Studying the dynamics of particle-emitting sources in p–Pb and Pb–Pb collisions with ALICE at LHC energies using femtoscopy

Romanenko G., Tomassini S. (University and INFN Bologna)

on behalf of the ALICE Collaboration

CosmicAntiNuclei

European Research Council
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ALICE

Istituto Nazionale di Fisica Nucleare
Sezione di Bologna

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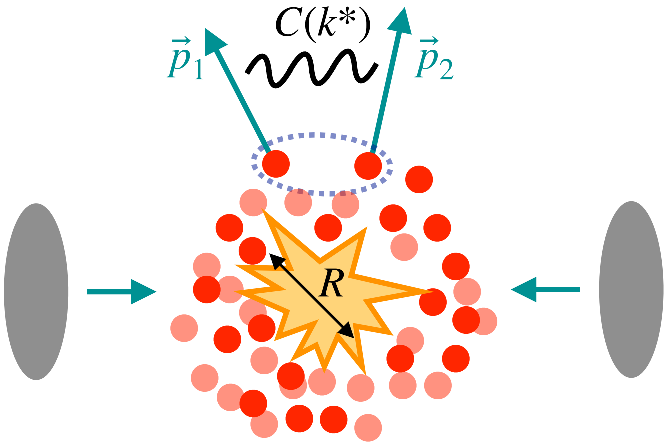
ICHEP 2024
Prague, 20/07/2024

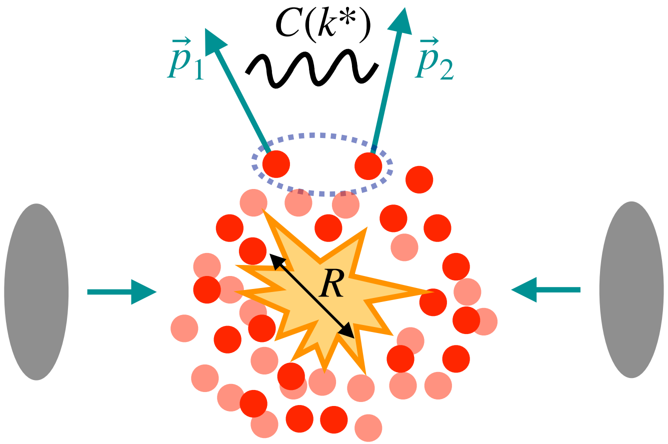
Femtoscopy



$2k^* = |\vec{p}_1 - \vec{p}_2|$ —> **rel. momentum of a pair**

Correlation femtoscopy is used for studying space–time properties of an emission source via particle correlations based on quantum statistics (QS), strong and Coulomb interactions.

Femtoscopy



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Correlation femtoscopy is used for studying space–time properties of an emission source via particle correlations based on quantum statistics (QS), strong and Coulomb interactions.

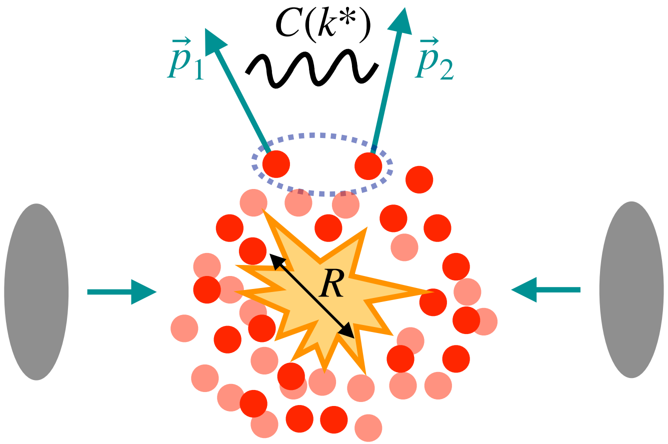
Femtoscopic correlation function (CF) experimentally obtained as a ratio:

$$\mathbf{C}(k^*) = \mathbf{N} \cdot \frac{\mathbf{S}(k^*)}{\mathbf{B}(k^*)}$$

$\mathrm{S}(k^*)$ — rel. momentum distribution of pairs measured in the same event;

$\mathrm{B}(k^*)$ — rel. momentum distribution of pairs measured in different events;

Femtoscopy



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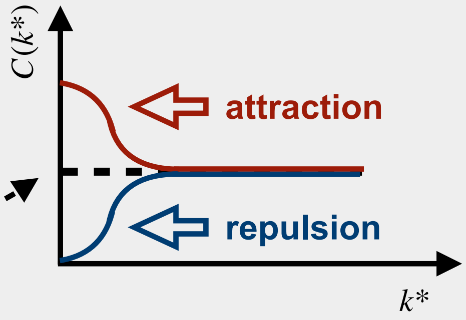
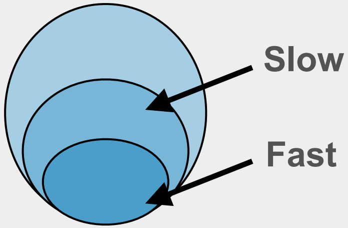
Correlation femtoscopy is used for studying space–time properties of an emission source via particle correlations based on quantum statistics (QS), strong and Coulomb interactions.

Motivation:

- Measure the spatial & temporal characteristics of the particle-emitting regions;
- Study strong interaction;
- Study collective dynamics (e.g. radial flow);
- Check and constrain theoretical models;



Expanding source -> x:p correlation



Parametrisation of the correlation function

1D parametrisation in Pair Rest Frame (PRF*):

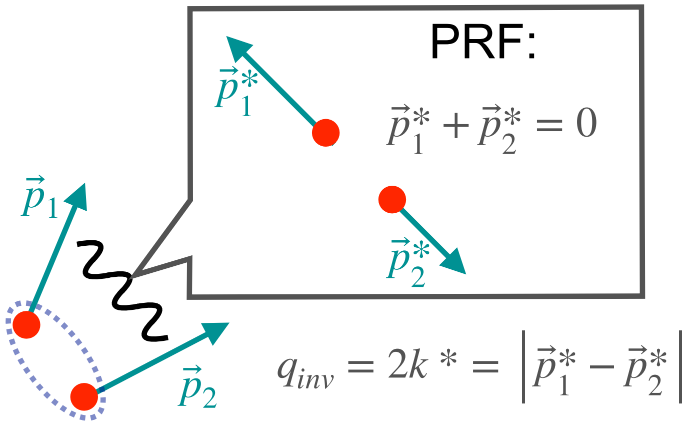
$$C(q_{\rm inv}) = N\left[(1-\lambda)+\lambda K(q_{\rm inv})\left(1+exp(-R^2_{\rm inv}q^2_{\rm inv})\right)\right]$$

λ — correlation strength

N — normalisation

$K(q_{inv}) = \frac{C(QS+Coulomb)}{C(QS)}$ — models Coulomb interaction

$R_{\rm inv}$ — 1D radius — corresponds to geometrical size of the system



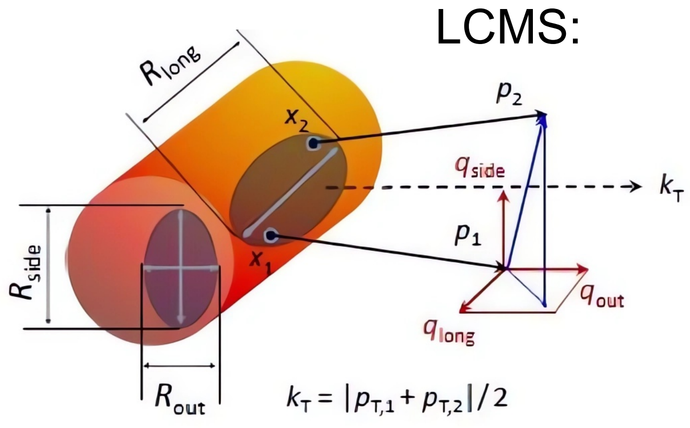
3D parametrisation in Longitudinally Co-Moving System (LCMS):

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

$R_{\rm side}$ — sensitive to transverse geometrical size of the system

$R_{\rm long}$ — sensitive to system's freeze-out duration

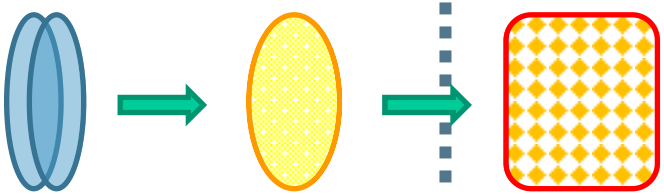
$R_{\rm out}/R_{\rm side}$ — sensitive to the duration of particle emission



Kaon source

Kaon femtoscopy: motivation

ALICE results on $K^{ch}K^{ch}$ femtoscopy at $\sqrt{s_{NN}}$ = 2.76 TeV showed that the models successfully describing pions might not be good for kaons (ALICE, PRC 96 (2017), p.064613): kaon radii are larger than the pion ones

