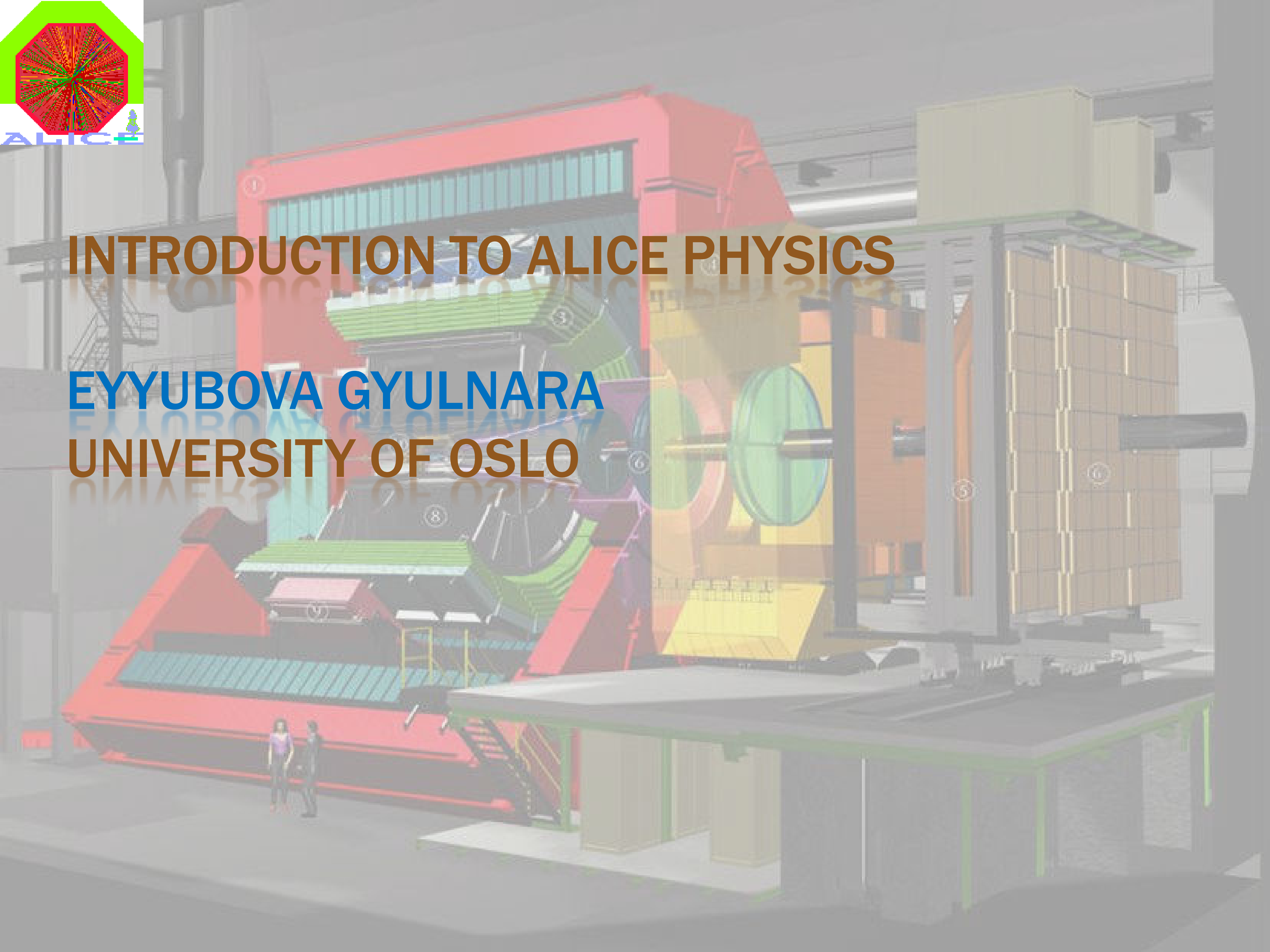


INTRODUCTION TO ALICE PHYSICS

EYYUBOVA GYULNARA
UNIVERSITY OF OSLO

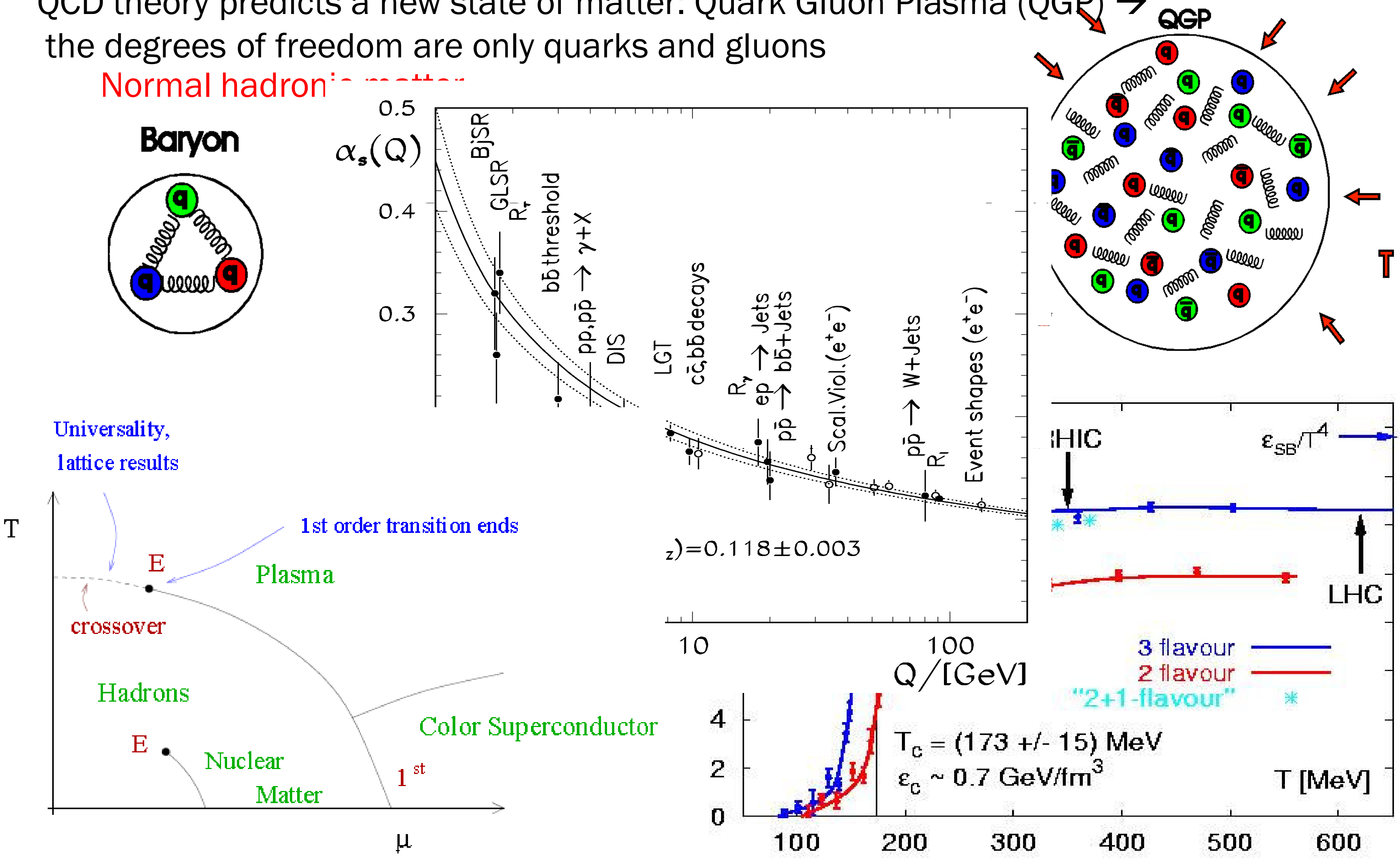
ALICE — A Large Ion Collider Experiment — is being prepared to study the physics of nuclear matter under extreme conditions of temperature and density.

Schematic view of high energy PbPb collisions by URQMD model.

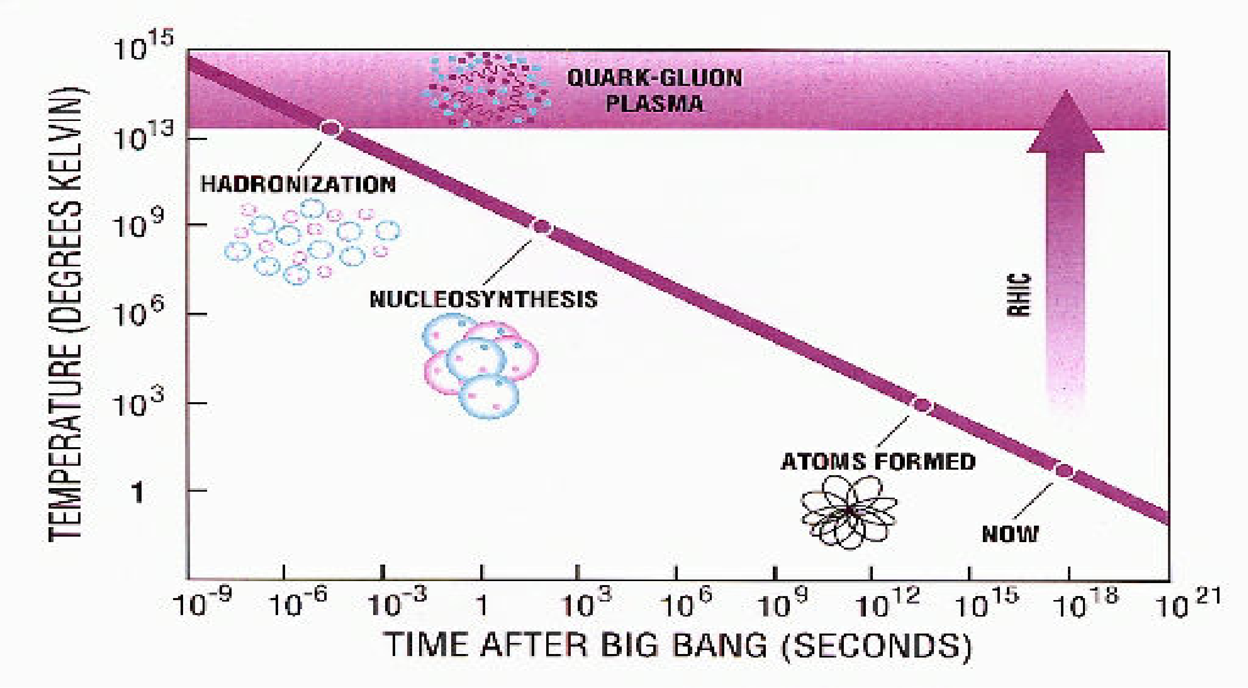
THE QUARK-GLUON PLASMA

QCD theory predicts a new state of matter: Quark Gluon Plasma (QGP) → the degrees of freedom are only quarks and gluons

