# News from heavy-ion collisions at RHIC and LHC

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**Hadron 2011**

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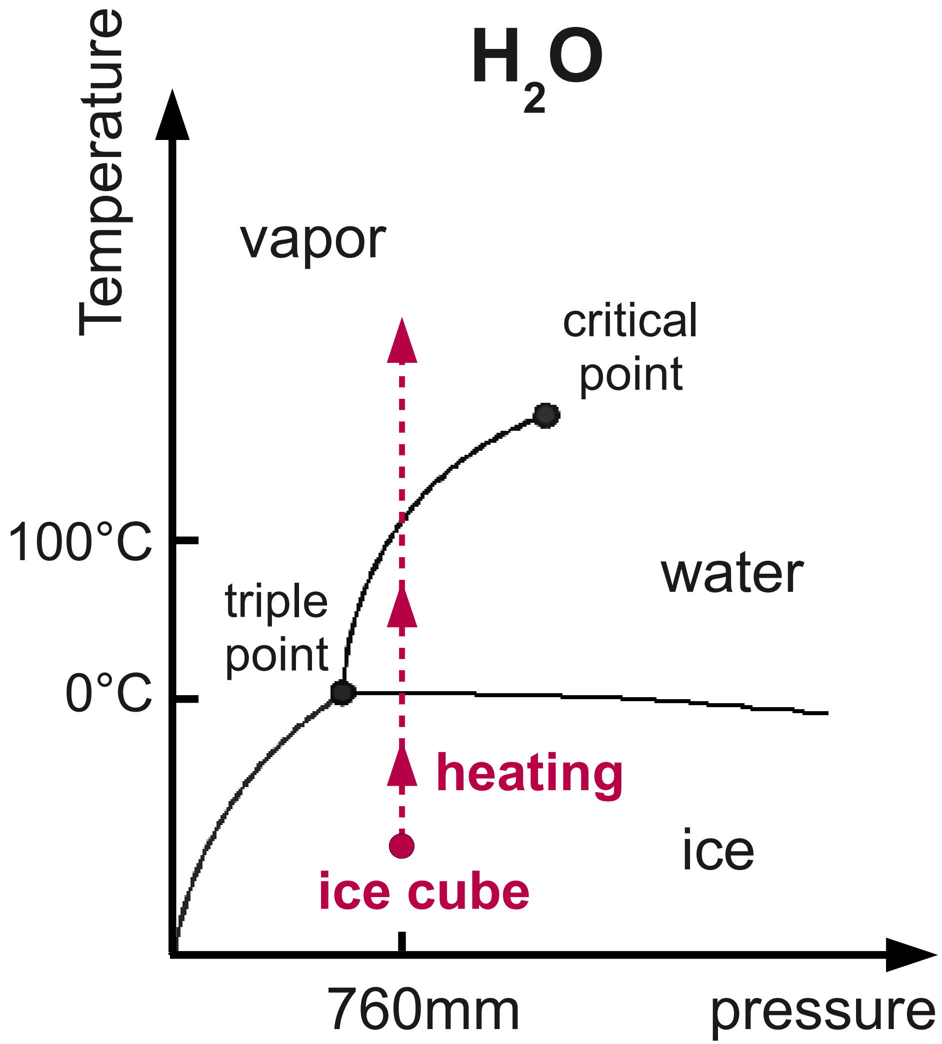
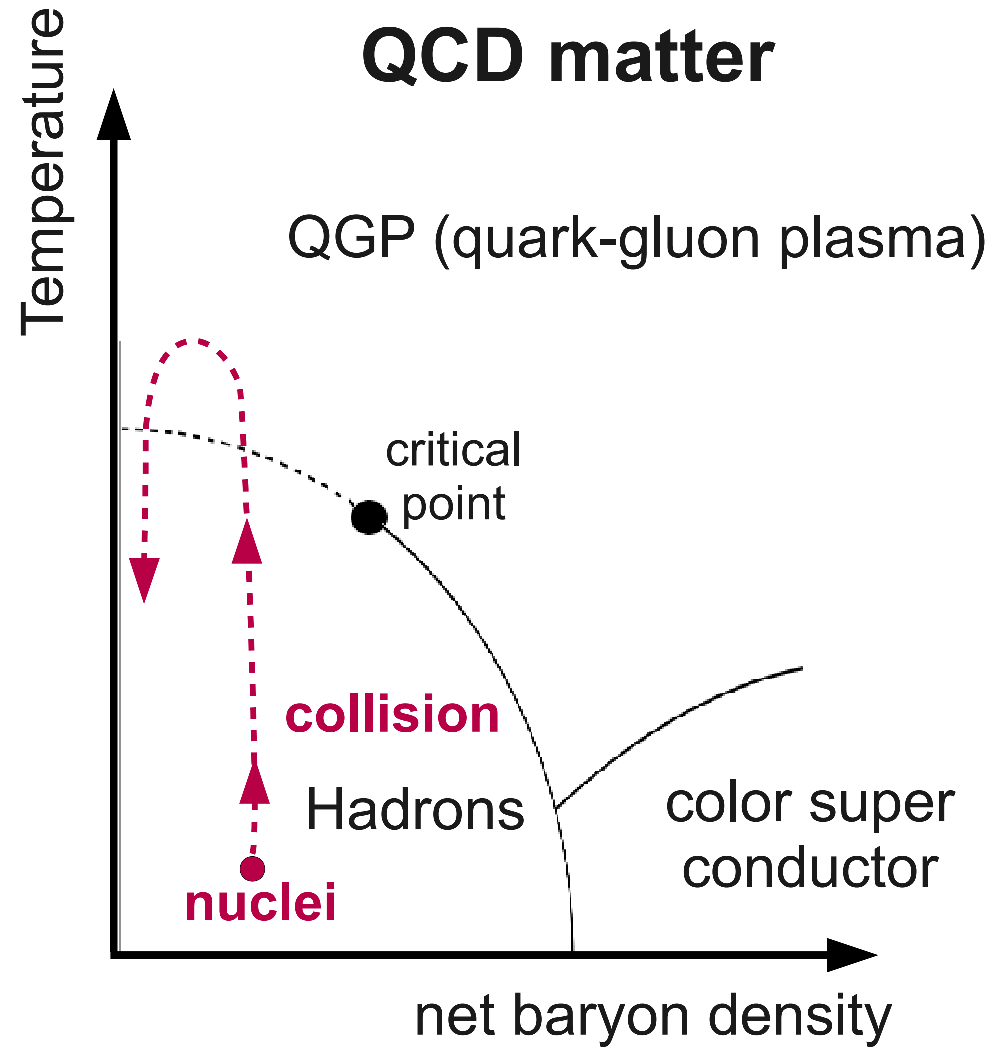
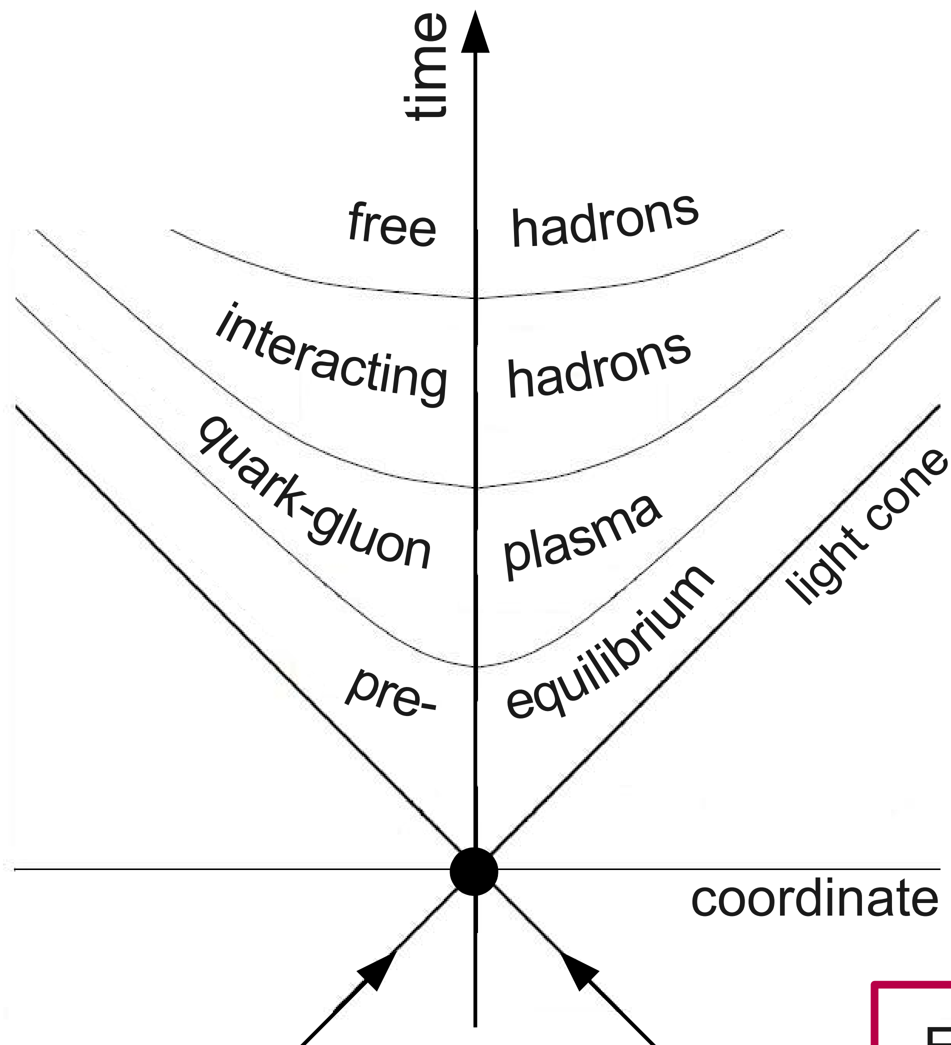
# Phase diagram: map of states and phase transitions




Experimental study of QGP phase diagram by:
smashing nuclei in head-on collision and
converting cold nuclear matter into a fireball of partons

# 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

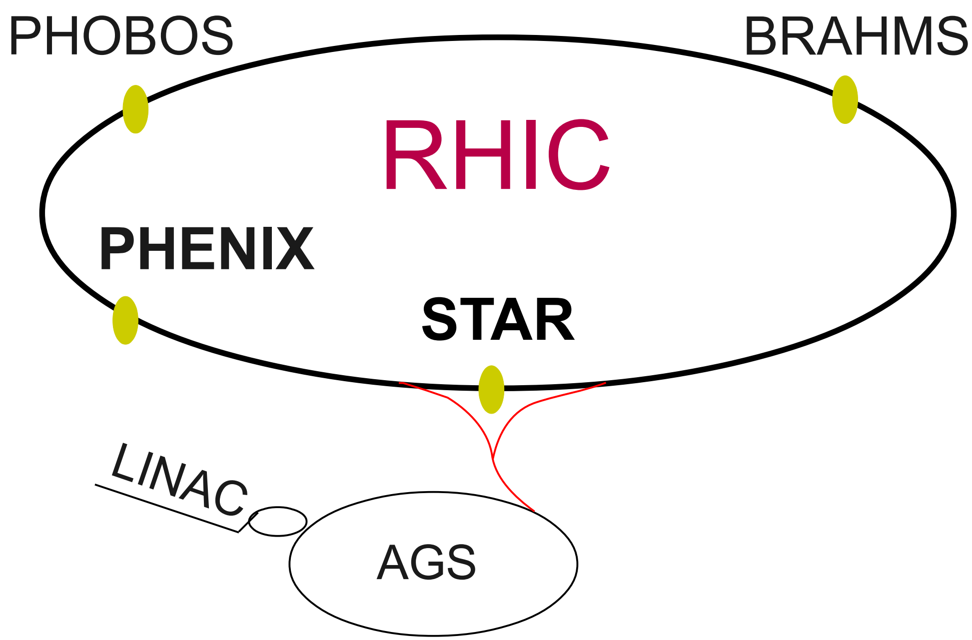
  - Hadronization
  - Rescattering & chemical freeze out
  - Kinetic freeze out (stop interacting)

Experimentally observe only hadronic state

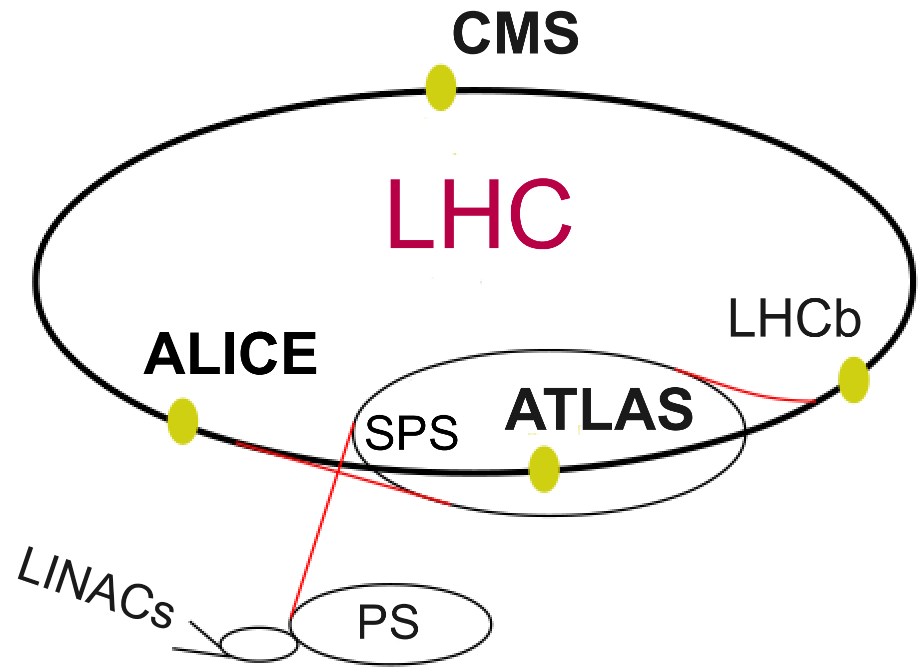
Many observables need to be studied
to establish the properties of QGP

# Modern ultra-relativistic HI colliders

## Relativistic Heavy Ion Collider



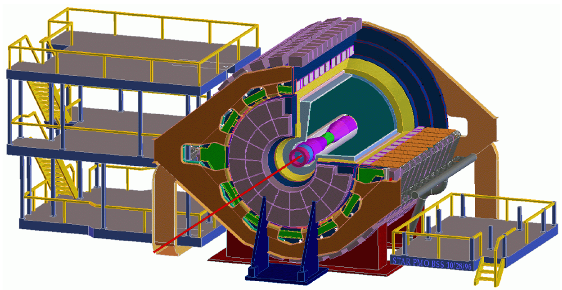

## Large Hadron Collider



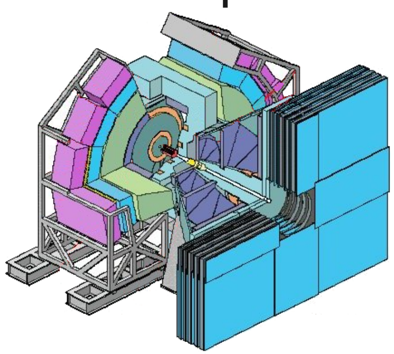

| | **RHIC** | **LHC** |
|---|---|---|
| Location | BNL (USA) | CERN (Europe) |
| Circumference | 3.8 km | 27 km |
| Species | p, d, Cu, Au, U<br>polarized protons | p, Pb |
| Center of mass energy per nucleon pair | in GeV<br>7-38, 62, 200<br>500 (pp only) | in TeV<br>0.9, 2.76, 7 (pp)<br>2.76 (Pb) |

# Current heavy ion experiments at RHIC and LHC

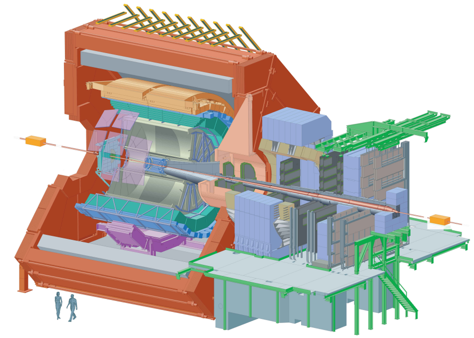
**STAR** (Solenoidal Tracker At RHIC)



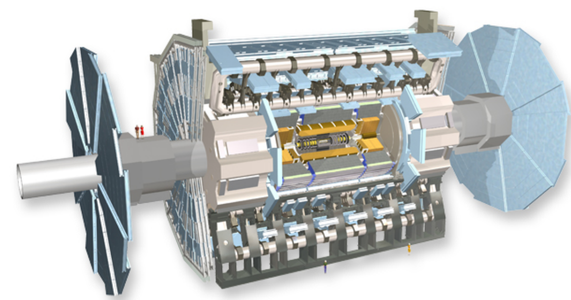
**PHENIX** (Pioneering High Energy Nuclear Ion Experiment)



