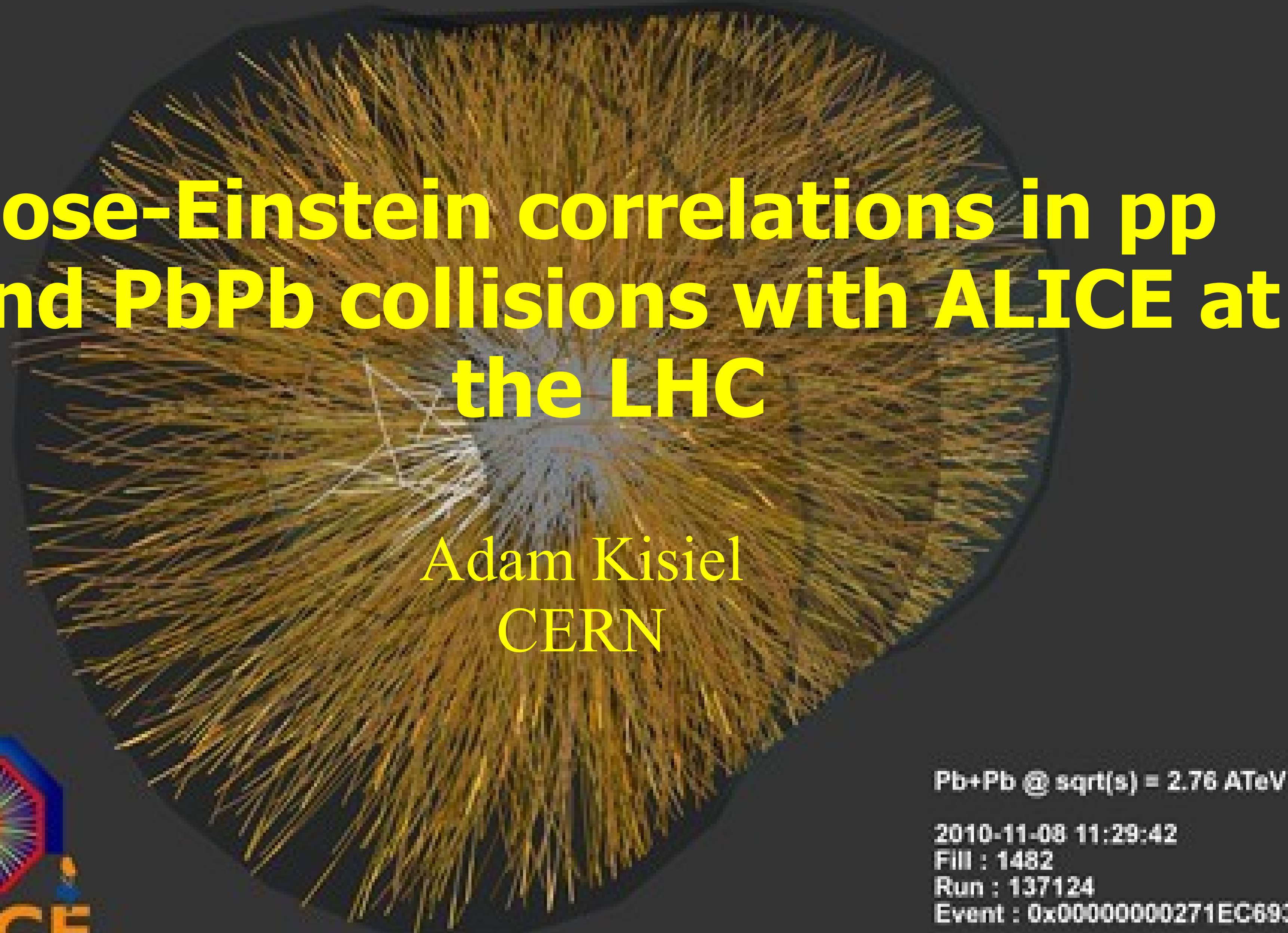
Bose-Einstein correlations in pp and PbPb collisions with ALICE at the LHC

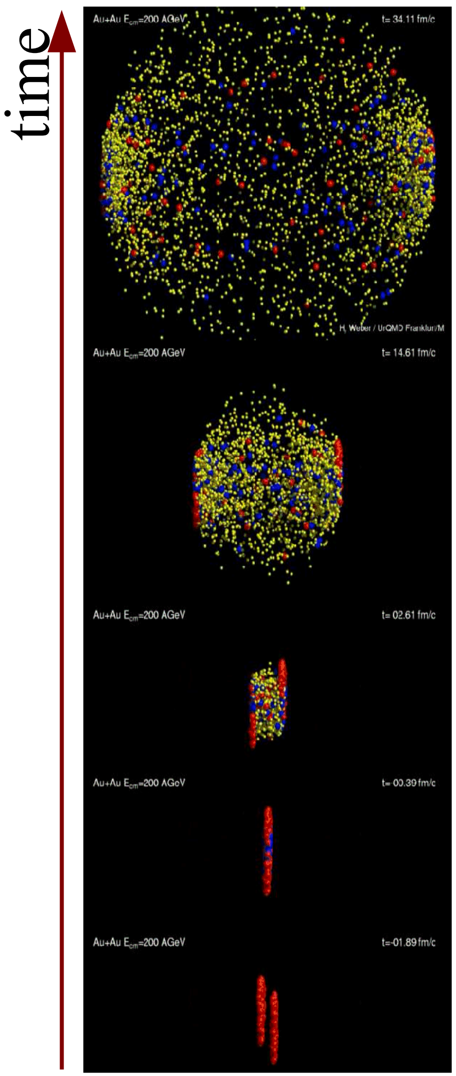
Adam Kisiel
CERN

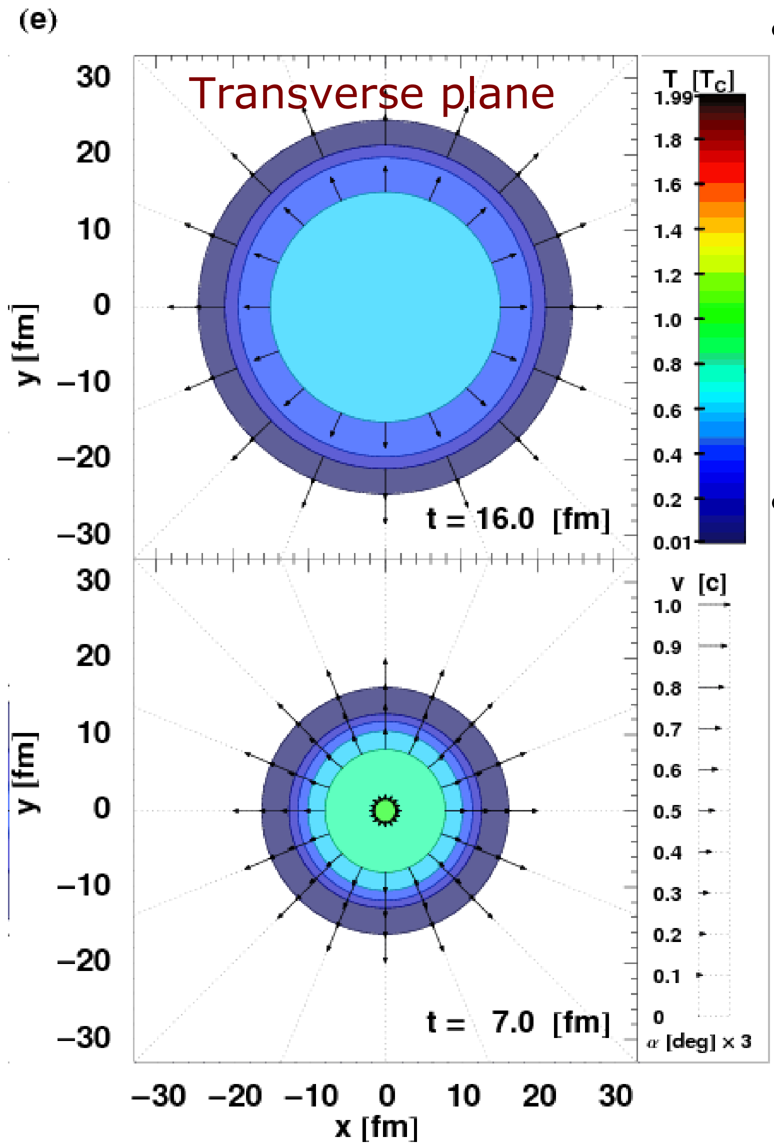


Outline

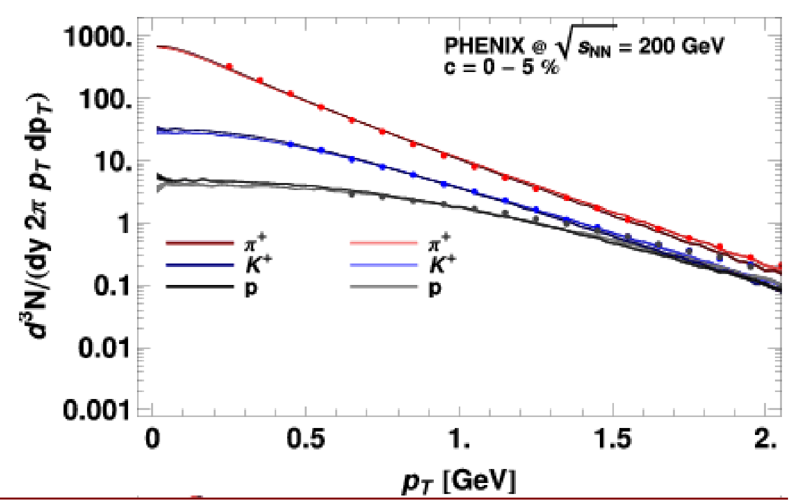
- Physics motivation:
  - Femtoscopy: measuring the size of the hadron collision
  - Lessons from RHIC: k_T dependence of the 3D radii as a signature of collective flow
  - How is p+p different from A+A?
- ALICE experiment
  - Data taking conditions
  - Event sample characteristics
- Results
  - Identifying 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 from the Pb+Pb run
  - Putting constrains on the collectivity description

Heavy Ion collision evolution at RHIC



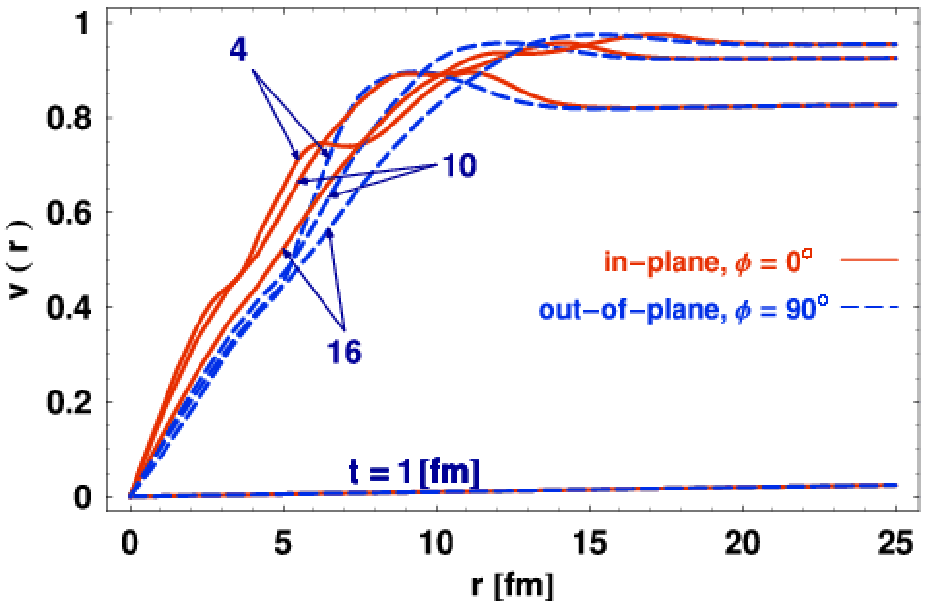


- HIC is expected to go through a Quark Gluon Plasma phase, where matter is strongly interacting – resulting in the development of collective motion
- Radial flow dominates, with elliptic flow as azimuthal modification



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

Describing collectivity: hydrodynamics

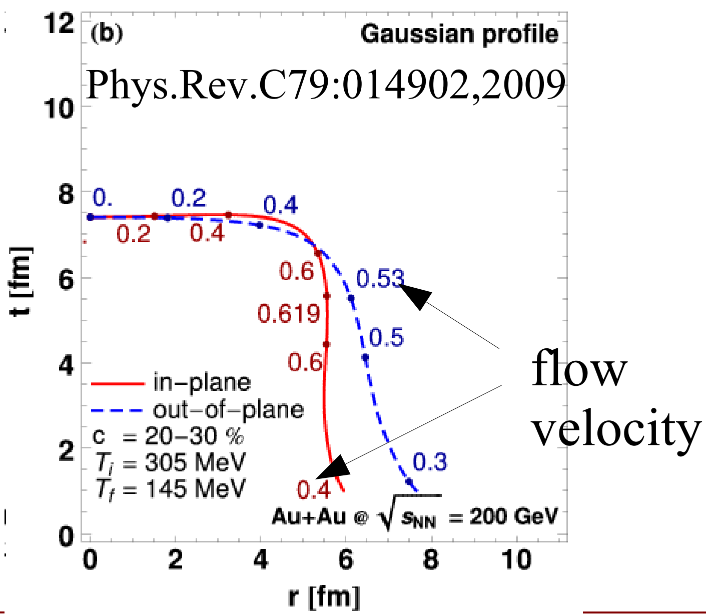


Chojnacki M., Florkowski W.
nucl-th/0603065, Phys. Rev. C74: 034905 (2006)

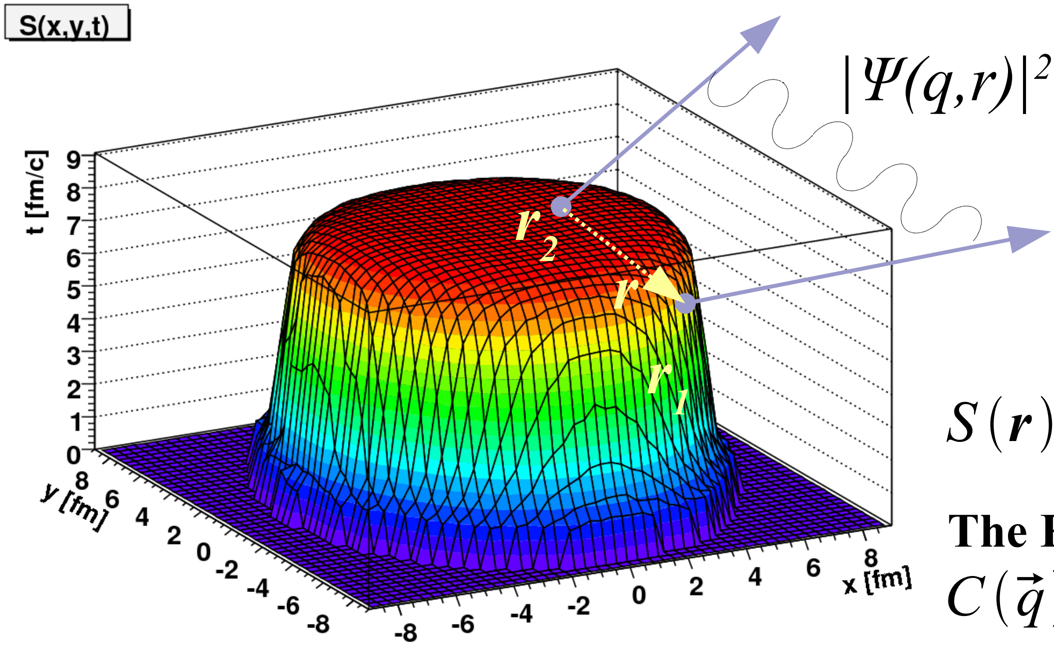
- Hydrodynamics produces collective flow: common velocity of all particles

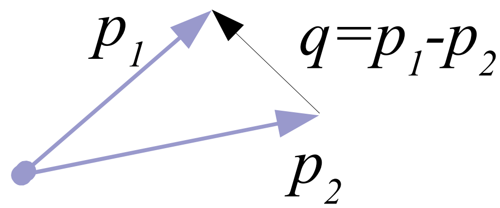
$$\left\langle v_{out} \right\rangle = \left\langle \frac{\vec{v}_T \vec{r}_T}{|\vec{r}_T|} \right\rangle \qquad \left\langle v_{side} \right\rangle = \left\langle \frac{\vec{v}_T \times \vec{r}_T}{|\vec{r}_T|} \right\rangle = 0$$

- The process drives the space-time evolution of the system
- The observables in the momentum sector: particle spectra, elliptic flow are well described with a variety of model parameters.



Measuring space-time extent: femtoscopy





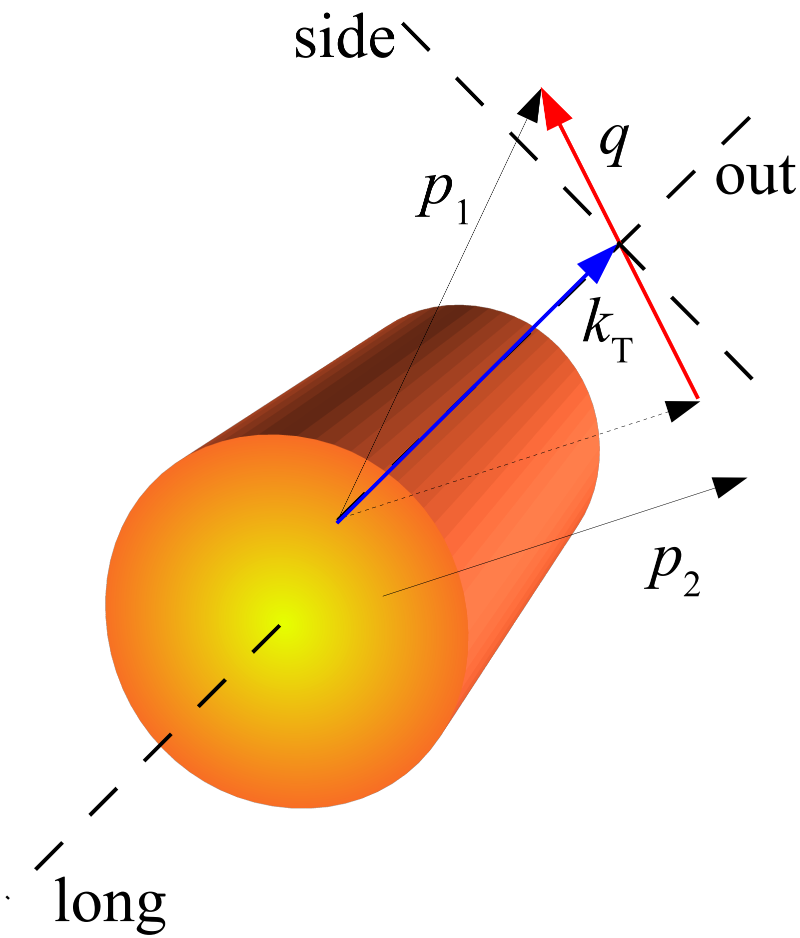
$$S(\mathbf{r})=\int S_a(\mathbf{r_1})S_b(\mathbf{r_2})\delta(\mathbf{r}-(\mathbf{r_1}-\mathbf{r_2}))d^4r_1 d^4r_2$$

The Koonin-Pratt Equation:

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

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.

