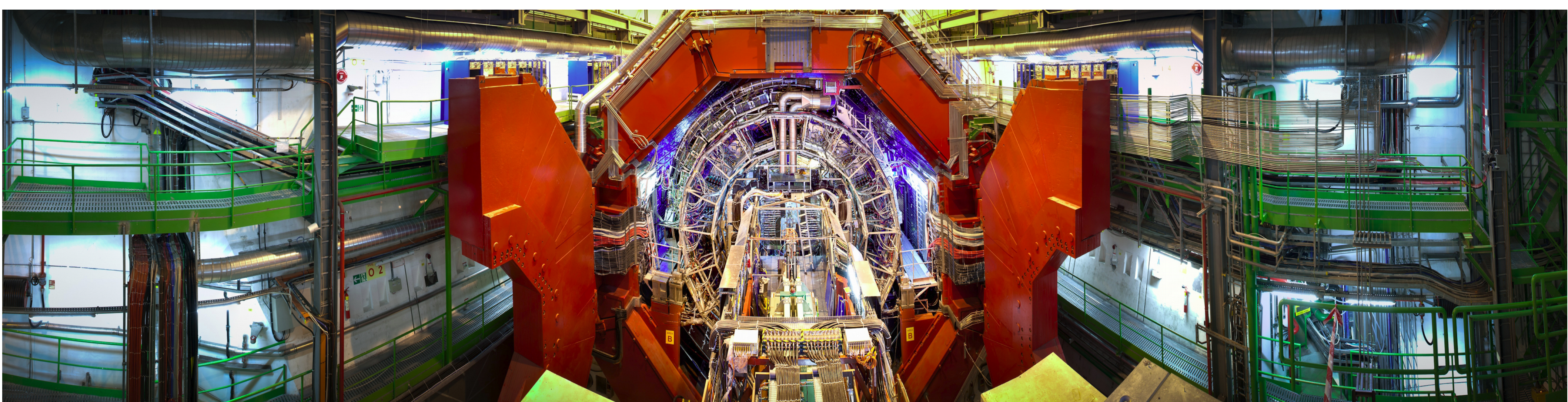
A Large Ion Collider Experiment (ALICE) at the LHC

Ionut Arsene
University of Oslo
2017/03/02



Contents

Introduction

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

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- Quarks

  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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  sizes: point-like (<10^{-19} m)

- … 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!)

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

- ...difficult to calculate
  - No analytical solutions (except 1+1)

Quantum Chromo-Dynamics (QCD)

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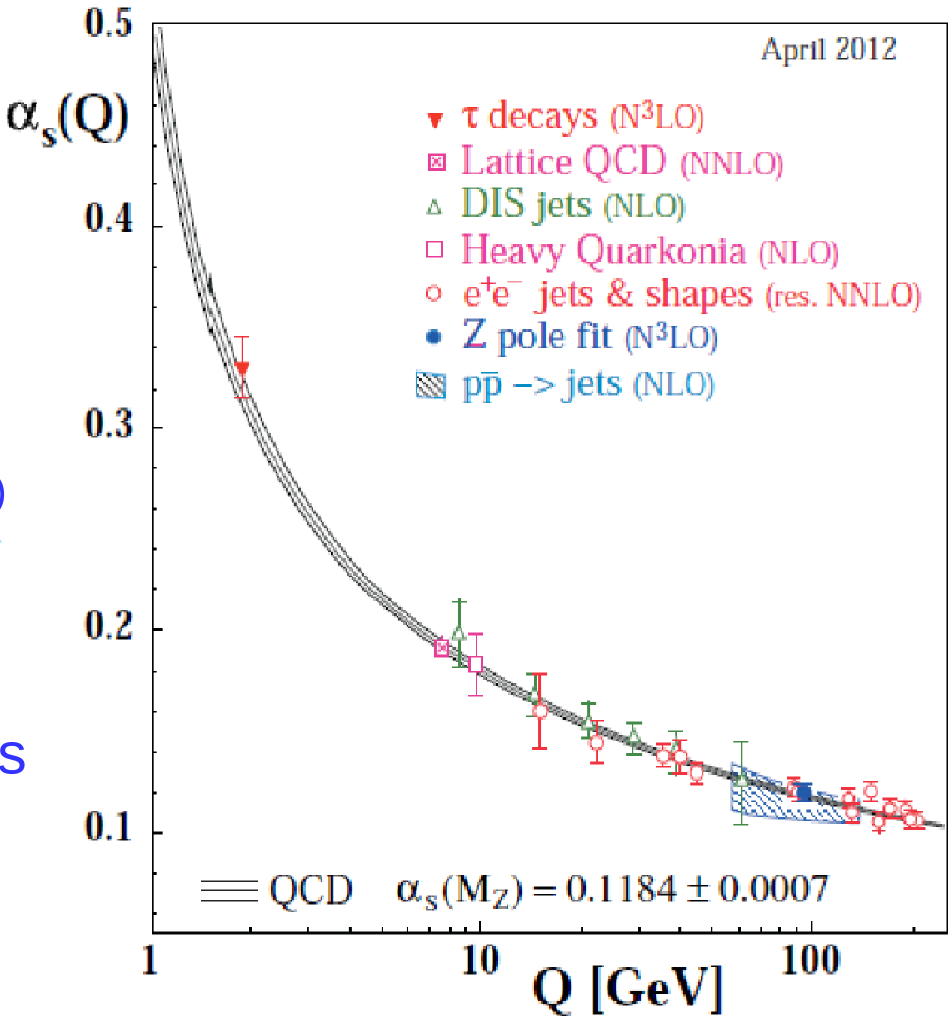
- ...difficult to calculate
  - No analytical solutions (except 1+1)
- **High *Q*:** asymptotic freedom

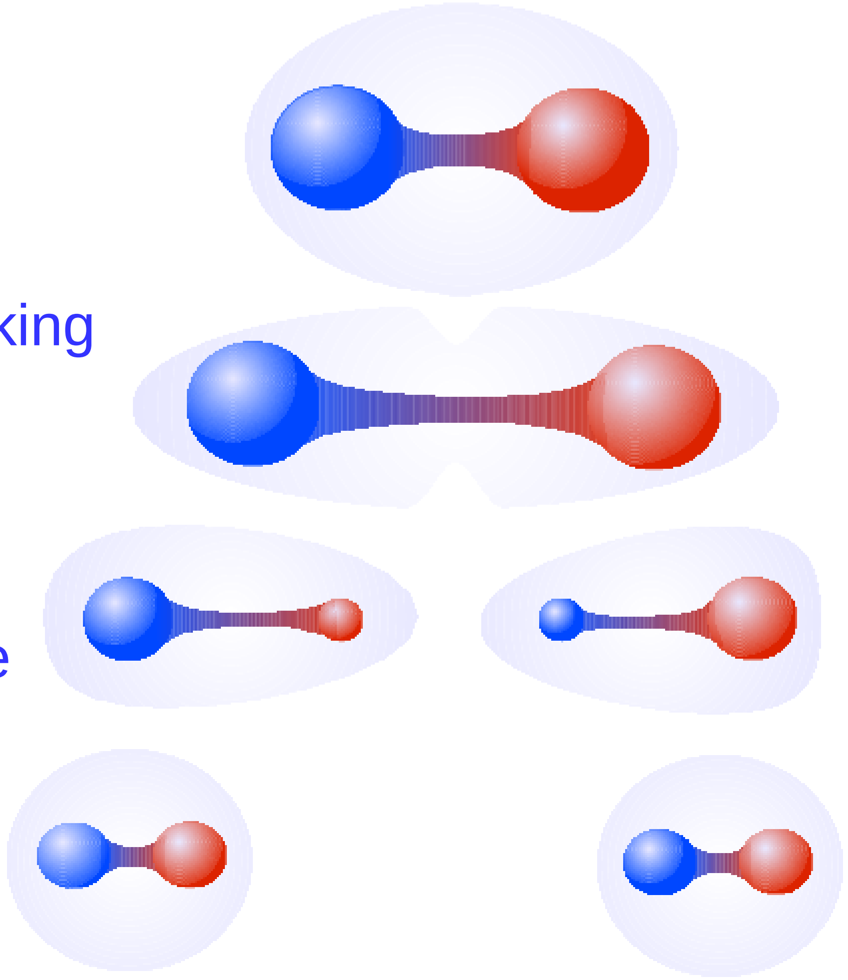
  Physics Nobel prize 2004 (Wilczek, Gross, Politzer)
- Typically solvable using perturbative theory
- Tested extensively at modern colliders



S.Bethke, arXiv:1210.0325

Quantum Chromo-Dynamics (QCD)

- 6 quarks, 3 colours (RGB)
  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 millenium problems
  - Most of the visible matter in the Universe



High energy nucleus-nucleus collisions: the scope

- What happens if “normal” nuclear matter is compressed and heated ?
  Is there an upper temperature limit (aka Hagedorn-temperature) ?
  Are there any phase transitions ?

High energy nucleus-nucleus collisions: the scope

- What happens if “normal” nuclear matter is compressed and heated ?
  Is there an upper temperature limit (aka Hagedorn-temperature) ?
  Are there any phase transitions ?
- Create in the laboratory a chunk of **deconfined matter** (also called Quark-Gluon Plasma, QGP / sQGP) 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

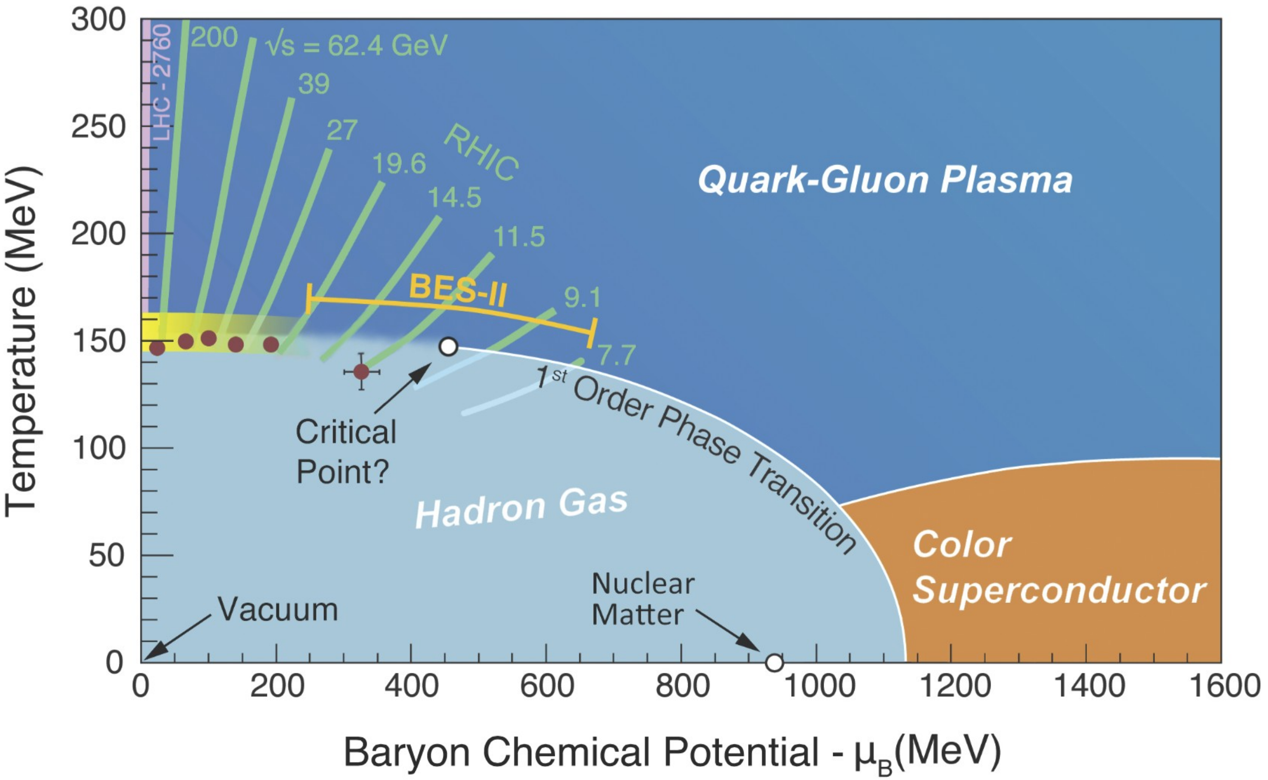
- *Volume*: about 2000 fm^3 (1 fm = 10^{-15} m)

- *Duration*: about 10 fm/c (or about 3*10^{-23} sec.)

Physics applications

- Relevance for:
  - QCD studies (low-Q, finite T and μ)

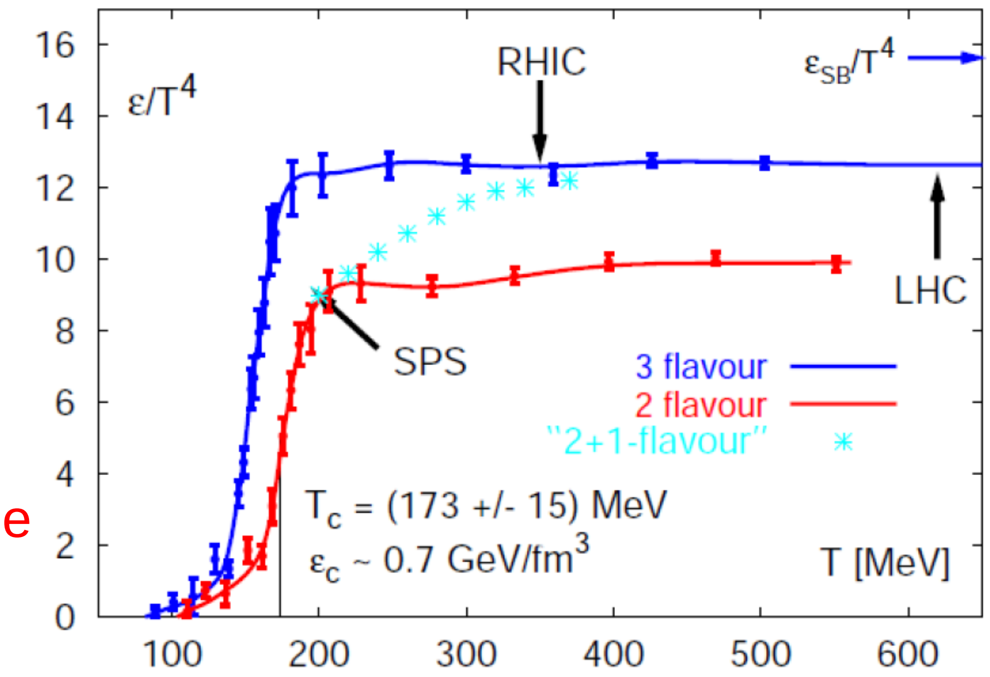
    Phase diagram of nuclear matter:
    - deconfinement phase transition



Physics applications

- Relevance for:
  - QCD studies (low-Q, finite T and μ)
    Phase diagram of nuclear matter:
    - deconfinement phase transition
    - Lattice QCD calculations conclude transition is cross-over type
      (Y.Aoki et al., Nature 443 (2006) 675)
    - “Critical” temperature: T_C≈155-160 MeV

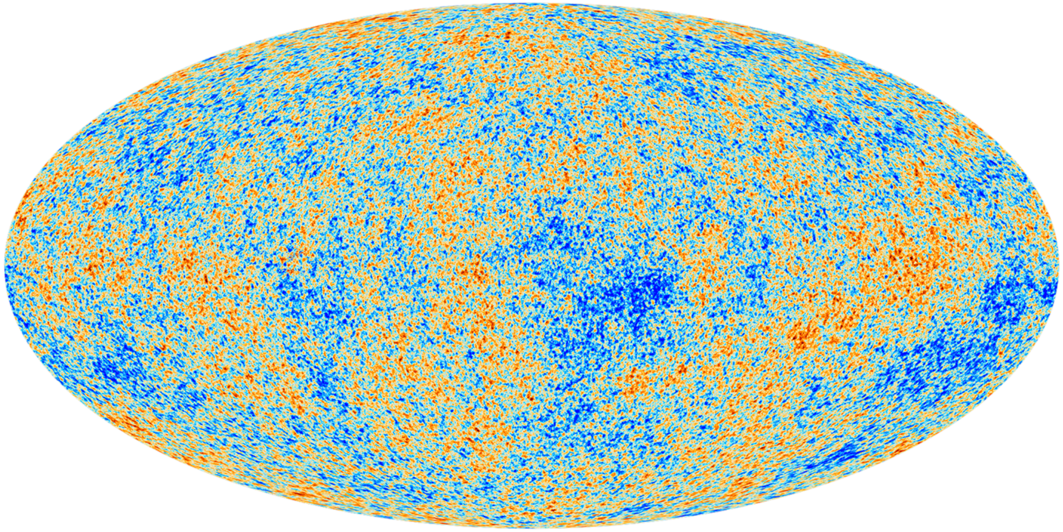
(A.Bazavov et al., arXiv:1111.1710, S.Borsanyi et al., arXiv:1005.3508)



F. Karsch, hep-lat/0106019

Physics applications

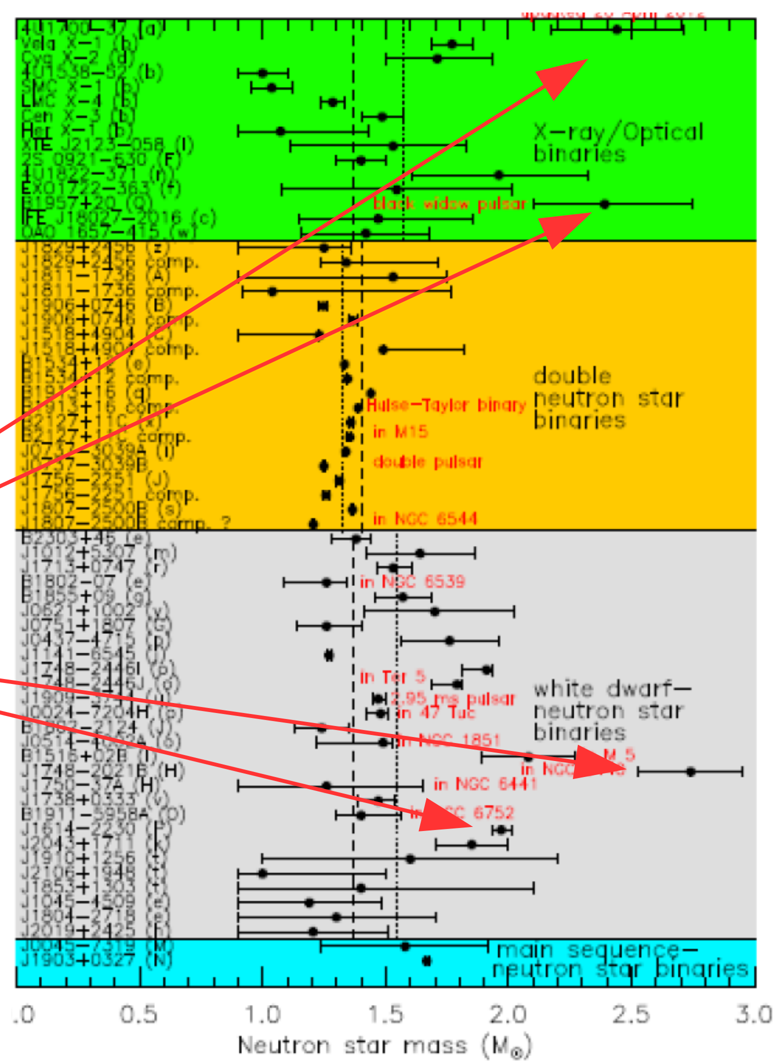
- Relevance for:
  - QCD studies
  - Cosmology: access early Universe conditions (10^{-5} s)



Cosmic microwave background seen by Planck

Physics applications

- Relevance for:
  - QCD studies
  - Cosmology
  - Astrophysics: neutron stars mass controlled by the equation of state (EoS) of nuclear matter
  - “Canonical” mass: 1.4 M_{sun}
  - How can the outliers exist ?
    - Stiffer EoS at larger nuclear densities



J.M.Lattimer, arXiv:1305.3510

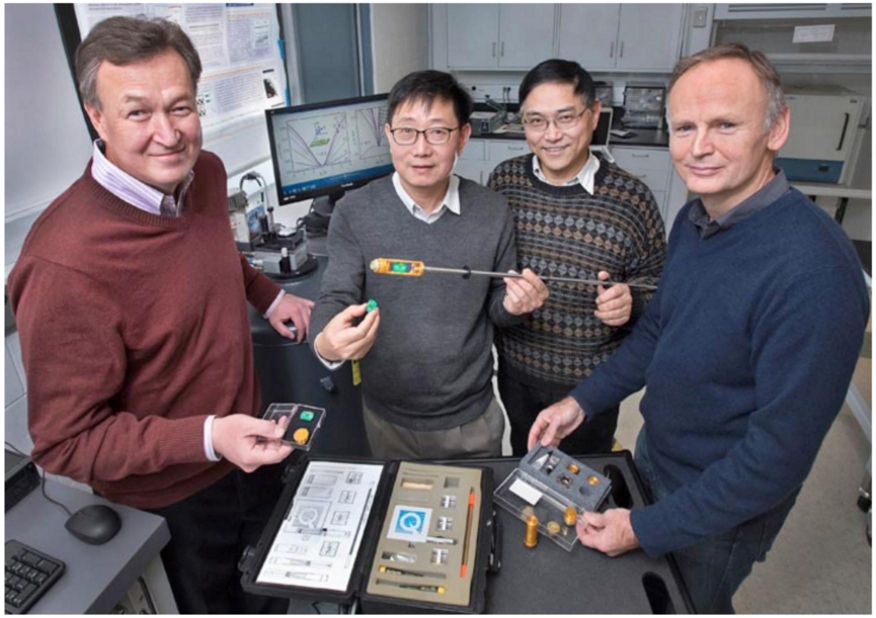
Physics applications

- Relevance for:
  - QCD studies
  - Cosmology
  - Astrophysics
  - Solid state physics:
    Chiral magnetic effect first studied in HIC, now discovered in condensed matter experiments
    - Potential applications in quantum computing, “quantum electricity generators”, high temperature superconductivity

Chiral Magnetic Effect Generates Quantum Current

Separating left- and right-handed particles in a semi-metallic material produces anomalously high conductivity

February 8, 2016



Nuclear theorist Dmitri Kharzeev of Stony Brook University and Brookhaven Lab with Brookhaven Lab materials scientists Qiang Li, Genda Gu, and Tonica Valla in a lab where the team measured the unusual high conductivity of zirconium pentatelluride. + ENLARGE

Q.Li, D.Kharzeev et al., Nature Physics Letters 2016

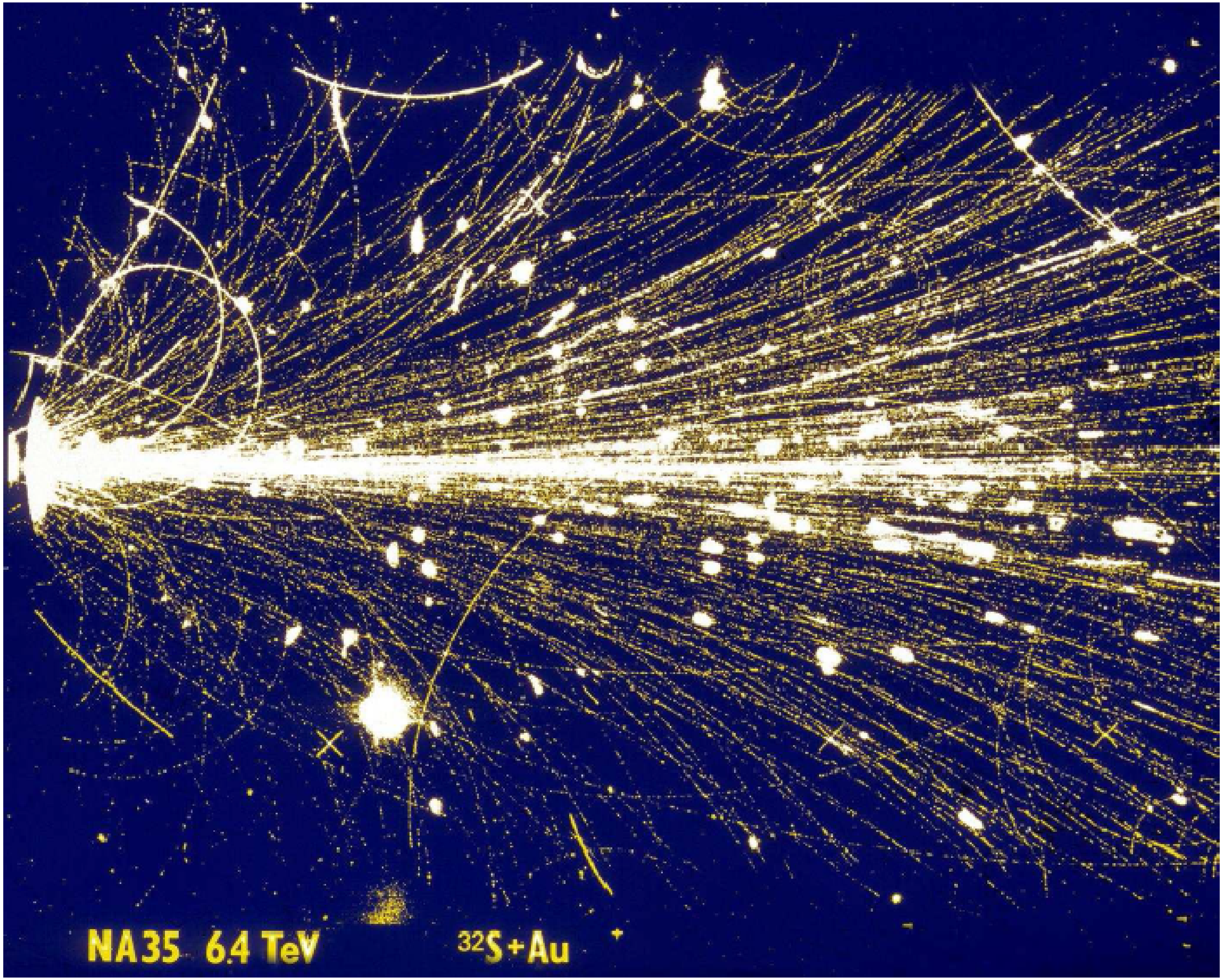
Physics applications

- Relevance for:
  - QCD studies
  - Cosmology
  - Astrophysics
  - Solid state physics

