# Bose–Einstein correlations of charged and neutral kaons in pp and Pb-Pb collisions at the LHC with the ALICE experiment

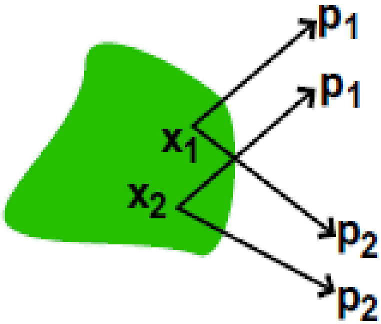
**Konstantin Mikhaylov**
**ITEP-JINR**
**for the ALICE collaboration**

**XX July 2015, SQM 2015, Dubna, Russia**

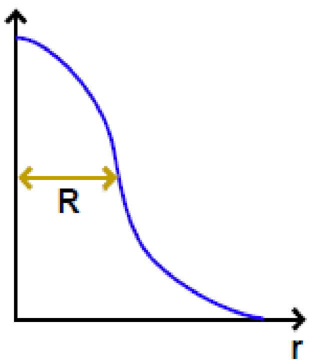
# Outline

- Introduction
- Motivation of kaon femtoscopy study
- Kaon femtoscopy at RHIC
- ALICE at the LHC
- ALICE results on kaon femtoscopy in Pb-Pb collisions
- ALICE results on kaon femtoscopy in pp collisions
- Conclusions

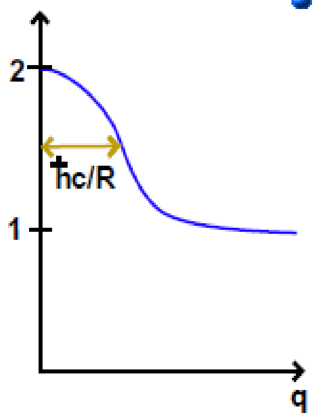
# Introduction




- Correlation femtoscopy is the direct tool to measure R, cτ ~ fm Based on Bose-Einstein or Fermi-Dirac symmetric properties and Final State Interactions




⇒




- Correlation function: $C(q)=\frac{N_2(p_1,p_2)}{N_1(p_1)\cdot N_2(p_1)}, C(\infty)=1$

$$C(q)=\frac{S(q)}{B(q)}, q=p_1-p_2$$

*S(q)* – pairs from same event

*B(q)* – pairs from different event

- Parametrization: $C(q_{inv})=1+\lambda\exp(-R^2 q_{inv}^2)$

***R*** Gaussian radius in Pair Rest Frame **(PRF)**

***λ*** correlation strength parameter

3-dimensional: $R_{side}$ transverse size, $R_{long}$ time of freeze-out, $R_{out}$ / $R_{side}$ emis. duration.

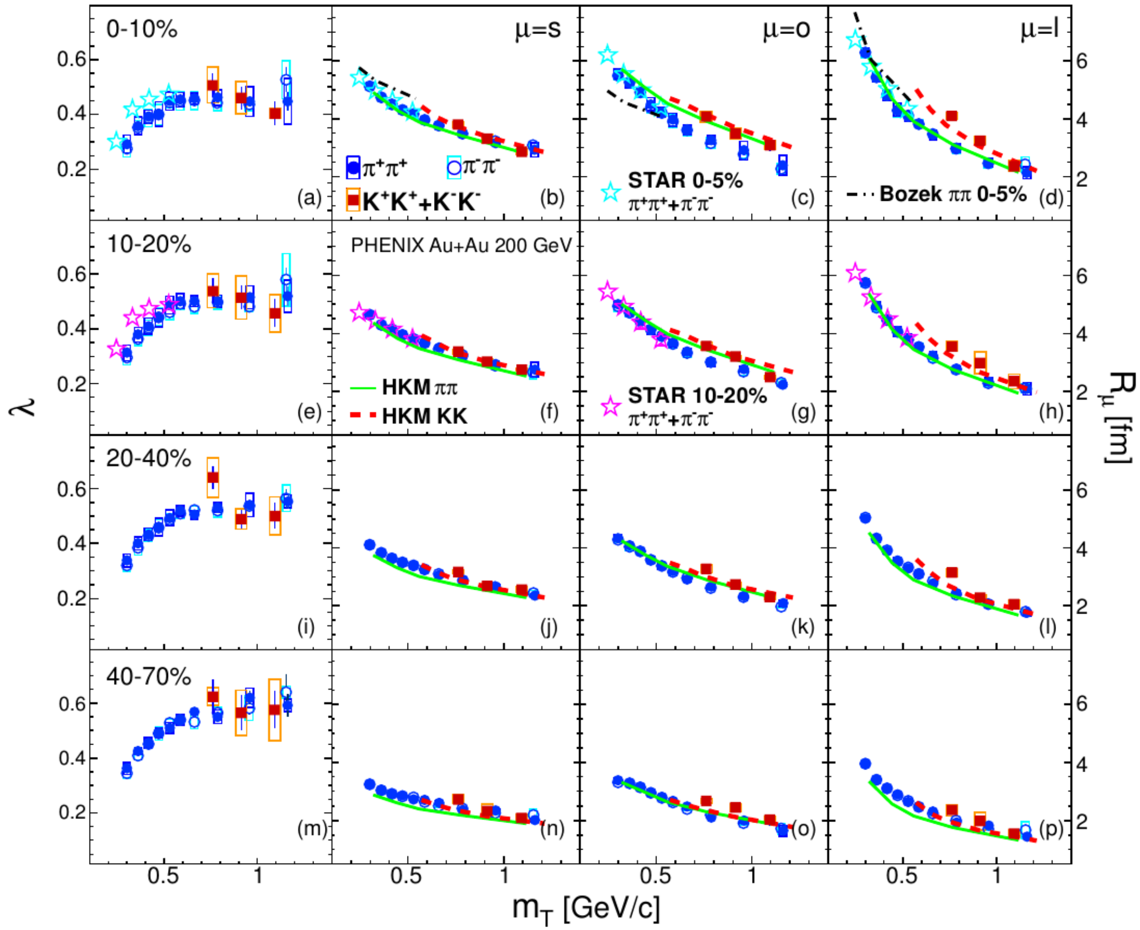
$$C(q_{out}, q_{side}, q_{long})=1+\lambda\exp(-R_{out}^2 q_{out}^2-R_{side}^2 q_{side}^2-R_{long}^2 q_{long}^2)$$

# Motivation of kaon femtoscopy study in ion collisions

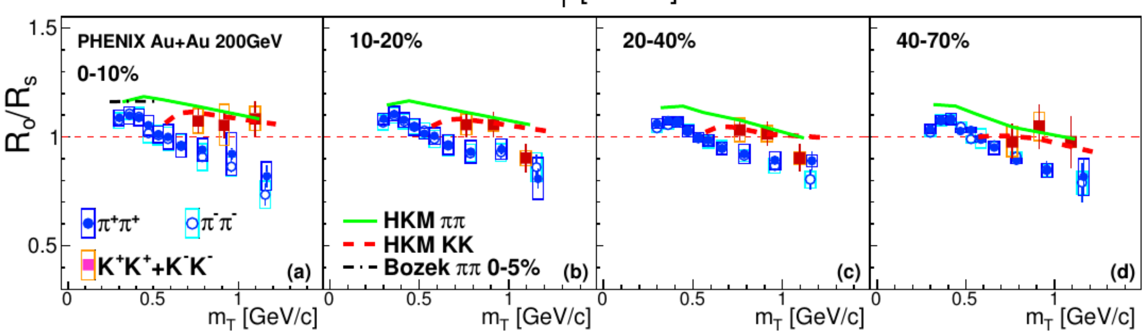
- Momentum correlations (due to QS and FSI) → space-time characteristic of production process
  - $K^{\pm}K^{\pm}$ : QS+Coulomb FSI (strong FSI is negligible)
  - $K^0_sK^0_s$ : QS+Strong FSI
  - Cross-check $K^{\pm}K^{\pm}$ and $K^0_sK^0_s$ (diff. physics and diff. method)
- **K** less influenced by resonance decays than **π** → more clear signal
- Study of collective dynamics (**K** together with **π** and **p**):

  $m_T$ dependence of correlation radii (collective flow)
- Check of hydrodynamic models predictions in comparison with data
- pp vs Pb-Pb. Does collectivity exist in pp?

# Kaon femtoscopy at RHIC (PHENIX and STAR)

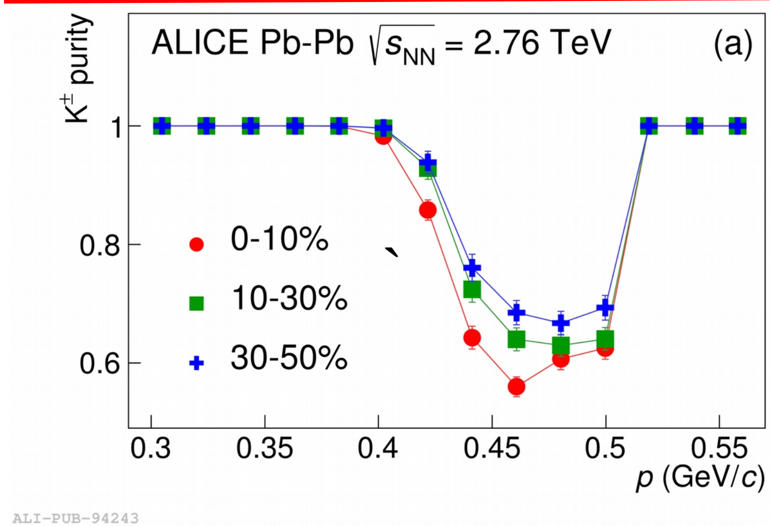


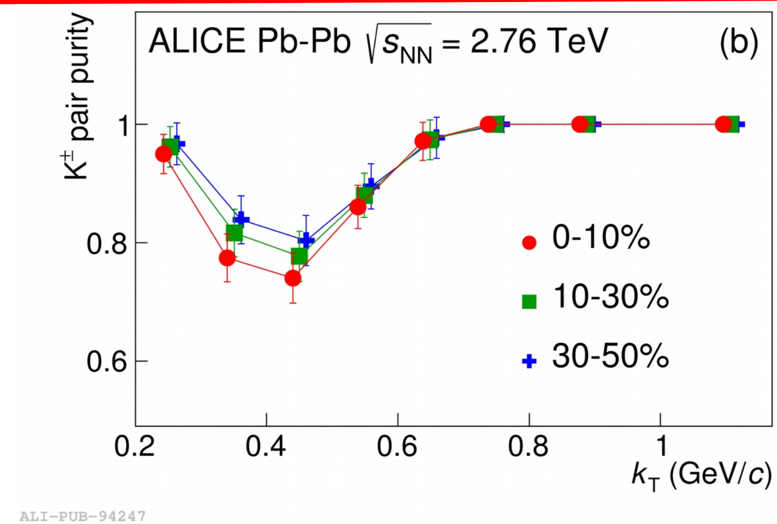

- ArXiv:1504.05168(PHENIX)
- K,π AuAu at $\sqrt{s_{NN}}$=200GeV
- R(π) STAR and PHENIX good agreement
- Radii decrease with $m_T$ → collective flow
- $R_{side}$ shows $m_T$ scaling
- $R_{out}$, $R_{long}$ of K show larger values than those of π → $m_T$ scaling is broken



