Femtoscopy of the Pb-Pb and pp collisions at the LHC with the ALICE experiment

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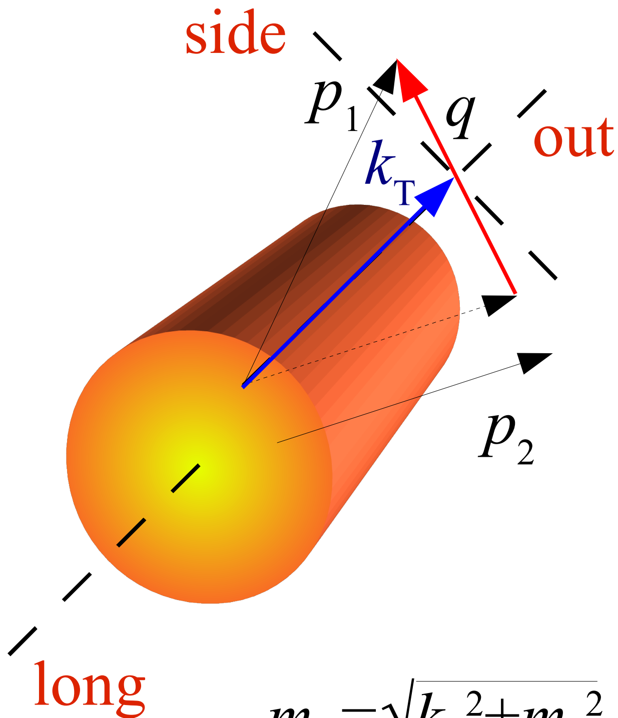
For the ALICE Collaboration

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:

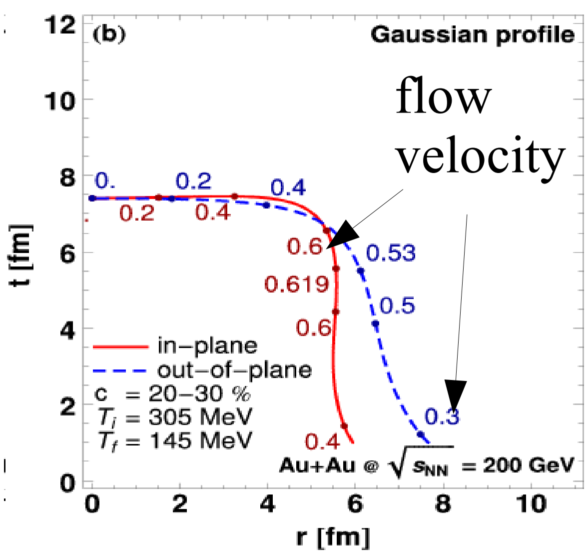
$$C(\vec{q}) = \int S(\mathbf{r}) |\Psi(\vec{q}, \mathbf{r})|^2 d^4 r$$

- Pion femtoscopy in Pb-Pb collisions
  - Measure the size of the homogeneity region from which the 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 and kaons 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 now directly compare pp and AA, address questions of collectivity in pp.

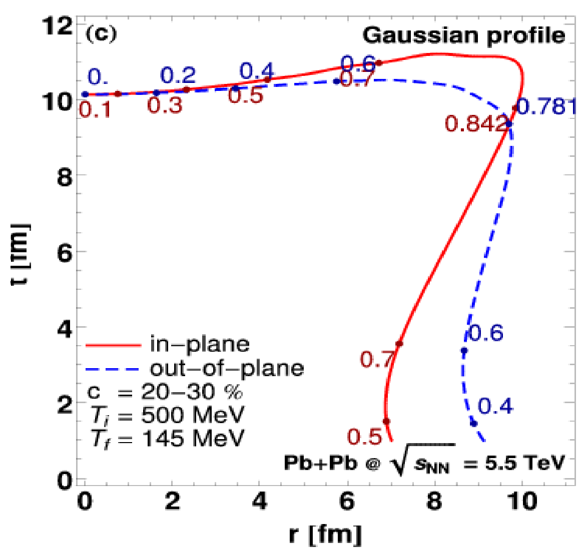
Expectations from hydrodynamics

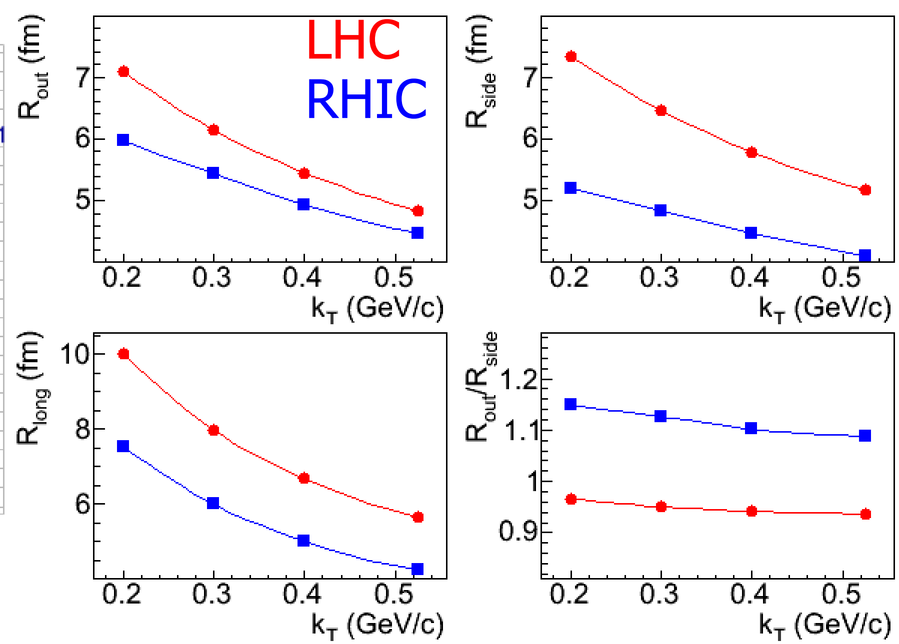
- Lessons from RHIC:
  - “Pre-thermal flow”: strong flows already at $\tau_0 = 1$ fm/c
  - EOS with no first-order phase transition
  - Careful treatment of resonances important
- Extrapolating to the LHC:
  - Longer evolution gives larger system → all of the 3D radii grow
  - Stronger radial flow → steeper k_T radii dependence
  - Change of freeze-out shape → lower R_{OUT}/R_{SIDE} ratio

