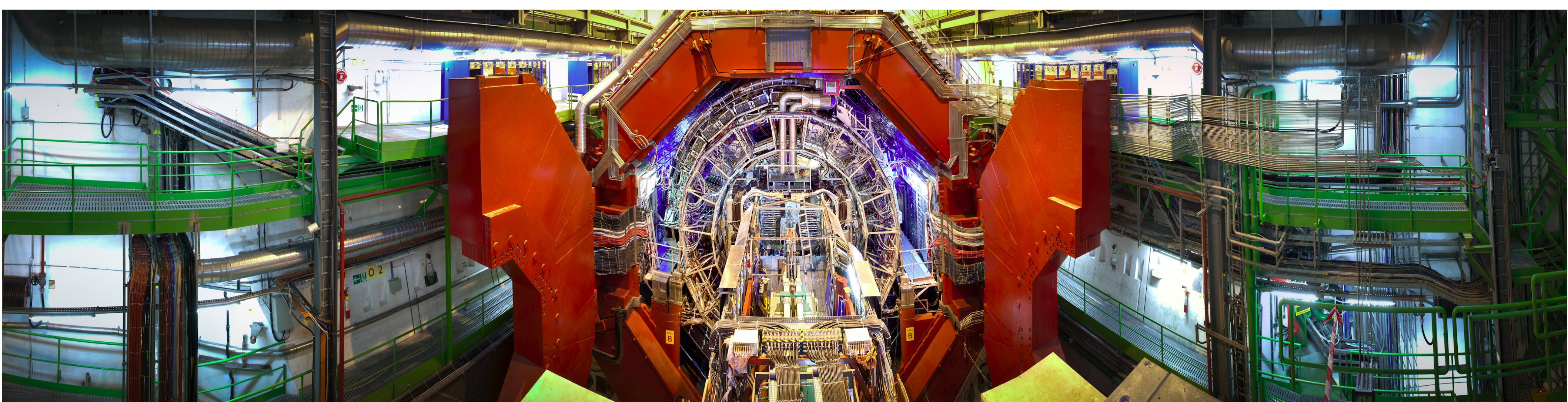
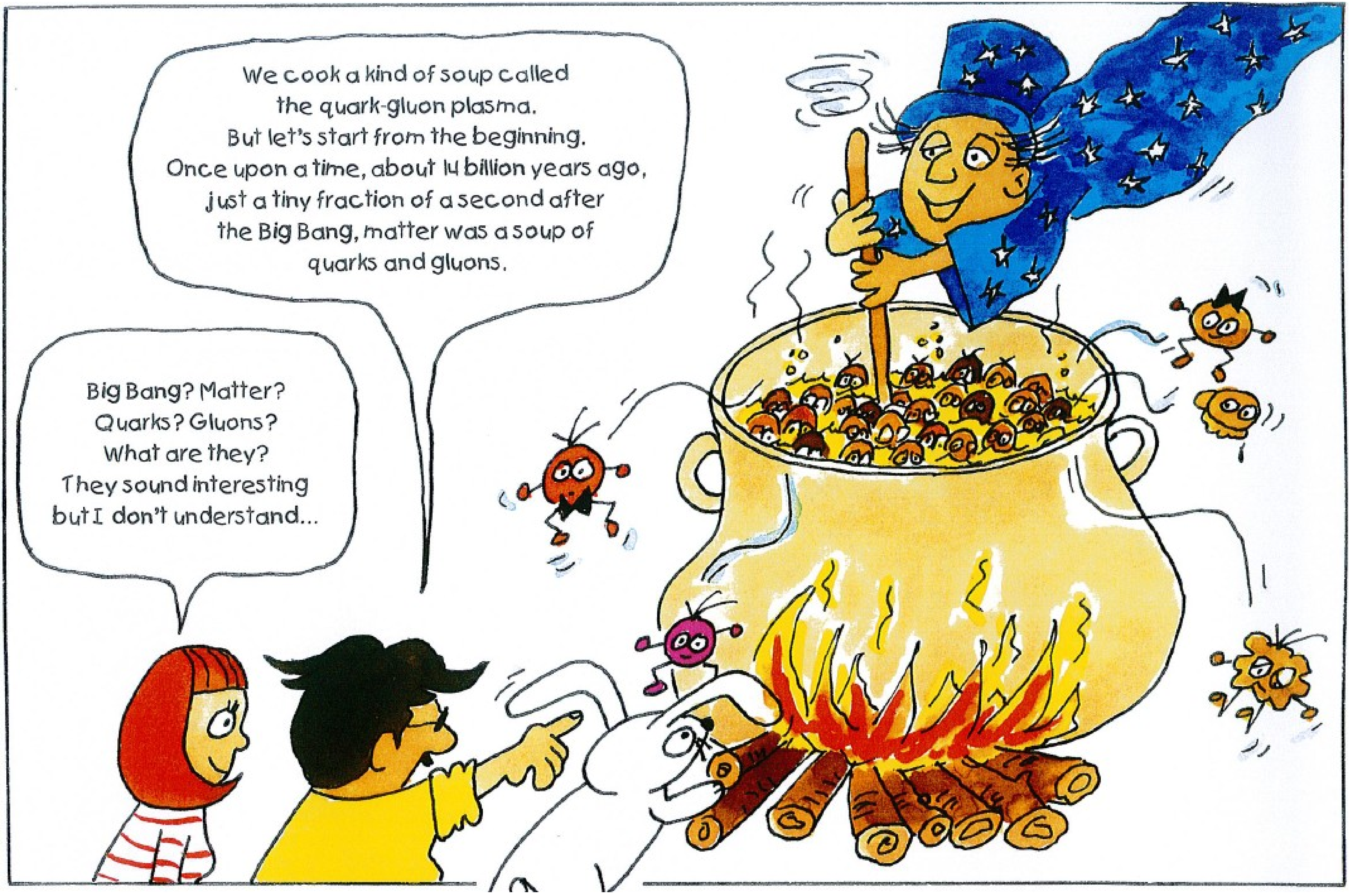
High energy nuclear physics at the LHC

Ionut Arsene
University of Oslo
2014/04/09



Part I: Introduction



A reminder: levels of the nuclear world

<u>Nuclei</u>

a large variety (Z=1-118, A=2-294), sizes: $\sim 10^{-14}$ m ($R \sim A^{1/3}$)
nucleons bound by about 1% of their mass ($m_p \simeq m_n = 1.7 \times 10^{-27}$ kg)

<u>Hadrons</u>

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

<u>Quarks</u>

6 flavors (light: u,d; "intermediate": s; heavy: c,b; "super-heavy": t)
each in 3 "colors" (to build colorless hadrons, qqq, $\bar{q}\bar{q}\bar{q}$, $q\bar{q}$)
point-like ($< 10^{-19}$ m)

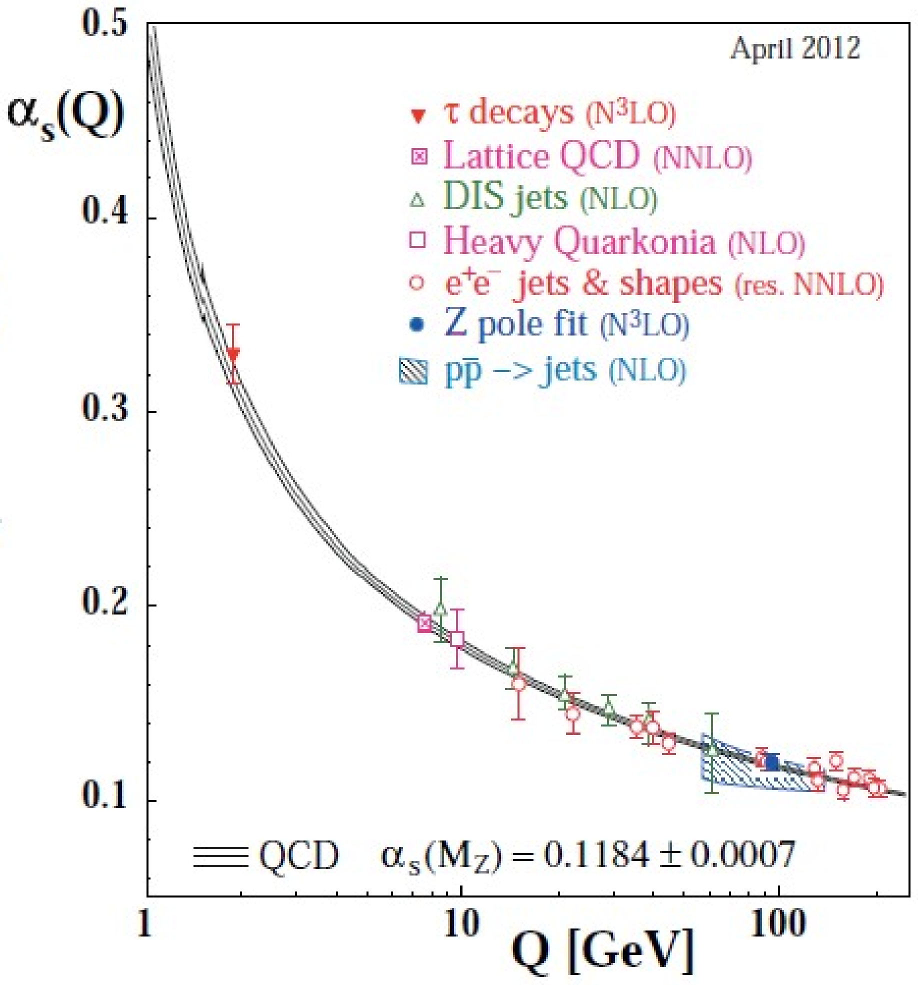
...all governed by the strong interaction

gravitation negligible
(electro)weak only indirectly (decays, final state interaction)

Quantum Chromodynamics Dynamics (QCD)

- 6 quarks, with 3 colors (RGB) and 8 gluons (**colored!**)
- ... it's very difficult (to calculate)
  - ▷ no analytical solutions (except 1+1)
  - ▷ *strong force*, running coupling (compare to QED: α=1/137.)
  - ▷ easier for higher momentum transfer
- low Q: confinement
  high Q: asymptotic freedom
  Physics Nobel prize 2004 (Wilczek, Gross, Politzer)
- not everything is understood
  (ex.: extremely complex vacuum)

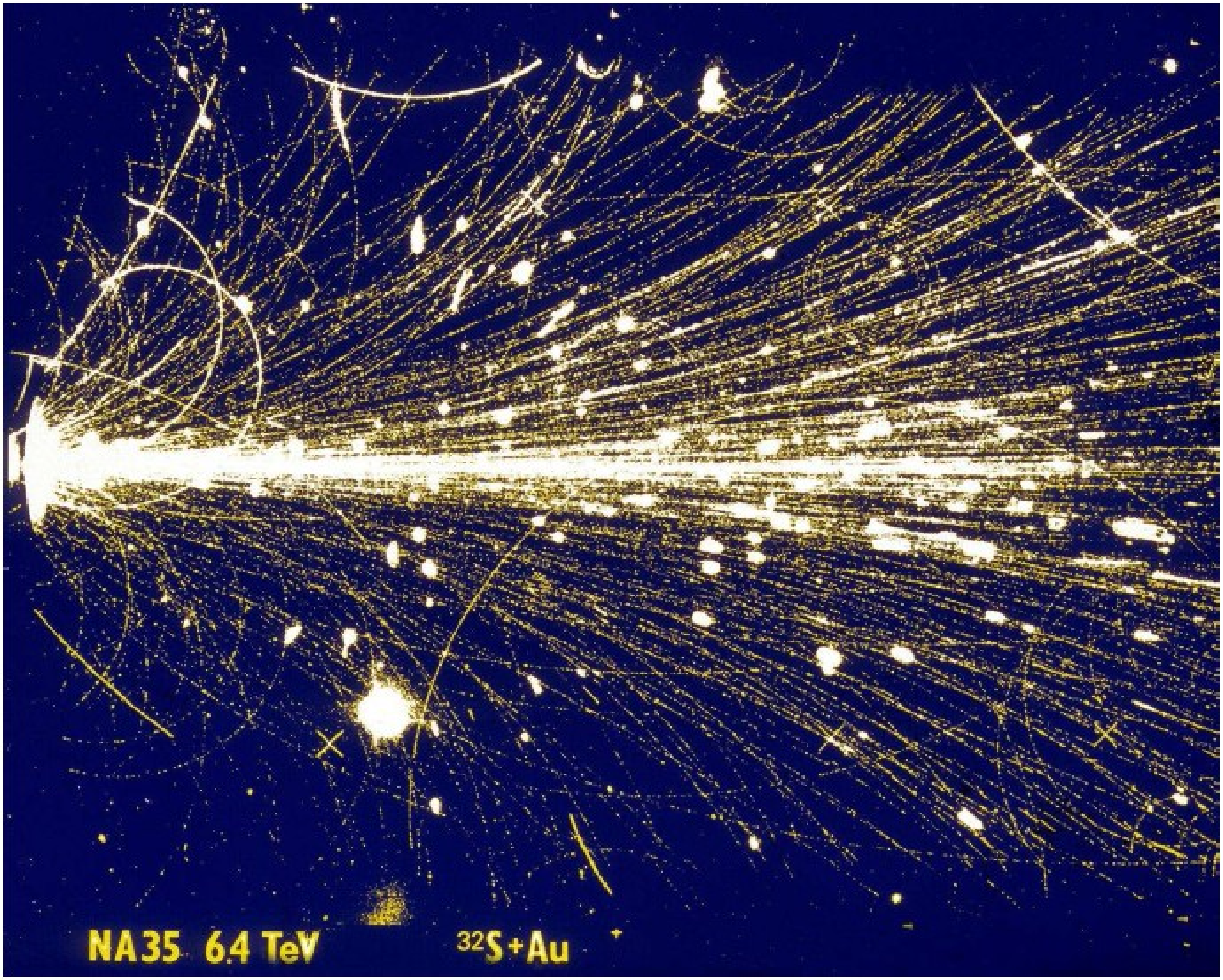
  ⇒ phenomenological models needed



S.Bethke, arXiv:1210.0325

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, E/A=1.15 GeV
- AGS @ BNL, Brookhaven (1985-1995): $\sqrt{s_{NN}}$=4.8 GeV, E/A=10.5 GeV
- SPS @ CERN, Geneva (1987-2004): $\sqrt{s_{NN}}$=17.3 GeV, E/A=157 GeV

Present:

- SIS @ GSI, Darmstadt: $\sqrt{s_{NN}}$=2.5 GeV, E/A=1.5 GeV
- RHIC @ BNL, Brookhaven: $\sqrt{s_{NN}}$=200 GeV, E/A=100 GeV
- LHC @ CERN, Geneva: $\sqrt{s_{NN}}$=2760 GeV, E/A=1380 GeV

Future:

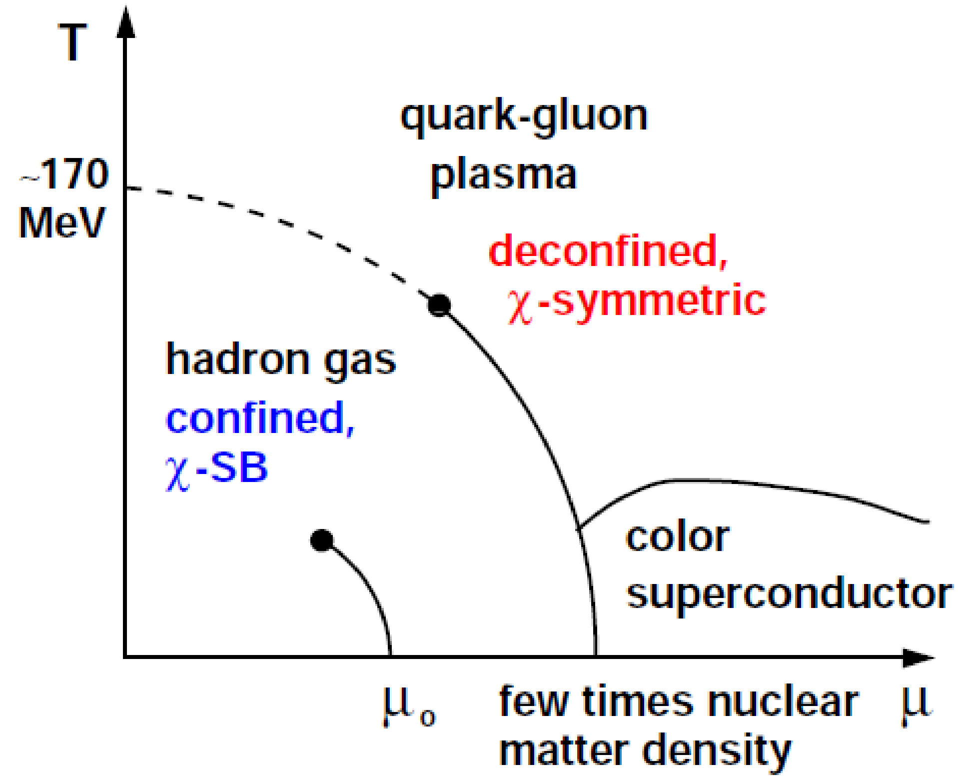
- FAIR @ GSI, Darmstadt (∼2018): $\sqrt{s_{NN}} \simeq$5 GeV, $E/A \simeq$10 GeV

High-energy nucleus-nucleus collisions: the scope

Create in laboratory a chunk of deconfined matter and study its properties (what we often call "medium", also called Quark-Gluon Plasma, QGP/sQGP)

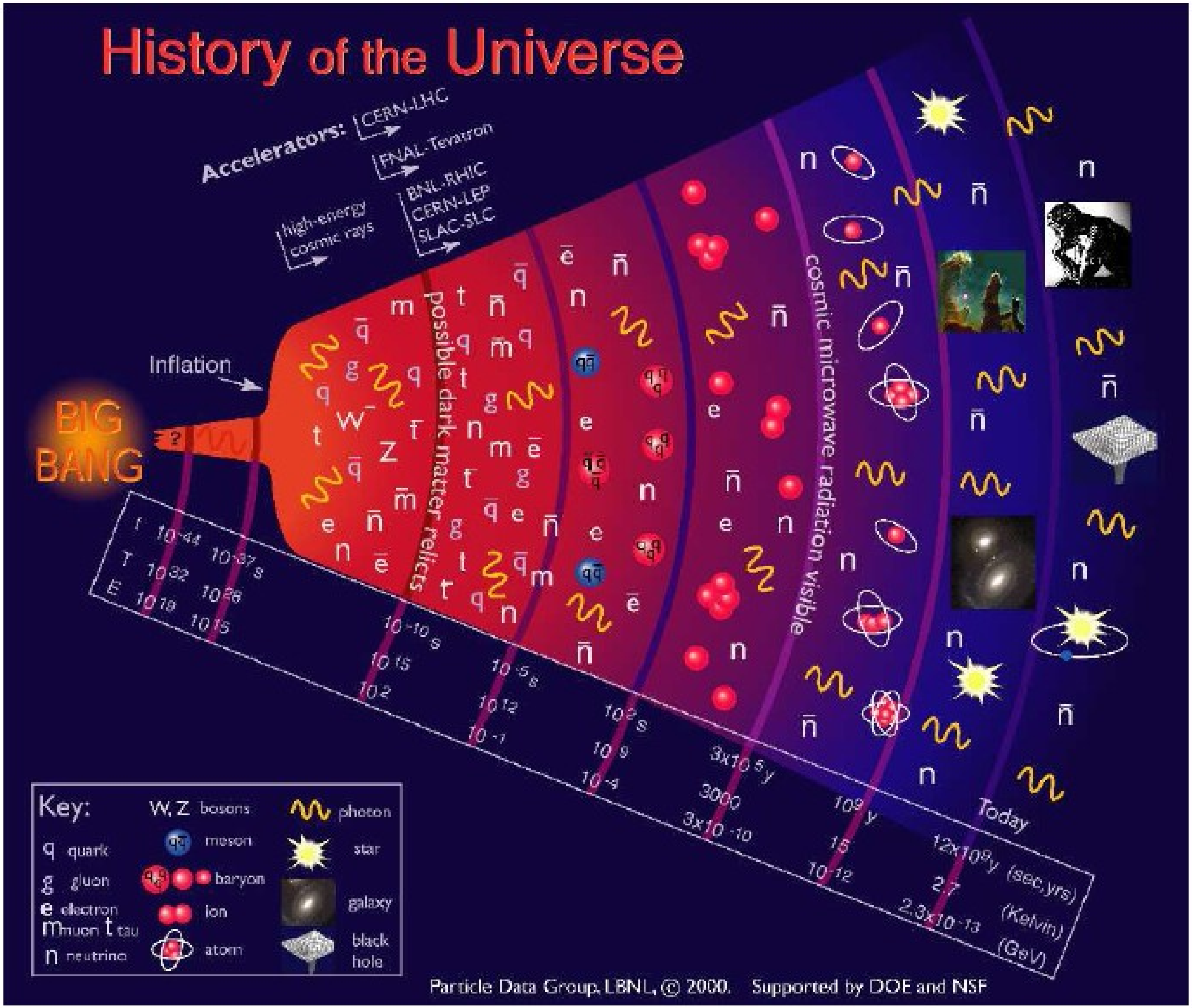
- Study of:
  - Phase diagram
    chiral/deconfinement transition(s)
    liquid-gas transition
- Relevance for:
  - early Universe (10^{-5} s)
  - neutron stars

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

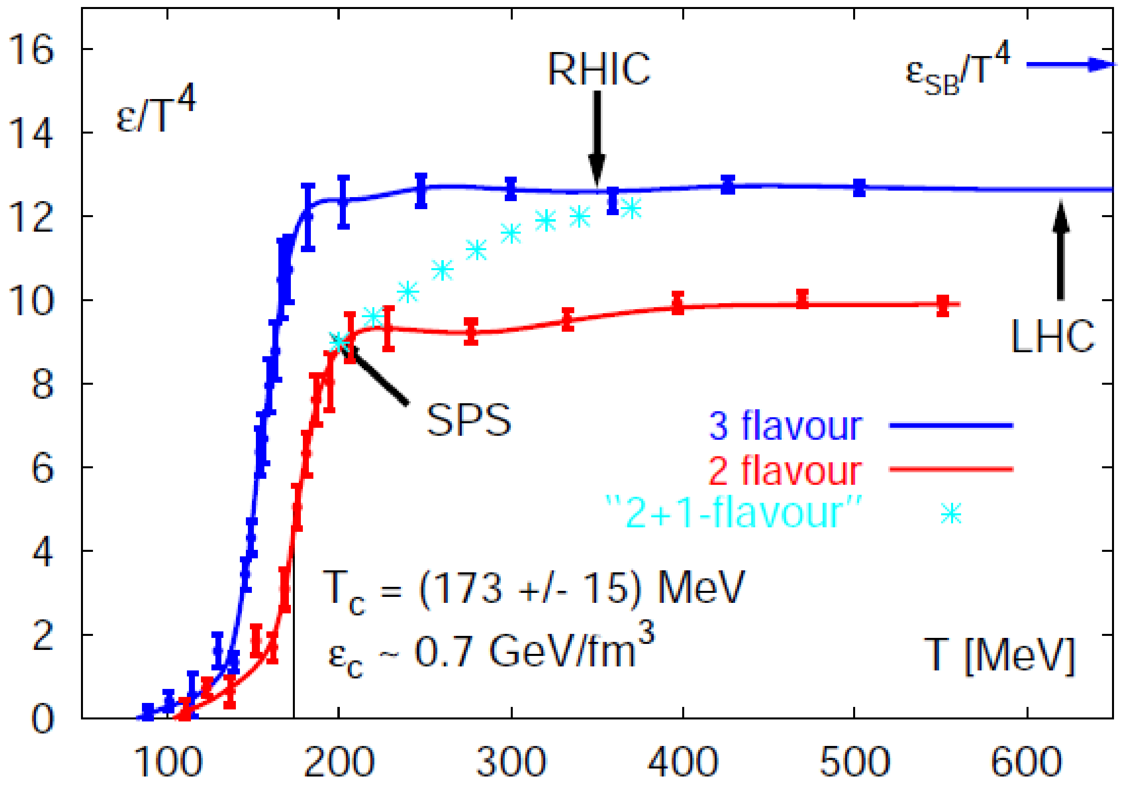


Because quarks cannot be observed in their free state (this phenomenon is called "confinement" and remains a mystery of modern science; chiral symmetry breaking: Physics Nobel prize 2008, Y.Nambu), the deconfined state can only be detected via the fingerprints it leaves on "normal" nuclear matter (hadrons) ...extremely challenging!

