PART III

Plasma of quarks and gluons

Content

- Introduction to Quark Gluon Plasma (QGP)
- Creation of QGP, asymptotic freedom, ideal gas of quarks and gluons, "bag" model
- Phase transition to QGP
- Ion collisions and components of the ion-ion collision
- QGP experimental signatures
- Experimental status
  [source: "Advances in Quark Gluon Plasma", G.M.Garcia, arXiv:1304.1452]
- QGP and cosmology
  [source: "Traveling through the Universe: back in time to the quark-gluon plasma era", J.Rafelski and J.Birrel, arXiv:1311.0075]

Introduction to QGP

- "Electromagnetic" plasma (or "chemical" plasma)
  - obtained when electrons and ions are free

    ⇒ appears when the energy given to the electron is larger than its binding energy

    ⇒ at the level of a few eV
    - Boltzmann constant $k = 8.617 \times 10^{-5}$ eV/K ⇒ (1 eV ⇔ 11600K)
- How to ionise a gas to create an "electromagnetic" plasma?
  - apply strong electric field
  - increase temperature
    - kinetic energy is larger than the binding energy ⇒ e^- are kicked off
  - increase pressure
    - decrease the distance between atoms ⇒ overlap ⇒ e^- not associated with a specific nucleus
- Extend this concept to the strong interaction ⇒ QGP

Creation of QGP

- Nucleus
  - density ≃ 0.13 hadron / fm^3
  - radius: $R_0 \simeq \kappa A^{1/3}\,\text{fm}$ (with experimental factor $\kappa \simeq 1.1 - 1.4$)

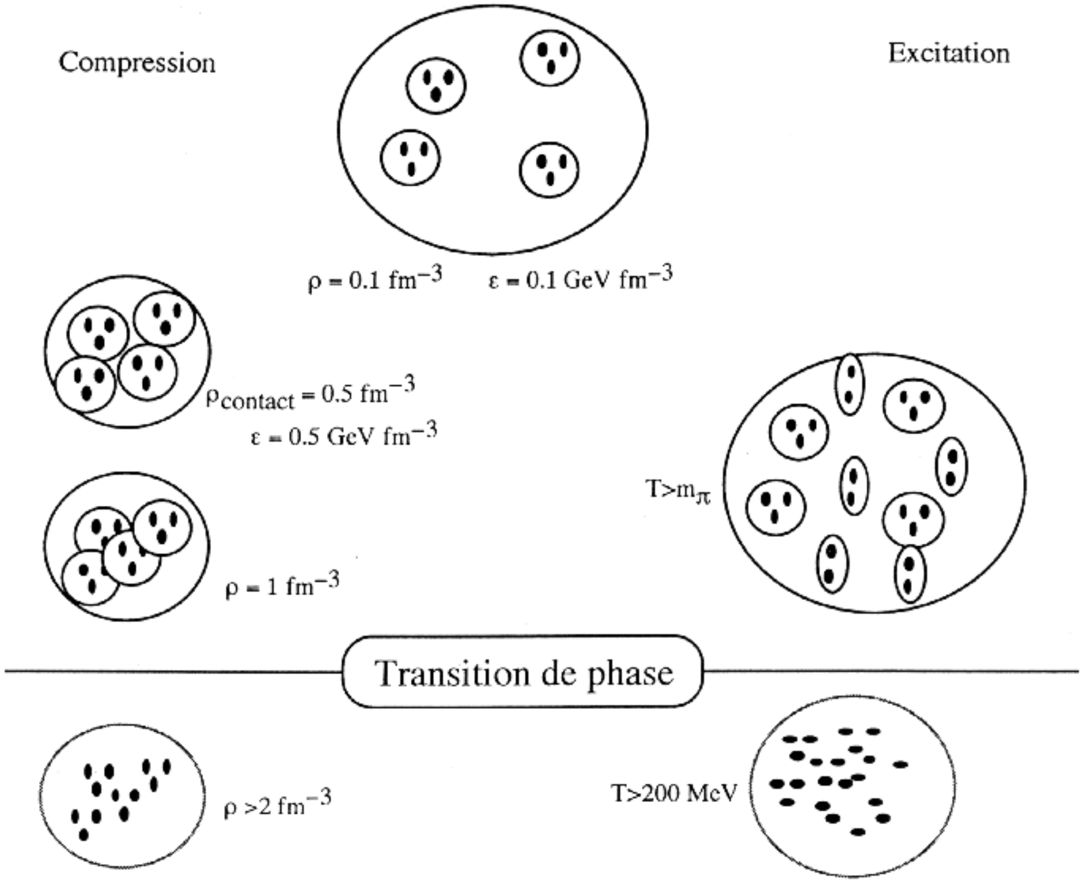
$$\rho_0 = \frac{A}{\text{Volume}} = \frac{A}{\frac{4}{3}\pi R_0^3} \approx \frac{1}{\frac{4}{3}\pi\kappa^3} \approx 0.13\text{n/fm}^3$$

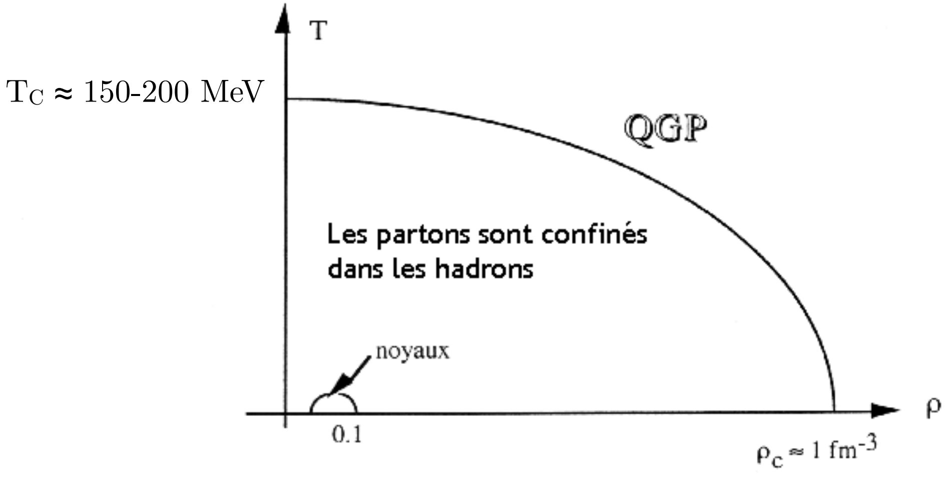
  - energy density: $$\epsilon_0 = \rho_0 \times m_{\text{proton}} \approx 0.13\text{GeV/fm}^3$$

- Initially: $T_0 \simeq 0\,\text{MeV}$ → compression ($T = \text{constant}$)
  - nucleon radius $\simeq 0.8\,\text{fm} \Rightarrow$ contact density $$\rho_{\text{contact}} \approx \frac{1}{\frac{4}{3}\pi 0.8^3} = 0.5\text{n/fm}^3$$
  - increase pressure such that $\rho \simeq 1\,\text{n/fm}^3 \Rightarrow$ wave functions overlap

  ⇒ deconfinement ⇒ free partons (quarks and gluons) ⇒ QGP!

QGP formation at densities $$\boxed{\rho > 10\rho_0 \approx 1\text{n/fm}^3}$$





- Temperature increase ↗
  - at $T \sim m_\pi$

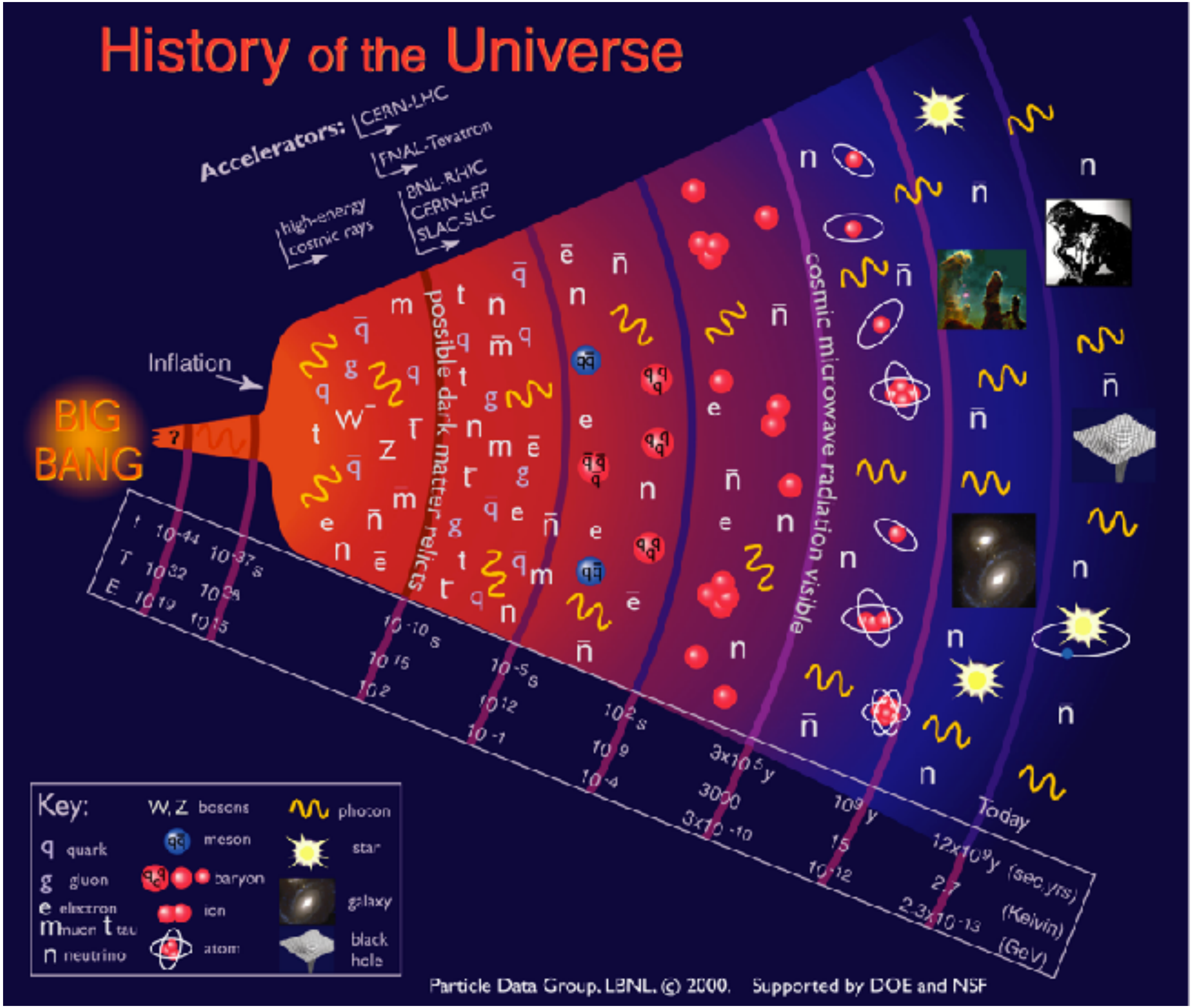
    ⇒ creation of quark pairs is possible

    ⇒ creation of pions
  - at $T_c \sim 150\,\mathrm{MeV}$

    ⇒ pions and nucleons mix

    ⇒ “deconfinement”

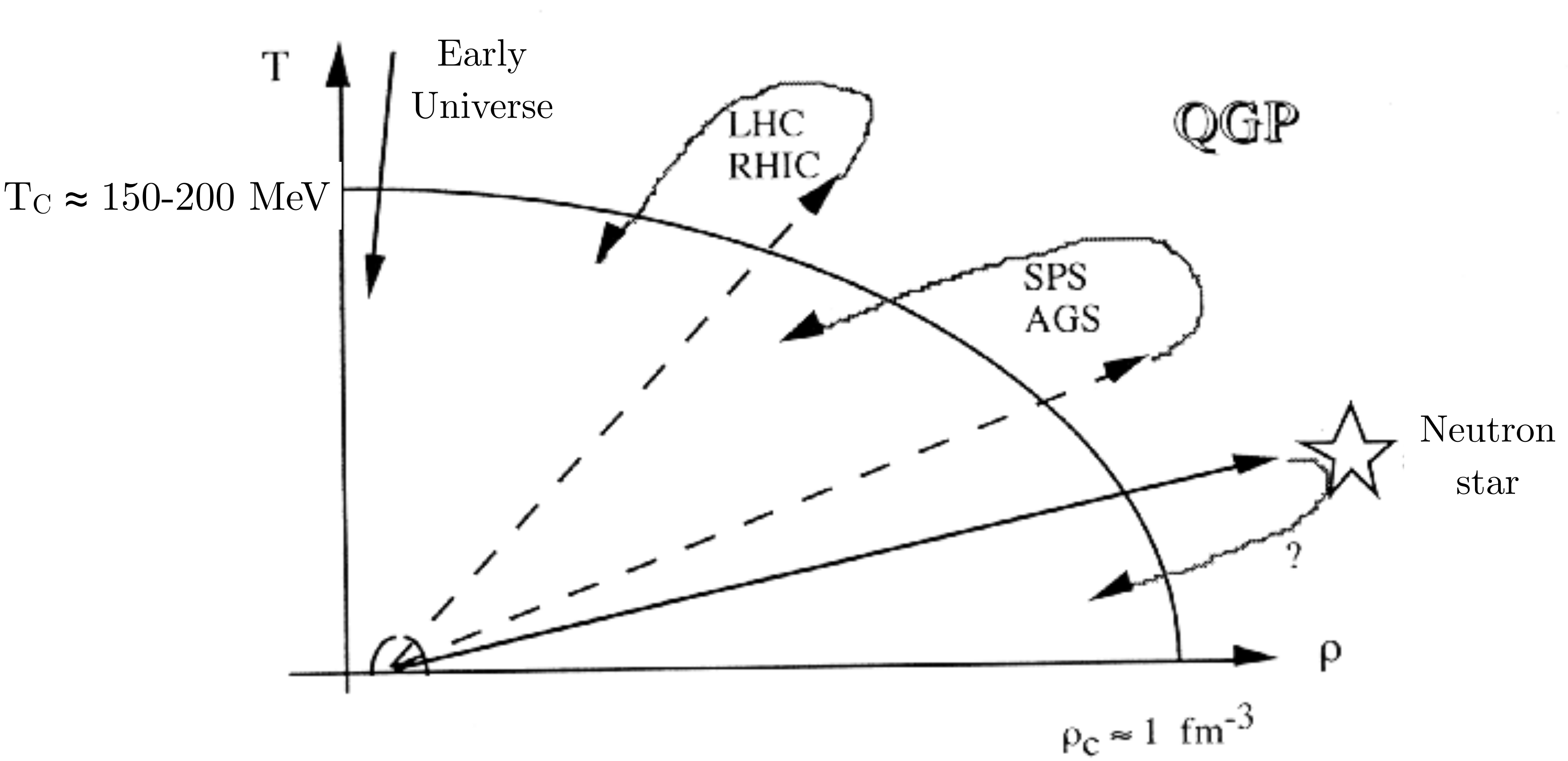
    ⇒ QGP ($T_c \sim 10^{12}\,\mathrm{K}$)
  - $T > 10^{16}\,\mathrm{K}$ ⇒ black holes?
  - $T > 10^{32}\,\mathrm{K}$⇒ superstring gas?



Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

(T, ρ) phase diagram

- Trajectories in the (T, ρ) phase diagram for various "objects"
  - the Universe
  - neutron star
  - collisions of ions at accelerators



Asymptotic freedom

- In QCD, the strong interaction becomes weak at large energies

$$\alpha_s(q^2) \approx \frac{\alpha_s(q_0^2)}{1 + \beta_s \ln \frac{q^2}{q_0^2}} \qquad \beta_s = \alpha_s(q_0^2)\frac{11N_c - 2N_f}{12\pi}$$

  - high q^2 ⇒ high E ⇒ creation of quark pairs ⇒ screening at short distances ⇒ reduced interaction strength

- At the Z^0 mass, $\alpha_s = 0.12 \;\Rightarrow\; \alpha_s(q_0^2 = (91.2)^2\,\mathrm{GeV}^2) = 0.12$

- For large q^2, use approximation: $$\alpha_s(q^2) = \frac{12\pi}{33 - 2N_f}\frac{1}{\ln \frac{q^2}{\Lambda^2_{\mathrm{QCD}}}}$$

- The number of quark flavours N_f depends on the energy of the system

- In most QGP we'll consider $\sim 1\,\mathrm{GeV/fm}^3 \Rightarrow N_f = 3$

- Effective qq potential $$V(r) = -\frac{4}{3}\alpha_s\frac{1}{r} + br$$

  - with string tension $b \simeq 1\,\mathrm{GeV/fm}$

quark	free-quark mass [MeV]
u	2.3 ± 0.7
d	4.8 ± 0.5
s	95 ± 5
c	1275 ± 25
b	~4500
t	~173000

Ideal gas of fermions and bosons

- Consider $\alpha_s \ll 1$ and chemical potential $\simeq 0$
- Quarks are fermions and gluons are bosons
  - energy density for bosons $\epsilon_i = g_i \tilde{\epsilon}$
  - energy density for fermions $\epsilon_i = \frac{7}{8} g_i \tilde{\epsilon}$
  - g_i is the number of degrees of freedom (degeneracy of species i)
  - with $\tilde{\epsilon} = \frac{\pi^2}{30} T^4$
- Total energy density $\epsilon = \left(\sum_{\text{bosons}} g_{\text{b}} + \frac{7}{8} \sum_{\text{fermions}} g_{\text{f}} \right) \frac{\pi^2}{30} T^4$
- Pressure $P = \frac{1}{3} \epsilon$

Ideal gas of quarks and gluons

- photons
  - $g_\gamma = 2$ ($m_\gamma = 0 \Rightarrow 2\,\text{polarisations}$) $\Rightarrow$ $\epsilon_\gamma = \dfrac{\pi^2}{15} T^4$
- gluons
  - $g_g = 8_{\text{gluons}} \times 2_{\text{polarisation}} = 16$ $\Rightarrow$ $\epsilon_g = \dfrac{8\pi^2}{15} T^4$
- quarks
  - $g_q = 2_{\text{spins}} \times 3_{\text{colors}} \times 2_{\text{antiparticles}} \times N_f = 12 \times N_f$ $\Rightarrow$ $\epsilon_q = \dfrac{7\pi^2}{20} T^4 N_\mathrm{f}$

- For quarks and gluons: $g_\mathrm{tot} = g_\mathrm{g} + \dfrac{7}{8} g_\mathrm{q}$
  - at $T = 1\,\text{MeV}$, we have $N_f = 0$ $\Rightarrow g_\text{tot} = 16$
  - at $T < m_s \Rightarrow N_f = 2\,(u, d\,\text{quarks})$ $\Rightarrow g_\text{tot} = 37$
  - at $T = 1\,\text{GeV} \Rightarrow N_f = 3\,(u, d, s\,\text{quarks})$ $\Rightarrow g_\text{tot} = 47.5$

Plasma properties

- Total plasma energy density and pressure

$$\epsilon = g_{\text{tot}}\frac{\pi^2}{30}T^4 + B \approx \frac{4\pi^2}{3}T^4 + B$$

$$P = \frac{1}{3}g_{\text{tot}}\frac{\pi^2}{30}T^4 - B \approx \frac{1}{3}\epsilon - \frac{4}{3}B$$

  - B is a phenomenological constant to account for interactions in the system. It is equal to the difference in energy density for vacuum with free or confined quarks
    (B can be interpreted as a type of latent heat)
  - $B \simeq 170\,\text{MeV/fm}^3 \Rightarrow B^{1/4} = (170\,\text{MeV/fm}^3(\hbar c)^3)^{1/4} = 190\,\text{MeV}$
  - B reflects the fact that the chemical potential is non-zero
  - B can be understood within the “bag model” (developed at MIT)

For conversions, use $\hbar c = 197\,\text{MeV fm}$

The Bag Model

- Hadron mass
  - $B \simeq 170\,\mathrm{MeV/fm^3}$
  - $C \simeq 6\,\mathrm{MeV\,fm}$

$$E = \frac{4}{3}\pi R^3 B + \frac{C}{R}$$

Energy to create the bag

Kinetic energy of quarks in the bag

- Confinement is the result of the equilibrium between the bag pressure B (inwards) and the kinetic pressure C (outwards)
- Inside the radius R, apply the Dirac equation $(\gamma^\mu p_\mu + m)\phi = 0$
- $m \to 0 \;\Rightarrow (\gamma^\mu p_\mu)\phi = 0 \Rightarrow p_0 R = 2.04$
- Total kinetic energy for N quarks: $E_{\mathrm{kin}} = N\dfrac{2.04}{R}$
- Equilibrium at minimum energy $\Rightarrow\; dE/dR = 0$

$$\Rightarrow \quad B = \frac{2.04N}{4\pi}\frac{1}{R^4}$$

- For baryons: $N = 3$ and $R = 0.8\,\mathrm{fm} \Rightarrow B \simeq 234\,\mathrm{MeV/fm^3}$

Hadron gas and QGP properties

- At low temperature, quarks "hadronise" into pions
  - 3 pions (isospin 1; spin 0) ⇒ $g_\pi = 3$
- At high temperature, formation of QGP
  - $g_{\mathrm{QGP}} \simeq 40$
- Energy densities

$$\epsilon_{\mathrm{QGP}} = g_{\mathrm{tot}} \frac{\pi^2}{30} T^4 + B = \frac{40}{30} \pi^2 T^4 + B$$

$$\epsilon_\pi = g_\pi \frac{\pi^2}{30} T^4 = \frac{\pi^2}{10} T^4$$

- Pressure

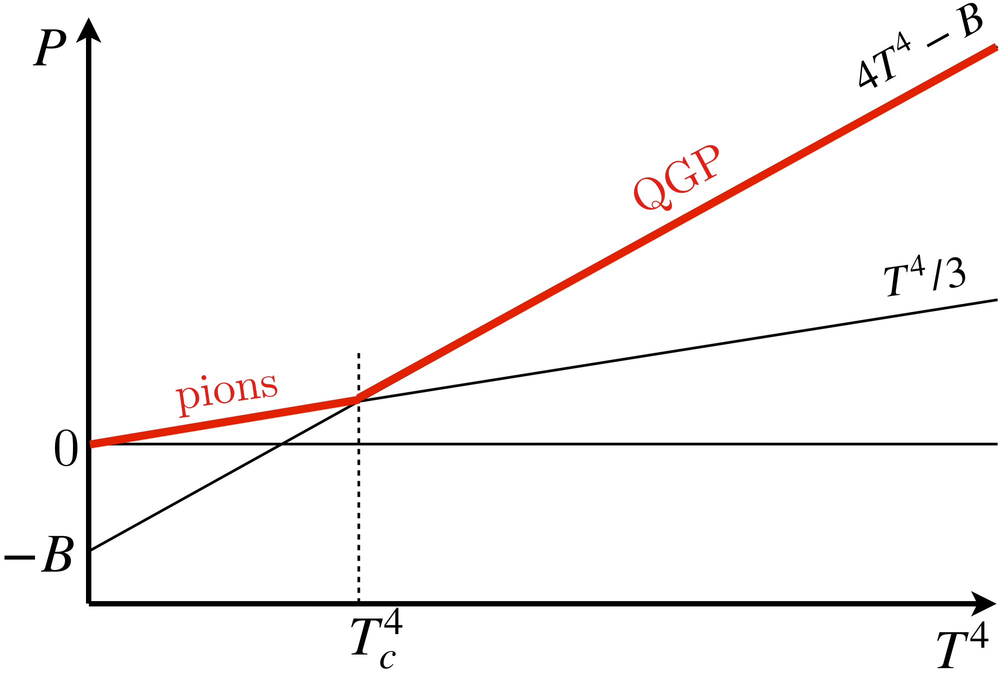
  (using the equation of state $p = \epsilon/3$, valid in the limit of massless particles)

$$p_{\mathrm{QGP}} = \frac{40}{90} \pi^2 T^4 - B$$

$$p_\pi = \frac{\pi^2}{30} T^4$$

Phase transition: hadron gas → QGP

- The pressure is always maximised ⇒ critical temperature T_c where the lines cross



