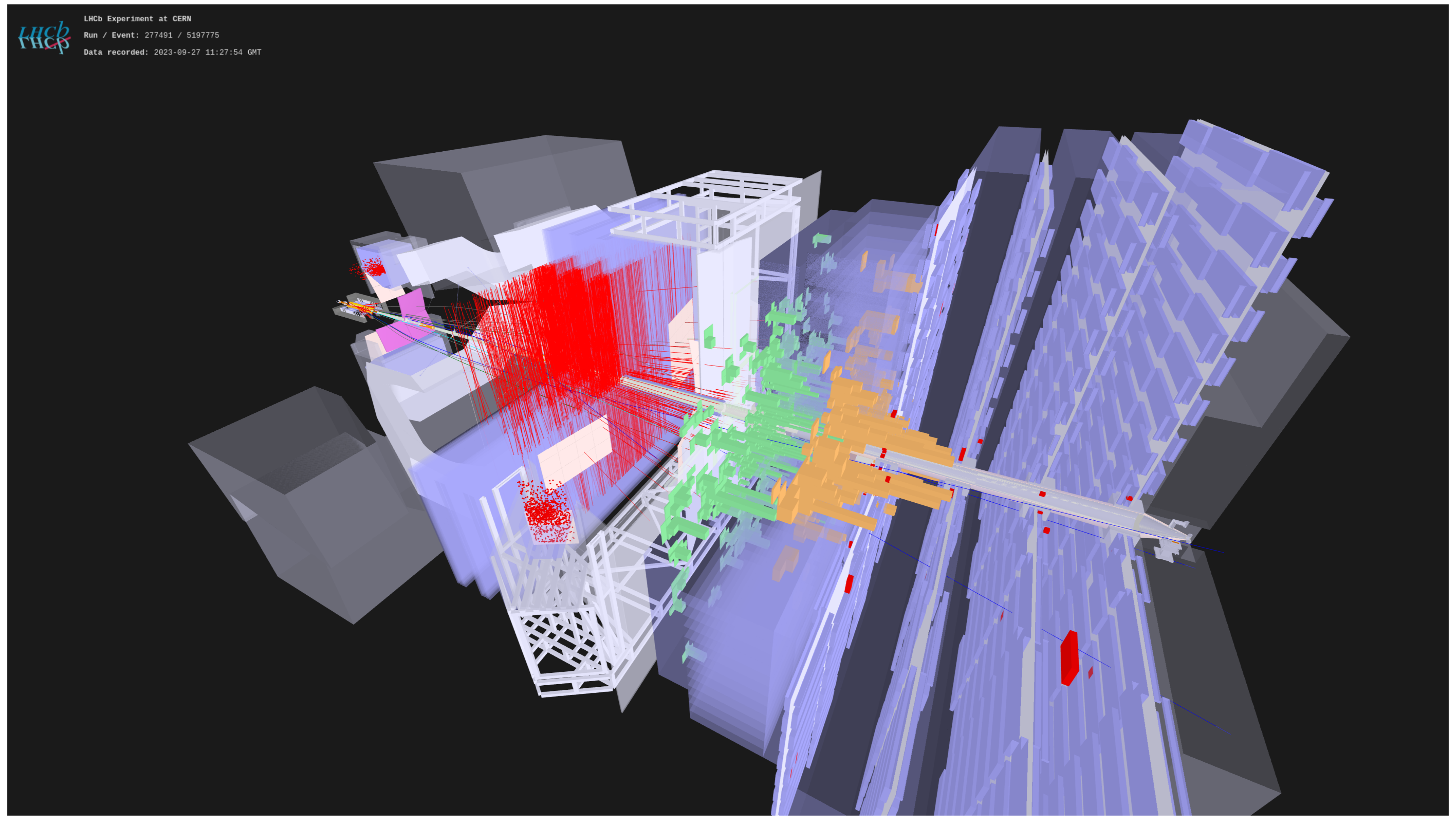


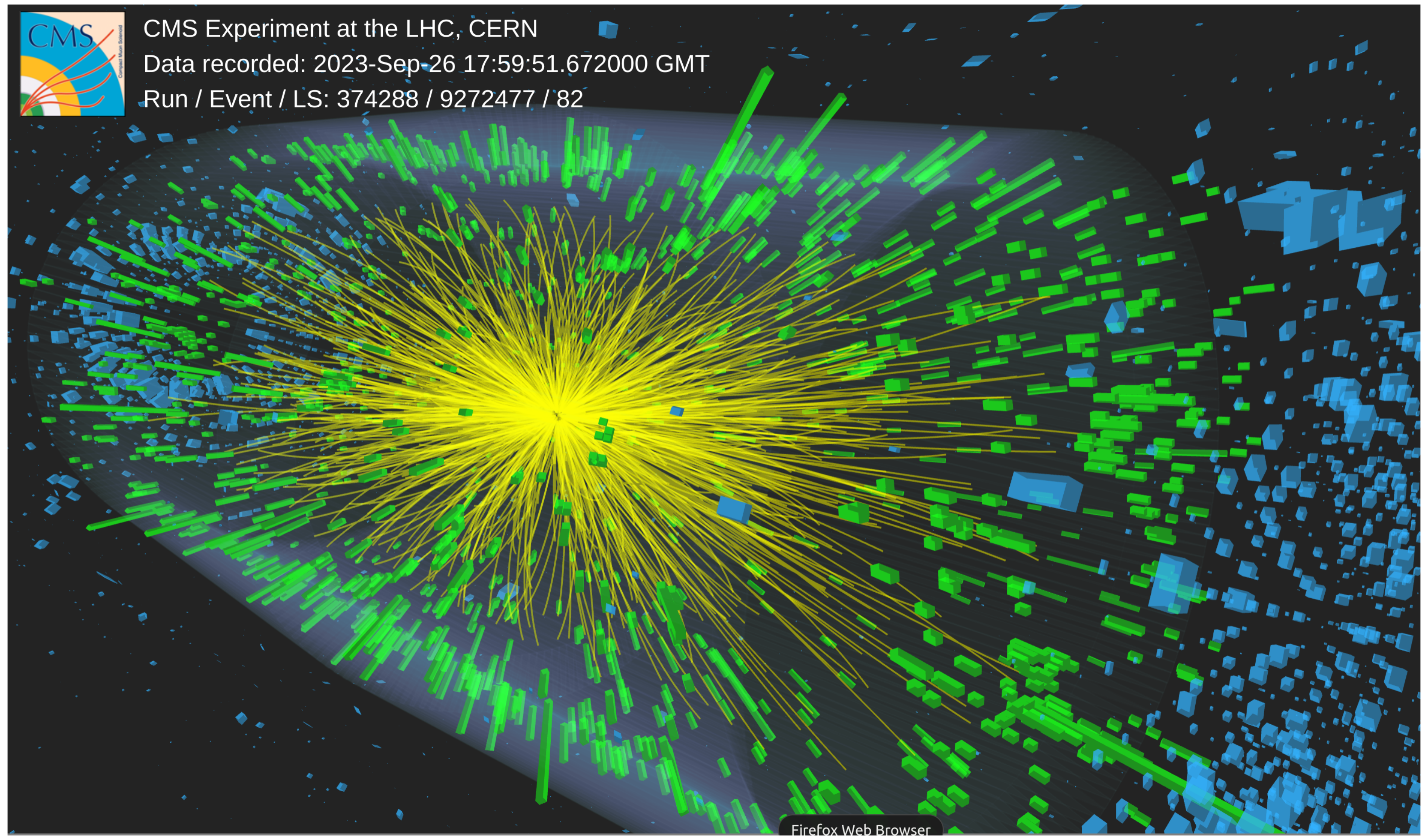
Central Pb-Pb collision:

- **Up to 10 thousand charged particles detected by ALICE in a single collision**
- **Up to 50 thousand collisions per second**





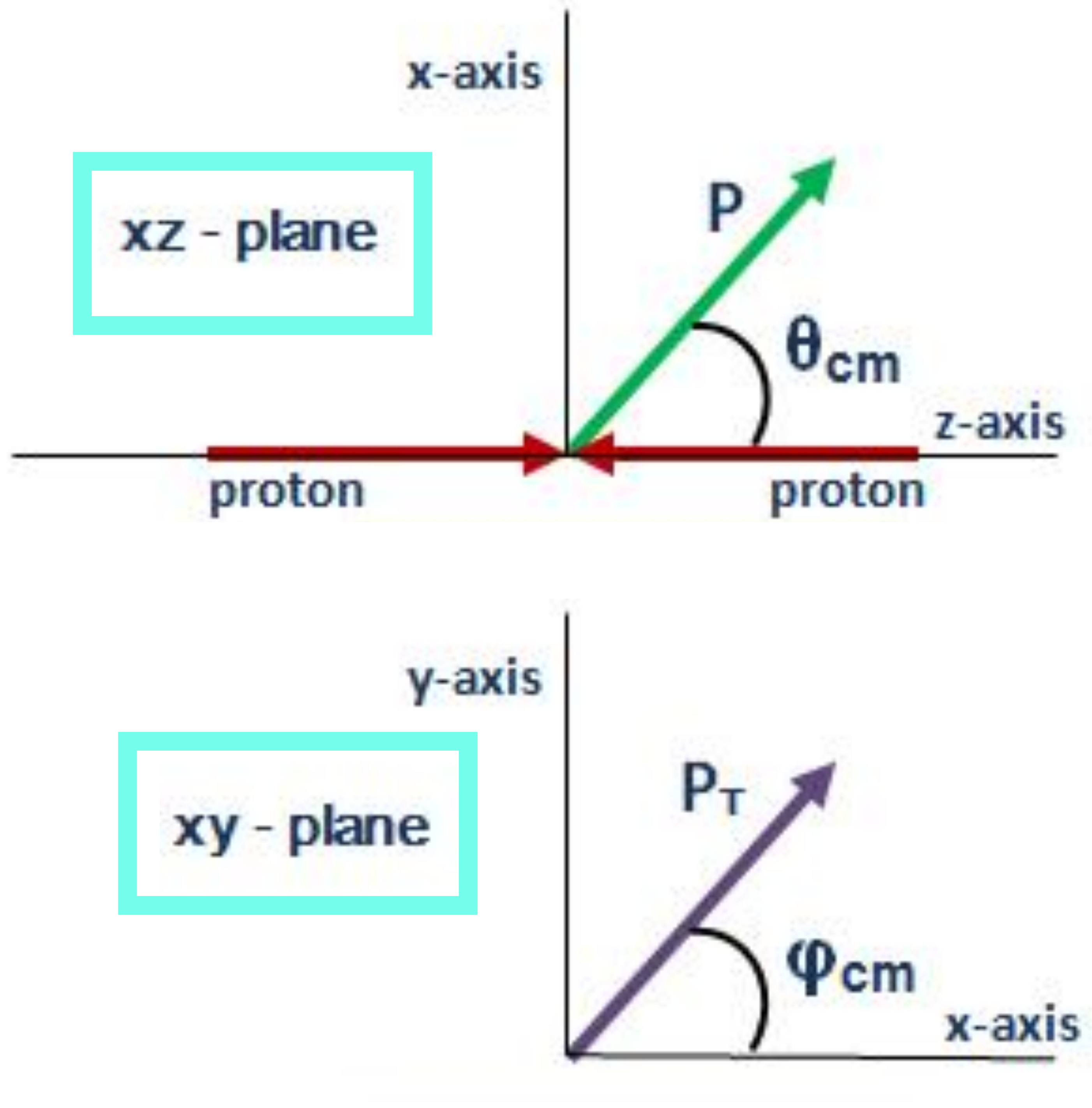




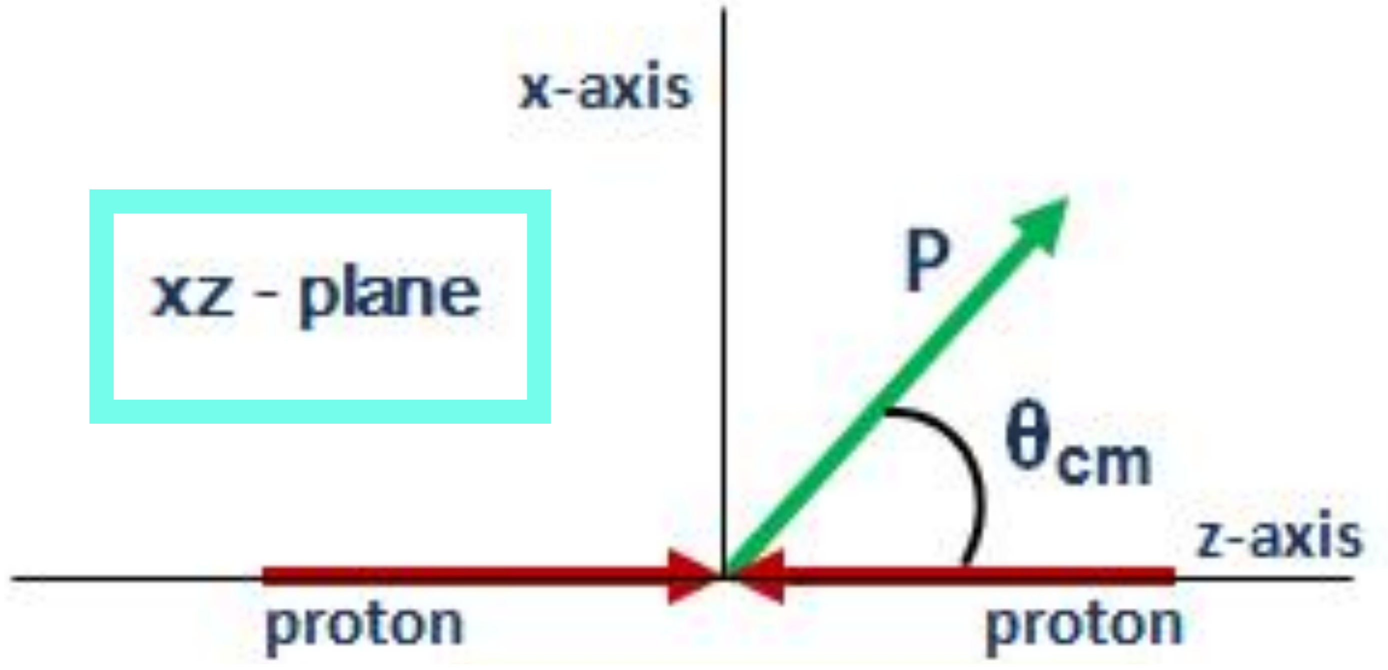
All main LHC experiments have exciting and complimentary heavy-ion programmes!