Quark-Gluon Plasma: the earliest incarnation



Lattice QCD predicts a phase transition (at μ_b=0)



F. Karsch, hep-lat/0106019

we now know it is of crossover type (Y. Aoki et al., Nature 443 (2006) 675)

current "critical" temperature: $T_c \simeq$155-160 MeV

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

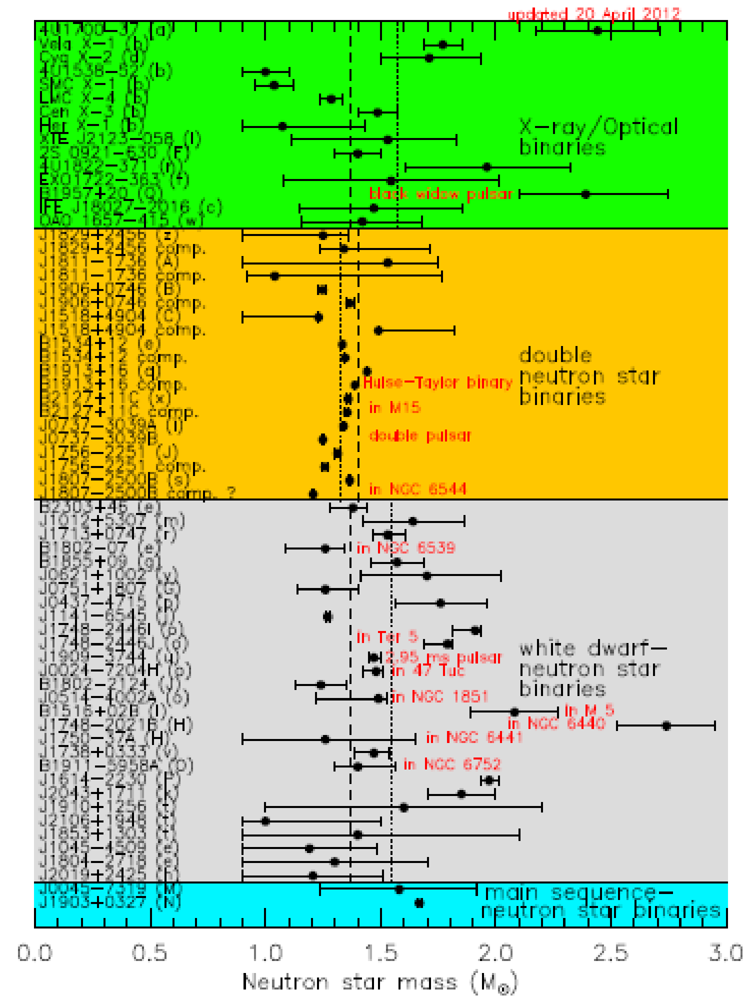
Maximum mass of neutron stars

...controlled by EoS of nuclear matter at a few times nuclear densities

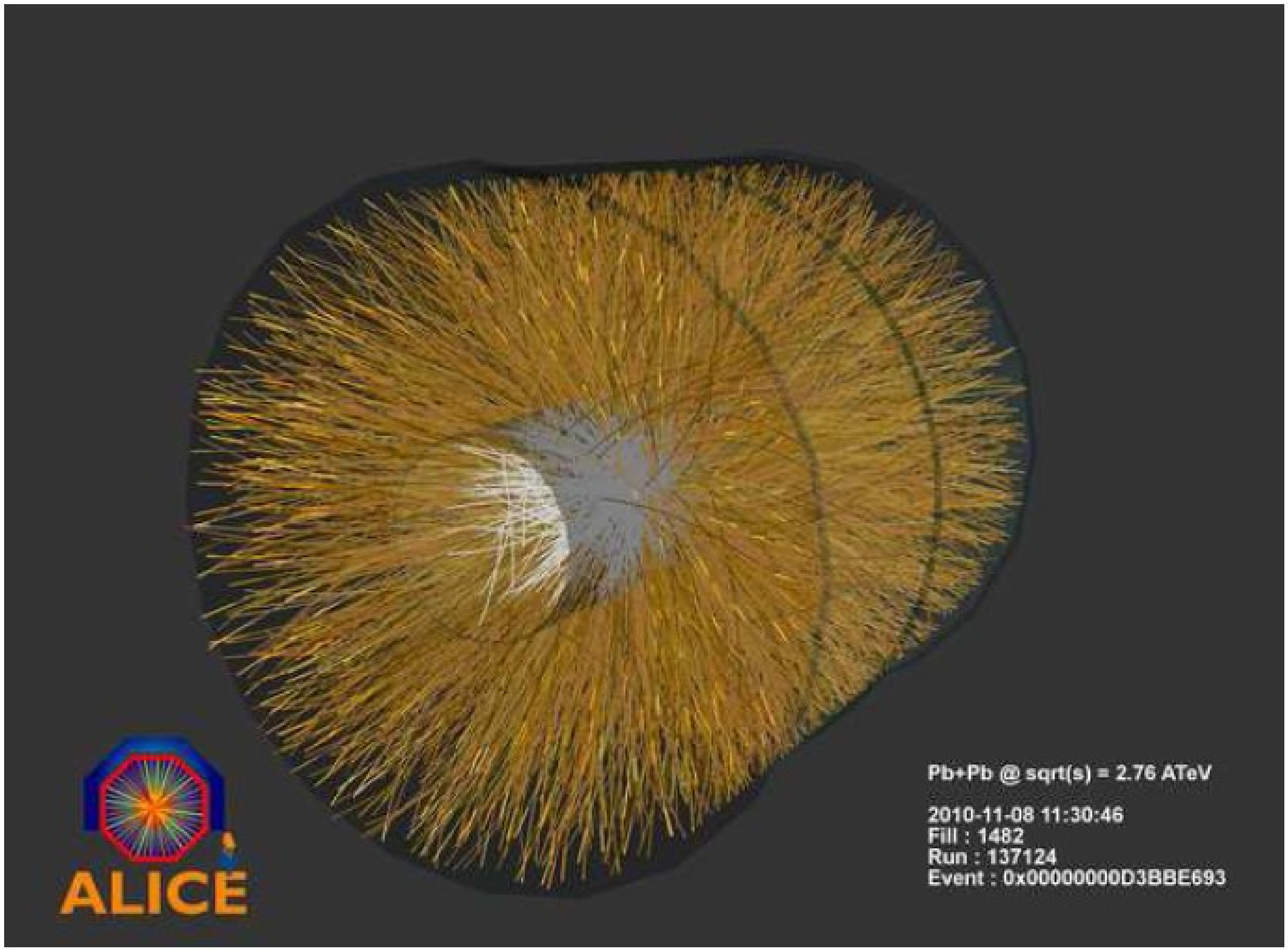
(and by many other details)
"canonical" mass: 1.4 M_{Sun}
(soft EoS around ρ_0)

how can the "outliers" exist?
...with stiffer EoS (at 2-3 ρ_0)

J.M. Lattimer, arXiv:1305.3510

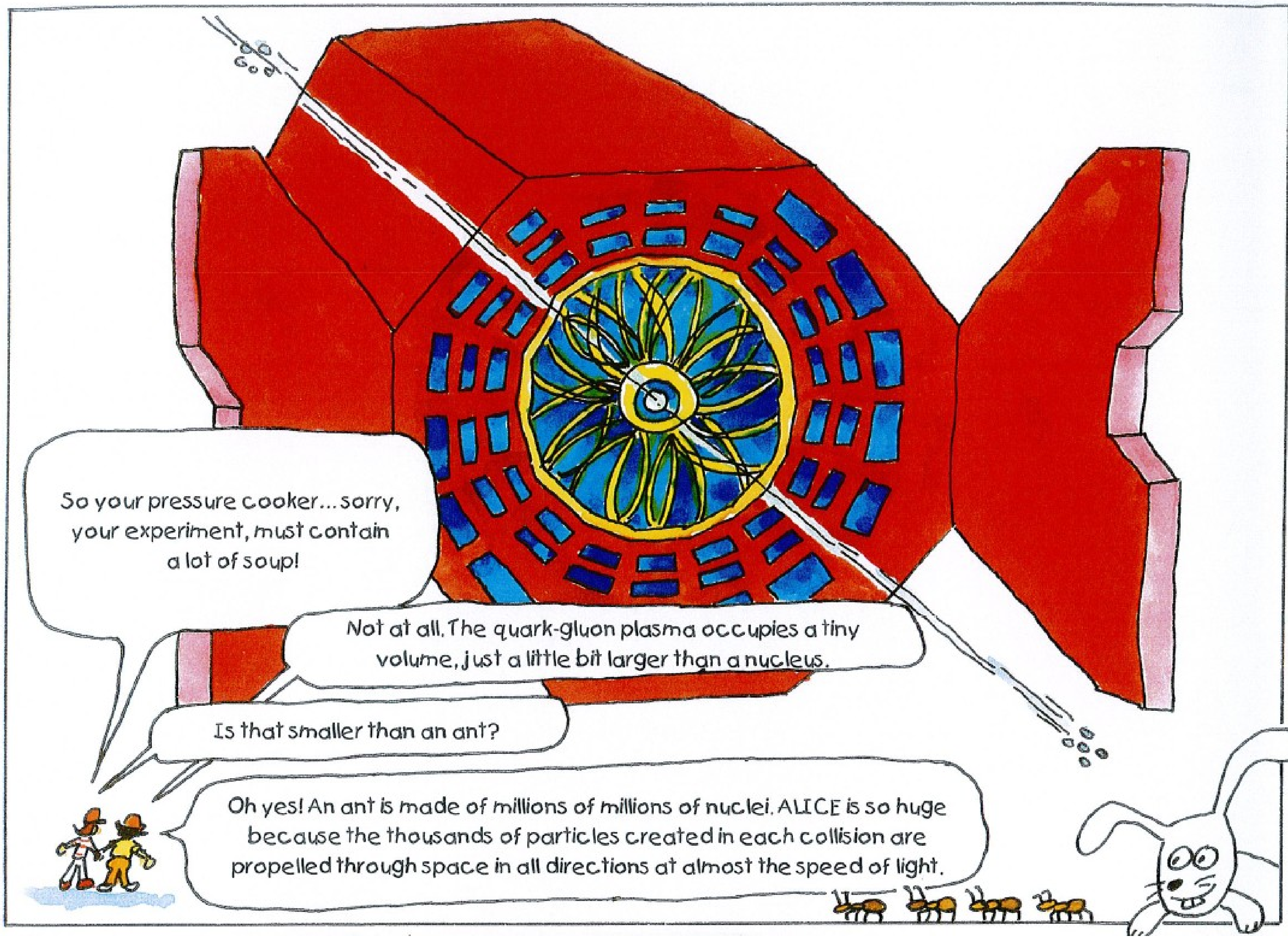


How to "measure" the early Universe in laboratory?

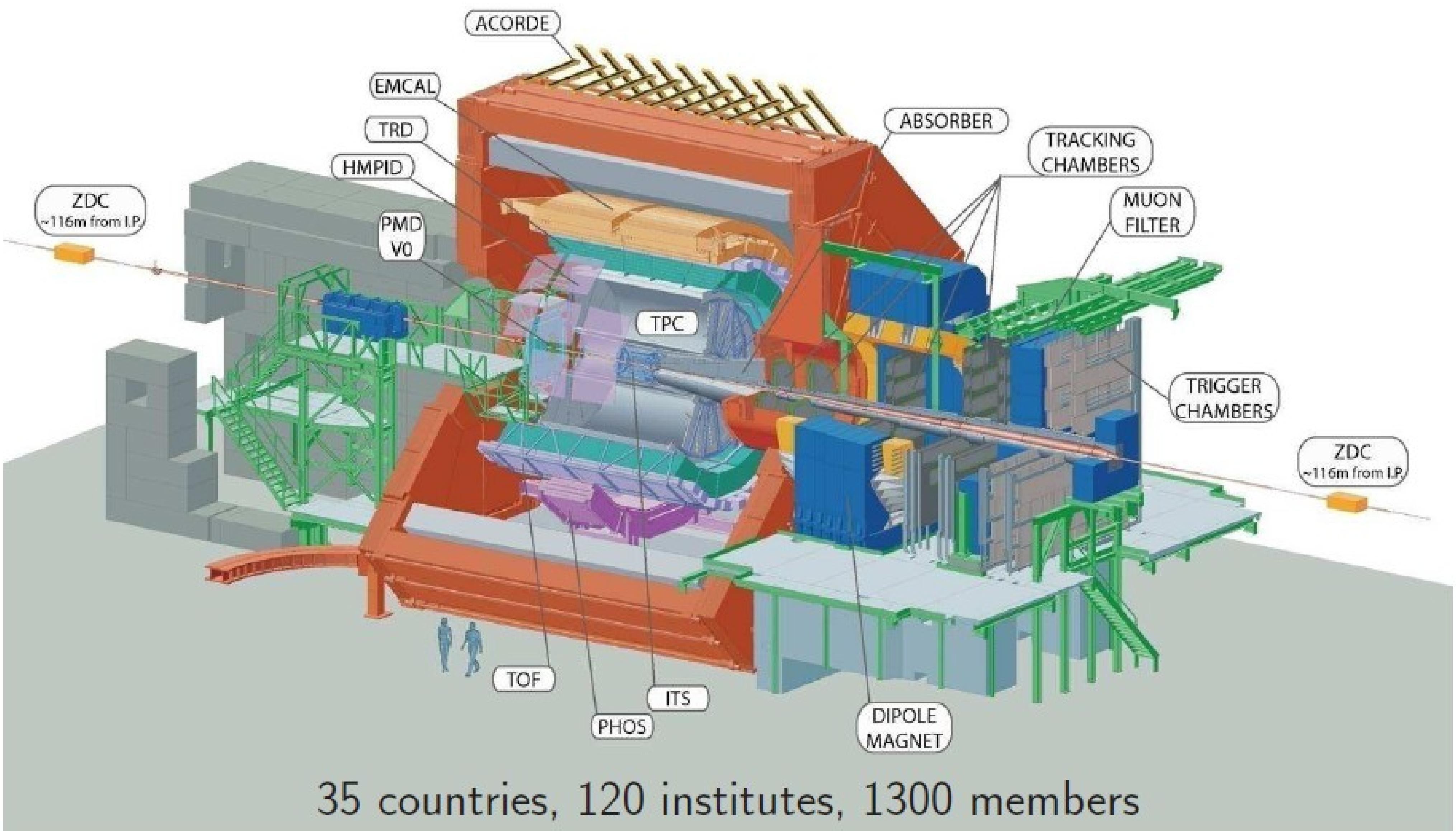


a picture (with 500 mil. pixels) of a central collision (about 3000 primary tracks)
we take millions of such "pictures" (events to be analyzed offline)

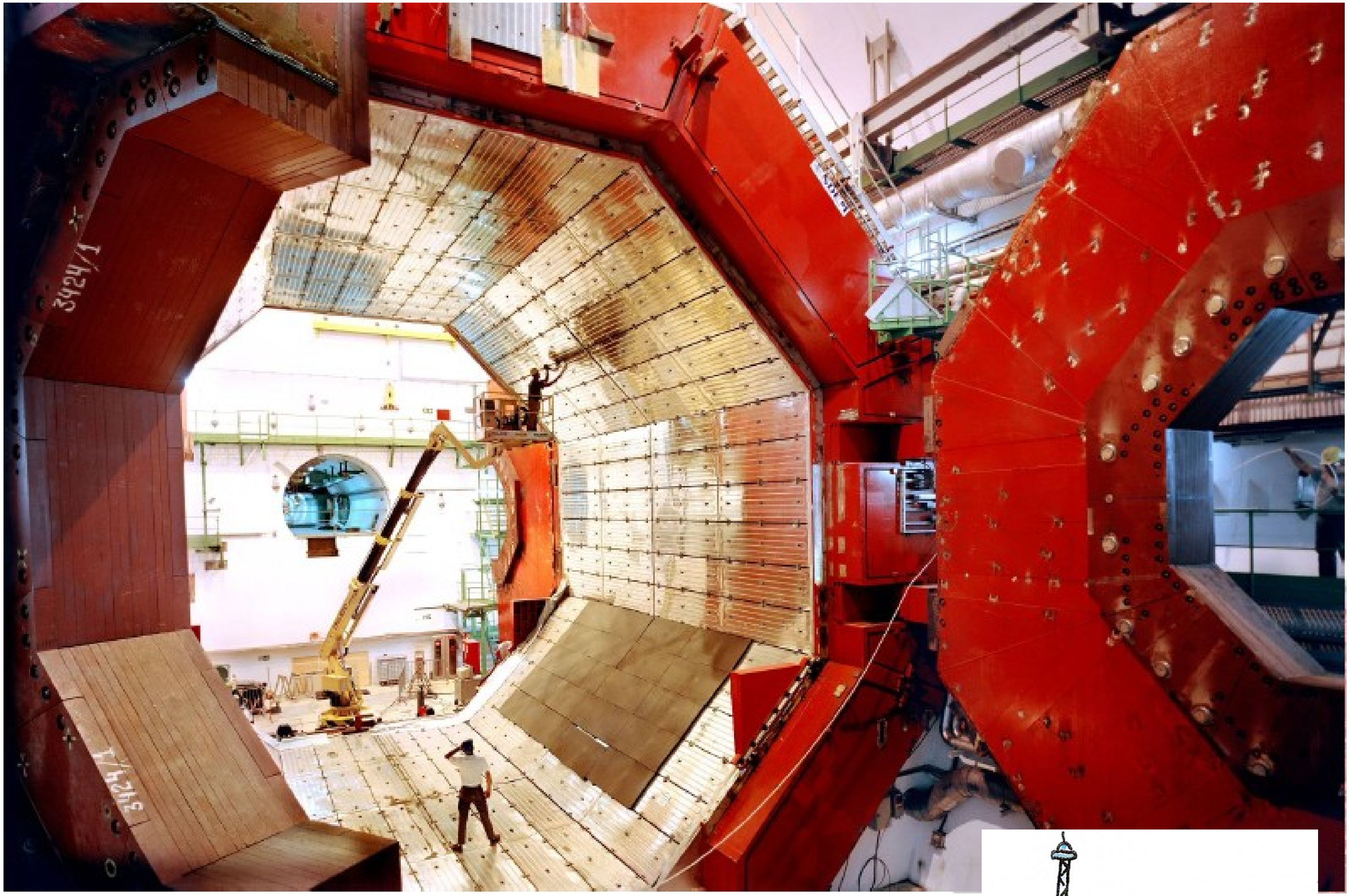
Part II: The ALICE apparatus

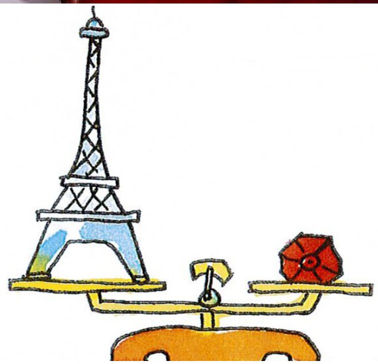


The ALICE experiment (LHC, CERN)



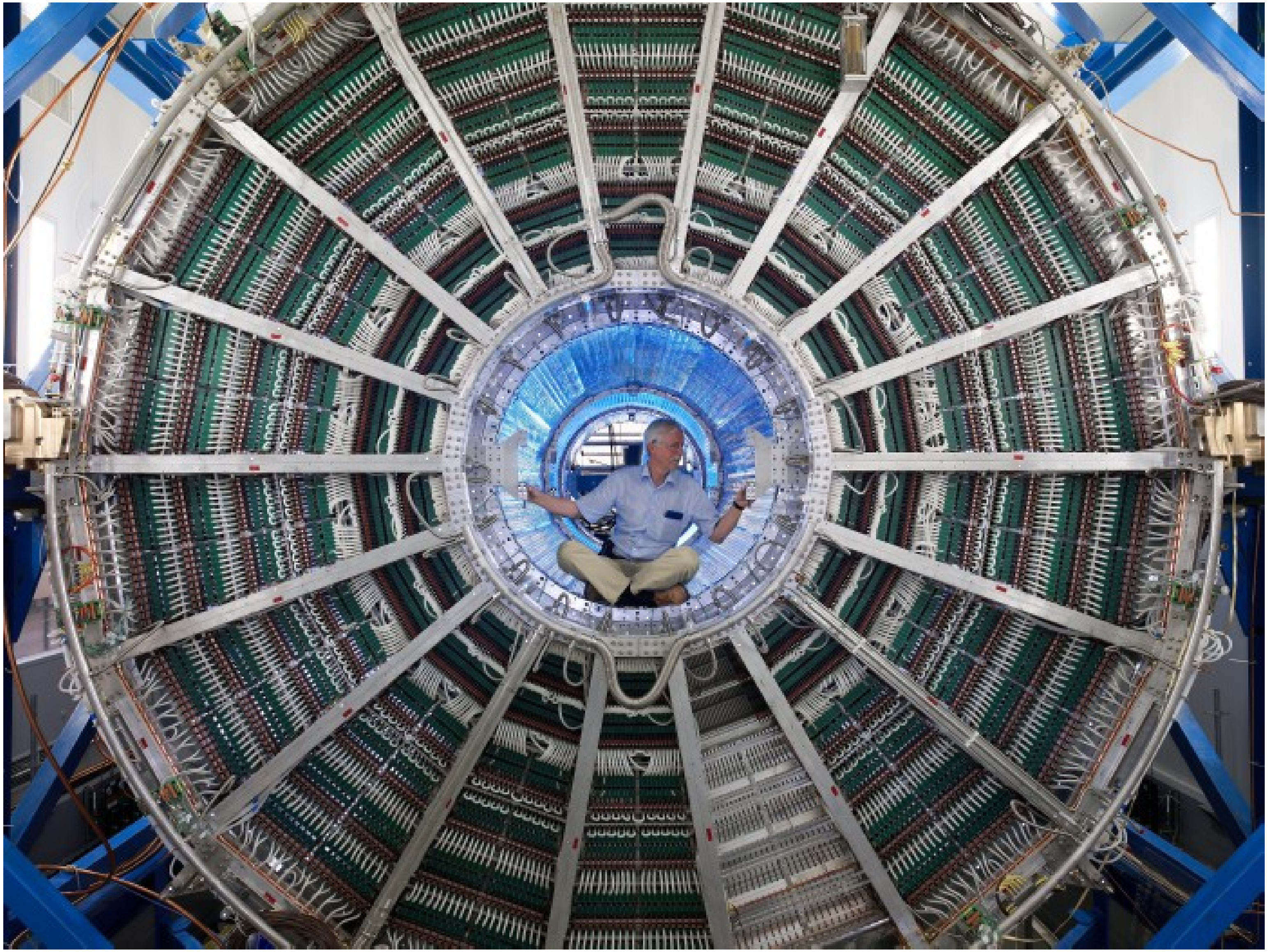
The L3 solenoid magnetic





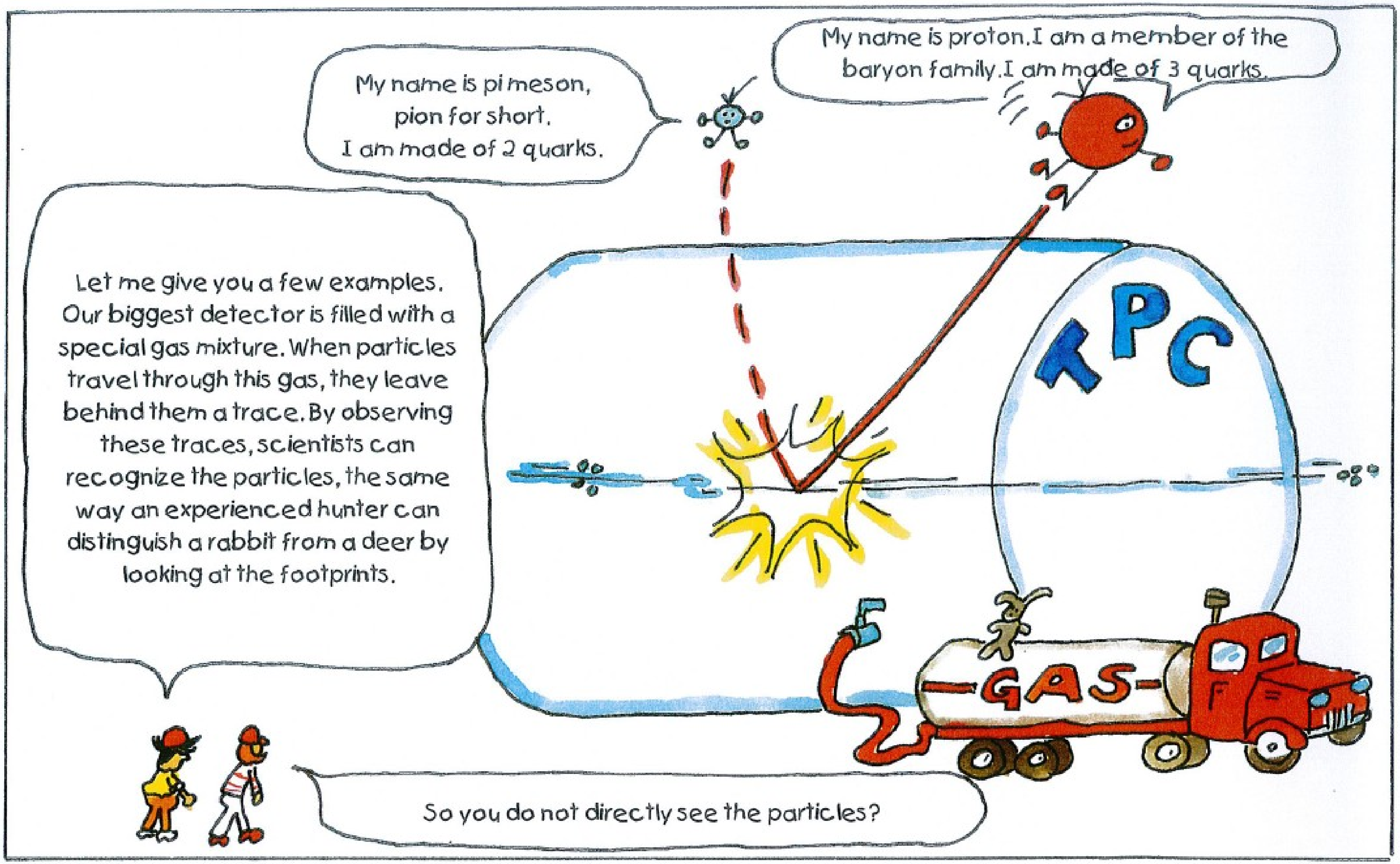
- It creates a uniform 0.5 T magnetic field
- As heavy as the Eiffel tower

