High energy nuclear physics at the LHC

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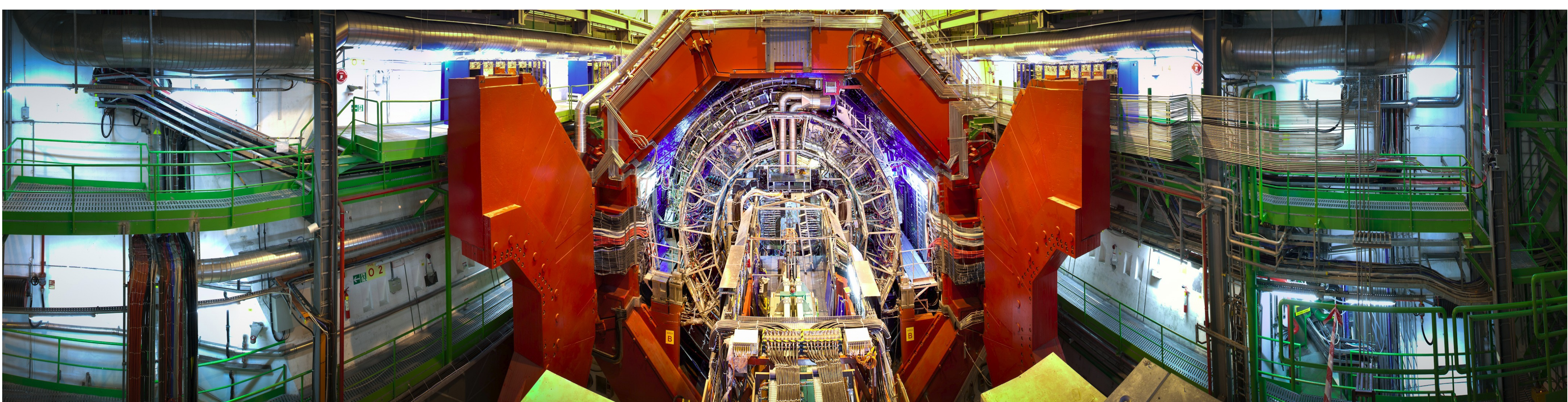
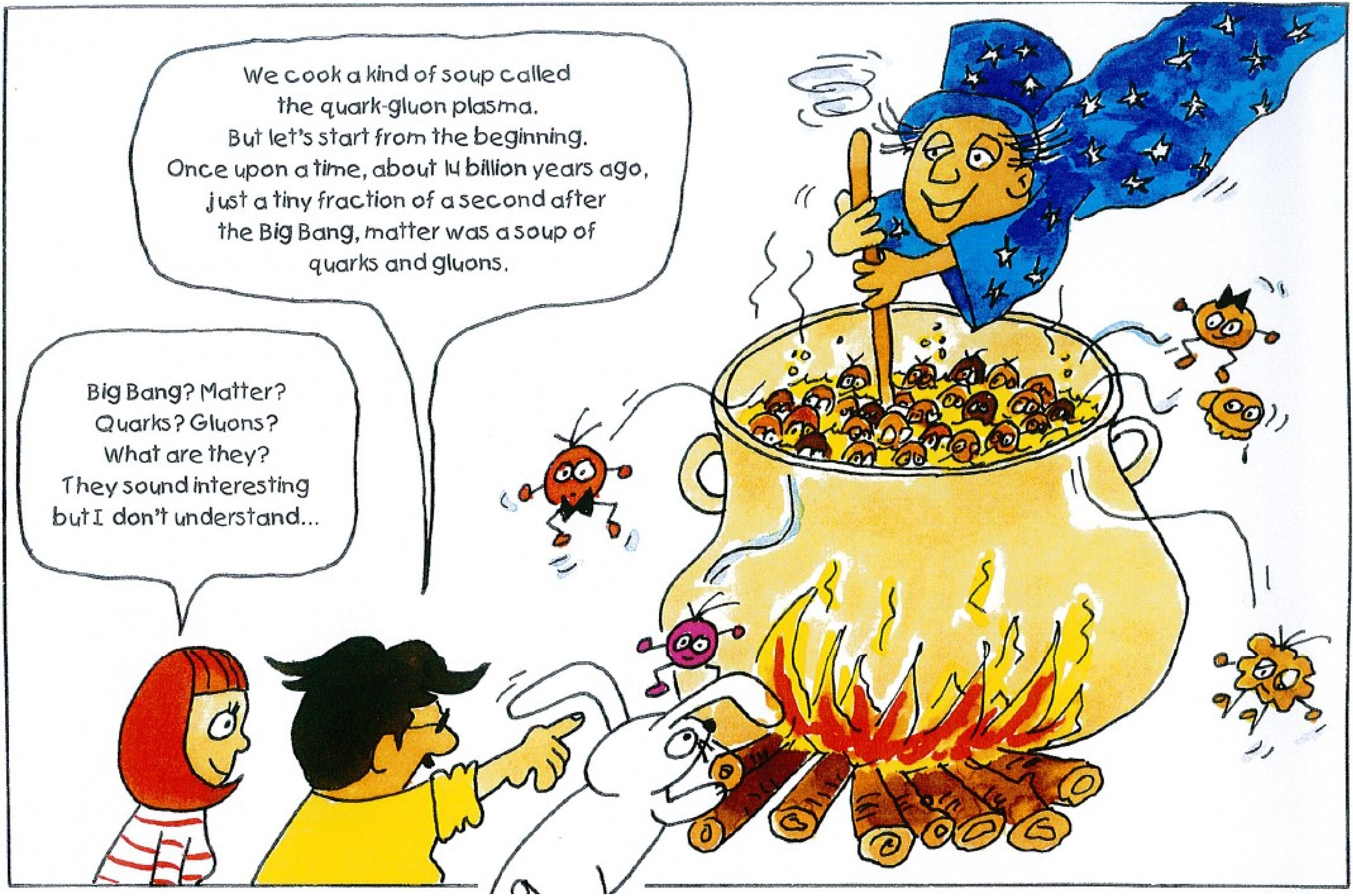
University of Oslo
2015/03/25



Part I: 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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- Quarks

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

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

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

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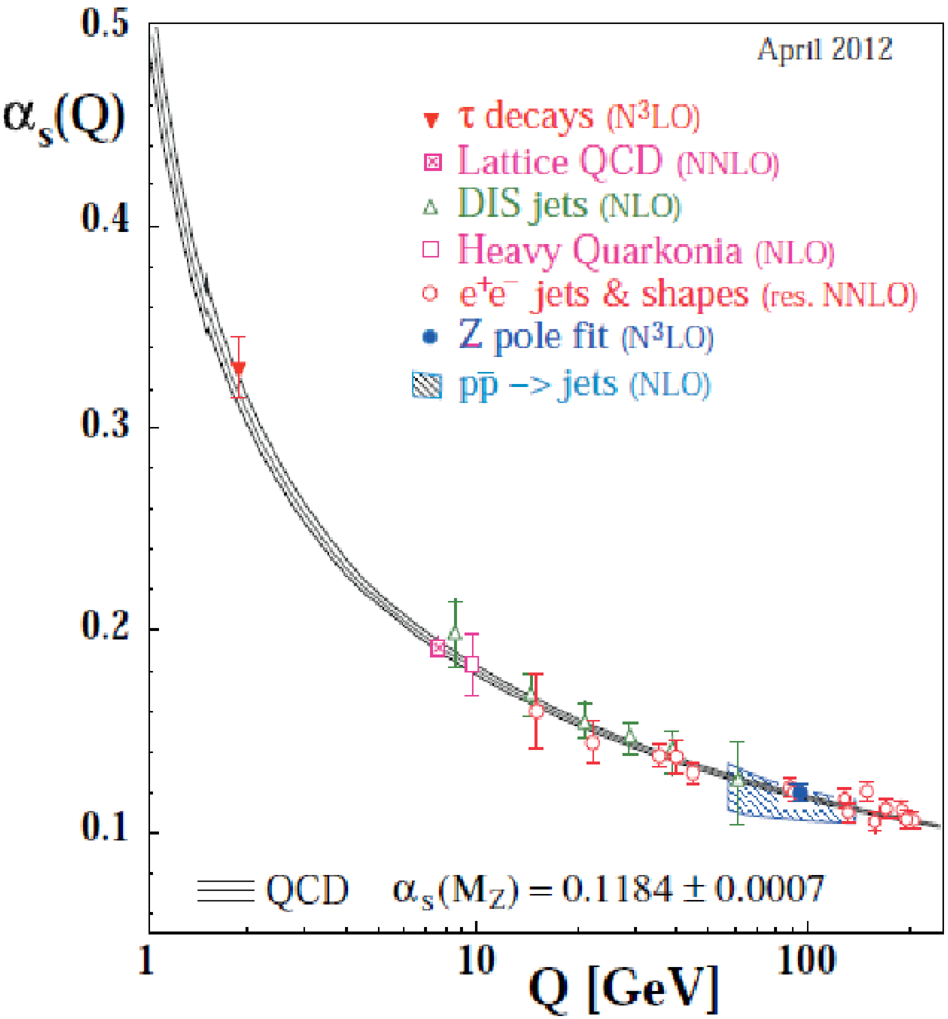
- … all governed by the strong interaction
- Gravitation is negligible
- (electro)weak interactions act only indirectly (decays, final state interactions)

Quantum Chromo-Dynamics (QCD)

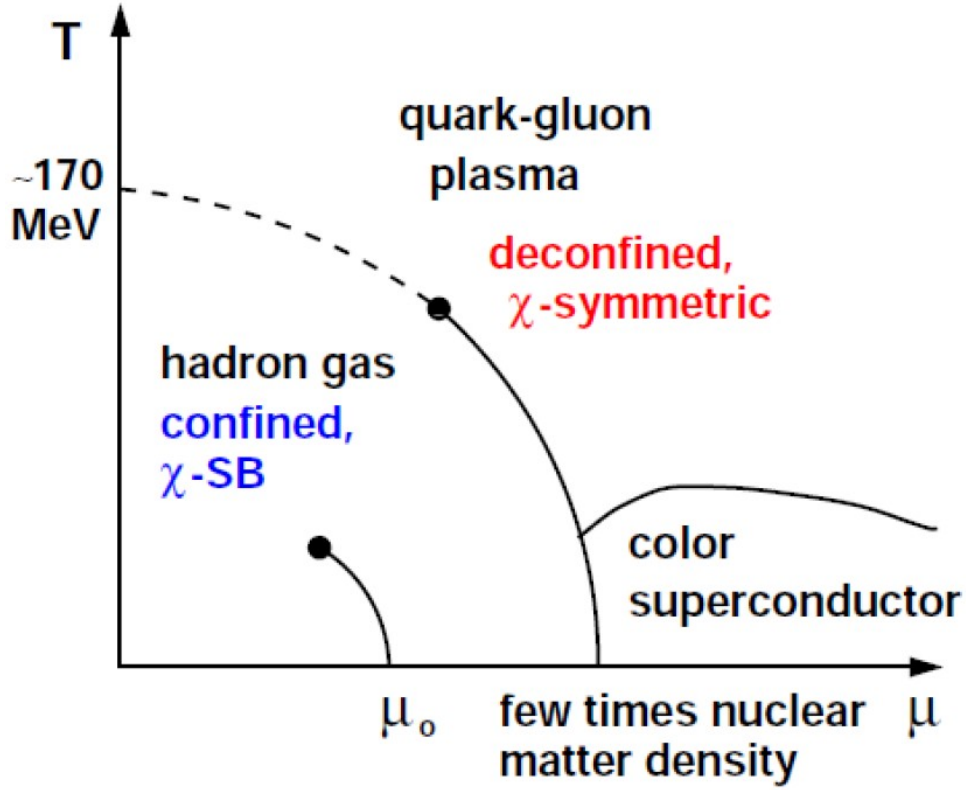
- 6 quarks, 3 colours (RGB)
  and 8 gluons (coloured!)
- ...difficult to calculate
  - No analytical solutions (except 1+1)
  - Strong force, running coupling
  - Easier for high momentum transfer
- Low *Q*: confinement
- High *Q*: asymptotic freedom
  Physics Nobel prize 2004 (Wilczek, Gross, Politzer)
- Not everything is understood
  → phenomenological models needed



S.Bethke, arXiv:1210.0325

High energy nucleus-nucleus collisions: the scope

- Create in the laboratory a chunk of deconfined matter and study its properties (also called Quark-Gluon Plasma, QGP / sQGP)
- Study of:
  - Phase diagram
  - Chiral / deconfinement transition(s)
  - Liquid-gas transition
- Relevance for:
  - QCD at finite temperature and chemical potential
  - Early Universe (10^{-5} s)
  - Neutron stars
  - ...



Braun-Munzinger, Wambach, Rev.Mod.Phys.81 (2009) 1031

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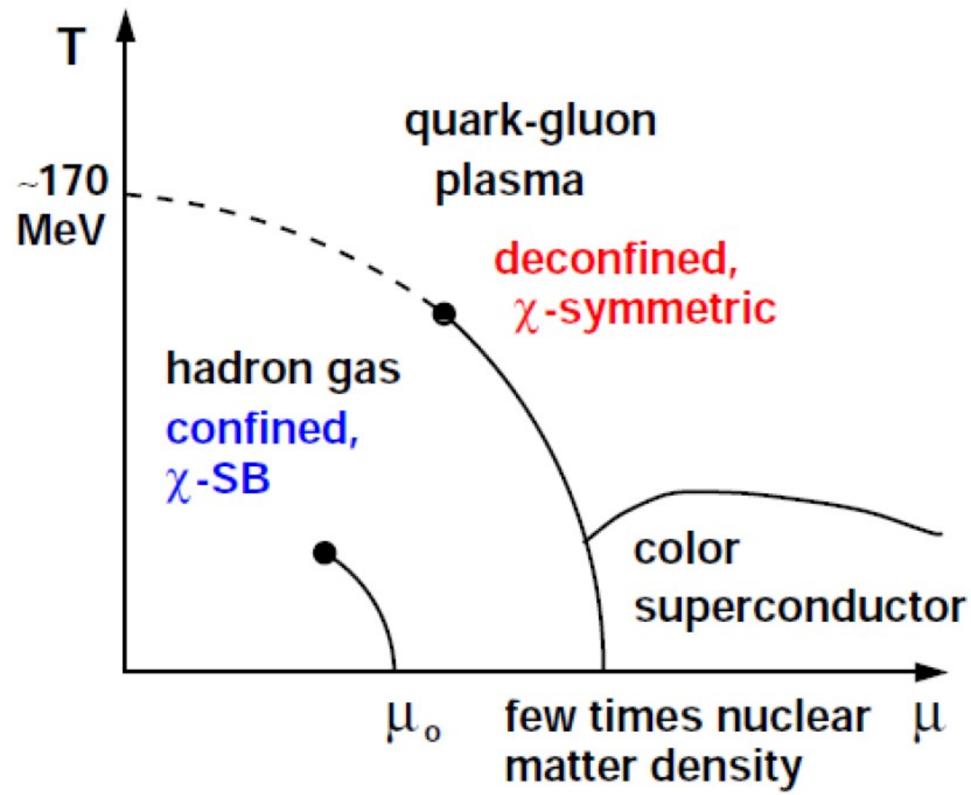
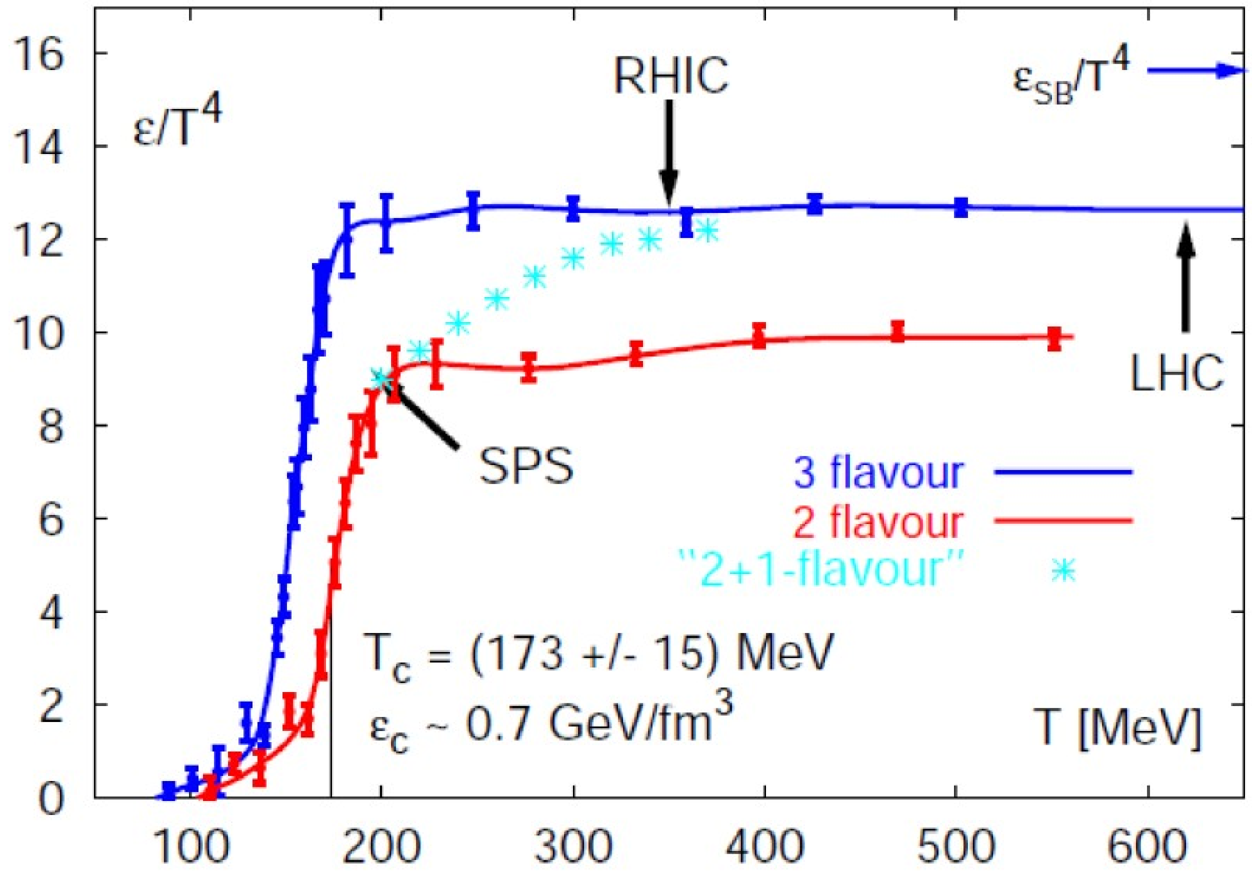


Braun-Munzinger, Wambach, Rev.Mod.Phys.81 (2009) 1031

- Because quarks cannot be observed in their free state the deconfined state can only be detected via the fingerprints it leaves on “normal” nuclear matter (hadrons) ...extremely challenging
- Confinement remains one of the major mysteries of modern science (chiral symmetry breaking: Physics Nobel prize 2008, Y.Nambu)

Lattice QCD predicts a phase transition

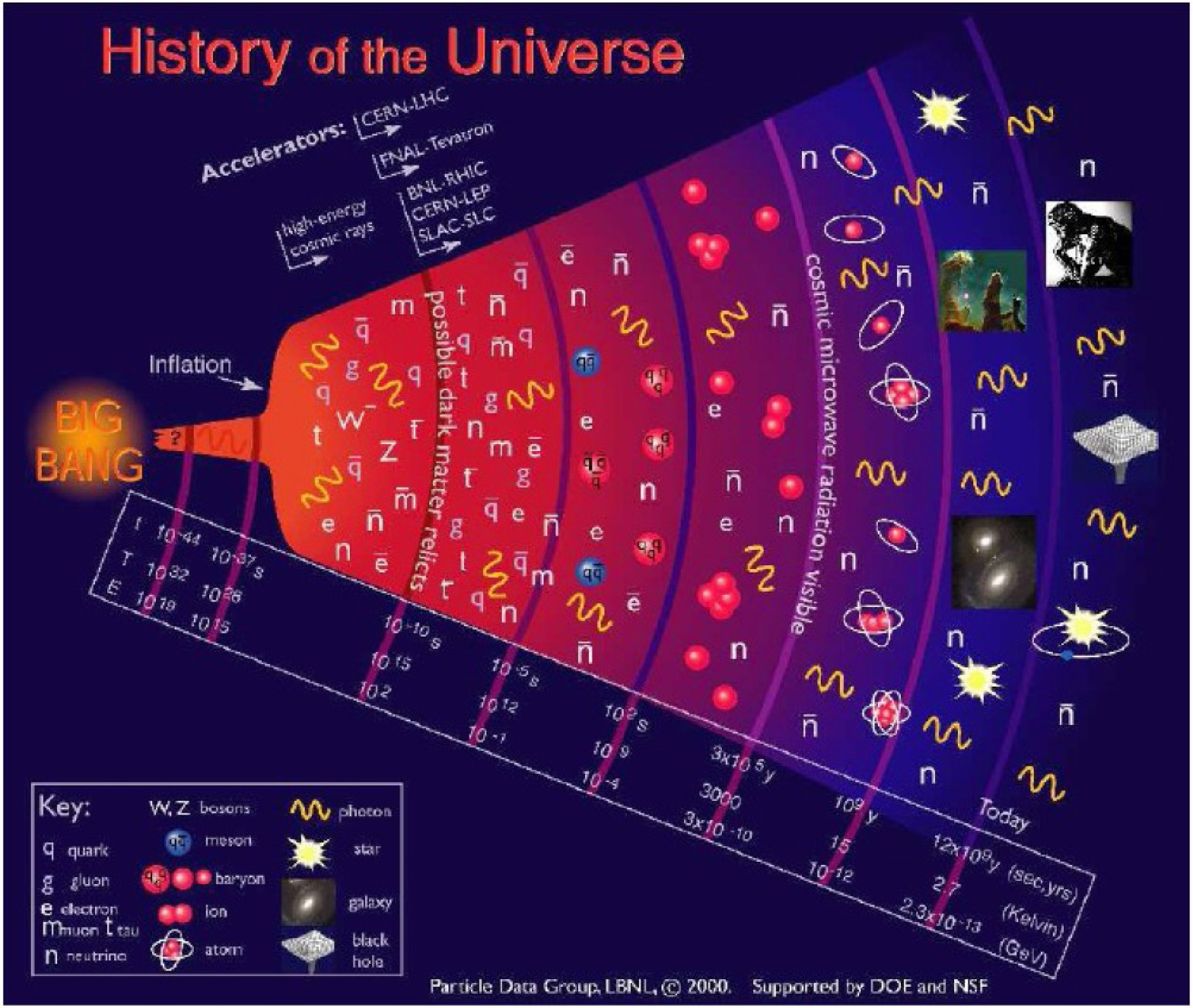


F. Karsch, hep-lat/0106019

- We now know it is of crossover 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)