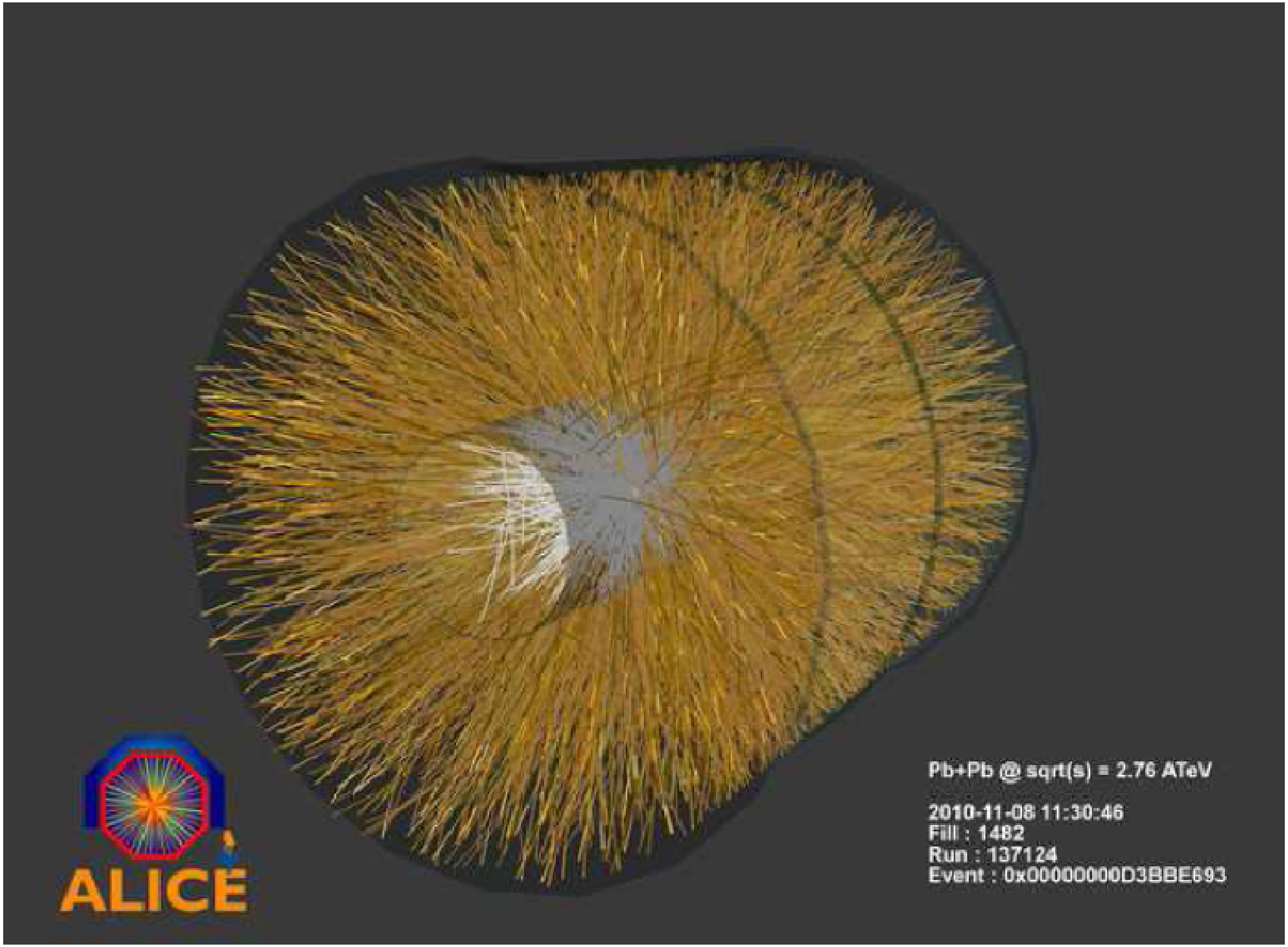
Heavy ion accelerators

- 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 (~2020): $\sqrt{s_{NN}}$=5 GeV

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



A Pb-Pb collision measured by ALICE



- A 3D picture (with 500 million voxels) of a central collision (about 3000 primary tracks)
- We take millions of such pictures to be analyzed offline

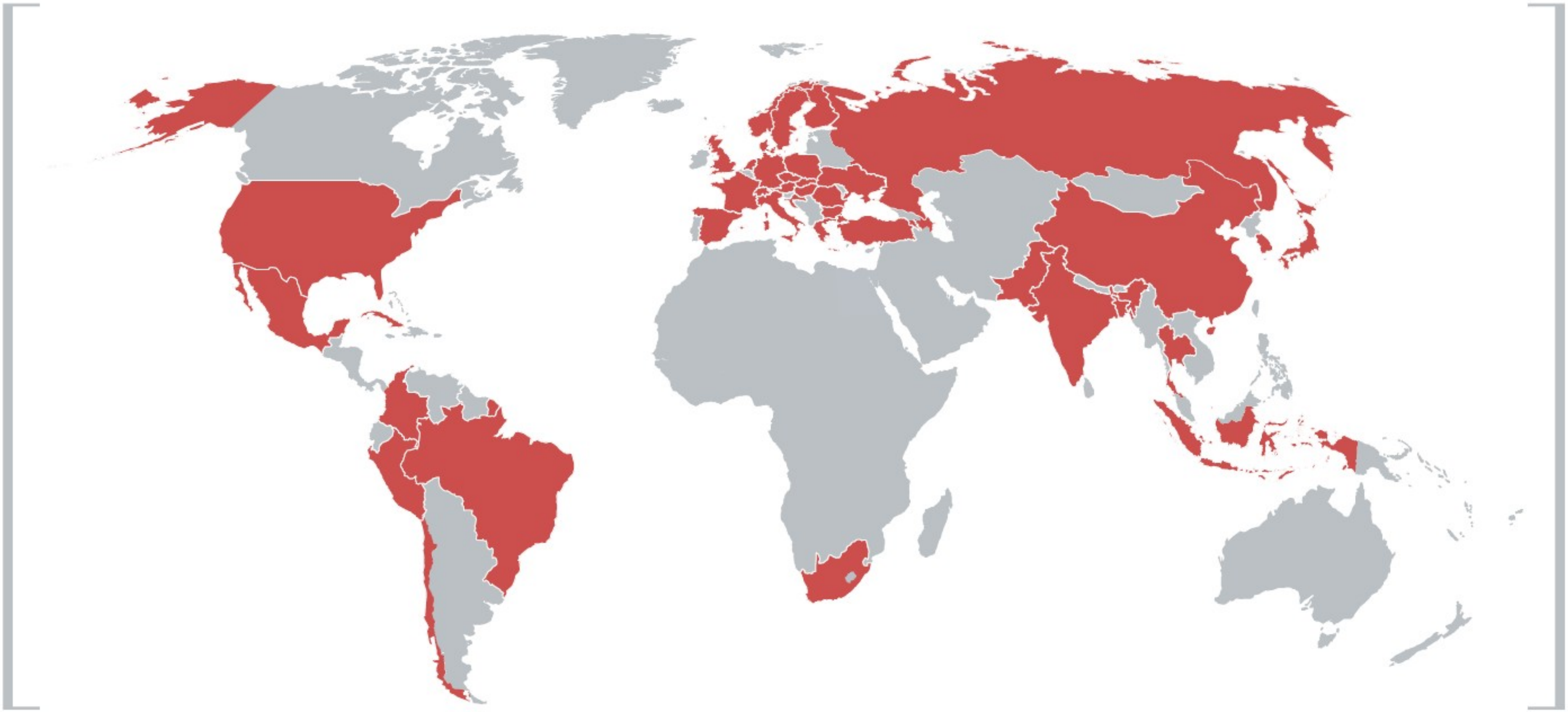
The ALICE Collaboration

A Large Ion Collider Experiment

ALICE COLLABORATION

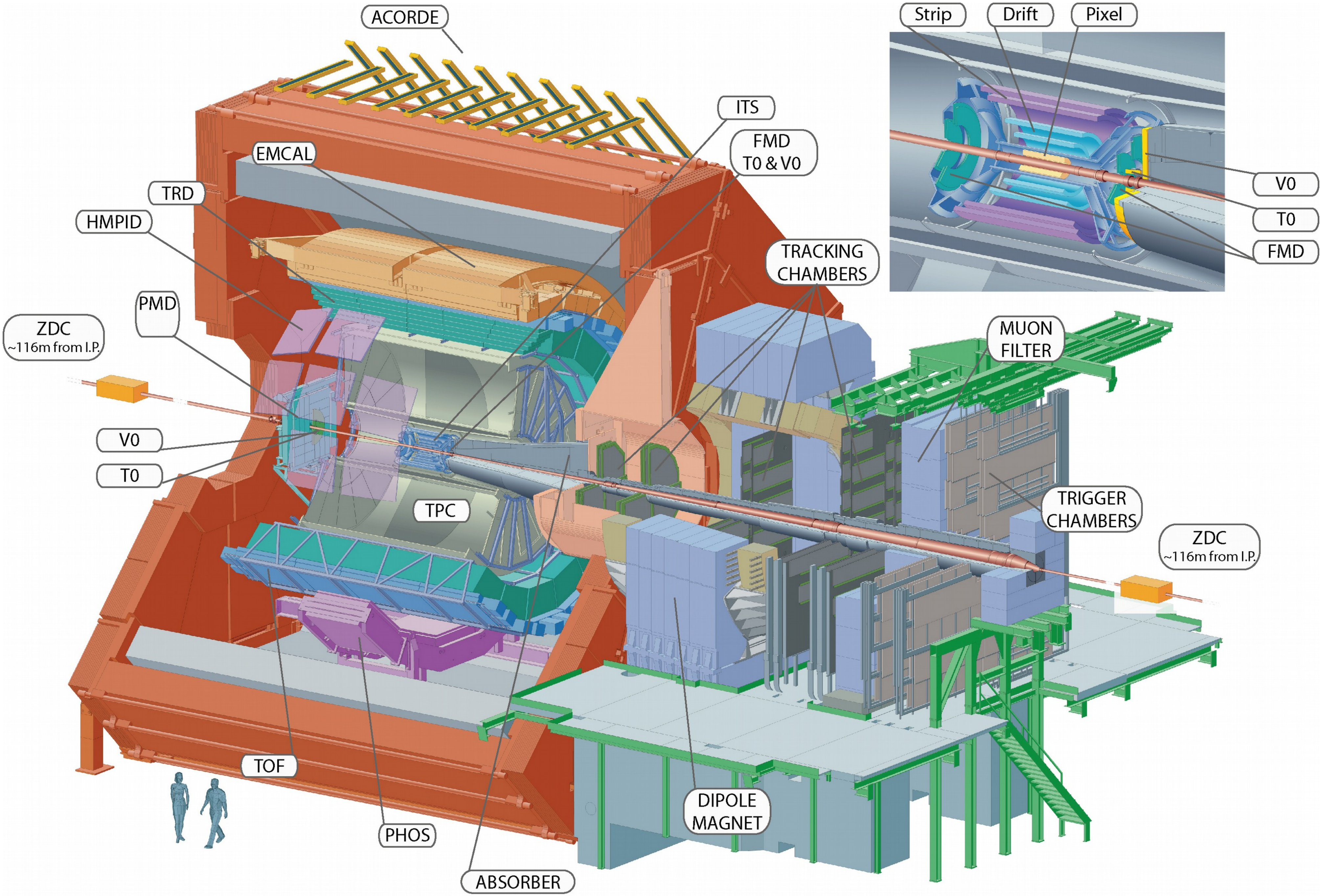
AS NOVEMBER 2016

ALICE

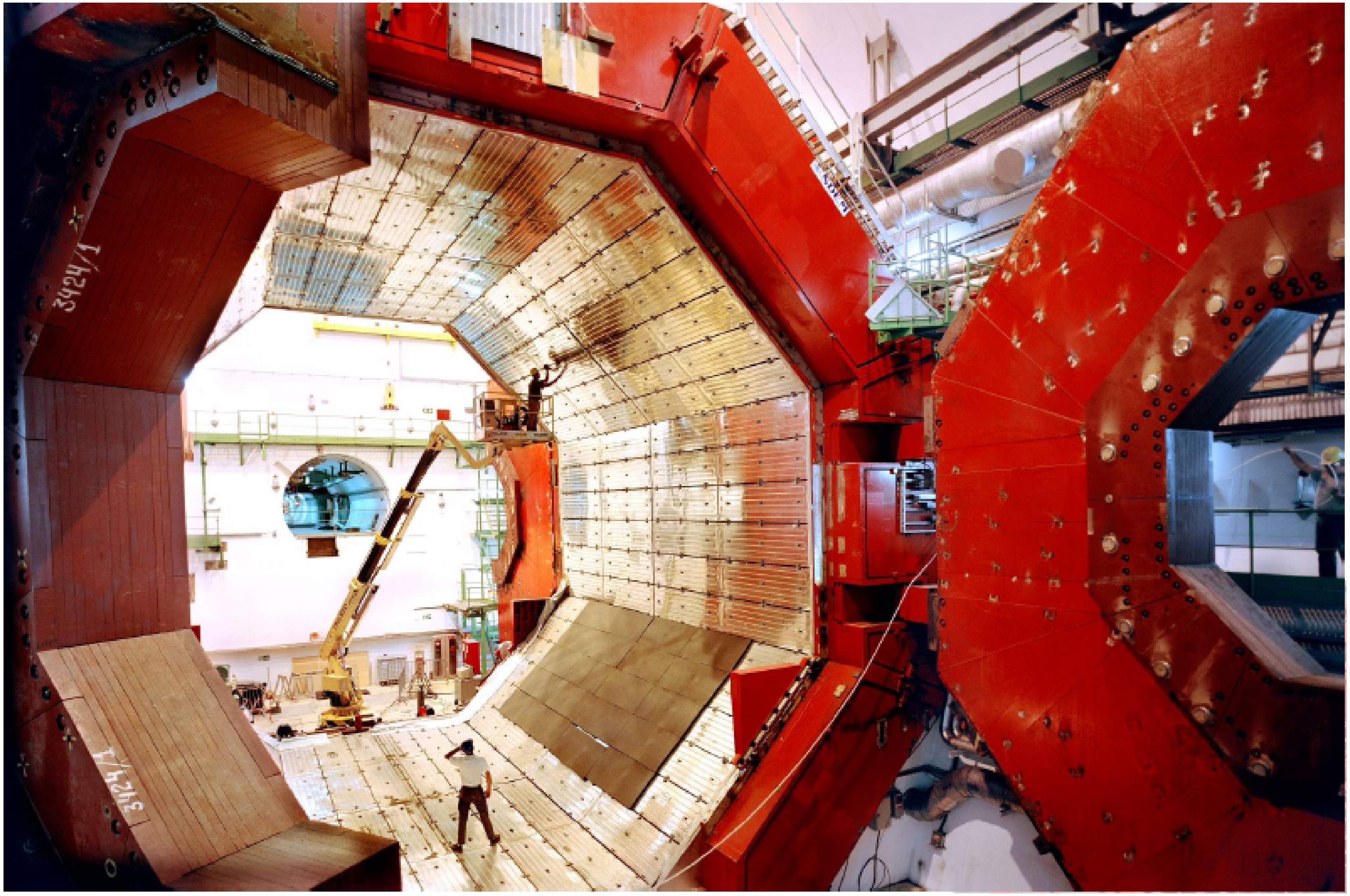


42 countries, 174 institutes and 1800+ members

The ALICE detector

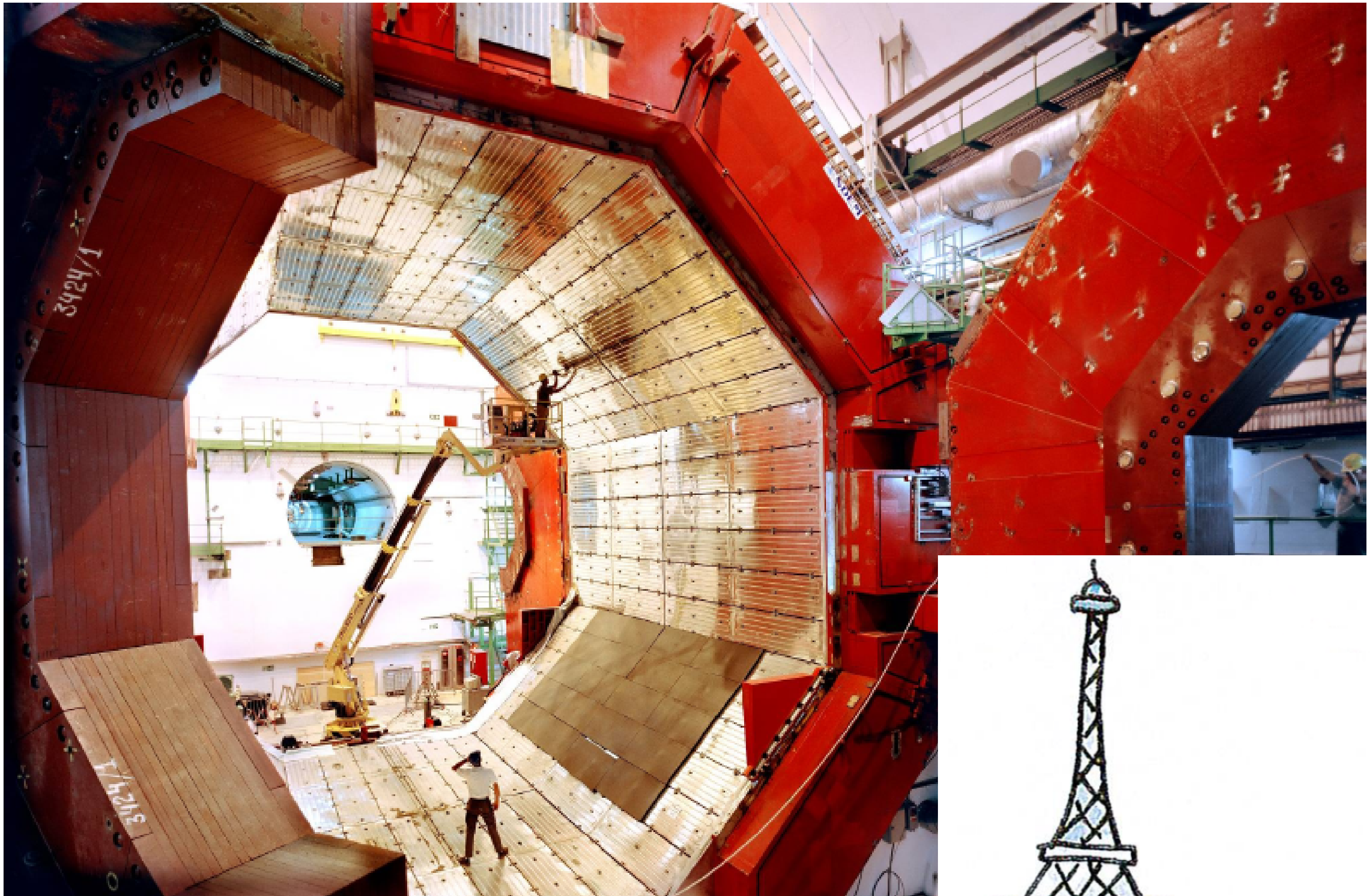


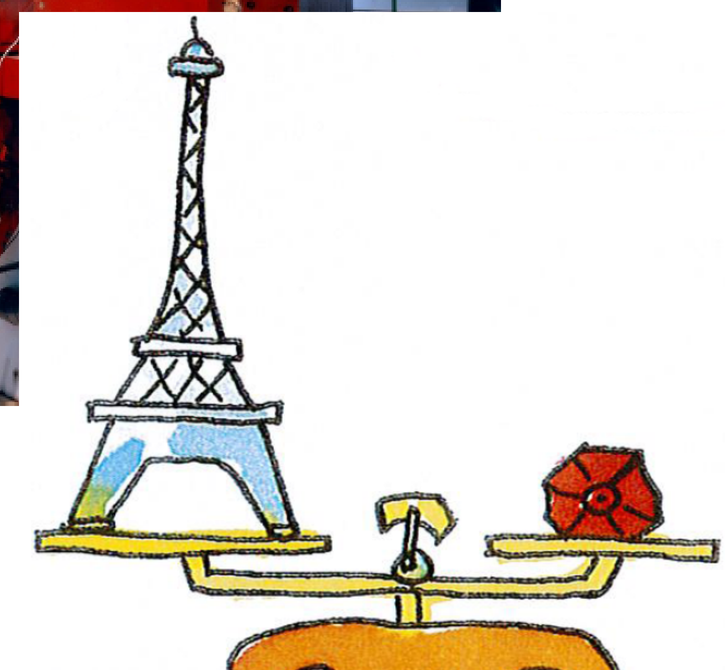
The L3 solenoid magnet



- It creates a uniform 0.5 T magnetic field

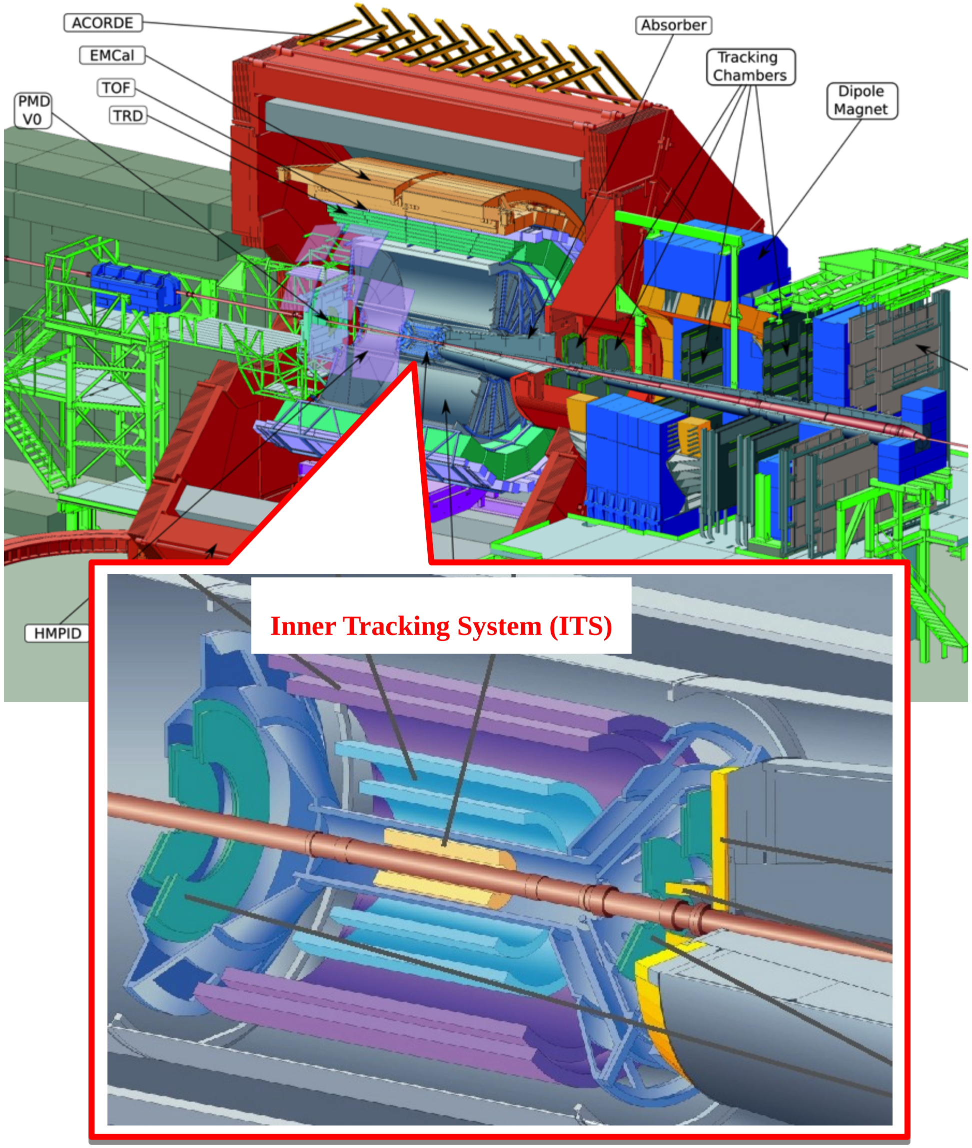
The L3 solenoid magnet





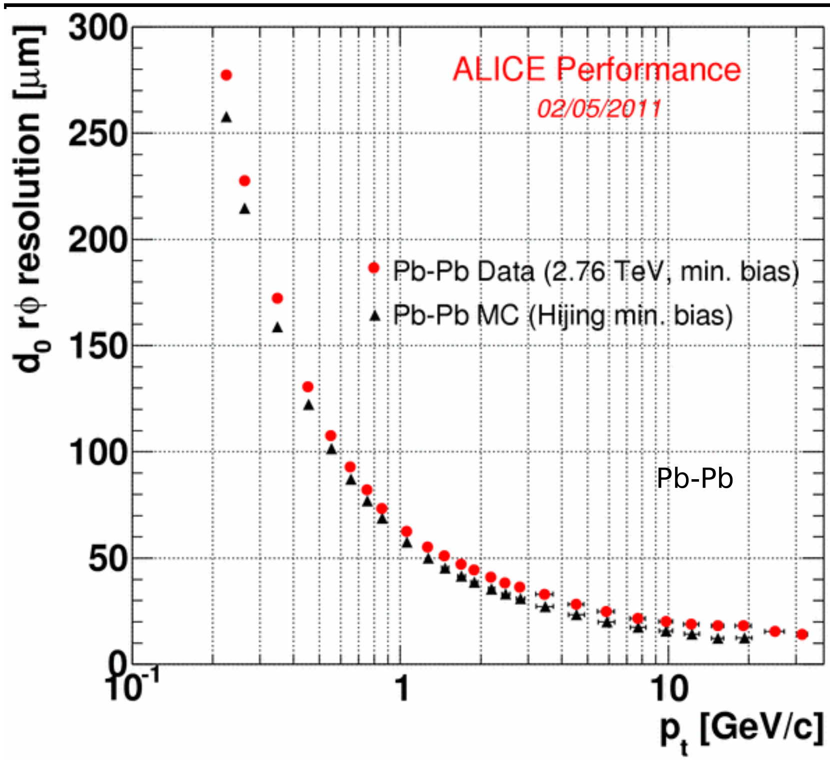
- It creates a uniform 0.5 T magnetic field
- As heavy as the Eiffel tower