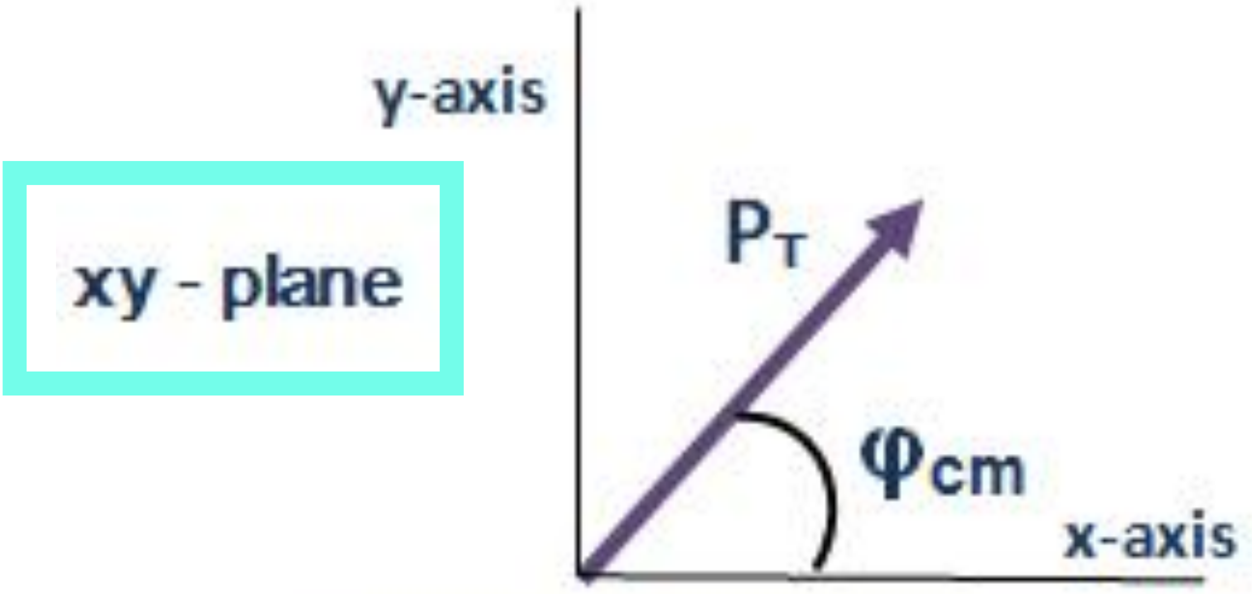
Collider coordinates

- **Momenta of produced particles** decomposed into:
  - Component parallel to beams (z-axis, longitudinal)
  - Component perpendicular to beams (x-y plane, transverse)
    $\rightarrow p_T = p\sin(\theta)$



Collider coordinates





- **Momenta of produced particles** decomposed into:
  - Component parallel to beams (z-axis, longitudinal)
  - Component perpendicular to beams (x-y plane, transverse) $\rightarrow p_T = p\sin(\theta)$

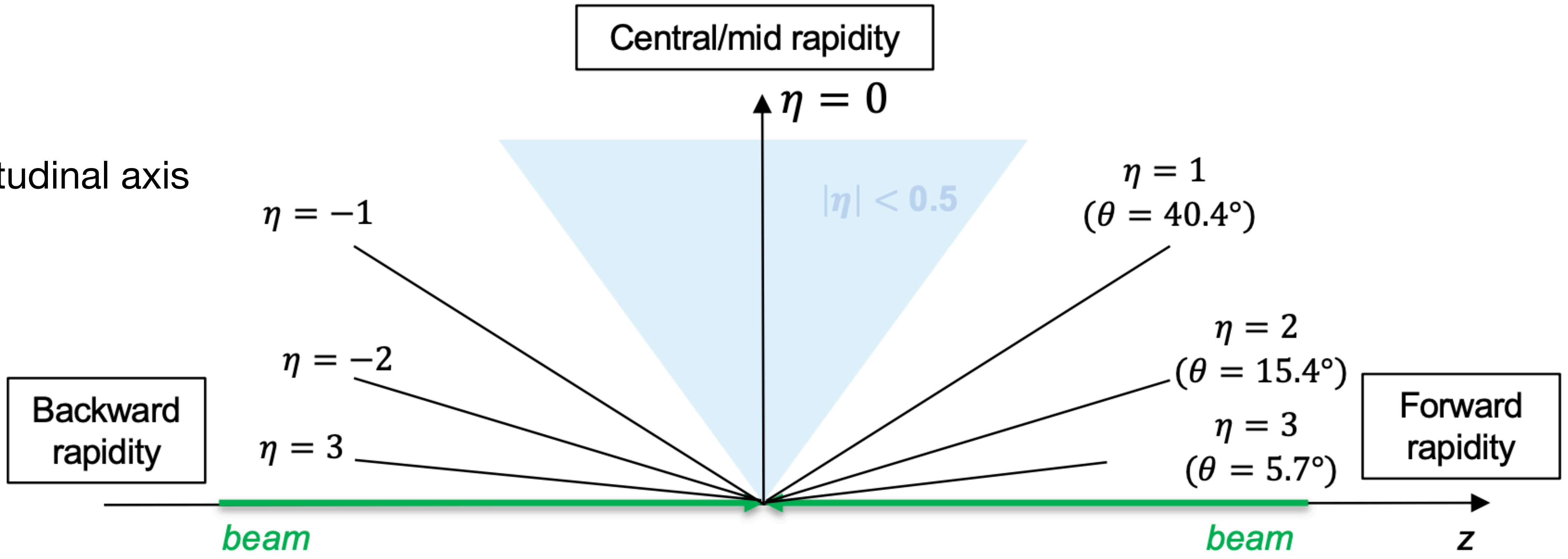
- **(Pseudo)rapidity** represents **longitudinal component of produced particles:**

Rapidity: $$y = \frac{1}{2}\ln\left[\frac{E+p_L}{E-p_L}\right]$$

Differences in rapidity are lorentz-invariant under boosts along longitudinal axis

Pseudorapidity: $$\eta = \frac{1}{2}\ln\left[\frac{|\mathbf{p}|+p_L}{|\mathbf{p}|-p_L}\right] = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$

In limit p>>m, y = η



(p_T, η, ϕ) **coordinates used !**

Measuring charged particle momentum in collider experiments

- Particle with charge q moving in B field proportional to perpendicular component of velocity v:

$$\vec{F} = q\,.\,[\vec{v} \times \vec{B}]$$

$$= q\,.\,v_{\perp}\,.\,B$$

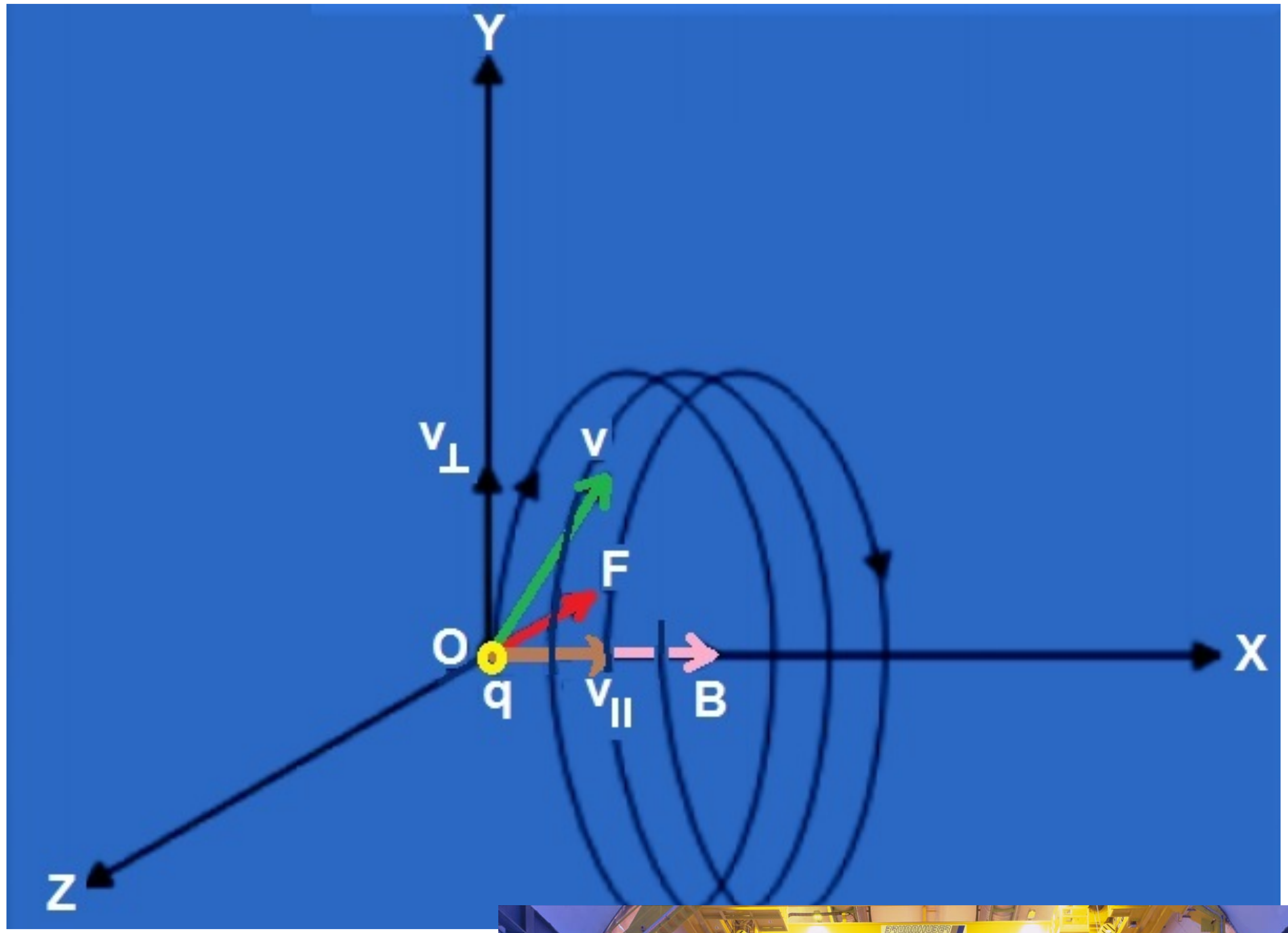
- Centripetal force for particle moving in radius R:

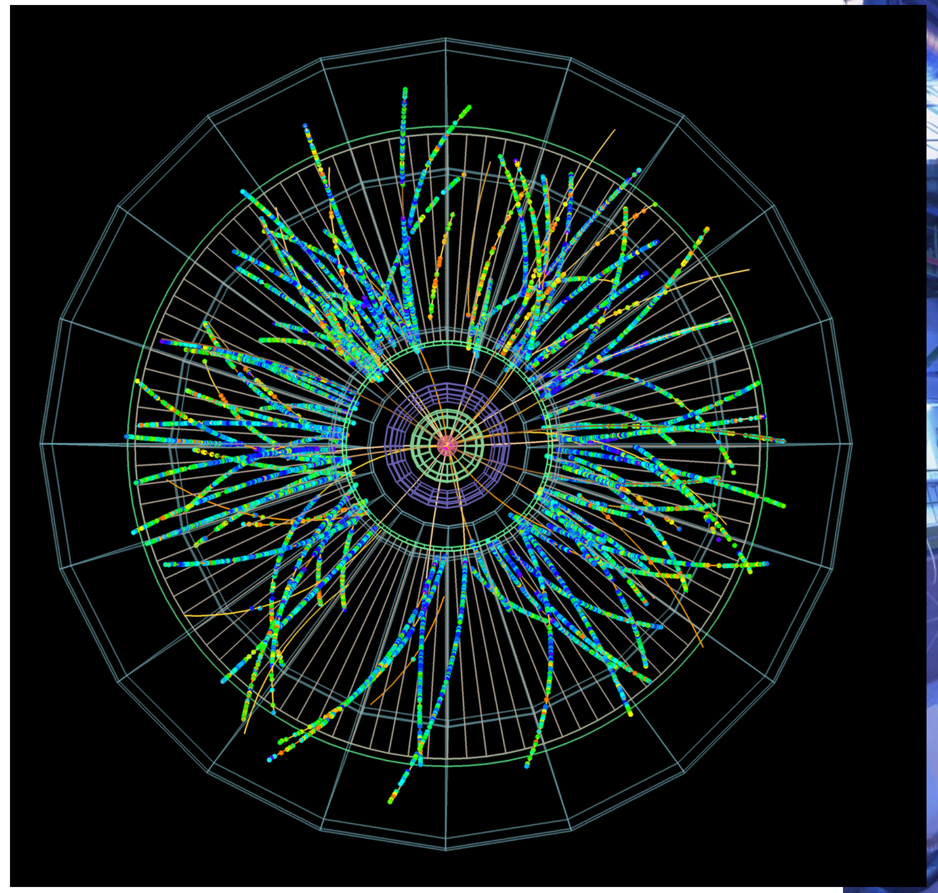
$$F = mv_{\perp}^{2}/R$$

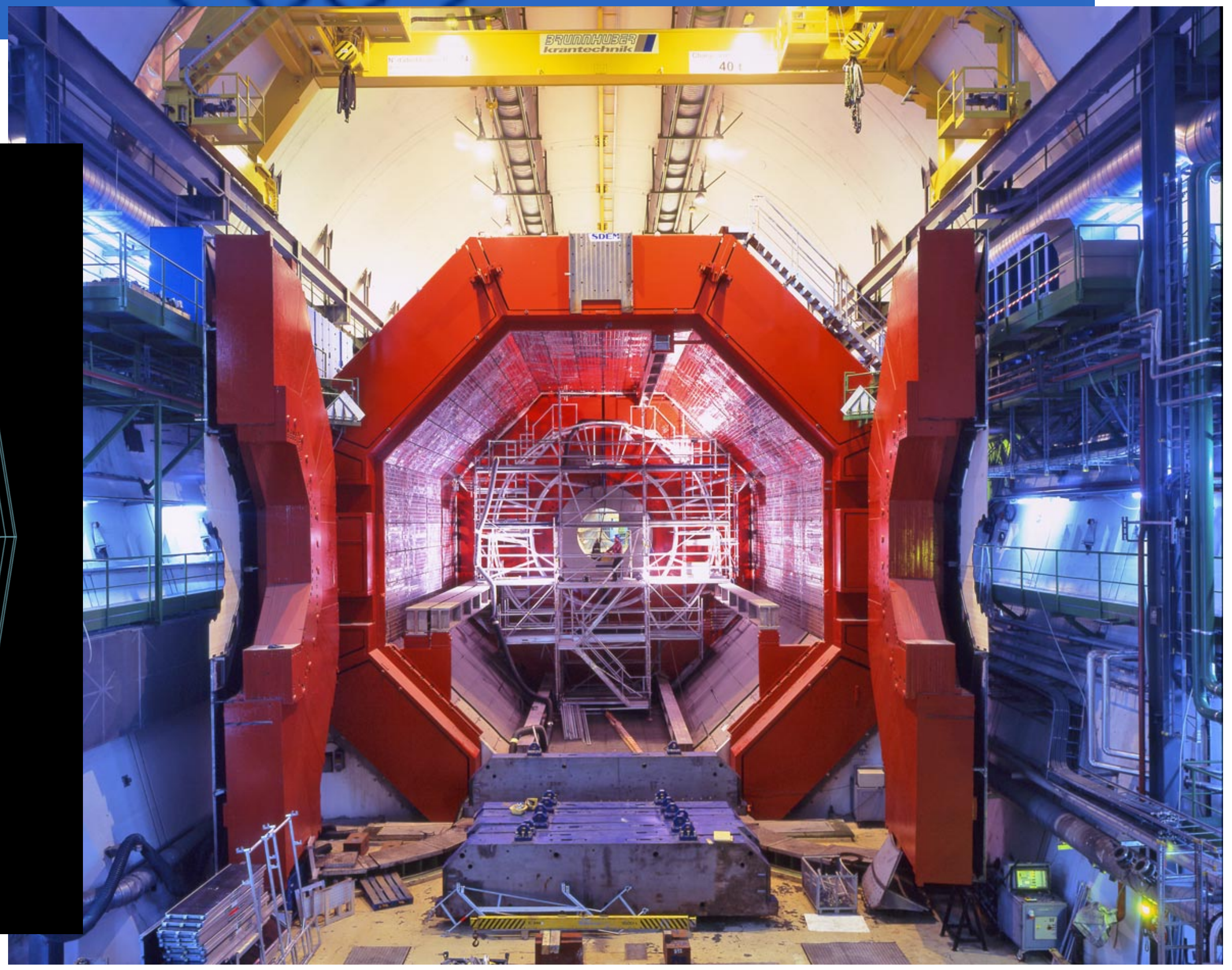
- Thus transverse momentum:

$$p_{\perp} = mv_{\perp} = q\,.\,R\,.\,B$$

- 0.5T solenoid magnet (central barrel) and 0.67T dipole magnet (muon arm) in ALICE

