quark - lepton

Štrbské Pleso, Slovakia, September 12-15, 2012

Hadron-hadron correlations in heavy-ion collisions

Peter Hristov

14/09/2012, PIC2012

Outline

Content

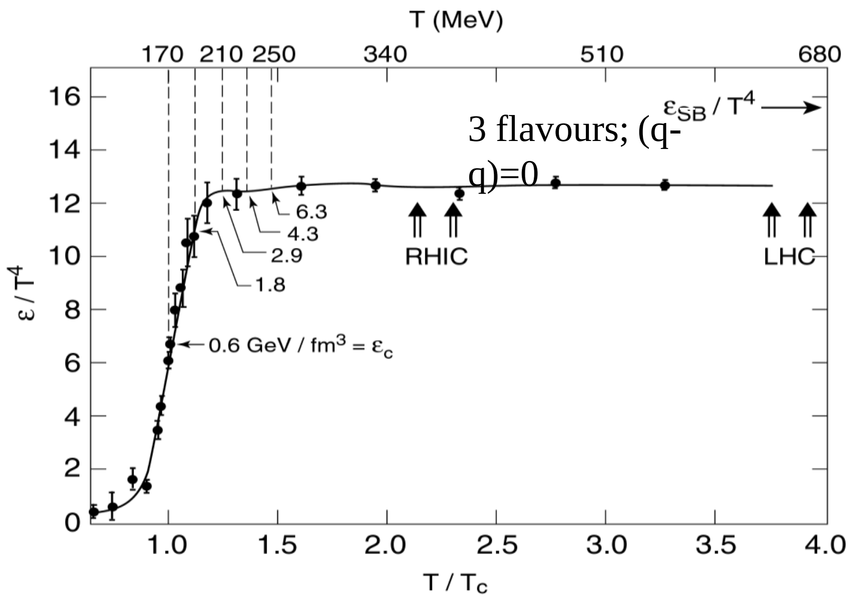
- Introduction
- Femtoscopy
- Anisotropic flow

Template

- Physics motivation
- Measurement methods
- Experimental results
- Summary and/or outlook

Introduction

Lattice QCD

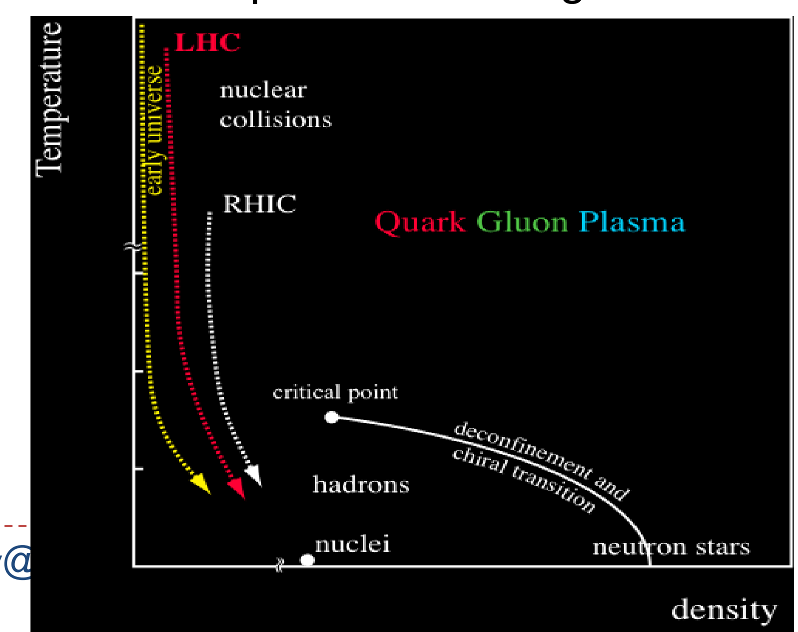


- At the critical temperature a strong increase in the degrees of freedom gluons, quarks =>deconfinement
- Transition expected to occur around 0.5 GeV/fm^3

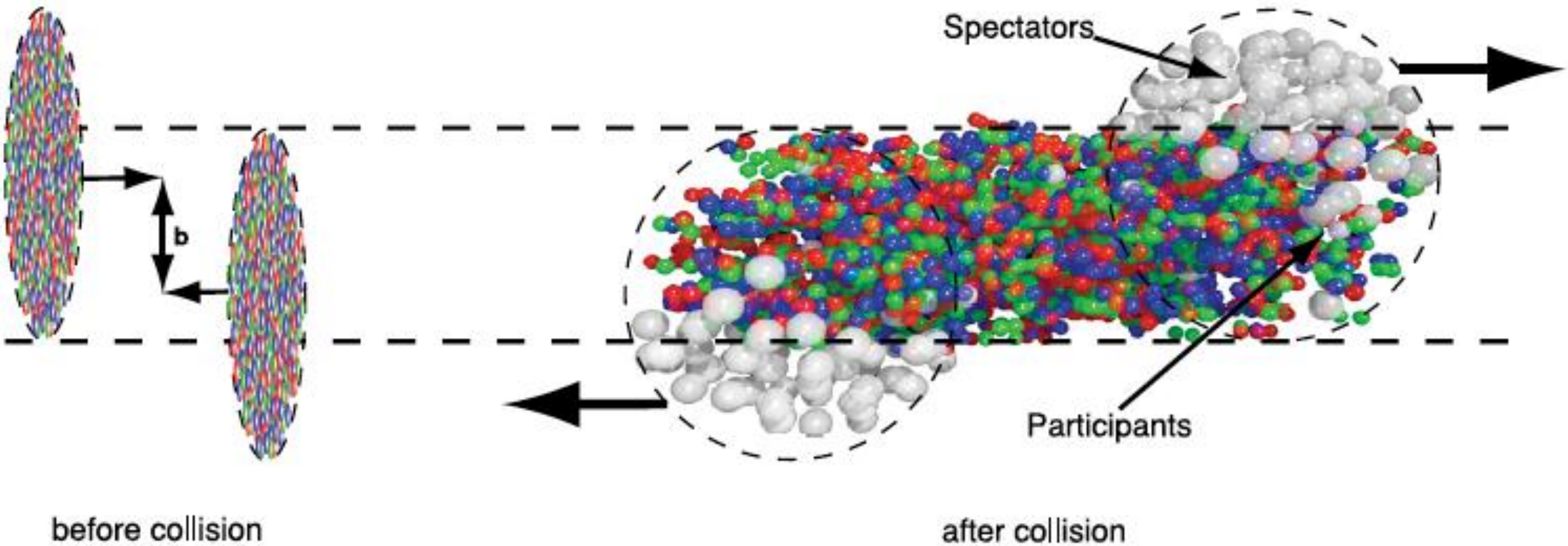
Borsanyi et al. JHEP 11 (2010) 077

HI physics: explore properties of QGP

- What happens when you heat and compress matter to very high temperatures and densities?
- From macroscopic quantities of the QGP to better understanding of the underlying microscopic theory (QCD) in the non-perturbative regime



Heavy ion collision



very hot and dense nuclear matter in more central collisions while we approach "simple" nucleon-nucleon collisions in very peripheral collisions

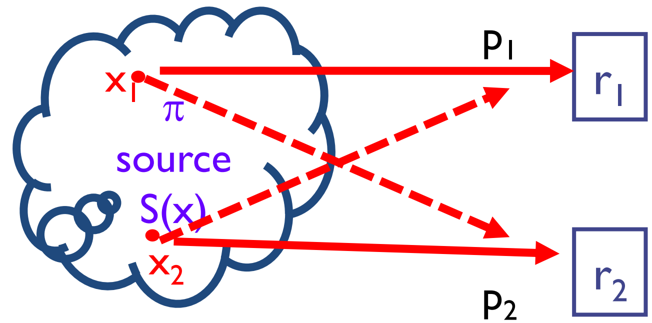
Correlations

- Correlations in "loose" sense: $\rho(p_1,p_2) \neq \rho(p_1)\rho(p_2)$
- Different sources (this classification is only an illustration)
  - Conservation laws (energy-momentum, charge, baryon number, etc)
  - Resonances
  - Quantum effects: Hanbury Brown – Twiss (HBT) interferometry / Bose – Einstein correlations (BEC) => femtoscopy
  - Collective effects: anisotropic flow
  - Medium effects (energy loss, quenching, re-scattering)
  - Interaction dynamics (jets, mini-jets, initial stage fluctuations, etc)
  - Final state re-scattering (e.g. Coulomb interaction)
  - Detector effects: acceptance, efficiency, trigger, reconstruction artifacts (e.g. fakes, track splitting)
  - Background (e.g. gamma conversion)
- For experts: Workshop on Particle Correlations and Femtoscopy

Femtoscopy

Physics motivation

- Quantum phenomenon: enhancement of correlation function for identical bosons
- First used with photons in the 1954 by astronomers Hanbury Brown and Twiss
  - measured size of star (Sirius) by aiming at it two photomultipliers separated by a few meters
- Goldhaber et al (PRL 3(1959) 181: application in particle physics
- Long history (see Csörgö@WPCF'11)

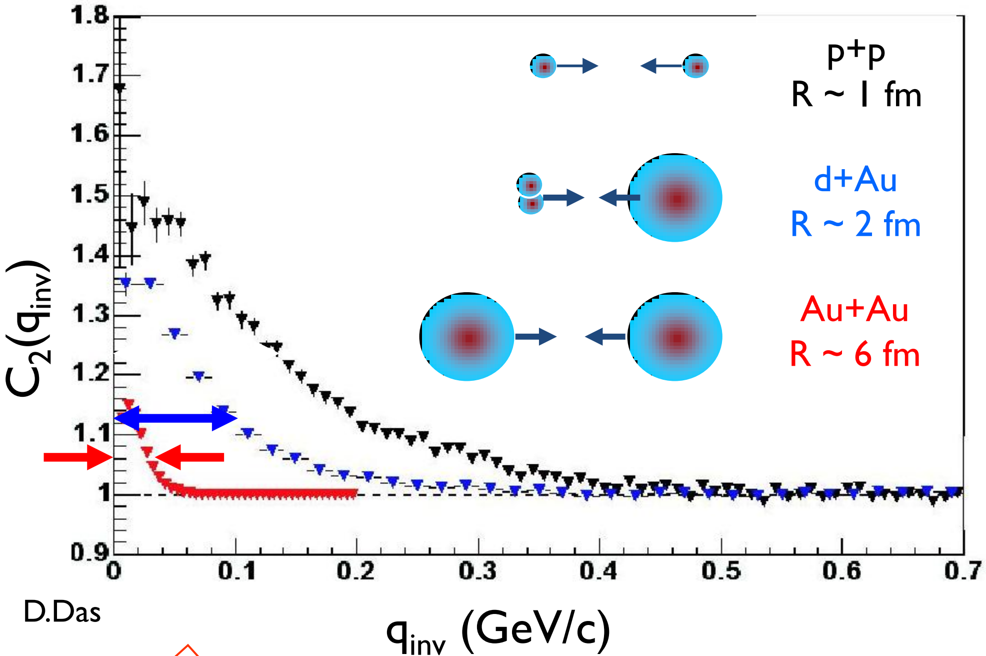


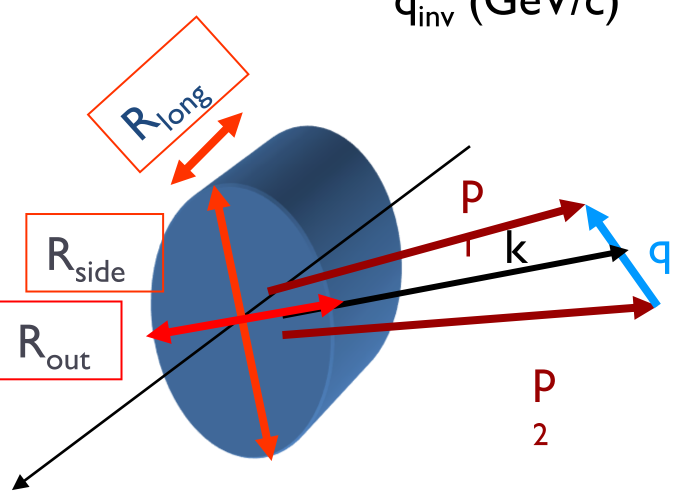
Bosons (pions) => symmetric wave function
Approximation:
plane-wave, no multi-particle symmetry, source thermalization, no coherent emission

Space-time extension: Koonin – Pratt equation

if gaussian source

Typical measurement: details





- $C_2(q)=A(q)/B(q)$,

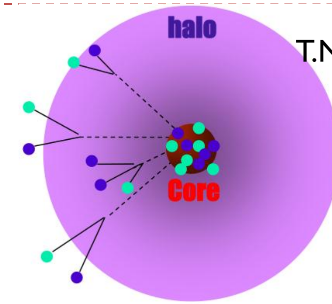
A(q) is the measured distribution,

B(q) is the distribution from mixed events

- 1D analysis using invariant relative momentum q_{inv}: average size over all directions
- 3D analysis in "*Out-Side-Long*" co-moving system where the pair momentum in *long* vanishes (Bertsch-Pratt).
  - *long* || beam axis
  - *out* || pair momentum
  - *side* perpendicular to the others

Typical measurement: details

- Fitting the correlation function
  - Core – halo model with gaussian source: the particles in the core are affected by Coulomb interaction. This is corrected by the factor $K(q_{inv})$: squared Coulomb wave function averaged over a spherical source (Sinyukov, 1998).



