# RNM Meeting 2011

FIAS Frankfurt, Germany

# One year of HBT in ALICE

## an overview

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A Large Ion Collider Experiment

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TECHNISCHE UNIVERSITÄT DARMSTADT

HGS-HIRe for FAIR
Helmholtz Graduate School for Hadron and Ion Research

# two particle correlations in pp at sqrt(s) = 900 GeV

## 1 dimensional

# motivation

- measuring space-time dimensions in pp collisions at sqrt(s) = 900 GeV with ALICE
  - using Bose-Einstein enhancement of identical pion pairs to get access to size of pion emitting source
- investigating collective behaviour in pp collisions at LHC energies
  - dependance of source size as function of event multiplicity $dN_{CH}/d\eta$ and transverse momentum $k_T$
- reference for long p+p run in 2010 and heavy ion measurements starting in November 2010

# HBT – Bose-Einstein correlations

„The only way to get access to space-time properties of the emitting source in elementary particle collisions is through the measurement of Bose-Einstein correlations (BEC) between identical pions“

*(U.Heinz,Ohio)*

- **building the correlation function (CF)**

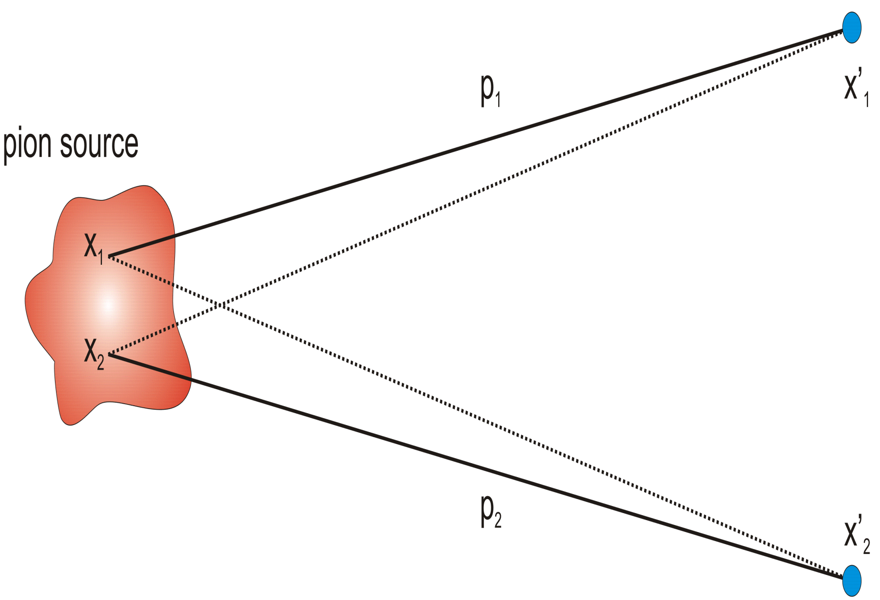
$$C_2(p_1,p_2)=\frac{P(p_1,p_2)}{P(p_1)P(p_2)}$$

- **transformation in relative momenta q**

$$q=\sqrt{-(p_1-p_2)^2}=\sqrt{m_{Inv}^2-4m_\pi^2}$$

- **correlation function in the experiment**

$$C_2(q)=\frac{A(q)}{B(q)}$$

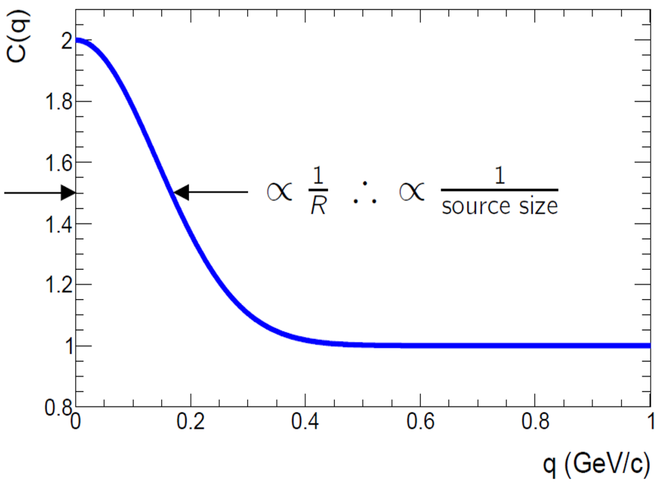



A(q) is the measured distribution of the pair momentum difference q, whereas B(q) is a reference distribution build by using pairs of particles from different events (event-mixing) or by rotating on particle of the pair in the transverse plane (rotation)

**Reference distribution should be without Bose-Einstein correlations**

# extracting the HBT radii

**To get the HBT-radii out of the correlations one has to use a proper parametrization**



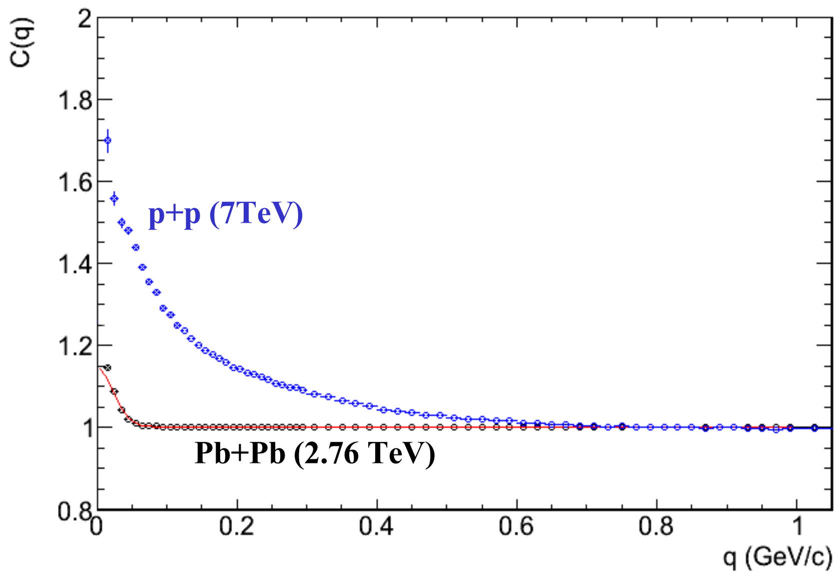

**If one assumes that the source function has a Gaussian shape the parametrization has also a Gaussian shape**

**A common parametrization is the following**

$$C_2(q) = 1 + \lambda \exp(-(Rq)^2)$$

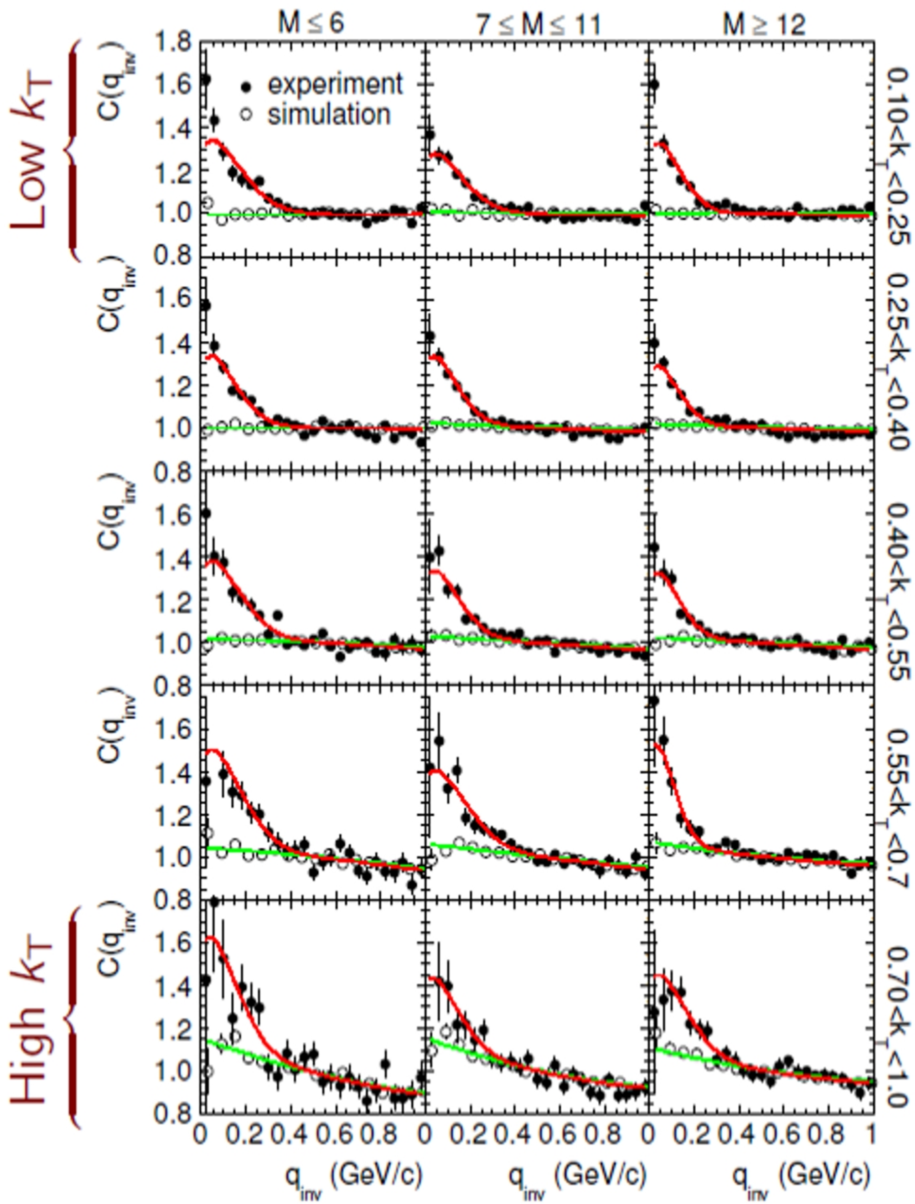
**R is the effective size of the emission region**

**λ is a parameter measuring the strength of the Bose-Einstein correlation**




**HBT in pp at sqrt(S) = 7 TeV will provide an interconnection between small systems (pp) and heavy systems (AA) at lower energies**

# correlation of identical pions at sqrt(s) = 900 GeV



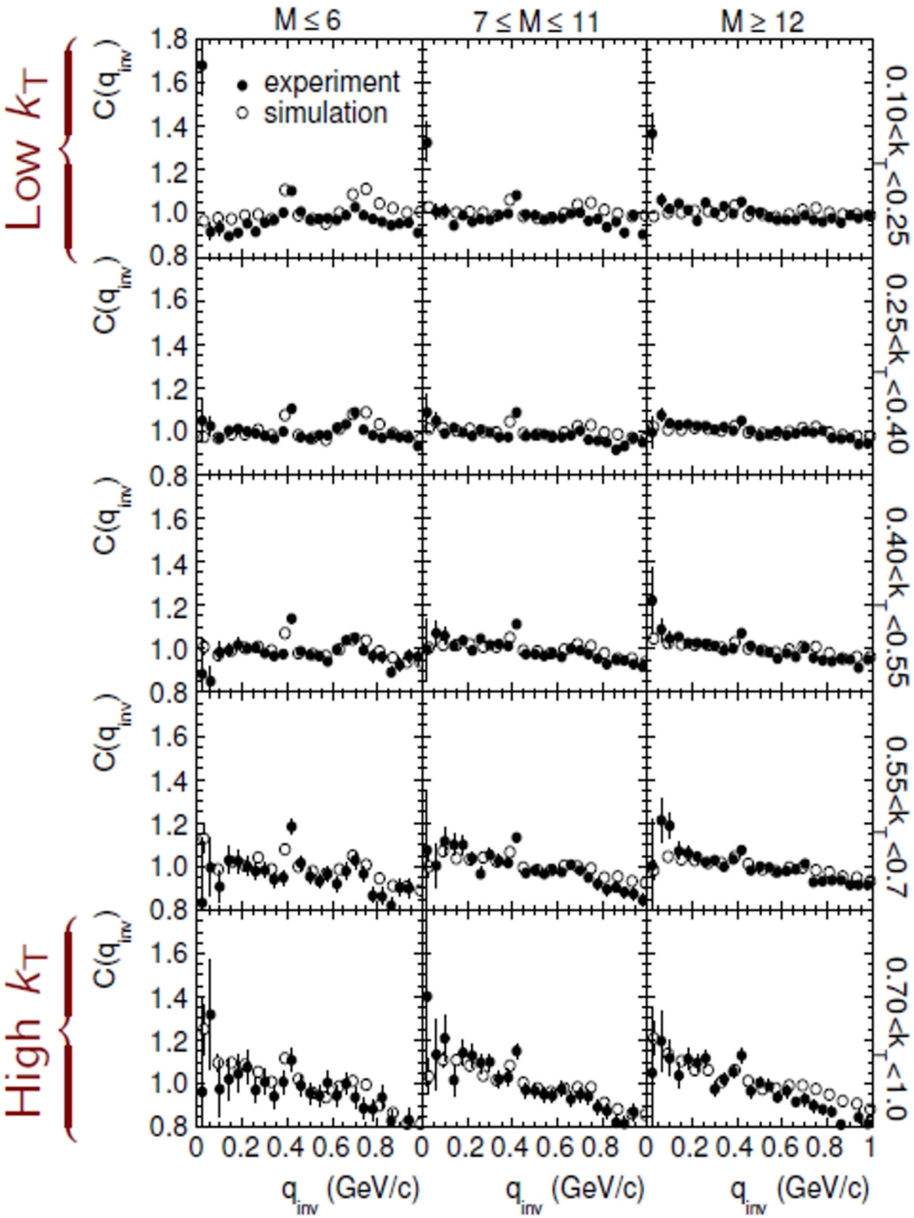

- $\pi^+\pi^-$ correlations in one dimension
- 2009 data not enough statistics for 3D
- 3 bins in event multiplicity
- 5 bins in transverse momentum
- Bose-Einstein effect clearly visible
- fixing the baseline with simulations (see next slide)
- used parametrization

$$C_2(q_{Inv})=((1-\lambda)+\lambda K(q_{Inv})\cdot(1+\exp(-(R_{Inv}q_{Inv})^2)))D(q_{Inv})$$

