Pion femtoscopy at the LHC in p+p collisions at √s=0.9 and 7 TeV and Pb+Pb collisions at 2.76 ATeV

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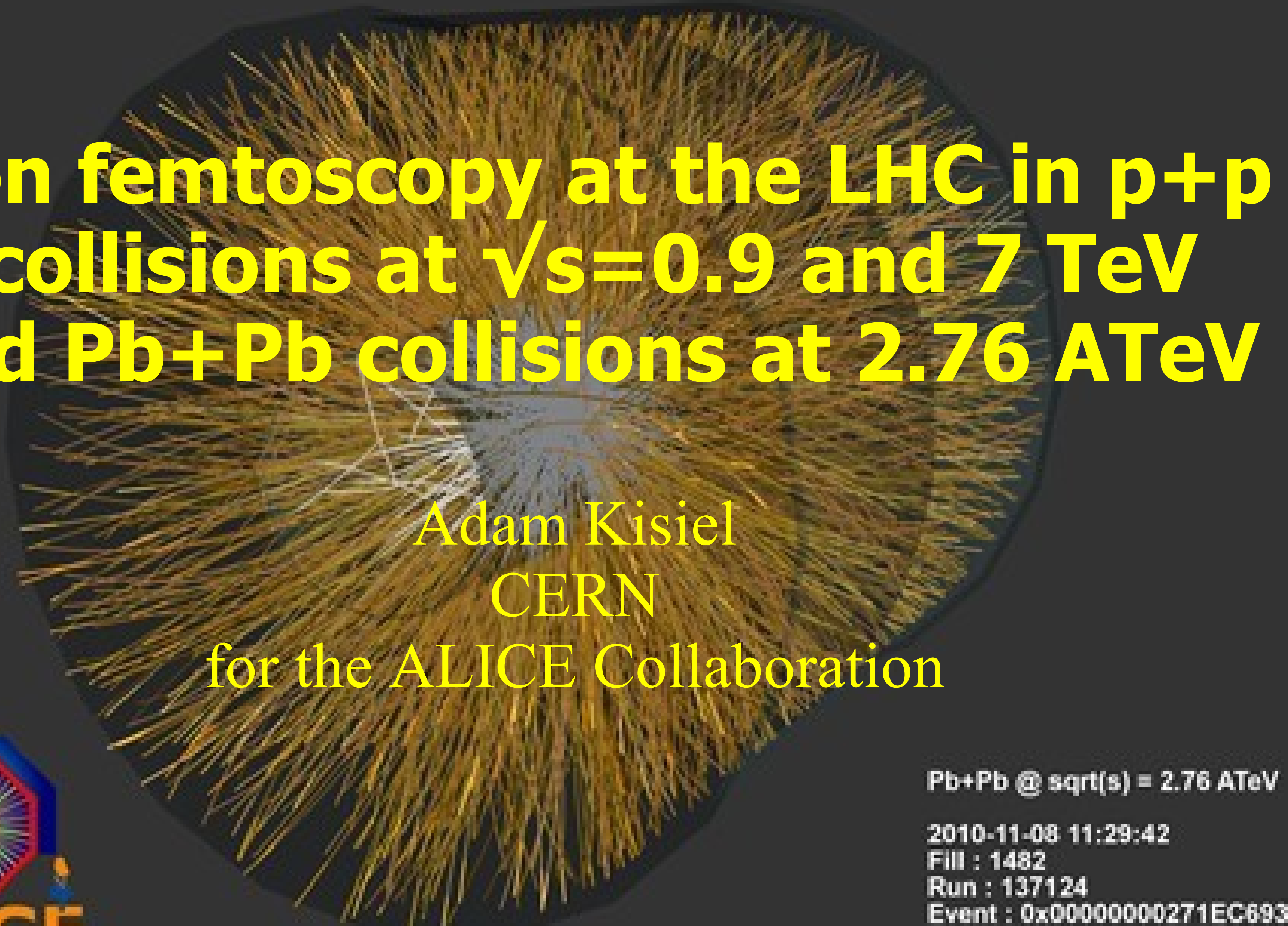
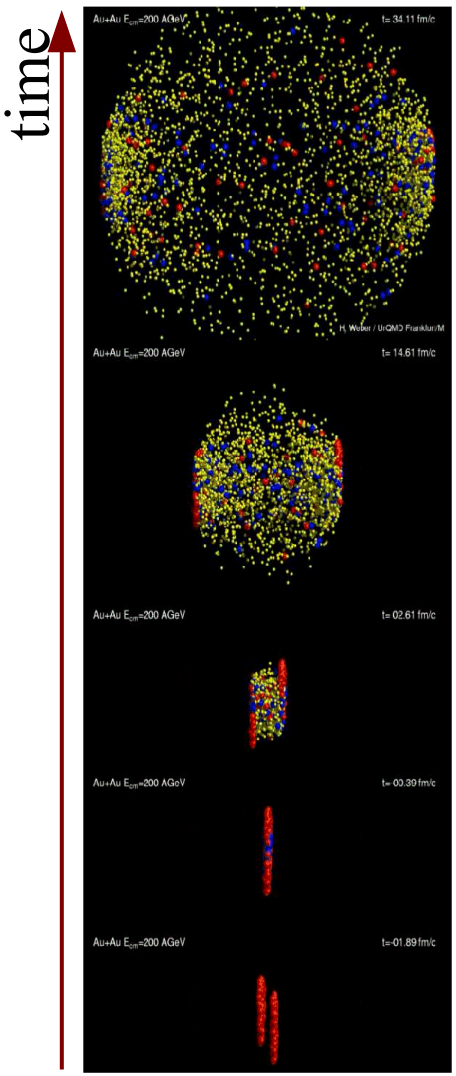
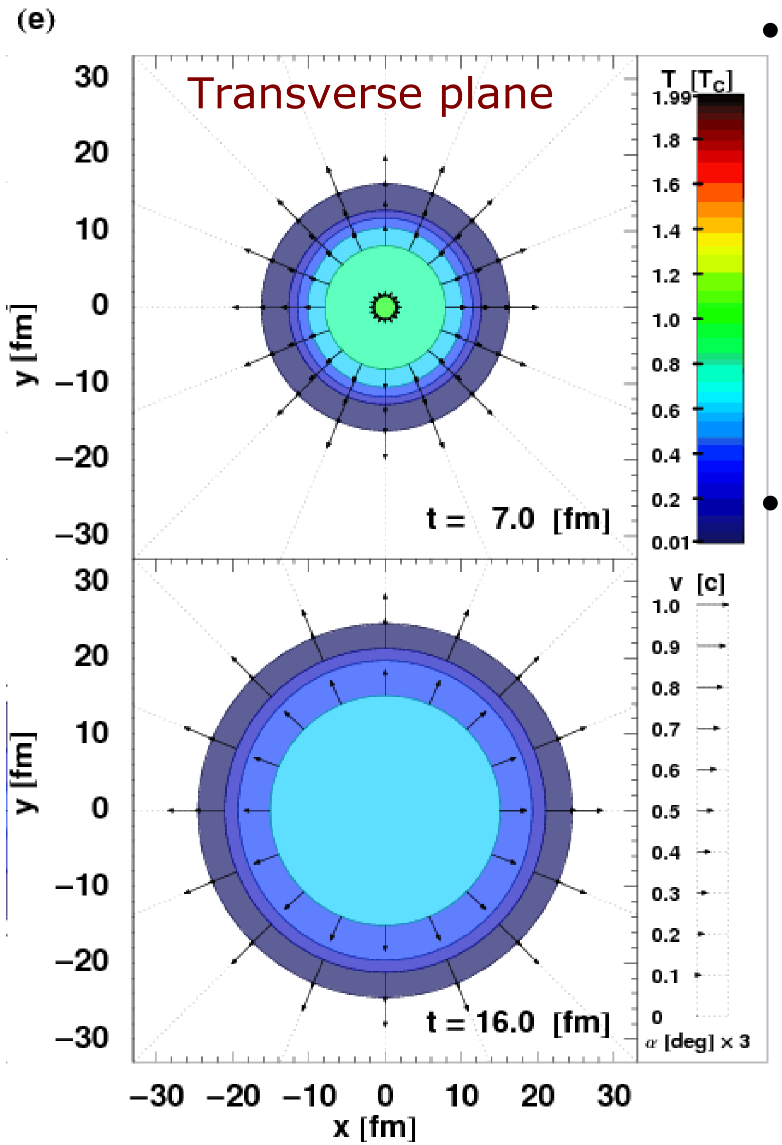


Outline

- Physics motivation:
  - Femtoscopy: measuring the size of the hadron collision
  - Lessons from RHIC: k_{T} dependence of the 3D radii as a signature of collective flow
  - How is p+p different from A+A?
- ALICE experiment
  - Data taking conditions
  - Event sample characteristics
- Results
  - Identifying scaling variables for the system size
  - Triply-differential analysis of the system sizes
  - Testing the multiplicity scaling of the radii
  - Comparing p+p and A+A results
- First results from the Pb+Pb run of the LHC

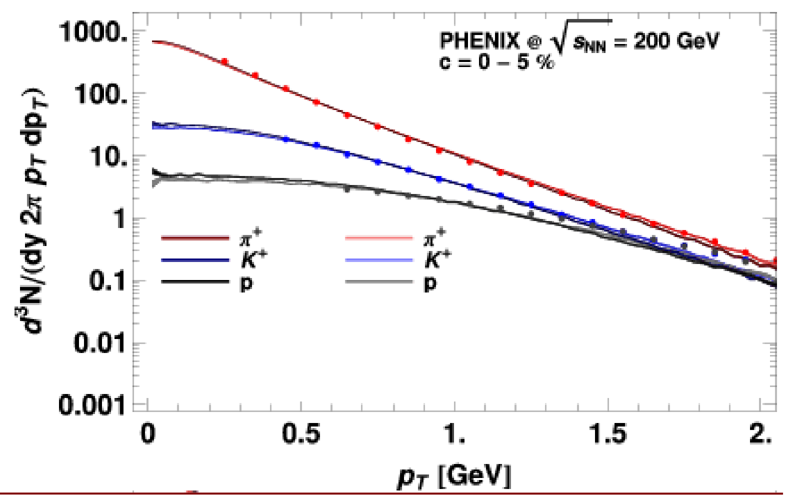
Heavy Ion collision evolution at RHIC



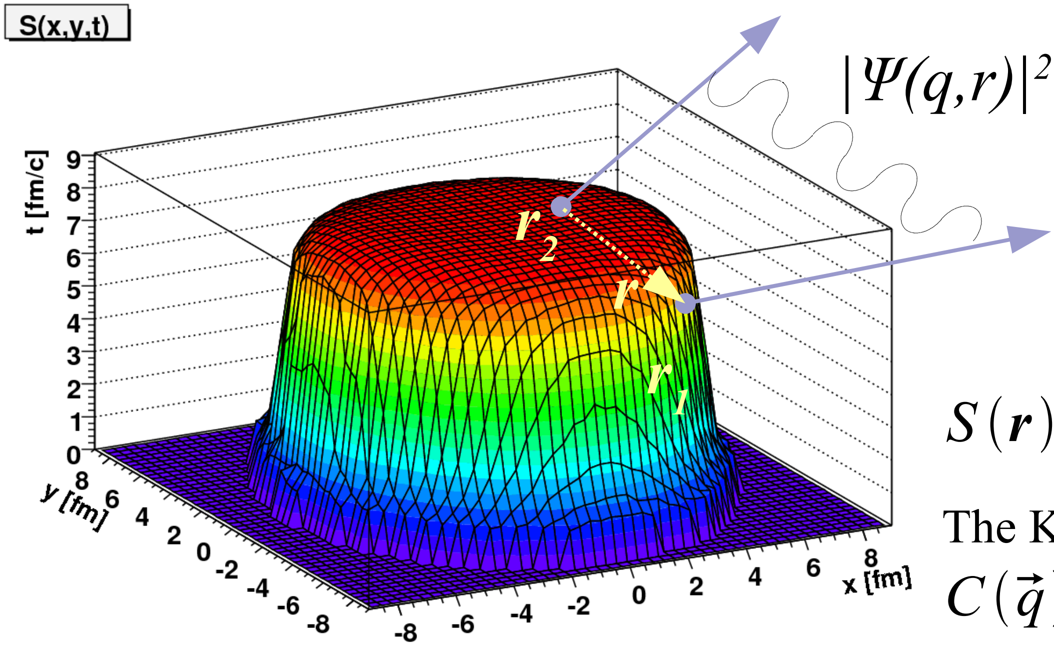


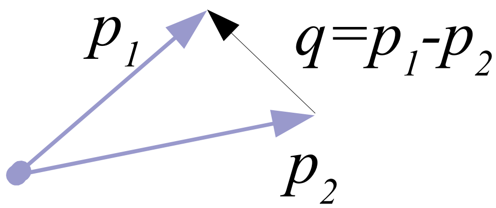
M. Chojnacki, W. Florkowski, PRC 74 (2006) 034905

- HIC is expected to go through a Quark Gluon Plasma phase, where matter is strongly interacting – resulting in the development of collective motion
- Radial flow dominates, with elliptic flow as azimuthal modification



Measuring space-time extent: femtoscopy





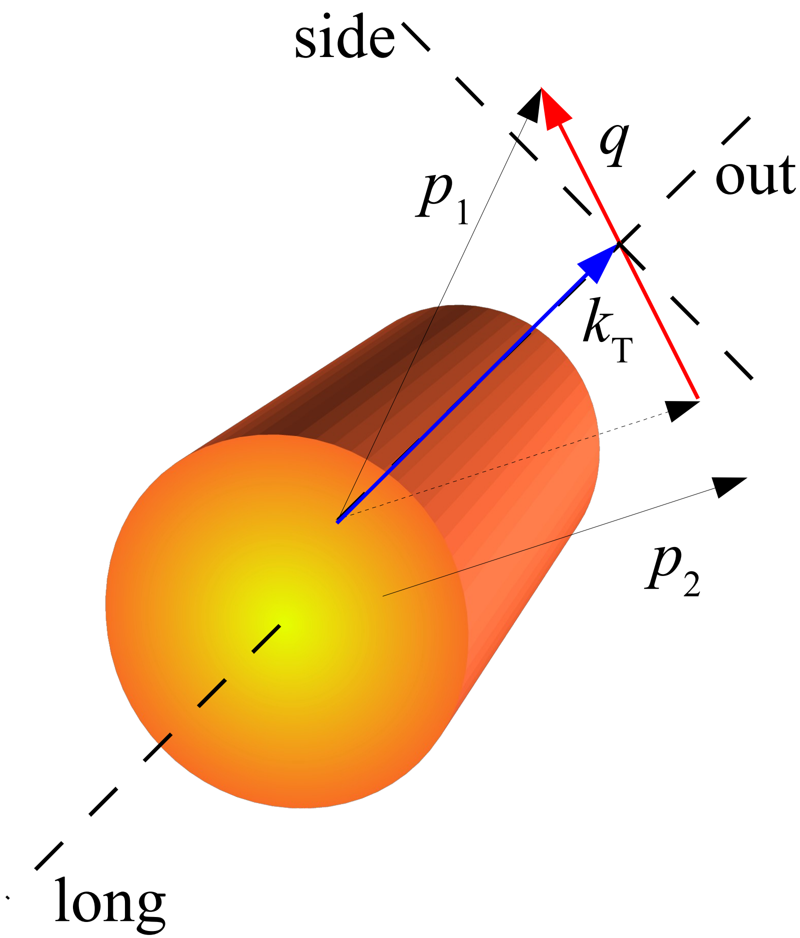
$$S(\boldsymbol{r})=\int S_a(\boldsymbol{r_1})S_b(\boldsymbol{r_2})\delta(\boldsymbol{r}-(\boldsymbol{r_1}-\boldsymbol{r_2}))d^4r_1d^4r_2$$

The Koonin-Pratt Equation:

$$C(\vec{q})=\int S(\boldsymbol{r})|\Psi(\vec{q},\boldsymbol{r})|^2d^4r$$

Femtoscopy uses the correlation between two particles, reflected in the pair wave function Ψ. It comes from a combination of the quantum statistics (anti-)symmetrization, Coulomb and strong interactions. Using the Koonin-Pratt equation, one tries to learn as much as possible about the source (i.e. the source emission function S), from the measured correlation C.