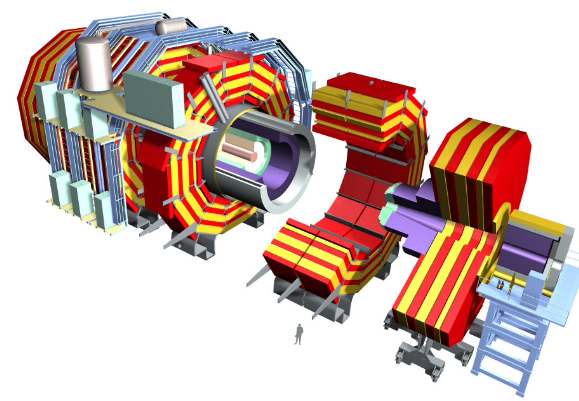
**ALICE** (A Large Ion Collider Experiment)



**ATLAS** (A Toroidal LHC Apparatus)



**CMS** (Compact Muon Solenoid)



**Main capabilities for heavy-ion studies**:

Charge particle tracking and identification:
 full azimuth, large rapidity coverage
 wide $p_t$ range: ~ 100 MeV/c to ~ 100 GeV/c

Calorimetry and rare probes:
 neutral particles, photons, jets, heavy flavor

# Experimental probes of QGP

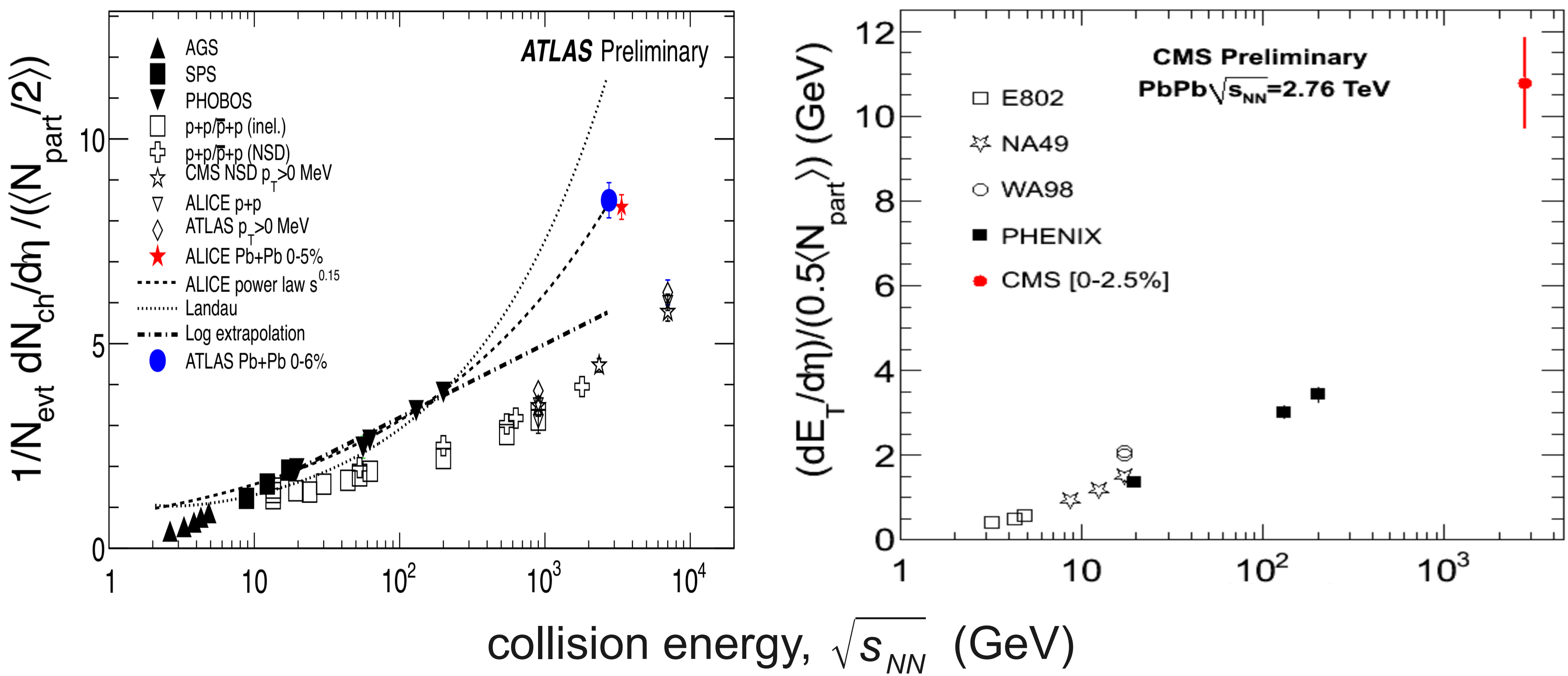
- **Initial energy density, temperature, & chemical potential**
  - ✓ Charge multiplicity and energy density
  - ✓ Particle yields
- **Freeze out volume and decoupling time**
  - ✓ Bose–Einstein correlations
- **Viscosity, η/s, and initial conditions**
  - ✓ Elliptic, triangular, and higher order harmonic flow
  - ✓ Multiplicity, momentum, charge fluctuations
- **Medium tomography and penetrating probes**
  - ✓ Jet quenching and high $p_t$ suppression of particle production
  - ✓ Direct photons
  - ✓ Heavy flavor (charm and beauty)
- **Critical point search**
  - ✓ Scanning the different collision energies

# Particle yields

# Charge multiplicity and energy density: from RHIC to LHC

## Charge multiplicity

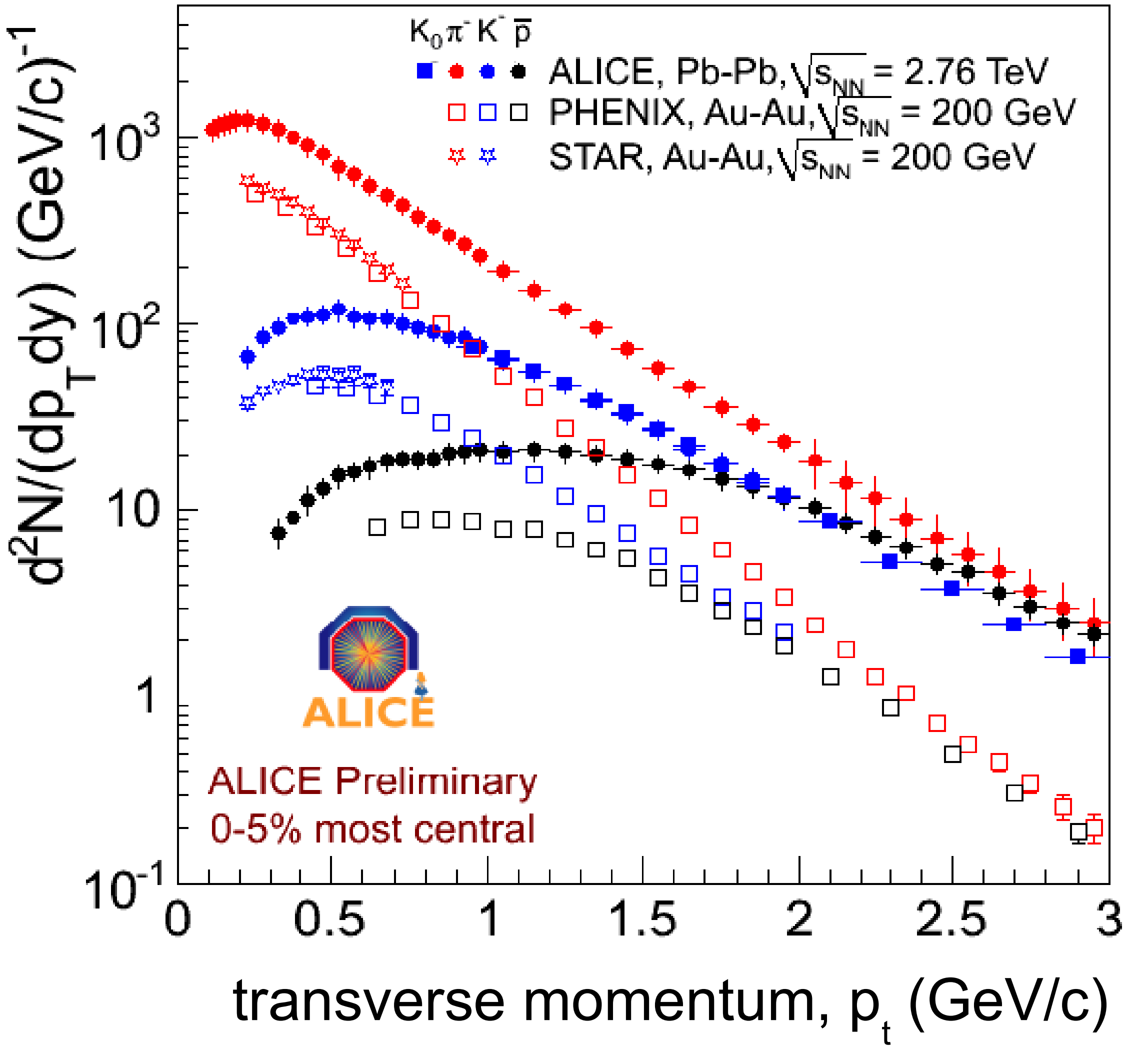
## Energy density




- x 2.1 increase in charge density
- x 1.9 increase compared to pp collisions at the same energy

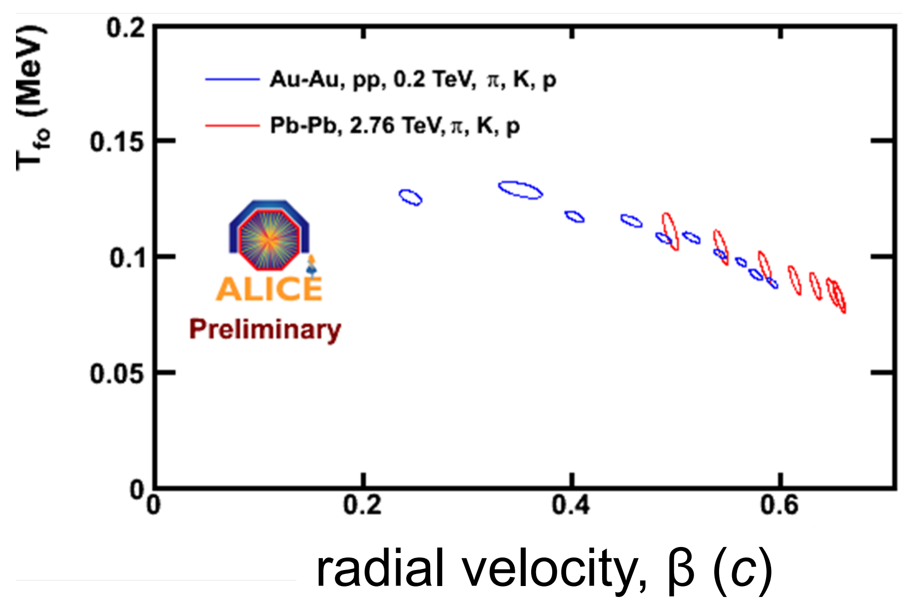
- 2.5-3 times larger energy density
- Midrapidity dE/dη ~ 2 TeV at LHC

# Identified particle spectra and radial expansion




Spectra shapes change significantly from RHIC to LHC

Freeze-out temperature & radial velocity from blast-wave fit




20% Stronger radial flow at LHC

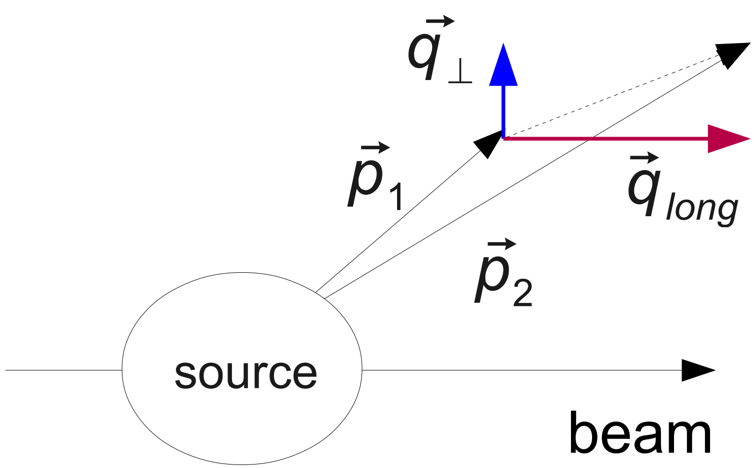
# Bose–Einstein correlations

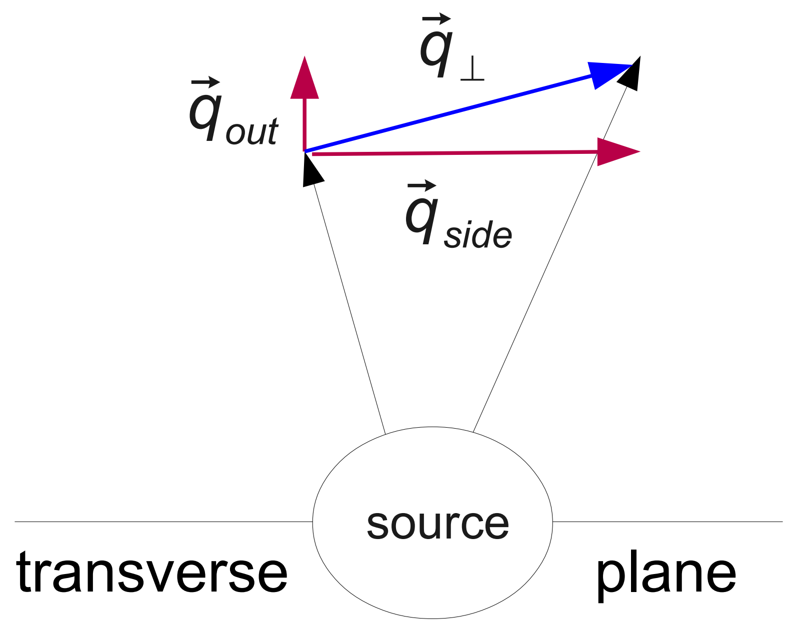
# HBT (Hanbury-Brown-Twiss) correlations

Momentum-space two-particle correlations of identical bosons:

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

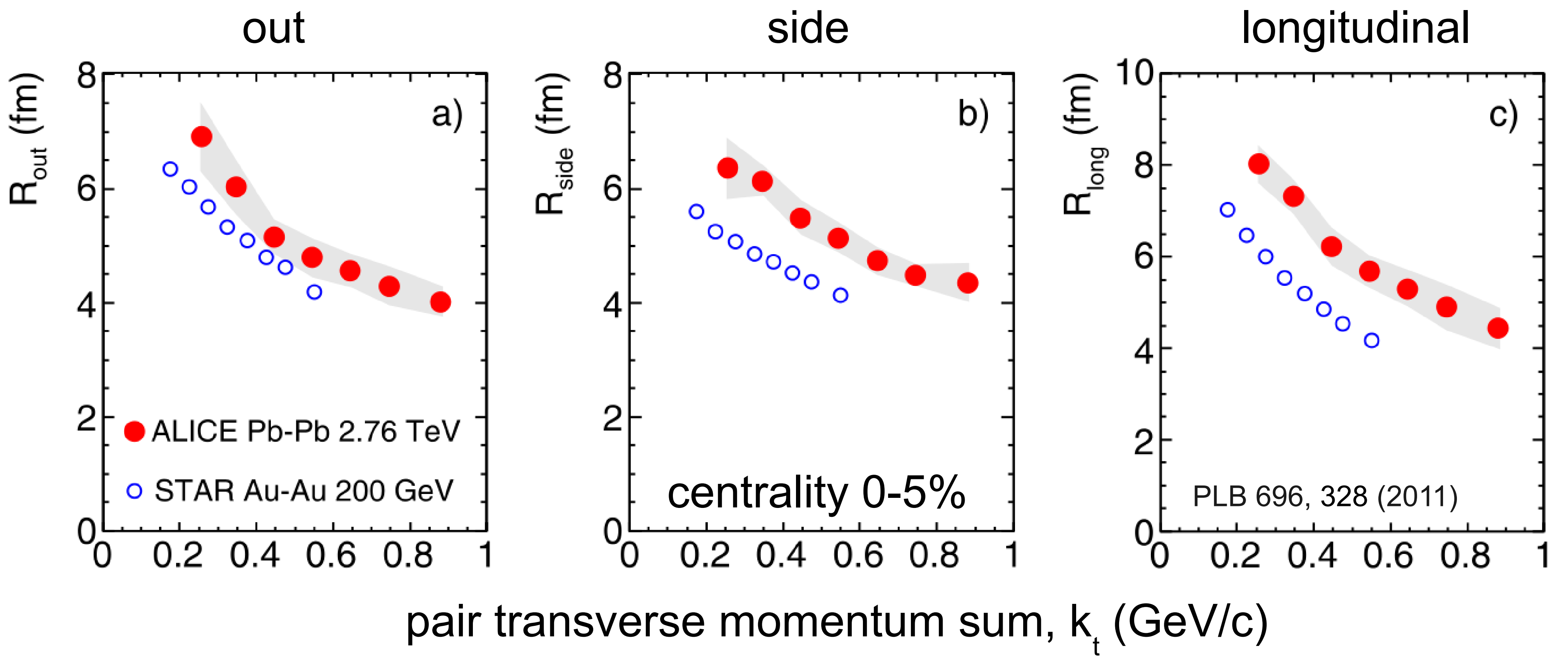
Correlation "width" in momentum space proportional to the **source size**