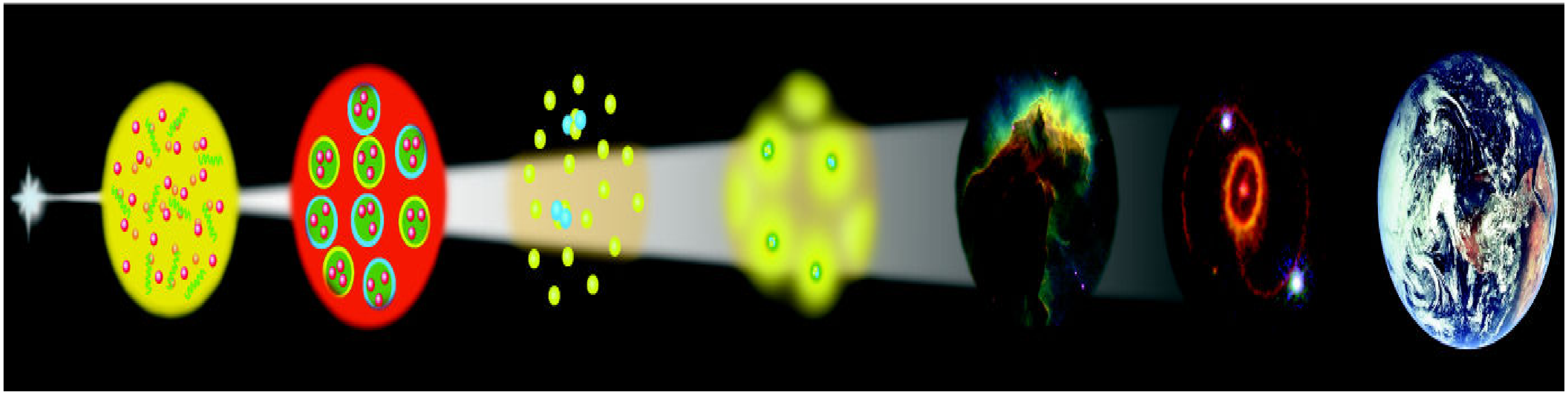
Normal hadron



QGP , the early state of matter of our universe



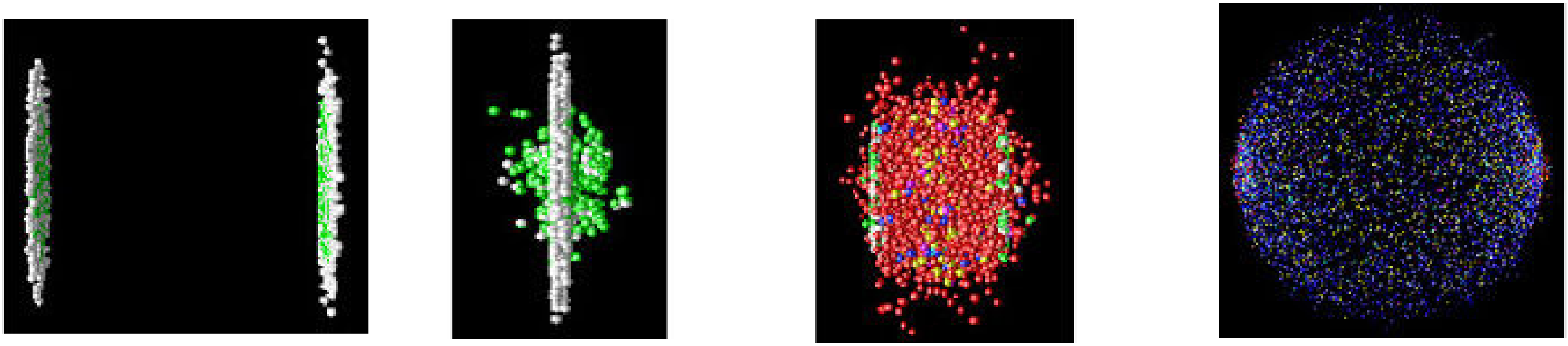
98 Contemporary Physics Education Project (CPEP)



Big Bang	quark-gluon plasma	p + n formation	low mass nuclei formation	neutral atom formation	star formation	dispersion of heavy elements	TODAY
time	10^{-6}s	10^{-4}s	3 min	400,000 yr	10^{9} yr	$>10^{9}$yr	5×10^{9}yr

A PROCESS OF COLLISION

Many-body system, statistical approach, hydro approach



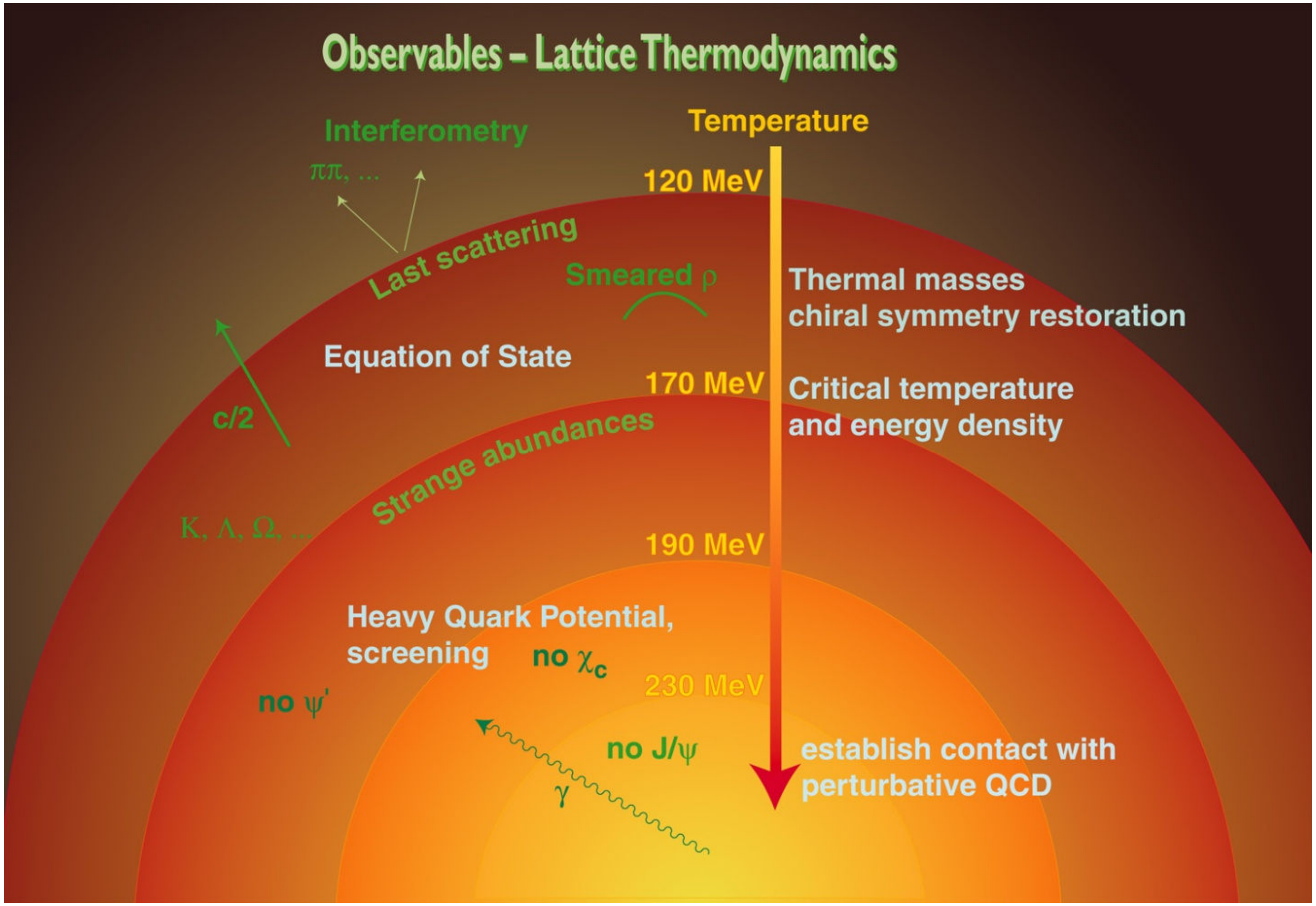
QG plasma formation

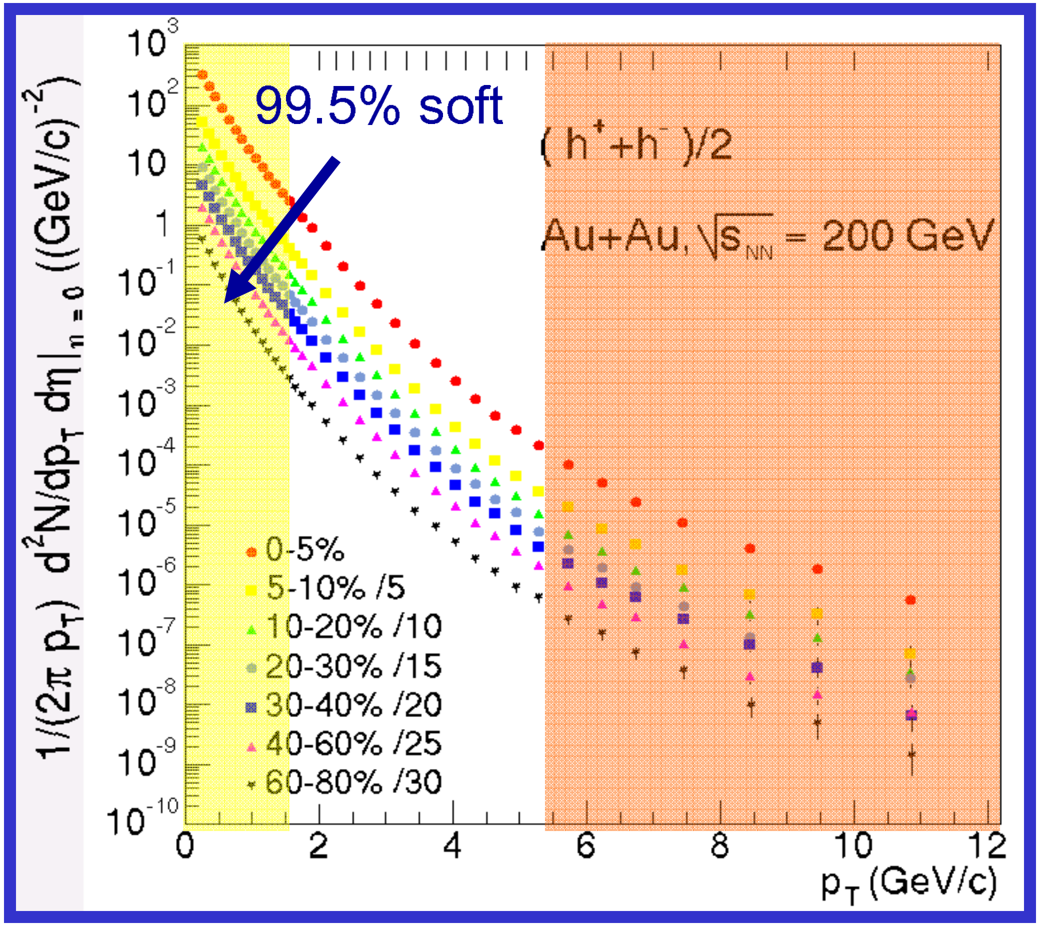
system expands and cools, hadronization

One important feature of relativistic heavy ion collisions is that hadrons show a collective behavior.