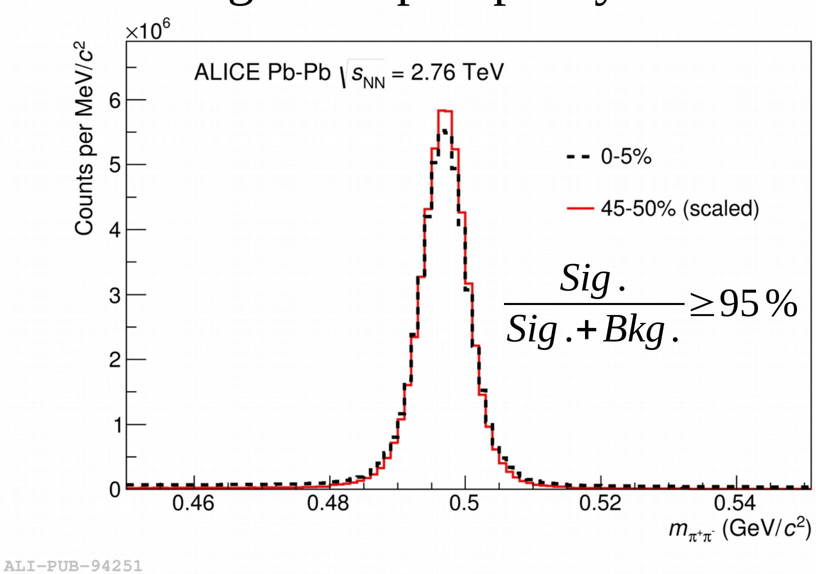

- $R_{out}/R_{side}$ sensitive to emission duration
- $R_{out}/R_{side}$(K) > $R_{out}/R_{side}$(π)
- Longer emission duration time for K than for π

# $K^{\pm}$ and $K^0_s$ PID (*ArXiv.org:1506.07884*)



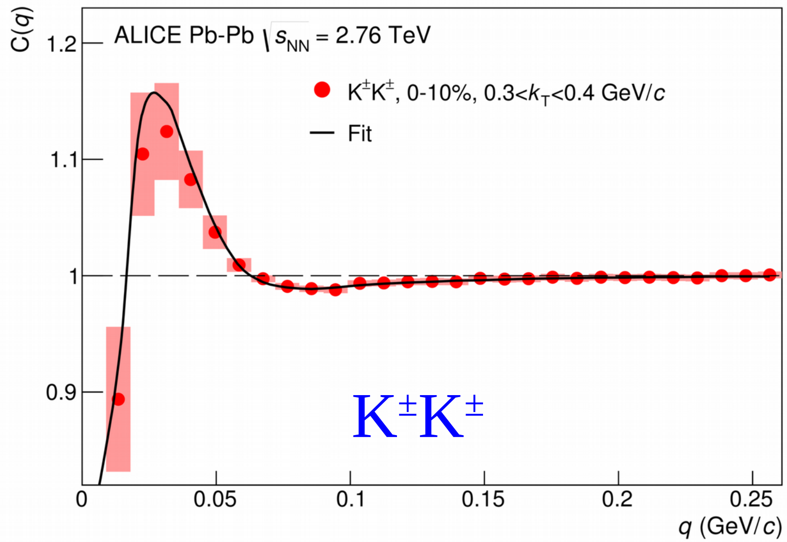




- $K^{\pm}$: $0.15<p_T<1.5$ GeV/c, $|\eta|<0.8$, TCP and TOF(p>0.5GeV/c) Nσ PID (N<3)
- Single and pair purity: main contamination (0.4<p<0.5 GeV/c) comes form $e^{\pm}$

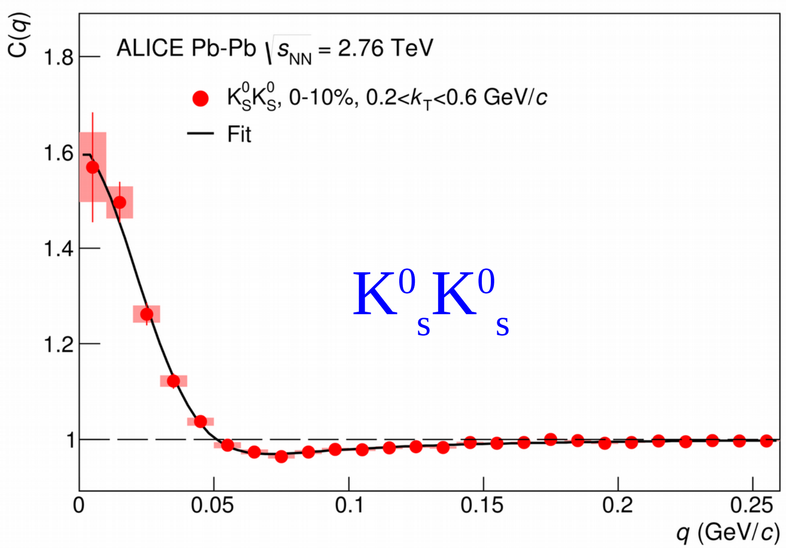



- $K^0_s \rightarrow \pi^+\pi^-$ (cτ=2.7cm)
- Daughter π: $p_T$>0.15 GeV/c, $|\eta|<0.8$
  TPC and TOF(p>0.8GeV/c) Nσ PID
- $K^0_s$: $|\eta|<0.8$, $\pi^+\pi^-$ DCA<0.3cm,
  DCA to prim. vertex <0.3cm
  decay length<30 cm, cos(point. angle)>0.99
  $0.480<m_{inv}<0.515$ GeV/$c^2$

# $K^{\pm}K^{\pm}$ and $K^0_sK^0_s$ in Pb-Pb at $\sqrt{s_{NN}}$=2.76 TeV: Correl. Function




ALI-PUB-94255




ALI-PUB-94259

*New results from ArXiv.org:1506.07884*

- Example $K^{\pm}K^{\pm}$ and $K^0_sK^0_s$ CFs are shown
- Both CF corrected momentum resolution and purity
- Bose-Einstein enhancement seen for both
- Coulomb FSI seen in drop at low *q* in $K^{\pm}K^{\pm}$
- Strong FSI seen in dip below C=1 in $K^0_sK^0_s$

- Curves corresponds to best fit:

Bowler-Sinyukov formula in case of $K^{\pm}K^{\pm}$

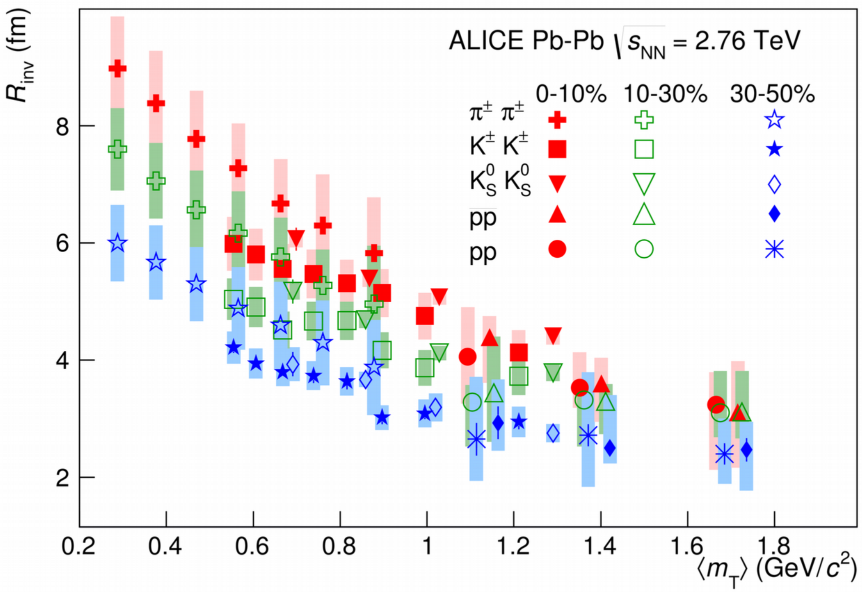
$$C(q)=N[1-\lambda+\lambda K(q)(1+\exp(-R_{inv}^2 q^2))],$$

