A Large Ion Collider Experiment (ALICE) at the LHC

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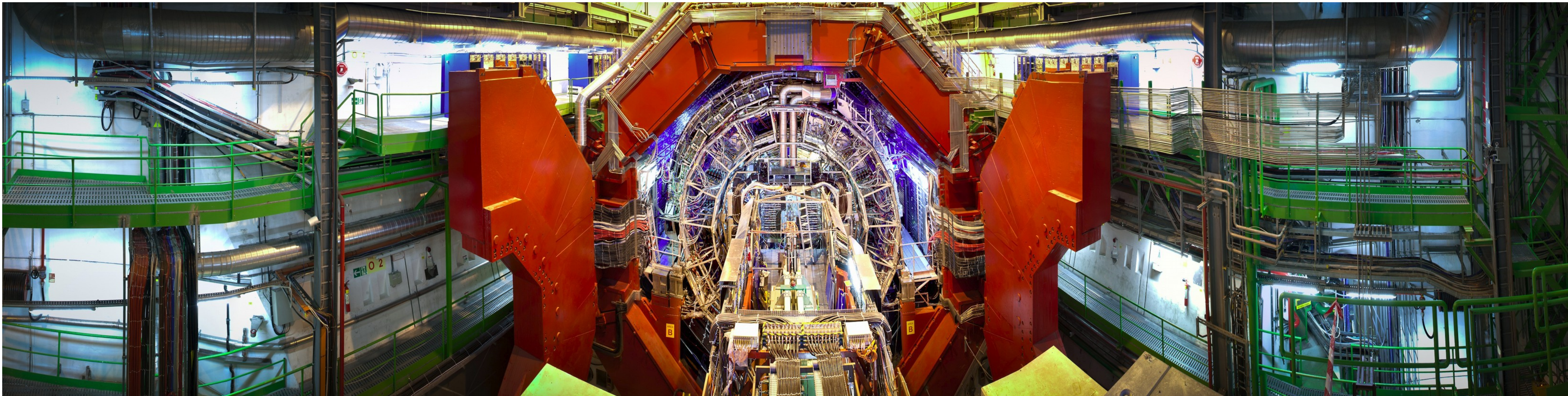
2020/02/20

A JOURNEY OF DISCOVERY



Outline

- Introduction and motivation
- The ALICE apparatus
- Physics results

Introduction and motivation

Levels of the nuclear world

- Nuclei

  a large variety (Z=1-118, A=2-294), sizes: ~10^{-14} m

  nucleons are bound by about 1% of their mass ($m_p \approx m_n = 1.7 \times 10^{-27}$ kg)

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- Hadrons

  baryons (p,n,...), mesons (π, K, …), sizes: 10^{-15} m

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  6 flavours (light: u,d; “intermediate”: s; heavy: c,b; “super-heavy”: t)

  each in 3 “colours” (to build colourless hadrons: qqq, $\overline{qqq}$, $q\overline{q}$, …)

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- … all governed by the strong interaction
- Gravitation is negligible
- (electro)weak interactions act only indirectly (decays, final state interactions)

Quantum Chromo-Dynamics (QCD)

- 6 quarks, 3 colours (RGB)
  and 8 gluons (coloured!)
- ...difficult to calculate
  - No analytical solutions (except 1+1)

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

Quantum Chromo-Dynamics (QCD)

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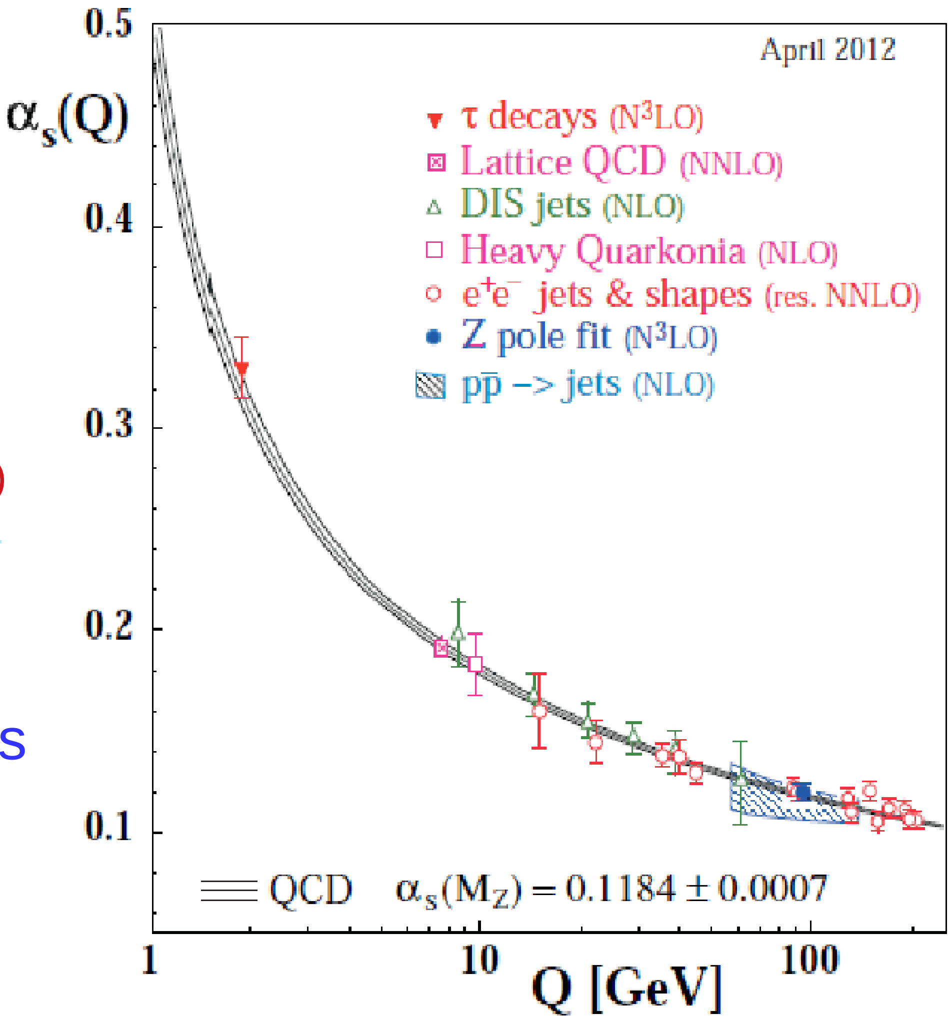
- ...difficult to calculate
  - No analytical solutions (except 1+1)
- **High *Q*:** asymptotic freedom
  Physics Nobel prize 2004 (Wilczek, Gross, Politzer)
- Typically solvable using perturbative theory
- Tested extensively at modern colliders



S.Bethke, arXiv:1210.0325

Quantum Chromo-Dynamics (QCD)

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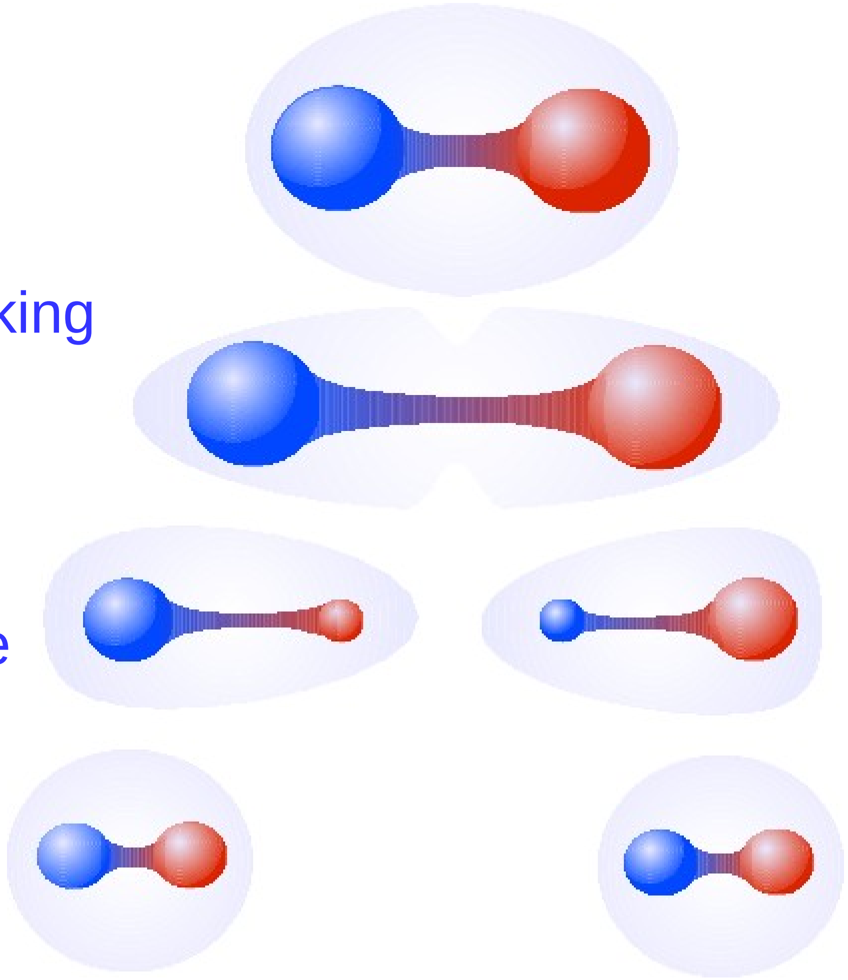
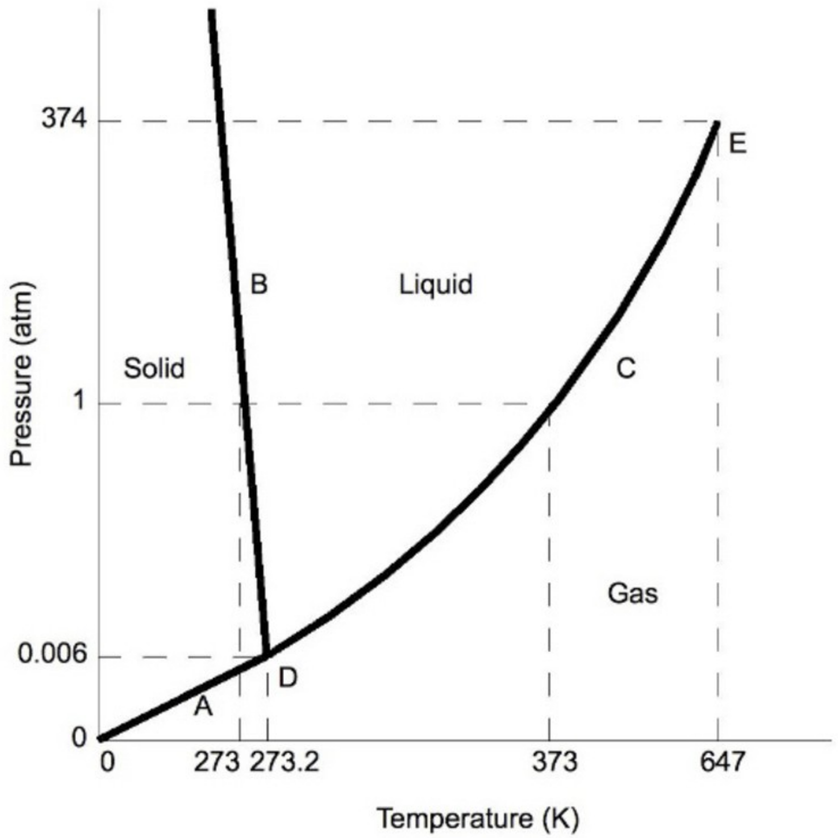
  and 8 gluons (coloured!)
- ...difficult to calculate
  - No analytical solutions (except 1+1)
- **Low *Q*:** confinement / chiral symmetry breaking

  Physics Nobel Prize 2008 (Y.Nambu)
  - Non-perturbative, largely unknown
  - One of the Millennium Prize problems
  - Most of the visible matter in the Universe



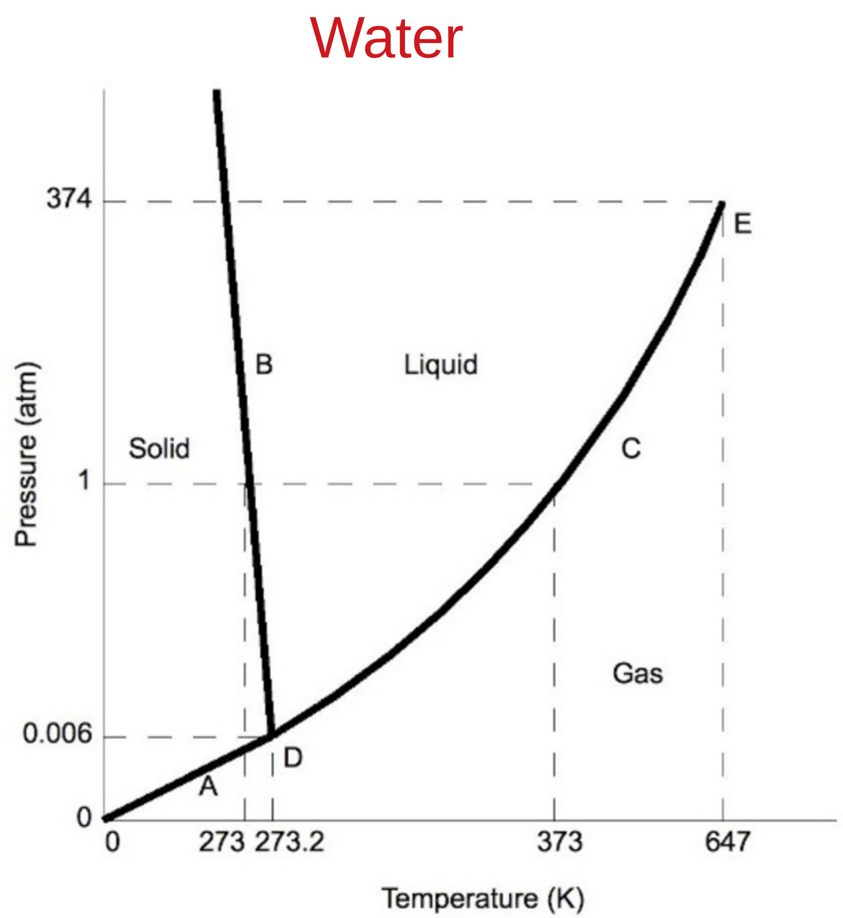
High energy nucleus-nucleus collisions: the scope

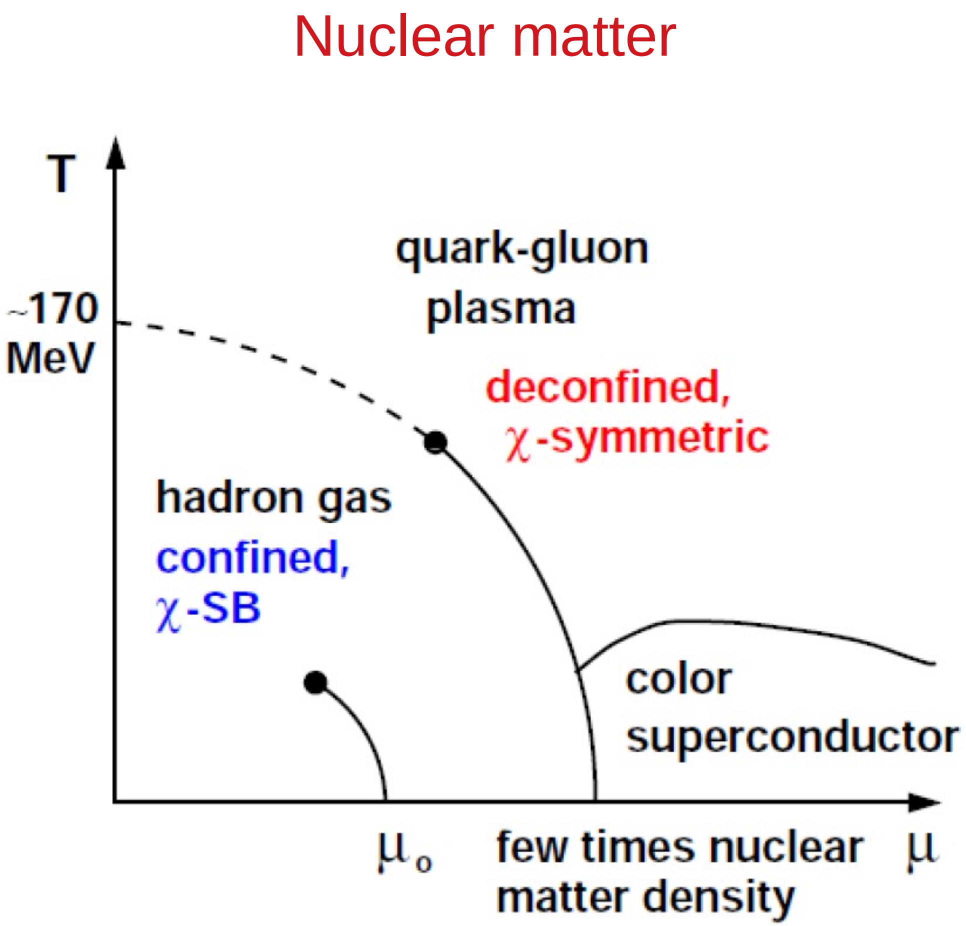
Water



- What happens if “normal” nuclear matter is compressed and/or heated ?
  - What are the degrees of freedom ?
  - Are there any phase transitions ?

High energy nucleus-nucleus collisions: the scope





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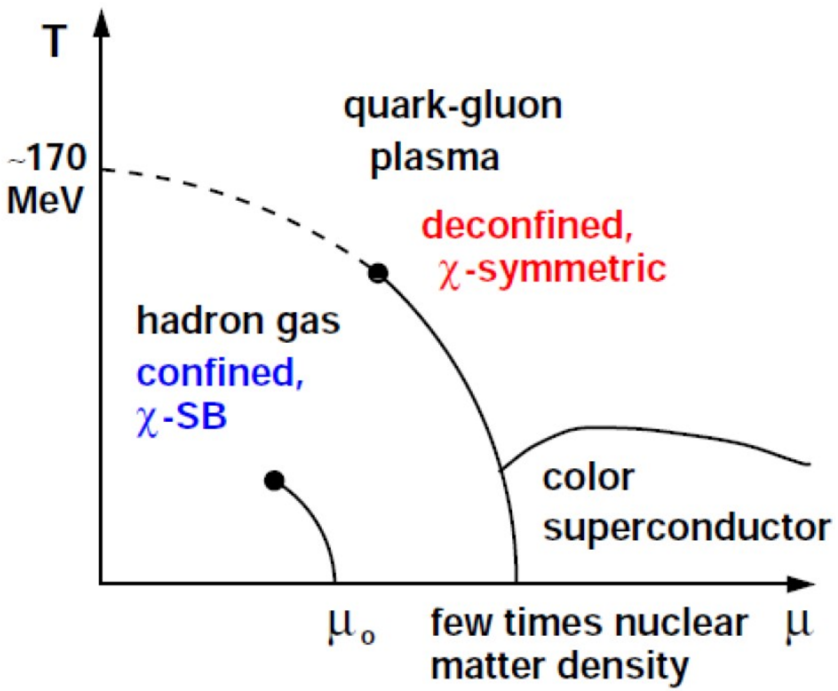
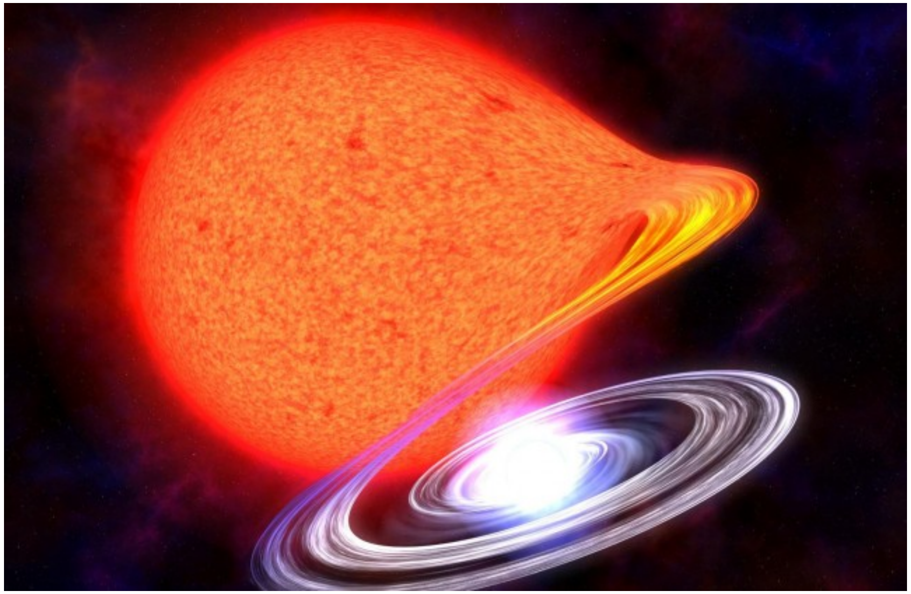
High energy nucleus-nucleus collisions: the scope

Nuclear matter



Pressure and low temperature

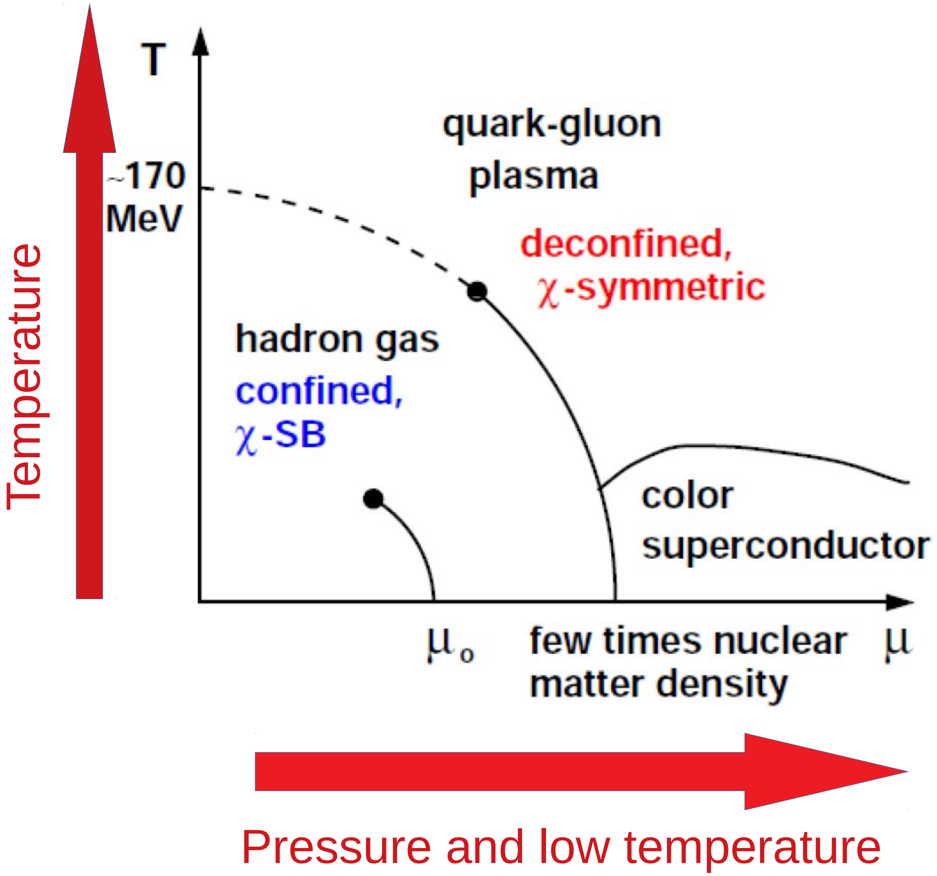


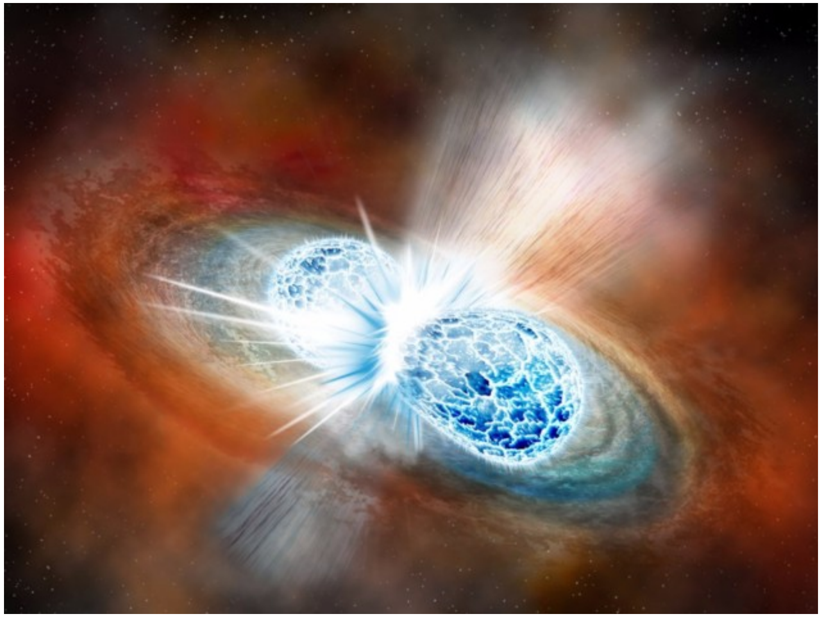
Double star system with one neutron star
Source: astronomie.nl

- Increasing nuclear matter density while keeping temperature low leads to phase transitions in color superconducting phases
  - e.g. neutron stars

