The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific
and Cultural Organization

International Atomic
Energy Agency

SMR 1773 - 6

SCHOOL ON PHYSICS AT LHC: "EXPECTING LHC"
11 - 16 September 2006

Heavy ion collisions at LHC
Part I

François ARLEO
C.E.R.N. - Theory Division, Department of Physics
CH-1211 Geneva 23, Switzerland

These are preliminary lecture notes, intended only for distribution to participants.

Strada Costiera 11, 34014 Trieste, Italy - Tel. +39 040 2240 111; Fax +39 040 224 163 - sci_info@ictp.it, www.ictp.it

Heavy ion collisions at the LHC

Part 1

François Arleo

CERN

Material

These slides are available at the school web site and at

http://cern.ch/arleo/expectingLHC

For further reading, go also to this web page to find bibliographical references on heavy ion collisions

You can also contact me at arleo@cern.ch for any question

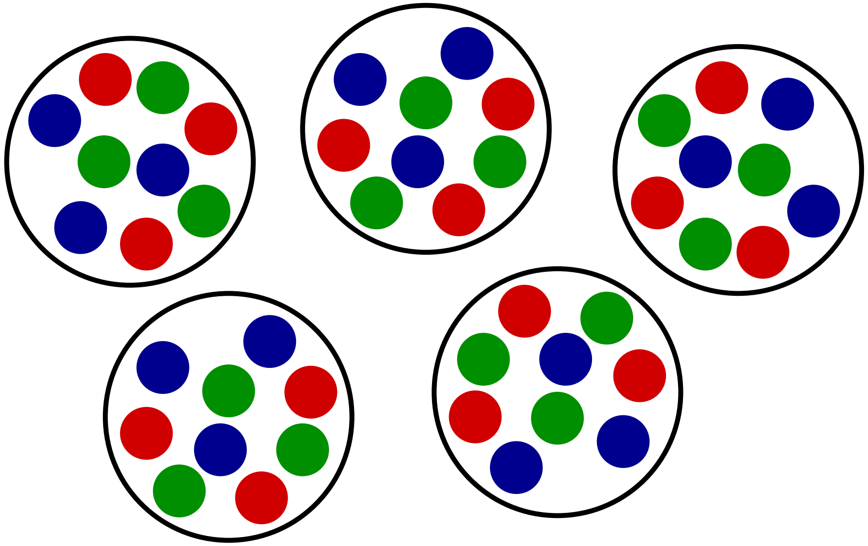
Outline

- Lattice QCD
  - A possible phase transition at finite temperature
- Heavy ion collisions
  - Facilities
  - Expected space-time evolution
- Need for signatures
  - A few interesting candidates. . .

Motivations

At zero temperature, quarks and gluons are confined into hadrons (pions, protons, . . .)

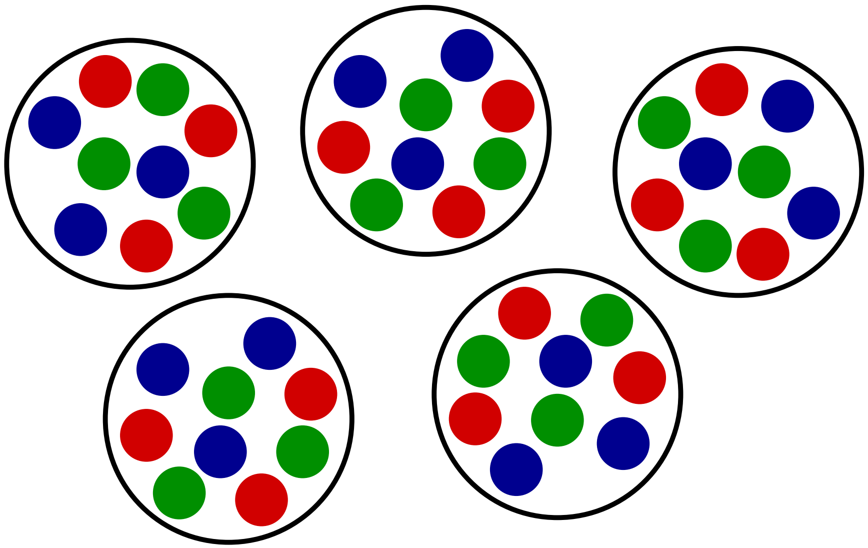
They cannot propagate over distances larger than $\Lambda_{\rm QCD}^{-1} \simeq 1$ fm



Motivations

At zero temperature, quarks and gluons are confined into hadrons (pions, protons, . . .)

They cannot propagate over distances larger than $\Lambda_{\rm QCD}^{-1} \simeq 1$ fm



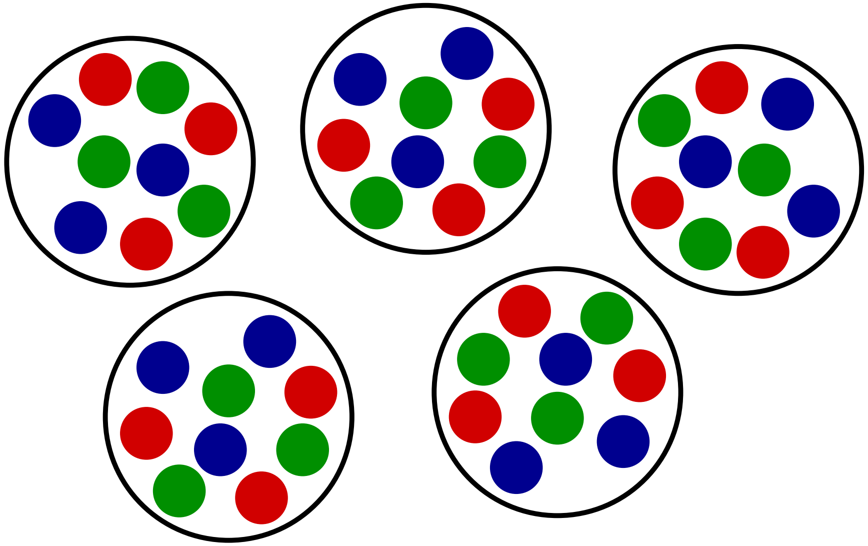
One of the most important properties of QCD

Confinement

Motivations

At zero temperature, quarks and gluons are confined into hadrons (pions, protons, . . .)

They cannot propagate over distances larger than $\Lambda_{\text{QCD}}^{-1} \simeq 1$ fm

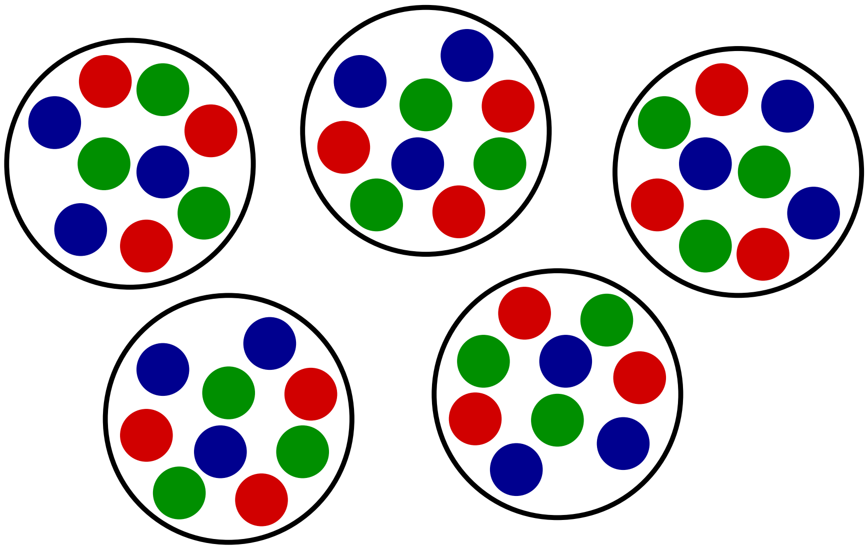


What happens at high temperature ?

Motivations

At zero temperature, quarks and gluons are confined into hadrons (pions, protons, . . .)

They cannot propagate over distances larger than $\Lambda_{\rm QCD}^{-1} \simeq 1$ fm



What happens at high temperature ?

That's what heavy ion physics is all about !

QCD at finite temperature

- What is the equation of state of QCD matter, e.g. $P(T)$, $\epsilon(T)$, under extreme conditions ?

QCD at finite temperature

- What is the equation of state of QCD matter, e.g. $P(T)$, $\epsilon(T)$, under extreme conditions ?
  - Can be accessed through heavy numerical (non-perturbative) calculations

QCD at finite temperature

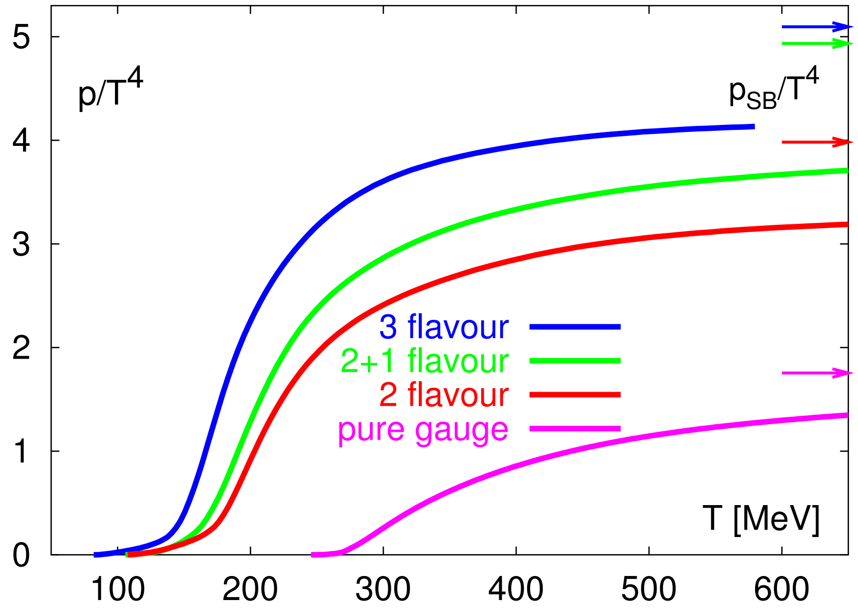
- What is the equation of state of QCD matter, e.g. $P(T)$, $\epsilon(T)$, under extreme conditions ?
  - Can be accessed through heavy numerical (non-perturbative) calculations

Lattice QCD at finite temperature T and (to a lesser extent)

at finite chemical potential μ

QCD at finite temperature

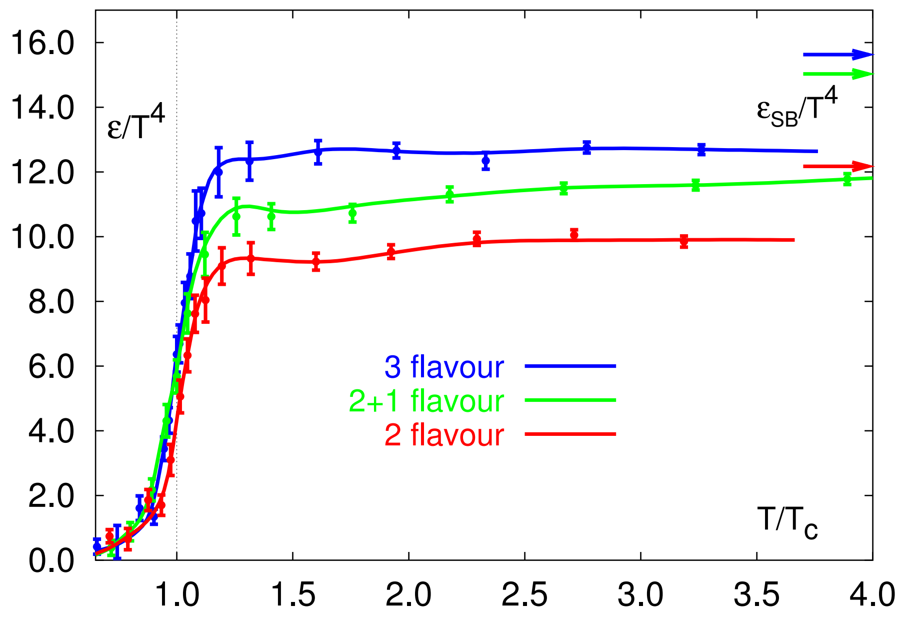
At finite T and $\mu = 0$



[Karsch et al. 2001]

QCD at finite temperature

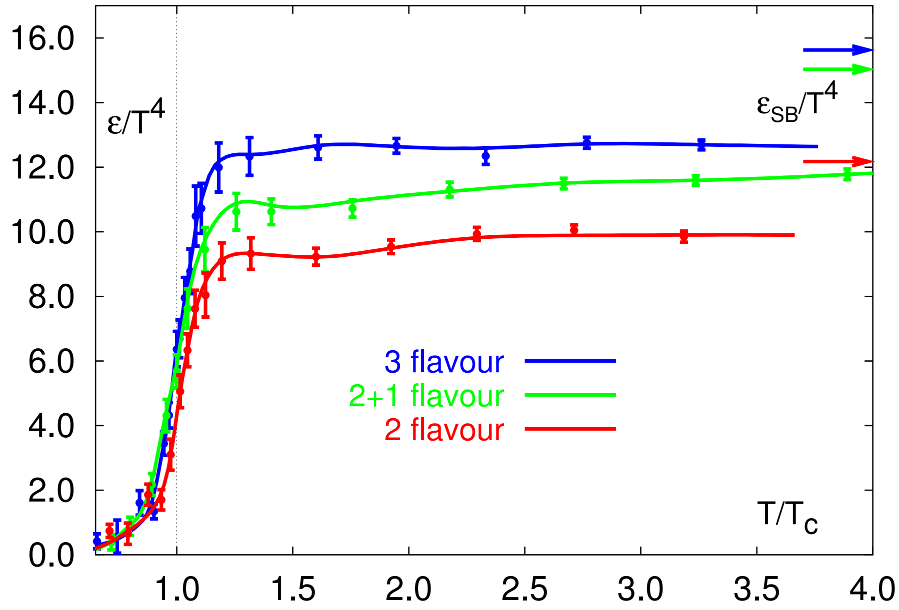
At finite T and $\mu = 0$



[Karsch et al. 2001]

QCD at finite temperature

At finite T and $\mu = 0$



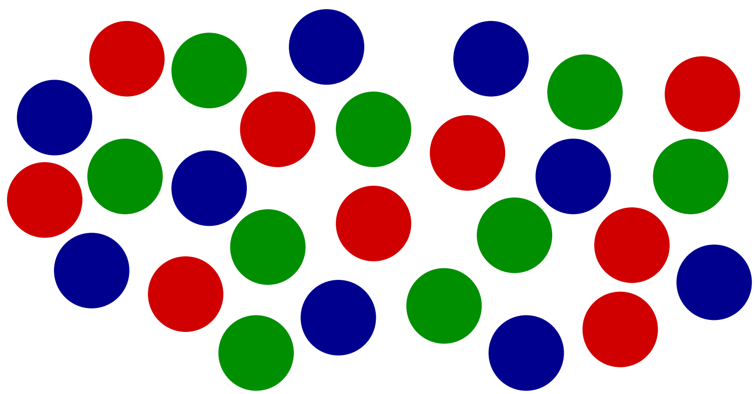
[Karsch et al. 2001]

Usual interpretation

Transition from a pion gas (with 3 degrees of freedom) to a gas of weakly interacting quarks and gluons (40 d.o.f.)

QCD at finite temperature

At finite T and $\mu = 0$



Usual interpretation

Transition from a pion gas (with 3 degrees of freedom) to a gas of weakly interacting quarks and gluons (40 d.o.f.)

Existence of Quark-Gluon Plasma

Questions

Once we know quark-gluon plasma should exist at high temperature, many questions need to be answered . . .

Questions

Once we know quark-gluon plasma should exist at high temperature, many questions need to be answered . . .