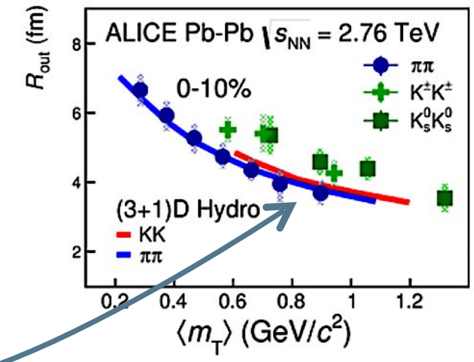


Pre-equilib. phase — Hydrodynamic phase — Rescattering phase

Hydrodynamic models – m_T-scaling exist

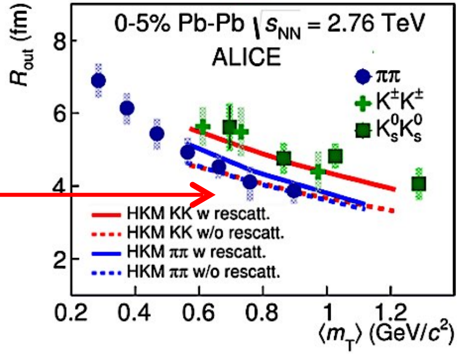
Hydrokinetic models – m_T-scaling is broken

$$m_T = \sqrt{k_T^2 + m^2}$$



Predictions are from the THERMINATOR 2 model which uses pure hydrodynamic approach

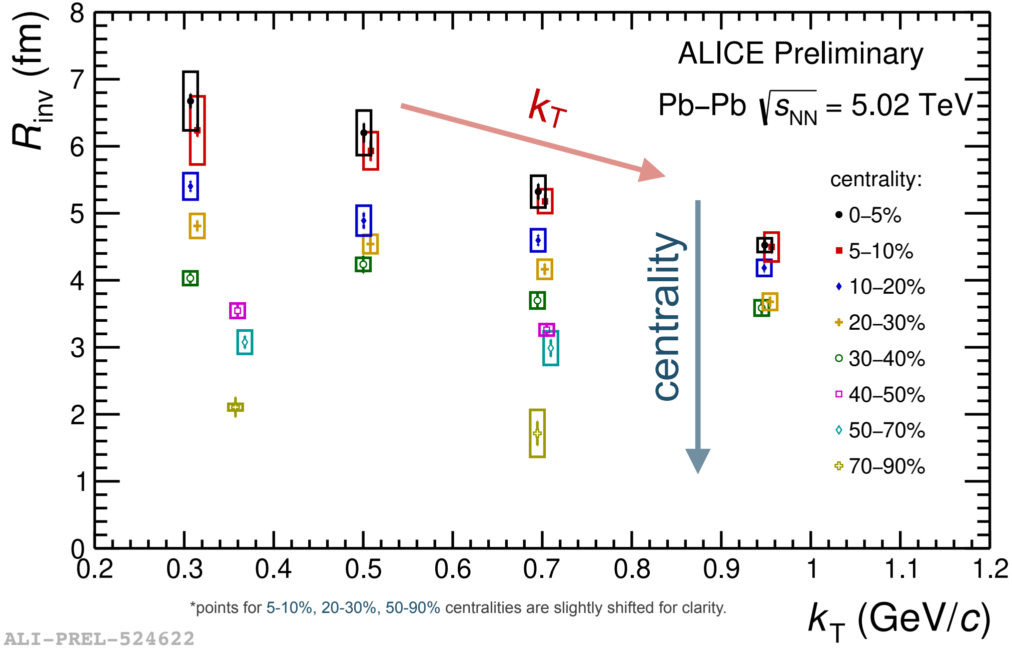
A. Kisiel et al. PRC 90, 064914

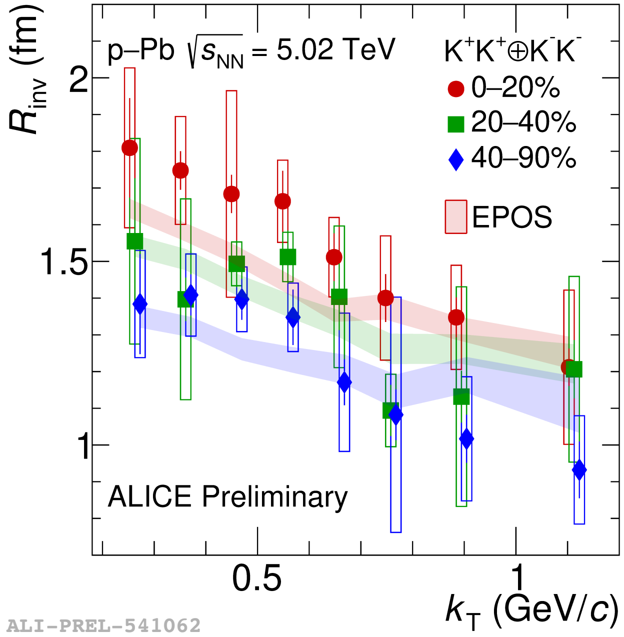


Integrated Hydrokinetic Model (iHKM) is used to check theoretical predictions for kaon femtoscopic radii

V. Shapoval et al., NPA 929 (2014)

Kaon 1D radii in Pb–Pb and p–Pb at 5.02 TeV



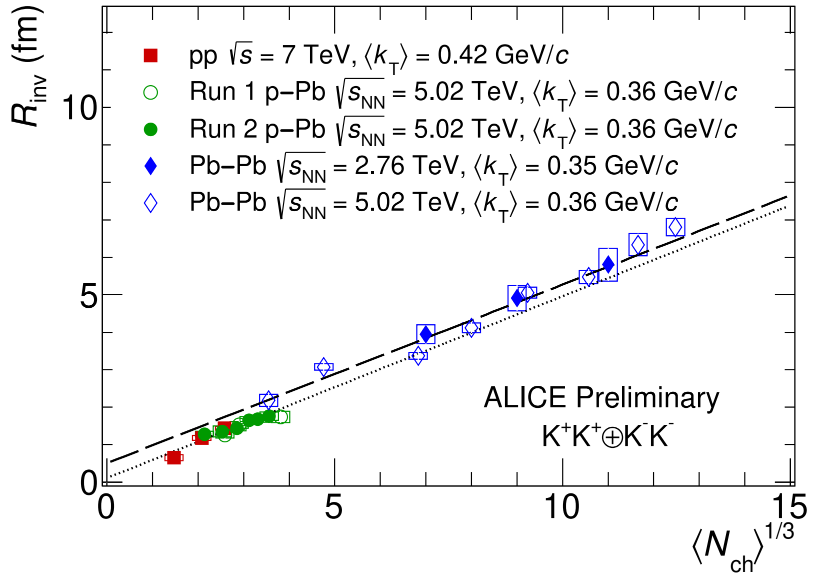


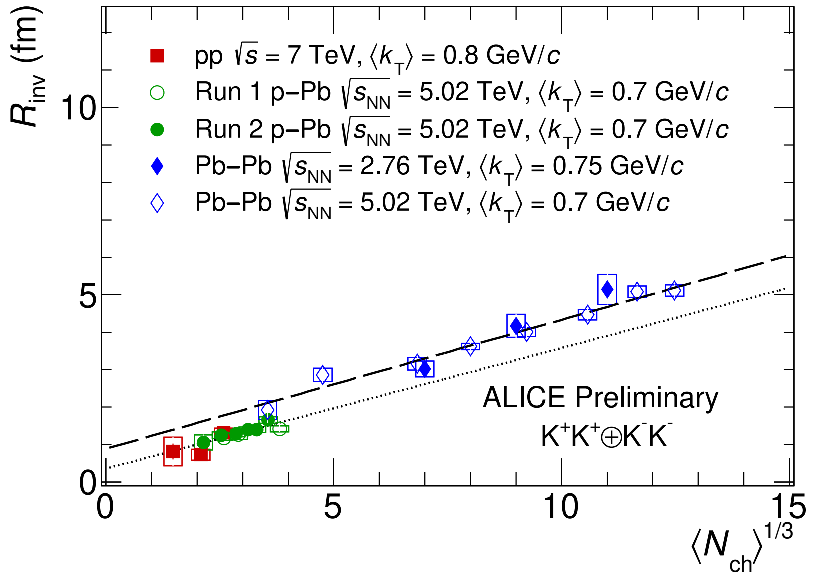
EPOS: hydro core evolution + hadronic phase modelled with UrQMD

K.Werner et al., PRC89(2014)064903

- The source size decreases from central towards peripheral events.
- R_{inv} decreases with increasing k_T → presence of collective (radial) flow.
- Radial flow weakens from central towards peripheral events.

