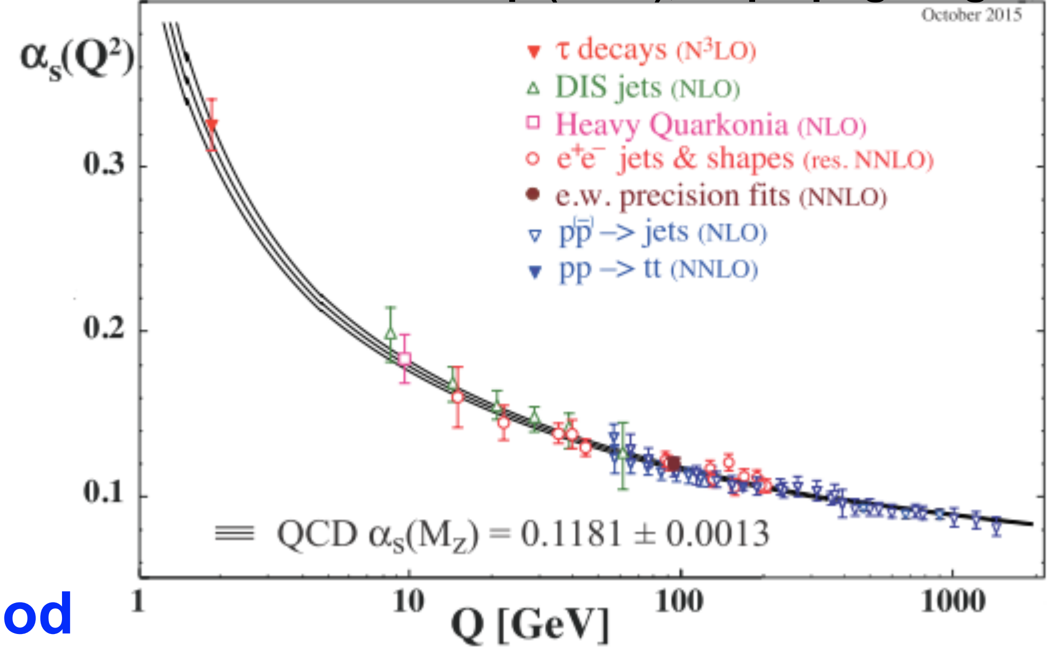
QCD (Quantum Chromo Dynamics)

- quantum field theory of strong interactions between quarks and gluons carrying color charges
  - 6 quarks (up, down, strange, charm, bottom, top): 3 color charges
  - 8 gluons: color and anti-color charge (!)
- not a simple theory (to calculate)
  - no analytic solution

Particle Data Group (2015), http://pdg.lbl.gov/

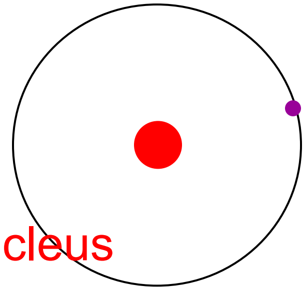


- strong force, depending on momentum transfer Q
  - running coupling: $\alpha_s = \alpha_s(Q)$
  - compare to QED: $\alpha = 1/137$
  - low Q: confinement
  - high Q: asymptotic freedom
  - → 2004 Nobel prize (Wilczek, Gross, Politzer)
- not everything is understood
  - extremely complex vacuum (not „empty“!) → phenomenological models

Confinement

- **free quarks have never been observed**

let’s look at an atom…



electron

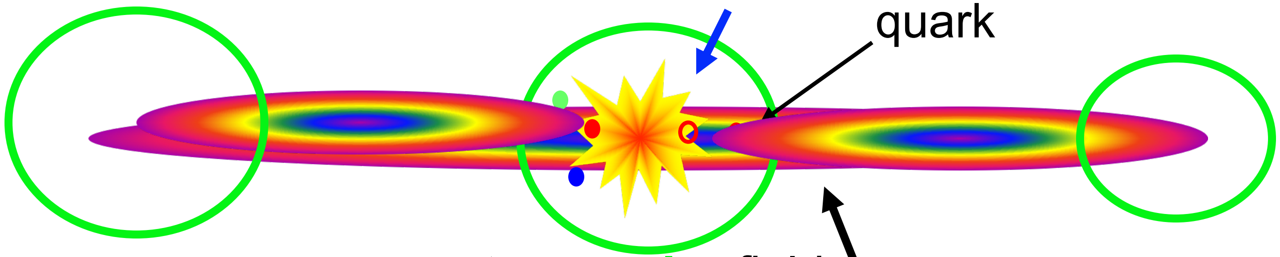
…isolating the constituents works

neutral atom

confinement: fundamental property of QCD:
- colored objects can’t be isolated

$$V(r) \propto -\frac{\alpha_s(r)}{r} + \kappa r$$

quark-antiquark pair from the vacuum



strong **color** field

“white” proton

potential energy grows with distance !!!

“white” π^0 (meson)

(confinement)

“white” proton (baryon)

(confinement)

Animation: C. Markert

Strongly interacting matter

- **asymptotic freedom towards high momentum transfer (energy, temperature, density)**

  → **strongly interacting partons become free**

  → **deconfined phase of matter**

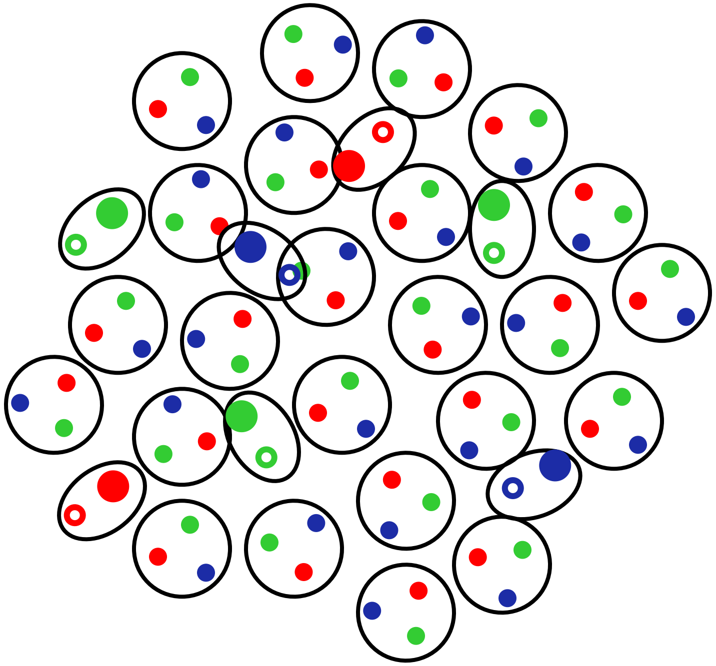
Cabibbo, Parisi, PLB 59 (1975) 67
Collins, Perry, PRL 34 (1975) 1353

- **naive picture of different phases of strongly interacting matter**
  - **increasing temperature**
    → **thermal motion**
    → **production of mesons**
  - **increasing density**

→ **hadrons „overlap“**

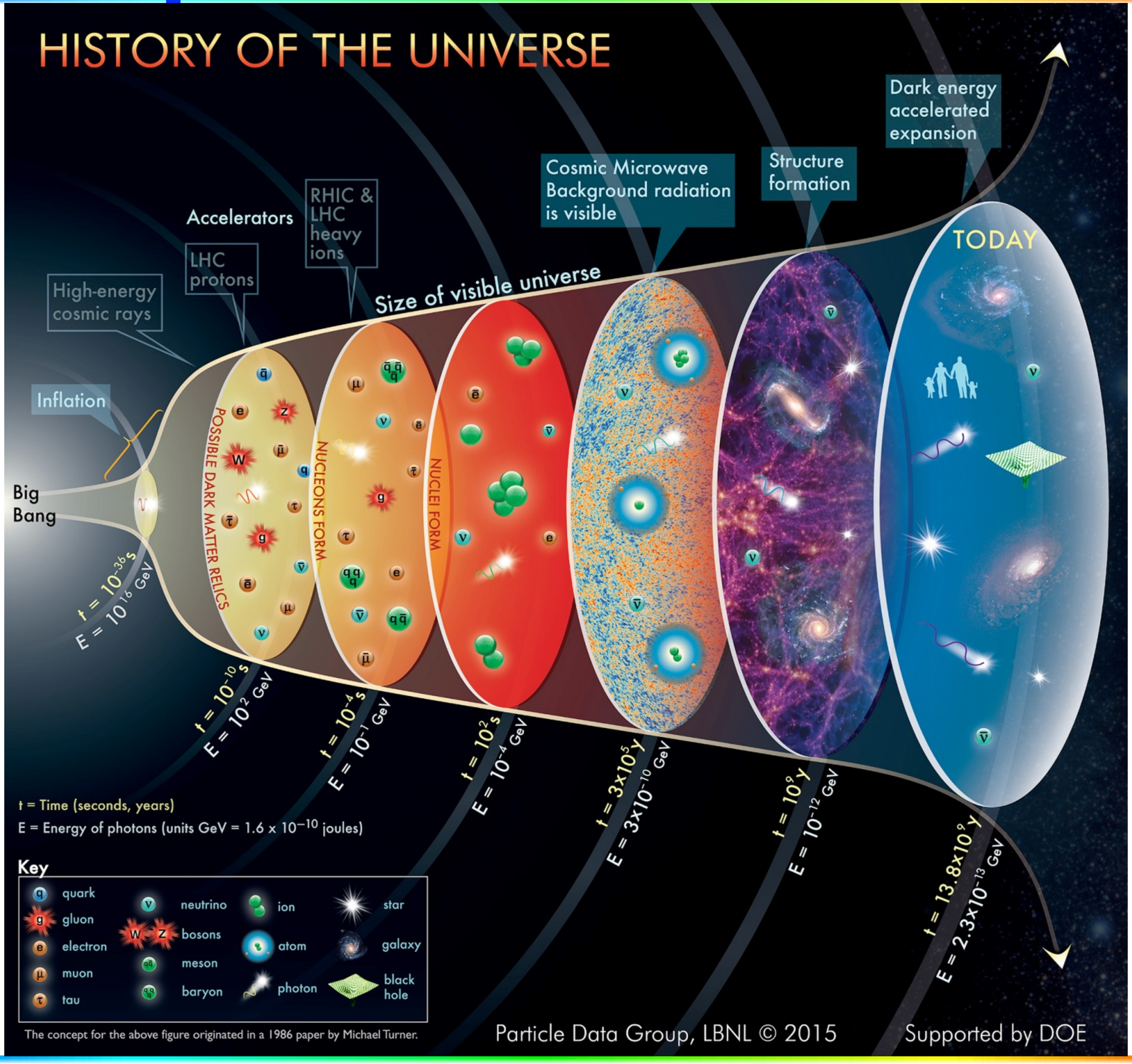
→ **quarks and gluons become the relevant degrees of freedom**

PHASE TRANSITION!



hadronic matter

Once upon a time …



The concept for the above figure originated in a 1986 paper by Michael Turner.

