Pion femtoscopy results from pp collisions at $\sqrt{s}$=900 GeV and 7 TeV, registered by the ALICE experiment

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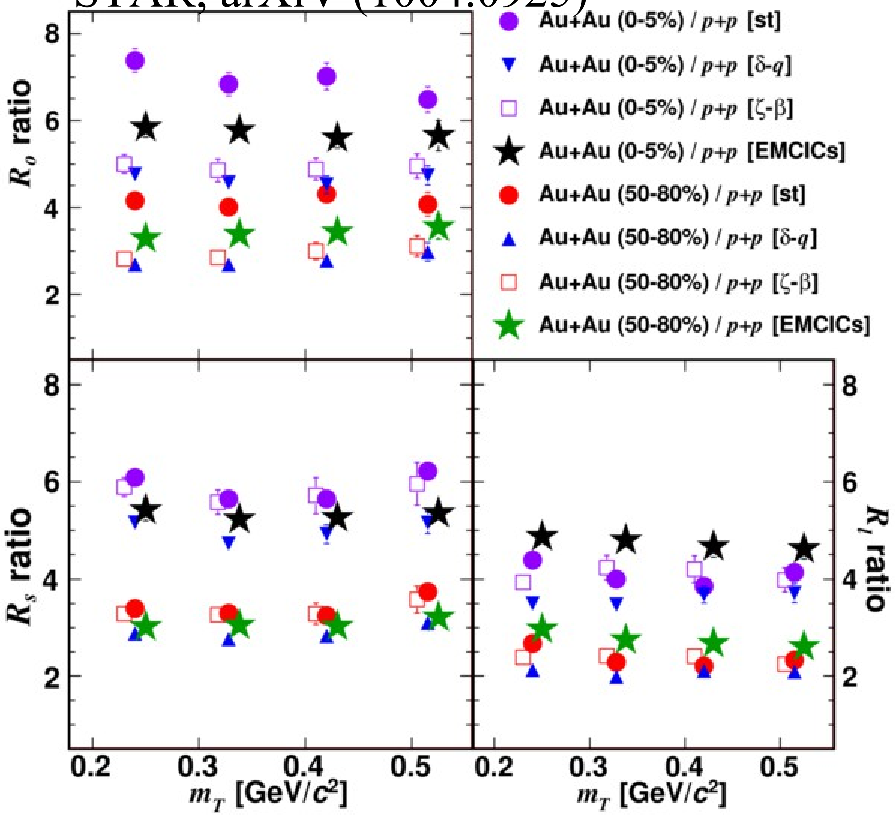
Outline

- Physics motivation:
  - k_T dependence of the 3D radii as a signature of collective flow
  - Multiplicity scaling of the 3D radii
- ALICE experiment
  - Datataking conditions
  - Data selection and sample size
  - Differential analysis
- Results
  - Correlation functions vs. multiplicity
  - Correlation functions vs. pair momentum
  - Correlation functions vs. beam energy
  - Underlying event correlations
  - Systematic uncertainties

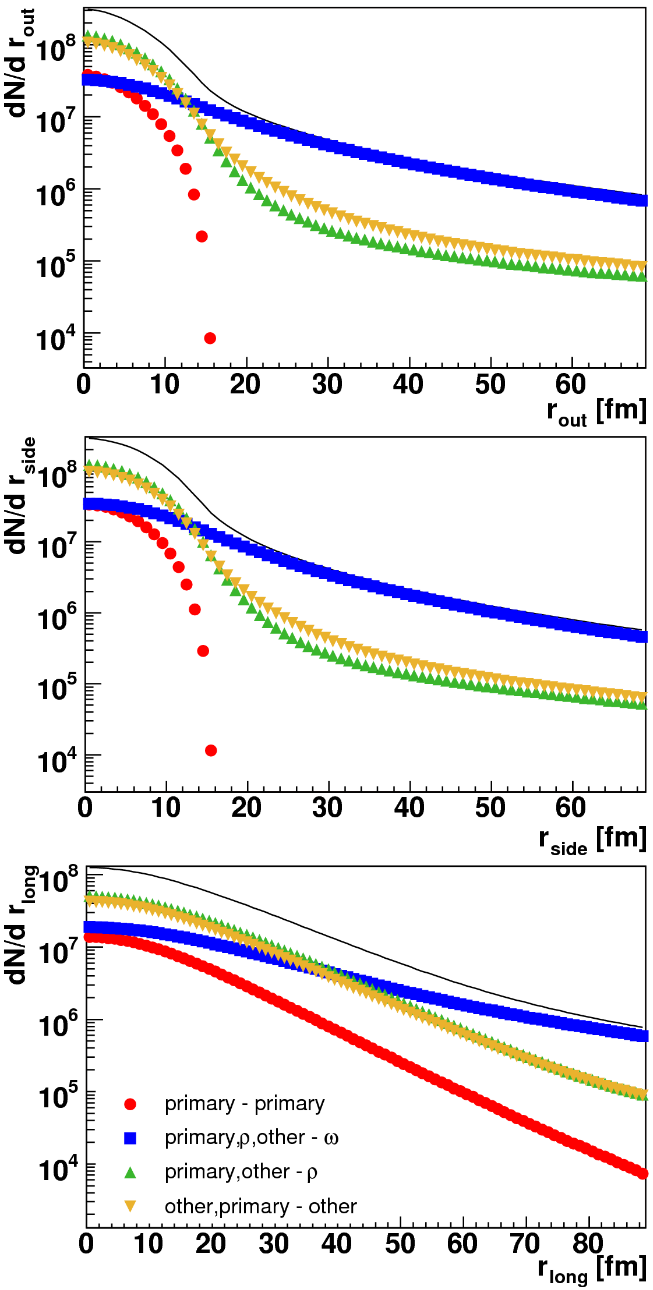
pp vs. AuAu: puzzling scaling ...

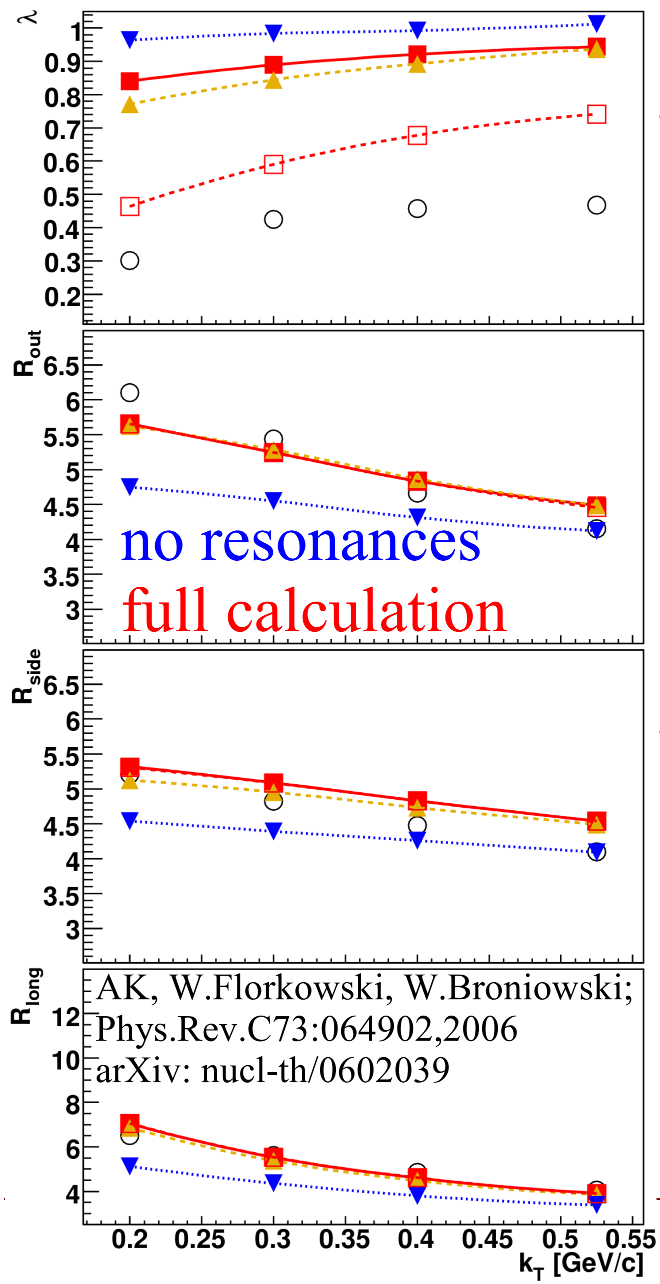
- STAR reports that 3D HBT radii scale in pp in a way very similar to AuAu
- m_T dependence of 3D radii in AuAu is taken as a signature of a flowing medium
- Is the scaling between pp and AuAu a signature of the universal underlying physics mechanism or a coincidence?

STAR, arXiV (1004.0925)