High energy nucleus-nucleus collisions: the scope

Nuclear matter



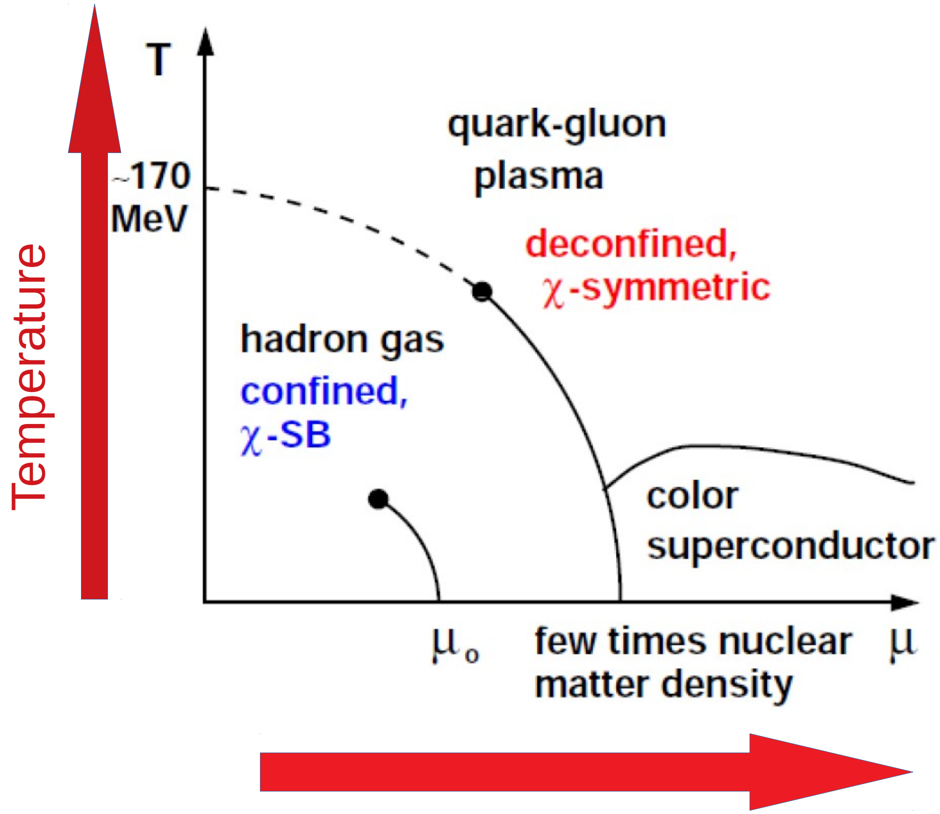


Neutron star merger
Source: NASA

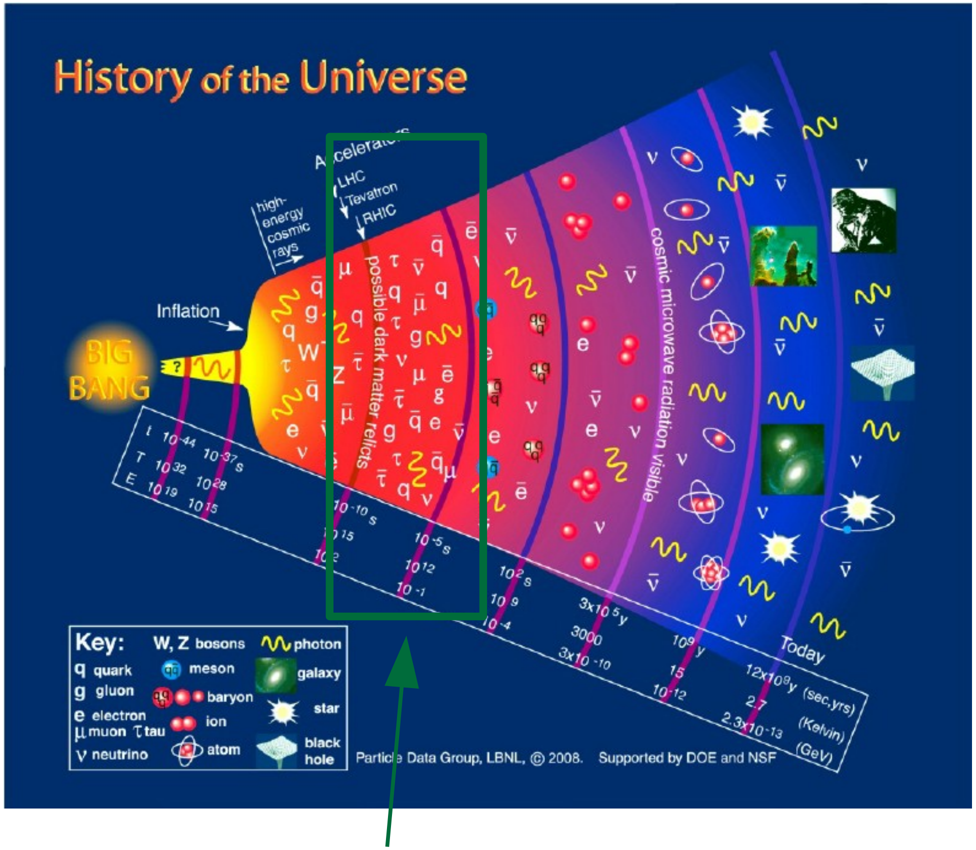
- Increasing both nuclear density and temperature, more phases appear and possibly a transition to QGP phases
    - e.g. neutron star merger events

High energy nucleus-nucleus collisions: the scope

Nuclear matter



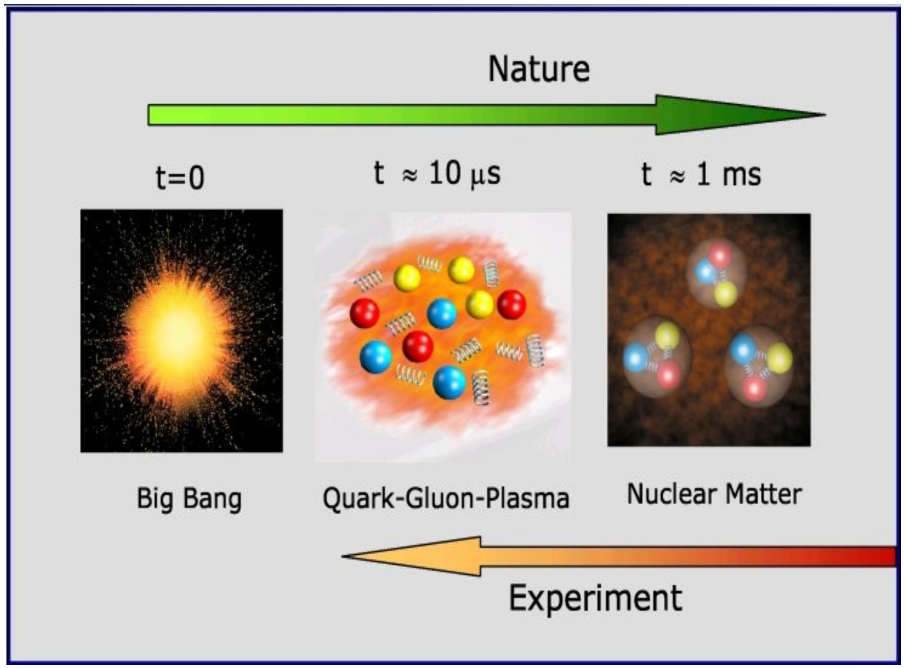
Pressure and low temperature



Similar conditions reached at nuclear colliders

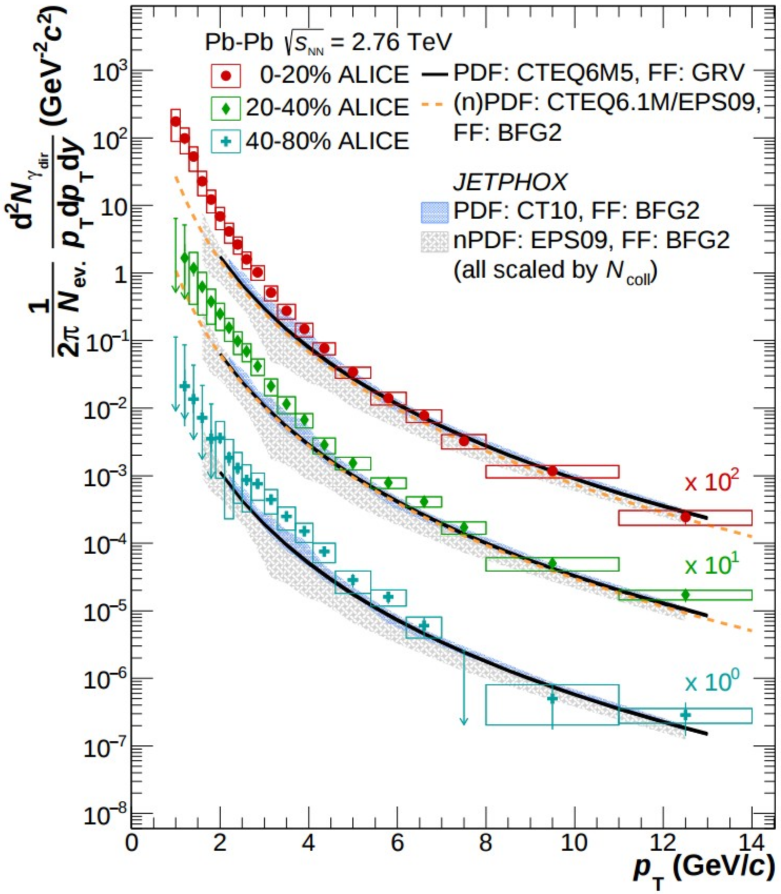
- Increasing sharply the temperature and energy density, at low densities of nucleons → transition to QGP phase

High energy nucleus-nucleus collisions: the scope



ALICE, PLB754 (2016) 235

Direct photon spectrum



T_{QGP}= 3500000000000 K (3x10^8 eV)

Highest temperature ever measured!

- Create in the laboratory a chunk of **deconfined matter** (also called Quark-Gluon Plasma, QGP) and study its properties and phase diagram

What are the conditions that can be achieved?

(extracted from data and models)

- *Temperature: T*=100-1000 MeV or up to 1 million times that in the center of the Sun

  1MeV ≈ 10 billion degrees Kelvin

- *Pressure*: *P*=100-300 MeV/fm^3 (1MeV/fm^3 ≈ 10^{28} atmospheres)

  center of the Earth: 3.6*10^6 atmospheres

- *Density*: ρ=1-10ρ_0 (ρ_0: density of a Au nucleus = 2.7*10^{14} g/cm^3)

  Density of Au = 19 g/cm^3

- *Volume*: about 2000 fm^3 (1 fm = 10^{-15} m)

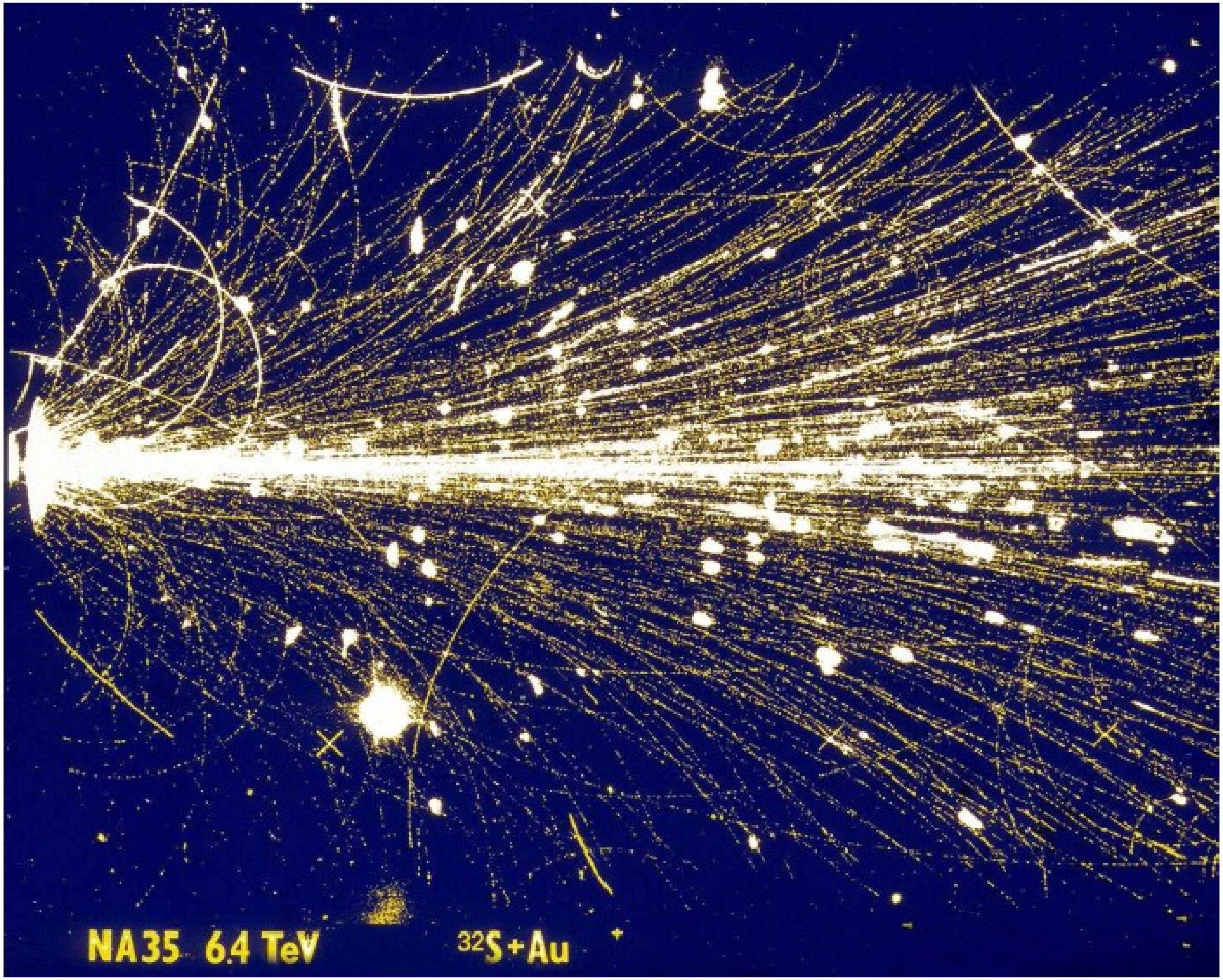
- *Duration*: about 10 fm/c (or about 3*10^{-23} sec.)
  - Sufficiently long lived to be studied

The apparatus

Heavy ion accelerators

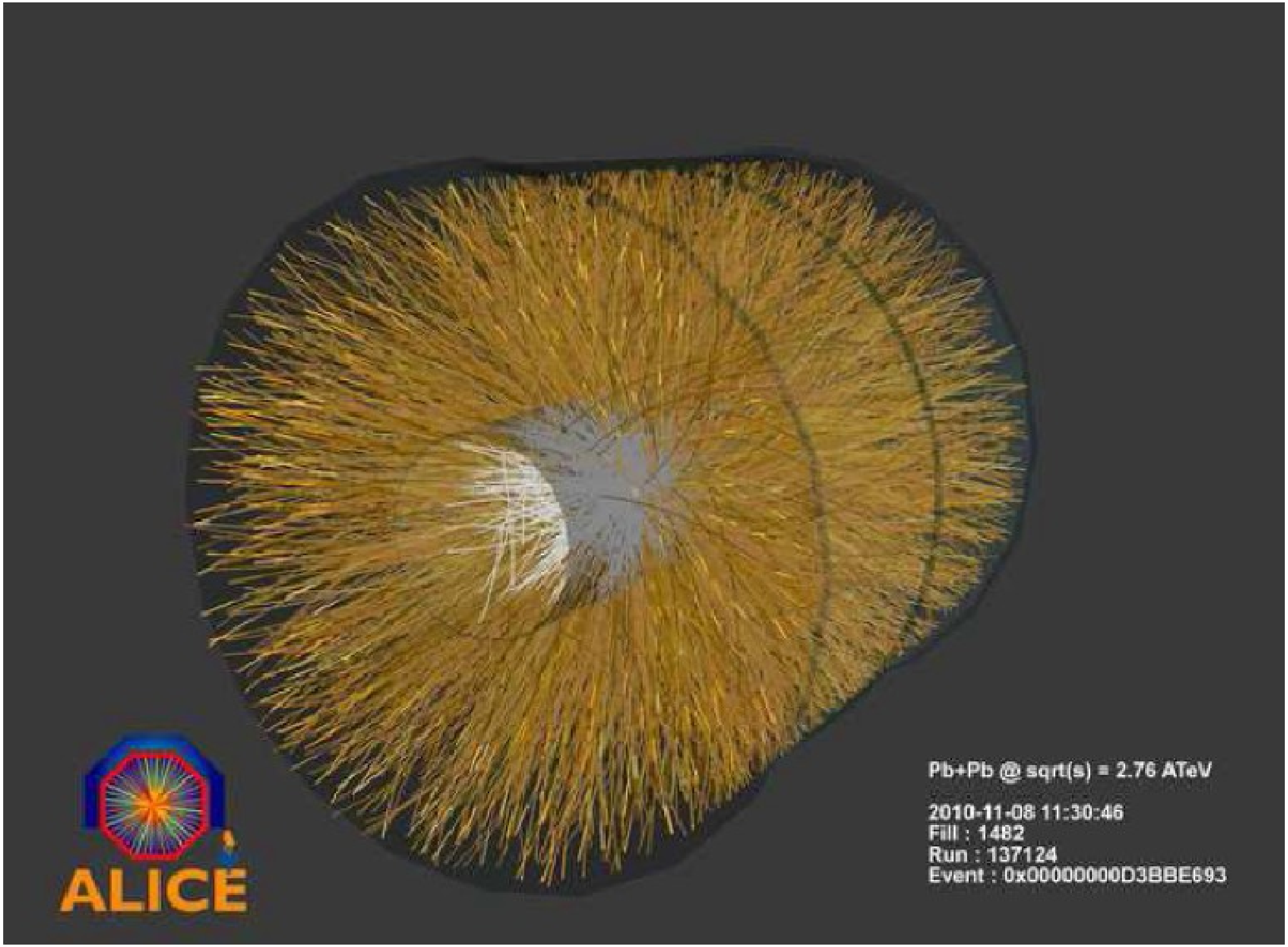
- Past:
  - Bevalac @ LBL, Berkeley (1980-1990): $\sqrt{s_{NN}}$=2.4 GeV
  - AGS @ BNL, Brookhaven (1985-1995): $\sqrt{s_{NN}}$=4.8 GeV
  - SPS @ CERN, Geneva (1987-2004): $\sqrt{s_{NN}}$=17.3 GeV
- Present:
  - SIS @ GSI, Darmstadt: $\sqrt{s_{NN}}$=2.5 GeV
  - RHIC @ BNL, Brookhaven: $\sqrt{s_{NN}}$=200 GeV
  - LHC @ CERN, Geneva: $\sqrt{s_{NN}}$=2760, 5020 GeV
- Future:
  - FAIR @ GSI, Darmstadt (~2023): $\sqrt{s_{NN}}$=5 GeV
  - NICA @ JINR, Dubna (~2023): $\sqrt{s_{NN}}$=5 GeV
  - eRHIC @ BNL, Brookhaven (~2030)
  - Future Circular Collider @ CERN, Geneva ?

An early picture of a heavy-ion collision (CERN)



A heavy ion collision recorded using a spark chamber

A Pb-Pb collision measured by ALICE



- A 3D picture of a central collision (about 3000 primary tracks)
- We take billions of such pictures to be analyzed offline