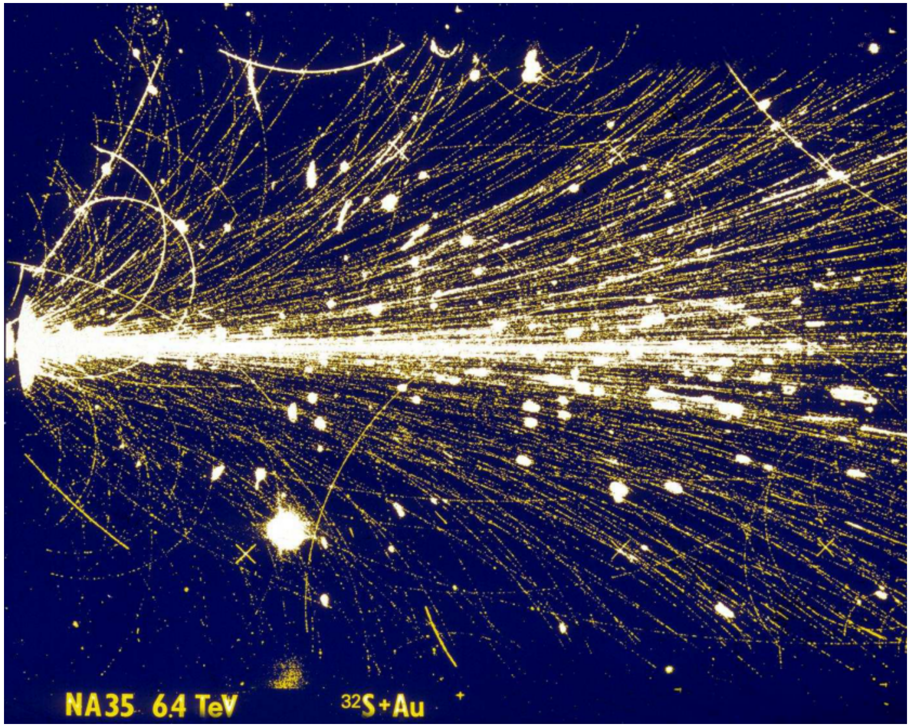
Particle Data Group, LBNL © 2015

Supported by DOE

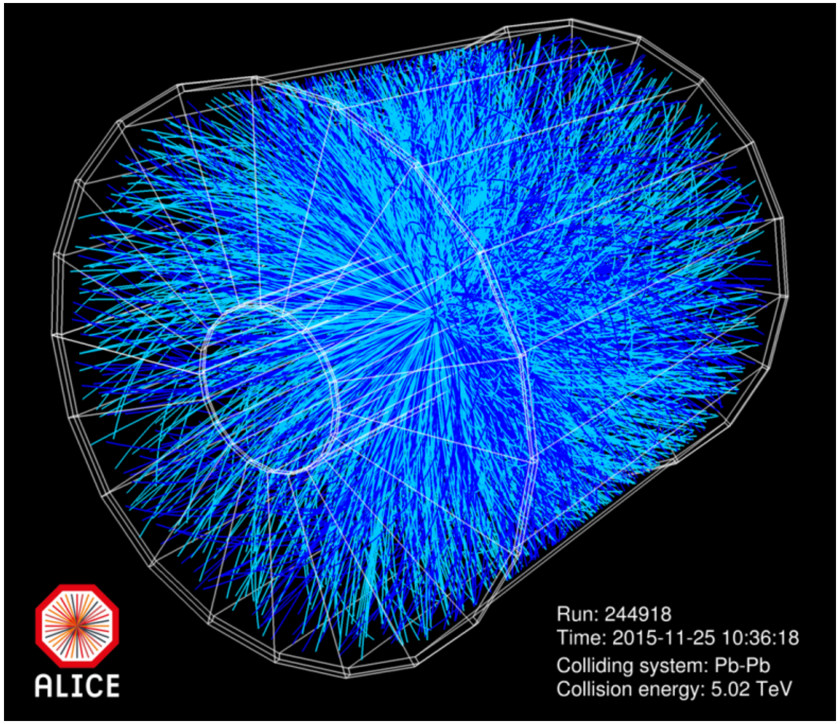
Little Bang in the laboratory

- how to reach energy densities sufficiently large to produce a deconfined QGP in the laboratory (T ~ 200.000 x T_{Sun})?
- unique experimental approach: collisions of heavy nuclei at ultra-relativistic energies

1986

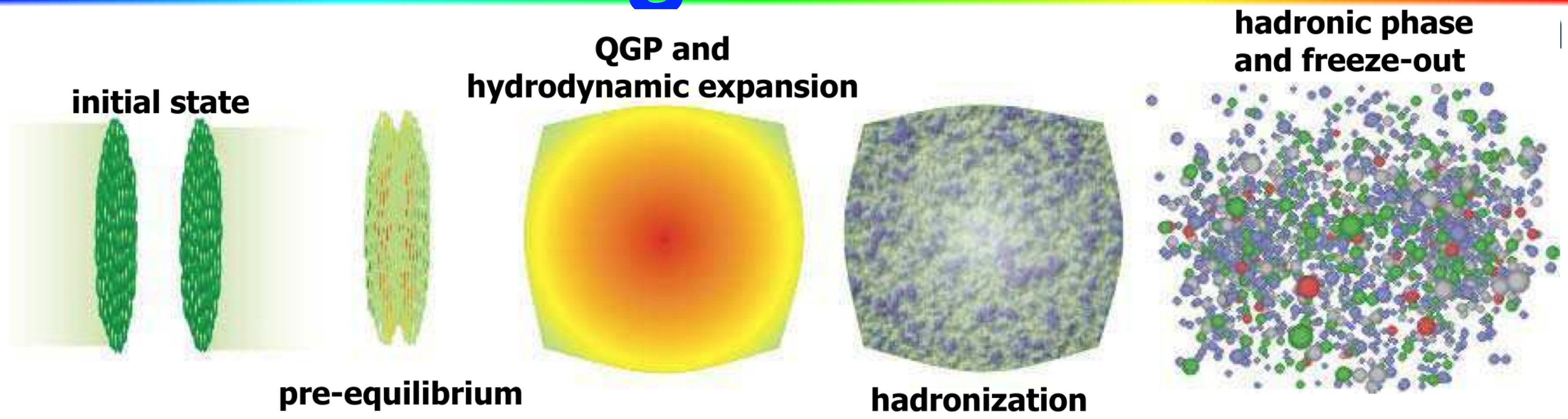


2015



Pb-Pb collision in UrQMD

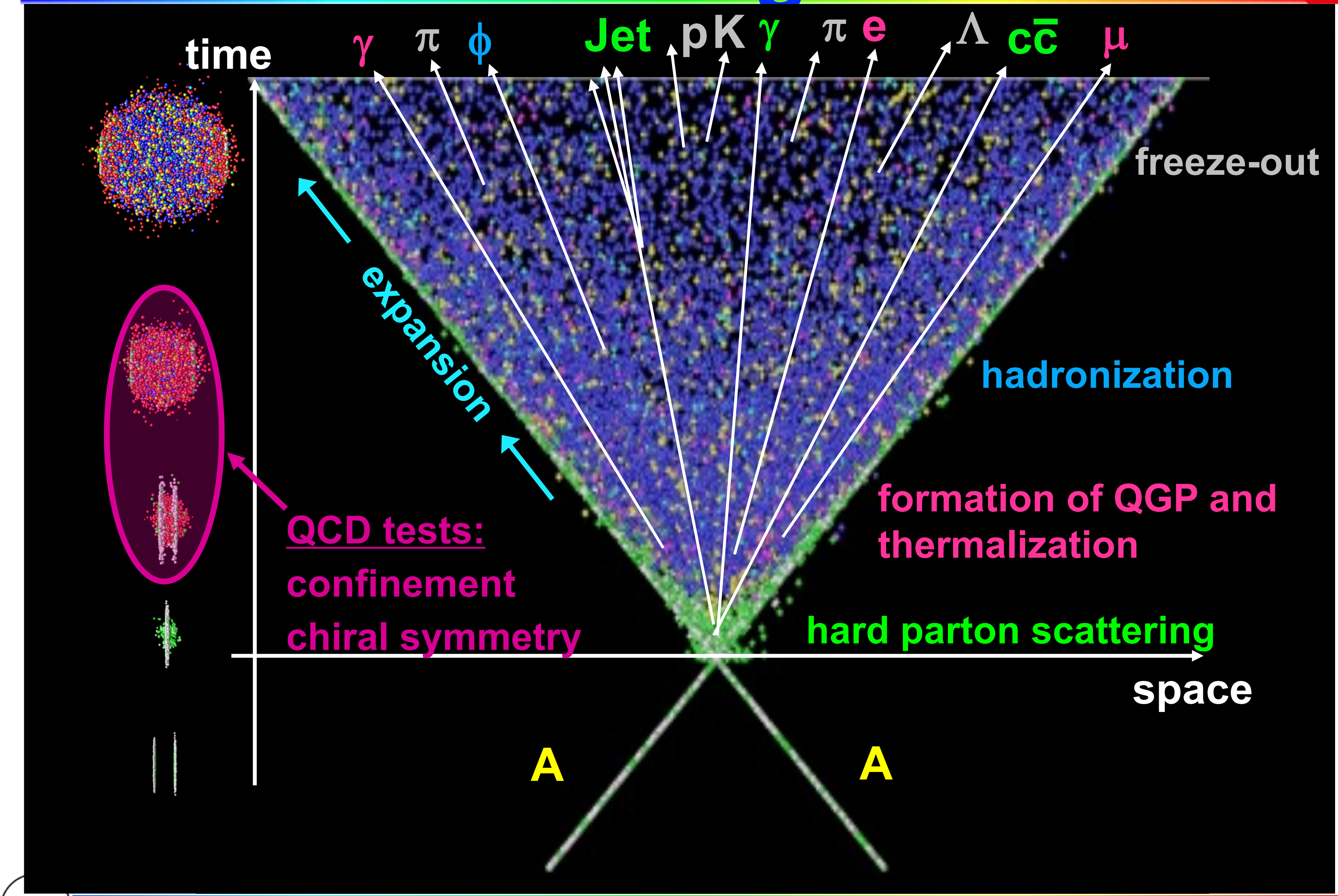
Collision stages



1. initial collisions, pre-equilibrium ($t \lesssim t_{coll} = 2R/\gamma_{cm}c$)
2. thermalization: equilibrium is established ($t \lesssim 1$ fm/c = 3×10^{-23} s)
3. expansion (~ 0.6 c) and cooling (t ~ 10-15 fm/c) … deconfined stage?
4. hadronization (quarks and gluons form hadrons)
5. chemical freeze-out: inelastic collisions cease
   → particle identities, i.e. yields, are frozen
6. kinetic freeze-out: elastic collisions cease
   → spectra are frozen (3-5 fm/c later)