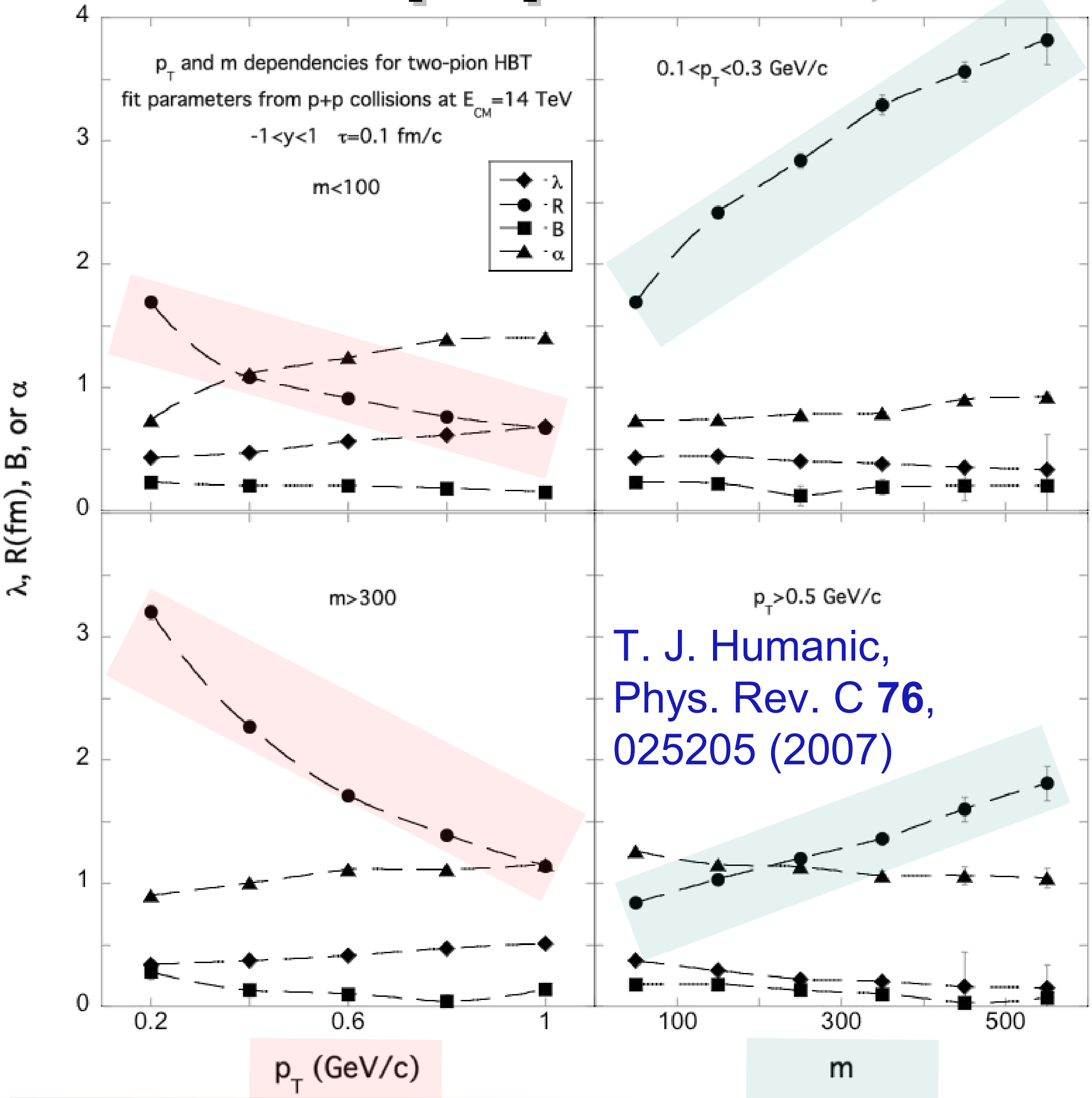
… but what about resonances?





- In AuAu simulations strong resonances produce two effects:
  - Source gets bigger by ~1 fm
  - Source becomes non-gaussian
- Both of these effects are on the order of a system size expected in pp. Will they dominate the signal?

Rescattering model
p+p ➔ ππ, √s = 14 TeV

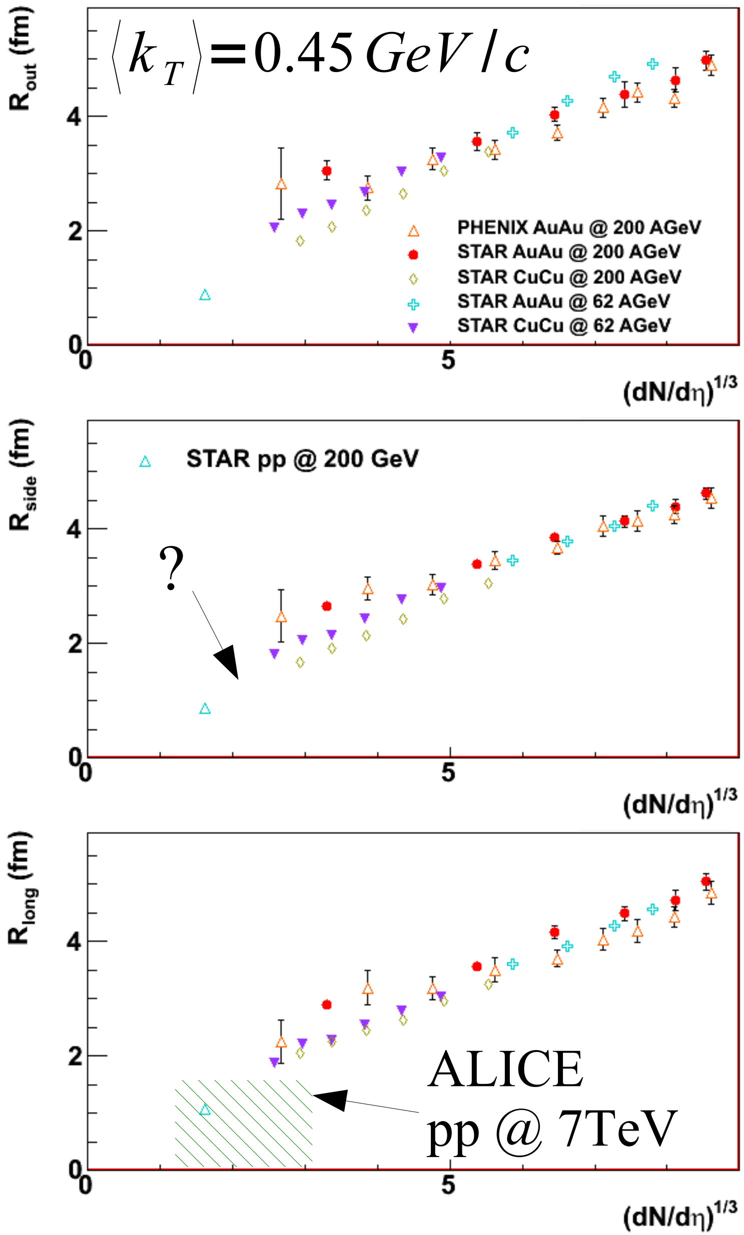


- Fit to $C(q_{inv})$ with:

$$C(q_{inv}) = \left[1 + \lambda \cos(B q_{inv}^2) \exp(-R^\alpha q_{inv}^\alpha)\right]$$

- Rescattering model predicts:
  - Growth of radius with multiplicity
  - Decrease of radius with pair momentum, more pronounced at higher multiplicity

Multiplicity dependence in pp and AA



- Do the data scale with multiplicity in pp in the same way as they do in AA? What does it mean if they do? What does it mean if they do not?
- STAR pp@200 GeV is separated by a considerable multiplicity gap from the heavy-ion measurements
- ALICE multiplicity reach in pp @ 7TeV extends to the RHIC heavy-ion data. For the **first time** we can measure HBT radii in pp and AA at comparable multiplicity.

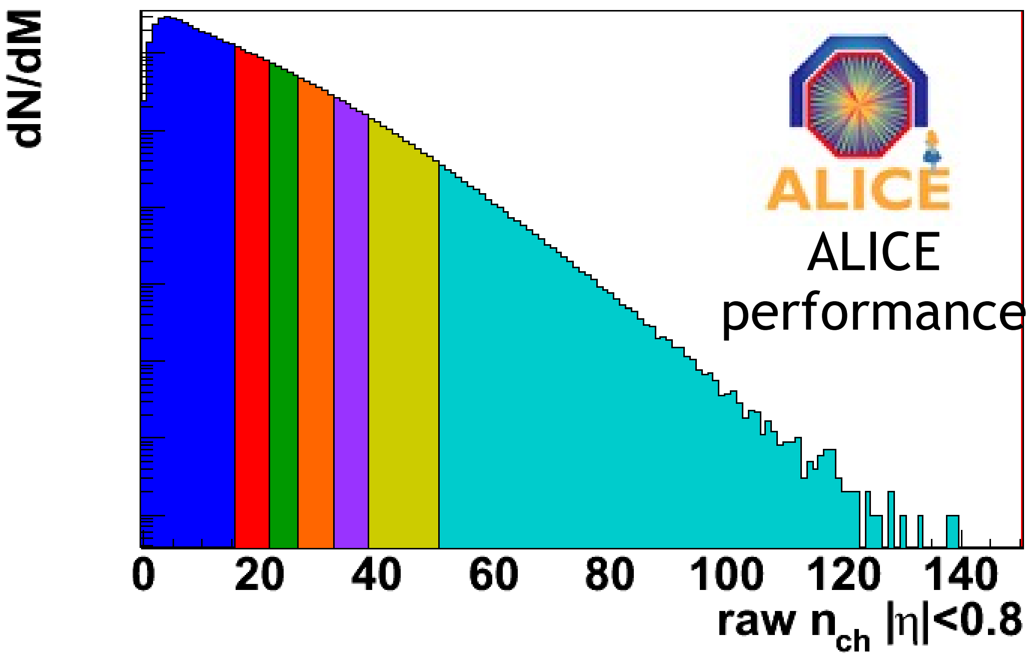
ALICE datataking in 2010

- ALICE has been taking data continuously since March 2010.
- A high statistics sample of pp collisions at 900 GeV (~8M minimum bias triggers) has been collected
- About 80M minimum bias triggers at 7 TeV used for this analysis (out of 500M total recorded up to now)
- Used fully calibrated data collected in May 2010
- All analysis done on the distributed computing environment: GRID

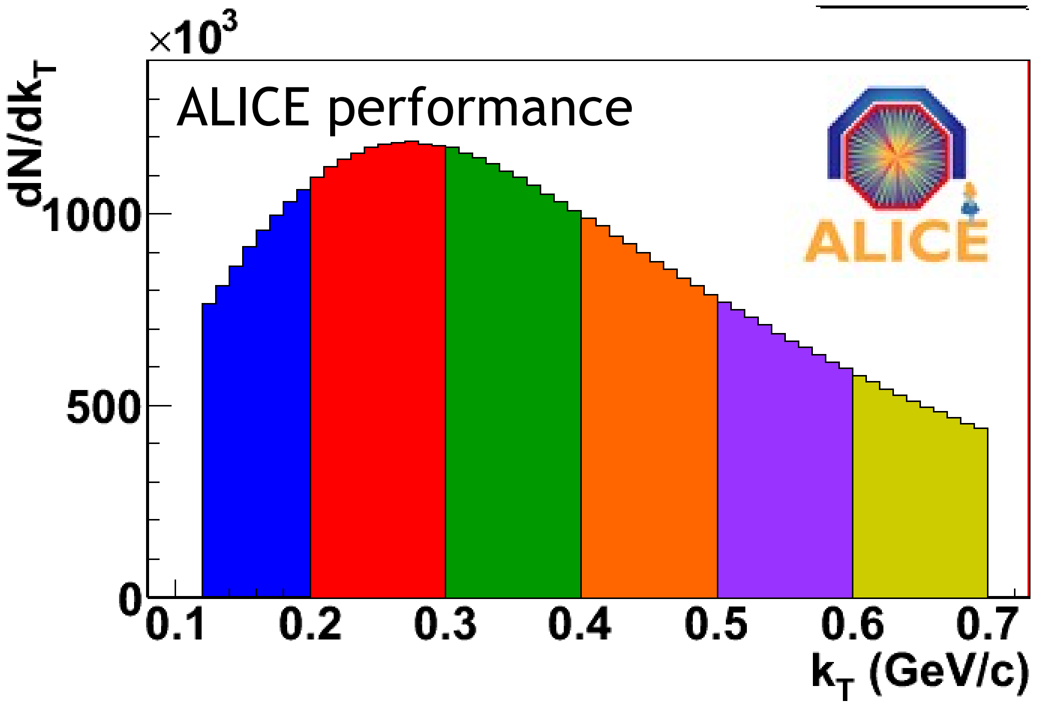
- Analyze primary particles in $|\eta|<0.8$, reconstructed by the combination of the ALICE Time Projection Chamber (TPC) and Inner Tracking System (ITS)
- Particles identified with the TPC dEdx method – small contamination by electrons at low p_T, kaons at high p_T.
- p_T from 120 MeV up to 2 GeV
- Excellent two track resolution of the detector makes two-track effects not a problem