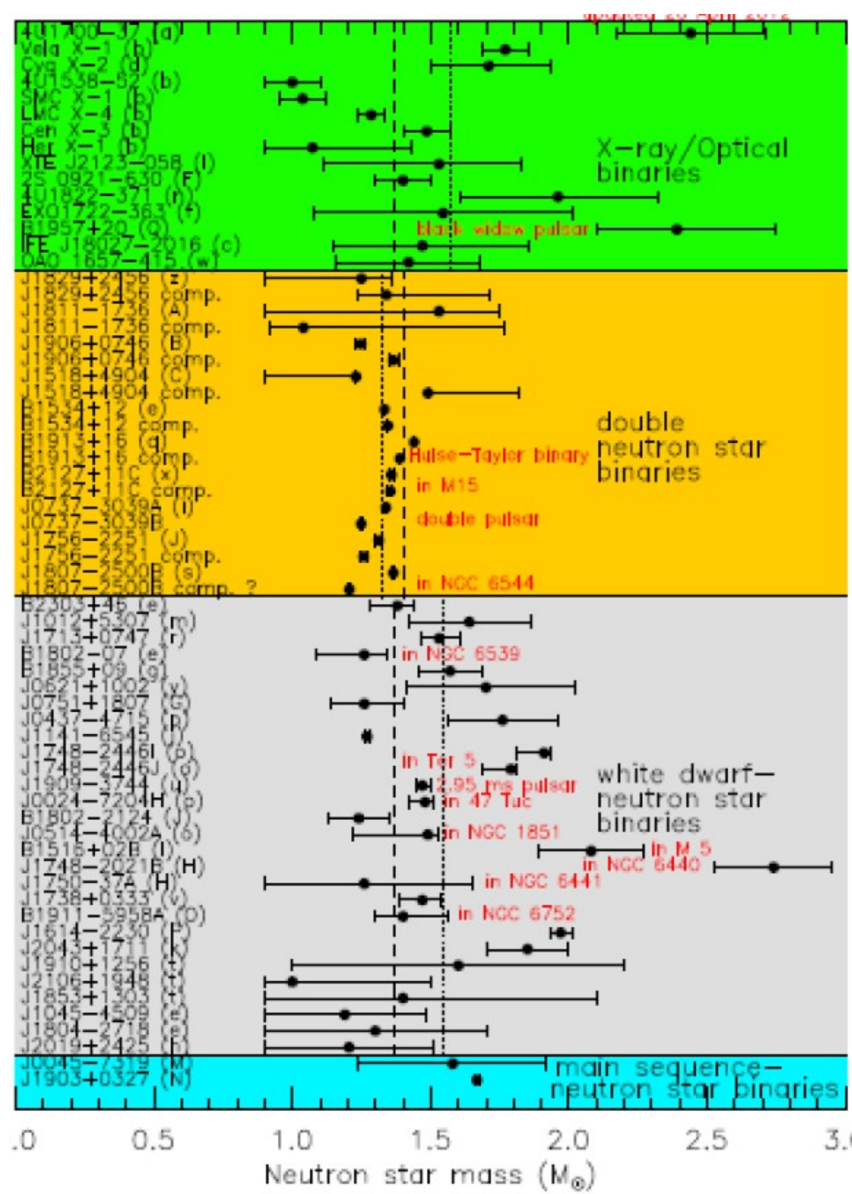
Quark-Gluon Plasma: the earliest incarnation



Maximum mass of neutron stars

- Controlled by the EoS of nuclear matter at a few times nuclear densities
  (and by many other details)

- "Canonical" mass: 1.4 M_{sun}
  (soft EoS around ρ_0)



J.M.Lattimer, arXiv:1305.3510

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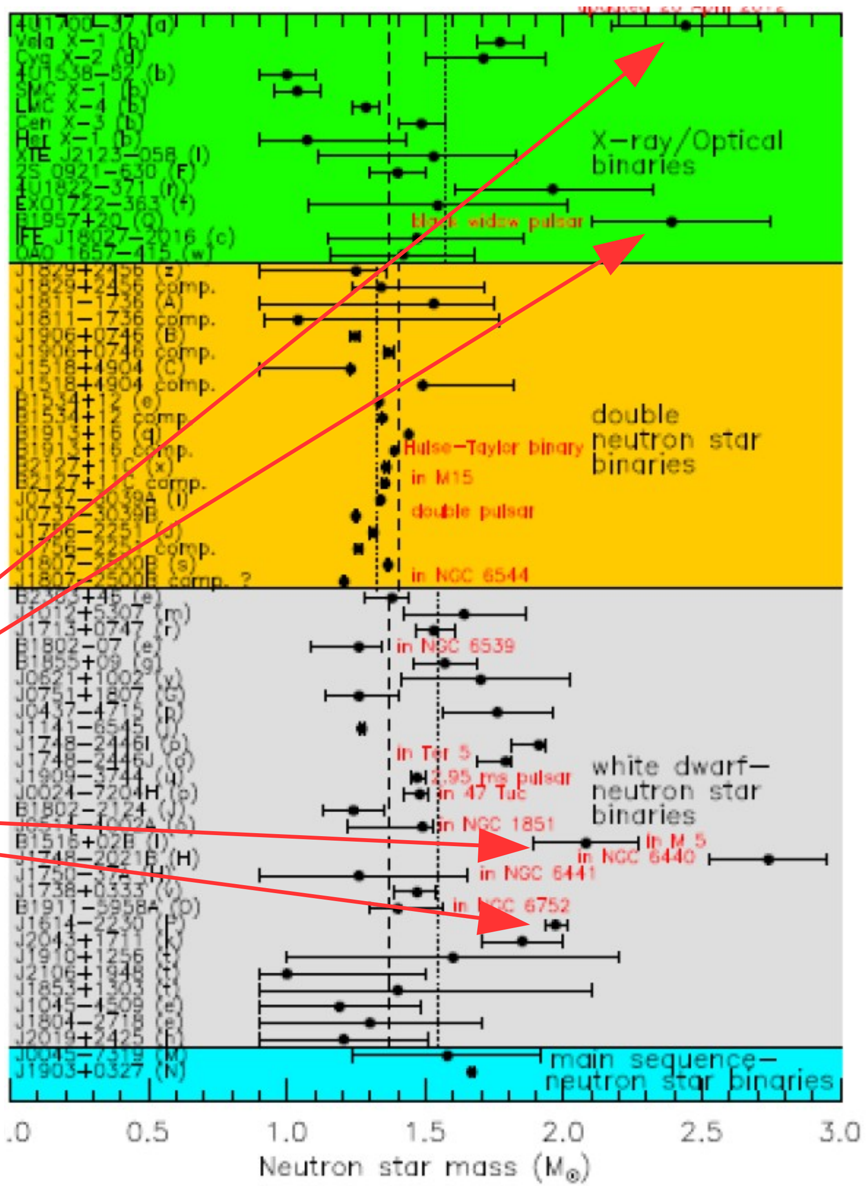
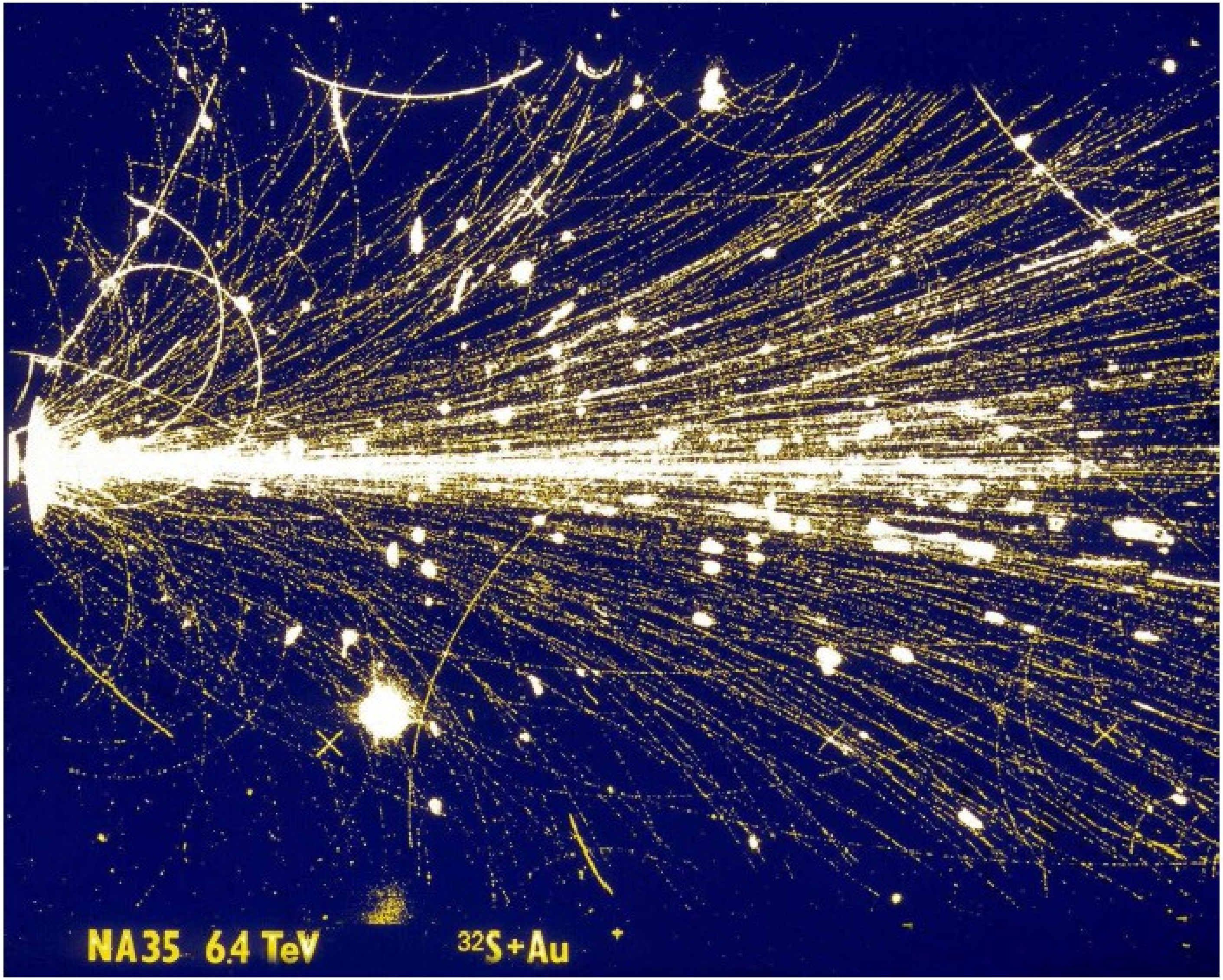
- How can the “outliers” exist?
  … with stiffer EoS (at 2-3 ρ_0)



J.M.Lattimer, arXiv:1305.3510

What are ultra-relativistic heavy-ion collisions?

- Collisions of (heavy) nuclei at energies much higher than nucleon mass

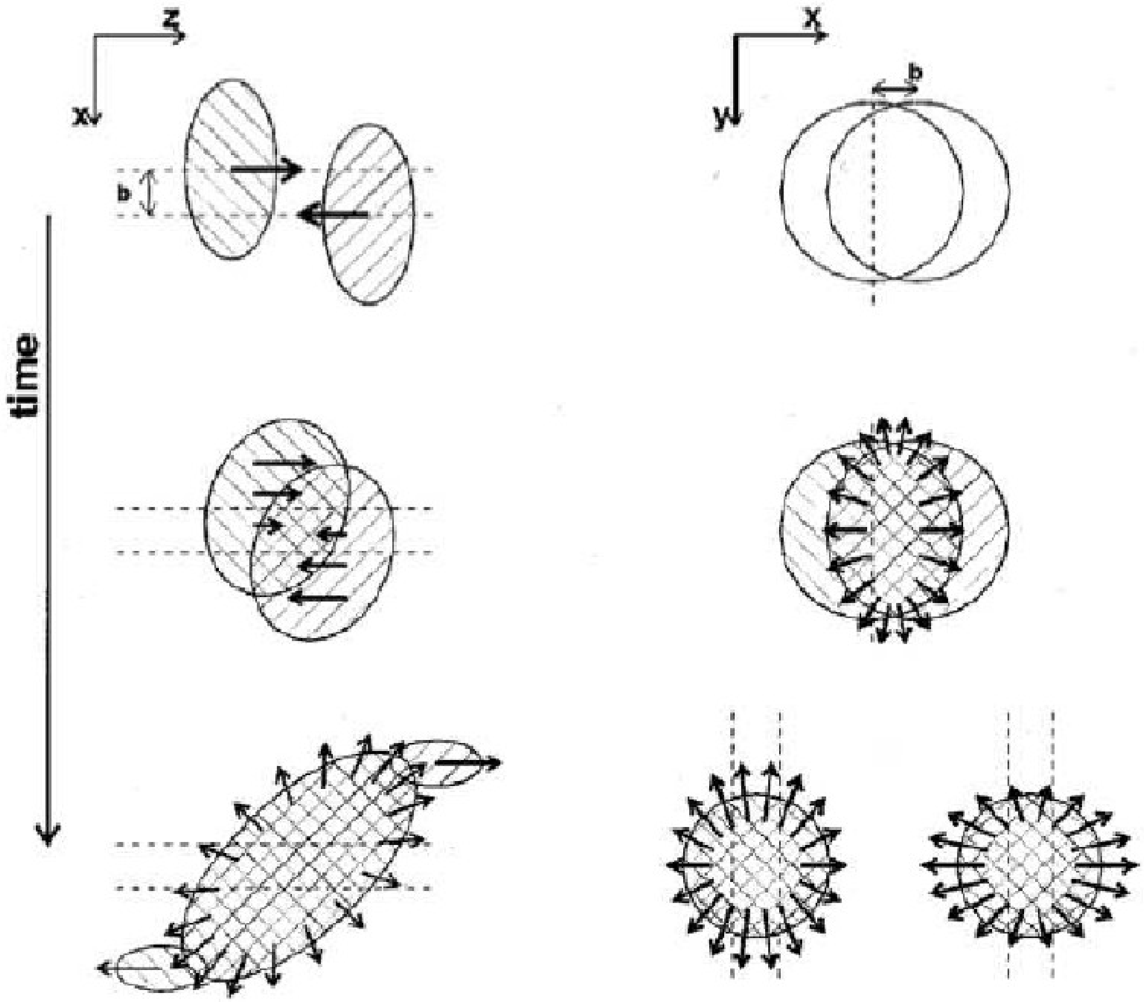


Heavy ion accelerators

- 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 GeV
- Future:
  - FAIR @ GSI, Darmstadt (~2020): $\sqrt{s_{NN}}$=5 GeV

Concepts: participants and spectators

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



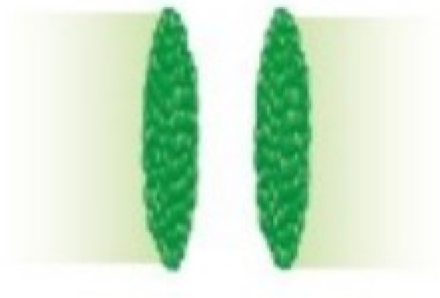
N.Herrman, J.P.Wessels, T.Wienold, Ann.Rev.Nucl.part.Sci. 49(1999) 581

Stages of a high-energy nucleus-nucleus collision

https://www.youtube.com/watch?v=CbhYxHSSqFE

Stages of a high-energy nucleus-nucleus collision

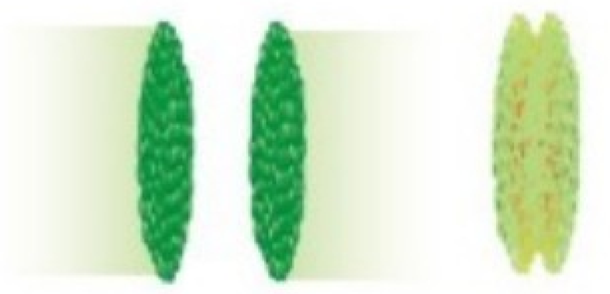
Initial state



- Lorentz contracted nuclei

Stages of a high-energy nucleus-nucleus collision

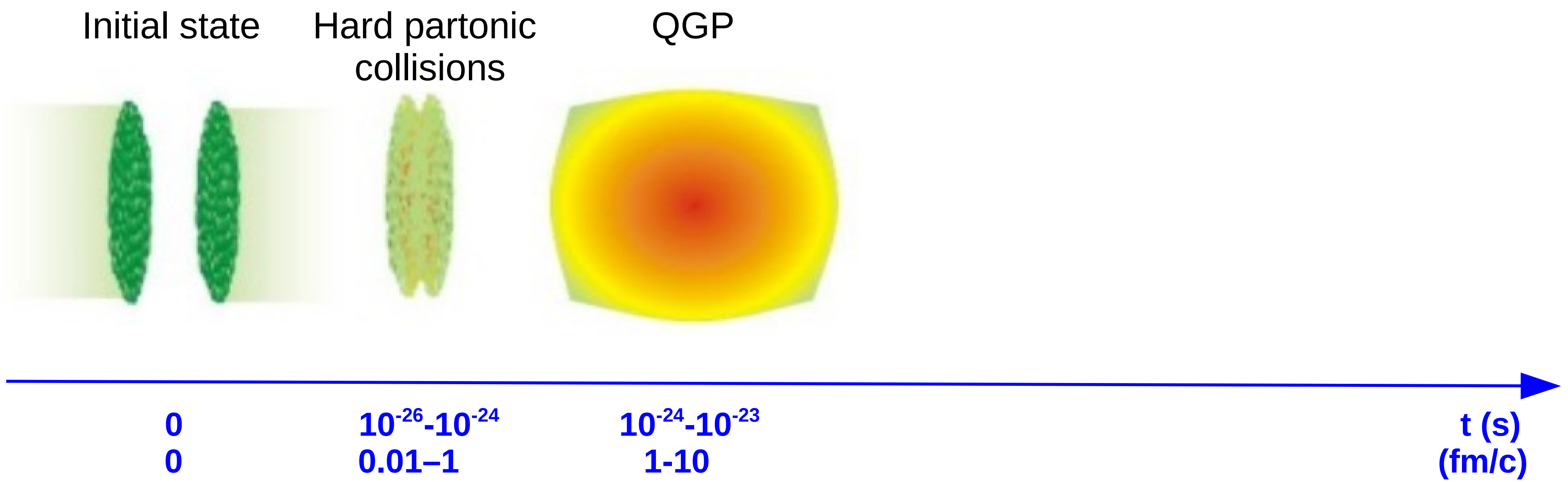
Initial state | Hard partonic collisions



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

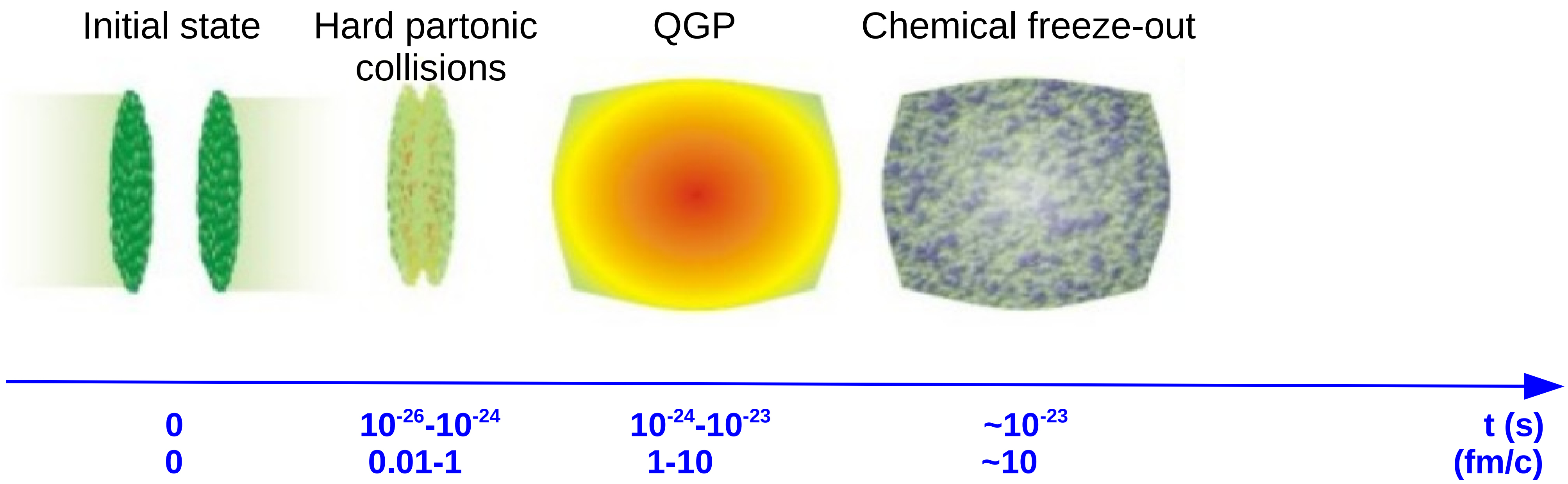
- Initial collisions take place
- Equilibrium (thermalization) takes place

Stages of a high-energy nucleus-nucleus collision



- Quark-Gluon Plasma phase
- System expands and cools

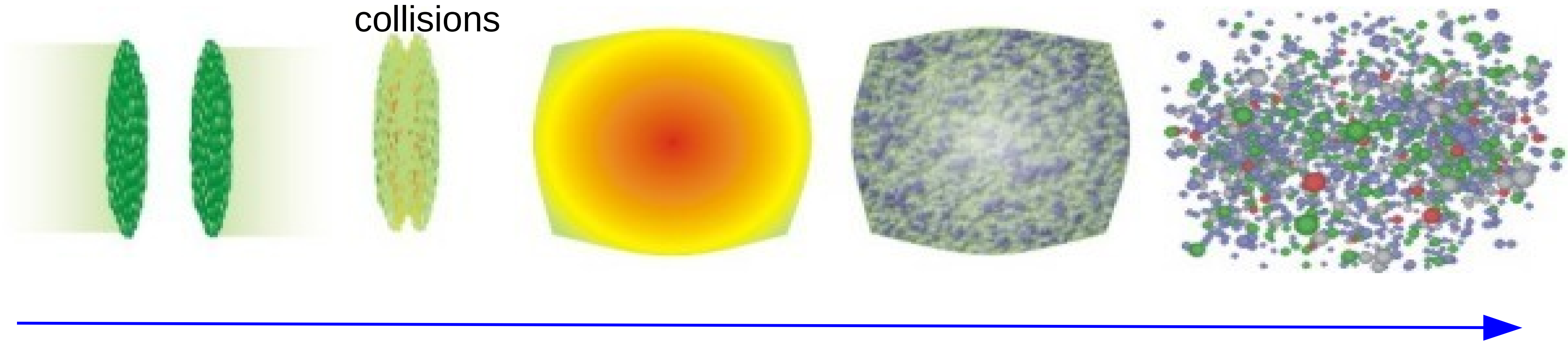
Stages of a high-energy nucleus-nucleus collision



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

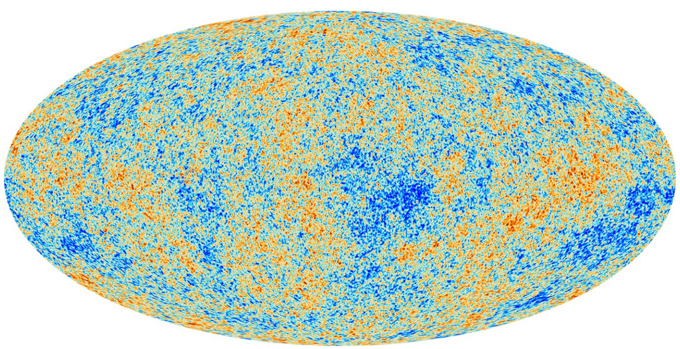
Stages of a high-energy nucleus-nucleus collision

Initial state	Hard partonic collisions	QGP	Chemical freeze-out	Kinetic freeze-out	



0	10^{-26}-10^{-24}	10^{-24}-10^{-23}	~10^{-23}	10^{-23}-10^{-22}	t (s)
0	0.01-1	1-10	~10	10-100	(fm/c)

- 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!

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.)