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

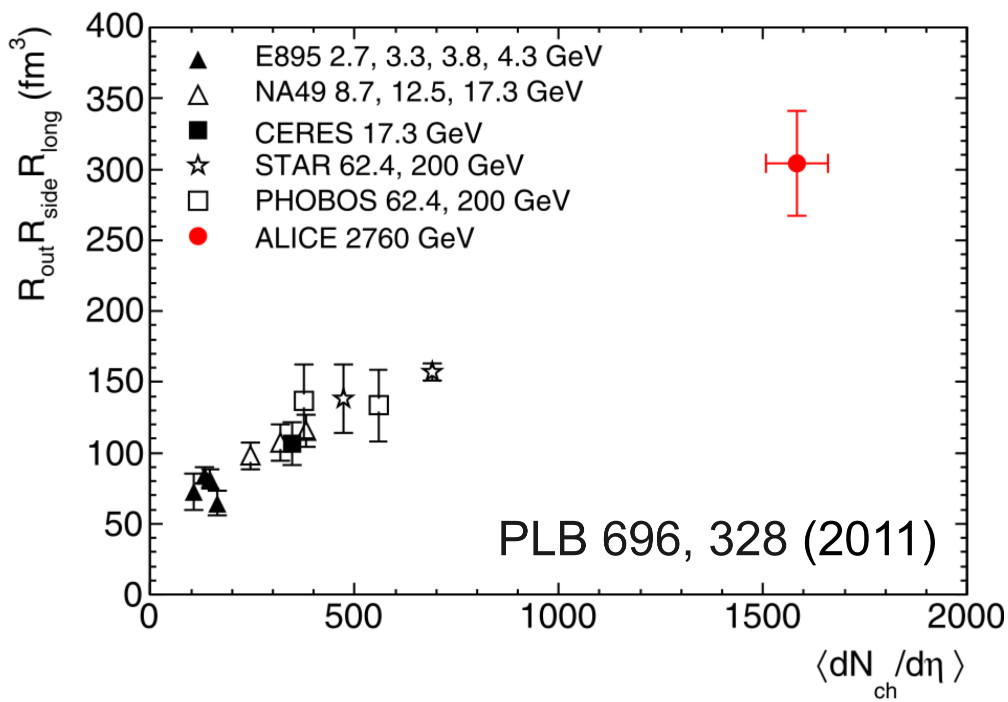
# HBT radii with pions: RHIC vs. LHC



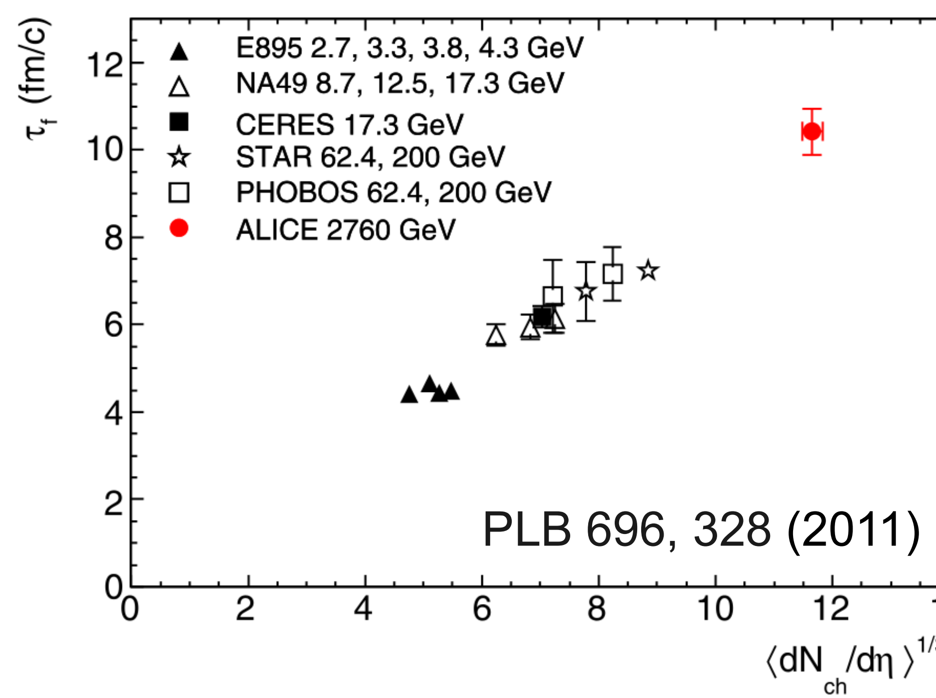

- Homogeneity length is 30% larger at LHC
- Stronger radial & longitudinal collective flow at LHC (strong $k_T$ dependence)

# Freeze-out volume and decoupling time at LHC

Homogeneity region, $R_{out} R_{side} R_{long}$




Emission time, $\tau_f$




Larger homogeneity region at LHC

x 2 increase in freeze-out volume compared to RHIC

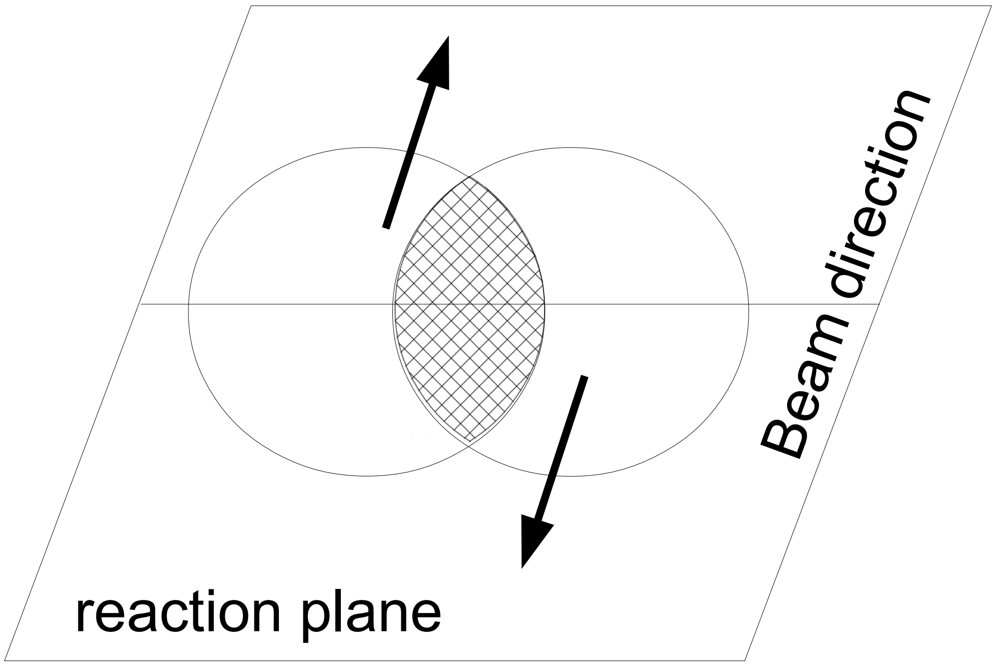
Volume ~ $(2\pi)^{3/2} R_{out} R_{side} R_{long}$

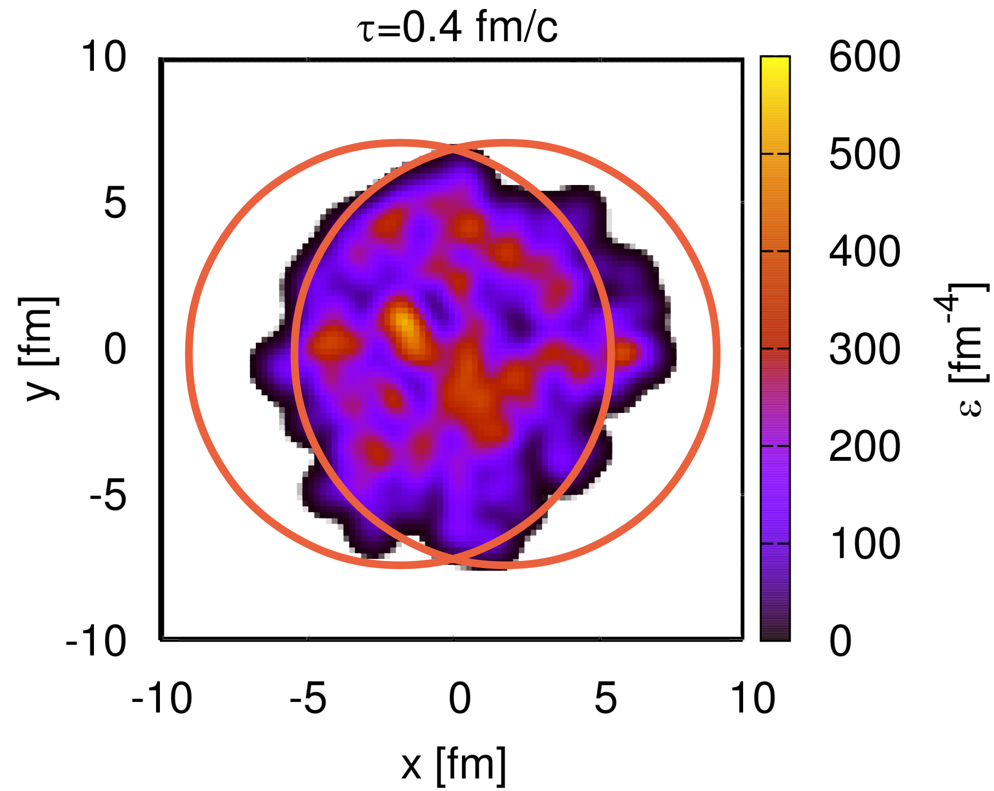
$$\tau_f \sim R_{long} \sqrt{m_T / T}$$

30% longer emission time at LHC

# Anisotropic transverse flow

# Event anisotropy in heavy-ion collision




Asymmetry of the overlap region
- non uniform density profile
- pressure gradient

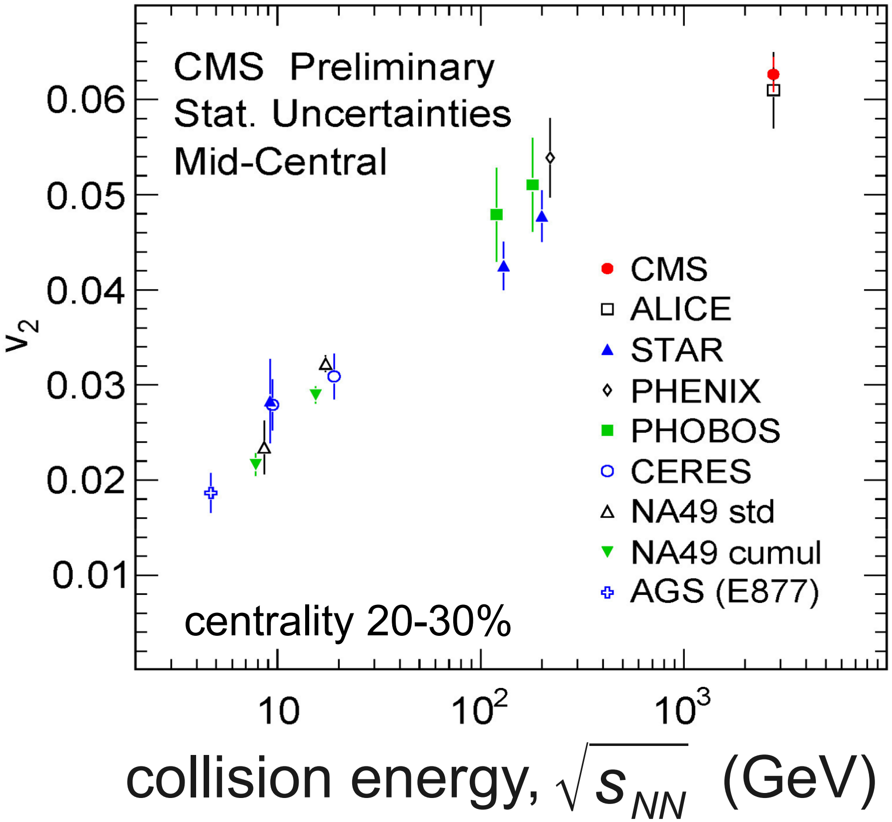
Viscous hydrodynamic simulation
Schenke *et al.*, PRL106:042301 (2011)

Initial spacial anisotropy develops into
measurable azimuthal asymmetry in momentum space:

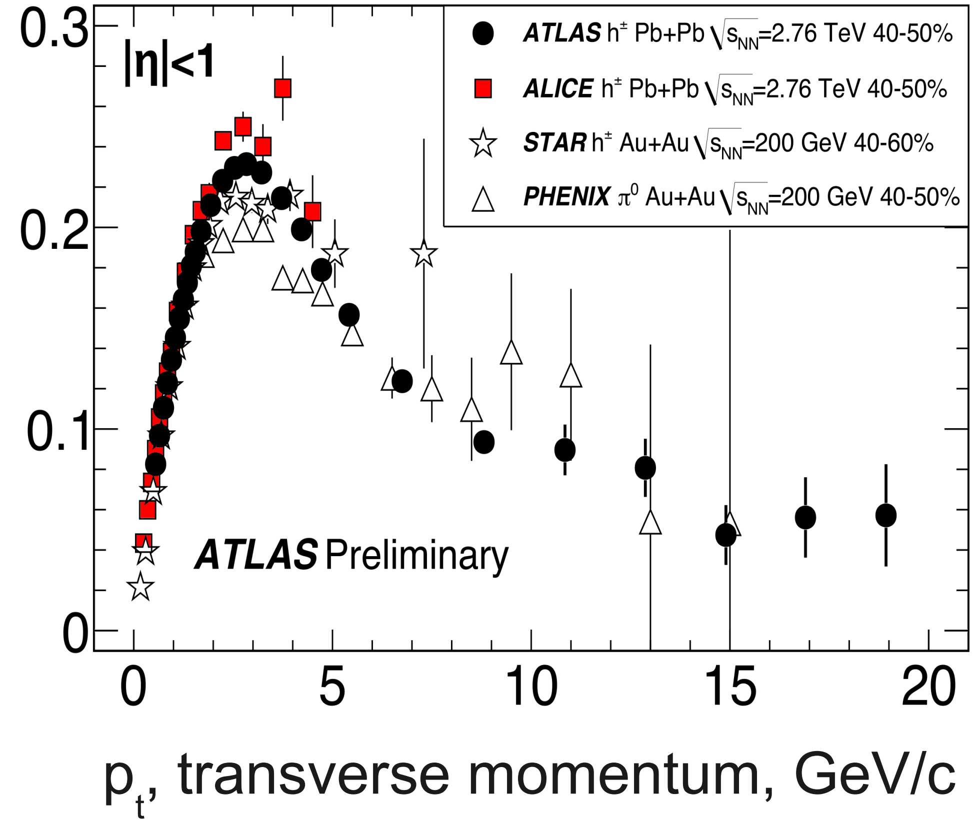
- Reflects orientation of the reaction plane (e.g. elliptic shape results in $v_2$)
- Sensitive to fluctuations (triangular shape)
- Viscous effects dumps higher order harmonics – constrains η/s