Mutliplicity and k_T selection

- Bins of raw N_{ch} in $|\eta|<0.8$ (#events/#pairs)
  - 1-15: 32M/81M
  - 16-21: 6M/73M
  - 22-26: 3.2M/64M
  - 27-32: 2.3M/69M
  - 33-38: 1.25M/55M
  - 39-50: 990k/64M
  - 51-140: 290K/32M

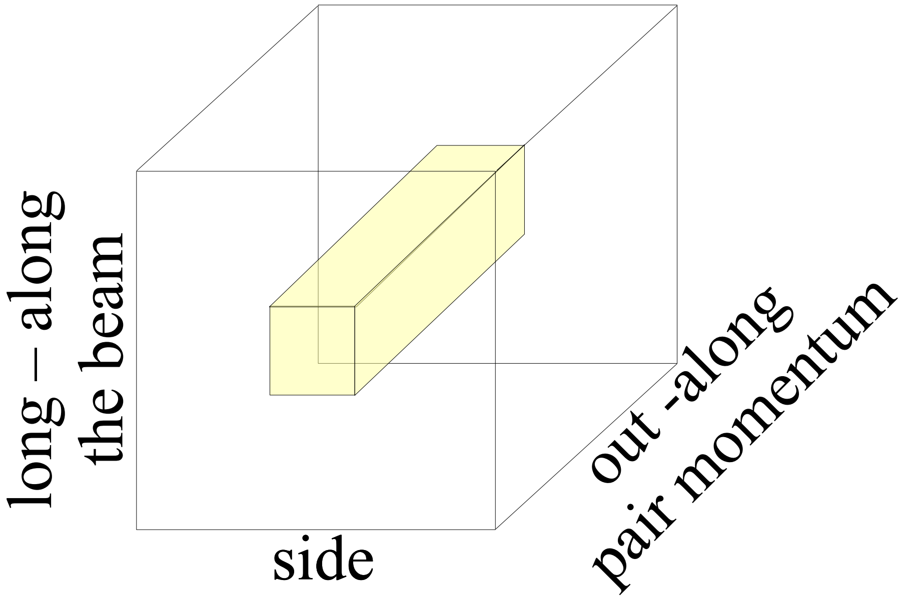


- Bins in pair transverse momentum $k_T=|p_{T,1}+p_{T,2}|/2$
  - (0.12-0.2)
  - (0.2-0.3)
  - (0.3-0.4)
  - (0.4-0.5)
  - (0.5-0.6)
  - (0.6-0.7)

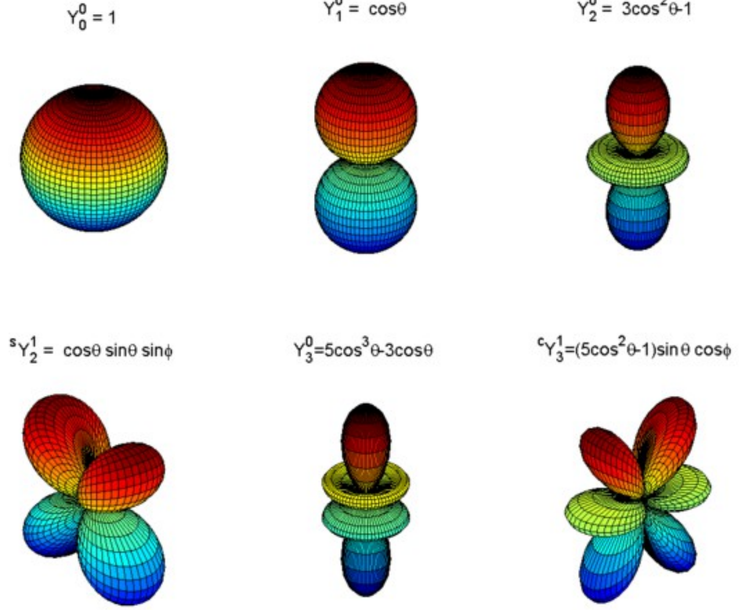


How to show 3D space via 1D plots?

- In traditional 3D cartesian representation one needs to integrate over a range in 1 or 2 directions to get a dependence of the CF on the third direction
- Statistics is diluted – symmetries of identical pair distributions are not exploited fully



- In spherical harmonics the 3D space is converted into infinite set of 1D q_{inv} histograms (Y_l^m components)
- Pair symmetries make most of them vanish, only three important components remain: C_0^0 (the average correlation function), C_2^0 (difference between transverse and long), C_2^2 (difference between out and side)



3D function representations: cartesian vs. spherical harmonics

Data analysis | Real pairs | Mixed pairs

Cartesian

Numerator
3D histo (q_o, q_s, q_l)

Denominator
3D histo (q_o, q_s, q_l)

$$C(q_o, q_s, q_l) = \frac{N(q_o, q_s, q_l)}{sD(q_o, q_s, q_l)}$$

Correlation
3D histo (q_o, q_s, q_l)

Spherical harmonics (histogram fit)

Numerator
3D histo $(q_o, \cos(\theta), \phi)$

Denominator
3D histo $(q_o, \cos(\theta), \phi)$

$$C(q, \cos\theta, \phi) = \frac{N(q, \cos\theta, \phi)}{sD(q, \cos\theta, \phi)}$$

Correlation
3D histo $(q_o, \cos(\theta), \phi)$

For each q fit Y_l^m coef.

Correlation
Set of 1D $Y_l^m(q)$ histos

Spherical harmonics (direct)

Numerator
Set of 1D Y_l^m histos

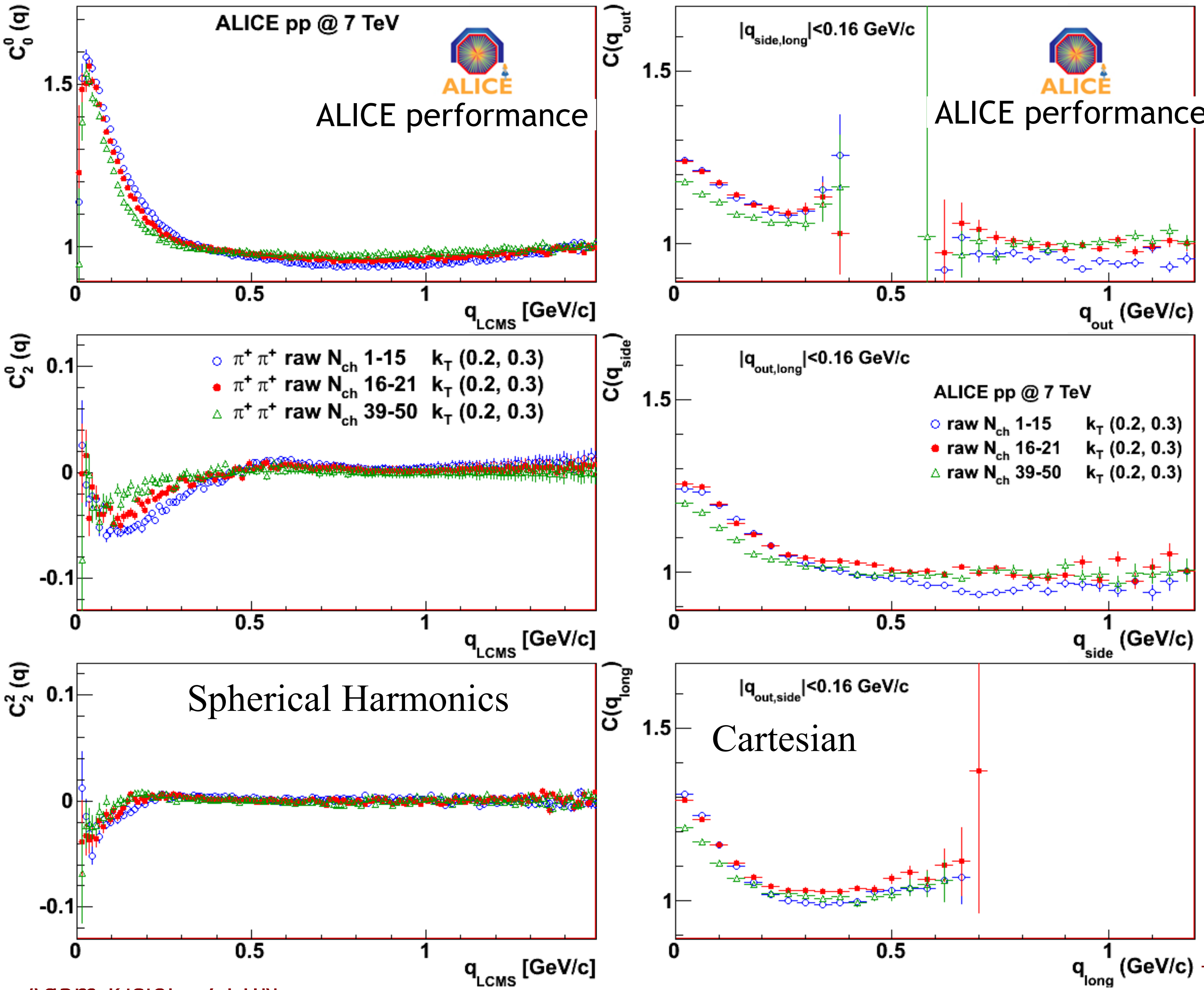
Denominator
Set of 1D Y_l^m histos

$$\boldsymbol{C} = \Delta^2 \boldsymbol{C}\, \tilde{\boldsymbol{D}}^T (\Delta^2 \boldsymbol{N})^{-1} \boldsymbol{N}$$

Phys.Rev.C80:064911,2009.
arXiv:0901.3527 [nucl-th]

