Experimental Studies of the Quark Guon Plasma*)

Studied in Heavy Ion Collision $\sqrt{s_{NN}}$

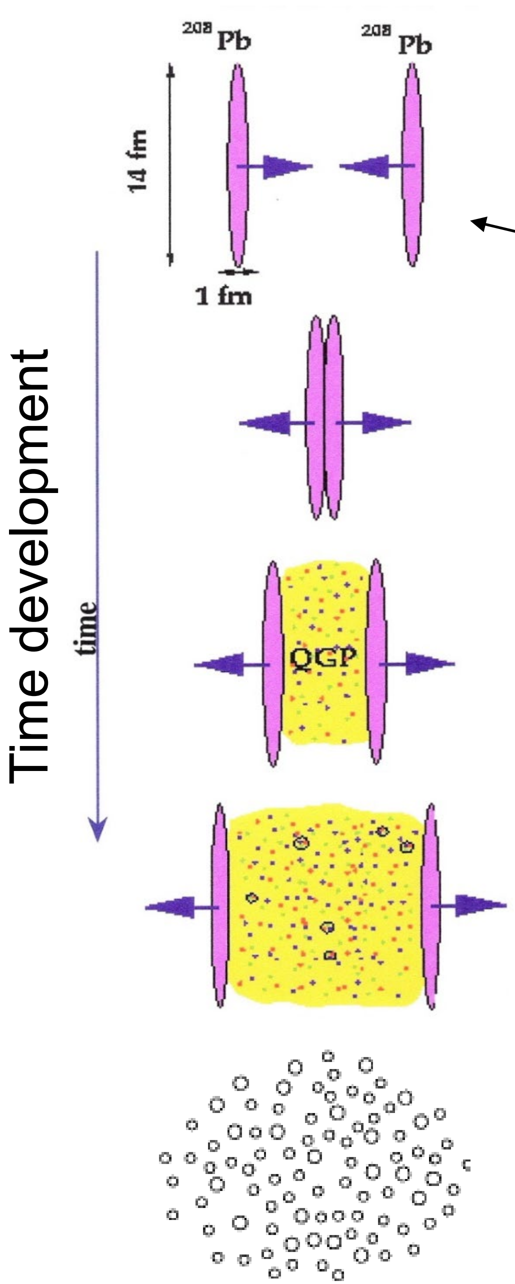
Facility	Location	System	Energy (CMS)
AGS	BNL, New York	Au+Au	2.6-4.3 GeV
SPS	CERN, Geneva	Pb+Pb	8.6-17.2 GeV
RHIC	**BNL, New York**	**Au+Au**	**200 GeV**
LHC	**CERN, Geneva**	**Pb+Pb**	**5.5 TeV**

Excellent lecture on QGP:

https://www.physi.uni-heidelberg.de/~reygers/lectures/2019/qgp/

*) Quark Gluon Soup (see Colloquium by Prof. Krishna Rajagopal)

A few basics



Heavy Ion Collision = ideal way to get conditions of extremely high T and ρ.

Lorentz contration: 100 (RHIC), 2700 (LHC)

Formation time τ_0 = 0.1 fm/c = 3,3*10^{-25}s
(fee quarks and gluons)

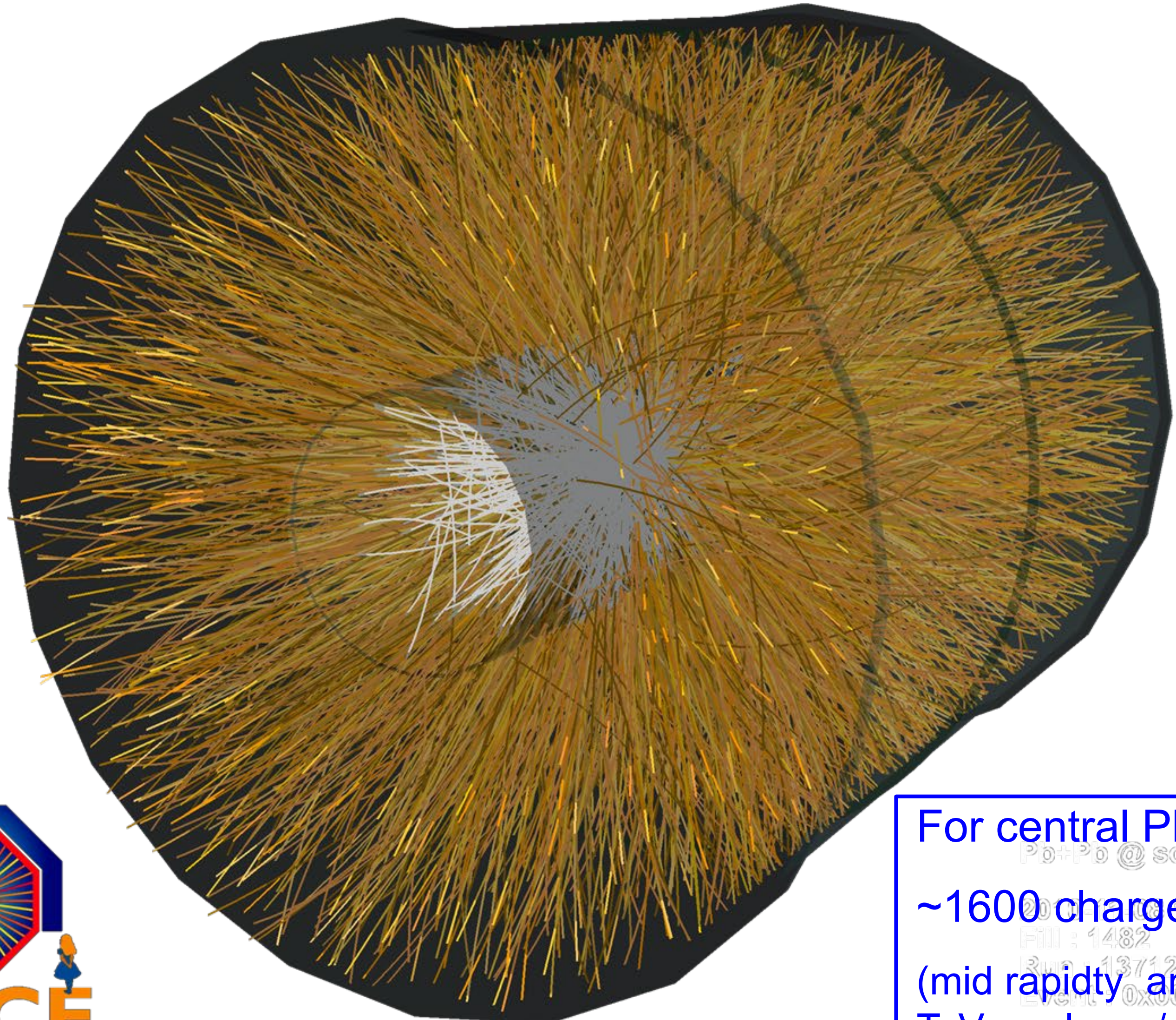
Rapid thermalization of quarks and gluons, after about 1 fm/c at QGP temperature order O(500 MeV)