Testing the "multiplicity-scaling hypothesis"





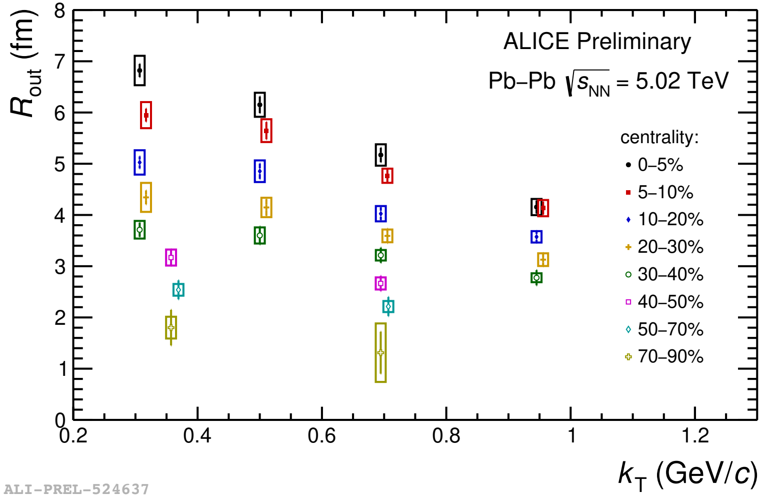
dashed line — fit of Pb–Pb (Run 1 + Run 2) radii;

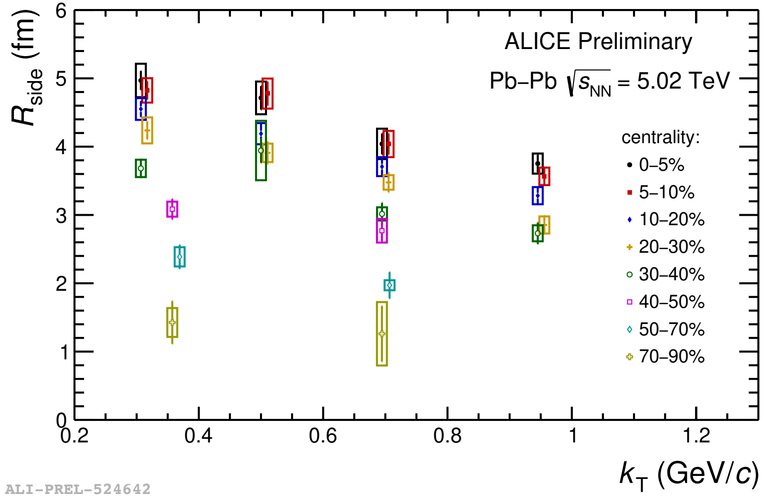
dotted line — fit of pp & p–Pb (Run 1 + Run 2) radii;

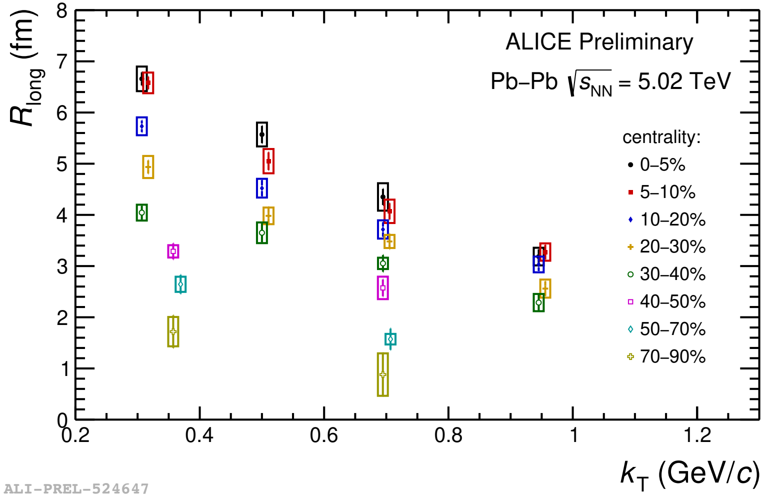
- At similar multiplicity: R_{inv}(Pb−Pb) > R_{inv}(p−Pb) ≈ R_{inv}(pp)
- R_{inv} obtained in pp and p−Pb do not follow the same trend of R_{inv} in Pb−Pb — similar effect was observed for pions (B. Abelev et al., PLB 739 (2014), pp. 139–151)
- Discrepancy between the two trends increases with increasing k_T

⇨ Models predicting "multiplicity-scaling" across different colliding systems are disfavoured (e.g. M. Lisa et al., Ann.Rev.Nucl.Part.Sci.55:357-402(2005)).

Kaon 3D radii in Pb–Pb at 5.02 TeV





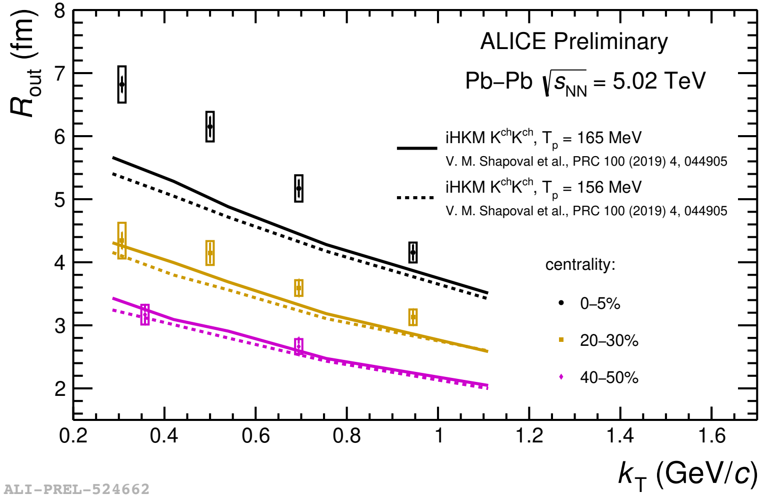


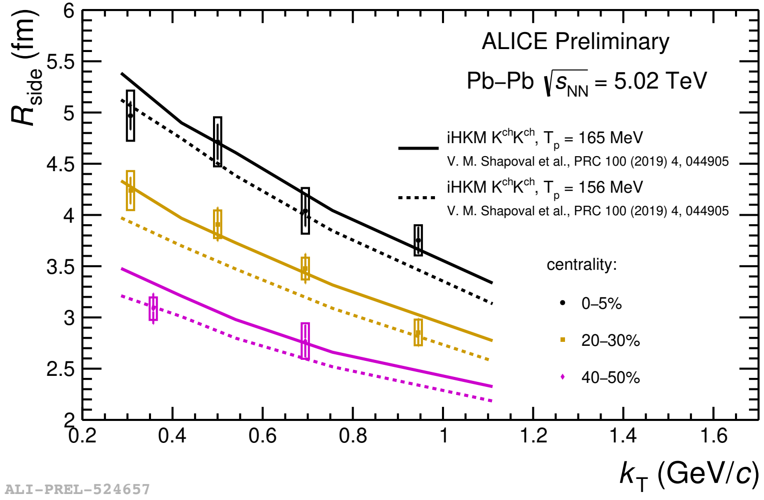
Extracted 3D radii show similar dynamics as 1D ones:

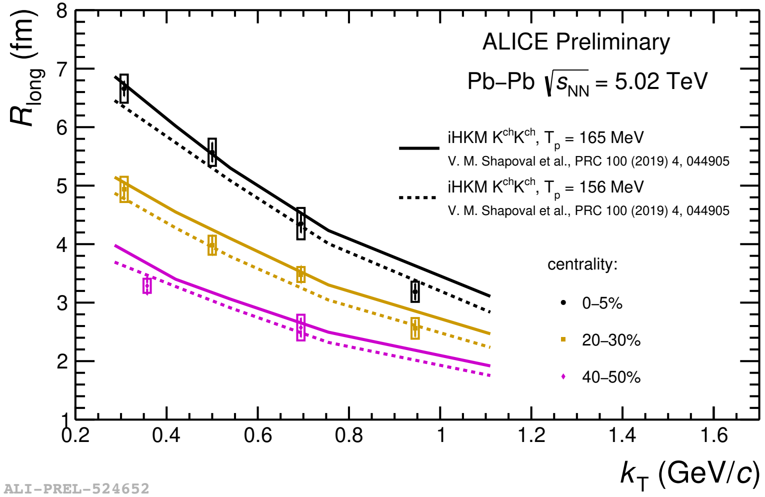
- Size decreases from central towards peripheral events.
- Presence of collective (radial) flow.
- Radial flow weakens from central towards peripheral events.

*points for 5–10%, 20–30%, 50–90% centralities are slightly shifted for clarity.