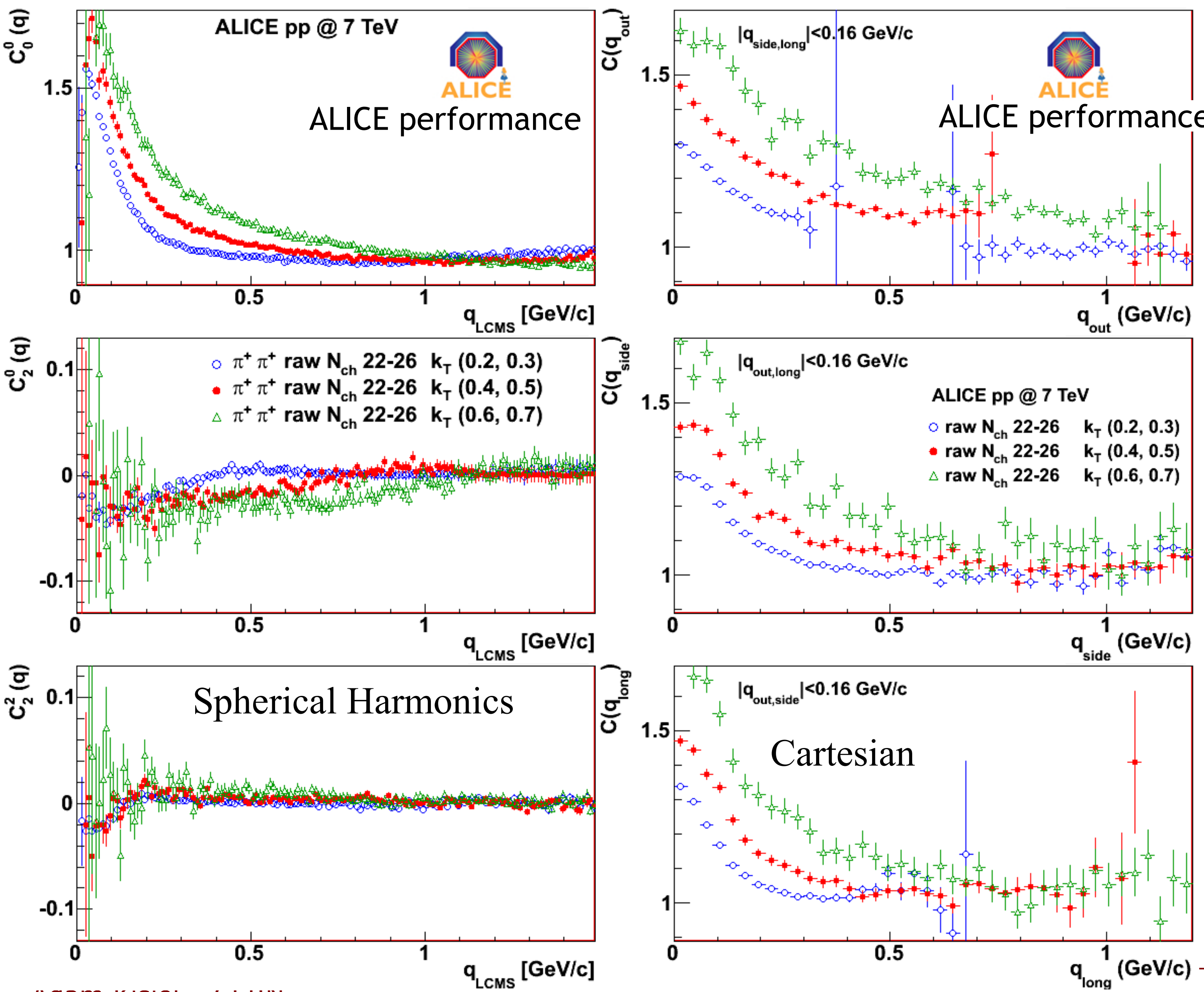
Correlation
Set of 1D $Y_l^m(q)$ histos
+ Y_l^m-Y_l^m covariances

Multiplicity dependence of the correlation function



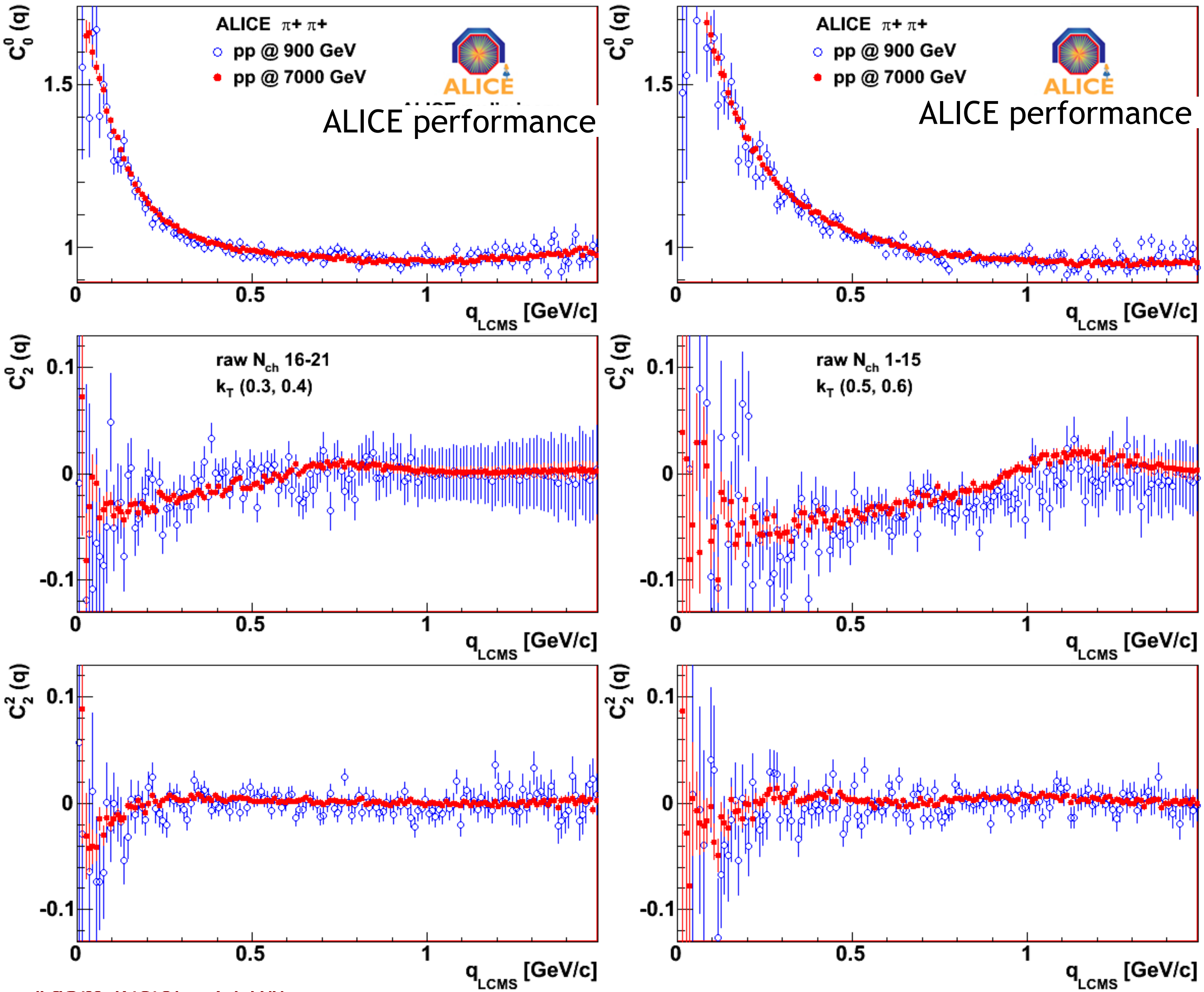
- Dependence of the CF on multiplicity visible, not strong
- Large holes in the acceptance in certain k_T bins
- Consistent behavior for Spherical Harmonics and cartesian CFs

k_T dependence of the correlation function



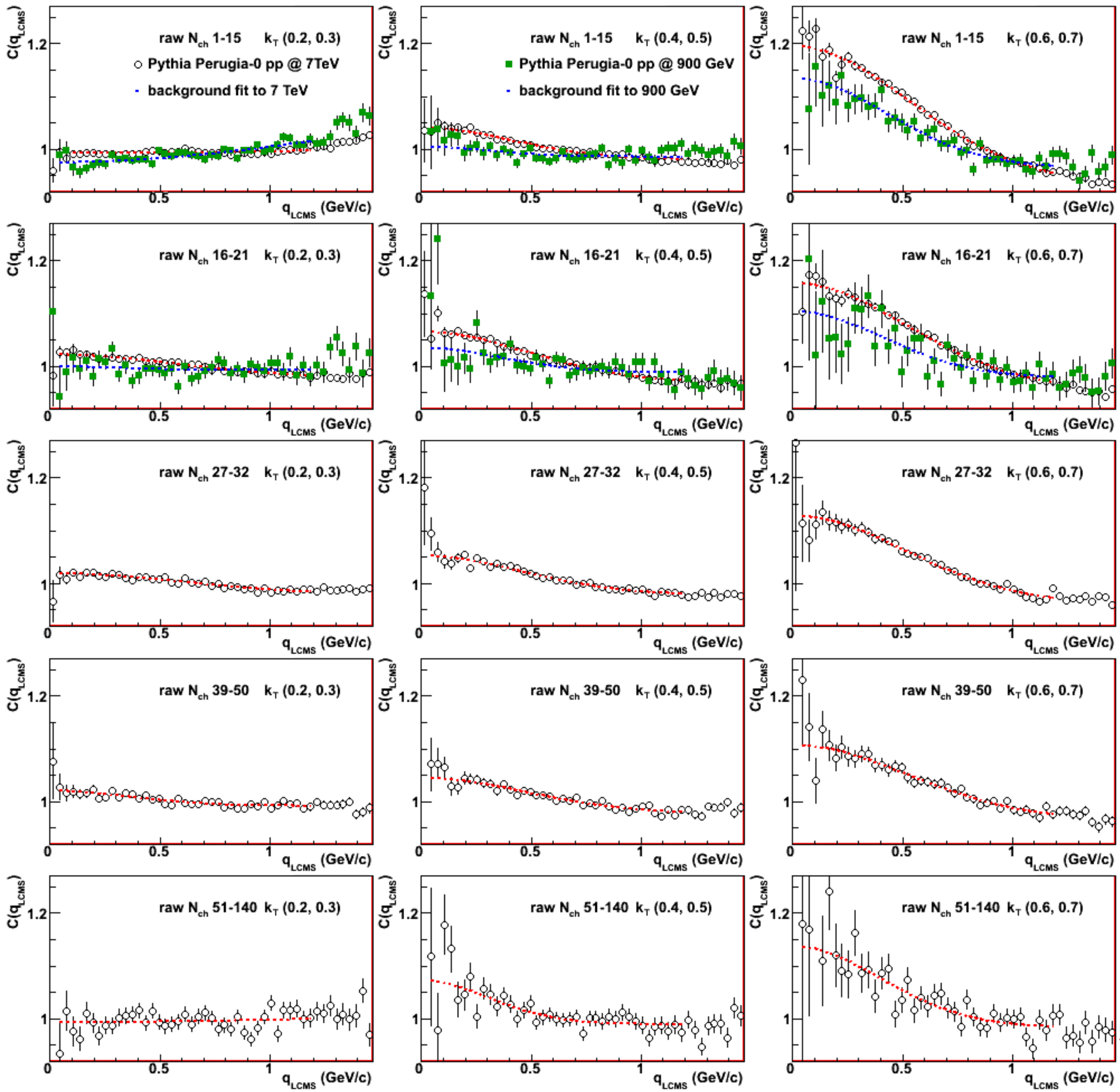
- Dependence on k_T also visible, stonger
- Acceptance holes in the CF depend directly on k_T (kinematics cut effect)
- Spherical Harmonics and cartesian qualitatively consistent