T.Niida, QM'12

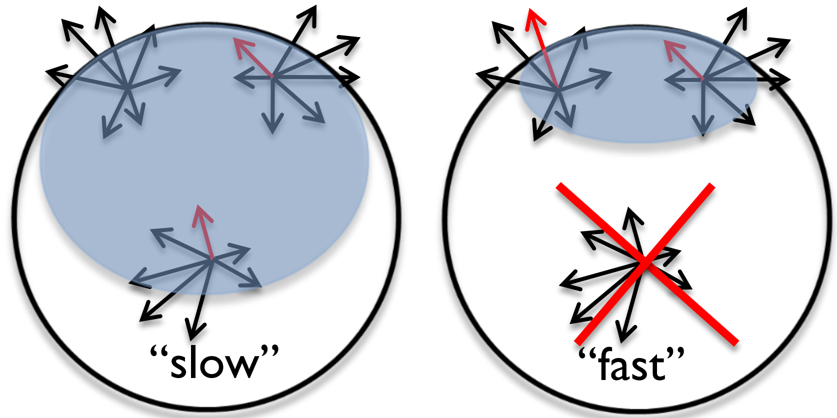
R_{long}: Longitudinal size, depends on the total evolution time
R_{side}: Transverse (geometrical) size
R_{out}: Transverse size + emission duration
R_{os}: Cross term between Out and Side
λ: Describes correlation strength
B: Account for non-femtoscopic background (e.g. resonances)

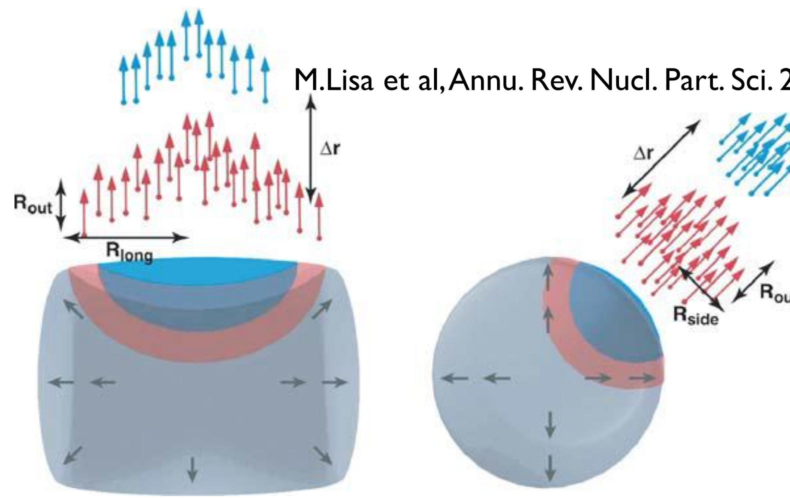
Measured sizes

- Expanding source
  - The longitudinal expansion is “scaling”: almost flat distribution in rapidity
  - The transverse expansion leads to deformation of p_T slope
- Each particle has collective velocity and thermal (random) velocity
- When the observed p_T grows, the region emitting such particles becomes smaller and shifted to the outside: “homogeneity size” (Sinyukov, 1995). This size corresponds roughly to

collective velocity ≥ thermal velocity

- Radial flow: higher m_T => emission close to the surface => smaller volume, radial offset
- Longitudinal flow: higher m_T => lower thermal velocity => smaller R_{long}



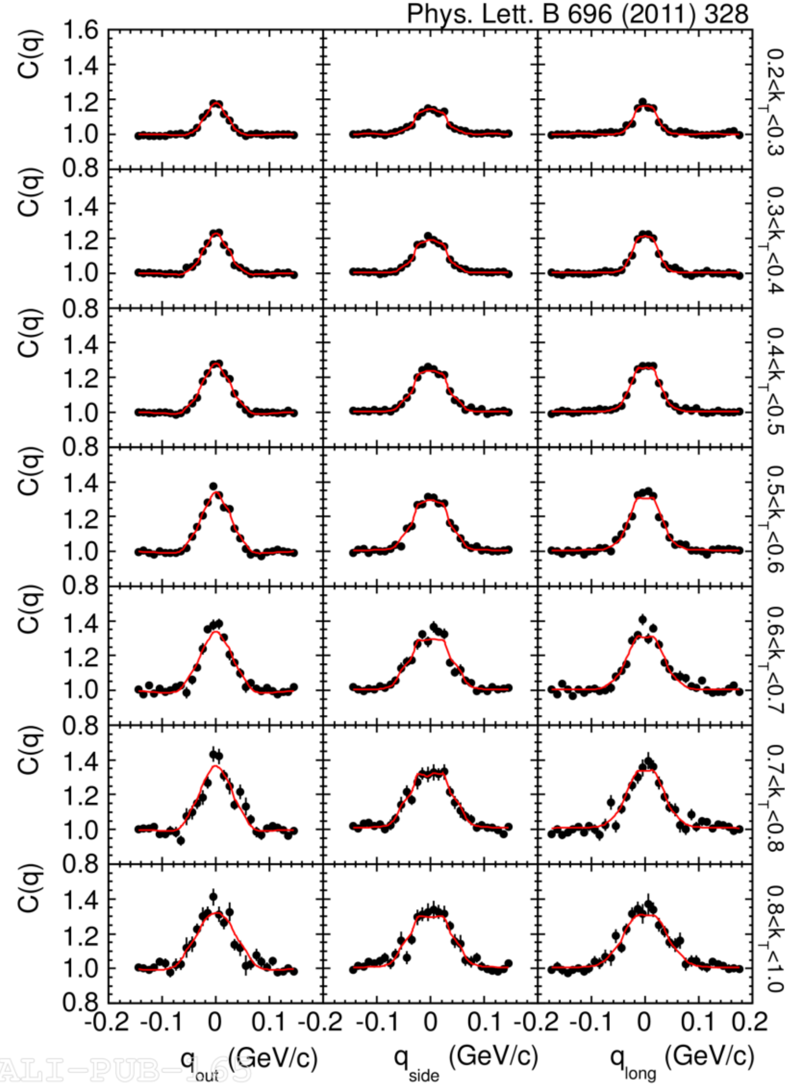


M.Lisa et al, Annu. Rev. Nucl. Part. Sci. 2005. 55:357

T_f: decoupling time, T: freeze-out temperature

Example of fit (ALICE)

- 3D correlation function fitted in bins of k_T
- 1D projections of the data and 3D fit for q_{out}, q_{side}, q_{long} while the other two q's are in the interval (-0.03,0.03)

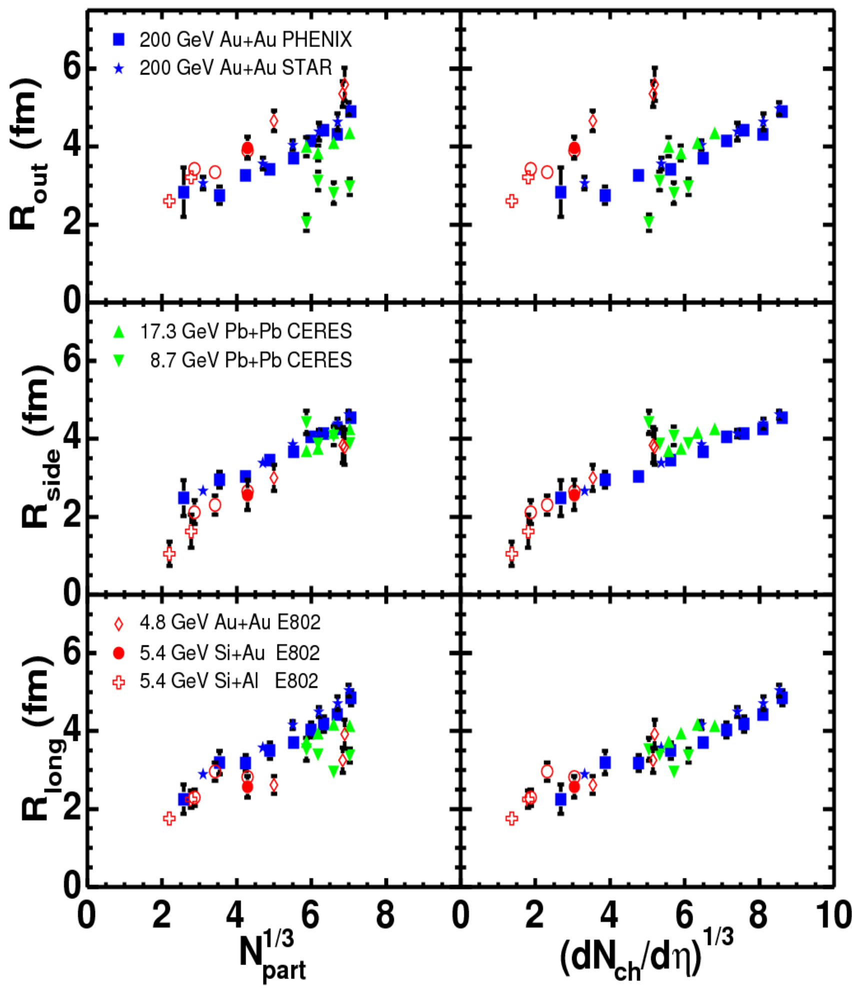


Measurement: alternative approaches

- Use different fitting functions
  - Non-"Out-Side-Long" systems, e.g. spherical harmonics
  - Non-gaussian form (e.g. account for resonances => exponential terms, etc)
- Unfolding of the source distribution (1D and 3D)
  - Numerical inversion of the Koonin-Pratt equation: difficult computing problem
  - Model independent results consistent with gaussian shape (Chung, WPCF'11)
- Comparison with transport models (hydro + additional effects)
  - RHIC Hydro-HBT puzzle:
    - First hydro calculations struggle to describe femtoscopic data: predicted too small R_{side}, too large R_{out} – too long emission duration
    - No evidence of the first order phase transition
  - Solution: revisited hydrodynamic assumptions (S.Pratt, 2009)
    - accounting for the buildup of collective flow in the first instants of the collision before thermalization is attained
    - realistic (stiffer) equation of state
    - smooth crossover instead of first order transition
    - resonance propagation and decay as well as particle rescattering after freeze-out need to be taken into account: similar in effects to viscosity

"Pre-LHC" experimental results

M.Lisa et al, Annu. Rev. Nucl. Part. Sci. 2005. 55:357

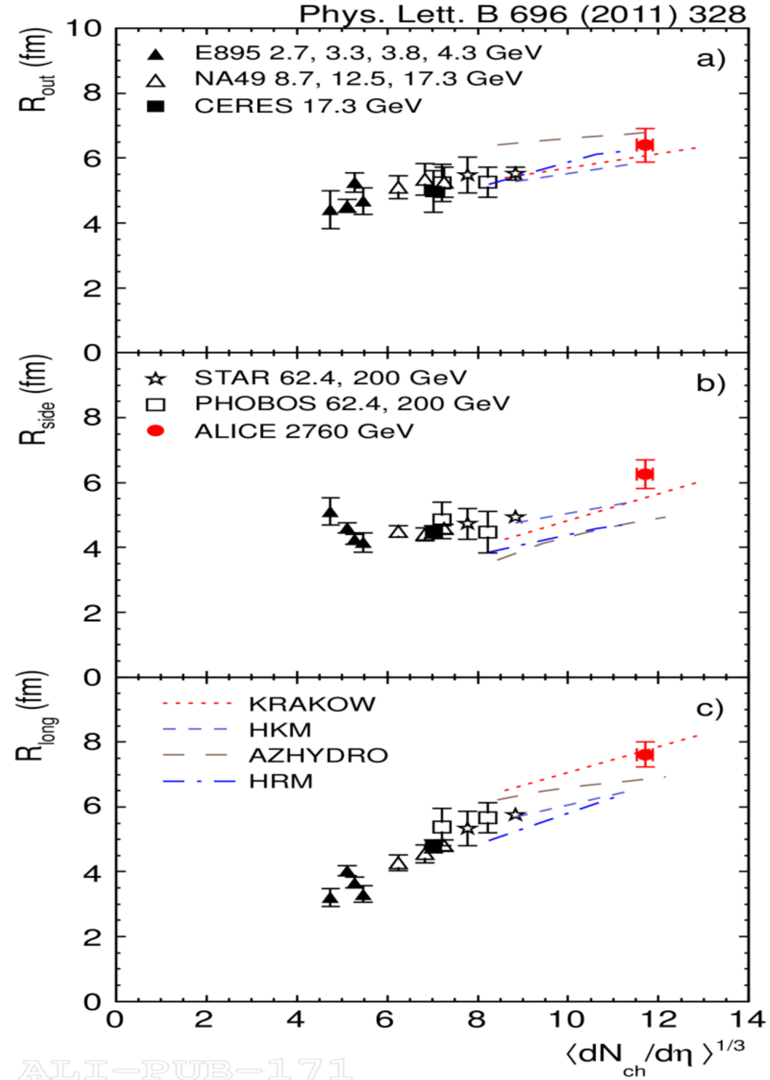


- Sizes measured in heavy-ion collisions scale with the observed particle density
- The scaling is linear over a broad range of system types, collision energies and centralities
- Observed multiplicity is a final state observable, for initial state ones (such as N_{part}) scaling is not as good
- Femtoscopy characterized the final state of the system

A.Kisiel@CERN

Experimental results: comparison with pre-LHC and with transport models

- The general trends observed at RHIC are confirmed
- The hydrodynamic models which were extensively tuned to reproduce the RHIC data work also at the LHC
- Only the models which introduce all the features important at RHIC (initial flow, crossover phase transition, realistic equation of state, full inclusion of resonances) continue to work at the LHC



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Experimental results: volume and lifetime

- The general trends observed at lower energy are maintained
- Clear increase of the emitting region size and the system lifetime between the largest system to date (central full energy RHIC) and the central LHC.