**Most measurements reflect stages 5 and 6.
We want to investigate properties of 2-4!**

Probes for all stages …



time

γ π ϕ **Jet** pK γ π e Λ $c\bar{c}$ μ

freeze-out

expansion

hadronization

formation of QGP and thermalization

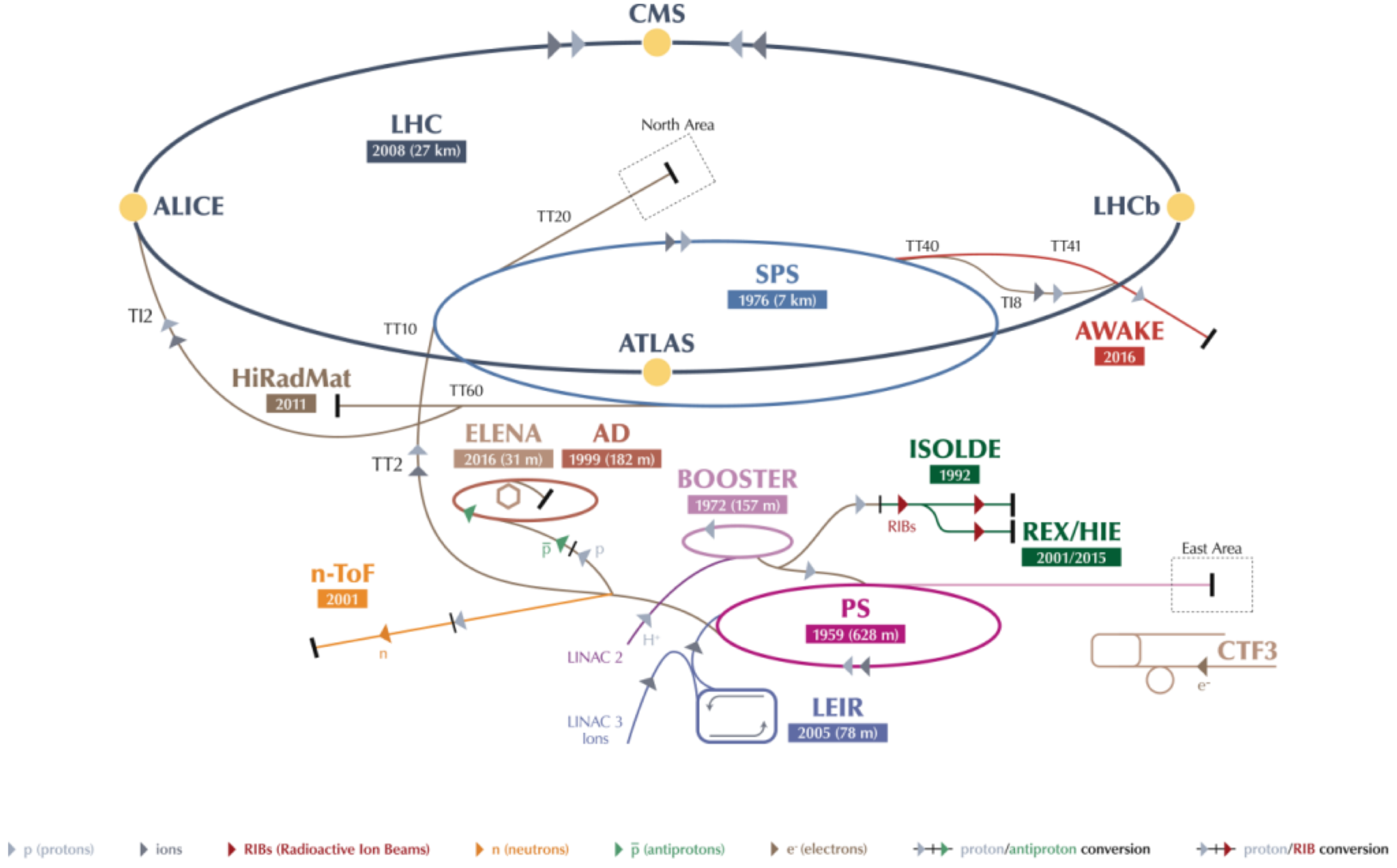
QCD tests:
confinement
chiral symmetry

hard parton scattering

space

A A

The CERN accelerator complex



LHC Large Hadron Collider SPS Super Proton Synchrotron PS Proton Synchrotron AD Antiproton Decelerator CTF3 Clic Test Facility

AWAKE Advanced WAKefield Experiment ISOLDE Isotope Separator OnLine REX/HIE Radioactive EXperiment/High Intensity and Energy ISOLDE

LEIR Low Energy Ion Ring LINAC LINear ACcelerator n-ToF Neutrons Time Of Flight HiRadMat High-Radiation to Materials

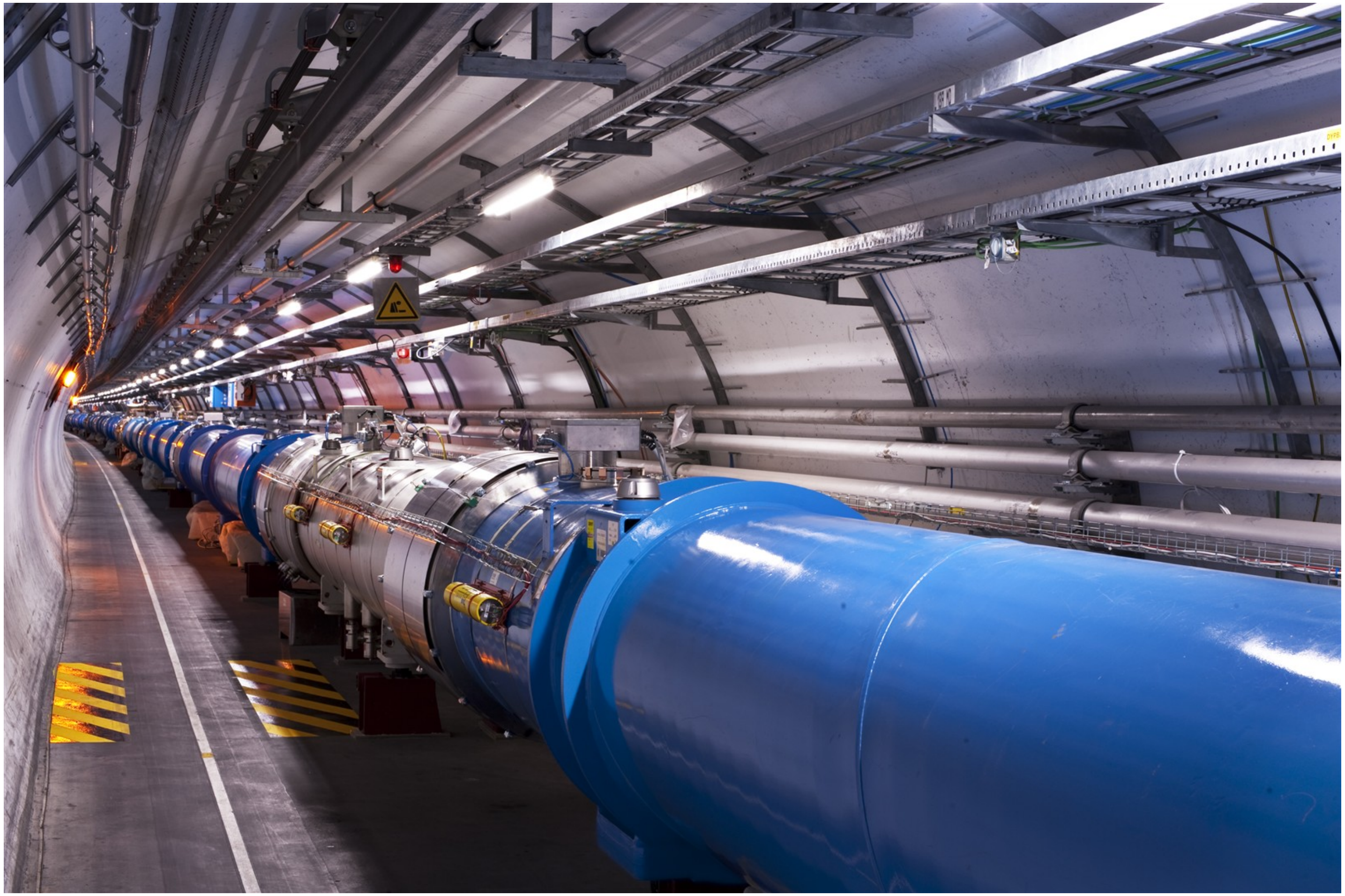
The CERN accelerator complex

Tunnel: ~100 m below ground

LARGE Hadron Collider

©2011 Google - Grafiken ©2011 TerraMetrics, Kartendaten ©2011 Tele Atlas - N

The LHC at CERN



- proton (or Pb ion) beams circle the ring about 11.000 times per second deflected by superconducting magnets at T = 1.9 K (superfluid He)
- produced the Higgs particle (H → γγ: ATLAS, CMS, 2012)
  - Nobel Prize 2013: P. Higgs, F. Englert

The LHC in numbers

- ~27 km long, 8 arcs (~3 km),
  each 46 x (1 quadrupole + 3 dipole magnets)
- 8 straight sections:
  RF cavities (IP4) + beam cleaning (IP3,7), dump (IP6)
- 1232 superconducting dipoles (+ 3700 correctors);
  392 quadrupoles (+ 2500 correctors);
  8 RF cavities/beam (400 MHz);
  108 collimators and absorbers
- cooled with 120 tons of He at 1.9 K; B = 8.33 T (1.5 kA/mm^2)
- 2808 bunches per ring, each with 1.15 x 10^{11} protons (8 min filling)
  592 bunches per ring, each with 7 x 10^7 Pb ions
- transverse beam size: $\sigma_{x,y}$ = 16 μm; bunch length: σ_z = 7.6 cm
- beam kinetic energy: 362 MJ per beam (1 MJ melts 2 kg copper)
  → equivalent to the ICE train (200 tons) at 200 km/h
- total electromagnetic energy stored (dipoles only): 8.5 GJ!

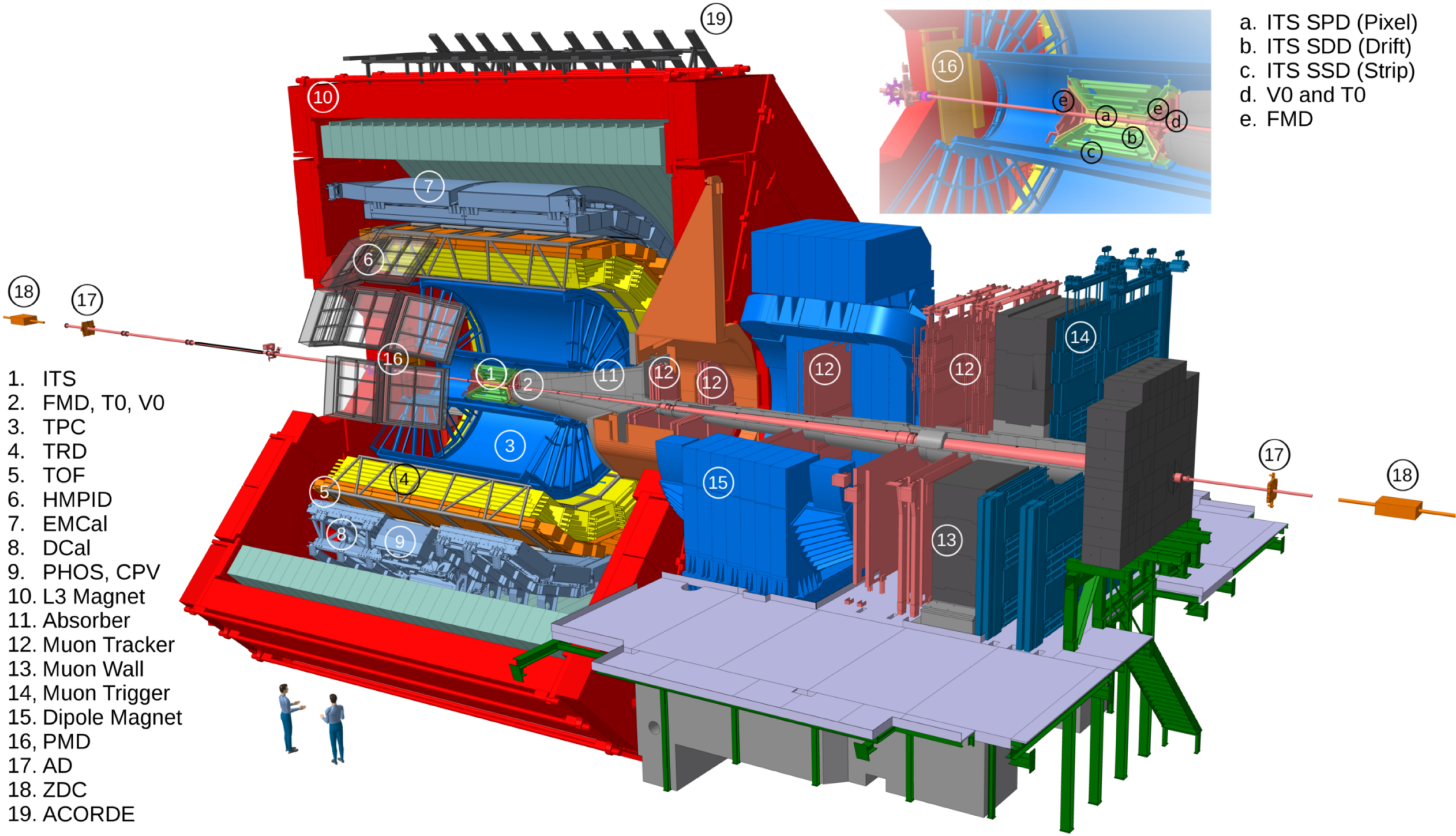
Conditions achieved

(extracted from data and models, vs. collision energy)