The TPC

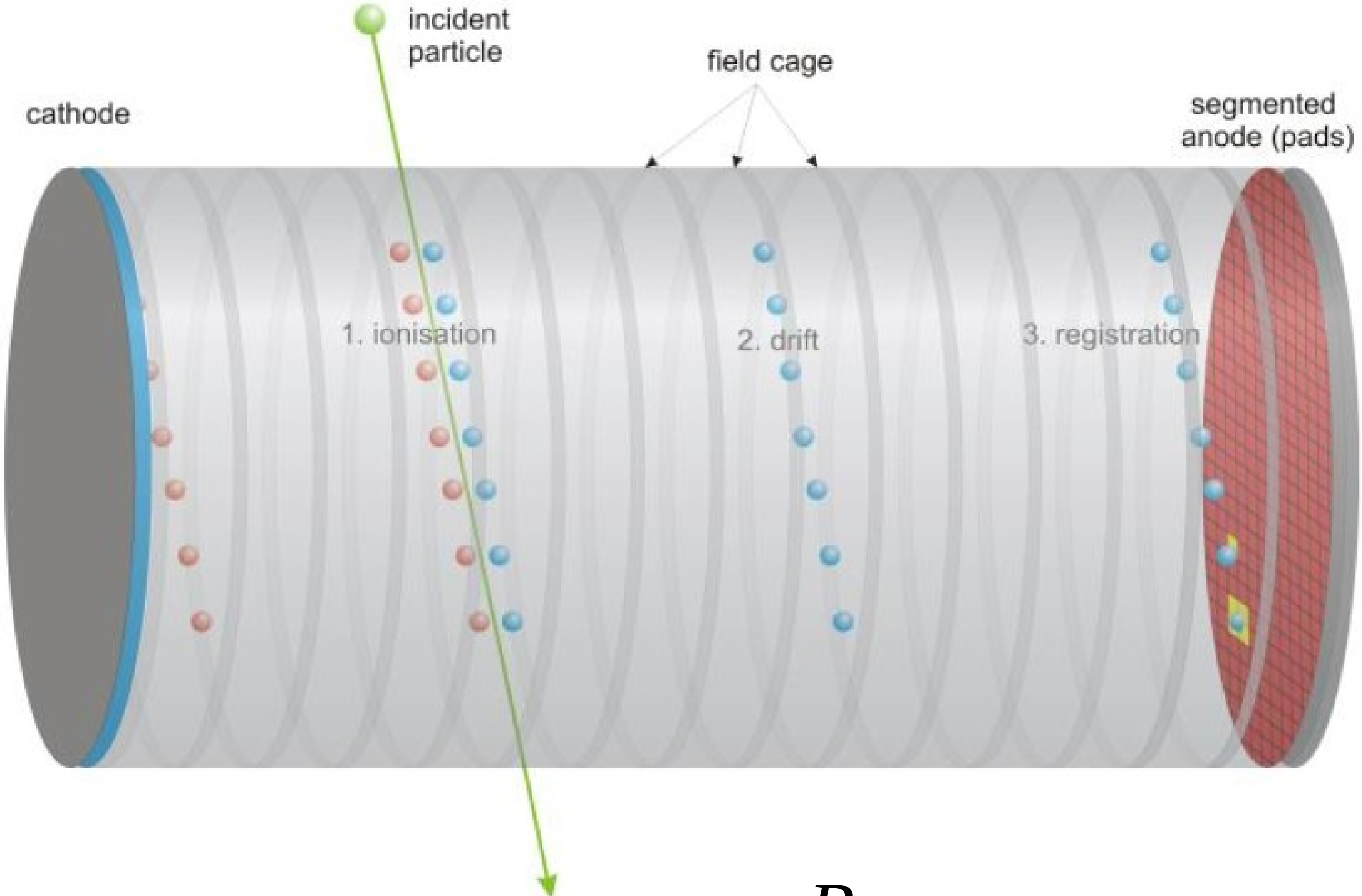


- The Time Projection Chamber is the main ALICE detector
- It is the largest TPC in the world
- 500 Mega-voxel 3D digital camera -> takes ca. 1000 pictures per second

TPC working principle

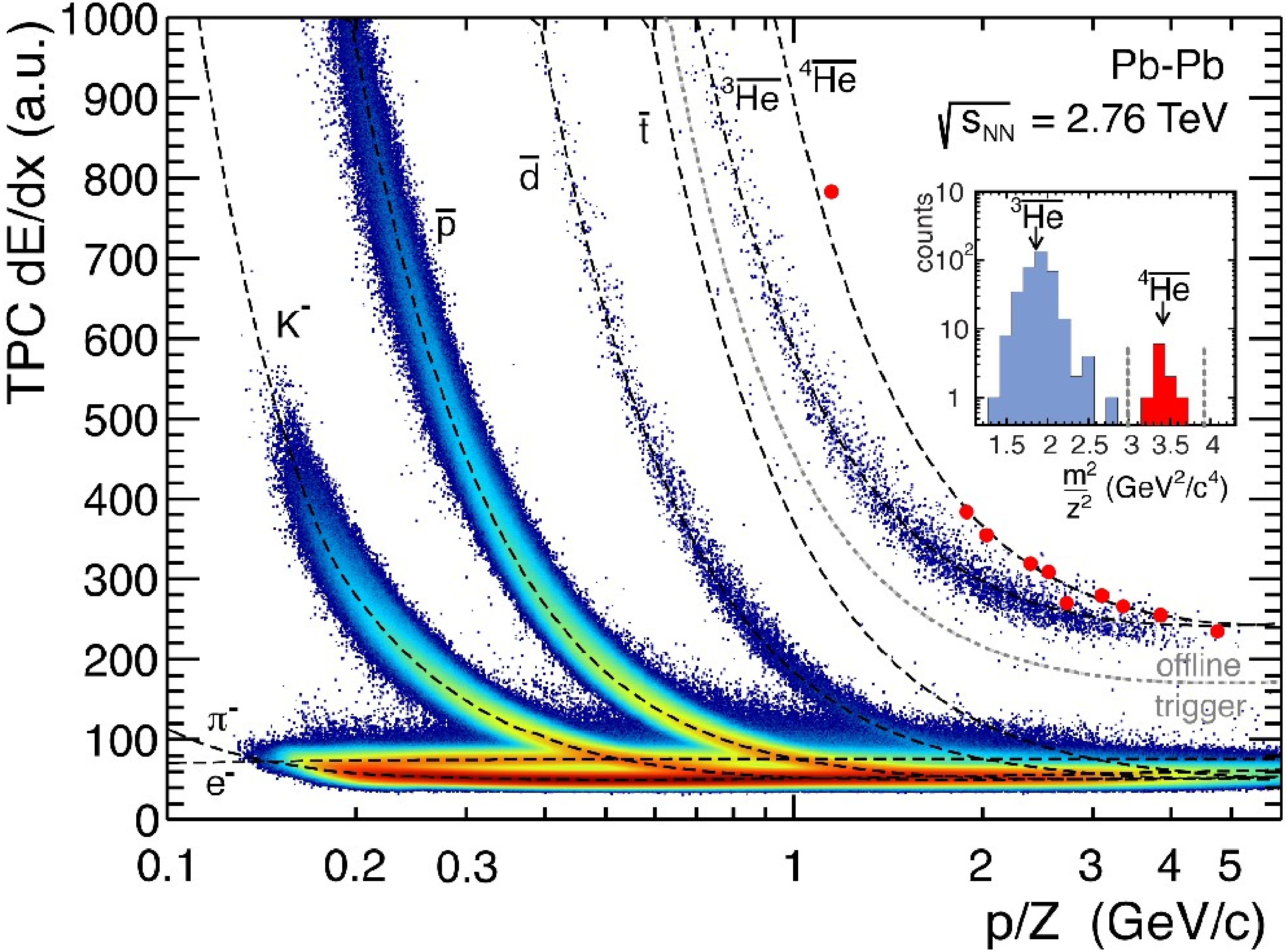


TPC working principle



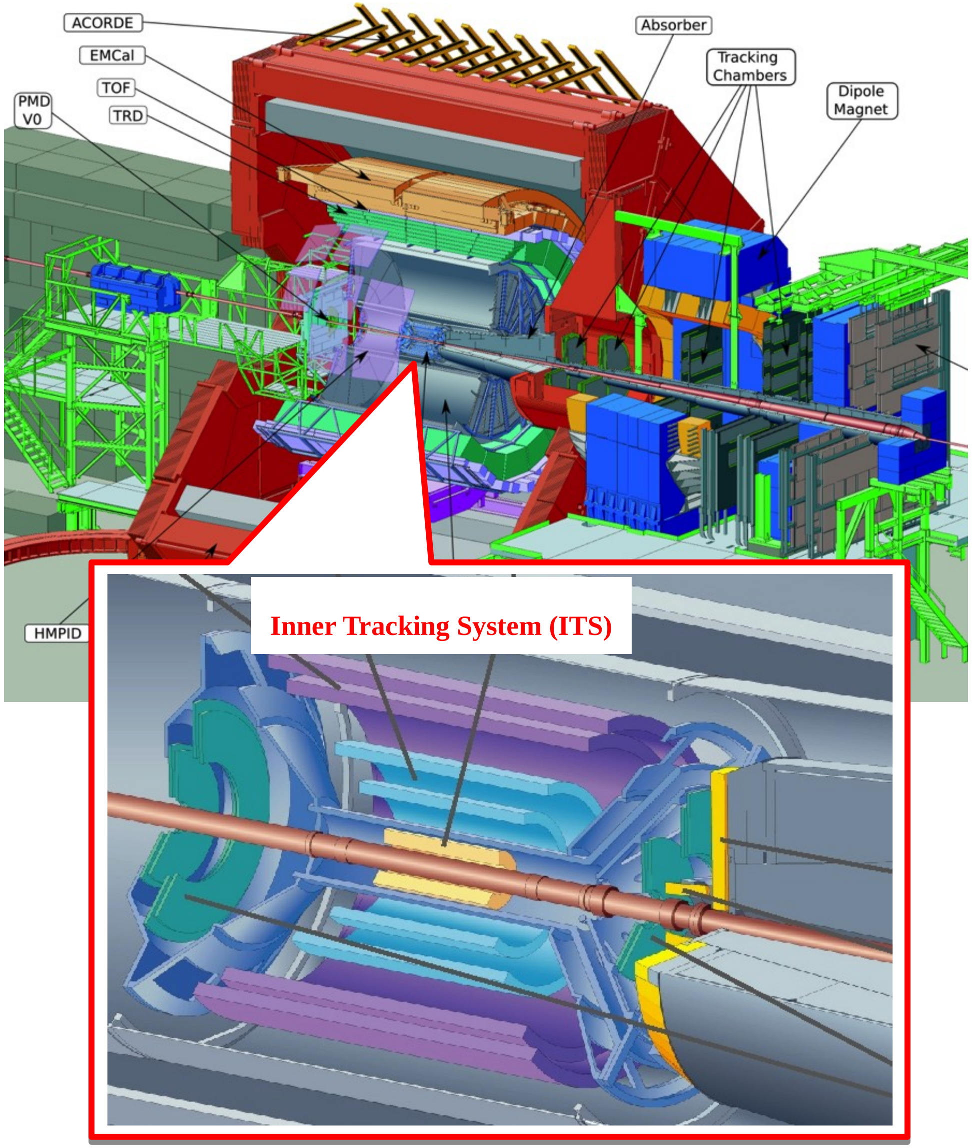
- Momentum measurement: $p_T = qBr$

Particle identification with TPC



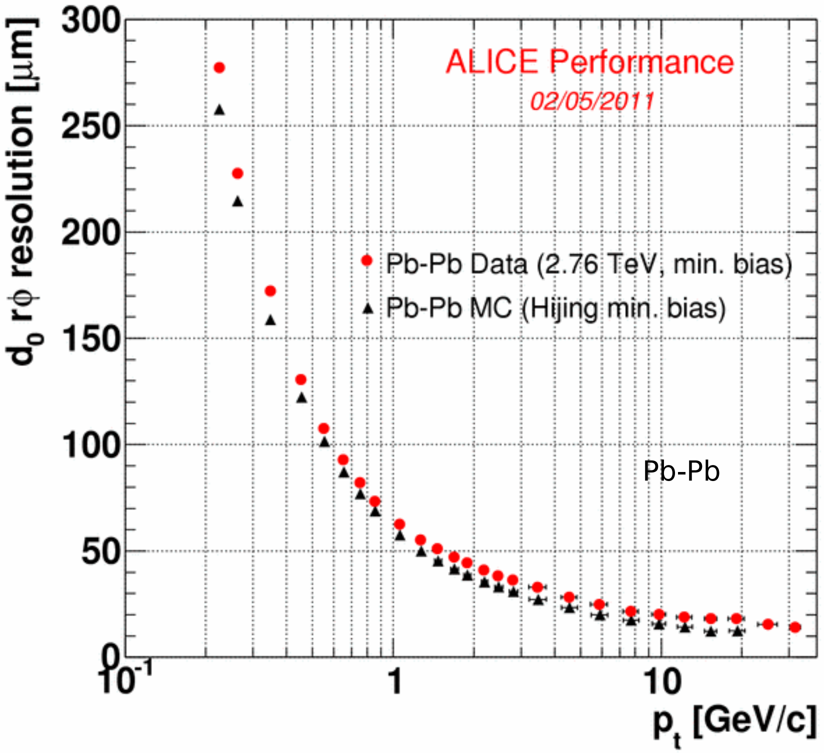
- Particles are identified using their specific energy loss in the TPC gas volume
- Highest mass anti-nuclei observed with the current data sample: anti-^{4}He

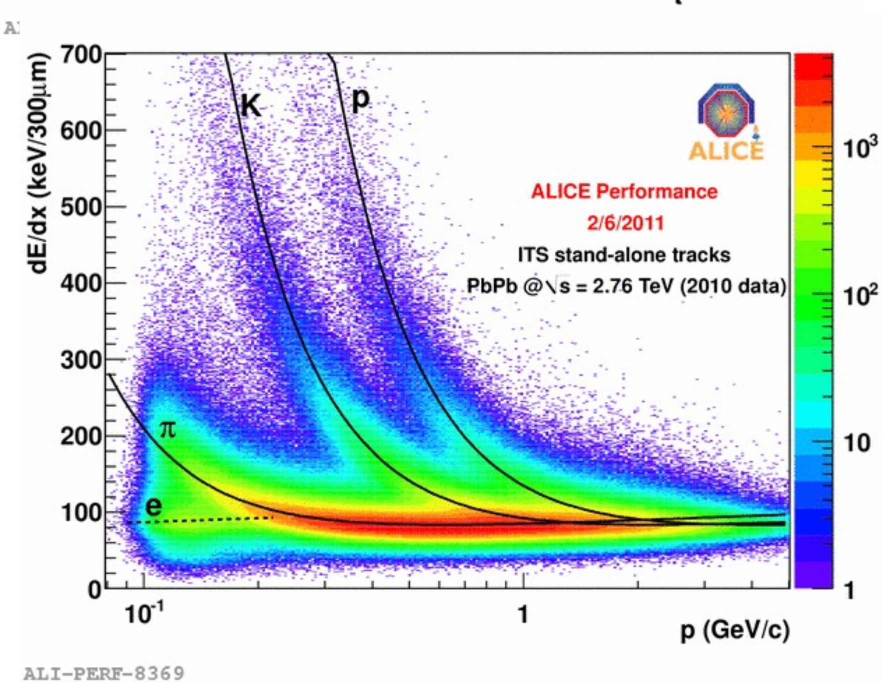
The Inner Tracking System (ITS)



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

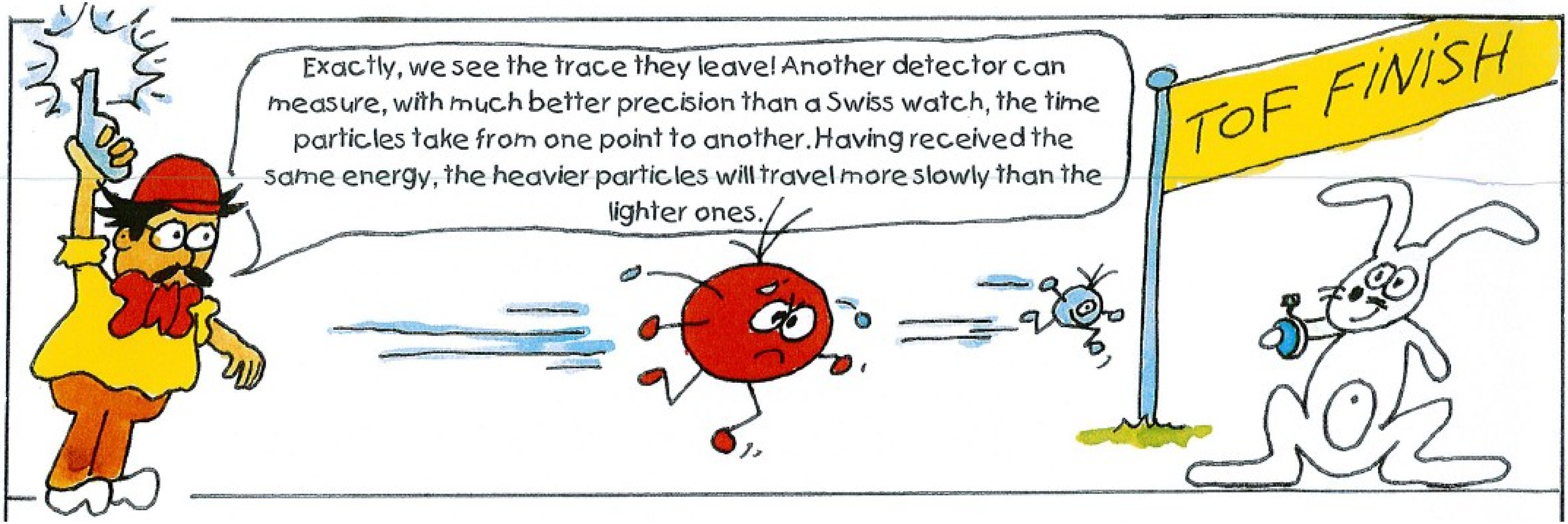
Inner Tracking System (ITS)



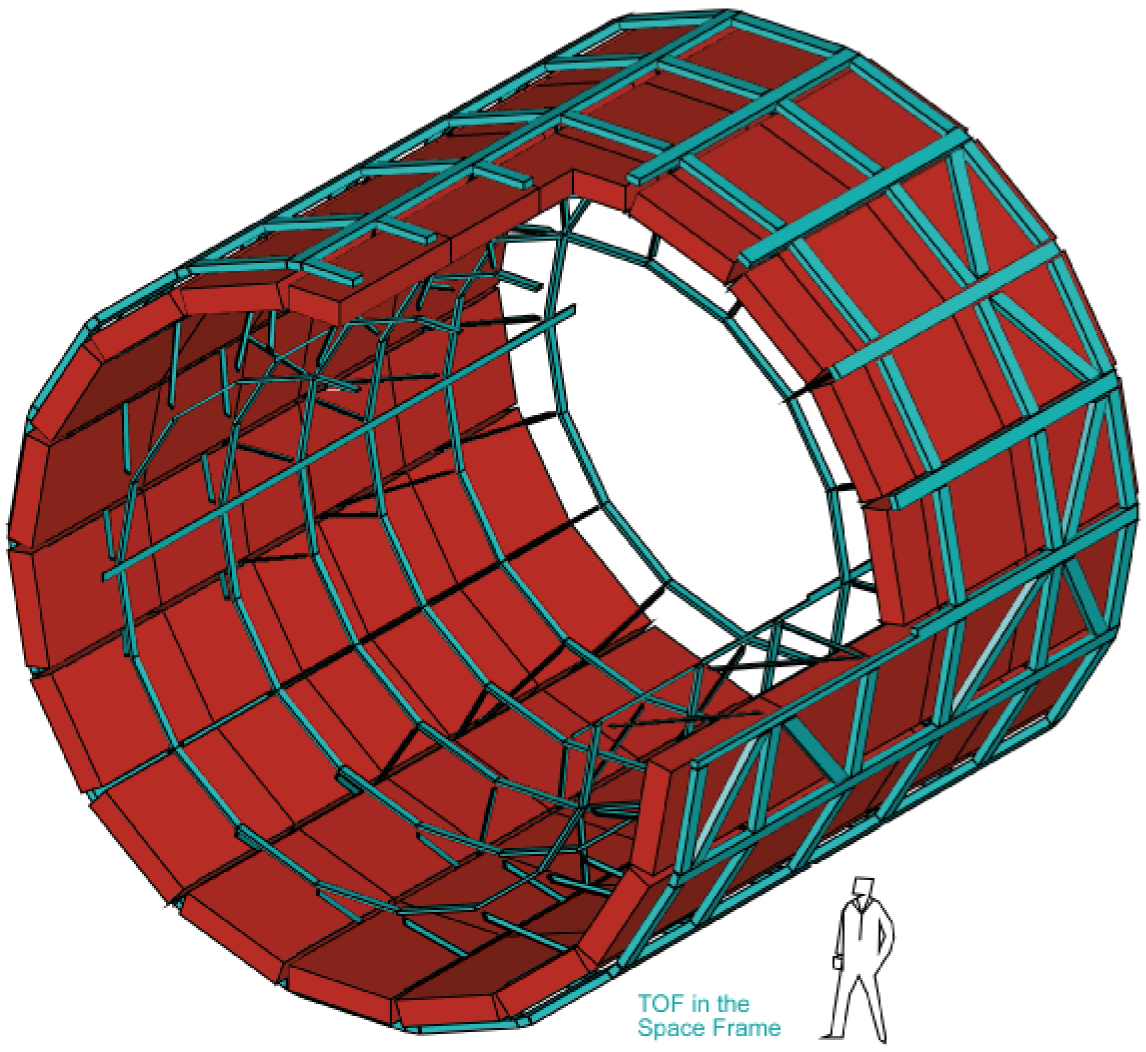


- 6 layers of silicon detectors with very high spatial resolution
  - Locates the collision vertex and secondary vertices from heavy quark decays
- It also performs particle identification via linear energy loss, but less precise than TPC

The Time-of-Flight detector (TOF)

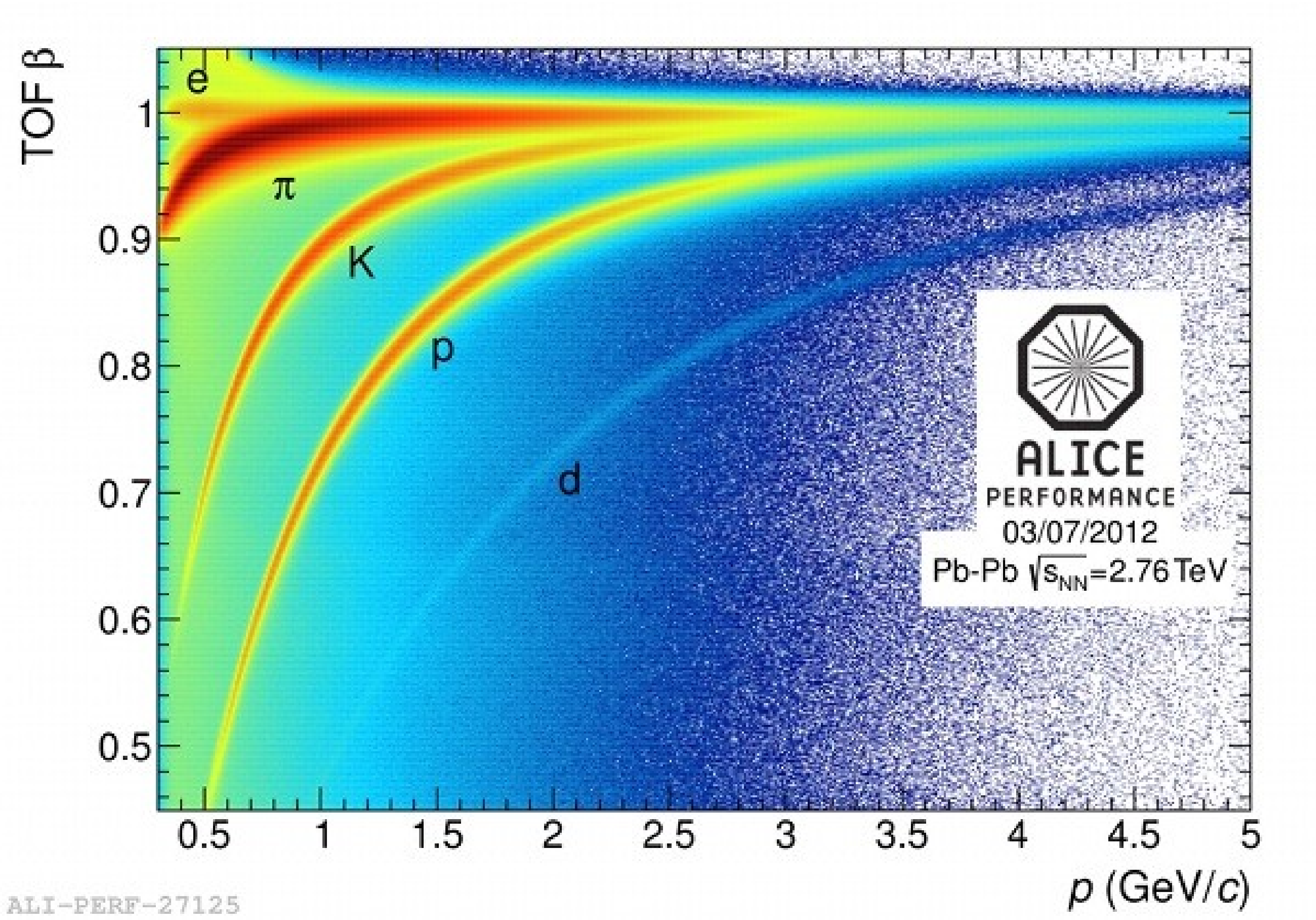


The Time-of-Flight detector (TOF)