Kaon 3D radii in Pb–Pb: comparison with iHKM

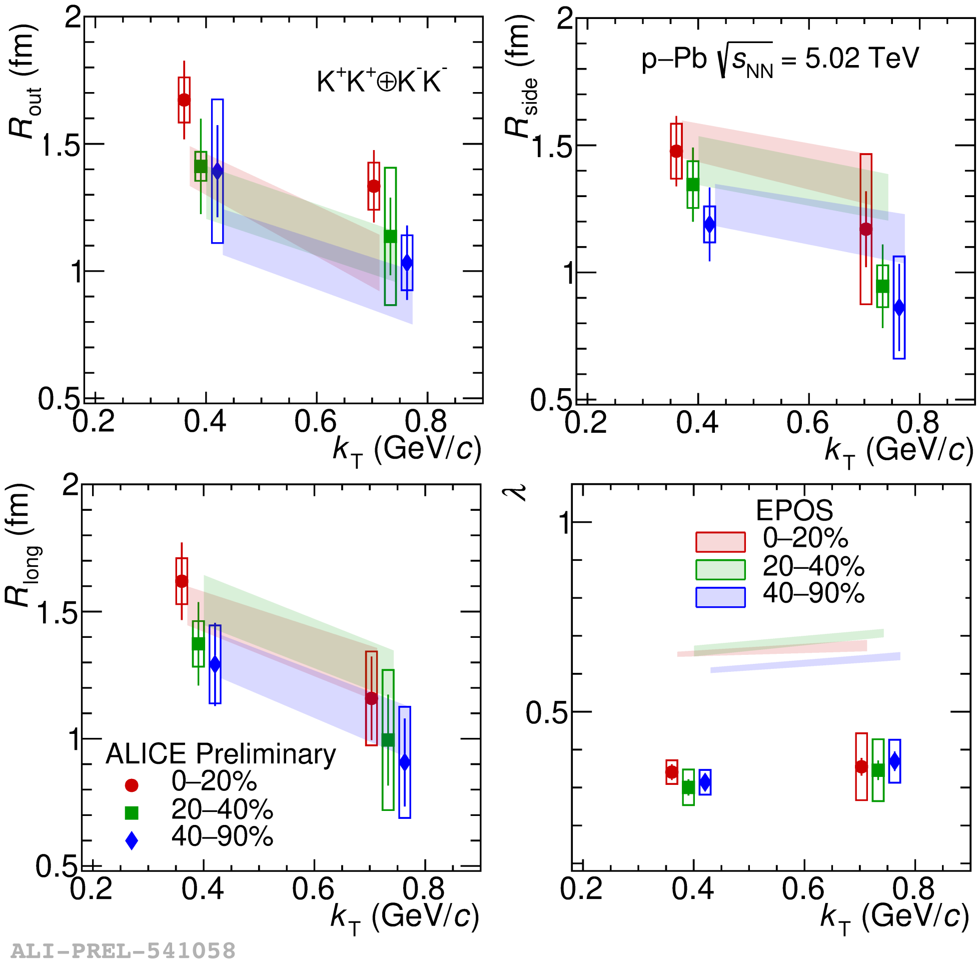






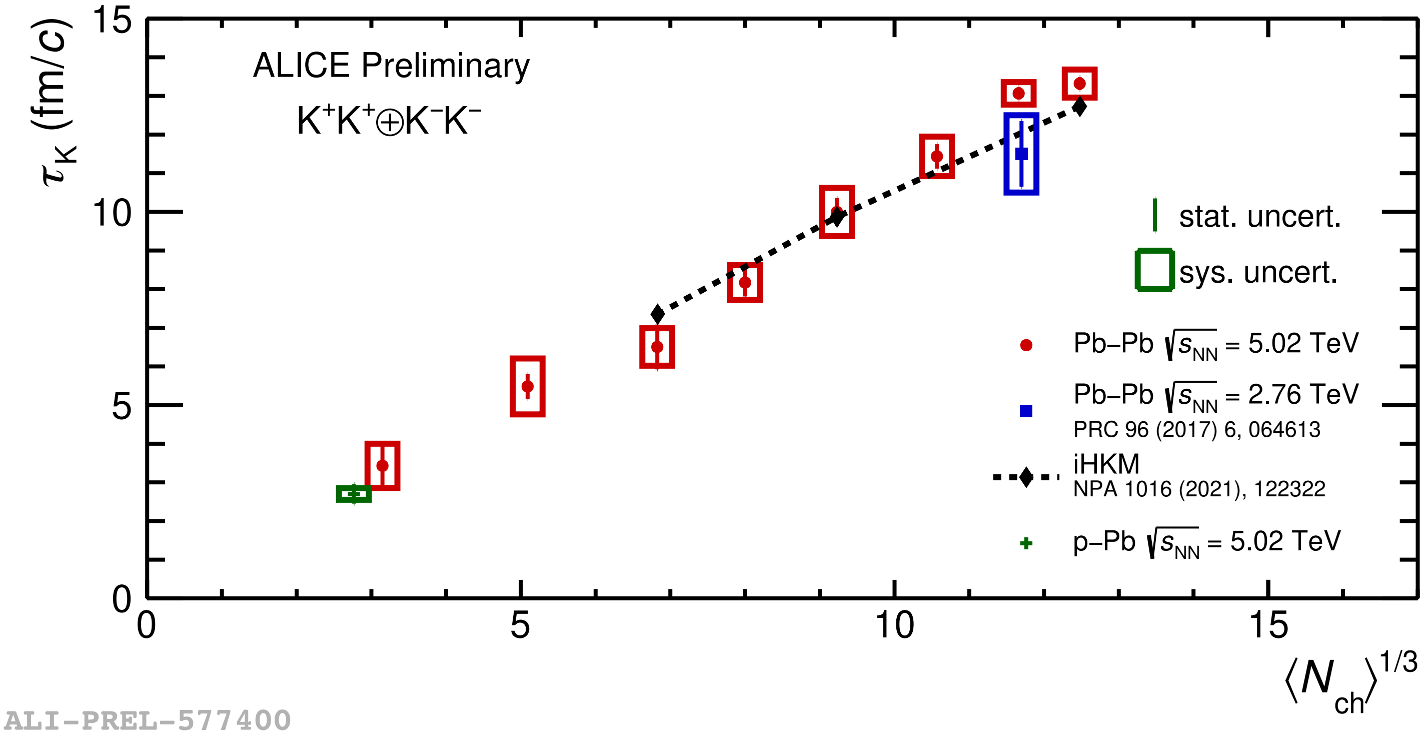
- Two particlization temperatures are considered.
- Both scenarios are in a good agreement with data.
- The model calculations underestimate R_{out} for for the most central events (0–5% cent.).

Kaon 3D radii in p–Pb: comparison with EPOS



- k_T and centrality dependence → hydrodynamic expansion
- EPOS describes radii within uncertainties
- EPOS overestimates λ → production of K from resonances like K* to be revised in the model?
- The model calculations underestimate R_{out} for the most central events (0-20% cent.).

Results: maximal emission time



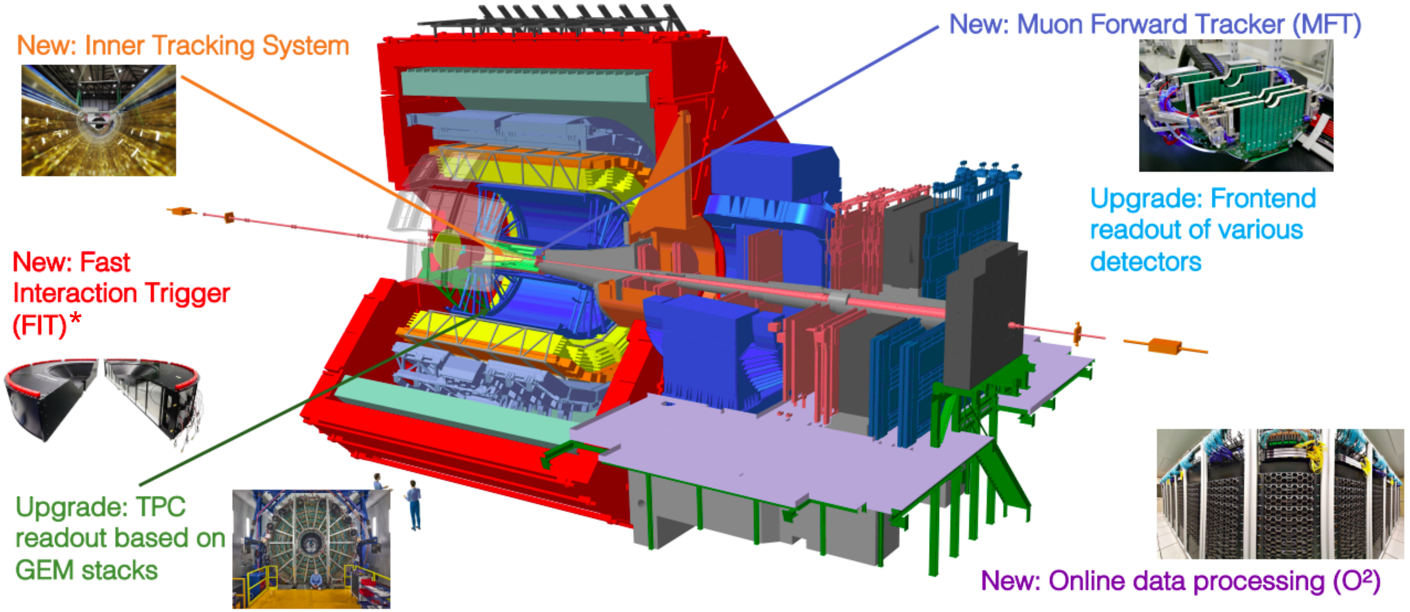
The lifetime τ of the expanding fireball is associated with the moment when the number of correlated particles emitted by the source is maximal.

Details about the extraction procedure:
V. Shapoval et al., EPJ. A 56, 260 (2020)

- Combining results on τ and radii → smaller systems evolve faster.
- iHKM calculations of τ are in good agreement with the experimental data.