RHIC → LHC

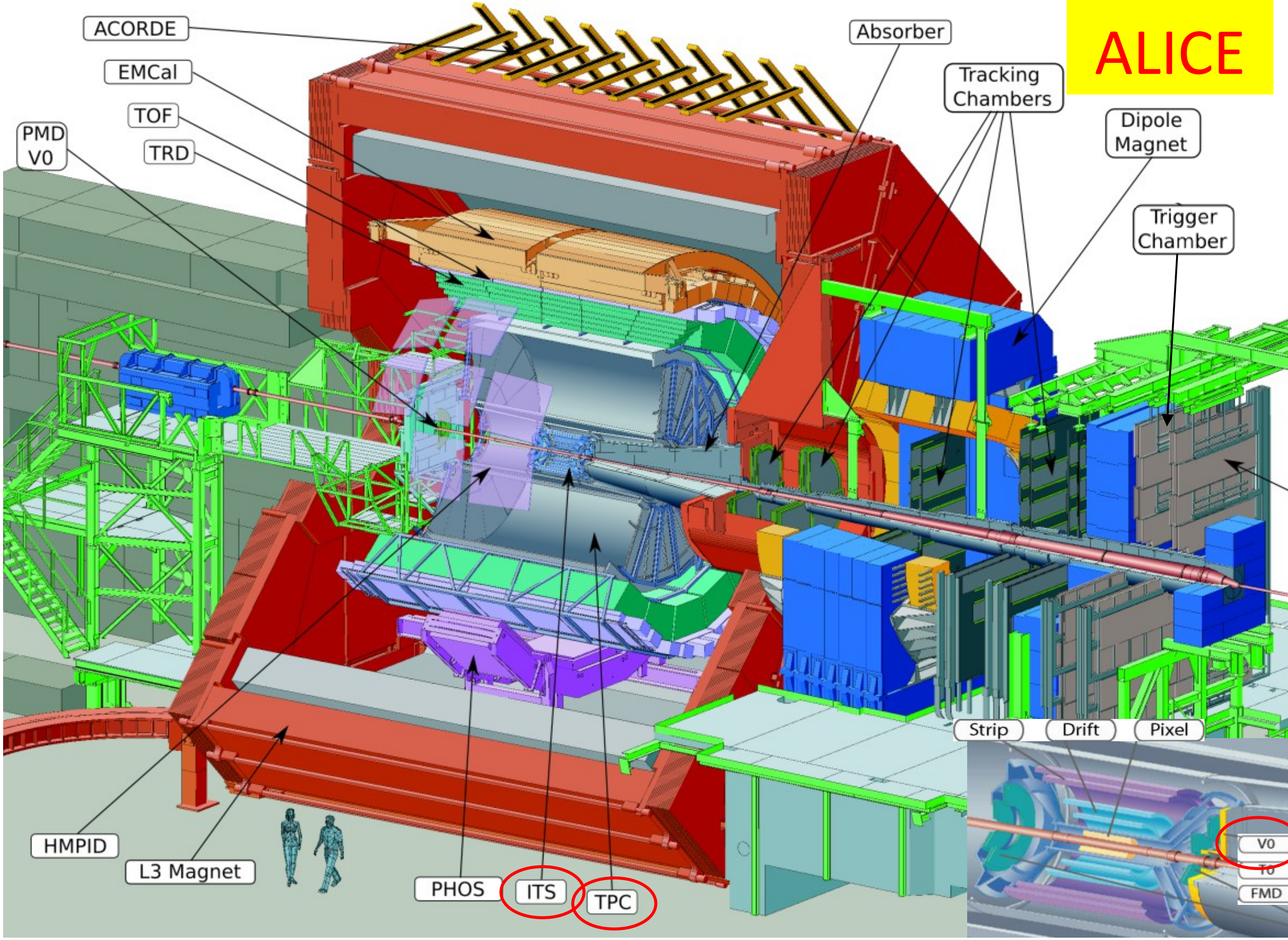


Phys.Rev.C79:014902,2009





The ALICE experiment

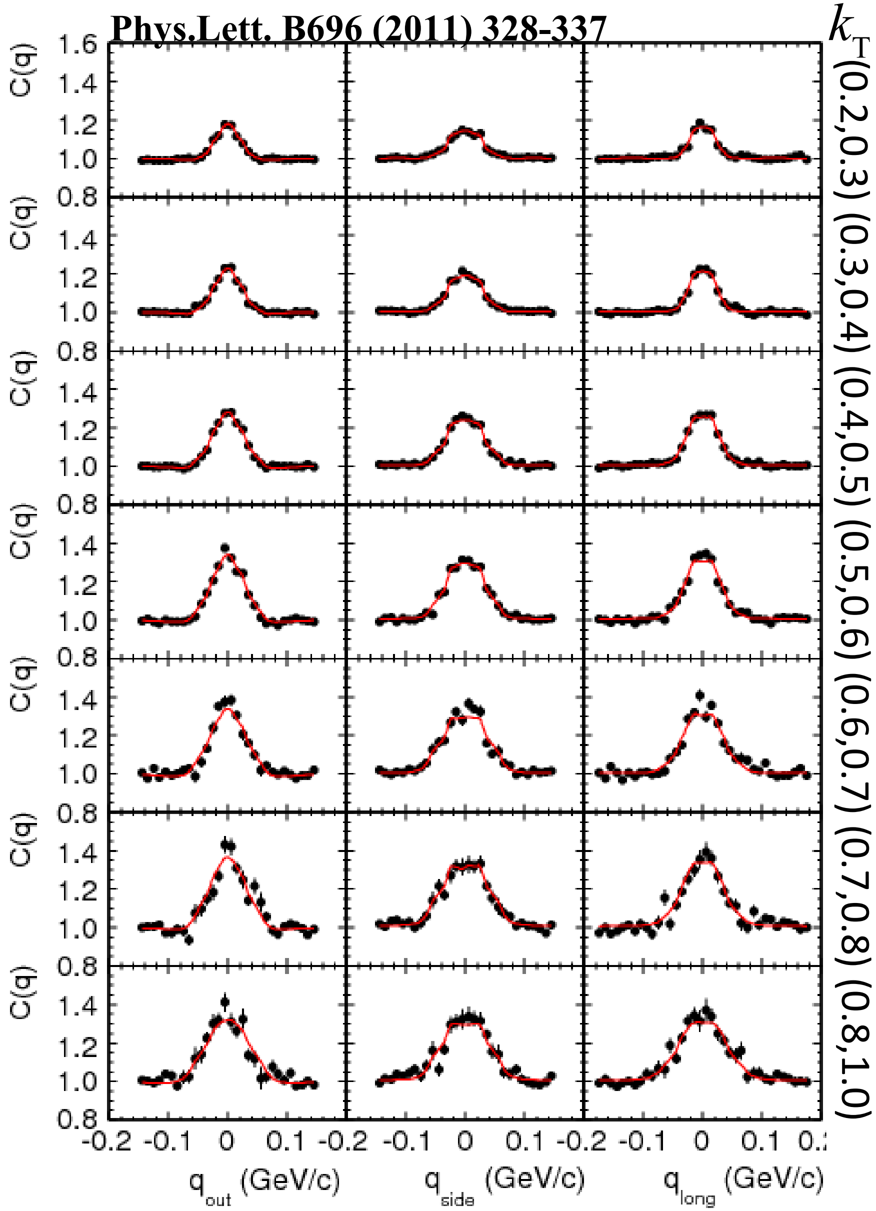


Main tracking and PID detector:
Time Projection Chamber

Vertexing and tracking:
Inner Tracker System

Trigger and centrality:
VZERO

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):

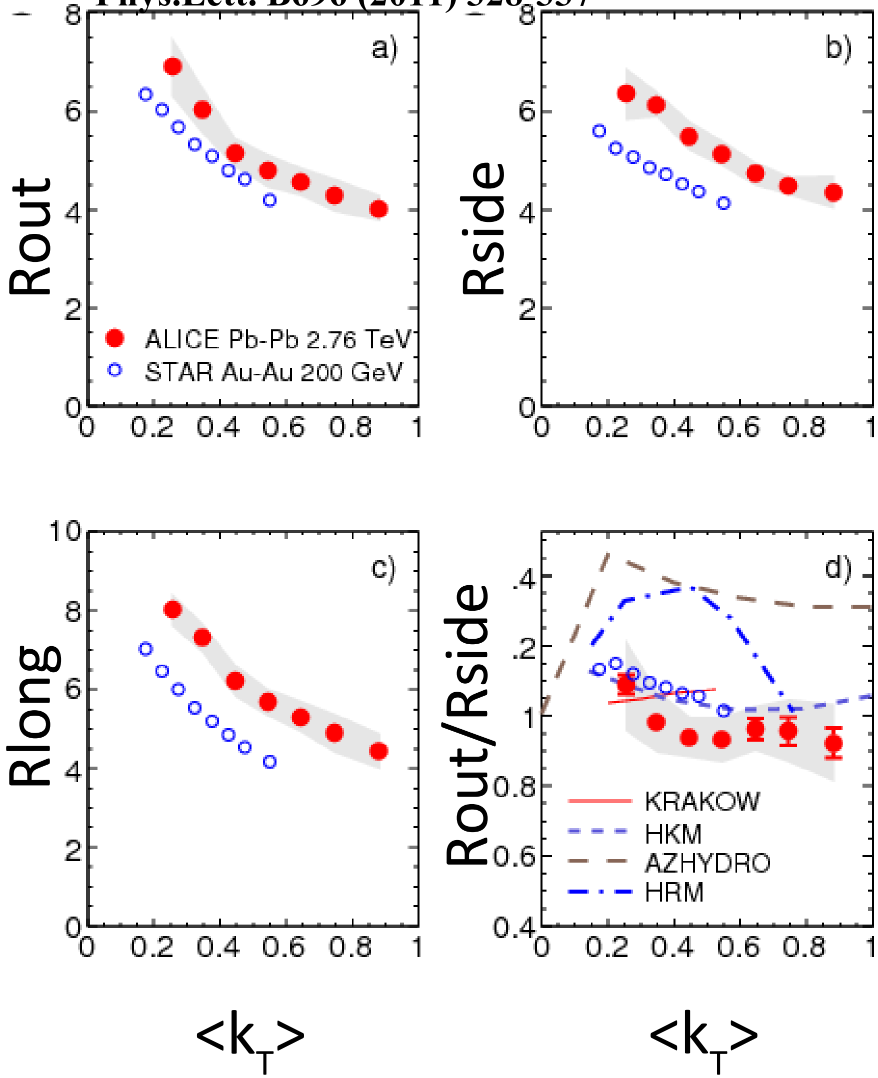
$$C = N\left[(1-\lambda)+\lambda K\left(1+\exp\left(-R^2_{out}q^2_{out}-R^2_{side}q^2_{side}-R^2_{long}q^2_{long}\right)\right)\right]$$

