Relativistic heavy ion collisions

Ionut-Cristian Arsene,
University of Oslo, 2015/05/15

- Why heavy ion collisions ?
- Accelerators and experiments
- Main results

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

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

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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)

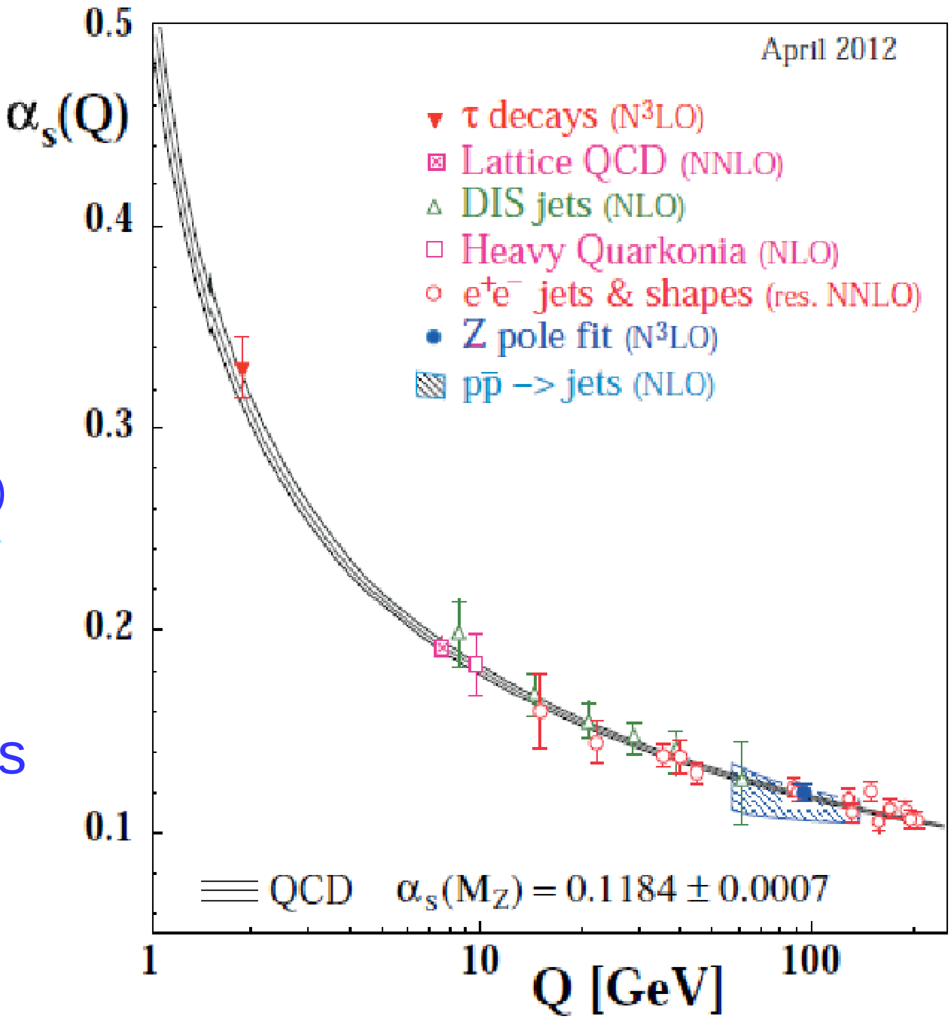
Quantum Chromo-Dynamics (QCD)

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

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

Quantum Chromo-Dynamics (QCD)

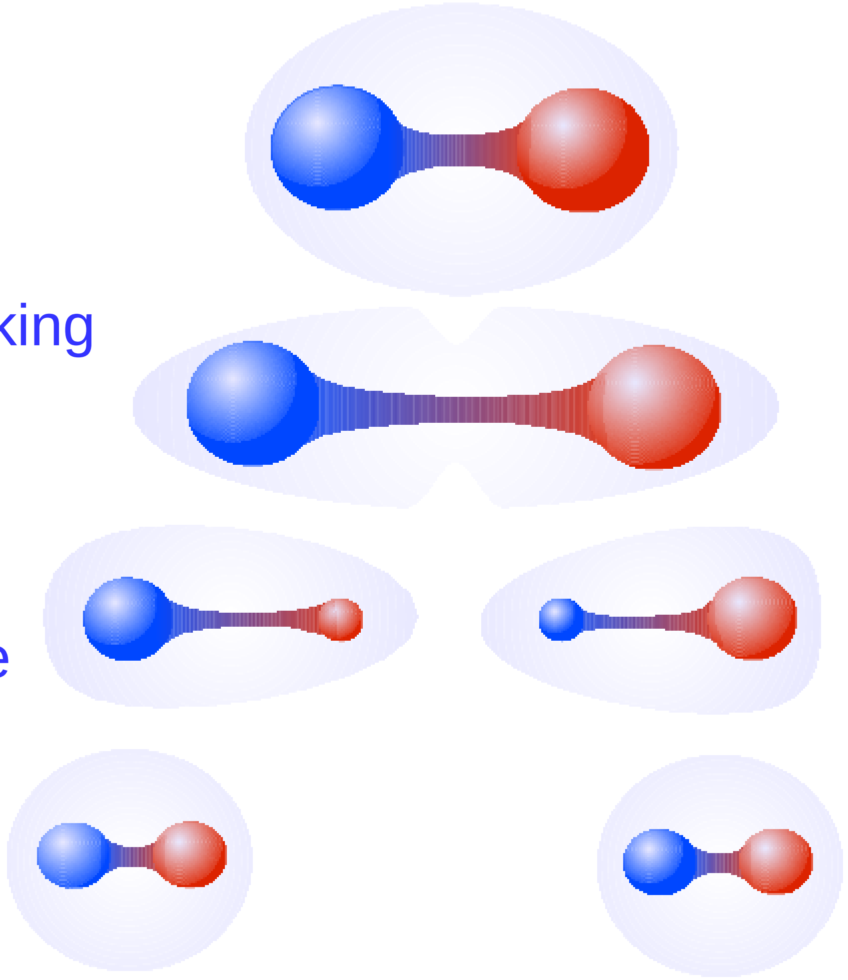
- 6 quarks, 3 colours (RGB)
  and 8 gluons (coloured!)
- ...difficult to calculate
  - No analytical solutions (except 1+1)
- **High *Q*:** asymptotic freedom
  Physics Nobel prize 2004 (Wilczek, Gross, Politzer)
- Typically solvable using perturbative theory
- Tested extensively at modern colliders



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



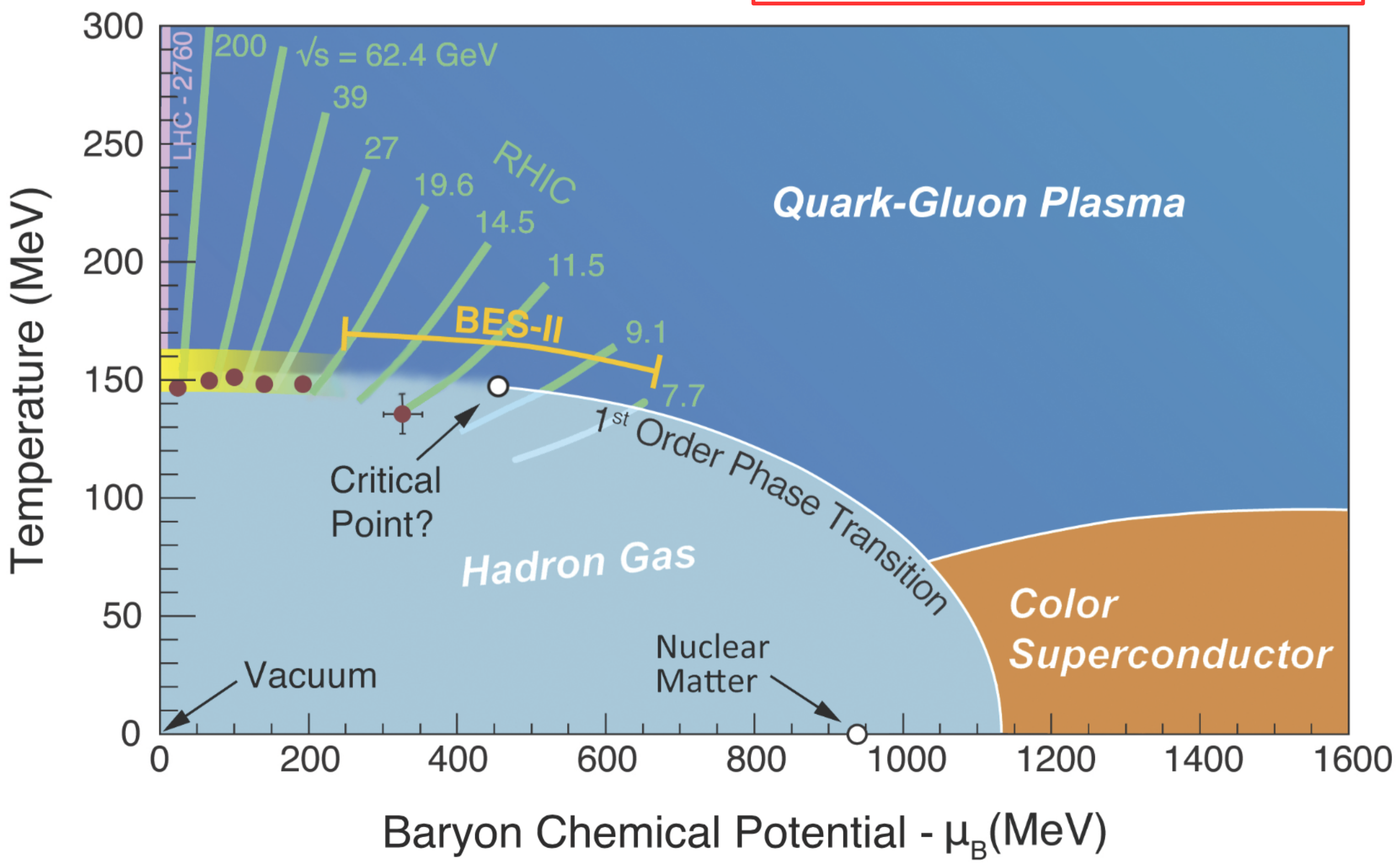
Relativistic heavy-ion collisions

- Creates in lab conditions a chunk of **deconfined nuclear matter** with a lifetime long enough to allow the study of its properties

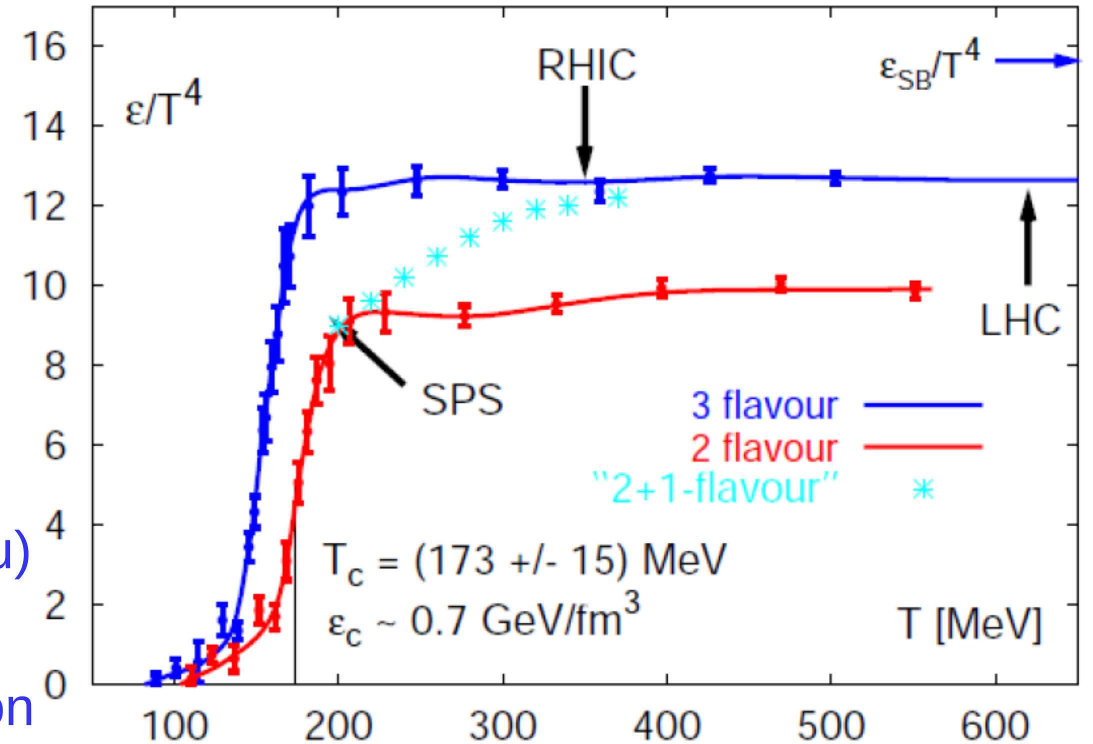
Relativistic heavy-ion collisions

- Relevance for:
  - QCD studies (low-Q, finite T and μ)
    Phase diagram of nuclear matter:
    - deconfinement phase transition

Igor Mishustin, thursday 18
Mark Gorenstein, wed 24



Relativistic heavy-ion collisions



F. Karsch, hep-lat/0106019

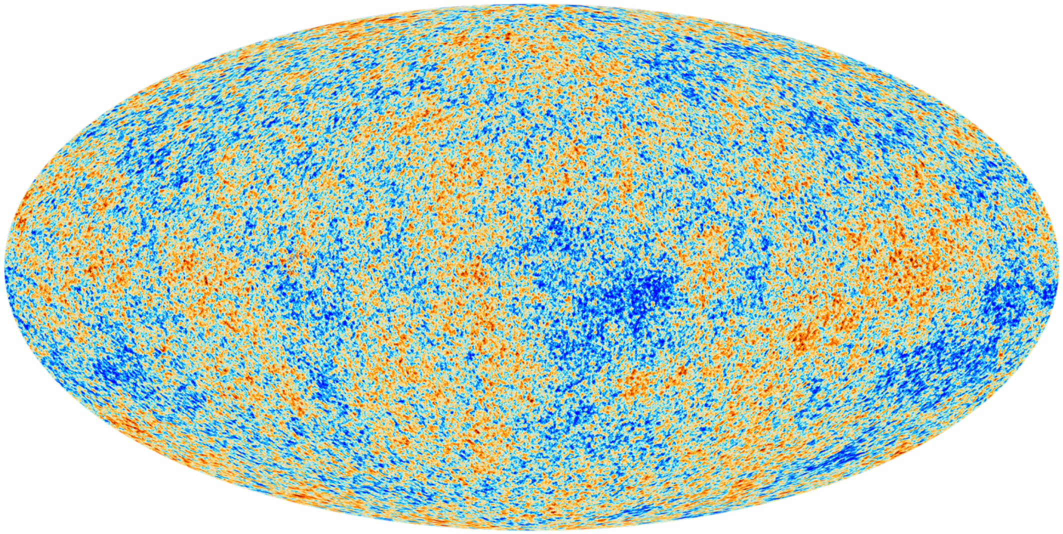
- Relevance for:
  - QCD studies (low-Q, finite T and μ)
    Phase diagram of nuclear matter:
    - deconfinement phase transition
    - Lattice QCD calculations conclude transition is cross-over type
      (Y.Aoki et al., Nature 443 (2006) 675)
    - "Critical" temperature: T_C≈155-160 MeV