- The **chemical** freeze out fixes the particle yields at the hadronization stage
- the **kinetic** freeze out affects particle momenta.

QGP OBSERVABLES (PROBES)





"Hard physics"
Particle production characterized by large momentum transfer

- **Interactions occur at the partonic level**
- **Small coupling constants**

"Soft physics"
pQCD is not valid
Phenomenological modeling

Particle production is dominated by soft particles

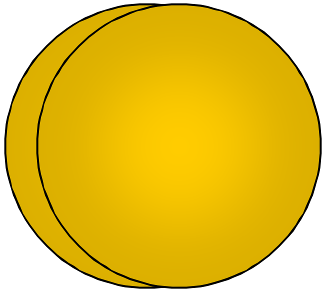
EFFECTS OF SOFT PROCESSES, DOMINATING THE LOW MOMENTUM REGION, ARE WELL INTERPRETED BY HYDRODYNAMICAL MODELS,

IN THE INTERMEDIATE MOMENTUM REGION (PT 2–5GEV/C) THE ROLE OF SOFT AND HARD PROCESSES IS STILL UNDER INVESTIGATION

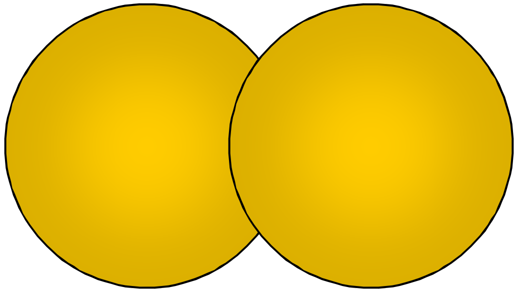
Central collisions	SPS	RHIC	LHC
$s^{1/2}$(GeV)	17	200	5500
dN_{ch}/dy	500	650	3-8 x10^3
ε (GeV/fm^3)	2.5	3.5	15-40
V_f(fm^3)	10^3	7x10^3	2x10^4
τ_{QGP} (fm/c)	<1	1.5-4.0	4-10

CENTRALITY

"Centrality" characterizes a collision and categorizes events.



central event



peripheral event

- N_{PART} number of participating nucleos
- N_{COLL} number of binary (nucleon-nucleon) collisions

QGP OBSERVABLES (PROBES)

In ALICE, the QGP observables are traditionally subdivided into three classes:

I. soft probes (with the typical p <2 GeV/c)

II. heavy-flavour probes (using the particles having c- and b-quarks)

III. high-pt probes (in the p range above 5-6 GeV/c).

soft probes

Multiplicity Measurements!

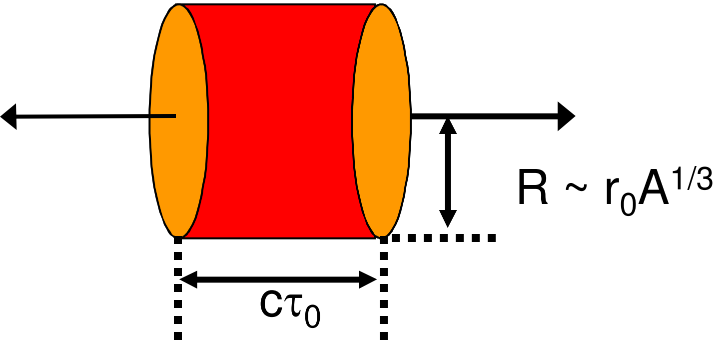
Why ?

Multiplicity provides insights on:

- Energy density of the system

  (via Bjorken formula)
- Mechanisms of particle production

  (hard vs. soft)
- Thermalization



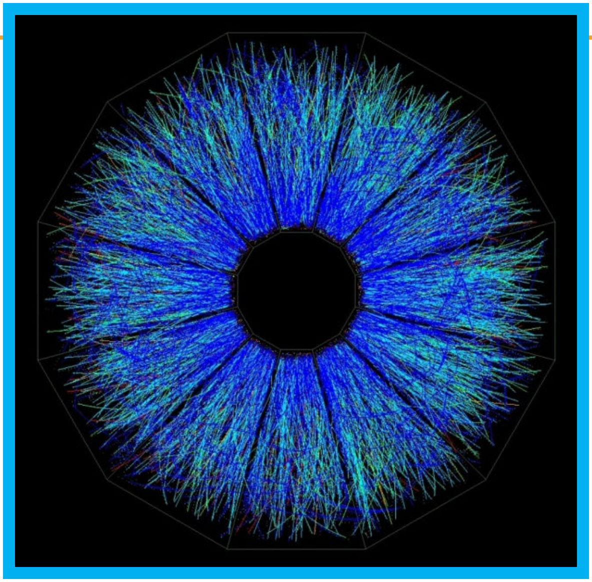
Bjorken

$$\varepsilon_{Bj} = \frac{1}{\pi R^2}\frac{1}{\tau_0}\frac{dE_T}{dy}$$

Phenix: E_T measurement at 130 GeV

ε_0 = 4.6 [GeV/fm^3] PRL 87, 052301 (2001)

Above the critical value $\varepsilon_c \sim 1$ GeV/fm^3

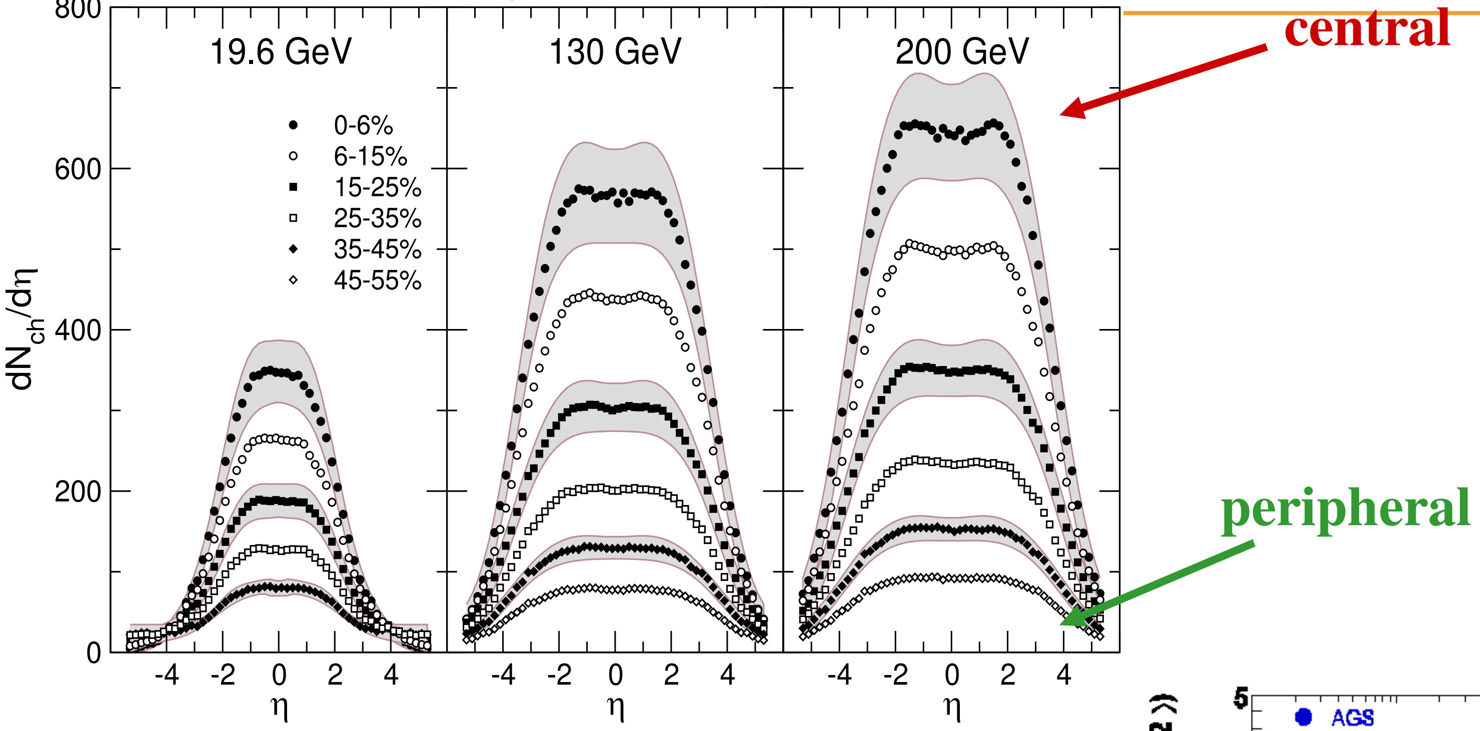


In central AuAu collisions at RHIC (√s=200 GeV) about 5000 particles are created

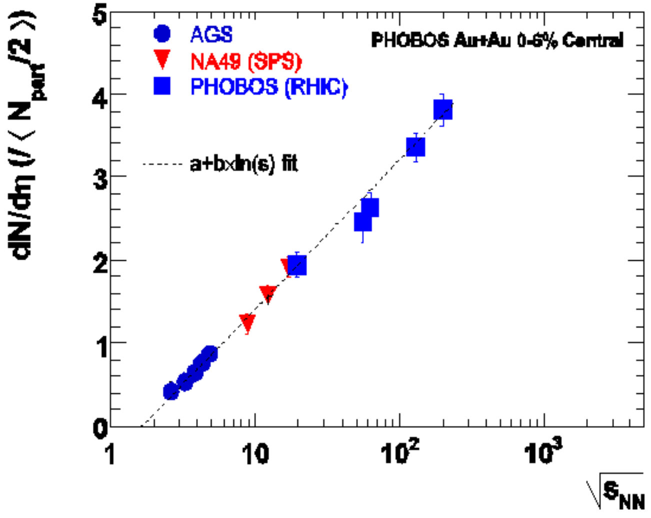
$$\eta = \frac{1}{2}\cdot\ln\left(\frac{|\mathbf{p}|+p_L}{|\mathbf{p}|-p_L}\right) = -\ln\left[\tan\left(\frac{\vartheta}{2}\right)\right]$$

$$y = \frac{1}{2}\cdot\ln\left(\frac{E+p_L}{E-p_L}\right)$$

Multiplicity Measurements!



