Experimental study of extreme matter produced in ultra-relativistic heavy ion collisions

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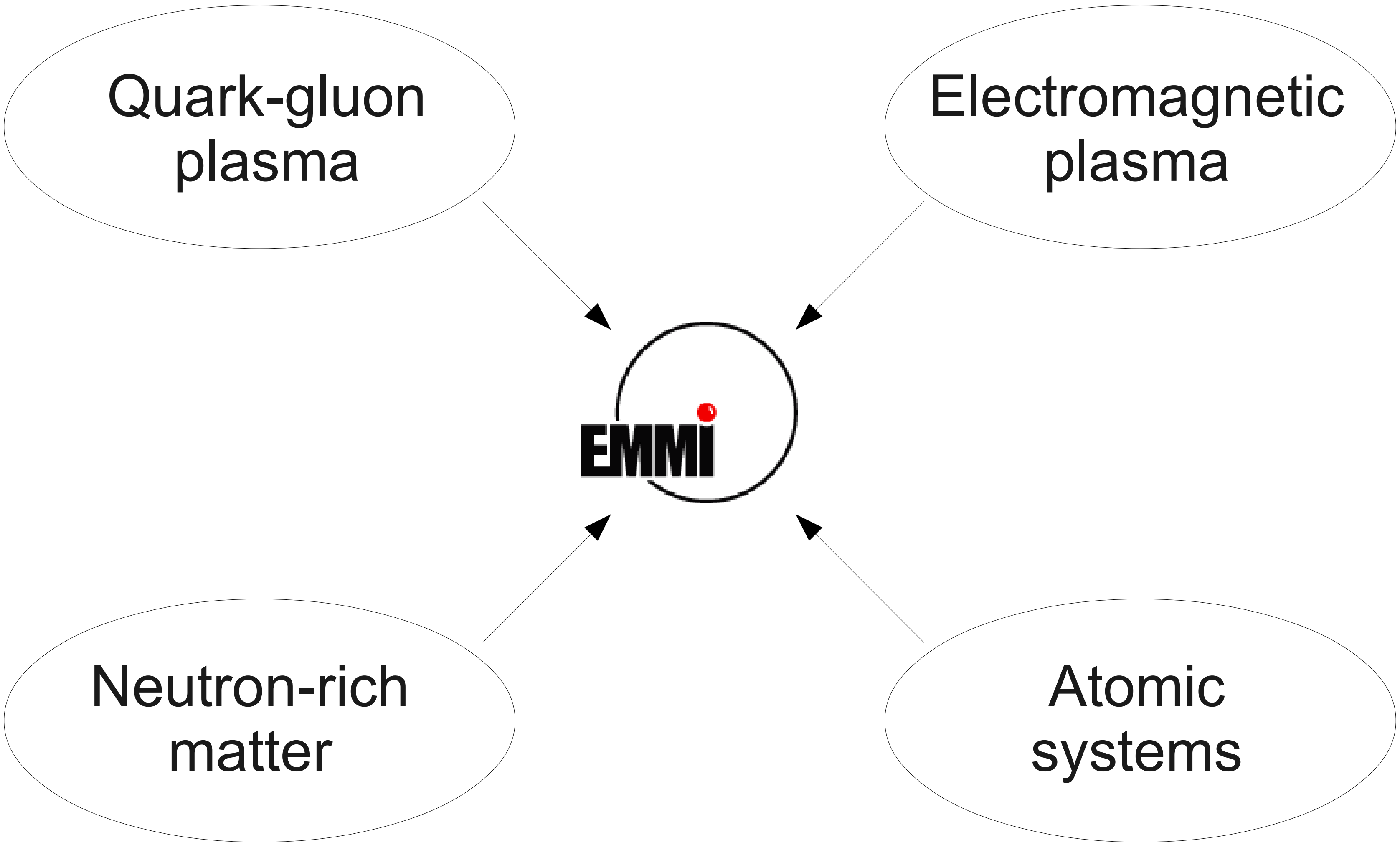
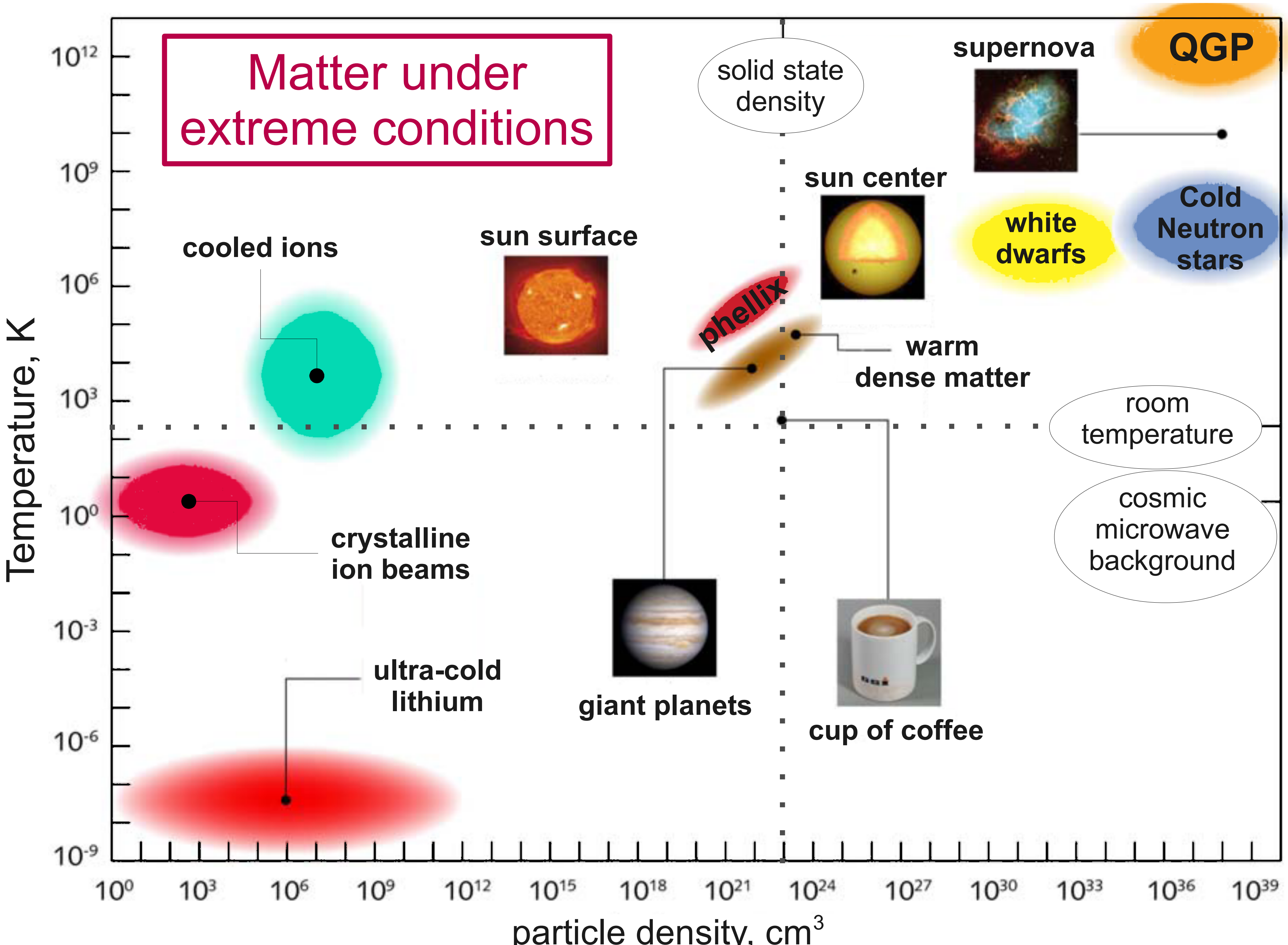
FIAS-EMMI day

January 11, 2011

EMMI: interdisciplinary approach

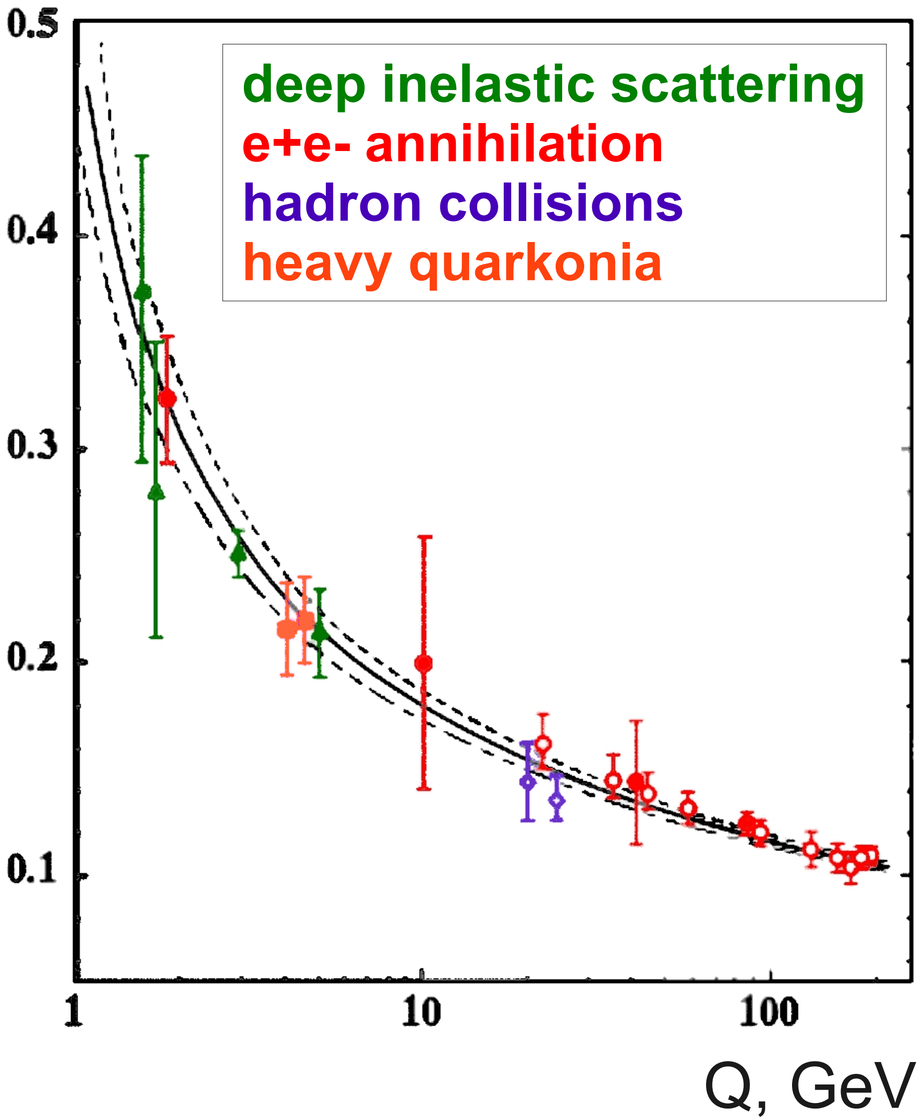
Goal: explore the matter at the extremes of density and temperature




Matter under extreme conditions
solid state density
supernova
QGP
sun center
white dwarfs
Cold Neutron stars
cooled ions
sun surface
phellix
warm dense matter
room temperature
cosmic microwave background
crystalline ion beams
ultra-cold lithium
giant planets
cup of coffee
Temperature, K
particle density, cm3

Quantum Chromo-Dynamics (QCD)

α_s strong coupling constant



QCD - theory of strong interactions

- Chiral symmetry:
  identical left & right handed quarks
- Asymptotic freedom
  running coupling
  renormalization scale:

$$\Lambda_{QCD} \sim 200 MeV$$

- Perturbative regime

$$Q^2 \gg \Lambda_{QCD}$$

Deconfined state of quark & gluons

- Non perturbative regime

$$Q^2 \sim \Lambda_{QCD}$$

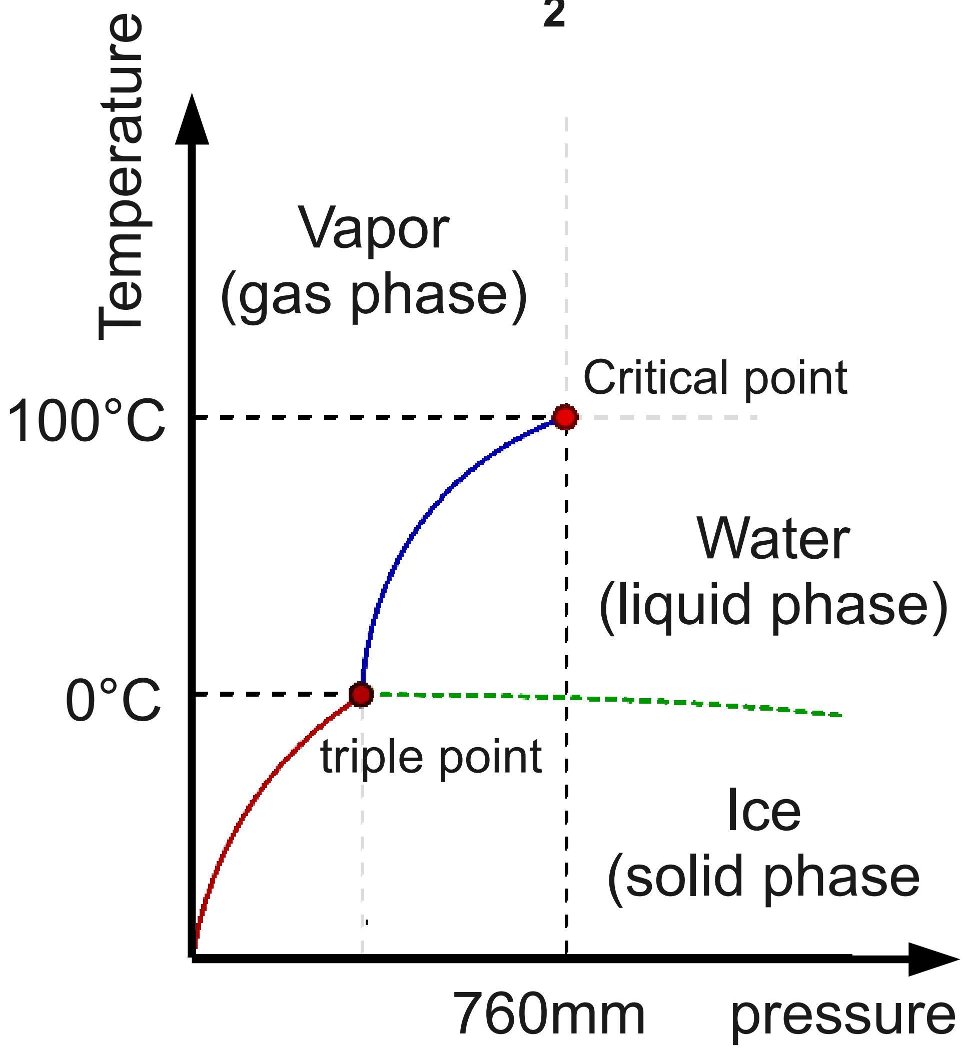
Quark & gluons confined in hadrons

Main questions about QCD

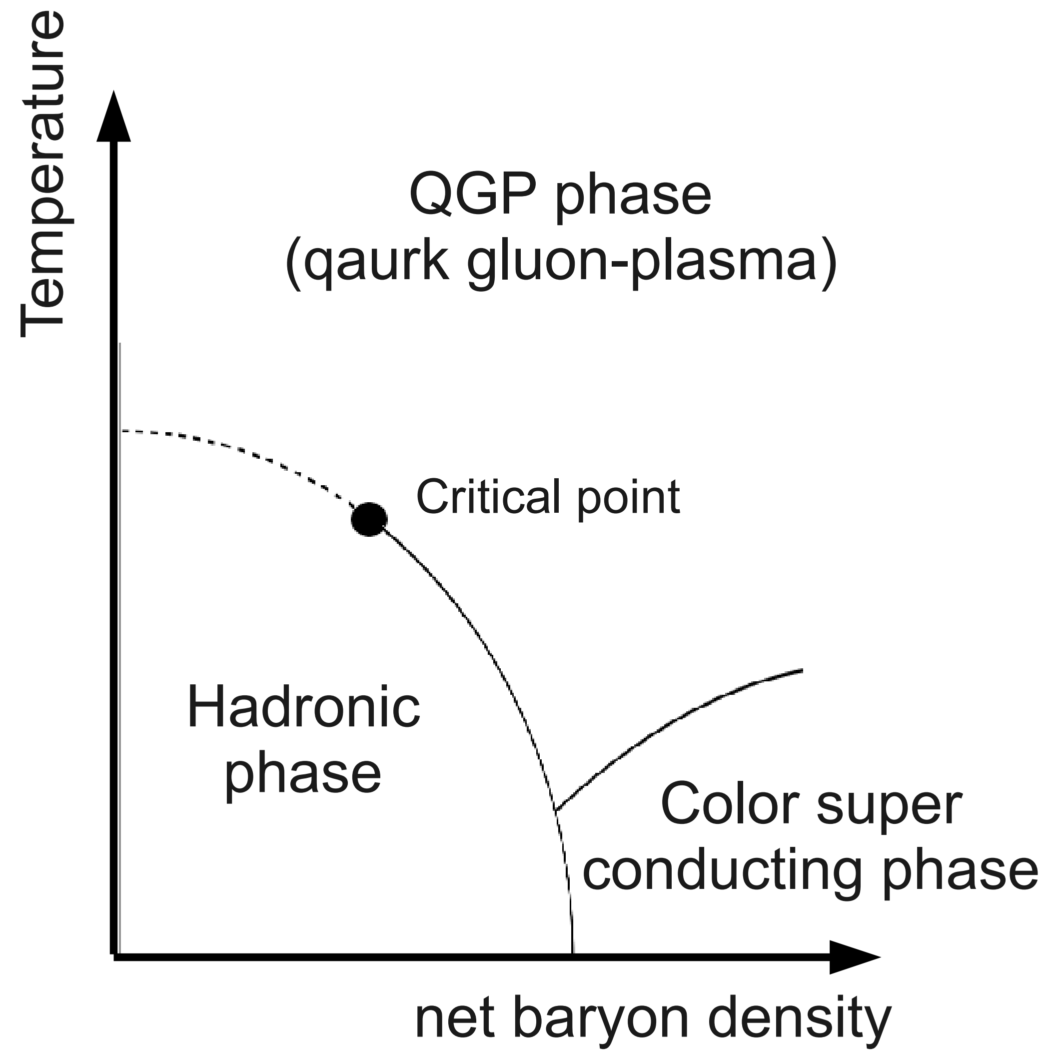
- What are the forms of extended QCD matter?
  - Properties of hadrons (confided quarks)
  - Properties of deconfined quarks and gluons
  - Relevant degrees of freedom for those states
- How & when the transition between different states of matter happens?
- What symmetries are preserved by QCD (chirality, Time, Parity, and C)
  Under what conditions they can be broked/restored?

Phase diagram:
map of possible states and phase transitions

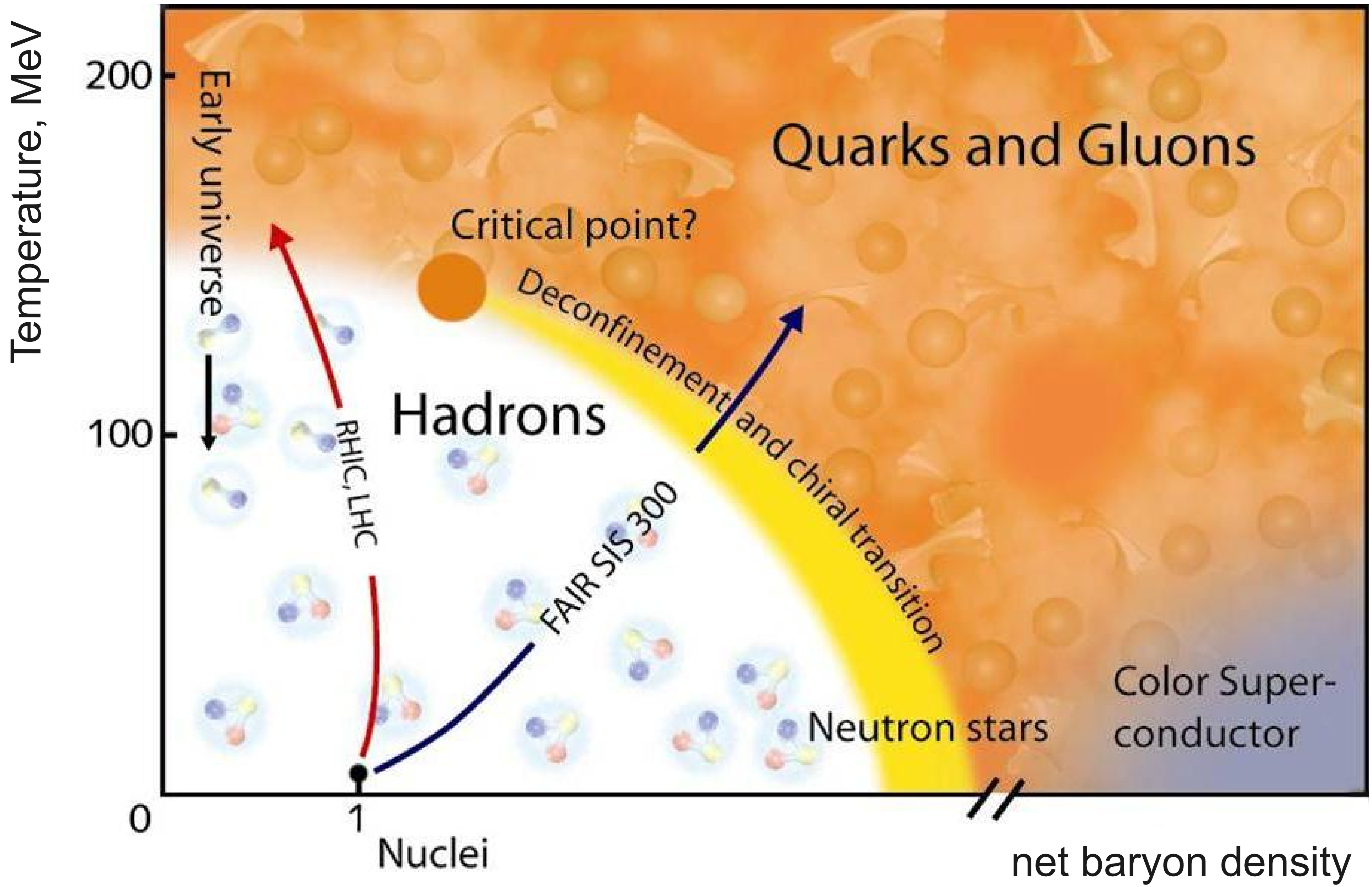
H_2O



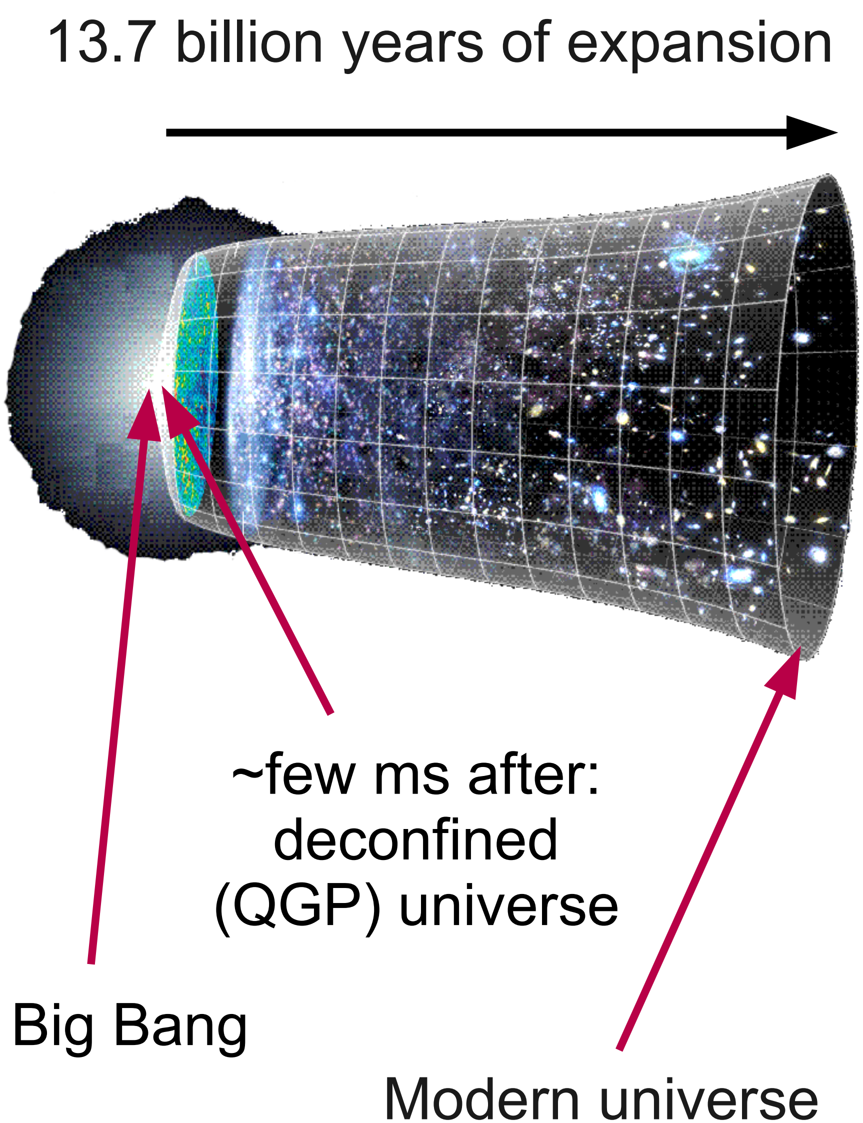
QCD



Phase diagram of the strongly interacting matter



How do we explore QCD phase diagram in laboratory?