to obtain the femtoscopic radii

talk by J. Mercado, Monday parallel session

Comparing LHC to RHIC

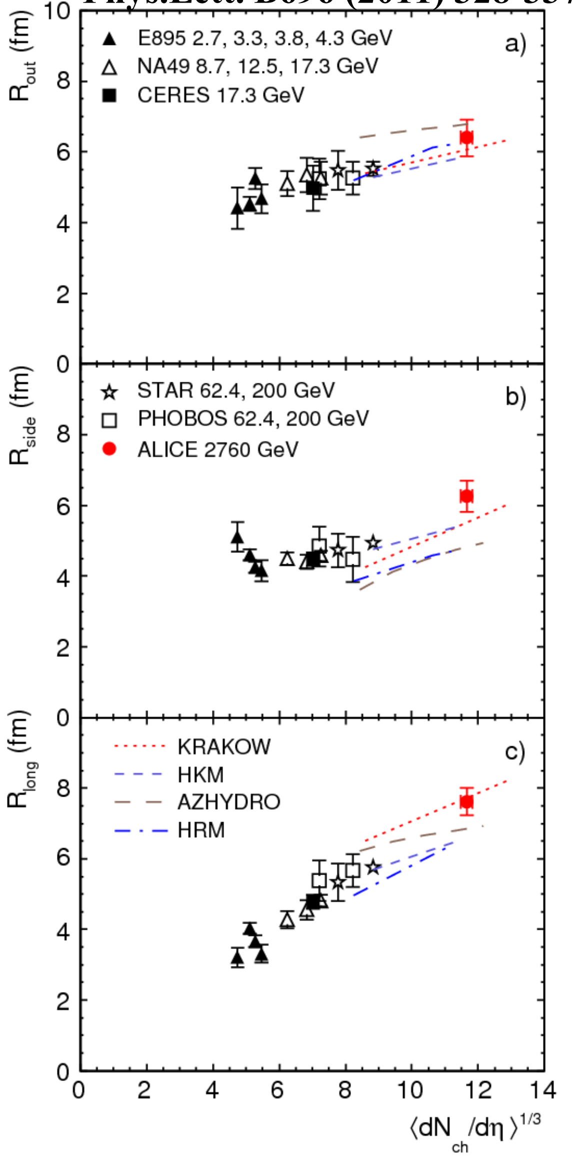
Phys.Lett. B696 (2011) 328-337



- 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

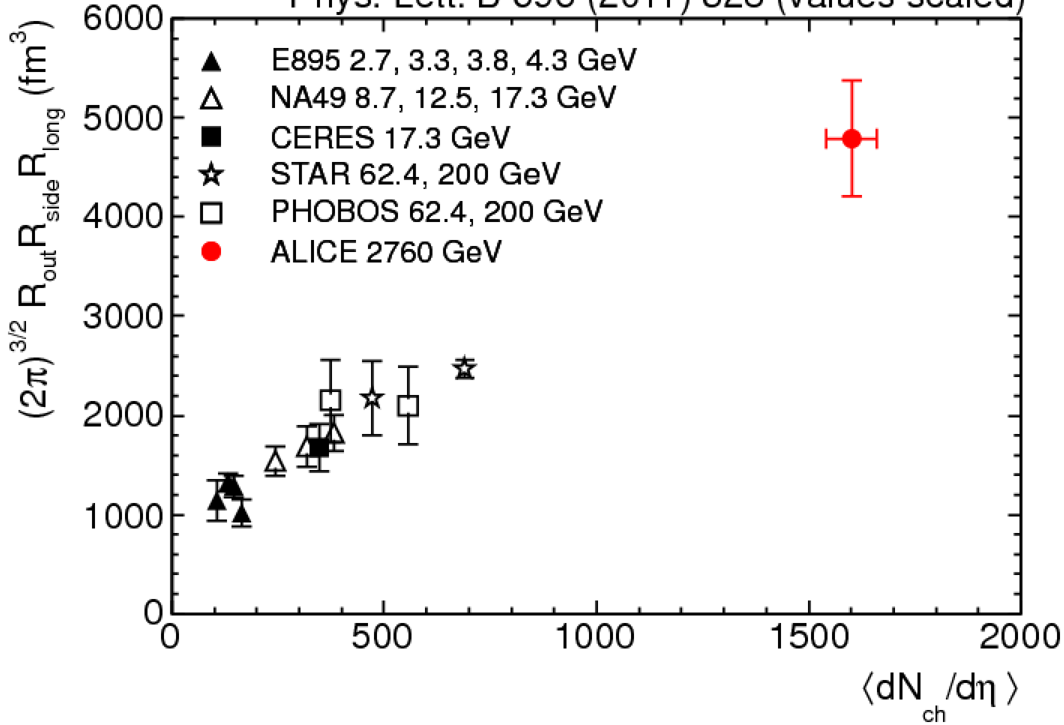
Scaling vs. $dN_{ch}/d\eta$

Phys.Lett. B696 (2011) 328-337



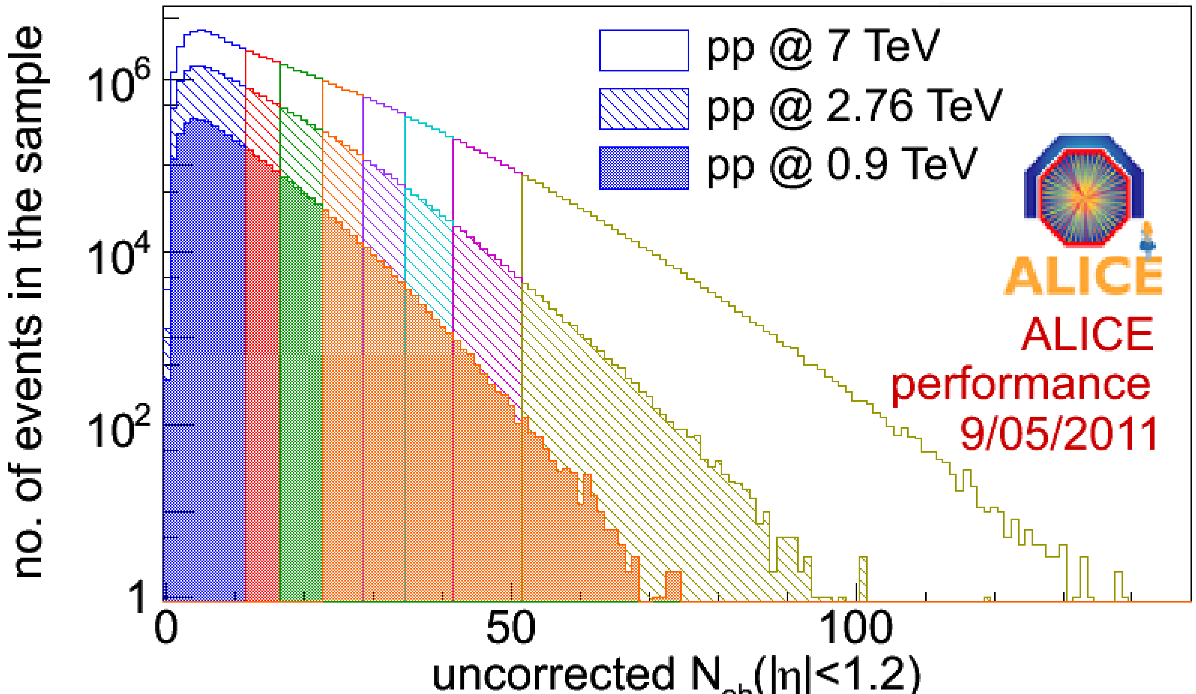
- Increase of the radii with $dN_{ch}/d\eta$ for central collisions consistent with models
- Increase of the "homogeneity volume" over most central RHIC by a factor of ~2

Phys. Lett. B 696 (2011) 328 (values scaled)



Femtoscopy of pp collisions

- Collisions used for the analysis: ~4M at 0.9 TeV, ~20M at 2.76 TeV and ~200M at 7 TeV (60M subsample enough for pion analysis), divided into 8 ranges, highest comparable to peripheral heavy-ion collision multiplicity.
- 3D differential measurement in LCMS vs. k_T

