CERN-Fermilab Hadron Collider Physics
Summer School 2013

Heavy Ions

Part 1/3

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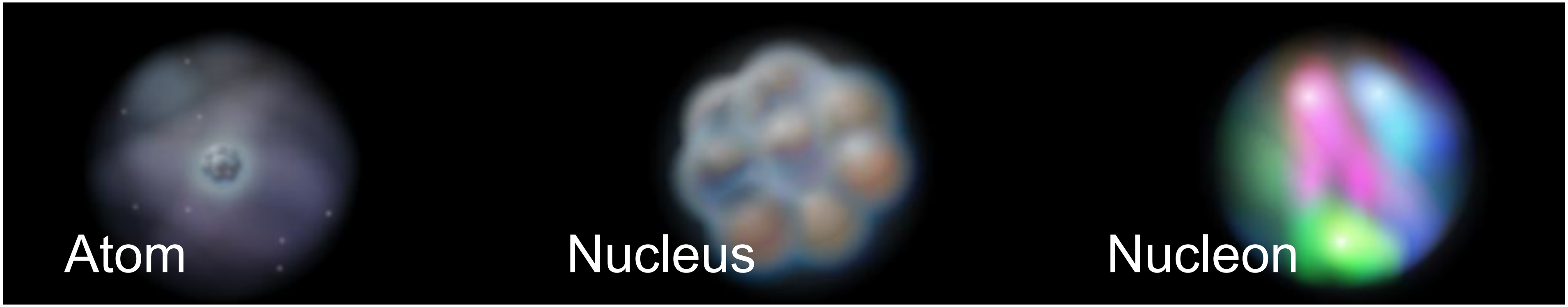
Disclaimer and Acknowledgements

- Ultra-relativistic Heavy Ions: a very rich field (6 large active experiments) with >20 years of experimental history + very active and broad theory community
- I will present a selection of topics (non exhaustive!), from an *experimental* point of view (only qualitative theory arguments)

- **Thanks to the Organizers for their invitation and support**
- **Thanks to those from whom I borrowed slides/figures: F.Antinori, N.Armesto, H.Caines, M.Floris, B.Hippolyte, C.Salgado, T.Ullrich, …**

Introductory remarks

Why Colliding Heavy Ions?



Fundamental Questions:

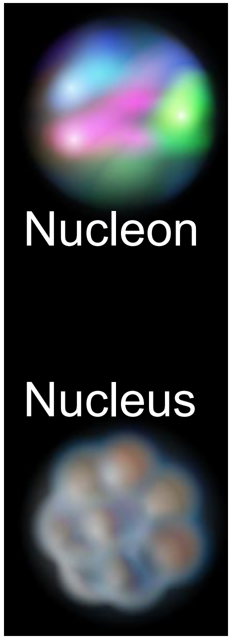
- *Can the quarks inside the protons and neutrons be freed?*
- *Why do protons and neutrons weigh 100 times more than the quarks they are made of?*
- *What happens to matter when it is heated to 100,000 times the temperature at the centre of the Sun?*

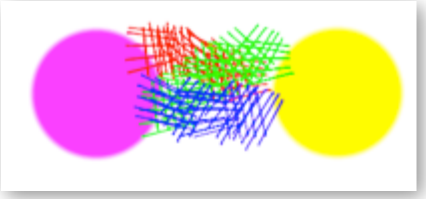
Strongly-interacting matter, QCD, and confinement

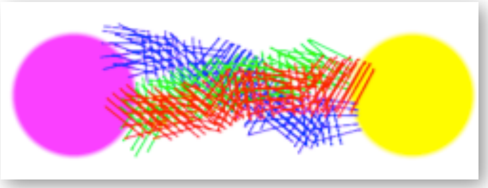
- Strong interaction: keeps together
  - quarks inside protons and neutrons
  - protons and neutrons inside atomic nuclei

  and is carried by the colour charge (quarks, gluons)
- Quantum ChromoDynamics (QCD) is the theory that describes the strong interaction
- Important feature of QCD: *confinement*

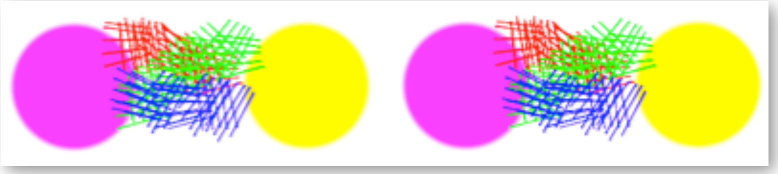
  → no free quarks



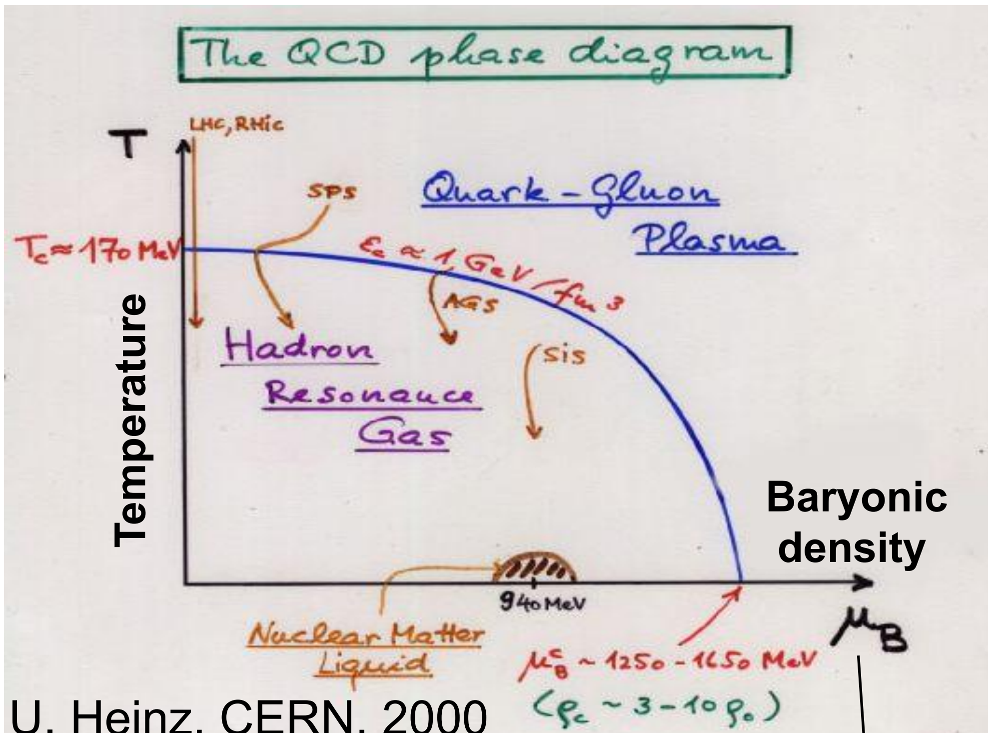




cartoon of a quark and anti-quark being "pulled apart" and their colour connection



Phase diagram of strongly-interacting (QCD) matter



U. Heinz, CERN, 2000

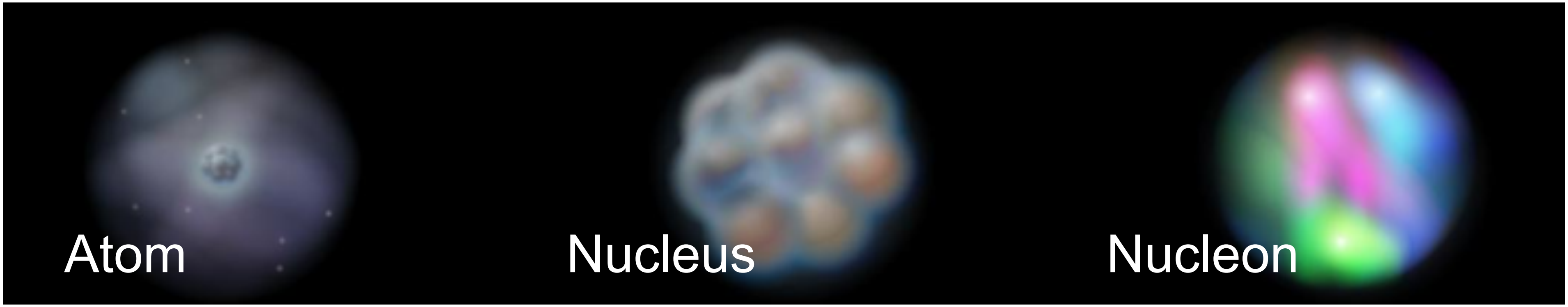
Density of baryons – anti-baryons

At high energy density ε (high temperature and/or high density) hadronic matter undergoes a phase transition to the *Quark-Gluon Plasma (QGP)*

- *a state in which colour confinement is removed*
- *and chiral symmetry is approximately restored*
- *a high-density QCD medium of "free" quarks and gluons*

critical energy density ε_c ~ 1 GeV/fm^3 ~ 10 $\varepsilon_{nucleus}$

Why Colliding Heavy Ions?



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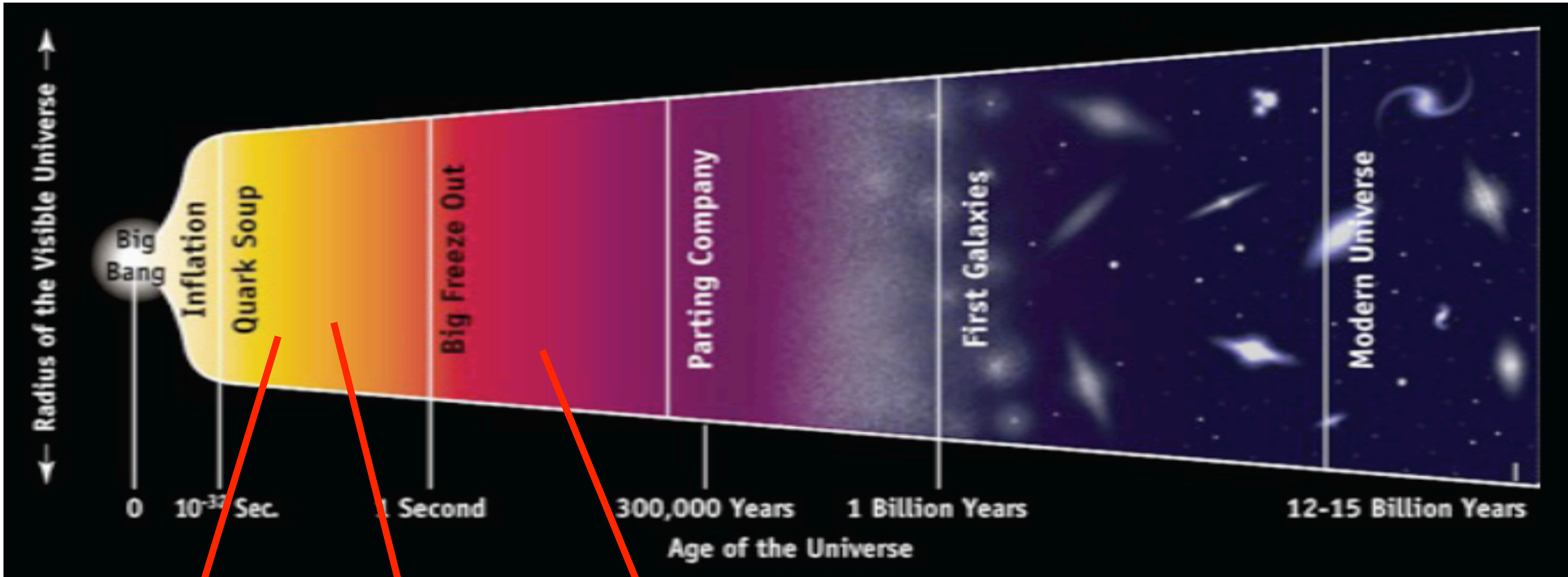
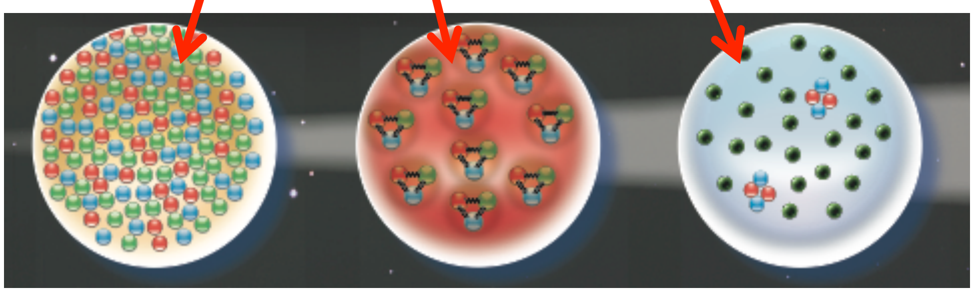
  a high-density QCD medium of "free" quarks and gluons

Quark-Gluon Plasma (QGP): the first "matter" in the primordial Universe



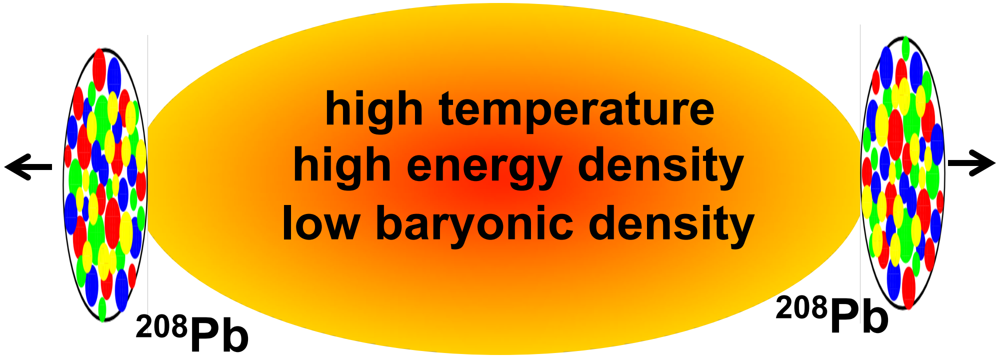


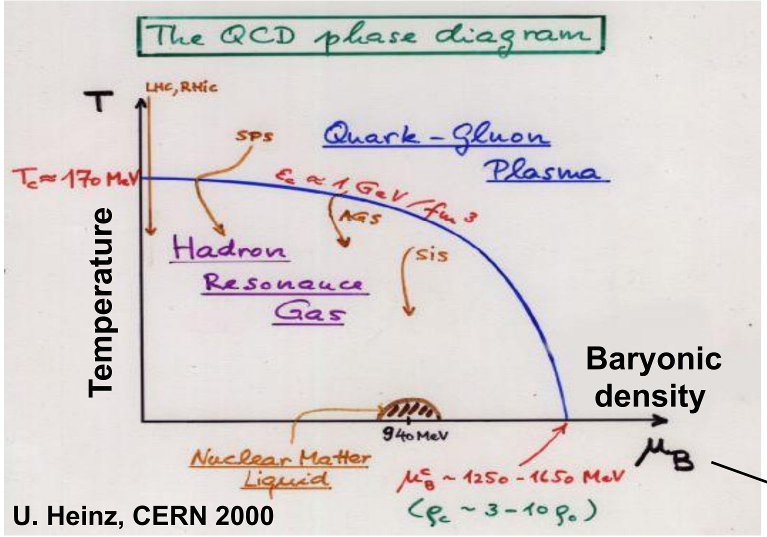
quark-gluon plasma　*formation of protons/neutrons*　*formation of atomic nuclei*

The phase transition from quarks to hadrons occured in the cooling Universe 10 μs after the Big Bang

The Little Bang in the lab

- QCD phase transition (QGP → hadrons) at $t_{Universe}$ ~10 μs
- In **high-energy** **heavy-ion** collisions, **large energy densities** (> 1 GeV/fm³) are reached over **large volumes** (> 1000 fm³)





Density of baryons – anti-baryons

Ultra-relativistic heavy-ion accelerators

- **BNL-AGS**, early '90s, Au-Au up to $\sqrt{s_{NN}} = 5$ GeV
  - Below critical energy density
- **CERN-SPS**, from 1994, Pb-Pb up to $\sqrt{s_{NN}} = 17$ GeV
  - Estimated energy density ~ 1 × critical value ε_c
  - First signatures of the QGP observed
- **BNL-RHIC**, from 2000, Au-Au $\sqrt{s_{NN}} = 8 - 200$ GeV
  - Estimated energy density ~ 10 × critical value ε_c
  - Discovery of several properties of the QGP
- **CERN-LHC**, from 2010, Pb-Pb $\sqrt{s_{NN}} = 2.76 - 5.5$ TeV
  - Estimated energy density ~ 15-30 × critical value ε_c
  - (Ongoing) Precise characterization of the QGP, new probes available

Outline of the Lectures

- **Introduction**
  - The QCD phase transition and deconfinement
  - Nucleus-nucleus collisions
- **Measurements and phenomenology**
  - Global observables ⟷ the QGP fireball
  - Strangeness production ⟷ historic signature of the QGP
  - Anisotropy, correlations ⟷ collective expansion of the QGP
  - Bulk particle production ⟷ hadronization of the QGP
  - High-p_T and jets ⟷ opacity of the QGP
  - Heavy flavour production ⟷ transport properties of the QGP
  - Quarkonium production ⟷ deconfinement in the QGP
  - Surprises from LHC p-Pb ⟷ current "hottest topic"

Part 1: Introduction; Global observables; Strangeness production

Part 2: Anisotropy, correlations; Bulk particle production; High-p_T and jets

Part 3: Heavy flavour production; Quarkonium production; Surprises from LHC p-Pb

The QCD phase transition

Two puzzles in QCD: i) Hadron Masses

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 bottom	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