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

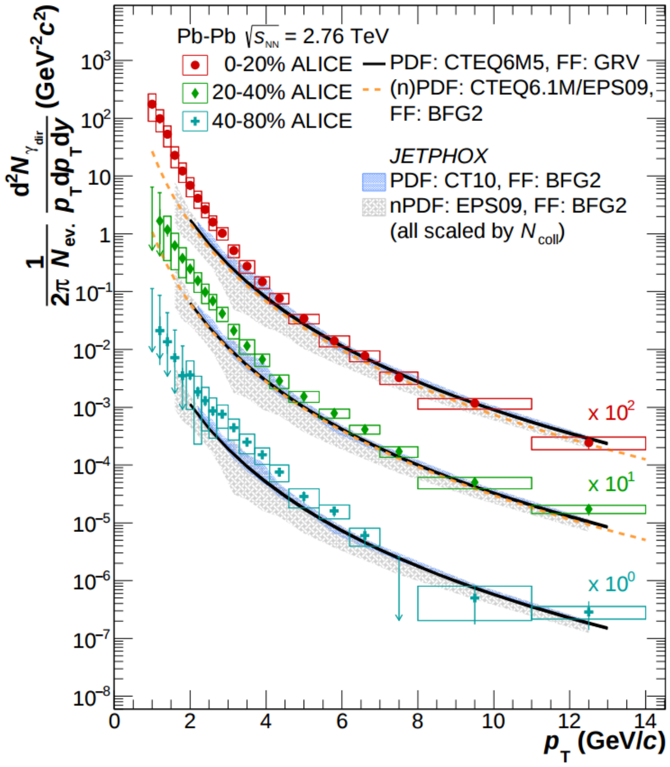
Relativistic heavy-ion collisions

- Creates in lab conditions a chunk of **deconfined nuclear matter** with a lifetime long enough to allow the study of its properties
- Relevance for:
  - QCD studies
  - Cosmology: access early Universe conditions (10^{-5} s)

Cosmic microwave background seen by Planck



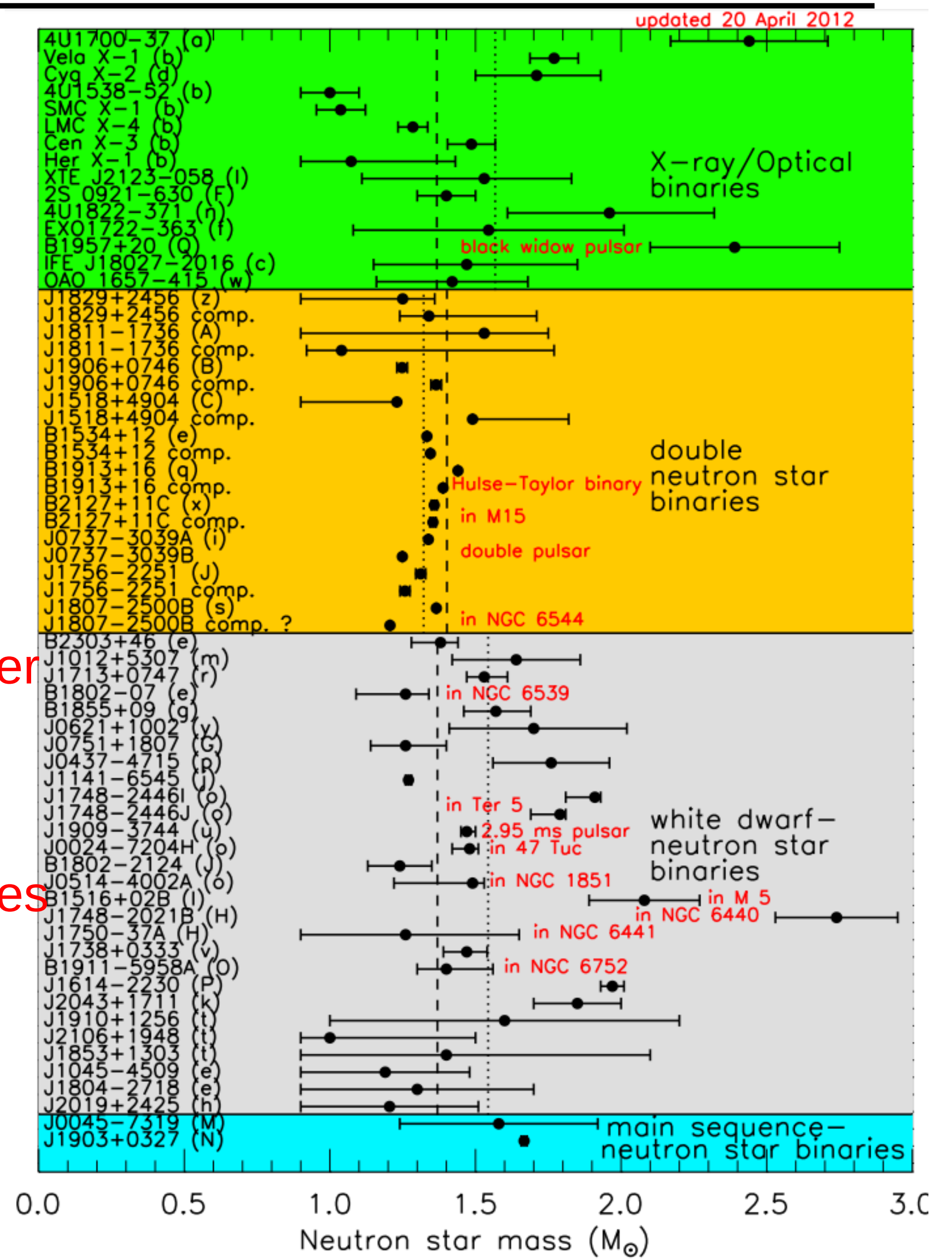
Direct photon production in Pb-Pb collisions at the LHC
T ~ 300 MeV



ALICE Collaboration, PLB754 (2016) 235

Relativistic heavy-ion collisions

- 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



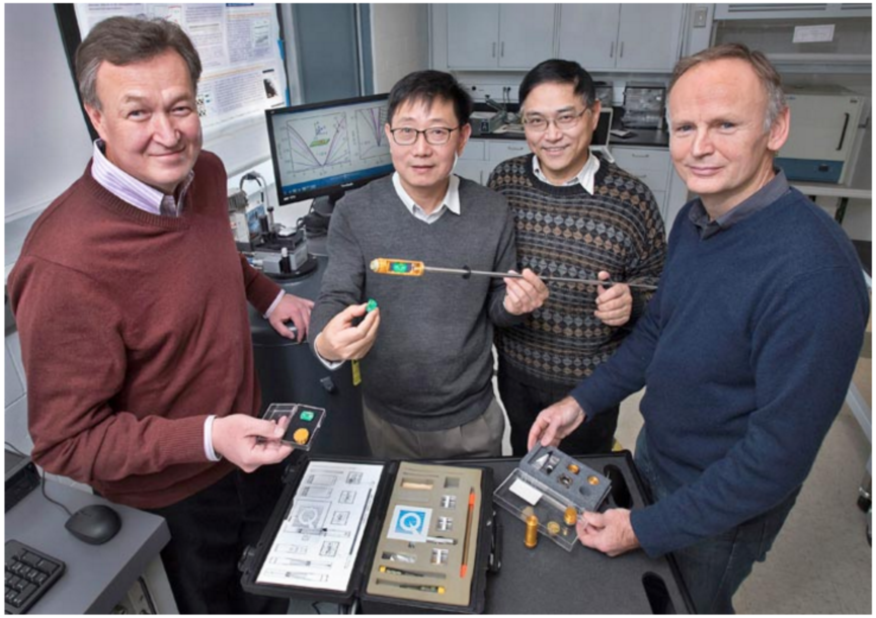
J.M.Lattimer, arXiv:1305.3510

Relativistic heavy-ion collisions

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

- 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

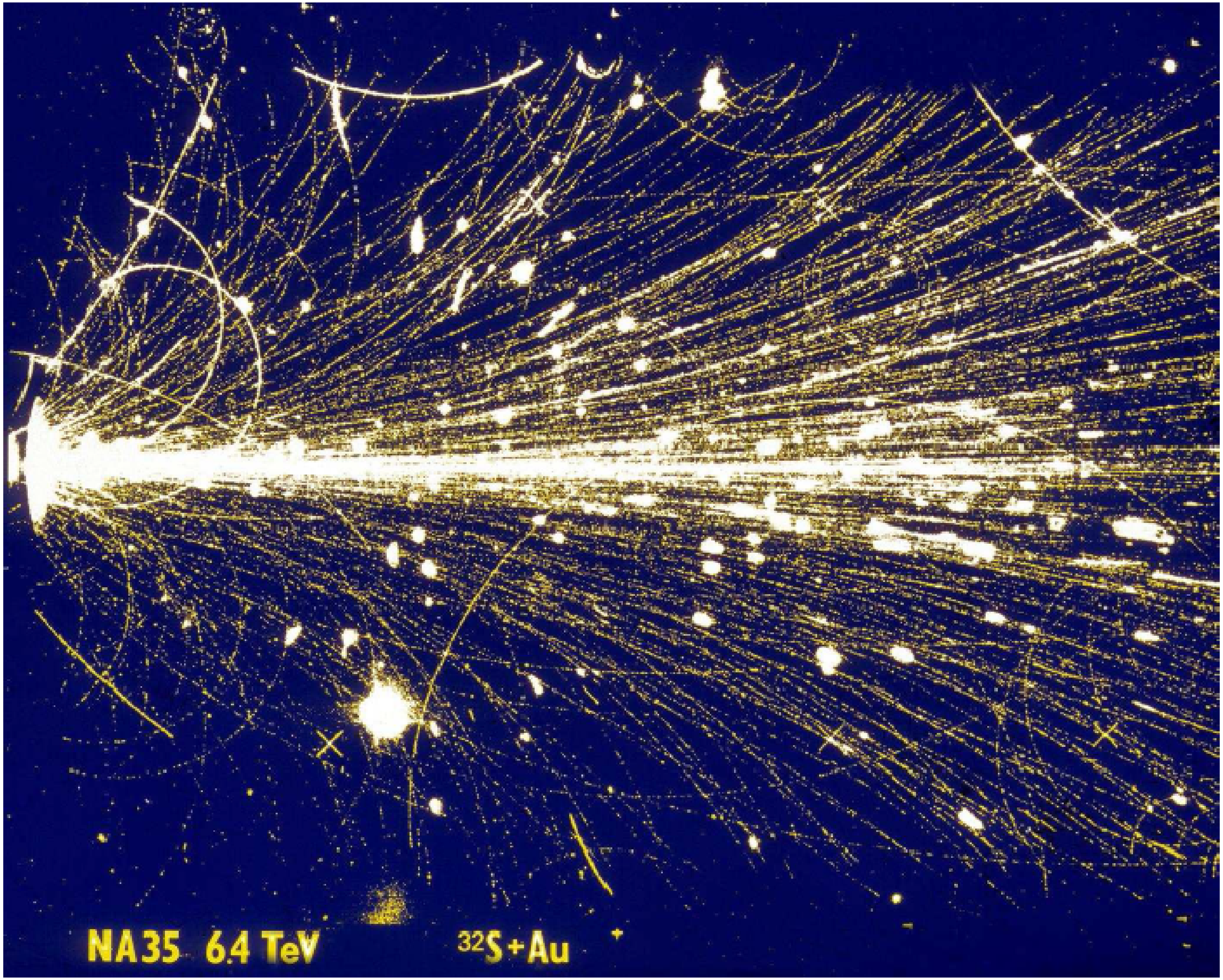
Q.Li, D.Kharzeev et al., Nature Physics Letters 2016