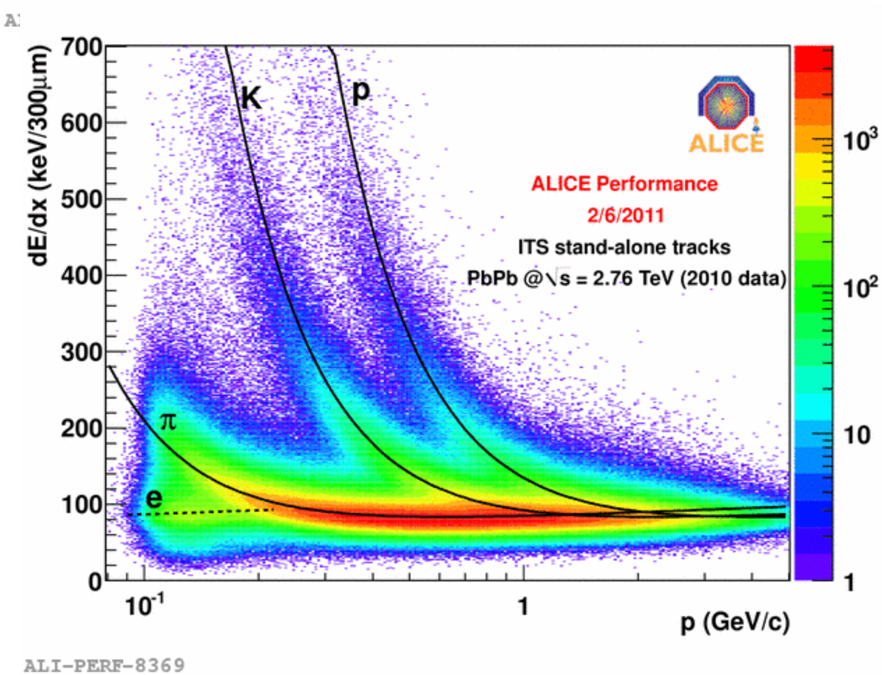
The Inner Tracking System (ITS)



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

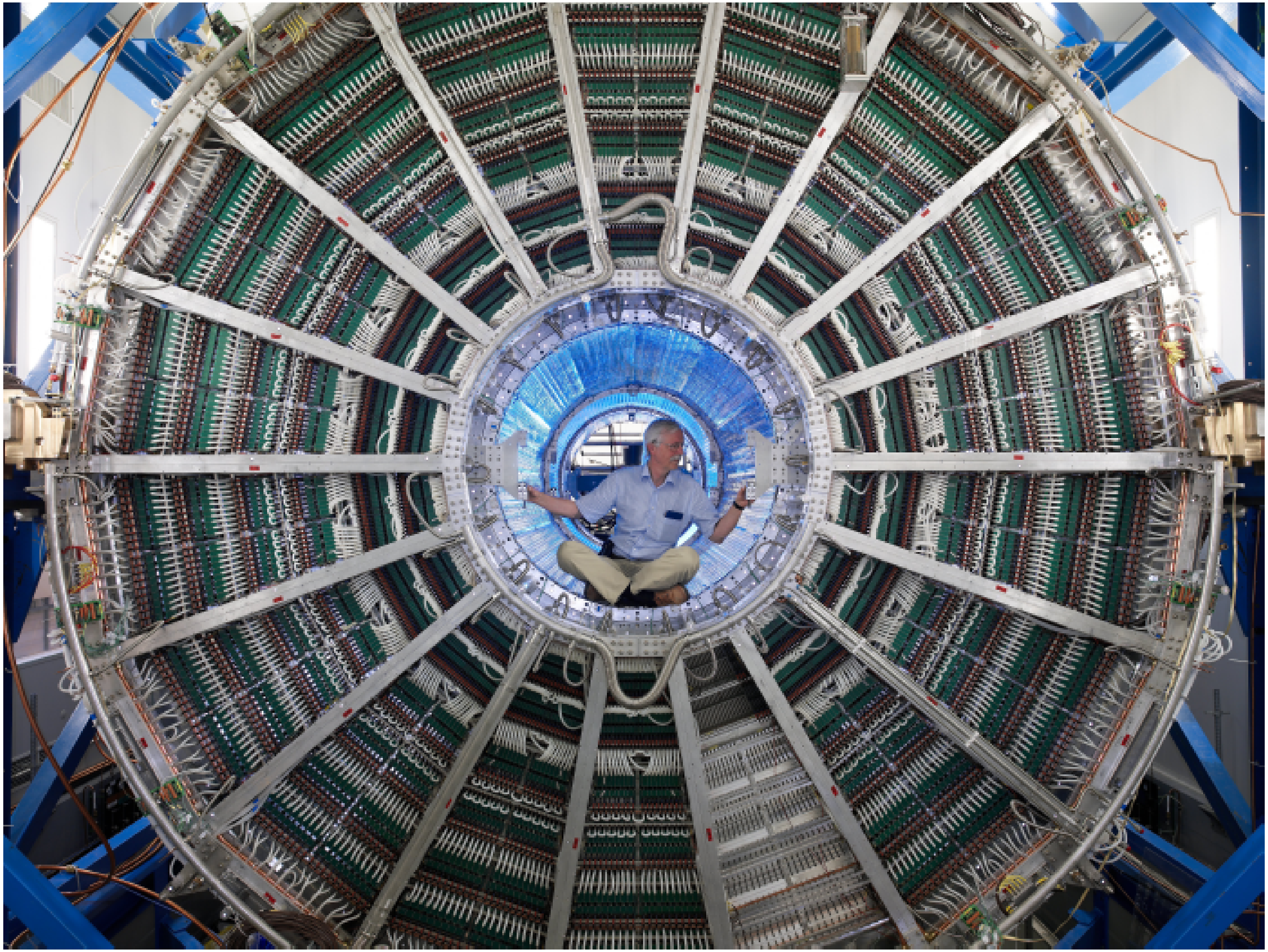
Inner Tracking System (ITS)





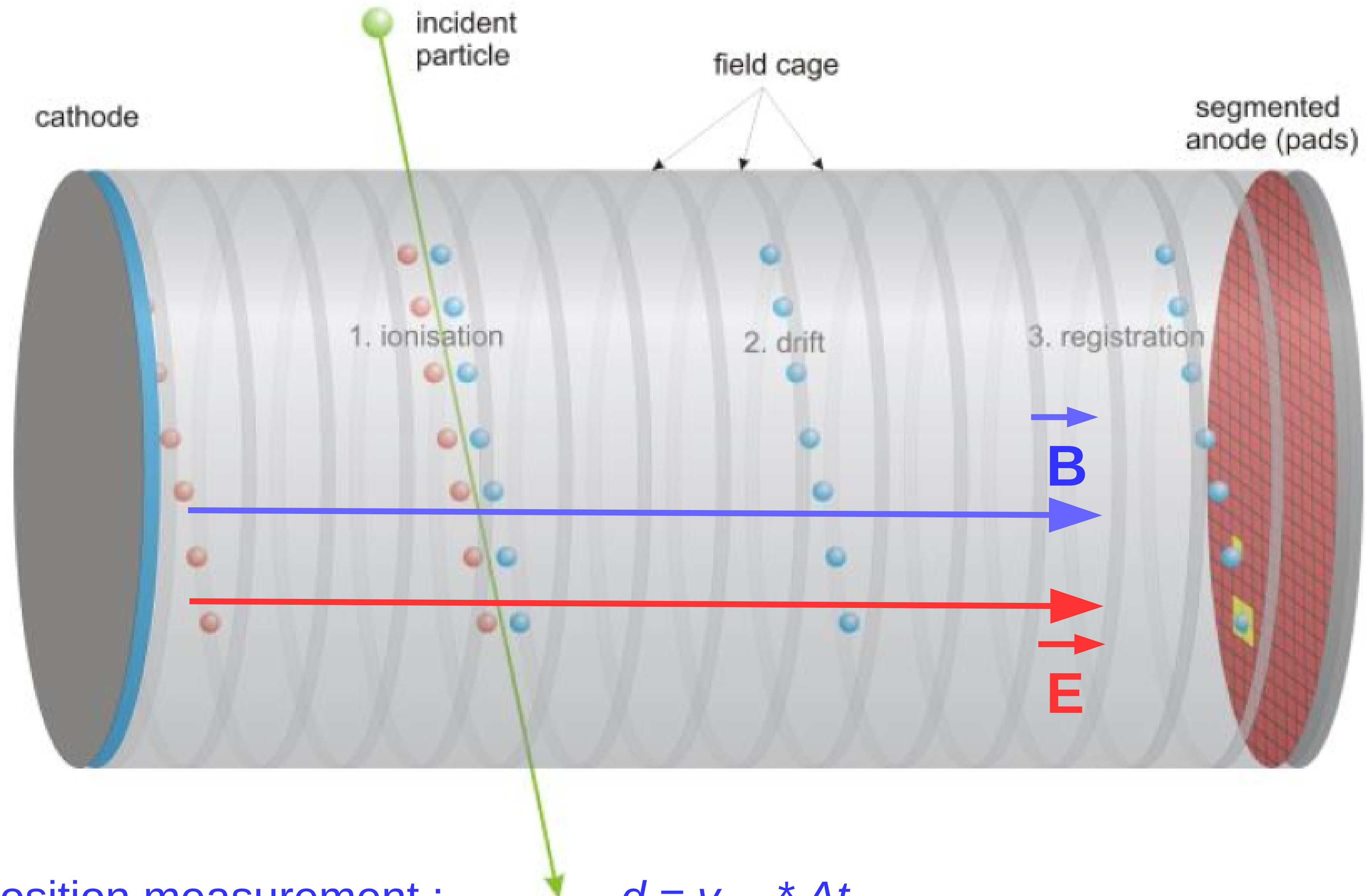
- Very high spatial resolution
  - Locates the collision vertex and secondary vertices from heavy quark decays
- It also performs particle identification via specific energy loss, but less precise than TPC

The TPC



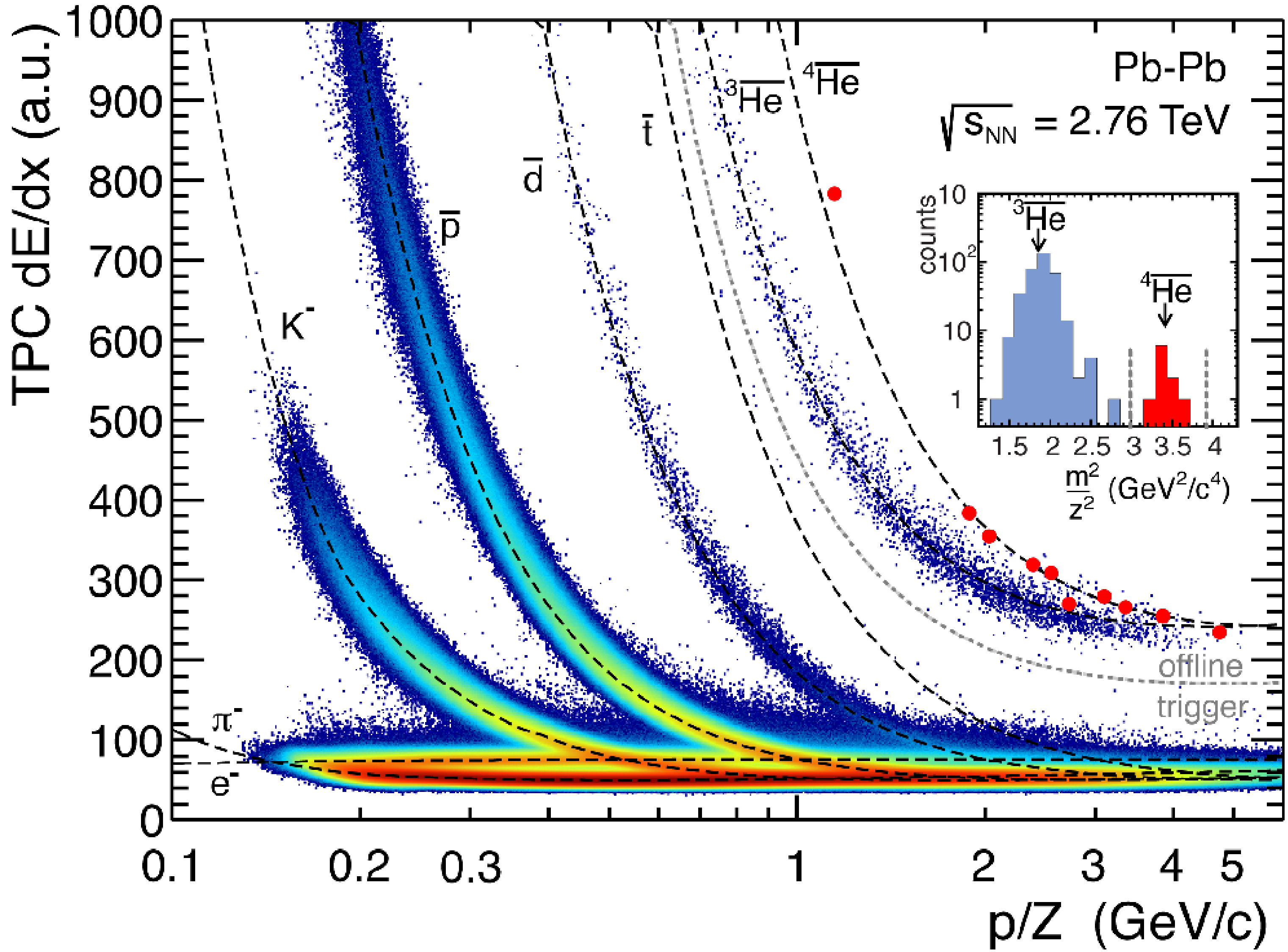
- The Time Projection Chamber is the main ALICE detector
- It is the largest TPC in the world
- 500 Mega-voxel 3D digital camera -> takes ca. 1000 pictures per second

TPC working principle



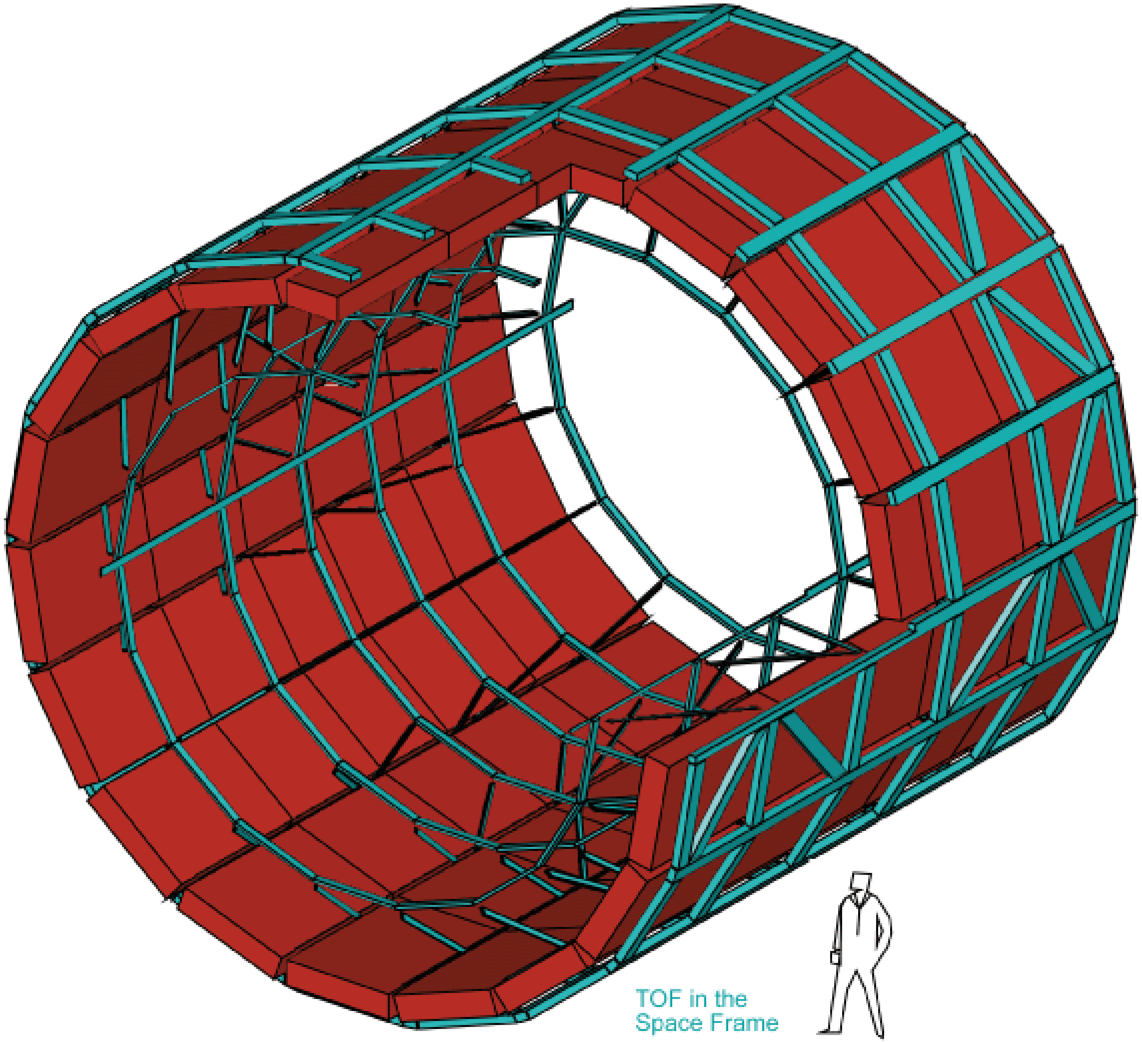
- Position measurement : $d = v_{drift} * \Delta t$
- Momentum measurement: $p_T = q*B*r$

Particle identification with the TPC



- Particles are identified using their specific energy loss in the TPC gas volume
- Highest mass anti-nuclei observed with the current data sample: anti-^{4}He

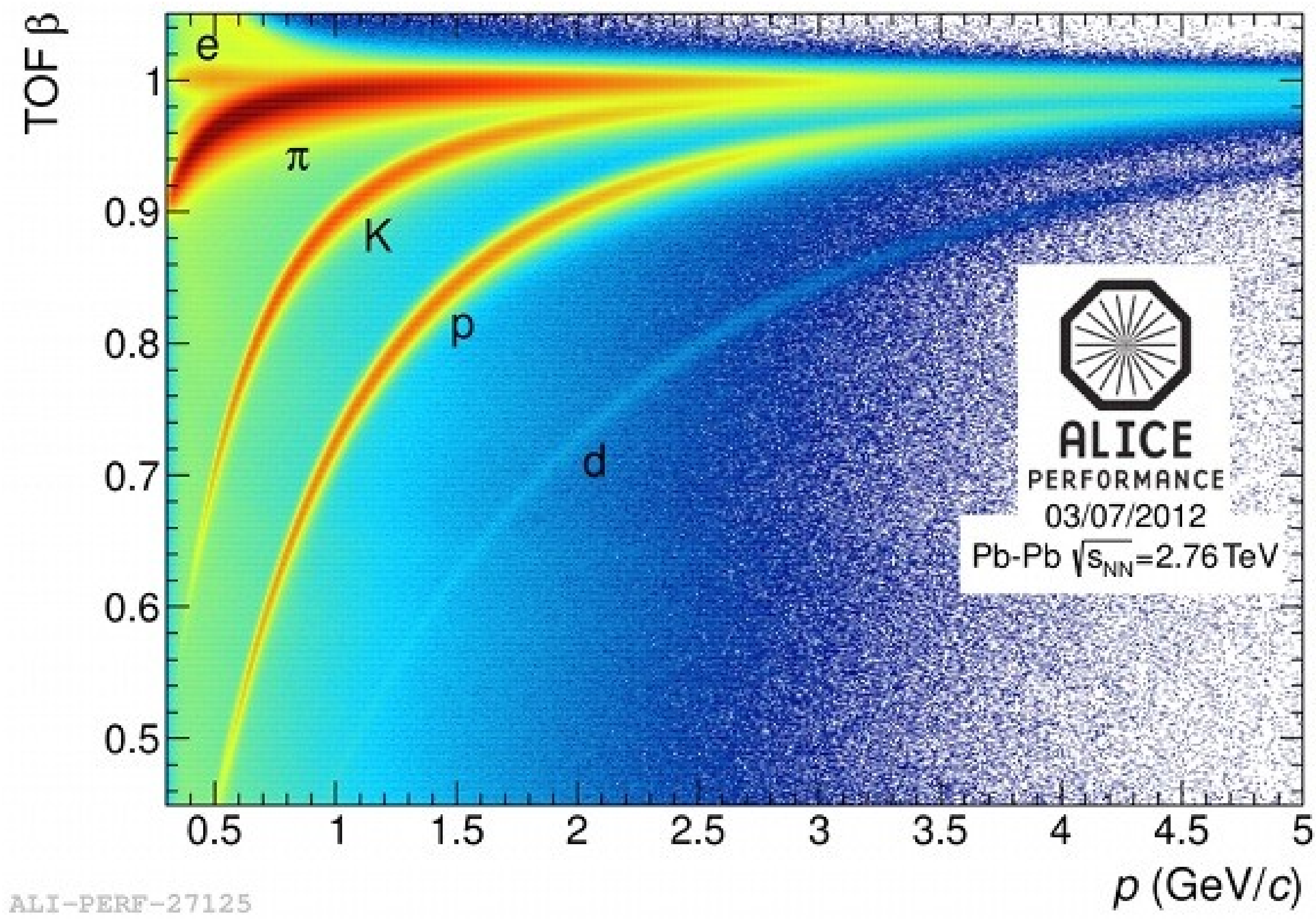
The Time-of-Flight detector (TOF)



$V = L/\Delta t$

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

Particle identification using TOF



- Extends the particle identification of the TPC to higher momentum

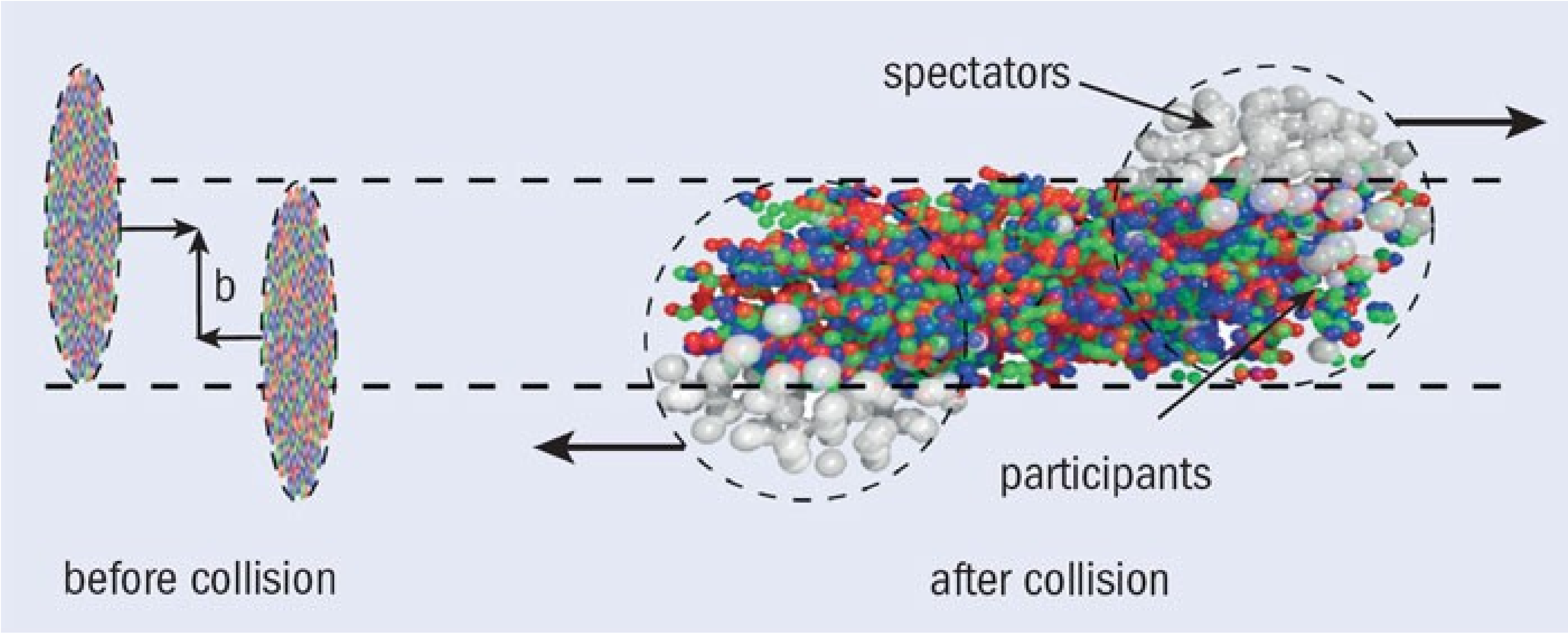
Other detectors

- 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 detector (HMPID): hadron identification at high momentum
  - ...