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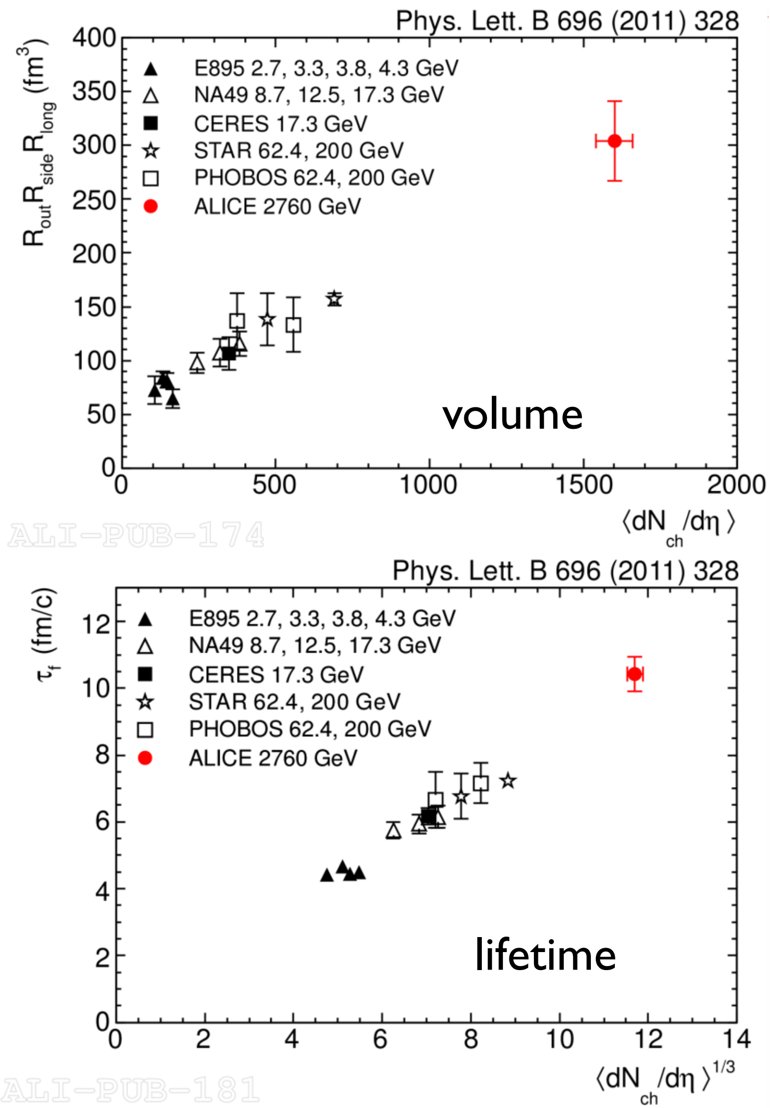
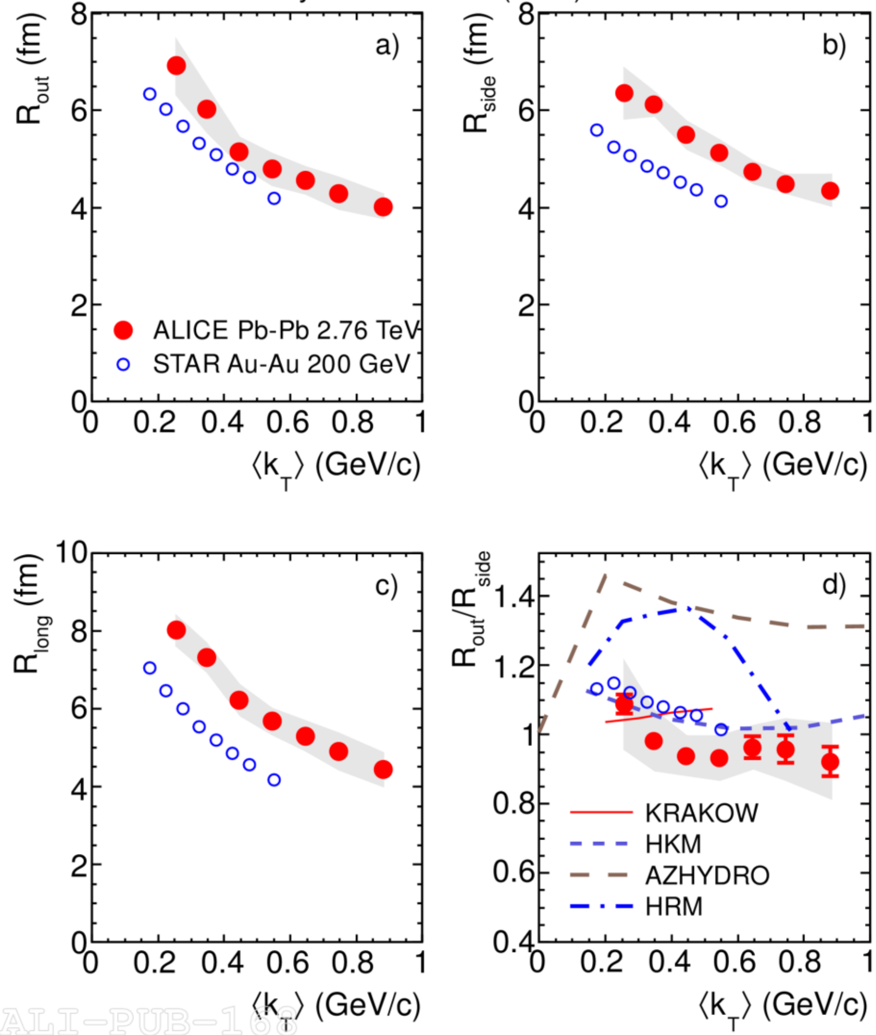


Experimental results: k_T dependence

- All the expected trends are observed:
  - Overall increase of the radii as compared to RHIC
  - Strong dependence of the radii on k_T
  - R_{out} /R_{side} ratio even smaller than the one at RHIC
- The "standard" model from RHIC, extrapolated to the LHC appears to work well

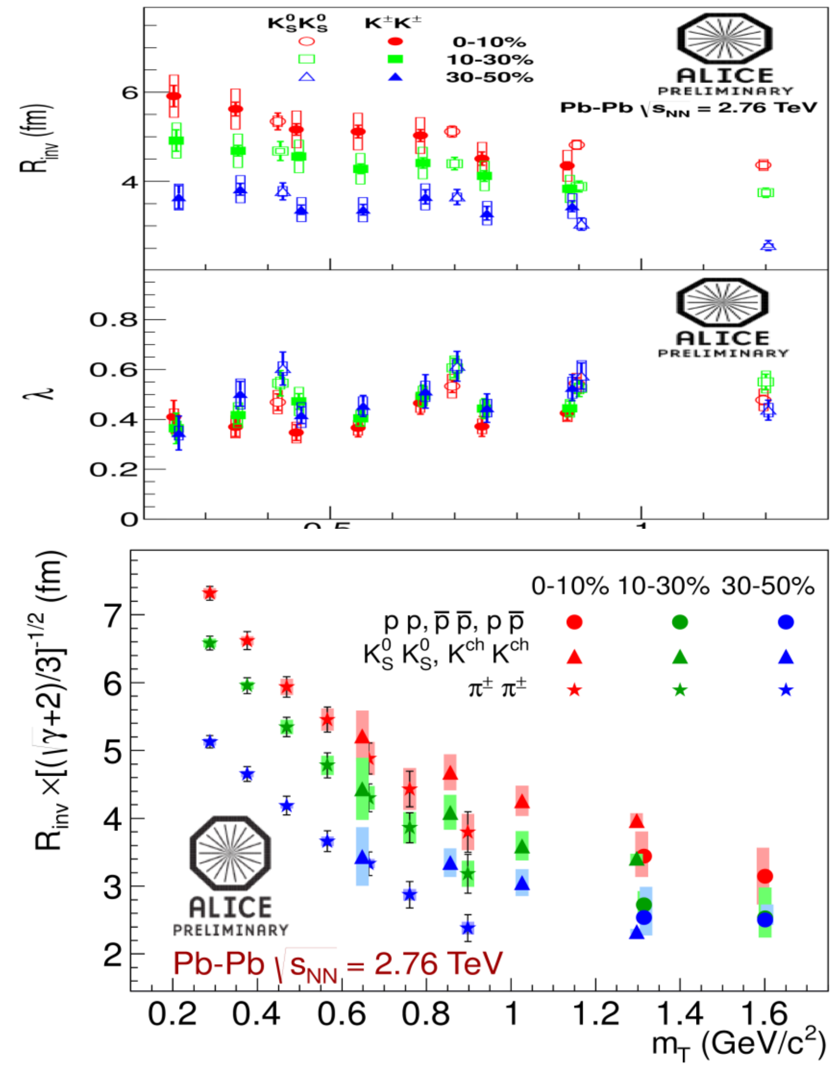
A.Kisiel@CERN

Phys. Lett. B 696 (2011) 328



Meson and baryon femtoscopy in heavy-ion collisions at ALICE

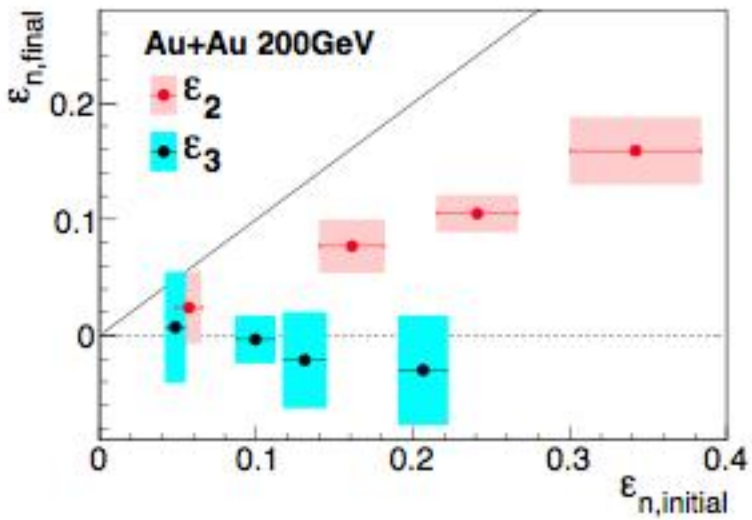
- Complete set of femtoscopic results (pions, kaons and protons)
  - Different sources of correlations: Quantum Statistics (QS), Coulomb and Strong Final State Interactions (FSI)
- m_T scaling for pions, kaons and protons observed with proper R_{inv} scaling (account for kinematics)
- Baryon-antibaryon correlations show significant annihilation which might be responsible for the decrease of proton yield at LHC energies

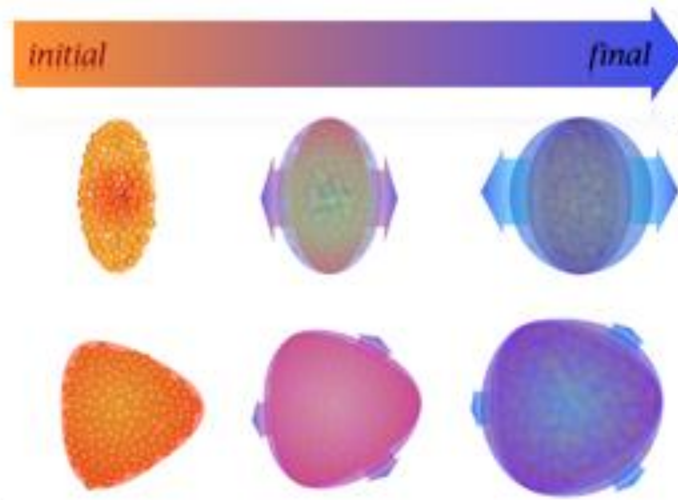


M.Szymański@QM'12

EVOLUTION WASHES OUT HIGHER HARMONIC ANISOTROPY

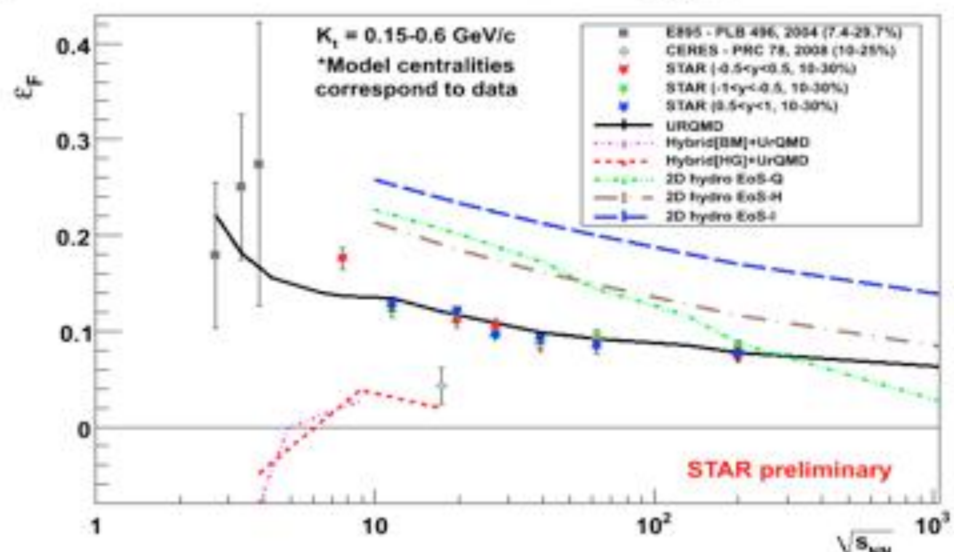
Azimuthal HBT





Talk of T. Niida: 1C

Excitation function for freeze-out eccentricity, ε_F



Excitation function of final eccentricity shows a monotonic behaviour

Talk of N. Shah: 1C

QM'12 summary talk "Global variables and correlations"

