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Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

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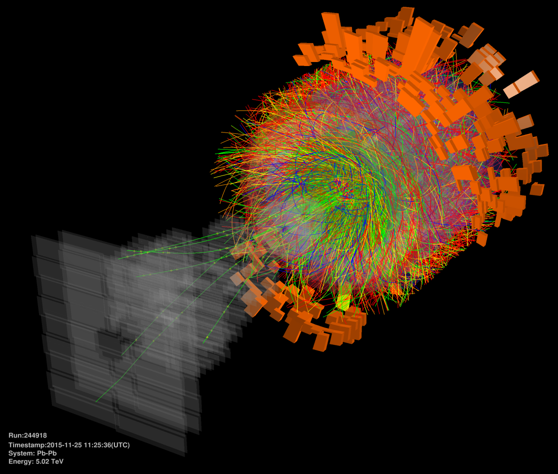

Introduzione alla fisica del plasma di quark e gluoni

Federico Antinori
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Laboratori Nazionali di Frascati, 4 ottobre 2017

Contents

- Open puzzles in Quantum Chromo-Dynamics
- Confinement and deconfinement
  - (an “intuitive” view)
- Ultra-relativistic nucleus-nucleus collisions
- Intermezzo: the Large Hadron Collider
- Intermezzo: kinematic variables
- A few selected results
- Conclusions

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The Standard Model and QCD

FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2		
Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	–1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	–1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	–1

Quarks spin = 1/2		
Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	175	2/3
b beauty	4.3	–1/3

BOSONS

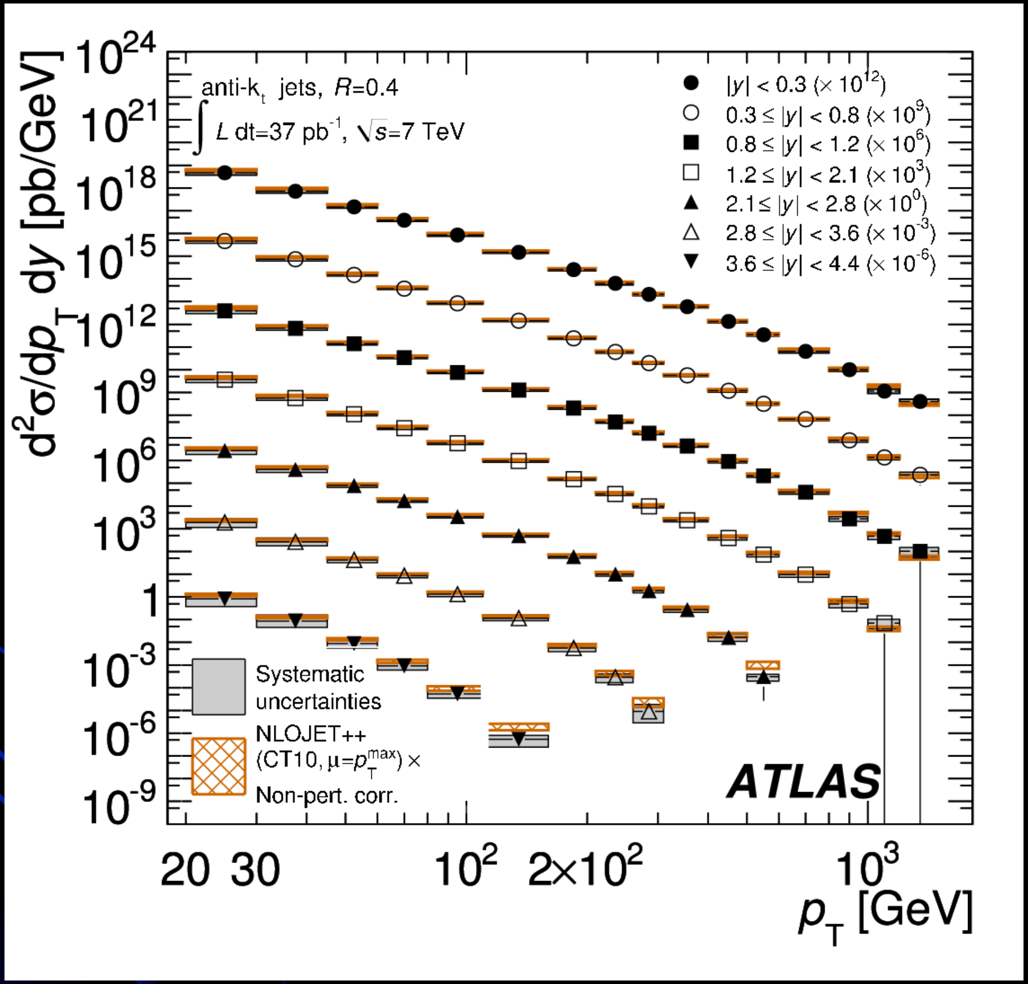
force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1		
Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W$^-$	80.4	–1
W$^+$	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1		
Name	Mass GeV/c^2	Electric charge
g gluon	0	0

- strong interaction:
  - binds quarks into hadrons
  - binds nucleons into nuclei
- described by QCD:
  - interaction between particles carrying colour charge (quarks, gluons)
  - mediated by strong force carriers (gluons)
- very successful theory

- e.g.: pQCD vs production of high energy jets



ATLAS: arXiv:1112.6297

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- very successful theory
  - jet production
  - particle production at high p_T
  - heavy flavour production
  - …
- … but with outstanding puzzles

Two puzzles in QCD: i) hadron masses

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- A proton is thought to be made of two u and one d quarks
- The sum of their masses is around 12 MeV
- ... but the proton mass is 938 MeV!
- how is the extra mass generated?

Two puzzles in QCD: ii) confinement

FERMIONS matter constituents spin = 1/2, 3/2, 5/2, ...

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- Nobody ever succeeded in detecting an isolated quark
- Quarks seem to be permanently confined within protons, neutrons, pions and other hadrons.
- It looks like one half of the fundamental fermions are not directly observable…

  why?

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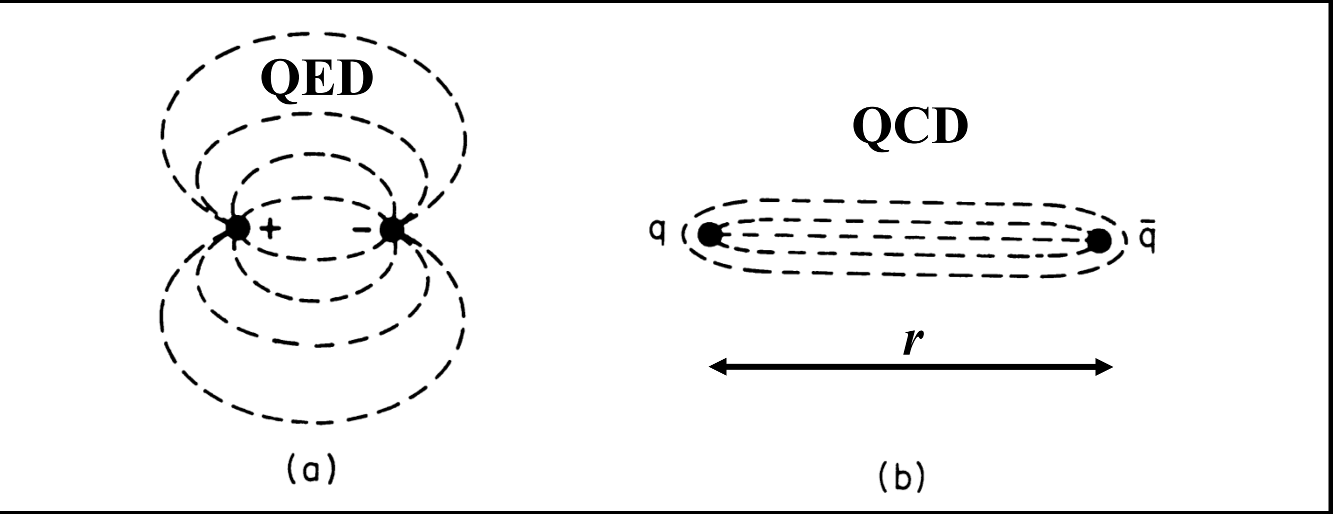
Confinement

- At scales of the order of the hadron size (~ 1 fm) perturbative methods lose validity
- Calculations rely on approximate methods (such as lattice theory or effective theories)
- There are compelling arguments (but no rigorous proof) that the non-abelian nature of QCD is responsible for the confinement of colour

[see e.g. Gottfried-Weisskopf, p. 99]

Confining potential in QCD



- In QCD, the field lines are compressed into a "flux tube" (or "string") of constant cross-section (~fm^2), leading to a long-distance potential which grows linearly with *r*:

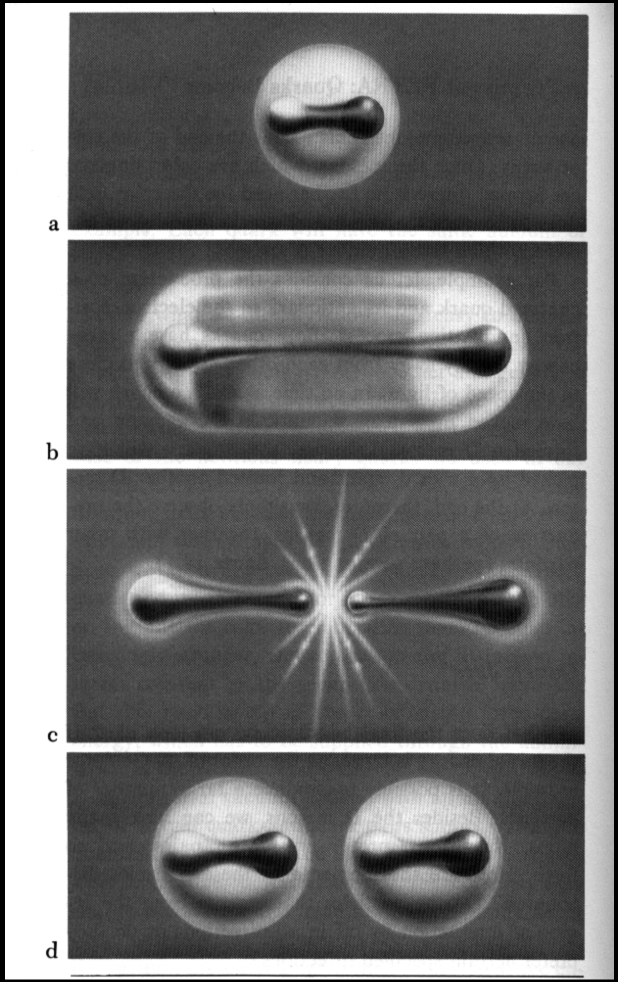
$$V_{long} = kr$$

with k ~ 1 GeV/fm

String breaking

- If one tries to pull the string apart, when the energy stored in the string ($k\ r$) reaches the point where it is energetically favourable to create a $q\bar{q}$ pair, the string breaks…

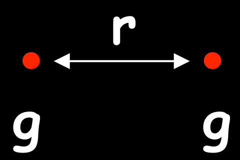
- ...and one ends up with two colour-neutral strings (and eventually hadrons)



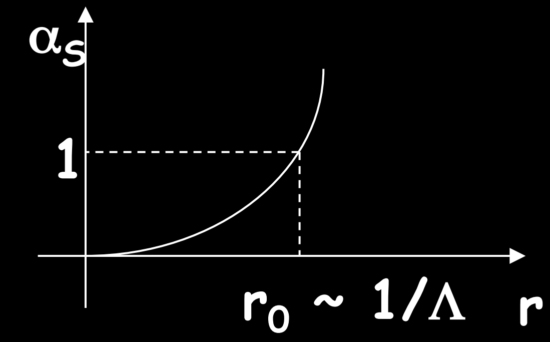
[illustration from Fritzsch]

QCD vacuum

- e.g.: 2 gluons in singlet state at a distance r



$$\Delta p \Delta r \sim \hbar = 1$$



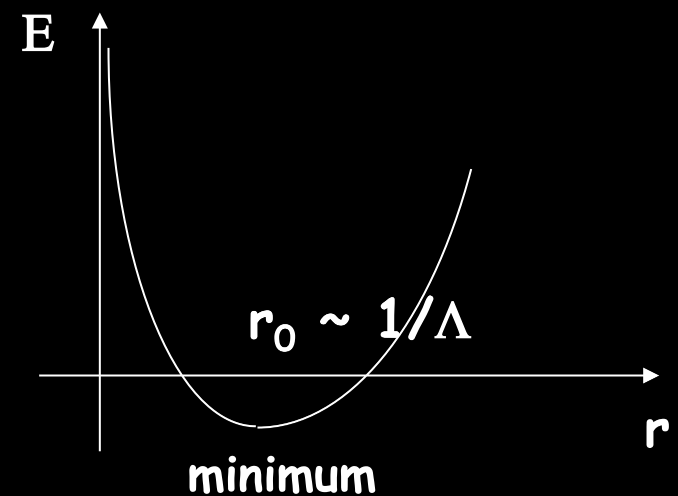
$$r \sim \frac{1}{p} \sim \frac{1}{E_{KIN}} \quad \rightarrow \quad E_{KIN} \sim \frac{1}{r}$$

$$E = \frac{1}{r} - C\frac{\alpha_S}{r} = \frac{1 - C\alpha_S}{r}$$

$$r \rightarrow 0 \qquad E \sim \frac{1}{r}$$

$$r \sim r_0 \qquad E <\sim 0$$

$$r \rightarrow \infty \qquad E \sim kr$$



QCD vacuum

- The “empty” vacuum is unstable. There is a state of lower energy that consists of cells, each containing a gluon pair in colour- and spin- singlet state. The size of these cells is of order r_0. We may speak of a “liquid” vacuum.

