

# Recent Results from ALICE

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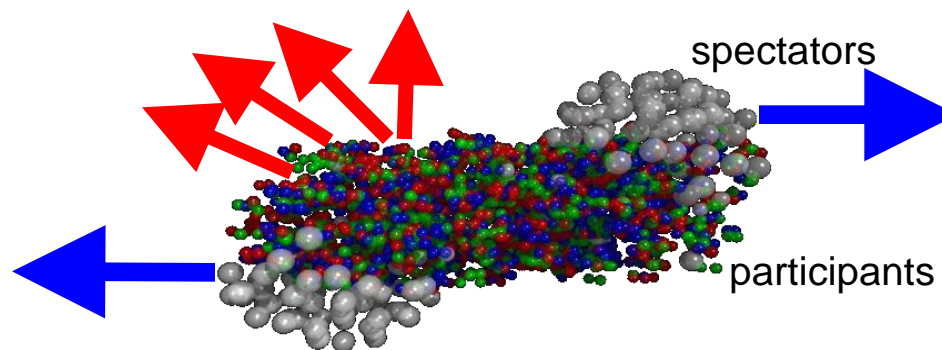
on behalf of the ALICE Collaboration

Aspen Center for Physics, Aspen, CO

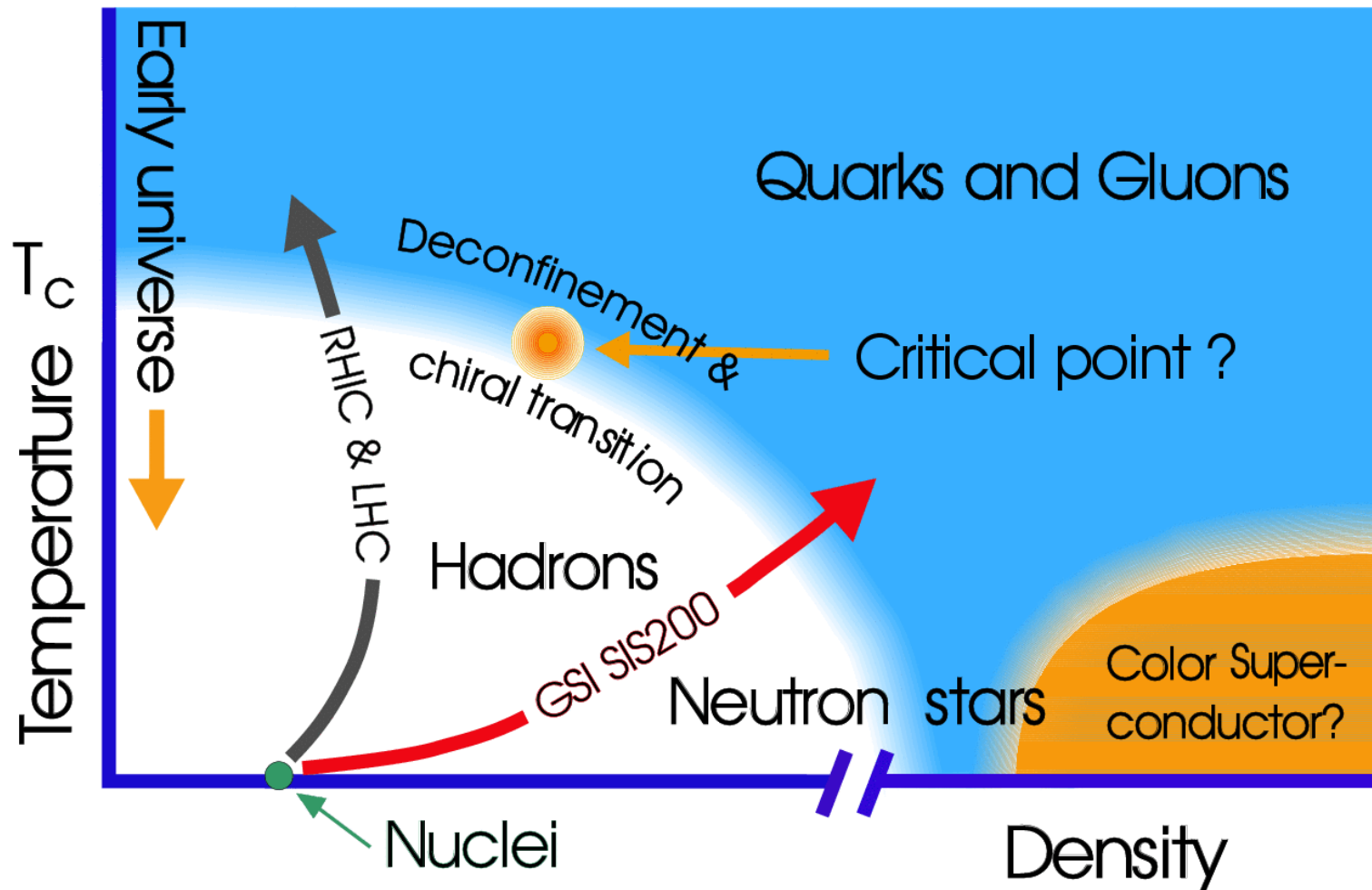
14 February, 2011

# Heavy Ion Nuclear Physics

- Ultrarelativistic heavy ion nuclear physics
- Investigate properties of nuclear matter at high temperature and density
  - Improve understanding of strong force concerning deconfinement and chiral symmetry breaking/restoration (transition from quark to hadronic matter).
  - Explore QCD in novel regimes. Study the phase diagram of QCD matter.
  - Probe conditions of quark/hadron phase transition (universe at  $10^{-6}$  s) and fully characterize the properties of the novel produced matter.

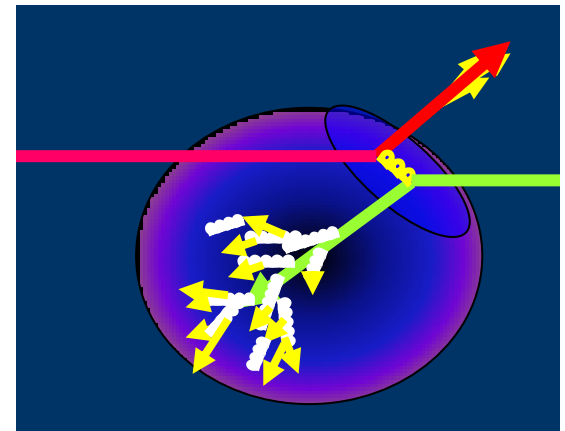
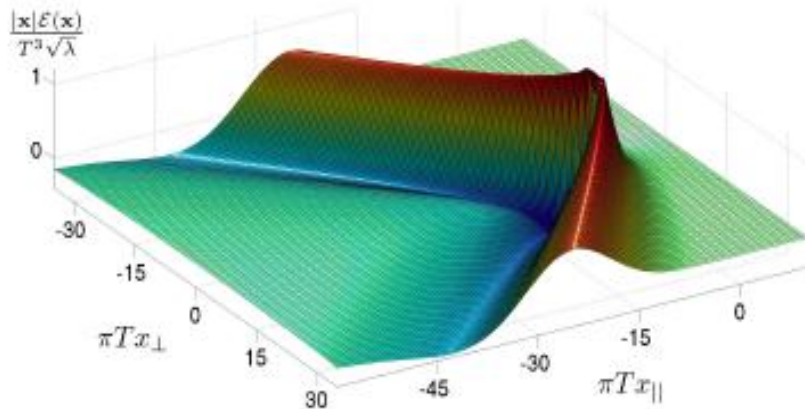