- $p_\pi(T_c) = p_\mathrm{QGP}(T_c)$

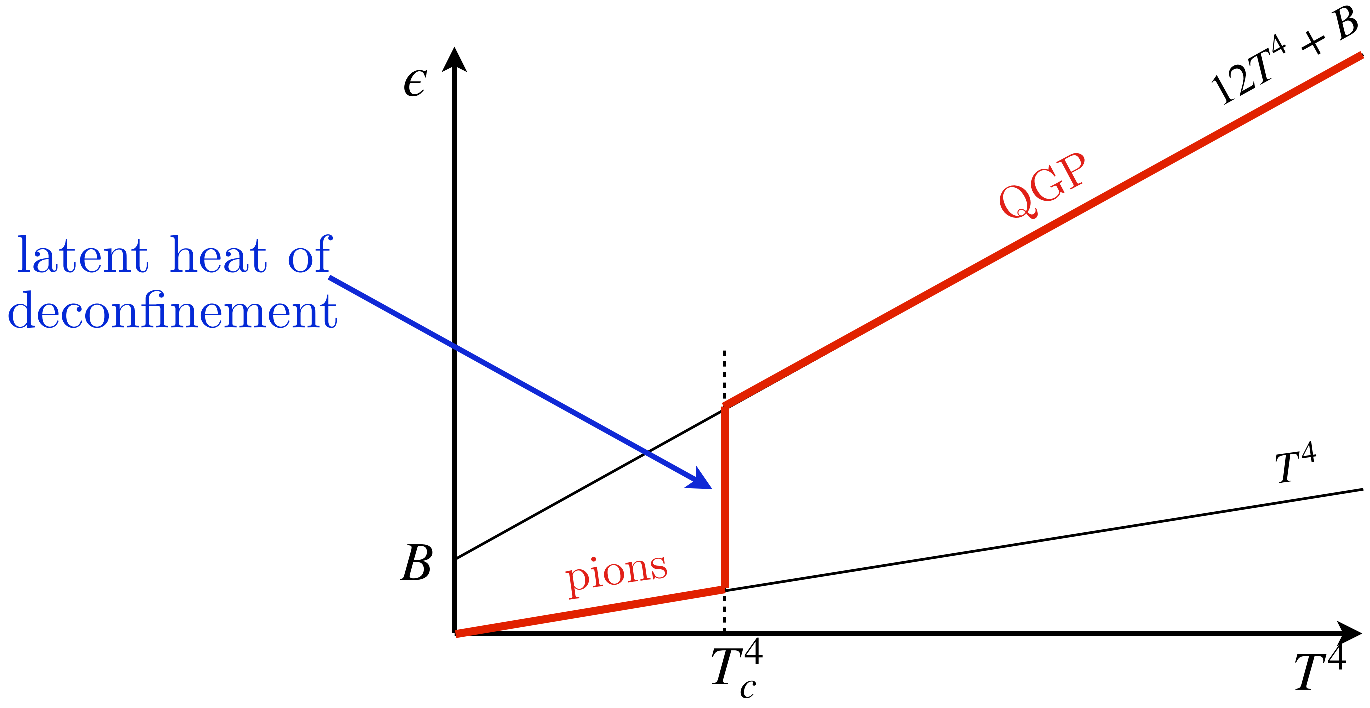
$$\Rightarrow \quad T_c^4 = \frac{90}{37\pi^2} B$$

$$\Rightarrow T_c \simeq 134\,\mathrm{MeV}$$

For conversions, use $\hbar c = 197\,\mathrm{MeV\,fm}$

Latent heat of deconfinement

- Plot the energy density as a function of T^4

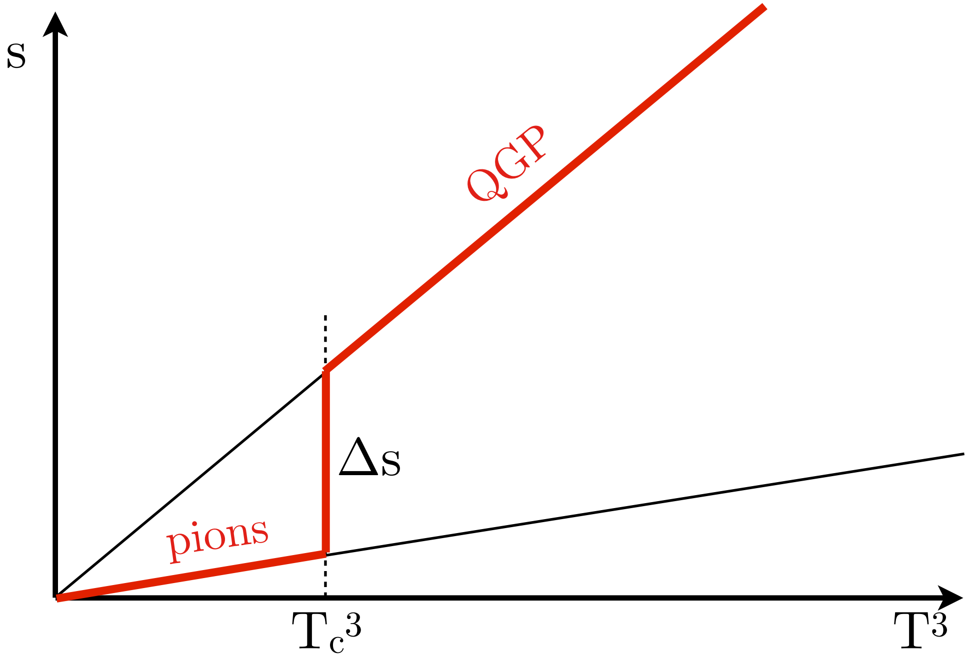


- The latent heat of deconfinement is equal to $4B$ (exercise)
- What is the physical origin of the latent heat?
  → the answer will come from considering the entropy of the system

Entropy density s

- Entropy density ($s = dS/dV$)

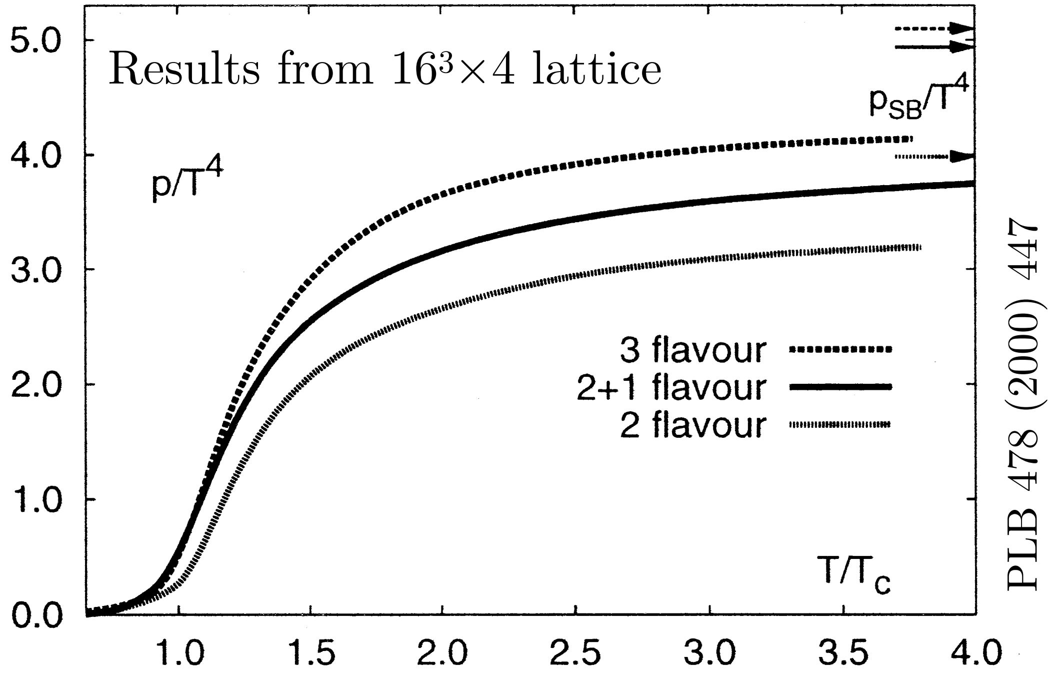
$$s = \frac{\partial P}{\partial T} \Rightarrow \begin{aligned} s_{\mathrm{QGP}} &= \frac{4}{3}\frac{40}{30}\pi^2 T^3 \\ s_\pi &= \frac{4}{3}\frac{1}{10}\pi^2 T^3 \end{aligned} \Rightarrow \Delta s(T_c) = \frac{4B}{T_c} = \frac{\Delta\epsilon}{T_c}$$



- The change in entropy is due to the increase in number of degrees of freedom ($g_\pi = 3 \rightarrow g_{\mathrm{QGP}} \simeq 40$)!

Deconfinement from Lattice QCD

- Above model valid in perturbative regime ($\alpha_s < 1$)
- $\alpha_s \sim 1 \Rightarrow$ non-perturbative $\Rightarrow$ QCD calculations on the lattice
- Model space-time on a 4D grid (e.g. $8^3 \times 16$)
  $\Rightarrow$ "lattice QCD"
- Calculate hadron masses, form factors
- Lattice QCD was used to simulate deconfinement



PLB 478 (2000) 447

Lattice predictions:

- $T_c \approx$ 160–180 MeV
- $\varepsilon \approx 0.5 - 1.0$ GeV/fm^3

[H. Satz arXiv:1101.3937]

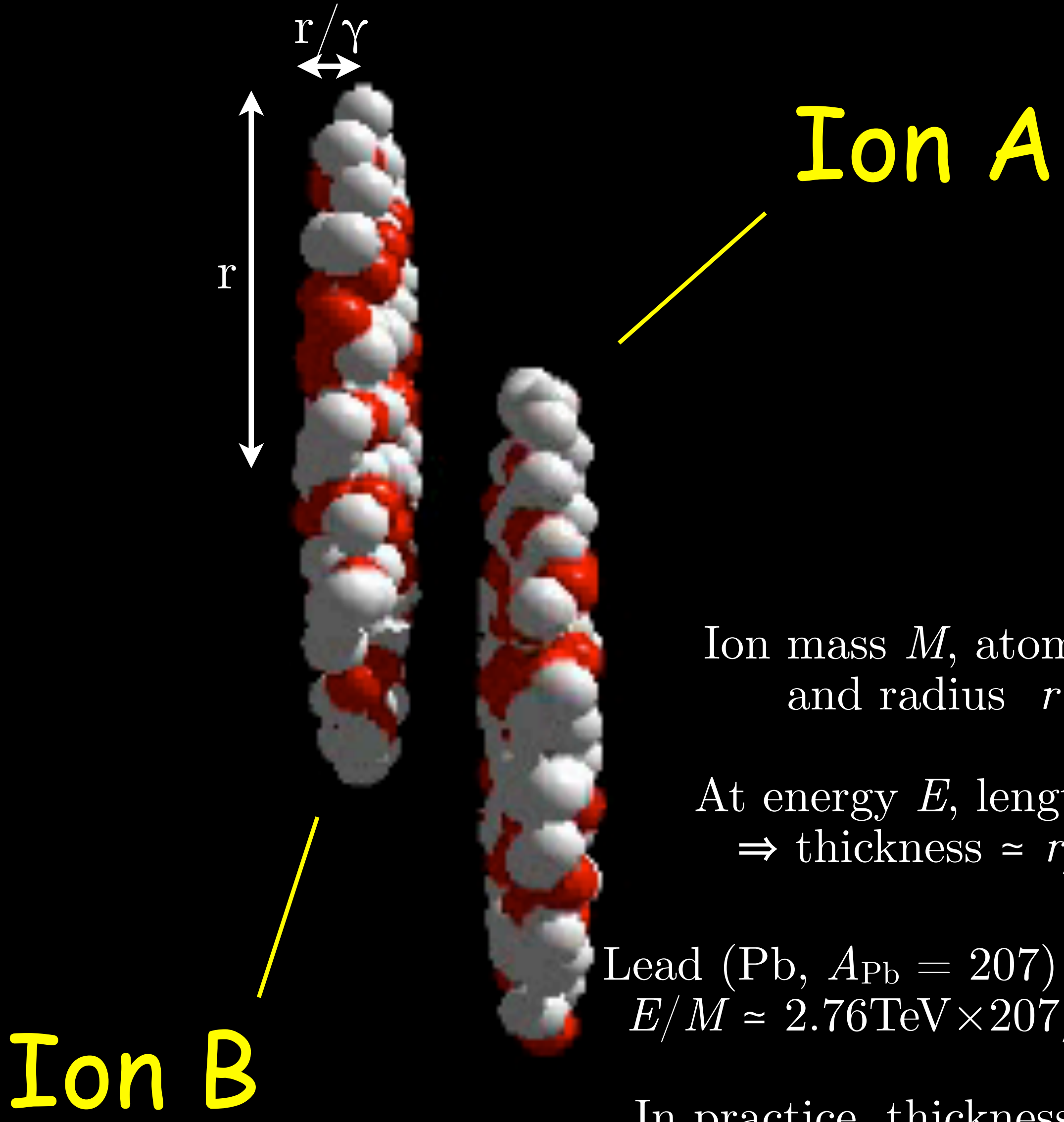
Questions

How can we create a plasma of quarks and gluons?

How can we demonstrate we have created a QGP?

(what are the experimental signature?)

Heavy ion collisions



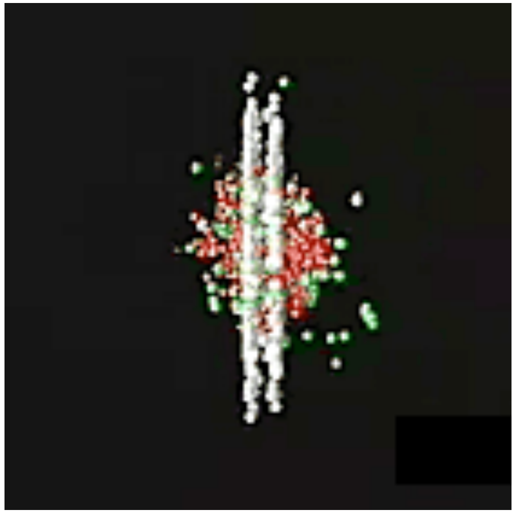
Ion mass M, atomic weight A ,
and radius $r \simeq 1.2A^{1/3}$

At energy E, length contraction
$\Rightarrow$ thickness $\simeq r/\gamma$ ($\gamma = E/M$)

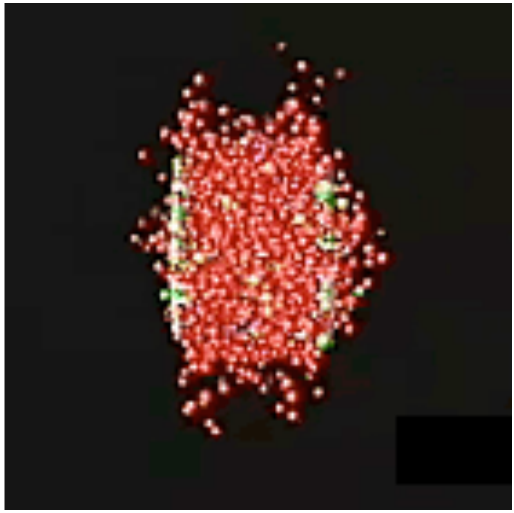
Lead (Pb, $A_{\mathrm{Pb}} = 207$) collisions at LHC:
$E/M \simeq 2.76\mathrm{TeV} \times 207/207\mathrm{GeV} = 2760$!

In practice, thickness no smaller than
1fm (because of QCD effects)

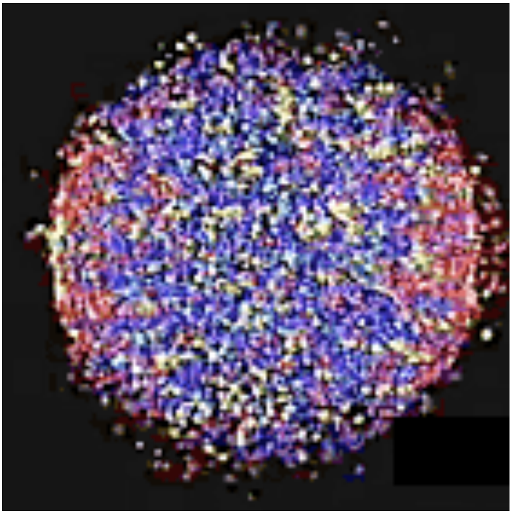
1. before collision



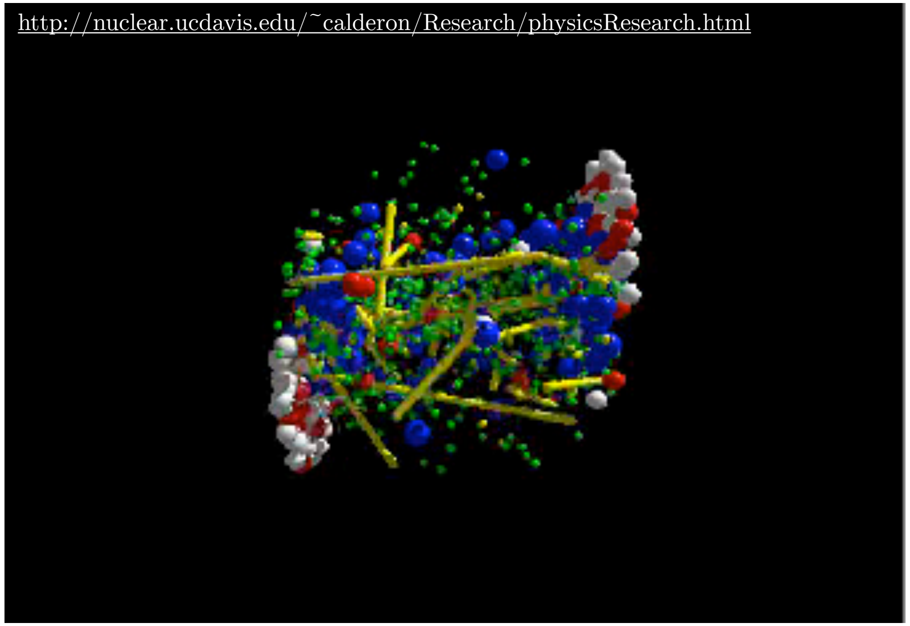
2. collision



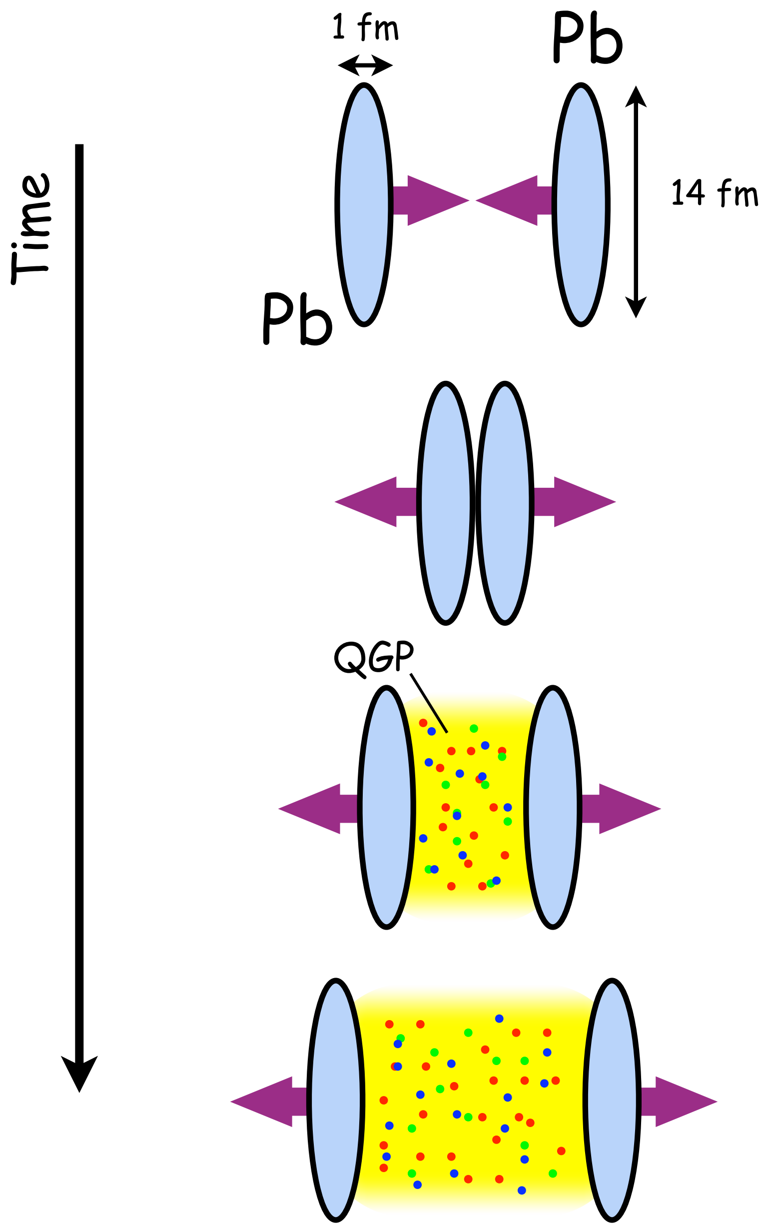
3. quarks and gluons



4. plasma created



http://nuclear.ucdavis.edu/~calderon/Research/physicsResearch.html



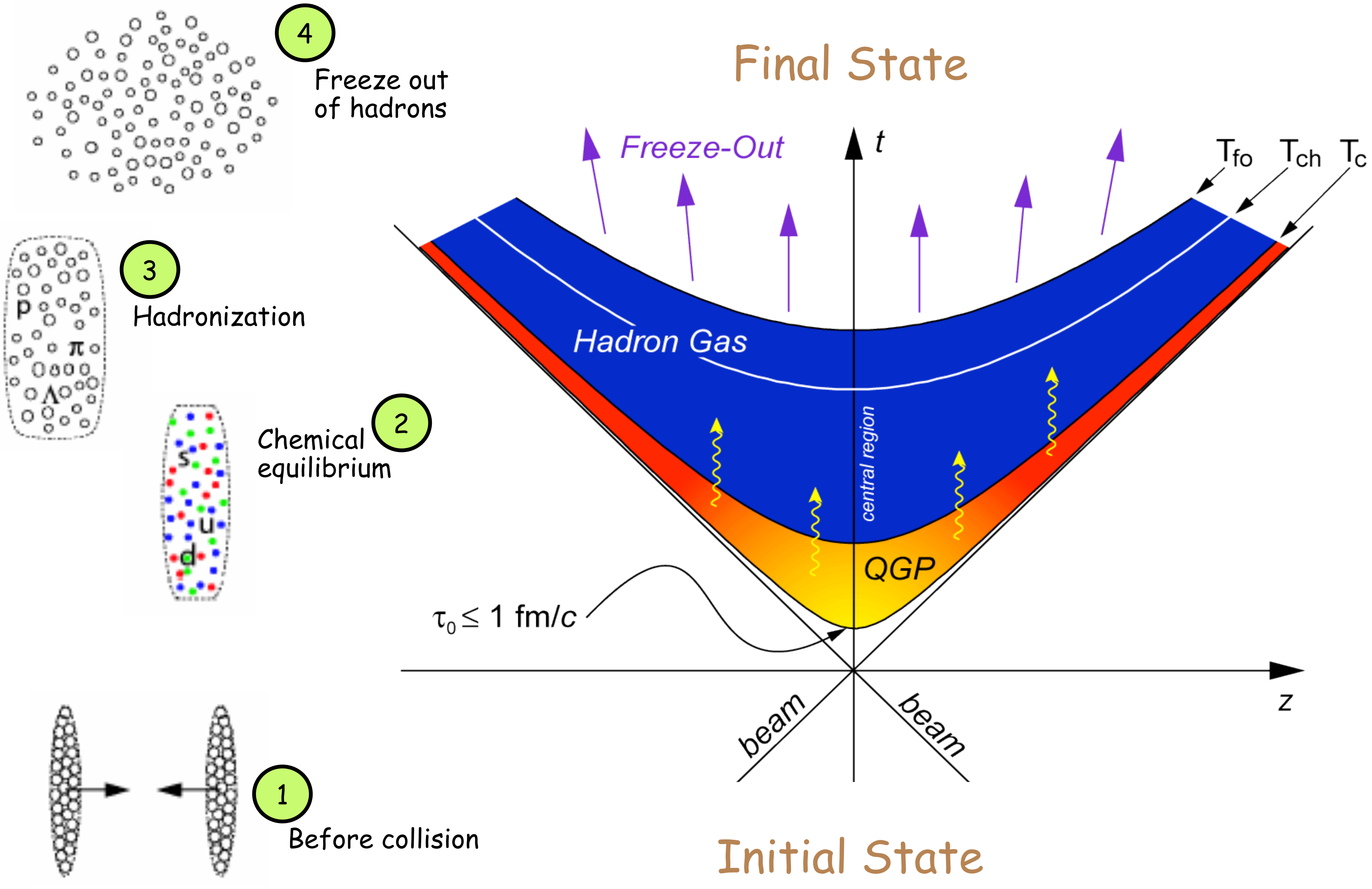
1. Heavy ion collision
   - used to create conditions at high temperature and high density