# Elliptic flow at RHIC and LHC

## Integral $v_2$




## Differential $v_2(p_t)$

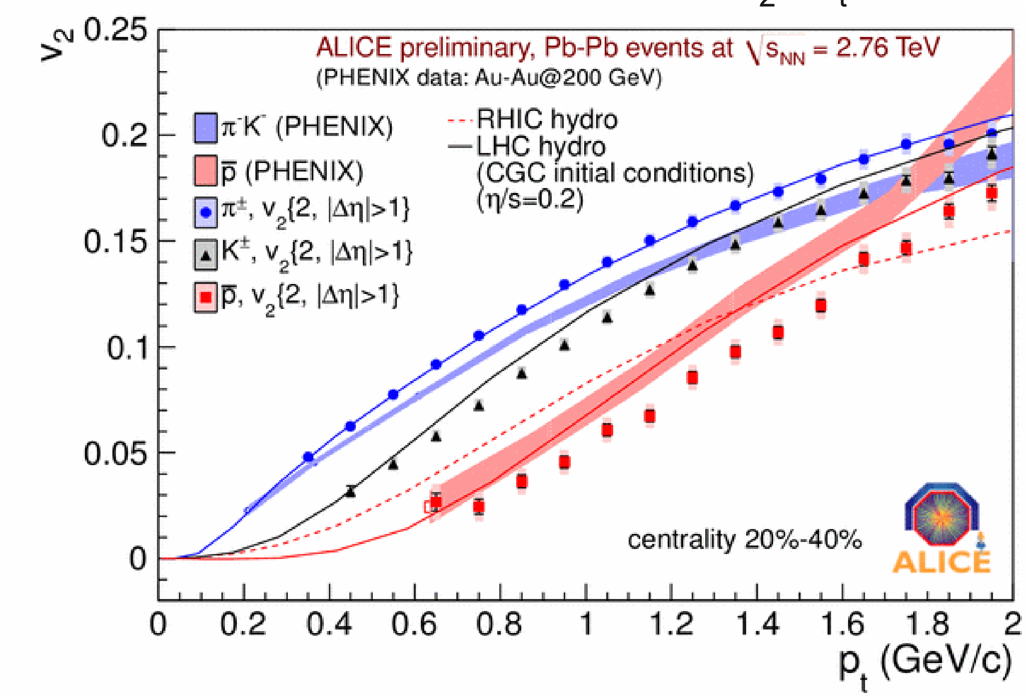



- 30% increase of integral $v_2$: perfect liquid behavior at LHC

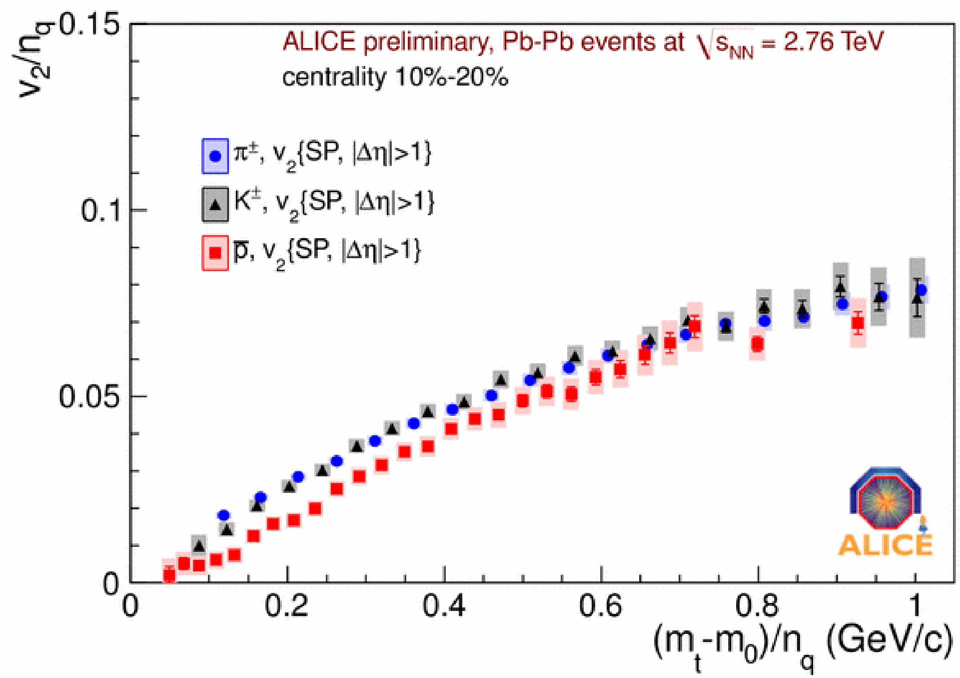
- $v_2(p_t)$ has similar shape and magnitude: increase of integral $v_2$ is driven by stronger radial flow (shift of mean $p_t$)

# Identified particle $v_2$ and coalesense at LHC

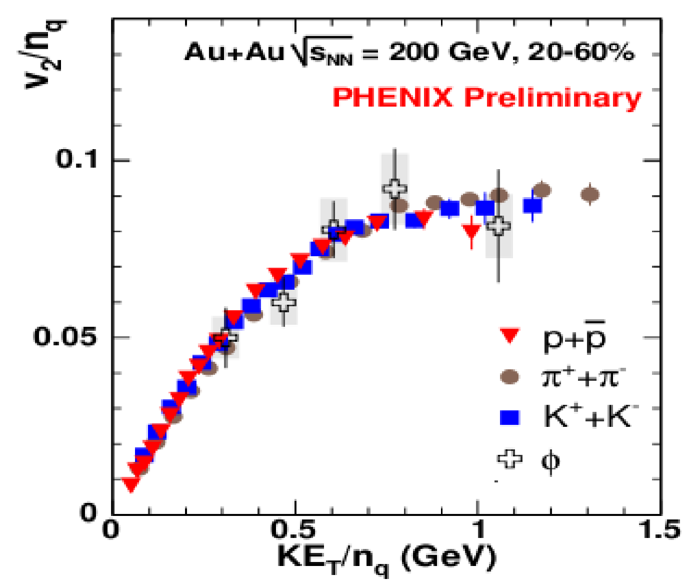
Identified particle $v_2$ ($p_t$)




Quark number scaling of $v_2$

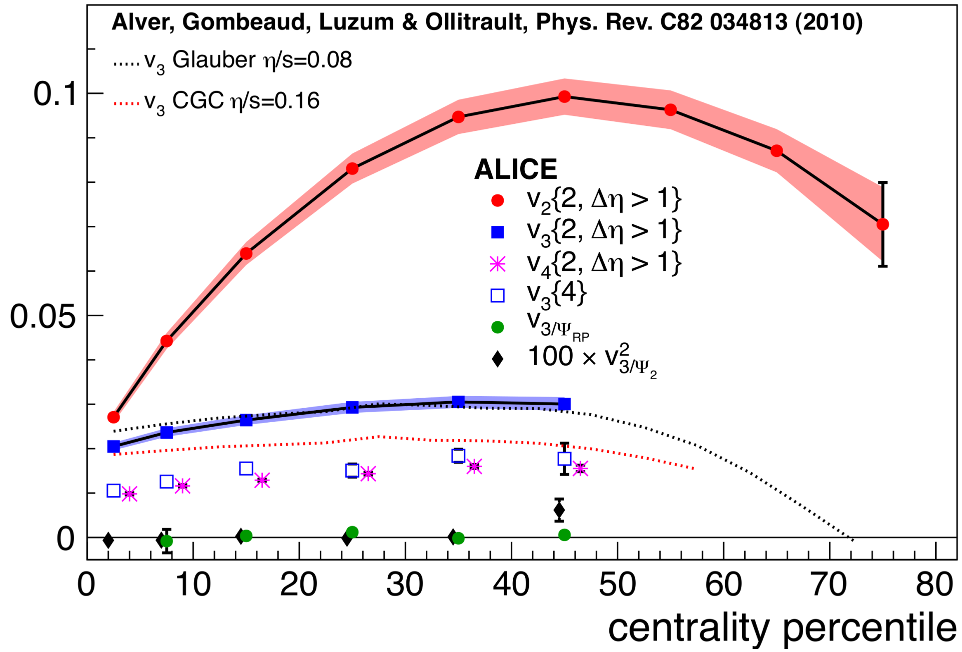



- Observed larger mass splitting of $v_2$ agrees well with viscous hydrodynamic predictions except for anti-protons for most central collisions
- Anti-protons do not follow the universal scaling seen at RHIC

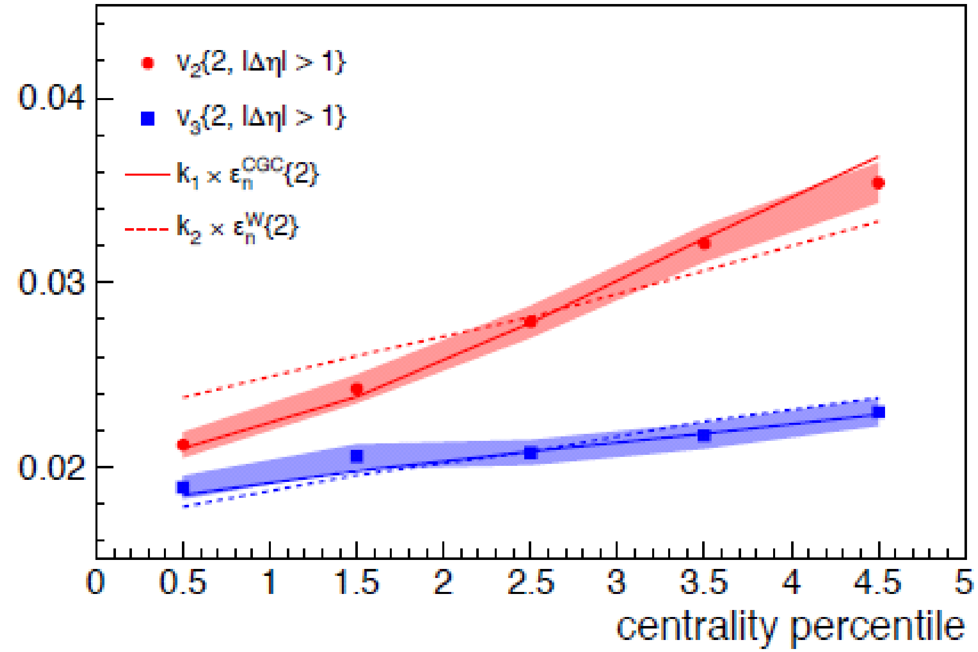


# Elliptic flow fluctuations and higher harmonic at LHC

## Higher flow harmonics: $v_2$,$v_3$,$v_4$




## $v_2$&$v_3$ for most central collisions

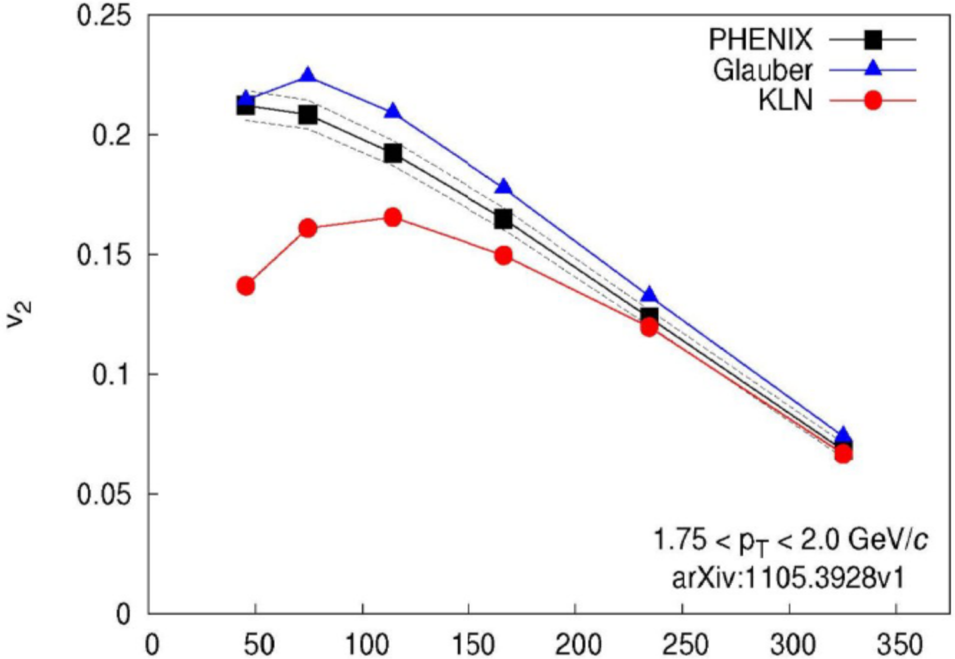



- $v_3$ originates from fluctuations in the initial geometry
- Glauber MC reproduces $v_3$ centrality dependence, while CGC MC under predict the magnitude
- For ultra-central collisions CGC describes better $v_2$ centrality dependence

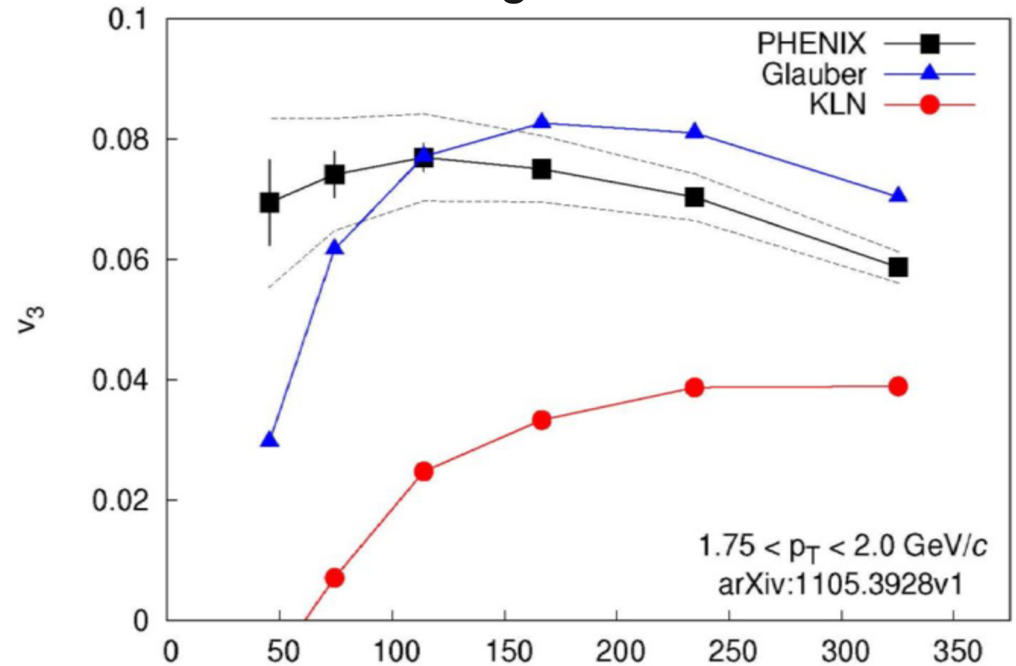
Observed non-zero $v_3$ helps to constrain initial conditions and η/s (viscosity over entropy density ratio)

# Discriminating initial conditions and η/s at RHIC

elliptic flow




triangular flow



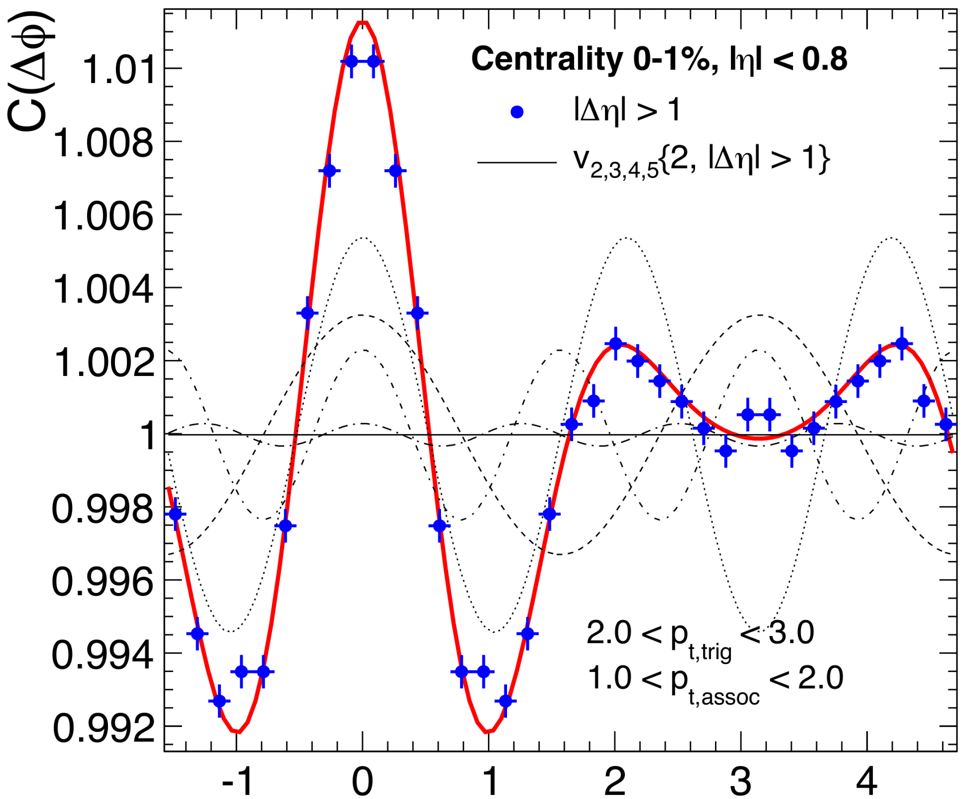

Number of participants, $N_{part}$

MC-KLN: Color Glass Condensate initial conditions with $\eta/s = 2/(4\pi)$
Glauber: Glauber initial conditions with $\eta/s = 1/(4\pi)$