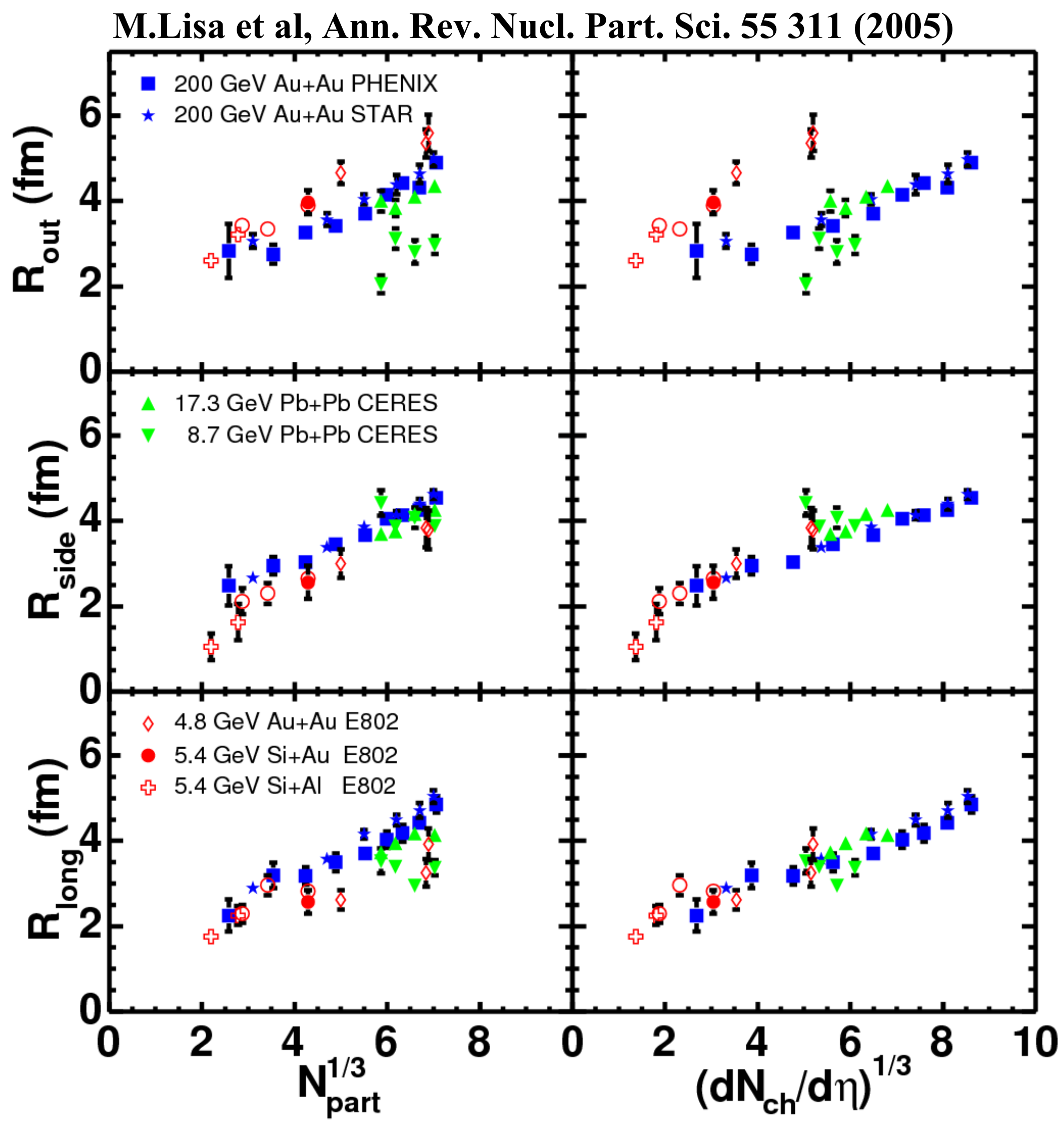
Directions and reference frames



$$m_T = \sqrt{k_T^2 + m_\pi^2}$$

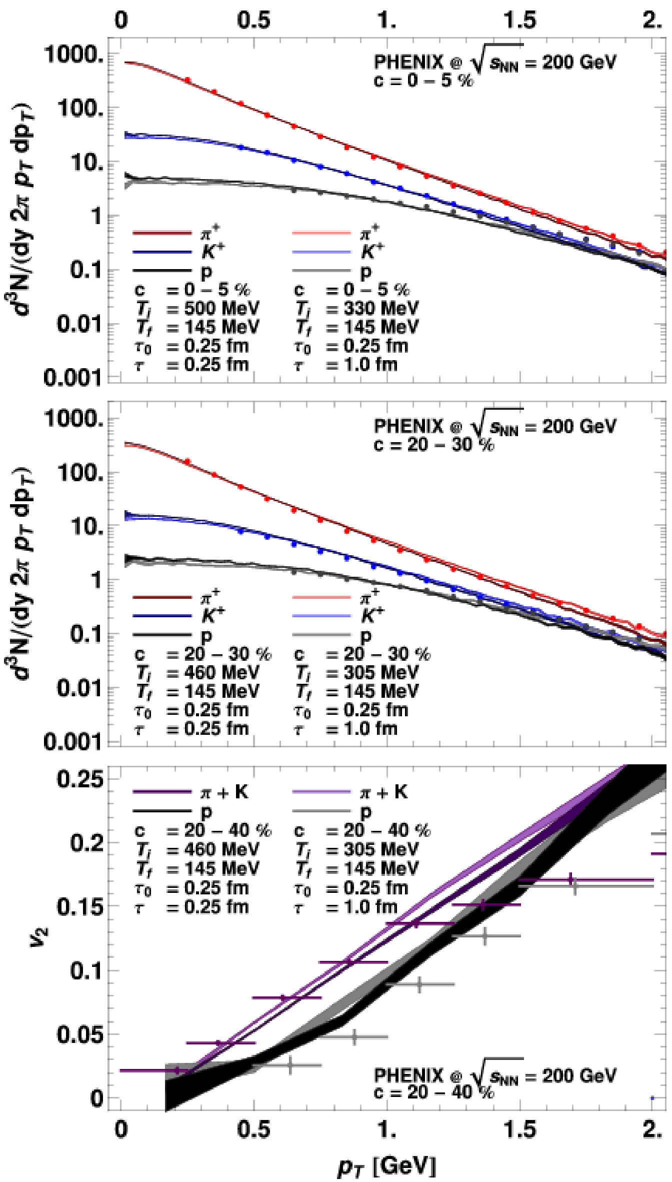
- The analysis is usually performed in two ways:
  - 1-dimensional analysis vs. the invariant relative momentum q_{inv} . Can only extract system size averaged over all directions.
  - In the Longitudinally Co-Moving System in 3 directions: *long* – the beam axis, *out* – the pair momentum, *side* – orthogonal to the others. In LCMS the pair momentum in *long* vanishes. Gives access to three system sizes in these directions separately. Focus is on the transverse direction, where *side* is interpreted as "geometrical size" while *out* has additional components from emission duration. *Long* is used to extract total evolution time.
- The 3-dimensional correlation is usually shown either as 1-dimensional slices along the axes or as a set of spherical harmonics components.

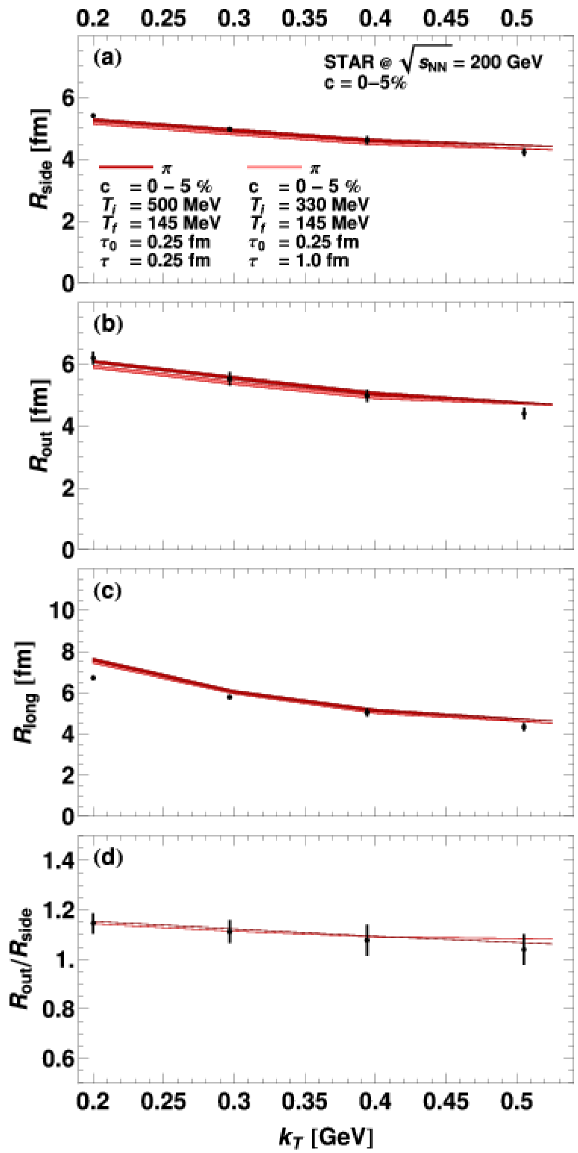
Final state geometry via femtoscopy



- 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

Description of the soft sector at RHIC





Dynamical model with hydrodynamical evolution, propagation of strong resonances

Reproduces spectra, elliptic flow and femtoscopy

Initial flow, smooth cross-over phase transition, resonance treatment naturally included

The pair momentum dependence of the radii a direct consequence of the radial flow in the system

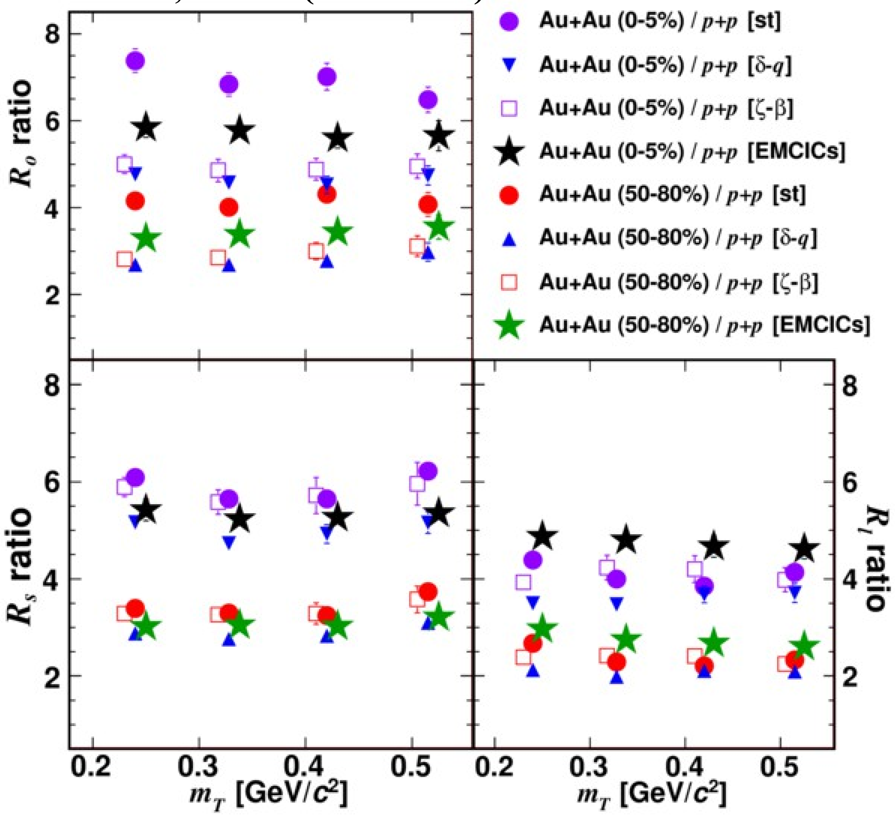
Soft sector data at RHIC understood in detail

