Physics of ultrarelativistic heavy-ion collisions

Jean-Philippe Lansberg
IPNO, Paris-Sud U.

Taller de Altas Energías 2015, Benasque, Sep 20 - Oct 02, 2015

1st Lecture: September 28, 2015

USEFUL REFERENCES:

- *Ultrarelativistic Heavy-Ion Collisions* by Ramona Vogt (Elsevier)
- *Introduction to Relativisitic Heavy Ion Collisions* by Lazlo Csernai (pdf freely available online)
  www.csernai.no/Csernai-textbook.pdf
- *Relativistic heavy-ion physics: three lectures* by L. McLerran
  cds.cern.ch/record/1009274/files/p75.pdf
- *Global Properties of Nucleus-Nucleus Collisions* by M. Kliemant *et al.*
  (Lect.Notes Phys. 785 (2010) 23-103) http://arxiv.org/pdf/0809.2482.pdf

USEFUL SLIDES FROM TALKS/LECTURES:

(in particular for me to prepare these lectures)

- David d'Enterria (CERN): webpage dde.web.cern.ch/dde
- Anton Andronic (GSI):
  webpage http://web-docs.gsi.de/~andronic/physics/act.html
- K. Reygers / J. Stachel (Heidelberg) webpage:
  http://www.physi.uni-heidelberg.de/~reygers/lectures/2011/qgp/qgp_lecture_ss2011.html
- Elena Ferreiro (USC)
- ...

Part I

(Ultra)(Relativistic)HIC:what for ?

Preface: why study (ultra relativistic) heavy-ion collisions

- STARTING POINT: QCD is the theory of strong interaction

Preface: why study (ultra relativistic) heavy-ion collisions

- STARTING POINT: QCD is the theory of strong interaction
- FUNDAMENTAL QUESTION: How do collective and macroscopic properties of matter emerge from the interactions of elementary particles ?

Preface: why study (ultra relativistic) heavy-ion collisions

- STARTING POINT: QCD is the theory of strong interaction
- FUNDAMENTAL QUESTION: How do collective and macroscopic properties of matter emerge from the interactions of elementary particles ?
- HEAVY-ION PHYSICS addresses this question in the regime of the highest temperature and densities accessible in the laboratories

Preface: why study (ultra relativistic) heavy-ion collisions

- STARTING POINT: QCD is the theory of strong interaction
- FUNDAMENTAL QUESTION: How do collective and macroscopic properties of matter emerge from the interactions of elementary particles ?
- HEAVY-ION PHYSICS addresses this question in the regime of the highest temperature and densities accessible in the laboratories
- HOW ? By colliding nucleus (or ions) and looking for specific signals

Example: looking for the quark-gluon plasma, *i.e.* a new state of matter, using specific probes

Part II

Confinement and Deconfinement in QCD

Confinement

Confinement

- QCD is a non-abelian gauge theory (Yang-Mills theory)
- The gauge bosons self interact

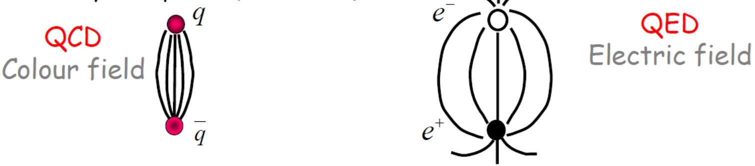
Confinement

- QCD is a non-abelian gauge theory (Yang-Mills theory)
- The gauge bosons self interact
- Exhibit asymptotic freedom at short distances
  (remember the sign of the coefficient of the log in α_s because of gluon loops)
- Exhibit confinement, which can also be attributed to gluon self coupling

Confinement

- QCD is a non-abelian gauge theory (Yang-Mills theory)
- The gauge bosons self interact
- Exhibit asymptotic freedom at short distances
  (remember the sign of the coefficient of the log in α_S because of gluon loops)
- Exhibit confinement, which can also be attributed to gluon self coupling

Qualitatively, compare QCD with QED:



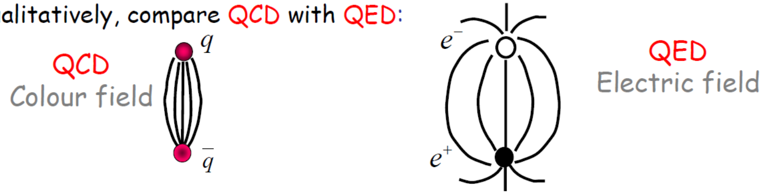
Self interactions of the gluons squeezes the lines of force into a narrow tube or STRING. The string has a "tension" and as the quarks separate the string stores potential energy.

Energy stored per unit length in field ~ constant $V(r) \propto r$

Confinement

- QCD is a non-abelian gauge theory (Yang-Mills theory)
- The gauge bosons self interact
- Exhibit asymptotic freedom at short distances
  (remember the sign of the coefficient of the log in α_S because of gluon loops)
- Exhibit confinement, which can also be attributed to gluon self coupling

Qualitatively, compare QCD with QED:



Self interactions of the gluons squeezes the lines of force into a narrow tube or STRING. The string has a "tension" and as the quarks separate the string stores potential energy.

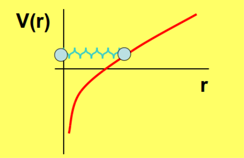
Energy stored per unit length in field ~ constant $V(r) \propto r$

- If $V(r) > 2m_\pi$, 2 π's pop up from the vacuum and the $q\bar{q}$

Deconfining the quark and gluons

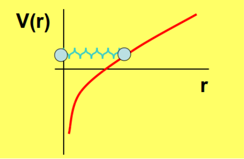
Deconfining the quark and gluons

- The potential between a static $q - \bar{q}$ pair grows linearly with r at large distances



Deconfining the quark and gluons

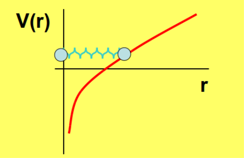
- The potential between a static $q - \bar{q}$ pair grows linearly with r at large distances



- This is the expected behaviour at normal conditions:
  $T = 0$ and $\rho \simeq 0.17$ nucleons /fm^3

Deconfining the quark and gluons

- The potential between a static $q - \bar{q}$ pair grows linearly with r at large distances



- This is the expected behaviour at normal conditions:
  $T = 0$ and $\rho \simeq 0.17$ nucleons /fm^3
- Is there a regime where the quarks and the gluons can be free ?