# Heavy Ion Nuclear Physics



# RHIC Discoveries

- Particles are flowing like an ideal hydrodynamical fluid. Viscosity/entropy ratio is lowest observed, near predicted quantum mechanical lower bound. A *perfect liquid*.
- Suppression of particles with a high transverse momentum in Au+Au collisions, but not d+Au (“**jet suppression**”). Opacity very high, effectively stops quarks and gluons.
- Significant correlated emission of partons (“**flow**”) with shock-wave dynamics. Rapid thermalization of created medium, fluid expansion, *even heavy quarks* are swept up by flow.



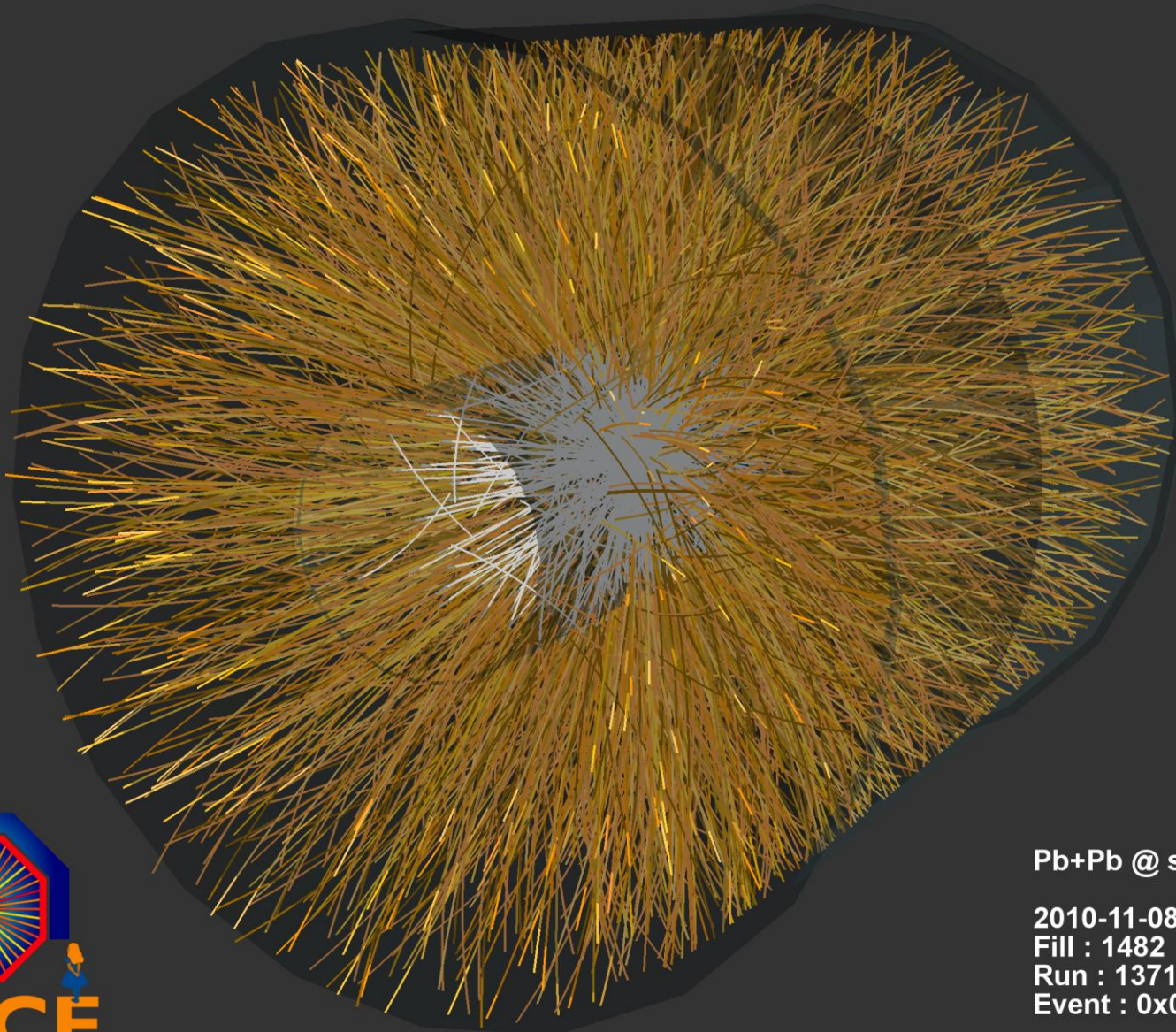
# RHIC Discoveries

- Almost as many anti-protons as protons produced at high transverse momentum.
- Energy density in the center of the collision is about 30 times that of a normal nucleus.
- The source of produced particles is large and short-lived.
- Modification of charm production measured via semileptonic decays.
- A *novel state of matter has indeed been created* at RHIC (and now the LHC).
- Fascinating Anti de Sitter space / Conformal Field Theory (AdS/CFT) correspondence between QCD (quark gluon plasma) and string theory. The RHIC “fireball” can be “mapped” to a “gravity dual” (mathematical black hole) via this correspondence.