*N* norm. factor, λ correlation strength,
*K(q)* symmetrized Coulomb factor
In case of $K^0_sK^0_s$: $C(q)=N[1-\lambda+\lambda C'(q)],$

$$C'(q)=1+\exp(-R_{inv}^2 q^2)+C_{strongFSI}(q,R)$$

*strongFSI* due to resonances $f_0(980)$ and $a_0(980)$

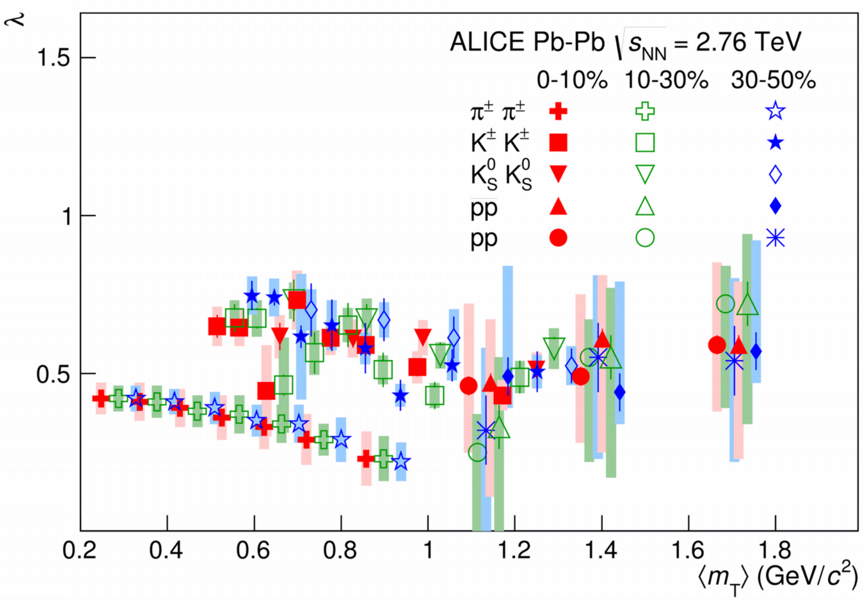
# $K^{\pm}K^{\pm}$ and $K^0_sK^0_s$ in Pb-Pb at $\sqrt{s_{NN}}$=2.76 TeV: R and λ param.




ALI-PUB-94271

*New* *results from* *ArXiv.org:1506.07884*

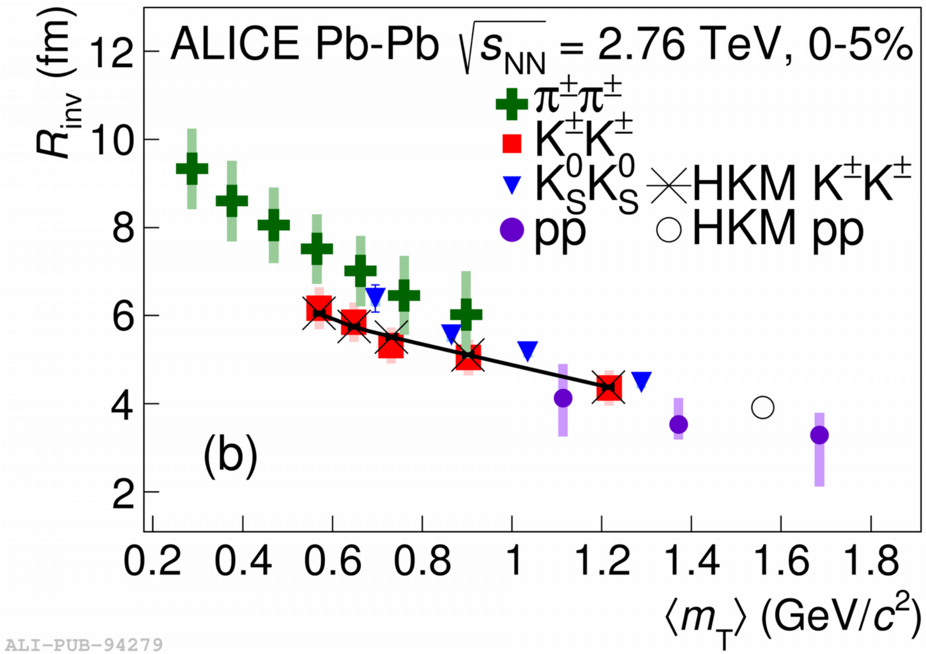
- R and λ for **$\pi^{\pm}\pi^{\pm}$,$K^{\pm}K^{\pm}$,$K^0_sK^0_s$, pp** and **$\overline{pp}$** vs $m_T$ for several centralities
- R for overlapping $m_T$ consistent
- $R_\pi > R_K$ due to pion Lorrentz factor
- $m_T$ dependence → collective flow
- Centrality dependence

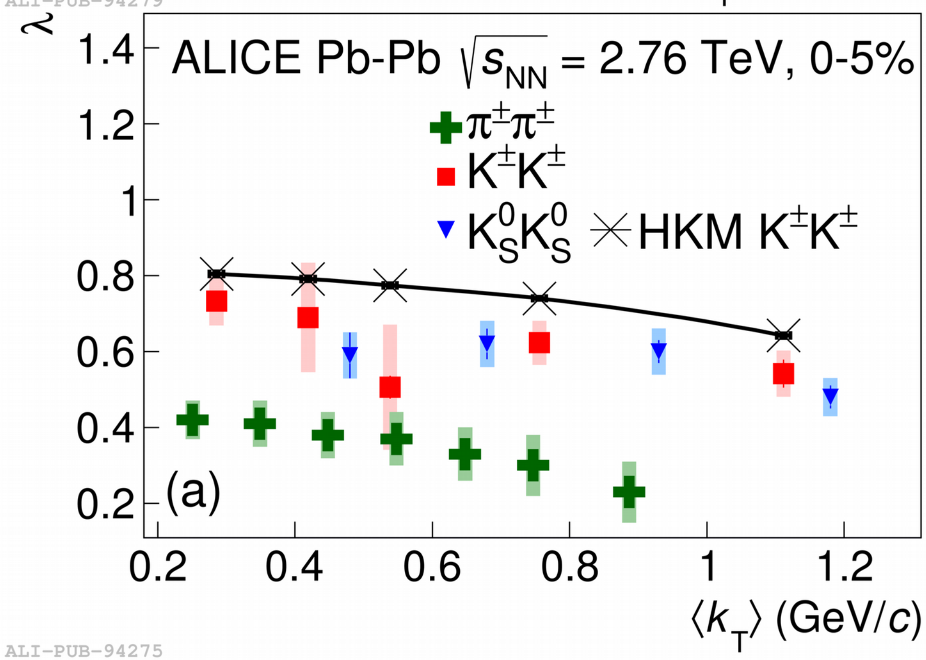



ALI-PUB-94267

- All λ lie mostly in 0.3-0.7 due to long-lived resonances, non-Gaussian shape.
- No significant centrality dependence
- $\lambda_\pi$ are lower than $\lambda_K$ due to the stronger influence of resonances

# $K^{\pm}K^{\pm}$ and $K^0_sK^0_s$ in Pb-Pb at $\sqrt{s_{NN}}$=2.76 TeV: HKM model



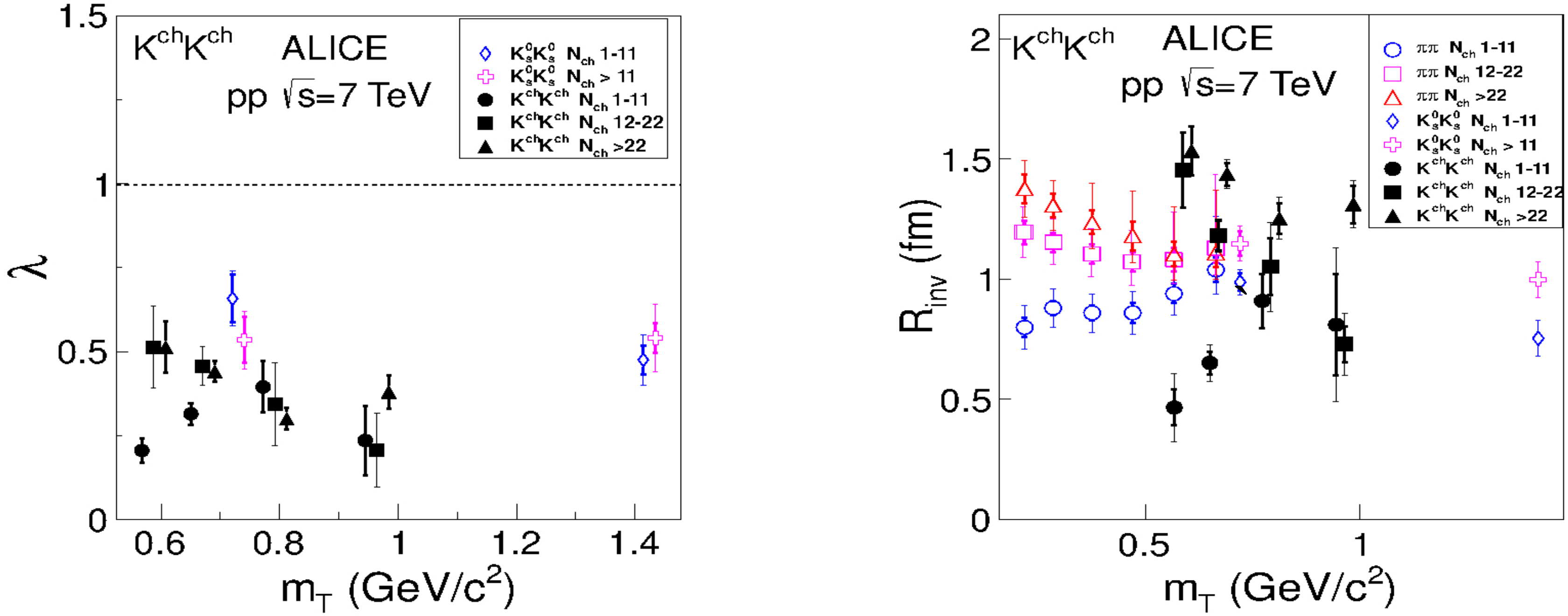




*New results from ArXiv.org:1506.07884*

- Points for 0-5% centrality
  R and λ for $\pi^{\pm}\pi^{\pm}$, $K^{\pm}K^{\pm}$, $K^0_sK^0_s$, pp
- R for K show very good agreement with HKM predictions for $K^{\pm}K^{\pm}$
- $R_p$ compatible with $R_k$ and HKM (arXiv:1404.4501)
- $R_{\pi} > R_K$
- λ decrease with $k_T$, both data and HKM
- HKM prediction for λ slightly overpredicts the data
- $\lambda_{\pi}$ are lower $\lambda_K$ due to the stronger influence of resonances