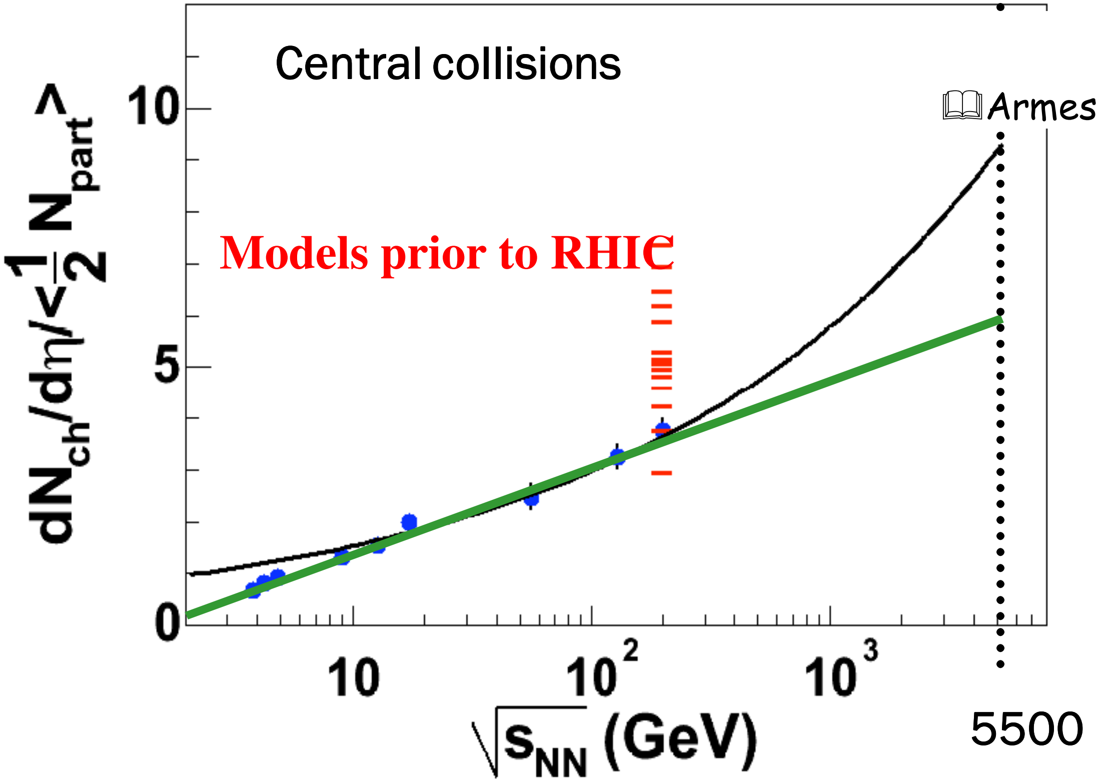
energy √s



The dN/dη per participant pair at mid-rapidity in central heavy ion collisions increases with In √s from AGS to RHIC energies

Soft physics at the LHC

- Extrapolation of $dN_{ch}/d\eta_{max}$ vs √s
  - Fit to $dN/d\eta \propto \ln s$
  - Saturation model ($dN/d\eta \propto \sqrt{s}^{\lambda}$ with $\lambda=0.288$)
  - The first 10k events at the LHC could be decisive



Saturation model

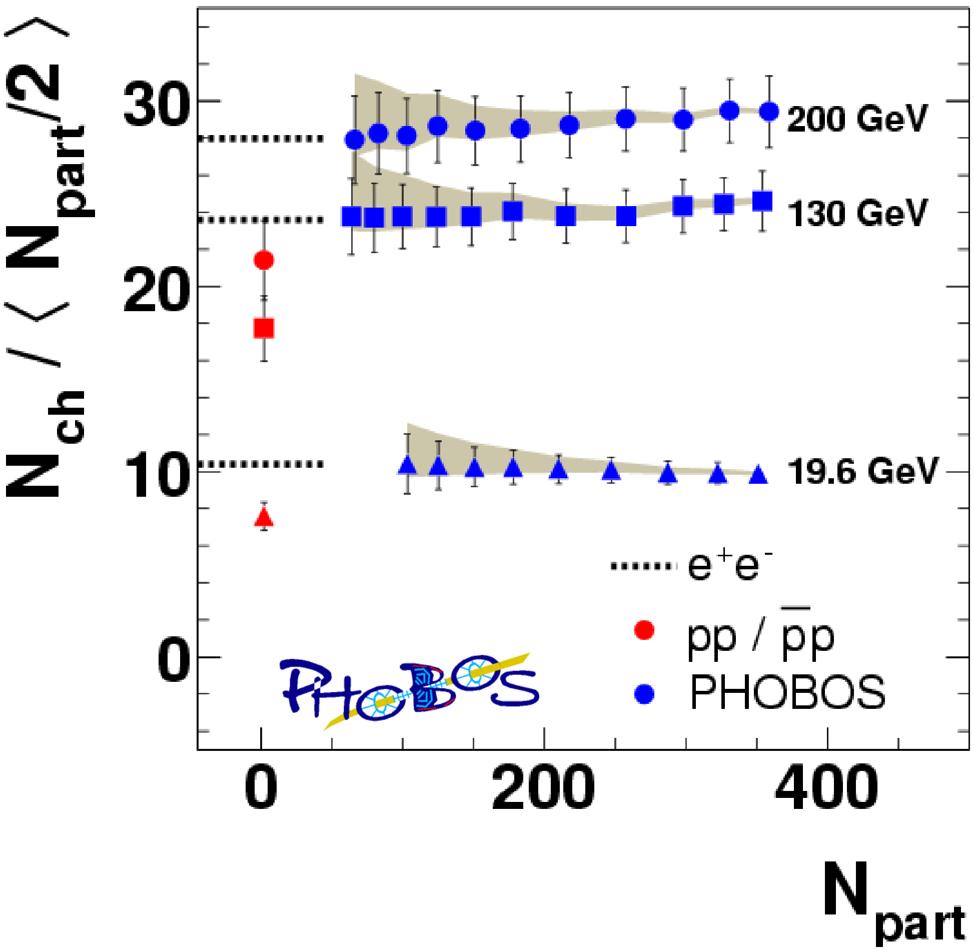
Armesto Salgado Wiedemann, PRL 94 (2005) 022002

$$\left.\frac{dN_{ch}/d\eta}{N_{part}/2}\right|_{\eta=0} \approx 8.2 \Rightarrow \left.\frac{dN_{ch}}{d\eta}\right|_{\eta=0} \approx 1650$$

Extrapolation of $dN/d\eta \propto \ln \sqrt{s}$

$$\left.\frac{dN_{ch}/d\eta}{N_{part}/2}\right|_{\eta=0} \approx 5.5 \Rightarrow \left.\frac{dN_{ch}}{d\eta}\right|_{\eta=0} \approx 1100$$

Scaling properties of Multiplicity Measurements!



- Total multiplicity:

$$N_{ch} = \int \frac{dN}{d\eta} d\eta$$

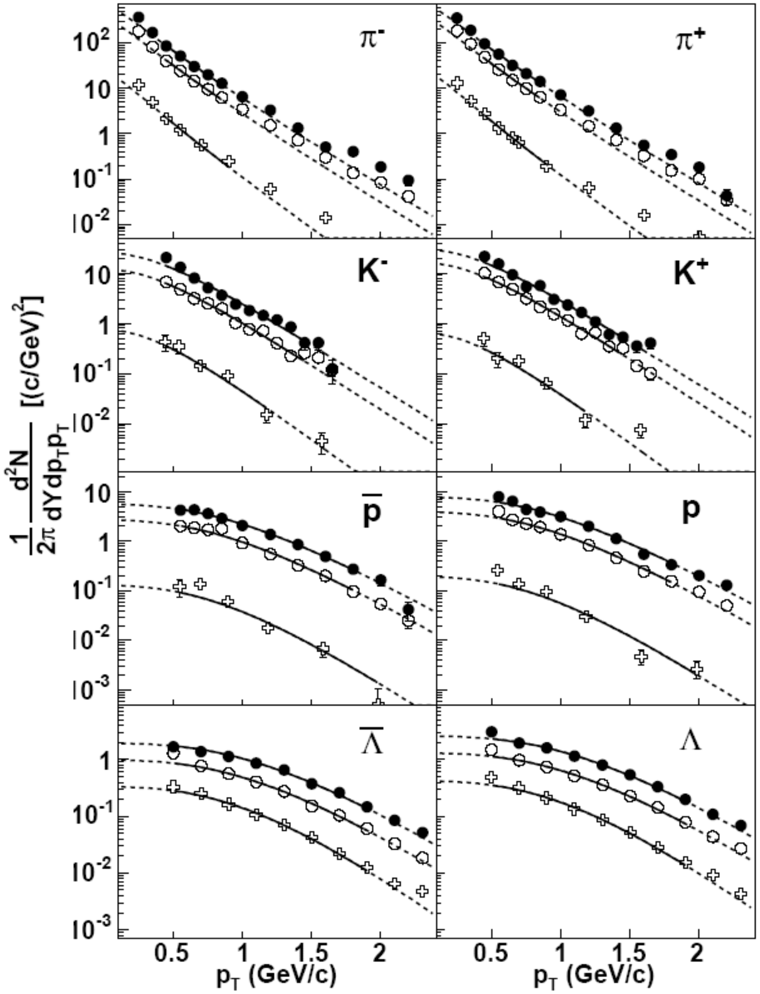
- N_{ch} scales with N_{part}
- N_{ch} per participant pair different from p-p, but compatible with e^+e^-, collisions at the same energy

Simple scaling rules dominate!

DETAILED ANALYSIS OF PARTICLE SPECTRA

Fit with hydro-dynamically motivated “blast waves” to gain insight into the dynamics of the collision.