Required to produce QGP:

- Energy density > 1GeV/fm^3
  ~ x10 more than of ground state nuclei
- Temperature ~ 200MeV
  ~ x10^5 hotter than the sun
- Enough volume for deconfinement
  ~ more than a few fm
- Enough life-time to equilibrate
  > 1fm/c

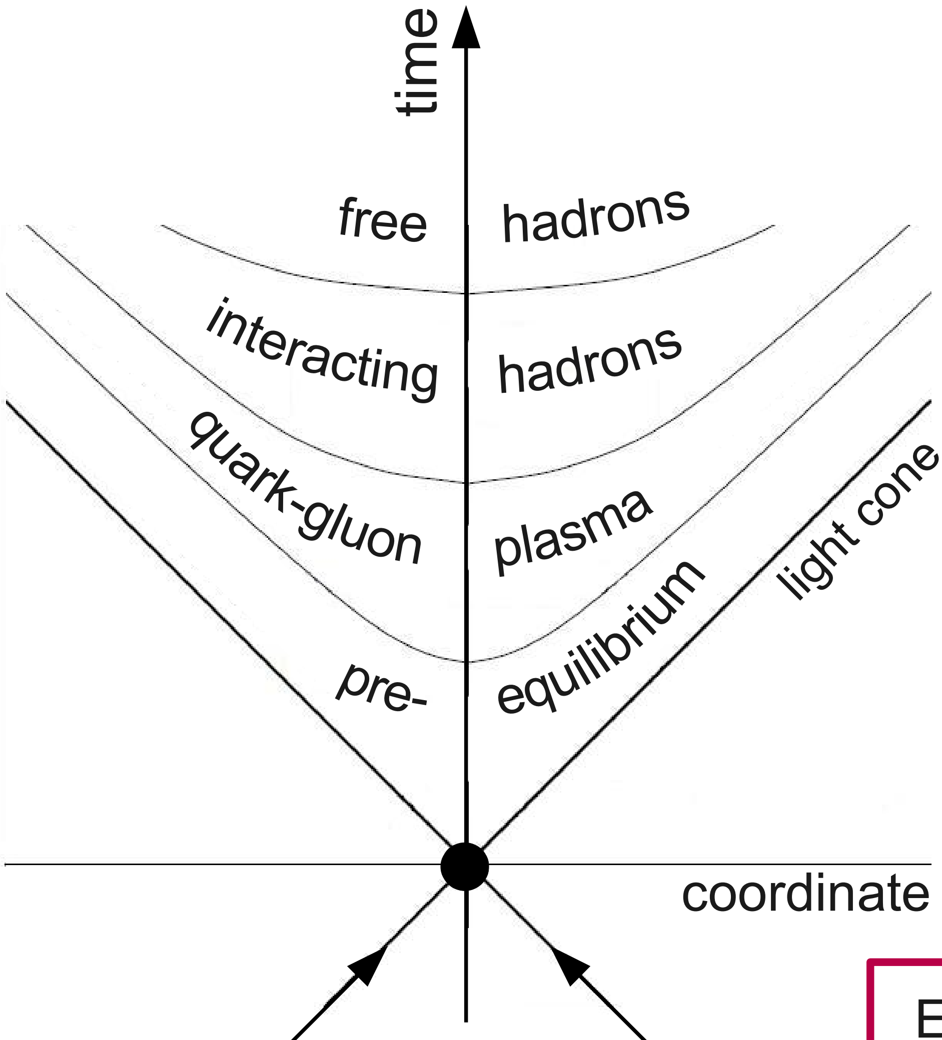
Approach:
Smashing nuclei in the head-on collisions

Cold nuclear matter into fireball of partons

Reproduce the early universe
just a few microseconds after Big Bang

Implication for cosmology (neutron stars)

Evolution of the system created in HIC



Nuclei just before collision

- Initial pre-equilibrium state

  hard parton scattering & jet production
  gluonic fields (Color Glass Condensate)

- Quark gluon plasma formation

  thermalization (hydrodynamics)

- QGP expansion and decay

  phase transition of partons into hadrons

  - Hadronization
  - Rescattering & chemical freeze out
  - Kinetic freeze out (stop interacting)

Experimentally observe only hadronic state

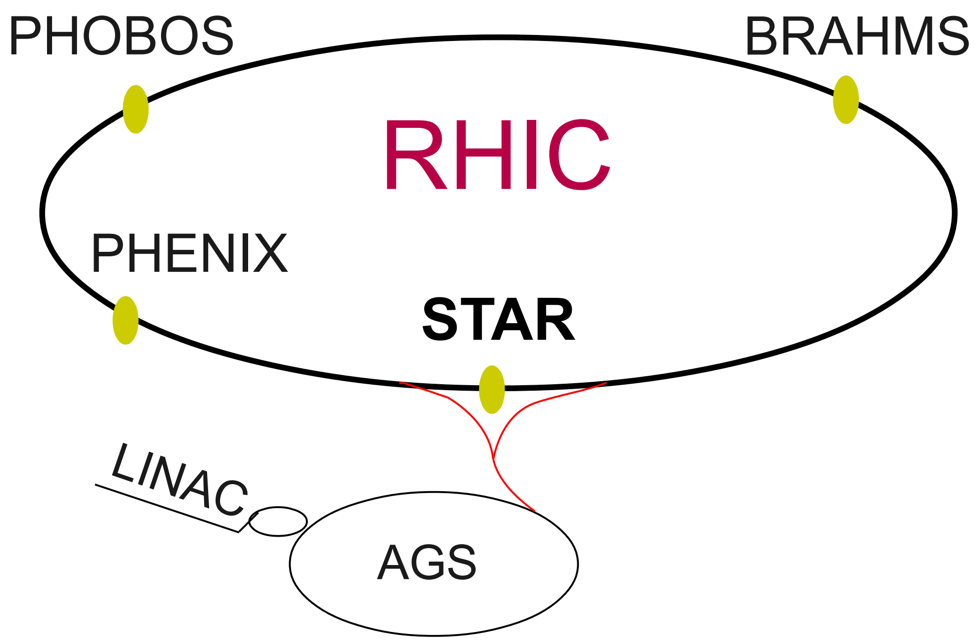
Careful systematic study is required
to form the evidence for QGP formation

Experimental signatures of QGP

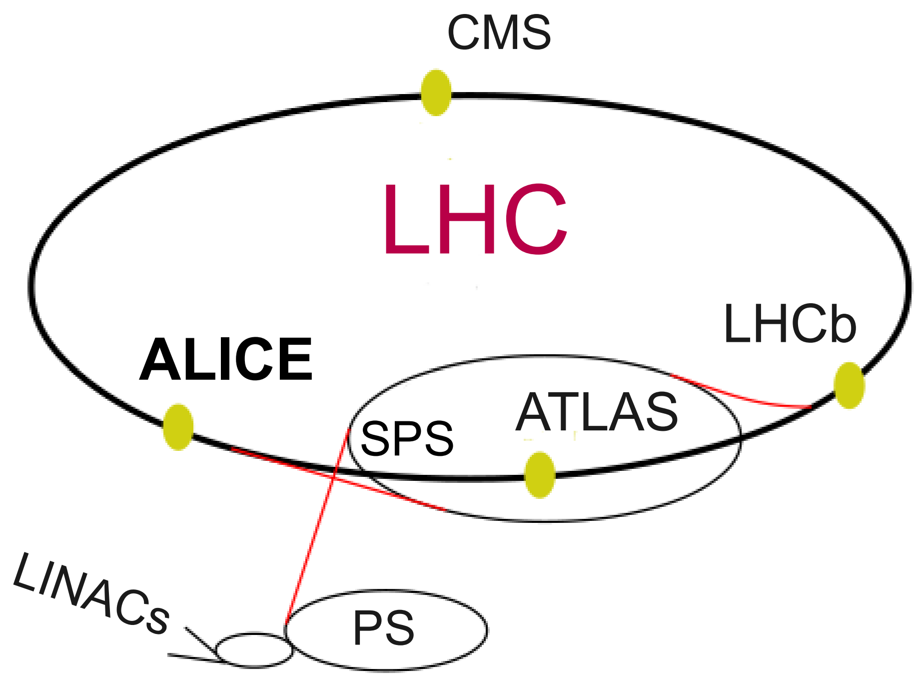
- **Particle yields**
  Chemical equilibrium: temperature & chemical potential
- **Strangeness**
  Enhancement relative to pp collisions
  More (light) s-quarks produced in QGP
- **Heavy flavor (charm and beauty)**
  J/ψ suppression due to color screening in QGP
  (heavy) c-quark produced very early in collision
- **Hard penetrating probes**
  Medium tomography with jets and direct photons
- **Event anisotropy** in the transverse plane
  Collectivity (flow): hydrodynamics, QGP viscosity
- **Bose-Einstein correlations**
  freeze out volume and QGP decoupling time
- **Fluctuations in the system**
  Multiplicity, momentum, charge correlations

Modern ultra-relativistic HI colliders

Relativistic Heavy ion Collider



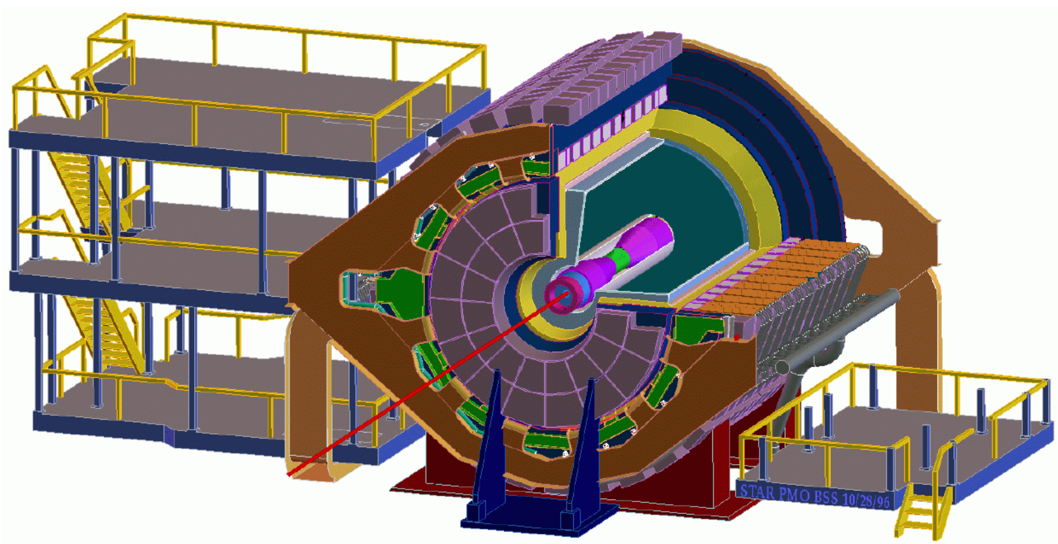
Large Hadron Collider



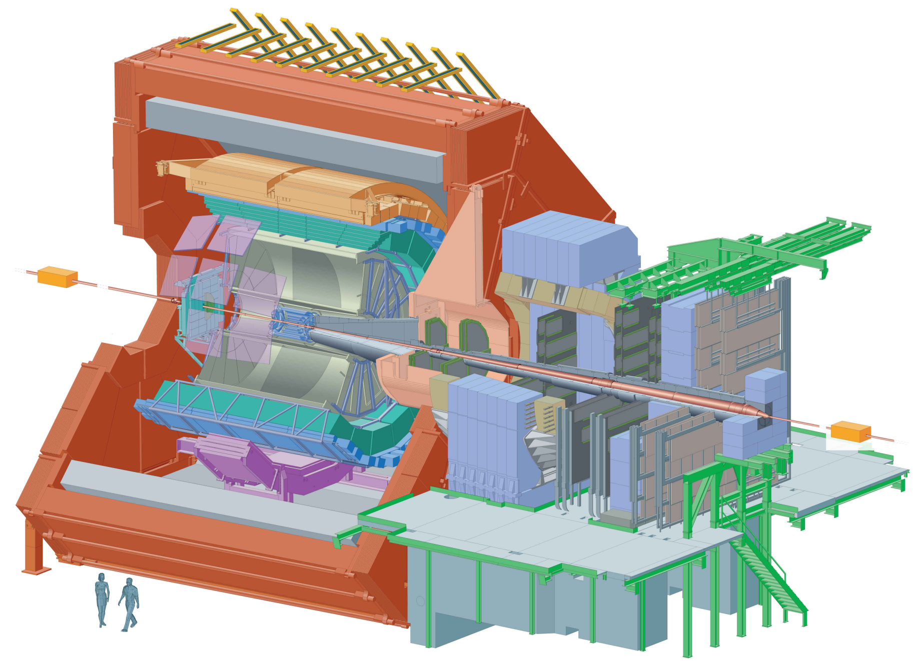
	RHIC	LHC
Location	BNL (USA)	CERN (Europe)
Circumference	3.8 km	27 km
Species	p, d, Cu, Au, U polarized protons	p, Pb
Energy/nucleon	in GeV 7-38, 62, 200 500 (pp only)	in TeV 7, 0.9 (pp) 2.76 (Pb)