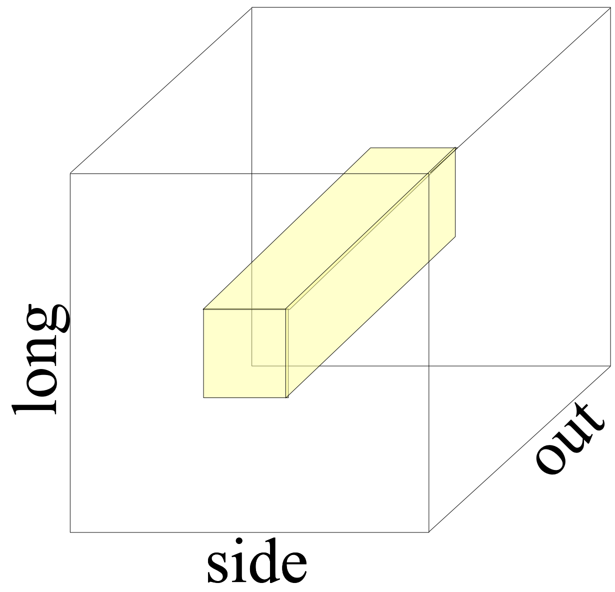
Directions and reference frames



$$m_T = (k_T{}^2 + m_\pi{}^2)^{1/2}$$

- 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.
  - ***side*** is interpreted as "**geometrical size**"
  - ***out*** has additional components from **emission duration**.
  - ***long*** used to extract total **evolution time**.

Representations of the correlation



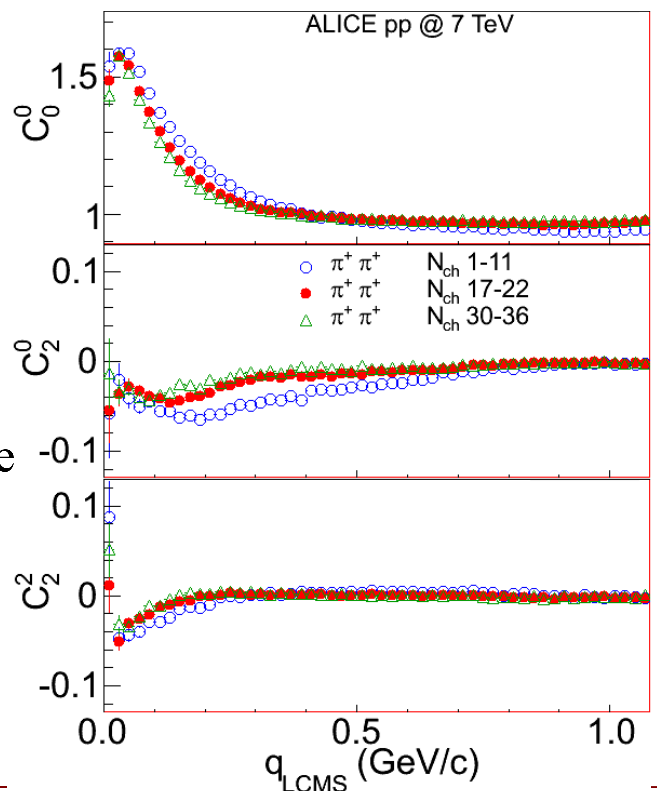
- 3D space can be viewed via 1D projections or spherical harmonics
- Projections used traditionally
- Spherical harmonics have synergy with symmetries of the correlation

$$C_l^m = \int C(\vec{q})\, Y_l^m(\vec{q})$$

C_0^0 - angle averaged similar to 1D CF

C_2^0 - $\cos^2\theta$ weight longitudinal vs. transverse difference

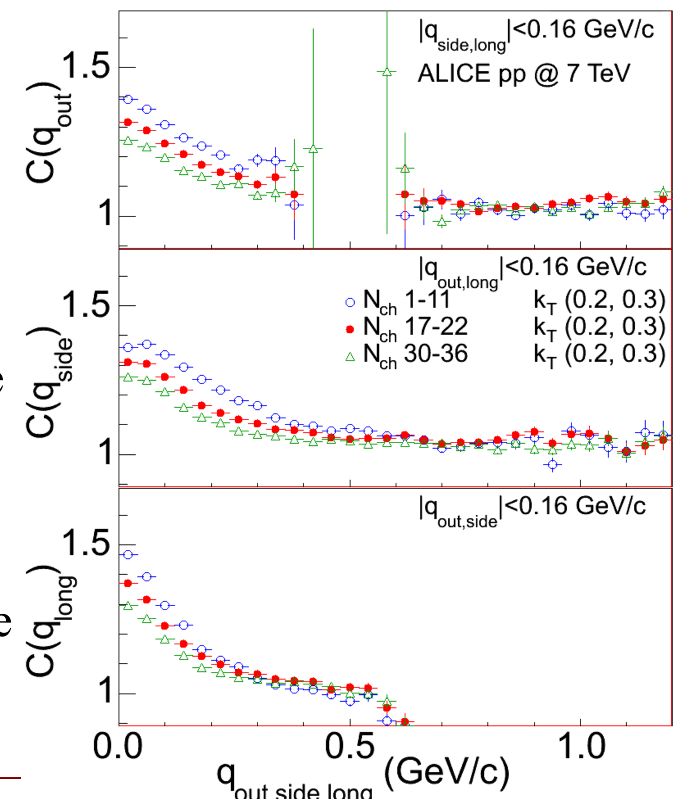
C_2^2 - $\cos^2\varphi$ weight out vs. side difference



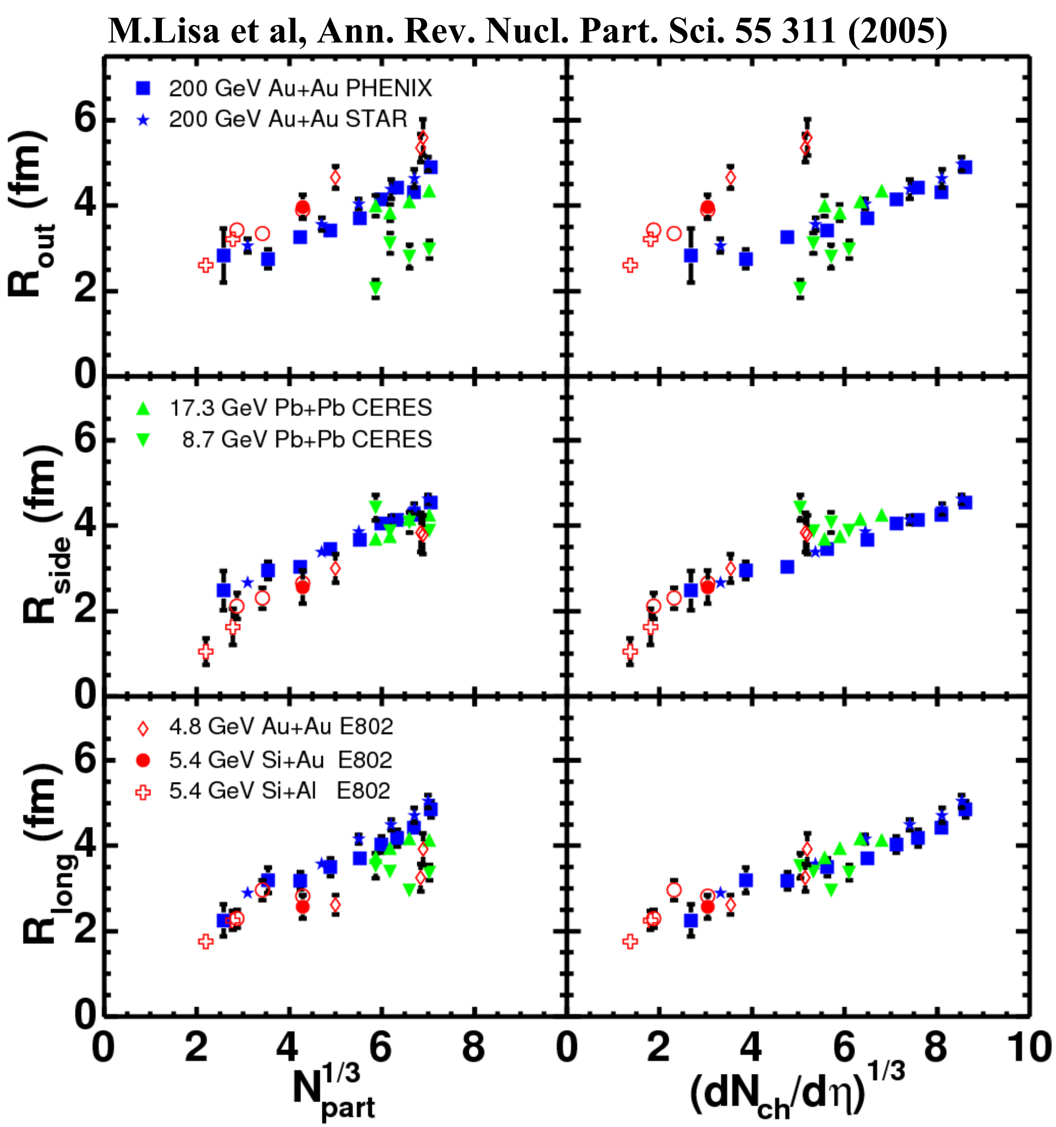
$C(q_{out})$ out size

$C(q_{side})$ side size

$C(q_{long})$ long size

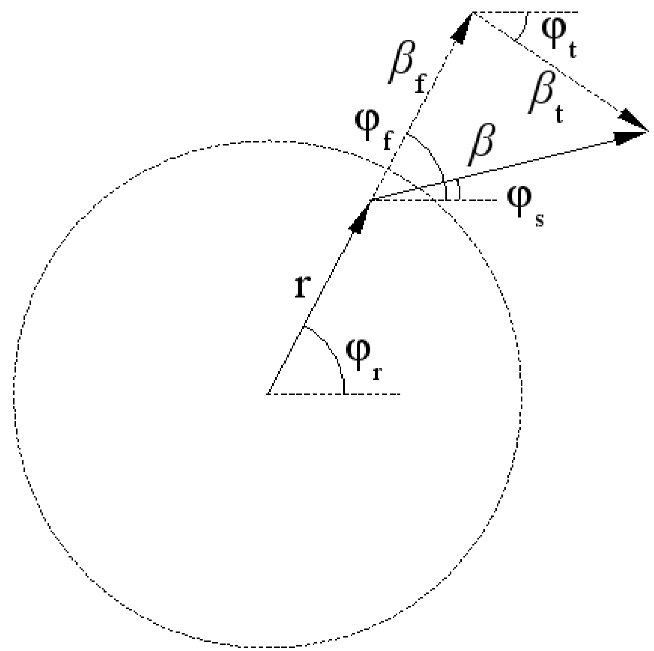


Final state geometry via femtoscopy

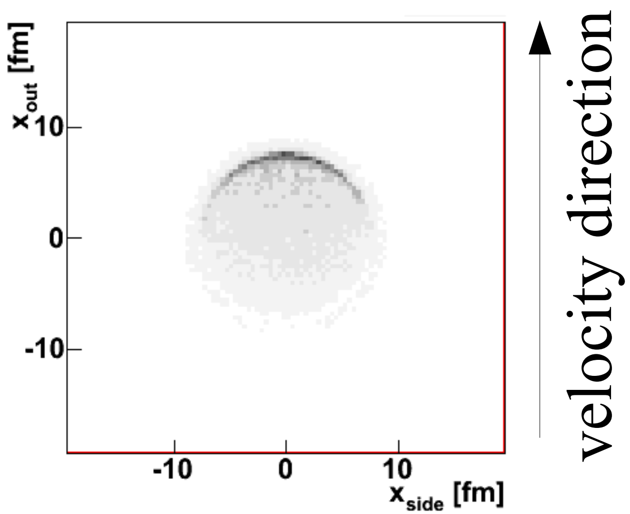


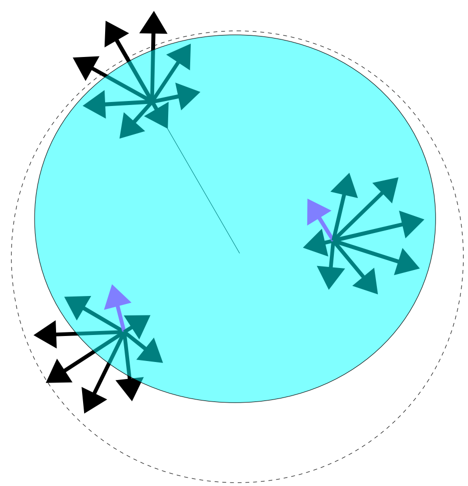
- Sizes measured in heavy-ion collisions scale with the observed particle density
- The scaling is linear over a broad range of system types, collision energies and centralities
- Observed multiplicity is a final state observable, for initial state ones (such as N_{part}) scaling is not as good
- Femtoscopy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

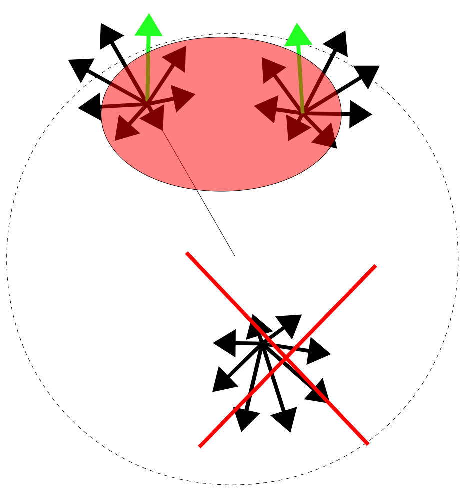
Dynamics via momentum dependence



- A particle emitted from a medium will have a collective velocity β_f and a thermal (random) one β_t
- As observed p_T grows, region emitting such particles gets smaller and shifted to the outside: "lengths of homogeneity". Femtoscopy always measures only the "homogeneity size".

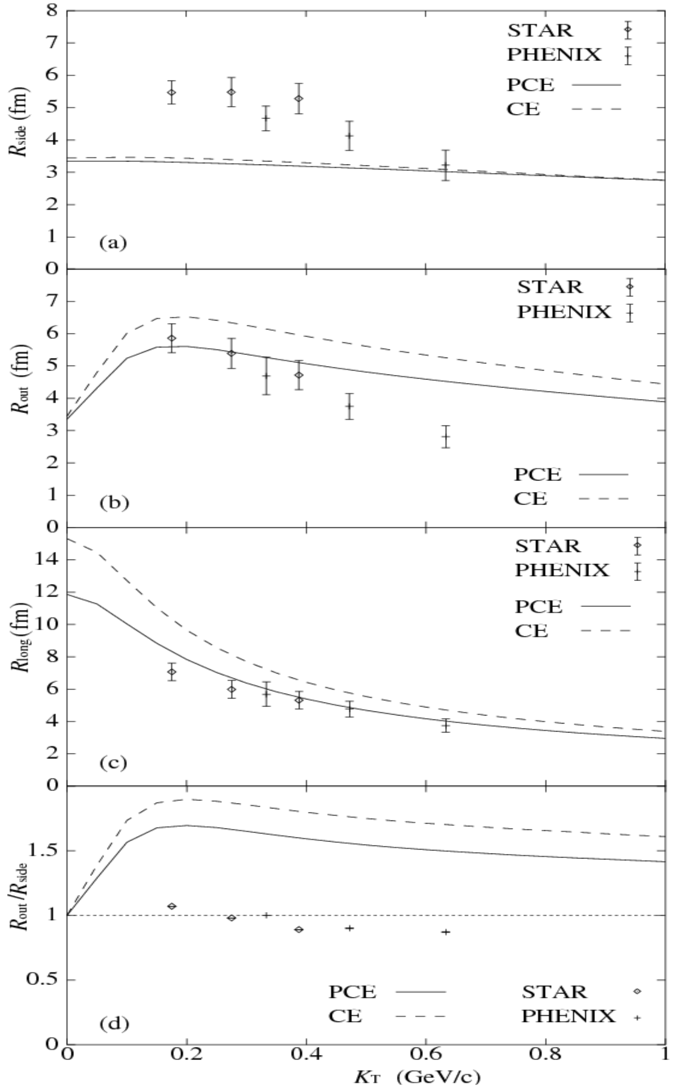




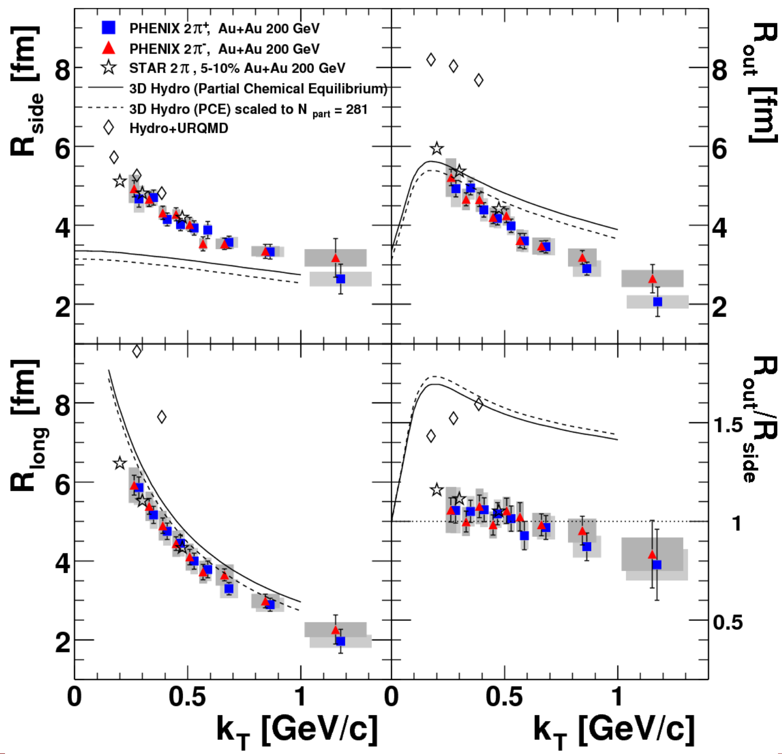


RHIC Hydro-HBT puzzle

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



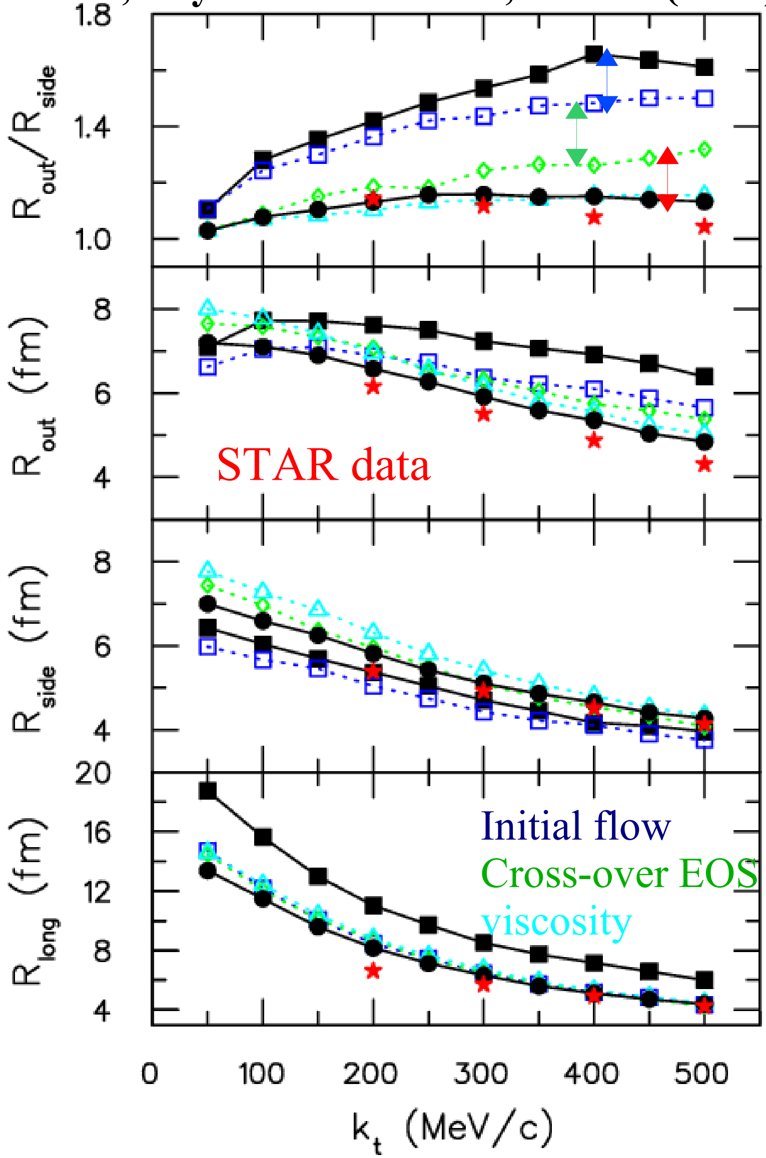
- First hydro calculations struggle to describe femtoscopic data: predicted too small R_{side} , too large R_{out} – too long emission duration
- No evidence of the first order phase transition