W.Broniowski, W.Florkowski, M.Chojnacki, AK
nucl-th/0801.4361; nucl-th/0710.5731

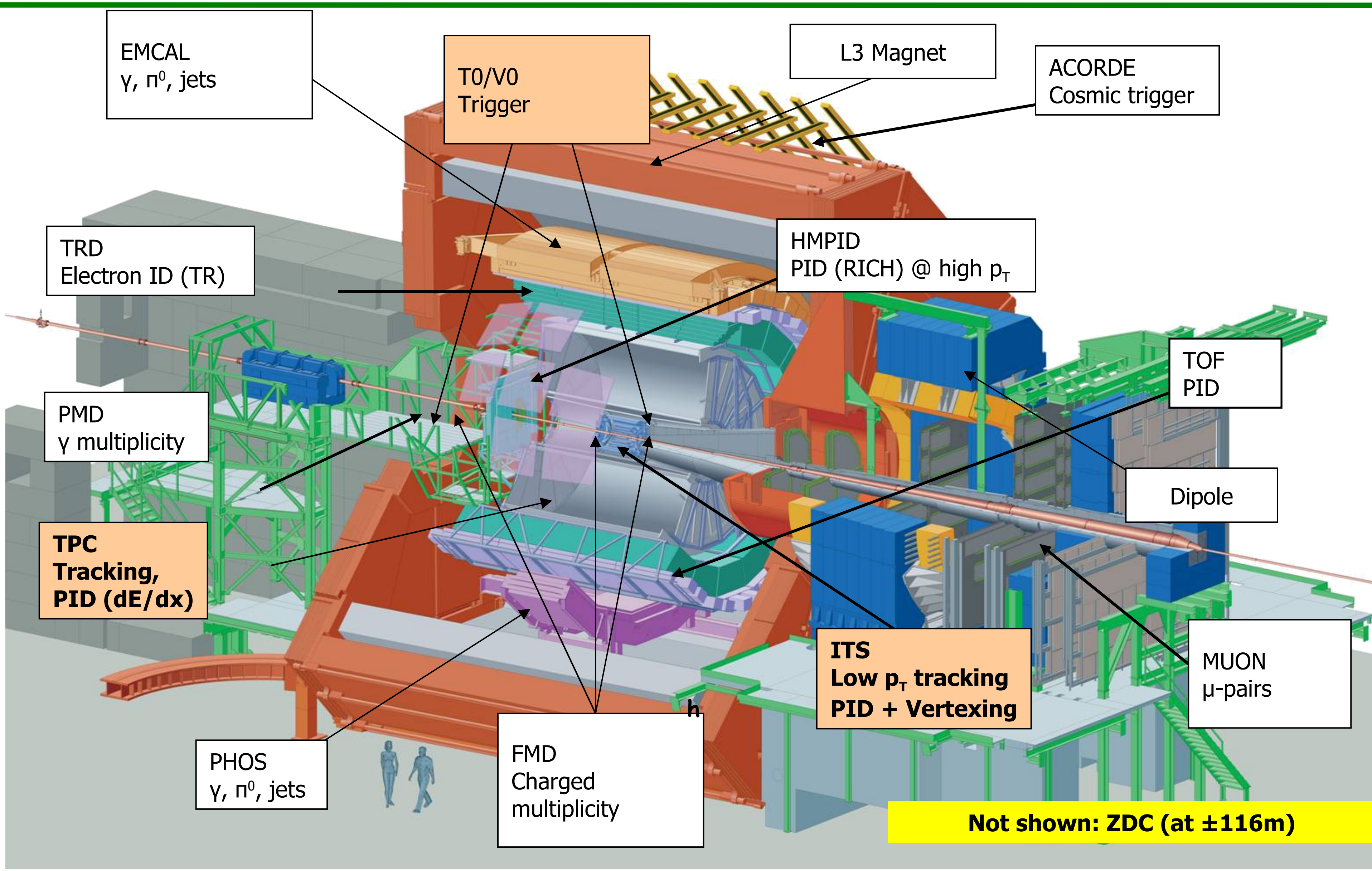
What about p+p? Puzzling scaling ...

- STAR reports that 3D HBT radii scale in p+p in a way very similar to Au+Au
- m_T dependence of 3D radii in Au+Au is taken as a signature of a flowing medium
- Is the scaling between p+p and Au+Au a signature of the universal underlying physics mechanism (collective flow) or a coincidence?

STAR, arXiV (1004.0925)

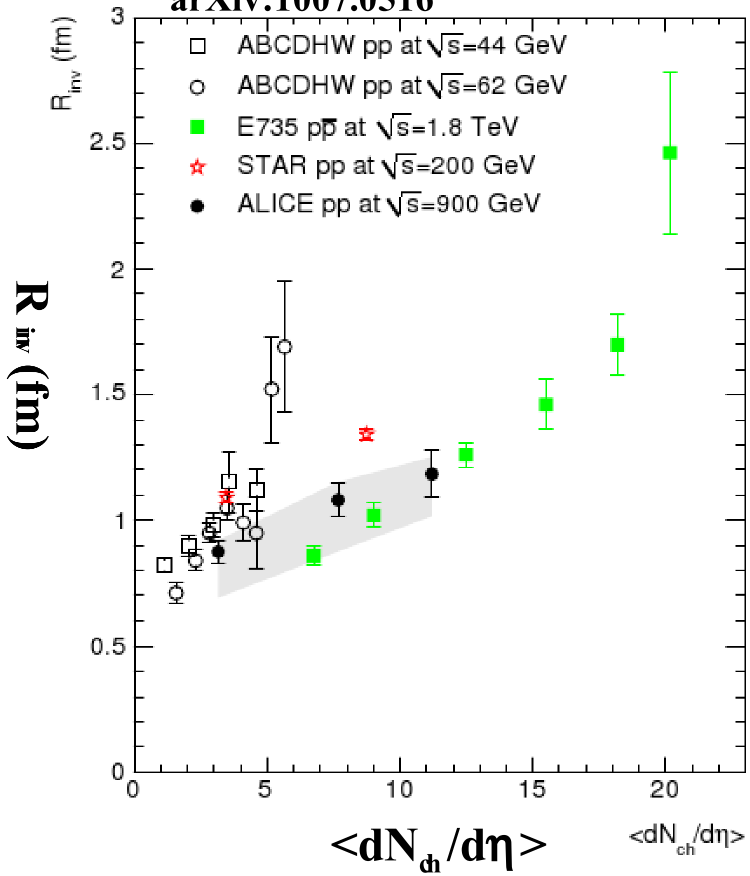


The ALICE detector



First look at system size at 0.9 TeV

Phys. Rev. D82, 052001 (2010)
arXiv:1007.0516

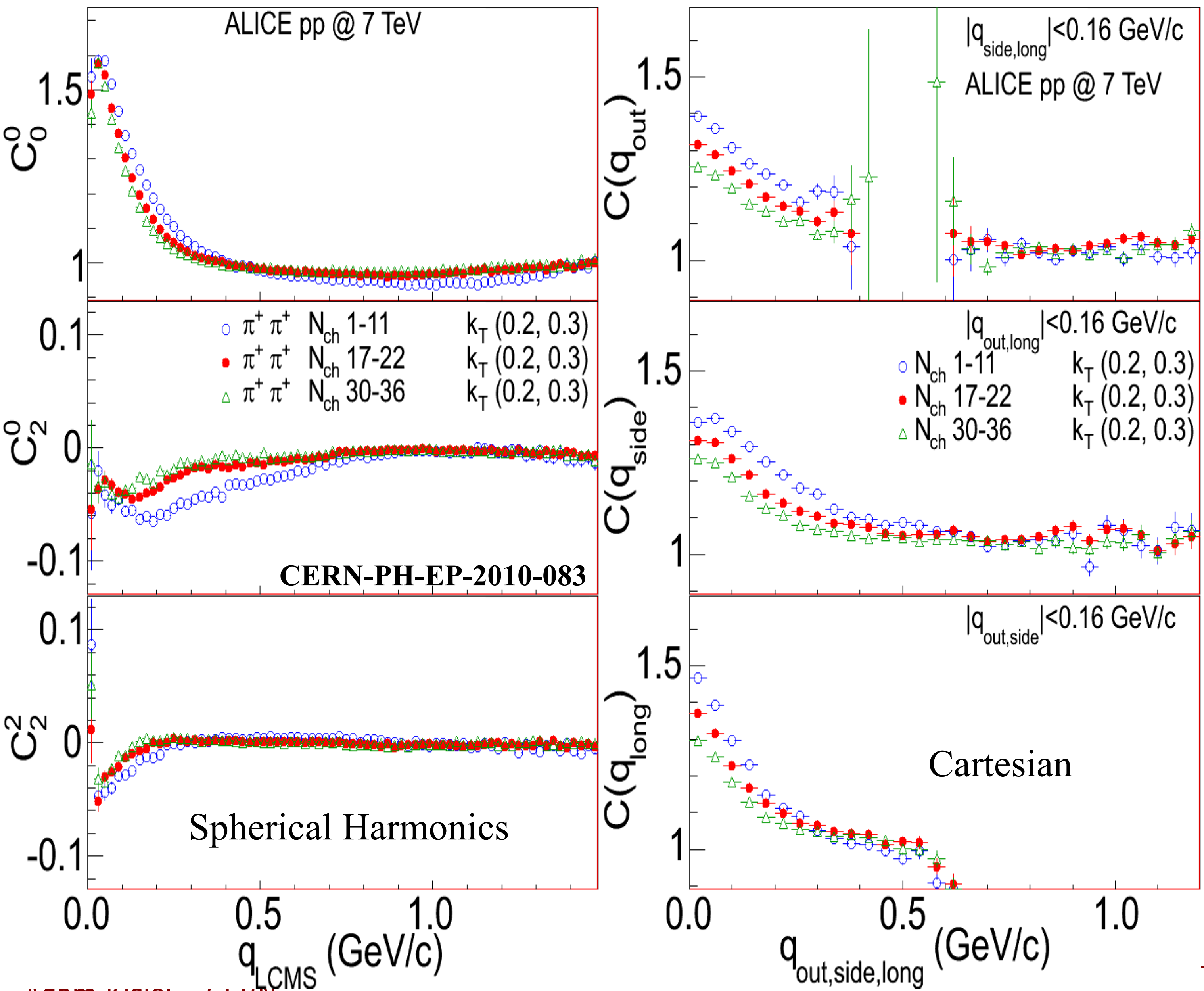


- 250k minimum-bias triggered events analyzed (full 2009 sample)
- ALICE observes the growth of the system size with multiplicity
- The results are given as a function of pseudorapidity density and can be compared to world systematics
- The observed trend is qualitatively similar to world data, but quantitative comparisons are complicated by large differences in experimental acceptances and analysis methods

ALICE p+p data taking in 2010

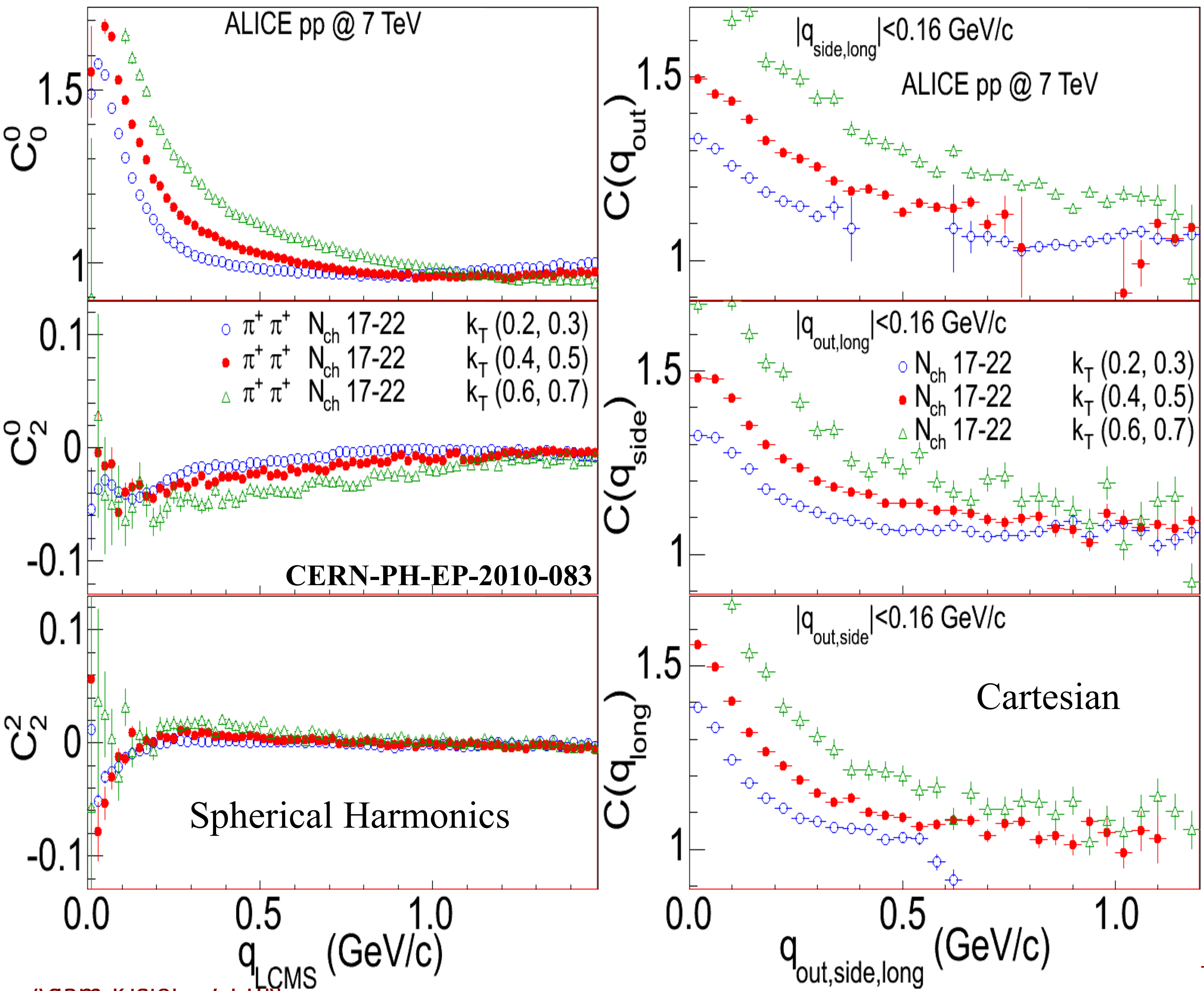
- ALICE has been taking data continuously since March 2010.
- A high statistics sample of p+p collisions at **0.9 TeV** (~**8M** minimum bias triggers) has been collected
- About **100M** minimum bias triggers at **7 TeV** used for this analysis (out of 750M total recorded up to now)
- Used fully calibrated data collected in June 2010
- All analysis done on the distributed computing environment: GRID
- Analyze **primary** particles in $|\eta|<1.2$, reconstructed by the combination of the ALICE Time Projection Chamber (**TPC**) and the Inner Tracking System (**ITS**)
- Particles **identified** with the TPC $\mathrm{d}E/\mathrm{d}x$ method – small contamination by electrons at low p_{T}, kaons at high p_{T}.
- p_{T} from 130 MeV/c up to 2 GeV/c
- Excellent two track resolution of the detector makes two-track effects negligible