- 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

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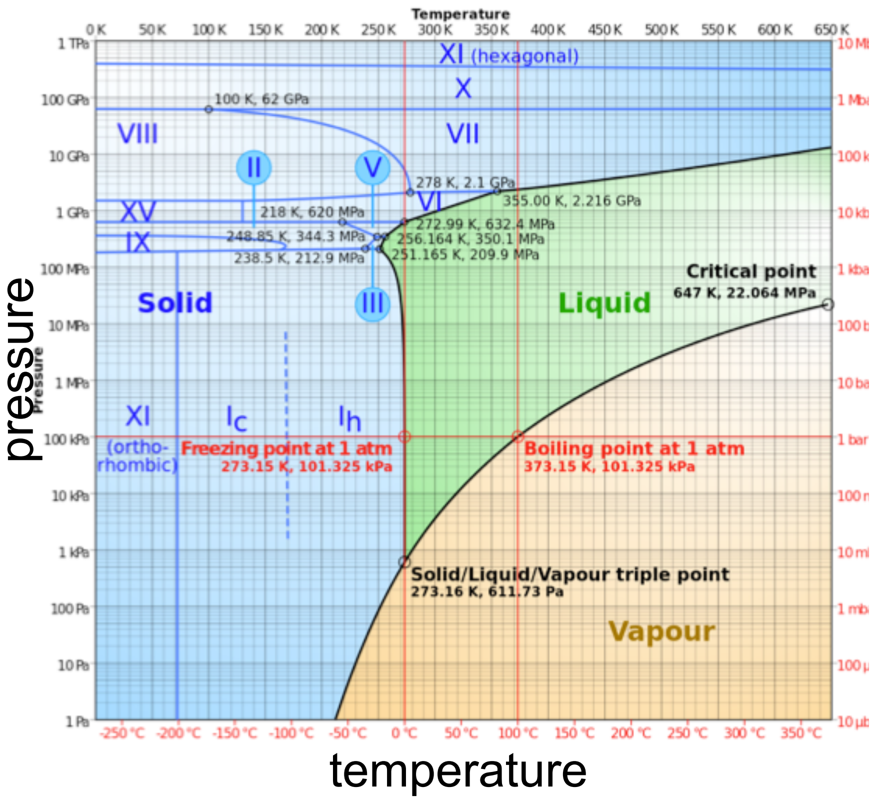
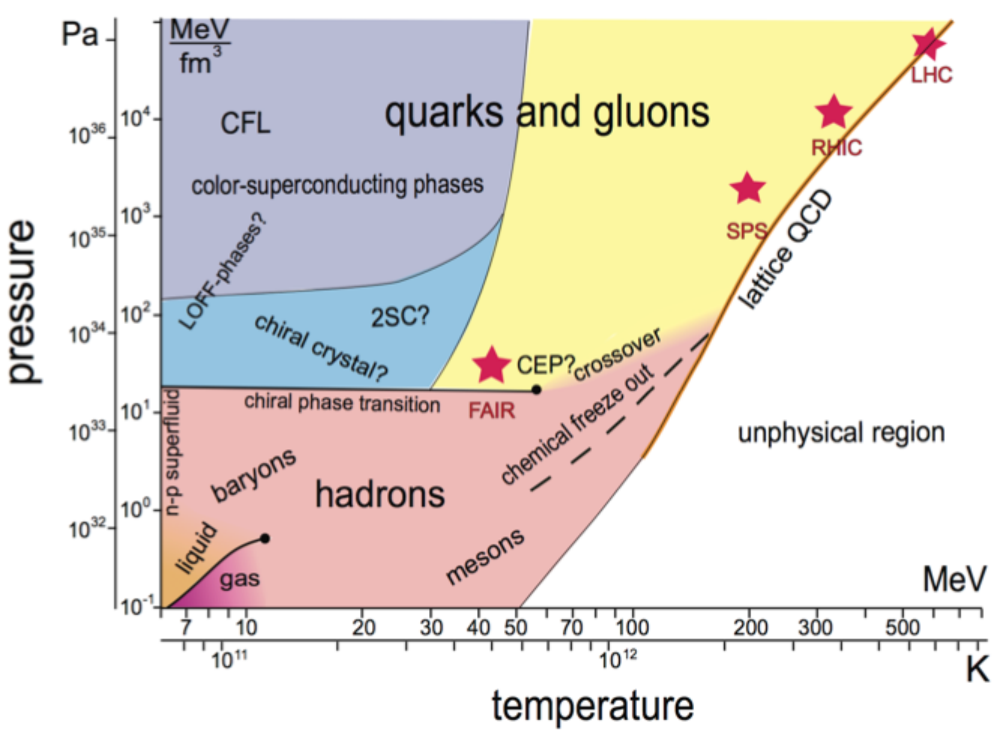
- Nobody ever succeeded in detecting an isolated quark
- Quarks seem to be permanently confined within protons, neutrons, pions and other hadrons.
- It looks like one half of the fundamental fermions are not directly observable… why?

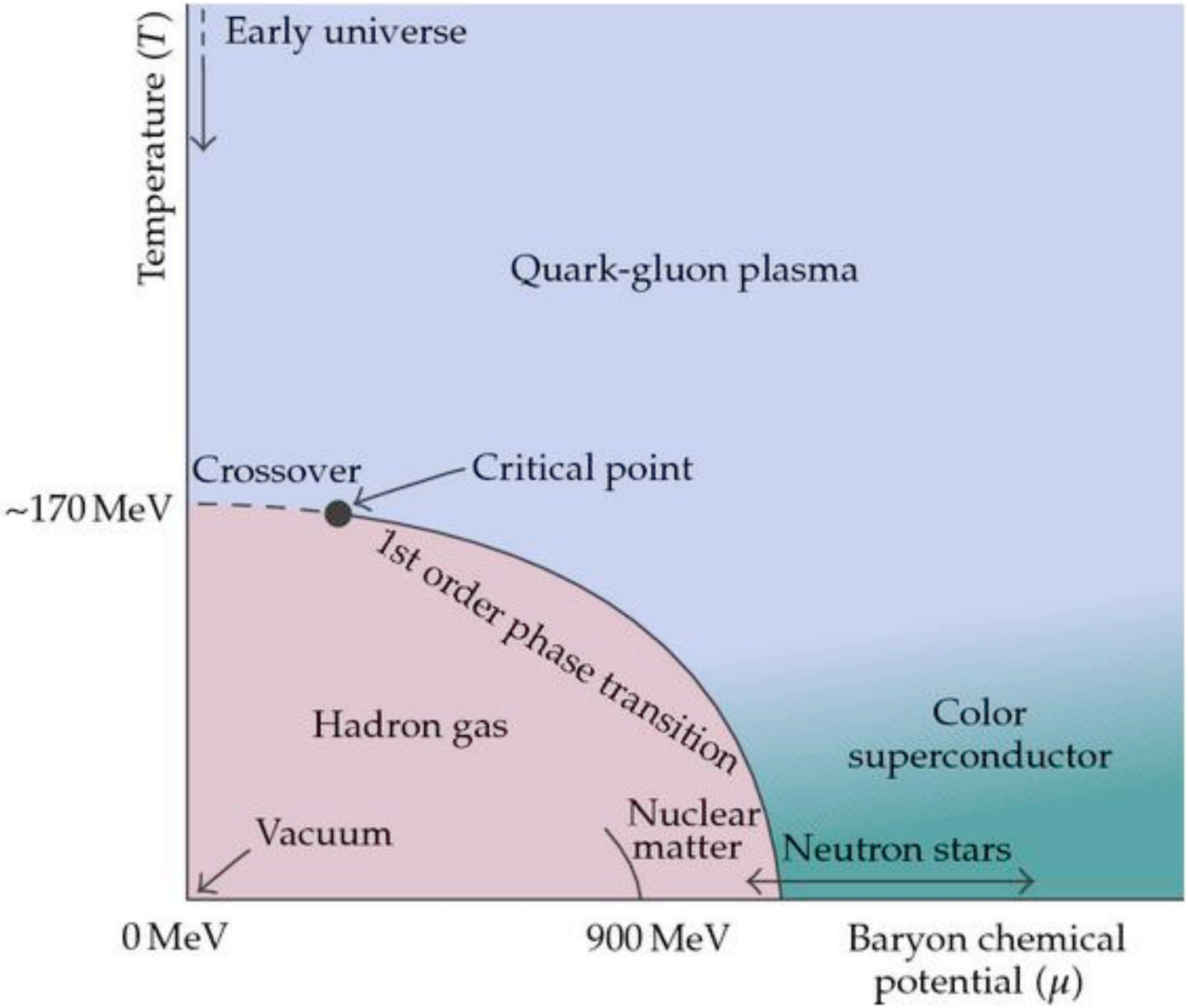
Water and QCD phase diagrams



arXiv:1111.5475



QCD phase diagram (Standard representation)



K. Rajagopal and F. Wilczek, Handbook of QCD

Lattice QCD

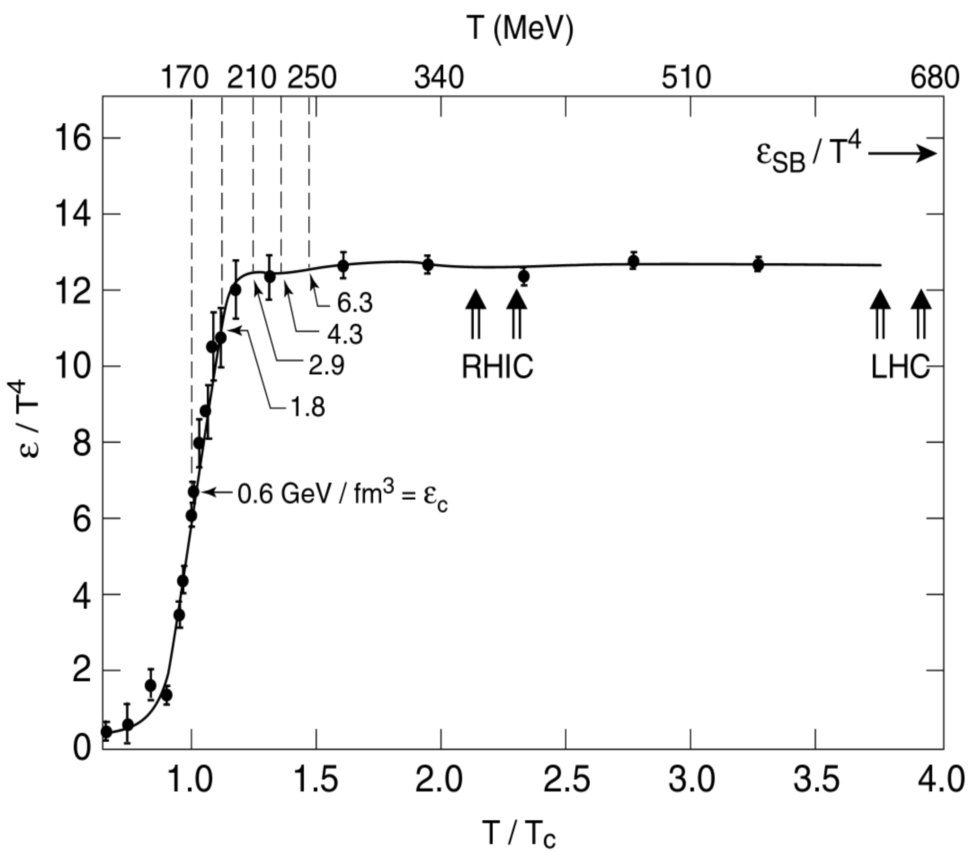
- Method for doing calculations in non-perturbative regime of QCD
- Discretization on a space-time lattice
- Ultraviolet (large momentum scale = small space-time scale) divergencies can be avoided

- Compute thermo-dynamical properties for a system of interacting quarks and gluons

Pressure density: $$p = \frac{\varepsilon}{3} = n_{dof} \frac{\pi^2 T^4}{90}$$ for an ideal gas

Lattice QCD: Phase Transition

$$\frac{\varepsilon}{T^4} \quad vs. \quad T$$

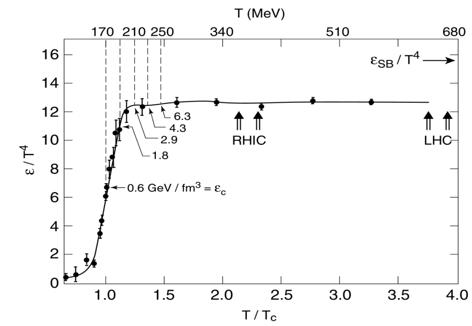


F. Karsch et al. PLB478 (2000)

- Zero baryon density, 2 quark flavours (u, d)
- 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})

Lattice QCD: Phase Transition

$$\frac{\varepsilon}{T^4} \;\; vs. \;\; T \qquad \propto n_{dof} = n_b + \frac{7}{8} n_f$$



Below T_c: gas of pions

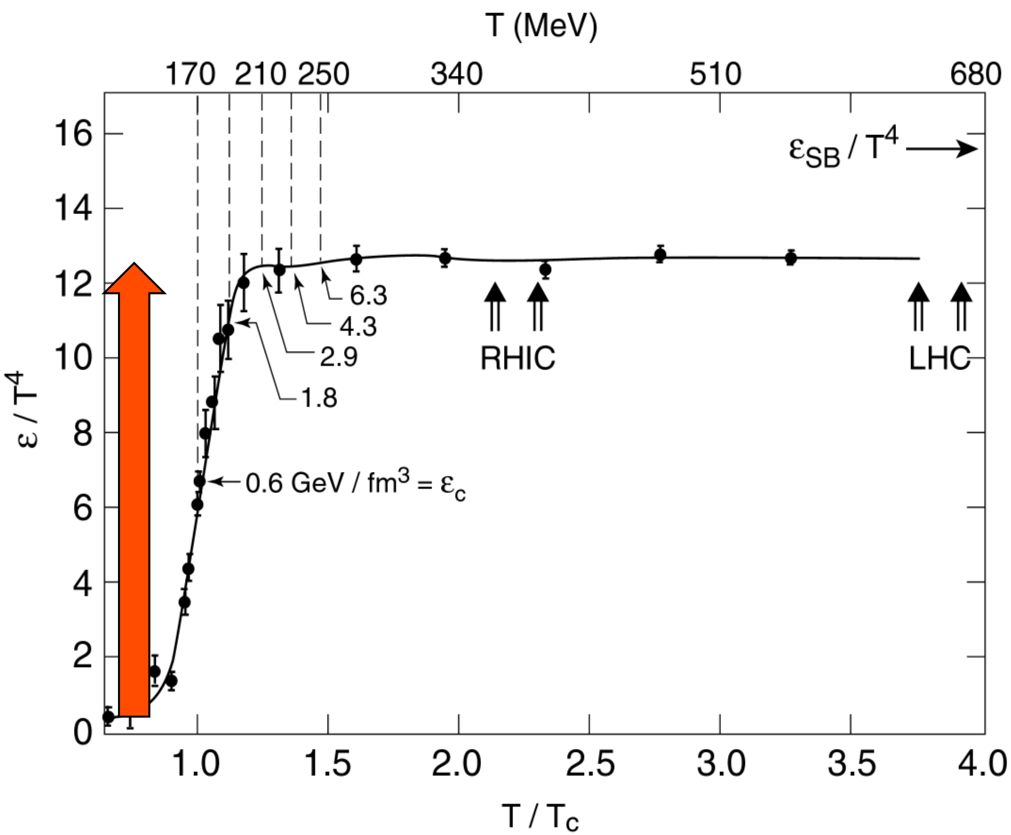
$$n_b = 3(\text{isospin}); \; n_f = 0 \quad \Rightarrow n_{dof} = 3$$

Above T_c: gas of g, u, d and anti-quarks

$$\begin{array}{c} n_b = 8(\text{colors}) \times 2(\text{polar.}) \\ n_f = 3(\text{colors}) \times 2(\text{polar.}) \times 2(\text{flav.}) \times 2(\text{charg.}) \end{array} \quad \Rightarrow n_{dof} = 37$$

Lattice QCD: Phase Transition

$$\frac{\varepsilon}{T^4} \quad vs. \quad T \qquad \propto n_{dof} = n_b + \frac{7}{8} n_f$$



F. Karsch et al. PLB478 (2000)

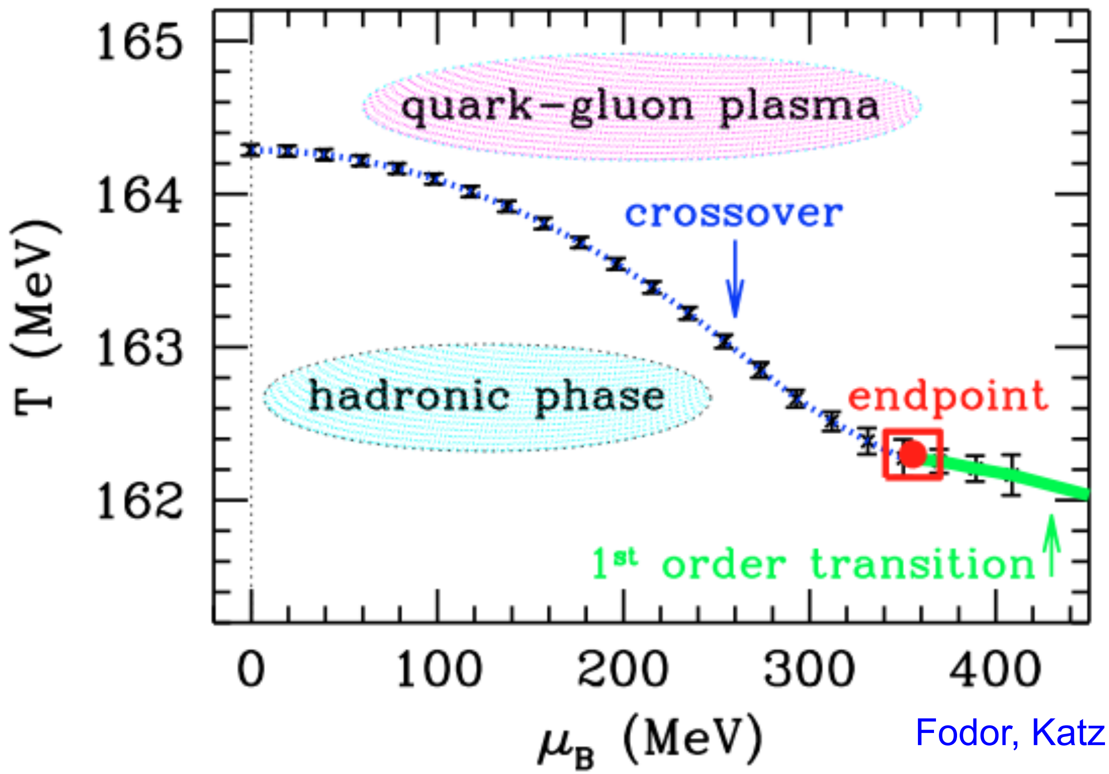
Below T_c: gas of pions

$$n_{dof} = 3$$

Above T_c: gas of g, u, d and anti-quarks

$$n_{dof} = 37$$

Calculating the phase diagram of QCD



Fodor, Katz, JHEP0404(2004)050

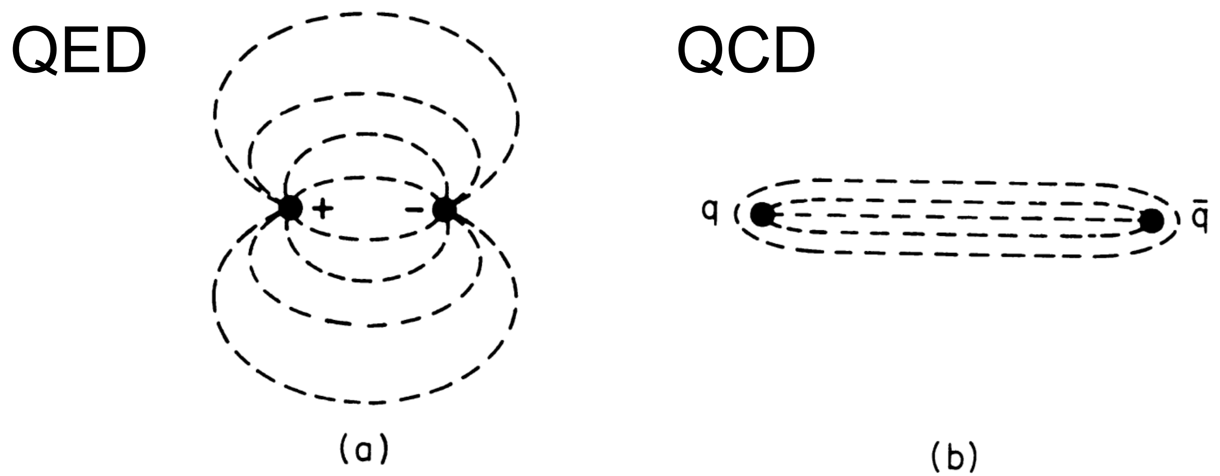
- Lattice QCD calculations at finite μ_B in recent years
- Map phase line on (μ_B, T) plane
- Study order of the phase transition
- Estimate position of the critical point