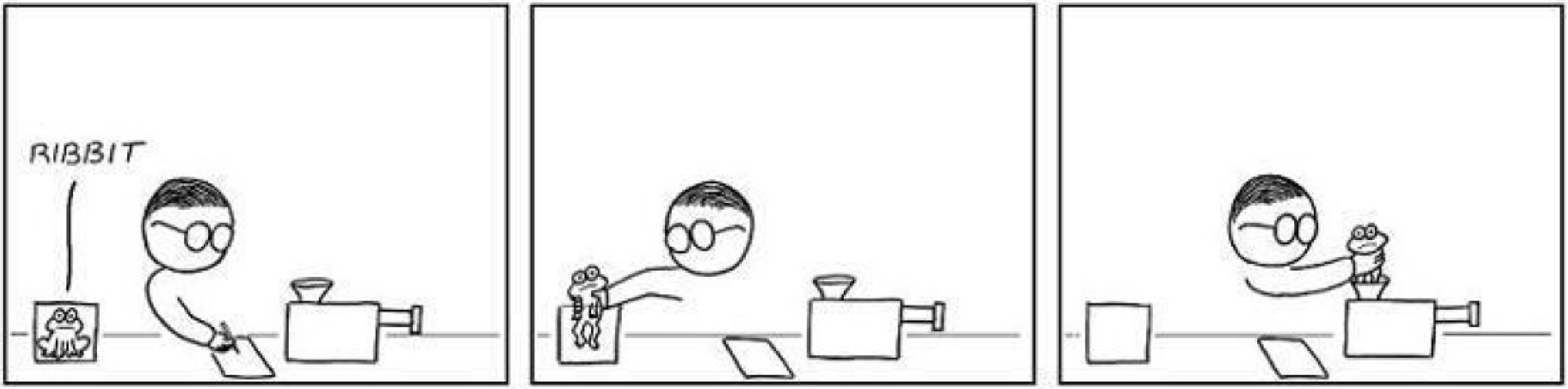
- Measures the time of flight between the collision start and arrival at the detector
- In conjunction with the momentum measurement from tracking -> particle identification
- Time resolution: 100 psec

Particle identification using TOF

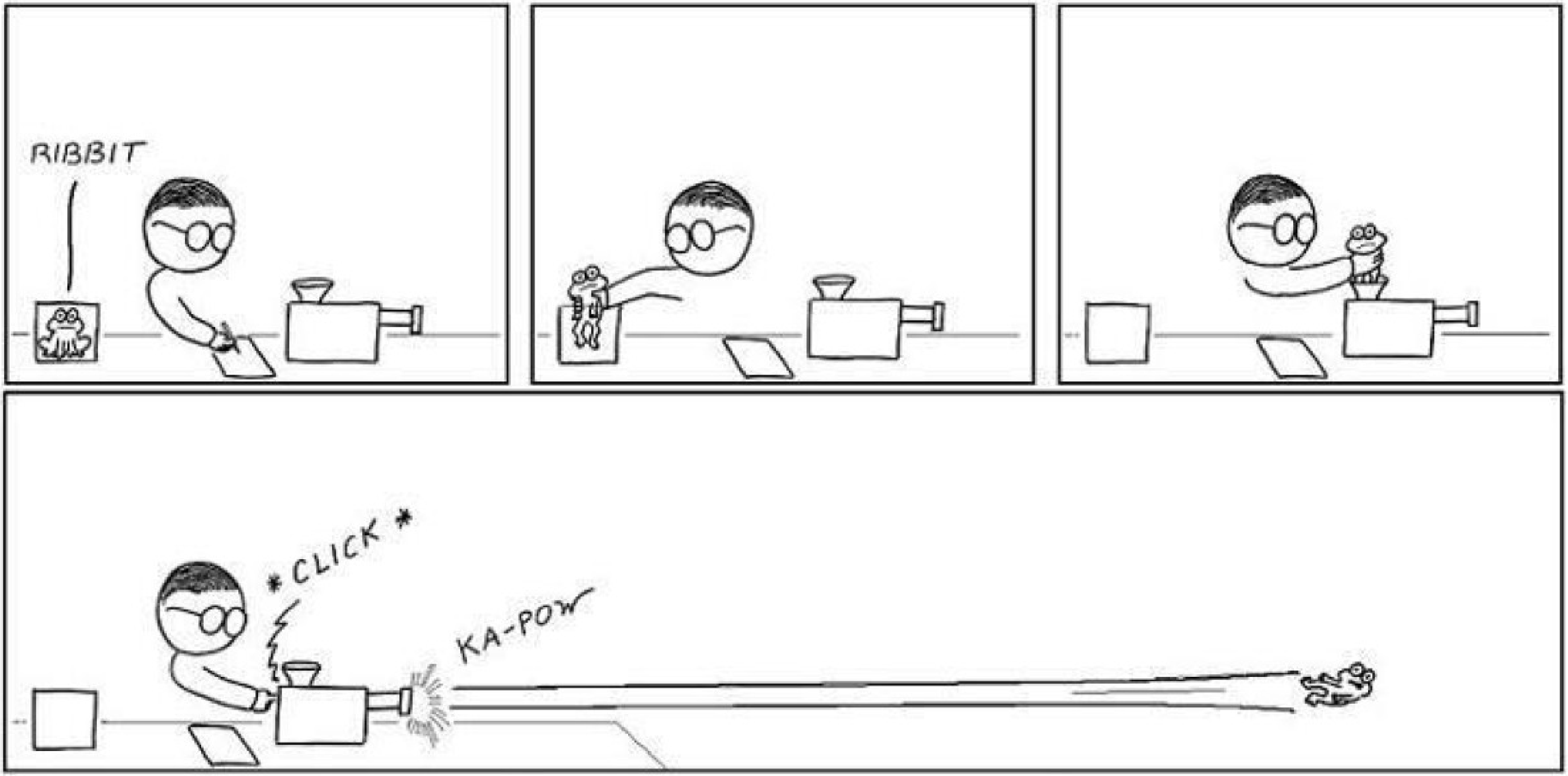


- Extends the particle identification of the TPC to higher momentum

In short...

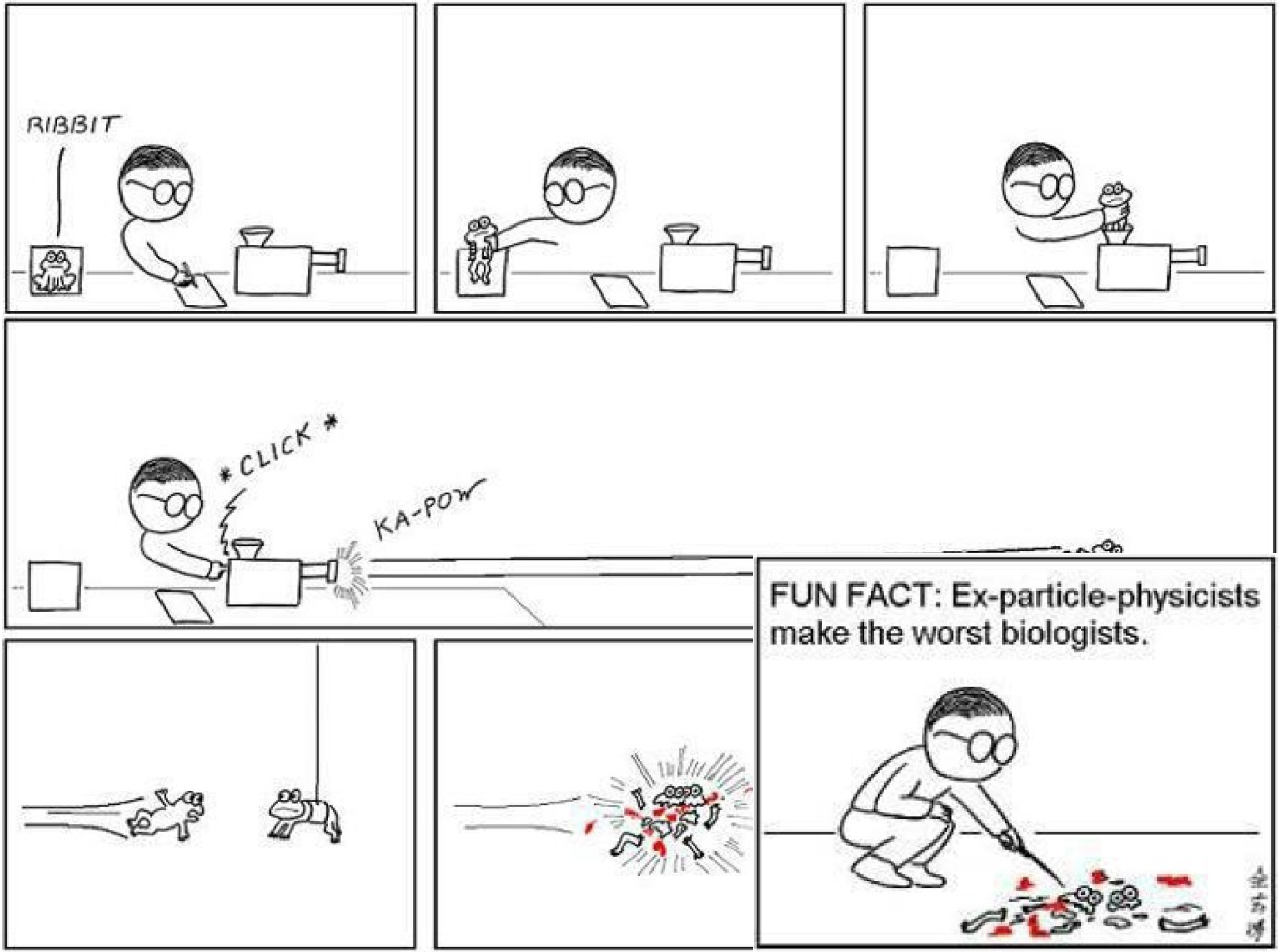


We carefully prepare the experiment ...

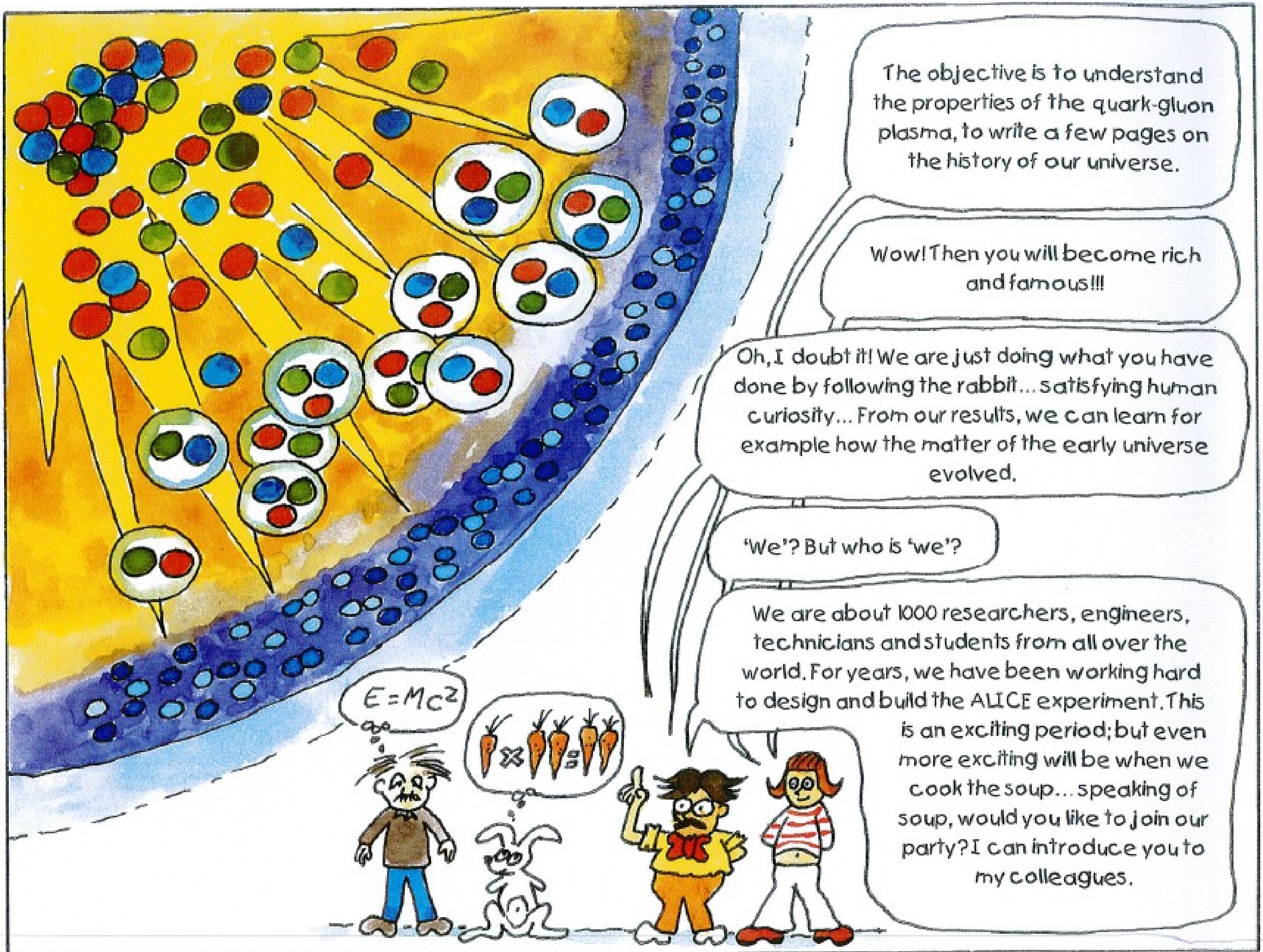


We accelerate the frogs, sorry nuclei.

Et voilà!!!

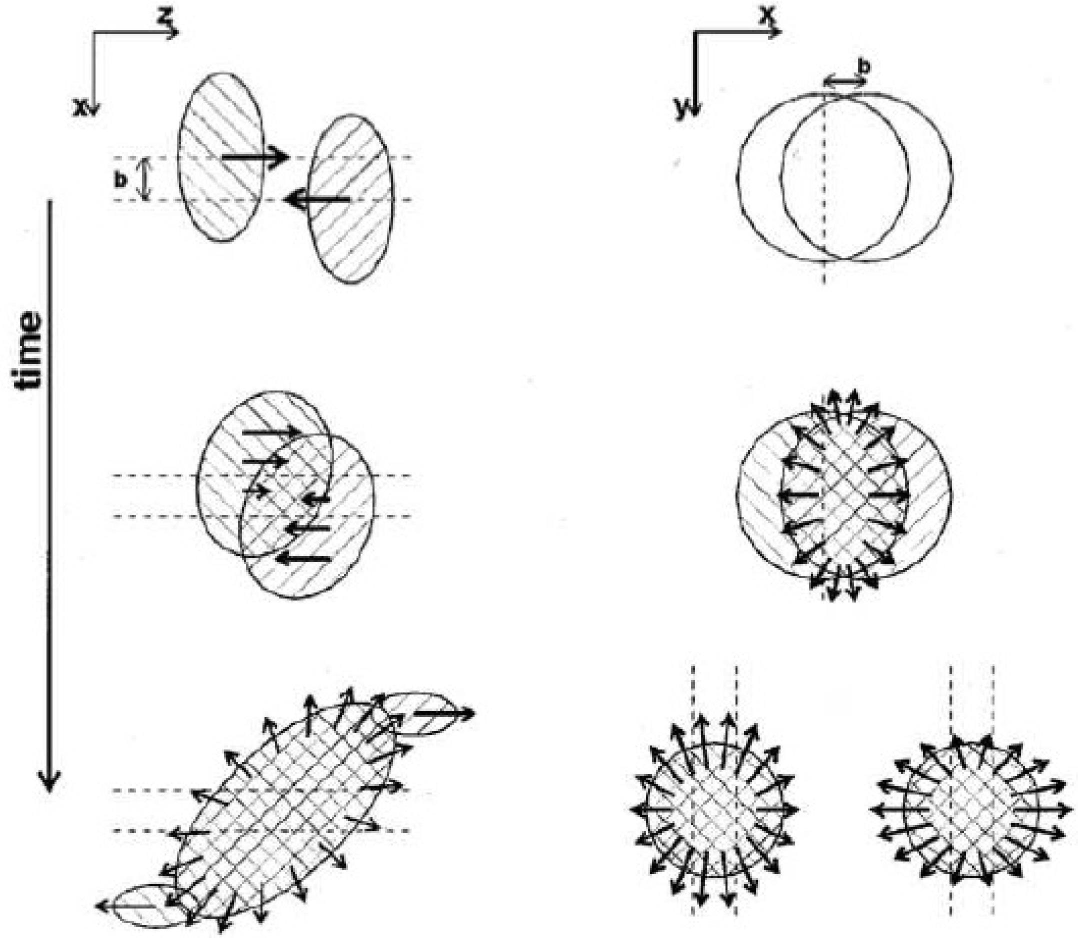

RIBBIT
CLICK
KA-POW
FUN FACT: Ex-particle-physicists make the worst biologists.

Part III: Global properties of QGP



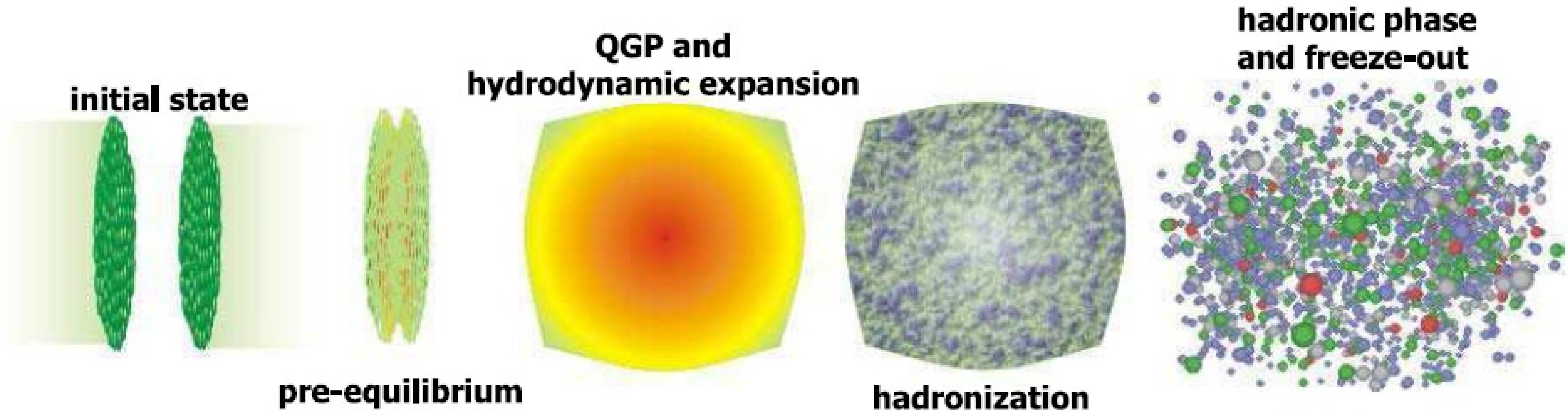
Concepts: participants and spectators

in AA collisions at high energies geometric concepts are applicable



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

Stages of a high-energy nucleus-nucleus collision



1. initial collisions ($t \leq t_{coll} = 2R/\gamma_{\rm cm}c$)
2. thermalization: equilibrium is established ($t \lesssim 1$ fm/c)
3. expansion and cooling ($t <$ 10-15 fm/c)
4. hadronization (quarks and gluons form hadrons)
5. chemical freeze-out: inelastic collisions cease; yields are frozen
6. kinetic freeze-out: elastic collisions cease; spectra are frozen ($t+ =$ 3-5 fm/c)

we measure at stages 5. and 6. want to know properties of 2.+3.

What conditions can be achieved?

(extracted from data and models)

Temperature: T=100-1000 MeV or up to a million times T at Sun's center;
1 MeV$\simeq$10 billion degrees

Pressure: P=100-300 MeV/fm^3 (1 MeV/fm^3 $\simeq 10^{28}$ atmospheres)
center of Earth: 3.6 million atm

Density: ρ=1-10ρ_0 ρ_0 density of a Au <u>nucleus</u>=2.7$\times 10^{14}$ 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$\times 10^{-23}$ s)

trully "extreme" ...a femto-world

What are the "control parameters"

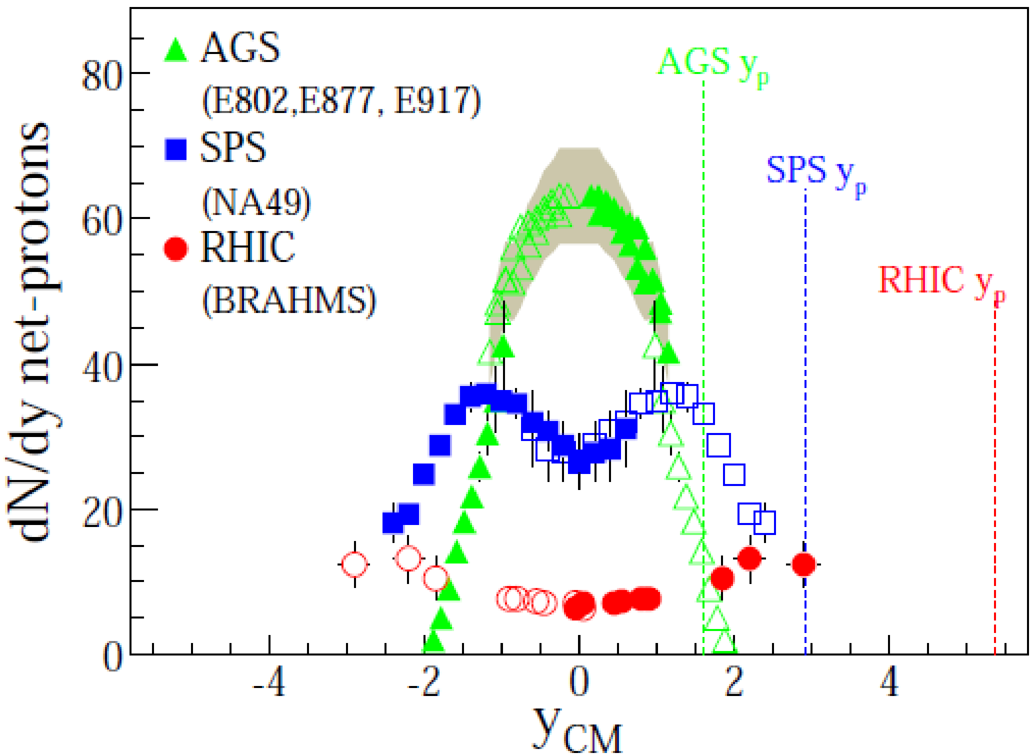
- Energy of the collision (per nucleon pair, $\sqrt{s_{NN}}$)
- Centrality of the collision (number of "participating" nucleons, N_{part}) measured in percentage of the geometric cross section ($\sigma_{geom} = \pi(2R)^2$) (i.e. 0-10% most central)

not all beam(s) energy is spent

...quantified by nuclear stopping net proton ($N_p - N_{\bar{p}}$) counting

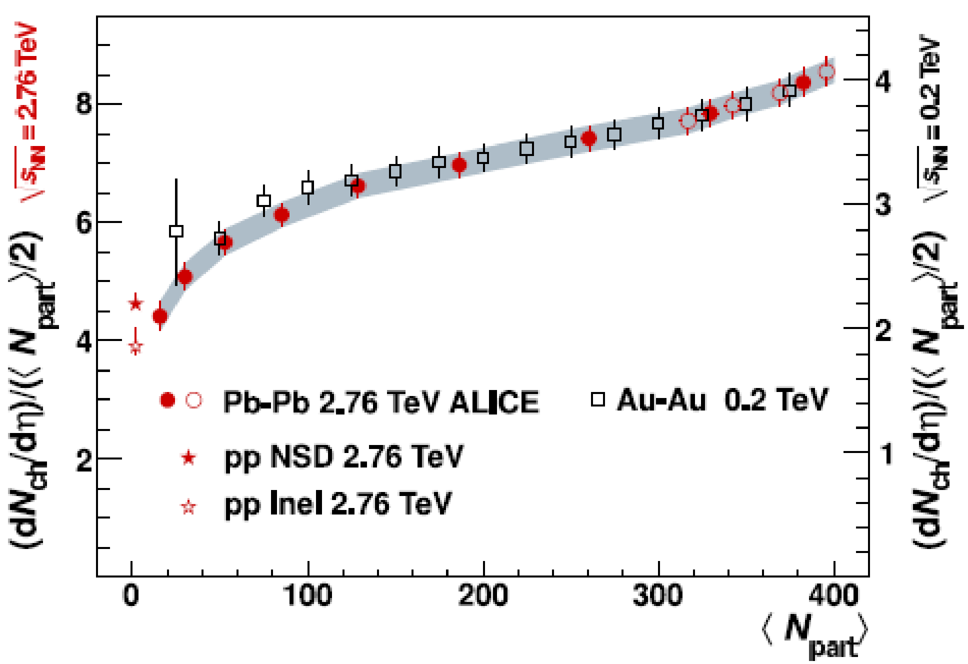
Brahms collaboration, Phys. Rev. Lett. 93, 102301 (2004) [arXiv:nucl-ex/0312023]

from now on we mostly discuss y_{CM} around 0 (mid-rapidity)