2. Formation time
   - $t_0 = 1\ \mathrm{fm/c} \ = 3.3{\times}10^{-24}\ \mathrm{s}$

3. Creation of QGP
   - is it in equilibrium?

4. Hadronisation
   - cool down, freeze-out

Time evolution of the collision



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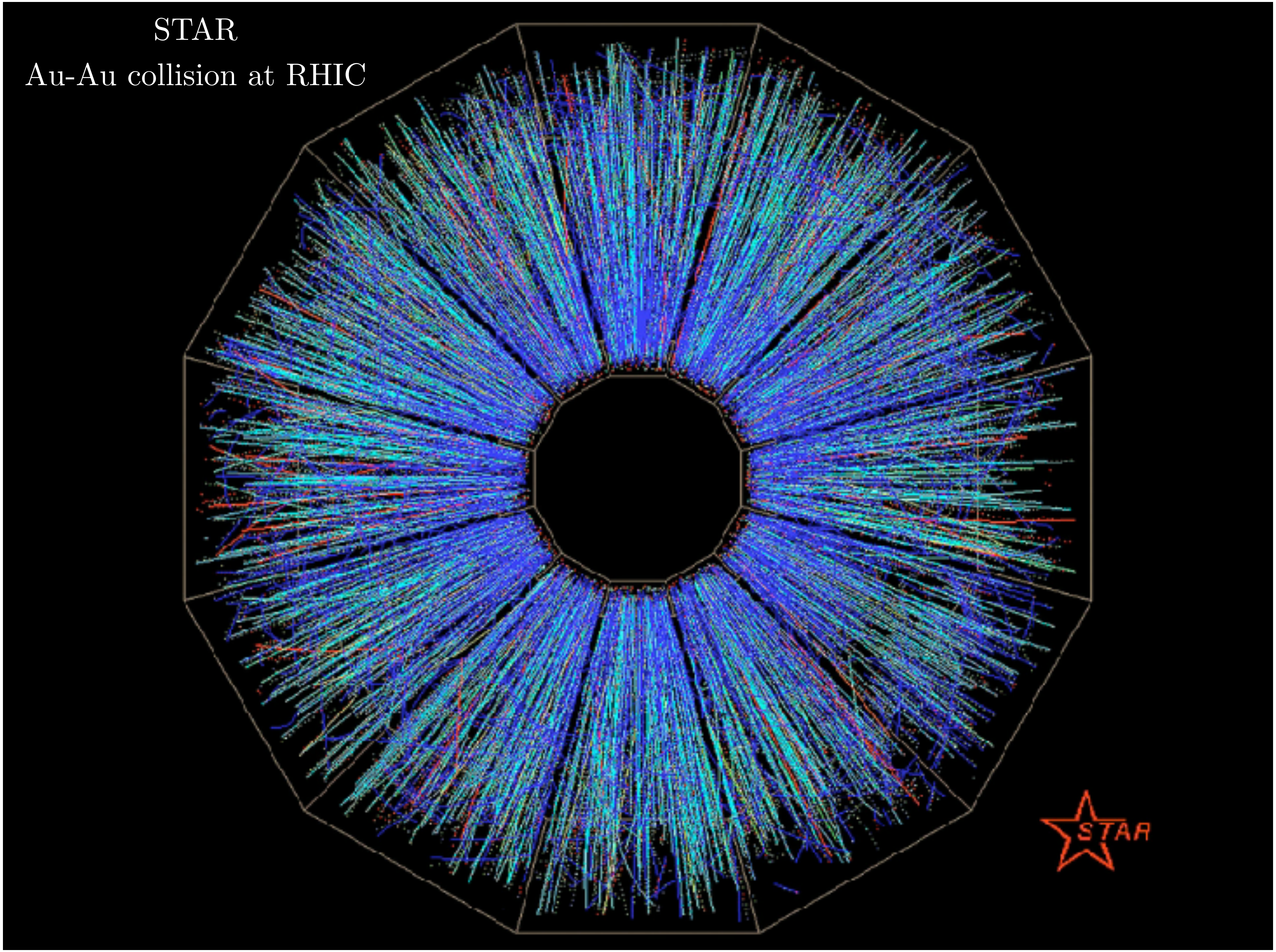
Au-Au collision at RHIC

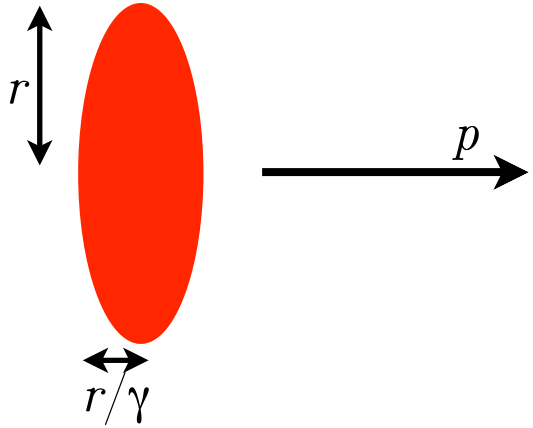


Identification of QGP

- We observe the hadrons created in the freeze out
  - the hadrons give information on the intermediate states

- Is the initial state dense enough?
  - particle multiplicities
  - energy density
- Is the initial state in equilibrium (thermalised)?
  - hadronic yields
  - hydrodynamic collective motion; “elliptic” flow
- Does the initial state behave like a QGP?
  - Jet quenching; suppression of dijets
  - J/ψ production; suppression or enhancement

Rapidity



- Particle with 4-momentum

$$(E, \vec{p}) = (E, \vec{p}_{\mathrm{T}}, p_z)$$

$$E^2 = p_z^2 + (\vec{p}_{\mathrm{T}})^2 + m^2 \equiv p_z^2 + m_{\mathrm{T}}^2$$

- Transverse mass

$$m_{\mathrm{T}}^2 = (\vec{p}_{\mathrm{T}})^2 + m^2 = E^2 - p_z^2 = (E + p_z)(E - p_z)$$

- m_{T} is invariant under boost along z

$$\begin{aligned} E' - p_z' &= \gamma(1+\beta)(E - p_z) \\ E' + p_z' &= \gamma(1-\beta)(E + p_z) \end{aligned} \quad \Rightarrow \quad m_{\mathrm{T}}'^2 = (E' + p_z')(E' - p_z') = \gamma^2(1+\beta)(1-\beta)m_{\mathrm{T}}^2 = m_{\mathrm{T}}^2$$

- Define the rapidity y as $$\boxed{y = \frac{1}{2} \ln \frac{E + p_z}{E - p_z}}$$

- The rapidity is an additive quantity, and depends on the boost y_0 given by $$y_0 = \ln(\gamma(1-\beta)) \quad \Rightarrow \quad y' = y + y_0$$

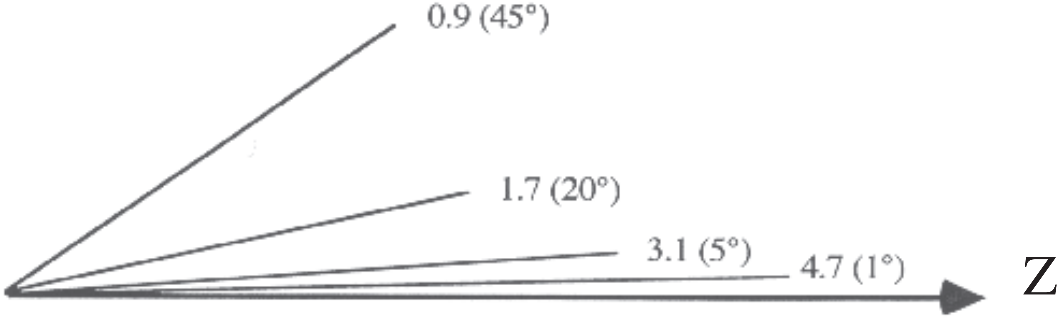
★ ⇒ differences of rapidities are invariant under a boost

Pseudorapidity vs rapidity

- Define the pseudorapidity η as

$$\eta = -\ln\tan\frac{\theta}{2}$$

- If $m \ll E$, then $\eta = y$



- At $\theta = 0$, $\eta = \infty$, and $y = \tanh^{-1}(p/E)$ $\Rightarrow$ maximum value of y

Under the assumption of negligible mass, $m \ll E$, we can write $E^2 \approx p_z^2 + p_\mathrm{T}^2$. With the definition $\tan\theta = \frac{p_\mathrm{T}}{p_z}$, we obtain

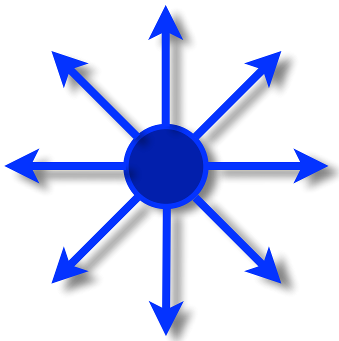
$$y \approx \frac{1}{2}\ln\frac{\sqrt{p_z^2+p_\mathrm{T}^2}+p_z}{\sqrt{p_z^2+p_\mathrm{T}^2}-p_z} = \frac{1}{2}\ln\frac{\sqrt{1+\tan^2\theta}+1}{\sqrt{1+\tan^2\theta}-1} = \frac{1}{2}\ln\frac{\left(\sqrt{1+\tan^2\theta}+1\right)^2}{\tan^2\theta} \tag{188}$$

$$= \ln\frac{1+\sqrt{1+\tan^2\theta}}{\tan\theta} = \ln\frac{1}{\tan\frac{\theta}{2}} = -\ln\tan\frac{\theta}{2} \tag{189}$$

Isotropic source

- What is the rapidity distribution for an isotropic source?

$$\frac{\mathrm{d}N}{\mathrm{d}y} = ?$$

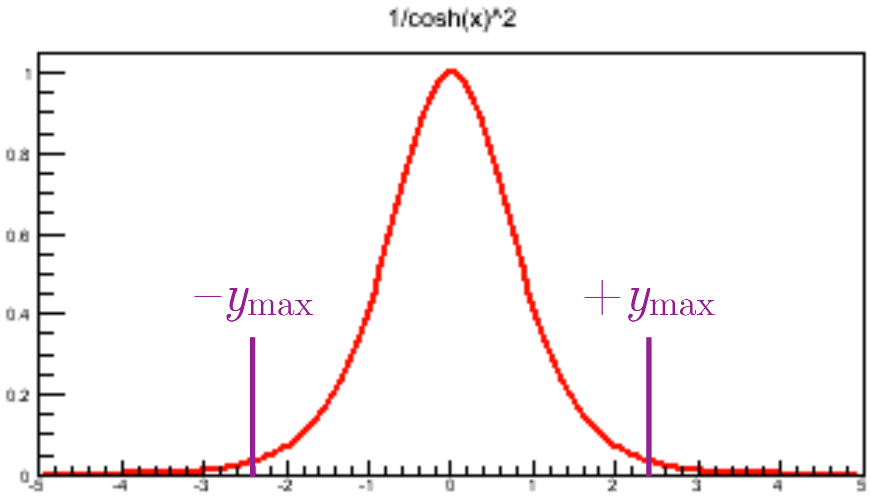


- With the definition of y and $\frac{\mathrm{d}N}{\mathrm{d}\Omega} = \frac{N}{4\pi}$, one obtains:

$$\mathrm{d}N = \frac{N}{2}\frac{E}{p}\frac{1}{\cosh^2 y}\mathrm{d}y$$

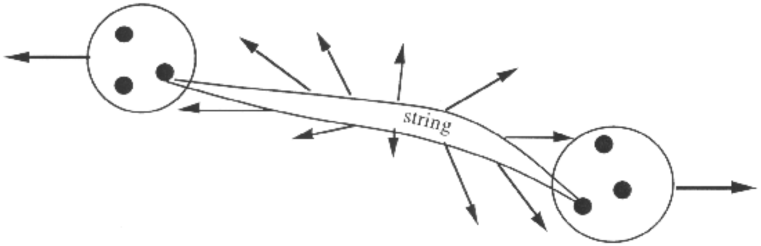
- Maximum rapidity:

$$y_{\max} = \tanh^{-1}\frac{p}{E}$$

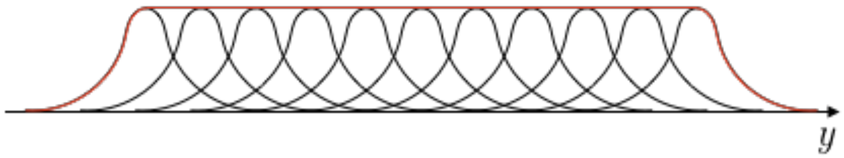


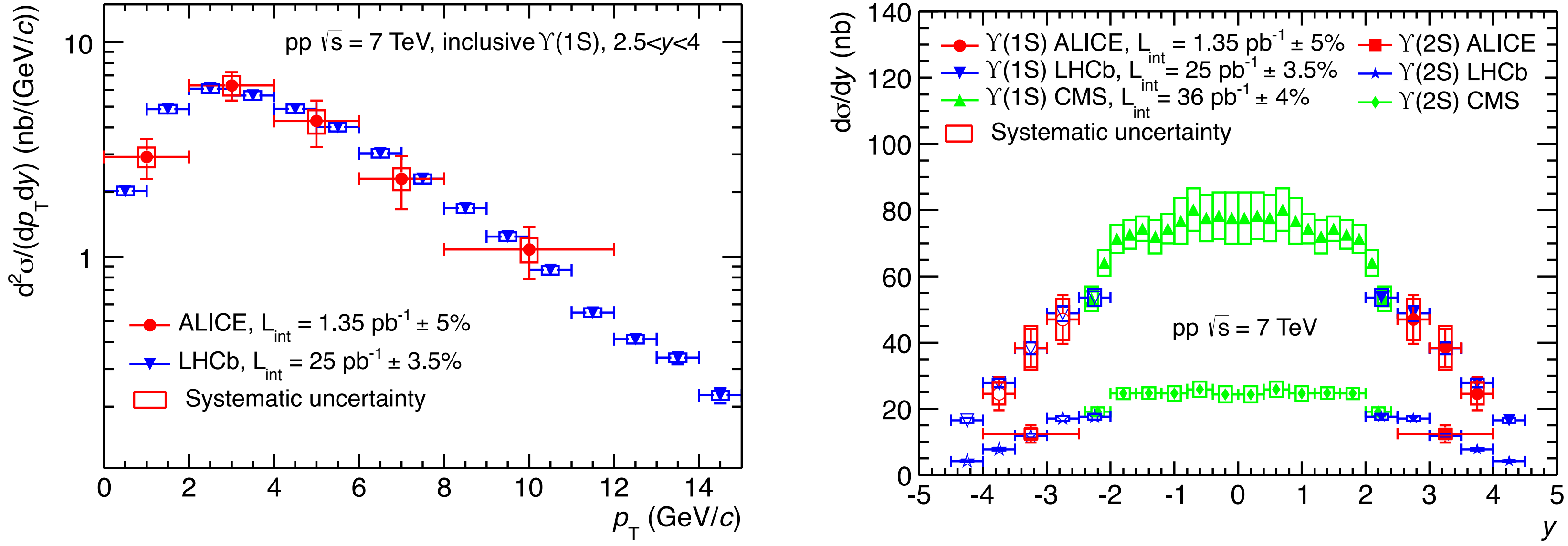
Rapidity distribution for a QCD string

- QCD strings between partons
  ⇒ production of quark pairs along the string



- rapidity distribution for all produced particles is approximately uniform in *y*





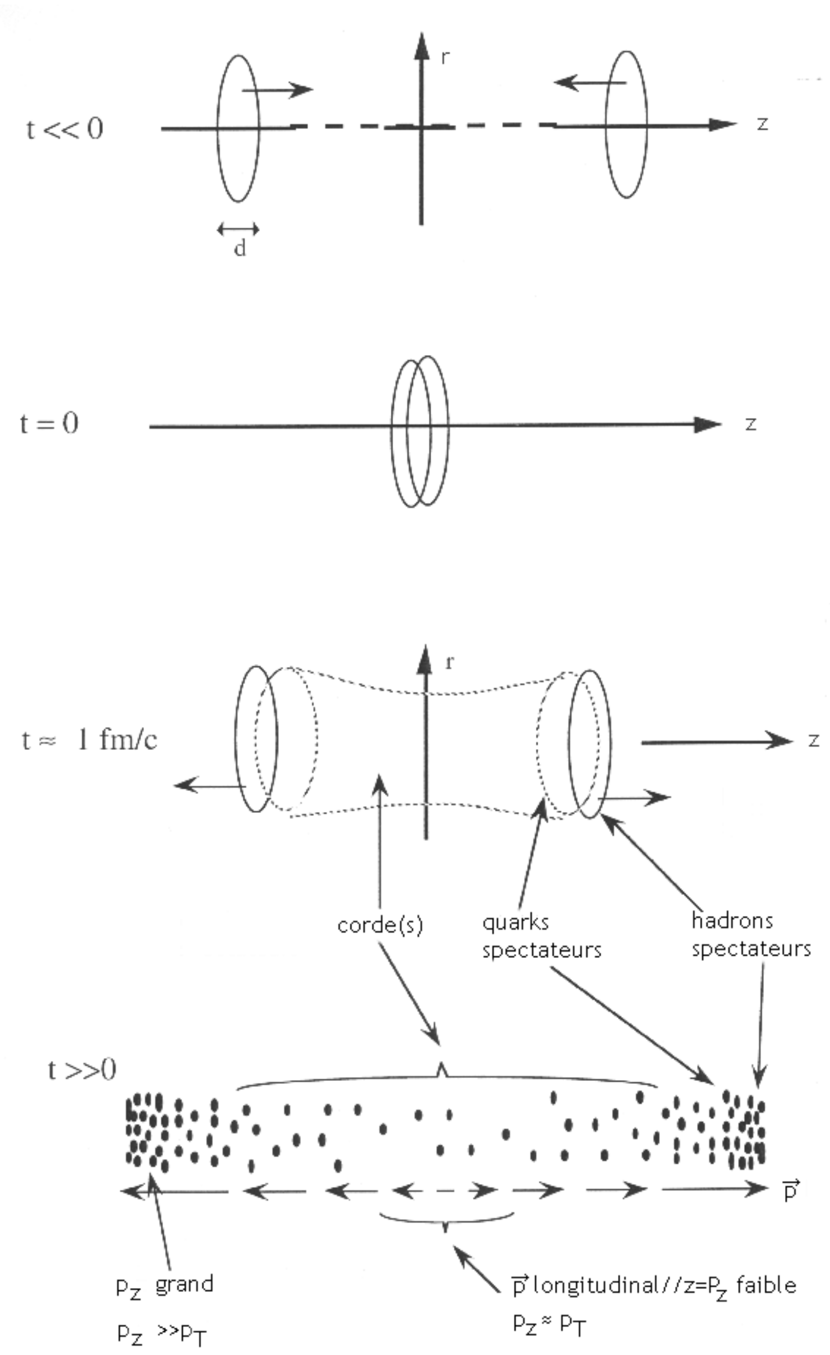
arXiv: 1403.3648

Fig. 4: Differential cross section of ϒ(1S) as a function of p_T (left) and differential cross sections of ϒ(1S) and ϒ(2S) as function of rapidity (right), measured by ALICE, LHCb [25] and CMS [42, 43]. The open symbols are reflected with respect to $y = 0$.

