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Femtoscopy results from ALICE

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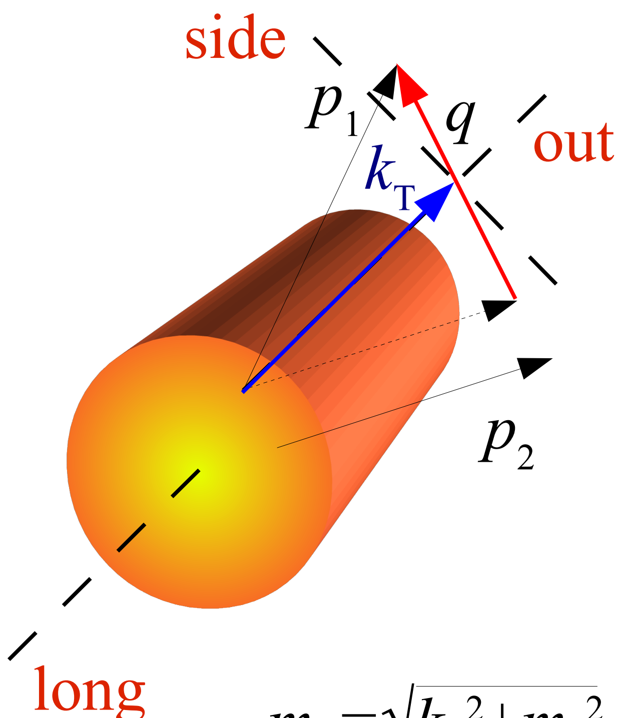
Overview

- Motivation for pion femtoscopy
- Pion femtoscopy of the Pb-Pb, pp and p-Pb at LHC
  - Lessons from RHIC
  - Pb-Pb results from the LHC
  - Azimuthally sensitive femtoscopy
  - Comparison of pp, PbPb and world systematics
  - p-Pb results vs. p-p and Pb-Pb data
- Femtoscopy of heavier particles
  - Baryon-baryon and baryon-antibaryon results at the LHC
- Pion coherent emission from 3-pion correlations

Physics motivation



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

Longitudinally Co-Moving System (LCMS):

$$p_{1,long} = -p_{2,long}$$

The Koonin-Pratt Equation:

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

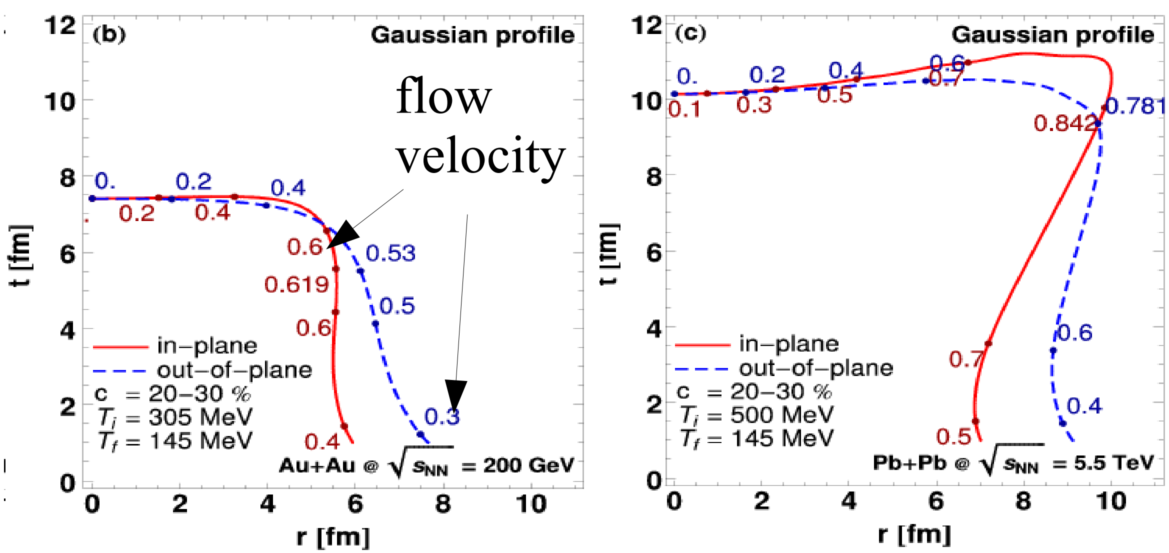
- Pion femtoscopy in Pb-Pb collisions
  - Measure the size of the homogeneity region from which volume of the QGP can be inferred
  - Transverse momentum dependence of the radii a manifestation of strong collective motion of matter
  - Strong constraints on timescales and sensitivity to the EOS in dynamic models
- Femtoscopy of pions in pp collisions
  - Need precise and differential data to address space-time characteristics of particle production in “elementary” systems
  - Significant multiplicities, comparable to peripheral heavy-ion data, now reachable in pp. Can directly compare pp and AA.

Expectations for the LHC

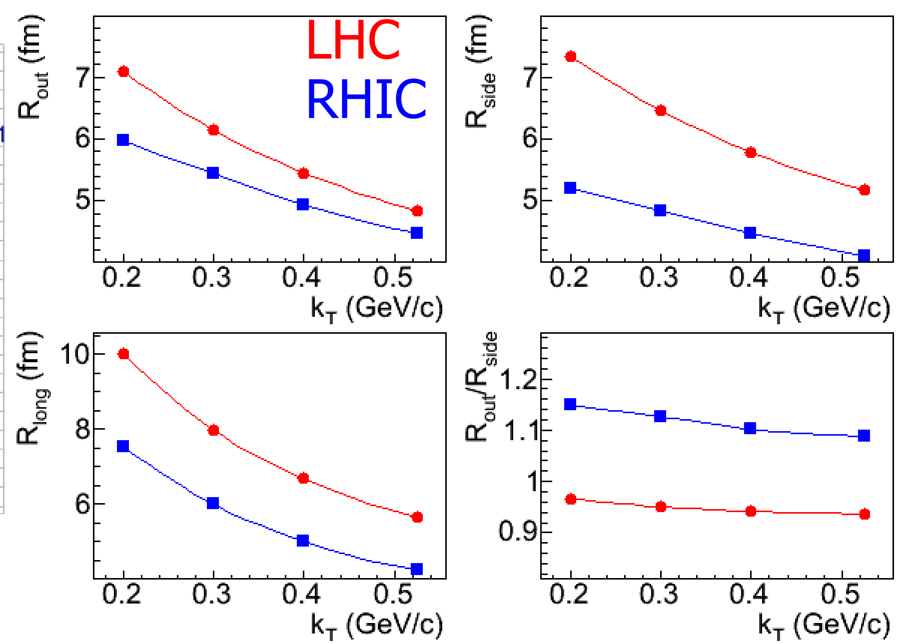
- Lessons from RHIC:
  - "Pre-thermal flow": strong flows already at τ_0=1 fm/c
  - EOS with no first-order phase transition
  - Careful treatment of resonances important

- Extrapolating to the LHC:
  - Longer evolution gives larger system → all of the 3D radii grow
  - Stronger radial flow → steeper k_T radii dependence
  - Change of freeze-out shape → lower R_{out}/R_{side} ratio

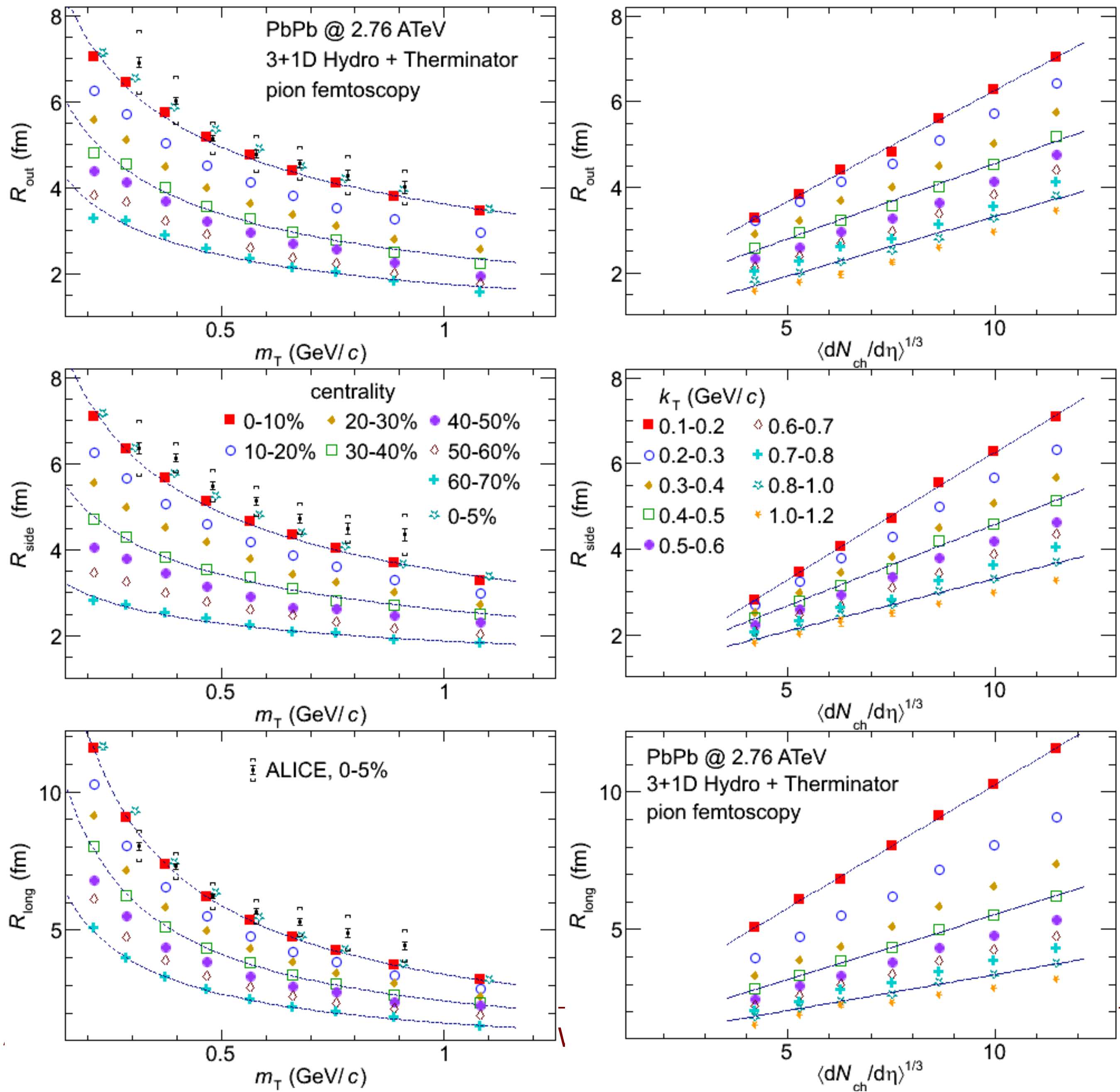
RHIC → LHC



Phys.Rev.C79:014902,2009



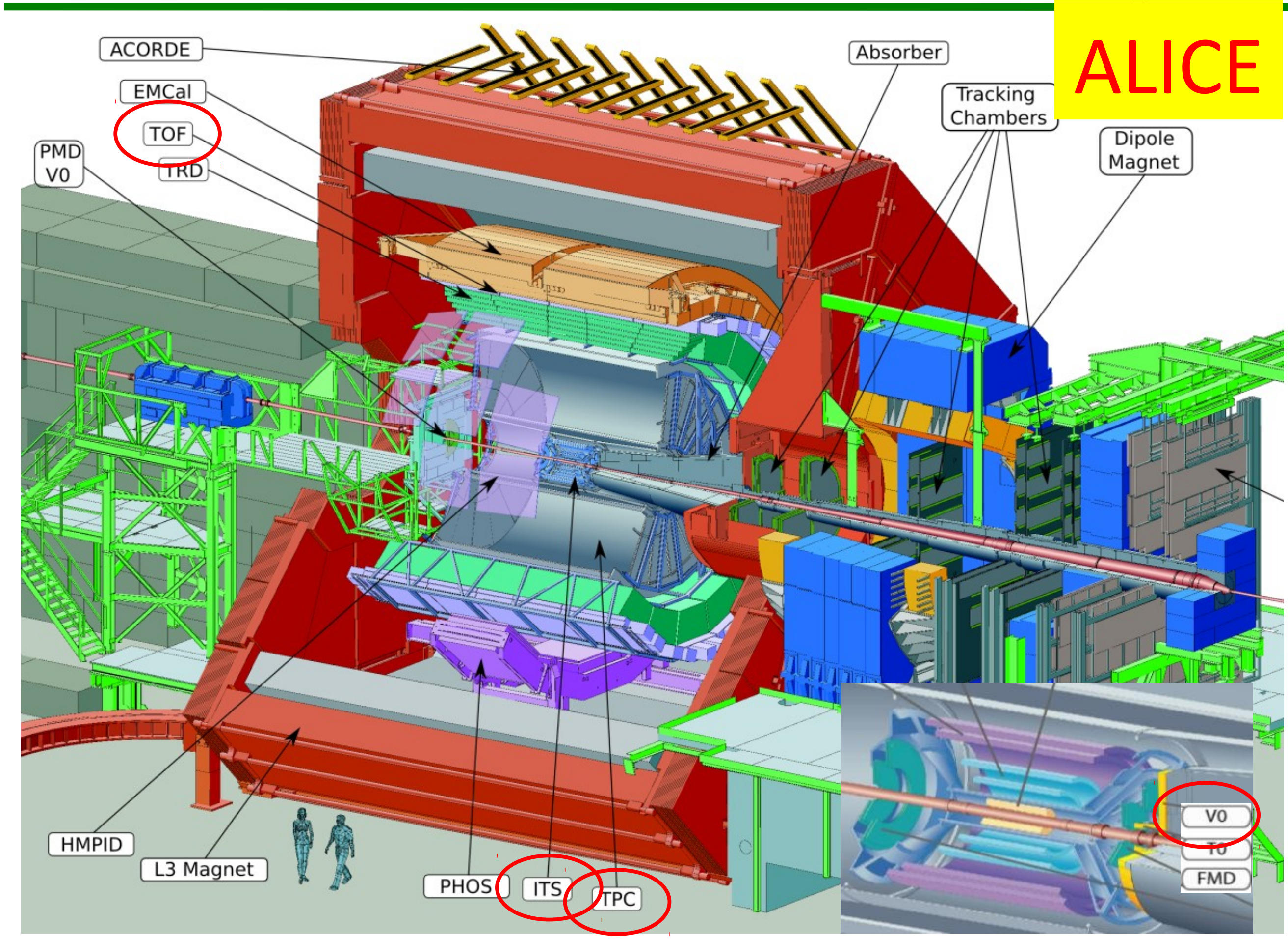
Multiplicity and m_T dependence



- For high multiplicity A+A collisions where hydro is applicable:
  - Strong flows result in clear m_T dependence (power-law)
  - Dependence is most steep in *long*
  - All radii scale linearly with final state multiplicity

A.Kisiel, M.Gałażyn, P.Bożek; arXiv:1409.4571

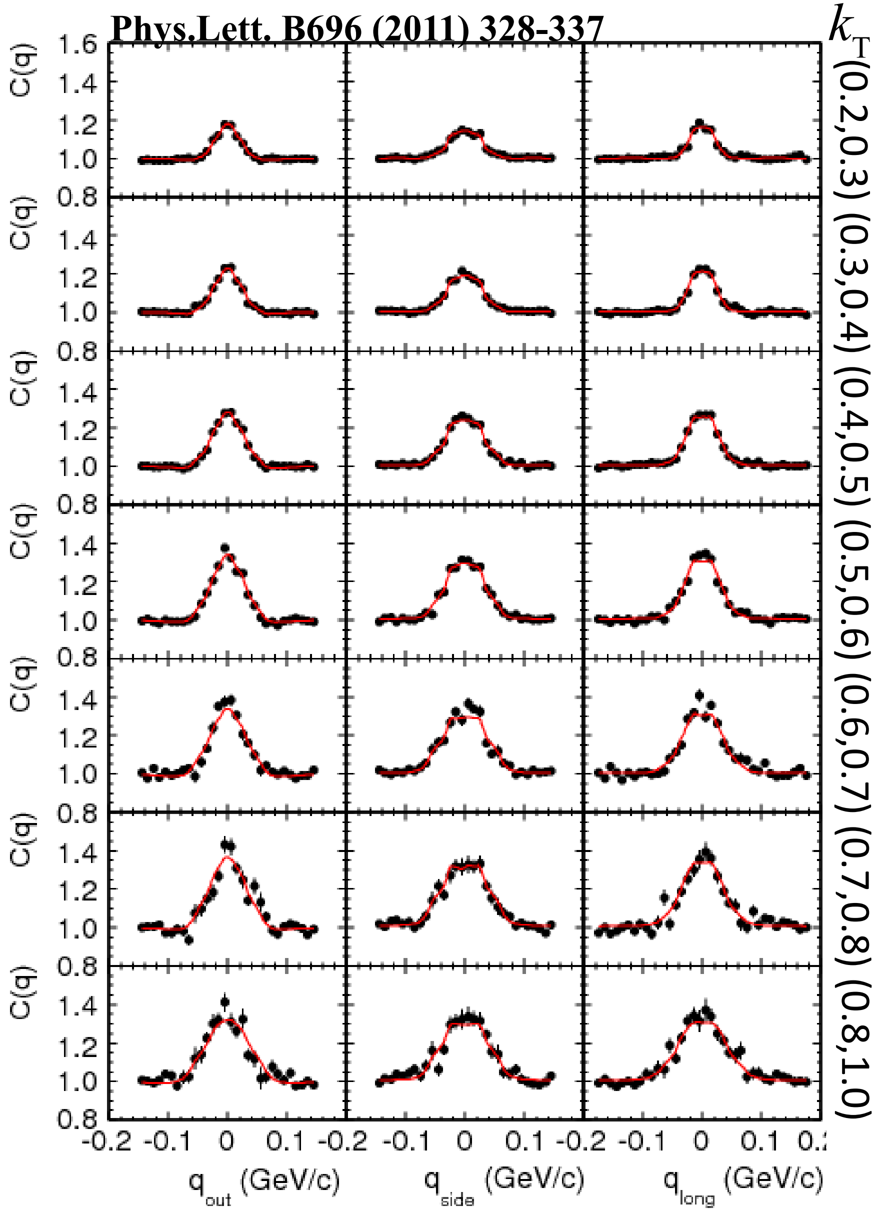
The ALICE experiment



- Main tracking and PID detector: Time Projection Chamber
- Vertexing and tracking: Inner Tracker System
- PID at higher momentum: Time-of-Flight
- Trigger and centrality: VZERO