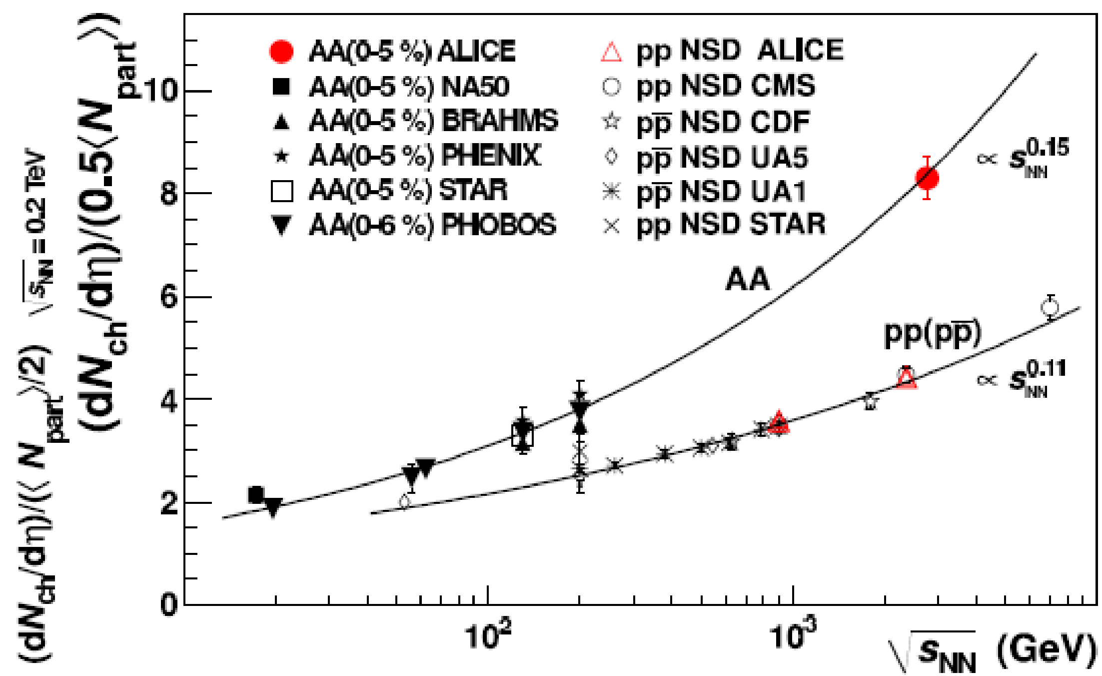
Global properties: particle production in the LHC era

N_{ch} "scaling" with N_{part}



ALICE collab., arXiv:1012.1657

dN_{ch}/dy at mid-y: power law vs. $\sqrt{s_{NN}}$

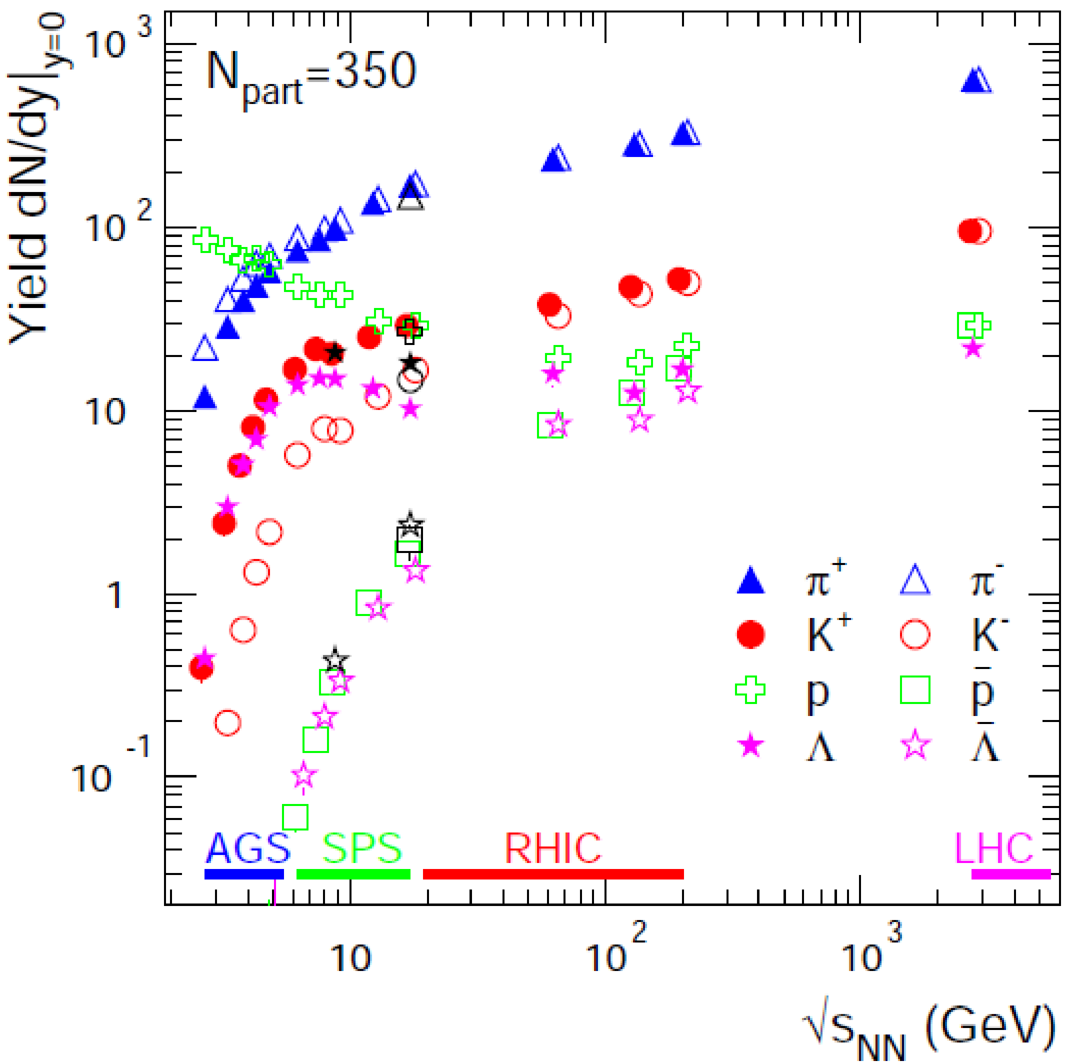


ALICE collab., arXiv:1011.3914

clearly, particle production is different in AA than in pp

Chemical freeze-out: hadron yields (central collisions)

lots of particles, mostly newly created ($m = E/c^2$)



- a great variety of species:

  $\pi^{\pm}$ $(u\bar{d},\ d\bar{u})$, m=140 MeV
  $K^{\pm}$ $(u\bar{s},\ \bar{u}s)$, m=494 MeV
  p (uud), m=938 MeV
  Λ (uds), m=1116 MeV
  also: $\Xi(dss)$, $\Omega(sss)$...

- mass hierarchy in production (at low en.: u, d quarks remnants from the incoming nuclei)

- chemistry explained by thermal model

  with 3 parameters: T, μ_b, V

Thermal fits of hadron abundances

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

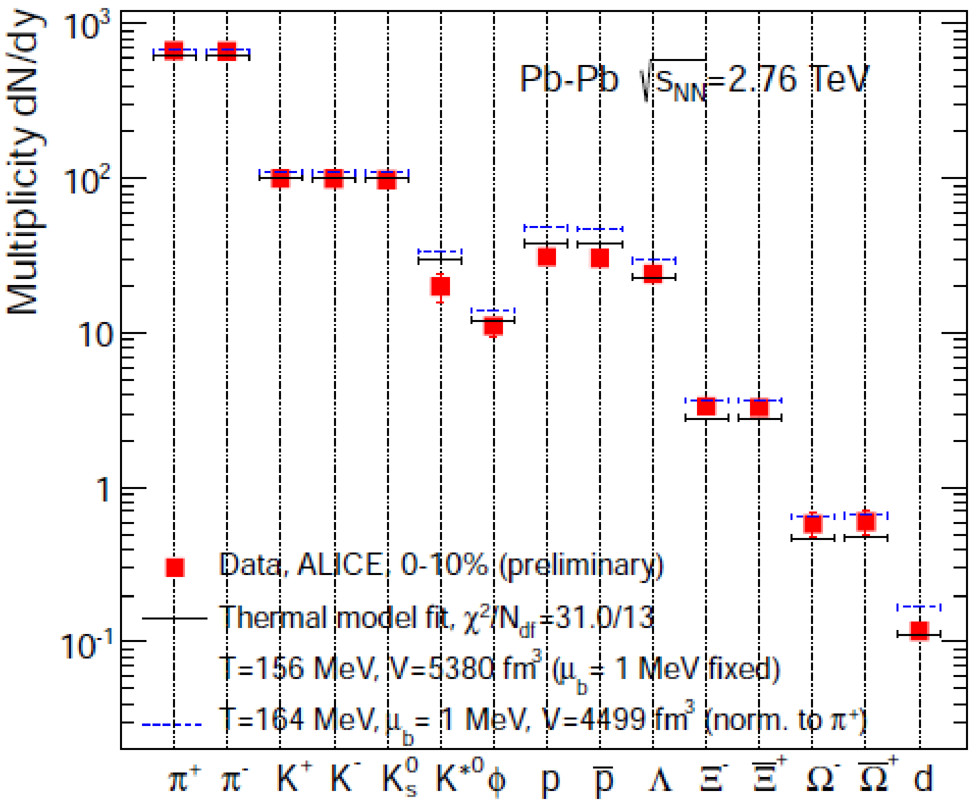
quantum nr. conservation:

$$\mu_i = \mu_b B_i + \mu_{I_3} I_{3i} + \mu_S S_i + \mu_C C_i$$

Latest PDG hadron mass spectrum (up to 3 GeV, 485 species)

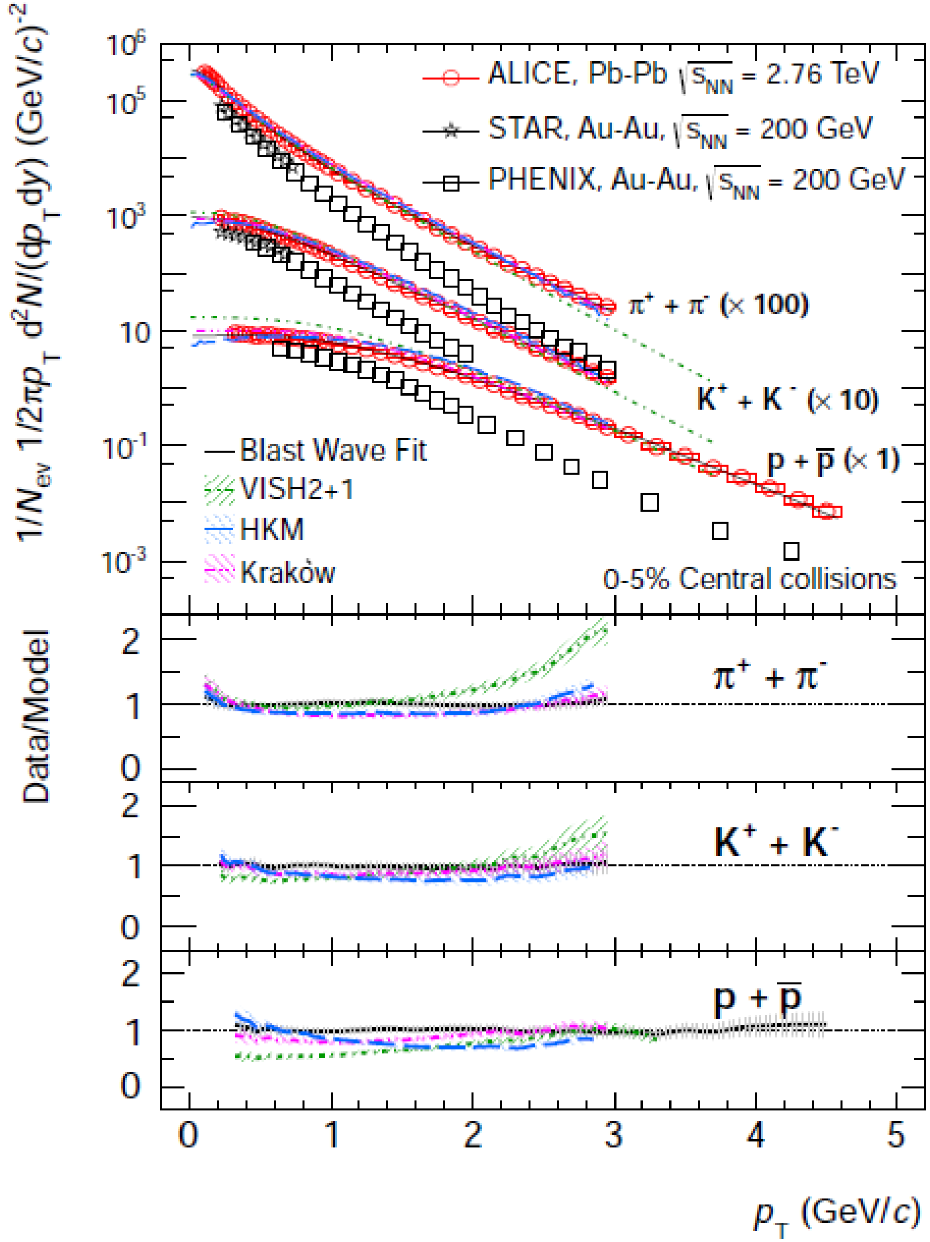
Minimize: $\chi^2 = \sum_i \frac{(N_i^{exp} - N_i^{therm})^2}{\sigma_i^2}$

N_i: hadron yield $\Rightarrow (T, \mu_b, V)$



The hadron abundances are in agreement with a thermally equilibrated system

...and the last stage, kinetic freeze-out: hadron spectra



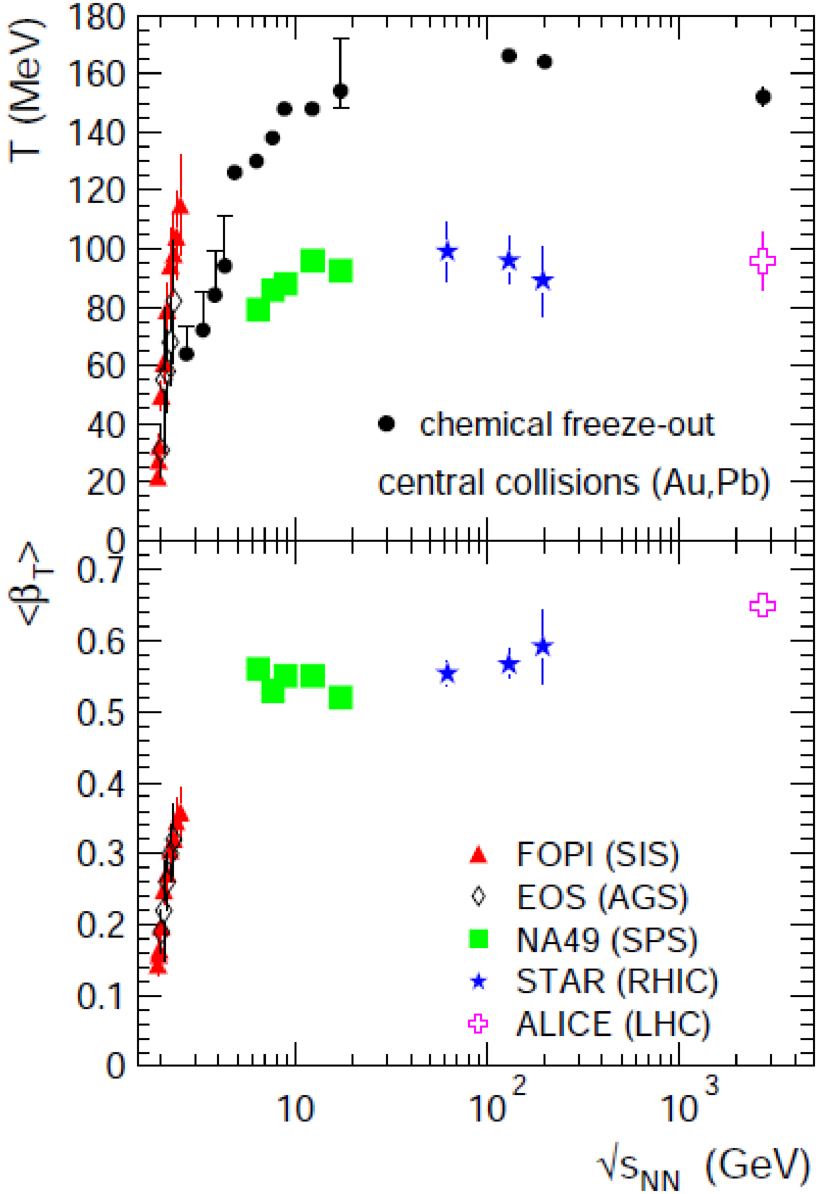
ALICE, PRL 109 (2012) 252301

at LHC spectra are harder than at RHIC ($\sqrt{s_{\rm NN}} = 200$ GeV)

mass dependence indicates collective flow

hydrodynamic models (VISH2+1, HKM, Krakow) reproduce the data with a very small ratio viscosity/entropy density

Collective flow in central collisions



Fit with "Blast wave" model ("hydro-like"):

$$\frac{1}{p_T} \cdot \frac{\mathrm{d}N}{\mathrm{d}p_T} \sim m_T \cdot I_0\left(\frac{p_T \sinh y_T}{T}\right) \cdot K_1\left(\frac{p_T \cosh y_T}{T}\right),$$

$$m_T = \sqrt{m_0^2 + p_T^2}, \qquad y_T = \tanh^{-1}(\beta)$$

Schnedermann et al., Phys. Rev. C 48 (1993) 2462

T = temperature (kinetic freeze-out)

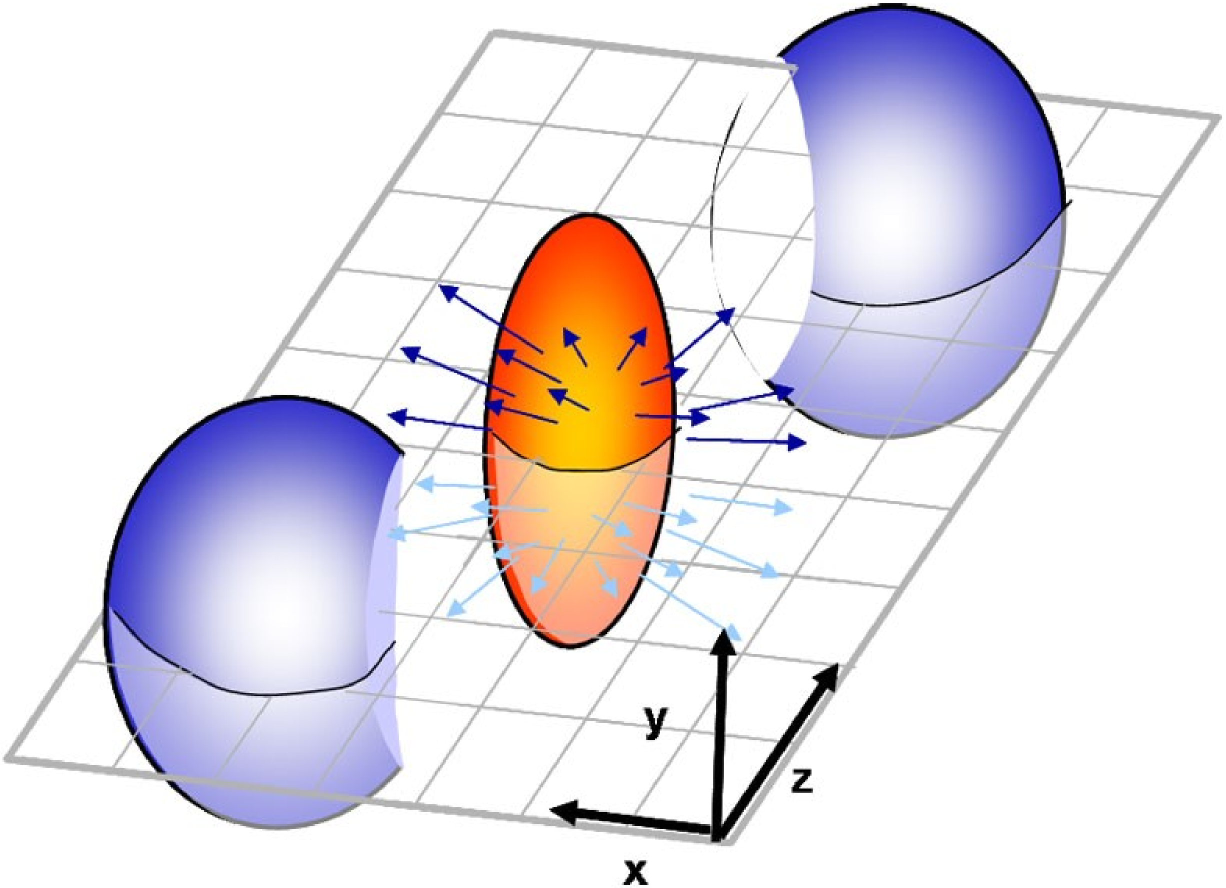
$\langle \beta_T \rangle$ = collective (average) velocity (QGP and hadronic stages)

hadrons (with light quarks) flow with a collective velocity up to 65% c

AA, arXiv:1210.8126

onset at SIS18 (GSI) energies

Hadron correlations: elliptic flow (v_2)



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

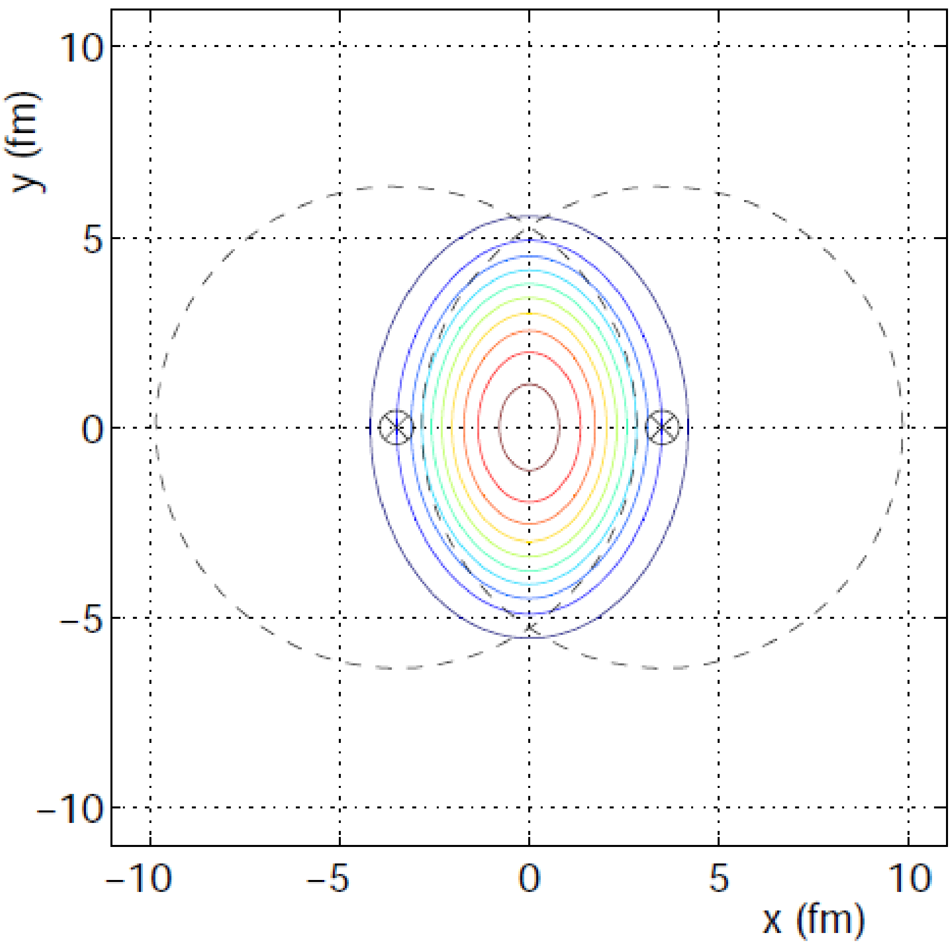
ϕ = azimuthal angle with respect to reaction plane,

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

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

Elliptic flow (non-central collisions)

density of binary collisions
U.Heinz, arXiv:0901.4355



...arising from different initial gradients along x and y

"self-quenching" (develops early)

determined by the spatial eccentricity

$$\varepsilon(b) = \frac{<y^2 - x^2>}{<y^2 + x^2>}$$

with energy dens. as weight

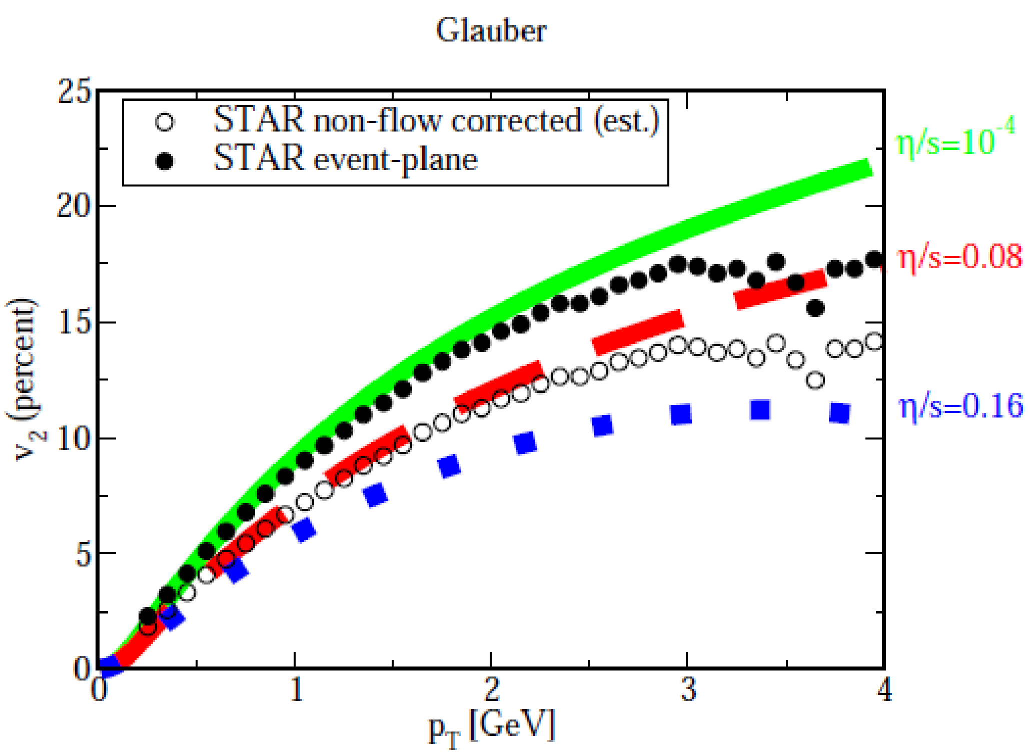
...transformed into momentum anisotropy

quantum mechanical? $(\Delta p_x > \Delta p_y)$
...no (QM only for p_t <50 MeV/c)