Expansion: lifetime of few fm/c

Expansion → cool-down
Hadronization when Tc =156.5 MeV reached

(inelastic processes stop)
Chemical freeze-out at T_{ch} (hadron species)
Kinematic freeze-out defines momenta

Pb+Pb collisions in ALICE

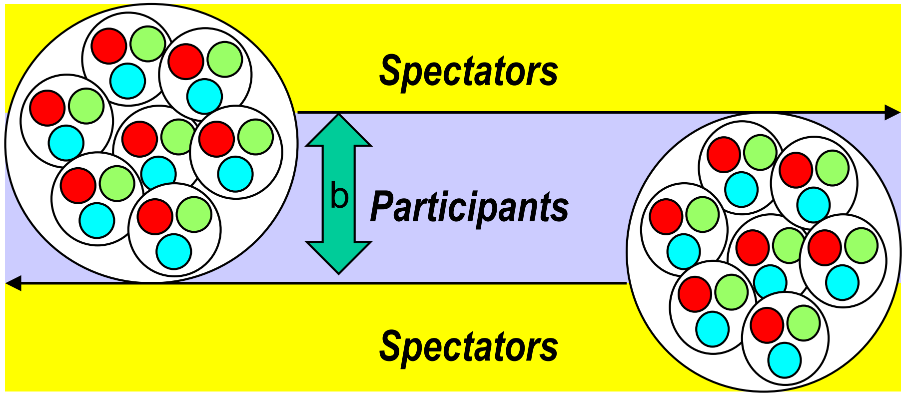


For central Pb-Pb collision:

~1600 charged particles / η

(mid rapidty and $\sqrt{s_{NN}}$=2.76 TeV, scales w/ $s_{NN}^{0.15}$)

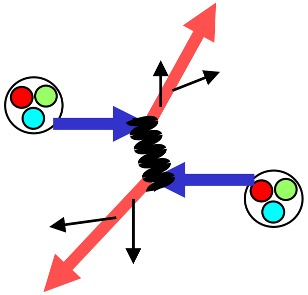
Geometry of AA collisions – Impact parameter