Confinement and deconfinement: an “intuitive” view

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

Confining potential in QCD



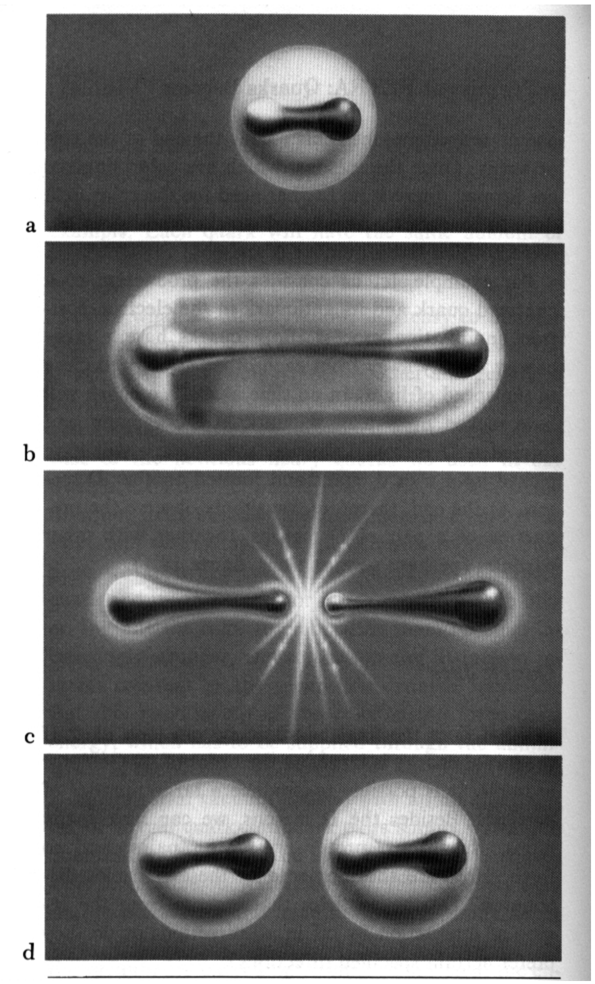
- In QCD, the field lines are compressed into a “flux tube” (or “string”) of constant cross-section (~fm^2), leading to a long-distance potential which grows linearly with distance *r* :

$$V(r) = -\frac{A}{r} + k \cdot r$$

with k ~ 1 GeV/fm

Confinement: 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]

Confinement and Deconfinement in the Bag Model

- Due to the non-abelian nature of QCD, the QCD vacuum is a rather complex object, behaving practically as a liquid of gg pairs in colour-singlet state
- 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*

(a) (b)

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

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).

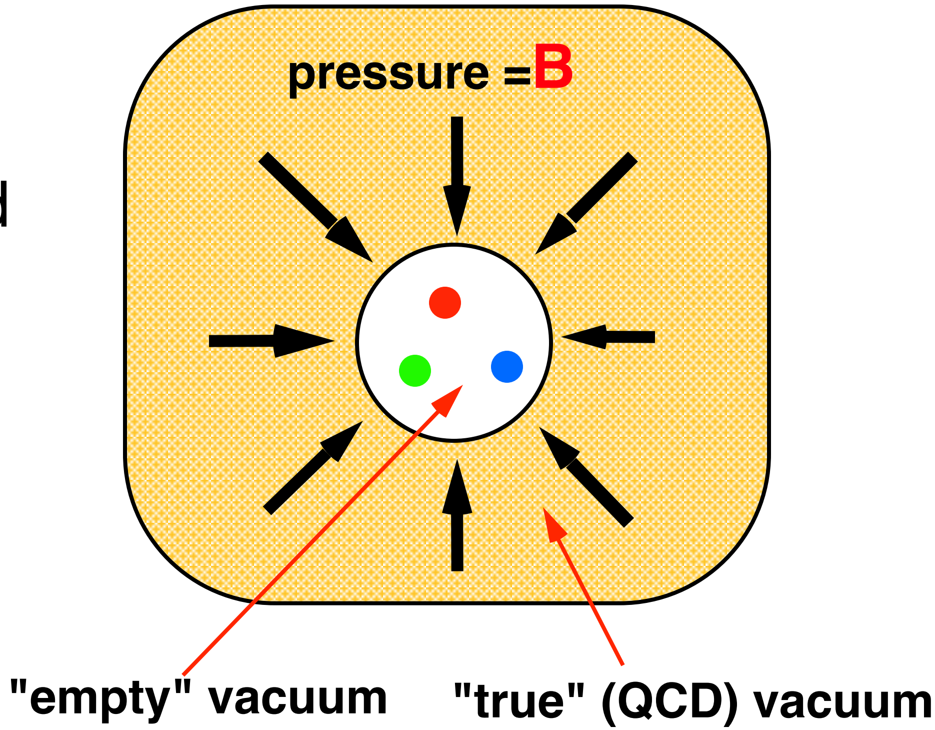
Bag Model

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

- From measured proton "radius" (→ *R*):

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

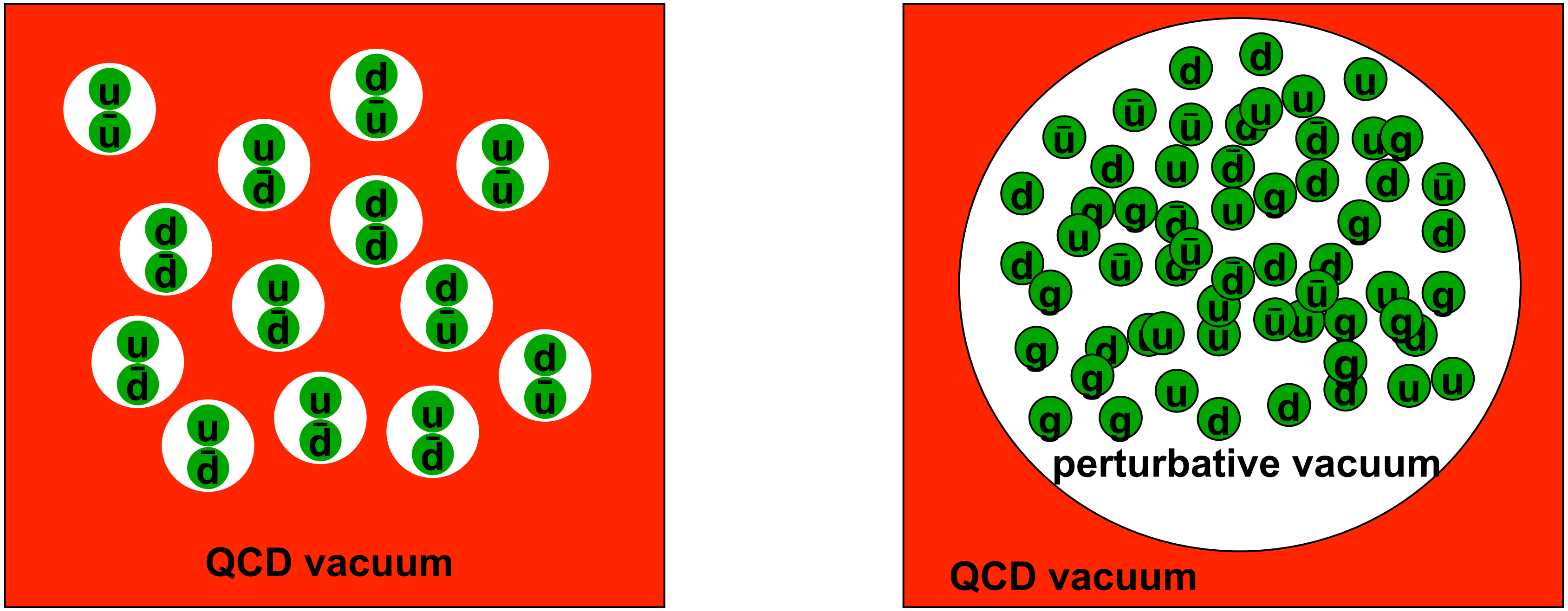
Bag model of a hadron:



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

Bag Model

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

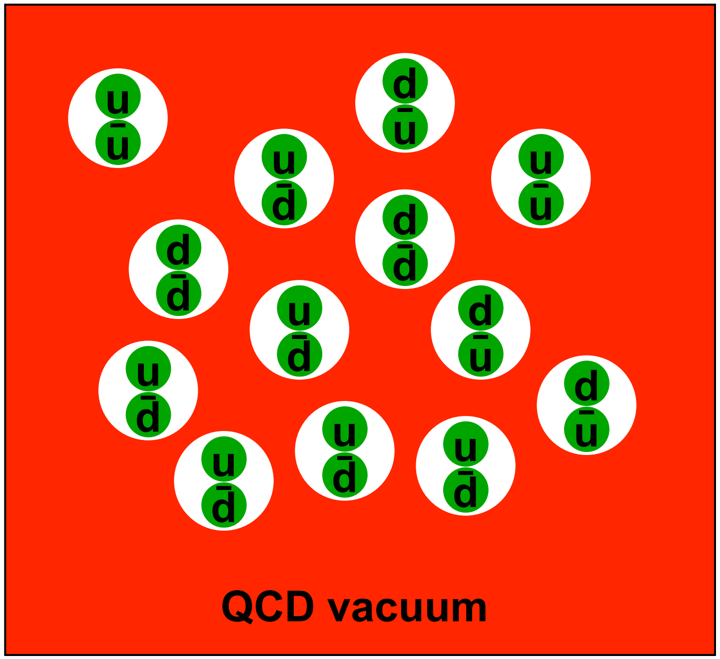


- Gibbs' criterion: the stable phase is the one with the largest pressure
- From statistical mechanics:
  (for an ideal gas)

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

Bag Model

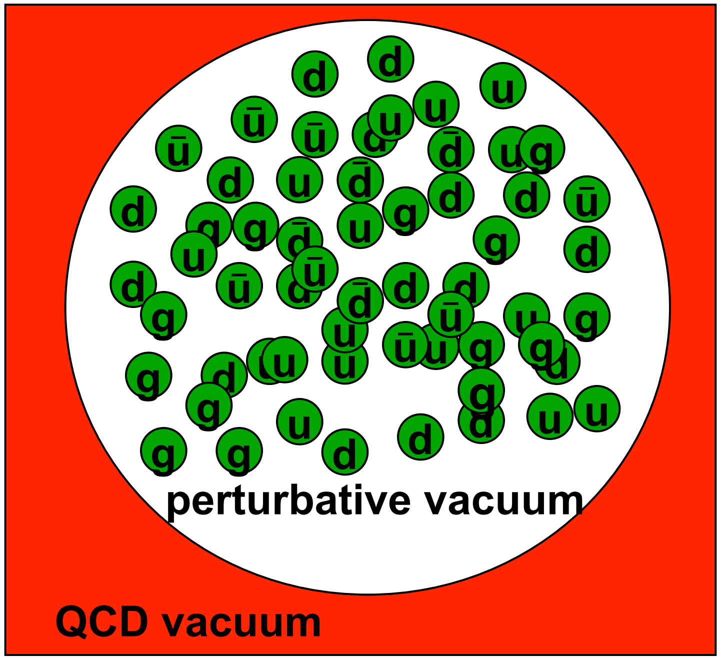
Hadron (pion) Gas



$$g_B = 3 \quad g_F = 0$$

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

Quark-Gluon Plasma



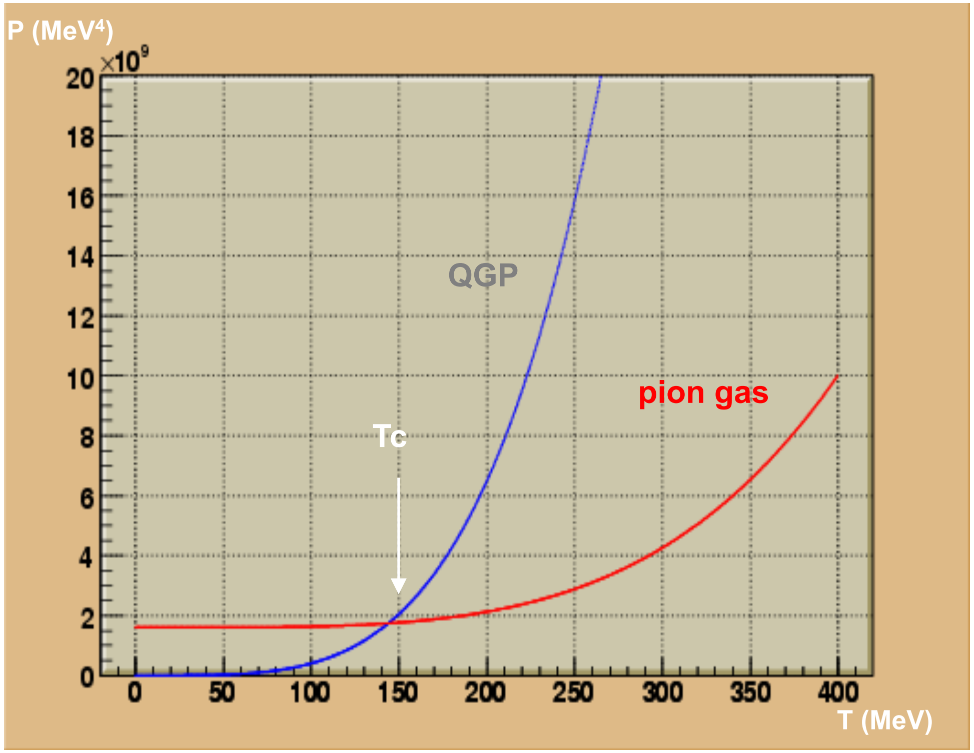
$$g_B = 16 \quad g_F = 24$$

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

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

Bag Model: Critical Temperature

- 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



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

- Consistent with lattice QCD value: 170 MeV

170 MeV ≈ 2 10^{12} K

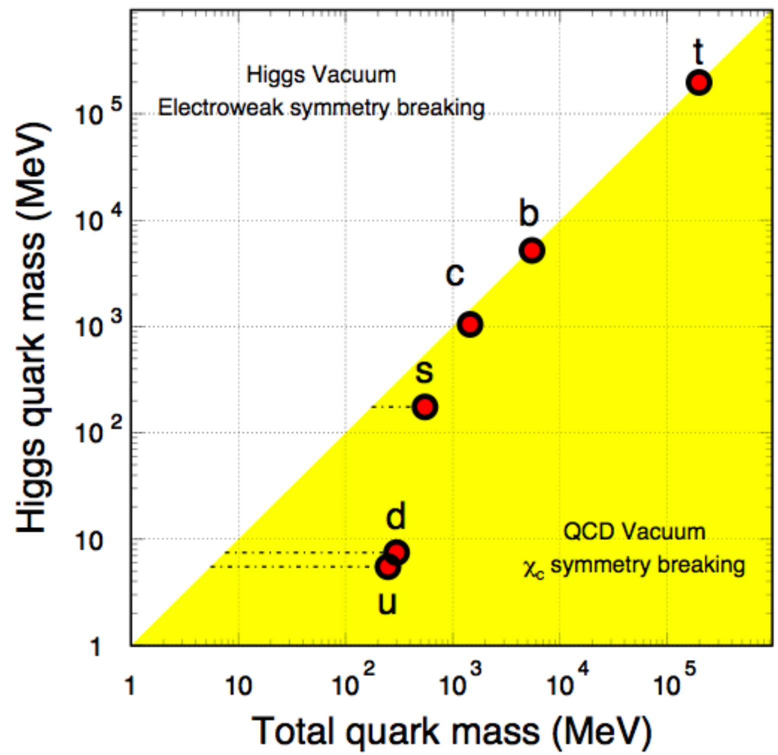
(compare Sun core: 1.5 10^{7} K)

Restoration of bare quark masses

- Confined quarks acquire an additional mass (~ 350 MeV) dynamically, through the confining effect of strong interactions

- Deconfinement is expected to be accompanied by a restoration of the masses to the "bare" values they have in the Lagrangian
  - m(u,d): ~ 350 MeV → a few MeV
  - m(s): ~ 500 MeV → ~ 150 MeV

- (This effect is usually referred to as "Partial Restoration of Chiral Symmetry". Chiral Symmetry: fermions and antifermions have opposite helicity. The symmetry is exact only for massless particles, therefore its restoration here is only partial)