# $m_T$-dependence of kaon and pion radii pp at $\sqrt{s}$=7TeV

ALICE: Phys. Rev. D 87, 052016 (2013), Phys. Lett. B 717 (2012) 151–161




- $m_T$ dependence of radii is different at small and large multiplicity bins
- Decrease of size with decreasing multiplicity
- Indication on breaking of $m_T$ scaling $R_K$>$R_\pi$ (K: stronger dependence)
- $m_T$ dependence at high multiplicity: expected by models incorporating some collective expansion even in small systems (HKM Rev. D87 094024 (2013) , EPOS arxiv:1104.2405)

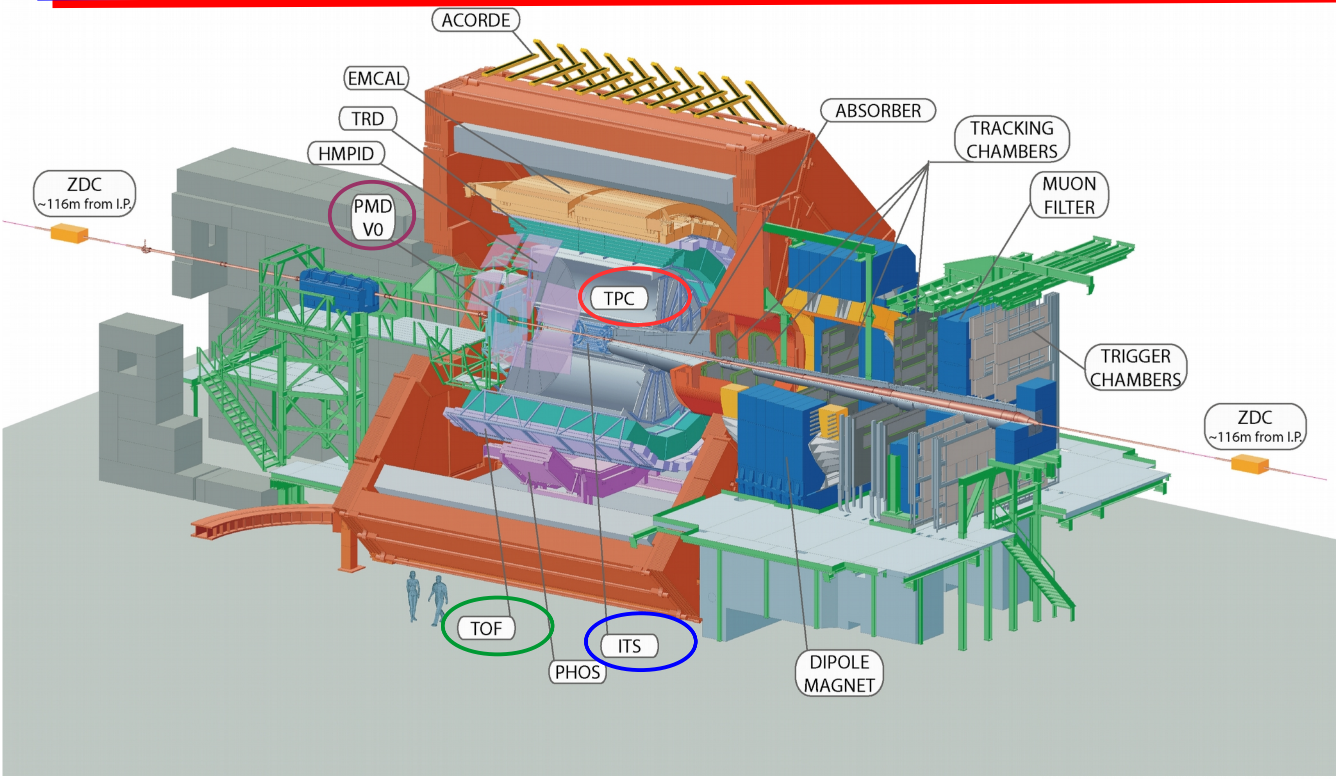
# Conclusions

- The new results from femtoscopic studies of $\pi^{\pm}\pi^{\pm}$, $K^{\pm}K^{\pm}$,$K^0_sK^0_s$, pp and $\overline{pp}$ correlation from **Pb-Pb** collisions at $\sqrt{s_{NN}}$=2.76 TeV have been presented
- *R* and $\lambda$ parameters were extracted from 1d CF in term of $q_{inv}$
- The emission source sizes of kaons and protons measured in Pb-Pb collisions exhibit $m_T$-scaling within uncertainties, which is consistent with a hydrodynamic model prediction assuming collective flow.
- The deviation from the scaling for the pions can be explained as a consequence of the increase of the Lorentz factor with decreasing particle mass during transformation from LCMS to PRF systems
- $\lambda$ parameters are less than 1, due to long-lived resonances and non-Gaussian CF.
- Prediction of HKM for *R* for $K^{\pm}$,$K^0_s$ and protons coincide well with the observations
- The results for $K^{\pm}K^{\pm}$,$K^0_sK^0_s$ correlation from pp at $\sqrt{s}$=7 TeV have been presented
- $m_T$ dependence at high multiplicity expected by models incorporating some collective expansion even in small systems (HKM, EPOS)

*Thank you for your attention!*

BACKUP

# ALICE at LHC




Tracking and vertex

- Time Projection Camber (TPC)

& Inner Tracking System (ITS)

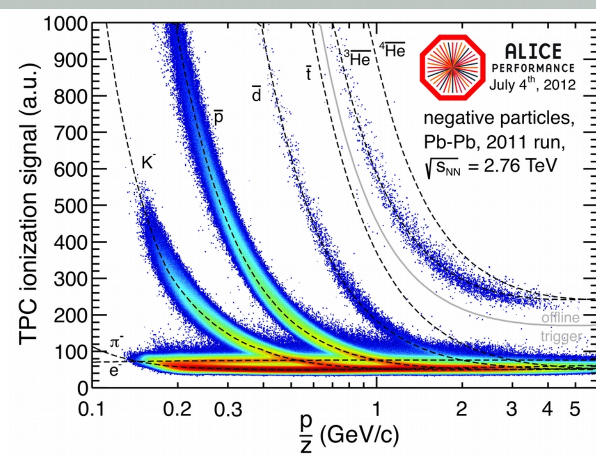
Centrality determination

- V0

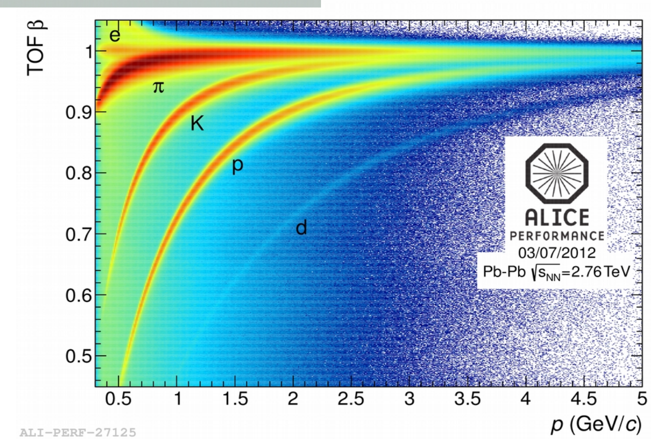
Particle Identification

- TPC and Time of Flight

PID TPC:

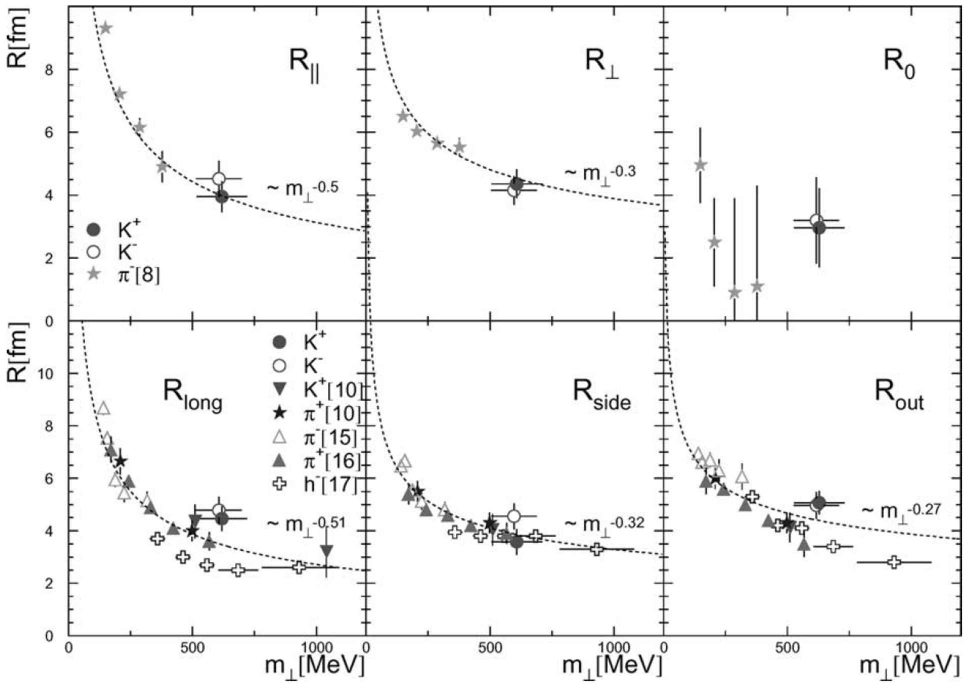


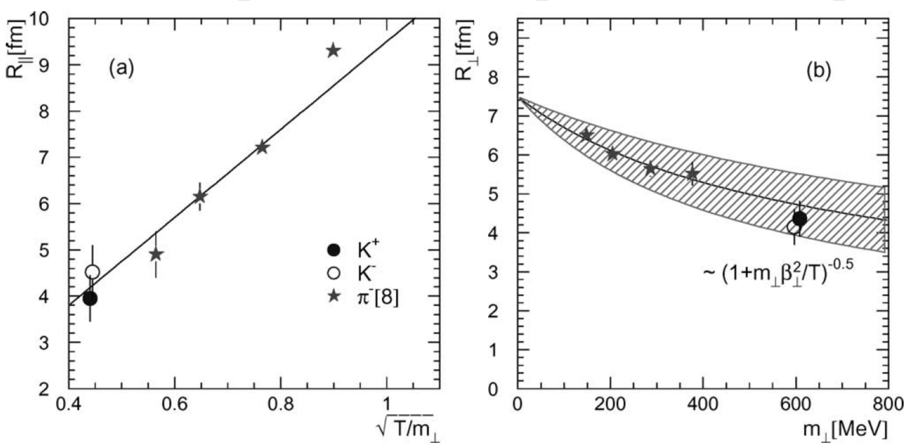

PID TOF:



# Existing world data on kaon femtoscopy: SPS

Bearden et al. [NA44],Phys.Rev. Lett. 87 112301 (2001);
Afanasiev et al.[NA49],Phys. Lett. B 557 157 (2003).