- temperature
  - T = 100-500 MeV (1 MeV ~ 10^{10} K, a million times temperature at the center of the Sun)
- pressure
  - P = 100-300 MeV/fm^3 (1 MeV/fm^3 ~ 10^{28} atmospheres, center of Earth: 3.6 million atm)
- density
  - ρ = 1-10 ρ_0 (ρ_0 density of a Au nucleus = 2.7 x 10^{14} g/cm^3, density of gold = 19 g/cm^3)
- volume
  - about 2000 fm^3 (1 fm = 10^{-15} m)
- life time
  - about 10 fm/c (or about 3 x 10^{-23} s)

a truly extreme femto world

A detector at the LHC - ALICE



a. ITS SPD (Pixel)
b. ITS SDD (Drift)
c. ITS SSD (Strip)
d. V0 and T0
e. FMD

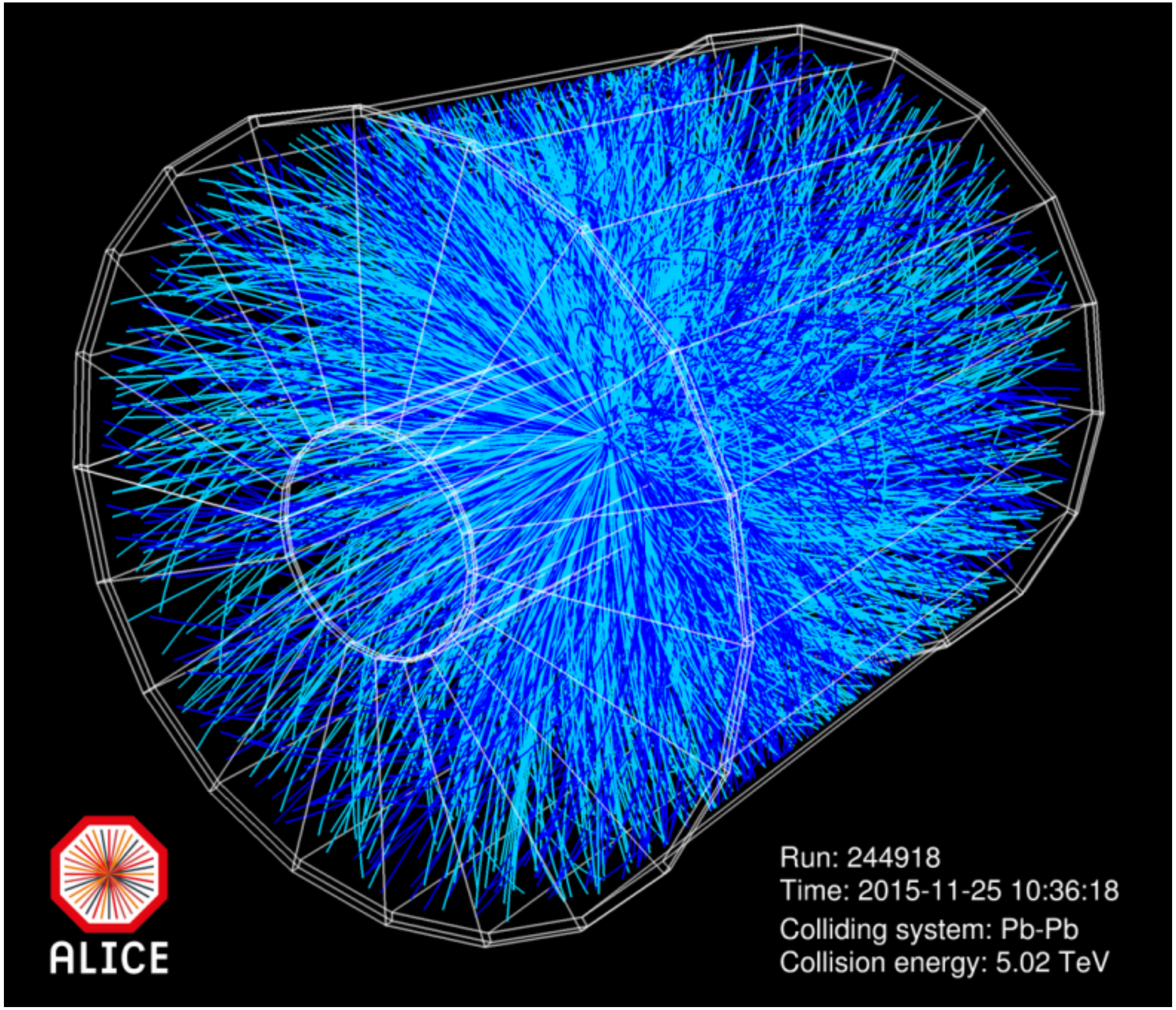
1. ITS
2. FMD, T0, V0
3. TPC
4. TRD
5. TOF
6. HMPID
7. EMCal
8. DCal
9. PHOS, CPV
10. L3 Magnet
11. Absorber
12. Muon Tracker
13. Muon Wall
14, Muon Trigger
15. Dipole Magnet
16, PMD
17. AD
18. ZDC
19. ACORDE

What do we measure?

- symmetric collisions of heavy nuclei (Pb-Pb, Au-Au) with proton-nucleus (p-Pb, d-Au) and proton-proton collisions as reference
- measurement of
  - charged particles, but neutral ones too (via their decays), photons
  - amount of particles (count tracks assembled from detector points)
  - momentum (via track curvature in magnetic field) or energy (via calorimetry) or velocity (via time-of-flight measurement, $\sigma \sim 80$ ps)
  - identify particles via their energy deposit in detector or via ToF or via invariant mass measurement
  - correlations between particles (in each collision)
  - focus on measurements in the transverse direction ($y, \eta \sim 0$) to separate from beam movement
  - single particle detection efficiency: ~70-80 %

Pb-Pb collision seen with ALICE

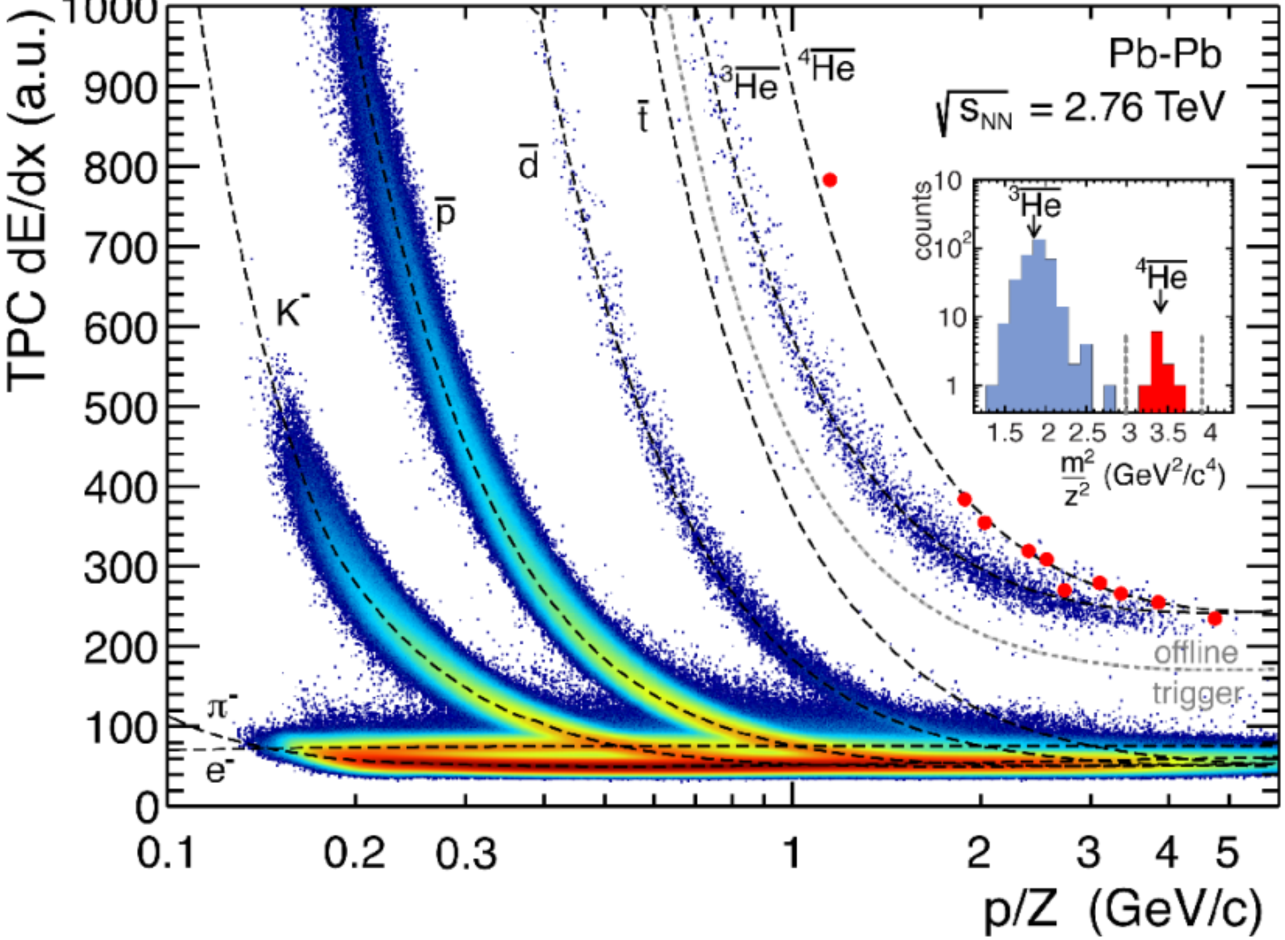
- „camera“: Time Projection Chamber
  - 5 m length, 5 m diameter, 500M „pixels“
    → few 100 pictures per second (preparing for 50000)