Heavy ion accelerators

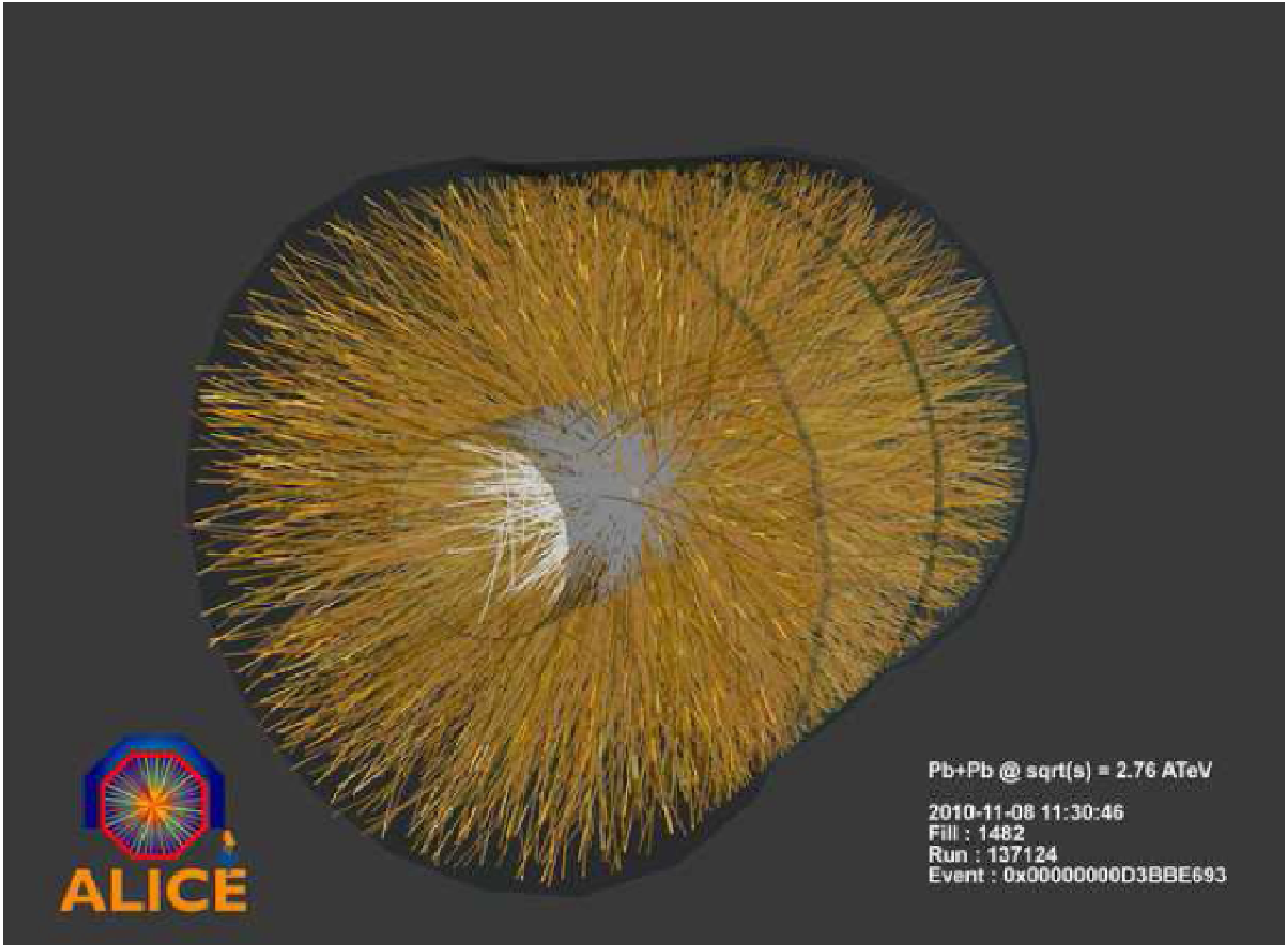
- Past:
  - Bevalac @ LBL, Berkeley (1954): $\sqrt{s_{NN}}$=2.4 GeV
  - Synchrophasotron @ JINR, Dubna (1957): $\sqrt{s_{NN}}$=4GeV
  - AGS @ BNL, Brookhaven (1960): $\sqrt{s_{NN}}$=4.8 GeV
  - SPS @ CERN, Geneva (1976): $\sqrt{s_{NN}}$=17.3 GeV
- Present:
  - SIS @ GSI, Darmstadt: $\sqrt{s_{NN}}$=2.5 GeV
  - SPS @ CERN, Geneva: $\sqrt{s_{NN}}$=17.3 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
  - NICA @ JINR, Dubna (~2020): $\sqrt{s_{NN}}$=5 GeV
  - FCC @ CERN (?): $\sqrt{s_{NN}}$ ~ 40 TeV

Alexander Sorin, monday 15

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)

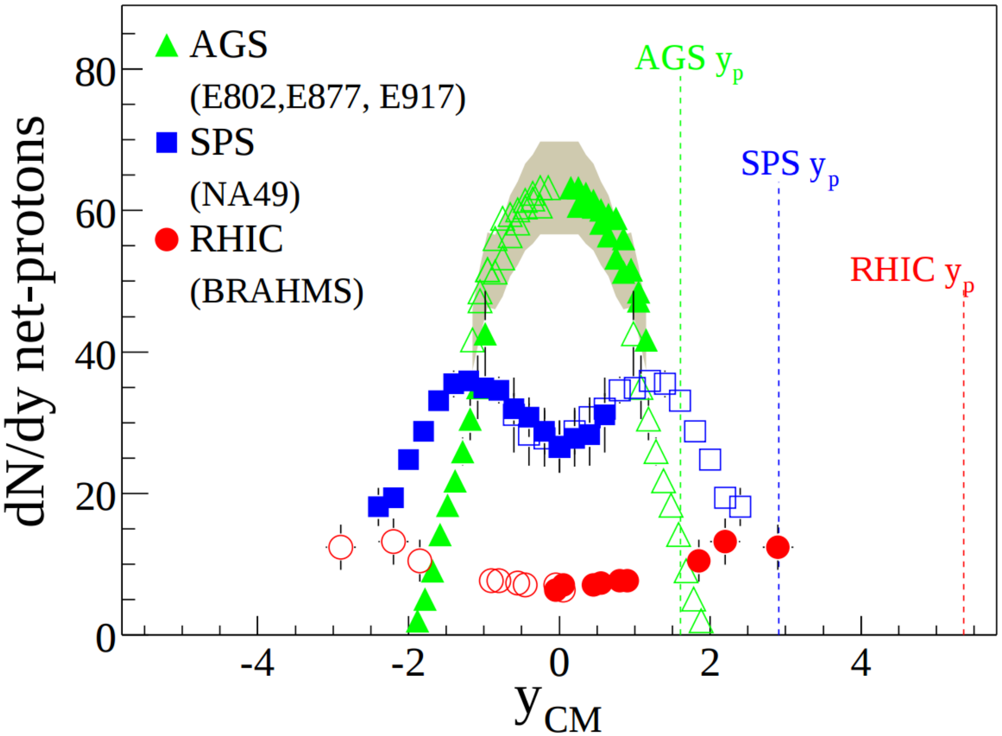
Physics results

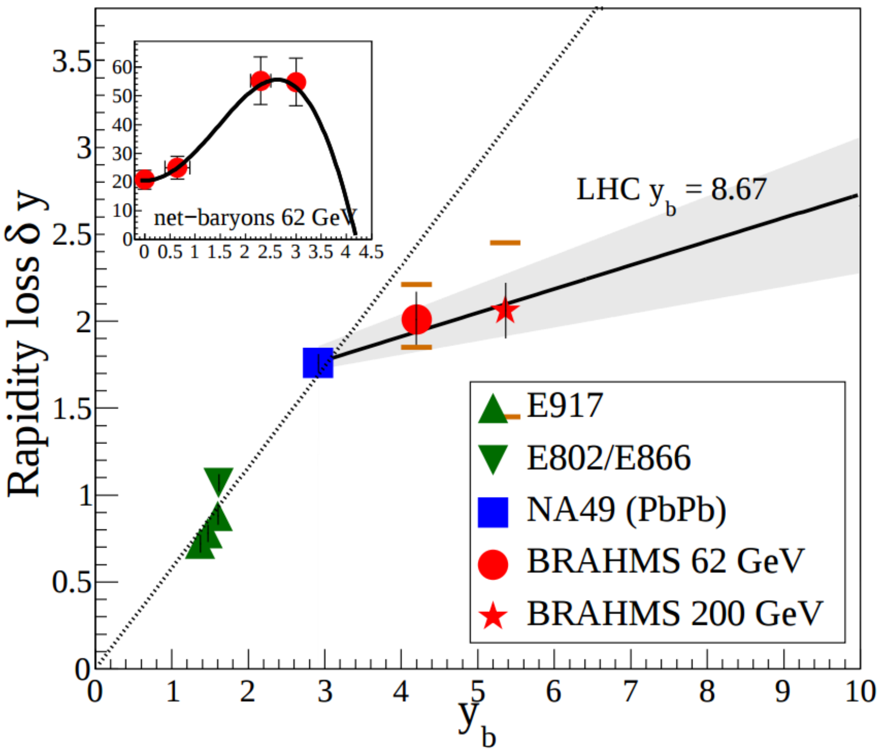
Collision energy ($\sqrt{s_{NN}}$)

- For relativistic heavy ion collisions, tipically $\sqrt{s_{NN}}$ >1 GeV
  - Bevalac, JINR-Dubna, AGS, SIS-GSI: few GeV
  - SPS: ~20 GeV
  - RHIC: 200 GeV
  - LHC: 5 TeV
- Defines the allowed processes and the phase space

Collision energy ($\sqrt{s_{NN}}$)

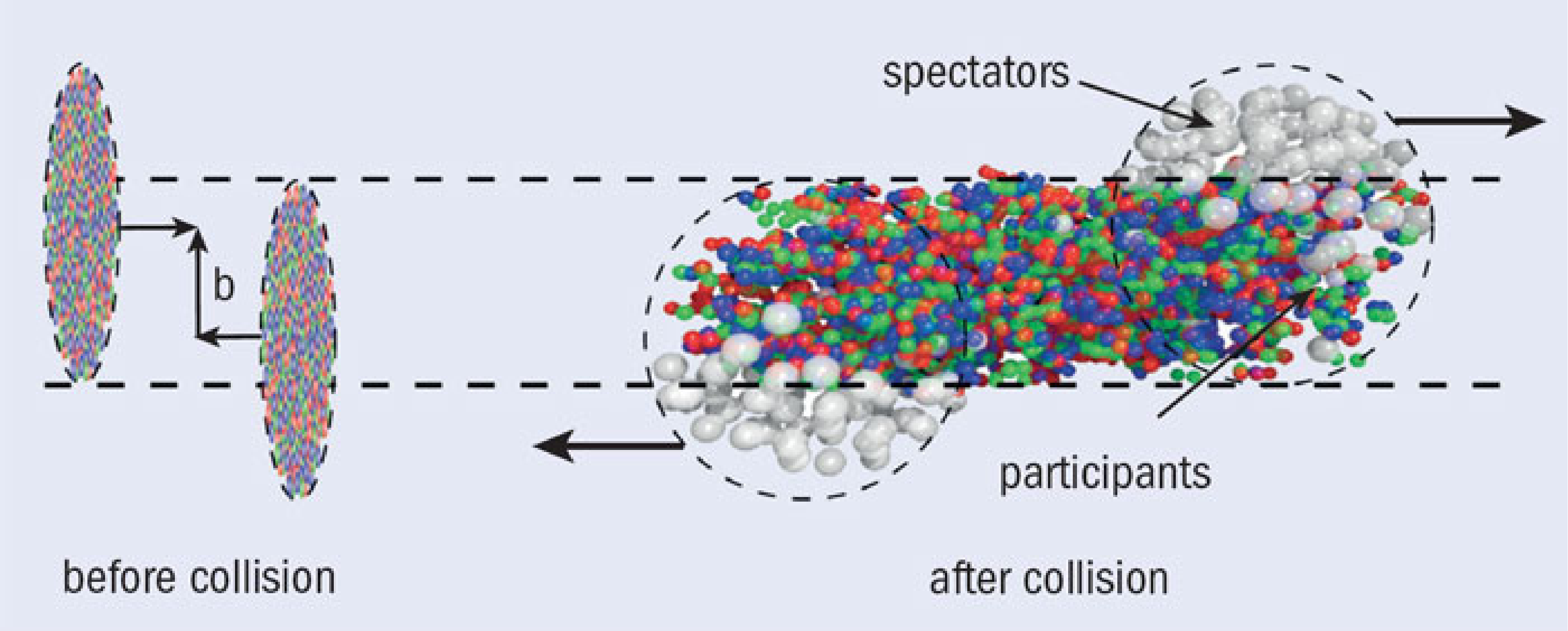
- *Nota bene:* Not all energy is spent in the collision !
  - BRAHMS: ~70% of beam energy available for excitations





BRAHMS Collaboration, PRL93 (2004) 102301
BRAHMS Collaboration, PLB677 (2009) 267

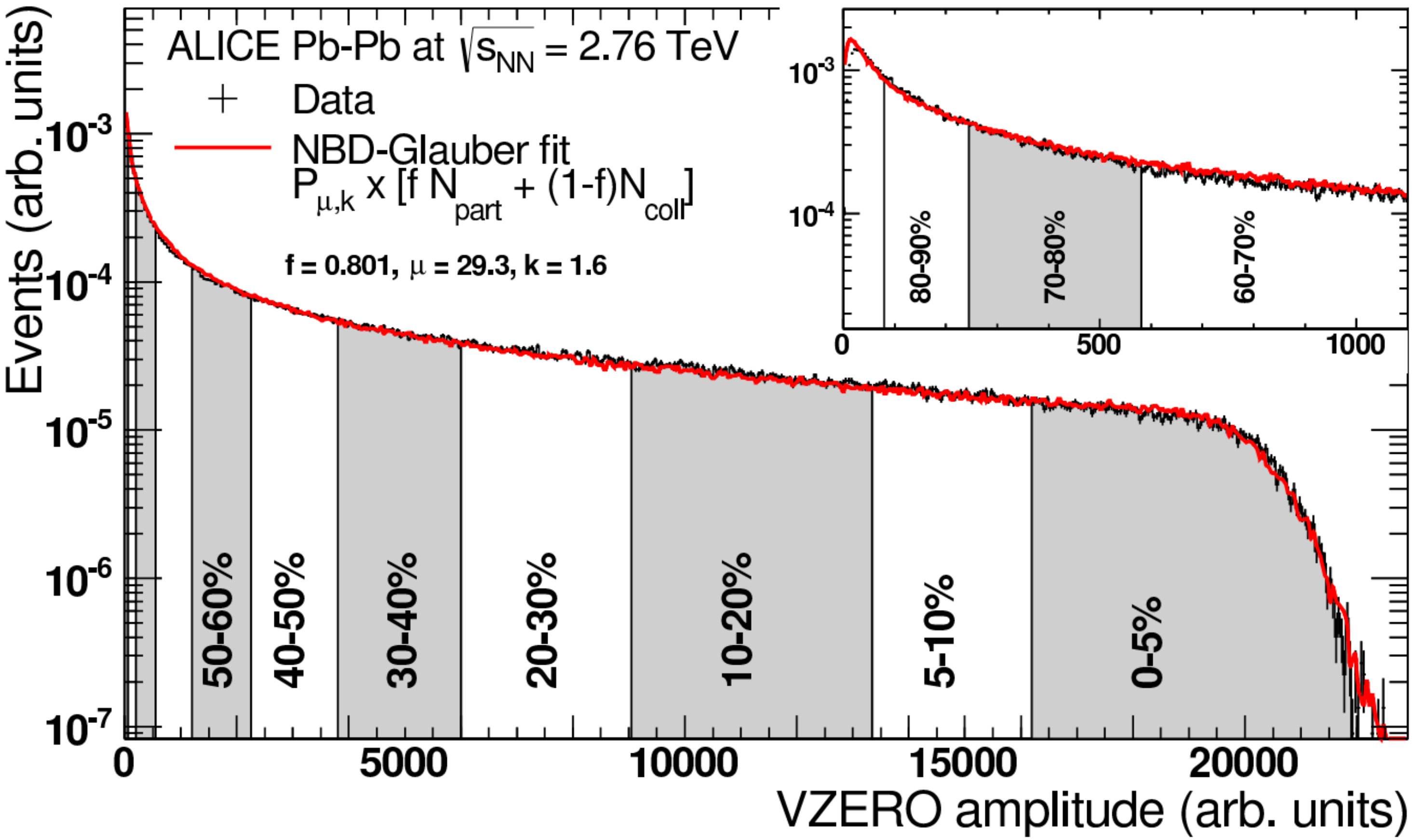
Collision centrality



- Impact parameter *b,* not measurable directly
- Assumption: strong correlation between *b* and event produced multiplicity
- Centrality tipically measured in percentage of the geometric cross-section
  - e.g. 0-10% → most central 10% collisions
- Number of participant pairs (npart)
- Number of binary collisions (ncoll)