- pp collisions at √s= 0.9, 2.36, 7 TeV (>500M minbias)
- Pb-Pb collisions at $\sqrt{s_{NN}}$= 2.76 TeV (~60M, various triggers)

Correlations, 0-5% central PbPb



- 3D analysis in LCMS for 7 ranges in pair transverse momentum k_T, 0-5% centrality
- Primary pions with $0.2<p_T<2.0$ GeV/c, $|\eta|<0.8$
- Two main systematic effects:
  - Track merging: reconstruction inefficiency for two tracks close in the detector, corrected for with a track separation cut
  - Momentum resolution: peak appears wider, up to 4% correction on the extracted radius
- Fit the correlation function with the Bowler-Sinyukov formula (K accounts for Coulomb):

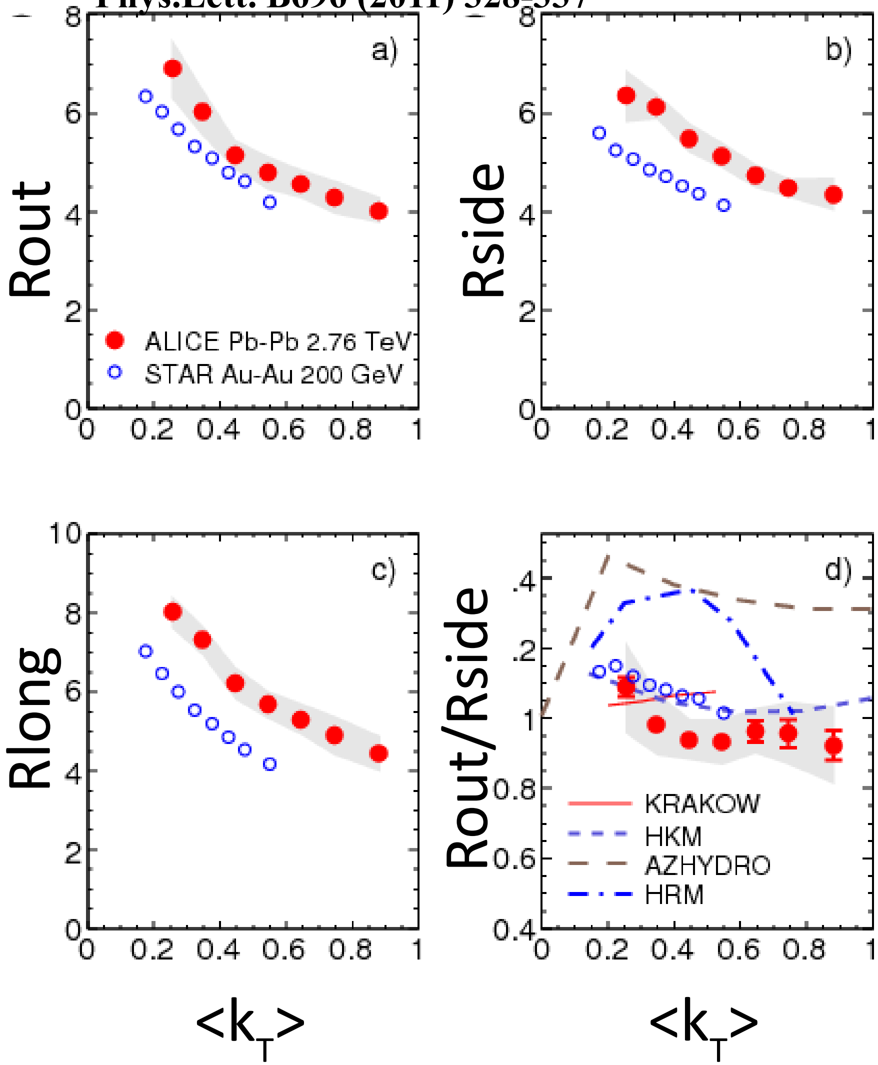
$$C=N\left[(1-\lambda)+\lambda K\left(1+\exp\left(-R_{out}^2 q_{out}^2-R_{side}^2 q_{side}^2-R_{long}^2 q_{long}^2\right)\right)\right]$$

to obtain the femtoscopic radii

First data from central LHC collisions

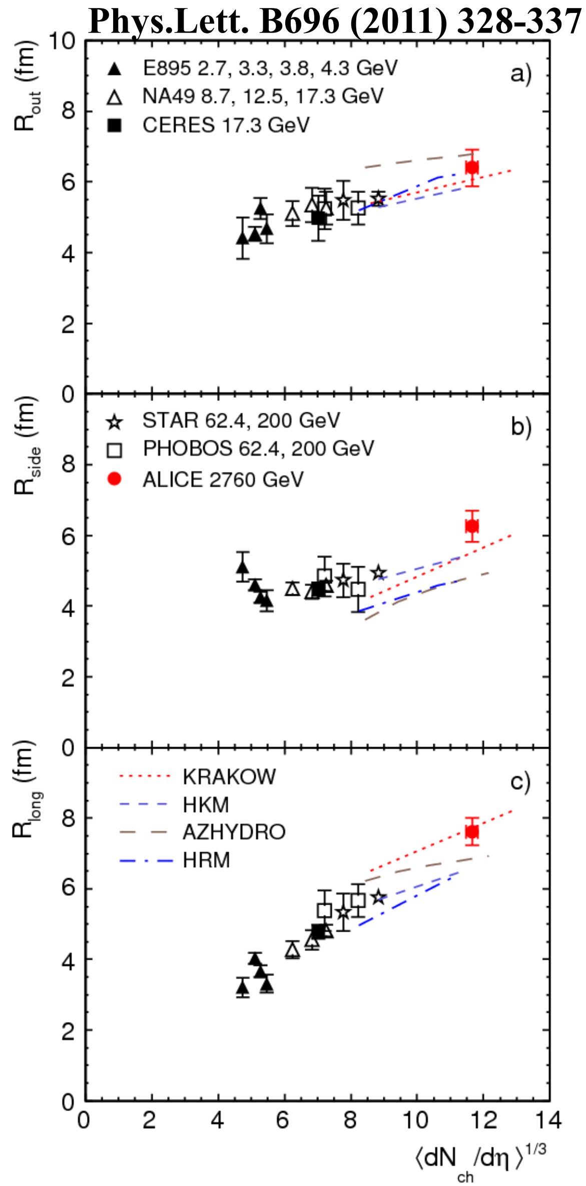
ALICE Pb-Pb

Phys.Lett. B696 (2011) 328-337

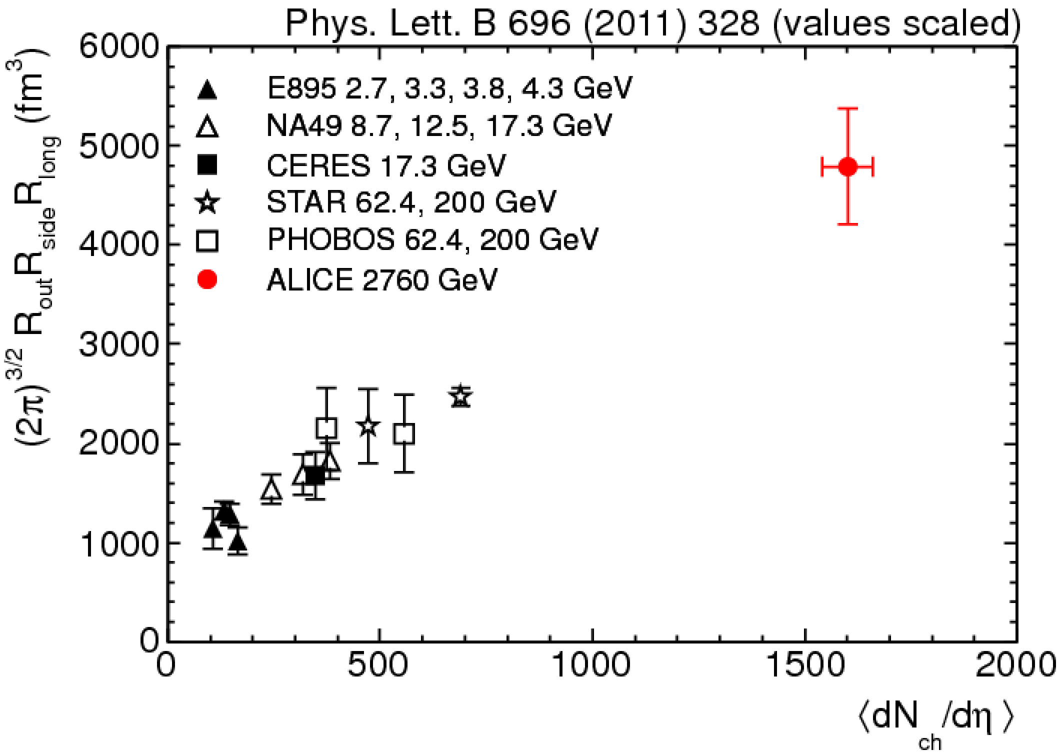


- 30% increase in homogeneity lengths between most central RHIC and LHC
- Strong dependence of all radii on pair momentum, consistent with strong collective radial and longitudinal flow
- The R_{out}/R_{side} ratio comparable or smaller than at RHIC: gives discriminating power to challenge models
- Only models tuned to reproduce RHIC data continue to work at the LHC
- All features expected from hydrodynamics extrapolation observed

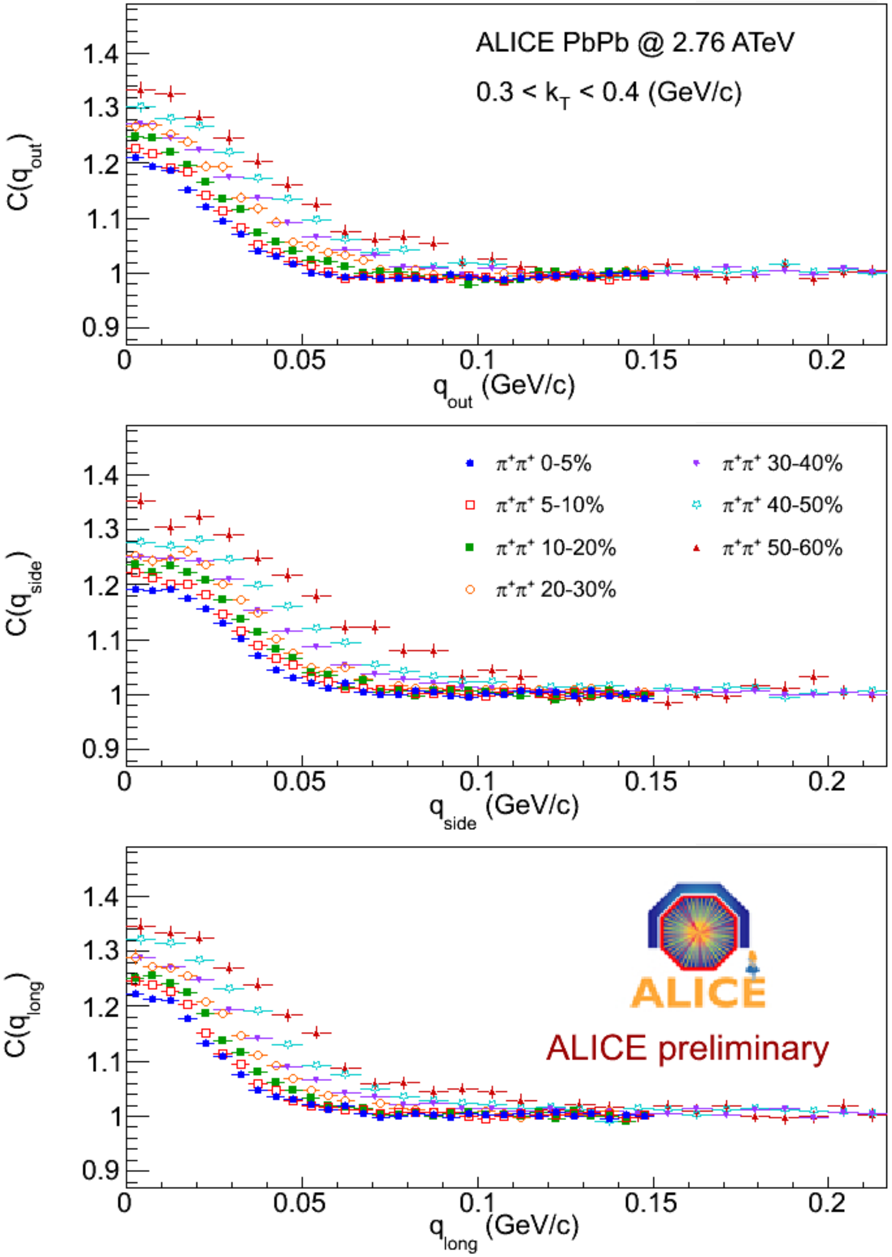
Scaling vs. $dN_{ch}/d\eta$



- Increase of the radii with $dN_{ch}/d\eta$ for central collisions consistent with models
- Increase of the "homogeneity volume" over most central RHIC by a factor of ~2

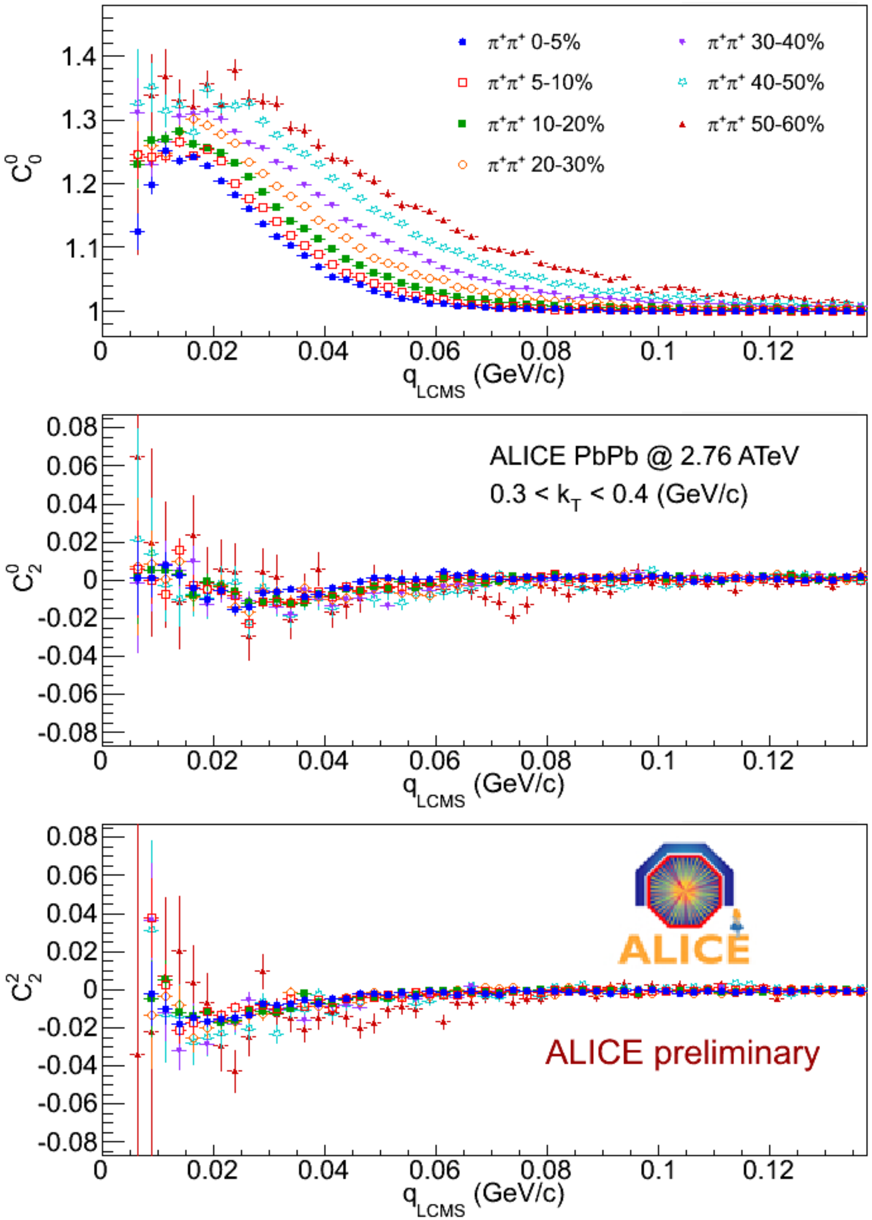


Cartesian 3D correlations vs. centrality



- Projections of the cartesian representation of the CF for 7 centrality bins (0-60%) for one of the pair momentum ranges
- Clear growth of the width of the correlation effect – decrease of size with decreasing multiplicity
- Flat background behavior at large q