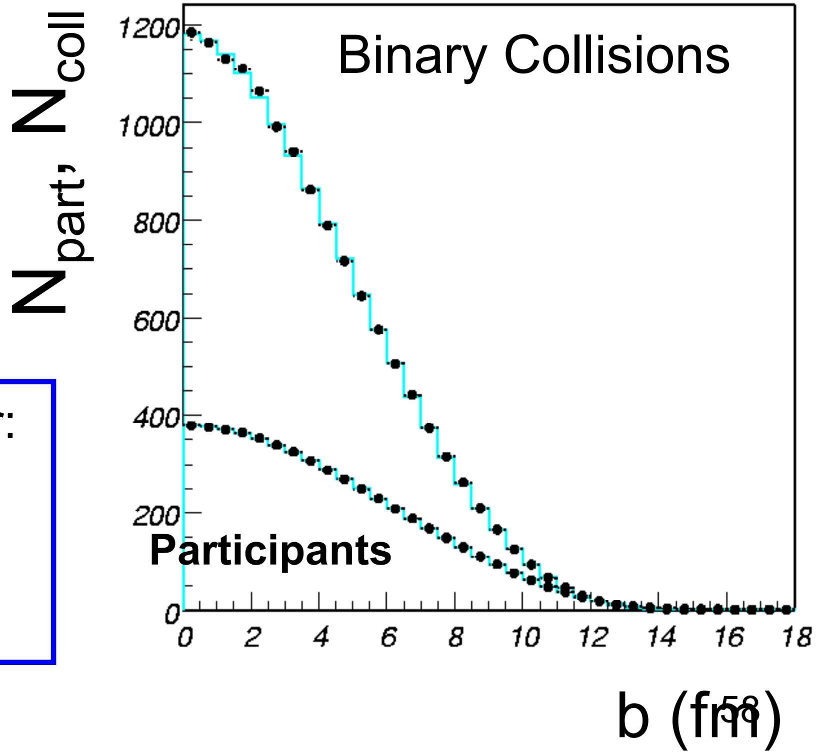


"Glauber" model of AA

<u>Binary Collisions:</u>

1. Jet Production
2. Heavy Flavor

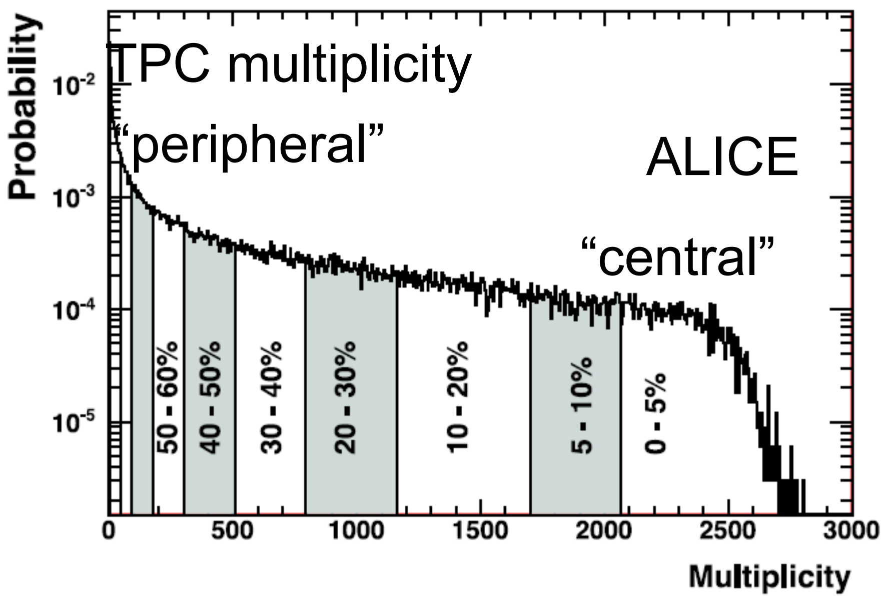




Cannot directly measure the impact parameter:

Use total number of produced particles and detected "spectators" as a measure for the "centrality" of the heavy ion collision.

Centrality measurement



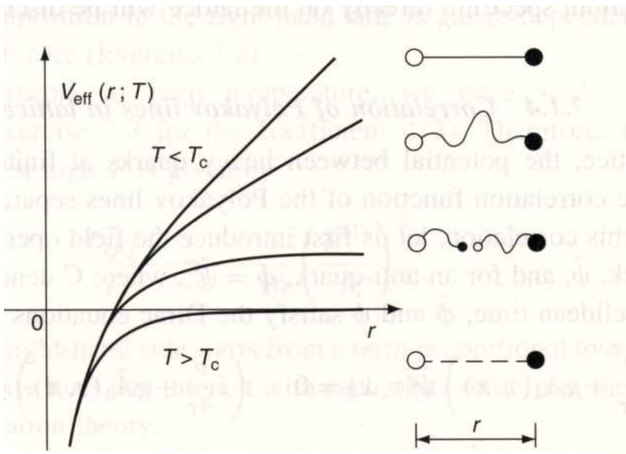
Discussed observables sensitive to QGP

- J/ψ suppression
- Jet quenching / suppression
- Elliptical flow

J/ψ suppression

Idea: J/ψ are formed early in AA collision and feel the effect of the hot medium.

qq-potential for different T:

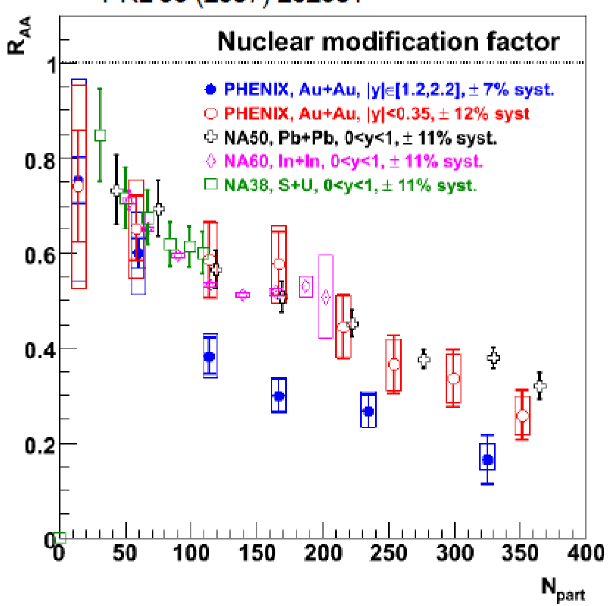


for T>Tc confining part disappears and short range Coulomb part is Debye-screened to give Yukawa type potential.

⇩

bound states can disappear
(predicted for J/ψ at T ≈ 160 MeV)

PRL 98 (2007) 232301



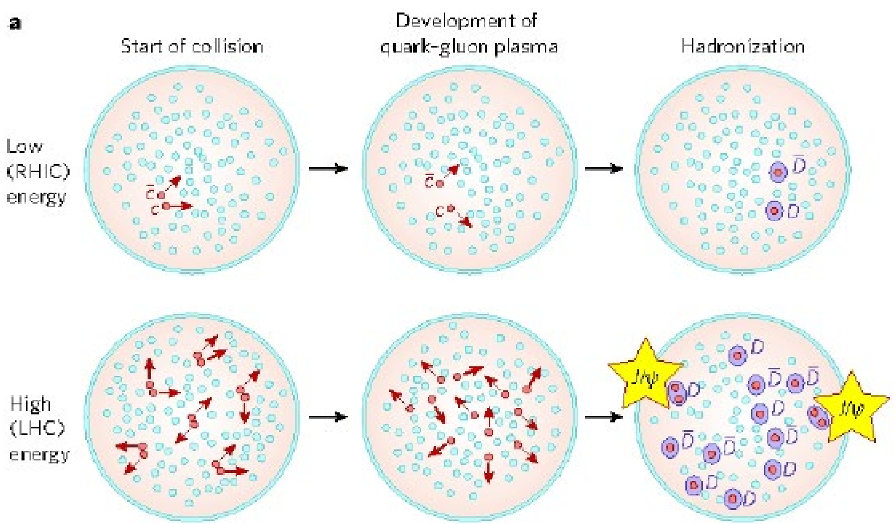
<u>J/ψ suppression as signature for QGP</u>