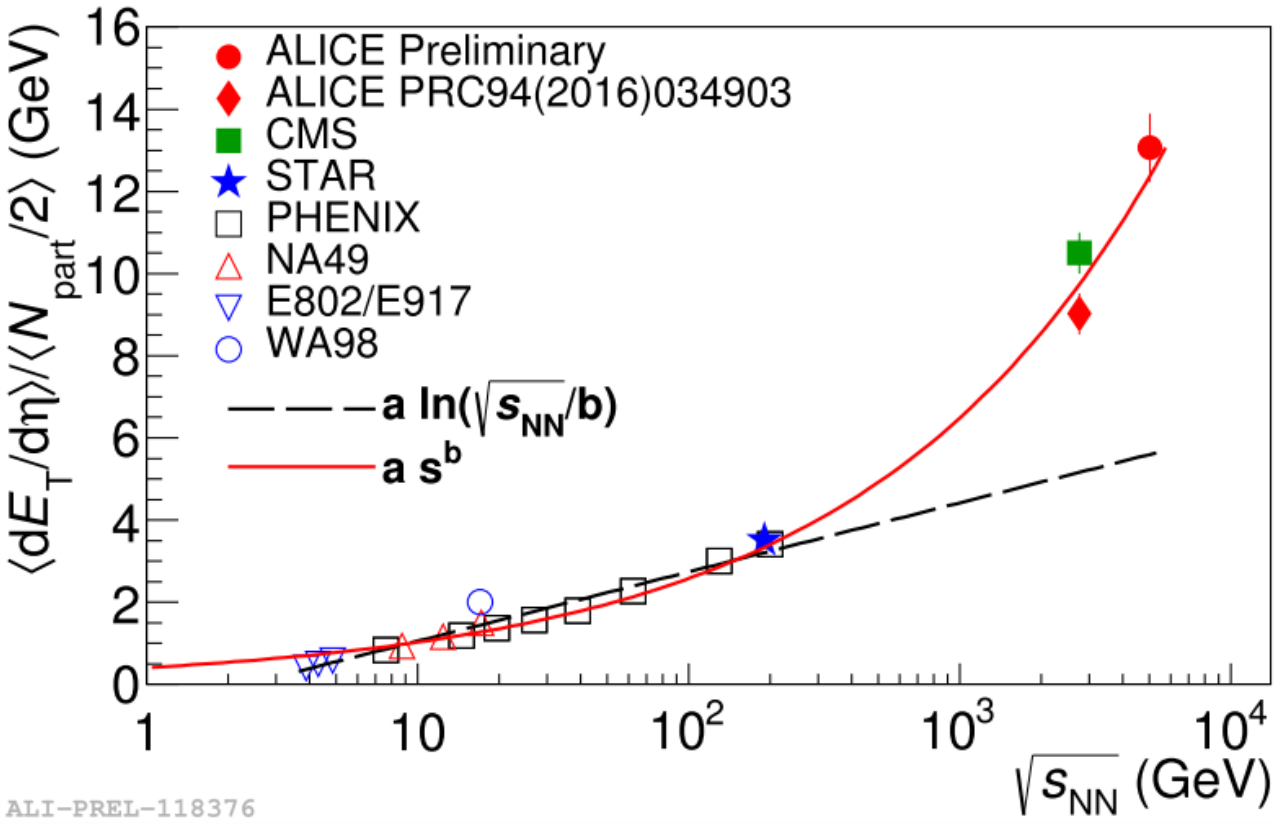
central Pb-Pb collision with total collision energy > 1 PeV: ~3200 primary, charged particle tracks in $|\eta|<0.9$

Particle identification

- p/Z from track curvature in magnetic field of B = 0.5 T
- ionization energy loss dE/dx from truncated mean of 159 samples along the track with resolution ~5.8 %
- m^2/Z^2 via time-of-flight with resolution ~80 ps



Energy density in AA collisions



E_T: transverse energy

ε_{LHC} ~ 20-40 GeV/fm^3

(much above ε_c)

ε_{FAIR} ~ 1 GeV/fm^3

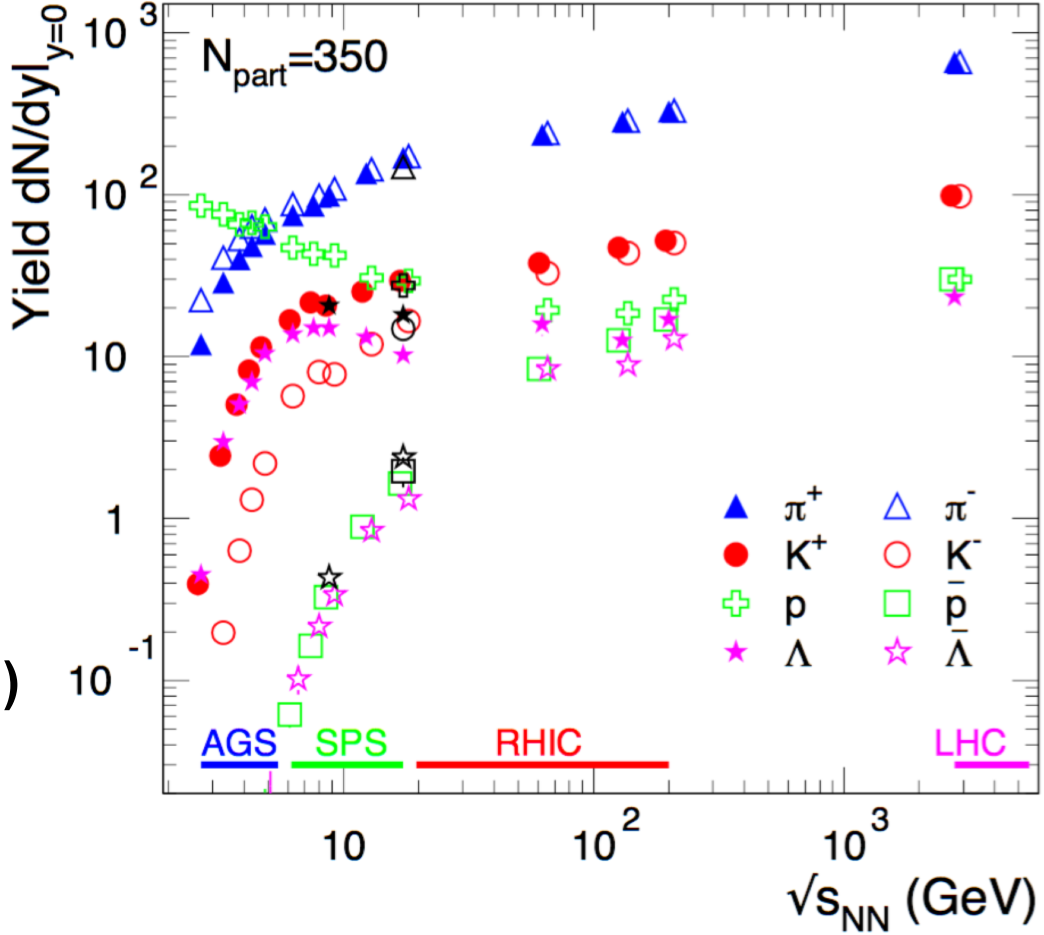
(around ε_c)

- **Bjorken model (1983): self-similar (Hubble-like) homogeneous (hydrodynamic) expansion of the fireball in longitudinal (beam) direction**
- **energy density: $\varepsilon = 1/A_T \, dE_T/dy \, 1/(c\tau)$**
  - **$A_T = \pi R^2$: transverse area (Pb-Pb: A_T = 154 fm^2)**
  - **τ ~ 1 fm/c: formation/equilibration time → not measureable!**

Chemical decoupling: hadron yields

- hadron yields in central collisions
- lots of particles, mostly newly produced ($m = E/c^2$)
  - a variety of species
    - $\pi^\pm$, m = 140 MeV
    - $K^\pm$, m = 494 MeV
    - p, m = 938 MeV
    - Λ, m = 1116 MeV
    - Ξ, Ω, ...
  - mass hierarchy in the production (low energy: u,d quarks remnants from the incoming nuclei)

A. Andronic, arXiv:1407.5003



Thermal fits of hadron yields

- hadron gas: grand-canonical ensemble

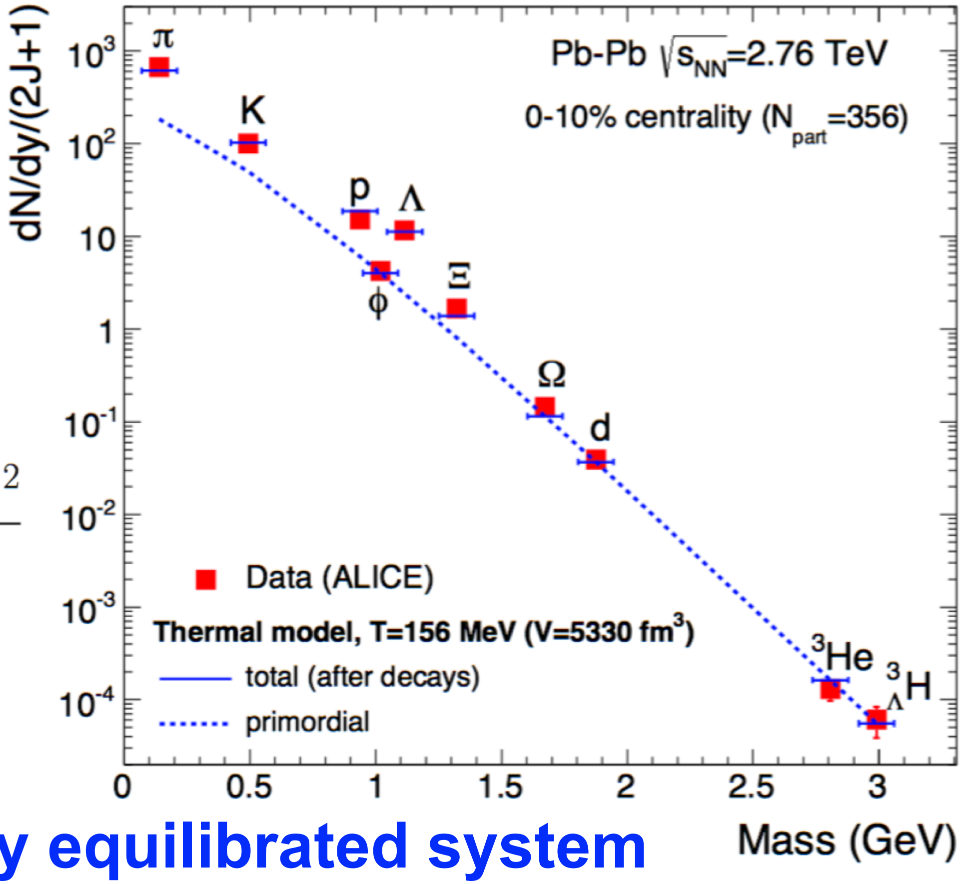
$$n_i = N_i/V = -\frac{T}{V}\frac{\partial \ln Z_i}{\partial \mu} = \frac{g_i}{2\pi^2}\int_0^\infty \frac{p^2 \mathrm{d}p}{\exp[(E_i - \mu_i)/T] \pm 1}$$