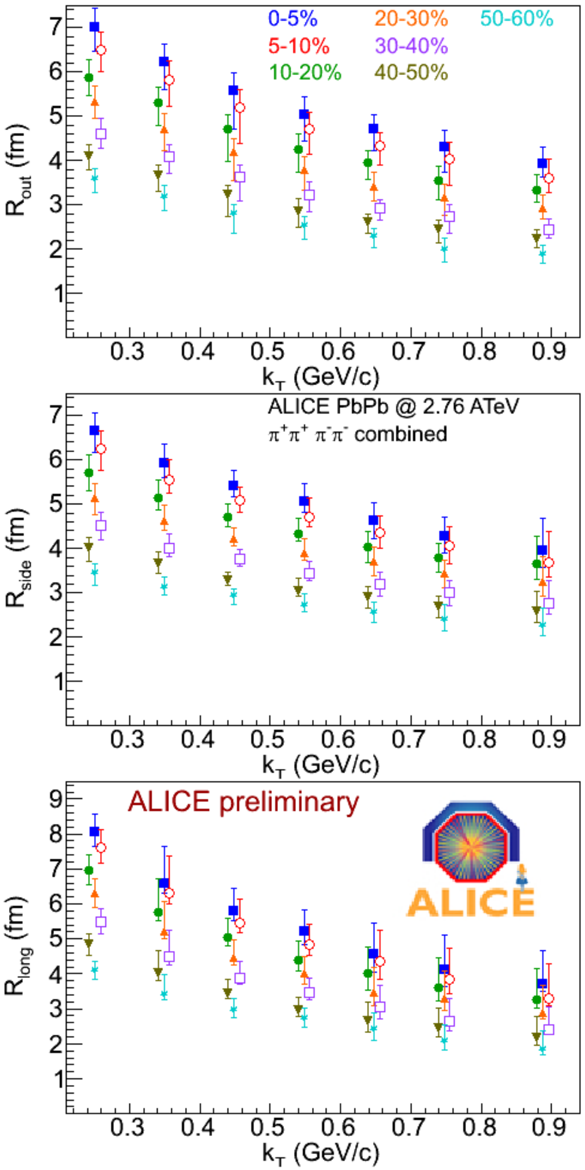
SH rep. vs. centrality



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

- Showing full 3D dependence via 3 1D plots: first three non-vanishing components of the spherical harmonics representation for 7 centrality bins (0-60%)
- Growth of the width of the correlation effect visible
- Full behavior of the CF at large q: also no surprising effects seen, no issues for the fitting procedure

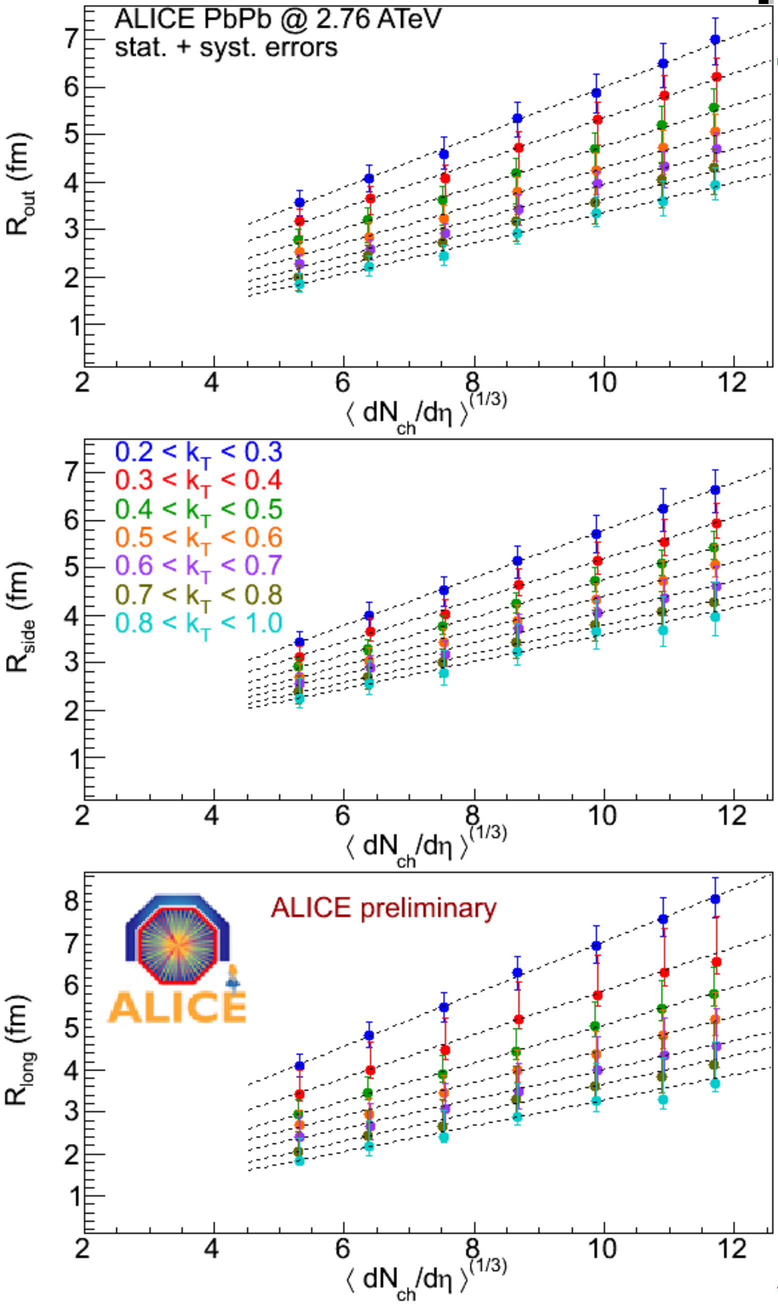
Radii vs. centrality and k_T



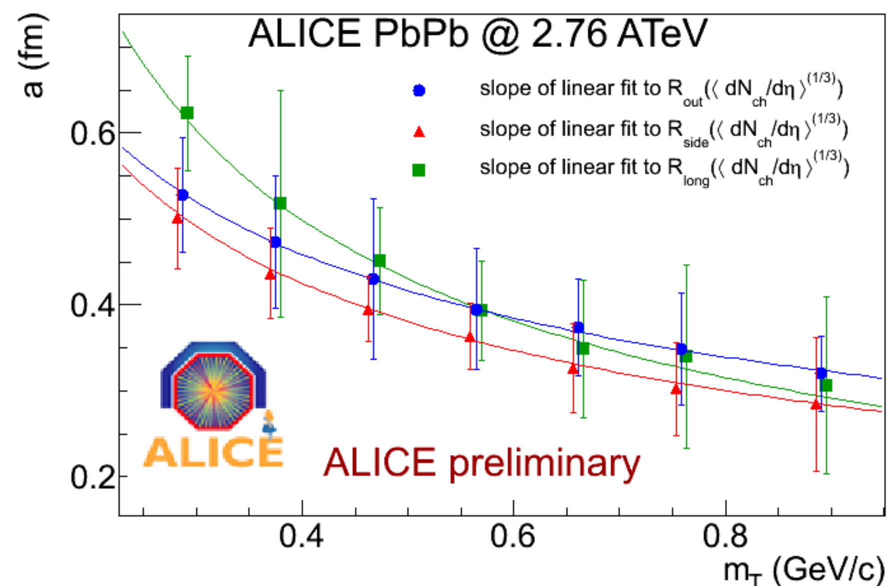
A.Kisiel, QM2011

- Femtoscopic radii vs. k_T for 7 centrality bins in central rapidity region
- Radii universally grow with event multiplicity and fall with pair momentum
- Both dependencies in agreement with calculations from collective models (hydrodynamics), both quantitatively and qualitatively
- Hydro calculations done after the release of preliminary femtoscopic data from ALICE, however reaching similar level of agreement at RHIC took 9 years!

Linear multiplicity scaling of radii

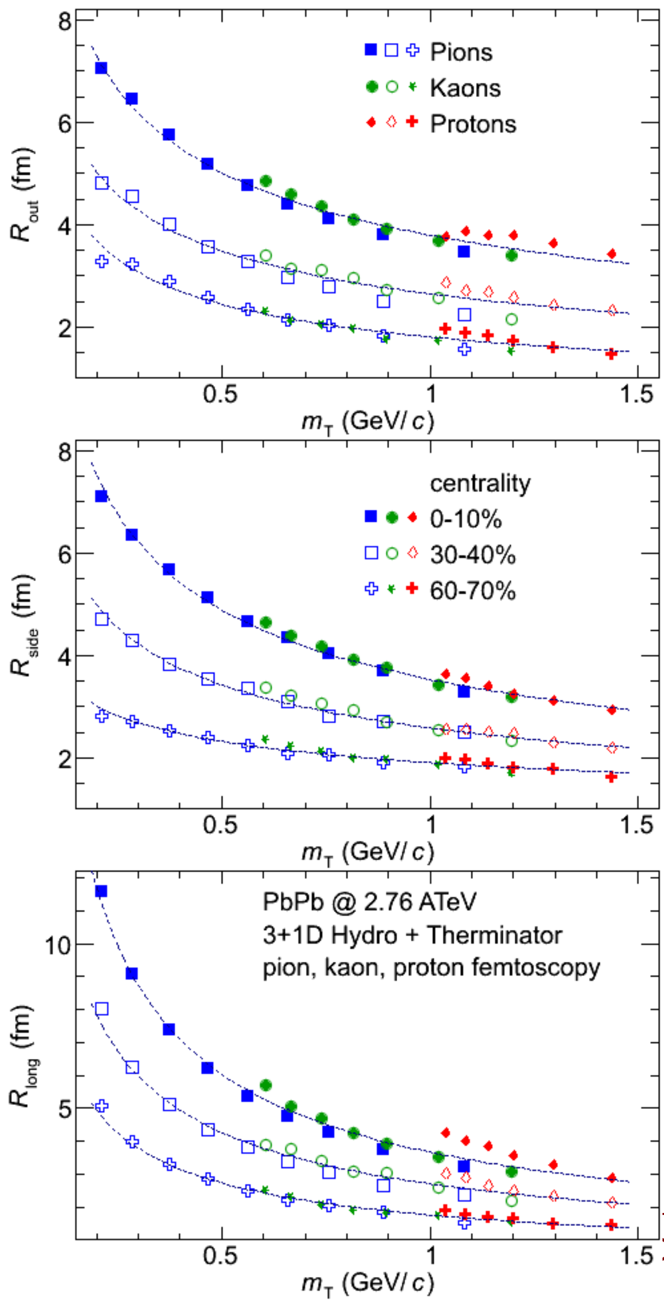


- Radii in 3 directions and all pair momentum ranges scale linearly with $dN_{ch}/d\eta$
- Slope parameters of this fit show power-law behavior, similar to hydrodynamics

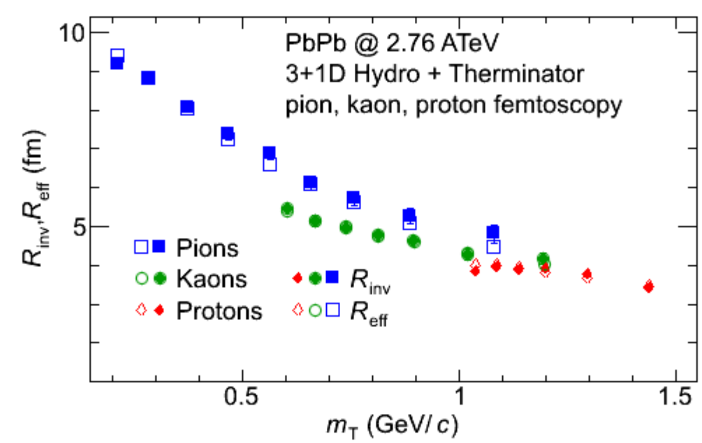


A.Kisiel, QM2011

m_T scaling for heavier particles



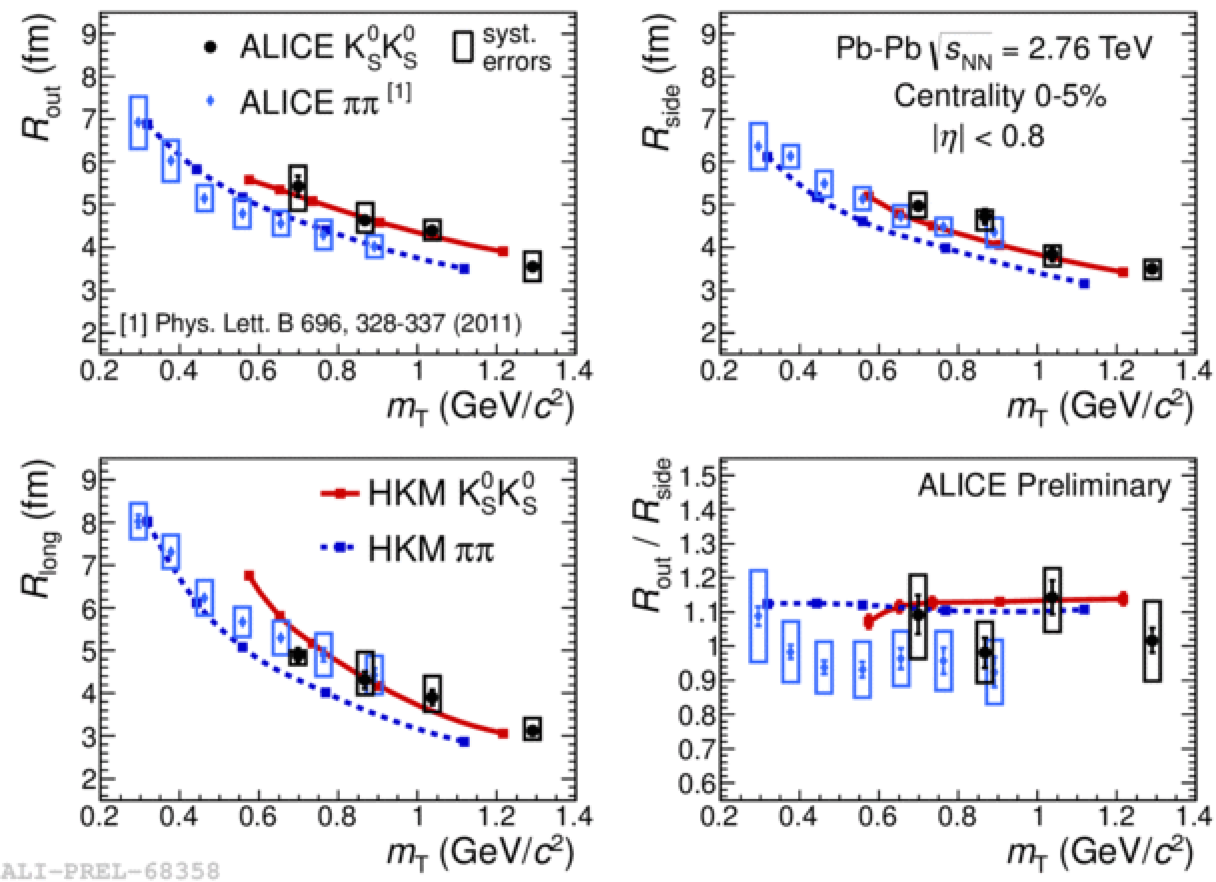
- "Collective" flow should apply to all particles
  - In ideal 1D hydro particles of all masses follow the same m_T scaling. What about "real" hydro in 3+1D and with viscosity?
  - The scaling still exists but only approximately, the deviations comparable to current experimental uncertainty
  - It only works in 3D in LCMS, not in PRF!