U. Heinz, P. Kolb, hep-ph/0204061

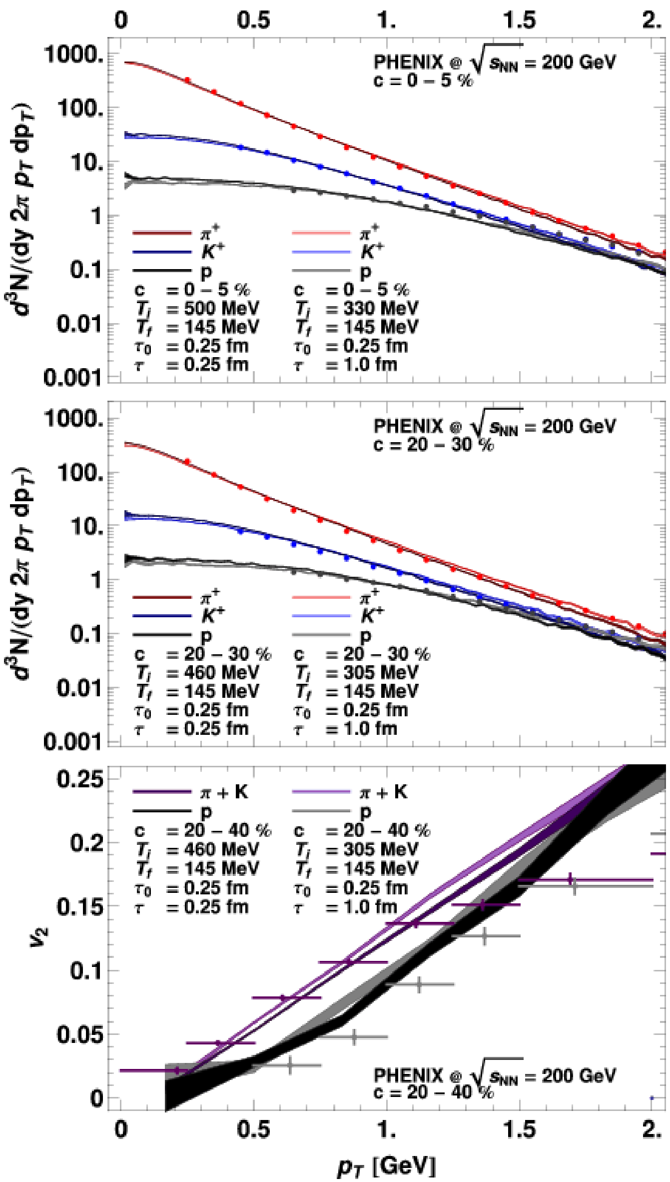
Revisiting hydrodynamics assumptions

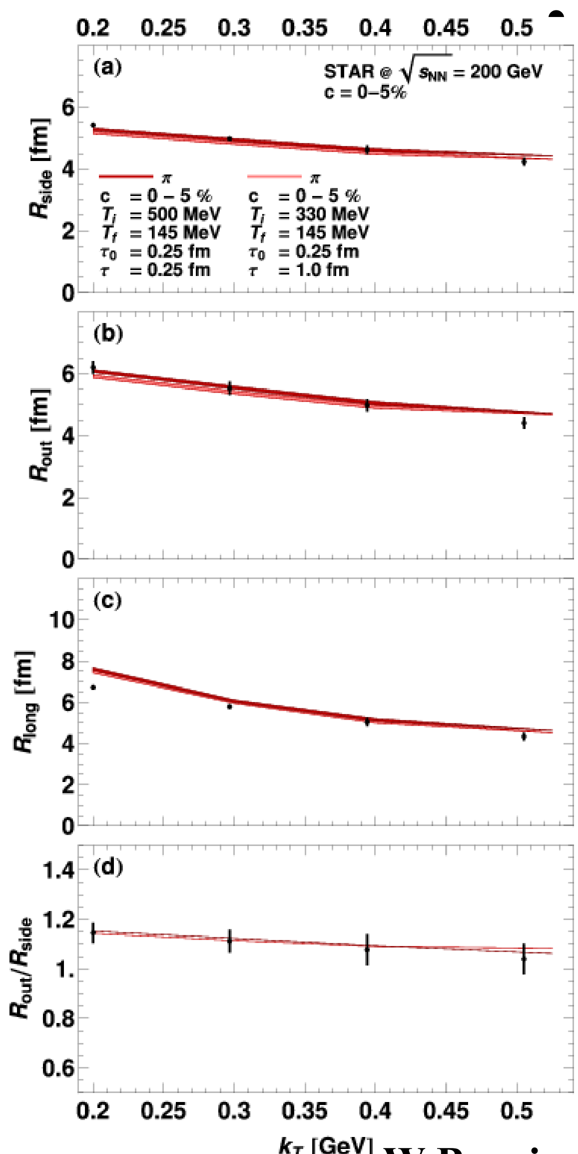
S. Pratt, Phys. Rev. Lett. 102, 232301 (2009)



- Data in the momentum sector (p_T spectra, elliptic flow) well described by hydrodynamics, why not in space-time?
- Usually initial conditions do not have initial flow at the start of hydrodynamics (~1 fm/c) – they should.
- Femtoscopy data rules out first order phase transition – smooth cross-over is needed
- Resonance propagation and decay as well as particle rescattering after freeze-out need to be taken into account: similar in effects to viscosity

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

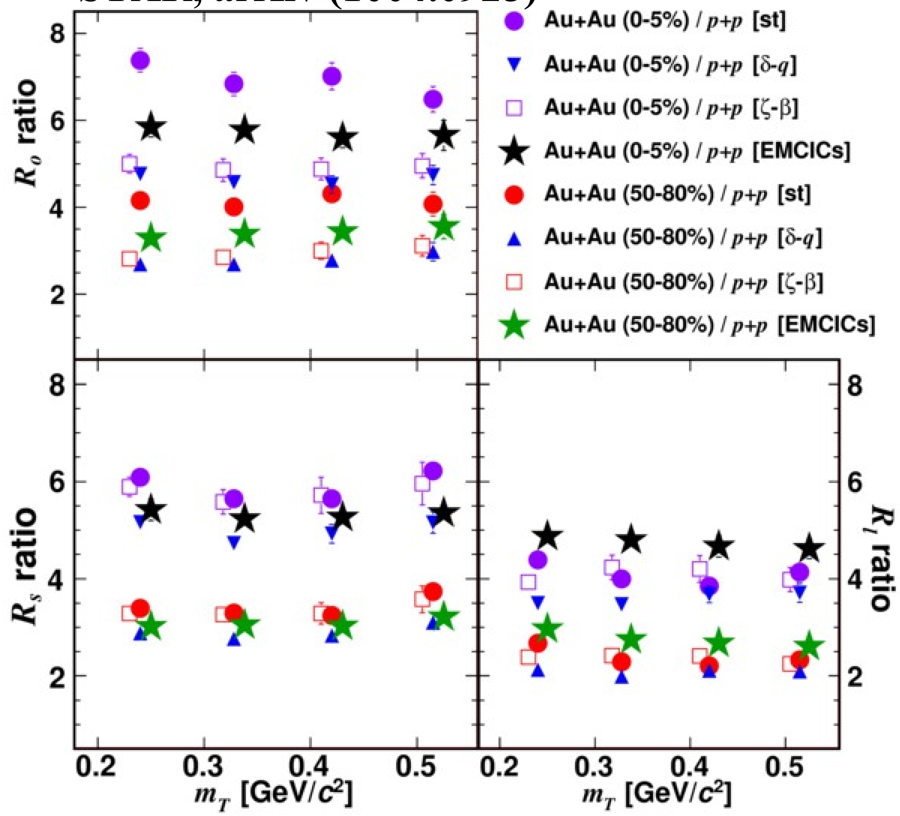
RHIC HBT puzzle solved: soft sector data at RHIC understood in detail

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

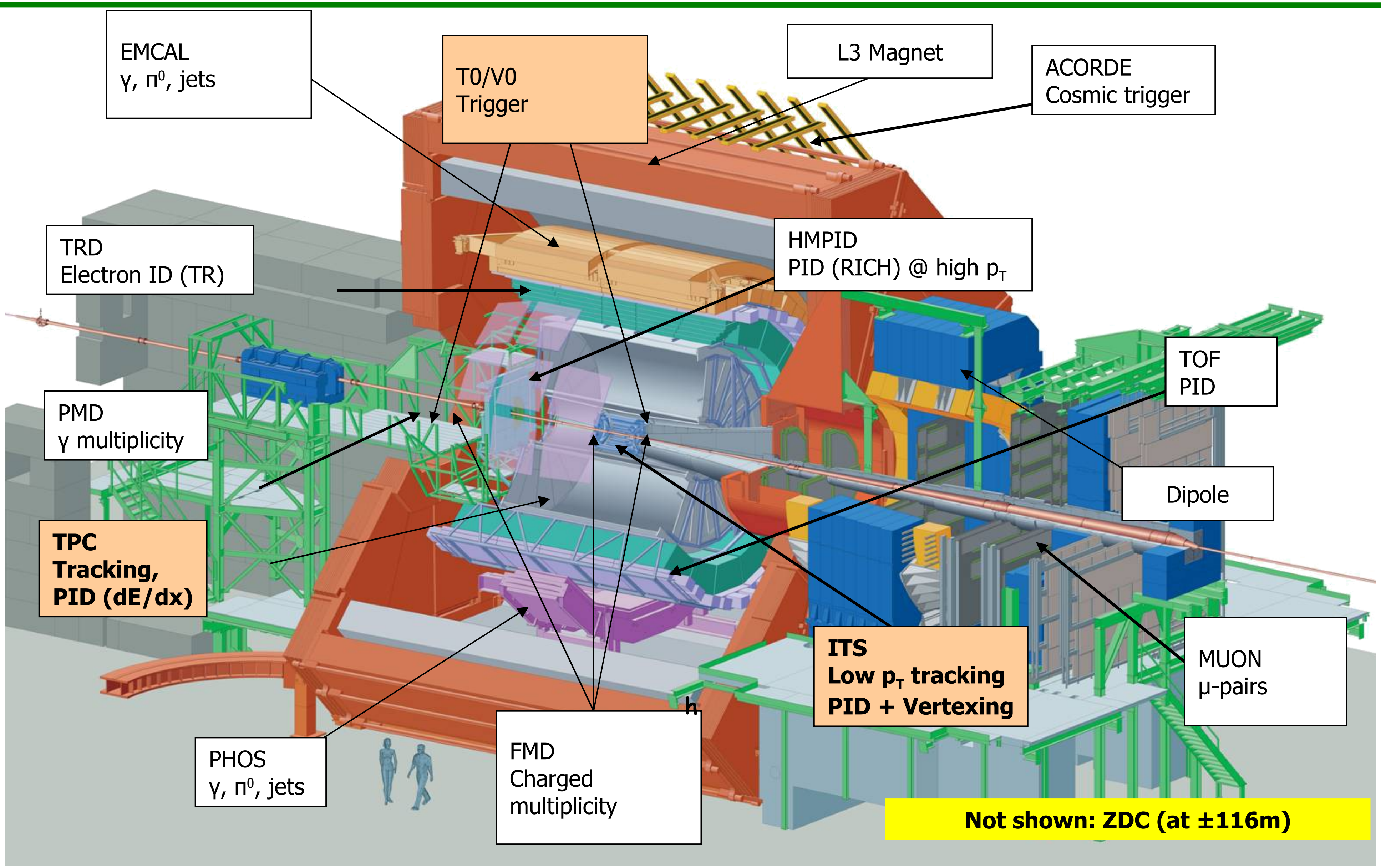
Physics case for femtoscopy in p+p

- STAR reports that 3D HBT radii scale in p+p in a way very similar to Au+Au
- Is the scaling between p+p and Au+Au a signature of the universal underlying physics mechanism (collective flow) or a coincidence?
- Femtoscopy characterizes the final state – will help understand the hadronization schemes
- Is a crucial reference (and warm-up) for the heavy ion analysis

STAR, arXiv (1004.0925)

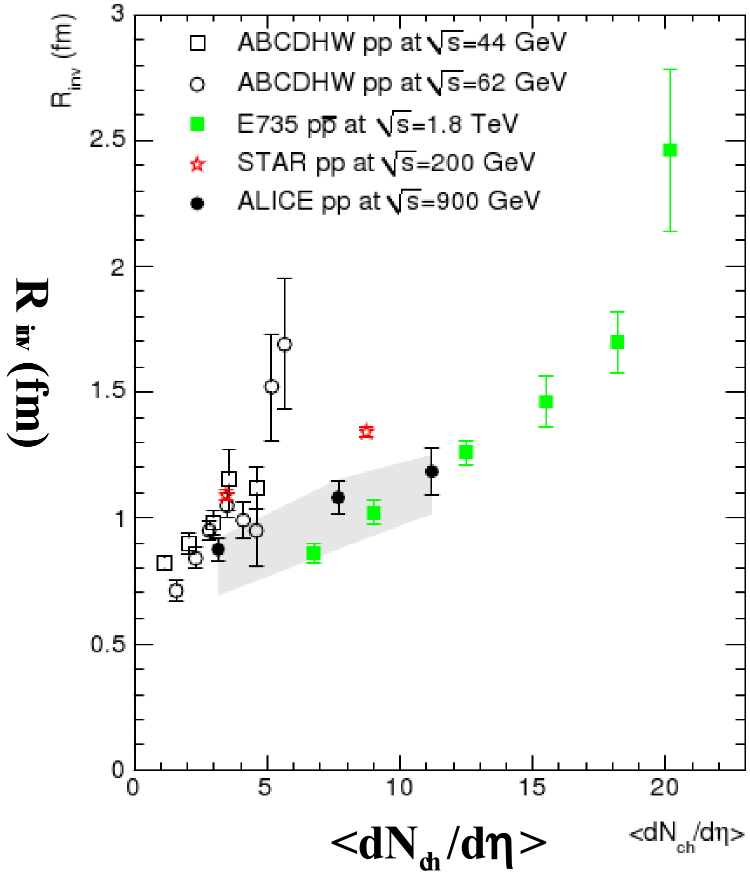


The ALICE detector

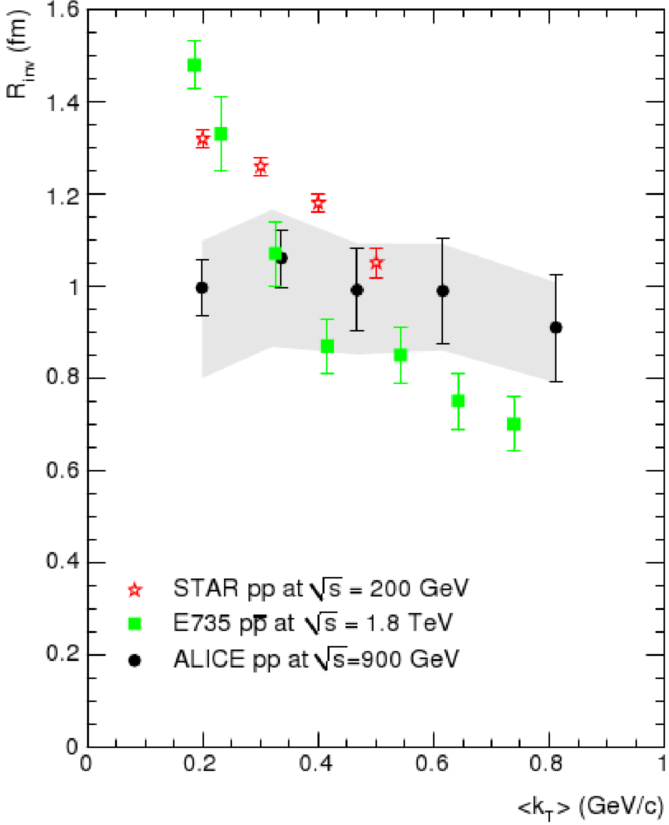


First look at system size at 0.9 TeV

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

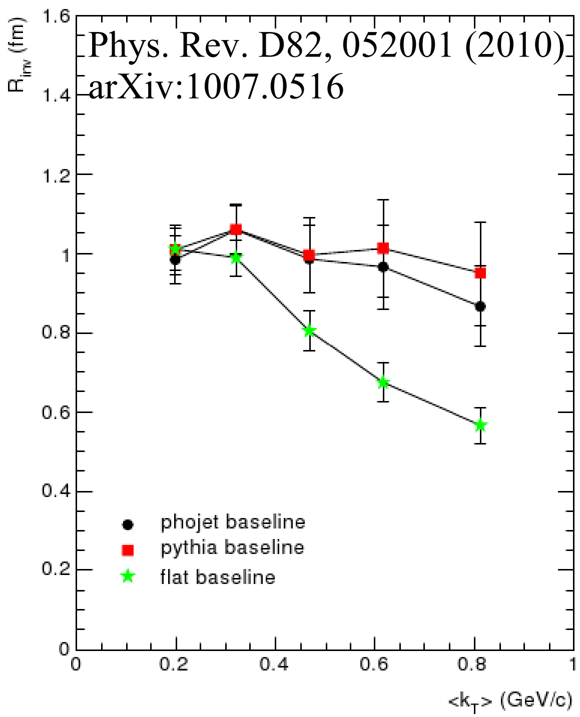


- 250k minimum-bias triggered events analyzed (full 2009 sample)
- ALICE observes the growth of the system size with multiplicity
- The results are given as a function of pseudorapidity density and can be compared to world systematics
- The observed trend is qualitatively similar to world data, but quantitative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