The phase diagram of strongly interacting matter

- At normal conditions, the quark and gluon are confined within hadrons
- whereas they behave as if they were free over very short distances

The phase diagram of strongly interacting matter

- At normal conditions, the quark and gluon are confined within hadrons
- whereas they behave as if they were free over very short distances
- At high T or ρ, it was postulated that they could really be free, *i.e.* deconfined

The phase diagram of strongly interacting matter

- At normal conditions, the quark and gluon are confined within hadrons
- whereas they behave as if they were free over very short distances
- At high T or ρ, it was postulated that they could really be free, *i.e.* deconfined

We suggest [...] the existence of a different phase of the vacuum in which quarks are not confined.”

N. Cabibbo, G. Parisi, PLB 59 (1975) 67

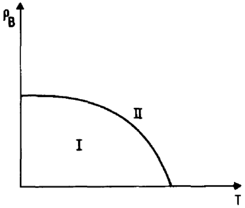


Fig. 1. Schematic phase diagram of hadronic matter. ρ_B is the density of baryonic number. Quarks are confined in phase I and unconfined in phase II.

When the asymptotic freedom leads to deconfinement

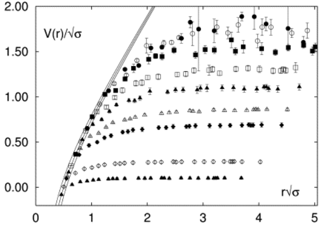
- Increasing the density [decreasing the distance] or increasing the temperature [increasing the momenta] may bring the matter into a regime where asymptotic freedom would be naturally at work

When the asymptotic freedom leads to deconfinement

- Increasing the density [decreasing the distance] or increasing the temperature [increasing the momenta] may bring the matter into a regime where asymptotic freedom would be naturally at work
- This could result into a screening of the long-range confining potential

When the asymptotic freedom leads to deconfinement

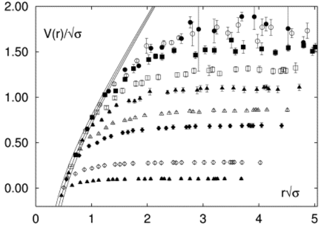
- Increasing the density [decreasing the distance] or increasing the temperature [increasing the momenta] may bring the matter into a regime where asymptotic freedom would be naturally at work
- This could result into a screening of the long-range confining potential
- Numerical simulations from the QCD lagrangian (Lattice QCD) show this at high T and high ρ



F. Karsch *et al.*, PLB 605 (2001) 579

When the asymptotic freedom leads to deconfinement

- Increasing the density [decreasing the distance] or increasing the temperature [increasing the momenta] may bring the matter into a regime where asymptotic freedom would be naturally at work
- This could result into a screening of the long-range confining potential
- Numerical simulations from the QCD lagrangian (Lattice QCD) show this at high T and high ρ



F. Karsch *et al.*, PLB 605 (2001) 579

- When $T \nearrow$, the long range potential decreases and becomes flat

T/T_c =0.58, 0.66, 0.74, 0.84, 0.9, 0.94, 0.97, 1.06 et 1.15 (top to bottom)

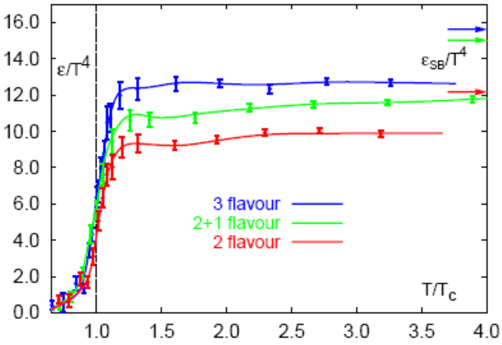
Equation of state: ideal case vs lattice QCD

Equation of state: ideal case vs lattice QCD

- Lattice QCD results hint at a phase transition near $T_c \sim 170$ MeV

Equation of state: ideal case vs lattice QCD

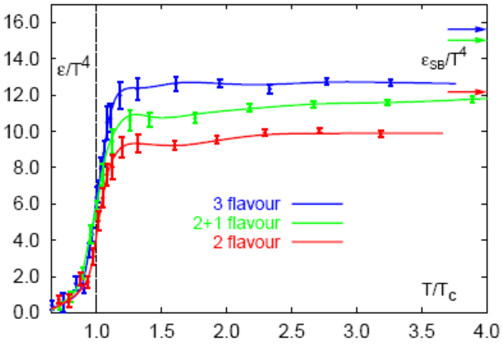
- Lattice QCD results hint at a phase transition near $T_c \sim 170$ MeV



Equation of state: ideal case vs lattice QCD

- Lattice QCD results hint at a phase transition near $T_c \sim 170$ MeV
- The ideal-case values a priori not reached:

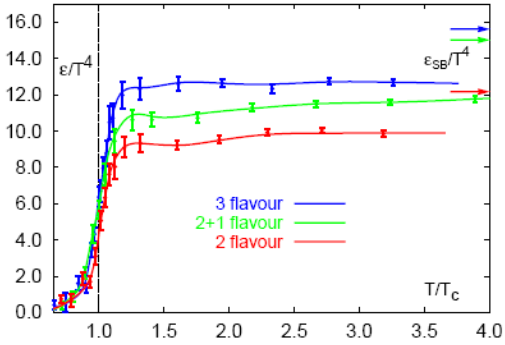
  the coupling remains “strong”



Equation of state: ideal case vs lattice QCD

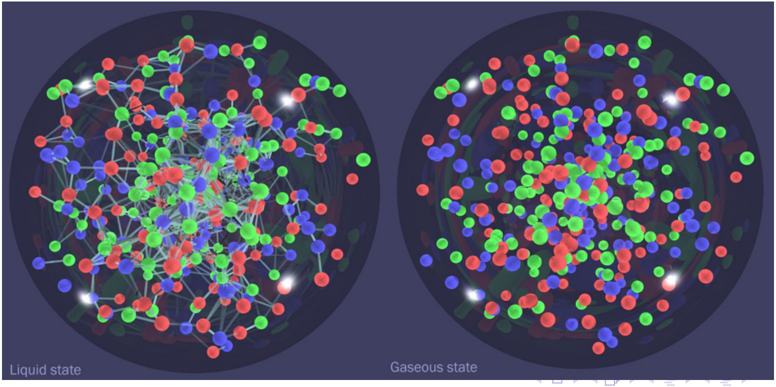
- Lattice QCD results hint at a phase transition near $T_c \sim 170$ MeV
- The ideal-case values a priori not reached:

  the coupling remains "strong"
- The GQP is expected to behave like a liquid rather than a gas