Hadrons from ion-ion collisions

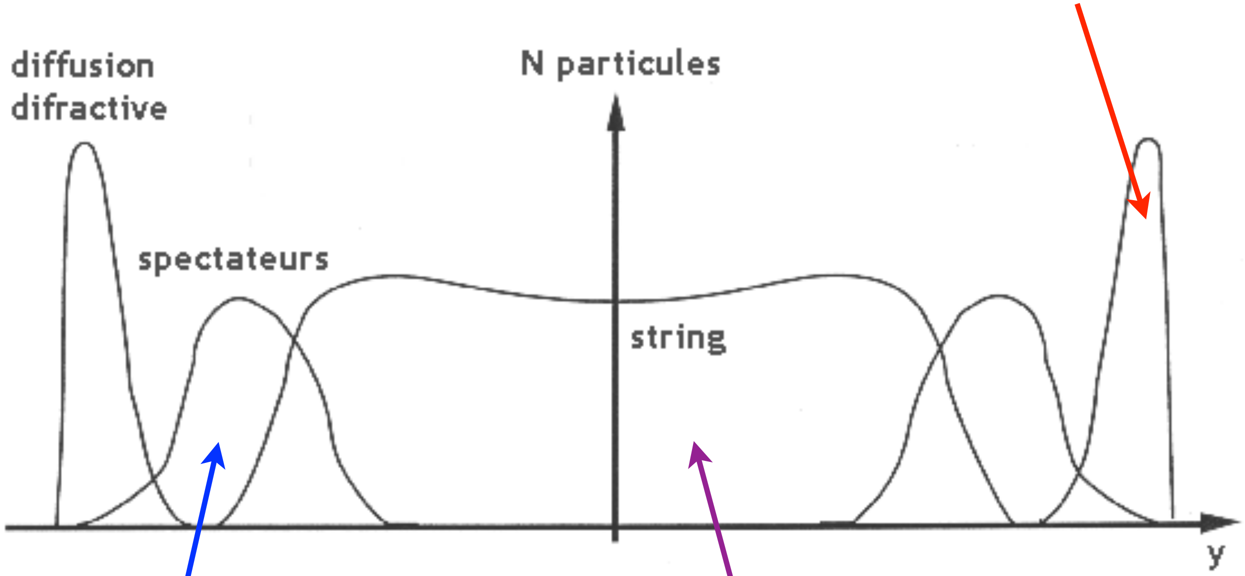
- At high energy, nuclei are almost transparent ⇒ fraction κ interact

- The products of the collision
  - nucleons that don't interact strongly ⇒ near maximum y
  - hadrons from spectator quarks at relatively high rapidity
  - strings between partons ⇒ fragmentation ⇒ hadrons in the intermediate rapidity region



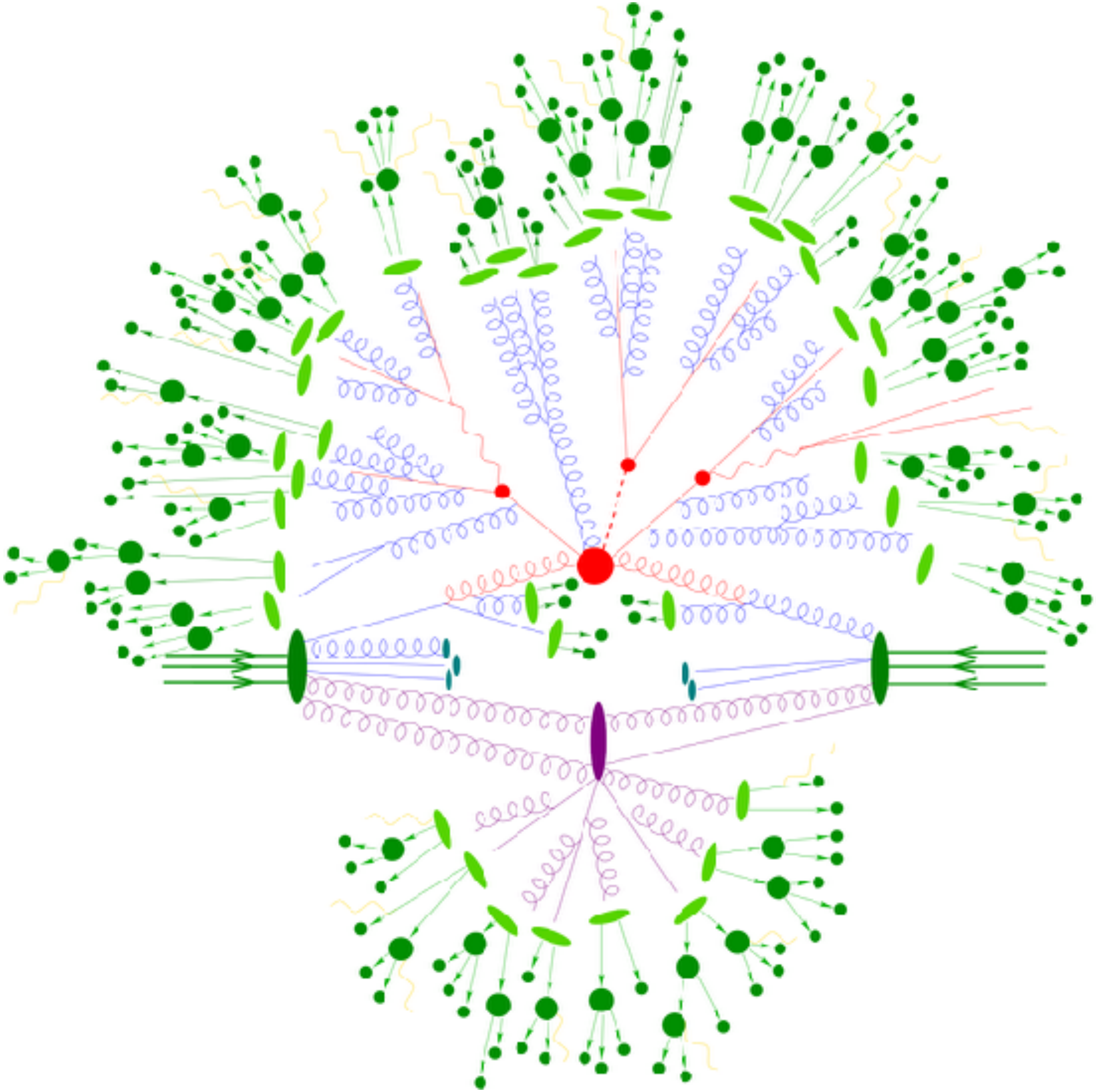
Rapidity distribution from ion-ion collision

nucleons from the nuclei
that have not interacted
$\Rightarrow$ mostly in the original
beam direction $(p_T = 0)$



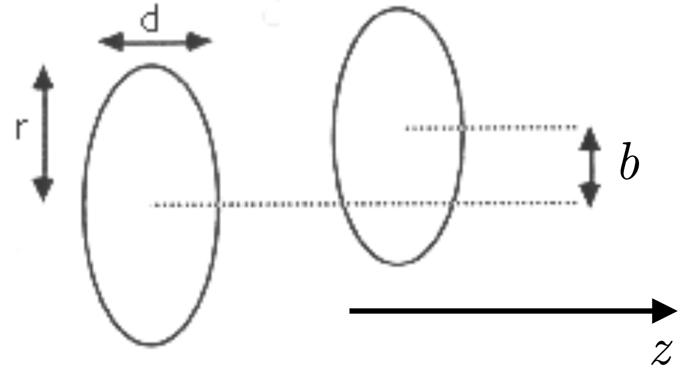
hadrons formed from
spectator quarks in
nucleons that interacted
strongly

hadrons formed from
string fragmentation

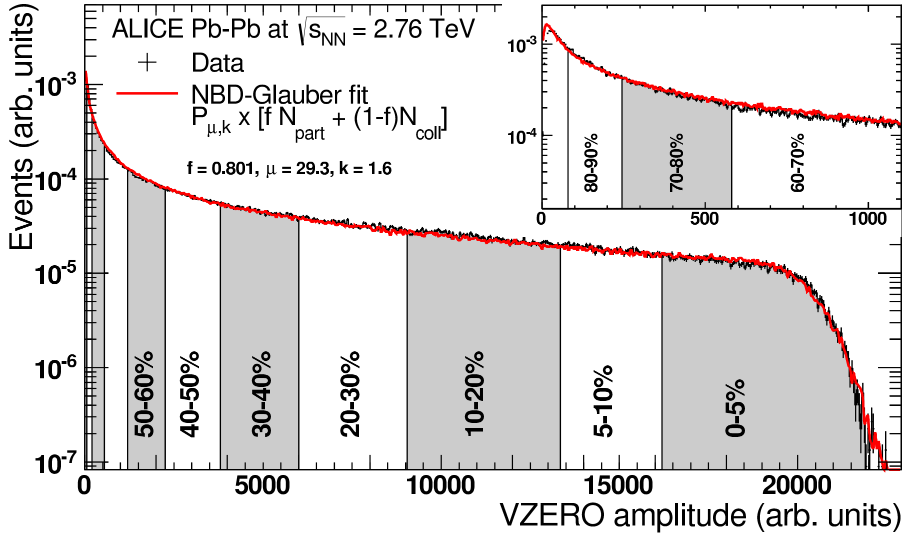


Frank Krauss/Durham University

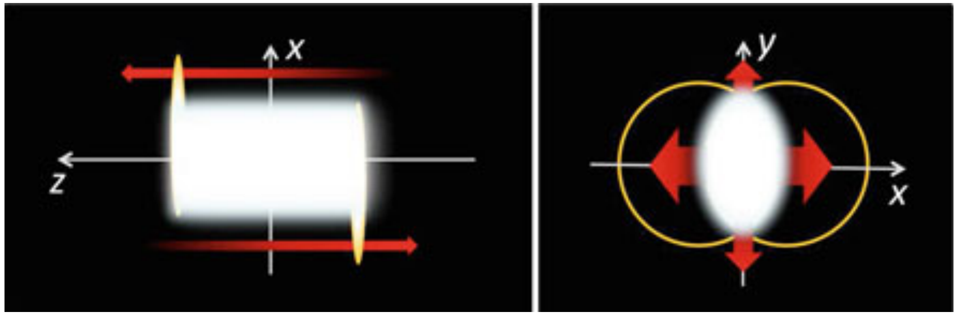
Collision geometry and centrality



- the two ions are not perfectly aligned in the collision
- the distance b in the transverse plane between the centres of the ions characterises the centrality
- very central collisions ⇒ many NN interactions ⇒ high track multiplicity
- in practice, the centrality is frequently measured using the track multiplicity in the event



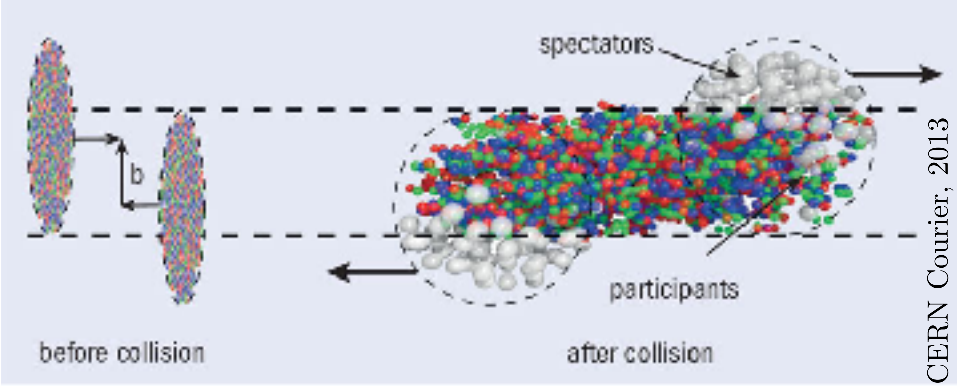
arXiv:1301.4361



A. Monnai, *Relativistic Dissipative Hydrodynamic Description of the Quark-Gluon Plasma*

ALICE VZERO scintillator detector is used for triggering: the signal amplitude is proportional to the multiplicity

Energy density in the central region



CERN Courier, 2013

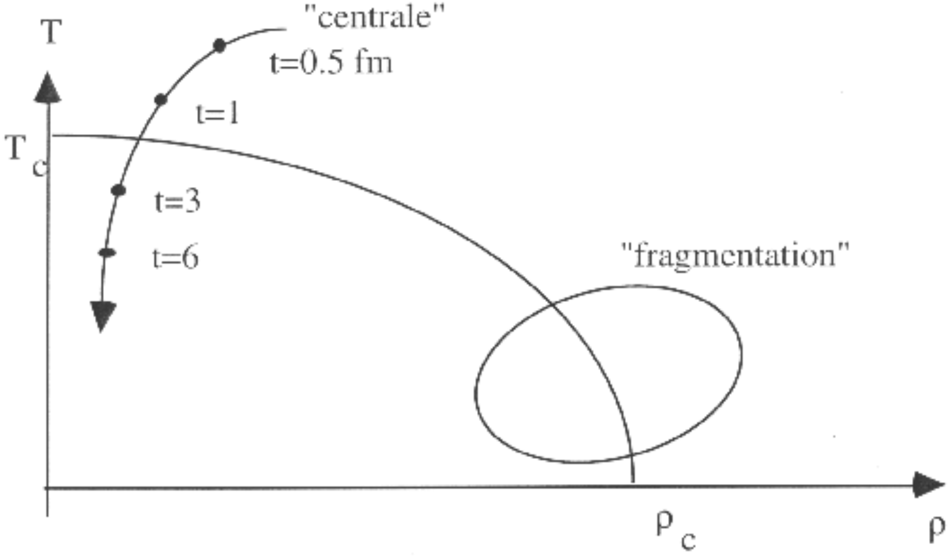
- Energy in the central region

$$\epsilon \approx \frac{A}{\pi r^2}\frac{\mathrm{d}N}{\mathrm{d}z}E_\pi$$

- From experimental data :
  - the number of particles (pions) produced per unit rapidity and per nucleon-nucleon collision at $100\,\mathrm{GeV}$: $dN/dy \simeq 5$
  - the typical pion transverse momentum: $p_\mathrm{T} \simeq 350\,\mathrm{MeV/c}$
- Assuming $v(z) = z/t$, we find :

$$\epsilon \approx \frac{A^{1/3}}{2\pi}\frac{\mathrm{d}N}{\mathrm{d}y}\frac{m_\mathrm{T}}{\tau} \sim \frac{0.5A^{1/3}}{t}\left[\frac{\mathrm{GeV}}{\mathrm{fm}^3}\right]$$

$\Rightarrow$ The energy density is larger than $1\,\mathrm{GeV/fm}^3$ if $t < 3\,\mathrm{fm}$



QGP Signatures

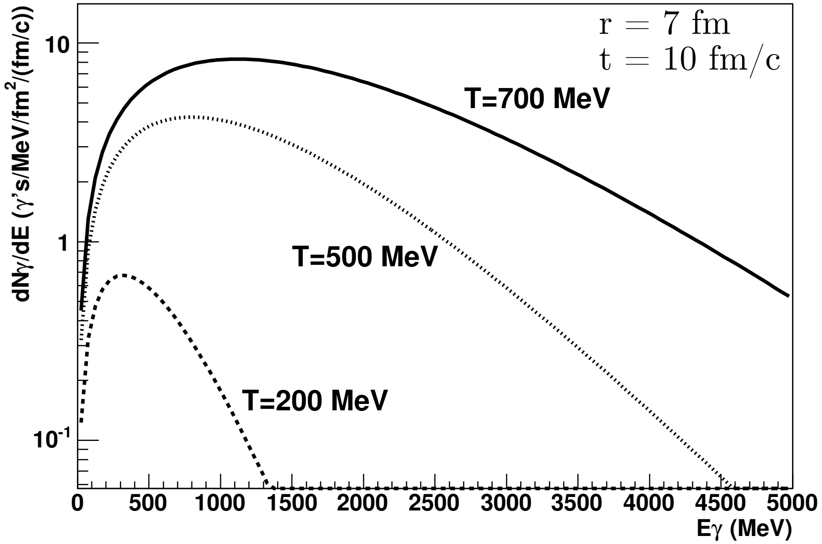
- High temperature
  ⇒ expect plasma of deconfined coloured quarks and gluons

- The interaction medium can be characterised by several observables used to identify the QGP:
  - hadron production
  - photon spectrum
  - pressure
  - dimensions, anisotropies
  - particle correlations
  - quarkonium (e.g. ϕ, J/ψ, Υ) production
  - strangeness production
  - jet production and jet quenching

Photon spectrum

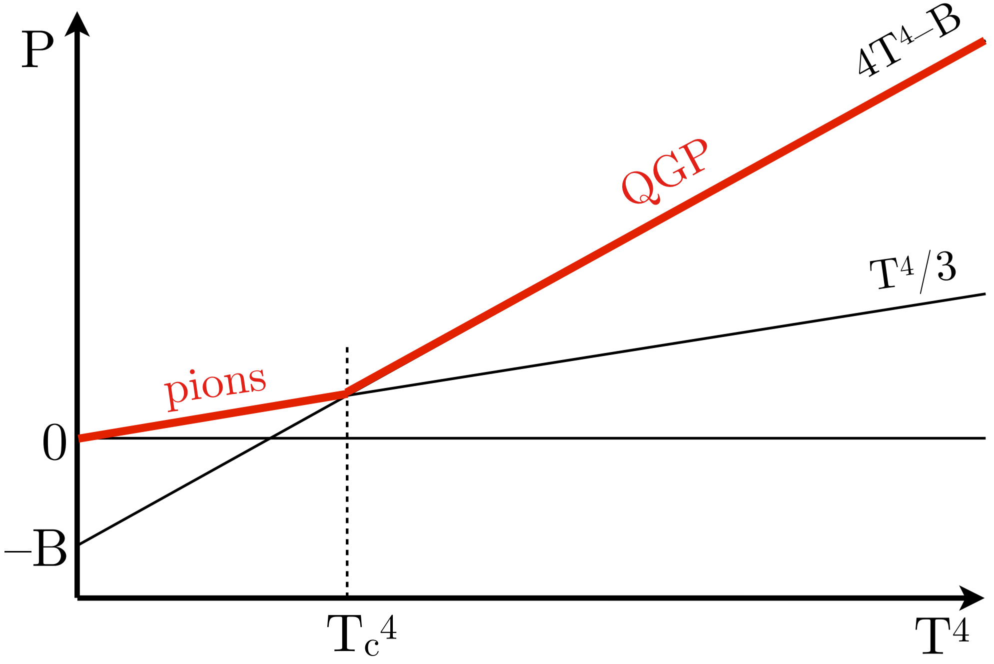
- Three categories of photons :
  1. prompt photons (produced in collision)
  2. thermal photons
  3. secondary photons (from decay of prompt particles, e.g. $\pi^0 \to \gamma\gamma$)
- Measure photon spectrum ⇒ temperature (⇒ pressure) $p = \frac{\epsilon}{3} = 0.22T^4$
  - Planck : $$\frac{\mathrm{d}p(E_\gamma, T)}{\mathrm{d}E_\gamma} = 0.034 \frac{E_\gamma^3}{\exp(E_\gamma/T) - 1} [\mathrm{MeV}^3]$$
  - valid for thermal photons emitted at the surface of QGP ($r > 0.1$Å)
  - small volumes (few fm^3) are transparent to photon ⇒ correction

but... probes the centre of the QGP!



Pressure

- Can we probe the (P, T^4) phase space?
- Pressure after collision $\Rightarrow$ information on the state of matter



- High pressure $\Rightarrow$ higher transverse momentum p_T

$\Rightarrow$ measure transverse momentum spectrum versus energy

$$(p_\mathrm{T}, E) \Leftrightarrow (P, T^4)$$

QGP dimensions

- Interferometry can be used to measure the dimensions of the volume in which the pions are produced
- Exploit Bose-Einstein correlations between identical bosons emitted close in phase space: Hanbury Brown-Twiss method
- Measure the 4D separation between pions of same charge

$$|p_1 - p_2|^2 = q^2$$

- Compare q^2 distributions for pions in same events with the distribution for pions in different events (i.e. uncorrelated)
  $\Rightarrow$ measure of the interference
- One obtains information on the dimensions and the lifetime of the source

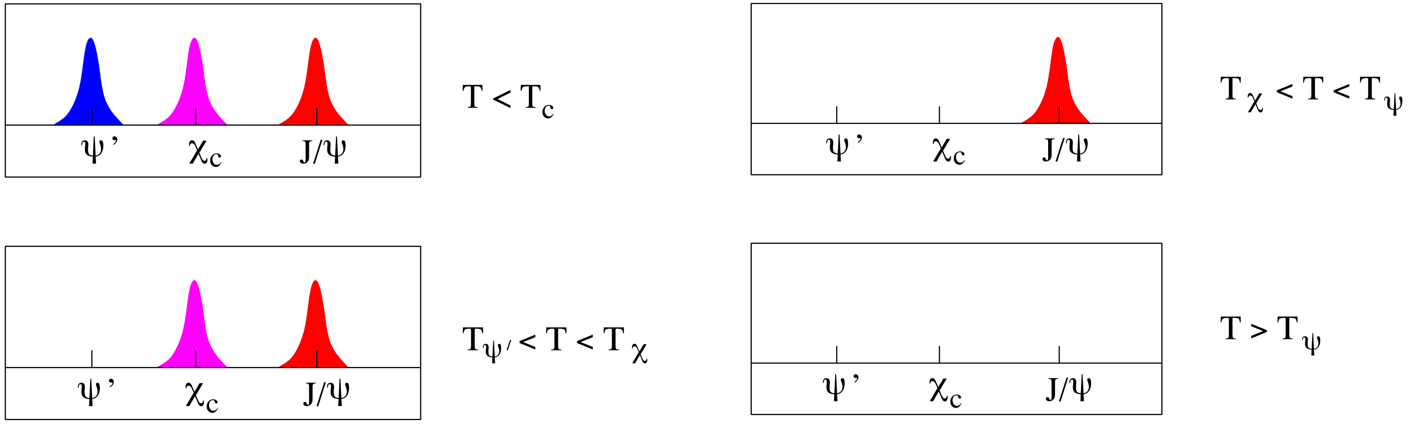
Quarkonium production

- Quarkonia of heavy quark-antiquark pairs
  - radius much smaller than for light hadrons ($r_Q \ll r_h \sim 1\,\mathrm{fm}$)
  - more tightly bound (binding energies up to 0.5 – 1GeV)

  $\Rightarrow$ can survive in QGP up to temperatures above deconfinement point; but will melt at temperature above binding energy

  $\Rightarrow$ are not produced when the colour screening radius is about the size of the quarkonium radius

- r_Q is different for each quarkonium state $\Rightarrow$ probe temperature from the quarkonium spectrum



J/ψ production at 200GeV / nucleon

CERN NA38 experiment

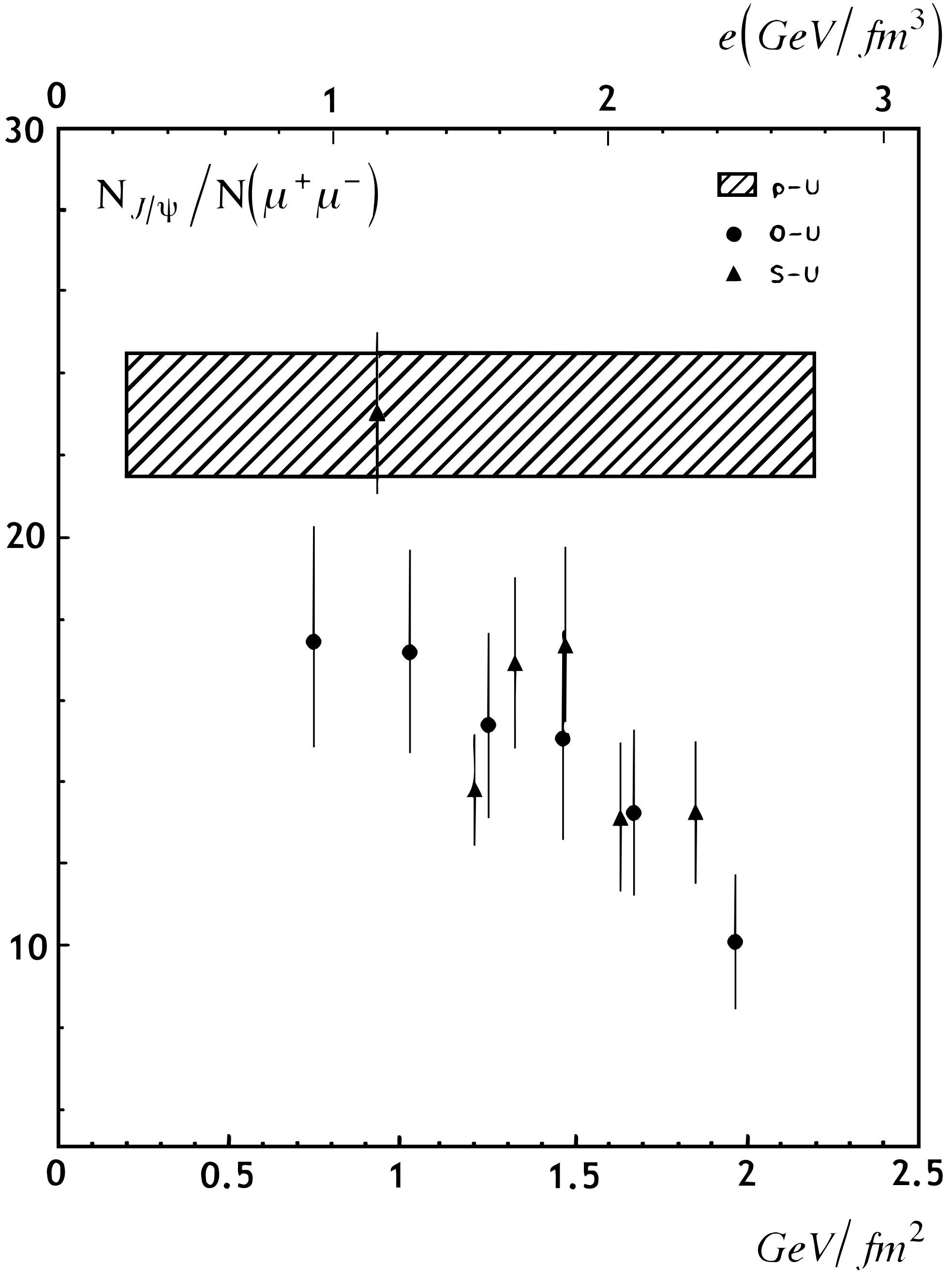
p-U, O-U, S-U collisions
200GeV/nucleon

J/ψ production normalised to
$\mu^+\mu^-$ production

Clear deficit in heavier ion
collisions above 1GeV/fm²

Is this a signature of QGP?