1. What is the critical temperature ?

Questions

Once we know quark-gluon plasma should exist at high temperature, many questions need to be answered . . .

1. What is the critical temperature ?
2. What is the nature of the transition ?

Questions

Once we know quark-gluon plasma should exist at high temperature, many questions need to be answered . . .

1. What is the critical temperature ?
2. What is the nature of the transition ?
3. What happens at finite chemical potential ?

Questions

Once we know quark-gluon plasma should exist at high temperature, many questions need to be answered . . .

1. What is the critical temperature ?
2. What is the nature of the transition ?
3. What happens at finite chemical potential ?
4. Where does the quark-gluon plasma exist ?

Questions

Once we know quark-gluon plasma should exist at high temperature, many questions need to be answered . . .

1. What is the critical temperature ?
2. What is the nature of the transition ?
3. What happens at finite chemical potential ?
4. Where does the quark-gluon plasma exist ?
5. How do we probe its formation ?

Questions

Once we know quark-gluon plasma should exist at high temperature, many questions need to be answered . . .

1. What is the critical temperature ?
2. What is the nature of the transition ?
3. What happens at finite chemical potential ?
4. Where does the quark-gluon plasma exist ?
5. How do we probe its formation ?

I will mainly focus on the last point in these lectures

(one of the hottest topic in heavy ions !)

Critical temperature

Lattice QCD predicts the critical temperature to be roughly

$$T_c \simeq 200 \text{ MeV}$$

Critical temperature

Lattice QCD predicts the critical temperature to be roughly

$$T_c \simeq 200 \text{ MeV}$$

However . . .

The critical temperature depends on the number of light flavours assumed in the calculation !

Critical temperature

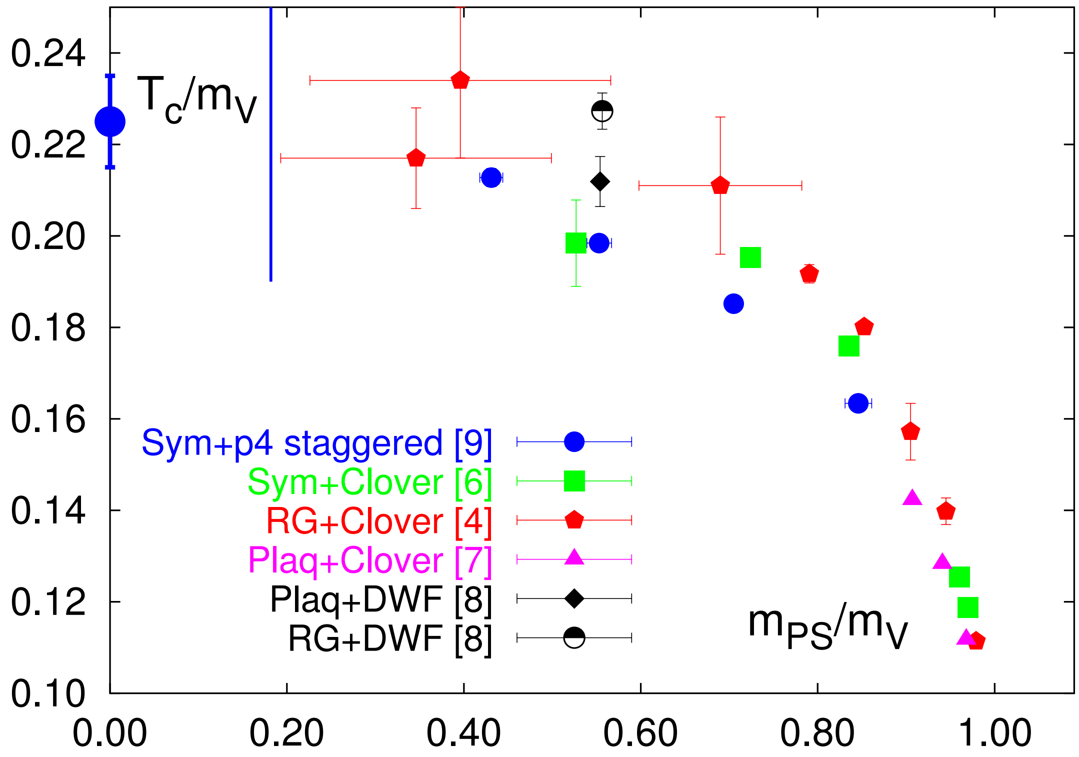
Lattice QCD predicts the critical temperature to be roughly

$$T_c \simeq 200 \text{ MeV}$$

Theory	T_c (MeV)
pure gauge	270
2 flavours	175
3 flavours	155

[Karsch et al. 2001]

Critical temperature

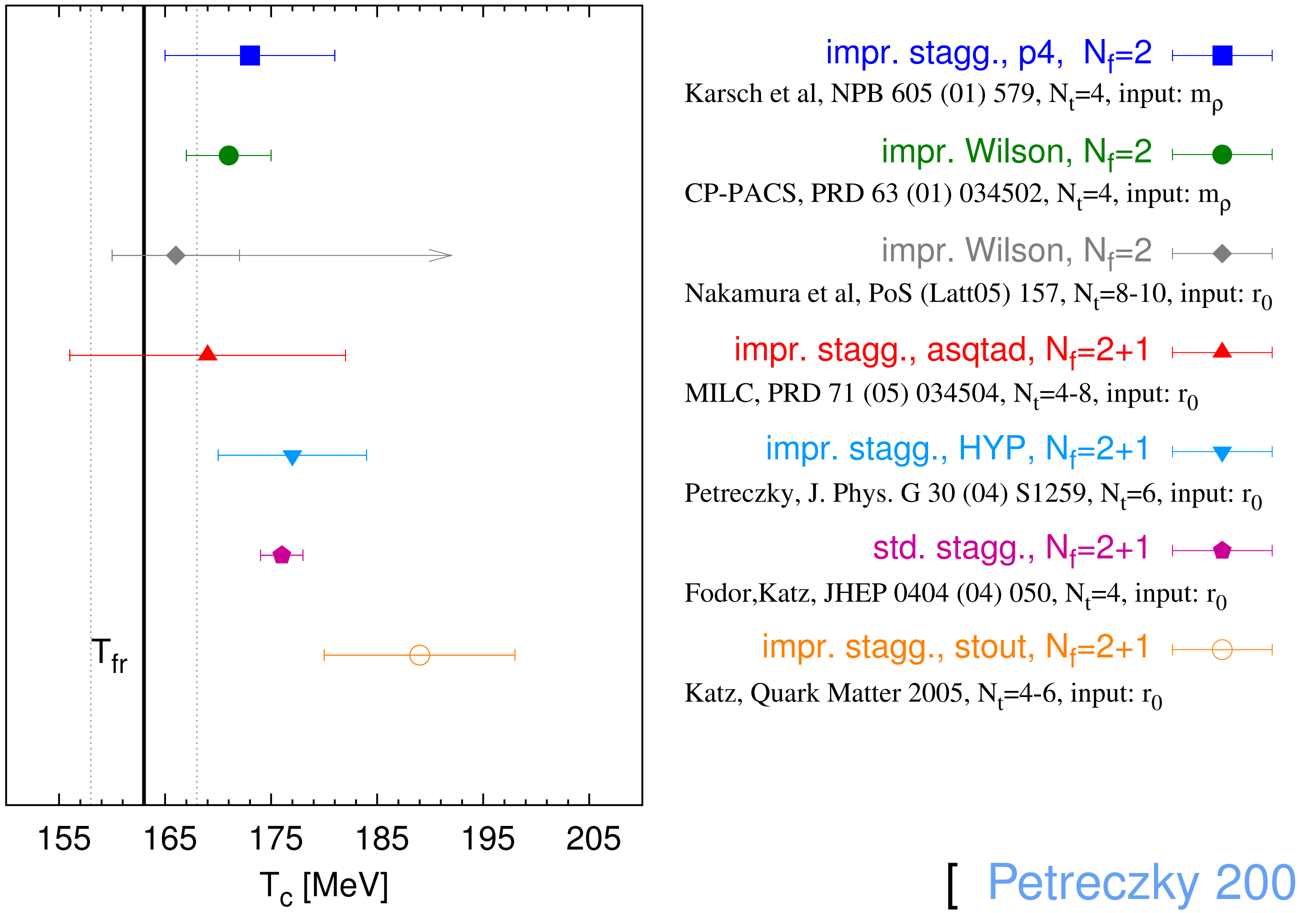


[Karsch et al. 2001]

Mind the large error bars !

- Statistical uncertainty (needs huge CPU-time)
- Systematic uncertainty (extrapolation to the chiral limit)

Critical temperature



[Petreczky 2006]

In 2+1 flavours, compiling the world “data”

$$T_c = 167\text{–}188\ \text{MeV}$$

Phase transition

What is the nature of the transition ?

Phase transition

What is the nature of the transition ?

Let Φ be the order parameter for the transition, with

$$\begin{aligned} \Phi(T=0) &= 1 \\ \Phi(T=\infty) &= 0 \end{aligned}$$

Phase transition

What is the nature of the transition ?

Let Φ be the order parameter for the transition, with

$$\begin{aligned} \Phi(T=0) &= 1 \\ \Phi(T=\infty) &= 0 \end{aligned}$$

How does Φ evolve with temperature T ?

Phase transition

What is the nature of the transition ?

Let Φ be the order parameter for the transition, with

$$\begin{aligned} \Phi(T=0) &= 1 \\ \Phi(T=\infty) &= 0 \end{aligned}$$

How does Φ evolve with temperature T ?

Three possibilities

Phase transition

What is the nature of the transition ?

Let Φ be the order parameter for the transition, with

$$\begin{aligned} \Phi(T=0) &= 1 \\ \Phi(T=\infty) &= 0 \end{aligned}$$

How does Φ evolve with temperature T ?

Three possibilities

1. 1st order: Φ has a discontinuity

Phase transition

What is the nature of the transition ?

Let Φ be the order parameter for the transition, with

$$\begin{aligned} \Phi(T=0) &= 1 \\ \Phi(T=\infty) &= 0 \end{aligned}$$

How does Φ evolve with temperature T ?

Three possibilities

1. 1st order: Φ has a discontinuity
2. 2nd order: $\partial_T \Phi$ has a discontinuity

Phase transition

What is the nature of the transition ?

Let Φ be the order parameter for the transition, with

$$\begin{aligned} \Phi(T=0) &= 1 \\ \Phi(T=\infty) &= 0 \end{aligned}$$

How does Φ evolve with temperature T ?

Three possibilities

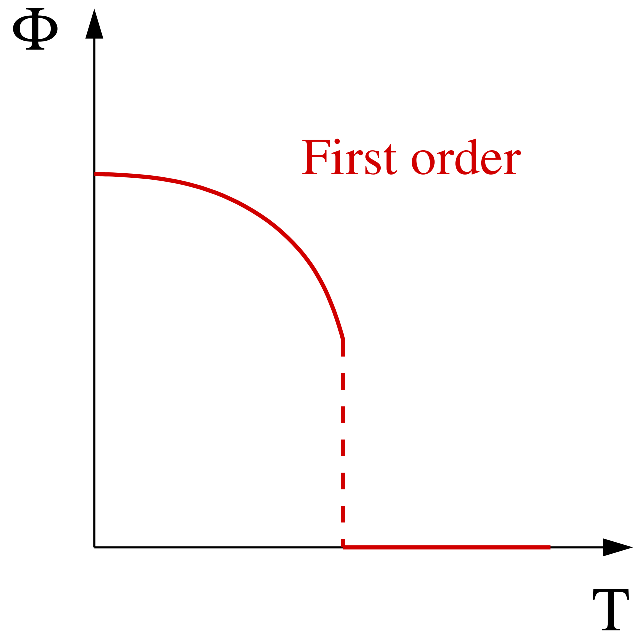
1. 1st order: Φ has a discontinuity
2. 2nd order: $\partial_T \Phi$ has a discontinuity
3. cross-over: smooth transition

Phase transition

What is the nature of the transition ?

Let Φ be the order parameter for the transition, with

$$\begin{aligned} \Phi(T = 0) &= 1 \\ \Phi(T = \infty) &= 0 \end{aligned}$$

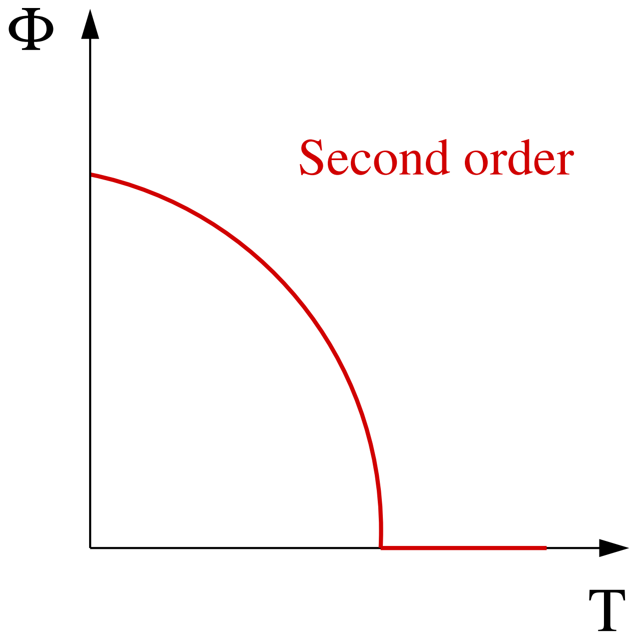


Phase transition

What is the nature of the transition ?

Let Φ be the order parameter for the transition, with

$$\begin{aligned}\Phi(T=0) &= 1 \\ \Phi(T=\infty) &= 0\end{aligned}$$

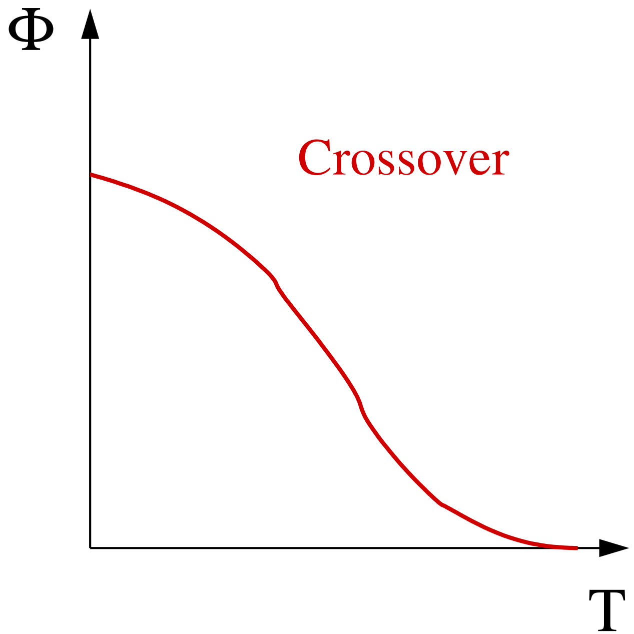


Phase transition

What is the nature of the transition ?

Let Φ be the order parameter for the transition, with

$$\begin{aligned}\Phi(T=0) &= 1 \\ \Phi(T=\infty) &= 0\end{aligned}$$



Which order parameter ?

Take the Polyakov loop

$$L(T) \sim \lim_{r \to \infty} \exp\left(-V(r)/T\right)$$

where $V(r)$ is the the heavy quark potential

Which order parameter ?

Take the Polyakov loop

$$L(T) \sim \lim_{r \to \infty} \exp\left(-V(r)/T\right)$$

where $V(r)$ is the heavy quark potential

- $T = 0$
  - Confining potential $V(r) \sim \sigma r$
  - $L \simeq 0$

Which order parameter ?