Energy dependence of the correlation function



- Correlation functions for 900 GeV and 7 TeV, for same multiplicity and k_T bins similar
- 3D shape (C20 and C22 components) also consistent
- Checked all multiplicity/k_T bins - all similar

Why is the baseline not flat? Comparing to Pythia (Perugia-0)



- MC background fitted with the assumption that it is described by 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
- Less background in 900 GeV

Better handle on the background

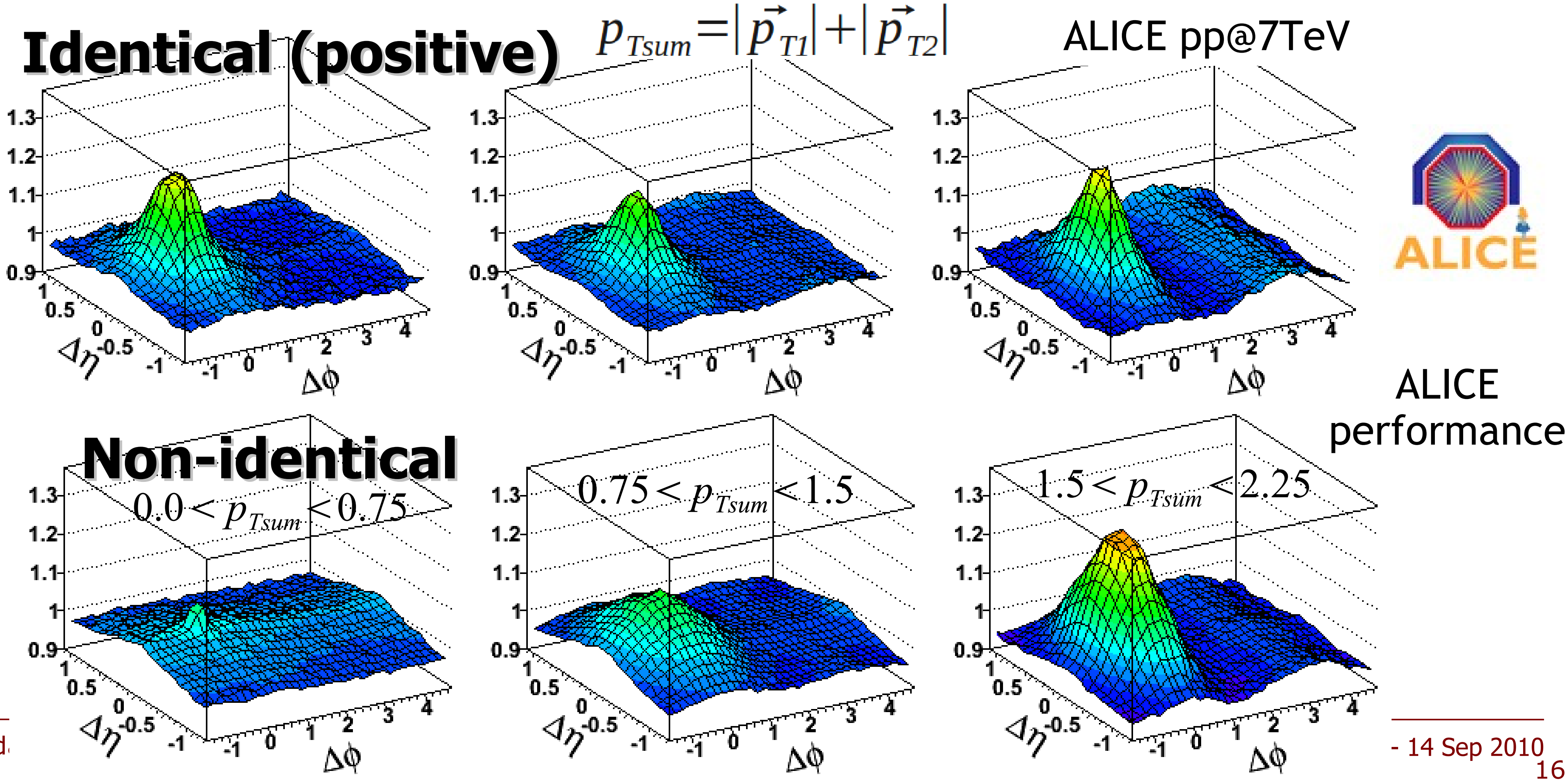
- Current hypothesis for the background origin: “mini-jets”
- “Mini-jets” are usually measured with un-triggered and triggered pair correlations vs. pseudorapidity $\Delta\eta$ and azimuthal angle difference $\Delta\varphi$
- There is direct connection between $\Delta\eta$, $\Delta\varphi$ and components of relative momentum q_{inv}

$$q_{out} \sim p_{T,1} - p_{T,2} \qquad q_{side} \sim \left(p_{T,1} + p_{T,2}\right) \Delta\phi \qquad q_{long} \sim \left(p_{T,1} + p_{T,2}\right) \Delta\eta$$

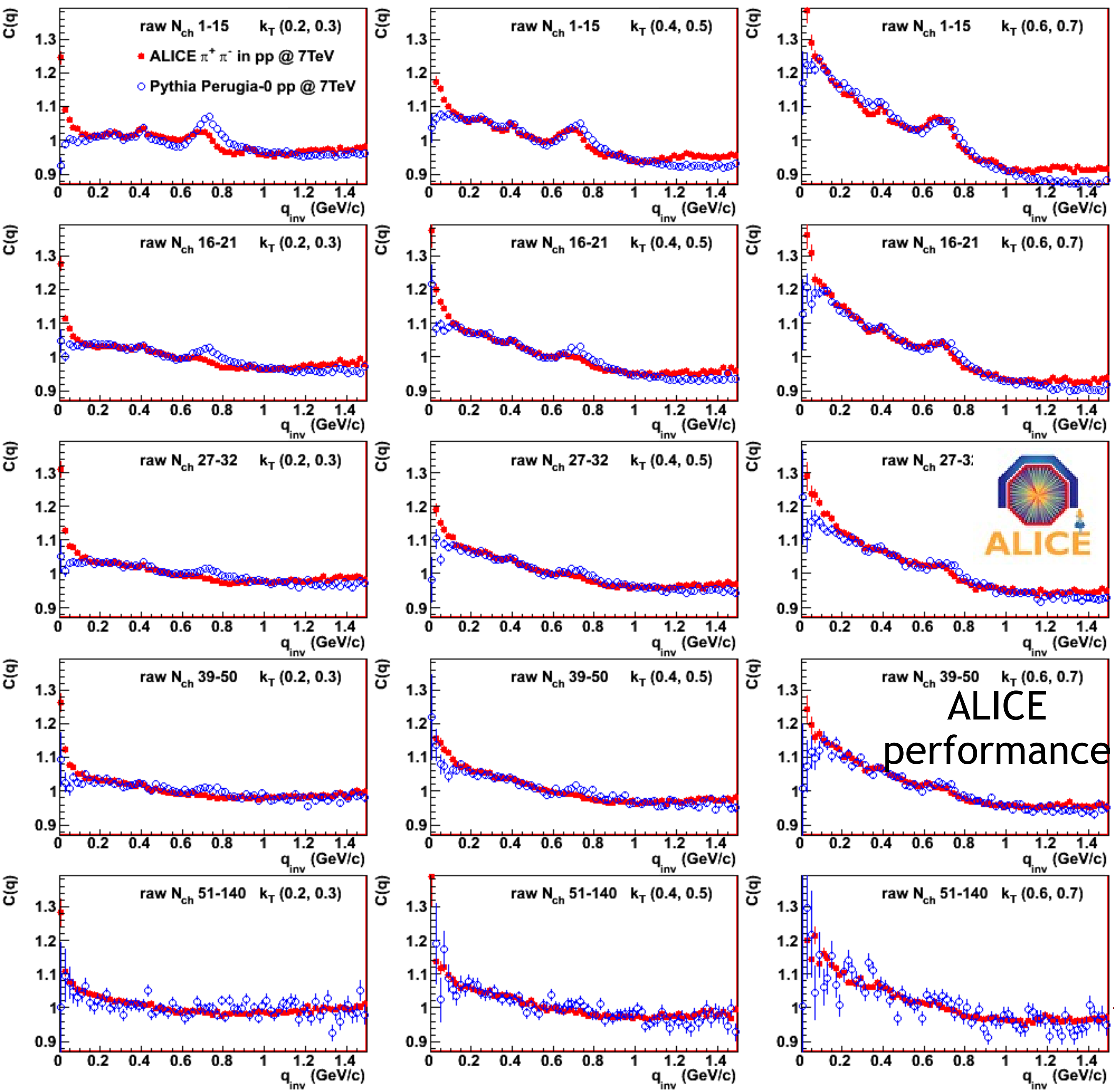
- Low $\Delta\eta$, $\Delta\varphi$ correspond to low q_{inv} (where femtoscopic effect is), but this relation gets more diluted, as p_{T} sum grows
- One expects that femtoscopic effect will be seen for identical-charge pairs, but not for non-identical, where only mini-jets and resonance pairs will contribute

Characterizing mini-jet correlations

- “femtoscopic effect” expected only in identical charge combinations, going away with increasing p_{T} sum
- Mini-jet-like correlations expected to be stronger for non-identical