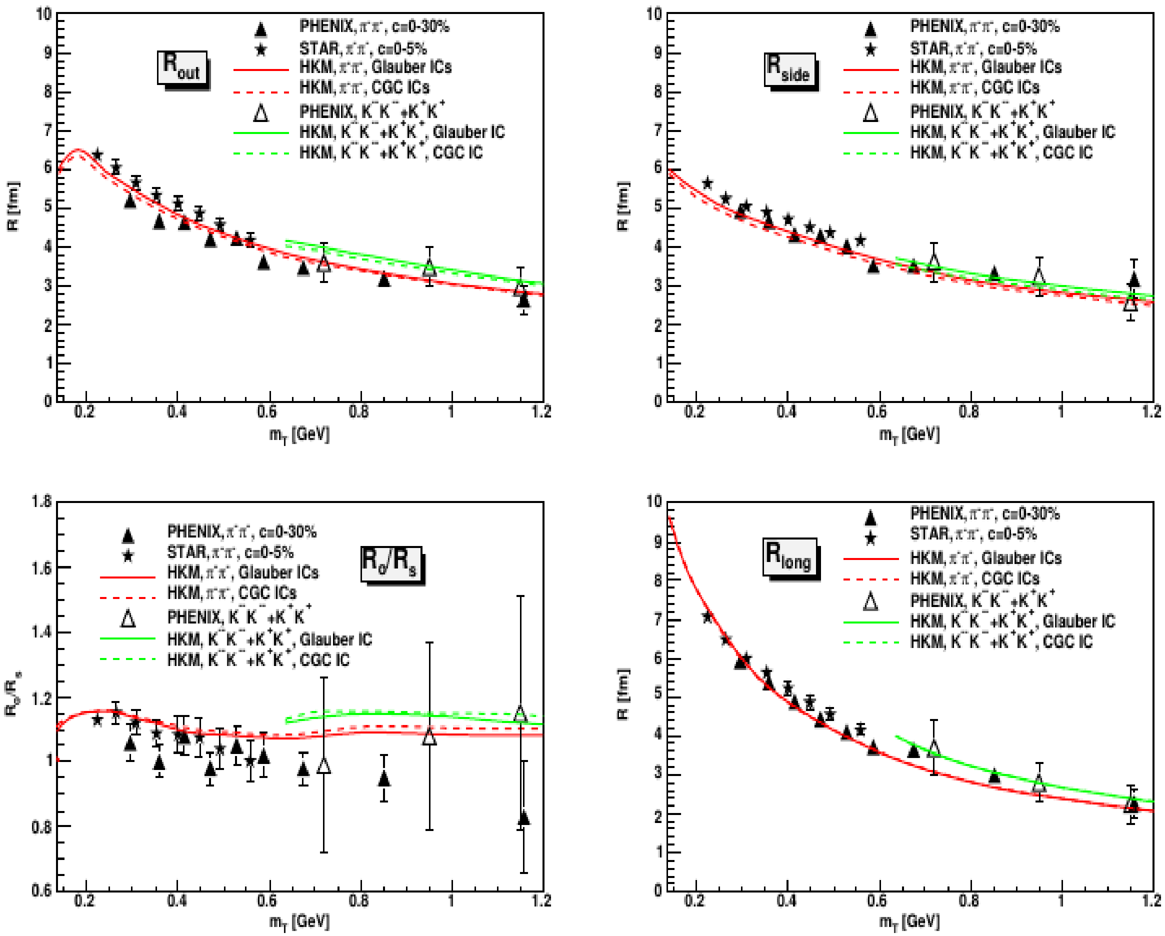

- Pb+Pb collision at $E_{beam}$=158 AGeV
- NA44 & NA49 reported the decrease of the long radii with $m_T$ as $\sim m_T^{-1/2}$ as sugested by Makhlin and Sinyukov in [Z. Phys. C 39 (1988) 69.]
- for transverse radii $\sim m_T^{-0.3}$
- common $m_T$ -scaling for π & K → thermal freeze-out occurs simultaneously for π & K and they receive a common Lorentz boost.

- Freeze-out time 9.5 fm: $R_{\parallel} = \tau_f \sqrt{T/m_{\perp}}$
- weak dependence of $R_T$ on $m_T$ was reproduced by hydrodynamic model with T~120 MeV and $\beta_T$~ 0.55

[S. Chapman, P. Scotto, U. Heinz, Phys. Rev. C 52 (1995) 2694.]

# Existing world data on kaon femtoscopy: RHIC

Adams J. et al. (STAR Collaboration) Phys. Rev. Lett. 92, 112301 (2004) & Phys. Rev.C 71, 044906(2004); Adler S.S. et al. (PHENIX Collaboration) Phys. Rev. C.69, 034909(2004) & Phys. Rev. Lett. 93, 152302 (2004) & Phys. Rev. Lett. 103, 142301 (2009)




- AuAu $\sqrt{s_{NN}}$=200 GeV
- no universal $m_T$ -scaling for long, out, side radii.
- for π & K flat dependencies of radii → consequence of the freeze-out at the same hyper-surface.
- Hydro Kinetic Model (HKM) [Iu.Karpenko, Yu.Sinyukov, Phys. Part. Nucl. Lett. 8 (2011)] reproduces well π & K spectra and femtoscopic radii at RHIC energies.

# $K^{\pm}K^{\pm}$ correlation functions p-p@7TeV

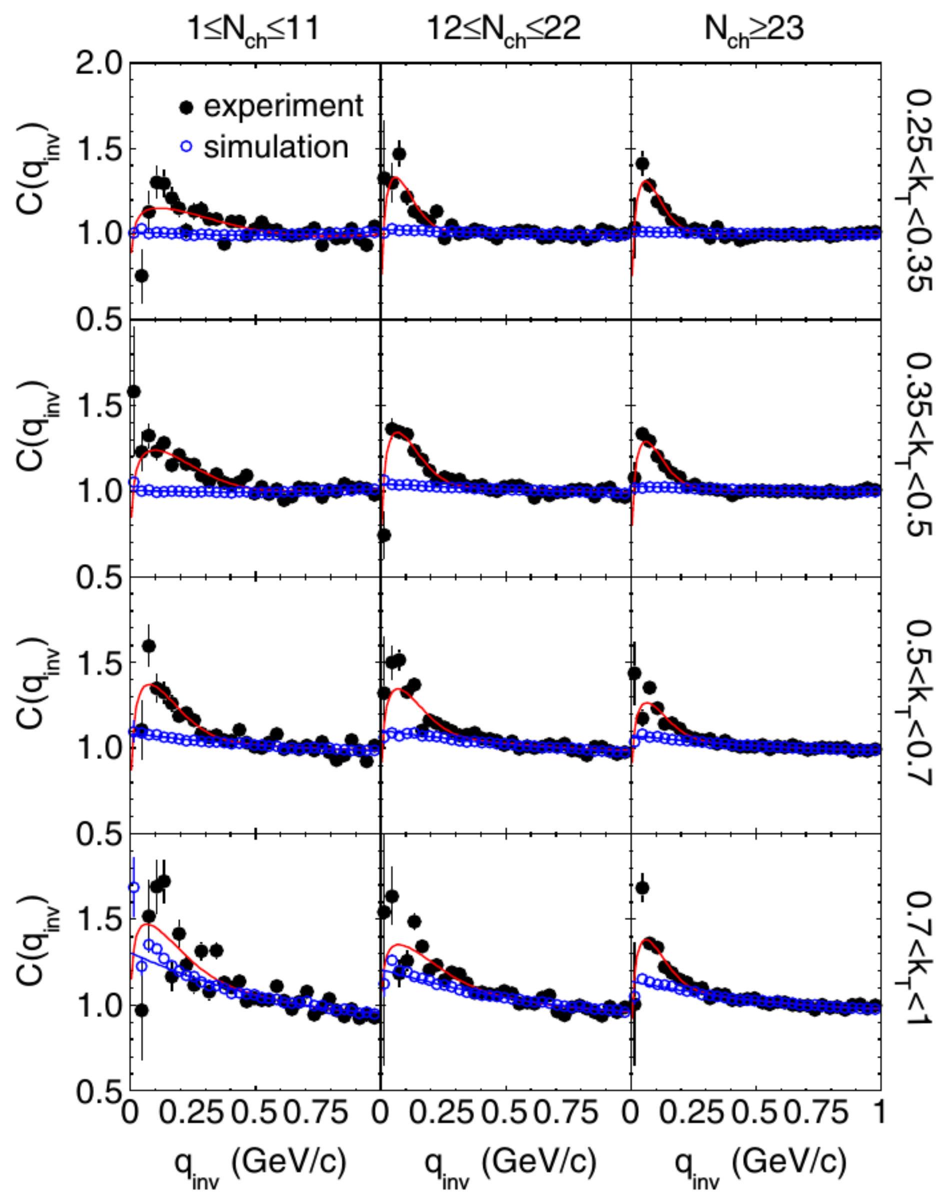
*B. Abelev et al. (ALICE Collaboration)*
*Phys. Rev. D 87, 052016 (2013)*

- 3 bins in charged particle multiplicity with **$\langle dN_{ch}/d\eta \rangle$: 3.2, 8.1, and 17.2**
- **4** bins in $k_T$ bins (0.2-0.35) (0.35-0.5) (0.5-0.7) (0.7-1.0) GeV/c.
- ~300 mln MB events
- Fit by Bowler-Sinyukov formula :

**$CF=N(1-\lambda+\lambda K_{coul}(1+\exp(-R^2 q_{inv}^2)))P_2$**

**$P_2=1+aq+bq^2$** - baseline, **$K_{coul}$** -Coulomb

- PYTHIA (PERUGIA2011) was used to model baseline. Parameters a,b were fixed. Fit with different functional forms: **$\sqrt{1 + a Q_{inv}^2 + b Q_{inv}^4}$** & Gaussian was performed to estimate systematic errors.



