NATIONAL SCIENCE CENTRE

Identical pion interferometry in ALICE at the LHC

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HUMAN CAPITAL
NATIONAL COHESION STRATEGY

EUROPEAN UNION
EUROPEAN
SOCIAL FUND

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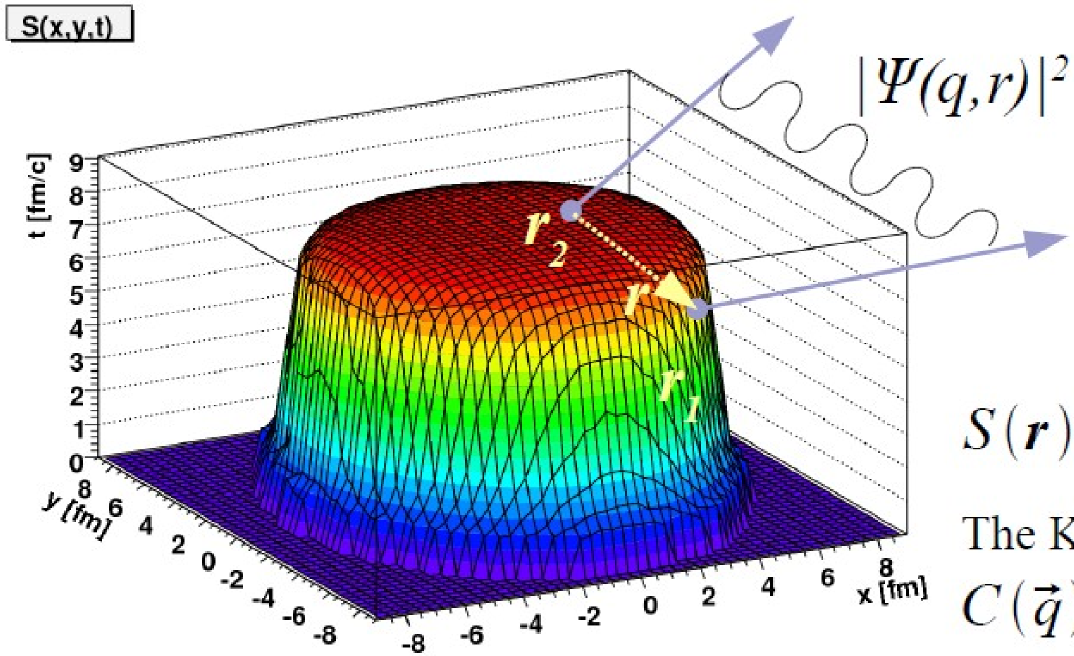
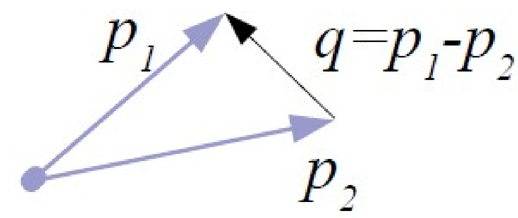
Measuring space-time extent: femtoscopy





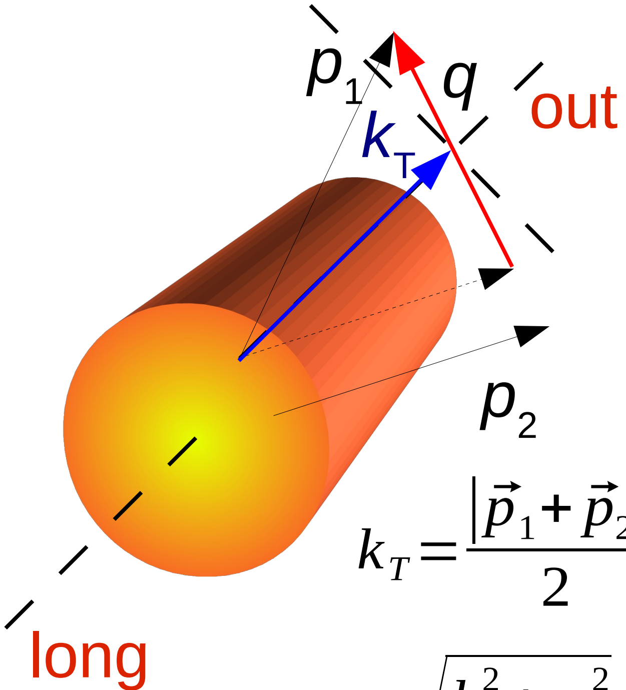
$$S(\boldsymbol{r}) = \int S_a(\boldsymbol{r_1}) S_b(\boldsymbol{r_2}) \delta(\boldsymbol{r} - (\boldsymbol{r_1} - \boldsymbol{r_2})) d^4 r_1 d^4 r_2$$

The Koonin-Pratt Equation

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

- Use two-particle correlation, coming from interaction Ψ
- Can be quantum statistics (HBT), coulomb and strong
- Try to invert Koonin-Pratt eq. to learn S from known Ψ and measured C

Physics motivation



$$k_T = \frac{|\vec{p}_1 + \vec{p}_2|}{2}$$

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

Longitudinally Co-Moving System (LCMS):

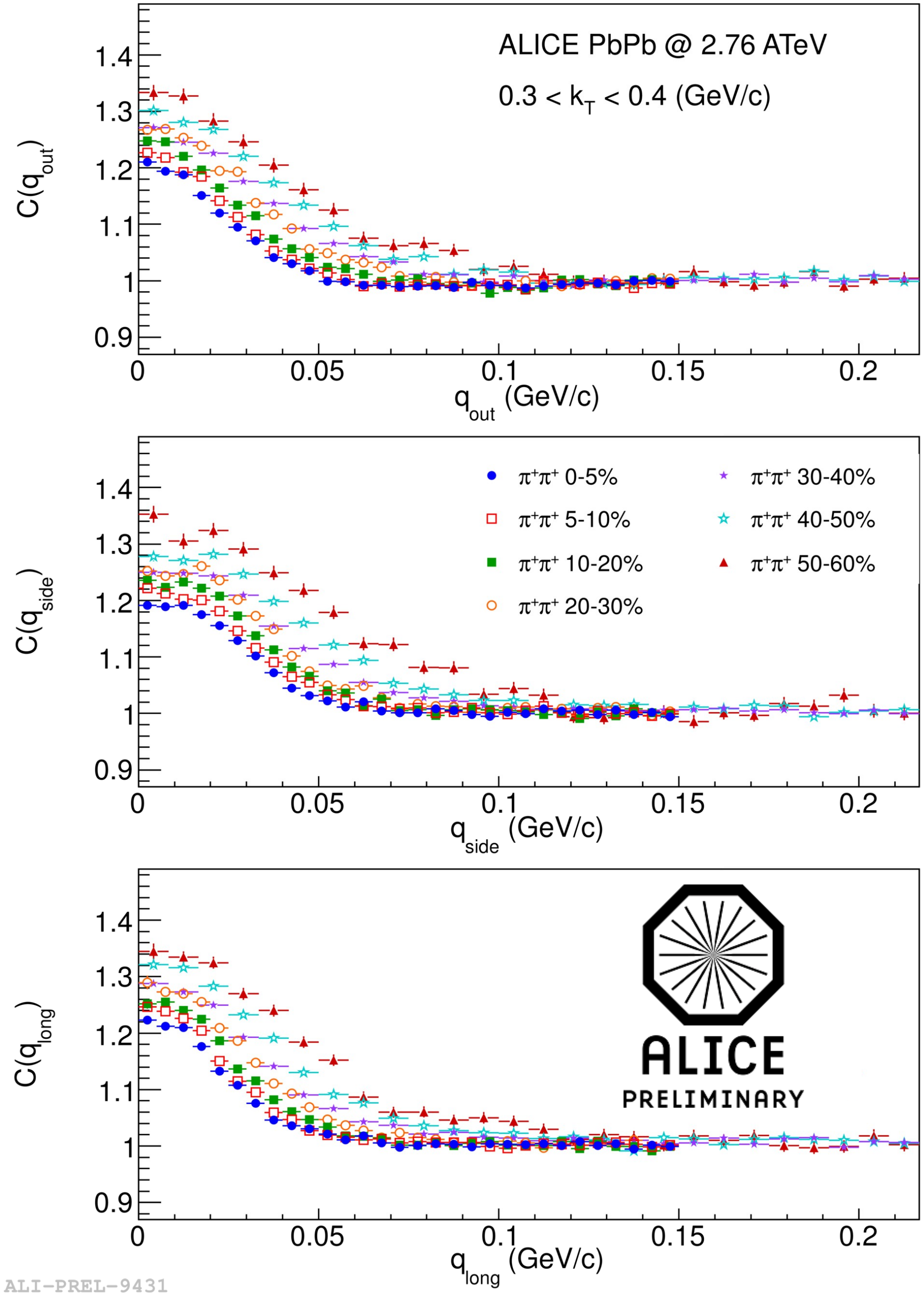
$$p_{1,long} = -p_{2,long}$$

The Koonin-Pratt Equation:

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

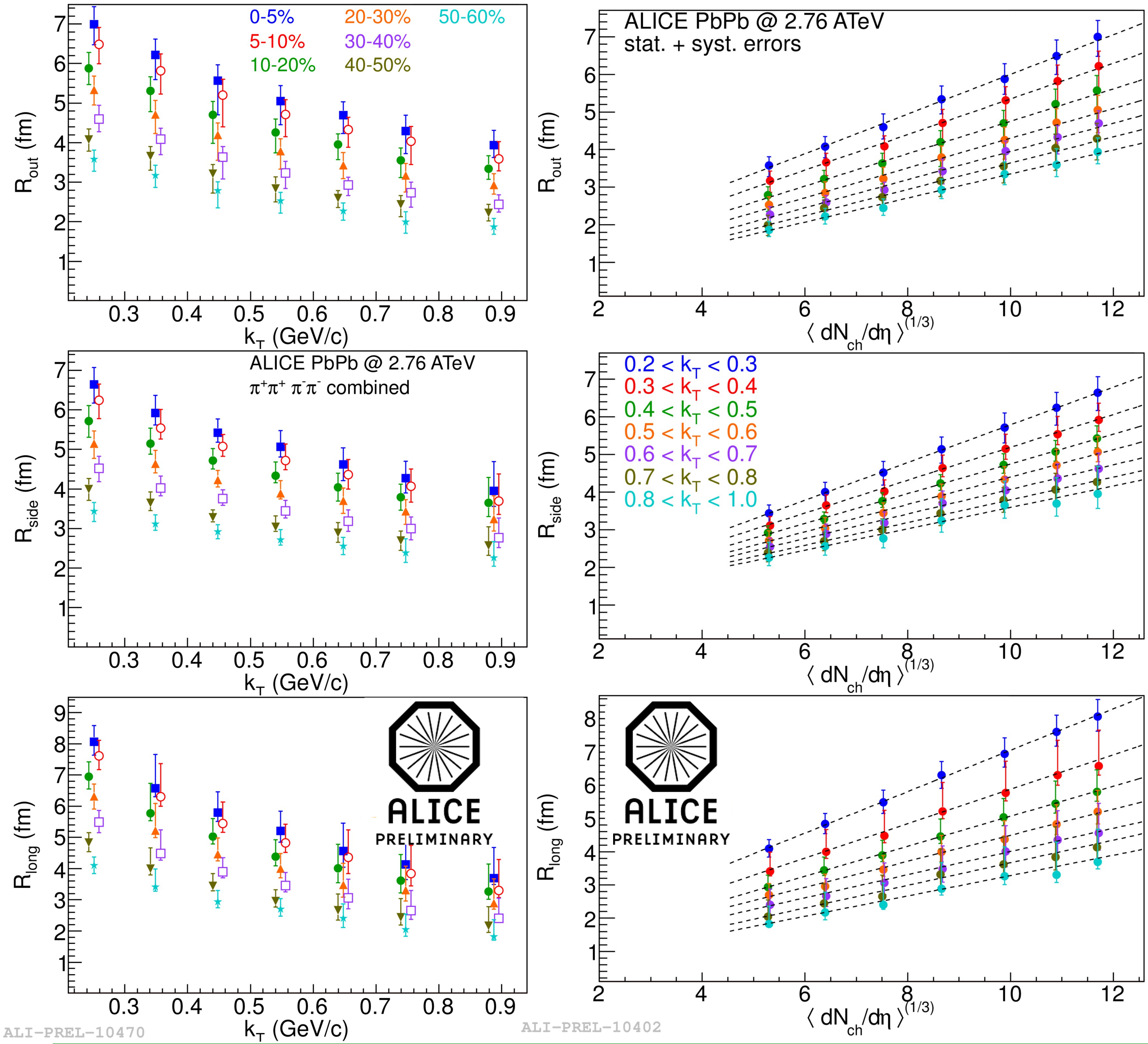
- Pion femtoscopy in Pb-Pb collisions
  - Measure the size of the homogeneity region from which volume of the QGP can be inferred
  - Transverse momentum dependence of the radii - strong collective motion of matter
  - Strong constraints on timescales and sensitivity to the EOS in dynamic models
- Pion femtoscopy in pp collisions
  - Precise data to address space-time characteristics of particle production in “elementary” systems
  - Significant multiplicities in pp, possible direct comparison of pp and AA