Physics results

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})
- Number of binary nucleon-nucleon collisions (N_{coll})

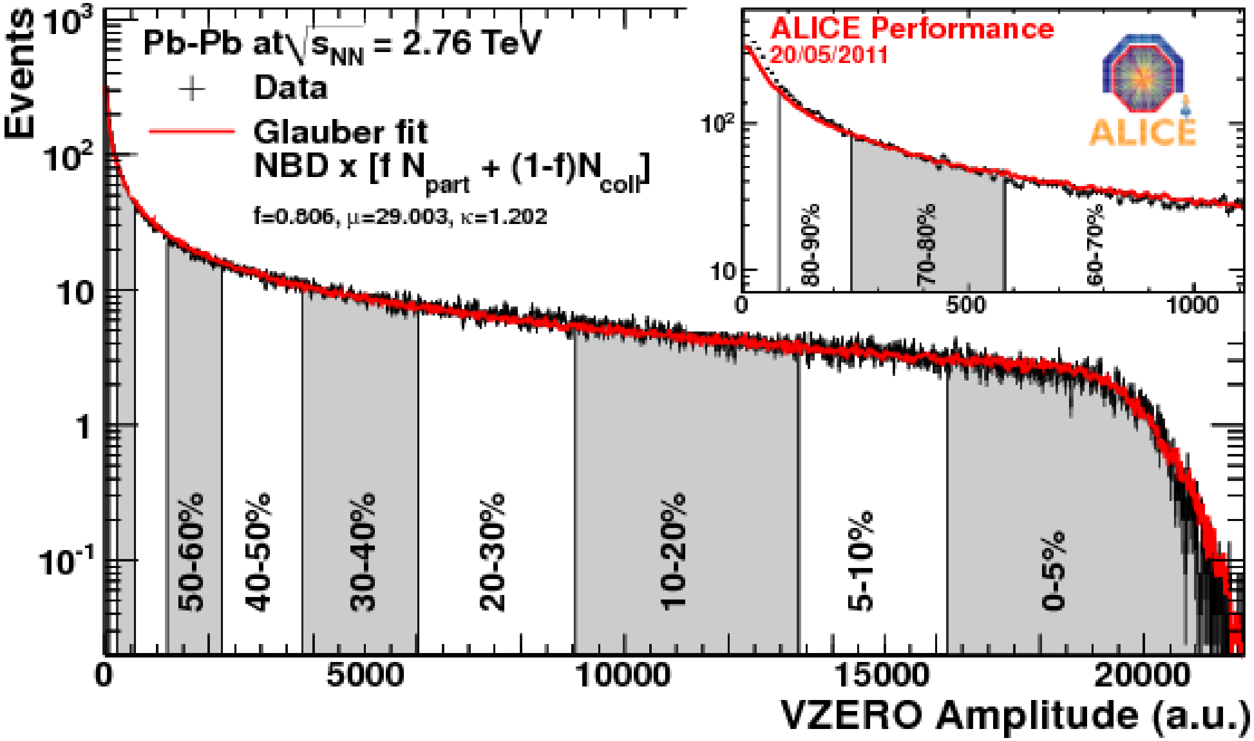


What are the "control parameters"

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

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

  - e.g. 0-10% are the 10% most central collisions
  - e.g. 90-100% are the 10% most peripheral collisions

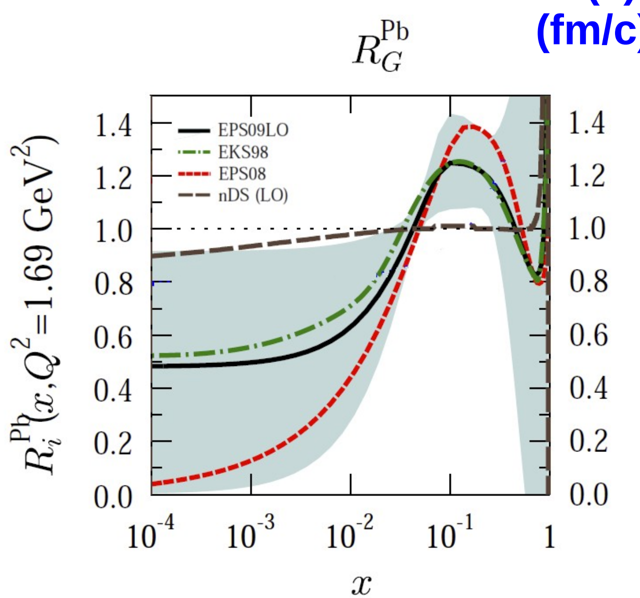


Stages of a high-energy nucleus-nucleus collision

Initial state

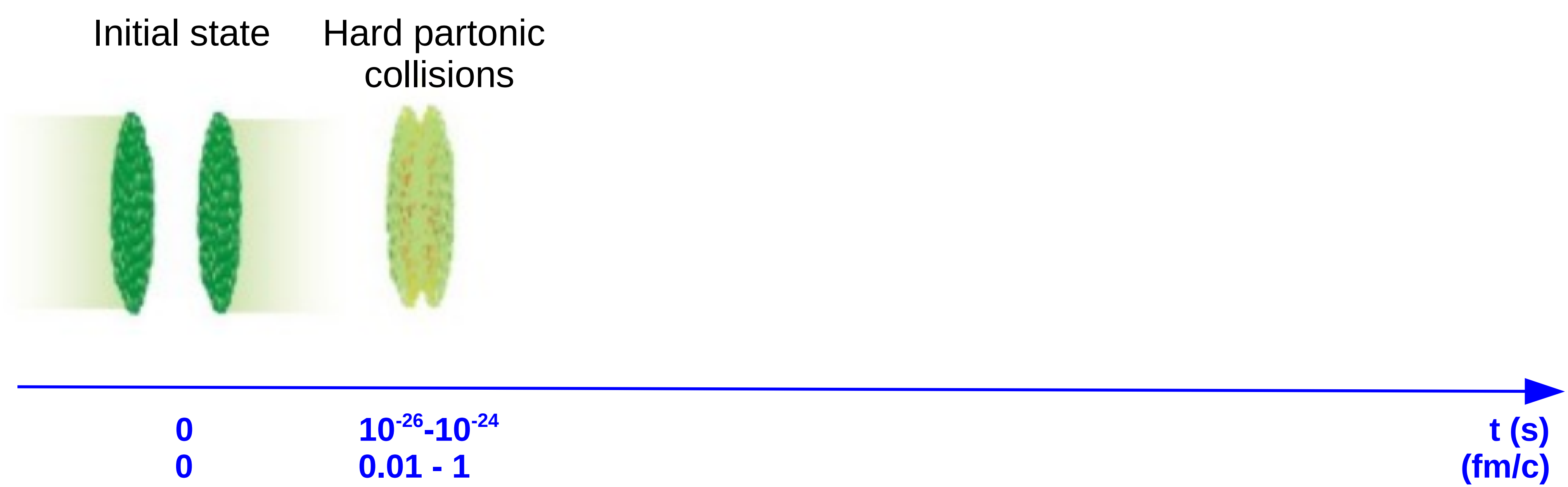
0
0

t (s)
(fm/c)



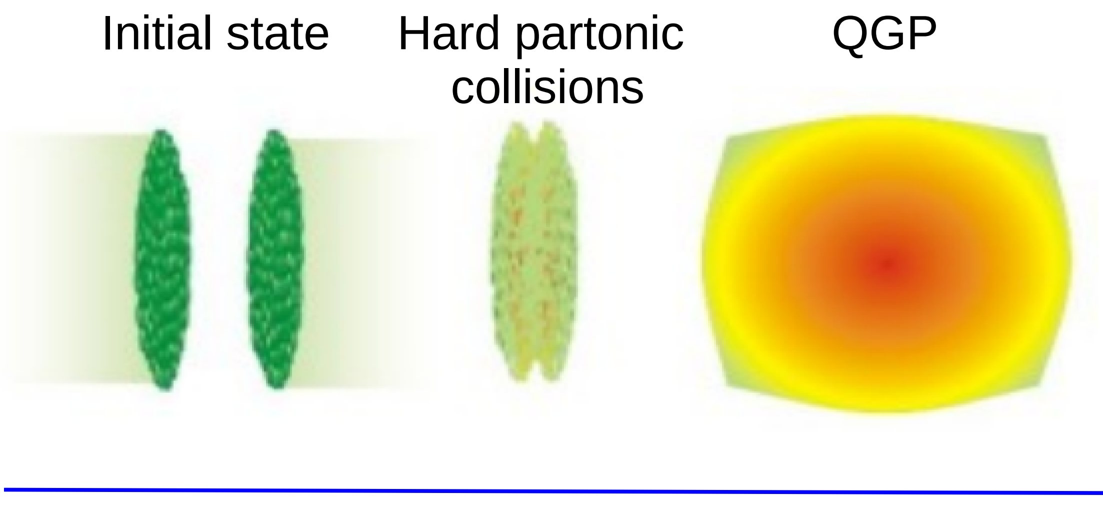
- Highly Lorentz contracted nuclei
- Initial state extremely important, interesting in itself
  - Gluon shadowing (modification of the gluon PDF in nuclei)
  - Crucial for disentangling the so called "cold nuclear matter"(CNM) effects from genuine hot medium effects

Stages of a high-energy nucleus-nucleus collision



- Initial hard collisions take place
- Most of the entropy is created now → gluons and quark pairs
- Equilibrium (thermalization) takes place rapidly

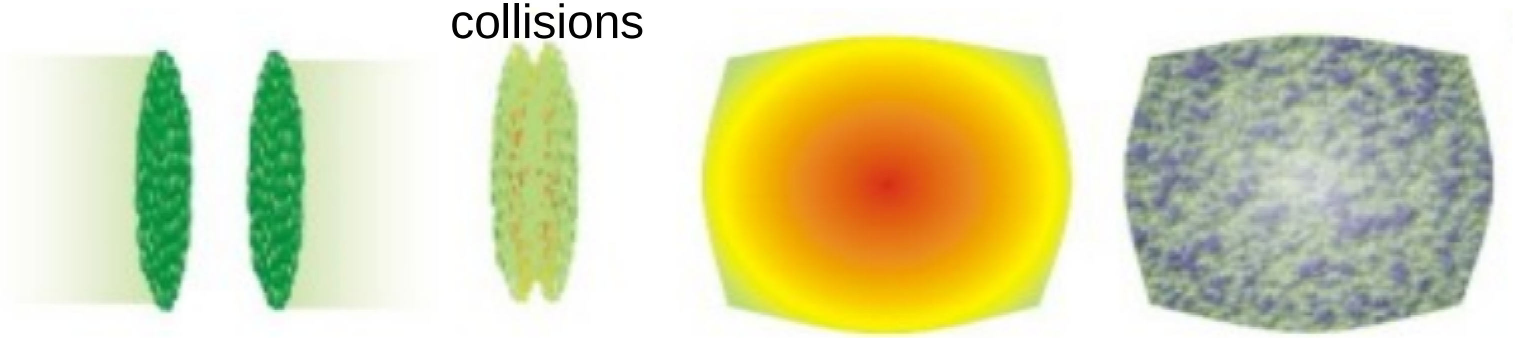
Stages of a high-energy nucleus-nucleus collision



t (s)	0	10^{-26}-10^{-24}	10^{-24}-10^{-23}
(fm/c)	0	0.01–1	1-10

- Deconfined Quark-Gluon Plasma phase
- System expands and cools hydrodynamically

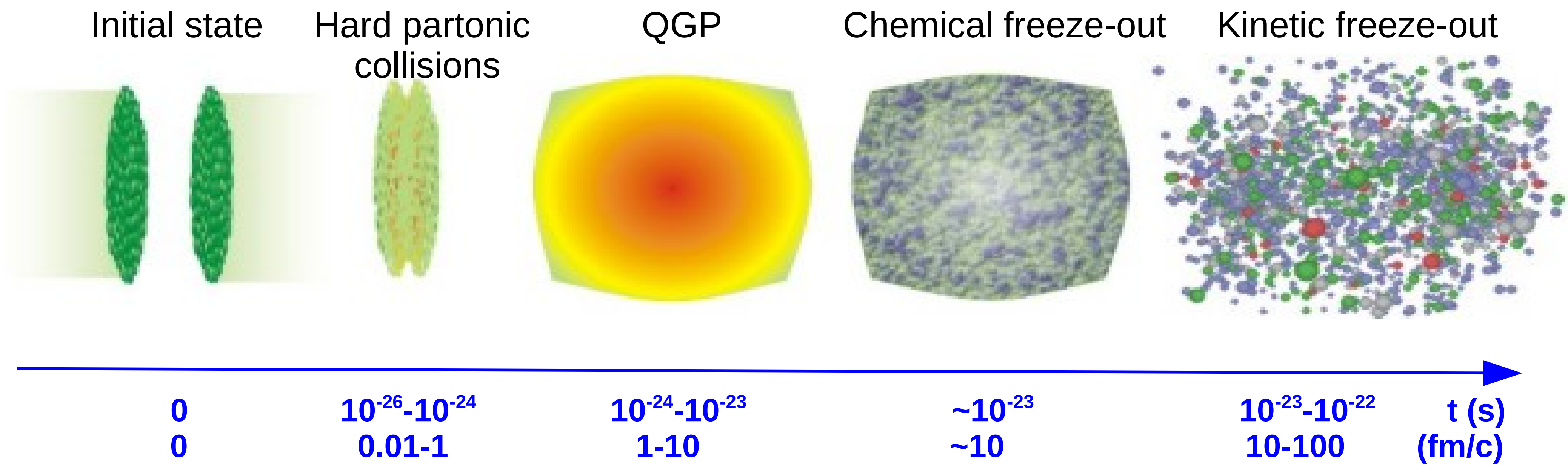
Stages of a high-energy nucleus-nucleus collision



	Initial state	Hard partonic collisions	QGP	Chemical freeze-out	
	0	10^{-26}-10^{-24}	10^{-24}-10^{-23}	$\sim 10^{-23}$	t (s)
	0	0.01-1	1-10	~10	(fm/c)

- Hadronization: quarks and gluons form hadrons
- Non-perturbative process
- Chemical freeze-out: inelastic collisions cease; yields of various particle species are frozen

Stages of a high-energy nucleus-nucleus collision

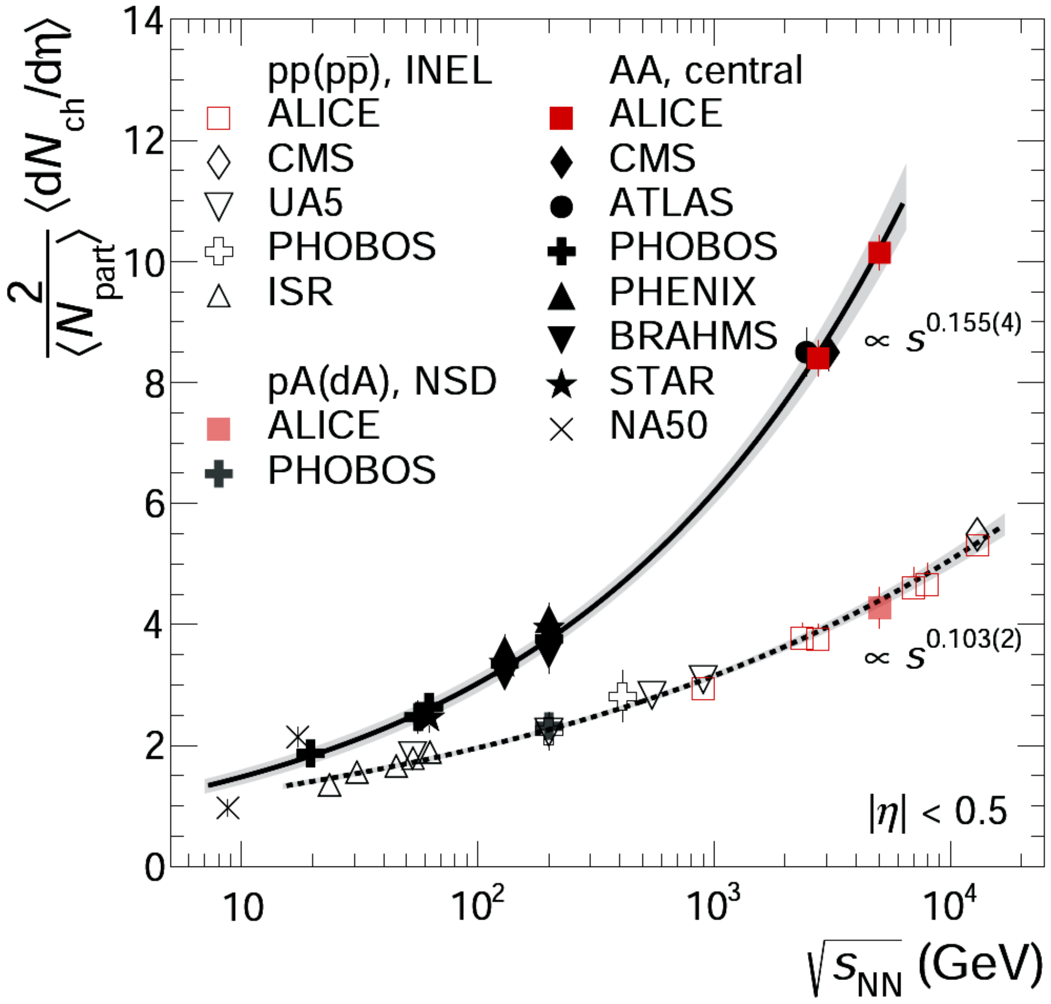


- Kinetic freeze-out:
  - Elastic collisions cease
  - Kinetic distributions are frozen

- We measure only at the latest stages but we want to understand the hard partonic and the QGP stages... extremely challenging!

Bulk particle production

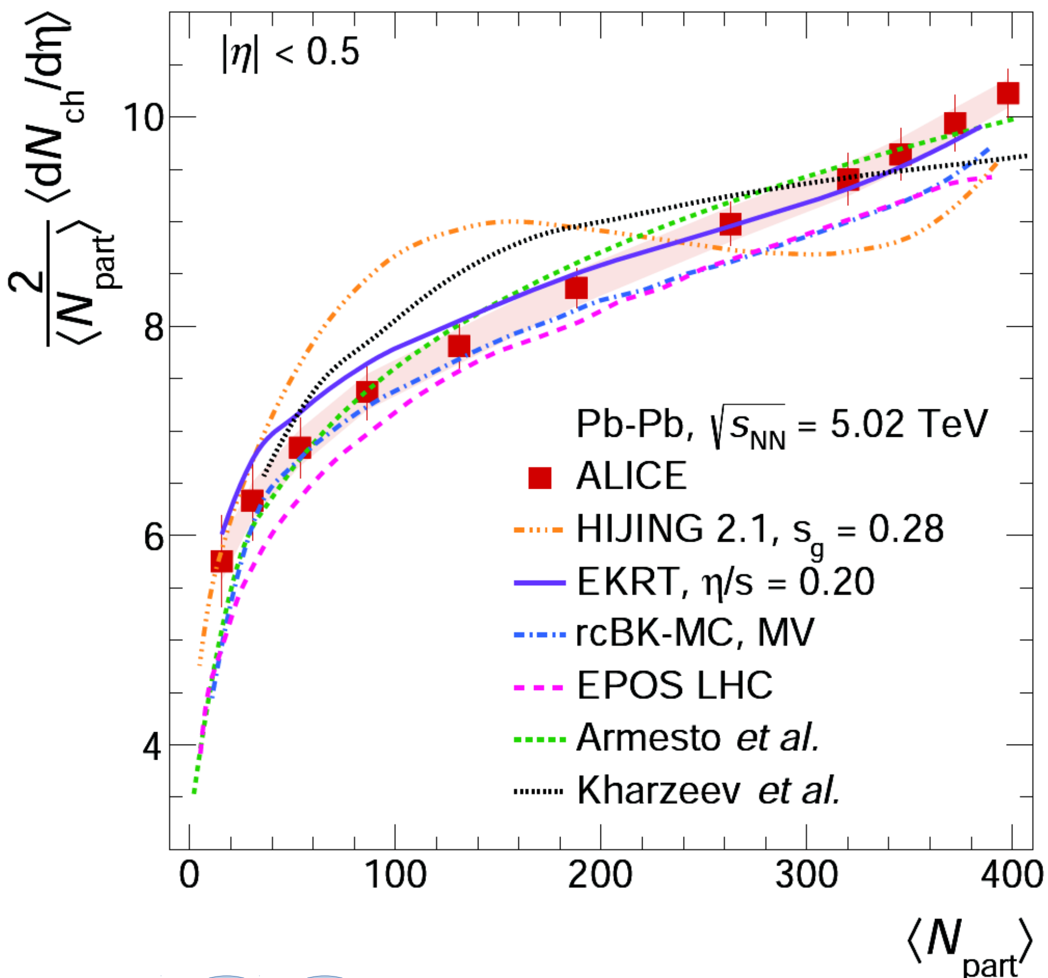
ALICE Collaboration, arXiv:1512.06104



- 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

Bulk particle production

ALICE Collaboration, arXiv:1512.06104



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- Yield per participant pair also grows towards more central collisions

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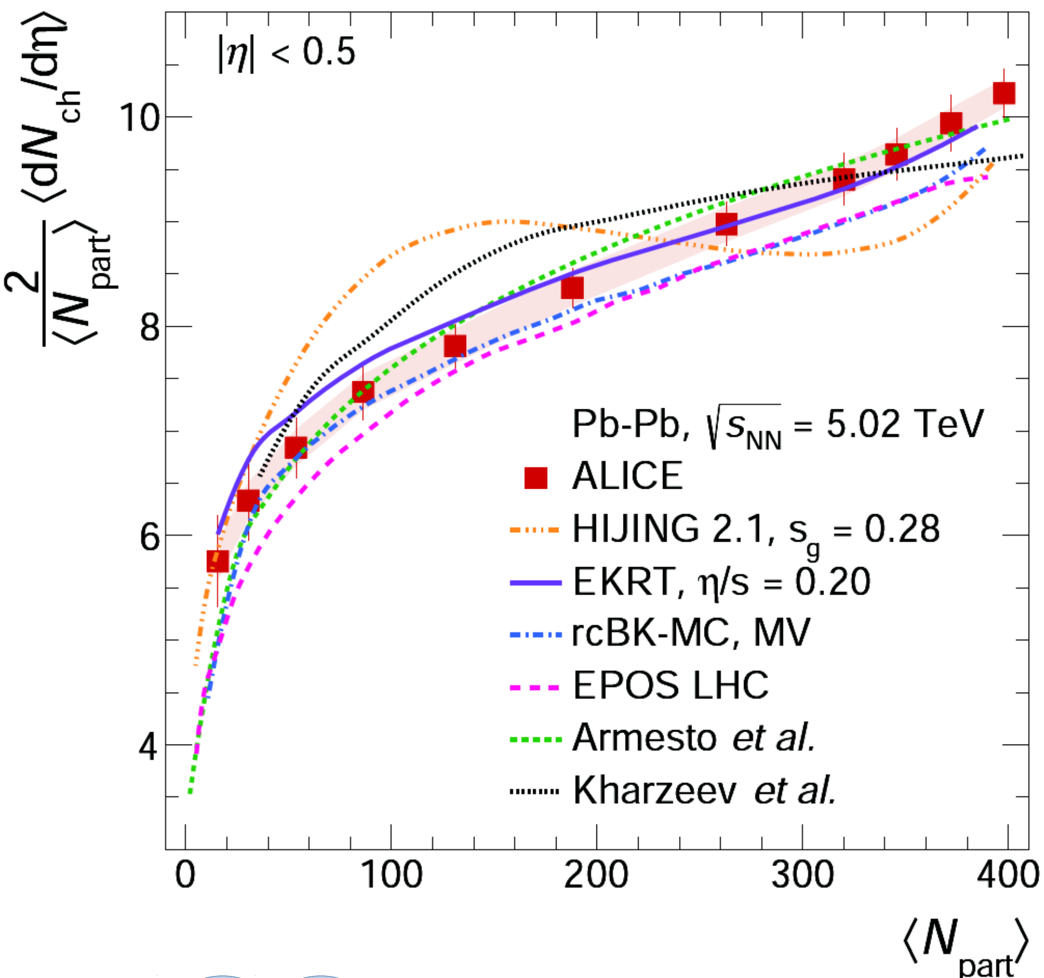
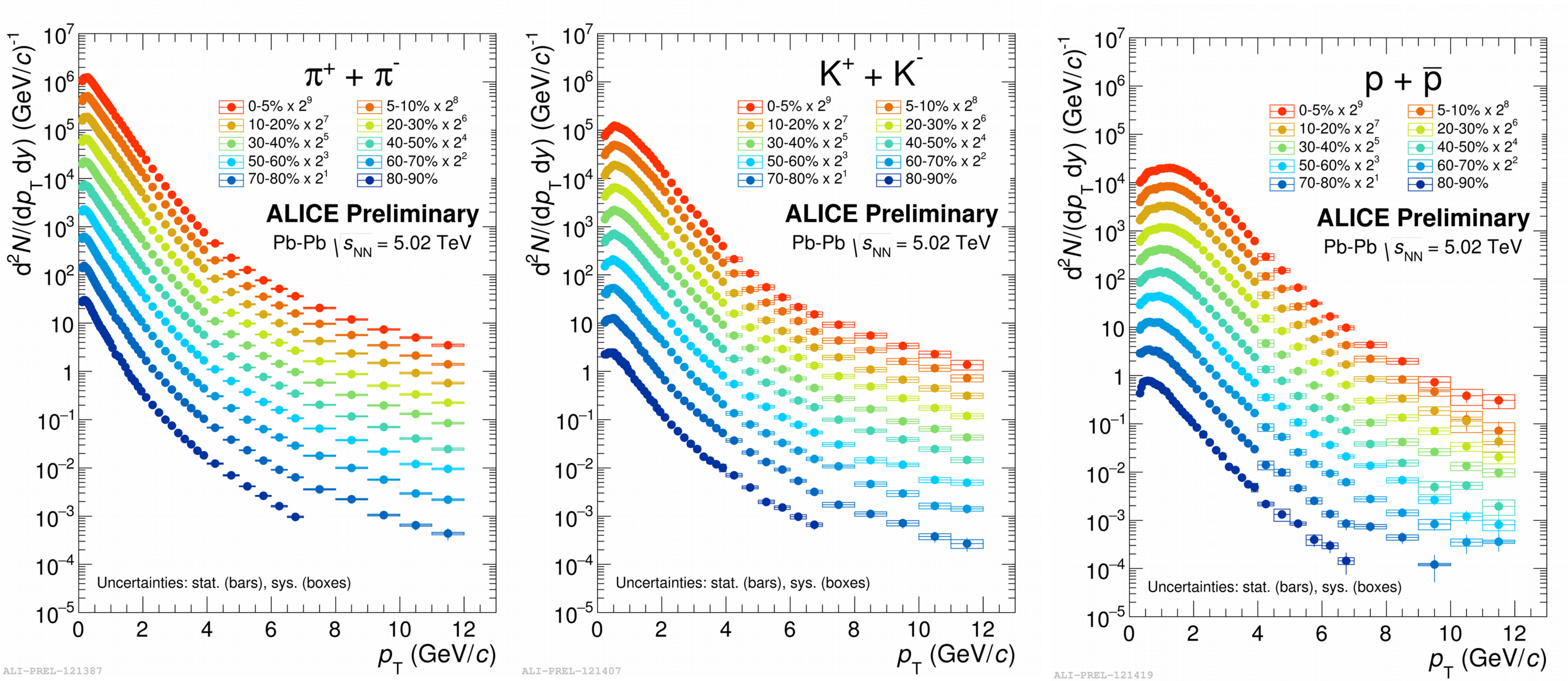