Gottfried-Weisskopf, IV C

Bag Model

- Due to the non-abelian nature of QCD and to the large value of the QCD coupling, the QCD vacuum is a rather complex object, behaving practically as a liquid

- The MIT bag model describes the essential phenomenology of confinement by assuming that quarks are confined within bubbles (bags) of perturbative (= empty) vacuum of radius *R* upon which the QCD vacuum exerts a confining pressure *B*

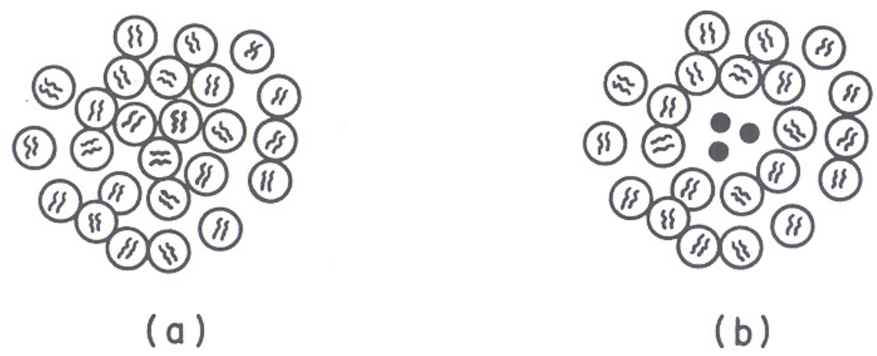


FIG. 9. The QCD vacuum state is depicted in (a). It is a random distribution of cells that contain a gluon pair in a color and spin singlet state. Quarks (in a color singlet configuration) displace these cells, creating a region (or "bag") of "empty" vacuum, as shown in (b).

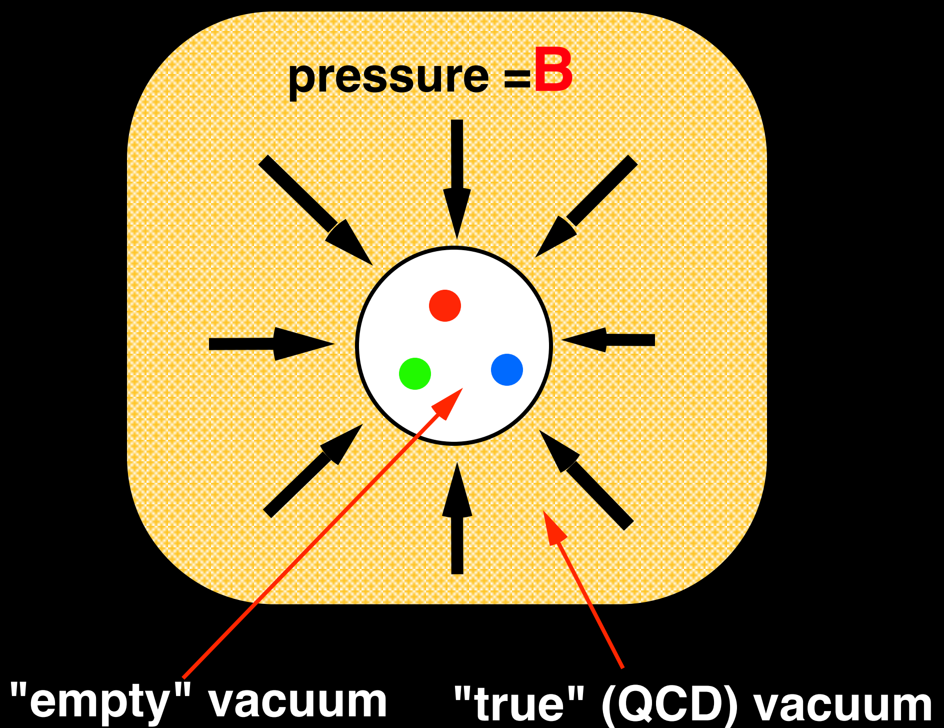
[see e.g. Gottfried-Weisskopf, p. 399]

- The bubble radius *R* is determined by the balance between the vacuum pressure *B* and the outward kinetic pressure exerted by the quarks

- From hadron spectra:

  $B \sim (200\ \text{MeV})^4$

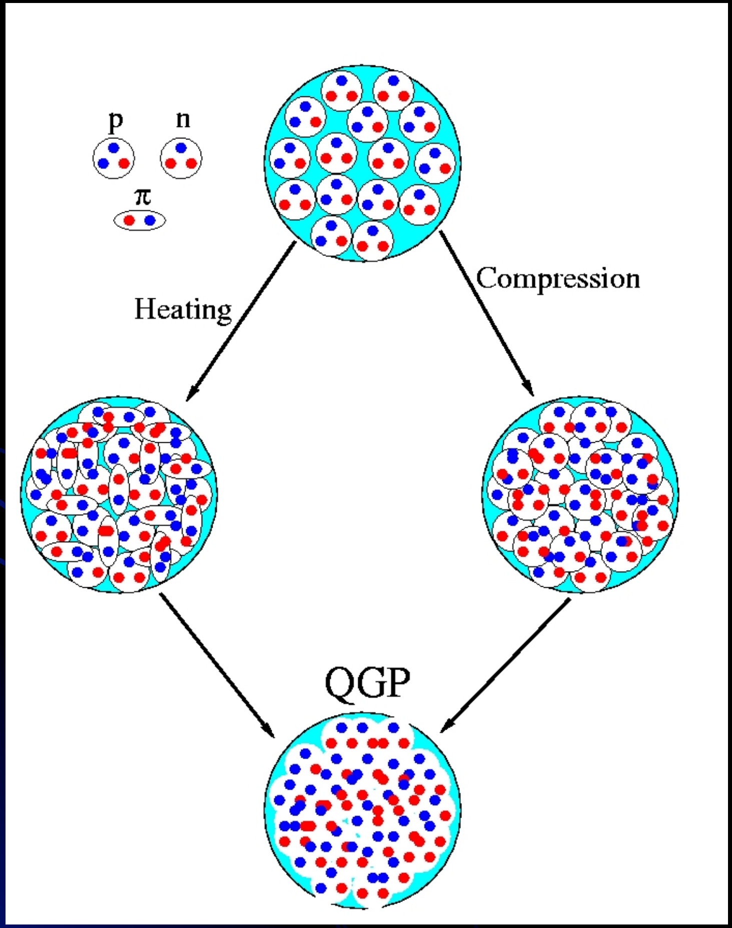
Bag model of a hadron



B = "bag constant" $B^{1/4} \sim 200$ MeV

Deconfinement

- What if we compress/heat matter so much that the individual hadrons start to interpenetrate?

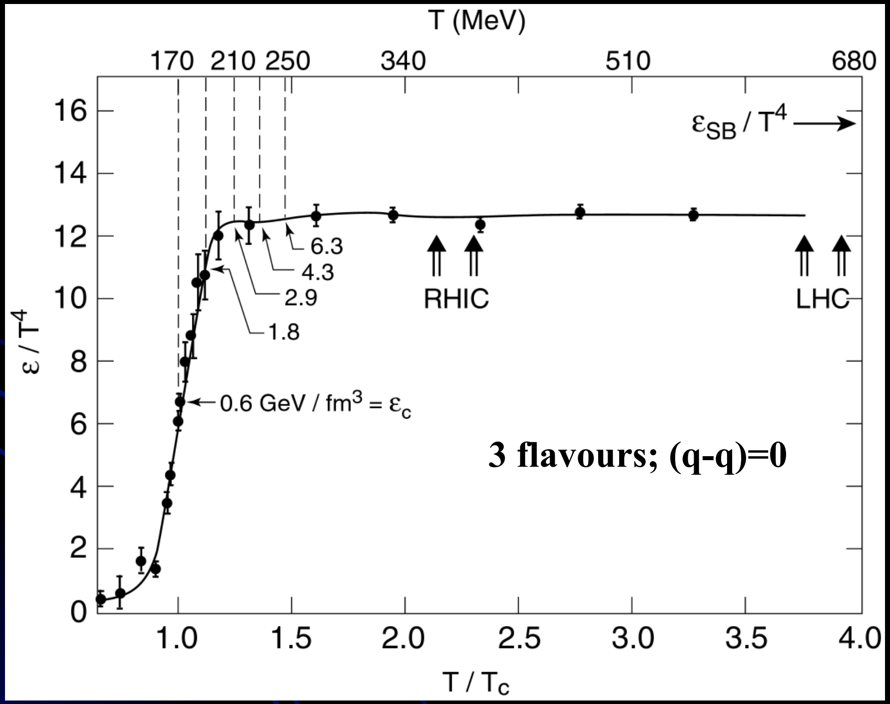


Lattice QCD predicts that if a system of hadrons is brought to sufficiently large density and/or temperature a deconfinement phase transition should occur

In the new phase, called Quark-Gluon Plasma (QGP), quarks and gluons are no longer confined within individual hadrons, but are free to move around over a larger volume

Lattice QCD

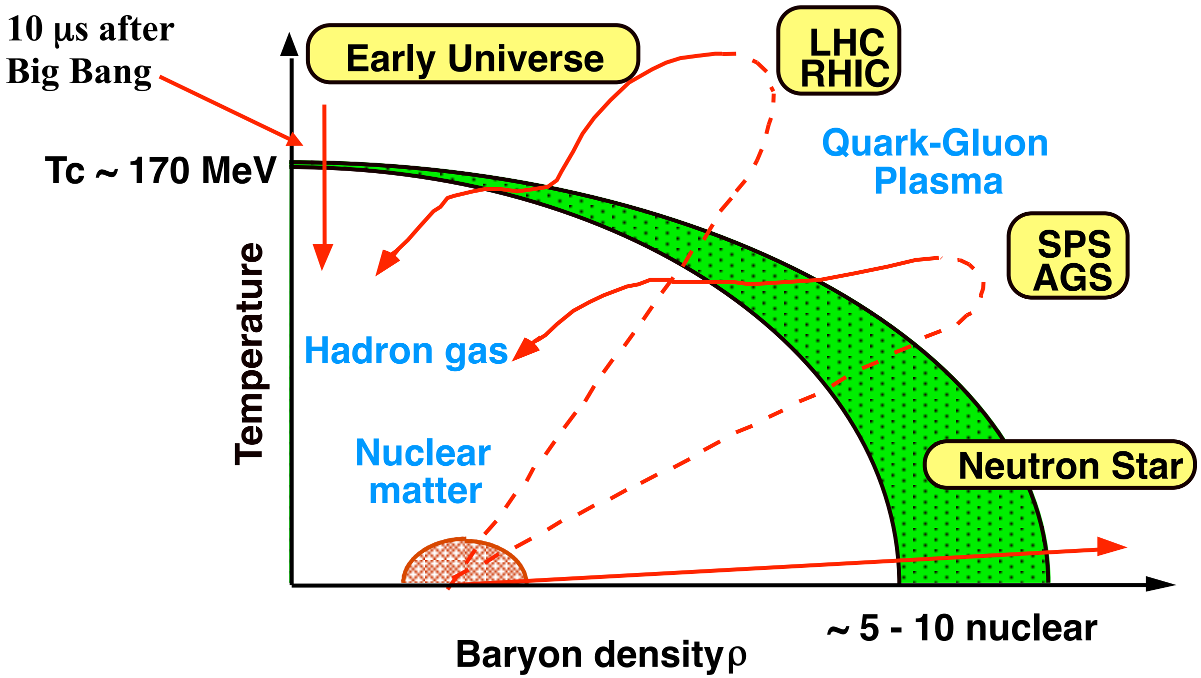
- rigorous way of doing calculations in non-perturbative regime of QCD
- discretization on a space-time lattice
  → ultraviolet (large momentum scale) divergencies can be avoided



- zero baryon density, 3 flavours
- ε changes rapidly around T_c
- T_c = 170 MeV:
  → ε_c = 0.6 GeV/fm^3
- at T~1.2 T_c ε settles at about 80% of the Stefan-Boltzmann value for an ideal gas of q,$\bar{q}$ g (ε_{SB})

QCD phase diagram

- an “artist’s view”…



$\varepsilon_c \sim 1$ GeV/fm^3

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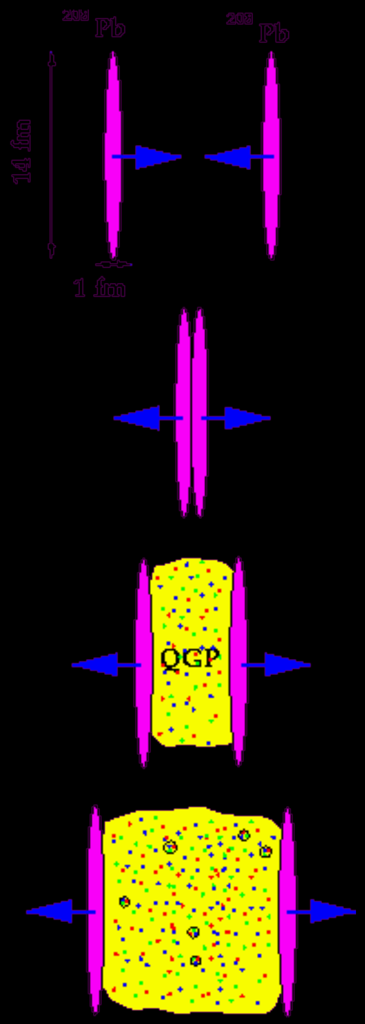
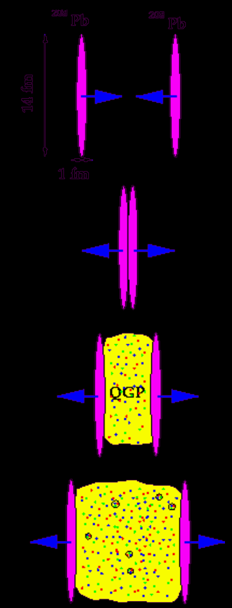
Nucleus-nucleus collisions