Multiplicity dependence of the correlation function



- Dependence of the CF on multiplicity visible, not strong
- Large holes in the acceptance in certain k_T bins
- Consistent behavior for Spherical Harmonics and cartesian CFs

k_T dependence of the correlation function



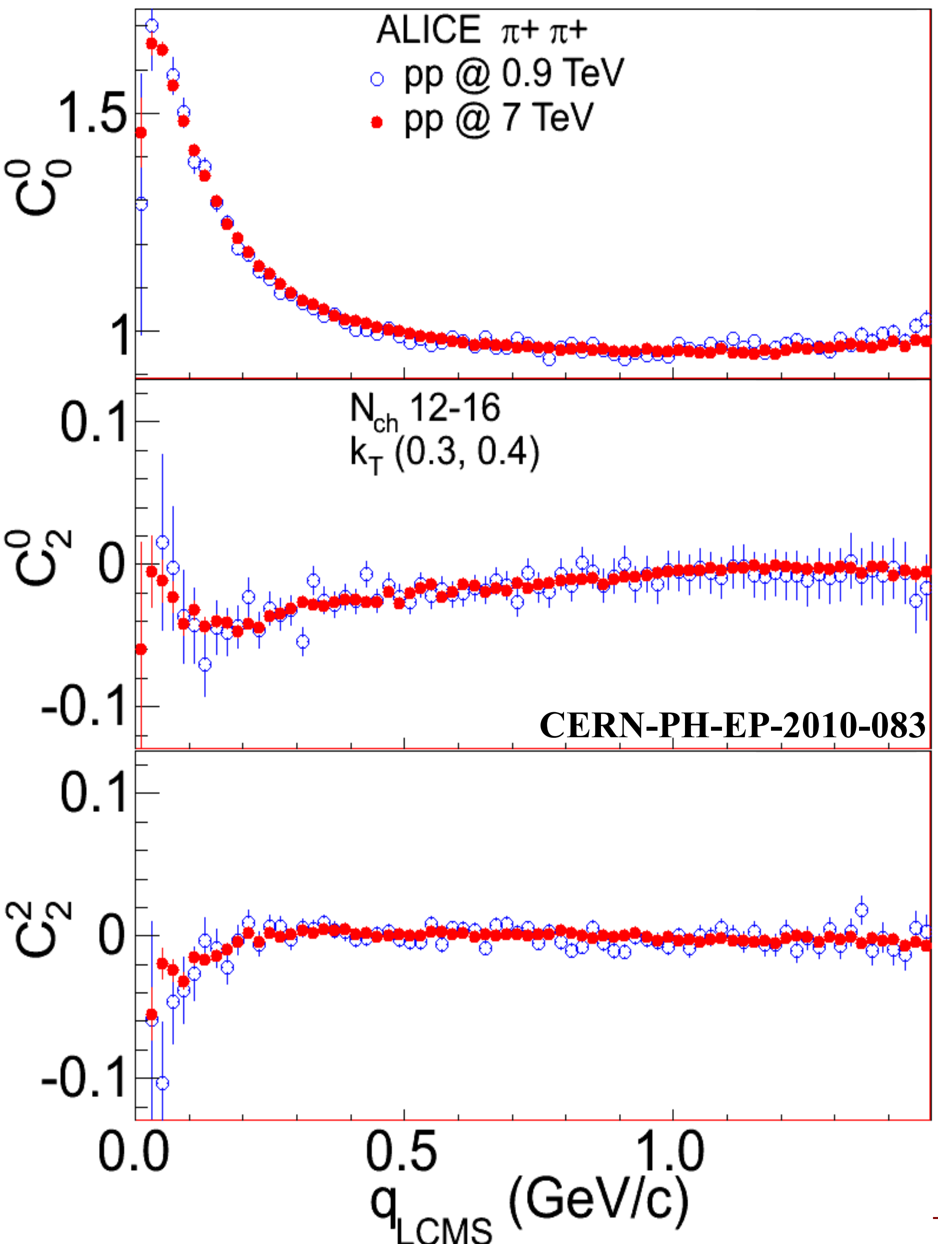
Dependence on k_T visible, stronger

Acceptance holes in the CF depend directly on k_T (kinematics cut effect)

Additional structures appear in the correlation at higher k_T ranges

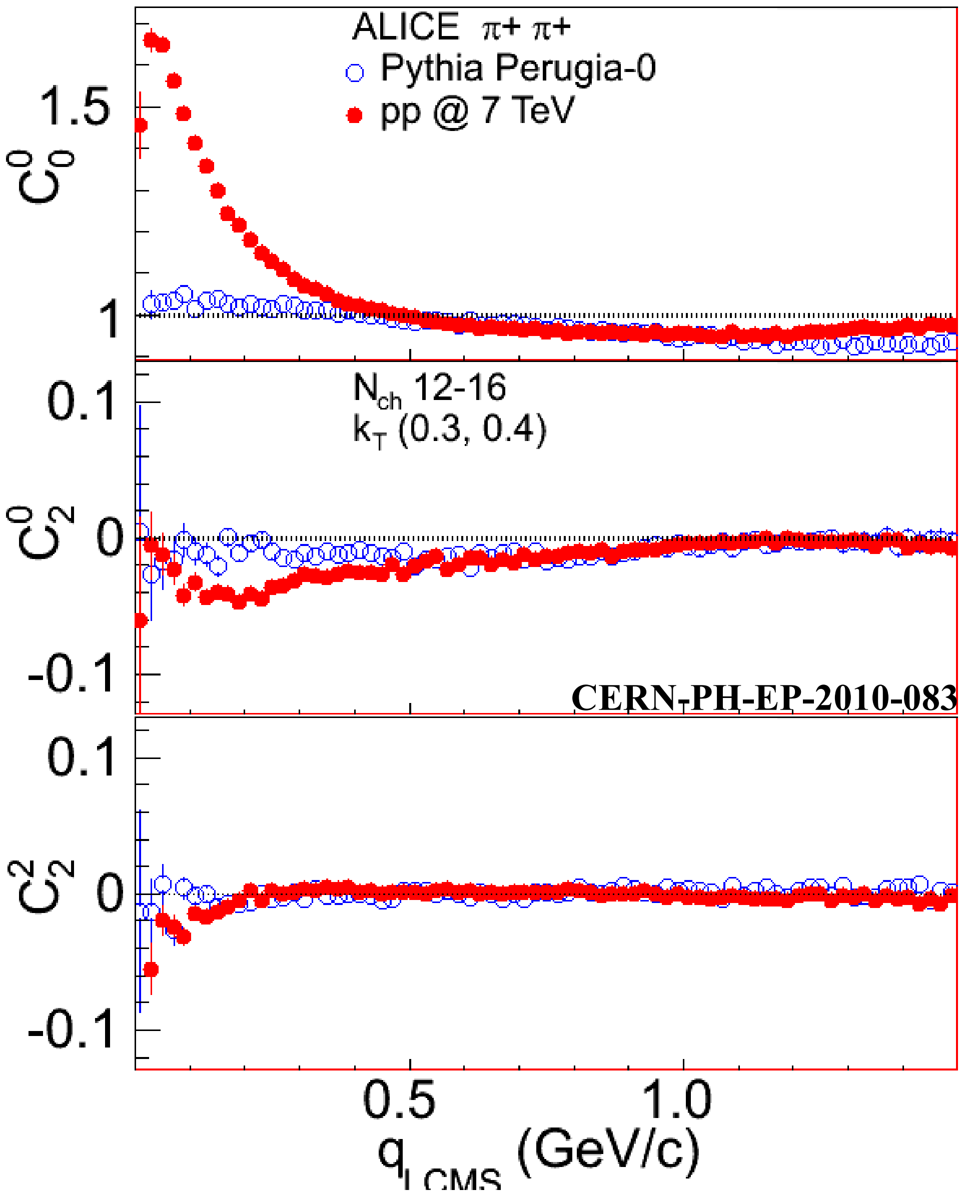
Extraction of the k_T dependence of the radii complicated by the need to account for the background

Energy dependence of the correlation function



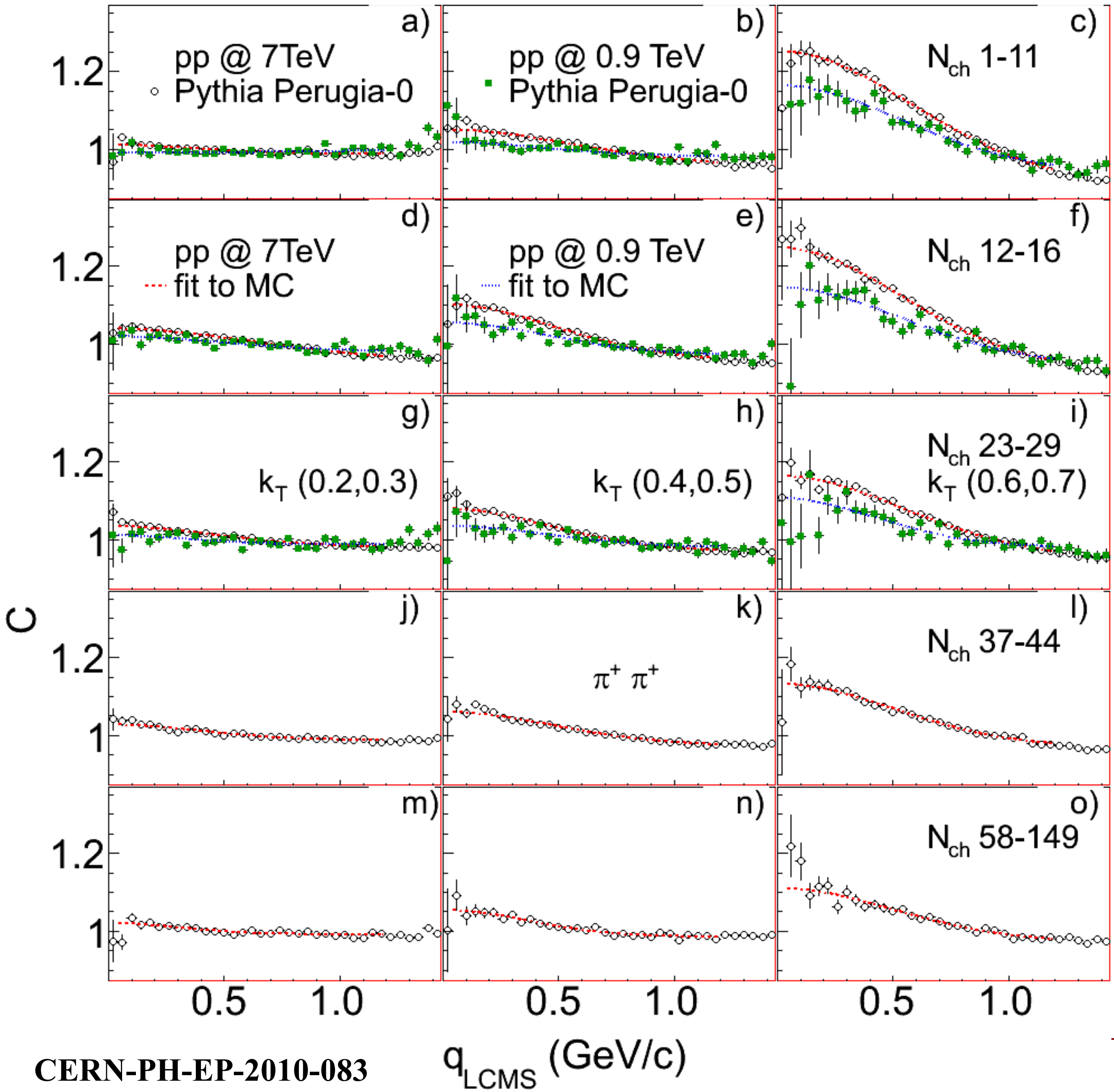
- Correlation functions for 0.9 TeV and 7 TeV similar, for same multiplicity and k_T ranges
- 3D shape ($C_2^{\,0}$ and $C_2^{\,2}$ components) also consistent
- Checked all multiplicity/k_T bins - all show comparable similarity
- First important finding: the scaling variables are the total event multiplicity and pair momentum. Dependence on collision energy is small in comparison.

Additional structures in MC and data



- In MC there is no femtoscopic effect (symmetrization), all structures are a “background”
- Structures seen in $C_0{}^0$ (angle-averaged correlation) and in $C_2{}^0$ (slight transverse – longitudinal structure)
- The non-femtoscopic structures in data and MC are similar, in regions where they can be compared. They are the main source of the systematic uncertainty.