Collision centrality

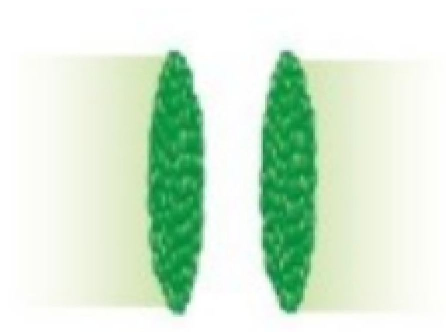
ALICE Collaboration, PRC88 (2013) 4, 044909



- Centrality determination in ALICE, using the charged particle measurement at forward rapidity (VZERO)
- Multiplicity distribution fitted well by an optical Glauber model which allows the determination of <npart> and <ncoll> for each centrality interval

Stages of a high-energy nucleus-nucleus collision

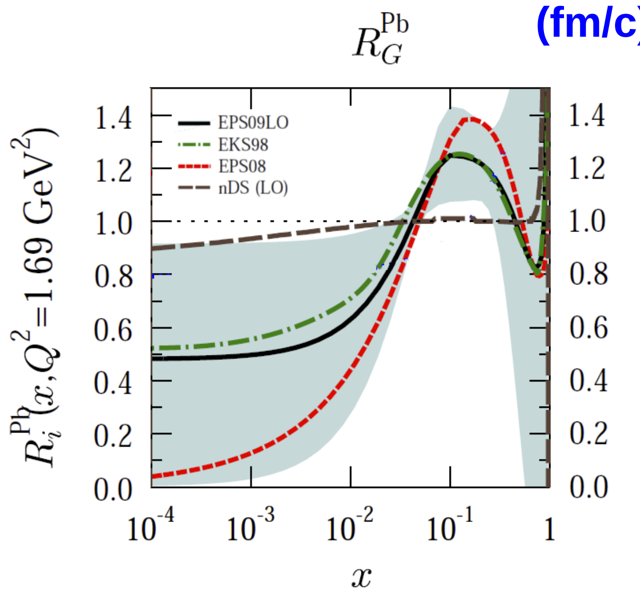
Initial state



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



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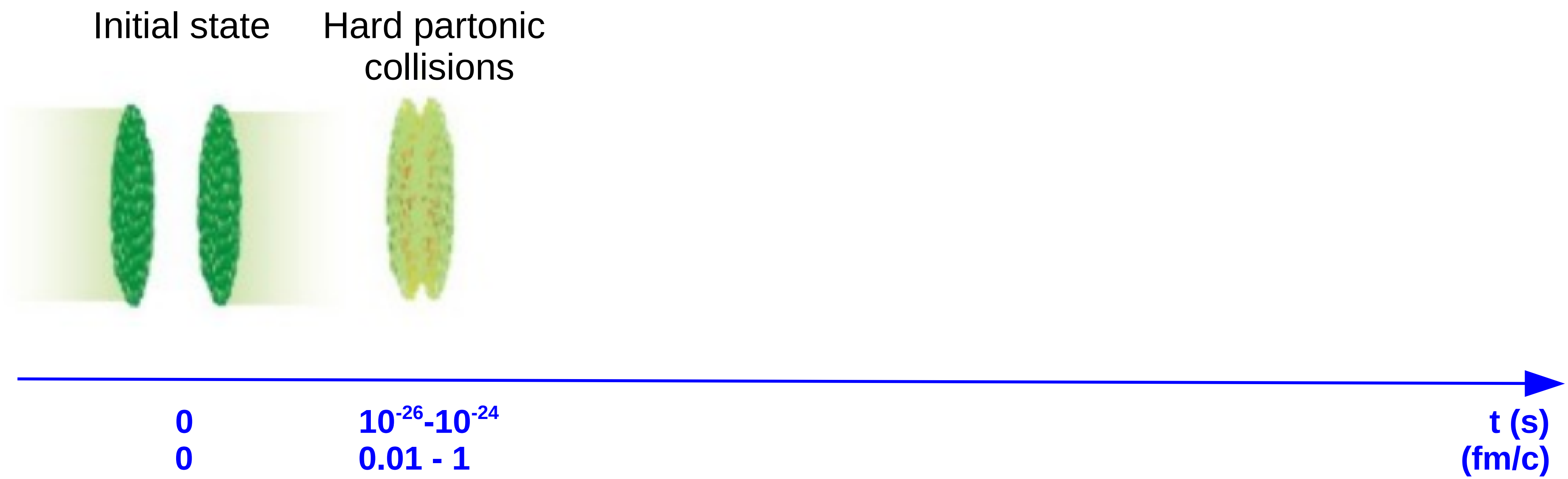
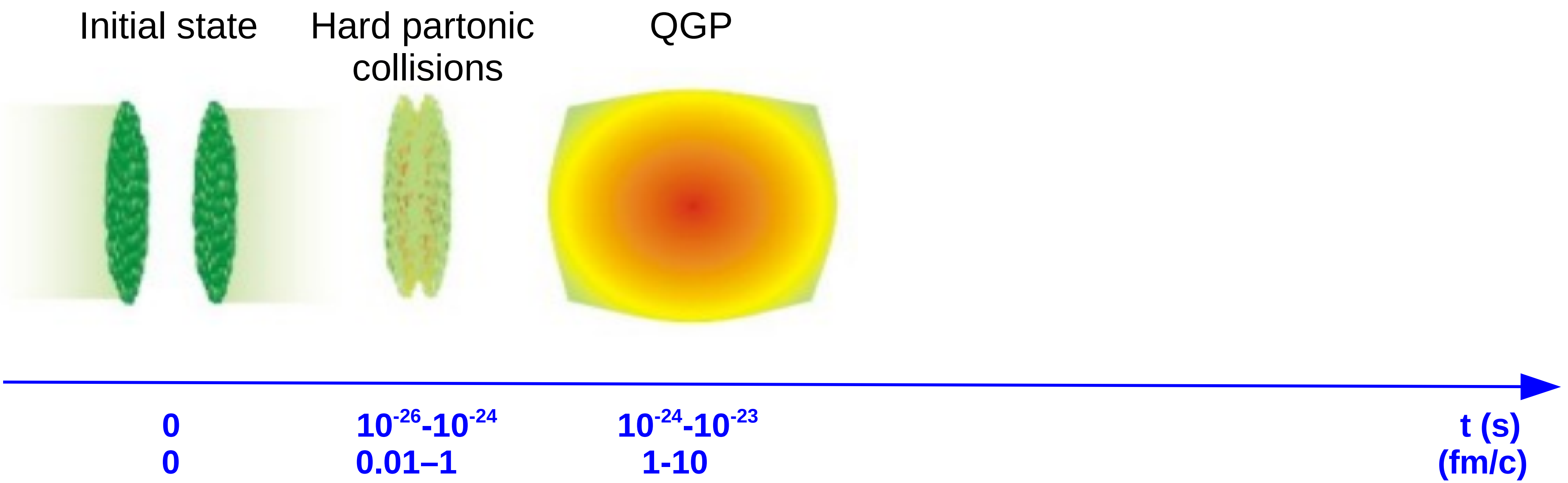


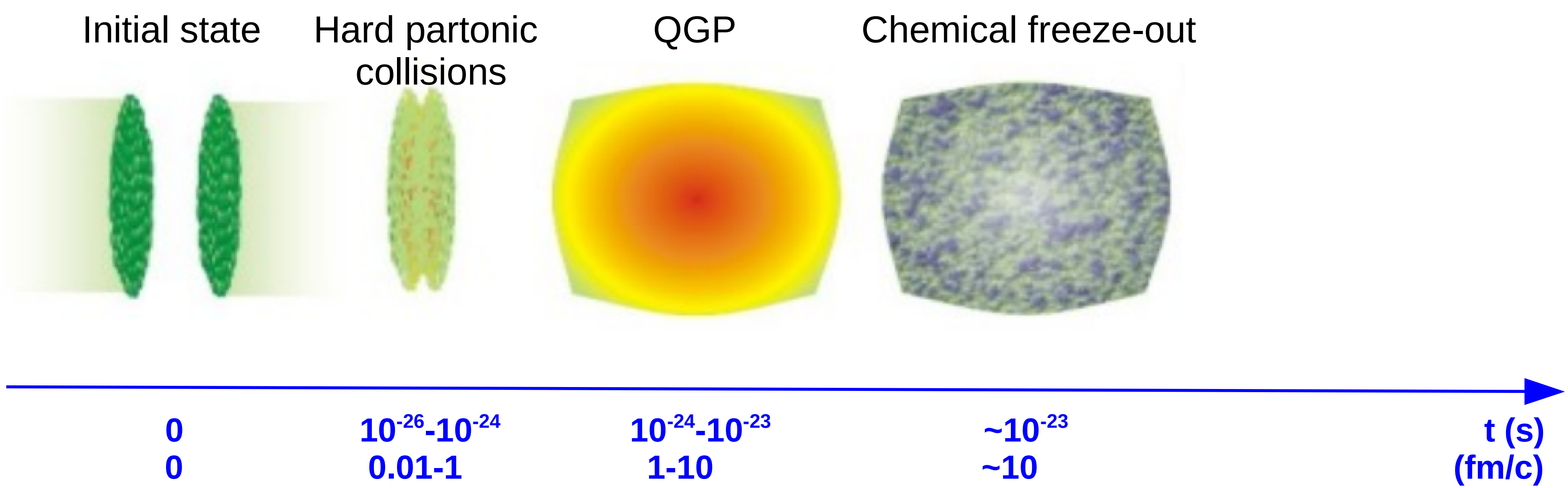
- Initial hard collisions take place
- Most of the entropy is created now → gluons and quark pairs
- Equilibrium (thermalization) takes place rapidly

Stages of a high-energy nucleus-nucleus collision



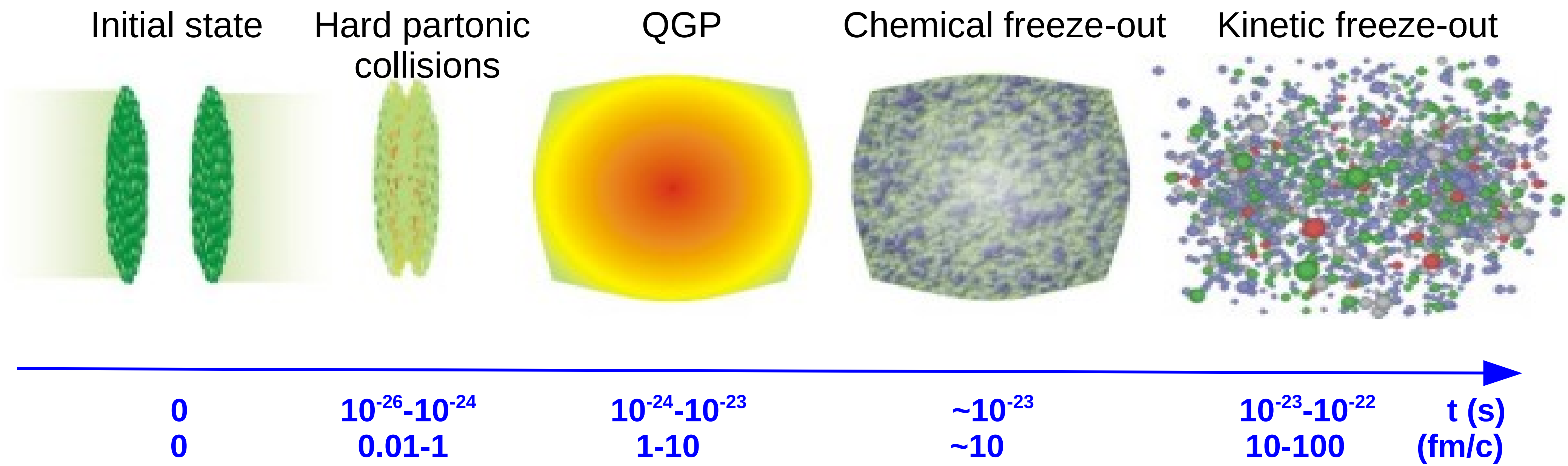
- Deconfined Quark-Gluon Plasma phase
- System expands and cools hydrodynamically

Stages of a high-energy nucleus-nucleus collision



- 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



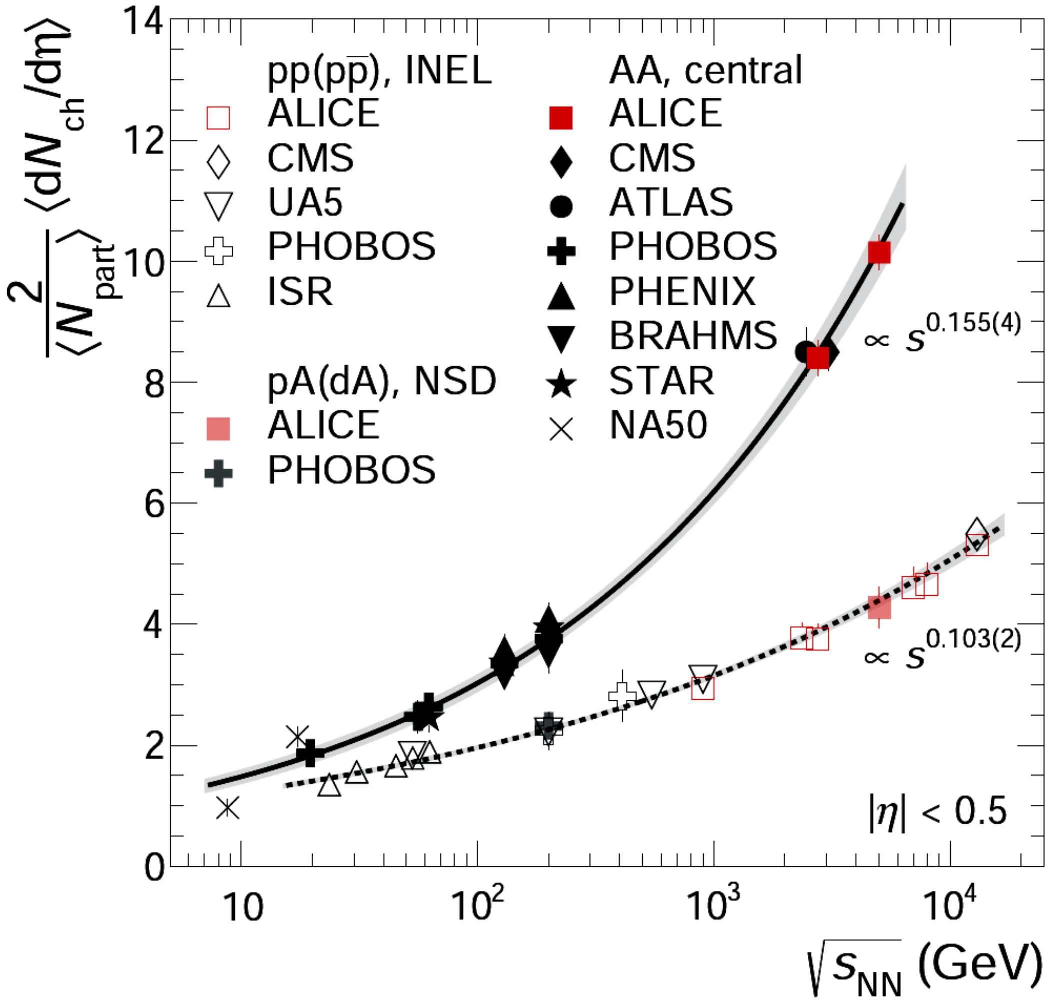
- Kinetic freeze-out:
  - Elastic collisions cease
  - Kinetic distributions are frozen