Femtoscopy of identified particles at STAR

- Proton femtoscopy
  - BES measurements shows source size increases with □sNN and for more central collisions
  - Measurement of homogeneity length for deuteron through coalescence agrees well with the proton femtoscopy measurements
- Systematic of nucleon-hyperon femtoscopy suggests strong baryon-strangeness correlations as compared to baryon-baryon correlations
- □-□ correlation
  - Attractive □□ interaction
  - Current fit from different potential models to data gives indication towards non-existence of bound H-dibaryon
- Azimuthal HBT
  - A monotonic decrease in the freeze-out eccentricity with increasing collision energy from 7.7 – 200 GeV
- □-K correlation
  - □-K emission asymmetry observed in Au+Au collisions at □sNN = 200 GeV

N.Shah@QM'12

PHENIX: Detailed HBT measurement with respect to event plane and collision energy in Au+Au collisions

- Azimuthal HBT radii w.r.t v_2 plane
  - Final eccentricity increases with increasing m_T, but not enough to explain the difference between π/K
    - Difference may indicate faster freeze-out of K due to less cross section
  - Relative amplitude of R_{out} in 0-20% doesn't depend on m_T
    - It may indicate the difference of emission duration between in-plane and out-of-plane
- Azimuthal HBT radii w.r.t v_3 plane
  - First measurement of final triangularity have been presented. It seems to vanish at freeze-out by expansion.
  - while Rout clearly has finite oscillation in most central collisions
    - It may indicate the difference of emission duration between $\Delta\varphi$=0°/60° direction
- Low energy in Au+Au collisions
  - No significant change between 200, 62 and 39 [GeV]
  - Volume is consistent with global trends

T.Niida@QM'12

Femtoscopy: Summary and outlook

- The long development of femtoscopic methods led to reliable measurement of "homogeneity sizes" for different collision systems
- These methods can be applied to any pair of (identified) particles taking into account different sources of correlations (e.g. annihilation in the FSI)
- They can be combined with the flow measurements to study in more details the source shape: azimuthal HBT
- Femtoscopy provides valuable data to the transport models and stimulates their development
- New results appear regularly

Anisotropic flow

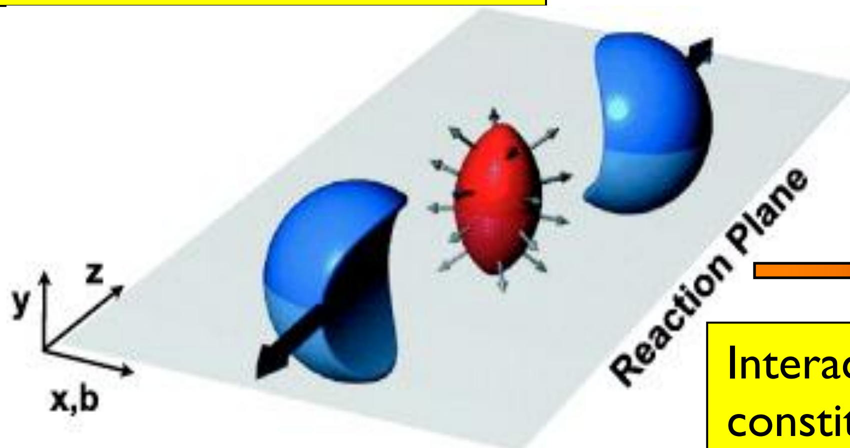
Physics motivation

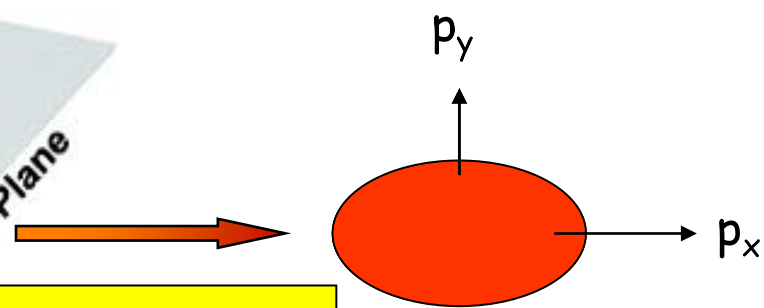
- Initial spatial eccentricity of the collision fireball

=> final momentum eccentricity

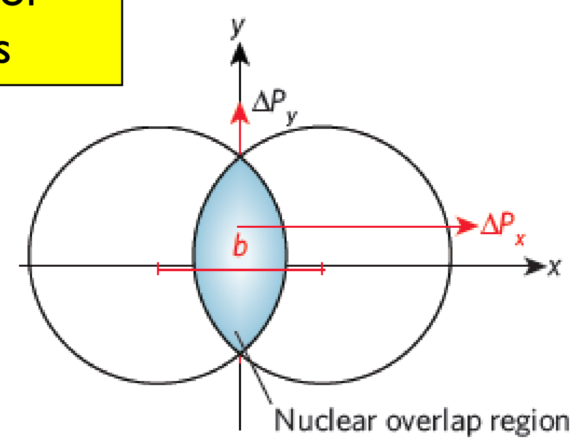
Initial spatial anisotropy

Final momentum anisotropy

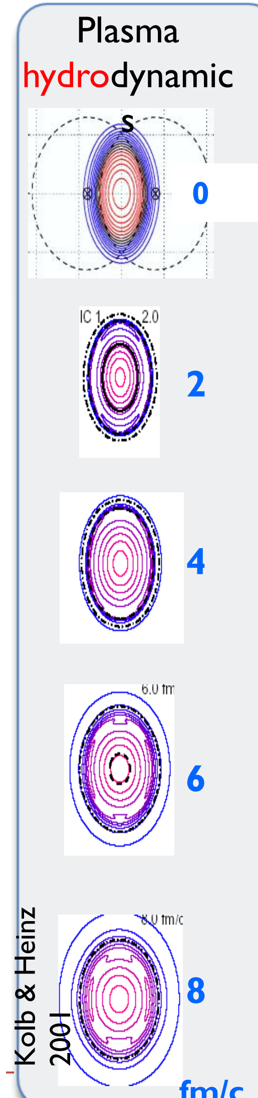




Interaction of constituents



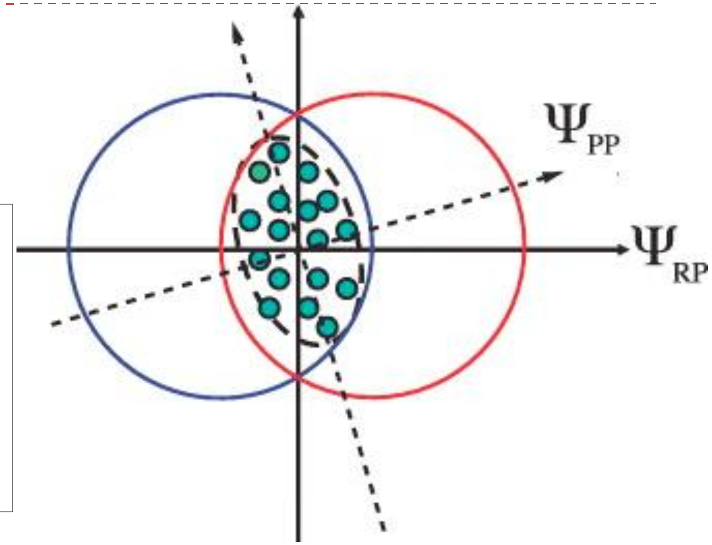
- Anisotropic pressure gradients drive particles in-plane
- Strong coupling + low specific viscosity => hydrodynamic flow



Peter.Hristov@cern.ch, PIC2012

Measurement: Event plane method

- Azimuthal distribution described by a Fourier expansion



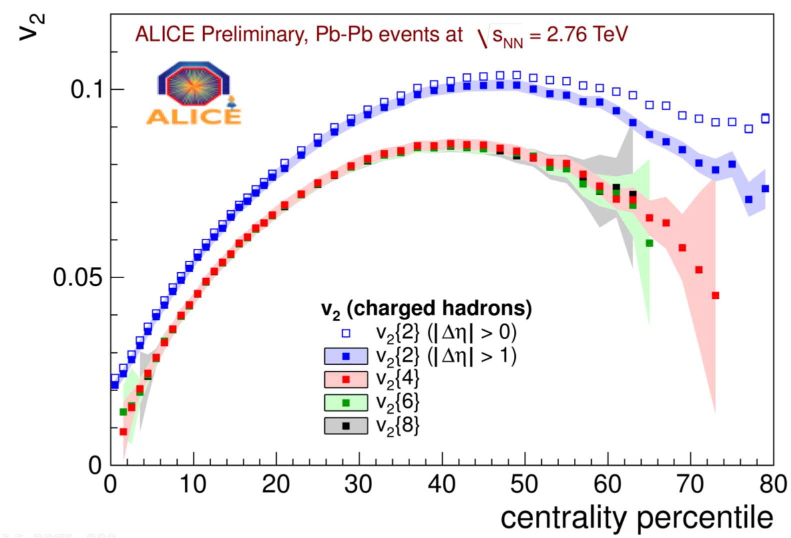
- Ψ^{RP} is the ideal reaction plane: averaging on all particles from one event
- Fluctuations: symmetry axes rotated from collision coordinates
- The n^{th} order event plane (of participants) is measured

C depends on the splitting to sub-events a,b;

Measurement: multi-particle cumulants

- No event plane measurement required
- 2-particle and 4-particle cumulants (average over all particles within an event, then average over all events)

- Different sensitivity to fluctuations and non-flow

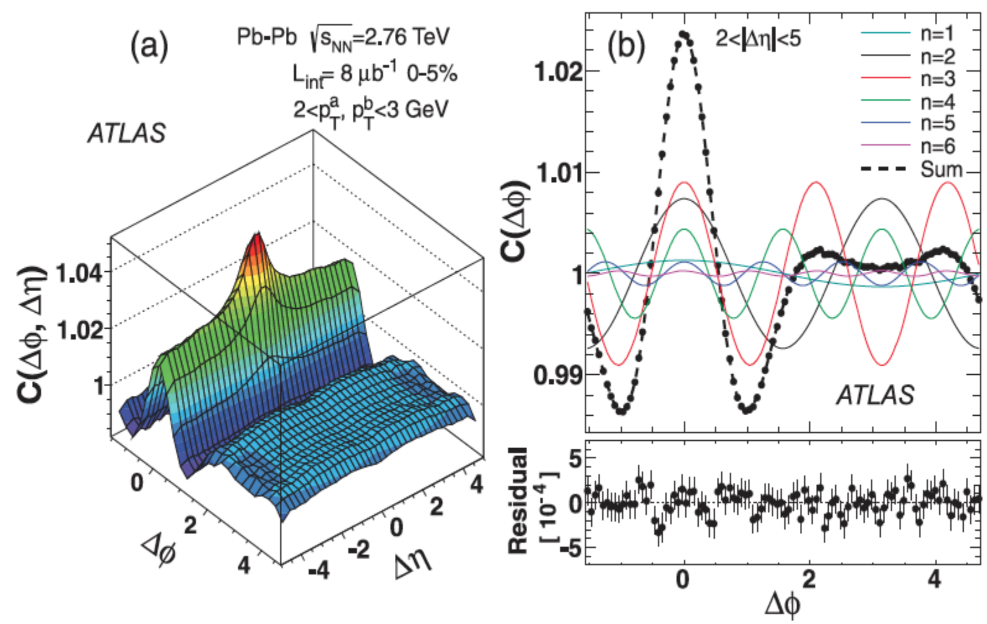


A.Adare@APS'12

Measurement: Fourier decomposition

- Extract harmonics from 2-particle correlation function
- Suppress the non-flow (peak at 0,0 from jets, resonances, etc) excluding $\Delta\eta$region
- Harmonic amplitude ≡ $v_{n\Delta}$ (ALICE, CMS) a.k.a. $v_{n,n}$ (ATLAS)
- Discrete Fourier transformation and calculation of v_n