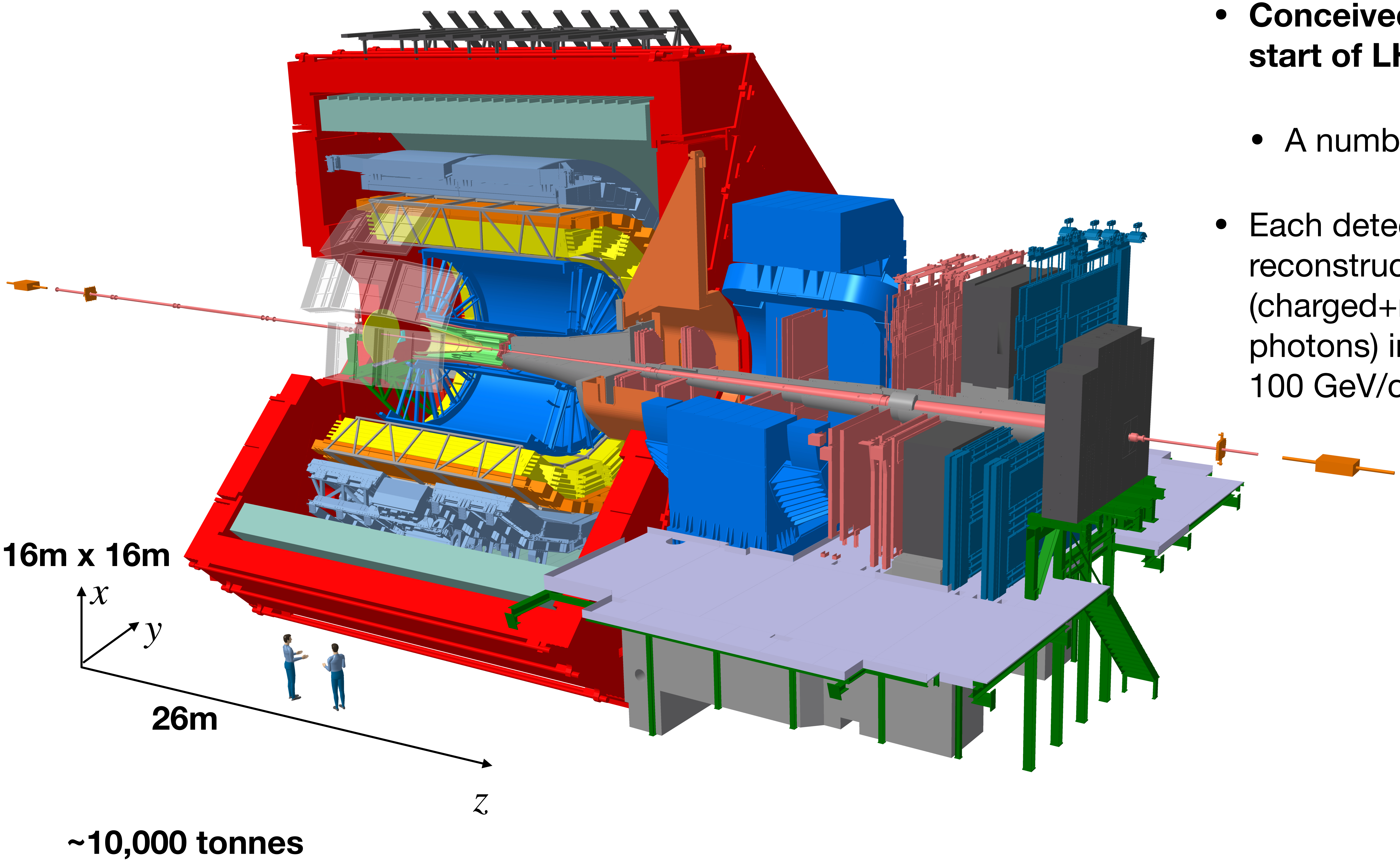






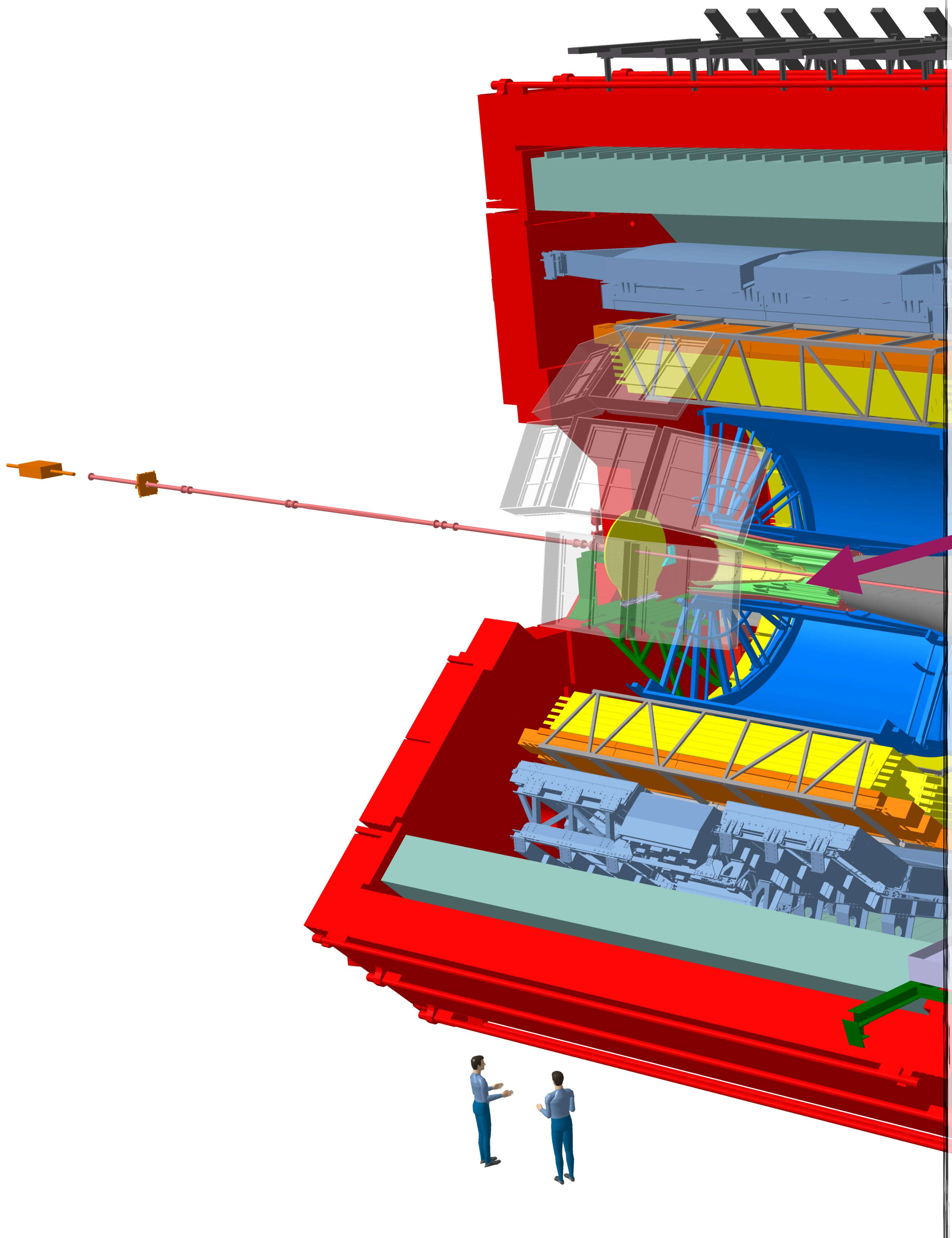
The ALICE experiment

ALICE experiment at the CERN LHC, *INST* 3 (2008) S08002



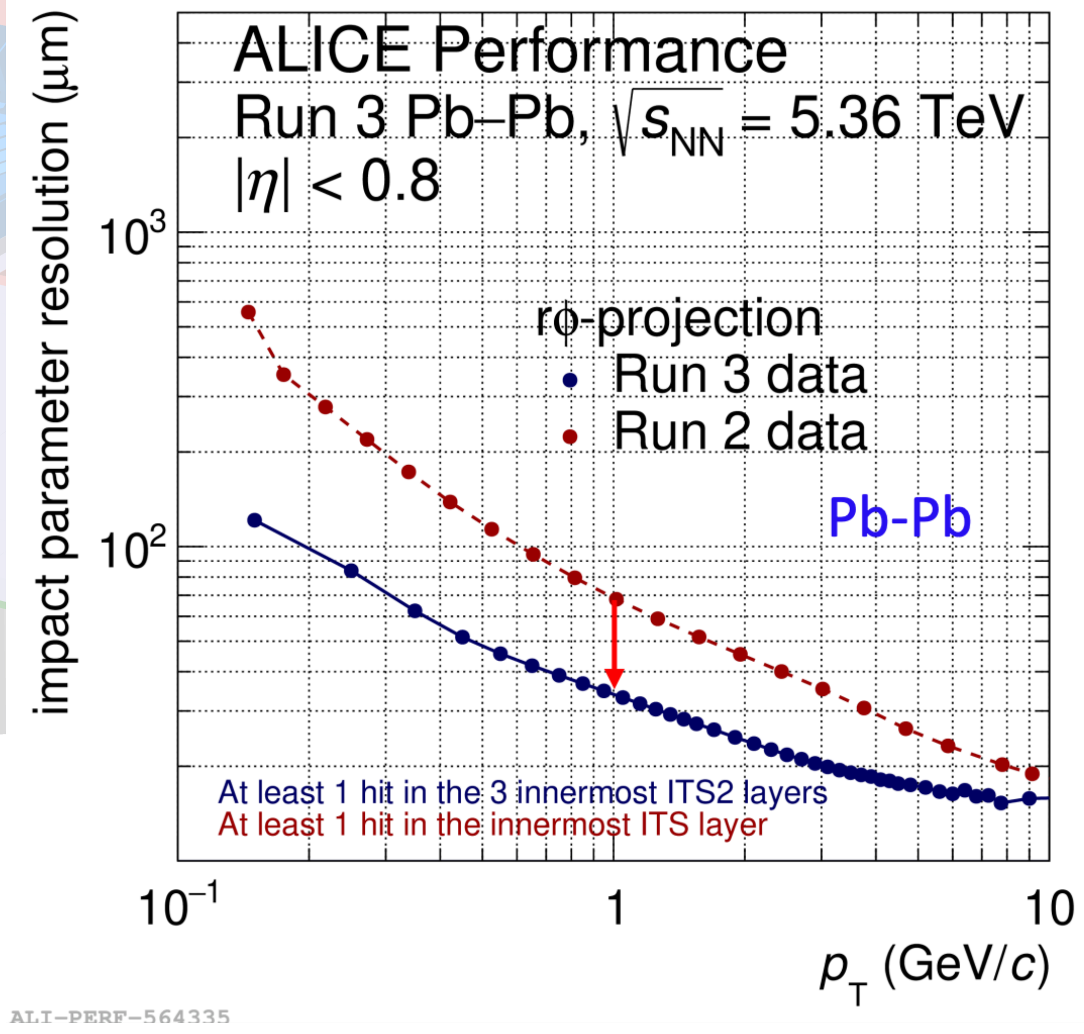
- **Conceived in 1992, began taking data with start of LHC in 2009**
  - A number of significant upgrades since then
- Each detector component designed to reconstruct different particle species (charged+neutral hadrons, electrons, muons photons) in wide kinematic regions from ~0.1 - 100 GeV/c