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

Soft physics

Particle production

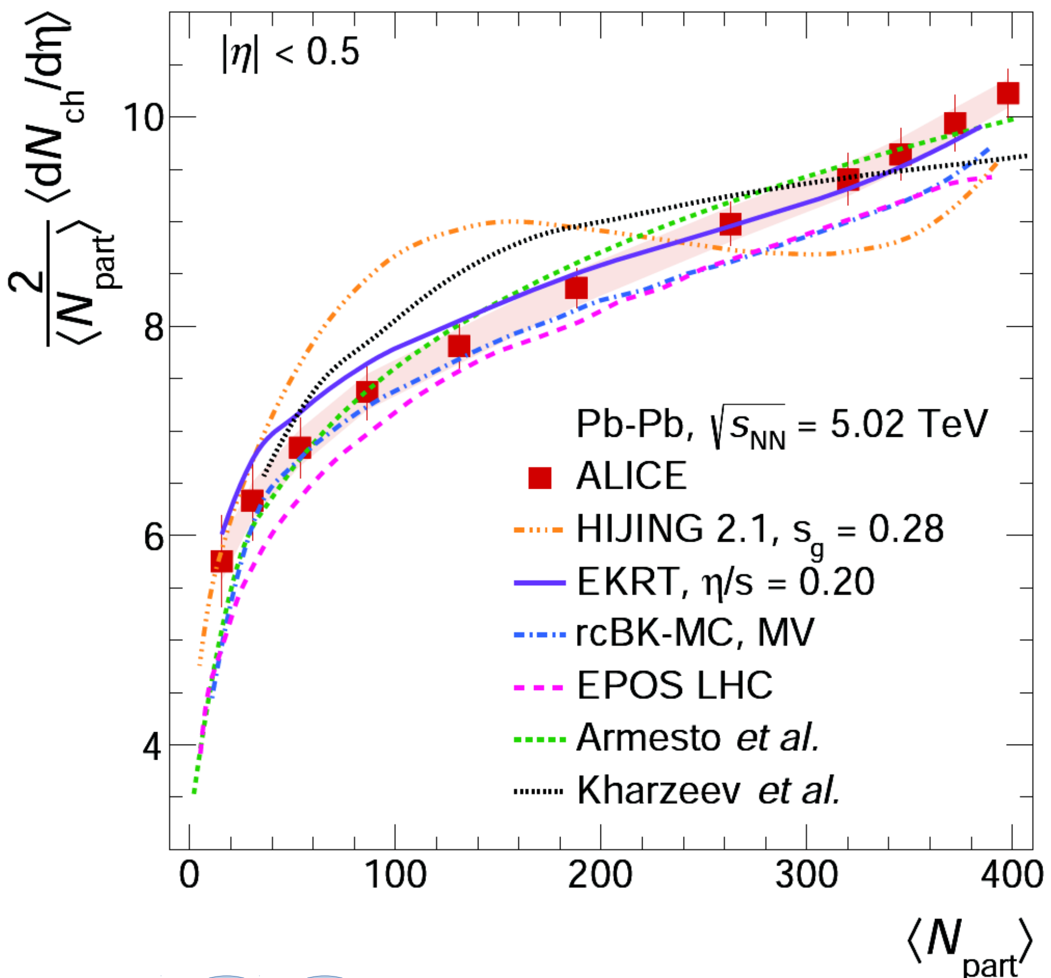
ALICE Collaboration, PRL116 (2016) 222302



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

Particle production

ALICE Collaboration, PRL116 (2016) 222302



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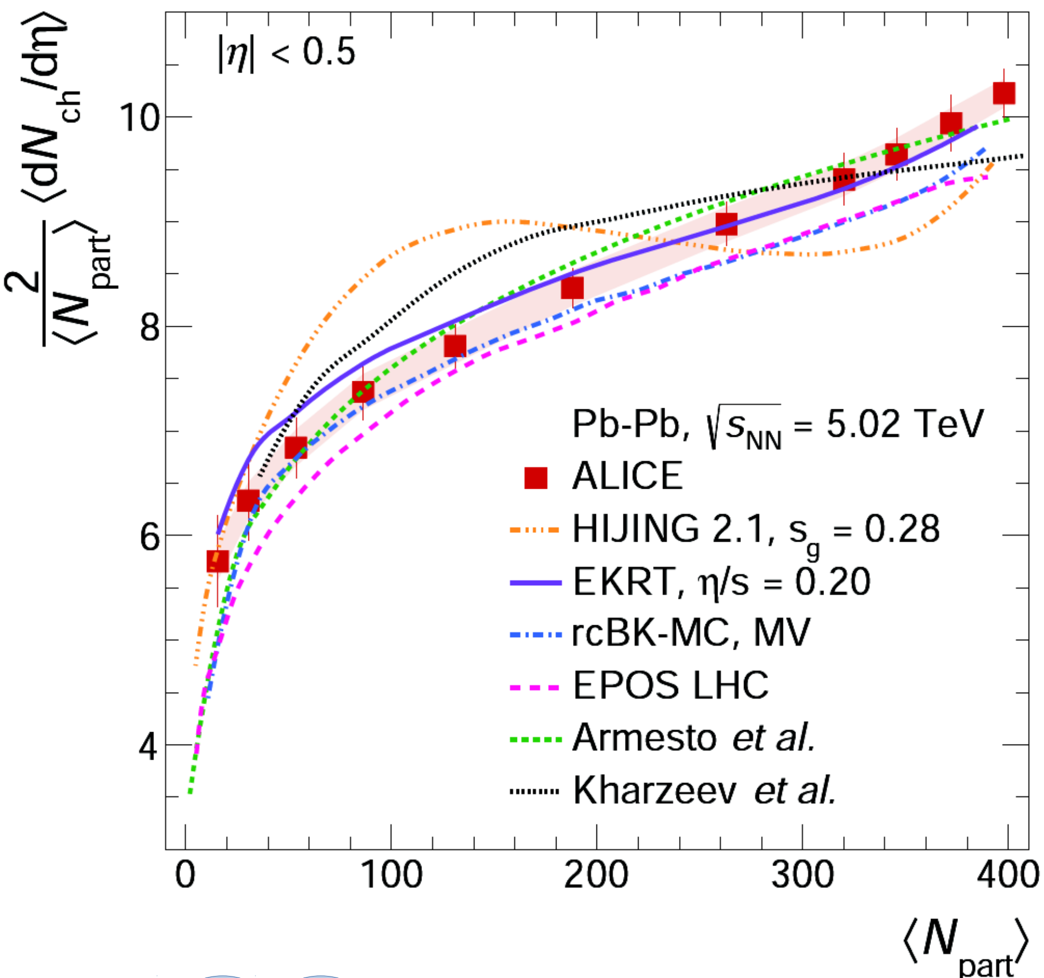
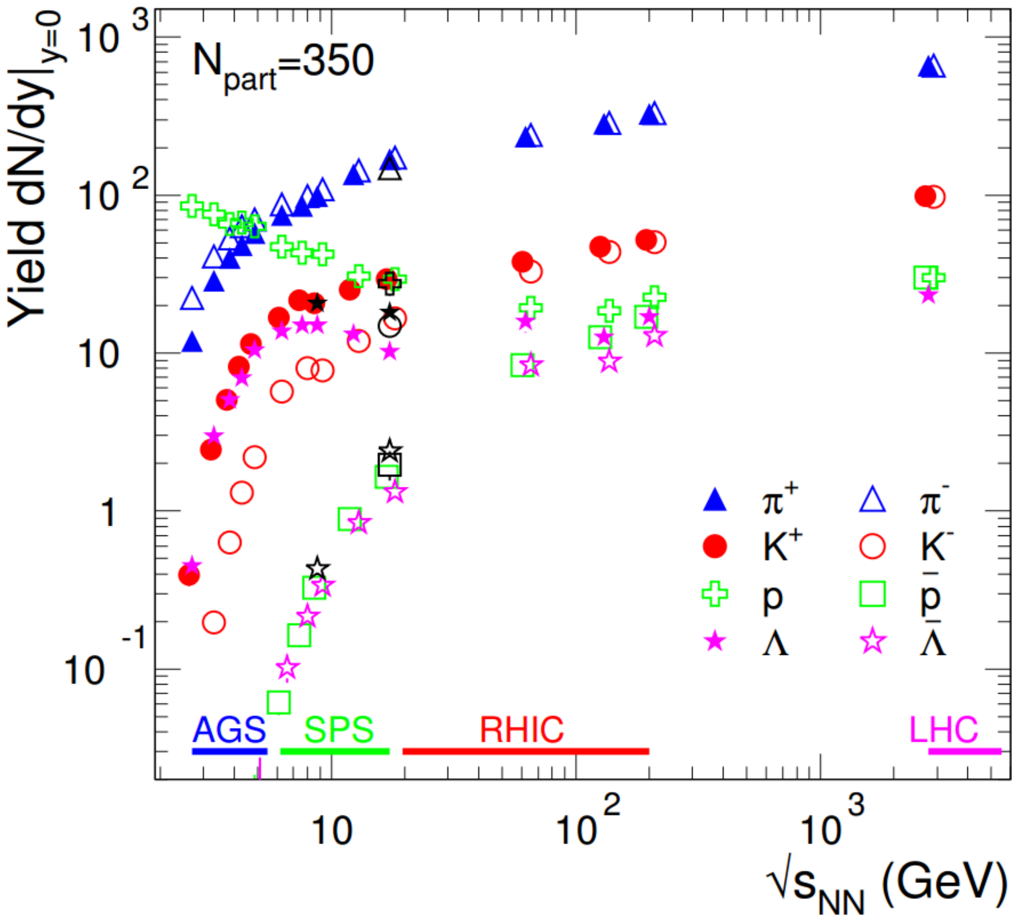
ALICE Collaboration, PRL116 (2016) 222302



- 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



- Lots of particles, most newly created from the excited gluon fields ($E=mc^2$)
- Large 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

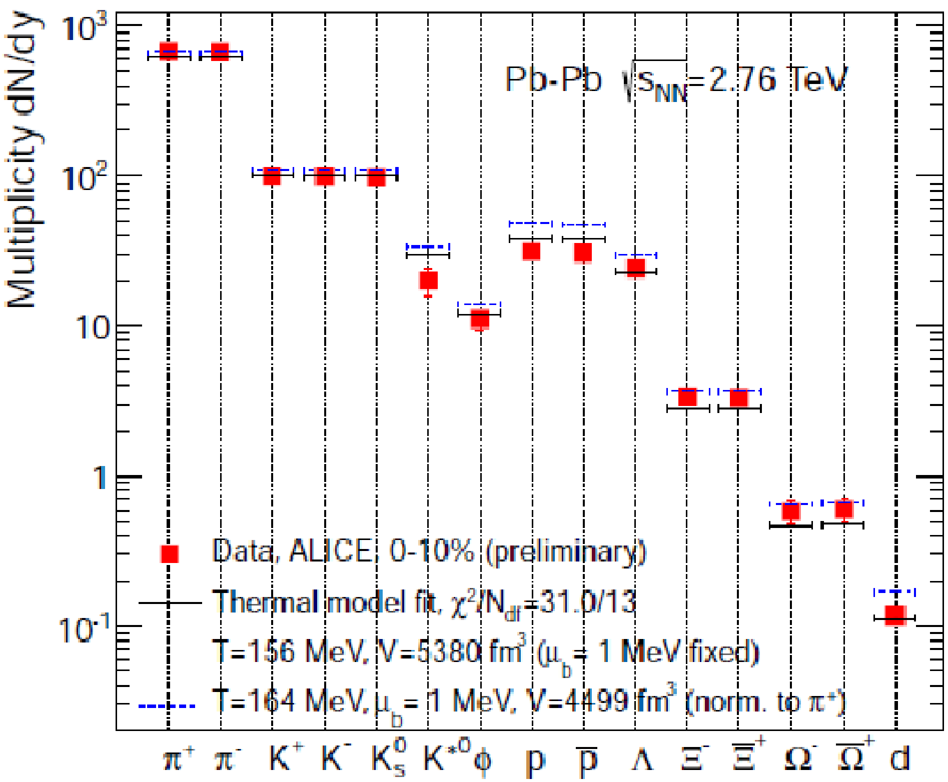
  p(uud), m=938 MeV

  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?