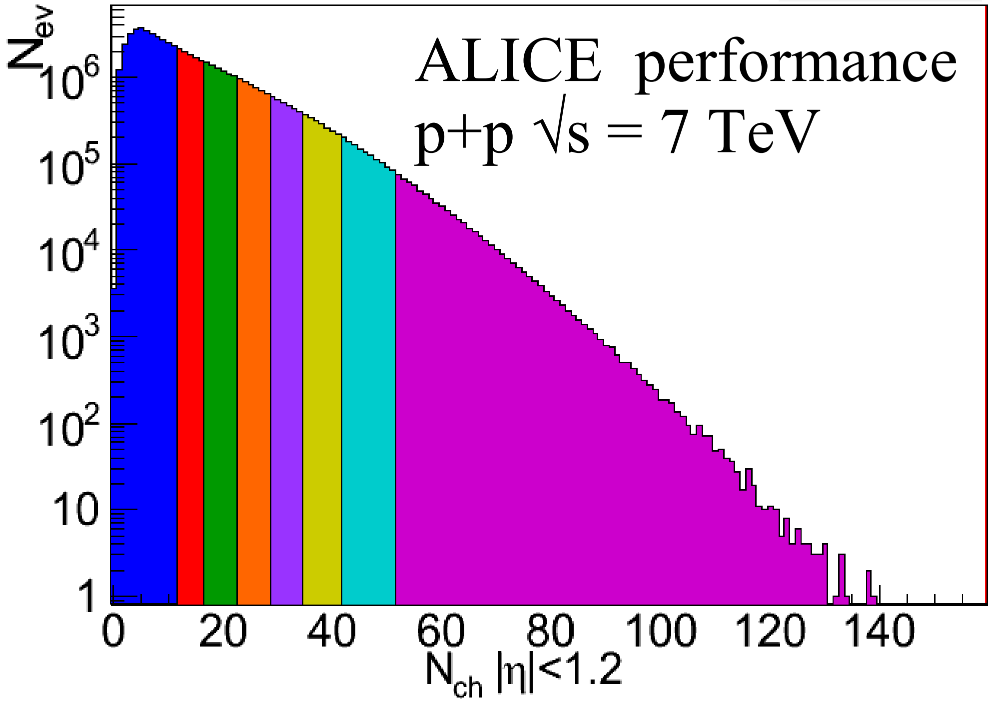
Pair momentum dependence

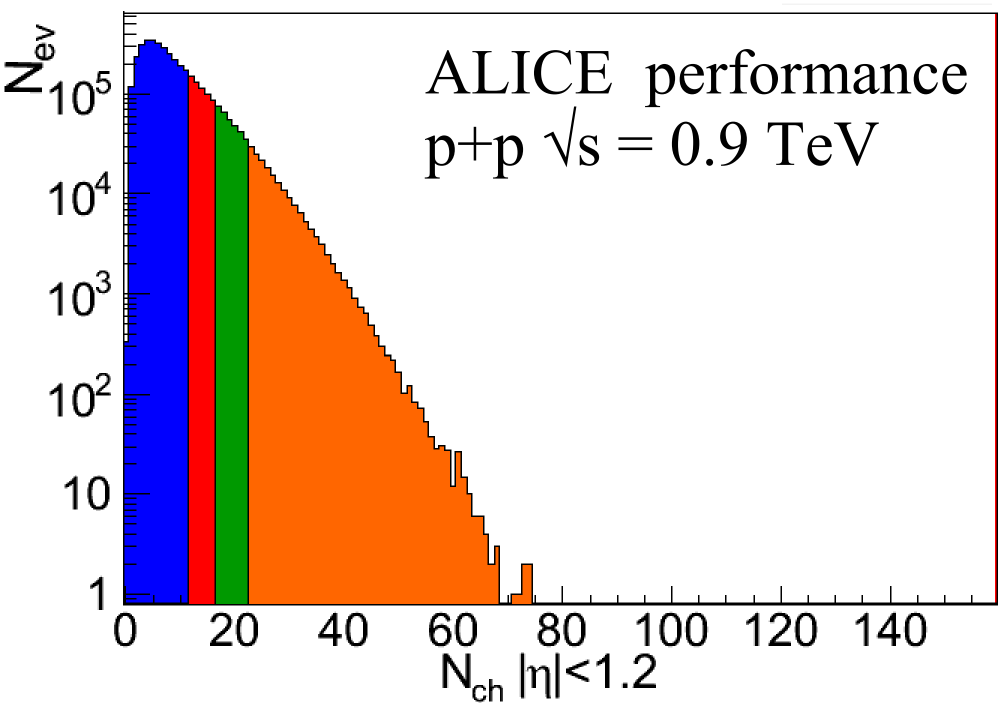
- First attempt in measuring pair momentum dependence limited by statistics and systematics
- Dominating systematic effect: appearance of "mini-jet" non-femtoscopic correlations at large p_T
- Integrated R_{inv} shows flat behaviour, but only if the systematic effects are treated properly
- Discrepancy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



ALICE p+p data taking in 2010

- ALICE has been taking data continuously since March 2010.
- A high statistics sample of pp 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 binning

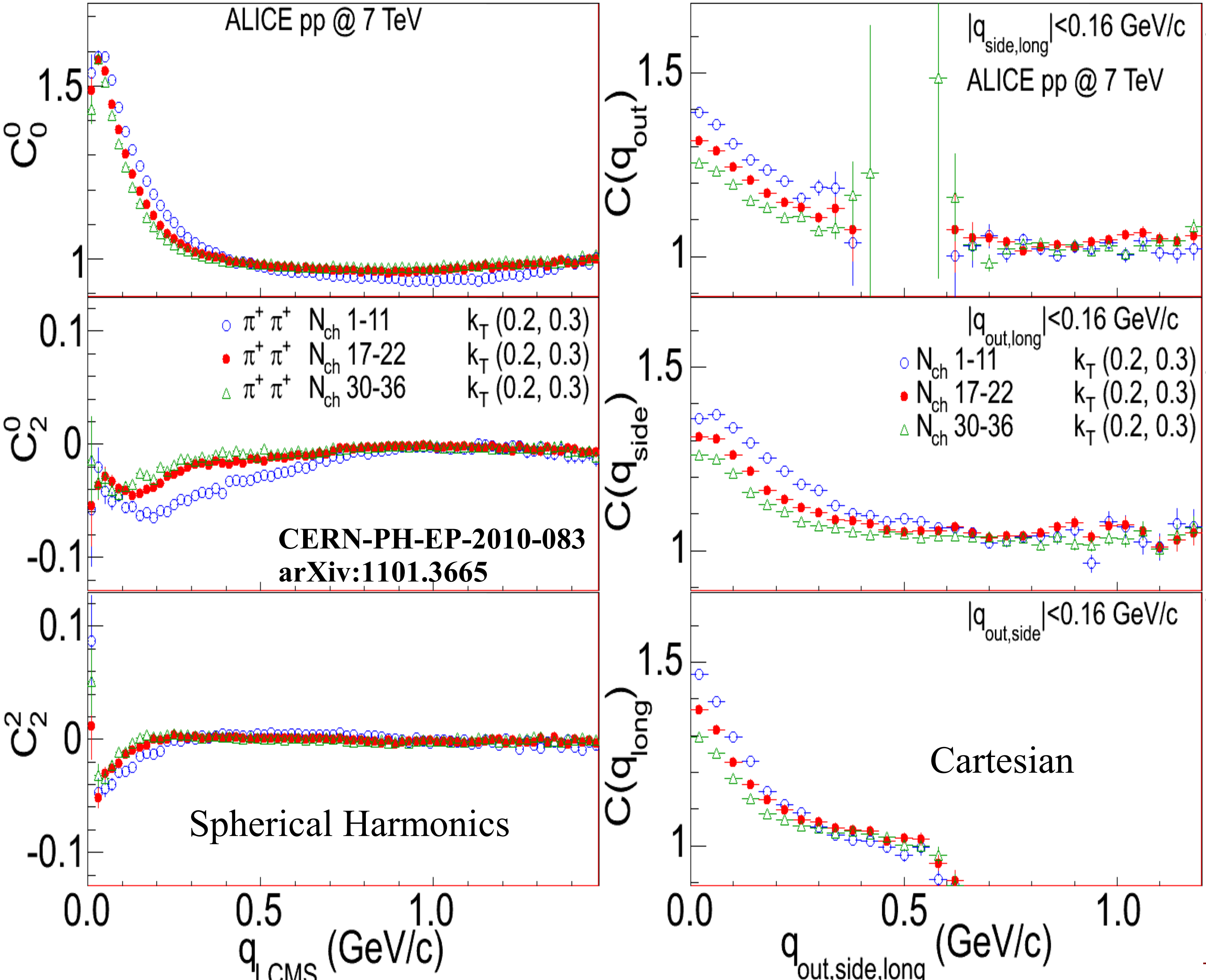
- Bins with equal pair multiplicity

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

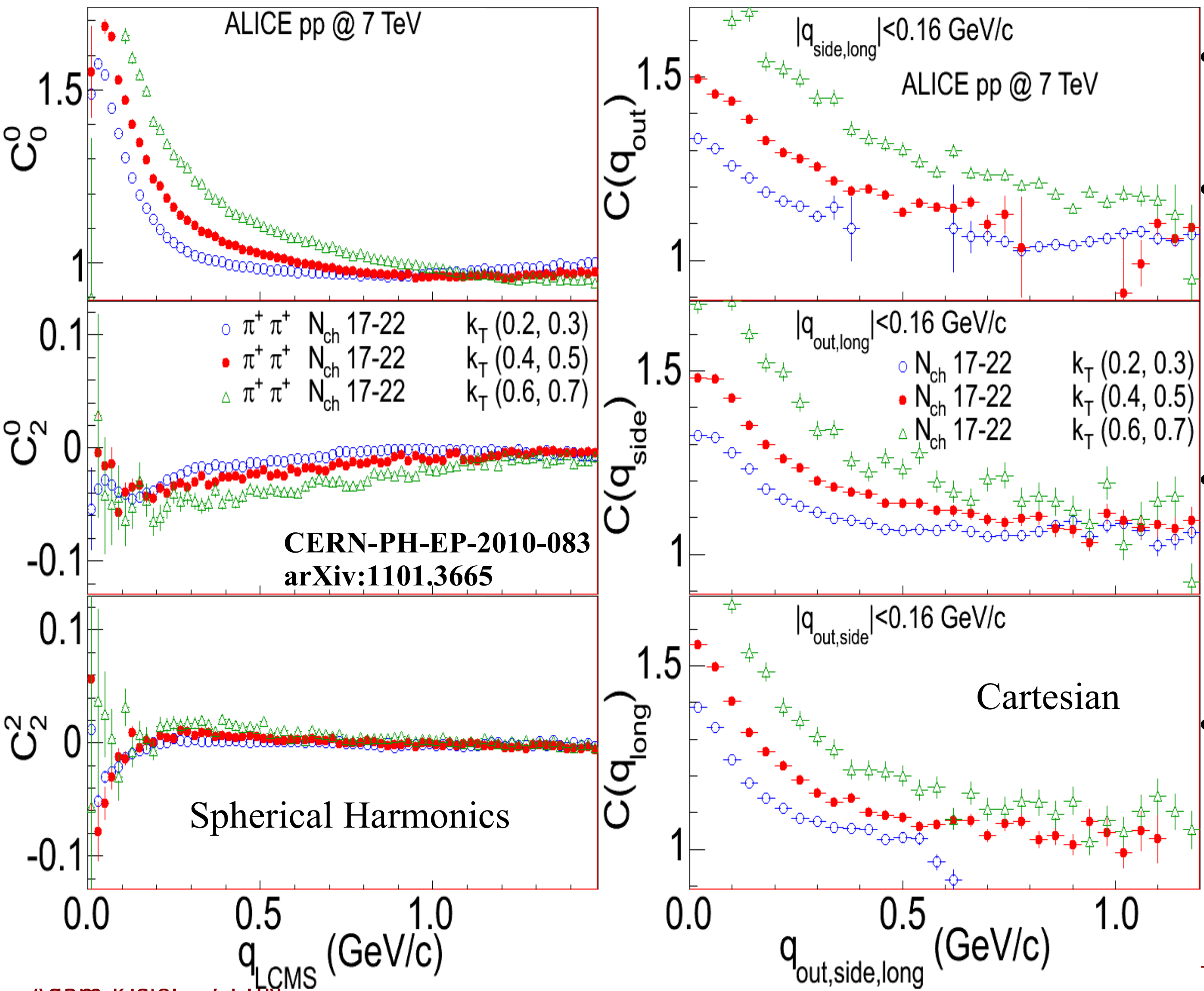
CERN-PH-EP-2010-083, arXiv:1101.3665

Multiplicity dependence of the correlation function



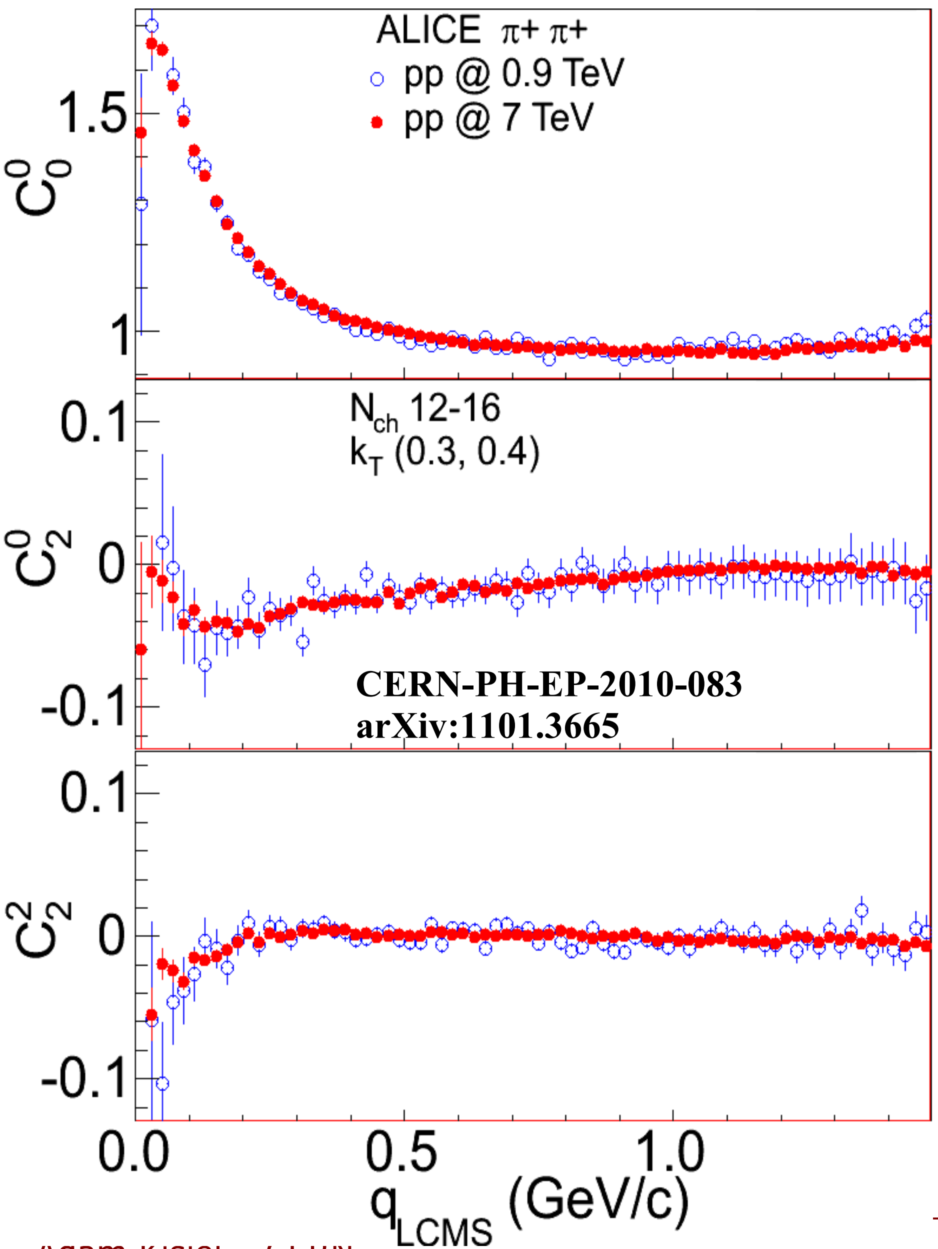
- Dependence of the CF on multiplicity visible, not strong
- Large holes in the acceptance in certain k_T bins
- Consistent behavior for Spherical Harmonics and cartesian CFs