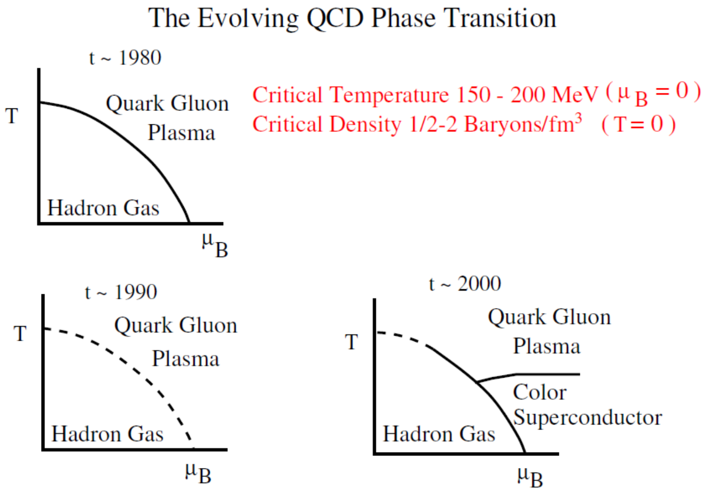
Equation of state: ideal case vs lattice QCD

- Lattice QCD results hint at a phase transition near $T_c \sim 170$ MeV
- The ideal-case values a priori not reached:
  the coupling remains "strong"
- The GQP is expected to behave like a liquid rather than a gas



Rapidly evolving field

Phase diagram as function of (scientific) time



Cartoon by L. McLerran

[Reminder: Quarks: 1964 ; Scaling: 1967 ; Asymptotic Freedom: 1973; Charm quark: 1974; ...]

Part III

Heavy-Ion Collisions: the quest for a phase transition

Melting the matter

Melting the matter

- If quarks and gluons effectively become free at high T and/or ρ, appearance of new d.o.f.

Melting the matter

- If quarks and gluons effectively become free at high T and/or ρ, appearance of new d.o.f.
- One expects a phase transition

Melting the matter

- If quarks and gluons effectively become free at high T and/or ρ, appearance of new d.o.f.
- One expects a phase transition
- Where can this happen ?:

Melting the matter

- If quarks and gluons effectively become free at high T and/or ρ, appearance of new d.o.f.
- One expects a phase transition
- Where can this happen ?:
  - in the Universe 10^{-5} second after the Big-Bang

Melting the matter

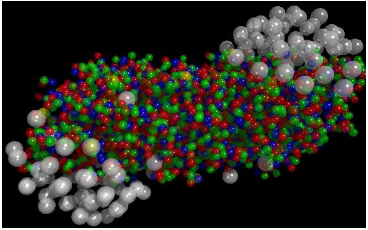
- If quarks and gluons effectively become free at high T and/or ρ, appearance of new d.o.f.
- One expects a phase transition
- Where can this happen ?:
  - in the Universe 10^{-5} second after the Big-Bang
  - in the core of neutron stars

Melting the matter

- If quarks and gluons effectively become free at high T and/or ρ, appearance of new d.o.f.
- One expects a phase transition
- Where can this happen ?:
  - in the Universe 10^{-5} second after the Big-Bang
  - in the core of neutron stars
  - in ultra-relativistic nucleus-nucleus collisions

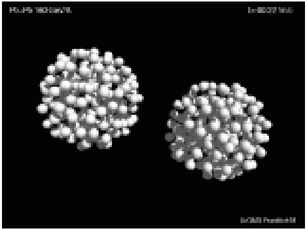
Melting the matter

- If quarks and gluons effectively become free at high T and/or ρ, appearance of new d.o.f.
- One expects a phase transition
- Where can this happen ?:
  - in the Universe 10^{-5} second after the Big-Bang
  - in the core of neutron stars
  - in ultra-relativistic nucleus-nucleus collisions



Melting the matter

- If quarks and gluons effectively become free at high T and/or ρ, appearance of new d.o.f.
- One expects a phase transition
- Where can this happen ?:
  - in the Universe 10^{-5} second after the Big-Bang
  - in the core of neutron stars
  - in ultra-relativistic nucleus-nucleus collisions



Conditions reached in a nucleus-nucleus collision

Conditions reached in a nucleus-nucleus collision

- Temperature: T= 100-1000 MeV

(1 MeV = 10 billion degrees)

[up to a million times the temperature at the center of the sun]

Conditions reached in a nucleus-nucleus collision

- Temperature: T= 100-1000 MeV

  (1 MeV = 10 billion degrees)

  [up to a million times the temperature at the center of the sun]

- Pressure: $P = 100 - 300$ MeV/fm^3

  (1 fm = 10^{-15}m,1MeV/fm$^3 = 10^{28}$atm)

  [at center of earth : 3.6 millions atm.]

Conditions reached in a nucleus-nucleus collision

- Temperature: T= 100-1000 MeV

(1 MeV = 10 billion degrees)

[up to a million times the temperature at the center of the sun]

- Pressure: $P = 100 - 300$ MeV/fm^3

(1 fm = 10^{-15}m,1MeV/fm$^3 = 10^{28}$atm)

[at center of earth : 3.6 millions atm.]

- Density: $\rho = 1 - 10\rho_0$ the density of a gold nucleus

$(\rho_0 = 3\,10^{24}$g/cm$^3)$

(density of a gold atom : 19 g/cm^3)

Conditions reached in a nucleus-nucleus collision

- Temperature: T= 100-1000 MeV

  (1 MeV = 10 billion degrees)

  [up to a million times the temperature at the center of the sun]
- Pressure: $P = 100 - 300$ MeV/fm^3

  (1 fm = 10^{-15}m,1MeV/fm$^3 = 10^{28}$atm)

  [at center of earth : 3.6 millions atm.]
- Density: $\rho = 1 - 10\rho_0$ the density of a gold nucleus

  ($\rho_0 = 3\,10^{24}$g/cm^3)

  (density of a gold atom : 19 g/cm^3)
- Volume: nearly 2000 fm^3

  nucleus radius: $r = 1.2A^{1/3}$ fm; lead ($A = 208$) $\sim$ 7.1 fm

  ($4/3\pi r^3 \leftrightarrow$ 1500 fm^3)

Conditions reached in a nucleus-nucleus collision

- Temperature: T= 100-1000 MeV

  (1 MeV = 10 billion degrees)

  [up to a million times the temperature at the center of the sun]

- Pressure: $P = 100 - 300$ MeV/fm^3

  (1 fm = 10^{-15}m,1MeV/fm^3 $= 10^{28}$atm)

  [at center of earth : 3.6 millions atm.]