Sonja Kabana – tuesday 16, friday 19

Chemical freeze-out



Mark Gorenstein, monday 22

- 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

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

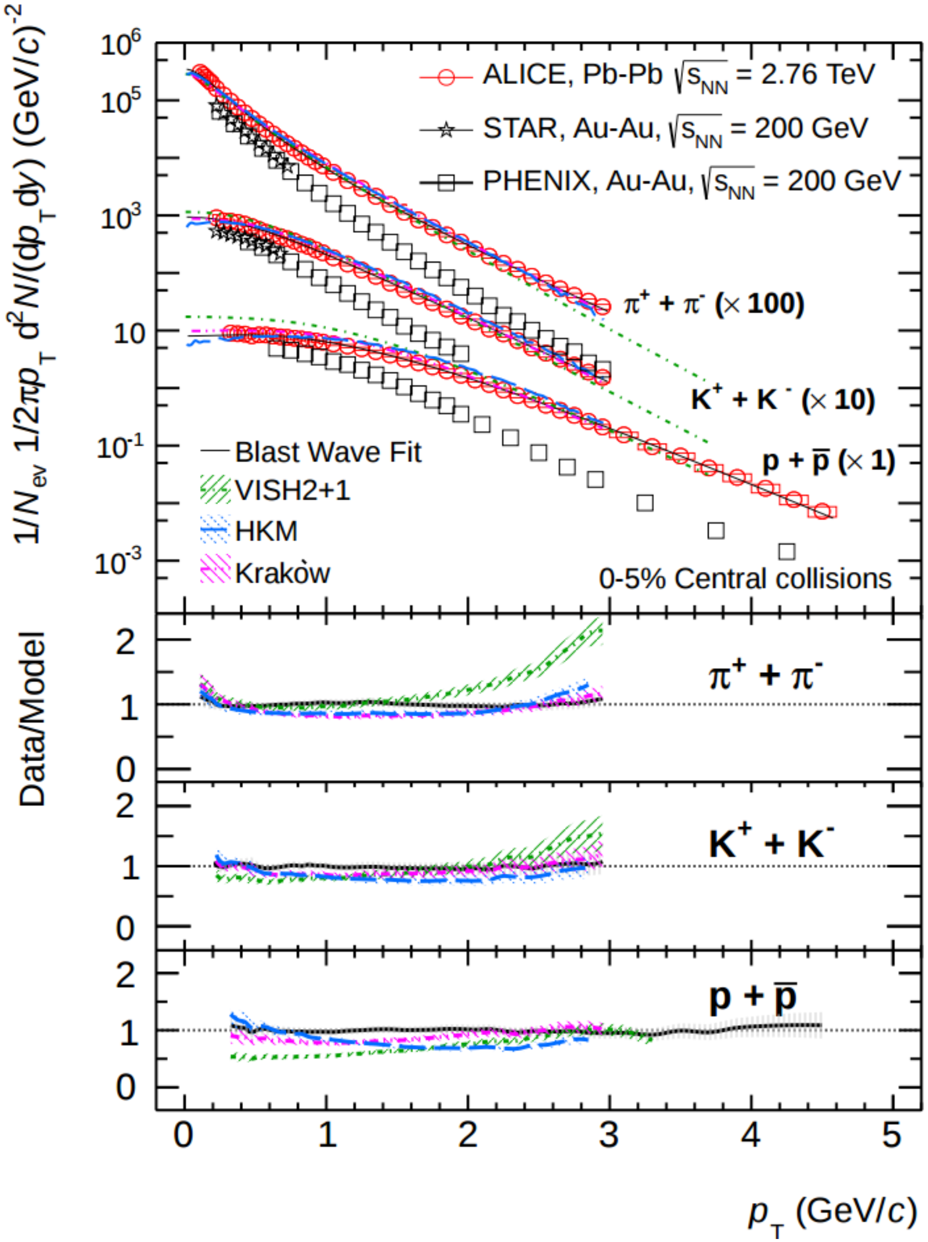
- Hadron yields N_i can be obtained using only 3 parameters: (T_{chem},μ_B,V)
- The hadron abundancies are in agreement with a thermally equilibrated system

  T_{chem}=155-165 MeV

  μ_B~0

Transverse momentum spectra

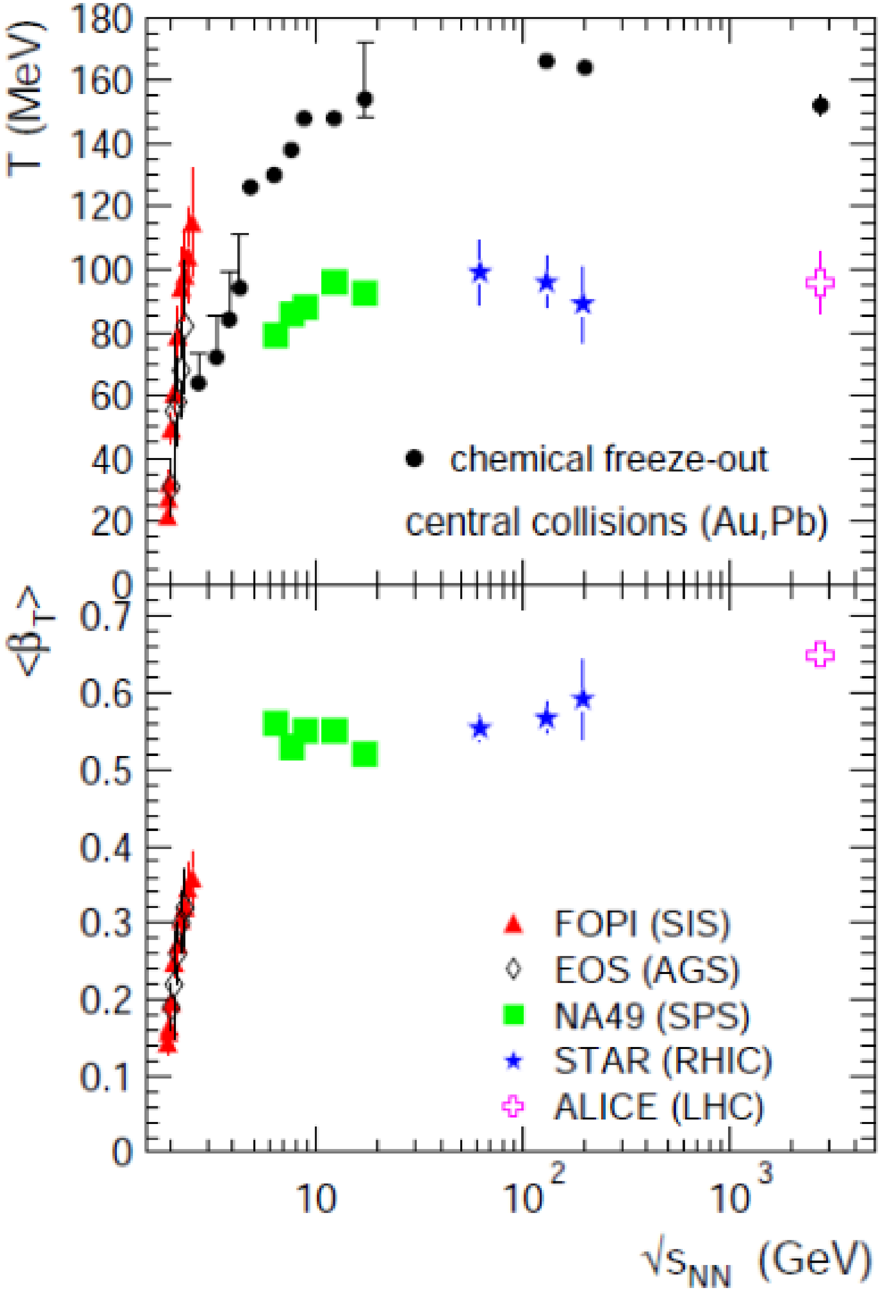
ALICE, PRL 109 (2012) 252301



- Provides information on the fireball properties at the thermal freeze-out
- Hardness of the spectra depends on the collision energy, centrality and particle specie
- 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)

The kinetic freeze-out

A.Andronic, arXiv: 1210.8126



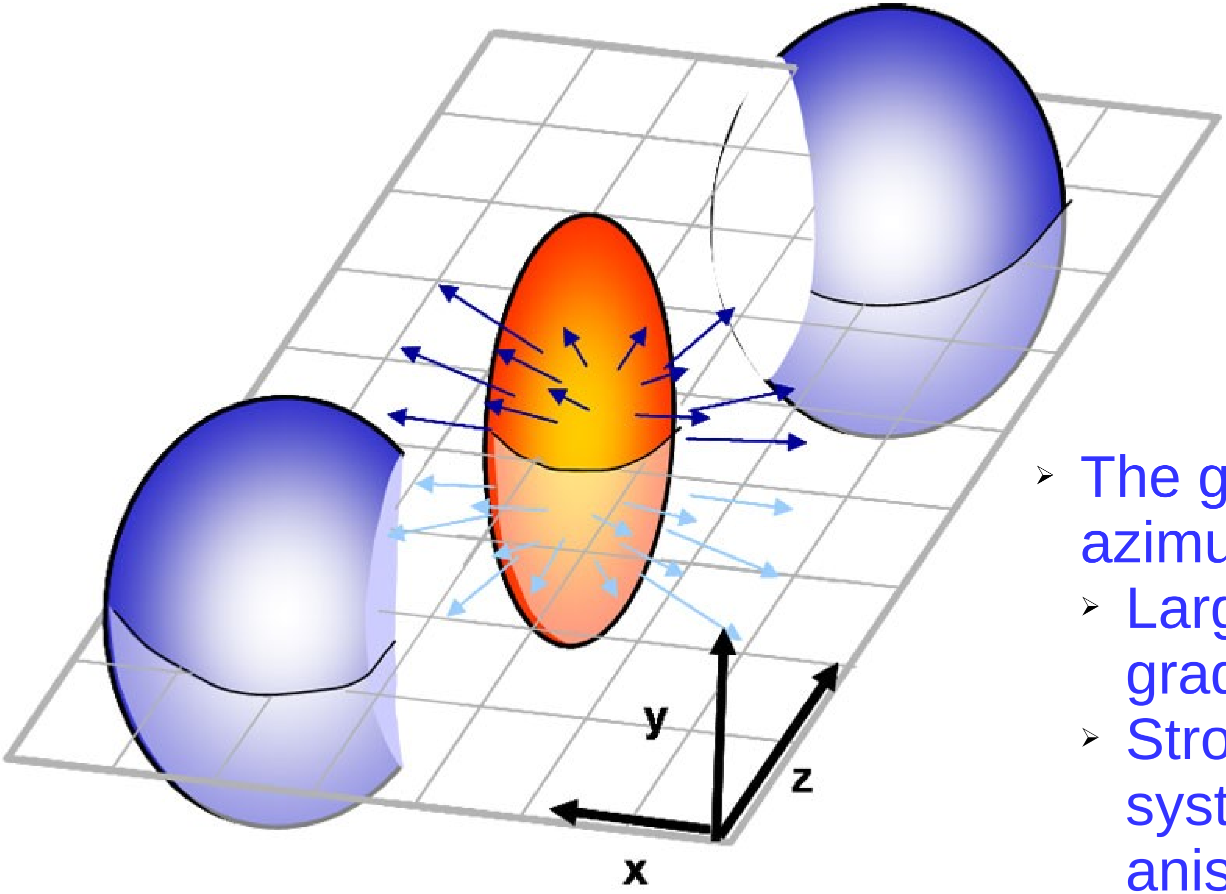
- Hydro-like “Blast-wave” fits allow to extract parameters like :

  T_{kine} = kinetic freeze-out temperature

  $<\beta>$ = collective average velocity

- Light quark hadrons “flow” with a collective velocity of 2/3 *c* additional to their own individual movement

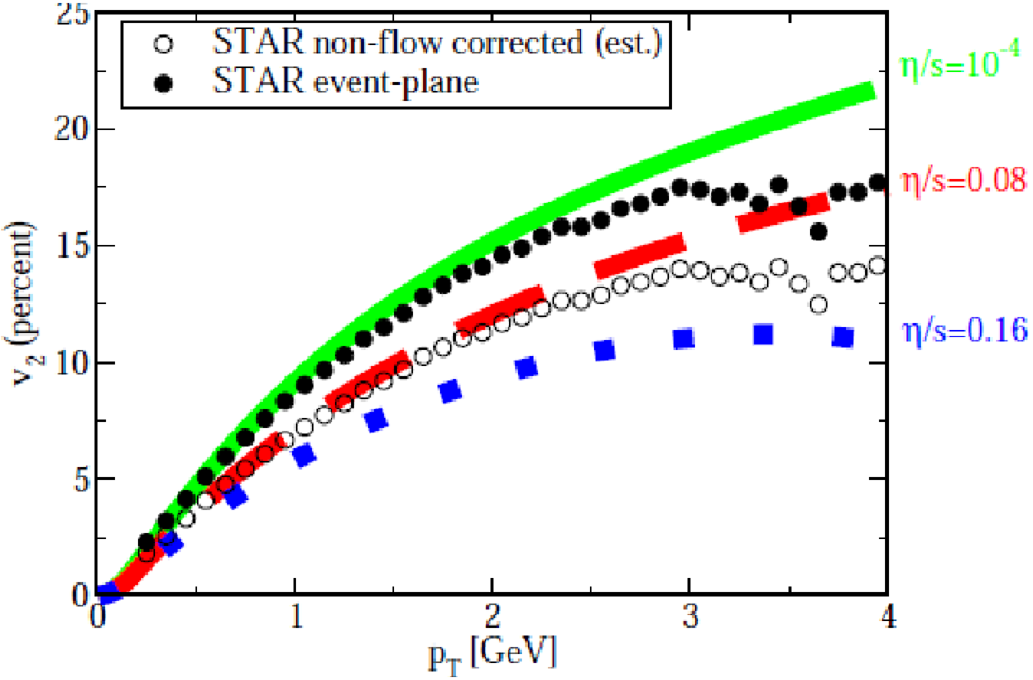
Anisotropic flow



- 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

$$\frac{dN}{d\varphi} \simeq [1 + 2v_1 \cos(\varphi - \Psi) + 2v_2 \cos 2(\varphi - \Psi) + 2v_3 \cos 3(\varphi - \Psi) + \ldots]$$

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: $\eta/s = 1/4\pi \approx 0.08$

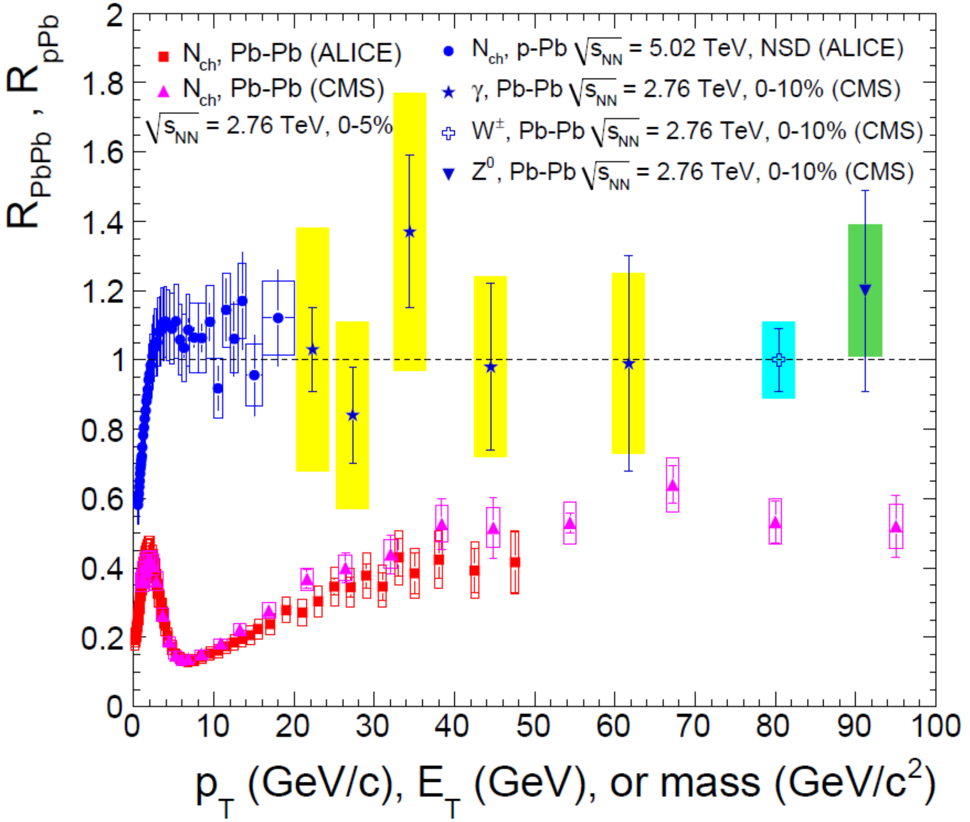
Kovtun, Son, Starinets hep-th/0405231

Laszlo Csernai, tuesday 16
Arkadiy Taranenko, friday 19
Yuriy Sinyukov, monday 22