Proton source

Results from the first Pb–Pb data of Run 3 with a “new” ALICE detector



…more Run 3 results in:

- Abhi Modak (18/07/24, 09:55)
- Luca Barioglio (20/07/24, 17:53)
- Nicoló Jacazio (22/07/24, 10:50)

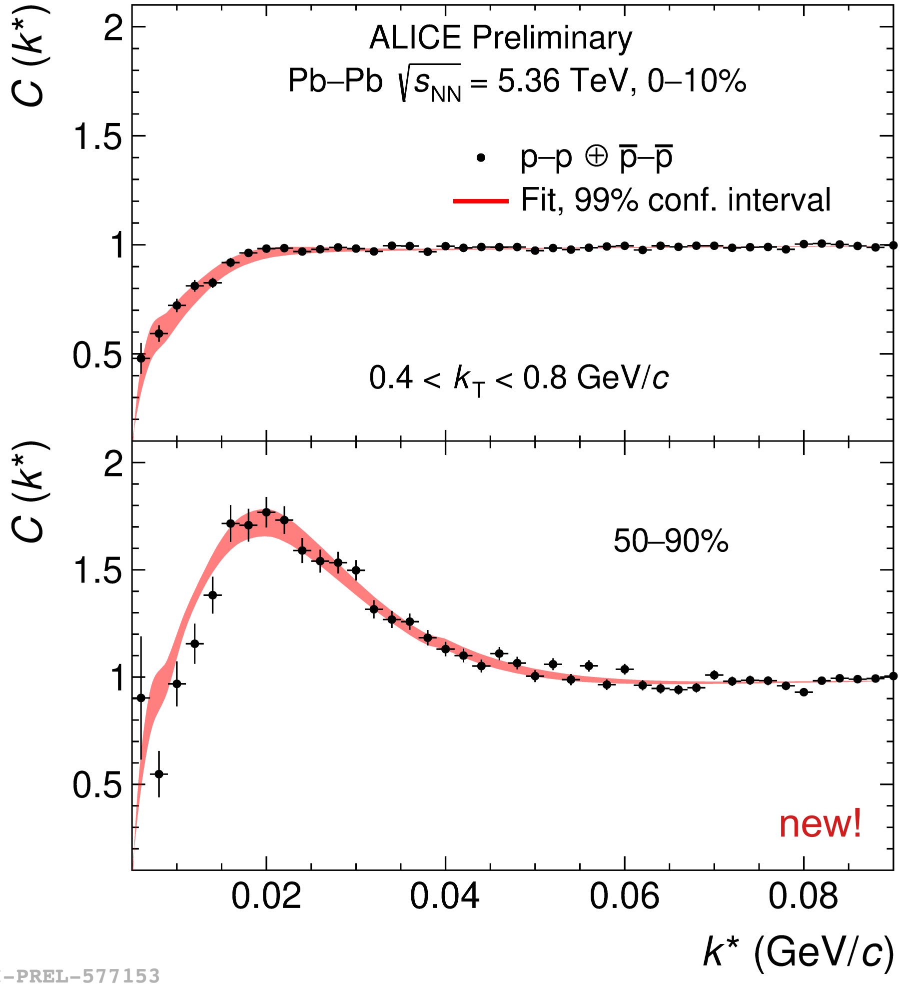
…more femtoscopy with ALICE:

- Maximilian Korwieser (19/07/24, 17:15)
- Marcel Lesch (19/07/24, 17:00)
- Sofia Tomassini (18/07/24, poster session)

*more about a “new” FIT: Yury Melikyan (19/07/2024, 08:48)

Proton CFs in Pb–Pb at 5.36 TeV

*example plot of 2 selected CFs



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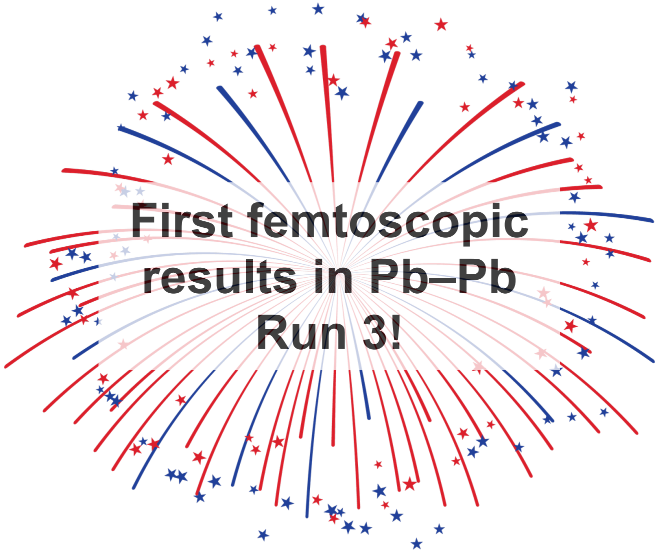
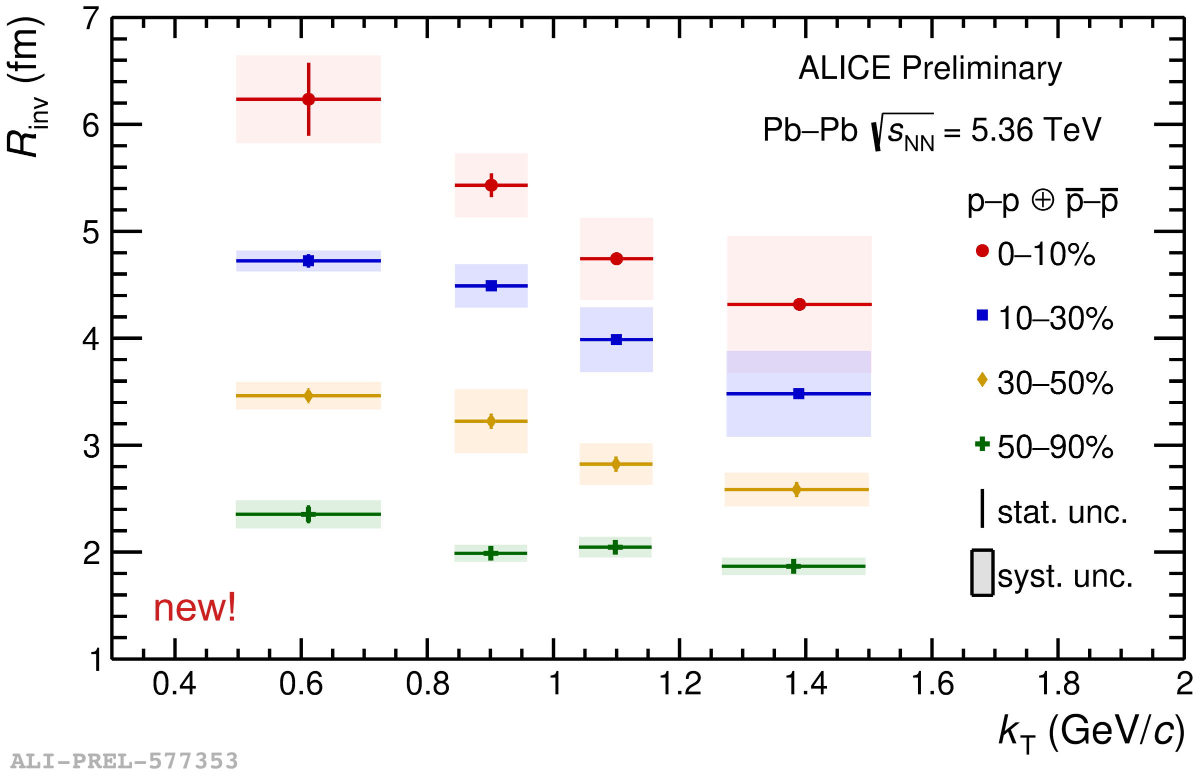


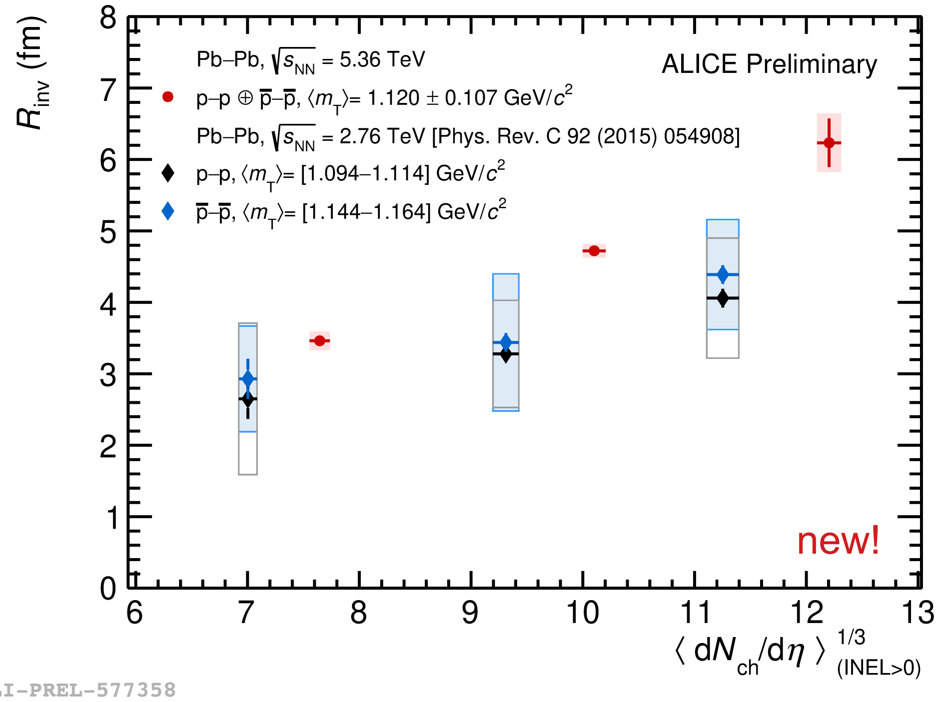
The total CF is fitted with the **Lednický-Lyuboshitz model with a box potential approach.**