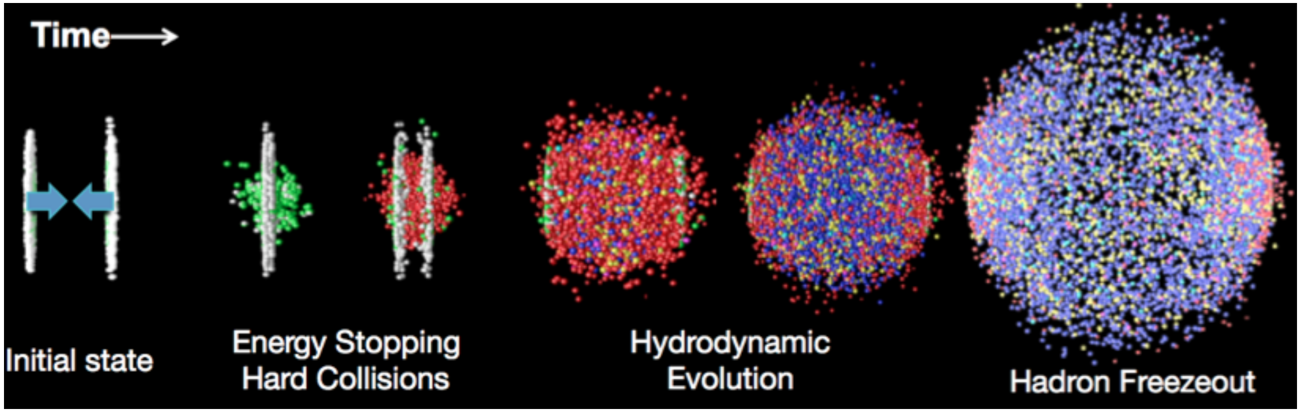


X.Zhu et al., PLB 647 (2007) 366

Nucleus – Nucleus Collisions

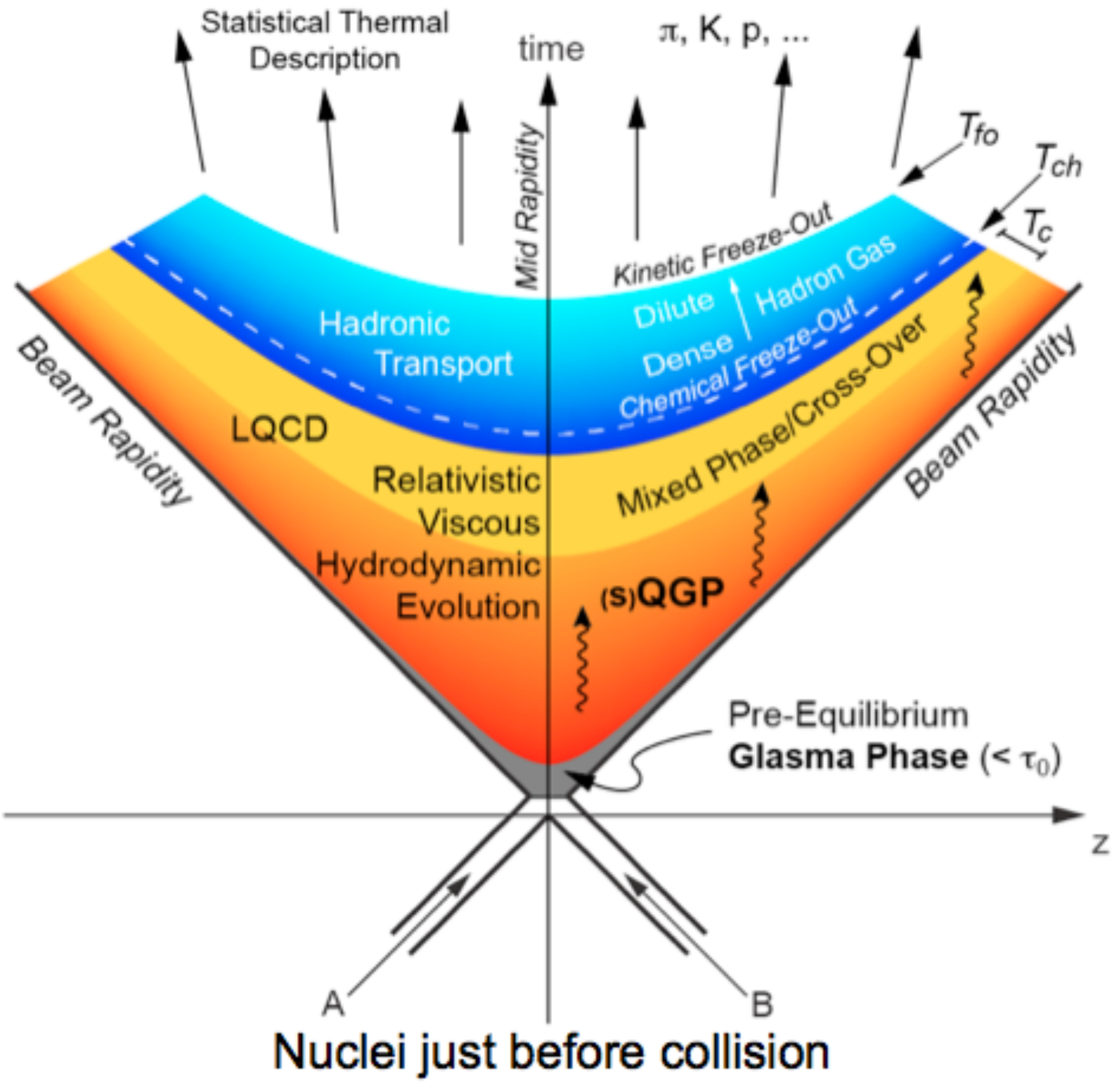
Nucleus-nucleus collisions

- How can we compress/heat matter to such high energy densities?

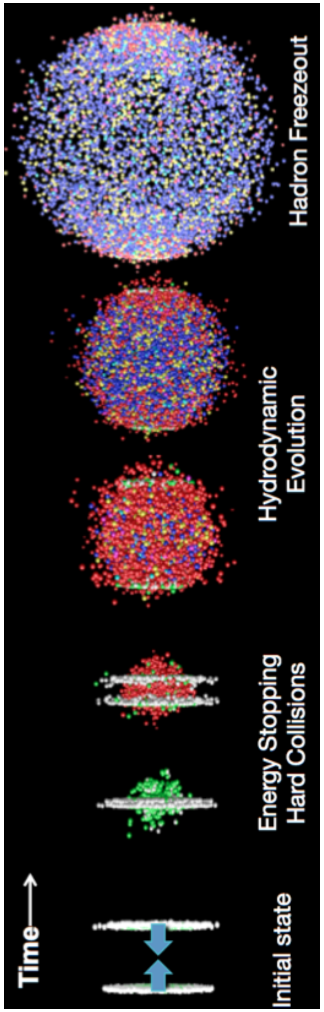


- By colliding two heavy nuclei at ultra-relativistic energies we recreate, for a short time span (about 10^{-23} s, or a few fm/c) the conditions for deconfinement
- As the system expands and cools down it will undergo a phase transition from QGP to hadrons again, like at the beginning of the life of the Universe: we end up with confined matter again

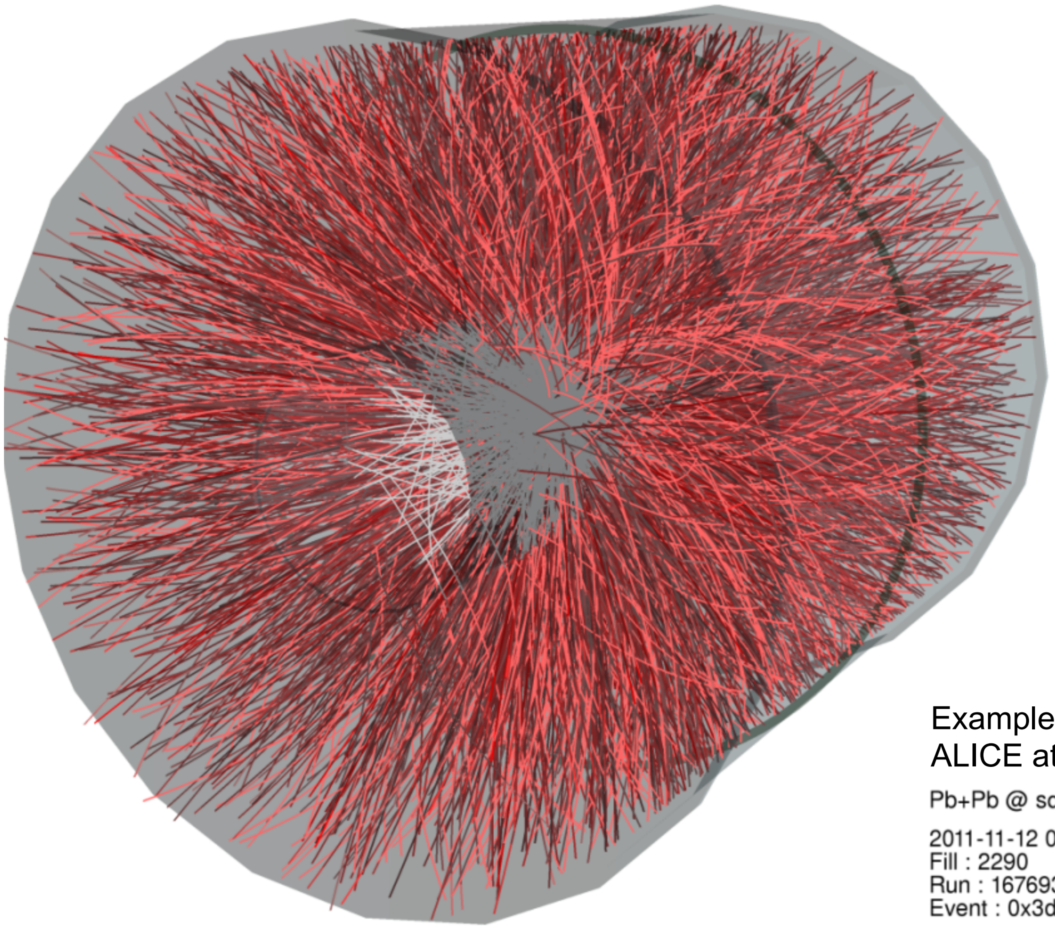
Evolution of a high-energy nuclear collisions



Courtesy B.Hippolyte



Final state of a high energy nuclear collision



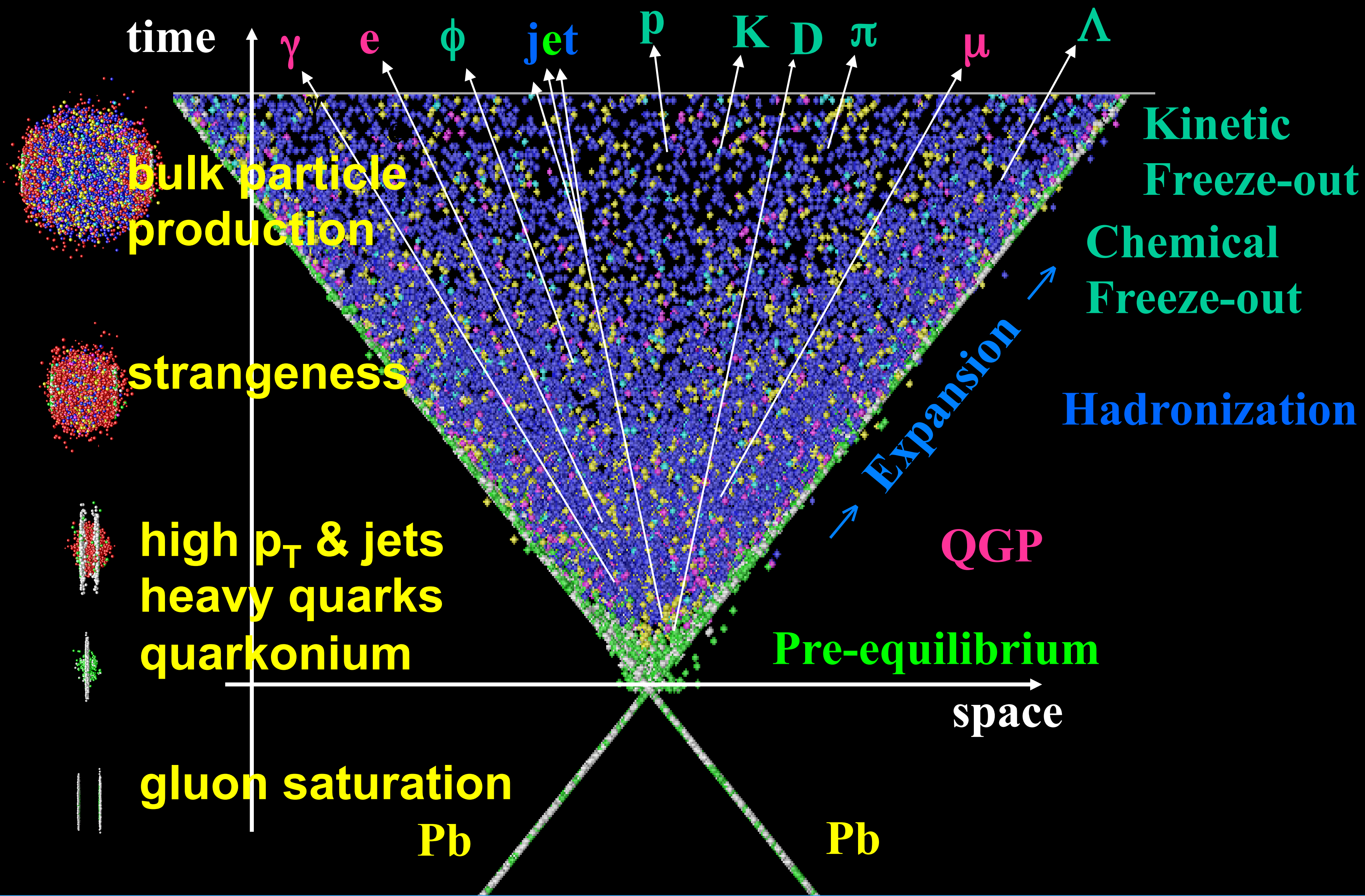
Example:
ALICE at LHC

Pb+Pb @ sqrt(s) = 2.76 ATeV

2011-11-12 06:51:12
Fill : 2290
Run : 167693
Event : 0x3d94315a

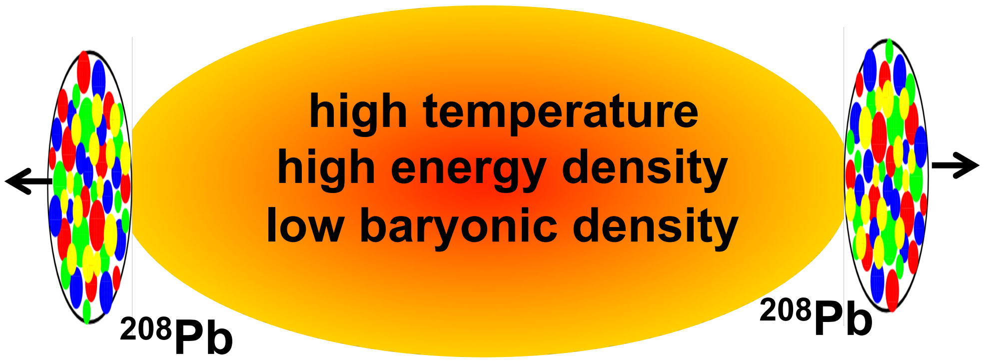
Use particles in the final state to investigate the stages of the collision evolution

Space-time evolution of the collision



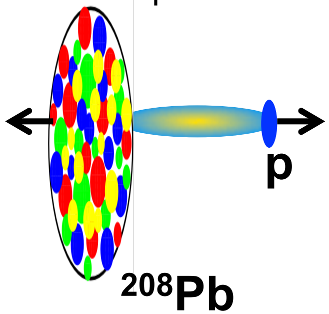
The role of proton-nucleus collisions

- In **high-energy nucleus-nucleus** collisions, **large energy density** (> 1 GeV/fm^3) over **large volume** (>> 100 fm^3)



- Control experiment: **high-energy proton-nucleus** collisions, **large energy densities** (?) in a **small volume** → no QGP (?)