Pb-Pb, centrality dependence



- 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

Radii vs. centrality and k_T



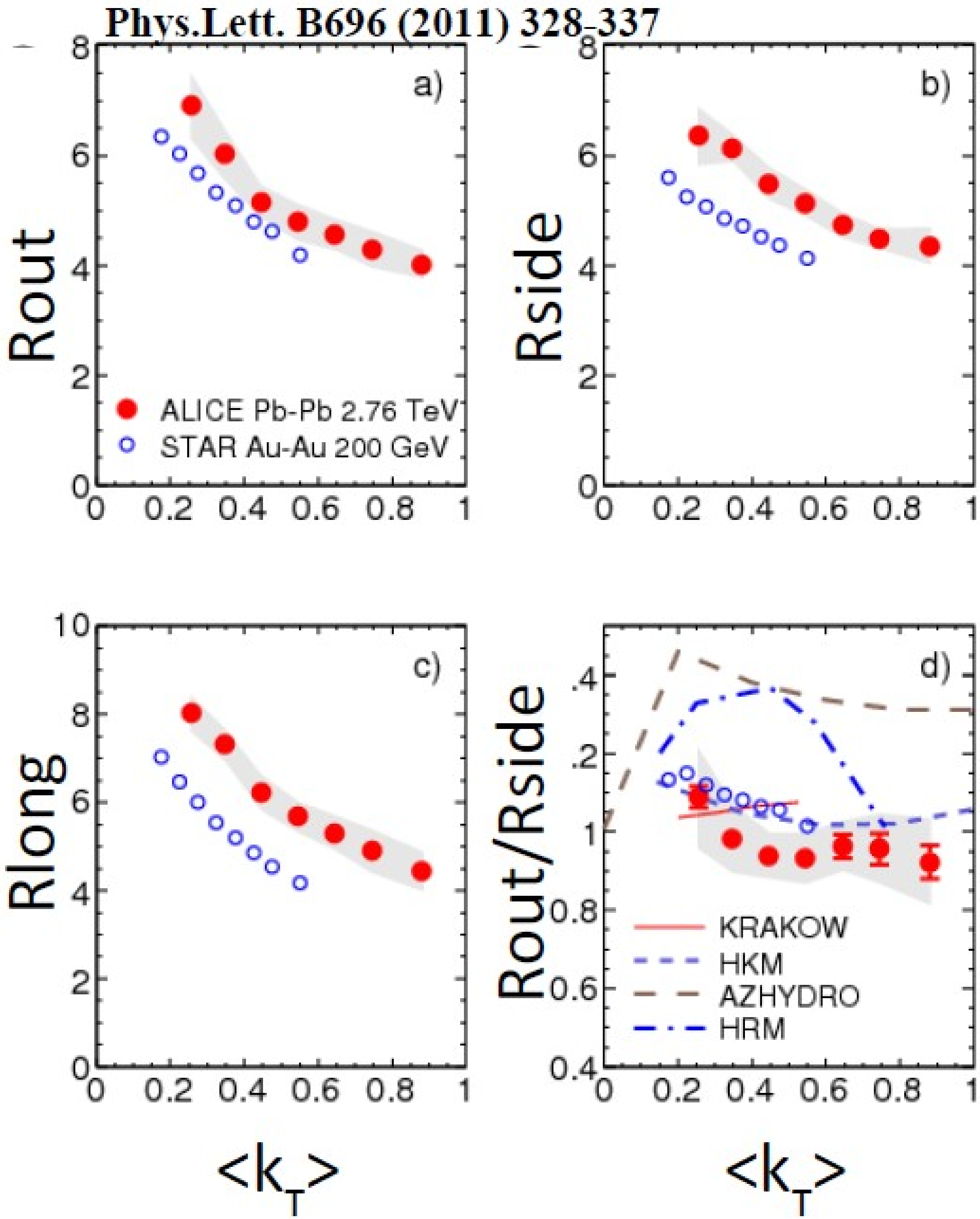
Femtoscopic radii vs. k_T for 7 centrality bins

Radii scaling: linear in multiplicity and power-law in k_T

Both dependencies in agreement with predictions from collective models (hydrodynamics)

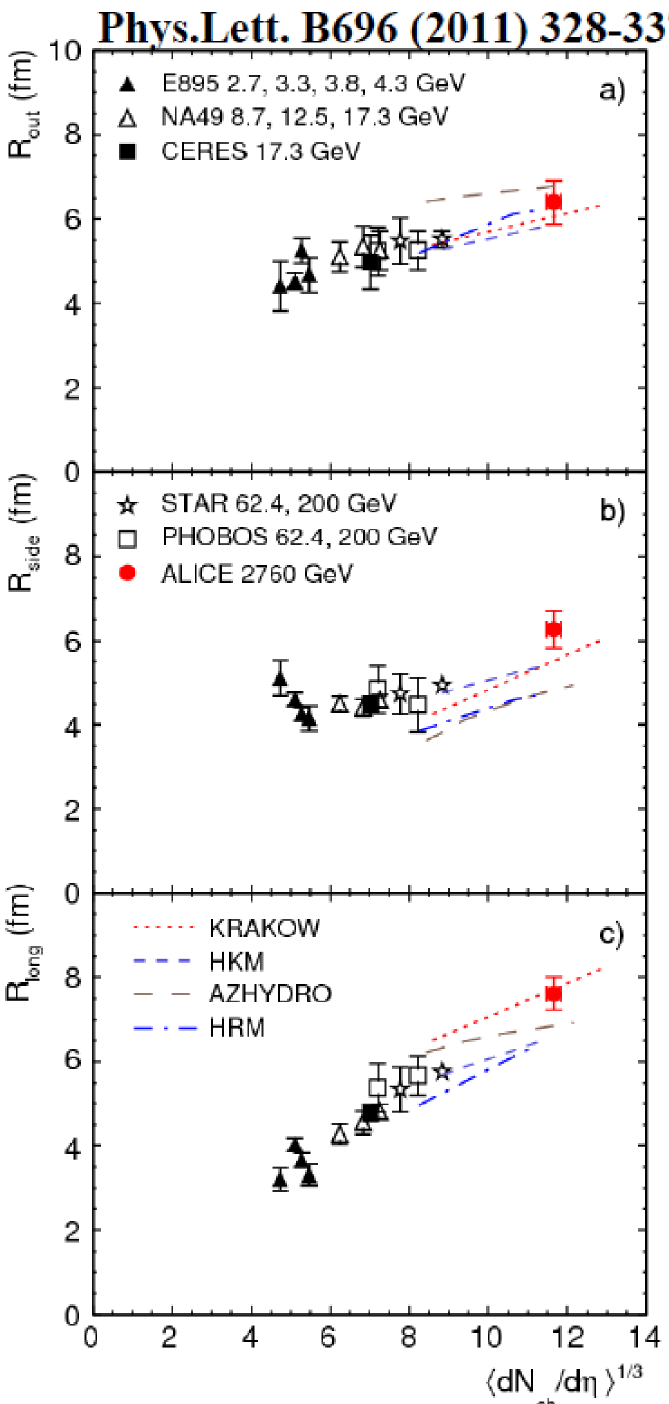
Comparing LHC to RHIC

ALICE Pb-Pb



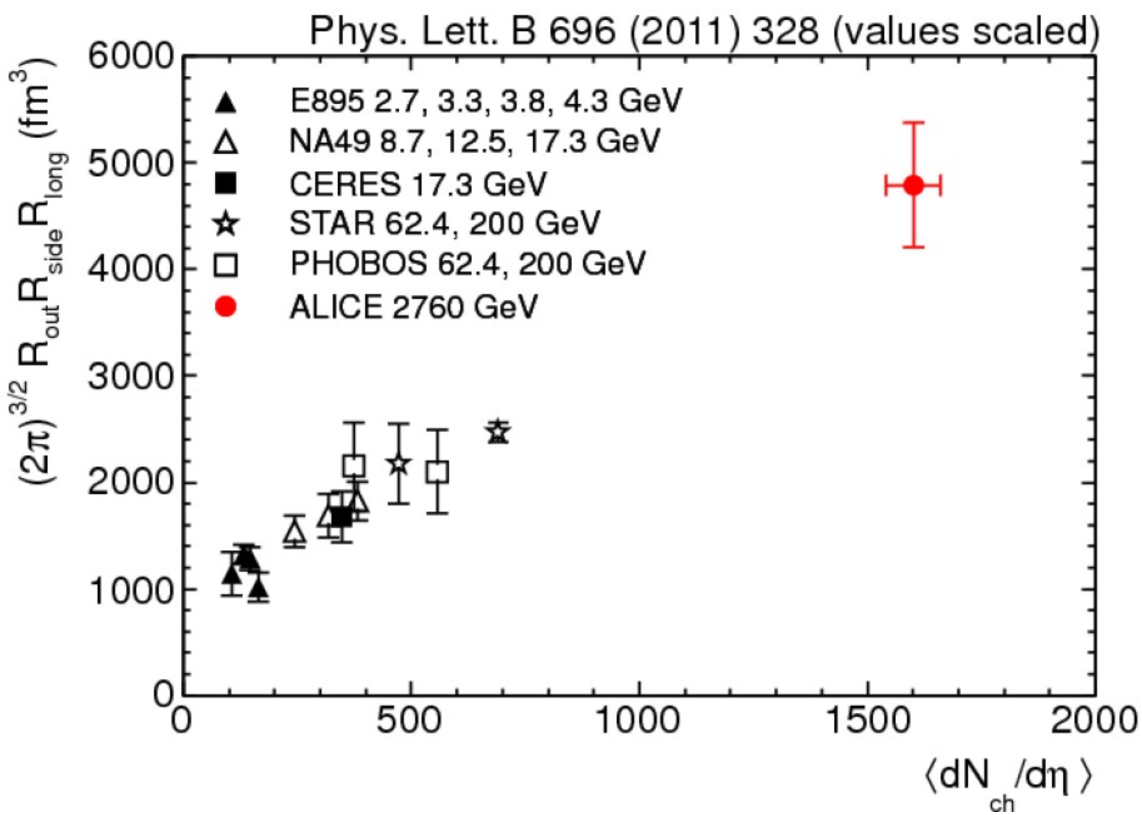
- 30% increase in homogeneity lengths between most central RHIC and LHC
- Strong dependence of all radii on pair momentum, consistent with strong collective radial and longitudinal flow
- The Rout/Rside ratio comparable or smaller than at RHIC: gives discriminating power to challenge models
- Only models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

Scaling vs. dN_{ch}/dη



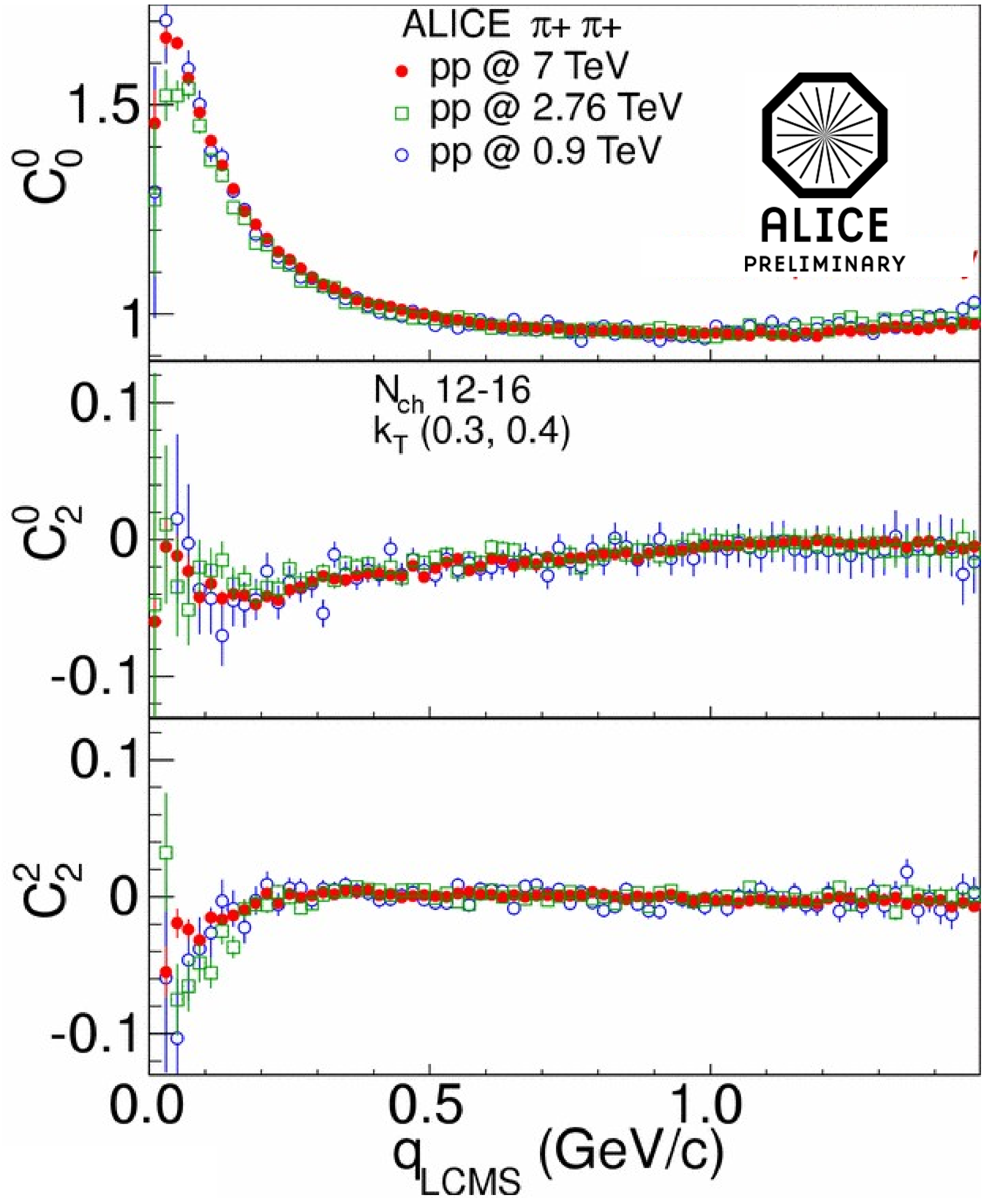
- Increase of the radii with $dN_{ch}/d\eta$ for central collisions consistent with models