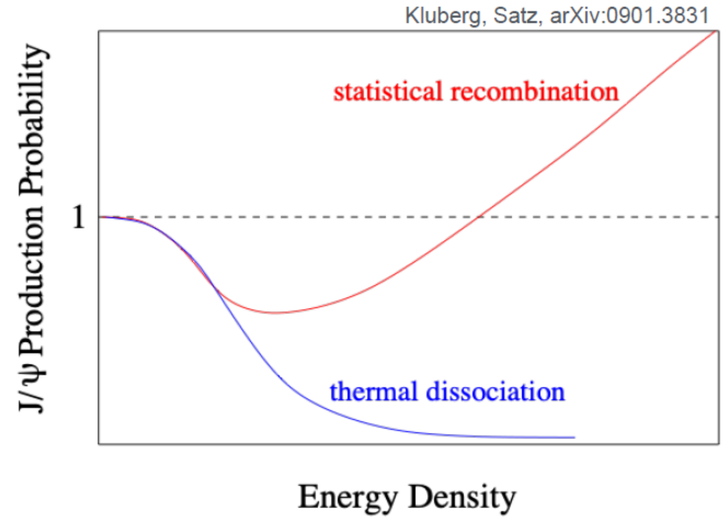
$$R_{AA} = \frac{dN_{AA}/p_T}{dN_{pp}/p_T} \frac{1}{< N_{coll} >}$$

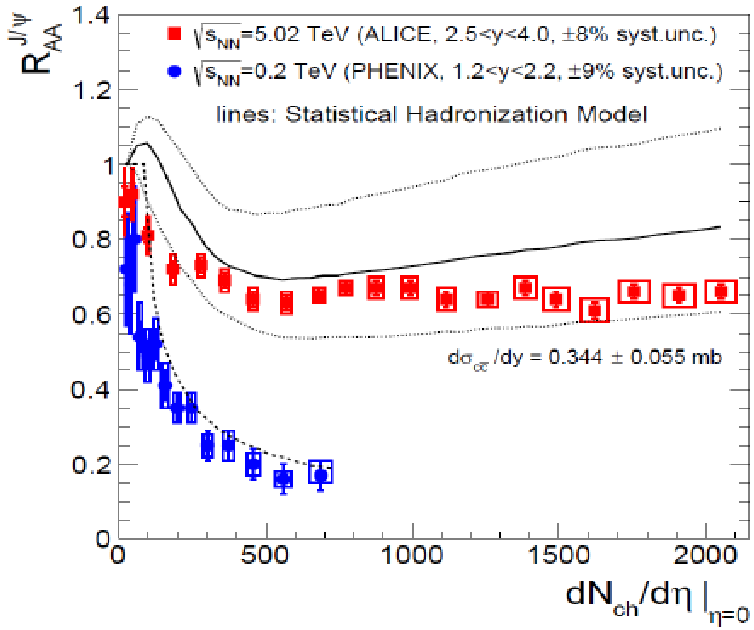
Observation by NA50 (CERN 2000):
→"controversial" discovery of QGP

… but ….

J/ψ “suppression” at LHC energies







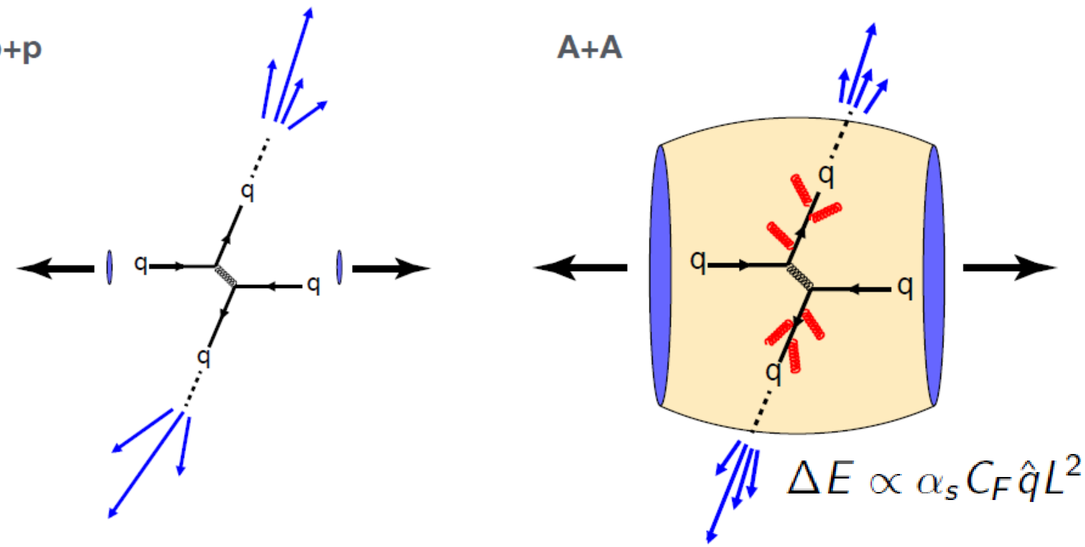
At LHC J/ψ is less strongly suppressed compared than at RHIC