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})

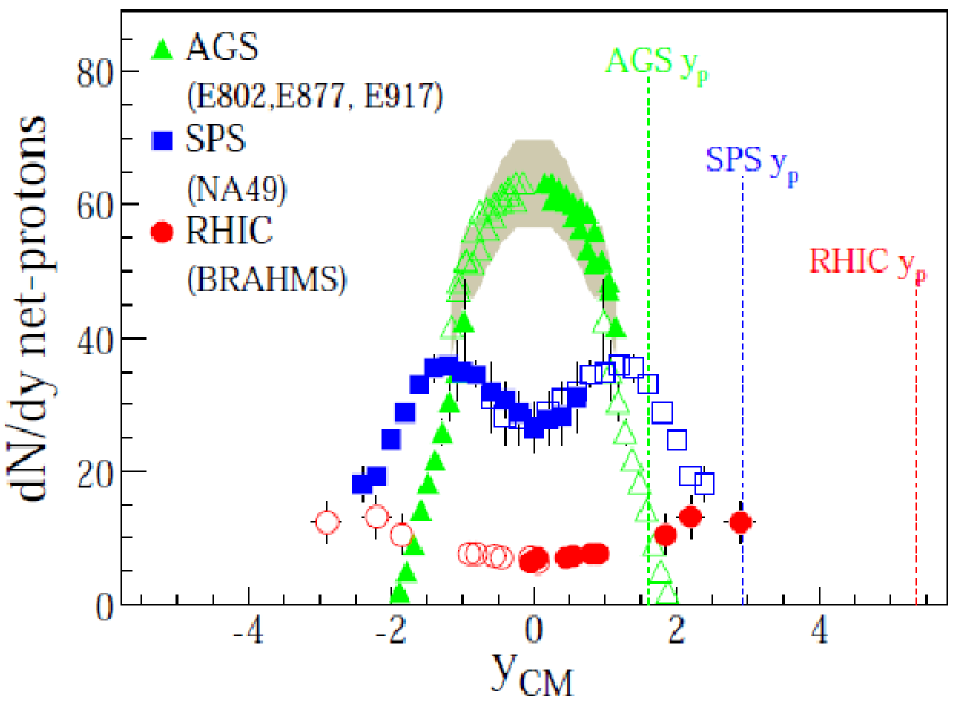
  typically measured in percentage of the geometric cross-section ($\sigma_{geom}=\pi(2R)^2$)

- Not all beam energy is spent

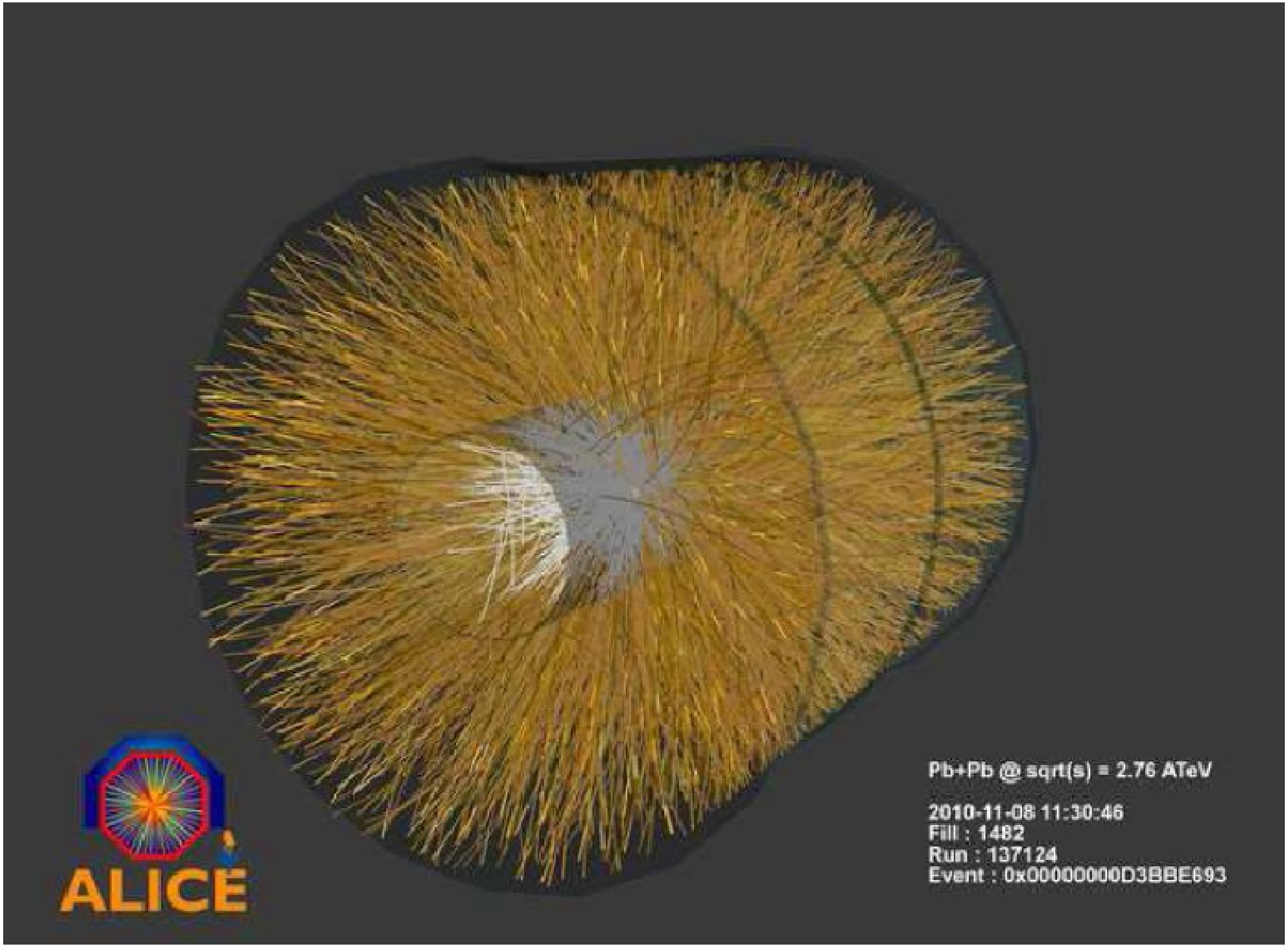
  … quantified by nuclear stopping

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

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

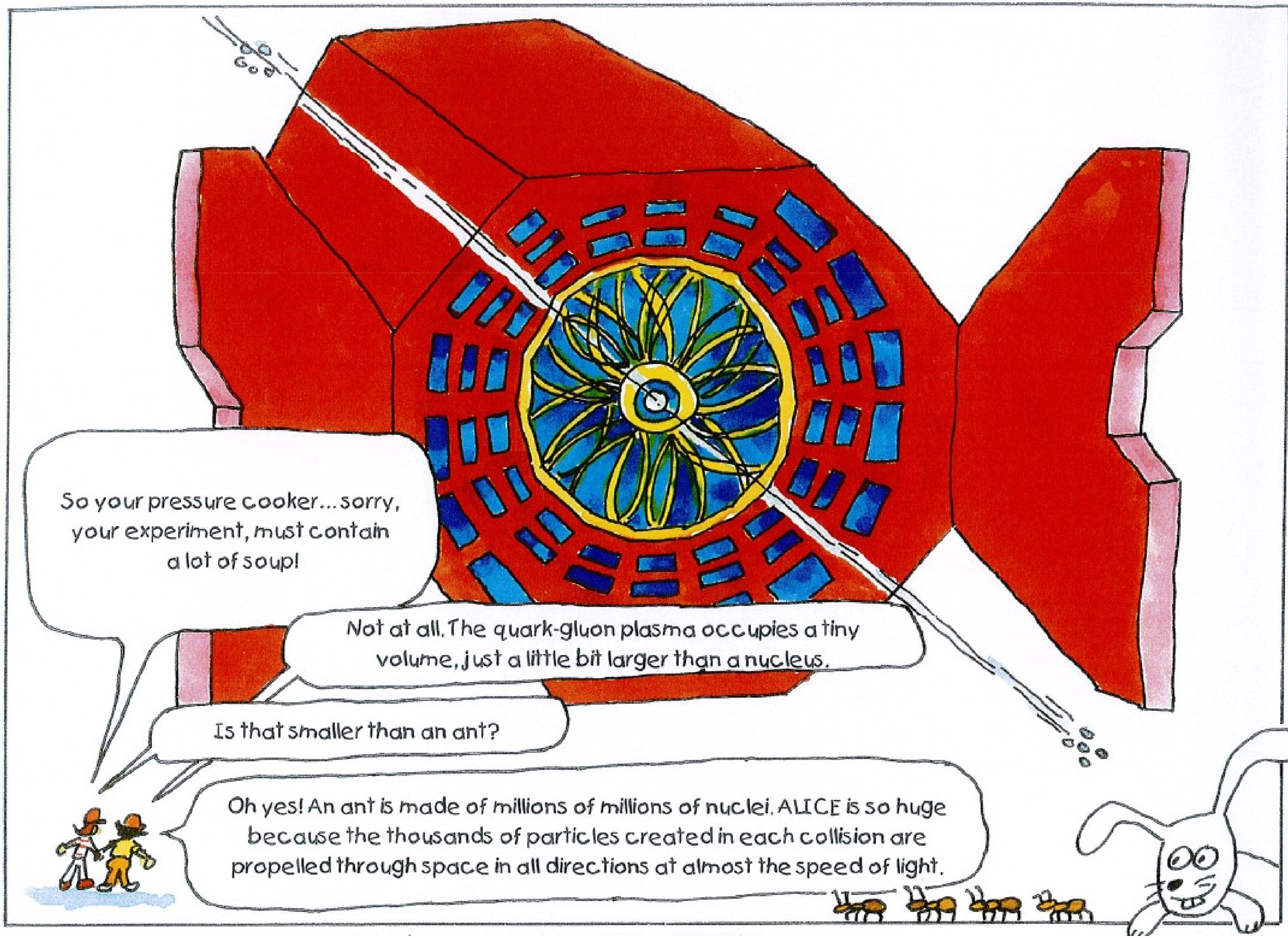


How to “measure” the early Universe in the lab?

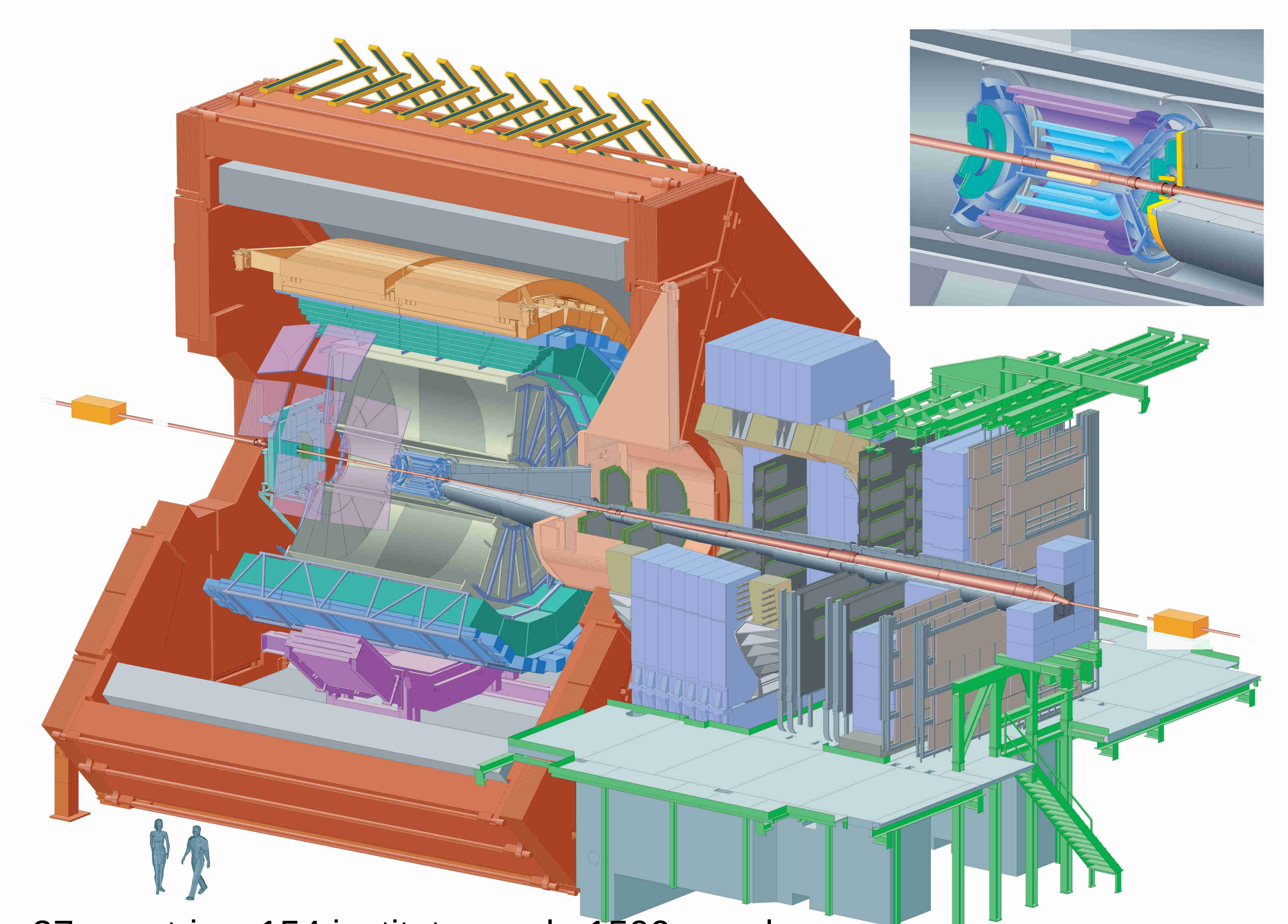


- A 3D picture (with 500 million voxels) of a central collision (about 3000 primary tracks)
- We take millions of such pictures to be analyzed offline