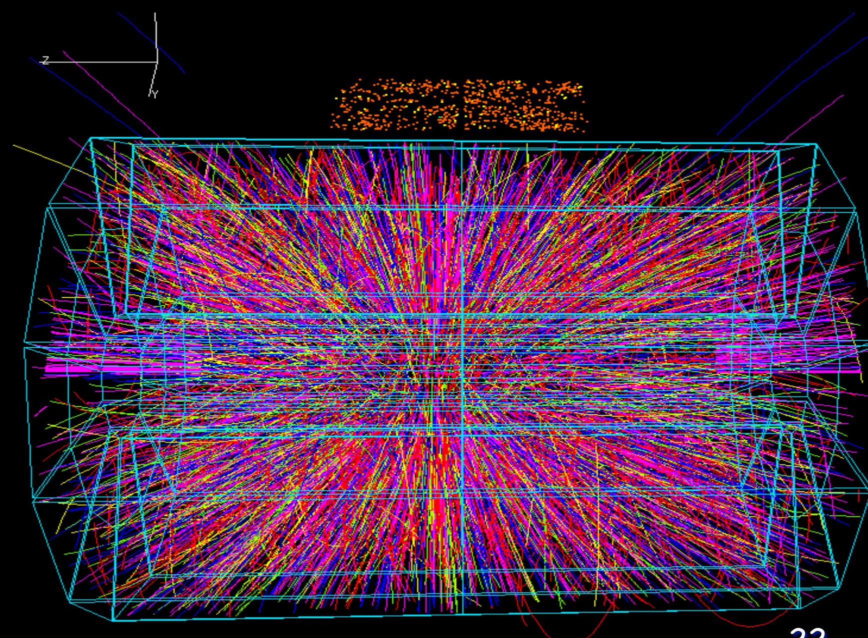
- How do we test this theory in the lab?
- How can we compress/heat matter to such cosmic energy densities?
- By colliding two heavy nuclei at ultrarelativistic energies we recreate, for a short time span (about 10^{-23}s, or a few fm/c) the conditions for deconfinement



- as the system expands and cools down it will undergo a phase transition from QGP to hadrons again, like at the beginning of the life of the Universe: we end up with confined matter again
  - QGP lifetime ~ a few fm/c

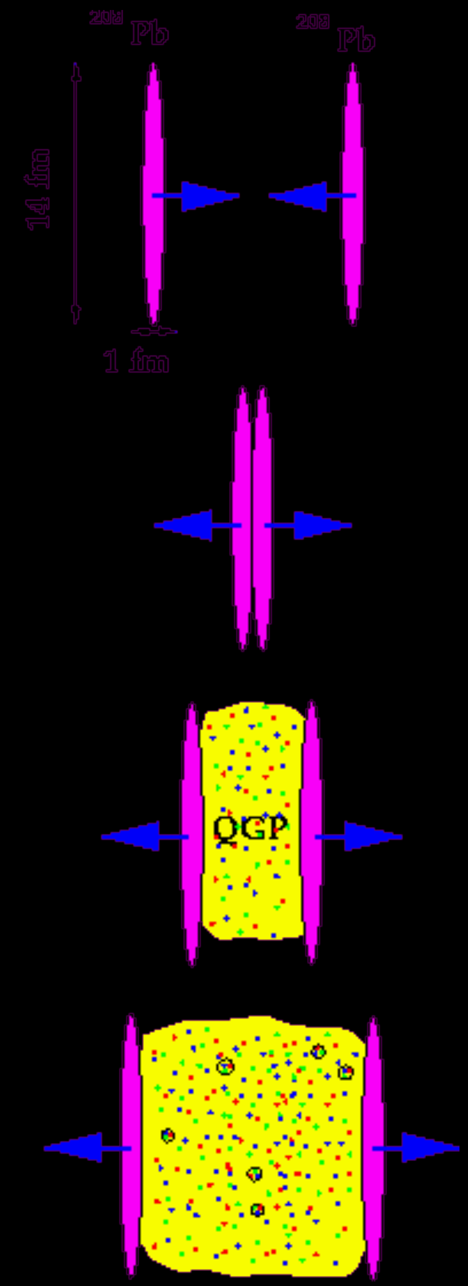


- The properties of the medium must be inferred from the properties of the hadronic final state



Free the quarks!

- Temperature ~ 2 10^{12} degrees
- 100 000 times the temperature at the centre of the Sun
- similar conditions are thought to have been present about 10 μs after the Big Bang
- quarks not any more confined inside protons, neutrons, etc…
- "Quark-Gluon Plasma"



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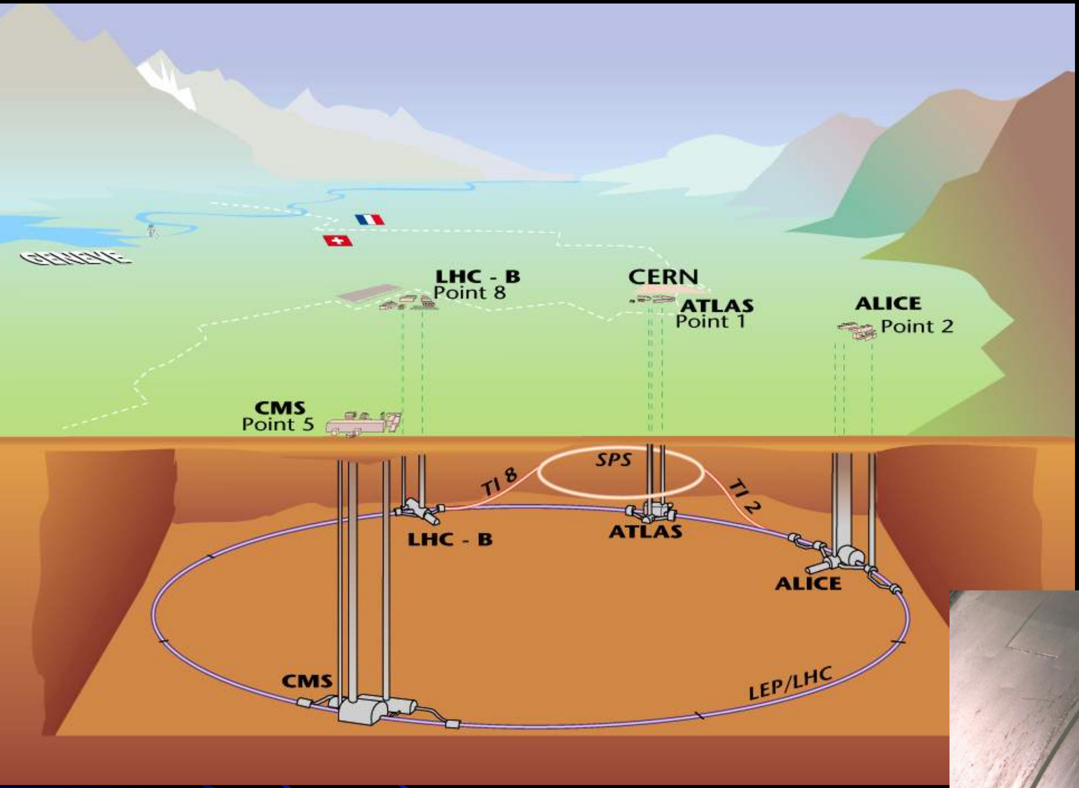
The LHC

Large Hadron Collider (LHC)

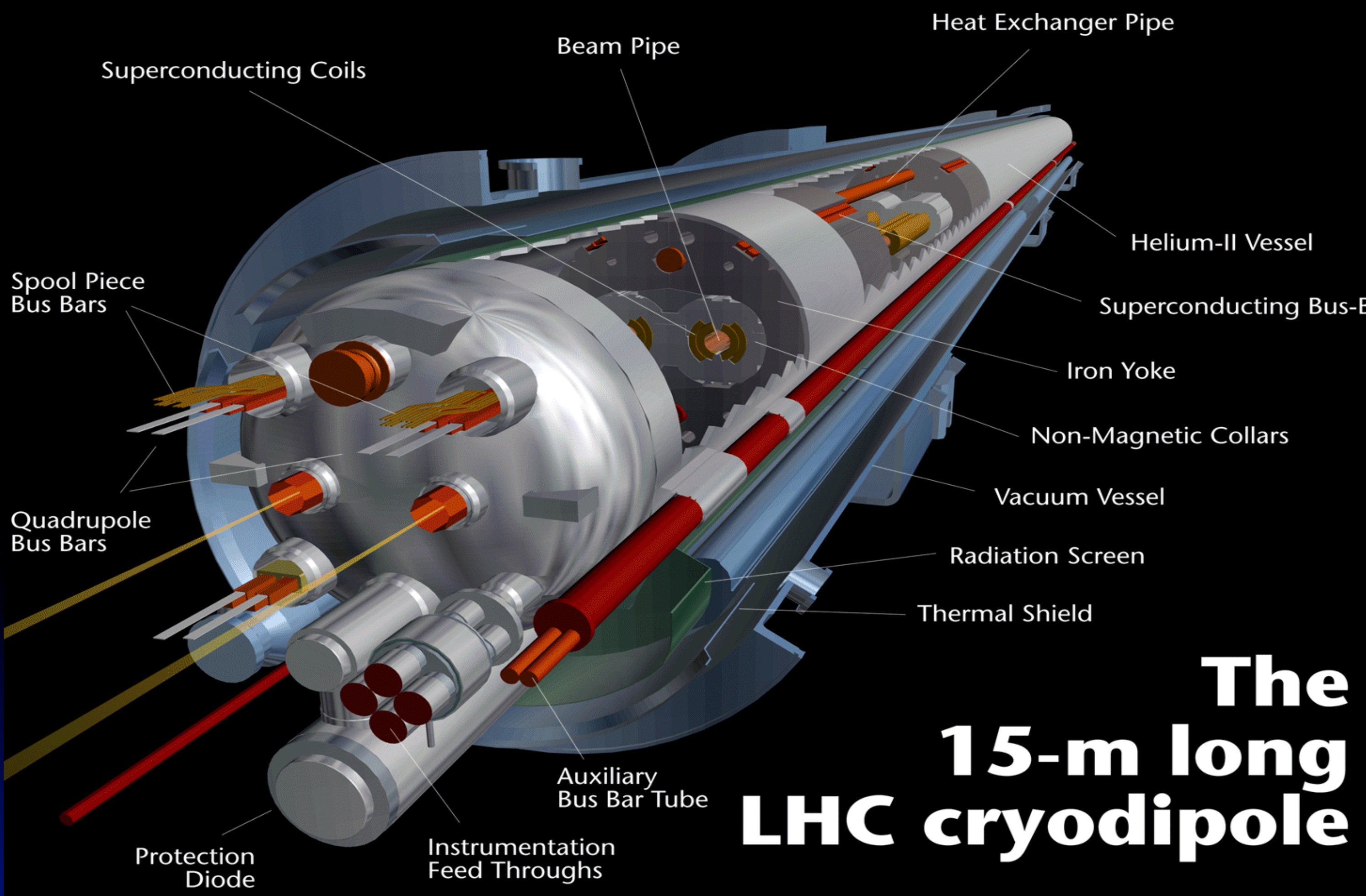


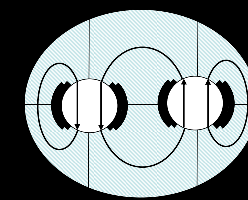
- 27 km circumference
- about 100 m underground
- particles accelerated to 99.9999991 % of light speed
- 11 245 orbits per second

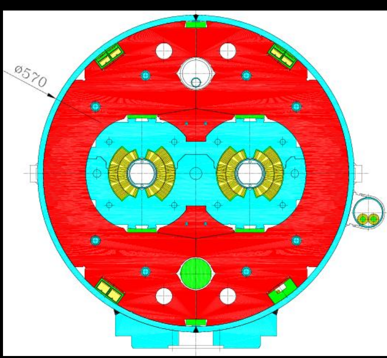
- superconducting magnets
- T = 1.9 K = -271.25 C
  (absolute zero: -273.15 C)

→ coldest place in the solar system!