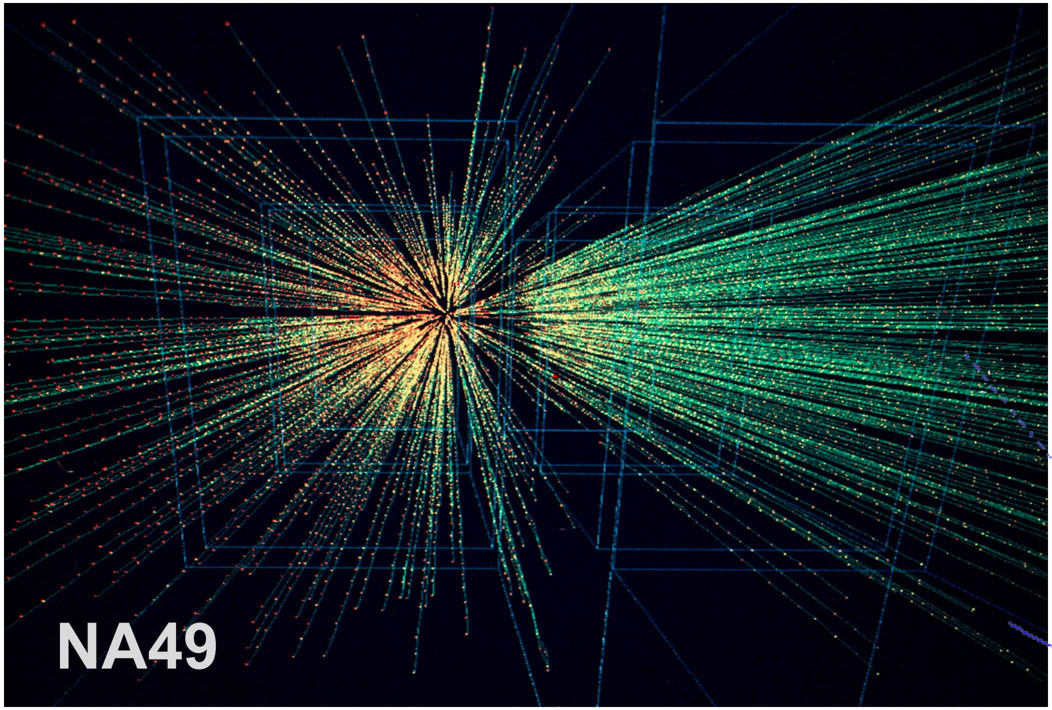
Control experiment:

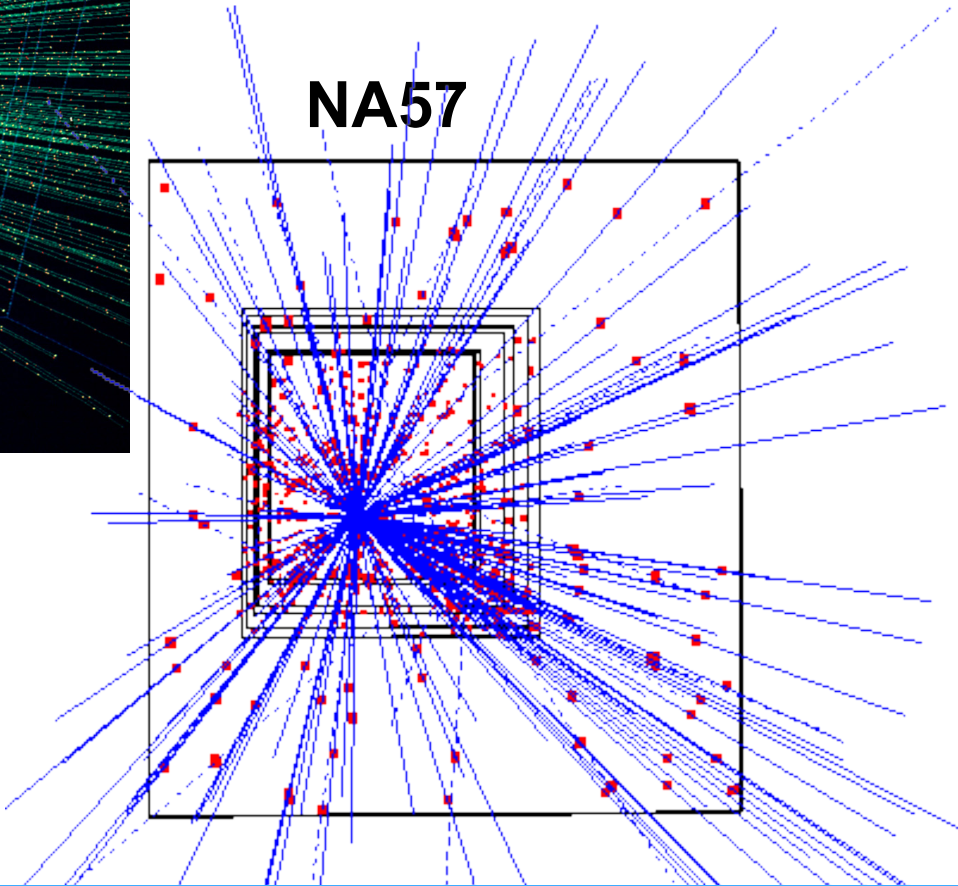


Heavy Ions at SPS and RHIC

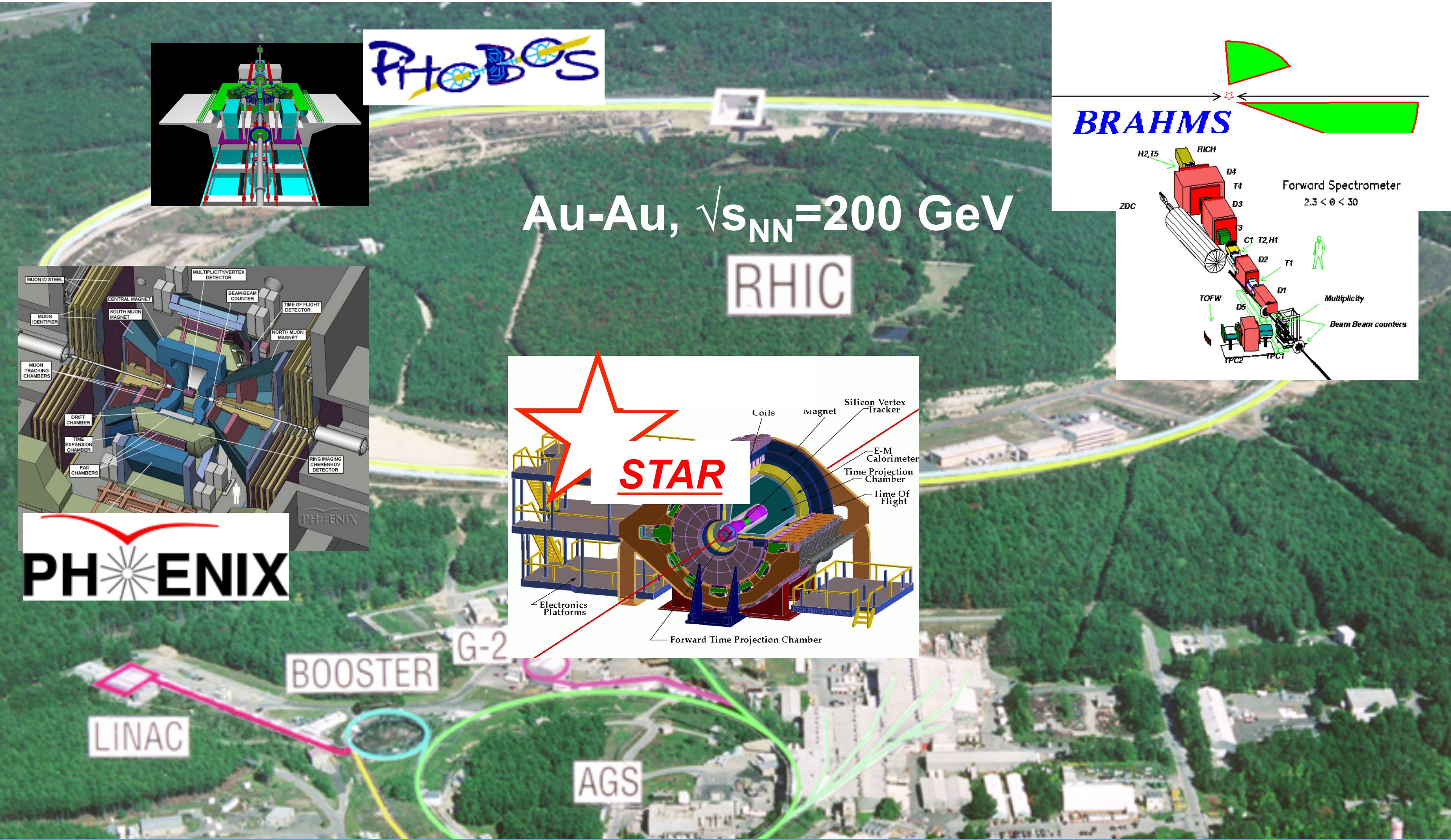
- Super Proton Synchrotron (SPS) at CERN (Geneva)
  - 1994-, Pb-Pb fixed target, p = 158 A GeV → $\sqrt{s_{NN}}$ = 17.3 GeV
  - 10 experiments:
    - WA97 (silicon pixel telescope spectrometer: production of strange and multiply strange particles)
    - WA98 (photon and hadron spectrometer: photon and hadron production)
    - NA44 (single arm spectrometer: particle spectra, interferometry, particle correlations)
    - NA45 (e^+e^- spectrometer: low mass lepton pairs)
    - NA49 (large acceptance TPC: particle spectra, strangeness, interferometry, event-by-event , …)
    - NA50 (dimuon spectrometer: high mass lepton pairs, J/ψ production)
    - NA52 (focusing spectrometer: strangelet search, particle production)
    - NA57 (silicon pixel telescope spectrometer: production of strange and multiply strange particles)
    - NA60 (dimuon spectrometer + pixels: dileptons and charm)
    - NA61 (extension/continuation of NA49) TAKING DATA
- Relativistic Heavy Ion Collider (RHIC) at BNL (Long Island, NY)
  - 2000-, collider, up to Au-Au, $\sqrt{s_{NN}}$ = 200 GeV
  - 4 experiments:
    - STAR (multi-purpose experiment: focus on hadrons) TAKING DATA
    - PHENIX (multi-purpose experiment: focus on leptons, photons) TAKING DATA
    - BRAHMS (two-arm spectrometer: particle spectra, forward rapidity), completed
    - PHOBOS (silicon array: particle spectra), completed

SPS: Pb-Pb, $\sqrt{s_{NN}}=17$ GeV

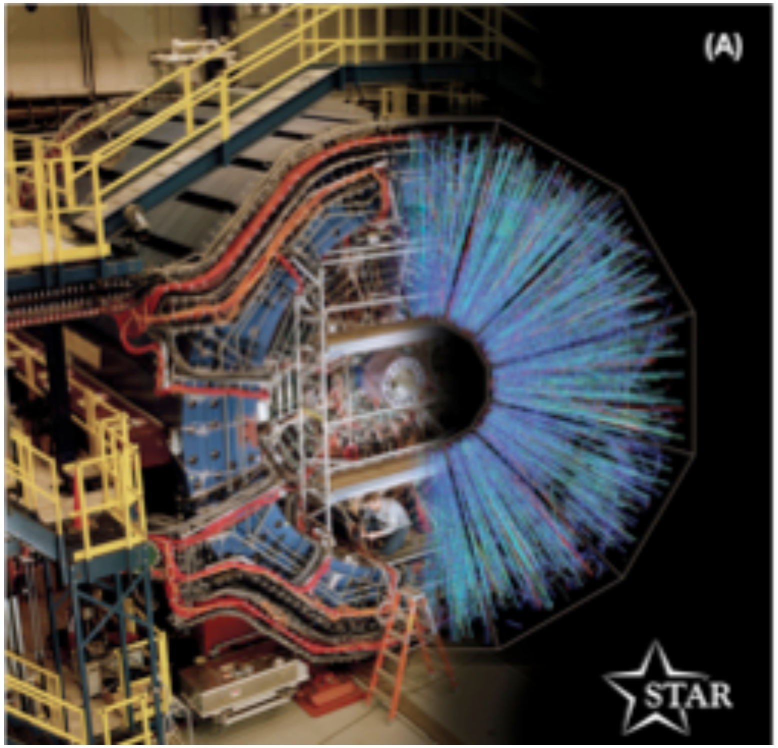


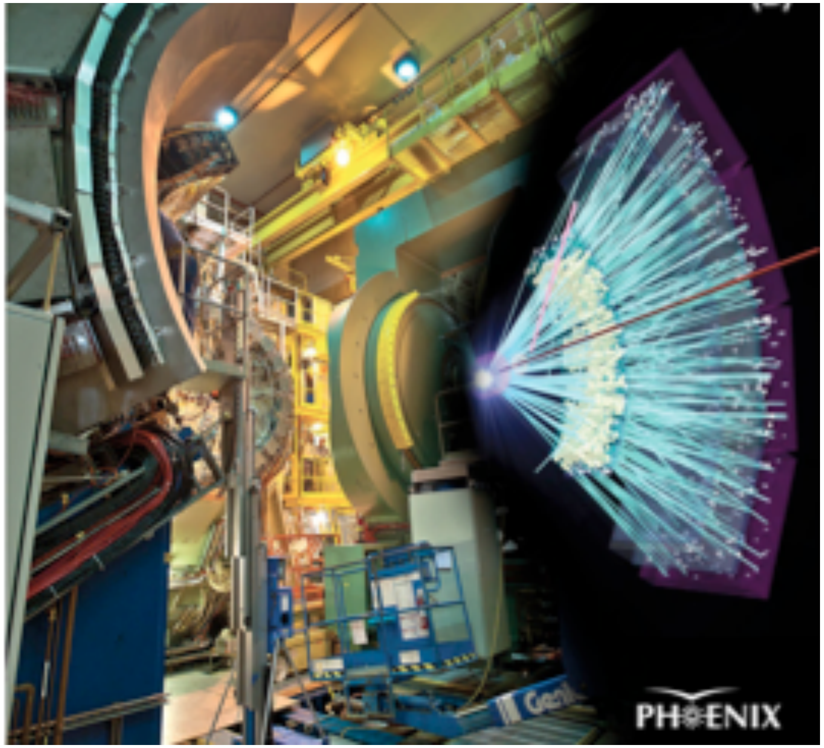


2000: beginning of the collider era, the RHIC experiments



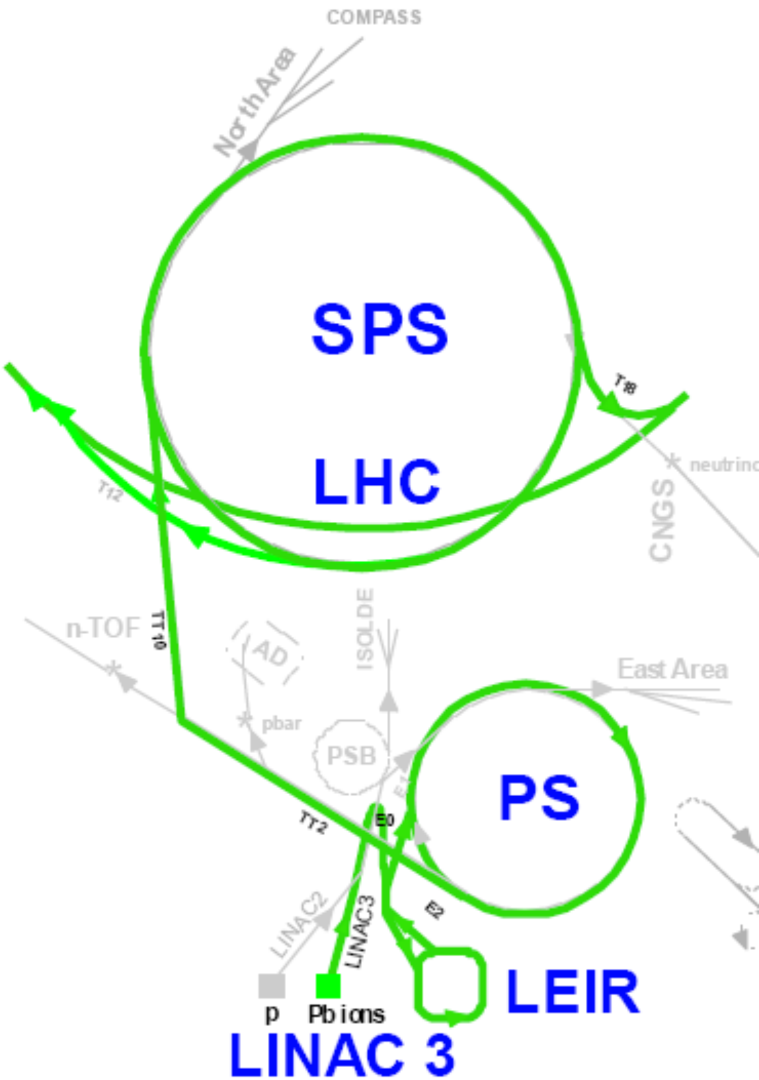
RHIC: Au-Au, $\sqrt{s_{NN}}$=200 GeV





Heavy Ions at the LHC

- Acceleration of Pb ions:
  - ECR source: Pb^{27+} (80 μA)
  - RFQ: Pb^{27+} to 250 A keV
  - Linac3: Pb^{27+} to 4.2 A MeV
  - Stripper: Pb^{53+}
  - PS Booster: Pb^{53+} to 95 A MeV
  - PS: Pb^{53+} to 4.25 A GeV
  - Stripper: Pb^{82+} (full ionisation)
  - SPS: Pb^{82+} to 158 A GeV
  - LHC: Pb^{82+} to 1.375 A TeV (2010-11)
    - 2.75 A TeV (2015-6?)