A.Kisiel, M.Gałażyn, P.Bożek; arXiv:1409.4571

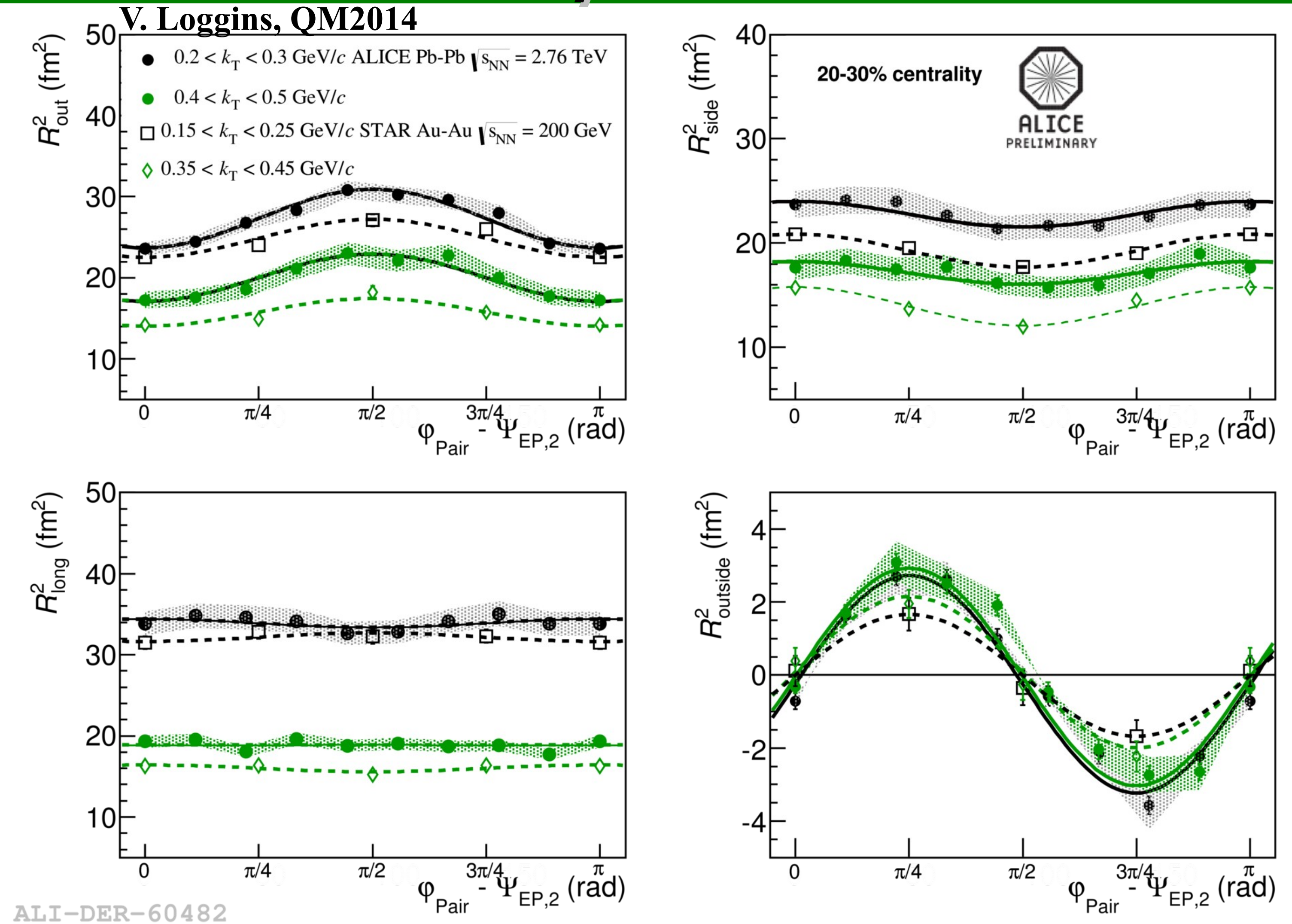
Collectivity with heavier particles

- The k_T dependence is tested with heavier mesons
- The 3D K^0_s results in central Pb-Pb consistent with collectivity (hydro) expectations
- Non-trivial data analysis (no analytic functional form for fitting QS+Strong femto signal)



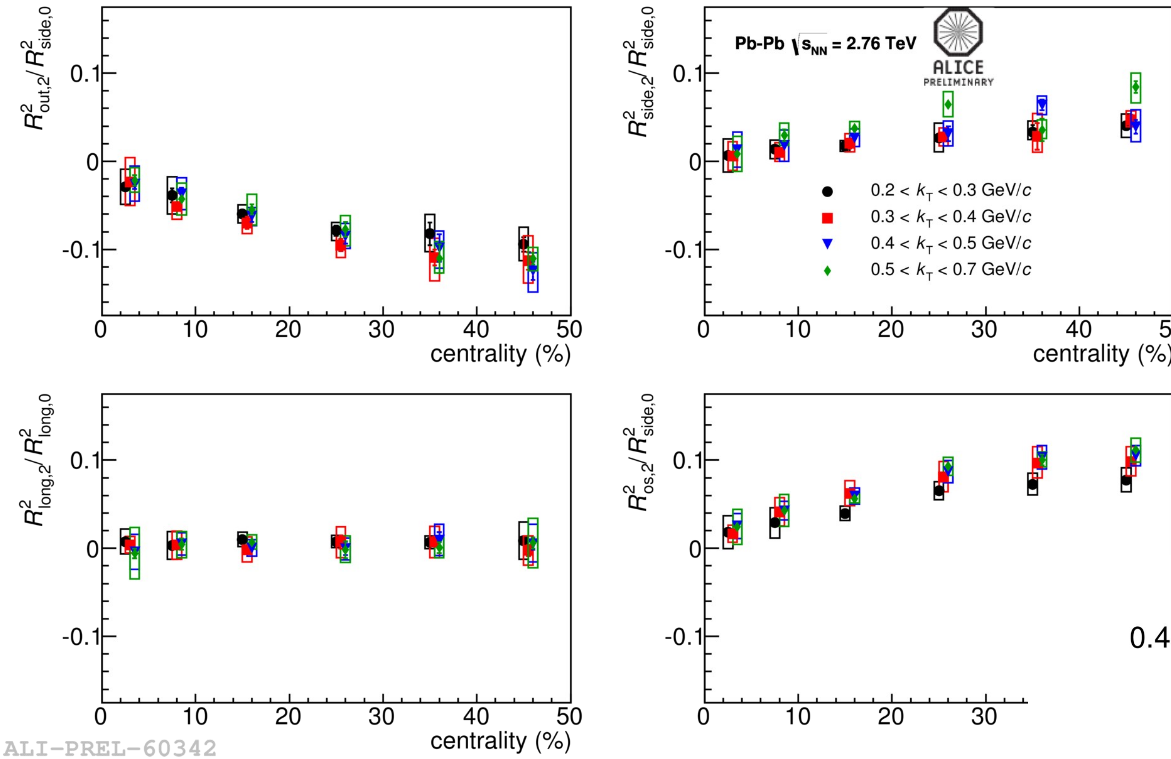
M. Steinpreis, QM2014

Azimuthally sensitive HBT

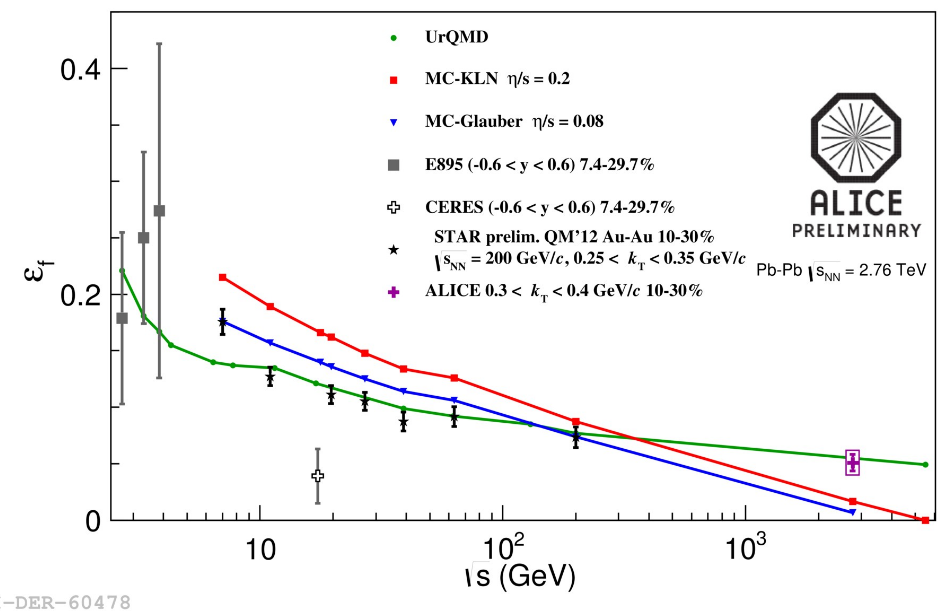


- Measurement of pion radii vs. reaction plane orientation – important cross-check of azimuthal evolution. Directly comparable to STAR.

Clocking the evolution



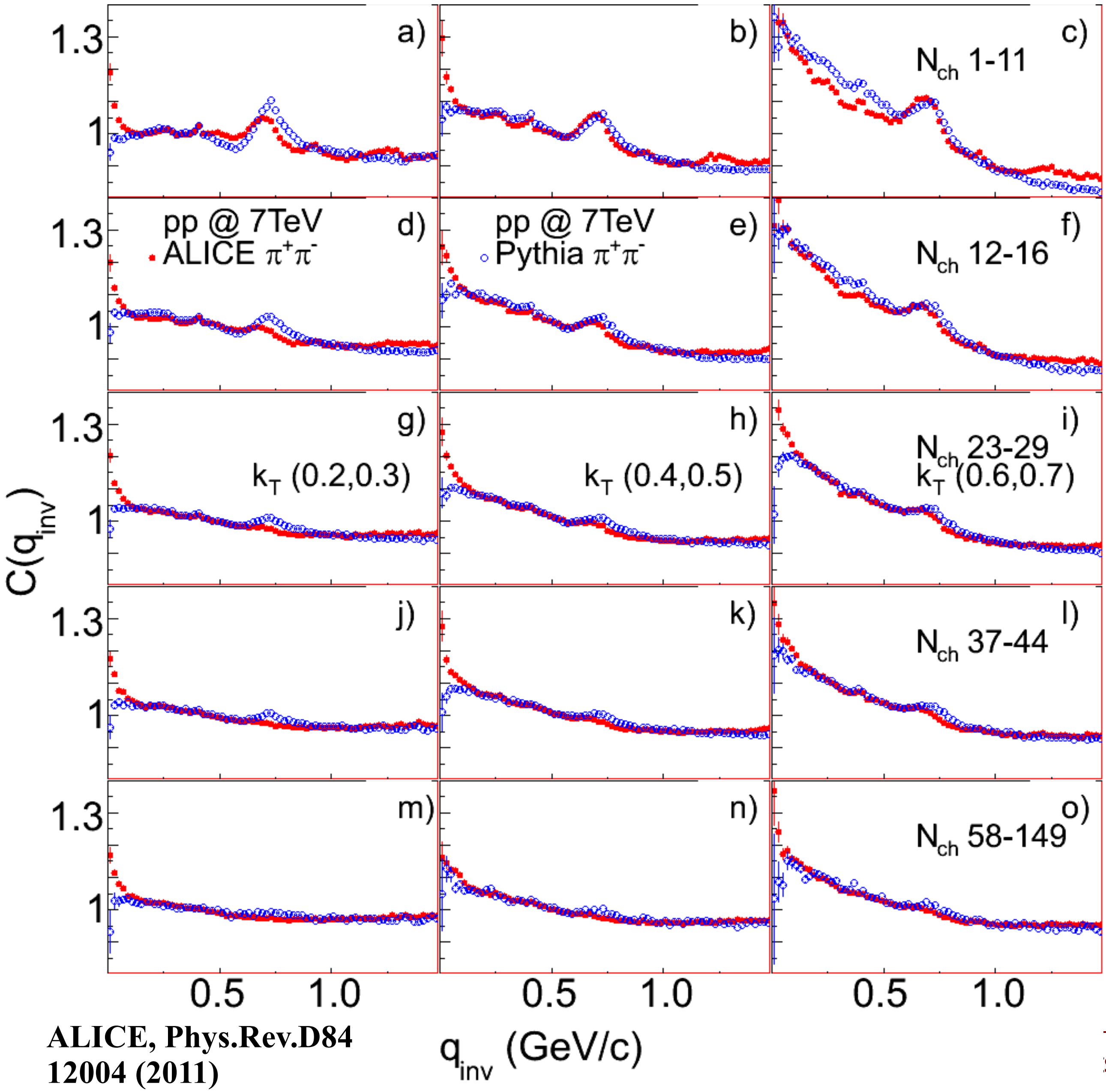
- Final eccentricity comparable but smaller than at RHIC, as expected for longer evolution duration
- Qualitatively confirms hydro



Femtoscopy in small systems

- The measurement can be done in “small” systems, such as p+p and p-Pb.
  - Need precise and differential data to address space-time characteristics of particle production in “elementary” systems
  - Significant multiplicities, comparable to peripheral heavy-ion data, now reachable in pp and p-Pb. Can directly compare pp and AA, to see if the influence of “collectivity” can be found
- But ...
  - Some basic assumptions of the femtscopic formalism are at the edge of validity (independence of emitters)
  - Conservation laws introduce large correlations for systems with small multiplicity
  - Jet phenomena a strong source of correlations as well

Mini-jets in $\pi^+\pi^-$ correlations

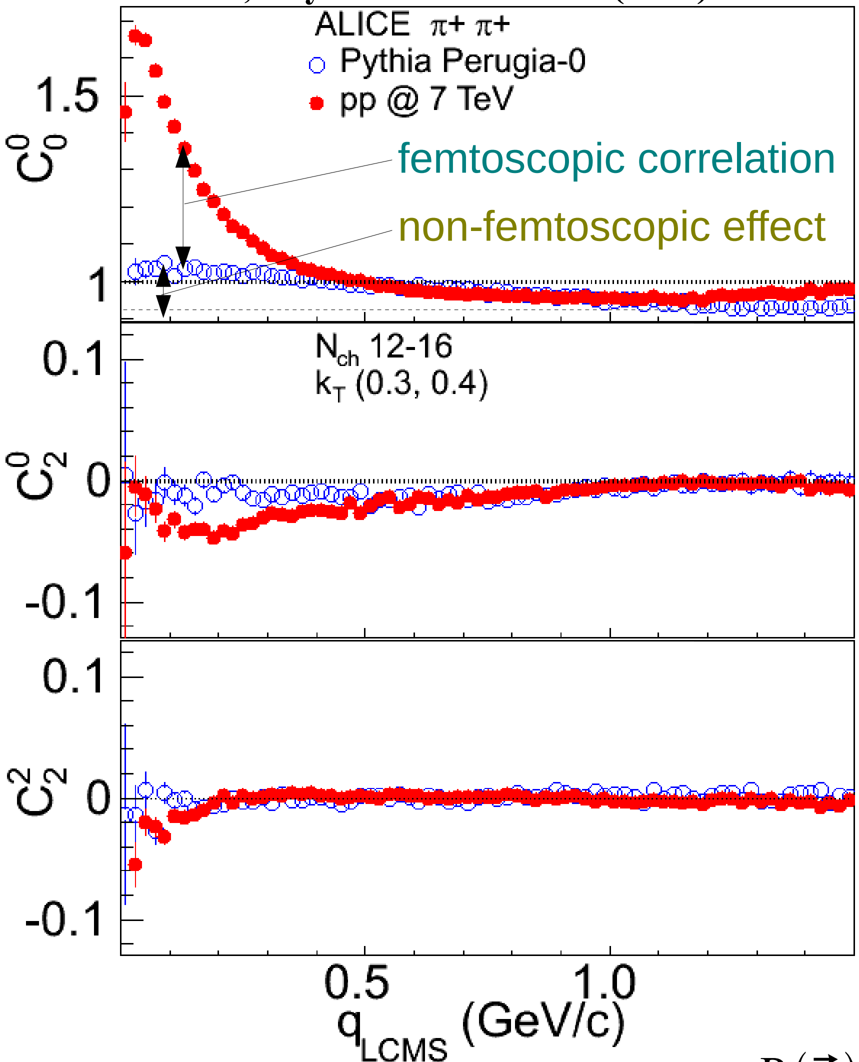


ALICE, Phys.Rev.D84 12004 (2011)

- Non-femtoscopic correlations present for opposite-charge pairs, a clear manifestation of the “mini-jet” pheonmena
- Pythia describes the correlation to within 10%
- Additional correlated yield due to resonances visible, Pythia's not able to describe it properly

Non-femtoscopic correlations

ALICE, Phys.Rev.D84 112004 (2011)