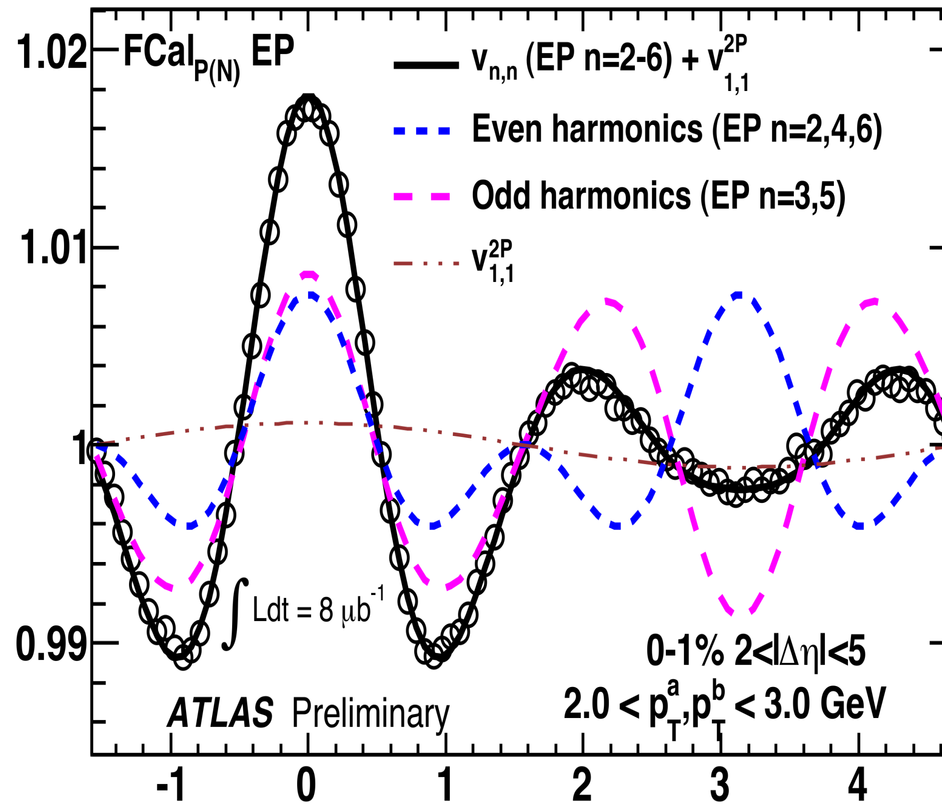
RHIC results favor
Glauber initial condition with a smaller viscosity?

# Understanding two particle correlations with higher harmonic flow

ALICE Collaboration ArXiv:1105.3865 (2011)




ATLAS Collaboration




two particle relative azimuthal angle, Δφ (rad)

- “ridge” and “mach-cone” structures naturally described by collective flow effects
- Similar observation by RHIC experiments

# Hard probes

# Nuclear modification factor, $R_{AA}$

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

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

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

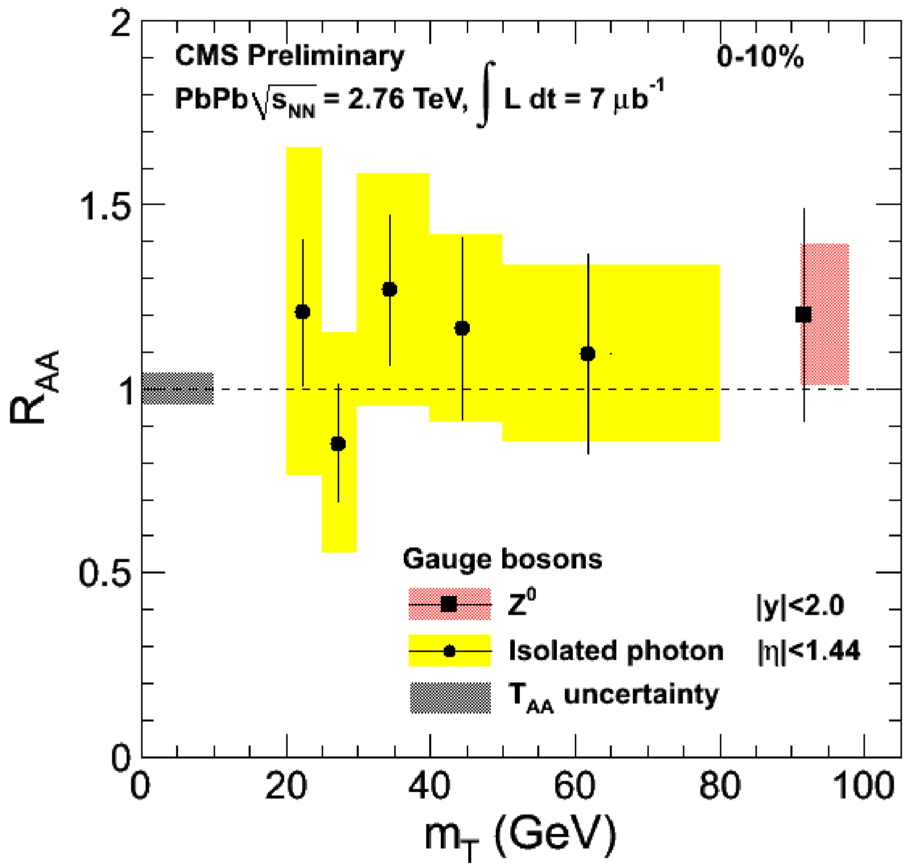
$$Y(p_T) = \frac{1}{N_{evt}} \frac{d^2 N_{ch}}{d\eta \, dp_T}$$

$p_T$ distribution of charge particles at midrapidity

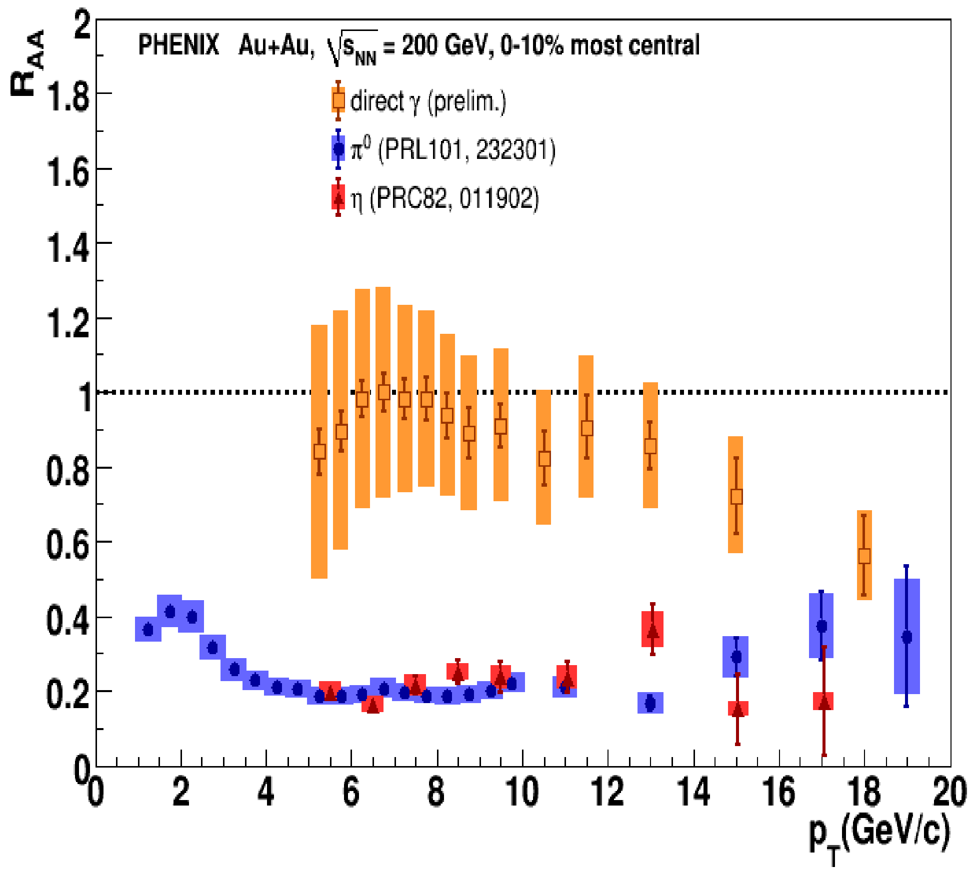
| | |
|---|---|
| $R_{AA}(p_T) = 1$ | no medium modification |
| $R_{AA}(p_T) < 1$ | suppression by medium |

# $R_{AA}$ of colorless probes at RHIC and LHC

## Isolated photon and Z-boson



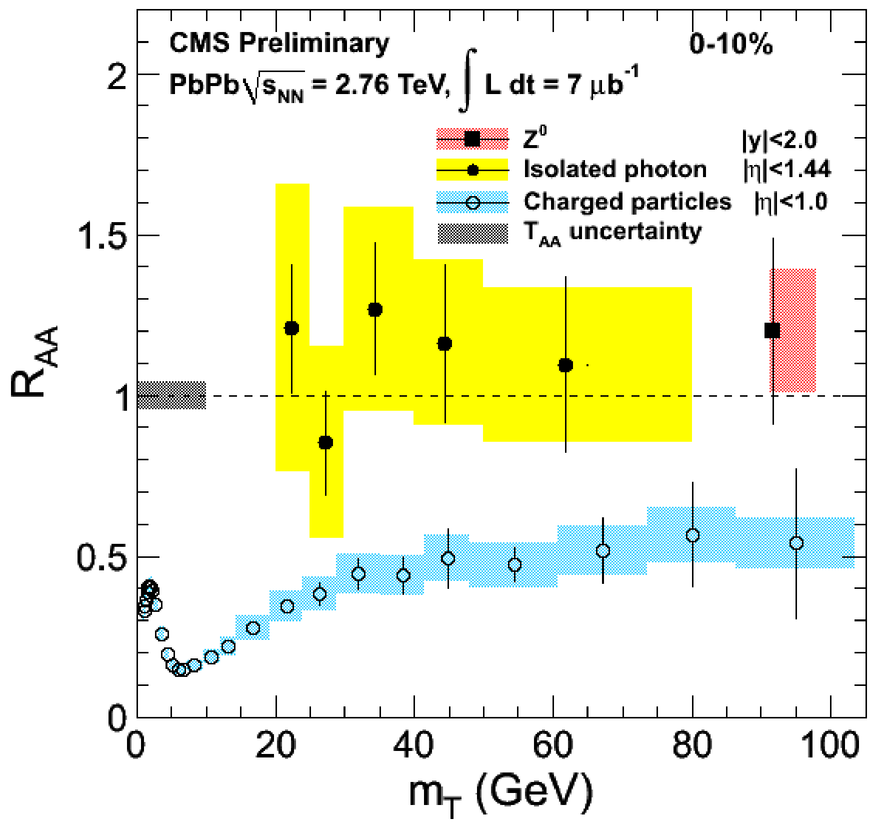

## Inclusive direct photons



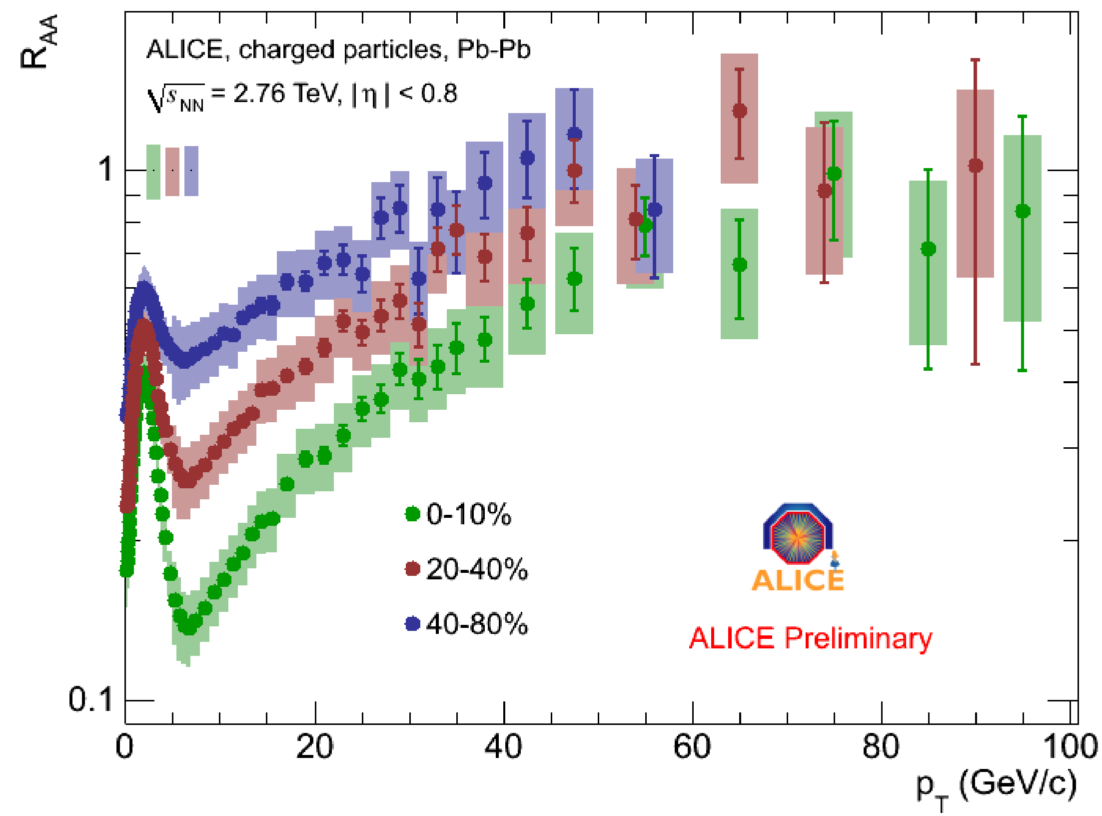

- No nuclear modifications for direct photons and Z bosons: hard scattering processes scale with number of binary collisions
- Provides baseline for study of charged particle production

# Charged particle suppression at LHC

CMS Collaboration

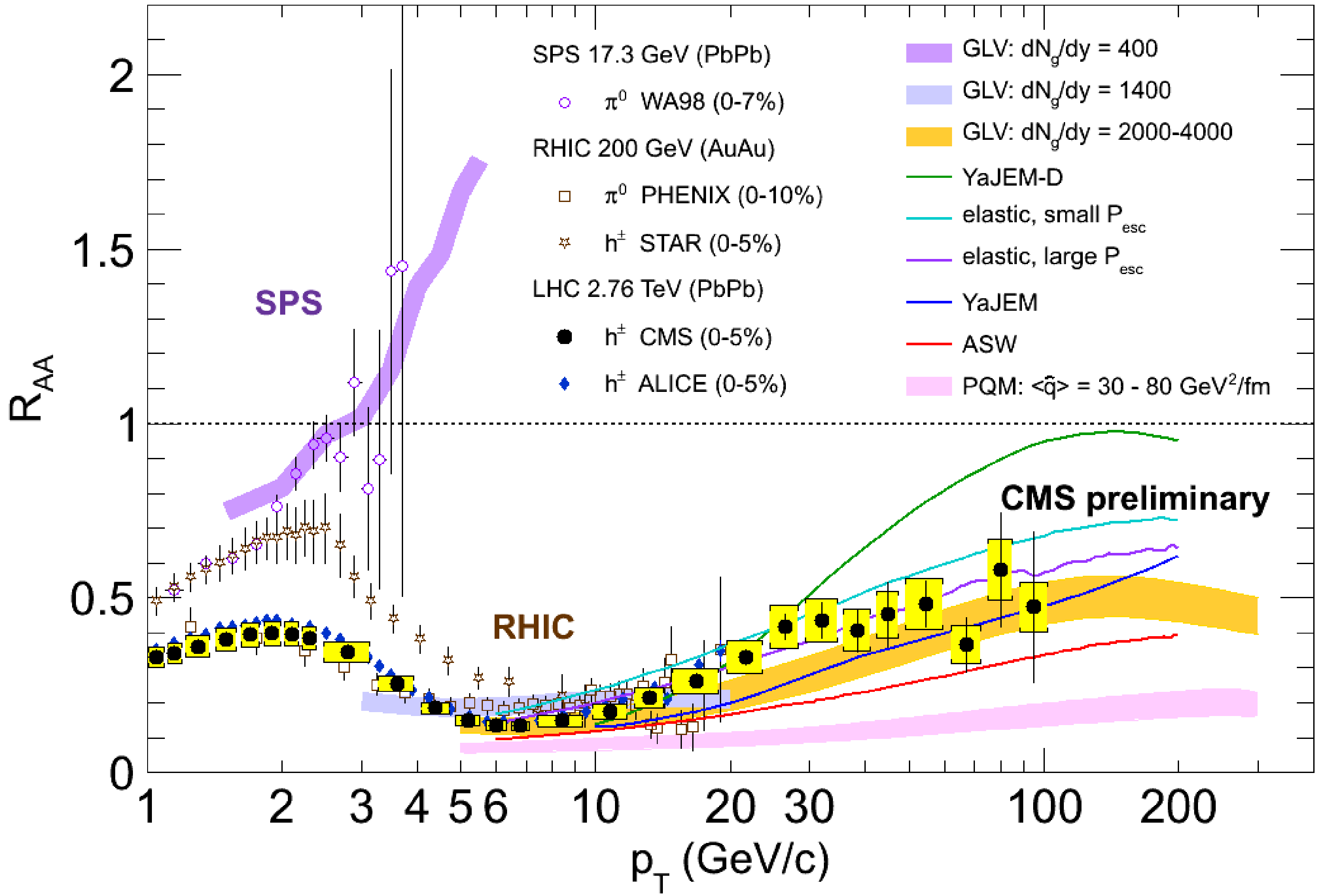



ALICE Collaboration




- Minimum at $p_t$ ~ 6-7 GeV/c with strong raise up to $p_t$ ~ 50 GeV/c
- Pronounced centrality dependence below $p_t$ ~ 50 GeV/c
- For most central collisions suppression observed even at $p_t$ ~ 100 GeV/c: $R_{AA}$ ~ 0.5