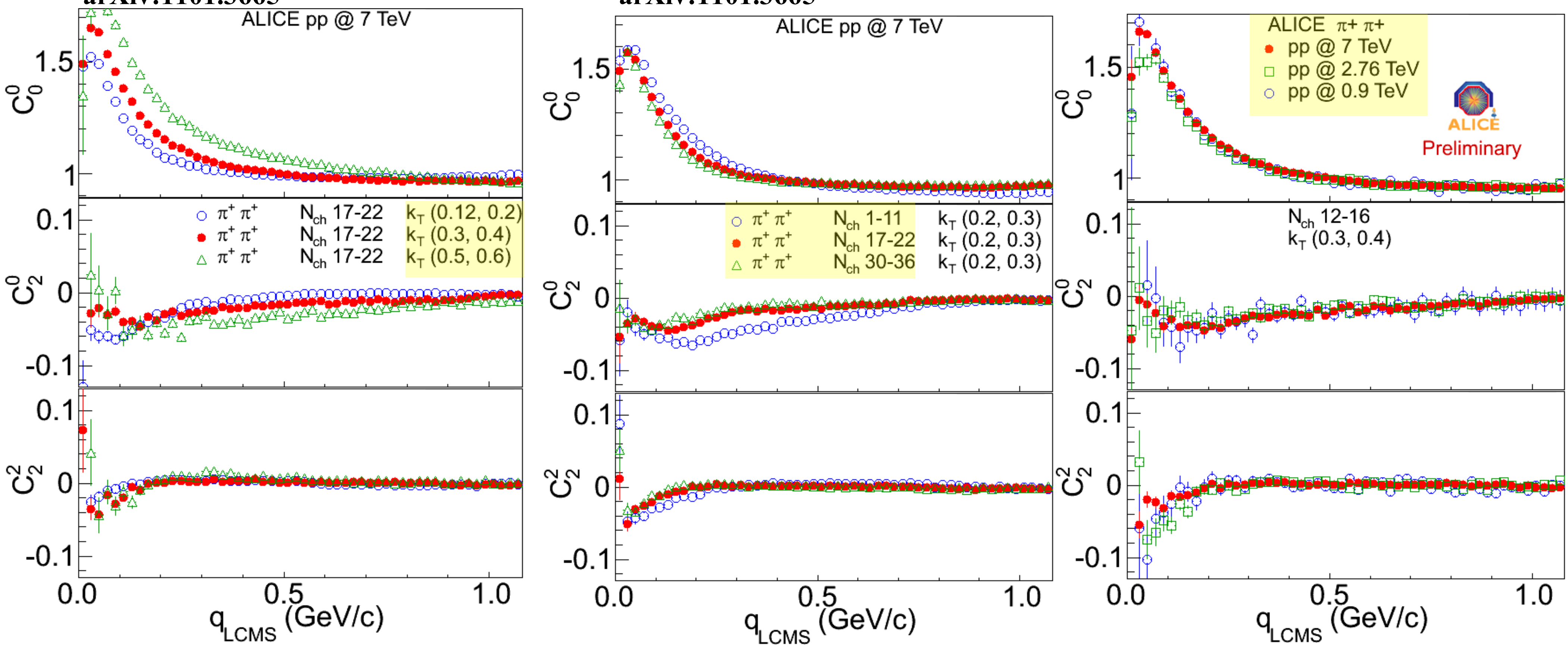


poster by A. Kisiel, Tuesday poster session

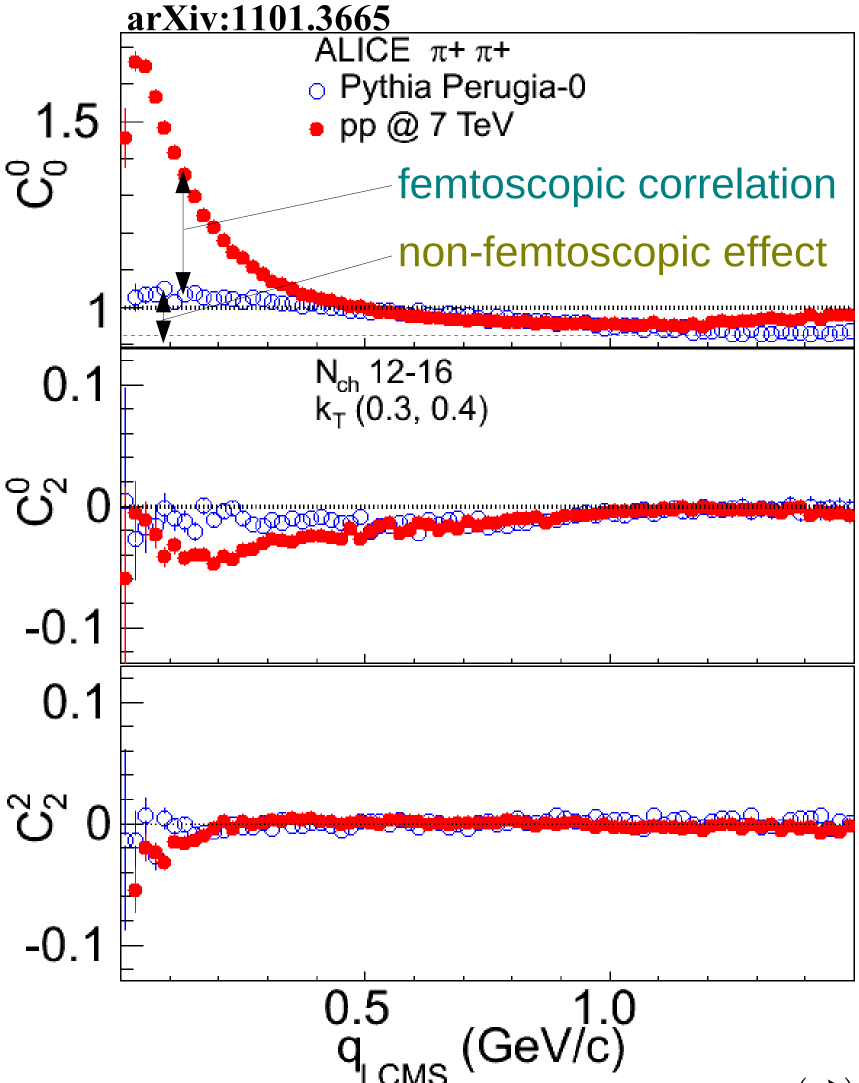
Looking for scaling variables

- 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 $\sqrt{s}$

arXiv:1101.3665 **arXiv:1101.3665**



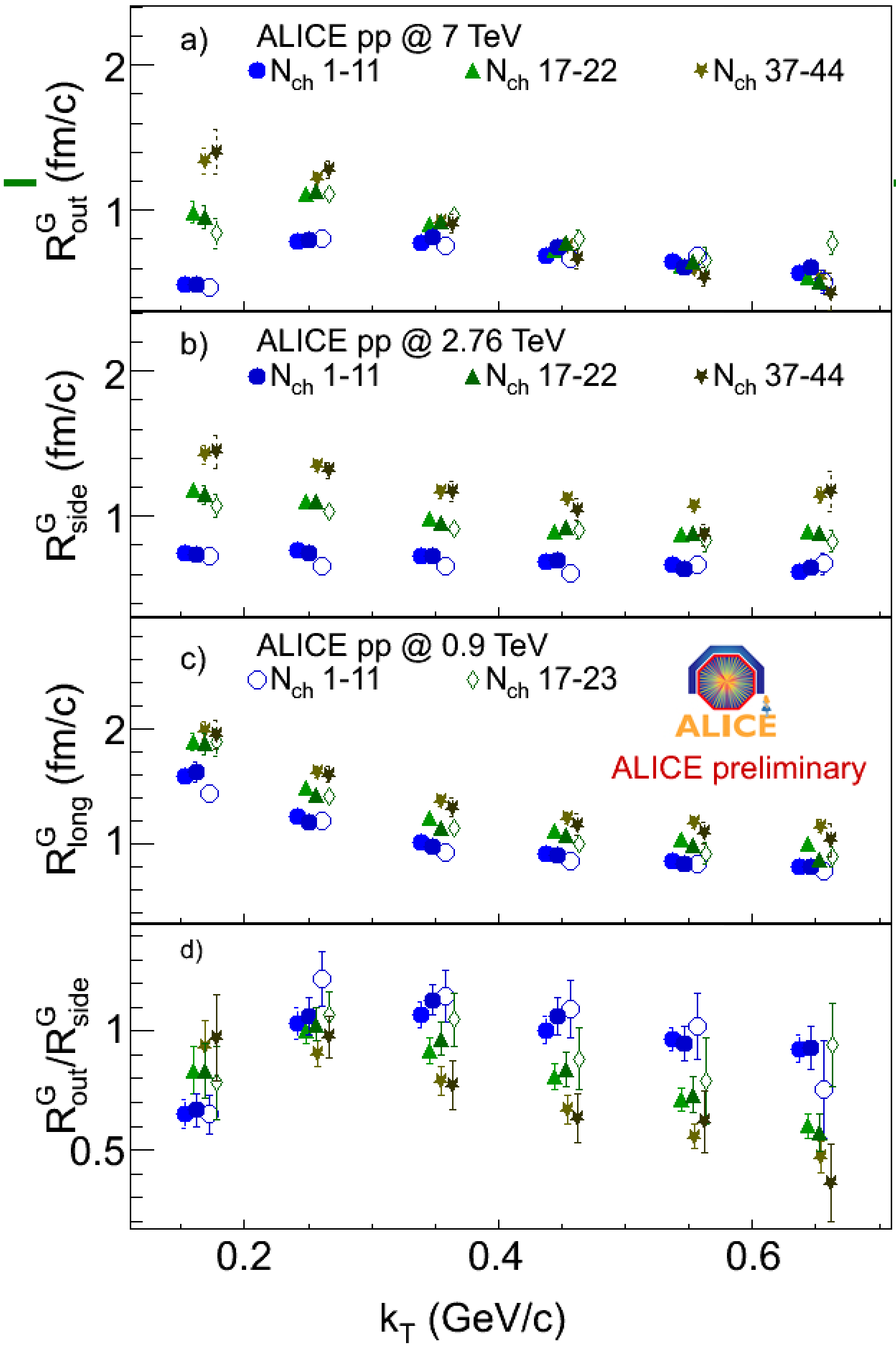
Non-femtoscopic correlations



- 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.

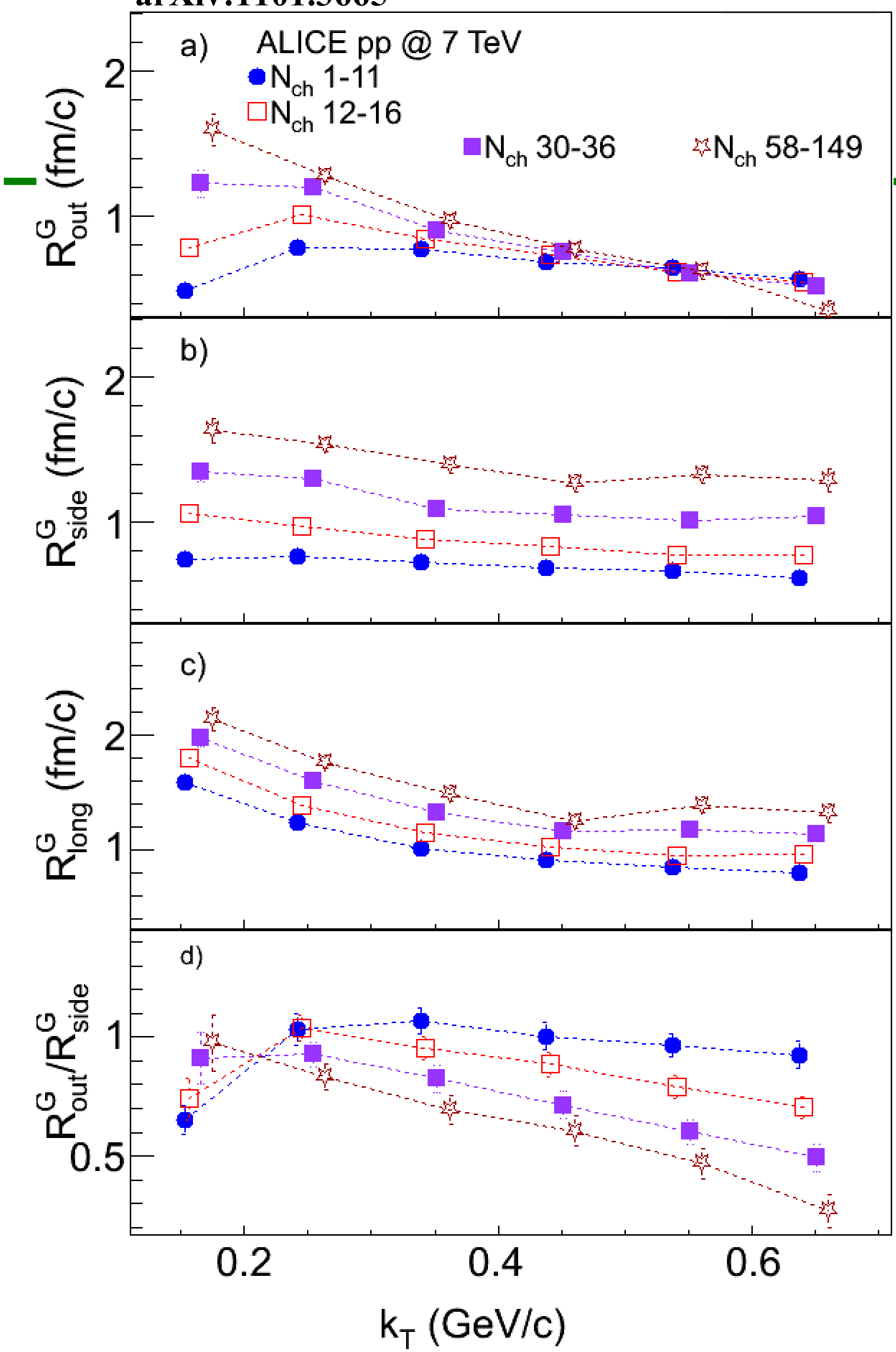
$$B(\vec{q}) = A_h \exp(-q^2 A_w^2) + B_h \exp\left(\frac{-(q-B_m)^2}{2B_w^2}\right)(\cos^2(\theta)-1)$$

Radii √s (in)dependence



- Radii change with event multiplicity and pair momentum
- Fitted radii independent of collision energy, where data for at least two energies available
- 7 TeV data can be used for comparisons with AA assuming energy independence, providing largest reach in multiplicity
- Fitted radii reflect the scaling observed for raw correlations.

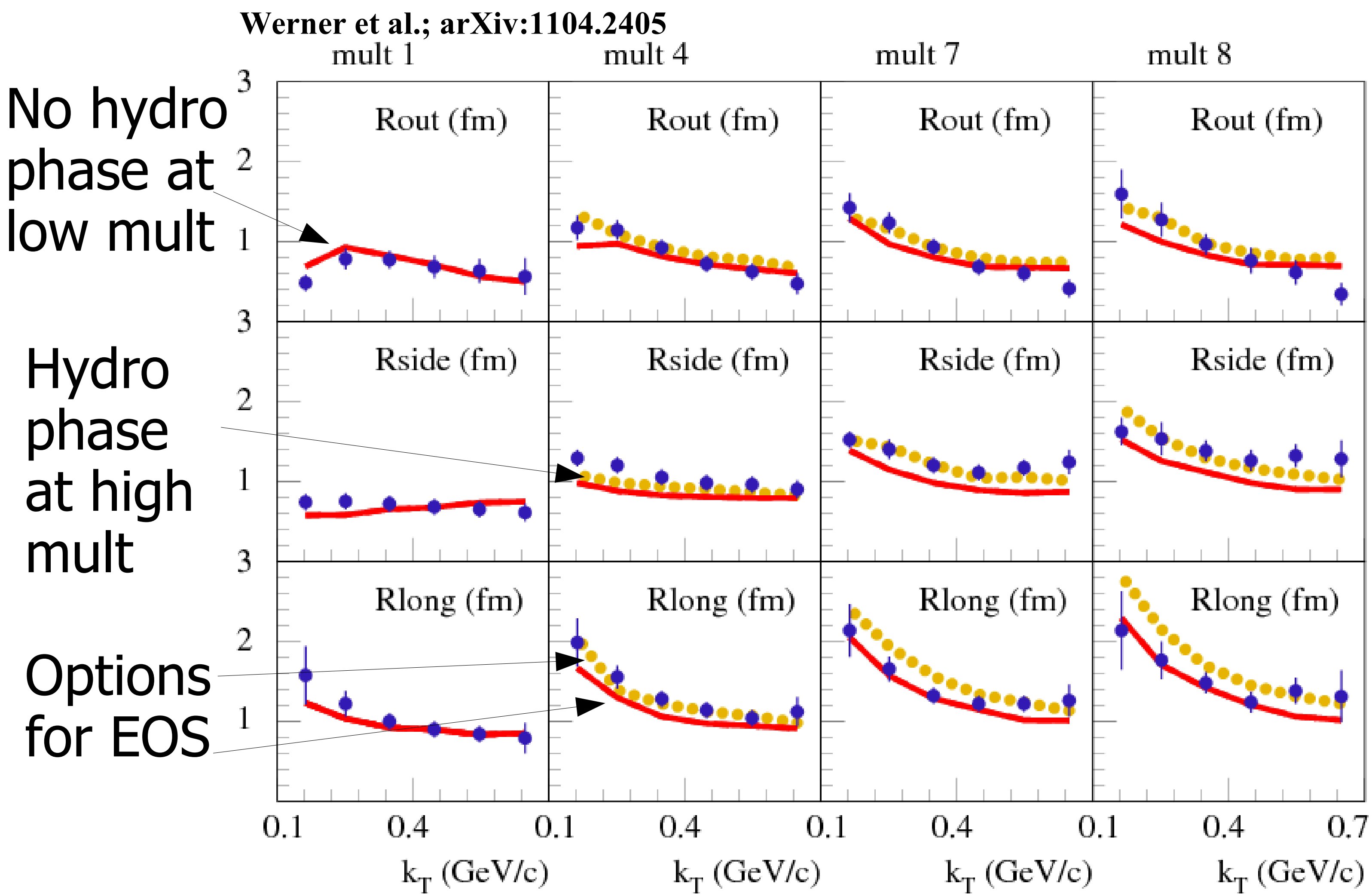
Radii vs. k_T



- Radii falling with k_T a signature of collective medium in heavy-ions
- 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_{OUT}/R_{SIDE} falls with multiplicity, goes significantly below 1.0
- Behavior in heavy-ions is not a simple scaling of pp, as suggested at RHIC