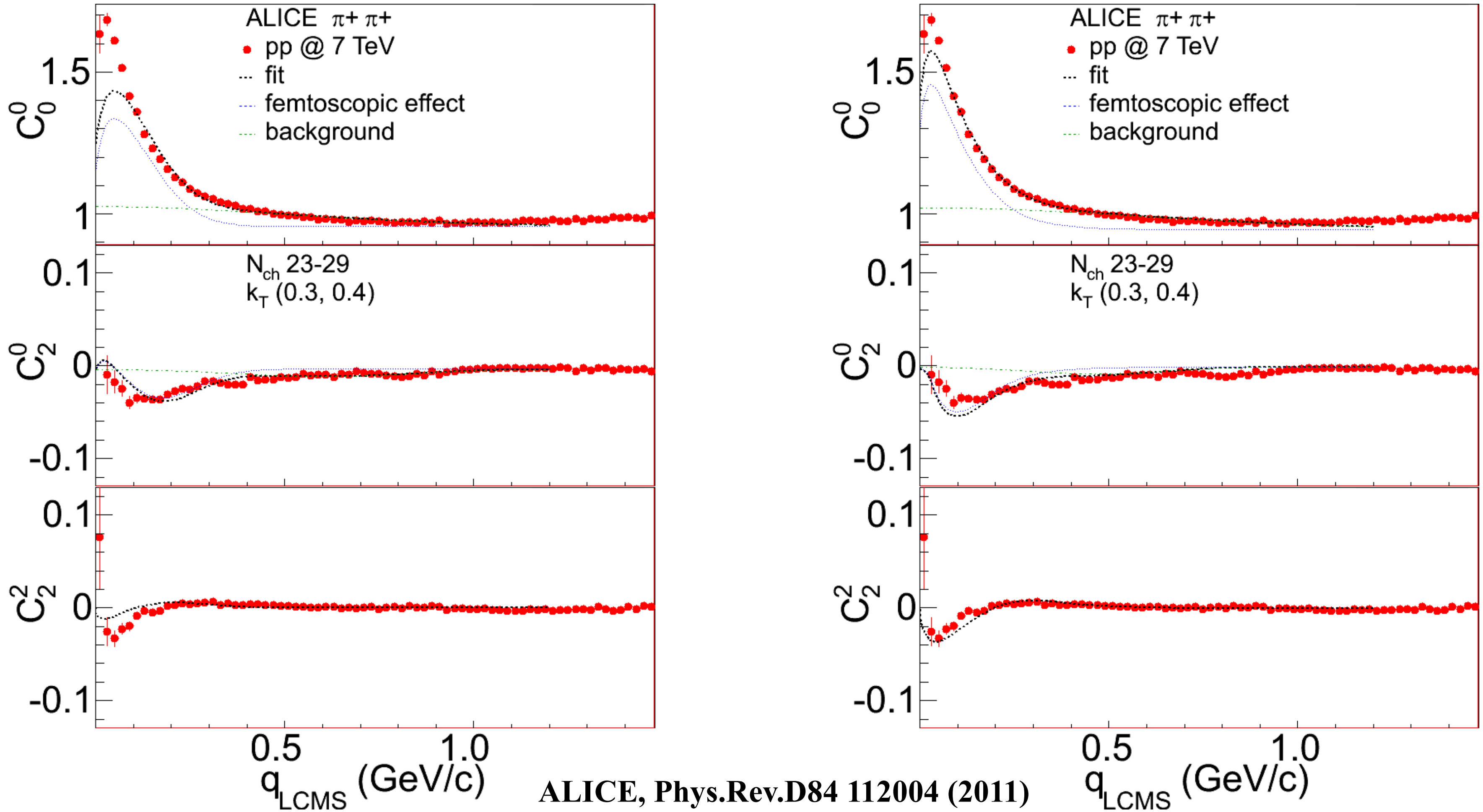


- Significant non-femtoscopic small-q correlations seen, qualitatively in agreement with the "mini-jet" effect. Similar is seen in Monte-Carlo. Cross-check with opposite-charge pions consistent with "mini-jets".
- Effect smaller than the femtoscopic one but significant.
- Effect gets stronger with pair momentum, slowly decreases with multiplicity. Included in fitting via the parametrization B – remains the main source of systematic error.

$$B(\vec{q}) = A_h \exp(-q^2 A_w^2) + B_h \exp\left(\frac{-(q-B_m)^2}{2 B_w^2}\right)(\cos^2(\theta)-1)$$

Functional form studies

- Correlation functions in p+p are better described by Exponential-Gaussian-Exponential, the radii trends are the same as with traditional 3D Gaussian

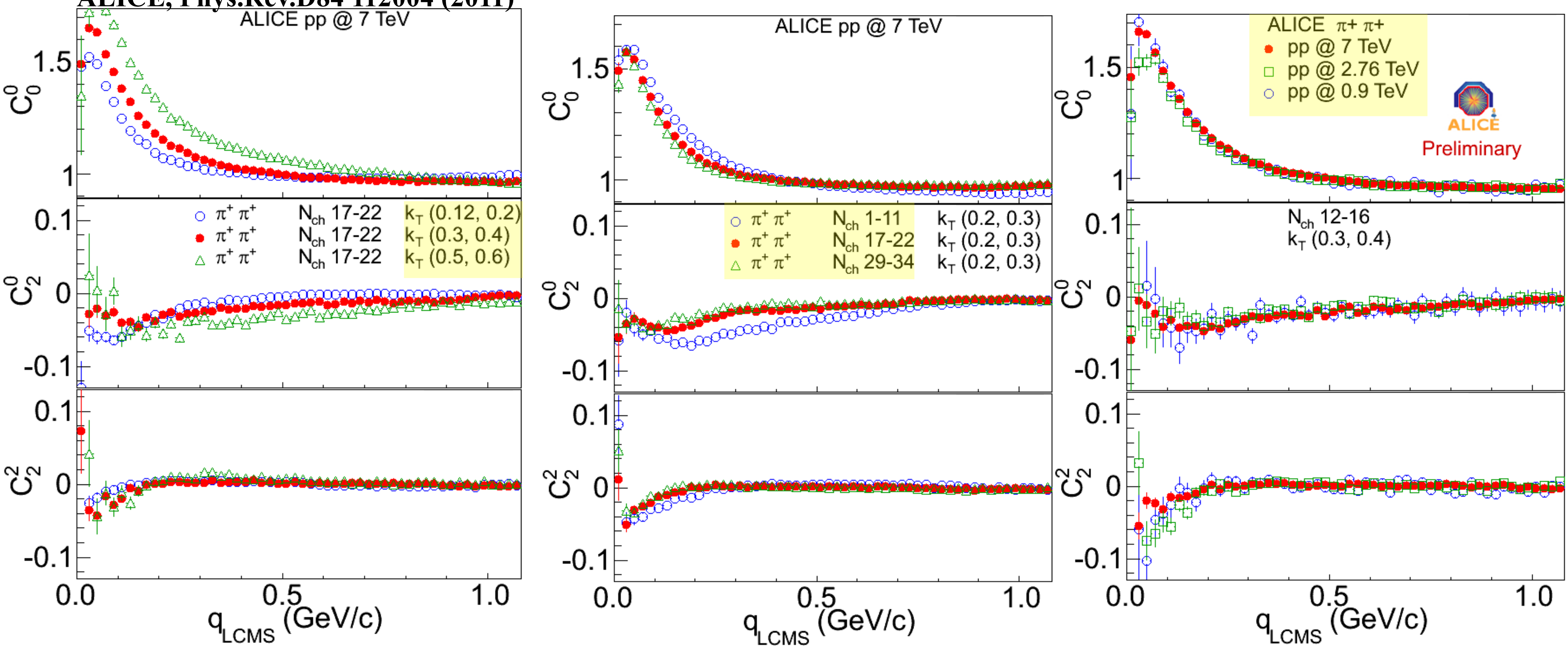


ALICE, Phys.Rev.D84 112004 (2011)

Looking for scaling variables

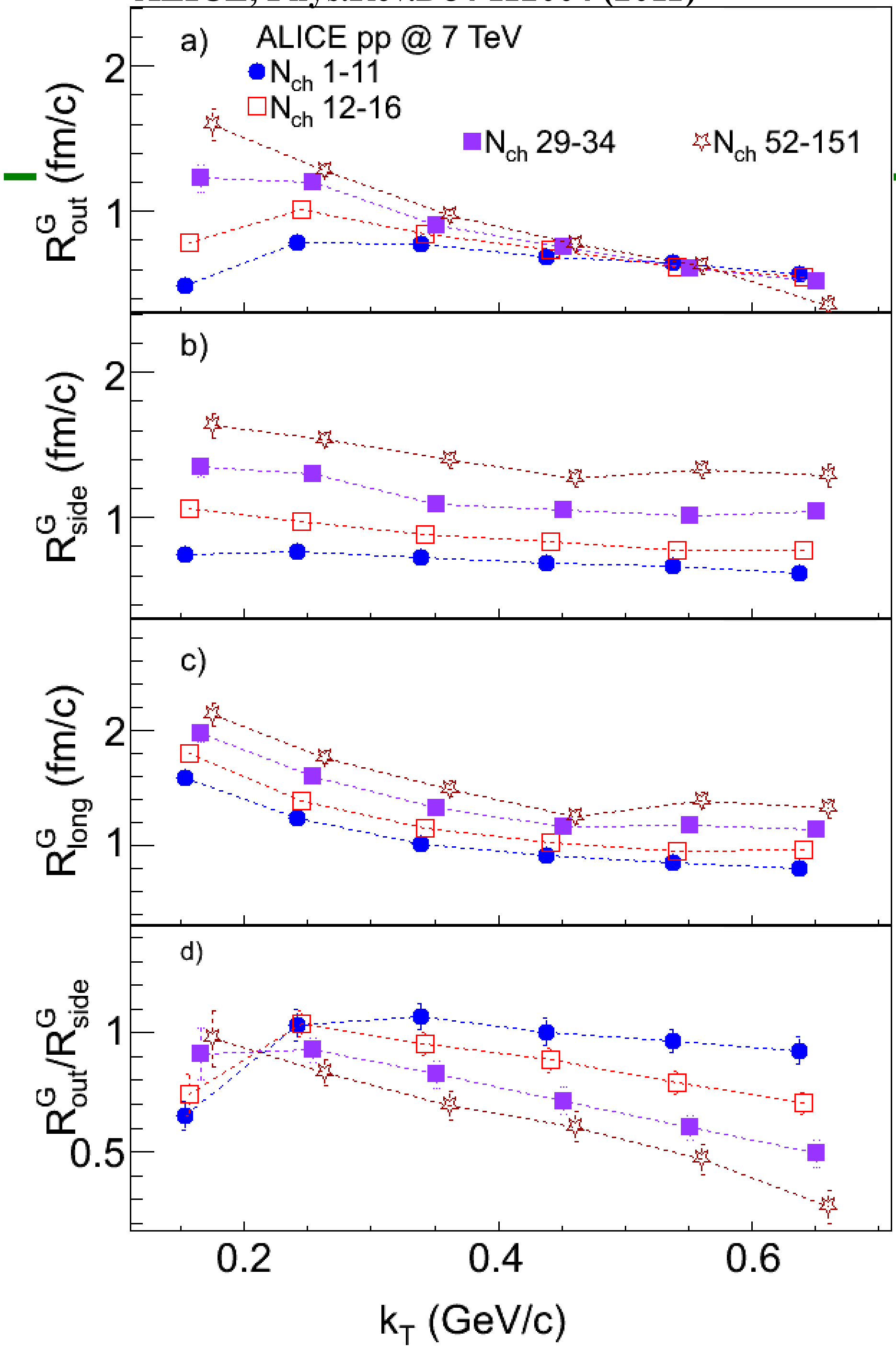
- 3D LCMS correlation decomposed into Spherical Harmonics, first 3 non-vanishing components shown
- Correlations vary with $dN_{ch}/d\eta$ and k_T, independent of $\sqrt{s}$

ALICE, Phys.Rev.D84 112004 (2011)



pp collisions: radii vs. k_T

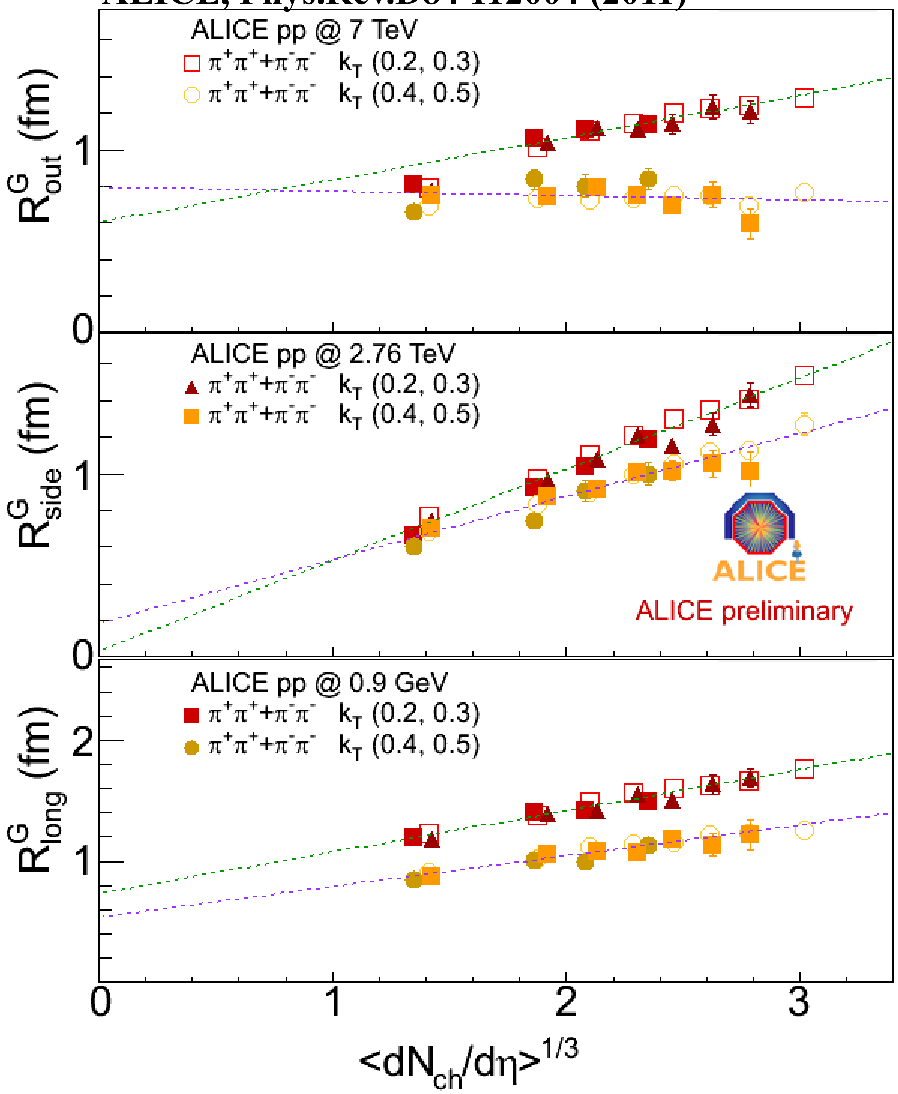
ALICE, Phys.Rev.D84 112004 (2011)



- R_{long} falls with k_T for all multiplicities
- R_{side} flat with k_T at lowest mult, develops dependence as mult increases
- R_{out} dependence on k_T evolves strongly with multiplicity and is steeply falling at top mult
- $R_{\mathrm{out}}/R_{\mathrm{side}}$ falls with multiplicity, goes significantly below 1.0
- Behavior in heavy-ions is not a simple scaling of pp, as suggested at RHIC