Elliptic flow and hydrodynamics

Hydrodynamics assumes local therm. equilibrium; treats whole collision history
Initial conditions (t_0): velocity, energy & baryon density (3 comp.) at (x, y, z)

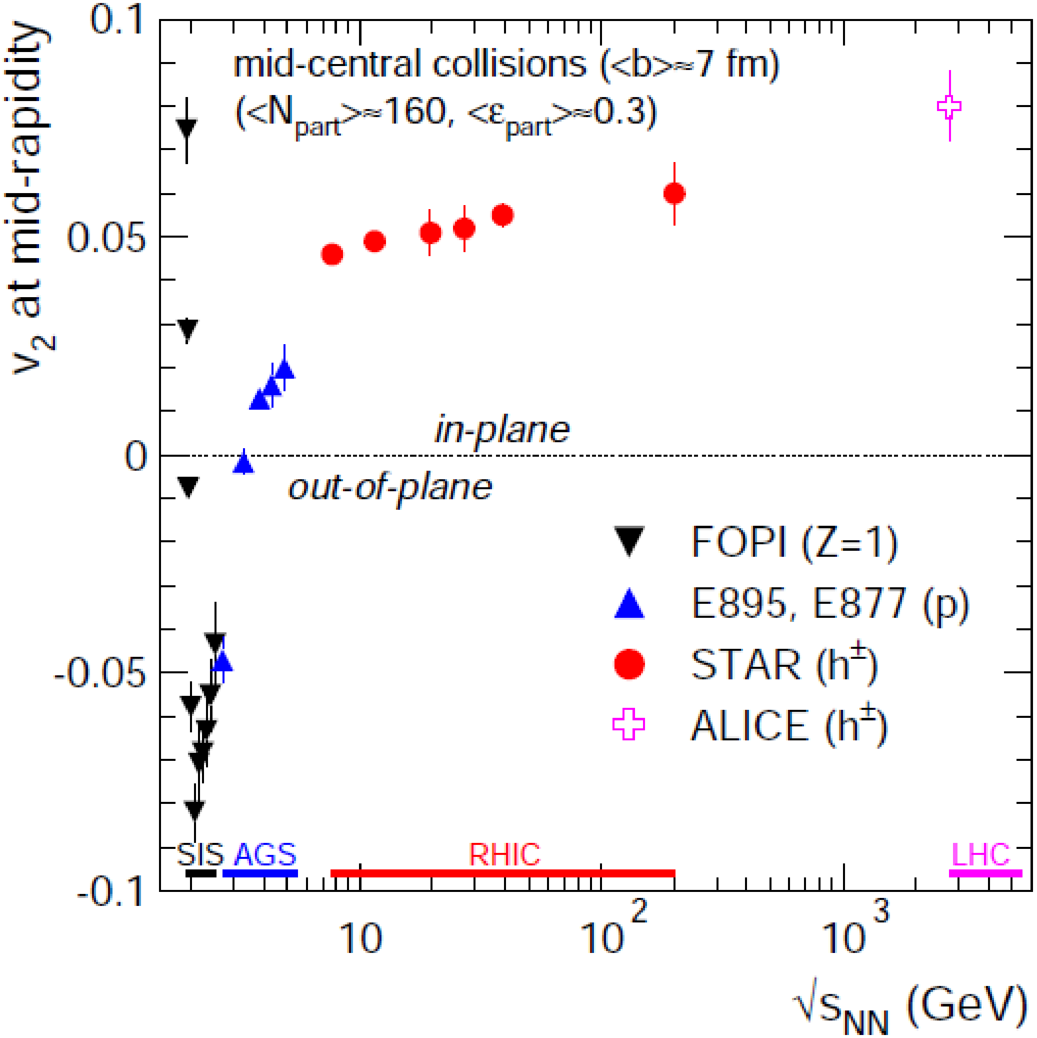
J.-Y. Ollitrault, arXiv:0708.2433



Luzum & Romatschke, arXiv:0804.4015

- points: data, STAR experiment
  lines: hydrodynamical model
- η/s: (shear) viscosity / entropy density
  much smaller than for any known substance
  Ex. (at T_c): He: 0.8, H_2O: 2.1
  $\eta/s \sim T\lambda c_s$
  Taranenko, Lacey, nucl-ex/0609025
- lower bound conjectured (AdS/CFT): $\eta/s{=}1/4\pi \simeq 0.08$
  Kovtun, Son, Starinets, hep-th/0405231

Elliptic flow: energy dependence



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

$v_2 < 0$ onset of expansion, in competition with shadowing by spectators (which act as a clock for the collective expansion, t_{pass}=40-10 fm/c)

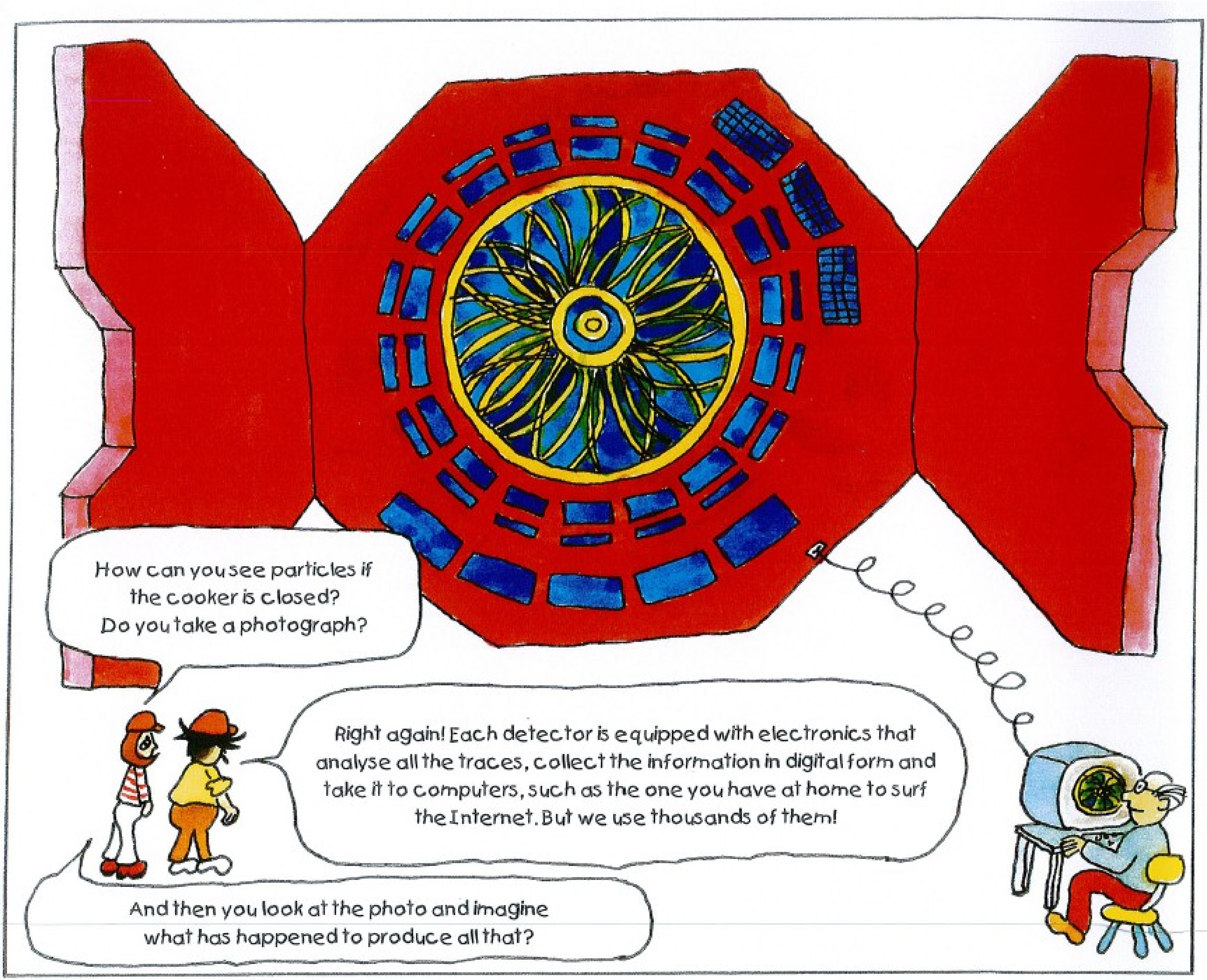
$v_2 > 0$ at high energies: “free” fireball (almond-shape) expansion (“genuine” elliptic flow)

≃35% larger v_2 than at RHIC

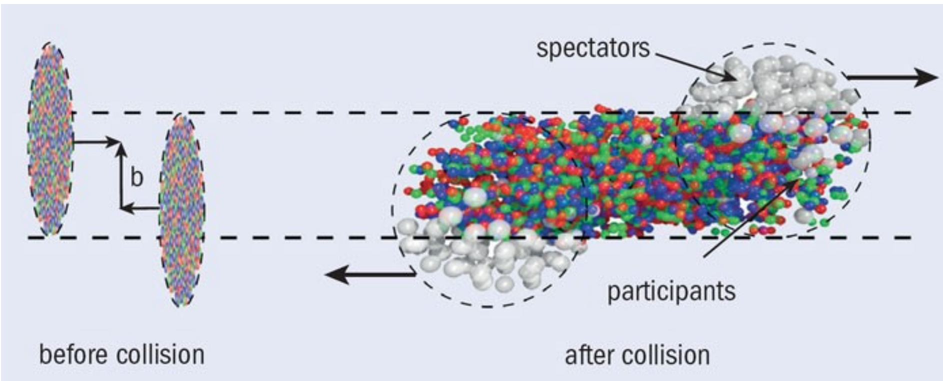
ALICE collab., arXiv:1011.3914

AA, arXiv:1210.8126

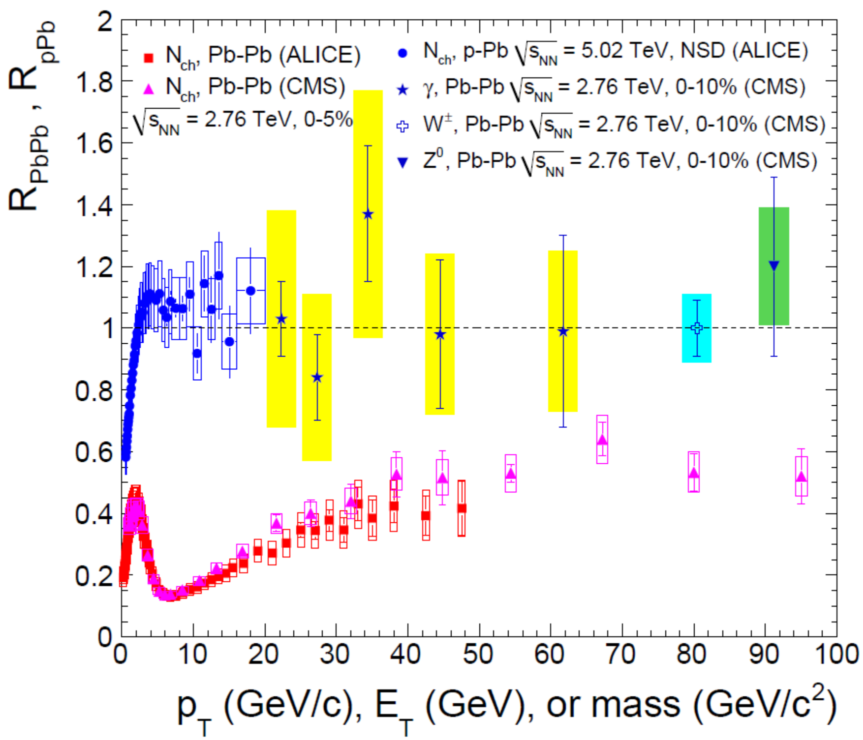
Part IV: “Hard” and electromagnetic probes



Quantifying medium effects
-nuclear modification factor-



$$R_{AA} = \frac{d^2 N_{AA} / dp_T dy}{N_{coll} \times d^2 N_{pp} / dp_T dy}$$

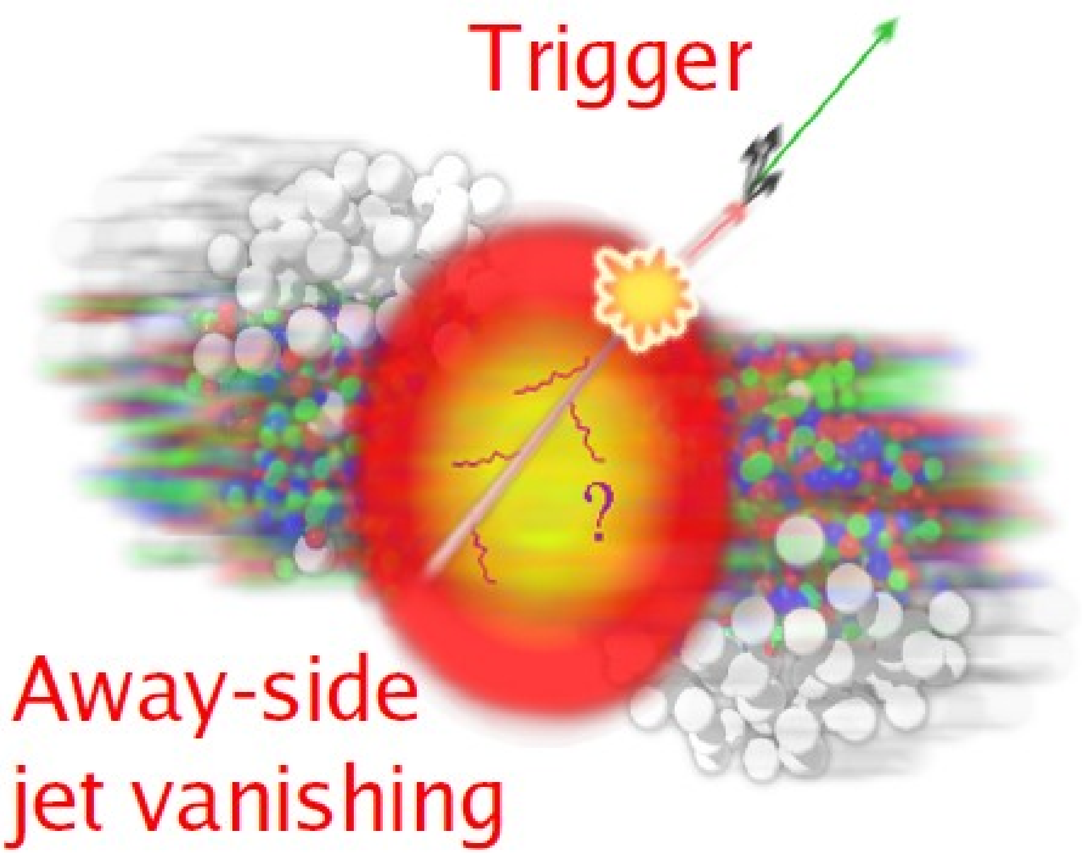


- Superposition of NN collisions → R_{AA}=1
- Strong suppression for light hadrons observed at LHC in Pb-Pb collisions
- Weakly interacting particles are not affected by the QGP
  - Photons, $W^{\pm}$ and Z^0 bosons R_{AA} are compatible with 1

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

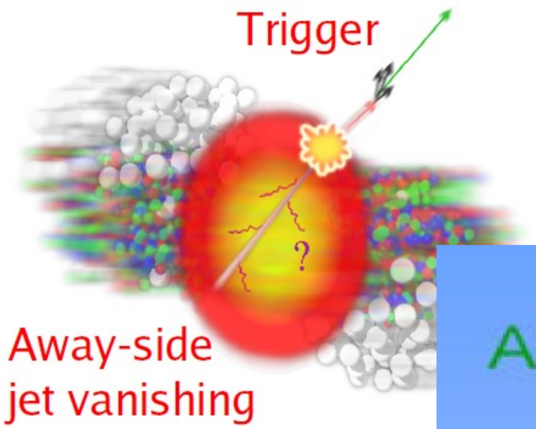
γ, CMS, PLB 710 (2012) 256
$W^{\pm}$, CMS, PLB715 (2012) 66
Z^0, CMS, PRL106 (2011) 212301

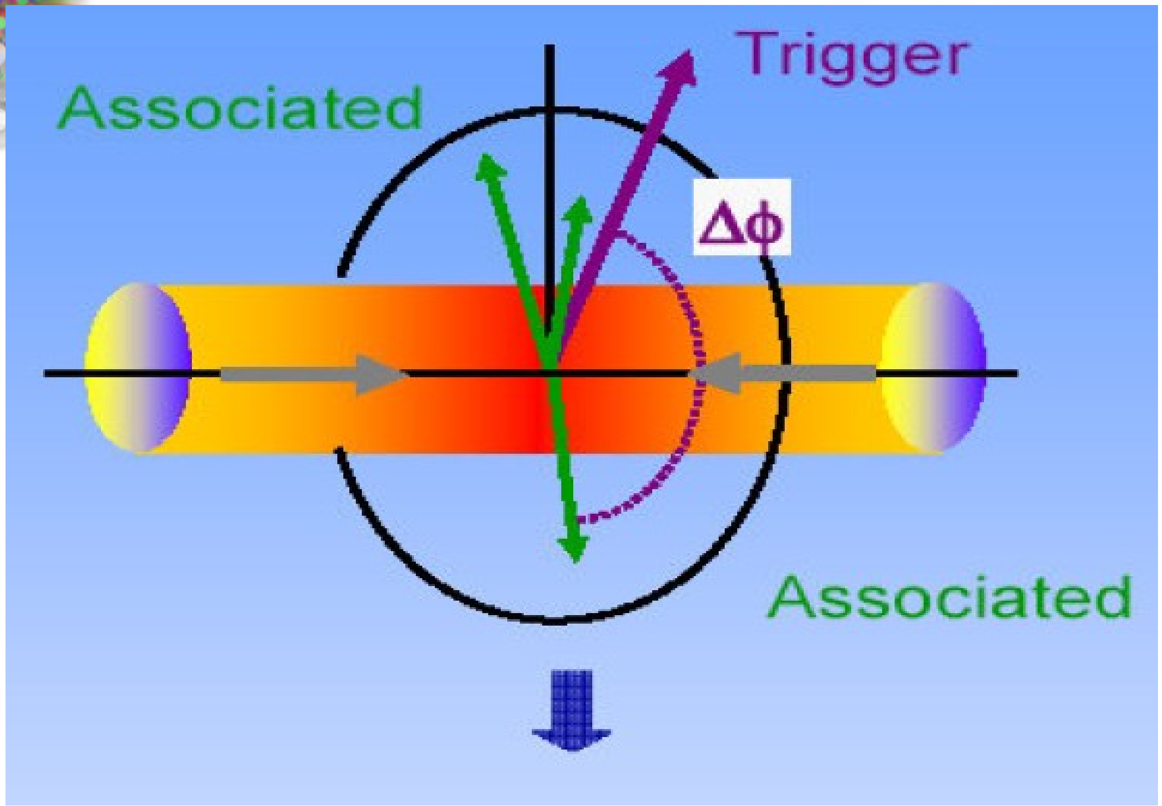
Two-particle azimuthal correlations



- 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

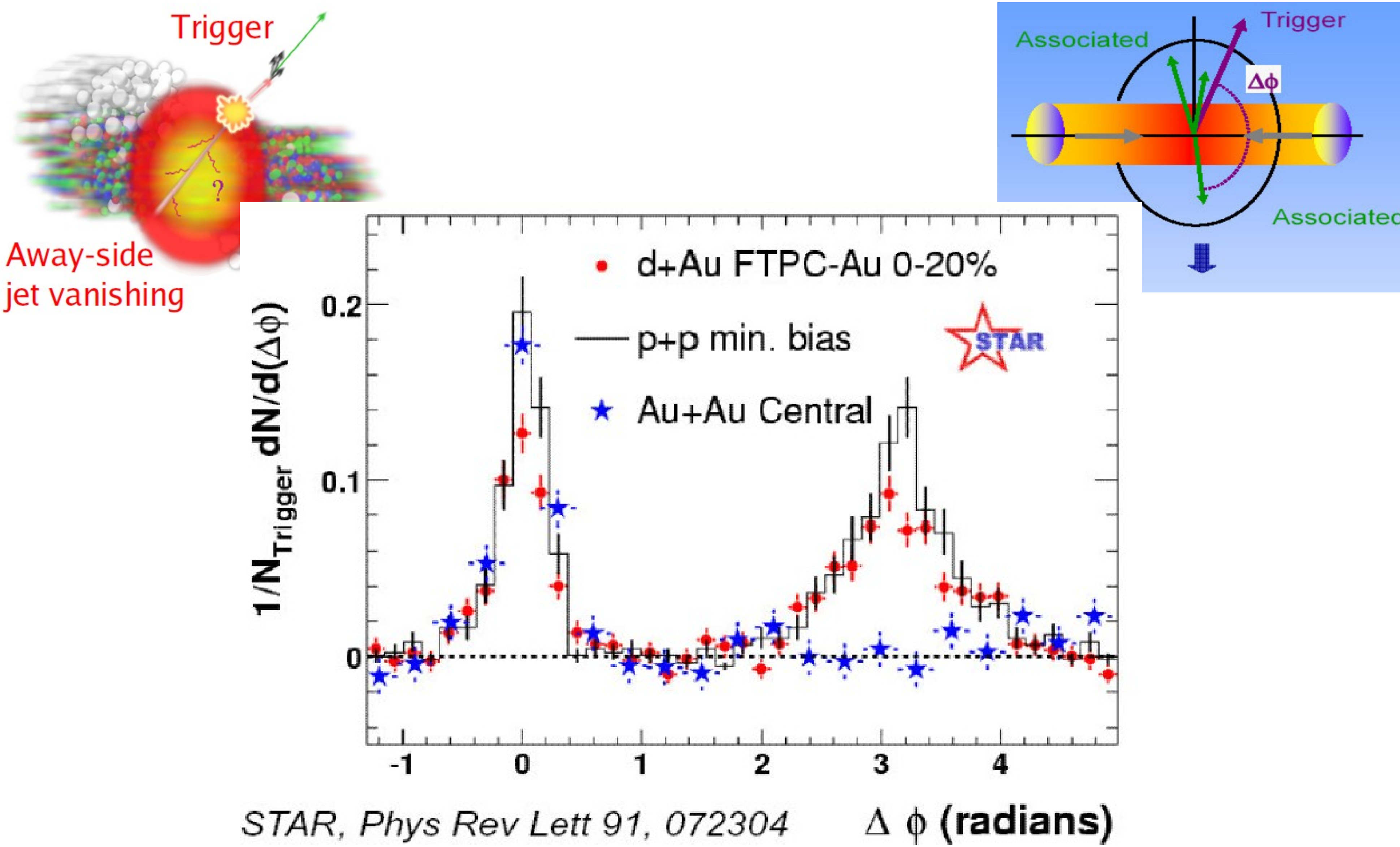
Two-particle azimuthal correlations





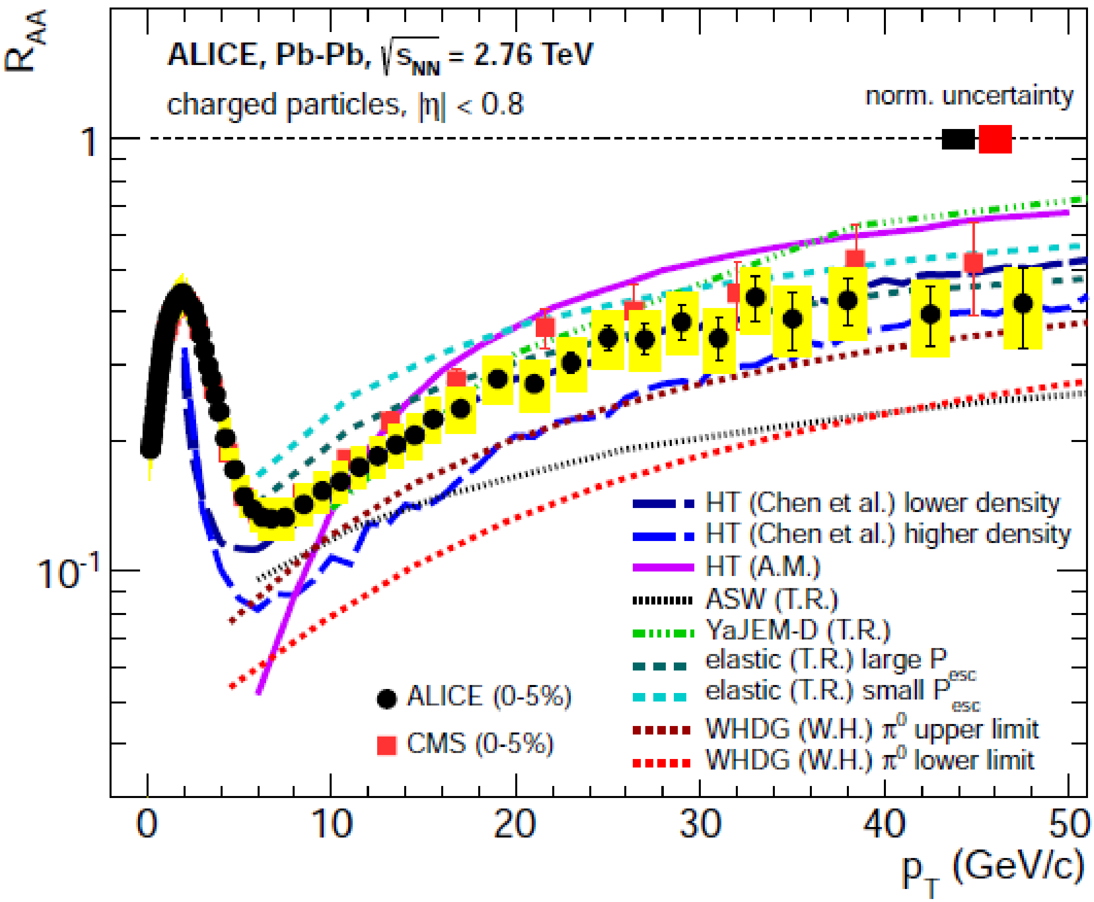
- Test the strength of this effect using two-particle correlations

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.