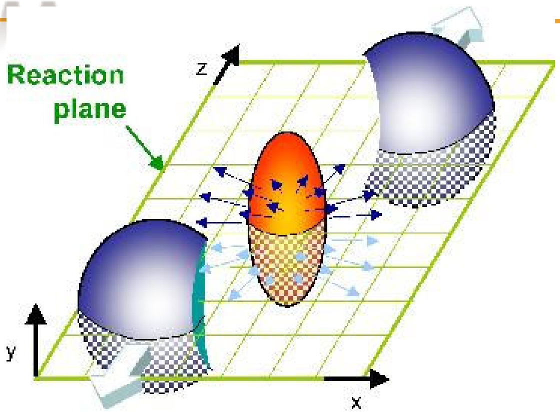
Retiere and Lisa – nucl-th/0312024



→ **Can describe the data with a common transverse “flow” velocity.**

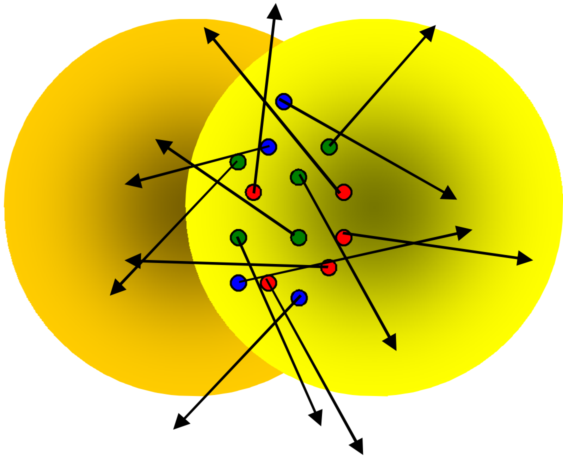
→ This velocity is large $<B_T>$~0.5c

SOFT QGP PROBES
ELLIPTIC FLOW



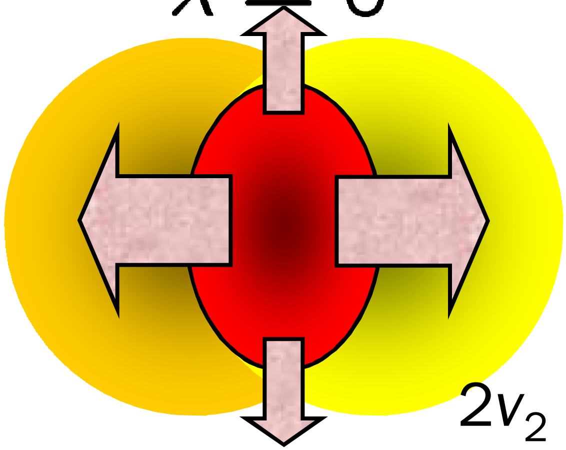
No secondary interaction

$$\lambda \to \infty$$



Hydro behavior

$$\lambda = 0$$

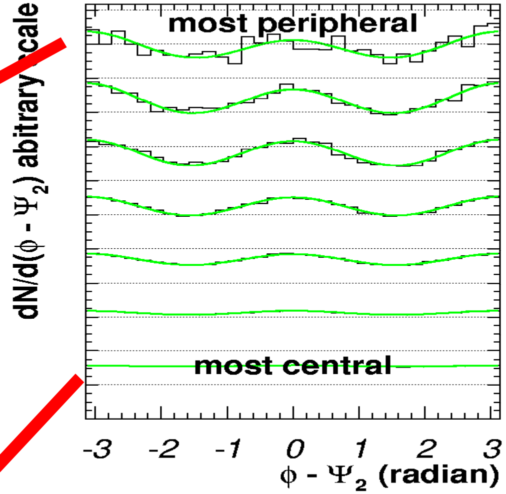


$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1+\sum_{n=1}^{\infty} 2v_n \cos\left[n(\phi-\Psi_r)\right]\right)$$

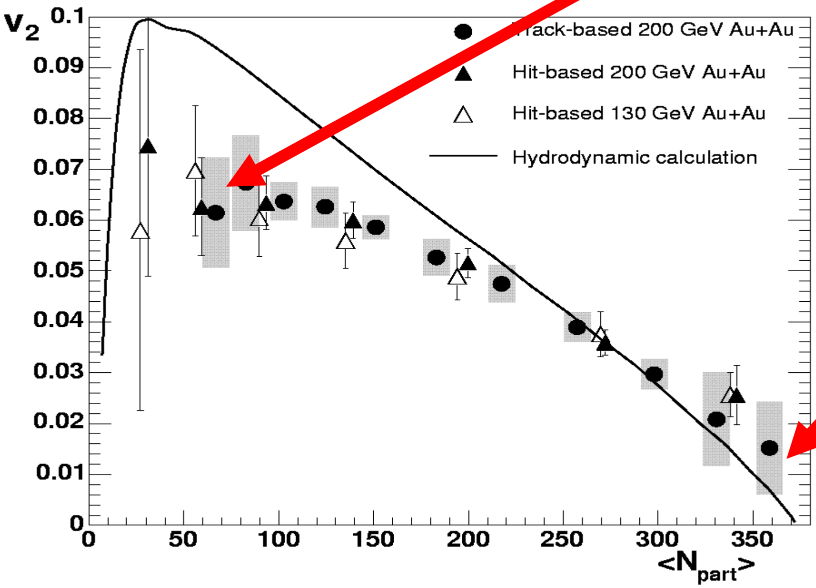
Fourier coefficient

Angle of reaction plane

FOURIER ANALYSIS OF EMISSION PATTERNS



PHOBOS: Phys. Rev. C72, 051901(R) (2005)



Increasing Collision Centrality

→ Find significant values of v_2 for non-central collisions

→ Collective Behavior

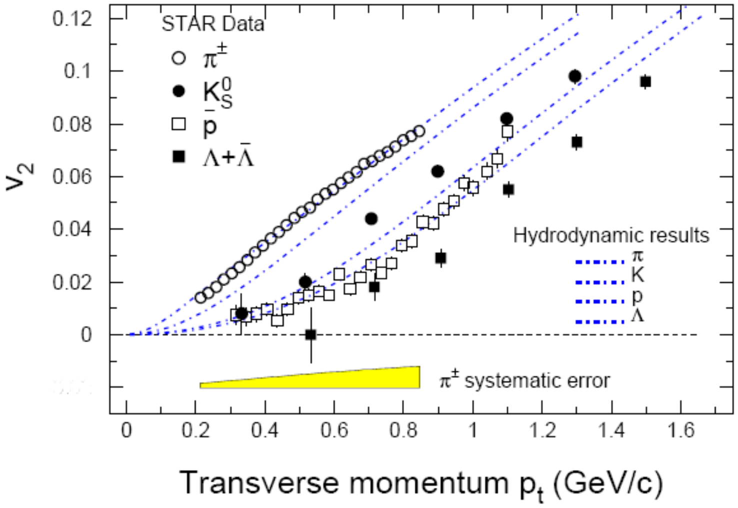
→ Reaches Hydro Limit (first time seen in HI collisions)

→ Fast Equilibration Timescales

MOMENTUM AND SPECIES DEPENDENCE OF V_2

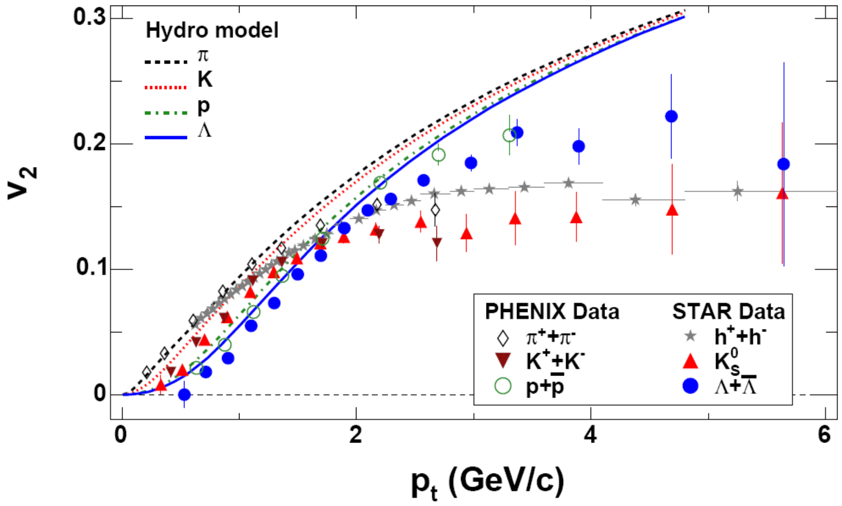
Lower Momentum

STAR PRC 72 (05) 014904



Higher Momentum

STAR PRC 72 (05) 014904

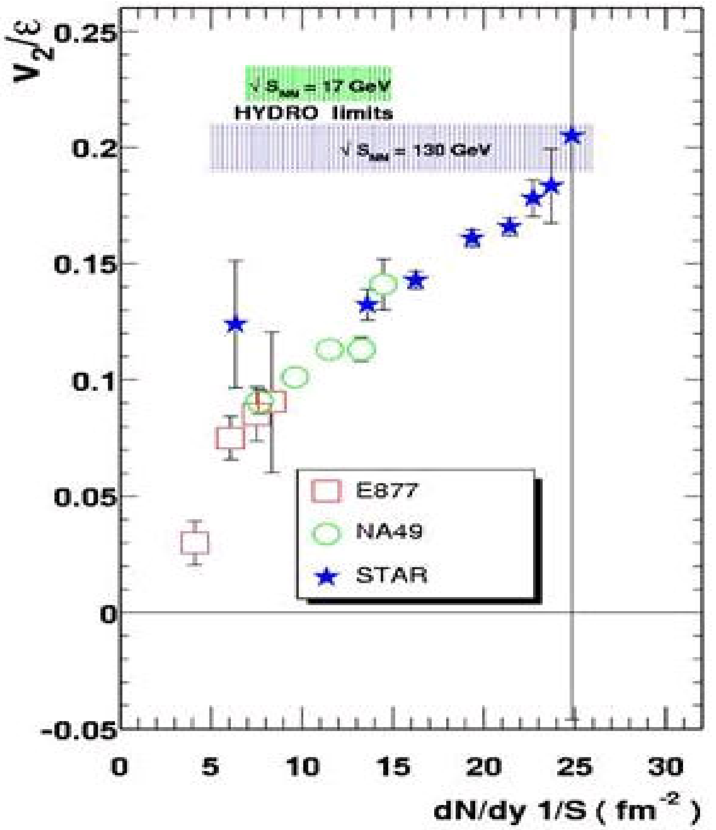


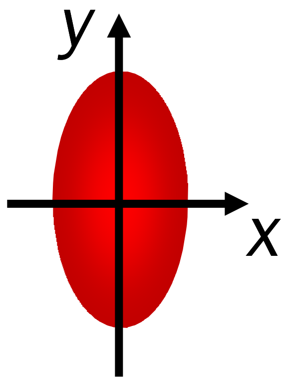
→ the mass splitting can be described in full hydro models
(with, e.g., the additional collective transverse flow velocity from spectra fits)

ARRIVAL AT HYDRODYNAMIC LIMIT

It's been predicted (Phys Lett B474 (2000) 27.) in the low density limit, $v_2 \propto \varepsilon$ and the density of scattering centres. Ie. $v_2/\varepsilon \propto (1/S)\, dN_{ch}/d\eta$

$v2/\varepsilon$ should saturate at large particle densities (hydro-limit).