PRC 86(2012)014907



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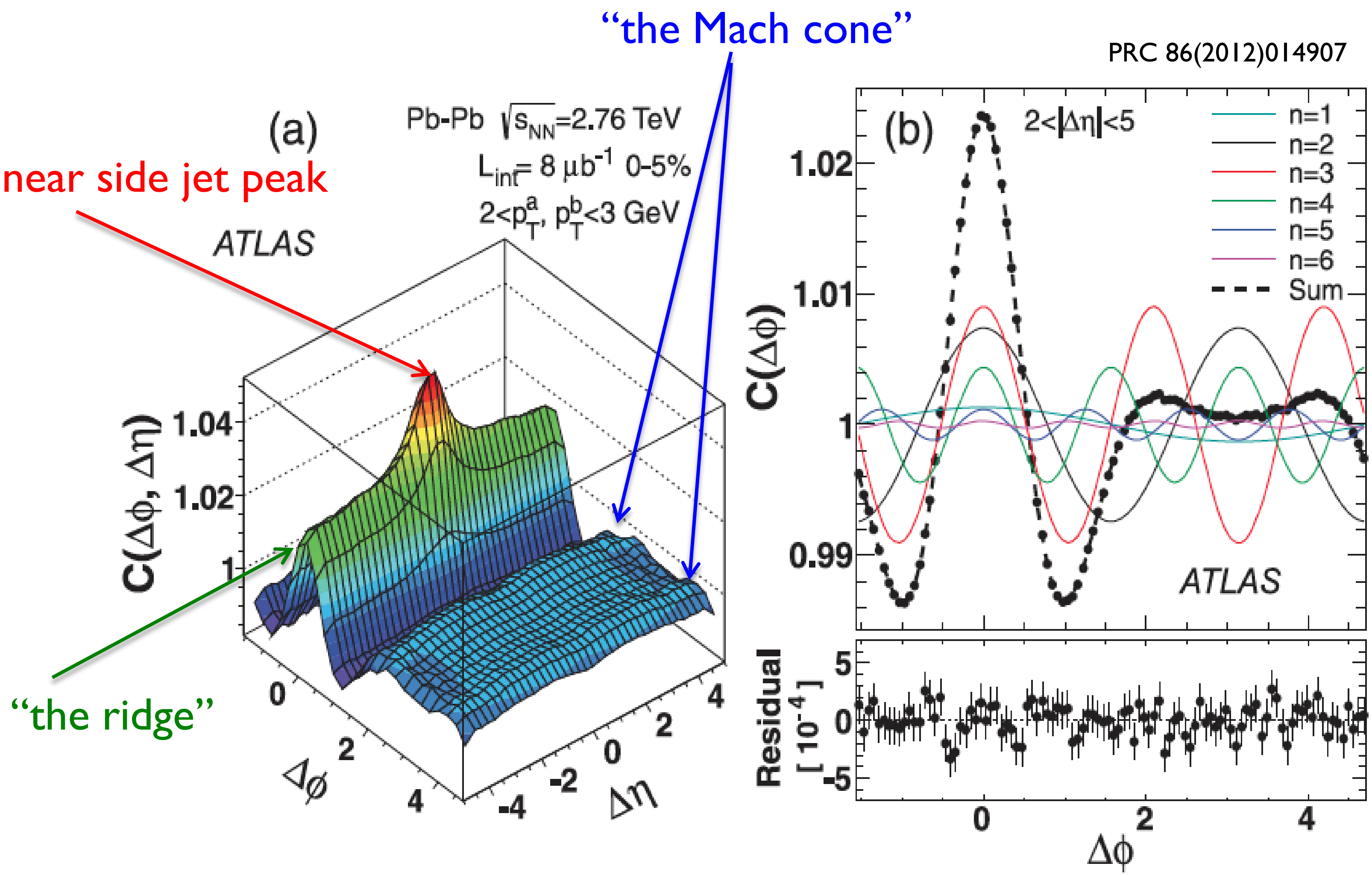


Two particle azimuthal correlations can be described efficiently with the first 6 v_n coefficients and naturally explain the so called ridge and Mach cone structure first observed at RHIC which were thought to be due to jet induced medium modifications.

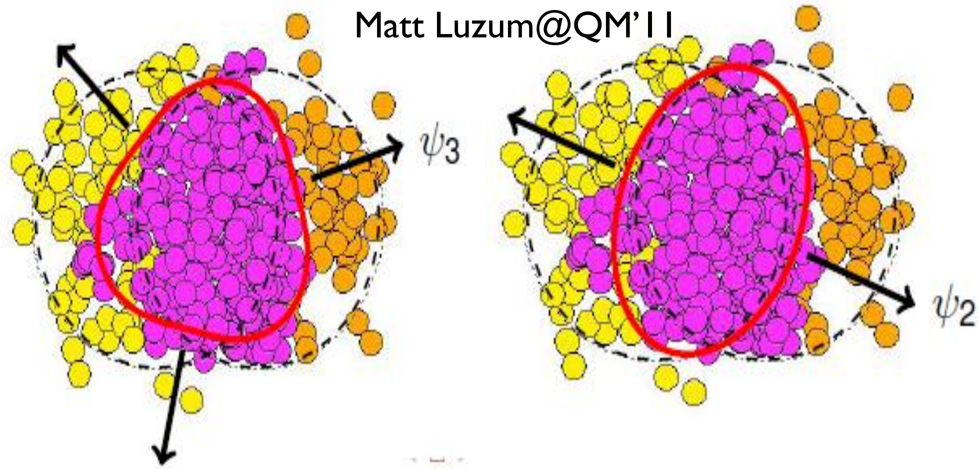
R.Snellings@ICPF'12

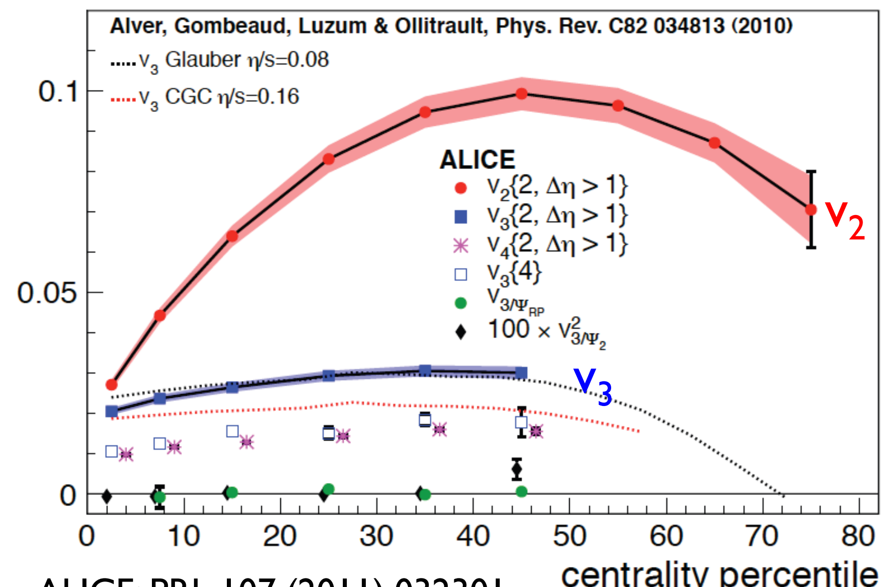
Initial state fluctuations => v_3

- "ideal" shape of participants' overlap is ~ elliptic
  - in particular: no odd harmonics expected
  - participants' plane coincides with event plane
- fluctuations in initial conditions:
  - participants plane ≠ event plane
  - → v_3 ("triangular") harmonic appears

  [B Alver & G Roland, PRC81 (2010)054905]
- v_3 has weaker centrality dependence than v_2
- when calculated wrt participants plane, v_3 vanishes
  - as expected, if due to fluctuations…

Matt Luzum@QM'11

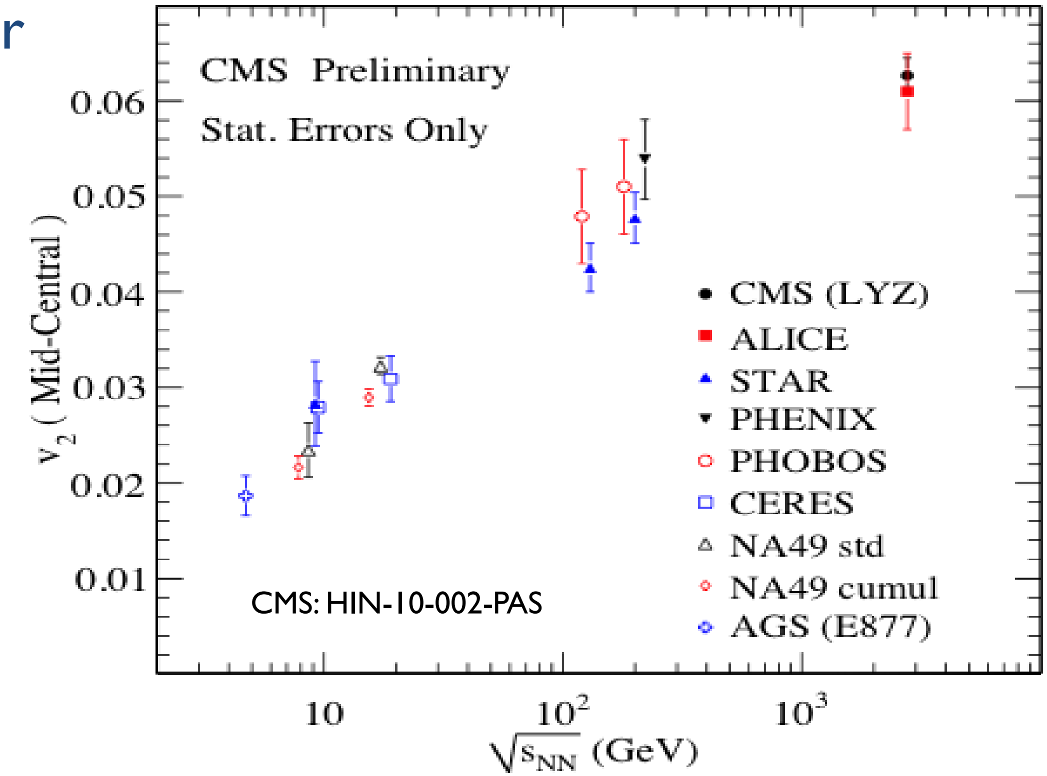




ALICE: PRL 107 (2011) 032301

v_2 vs. collision energy

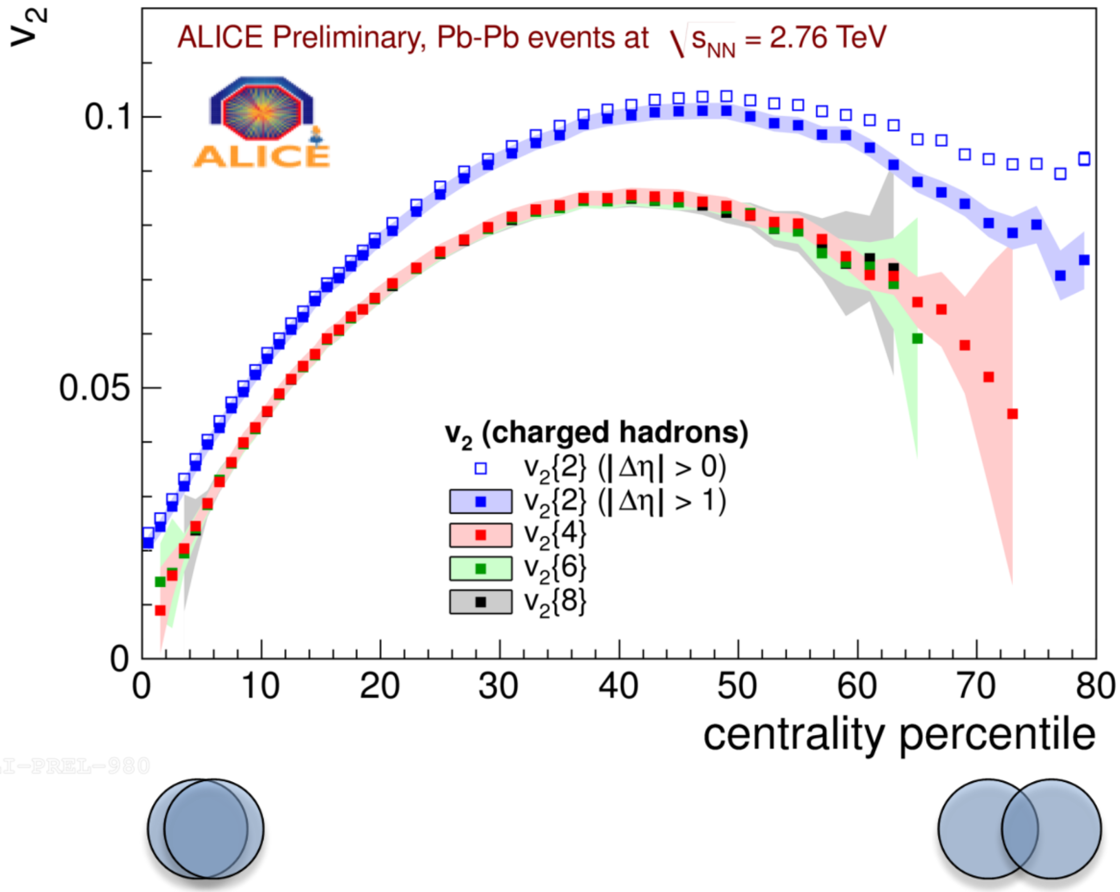
- 20-30% most central collisions
- Good agreement between CMS and ALICE
- Hydro behavior follows extrapolated RHIC trend
  - Flow is 30% higher than at RHIC
  - Expected: larger radial flow velocity => higher <p_T>



A.Adare@APS'12

v_2 vs. centrality

- Sharp rise from central to mid-central collisions
  - reflects increasing eccentricity
- Declines in most peripheral events
  - weaker pressure from smaller system
- Large difference between 2- and 4-particle cumulants
  - Quantifies fluctuations