# Denser and Hotter

Central Collisions	SPS	RHIC	LHC measured	LHC anticipated
$s^{1/2}$ (GeV)	17	200	2760	5500
$\varepsilon$ (GeV/fm <sup>3</sup> )	3	5	~3 x RHIC	15 – 60
initial T (MeV)	200	300		600
$\tau_{\text{QGP}}$ (fm/c)	< 1	1.5 – 4.0		4 – 10

# ALICE



Pb+Pb @  $\sqrt{s} = 2.76$  ATeV

2010-11-08 11:29:52

Fill : 1482

Run : 137124

Event : 0x0000000042B1B693

# ALICE Results

- Recent Pb+Pb collision measurements:
  - Two-pion **Bose-Einstein correlations** in central Pb-Pb collisions at  $\sqrt{s_{NN}} = 2.76$  TeV, Phys. Lett. B 696 (2011) 328-337.
  - **Centrality dependence** of the charged-particle multiplicity density at mid-rapidity in Pb-Pb collisions at  $\sqrt{s_{NN}} = 2.76$  TeV, arXiv:1012.1657v1 [nucl-ex].
  - **Suppression** of Charged Particle Production at Large Transverse Momentum in Central Pb-Pb Collisions at  $\sqrt{s_{NN}} = 2.76$  TeV, Phys. Lett. B 696 (2011) 30-39.
  - **Elliptic flow** of charged particles in Pb-Pb collisions at 2.76 TeV, Phys. Rev. Lett. 105, 252302 (2010).
  - Charged-particle **multiplicity density** at mid-rapidity in central Pb-Pb collisions at  $\sqrt{s_{NN}} = 2.76$  TeV, Phys. Rev. Lett. 105, 252301 (2010).
  - Numerous other analyses of recent data are underway.  
<http://aliweb.cern.ch/Documents/generalpublications>

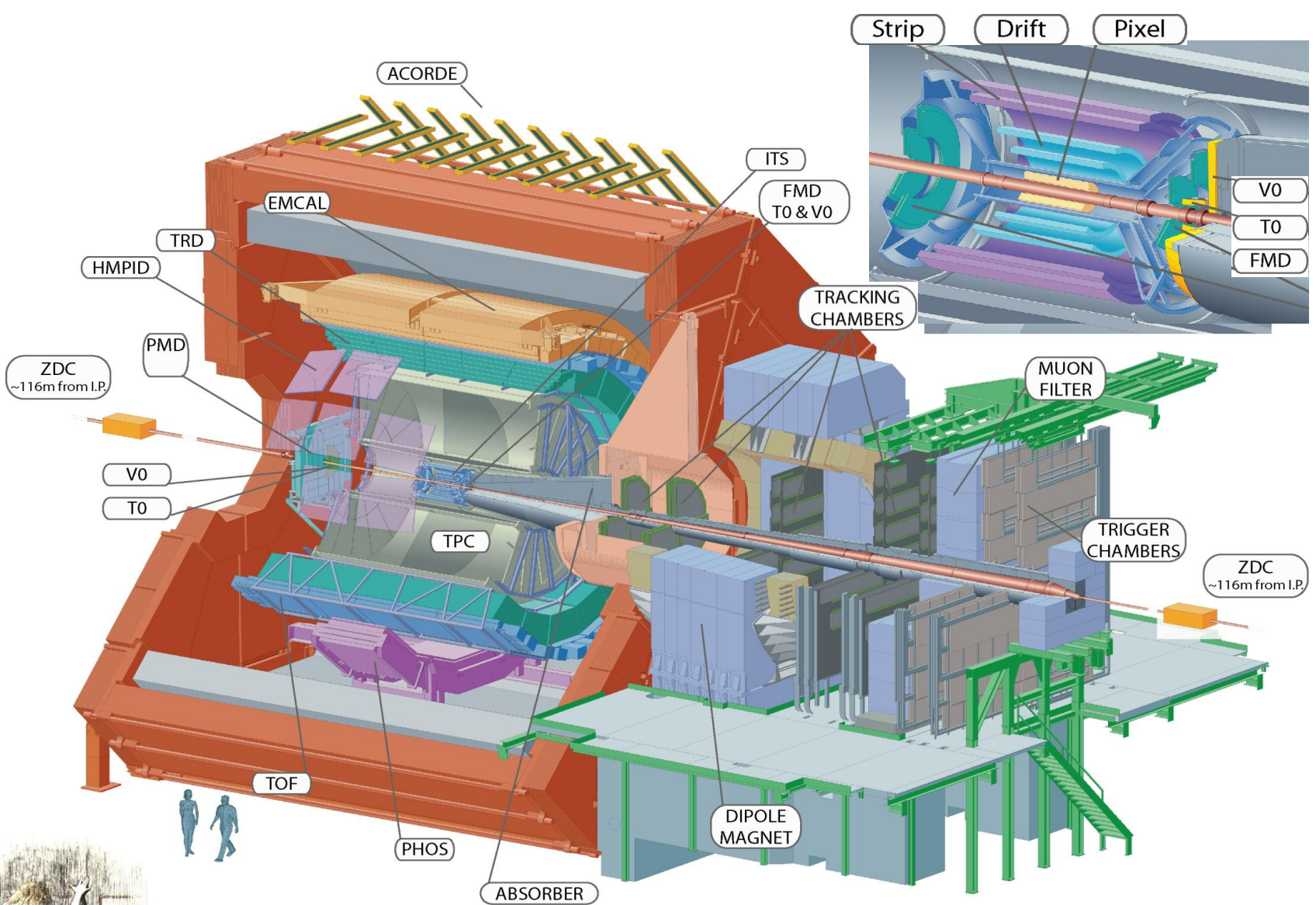


# ALICE Results

- Recent p+p collision measurements:
  - Transverse **momentum spectra** of charged particles in proton–proton collisions at  $\sqrt{s} = 900$  GeV with ALICE at the LHC, Physics Letters B 693 (2010) 53–68.
  - Two-pion **Bose-Einstein correlations** in pp collisions at  $\sqrt{s} = 900$  GeV, Phys. Rev. D 82, 052001 (2010).
  - Midrapidity **Antiproton-to-Proton Ratio** in pp Collisions at  $\sqrt{s} = 0.9$  and 7 TeV Measured by the ALICE Experiment, Phys Rev Lett Vol.105, No.7, (2010).
  - Charged-particle **multiplicity** measurement in proton–proton collisions at  $\sqrt{s} = 7$  TeV with ALICE at LHC, Eur. Phys. J. C (2010) 68: 345–354.
  - Charged-particle **multiplicity** measurement in proton–proton collisions at  $\sqrt{s} = 0.9$  and 2.36 TeV with ALICE at LHC, Eur. Phys. J. C (2010) 68: 89–108.
  - First proton–proton collisions at the LHC as observed with the ALICE detector: measurement of the **charged-particle pseudorapidity density** at  $\sqrt{s} = 900$  GeV, Eur. Phys. J. C (2010) 65: 111-125.