The LHC Superconducting Dipole





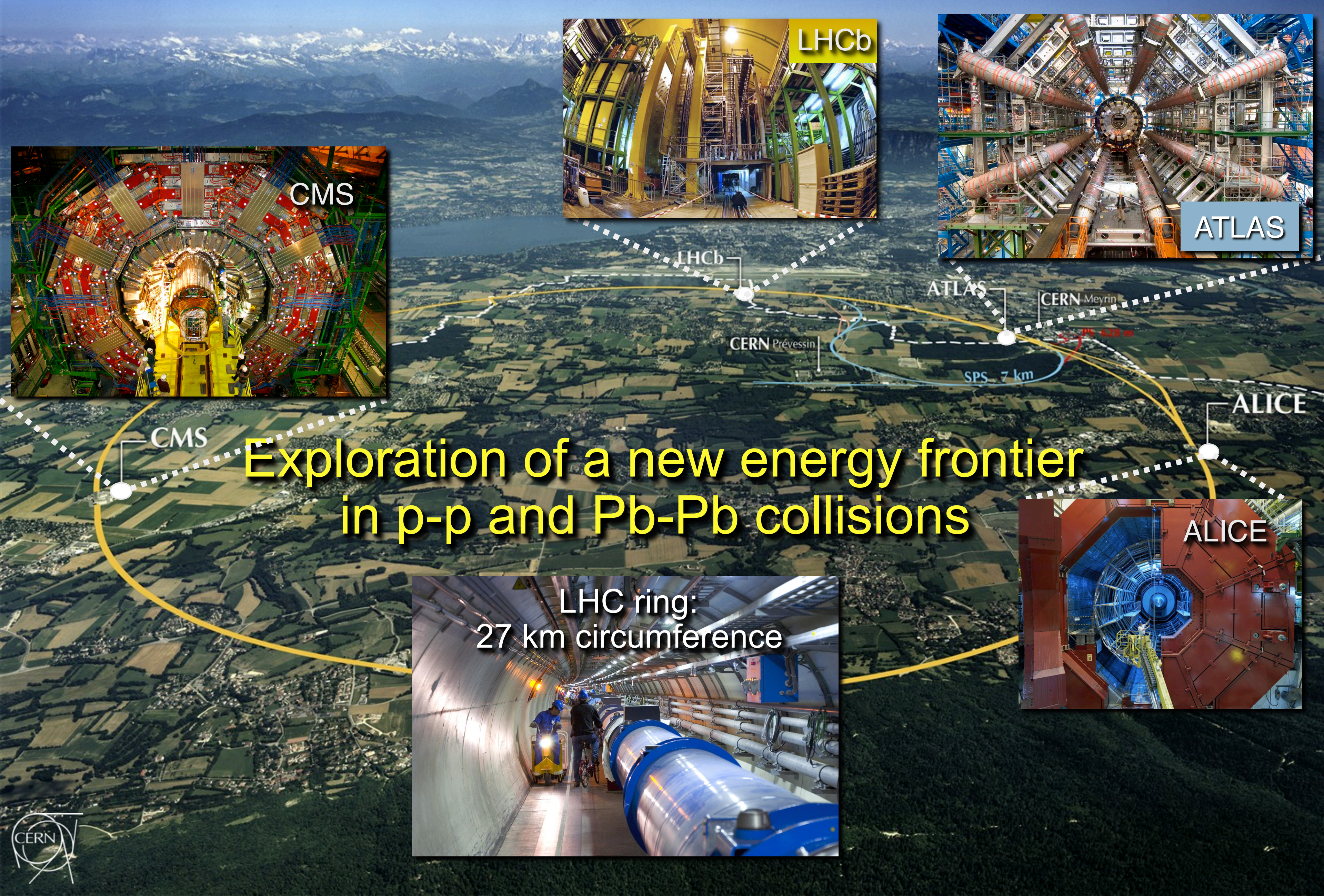


LHC: main parameters

(pp, 2017 run)

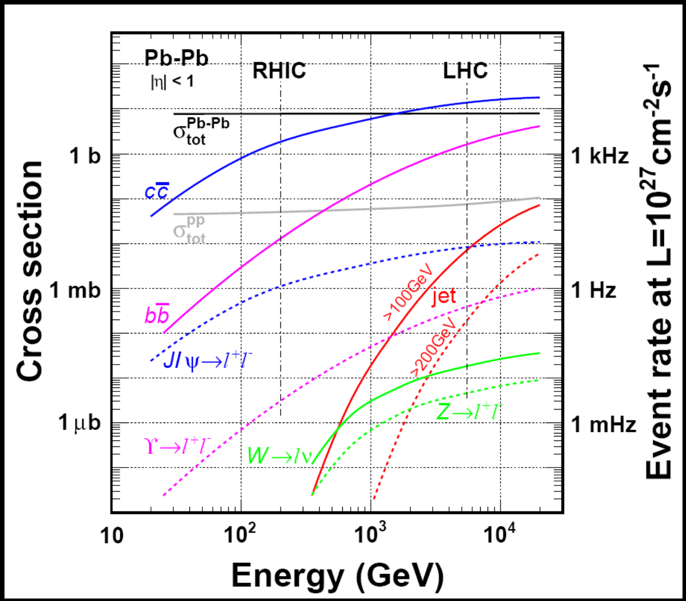
Parameter	Value
Proton energy [GeV]	6500
Number of particles/bunch	1.2×10^{11}
Number of bunches	2500
Transverse Emittance [µm rad]	2.3
β*IP1/5 [m]	0.40
Transverse beam size IP1/5 [µm]	12
Bunch length [ns]	1.05
Peak luminosity IP1/5 [$cm^{-2}s^{-1}$]	1.7×10^{34}
Peak pileup IP1/5	50
Stored Energy [MJ]	320

A New Era in Fundamental Science

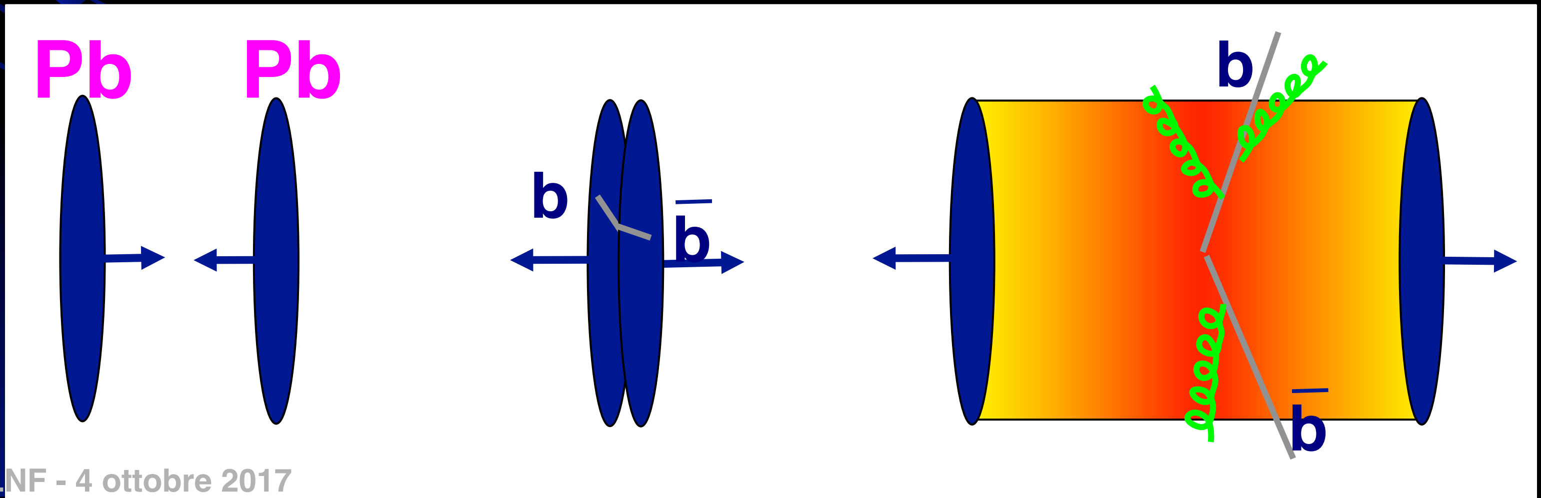


Nucleus-Nucleus collisions at the LHC!

		SPS	RHIC	LHC
$\sqrt{s_{NN}}$	[GeV]	17.3	200	5500
dN_{ch}/dy		450	800	1600
ε	[GeV/fm^3]	3	5.5	~ 10

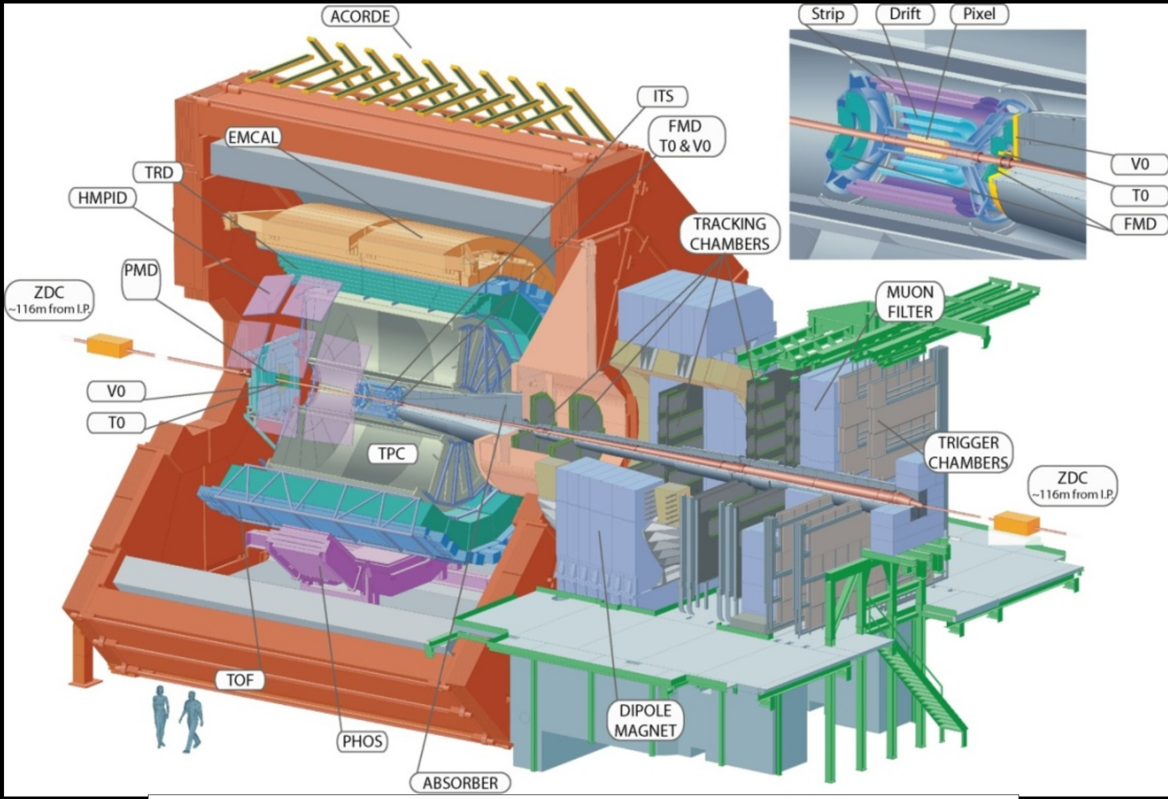


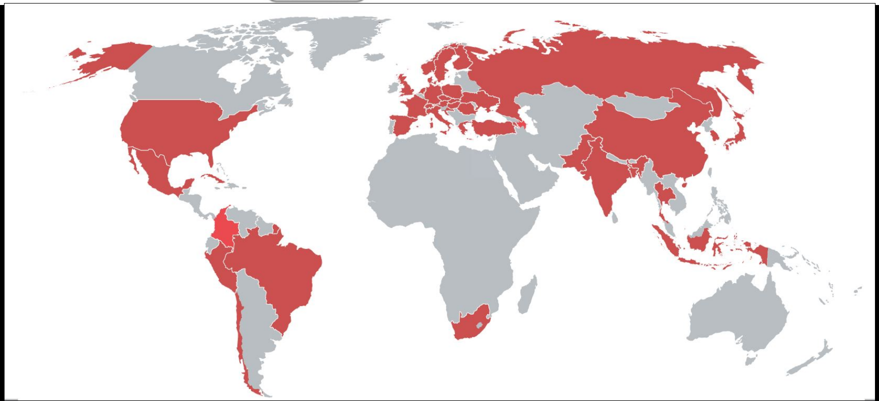
- large ε → deep deconfinement region
  - → closer to "ideal" QGP behaviour
- large cross section for "hard probes" !
  - → a new set of tools to probe the medium properties
  - e.g.:

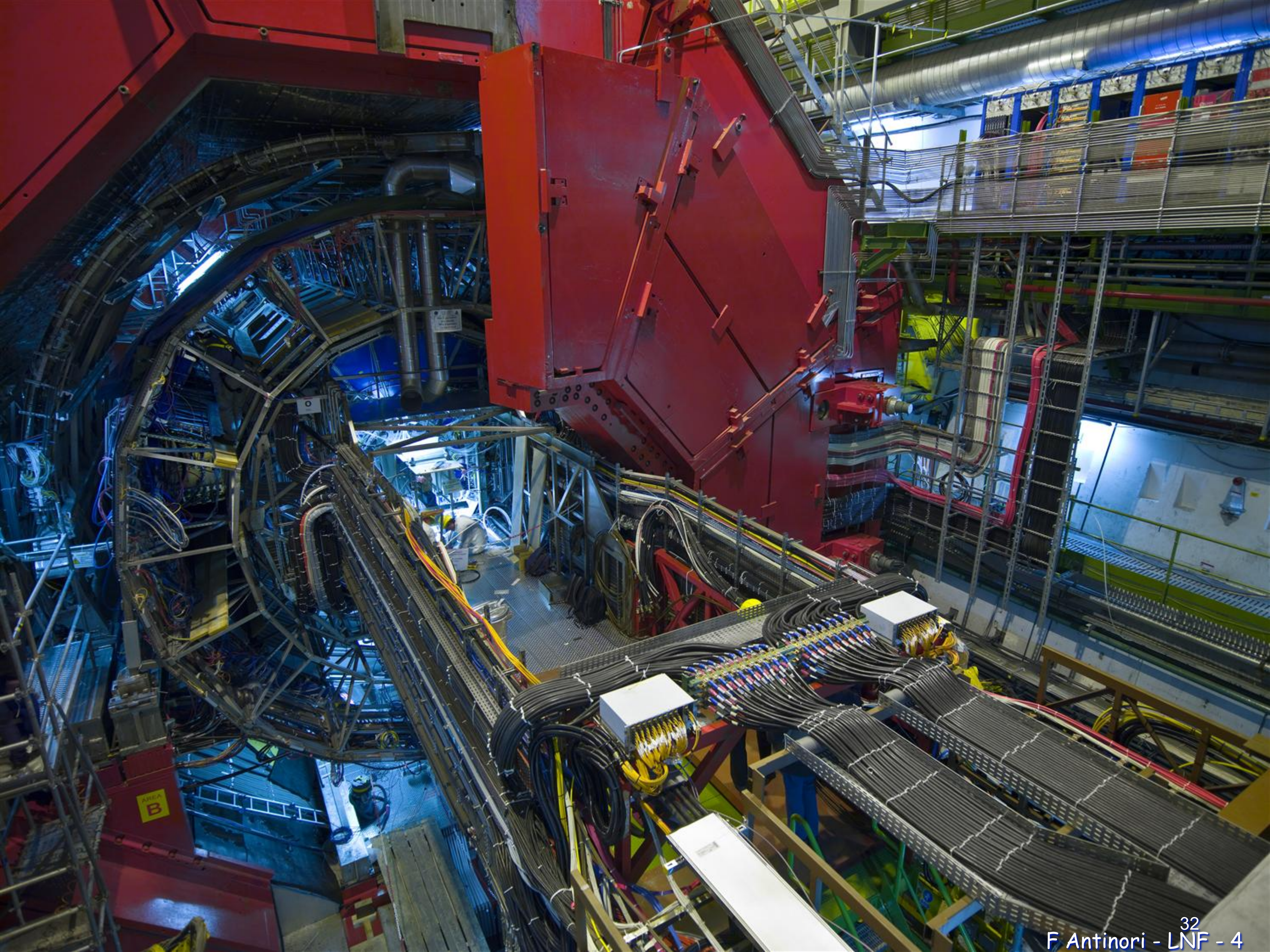


An LHC experiment: ALICE

- dedicated to AA collisions
- 16 x 16 x 26 m^3
- 10 000 tonnes (~ Tour Eiffel)
- ~ 1900 collaborators
- 174 institutes, 42 countries
- largest contingent: Italy
  15 institutes, 232 scientists
- 15 years for conception, design, construction
- cost ~ 160 MCHF

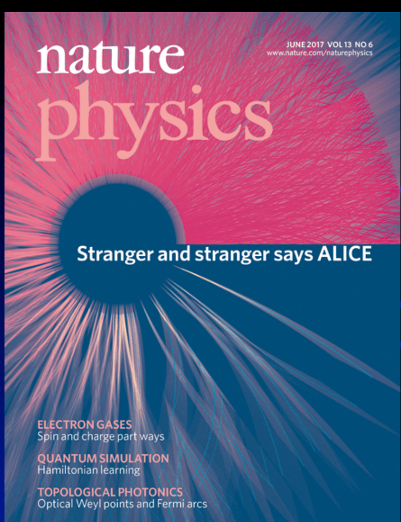


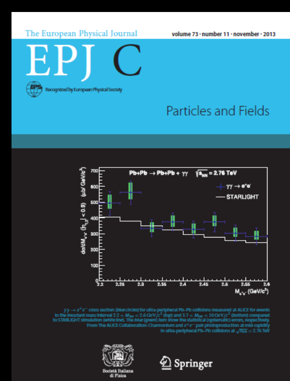


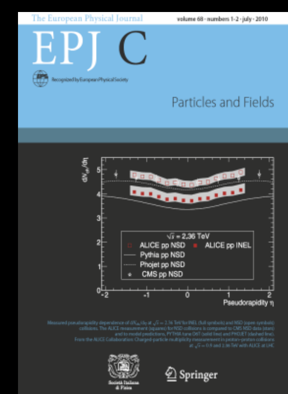

AREA
B

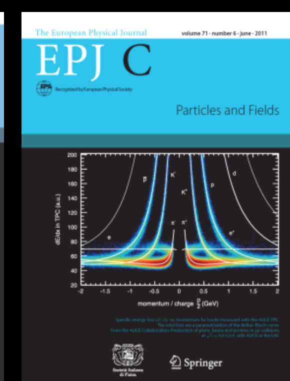
High scientific impact

- major scientific output
  - 177 ALICE papers on scientific journals
  - high-impact papers (*average of ~ 80 citations per paper*)
    - top-cited papers at the LHC after the Higgs discovery ones (source: ISI).
  - several hundred presentations at international conferences *each year*









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Rapidity

Four-momentum: (c = 1 , z coordinate along collision axis)

$$p^\mu = (p^0, p^1, p^2, p^3) = (E, \vec{p}) = (E, \vec{p}_T, p_z = p_{//})$$

Addition of velocities along z:

$$v = v_1 + v_2 \quad \text{(Galileo)} \qquad \beta = \frac{\beta_1 + \beta_2}{1 + \beta_1 \beta_2} \quad \text{(relativistic)}$$

$$\tanh(y_1 + y_2) = \frac{\tanh y_1 + \tanh y_2}{1 + \tanh y_1 \tanh y_2}$$

$$y = \tanh^{-1}\beta = \frac{1}{2}\log\left(\frac{1+\beta}{1-\beta}\right)$$ "rapidity"

- so under a Lorentz transformation to a frame moving with velocity *b* along *z* :

$y \rightarrow y' = y - y_\beta$ (rapidities "add-up")

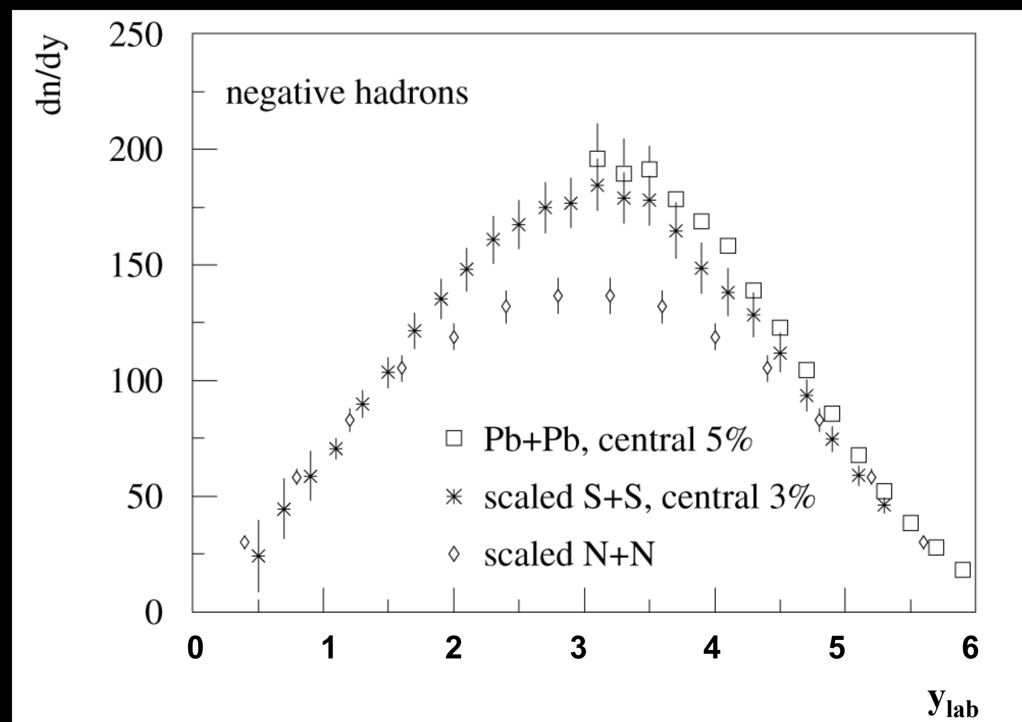
compare → $p'_z = \gamma(p_z - \beta E)$

- e.g.: rapidity distributions

$$\frac{dN}{dy'}(y') = \frac{dN}{dy}(y = y' - y_\beta)$$

- e.g. at SPS: →

$y_{cm} = y_{lab} - y_\beta$ with $y_\beta \approx 3$



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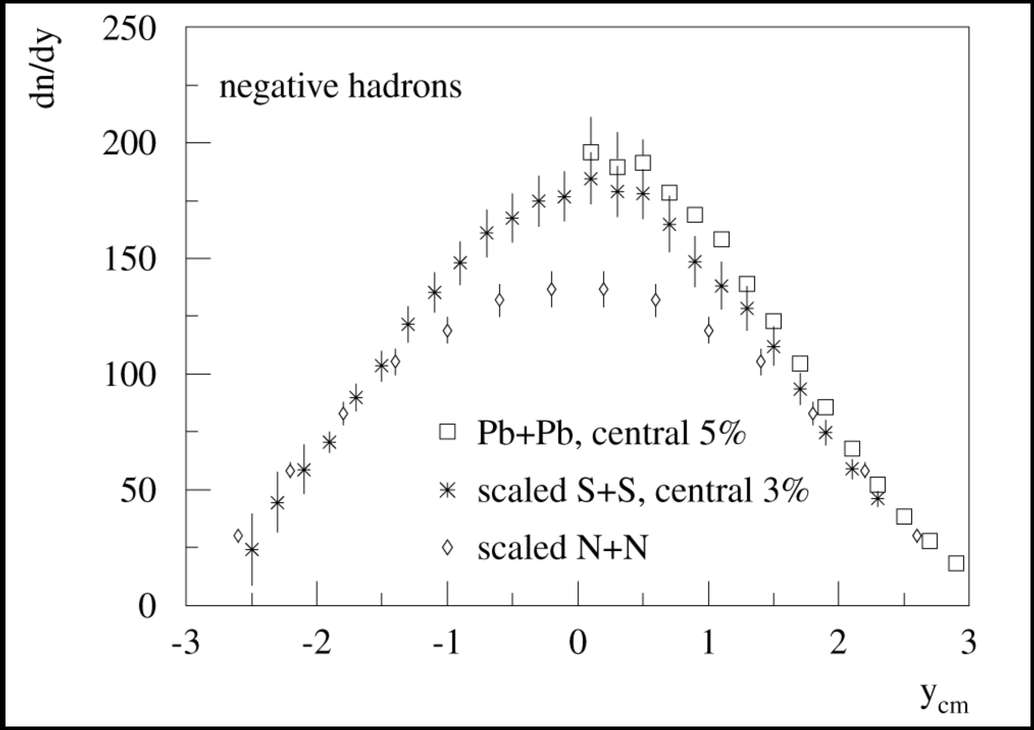


$$y = \tanh^{-1}\beta = \frac{1}{2}\log\left(\frac{1+\beta}{1-\beta}\right)$$

- in the non-relativistic limit:

$$y = \beta$$

- it can be shown that:

$$y = \frac{1}{2}\log\left(\frac{E+p_z}{E-p_z}\right)$$

Transverse variables

- Transverse momentum:

$$\vec{p}_T = (p_x, p_y)$$

$$p_T = \sqrt{p_x^2 + p_y^2}$$

- Transverse mass:

$$m_T = \sqrt{m^2 + p_T^2}$$

$$E = \sqrt{m^2 + p^2} = \sqrt{m_T^2 + p_z^2}$$

$$p_z = m_T \sinh(y)$$

$$E = m_T \cosh(y)$$

Pseudorapidity

rapidity

$$y = \frac{1}{2}\log\left(\frac{E+p_z}{E-p_z}\right)$$

pseudorapidity

$$\eta = \frac{1}{2}\log\left(\frac{p+p_z}{p-p_z}\right)$$

- in the ultrarelativistic limit: $p \sim E \quad \rightarrow \quad \eta \sim y$
- for the transverse variables:

rapidity

$$p_z = m_T \sinh(y)$$
$$E = m_T \cosh(y)$$

pseudorapidity

$$p_z = p_T \sinh(\eta)$$
$$p = p_T \cosh(\eta)$$

- it can be shown that:

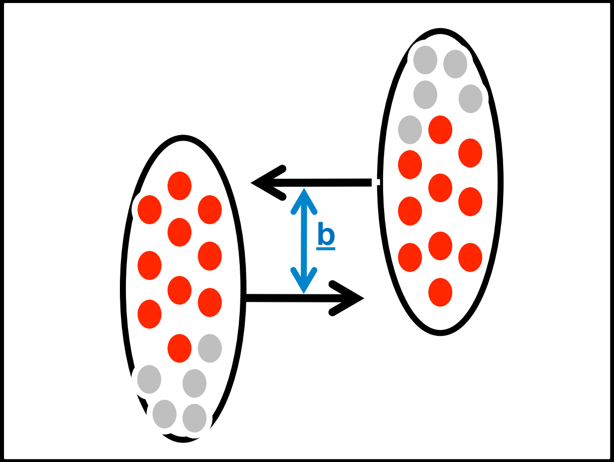
$$\eta = -\log \tan(\theta / 2)$$

- so for ultra-relativistic particles *(y ~ η)*
  - → rapidity only depends on emission angle

Contents

- Open puzzles in Quantum Chromo-Dynamics
- Confinement and deconfinement
  - (an “intuitive” view)
- Ultra-relativistic nucleus-nucleus collisions
- Intermezzo: the Large Hadron Collider
- Intermezzo: kinematic variables
- A few selected results
- Conclusions