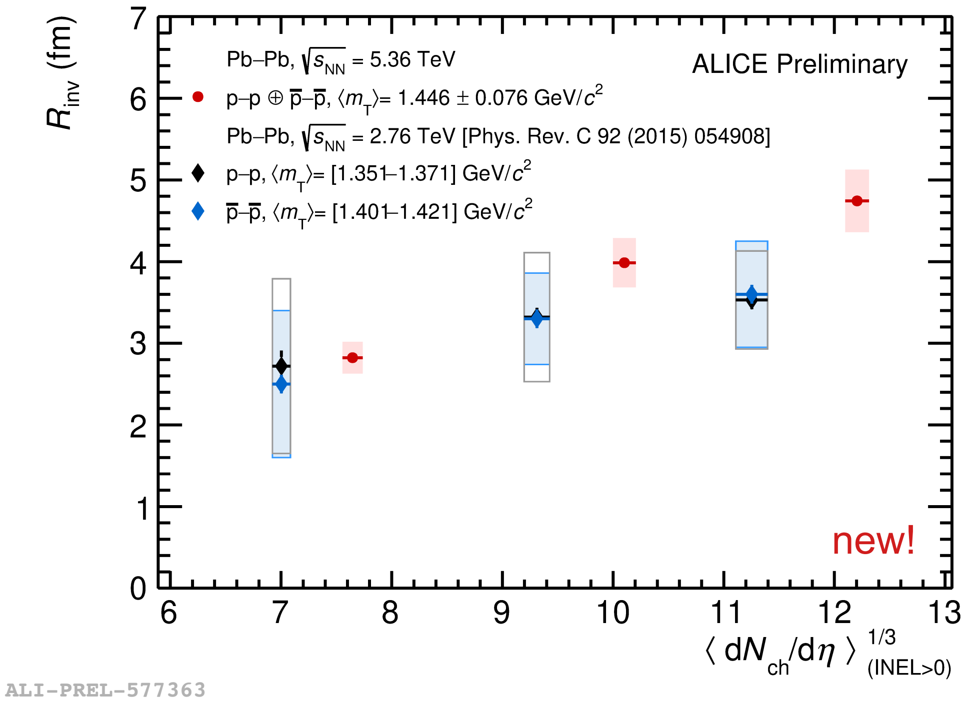
Proton 1D radii in Pb–Pb at 5.36 TeV



- Proton radii demonstrate the dynamics that is typical for heavy-ion collisions.
- R_{inv} decreases with increasing k_T → collective (radial) flow (weaker for more peripheral events)

Proton 1D radii: comparison with Run 1





- The new Run 3 results are consistent with Run 1 data (at close <m_T>)
- The precision has improved w.r.t. Run 1
- More peripheral events are accessed w.r.t. Run 1 results
  (50-90% from Run 3 not shown here)

Summary

Kaon results in Pb–Pb at $\sqrt{s_{NN}}$ = 5.02 TeV Run 2:

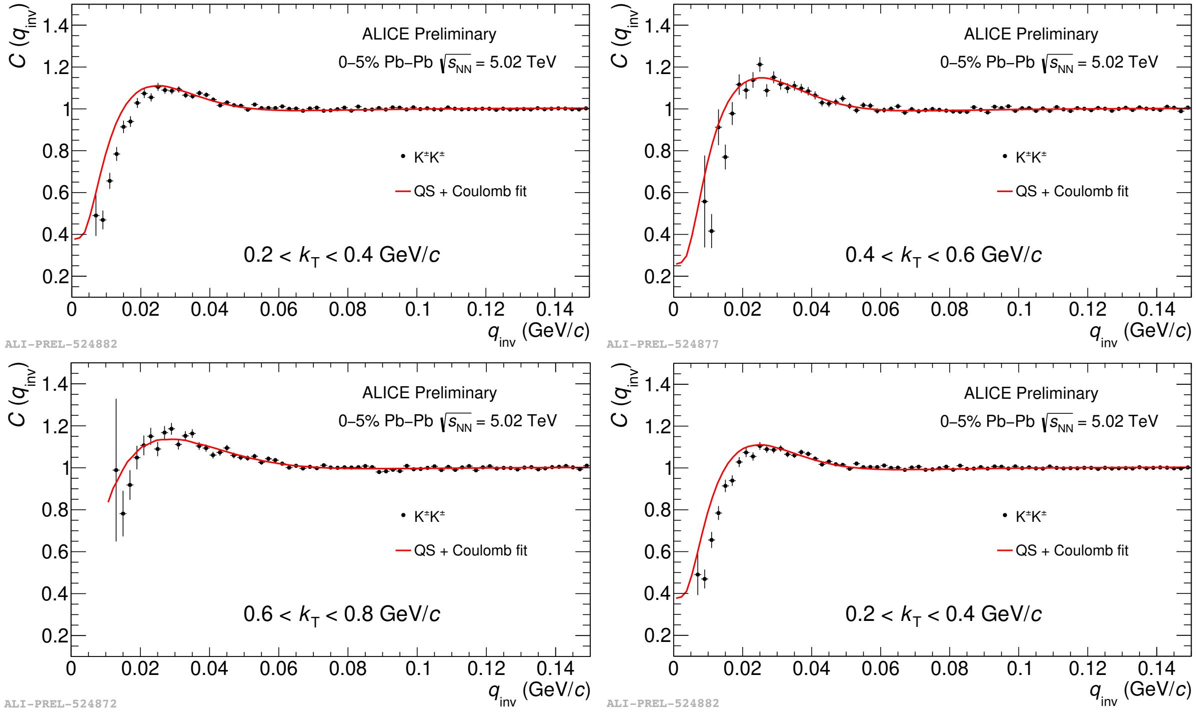
- Signs of hydrodynamic expansion of matter created in p–Pb and Pb–Pb
- p–Pb and peripheral Pb–Pb evolve similarly with time in terms of Kaon production
- The extracted times of maximal emission τ show that systems created in more peripheral events evolve faster

Proton results in Pb–Pb at $\sqrt{s_{NN}}$ = 5.36 TeV Run 3:

- First femtoscopic measurement with ALICE's Run 3 Pb–Pb data is performed;
- Proton radii demonstrate the dynamics typical for heavy-ion collisions → collectivity;
- New Run 3 results are in a good agreement with Run 1 ones;
- Significant improvements are expected (more statistics, better reconstruction, etc.)

Backup slides

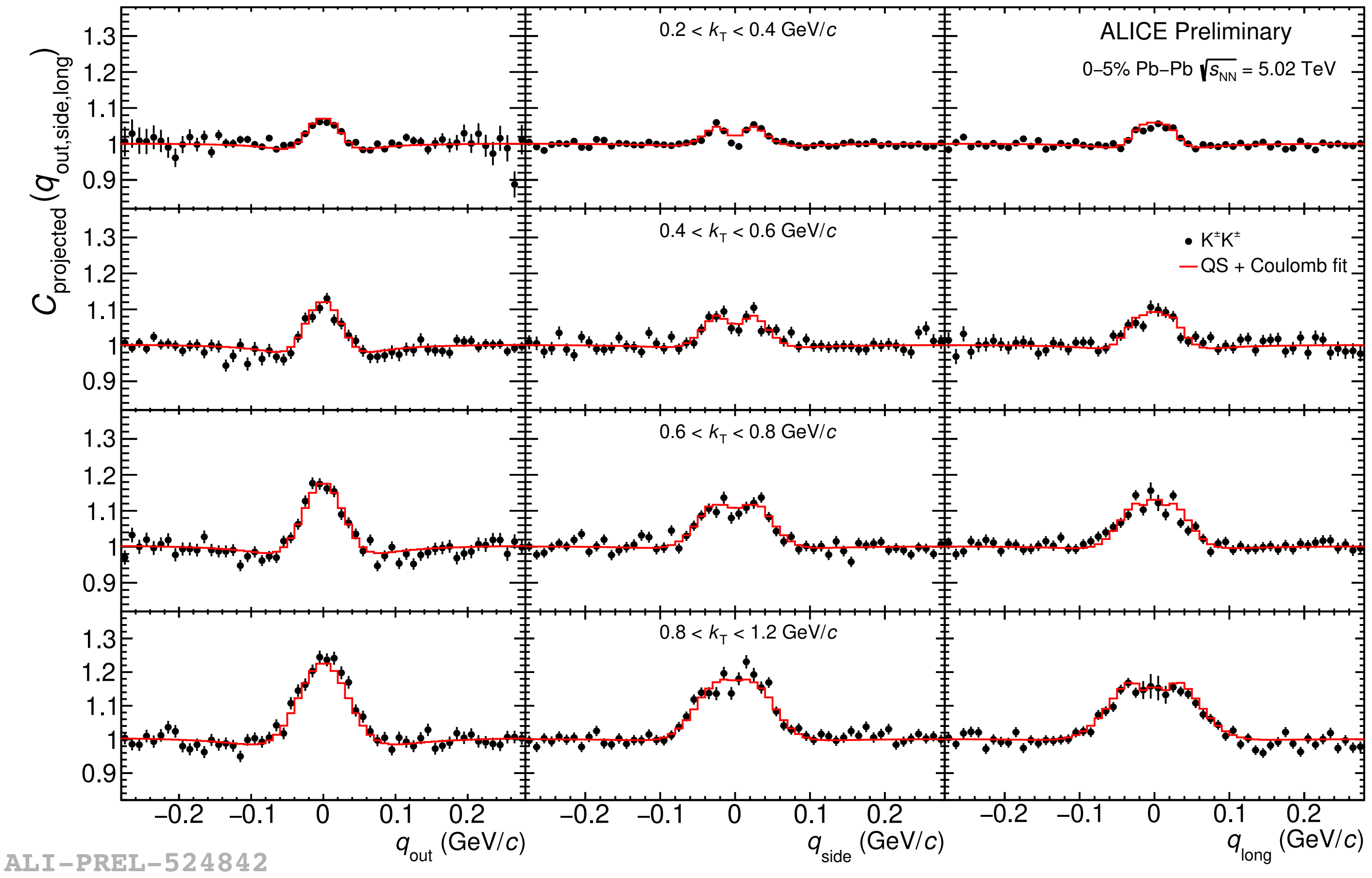
CFs in Pb–Pb 0–5% cent.: 1D fit



Fit function: Bowler–Sinyukov formula (e.g. PLB 270 (1991), 69-74)