Note: ss production is suppressed because the
screening effect is much larger for the lighter s
quark (~200MeV vs 1840MeV for c quark)



Jet and lepton production

- Jets are created in nucleon interactions
  - in QGP, expect strong interaction of jets with the medium ⇒ absorbed
  - compare rate of di-jet events in pp and in ion-ion interactions
  - suppression of jets in ion-ion collisions may be a sign of QGP

- Other tests have been suggested
  - lepton production rate
  - photon production rate

  ...and any observable may have power to discriminate between QGP and other states of matter (hadron gas)

Experimental methodology

1. Understand the dynamics of the collision
   - systematic study of the colliding system: centre of mass energies and impact parameter

2. Experimental probes
   - detection, identification, kinematic characterisation of the particles produced in the ion-ion collision
   - deduce: particle multiplicities; unflavoured and strange hadron yields; p_T and η distributions; asymmetries in the distributions; heavy quarks; quarkonia (J/ψ); photons; jets; etc...

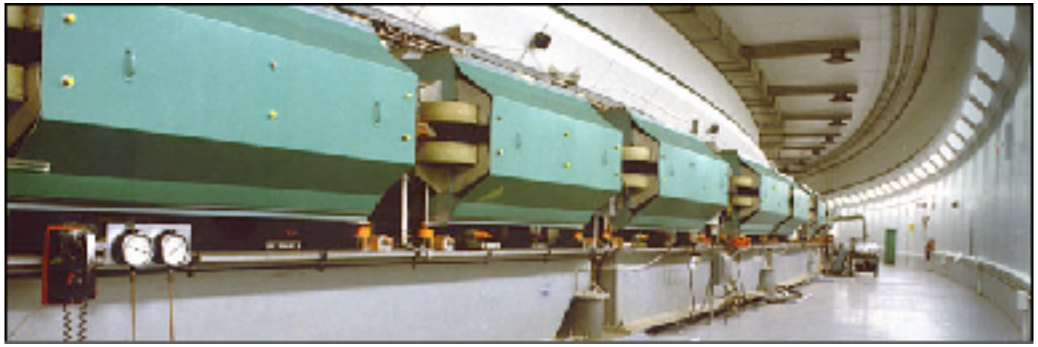
3. Global interpretation
   - interpretation of all the results into phenomenological models, and identify the models that give a good description of all the observations

Heavy ion collisions in laboratories

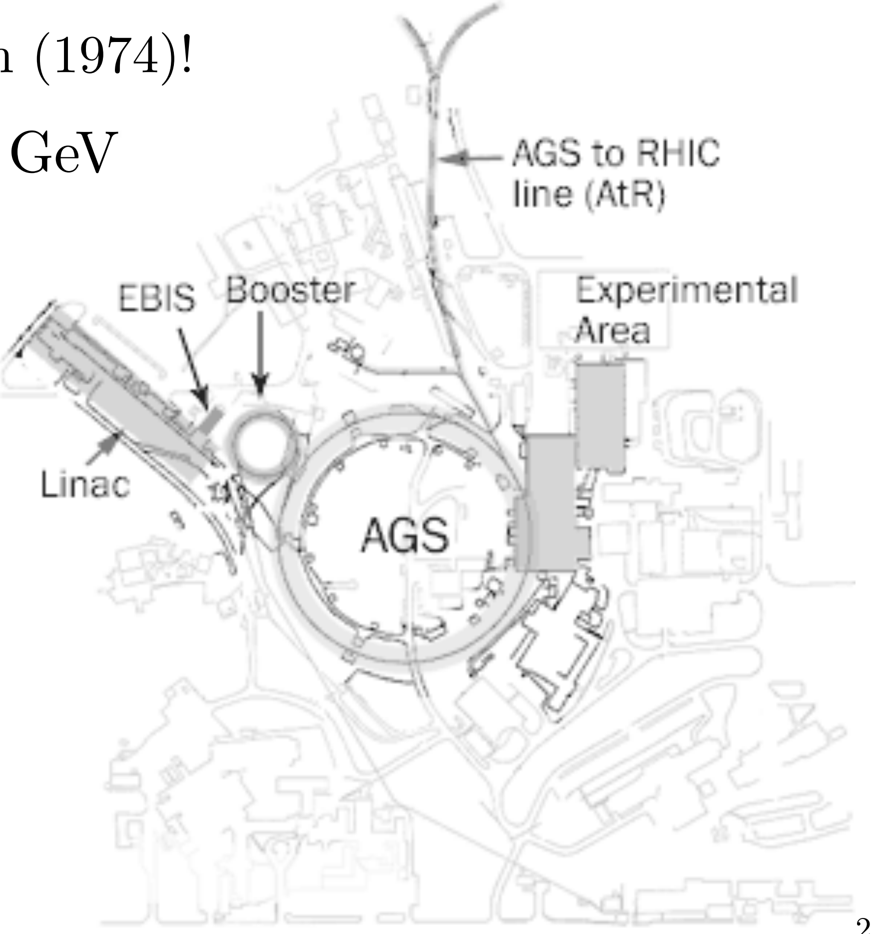
- Main laboratories involved in high-energy nuclear matter experiments
  - CERN, Geneva, Switzerland
  - Brookhaven National Laboratory (BNL) , New York, USA
  - GSI, Darmstadt, Germany
  - GANIL, Caen, France
- First ion beams at ultra-relativistic energies in the 1980's (used for fixed-target experiments) :
  - AGS (BNL), 5GeV/nucleon pair,
  - SPS (CERN), 18GeV/nucleon pair
- First heavy-ion colliders in 2000's:
  - RHIC (BNL)
    - Au-Au collisions at $\sqrt{s_{NN}} = 130$ GeV (2000)
    - Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV (2001)
  - LHC (CERN)
    - Pb-Pb collisions at $\sqrt{s_{NN}} = 2760$ GeV (2010)
    - p-Pb collisions at $\sqrt{s_{NN}} = 5020$ GeV (2013)
    - Pb-Pb collisions at $\sqrt{s_{NN}} = 5020$ GeV (2015)
    - Pb-Pb collisions at $\sqrt{s_{NN}} = 5360$ GeV (2023)

⇒ Total energy in the collision: $5360 \times A_{Pb}(=207) = 1110$ TeV

Alternating Gradient Synchrotron (AGS)



- AGS at BNL
  - built in 1957
  - proton beams at 33GeV
  - Nobel prizes for the discovery of the muon neutrino ν_μ (1962), of CP violation (1963), of the J/ψ meson (1974)!
- 1986: acceleration of Silicon ions at 14 GeV
- 1991: booster
  - Si and Au ions with energies up to $\sqrt{s_{\mathrm{NN}}} = 11$ GeV
- Probably never reached the critical density of 1 GeV/fm³



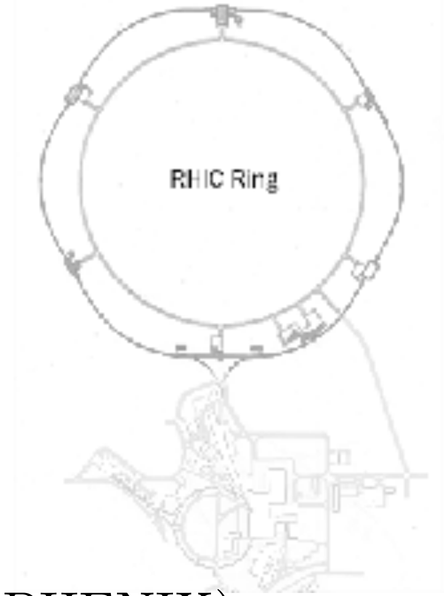
http://www.bnl.gov/rhic/ags.asp

CERN Super Proton Synchrotron (SPS)

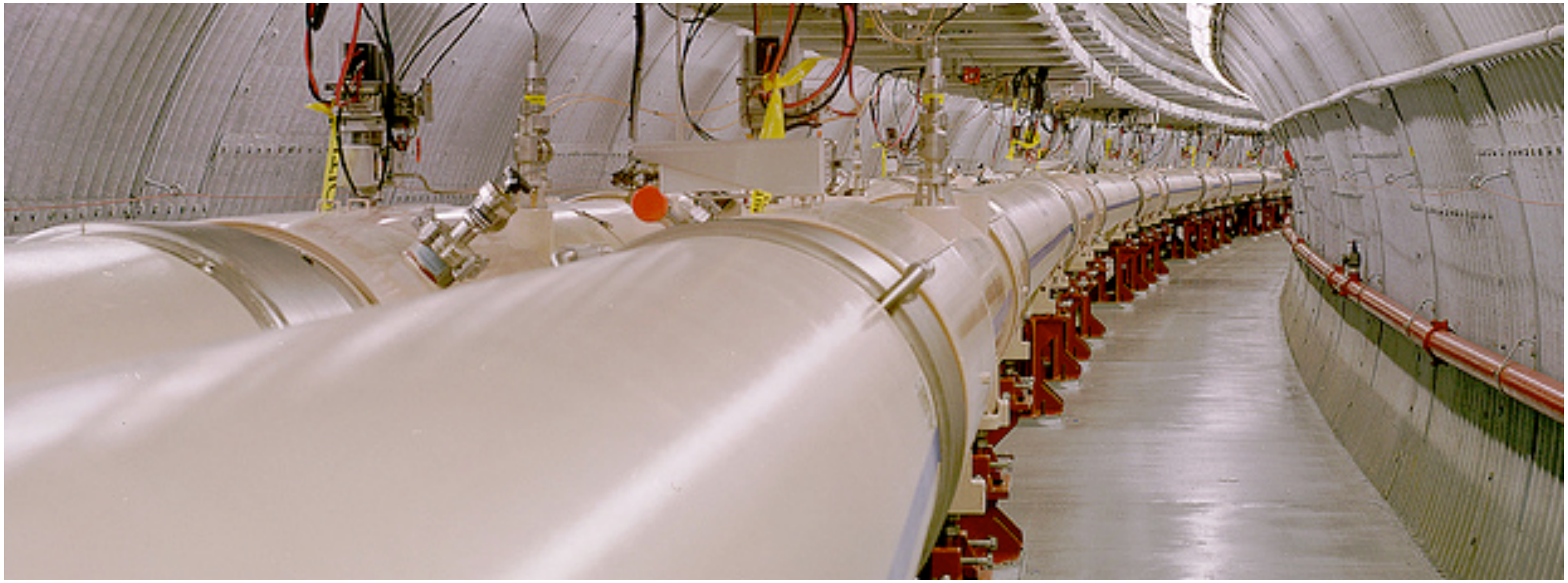
- Proton accelerator, 500GeV (1976); fixed target experiments
- Became a proton-antiproton collider in 1981
  - discovery of the W and Z bosons → Nobel prize in 1984
- 1986: inject Pb ions
  - Pb ions with charge Q=+27e, and energy 2.5keV
  - stripped of the remaining electrons in thin (~1 μm) carbon and Aluminium foils
  - final energy: $\sqrt{s_{NN}} = 158$ GeV

- CERN announcement in 2000:
  - the results of the experiments hint at a new state of matter: Quark Gluon Plasma

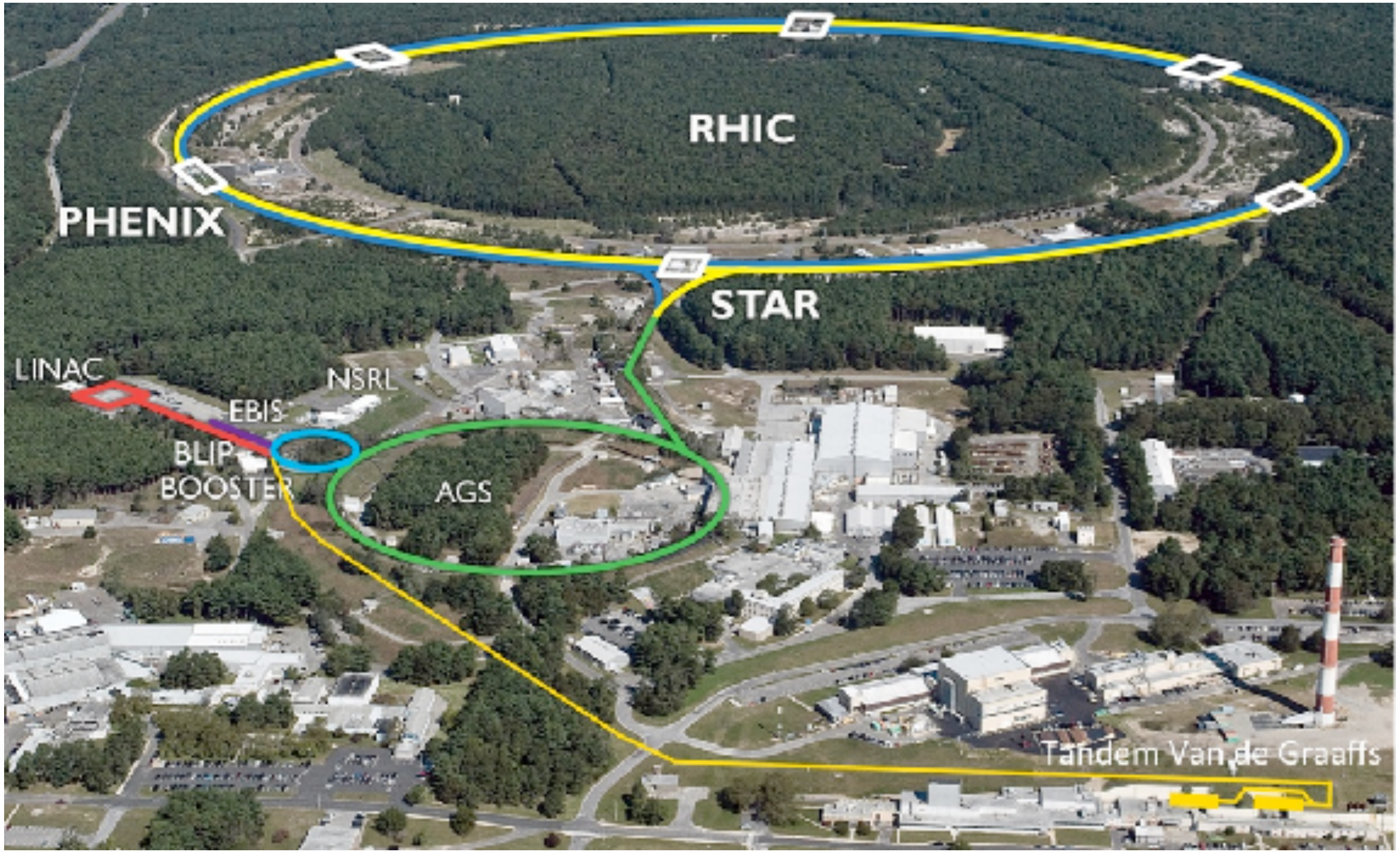
Relativistic Heavy Ion Collider (RHIC)



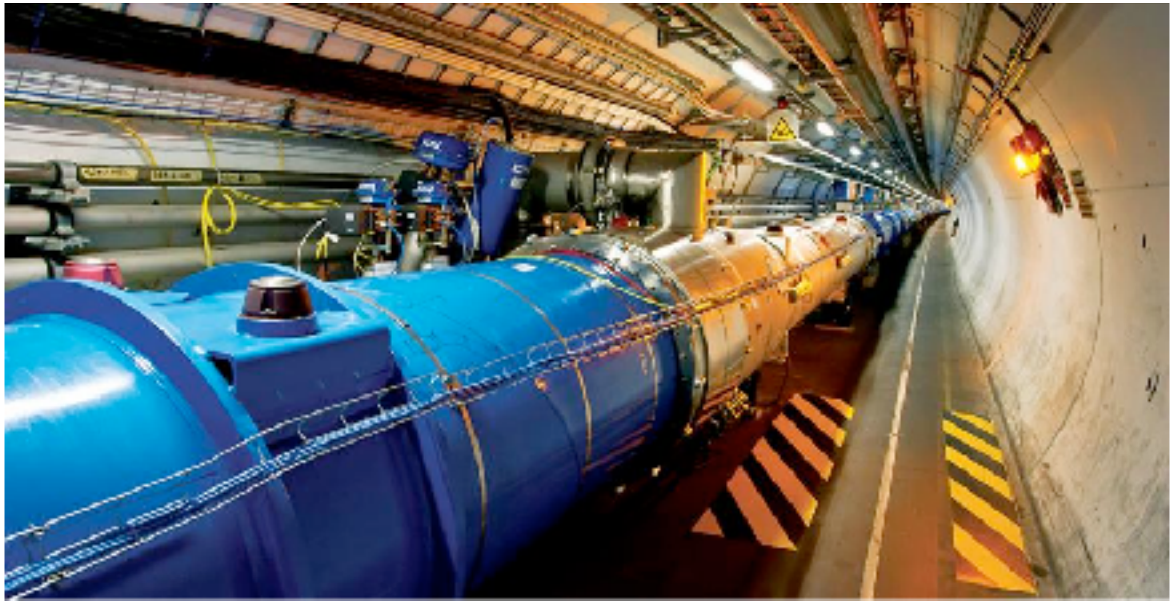
- RHIC (BNL)
  - first collisions in 2000
  - 3.85km circumference
  - Au-Au collider at $\sqrt{s_{NN}} = 200$ GeV
  - the AGS is used as injector (9 GeV)
  - 60 bunches per beam; luminosities ~10^{27} cm^{-2} s^{-1}
  - 4 collision points (currently only two are used: STAR, PHENIX)



Relativistic Heavy Ion Collider (RHIC)

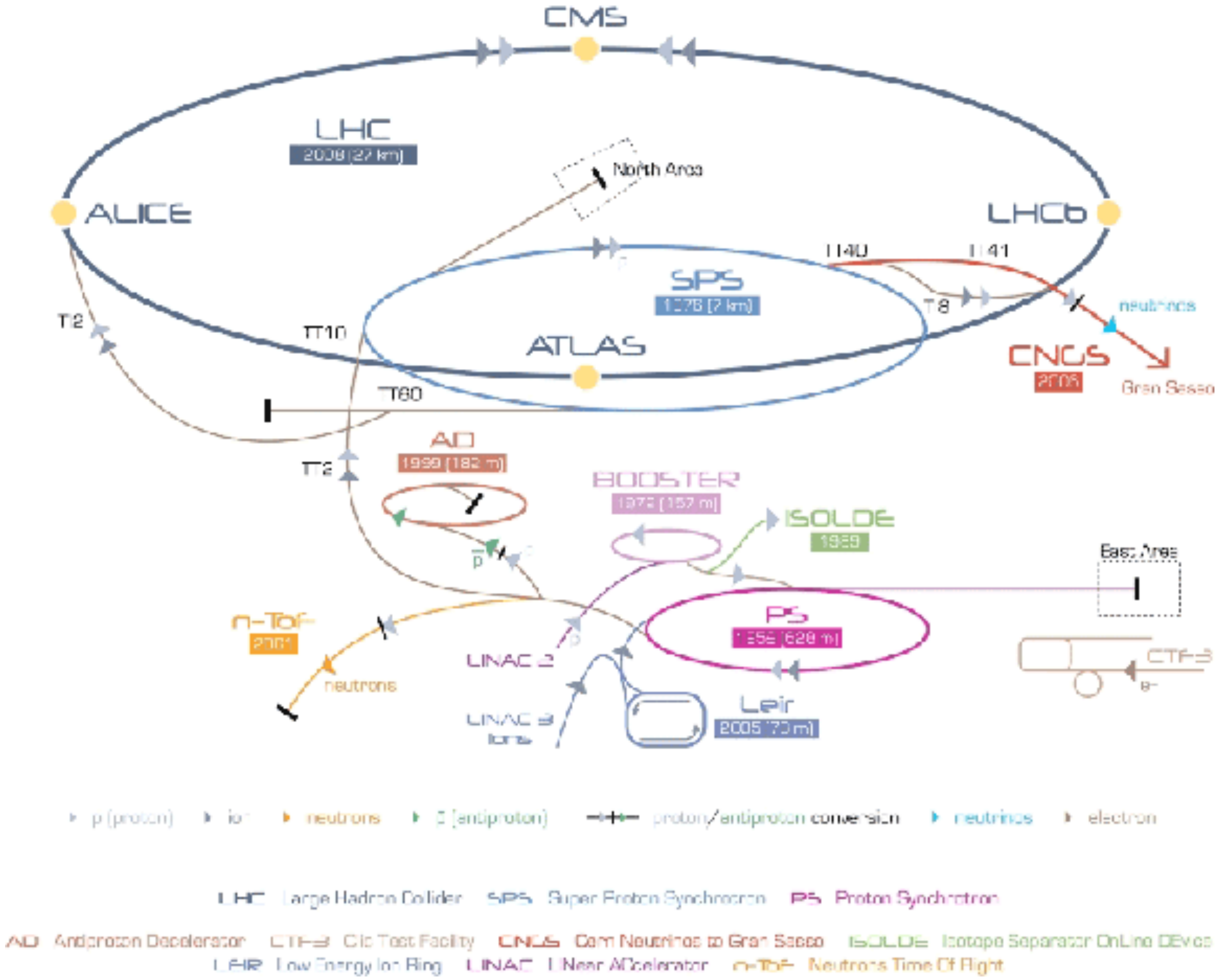


Large Hadron Collider (LHC)



- LHC (CERN), since 2009
- Uses the SPS as injector
- 2010:
  - first Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV
- Luminosity ~5×10^{26} cm^{-2} s^{-1}
- $\sqrt{s_{NN}} = 5.36$ TeV since 2023
- Beam lifetime reduced because of two main processes
  - electromagnetic production of e^+e^- pairs followed by e^- capture in Pb ion
  - neutron emission resulting from electromagnetic excitation of the Pb ion