# $K^0_s K^0_s$ Correlation functions p-p@7TeV

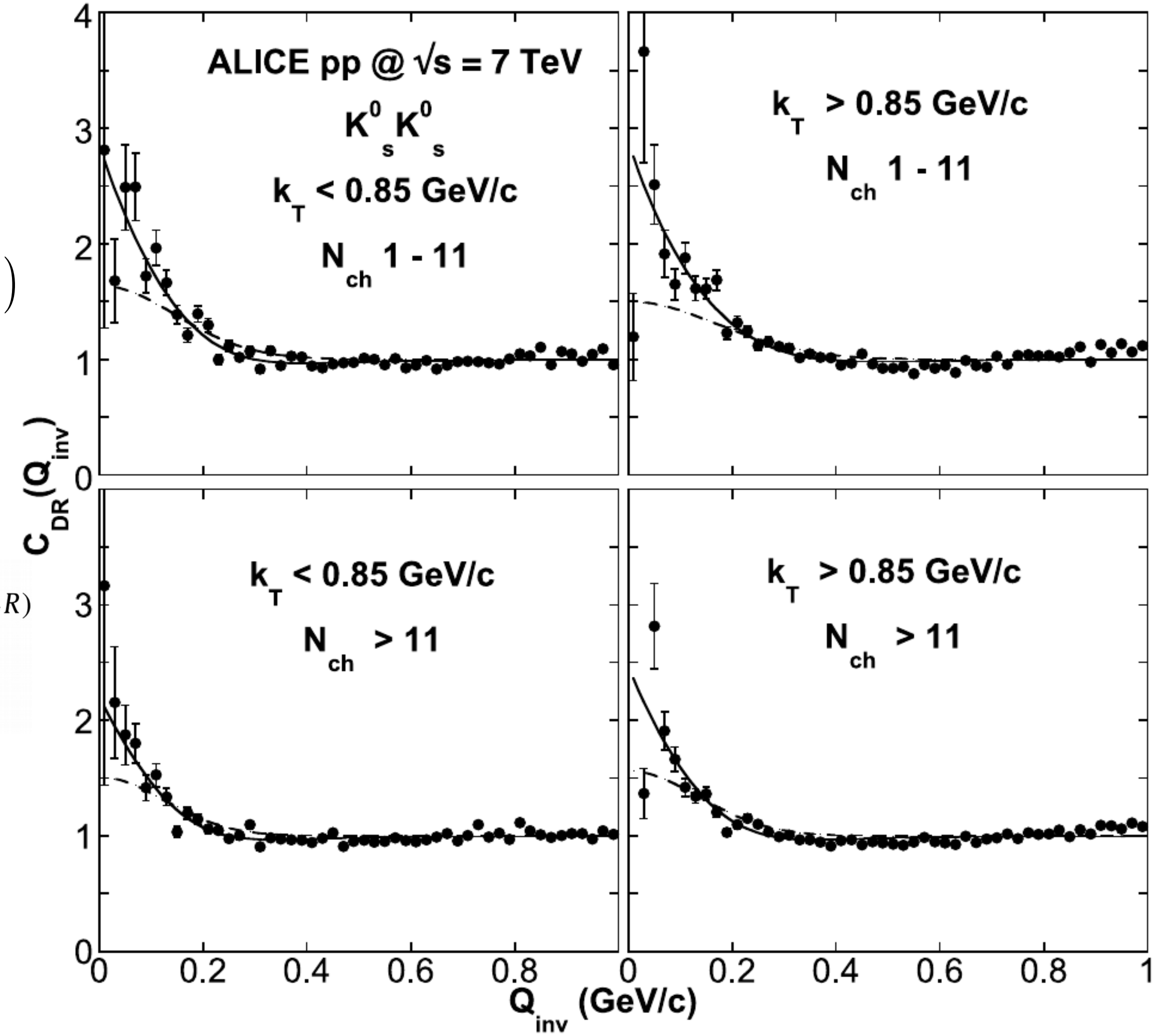
B. Abelev et al. (ALICE Collaboration) Physics Letters B 717 (2012) 151–161

- **$C_{DR}(Q_{inv})$** experimental $K^0_s\,K^0_s$ correlation functions divided by PYTHIA correlation function

- **Fit:** $C_{DR}(Q_{inv}) = 1 - \lambda + \lambda C'(Q_{inv})$
*$C'(Q_{inv})$* theoretical CF (full line), includes QS(dashed line) and Strong FSI ($a_0$,$f_0$ resonanses)

$$C'(Q_{\text{inv}}) = 1 + e^{-Q_{\text{inv}}^2 R^2} + \alpha\left[\left|\frac{f(k^*)}{R}\right|^2 + \frac{4\Re f(k^*)}{\sqrt{\pi}R}F_1(Q_{\text{inv}}R) - \frac{2\Im f(k^*)}{R}F_2(Q_{\text{inv}}R)\right]$$

$$F_1(z) = \int_0^z dx\,\frac{e^{x^2-z^2}}{z};\qquad F_2(z) = \frac{1-e^{-z^2}}{z}$$