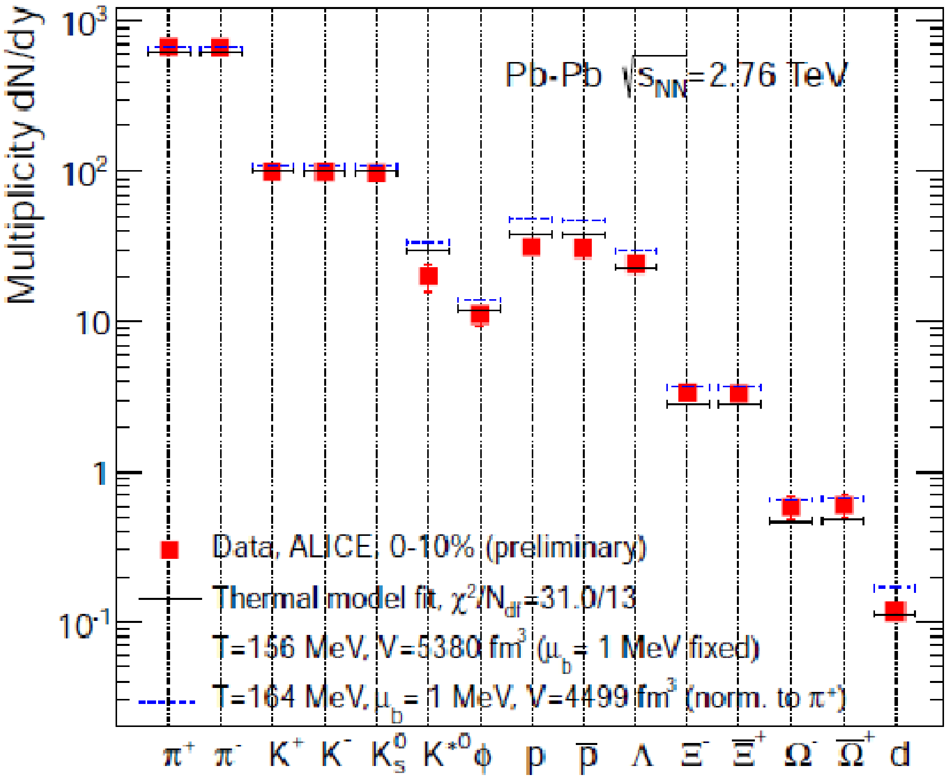
- Yield per participant pair is larger in nuclear collisions than in proton-proton collisions:
  - large entropy production
- The difference between nuclear and pp collisions also grows rapidly with energy
- Yield per participant pair also grows towards more central collisions
- These results allow to 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



- Thermal fits of hadron abundancies:

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

- Quantum numbers conservation

  $\mu=\mu_B B+\mu_{I3} I_3+\mu_S S+\mu_C C$

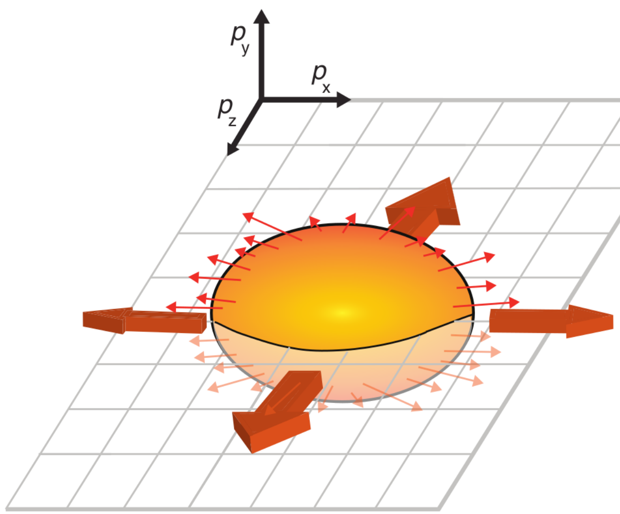
- Hadron yields N_i can be obtained using only 3 parameters: (T_{chem},μ_B,V)

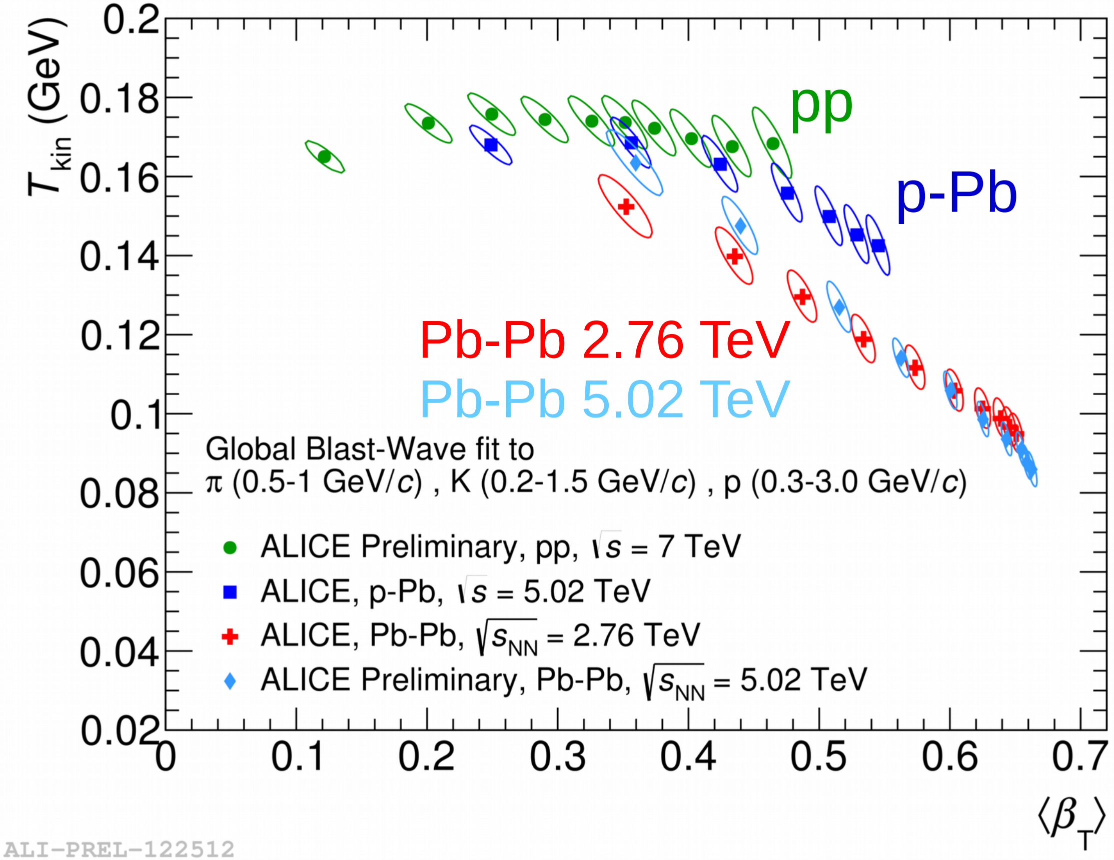
- The hadron abundancies are in agreement with a thermally equilibrated system

  T_{chem}=155-165 MeV

  $\mu_B \sim 0$

Kinetic freeze-out: p_T spectra

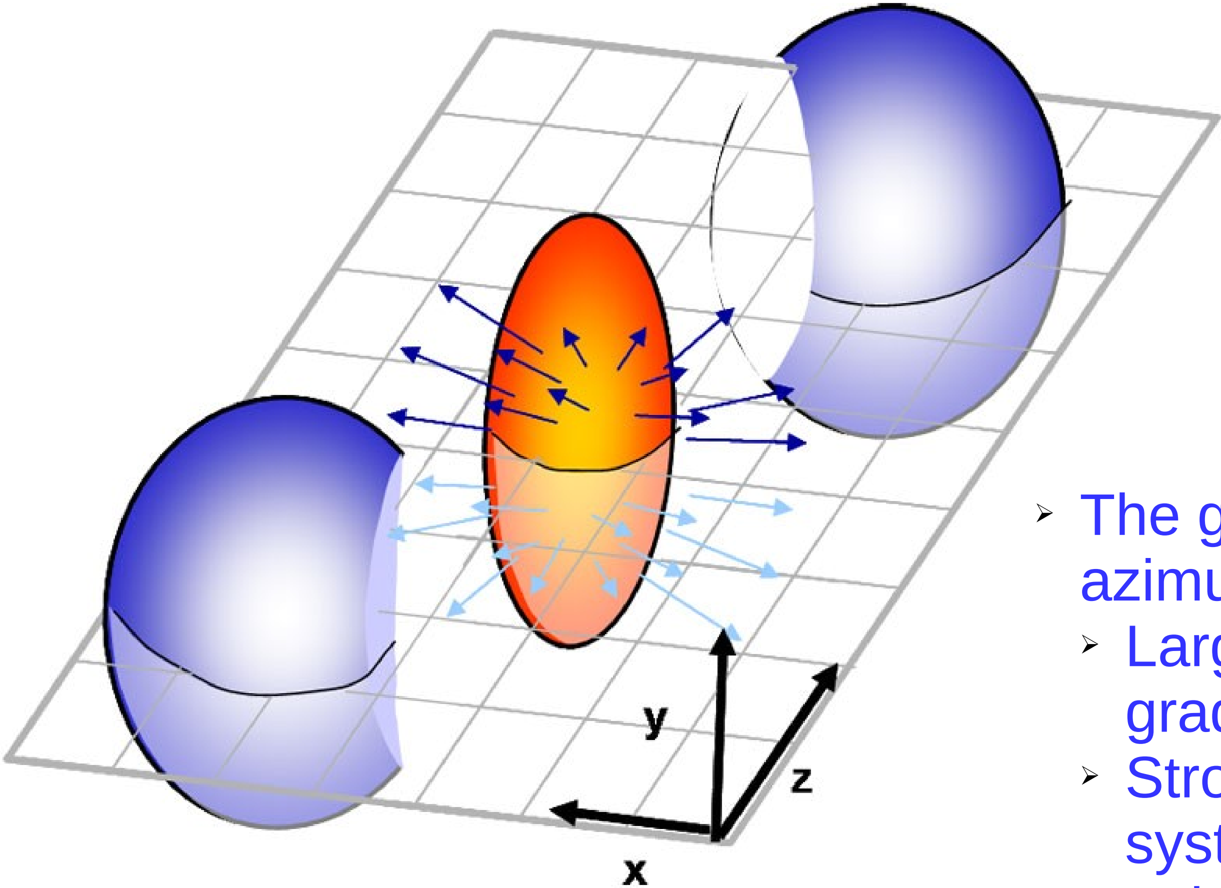




- Boltzmann-Gibbs Blast-wave model: expanding system characterized by a fluid velocity β_T and a kinetic freeze-out temperature T_{kin}

- 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

Elliptic flow (v_2). What is that?



$$\frac{dN}{d\phi} \sim [1 + 2v_1 \cdot \cos(\phi) + 2v_2 \cdot \cos(2\phi)]$$

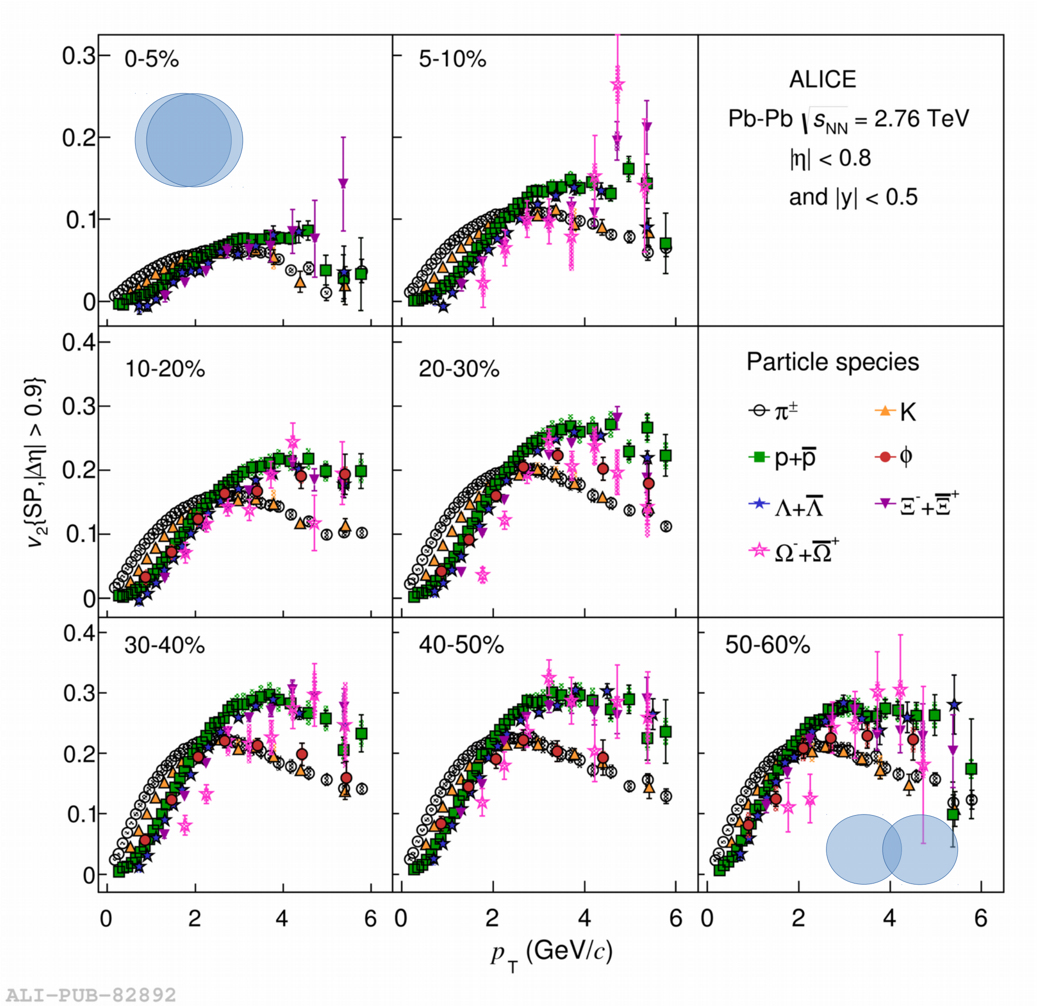
ϕ = azimuthal angle with respect to reaction plane,

$$v_2 = \langle \cos(2\phi) \rangle$$

0,180°: in-plane, 90,270°: out-of-plane

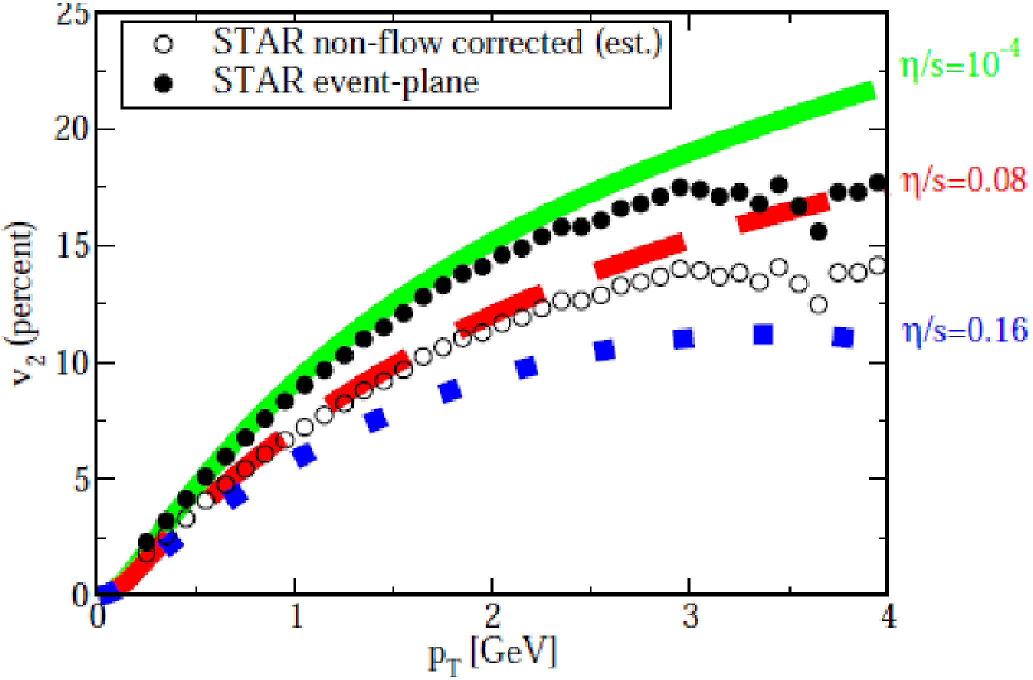
- The geometry of the collision is azimuthally non-uniform
  - Large initial energy density gradients
  - Strong multiple rescatterings in the system transform the geometrical anisotropy into a momentum anisotropy
- Measured using Fourier decomposition

Elliptic flow in high energy HIC



- Why is elliptic flow important?
- Quantifies the medium response to the initial state geometry, which is sensitive to:
  - Initial state properties
  - QGP properties like equation of state, transport coefficients, viscosity
  - hadronization

Elliptic flow in high energy HIC



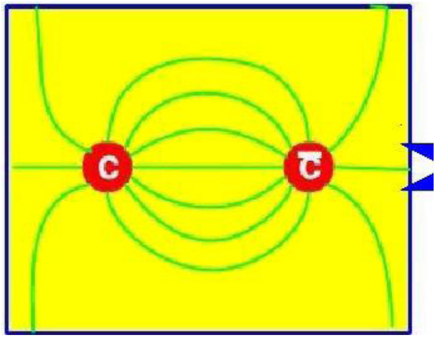
Luzum & Romatschke, arXiv:0804.4015

- Why is elliptic flow important?
- Quantifies the medium response to the initial state geometry, which is sensitive to:
  - Initial state properties
  - QGP properties like equation of state, transport coefficients, viscosity
  - hadronization
- 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

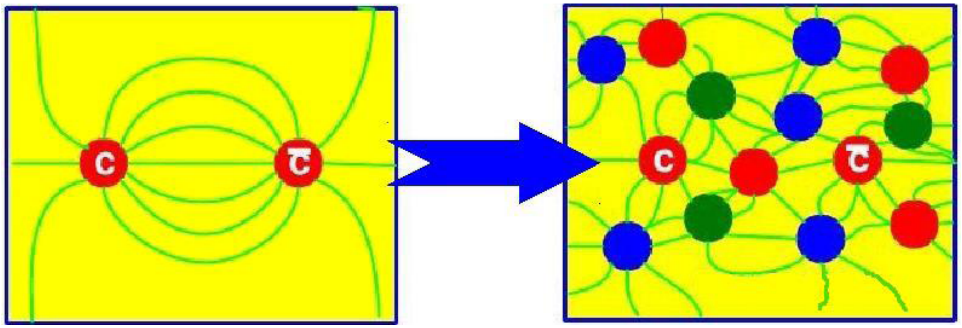
Heavy quarkonium and the QGP

- What are heavy quarkonia ?
  - Bound states of heavy quark anti-quark pairs, e.g. ψ ($c\bar{c}$) and Υ ($b\bar{b}$) families
  - Relatively large binding energy, e.g. for J/ψ is ~600 MeV
- Due to their large mass, heavy quarks can be produced only in initial hard partonic collisions and their number is conserved during the collision history
  - Ideal probe for QGP



Heavy quarkonium and the QGP

- The original idea (Matsui and Satz, PLB 178 (1986) 416):
  - In a deconfined medium with high density of color charges, the QCD analogue of the Debye screening can lead to heavy quarkonium suppression
  - No J/ψ if $\lambda_D < r_{J/\psi}$



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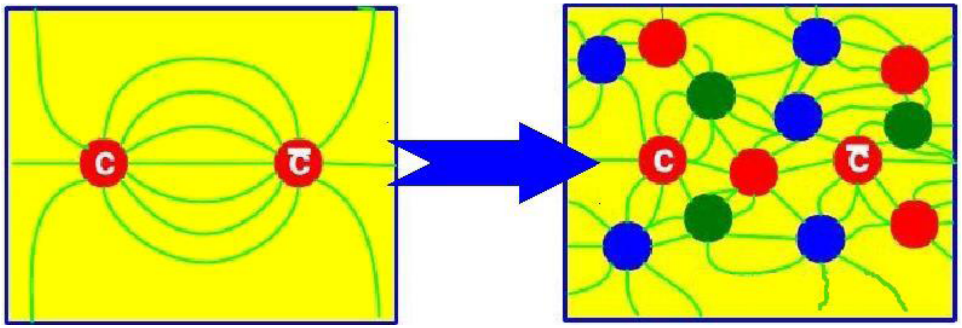
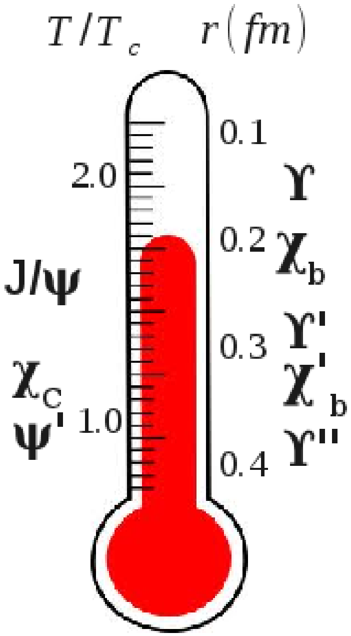
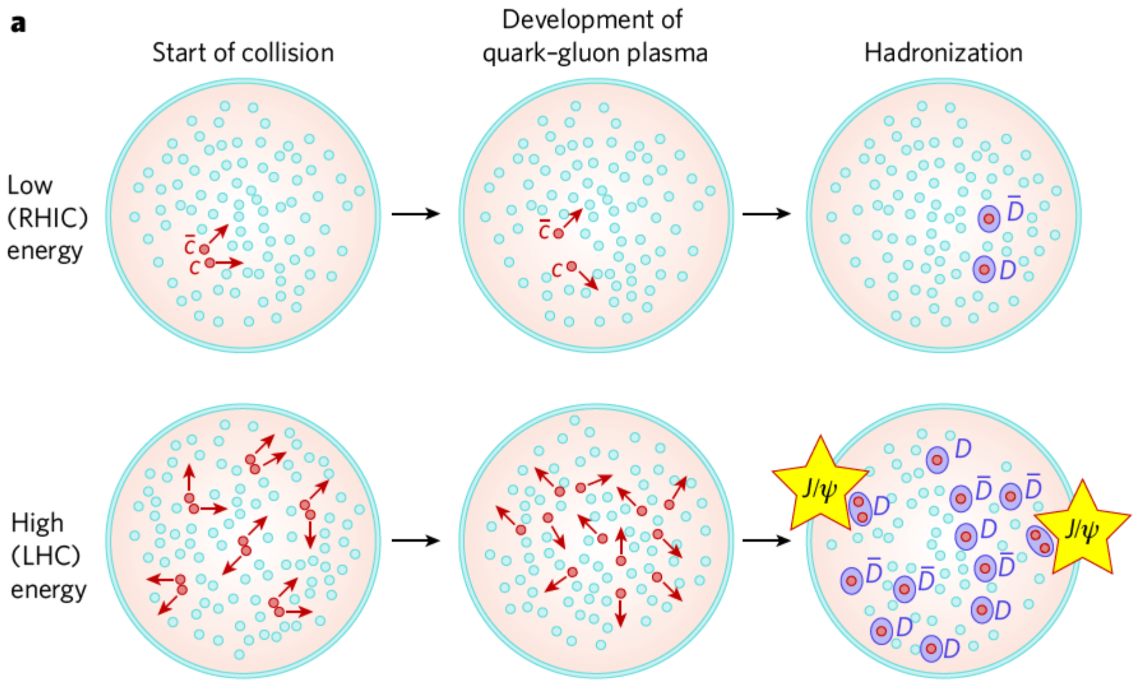
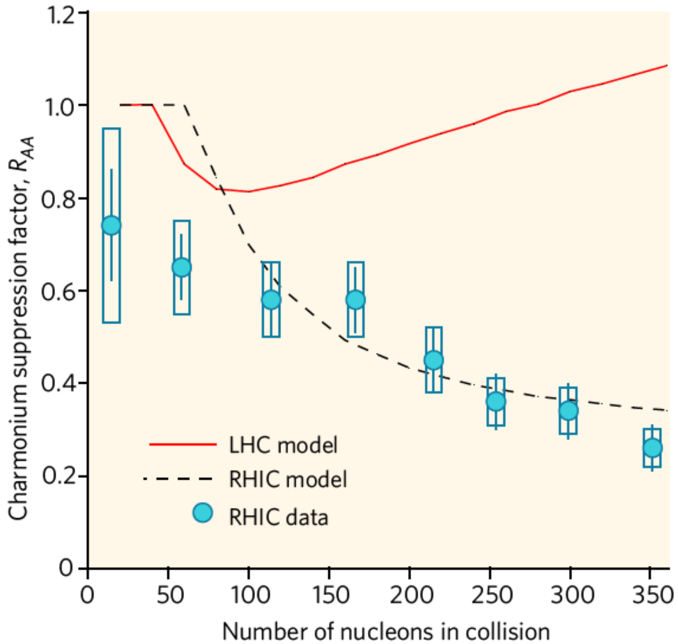


- The Debye length in QGP is a function of temperature so J/ψ and the other quarkonium states are expected to melt at different temperatures:
  - "Sequential melting"



Heavy quarkonium at the LHC (re-generation)





Nature 448 (2007) 302-309

- At the LHC, there are many charm quark-pairs created in one single collision (~100)
- Possible to create charmonium states on a statistical basis → enhancement of charmonium states at LHC
  - Open charm and quarkonia abundancies calculated assuming statistical hadronization.