Take the Polyakov loop

$$L(T) \sim \lim_{r \to \infty} \exp\left(-V(r)/T\right)$$

where $V(r)$ is the heavy quark potential

- $T = 0$
  - Confining potential $V(r) \sim \sigma r$
  - $L \simeq 0$
- $T \neq 0$
  - Screened potential $V(r) \sim \exp\left(-m_D r\right)/r$
  - $L \simeq 1$

Which order parameter ?

Take the Polyakov loop

$$L(T) \sim \lim_{r \to \infty} \exp\left(-V(r)/T\right)$$

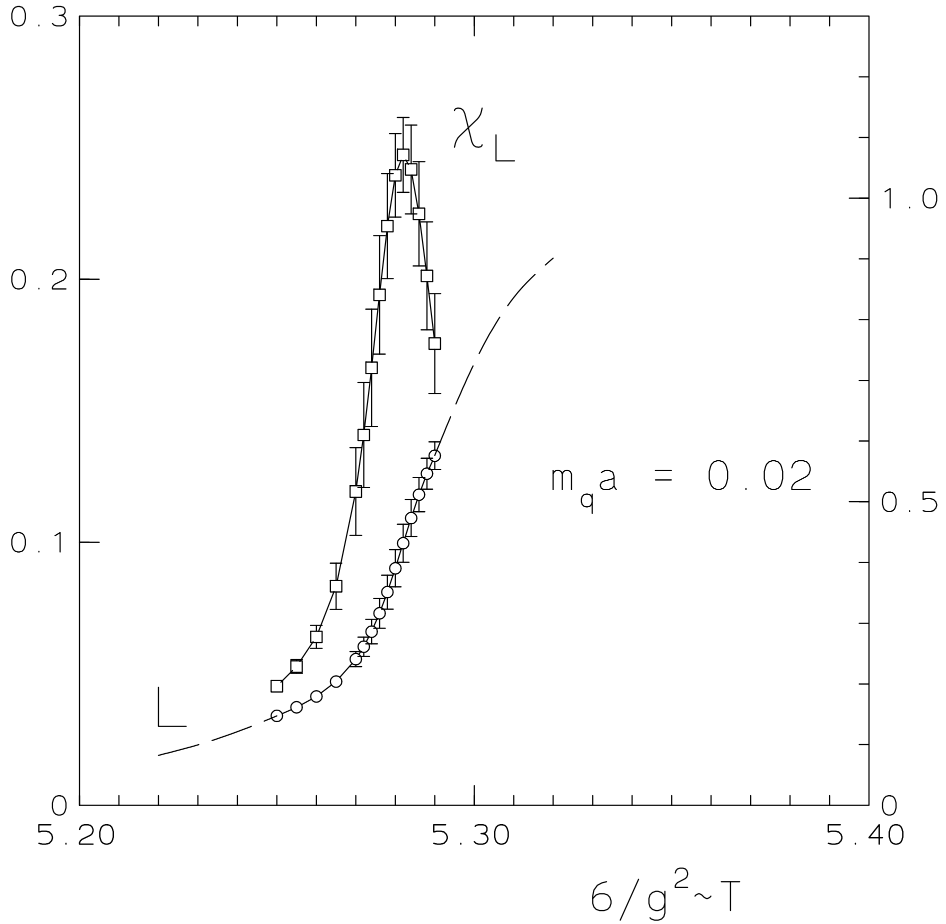
where $V(r)$ is the heavy quark potential

- $T = 0$
  - Confining potential $V(r) \sim \sigma r$
  - $L \simeq 0$
- $T \neq 0$
  - Screened potential $V(r) \sim \exp\left(-m_D r\right)/r$
  - $L \simeq 1$

The Polyakov loop is an order parameter

for the deconfinement transition

Which order parameter ?



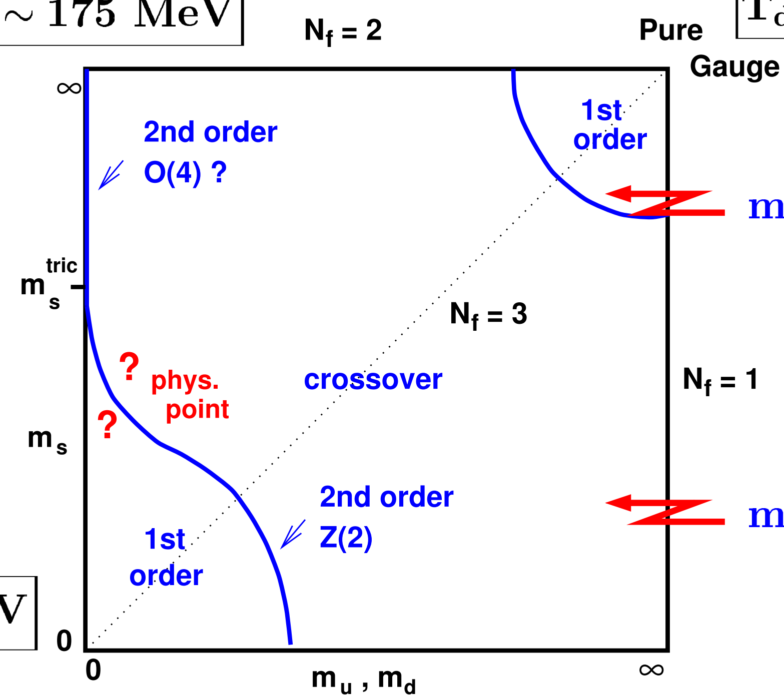
[Karsch, Laermann 1994]

QCD phase diagram

3-flavour phase diagram

$T_\chi^{n_f=2} \sim 175$ MeV

$T_d \sim 270$ MeV



$m_{PS}^{crit} \simeq 2.5$ GeV

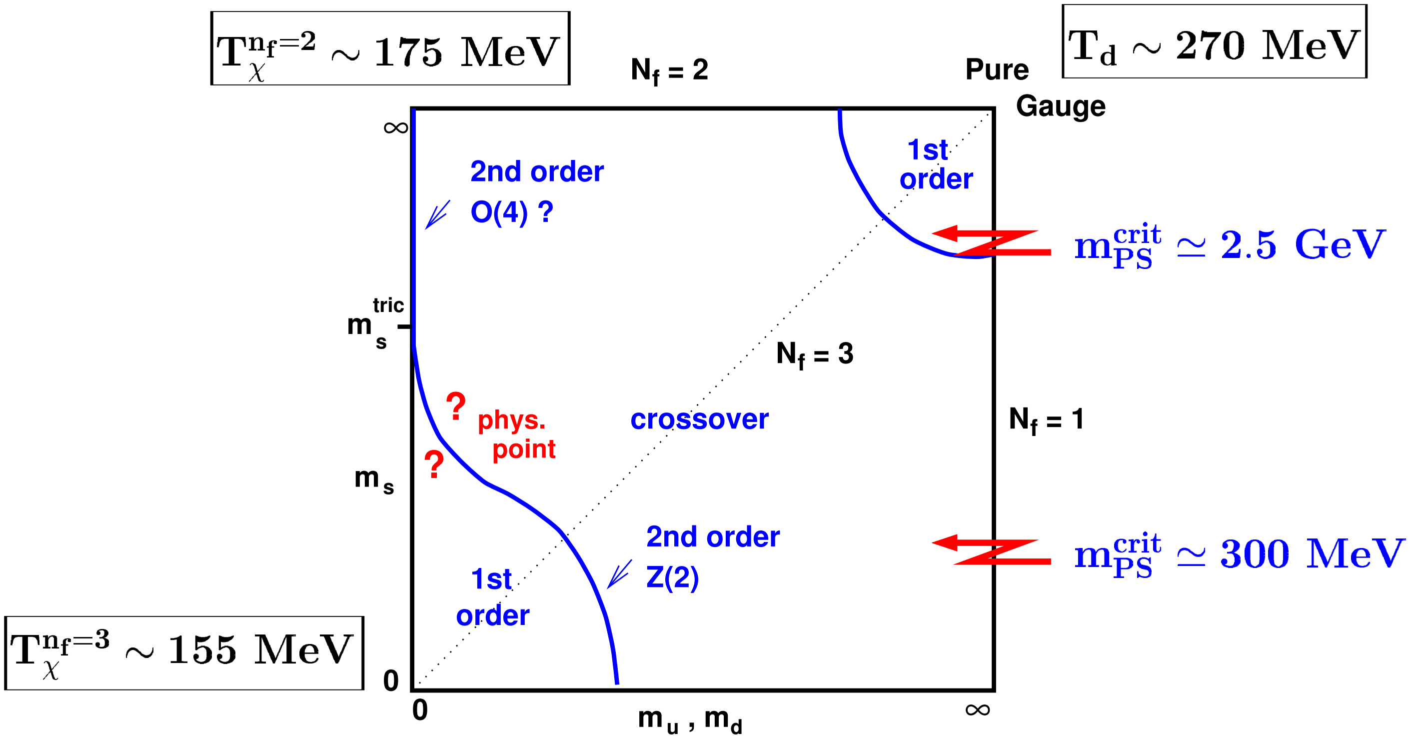
$m_{PS}^{crit} \simeq 300$ MeV

$T_\chi^{n_f=3} \sim 155$ MeV

[Karsch 2001]

QCD phase diagram

3-flavour phase diagram

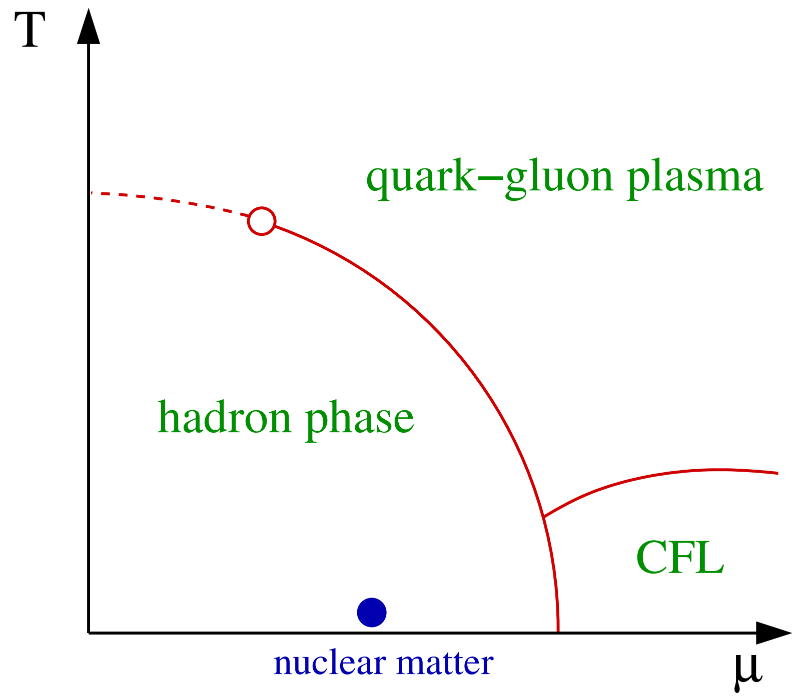


[Karsch 2001]

- The order of the transition crucially depends on the light quark mass
- The physical point most likely lies in the crossover region

Finite chemical potential

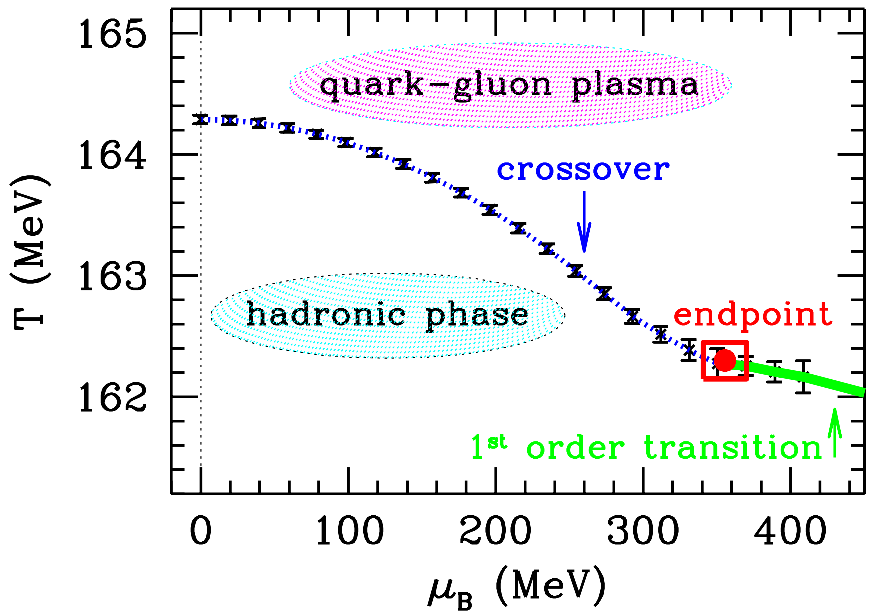
Schematically



- Rich structure in the $T - \mu$ plane !
- Existence of a critical point

Finite chemical potential

Schematically



[Fodor Katz 2004]

- Rich structure in the $T - \mu$ plane !
- Existence of a critical point
- ... confirmed by lattice QCD calculations

Heavy ion collisions

Towards heavy ions

Where does the quark-gluon plasma exist ?

Towards heavy ions

Where does the quark-gluon plasma exist ?

In the Universe

- A long time ago, one micro-second after the Big Bang (it was really hot !)
- In the core of neutron stars (it is really dense)

Towards heavy ions

Where does the quark-gluon plasma exist ?

In the Universe

- A long time ago, one micro-second after the Big Bang (it was really hot !)
- In the core of neutron stars (it is really dense)

How to study the quark-gluon plasma ?

Towards heavy ions

Where does the quark-gluon plasma exist ?

In the Universe

- A long time ago, one micro-second after the Big Bang (it was really hot !)
- In the core of neutron stars (it is really dense)

How to study the quark-gluon plasma ?

Colliding heavy ion collisions at high energy !

(and have a look to what happens)

Facilities

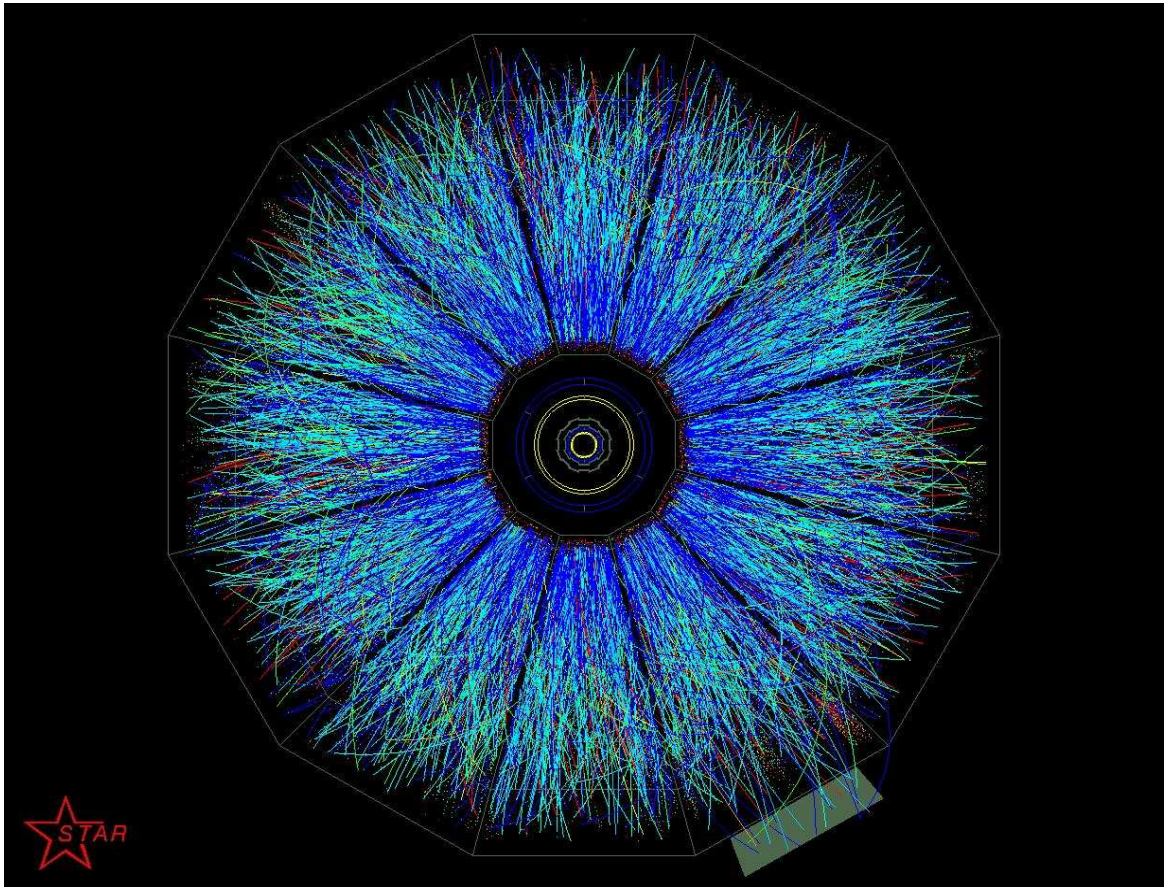
- SPS (CERN), since 1988
  - p-A, S-U, Pb-Pb at $\sqrt{s} \simeq 20 - 30$ GeV
  - NA44, NA49, NA50, WA97, WA98, CERES ...