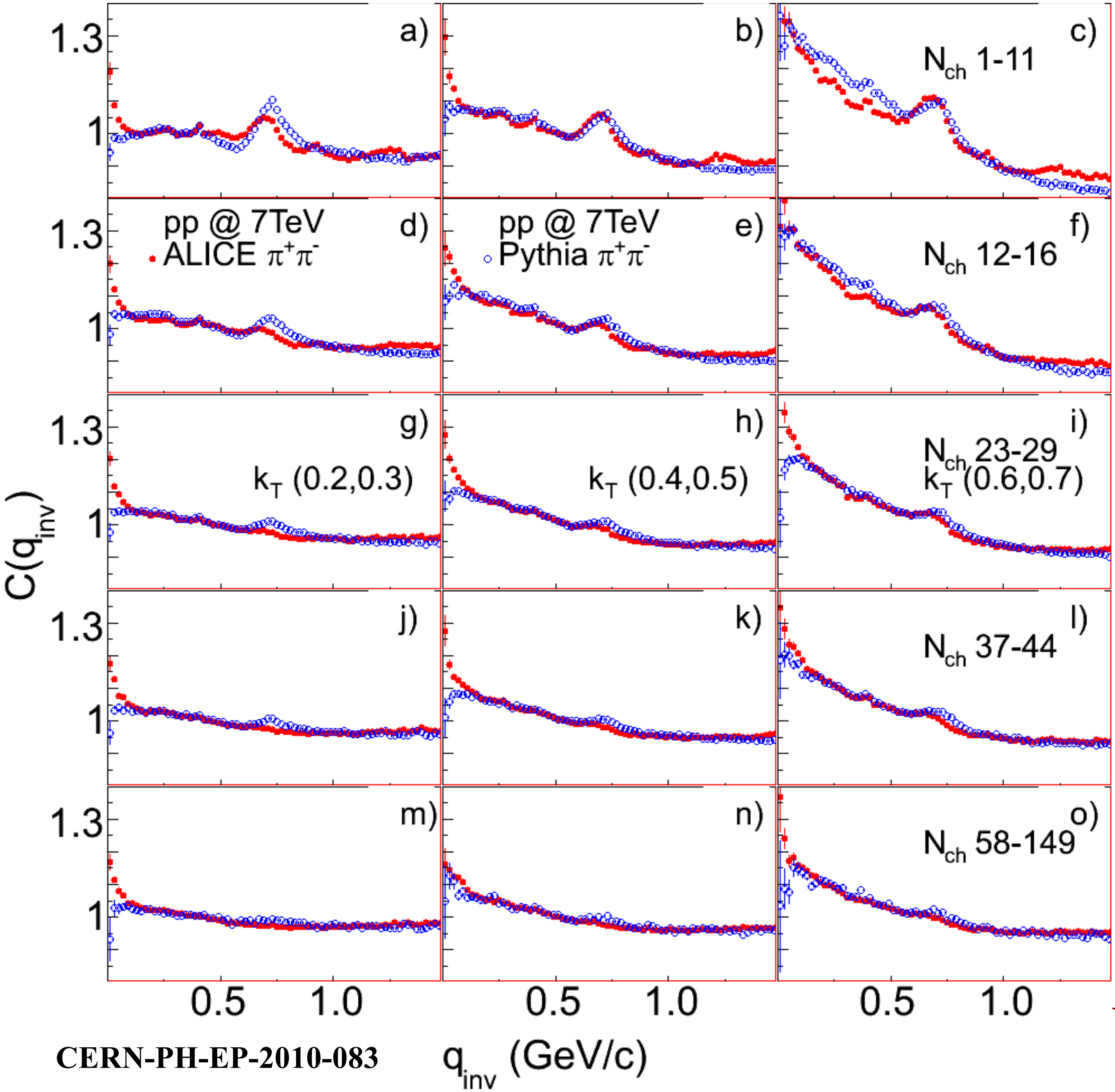
The baseline in Pythia (Perugia-0)



CERN-PH-EP-2010-083

- Pythia Perugia-0 tune background fitted with a 3D Gaussian peak with one averaged radius in LCMS
- Width of the peak varies by only 10% between multiplicity, k_T ranges
- Height of the peak grows with k_T, falls with multiplicity
- Background at 0.9 TeV smaller than at 7 TeV

Background cross-check – π+ π-



CERN-PH-EP-2010-083

- Reasonable match between Pythia and data across multiplicity and k_T ranges
- Visible resonance structures (non-id **not** a suitable background for identical pairs, and vice-versa)
- Details of resonance structure not reproduced – a limitation of resonance treatment in Pythia.

Fitting a 3D CF

- The Koonin-Pratt equation:

$$C(\vec{q}) = \int S(\boldsymbol{r}) |\Psi(\boldsymbol{r}, \vec{q})|^2 d\boldsymbol{r}$$

  requires that the functional form of S is postulated.

- The 3D Gaussian is the most commonly used form.

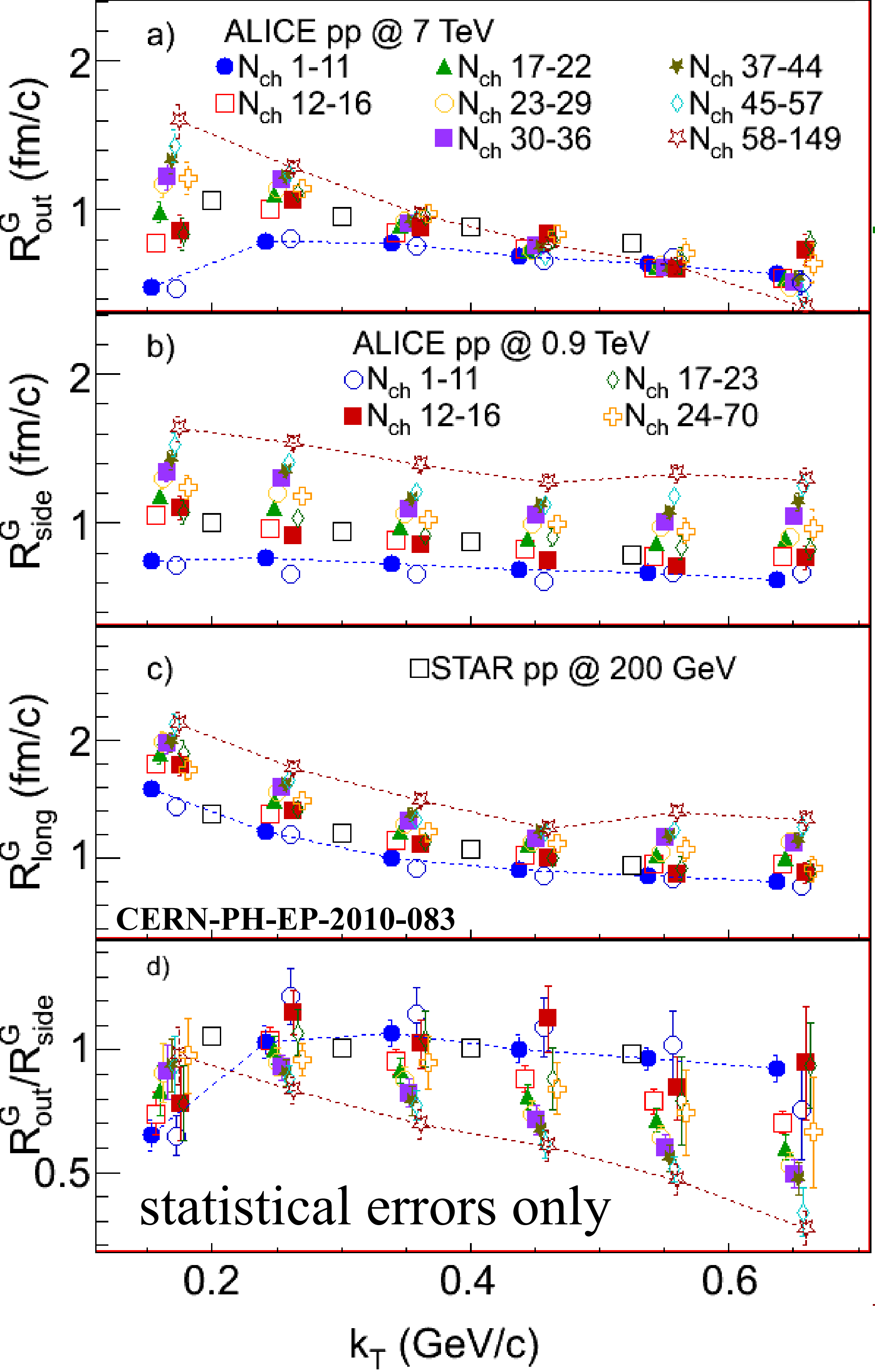
- Coulomb K is factorized out of Ψ, it is then $1+\cos(q\boldsymbol{r})$. This gives the femtoscopic part of the CF:

$$C = (1-\lambda) + \lambda K \left(1 + \exp(-R_{out}^2 q_{out}^2 - R_{side}^2 q_{side}^2 - R_{long}^2 q_{long}^2)\right)$$

  where the radii R and q can be in Pair Rest Frame (PRF) or LCMS (this study)

- We need to add the non-femtoscopic background and normalization to form the final version of the fit function:

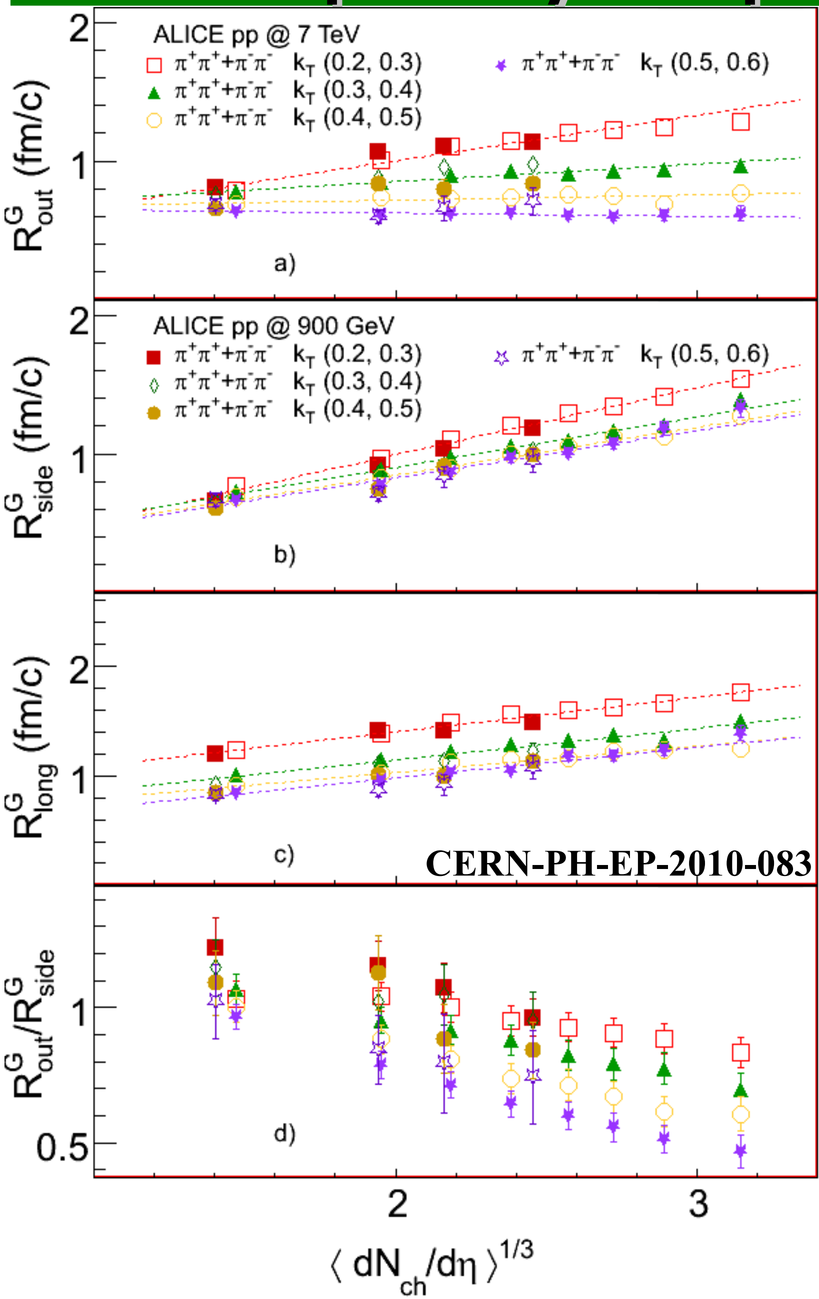
$$C = N\left[(1-\lambda) + \lambda K \left(1 + \exp(-R_{out}^2 q_{out}^2 - R_{side}^2 q_{side}^2 - R_{long}^2 q_{long}^2)\right)\right] B$$



Gaussian radii at 0.9 and 7 TeV

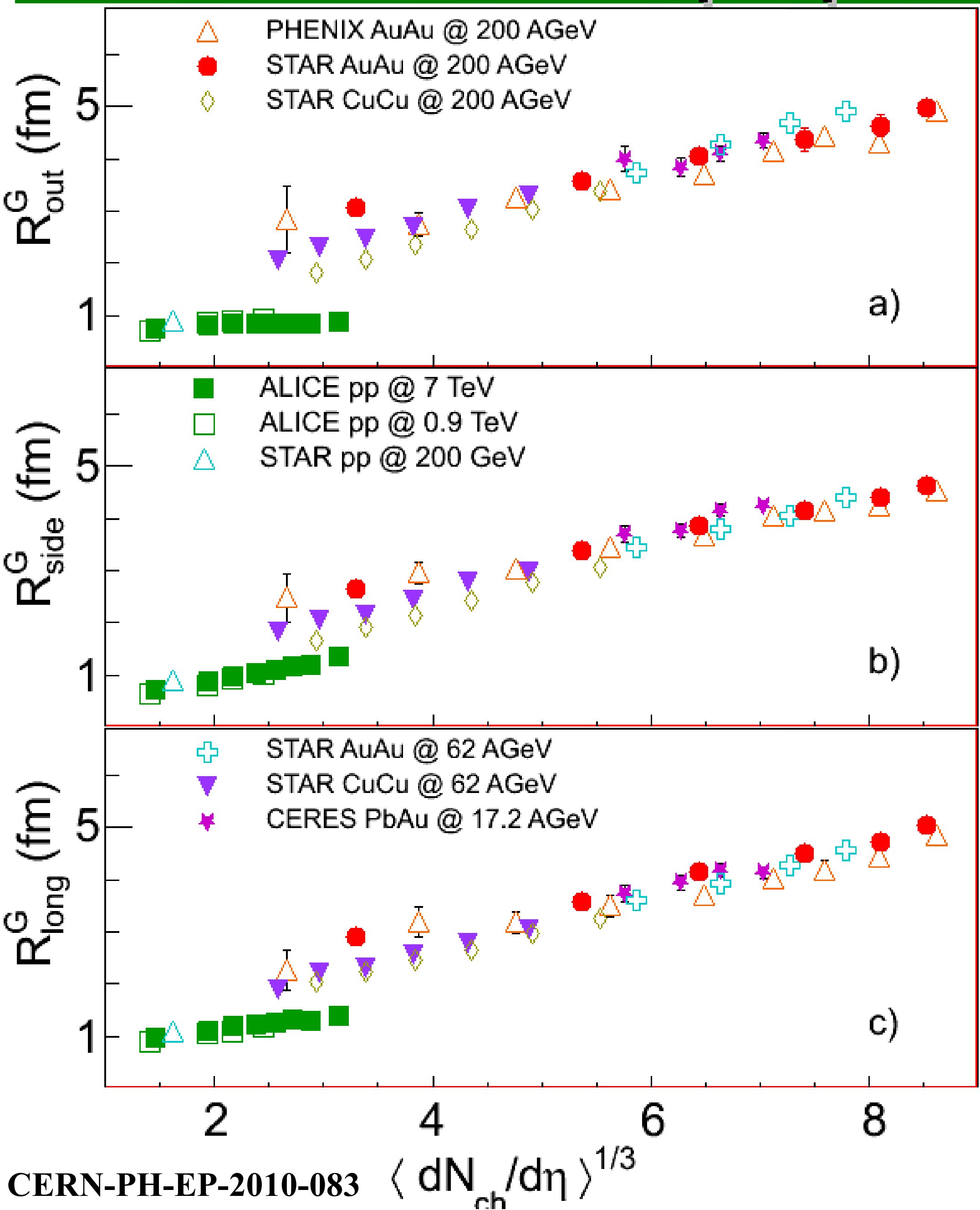
- Gaussian radii in LCMS grow with multiplicity, fall with k_T
- Fall with k_T very prominent for R_{long}, develops with multiplicity for R_{out}, less pronounced for R_{side}
- The different evolution of R_{out} and R_{side} reflected in low R_{out}/R_{side} values – p+p vs. A+A scaling not obvious anymore.
- Radii comparable to STAR (EMCICs fit). Transverse size similar to the one in ALICE at similar multiplicity