Interpreting k_T dependence

- EPOS model post-dictions, pp collisions with hydro phase

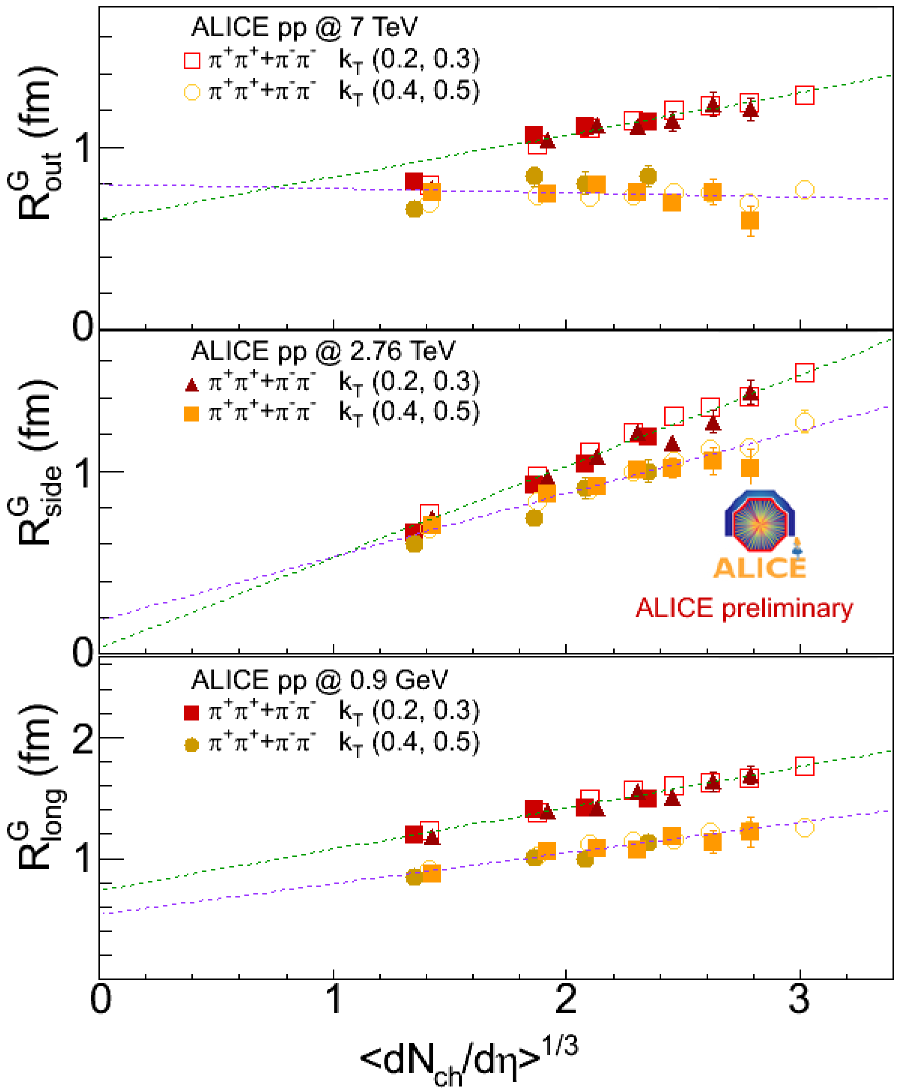


Hydro phase is consistent with HBT data, but is it the only explanation?

How big is the role of resonances?

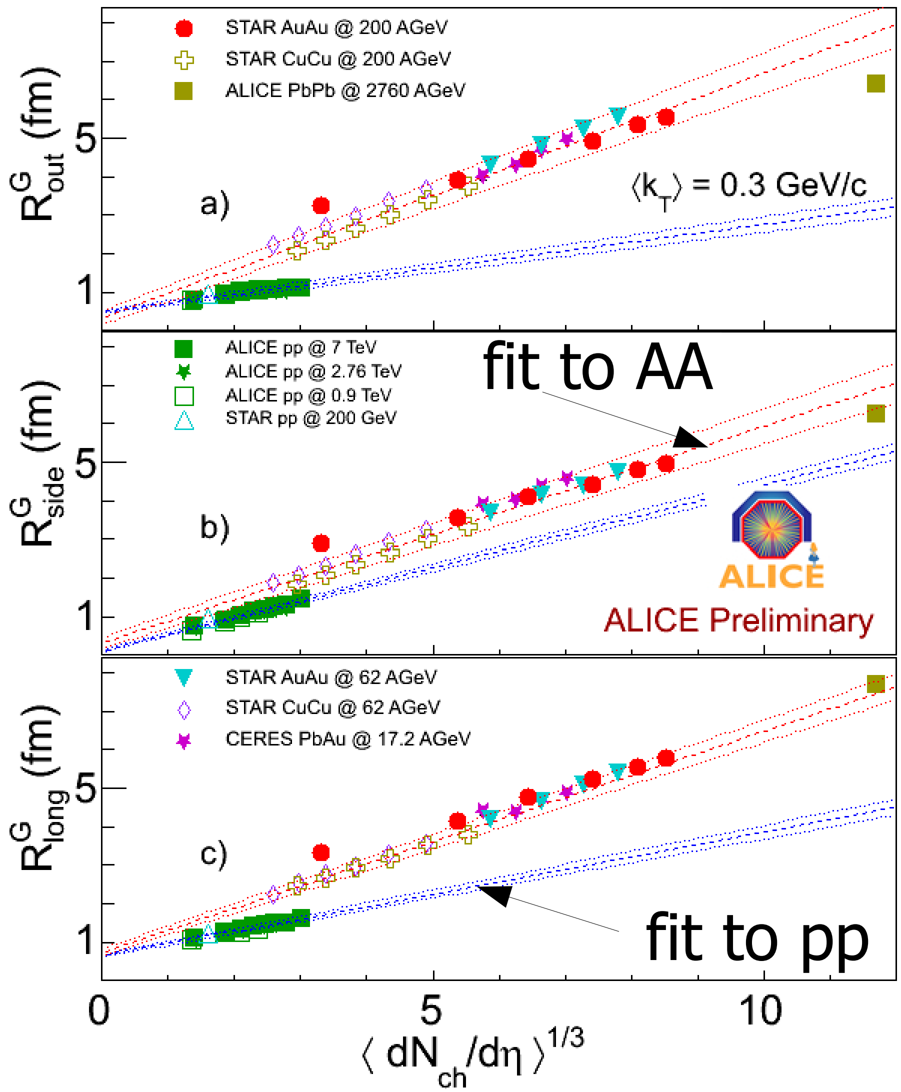
What drives the radii behavior?

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



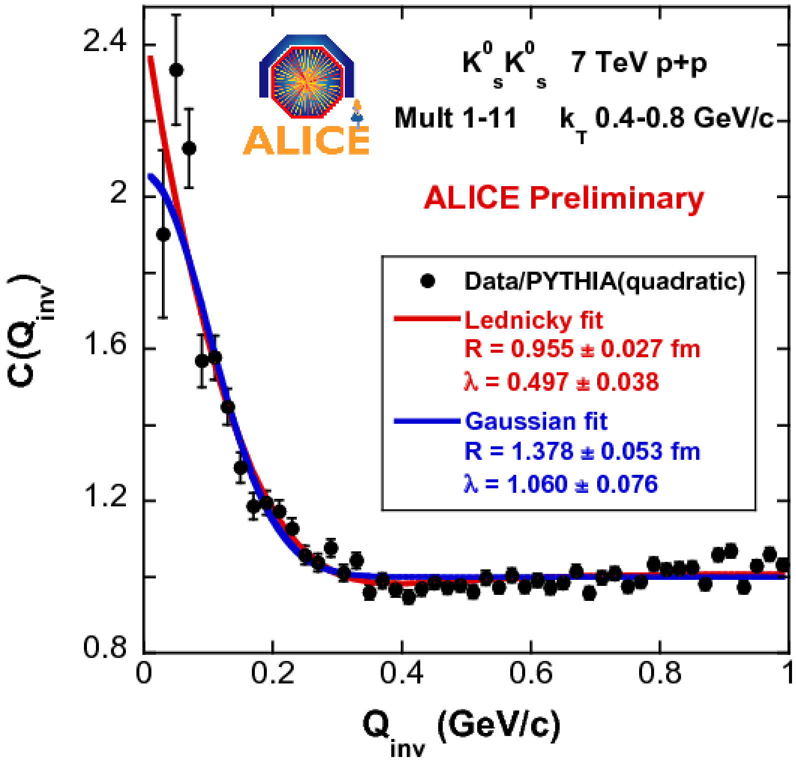
- Radii scale linearly with $dN_{ch}/d\eta$ for 3 dimensions and all pair momentum ranges
- Radii from all collision energies follow the same trend (χ^2/N_{dof}<1.0 for the fit); lowest multiplicity R_{OUT} points (all energies) slightly below.
- Radii grow with multiplicity for R_{SIDE} and R_{LONG}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

pp vs. AA



- Linear scaling of radii in pp and AA gives significantly different slopes and offsets.
- Radii can be compared directly at the same $dN_{ch}/d\eta$ between systems of very different initial conditions: “elementary” vs. “compound”.
- The pp data scale linearly, scaling in AA only approximately linear, depends on dataset, initial state must be taken into account in any scaling argument.
- ALICE Pb-Pb R_{SIDE}, R_{LONG} at 2.76 TeV in agreement with lnear AA scaling, R_{OUT} below the trend, if all centralities at large $\sqrt{s_{NN}}$ taken into account.