Facilities

- SPS (CERN), since 1988
  - p-A, S-U, Pb-Pb at $\sqrt{s} \simeq 20 - 30$ GeV
  - NA44, NA49, NA50, WA97, WA98, CERES . . .
- RHIC (Brookhaven, USA), since 2000
  - d-Au, Au-Au at $\sqrt{s} \simeq 200$ GeV
  - BRAHMS, PHENIX, PHOBOS, STAR

Facilities

Snap-shot of a heavy ion collision at RHIC seen by STAR



Facilities

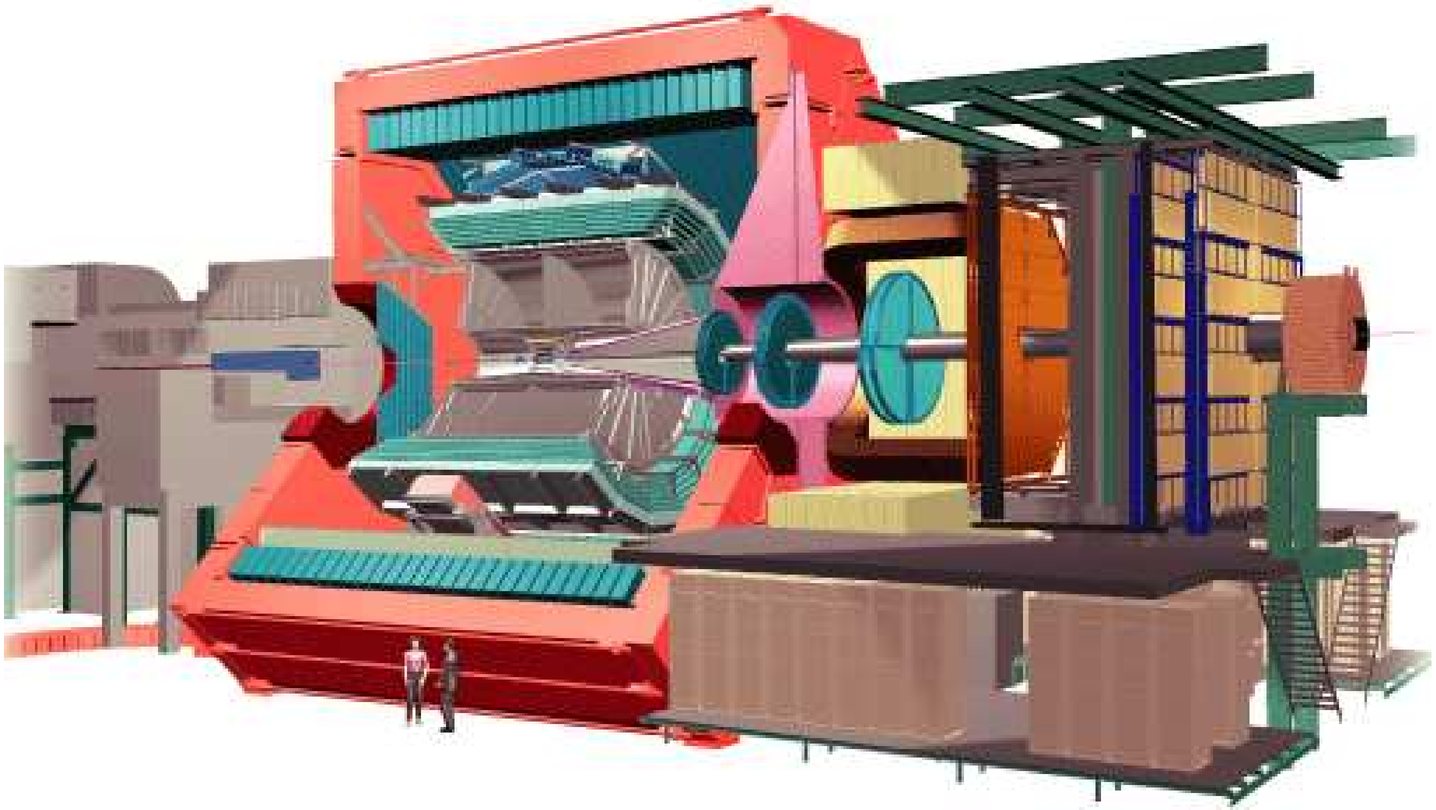
- SPS (CERN), since 1988
  - p-A, S-U, Pb-Pb at $\sqrt{s} \simeq 20 - 30$ GeV
  - NA44, NA49, NA50, WA97, WA98, CERES . . .
- RHIC (Brookhaven, USA), since 2000
  - d-Au, Au-Au at $\sqrt{s} \simeq 200$ GeV
  - BRAHMS, PHENIX, PHOBOS, STAR
- LHC (CERN), starting 2008
  - Pb-Pb at $\sqrt{s} = 5.5$ TeV
  - p-Pb at $\sqrt{s} = 8.8$ TeV (?)
  - ALICE, CMS (ATLAS)