Multiplicity dependence of gaussian radii



- Test if the data scales linearly with $dN_{ch}/d\eta^{1/3}$ for all energies, separately for each k_T range.
- Multiplicity scaling is visible for all k_T, all directions
- 0.9 TeV data follows a trend similar to 7 TeV data – confirming the finding with pure correlations comparison
- The scaling in the *side* and *long* directions similar, in *out* the gradient strongly depends on pair momentum

ALICE p+p vs. heavy-ions

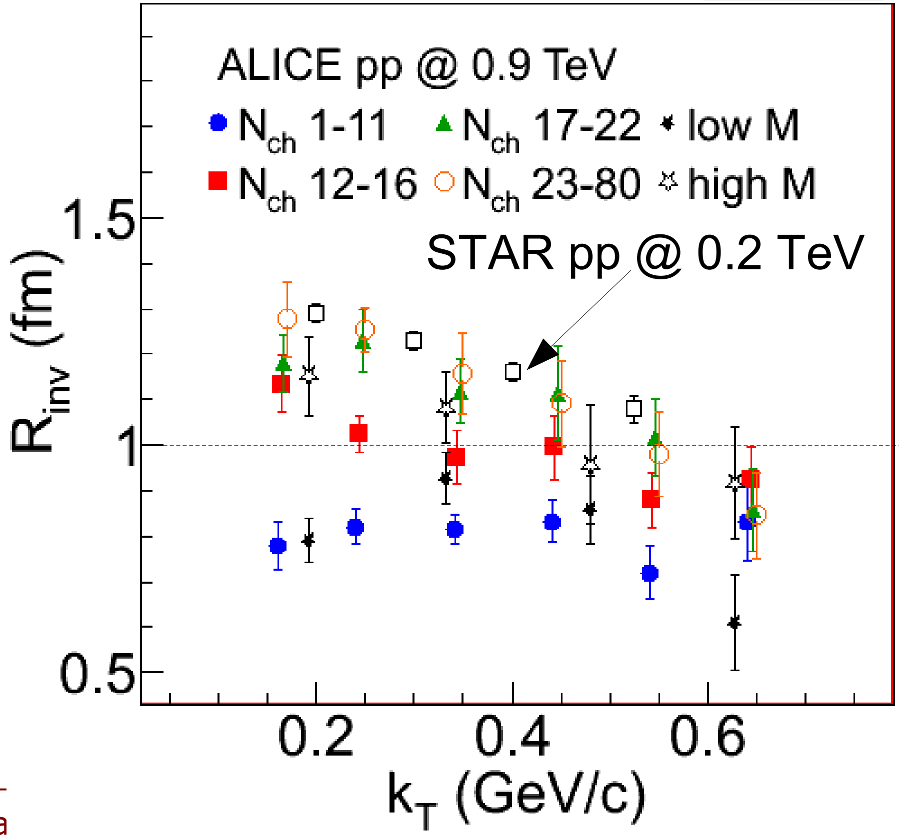


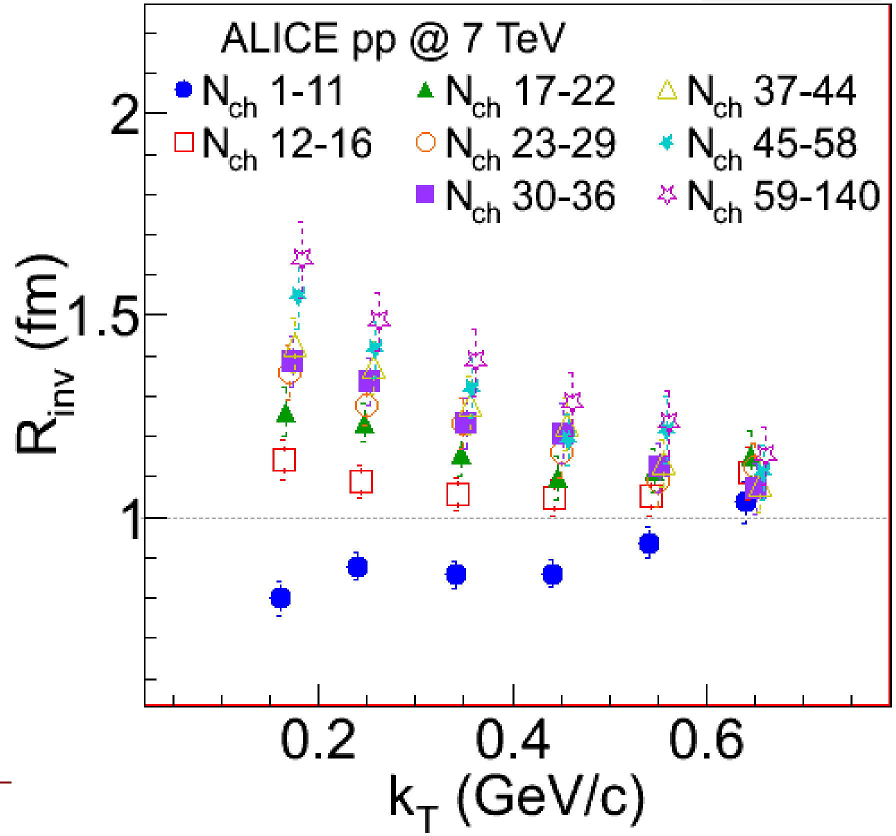
CERN-PH-EP-2010-083

- Heavy-ion data at ultra-relativistic energies show $dN_{ch}/d\eta$ scaling
- ALICE p+p does grow linearly with $dN_{ch}/d\eta^{1/3}$, but not with the same offset and slope as heavy-ions
- Comparison at same $dN_{ch}/d\eta$ in p+p and A+A possible for the first time
- Violation of the scaling shows that initial geometry does play a role in the final freeze-out shape

Cross-checking 1D radii

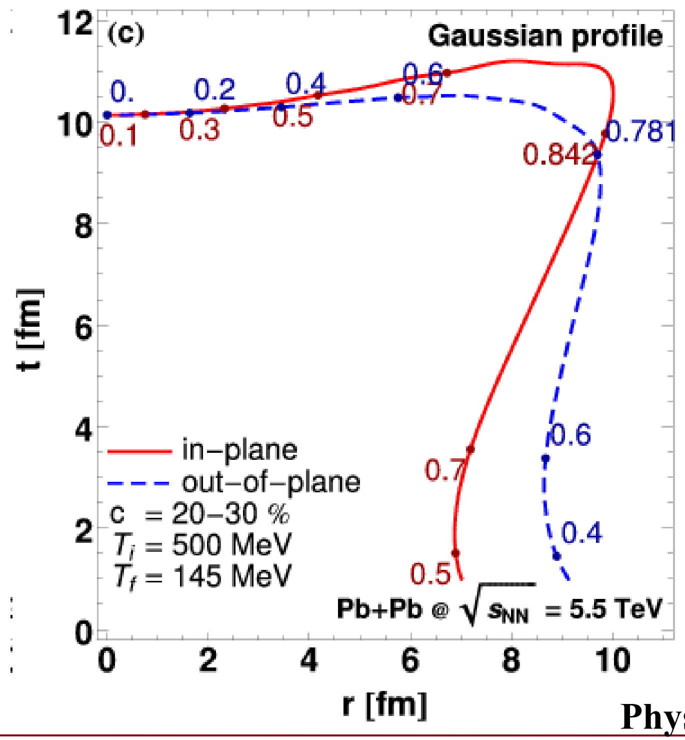
- 1D R_{inv} analysis (in Pair Rest Frame) done for comparison with previous publications: new results consistent with published
- Development of k_{T} slope with multiplicity also for R_{inv} at high multiplicity
- Important to perform the analysis differentially vs. the correct scaling variables, measurement integrated over multiplicity or k_{T} hides important physics message

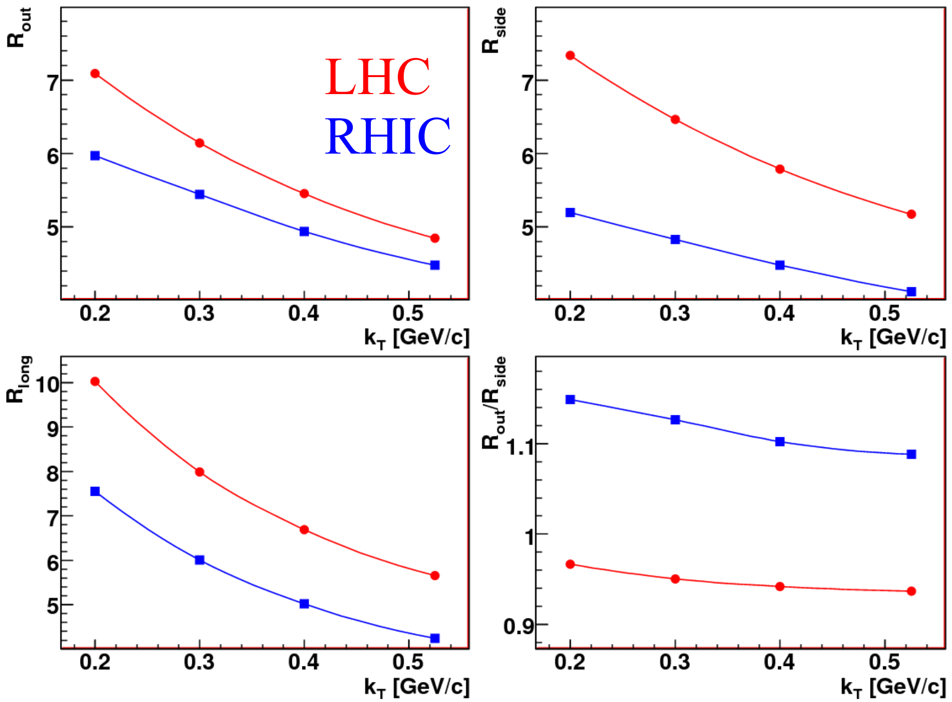




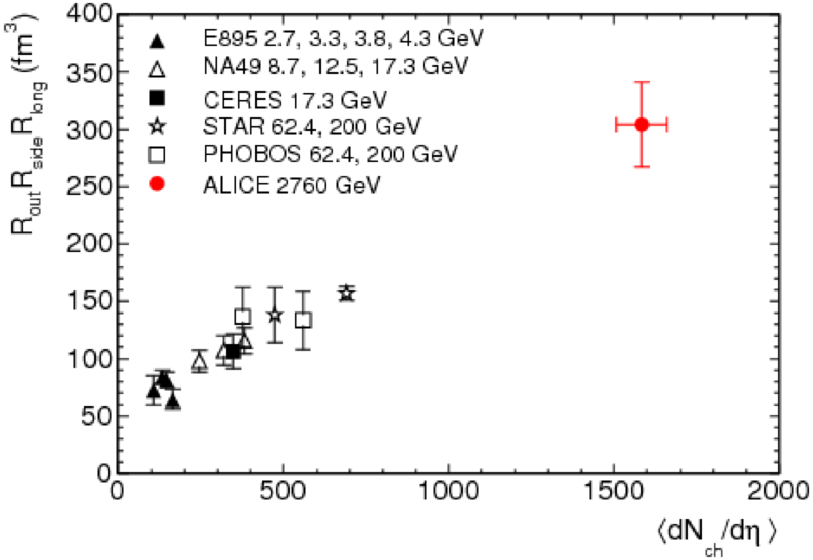
Collectivity predictions in Pb+Pb at LHC

- Hydrodynamics predicts for LHC: steeper m_T dependence of the size from larger flow, larger size from longer evolution and the reversal of the azimuthal anisotropy in space-time. The R_{out}/R_{side} ratio is even smaller than at RHIC: due to a longer evolution time the freeze-out shape changes from inside-out to outside-in.





Phys.Rev.C79:014902,2009



arXiv:1012.4035, accepted for publication

Figure 4: Product of the three pion HBT radii at $k_T = 0.3$ GeV/c. The ALICE result (red filled dot) is compared to those obtained for central gold and lead collisions at lower energies at the AGS [35], SPS [36, 37, 38], and RHIC [39, 40, 41, 42, 30, 43].