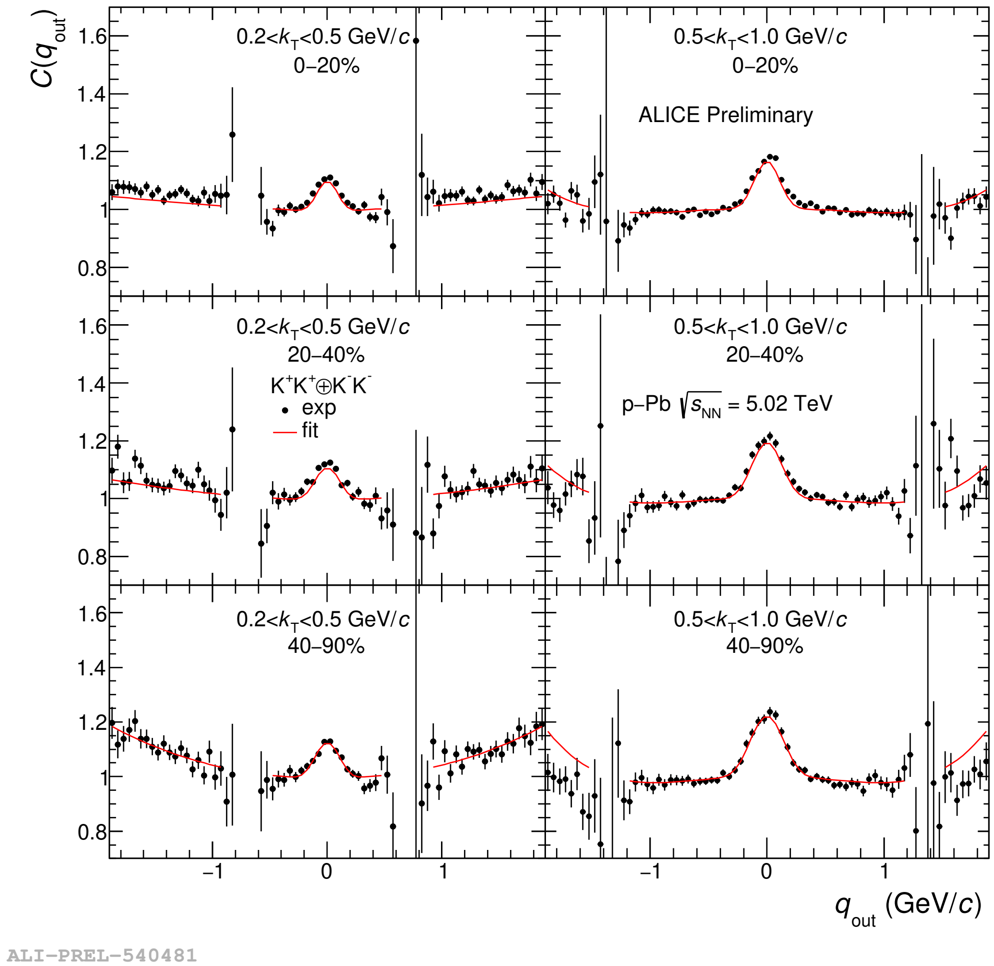
The gap near zero is caused by the Coulomb interaction between kaons

CFs in Pb–Pb 0–5% cent.: 3D fit



Fit function: Bowler–Sinyukov formula (e.g. PLB 270 (1991), 69-74)

CFs in p–Pb: 3D fit (“out” component)



Fit function:

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

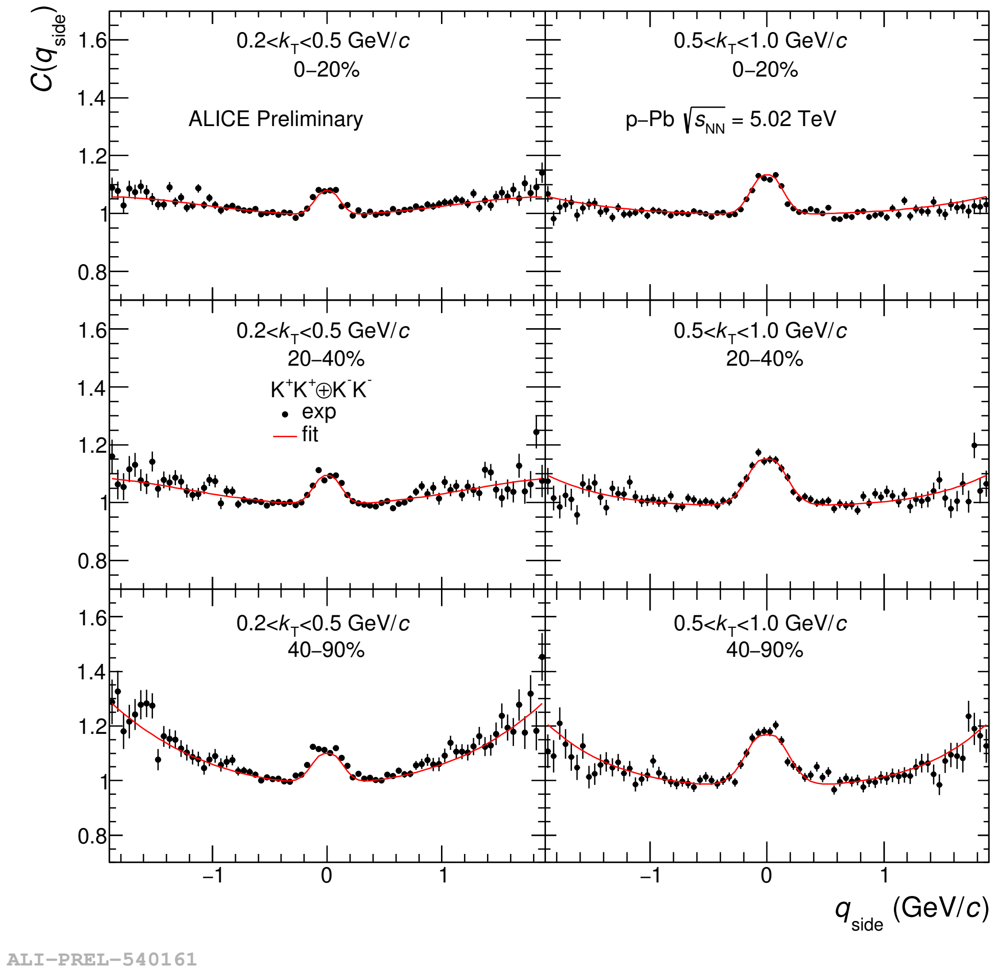
Baseline:

$$D(q) = 1 + a_{out} q_{out}^2 + a_{side} q_{side}^2 + a_{long} q_{long}^2 + a_{out} q_{out}^4 + a_{side} q_{side}^4 + a_{long} q_{long}^4$$

The fit reproduces well the shape of the correlation peak and also captures non-femtoscopic behavior of C_{out}.

Fit function: Bowler–Sinyukov formula (e.g. PLB 270 (1991), 69-74)

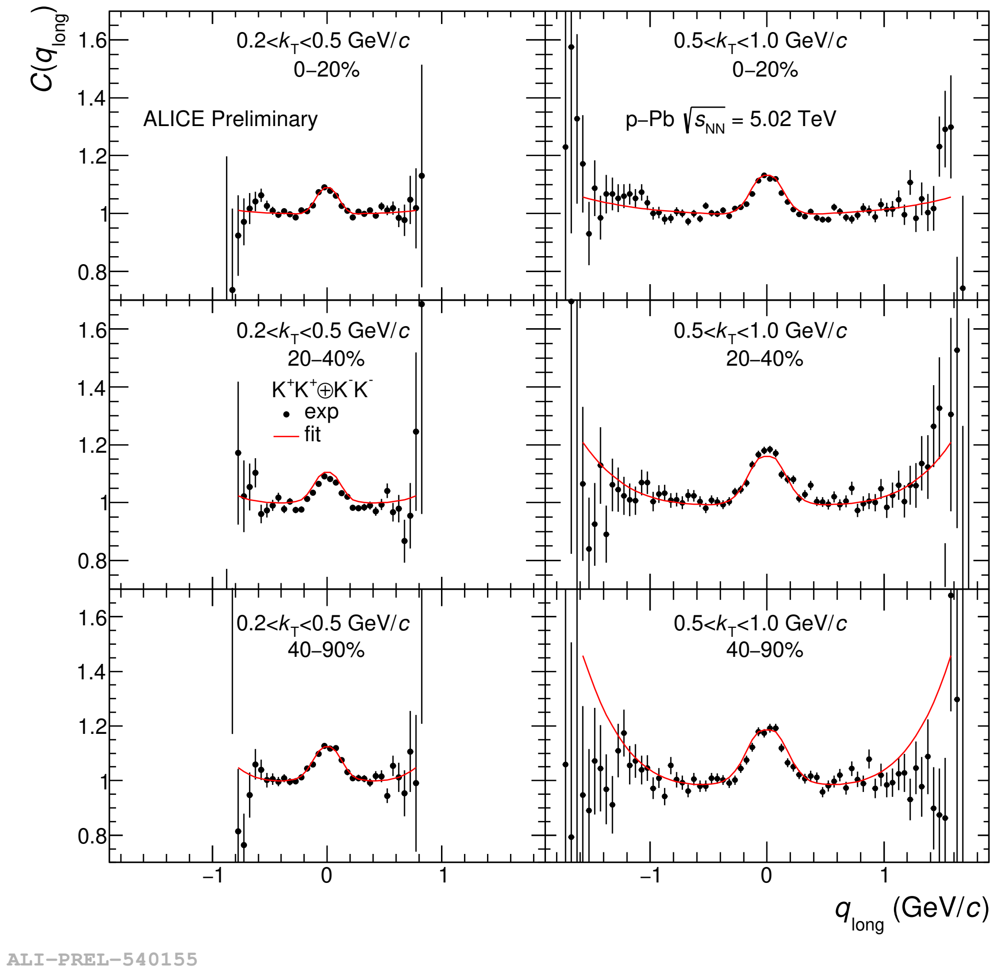
CFs in p–Pb: 3D fit (“side” component)



The fit reproduces well the shape of the correlation peak and also captures non-femtoscopic behavior of C_{side}.