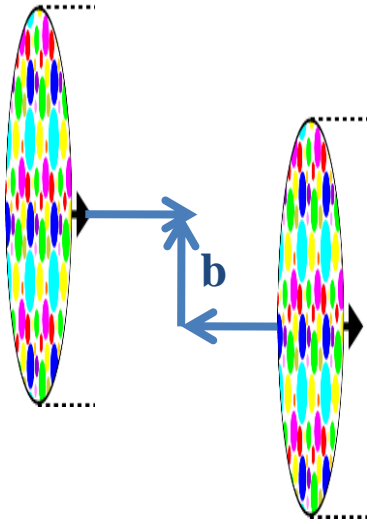
# ALICE Data

YEAR	BEAM	$\sqrt{s_{NN}}$	EVENTS
2009	p+p	0.9 TeV	$3 \times 10^5$ (MB)
2009	p+p	2.36 TeV	$4 \times 10^4$ (MB)
2010	p+p	0.9 TeV	$8 \times 10^6$ (MB)
2010	p+p	7.0 TeV	$8 \times 10^8$ (MB)
			$1 \times 10^8$ (muons)
			$2 \times 10^7$ (high $N_{ch}$ )
2010	Pb+Pb	2.76 TeV	few $\times 10^7$

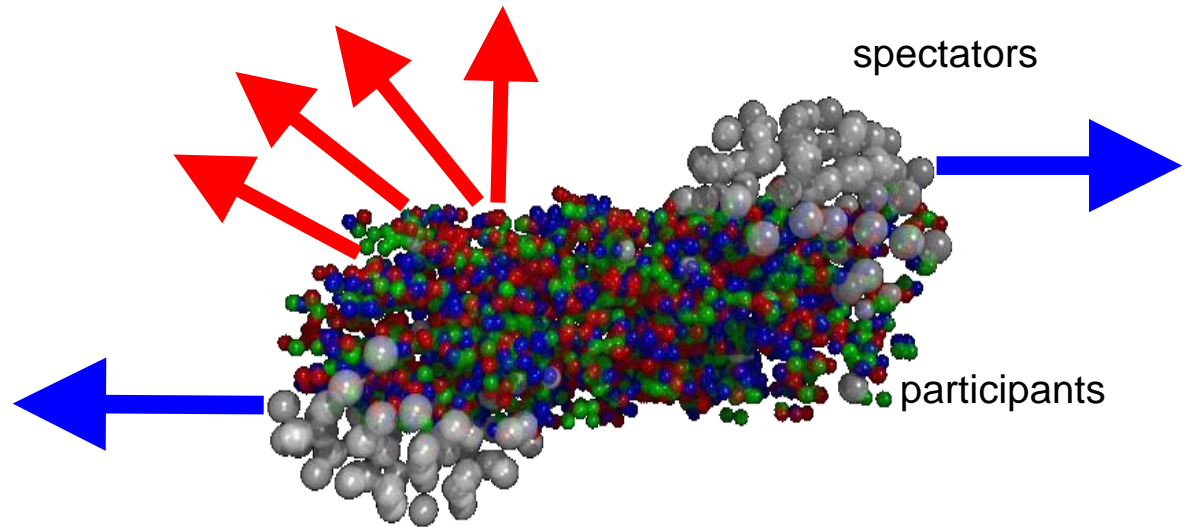


ALICE: Dedicated Heavy Ion LHC Experiment  
 over 30 countries, over 100 institutes, over 1000 members

# Centrality



Lorentz-contracted ions  
in center of mass frame



- Centrality corresponds to impact parameter.
- For a given  $b$ , Glauber model predicts  $N_{\text{part}}$  and  $N_{\text{coll}}$ .
- Hard processes tend to scale as  $\sim N_{\text{coll}}$ .
- Can classify events based on centrality class.

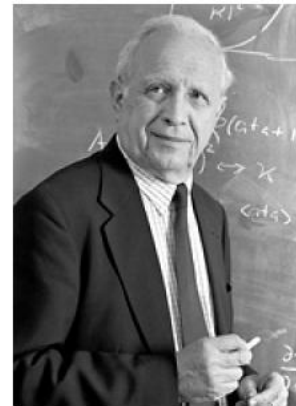
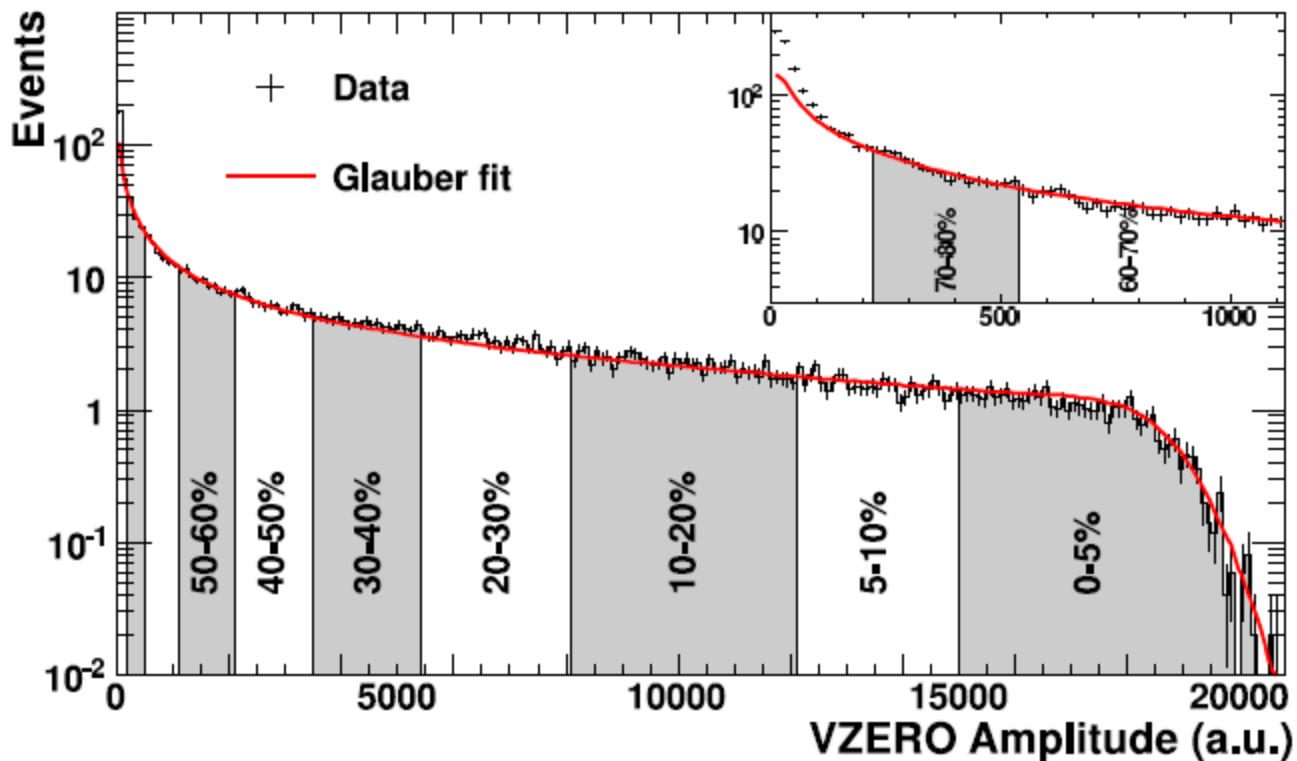