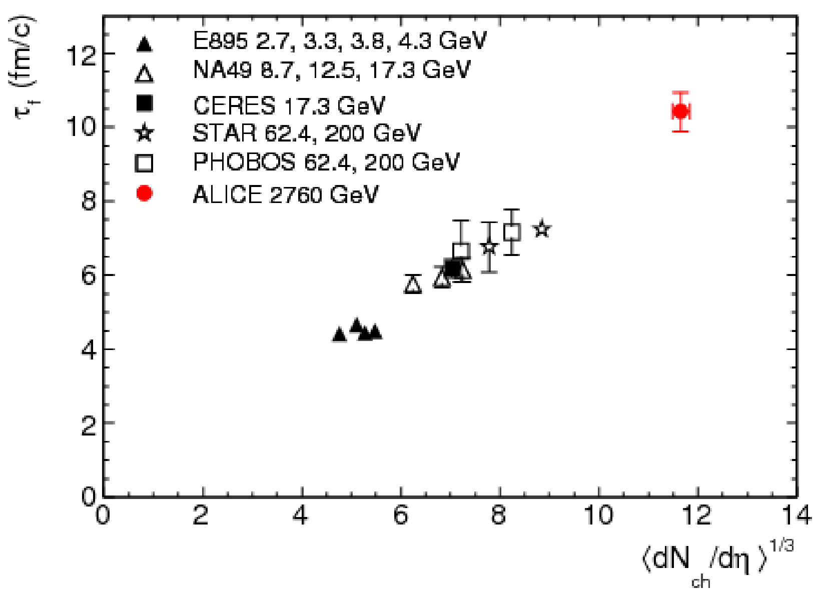
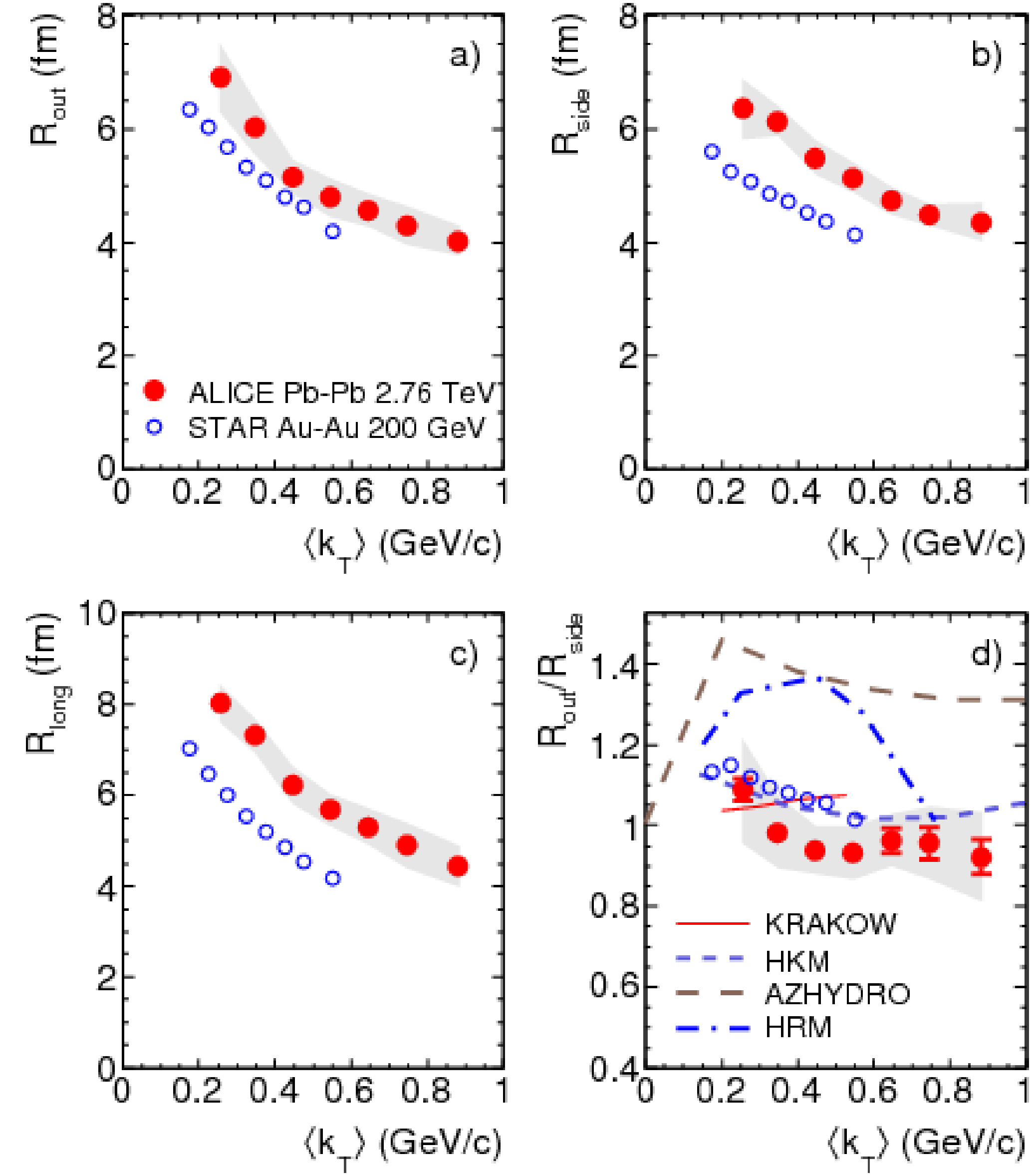


Figure 5: The decoupling time extracted from $R_{\rm long}(k_T)$. The ALICE result (red filled dot) is compared to those obtained for central gold and lead collisions at lower energies at the AGS [35], SPS [36, 37, 38], and RHIC [39, 40, 41, 42, 30, 43].

Energy dependence

- Clear increase of the emitting region size and the system lifetime between the largest system to date (cental full energy RHIC) and the central LHC. This means that the "quark-gluon plasma", if produced, lives longer and in a significantly bigger volume.
- The dependence with energy follows the multiplicity scaling – this will be tested in more detail with the full centrality dependence from ALICE



arXiv:1012.4035, accepted for publication

Figure 2: Pion HBT radii for the 5% most central Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, as function of $\langle k_T \rangle$ (red filled dots). The shaded bands represent the systematic errors. For comparison, parameters for Au–Au collisions at $\sqrt{s_{NN}} = 200$ GeV [30] are shown as blue open circles. (The combined, statistical and systematic, errors on these measurements are below 4%.) The lines show model predictions (see text).

Pair momentum 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
- All results are consistent with the collectivity signatures

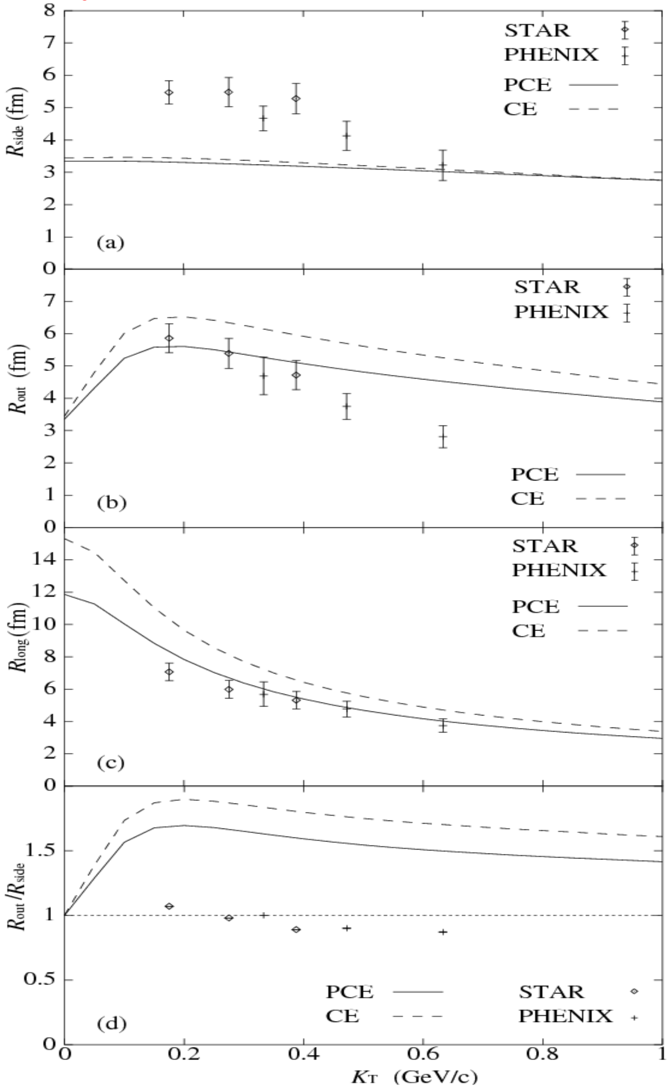
Summary

- ALICE measured pion femtoscopic correlation functions at 0.9 TeV and 7 TeV, providing a link between multiplicities in p+p and heavy-ions at RHIC
- ALICE observes dependence of the correlation function on the multiplicity and strong dependence on the pair momentum
- Significant non-femtoscopic correlations are present, strong in 0.9 TeV, stronger in 7 TeV, developing with pair momentum, relatively well reproduced by Monte Carlo. Current hypothesis: mini-jet correlations.
- The evolution of the transverse radii on pair momentum complicated, changes dramatically with multiplicity. Simple p+p vs. A+A scaling arguments should be revisited, but the question of collectivity in p+p is still valid.
- Taking into account the underlying event correlations, ALICE sees radii growing with multiplicity, approximately linearly, with cube root of event multiplicity, in all 3 dimensions. 3D radii also fall with growing pair momentum.
- First results from the Pb+Pb run of the LHC show Quark Gluon Plasma that is bigger and lives longer than at RHIC, behaves hydrodynamically.

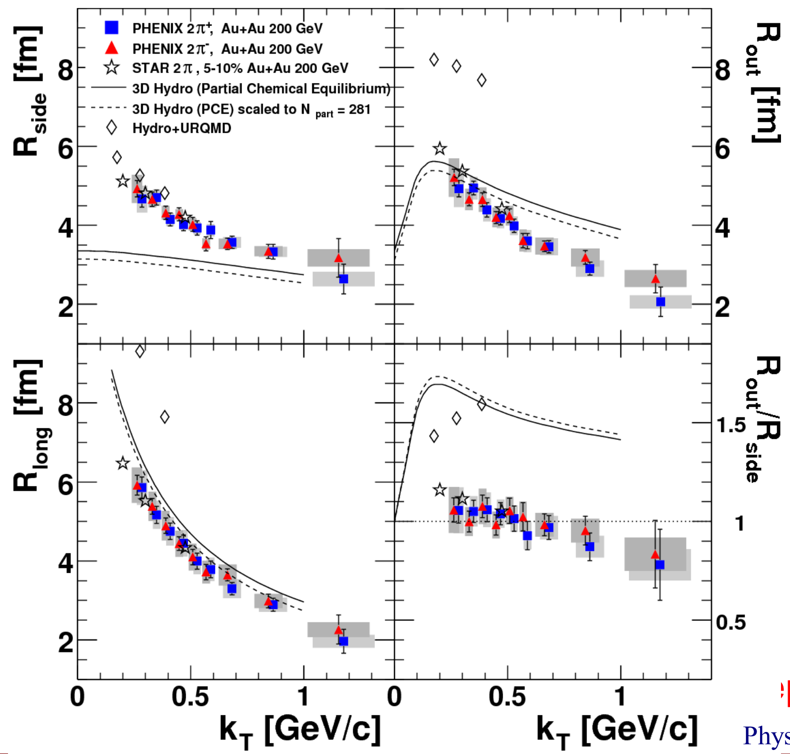
Backup slides

RHIC Hydro-HBT puzzle

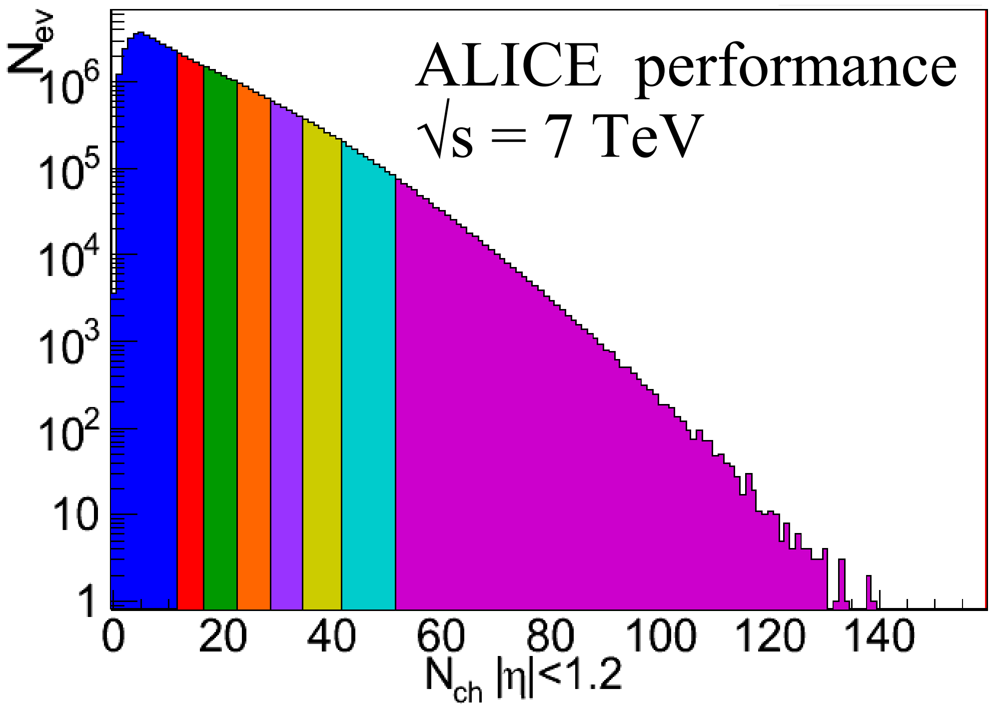
T. Hirano, K. Tsuda, nucl-th/0205043
Phys.Rev.C66:054905,2002.