Part II: The ALICE apparatus

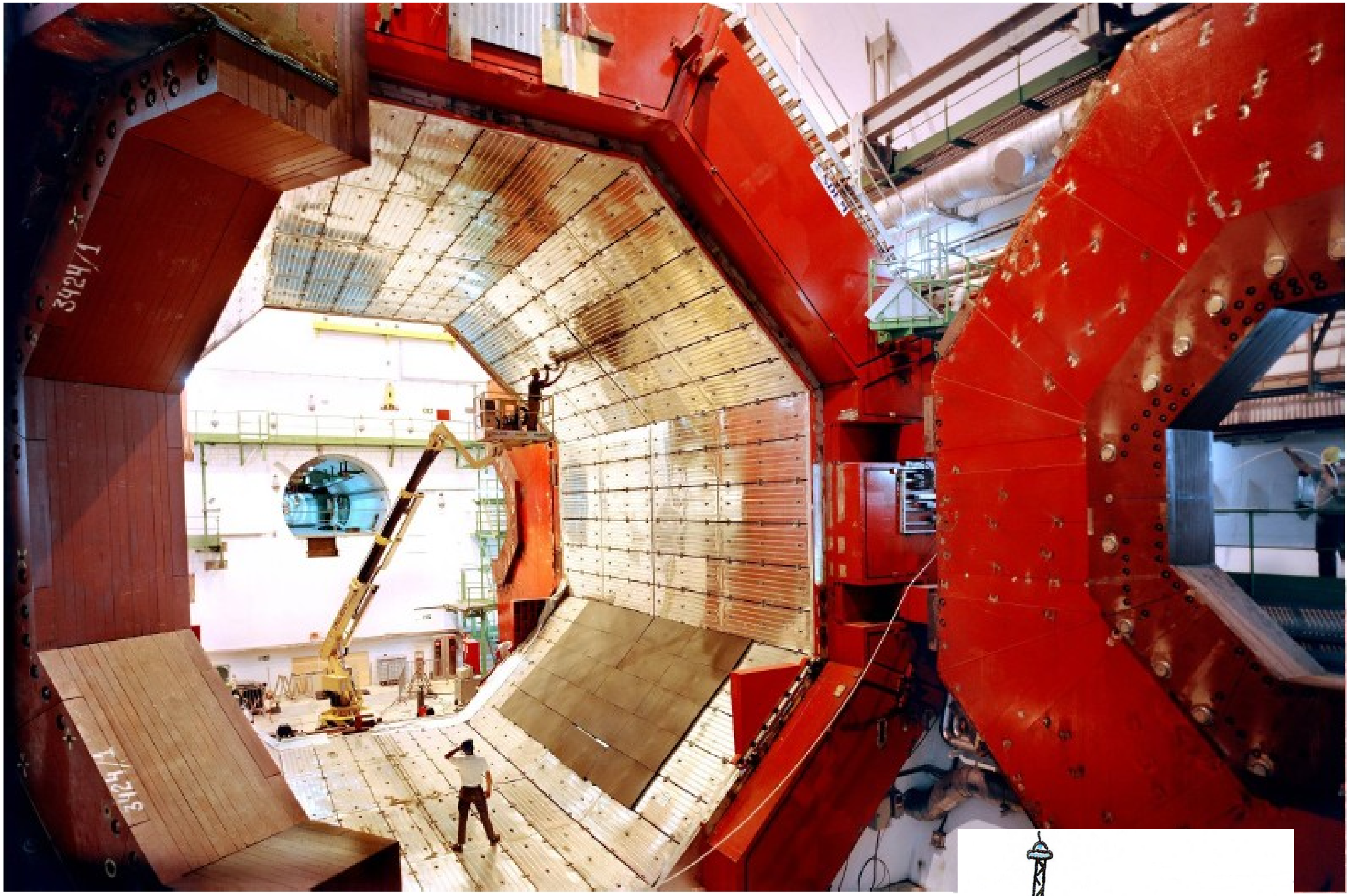


The ALICE detector

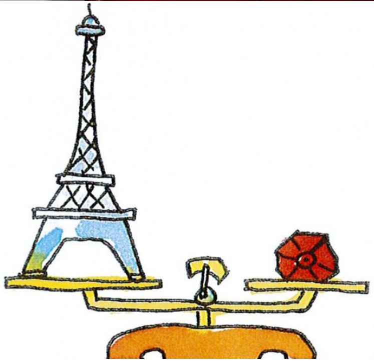


37 countries, 154 institutes and >1500 members

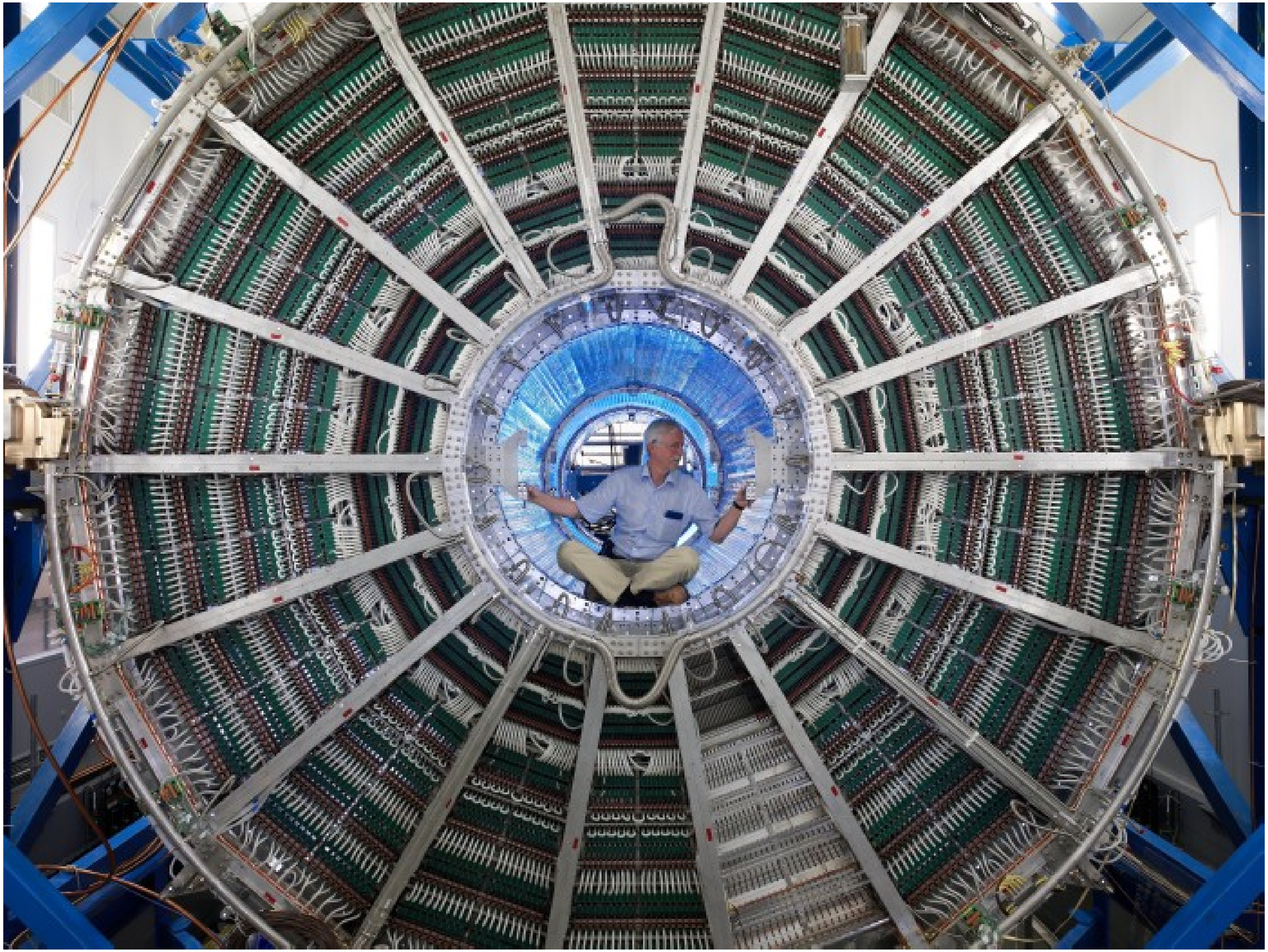
The L3 solenoid magnet



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

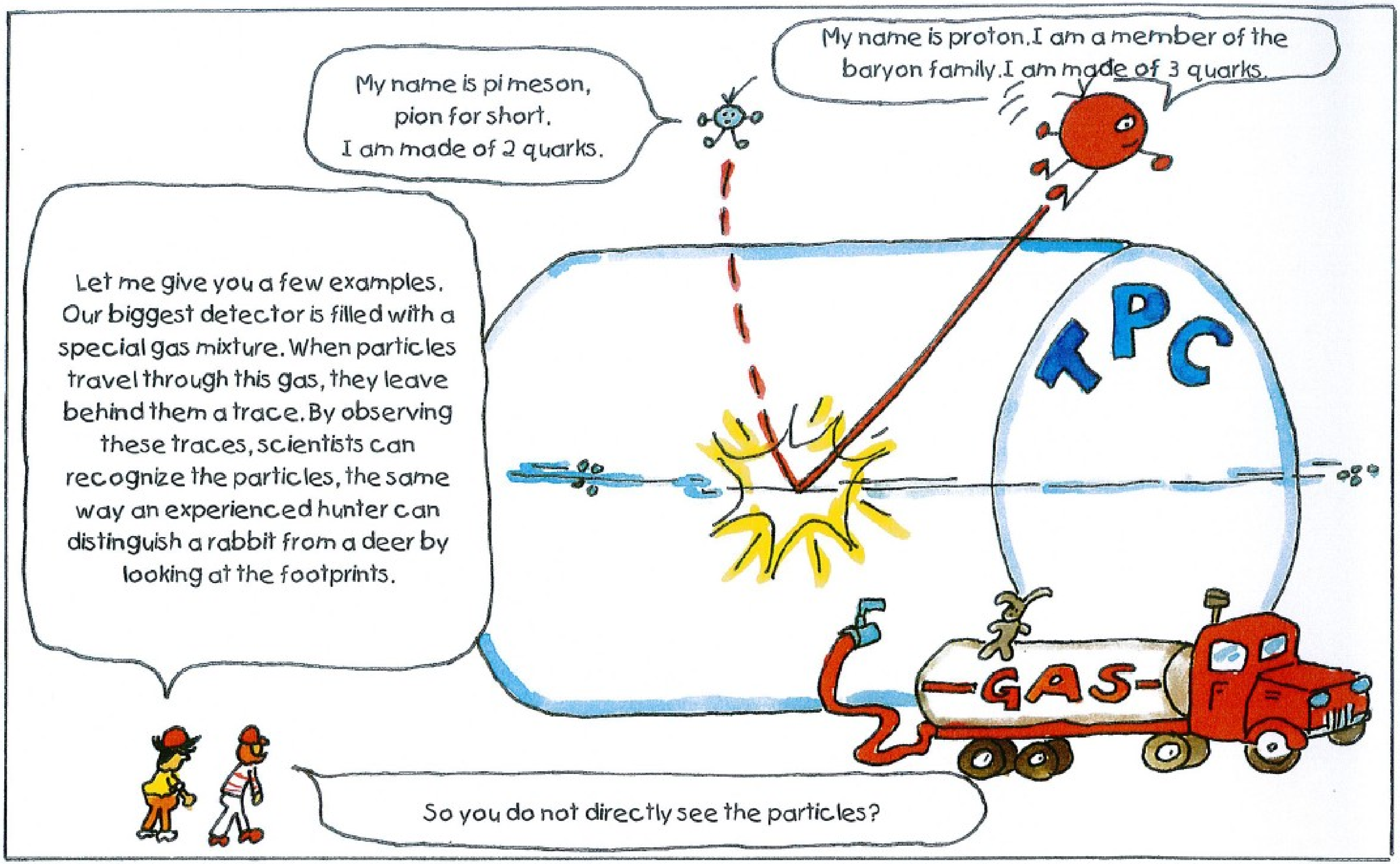


The TPC



- 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



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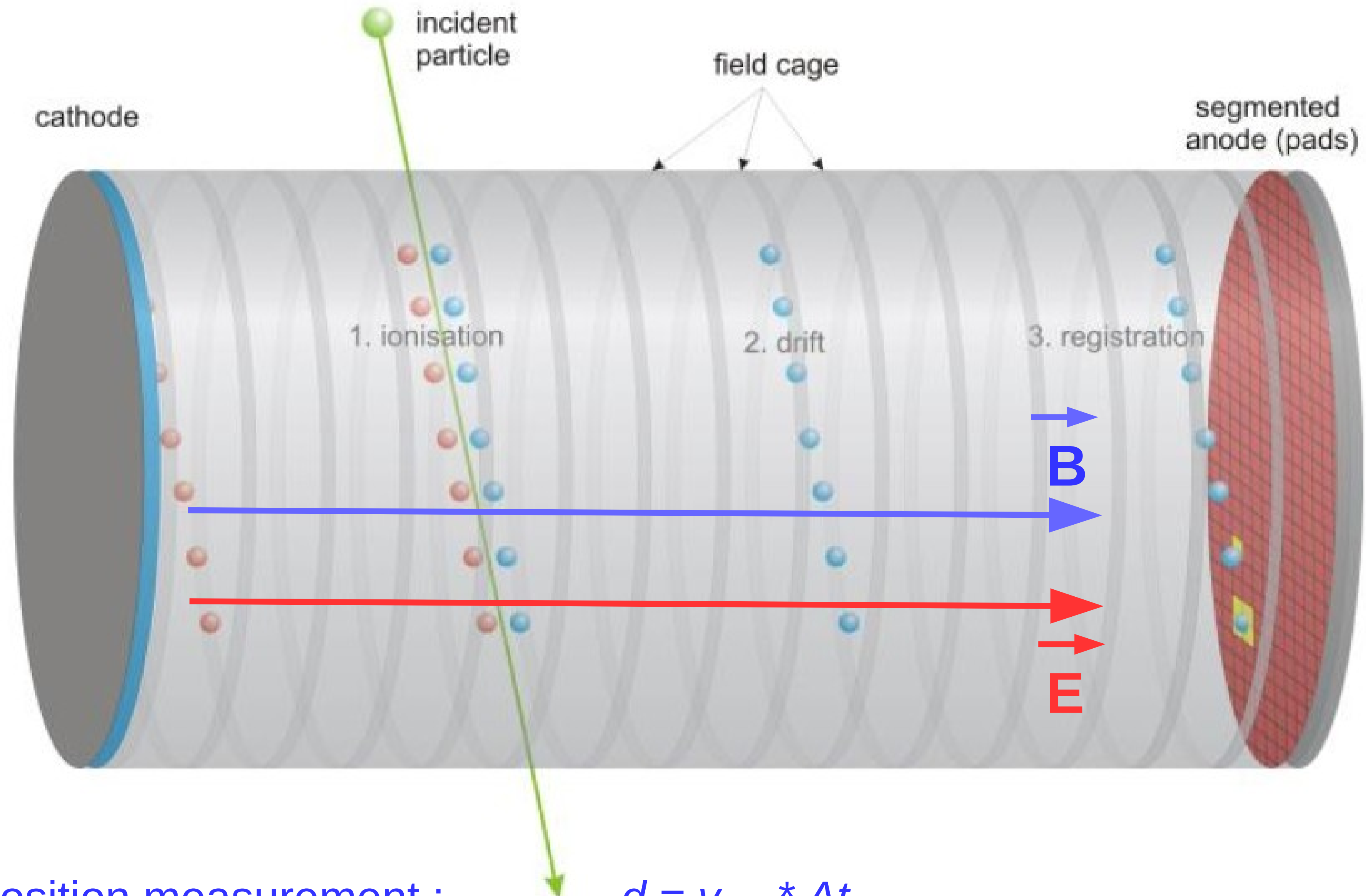
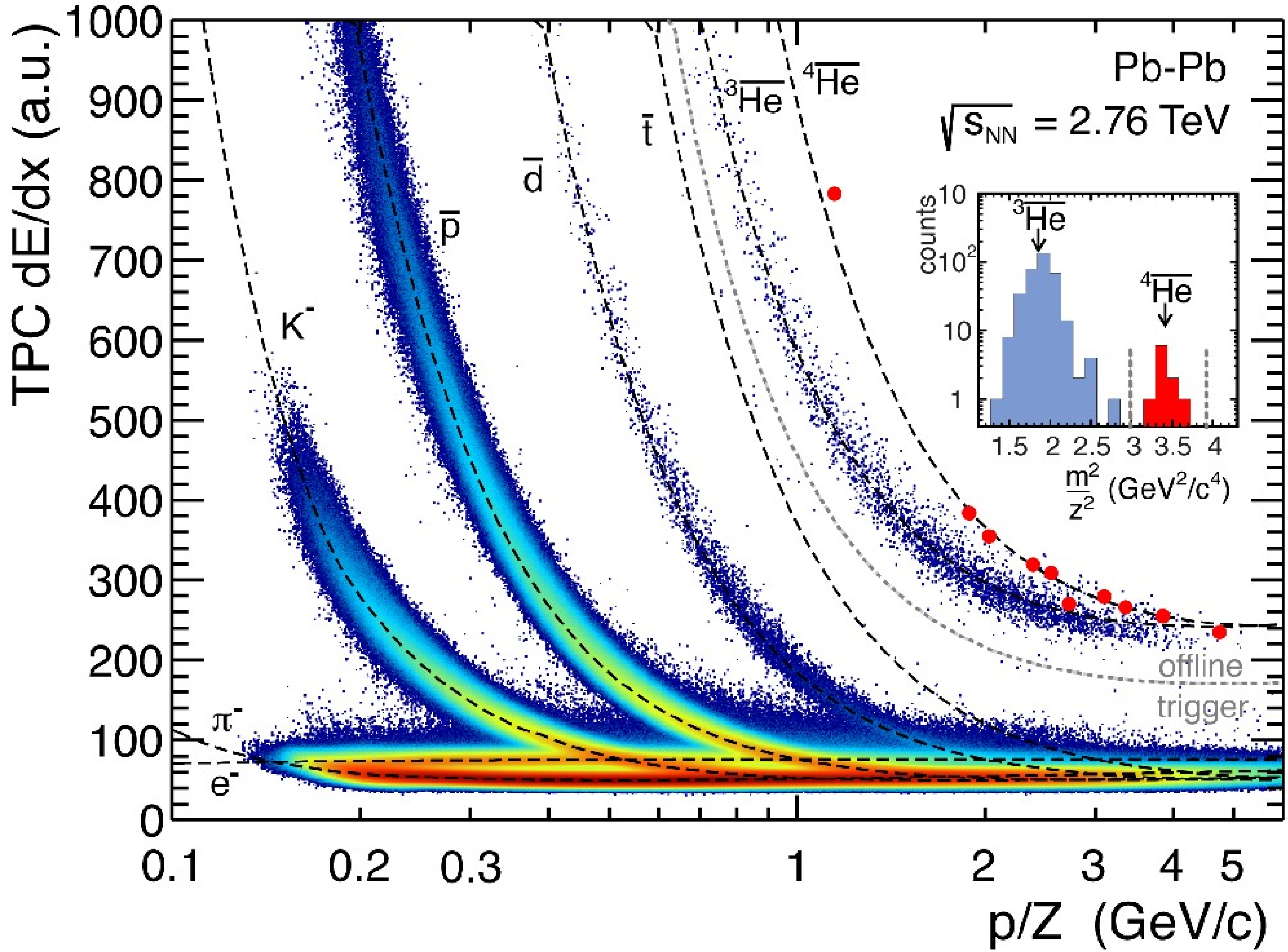


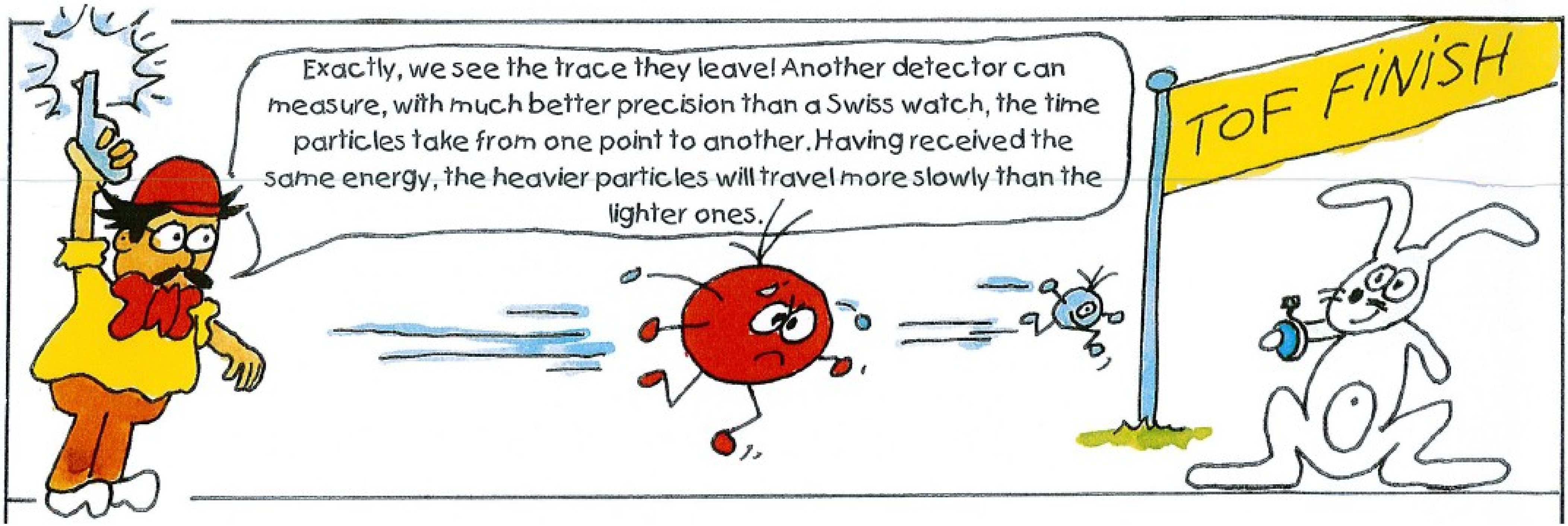
- Position measurement : $d = v_{drift} * \Delta t$
- Momentum measurement: $p_T = q*B*r$

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)



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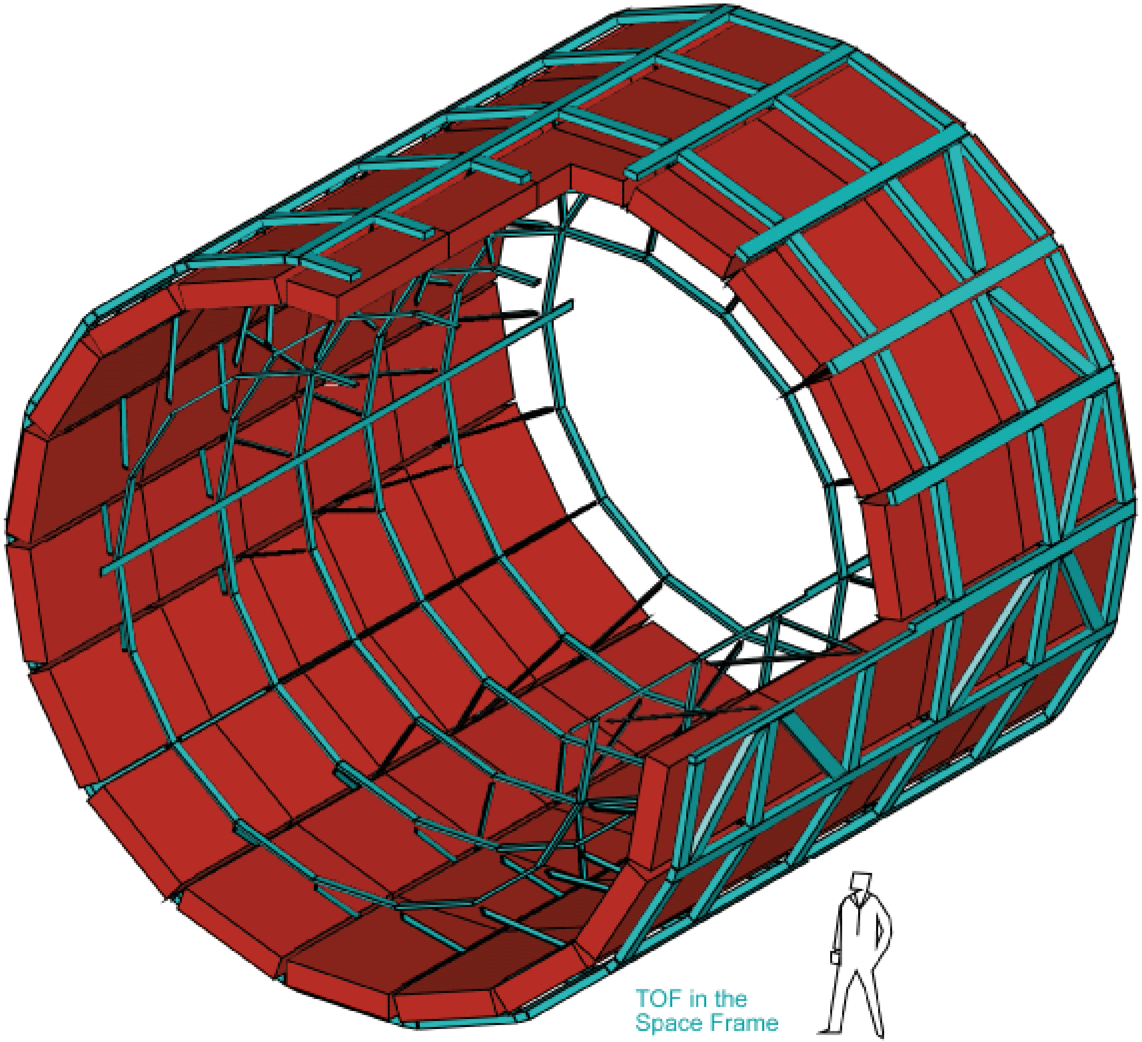
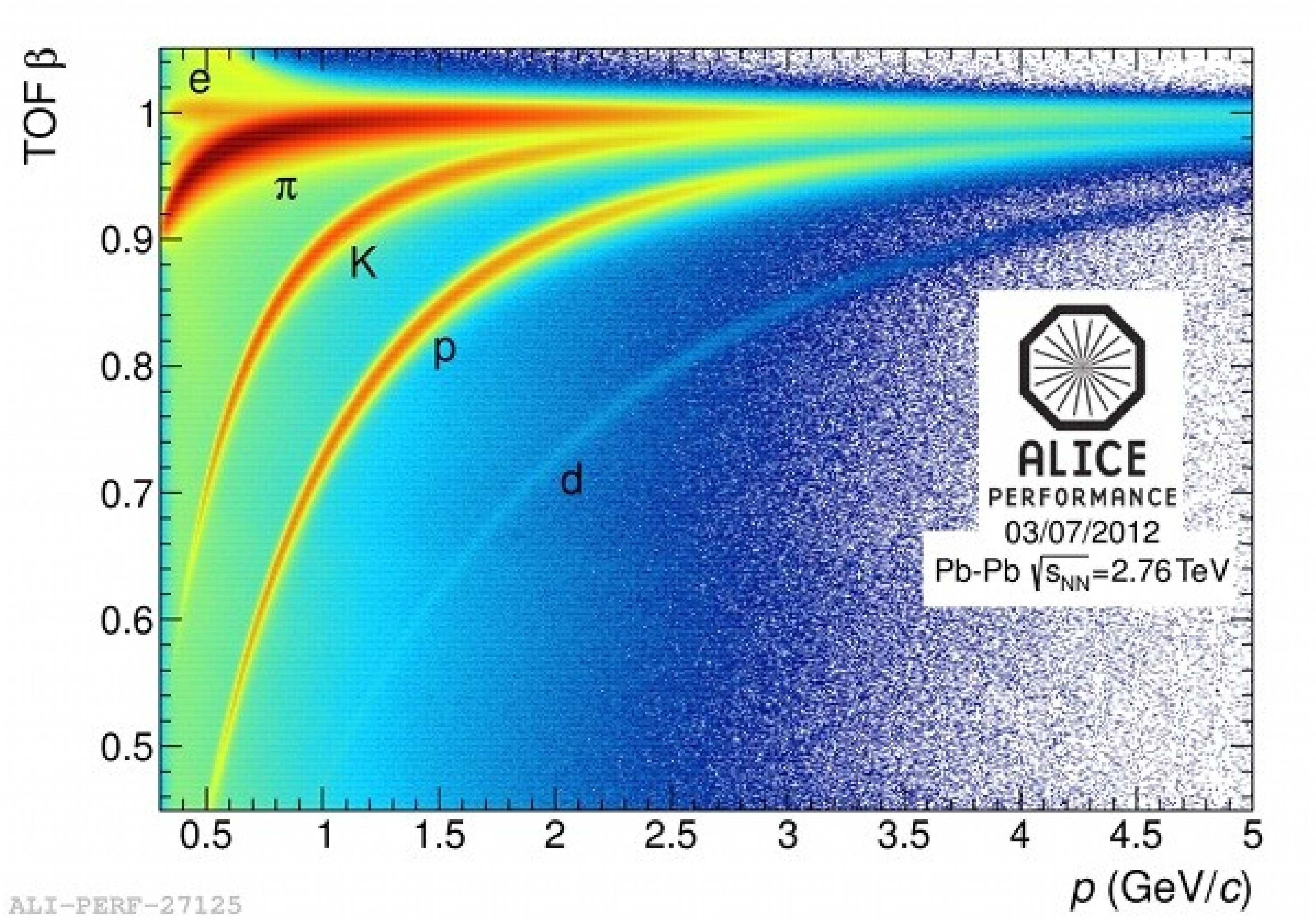


$V = L/\Delta t$

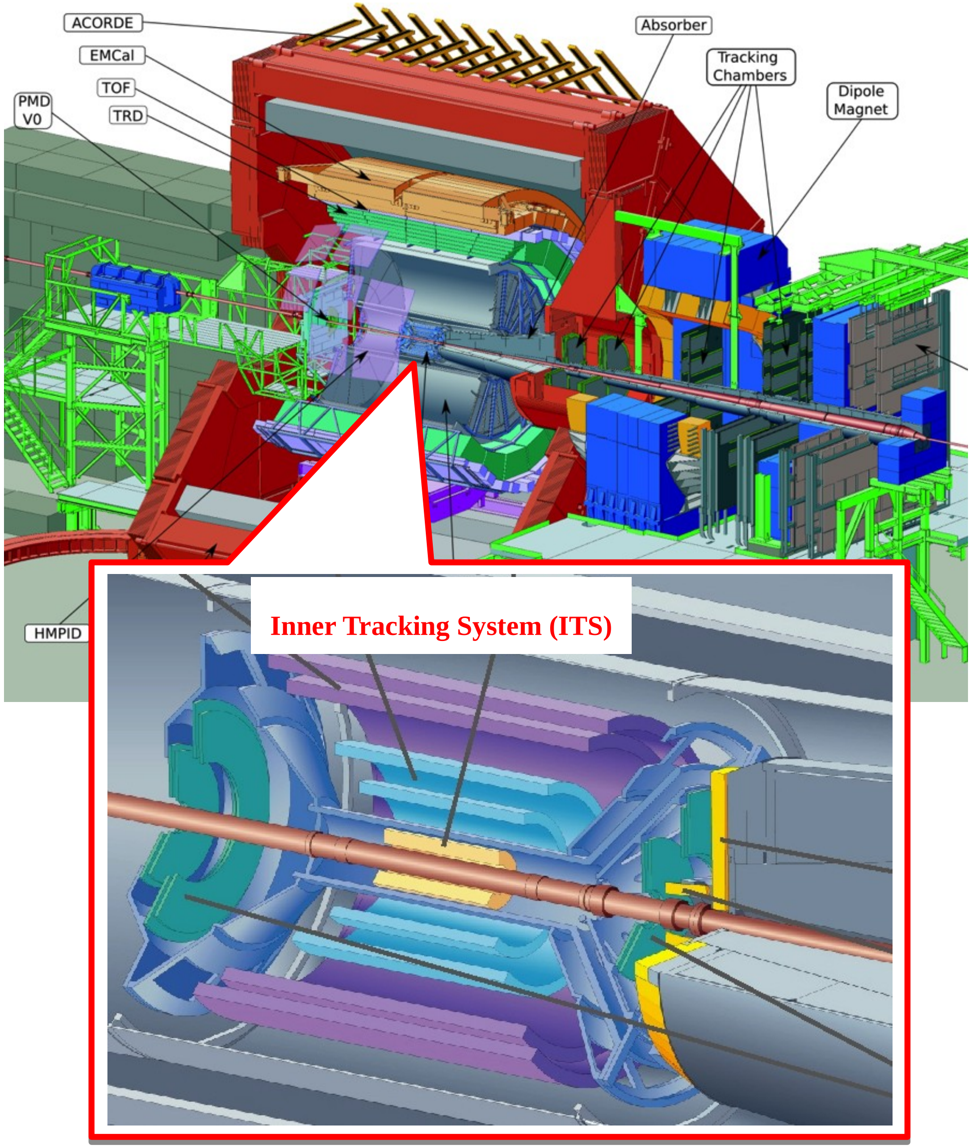
- Measures the time of flight between the collision start and arrival at the detector
- In conjunction with the momentum measurement from tracking -> particle identification
- Time resolution: 10^{-10} s

Particle identification using TOF



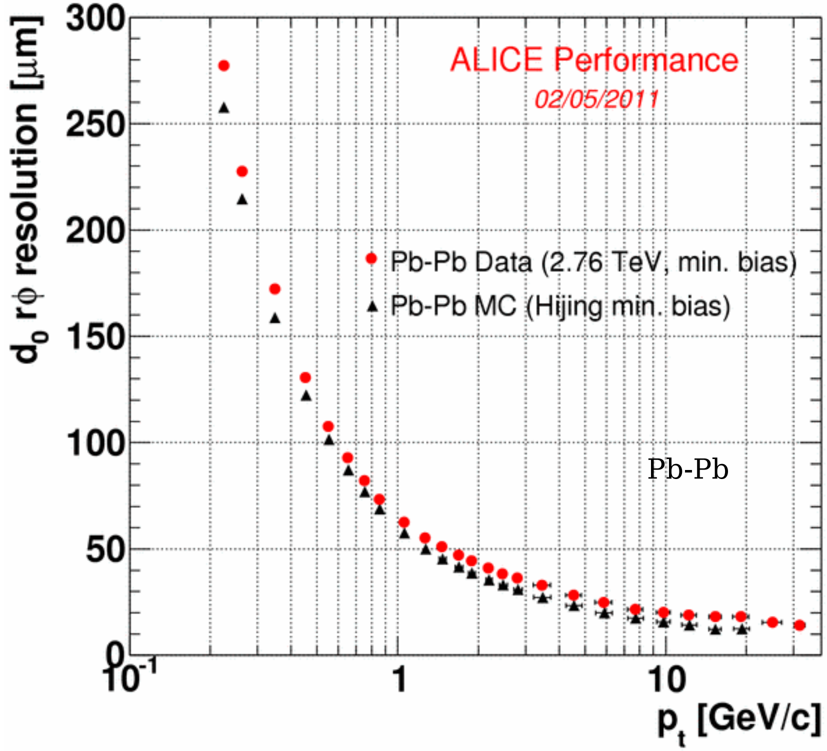
- Extends the particle identification of the TPC to higher momentum