LHC as a HI accelerator

- Fully ionised ^{208}Pb nucleus accelerated in LHC (magnet configuration identical to that for pp), e.g. (2011 numbers):

$$\sqrt{s_{\mathrm{NN}}} = \sqrt{4 p_1 p_2} = \sqrt{4 \frac{Z_1 Z_2}{A_1 A_2} p_p p_p} = \frac{Z}{A} \sqrt{s_{\mathrm{pp}}} = \frac{82}{208} \sqrt{s_{\mathrm{pp}}} = 2.76\ \mathrm{TeV}$$

- … of course, real life is more complicated…
  - ion collimation
  - sensitivity of LHC instrumentation
  - injection chain
  - …

Luminosity and its limitations

- Bound-Free Pair Production (BFPP):

$$^{208}Pb^{82+} + ^{208}Pb^{82+} \xrightarrow{\gamma} ^{208}Pb^{82+} + ^{208}Pb^{81+} + e^{+}$$

with subsequent loss of the $^{208}Pb^{81+}$

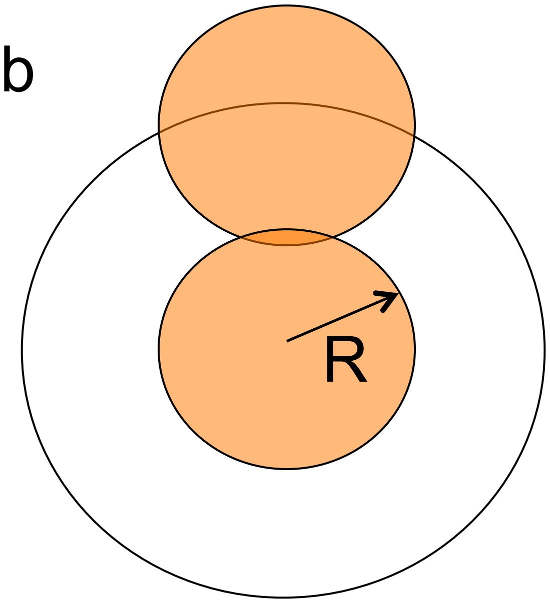
- creates a small beam of $^{208}Pb^{81+}$, with an intensity ∝ Luminosity
- impinging on a superconducting dipole (that you don't want to quench…)

- Collimation losses
  - collimation for ions (which can break up into fragments) is harder than for protons
  - limitation on the total intensity

→ luminosity limited to ~ 10^{27} cm^{-2}s^{-1}

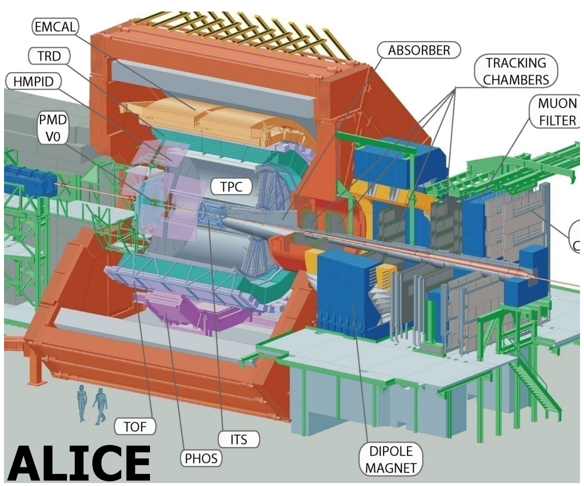
Pb-Pb cross section and interaction rate

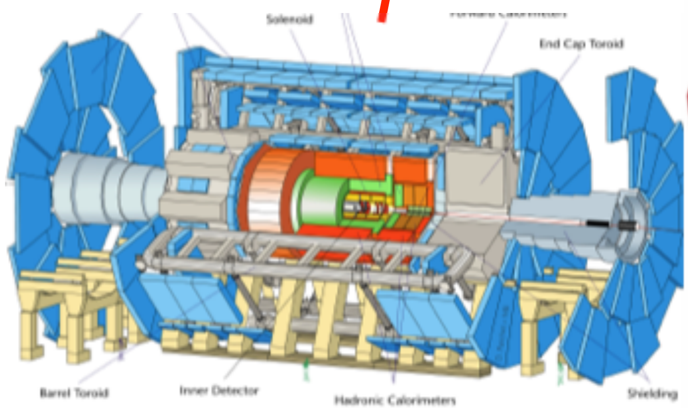
- Pb-Pb interaction cross section: $\sigma_{geom} \sim 7.7$ b
  - ^{208}Pb radius, $R \sim 1.2 * A^{1/3}$ fm ~ 7 fm
  - $\sigma_{geom} \sim \pi (2R)^2 \sim 7.7$ b



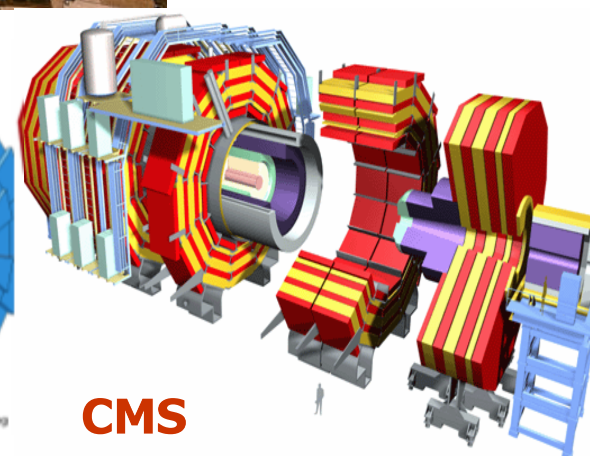
- For 2011 Pb-Pb run:
  - ~ 1.1 10^8 ions/bunch
  - 358 bunches (200 ns basic spacing)
  - $\beta^* = 1$ m
  - $L \sim 5\ 10^{26}$ cm^{-2}s^{-1}
  - → $R = L\ \sigma_{geom} \sim 4$ kHz interaction rate

Heavy-ion experiments at the LHC





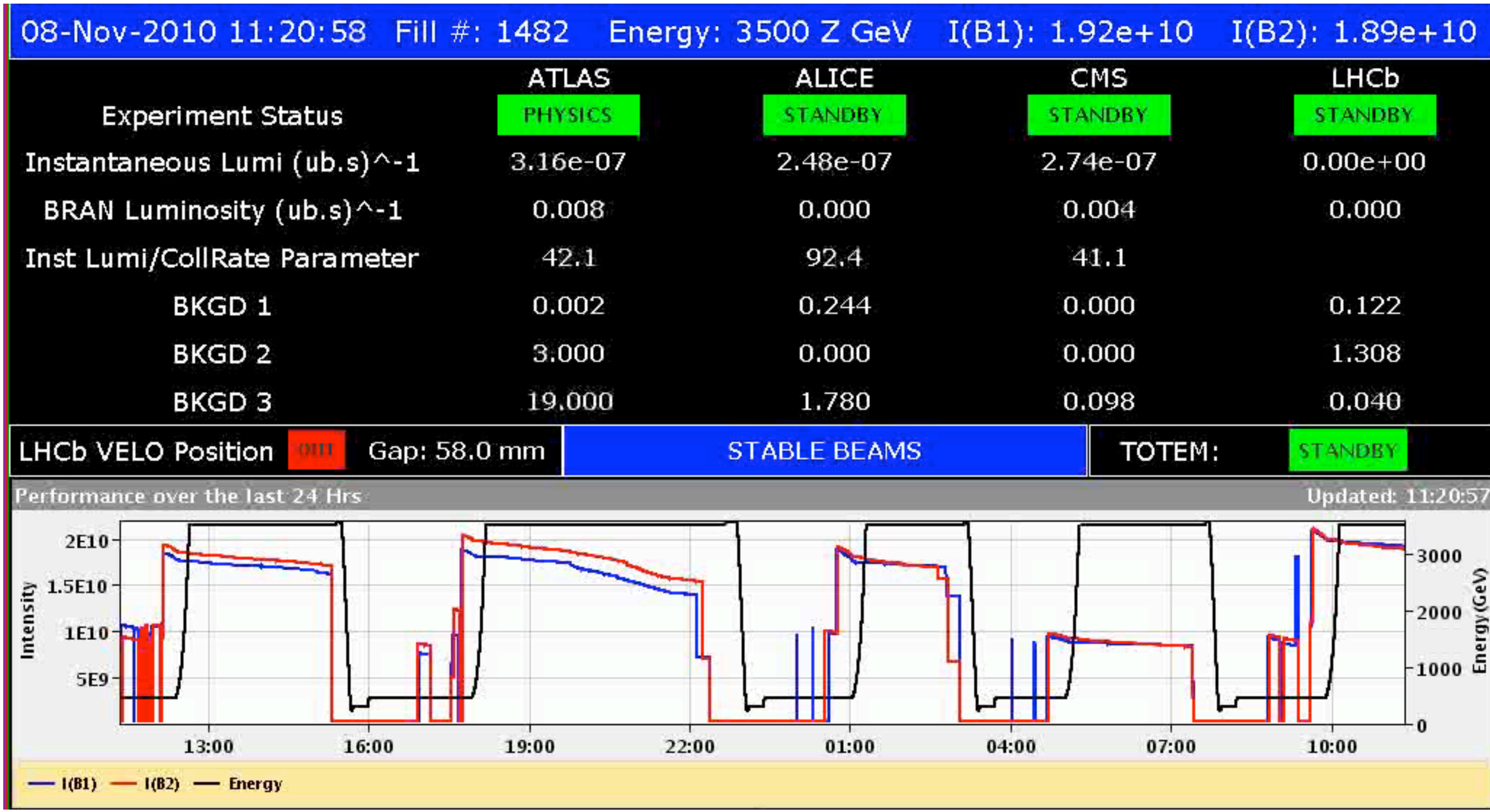
ATLAS

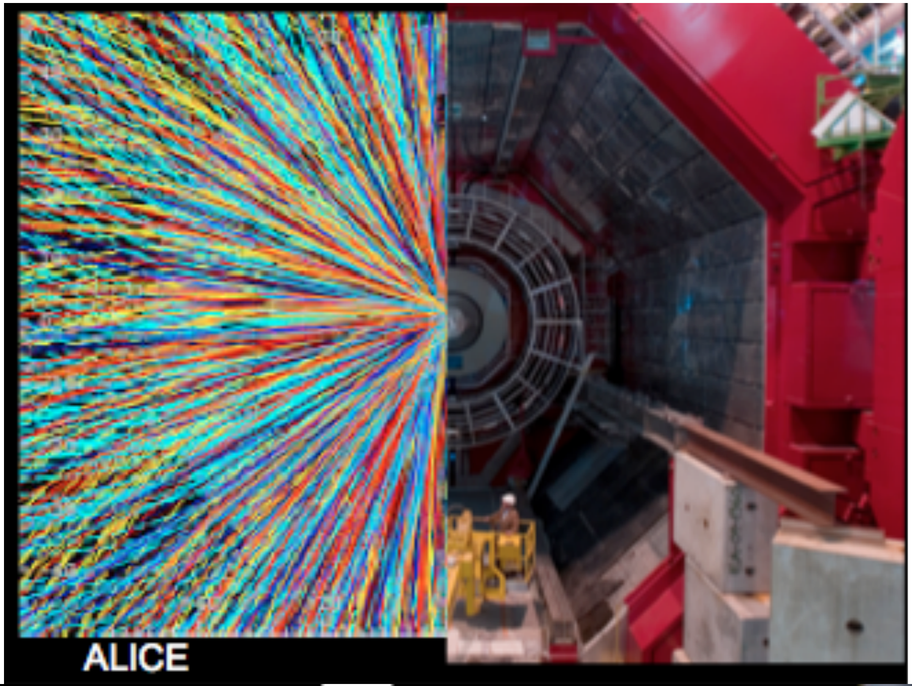


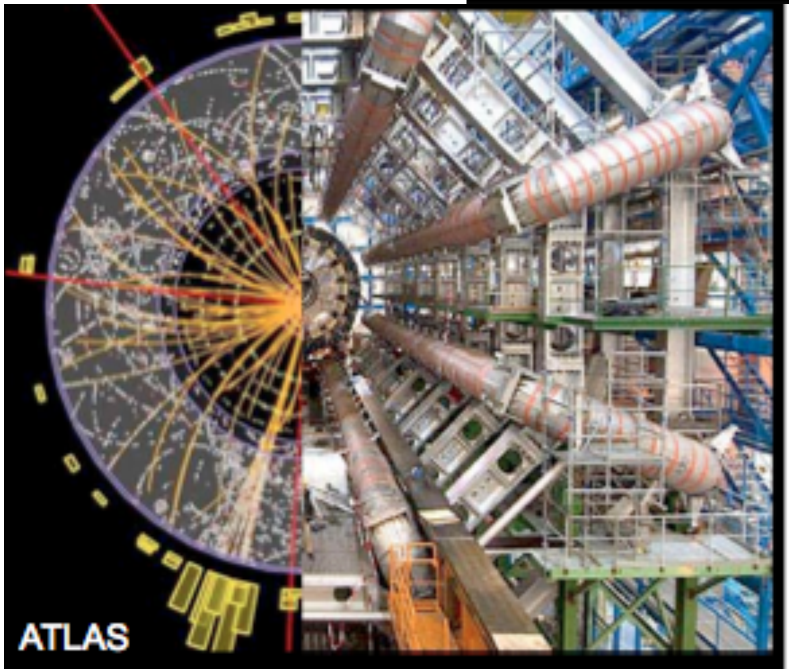
for p-Pb also LHCb

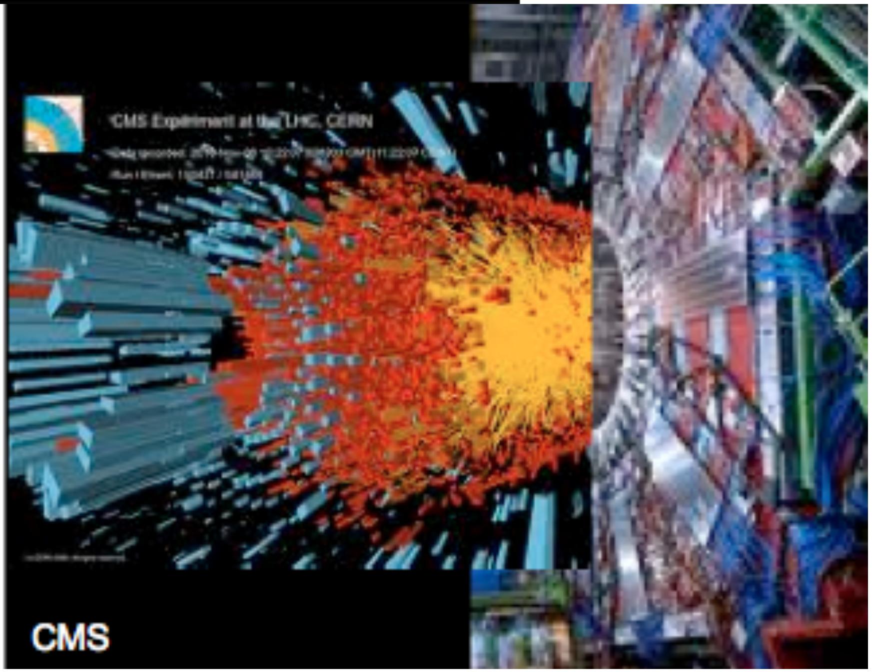
Pb-Pb collisions in the LHC!

- 8 November 2010: the beginning of a new era for Heavy Ion Physics




ALICE


ATLAS


CMS Experiment at the LHC, CERN
CMS

LHC Heavy-Ion running: where we are

- Two Pb-Pb runs at the LHC so far:
  - in 2010 – commissioning and the first data taking
  - in 2011 – already above nominal instant luminosity!
- A p-Pb run in 2013
- Now, Long Shutdown–1 (LS1)
  - Till autumn 2014; next Pb-Pb run in 2015

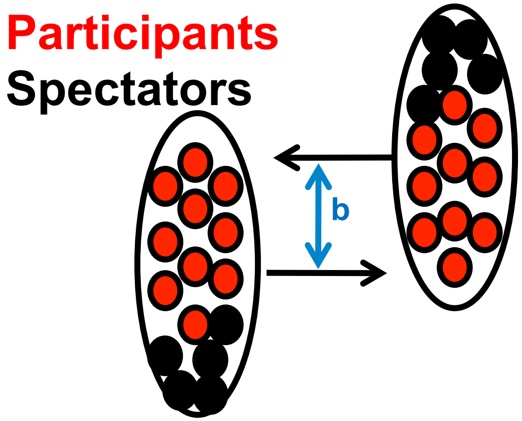
year	system	energy $\sqrt{s_{NN}}$ TeV	integrated luminosity
2010	Pb – Pb	2.76	~ 10 μb^{-1}
2011	Pb – Pb	2.76	~ 150 μb^{-1}
2013	p – Pb	5.02	~ 30 nb^{-1}

Observables and Probes of the QGP

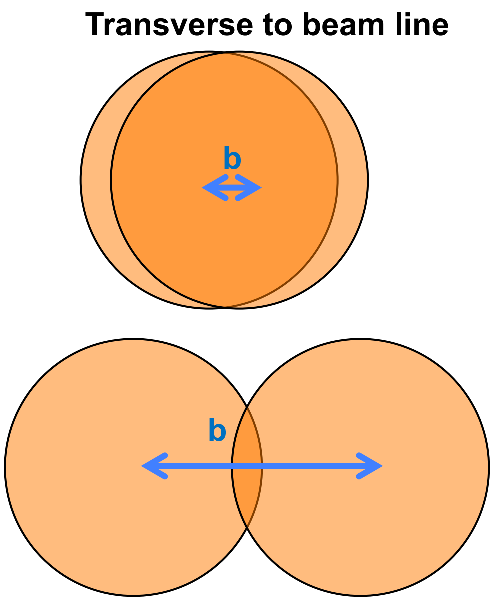
Phenomenology and measurements from heavy-ion collisions at SPS, RHIC, LHC

- Global observables ⟷ the QGP fireball
- Strangeness production ⟷ historic signature of the QGP
- Anisotropy, correlations ⟷ collective expansion of the QGP
- Bulk particle production ⟷ hadronization of the QGP
- High-p_T and jets ⟷ opacity of the QGP
- Heavy flavour production ⟷ transport properties of the QGP
- Quarkonium production ⟷ deconfinement in the QGP
- Surprises from LHC p-Pb ⟷ current “hottest topic”

Geometry of a nucleus-nucleus 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

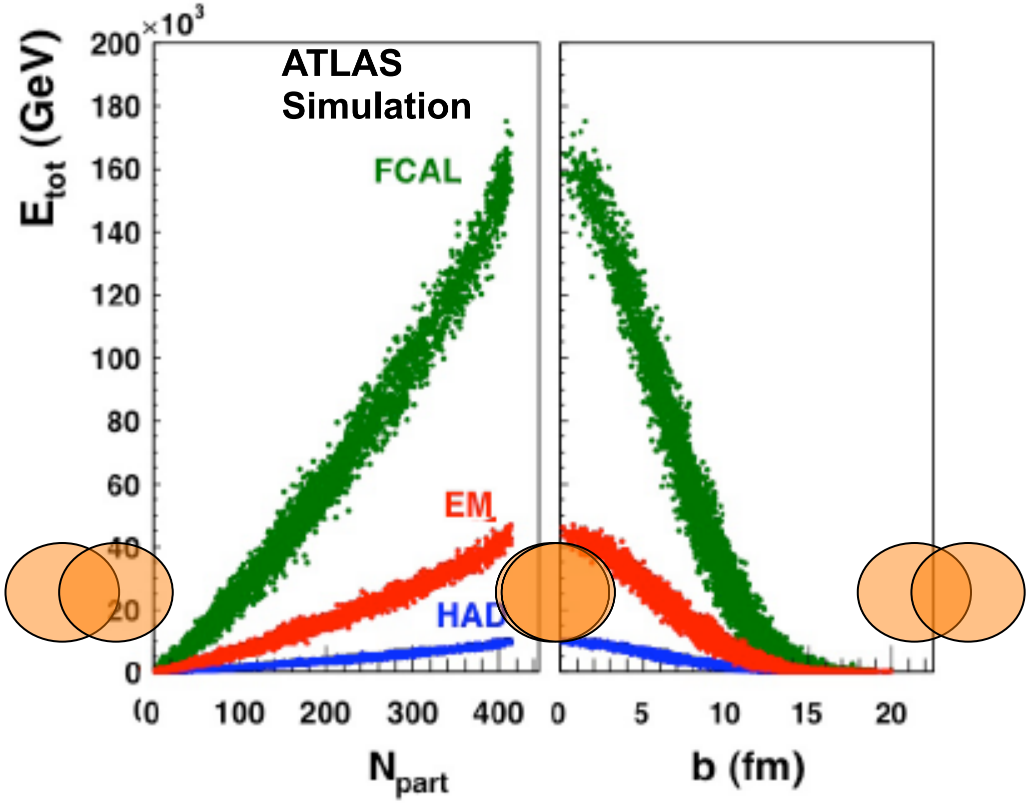


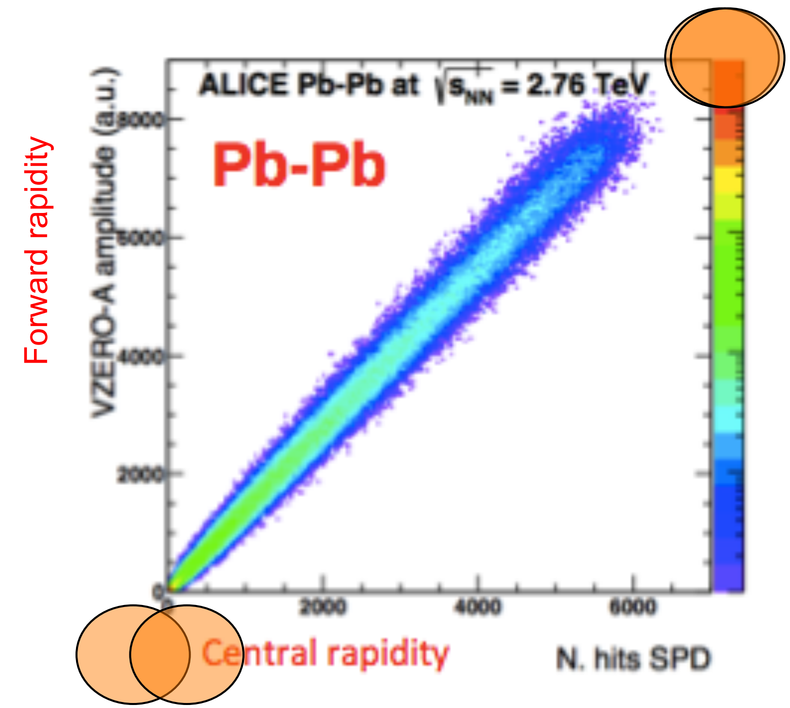
- System size strongly dependent on collision centrality
- Classify events in "centrality classes"
  - In terms of percentiles of total hadronic AA cross section
  - Determine $\langle N_{participants} \rangle$ and $\langle N_{collisions} \rangle$ with a model of the collision geometry (Glauber model)