- Density: $\rho = 1 - 10\rho_0$ the density of a gold nucleus

  ($\rho_0 = 3\,10^{24}$g/cm^3)

  (density of a gold atom : 19 g/cm^3)

- Volume: nearly 2000 fm^3

  nucleus radius: $r = 1.2A^{1/3}$ fm; lead ($A = 208$) ~ 7.1 fm

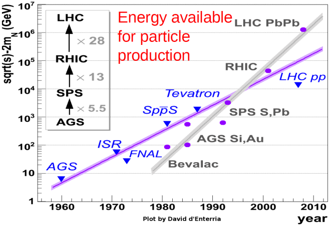
  ($4/3\pi r^3 \leftrightarrow 1500$ fm^3)

- Duration: about 10 fm/c (*i.e.* $3\,10^{-23}s$)

Energy density and center-of-mass energy

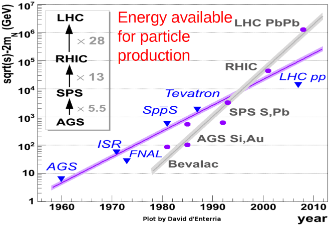
Energy density and center-of-mass energy

Stronger energy rise for HIC lately (first colliders, see next slides)

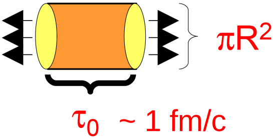


Energy density and center-of-mass energy

Stronger energy rise for HIC lately (first colliders, see next slides)

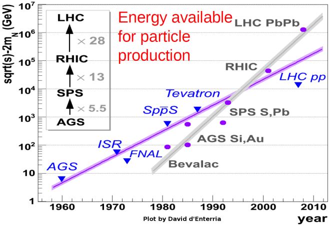


Energy density computed with the "Bjorken estimate": $\varepsilon_{Bj} = \frac{dE_T}{dy}\frac{1}{\tau_0 \pi R^2}$

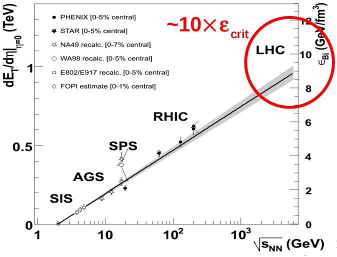


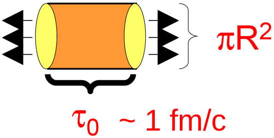
Energy density and center-of-mass energy

Stronger energy rise for HIC lately (first colliders, see next slides)



Energy density computed with the "Bjorken estimate": $\varepsilon_{Bj} = \frac{dE_T}{dy}\frac{1}{\tau_0 \pi R^2}$





Heavy-ion accelerators

FIXED-TARGET EXPERIMENTS :

$$\sqrt{s_{NN}} = \sqrt{2 m_N E_N}$$

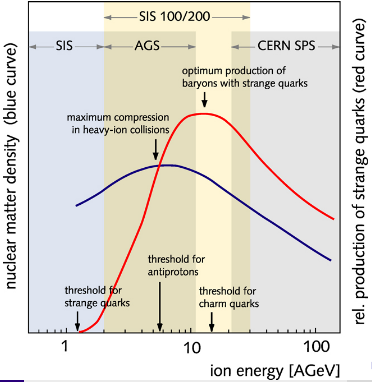
- LBL-Bevalac, Berkeley (1980-1990): $E_N = 1.15$ GeV $\rightarrow \sqrt{s_{NN}} = 2.4$ GeV
- BNL-AGS, Brookhaven (1985-1995): $E_N = 10.5$ GeV $\rightarrow \sqrt{s_{NN}} = 4.8$ GeV
- CERN-SPS, Geneva (1987-2004): $E_N = 157$ GeV $\rightarrow \sqrt{s_{NN}} = 17.3$ GeV
- GSI-SIS, Darmstadt: $E_N = 1.5$ GeV $\rightarrow \sqrt{s_{NN}} = 2.5$ GeV
- GSI-FAIR, Darmstadt (2018+): $E_N = 35$ GeV $\rightarrow \sqrt{s_{NN}} = 8.3$ GeV

Heavy-ion accelerators

FIXED-TARGET EXPERIMENTS :

$$\sqrt{s_{NN}} = \sqrt{2 m_N E_N}$$

- LBL-Bevalac, Berkeley (1980-1990): $E_N = 1.15$ GeV $\rightarrow \sqrt{s_{NN}} = 2.4$ GeV
- BNL-AGS, Brookhaven (1985-1995): $E_N = 10.5$ GeV $\rightarrow \sqrt{s_{NN}} = 4.8$ GeV
- CERN-SPS, Geneva (1987-2004): $E_N = 157$ GeV $\rightarrow \sqrt{s_{NN}} = 17.3$ GeV
- GSI-SIS, Darmstadt: $E_N = 1.5$ GeV $\rightarrow \sqrt{s_{NN}} = 2.5$ GeV
- GSI-FAIR, Darmstadt (2018+): $E_N = 35$ GeV $\rightarrow \sqrt{s_{NN}} = 8.3$ GeV



http://www.gsi.de

Heavy-ion accelerators

COLLIDER EXPERIMENTS : $\sqrt{s_{NN}} = 2E_N$ (in symmetric collisions)

- BNL-RHIC, Brookhaven (2000): $E_N = 100$ GeV $\to \sqrt{s_{NN}} = 200$ GeV
- CERN-LHC, Geneva (2009): $E_N = 2760$ GeV $\to \sqrt{s_{NN}} = 5520$ GeV

[so far “only”, $E_N = 1380$ GeV $\to \sqrt{s_{NN}} = 2760$ GeV]

Heavy-ion accelerators

COLLIDER EXPERIMENTS :

$\sqrt{s_{NN}} = 2E_N$ (in symmetric collisions)

- BNL-RHIC, Brookhaven (2000): $E_N = 100$ GeV $\rightarrow \sqrt{s_{NN}} = 200$ GeV
- CERN-LHC, Geneva (2009): $E_N = 2760$ GeV $\rightarrow \sqrt{s_{NN}} = 5520$ GeV

[so far "only", $E_N = 1380$ GeV $\rightarrow \sqrt{s_{NN}} = 2760$ GeV]

COMPARISONS:

- Pros for colliders: cms energy (1 to nearly 3 orders of magnitude higher)
  [can't do anything against momentum conservation]
- Cons for colliders: collision rate (8000 per sec at the LHC vs. 10^7 per sec at FAIR)
  [can't beat a target density with a (collimated) beam]

Heavy-ion accelerators

COLLIDER EXPERIMENTS : $\sqrt{s_{NN}} = 2E_N$ (in symmetric collisions)