Hard probes

High-p_T suppression

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

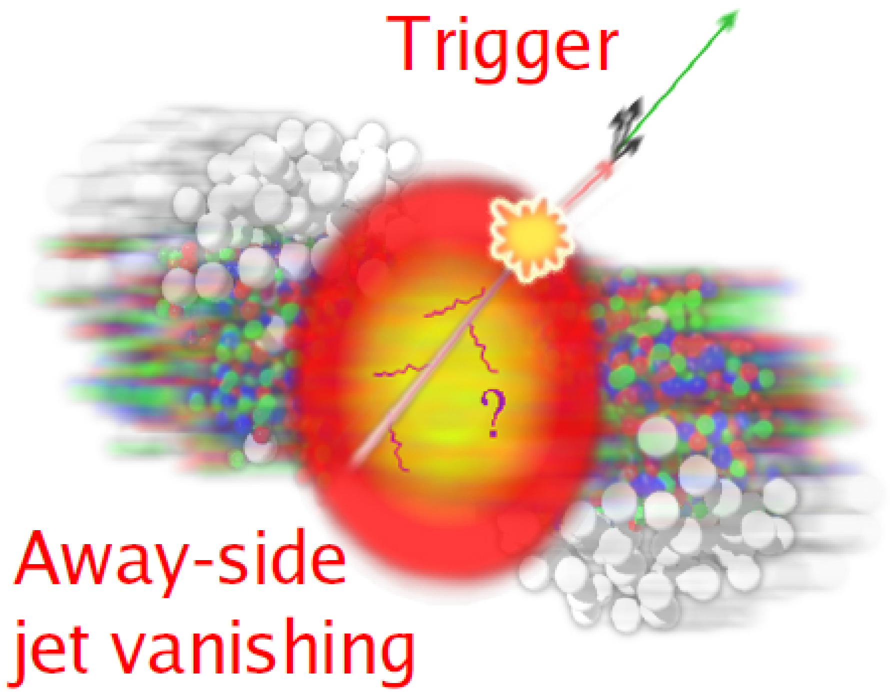


$$R_{AA} = \frac{1}{N_{coll}} \times \frac{Y_{AA}}{Y_{pp}}$$

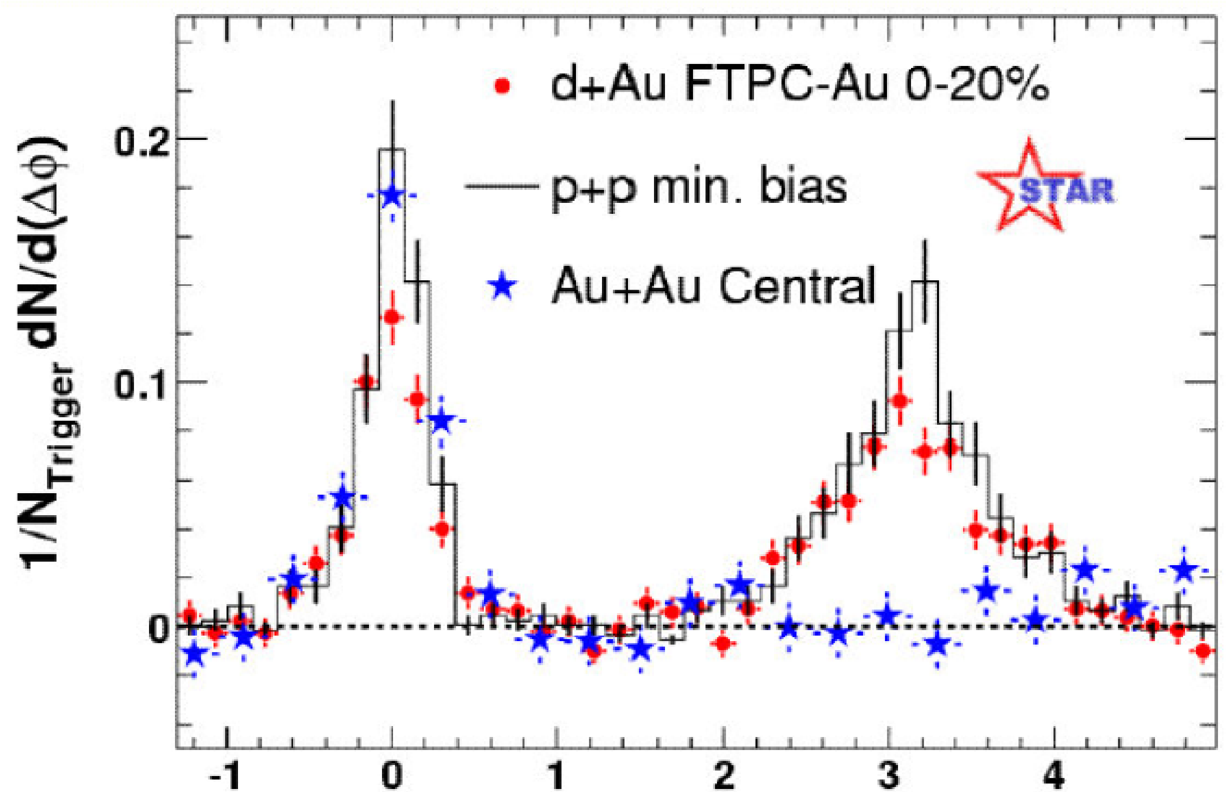
Superposition of NN collisions → $R_{AA}=1$
Suppression → $R_{AA}<1$
Enhancement → $R_{AA}>1$

- High-p_T hadrons strongly suppressed in central heavy-ion collisions
- Suppression persists even at 100 GeV/c
- No hadron high-p_T suppression in p-Pb collisions
- Photons and electroweak bosons production is compatible with binary collision scaling

Two-particle azimuthal correlations



Two-particle azimuthal correlations

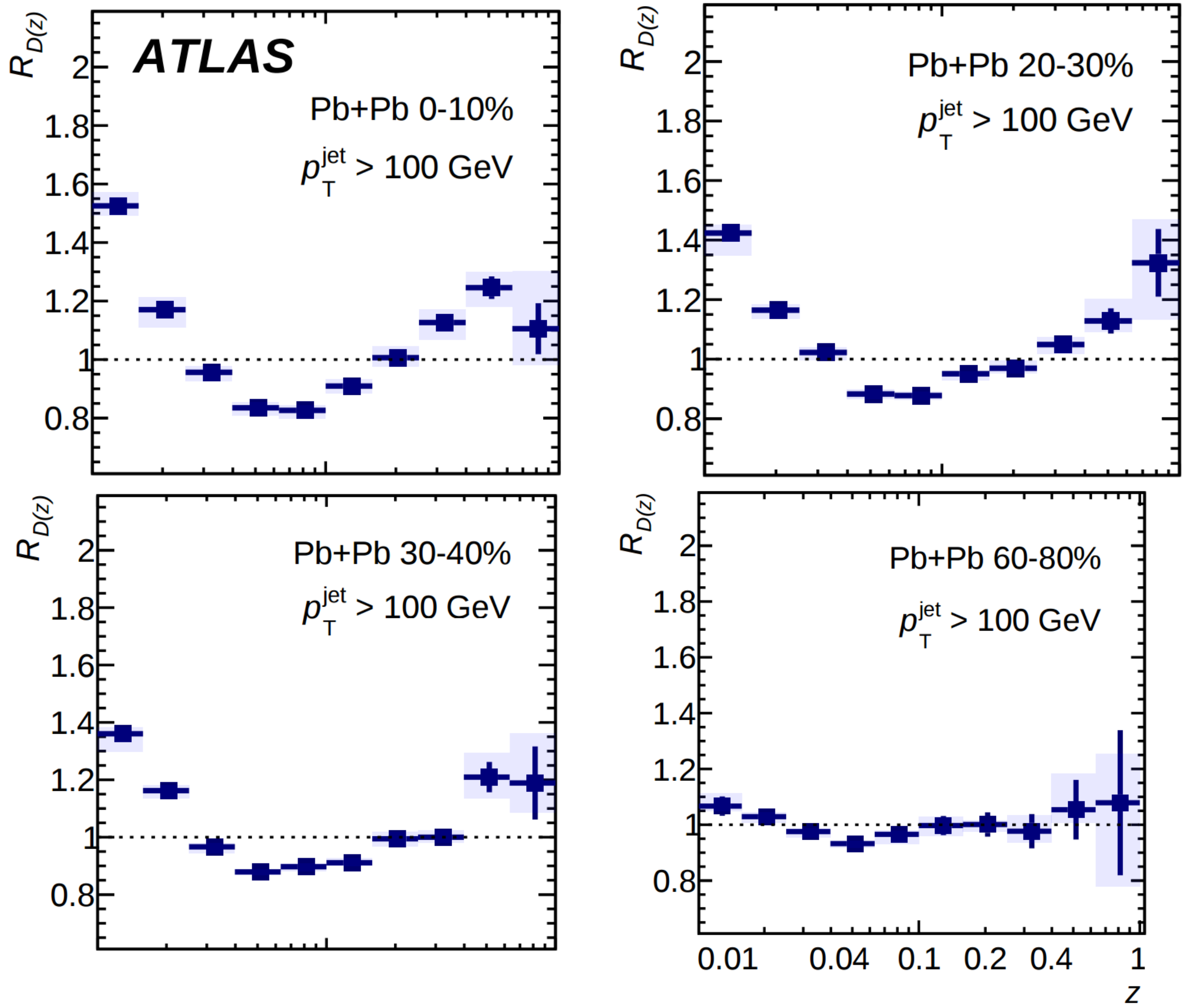


STAR, Phys Rev Lett 91, 072304

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

Jets

ATLAS arXiv: 1702.00674



$z = p_T/p_T^{jet}$

$R_{D(z)} = D(z)^{PbPb} / D(z)^{pp}$

Konrad Tywoniuk, monday 22

- Full jet reconstruction provides detailed insight into medium modification of the jet fragmentation

Electromagnetic probes

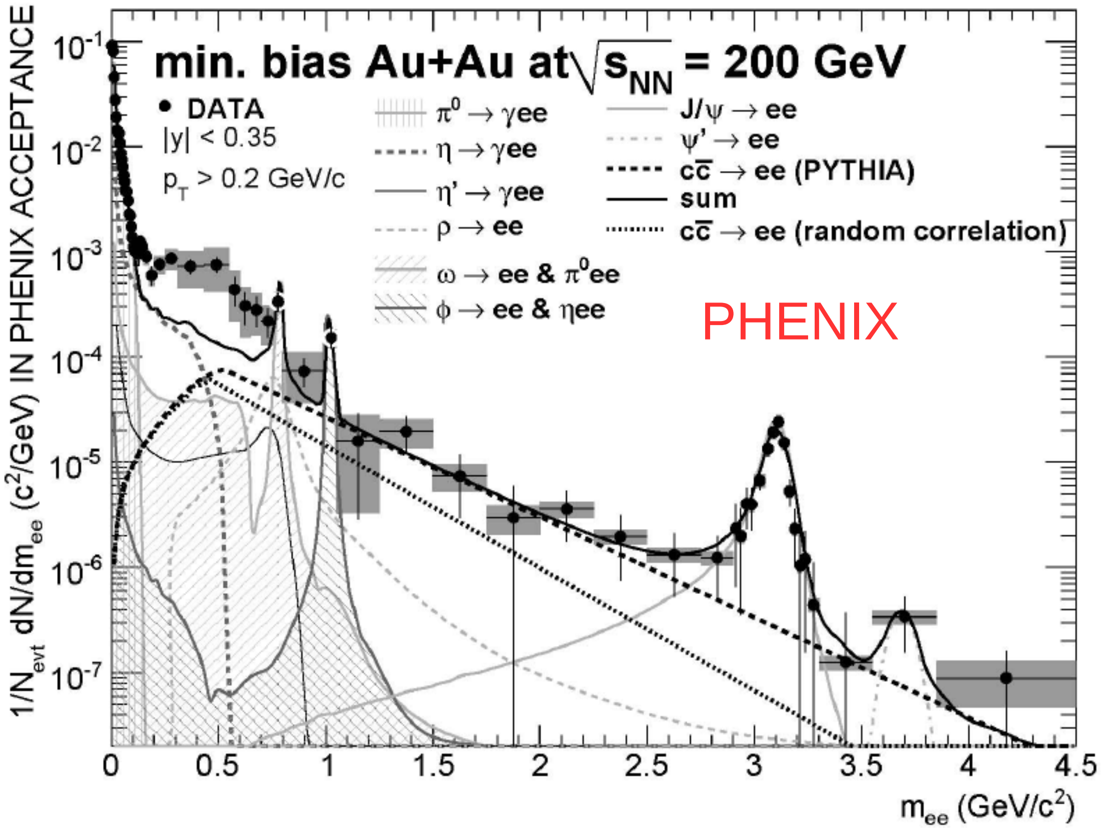
- Direct photons and low mass di-leptons
  - Clean information because of no re-interactions with the QCD medium
  - Emitted through the entire history of the collision