Jet quenching at the LHC



...stronger than previously measured at RHIC

reaching a factor of about 7 around p_T=7 GeV$/c$

remains substantial even at 50-100 GeV$/c$

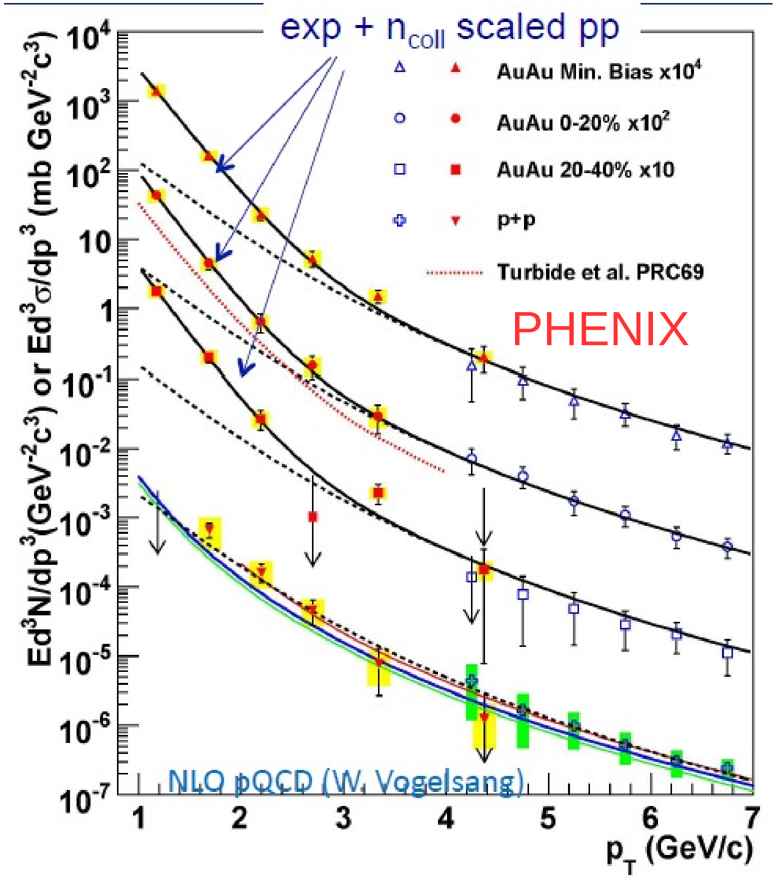
ALICE, arXiv:1208.2711

CMS, EPJC (2012) 72

a lot of activity in theoretical description of parton energy loss in hot deconfined matter

Electromagnetic probes

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



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

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

Electromagnetic probes

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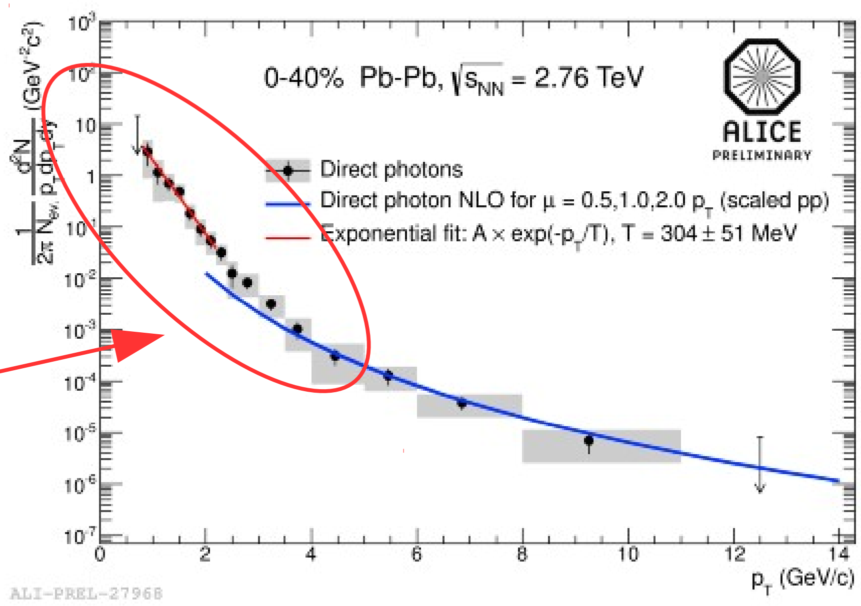
The highest temperature ever recorded!!!

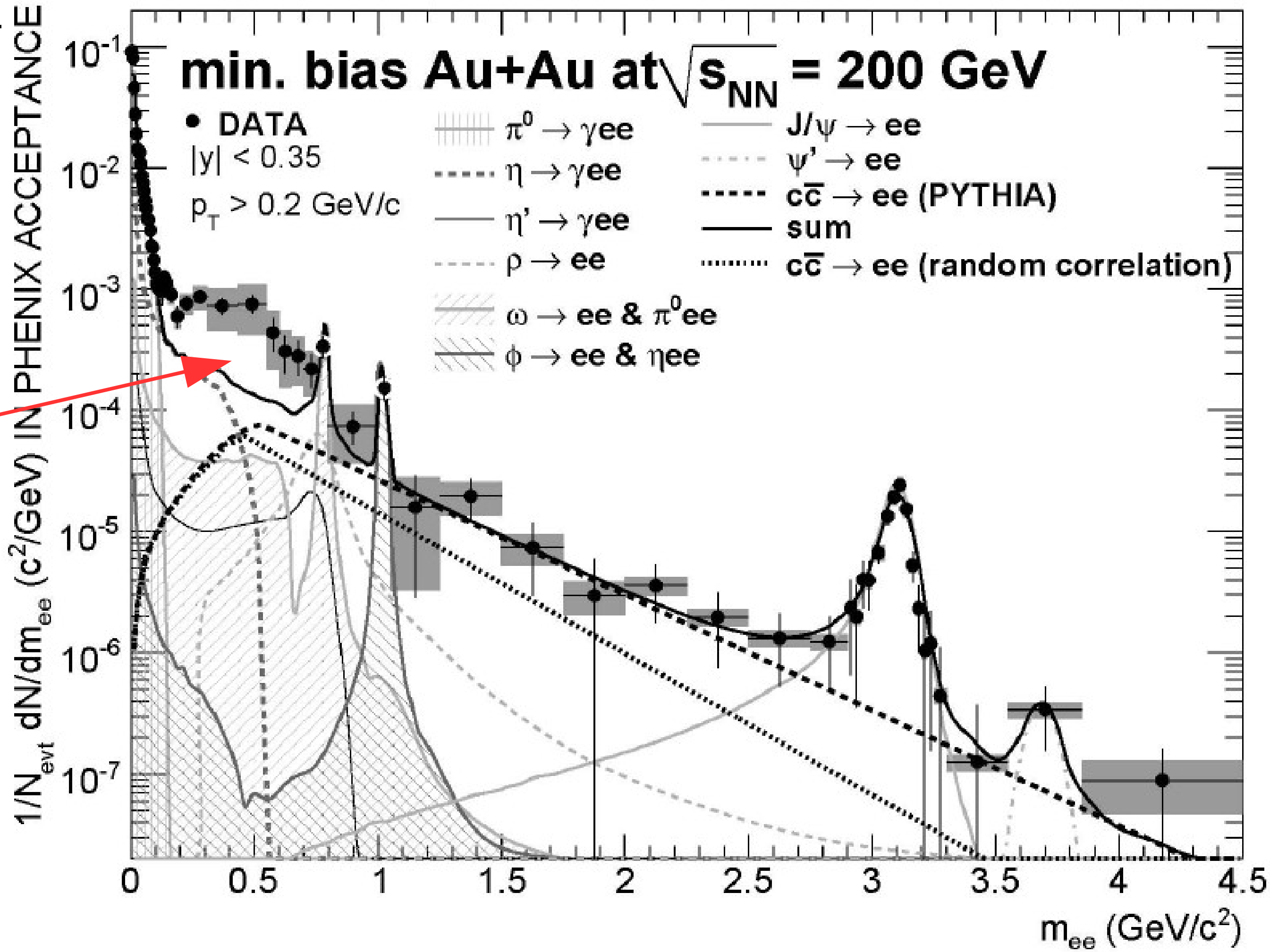


T = 304 ± 51 MeV
T ~3.0 x 10^{12} K

Electromagnetic probes

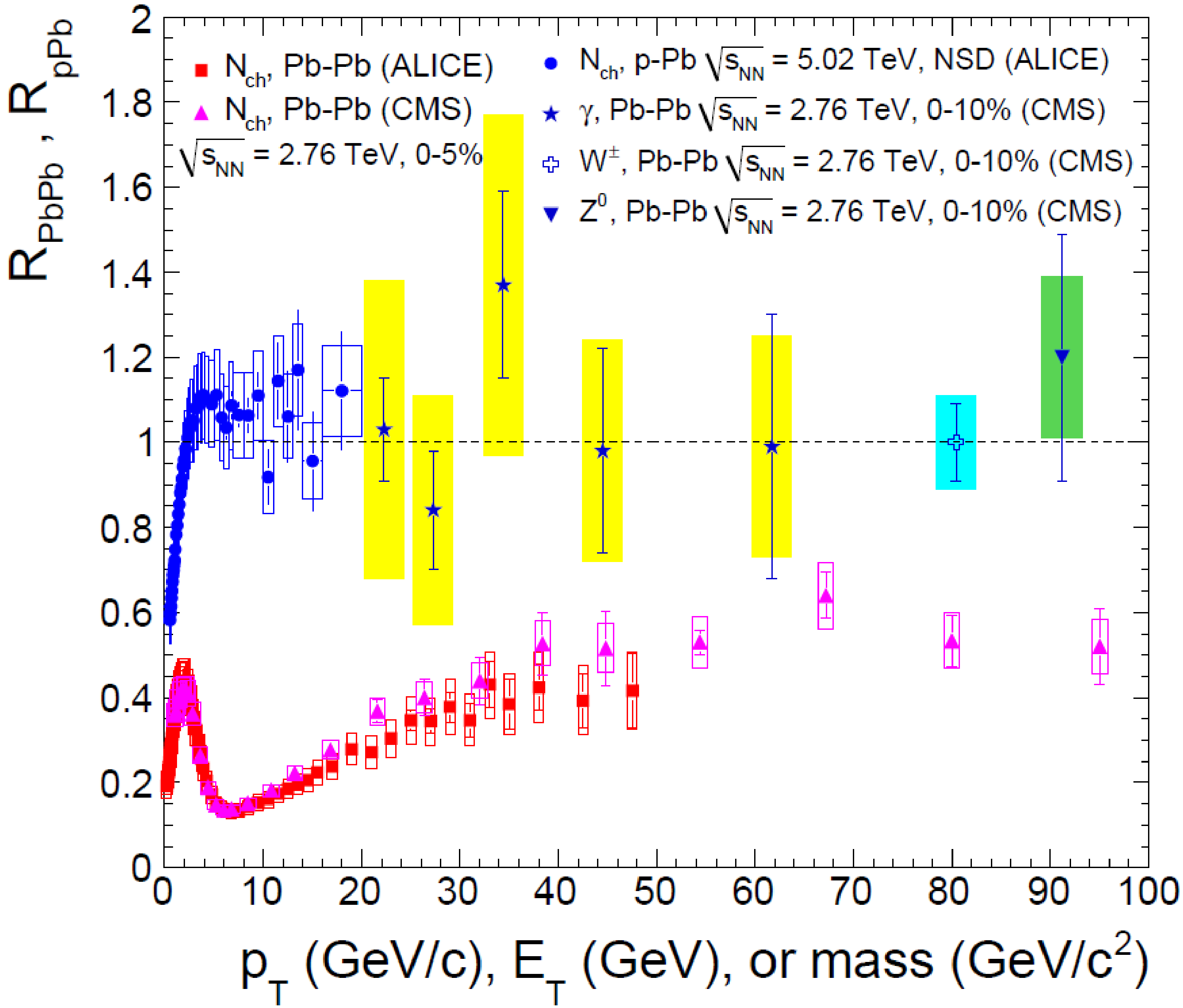
- Low momentum photons and low mass di-leptons
  - Direct probe of the thermal radiation of the fireball
  - Very clean information because of no re-interactions with QCD medium

Low mass di-electrons in PHENIX data



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

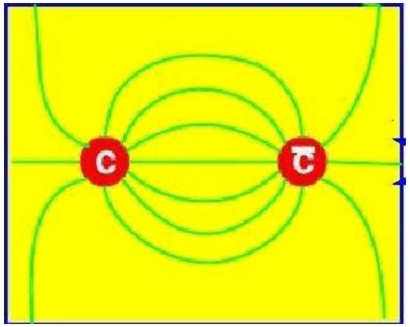
Electromagnetic probes



- 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

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



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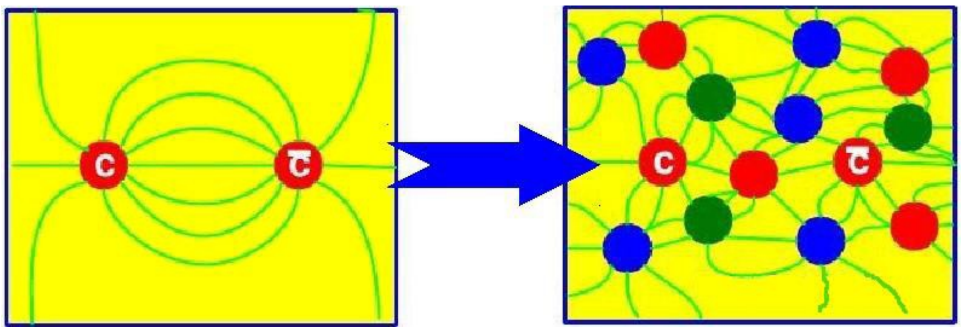
- The original idea: Matsui and Satz, PLB 178 (1986) 416:
  - In a deconfined medium with high density of color charges, the QCD analogue of the Debye screening can lead to quarkonium suppression
  - No J/ψ if $\lambda_D < r_{J/\psi}$



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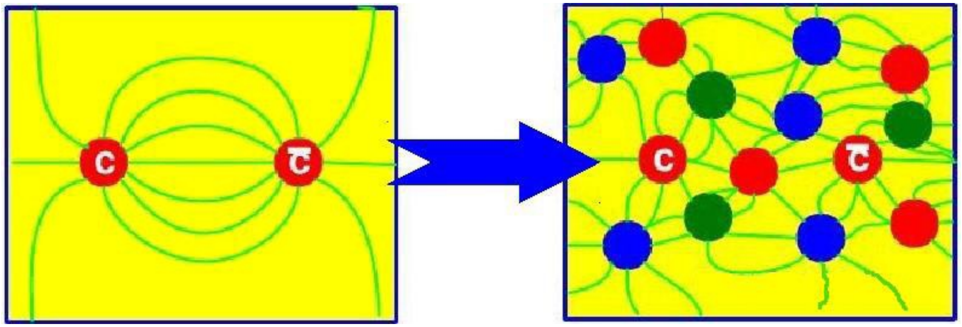
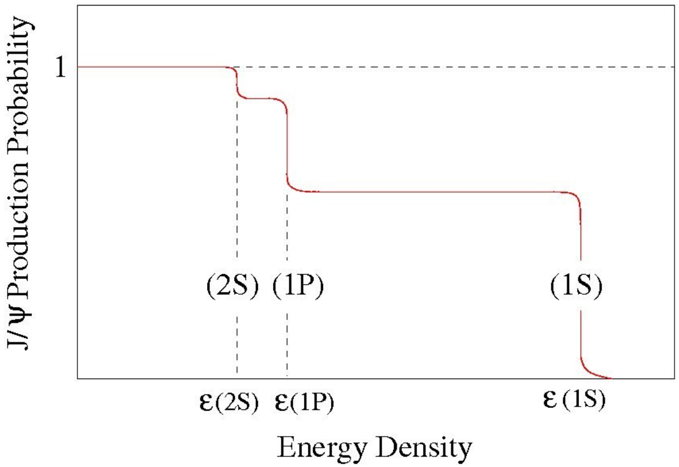
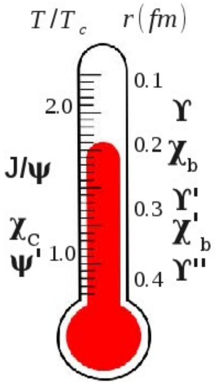
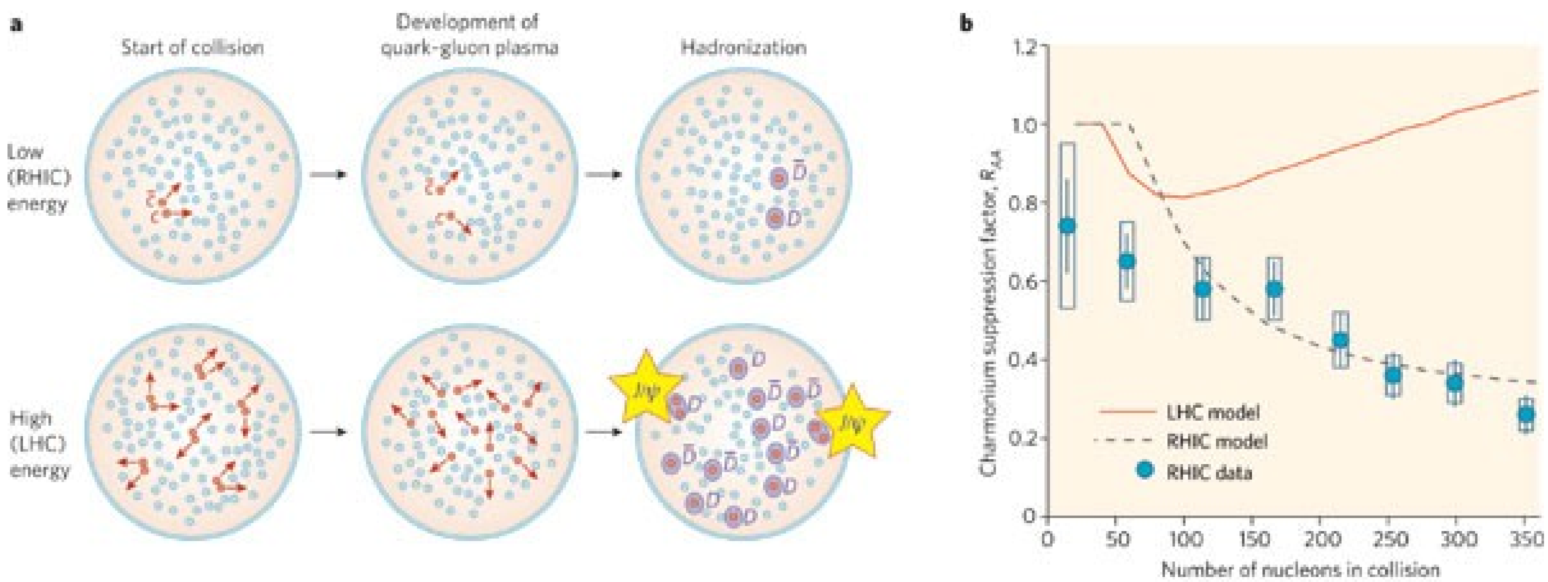
  - No J/ψ if $\lambda_D < r_{J/\psi}$
  - The Debye length in QGP is a function of temperature so J/ψ and the other quarkonium states act as a thermometer of the plasma







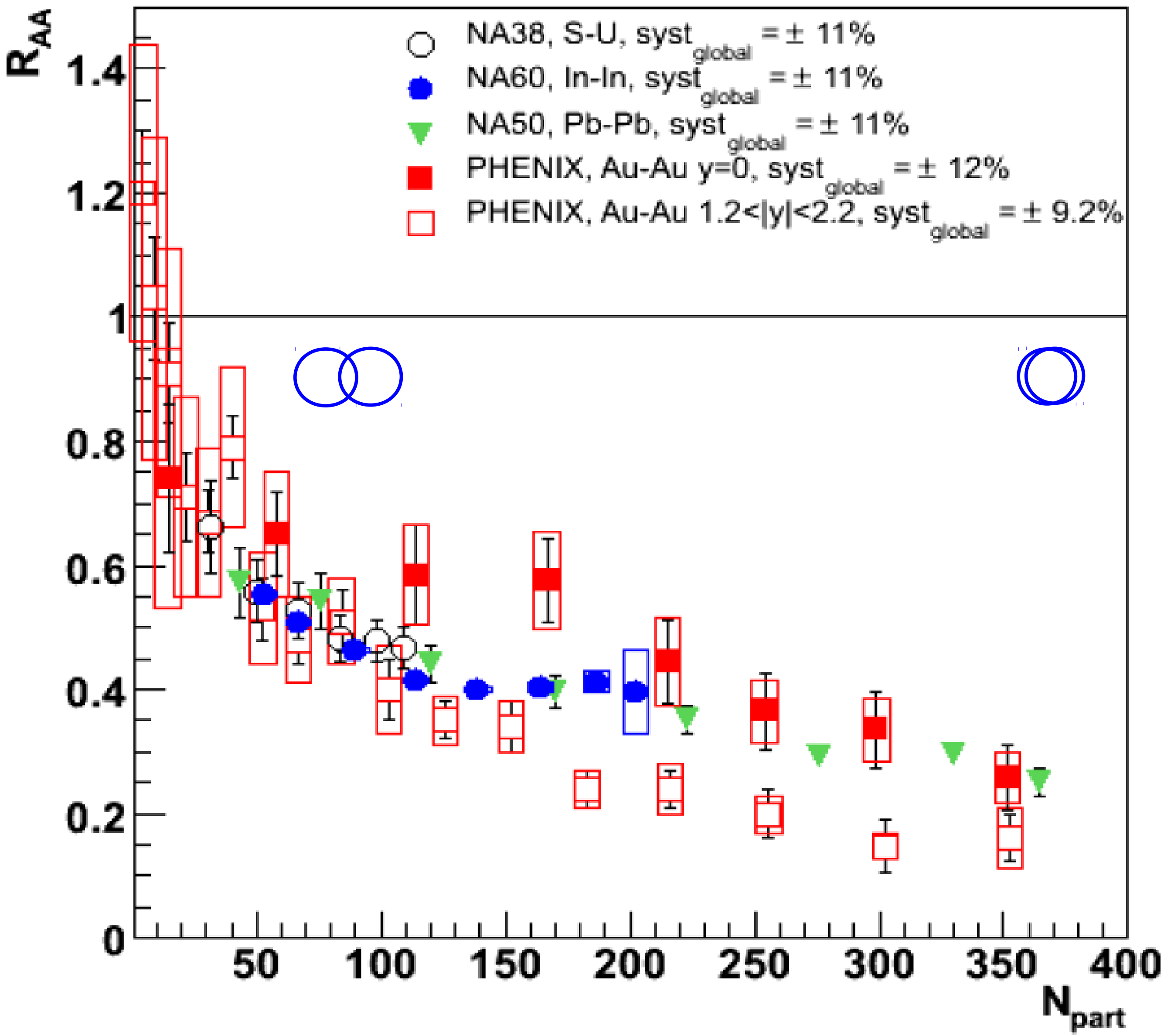
Quarkonium in the QGP (re-generation)