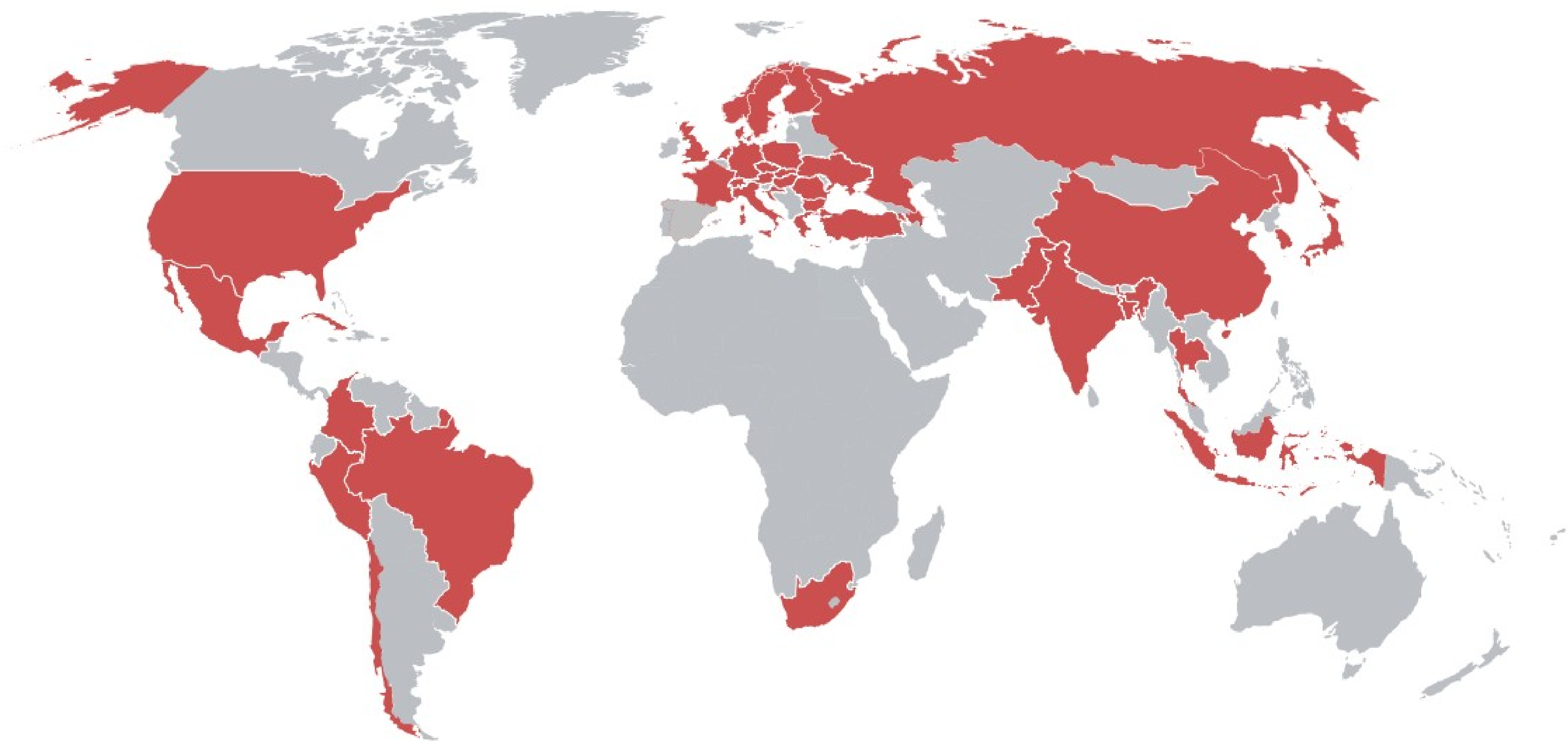
The ALICE Collaboration

A Large Ion Collider Experiment

ALICE COLLABORATION

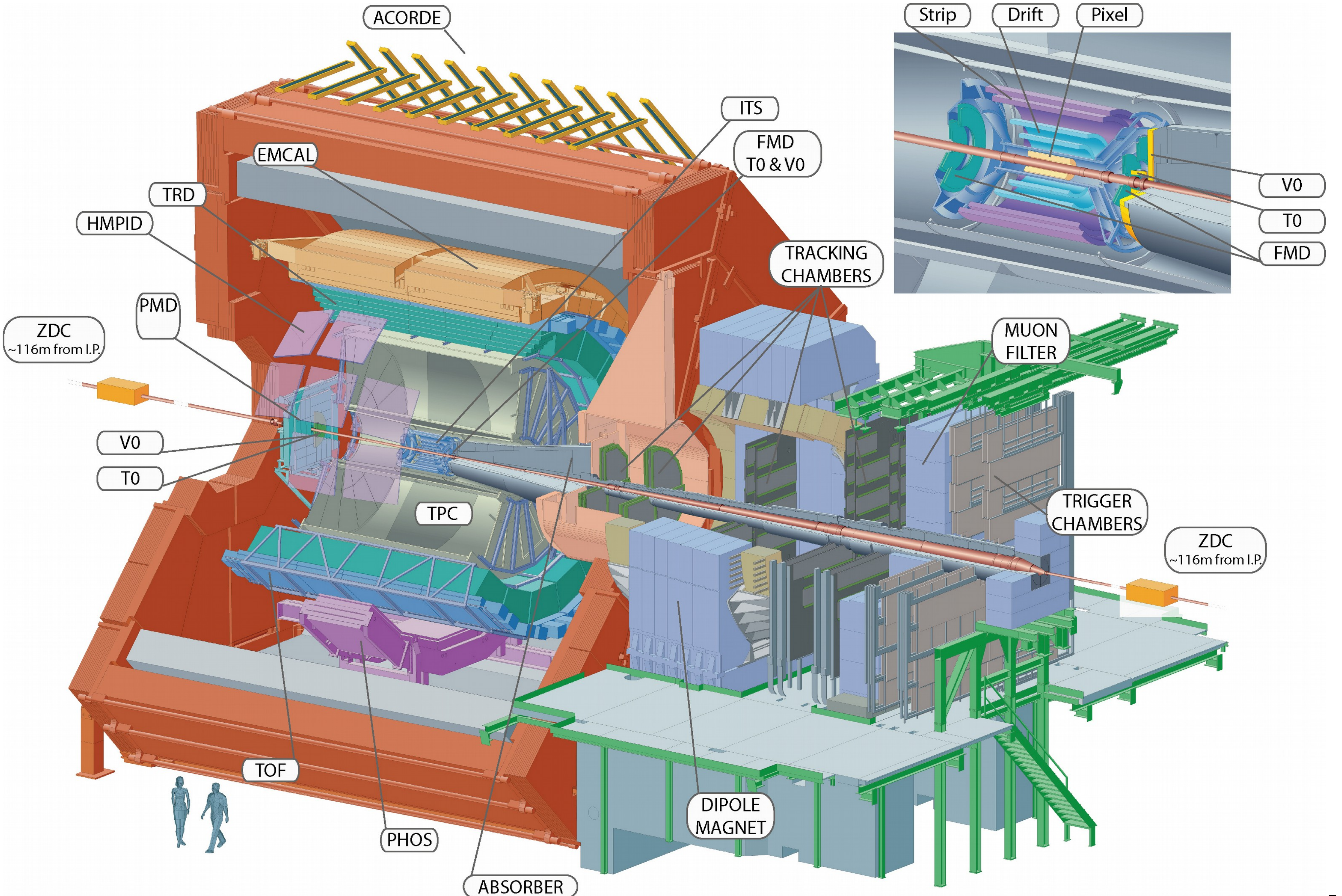
AS JANUARY 2018

ALICE

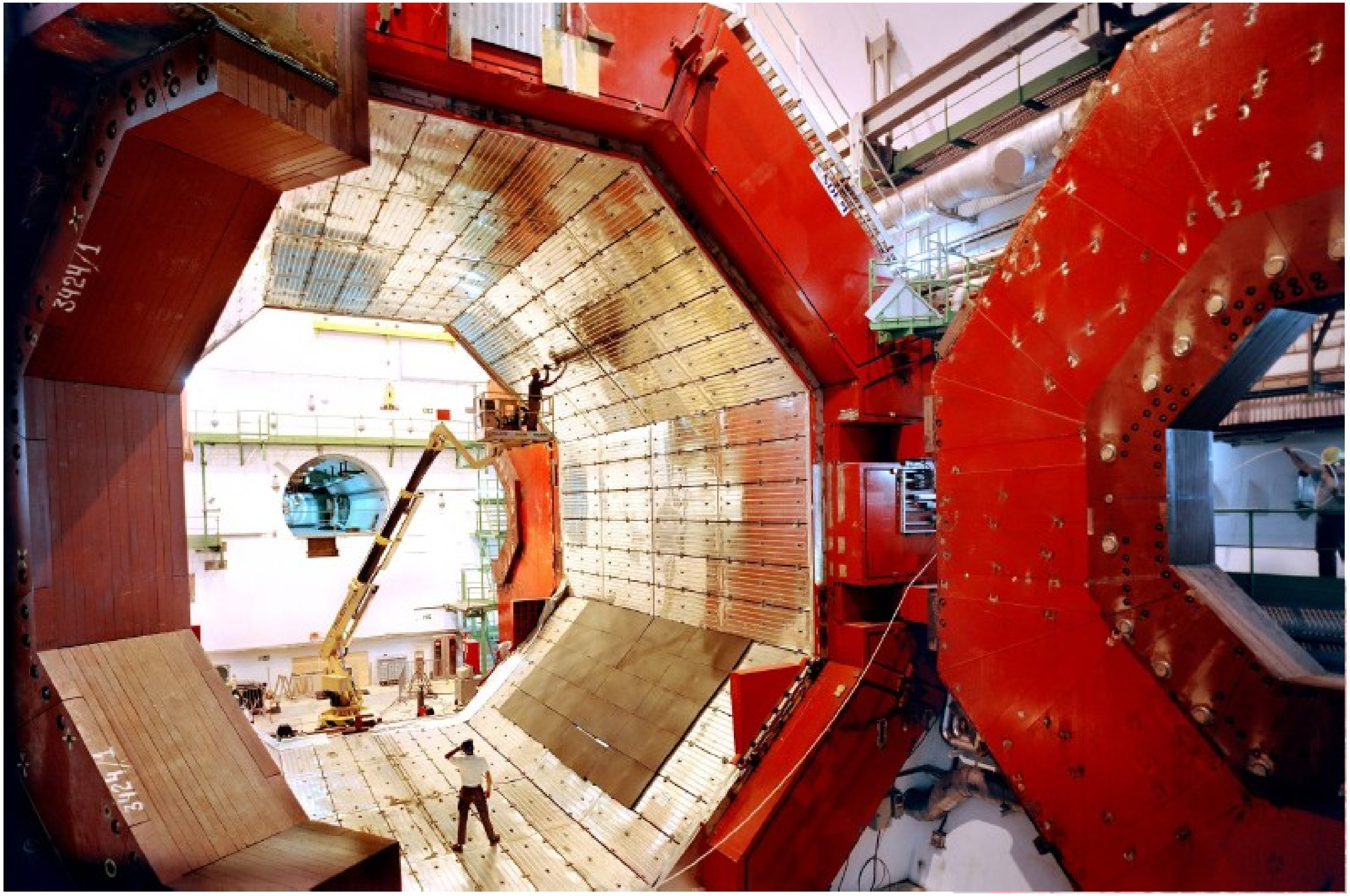


39 countries, 175 institutes and 1900+ members

The ALICE detector



The L3 solenoid magnet



- It creates a uniform 0.5 T magnetic field

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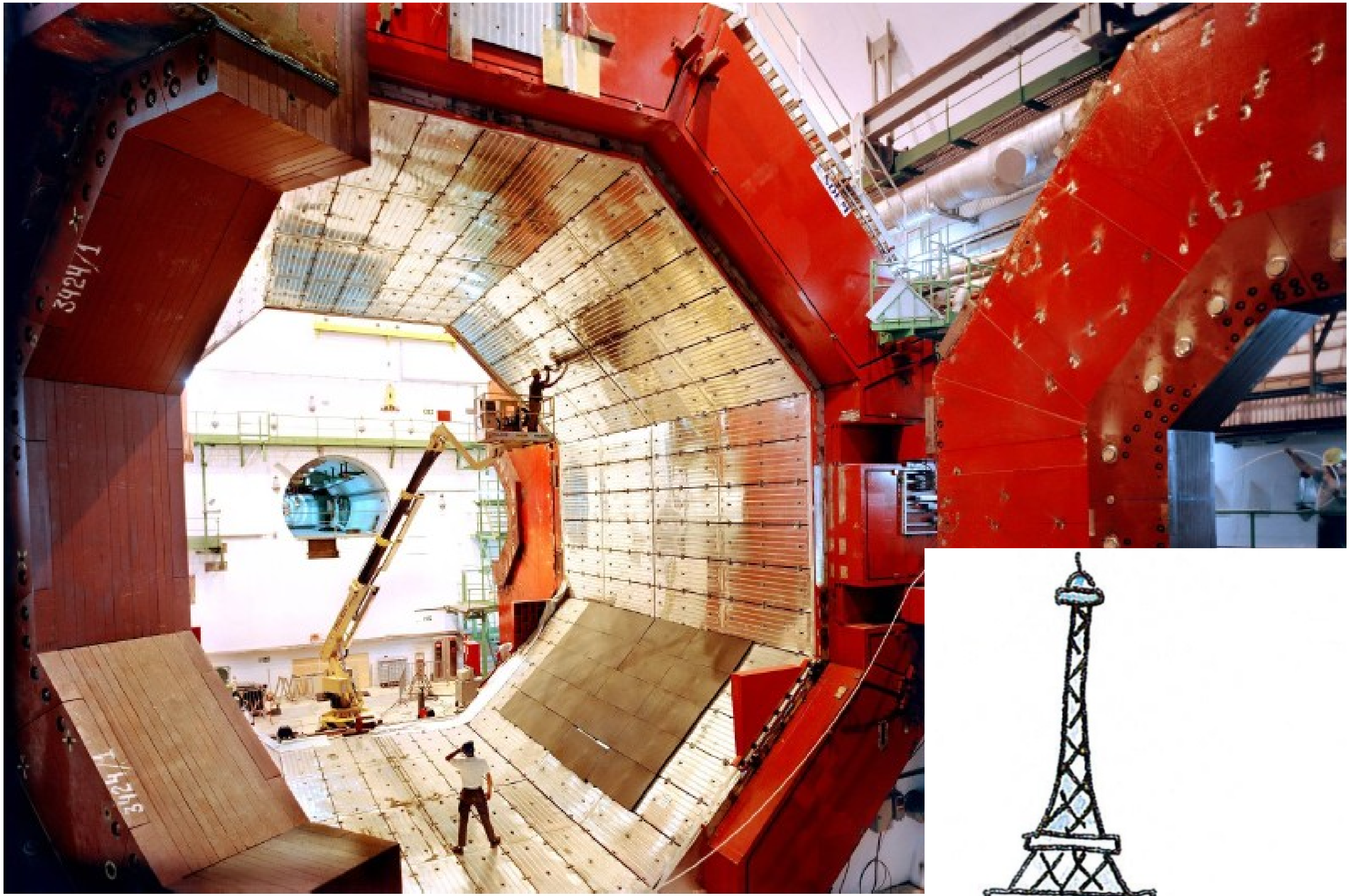
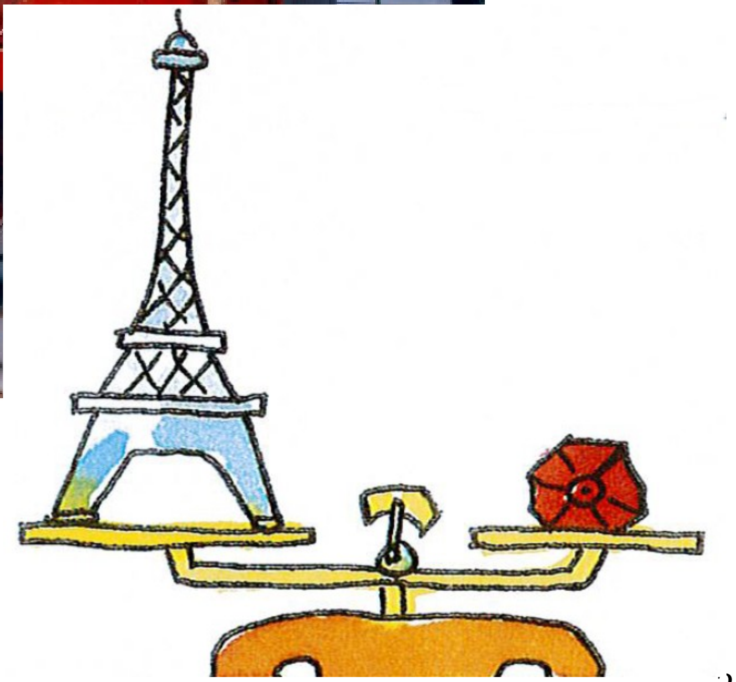
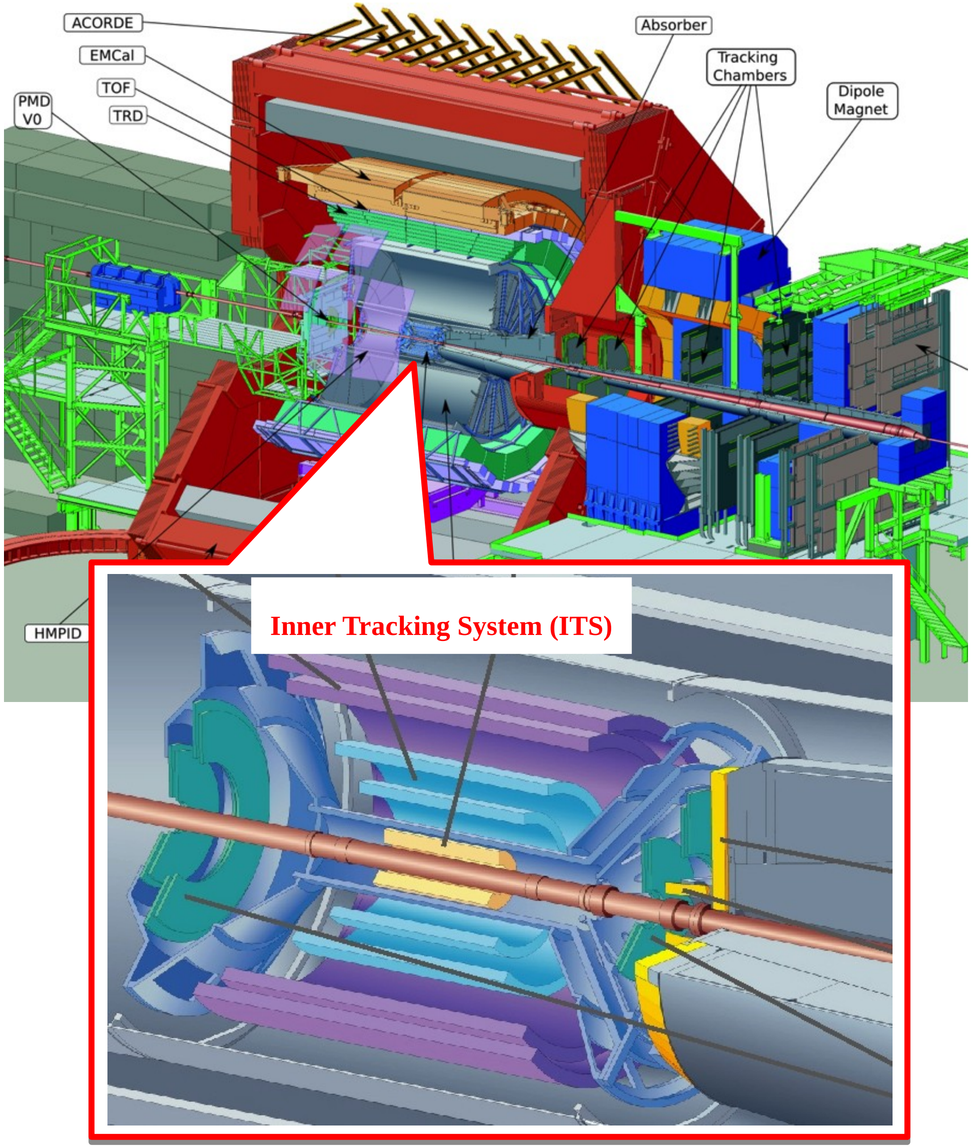




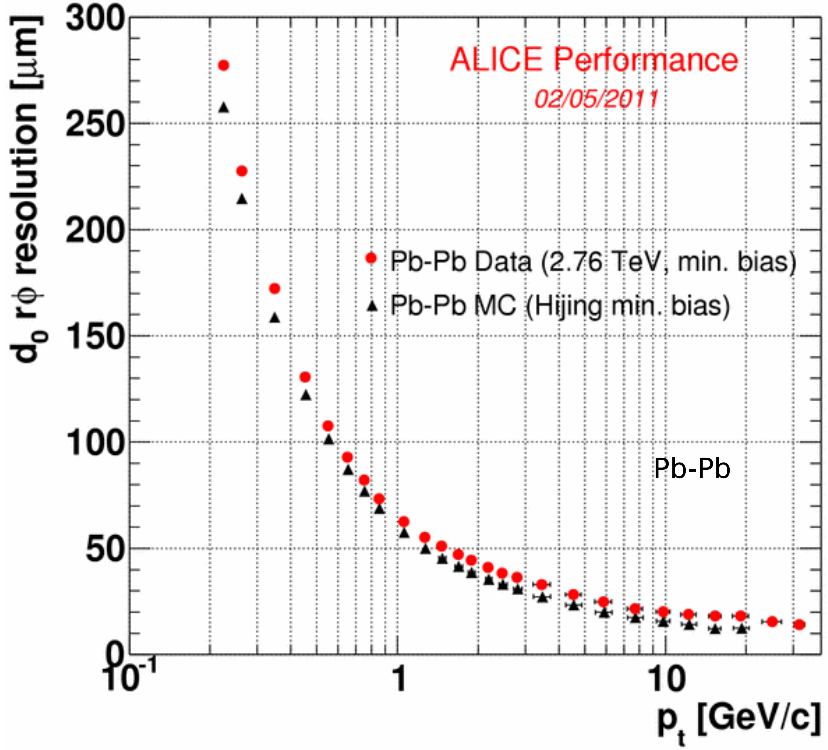
- It creates a uniform 0.5 T magnetic field
- As heavy as the Eiffel tower

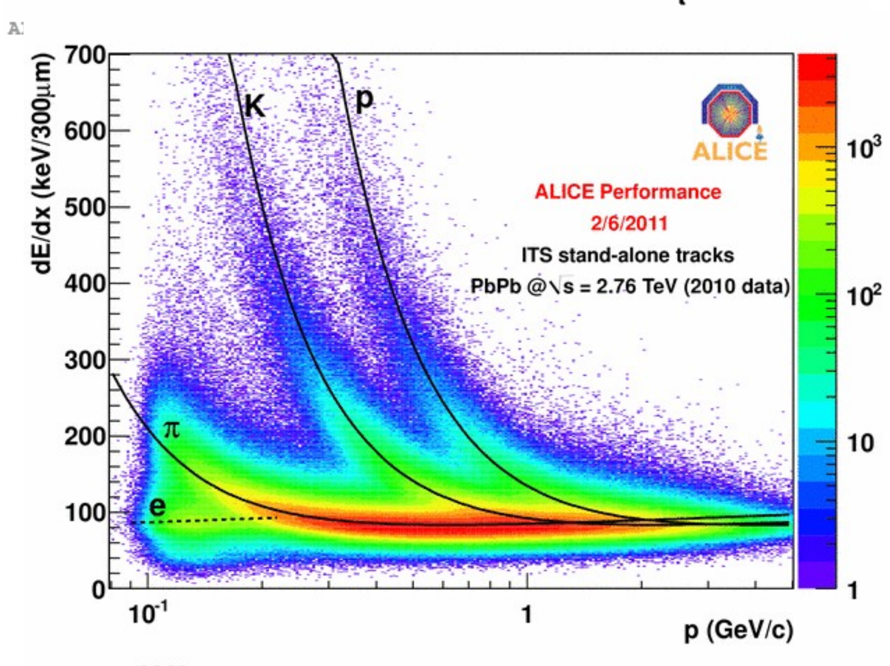
The Inner Tracking System (ITS)



- Barrel geometry detector
  - 6 layers of silicon detectors
- Key detector for ALICE tracking and trigger system
- Measures global properties of the event: particle multiplicity

Inner Tracking System (ITS)

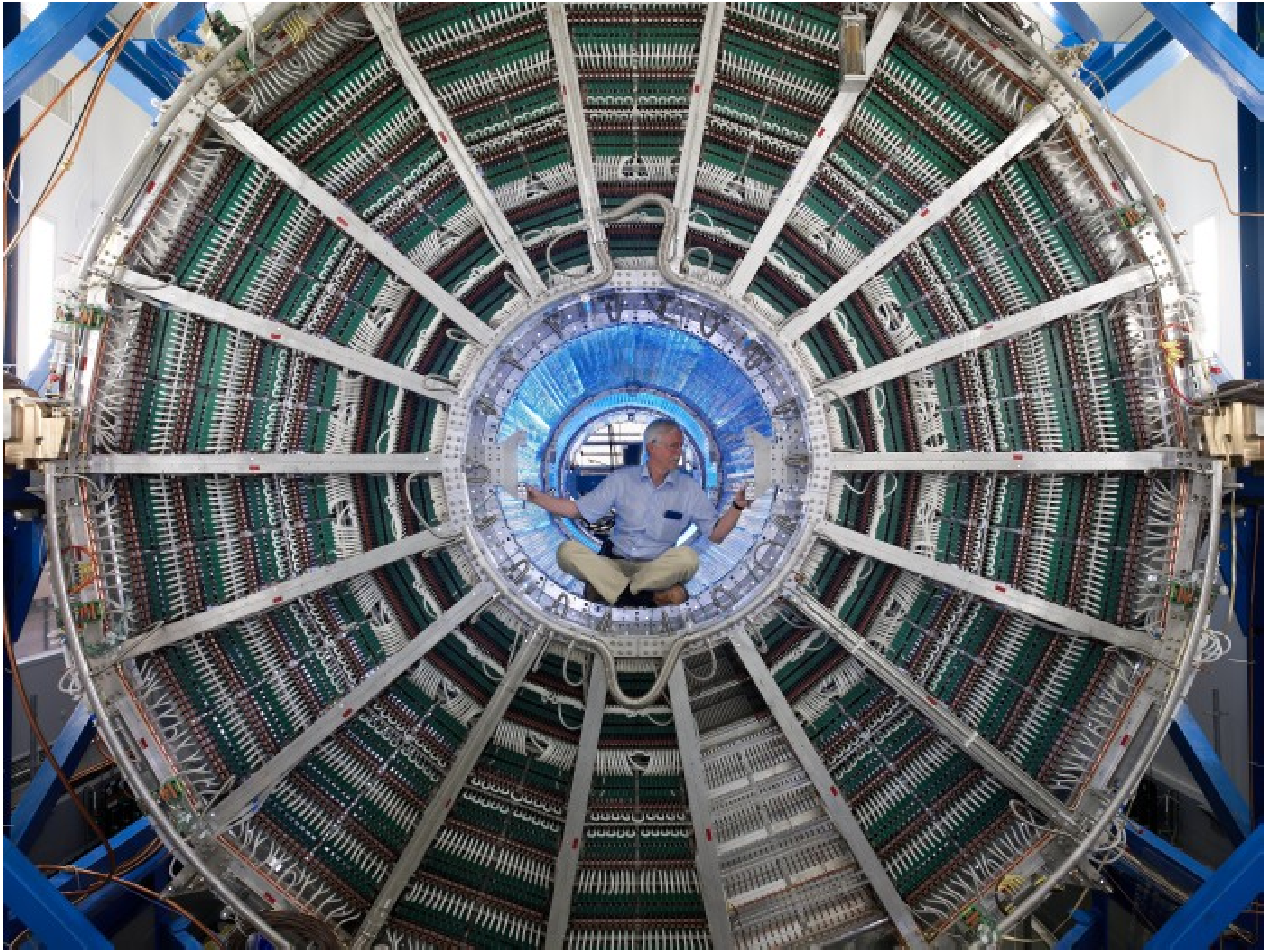




- Very high spatial resolution
  - Locates the collision vertex and secondary vertices from long lived particles like decaying heavy quarks

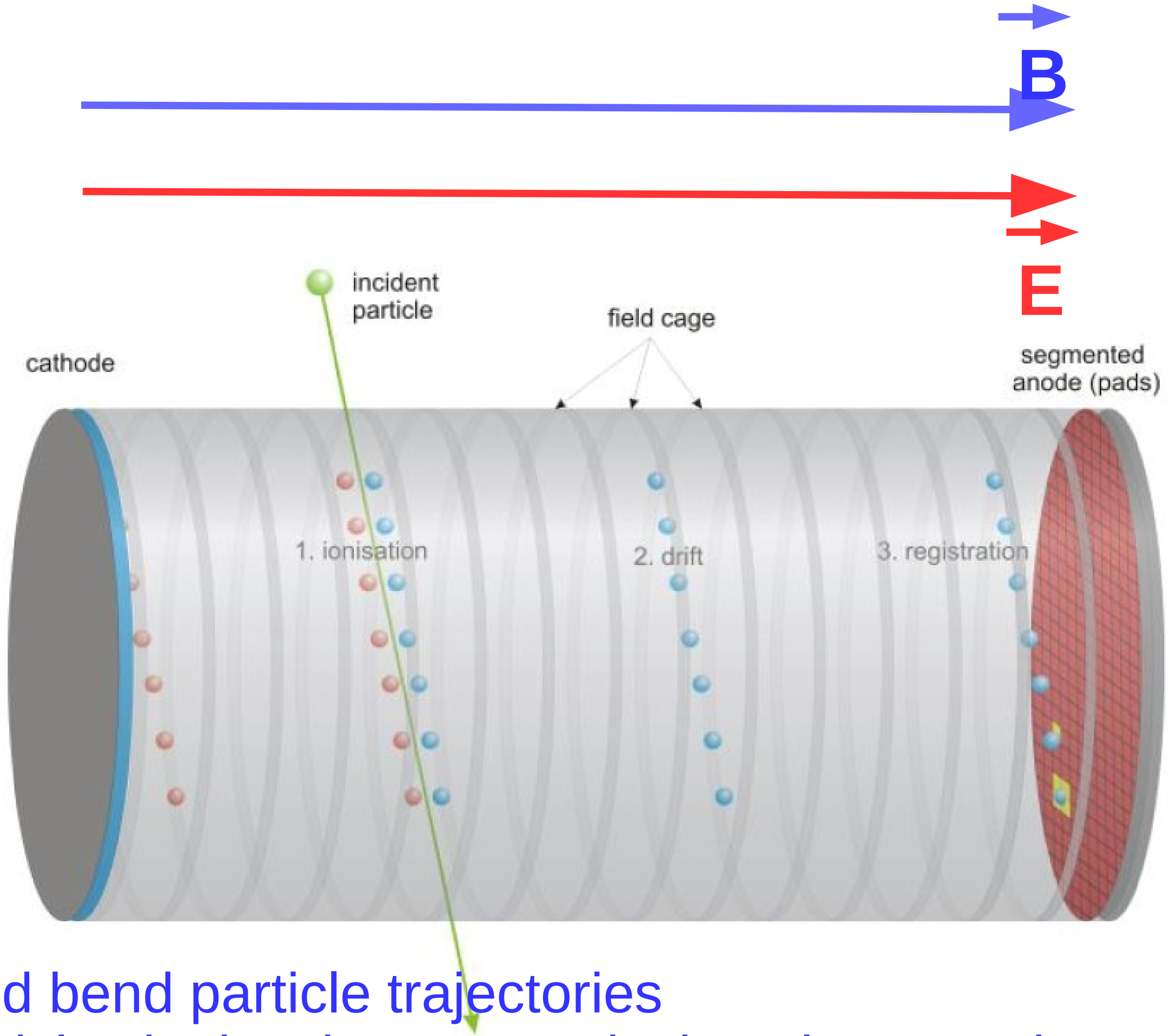
- It also performs particle identification via specific energy loss in the detector active area

The Time Projection Chamber (TPC)



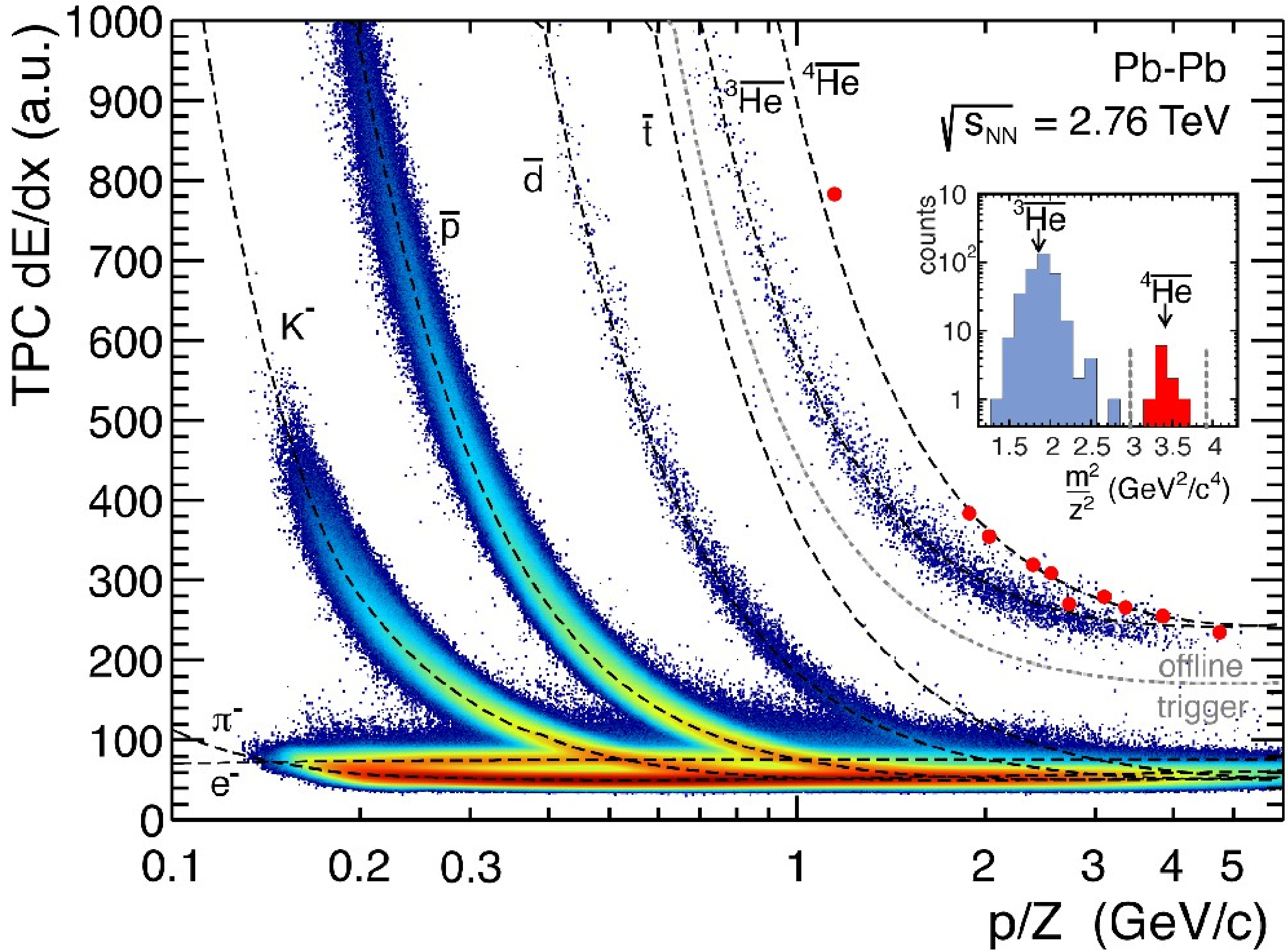
- TPC is the main ALICE detector
- It is the largest detector of its kind in the world
- 500 Mega-voxel 3D digital camera -> takes ca. 2000 pictures per second

TPC working principle



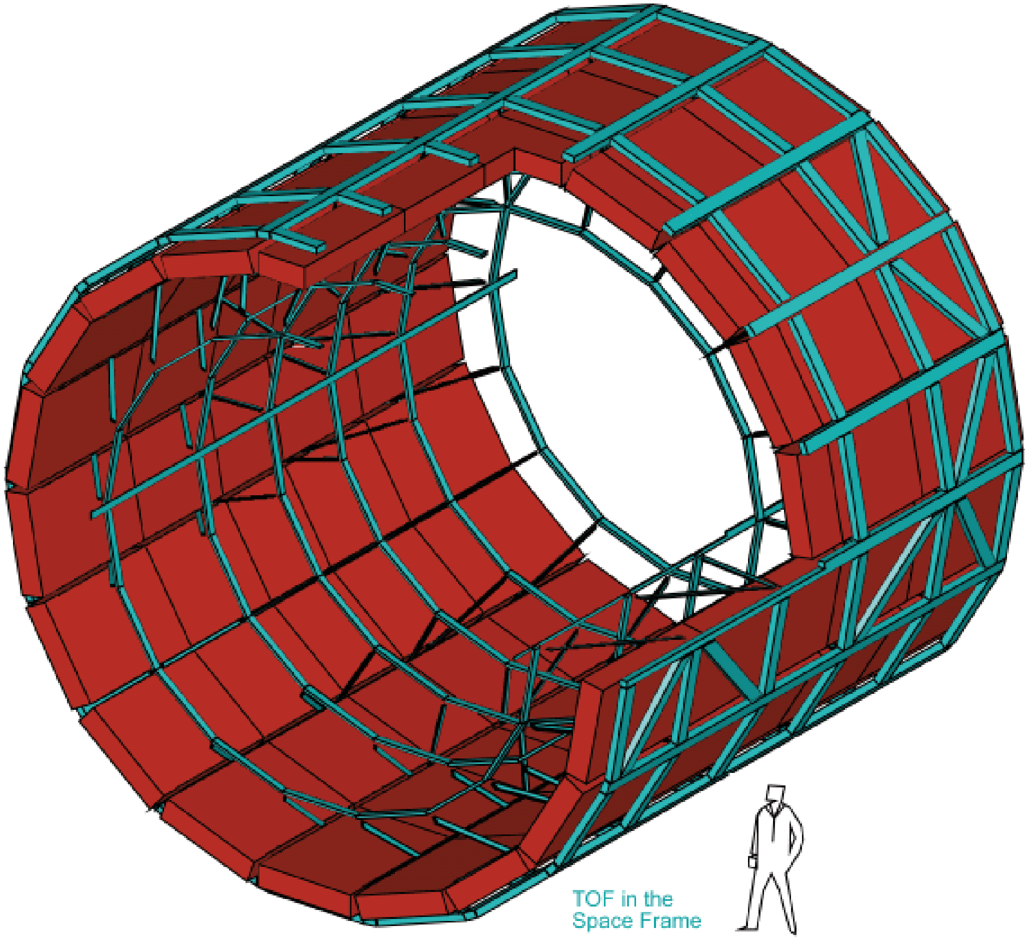
- Magnetic field bend particle trajectories
- Charged particles ionize the gas producing electron – ion pairs
- Electrons drift uniformly towards an anode and are recorded as clusters
- Position measurement : $d = v_{drift} * \Delta t$
- Momentum measurement: $p_T = q*B*r$