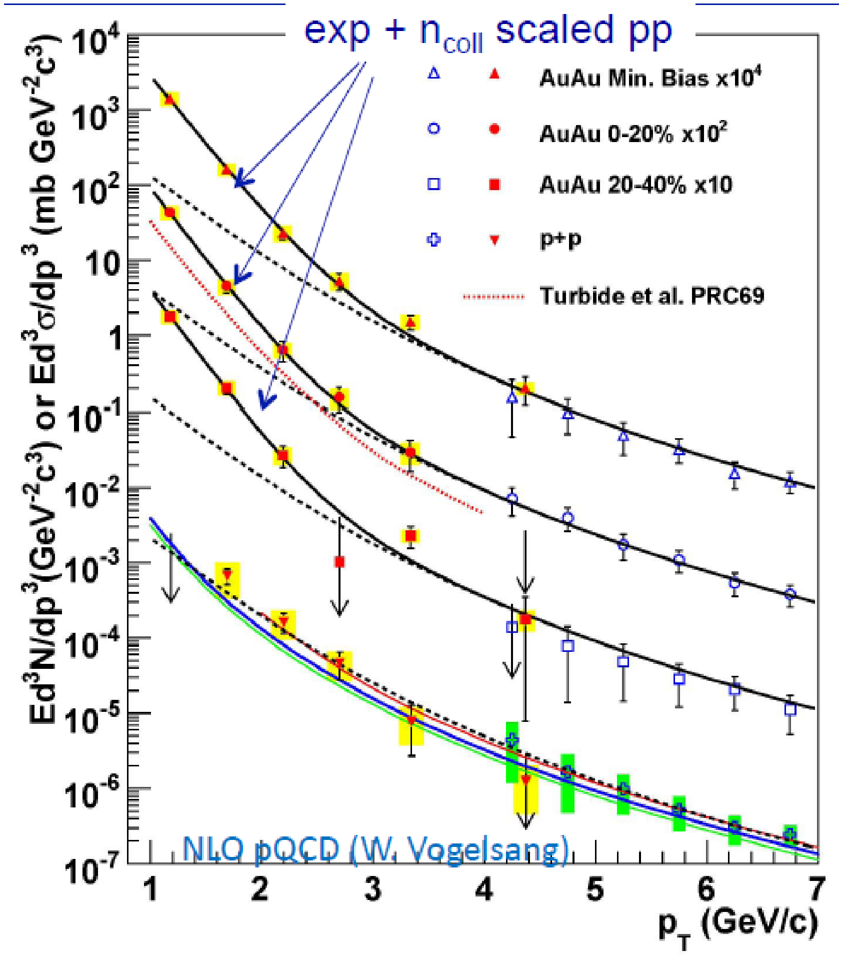
- Hard photons
  - from initial N+N collisions and jet fragmentation

- Soft photons
  - Hadronic sources
  - Thermal photons (both real and virtual) from $q\bar{q}$ annihilations and Compton scattering

- Chiral symmetry restoration
  - ρ-meson broadening and mass shift

EM probes: low mass dielectrons



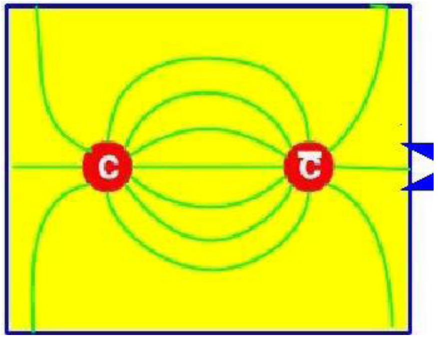


Ana Marin, monday 22

- Excess observed in the low mass dielectron spectrum in the region 0.3-0.7 GeV/c associated with thermal radion
- Strong direct photon excess at p_T<3 GeV/c

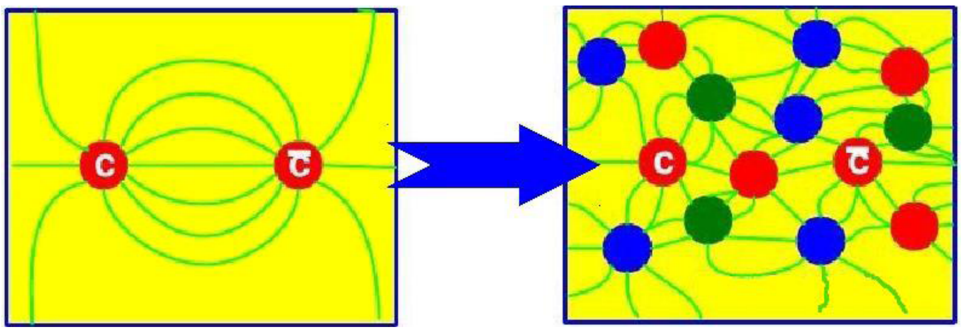
Heavy quarkonium and the QGP

- 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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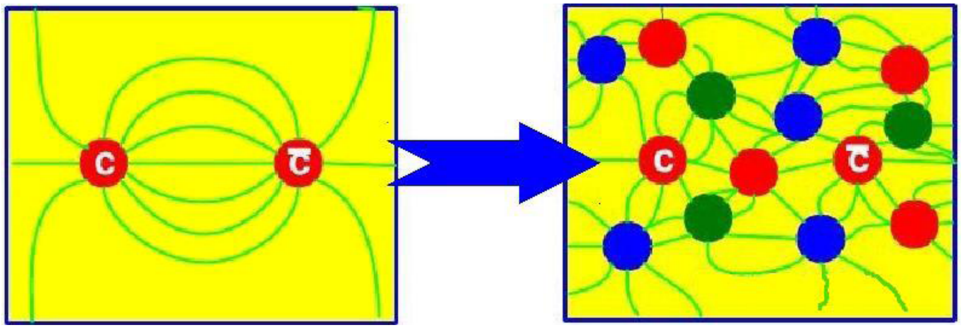
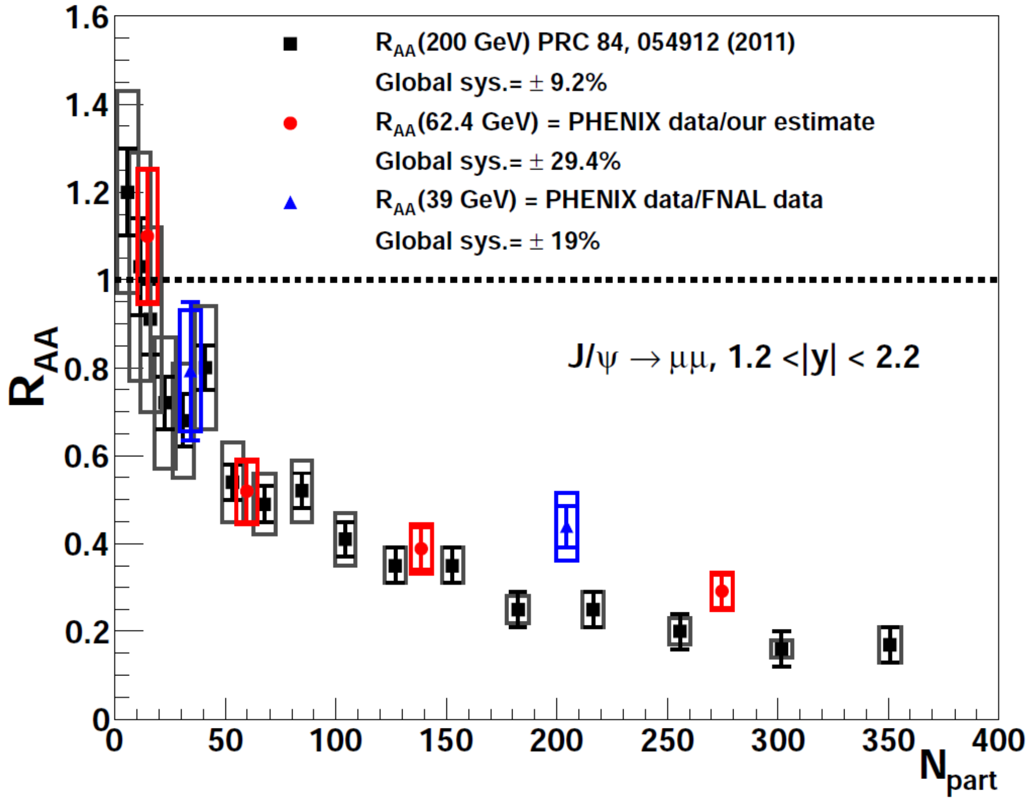
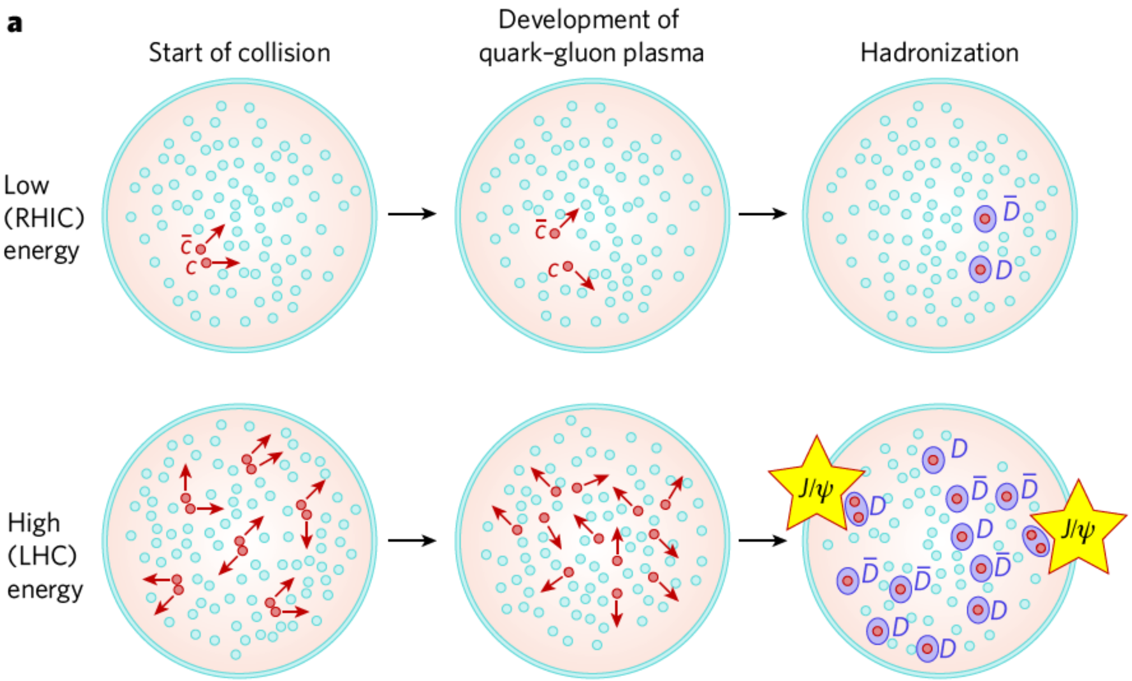
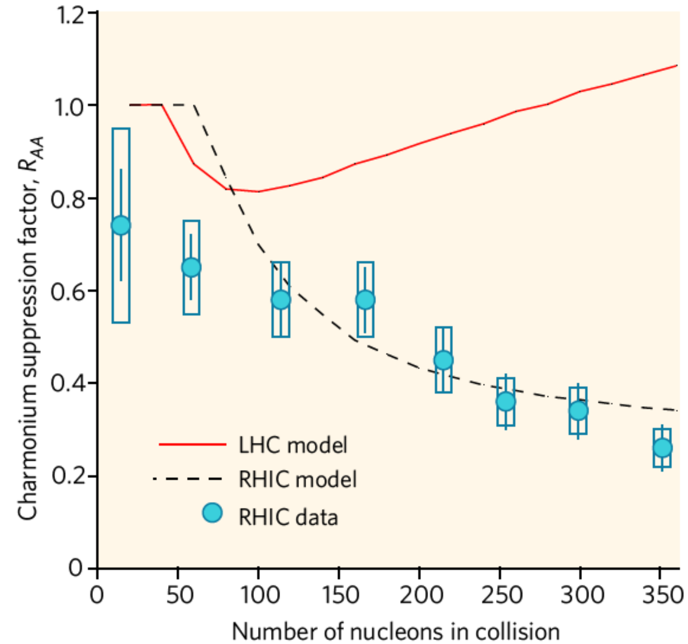




- Evidence of color screening?
- Not completely clear yet: we still need to take into account feed-down from higher mass states (e.g., χ_c, ψ(2S)) and CNM effects

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 at the LHC

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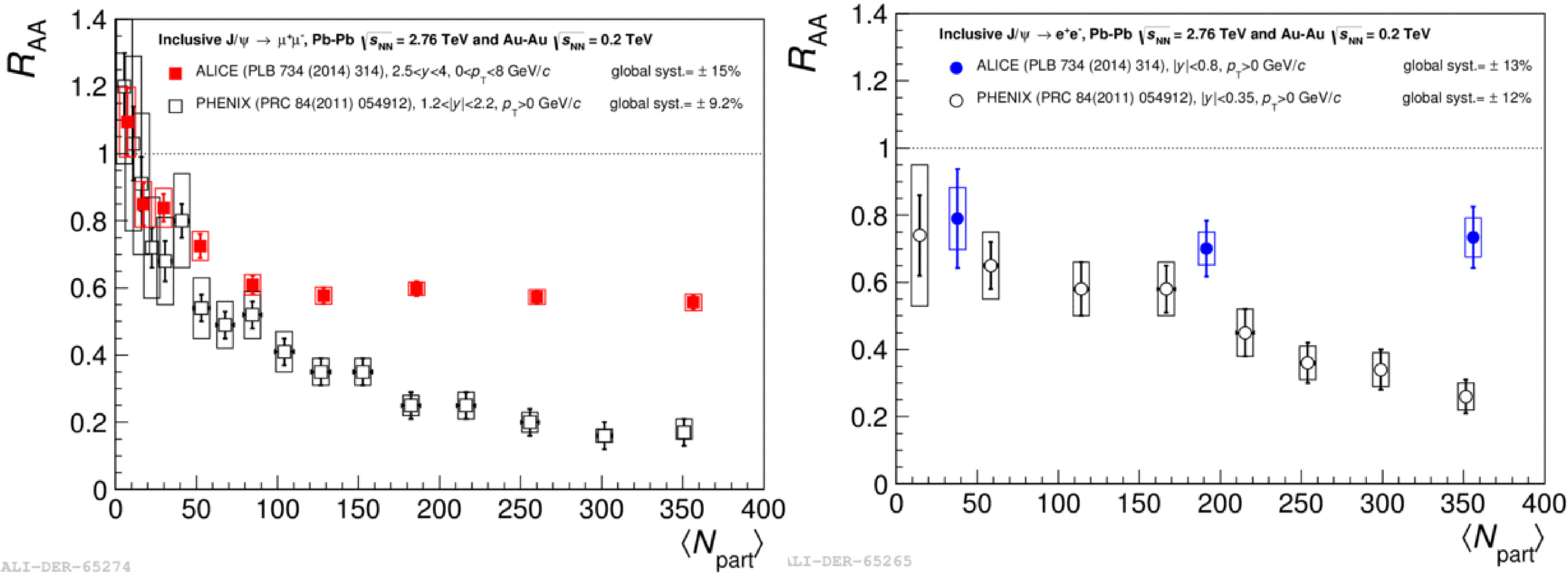

- ALICE results show smaller suppression compared to lower energies (PHENIX) in central collisions
- Indication that regeneration plays an important role in the production of charmonium

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

Backup