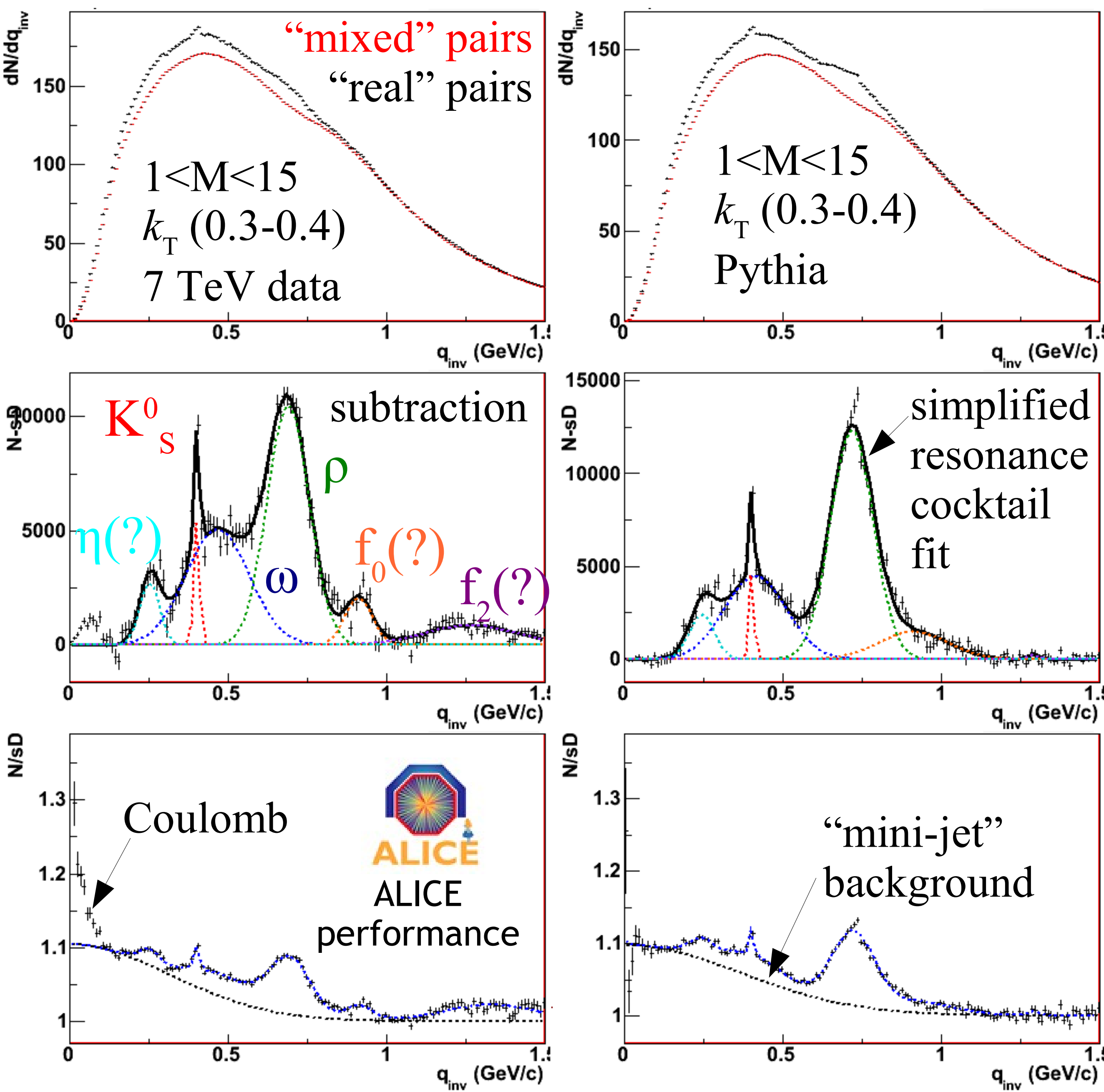


Background cross-check – π+ π-



- 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
  - Is it really resonances ?

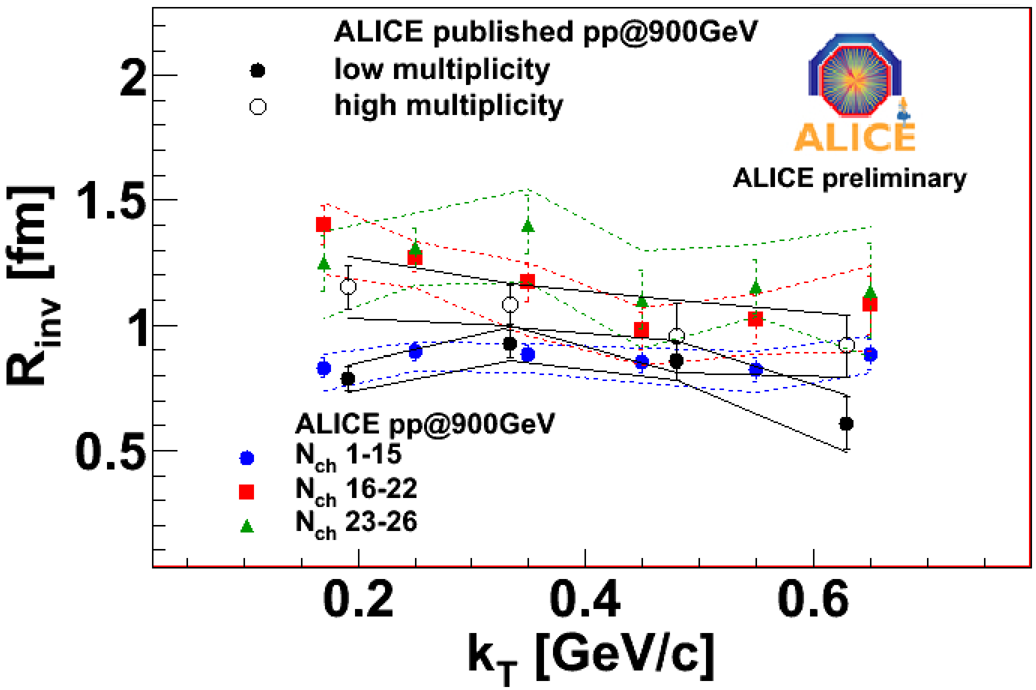
Resonance structures: Data vs. MC

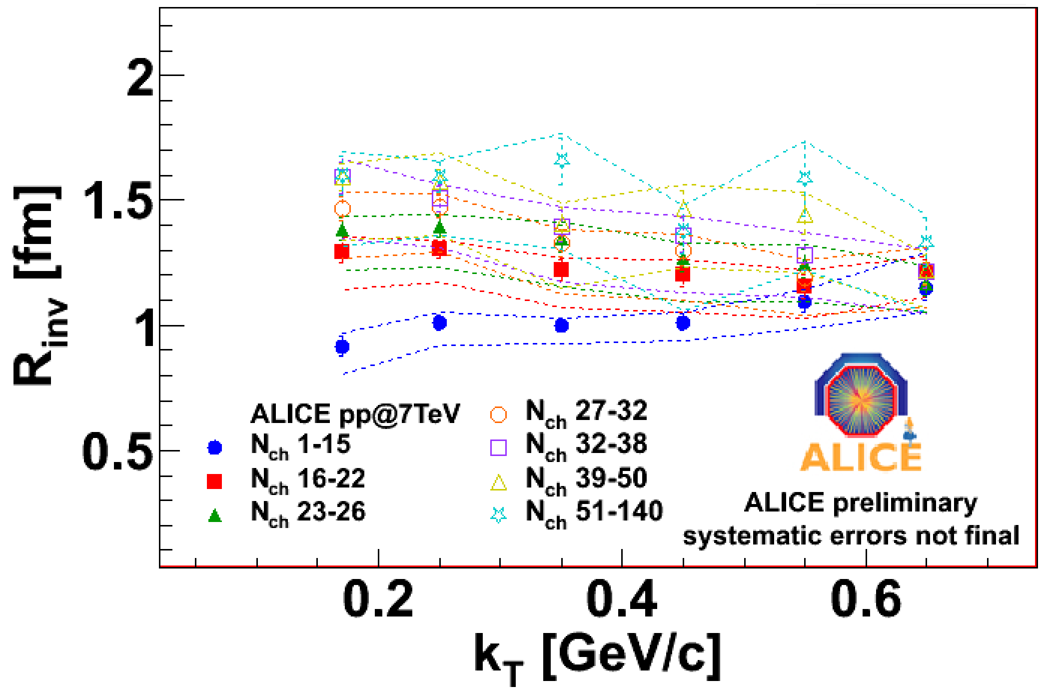


- Different resonance widths
- ρ is shifted by 40 MeV, f_0, f_2 small in MC
  - Pythia does not take into account phasespace and rescattering
- "Underlying event" background similar
- MC good for baseline for identical pairs, not for non-identical

HBT 1D radius

- 1D R_{inv} radii (in Pair Rest Frame), done with 1[st] paper methods, consistent between published and new 900 GeV data
- 7 TeV radii similar but slightly larger
- Growth of R_{inv} with multiplicity at 7TeV continues





Fitting a 3D CF

- Pair emission function comes from single-particle functions:

$$S(\boldsymbol{r}) = \int S_1(\boldsymbol{x_1}) S_1(\boldsymbol{r} - \boldsymbol{x_1}) d\boldsymbol{x_1}$$

- 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 $1+\cos(q\boldsymbol{r})$. Usually S is Gaussian, giving the femtoscopic part of CF:

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

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

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

$$C = N\left[(1-\lambda) + \lambda K \left(1 + \exp(-R_o^2 q_o^2 - R_s^2 q_s^2 - R_l^2 q_l^2)\right)\right]\left(1 + \beta \exp(-R_B^2 (q_o^2 + q_s^2 + q_l^2))\right)$$

Generalized 3D fit function

- 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 femtoscopic part of the correlation function