k_T dependence of the correlation function



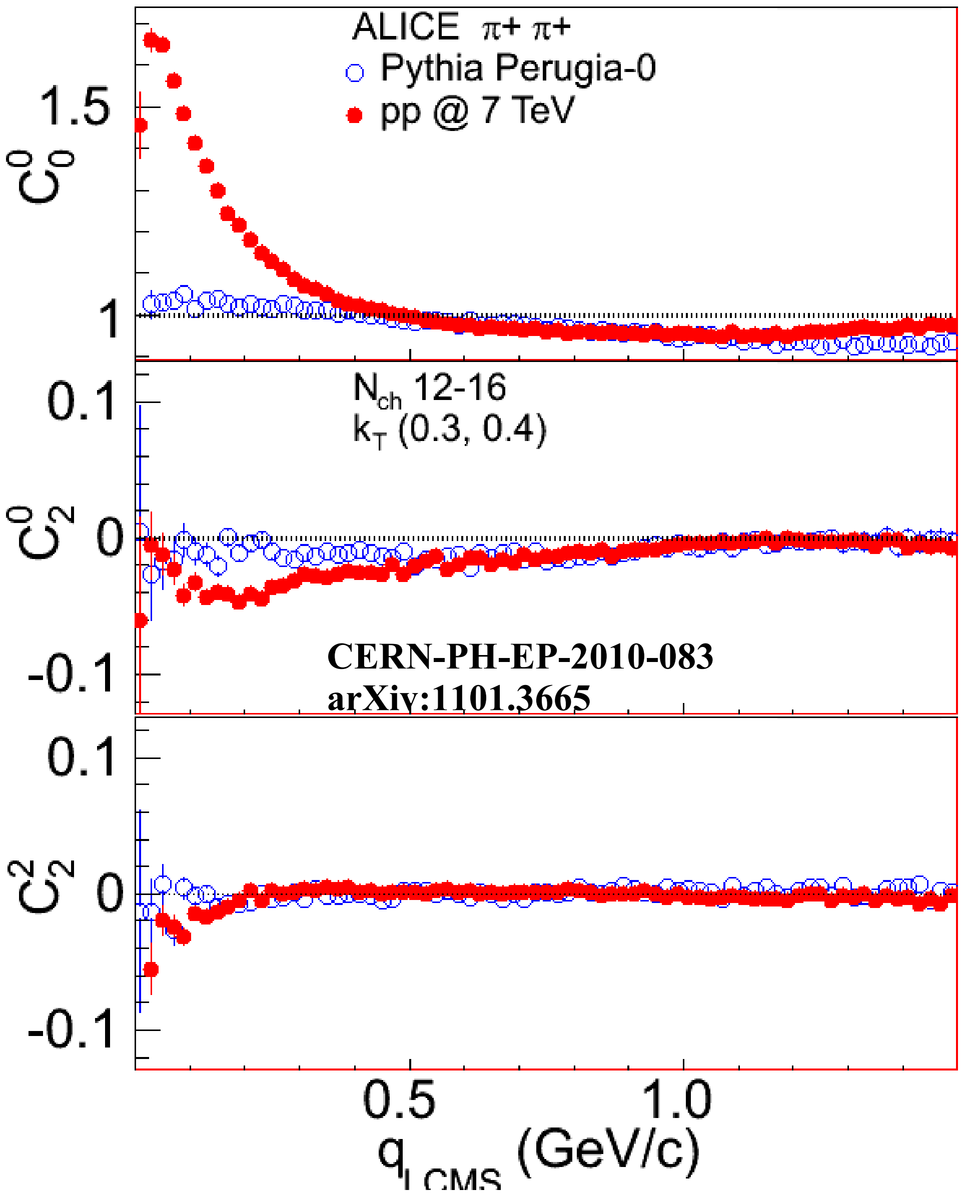
- Dependence on k_T visible, stronger
- Acceptance holes in the CF depend directly on k_T (kinematics cut effect)
- Additional structures appear in the correlation at higher k_T ranges
- Extraction of the k_T dependence of the radii complicated by the need to account for the background

Energy dependence of the correlation function



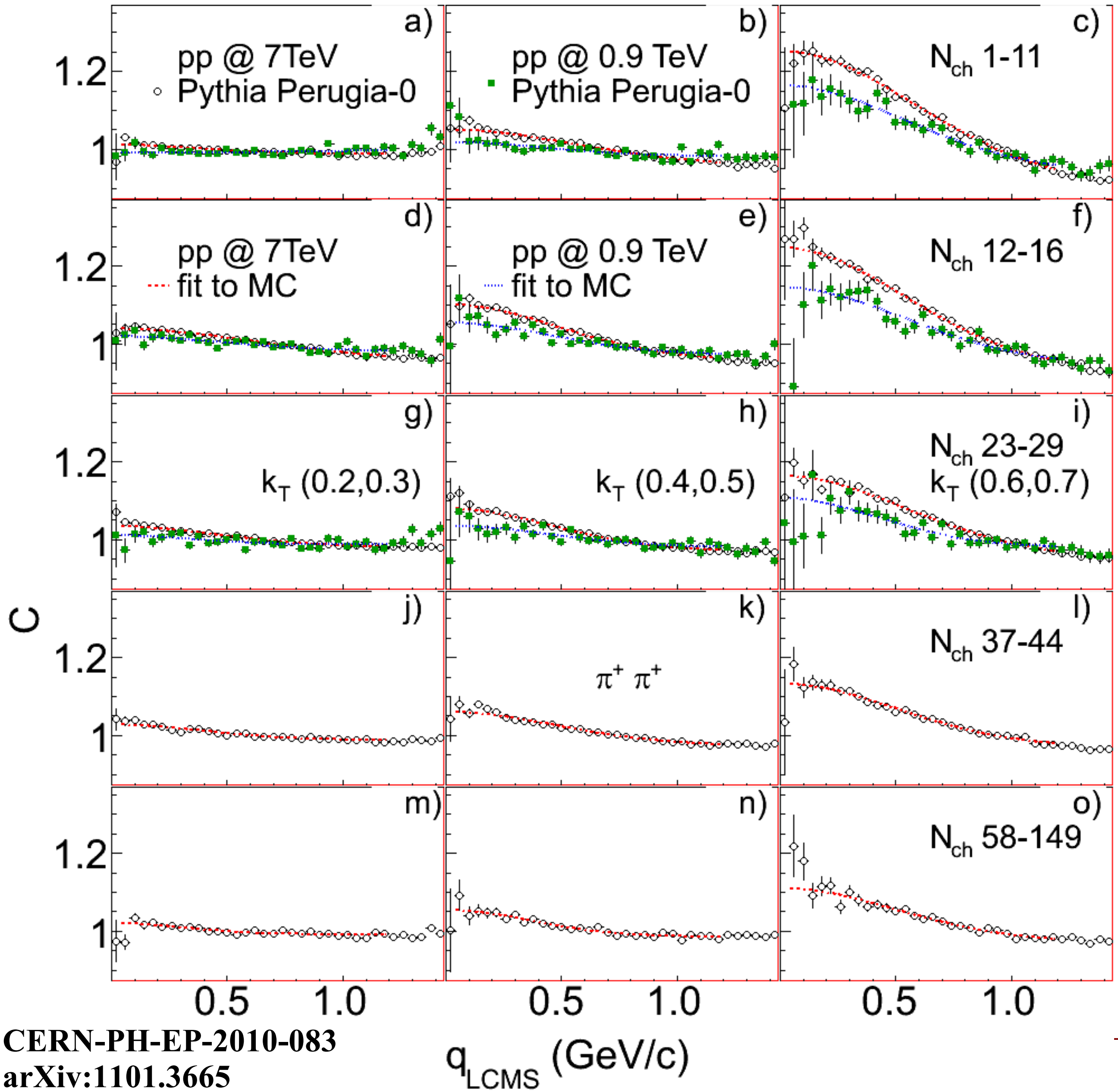
- Correlation functions for 0.9 TeV and 7 TeV, for same multiplicity and k_T bins similar
- 3D shape ($C_2^{\ 0}$ and $C_2^{\ 2}$ components) also consistent
- Checked all multiplicity/k_T bins - all show comparable similarity
- First important finding: the scaling variables are the total event multiplicity 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 $C_0^{\,0}$ and $C_2^{\,0}$
- 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 current hypothesis for the background origin: "mini-jets"

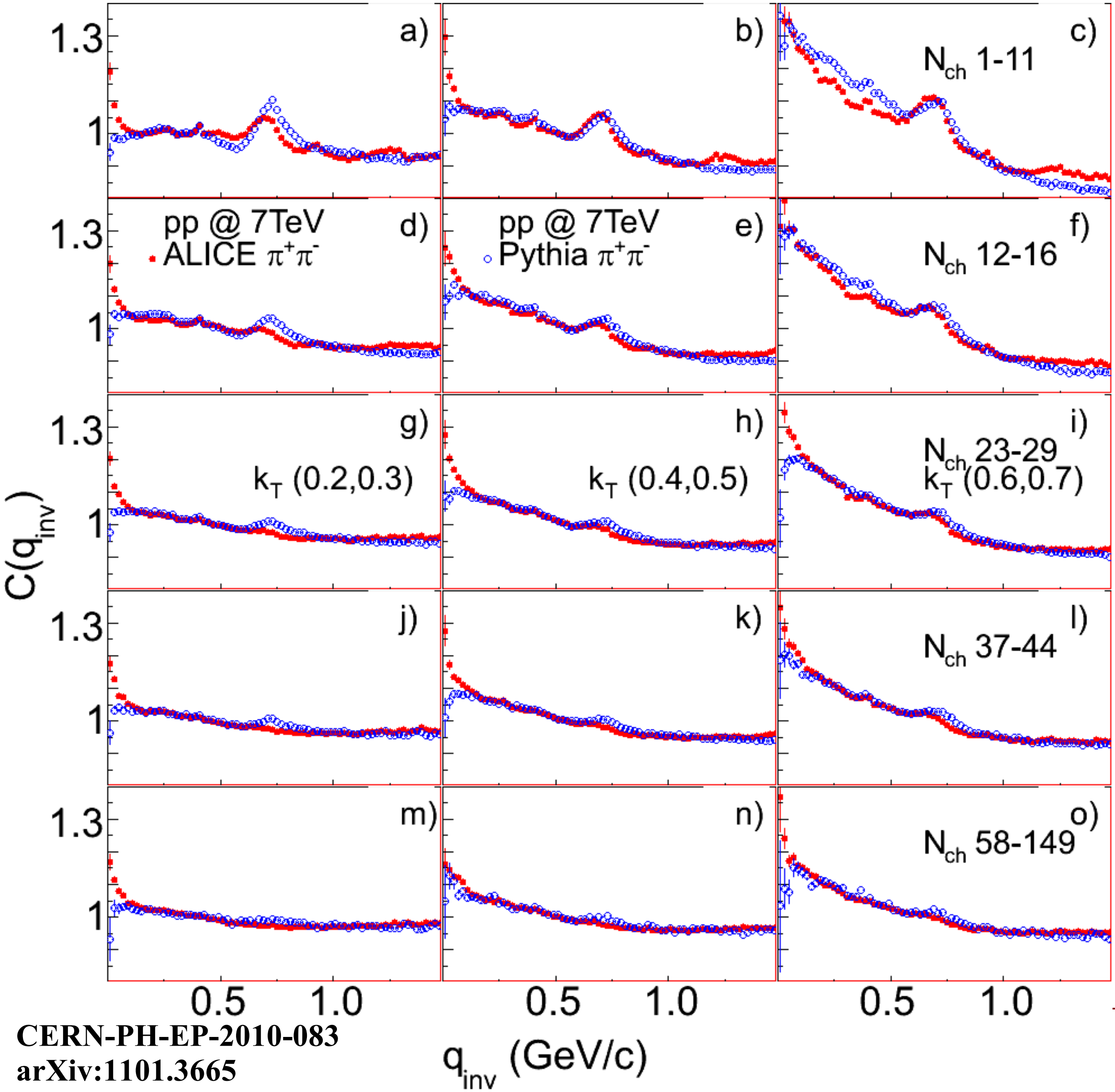
The baseline in Pythia (Perugia-0)



CERN-PH-EP-2010-083
arXiv:1101.3665

- Pythia Perugia-0 tune background fitted with a 3D Gaussian peak with equal radii in LCMS
- Width of the peak varies by only 10% between multiplicity, k_T bins
- 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
arXiv:1101.3665

- Reasonable match between Pythia and data across multiplicity and k_T bins
- 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 the functional form of the source S to be postulated.

- The 3D Gaussian is commonly used in heavy-ions.

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

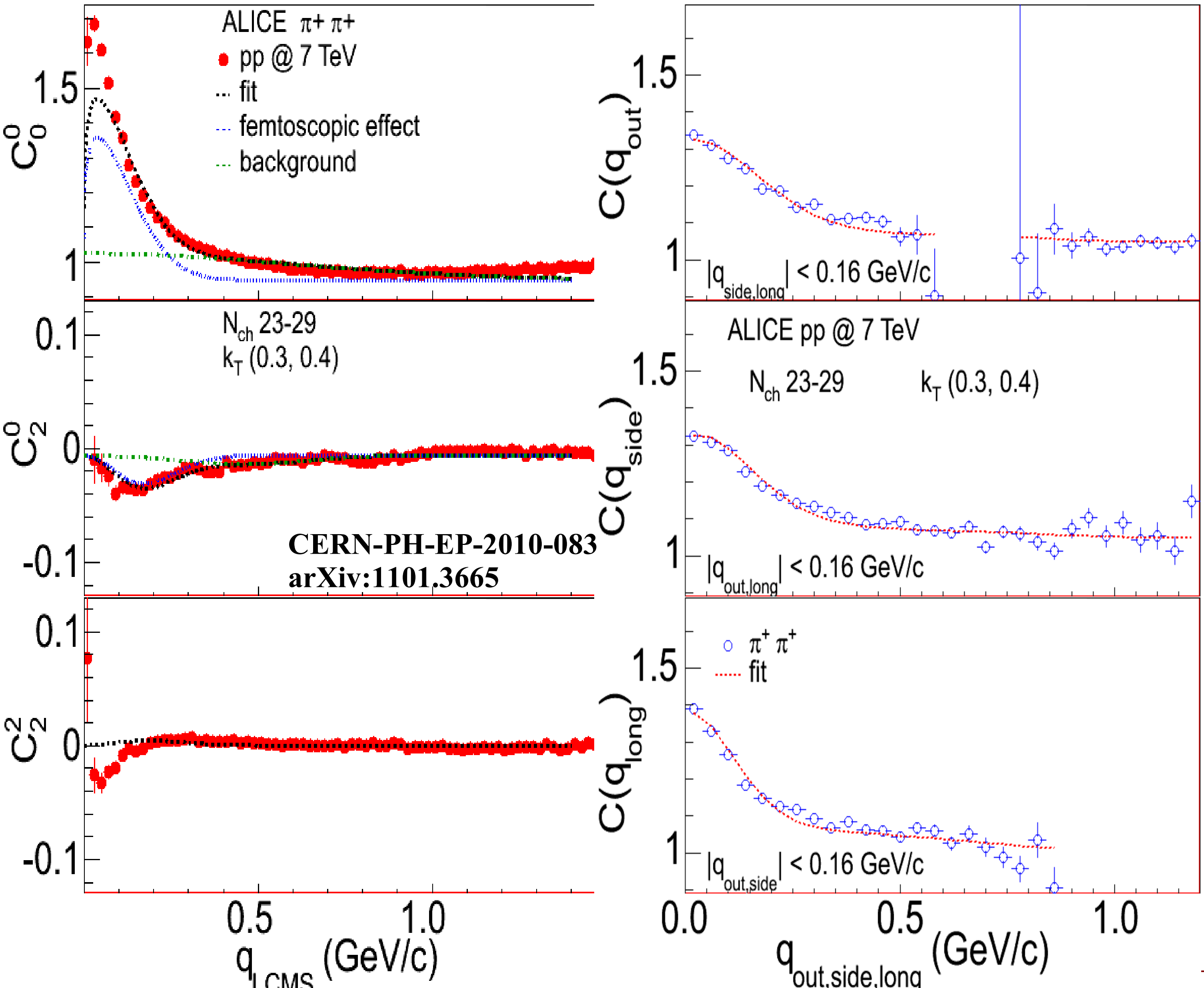
$$C = (1-\lambda) + \lambda K \left(1 + \exp(-R_{out}^2 q_{out}^2 - R_{side}^2 q_{side}^2 - R_{long}^2 q_{long}^2)\right)$$

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

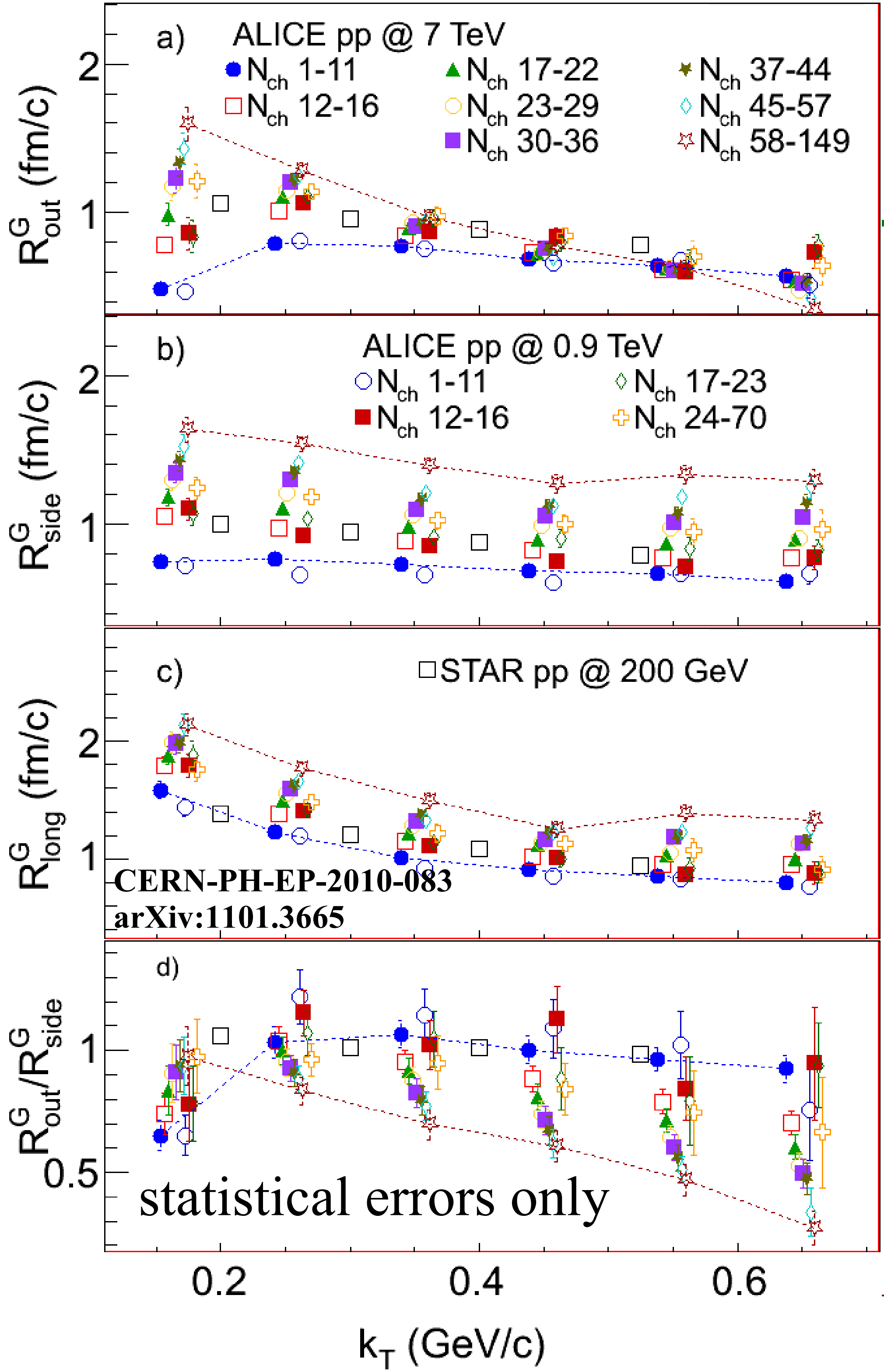
- We need to add the non-femtoscopic background and normalization for the final version of the fit function:

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

3D Fitting example: Gaussian



- Background B fixed to MC fit. Significant contribution seen
- Width reasonably described
- *Out*/*side*/*long* radii can be obtained both from SH and cartesian fits
- Fit undershoots at low q (Gaussian not perfect)

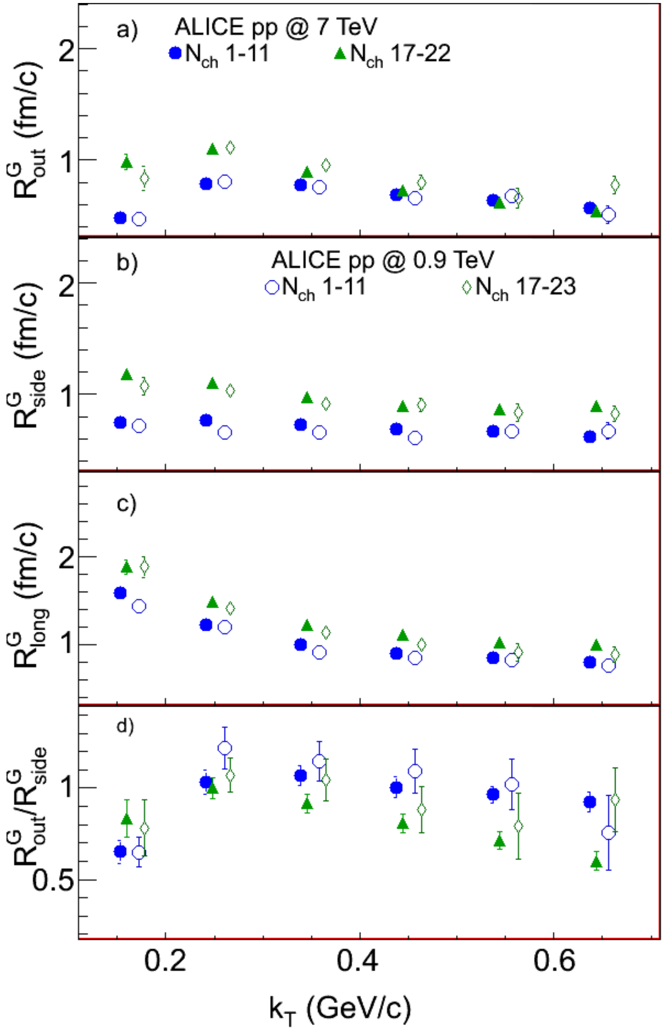


Gaussian radii at 0.9 and 7 TeV

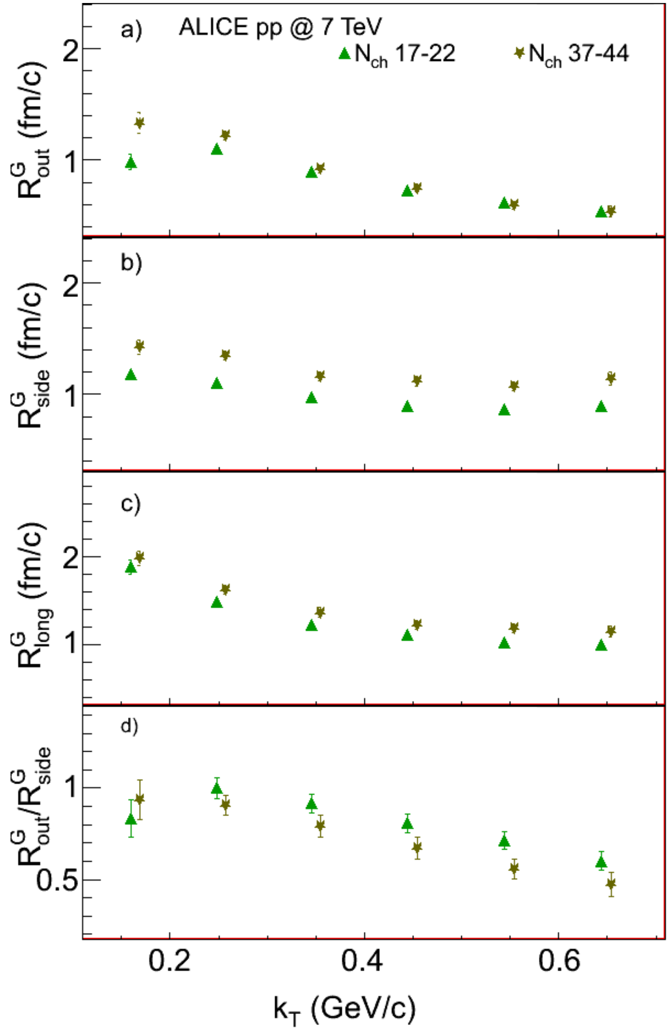
- Gaussian radii in LCMS grow with multiplicity, fall with k_T
- Fall with k_T very prominent for R_{long} , develops with multiplicity for R_{out} , less pronounced for R_{side}
- The different evolution of R_{out} and R_{side} reflected in low R_{out}/R_{side} values – p+p vs. A+A scaling not obvious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

Main trends in the data

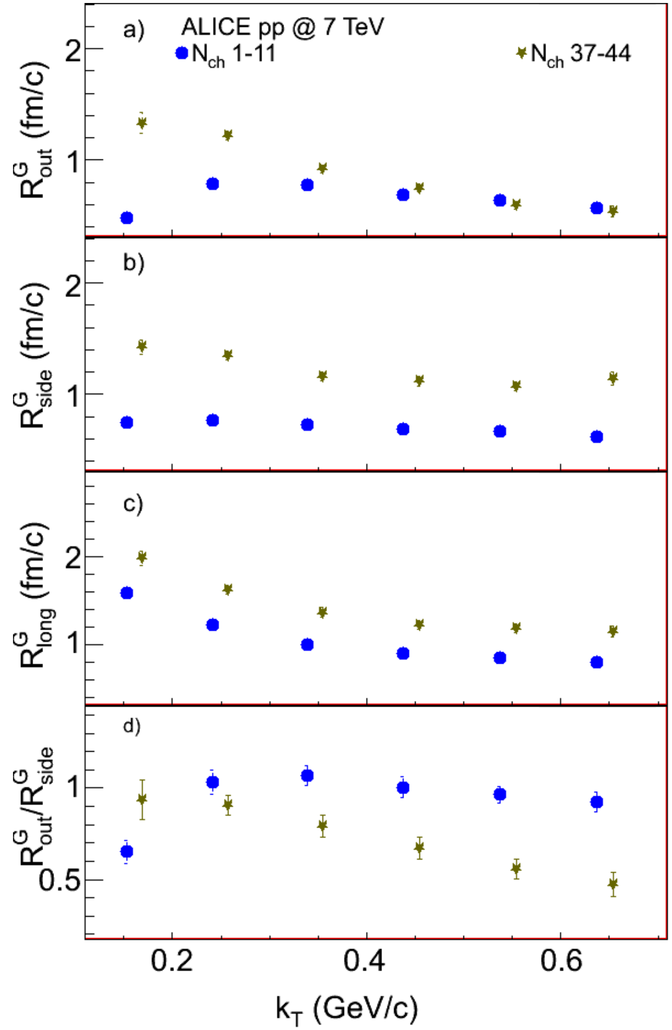
- Collision energy independence



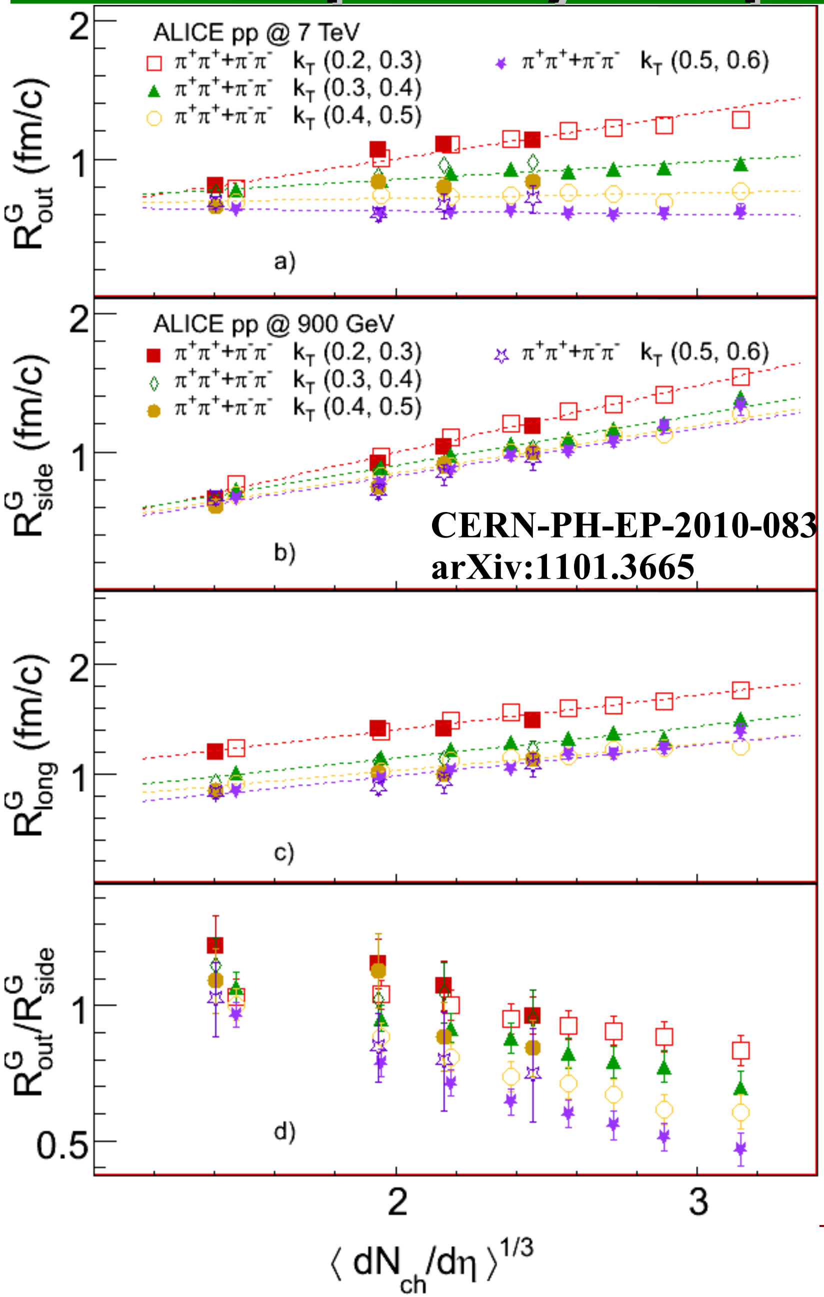
- Radius decreasing with pair momentum



- Change of behavior with multiplicity

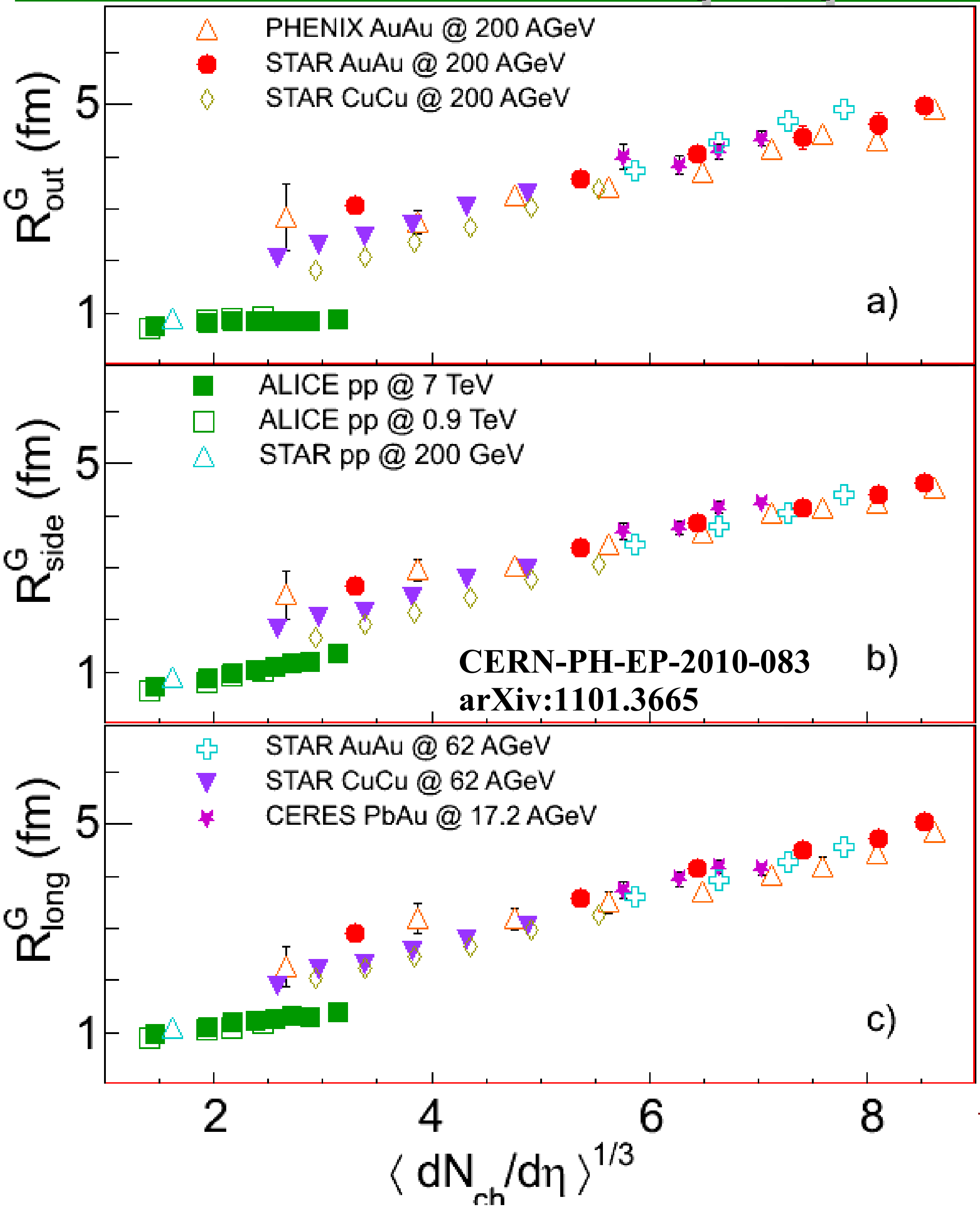


Multiplicity dependence of gaussian radii



- Test if the data scales linearly with $dN/d\eta^{1/3}$ for all energies, separately for each k_T bin.
- 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 for all pair momenta, in *out* the gradient strongly depends on pair momentum

ALICE p+p vs. heavy-ions



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

Better functional form

- The Gaussian source function is clearly oversimplified – the correlation shape is not described in detail
- One can assume the emission function factorizes:

$$S(r_{out}, r_{side}, r_{long}) = S_o(r_{out}) S_s(r_{side}) S_l(r_{long})$$

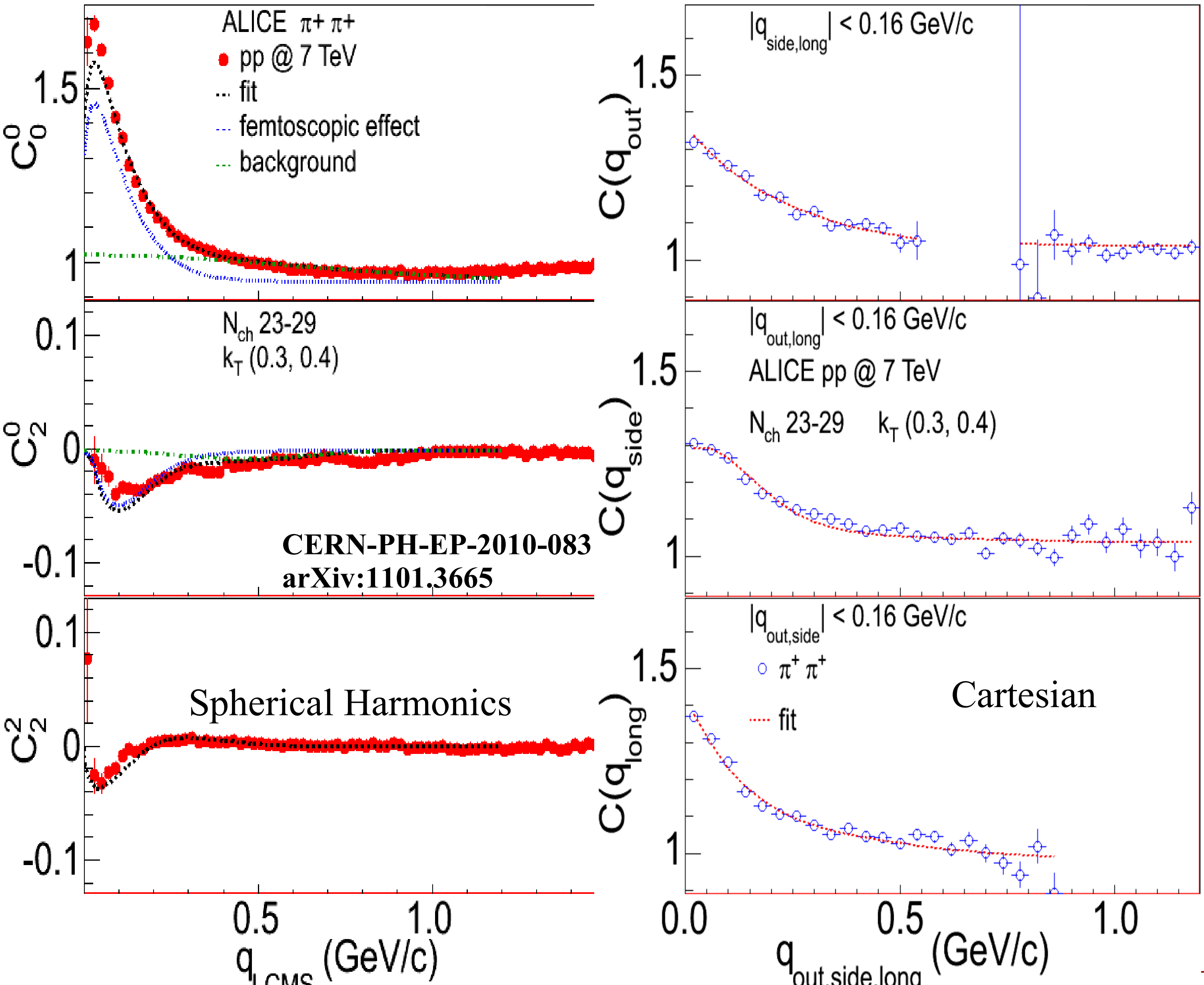
- Which factorizes the femtoscopic part of the correlation function

$$C(q_{out}, q_{side}, q_{long}) = 1 + \lambda C_o(q_{out}) C_s(q_{side}) C_l(q_{long})$$