Particle identification with the TPC



- Tracks are identified using their specific energy loss in the TPC gas volume
- Highest mass anti-nuclei observed until now: anti-^{4}He

The Time-of-Flight detector (TOF)



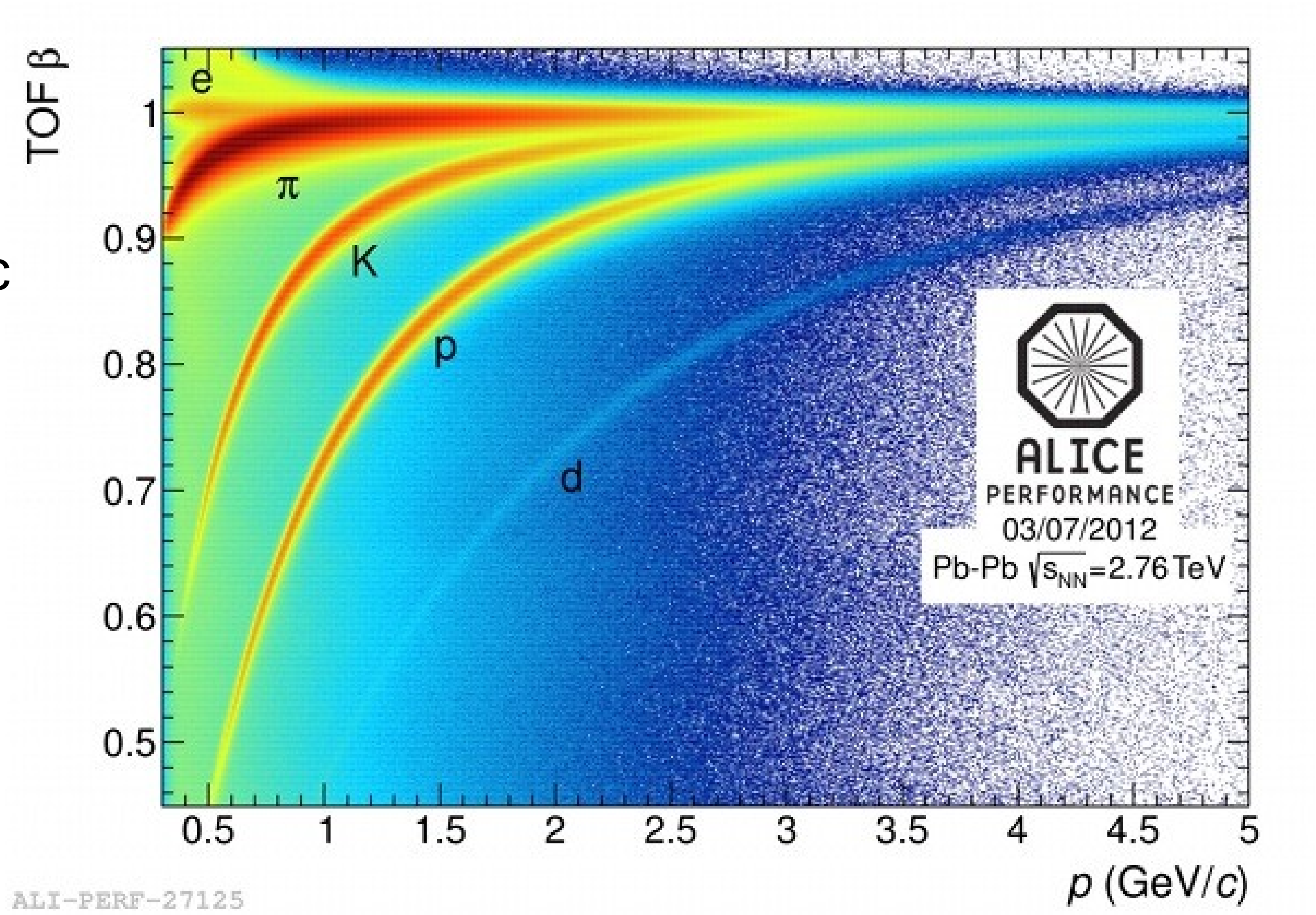
$v = L/\Delta t$

$p = m * v$

- Measures the time of flight between the collision start and particle arrival at the detector
- In conjunction with the momentum measurement from tracking -> particle identification
- Time resolution: 10^{-10} s

Particle identification using TOF

$\beta = v/c$



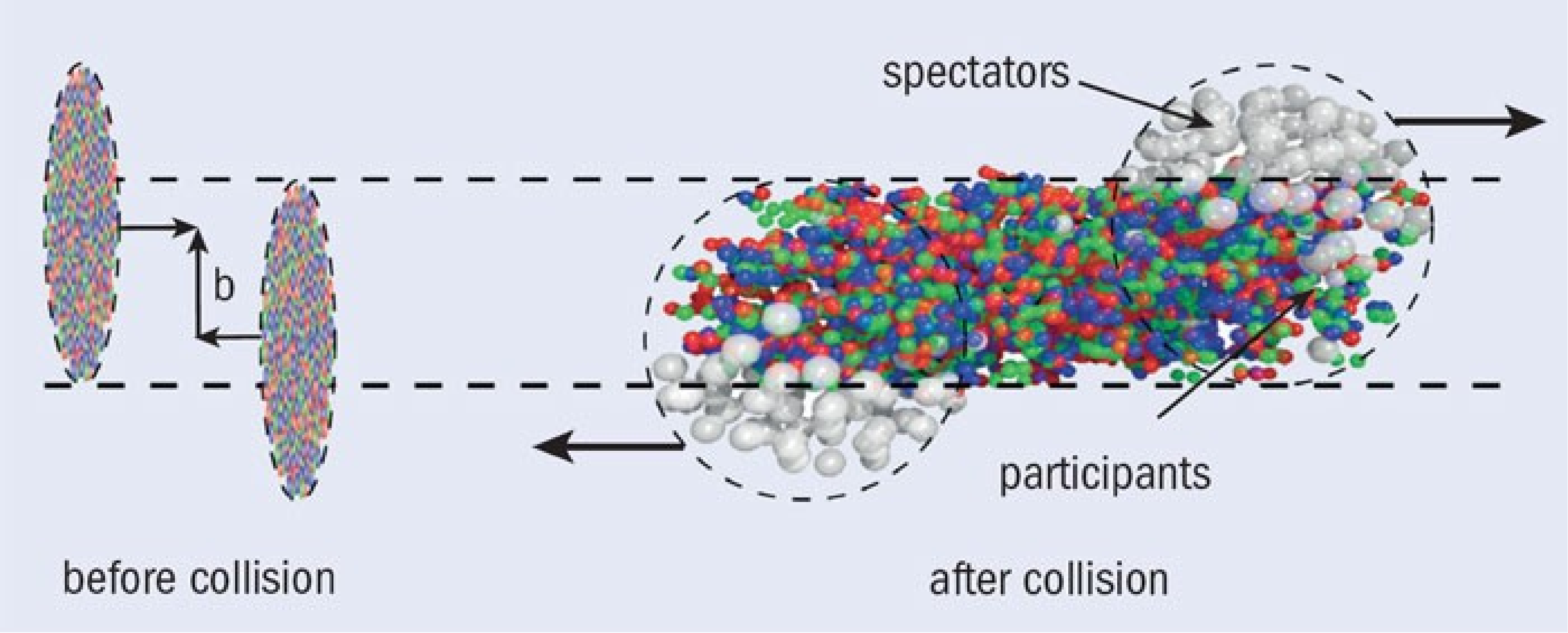
- Extends the particle identification of the TPC to higher momentum

Other detectors

- ALICE is using a wide range of detector technologies covering a large portion of the available kinematics
- Some of the not mentioned detectors are:
  - Transition Radiation Detector (TRD): electron identification
  - Electromagnetic Calorimeter (EMCAL): electrons and photons
  - Photon Spectrometer (PHOS): electrons and photons
  - Zero Degree Calorimeter (ZDC): spectator neutrons and protons
  - Muon Spectrometer (MUON): muon reconstruction at forward rapidity
  - VZERO, TZERO: trigger detectors
  - Cerenkov radiation detector (HMPID): hadron identification at high momentum
  - ...

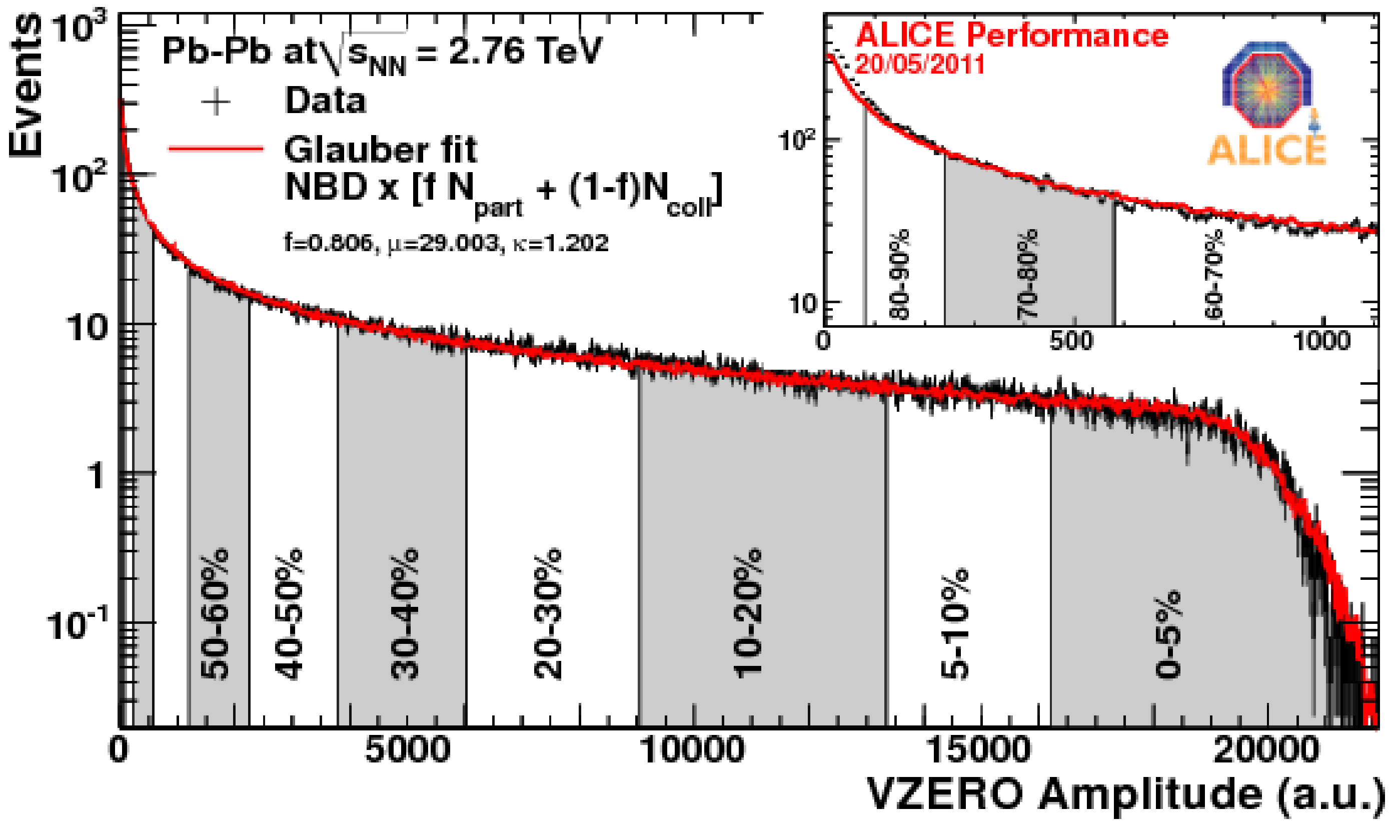
Physics results

What are the "control parameters" ?



- **Energy** of the collision (per nucleon pair $\sqrt{s_{NN}}$)
- **Impact parameter or centrality** of the collision
  - number of "participating" nucleons, N_{part}
- Number of **binary nucleon-nucleon collisions** (N_{coll})

What are the “control parameters” ?



- Experimentally, the impact parameter of a collision cannot be measured
- Assumptions need to be used
  - The most central collision have the highest produced multiplicity
  - Centrality usually expressed in percentage of the geometric cross-section:
    - 0-10% are the most central 10% of the collisions
    - 90-100% are the most peripheral 10% of the collisions

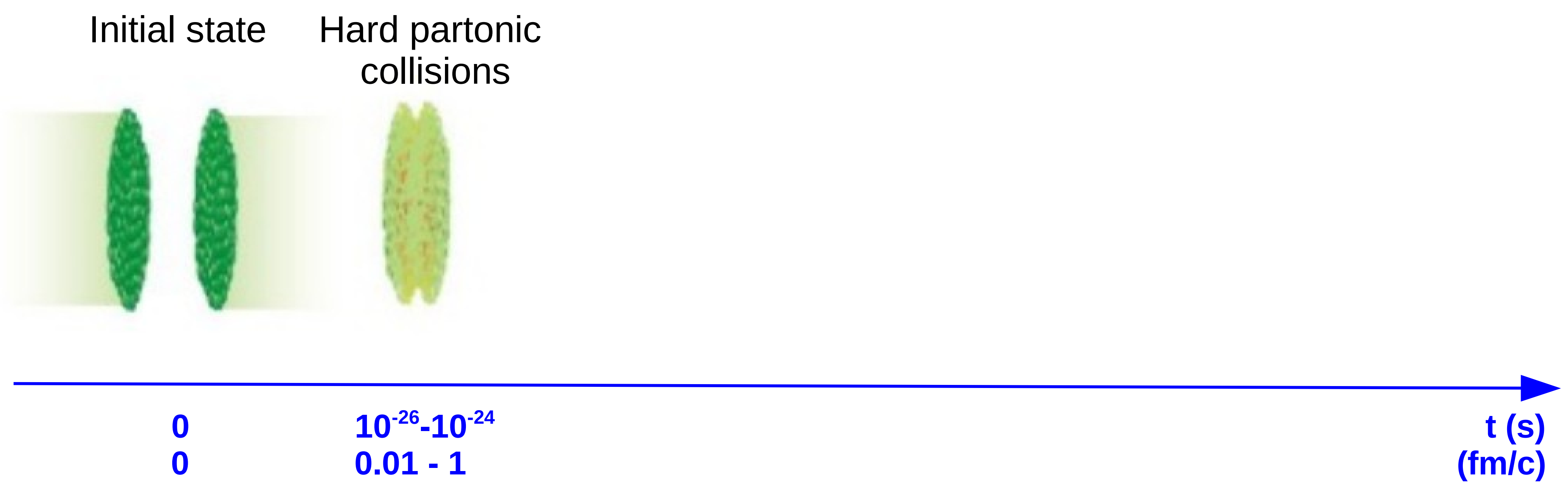
Stages of a high-energy nucleus-nucleus collision

Initial state

0 | t (s)
0 | (fm/c)

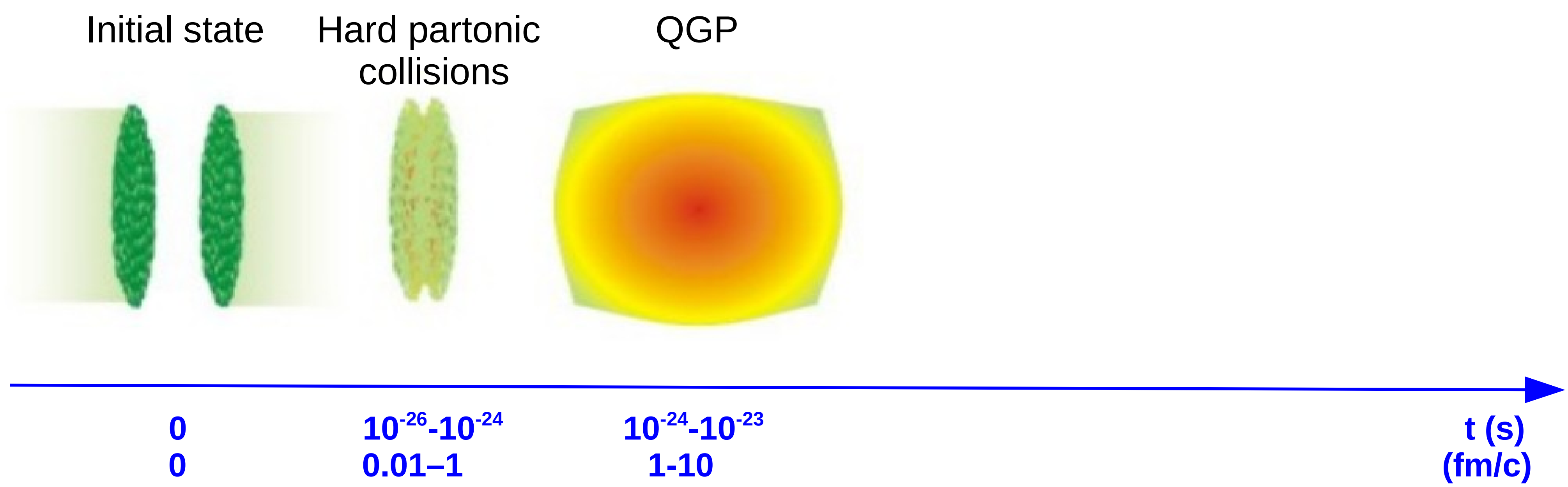
- Highly Lorentz contracted nuclei (2 pancakes)
- Initial state extremely important, interesting in itself:
  - Color Glass Condensate
  - Gluon shadowing (modification of the Parton Distribution Functions in nuclei)

Stages of a high-energy nucleus-nucleus collision



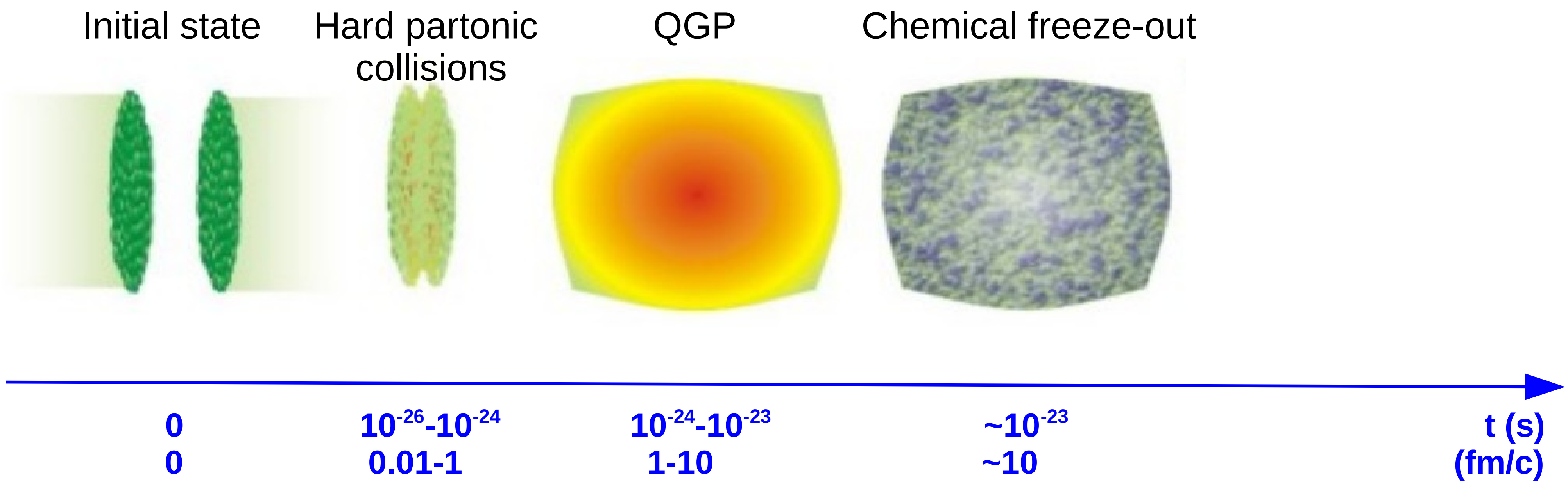
- Initial highly energetic collisions take place
- Creates a volume with extremely high density of gluons and quark pairs
- Strong re-interactions leads to a rapid creation of an equilibrated / thermalized medium → Quark Gluon Plasma

Stages of a high-energy nucleus-nucleus collision



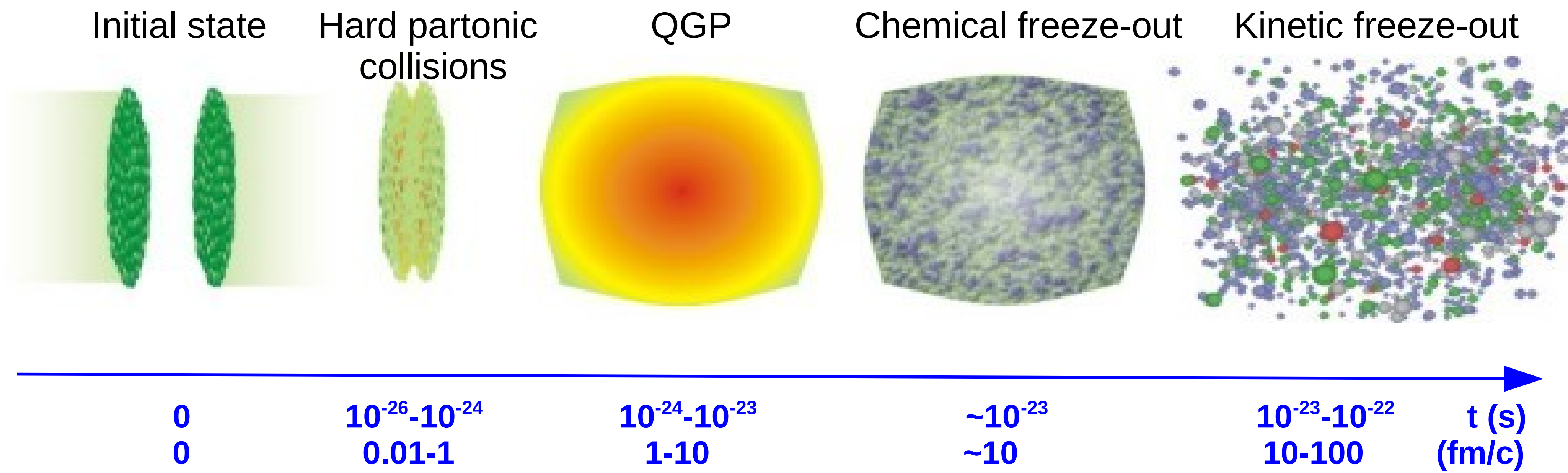
- Deconfined Quark-Gluon Plasma (QGP) phase, our main object of study
- QGP survives for about 10 fm/c ($3*10^{-23}$ s) before decaying back into bound hadrons

Stages of a high-energy nucleus-nucleus collision



- Hadronization (chemical freezeout): quarks and gluons become bound into hadrons
- All inelastic collisions stop and yields of the various particle species are frozen

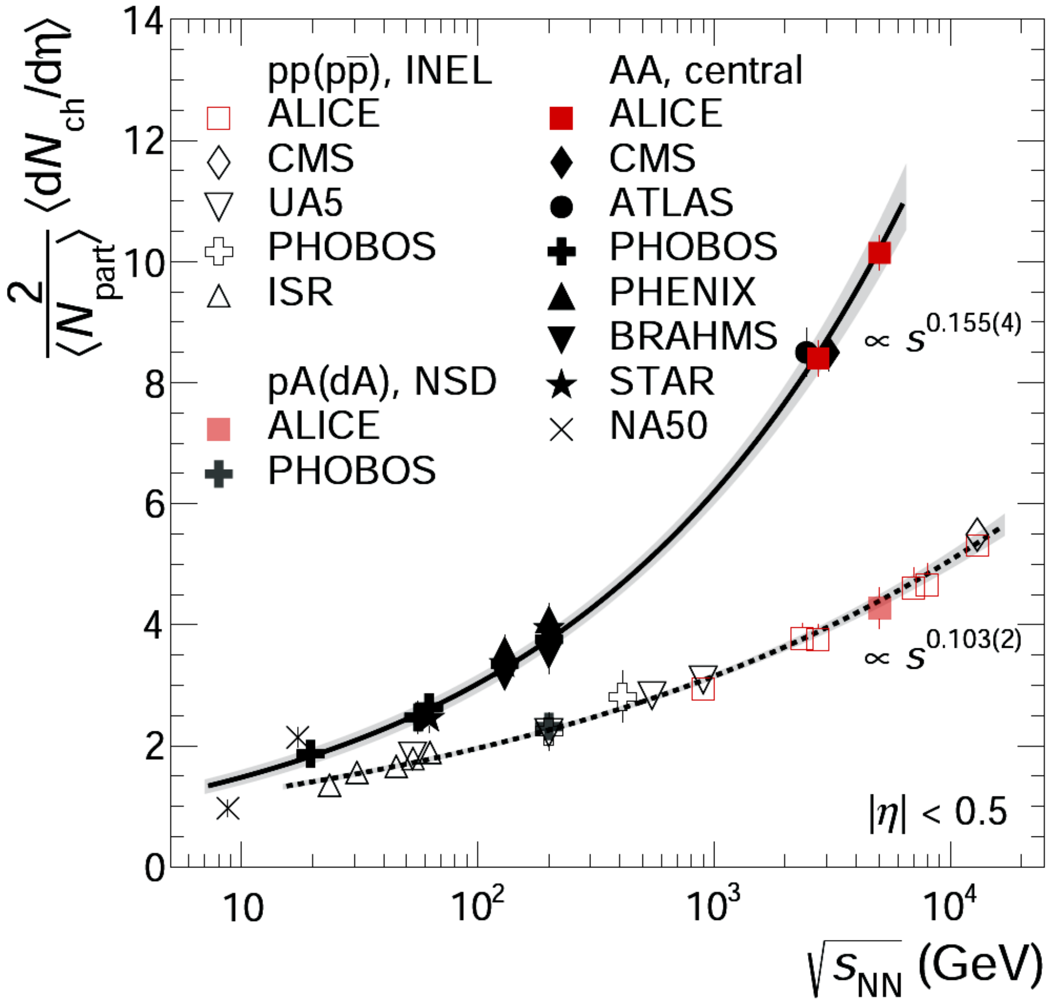
Stages of a high-energy nucleus-nucleus collision



- Kinetic freeze-out:
  - Elastic collisions also stop
  - Kinetic distributions are frozen
  - Free streaming of particles towards our detectors
- We measure only at the latest stages but we want to understand the hard partonic and the QGP stages... extremely challenging!