Dedicated heavy ion experiments at RHIC and LHC

Solenoidal Tracker At RHIC

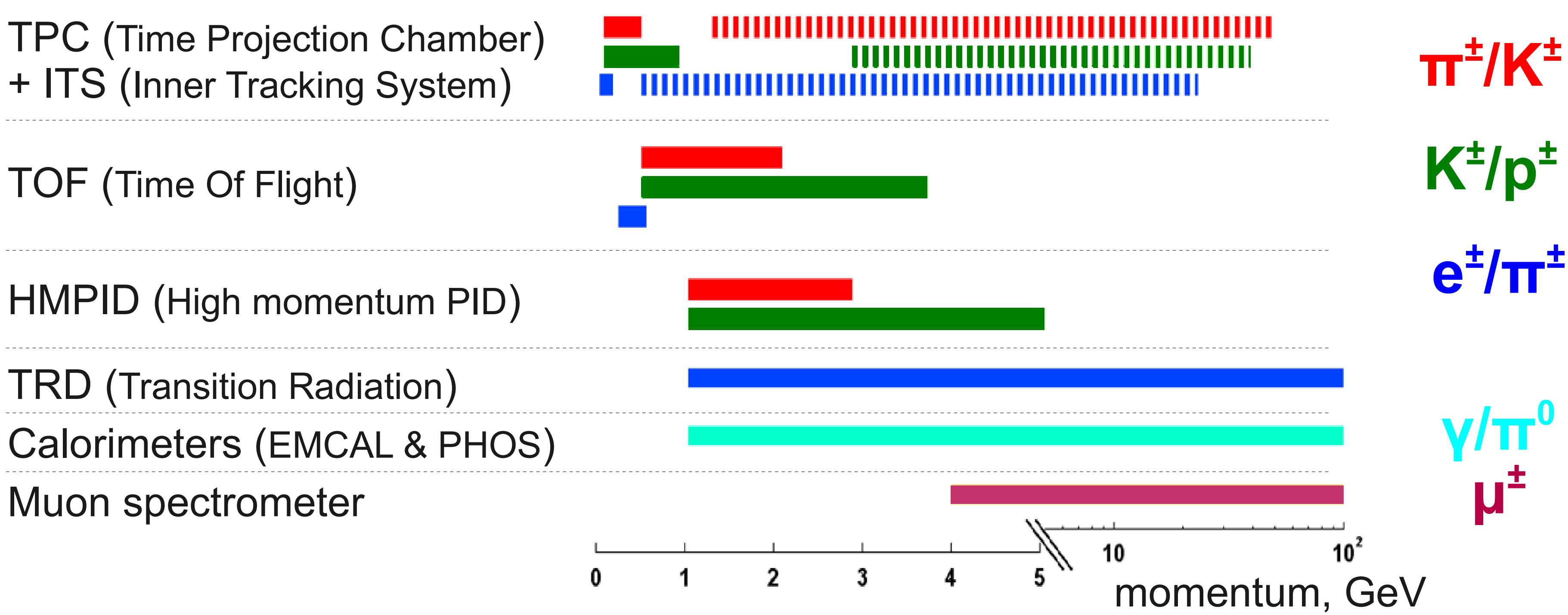


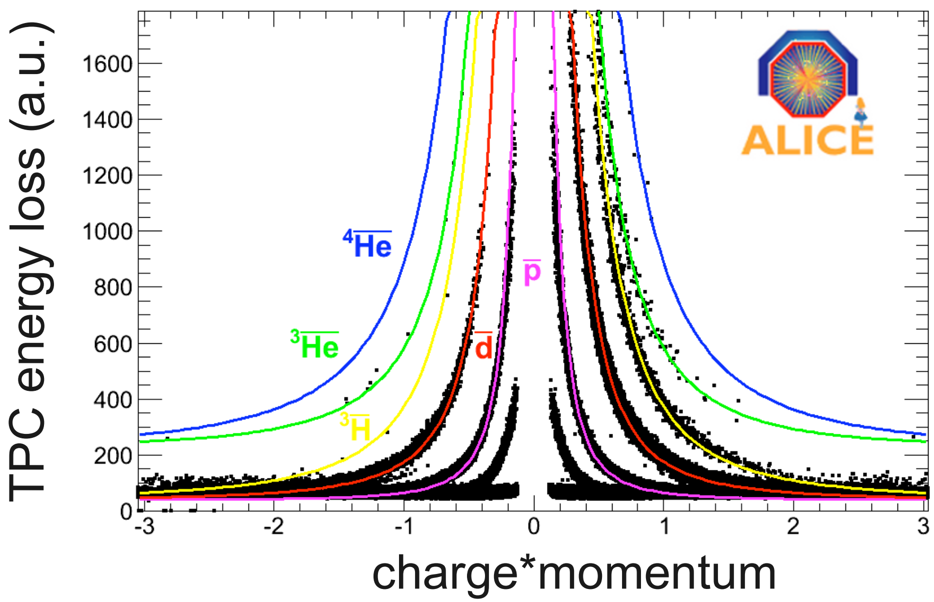
A Large Ion Collider Experiment



Collaboration	**STAR**	**ALICE**
Members	>500	>1000
Countries	12	33
Institutes	54	115
Main detector capabilities	Charge particle tracking and identification Calorimetry (electromagnetic energy) Event vertexing, triggering	

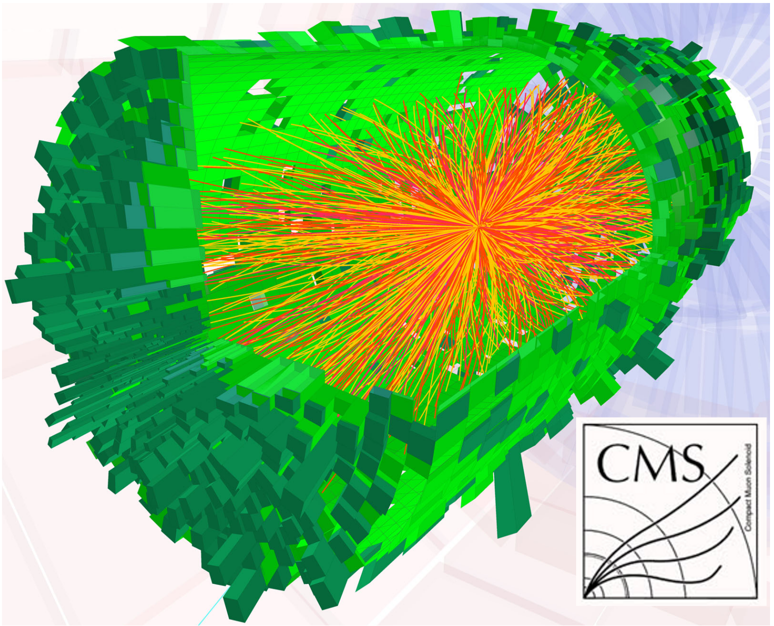
Particle identification with ALICE



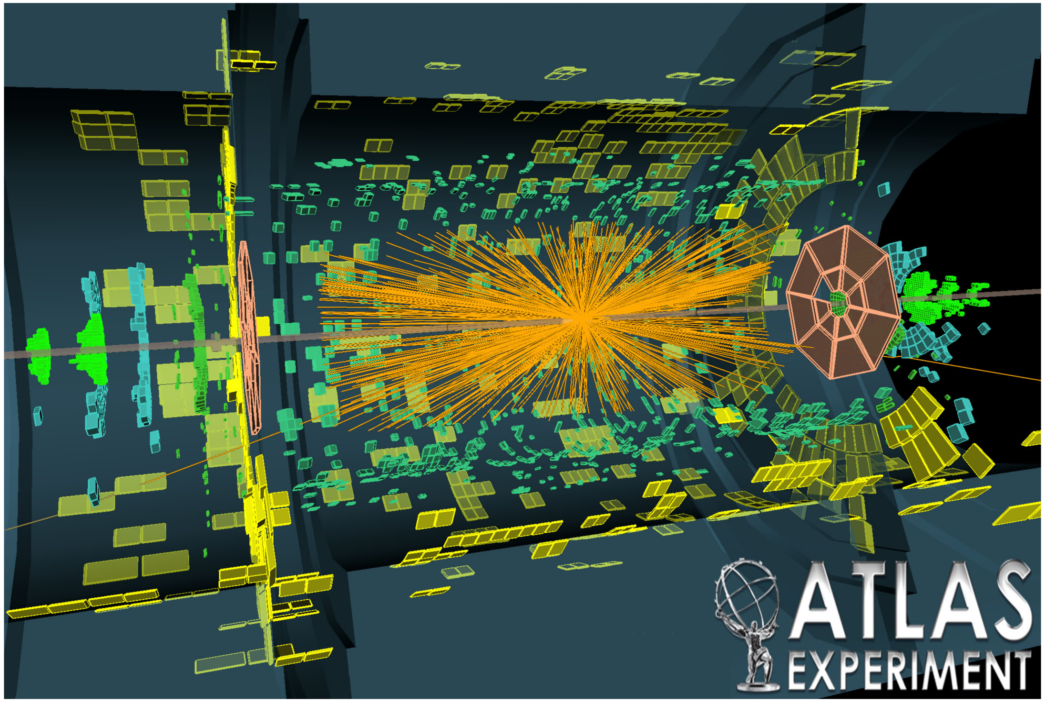


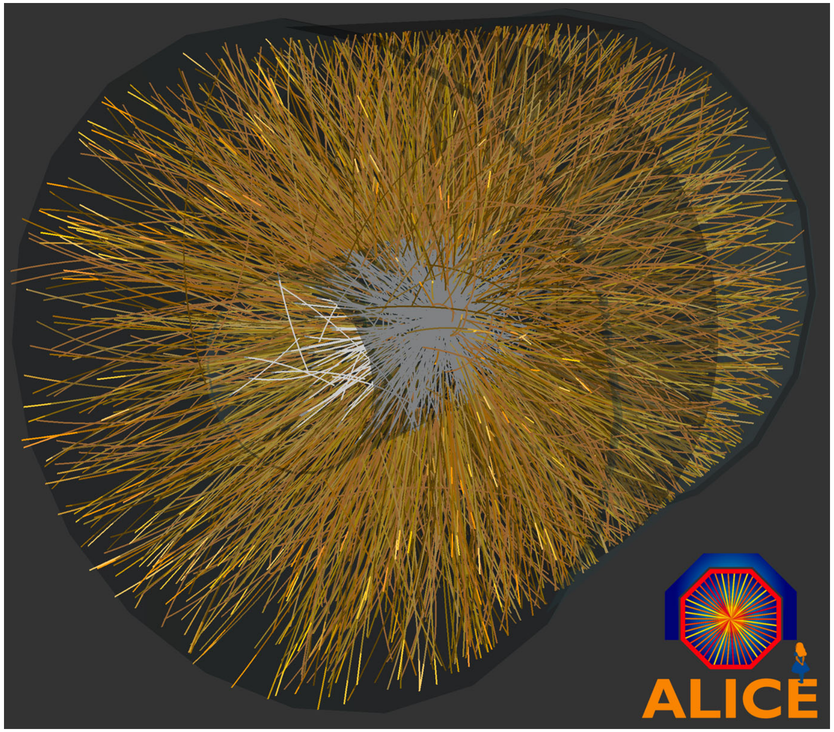
Excellent PID covers wide momentum range 0.15-100GeV
Light anti-nuclei can be identified!
+
full azimuthal coverage
wide beam angle coverage, |η|<1

November 2010: heavy ion run started at LHC!



LHC experiments
recorded first heavy ion events!





Exiting first results from Pb+Pb collisions at 2.76 TeV

- **Charge multiplicity density at mid-rapidity**

  $dN/d\eta$ in most-central: arXiv:1011.3916

  $dN/d\eta$ vs. centrality: arXiv:1012.1657

- **High pt suppression**

  R_{AA}, nuclear modification factor arXiv:1012.1004

- **Elliptic flow**

  v_2 vs. centrality and p_T: PRL105, 252302 (2010)

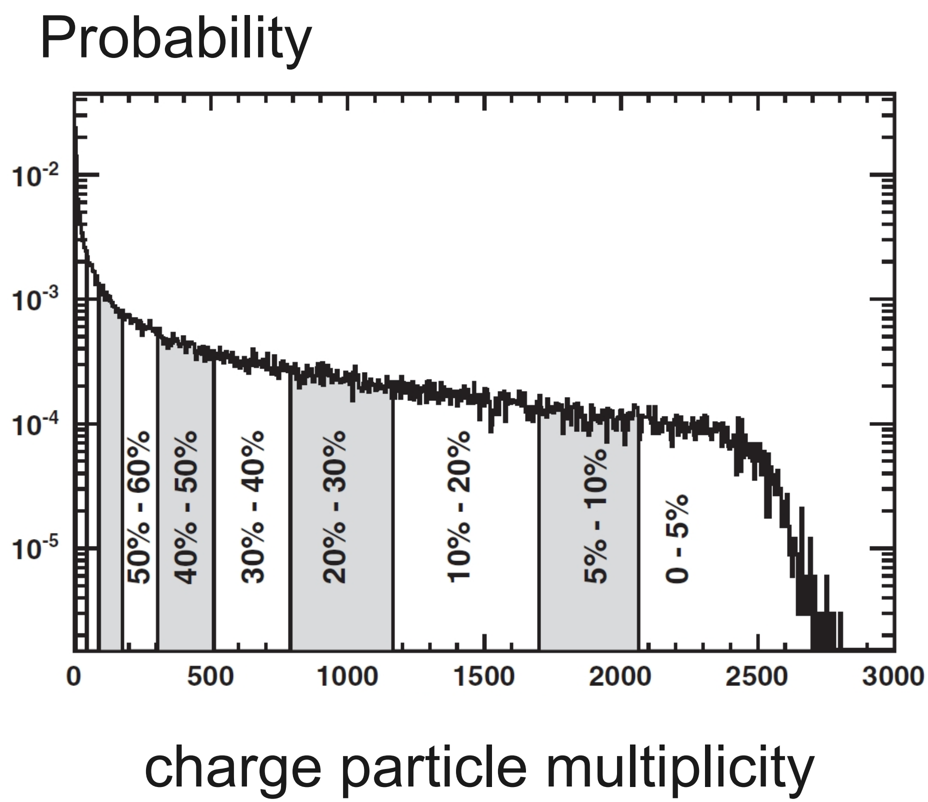
- **Bose–Einstein correlations**

  Two pion HBT arXiv:1012.4035

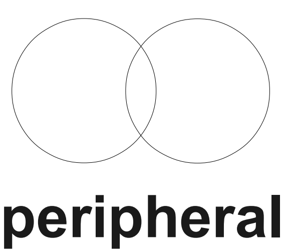
- **Jet quenching**

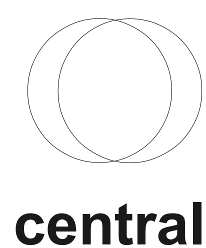
  ATLAS di-jets PRL105, 252303 (2010)