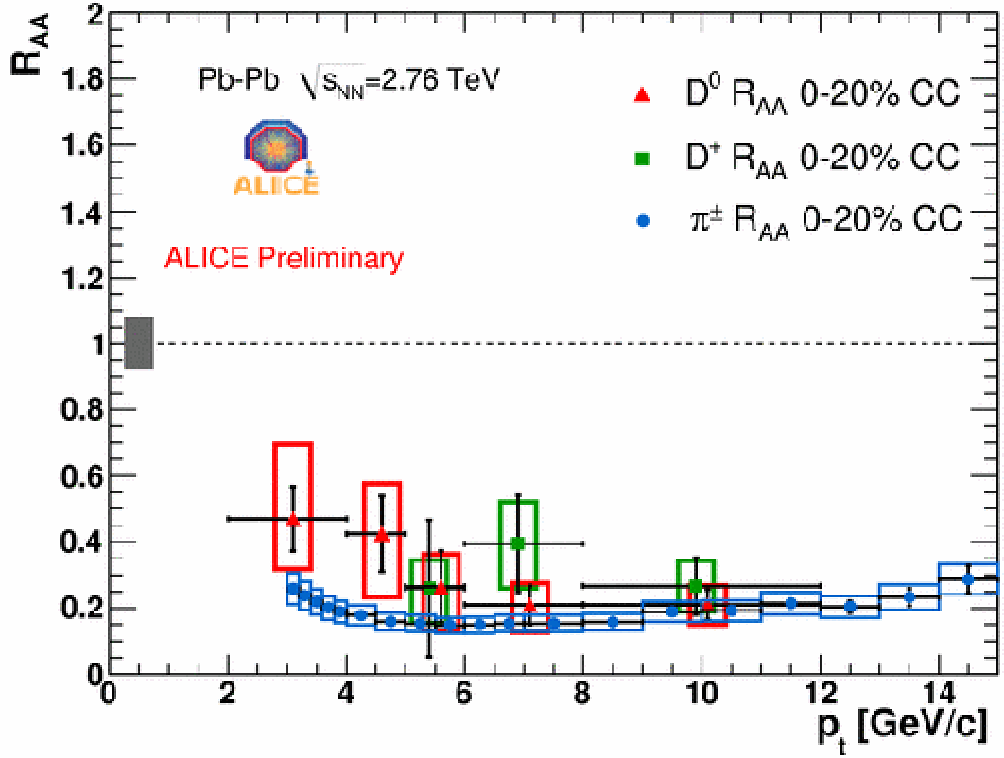
# $R_{AA}$ at RHIC and LHC vs. theoretical calculations



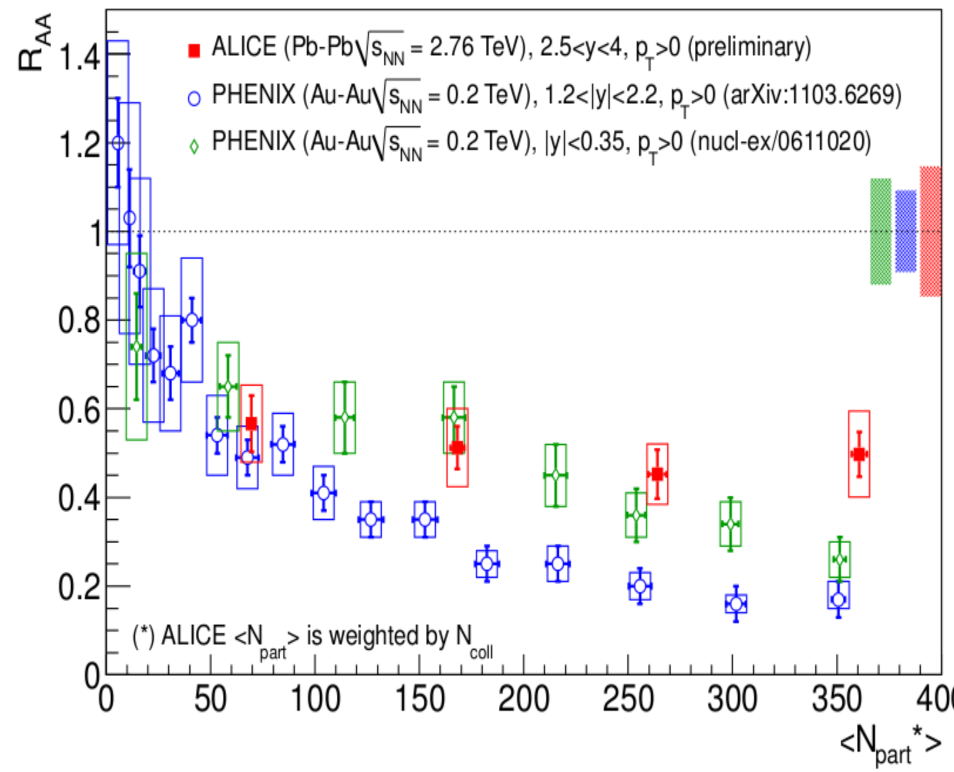

- Similar shape between LHC and RHIC above $p_t$ ~ 6 GeV/c
- Strong constraint on parton energy loss models

# Suppression of heavy flavor production at RHIC and LHC

Open charm




J/ψ




Heavy flavor production at LHC is suppressed similar to light quarks

Other talks at Hadron 2011 on heavy flavor at LHC:

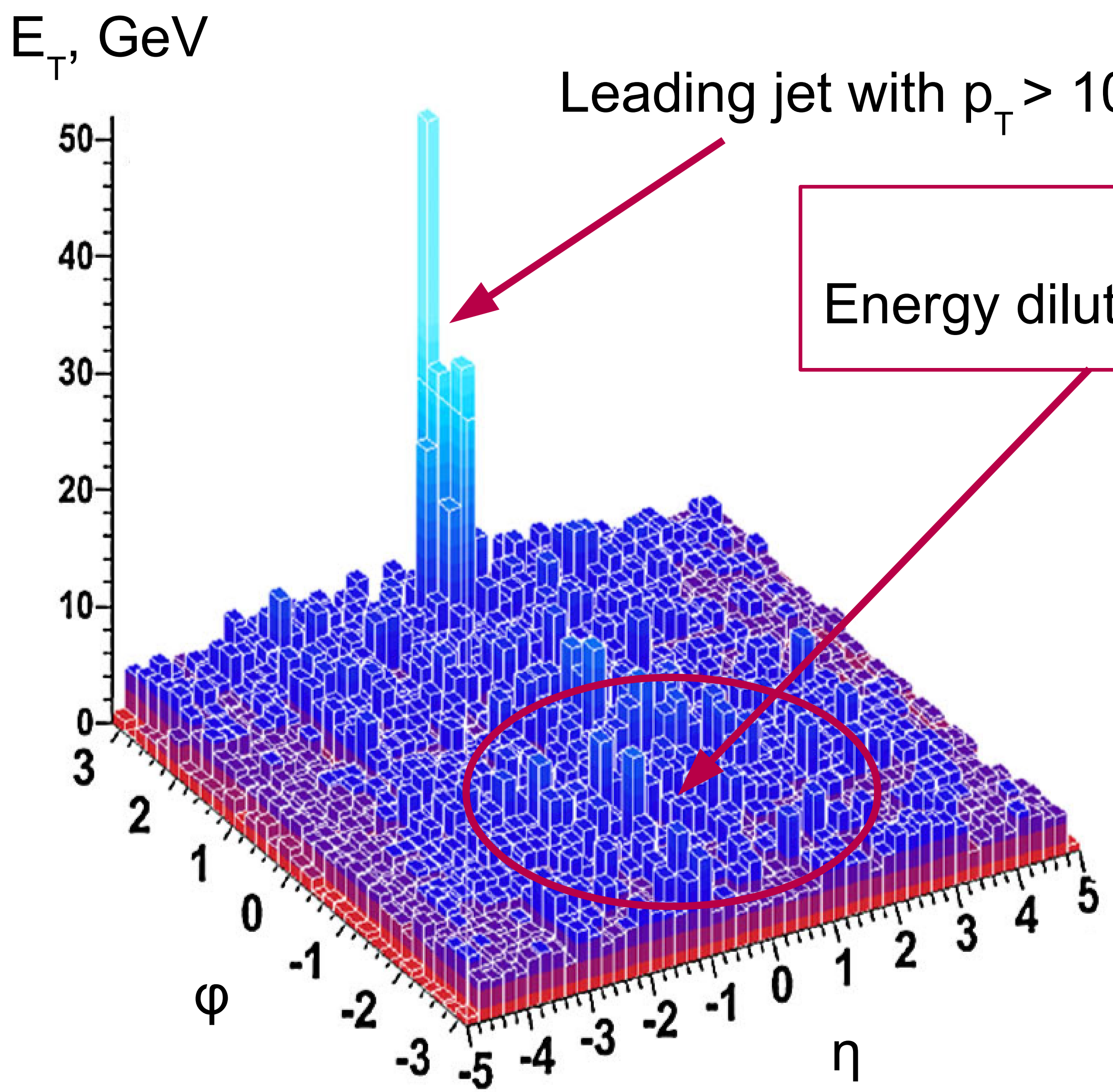
Plenary:
- Y. Gao (quarkonia)
- H. Evans (heavy mesons)
- N. Leonardo (bottomonium)

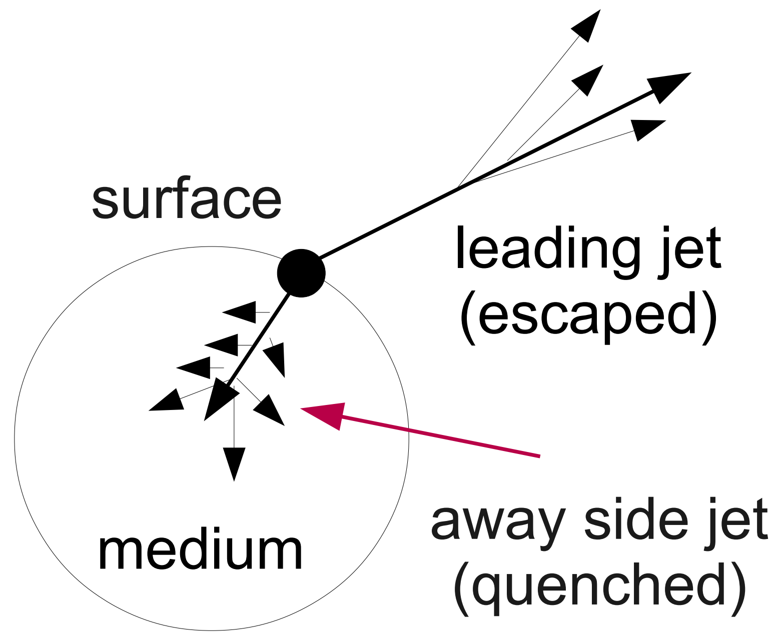
Parallel:
- F. Kramer (quarkonia)
- K. Schweda (open charm)

# Highly asymmetric di-jets observed at LHC

Leading jet with $p_T$ > 100 GeV/c

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

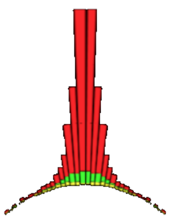
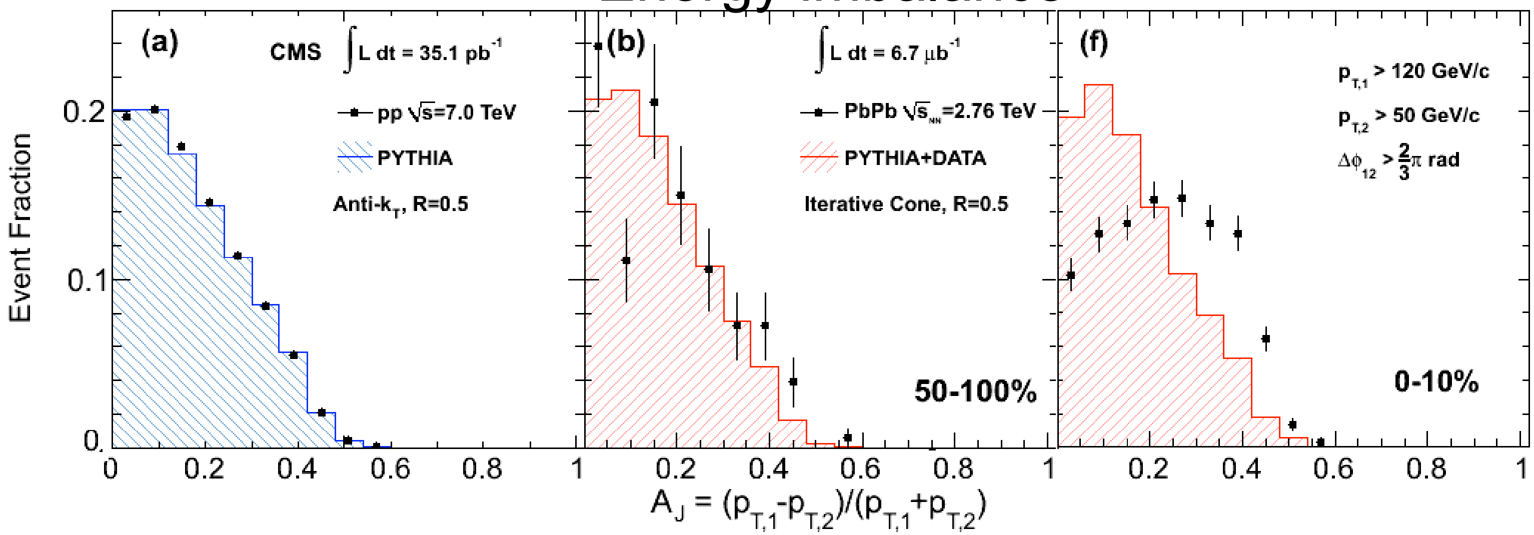