Bulk particle production

ALICE Collaboration, arXiv:1512.06104

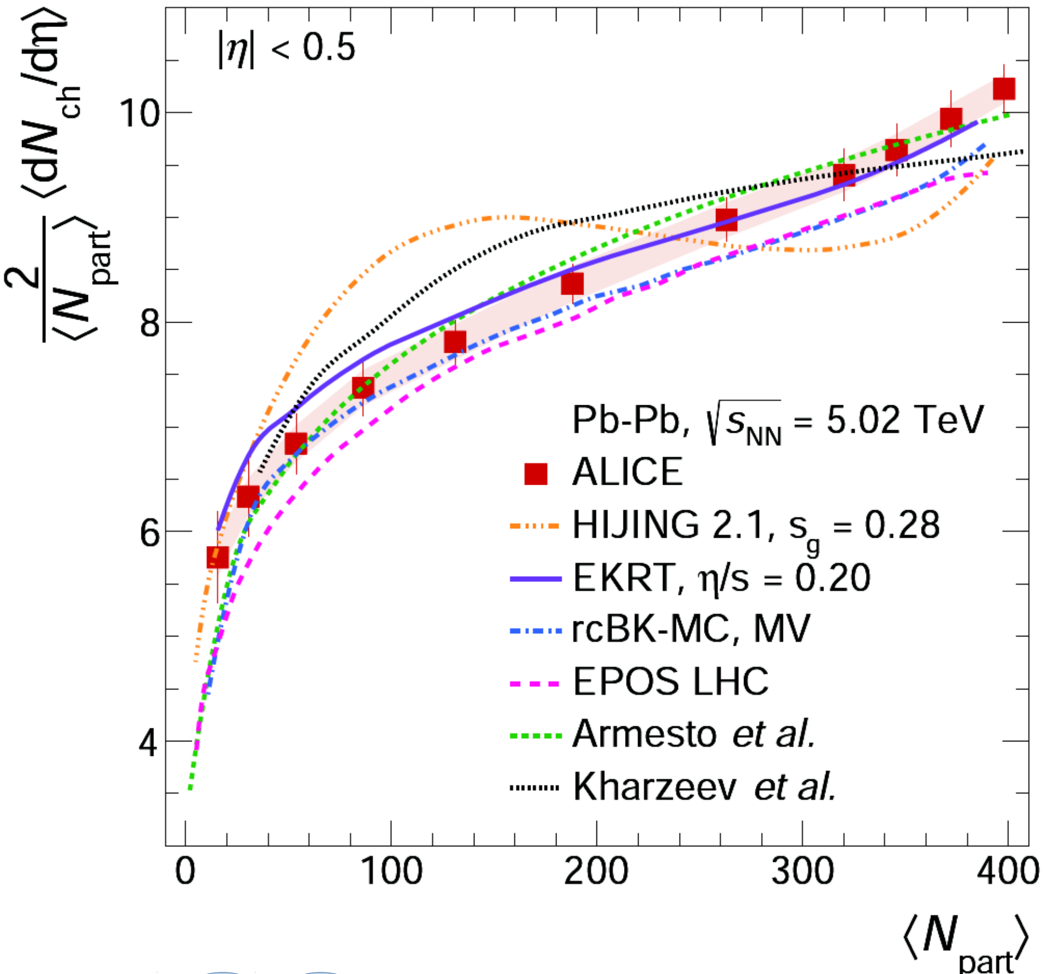


- Yield per participant pair is larger in nuclear collisions than in proton-proton collisions:
  - large entropy production
- The difference between nuclear and pp collisions also grows rapidly with energy

Charged particle production in heavy-ion collisions vs proton-proton collisions

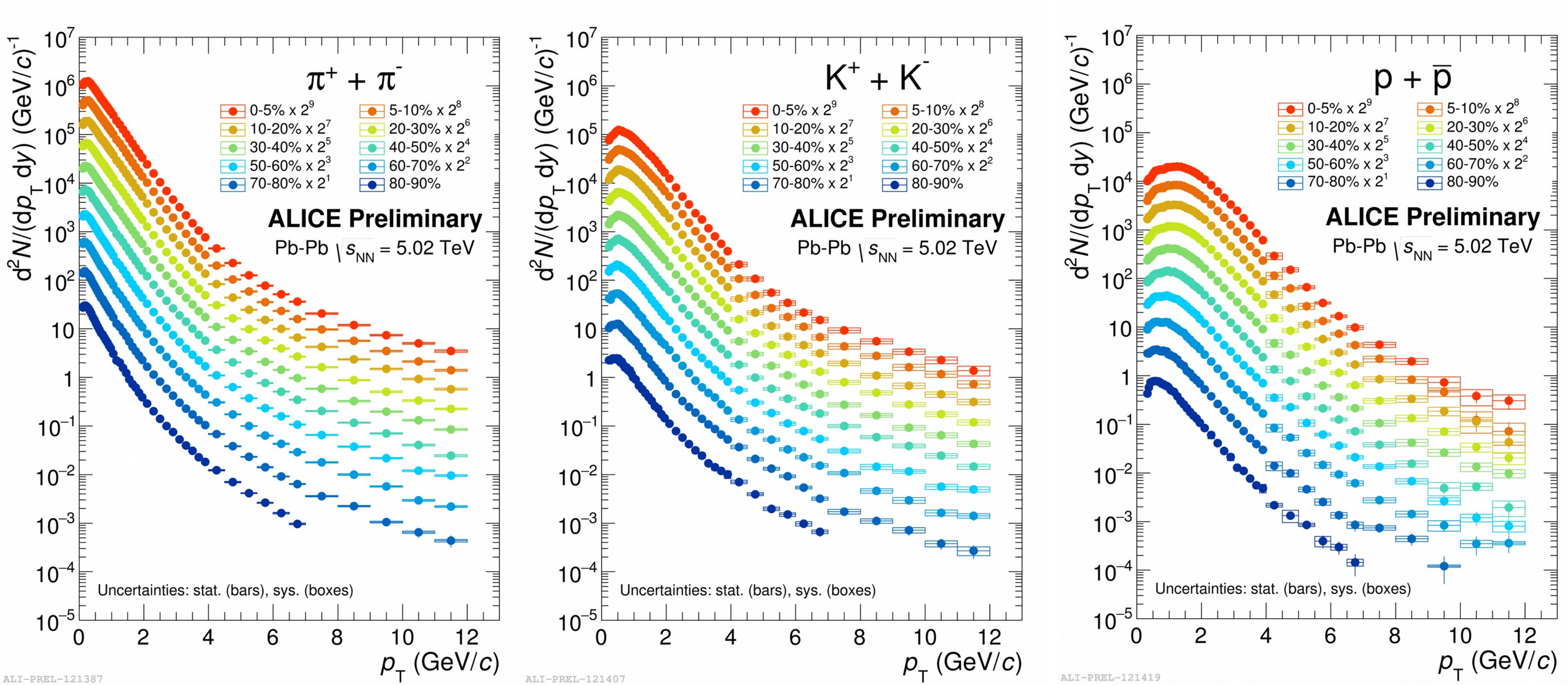
Bulk particle production

ALICE Collaboration, arXiv:1512.06104



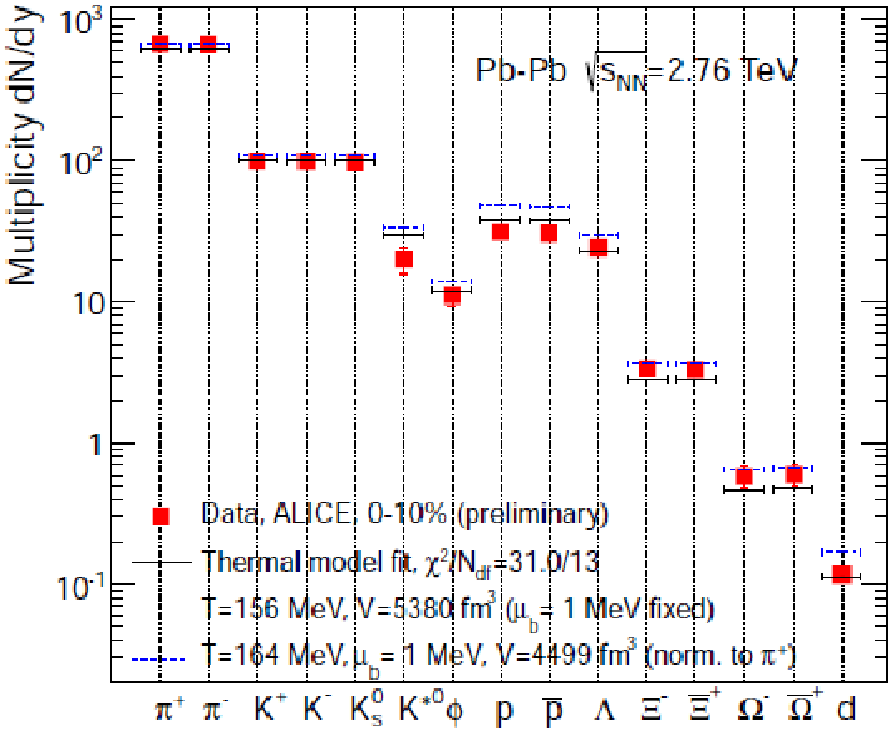
- Yield per participant pair also grows towards more central collisions
- These results allow to quantify the initial energy density and set constraints on initial state models

Identified hadron yields



- Particle identification and tracking over a wide momentum range
- ALICE measures many other particle species, e.g. γ, e, μ, π^0, η, K^0, ρ, ω, φ, ψ, Υ, Λ, Σ, Ξ, Ω, Z^0, W, d, t, ^{3}He, ^{4}He

Chemical freeze-out: hadron yields

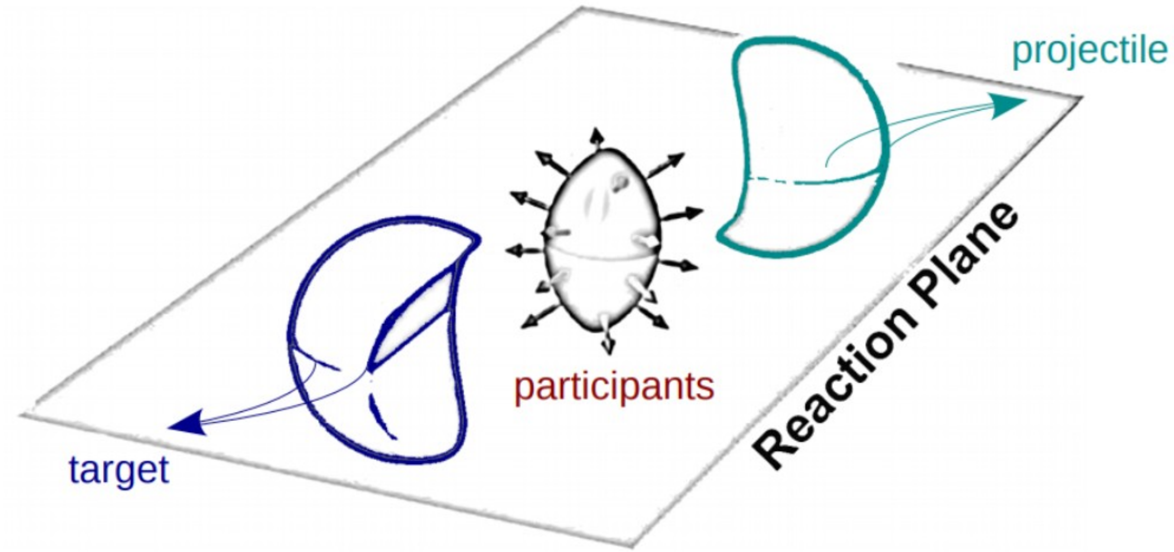


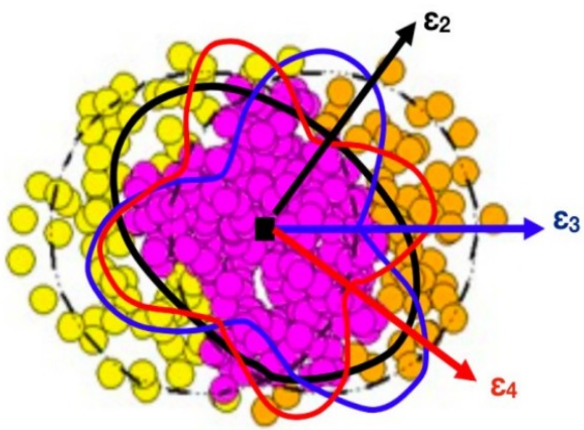
$$n_i = N_i/V = -\frac{T}{V}\frac{\partial \ln Z_i}{\partial \mu} = \frac{g_i}{2\pi^2}\int_0^\infty \frac{p^2 \mathrm{d}p}{\exp[(E_i-\mu_i)/T]\pm 1}$$

- If the QGP medium is thermalized, particle yields can be calculated using
  - Bose-Einstein for bosons and
  - Fermi-Dirac for fermions distributions
- Only 3 parameters: temperature T, chemical potential μ and volume V
- The observed hadron abundancies are in very good agreement with a thermally equilibrated system

T_{chem}=155-165 MeV and μ_B~0

Anisotropic flow (v_2). What is that?



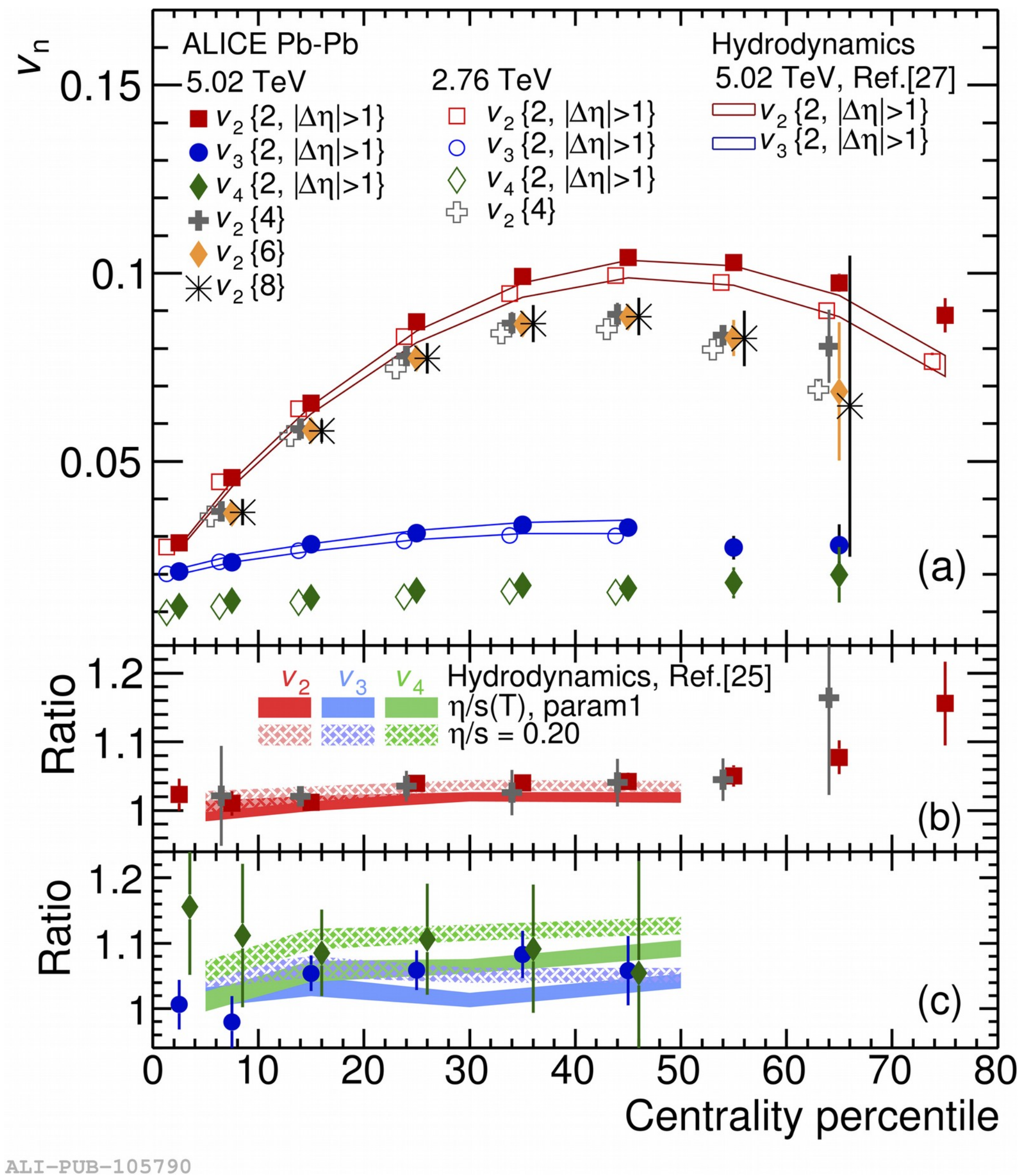


Decomposed transverse projection of participant region in Fourier series

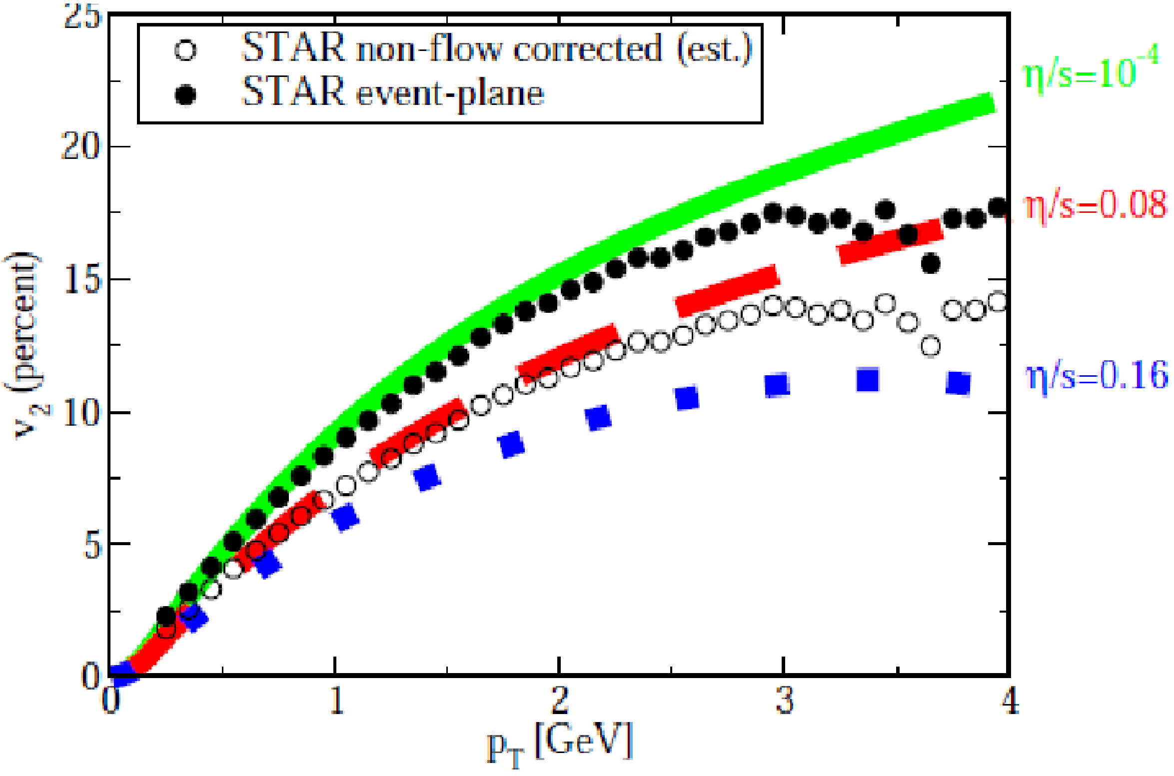
Azimuthal anisotropy of particle production: probe of QGP macroscopic properties (e.g. equation of state, viscosity)

Anisotropic flow in heavy-ion collisions with ALICE

- Fourier coefficients measured for Pb-Pb collisions at the top LHC energy
- Strong variation with the collision impact parameter
  - Coefficients reflect the asymmetry of the initial state



Anisotropic flow in heavy-ion collisions



Luzum & Romatschke, arXiv:0804.4015

- Shear viscosity much smaller than for any known substance
- Lower bound conjectured from AdS/CFT: $\eta/s = 1/4\pi \approx 0.08$

Kovtun, Son, Starinets hep-th/0405231

Heavy quarkonia

- Bound states of heavy quark pairs: $c\bar{c}$ and $b\bar{b}$
- Typical masses:

  > 2.9 GeV/c^2 for charmonium (${m_c}$ ~ 1.27 GeV/c^2)

  > 9.3 GeV/c^2 for bottomonium (${m_b}$ ~ 4.6 GeV/c^2)
- Non-relativistic quark – antiquark system !

Spectroscopy of quarkonia (simple minded model)

- Lets assume a quark – antiquark pair
- Potential seen by the two quarks will have two components:
  - a Coulomb term (quark electric charge) : $V_{Coulomb}(\boldsymbol{r})=\frac{q}{4\pi r}$
  - and a linear term (strong force): $V_{linear}(\boldsymbol{r})=k\,r$

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- The potential energy of the pair is then $V_{total} = (-q)\frac{q}{4\pi r} + kr$
- The Hamiltonian can be written as $H = \frac{\boldsymbol{p}^2}{2\mu} - \frac{\alpha_{eff}}{r} + kr$ $\quad \alpha_{eff} = q^2/4\pi$, $\mu = m_c/2$

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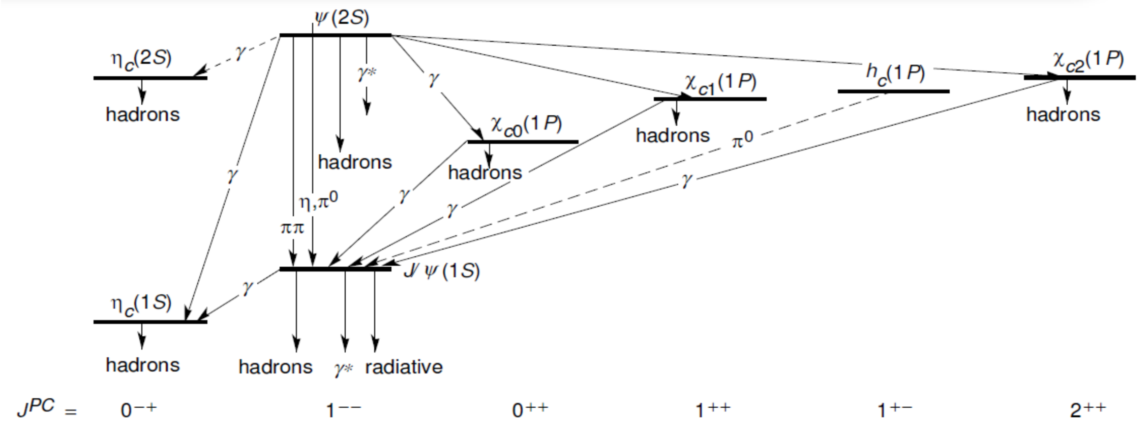
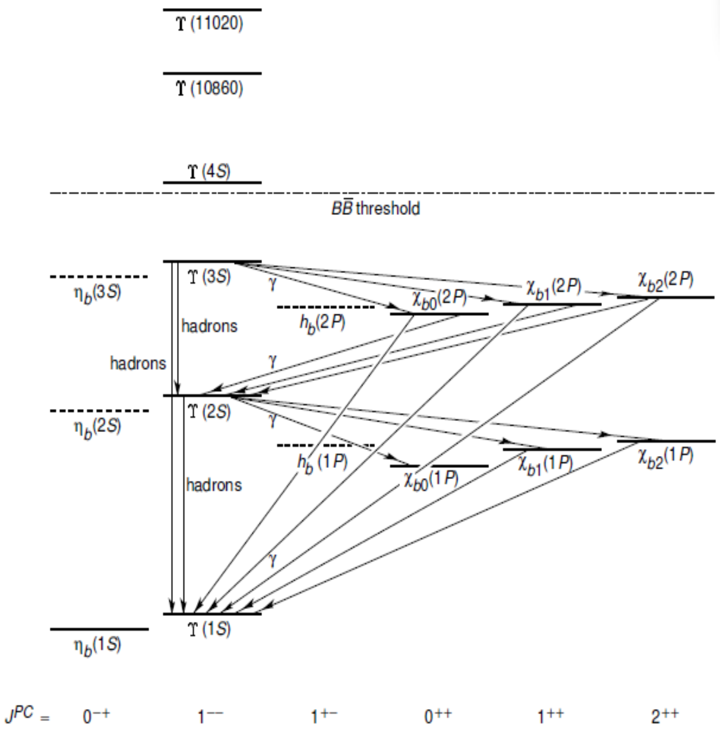
- Surprisingly good quantitative description of the heavy quarkonia spectroscopy can be obtained with such a simple Hamiltonian

Spectroscopy of quarkonia

- Rich spectroscopy, many observed states …





Data from CLEO, BELLE, BABAR, CDF

Spectroscopy of quarkonia

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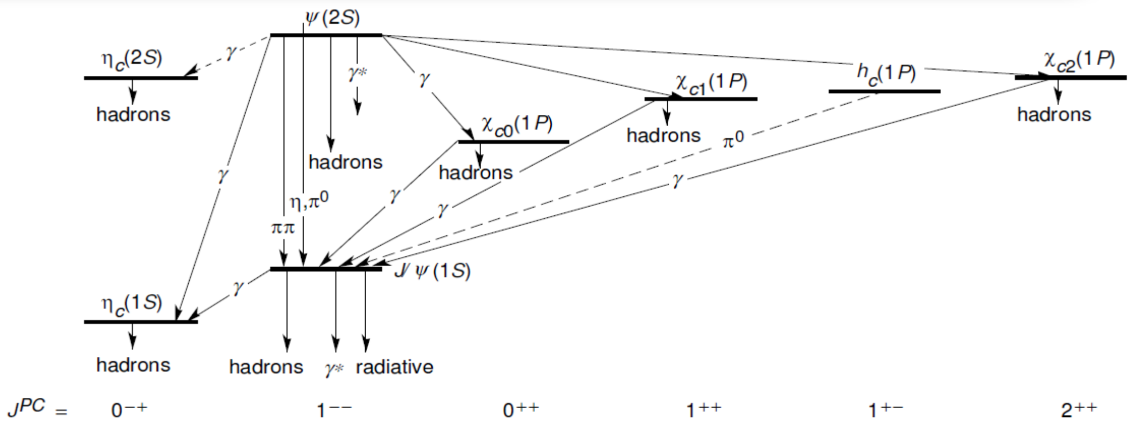
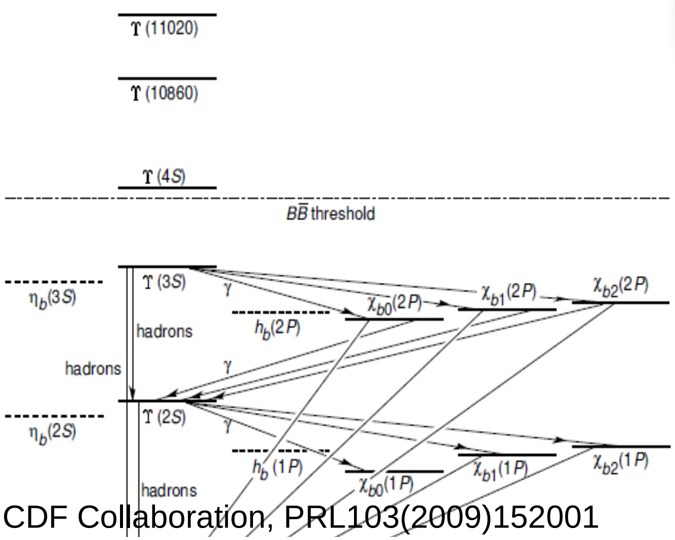
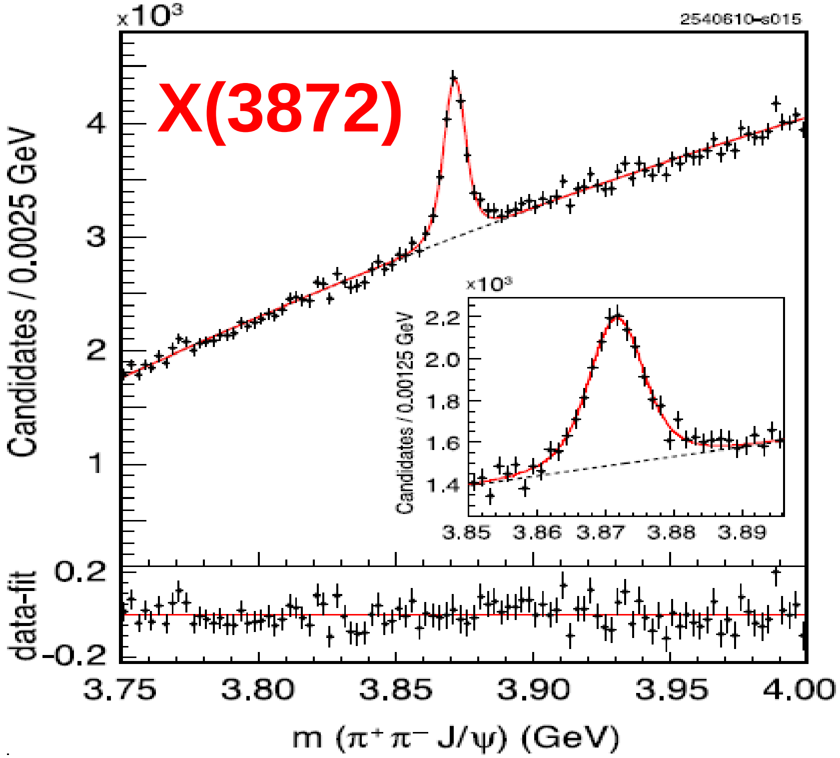