- BNL-RHIC, Brookhaven (2000): $E_N = 100$ GeV $\rightarrow \sqrt{s_{NN}} = 200$ GeV
- CERN-LHC, Geneva (2009): $E_N = 2760$ GeV $\rightarrow \sqrt{s_{NN}} = 5520$ GeV

[so far “only”, $E_N = 1380$ GeV $\rightarrow \sqrt{s_{NN}} = 2760$ GeV]

COMPARISONS:

- Pros for colliders: cms energy (1 to nearly 3 orders of magnitude higher)
  [can’t do anything against momentum conservation]
- Cons for colliders: collision rate (8000 per sec at the LHC vs. 10^7 per sec at FAIR)
  [can’t beat a target density with a (collimated) beam]

REMARK: The LHC in the fixed-target mode : $\sqrt{s_{NN}} = 72$ GeV
$\rightarrow$ energy comparable to RHIC, with extremely high rate

Heavy-ion accelerators

COLLIDER EXPERIMENTS : $\sqrt{s_{NN}} = 2E_N$ (in symmetric collisions)

- BNL-RHIC, Brookhaven (2000): $E_N = 100$ GeV $\rightarrow \sqrt{s_{NN}} = 200$ GeV
- CERN-LHC, Geneva (2009): $E_N = 2760$ GeV $\rightarrow \sqrt{s_{NN}} = 5520$ GeV

[so far "only", $E_N = 1380$ GeV $\rightarrow \sqrt{s_{NN}} = 2760$ GeV]

COMPARISONS:

- Pros for colliders: cms energy (1 to nearly 3 orders of magnitude higher)
  [can't do anything against momentum conservation]
- Cons for colliders: collision rate (8000 per sec at the LHC vs. 10^7 per sec at FAIR)
  [can't beat a target density with a (collimated) beam]

REMARK: The LHC in the fixed-target mode : $\sqrt{s_{NN}} = 72$ GeV
$\rightarrow$ energy comparable to RHIC, with extremely high rate

Strong motivation for A Fixed Target ExpeRiment @ LHC
(AFTER@LHC)

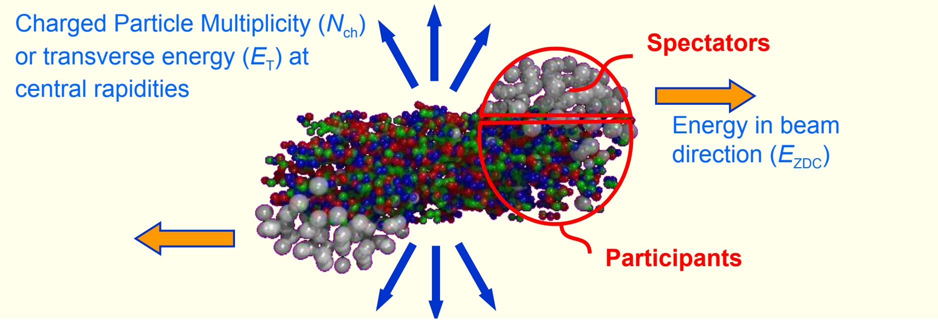
Part IV

Tuning an Heavy-Ion Collision: the centrality

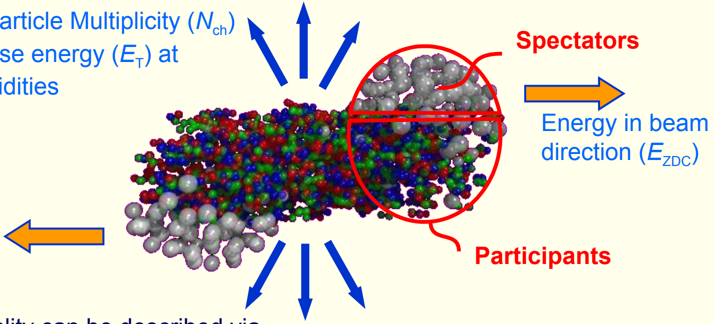
Smooth phase transition $\leftrightarrow$ complications

- We must study properties of the medium in detail
  without a smoking-gun phase-transition signature
- Most of observables will show
  a smooth dependence on energy
- Apart from changing the beam energy and colliding species,
  one can select (bias) the geometry of the collisions
- Preferred way of varying the energy density
  ($\leftrightarrow$ centrality, impact parameter b)

Two important definitions: N_{part} and N_{coll}



Two important definitions: N_{part} and N_{coll}

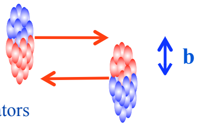


- Centrality can be described via
  - N_{coll}: number of inelastic nucleon-nucleon collisions
  - N_{part}: number of nucleons which underwent at least one inelastic nucleon-nucleon collisions
- This simplifies the comparison between theory and experiment and between different experiments
- Typically not directly measured but determined from Glauber calculations

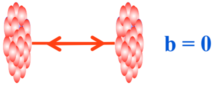
Slide borrowed from K. Reygers

Pratical example with ALICE (2011 PbPb data)

semi-central collision



central collision



	$N_{part} = 2$	$N_{coll} = 1$
	$N_{part} = 5$	$N_{coll} = 6$
Pb-Pb cent.	$N_{part} = 360$	$N_{coll} = 1500$
p-Pb cent.	$N_{part} = 16$	$N_{coll} = 15$

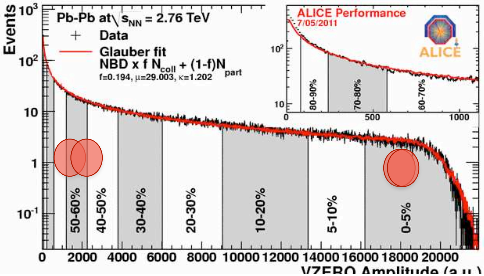
Spectators
Participants
b impact parameter

→ Glauber model used to determine the geometry of the collision

Centrality determination

Multiplicity measurements with forward or central detectors

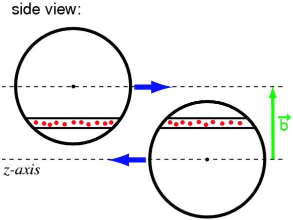
Relate the measured multiplicity in A-A collisions to N_{part} and N_{coll}



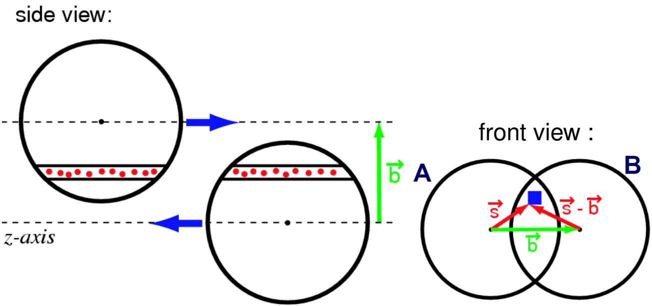
Slide borrowed from C. Hadjidakis (HIF@CERN, June 2013)