Nature 448 (2007) 302-309

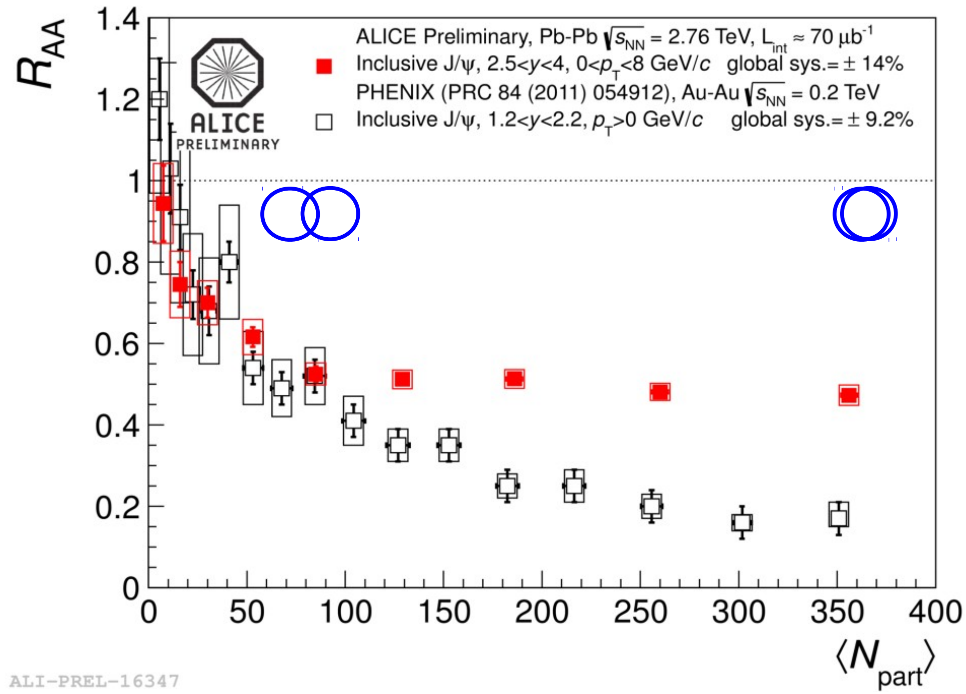
- Melting ↔ formation of quarkonium states
  - Thews et al., PRC 63 (2001) 054905
  - Transport models
- Enhancement of quarkonia states from qqbar pairs at the chemical freeze-out
- Open charm and quarkonia abundancies calculated assuming statistical hadronization.
  - Braun-Munzinger and Stachel, PLB 490 (2000) 196

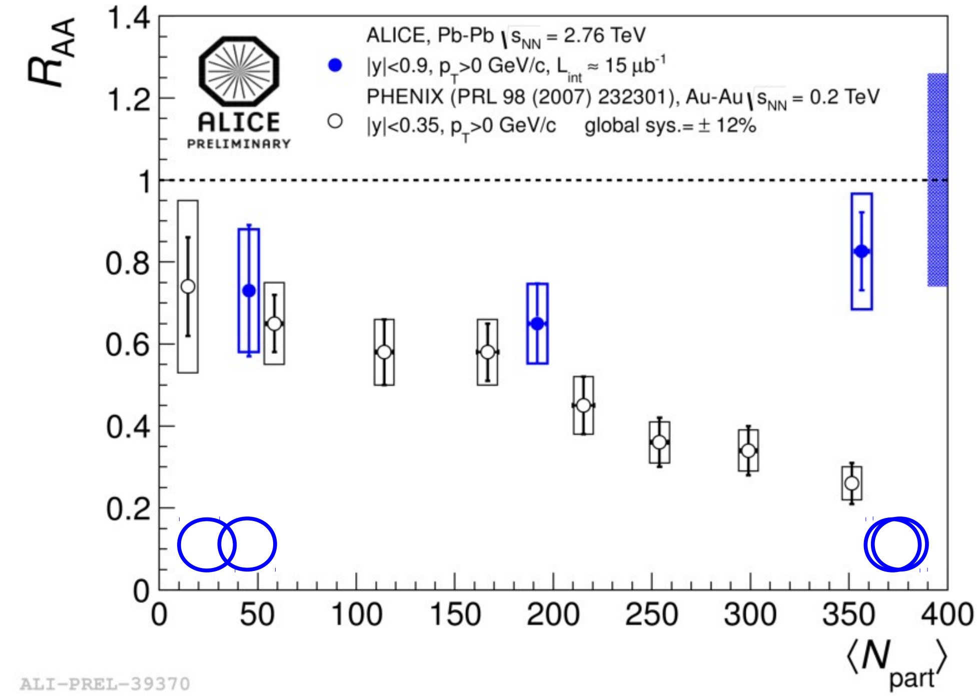
The lower energy results



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

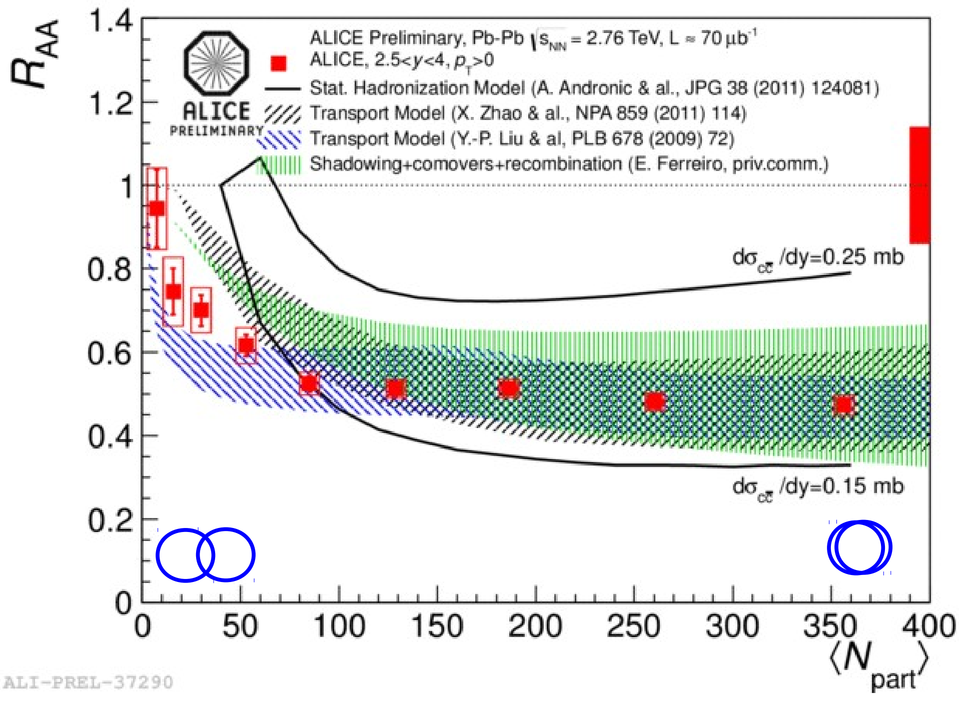
J/ψ at the LHC

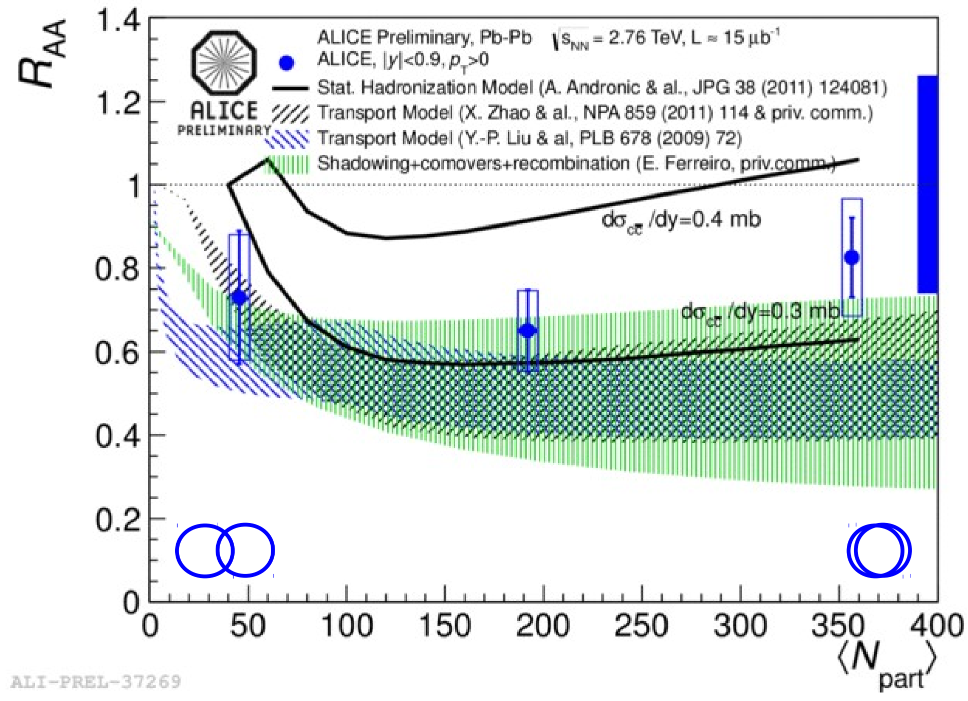




- Clear J/ψ suppression seen for all centralities
- Indication of less suppression at mid-rapidity
- ALICE results show smaller suppression compared to lower energies (PHENIX) in central collisions

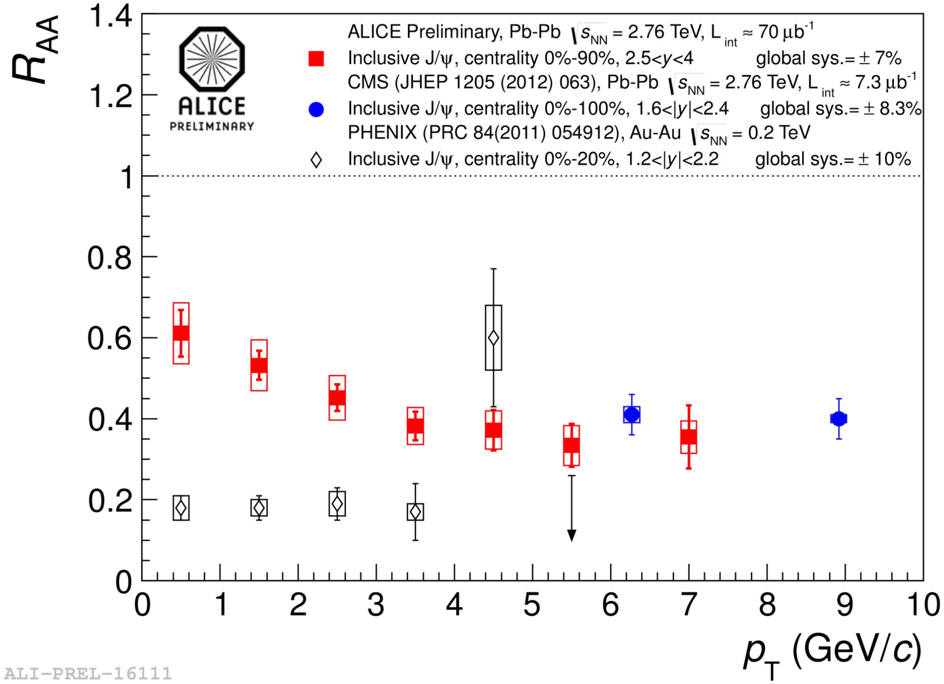
Inclusive J/ψ at the LHC



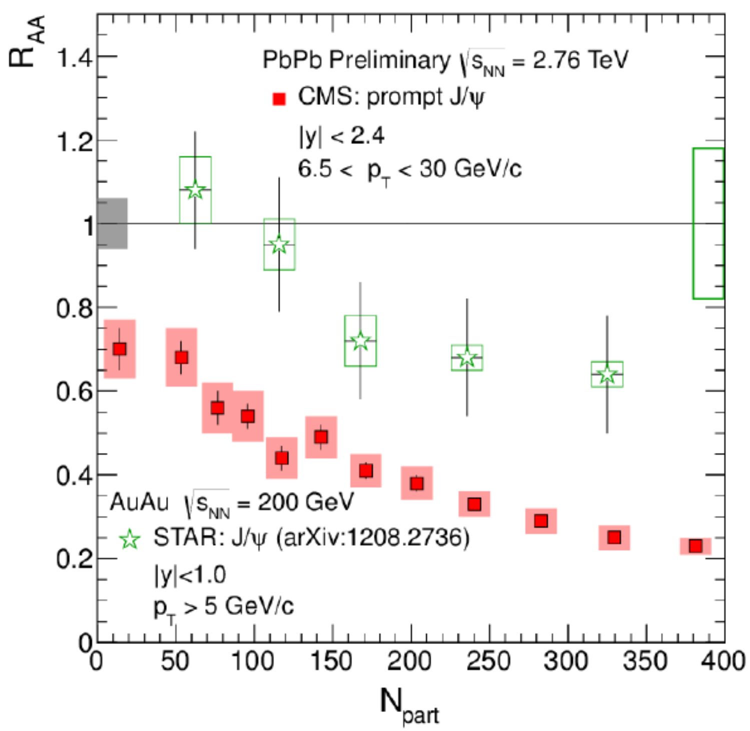


- Models which include (re)combination agree with the data.

J/ψ as a function of p_T



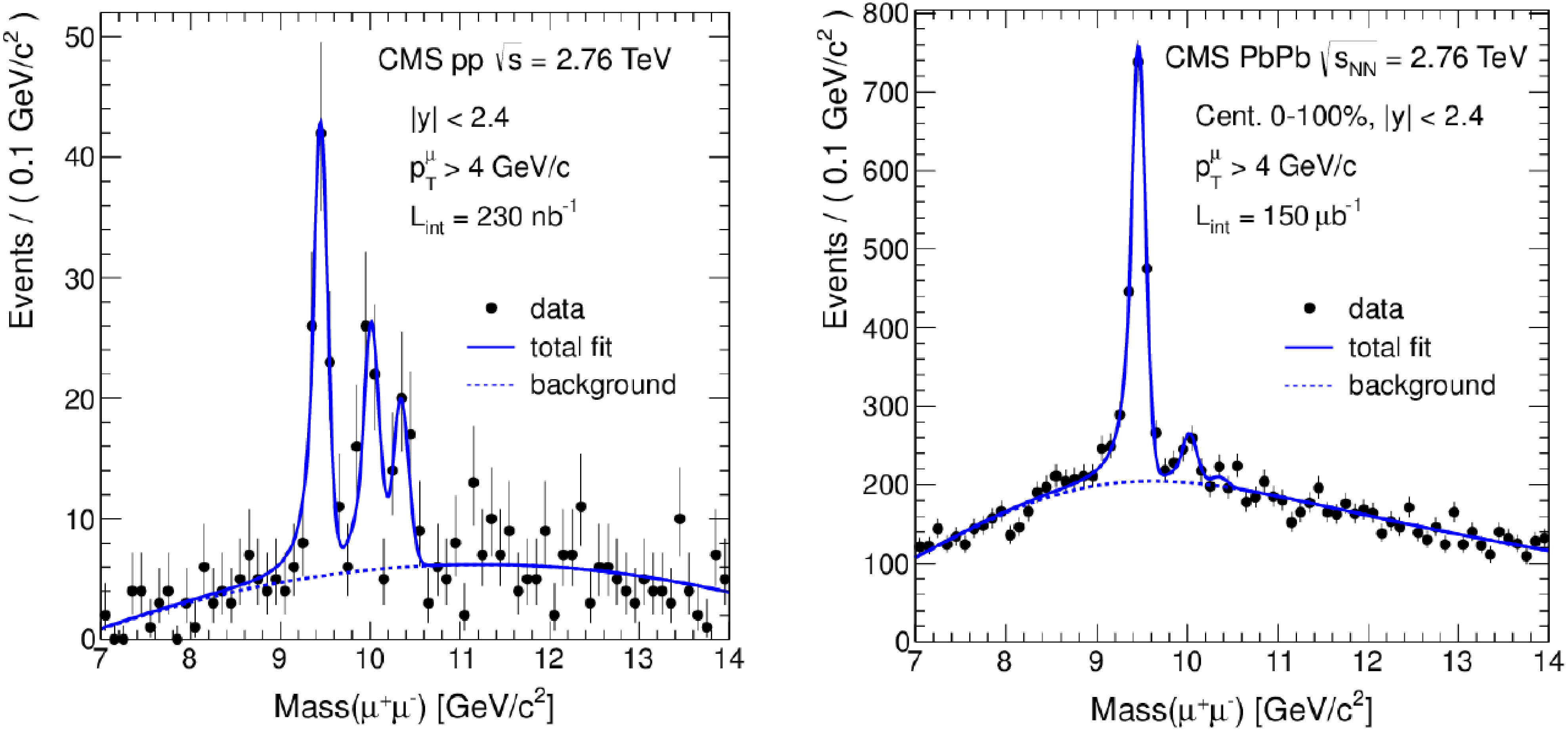
- Striking difference between LHC and RHIC at low-p_T
  - "Smoking gun" for (re)combination ?
- Good agreement between ALICE and CMS data



- Stronger suppression at LHC for high-p_T J/ψ's
  - Negligible (re)combination expected in this kinematic range
  - Higher energy density at LHC at play

Bottomonia

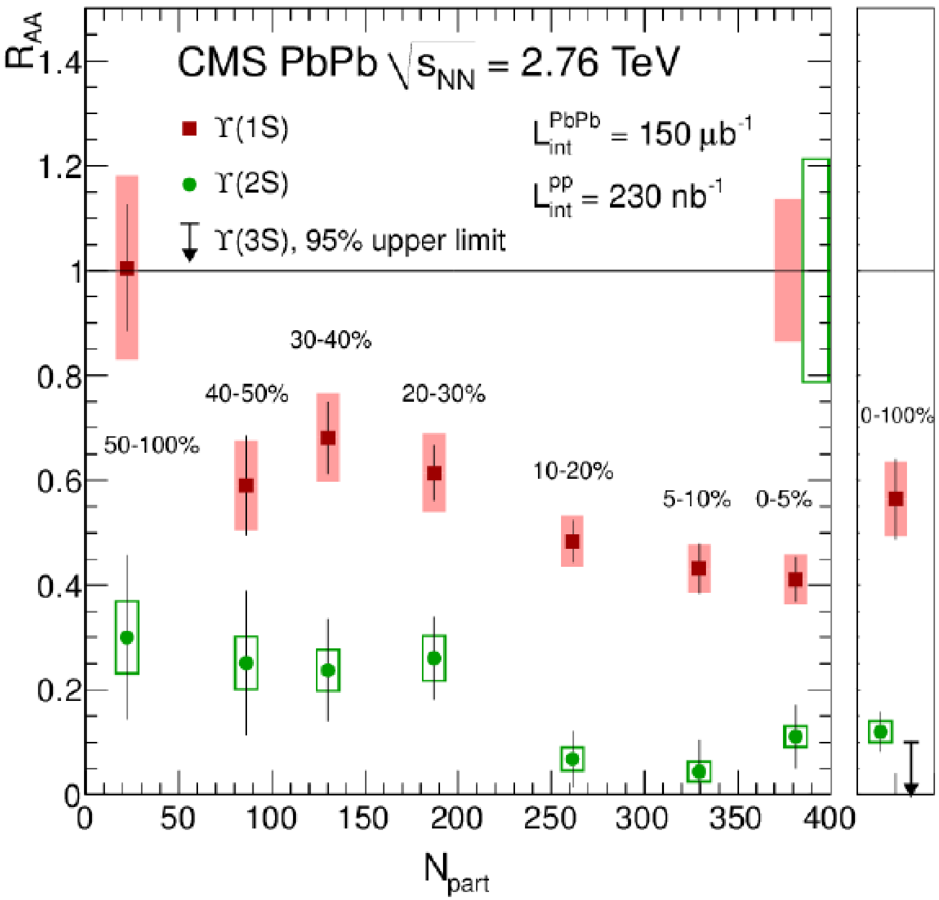
PRL109 (2012) 222301

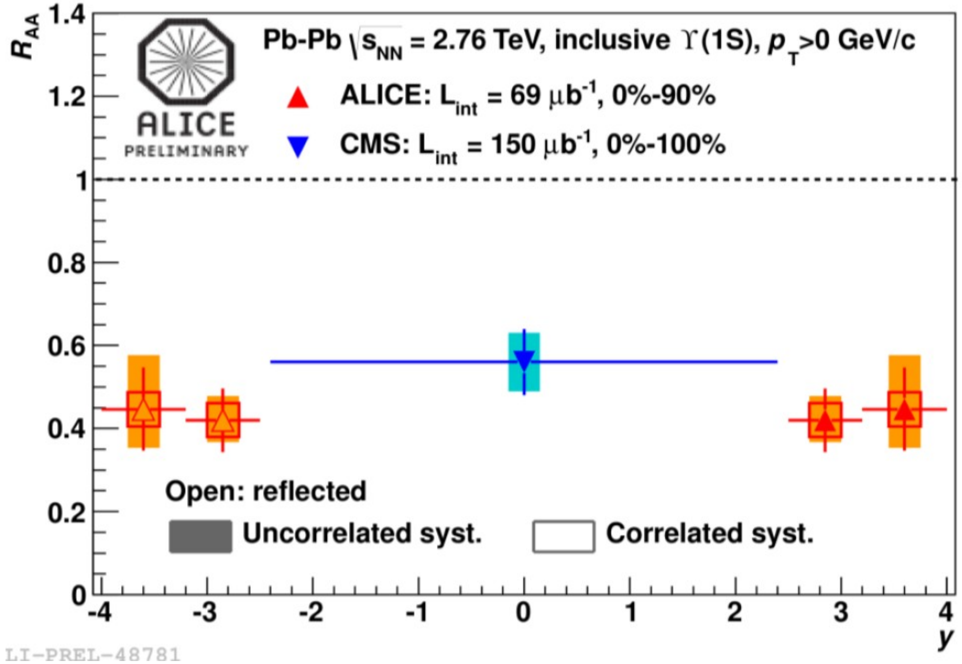


- Suppression of Y(2S) and Y(3S) states w.r.t. Y(1S) in Pb-Pb already visible from the invariant mass spectra.

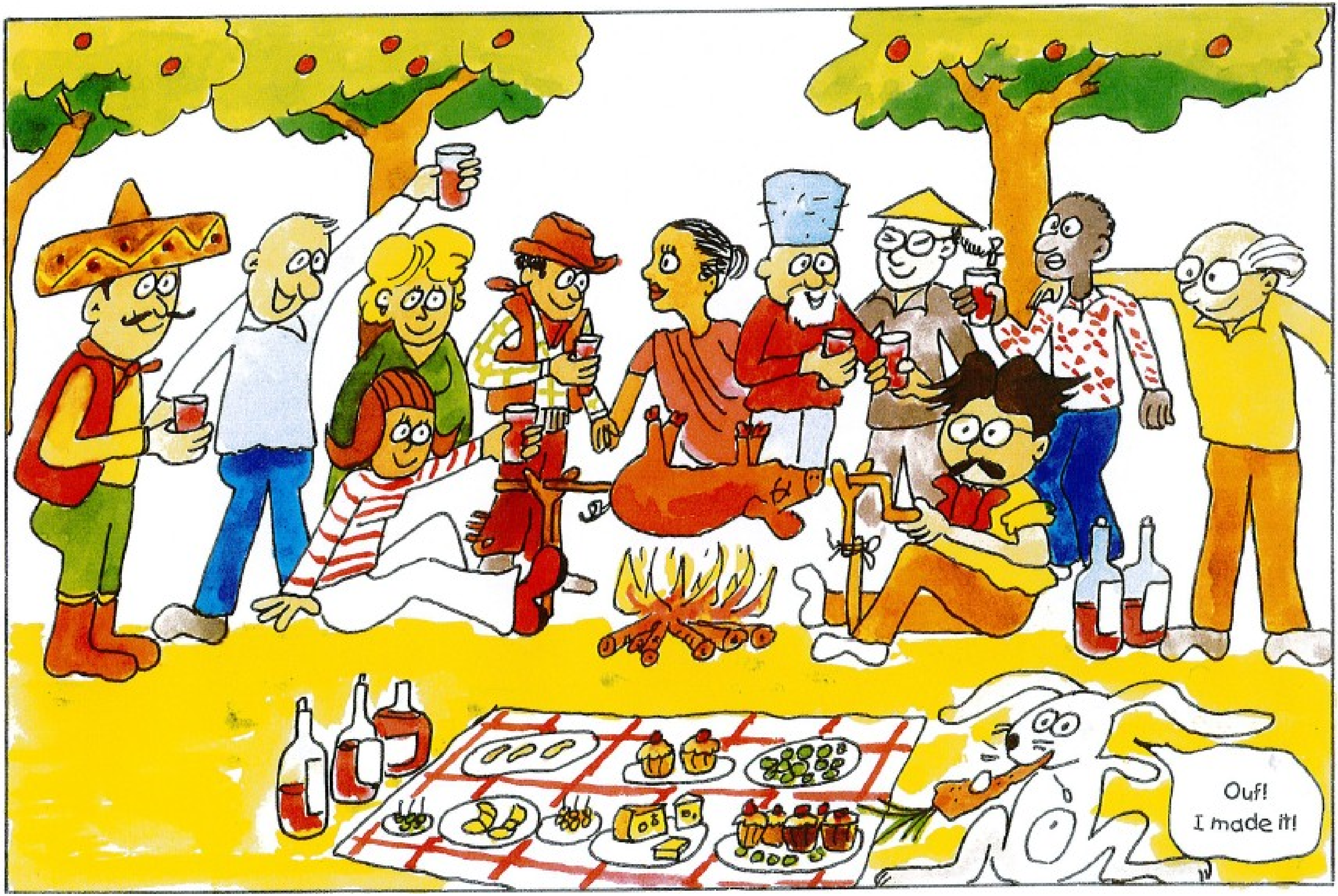
Υ suppression

PRL109 (2012) 222301





- Acceptance down to p_T=0 for both CMS and ALICE
- Strong centrality dependence for the R_{AA} of both Υ(1S) and Υ(2S)
  - (Re)combination should have a much smaller effect compared to charmonia
- $R_{AA}^{Υ(3S)} < R_{AA}^{Υ(2S)} < R_{AA}^{Υ(1S)}$ → sequential suppression of Υ states
- No strong rapidity dependence within uncertainties



Thank you for your attention!