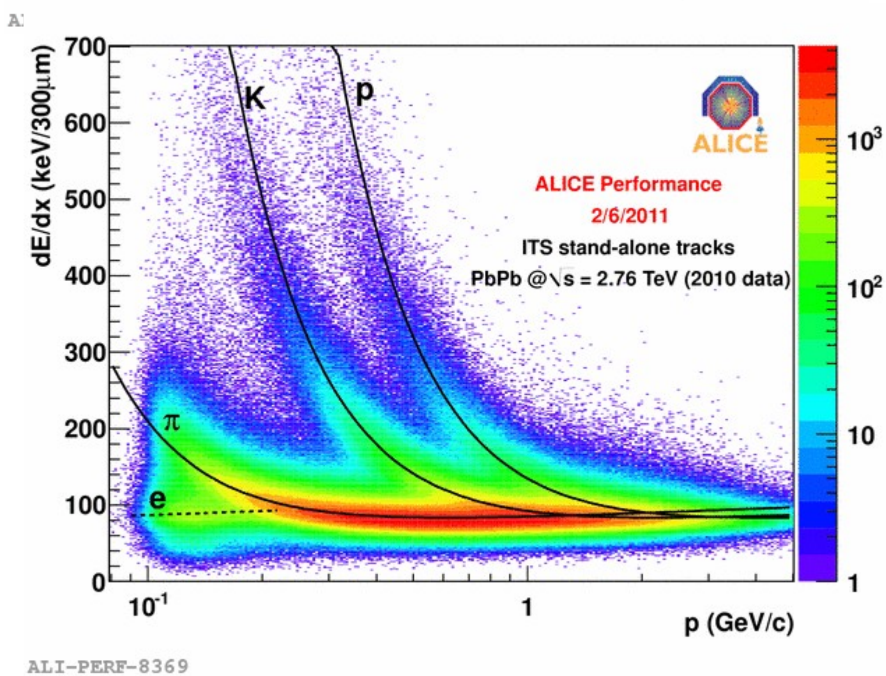
The Inner Tracking System (ITS)



- Barrel geometry detector
- Key detector for ALICE trigger system
- Measures global properties of the event: particle multiplicity

Inner Tracking System (ITS)





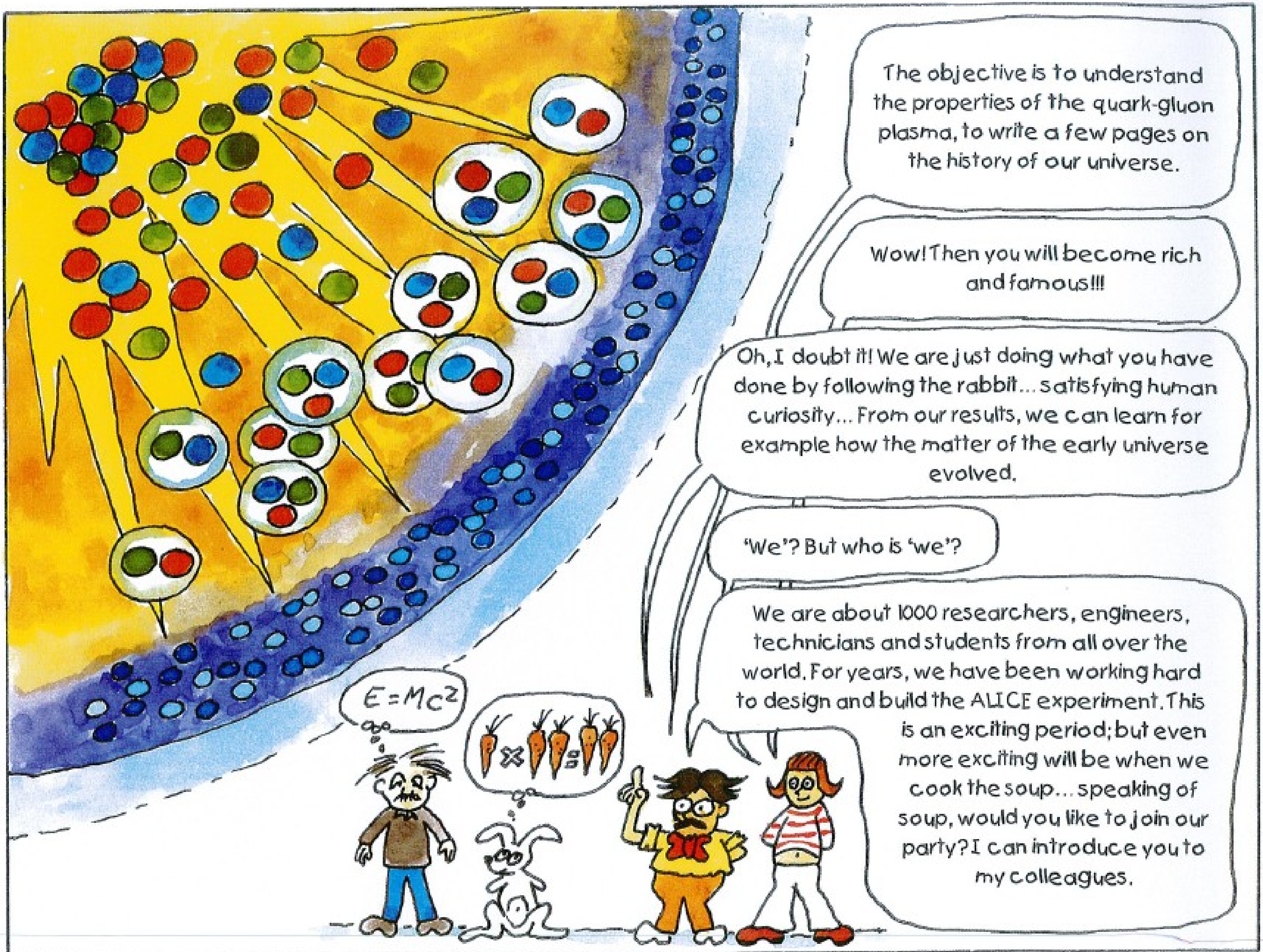
- 6 layers of silicon detectors with very high spatial resolution
  - Locates the collision vertex and secondary vertices from heavy quark decays

- It also performs particle identification via linear energy loss, but less precise than TPC

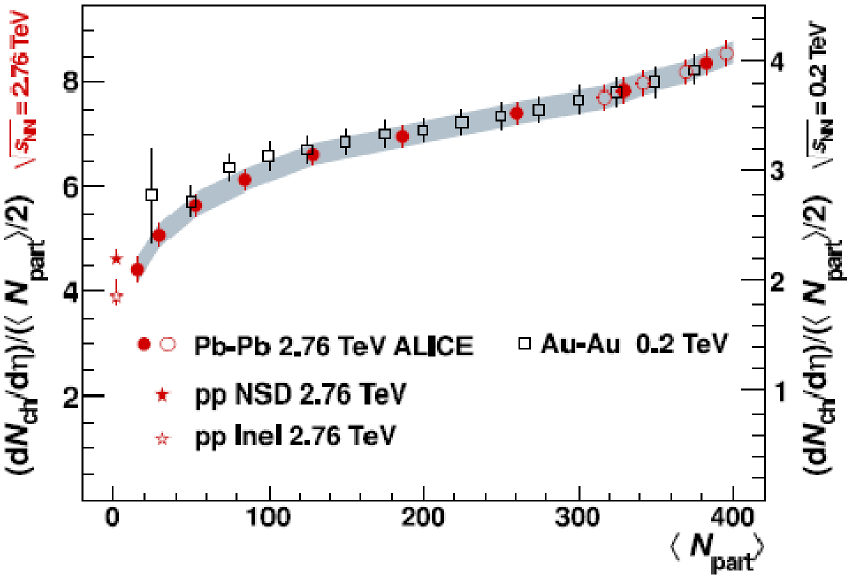
Other detectors

- 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
  - ...

Part III: Global properties of QGP



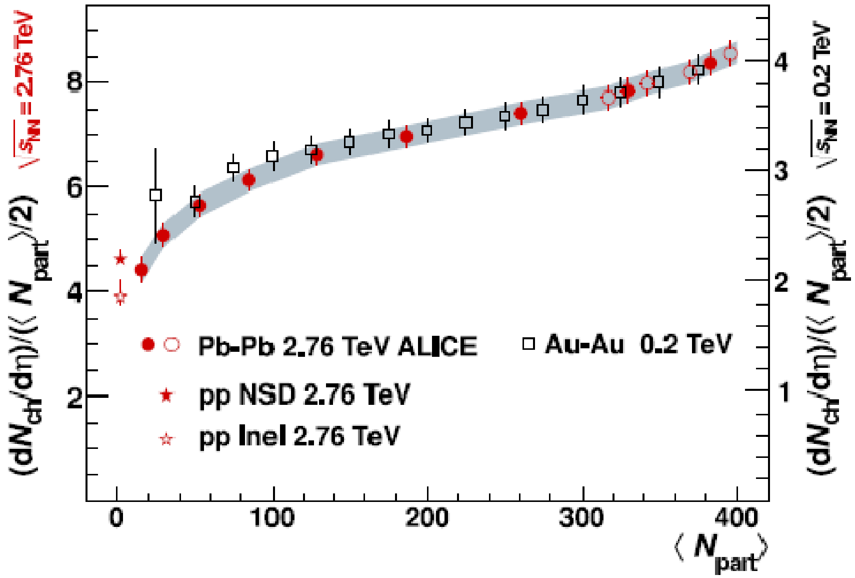
Bulk particle production



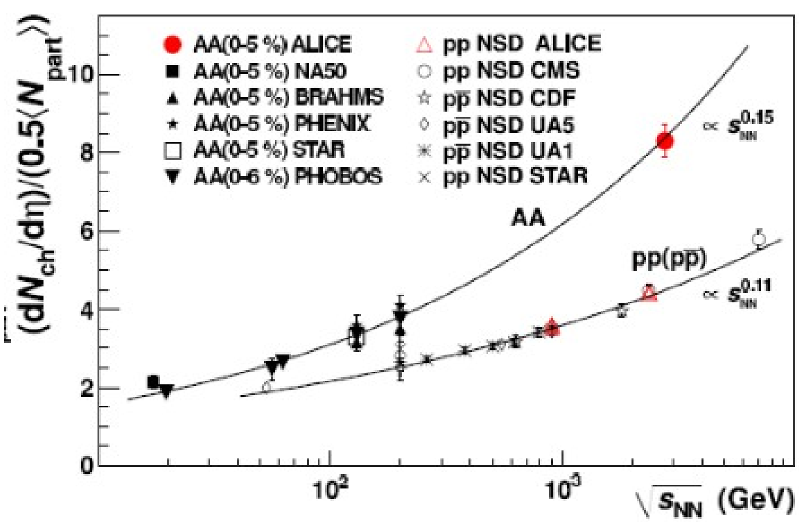
ALICE collab., arXiv:1012.1657

- Yield per participant pair is larger in nuclear collisions than pp and grows with centrality → larger entropy production

Bulk particle production



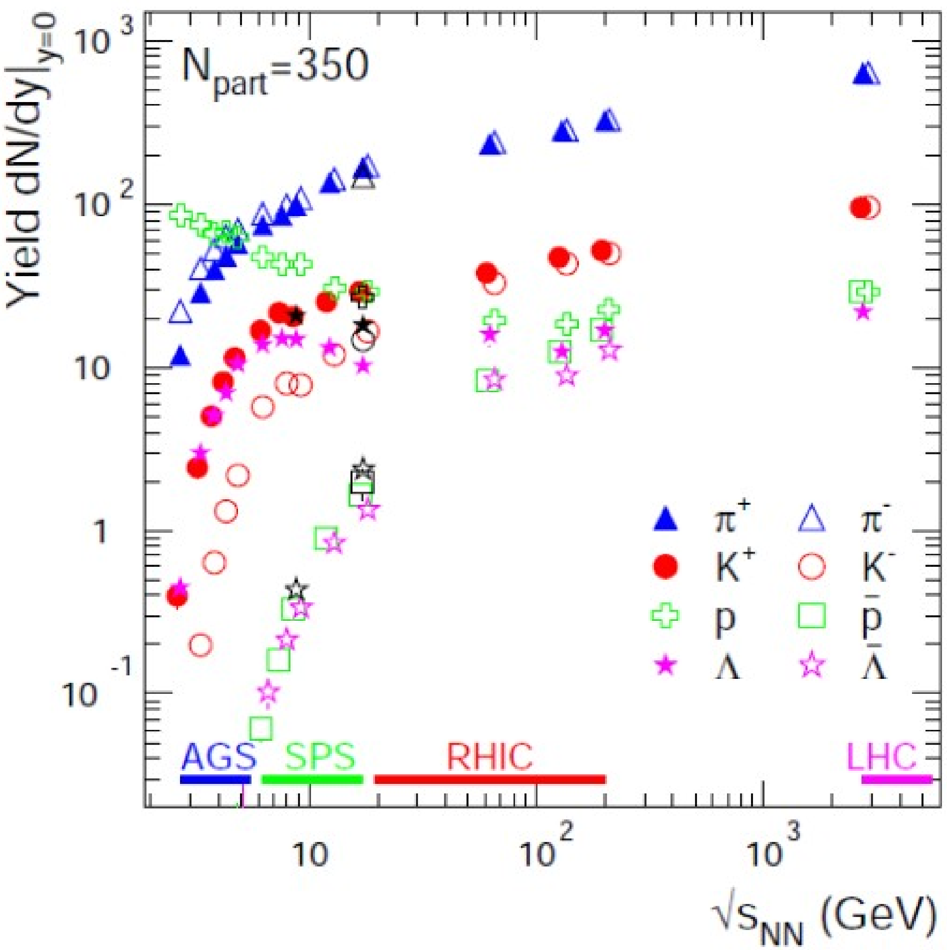
ALICE collab., arXiv:1012.1657



ALICE collab., arXiv:1011.3914

- Yield per participant pair is larger in nuclear collisions than pp and grows with centrality → larger entropy production
- … and the difference between AA and pp grows with energy

Chemical freeze-out: 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

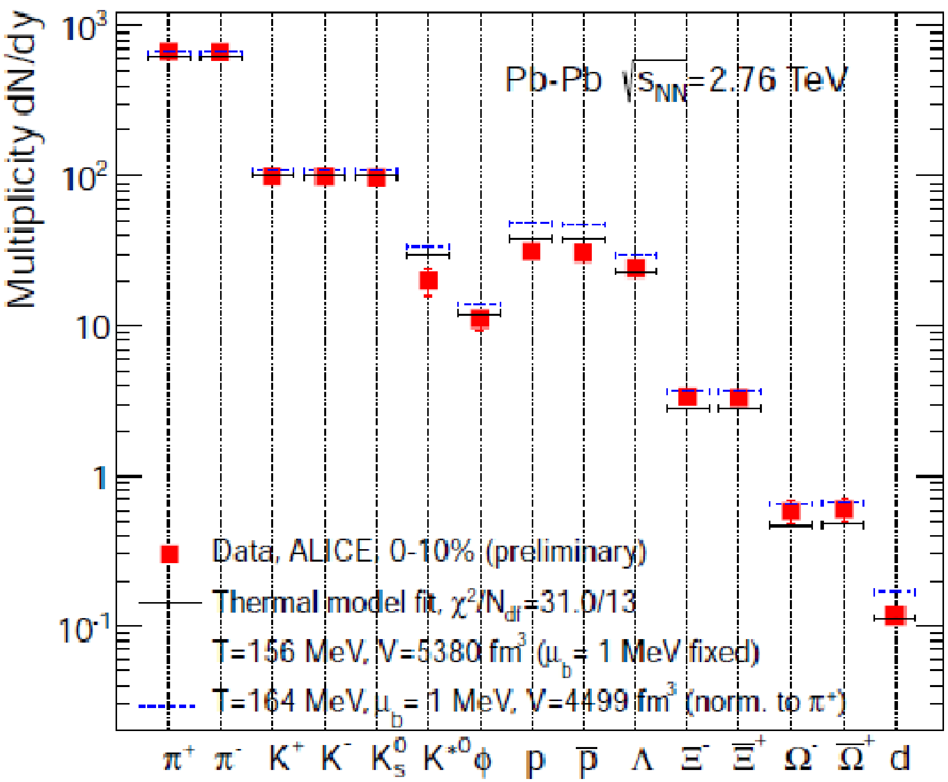
  Λ(uds), m=1116 MeV

  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?

Chemical freeze-out: hadron yields



- Thermal fits of hadron abundancies:

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

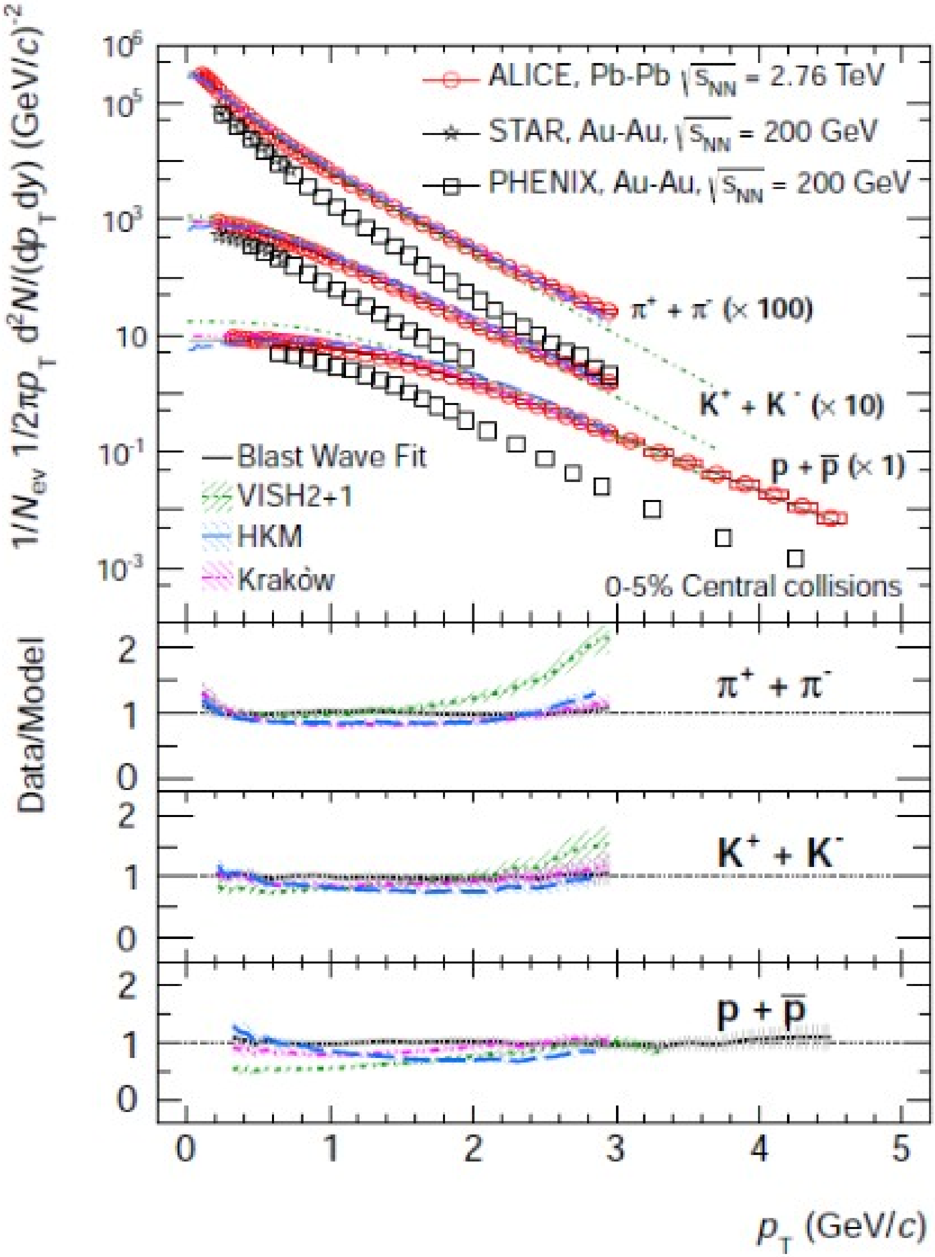
- Quantum numbers conservation

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

- 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

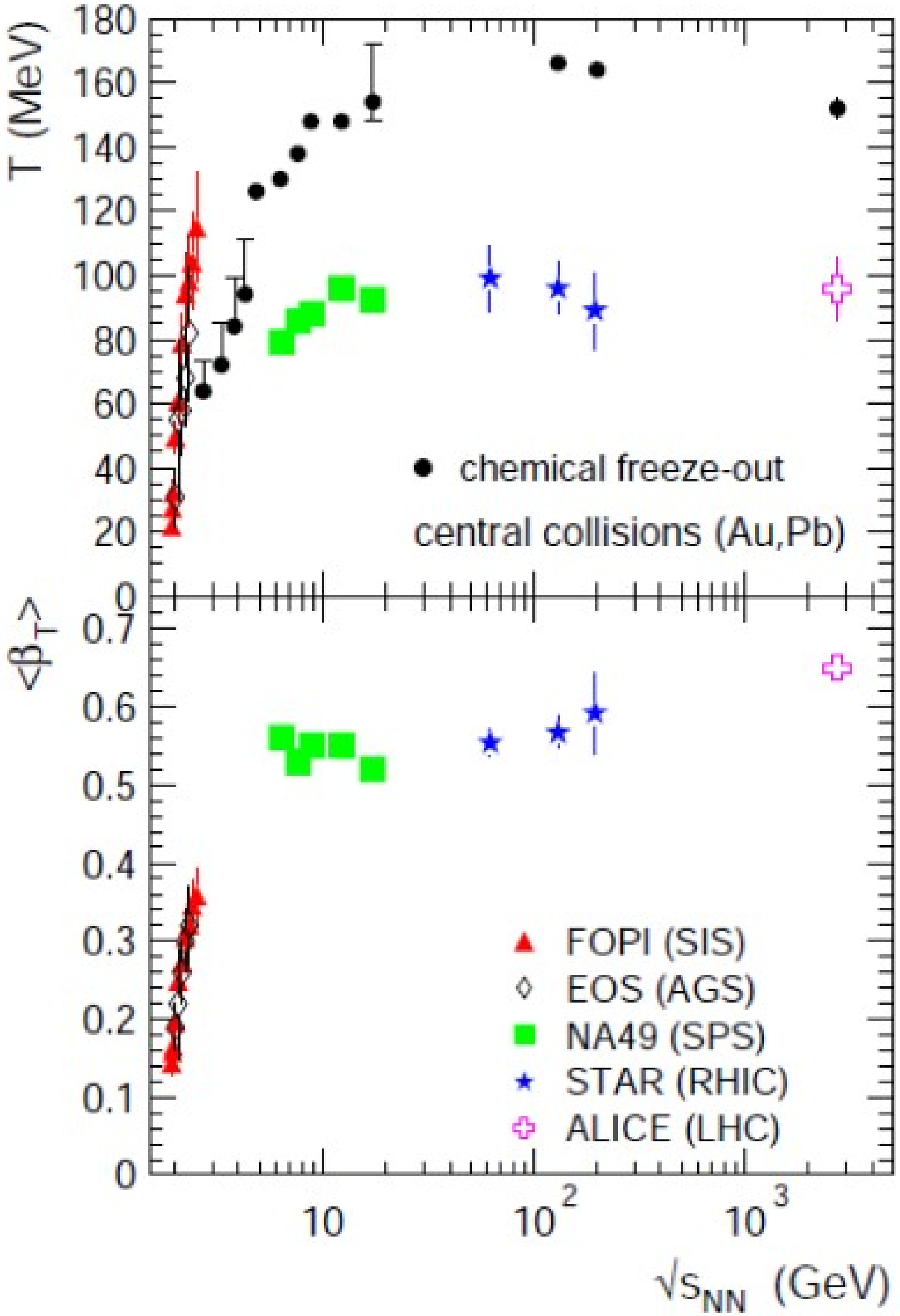
The kinetic freeze-out



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)