Kaon femtoscopy

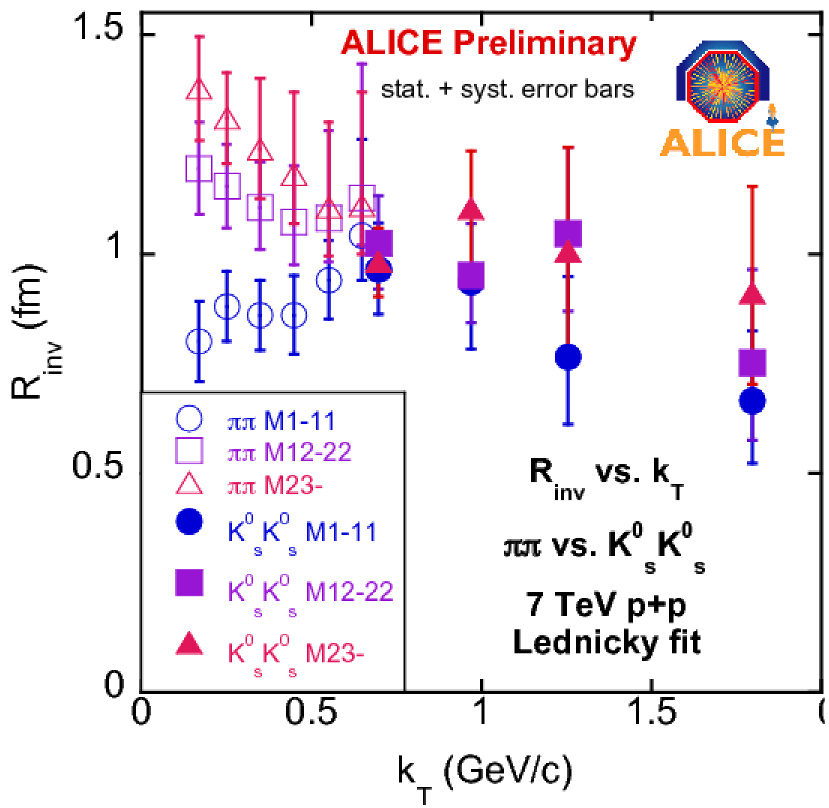


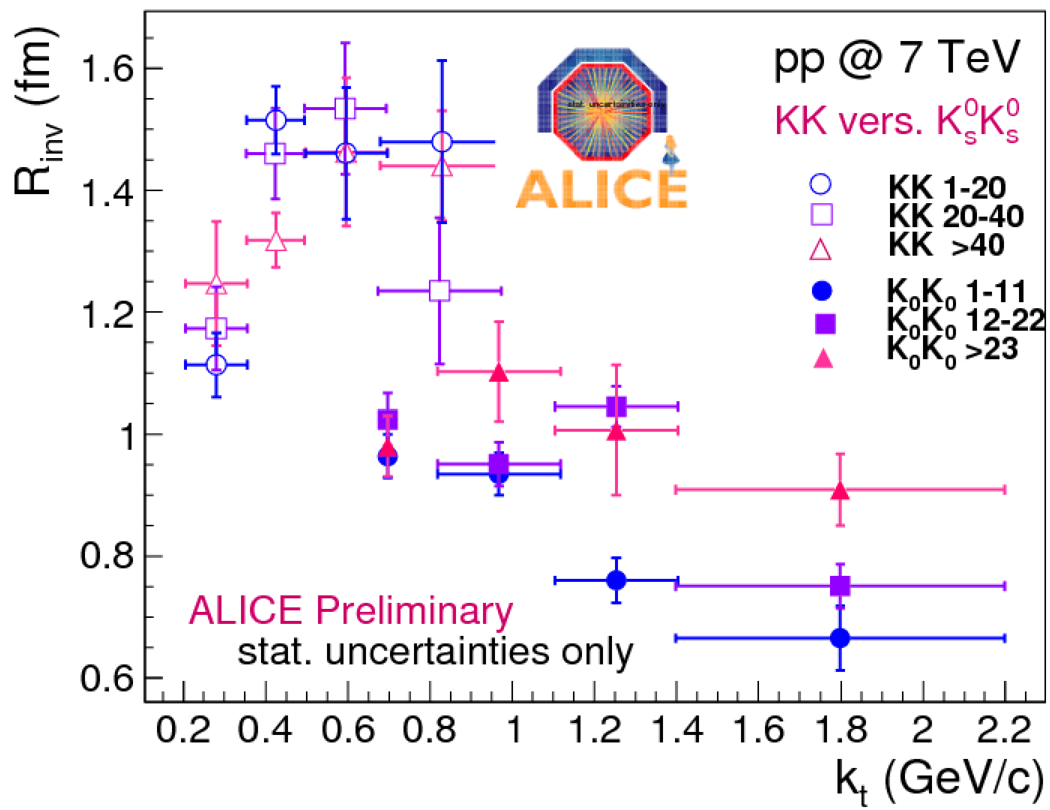
- Femtoscopic analysis of neutral and charged kaons is limited to 1D radii, but extends the pair momentum range
- Scaling of radii with m_T observed in AA hydrodynamics but it is unclear if this scaling persists in a small system where pion production is dominated by resonances.
- Significant systematics from non-femtoscopic background observed for charged kaons
- Correlation of neutral kaons strong: comes from a combination of Bose-Einstein symmetrization and strong interaction, helps to reduce systematics.

talk by T. Humanic, Monday parallel session
poster by L. Malinina, Tuesday poster session

k_T dependence of 1D radii

- K^0_s radii grow with multiplicity, decrease with pair momentum
- Pion and K^0_s radii comparable, K^+, K^- radii larger than for pions
- Need model calculations for "hydro m_T scaling" in pp





Summary

- Central Pb-Pb collisions at LHC
  - Radii in central Pb-Pb larger than Au-Au at RHIC by up to 30%
  - k_T dependence consistent with hydrodynamics
  - Hydro models tuned to RHIC data also work at LHC
- pp collisions at 0.9, 2.76 and 7 TeV
  - Linear scaling of radii with $\langle dN_{ch}/d\eta \rangle^{1/3}$, all directions, all $\sqrt{s}$
  - Dependence on k_T consistent with calculations with hydro part, but details and the extension to larger k_T with kaons still need satisfactory model description
  - Radii independent of $\sqrt{s}$, use 7 TeV data to extend $\langle dN_{ch}/d\eta \rangle^{1/3}$ range
- No common scaling for pp and AA, initial state important

Related contributions

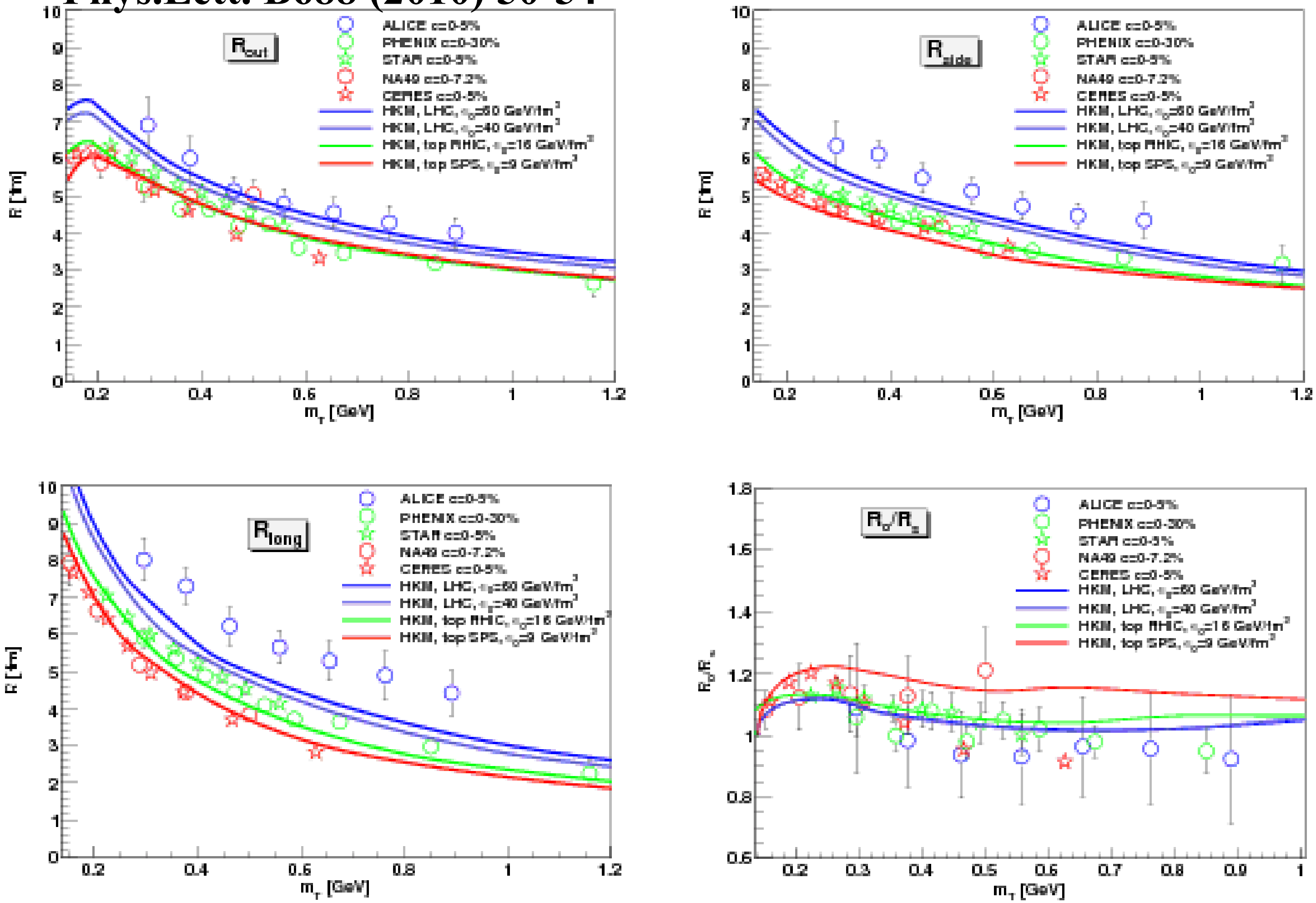
- Jorge Mercado, "Two-pion Bose-Einstein correlations in Pb-Pb collisions at 2.76 TeV with ALICE", Monday May 23rd, Parallel session "Correlations and Fluctuations"
- Thomas Humanic, "K0sK0s correlations in 7 TeV proton+proton collisions from the ALICE Experiment at the LHC", Monday May 23rd, Parallel session "Correlations and Fluctuations"
- Ludmila Malinina, "Charged KK femtoscopy correlations from 7 TeV pp collisions measured by ALICE collaboration.", Poster session
- Adam Kisiel, "Femtoscopy of the proton-proton collisions at the LHC with pion-pion Bose-Einstein correlations in ALICE", Poster session

Backup slides

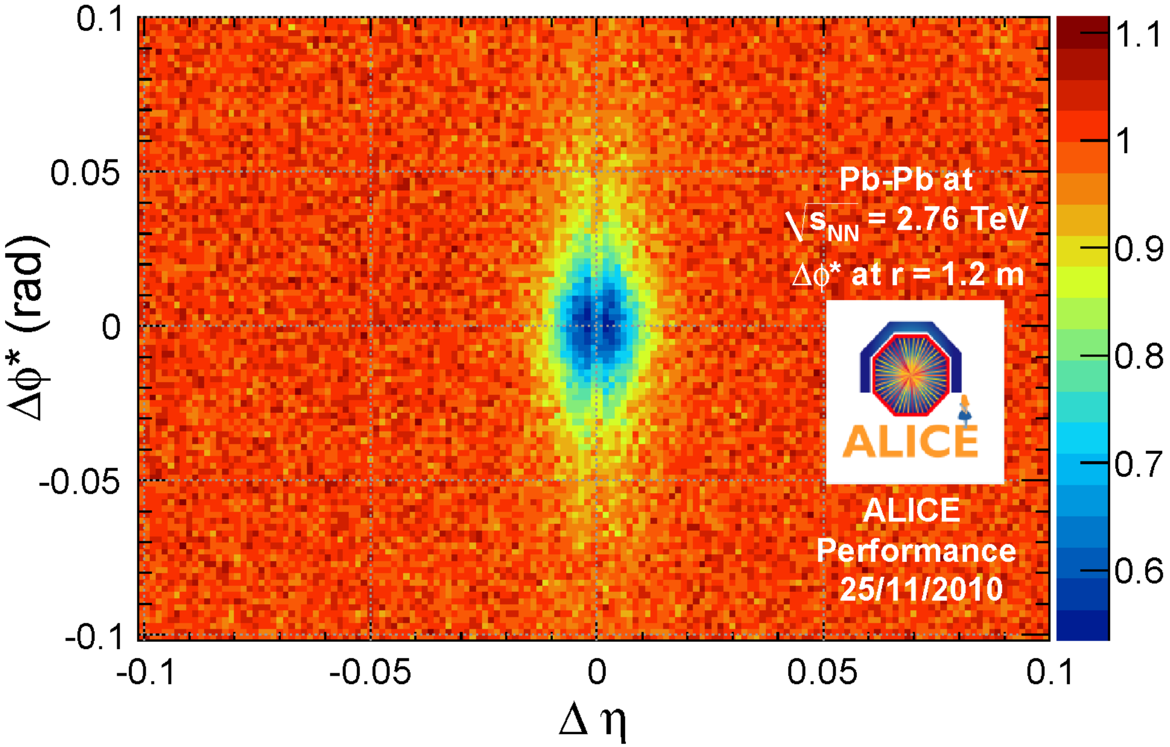
Predictions from hydrodynamics

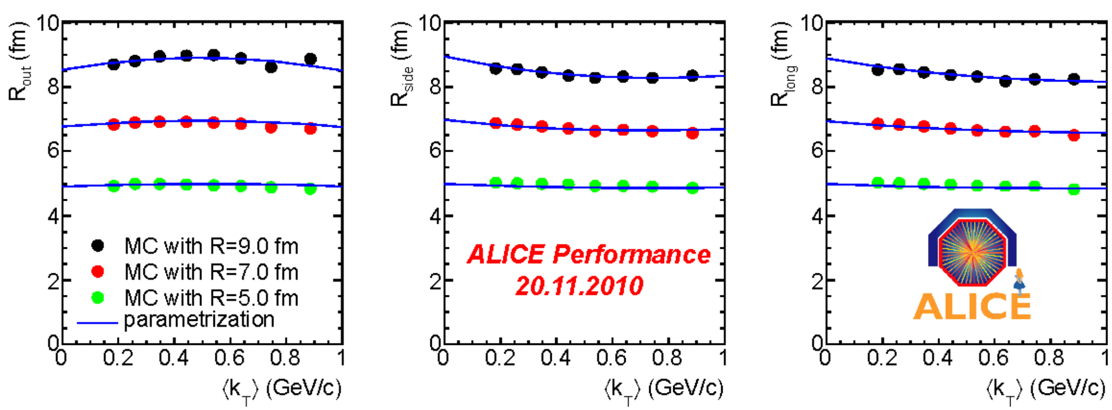
- Hydro-Kinetic Model predictions for pion HBT radii at the LHC