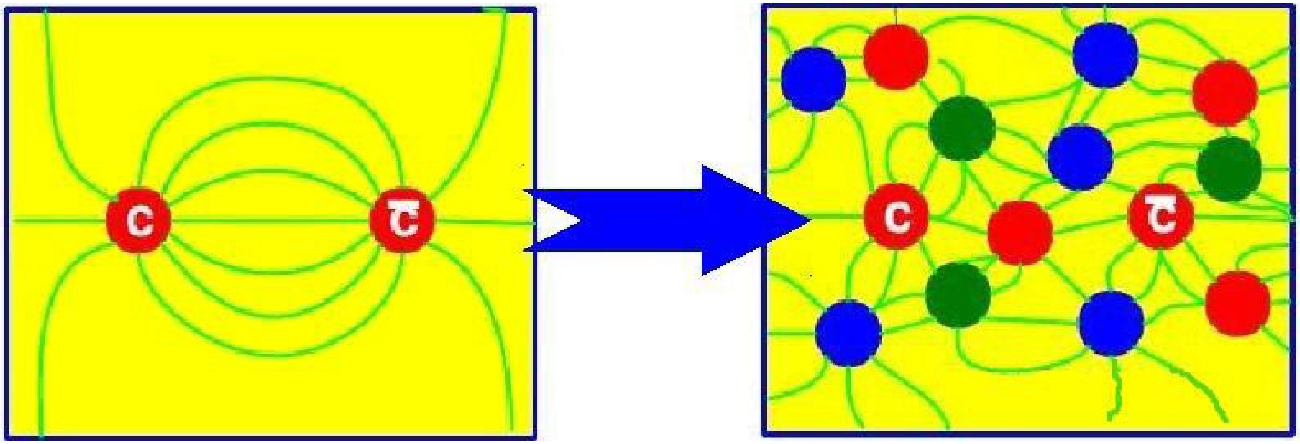
Data from CLEO, BELLE, BABAR, CDF

CDF Collaboration, PRL103(2009)152001



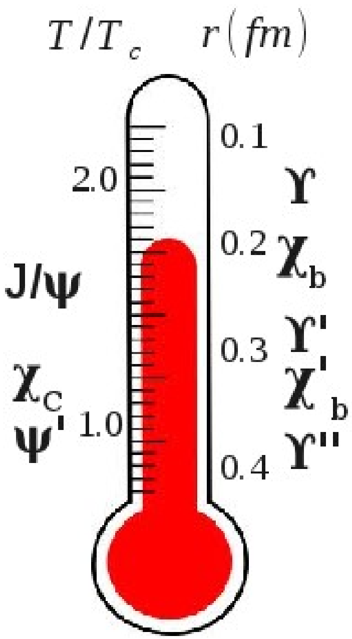
- … including some less conventional

Heavy quarkonia and the QGP



$$V_{total} = (-q)\frac{q}{4\pi r} + kr$$

- In a deconfined medium two main phenomena affects quarkonia:
  - String tension dissapears
  - Coulomb potential is screened by other charges (Debye-screening)
- Quarkonium states will be melted if the temperature of the QGP is high enough → **QGP thermometer**
- **Less bound states will be melted easier !**



Matsui and Satz, PLB 178 (1986) 416

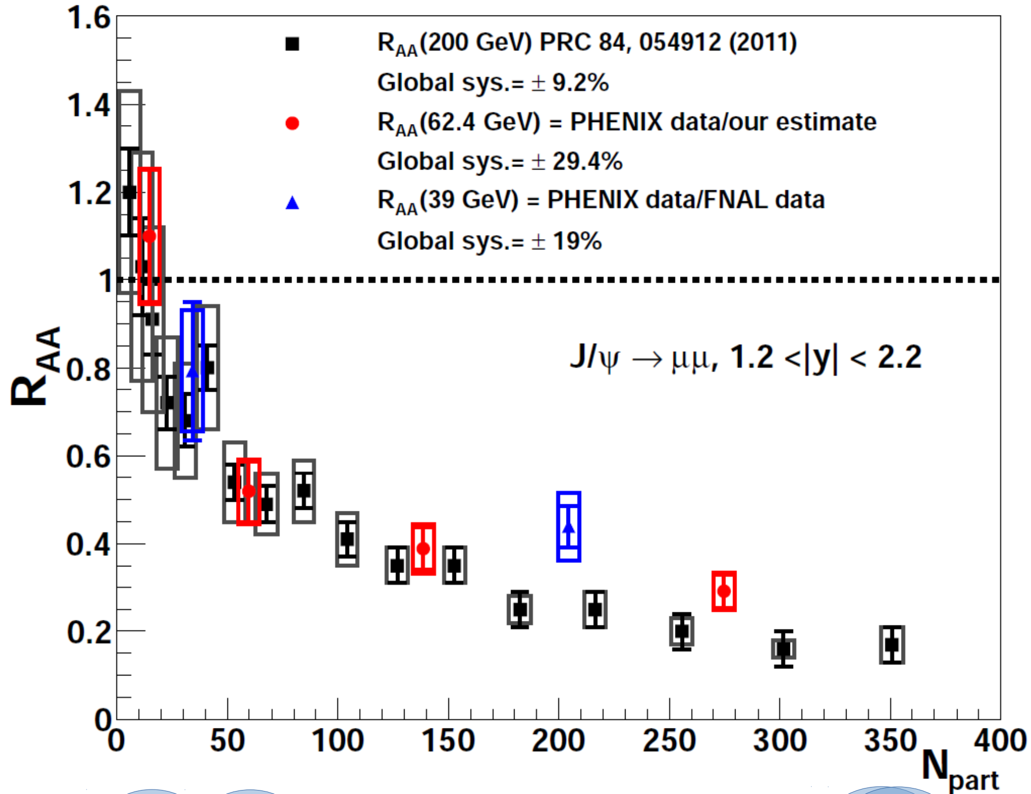
J/ψ suppression in Au-Au collisions at RHIC

- Au-Au collisions at 200 GeV
  - Roughly 20x less energy wrt LHC

- Strong suppression observed in central Au-Au collisions at RHIC energies

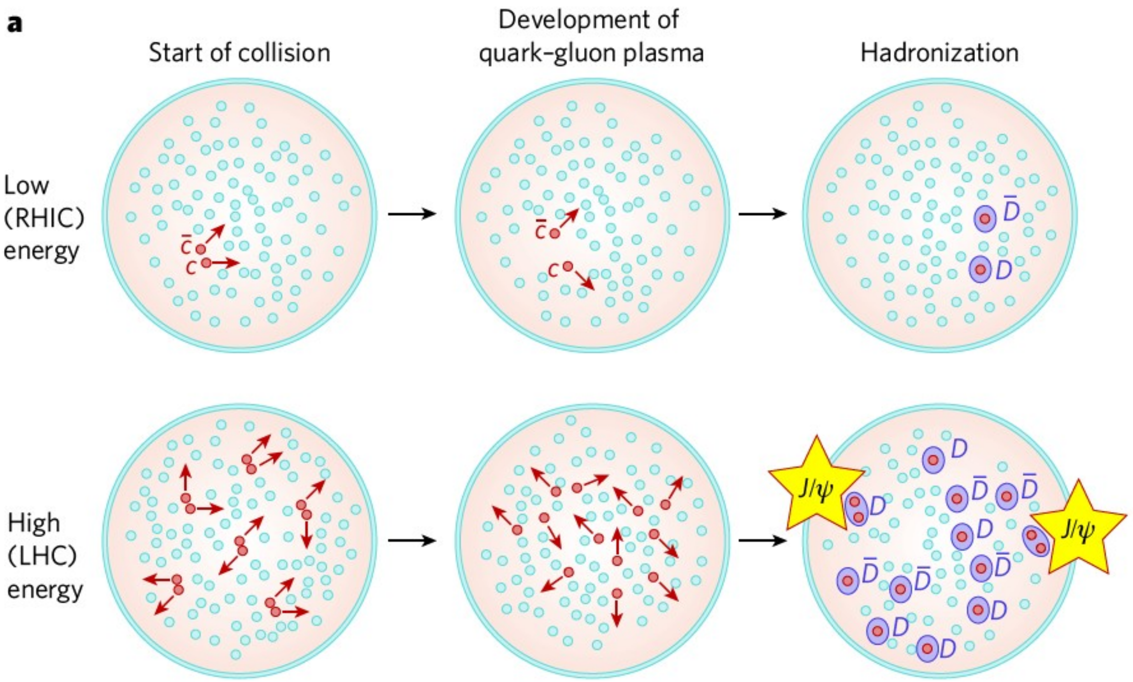
- Confirms the proposed idea of color screening in hot and dense deconfined nuclear matter

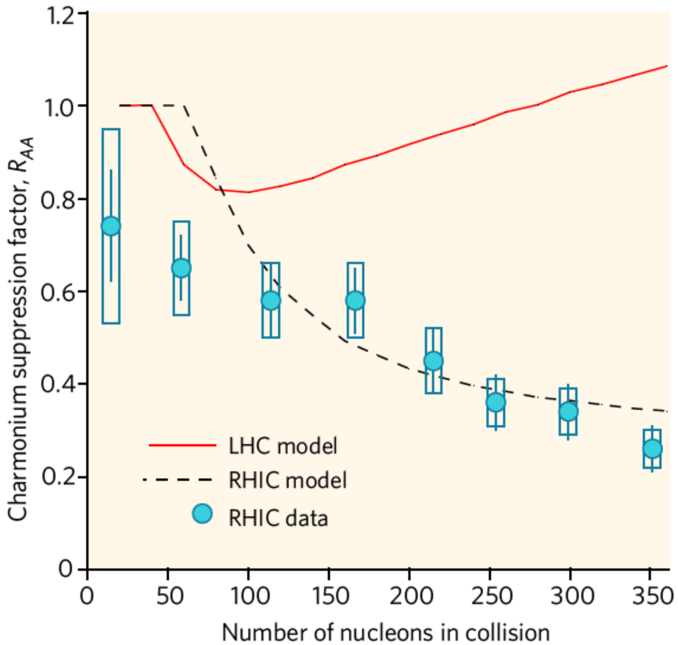
PHENIX arXiv:1208.2251



$$R_{AA} = \frac{1}{N_{coll}} \times \frac{Y_{AA}}{Y_{pp}}$$

Heavy quarkonium at the LHC (re-generation)





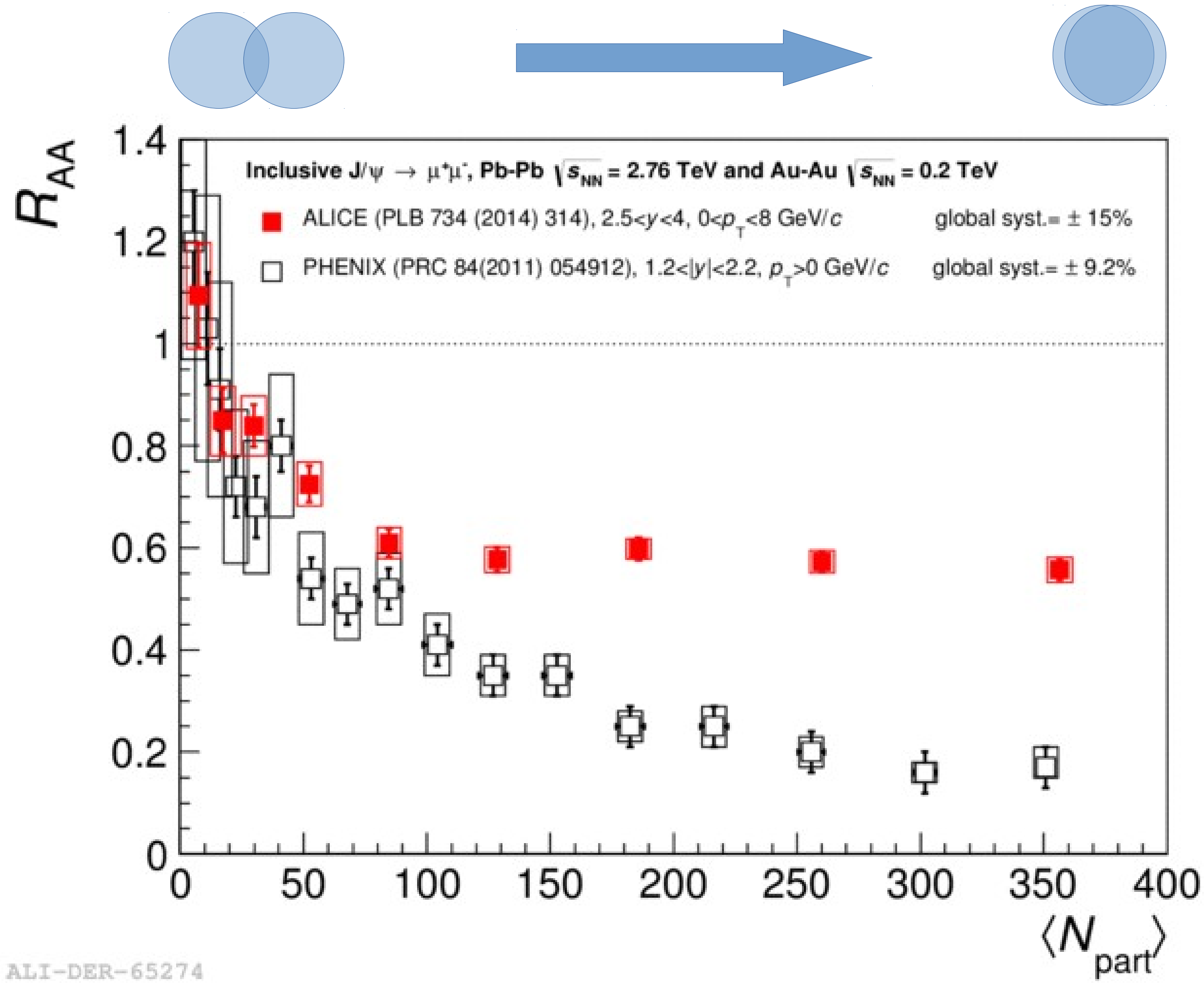
Nature 448 (2007) 302-309

- Many charm quark-pairs created in one single collision (~100)
- Possible to create charmonium states on a statistical basis when system temperature is low enough
  - enhancement of charmonium states at LHC

    Braun-Munzinger and Stachel, PLB 490 (2000) 196

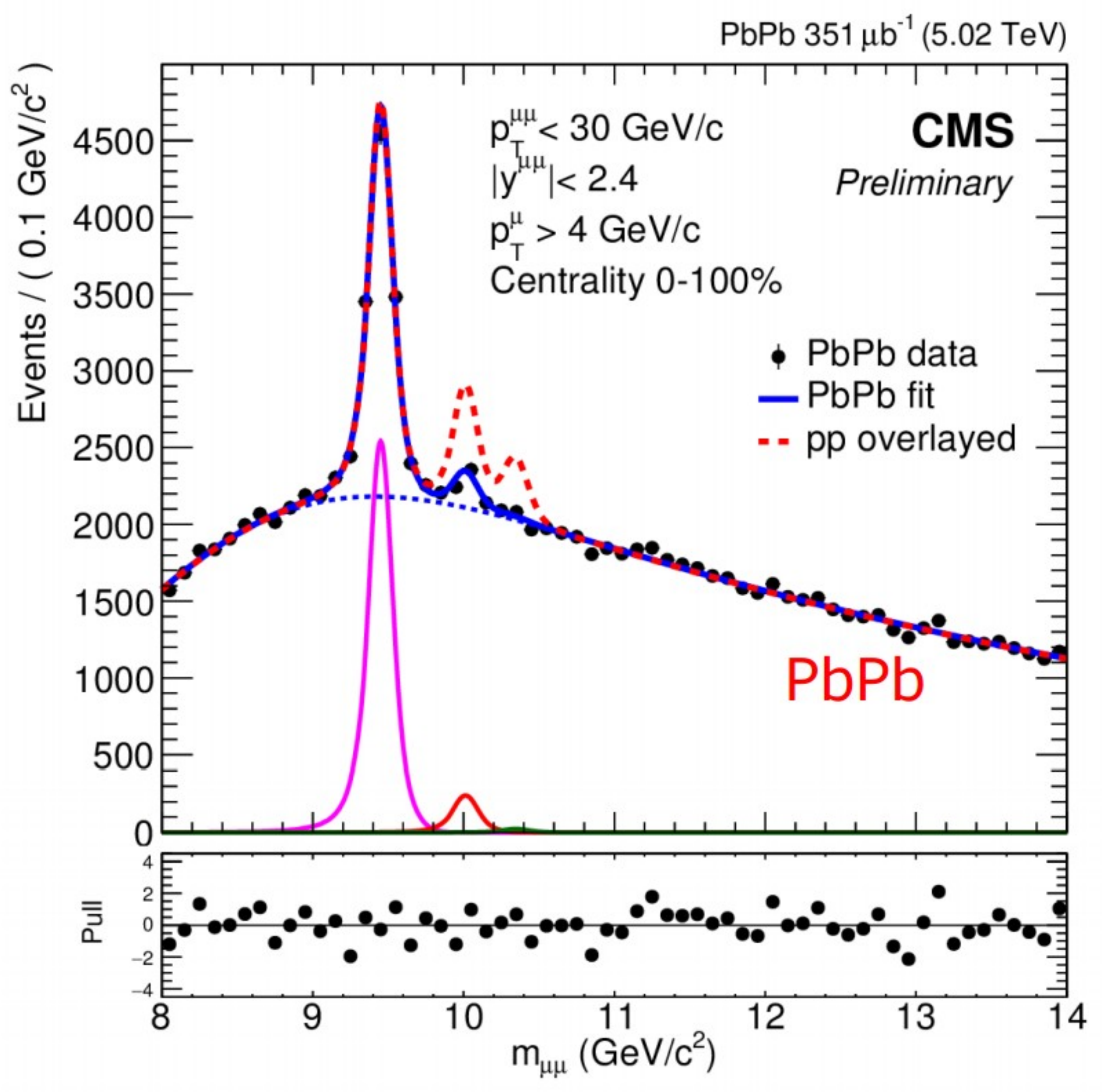
    Thews et al., PRC 63 (2001) 054905

J/ψ measurements with ALICE



- ALICE results show smaller suppression compared to lower energies (PHENIX) in central collisions
- Indication that regeneration plays an important role in the production of charmonium

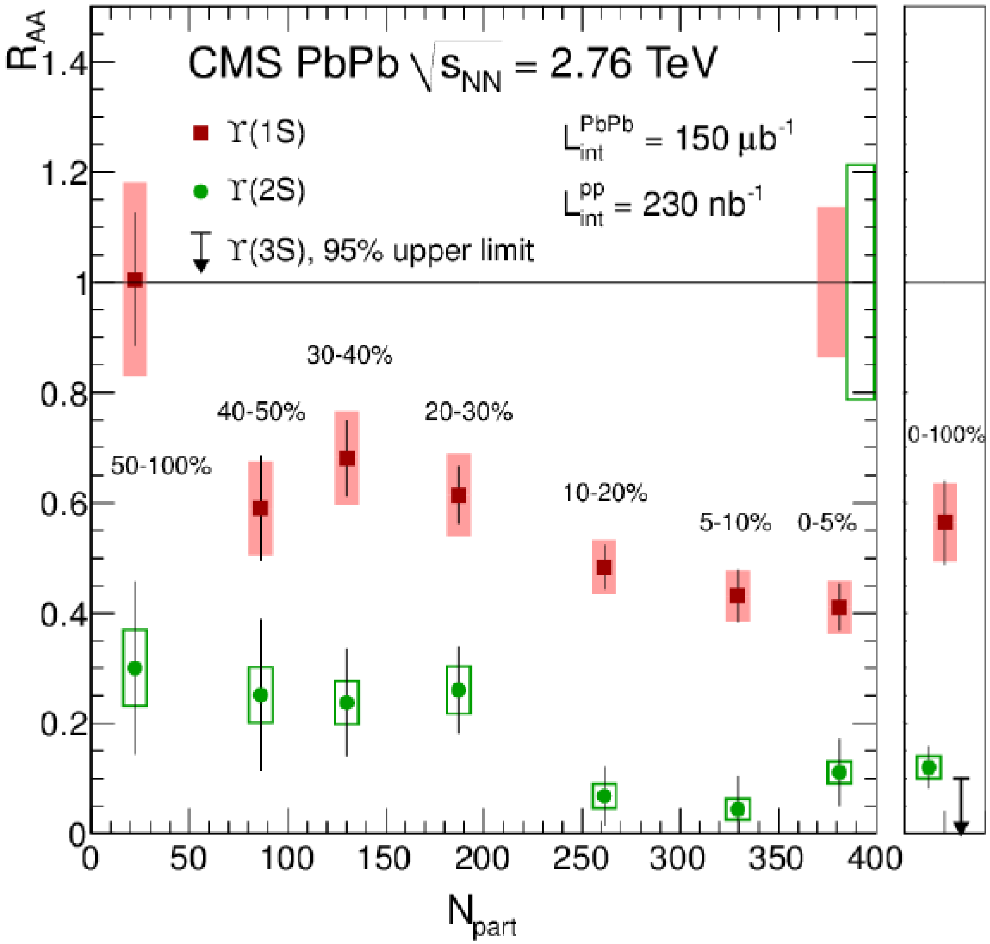
Bottomonium ($b\bar{b}$)



- Bottomonium states ($b\bar{b}$) provide a unique test of sequential melting
- Ordering of binding energies E(1S) > E(2S) > E(3S)

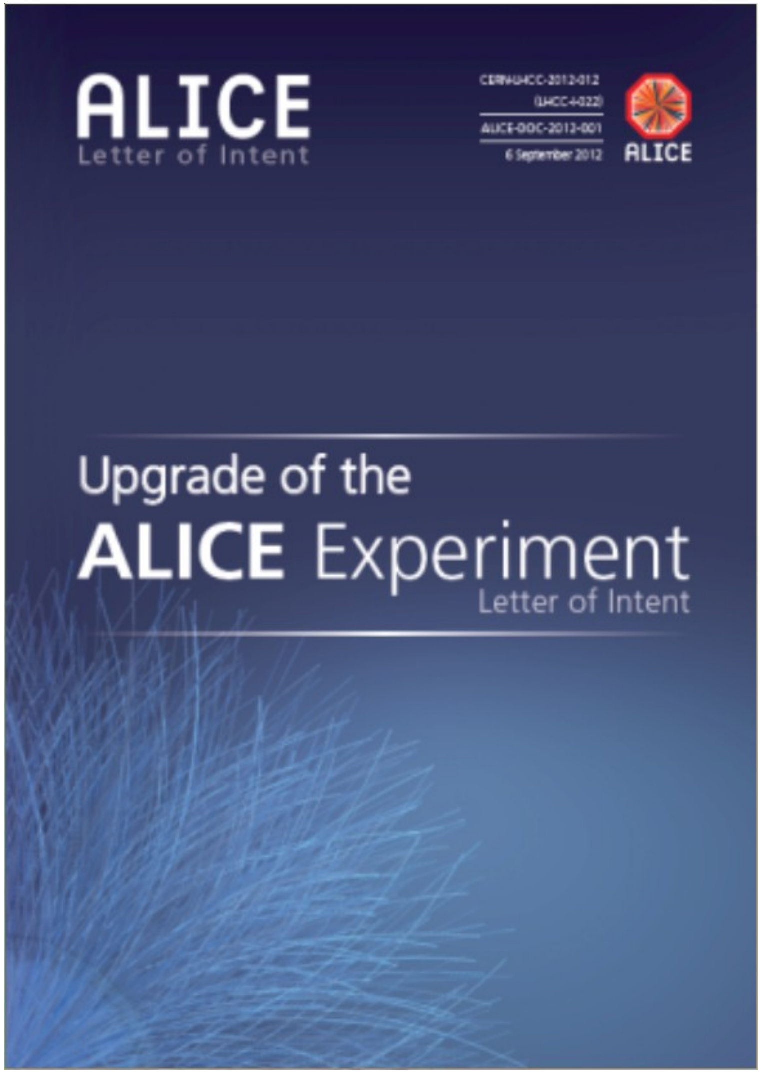
Inclusive Y production vs centrality

PRL109 (2012) 222301



- Hierarchy of the nuclear suppression : R_{AA}\{Y(1S)\} > R_{AA}\{Y(2S)\} > R_{AA}\{Y(3S)\}

ALICE Upgrade



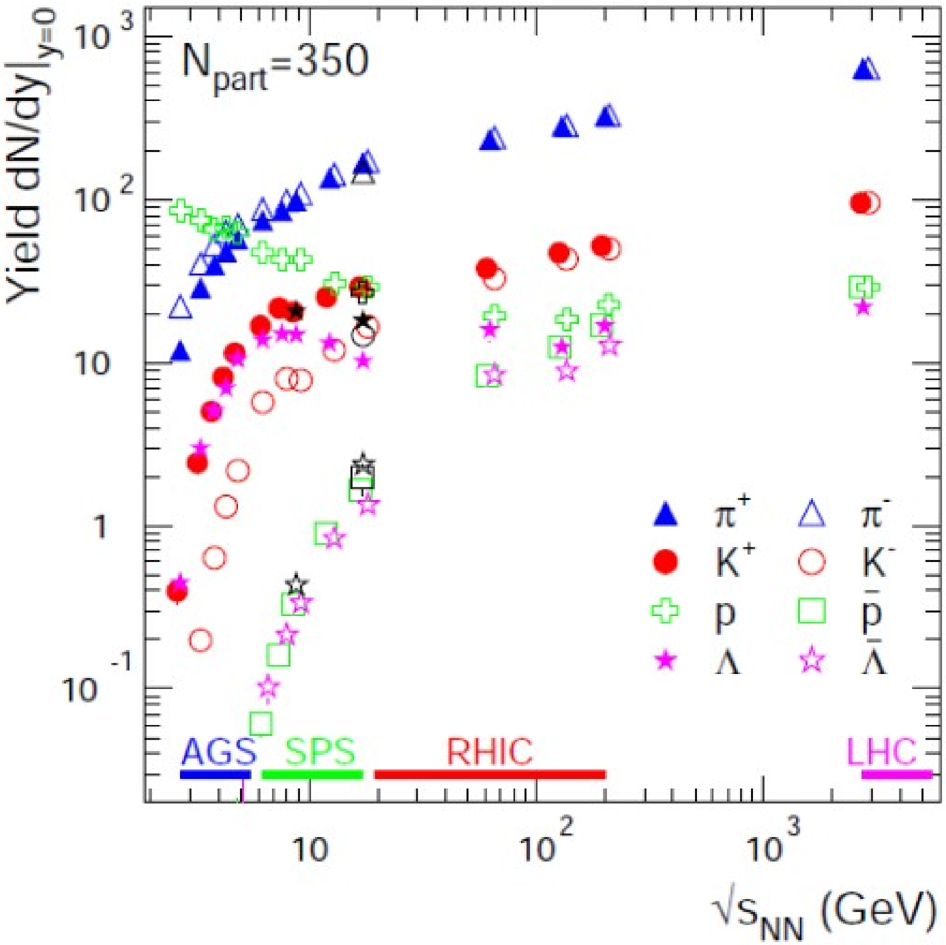
- High precision measurements of rare probes:
  - Heavy flavour and quarkonia
  - Low mass dileptons
  - Jets
  - Heavy nuclear states
- 100x increase in the number of events to be collected

Conclusions

- The aim of studying the high energy heavy ion collisions is to better understand QCD in conditions not possible in particle physics: confinement, phase diagram of nuclear matter, chiral symmetry restoration
- Conditions reachable are similar to the ones during the early Universe (few microseconds) and in the core of neutron stars
- This field incorporates knowledge from many other areas of physics:
  - Thermodynamics, hydrodynamics, string theory
- … and technology
  - Detector, Electronics, High Performance Computing
- and provides input for fields like:
  - cosmology, astrophysics, solid-state physics, etc.
- A relatively young and very challenging field of study with a rich phenomenology, the manifestation of many-body QCD

Backup

Identified hadron yields



- Lots of particles, most newly created ($E=mc^2$)
- A great variety of species:

  $\pi^\pm(u\bar{d}, d\bar{u})$, m=140 MeV

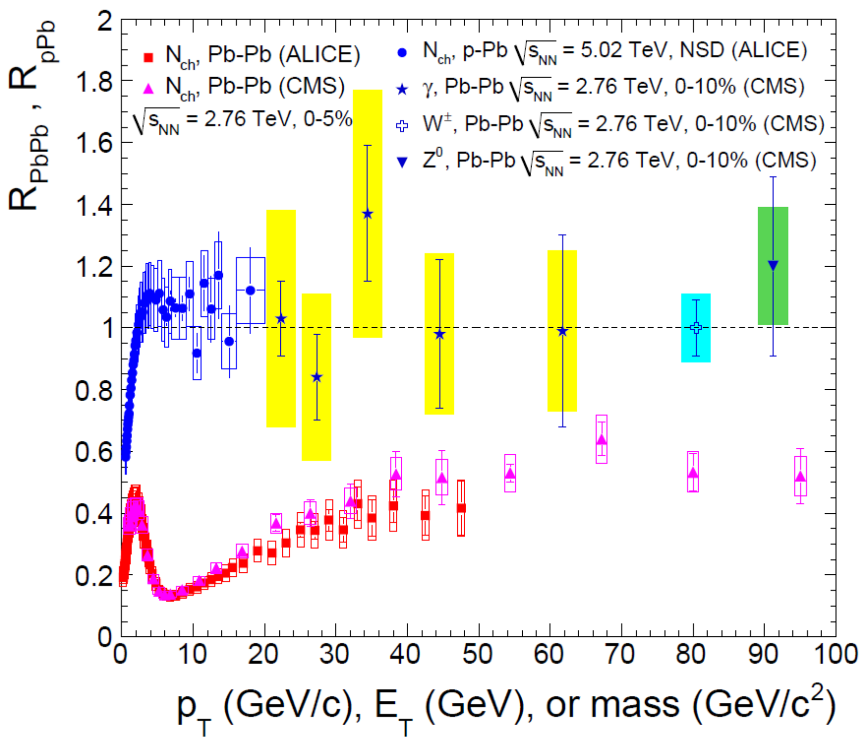
  $K^\pm(u\bar{s}, s\bar{u})$, m=494 MeV

  p(uud), m=938 MeV

  Λ(uds), m=1116 MeV

  also: Ξ(dss), Ω(sss), …
- Abundancies follow mass hierarchy, except at low energies where remnants from the incoming nuclei are significant
- What do we learn?