- developing of long range correlations with increasing $k_T$

**Phys. Rev. D 82, 052001 (2010)**

# correlation of non-identical pions at sqrt(s) = 900 GeV




- $\pi^+\pi^-$ correlations in comparison with PHOJET simulations
- description of the background of the CF
- rich spectrum of meson resonances
- Coulomb effect in the first bins

- using the background of the CF for the parametrization of the CF of identical pions

- proper treatment of baseline very important when studying the dependance of the radii from transverse momentum and multiplicity

- parametrization of the background

$$D(q_{Inv}) = a + bq_{Inv} + cq_{Inv}^2$$

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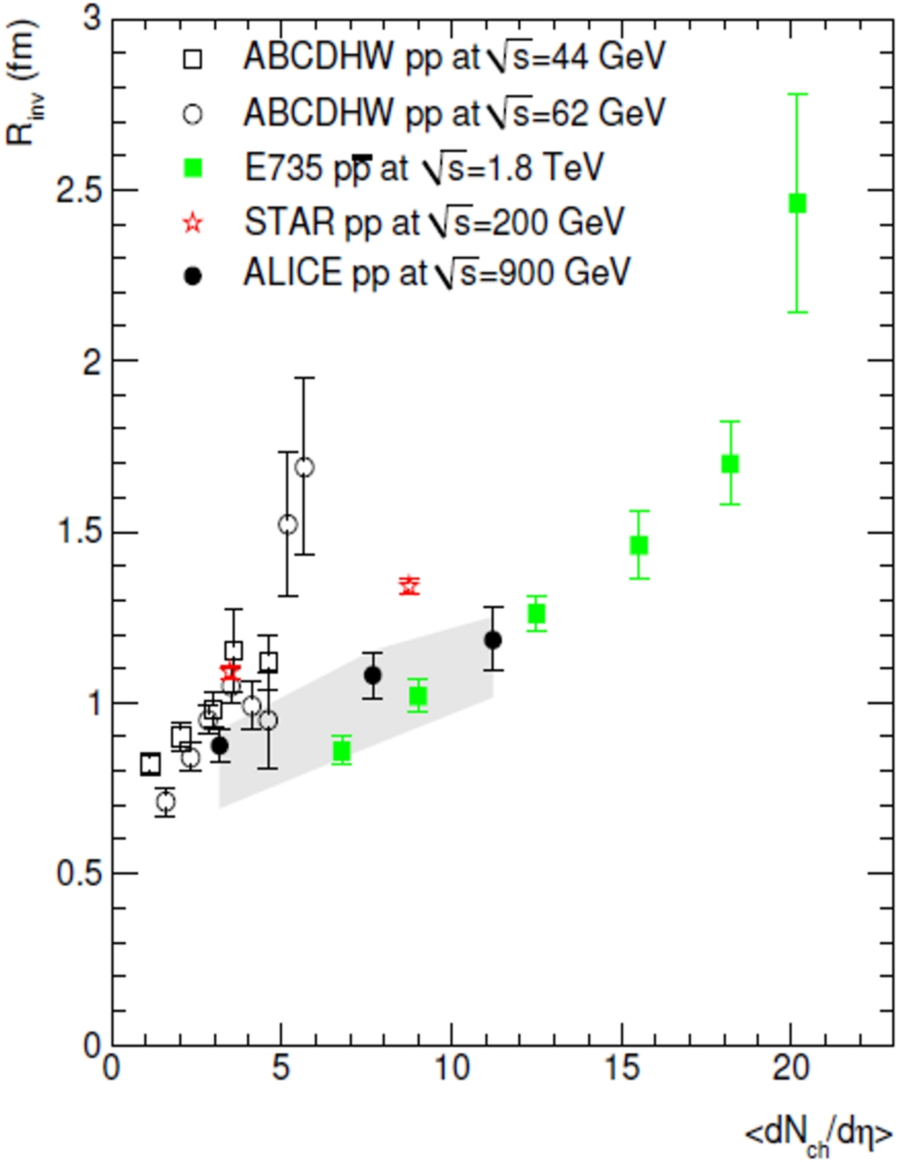
# multiplicity dependance

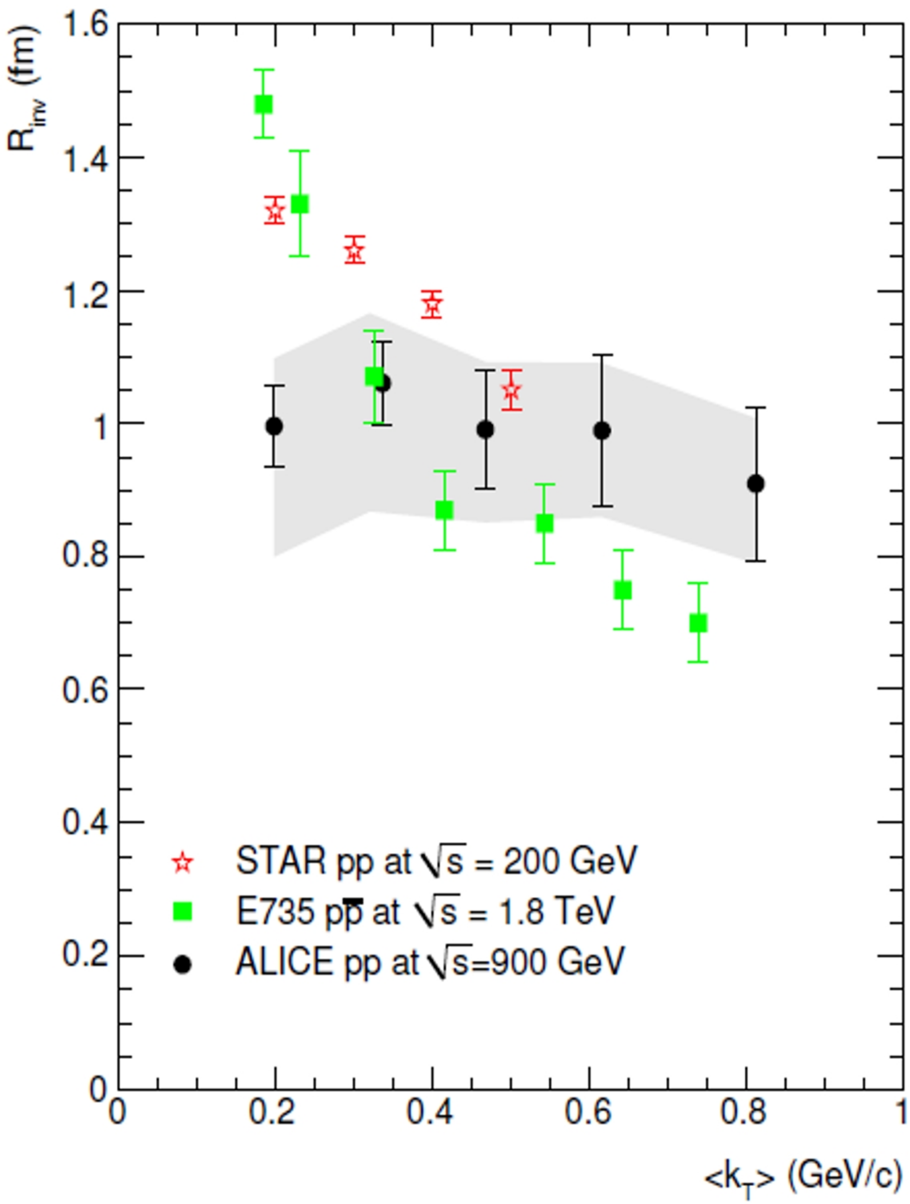



- HBT radii increase with multiplicity
- same dependance like older measurements
- HBT radii seem to depend more on multiplicity than on geometry (pp)

- grey shadowed band (systematic error)

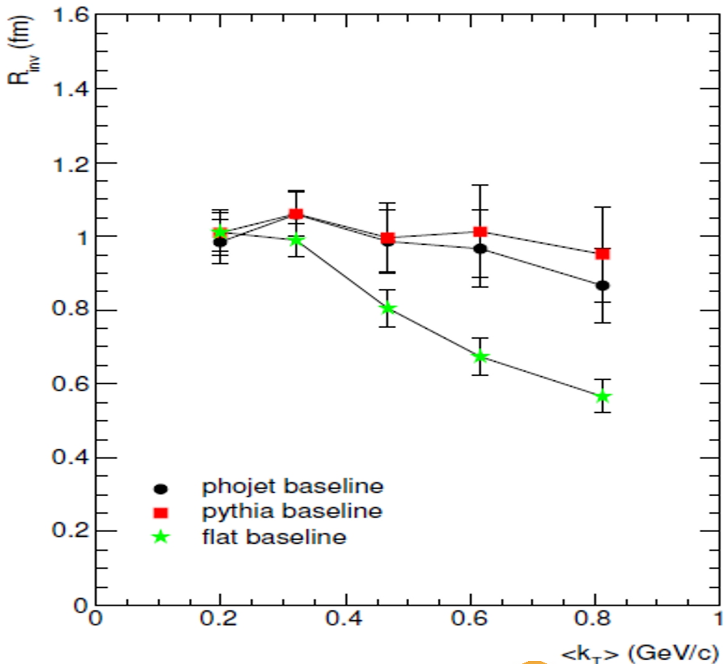
  Systematic error from:
  - baseline assumption
  - fitting
  - background construction
  - UNICOR vs. ALIFEMTO

# $k_T$ dependance - baseline




- **HBT radii independant of $k_T$**
- **no sign of collective behaviour (presence of a bulk) in pp at 900 GeV**

- **very sensitive to baseline assumption**
- **if fitted free (flat baseline) – dependance emerges**



## parametrization with a Gaussian

$$C_2(q_{Inv})=((1-\lambda)+\lambda K(q_{Inv})\left[1+\exp(-(R_{Inv}q_{Inv})^2)\right])\cdot D(q_{Inv})$$

| $dN_{CH}/d\eta$ | λ | $R_{Inv}$/fm |
|---|---|---|
| 3.2 | 0.386 (0.022) | 0.874 (stat 0.047) (sys 0.181) |
| 7.7 | 0.331 (0.023) | 1.082 (stat 0.068) (sys 0.206) |
| 11.2 | 0.310 (0.026) | 1.184 (stat 0.092) (sys 0.168) |