Glauber model for *pA* and *AA* collisions

- Input:
  - density profile of the nucleus: Woods-Saxon
  - inelastic nucleon-nucleon cross section (which is a function of the collisions energy: $\sigma_{NN}^{inel.}(\sqrt{s})$)
- Nucleons travel on straight trajectories along the beam axis (after a nucleon-nucleon collisions)
- Nucleon-nucleon cross section is independent of the number of collisions a nucleon underwent before [neglect the possible decrease of the inelastic nucleon-nucleon cross section for the consecutive scattering]

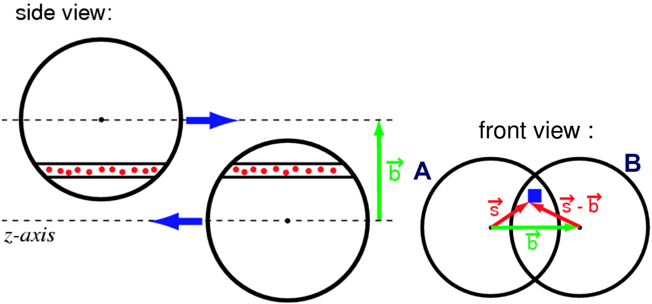


Number of Nucleon-Nucleon Collisions N_{coll}



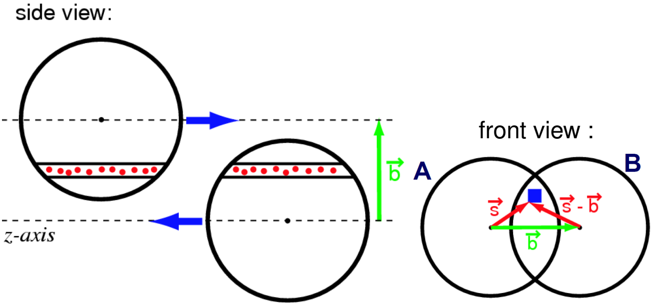
- Nuclear thickness : integral of the density on z as function of the distance $\vec{s}$ from the nucleus center: $\int \rho(\vec{s}, z)dz = T_A(\vec{s})$

Number of Nucleon-Nucleon Collisions N_{coll}



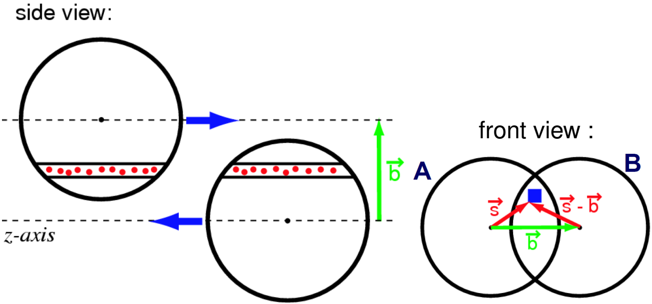
- Nuclear thickness : integral of the density on z as function of the distance $\vec{s}$ from the nucleus center: $\int \rho(\vec{s}, z)dz = T_A(\vec{s})$
- A: density integrated over the volume: $A = \int T_A(\vec{s})d^2s$

Number of Nucleon-Nucleon Collisions N_{coll}



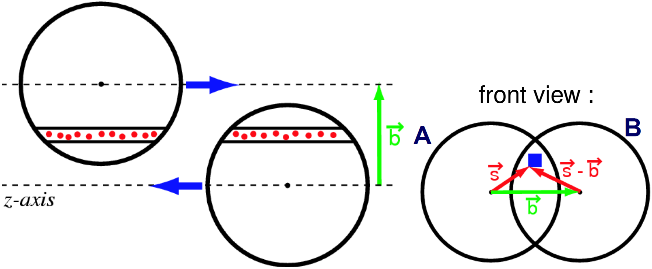
- Nuclear thickness : integral of the density on z as function of the distance $\vec{s}$ from the nucleus center: $\int \rho(\vec{s}, z) dz = T_A(\vec{s})$
- A: density integrated over the volume: $A = \int T_A(\vec{s}) d^2 s$
- Collision nucleon “luminosity” :$dT_{AB}(\vec{s}) = T_A(\vec{s}) T_A(\vec{s} - \vec{b}) d^2 s$

Number of Nucleon-Nucleon Collisions N_{coll}



- Nuclear thickness : integral of the density on z as function of the distance $\vec{s}$ from the nucleus center: $\int \rho(\vec{s}, z)dz = T_A(\vec{s})$
- A: density integrated over the volume: $A = \int T_A(\vec{s})d^2s$
- Collision nucleon “luminosity” :$dT_{AB}(\vec{s}) = T_A(\vec{s})T_A(\vec{s} - \vec{b})d^2s$
- Nucleon overlap function as function of b: $T_{AB}(b) = \int T_A(\vec{s})T_A(\vec{s} - \vec{b})d^2s$

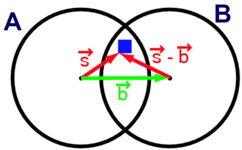
Number of Nucleon-Nucleon Collisions N_{coll}



- Nuclear thickness : integral of the density on z as function of the distance $\vec{s}$ from the nucleus center: $\int \rho(\vec{s}, z) dz = T_A(\vec{s})$
- A: density integrated over the volume: $A = \int T_A(\vec{s}) d^2 s$
- Collision nucleon "luminosity" :$dT_{AB}(\vec{s}) = T_A(\vec{s}) T_A(\vec{s} - \vec{b}) d^2 s$
- Nucleon overlap function as function of b: $T_{AB}(b) = \int T_A(\vec{s}) T_A(\vec{s} - \vec{b}) d^2 s$
- Average number of collisions: overlap times the cross section

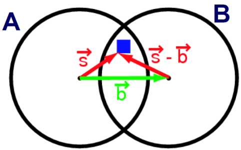
$$\langle N_{coll}(b) \rangle = T_{AB}(b) \times \sigma_{NN}^{inel.}$$

Number of participants N_{part}



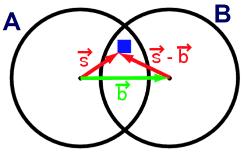
- Proba that a given nucleon from *A* scatters with another from B: $\mathcal{P} = \frac{T_B(\vec{s})}{B} \times \sigma_{NN}^{inel}$.