High-pT suppression (nuclear modification factor)



p-Pb, ALICE PRL110(2013)082302
Pb-Pb, ALICE, Phys.Lett.B720 (2013)52
Pb-Pb, CMS, EPJC (2012) 72

γ, CMS, PLB 710 (2012) 256
$W^{\pm}$, CMS, PLB715 (2012) 66
Z^0, CMS, PRL106 (2011) 212301

$$R_{AA} = \frac{1}{N_{coll}} \times \frac{Y_{AA}}{Y_{pp}}$$

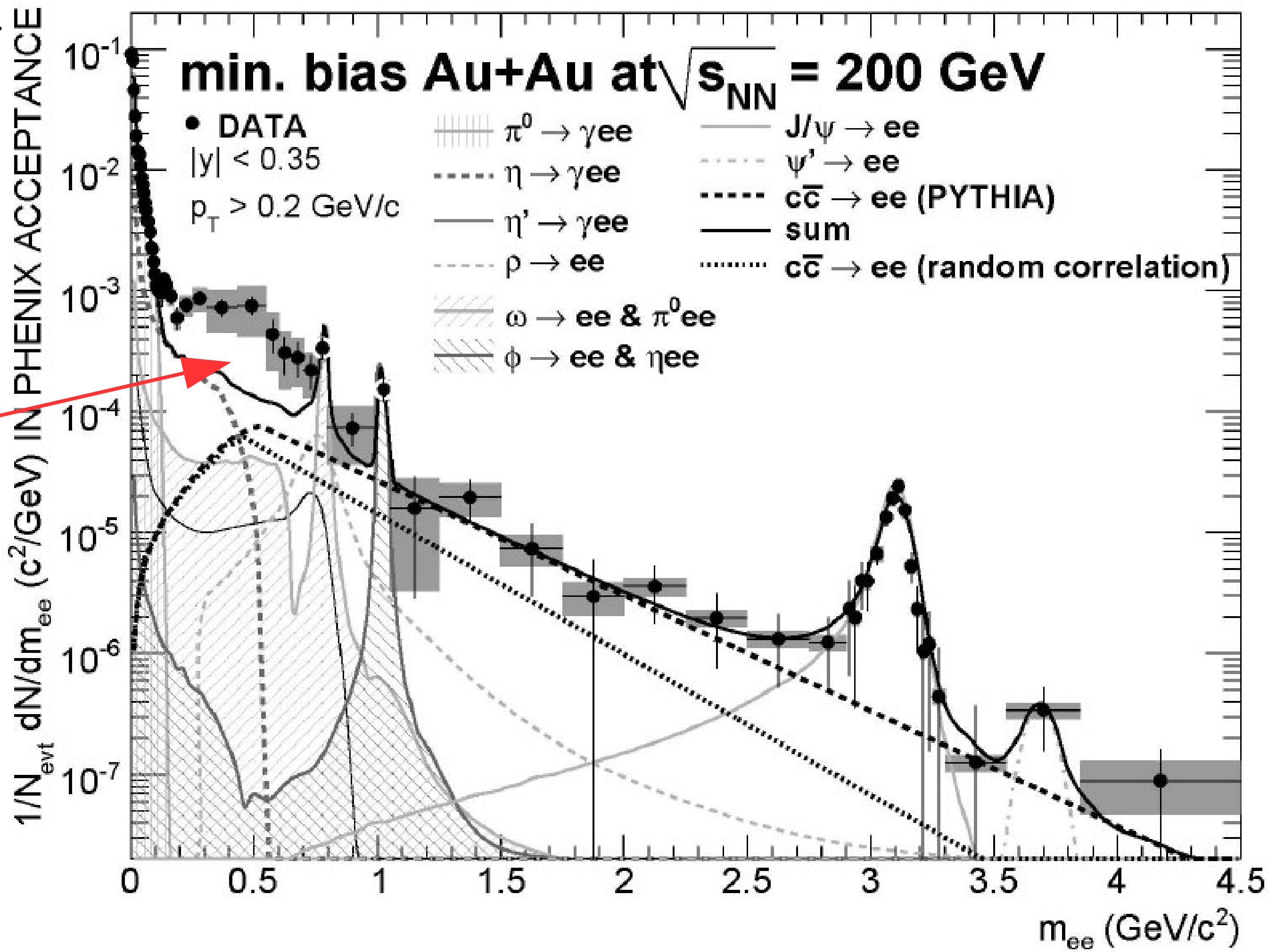
- N_{coll}: the number of binary nucleon-nucleon collisions
- Superposition of NN collisions → $R_{AA}=1$
  Suppression → $R_{AA}<1$
  Enhancement → $R_{AA}>1$

- Weakly interacting particles are not affected by the QGP
  - Photons, $W^{\pm}$ and Z^0 bosons R_{AA} are compatible with 1

Electromagnetic probes

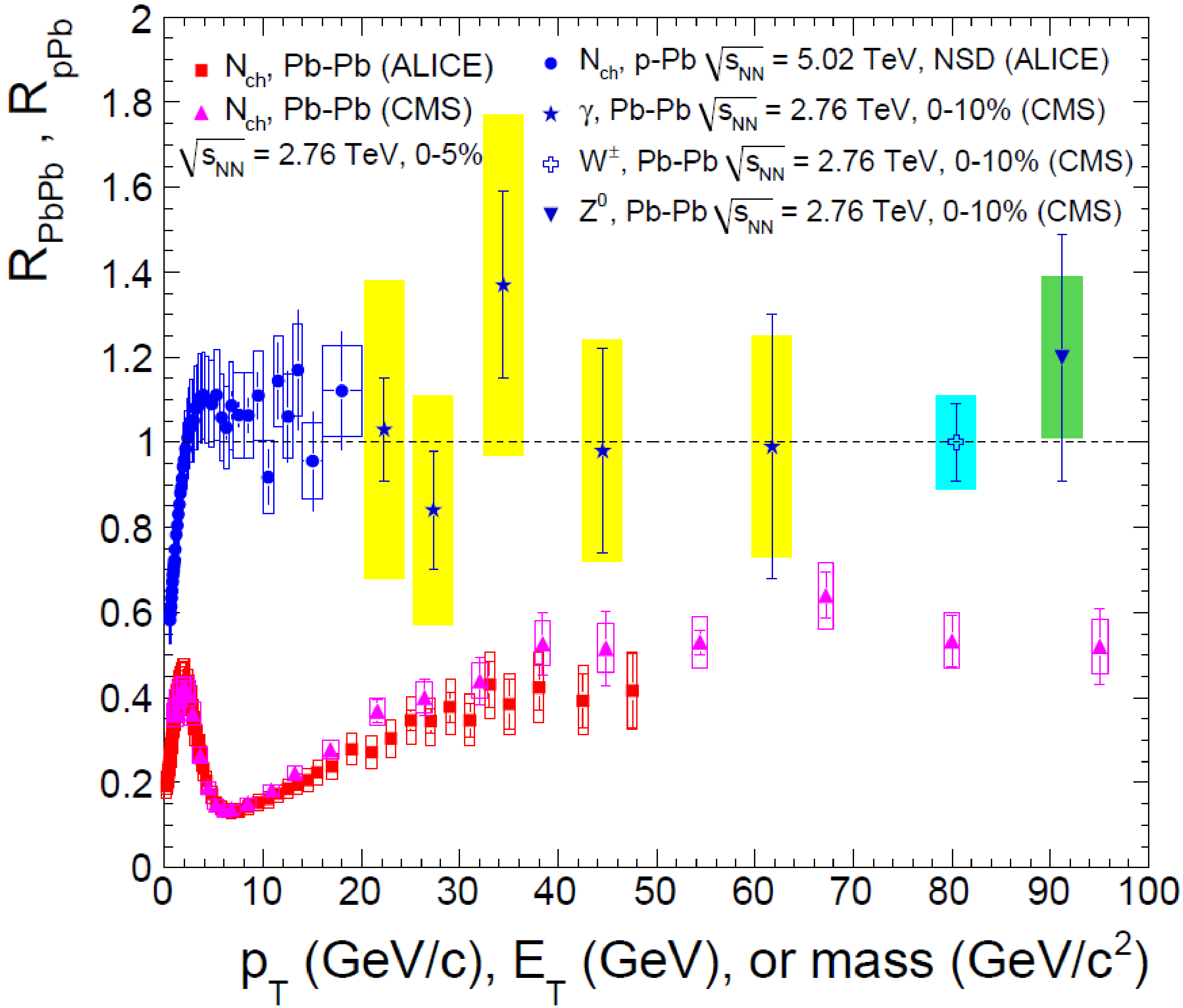
- Direct photons and low mass di-leptons
  - Probe of the thermal radiation of the fireball
  - Very clean information because of no re-interactions with QCD medium

Low mass di-electrons in PHENIX data



An excess is found at masses below 0.6-0.7 GeV/c^2

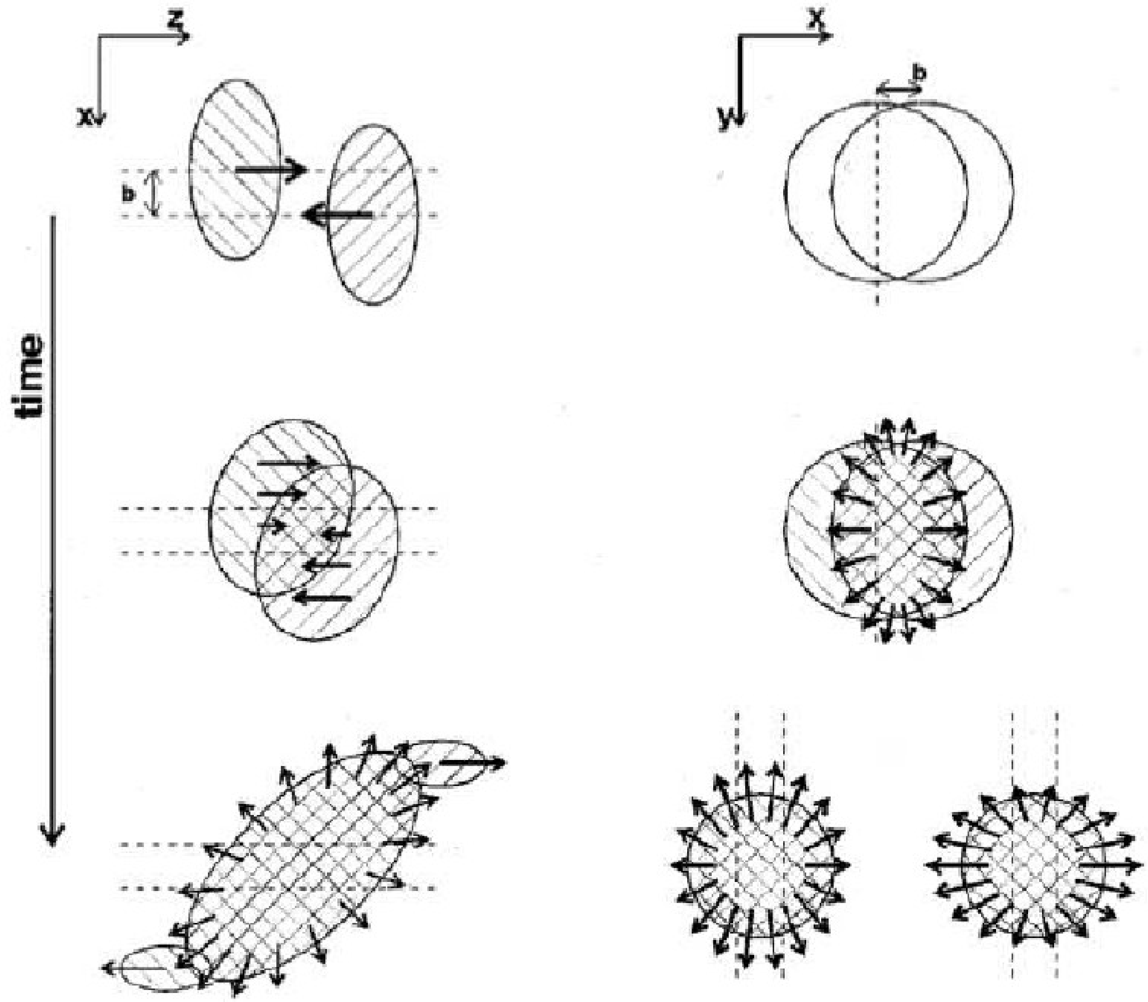
Electromagnetic probes



- Z^0, $W^{\pm}$, high momentum photons
  - No direct information on the QGP, but they act as standard candles for the nuclear modification effects: R_{AA}=1

Concepts: participants and spectators

- In nucleus-nucleus collisions at high energies, geometric concepts are applicable



N.Herrman, J.P.Wessels, T.Wienold, Ann.Rev.Nucl.part.Sci. 49(1999) 581

What are the “control parameters”

- Energy of the collision (per nucleon pair $\sqrt{s_{NN}}$)
- Centrality of the collision (number of “participating” nucleons, N_{part})

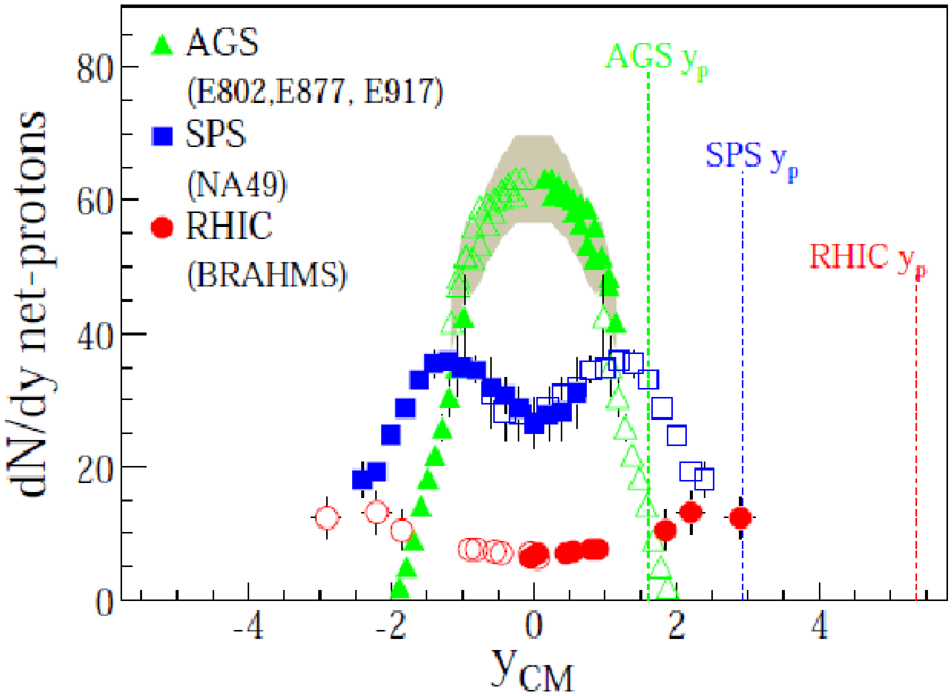
  typically measured in percentage of the geometric cross-section ($\sigma_{geom}=\pi(2R)^2$)

- Not all beam energy is spent

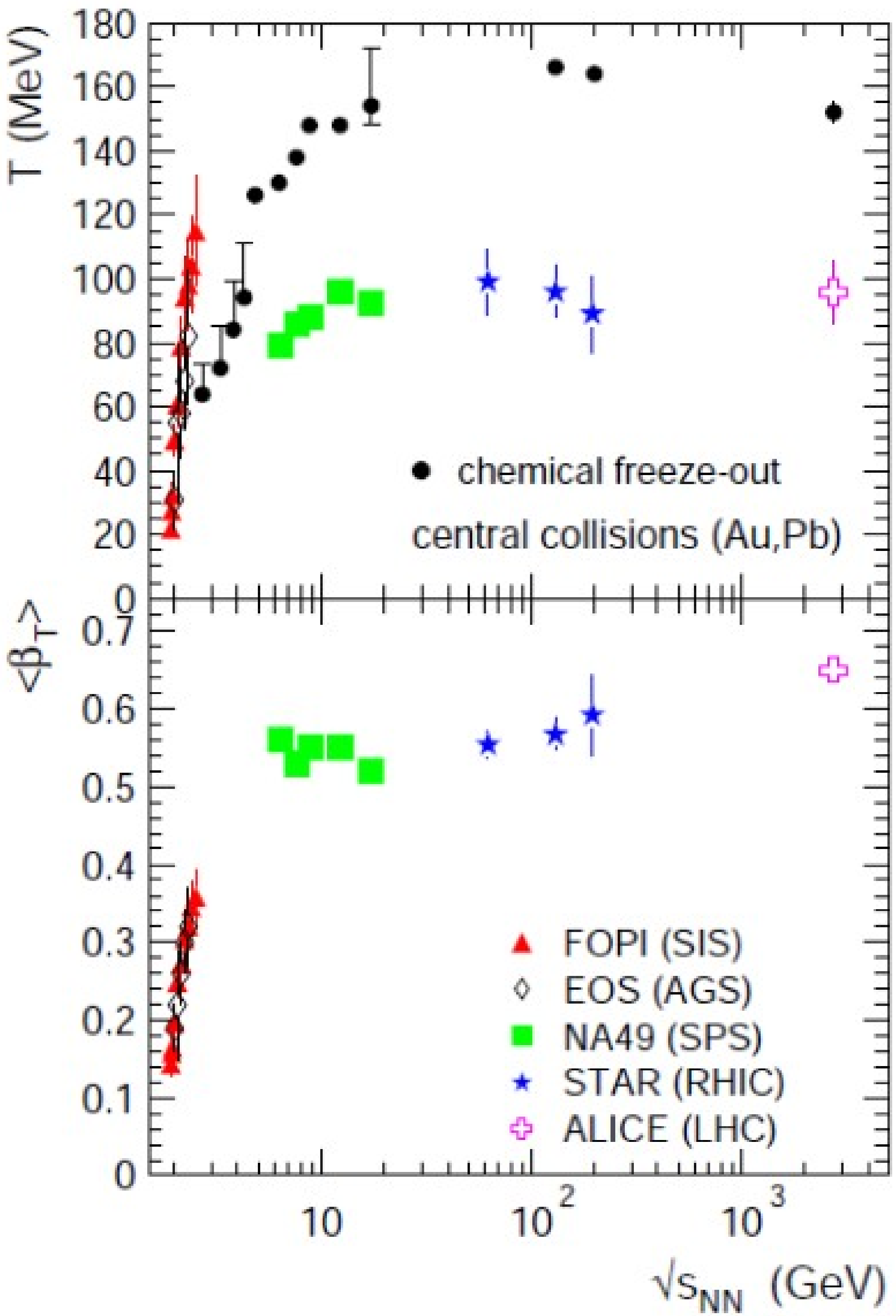
  … quantified by nuclear stopping

  net proton counting (N_p-$N_{\bar{p}}$)

  BRAHMS Collaboration, Phys.Rev.Lett.93 (2004) 102301



The kinetic freeze-out



- Hydro-like "Blast-wave" fits allow to extract parameters like :

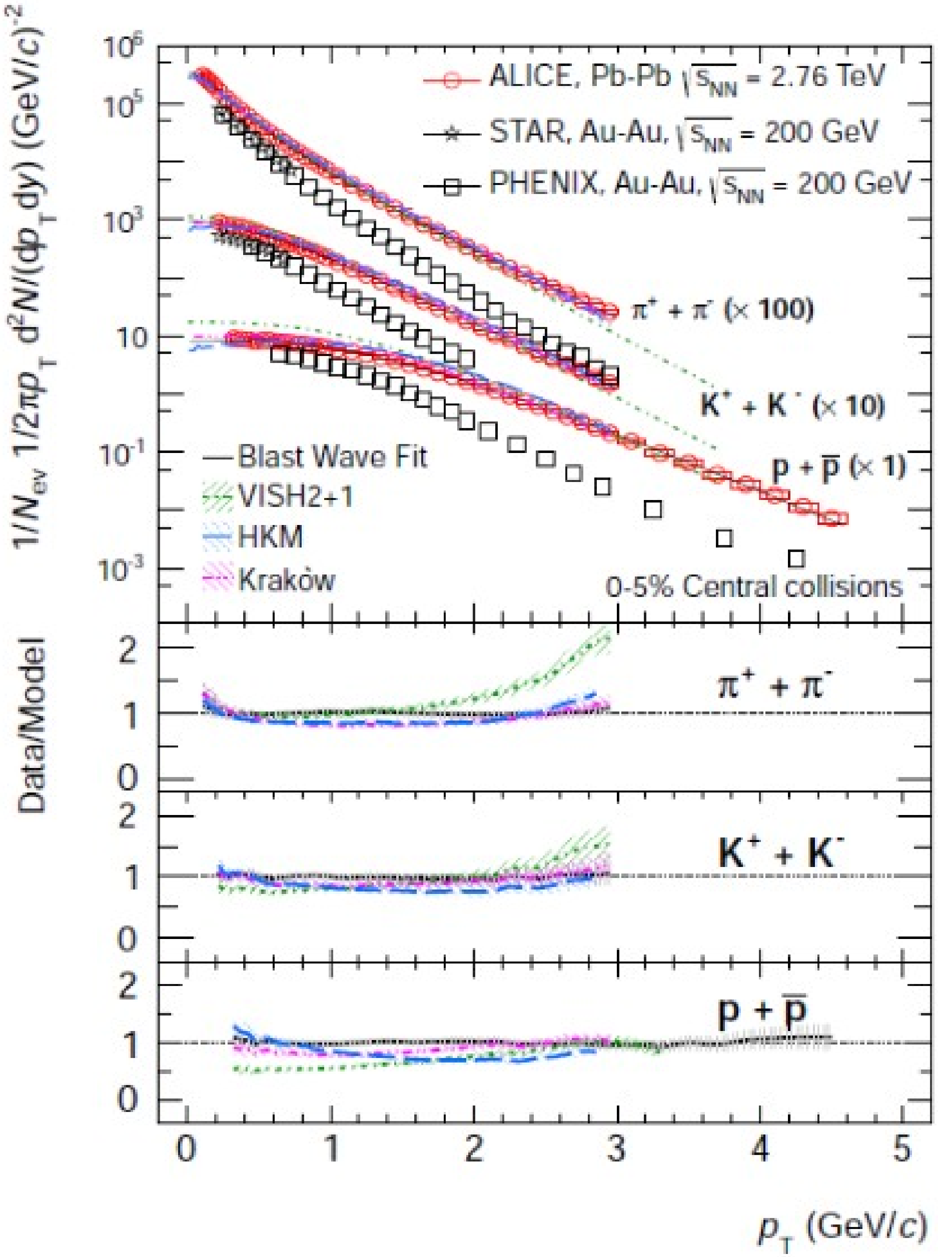
  T_{kine} = kinetic freeze-out temperature

  <β> = collective average velocity

- Light quark hadrons "flow" with a collective velocity of 65% c additional to their own individual movement