CERN accelerator complex



Heavy-ion collider experiments

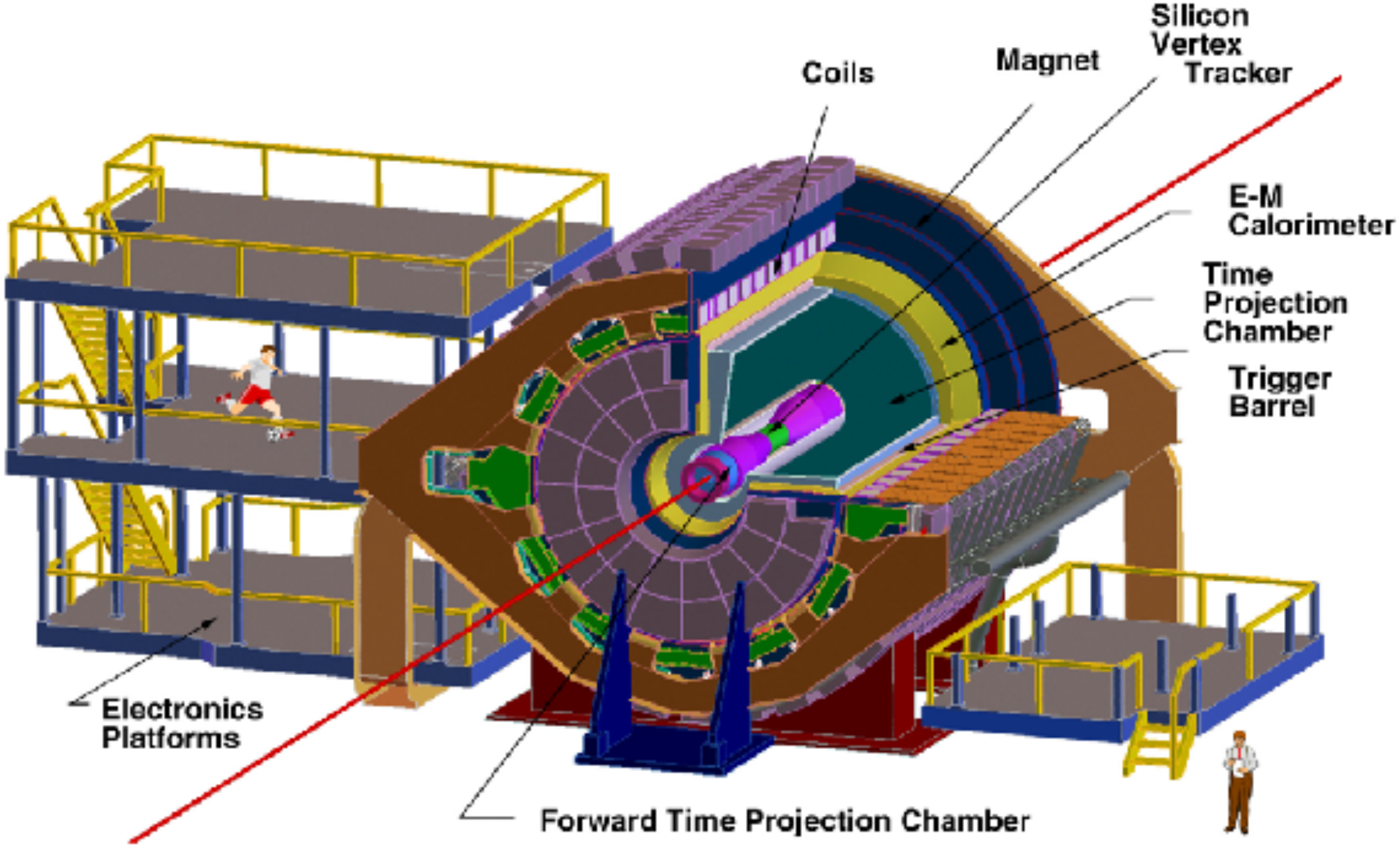
- Main experiments used for the study of ion-ion collisions at high energies:

  - experiments at RHIC
    - **STAR**
    - **PHENIX**

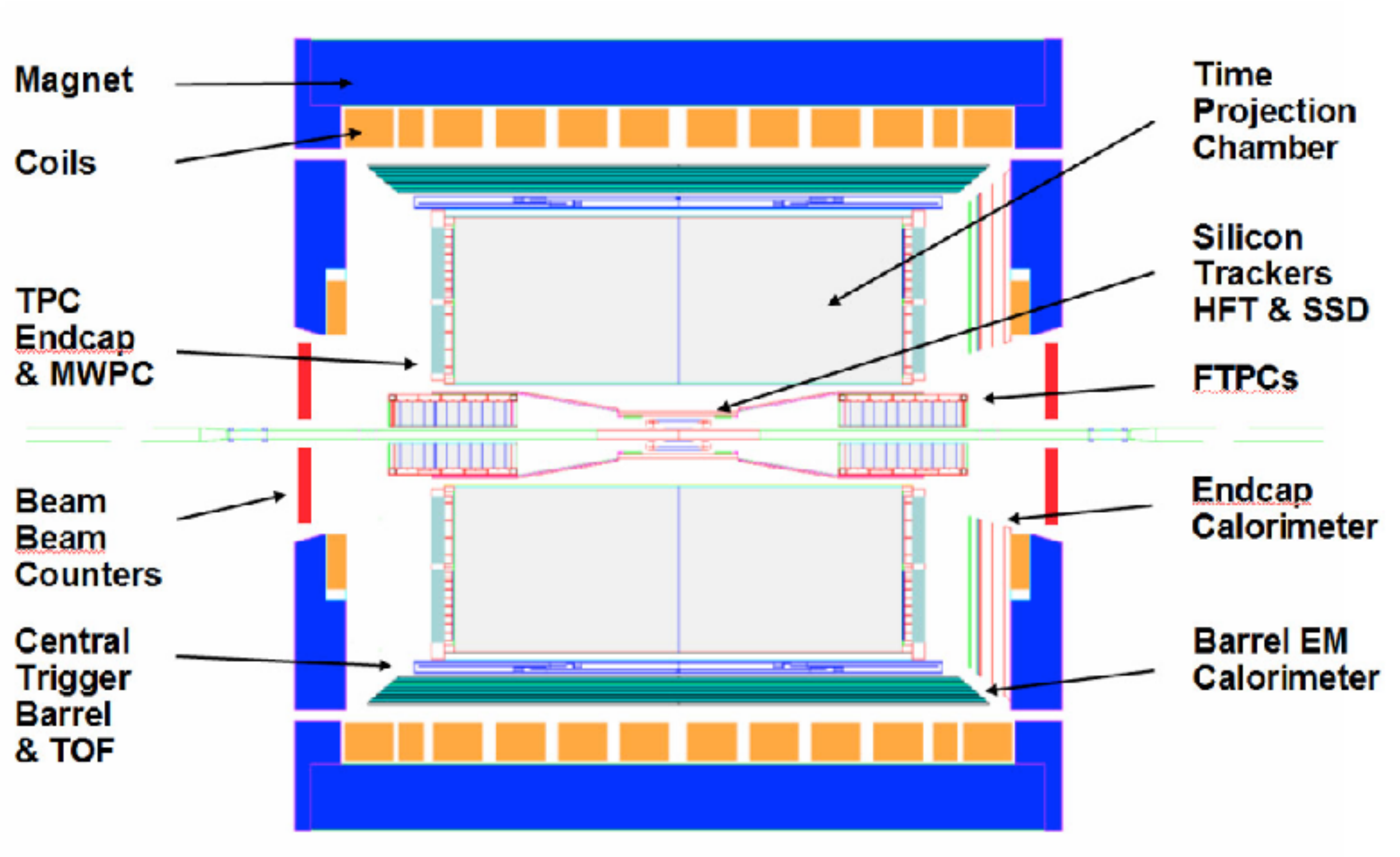
  - experiments at LHC
    - **ALICE**
    - ATLAS, CMS, LHCb

The STAR experiment (at RHIC)

- Typical 4π detector geometry
- Tracking with Silicon vertex tracker and a large time-projection chamber (TPC)
- Particle identification with time-of-flight and calorimeter

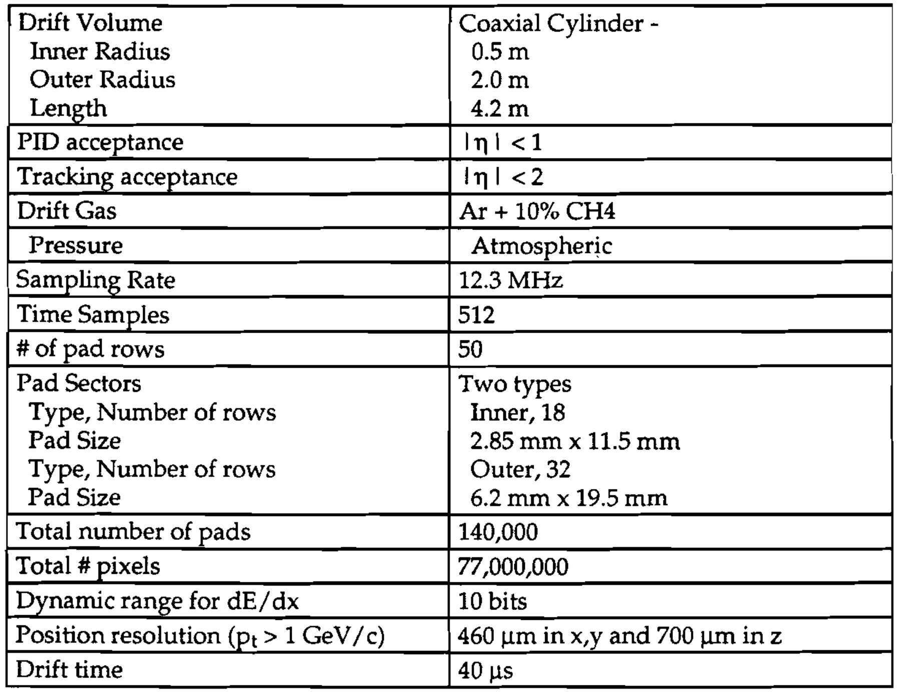


The STAR detector

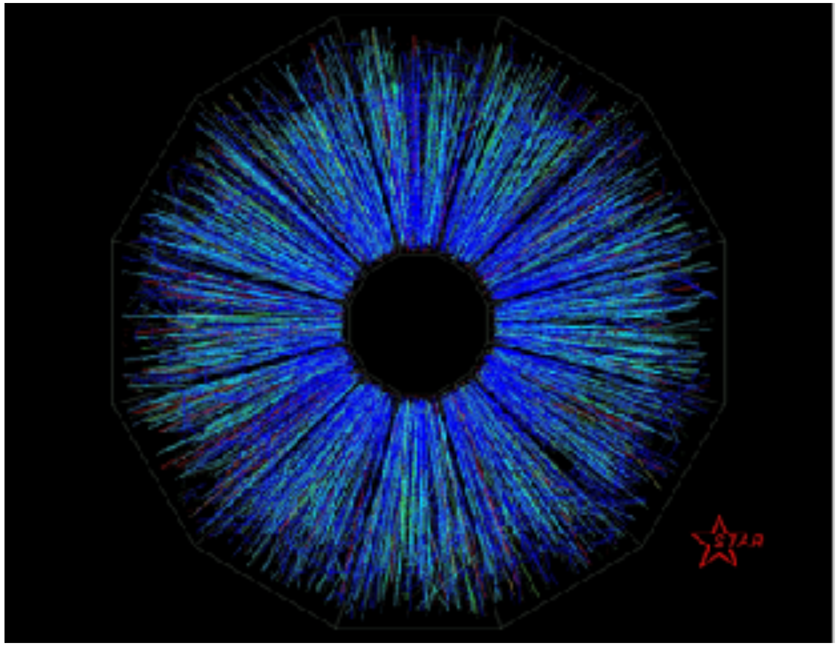


The STAR TPC

Table 2-2 Time Projection Chamber.

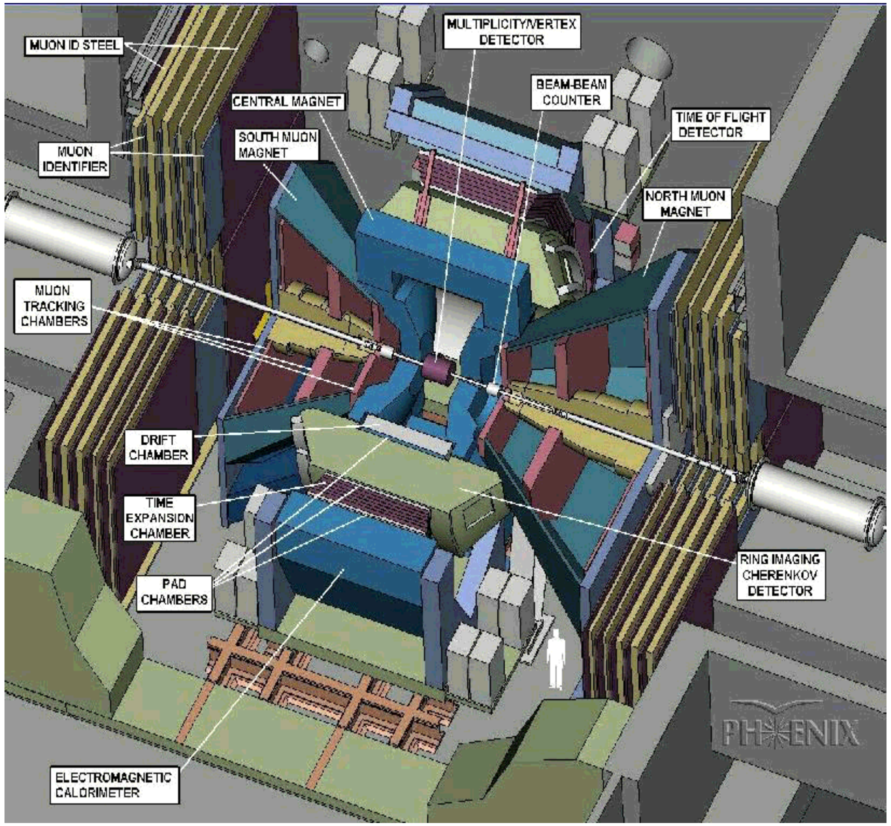


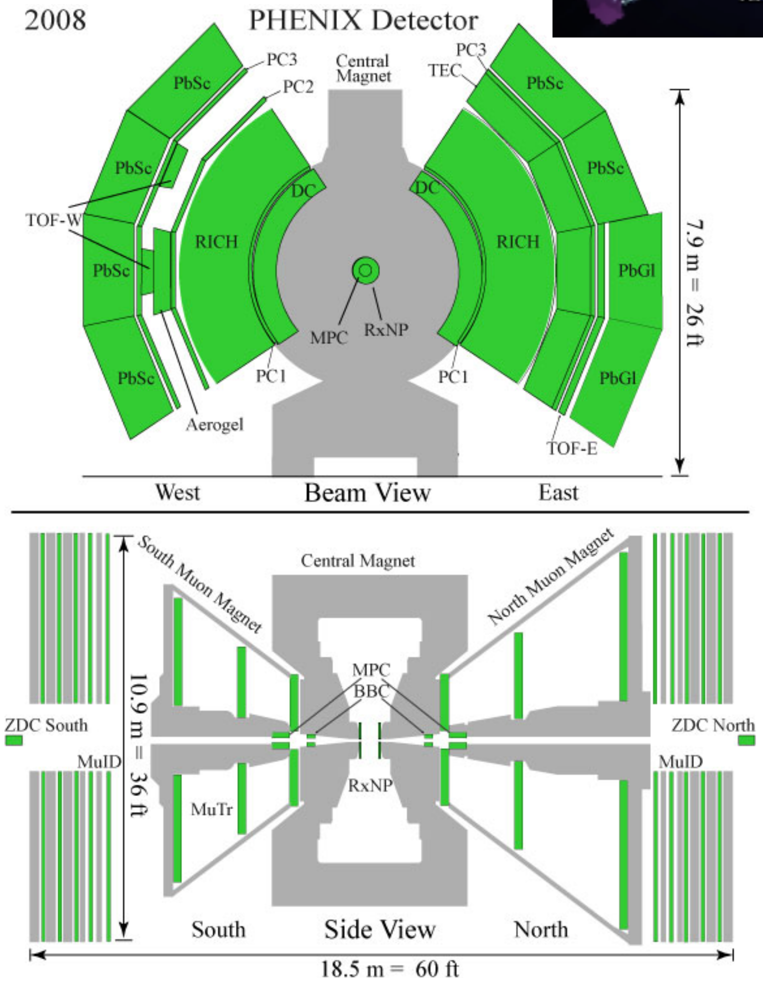
Drift Volume Inner Radius Outer Radius Length	Coaxial Cylinder - 0.5 m 2.0 m 4.2 m
PID acceptance	$\lvert\eta\rvert < 1$
Tracking acceptance	$\lvert\eta\rvert < 2$
Drift Gas	Ar + 10% CH4
Pressure	Atmospheric
Sampling Rate	12.3 MHz
Time Samples	512
# of pad rows	50
Pad Sectors Type, Number of rows Pad Size Type, Number of rows Pad Size	Two types Inner, 18 2.85 mm x 11.5 mm Outer, 32 6.2 mm x 19.5 mm
Total number of pads	140,000
Total # pixels	77,000,000
Dynamic range for dE/dx	10 bits
Position resolution ($p_t > 1$ GeV/c)	460 μm in x,y and 700 μm in z
Drift time	40 μs



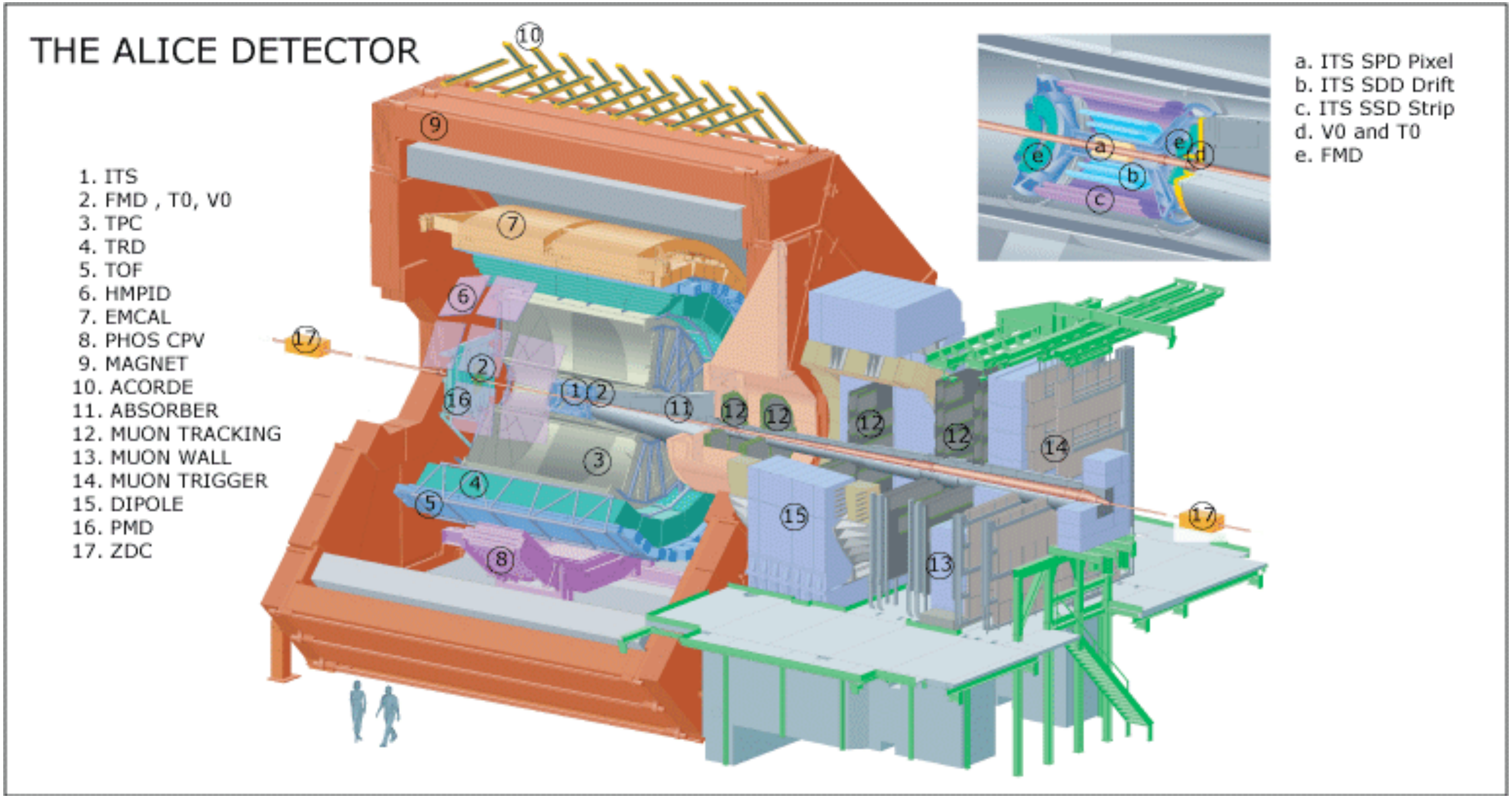
The PHENIX experiment (at RHIC)

- Pioneering High Energy Nuclear Interaction eXperiment
- Designed to measure direct probes of the ion-ion collisions, such as electrons, muons and photons
- Asymmetric design