Number of participants N_{part}



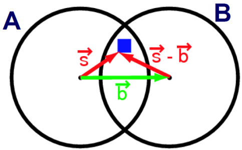
- Proba that a given nucleon from A scatters with another from B: $\mathcal{P} = \frac{T_B(\vec{s})}{B} \times \sigma_{NN}^{inel}$.
- Proba that a given nucleon from A scatters with none from B: $(1 - \mathcal{P})^B$

Number of participants N_{part}



- Proba that a given nucleon from A scatters with another from B: $\mathcal{P} = \frac{T_B(\vec{s})}{B} \times \sigma_{NN}^{inel}$.
- Proba that a given nucleon from A scatters with none from B: $(1 - \mathcal{P})^B$
- Proba that a given nucleon from A scatters with at least one from B:$1 - (1 - \mathcal{P})^B$

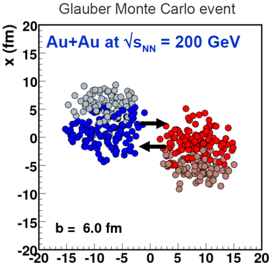
Number of participants N_{part}



- Proba that a given nucleon from A scatters with another from B: $\mathcal{P} = \frac{T_B(\vec{s})}{B} \times \sigma_{NN}^{inel.}$
- Proba that a given nucleon from A scatters with none from B: $(1 - \mathcal{P})^B$
- Proba that a given nucleon from A scatters with at least one from B:$1 - (1 - \mathcal{P})^B$
- Number of participant in A: $\langle N_{part}^A(b)\rangle = A \int \frac{T_A(\vec{s})}{A}(1 - (1 - \frac{T_B(\vec{s})}{B} \times \sigma_{NN}^{inel.})^B) d^2 s$
- Total mean number of participant: $\langle N_{part}^A(b)\rangle + \langle N_{part}^B(b)\rangle$

Glauber Monte Carlo (probabilistic Glauber approach)

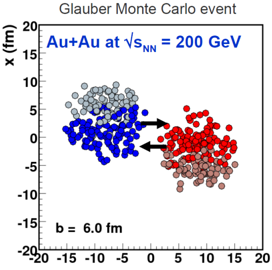
- As illustrated by the ALICE example, the experiments use Glauber MC to determine N_{part} vs N_{coll}



From K. Reygers

Glauber Monte Carlo (probabilistic Glauber approach)

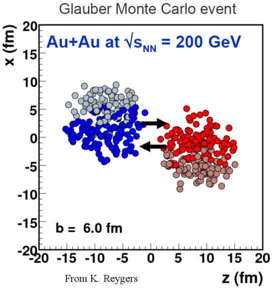
- As illustrated by the ALICE example, the experiments use Glauber MC to determine N_{part} vs N_{coll}
- A given simulated collision translates into observables: E_T, N_{tracks}, ...



From K. Reygers

Glauber Monte Carlo (probabilistic Glauber approach)

- As illustrated by the ALICE example, the experiments use Glauber MC to determine N_{part} vs N_{coll}
- A given simulated collision translates into observables: E_T, N_{tracks}, ...
- Configuration generated with Woods-Saxon density profile

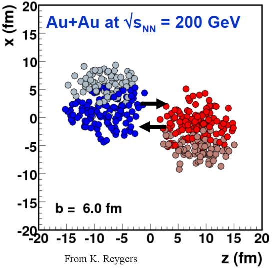


From K. Reygers

Glauber Monte Carlo (probabilistic Glauber approach)

- As illustrated by the ALICE example, the experiments use Glauber MC to determine N_{part} vs N_{coll}
- A given simulated collision translates into observables: E_T, N_{tracks}, ...
- Configuration generated with Woods-Saxon density profile
- Impact parameter b determined randomly from $d\sigma/db = 2\pi b$

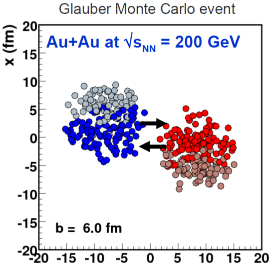
Glauber Monte Carlo event



From K. Reygers

Glauber Monte Carlo (probabilistic Glauber approach)

- As illustrated by the ALICE example, the experiments use Glauber MC to determine N_{part} vs N_{coll}
- A given simulated collision translates into observables: E_T, N_{tracks}, ...
- Configuration generated with Woods-Saxon density profile
- Impact parameter b determined randomly from $d\sigma / db = 2\pi b$
- Like many MC code, one collision is switched on if two nucleons are closer than $\sqrt{\sigma_{NN}^{inel} / \pi}$

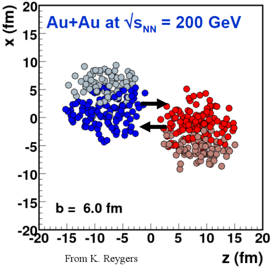


From K. Reygers

Glauber Monte Carlo (probabilistic Glauber approach)

- As illustrated by the ALICE example, the experiments use Glauber MC to determine N_{part} vs N_{coll}
- A given simulated collision translates into observables: E_T, N_{tracks}, ...
- Configuration generated with Woods-Saxon density profile
- Impact parameter b determined randomly from $d\sigma / db = 2\pi b$
- Like many MC code, one collision is switched on if two nucleons are closer than $\sqrt{\sigma_{NN}^{inel} / \pi}$
- The larger the number of collisions is, the larger the energy released is, the larger the energy density is