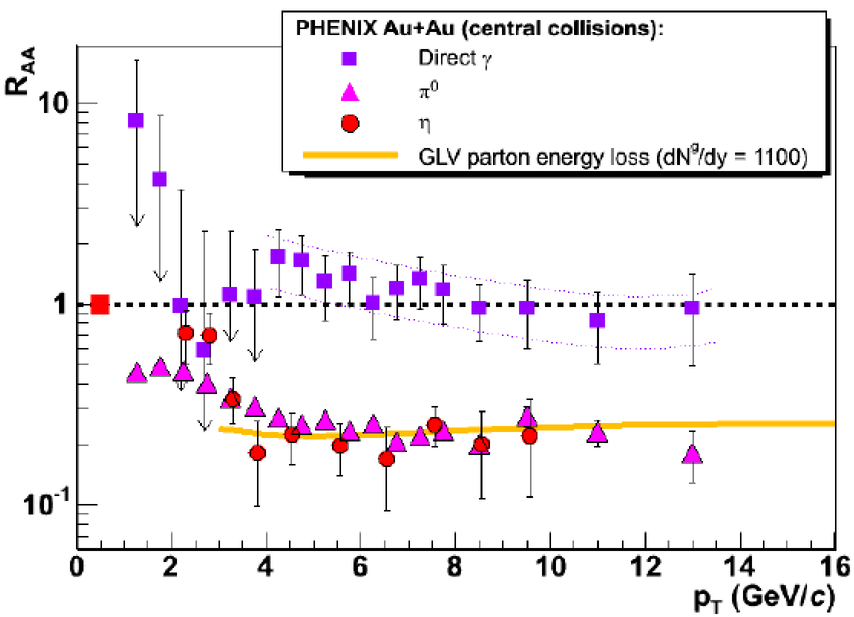
J/ψ production in PbPb collisions at LHC is consistent with deconfinement and subsequent statistical hadronization within present uncertainties

Jet quenching in heavy ion collisions

Hard scattering:

→ 2 jets which have to pass the medium (QGP)

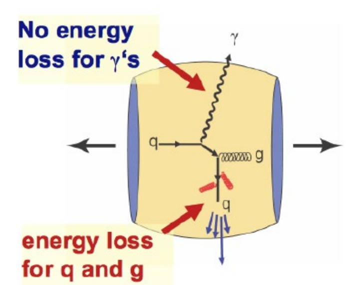




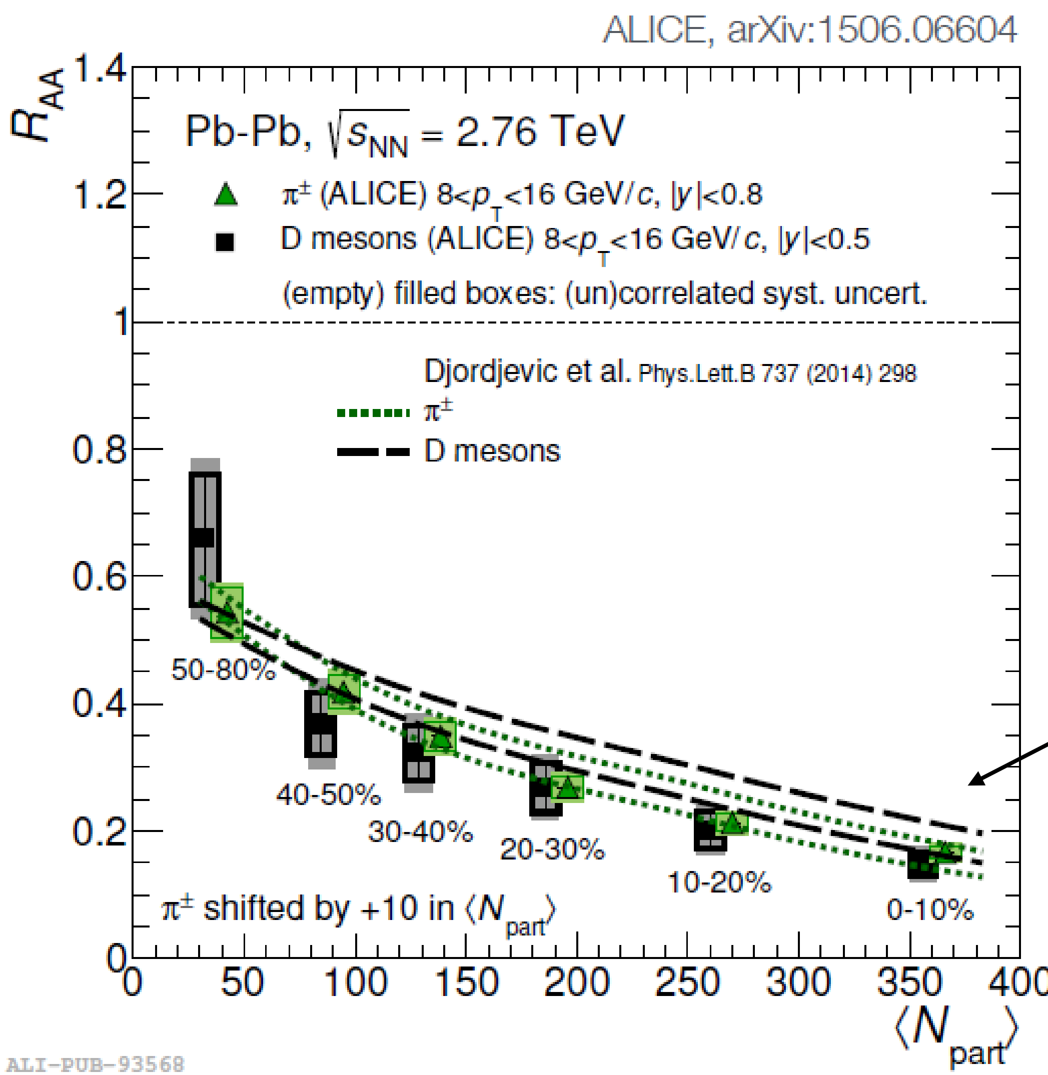
Inelastic scattering of leading parton w/ medium → energy loss in QGP (depends where the parton started)

Suppression of "high-pt" hadrons (from primary parton collision).