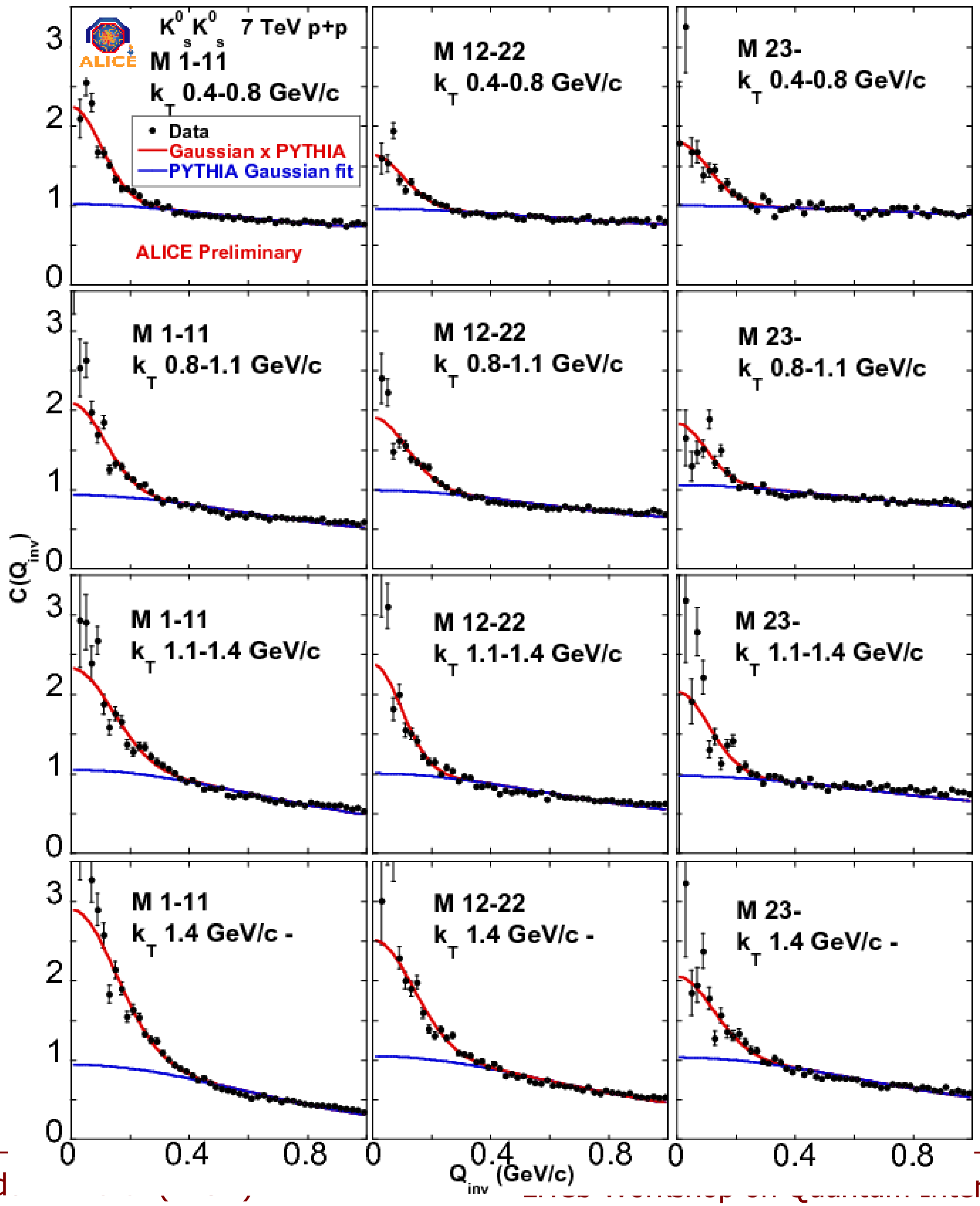
Radii vs. $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$

ALICE, Phys.Rev.D84 112004 (2011)



- Radii scale linearly with $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$ for 3 dimensions and all pair momentum ranges
- Radii from all collision energies follow the same trend ($\chi^2/N_{\mathrm{dof}}<1.0$ for the fit); lowest multiplicity R_{out} points (all energies) slightly below.
- Radii grow with multiplicity for R_{side} and R_{long}
- Behavior in R_{out} is different: has flat or decreasing trend at high k_{T}.

K^0_s-K^0_s correlations

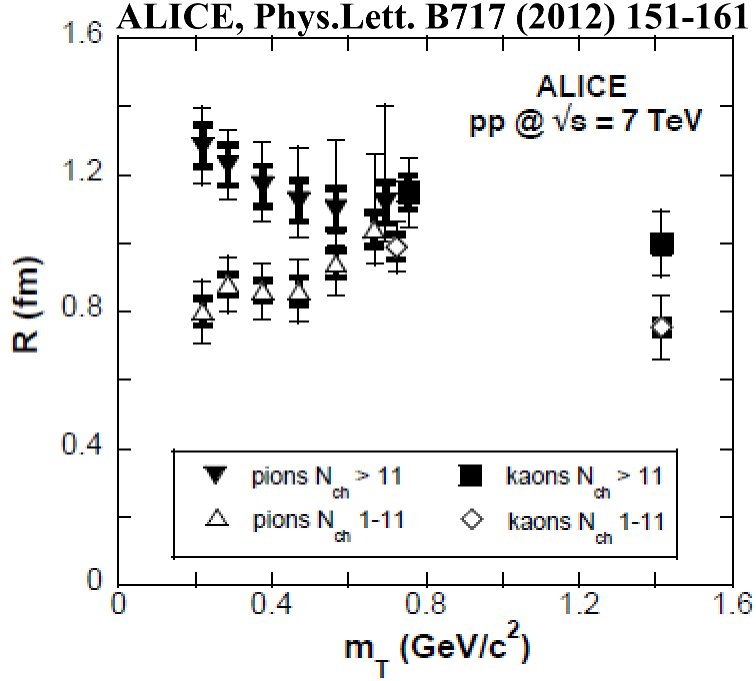


- Get the background from parametrization of the Pythia correlation via a Gaussian form
- Fit the correlation with the full correlation form, including strong interaction and quantum statistics
- Fit done in three bins in multiplicity and four bins in pair transverse momentum

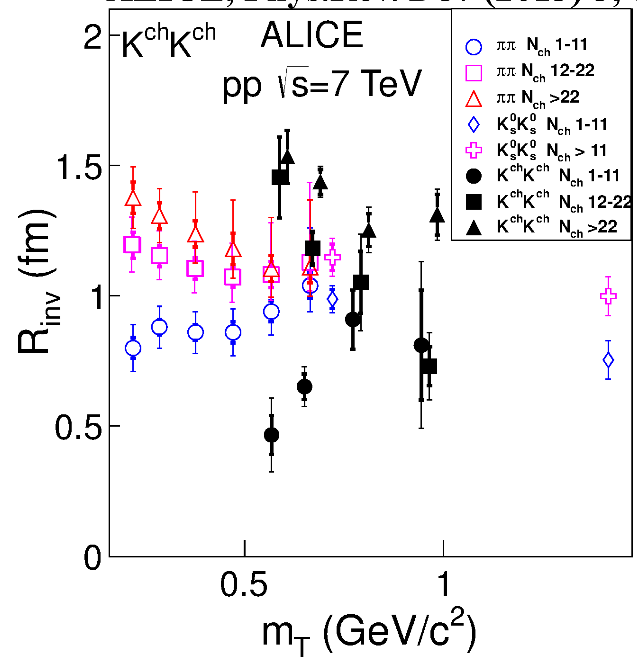
K^0_s-K^0_s and charged kaon results

- Pair momentum range extended 3 times (w.r.t. pions)
- For neutral kaons, smooth extension of the trend for pions, slope of the dependence on pair momentum not the same
- For charged kaons radii different than pions at same m_T
- Clear dependence of radius on multiplicity

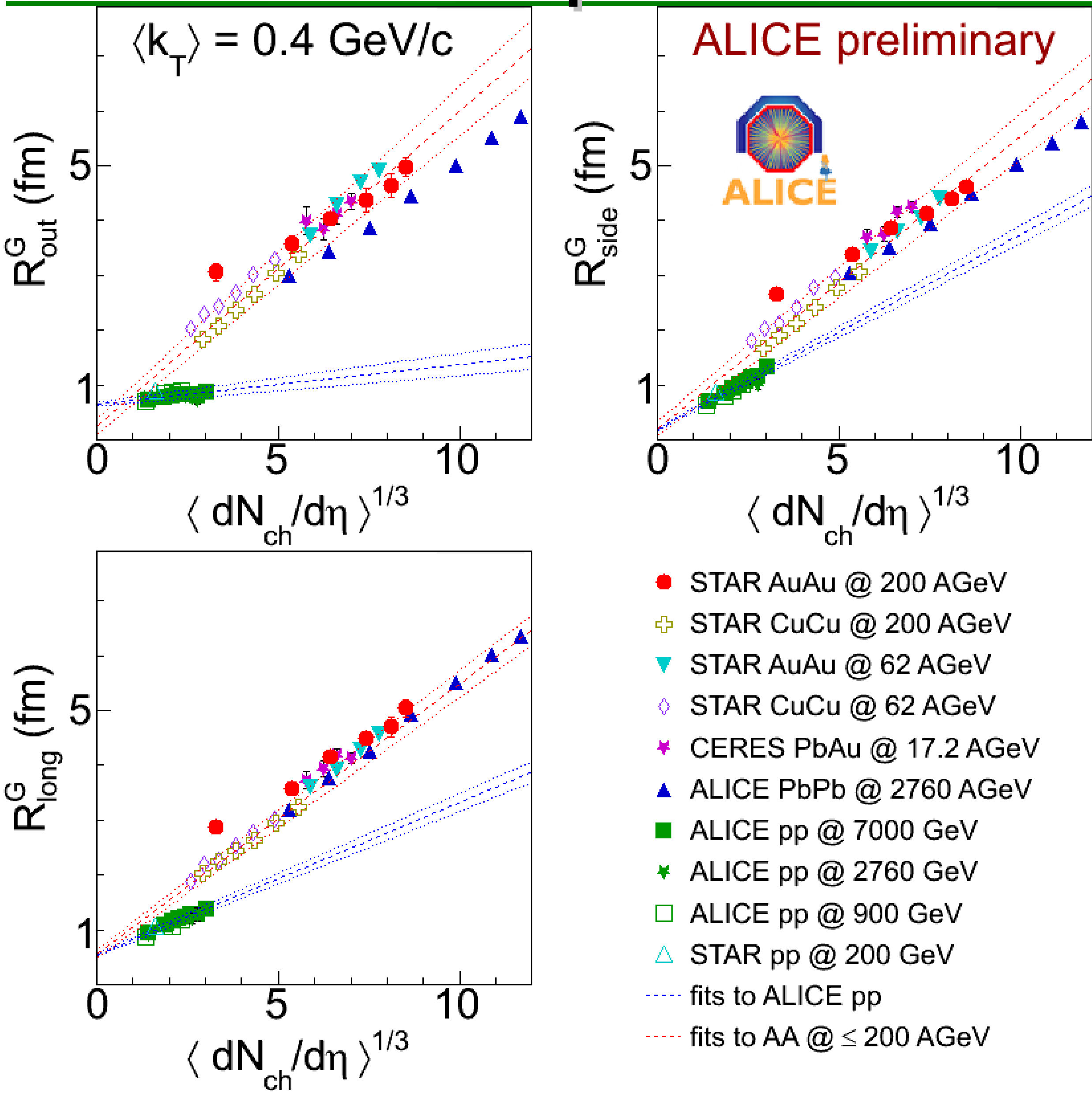
ALICE, Phys.Lett. B717 (2012) 151-161



ALICE, Phys.Rev. D87 (2013) 5, 052016



Comparison LHC vs. world

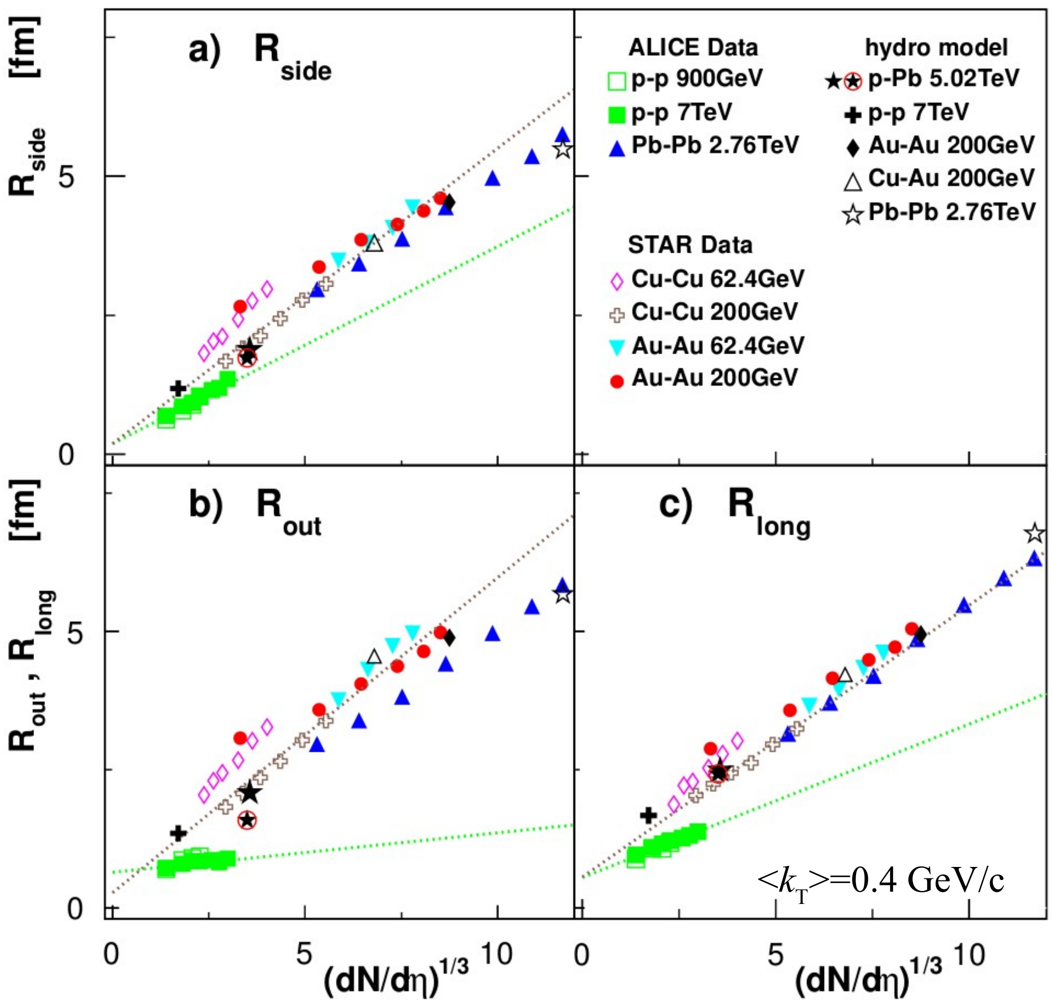


- pp and AA linear scaling clearly different, no simple pp/AA scaling
- ALICE PbPb R_{long} in perfect agreement with world data
- ALICE PbPb R_{side} in reasonable agreement with world data
- ALICE R_{out} clearly below the linear scaling
- Behavior of all 3 radii in PbPb @ 2.76 TeV in qualitative agreement with hydrodynamical model expectations.

p-Pb like pp or PbPb?

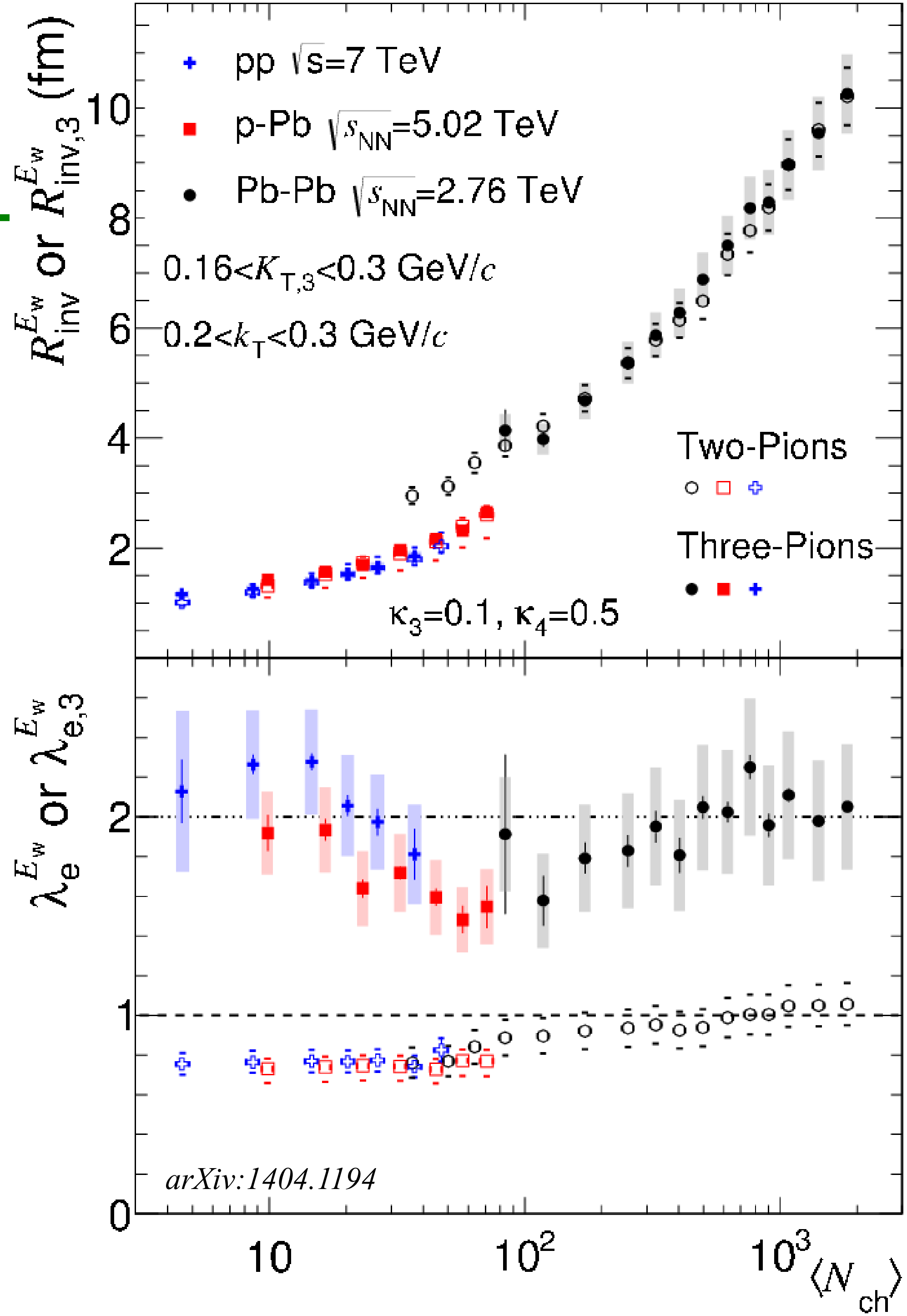
Phys. Lett. B720 (2013) 250
arXiv:1301.3314