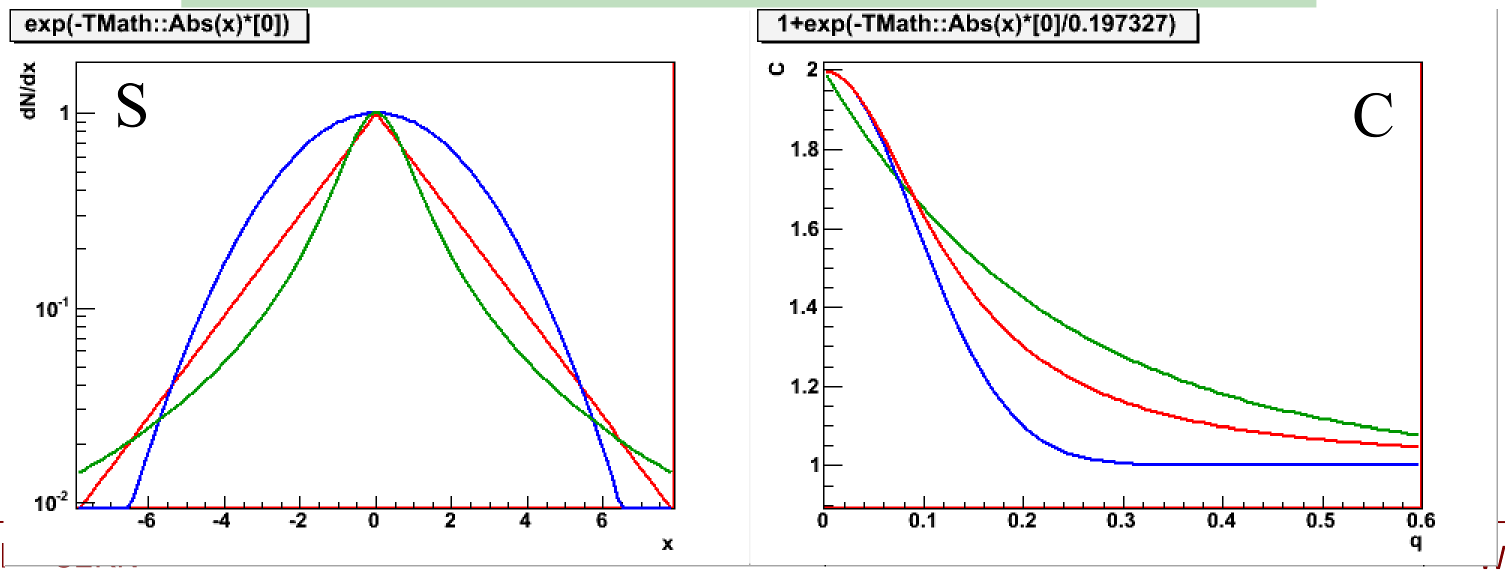
$$C(q_{out}, q_{side}, q_{long}) = 1 + \lambda C_o(q_{out}) C_s(q_{side}) C_l(q_{long})$$

- Where S-C correspondence is as follows:

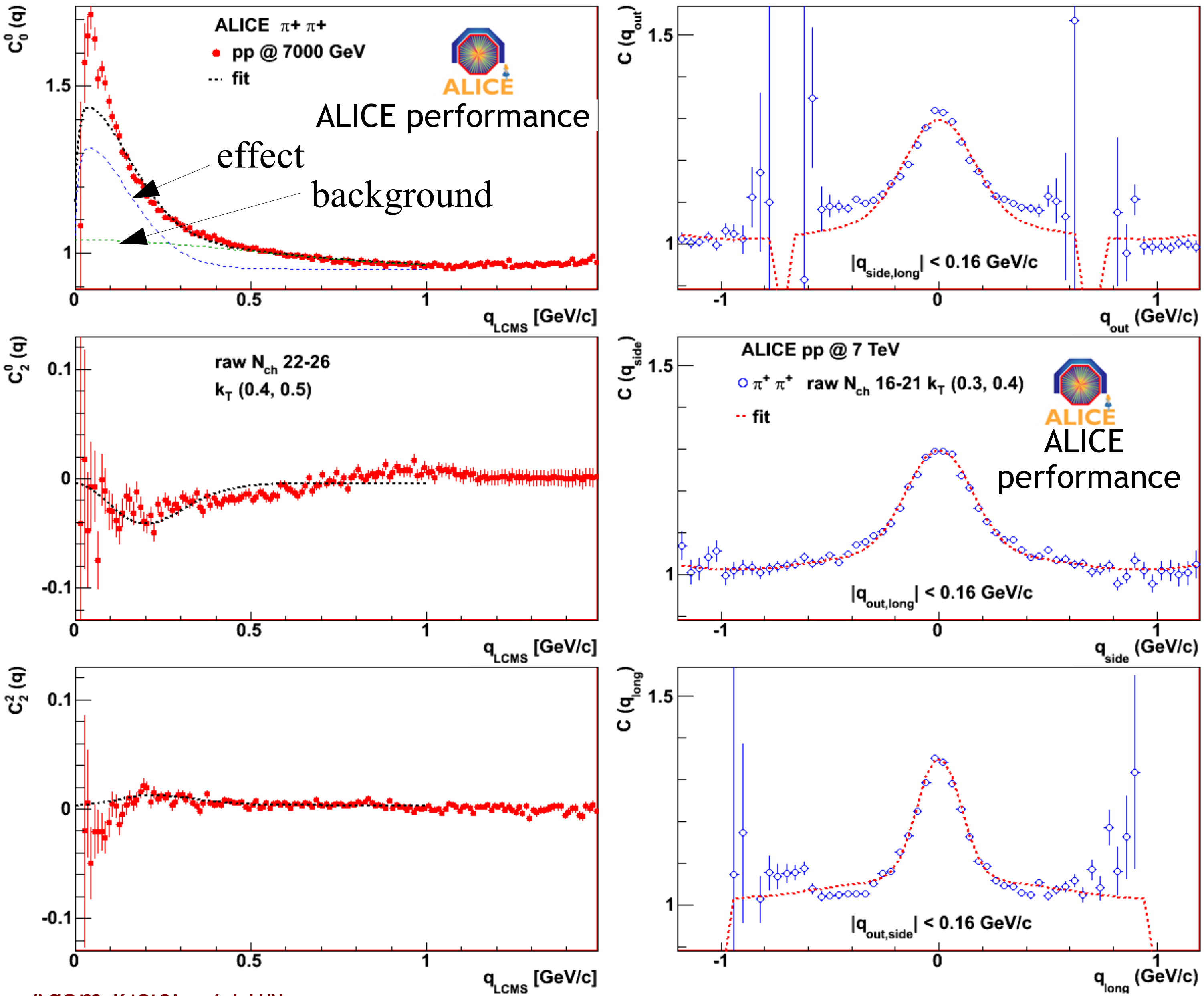
$$S(x) = \exp(-x^2/2R^2) \quad \text{->} \quad C(q) = 1 + \exp(-q^2 R^2)$$