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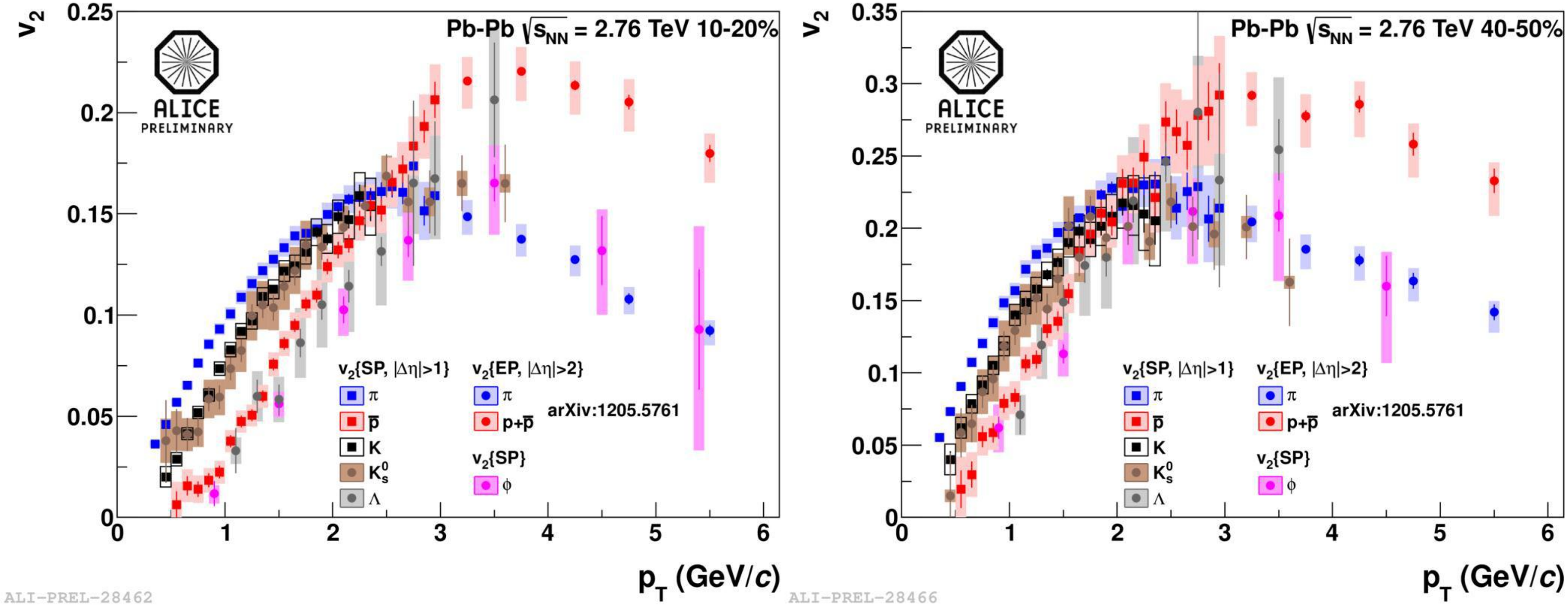
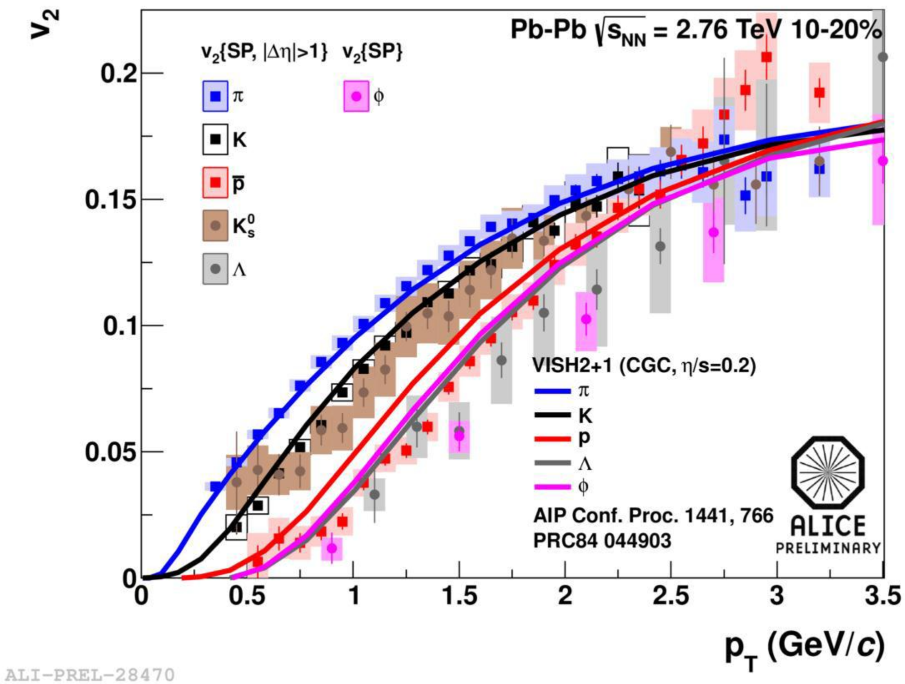
v_2 of identified particles

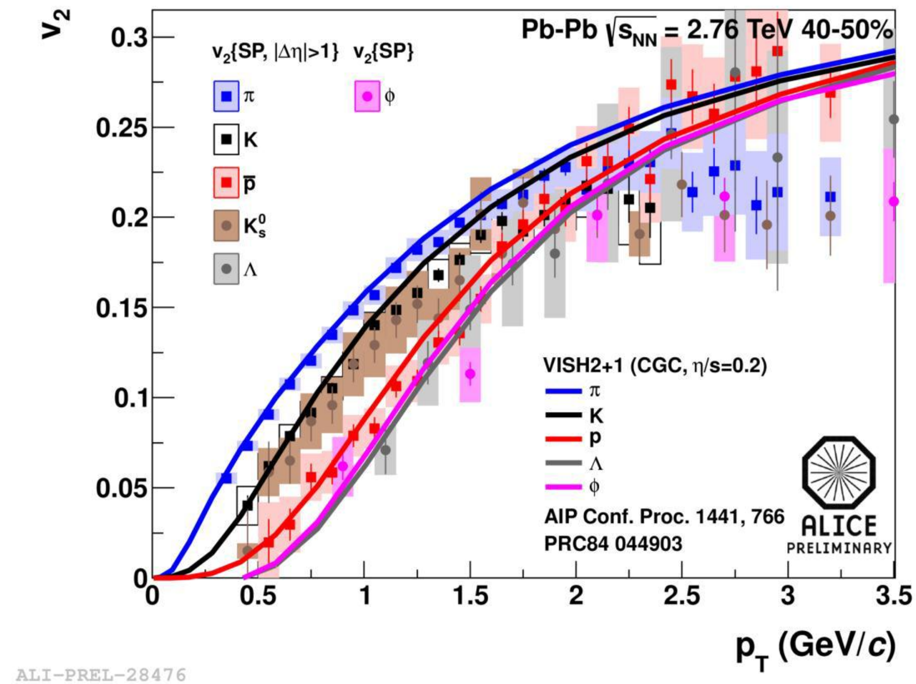


- v_2 is measured for a number of particles with light and strange quark content: □, K, p/pbar, K0s, □, □, □ and □
- Evident mass hierarchy at low and high p_T which changes with the collision centrality

F.Noferini@QM'12

Identified particle v_2 vs. hydro





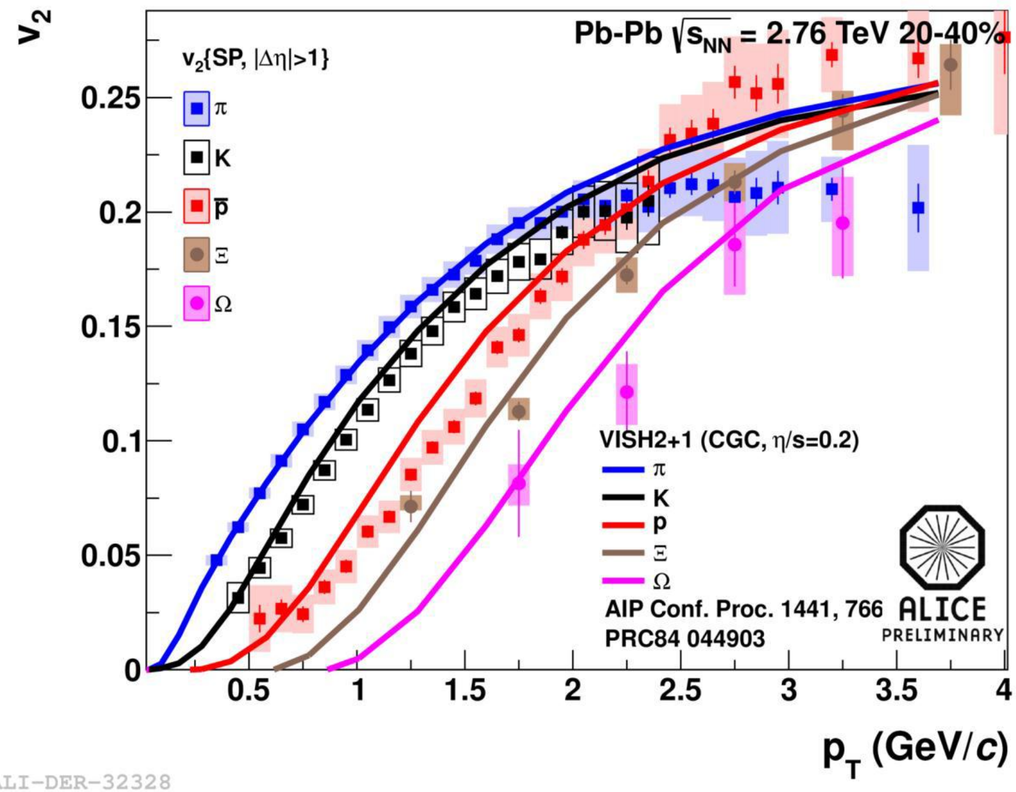
Viscous hydrodynamic model calculations reproduce the main features of v2 at p_T:

- mass dependence is better modeled for peripheral collisions
- for central collisions overestimate proton flow
- Adding hadronic rescattering phase improves the agreement with data

Heinz, Shen, Song, AIP Conf. Proc. 1441, 766 (2012)

F.Noferini@QM'12

□ and □ flow vs. hydro



- Hydrodynamic model calculations reproduce larger boost towards higher p_T for □ and □

(Heinz, Shen, Song, AIP Conf. Proc. 1441, 766 (2012); PRC84 044903

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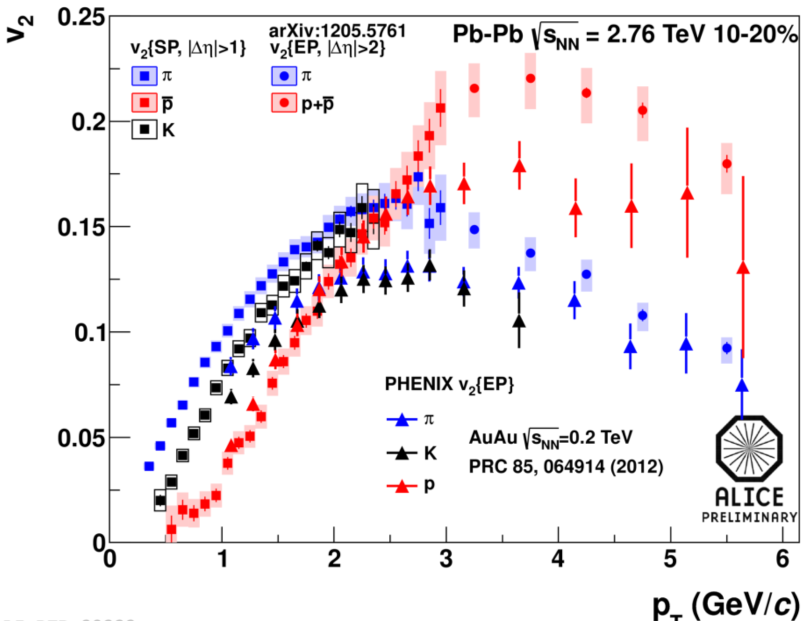
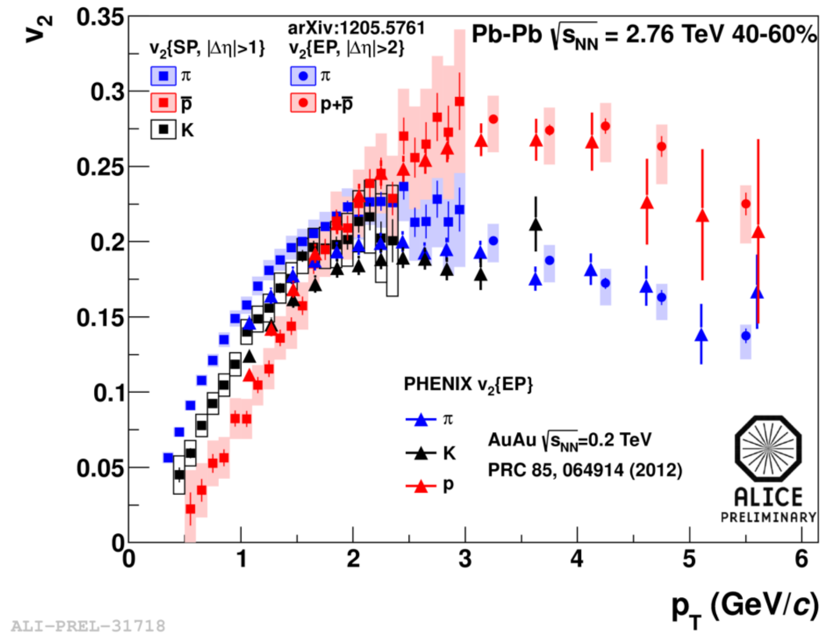
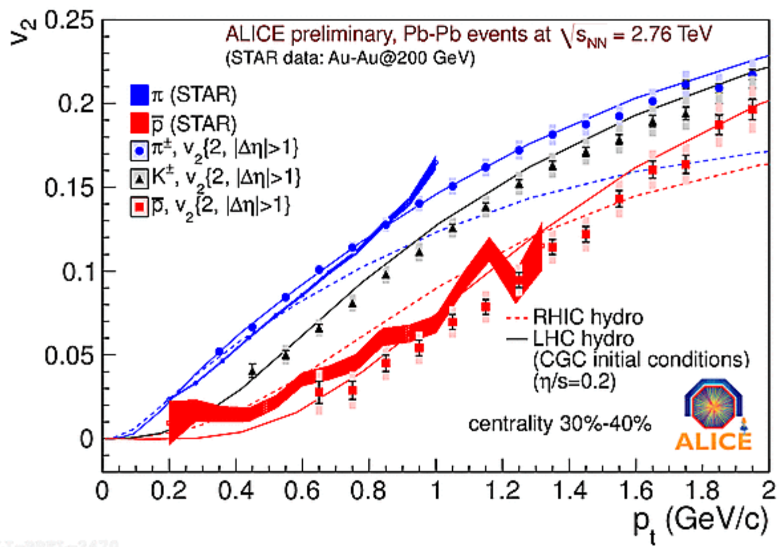
v_2 of π, K, p at LHC vs. RHIC