Glauber model: see e.g. M. Miller et al. Ann.Rev.Nucl.Part.Sci.57(2007)205

Geometry of a nucleus-nucleus collision

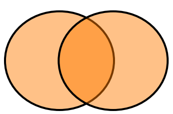
- Use multiplicity of produced particles in the acceptance of a given detector
- Or "Zero Degree Calorimeters" to measure the energy of the spectator nucleons

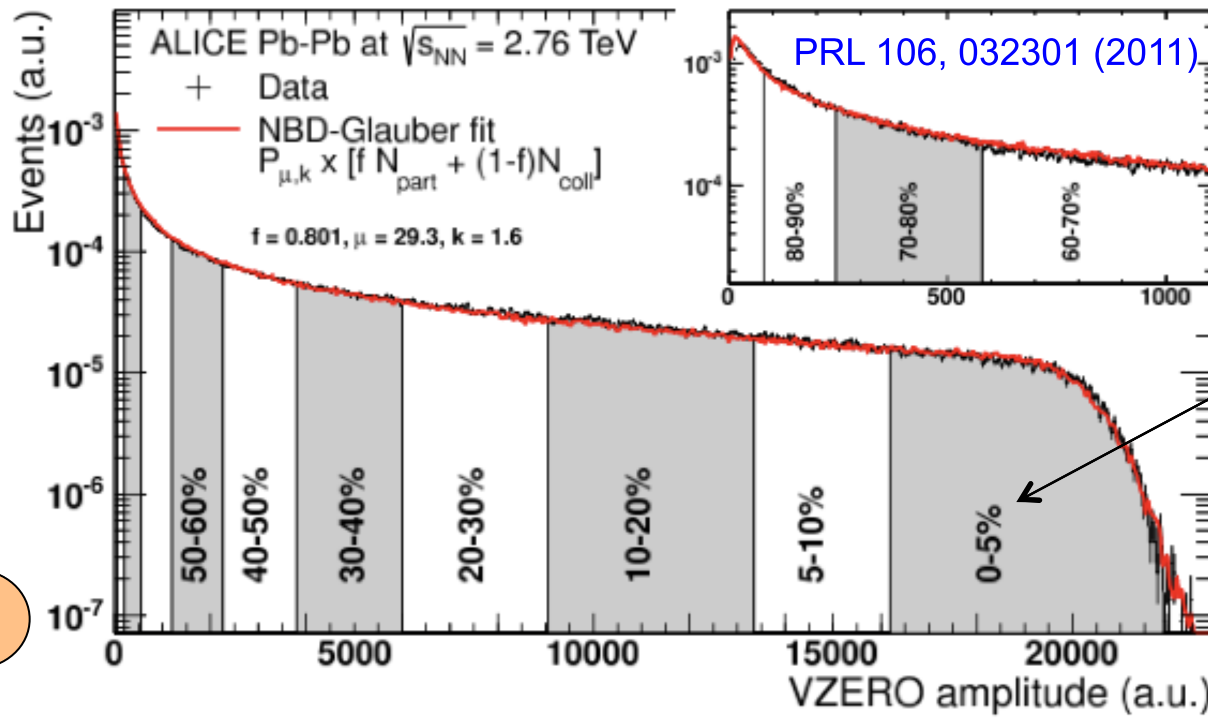




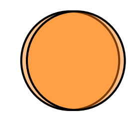
Geometry of a nucleus-nucleus collision

Example: sum of the amplitudes in the ALICE VZERO scintillators





Percentiles of Pb-Pb cross section

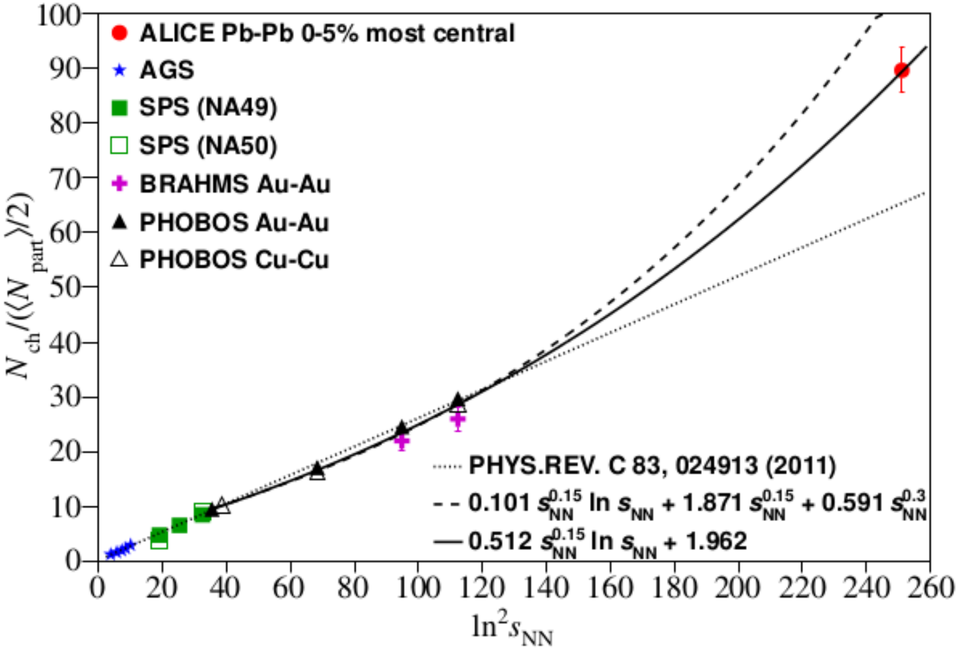


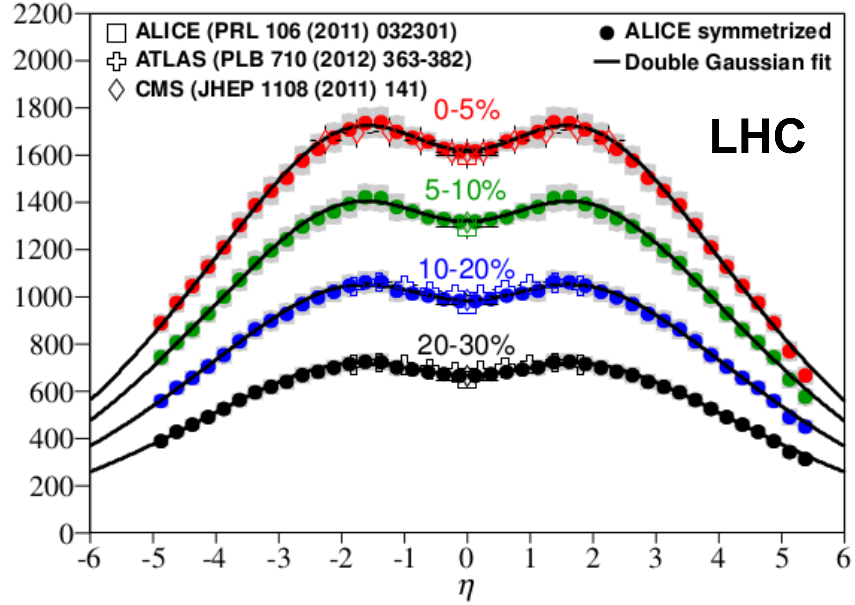
Reproduced by simple model (red):

- $N_{charged} = P \times [\, f\, N_{part} + (1-f)\, N_{coll}]$
- With N_{part} and N_{coll} distributions from Glauber model
  - Inputs: Wood-Saxon nuclear density profile, inelastic NN cross section

Bulk observables: multiplicity, size and temperature of the system

Particle multiplicity





Central collisions at LHC: ~17,000 charged particles!

x3 increase with respect to RHIC

ALICE, arXiv:1304.0347

Energy density: Bjorken's formula

- To evaluate the energy density reached in the collision:

$$\varepsilon = \frac{E}{V} = \frac{1}{Sc\tau_0} \frac{dE_T}{dy}\bigg|_{y=0}$$

S = transverse dimension of nucleus
τ_0 = "formation time" $\sim 1\ \mathrm{fm}/c$

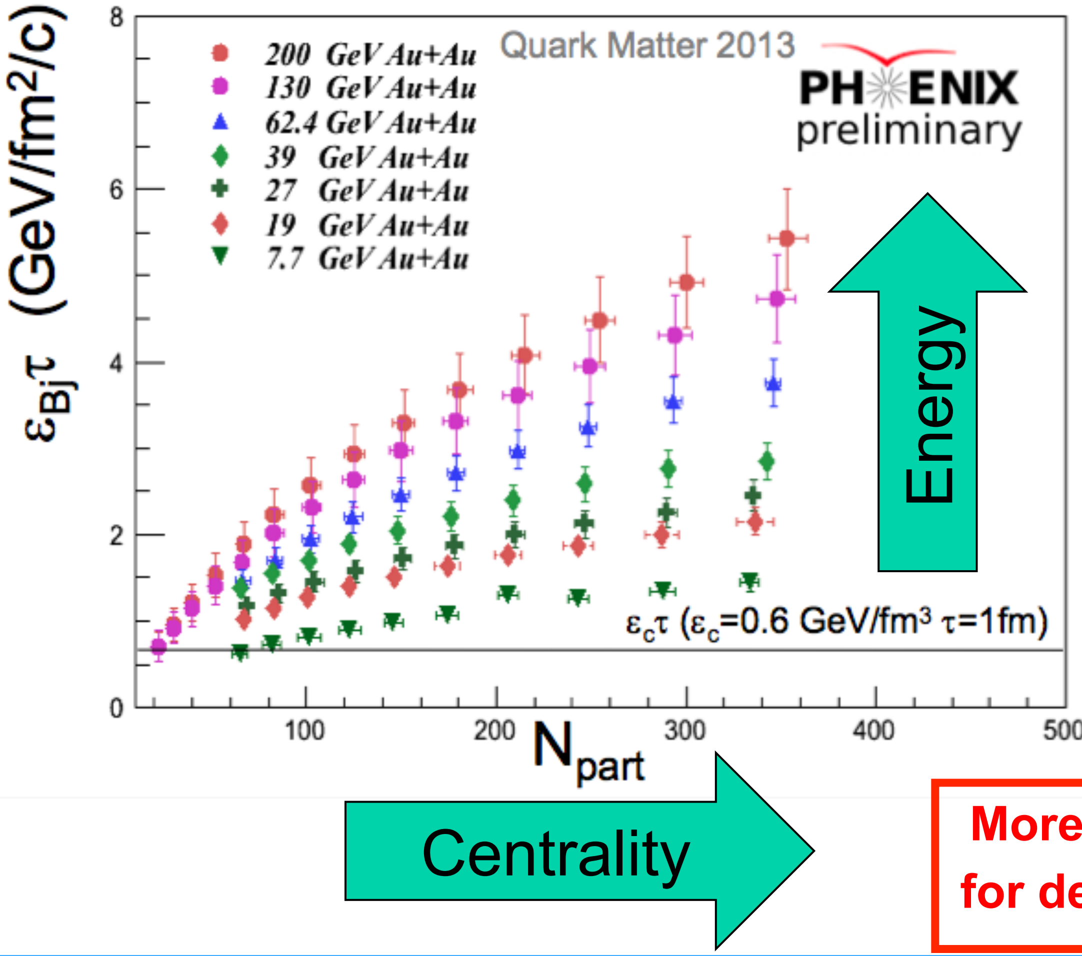
- Initial time τ_0 normally taken to be ~ 1 fm/c
  - i.e. equal to the "formation time": the time it takes for the energy initially stored in the field to materialize into particles
- Transverse dimension: $S \approx 160\ \mathrm{fm}^2 \qquad (R_A \approx 1.2 A^{1/3}\ \mathrm{fm})$

Energy density at RHIC energies

- Estimated from measured transverse energy
- As a function of centrality and collision energy

$$\varepsilon\tau_0 = \frac{1}{S}\frac{dE_T}{dy}\bigg|_{y=0}$$

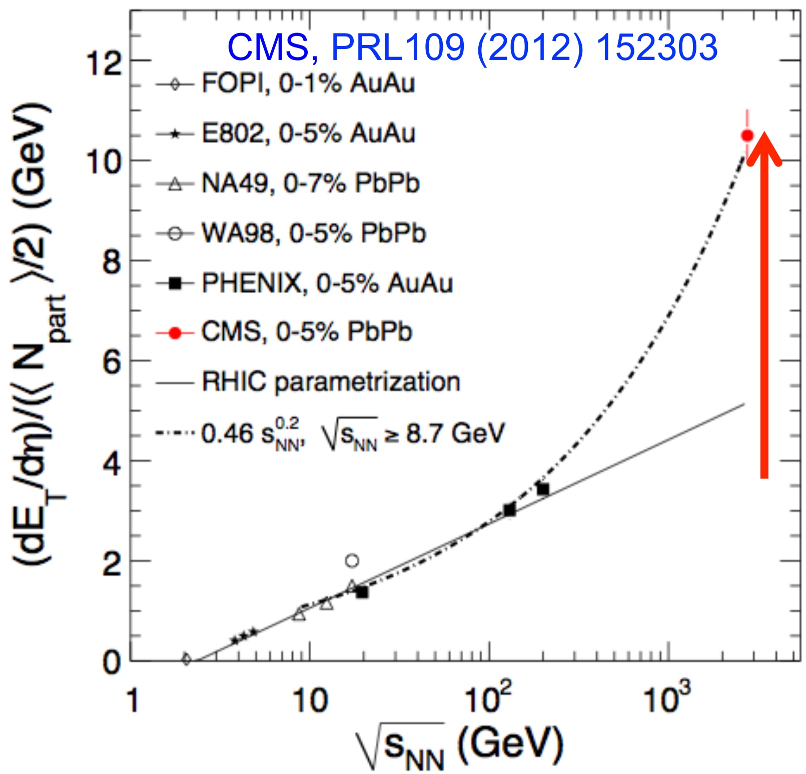
= ε for τ_0=1 fm/c



More than enough for deconfinement!