Geometry of a Pb-Pb collision

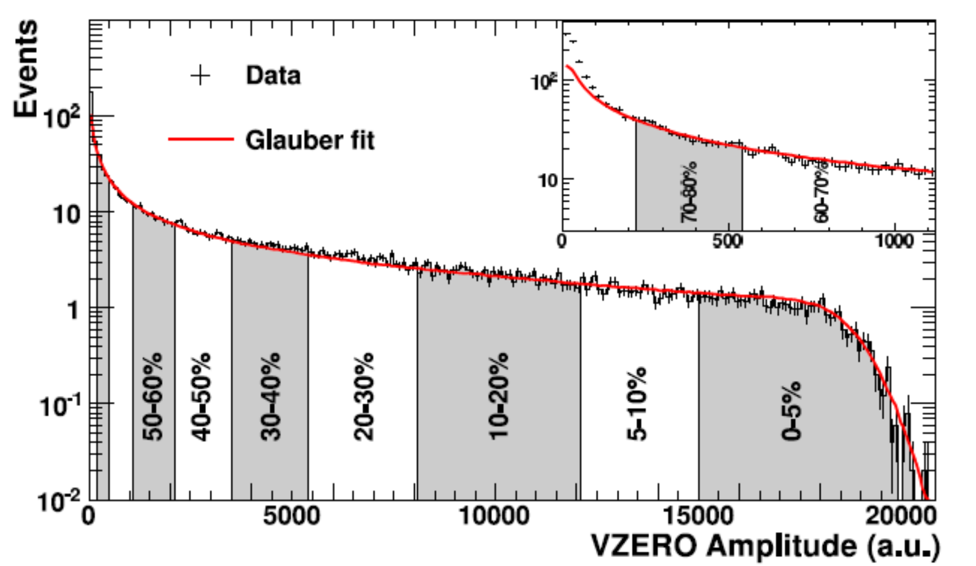


- central collisions
  - small impact parameter b
  - high number of participants → high multiplicity
- peripheral collisions
  - large impact parameter b
  - low number of participants → low multiplicity

for example: sum of the amplitudes in the ALICE V0 scintillators →

reproduced by simple model (red):

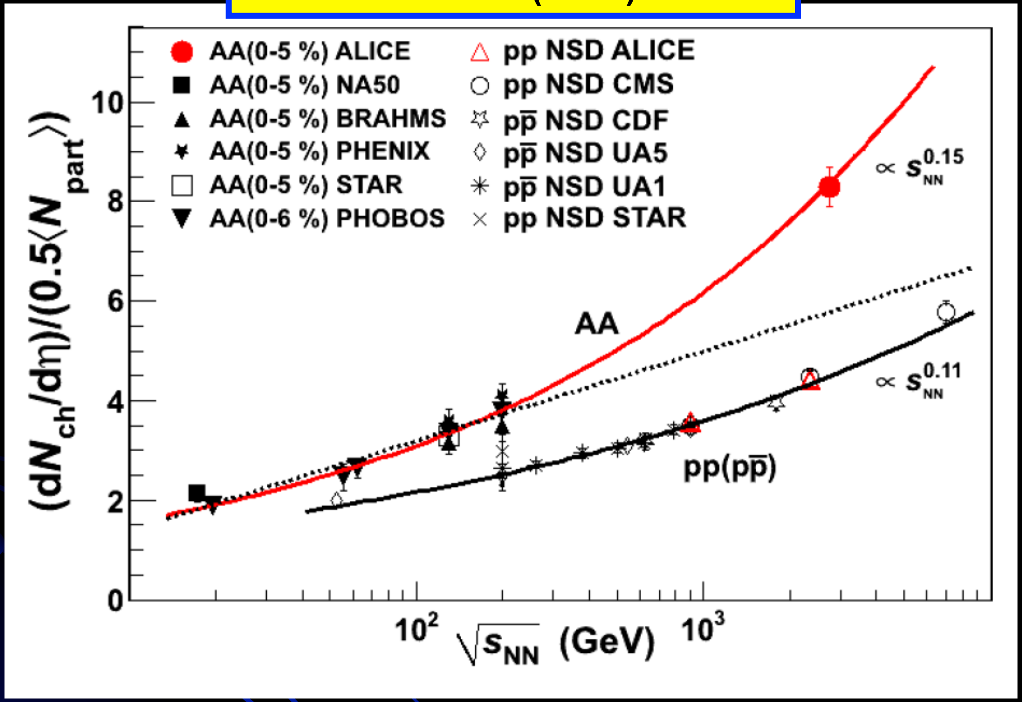
- random relative position of nuclei in transverse plane
- Woods-Saxon distribution inside nucleus
- deviation at very low amplitude expected due to non-nuclear (electromagnetic) processes



Particle multiplicity

most central collisions at LHC: ~ 1600 charged particles per unit of η

ALICE: PRL105 (2010) 252301



- log extrapolation:
  - OK at lower energies
  - finally fails at the LHC

$\sqrt{s_{NN}}$=2.76 TeV Pb-Pb, 0-5% central, |η|<0.5

dNch/dη / (<Npart>/2) = 8.3 ± 0.4 (sys.)

Bjorken's formula

- To evaluate the energy density reached in the collision:

$$\varepsilon = \frac{1}{Sc\tau_0} \left.\frac{dE_T}{dy}\right|_{y=0}$$

S = transverse dimension of nucleus

τ_0 = "formation time" ~ 1 fm/c

- for central collisions at LHC:

$$\left.\frac{dE_T}{dy}\right|_{y=o} \approx 1800\ \text{GeV}$$

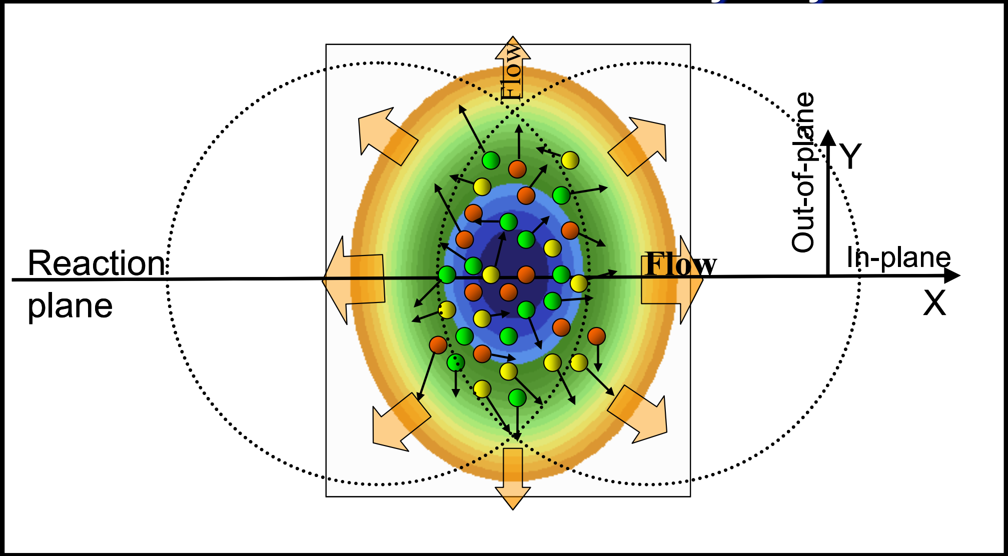
- Initial time t_0 normally taken to be ~ 1 fm/c
  - i.e. equal to the "formation time": the time it takes for the energy initially stored in the field to materialize into particles

- Transverse dimension: $S \approx 160\ \text{fm}^2 \qquad (R_A \approx 1.2 A^{1/3}\ \text{fm})$

→ $\varepsilon \sim (1800/160)\ \text{GeV/fm}^3 \sim 10\ \text{GeV/fm}^3$ → **More than enough for deconfinement!**

Elliptic Flow

- Non-central collisions are azimuthally asymmetric



→ The transfer of this asymmetry to momentum space provides a measure of the strength of collective phenomena

- Large mean free path
  - particles stream out isotropically, no memory of the asymmetry
  - extreme: ideal gas (infinite mean free path)
- Small mean free path
  - larger density gradient -> larger pressure gradient -> larger momentum
  - extreme: ideal liquid (zero mean free path, hydrodynamic limit)

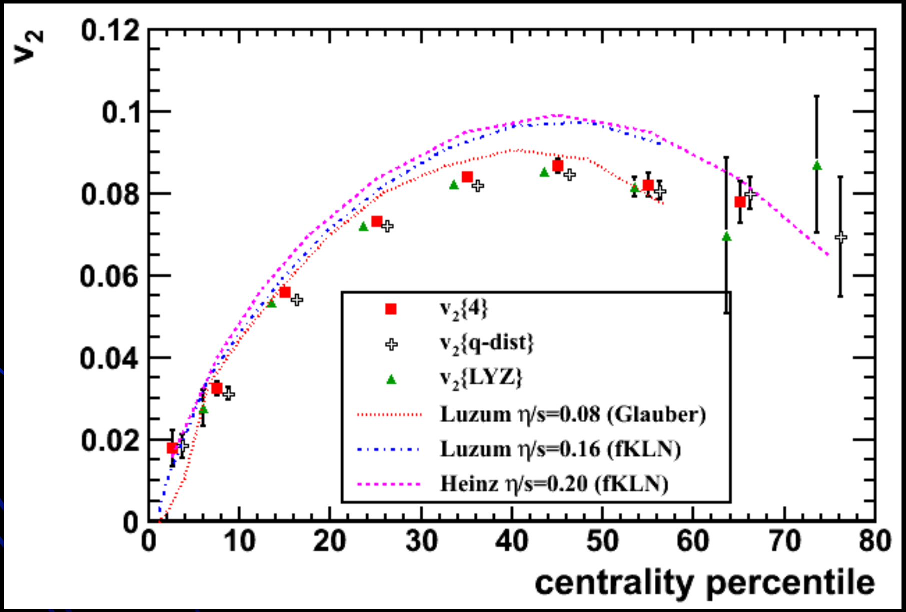
Azimuthal asymmetry

- to quantify the asymmetry:

  → Fourier expansion of the angular distribution:

  $$\propto 1 + 2v_1 \cos(\varphi - \psi_1) + 2v_2 \cos(2[\varphi - \psi_2]) + \ldots$$

  - in the central detector region ($\vartheta \sim 90^o$) → $v_1 \sim 0$ → asymmetry quantified with v_2
- experimentally: v_2 ~ as large as expected by hydrodynamics

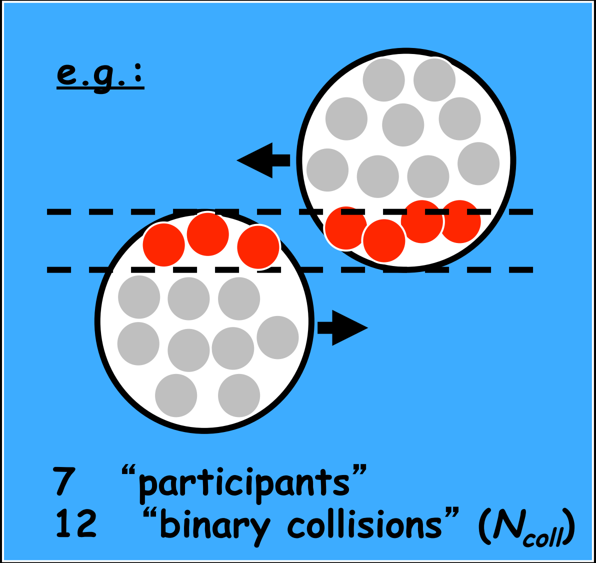


→ "perfect liquid"

High p_T suppression: R_{AA}

- production of particles at high p_T
- is expected to scale like the number of binary nucleon-nucleon collisions:

$$\left.\frac{dN}{dp_T}\right|_{AA} = \langle N_{coll} \rangle \left.\frac{dN}{dp_T}\right|_{pp}$$



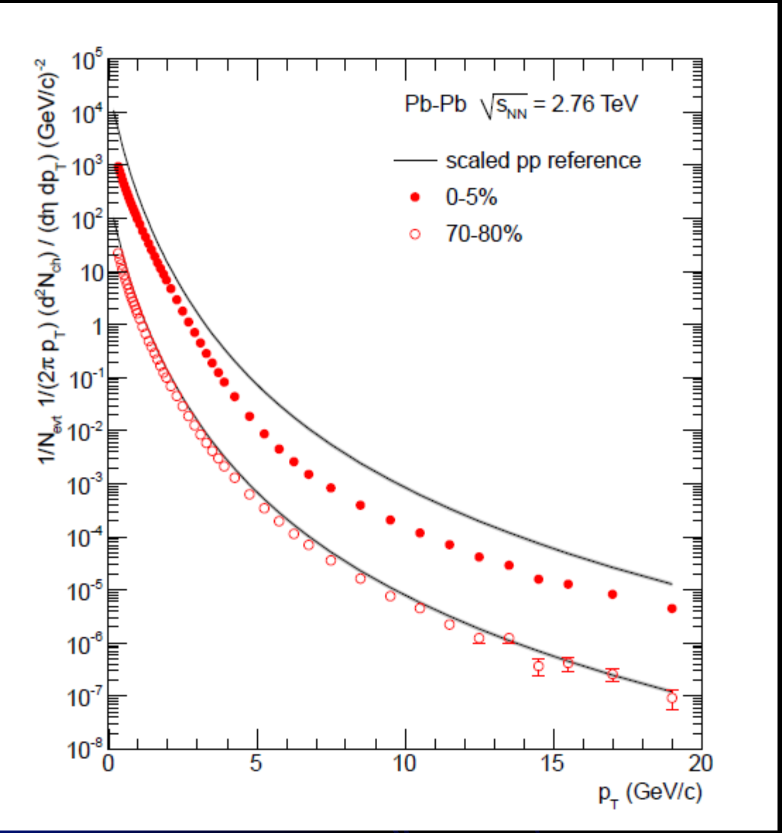
- can be modified by “nuclear” effects
  - e.g.: particles can lose energy when traversing the QCD plasma fireball (“jet quenching”)
    → suppression of particle production at high p_T
- define a “nuclear modification factor” R_{AA}

$$R_{AA} = \frac{\left.\frac{dN}{dp_T}\right|_{AA}}{\langle N_{coll} \rangle \left.\frac{dN}{dp_T}\right|_{pp}}$$