## parametrization with an exponential

$$C_2(q_{Inv})=\left[1+\lambda\exp(-R_{Inv}q_{Inv})\right]\cdot D(q_{Inv})$$

| $dN_{CH}/d\eta$ | λ | $R_{Inv}$/fm |
|---|---|---|
| 3.2 | 0.704 (0.048) | 0.808 (stat 0.061) (sys 0.208) |
| 7.7 | 0.577 (0.054) | 0.967 (stat 0.095) (sys 0.206) |
| 11.2 | 0.548 (0.051) | 1.069 (stat 0.104) (sys 0.203) |

## results (part 2)

- observation of HBT enhancement in first LHC p+p data at sqrt(s) = 900 GeV
- HBT radii increase with multiplicity
- HBT radii dependance on pair momentum $k_T$ not significant (contrary to other experiments)
- pair momentum dependance highly sensitive to baseline assumption

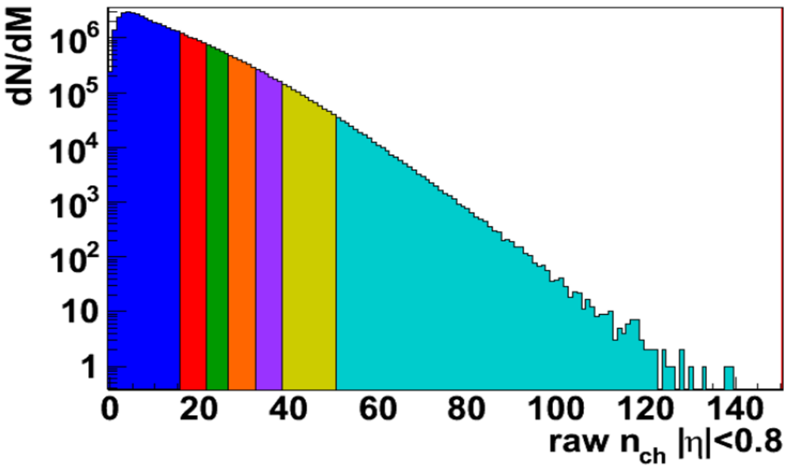
# two particle correlations in pp at sqrt(s) = 7 TeV

1 dimensional

3 dimensional

# motivation

- measuring space-time dimensions in pp collisions at sqrt(s) = 900 GeV and at sqrt(s) = 7 TeV at ALICE
  - using Bose-Einstein enhancement of identical pion pairs to assess size of pion emitting source
- investigating collective behaviour in pp collisions at LHC energies
  - dependance of source size as function of event multiplicity $dN_{CH}/d\eta$ and transverse momenta $k_T$
- more statistics makes it possible to go into more than one dimension
  - cartesian parametrization in out, side and long (Bertsch-Pratt)
  - expansion in spherical harmonics




- getting deeper into the physics of the system
  - difference between 900 GeV and 7 TeV
  - understanding the background – non BE correlations – EMCIC
  - no Gaussian shape of the CF
  - collective behaviour of the pion emitting fireball

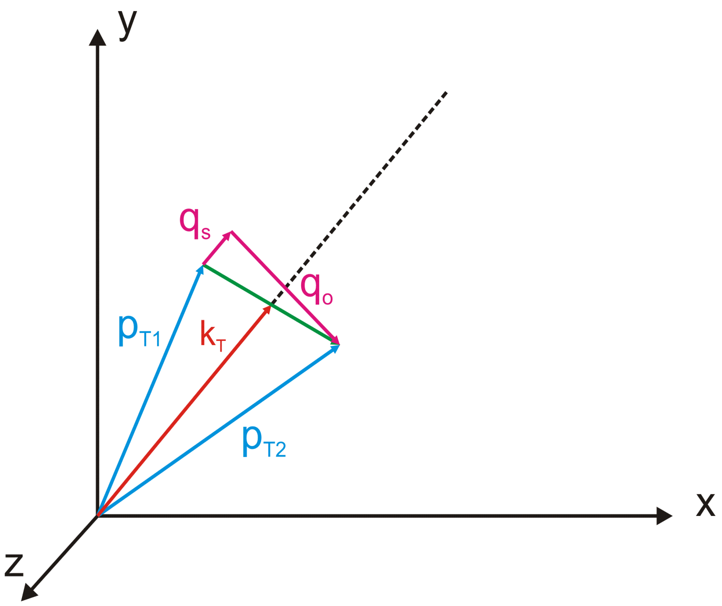
# extracting the HBT radii in three dimensions (part 1)

To get the HBT-radii out of the correlations one has to use a proper parametrization

If one assumes that the source function has a Gaussian shape also the parametrization has a Gaussian shape

A common parametrization was introduced by Bertsch and Pratt

$$C_2(q_o, q_s, q_l) = \left[(1-\lambda) + \lambda K (1 + \exp(-(R_o q_o)^2 - (R_s q_s)^2 - (R_l q_l)^2)\right] (1 + \beta \exp(-R_B^2 (q_o^2 + q_s^2 + q_l^2)))$$




$q_l$ in longitudinal direction.

$q_o$ in the direction of the $k_T$

$q_s$ perpendicular to $q_o$

second Gaussian describes the non-femtoscopic background

$\lambda$ is a parameter measuring the strength of the Bose-Einstein correlation

Longitudinal CoMoving System (LCMS)

better parametrization of the data using an exponential function

Assumption that the emission function factorizes into out, side and long

$$S(r) = S_o(r_o) \cdot S_s(r_s) \cdot S_l(r_l)$$

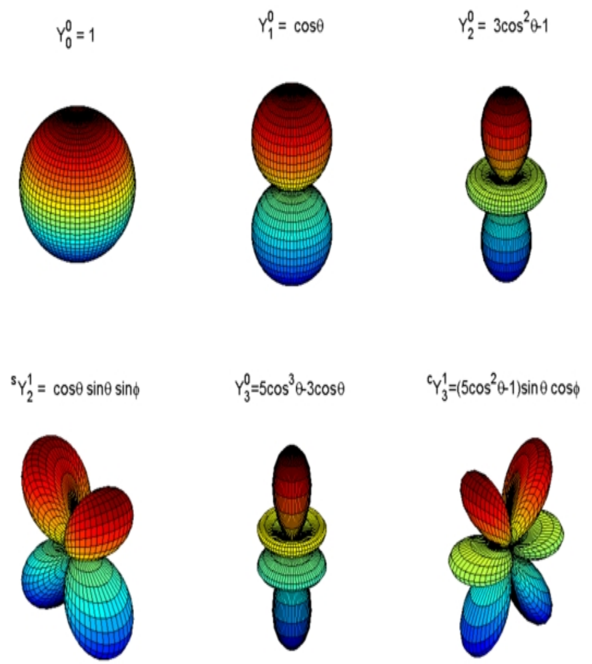
# extracting the HBT radii in three dimensions (part 2)

**assumption of an exponential emission in out and long**

$$S(r)=\frac{1}{r_o^2+R_o^{E^2}}\exp\left(-\frac{r_s^2}{4R_s^{E^2}}\right)\frac{1}{r_l^2+R_l^{E^2}}$$

**leads to an exponential parametrization**

$$C_2(q_o,q_s,q_l)=1+\lambda\exp\left(-\sqrt{R_o^{E^2}q_o^2}-R_s^{G^2}q_s^2-\sqrt{R_l^{E^2}q_l^2}\right)$$




**expansion of the correlation function in spherical harmonics**

- **more complete representation of 3D structure of the source**
- **better diagnostic of non-femtoscopic correlations**

$$A_{l,m}(Q)=\frac{1}{\sqrt{4\pi}}\int d\varphi d(\cos(\theta))C(Q,\theta,\varphi)Y_{l,m}(\theta,\varphi)$$

**with** $q_l=Q\cos\theta$ **and** $q_o=Q\sin\theta\cos\varphi$

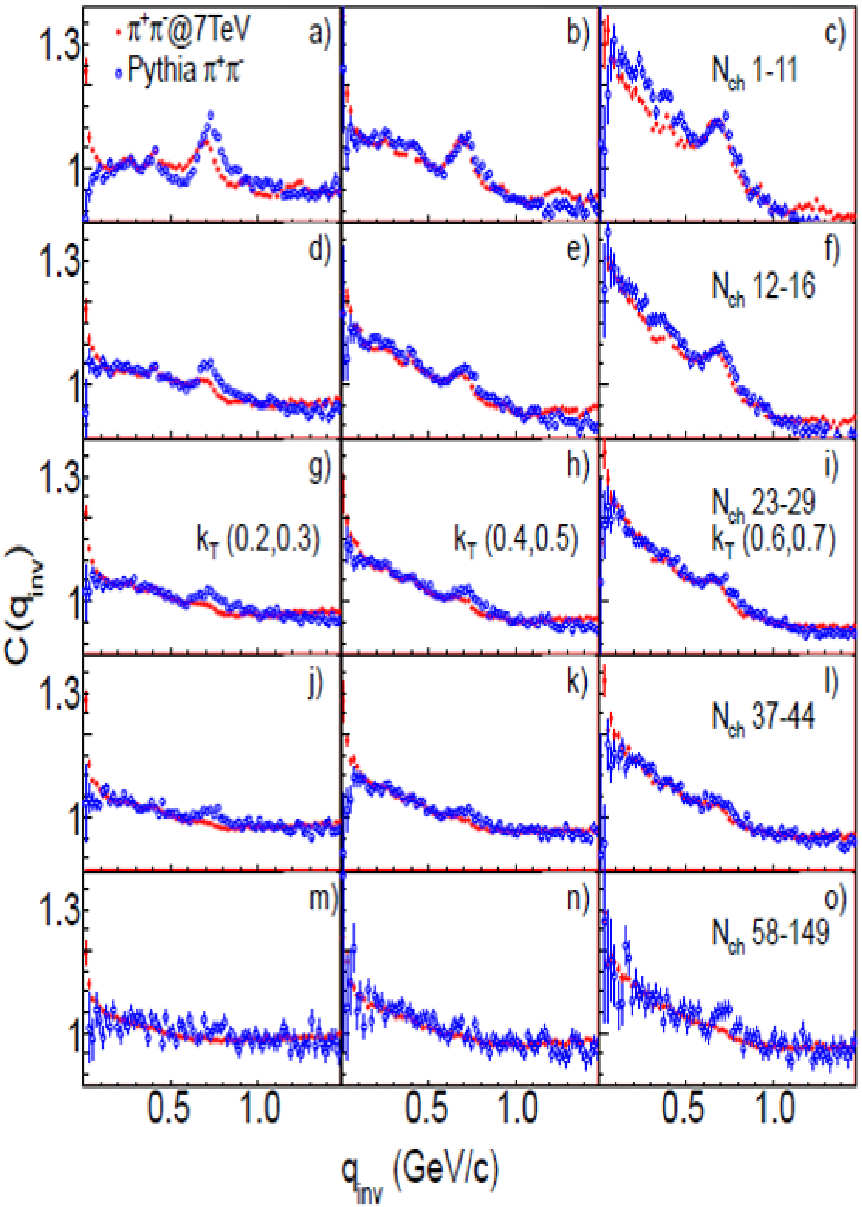
**first three non vanishing momenta are** $C_0^0\ C_2^2\ \ C_2^0$

$C_0^0$ **angle average component – general shape**

$C_2^2$ **comparison longitudinal and transverse size**

$C_2^0$ **comparison out and side component –** ***HBT puzzle***

# underlying physics (part 1)




**non-femtoscopic correlations in p+p**

- long-range structures at large $k_T$
- if femtoscopic they would correspond to a source of 0.2 fm
- above $k_T$ 0.7 GeV/c → no HBT effect measurable

**hypothesis of mini-jets**

**investigation of non-identical pion correlations**

- due to charge conversation it is easier to produce an oppositely charged pion pair via mini-jet fragmentation
- femtoscopic effects from Coulomb interactions (first bins)
- identify signals from wide variety of decays in $\pi^+\pi^-$