Facilities

Air view of the SPS and the LHC

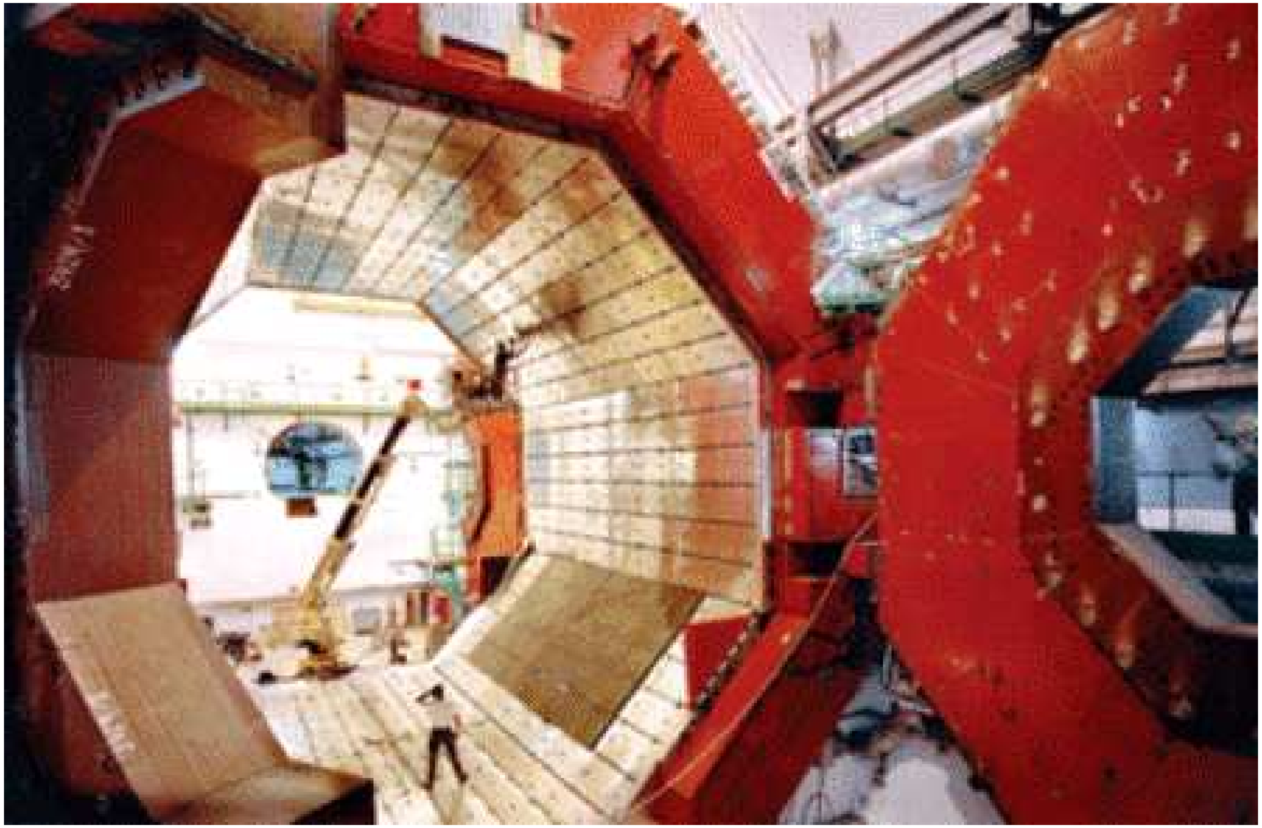
ALICE experiment

A Large Heavy Ion Collider Experiment



ALICE experiment

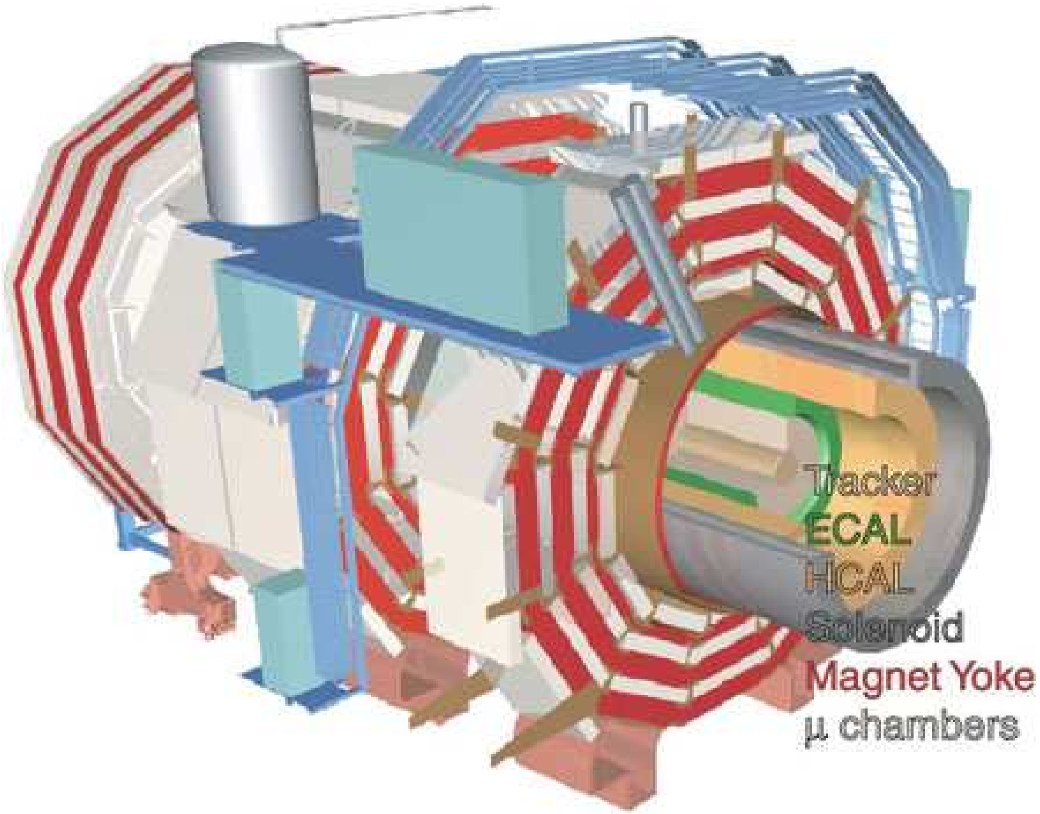
A Large Heavy Ion Collider Experiment



- Dedicated experiment for heavy ion physics

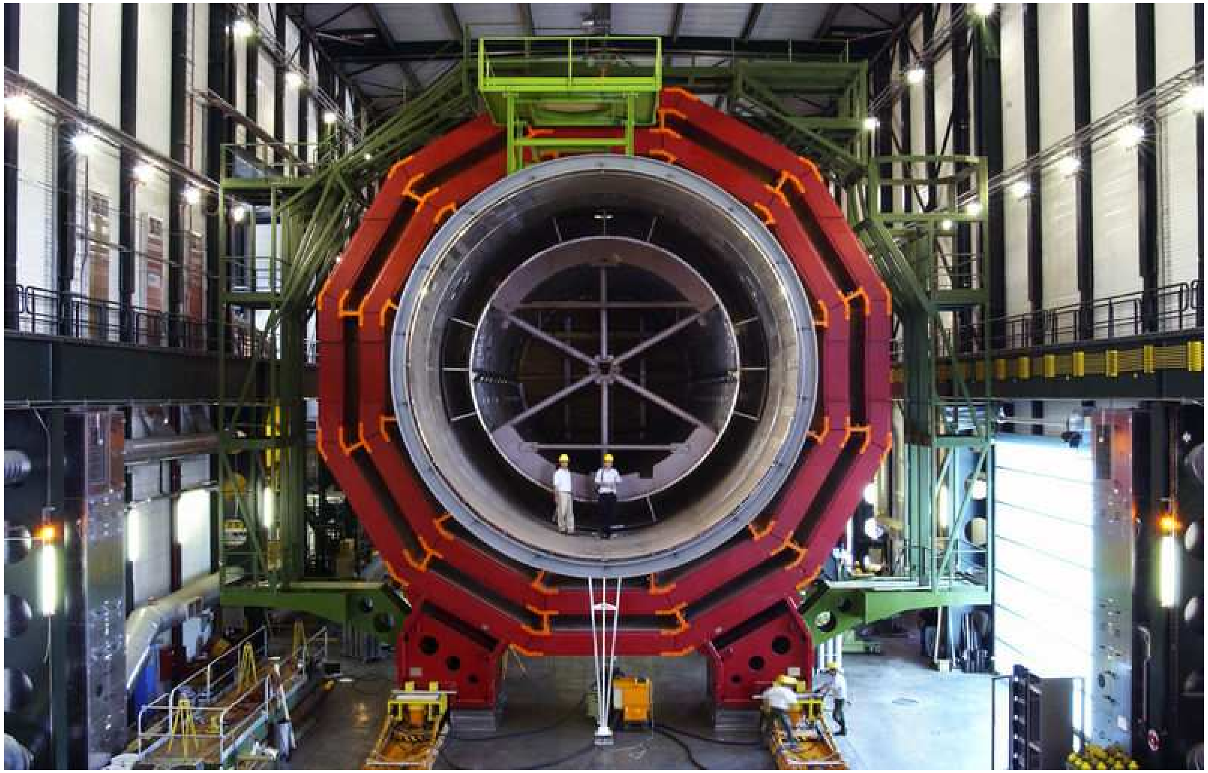
CMS experiment

Compact Muon Solenoid



CMS experiment

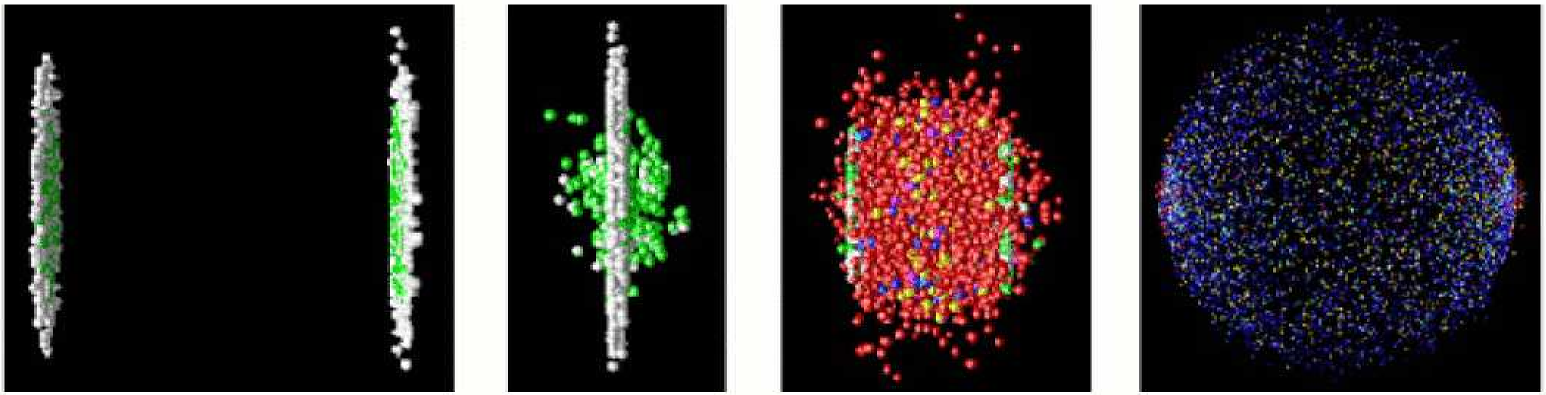
Compact Muon Solenoid



- Multipurpose experiment
- Good capabilities at large transverse momentum

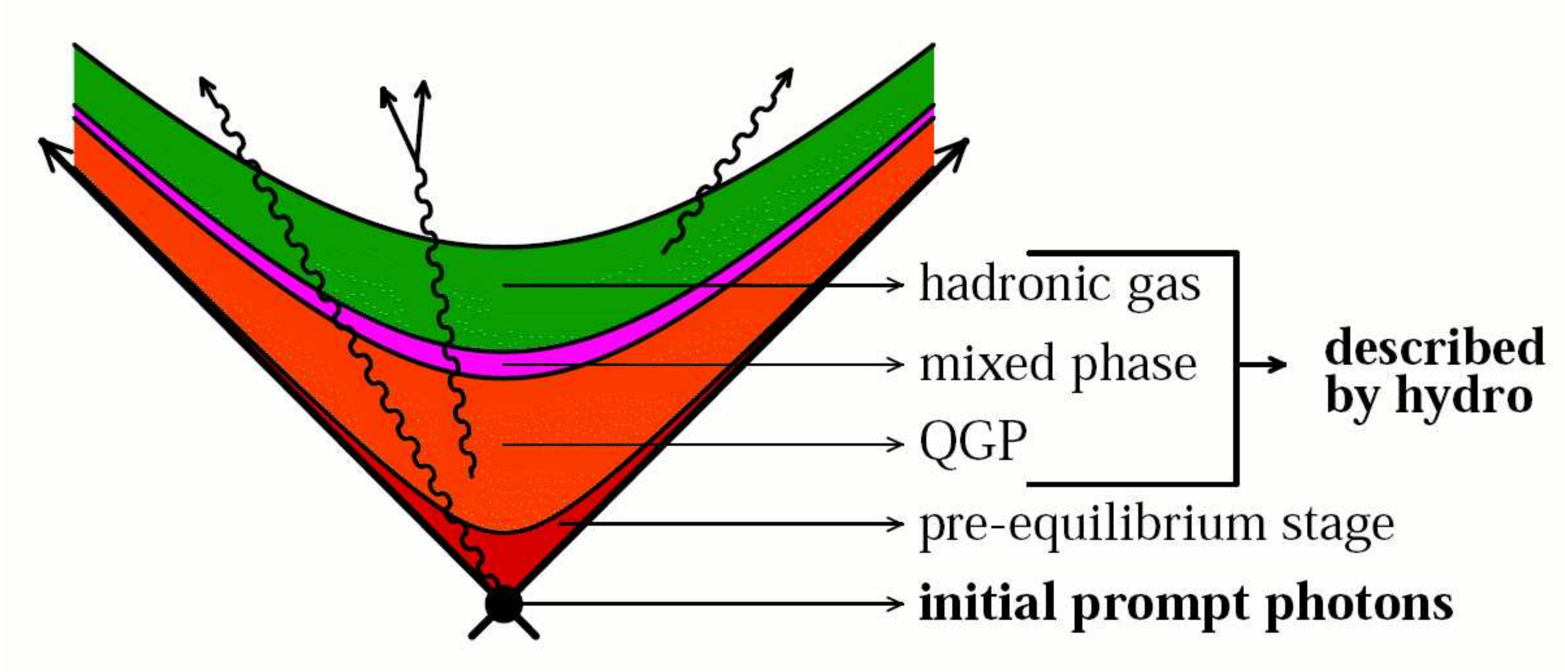
Stages of heavy ion collisions

The different phases of a heavy ion collision



A miscroscopic simulation by UrQMD

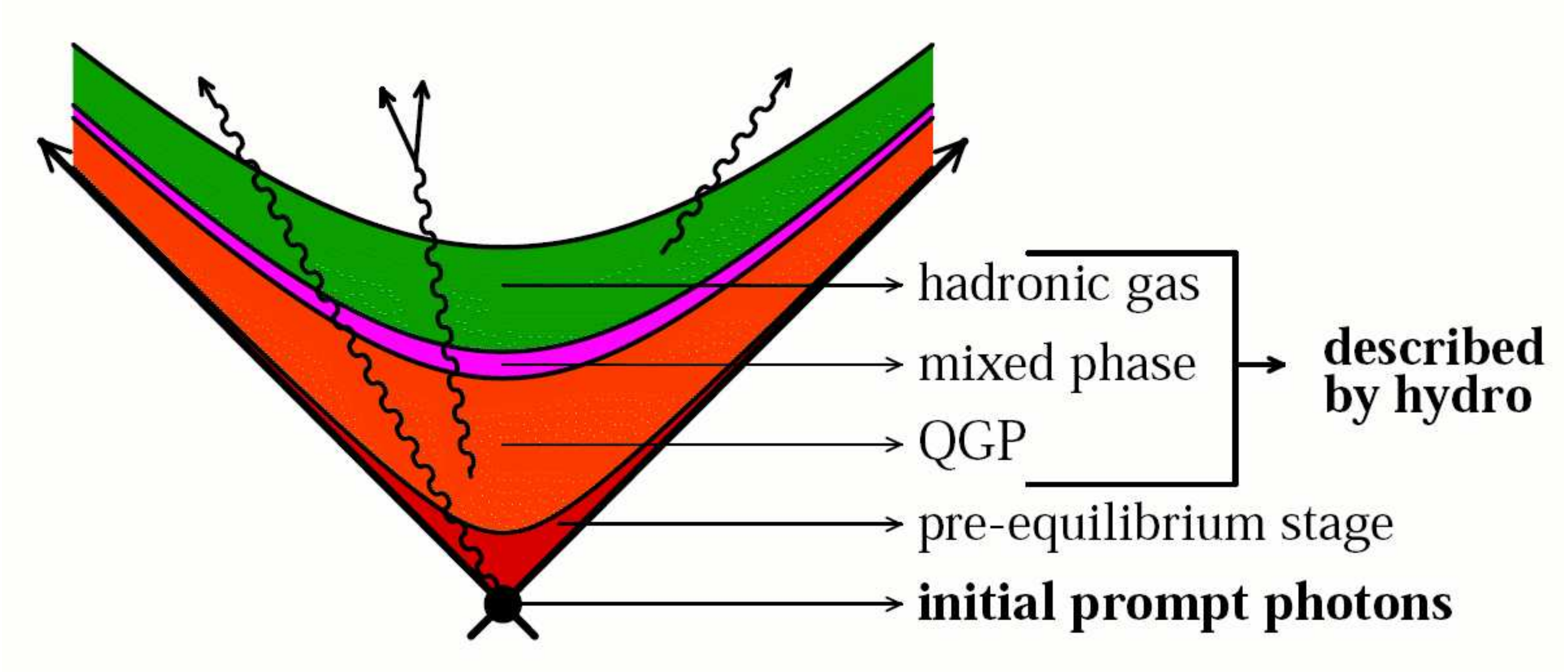
Stages of heavy ion collisions



[from F. Gelis]

- $t \simeq 0$ fm: The two nuclei cross
  - Particles with large mass (heavy quarks, Drell-Yan pairs) or transverse momentum (jets) are produced

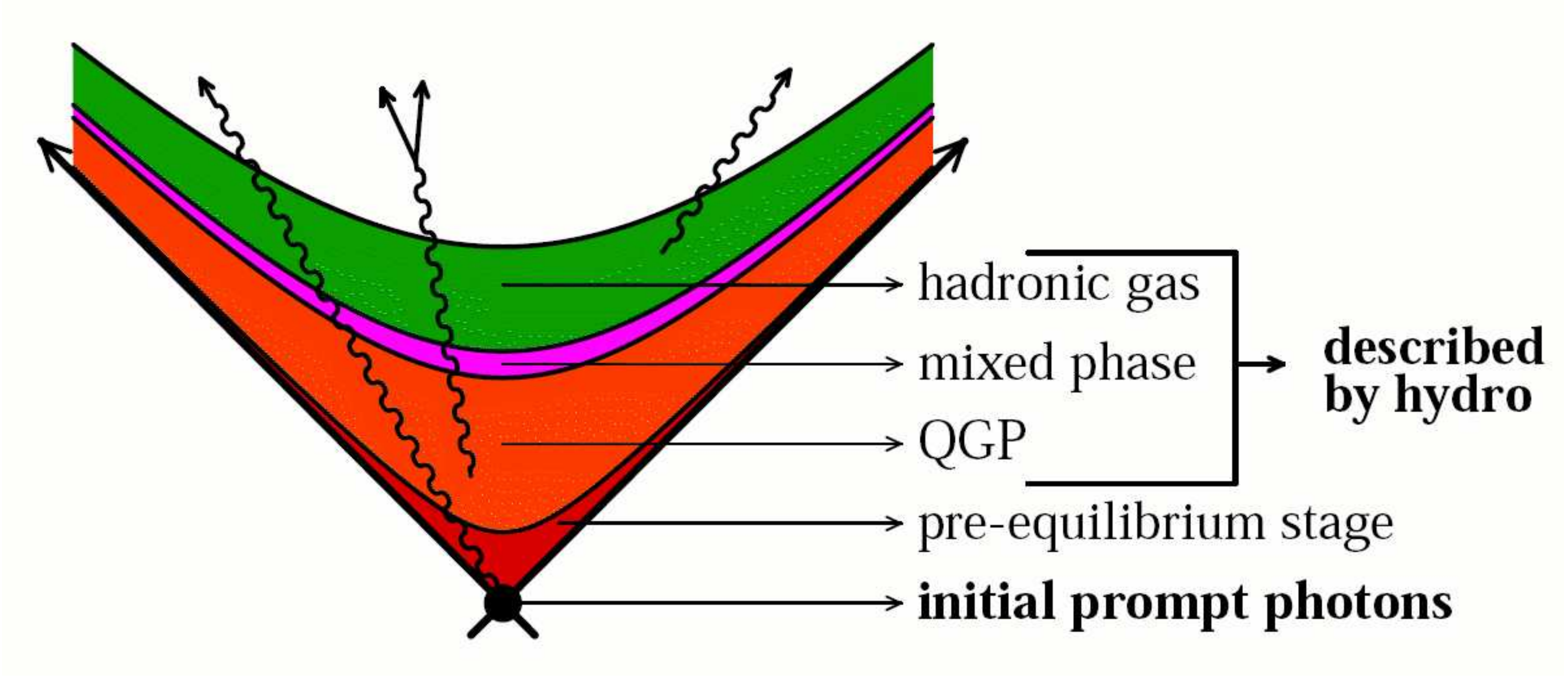
Stages of heavy ion collisions



[from F. Gelis]

- $t \lesssim 1$ fm: Pre-equilibrium stage
  - Quarks, and mostly gluons, are produced

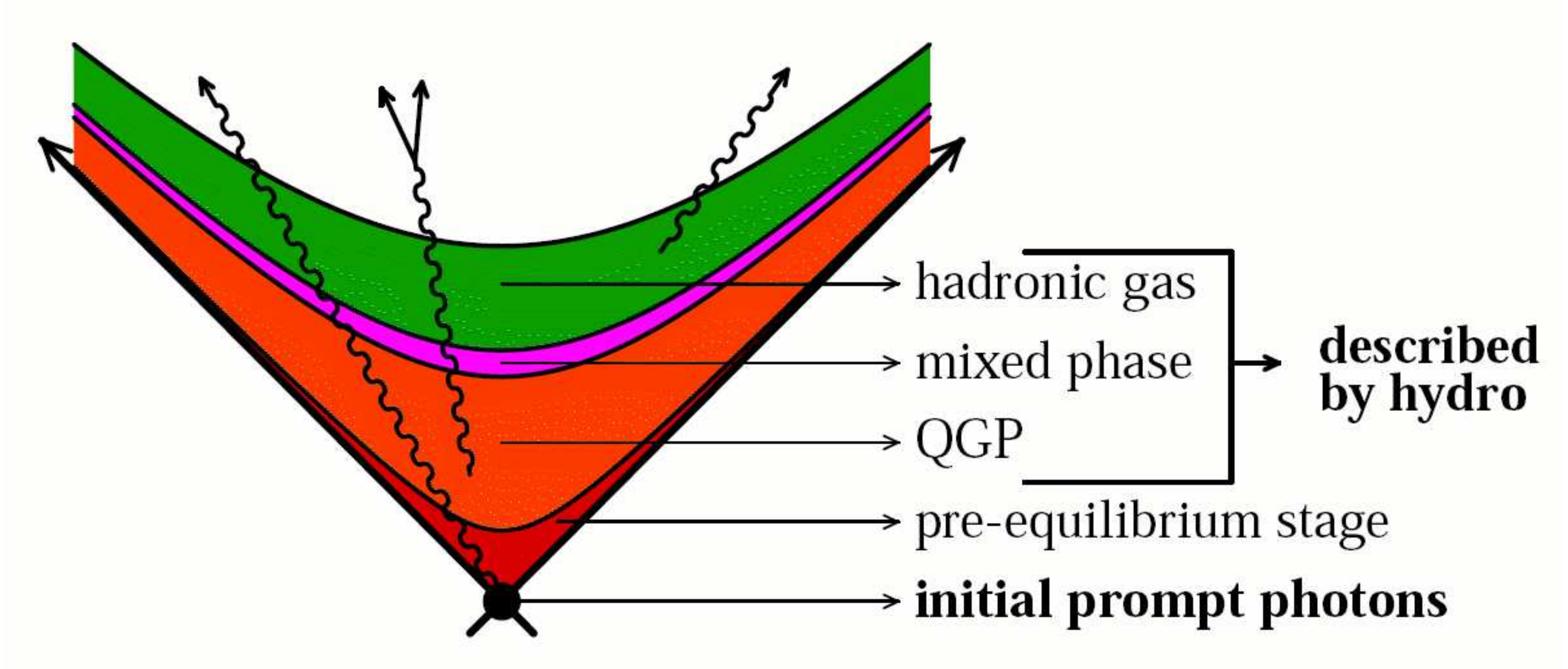
Stages of heavy ion collisions



[from F. Gelis]