- quantum number conservation

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

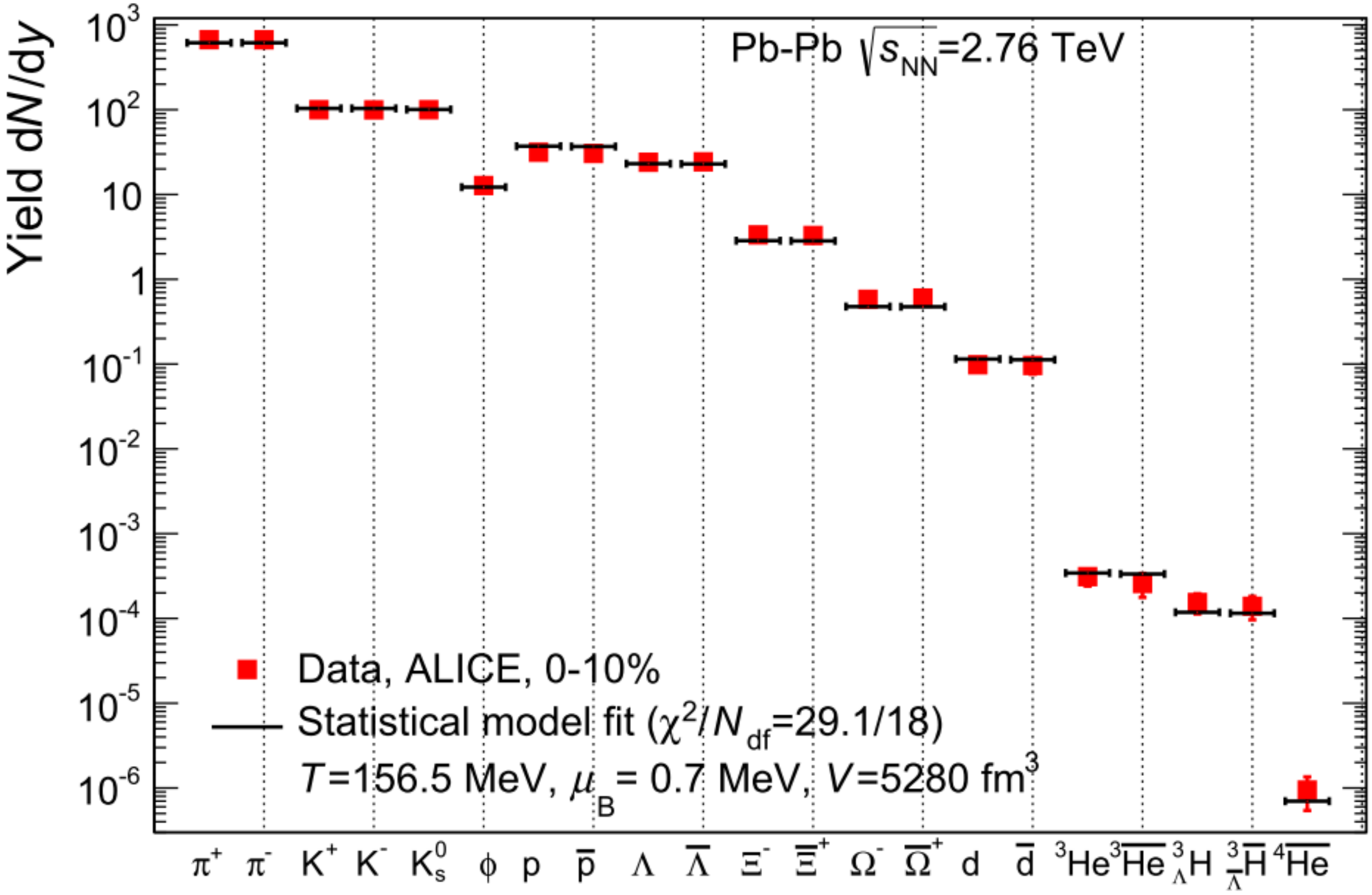
- hadron properties from PDG (up to m = 3 GeV, 500 species)
- minimize $\chi^2 = \sum_i \frac{(N_i^{exp} - N_i^{therm})^2}{\sigma_i^2}$
  → (T, μ_B, V)
  → all hadron yields
- hadron abundances in agreement with a thermally equilibrated system

A. Andronic, arXiv:1407.5003



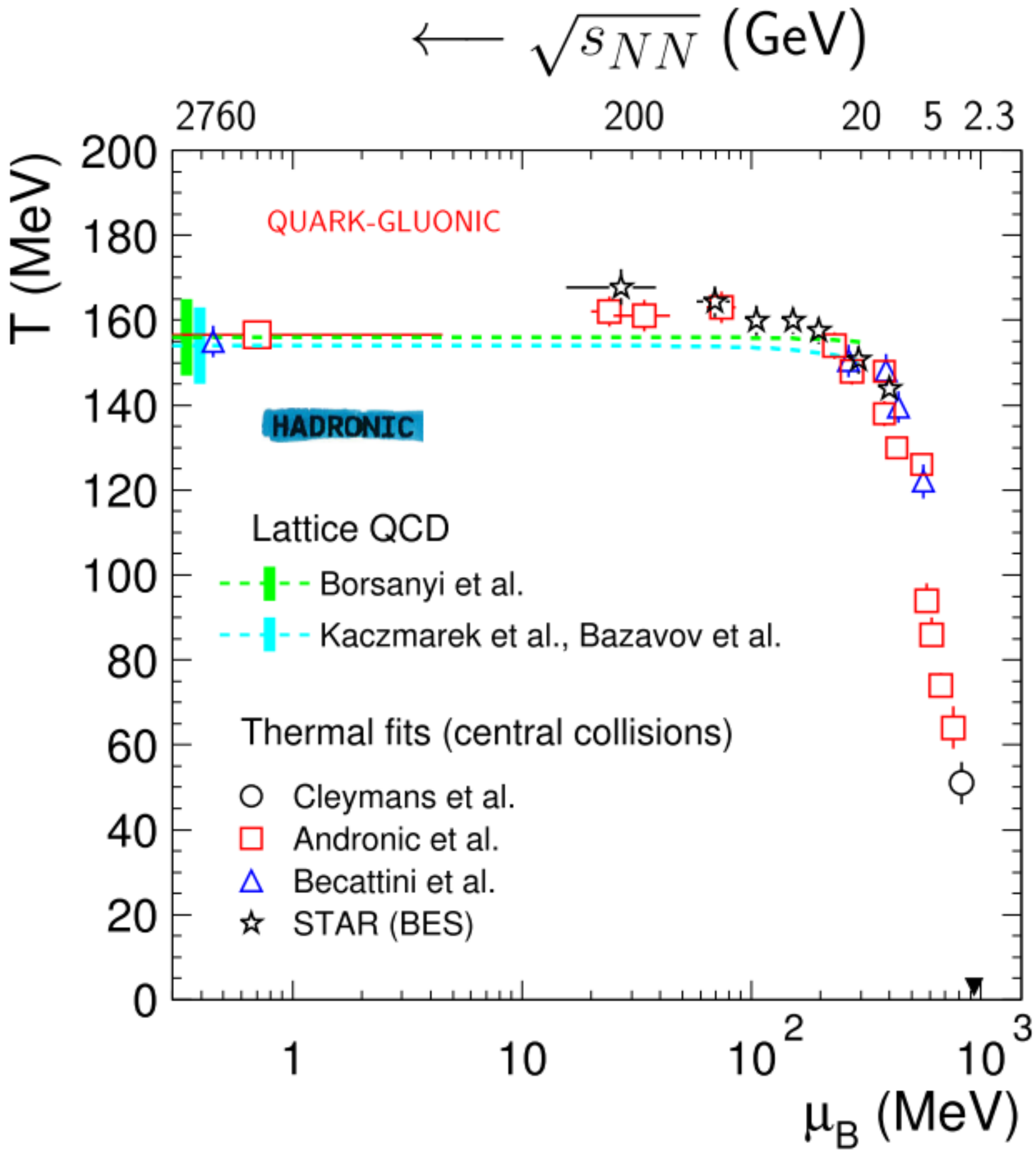
From quarks and gluons to hadrons

- matter and antimatter produced in equal amounts in high-energy Pb-Pb collisions at the LHC



→ laboratory creation of a piece of hot Universe (when it was ~10 μs old): T ~ 10^{12} K

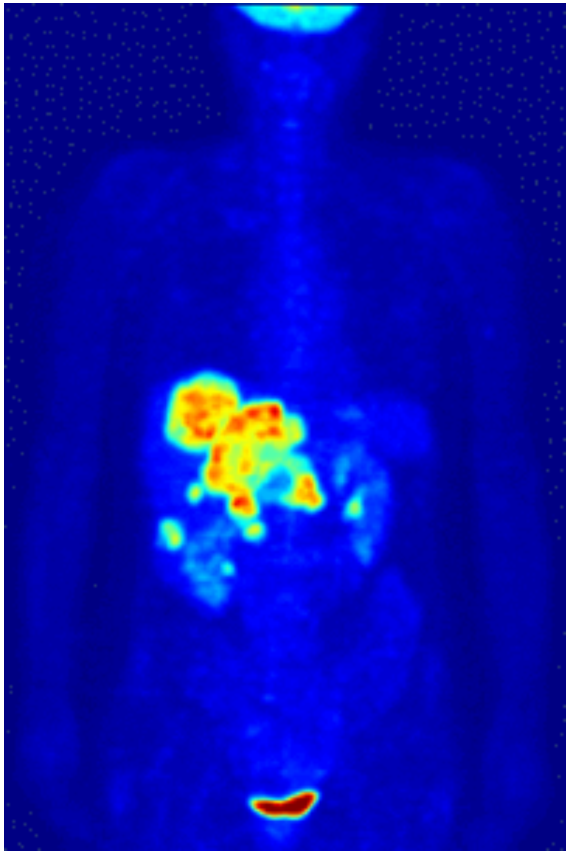
Chemical freeze-out curve



- at the LHC: remarkable „coincidence“ with lattice QCD results
- μ_B ~ 0 (at LHC):
  - purely produced (anti)matter (m = E/c^2), as in the early Universe
- μ_B > 0:
  - more matter, from „remnants“ of the colliding nuclei
- μ_B ~ 400 MeV:
  - critical point awaiting discovery (at FAIR?)

Hard probes for hot matter

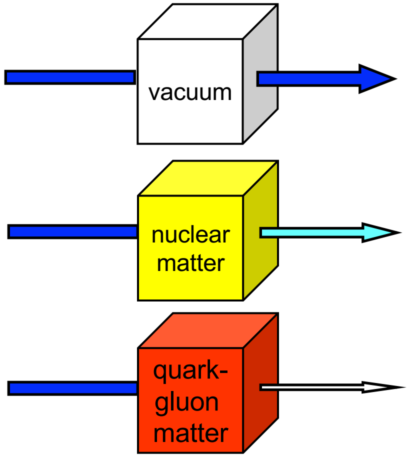
- going back to 1909
  - Geiger, Marsden, and Rutherford discover the atomic nucleus via scattering of α particles on a gold foil
- tomography – studying matter with probes



  - calibrated probe
  - calibrated interaction

  → scattering experiment to study properties of matter
- at the LHC
  - external probe not available
  - probe has to be "auto generated" in the earliest phase of the collision

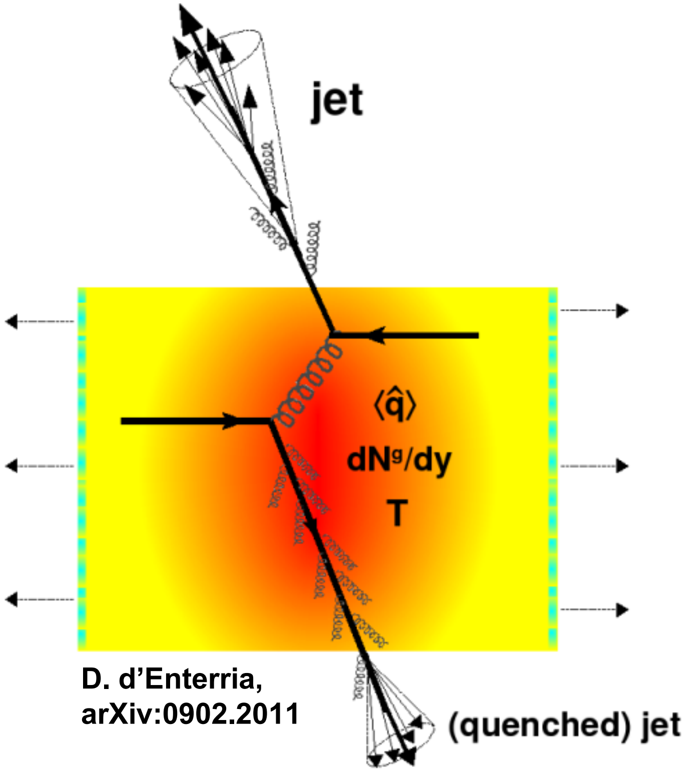
  → hard scattering processes of partons!