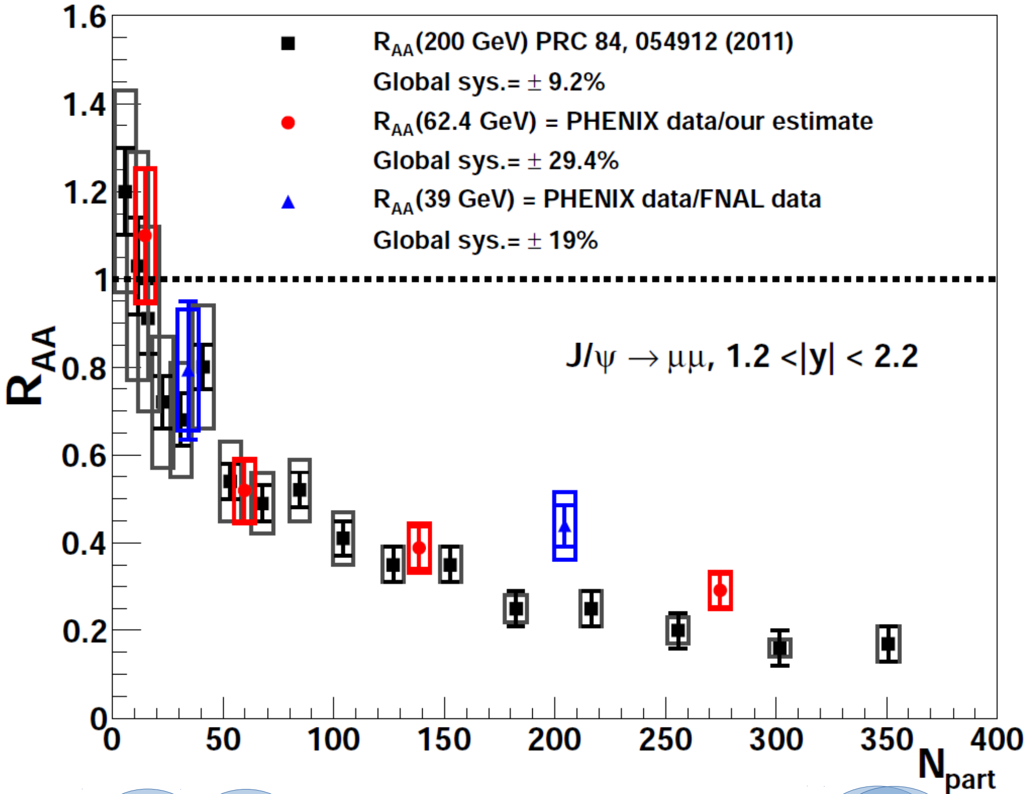
    Braun-Munzinger and Stachel, PLB 490 (2000) 196

    Thews et al., PRC 63 (2001) 054905

J/ψ suppression in Au-Au collisions at RHIC

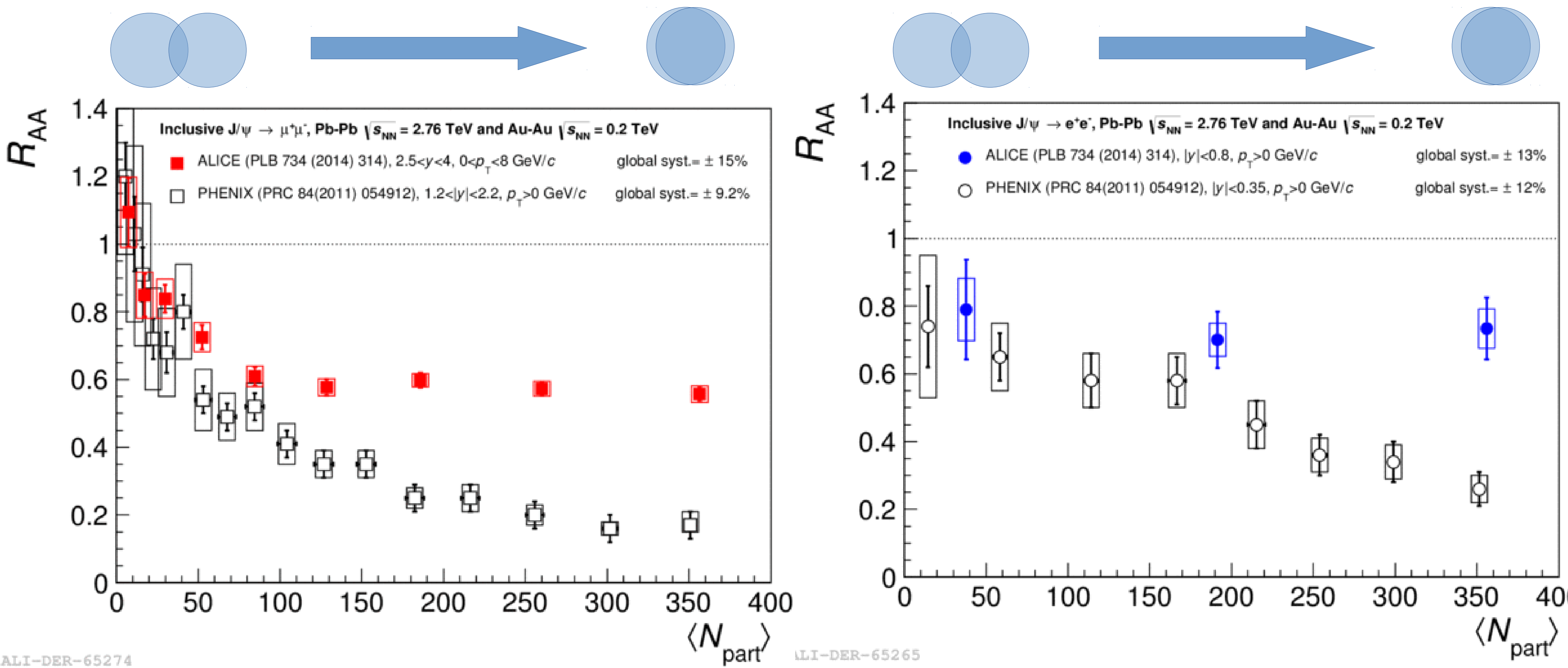
- Strong suppression observed in central Au-Au collisions at RHIC energies
- Evidence of color screening?
- Not completely clear yet: we still need to take into account feed-down from higher mass states (e.g., χ_c, ψ(2S)) and “cold nuclear matter” effects
  - Work ongoing

PHENIX arXiv:1208.2251



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

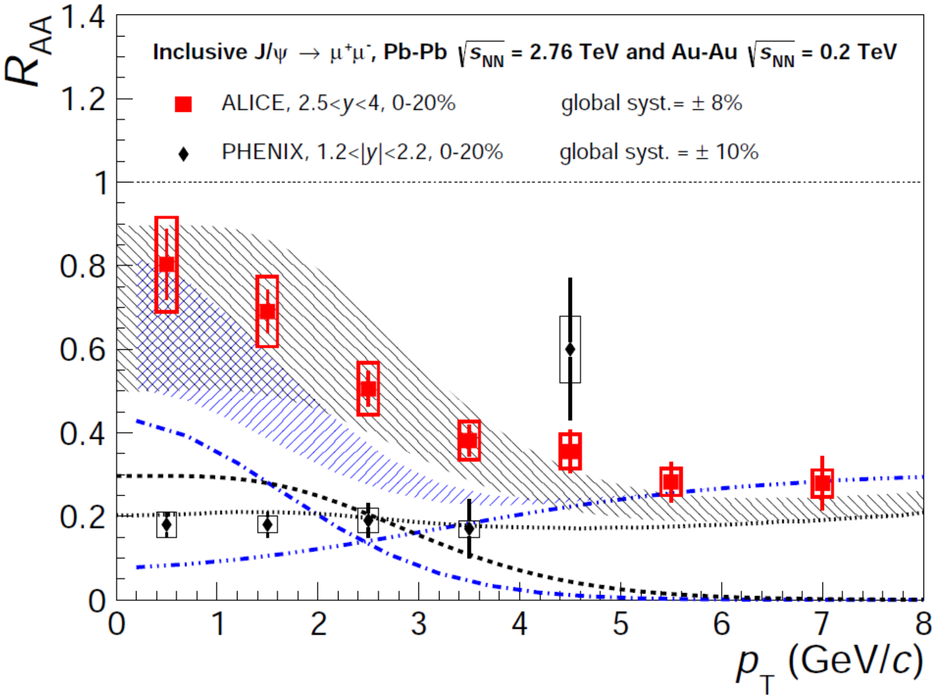
J/ψ at the LHC



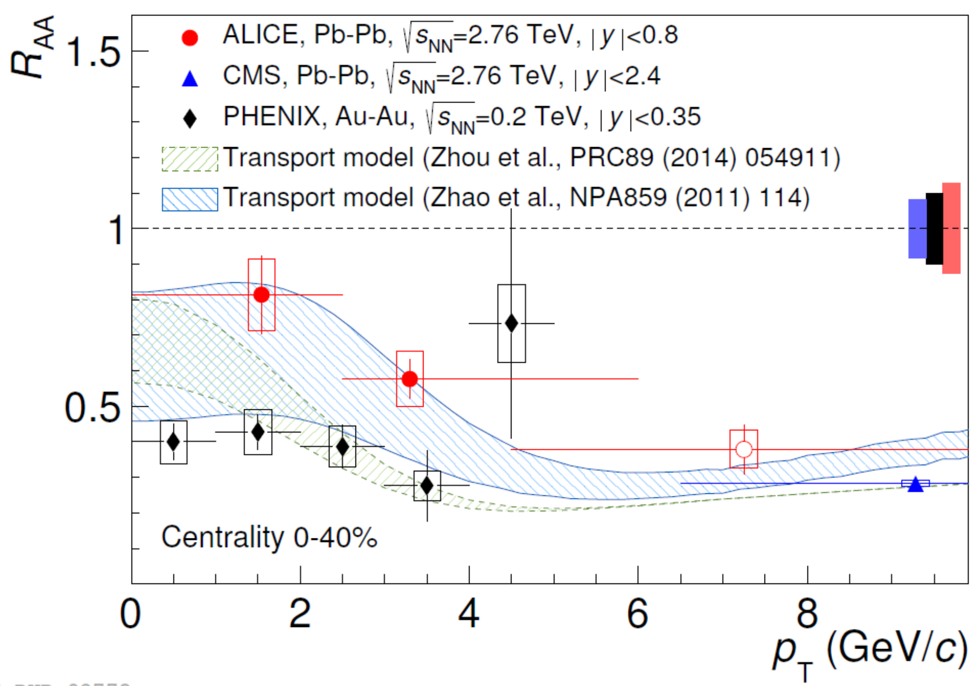
- ALICE results show smaller suppression compared to lower energies (PHENIX) in central collisions
- Indication that regeneration plays an important role in the production of charmonium

J/ψ suppression vs p_T

arXiv: 1506.08804

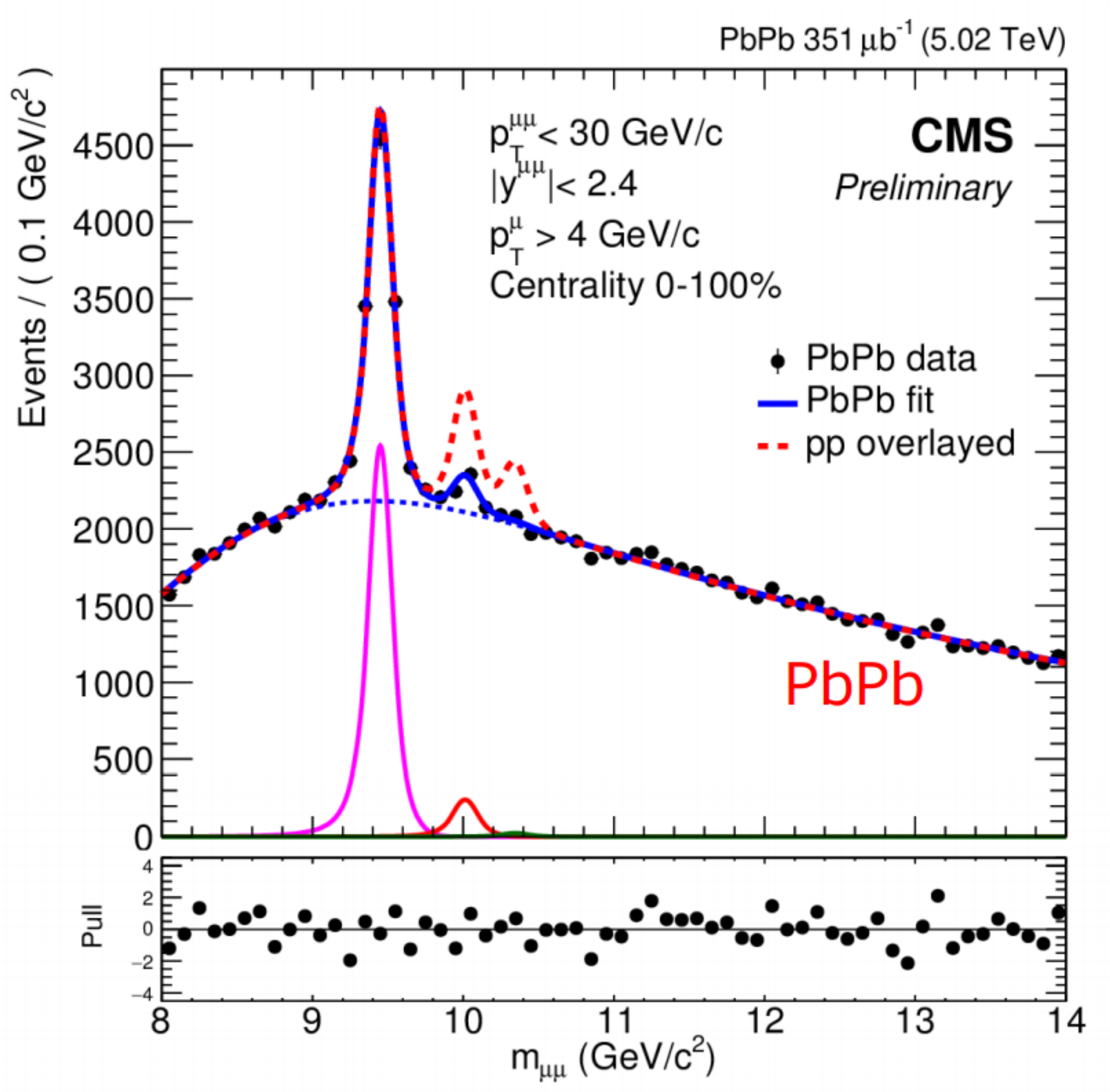


arXiv: 1504.07151



- 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

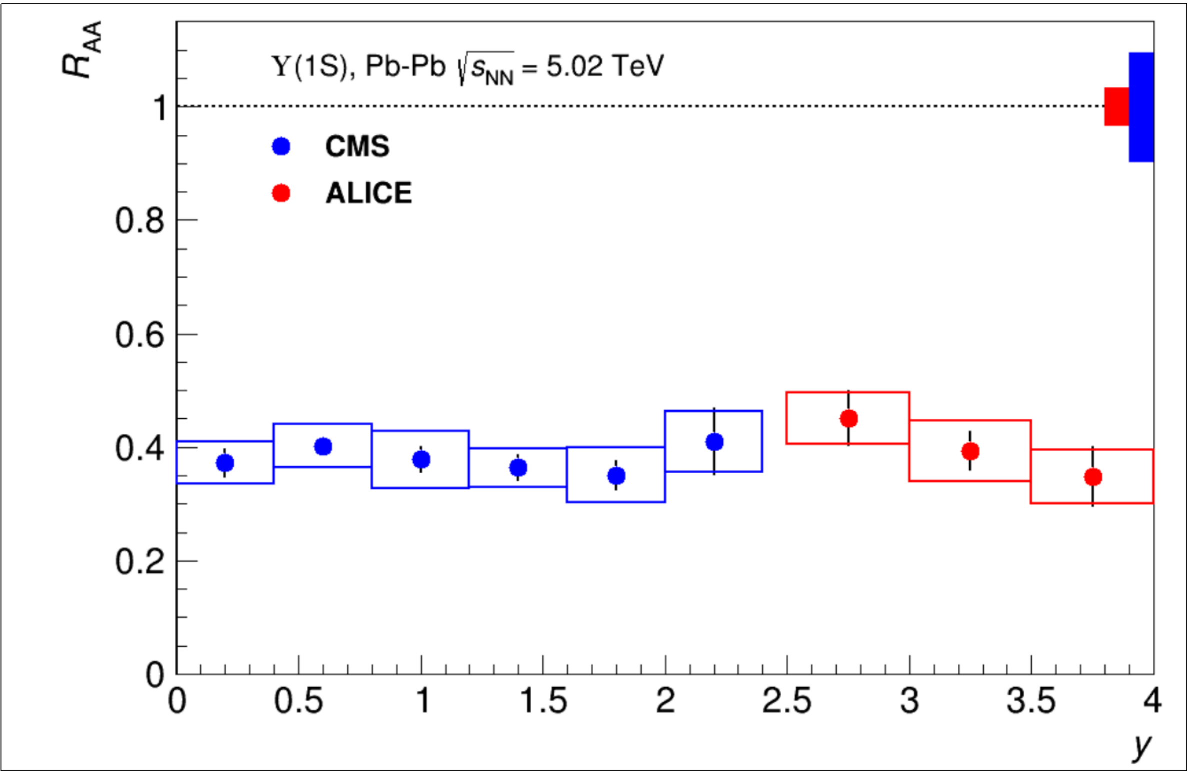
Bottomonium ($b\bar{b}$)

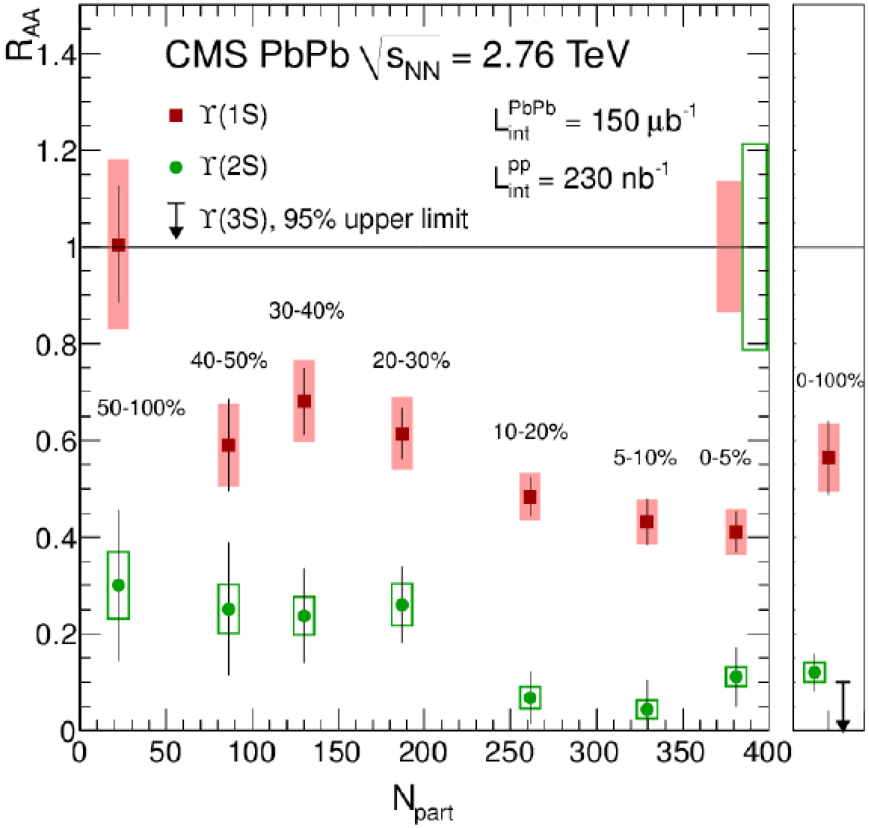


- CMS and ALICE measured the suppression of the Upsilon meson family
- A clear suppression of the Upsilon(2S) and Upsilon(3S) relative to the ground state is observed in Pb-Pb

Inclusive Υ production vs centrality

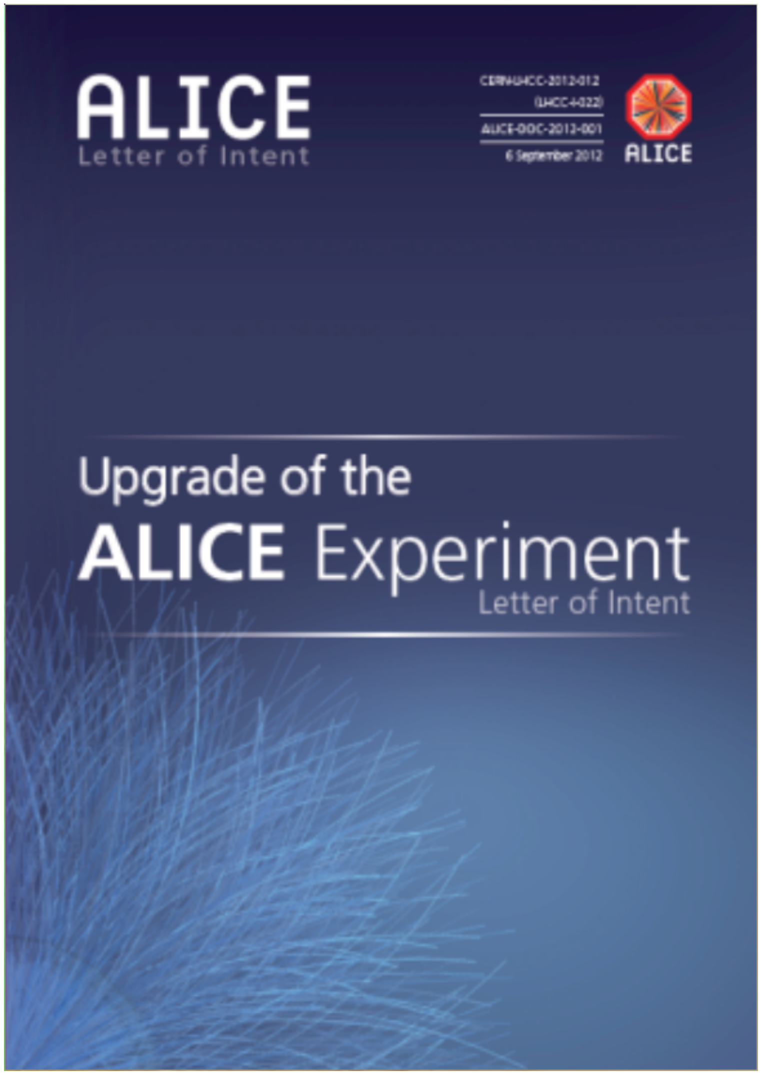
PRL109 (2012) 222301





- CMS and ALICE measured the suppression of the Upsilon meson family
- A clear suppression of the Upsilon(2S) and Upsilon(3S) relative to the ground state is observed in Pb-Pb
- Evidence for sequential melting: 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 collected

Conclusions

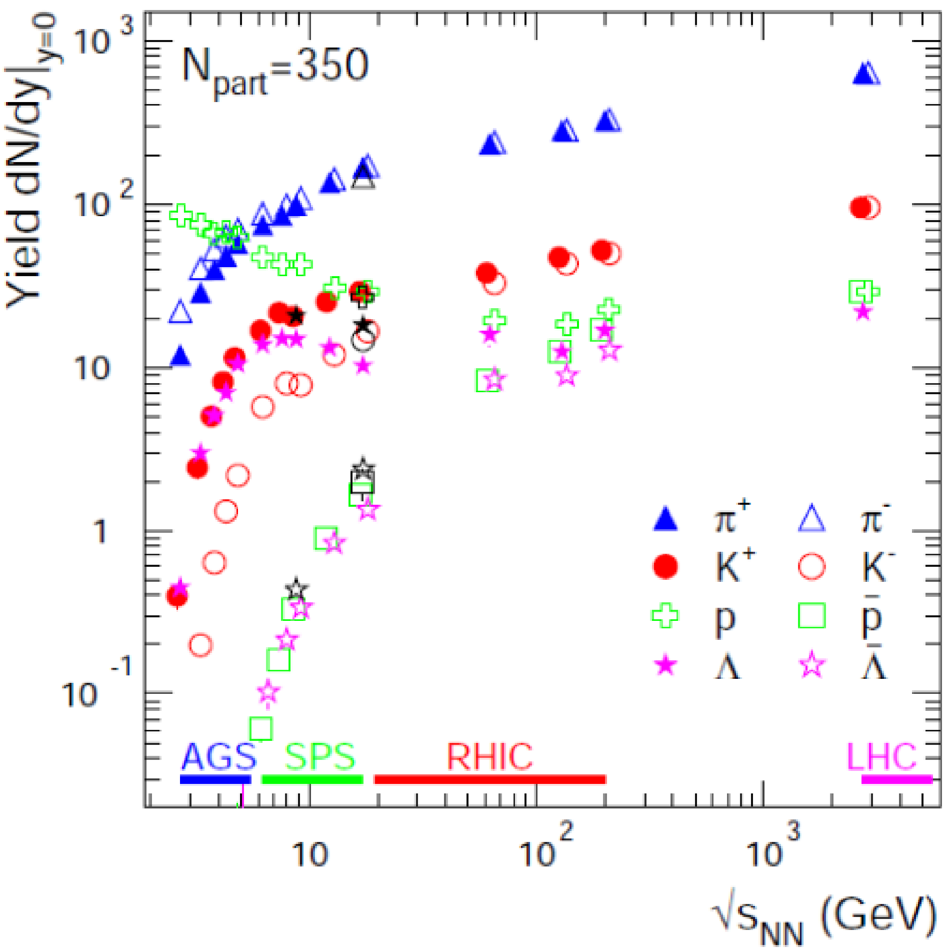
- The aim of studying the high energy heavy ion collisions is to better understand QCD in conditions not possible in particle physics: confinement, phase diagram of nuclear matter, chiral symmetry restoration
- Conditions reachable are similar to the ones during the early Universe (few microseconds) and in the core of neutron stars
- This field incorporates knowledge from many other areas of physics:
  - Thermodynamics, hydrodynamics, string theory
- … and technology
  - Detectors, Electronics, Scientific 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