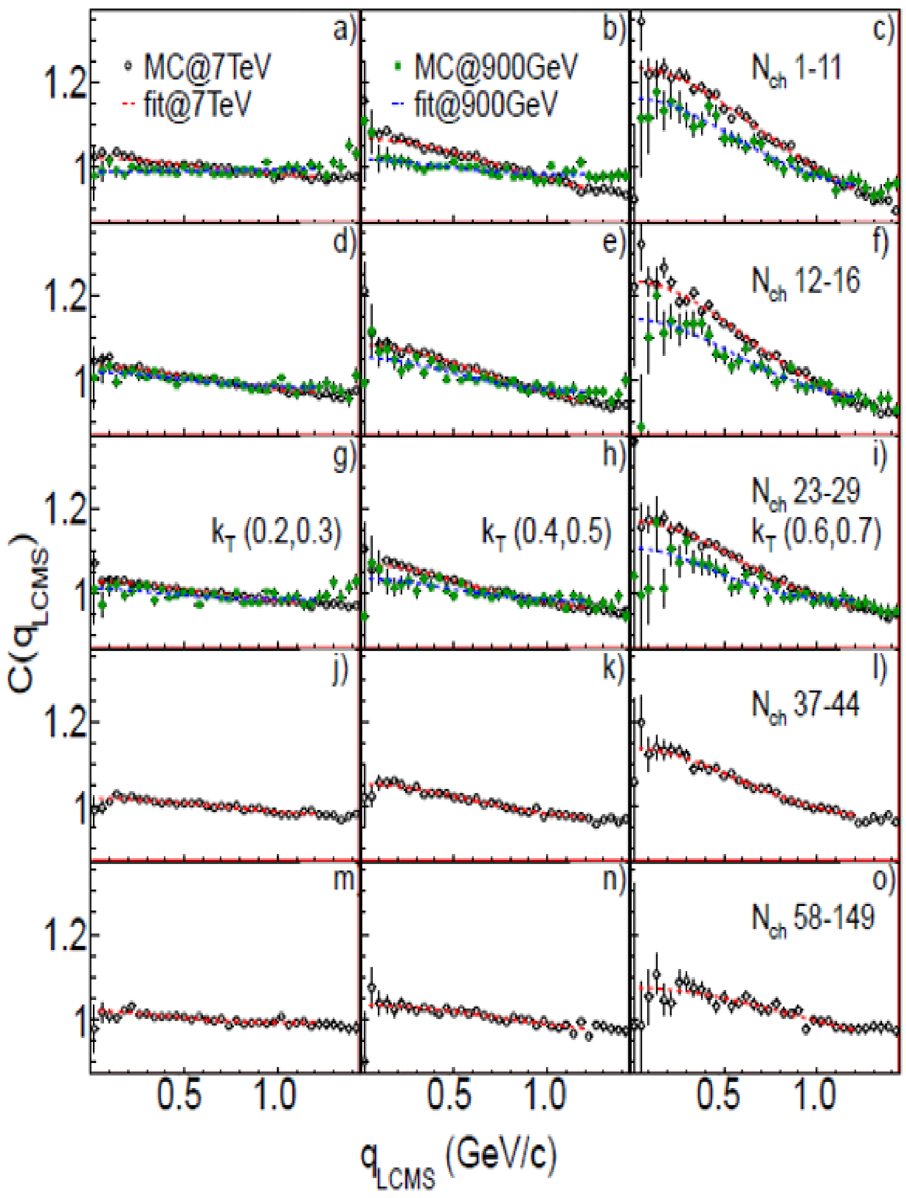
  $\rho$, $f_0$, $f_2$, $\omega$ (three body), $\eta$, $K^0_S$

**Non identical pions not usable for baseline parametrization because**

- stronger mini-jet contribution in $\pi^+\pi^-$ than in $\pi^+\pi^+$
- resonances

→ simulations

# underlying physics (part 2)




**simulations to estimate the underlying physics**

- **PYTHIA with Perugia-0 tuning**

**what we learned out of simulations**

- **successful comparison simulations $\pi^+\pi^-$**
- **fitting the baseline**
- **needed to be taken into account while extracting the HBT peak**
- **verification of mini-jet hypothesis**

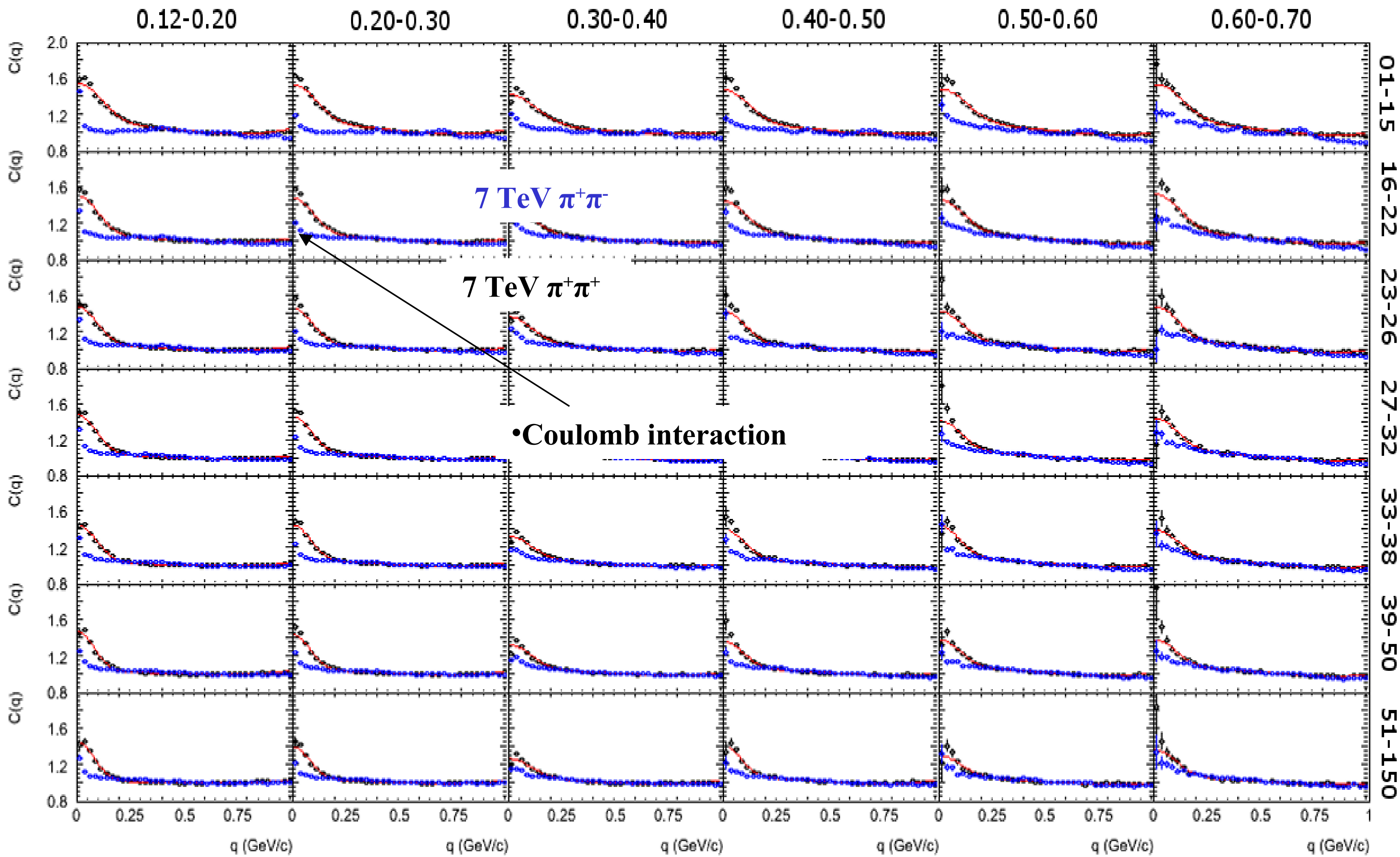
**study of $\pi^+\pi^-$ correlations confirm that MC reproduce the structure of the underlying events.**

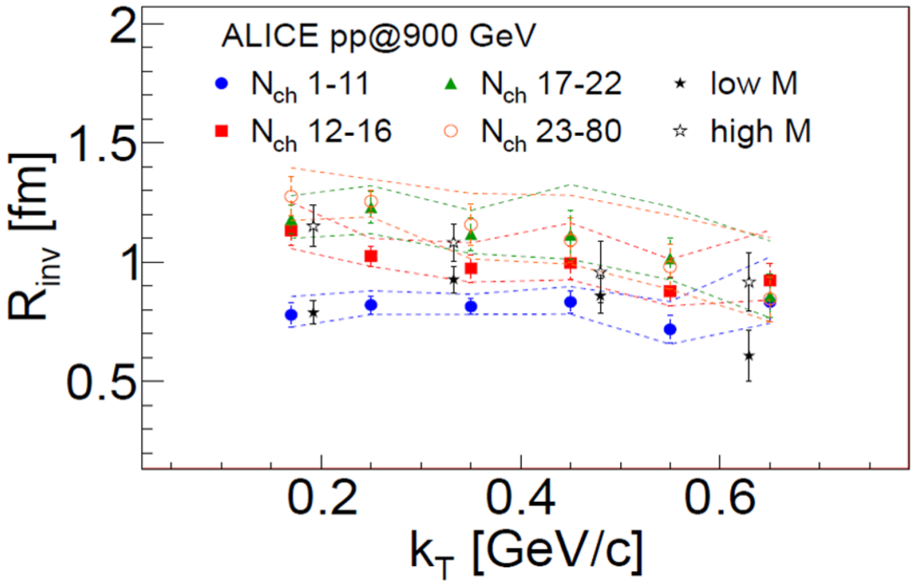
- **What happens with the $k_T$ dependance**

**correlations in sphericals very useful to understand the underlying physics**

**arXiv:1101.3665v1**

# 1 dim 7TeV – $k_T$ and $dN_{Ch}/d\eta$



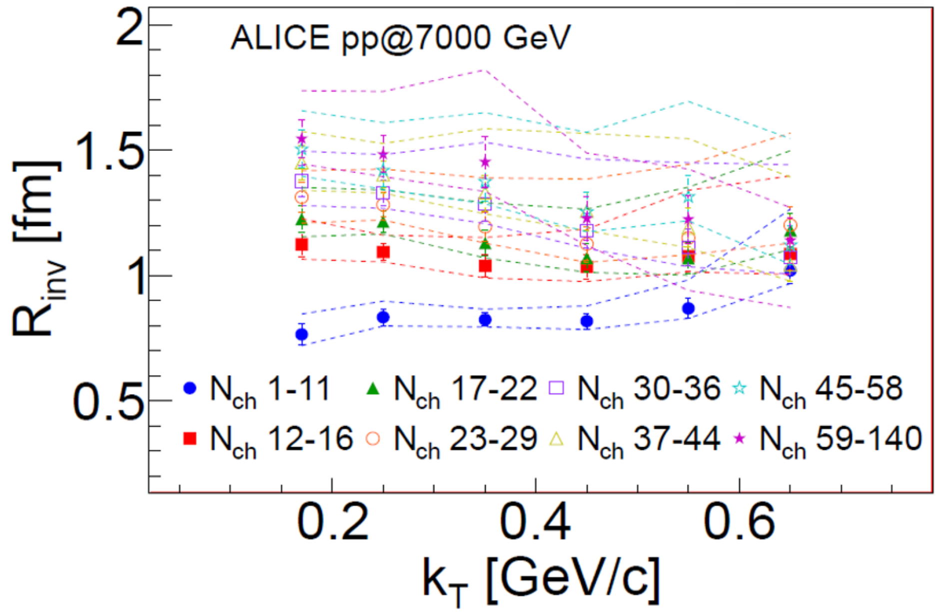



**comparison of the results with the first paper**

- source radii independant of $k_T$ in p+p at 900 GeV
- very sensitive to baseline assumption
- results show same scaling as in first paper