Jet quenching: the idea

- “hard” probes: E >> T
  - jets (sprays of hadrons from high-momentum quarks or gluons)
  - high-p_T hadrons (“leading” hadrons from jets)
  - heavy quarks (charm or bottom)
- hard probes for hot matter
  - produced very early in the collision (t ~ 1/E)
  - q, $\bar{q}$, g travel through QGP and loose energy (“jet quenching”)
  - hadronize (neutralize color picking up partners from the vacuum)
  - hadrons travel towards detector
  - jet quenching
    → deficit of high-momentum hadrons in Pb-Pb collisions compared to pp (properly scaled for geometry)
  - quantified by the nuclear modification factor

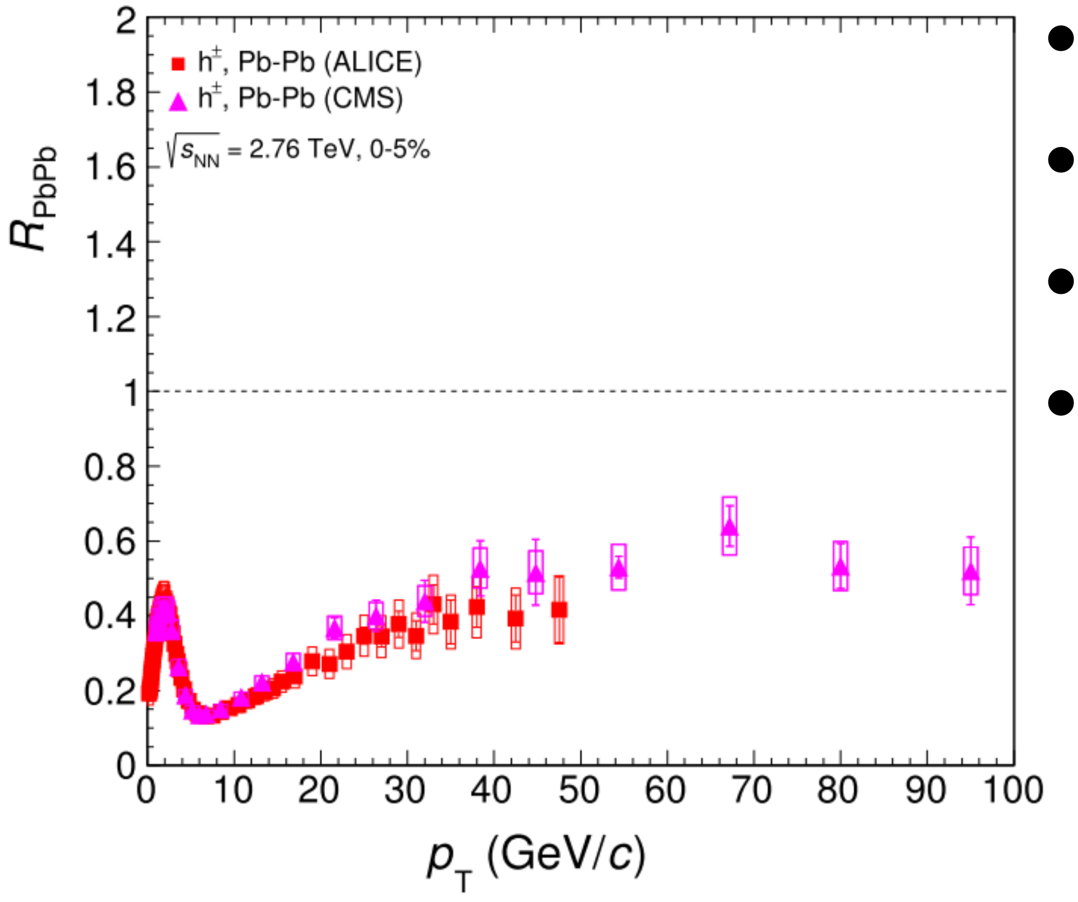
$$R_{AA} = \frac{\mathrm{d}N_{AA}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}{N_{coll}\cdot\mathrm{d}N_{pp}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}$$



D. d’Enterria, arXiv:0902.2011

Jet quenching at the LHC

- **measured via “leading hadrons” ($h^{\pm}$)**

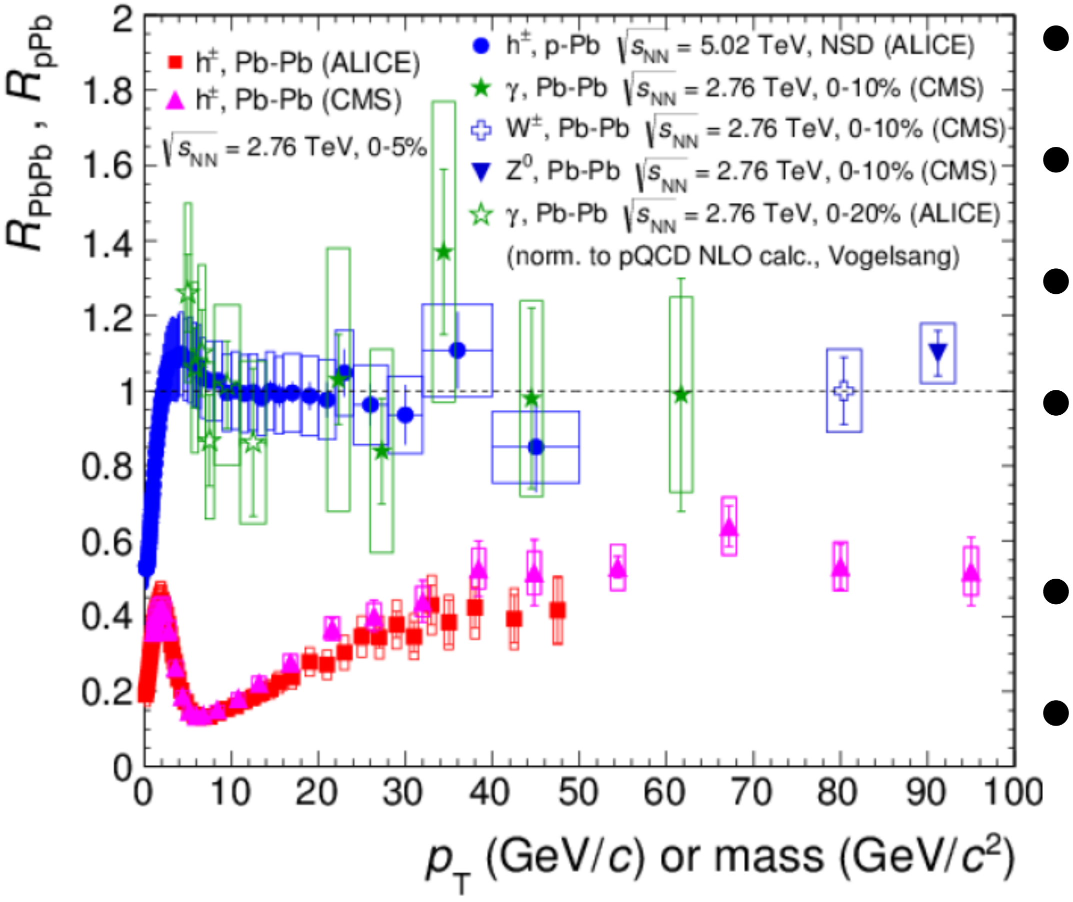


- **stronger than measured at RHIC (where it was discovered)**
- **reaching a suppression factor of ~7 at p_T ~ 7 GeV/c**
- **remains substantial even at 50-100 GeV/c**
- **observed also for reconstructed jets (ALICE; ATLAS, CMS)**

ALICE: PLB 720(2013)52
CMS: EPJC 72(2012)1945

Jet quenching at the LHC

- measured via “leading hadrons” ($h^\pm$)



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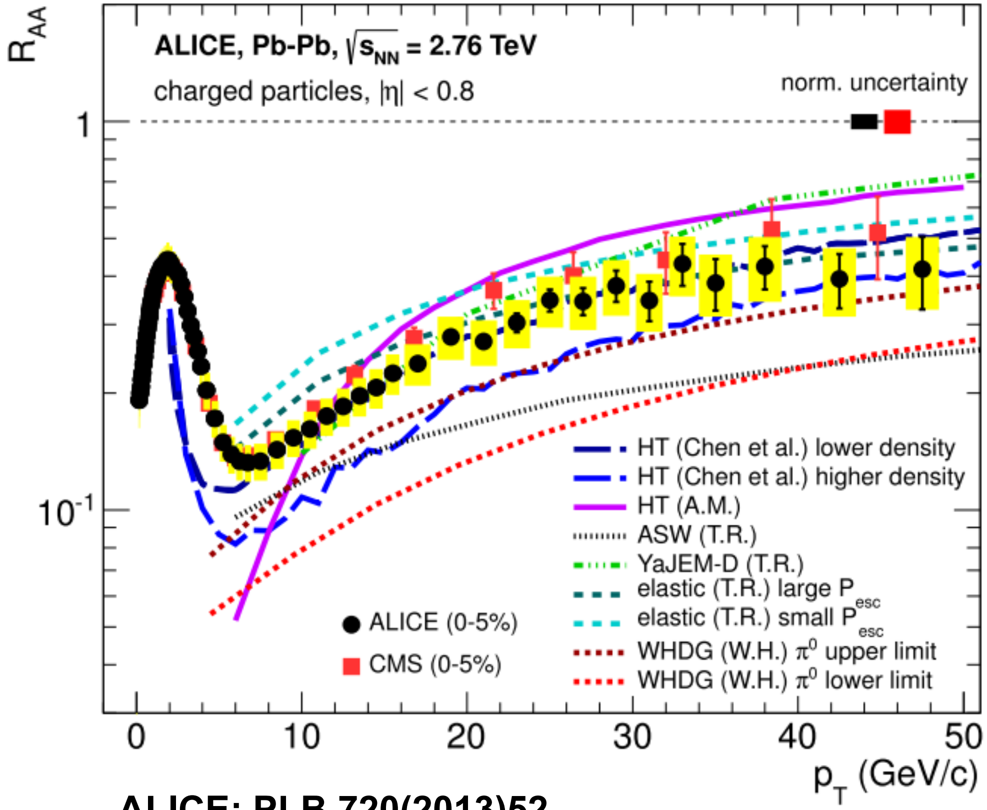
- **reaching a suppression factor of ~7 at p_T ~ 7 GeV/c**
- **remains substantial even at 50-100 GeV/c**
- **observed also for reconstructed jets (ALICE; ATLAS, CMS)**