- Increase of the "homogeneity volume" over most central RHIC by a factor of ~2



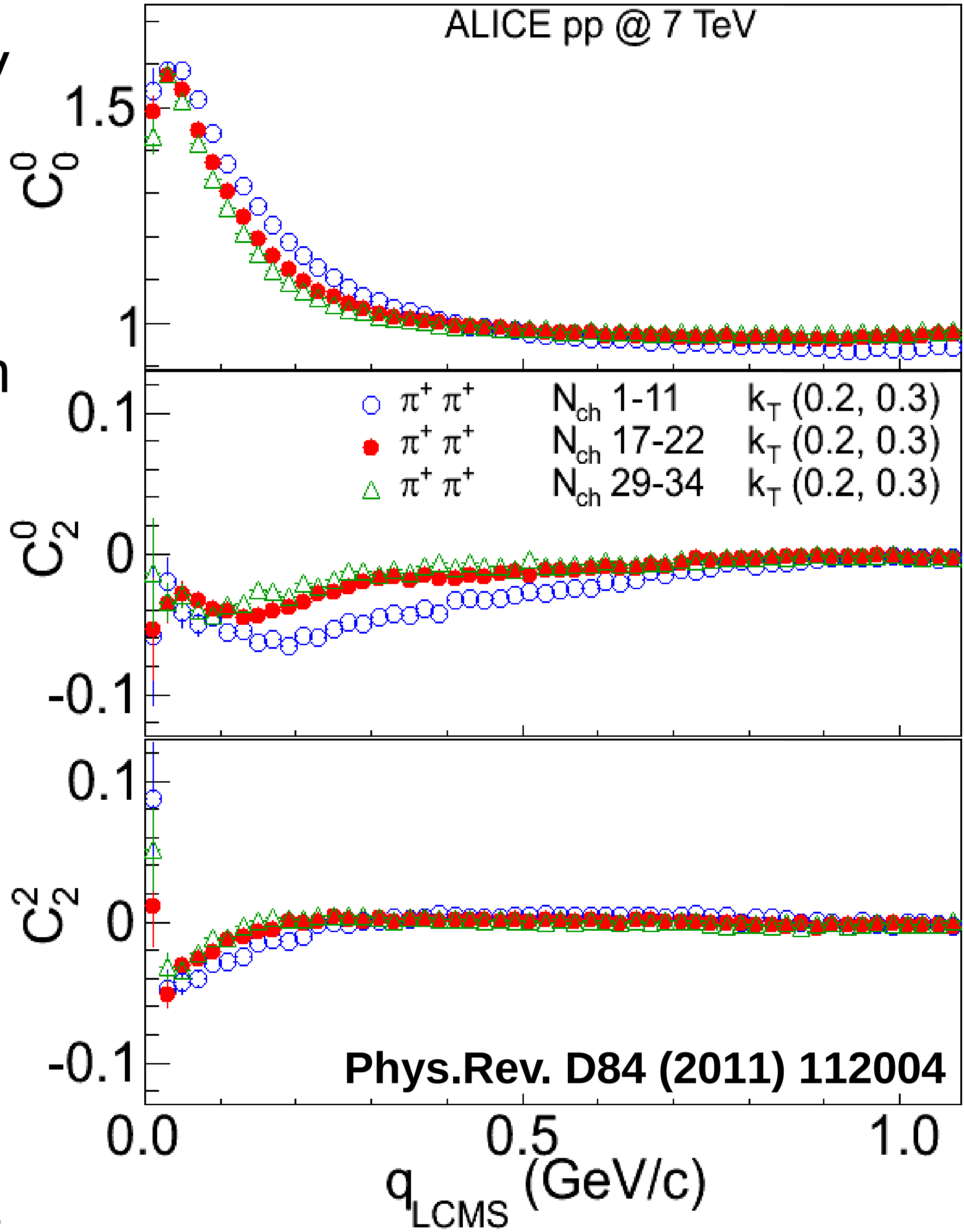
pp, energy dependence

- 3D LCMS correlations decomposed to spherical harmonics, first 3 non-vanishing components shown
- The correlation functions for 900 GeV, 2.76 TeV and 7 TeV data for the same multiplicity and pair transverse momentum ranges.
- Correlation functions for all the energies are similar.
- The similarity is observed for all multiplicity and k_T ranges.



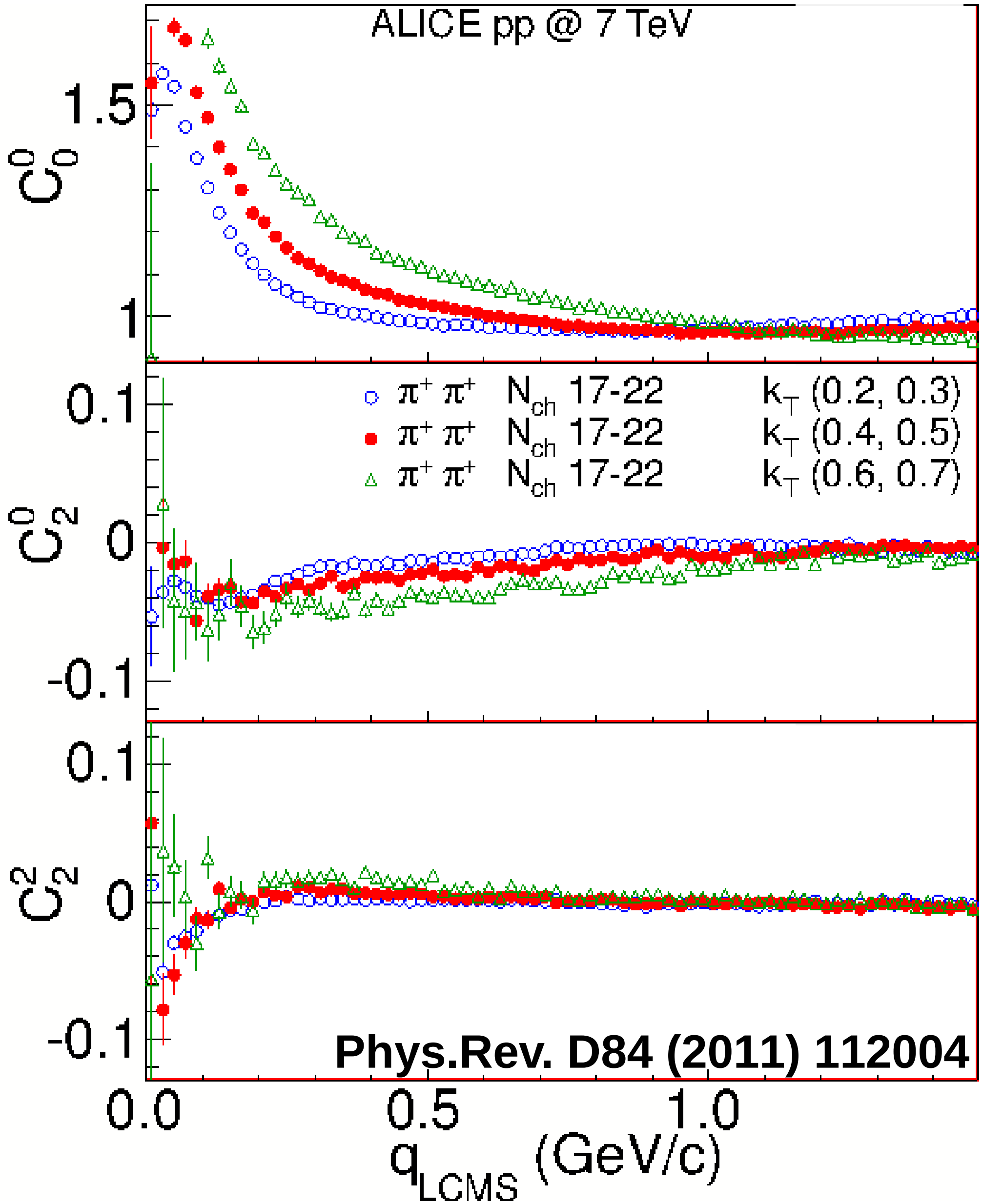
pp, multiplicity dependence

- The correlation functions for 7 TeV collisions for three multiplicity ranges and the same pair transverse momentum range.
- The dependence of the correlation function on the multiplicity is visible (decreasing width with increasing multiplicity).
- Changing the collision energy by an order of magnitude has less impact on correlation functions than changing the multiplicity by 50%.
- The observation holds the same for every k_T range.



pp, k_T dependence

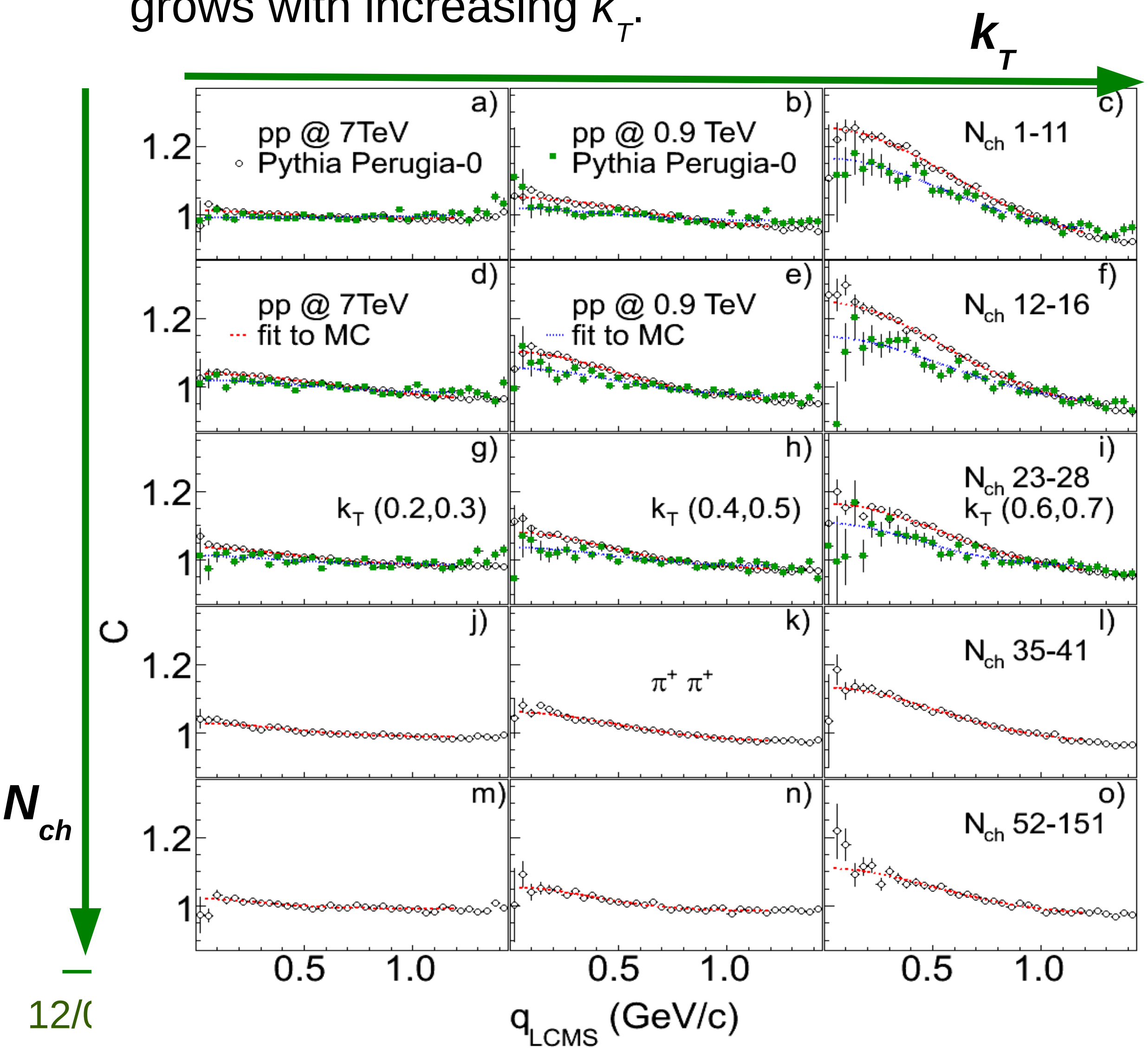
- The correlation functions for 7 TeV collisions for three k_T ranges and the same multiplicity range.
- There is strong dependence of the correlation function on the pair transverse momentum k_T (increase of the correlation width with increasing k_T, development of long range structures at high k_T).
- The observation holds the same for every multiplicity range.

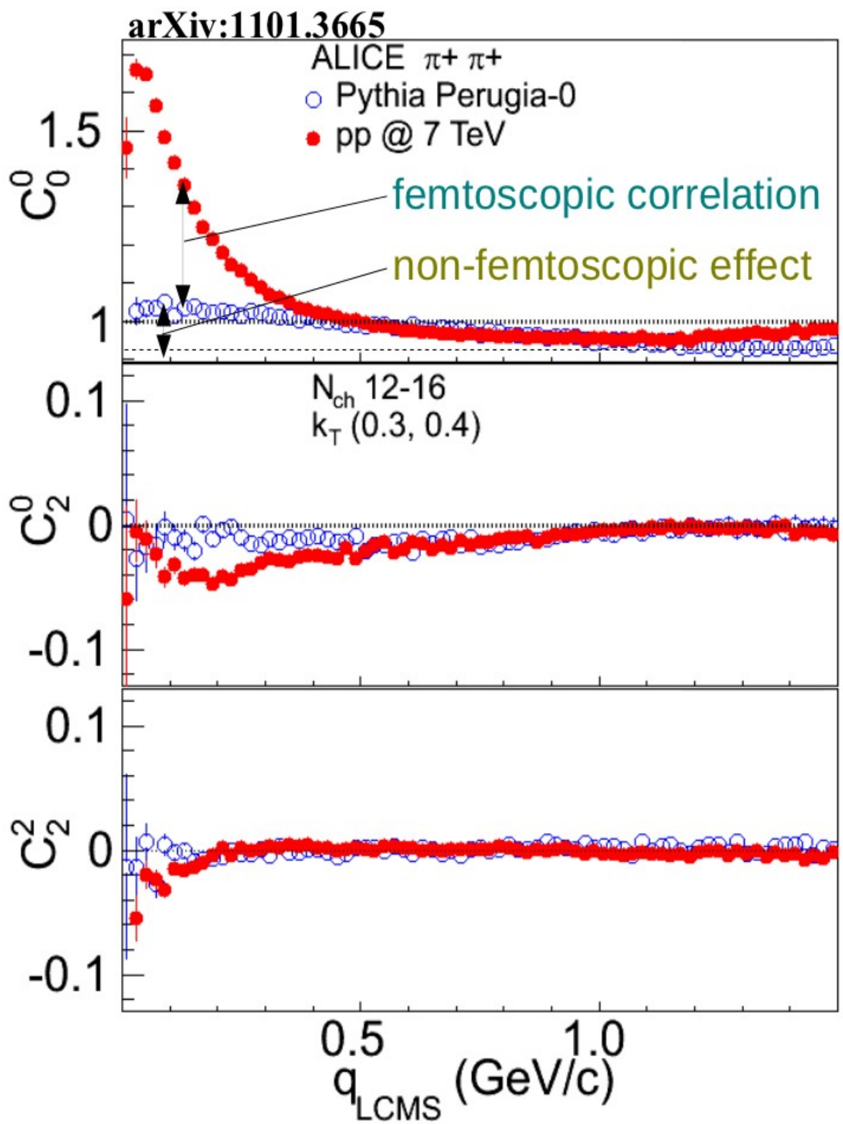


pp, baseline of the CF

- Non-flat baseline is clearly seen in the experimental data.
- The baseline is described well by the MC models (in this case *Pythia Perugia-0*) – the correlation grows with increasing k_T.