- Pure Gaussian fit (dashed line) gives 10-40% larger radius

# $K^0_s$ PID p-p@7TeV

*B. Abelev et al. (ALICE Collaboration)*
*Physics Letters B 717 (2012) 151–161*

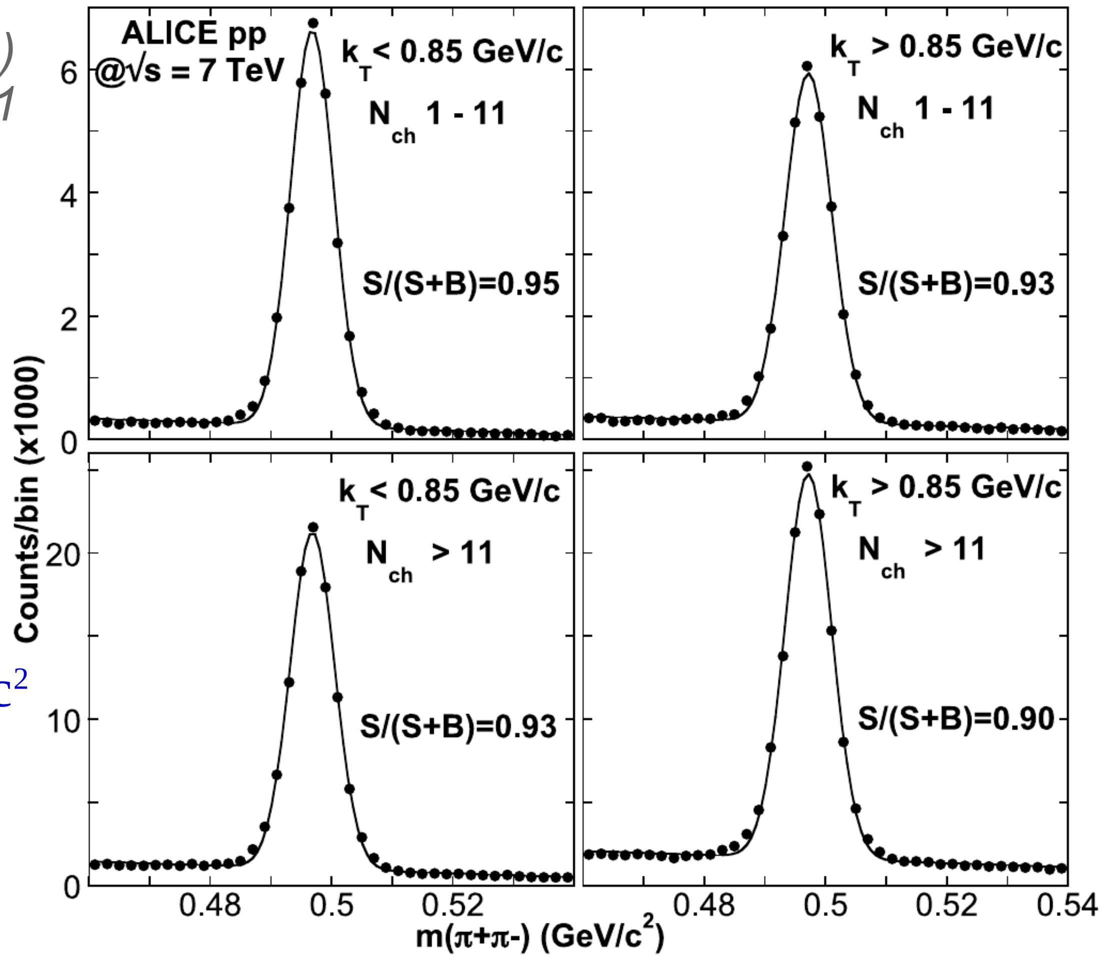
$K^0_s \rightarrow \pi+\pi-$ as PID

Mometnum resolution ~ 1%

Average peak width 3.72 MeV/c²

Invariant mass at peak 0.497 MeV/c²

S/(S+B) is greather than 0.90



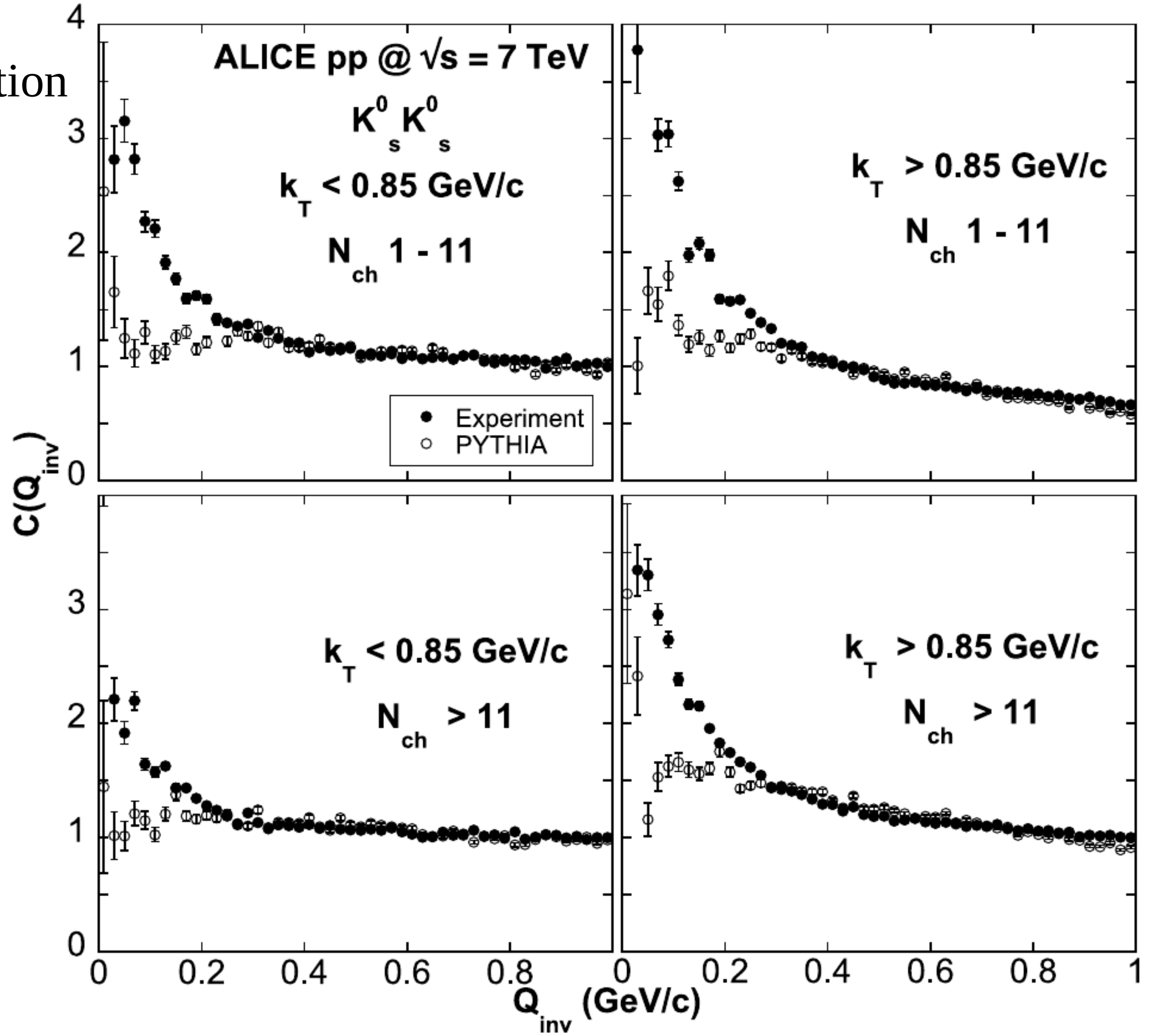
# $K^0_sK^0_s$ Raw correlation functions p-p@7TeV

*B. Abelev et al. (ALICE Collaboration) Physics Letters B 717 (2012) 151–161*

- $K^0_sK^0_s$ experimetal correlation funtion
- An enhancement at low Qinv is a femtoscopic correlation

o PYTHIA correlation function does not show such an enhacement

o PYTHIA describe an experimental baseline



# Hadronic rescattering model

*T. Humanic Phys. Rev. C 57 (1998) 866*

Rescattering is simulated with a semiclassical MC calculation which assumes strong binary collition between hadrons:

1) initialization and hadronization
2) rescattering and freeze-out
3) calculation of hadronic observables

Momentum: $\frac{1}{m_T}\frac{dN}{dm_T}=C\cdot\exp\left(-\frac{m_T}{B_{init}}\right), m_T=\sqrt{p_T^2+m^2}$ $\quad\frac{dN}{dy}=D\cdot\exp\left(-\frac{(y-y_0)^2}{2\sigma_y^2}\right), y=\frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right)$

$$B_{init}=T_{init}+m\beta_{init}^2$$

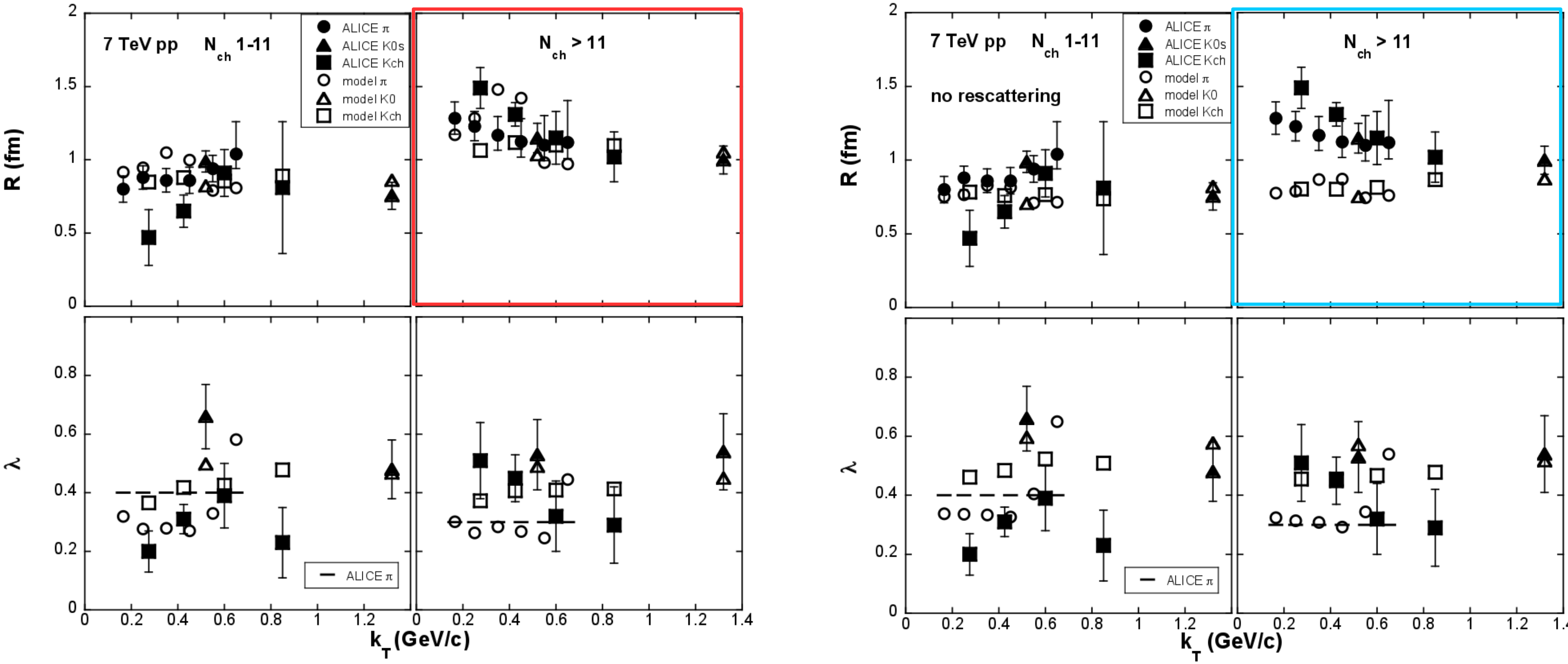
Space-time, transverse uniform sphere : $x_{had}^2+y_{had}^2=R, R=rndm()\cdot r_0 A^{1/3}, r_0=1.12\,fm$

Longitudinal hadronization($z_{had}$) position and time($t_{had}$): $z_{had}=\tau_{had}\cdot\sinh(y), t_{had}=\tau_{had}\cdot\cosh(y)$

Rescattering model have four free parameters: $\sigma_{y,init}, T_{init}, \beta_{init}, \tau_{init}$