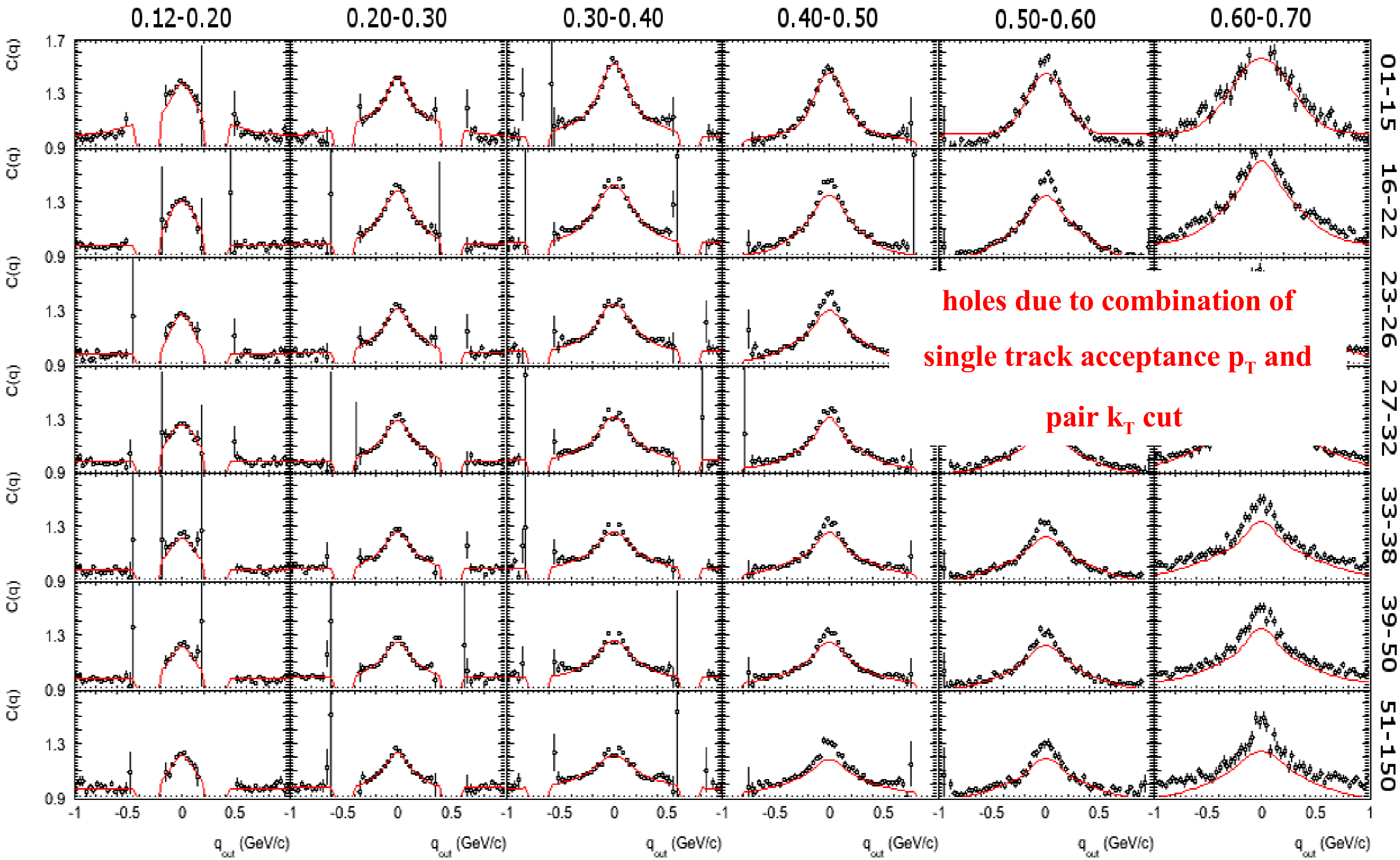
**One dimensional correlations in pair rest frame in p+p at 7 TeV**

- HBT radii independant of $k_T$ in p+p at 7 TeV
- very sensitive to baseline assumption
- same scaling as 900 GeV data