ALICE-Norway

- Team leader: Prof.Dieter Rohrich (UiB) and Prof. Trine Tveter (UiO)
- We are strongly involved in both instrumentation and physics analyses
- Main physics topics:
  - Charmonium production in Pb-Pb, p-Pb and pp collisions
  - Three-particle correlations
  - Elliptic flow
- Detector expertise:
  - Time Projection Chamber
  - Inner Tracking System
  - Photon Spectrometer
  - Transition Radiation Detector

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

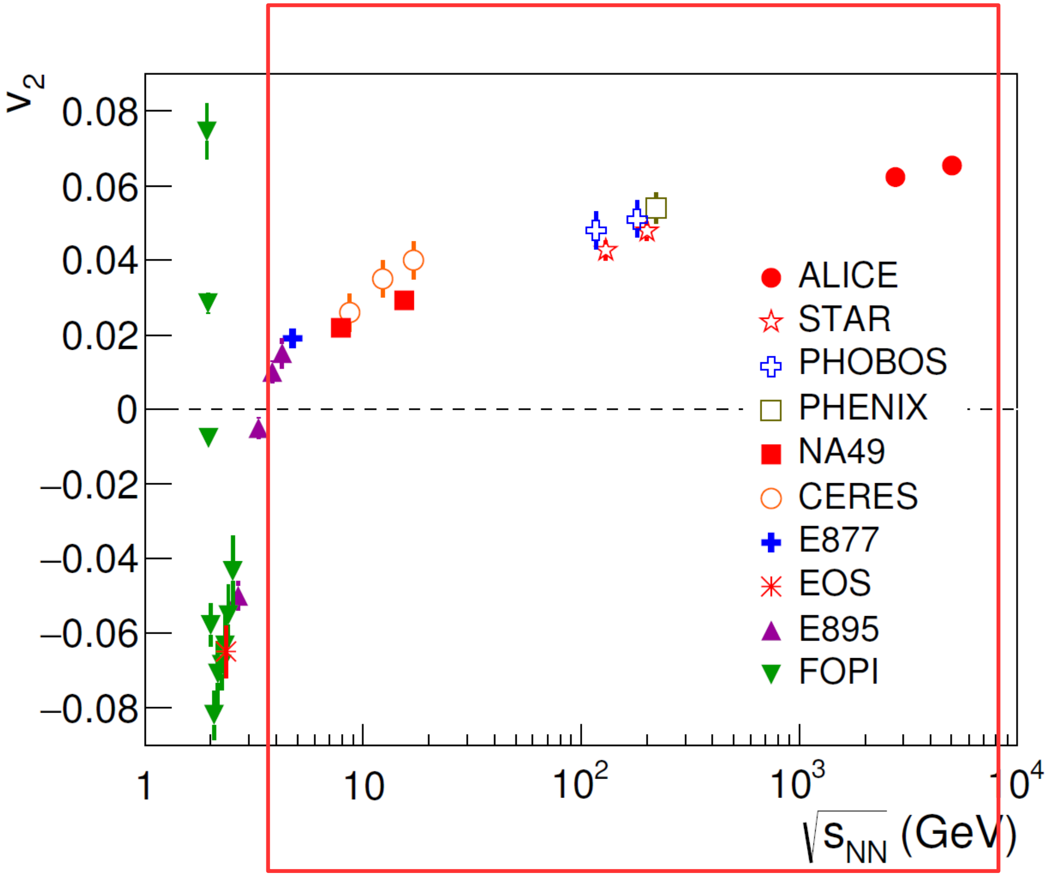
  Λ(uds), m=1116 MeV

  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?

Elliptic flow. Energy dependence

ALICE Collaboration, arXiv:1602.01119

- Provides information on the reaction dynamics
- v_2>0 at high energies: “free” fireball expansion → genuine elliptic flow



Reverse the order of these slides and find cartoons

Elliptic flow. Energy dependence

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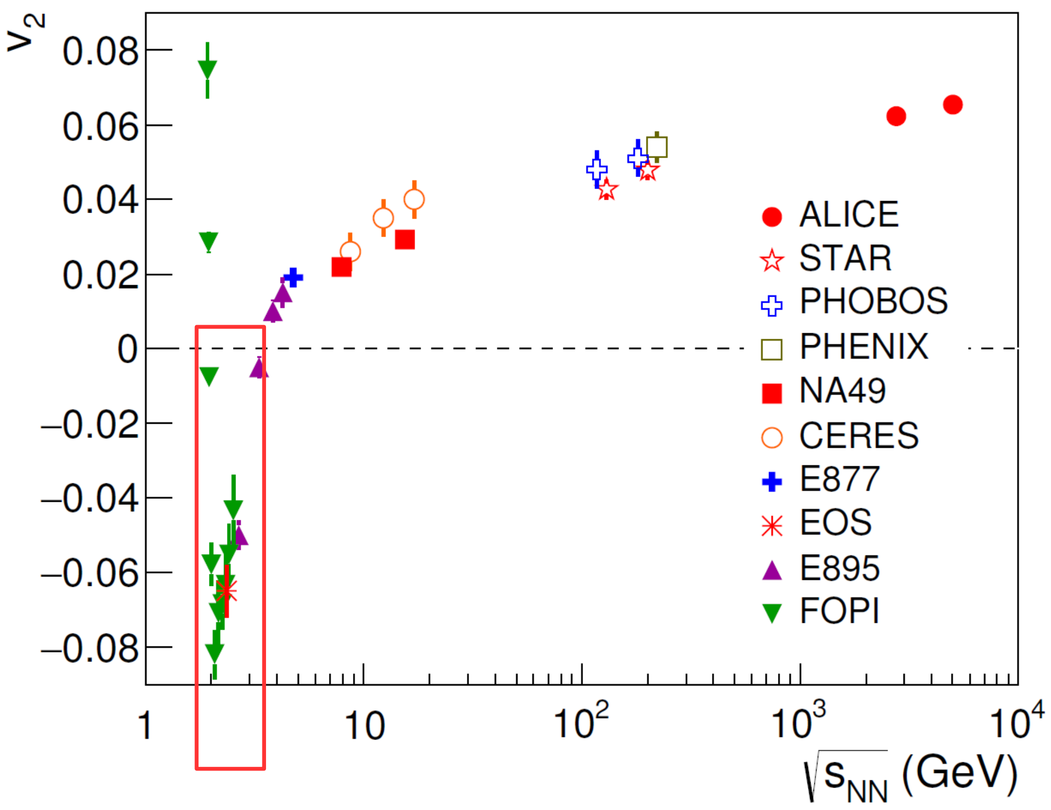

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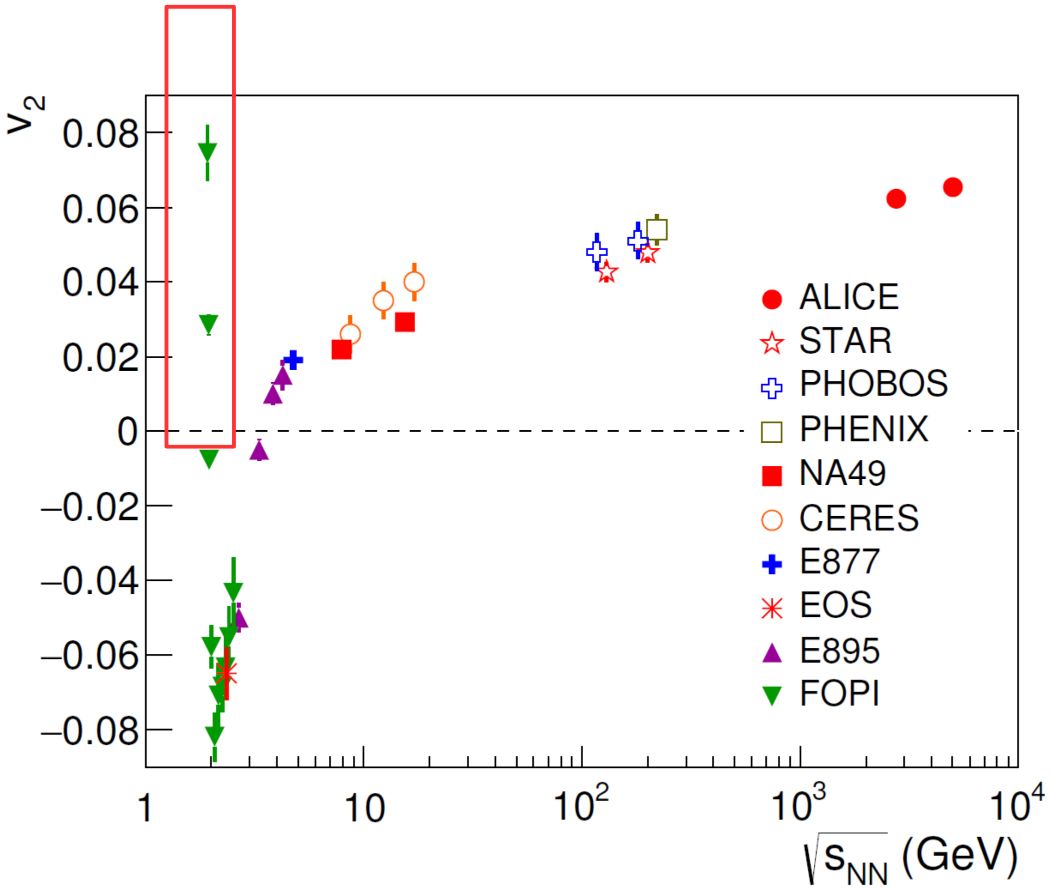
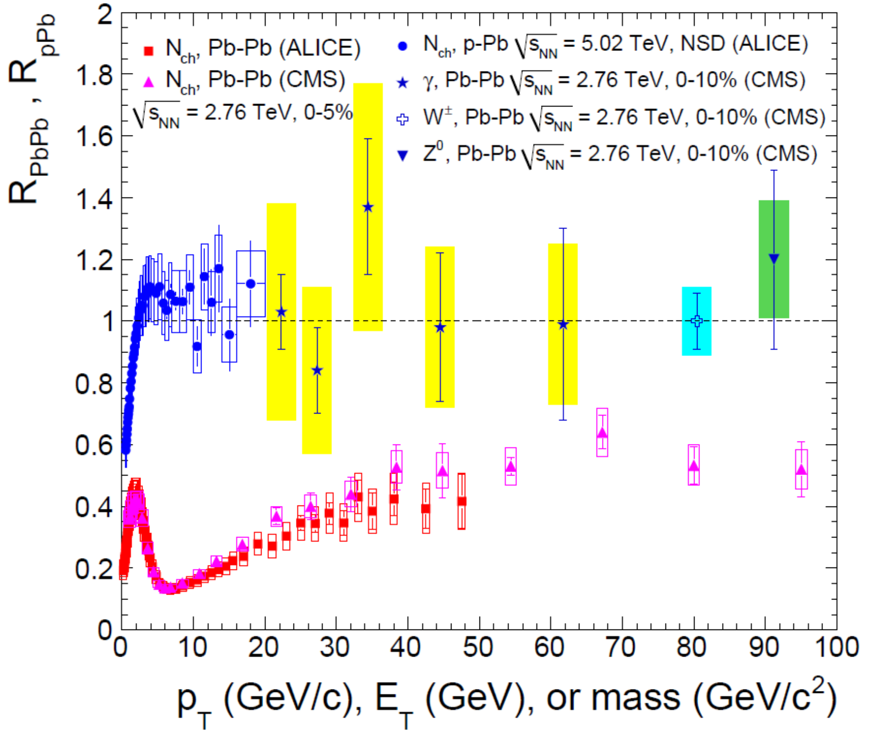
- v_2>0 at low energies: in-plane, rotation like emission



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

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

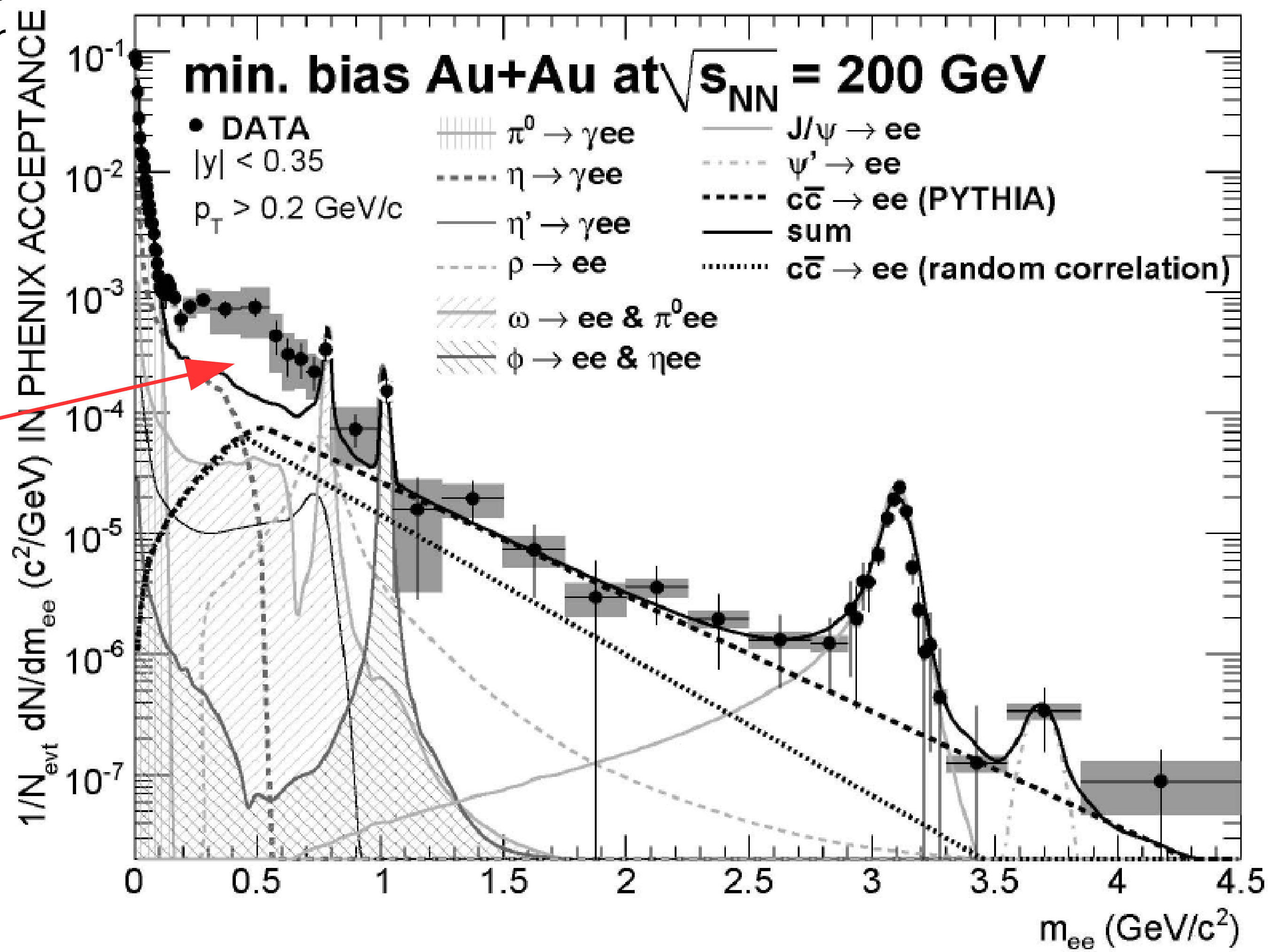
- N_{coll}: the number of binary nucleon-nucleon collisions
- Superposition of NN collisions → $R_{AA}=1$
  Suppression → $R_{AA}<1$
  Enhancement → $R_{AA}>1$

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

Electromagnetic probes

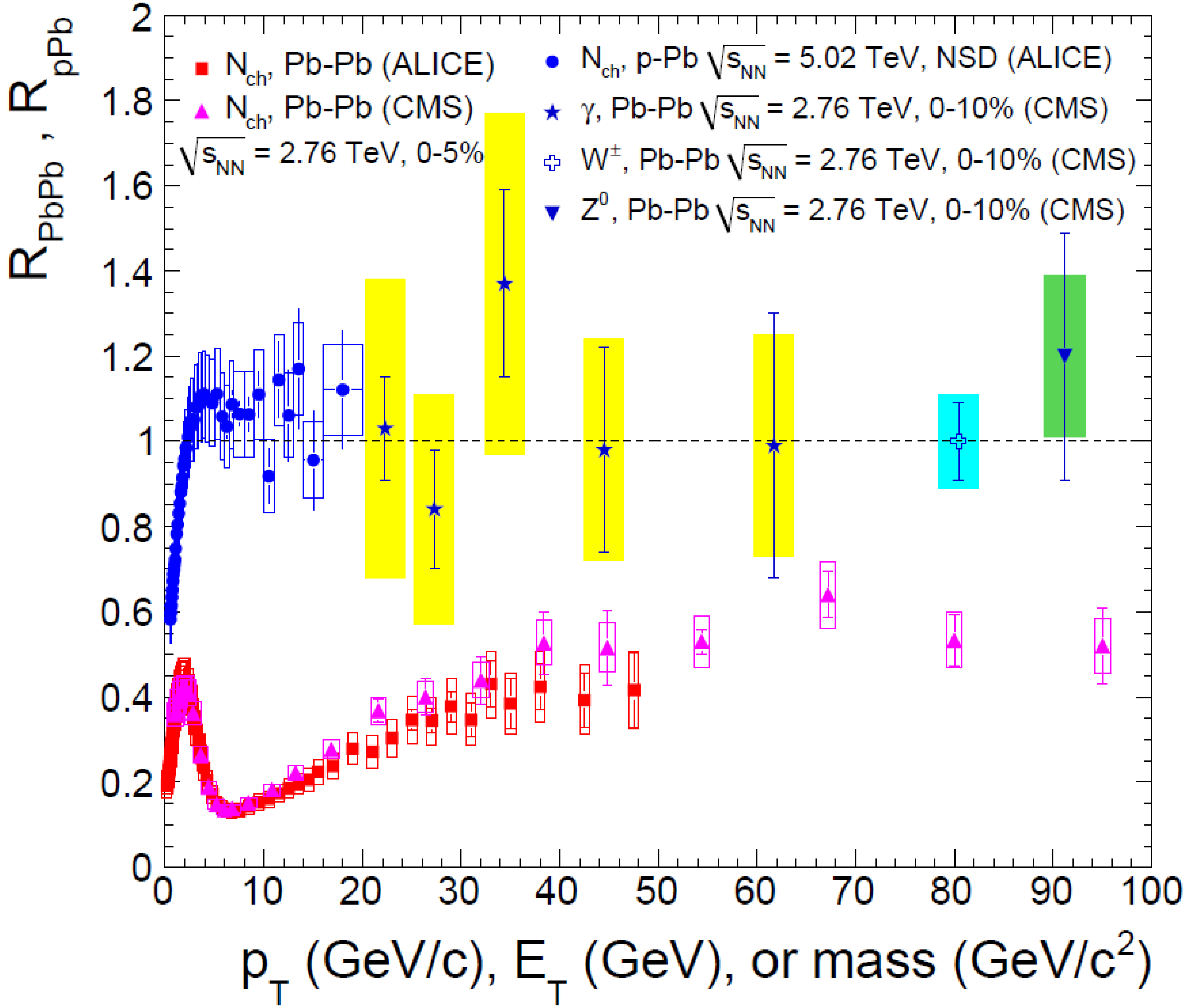
- Direct photons and low mass di-leptons
  - Probe of the thermal radiation of the fireball
  - Very clean information because of no re-interactions with QCD medium

Low mass di-electrons in PHENIX data



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

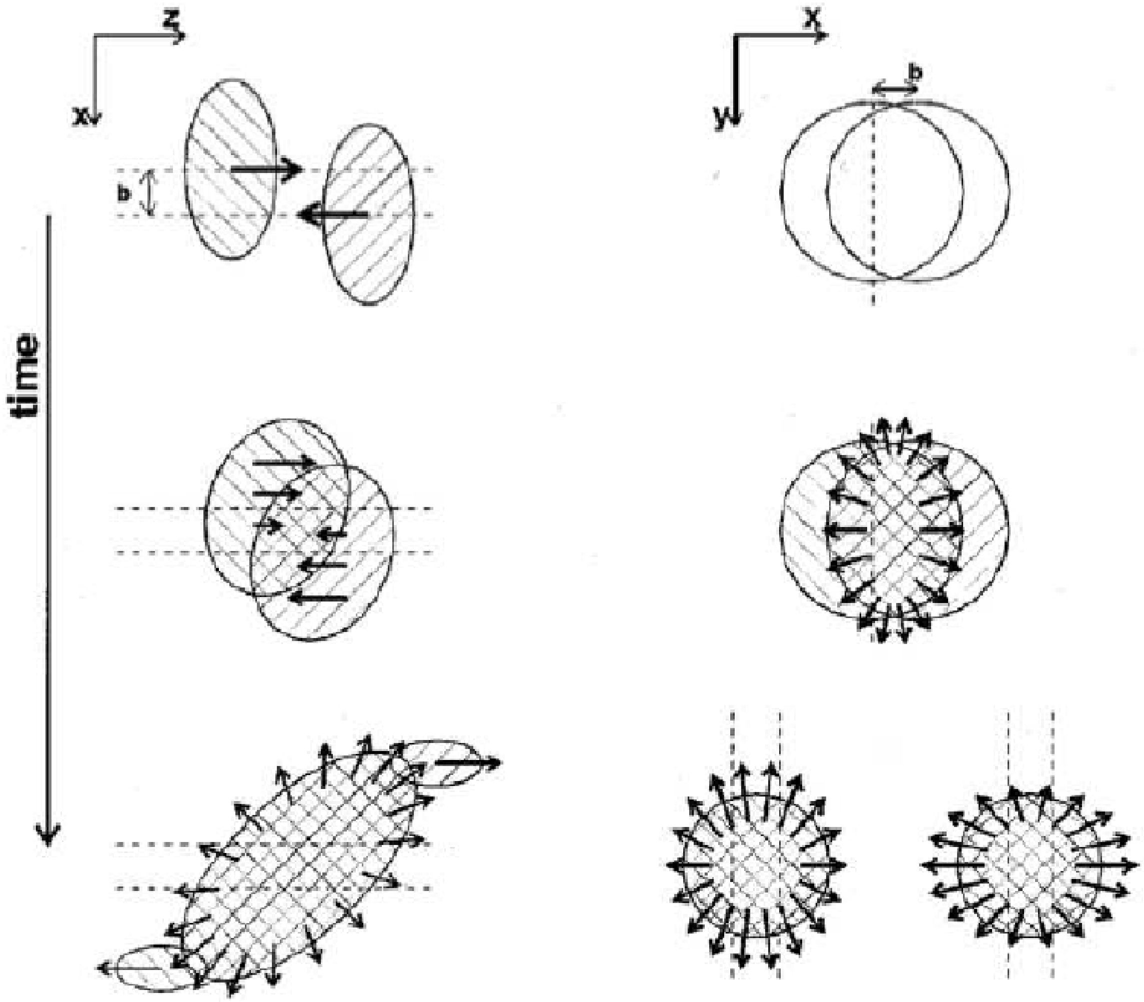
Electromagnetic probes



- 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})

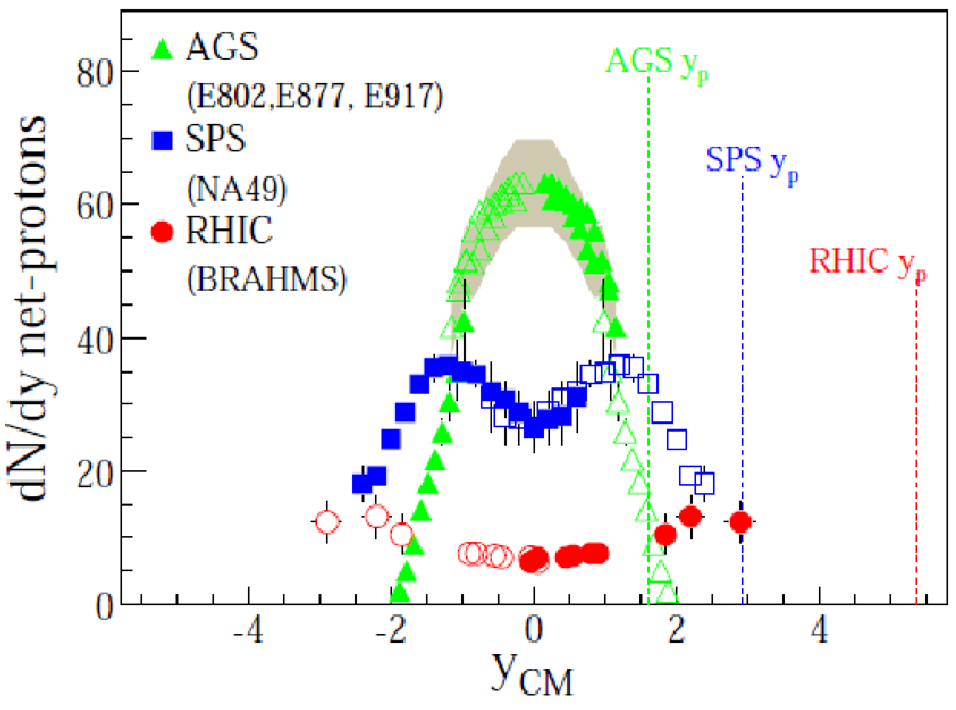
  typically measured in percentage of the geometric cross-section ($\sigma_{geom}=\pi(2R)^2$)