Some key variables of heavy ion collisions

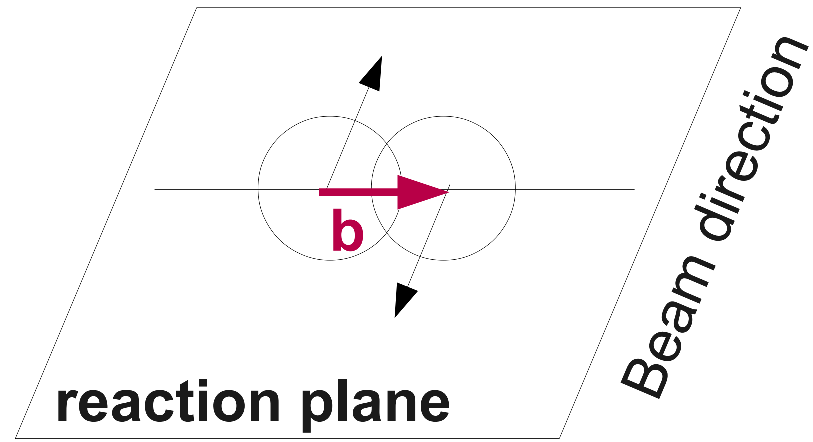


Centrality





Impact parameter, b & reaction plane



N_{part} - number of participating nucleons

N_{coll} - number of binary NN collisions

$$\eta = -\ln\tan\left(\frac{\theta}{2}\right)$$ - particle pseudo-rapidity

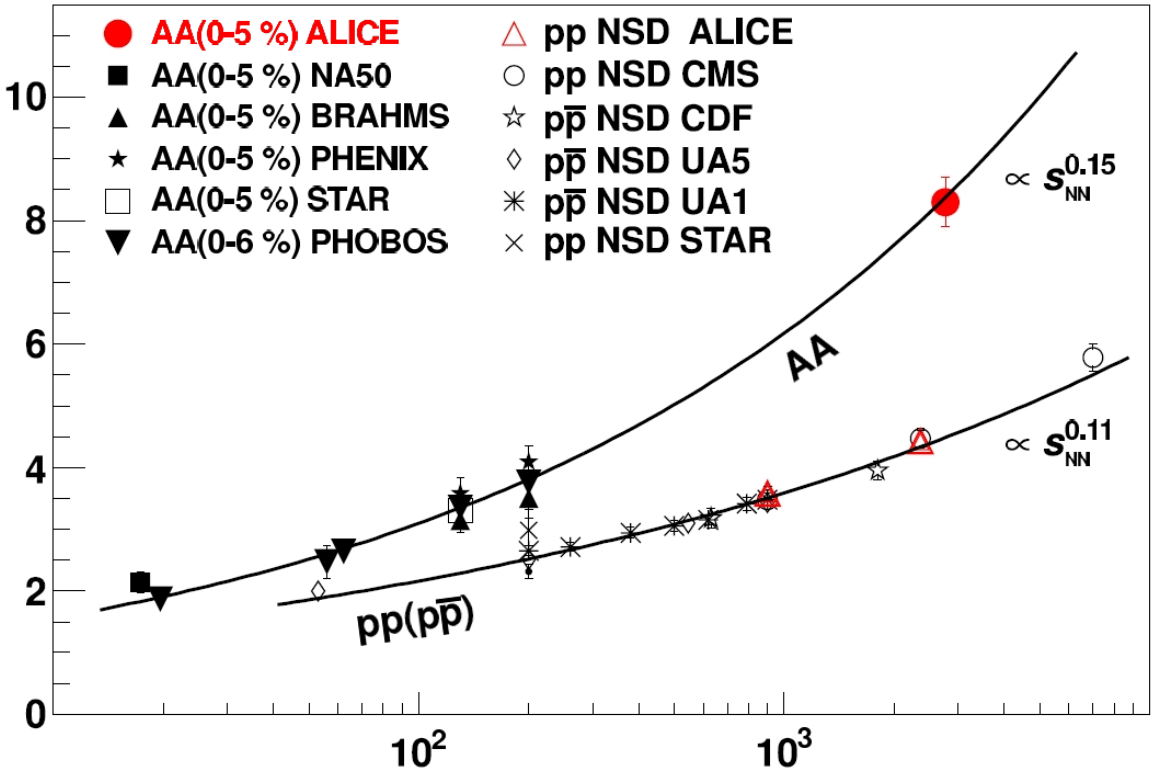
θ - polar angle wrt. beam axis

p_T - transverse momentum ($\perp$ to beam)

Reflect "hardness" of the particle production

Charge multiplicity density vs collision energy

$$\left(2/N_{part}\right)\frac{dN}{d\eta}$$ charge density at midrapidity per nucleon participant pair



$\sqrt{s_{NN}}$ collision energy, GeV

$$\left(2/N_{part}\right)\frac{dN}{d\eta} = 8.4 \pm 0.3$$

x2.2 increase from RHIC

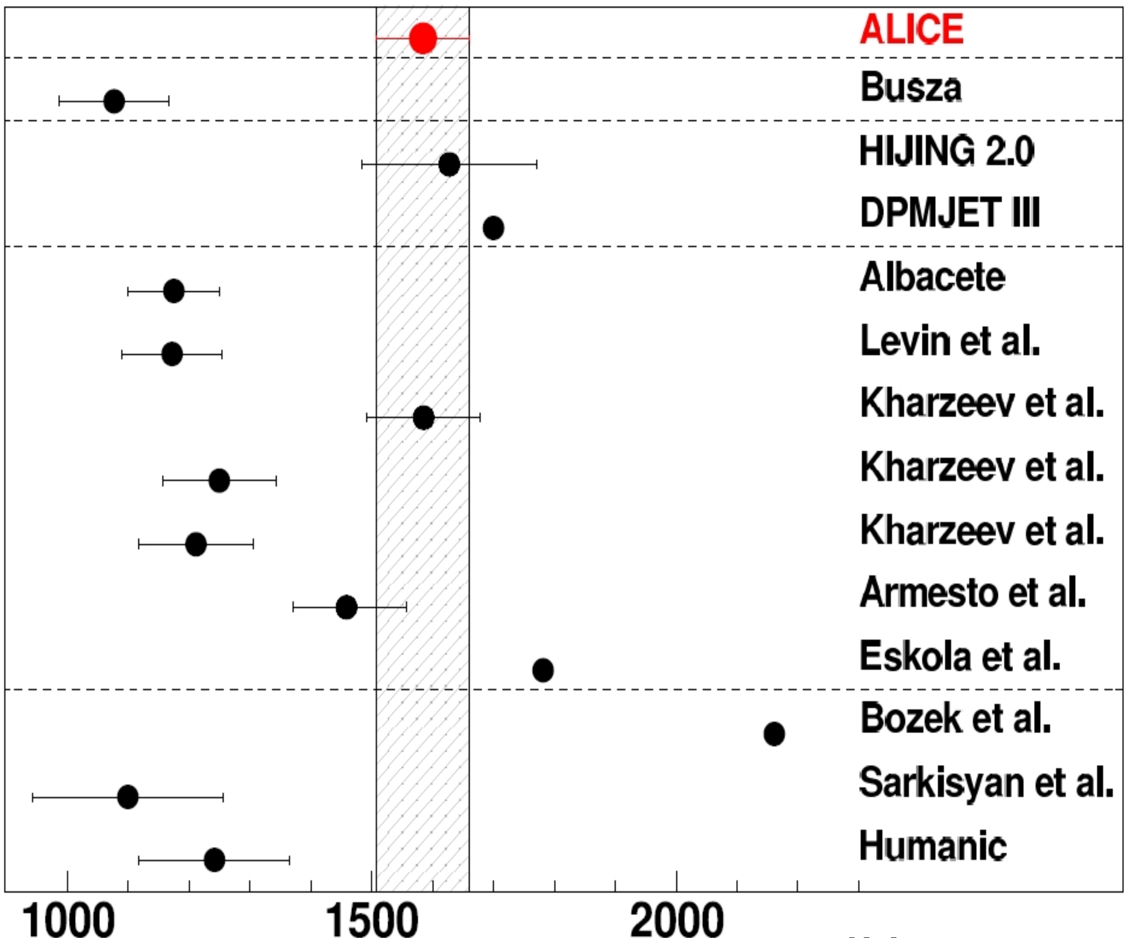
x1.9 increase from pp

- Constrains particle production mechanisms
- Estimate of the initial energy density
- Reflects hard vs. soft processes interplay

LHC multiplicity density vs. models tuned for RHIC/SPS

charge density at midrapidity, 0-5%

$$\frac{dN}{d\eta} = 1601 \pm 60$$



$$\frac{dN}{d\eta}$$

Extrapolated from lower energies

pQCD Monte Carlo generators

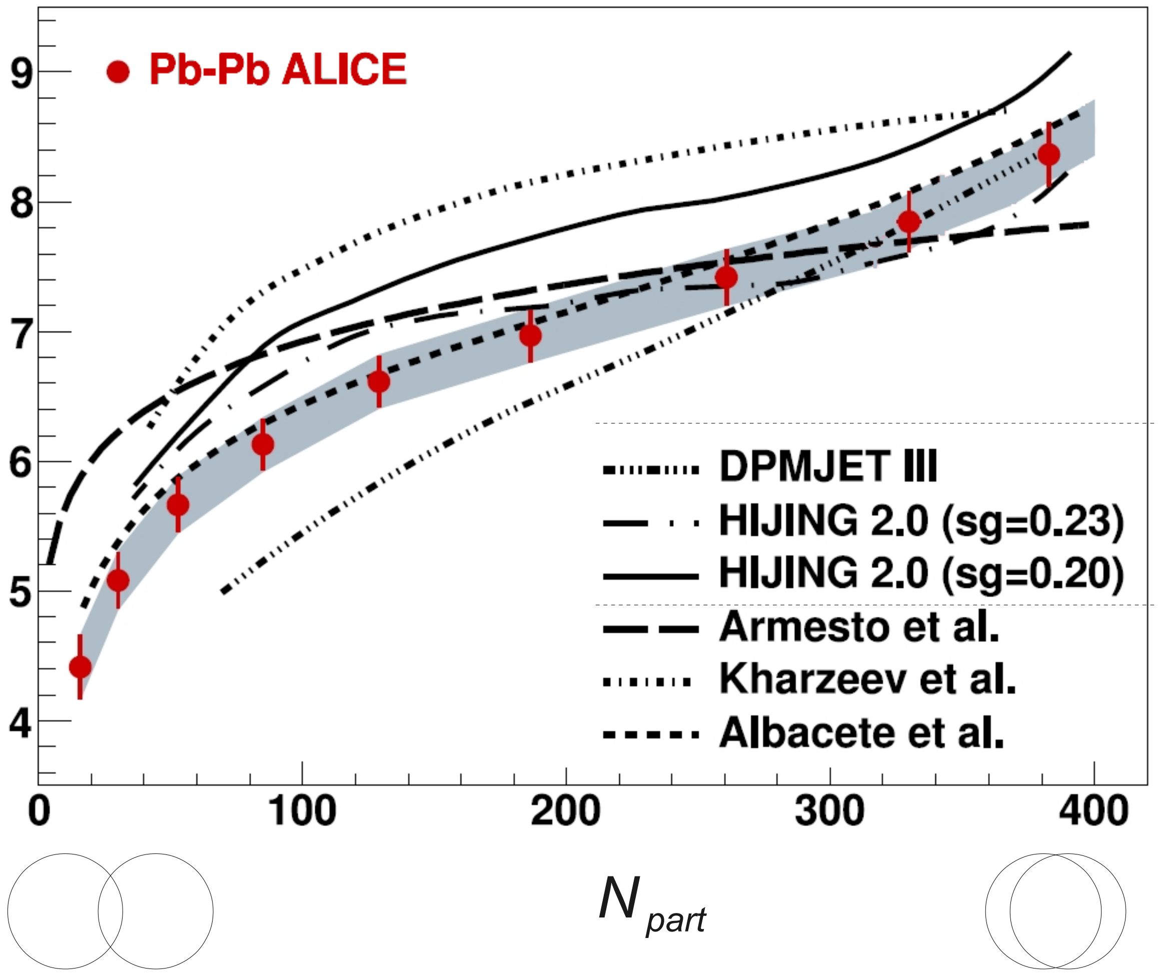
Models with initial state
Gluon density saturation

Hydrodynamic models

PYTHIA + hadronic rescattering

Centrality dependence of charge multiplicity density

$\left(2/N_{part}\right)\frac{dN}{d\eta}$ charge density at midrapidity per nucleon participant pair



New challenge for theoretical models!

pQCD (jets and mini-jets) + soft interactions

Models with initial state gluon density saturation

Nuclear modification factor, R_{AA}

Quantifying medium effects in heavy ion collisions
by deviation from particle production in pp interaction