- $t \simeq 1 - 5$ fm: Quark-gluon plasma
  - Quark and gluons in thermal equilibrium

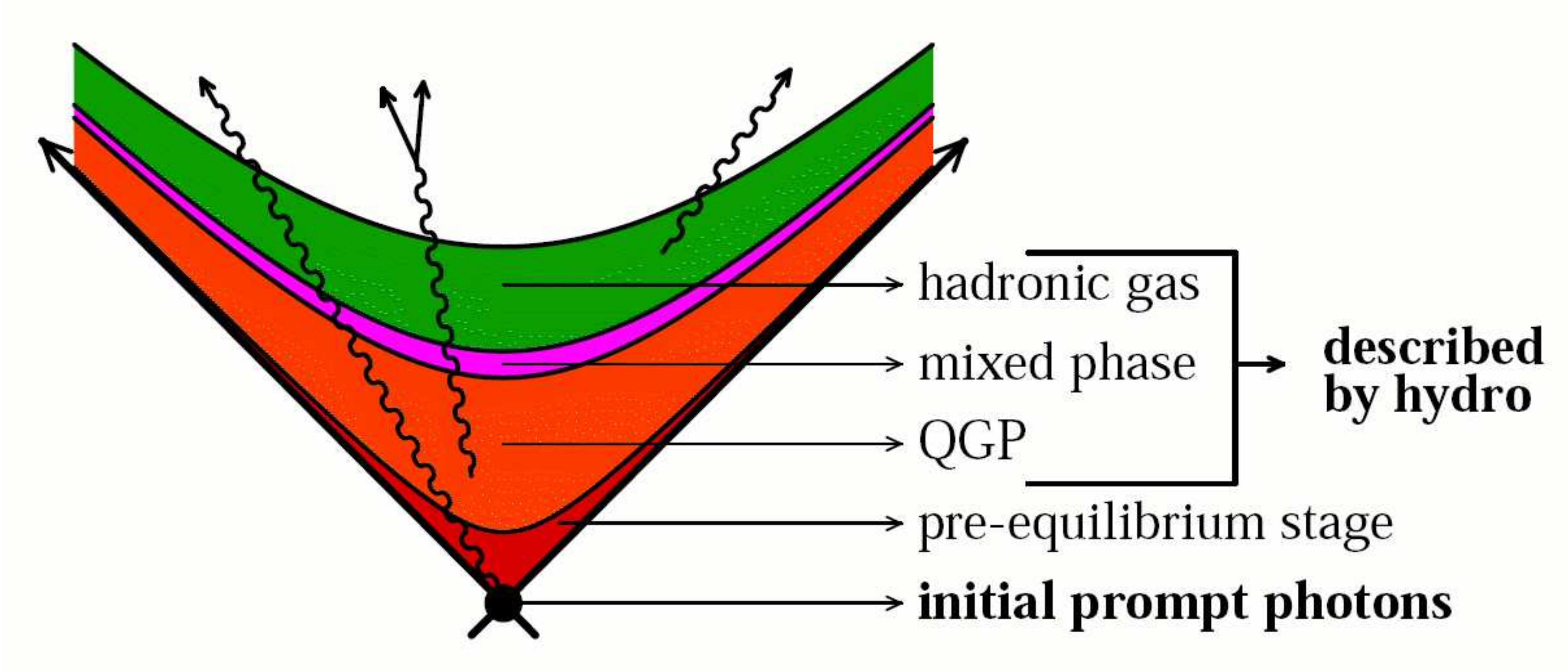
Stages of heavy ion collisions



[from F. Gelis]

- $t \simeq 5 - 15$ fm: Hadronic phase
  - Hadrons in thermal equilibrium

Stages of heavy ion collisions

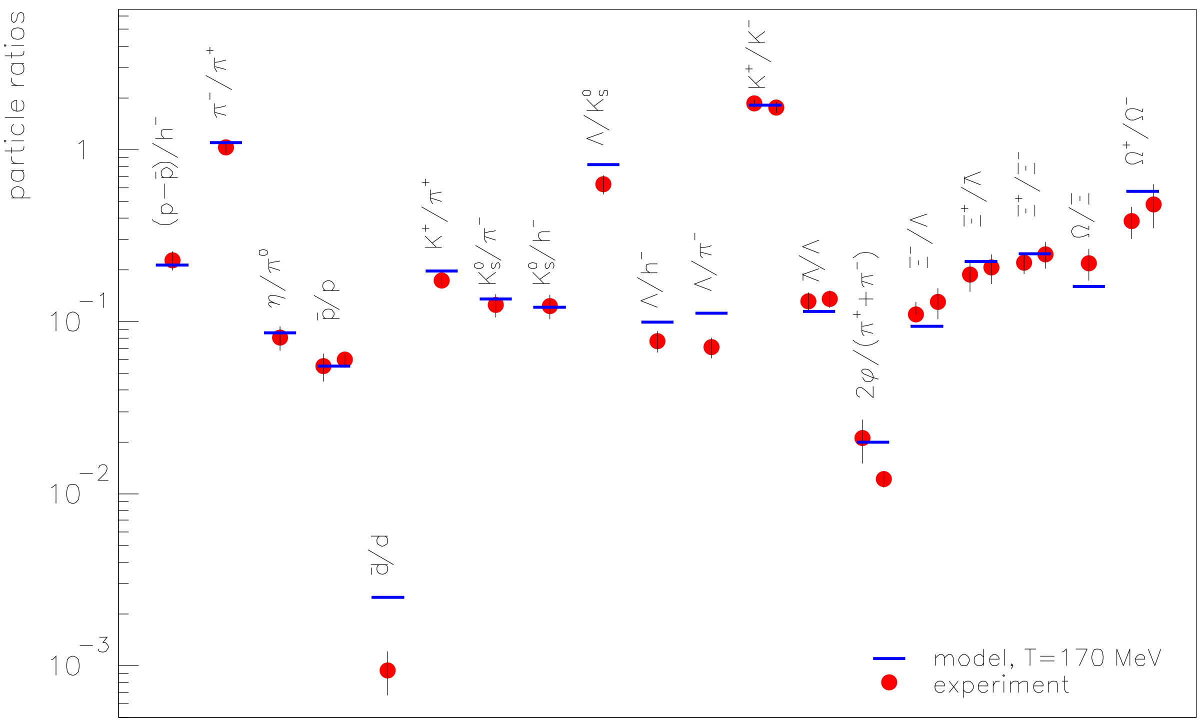


[from F. Gelis]

- $t \gtrsim 15$ fm: Freeze-out
  - Particles no longer interact

Heavy ions on the phase diagram

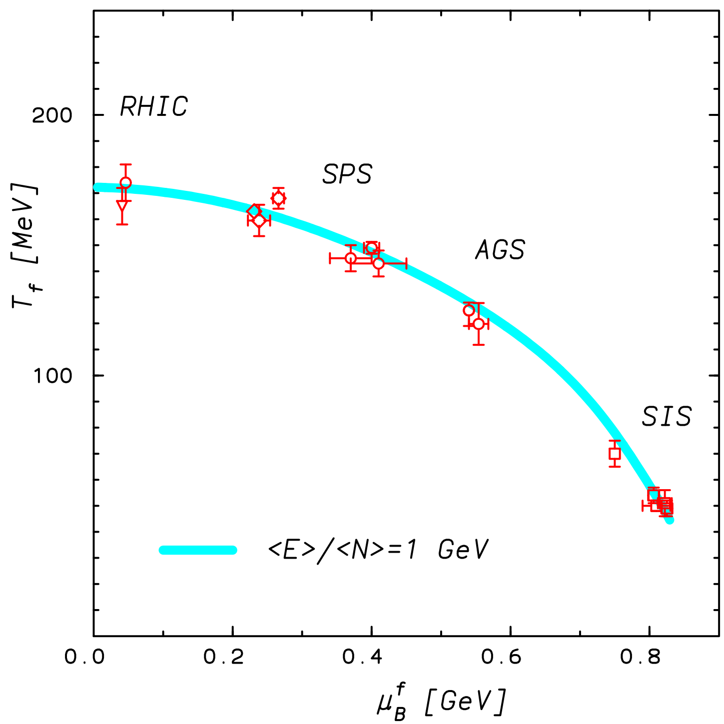
Statistical models allow for an estimate of both T and μ by fitting the relative hadron abundancies



[Braun-Munzinger et al. 2003]

Heavy ions on the phase diagram

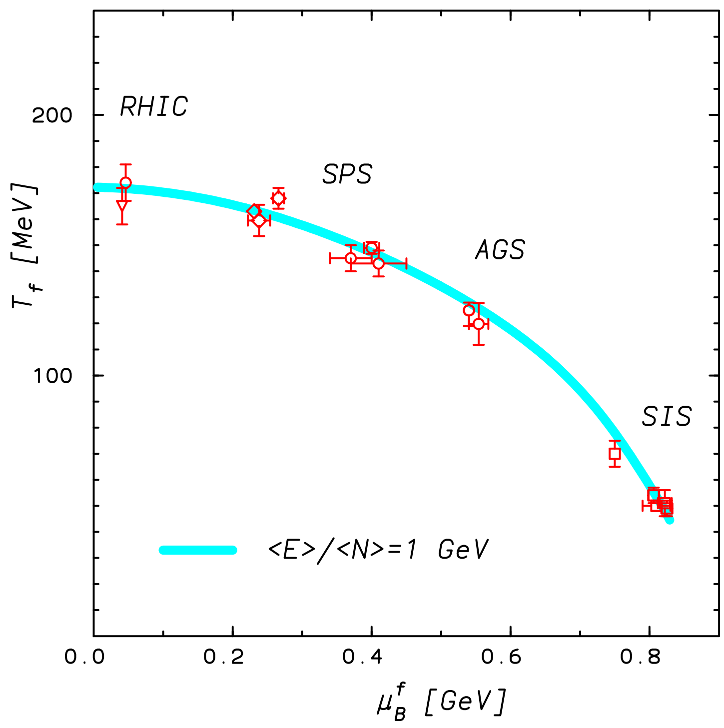
Statistical models allow for an estimate of both T and μ by fitting the relative hadron abundancies



- Low energy collisions (SIS, AGS) occur at small T but large μ

Heavy ions on the phase diagram

Statistical models allow for an estimate of both T and μ by fitting the relative hadron abundancies



- RHIC and LHC experiments essentially probe the vanishing chemical potential region

Signatures

Probing quark-gluon plasma formation

Remember one of the (most important) questions:

5. How do we probe its formation ?

Probing quark-gluon plasma formation

Remember one of the (most important) questions:

5. How do we probe its formation ?

Need for unambiguous observables

to probe quark-gluon plasma formation !

Probing quark-gluon plasma formation

Remember one of the (most important) questions:

5. How do we probe its formation ?

Need for unambiguous observables

to probe quark-gluon plasma formation !

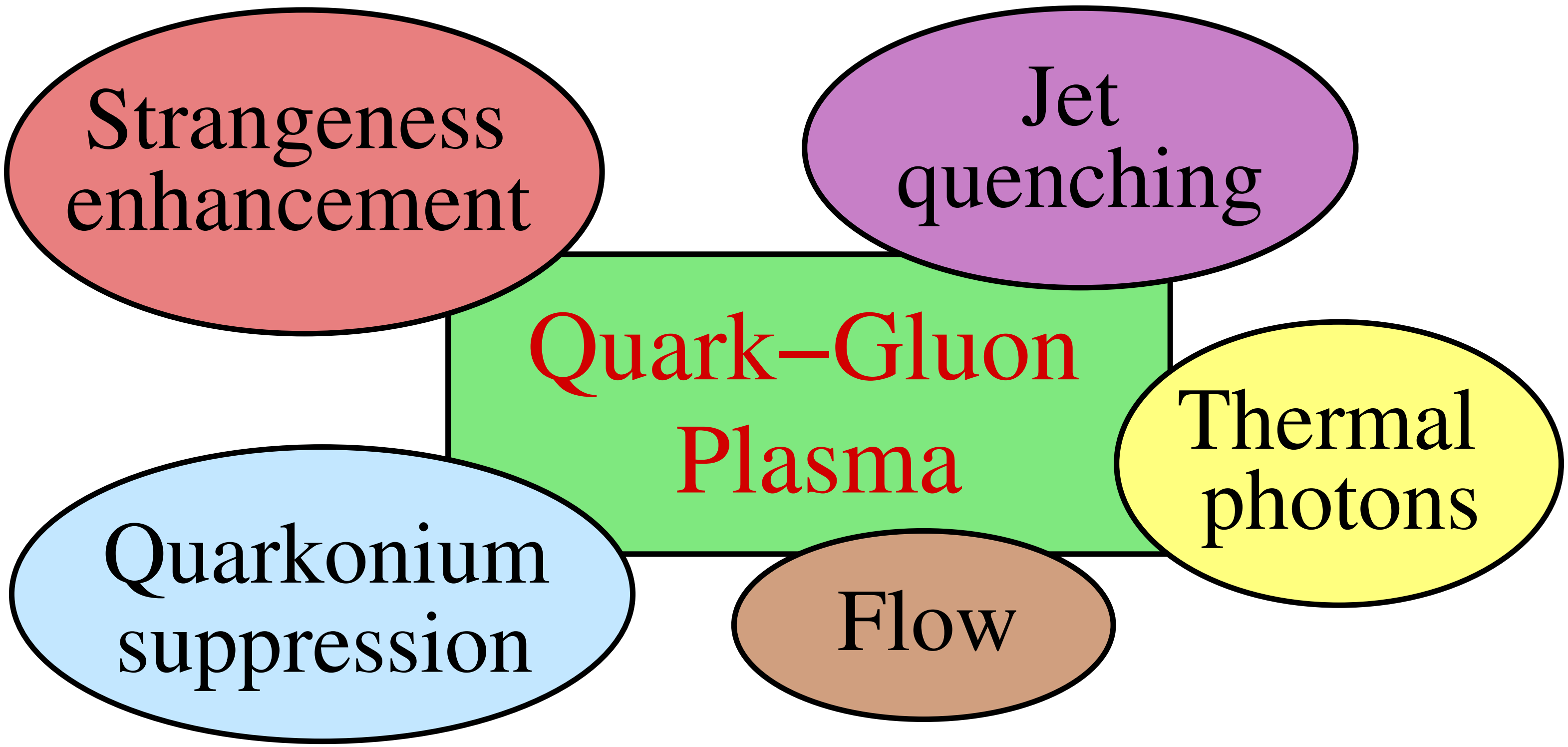
By unambiguous, we mean signals which should behave significantly differently if QGP formation occurs or not

Signatures

Many theoretical ideas have yet been advanced . . .