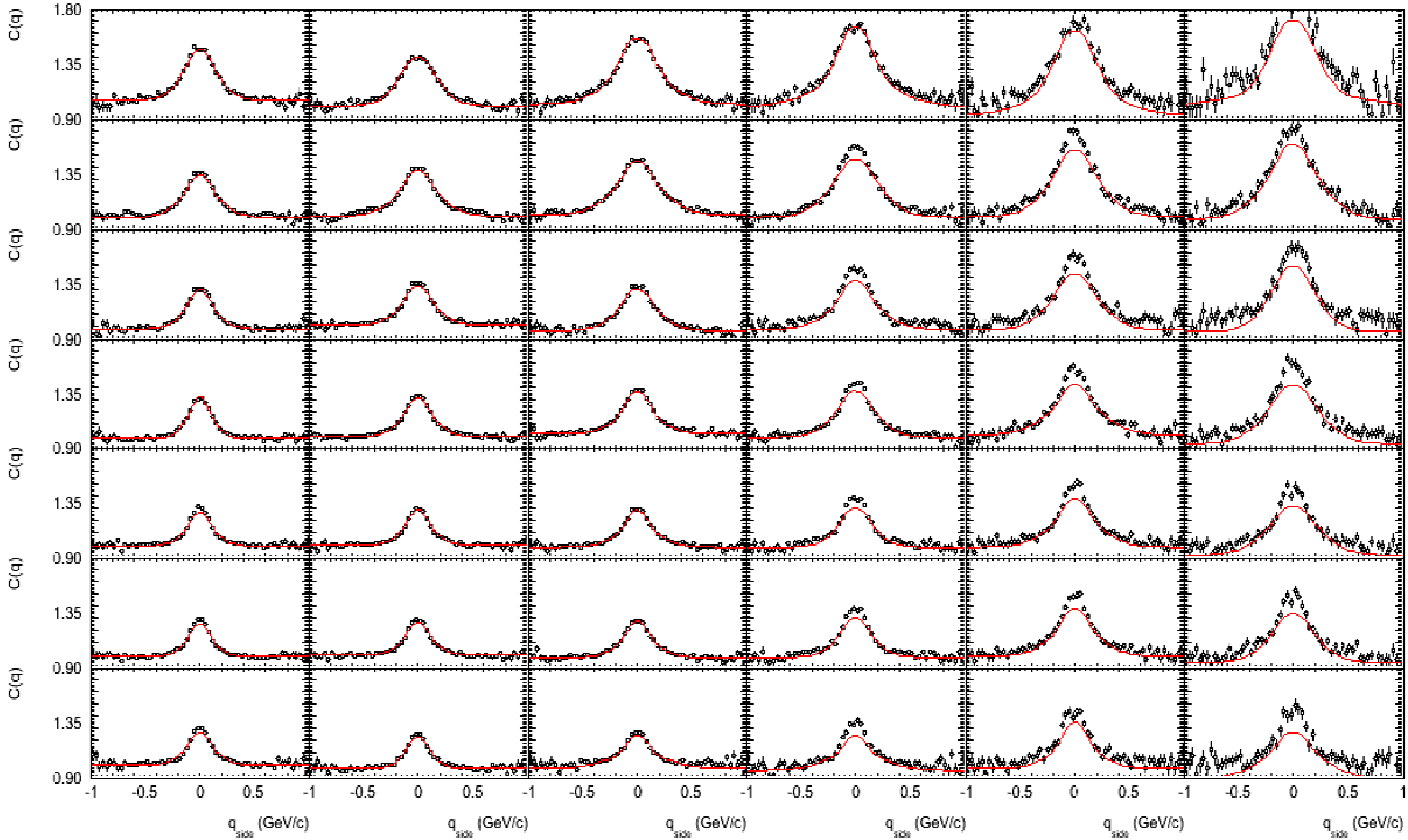



**no significant difference between the two energies (at same multiplicity)!**

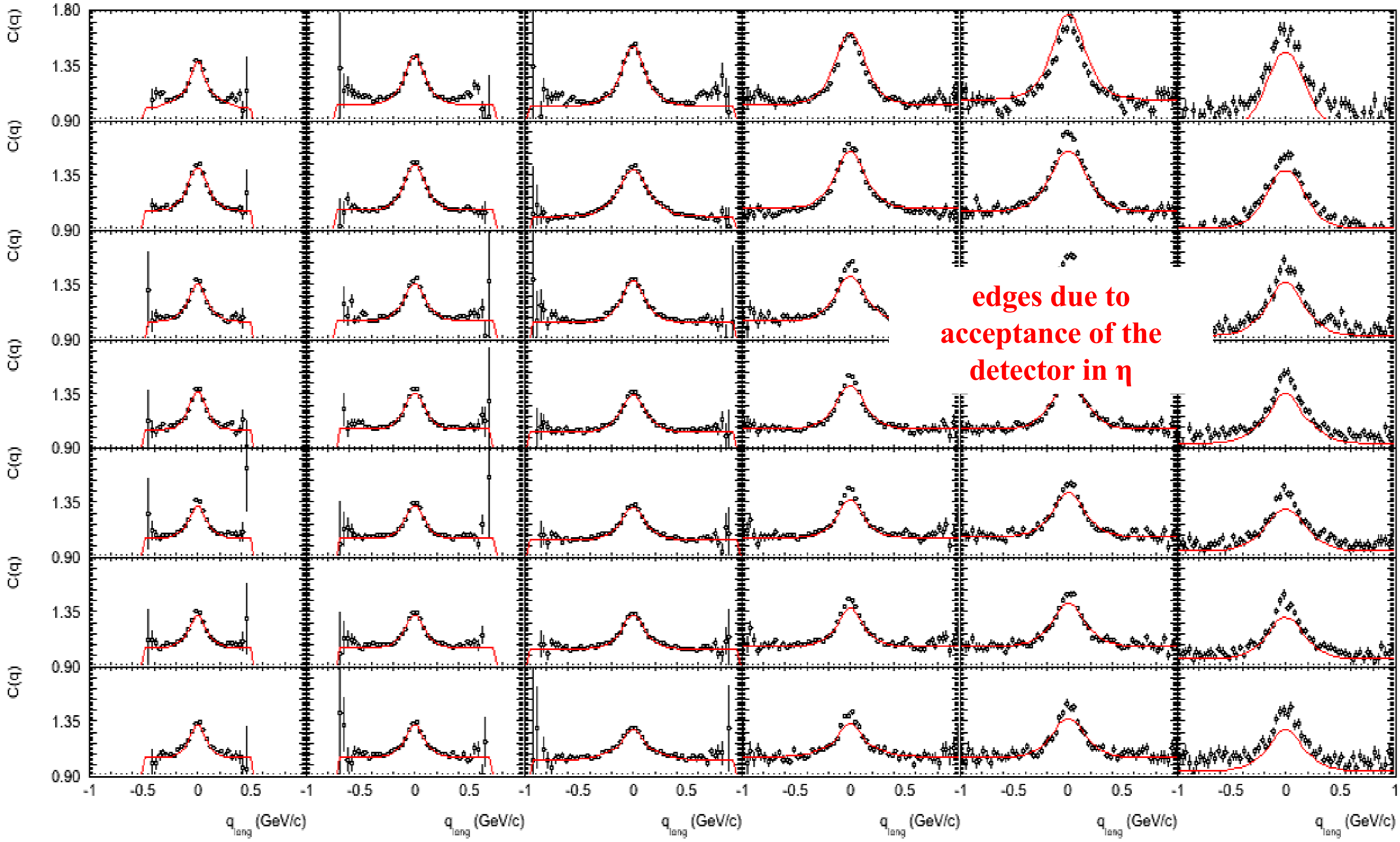
# out-direction



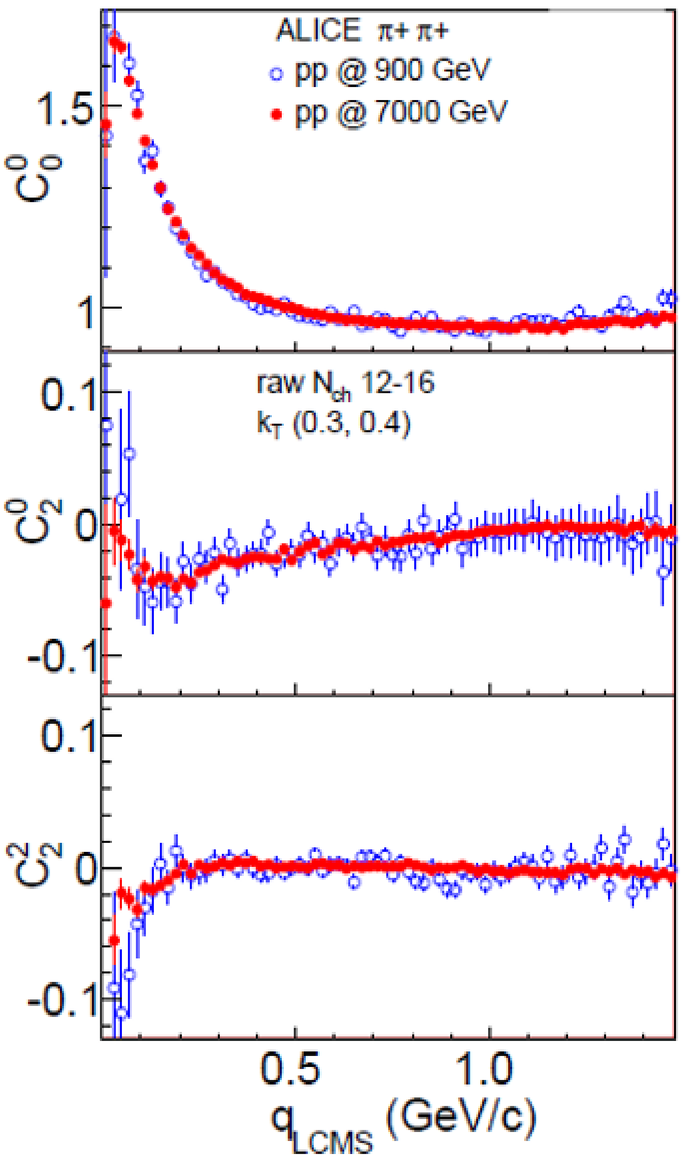
# side-direction



# long-direction



# comparison 7 TeV and 900 GeV




**p+p correlation in 900 GeV and 7 TeV – spherical harmonics**

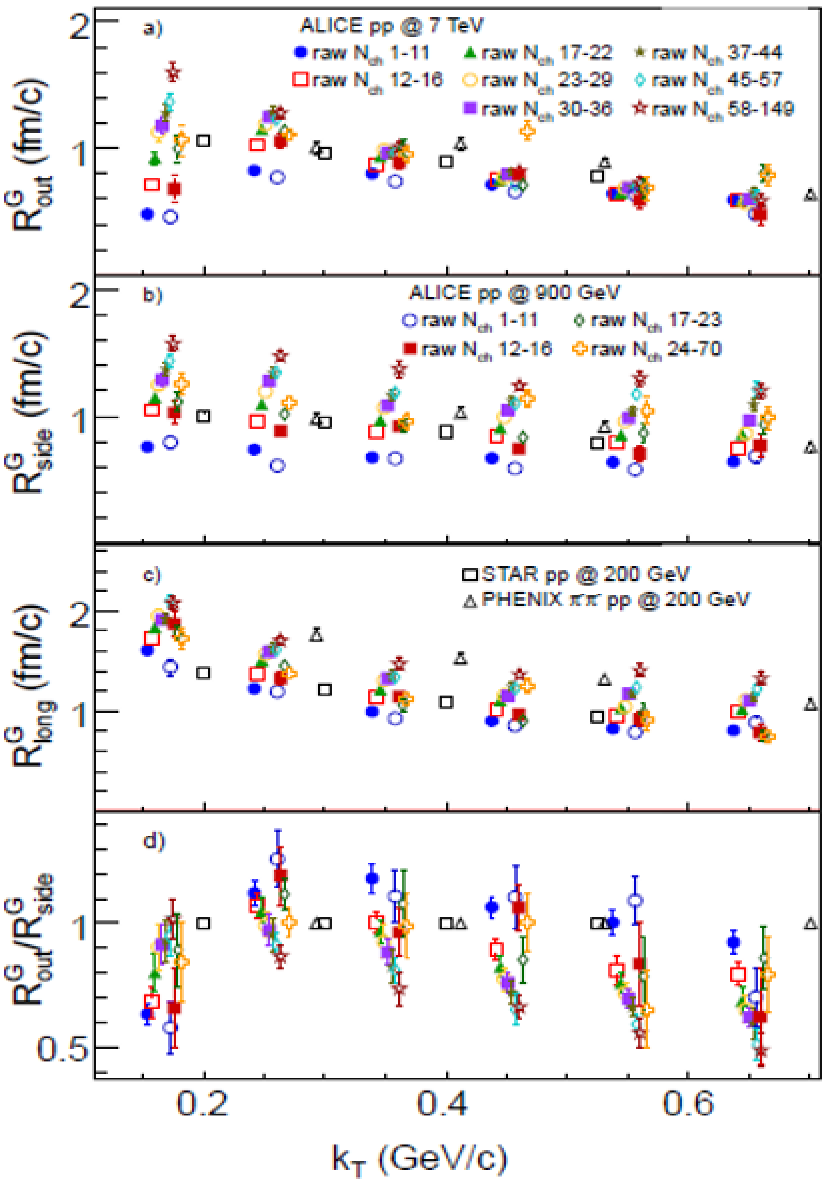
- **no significant difference between two energies (for same multiplicities)**
- **same behaviour for other kT and multiplicity bins**

***changing the collision energy of an order of magnitude has not as much impact as changing the multiplicity or the pair momentum***

**main scaling variables for the correlation function are global event multiplicity and the transverse momentum**

**analysis of 72 correlation functions**

- **4 multiplicity bins in 900 GeV**
- **8 multiplicity bins in 7 TeV**
- **6 kT bins**




**$k_T$ dependance for Gaussian parametrization in p+p LHC collisions at 900 GeV and 7 TeV**

- comparison between the two energies shows that they are universally similar for all multiplicities, pair-momenta and in all directions
- no changes between LHC and RHIC energies

**Different directions**

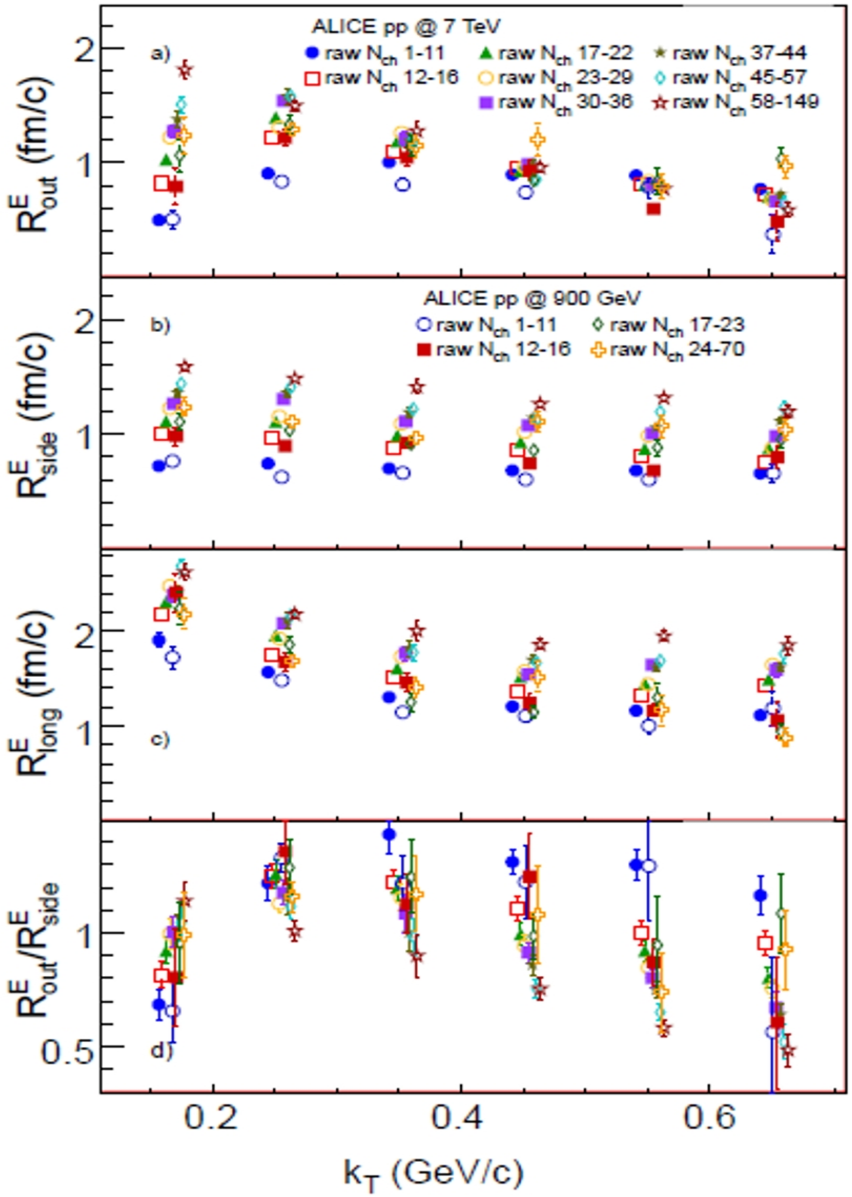
- $R_l$ - falls with $k_T$ at all multiplicities and energies
- $R_o$ - $k_T$ dependance flat at low multiplicities
  - developes a negatvie slope at high multiplicities
- $R_s$ – general small negative slope

**$R_o/R_s$**

- signature of strong collective behaviour → HBT puzzle
- Ro/Rs decreases with multiplicity

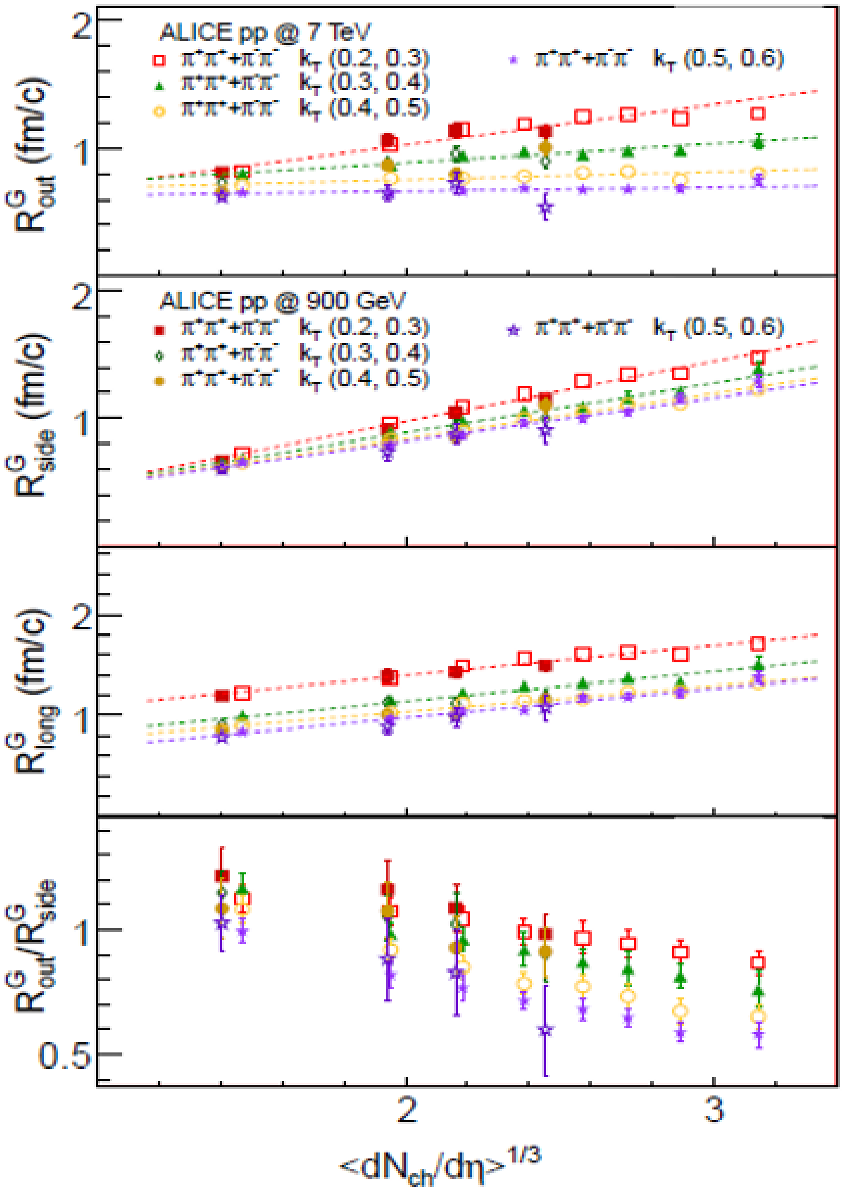
→ **The larger the multiplicity the more collective and self interacting is the system**

# $k_T$ dependance (exponential parametrization)




**$k_T$ dependance for exponential parametrization in p+p LHC collisions at 900 GeV and 7 TeV**

- **same results as for Gaussian parametrization**




$\langle dN_{Ch}/d\eta \rangle^{1/3}$ dependance for Gaussian parametrization in p+p LHC collisions at 900 GeV and 7 TeV

- all radii grow with event multiplicity $\langle dN_{Ch}/d\eta \rangle$
- same scaling for both energies 900 GeV and 7 TeV