- **NOT seen for hard, electroweak probes (γ, $W^\pm$, Z^0)**
- **NOT seen in in p-Pb collisions (p_T < 3 GeV/c: gluon saturation)**

ALICE: EPJC 74(2014)3054
and references therein

Jet quenching at the LHC

- can be explained theoretically only when considering a high-density partonic medium at initial T ~ 500 MeV



ALICE: PLB 720(2013)52

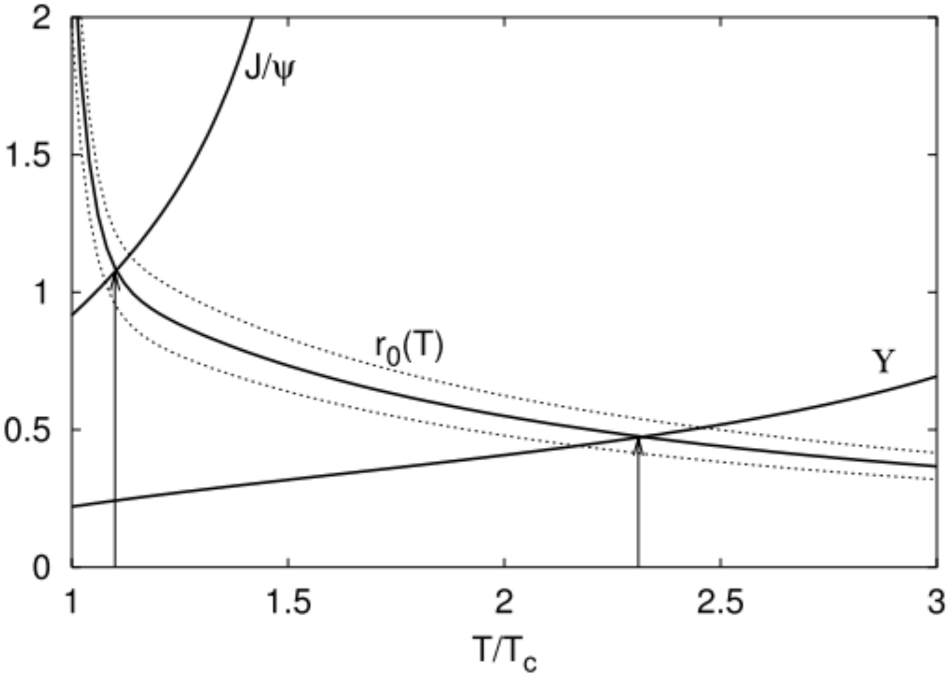
- energy loss mechanisms: collisional, gluon radiation (different T and L dependence)
- models: MC shower, analytic
- notable recent advances in conceptual understanding (Y. Mehtar-Tani, arXiv:1602.01047)
- determination of transport coefficient ($\hat{q} = d\langle k_T^2\rangle/dx$) in sight (JET Collab., PRC 90(2014)014909)

- note: bulk hadron production (~ N_{part}) and radial flow (~ 65% c) are relevant at low p_T (below 4-5 GeV/c)

Charmonium and deconfined matter

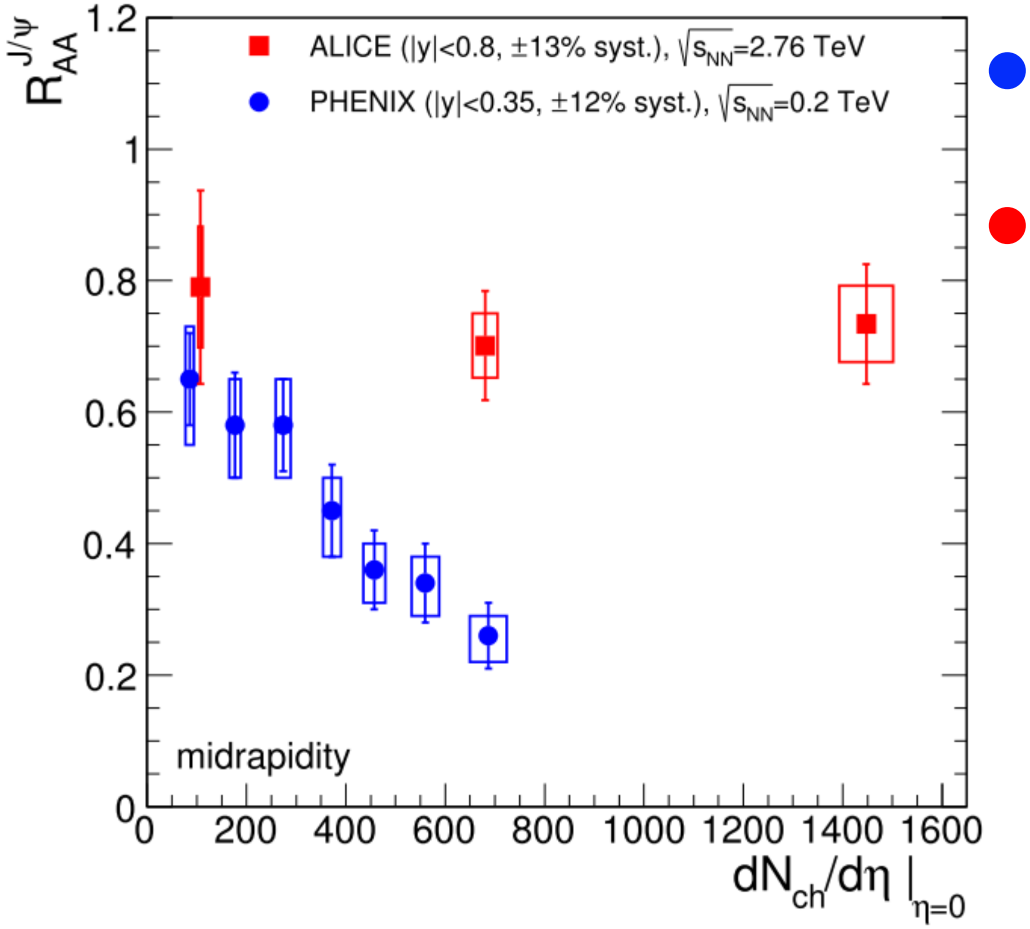
- idea considered originally as “smoking gun” for QGP formation: Matsui & Satz, PLB 178(1986)178
  - “If high energy heavy-ion collisions lead to the formation of a hot quark-gluon plasma, then color screening prevents $c\bar{c}$ binding in the deconfined interior of the interaction region.”
- “Debye screening”: no J/ψ formation if $r_{J/\psi} > \lambda_D$
- refinement: sequential suppression (Digal et al., PRD 64(2001)75)
- Debye length in QGP: $\lambda_D \sim 1 / (g(T)\ T)$
- $r_{q\bar{q}} = f(T)$ (lattice QCD result)

→ $q\bar{q}$ “thermometer” of QGP



- thermal picture ($n_{partons} = 5.2\ T^3$ for 2 flavors)
  → for T = 500 MeV: $n_{partons} \sim 85/\text{fm}^3$
  → mean separation $r \sim 0.2$ fm $< r_{J/\psi}$

Charmonium data: RHIC vs. LHC

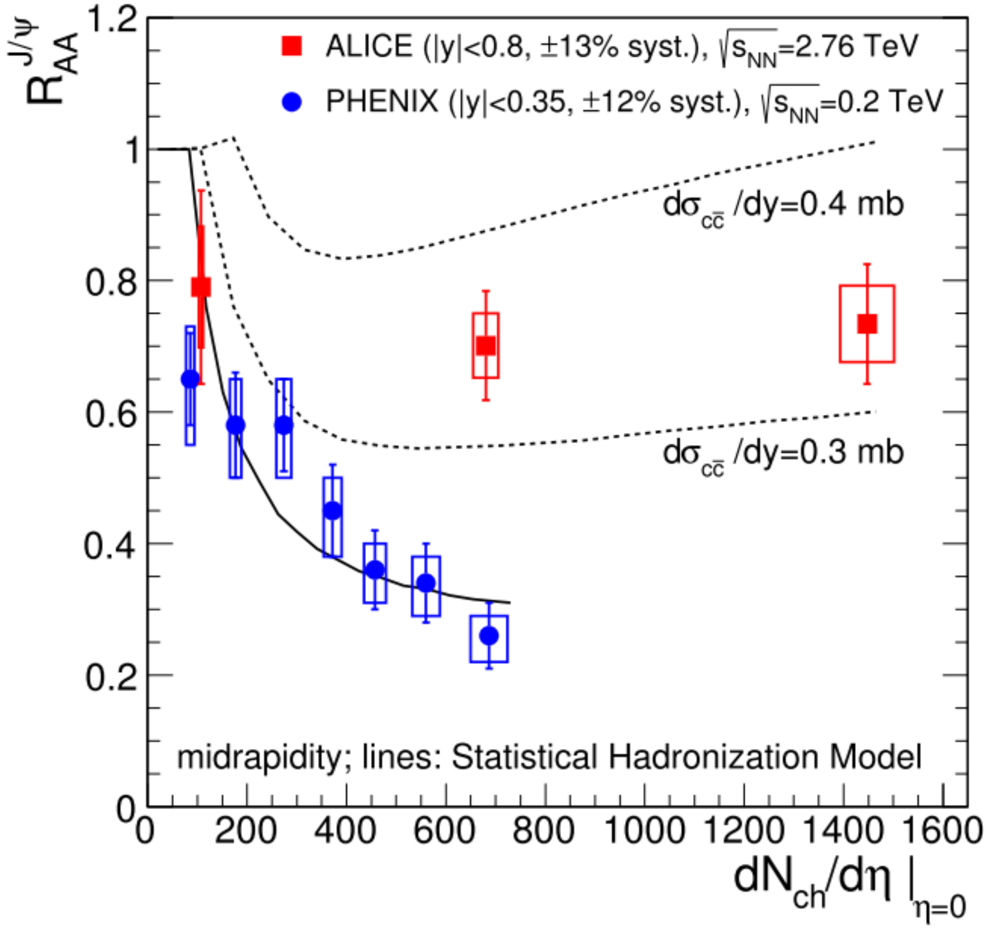


- suppression at RHIC ($\sqrt{s_{NN}}$ = 0.2 TeV)
- dramatically different at LHC

$dN_{ch}/d\eta \sim \varepsilon$ (>16 GeV/fm^3 for $dN_{ch}/d\eta \sim 1500$)

ALICE, PLB 734(2914)314

Charmonium data: RHIC vs. LHC



- suppression at RHIC ($\sqrt{s_{NN}}$ = 0.2 TeV)
- dramatically different at LHC
  - statistical hadronization model $N_{J/\psi} \sim (N_{c\bar{c}}^{dir})^2$
  - what is so different at the LHC (compared to RHIC)?
    - ~10 x larger charm cross section
    - ~2.2 x larger volume
  - what to conclude?
    - charmonium R_{AA} is NOT a QGP thermometer
    - smoking gun for deconfinement?
    - J/ψ (charm) is another observable for the phase boundary (calculations are for T = 156 MeV)

$dN_{ch}/d\eta \sim \varepsilon$ (>16 GeV/fm^3 for $dN_{ch}/d\eta \sim 1500$)

ALICE, PLB 734(2914)314
A. Andronic et al., PLB 652(2007)259