Phys.Rev. D84 (2011) 112004





pp, Gaussian and non-Gaussian fits (1)

- The Gaussian fit does not reproduce the data very well – the correlation function has clearly non-Gaussian shape.

- Assume factorization of the source function:

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

- Factorization of the correlation function:

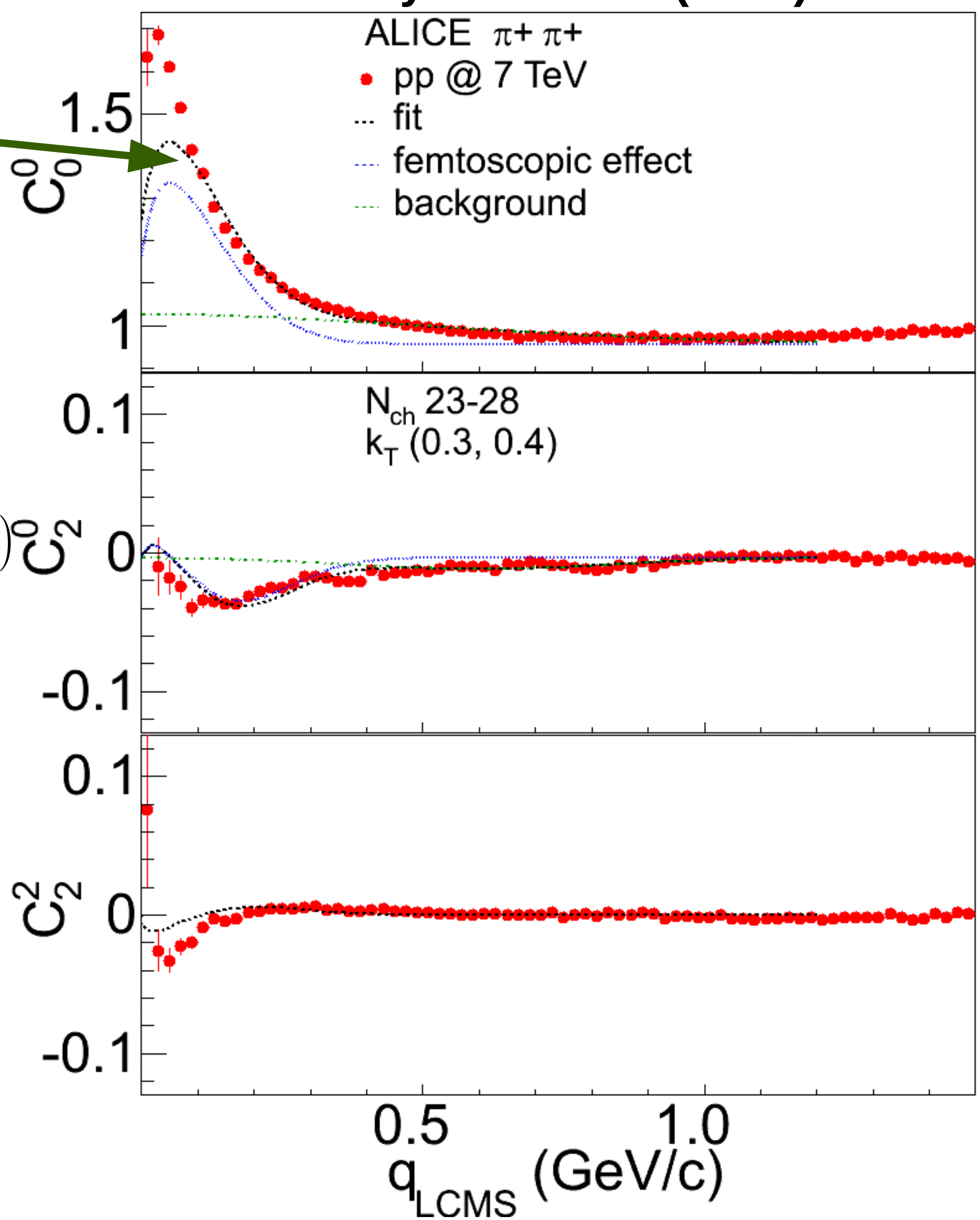
$$C(q_{out}, q_{side}, q_{long}) = 1 + \lambda C_o(q_{out}) C_s(q_{side}) C_l(q_{long})$$

- Components: Gaussian (G), exponential (E) or lorentzian (L) (27 combinations).

- We fitted all the 27 combinations and chose exponential-Gaussian-exponential form.

- The non-Gaussian (in this case EGE) fit describes data much better.

Phys.Rev. D84 (2011) 112004



pp, Gaussian and non-Gaussian fits (2)

- The Gaussian fit does not reproduce the data very well – the correlation function has clearly non-Gaussian shape.
- Assume factorization of the source function:

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- Factorization of the correlation function:

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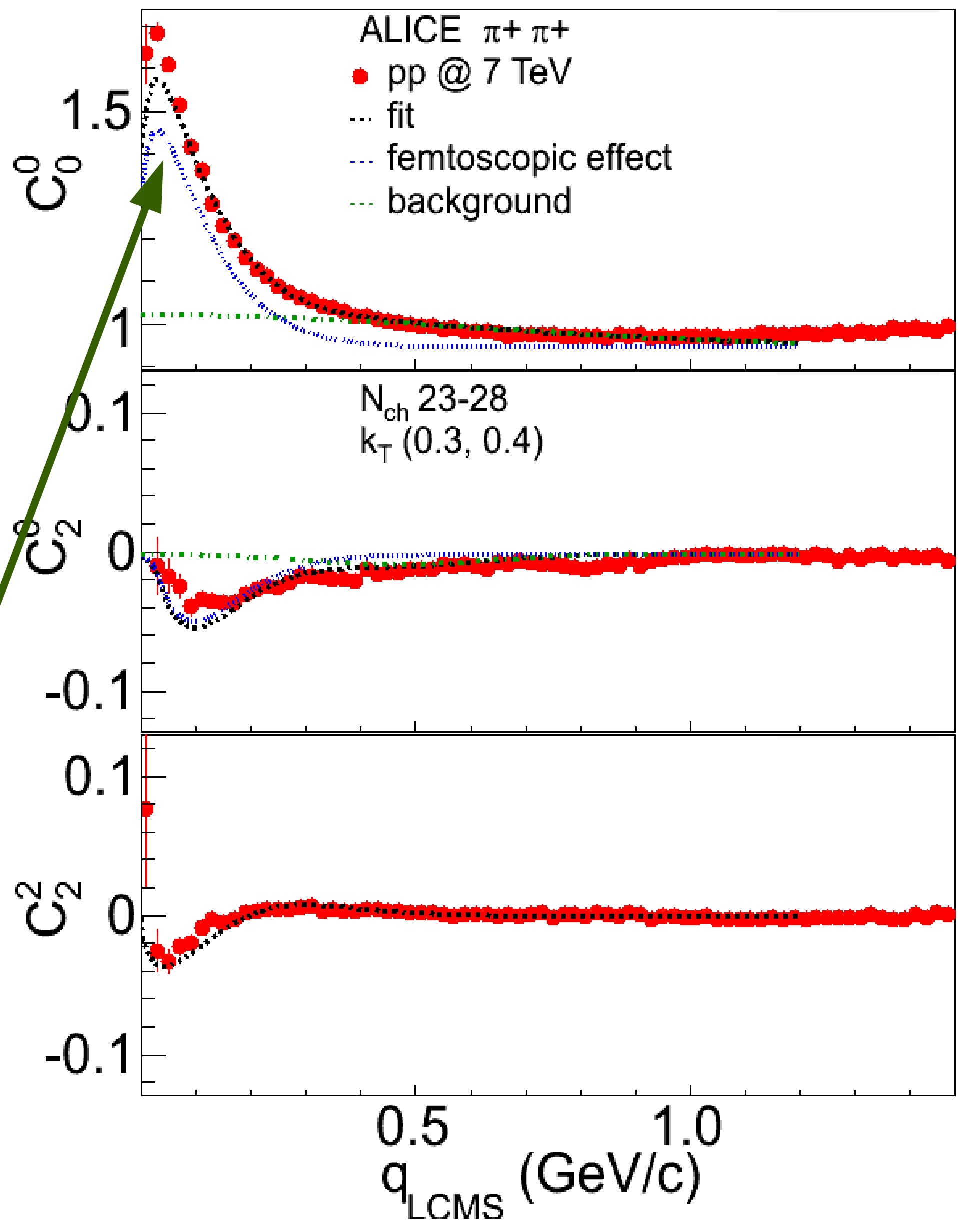
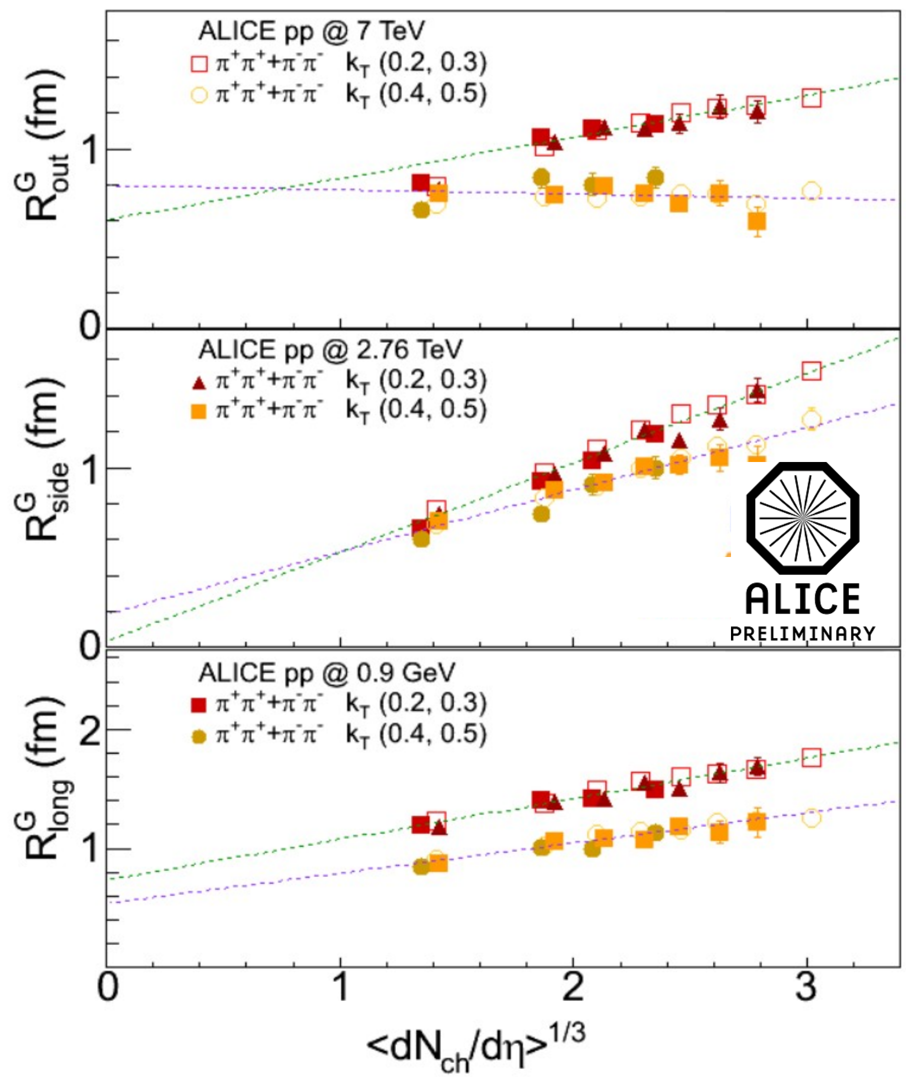


pp, multiplicity dependence of Gaussian radii

- Linear scaling of all the femtoscopic radii with multiplicity is visible.
- Observed for every k_T range.
- The scaling trend for the radii from all the collision energies is the same.
- R_{side} and R_{long} radii grow with multiplicity.
- R_{out} radius grows for low k_T and falls for high k_T range.

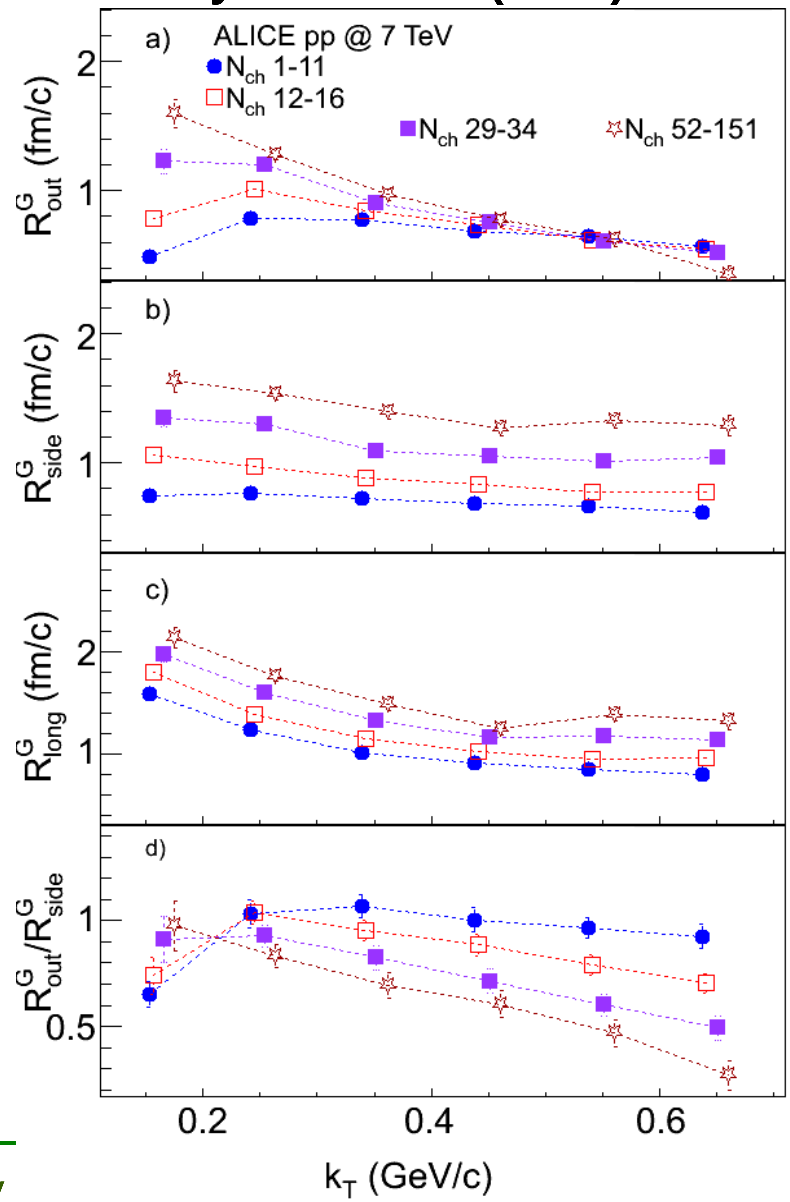


pp, k_T dependence of Gaussian radii

- Falling of radii with k_T is a signature of collective behavior in heavy ions.
- R_{long} falls with k_T for all multiplicity ranges.
- R_{side} is flat for the lowest multiplicity range and the dependence increases with increasing multiplicity.
- R_{out} dependence changes with increasing multiplicity (decreasing for the highest multiplicity range).
- Non-Gaussian fits show similar behavior.