Phys.Lett. B688 (2010) 50-54



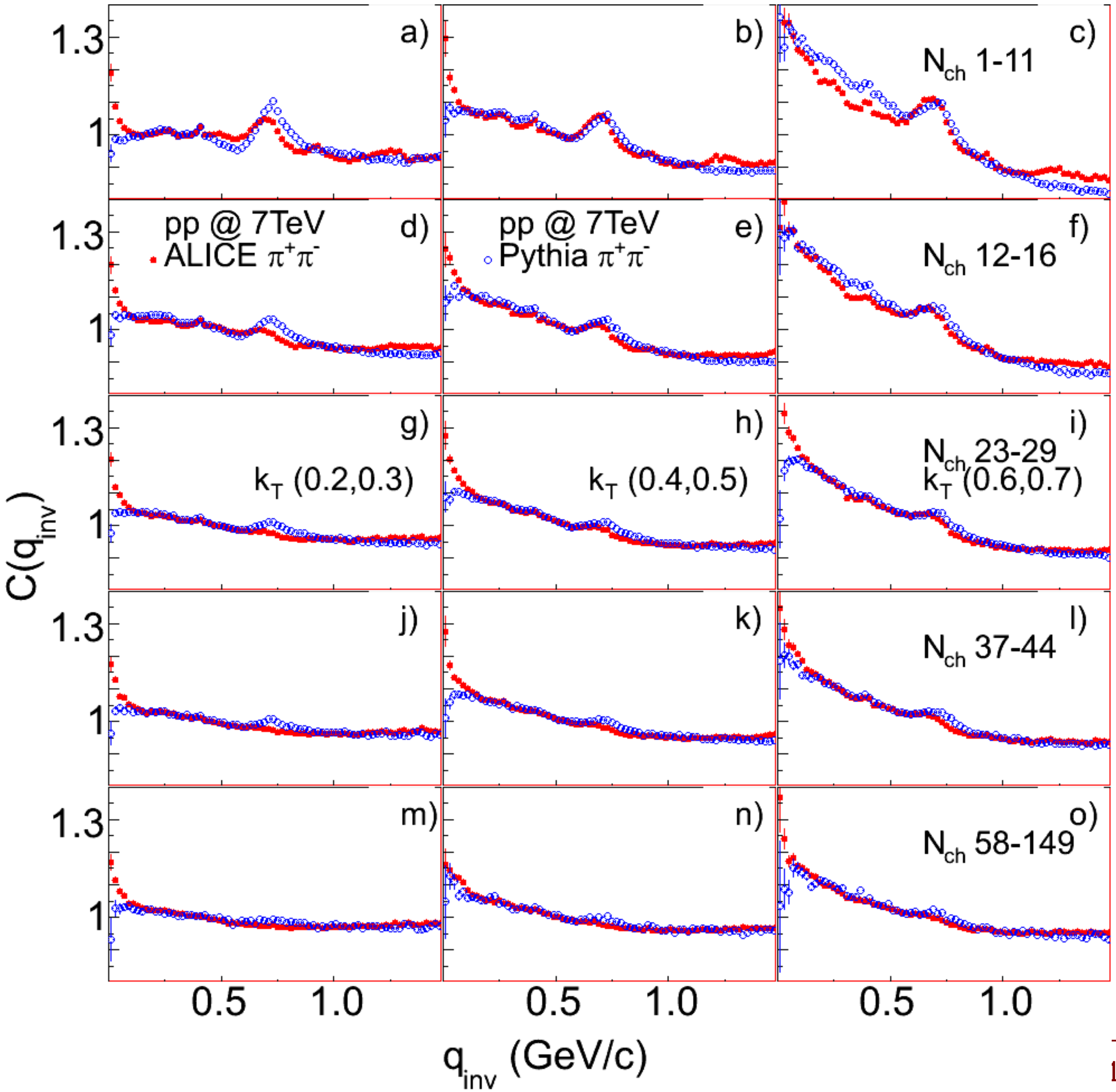
Systematic effects in AA analysis





- Track merging: regions in phase space where two tracks cannot be distinguished by ALICE. Dealt with by removing from the background tracks that would be merged, if they were in the same event.
- Momentum resolution makes the peak appear smaller and wider (larger radius). Correction applied to the extracted radii.

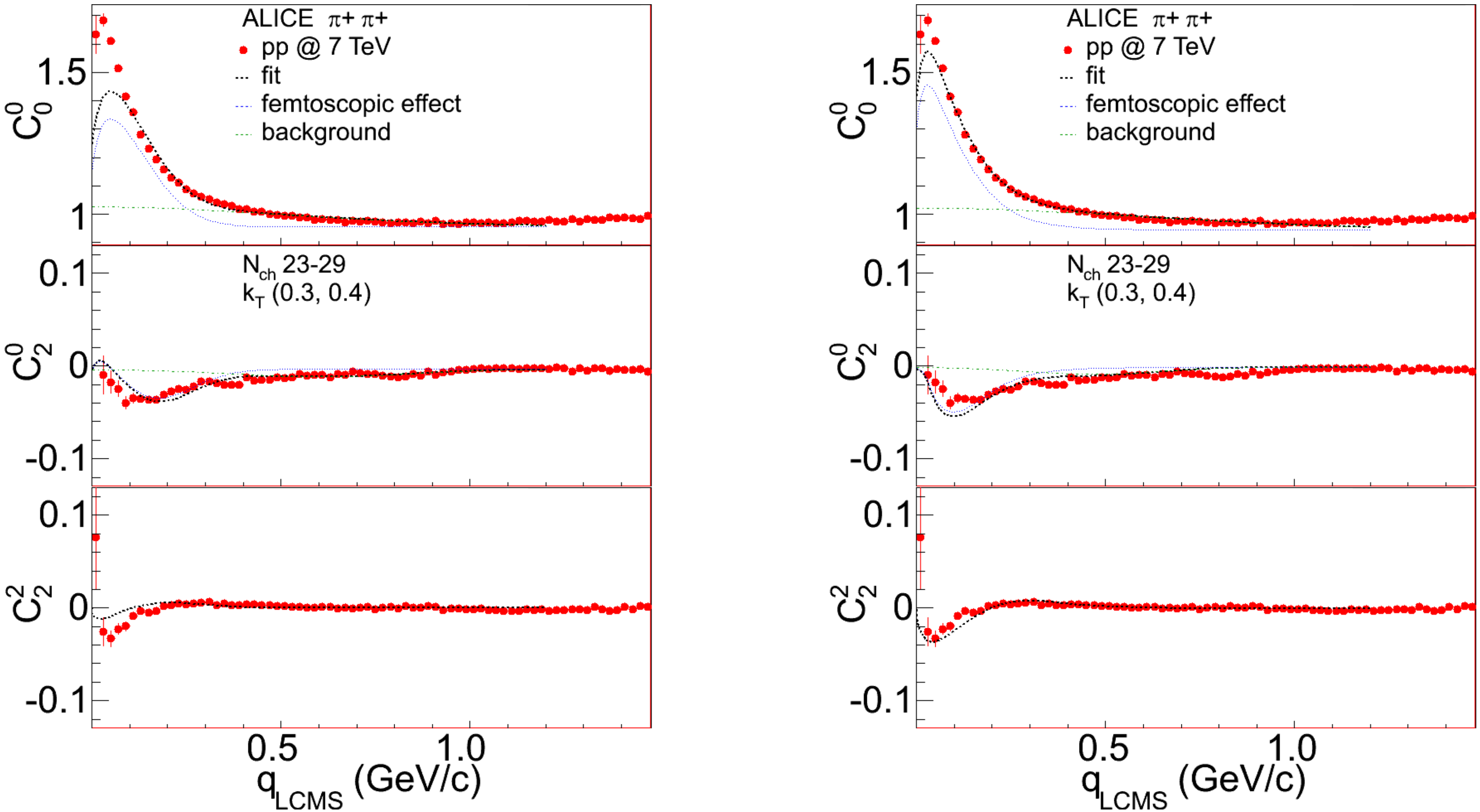
$\pi^+\pi^-$ correlations cross-check



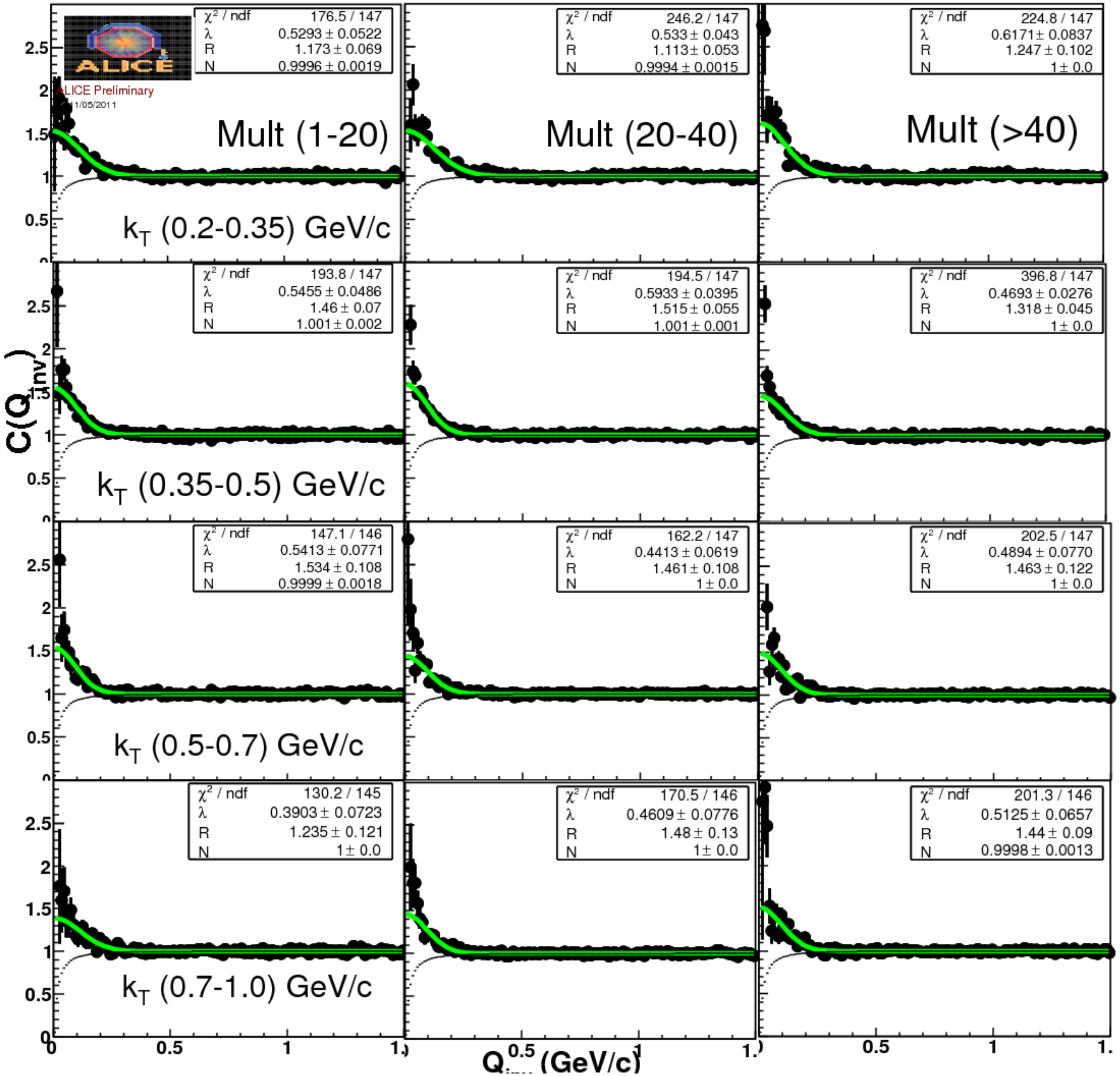
- Non-femtoscopic correlations present for opposite-charge pairs, somewhat stronger than for same-charge, consistent with the “mini-jet” origin, described by Pythia to within 10%
- Additional correlated yield due to resonances visible, Pythia's not able to describe it properly