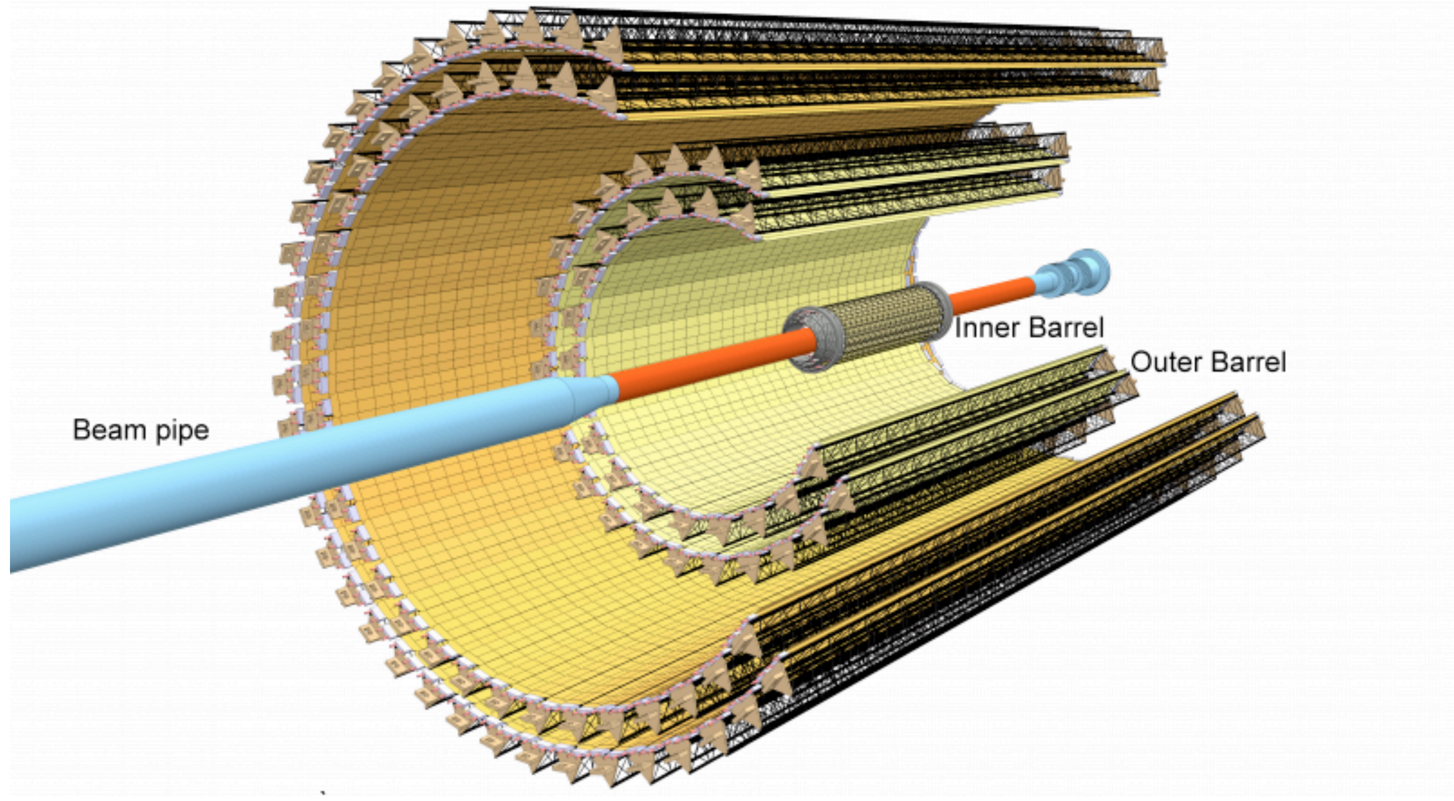
ALICE layout



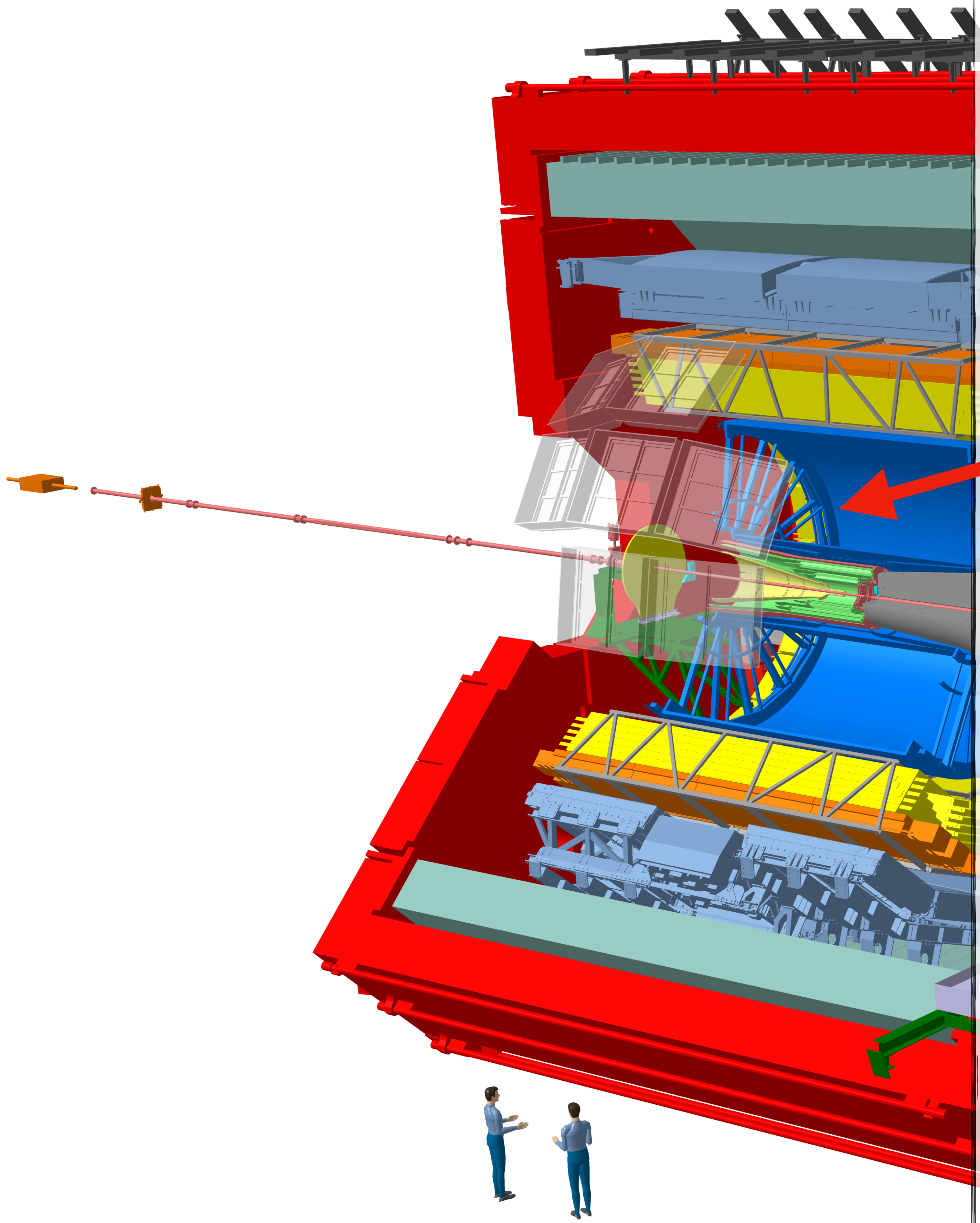
- **Inner Tracking System (ITS2)** used for tracking charged particles
  upgraded during 2019-2022 long shutdown
  - **7-layer silicon pixel tracker** covering ~10m², with 12.5 billion channels
    4π, $|\eta| < 1.22$ coverage
    - **CMOS sensor detector technology**
      sensor thickness: 50 (IB) or 100 (OB) μm
      Pixel pitch: 27 μm x 29 μm → spatial resolution: ~5 μm
      Power consumption: 47.5 mW/cm2
      Fake-hit rate: << 10-6 /pixel/event
      Continuous or triggered readout
  - Detector readout rates up to 500 kHz (pp) and 50 kHz (Pb-Pb)

~2x improvement in impact parameter resolution for tracks ~1 GeV w.r.t. ITS1

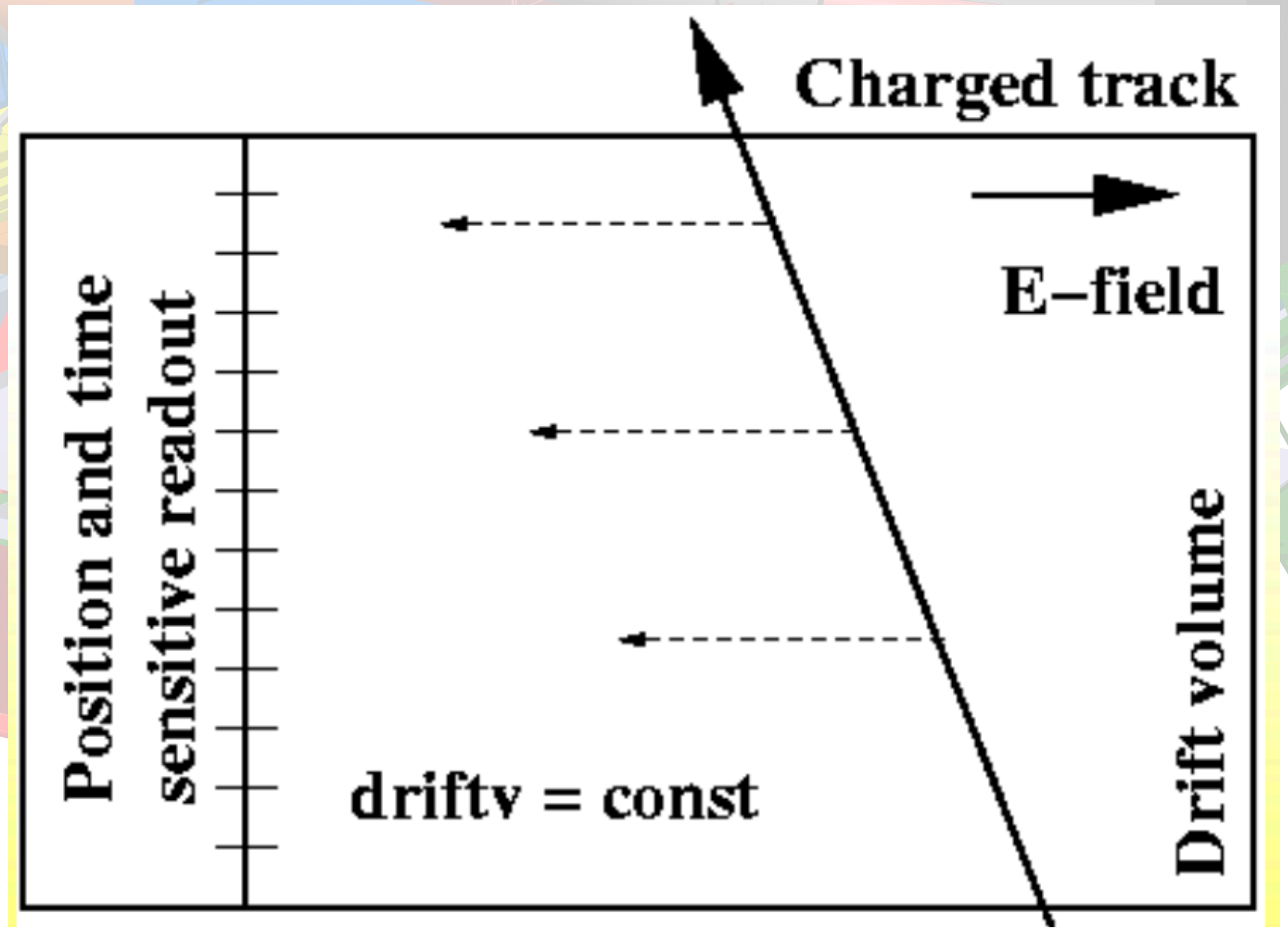


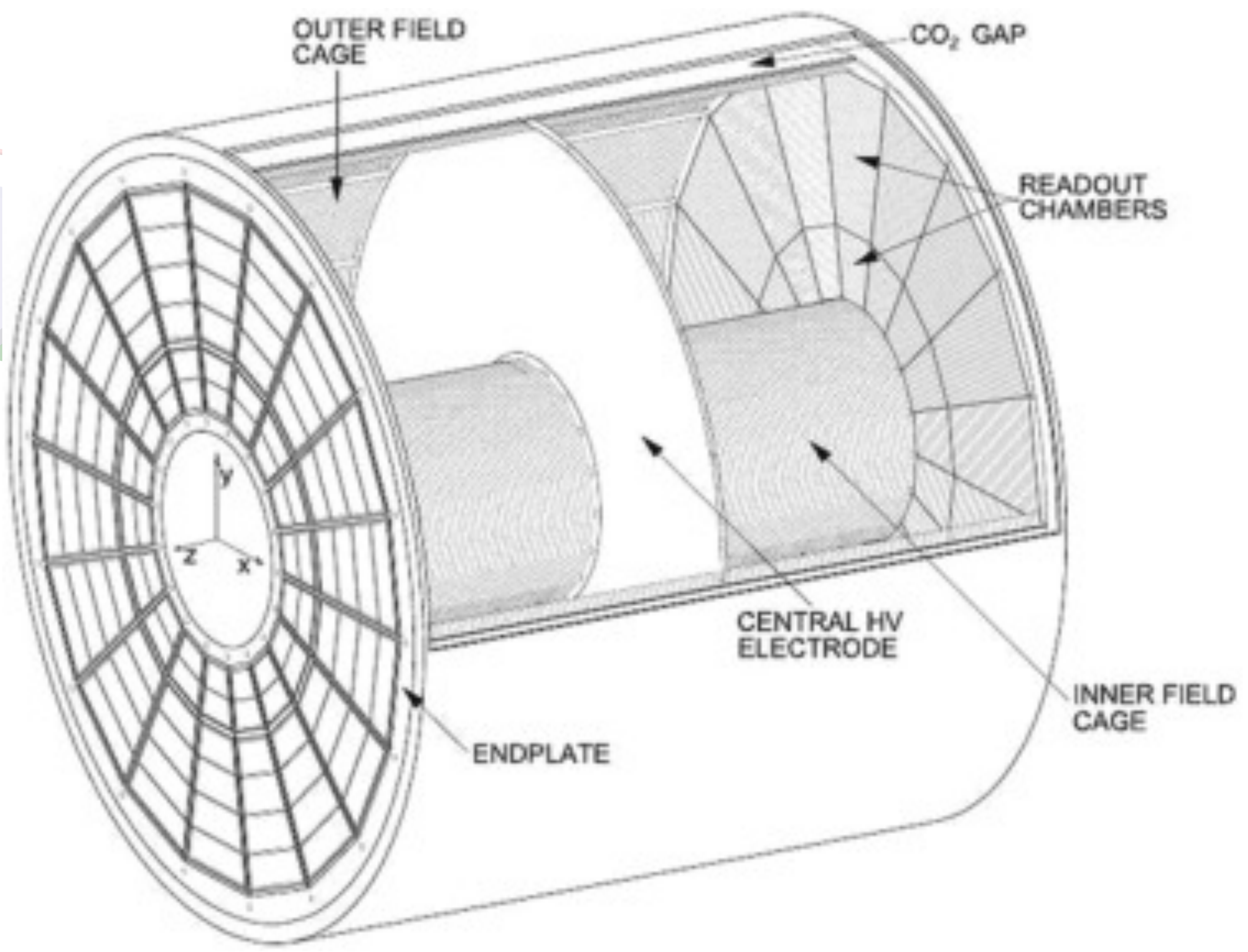


ALICE layout

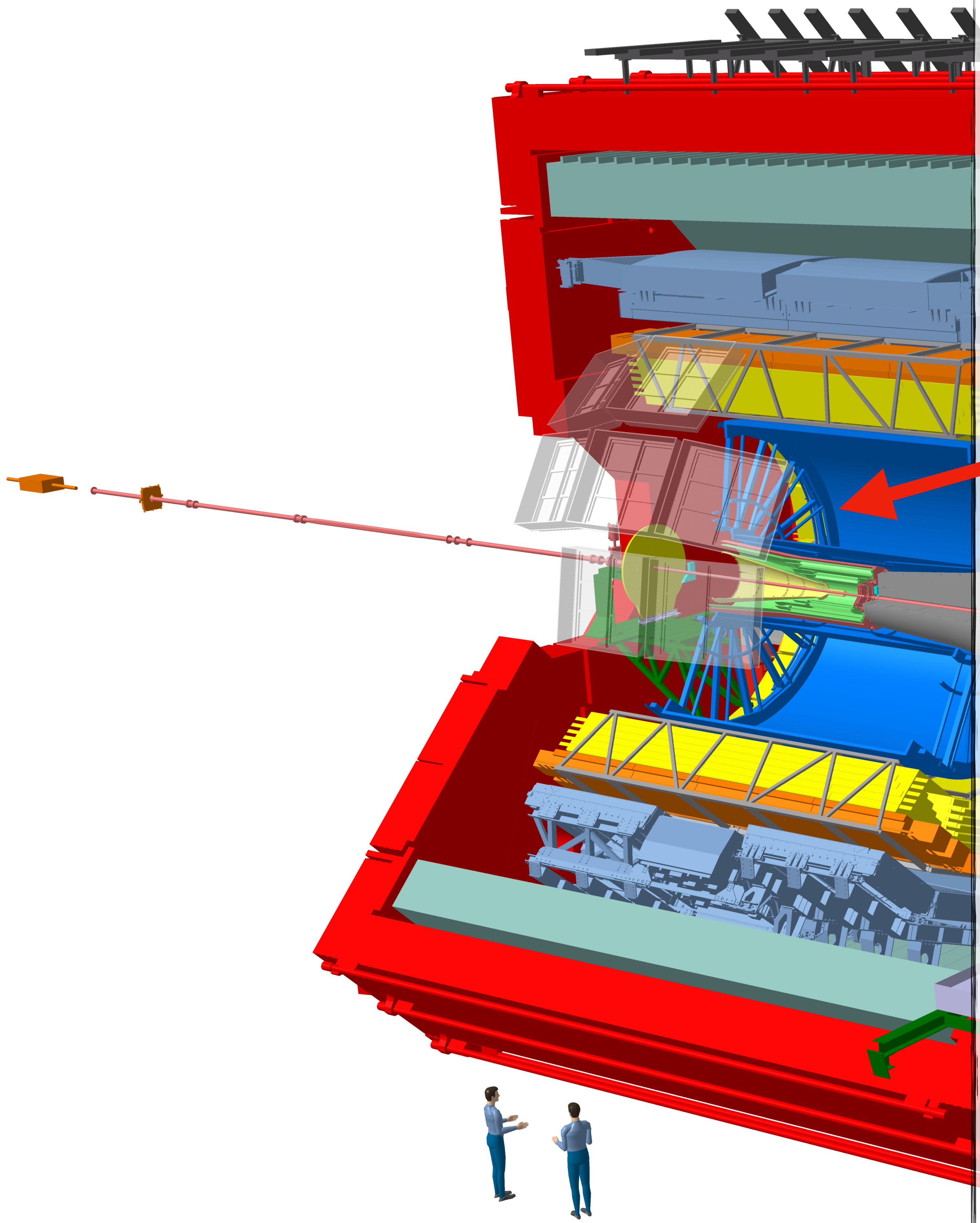


- **Time Projection Chamber (TPC)** used for tracking and identification of charged particles (4π, $|\eta| < 0.9$ coverage)
  - **90 m**^{3} cylinder filled with gas
  - Basics of a TPC:
    - Charged track ionises gas molecules
      Ionised electrons drift due to E field (at constant velocity) to readout
      readout measures 2d position (x-y), vs time (z = time x drift velocity)
      → **3d tracking**