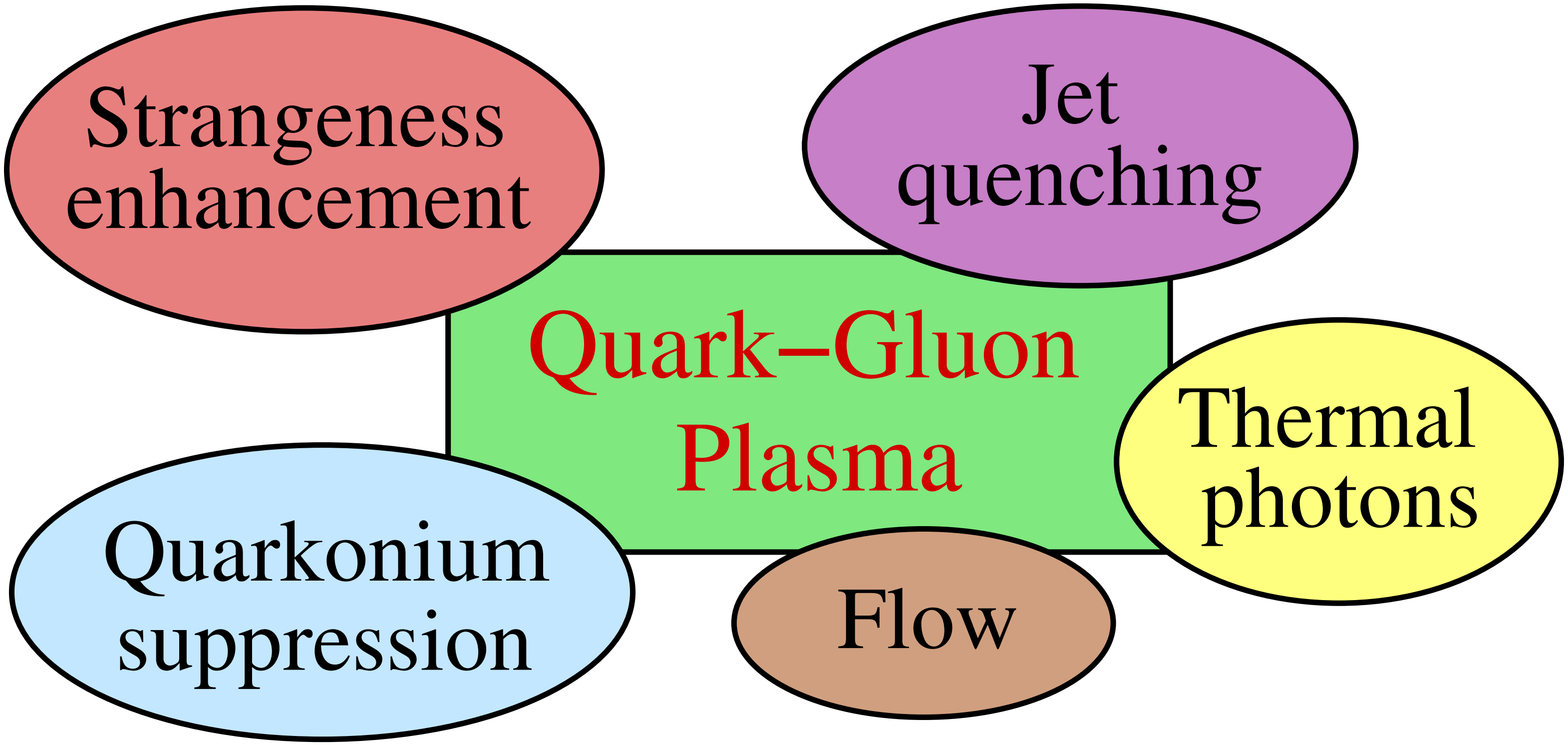
Signatures

Many theoretical ideas have yet been advanced . . .



Signatures

Many theoretical ideas have yet been advanced . . .



Let's discuss them !

Classification

Usual distinction between soft (bulk) and hard probes (hard scale) of QGP formation

Classification

Usual distinction between soft (bulk) and hard probes (hard scale) of QGP formation

- Soft probes
  - Strangeness production
  - Flow of particles

Advantage: many particles are produced !

Classification

Usual distinction between soft (bulk) and hard probes (hard scale) of QGP formation

- Soft probes
  - Strangeness production
  - Flow of particles

Advantage: many particles are produced !

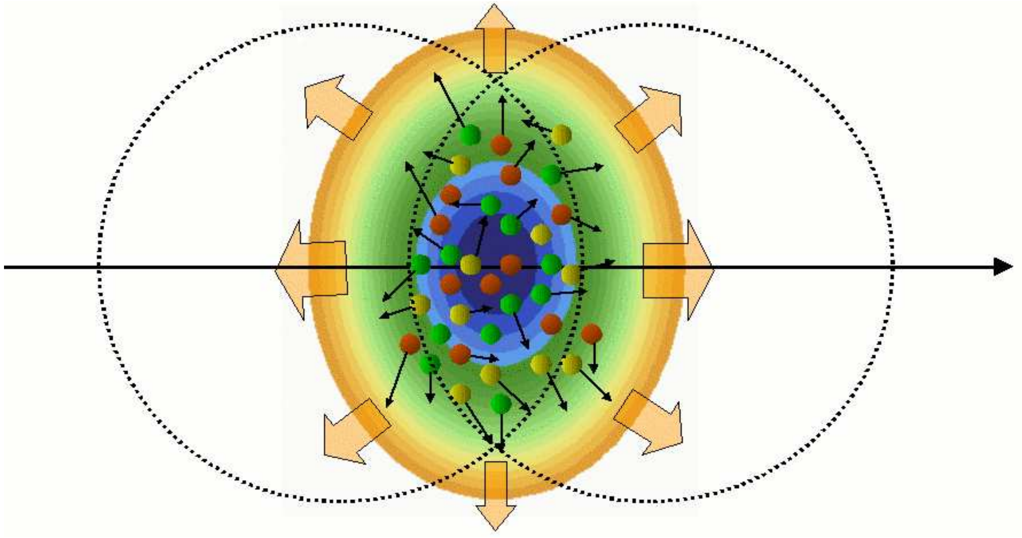
- Hard probes
  - Heavy-quarkonium production
  - Jet quenching

Advantage: computable in perturbative QCD !

Flow

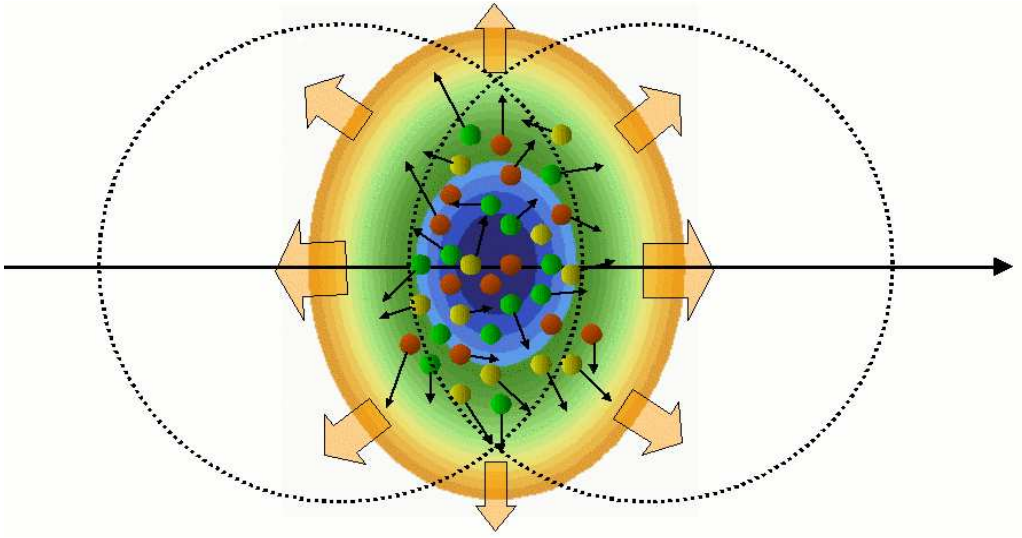
Flow

Consider a semi-peripheral heavy ion collision in the transverse plane



Flow

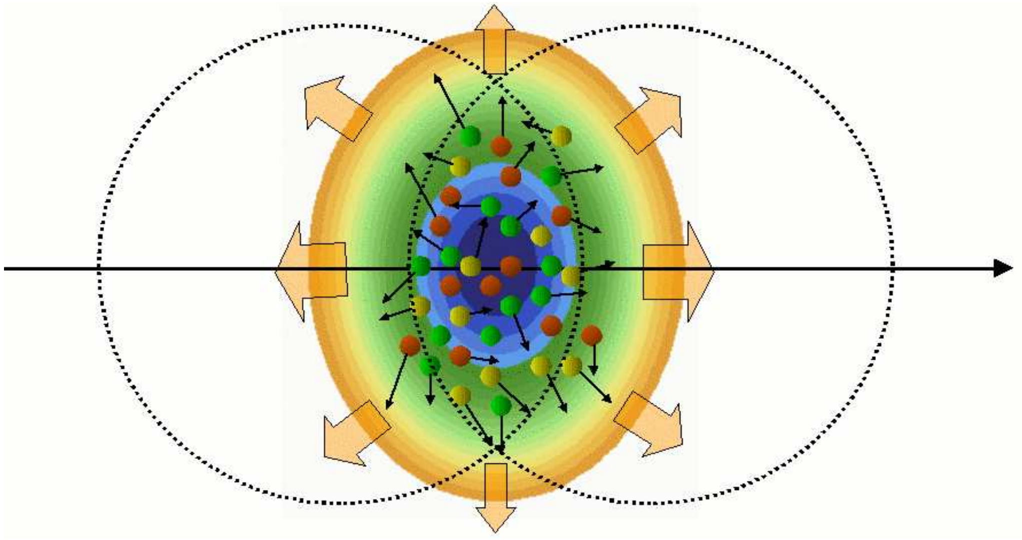
Consider a semi-peripheral heavy ion collision in the transverse plane



Asymmetry of the overlap region (almond shape) while momentum distribution are spherically symmetric

Flow

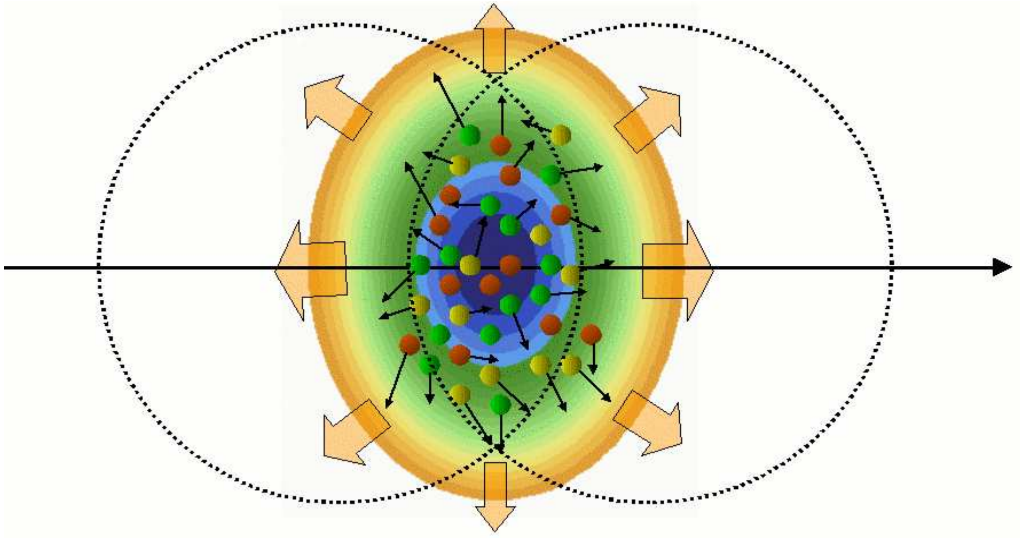
Consider a semi-peripheral heavy ion collision in the transverse plane



Rescattering process responsible for strong pressure gradient

Flow

Consider a semi-peripheral heavy ion collision in the transverse plane

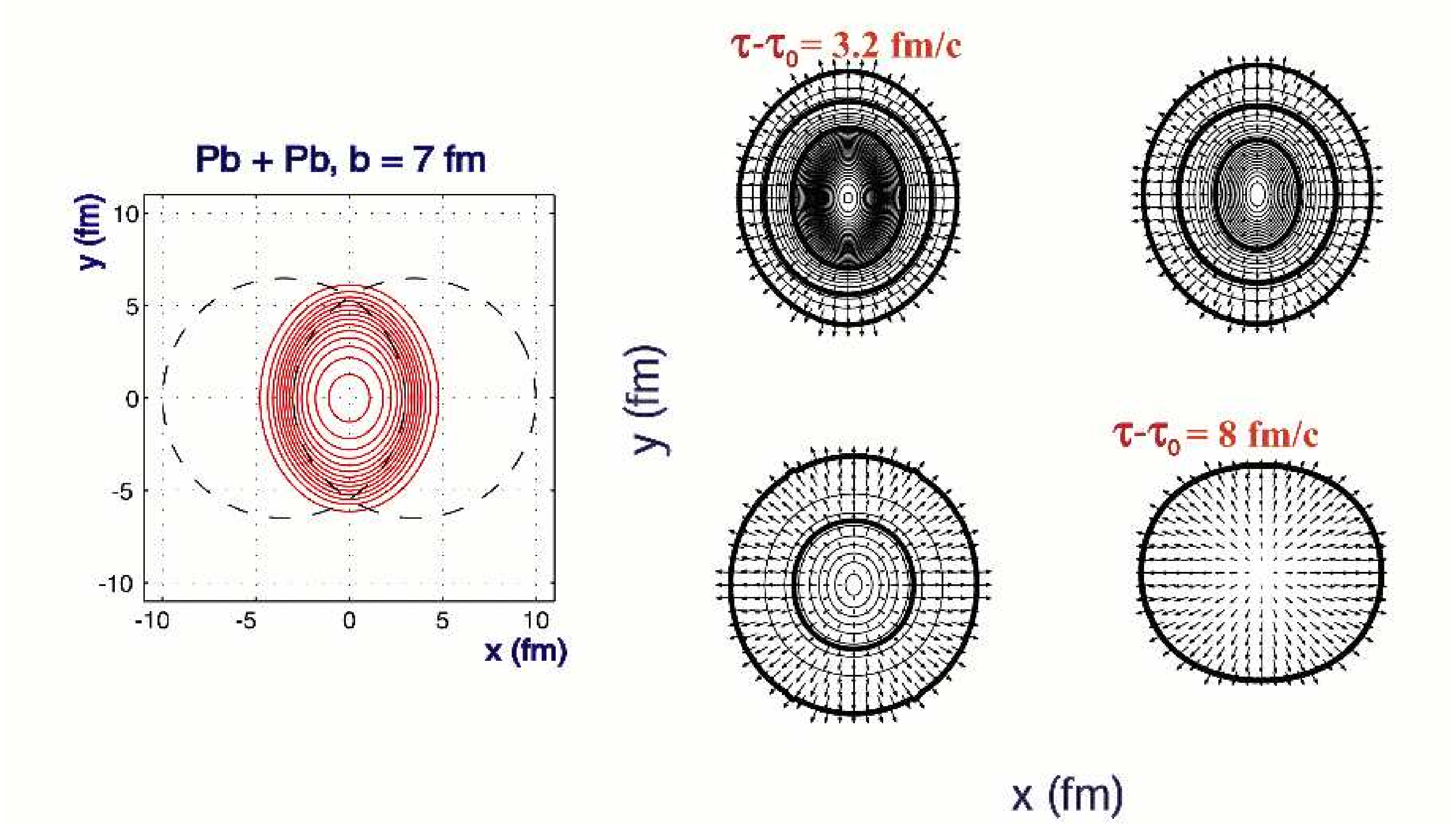


Rescattering process responsible for strong pressure gradient

- Converts space to momentum anisotropy
- Particles emitted preferably along the impact parameter axis
- The medium becomes more and more spherical: "self-quenching"

Flow

A hydrodynamical picture



Quantifying elliptic flow

How to quantify the asymmetry in momentum space ?

Quantifying elliptic flow

How to quantify the asymmetry in momentum space ?