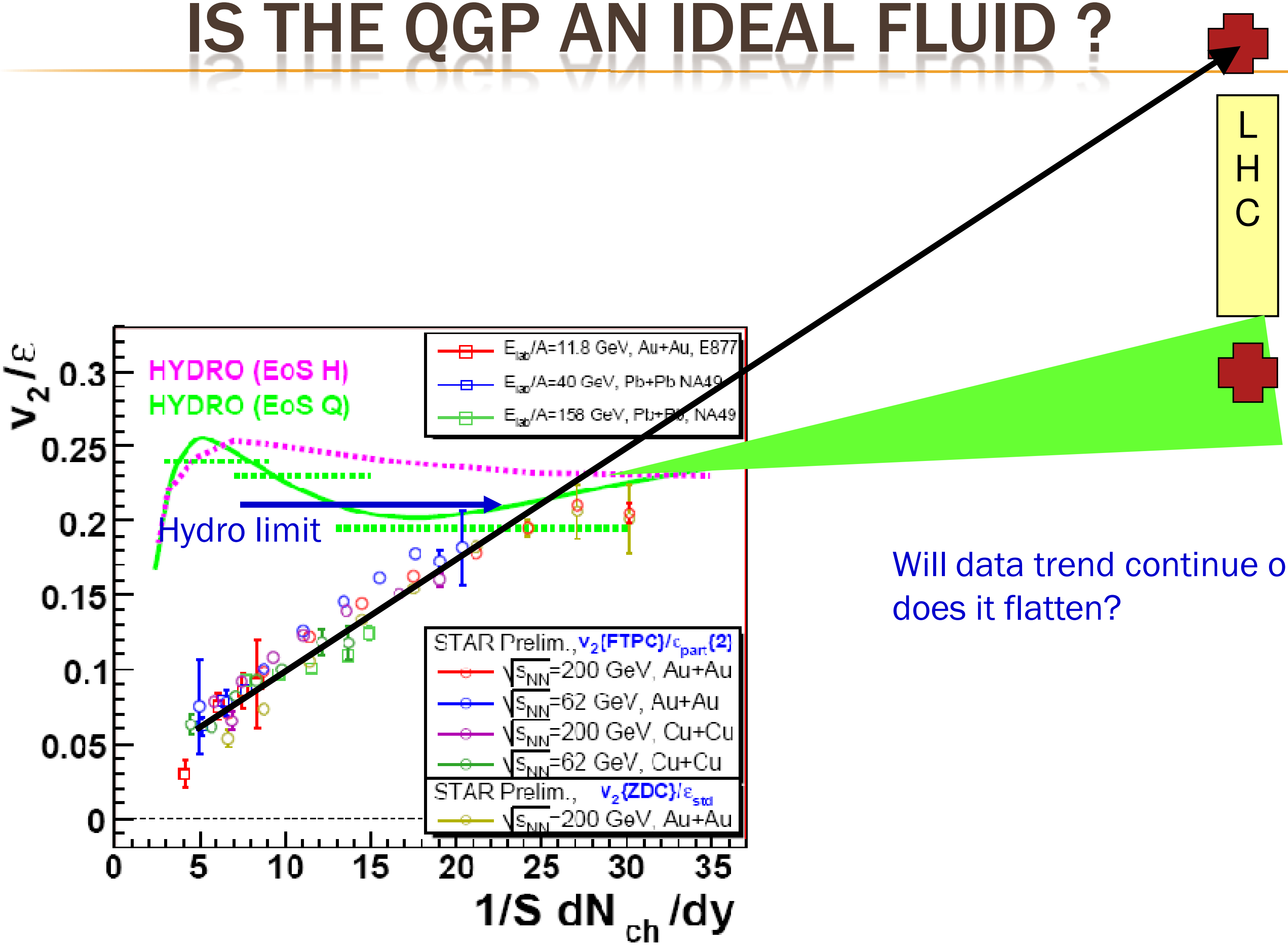


$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle x^2 + y^2 \rangle}$$

$$\frac{v_2}{\varepsilon} = \frac{\text{momentum anisotropy}}{\text{spatial anisotropy}} = \frac{\text{output}}{\text{input}} = \text{response}$$

Experimental data reach hydrodynamic limit curve for the first time at RHIC.

IS THE QGP AN IDEAL FLUID ?

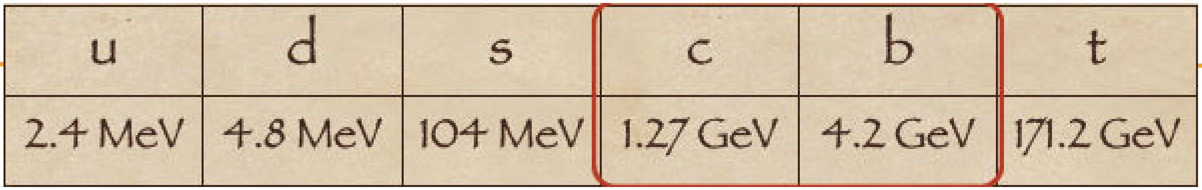


Will data trend continue or does it flatten?

J. Phys. G: Nucl. Part. Phys. 34 (2007) S883–S886

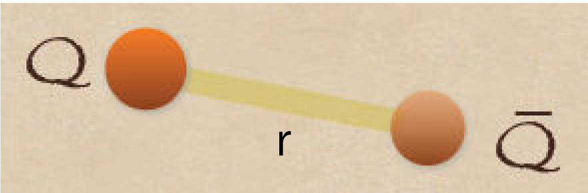
heavy-flavour probes

Quarkonium is bound state of a heavy quark and its antiquark



u	d	s	c	b	t
2.4 MeV	4.8 MeV	104 MeV	1.27 GeV	4.2 GeV	171.2 GeV

quark mass $m_Q >> \Lambda_{QCD}$ and quark velocity $v << 1$ allows *nonrelativistic* treatment, production described in pQCD



The effective potential of interaction:

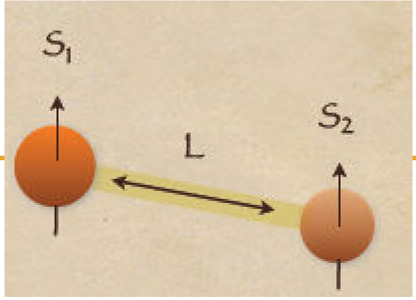
$$V(r) = -\frac{\alpha_{eff}}{r} + kr$$

$$V_{color} = \frac{q}{4\pi r}$$

The Coulomb part is potential induced by one-gluon exchange

$$V_{confinement} = kr$$

k- string tension coefficient (1 GeV/fm)



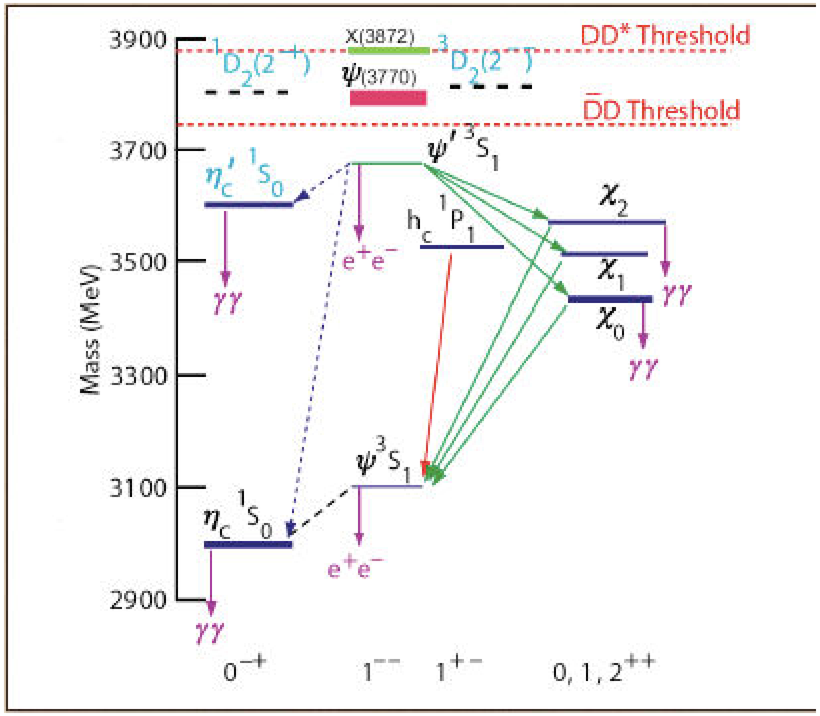
$$\Psi(1S) \equiv J/\Psi$$

$$\Psi(2S) \equiv \Psi'$$

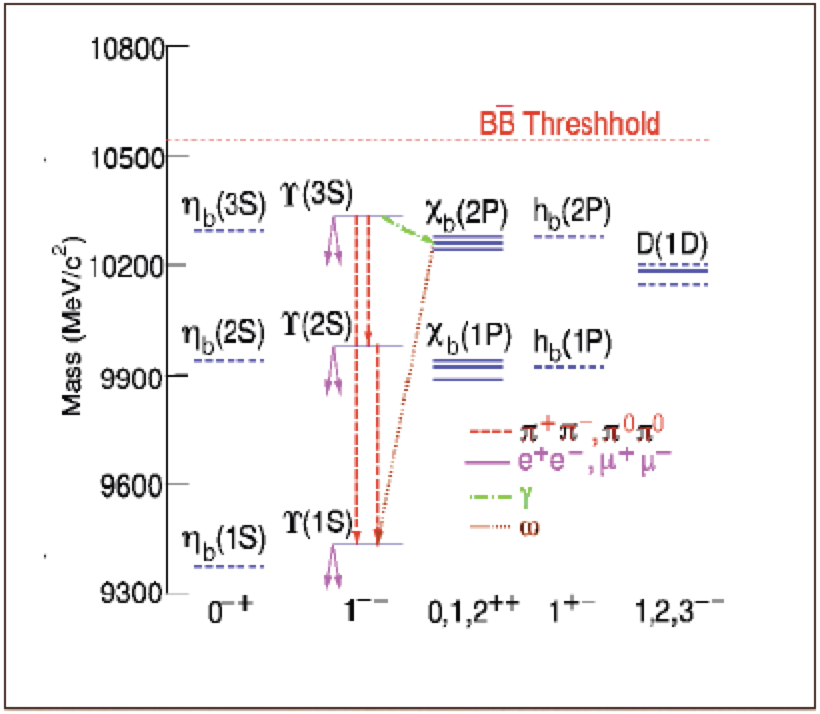
$$\Psi(1P) \equiv \chi_c$$

S(L=0) and P(L=1) states

Charmonium family



Bottomonium family

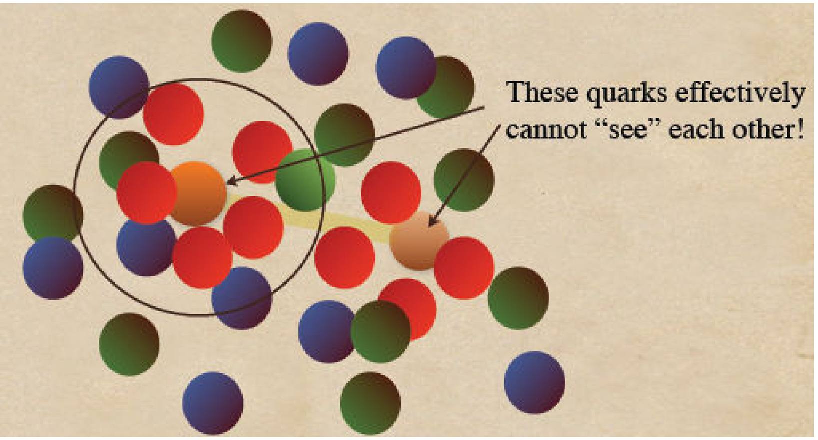


J/ψ suppression – classic QGP signature

proposed by T. Masui, H. Satz, Phys. Lett. B178, 416 (1986).