Gaussian fits

Phys.Rev. D84 (2011) 112004

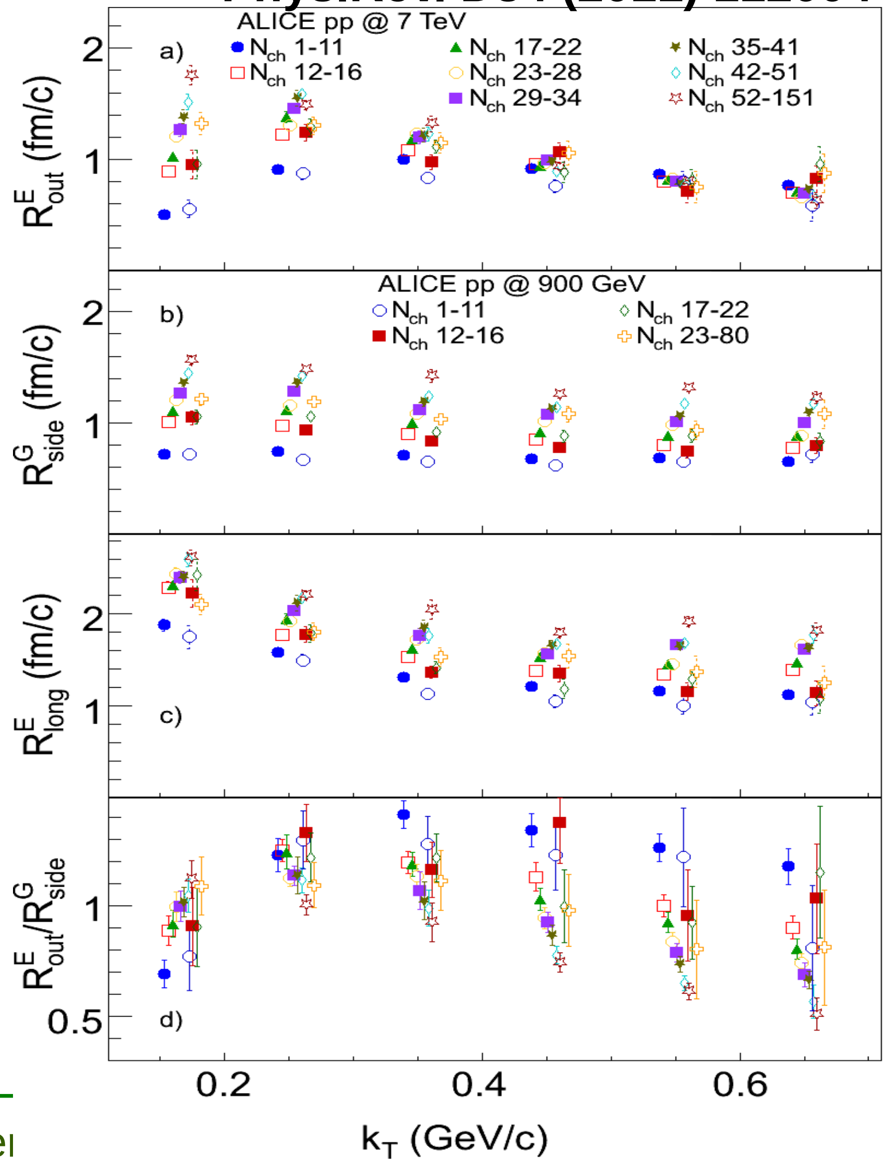


pp, k_T dependence of non-Gaussian radii

- Falling of radii with k_T is a signature of collective behavior in heavy ions.
- R_{long} falls with k_T for all multiplicity ranges.
- R_{side} is flat for the lowest multiplicity range and the dependence increases with increasing multiplicity.
- R_{out} dependence changes with increasing multiplicity (decreasing for the highest multiplicity range).
- Non-Gaussian fits show similar behavior.

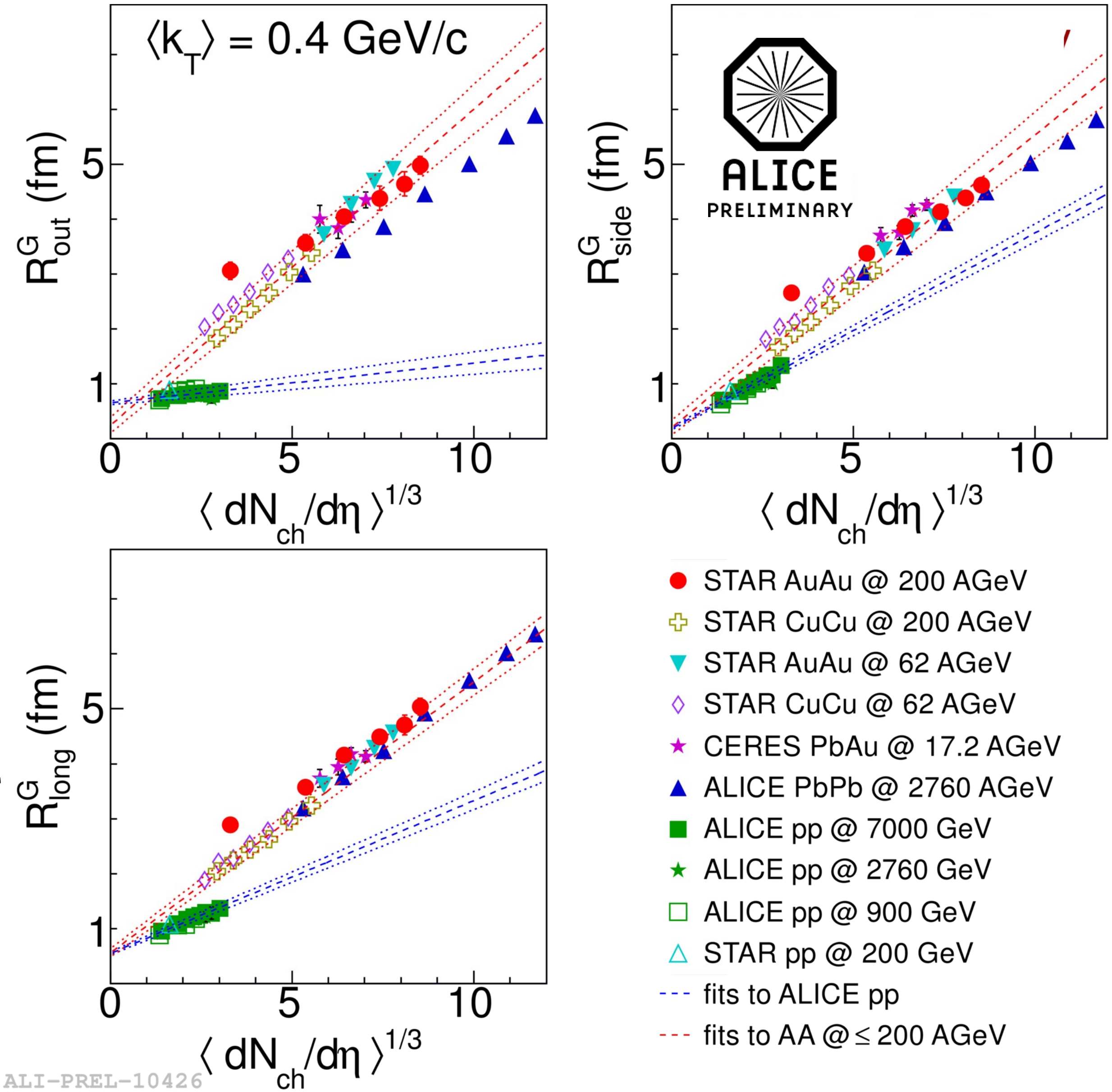
Non-Gaussian fits (EGE example)

Phys.Rev. D84 (2011) 112004



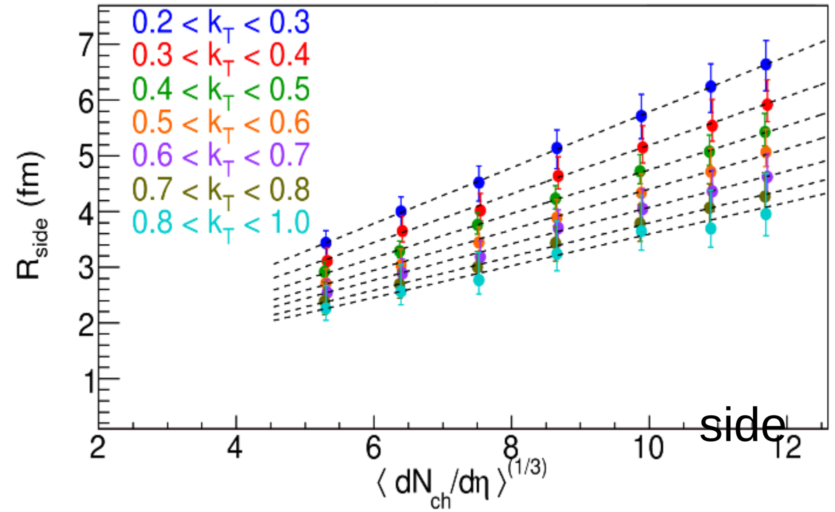
Comparing pp to AA

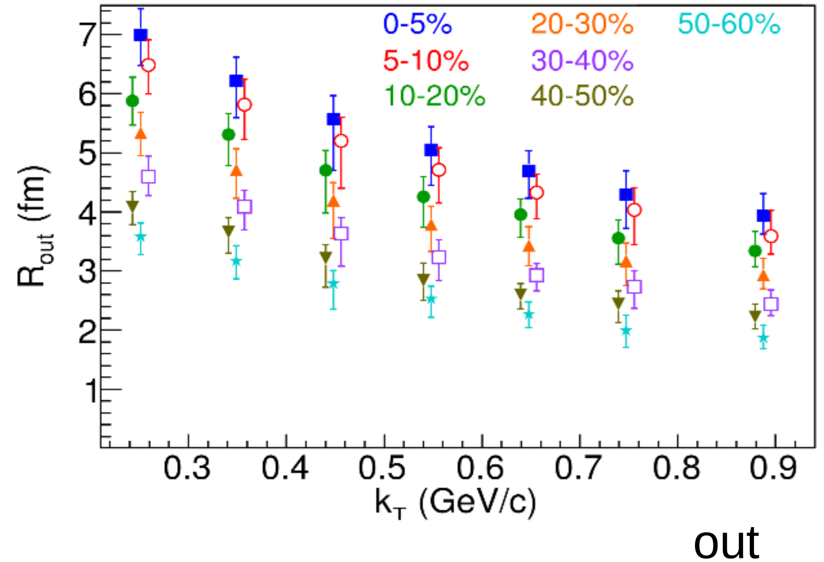
- Direct pp to AA comparison with no extrapolation possible for the first time.
- Linear scaling for pp and AA, but scaling parameters of pp and AA differ.
- The radii at the same multiplicity not the same in pp and AA: initial state matters for the final radii.
- "Trivial" scaling between pp and AA, as reported e.g. by the STAR experiment: **Phys.Rev. C83 (2011) 064905** is not observed by ALICE.