$$R_{AA}(p_T) = \frac{1}{N_{coll}} \frac{Y_{AA}(p_T)}{Y_{pp}(p_T)}$$

Normalized by N_{coll} ratio of p_T yields in AA to that in pp

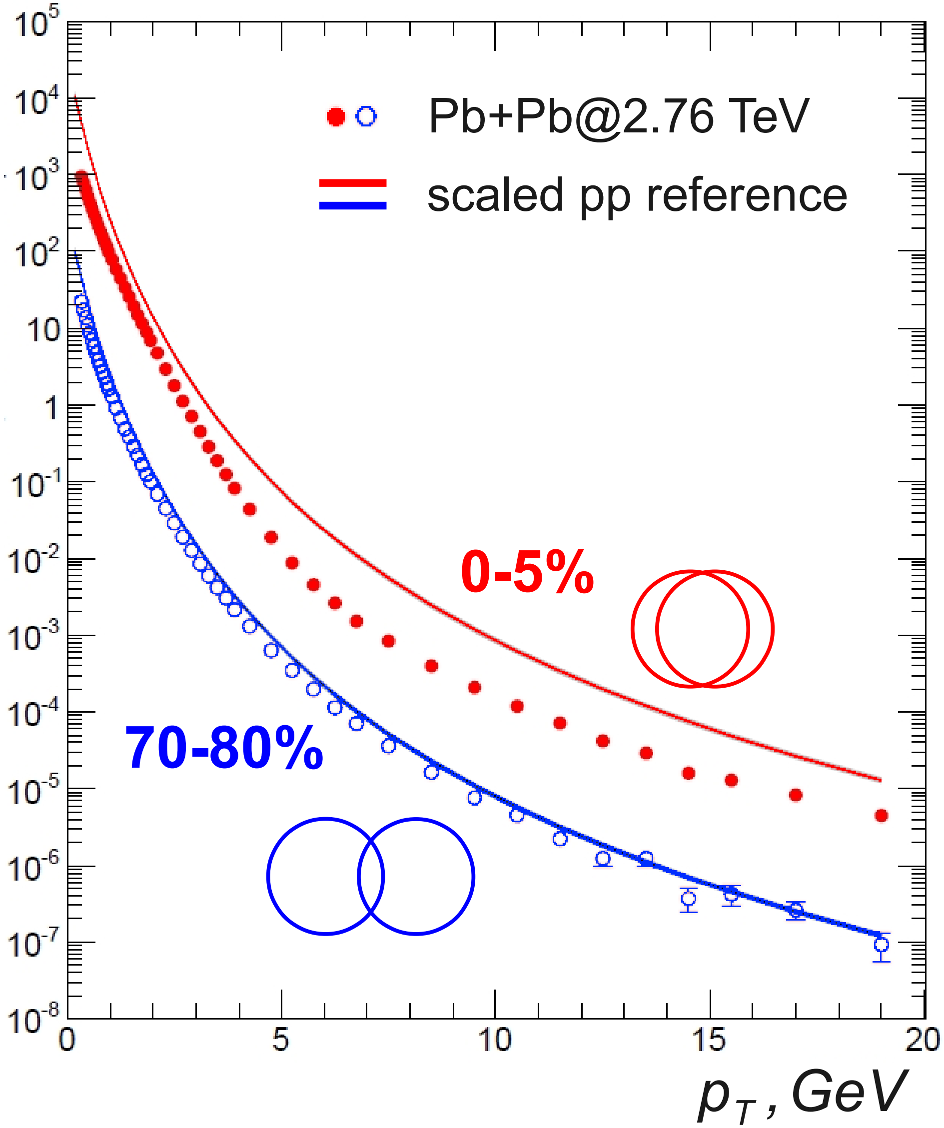
$$Y(p_T) = \frac{1}{N_{evt}} \frac{d^2 N_{ch}}{d\eta \, dp_T}$$

p_T distribution of charge particles at midrapidity

$R_{AA}(p_T) = 1$	no medium modification
$R_{AA}(p_T) < 1$	suppression by medium

R_{AA} ingredients: pp reference and p_T yield in Pb+Pb

$$\frac{1}{N_{evt}} \frac{1}{2\pi p_T} \frac{d^2 N_{ch}}{d\eta dp_T}, (GeV/c)^2$$



Very good statistics!
covers 9 decades in p_T reach

Experimental challenge:
no pp measurements at 2.76 TeV

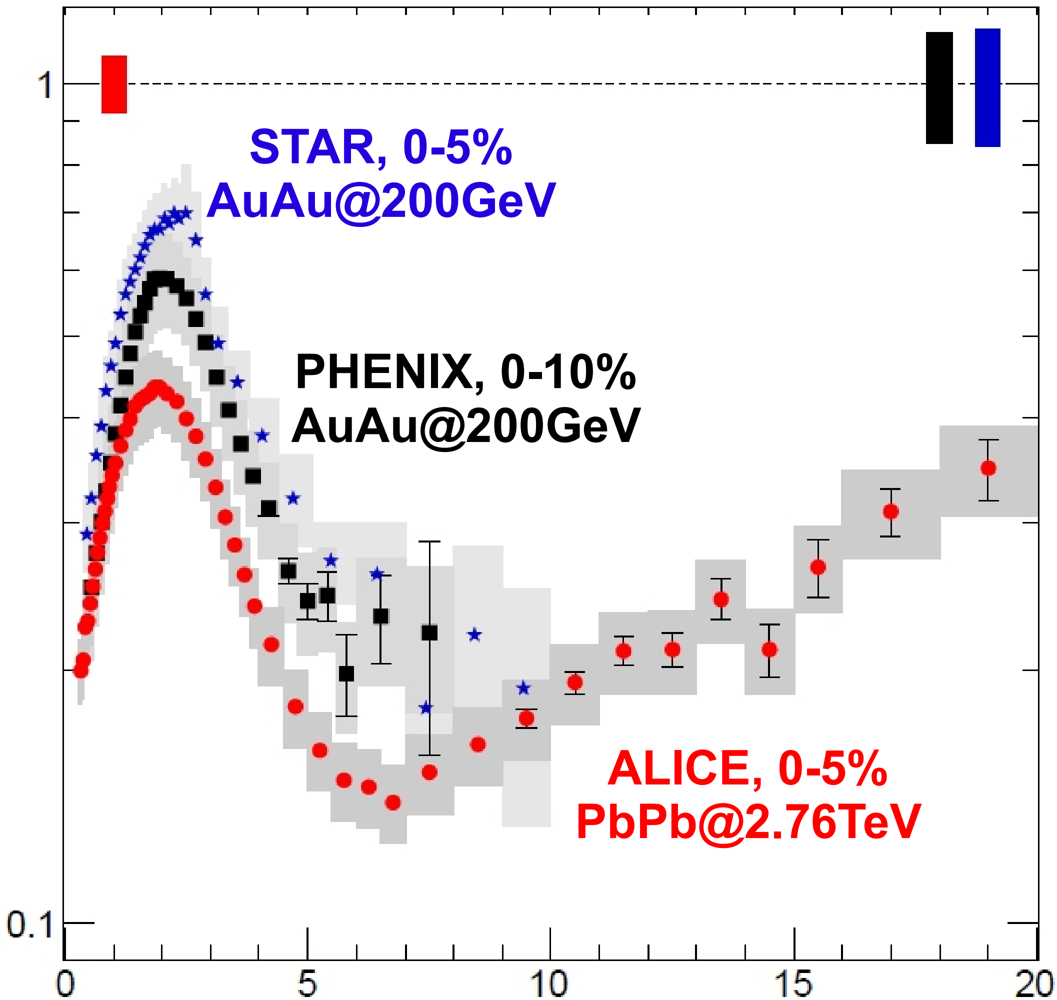
Extrapolate between pp@ 900GeV & 7TeV
Additional systematic uncertainties in R_{AA}

Peripheral: pp and AA similar

Central: strong modification

Suppression at RHIC and LHC

R_{AA} (nuclear modification factor)



p_T, GeV

Similar shape between LHC and RHIC

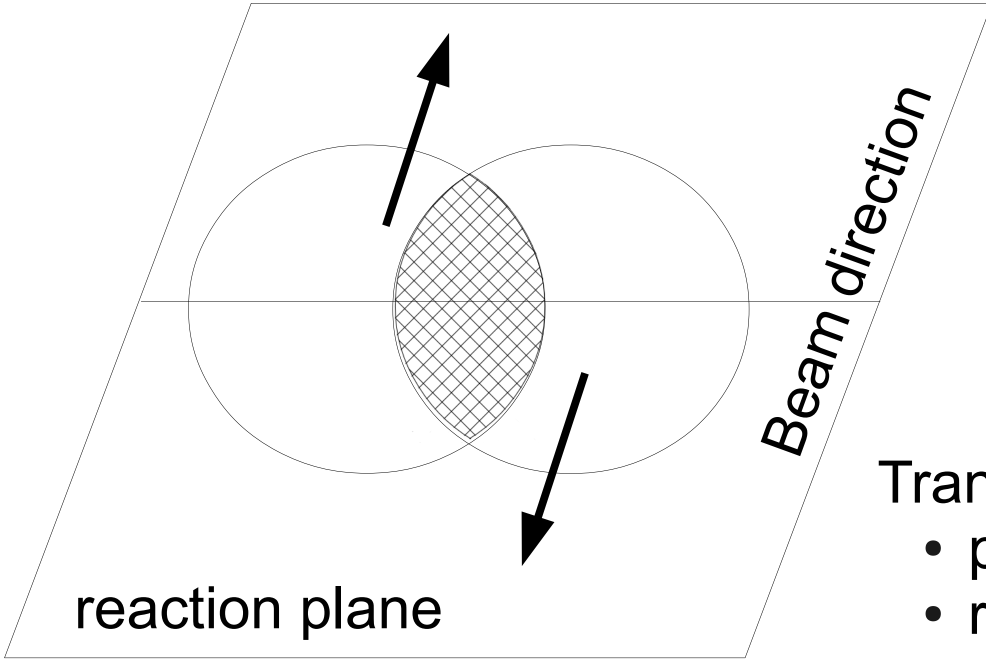
Minimum $R_{AA}^{LHC} = 0.14$ at $p_T \sim 6$GeV

x5 suppression event at 20GeV!

Much flatter pT spectra at LHC but R_{AA} is smaller than at RHIC:

Enhanced parton energy loss
More dense medium

Event anisotropy in non-central collision



Almond shape of the overlap region
- non uniform density profile
- pressure gradient

Transverse anisotropy in particles production
- probes/scans the medium
- reveals particle collectivity

Initial space anisotropy evolves into momentum space
- Measurable experimentally

Self quenching effect:
- with more rescattering less anisotropy
- sensitivity to the early stage of the collision

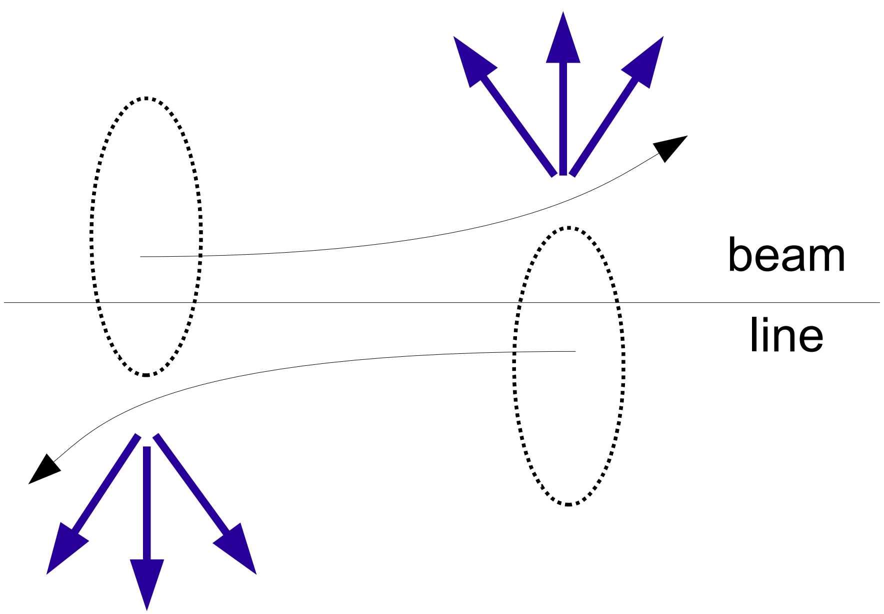
Experimental determination of the transverse flow

Fourier decomposition of particle azimuthal distribution wrt. the reaction plane:

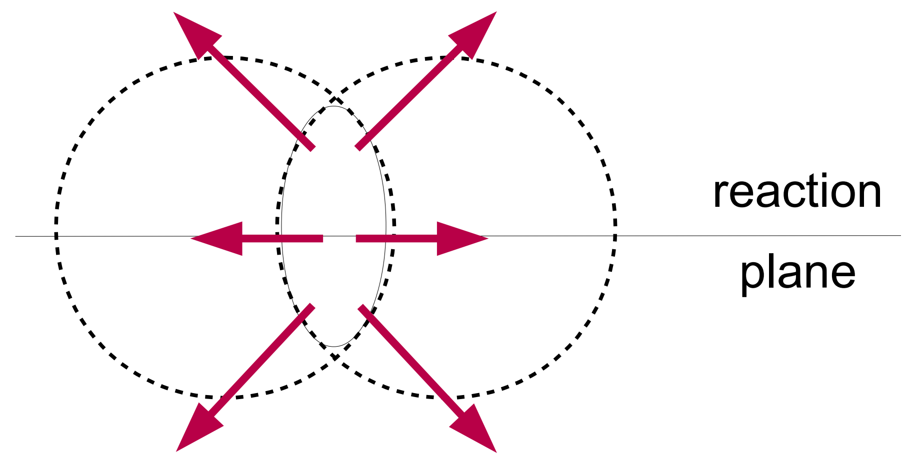
$$\frac{dN}{d\phi} \sim 1+2\sum_{n=1} v_n(p_T,\eta)\cos(n[\phi-\Psi_{RP}])$$