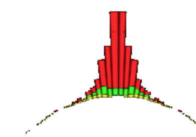




Sample di-jet event reconstructed
by ATLAS in central Pb+Pb collision

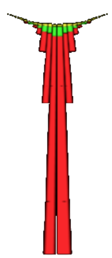
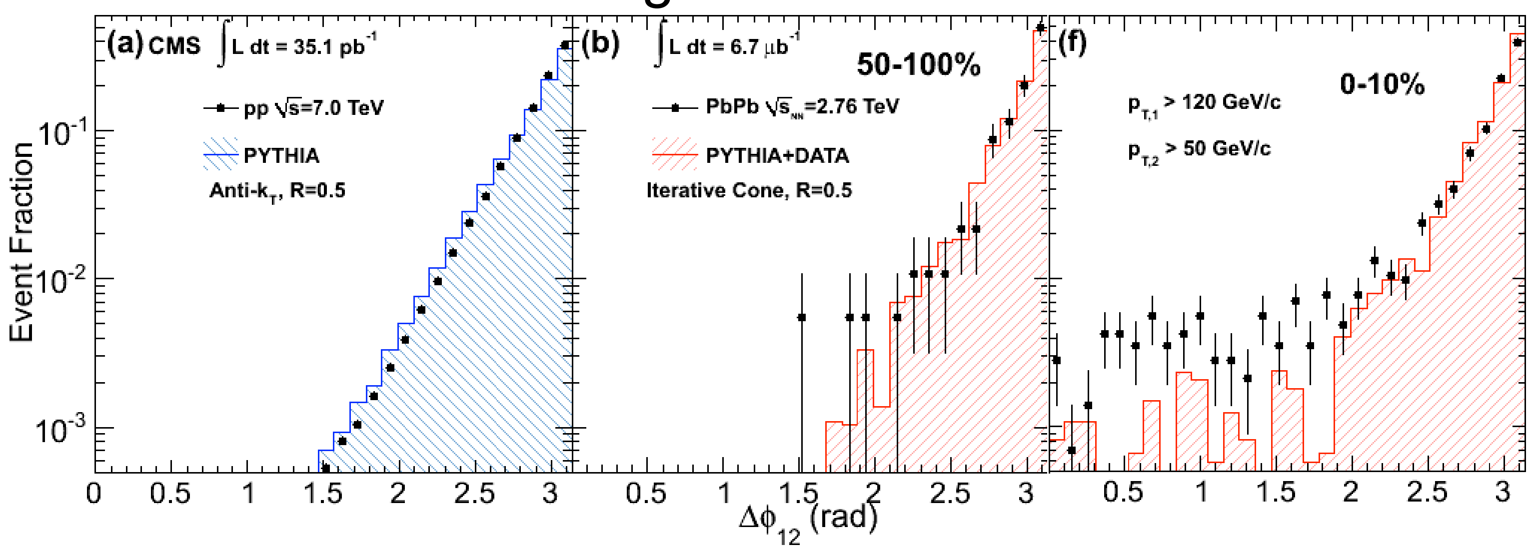
# Dijet energy imbalance and angular correlations

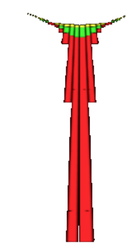
## Energy imbalance



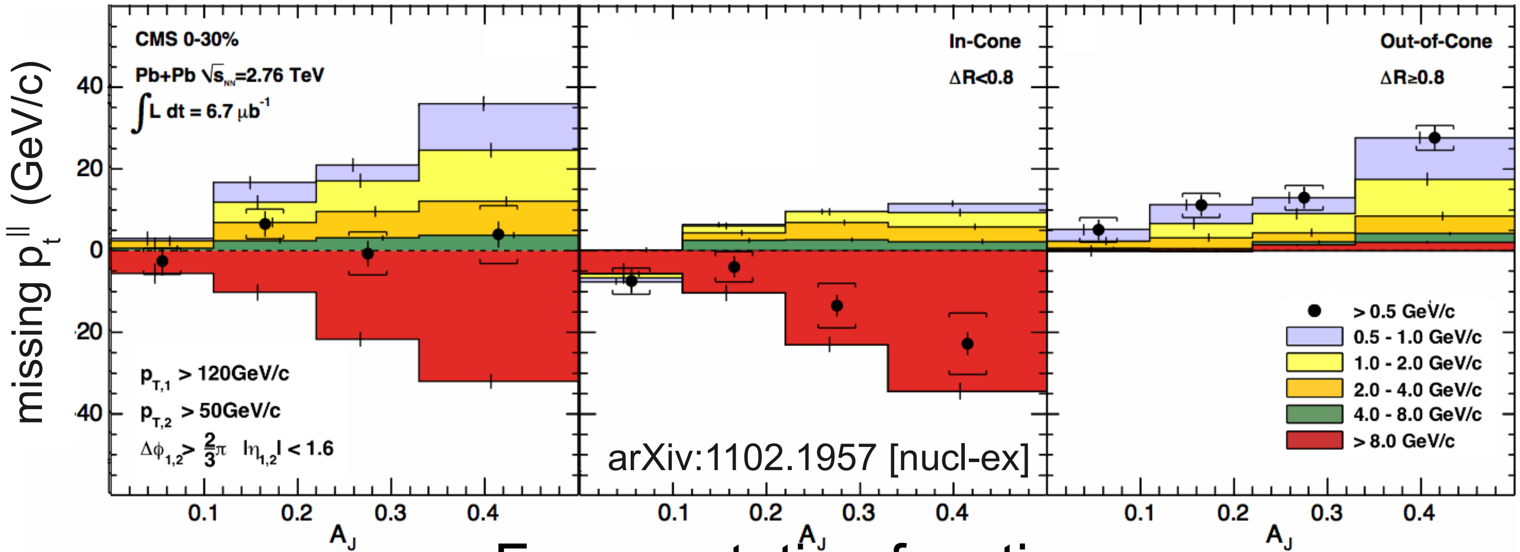
## Angular correlations

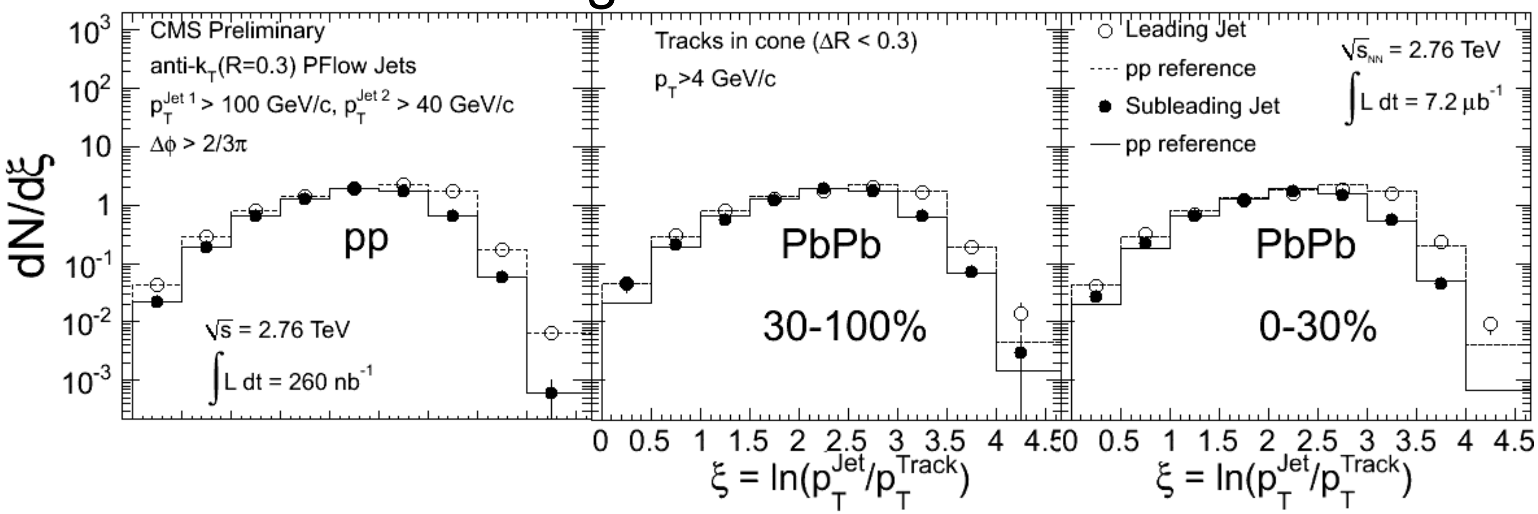


- Strong imbalance - away side jet quenched by dense medium
- Back-to-back $\Delta\varphi \sim \pi$ for all centralities

# Dijet missing momentum and jet fragmentation




## Fragmentation function

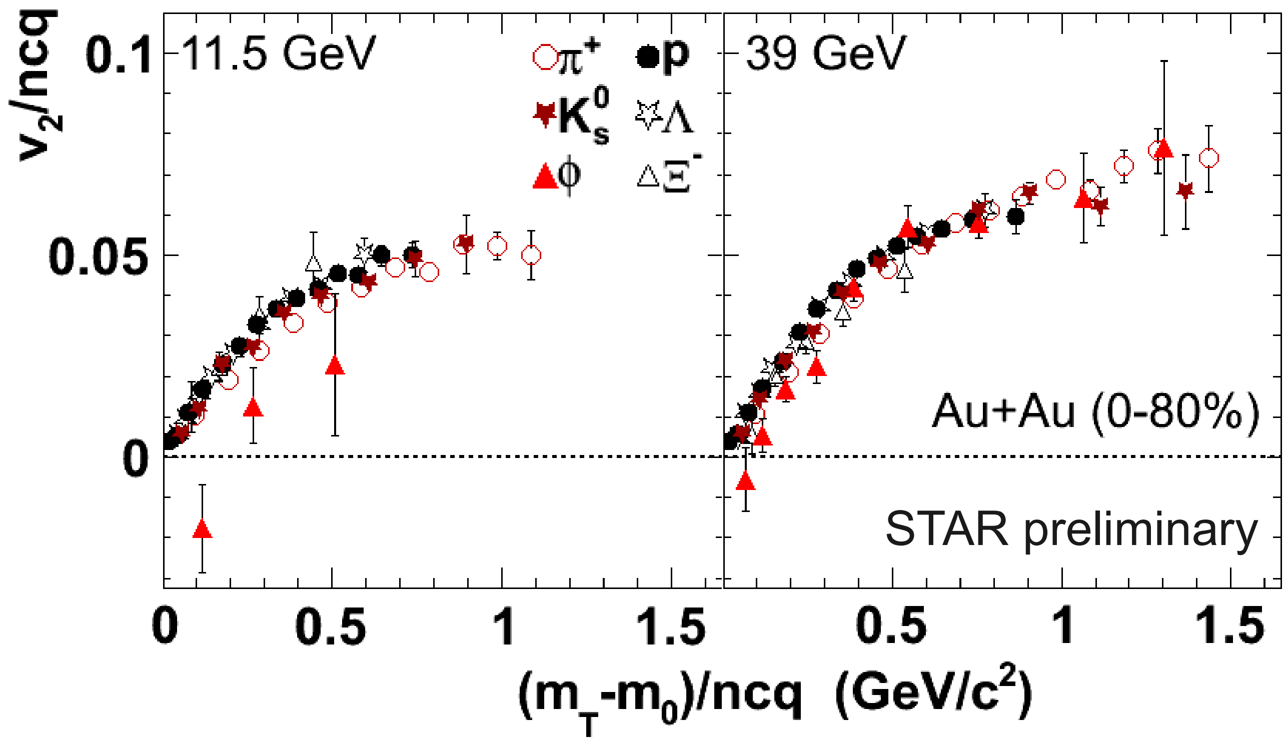



- Momentum difference is balanced by low momentum particles spread at large angles relative to the away side
- Fragmentation function similar for Pb-Pb and pp: in Pb-Pb jet fragments in vacuum

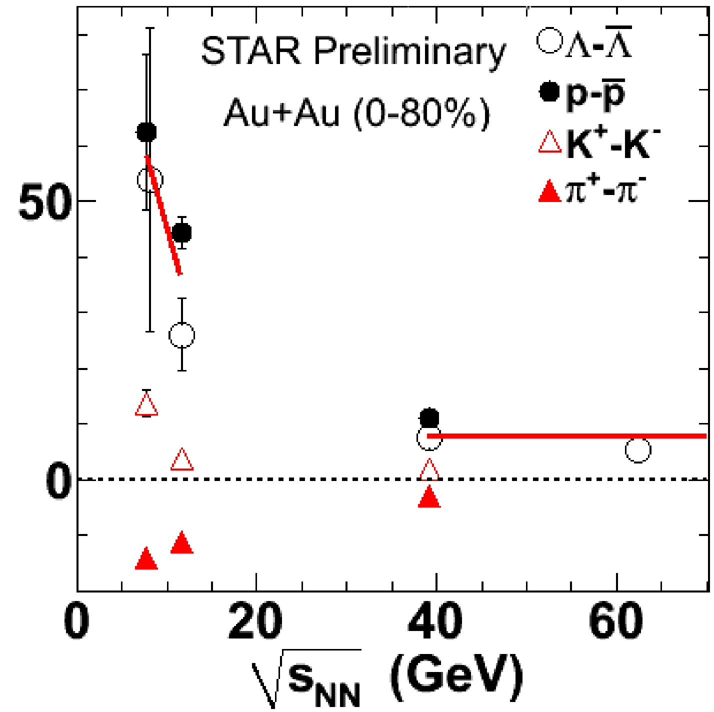
# Beam energy scan at RHIC:
# search for critical point

# Number of quark scaling & particle/anti-particle $v_2$

$v_2$ scaled with number of quark



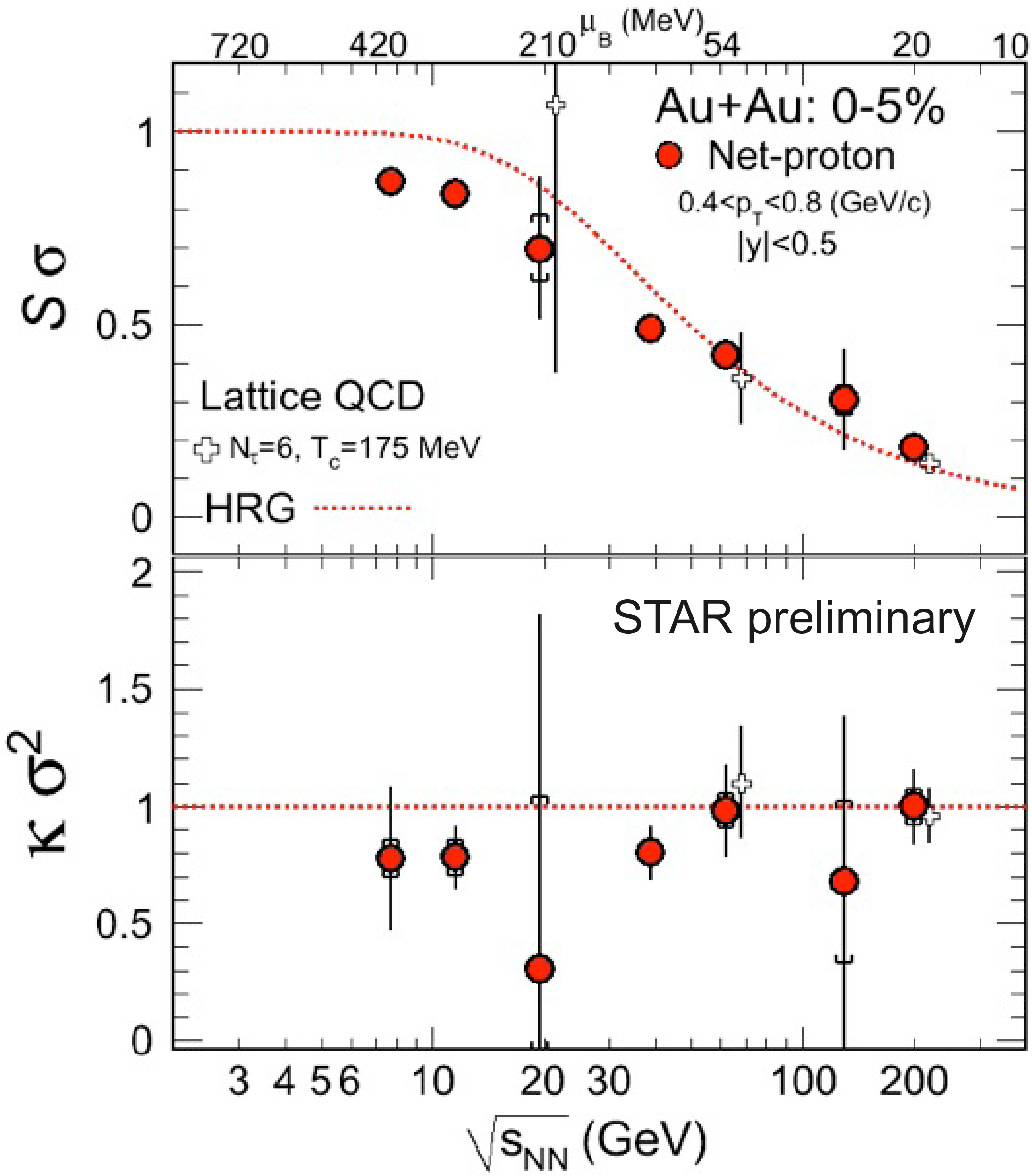

$[v_2^p - v_2^{\bar{p}}]/v_2^p$ ,%




- $v_2$ of $\phi$ meson does not follow the trend for other hadrons at 11.5 GeV
- Significant difference between baryon/anti-baryon $v_2$ @ 7.7&11.5 GeV

  No scaling between particles and anti-particles

# Higher moments of net-proton distribution




Moments of net proton distribution ($\chi$):

1[st] - mean, 2[nd] - variance ($\sigma^2$)

3[rd] - skewness ($S$), 4[th] - kurtosis ($k$)