Glauber Monte Carlo event

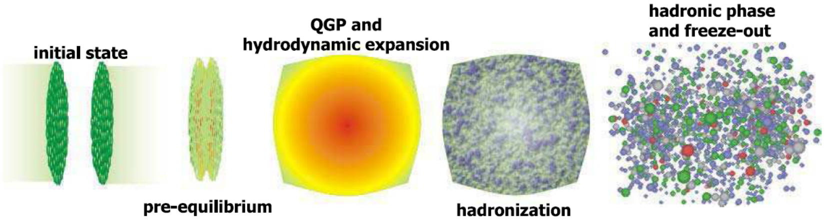


From K. Reygers

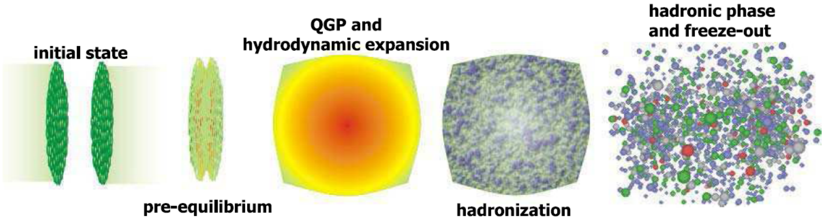
Part V

Snapshots of a nucleus-nucleus collision

Evolution stages of a nucleus-nucleus collision

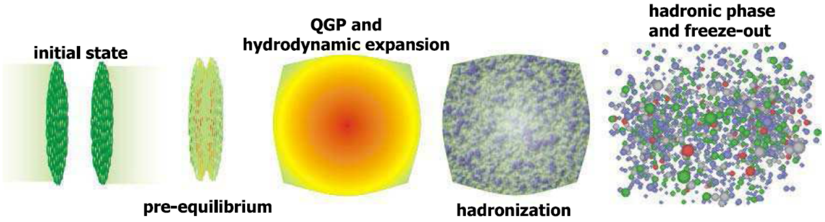


Evolution stages of a nucleus-nucleus collision



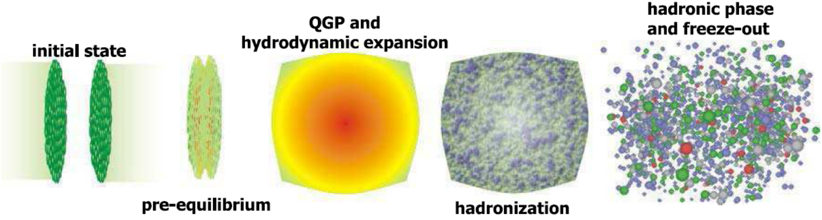
1. initial collision: $t \leq t_{coll} \simeq \frac{2R}{\gamma_{\rm cms}^{\rm boost} c}$

Evolution stages of a nucleus-nucleus collision



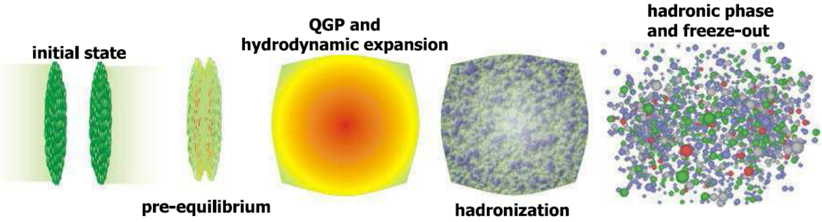
1. initial collision: $t \leq t_{coll} \simeq \frac{2R}{\gamma_{\rm cms}^{\rm boost} c}$
2. thermalisation: equilibrium is reached : $t \leq 1$fm/c

Evolution stages of a nucleus-nucleus collision



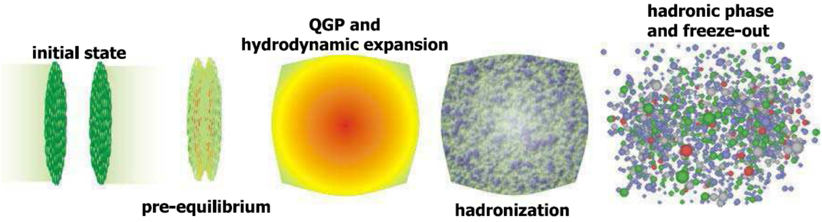
1. initial collision: $t \le t_{coll} \simeq \frac{2R}{\gamma_{\rm cms}^{\rm boost} c}$
2. thermalisation: equilibrium is reached : $t \le 1$fm/c
3. expansion and cooling : $t \le 10 - 15$fm/c

Evolution stages of a nucleus-nucleus collision



1. initial collision: $t \leq t_{coll} \simeq \frac{2R}{\gamma_{\rm cms}^{\rm boost} c}$
2. thermalisation: equilibrium is reached : $t \leq$ 1fm/c
3. expansion and cooling : $t \leq 10 - 15$fm/c
4. hadronisation

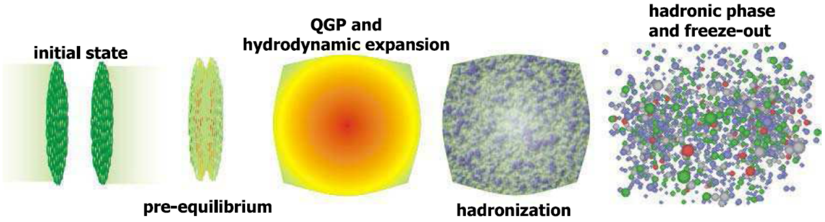
Evolution stages of a nucleus-nucleus collision



1. initial collision: $t \leq t_{coll} \simeq \frac{2R}{\gamma_{\rm cms}^{\rm boost} c}$
2. thermalisation: equilibrium is reached : $t \leq 1$fm/c
3. expansion and cooling : $t \leq 10 - 15$fm/c
4. hadronisation
5. Chemical freeze-out: the inelastic collisions stop

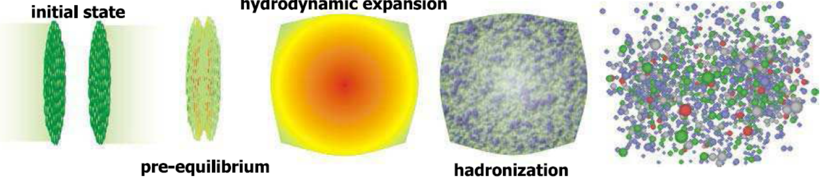
   $\rightarrow$ the yields are fixed

Evolution stages of a nucleus-nucleus collision



1. initial collision: $t \leq t_{coll} \simeq \frac{2R}{\gamma_{\rm cms}^{\rm boost} c}$
2. thermalisation: equilibrium is reached : $t \leq$ 1fm/c
3. expansion and cooling : $t \leq 10 - 15$fm/c
4. hadronisation
5. Chemical freeze-out: the inelastic collisions stop
   $\rightarrow$ the yields are fixed
6. Kinetic freeze-out : the elastic collisions stop
   $\rightarrow$ the spectra are fixed : $t \leq 3 - 5$fm/c

Evolution stages of a nucleus-nucleus collision



1. initial collision: $t \leq t_{coll} \simeq \frac{2R}{\gamma_{\rm cms}^{\rm boost} c}$
2. thermalisation: equilibrium is reached : $t \leq 1$fm/c
3. expansion and cooling : $t \leq 10 - 15$fm/c
4. hadronisation
5. Chemical freeze-out: the inelastic collisions stop
   $\rightarrow$ the yields are fixed
6. Kinetic freeze-out : the elastic collisions stop
   $\rightarrow$ the spectra are fixed : $t \leq 3 - 5$fm/c

Measurement at stage 5 & 6 to learn about stage 3