The kinetic freeze-out



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

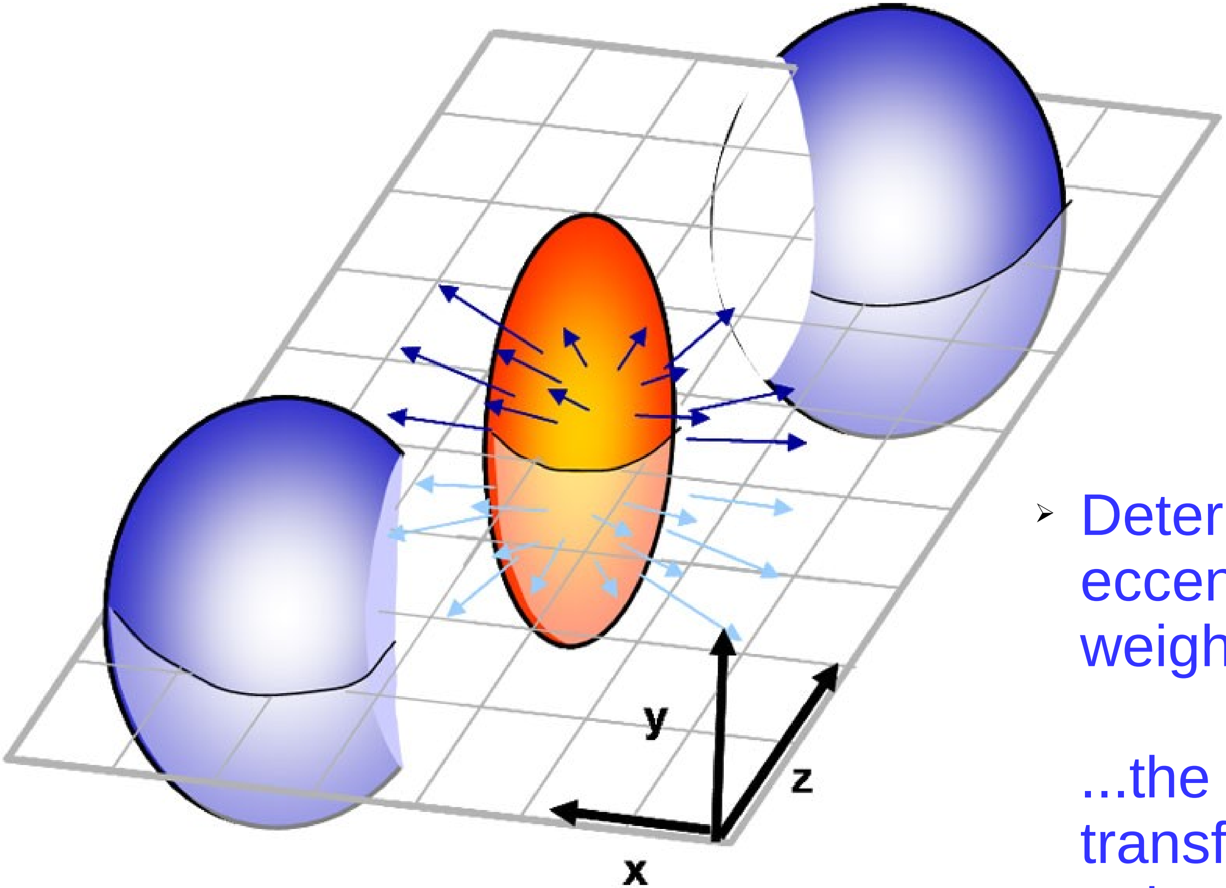
  T_{kine} = kinetic freeze-out temperature

  <β> = collective average velocity

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

- arXiv: 1210.8126

Elliptic flow (v_2). What is that?



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

$\phi =$ azimuthal angle with respect to reaction plane,

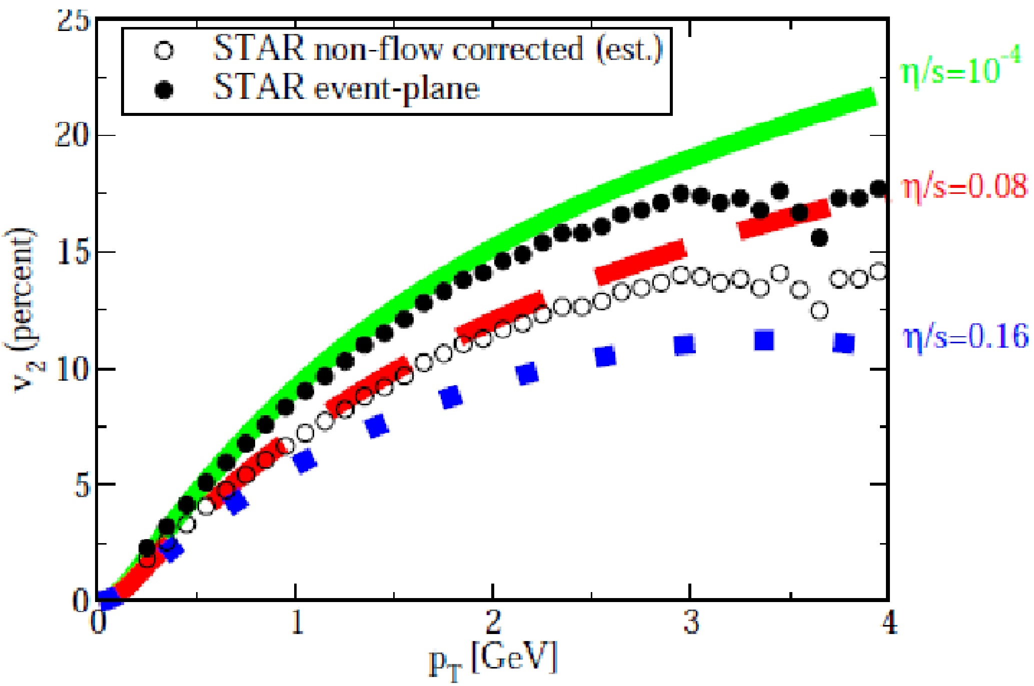
$$v_2 = \langle \cos(2\phi) \rangle$$

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

- Determined by the initial spatial eccentricity, with energy density as weight

  ...the strongly coupled system transforms it into momentum anisotropy

Elliptic flow and hydrodynamics



Luzum & Romatschke, arXiv:0804.4015

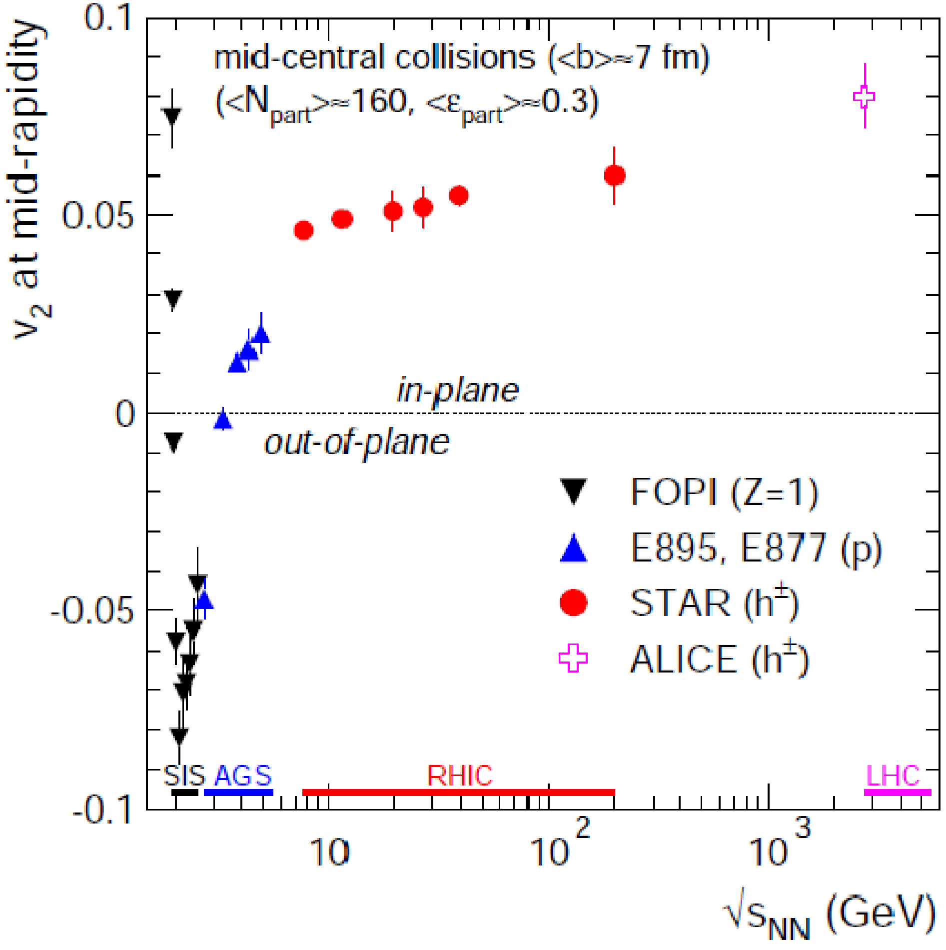
- Hydrodynamical models assume local thermal equilibrium
- Treats the whole collision history starting from the moment the system reaches equilibrium

- What do we learn from data?
  - Equation of state of the QGP
  - Shear viscosity

- 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

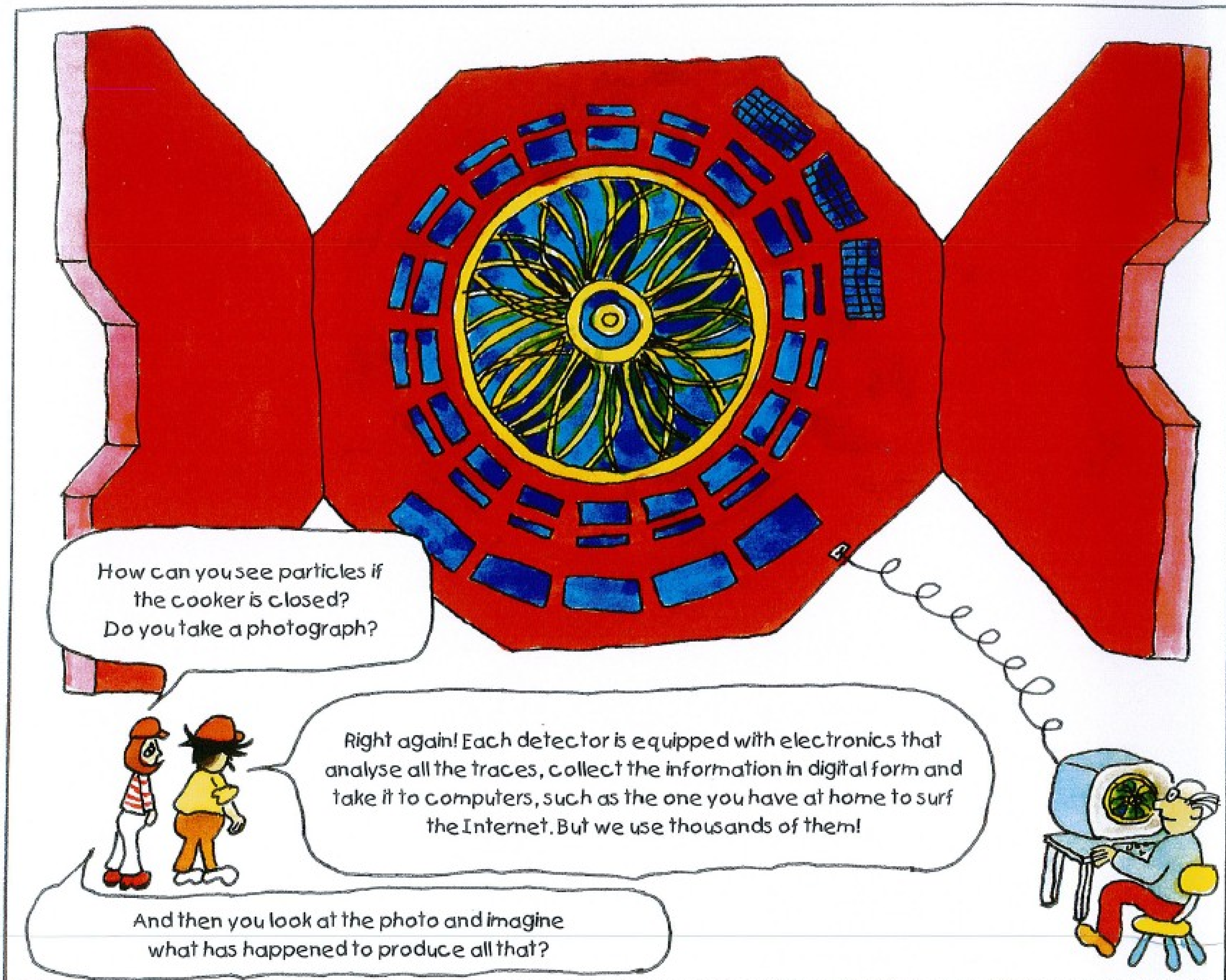
Elliptic flow. Energy dependence



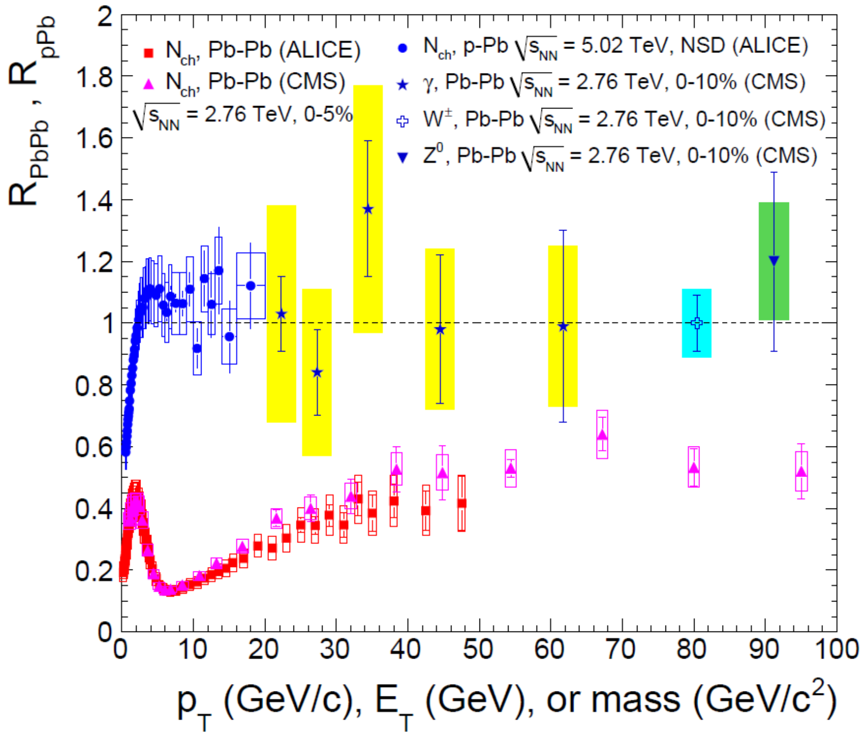
- Provides information on the reaction dynamics
- $v_2>0$ at low energies: in-plane, rotation like emission
- $v_2<0$: onset of expansion in competition with shadowing from spectators → precise clock for the collective expansion (10-40 fm/c)
- $v_2>0$ at high energies: “free” fireball expansion → genuine elliptic flow

ALICE, arXiv:1011.3914

Part IV: “Hard” and electromagnetic probes



Medium effects (the nuclear modification factor)



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

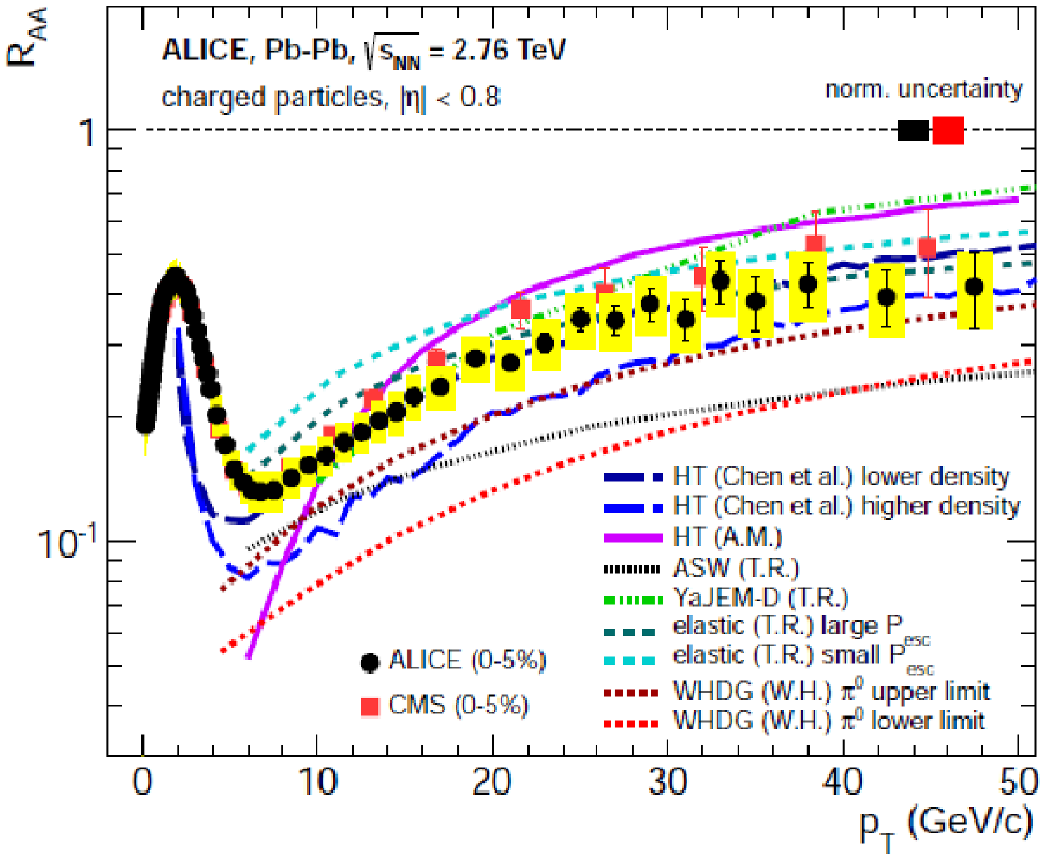
γ, CMS, PLB 710 (2012) 256
$W^{\pm}$, CMS, PLB715 (2012) 66
Z^0, CMS, PRL106 (2011) 212301

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

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

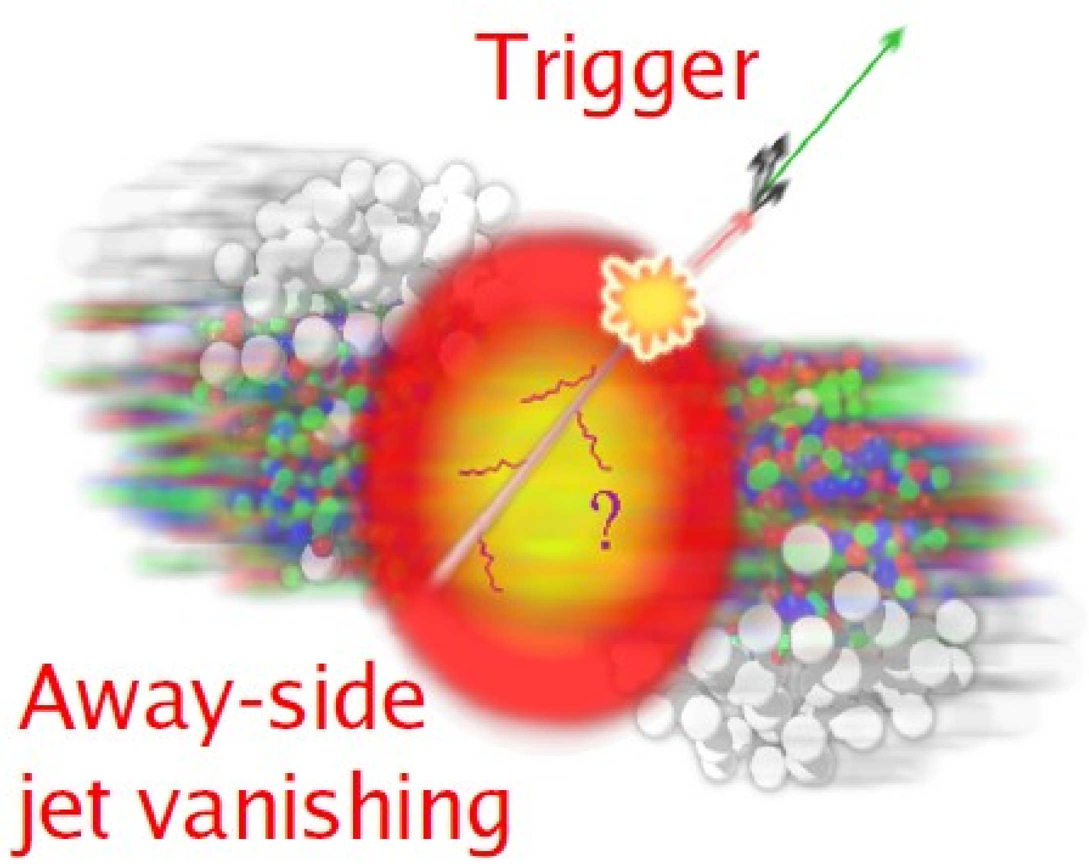
- Weakly interacting particles are not affected by the QGP
  - Photons, $W^{\pm}$ and Z^0 bosons R_{AA} are compatible with 1

Jet quenching at the LHC



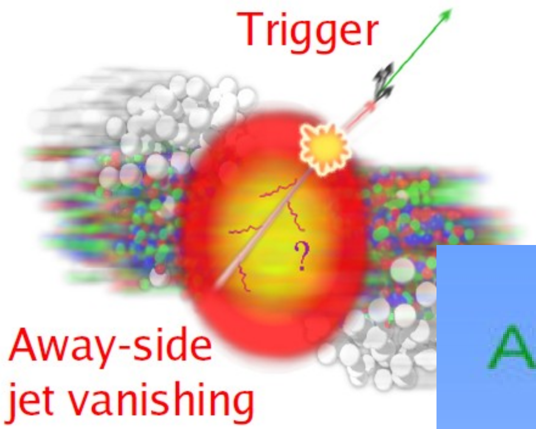
- Strong suppression observed (stronger than at RHIC)
- Reaching a factor of about 7 at p_T=7-8 GeV/c
- Remains substantial even beyond 50 GeV/c
- A lot of activity in theoretical description of parton energy loss in hot deconfined matter