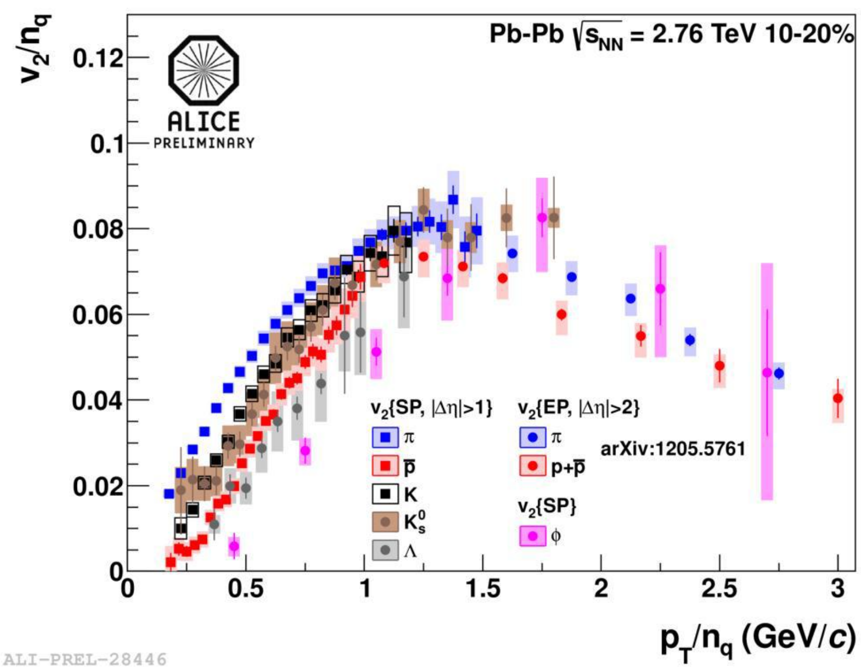


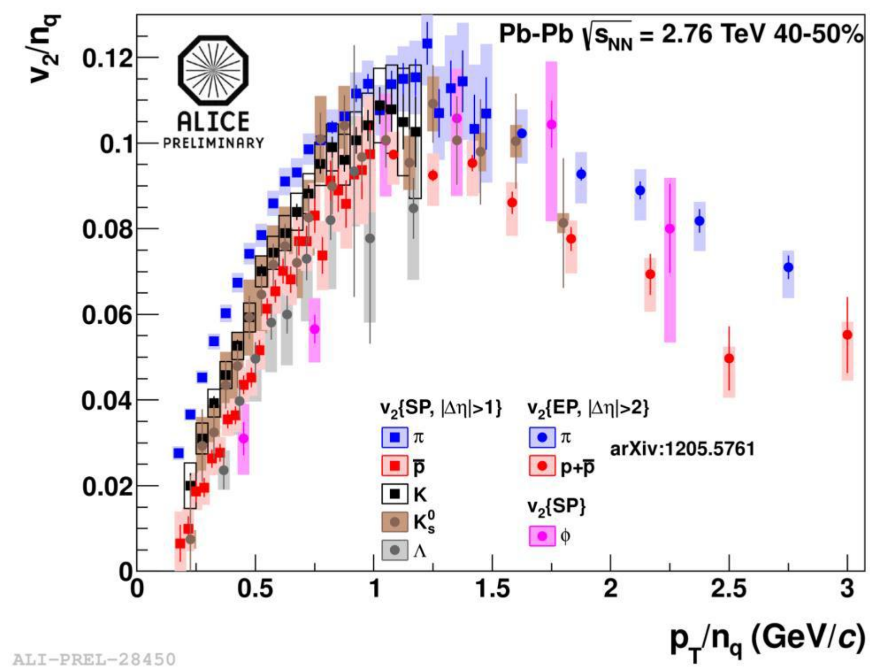


- v_2 measured at the LHC is slightly above the RHIC v2 for pions and kaons
- v_2 of (anti-)protons reflects effect of larger radial flow at LHC

F.Noferini@QM'12

Number of Constituent Quarks (NCQ) scaling of v_2

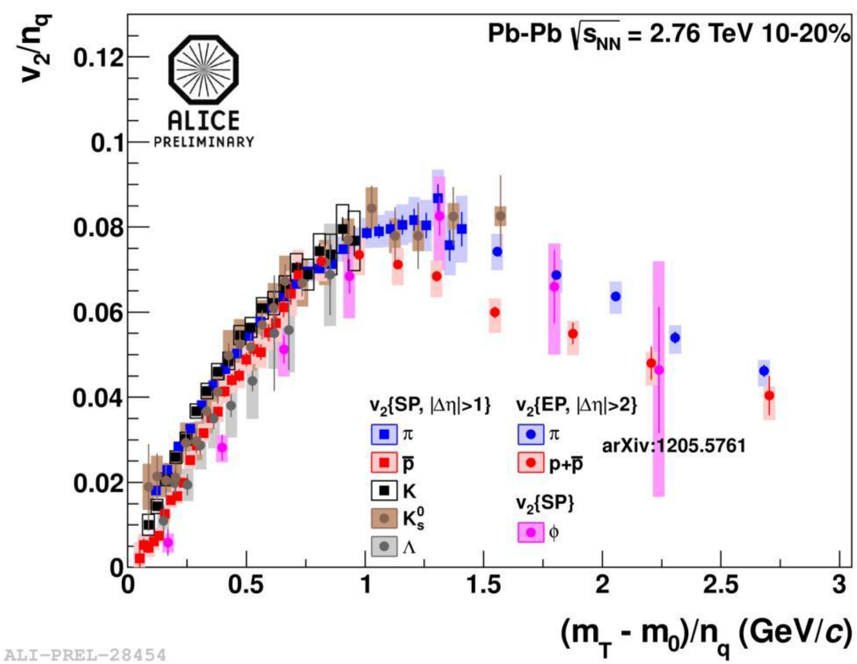


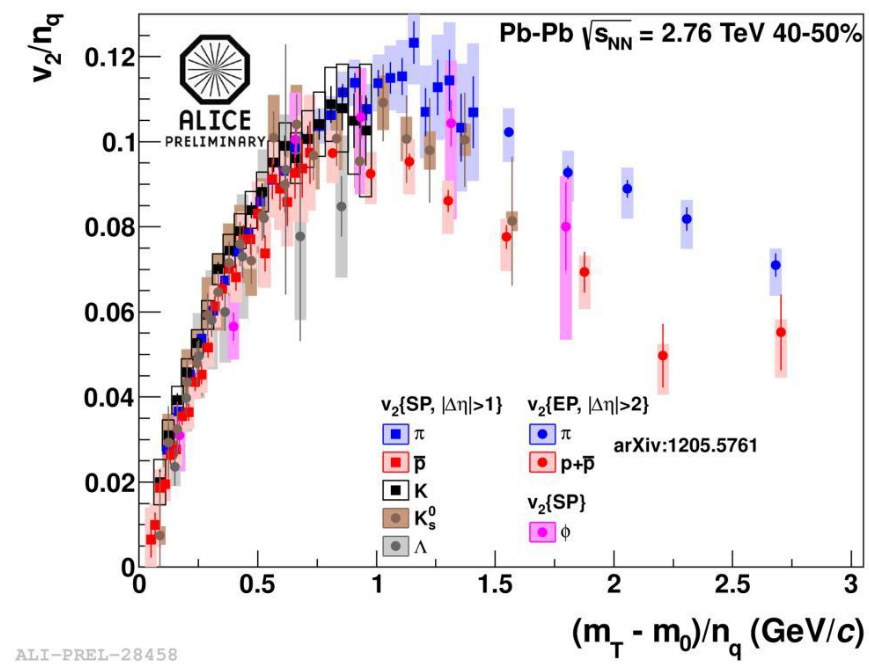


- v_2 measured in the p_T region of 3-6 GeV/c can be used to test the model of the hardon production via quark coalescence
- v_2/n_q vs. p_T/n_q (n_q is the number of quarks per meson/baryon) shows that if such scaling exists it is only approximate (holds within 20%)

F.Noferini@QM'12

NCQ scaling of v2 vs. transverse kinetic energy

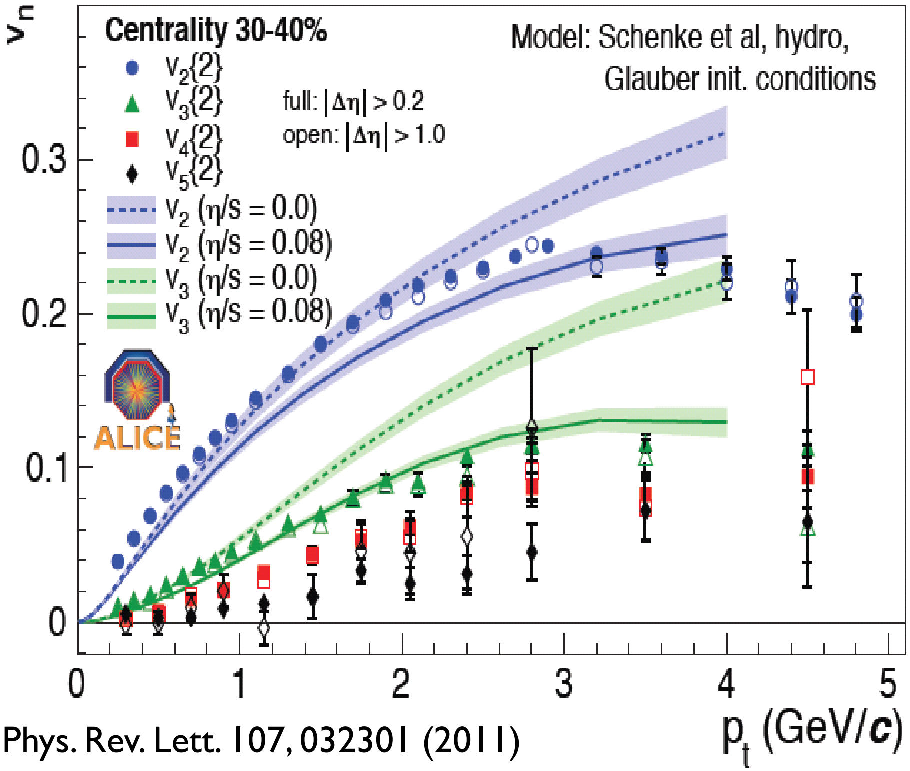




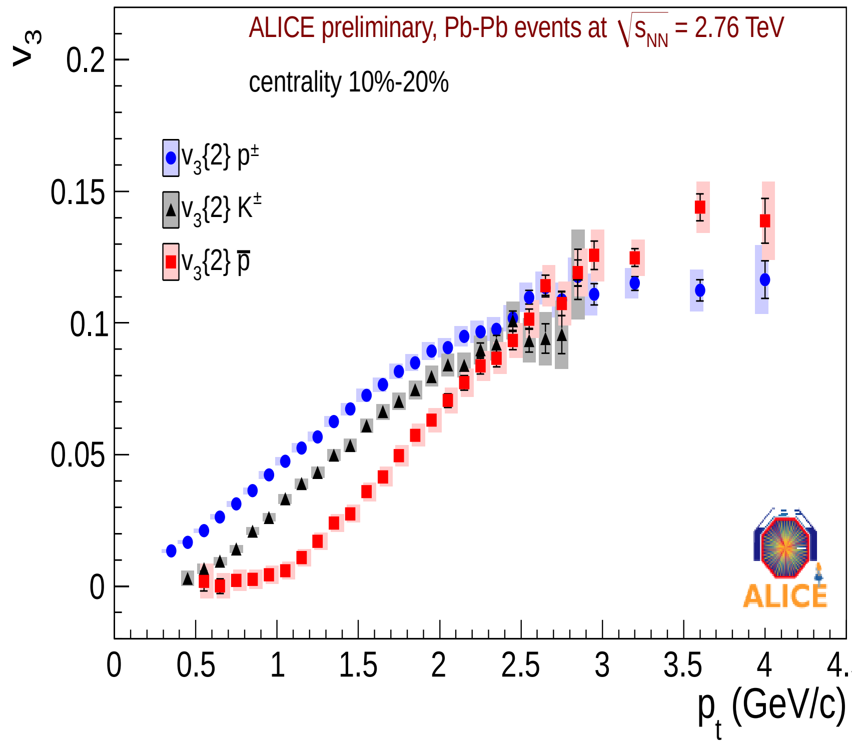
- For low p_T: v_2/n_q together with KE_T scaling is violated at LHC
- For KE_T/n_q > 1 GeV/c antiproton's v_2 is lower than that of pions
- NCQ scaling maybe violated also for heavier particles, including the □-meson