Ψ_{RP} - reaction plane (RP) angle ϕ - particle azimuthal angle

Directed flow: $v_1=\langle\cos(\phi-\Psi_{RP})\rangle$

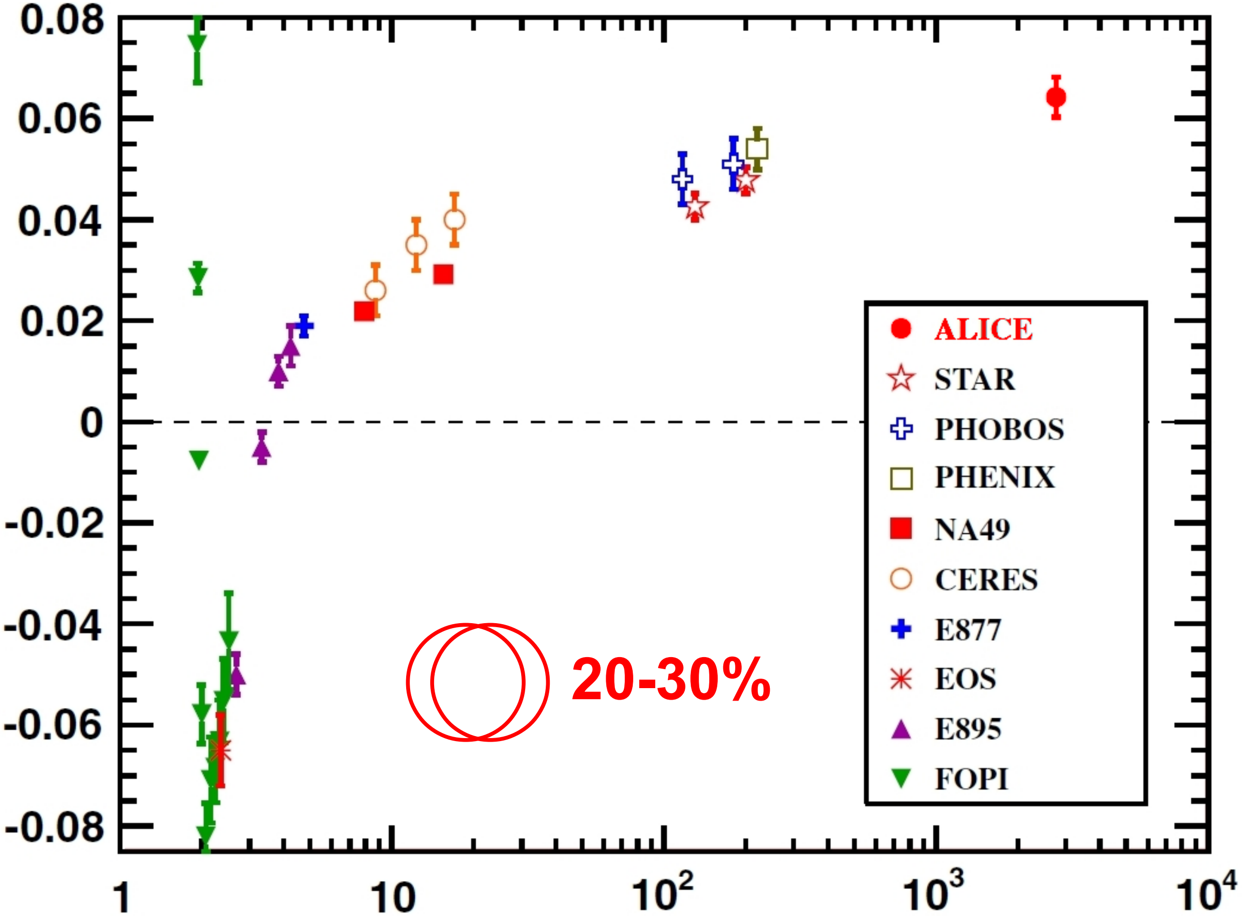


Elliptic flow: $v_2=\langle\cos(2[\phi-\Psi_{RP}])\rangle$



Integrated elliptic flow vs. collision energy

v_2 elliptic transverse flow



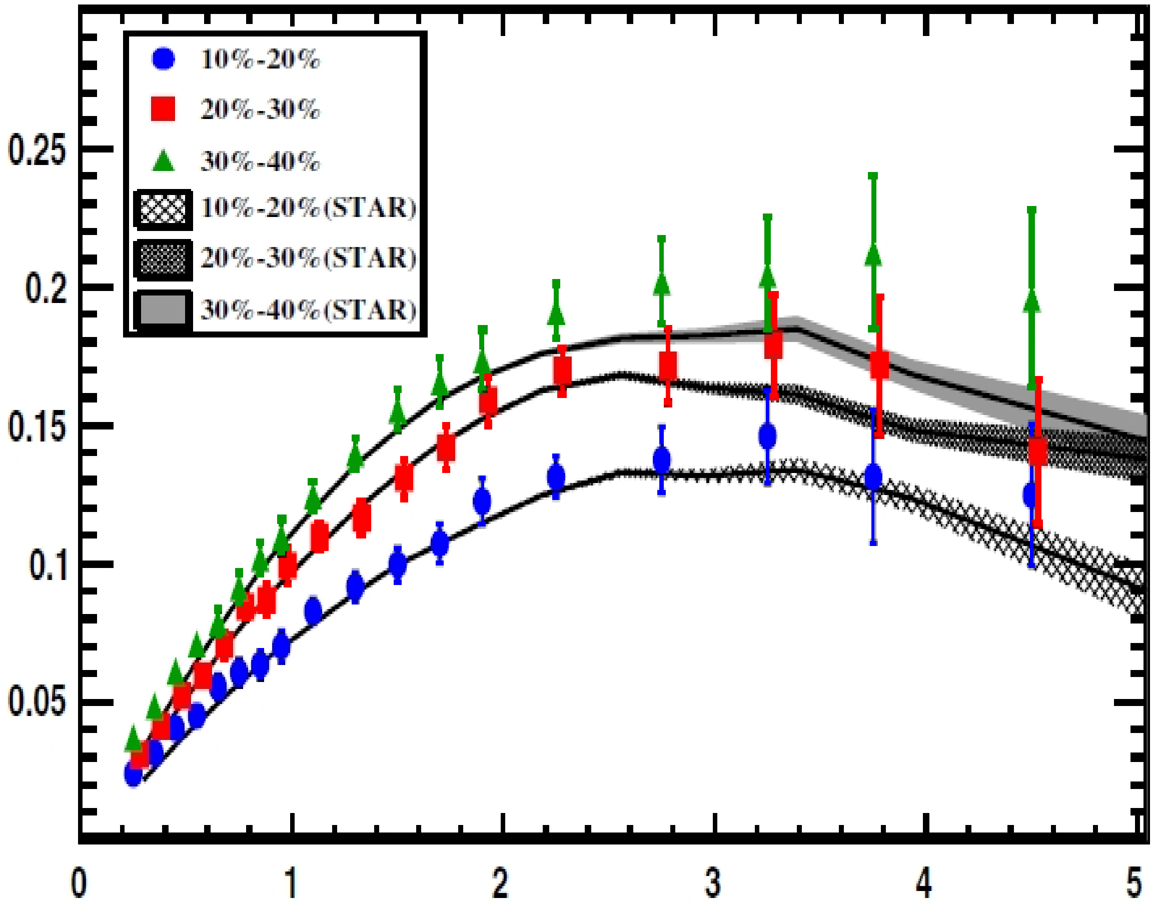
$\sqrt{s_{NN}}$ collision energy, GeV

Integrated midrapidity flow shows 30% increase at LHC

Stronger collectivity at LHC
Perfect liquid even at LHC?

Elliptic flow vs. transverse momentum

v_2 elliptic transverse flow



p_T, transverse momentum, GeV

Similar flow at RHIC and LHC

Integrated flow difference driven by mean p_T shift

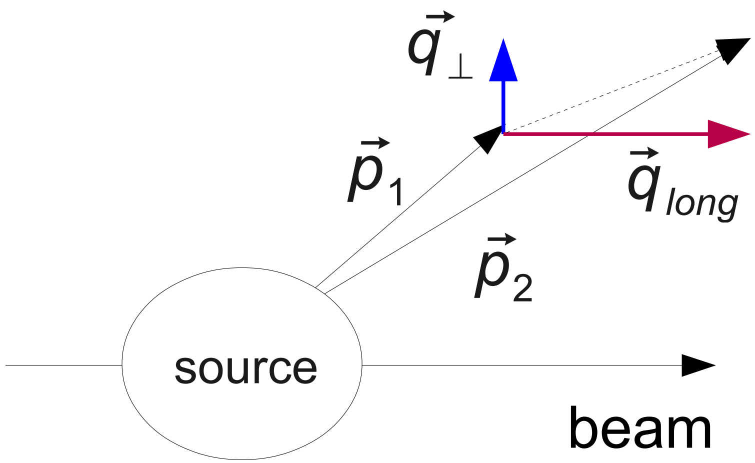
stronger radial flow?

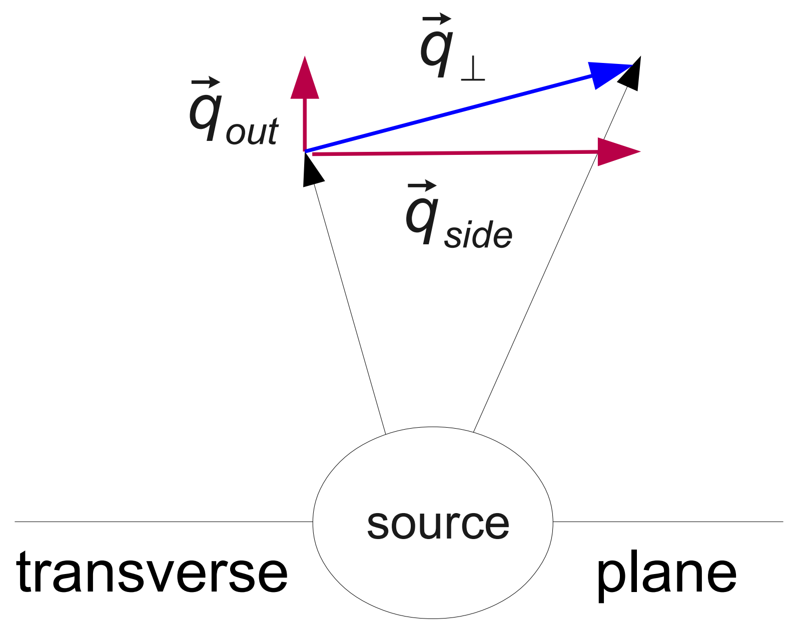
HBT (Hanbury-Brown-Twiss) correlations

Momentum-space two-particle correlations of identical bosons:

$$C(\vec{p}_1, \vec{p}_2) = \frac{P(\vec{p}_1, \vec{p}_2)}{P(\vec{p}_1)P(\vec{p}_2)} \sim \int |\Phi(\vec{r}, \vec{q})| S(\vec{r}, \vec{q}) d\vec{r} \qquad \vec{q} = \vec{p}_1 - \vec{p}_2$$

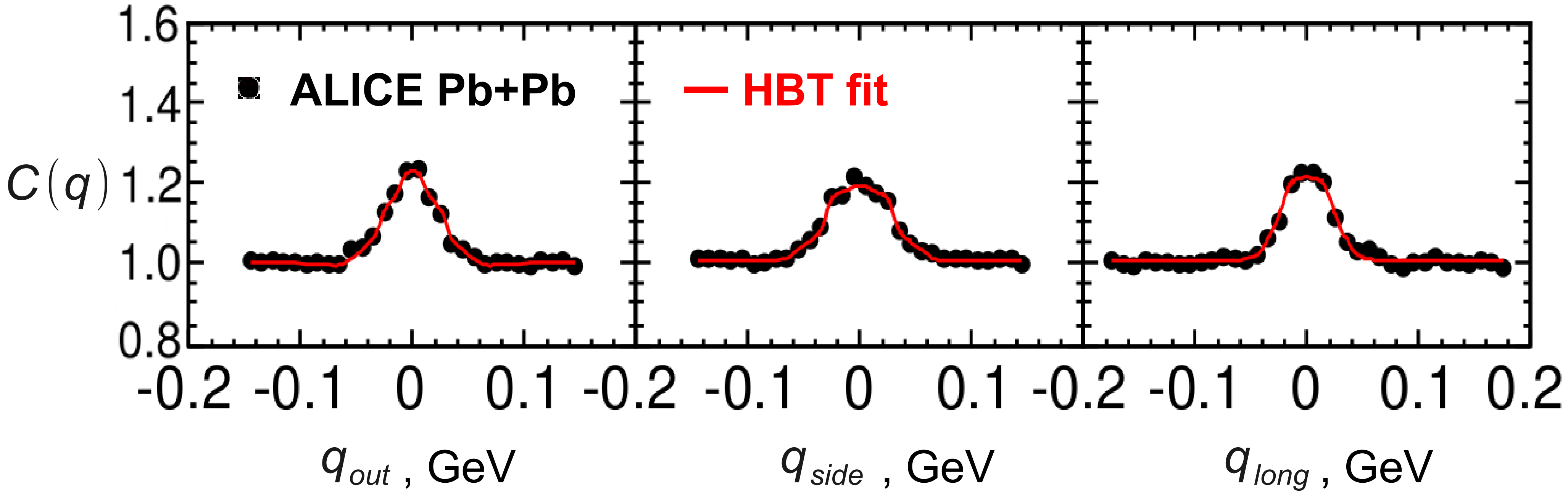
Correlation "width" in momentum space proportional to the **source size**





Decompose into longitudinal, out, and side components
Study the source function in 3 dimensions

3D fit to the two same charge pion correlations



Fit parametrization: $C(\vec{q}) \sim 1 + \lambda K(q_{inv})[1 + G(\vec{q})]$

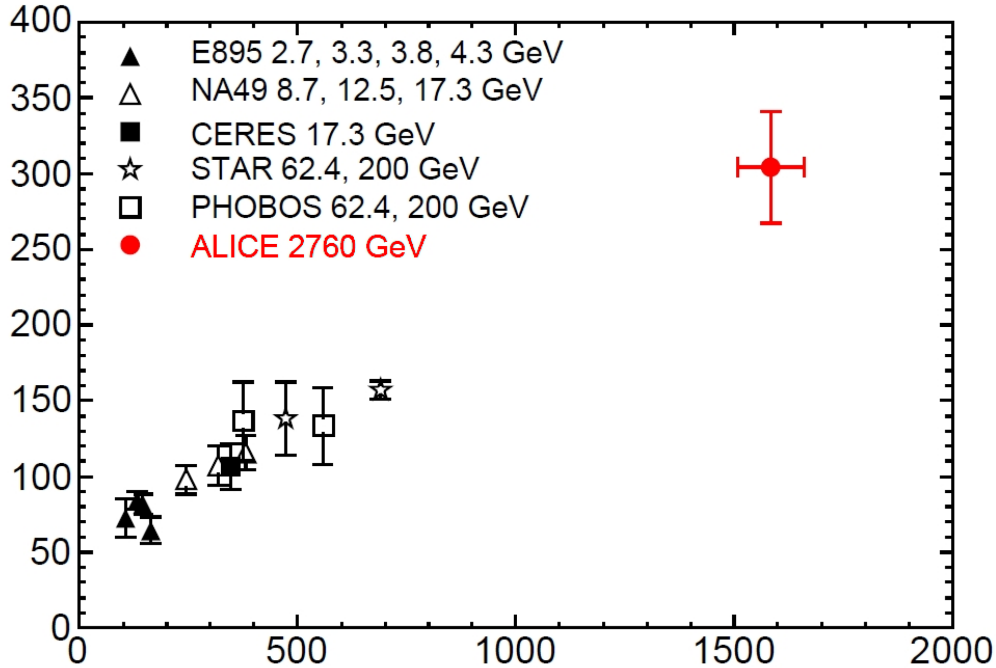
$G(\vec{q}) = \exp\left(-(R_{out}^2 q_{out}^2 + R_{side}^2 q_{side}^2 + R_{long}^2 q_{long}^2)\right)$ Bose-Einstein enhancement