ALICE layout



- **Time Projection Chamber (TPC)** used for tracking and identification of charged particles (4π, $|\eta| < 0.9$ coverage)
  - **Particle identification (PID)** performed by measuring the specific energy loss (dE/dx) of charged particles

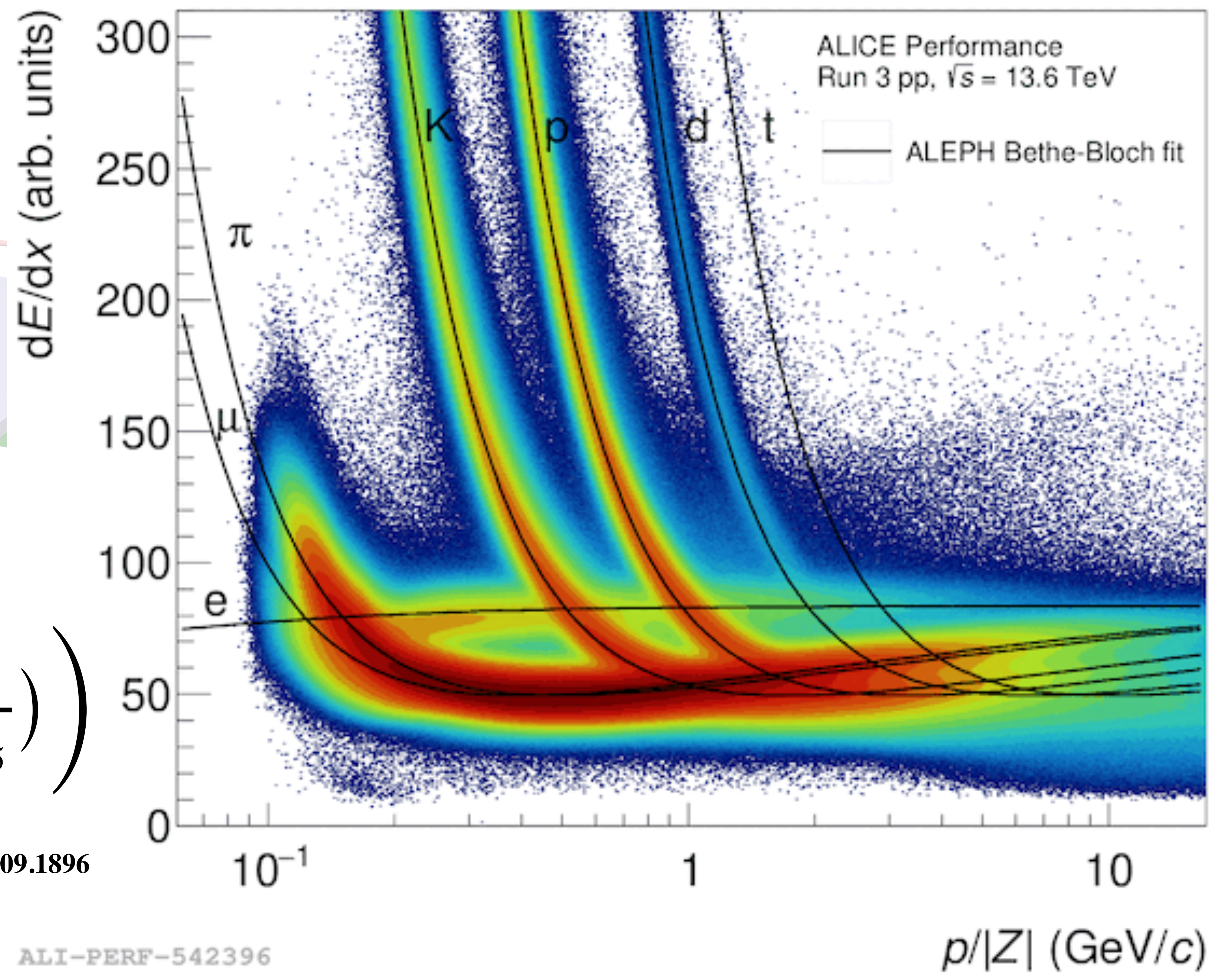
$$\left\langle -\frac{dE}{dx} \right\rangle = Kz^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 W_{max}}{I^2} - \beta^2 - \frac{\delta(\beta)}{2} \right]$$

<u>**Bethe-Bloch PDG**</u>

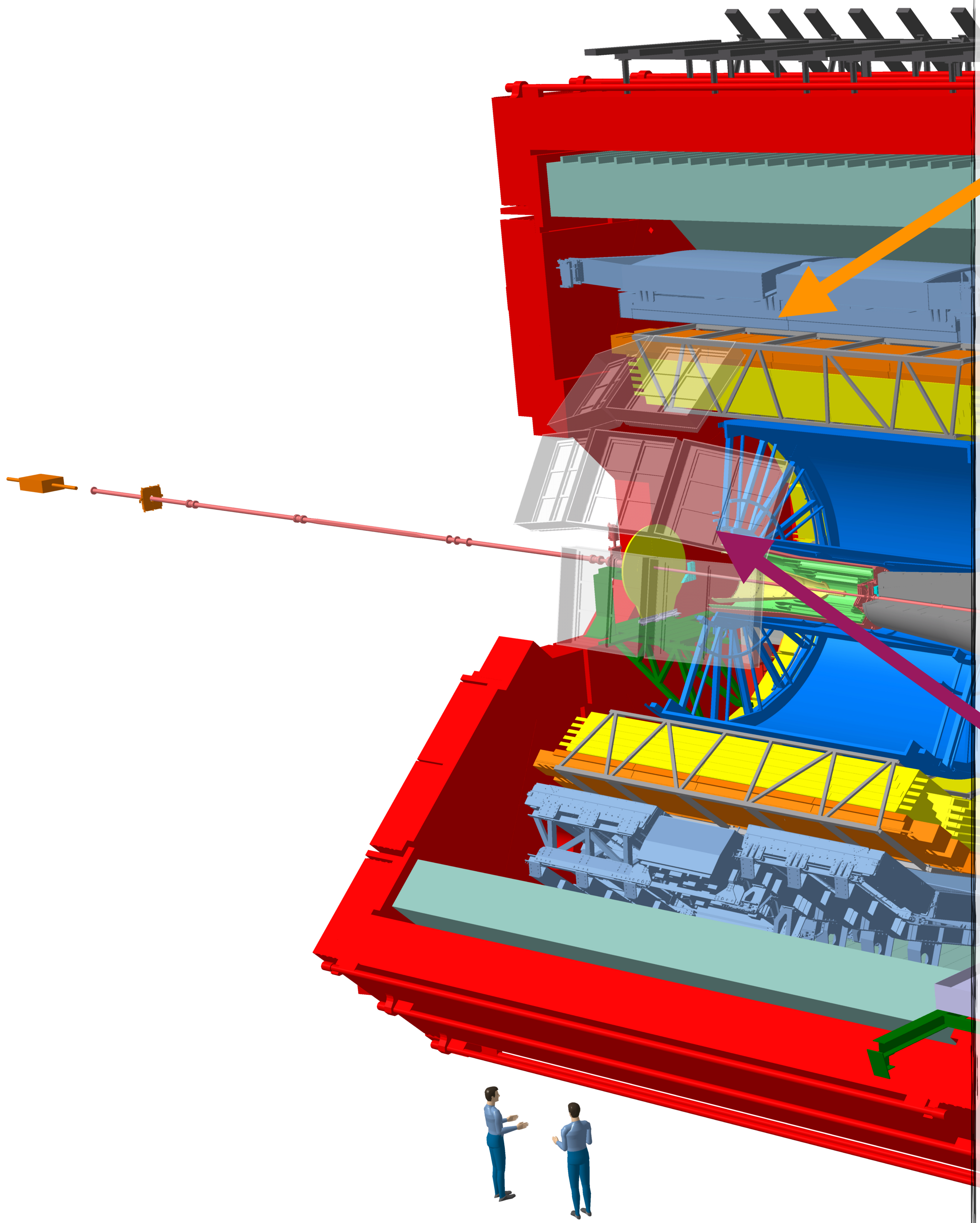
  - $\beta = v/c, \gamma = 1/\sqrt{1 - \beta}$
  - For fixed conditions, dE/dx only dependent on charge and rest mass at fixed momentum
  - Parameterisation used in practice

$$f(\beta\gamma) = \frac{P_1}{\beta^{P_4}} \left(P_2 - \beta^{P_4} - \ln\left(P_3 + \frac{1}{(\beta\gamma)^{P_5}}\right) \right)$$

ALEPH experiment, arxiv:1109.1896

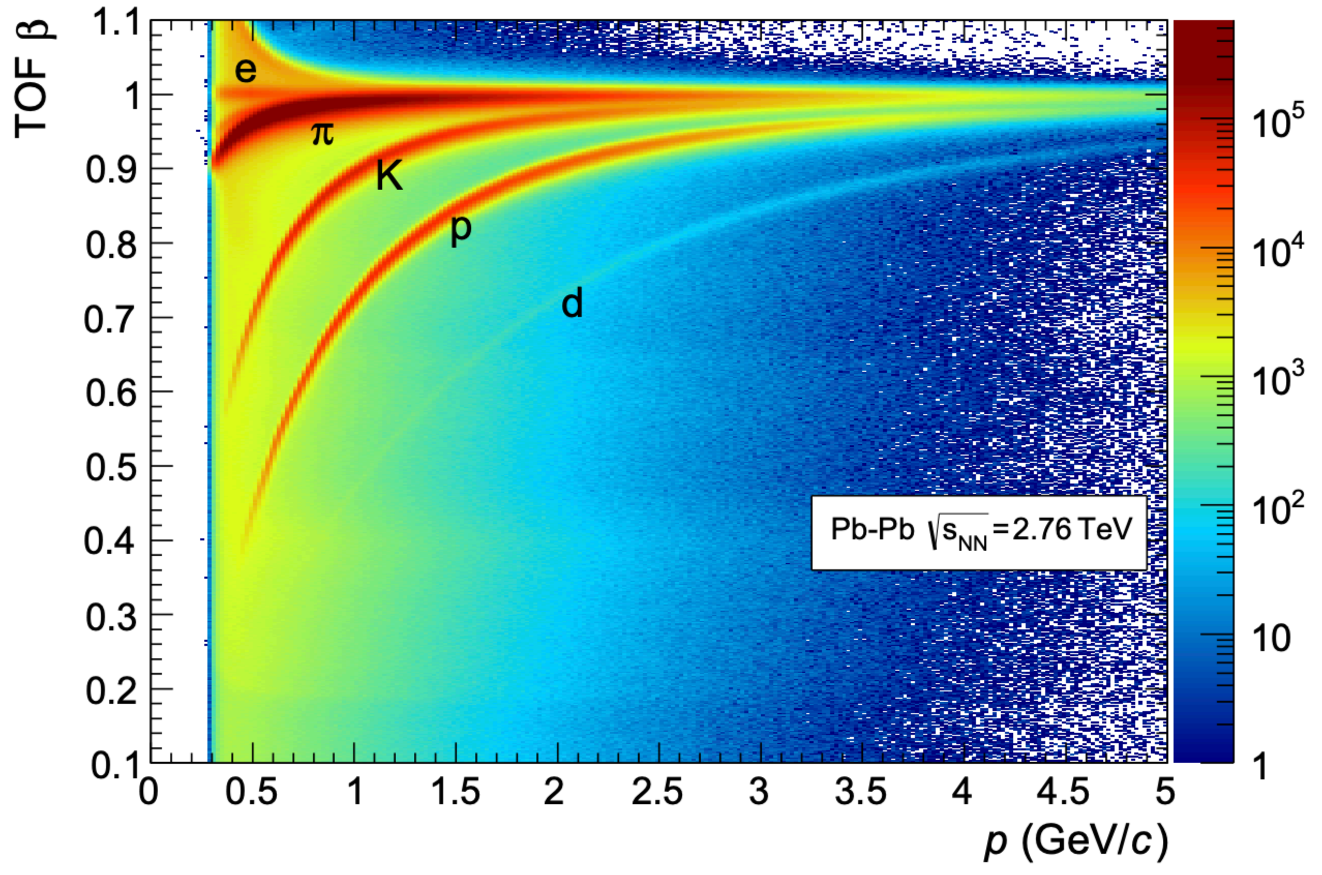


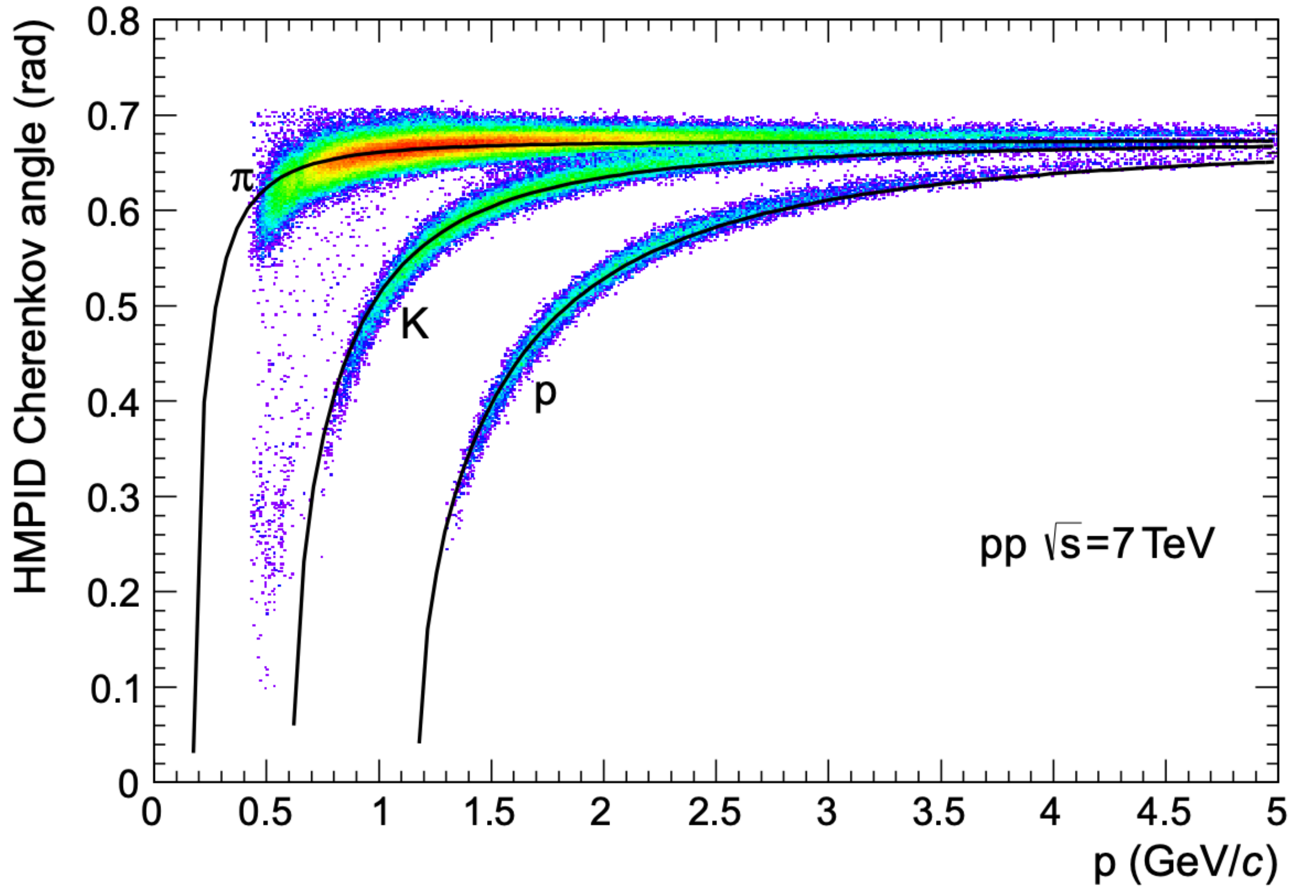
ALICE layout



- **Time Of Flight (TOF)** detector used for identifying charged particles at intermediate momentum
  - Multi Resistive Plate Chambers (MRPCs) provide ~150000 total readout channels
  - **Particle identification (PID)** performed by measuring time of flight between collision point and TOF detector
- **High-Momentum PID (HMPID)** detector used for identifying charged particles at high momentum
  - **Ring-Imaging Cherenkov detector** which measures Cherenkov radiation emitted when traversing medium with refractive index $n>1$