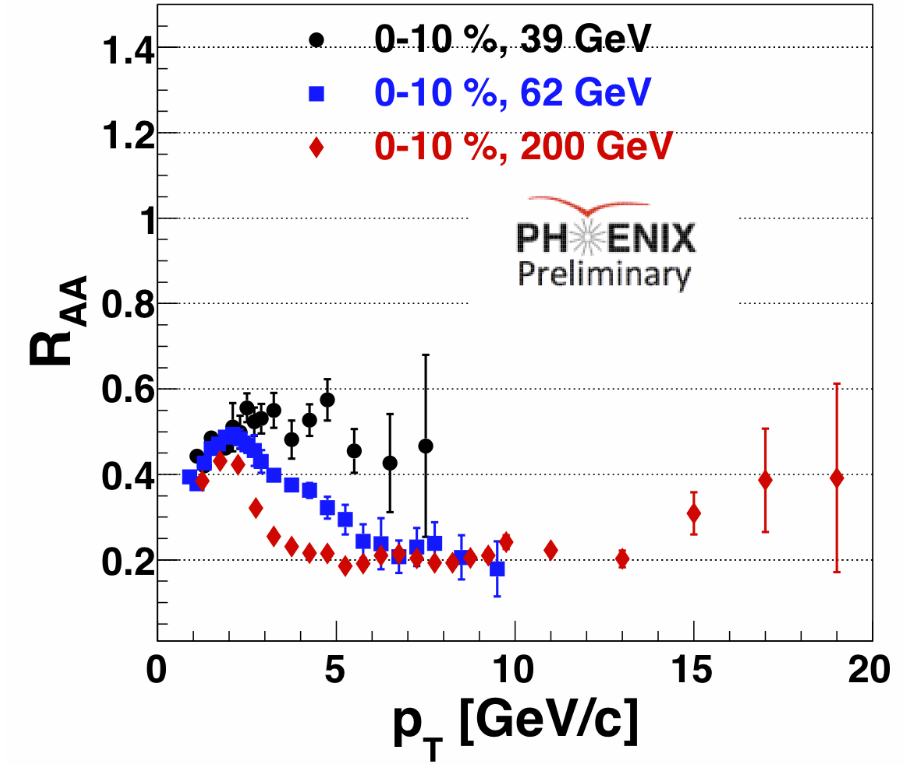
- Connected to hydrodynamic susceptibilities
- Sensitive to the correlation length of the system

$$S\sigma=\chi^{(3)}/\chi^{(2)} \qquad k\sigma^2=\chi^{(4)}/\chi^{(2)}$$

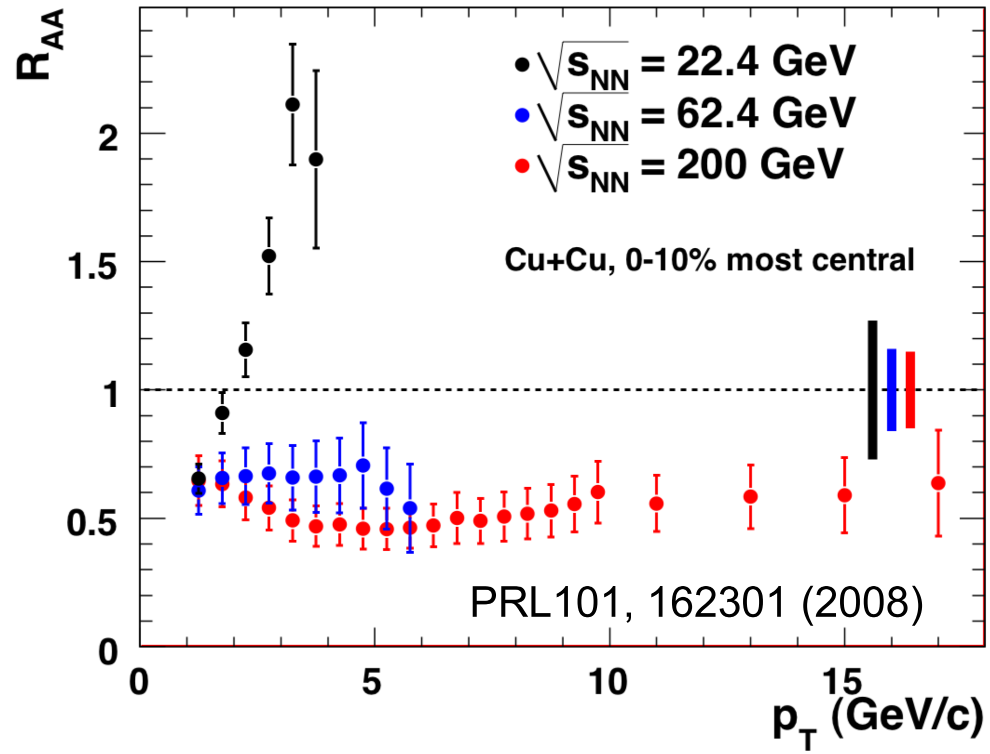
- Consistent with Lattice QCD and Hadron Resonance Gas (HRG) model at higher energies
- Deviates from HRG below 39 GeV

# Change in $R_{AA}$ between 22.4 and 39 GeV

Neutral pion $R_{AA}$




PHENIX Collaboration




- Suppression $p_t$ > 3 GeV/c consistent with parton energy loss at 62.4, 200 GeV:
- No suppression at 22.4 GeV
  Enhancement consistent with Cronin enhancement
- Some hints from Beam Energy Scan program at RHIC on critical points between 7 and 20 GeV - **stay tuned!**

## Physics beyond the study of QGP properties

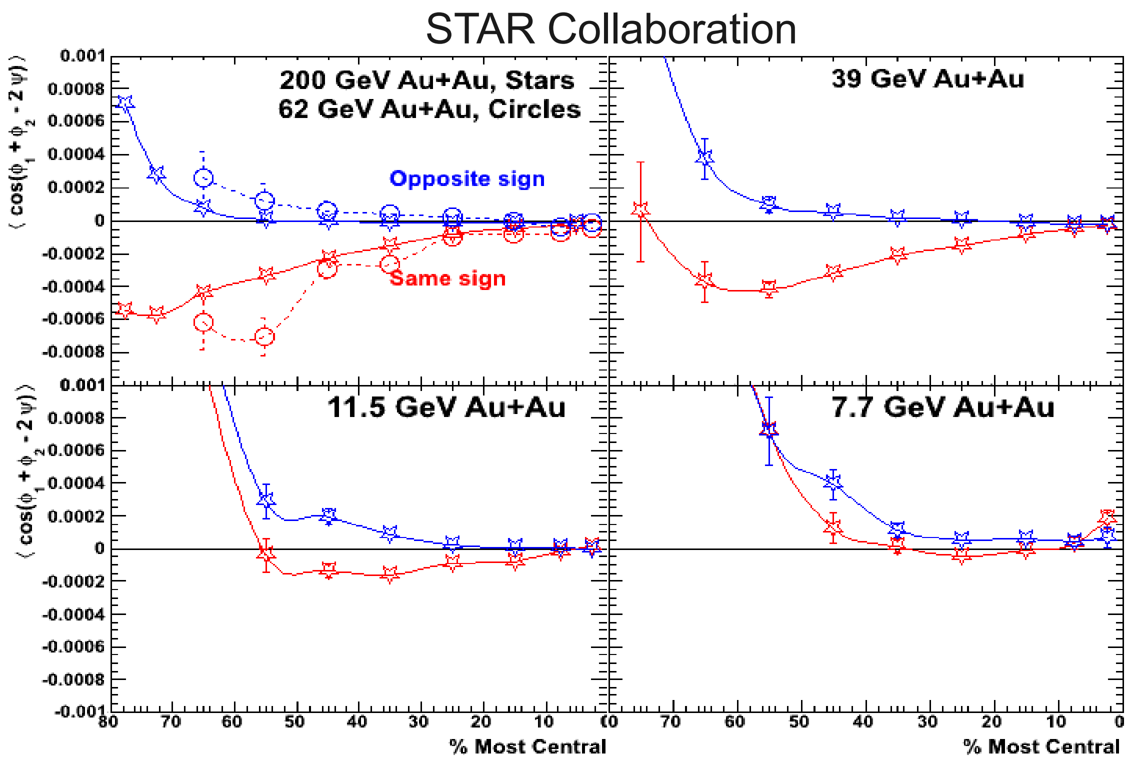
- Probes of local parity violation in strong interactions
- Observation of anti-matter particles

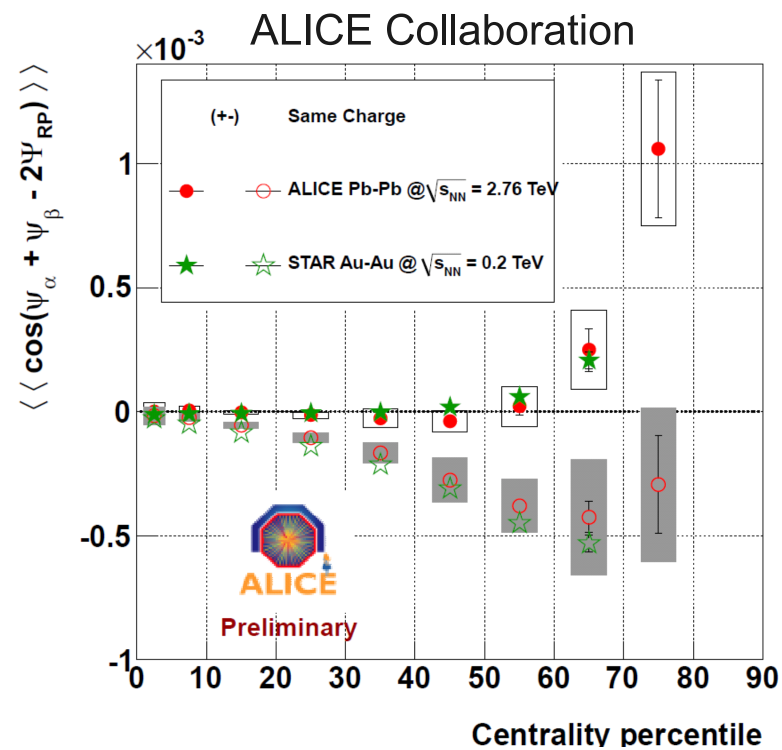
# Probes of local parity violation

Search for event-be-event charge fluctuations.
P-even observable but sensitive to P-violation:

$$\langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP}) \rangle$$

Voloshin PRC**70,** 057901 (2004)

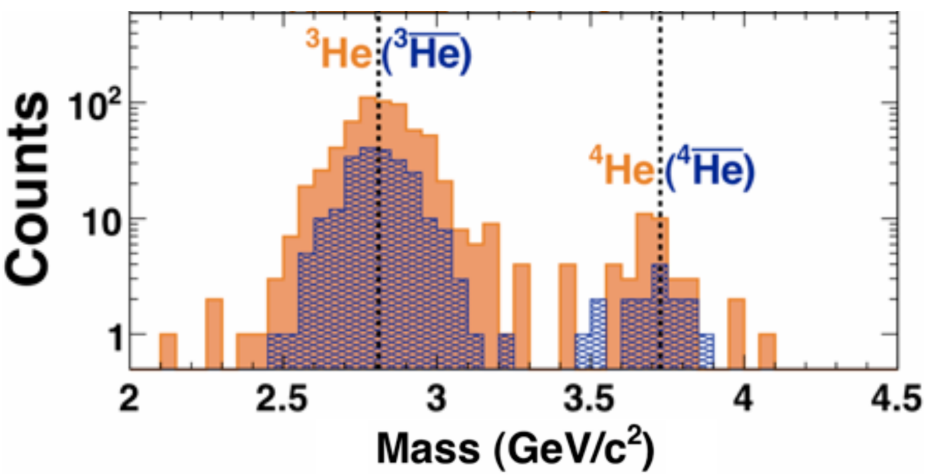


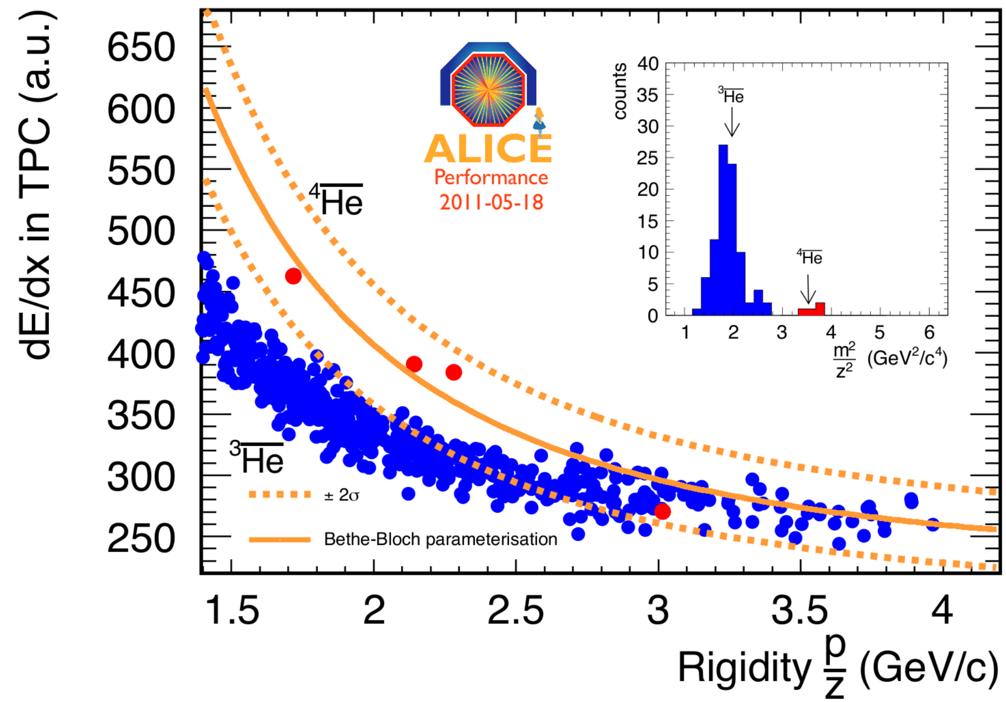

- RHIC and LHC observe charge separation
- Separation disappears between 11.5 and 7.7 GeV energies
- Recent progress in understanding parity even backgrounds, i.e. large flow fluctuations in the first harmonic
  **but still a long way to go before any final conclusion**

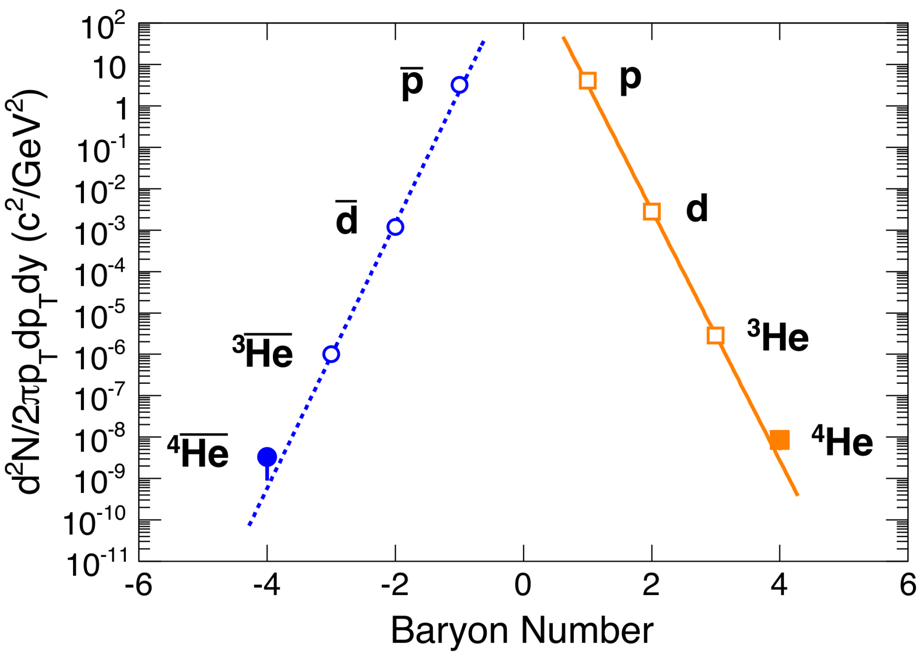
# Anti matter production at RHIC and LHC

STAR Collaboration
Nature 473, 353-356, (May 2011)




ALICE Collaboration




- STAR discovered 18 anti-$^4$He particles (heaviest anti-matter observed so far). Yields are consistent with thermal & coalescence model expectations
- ALICE Collaboration sees 4 candidates for anti-$^4$He (after one month of Pb-Pb!)
- Analysis on strange antimatter (e.g. anti-hyper-triton) is ongoing

# 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 results from first heavy ion run at LHC in November 2010 and new high statistics data from RHIC:

- Provides an additional constrain on the models of heavy-ion collisions
- Key ingredients for building a consistent picture of QGP phase diagram

**Looking forward to further studies and more results from LHC and RHIC communities!**