λ correlation strength

$K(q_{inv})$ average Coulomb function

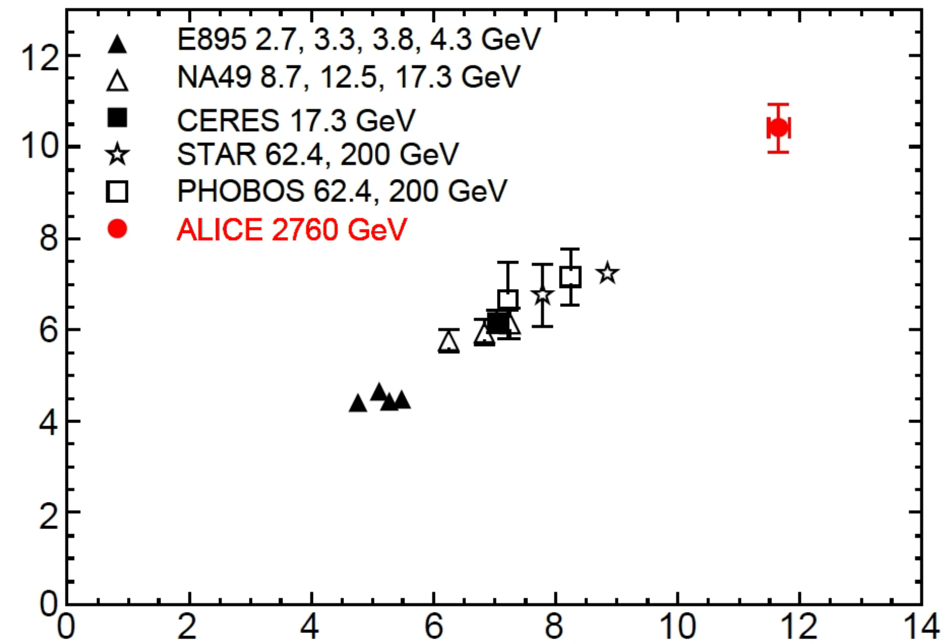
Freeze-out volume and decoupling time at LHC

$R_{out} R_{side} R_{long}$, fm^3



$\langle dN/d\eta \rangle$

τ_f , fm/c



$\langle dN/d\eta \rangle^{1/3}$

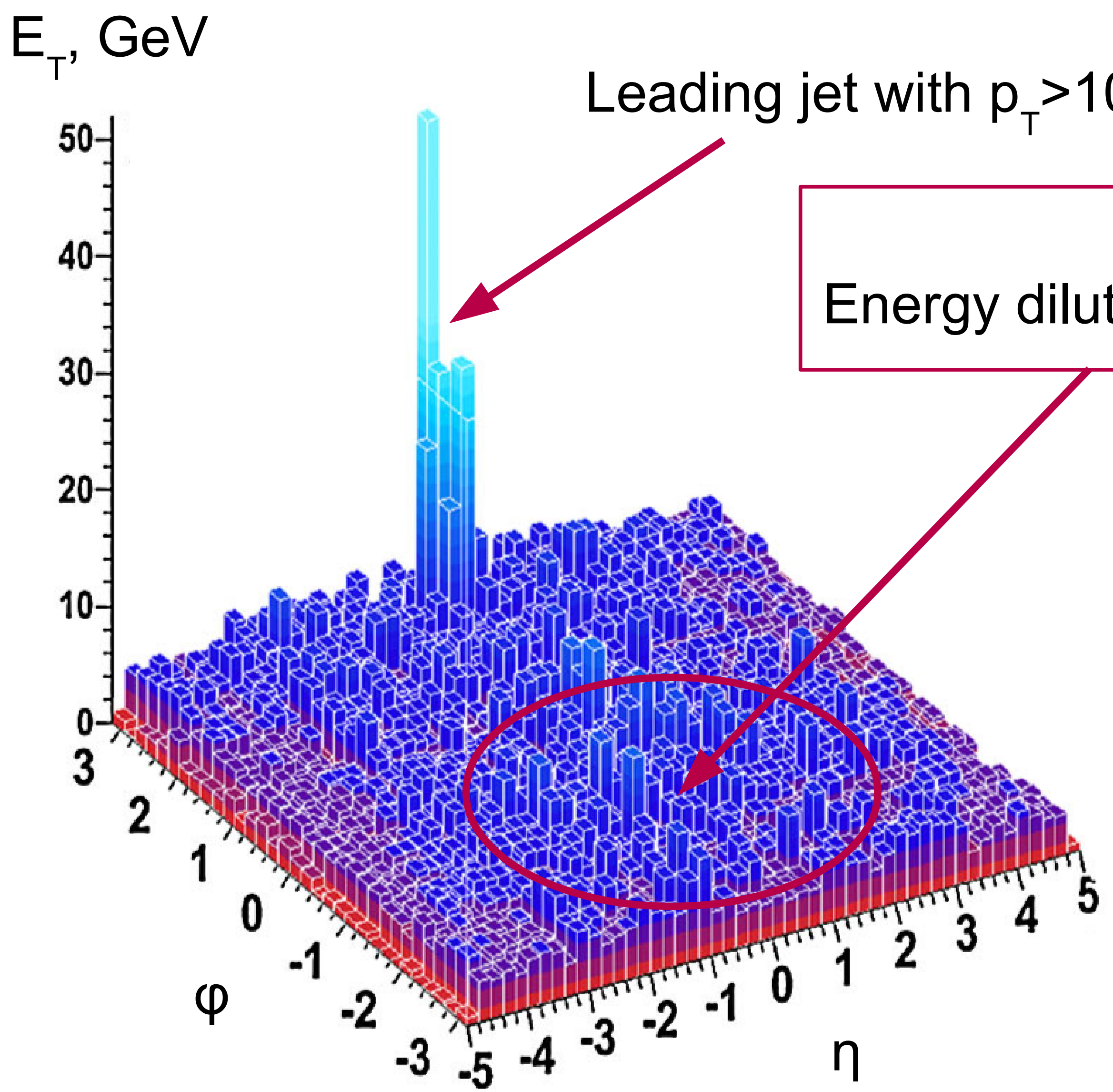
Larger homogeneity region at LHC

x2 increase in freeze-out volume compared to RHIC

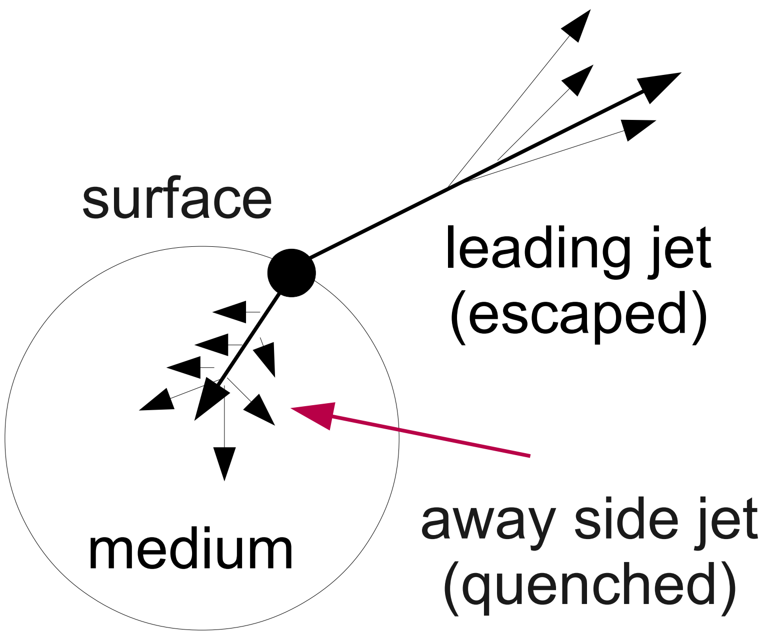
$\tau_f \sim R_{long} \sqrt{m_T / T}$

by 30% longer emission time

Highly asymmetric di-jets observed by ATLAS at LHC

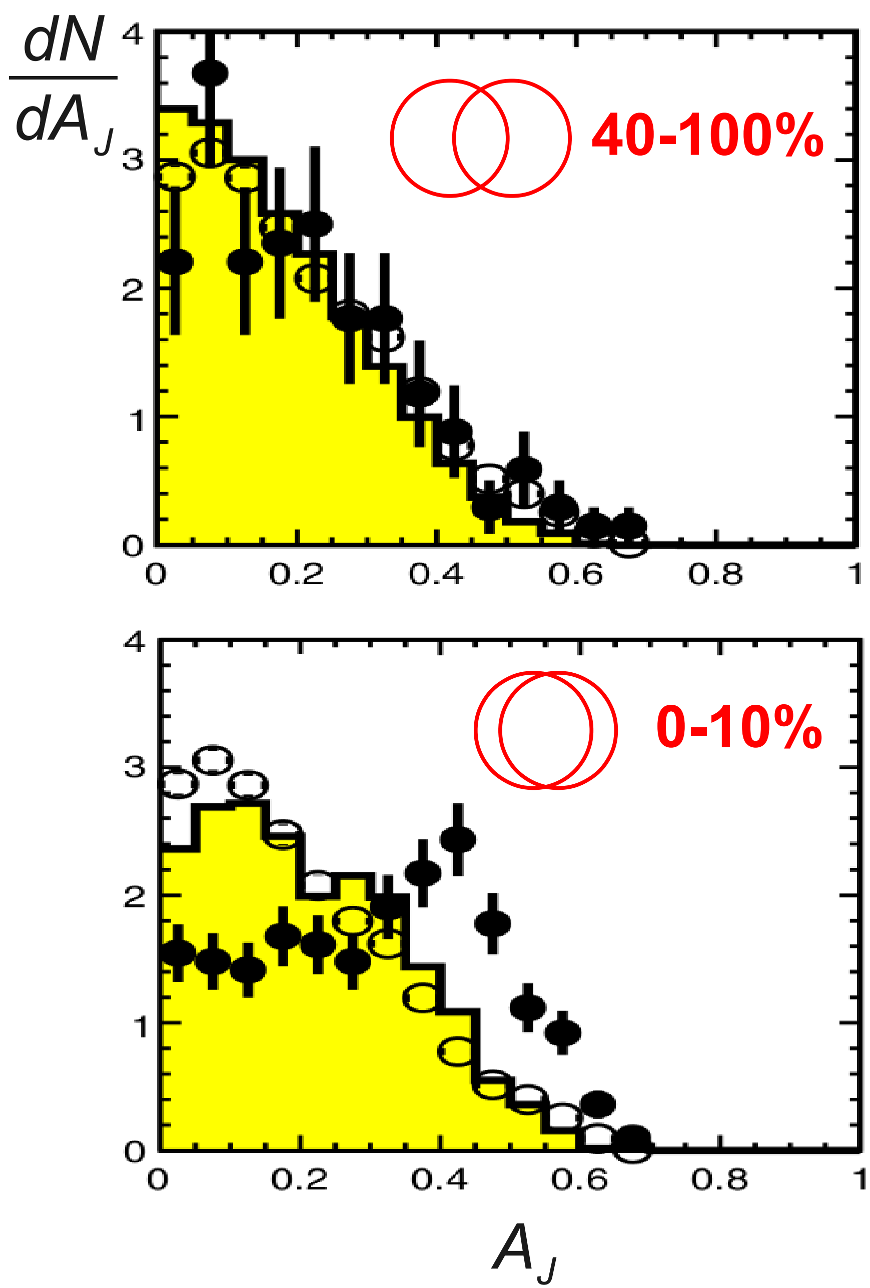


No away side jet?
Energy diluted over wide range in azimuth



Sample di-jet event reconstructed
by ATLAS in central Pb+Pb collision

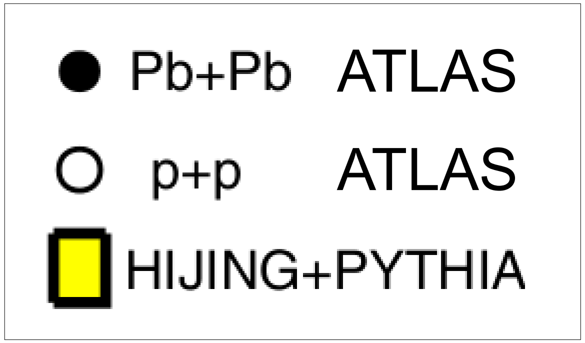
Jet quenching at LHC



Introduce di-jet energy imbalance:

$$A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}$$

E_{T1}, E_{T2} - transverse jet energies



Strong di-jet energy imbalance
Away side jet quenched by dense medium

Summary

Field of heavy ion collisions provides valuable information on:

- Fundamental properties of strong interactions
  (deconfinement, chiral symmetry restoration, etc)

- Existence of QCD phase transition & deconfined quark matter (QGP)

- Gives insights on the properties of early universe,
  just after a few microseconds after Big Bang

Exciting first heavy ion results from LHC run in November 2010

- Provides an additional constrains on the models of HIC

- Key ingredients for building a consistent picture of QGP phase diagram

Looking forward to further studies and upcoming results from LHC!