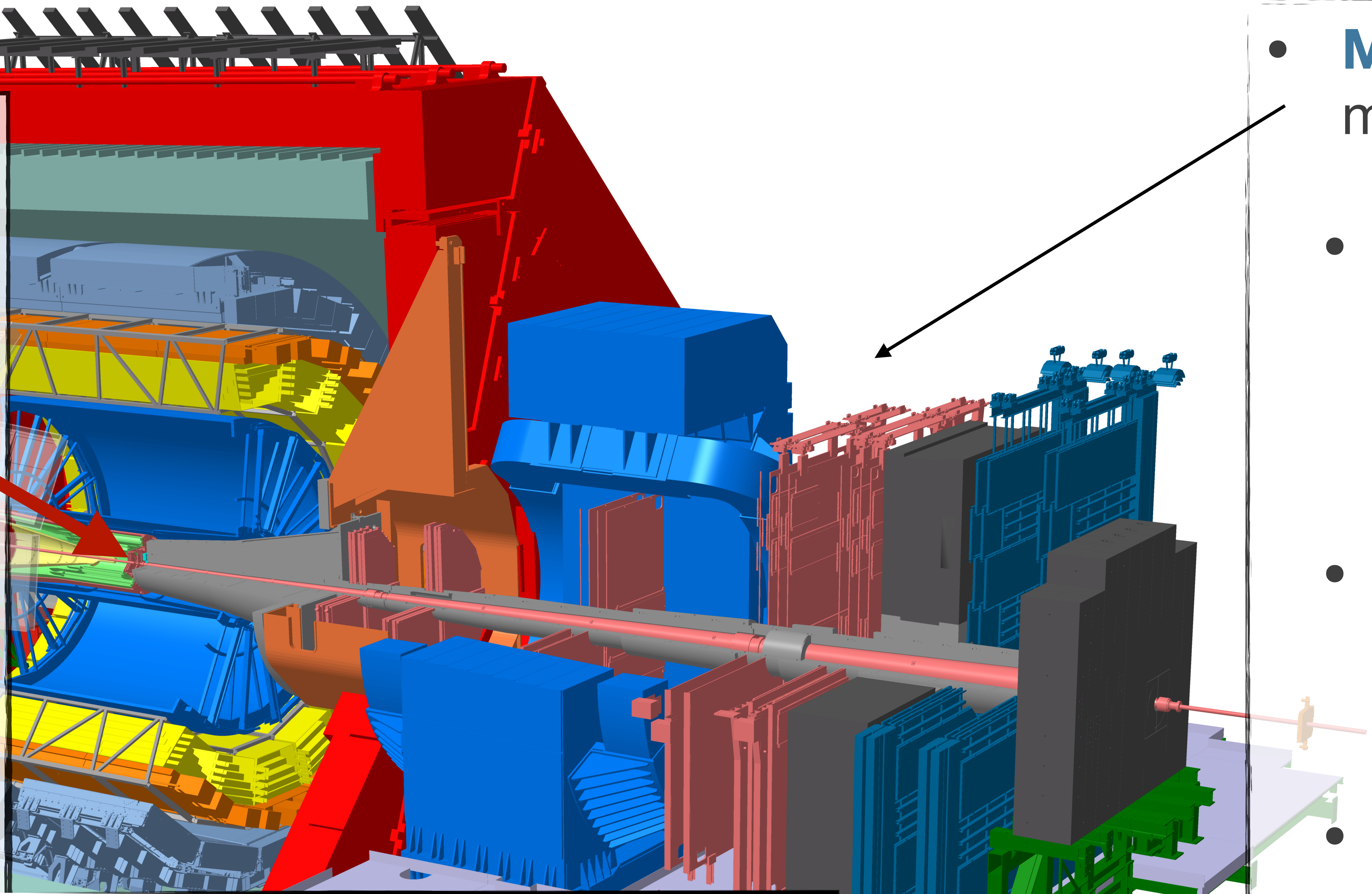
$$\cos\theta_c = \frac{c}{nv}$$



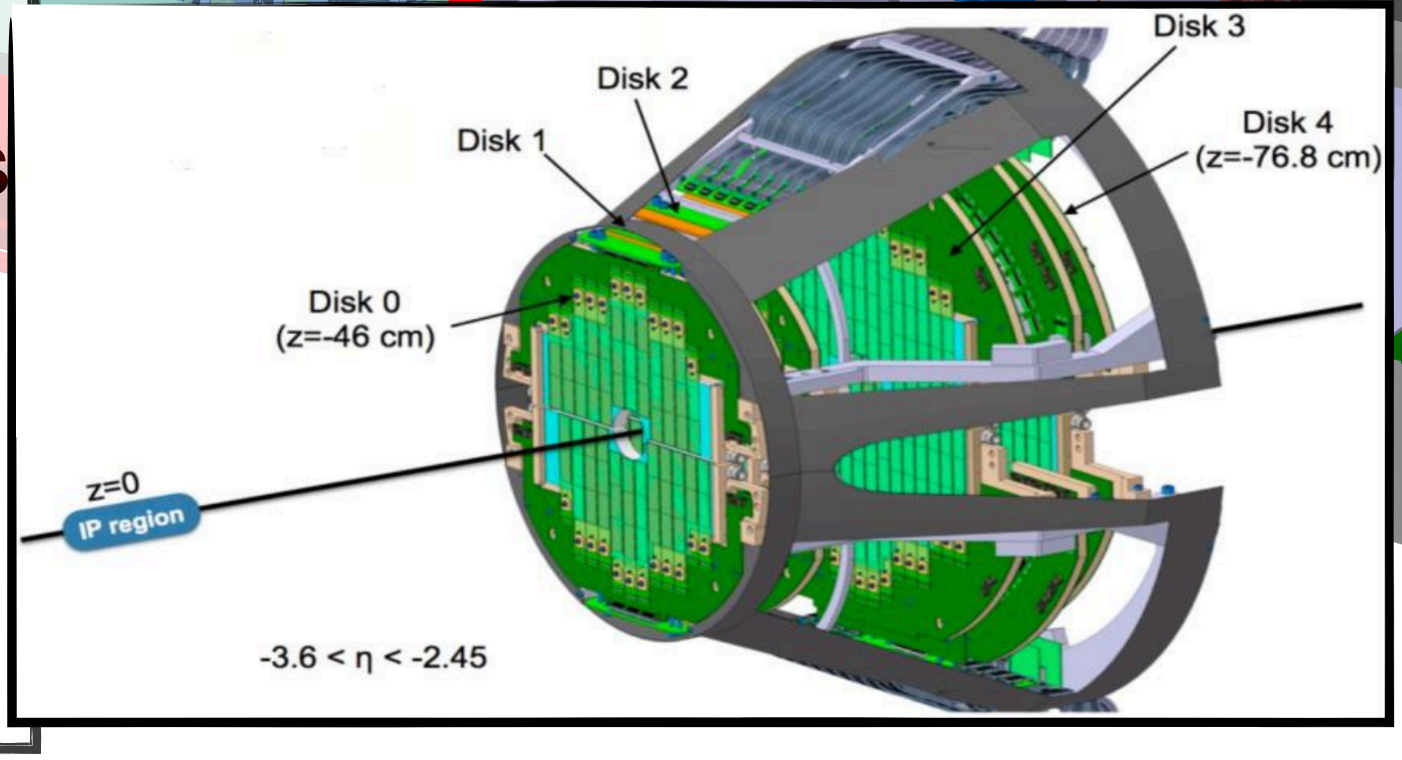


ALICE layout

- **Muon trackers and spectrometers** positioned at forward rapidity



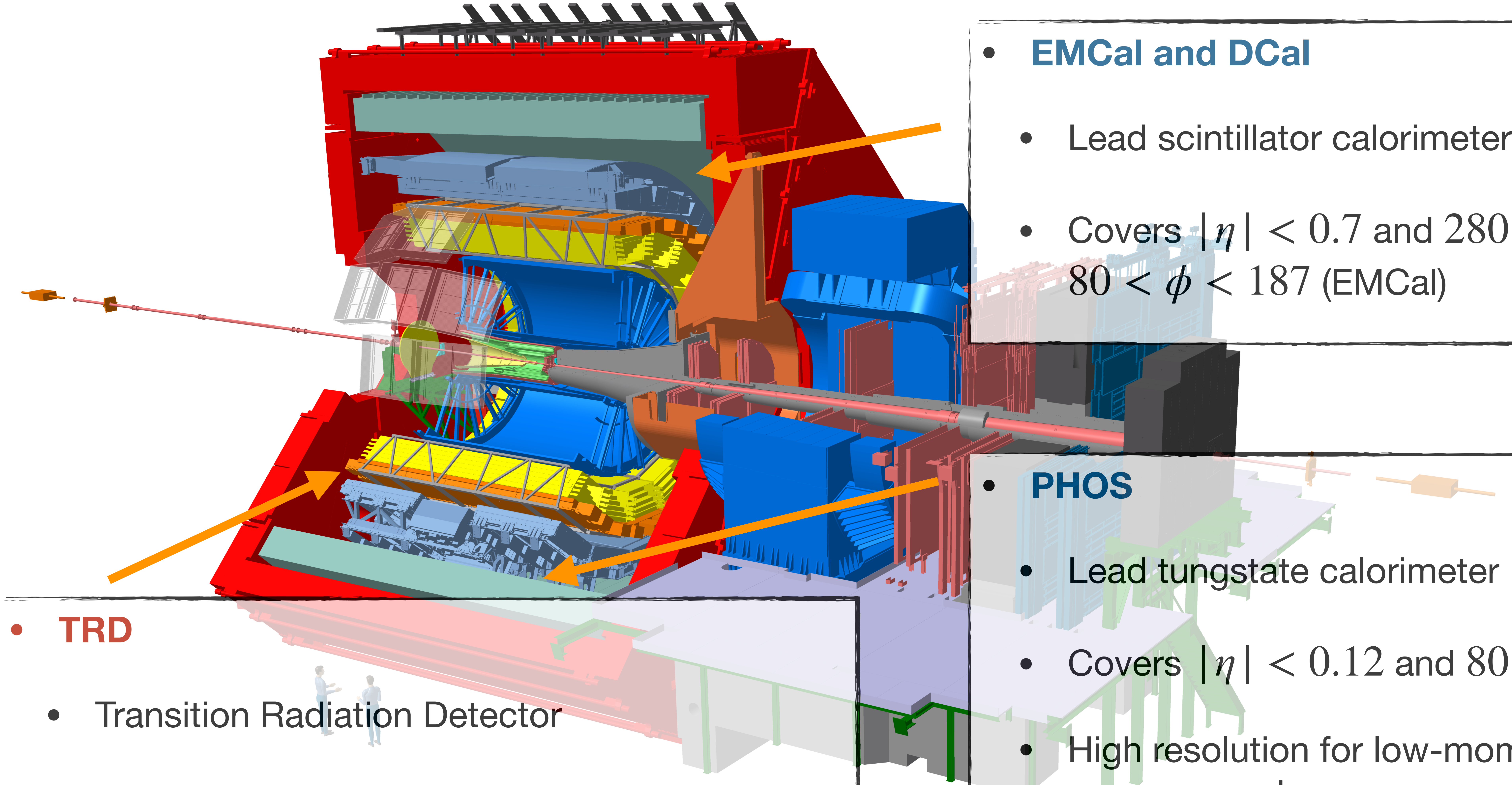
- **Muon Forward Tracker (MFT)** - Pixel detector installed during 2019-2022 long shutdown
  - 5-later silicon pixel tracker
  - Same sensor as ITS2
  - Precise muon tracking and reconstruction of particle decay vertices



- **Muon Spectrometer** - Identify muons through series of
  - **Front absorber** - carbon/concrete shield to suppress non-muonic charged particles while minimising energy loss of muons
  - **Tracking system** - 5 layers of cathode pad/strip chambers to track muons
  - **Trigger system** - Resistive plate chambers to select quarkonium resonance decays based on p_T of two muons
  - Dipole magnet (0.7T) for muon momentum measurement

ALICE layout

- **Electromagnetic calorimeters** measure photons, electrons, neutral pions



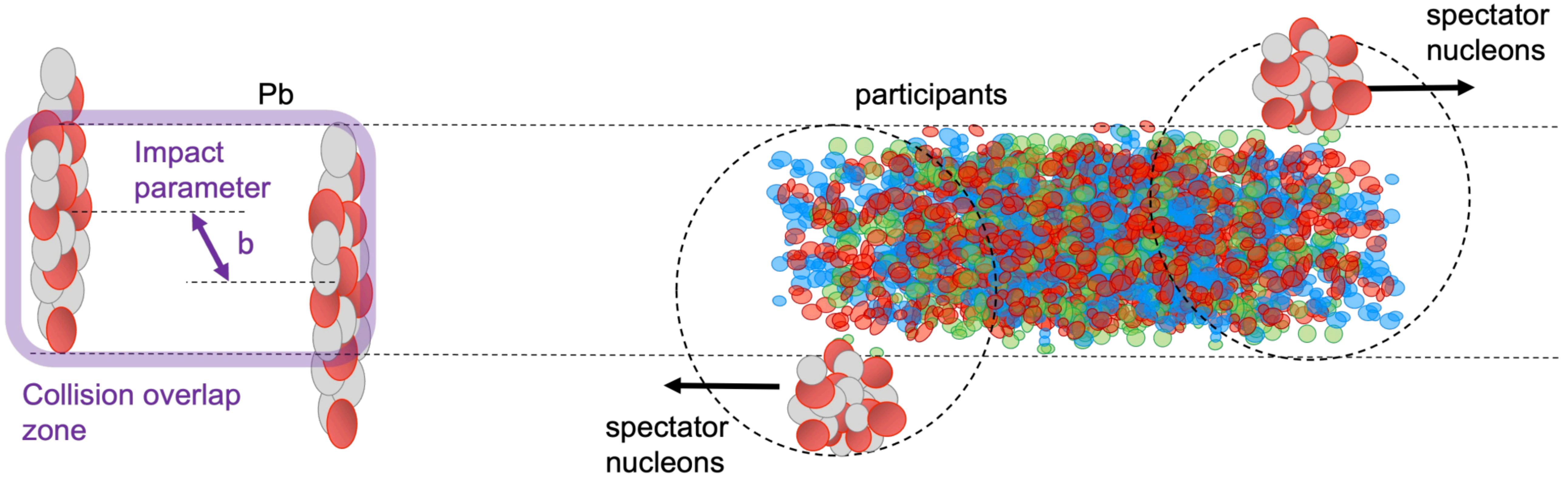
- **EMCal and DCal**
  - Lead scintillator calorimeter
  - Covers $|\eta| < 0.7$ and $280 < \phi < 320$ (DCal), $80 < \phi < 187$ (EMCal)