- arXiv: 1210.8126

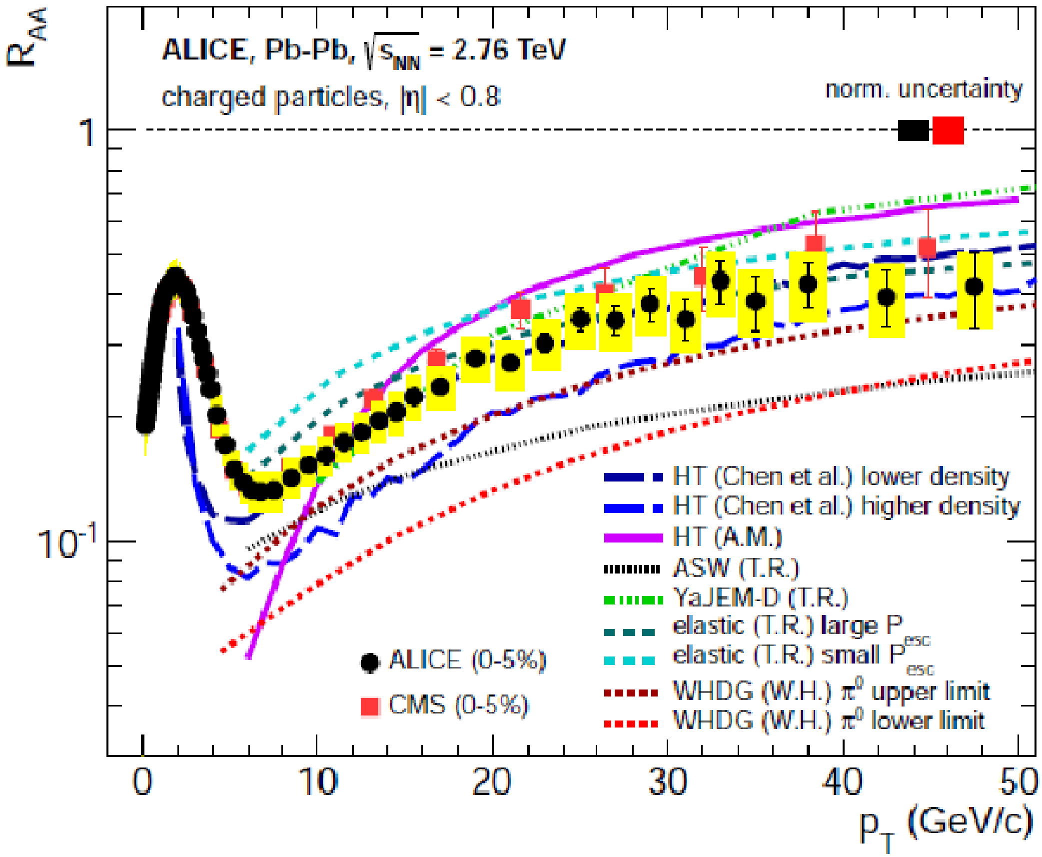
The kinetic freeze-out



ALICE, PRL 109 (2012) 252301

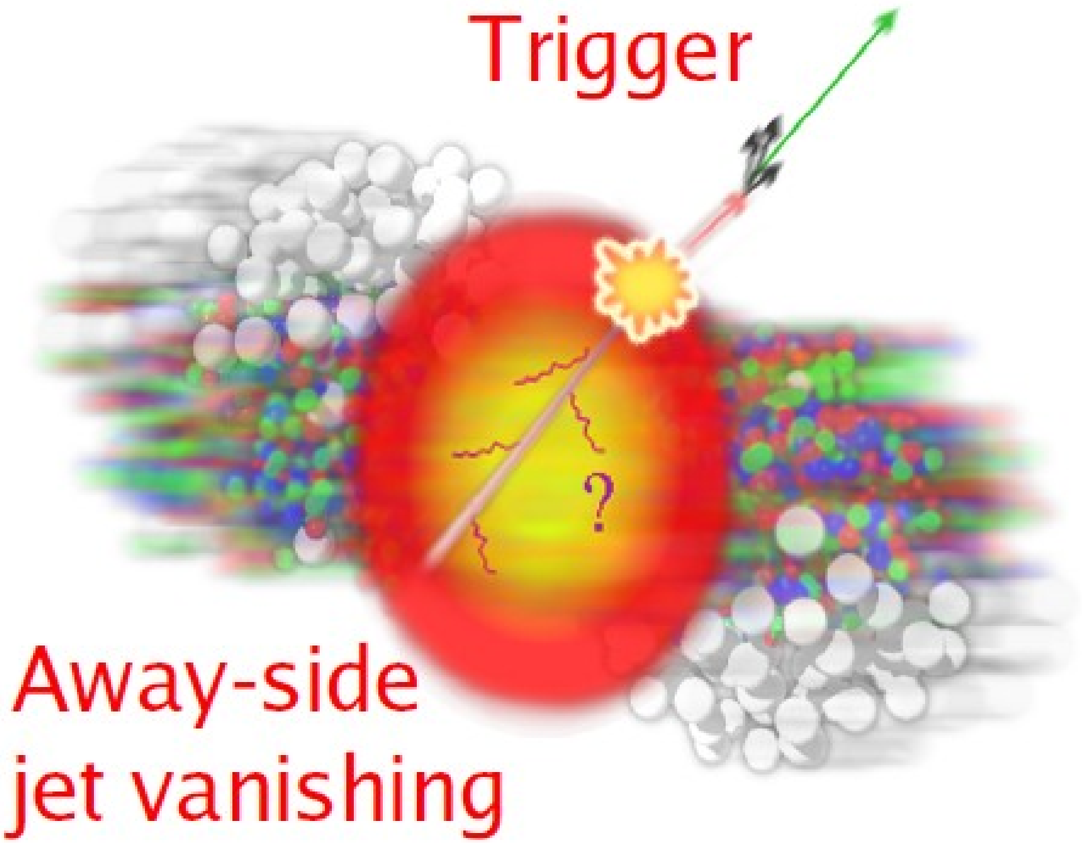
- At the LHC, spectra are harder than at RHIC ($\sqrt{s_{NN}}$=200GeV)
- The mass dependence of the spectra “hardness” indicates collective motion / flow
- Hydrodynamical models reproduce the data → the fireball expands hydrodynamically nearly as a perfect fluid (very low viscosity)

Jet quenching at the LHC



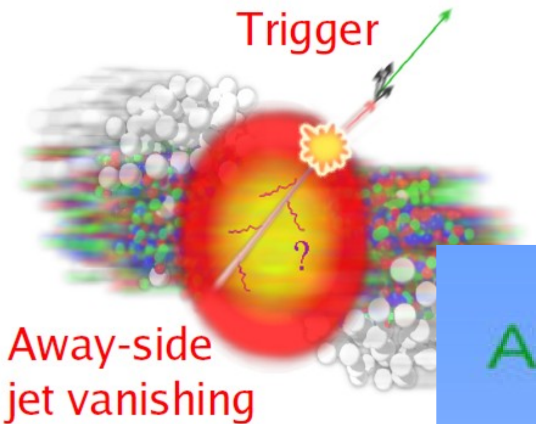
- Strong suppression observed (stronger than at RHIC)
- Reaching a factor of about 7 at p_T=7-8 GeV/c
- Remains substantial even beyond 50 GeV/c
- A lot of activity in theoretical description of parton energy loss in hot deconfined matter

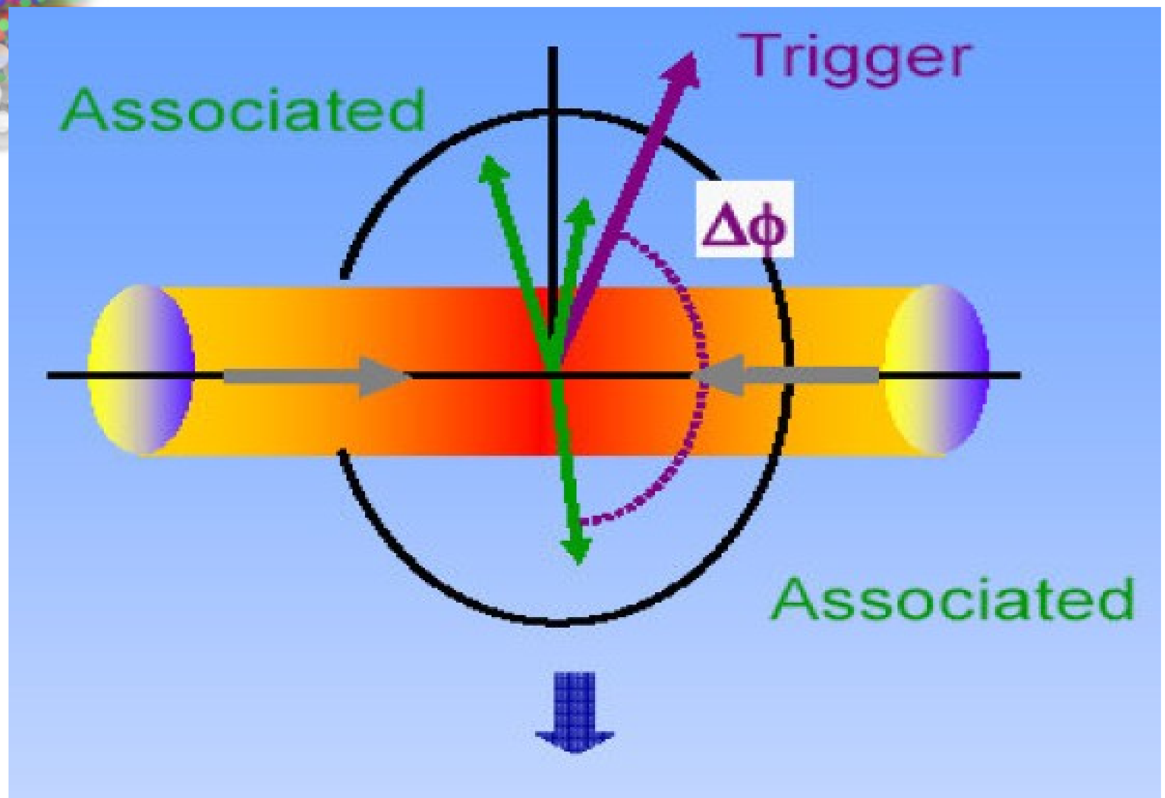
Two-particle azimuthal correlations



- High momentum di-jets are created in hard interactions of the initial partons
- Tipically, one of the jets traverse a smaller path through the QGP and escapes, while the other can be quenched (surface bias)

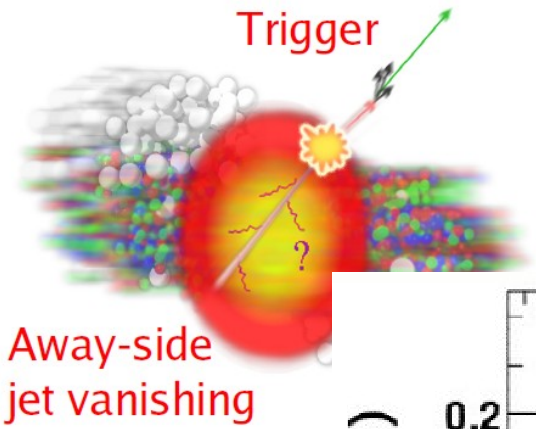
Two-particle azimuthal correlations

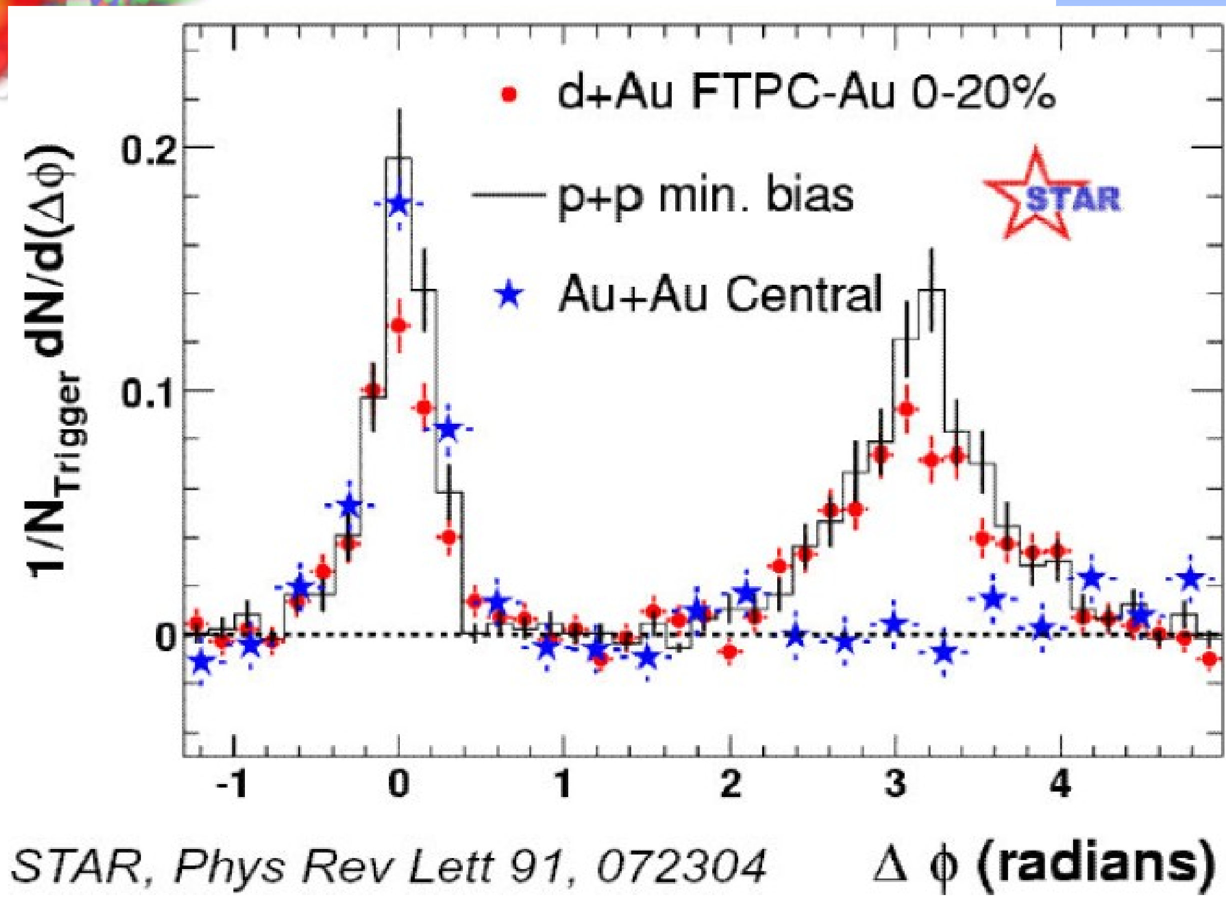


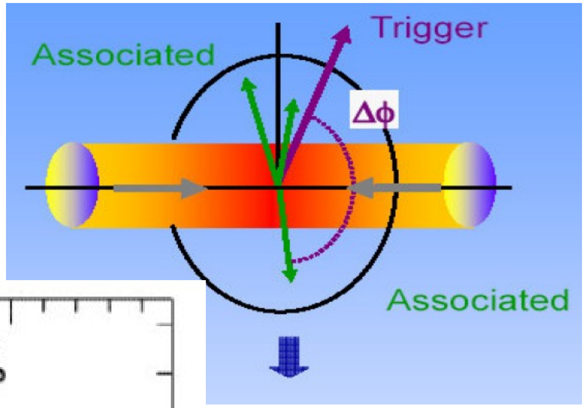


- Test the strength of this effect using two-particle correlations

Two-particle azimuthal correlations



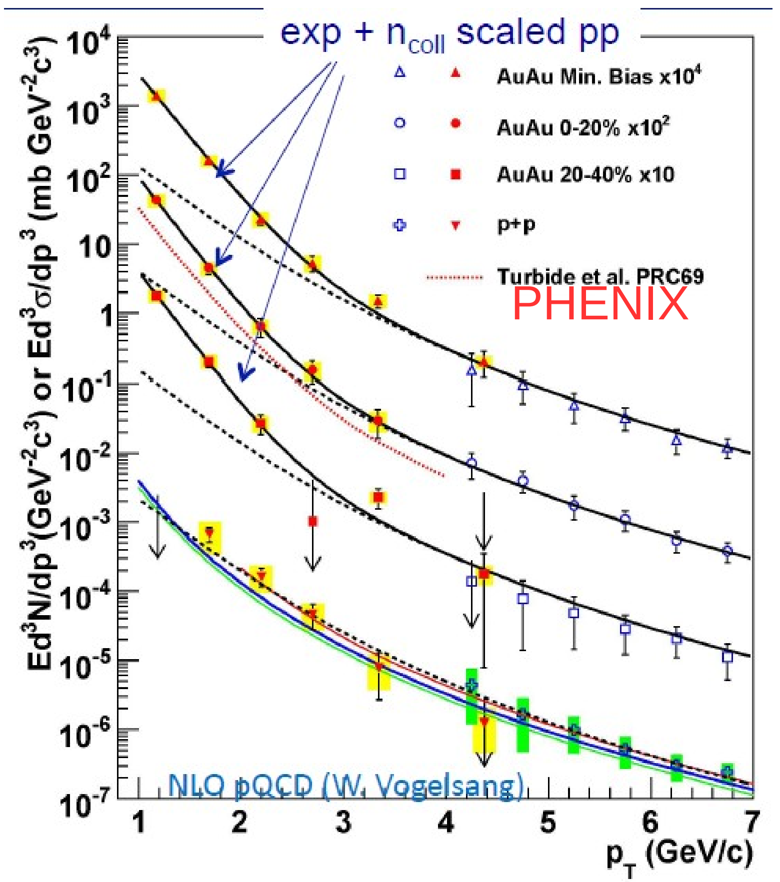




- Dissapearance of the associated particle is observed in nuclear collisions, while no effect is observed in pp and d-Au collisions.

Electromagnetic probes

- Direct photons and low mass di-leptons
  - Probe of the thermal radiation of the system via quark anti-quark annihilation
  - Very clean information because of no re-interactions with the QCD medium



$T_{ave} = 221 \pm 19^{stat} \pm 19^{syst}$ MeV

$T_{ave} \sim 2.2 \times 10^{12}$ K

Electromagnetic probes

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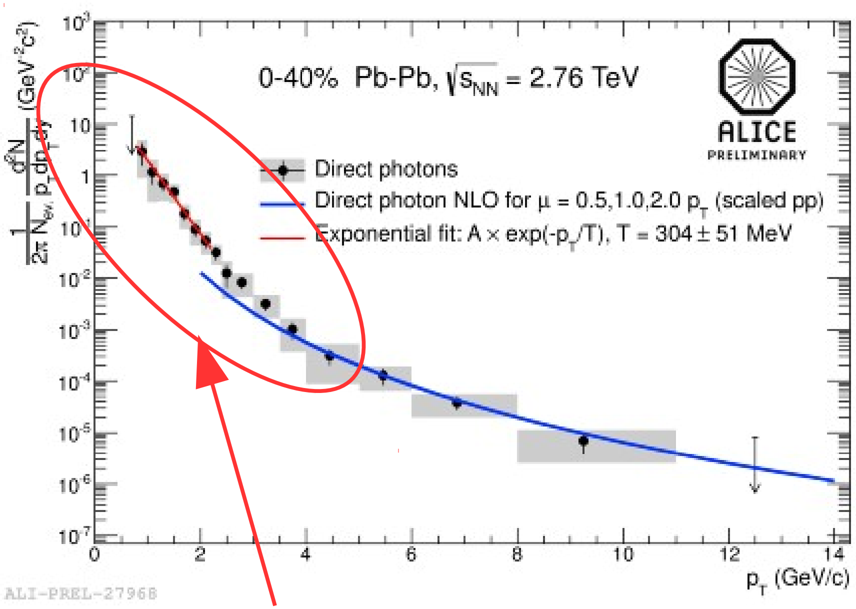
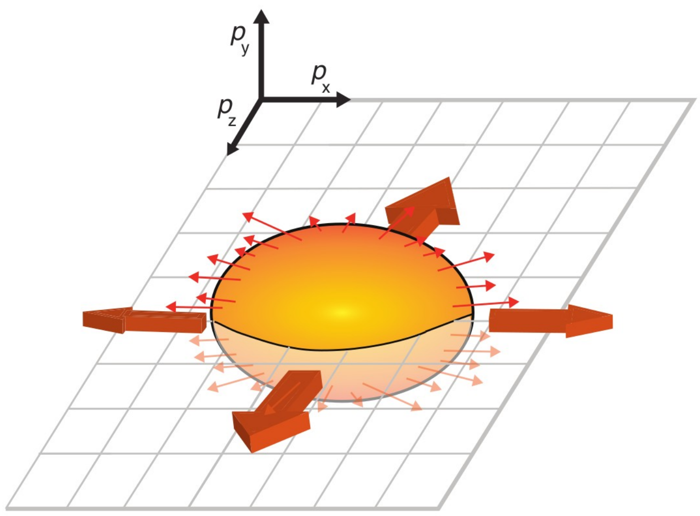
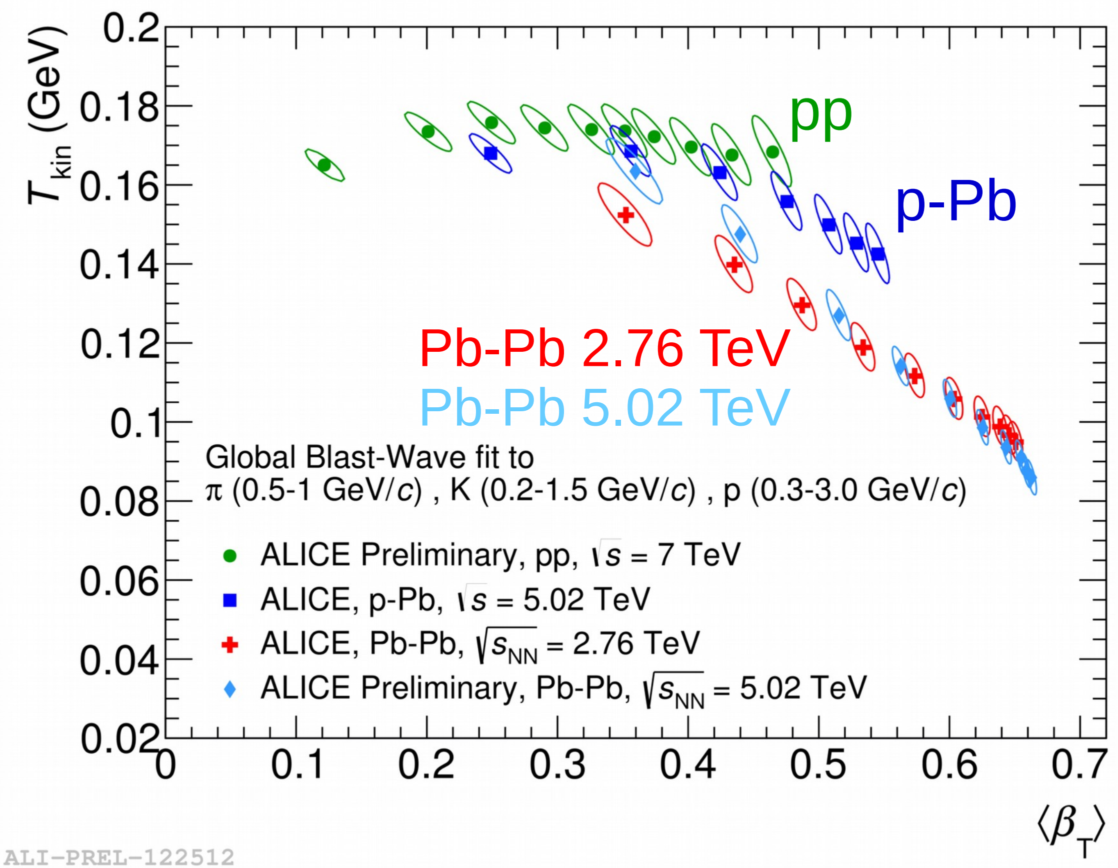


T = 304 ± 51 MeV
T ~3.0 x 10^{12} K

The highest temperature ever recorded!!!

Kinetic freeze-out: p_T spectra



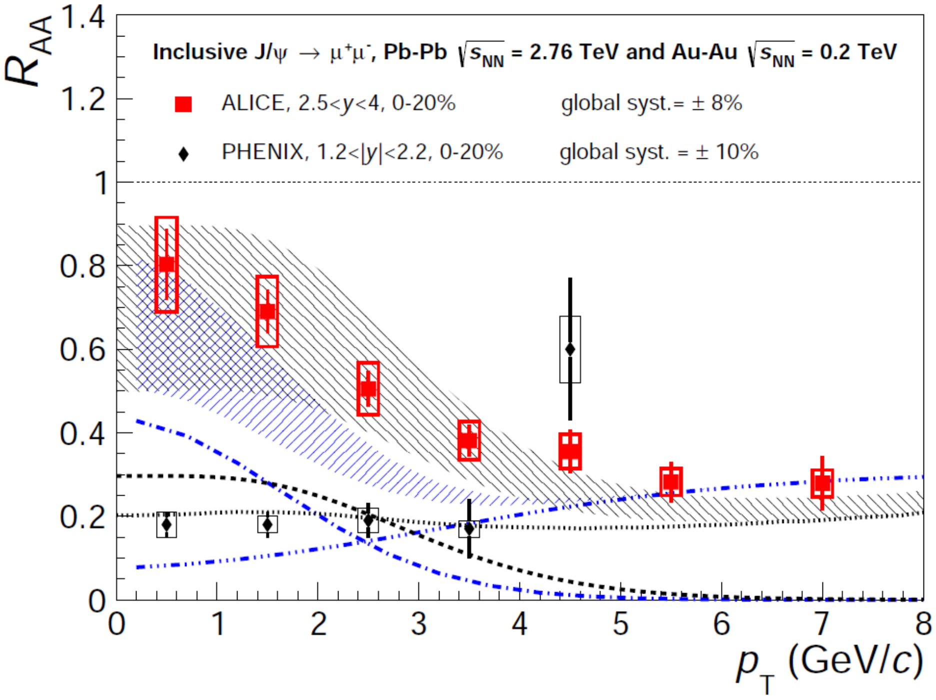


- Boltzmann-Gibbs Blast-wave model: expanding system characterized by a fluid velocity β_T and a kinetic freeze-out temperature T_{kin}

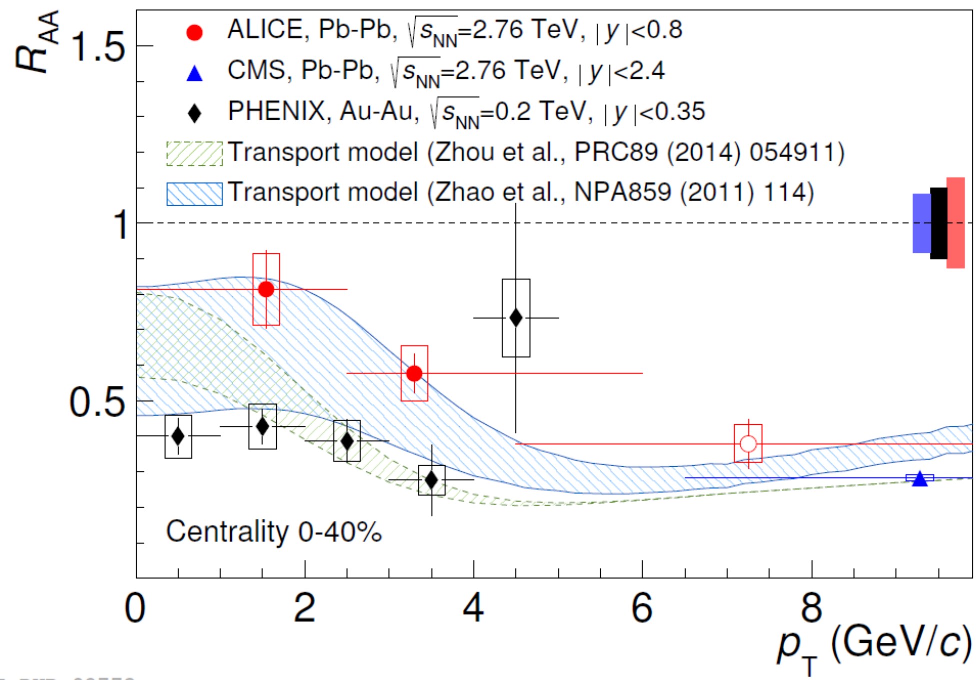
- Simultaneous fit of the pion, kaon and proton p_T spectra
  - Largest radial flow ever observed: nearly 2/3 c
  - Kinetic freeze-out temperature as low as 85 MeV

J/ψ suppression vs p_T

arXiv: 1506.08804



arXiv: 1504.07151



ALI-PUB-92773

- Striking difference between LHC and RHIC data at low p_T
- Clear evidence for (re)generation ?
  - From simple phenomenological considerations a large J/ψ enhancement is expected at low transverse momentum