Hard photons are not suppressed – don't interact w/ QGP

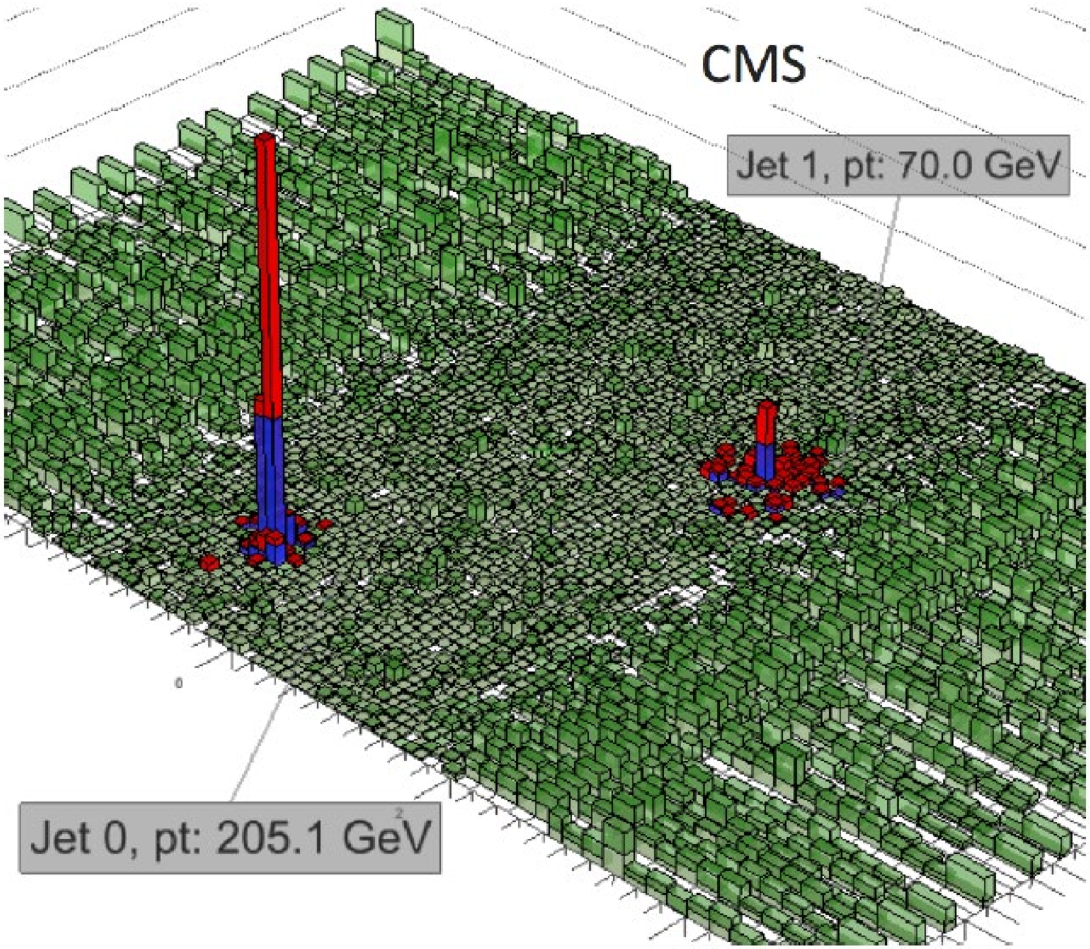


π / D suppression at LHC



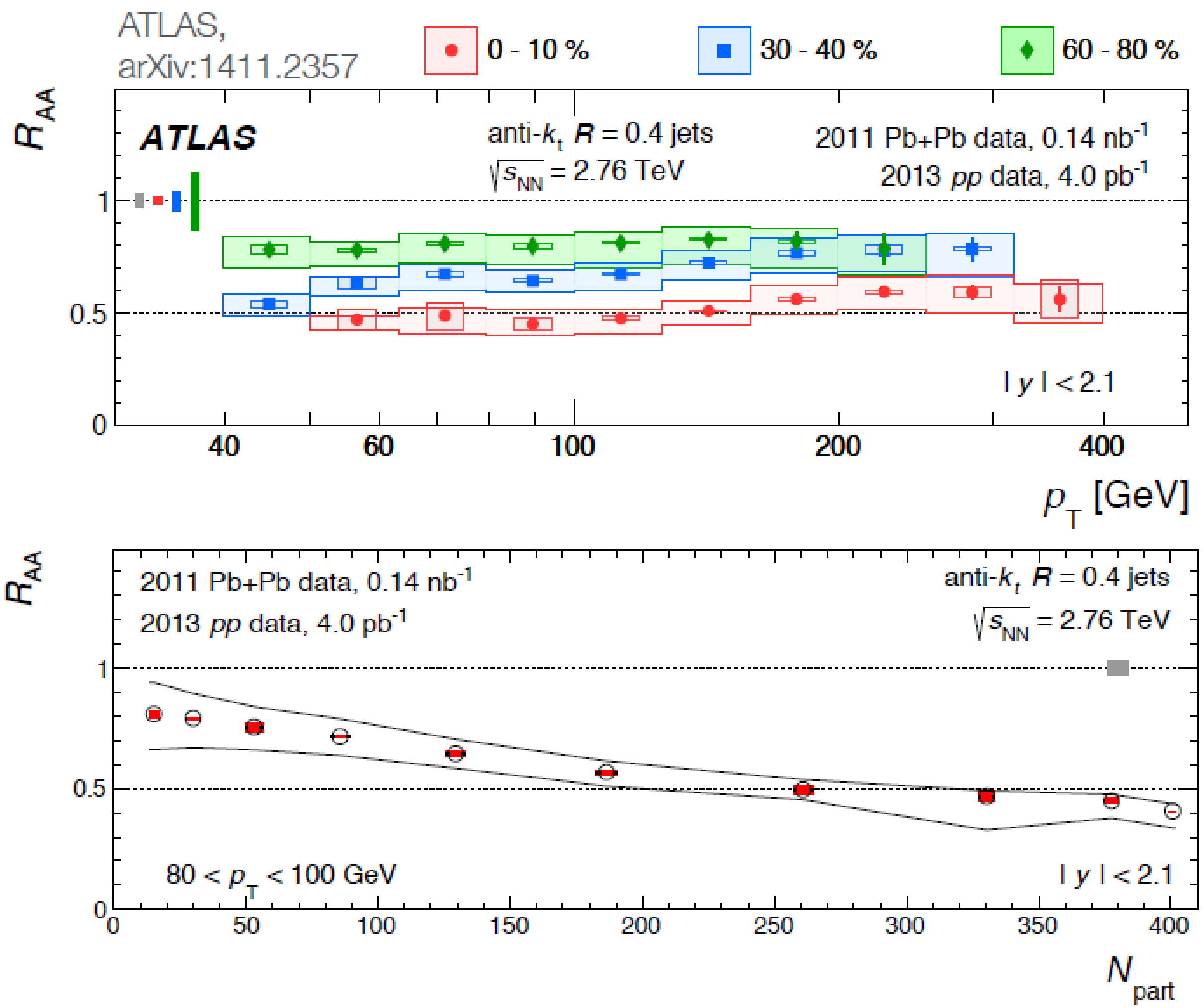
Most central-collision: Carful beside the effect of the QGP there might be also nuclear matter effects from the PbPb nuclei.