Photo: J.Reed  
Roy J. Glauber

# Centrality Dependence

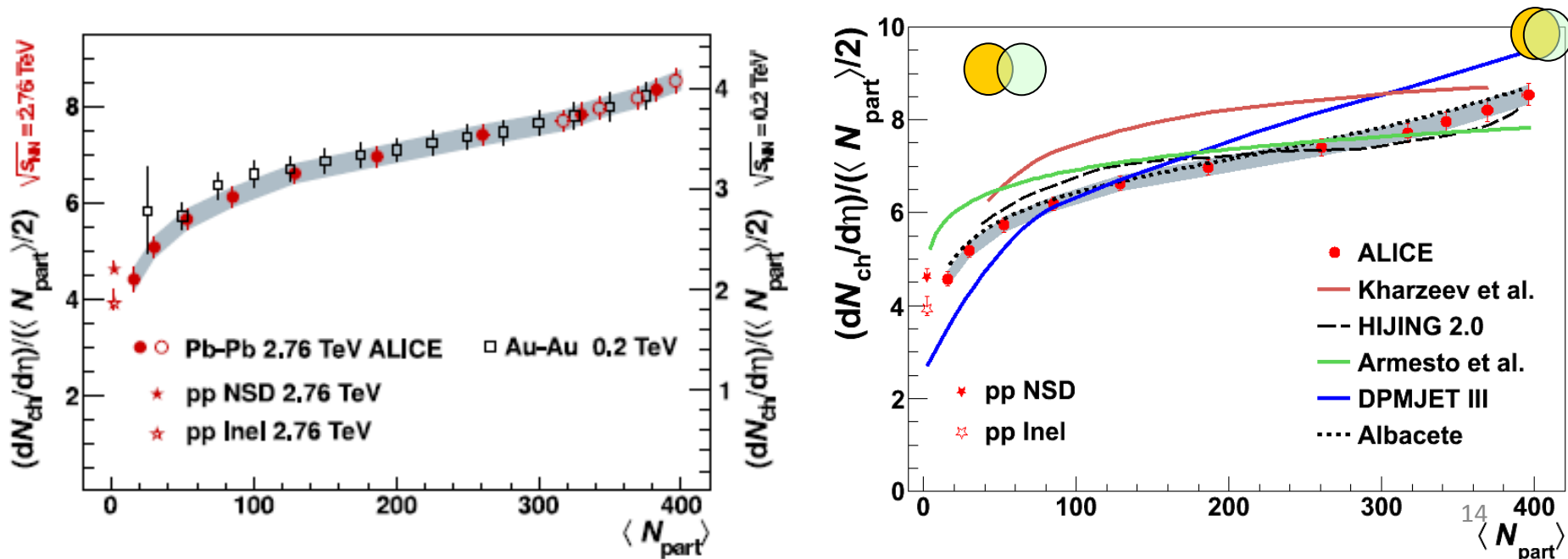
- Study  $dN_{ch}/d\eta$  as a function of centrality (impact parameter) for Pb+Pb collisions at 2.76 TeV.
- Classify collisions into 9 centrality percentile ranges.



# Centrality Dependence

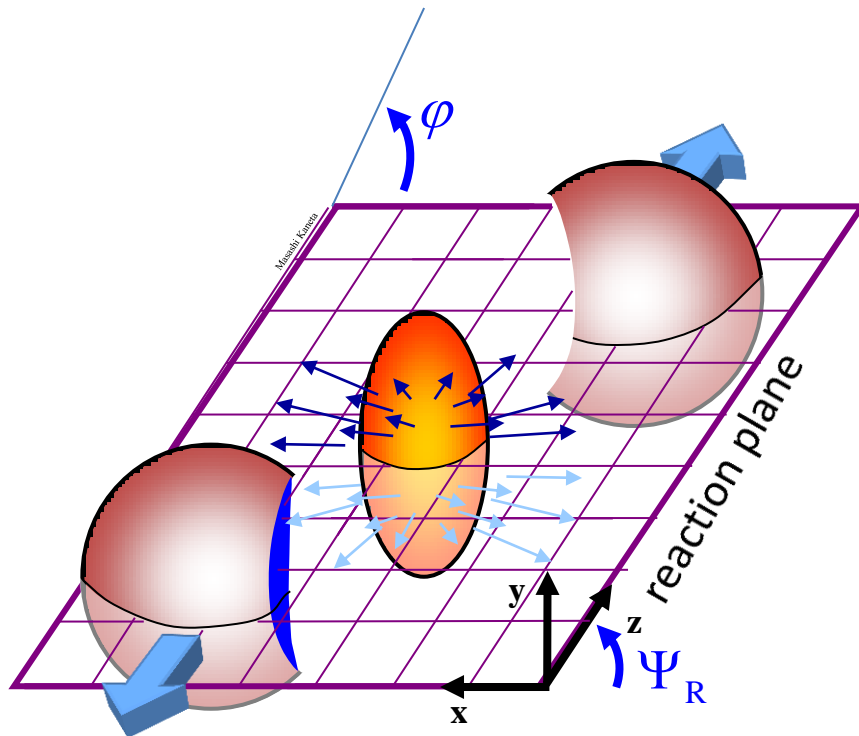
arXiv:1012.1657v1 [nucl-ex], submitted to PRL

- $dN_{ch}/d\eta$  normalized per participating nucleon pair increases by about a factor of 2 from peripheral (70–80%) to central (0–5%) collisions.
- Dependence of multiplicity on centrality at 2.76 TeV very similar to that observed at 0.2 TeV (RHIC). Observation discriminates between possible theoretical models.



# Flow

- Initial state spatial anisotropy of reaction zone leads to final state momentum anisotropy.
- Results in asymmetric particle emission.
- Second component of Fourier decomposition,  $v_2$ , indicates degree of azimuthal anisotropy.



$$E \frac{d^3 N}{d^3 p} = \frac{d^3 N}{p_T d\varphi dp_T dy} \sum_{n=0}^{\infty} 2v_n \cos(n(\varphi - \Psi_R))$$