Energy density at LHC energy

- Transverse energy x3 from RHIC to LHC:

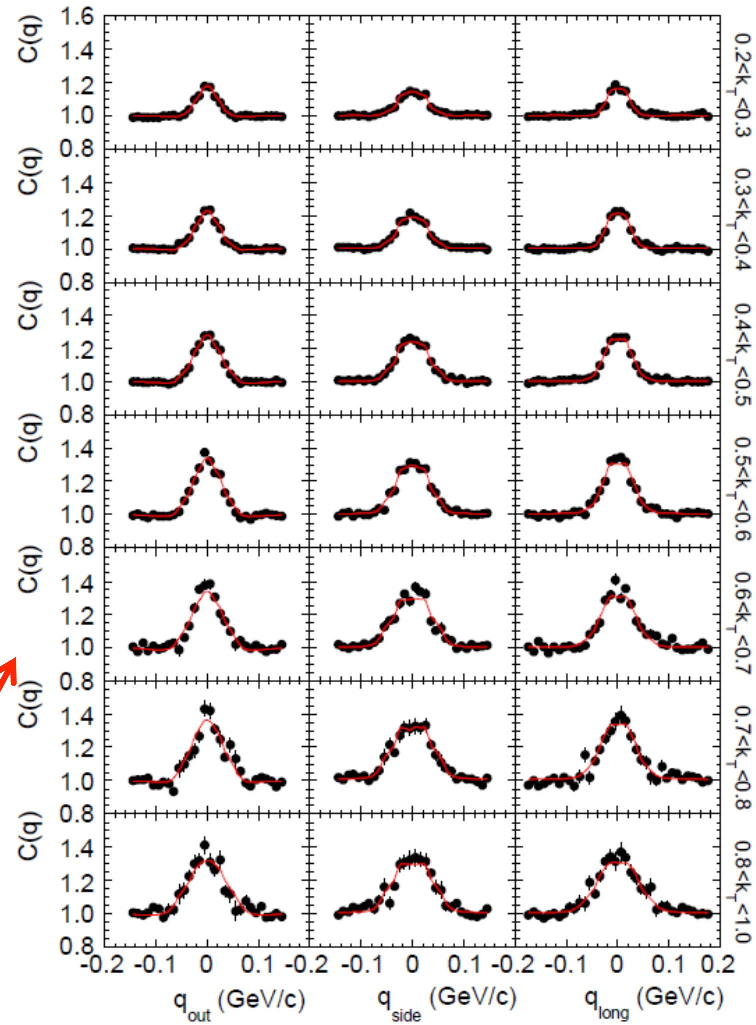


$$\left.\frac{dE_T}{dy}\right|_{y=o} \approx 2 \text{ TeV}$$

$$\varepsilon \sim (2000 / 160) \text{ GeV/fm}^3 \approx 12 \text{ GeV/fm}^3$$

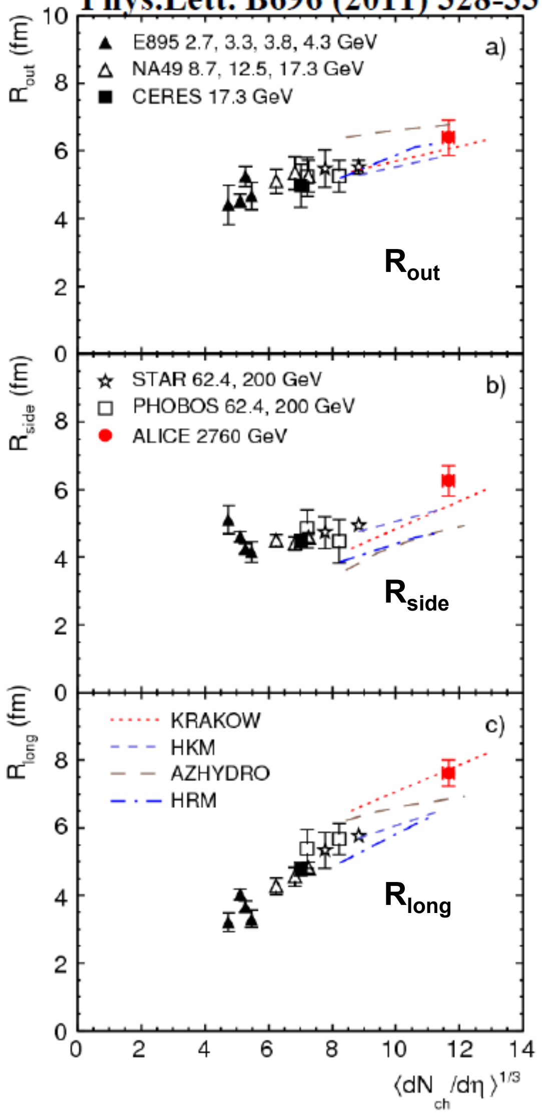
Size of the fireball: Hanbury Brown - Twiss interferometry

- Quantum phenomenon: enhancement of correlation function for identical bosons, e.g. pairs of pions
- From Heisenberg's uncertainty principle:
  - $\Delta p \cdot \Delta x \sim \hbar$ (Planck's constant)
  - → (width of enhancement) · (source size) ~ ħ
  - → extract source size from correlation function
- First used with photons in the 1950s by astronomers Hanbury Brown and Twiss
  - measured size of star Sirius by aiming at it two photomultipliers separated by a few metres
- E.g.: three components of correlation function C(q = momentum difference) for pairs of pions for eight intervals of pair transverse momentum (k_T)



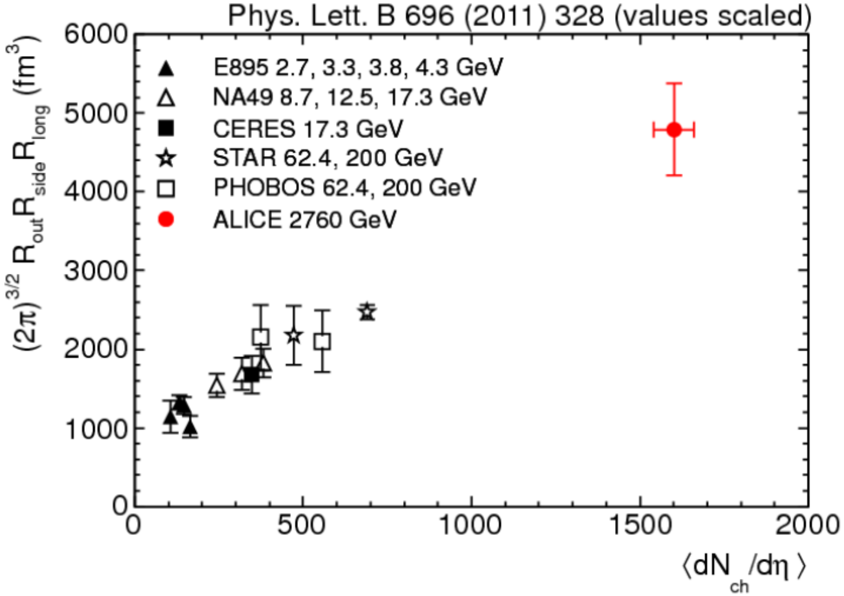
Size of the fireball: Hanbury Brown - Twiss interferometry

Phys.Lett. B696 (2011) 328-337



From RHIC to LHC:

- increase of size in the 3 dimensions
  - out, long, and side
- "homogeneity" volume ~ 5000 fm^3 ~ x 2



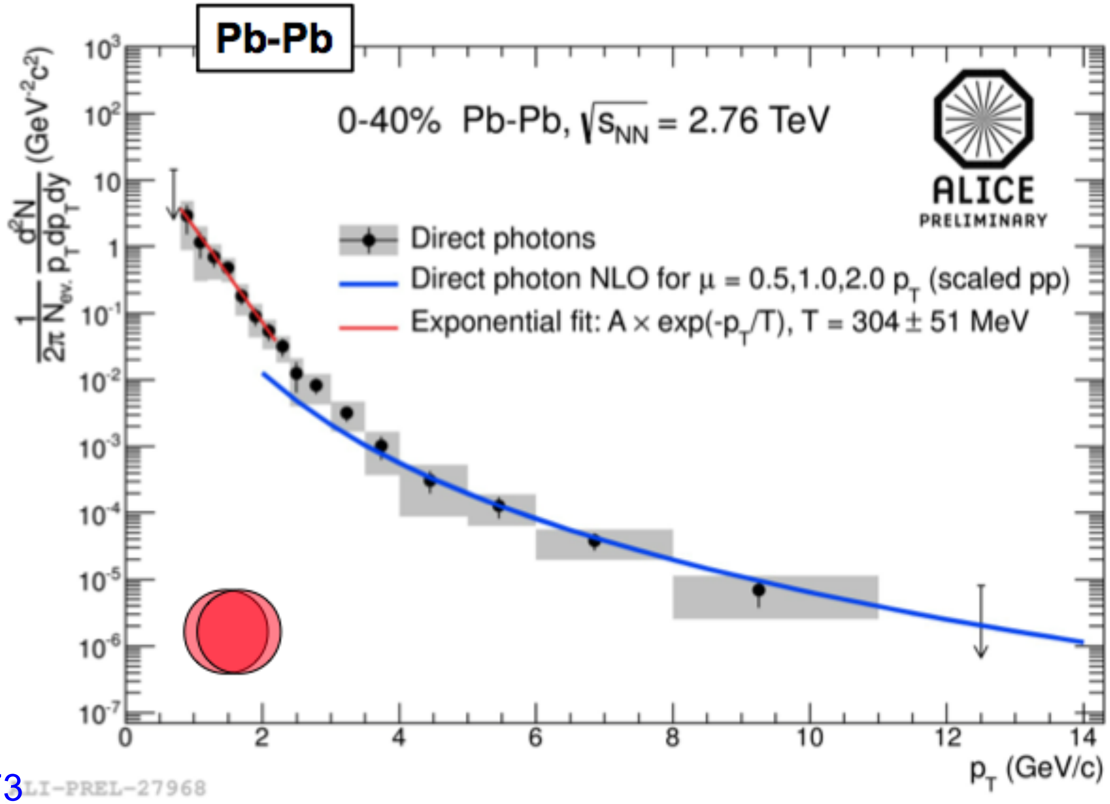
- for comparison: R_{Pb} ~ 7 fm → V ~ 1500 fm^3

→ **substantial expansion!**

Temperature from Photon spectrum

- Prompt γ = Inclusive γ – γ from π^0 decays
  - Direct photons from QCD processes: power law spectrum – dominant at high p_T
  - Thermal photons, emitted by the hot system (analogy with black body radiation): exponential spectrum – dominant at low p_T
    - From inverse slope:

T = 304 ± 51 MeV
~ 2 T_c
~ 1.4 T_{RHIC}



M. Wilde (ALICE), NPA904-905 2013 (2013) 573

Strangeness enhancement

The first predicted signature of the QGP (1982)

[the second is the J/ψ suppression (1986), discussed in the third lecture]

Historic QGP signature

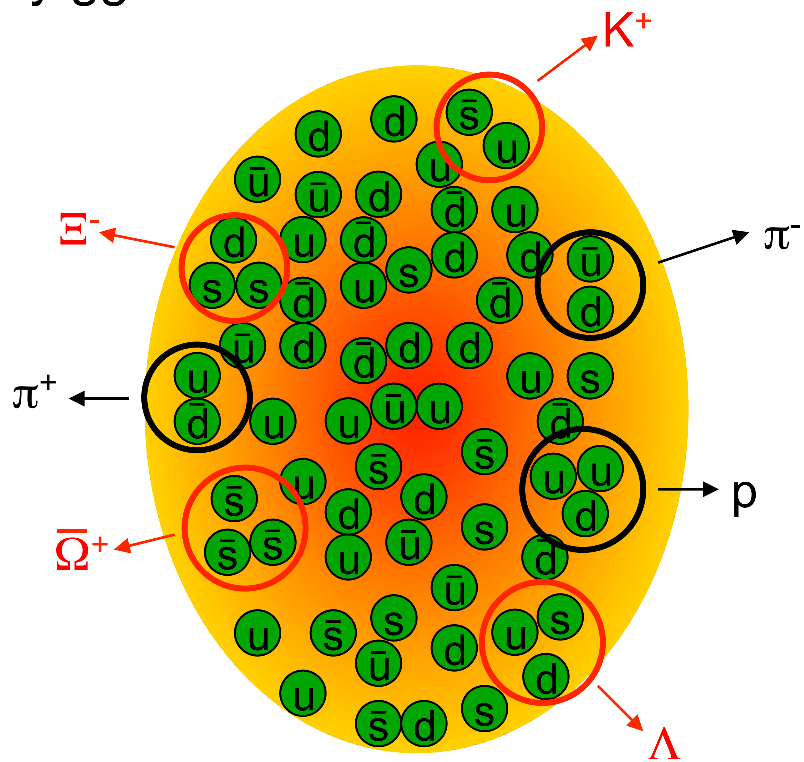
- **Restoration of χ symmetry → increased production of s**
  - mass of strange quark in QGP expected to go back to current value
    - $m_s \sim 150$ MeV $\sim T_c$
  - → copious production of $s\bar{s}$ pairs, mostly by gg fusion

[Rafelski: PR 88 (1982) 331]

[Rafelski-Müller: PRL 48 (1982) 1066]

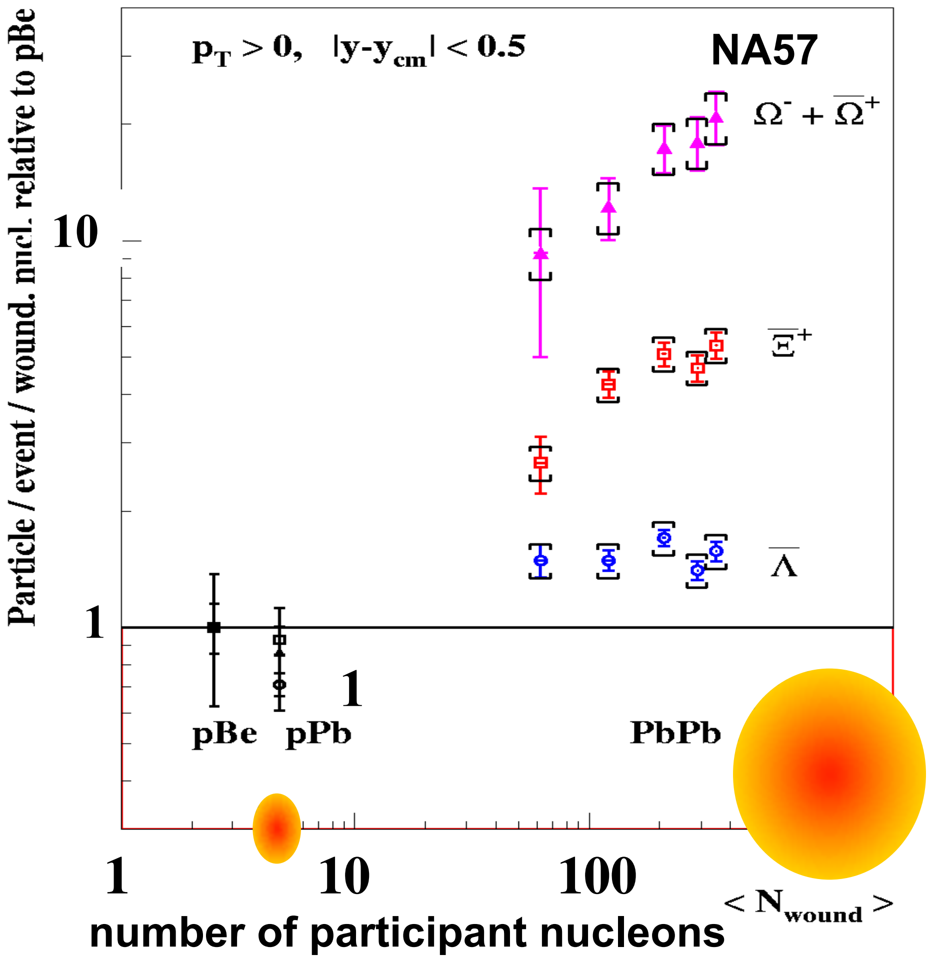
- **Deconfinement → stronger effect for multi-strange baryons**
  - can be built recombining s quarks
  - → strangeness enhancement increasing with strangeness content

[Koch, Müller & Rafelski: PR 142 (1986) 167]



Strangeness enhancement at the SPS

- Enhancement in Pb-Pb relative to p-Be (WA97/NA57)



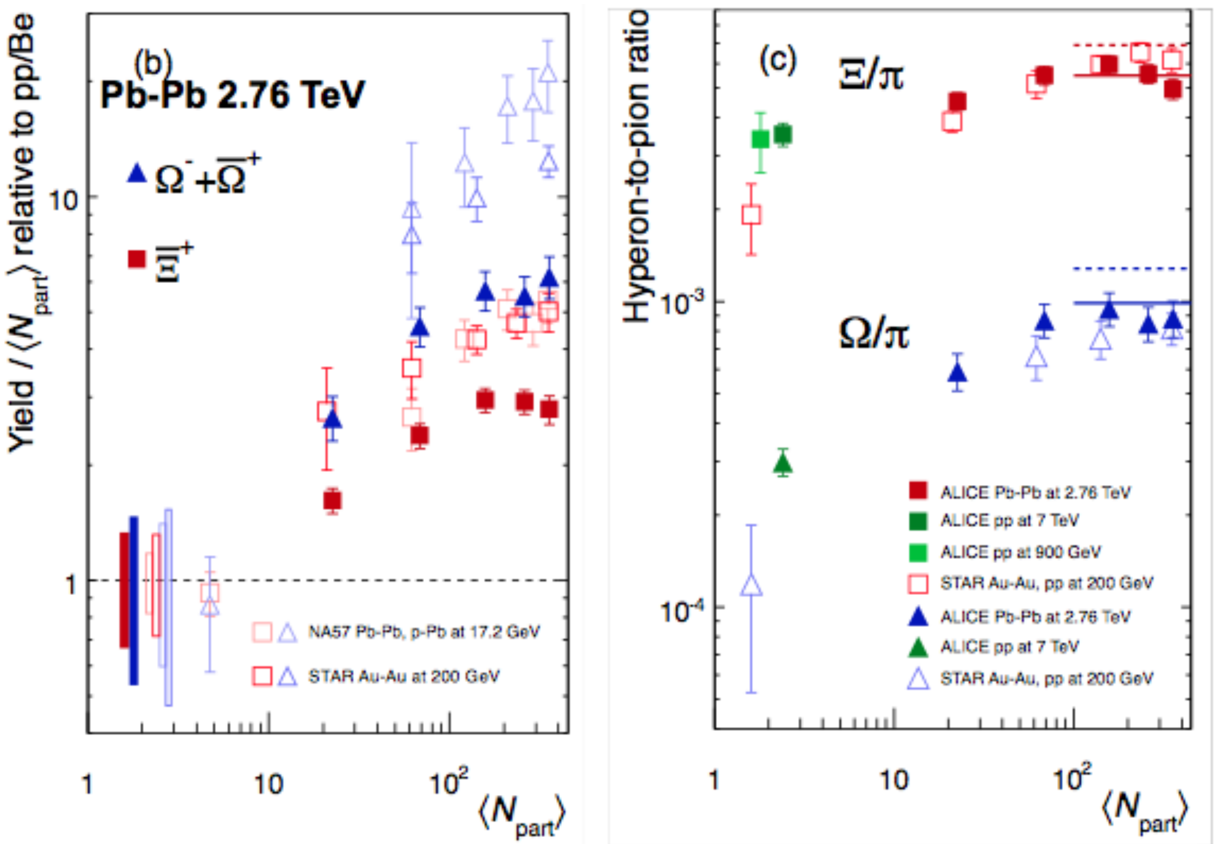
Enhancement is larger for particles of higher strangeness content (QGP prediction!)
up to a factor ~ 20 for Ω

No model without QGP has reproduced these observations

First unambiguous indication for QGP formation in these collisions

NA57, JPG 32, 427 (2006), JPG 37, 045105 (2010)

Strangeness: SPS, RHIC, LHC



- Enhancement relative to pp also there at RHIC and LHC
  - ➢ decreases with increasing √s: E(17 GeV) > E(200 GeV) > E(2.76 TeV)
  - → strange/non-strange increases with √s in pp reference

→ Suggests hadron formation by parton recombination from a strangeness-rich system

STAR, PRC 77, 044908 (2008)
ALICE, arXiv:1307.5543

End of Part I