Suppression of complete "hard-pt" jets:



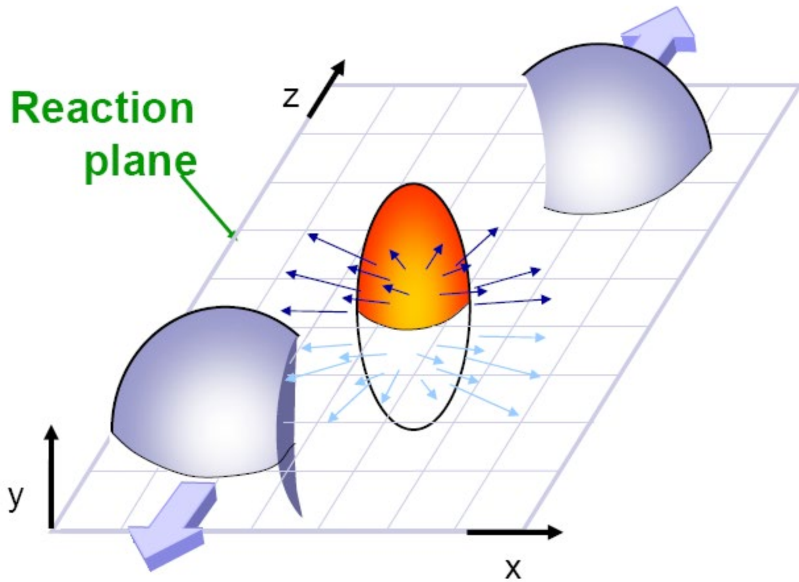
Large dijet energy asymmetries in Pb-Pb

Jet quenching



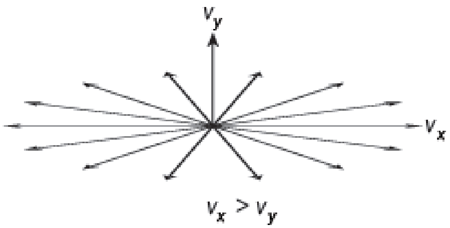
Strongest suppression at most central collision, nearly independent of pt.

Elliptical flow – properties of the QGP



Anisotropy and elliptical flow:

Pressure gradients of almond-shape will lead to preferential expansion in the reactions plane.

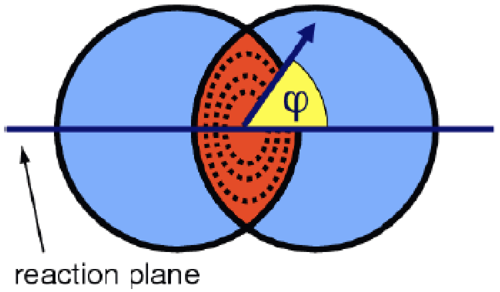


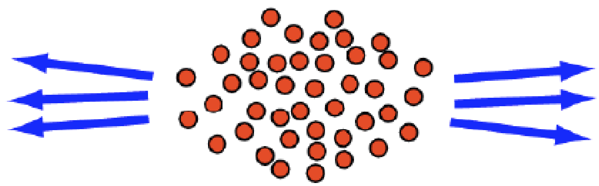
Hydrodynamic models to relate the observed anisotropy to the properties of the QGP.

E.g.: shear viscosity η acts against buildup of flow anisotropies.

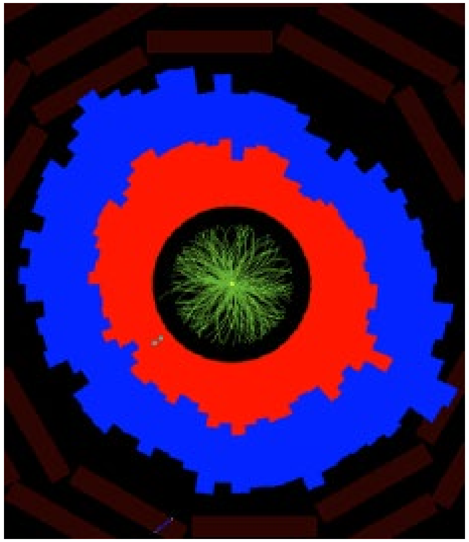
Hydrodynamic models:
-EoS from lattice QCD
-viscous hydrodynamics
-fluctuating initial conditions
-hydrodynamic evolution + hadronic cascade