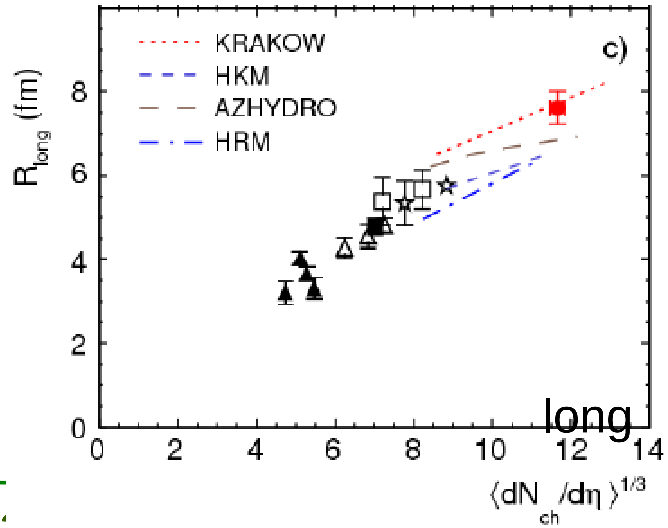
Summary

- Pb-Pb results:
  - Pion radii in PbPb show factorization of scaling into **linear dependence on multiplicity** and **power-law dependence on pair momentum**



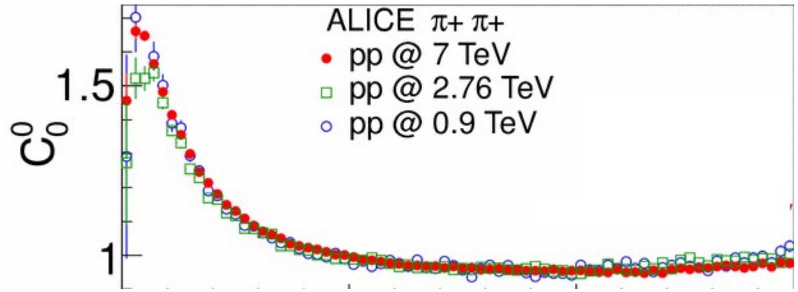


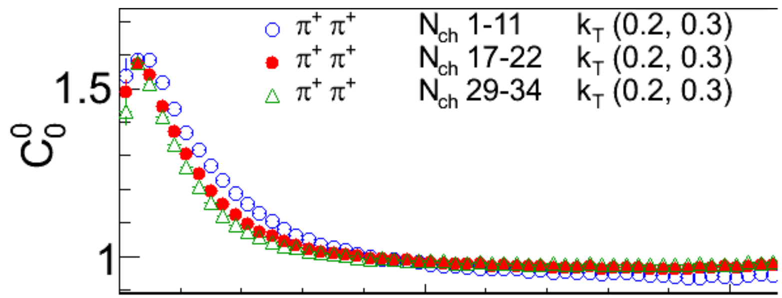
  - **Hydrodynamic model predictions agree** qualitatively well with AA data, strong argument for the correctness of this description

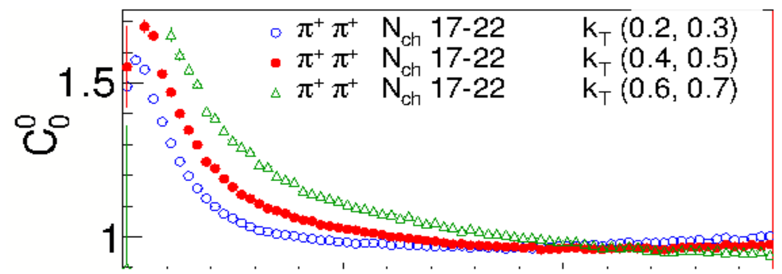


Summary

- pp results:
  - **Correlation functions independent on collision energy, depend on multiplicity and (more strongly) on pair transverse momentum.**
  - Significant non-femtoscopic correlations seen, growing with increasing pair transverse momentum, well reproduced by the Monte Carlo models: included in the fitting formula.
  - The experimental correlation functions not Gaussians, better forms proposed. The trends of the radii stay the same for all forms.
  - First direct comparison of pp and AA vs. multiplicity performed. Scaling linear in pp and AA but with significantly different parameters. No trivial pp/AA scaling seen.







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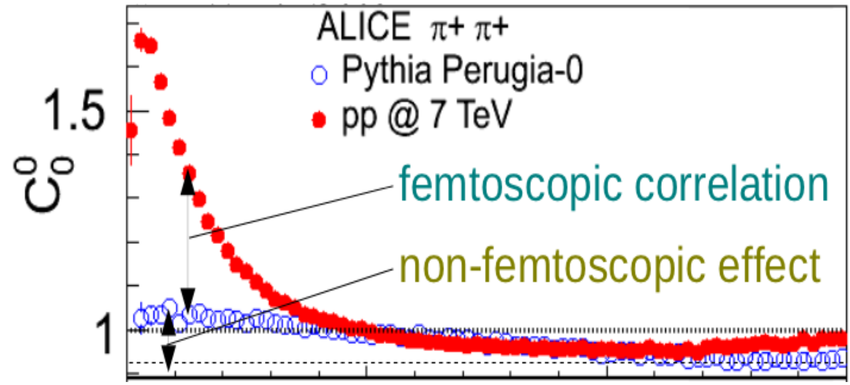

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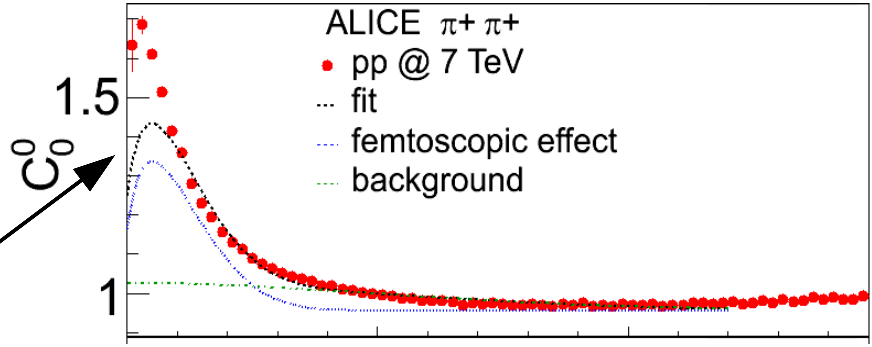
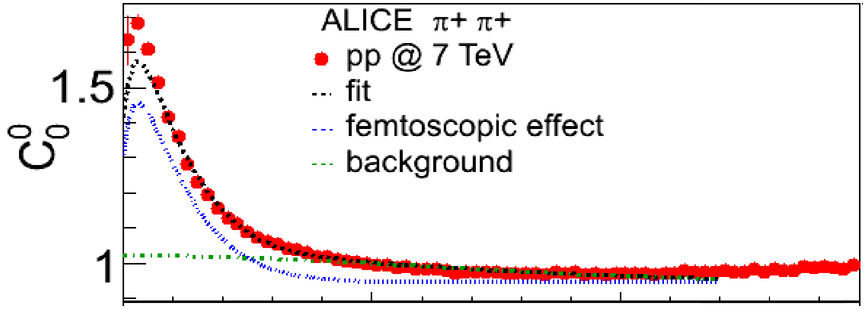
Gassian





Exponential-Gassian-Exponential

Summary

- pp results:
  - Correlation functions independent on collision energy, depend on multiplicity and (more strongly) on pair transverse momentum.
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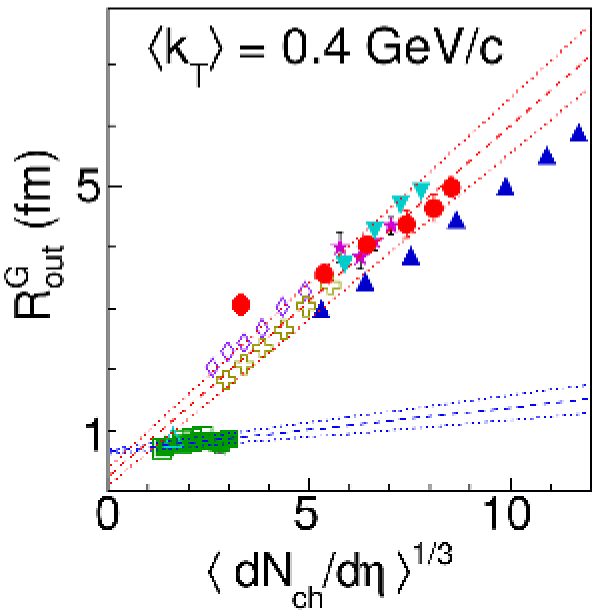
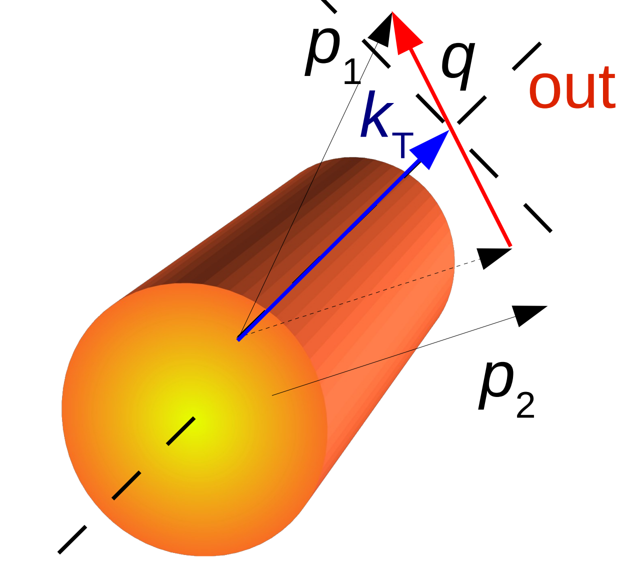
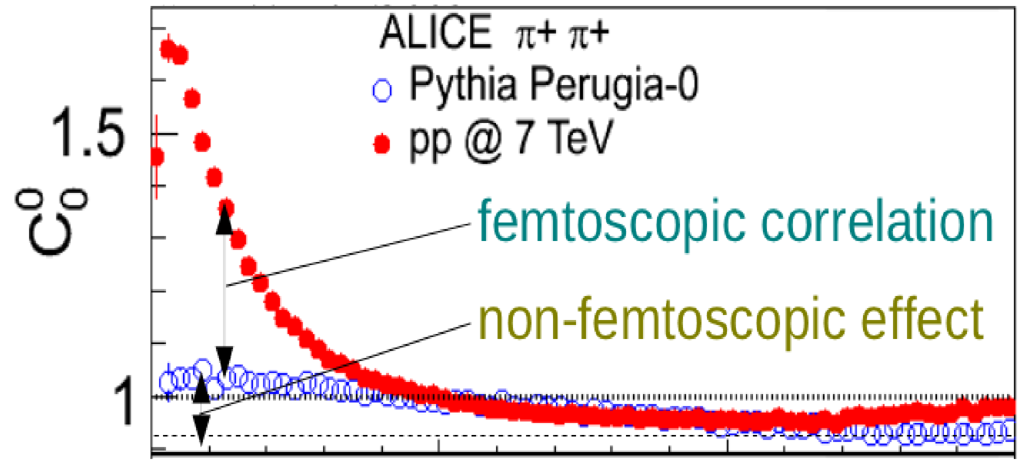
  - **First direct comparison of pp and AA vs. multiplicity performed. Scaling linear in pp and AA but with significantly different parameters. No trivial pp/AA scaling seen.**

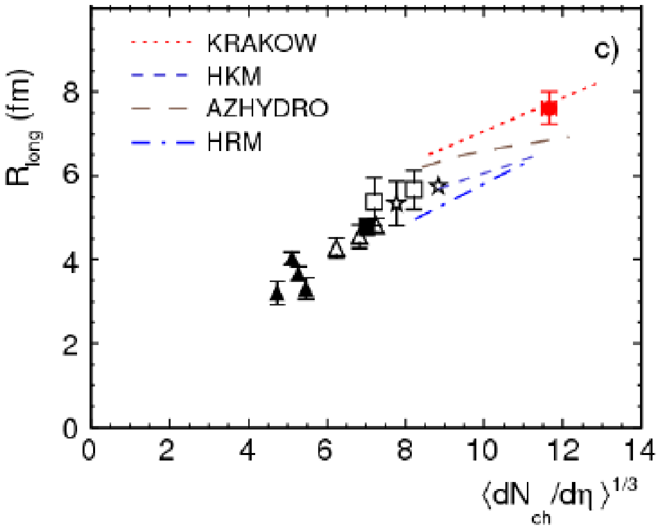




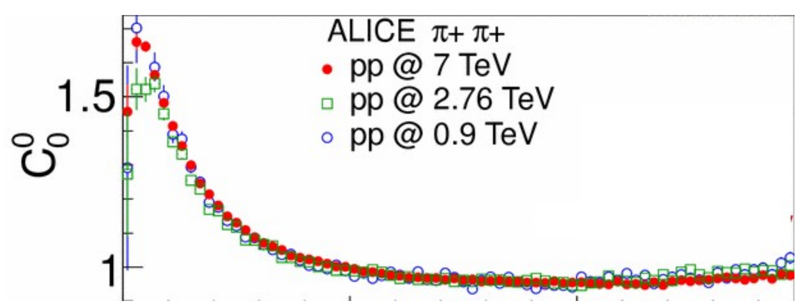
$$k_T = \frac{|\vec{p}_1 + \vec{p}_2|}{2}$$

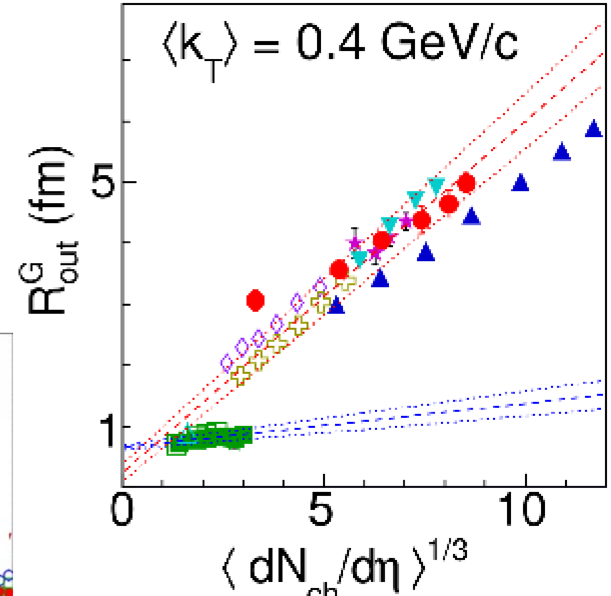


$$B(\vec{q}) = A_h \exp(-|\vec{q}|^2 A_w^2) + B_h \exp\left(\frac{-(|\vec{q}| - B_m)^2}{2 B_w^2}\right)(3\cos^2(\theta) - 1)$$



Thank you!