The idea is :

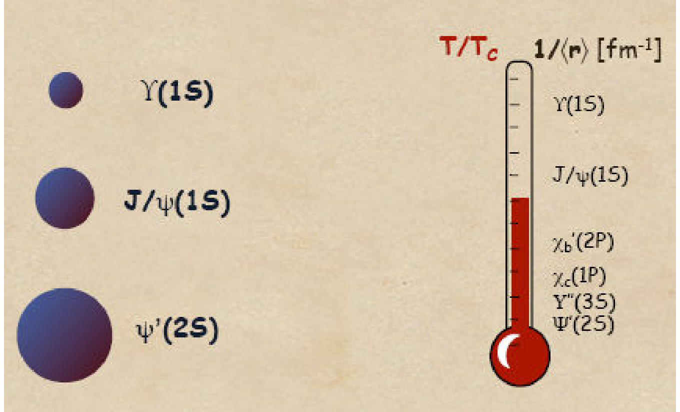
The modification of charmonia in the QGP, in terms of suppressed (or enhanced) production



color screening

The potential in QGP:

$$\frac{q}{4\pi r} \to \frac{q}{4\pi r} e^{-r/\lambda_D}$$



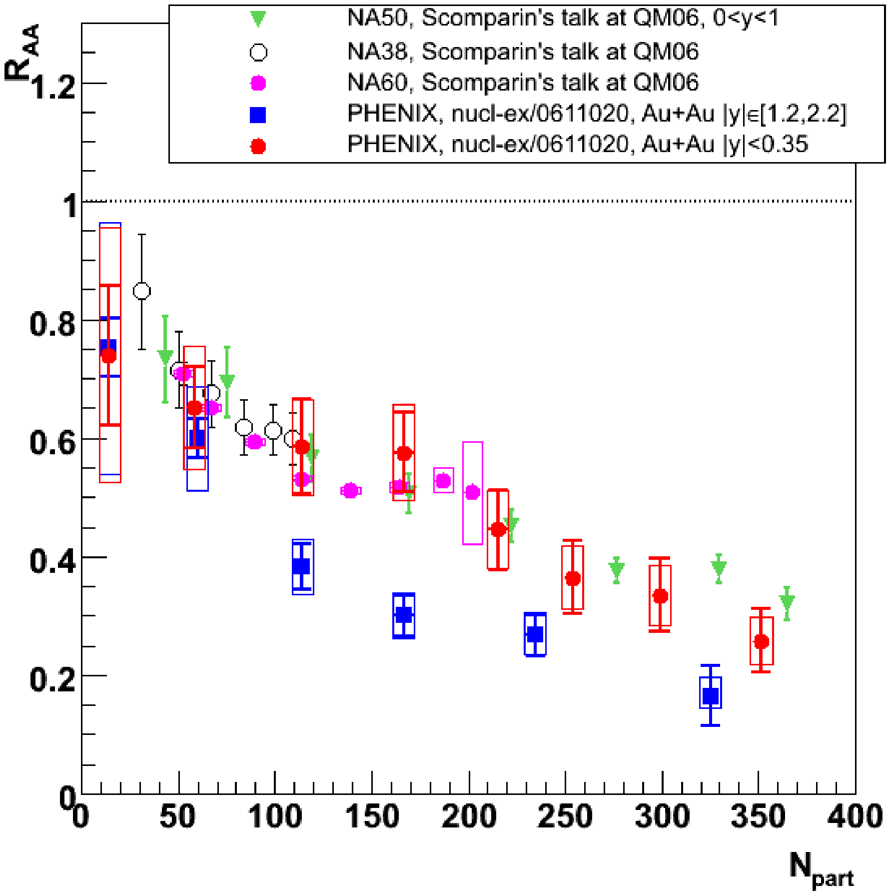
$\lambda_D(T)$ (Debye length) is the distance at which the effective charge is reduced 1/e

$r>\lambda_D$ → No bound state

$T_{diss}(\Psi') < T_{diss}(\Upsilon(3S)) < T_{diss}(J/\Psi) \approx T_{diss}(\Upsilon(2S)) \leq T_C < T_{diss}(\Upsilon(1S))$

COMPARISON OF RHIC AND SPS RESULTS

$$R_{AA}^{J/\psi} = \frac{\mathrm{d}N_{J/\psi}^{AuAu}/\mathrm{d}y}{N_{coll}\cdot \mathrm{d}N_{J/\psi}^{pp}/\mathrm{d}y}$$

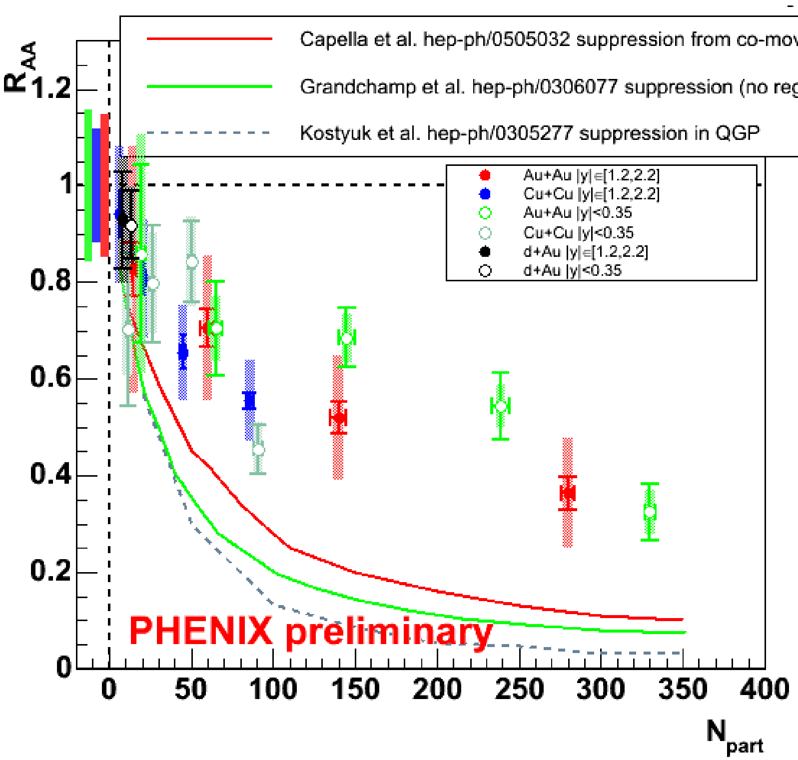


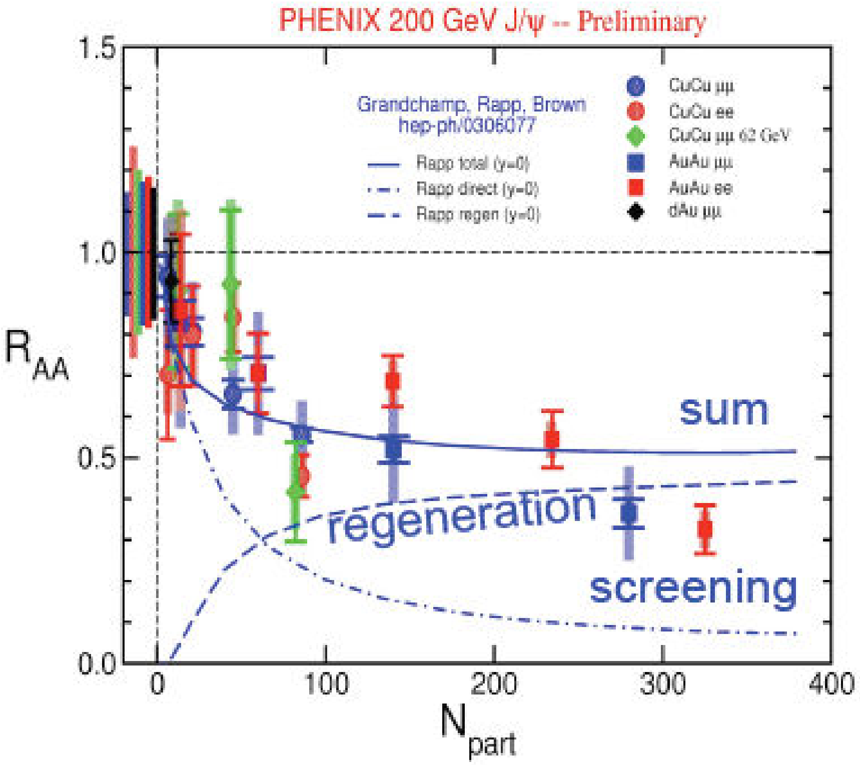
J/Ψ Suppression—R_{AA} PHENIX mid-rapidity the same as NA50

Recent lattice analyses indicate that that the ground state (J/Ψ , ϒ) survive at least up to T ≈2Tcrit, while the less bounded state Ψ ‘ melt near Tcrit

Too much suppression at RHIC in Standard QGP Scenario

Most actual models have Suppression + various regeneration mechanisms





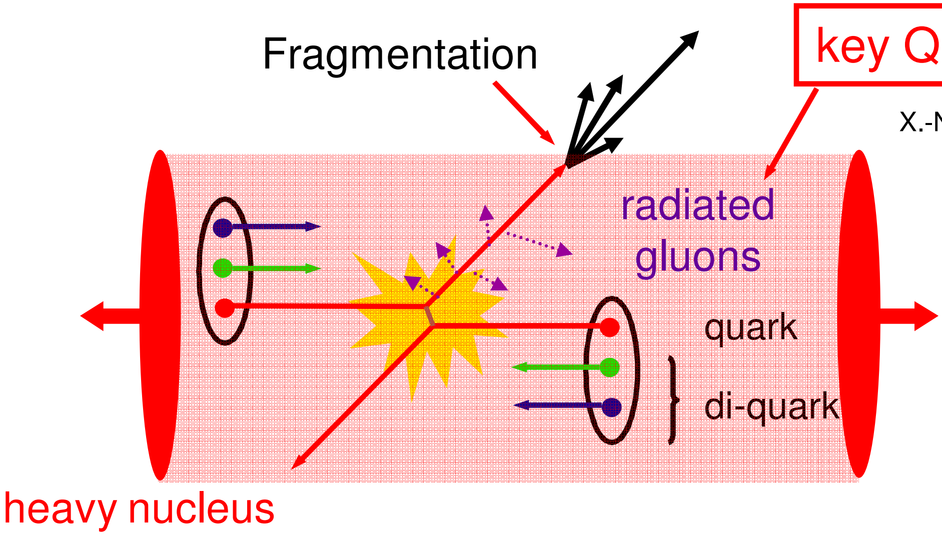
However, at higher energies (RHIC, LHC) the situation becomes more complicated, because the charmonia can be regenerated in the hot medium by recombination.

high-p_t probes

JETS IN HEAVY ION COLLISIONS

key QCD prediction: jets are quenched

X.-N. Wang and M. Gyulassy, *Phys. Rev. Lett.* 68 (1992) 1480



Interaction at the quark (parton) level

- Models of jet suppression

Various approaches; main points:

ΔE_{med} is independent of parton energy.

ΔE_{med} depends on length of medium, L.