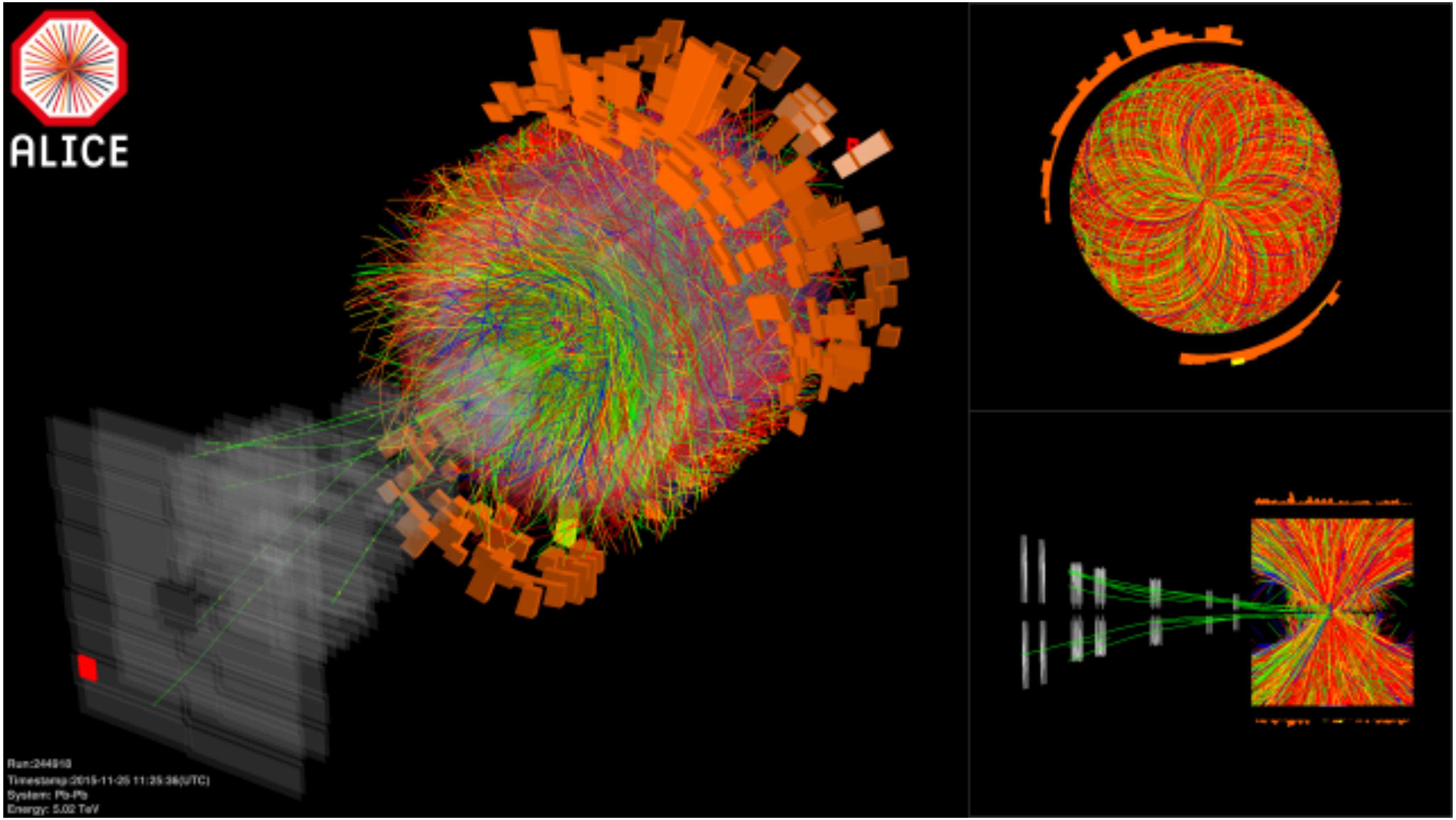




The ALICE experiment (at LHC)



ALICE event at $\sqrt{s_{\mathrm{NN}}}$=5.02 TeV



Selection of experimental results

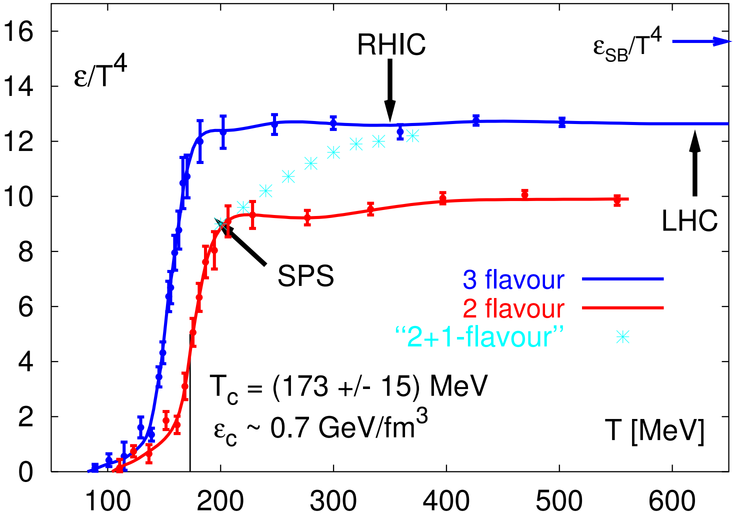
- Energy densities
- Particle multiplicities
- Measurements of the freeze-out temperature
- Initial temperature
- Correlations (including QGP dimensions)
- Opacity of the hadronic matter
- Jet production asymmetry

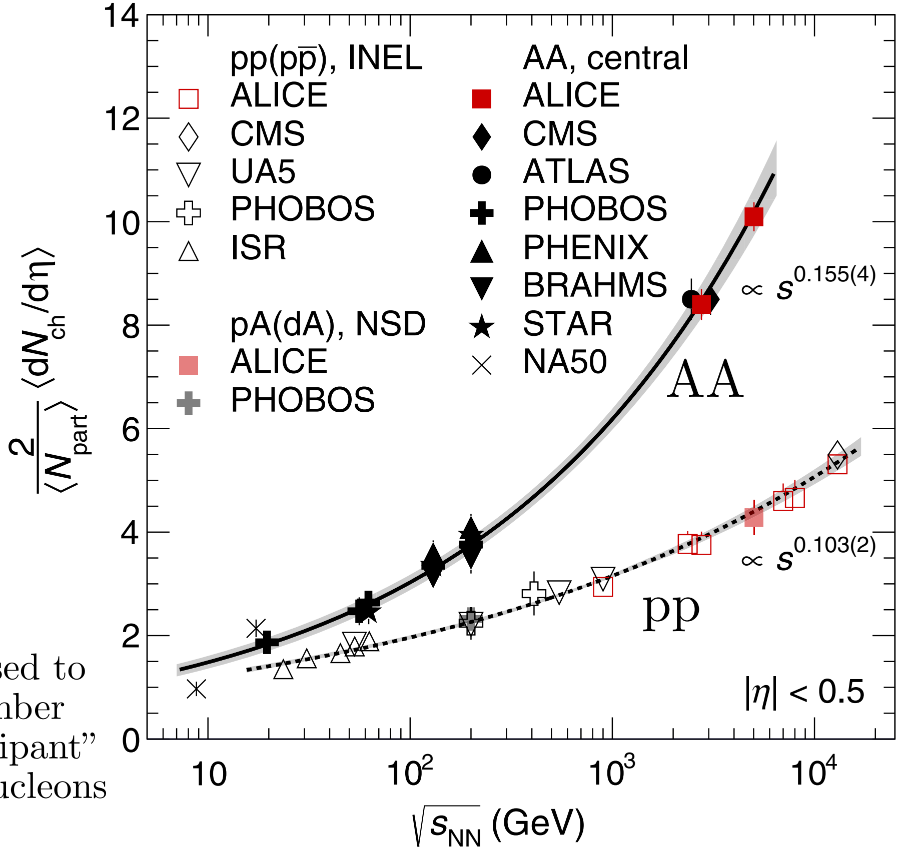
Energy densities

- Charged particle pseudorapidity densities for pp and PbPb collisions
- At RHIC: ~600 charged (~900 total) particles per unit of η
  $\Rightarrow$ estimate energy density at the level of $5 - 15$ GeV/fm^3
- At 2.76 TeV, transverse energy ~ 2 TeV and ~ 1600 charged particles per unit of $\eta \Rightarrow$ initial temperature $\sim 310 - 370$ MeV

  $\Rightarrow$ above the phase transition!

Prediction from lattice QCD:





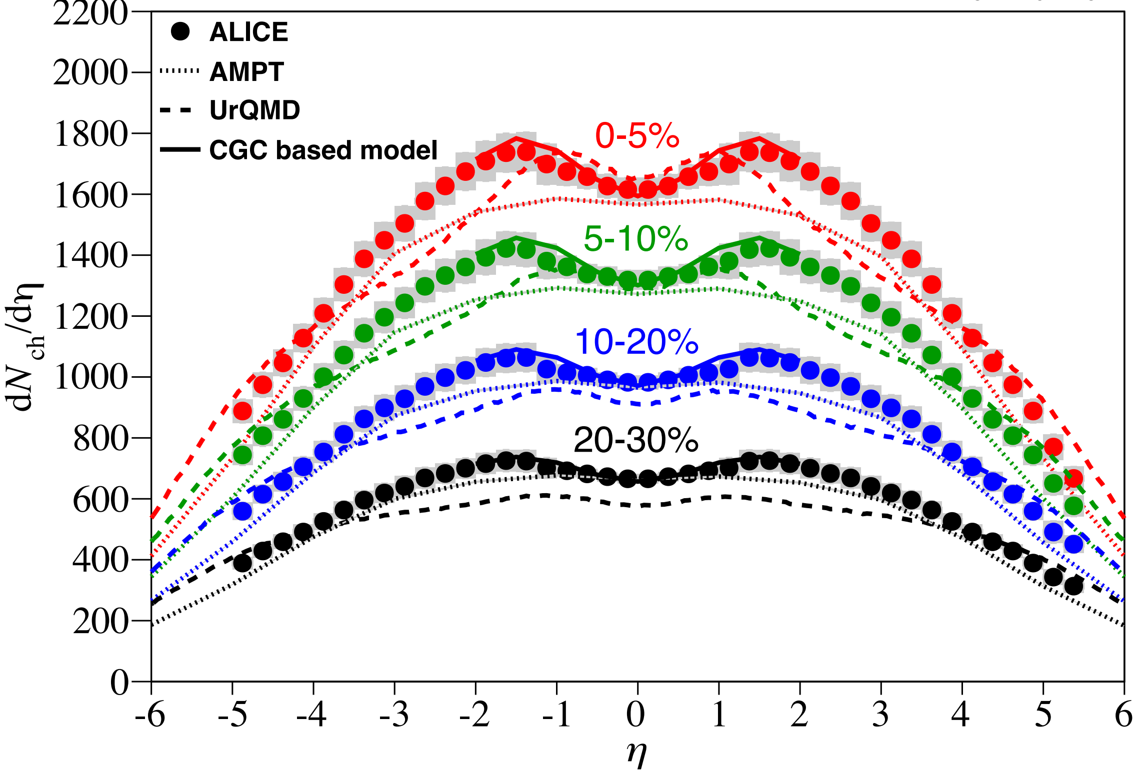
Normalised to
the number
of "participant"
pairs of nucleons

ALICE, Phys. Rev. Lett. 116 (2016) 222302

Multiplicity distributions

- Pseudorapidity density distributions for various centralities
- Measurement by ALICE at 2.76TeV:

arXiv:1511.02151

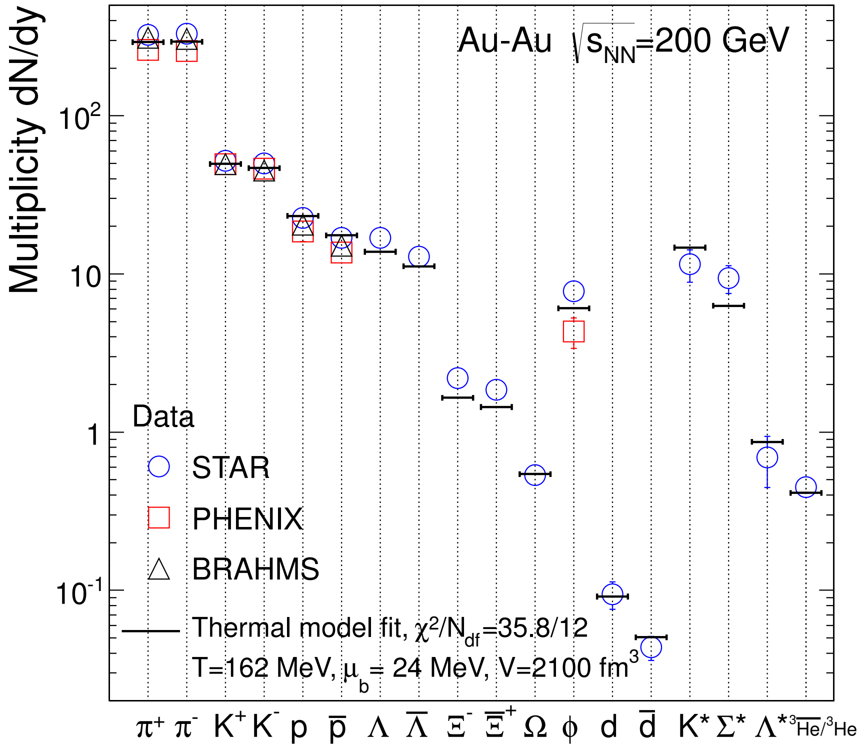


- Total integrated charged multiplicity from integration of these plots: $N_{ch} = 17165 \pm 772$ for $0 - 5\,\%$ centrality
- The models don't describe the data accurately

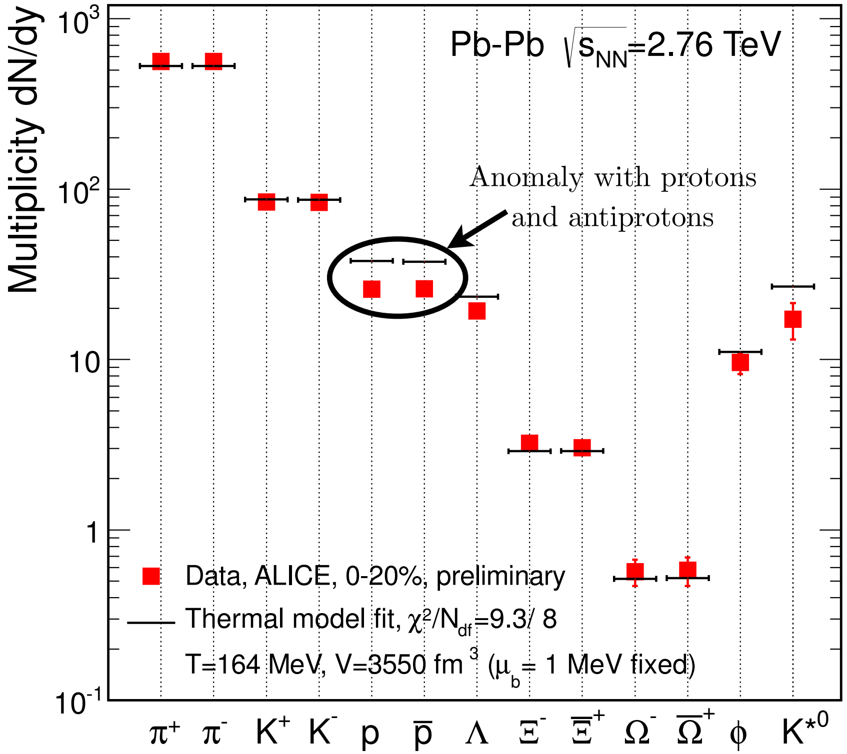
Freeze-out temperature

- Measure hadron multiplicities to determine the temperature
  - the expanding hot system hadronises statistically at freeze-out.
  - if thermal equilibrium, temperature can be determined from particle multiplicities
- Freeze-out temperature measured at RHIC and LHC:

RHIC: $T_{\text{freeze-out}} = 162\text{MeV}$



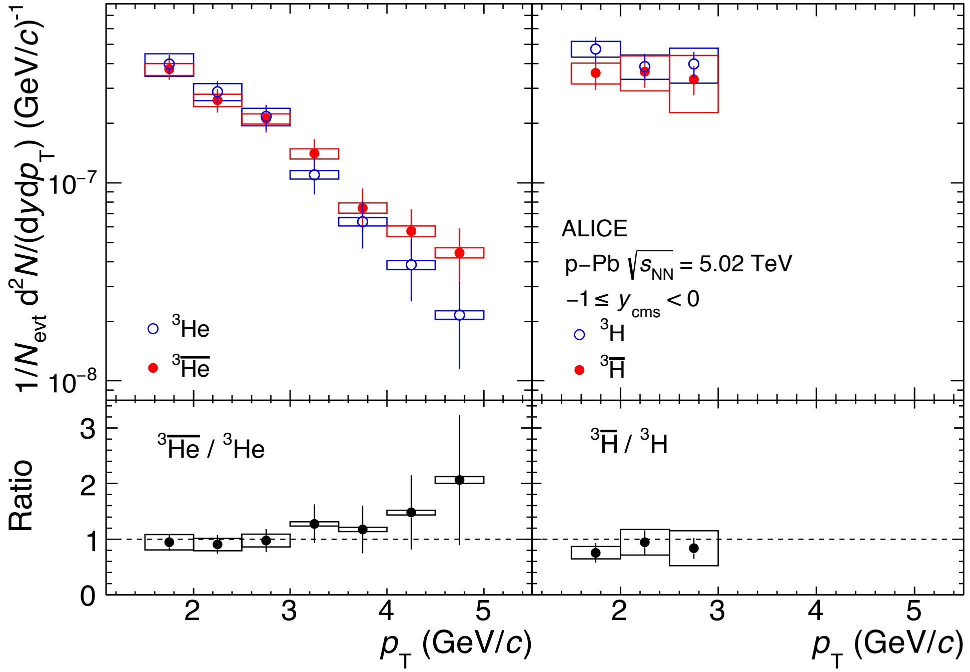
LHC: $T_{\text{freeze-out}} = 164\text{MeV}$



Anomaly with protons and antiprotons

Production of matter and antimatter

- ALICE measured the production rates of deuterium, ^{3}He, ^{3}H, and the corresponding anti-nuclei in p–Pb collisions
  - rates for nuclei and anti-nuclei are compatible
    ⇒ symmetric production
  - these results have implications for the predictions of rates of nuclei in cosmic rays, and the search for Dark Matter (cf. AMS measurements)

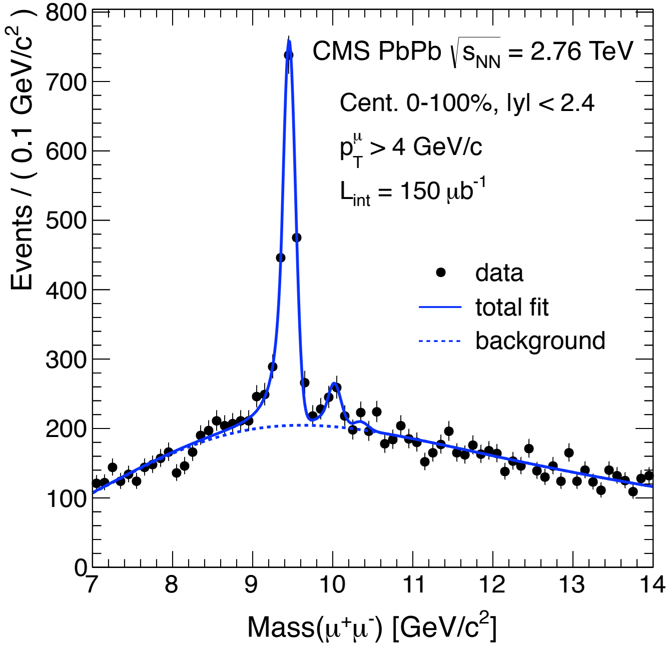


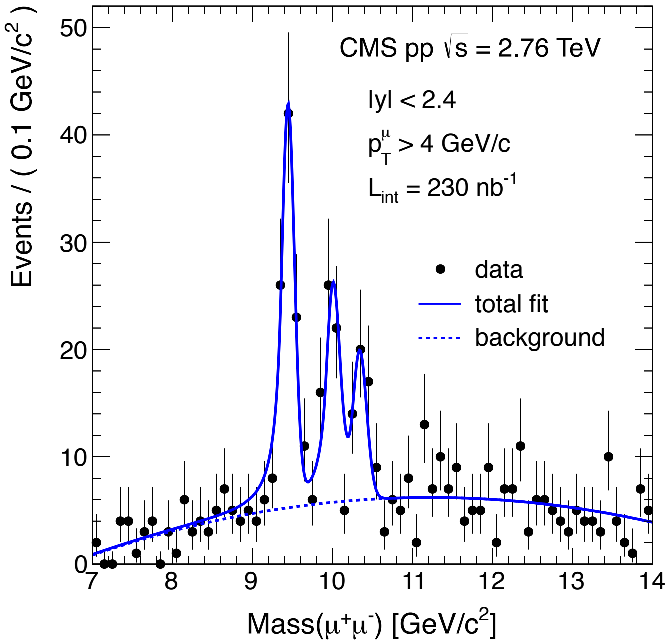
arXiv:1910.14401

Figure 4: p_T spectra of (anti-)^{3}He (left) and (anti-)^{3}H (right) measured in INEL > 0 p–Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV. The bottom panels show the corresponding antiparticle-to-particle ratios as a function of p_T. Statistical and systematic uncertainties are indicated by vertical bars and boxes, respectively.

Initial temperature (I)

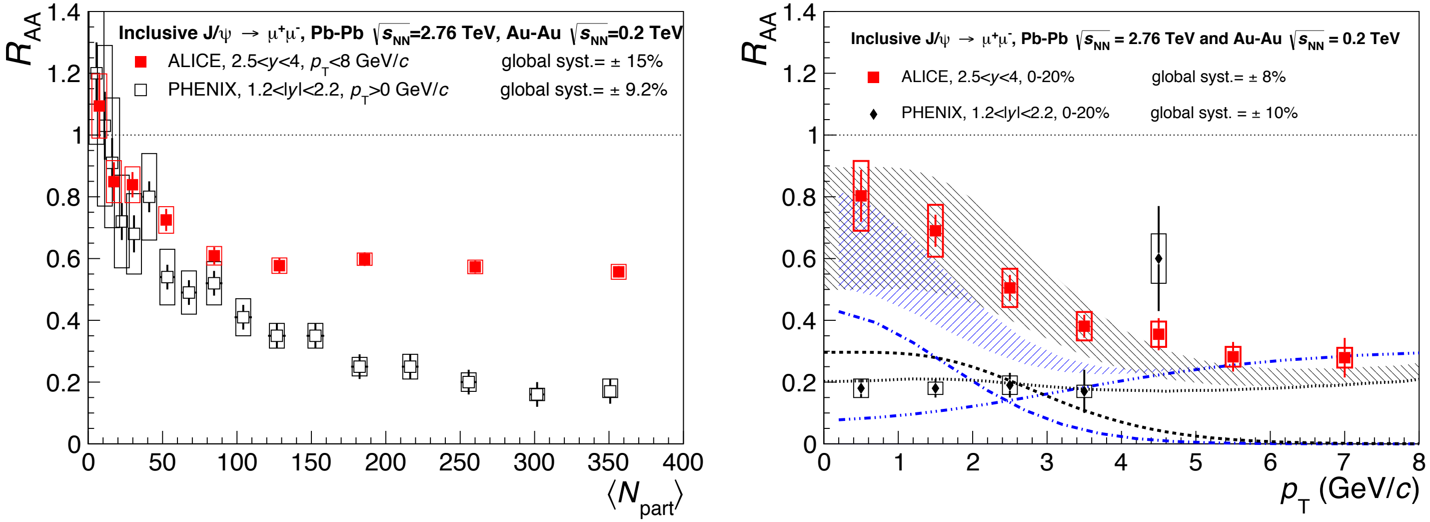
- PHENIX measured the photon spectrum in Au–Au collisions
  - QGP thermal radiation ⇒ expect high energy photons
  - results incompatible with perturbative QCD calculations, but can be described by hydrodynamical models ⇒ T = 300–600MeV
- Temperature estimated from quarkonium production rates
  - suppression of $\Upsilon(2S)$ and $\Upsilon(3S)$ resonances in CMS Pb–Pb data
  - compatible with formation of QGP with T = 200–400MeV





Initial temperature (II)

- Temperature estimated from quarkonium production rates
  - suppression of J/ψ production is observed at RHIC and LHC, but less reduction at higher LHC energy! (⇒ “regeneration” ?)