Backup

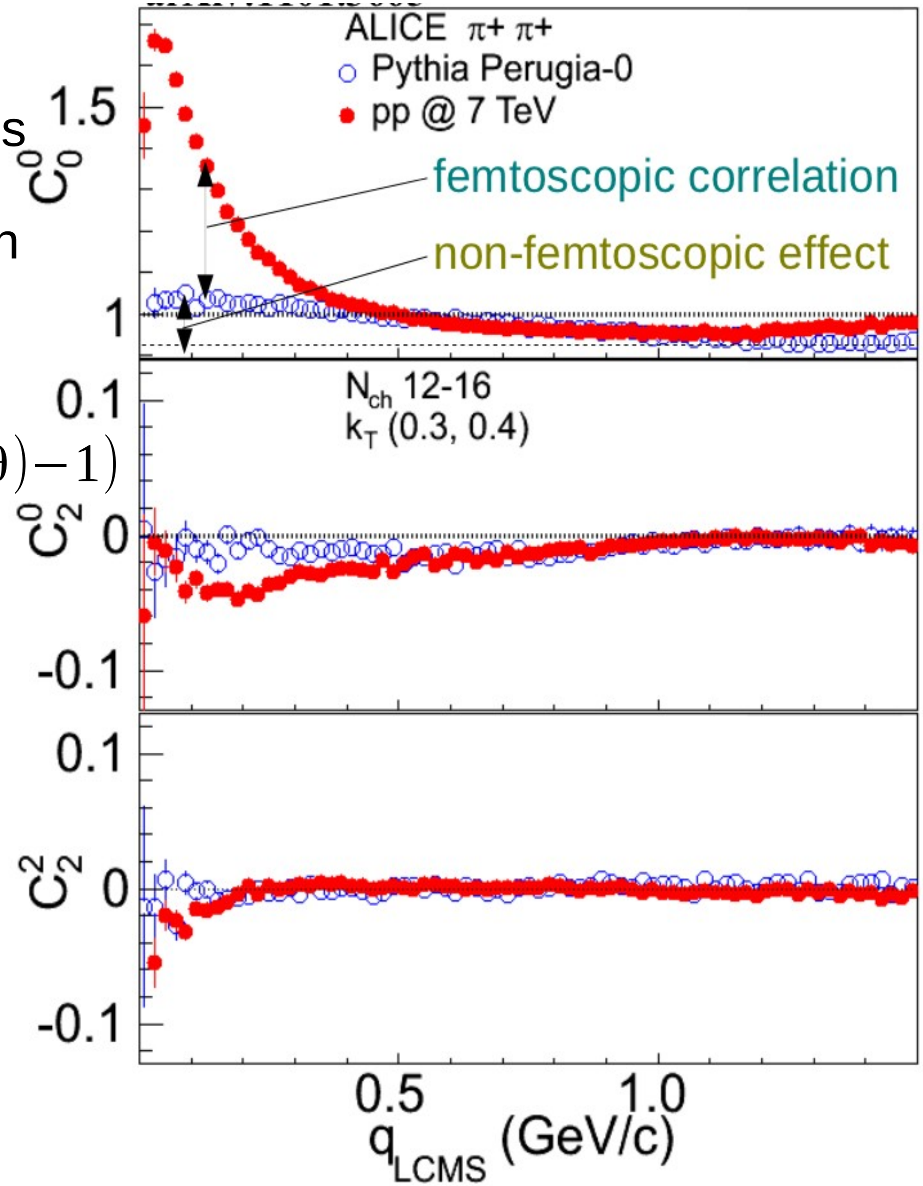
pp, baseline of the CF

- Non-flat baseline is clearly seen in the experimental data.
- The baseline is described well by the MC models (in this case *Pythia Perugia-0*) – the correlation grows with increasing k_T. Parameterization taken from the MC (data-driven functional form):

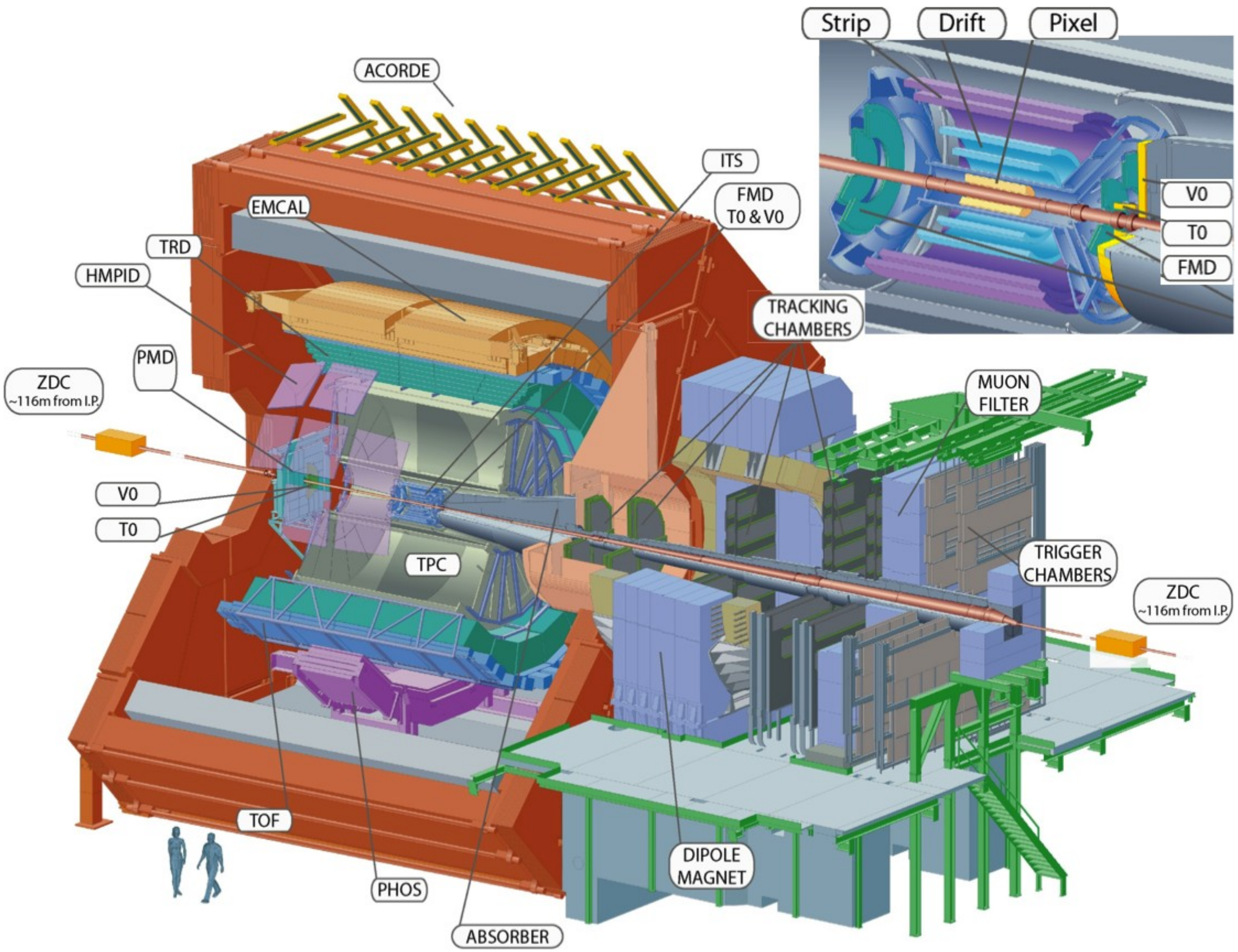
$$B(\vec{q}) = A_h \exp(-|\vec{q}|^2 A_w^2) + B_h \exp\left(\frac{-(|\vec{q}| - B_m)^2}{2 B_w^2}\right)(3\cos^2(\theta) - 1)$$

- Two competitive explanations (minijets, hydro): Akkelin, Sinyukov **arXiv:1106.5120**.

arXiv:1101.3665



ALICE



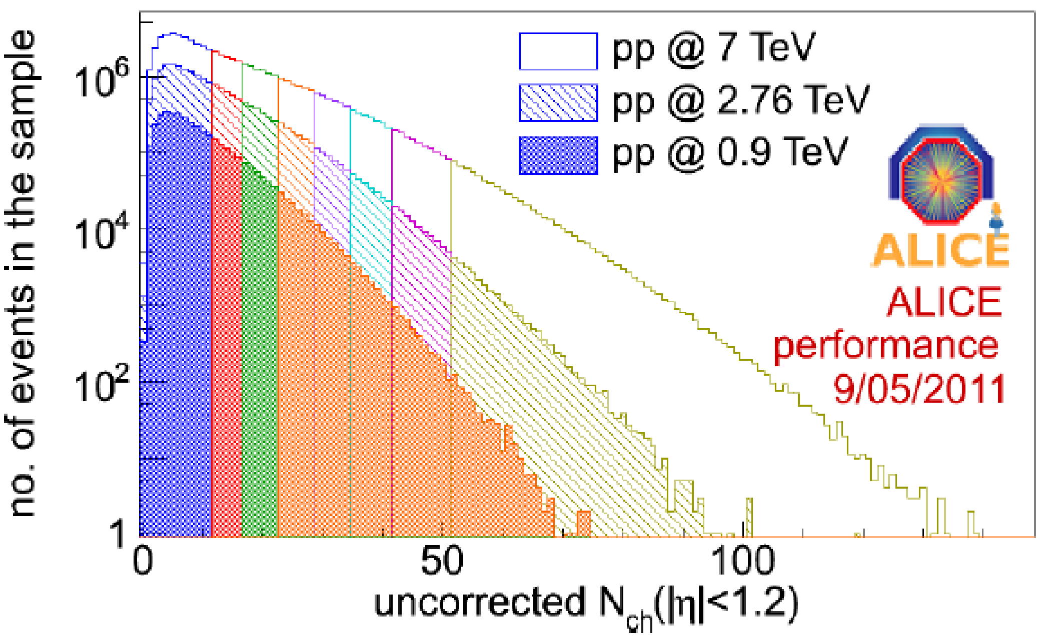
- Tracking and PID: Time Projection Chamber (TPC)
- Tracking and vertexing: Inner Tracking System (ITS)
- PID at high momenta: Time-of-Flight (TOF)
- Trigger and centrality: VZERO

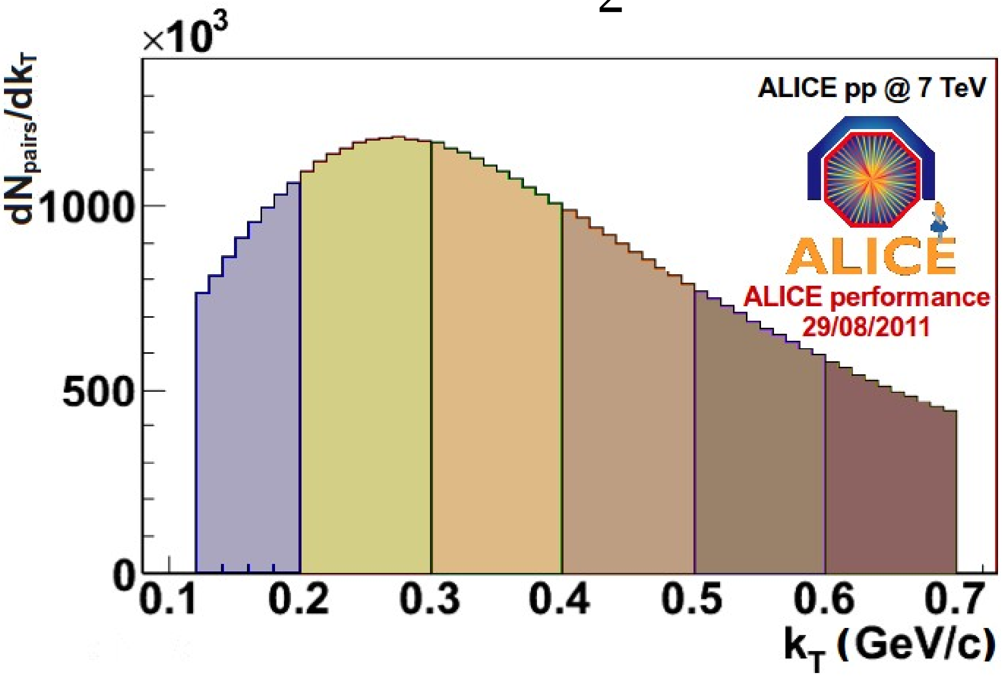
- pp collisions at $\sqrt{s}$ = 0.9, 2.36 and 7 TeV (>500M minimum bias events)
- Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV (~60M events, various triggers)

Multiplicity and k_T selection

- 8 multiplicity ranges (#events / #pairs for 7 TeV data):
  - **Nch: 2-11 (31.4M / 48.7M)**
  - **Nch: 12-16 (9.2M / 65M)**
  - **Nch: 17-22 (7.4M / 105.7M)**
  - **Nch: 23-28 (4.8M / 120.5M)**
  - **Nch: 29-34 (3.0M / 116.3M)**
  - **Nch: 35-41 (2.0M / 115.6M)**
  - **Nch: 42-51 (1.3M / 114.5M)**
  - **Nch: 52-151 (0.72M / 108.8M)**
- 6 pair transverse momentum ranges:
  - **kT: 0.12-0.2 GeV/c**
  - **kT: 0.2-0.3 GeV/c**
  - **kT: 0.3-0.4 GeV/c**
  - **kT: 0.4-0.5 GeV/c**
  - **kT: 0.5-0.6 GeV/c**
  - **kT: 0.6-0.7 GeV/c**