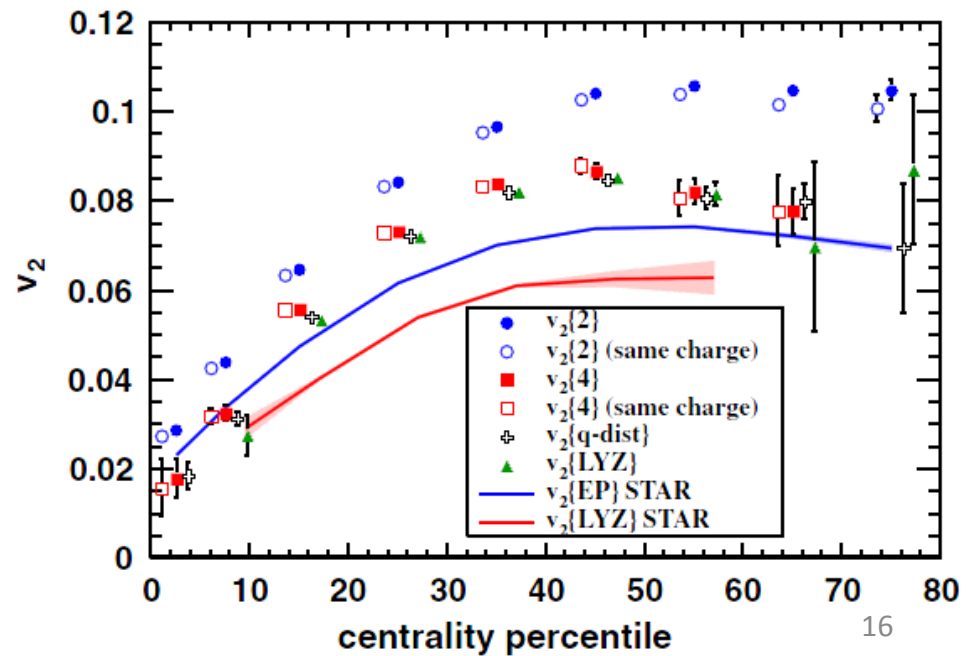
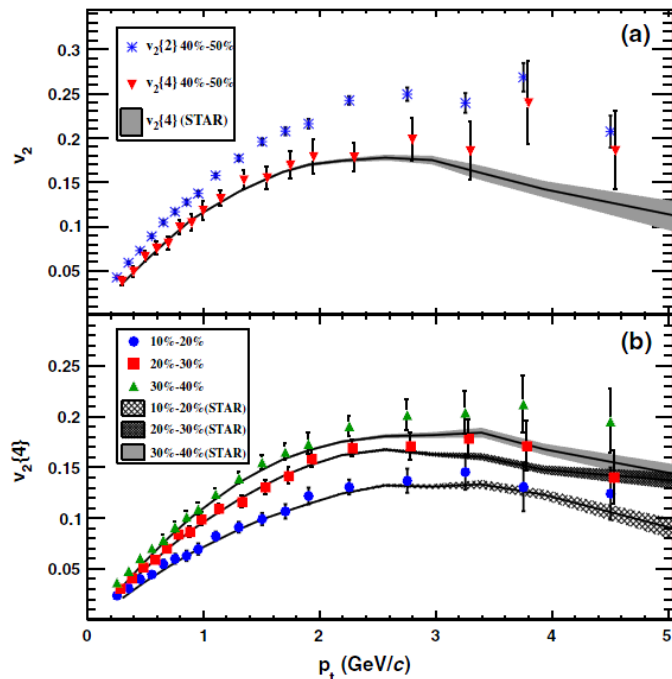
$$v_2 = \langle \cos 2(\varphi - \Psi_R) \rangle$$

$\Psi_R \equiv$  reaction plane angle

# Flow

Phys. Rev. Lett. 105, 252302 (2010)

- First elliptic flow measurement at the LHC. Consistent with predictions of hydrodynamical flow models.
- $v_2(p_T)$  agrees with RHIC measurements to within uncertainties.
- Integrated flow increases  $\sim 30\%$  from  $\sqrt{s_{NN}} = 200$  GeV to 2.76 TeV.
- Future elliptic flow measurements for identified particles will clarify the situation further.





# Nuclear Modification Factor

- Charged particle production at high transverse momentum in Pb+Pb collisions.
- Nuclear medium effects quantified using modification factor  $R_{AA}$ .
- Study dependence of  $R_{AA}$  on centrality.

$$R_{AA}(p_T) = \frac{(1/N_{evt}^{AA}) d^2 N_{ch}^{AA} / d\eta dp_T}{\langle N_{coll} \rangle (1/N_{evt}^{pp}) d^2 N_{ch}^{pp} / d\eta dp_T}$$

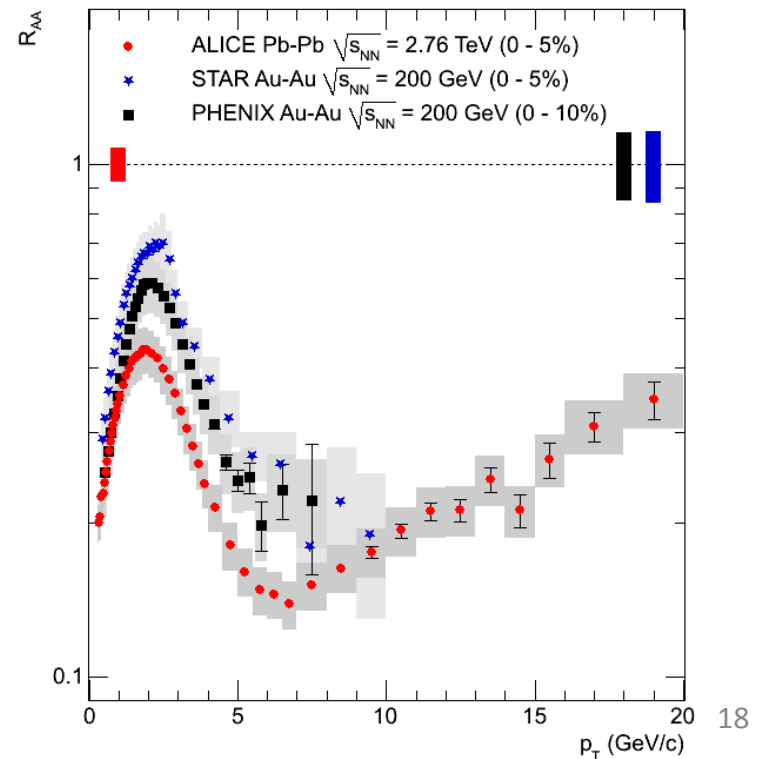
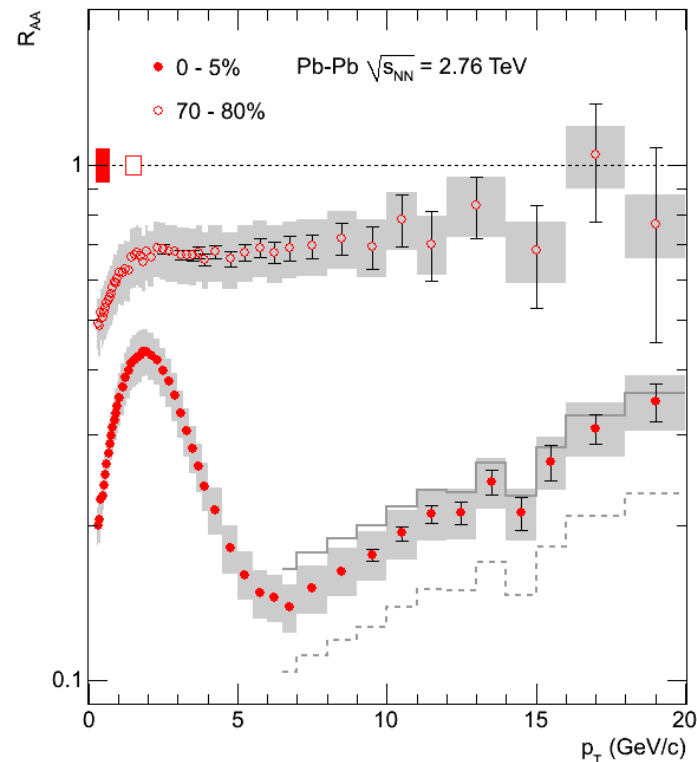
$= \frac{\text{what you get}}{\text{naively scaled expectation}}$