- Models predict that large fraction of pions comes from resonance decays. Exponential decay time is transformed into space in directions with non-vanishing pair momentum (out and $long$). Combination of many exponents from different resonances gives Lorentzian source function, producing Exponential correlation. Our function of choice is then:

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

3D non-gaussian fit example

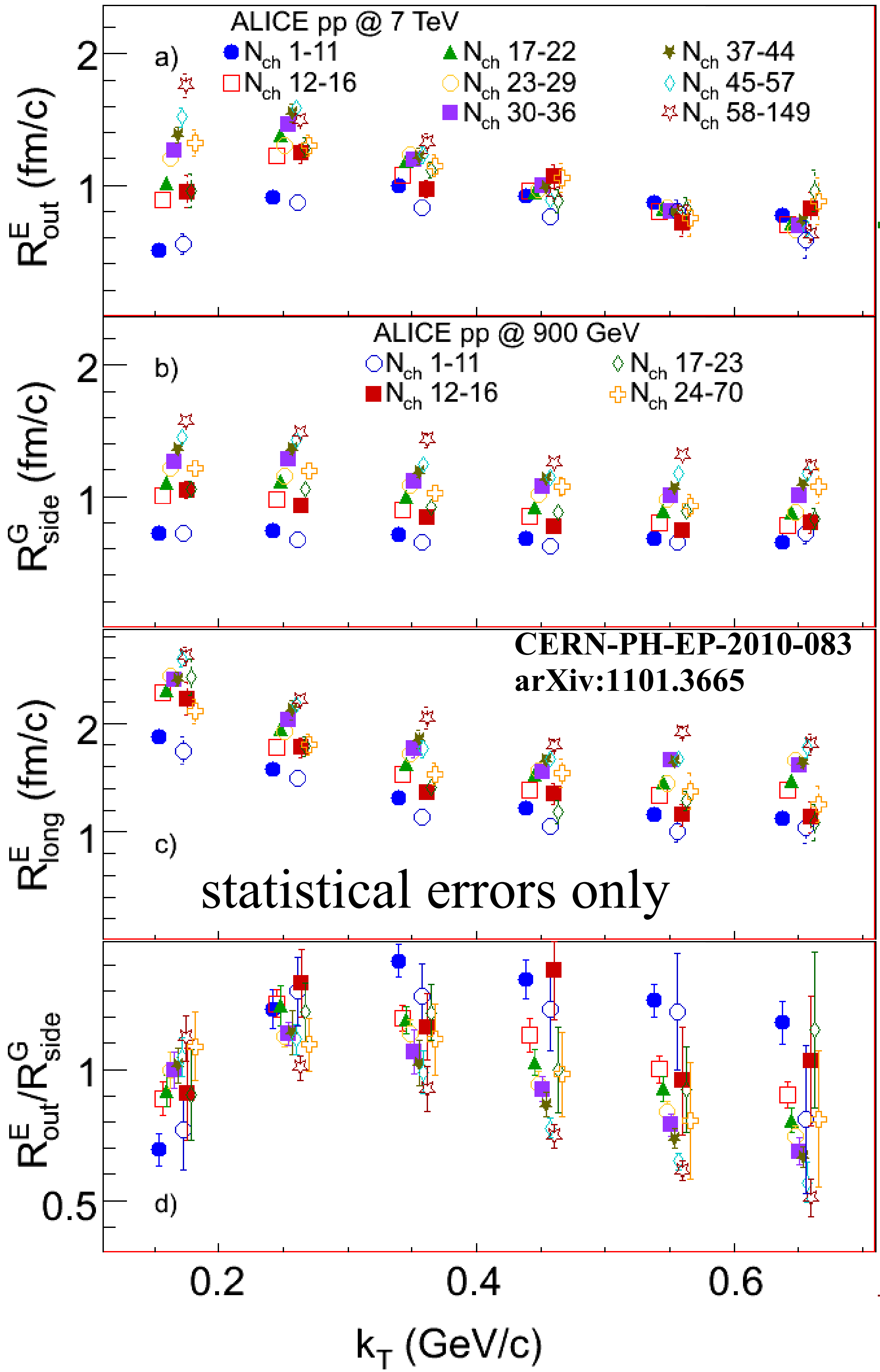


Exponential-Gaussian-Exponential fit is best or second-best for all k_T/multiplicity bins, χ^2/Ndof comparable to 1.0

Specific features of the correlation function captured:

- Steep rise of the CF at low q
- Additional structures in the C_2^0 and C_2^0 SH components

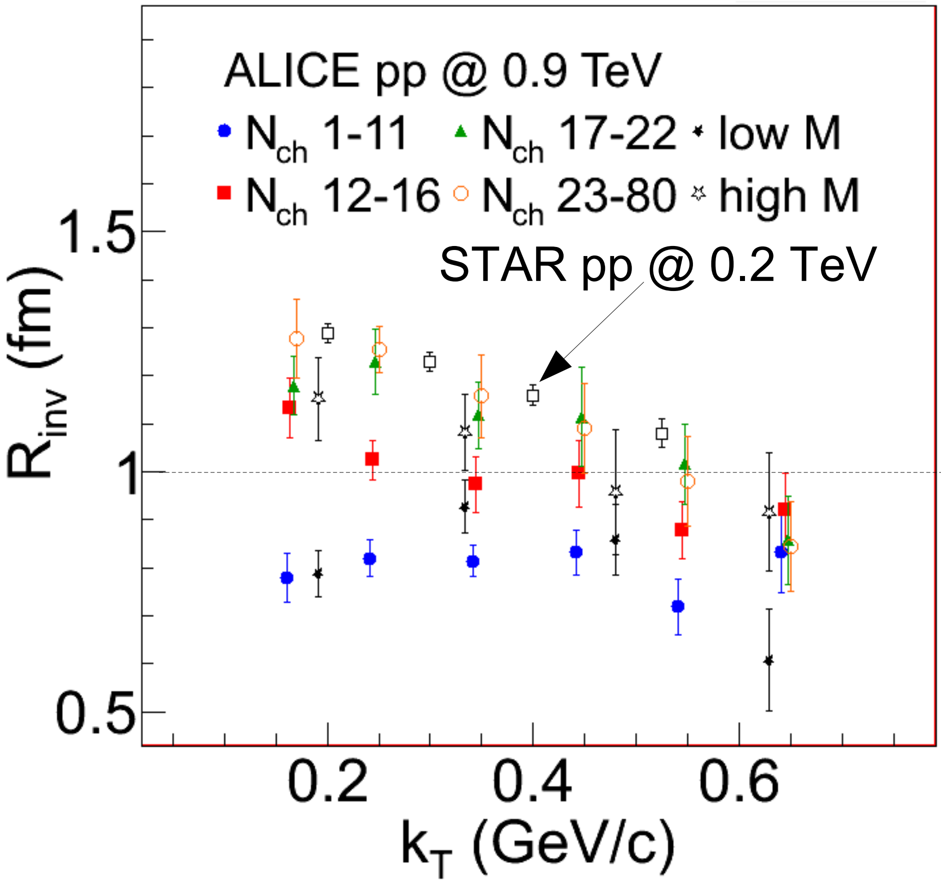
Non-gaussian radii at 0.9 and 7 TeV

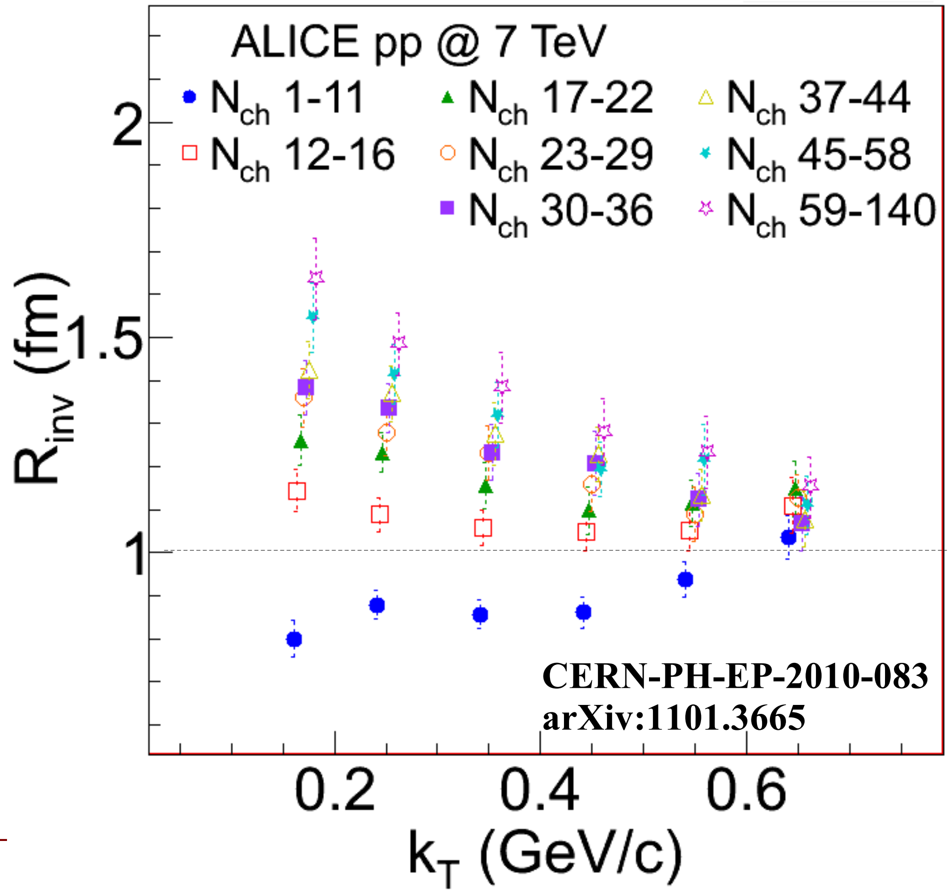


- Radii in *out* and side are not directly comparable to the Gaussian ones. The radii in *side* are the same as in the Gaussian fit within statistical error.
- Fit quality (judged by χ^2/N_{df}) is better. The λ parameter is higher by ~0.2 – a confirmation that the postulated functional form describes the true one better.
- Non-gaussian radii in LCMS grow with multiplicity, fall with k_T, all dependencies are the same as for Gaussian radii.
- After changing the functional form to a better one physics message stays the same: it gives us confidence that the Gaussian form, used for comparisons to other experiments and to heavy-ions, is reasonable

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}





Feedback

- The results from p+p collisions were received with considerable interest by the community:

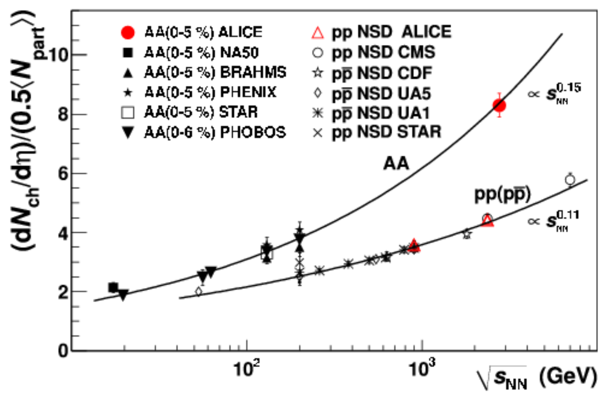
K.Werner et al., "*Evidence for Hydrodynamic Evolution in Proton-Proton Scattering at LHC Energies.*", arXiv:1010.0400 [nucl-th]

AK, "*Signatures of collective flow in high multiplicity pp collisions.*", arXiv:1012.1517 [nucl-th]

V.A. Schegelsky, A.D. Martin, M.G. Ryskin, V.A. Khoze, "*Pomeron universality from identical pion correlations*", arXiv:1101.5520

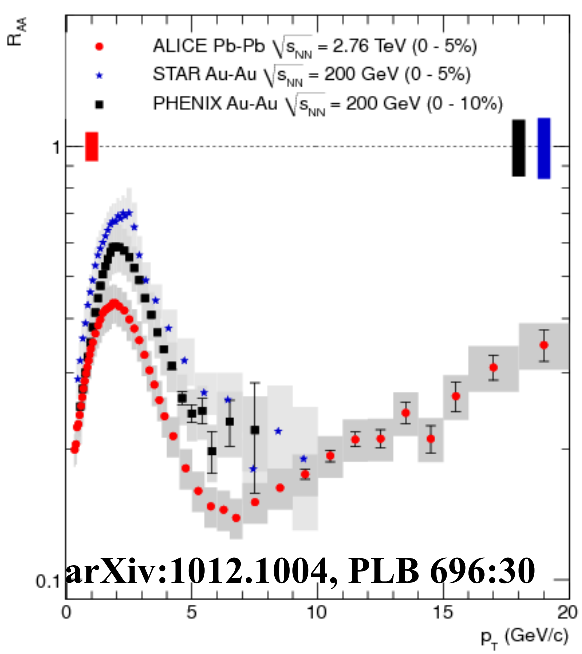
- Interest in high-multiplicity measurements: interpreted as a collective system with strong expansion. Should be combined with other measurements for a stronger case.
- Energy independence interpreted as a signature of the Pomeron exchange mechanism.

Moving to heavy ions

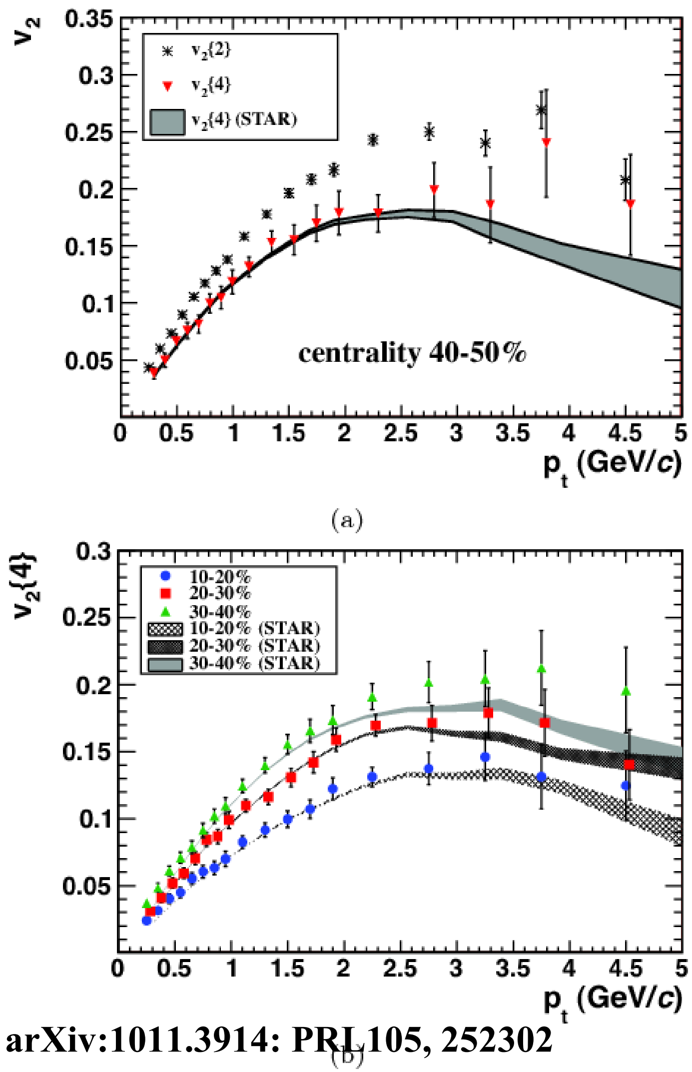


arXiv:1011.3916; PRL 105, 252301

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–



arXiv:1012.1004, PLB 696:30



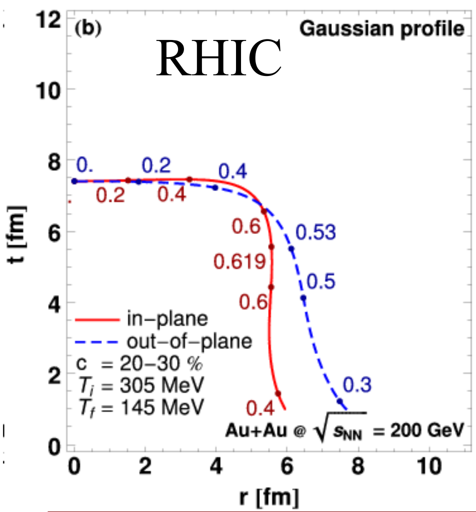
arXiv:1011.3914: PRL105, 252302

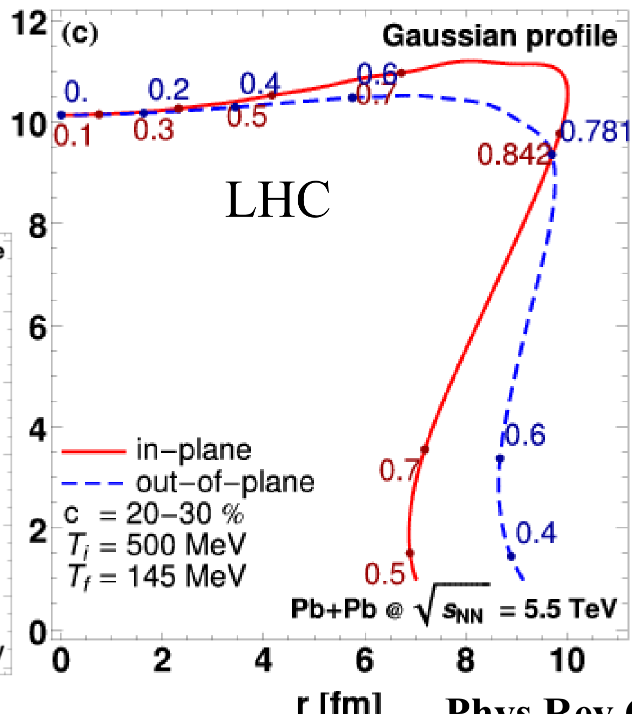
FIG. 2. (color online) a) $v_2(p_t)$ for the centrality bin 40–50% from the 2- and 4-particle cumulant methods for this measurement and for Au–Au collisions at $\sqrt{s_{NN}}$ = 200 GeV. b) $v_2\{4\}(p_t)$ for various centralities compared to STAR measurements. The data points in the 20–30% centrality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