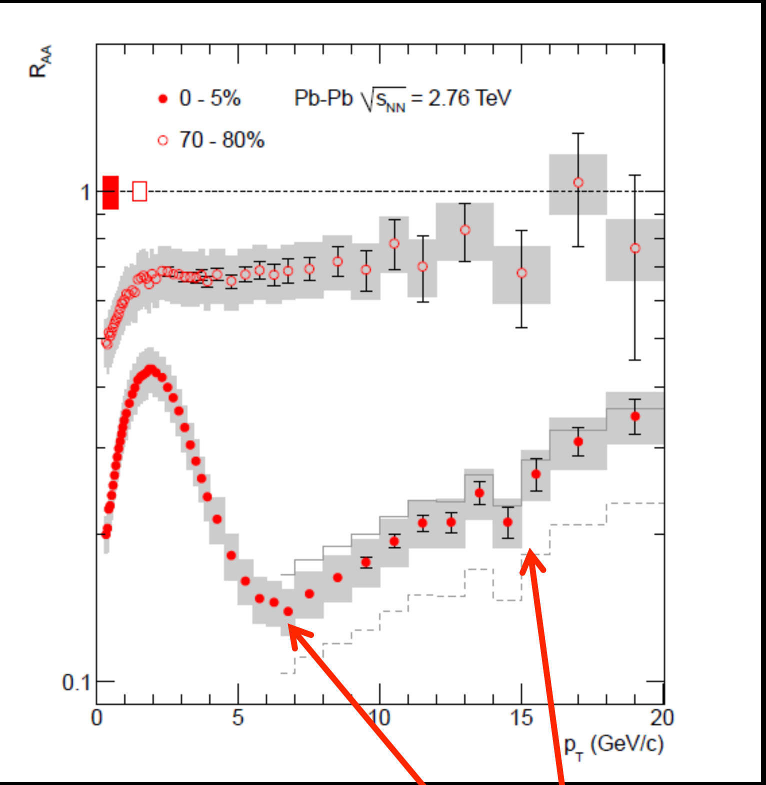
- in the absence of nuclear effects → $R_{AA} = 1$

Strong suppression!

- Pb-Pb significantly below scaled pp for central collisions (filled points)



- R_{AA}:

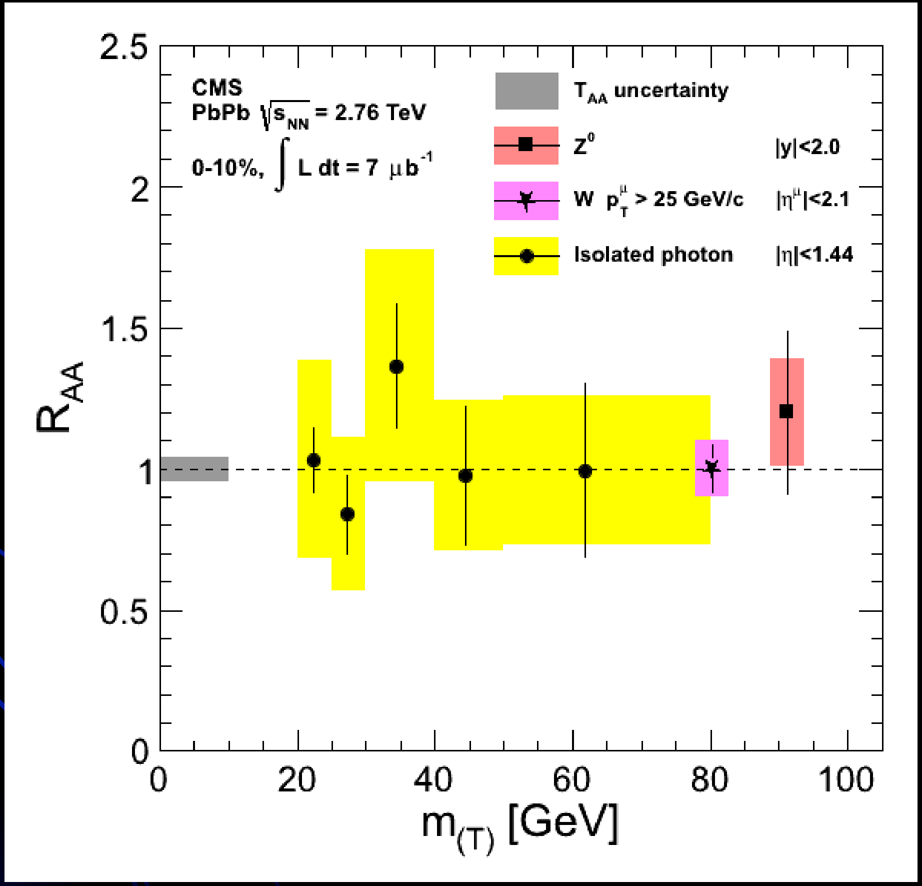


- minimum around 6-7 GeV (R_{AA} ~ 0.14)
- clear increase at higher p_T

R_{AA} for vector bosons

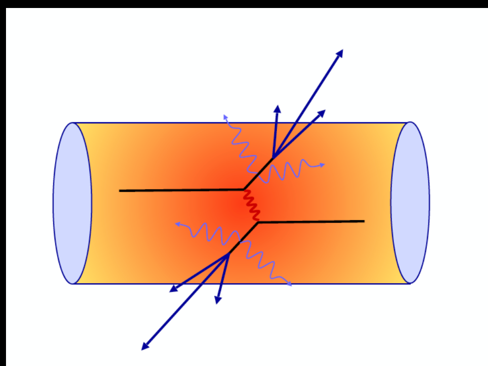
- electroweak probes (γ, $W^{\pm}$, Z^0), on the other hand, are unmodified

→ (essential cross check!)

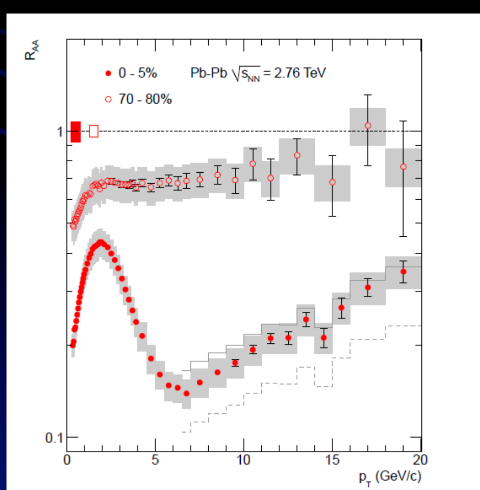


Parton energy loss

- partons (quarks, gluons) lose energy while traversing the QGP



→ high-energy particles are suppressed



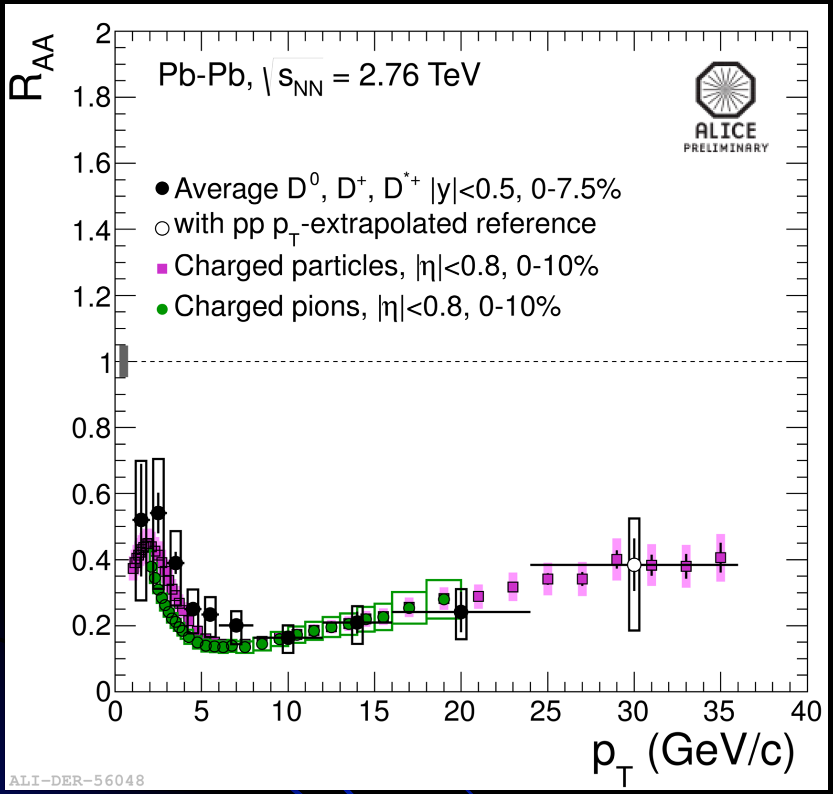
- next step:
  - study QGP with heavy probes:
    charm (c) $m_c \sim 1.3$ GeV
    beauty (b) (or bottom in the US) $m_b \sim 4.3$ GeV)
  - analogous to Brownian Motion…

→ study production of heavy-flavour hadrons (particles containing c or b quarks)

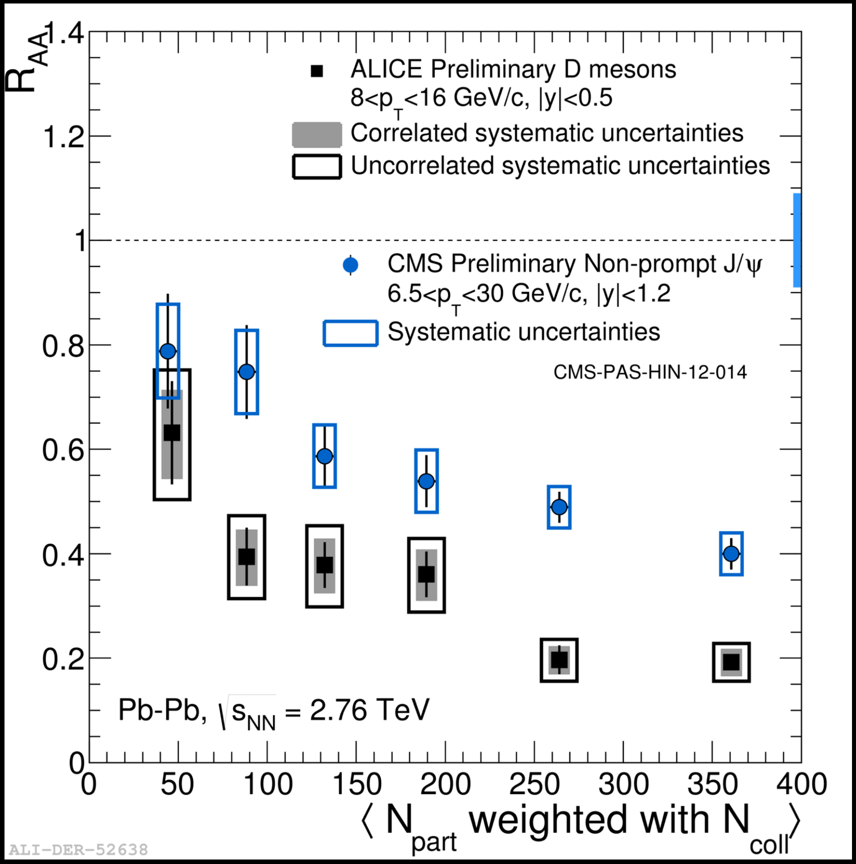
Quarks spin = 1/2		
Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	175	2/3
b bottom	4.3	–1/3

→ D mesons (c quarks) and B mesons (b quarks)

Heavy Flavours R_{AA}



- + indication of less suppression for beauty than for charm!