Anisotropy in Heavy Ion Collisions



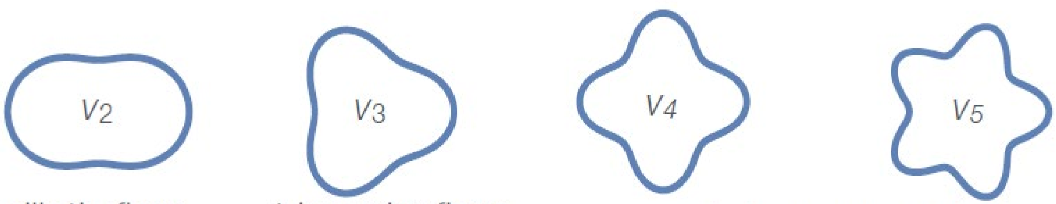


$$\frac{dN}{d\varphi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos[n(\varphi - \Psi_n)]$$



Example: AuAu collision in STAR

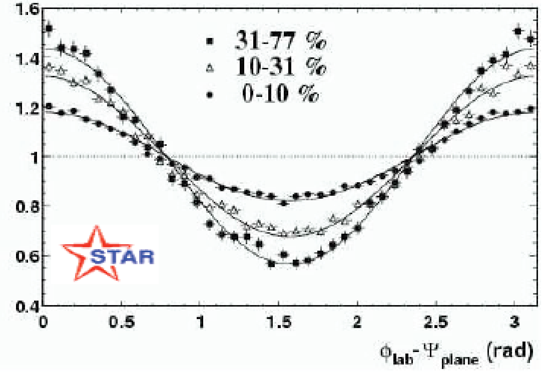
[Fourier coefficients](#)



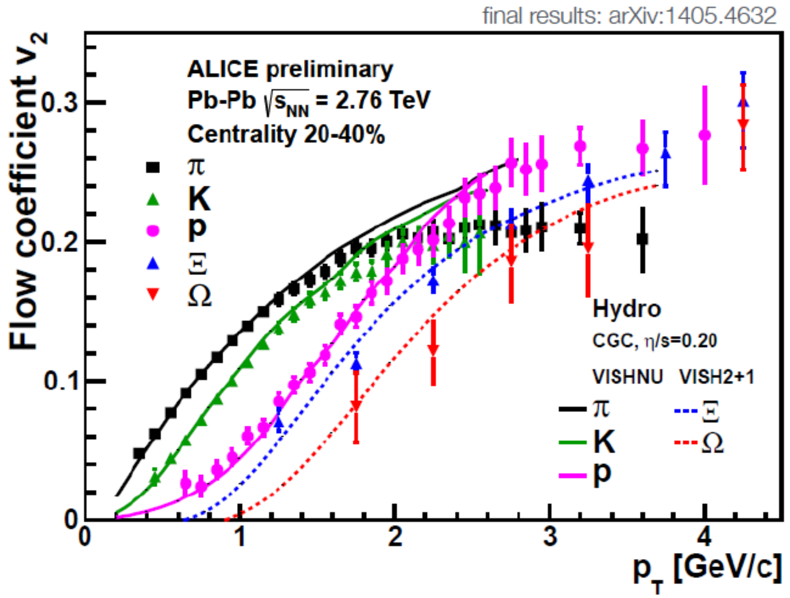
elliptic flow

triangular flow

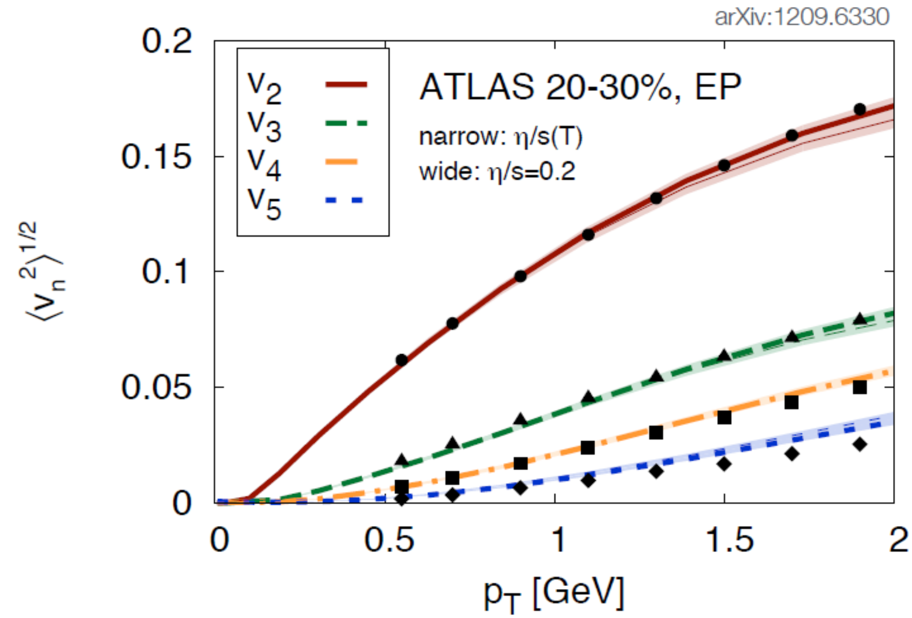
$f(\varphi) = 1 + 2v_n \cos(n\varphi)$



Observed anisotropy and QGP properties



Measured elliptical flow reproduced by viscous hydro models with η/*s* = 0.2



Anisotropies also reproduced by viscous models with η/*s* = 0.2

QGP is a strongly coupled liquid, with (η/s) — the dimensionless characterization of how much dissipation occurs as a liquid flows — much smaller than that of all other known liquids (but one).