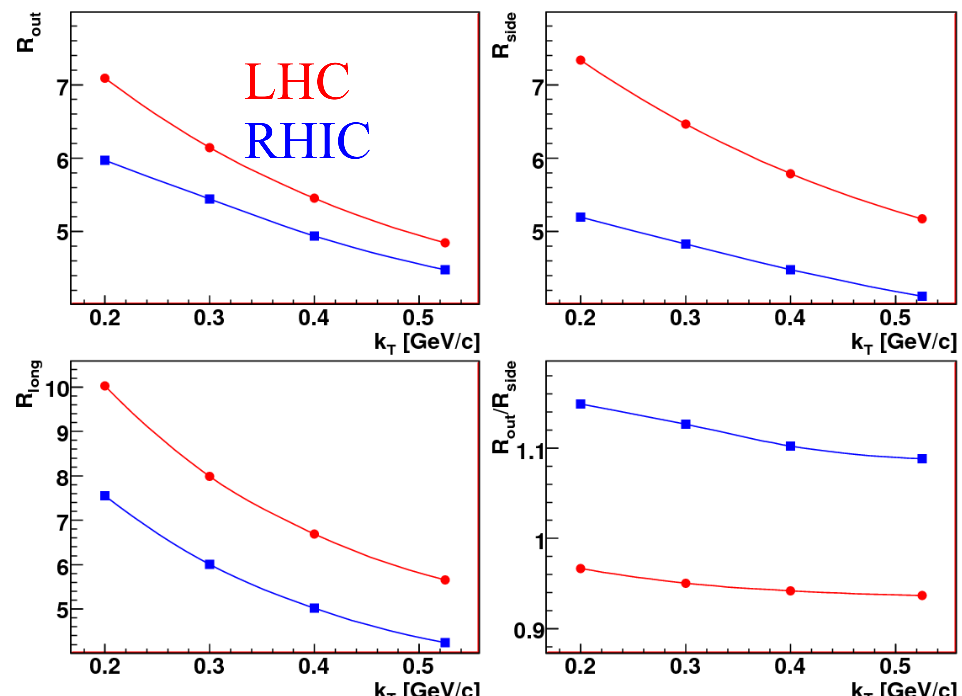
- The heavy-ion program in ALICE is progressing quickly. “First” measurements show (in comparison to RHIC):
  - Significant increase in event multiplicity
  - Decrease in R_{AA} (stronger “high-p_T suppression”)
  - Elliptic flow: similar $v_2(p_T)$, but stronger integrated v_2, due to a harder spectrum

Predictions for collectivity at LHC

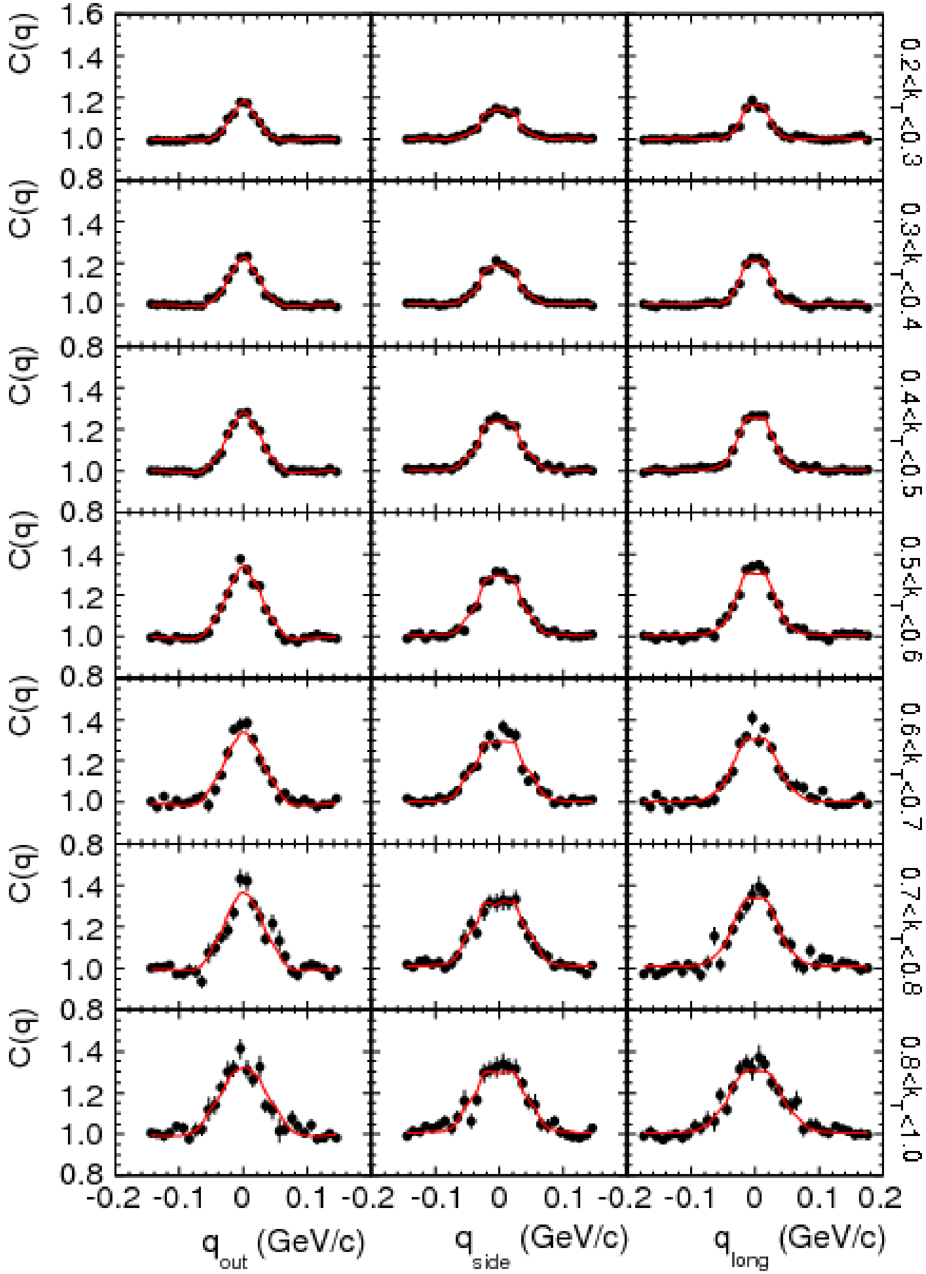
- Specific predictions for LHC: steeper m_T dependence of the system size from larger flow, longer evolution gives larger size and the reversal of the azimuthal anisotropy in space-time. The R_{out} $/R_{side}$ ratio is even smaller than at RHIC – due to a longer evolution time the freeze-out shape changes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







Phys.Rev.C79:014902,2009

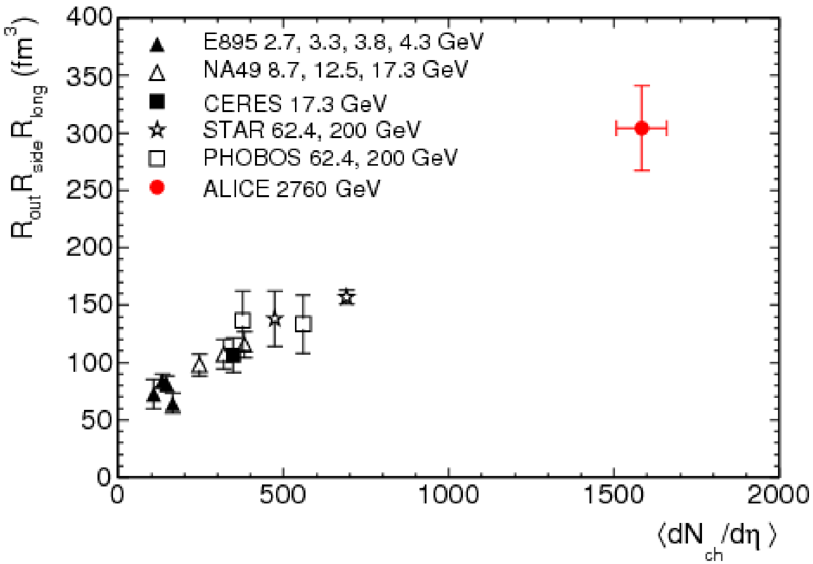


arXiv:1012.4035; PLB696:328

Figure 1: Projections of the three-dimensional $\pi^-\pi^-$ correlation function (points) and of the respective fits (lines) for seven k_T intervals. When projecting on one axis the other two components were required to be within (-0.03,0.03) GeV/c. The k_T range is indicated on the right hand side axis in GeV/c.

Correlations in Pb+Pb

- The correlation functions in Pb+Pb have been measured in the limited sample of events recorded at the beginning of November
- First analysis was performed only for top 5% central events
- The pair momentum dependence was the main focus of the paper
- Specifically the fall of radii with pair momentum as well as the overall increase of radii as compared to RHIC was expected



arXiv:1012.4035; PLB696:328

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].

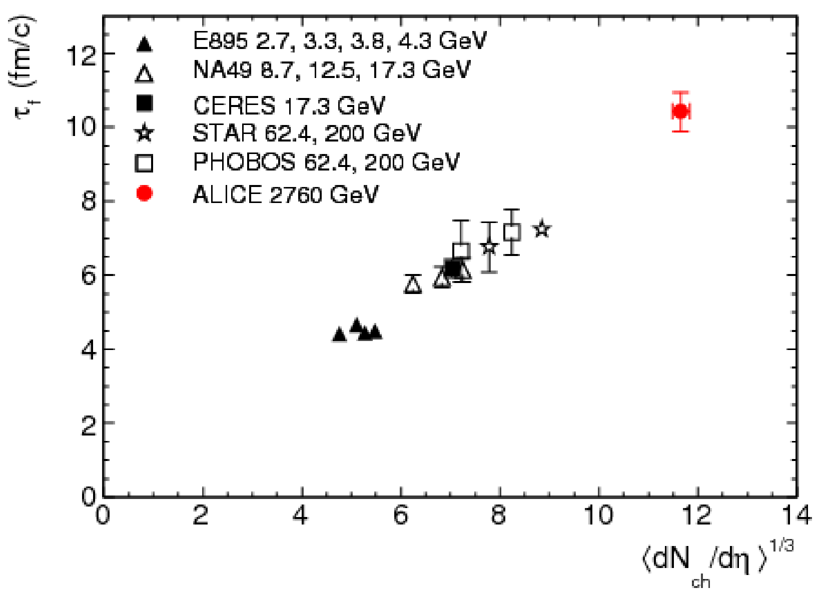
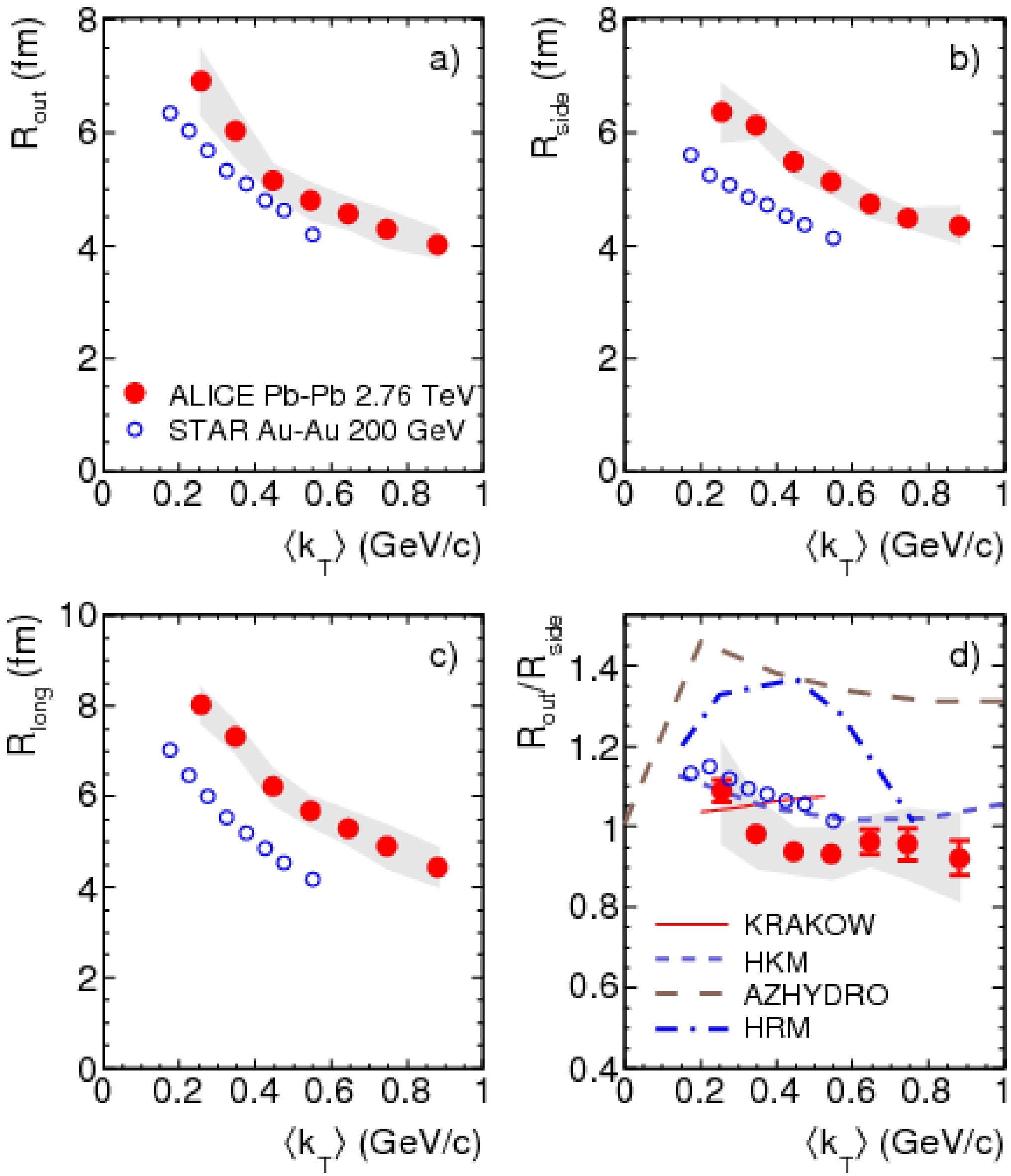


Figure 5: The decoupling time extracted from $R_{\mathrm{long}}(k_T)$. The ALICE result (red filled dot) is compared to those obtained for central gold and lead collisions at lower energies at the AGS [35], SPS [36, 37, 38], and RHIC [39, 40, 41, 42, 30, 43].

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



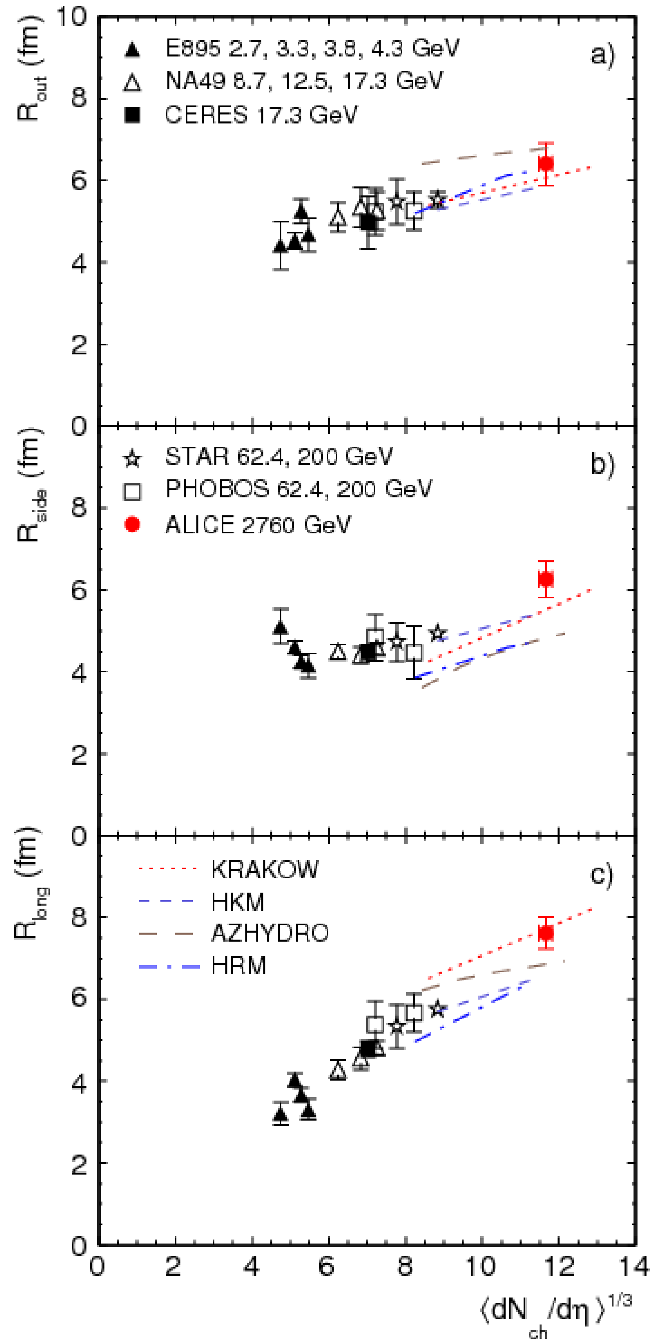
arXiv:1012.4035; PLB696:328

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
- The “standard” model from RHIC, extrapolated to the LHC appears to work well

Comparing to models



arXiv:1012.4035; PLB696:328

Figure 3: Pion HBT radii at $k_T = 0.3$ GeV/c for the 5% most central Pb–Pb at $\sqrt{s_{NN}} = 2.76$ TeV (red filled dot) and the radii 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]. Model predictions are shown as lines.

- The hydrodynamic models which were extensively tuned to reproduce the RHIC data work also at the LHC
- It is still not trivial to simultaneously reproduce the overall magnitude of the radii and the change between RHIC and the LHC. Only the models which introduce all the features important at RHIC (initial flow, cross-over phase transition, realistic equation of state, full inclusion of resonances) continue to work at the LHC.

Outlook for measurements in PbPb

- Strict validity test of the “standard” hydrodynamics evolution picture in all centralities: full centrality vs. transverse momentum dependence. Should constrain the initial state description and the equation of state.
- Address questions of the equation of state and viscosity in the system (do we have “perfect fluid”, like in RHIC?) by making a complementary check of azimuthal asymmetry in space. Cross-check azimuthally sensitive femtoscopy against elliptic flow.
- Is collectivity universal? Does it break down at high pT? Make the check for pions with high pT and heavy particles (kaons, protons)
- Can we differentiate between evolution scenarios (collectivity vs. temperature gradients): check the emission asymmetries between particles of different mass via non-identical particle femtoscopy.

Summary

- ALICE has 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.
- Obtained correlation functions visibly non-gaussian, combination of Exponential and Lorentzian functions in 3 dimensions necessary to better describe the full behaviour.
- Taking into account the underlying event correlations, ALICE sees radii grow 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 a system that is bigger and lives longer than at RHIC, behaves hydrodynamically.