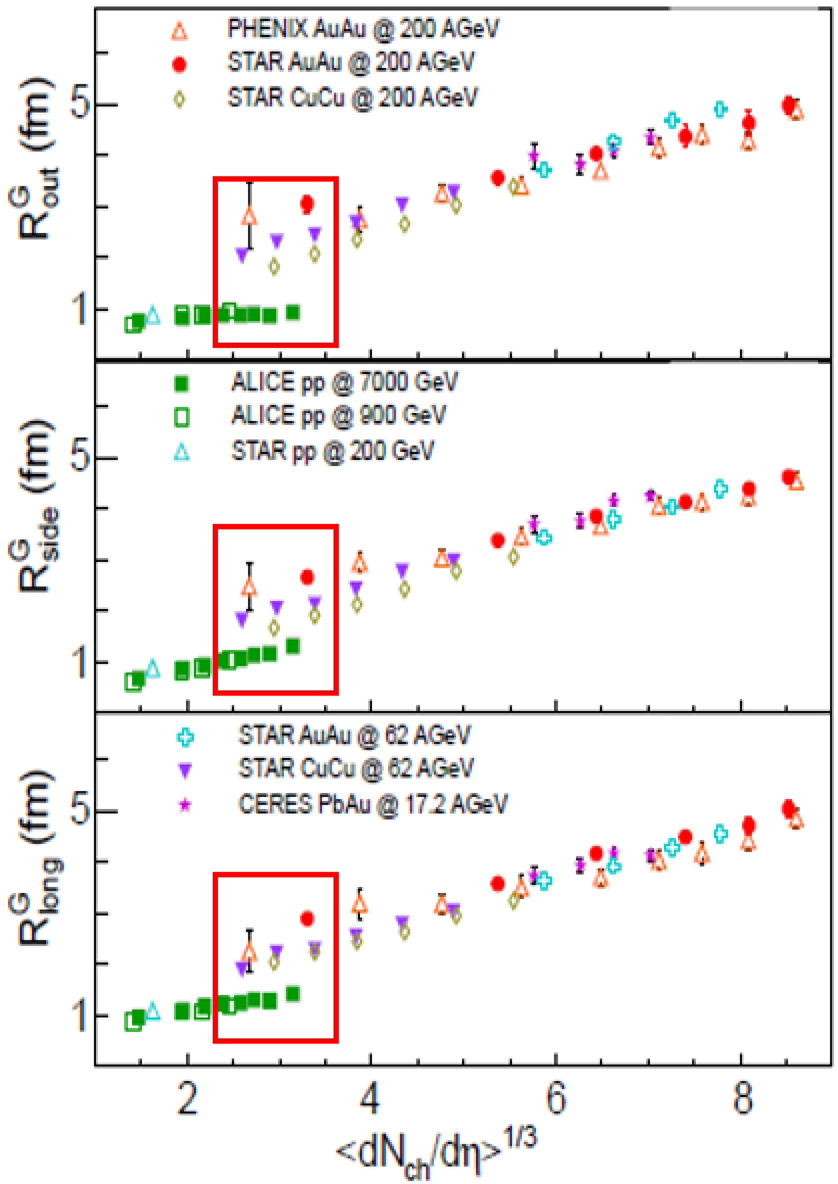
**Different directions**

- $R_l$ grows linearly with $\langle dN_{Ch}/d\eta \rangle^{1/3}$ in all $k_T$
- $R_s$ grows linearly with $\langle dN_{Ch}/d\eta \rangle^{1/3}$ in all $k_T$ but with different slopes for different $k_T$
- $R_o$ grows linearly with $\langle dN_{Ch}/d\eta \rangle^{1/3}$ for the lowest $k_T$ but not at all for the highest $k_T$

**$R_o/R_s$**

- signature of strong collective behaviour → HBT-puzzle
- $R_o/R_s$ decreases with multiplicity (as expected)

# multiplicity dependance (part 2)




**Multiplicity dependance compared to world systematics in heavy ions**

- similar multiplicity scaling in heavy-ions for RHIC and lower energies (f.e. CERES)

**<u>for the first time</u> ALICE provides a multiplicity link to peripheral heavy ion systems**

- similar $<dN_{Ch}/d\eta>$ than measured in peripheral Cu+Cu and Au+Au collisions
- both heavy-ions and p+p scale linear with $<dN_{Ch}/d\eta>$
- slope is clearly different
- p+p radii are below heavy-ion radii

→ **No universal multiplicity scaling in heavy ions <u>and</u> p+p**

→ **A heavy ion collision is not a simple compound of many p+p collisions!!!**

- one dimensional analysis reveals same results as in the first paper
  - HBT radii increase with multiplicity
  - HBT radii dependance of the pair momentum not significant (contrary to other experiments)
  - pair momentum dependance highly sensitive to baseline assumption

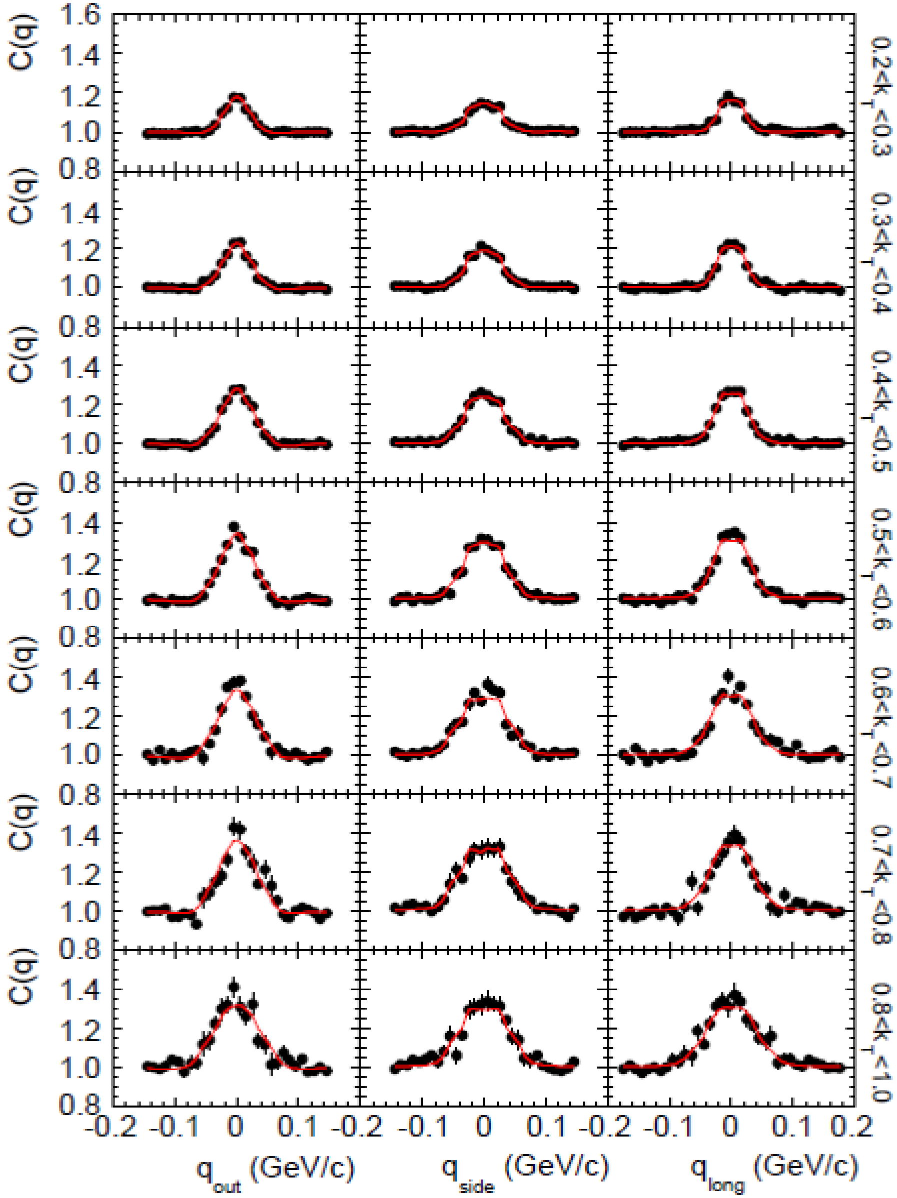
- in three dimensions
  - underlying event structure reproduced by MC and $\pi^+\pi^-$ → mini-jets at high $k_T$
  - decreasing size of the HBT radii with pair momentum $k_T$
  - increasing size of the HBT radii with multiplicity

- link between heavy ion data and p+p
  - heavy ions not a substitution of p+p → shift in size of HBT radii
  - no universal scaling in multiplicity for heavy ions <u>and</u> p+p

# two particle correlations in PbPb at sqrt(s) = 2.76 TeV

## 3 dimensional

- measuring space-time dimensions in PbPb collisions at sqrt(s) = 2.76 TeV
  - comparing results to world systematics
  - dependance of source size as function of transverse momenta $k_T$
  - dependance of HBT radii as function of energy and multiplicity
  - comparison to model predictions




**5% most central events**

- Bose-Einstein enhancement visible at low q
- 16000 Pb+Pb events minimum bias
- 6 $k_T$ bins

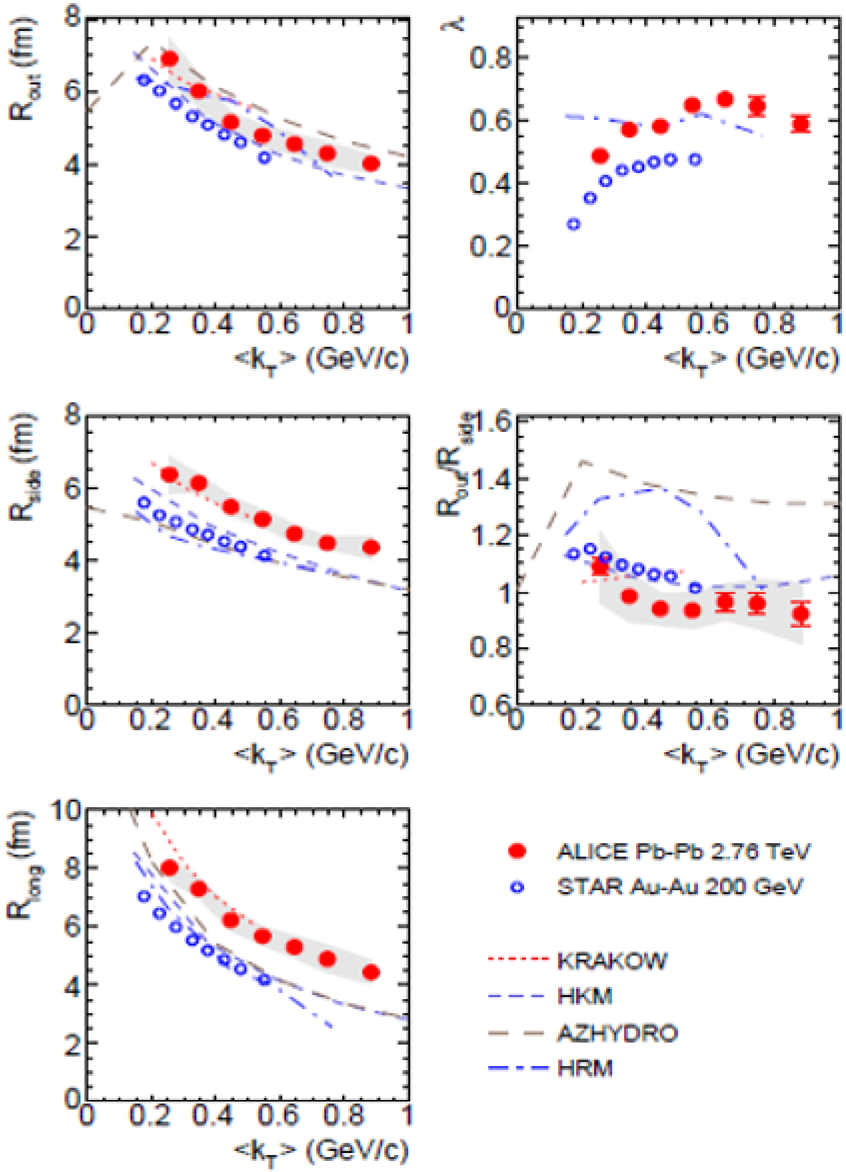
**projection in out, side and long (Bertsch, Bratt)**