F.Noferini@QM'12

Triangular flow: results



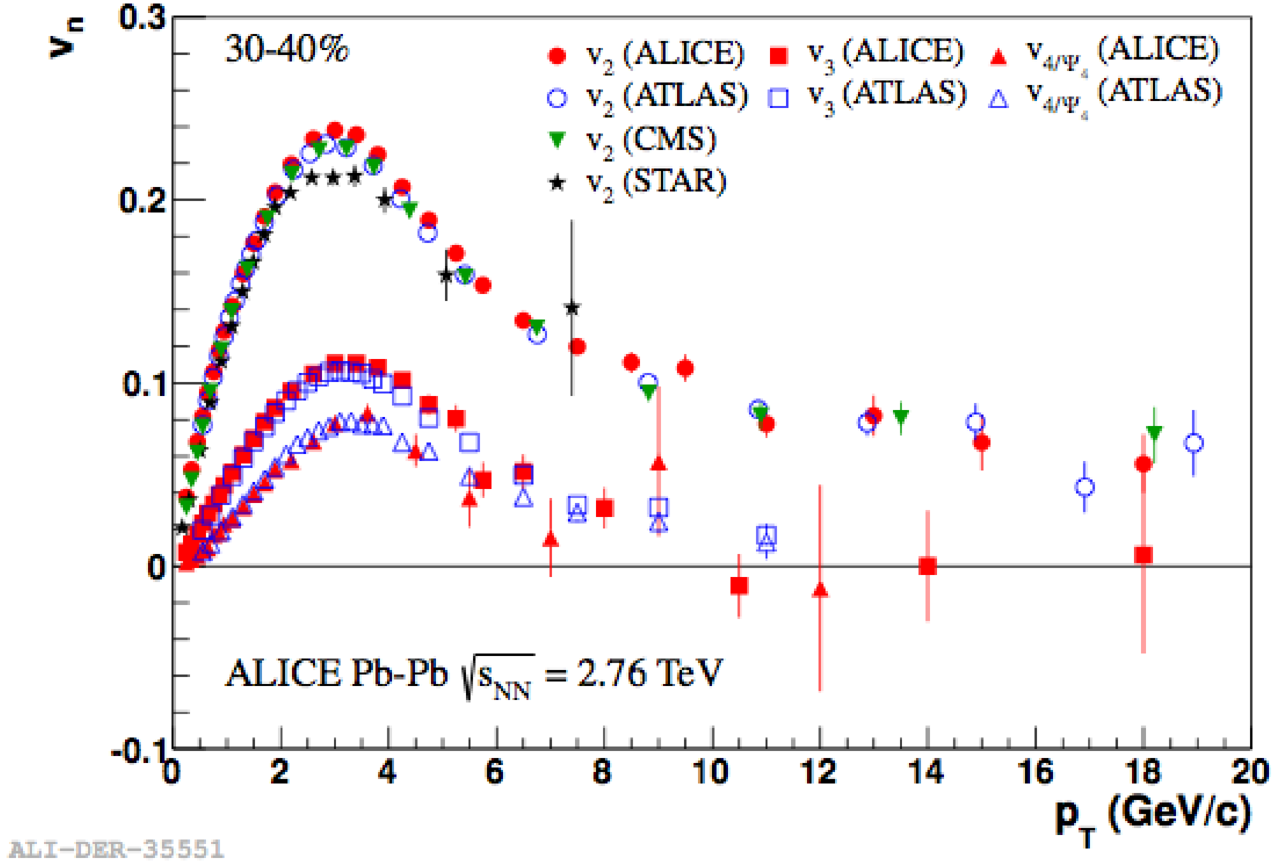
Phys. Rev. Lett. 107, 032301 (2011)



- Models can not describe successfully the elliptic and triangular flow with the same values of η/s (shear viscosity/entropy density)
- Similar mass splitting expected by hydro

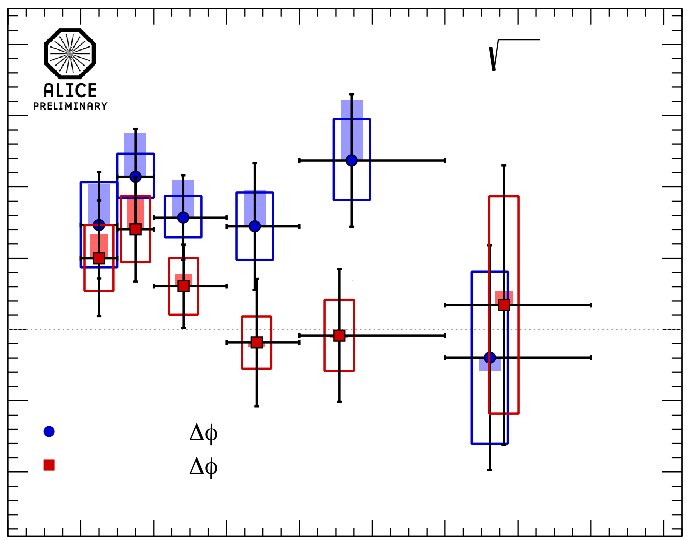
P.Christakoglou@ICPF'12

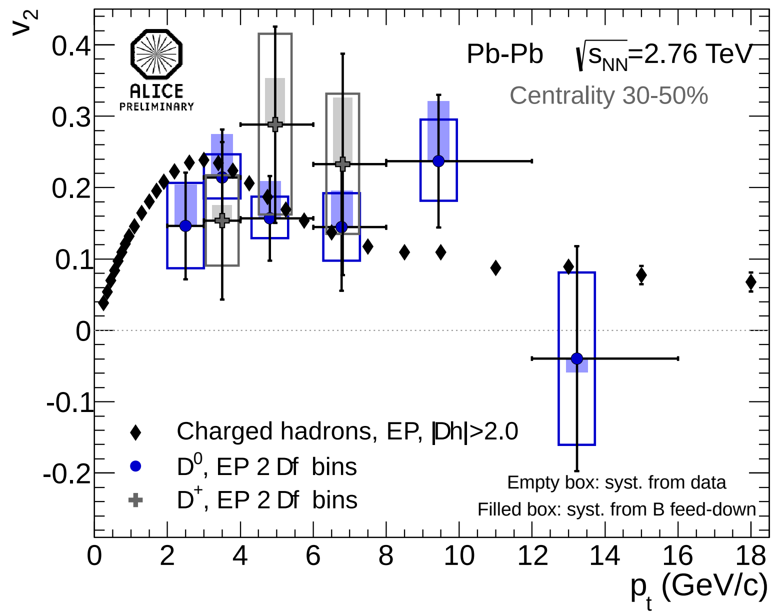
v_n vs. p_T



- Good agreement between the experiments
- From flow anisotropy at low p_T to anisotropic quenching at high p_T

Heavy flavor elliptic flow





- Elliptic flow measured with the event plane method at two centralities
- First indication of a non-vanishing v_2 for D^0
- Elliptic flow values compatible with the charged hadrons within the large uncertainties.

P.Christakoglou@ICPF'12

Future directions

Can we probe hydrodynamic flow at the partonic level?

What is the nature of the initial state?

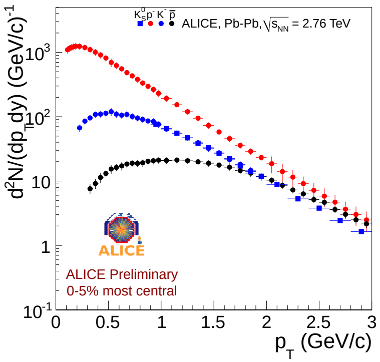
What are the state properties of the QGP (sound speed, η/s, …)

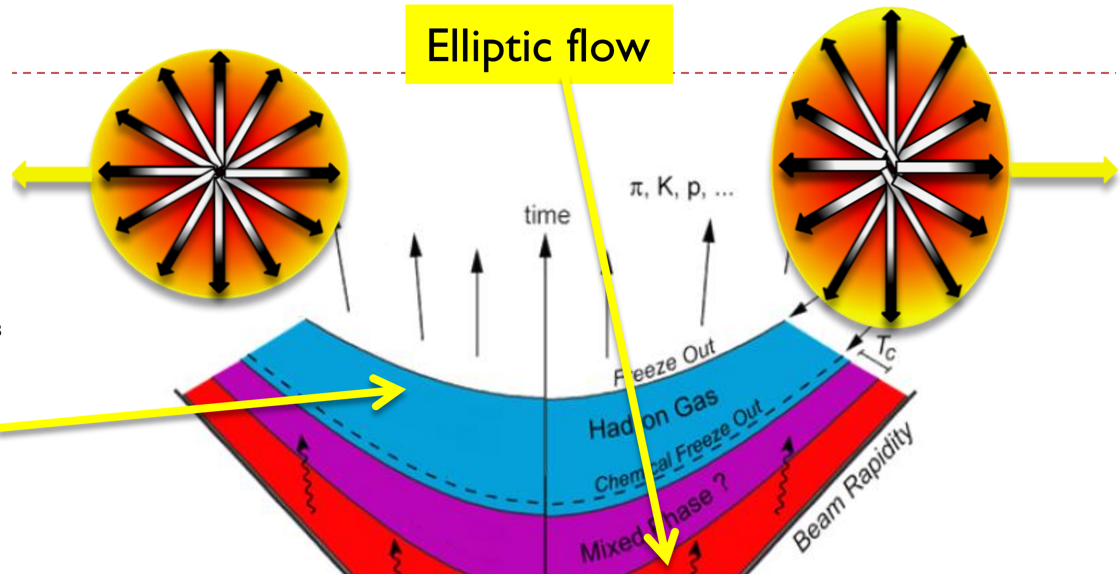
How does hadronization occur?

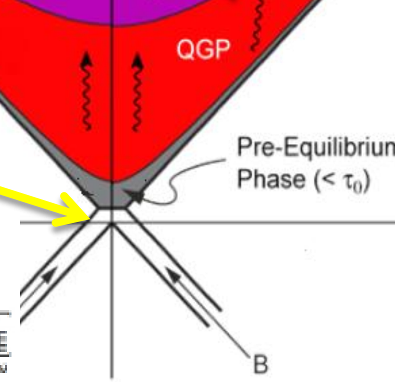
- Experimental:
  - Joint-harmonic observables (e.g. PRC 84, 034910 (2011))
  - PID at high p_T <--constituent quark scaling violation?
  - Prompt photons (both thermal and hard QCD γs)
  - Heavy flavor
  - v_n of fully reconstructed jets
- Theoretical: enormous recent progress.
- Given the recent bounty of data, much catching up to do!
  - v_n for higher harmonics (n > 3)
  - models predicting suppression (R_{AA}) and v_n simultaneously (especially for heavy quarks)
  - Full evolution: initial state, hydro, freeze-out/hadronization matching data

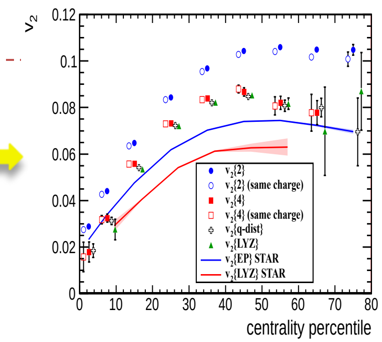
A.Adare@APS'12

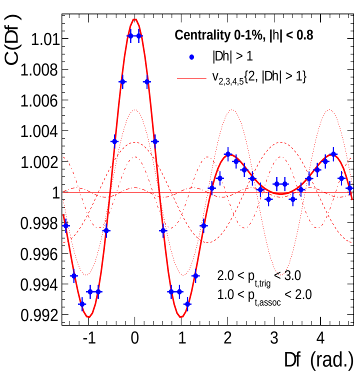
Instead of summary

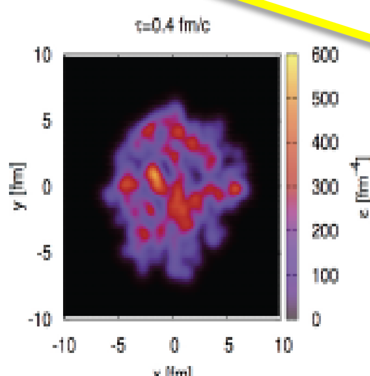












The studies of anisotropic flow:

- provide strong constrains on the bulk properties described by the hydrodynamic models
- led to new paradigm of QGP as the so called perfect liquid
- quantify the fluctuations of the initial state eccentricity (geometry) and further constrained η/s and initial conditions