Functional form studies

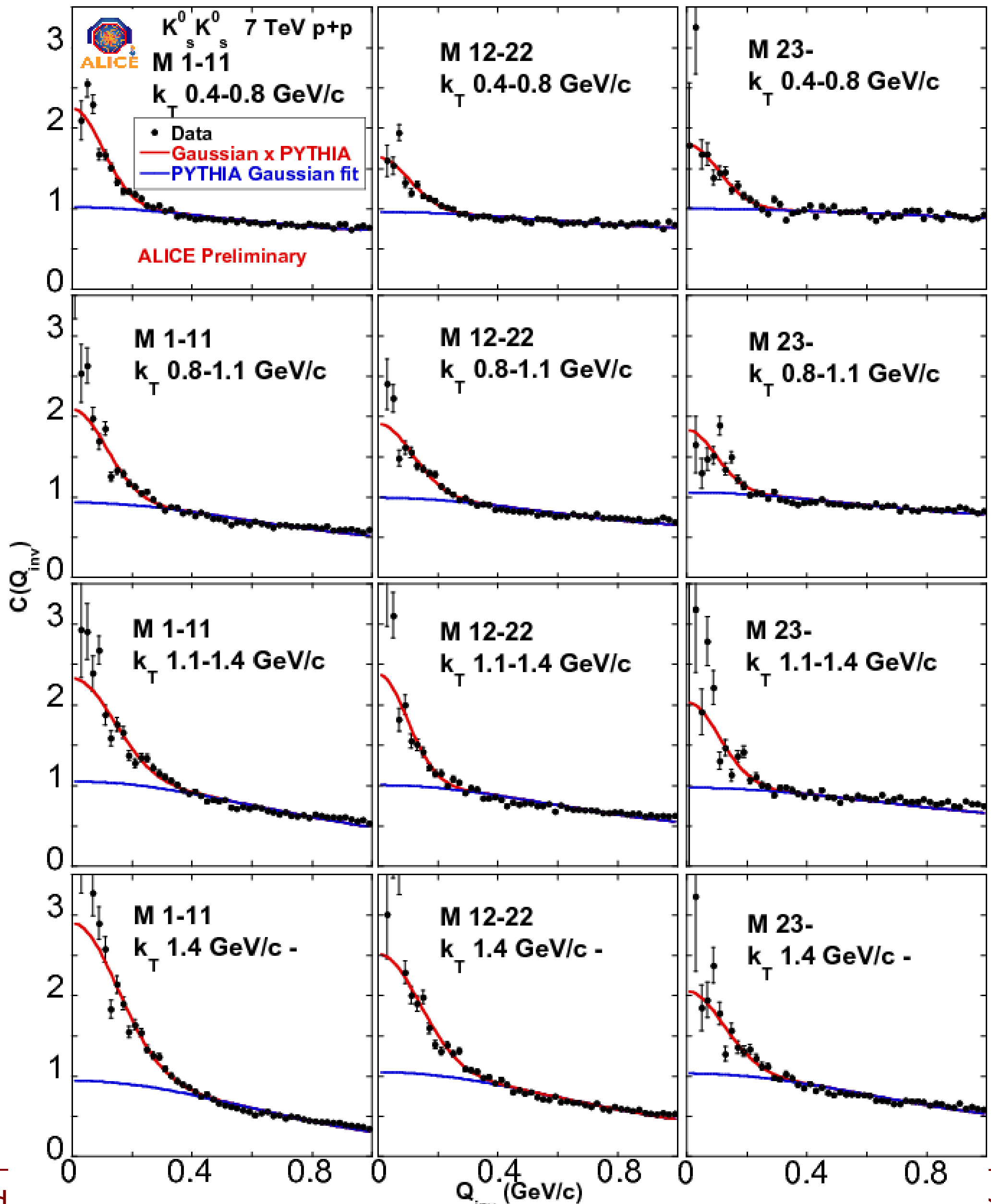
- Correlation functions in pp are better described by Exponential-Gaussian-Exponential, the physics message is the same as with traditional 3D Gaussian



Charged kaon correlations

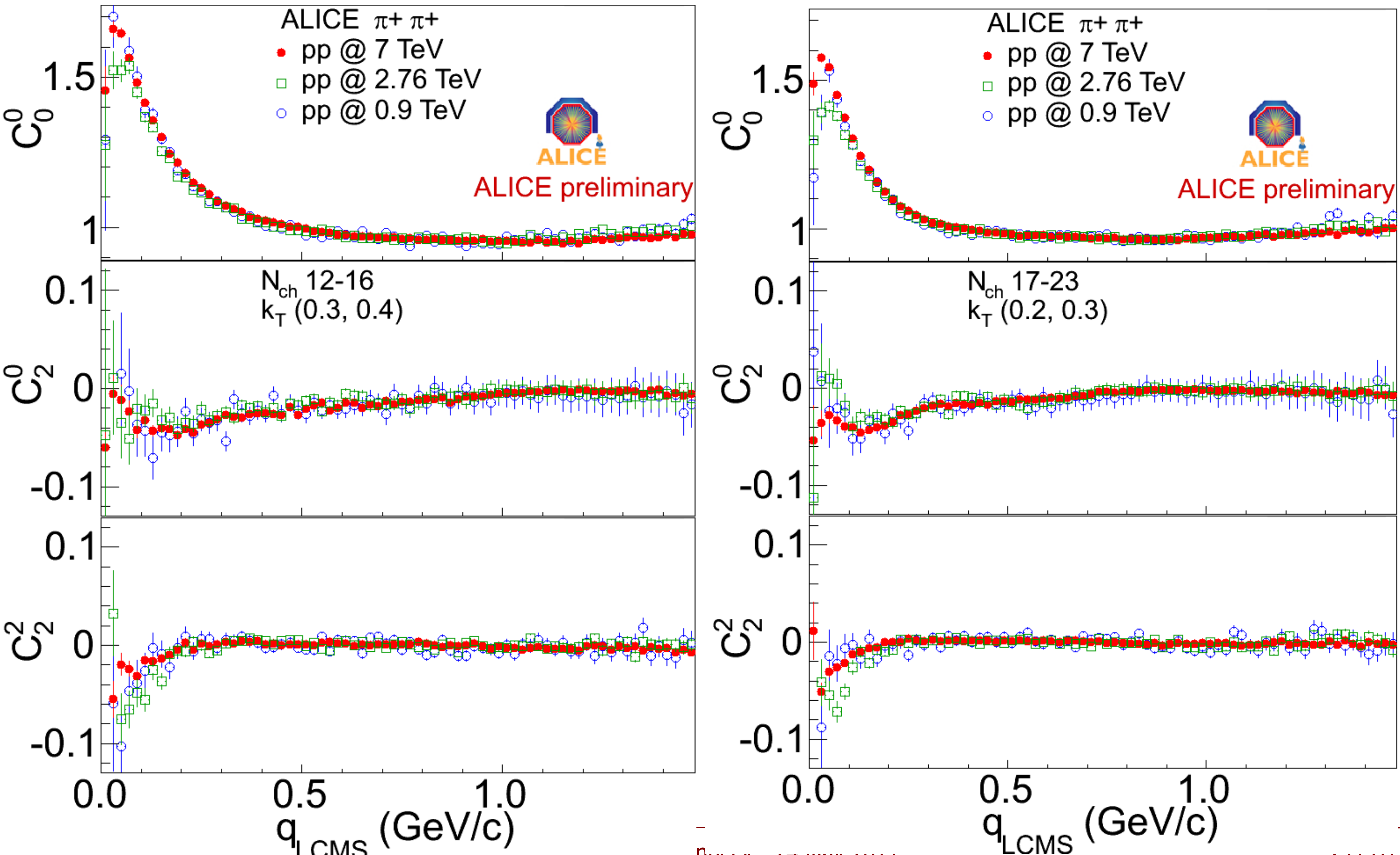


K0s-K0s correlations



- 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 quatum statistics
- Fit done in three bins in multiplicity and four bins in pair transverse momentum

Collision energy comparison



Quantitative analysis

- Pair emission function comes from single-particle functions:

$$S(\boldsymbol{r}) = \int S(\boldsymbol{x}_1) S(\boldsymbol{r} - \boldsymbol{x}_1) d\boldsymbol{x}_1$$

- This is integrated with pair wave-function to get the CF:

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

- Coulomb K is factorized out, Ψ is then $1+\cos(qr)$. Usually S is Gaussian, giving the femtoscopic part of CF:

$$C_f = (1-\lambda) + \lambda K \left(1 + \exp\left(-R_o^2 q_o^2 - R_s^2 q_s^2 - R_l^2 q_l^2\right)\right)$$

  where both R and q can be in Pair Rest Frame (PRF) or Longitudinally Co-Moving Frame (LCMS). PRF is used for 1D analysis (1^{st} ALICE paper), LCMS for 3D (this paper).

- The Coulomb factor K is the Coulomb wave-function integrated over a Gaussian source. The Bowler-Sinyukov method has known limitations, but it is well applicable here.

Accounting for background

- The background from mini-jets can be parametrized as a Gaussian in LCMS plus a small modification in the C20 component (slight transverse vs. longitudinal modulation):

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

- The parameters A_h, A_w, B_h, B_m, B_w are fixed to the values fit to MC (fit is done independently for Pythia and Phojet backgrounds, difference is the systematic error)
- The final form of the fitting function is then:

$$C = N C_f(\vec{q}) B(\vec{q})$$

pp vs. AuAu: puzzling scaling ...

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

STAR, arXiV (1004.0925)