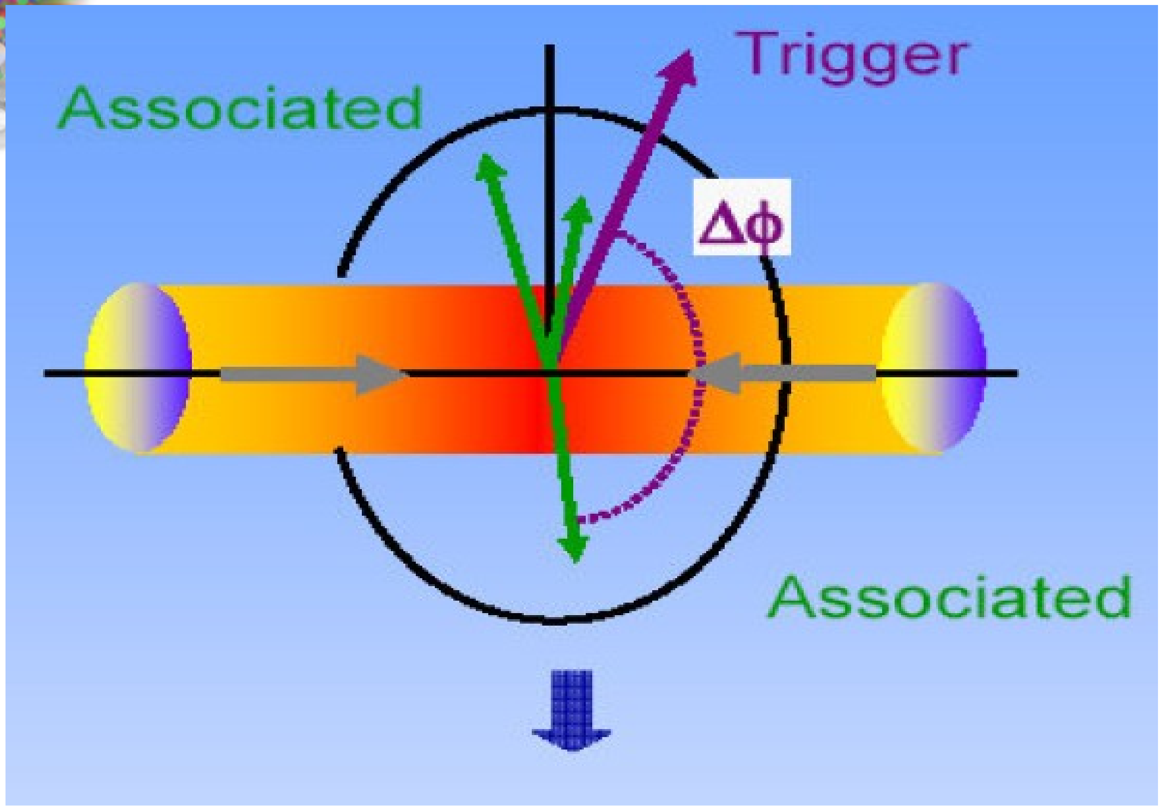
Two-particle azimuthal correlations



- 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)

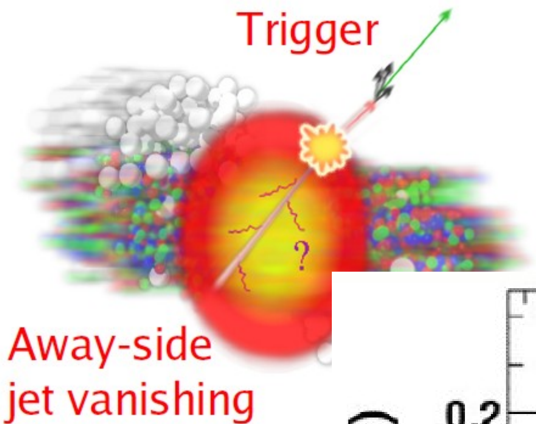
Two-particle azimuthal correlations

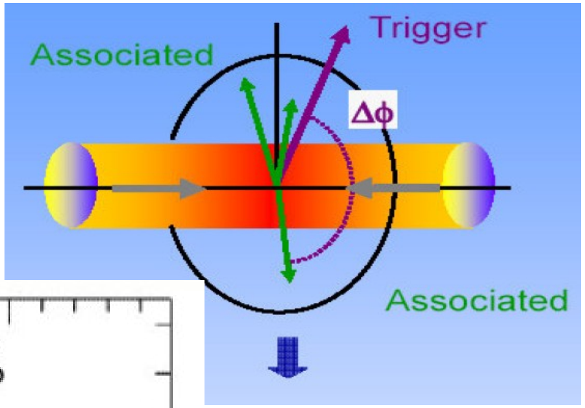


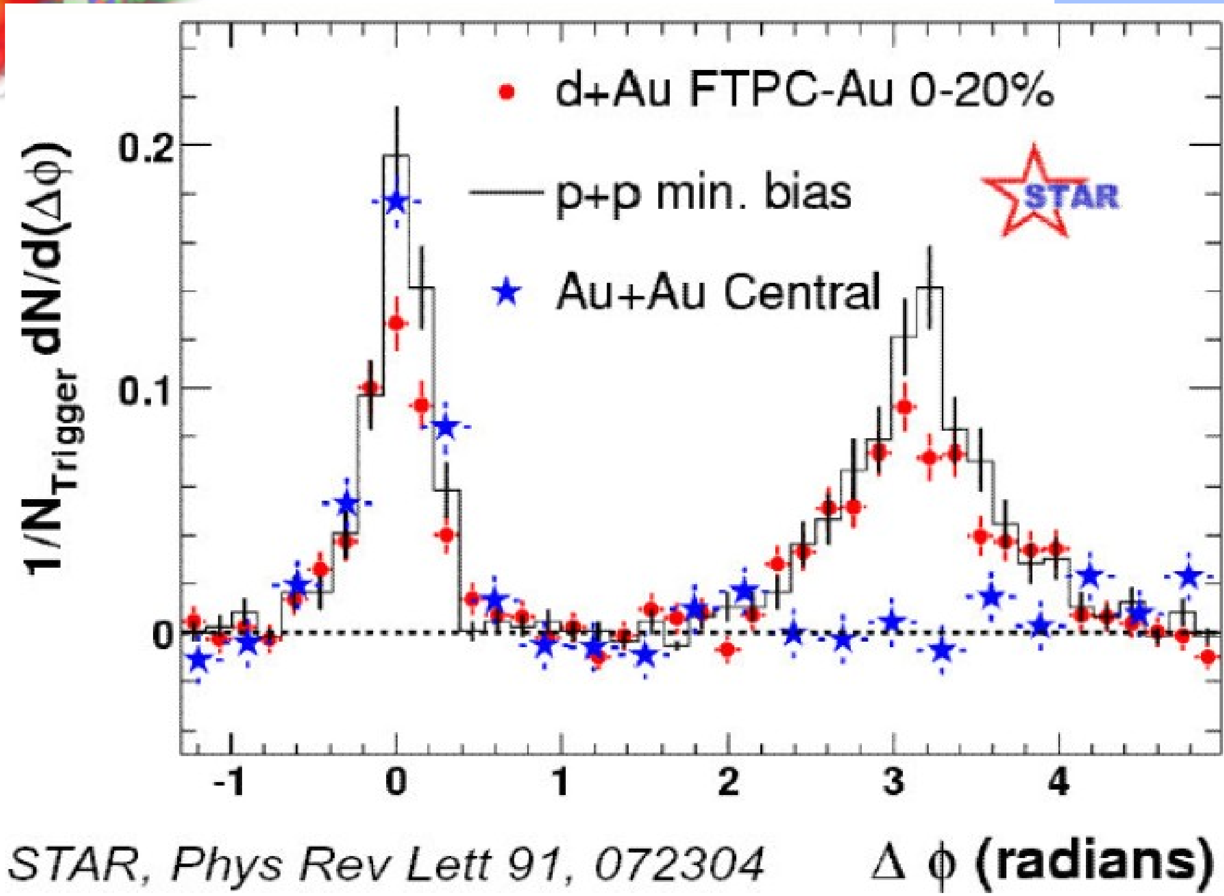


- Test the strength of this effect using two-particle correlations

Two-particle azimuthal correlations





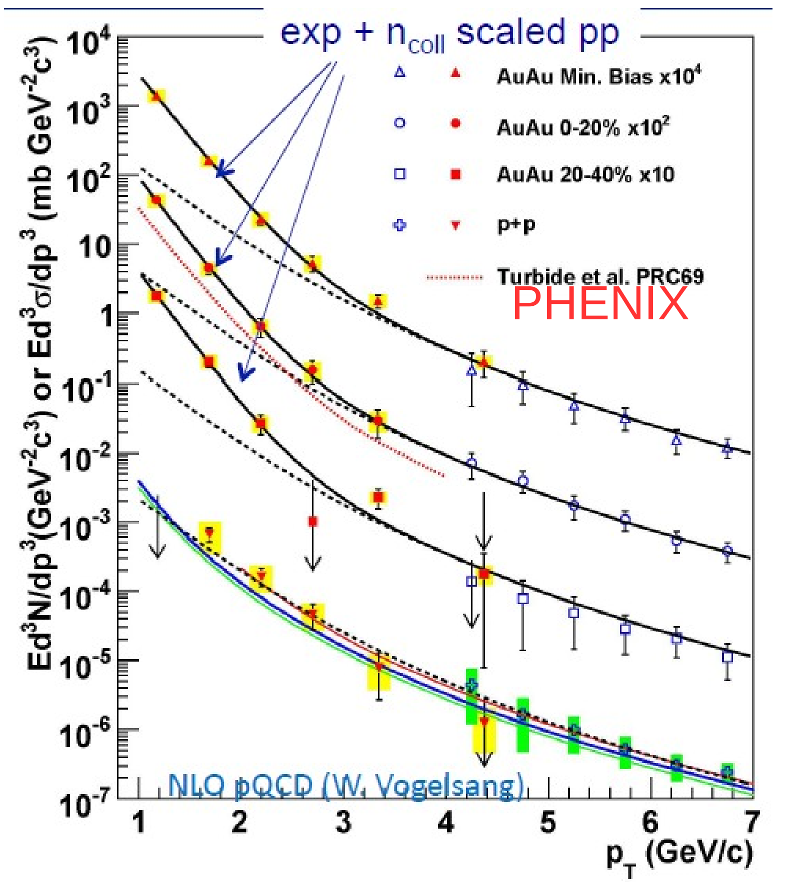


STAR, Phys Rev Lett 91, 072304

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

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

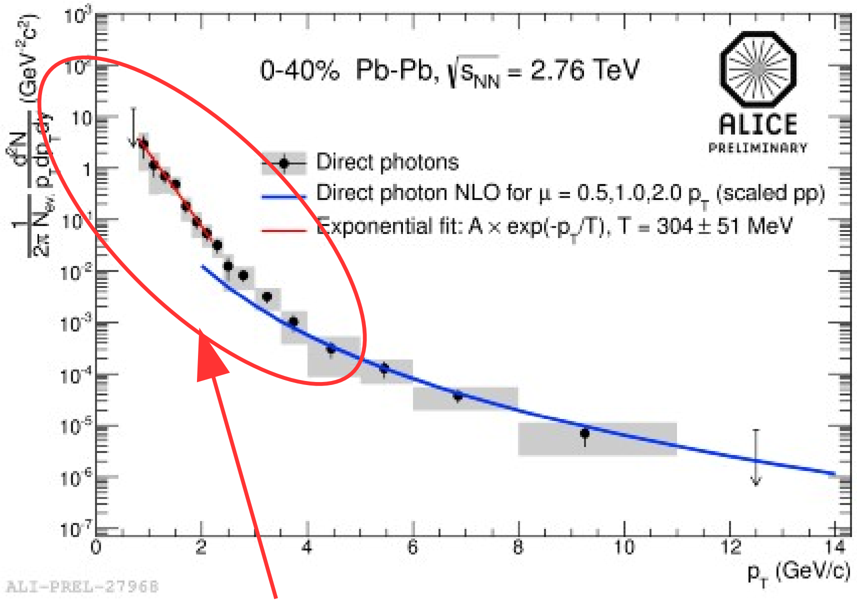


$T_{ave} = 221 \pm 19^{stat} \pm 19^{syst}$ MeV

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

Electromagnetic probes

- 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



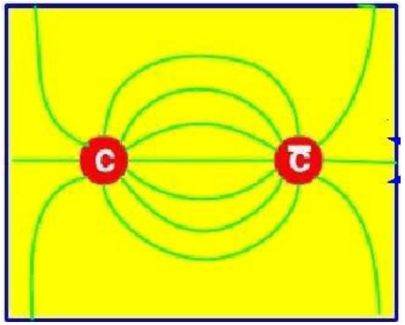
T = 304 ± 51 MeV

T ~3.0 x 10^{12} K

The highest temperature ever recorded!!!

Quarkonium and the QGP

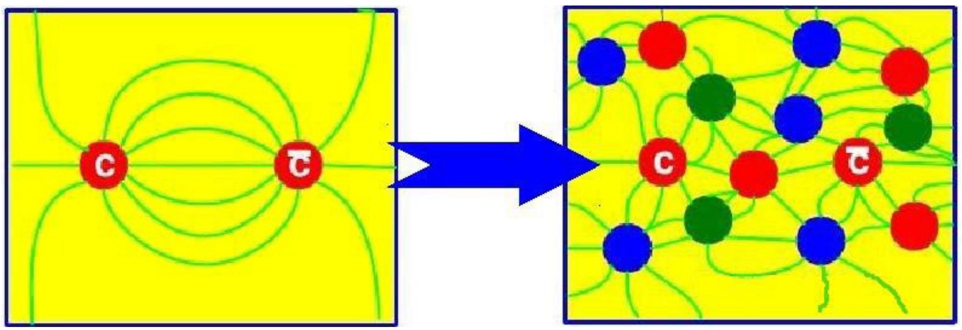
- Bound states of heavy quark anti-quark pairs, e.g. J/ψ, Υ
- Relatively large binding energy, e.g. for J/ψ is ~600 MeV



Quarkonium and the QGP

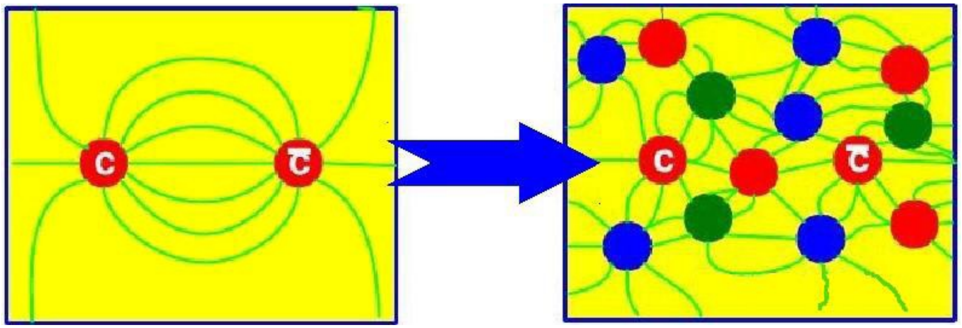
- Bound states of heavy quark anti-quark pairs, e.g. J/ψ, Υ
- Relatively large binding energy, e.g. for J/ψ is ~600 MeV
- The original idea: Matsui and Satz, PLB 178 (1986) 416:
  - In a deconfined medium with high density of color charges, the QCD analogue of the Debye screening can lead to quarkonium suppression

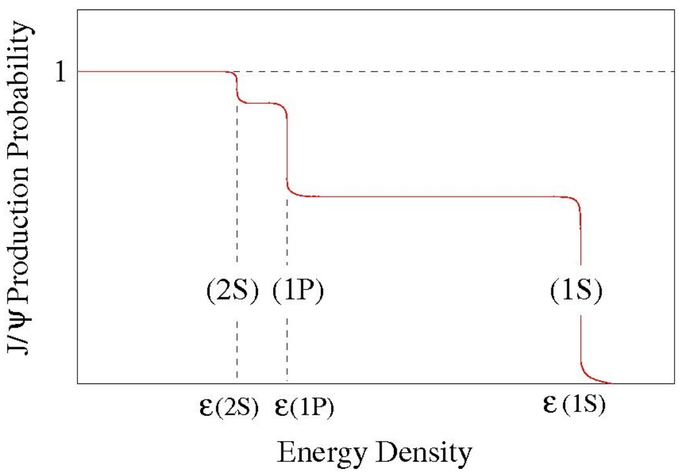
  - No J/ψ if $\lambda_D < r_{J/\psi}$

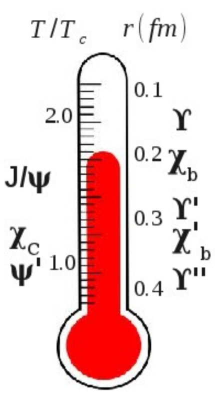


Quarkonium and the QGP

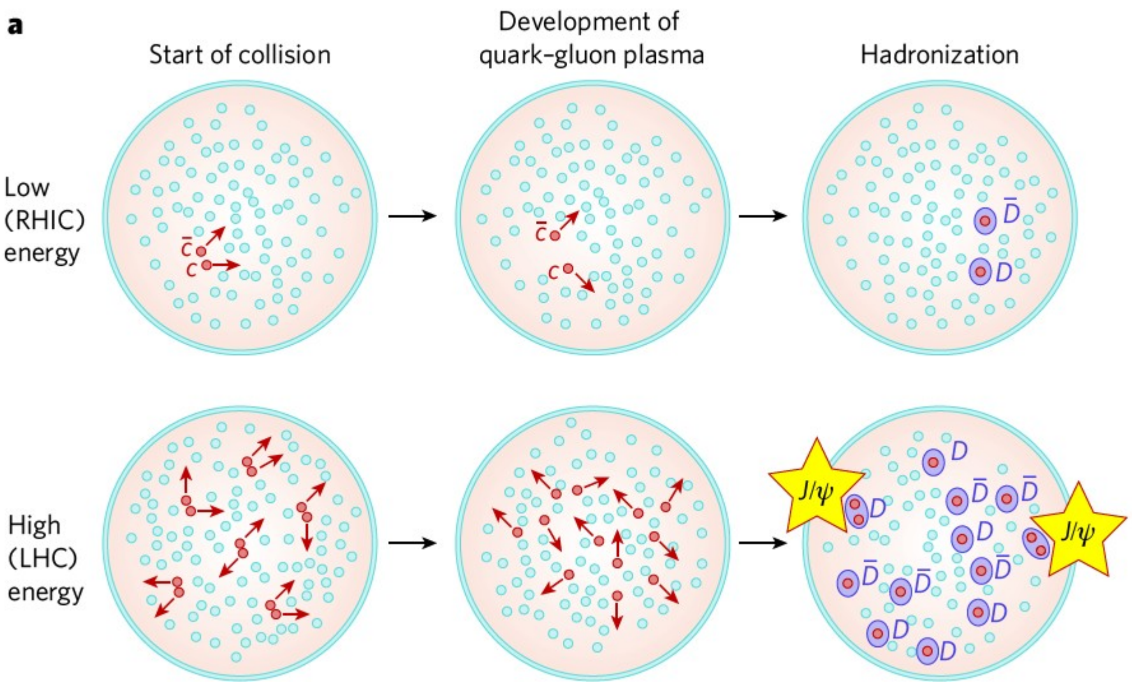
- Bound states of heavy quark anti-quark pairs, e.g. J/ψ, Υ
- Relatively large binding energy, e.g. for J/ψ is ~600 MeV
- The original idea: Matsui and Satz, PLB 178 (1986) 416:
  - In a deconfined medium with high density of color charges, the QCD analogue of the Debye screening can lead to quarkonium suppression
  - No J/ψ if $\lambda_D < r_{J/\psi}$
  - The Debye length in QGP is a function of temperature so J/ψ and the other quarkonium states act as a thermometer of the plasma

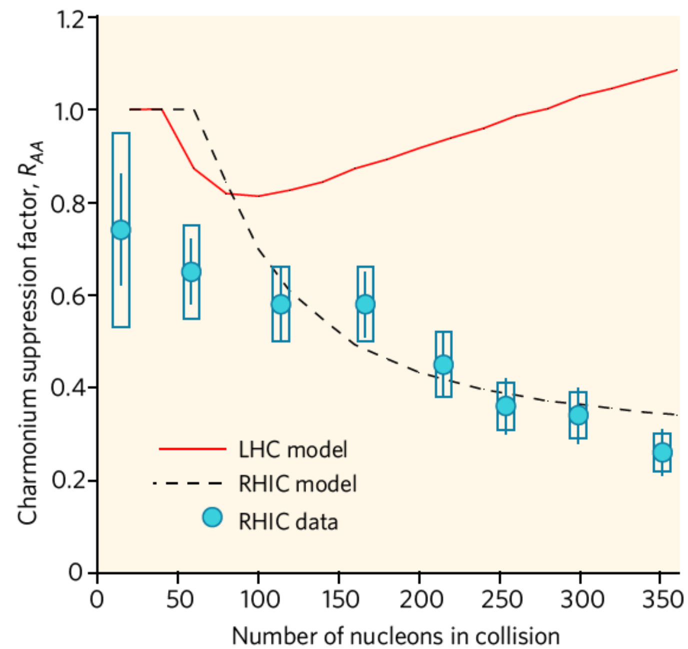






Quarkonium in the QGP (re-generation)