$$S(x) = \exp(-|x|/R) \quad \text{->} \quad C(q) = 1 + 1/(R^2 q^2 + 1)$$

$$S(x) = 1/(R^2 x^2 + 1) \quad \text{->} \quad C(q) = 1 + \exp(-q R)$$

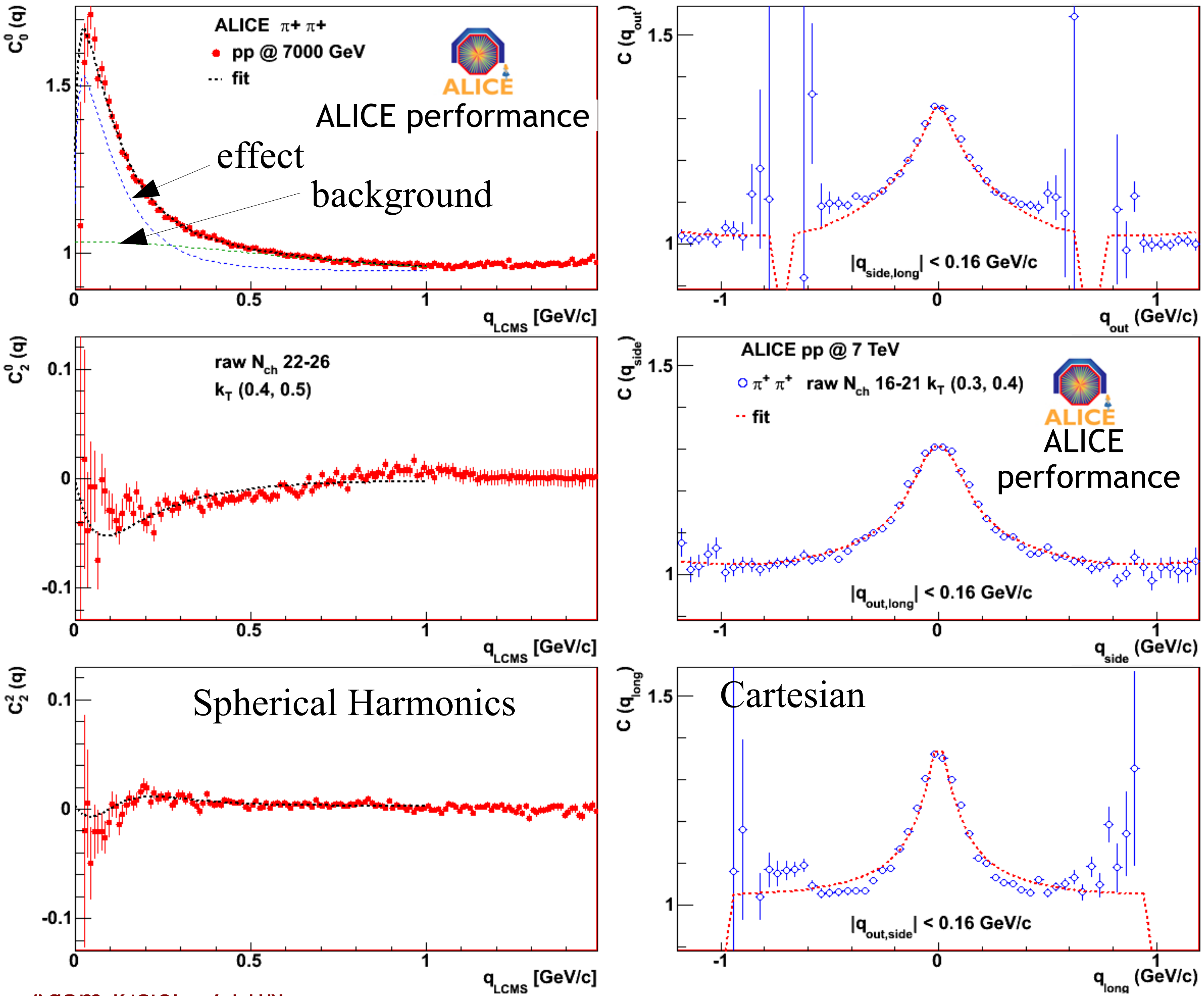


3D Fitting example: Gaussian



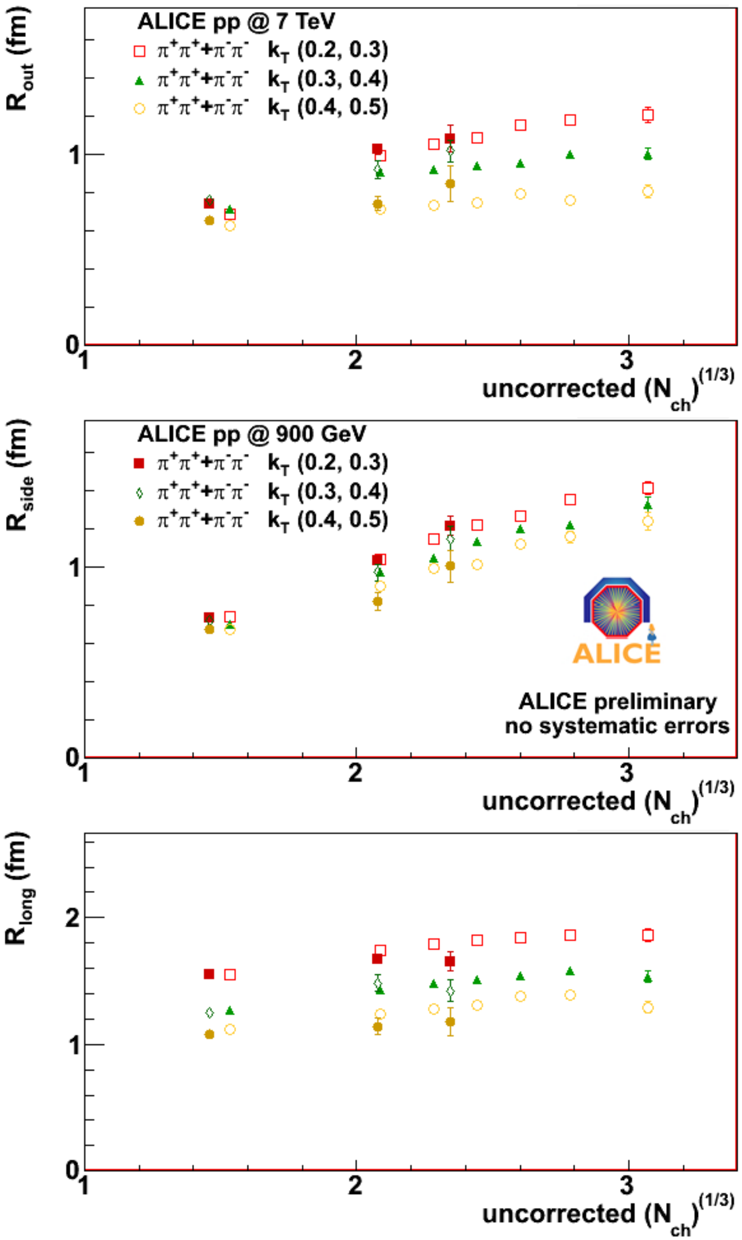
- Background β and R_{B} fixed to the values fitted to MC
- Fit undershoots at low q (Gaussian not good enough)
- Width reasonably described
- Out/side/long radii can be obtained both from SH and cartesian fits

3D non-gaussian fit example



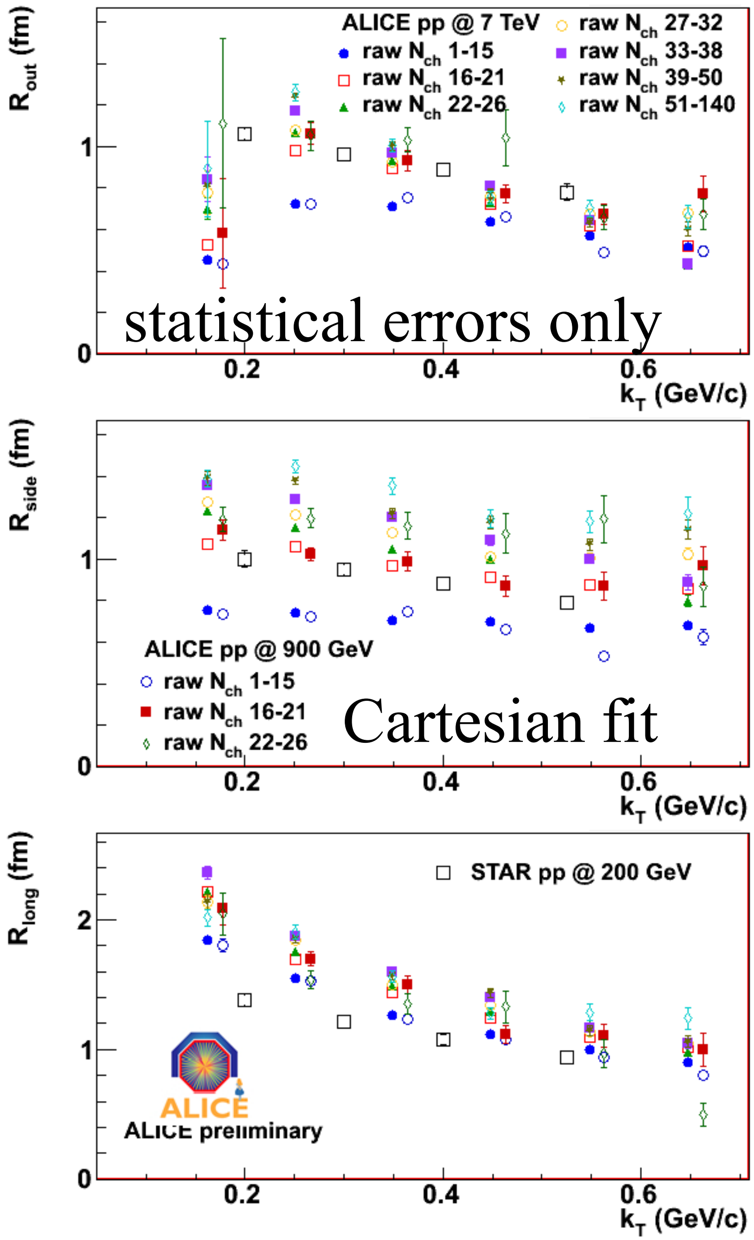
- Exponential-Lorentzian-Exponential fit is best or second-best for all k_T/multiplicity bins, χ^2/Ndof comparable to 1.0
- Specific features of the correlation function captured:
  - Steep rise of the CF at low q
  - Additional structures in the C_2^0 and C_2^2 SH components

Multiplicity dependence of gaussian radii



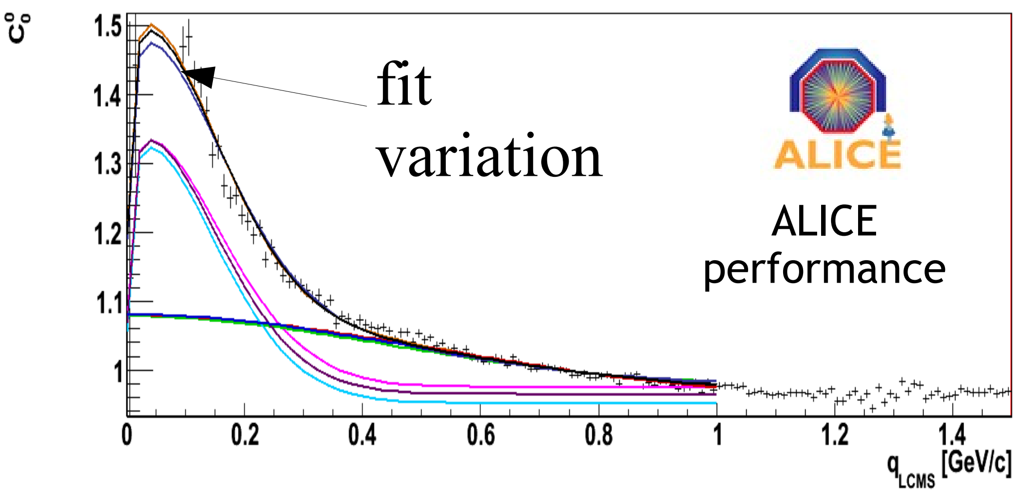
- Test if the data scales linearly with $\mathrm{d}N/\mathrm{d}\eta^{1/3}$ for all energies, separately for each k_{T} bin.
- Very rough estimate of $\mathrm{d}N/\mathrm{d}\eta$ used for this plots – uncorrected number of charged primaries in one unit of pseudorapidity
- Multiplicity scaling is visible for all k_{T}, all directions
- 900 GeV data seem to follow similar trend as 7 TeV

Gaussian radii at 900 GeV and 7 TeV

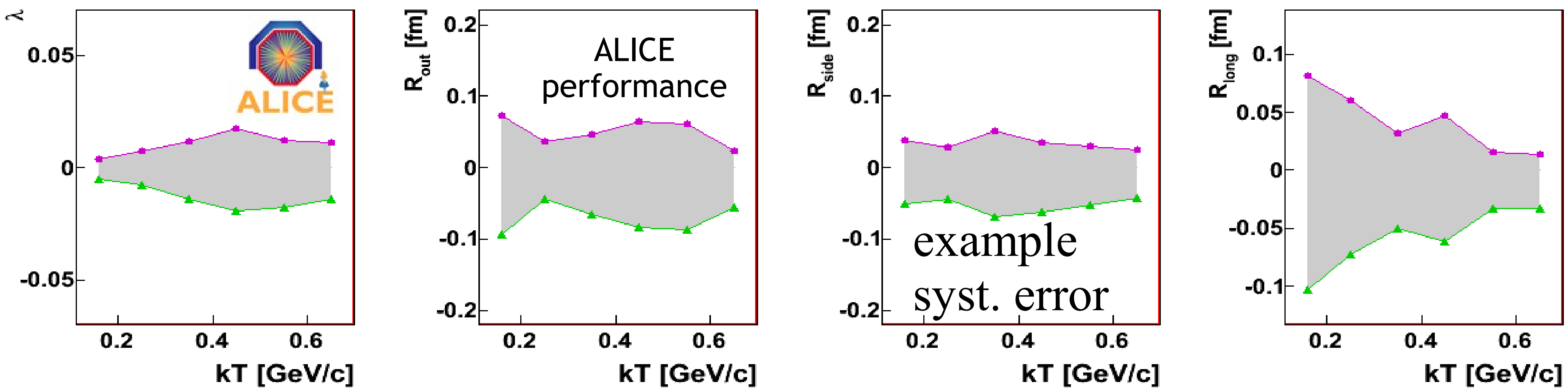


- Gaussian radii in LCMS grow with multiplicity, fall with k_T
- Fall with k_T very prominent for R_{long} , develops with multiplicity for R_{out} , less pronounced for R_{side}
- Radii comparable to STAR (EMCICs fit), but not clear which STAR fit to take for comparisons
  - Transverse size similar to the one at ALICE at similar multiplicity
  - Longitudinal size seems to be larger in ALICE – depends on energy in addition to multiplicity?

Systematic error estimation



- Systematic error coming from the background estimation evaluated with:
  - Changing the width and magnitude by +/- 10%
  - Using Pythia and Phoject
- Change fitting range



Summary

- ALICE has measured pion femtoscopic correlation functions at 900 GeV and 7 TeV, providing a link between multiplicities in pp and heavy-ions at RHIC
- ALICE observes dependence of the correlation function on multiplicity and strong dependence on the pair momentum
- Significant non-femtoscopic correlations are present, strong in 900 GeV, stronger in 7TeV, 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 describe the full behavior.
- Taking into account 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.
- Full systematic analysis vs. energy vs. event multiplicity and vs. pair momentum ongoing.