- **PHOS**
  - Lead tungstate calorimeter
  - Covers $|\eta| < 0.12$ and 80 degrees in ϕ
  - High resolution for low-momenum photon measurements

- **TRD**
  - Transition Radiation Detector
  - Used for identifying, triggering on electrons

Properties of the collision - Centrality

- **Heavy nuclei are (relatively) large with many constituents! How ‘head-on’ collision is determines size/lifetime/properties of ‘medium’ produced**



- **Centrality** = fraction of the total hadronic cross section of a nucleus-nucleus collision
- Expressed in percentile, related to impact parameter b of the collision

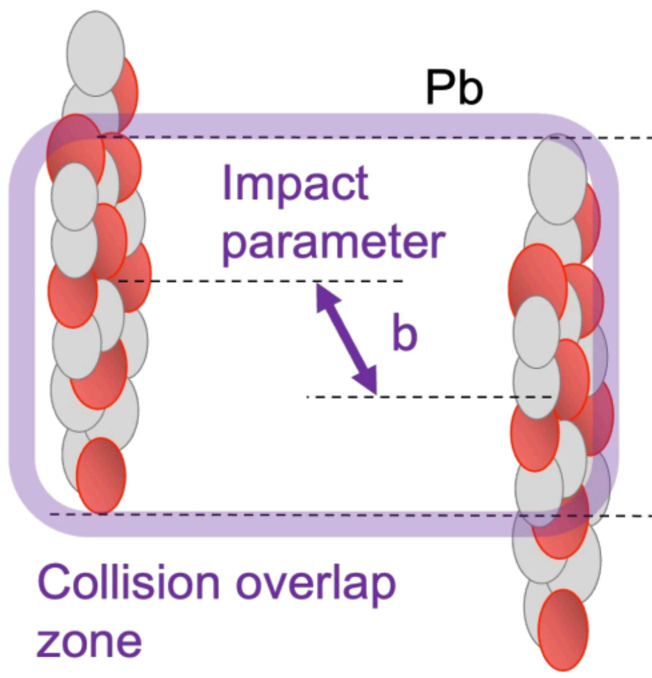
- **Central collision (e.g. 0-10%)**
  - Larger overlap region
    - more ‘nucleon-nucleon’ collisions
  - Longer lifetime, hotter temperature
  - More final state particles produced

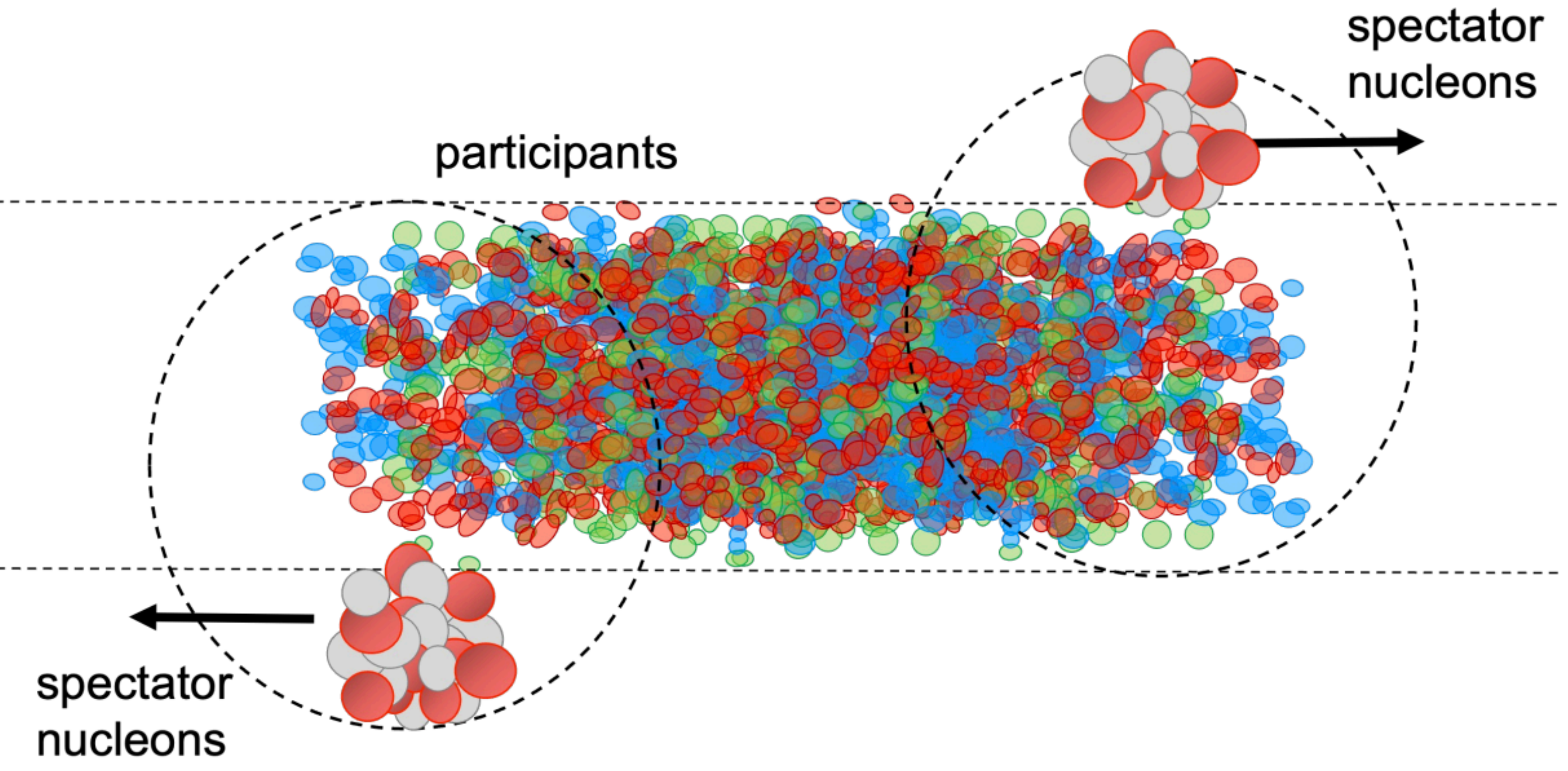
- **Peripheral collision (e.g 70-80%)**
  - Smaller overlap region
    - less ‘nucleon-nucleon’ collisions
  - Shorter lifetime, cooler temperature
  - Fewer final state particles produced

→ Final state properties measured by detector can be used to determine b

Properties of the collision - Centrality

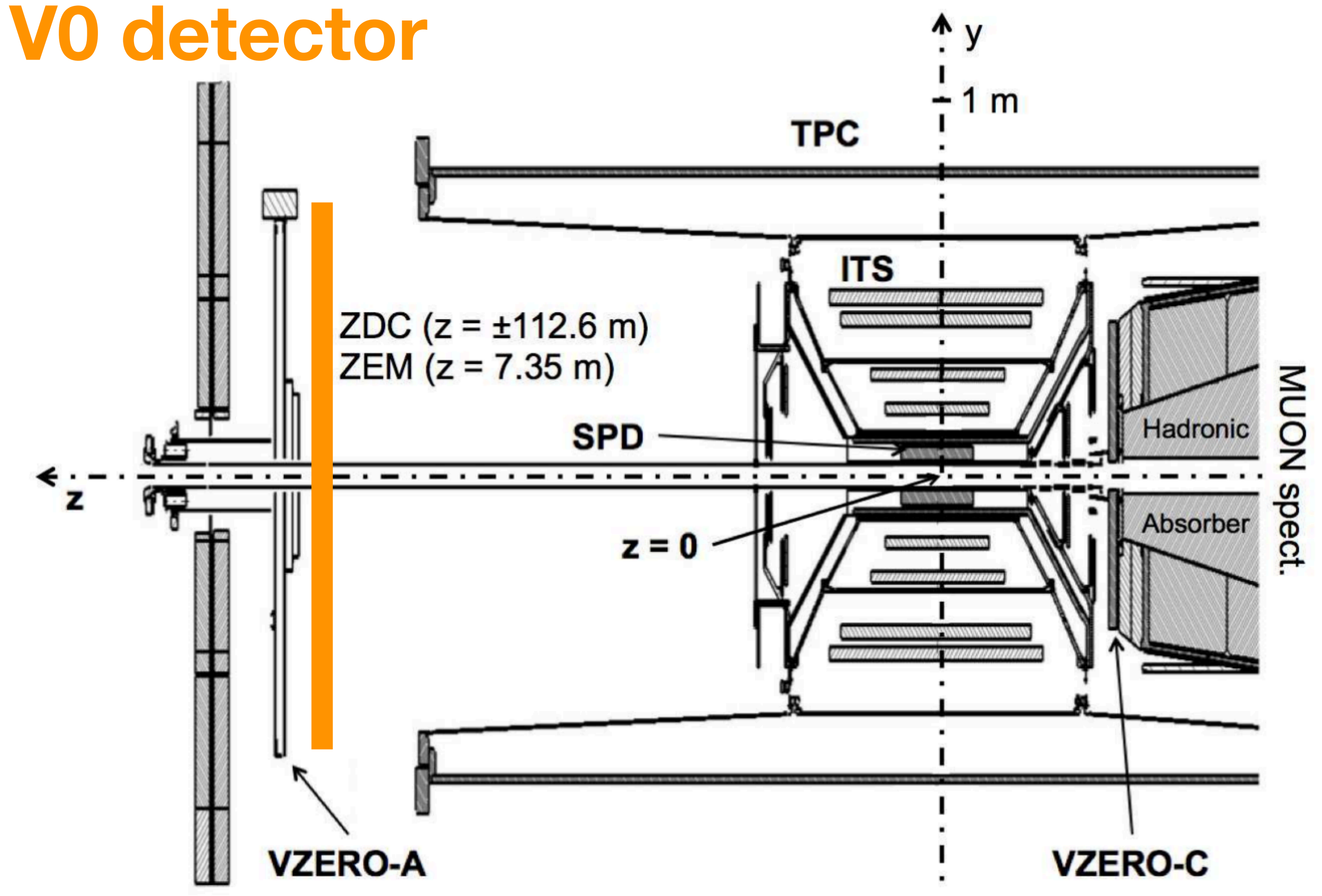
- **Heavy nuclei are (relatively) large with many constituents! How ‘head-on’ collision is determines size/lifetime/properties of ‘medium’ produced**





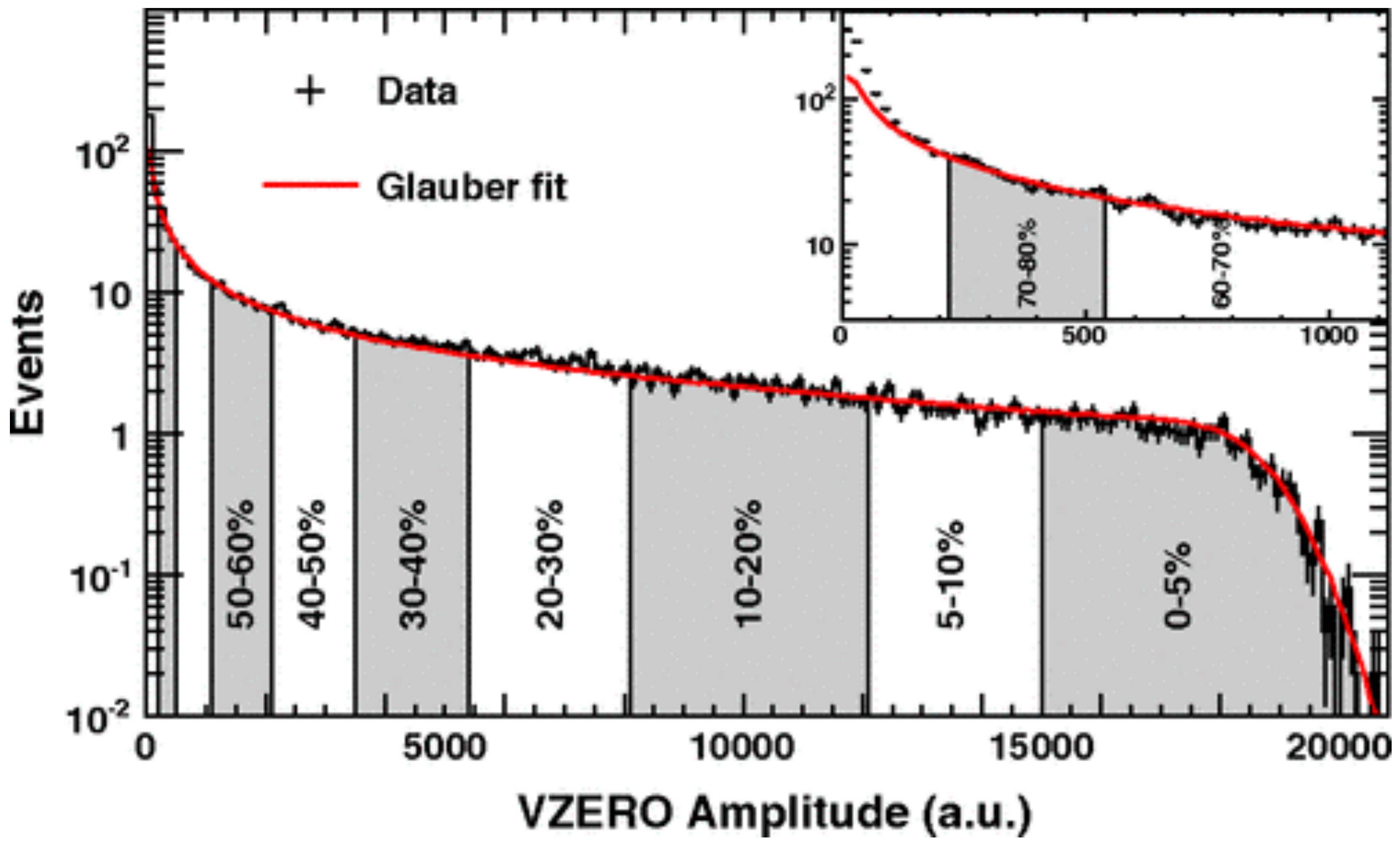
- **Centrality** = fraction of the total hadronic cross section of a nucleus-nucleus collision
- Expressed in percentile, related to impact parameter b of the collision

V0 detector



Glauber calculation: relationship between nucleon distribution in projectile and particle production

ALICE: Phys. Rev. Lett. 106, 032301



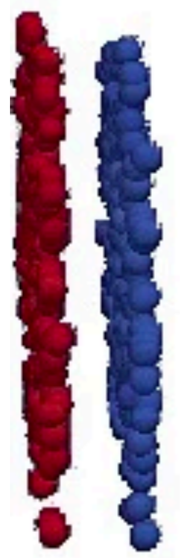
Can also be determined from multiplicity in other detectors or measuring spectator nucleons with ZDC - further reading arxiv:1402.4476