- Hydrodynamics predicts that radii for pPb are consistent with PbPb scaling
- Important to compare the pp, pPb and PbPb results at similar multiplicity
- The GCG-type calculations predict size in pPb generally similar to that observed in pp, some expansion possible



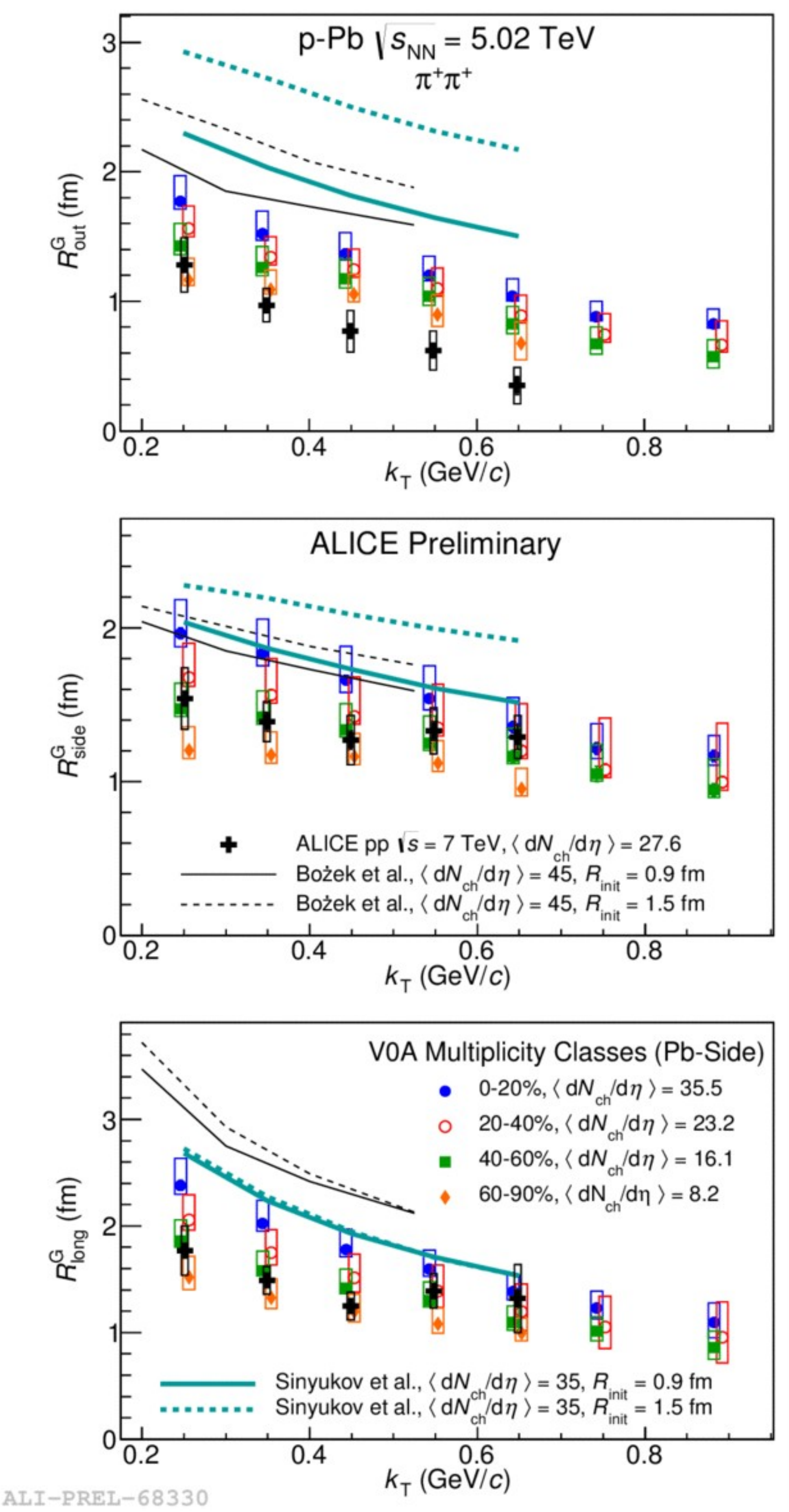
1D pPb from ALICE

- 1D analysis performed for pp, pPb and PbPb
- Uses 2-pion and 3-pion formalism, with different sensitivity to backgrounds
- pPb results 10-20% higher than pp at similar multiplicity, up to 40% smaller than PbPb
- Comparing only LHC results, not "AA line" from lower energies



3D pPb in ALICE

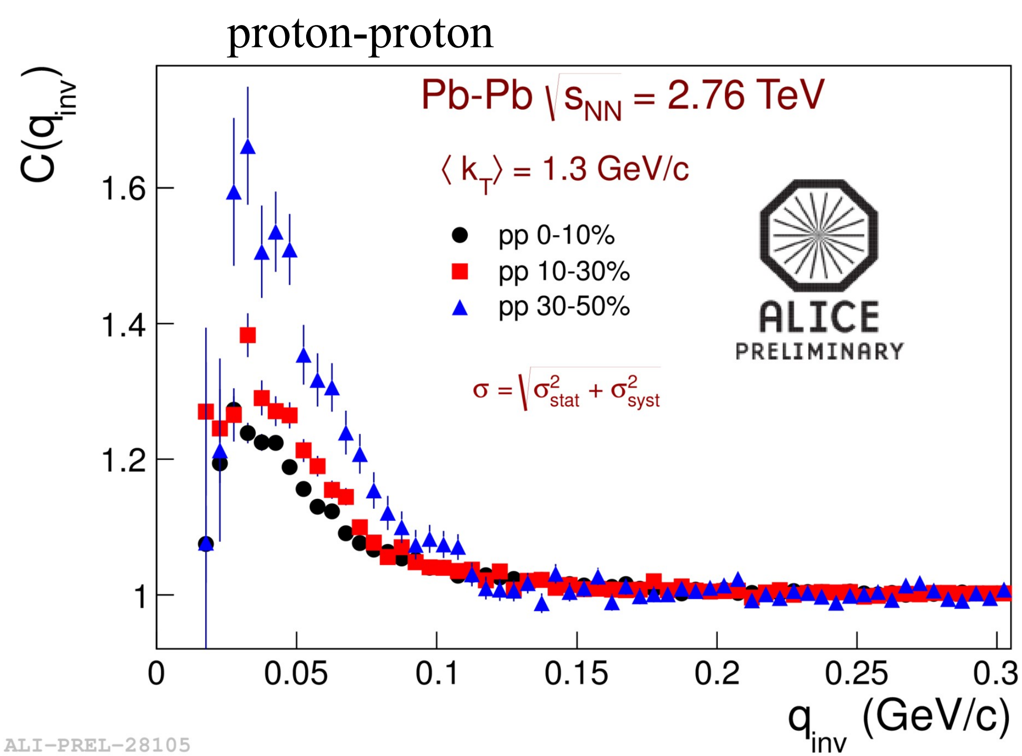
- Analysis of pion femtoscopcy in 3D sensitive to collectivity signatures
- pPb radii are 10-20% larger than pp at similar multiplicity in Side and Long, Out shows larger difference at high k_T
- Hydro predictions are comparable to high-multiplicity pPb in Side and Long and overestimate Out
- k_T dependence similar in models and data
- Lower initial size brings models closer to data

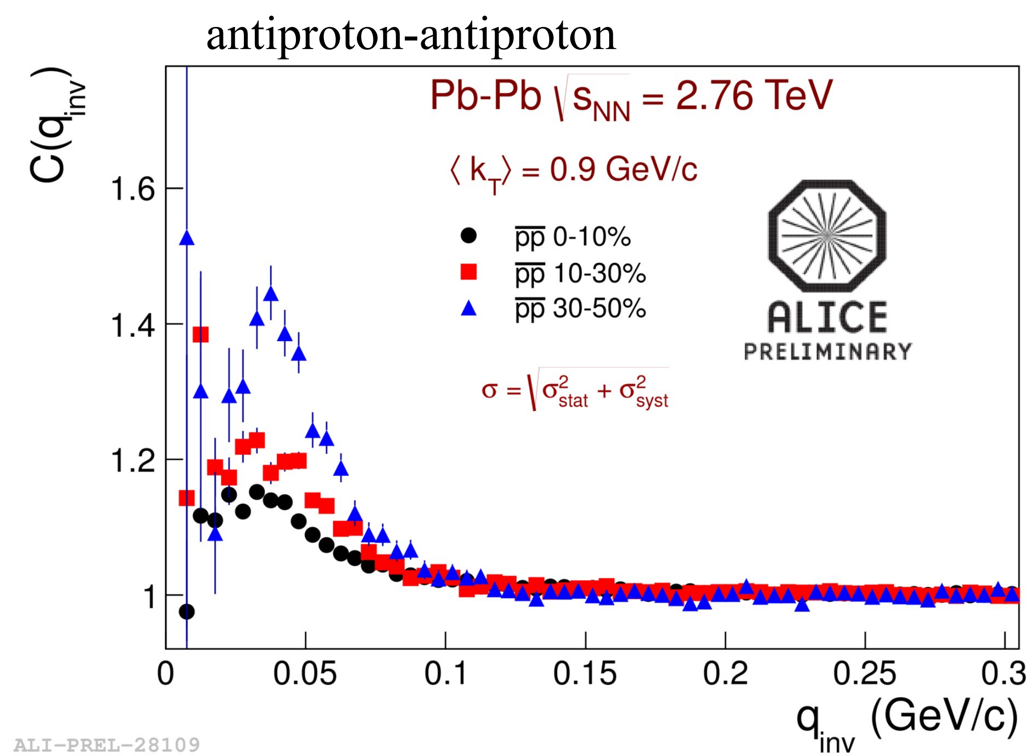


Heavier particles: physics motivation

- Full set of pion, kaon and proton femtoscopic results
  - wide range of transverse mass: test of hydrodynamic collectivity prediction (if truly general, it should include heavier mesons and baryons)
  - non-trivial consistency checks – different sources of femtoscopic correlations (QS, Coulomb FSI, Strong FSI), different detection procedures and systematics (primary, V0, PID techniques)
- Deviation of proton yields from chemical models expectations
  - Proton (and Lambda) yield in Pb-Pb at LHC below thermal model expectations (extrapolated from RHIC)
  - models claim that annihilation in "rescattering" phase should be taken into account while determining yields
  - Annihilation **is** the source of the femtoscopic correlation observed for many $B\bar{B}$ pairs – must be observed if this explanation is correct.

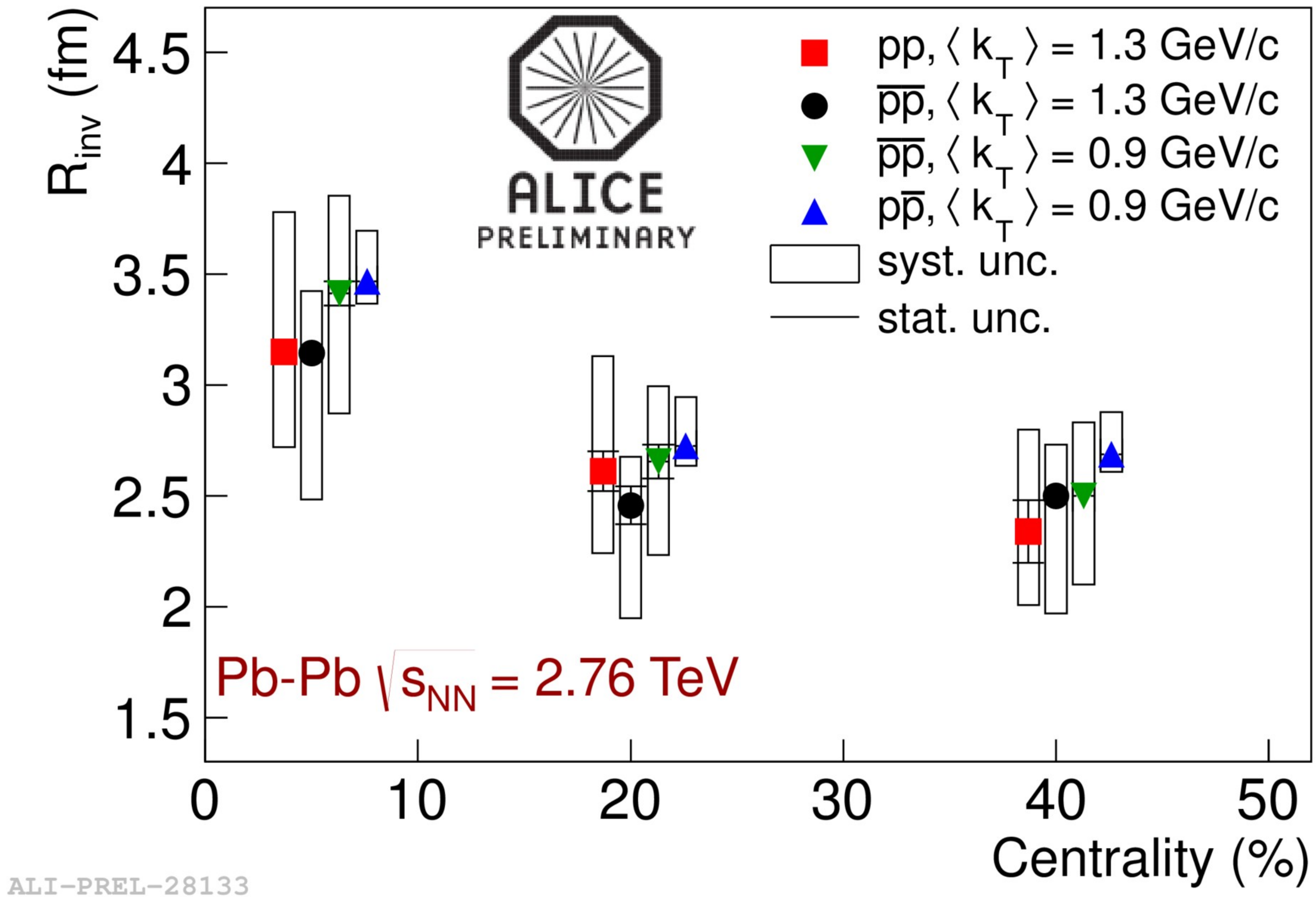
pp and $\overline{pp}$ correlation functions





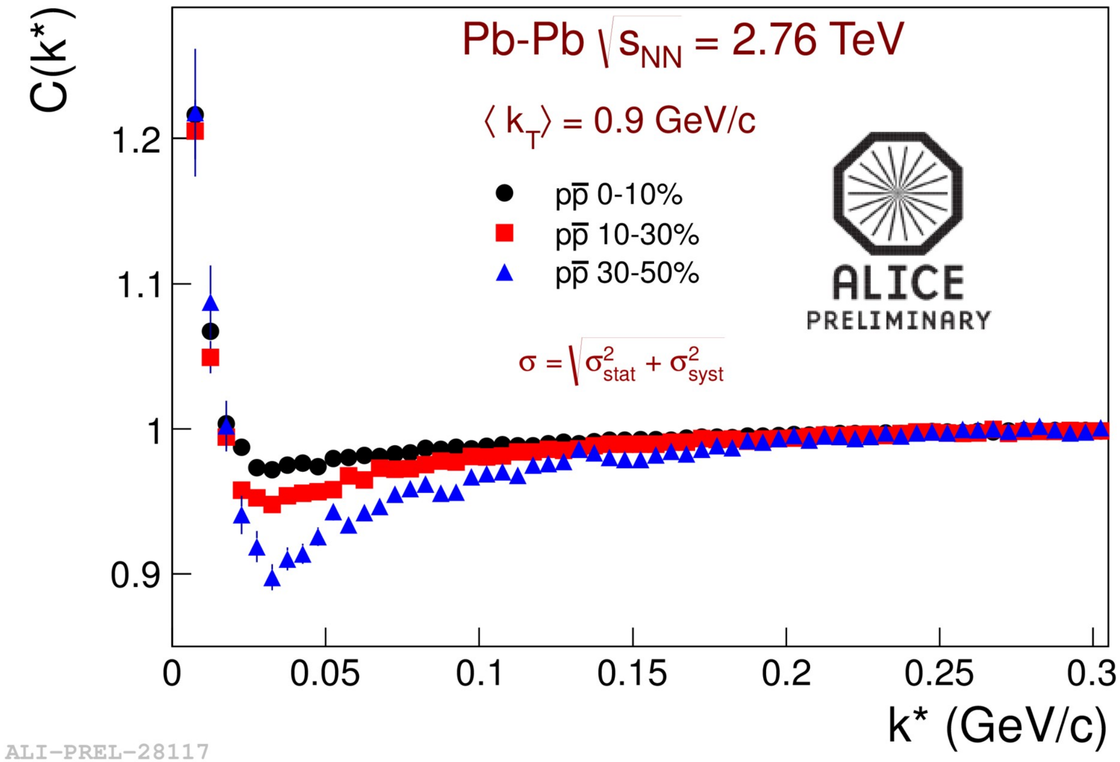
- Correlation effect increases for more peripheral events - size decreases with decreasing multiplicity
- QS, Coulomb and Strong FSI contribute to measured correlations
- Possible to extract the source radius for heavy particles