- pair selection cuts (track splitting & track merging)
- peak width increases when going from low to high $k_T$

**extracting $R_o$, $R_s$, $R_l$**

- correction for finite momentum resolution

**arXiv:1012.4035v2**




scaling of $R_o$, $R_s$, $R_l$ with $k_T$

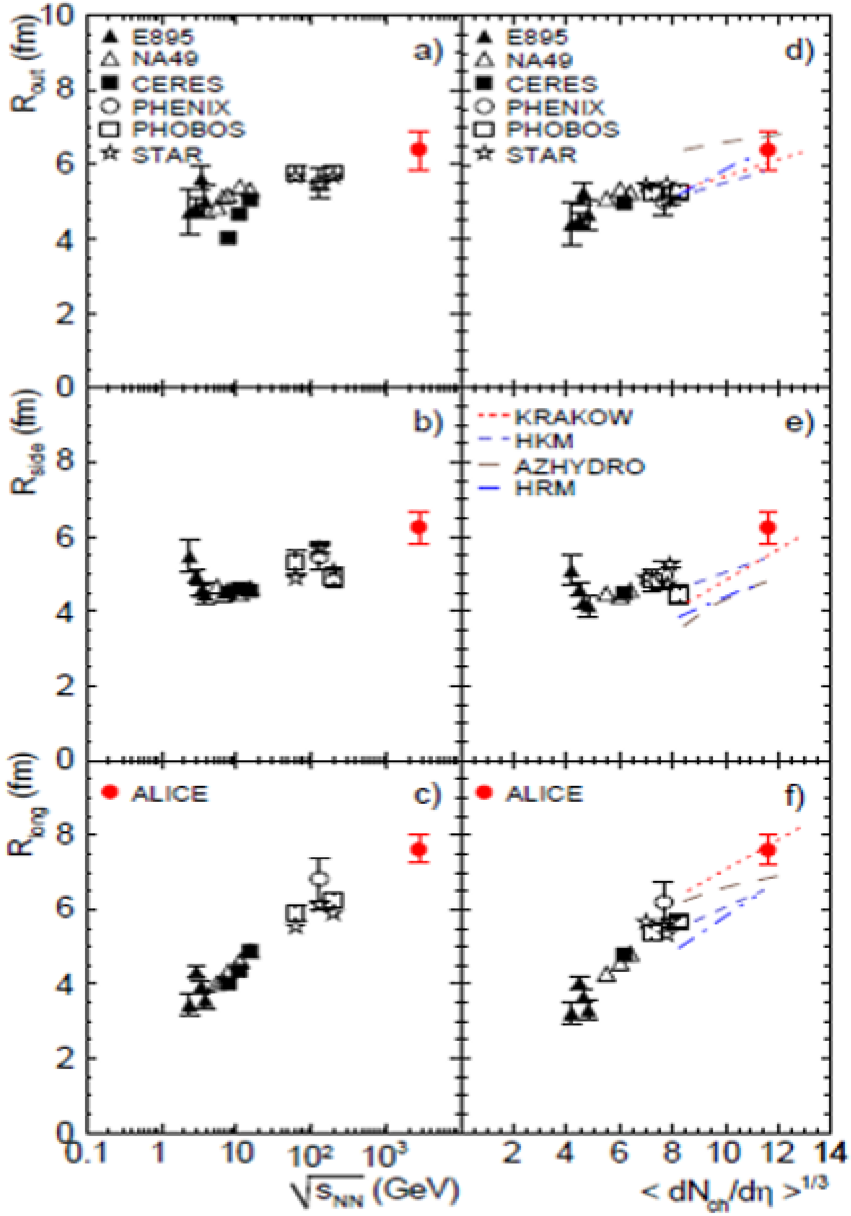
- decreasing of the HBT radii with increasing $k_T$
- HBT radii describe length of homogenity

comparison with model predictions

- all models predict decrease of the HBT radii in all three directions with $k_T$
- best prediction by KARKOW

$R_o/R_s$

- $R_o/R_s$ flat within systematic errors



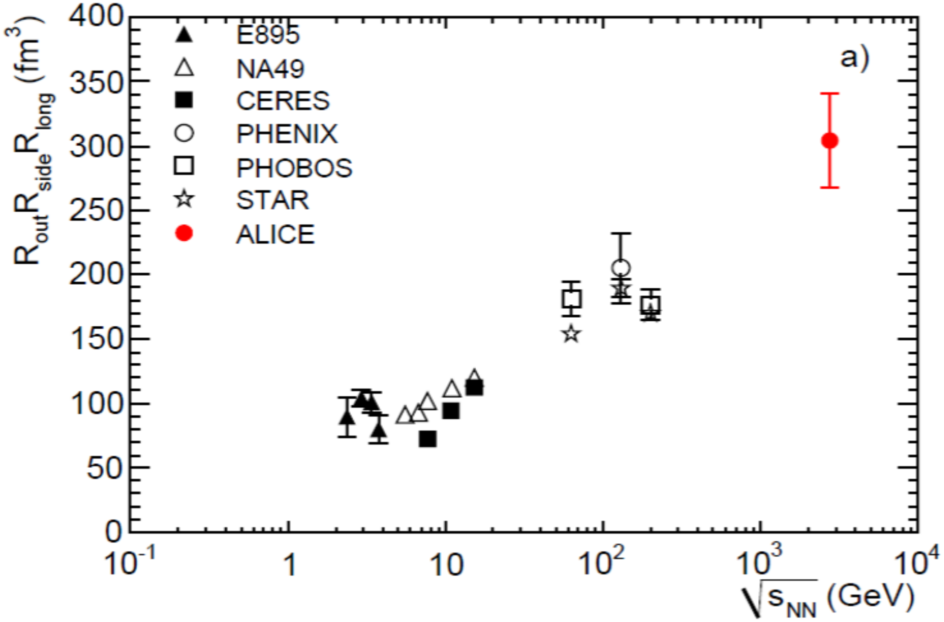

energy dependance

- $k_T$ of 0.3 GeV/c
- scaling of the HBT radii (to compare with the other results)
- all HBT radii increase with energy

multiplicity dependance

- multiplicity better parameter to compare with model predictions (hydro)
- all HBT radii increase with multiplicity
- increase in agreement with model predictions

# freeze out volume and freeze out time




volume of the homogenity region

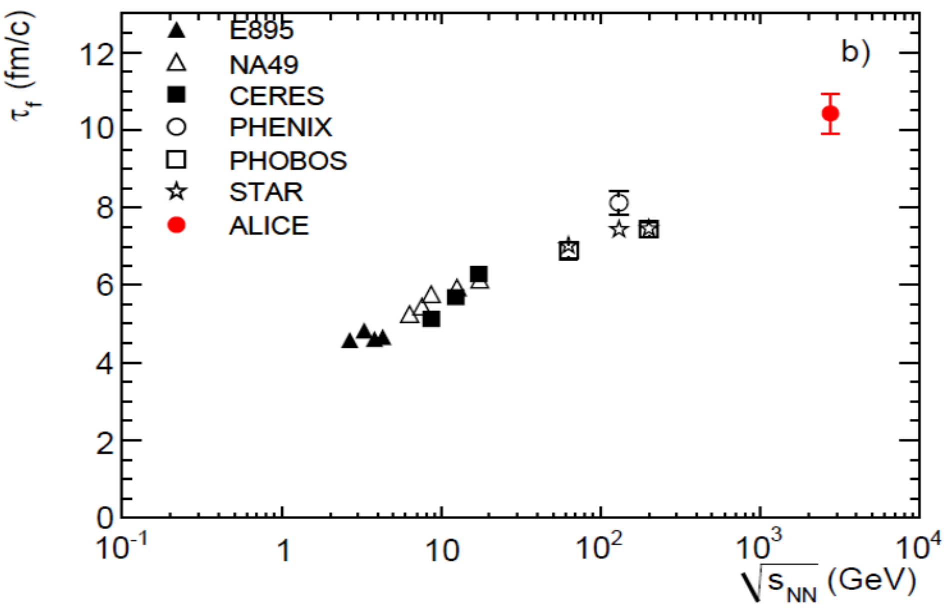
- $R_o*R_s*R_l$
- volume nearly two times as large as at RHIC
- freeze out volume 320 fm³

freeze out time

- $R_l$ proportional to duration of longitudinal expansion (freeze out time)

$$R_{l^2}(k_T)=\frac{\tau_f^2 T}{m_T}\frac{K_2(m_T/T)}{K_1(m_T/T)}$$

- freeze out Ttemperature T = 0.12 GeV (?)
- freeze out time 10 fm/c



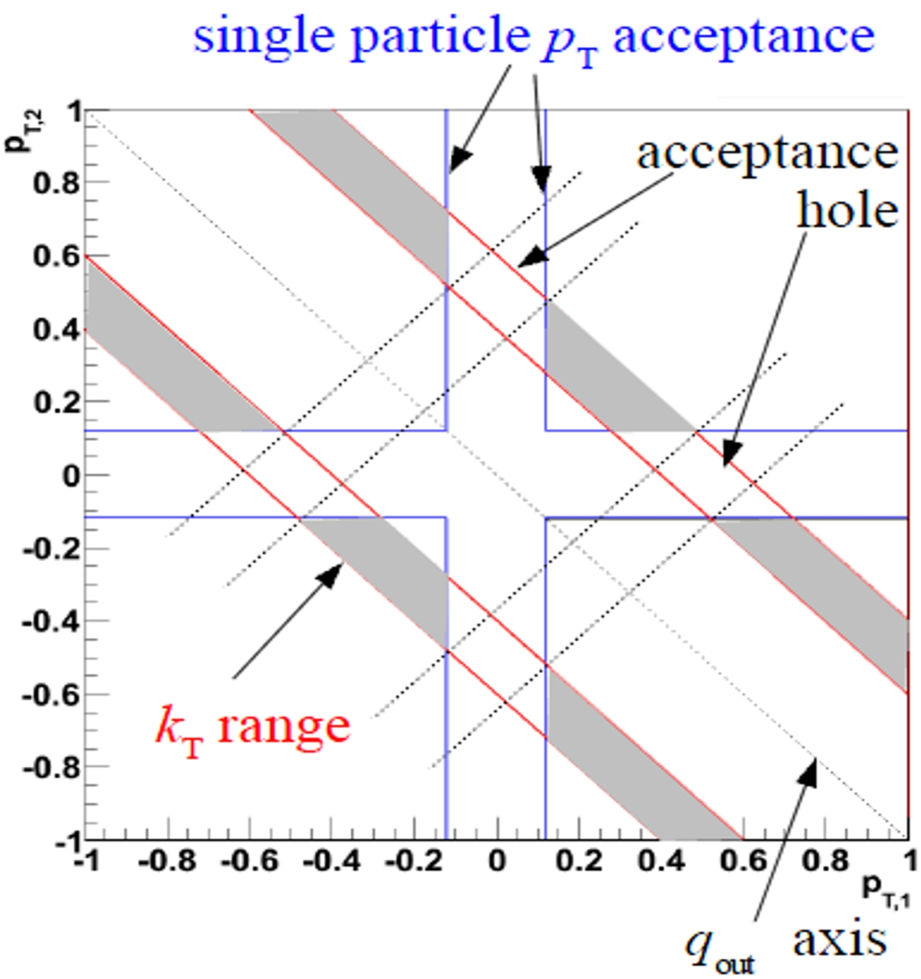
- **link between heavy ion data and p+p**
  - **ALICE Pb+Pb results significantly broaden the range of world systematics in HBT**
  - **first HBT results in Pb+Pb at sqrt(s) = 2.76 TeV**
  - **decreasing HBT radii with increasing $k_T$ → developement of a bulk**
  - **increasing HBT radii with energy sqrt(s) and multiplicity (as predicted)**

# outlook

- zero order HBT in ALICE done
- first order HBT → next year
    - analyzing other systems than ππ
    - HBT in charged Kaons
    - HBT in neutral Kaons (V0 finder)
    - HBT with protons
    - azimutal dependance of the HBT radii
    - higher order sphericals
    - …

# Backup

# holes and edges




## holes in $q_{out}$

- $q_{long}$ and $q_{side}$ vanish
- $p_T$ is sum of $p_{T1}$ and $p_{T2}$
- $k_T$ is difference of $p_{T1}$ and $p_{T2}$

**combination of single particle acceptance and two particle cut leads to holes**

## edges in $q_{long}$

**η acceptance of the detector**