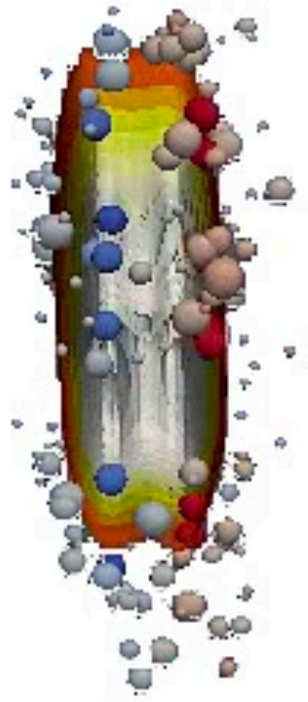
Anatomy of a heavy ion collision

t = 0 → t ~ 0.5 fm/c → t > 15 fm/c (~5x10^{-23} s)

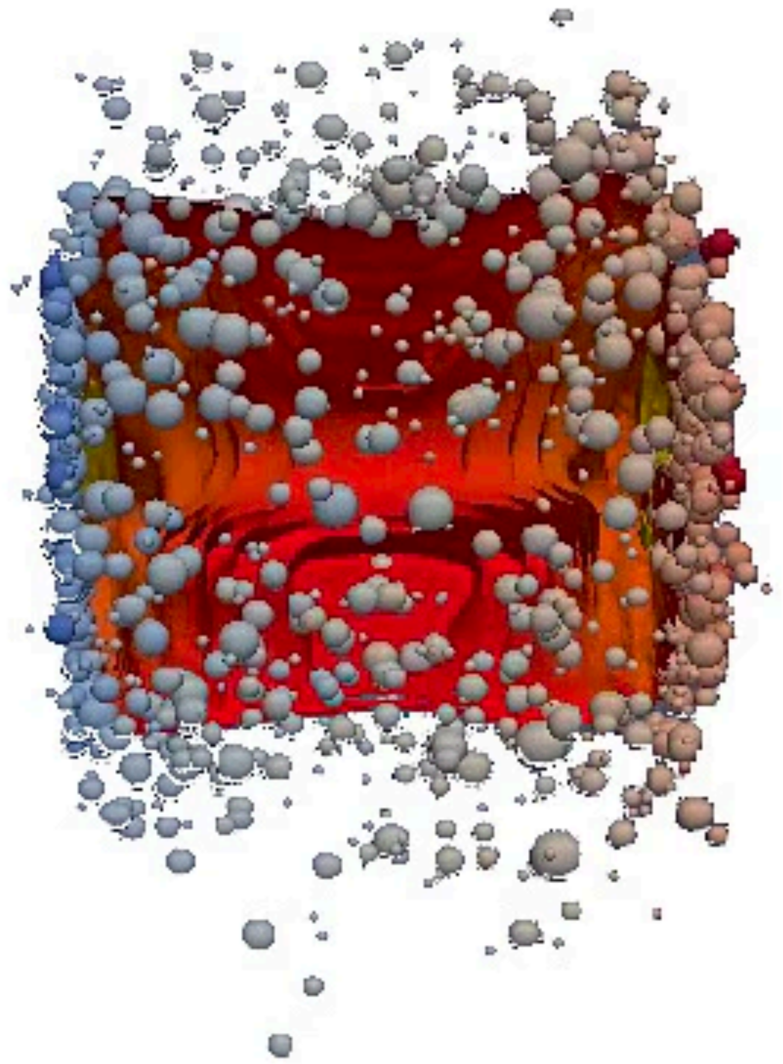
t ~ 10^{-6} s

Collision

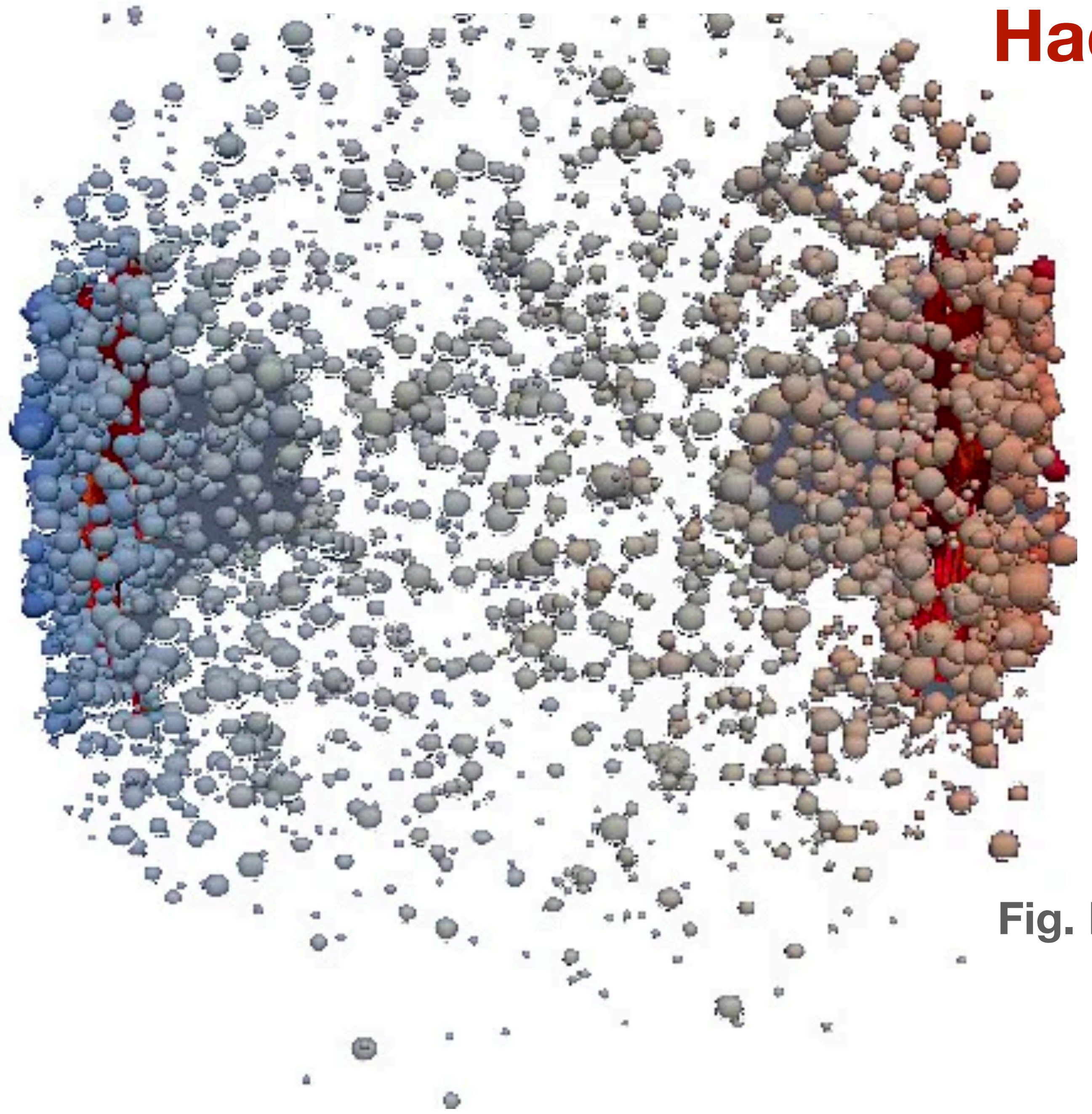




Pre-equilibrium

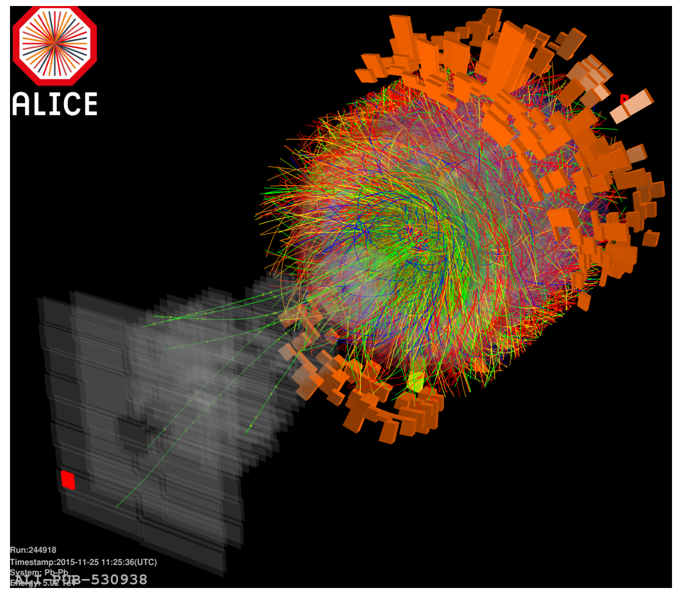


QGP expansion



Hadronisation

Fig. MADAI collaboration



Detection

T > 300 MeV → T ~ 150 MeV

We create a QGP then measure its remnants

- How can it be investigated and its physical properties determined?

Anatomy of a heavy ion collision

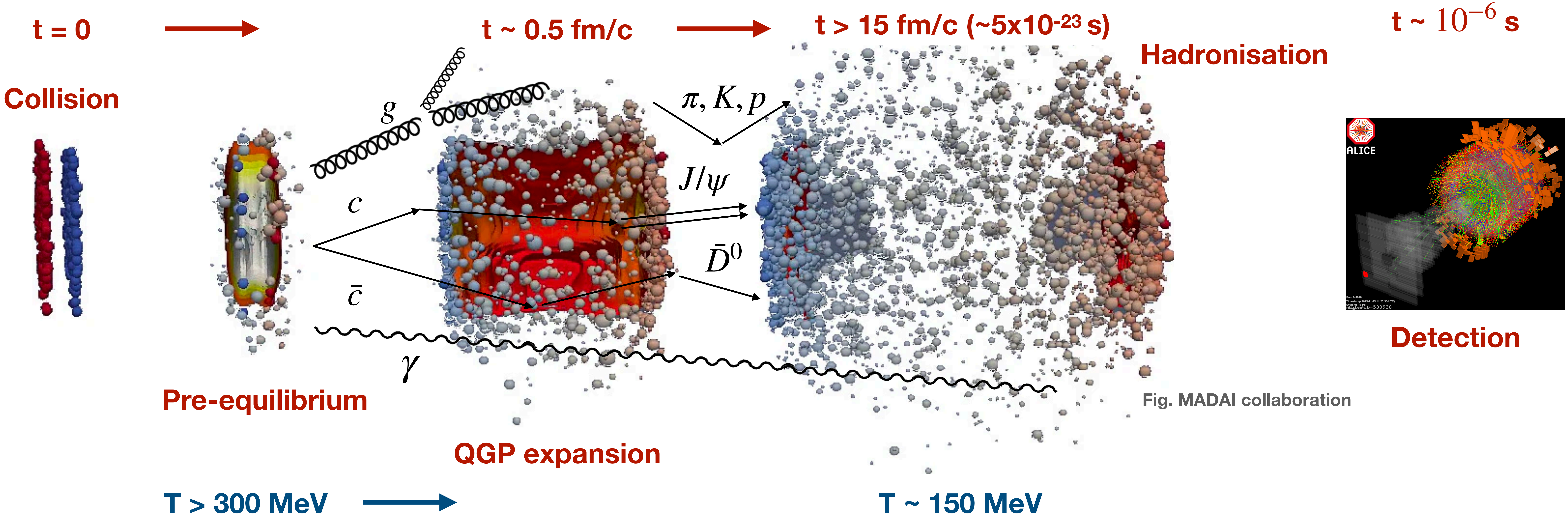


Fig. MADAI collaboration

Many QGP signatures that can be measured!

Summary

- **ALICE** (**A** **L**arge **I**on **C**ollider **E**xperiment) is the experiment at the LHC dedicated to studying the deconfined state of QCD known as the Quark-Gluon Plasma (QGP)

  - It was the state of the universe a few microseconds after the big bang, and is recreated using heavy-ion collisions

Today

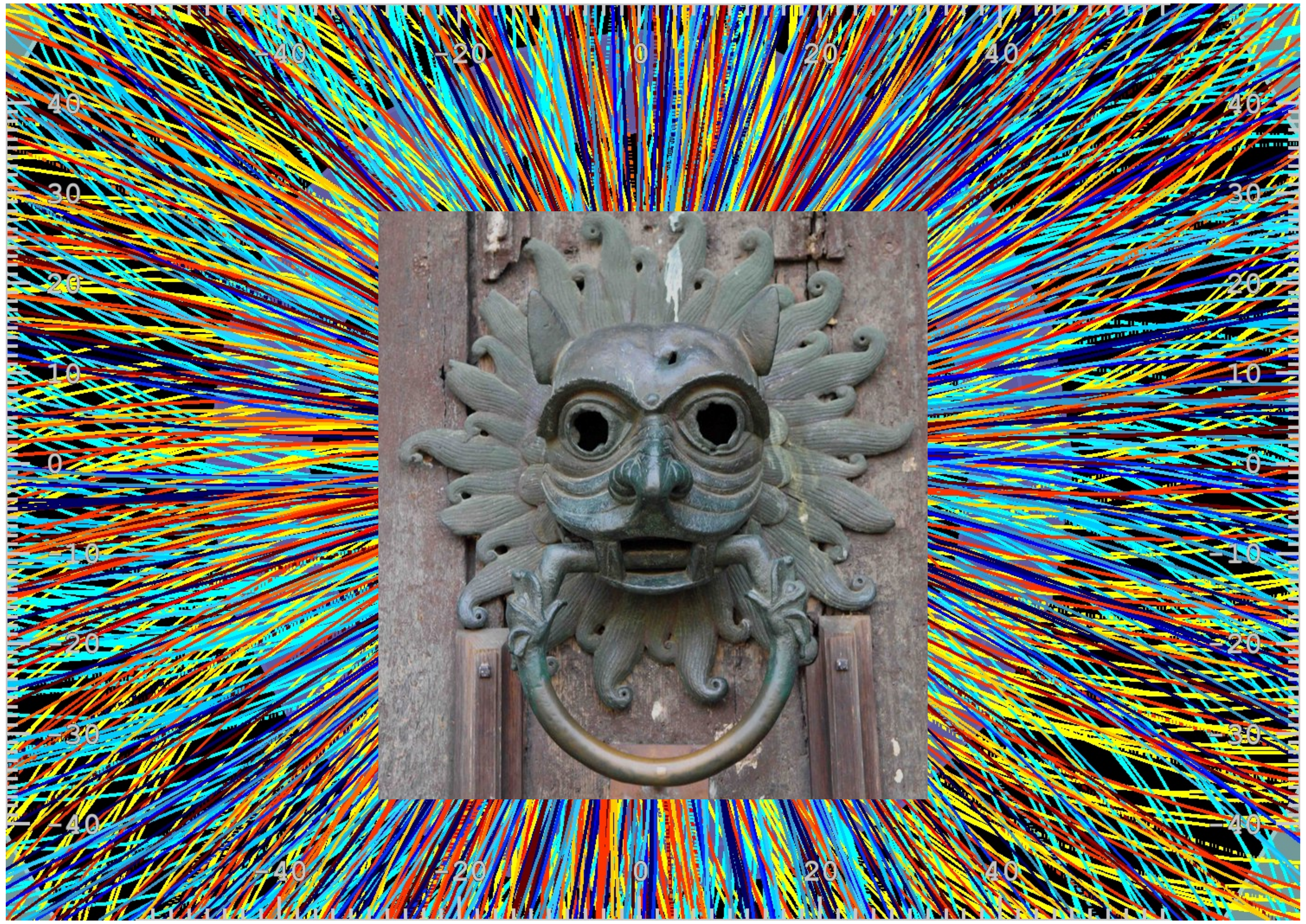
  - Basic concepts of QCD, the QGP and heavy-ion physics

  - The ALICE experiment

  - How do we probe the QGP? What have we discovered?

  - Future plans of heavy-ion physics

Tomorrow!



Contact: jknorman@liverpool.ac.uk