# Theoretical considerations of femtoscopy results in pp

T. Humanic J.Phys. G41 (2014) 075105, arXiv:1312.2303



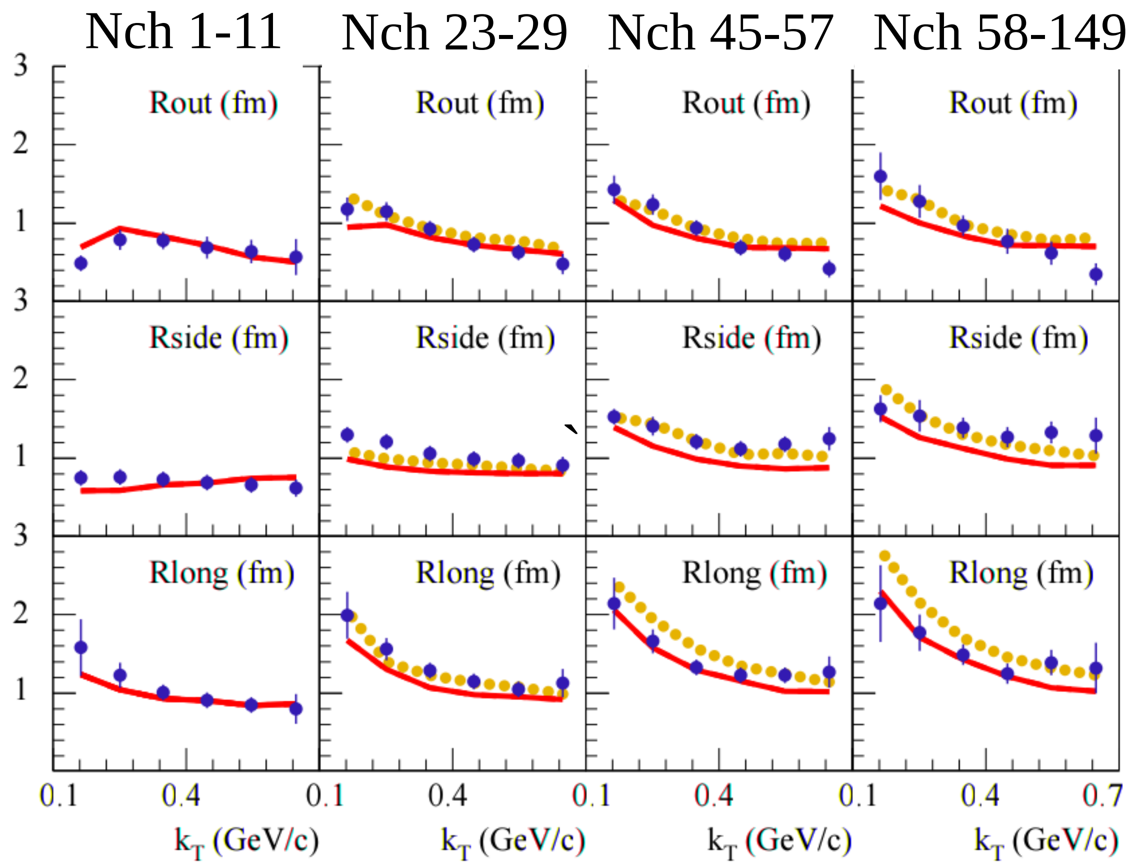

- hadronic rescattering model with proper time (τ free par.) was compared with ALICE
- reasonable description of the measured source parameters for τ=0.4±0.1 fm/c
- "collective motion" of the system due to rescattering is needed to explain the data

# EPOS model

*K.Werner arXiv:1104.2405*

Dots pion radii (pp@7TeV) from PhysRevD.84.112004

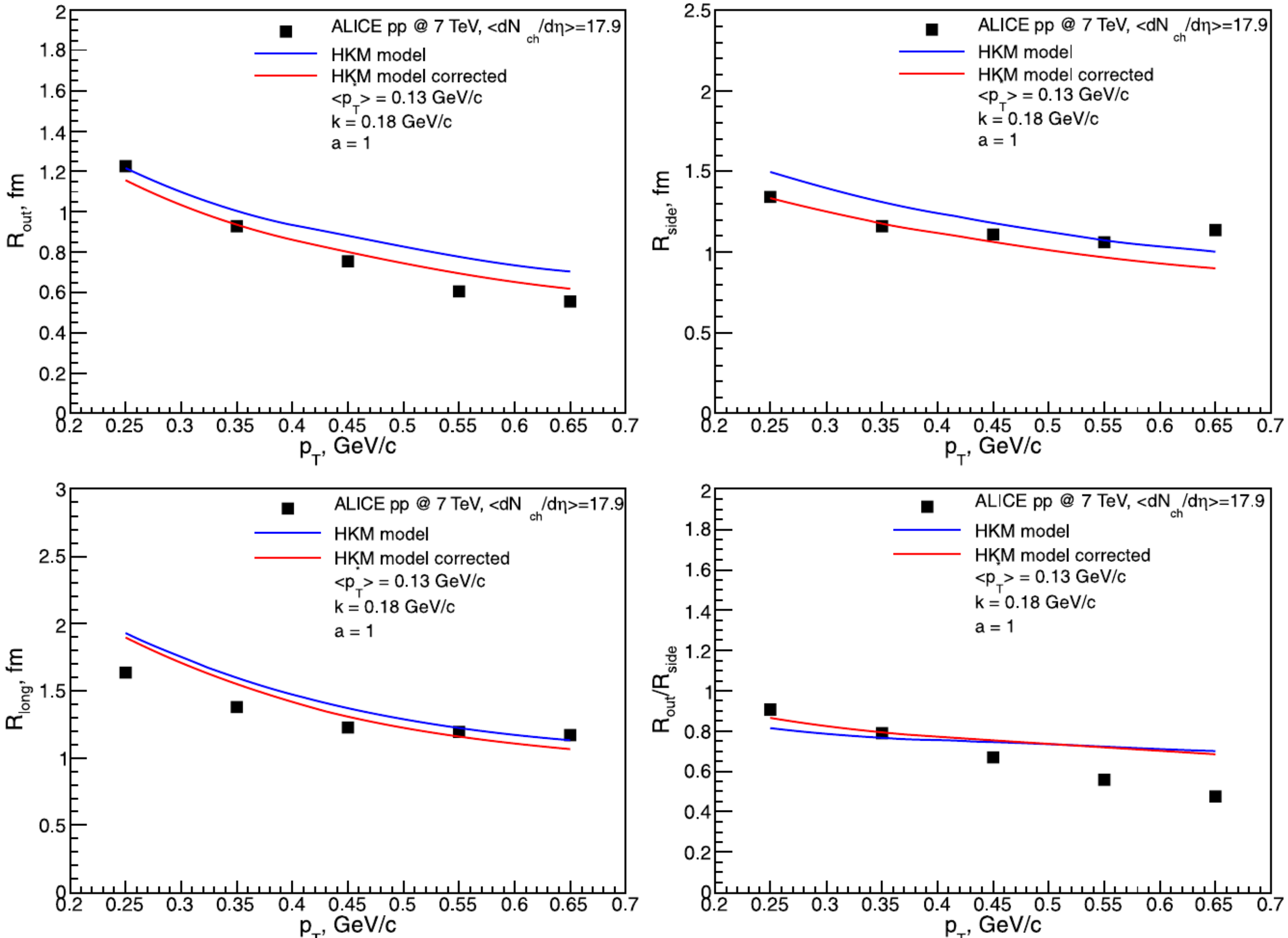
Curves is EPOS calculation with two different EoS




All radii indeed show a more and more pronounced decrease with increasing kT , for data and simulations, which can – in the calculations – clearly be attributed to collective flow. For the case Milt 1 the radii Rout and Rside are essentially flat, only Rlong has already some kT dependence. So we see here nicely the transition from a longitudinal expansion (string) towards a three-dimensional hydrodynamical expansion for higher multiplicities.

# HKM model

*V.M. Shapoval a, P. Braun-Munzinger, Iu.A. Karpenko, Yu.M. Sinyukov, Phys. Let. B 725 (2013) 139–147*




Dots pion radii (pp@7TeV)
from PhysRevD.84.112004

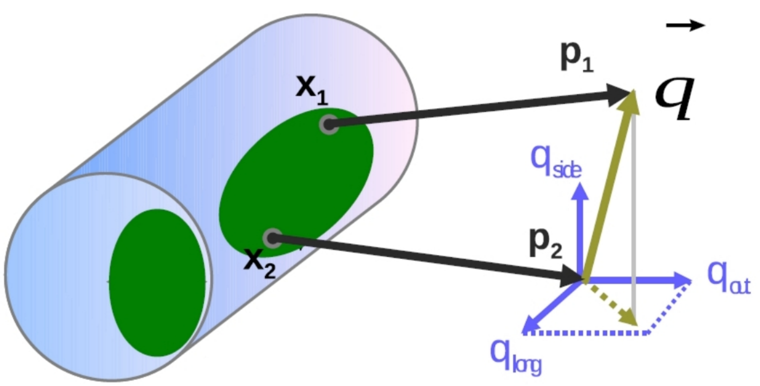
Curves: HKM calculation

# LCMS

The correlation function usually parametrized in term of the Gaussian correlation radius ***R*** : $C(q_{inv}) = 1 + \lambda \exp(-R^2 q_{inv}^2)$ one dimensional case.
***R*** is a Gaussian radius in Pair Rest Frame (**PRF**). 1d- analysis is only sensitive to the system size averaged over all directions.The correlation strength parameter
***λ*** represents a fraction of identical particles emitted by independent short-lived sources.

Three dimensional: $C(q_{out}, q_{side}, q_{long}) = 1 + \lambda \exp(-R_{out}^2 q_{out}^2 - R_{side}^2 q_{side}^2 - R_{long}^2 q_{long}^2)$
$\boldsymbol{q_\mu}$, $R_\mu$ ($\boldsymbol{\mu}$=out,side,long) decompositon in Longitudinally Co-Moving Frame (**LCMS**):

long || beam direction
out || transverse pair velocity $\mathbf{v_T}$, $\mathbf{k_T}$
side normal to out,long




$R_{side}$ sensitive to geometrical transverse size.
$R_{long}$ sensitive to time of freeze-out.
$R_{out} / R_{side}$ ~ sensitive to emission duration.

# Bose–Einstein correlations of charged and neutral kaons in pp and Pb-Pb collisions at the LHC with the ALICE experiment.

Konstantin Mikhaylov (ITEP-JINR) for ALICE collaboration

*Abstract*

Due to the effects of quantum statistics and final state interactions, the momentum correlations of two or more particles at small relative velocities, i.e. at small relative momenta in their center-of-mass system, are sensitive to the space-time characteristics of the production processes on the level of fm = $10^{-15}$ m. Kaons are the perfect tool to study Bose-Einstein correlations due to the fact that kaons are less influenced by resonance decays and therefore more effectively probe directly produced particles. In conjunction with femtoscopic measurements of pions and protons, they can also reveal properties of collective dynamics in heavy-ion collisions. We report on the results of Bose–Einstein correlations of charged and neutral kaons in pp collisions at sqrt(s) = 7 TeV and in Pb-Pb collisions at sqrt($s_{NN}$) =2.76 TeV by the ALICE experiment at the LHC. The results are compared to existing data from Bose-Einstein correlations of identical pions at LHC energies, and of kaons in different collision systems. A comparison of experimental data to theoretical expectations will be carried out.