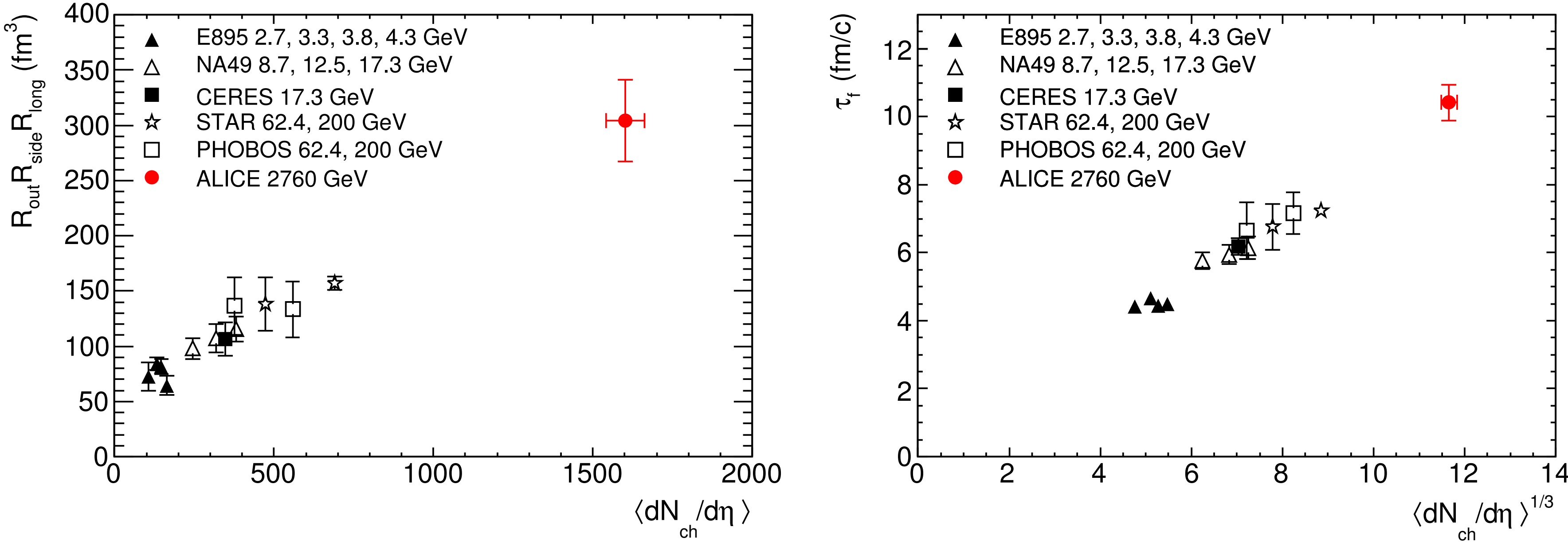
arXiv:1511.02151

  - but it is not clear whether the suppression is because the J/ψ melted or if it is due to the melting of higher resonances from which part of the J/ψ are the decay products

⇒ not an unambiguous evidence for deconfinement

Intensity interferometry

- Apply Hanbury Brown-Twiss method using correlated pions



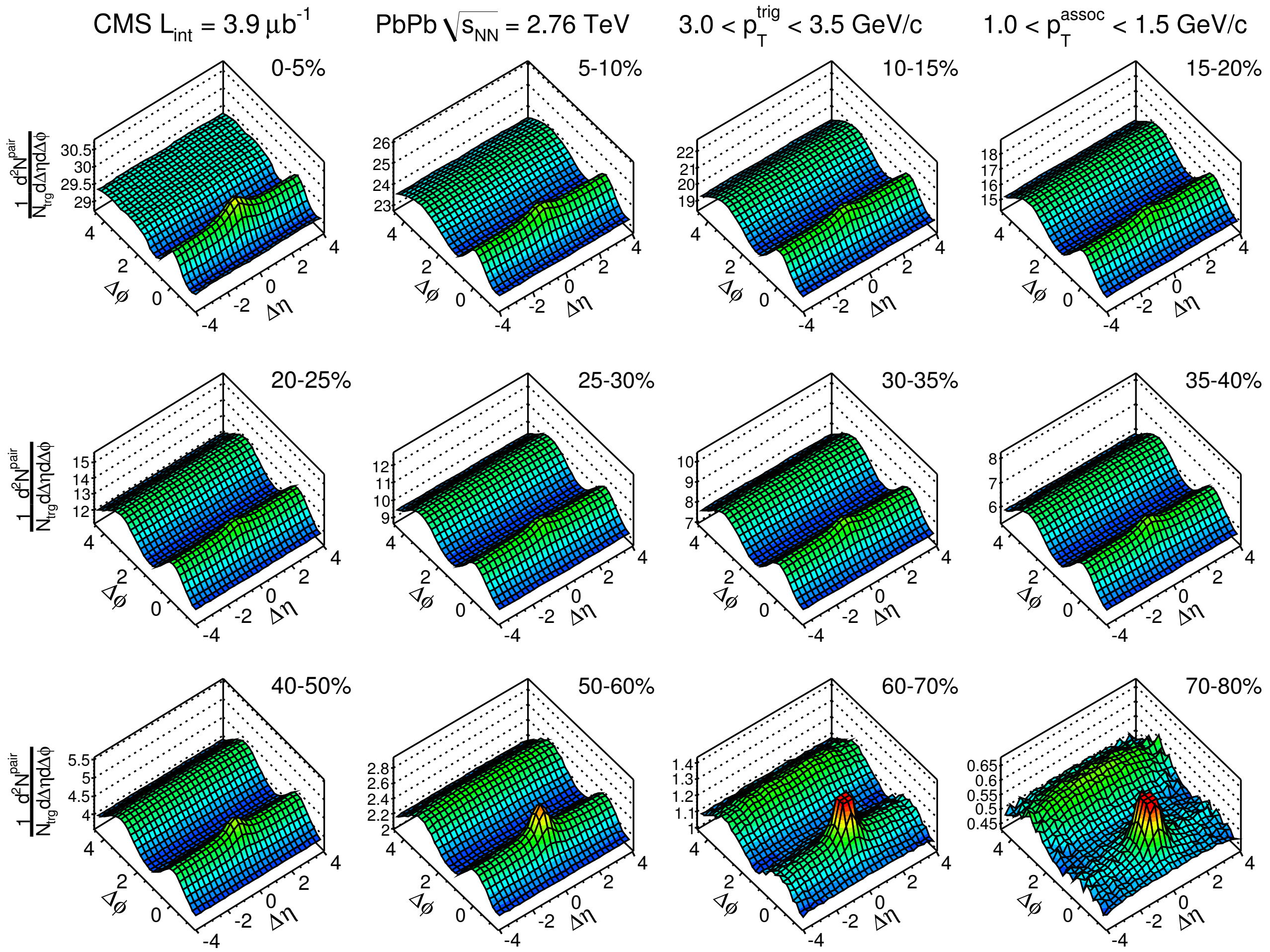
arXiv:1605.03939

Fig. 1. Product of the three pion HBT radii at $k_T = 0.3\,\mathrm{GeV}/c$ (left) and decoupling time (right). The ALICE results (full circles) are compared to those obtained for central Au and Pb collisions at lower energies.

$\Rightarrow$ uniform volume of 300 fm^3 and time of 10 fm/c

Correlations

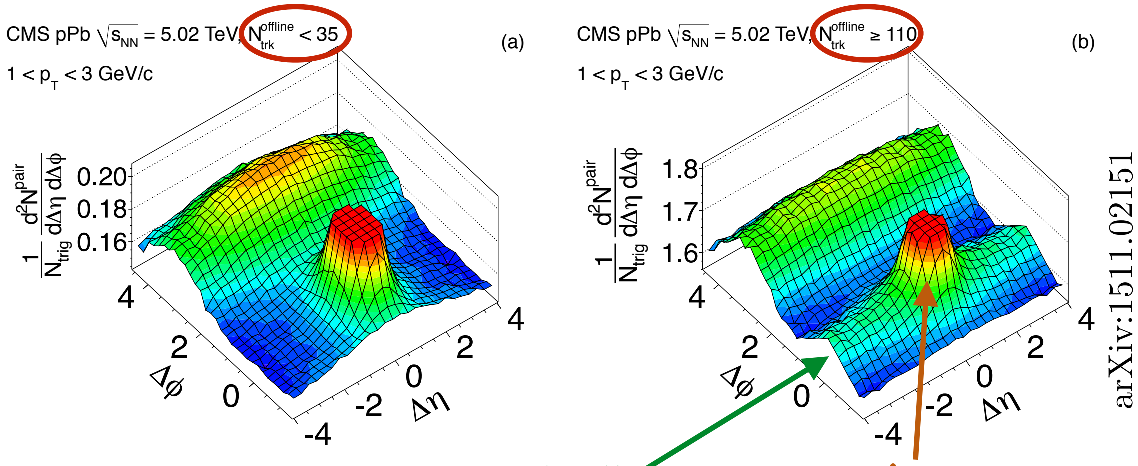
- Study $(\Delta\eta, \Delta\phi)$ correlation plots between pairs of particles



arXiv:1511.02151

- Particles at $\Delta\phi = 0\,,\pi$ with wide range of $\Delta\eta \Rightarrow$ "ridge" effect
- Effect is strong with increasing centrality

Ridge effect



arXiv:1511.02151

"ridge"

jets

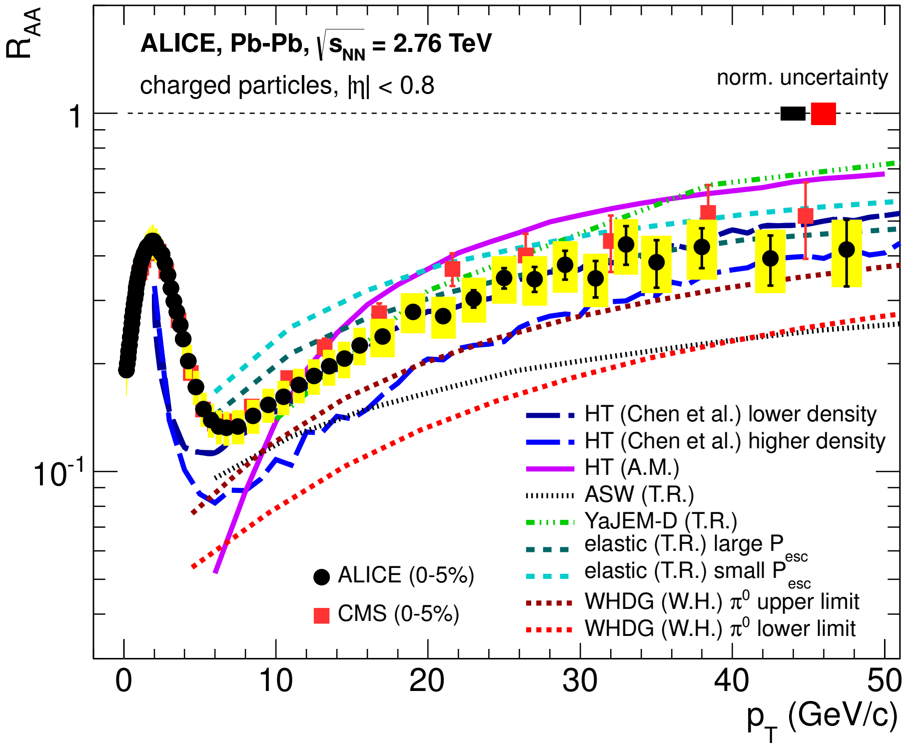
$(\Delta\eta, \Delta\phi) = (0,0)$

- Effect also seen in p-Pb collisions
- Implication:
  large correlation between particles at very different rapidities
- Possible theoretical explanations:
  - hydrodynamics: initial long-range η correlation $\Rightarrow$ ϕ correlation through the dynamical expansion of the medium
  - azimuthal asymmetry comes from the wave function of the colliding hadrons
- These effects were unexpected ⇒ active search area

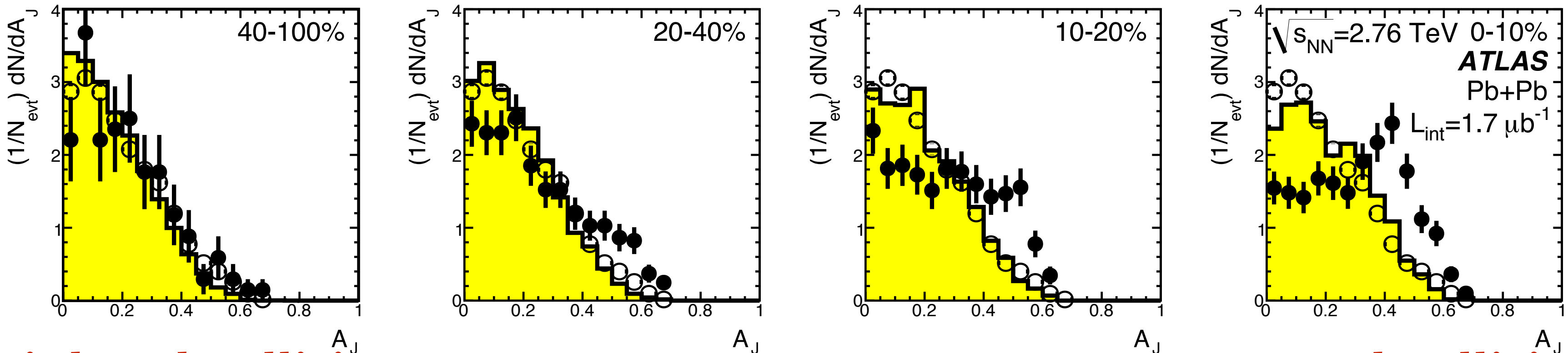
R_{AA} = ratio of single hadron transverse momentum spectra in heavy-ion collisions to the same quantity obtained in proton proton collisions, normalised to the number of binary collisions

Opacity

- Charged pion nuclear modification factor R_{AA} in Pb–Pb collisions
  - strong suppression of $\pi^{\pm}$ at $p_T = 6 - 7\,\mathrm{GeV}/c$
  - rise above $7\,\mathrm{GeV/c}$ in good agreement with QGP formation



- Di-jet production asymmetry
  - strong suppression of one jet in central collisions



peripheral collisions **central collisions**

Summary of experimental results

- Search for QGP signatures in high-energy ion-ion collision
  - mainly at BNL and CERN

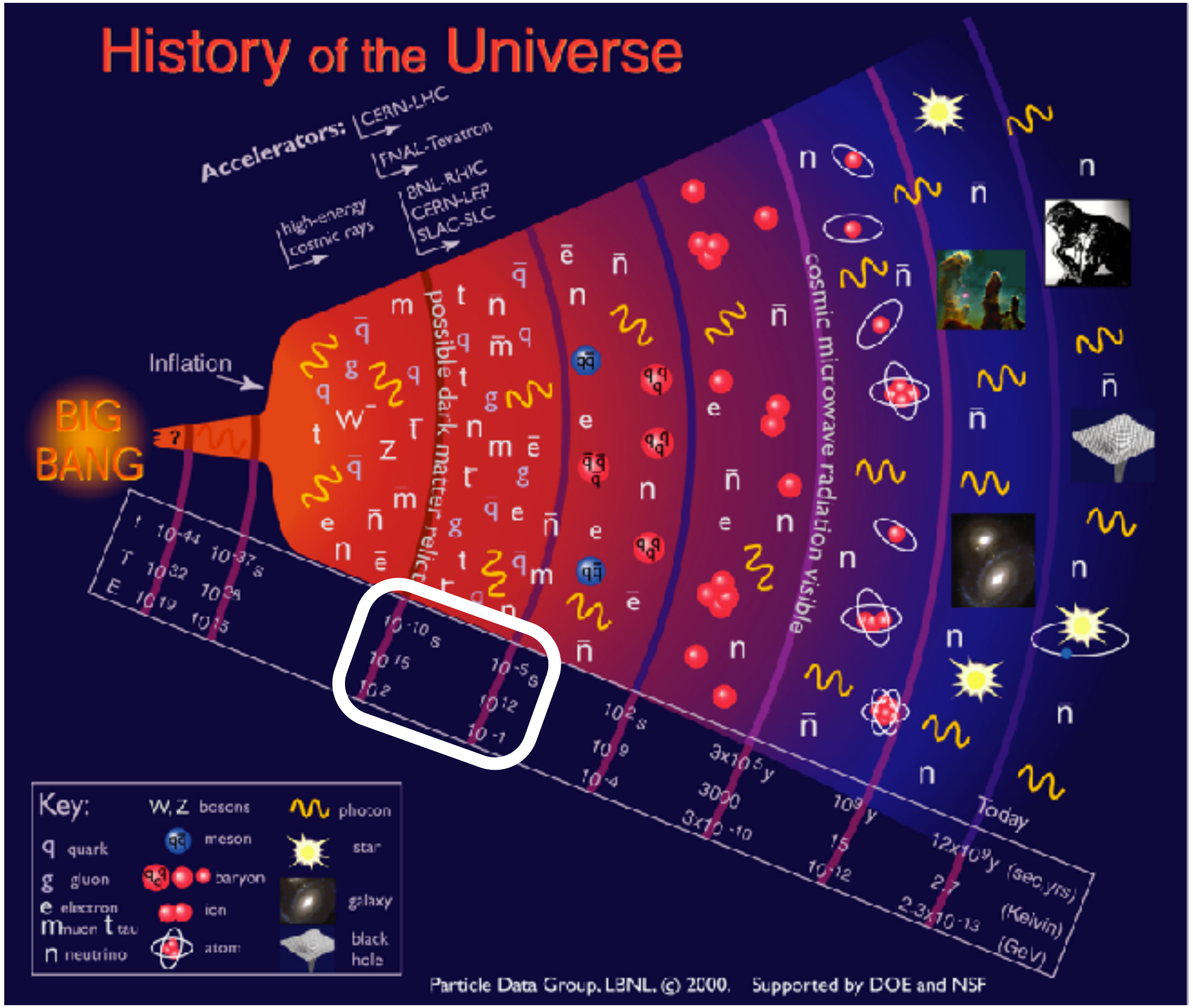
- Many experimental results in agreement with QGP formation, which can be considered to have been produced as a new state of matter

  ...but no single observation of a QGP can be claimed, because alternative explanations are not ruled out

- Future measurements at RHIC and at LHC will help to further understand QGP

...a word on QGP and cosmology

- QGP during period $\sim 10^{-10}$ to $\sim 10^{-5}$ s
  - from quark formation to dense QGP stage to baryon formation

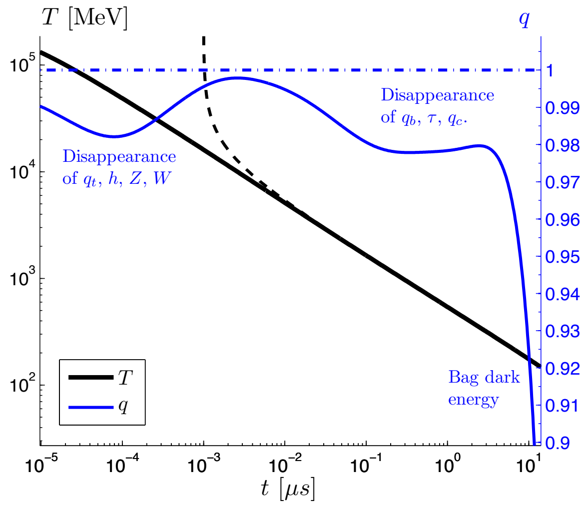


Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

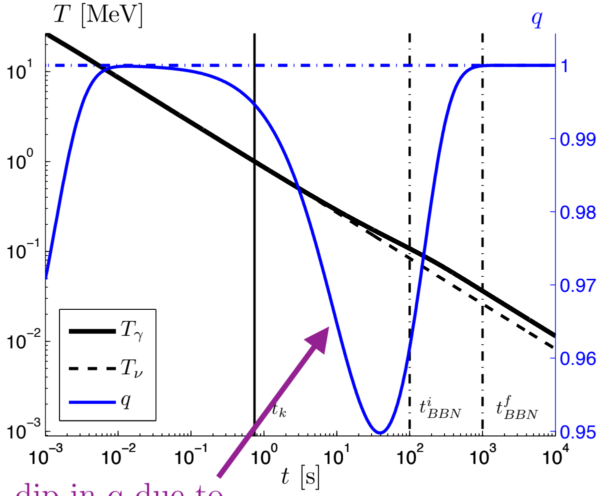
Another view of the cosmological evolution

- Evolution of the temperature and the parameter of deceleration q as a function of time $q = -\dfrac{a\ddot{a}}{\dot{a}^2} = \dfrac{1}{2}\left(1 + 3\dfrac{P}{\epsilon}\right)\left(1 + \dfrac{k}{\dot{a}^2}\right)$

QGP period

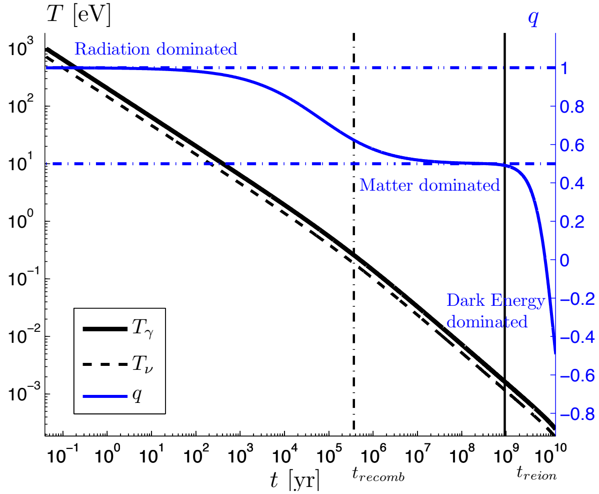


From end of matter-antimatter annihilation to BBN



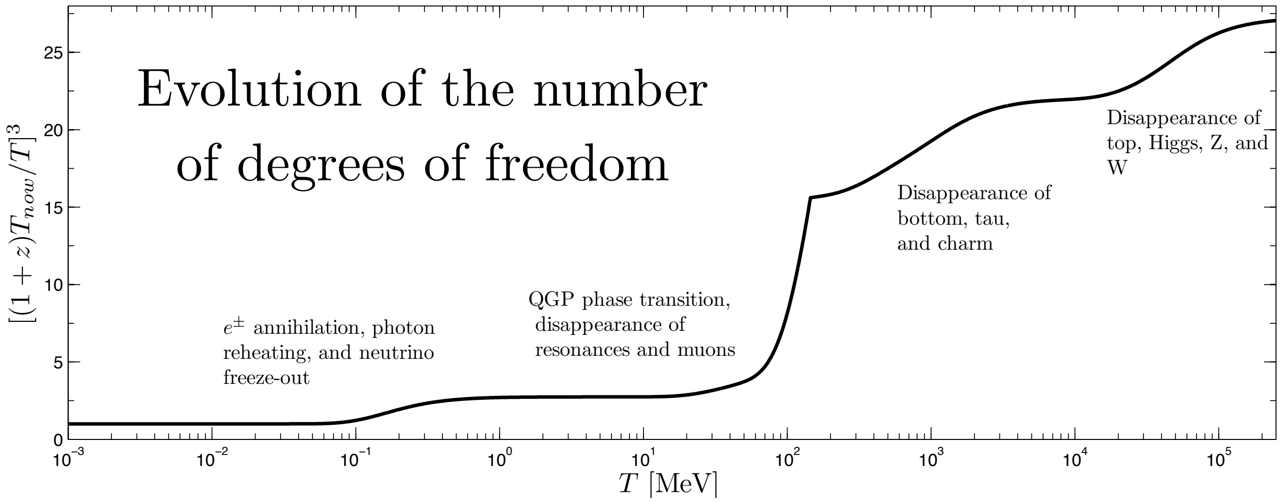
dip in q due to non-relativistic e⁺e⁻ pairs

From BBN to now



Fractional drop of temperature compared to redshift

Evolution of the number of degrees of freedom



arXiv:1311.0075