R_{inv} from proton femtoscopy



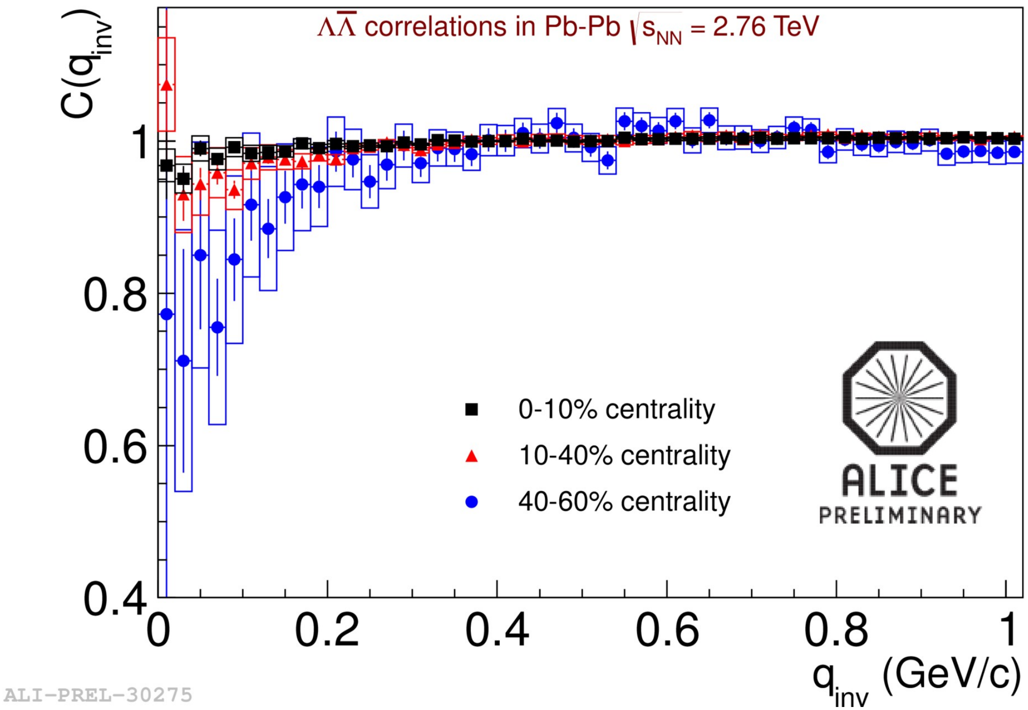
- Radii increase with multiplicity, higher k_T gives smaller radii, consistent with hydro collectivity

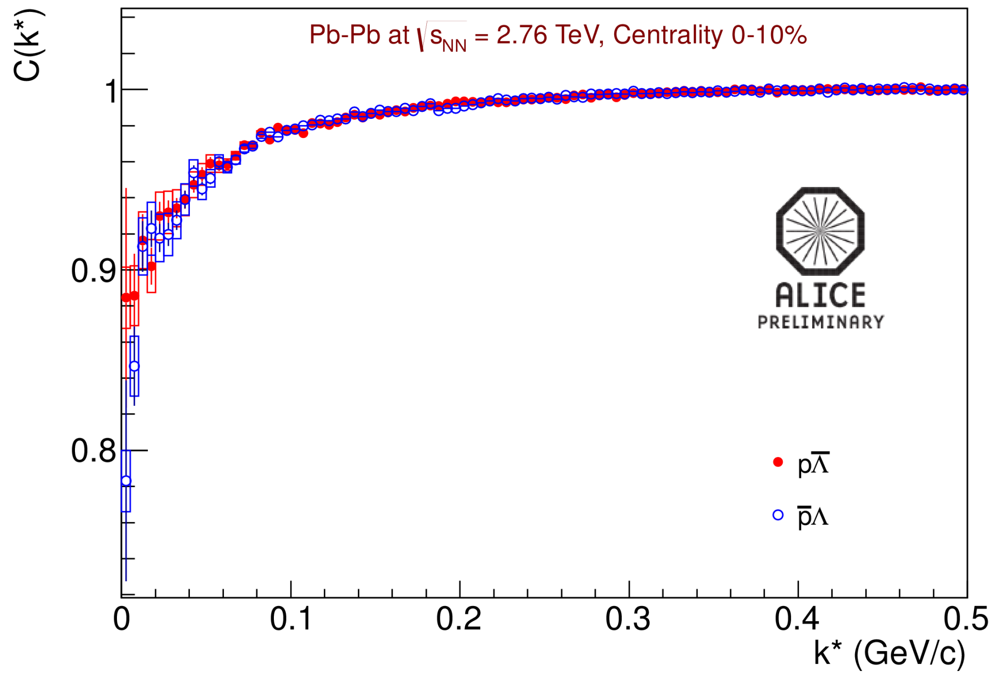
$p\bar{p}$ correlation functions



- Shape dominated by Coulomb and Strong FSI
- Wide negative correlation consistent with annihilation in the strong FSI
- Femtoscopic effect very wide, better statistical handle on the system size (compared to pp)

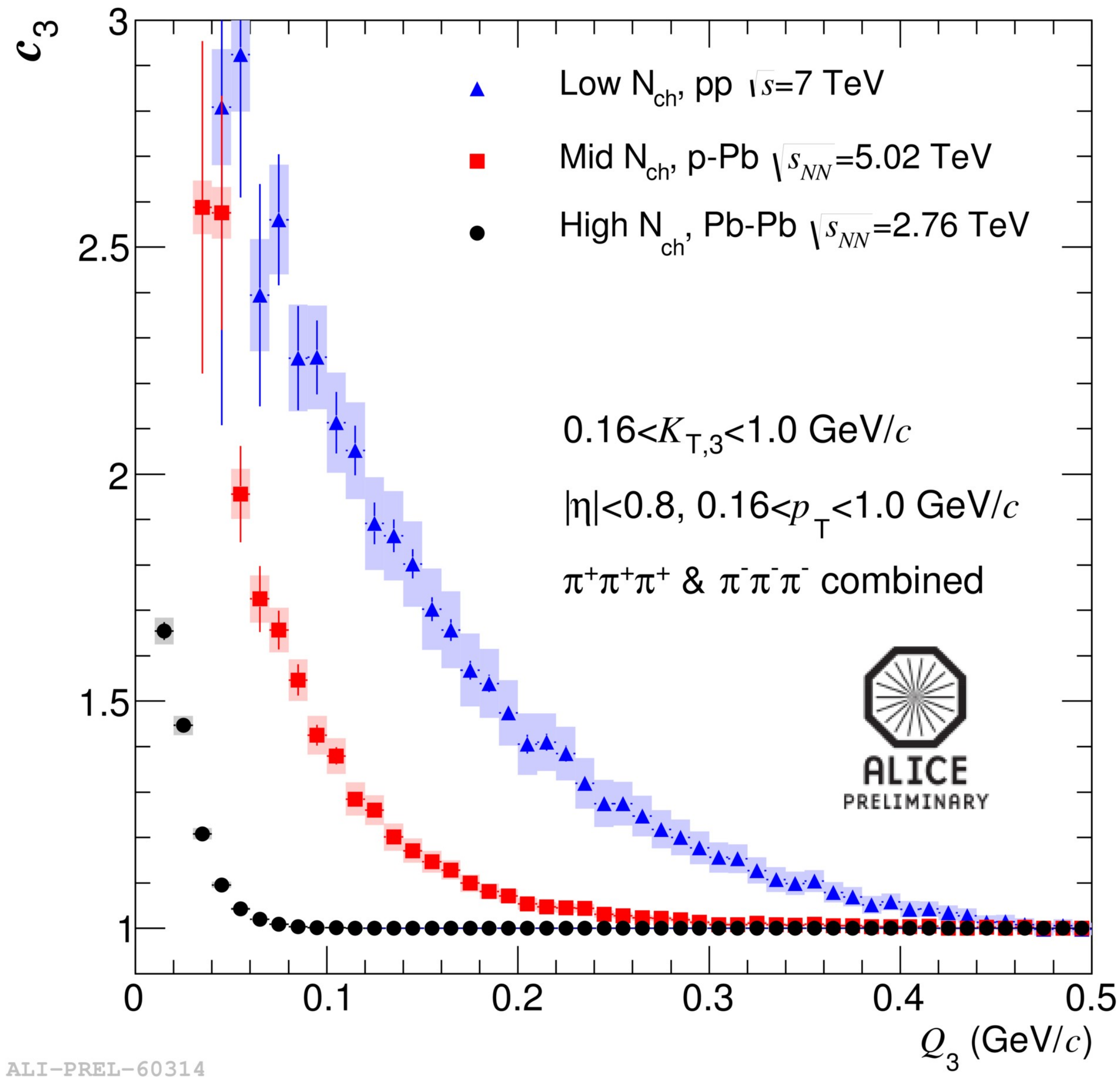
$\Lambda\overline{\Lambda}$ and $p\overline{\Lambda}$ correlation functions





- Wide negative correlation observed, consistent with annihilation in the strong FSI
- Annihilation not limited to particle-antiparticle systems!
- Correlation strength increases with decreasing multiplicity (consistent with decrease of the system size)
- Quantitative analysis requires careful consideration of the residual correlations (feed-up from $p\overline{p}$, correlations with $\overline{\Sigma}^0$ and others)

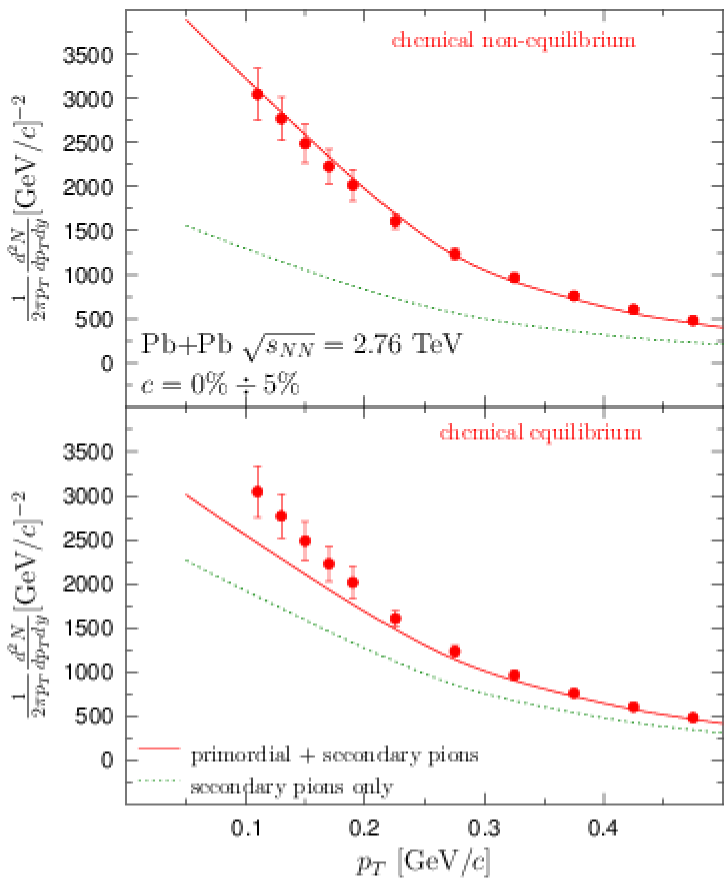
3-pion correlations



- 3-pion cumulant extracts the genuine 3-particle correlation
- Has higher signal/background ratio
- Is sensitive to source size
- Is much more sensitive to coherent pion production than the 2-pion correlation

Interpretation of 3-particle results

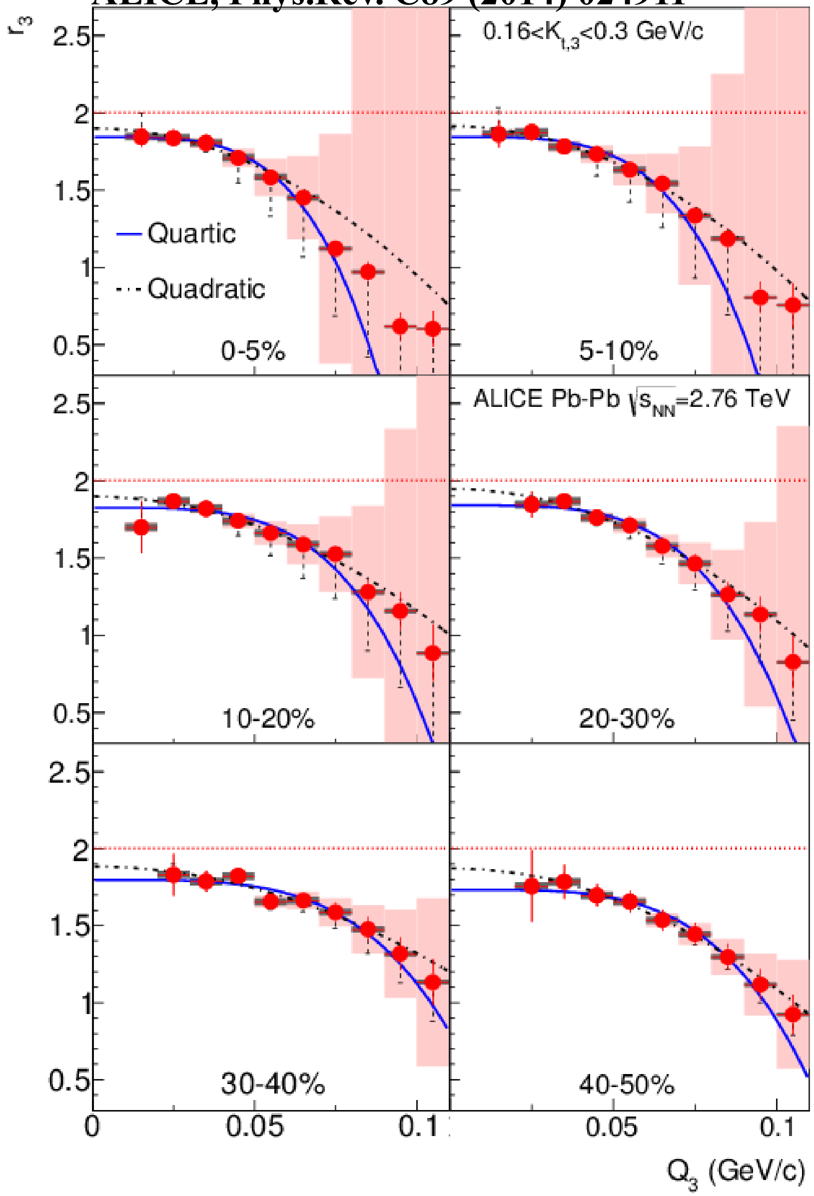
Biegun, Florkowski, Rybczyński; arXiv:1312.1487



- Other possible effect of coherent pion production: increase of pion multiplicity at low momentum
- Preliminary model calculations show intriguing effects in the low-p_T region
- Are the two effects consistent and/or connected?

Extracting coherent fraction

ALICE, Phys.Rev. C89 (2014) 024911



- The r_3 variable should approach 2 for Q_3 -> 0 for fully chaotic emission
- At low triplet momentum the extrapolated intercept is below 2, does not depend strongly on centrality
- At high triplet momentum the intercept is consistent with 2
- Deviation from theoretical limit of 2 consistent with up to 20% coherent pion production

Summary

- Femtoscopy is sensitive to system size (lengths of homogeneity) and collision dynamics and provides important constraints on system dynamics and Equation of State at RHIC and at the LHC
- Heavy-ion data in striking agreement with hydrodynamics
- Azimuthally sensitive femtoscopy an important cross-check of the hydrodynamic evolution of the system – qualitatively consistent
- Precise pion femtoscopy in p+p and p-Pb reveals multiplicity scaling, m_{T} dependence, collision energy independence. Qualitative differences to heavy-ion observed.
- Correlation for heavy particles consistent with hydro collectivity
- Significant annihilation for $\mathrm{B\overline{B}}$ systems observed, could provide better data on cross-sections
- Possible coherent pion production at low momentum observed