ΔE_{med} gives access to gluon density dN_g/dy or transport coefficient $\hat{q} = \frac{\langle k_T^2 \rangle}{\lambda}$

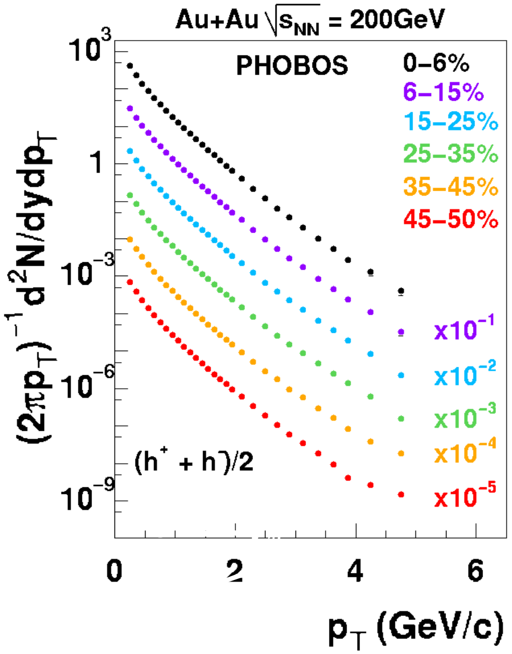
Leads to a deficit of high p_T hadrons compared to p+p collisions (no medium).

COMPARING AU+AU SPECTRA TO PP

Use The Nuclear Modification Factor

$$R_{AA} = \frac{dN^{AA}/dp_{\mathrm{T}}d\eta}{\langle N_{\mathrm{coll}}\rangle dN^{pp}/dp_{\mathrm{T}}d\eta}$$

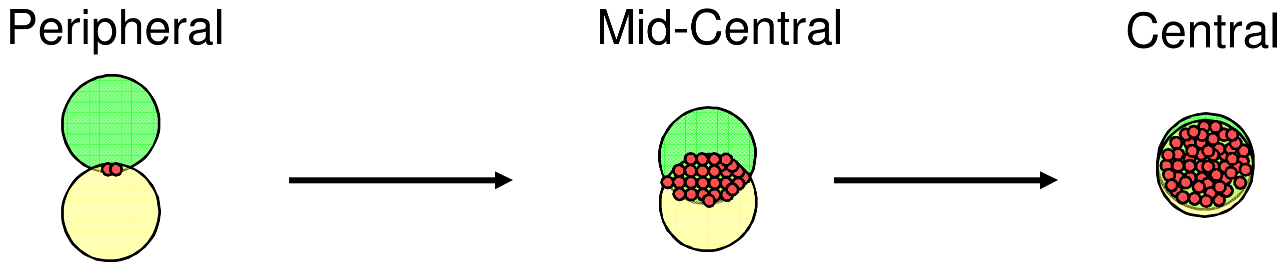
PHOBOS: Phys. Lett. B578, 297 (2004)



→R_{AA} = 1 if Au+Au is simply an incoherent sum of pp collisions

Jet quenching was discovered for the first time at RHIC.

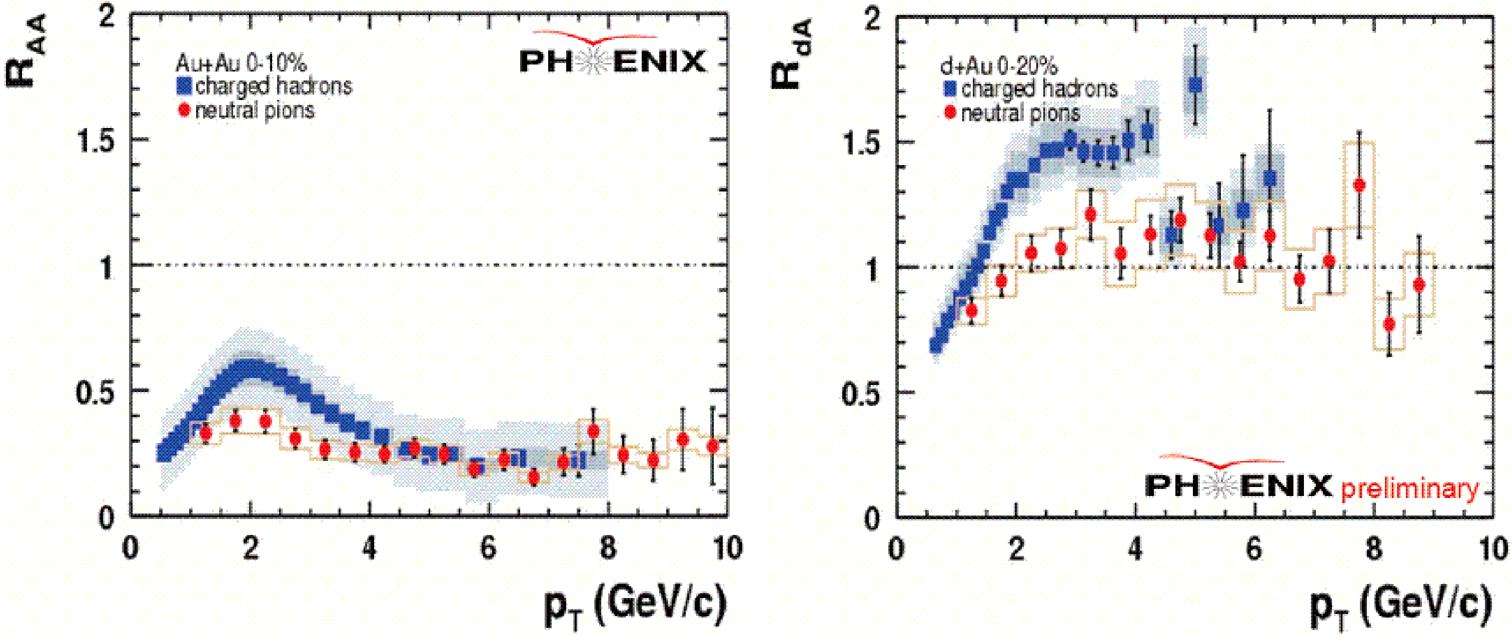
SUPPRESSION OF HIGH MOMENTUM PARTICLES



Peripheral

Mid-Central

Central



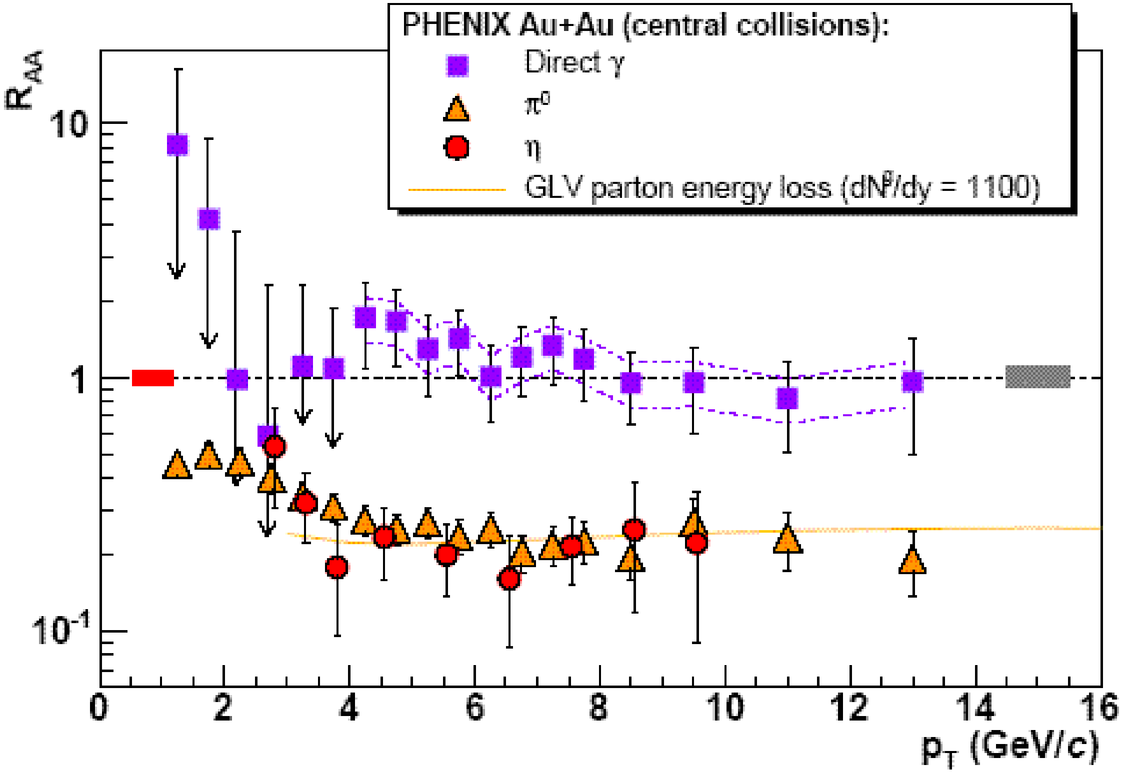
Binary collision expectation

→ strong suppression of high p_T yields in AuAu Central Collisions

IMPORTANT CROSS CHECK OF N_{COLL} EXPECTATION

Direct Photons

PHENIX: Phys.Rev.Lett. 96 (2006) 202301

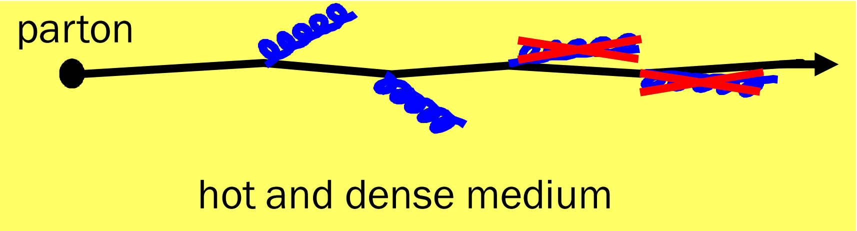


Binary collision expectation

→ Direct photons scale as N_{coll}
(and they don't interact with the medium)

HIGH-PT PROBES
HEAVY QUARKS ENERGY LOSS IN QGP

- The heavy quarks at intermediate pt will lose less energy as compared with the light quarks at the same momenta due to the ‘dead-cone’ effect .



CAPABILITY OF ALICE DETECTOR

ALICE unique features:

- Possibility to measure charged-particle density up to dNch/dy = 8000
- Excellent tracking and impact parameter resolution.

(Typical p resolution obtained with the magnetic field of 0.5 T is 1% at pt 1 GeV/c and 4% at pt 100 GeV/c.)

- Acceptance at low p_T (~0.2 GeV)
- Excellent PID capabilities

From p 0.1 GeV/c to a few GeV/c the charged particles are identified by combining the PID information provided by ITS, TPC, TRD, TOF and HMPID. Electrons above 1 GeV/c are identified by TRD, and muons are registered by the muon spectrometer.

HEAVY-ION PHYSICS WITH ALICE

- Pb-Pb (Summer 2010 – 4 weeks):

  1/20 of nominal luminosity $\int L dt = 5 \cdot 10^{25}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1} \times 10^{6}\mathrm{s}$

  Alignment calibration available from pp
- Global event properties (10^5 events):
  - Multiplicity, rapidity density
  - Elliptic flow
- Source characteristic (10^6 events):
  - Particle spectra, resonances
  - Differential flow
  - interferometry
- High pt and heavy flavours (10^7 events):
  - Jet quenching
  - Quarkonia production