$$k_T = \frac{|\vec{p}_{T,1} + \vec{p}_{T,2}|}{2}$$

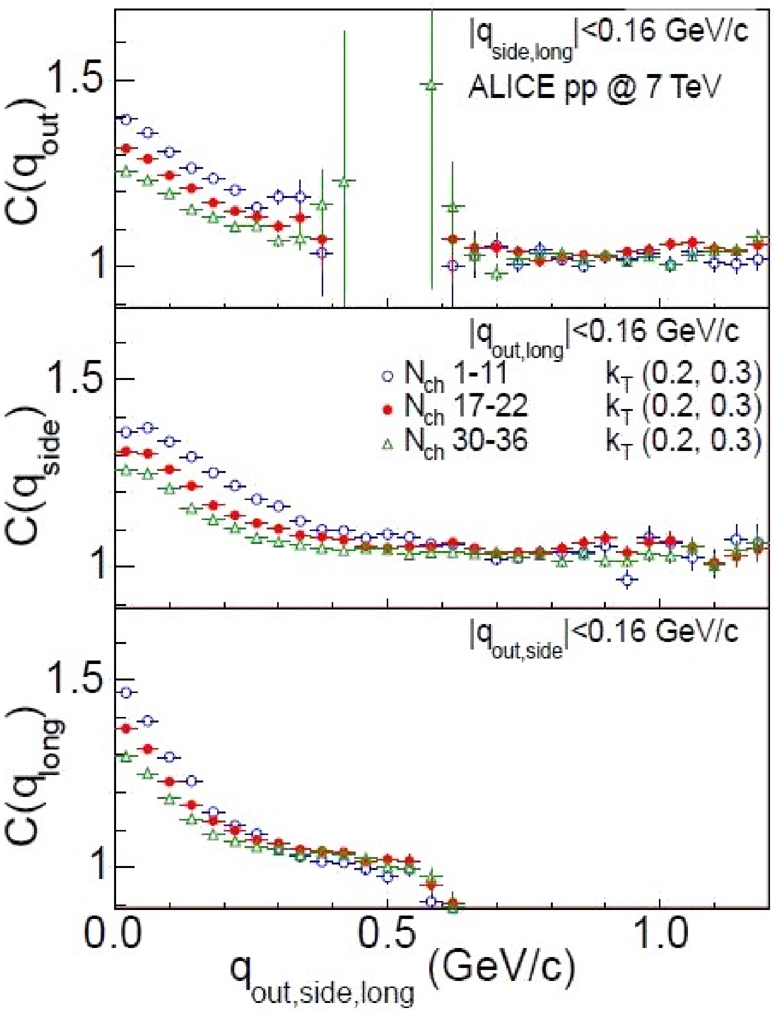




Comparison between cartesian and SH

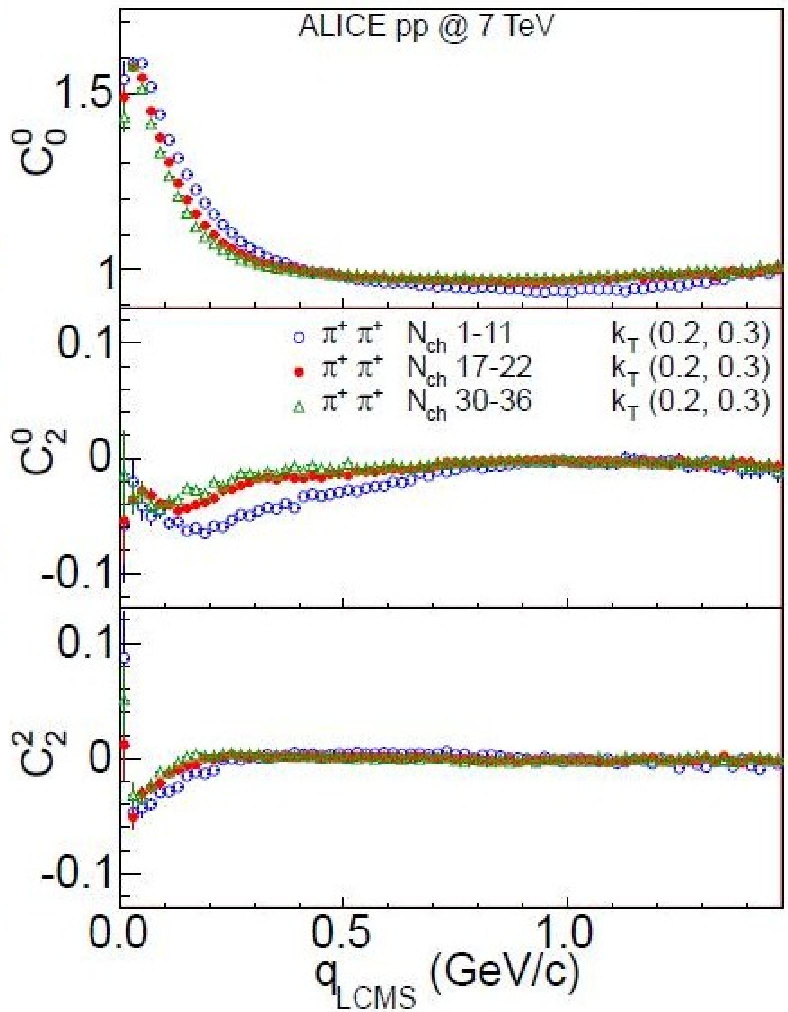
Cartesian

arXiv:1101.3665



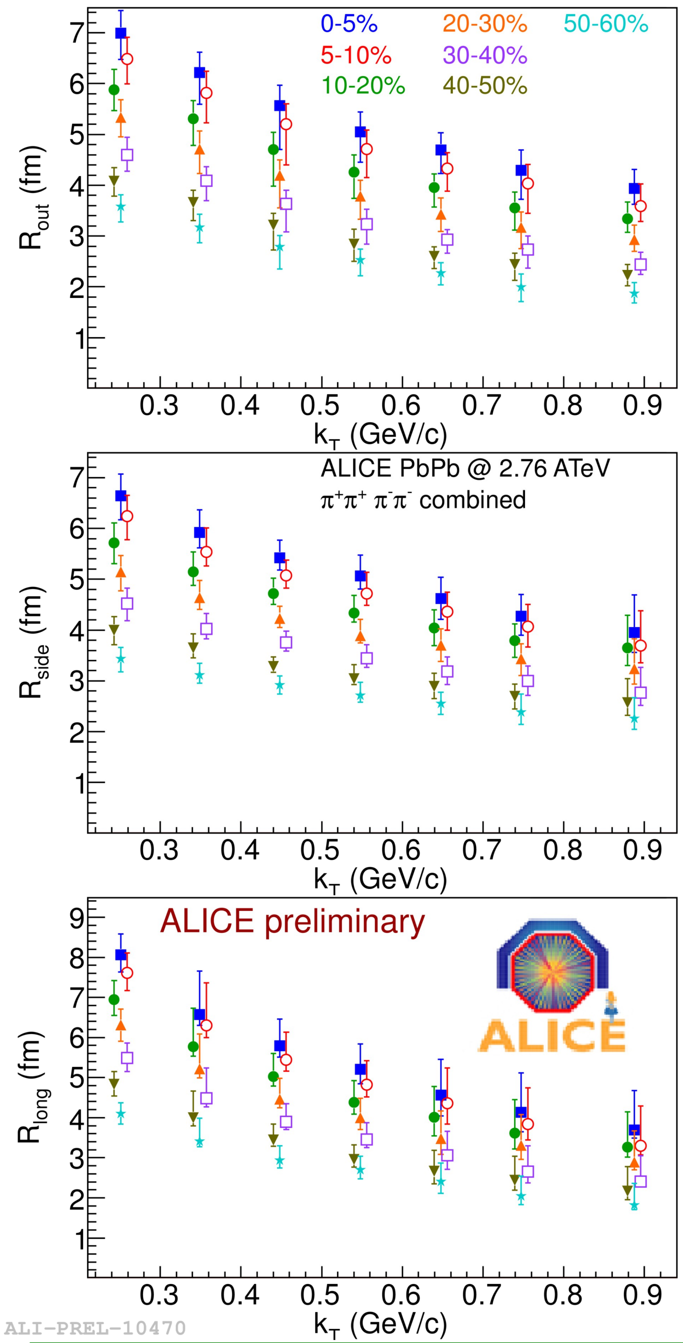
Spherical Harmonics

arXiv:1101.3665



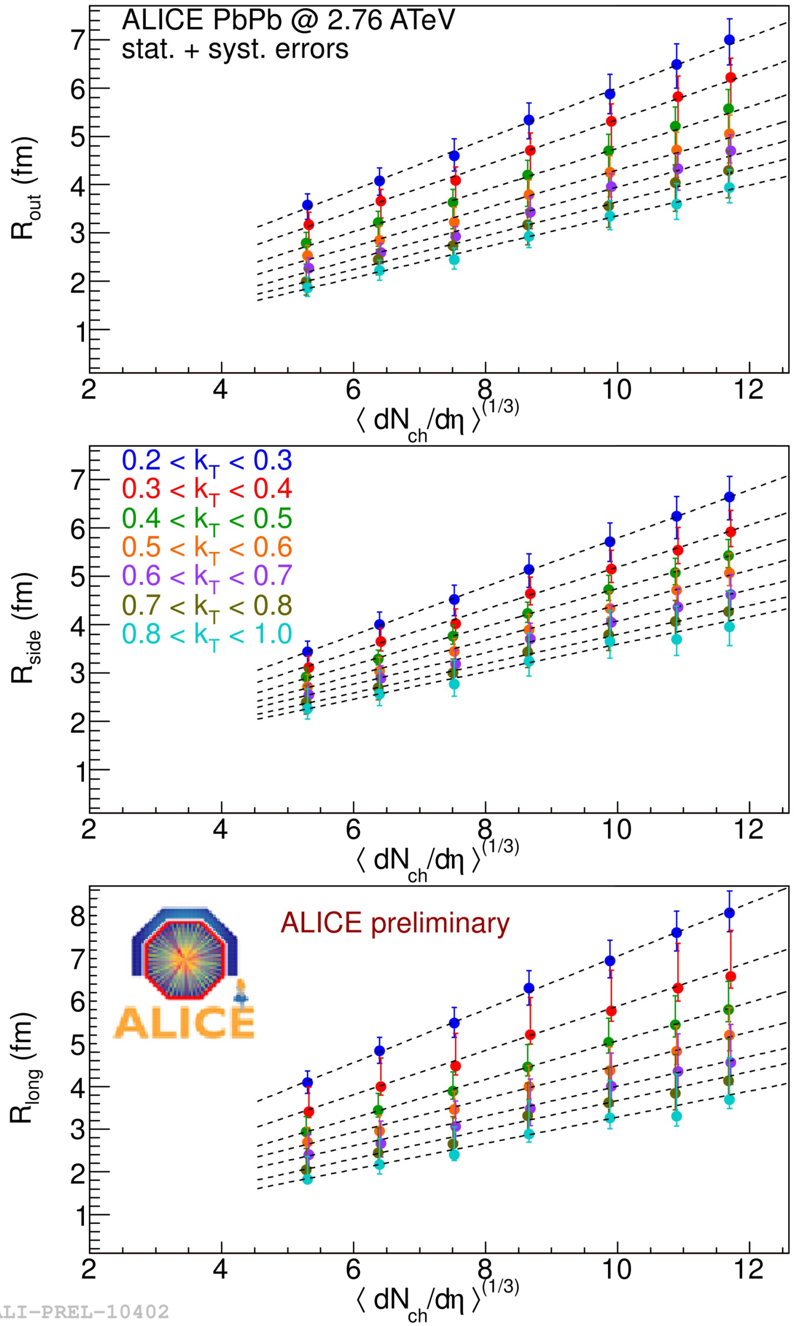
- The correlation functions for 7 TeV collisions for three multiplicity ranges and the same pair transverse momentum range.
- Holes visible in cartesian due to the cut on pair transverse momentum.
- Cartesian and SH representations are consistent.

Pb-Pb, radii vs. centrality vs. k_T

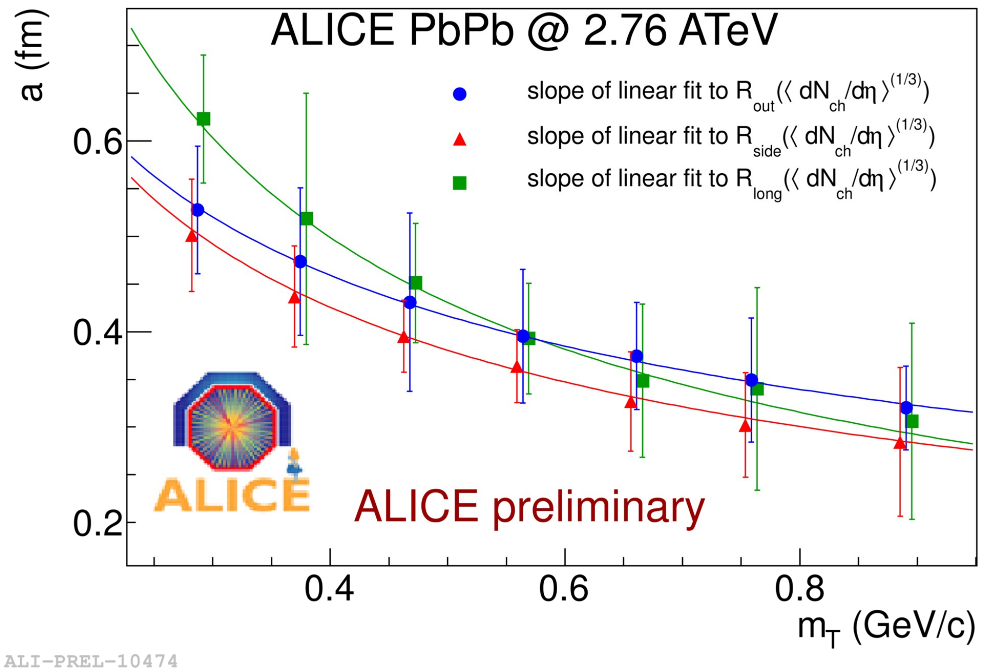


- Femtoscopic radii vs. k_T for 7 centrality bins
- Statistical error smaller than the symbol size, systematic+statistical errors shown as errorbars
- Dominating systematic error: two-track effect correction (especially large at large k_T)
- Other systematic effects: Bowler-Sinyukov Coulomb correction method uncertainty, momentum resolution correction uncertainty, fit range dependence, non-gaussian effects, pion identification

Pb-Pb, linear 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



Non-Gaussian fitting forms comparison

- Best fit (lowest χ2/ndf)

M\kT	0	1	2	3	4	5
0	ELL	ELL	ELE	EEG	EEG	ELG
1	ELL	ELE	ELE	ELG	ELG	EGG
2	ELL	ELL	ELE	ELE	ELG	EGG
3	ELL	ELL	ELE	ELE	ELG	ELL
4	ELL	ELL	ELL	ELE	ELL	ELL
5	ELE	ELE	ELE	ELL	ELE	LEE
6	ELE	ELL	ELE	ELE	ELL	ELL

- Second best fit

M\kT	0	1	2	3	4	5
0	EEE	ELE	EEE	ELG	EEE	EEG
1	ELE	ELL	ELL	ELE	ELE	LGG
2	ELE	ELE	EEE	ELL	LLG	ELG
3	ELE	ELE	EEL	ELL	EGG	LGG
4	LLL	ELE	EEE	EEE	ELE	ELE
5	LLE	EEE	ELL	ELE	ELL	EGE
6	ELL	EGL	EEE	EEE	ELE	EEL

- We performed detailed study and fitted all 27 combinations in every multiplicity and k_T range.
- In *out* direction almost always exponential form fits best.
- In *side* direction mostly lorentzian form fits best.
- In *long* direction moslty exponential or lorentzian forms fit best.

Functional forms: G – Gaussian, E – exponential, L – lorentzian
Order convention: Out-Side-Long