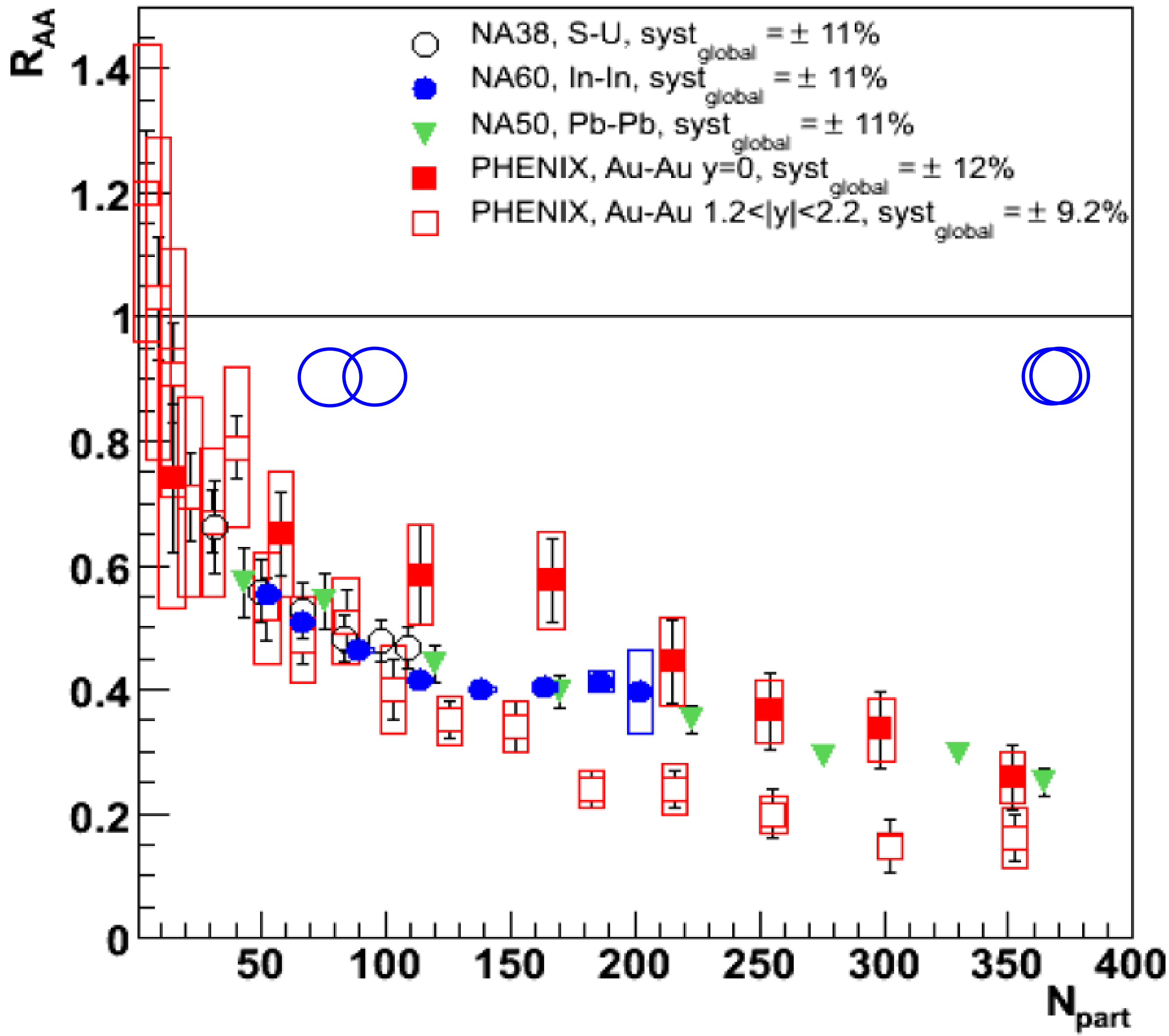




Nature 448 (2007) 302-309

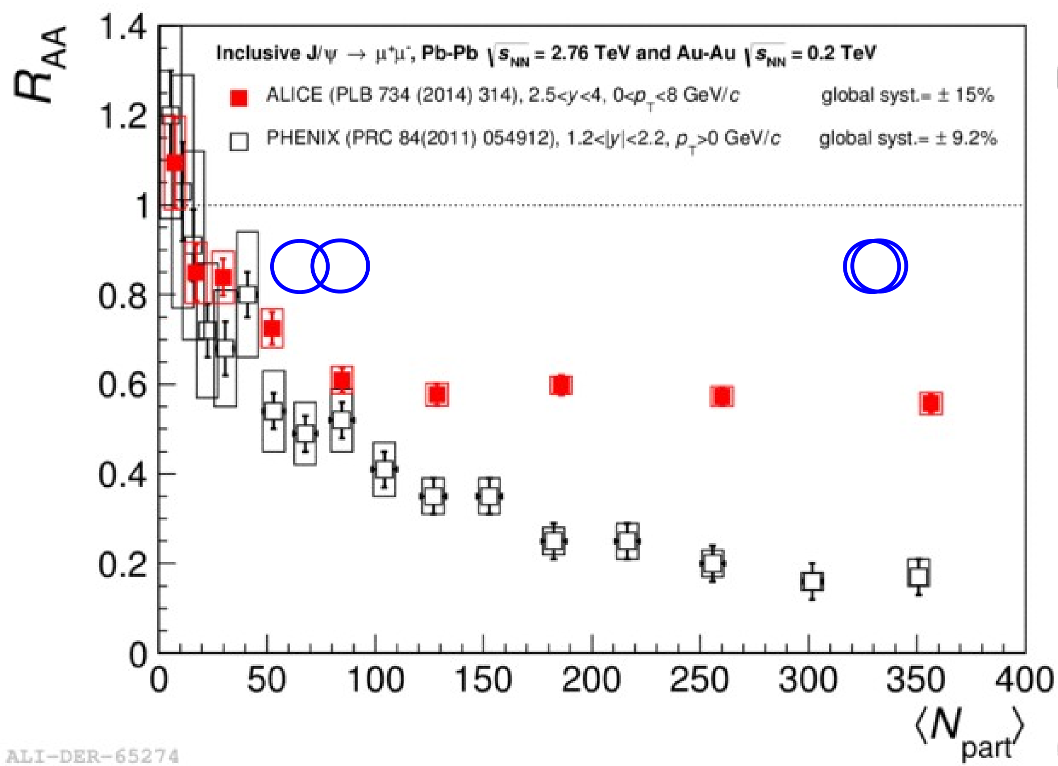
- Melting ↔ formation of quarkonium states
  - Thews et al., PRC 63 (2001) 054905
  - Transport models
- Enhancement of quarkonia states from $Q\bar{Q}$ pairs at the phase boundary
- Open charm and quarkonia abundancies calculated assuming statistical hadronization.
  - Braun-Munzinger and Stachel, PLB 490 (2000) 196

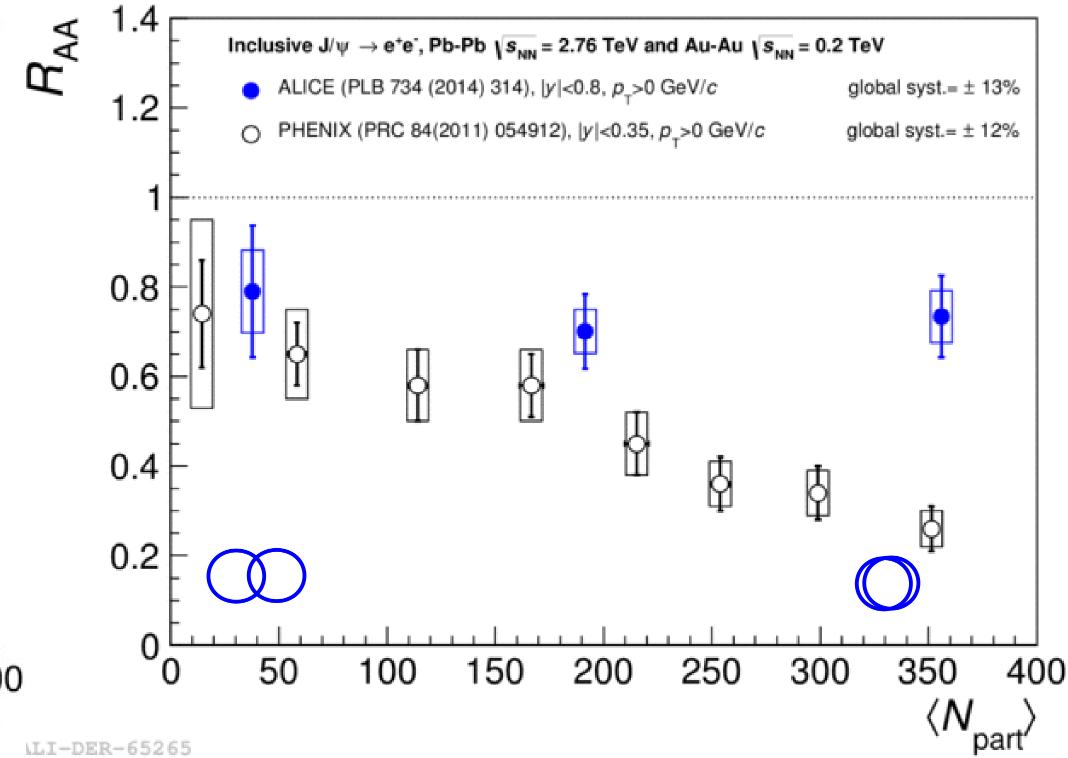
The lower energy results



- Strong suppression observed in central collisions, as predicted by the Matsui and Satz

J/ψ at the LHC





- Clear J/ψ suppression seen for all centralities
- Indication of less suppression at mid-rapidity
- ALICE results show smaller suppression compared to lower energies (PHENIX) in central collisions
- A new regime of quarkonium production has been reached at LHC!!!

Impact on the physics community

(ALICE publications)

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1. **The ALICE experiment at the CERN LHC**
(961) ALICE Collaboration (K. Aamodt (Oslo U.) *et al.*). 2008. 259 pp.
Published in **JINST 3 (2008) S08002**
DOI: 10.1088/1748-0221/3/08/S08002
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Technical

2. **Elliptic flow of charged particles in Pb-Pb collisions at 2.76 TeV**
(483) ALICE Collaboration (K Aamodt (Bergen U.) *et al.*). Nov 2010. 10 pp.
Published in **Phys.Rev.Lett. 105 (2010) 252302**
DOI: 10.1103/PhysRevLett.105.252302
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Heavy ion physics

3. **ALICE: Physics performance report, volume II**
(477) ALICE Collaboration (B Alessandro (ed.) (Turin U. & INFN, Turin) *et al.*). 2006. 746 pp.
Published in **J.Phys. G32 (2006) 1295-2040**
DOI: 10.1088/0954-3899/32/10/001
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Technical

4. **ALICE: Physics performance report, volume I**
(403) ALICE Collaboration (F Carminati (ed.) *et al.*). 2004. 247 pp.
Published in **J.Phys. G30 (2004) 1517-1763**
DOI: 10.1088/0954-3899/30/11/001
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Technical

5. **Suppression of Charged Particle Production at Large Transverse Momentum in Central Pb--Pb Collisions at $\sqrt{s_{NN}} = 2.76$ TeV**
(399) ALICE Collaboration (K. Aamodt (Bergen U.) *et al.*). Dec 2010. 16 pp.
Published in **Phys.Lett. B696 (2011) 30-39**
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DOI: 10.1016/j.physletb.2010.12.020
e-Print: **arXiv:1012.1004 [nucl-ex]** | PDF
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Heavy ion physics

6. **Centrality dependence of the charged-particle multiplicity density at mid-rapidity in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV**
(334) ALICE Collaboration (Kenneth Aamodt (Bergen U.) *et al.*). Dec 2010. 14 pp.
Published in **Phys.Rev.Lett. 106 (2011) 032301**
DOI: 10.1103/PhysRevLett.106.032301
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Heavy ion physics

7. **Charged-particle multiplicity density at mid-rapidity in central Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV**
(289) ALICE Collaboration (K Aamodt (Bergen U.) *et al.*). Nov 2010. 10 pp.
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Heavy ion physics

8. **Higher harmonic anisotropic flow measurements of charged particles in Pb-Pb collisions at $\sqrt{s_{NN}}$=2.76 TeV**
(263) ALICE Collaboration (K. Aamodt (Bergen U.) *et al.*). May 2011. 10 pp.
Published in **Phys.Rev.Lett. 107 (2011) 032301**
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Heavy ion physics

9. **Charged-particle multiplicity measurement in proton-proton collisions at $\sqrt{s} = 7$ TeV with ALICE at LHC**
(225) ALICE Collaboration (K. Aamodt (Oslo U.) *et al.*). 2010. 11 pp.
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Heavy ion physics

10. **Charged-particle multiplicity measurement in proton-proton collisions at $\sqrt{s} = 0.9$ and 2.36 TeV with ALICE at LHC**
(224) ALICE Collaboration (K. Aamodt (Oslo U.) *et al.*). Apr 2010.
Published in **Eur.Phys.J. C68 (2010) 89-108**
DOI: 10.1140/epjc/s10052-010-1339-x
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Heavy ion physics

- ALICE top 10 cited papers, all with > 200 citations
- Moreover ...

Impact on the physics community

(ATLAS publications)

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1. **Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the L**
(4121) ATLAS Collaboration (Georges Aad (Freiburg U.) *et al.*). Jul 2012. 24 pp.
Published in **Phys.Lett. B716 (2012) 1-29**
CERN-PH-EP-2012-218
DOI: 10.1016/j.physletb.2012.08.020
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Higgs discovery

2. **The ATLAS Experiment at the CERN Large Hadron Collider**
(3414) ATLAS Collaboration (G. Aad (Marseille, CPPM) *et al.*). 2008. 437 pp.
Published in **JINST 3 (2008) S08003**
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Technical

3. **Expected Performance of the ATLAS Experiment - Detector, Trigger and Physics**
(1705) ATLAS Collaboration (G. Aad *et al.*). Jan 2009. 1852 pp.
SLAC-R-980, CERN-OPEN-2008-020
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Technical

4. **The ATLAS Simulation Infrastructure**
(991) ATLAS Collaboration (G. Aad (Freiburg U.) *et al.*). 2010. 53 pp.
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DOI: 10.1140/epjc/s10052-010-1429-9
e-Print: **arXiv:1005.4568 [physics.ins-det]** | PDF
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
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Technical

5. **Electron performance measurements with the ATLAS detector using the 2010 LHC proton-proton collision data**
(614) ATLAS Collaboration (Georges Aad (Freiburg U.) *et al.*). Oct 2011. 45 pp.
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DOI: 10.1140/epjc/s10052-012-1909-1
e-Print: **arXiv:1110.3174 [hep-ex]** | PDF
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Detailed record - Cited by 614 records 500+

Technical

6. **ATLAS: Detector and physics performance technical design report. Volume 1**
(583) ATLAS Collaboration (A. Airapetian *et al.*). May 1999. 475 pp.
CERN-LHCC-99-14, ATLAS-TDR-14
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Technical

7. **Jet energy measurement with the ATLAS detector in proton-proton collisions at $\sqrt{s} = 7$ TeV**
(552) ATLAS Collaboration (Georges Aad (Freiburg U.) *et al.*). Dec 2011. 100 pp.
Published in **Eur.Phys.J. C73 (2013) 3, 2304**
CERN-PH-EP-2011-191
DOI: 10.1140/epjc/s10052-013-2304-2
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References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
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pp jet physics

8. **Combined search for the Standard Model Higgs boson using up to 4.9 fb^{-1} of pp collision data at $\sqrt{s} = 7$ TeV with the ATLAS detector at the LHC**
(532) ATLAS Collaboration (Georges Aad (Freiburg U.) *et al.*). Feb 2012. 8 pp.
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DOI: 10.1016/j.physletb.2012.02.044
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Higgs discovery

9. **ATLAS: Detector and physics performance technical design report. Volume 2**
(522) ATLAS Collaboration (A. Airapetian *et al.*). May 1999. 519 pp.
CERN-LHCC-99-15, ATLAS-TDR-15
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Technical

10. **Luminosity Determination in pp Collisions at $\sqrt{s} = 7$ TeV Using the ATLAS Detector at the LHC**
(458) ATLAS Collaboration (Georges Aad (Freiburg U.) *et al.*). Jan 2011. 24 pp.
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e-Print: **arXiv:1101.2185 [hep-ex]** | PDF
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Technical

- ATLAS top 3 most cited scientific papers include the Higgs discovery papers and pp jet physics (as expected)

Impact on the physics community

(ATLAS publications)

11. **Observation of a Centrality-Dependent Dijet Asymmetry in Lead-Lead Collisions at $\sqrt{s_{NN}} = 2.77$ TeV with the ATLAS Detector at the LHC**
(406) ATLAS Collaboration (Georges Aad (Freiburg U.) *et al.*). Nov 2010. 19 pp.
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DOI: 10.1103/PhysRevLett.105.252303
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Heavy ion physics

12. **ATLAS: Technical proposal for a general-purpose p p experiment at the Large Hadron Collider at CERN**
(404) ATLAS Collaboration (W.W. Armstrong (Alberta U.) *et al.*). Dec 1994. 289 pp.
CERN-LHCC-94-43
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Detailed record - Cited by 404 records 250+

Technical

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Higgs discovery

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Top-quark

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Soft-QCD pp physics

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Supersymmetry searches

- Heavy-ion physics papers rank among the highest cited papers in ATLAS, despite the very small physics working group
- Most cited heavy-ion paper by ATLAS rankes 4th, but several others are following closely ...

Impact on the physics community

(CMS publications)

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Higgs discovery

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Heavy ion physics

- CMS has a few heavy-ion papers in its top-cited scientific papers

Impact on the physics community

(CMS publications)

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Heavy ion physics

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Soft-QCD pp physics

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Soft-QCD pp physics

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Beauty-quark

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Supersymmetry searches

- CMS has a few heavy-ion or heavy-ion inspired papers in its top-cited scientific papers

Conclusions

- The aim of studying the high energy heavy ion collisions is to better understand QCD in conditions not posible in particle physics: confinement, phase diagram of nuclear matter, chiral symmetry restoration
- The conditions reachable are similar to the ones during the early Universe (1 microsecond) and in the core of neutron stars
- This field incorporates knowledge from many other areas of physics:
  - Thermodynamics
  - Hydrodynamics
  - String theory (AdS/CFT)
  - Etc.
- … and of technology
  - Detection technologies
  - Electronics
  - Computing
- It is a challenging and fast evolving field … time to join :)

What we do in the ALICE-Oslo group

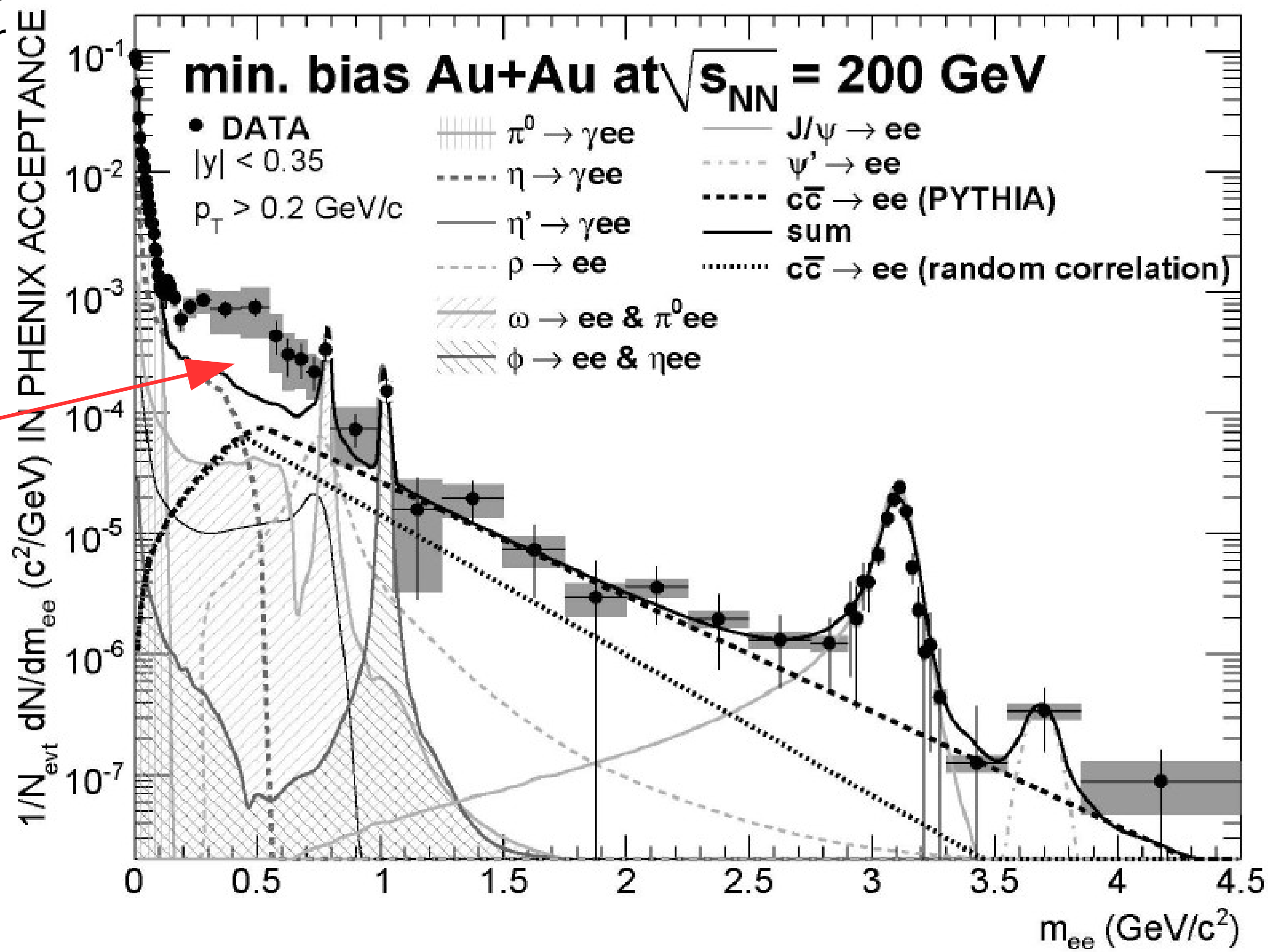
- Team leader: Prof.Trine Tveter
- Main physics topics:
  - Charmonium production in Pb-Pb, p-Pb and pp collisions
  - Three-particle correlations
  - Elliptic flow
- Detector expertise:
  - Time Projection Chamber (TPC)
  - Photon Spectrometer (PHOS)
  - Transition Radiation Detector (TRD)

Backup

Electromagnetic probes

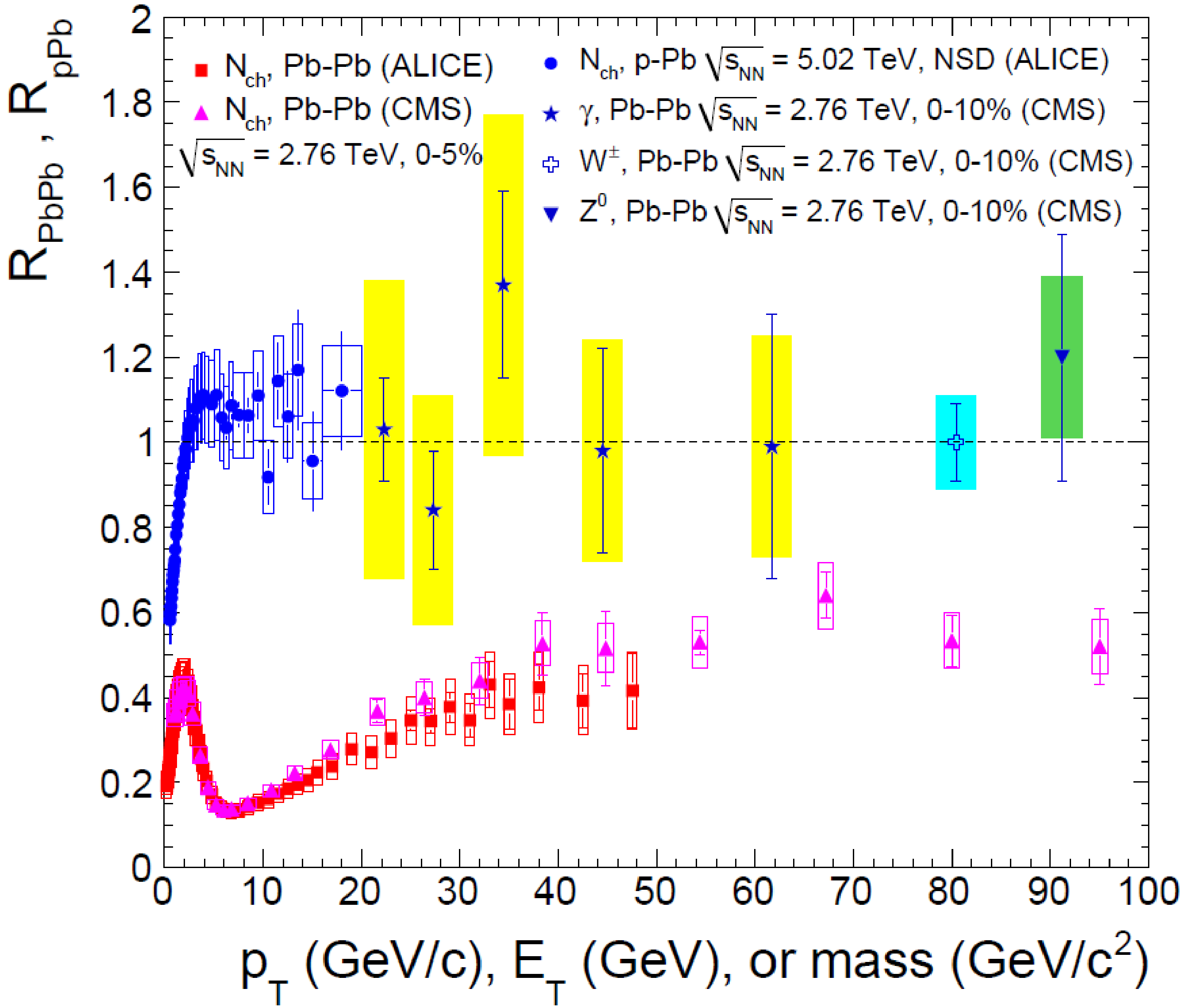
- Direct photons and low mass di-leptons
  - Probe of the thermal radiation of the fireball
  - Very clean information because of no re-interactions with QCD medium

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