pseudorapidity  $\equiv \eta \equiv -\ln\left(\tan\frac{\theta}{2}\right)$

# Nuclear Modification Factor

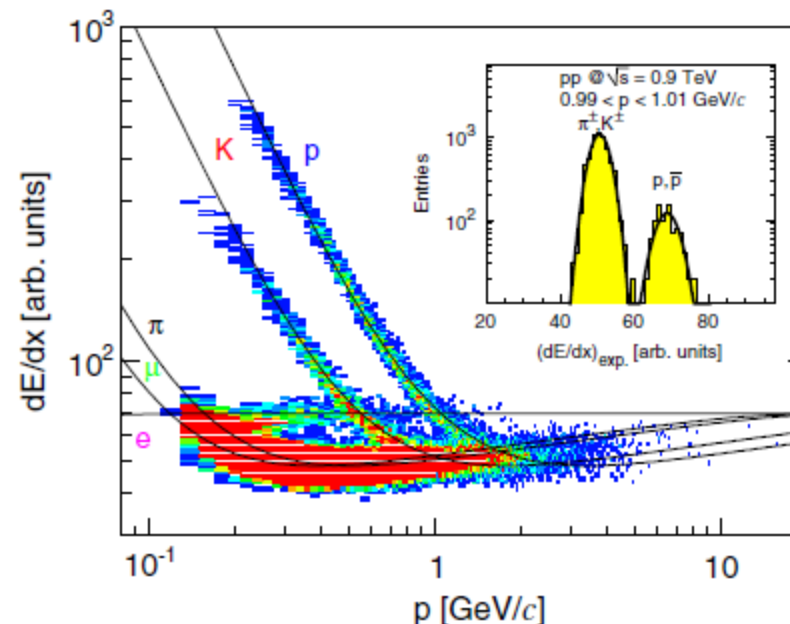
Phys. Lett. B 696 (2011) 30-39

- Only weak parton energy loss for peripheral collisions.
- For central collisions, large enhanced parton energy loss at the LHC and an *even denser medium* than observed at RHIC.
- Studies concerning energy loss and medium density will benefit from improved understanding of gluon shadowing and saturation.



# Antiproton to Proton Ratio

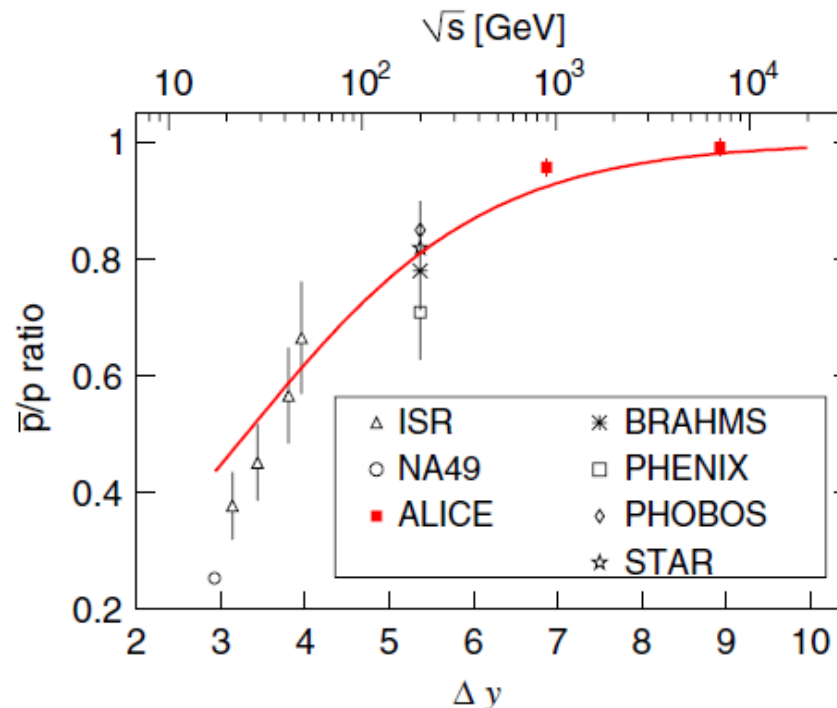
- Measure ratio of yields of antiprotons and protons in p+p collisions at 0.9 and 7.0 TeV.
- Test models of baryon-number transport and set limits on any additional contributions to baryon-number transfer.
- ALICE's p+p collision data, a control measurement for A+A studies, provides a rich area of study in and of itself.



# Antiproton to Proton Ratio

Phys. Rev. Lett. 105, 072002 (2010)

- Ratio rises from 0.9 to 7.0 TeV.
- Ratio is independent of rapidity and transverse momentum.
- Consistent with standard models of baryon number transport (e.g. baryon number transfer with the existence of the string junctions based on the Veneziano et al. model with string junction intercept  $a_j = 0.5$ ).
- Stringent limits set on any additional contributions constrains models.