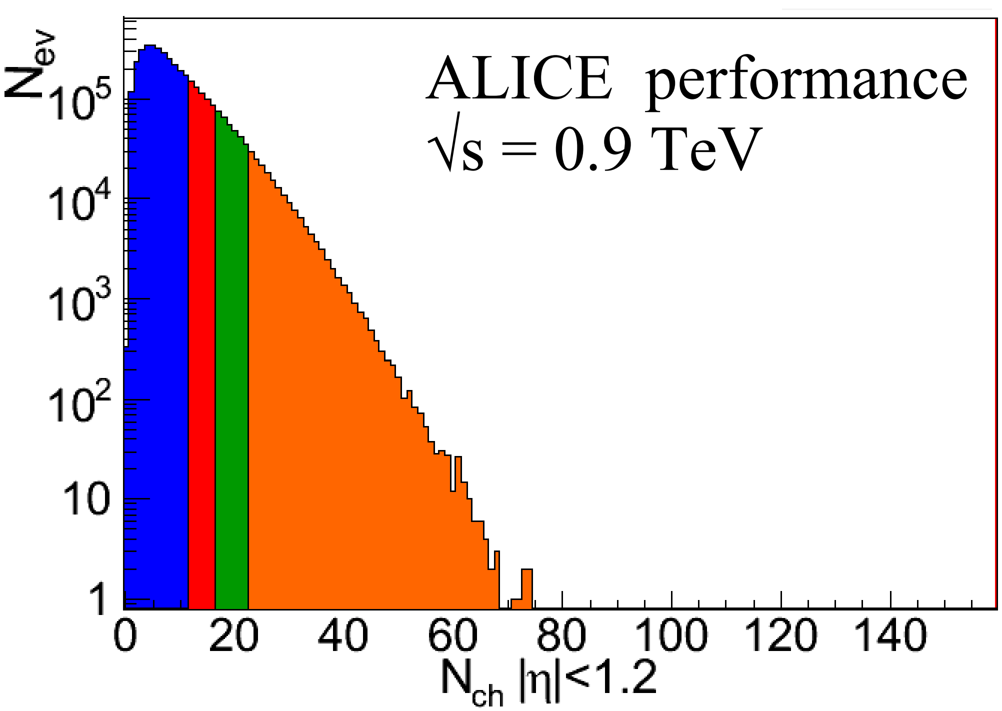


- First hydro calculations struggle to describe femtoscopic data: predicted too small R_{side} , too large R_{out} – too long emission duration
- No evidence of the first order phase transition



Heinz, P. Kolb,
p-ph/0204061
Phys. Rev. Lett. 93, 152302 (2004)





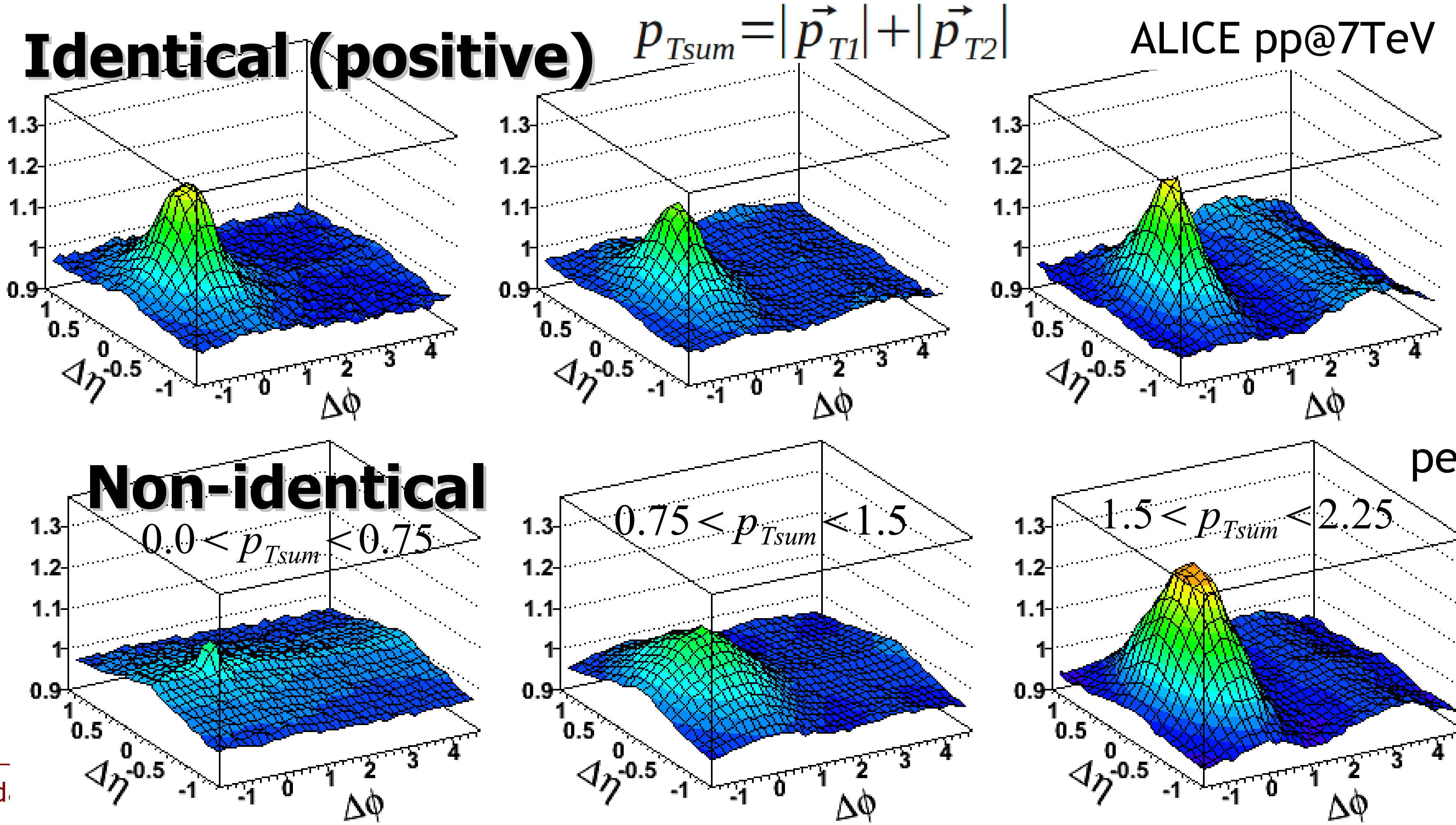
Multiplicity binning

TABLE I. Multiplicity selection for the analyzed sample. Uncorrected N_{ch} in $|\eta| < 1.2$, $\langle dN_{ch}/d\eta \rangle|_{N_{ch}\geq 1}$ (see text for the definition), number of events and number of identical pion pairs in each range are given.

Bin	N_{ch}	$\langle dN_{ch}/d\eta \rangle\|_{N_{ch}\geq 1}$	No. events $\times 10^6$	No. pairs $\times 10^6$
		$\sqrt{s} = 0.9$ TeV		
1	1–11	2.7	3.1	8.8
2	12–16	7.0	0.685	8.6
3	17–22	9.7	0.388	9.5
4	23–80	14.6	0.237	12.9
		$\sqrt{s} = 7$ TeV		
1	1–11	3.2	31.4	48.7
2	12–16	7.4	9.2	65.0
3	17–22	10.4	7.4	105.7
4	23–29	13.6	4.8	120.5
5	30–36	17.1	3.0	116.3
6	37–44	20.2	2.0	115.6
7	45–57	24.2	1.3	114.5
8	58–149	31.1	0.72	108.8

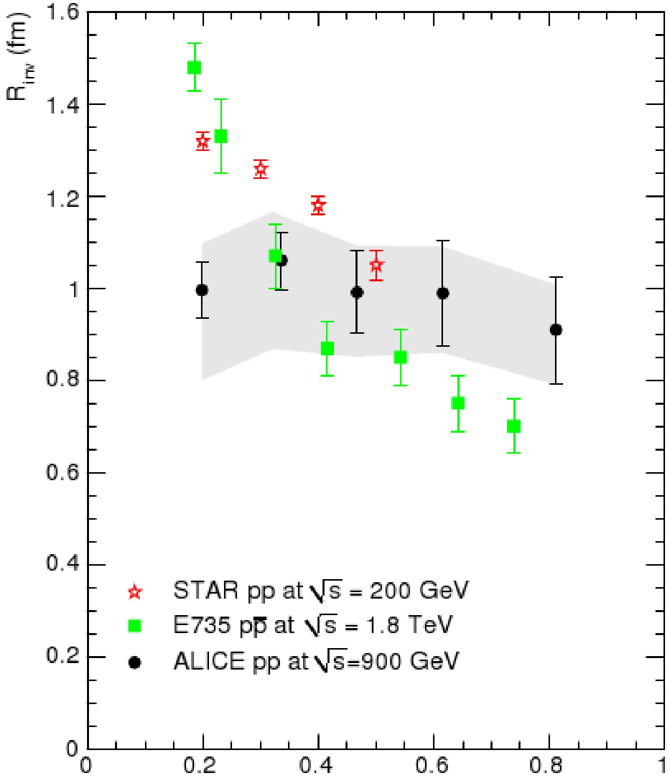
Characterizing mini-jet correlations

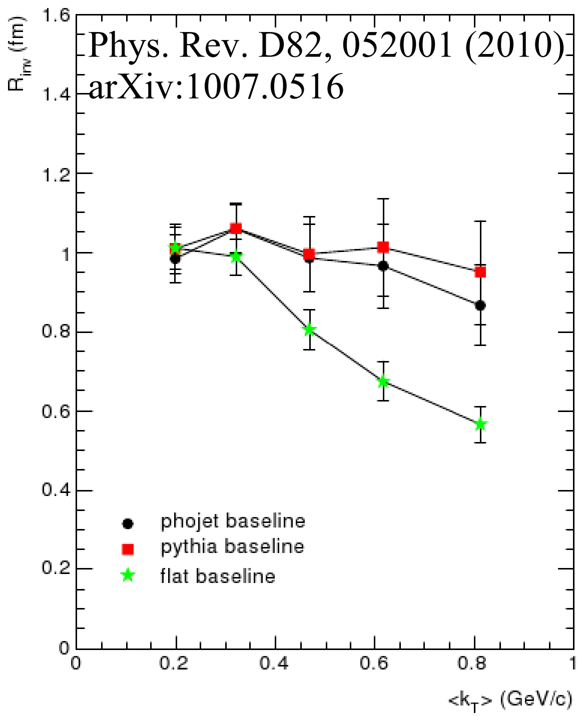
- "femtoscopic effect" expected only in identical charge combinations, going away with increasing p_T sum
- Mini-jet-like correlations expected to be stronger for non-identical



ALICE performance

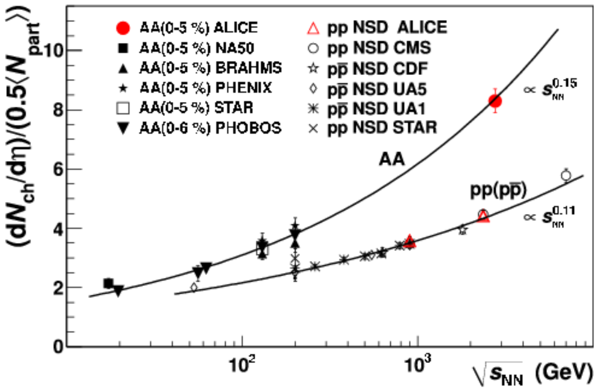
Pair momentum dependence





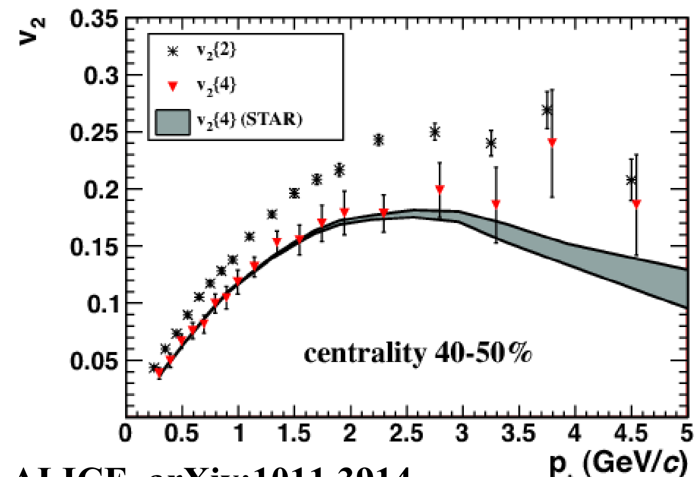
- First attempt in measuring pair momentum dependence limited by statistics and systematics
- Dominating systematic effect: appearance of “mini-jet” non-femtoscopic correlations ar large p_T
- Integrated R_{inv} shows flat behaviour, but only if the systematic effects are treated properly
- Discrepancy with data at lower (STAR) and higher (E735) energy is apparent, but acceptance (in particle momenta and event multiplicities) differs significantly

Heavy ions at ALICE



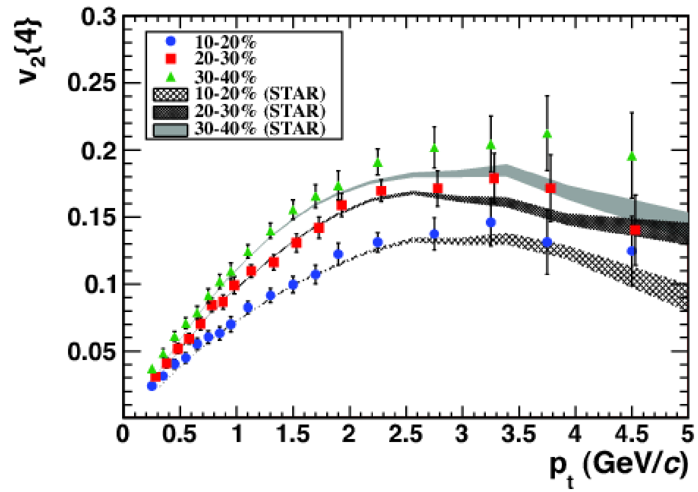
ALICE, arXiv:1011.3916

FIG. 3. Charged particle pseudo-rapidity density per participant pair for central nucleus–nucleus [16–24] and non-single diffractive pp/pp̄ collisions [25–31], as a function of $\sqrt{s_{NN}}$. The energy dependence can be described by $s_{NN}^{0.15}$ for nucleus–



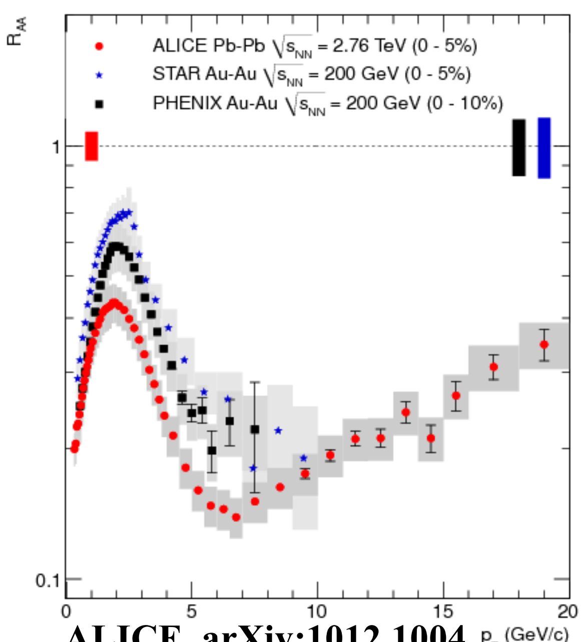
ALICE, arXiv:1011.3914

(a)



(b)

FIG. 2. (color online) a) $v_2(p_t)$ for the centrality bin 40–50% from the 2- and 4-particle cumulant methods for this measurement and for Au–Au collisions at $\sqrt{s_{NN}}$ = 200 GeV. b) $v_2\{4\}(p_t)$ for various centralities compared to STAR measurements. The data points in the 20–30% centrality bin are shifted in p_t for visibility.



ALICE, arXiv:1012.1004

- The heavy-ion program in ALICE is progressing quickly. “First” measurements show (in comparison to RHIC):
  - Significant increase in event multiplicity
  - Decrease in R_{AA} (stronger “high-p_T suppression”)
  - Elliptic flow: similar $v_2(p_T)$, but stronger integrated v_2, due to a harder spectrum

Cross-checking 1D radii

- 1D R_{inv} analysis (in Pair Rest Frame) done for comparison with previous ALICE and CMS publications
- New results consistent with published
- Development of k_T slope with multiplicity also in R_{inv}