- p_T < 8 GeV/c:
  - hint of less suppression than for π ?
- p_T > 8 GeV/c
  - same suppression as for π…

Conclusions

- what have we acheved so far?
  - study of the QGP properties
    - first measurements of viscosity, couplings, diffusion coefficient..
  - discovery of new phenomena
    - observation of “hadronisation” by recombination of quarks
    - collective effects in smaller systems…

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- what next?
  - upgrades of LHC detectors (installation in 2019 – 2020)
  - high statistics campaign (2021 – 2029)

  → comprehensive meausrement of physical properties of Quark-Gluon Plasma

  → good potential for discoveries

Conclusions

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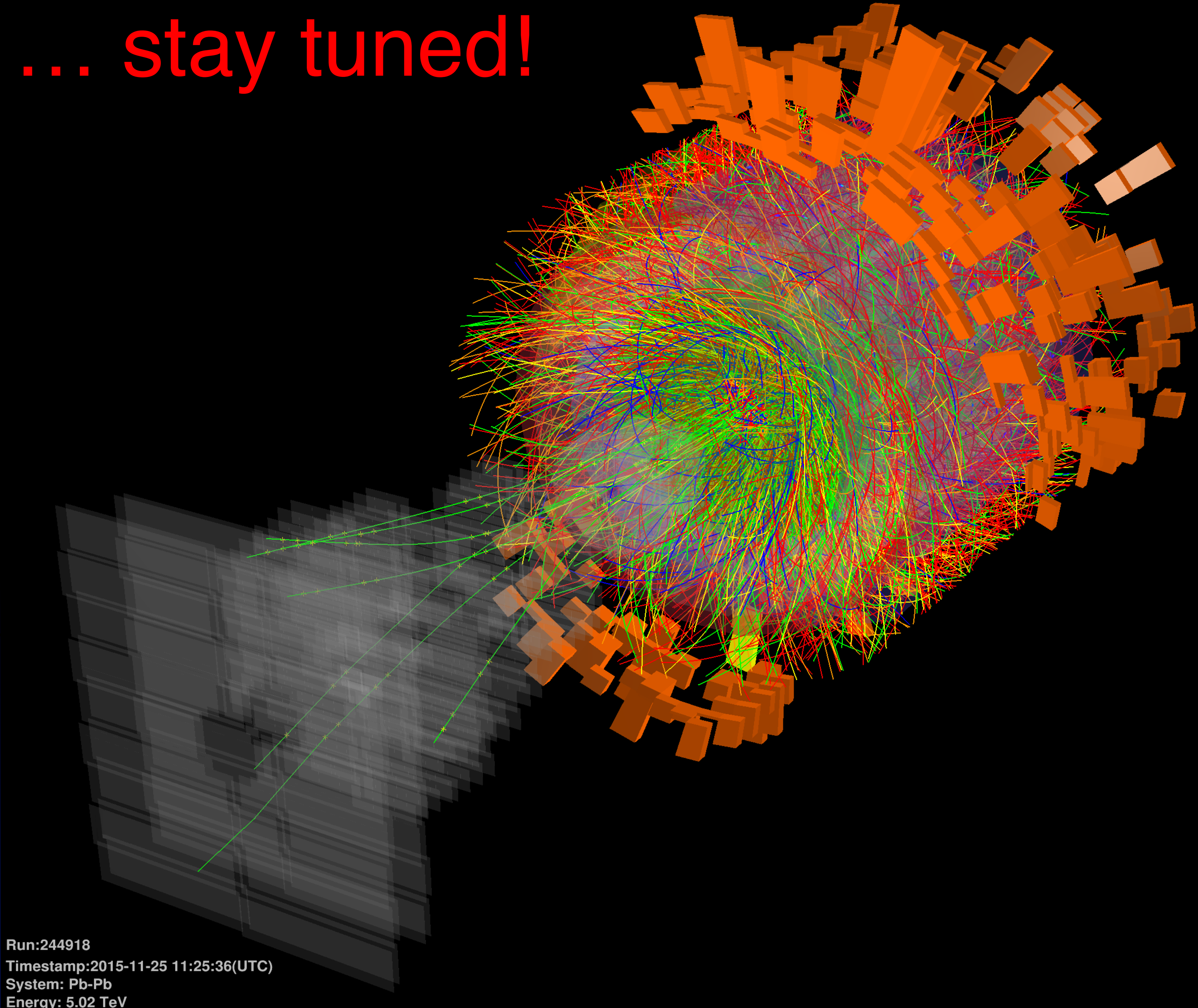
→ so…

… stay tuned!


Run:244918
Timestamp:2015-11-25 11:25:36(UTC)
System: Pb-Pb
Energy: 5.02 TeV

Some bibliography

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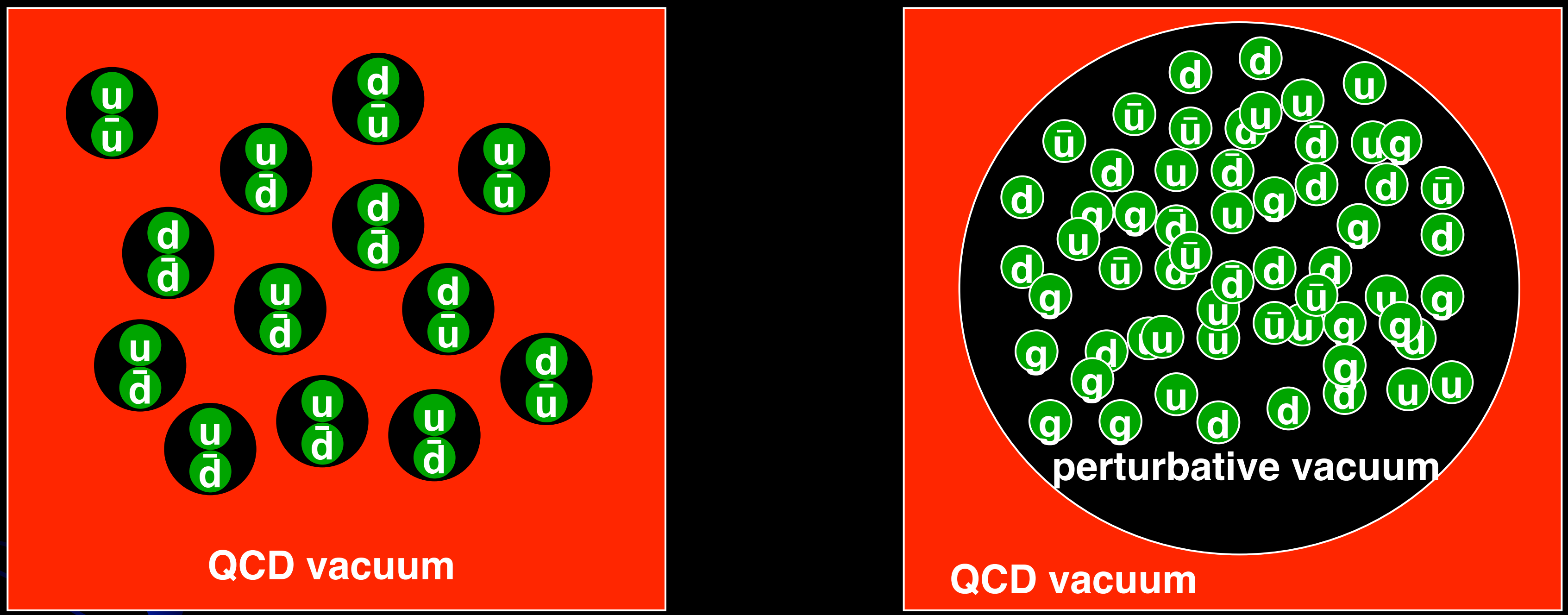
- H Fritzsch: ***Quarks***, Basic Books (English Edition)
- K Gottfried and V F Weisskopf: ***Concepts of Particle Physics***, Oxford University Press (2 vol.)
- J Letessier and J Rafelski: ***Hadrons and QGP***, Cambridge University Press
- C Y Wong, ***Introduction to High-Energy Heavy-Ion Collisions***, World Scientific

Deconfinement: a toy model

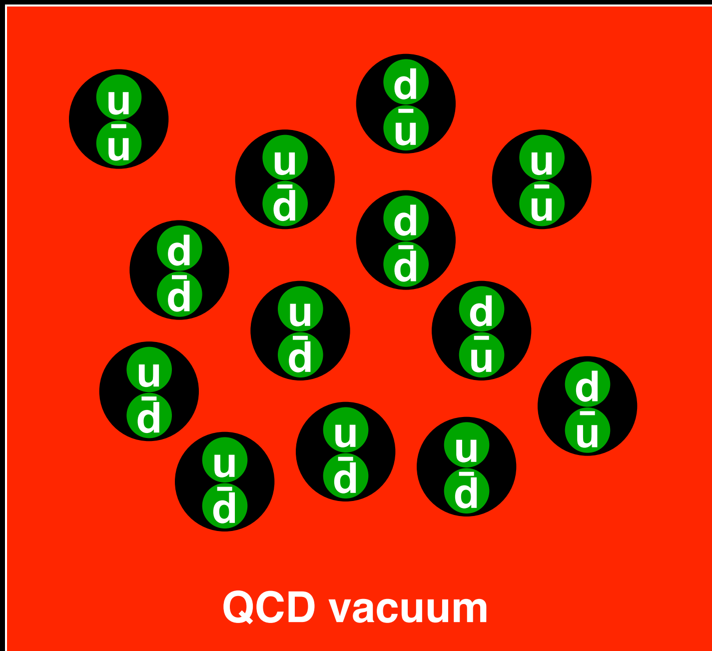
Hadron (pion) Gas | **Quark-Gluon Plasma**



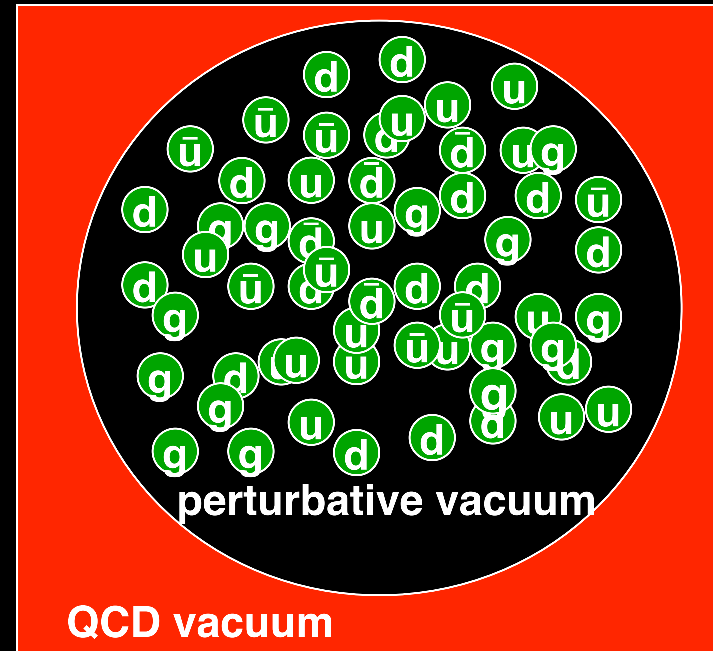
- Gibbs' criterion: the stable phase is the one with the largest pressure
- From statistical mechanics:
  (for an ideal gas)

$$p = \frac{\varepsilon}{3} = \left(g_B + \frac{7}{8} g_F \right) \frac{\pi^2 T^4}{90}$$

Hadron (pion) Gas



Quark-Gluon Plasma



$$g_B = 3 \qquad g_F = 0$$

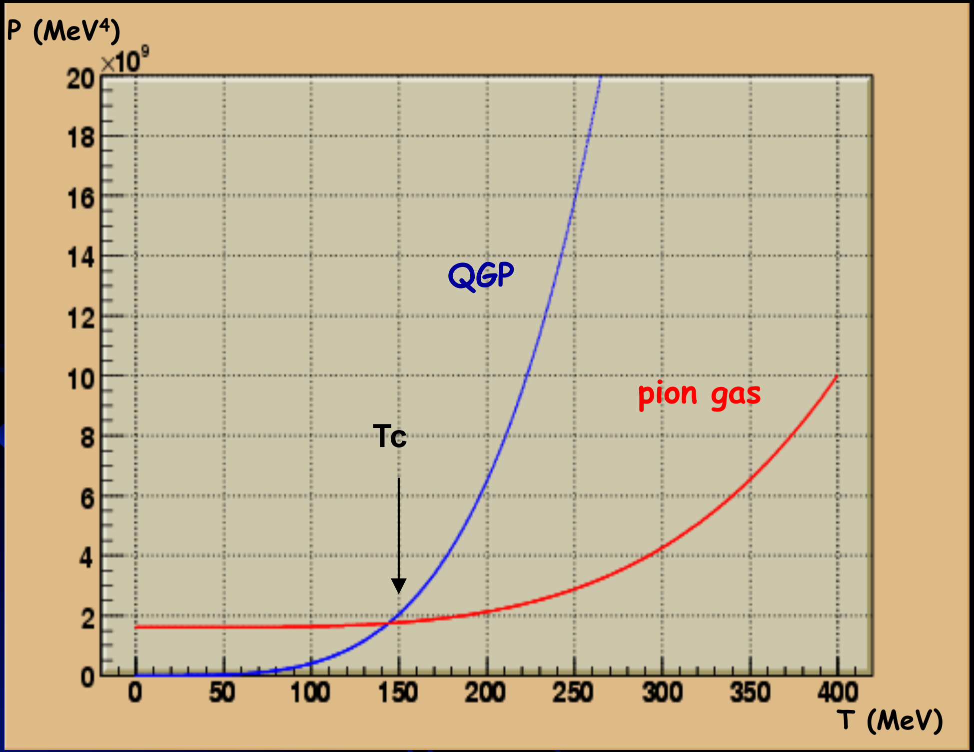
$$p = \frac{\varepsilon}{3} = \left(g_B + \frac{7}{8} g_F \right) \frac{\pi^2 T^4}{90}$$

$$g_B = 16 \qquad g_F = 24$$

$$p = \frac{3}{90} \pi^2 T^4 + B$$

$$p = \frac{37}{90} \pi^2 T^4$$

- At low temperature the hadron gas is the stable phase
- There is a temperature T_C above which the QGP "wins", thanks to the larger number of degrees of freedom



$$T_C = \left(\frac{90}{34\,\pi^2}\right)^{1/4} B^{1/4} \approx 150\,\mathrm{MeV}$$

- very simplified calculation…
  - more refined estimates:

  → Tc ≈ 170 MeV

- 170 MeV?

  recall: T_{room} (300 K) ~ 25 meV

  (of course, lowercase m)

→ Tc ≈ 170 MeV ≈ 2000 billion K

(compare Sun core: 15 million K)