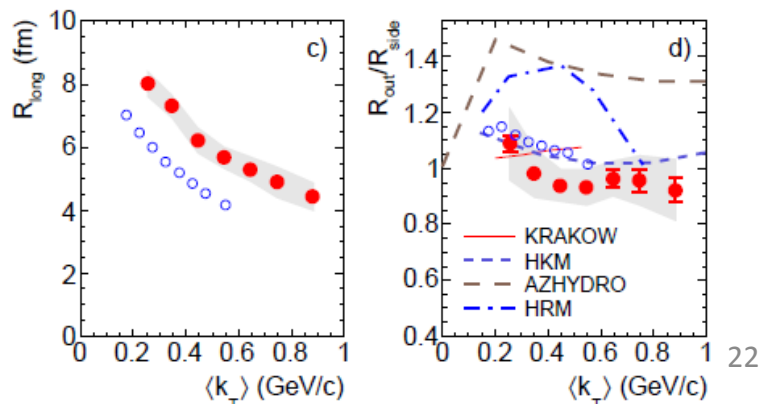
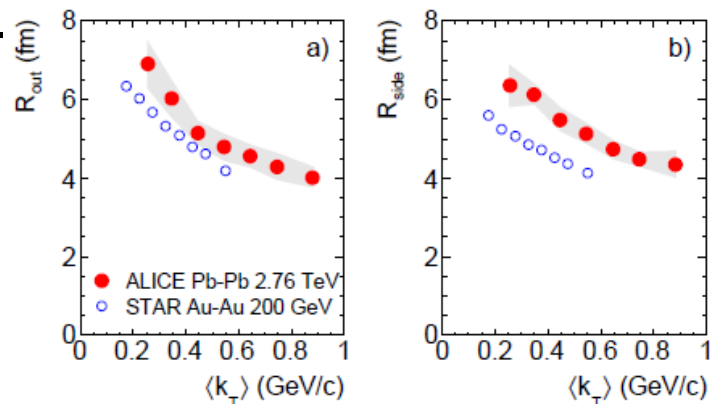
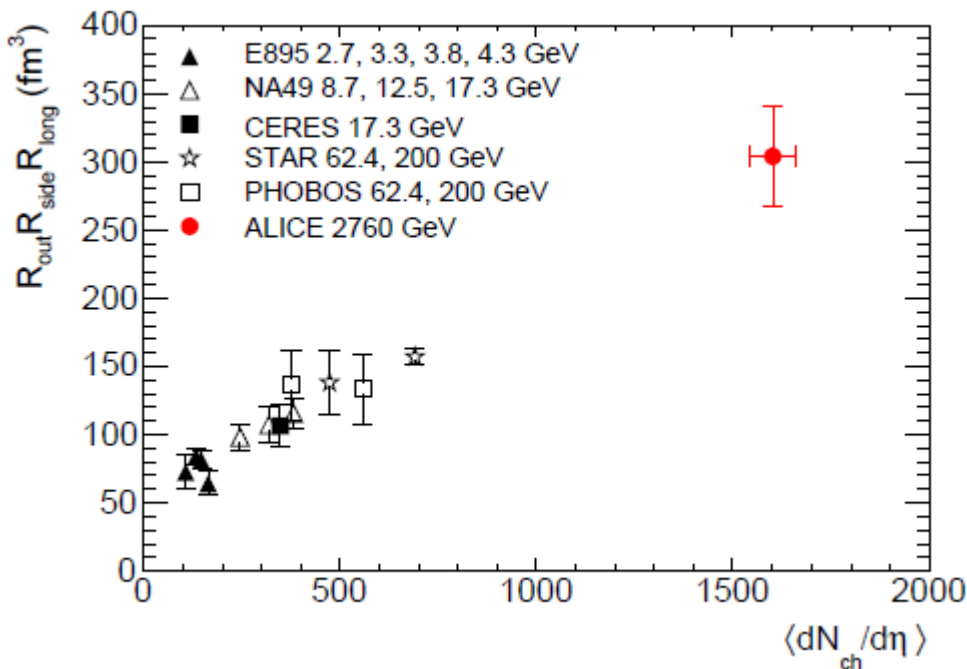
# Bose-Einstein Correlations

- Study Hanbury-Twiss two-pion correlations in central Pb+Pb collisions at  $\sqrt{s_{NN}} = 2.76$  TeV (and previously in p+p collisions at 900 GeV).
- First two-pion Bose-Einstein correlation measurement for Pb+Pb collisions at the LHC.
- Measure one-dimensional Gaussian HBT radii as a function of  $k_T$  .

# Bose-Einstein Correlations

Phys. Lett. B 696 (2011) 328-337

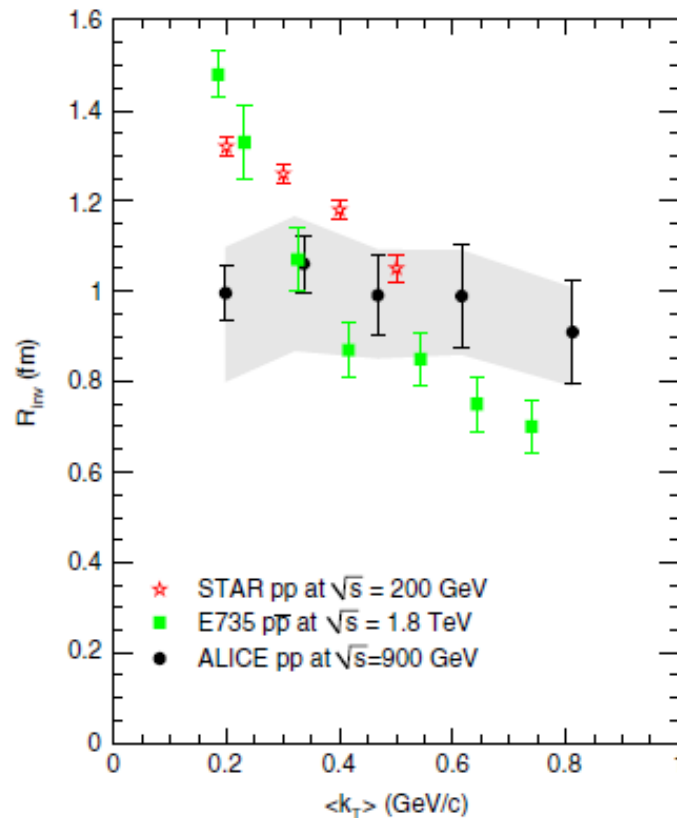
- Extracted pion source radii exceed those at RHIC by ~30%.
- Increase is present for both longitudinal and transverse radii.
- Decoupling time for mid-rapidity pions 40% greater than at RHIC.
- ALICE measurements indicate LHC fireball is indeed hotter, lives longer, expands larger than at RHIC.



# Bose-Einstein Correlations

Phys. Rev. D 82, 052001 (2010)

- Previous result for p+p collisions.
- Extracted HBT radius  $R_{inv}$  increases with event multiplicity as observed by other experiments.
- However, dependence of  $R_{inv}$  on  $k_T$  is much less steep.



# Conclusions

- First observation of elliptical flow for Pb+Pb collisions at the LHC.
- Jet suppression with even greater parton energy loss and medium density than observed at RHIC.
- Exciting analyses of Pb+Pb collisions at unprecedented energies and p+p collisions are underway.
- See <http://aliweb.cern.ch/> for much more information.