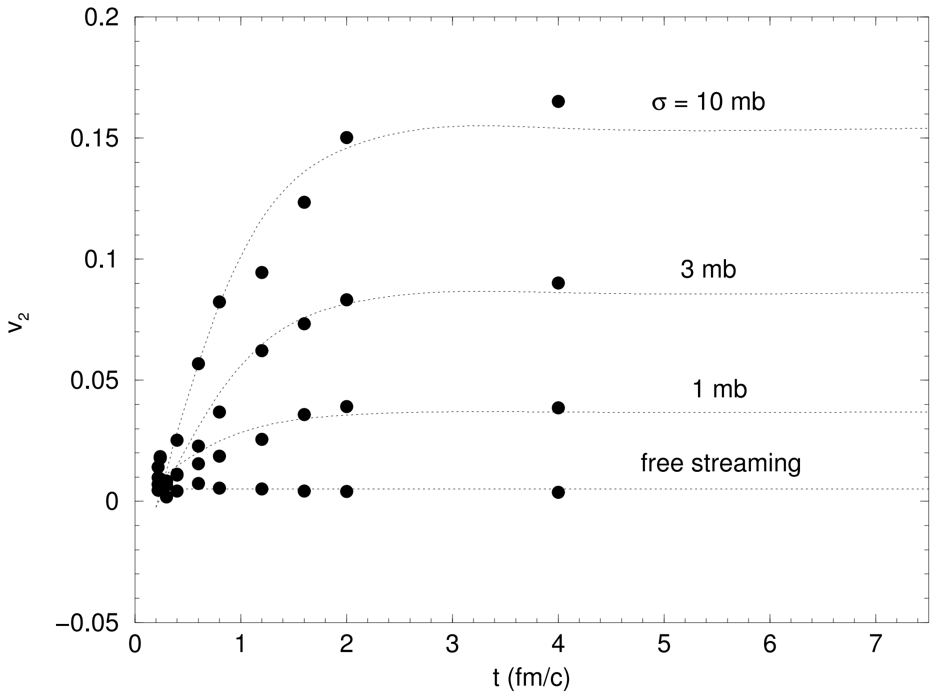
Adopt the Fourier decomposition of the momentum distribution

$$\frac{1}{N}\,\frac{\mathrm{d}N}{\mathrm{d}\phi} = 1 + \sum_{n=1}^{\infty} 2\, v_n \cos\left(n\phi\right)$$

Elliptic flow characterized by the second harmonics v_2

Time dependence

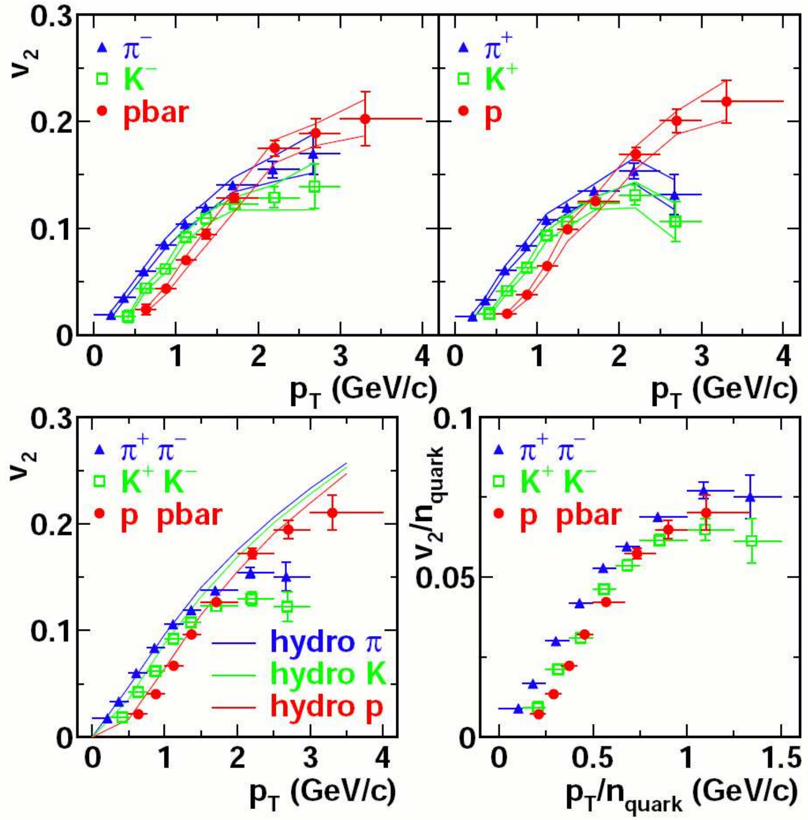
Since the asymmetry gets smaller as time goes by, elliptic flow sets in pretty early in the collision



Confirmed by transport model calculations

[Zhang, Gyulassy, Ko 1999]

Elliptic flow at RHIC

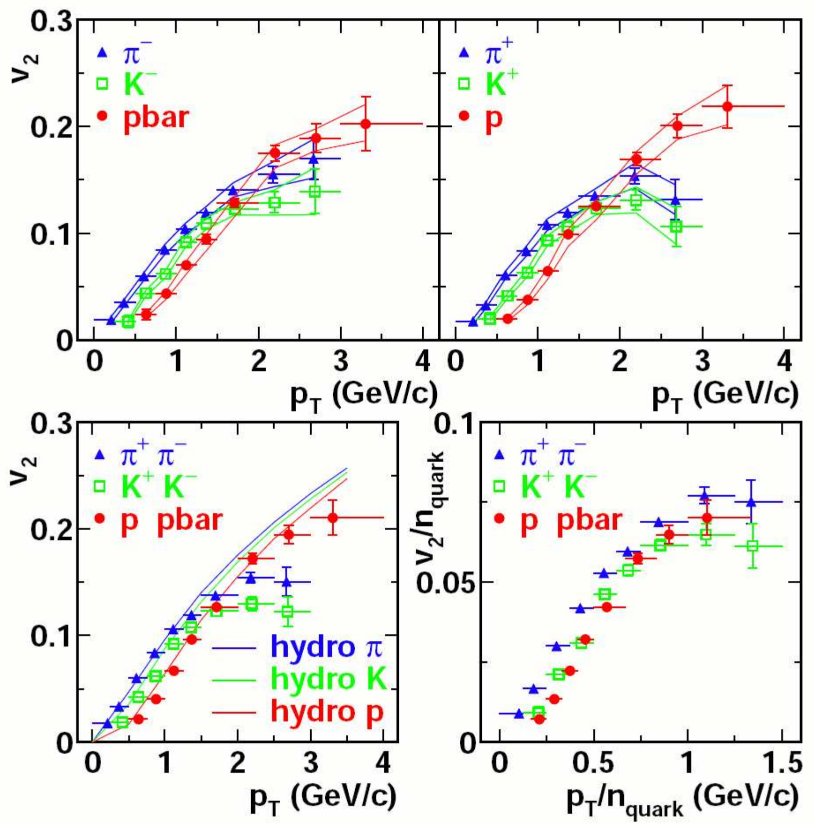


[STAR]

Elliptic flow at RHIC

Introduction
Phase transition
Heavy ion collisions
Signatures
Flow
- Flow
- Quantifying elliptic flow
- Time dependence
- Elliptic flow at RHIC
- Elliptic flow at LHC

Summary

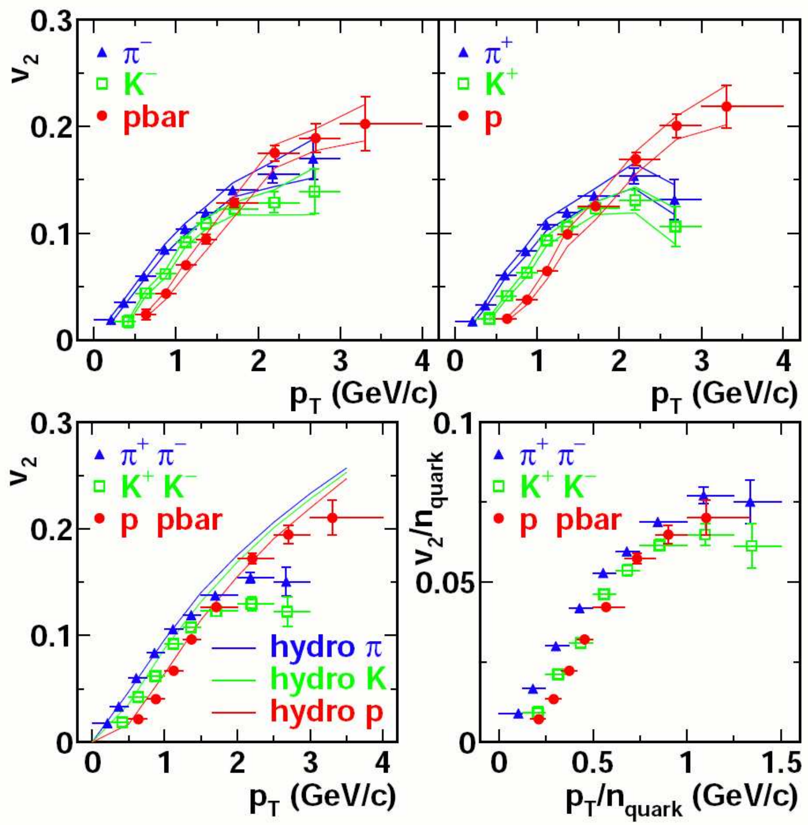


[STAR]

Hydrodynamical calculations reproduce well (with $t_0 \simeq 0.5$ fm)

- the elliptic flow as a function of $p_\perp$
- the mass ordering $v_2 = v_2(p_\perp/m)$ seen in data

Elliptic flow at RHIC



[STAR]

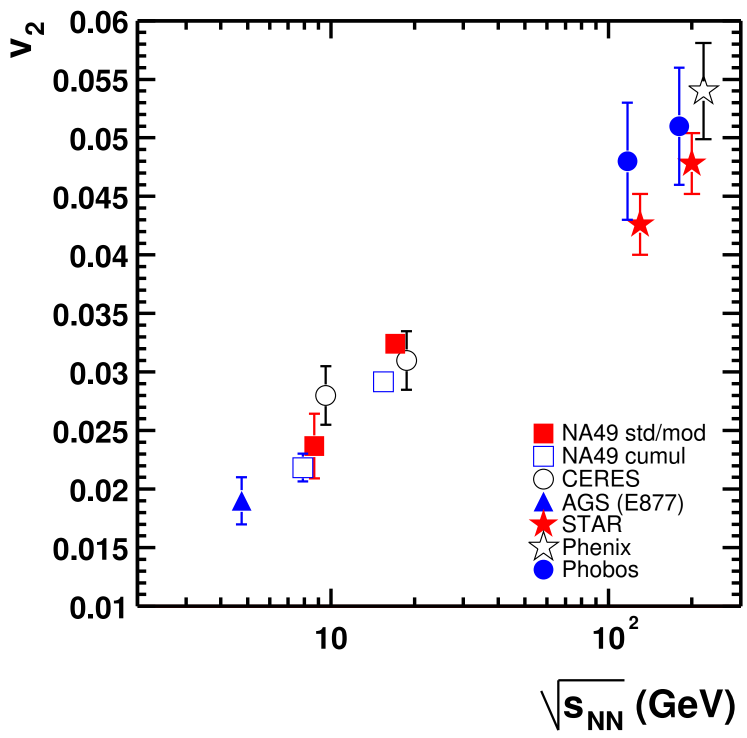
Evidence for strong rescattering process at RHIC !

Elliptic flow at LHC

What is the expected v_2 at the LHC ?

Elliptic flow at LHC

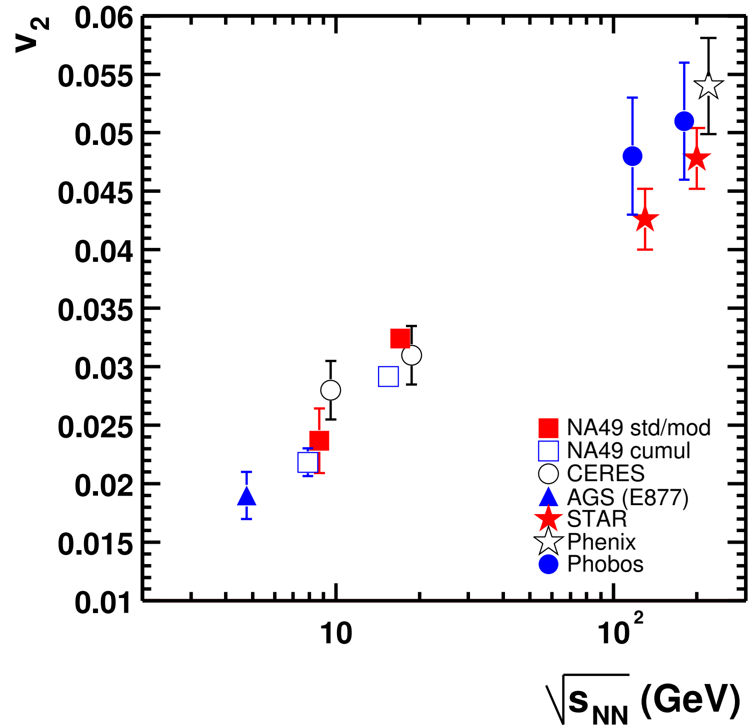
What is the expected v_2 at the LHC ?



[NA49]

Elliptic flow at LHC

What is the expected v_2 at the LHC ?

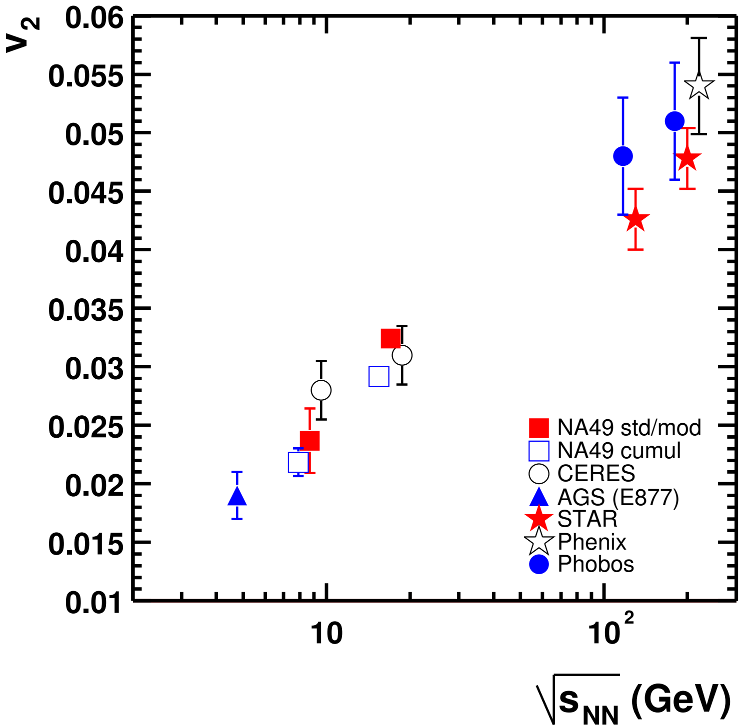


[NA49]

- If thermal equilibration at RHIC
  - $v_2(\text{LHC}) \simeq v_2(\text{RHIC})$

Elliptic flow at LHC

What is the expected v_2 at the LHC ?



[NA49]

- If incomplete thermalization at RHIC
  - v_2(LHC) $\gg$ v_2(RHIC)

Summary

Summary

- Lattice QCD predicts a transition from hadronic matter to quark-gluon plasma at $T_c \simeq 200$ MeV

Summary

- Lattice QCD predicts a transition from hadronic matter to quark-gluon plasma at $T_c \simeq 200$ MeV
- Deconfinement occurs most probably through a crossover transition

Summary

- Lattice QCD predicts a transition from hadronic matter to quark-gluon plasma at $T_c \simeq 200$ MeV
- Deconfinement occurs most probably through a crossover transition
- Heavy ion collisions at high energy allow for quark-gluon plasma formation

Summary

- Lattice QCD predicts a transition from hadronic matter to quark-gluon plasma at $T_c \simeq 200$ MeV
- Deconfinement occurs most probably through a crossover transition
- Heavy ion collisions at high energy allow for quark-gluon plasma formation
- Need for experimental signatures
    - Flow, strangeness, thermal photons, quarkonium production, jet quenching . . .

Summary

- Lattice QCD predicts a transition from hadronic matter to quark-gluon plasma at $T_c \simeq 200$ MeV
- Deconfinement occurs most probably through a crossover transition
- Heavy ion collisions at high energy allow for quark-gluon plasma formation
- Need for experimental signatures
  - Flow, strangeness, thermal photons, quarkonium production, jet quenching . . .

These will be further discussed in the next lecture !