- Not all beam energy is spent

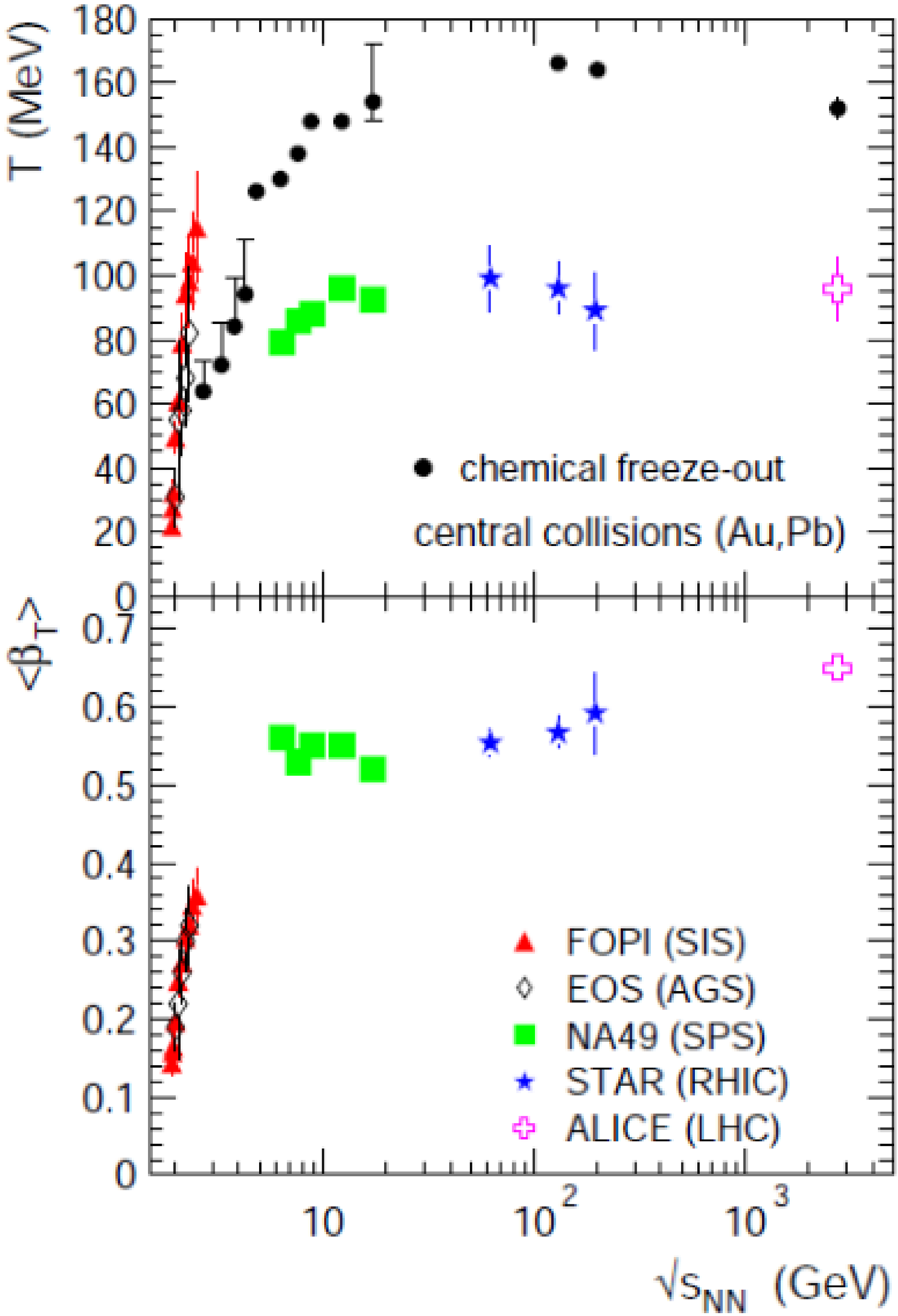
  … quantified by nuclear stopping

  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 :

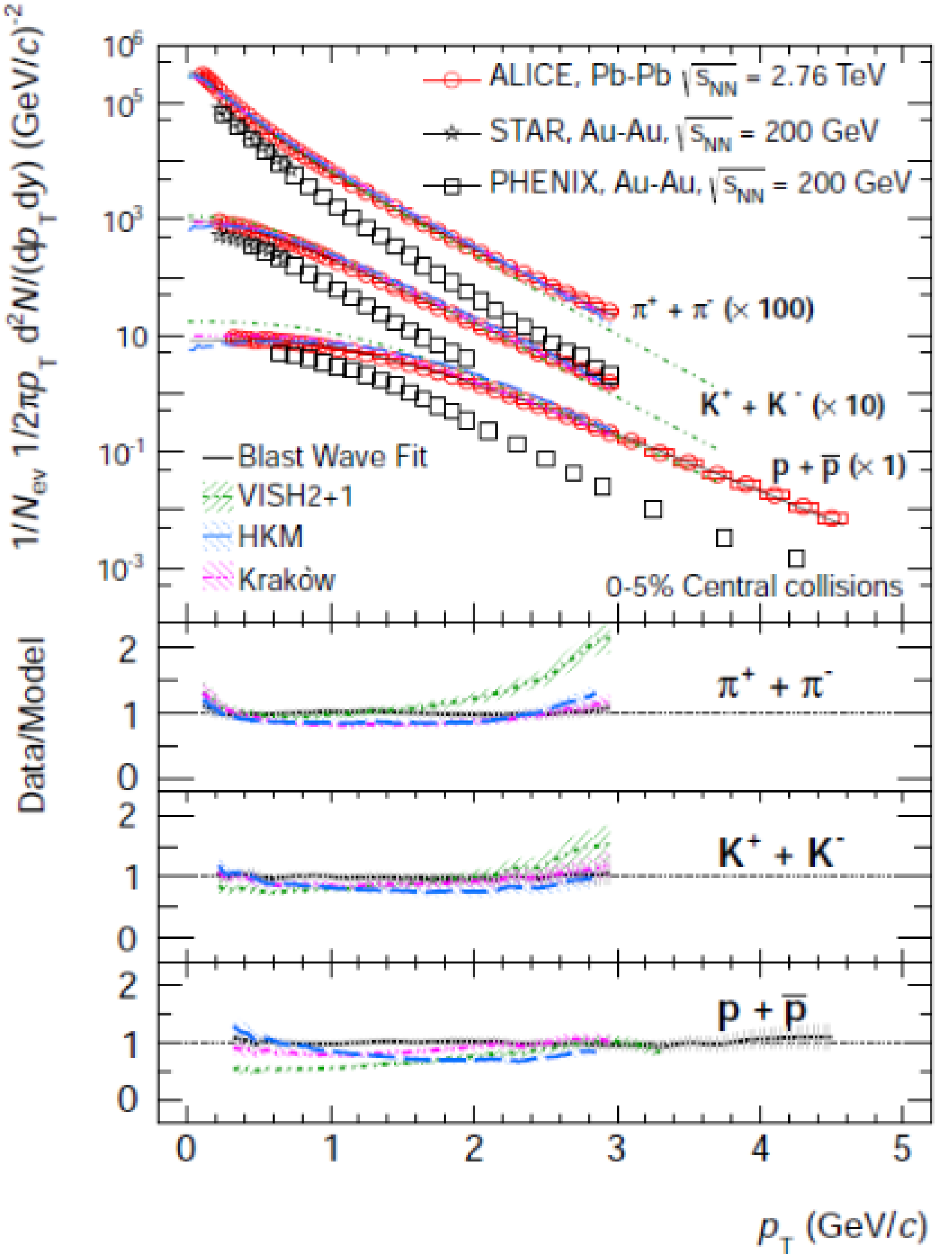
  T_{kine} = kinetic freeze-out temperature

  <β> = collective average velocity

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

- arXiv: 1210.8126

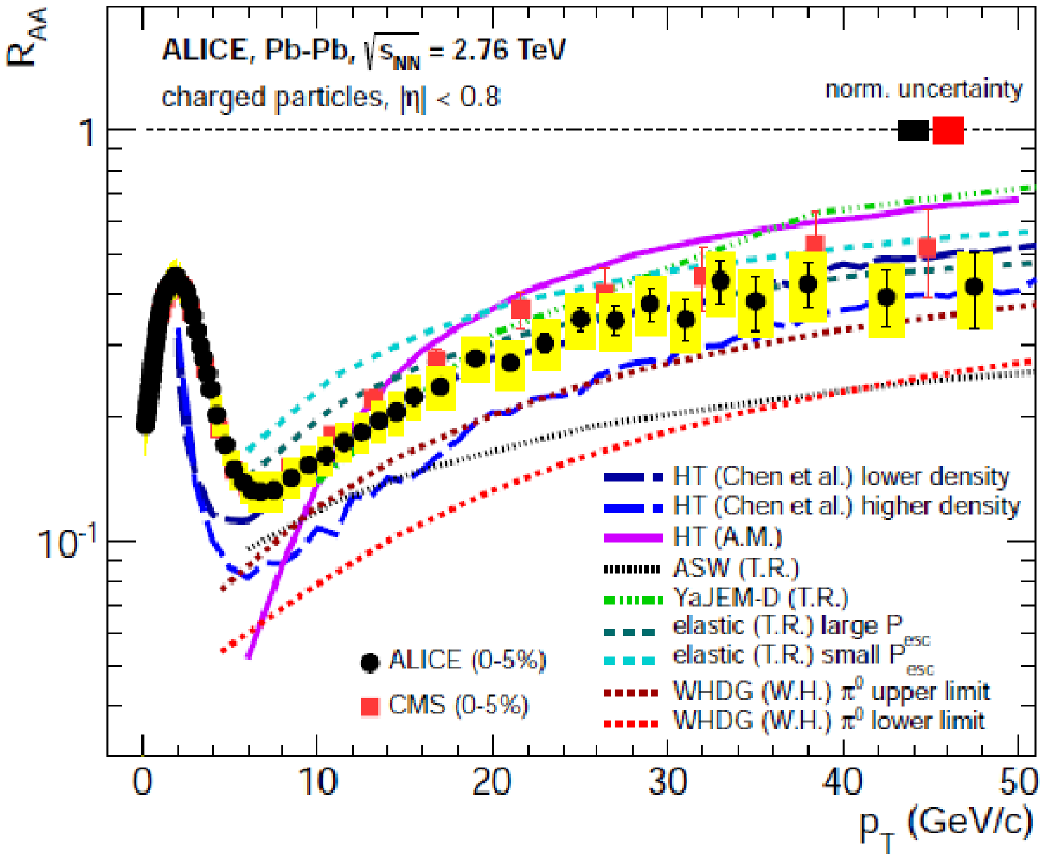
The kinetic freeze-out



ALICE, PRL 109 (2012) 252301

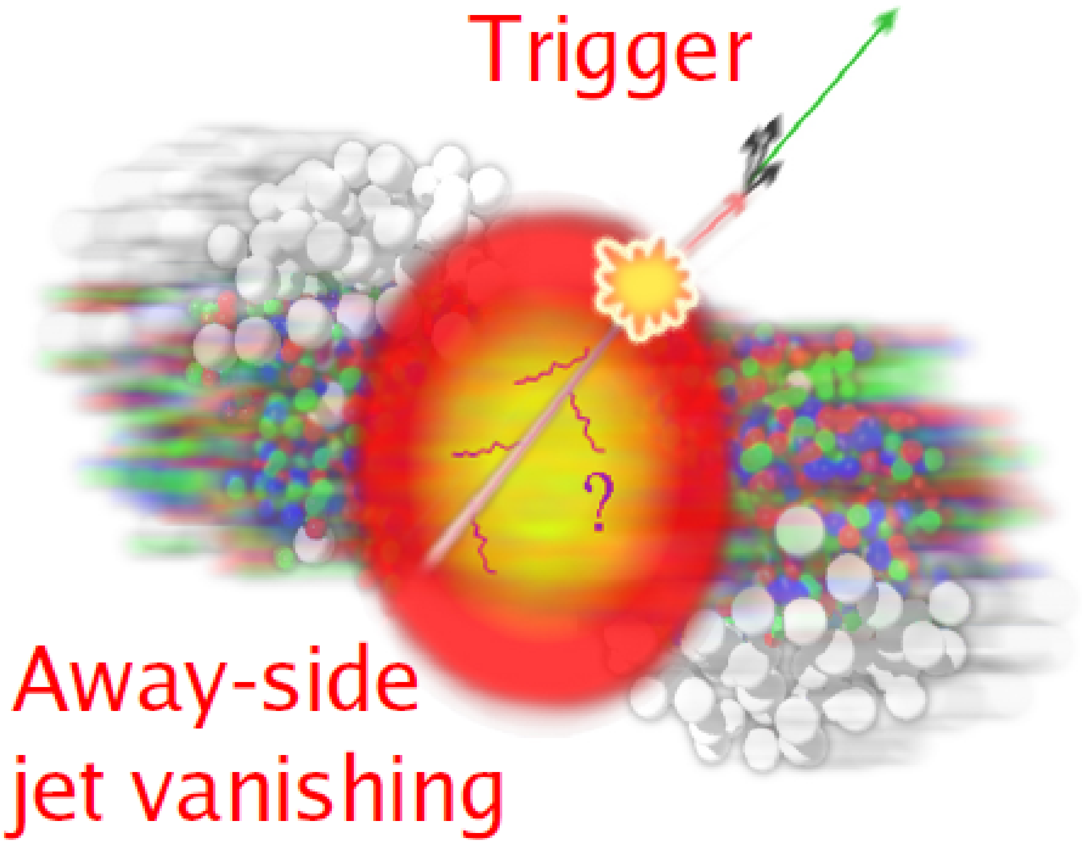
- At the LHC, spectra are harder than at RHIC ($\sqrt{s_{NN}}$=200GeV)
- The mass dependence of the spectra “hardness” indicates collective motion / flow
- Hydrodynamical models reproduce the data → the fireball expands hydrodynamically nearly as a perfect fluid (very low viscosity)

Jet quenching at the LHC



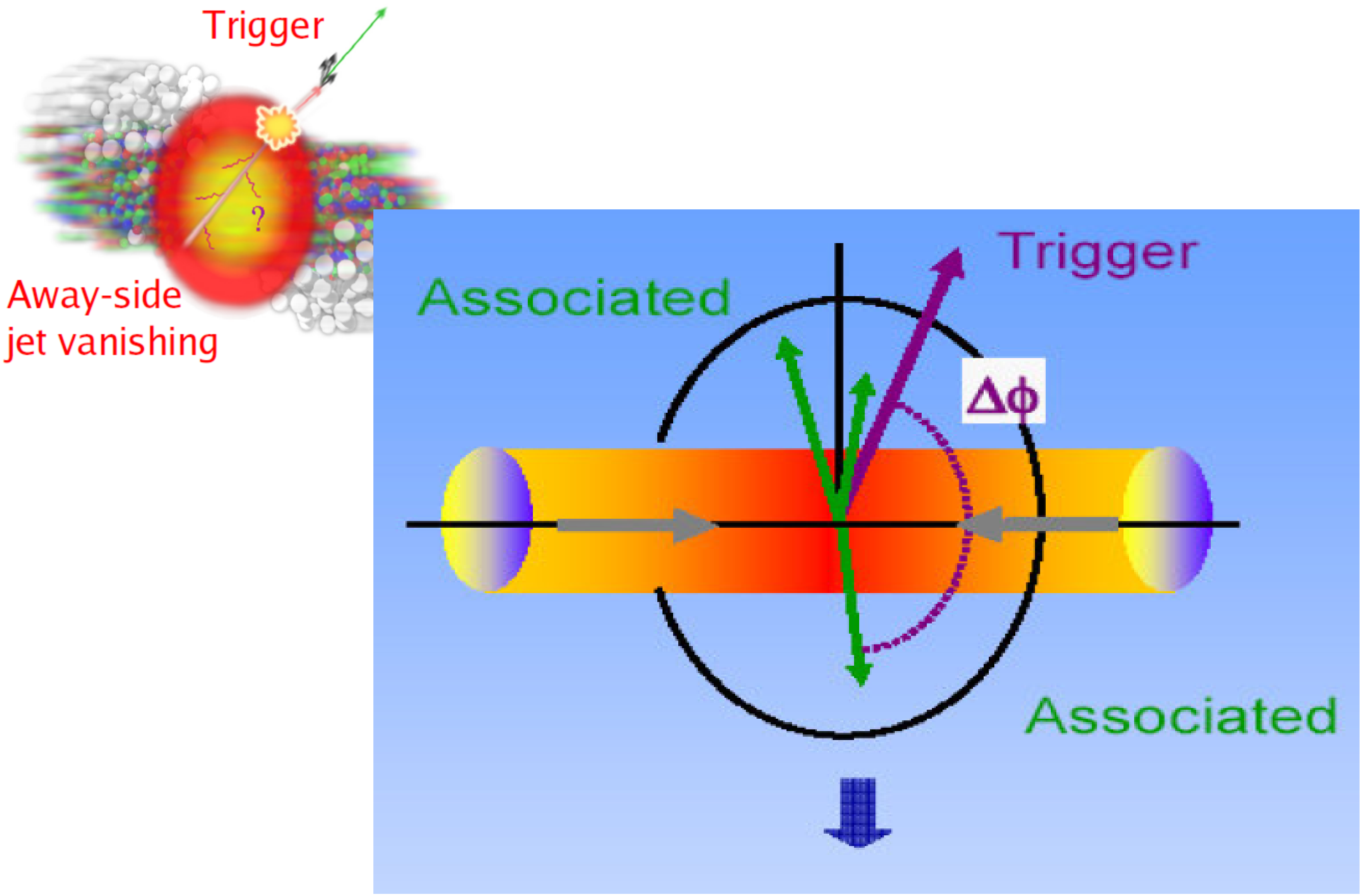
- Strong suppression observed (stronger than at RHIC)
- Reaching a factor of about 7 at p_T=7-8 GeV/c
- Remains substantial even beyond 50 GeV/c
- A lot of activity in theoretical description of parton energy loss in hot deconfined matter

Two-particle azimuthal correlations



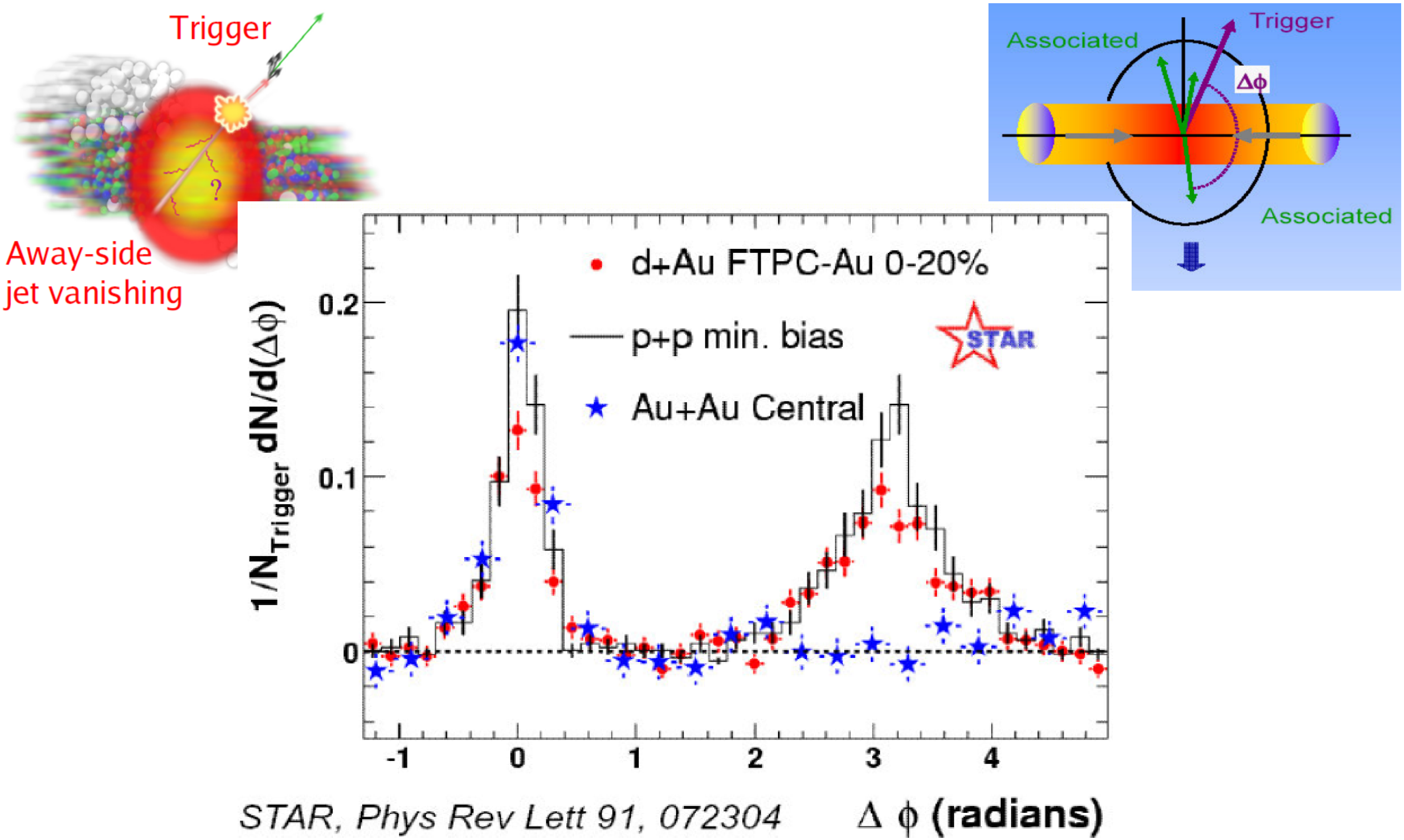
- High momentum di-jets are created in hard interactions of the initial partons
- Tipically, one of the jets traverse a smaller path through the QGP and escapes, while the other can be quenched (surface bias)

Two-particle azimuthal correlations



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

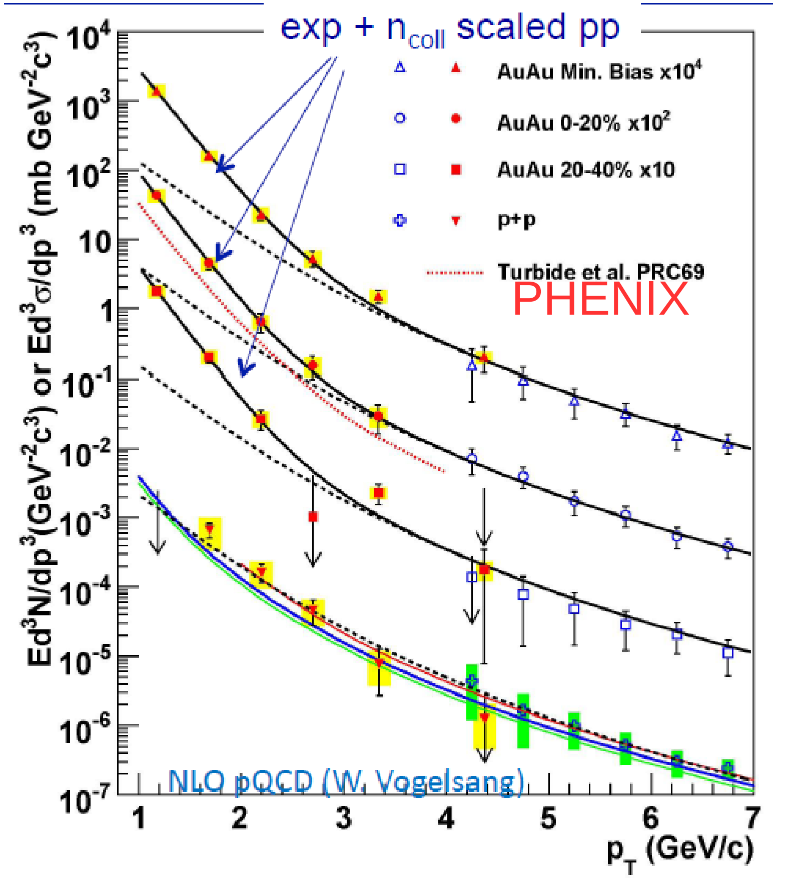
Two-particle azimuthal correlations



- 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

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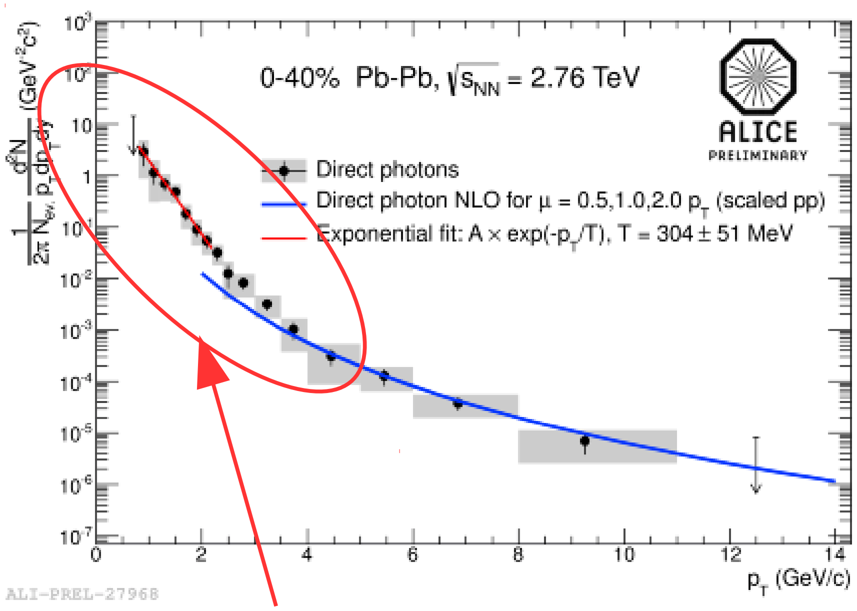

T = 304 ± 51 MeV

T ~3.0 x 10^{12} K

The highest temperature ever recorded!!!