Fit function: Bowler–Sinyukov formula (e.g. PLB 270 (1991), 69-74)

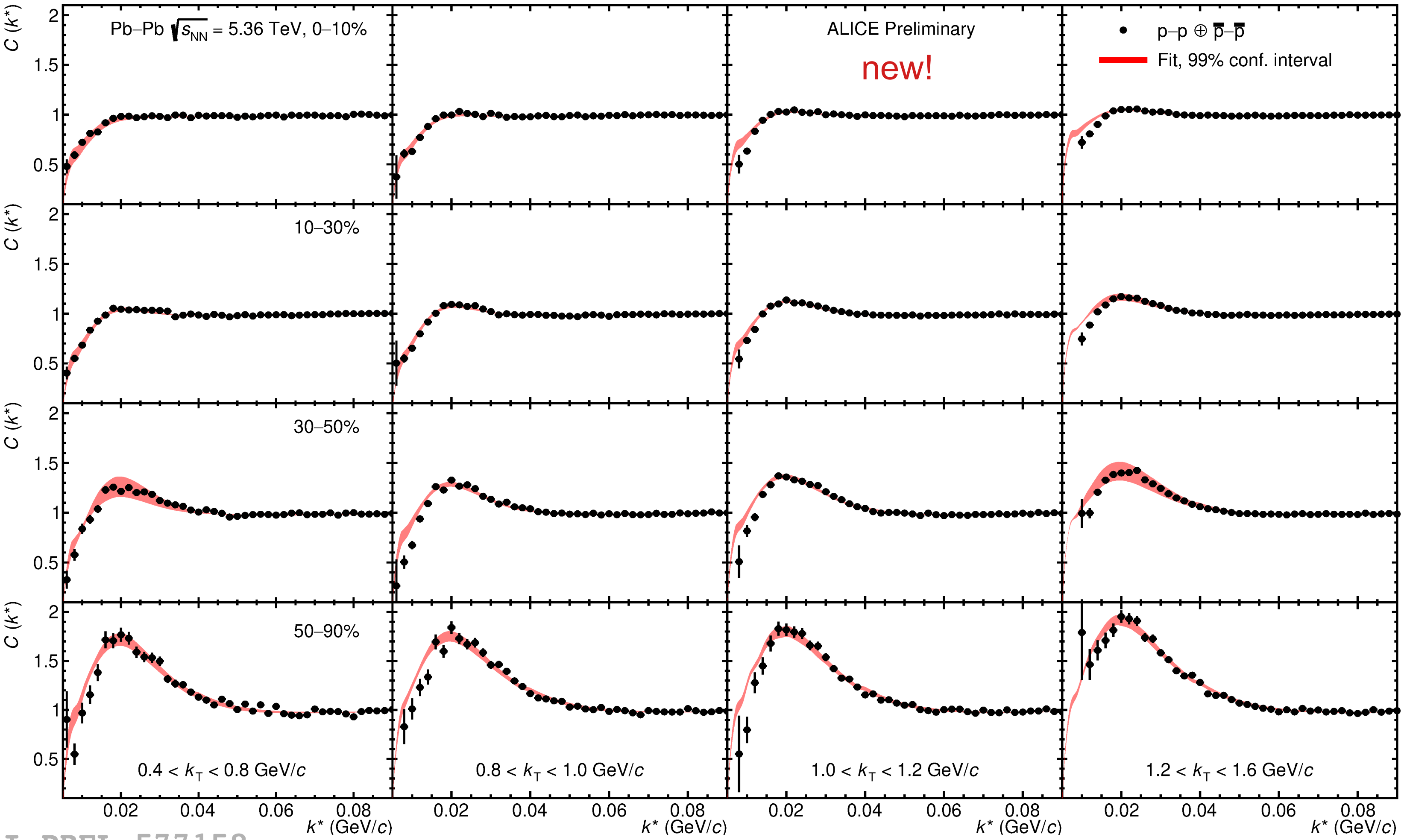
CFs in p–Pb: 3D fit (“long” component)



The fit reproduces well the shape of the correlation peak and also captures non-femtoscopic behavior of C_{long}.

Fit function: Bowler–Sinyukov formula (e.g. PLB 270 (1991), 69-74)

Proton CFs in Pb–Pb at 5.36 TeV



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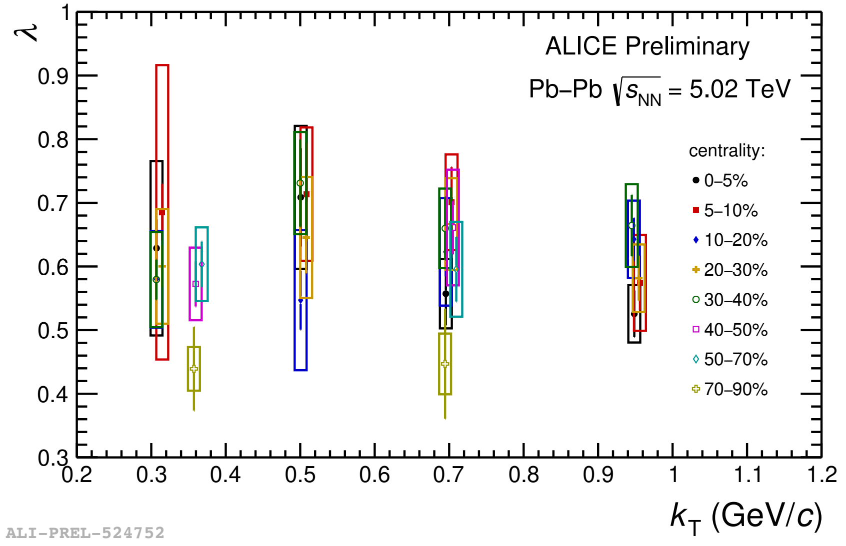
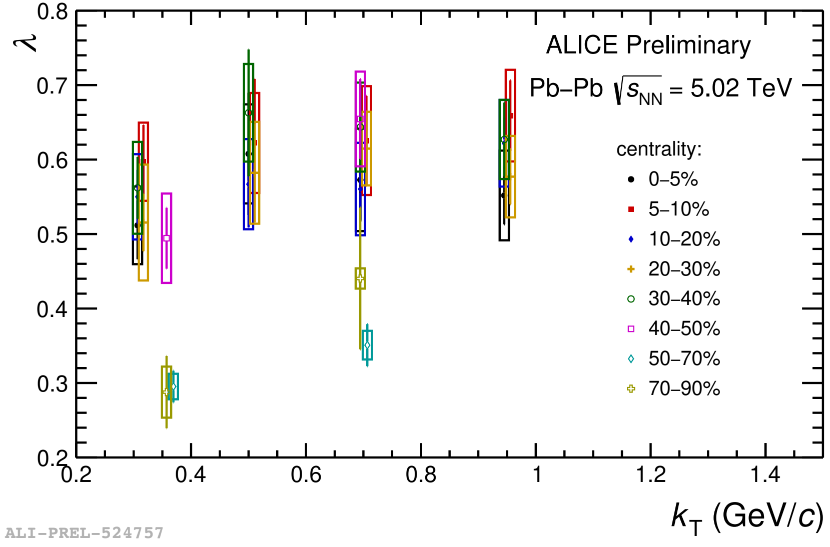
Extracted λ parameters for kaons in Pb–Pb

Extracted from 1D fit



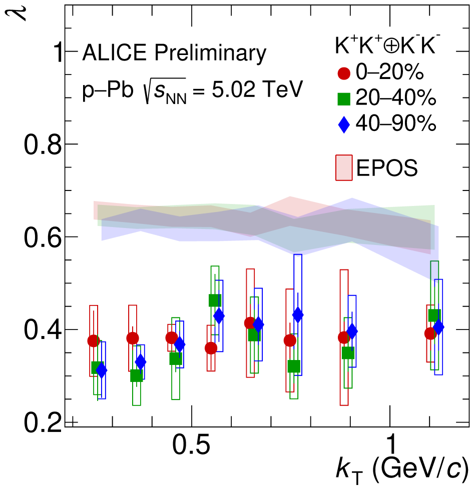
Extracted from 3D fit



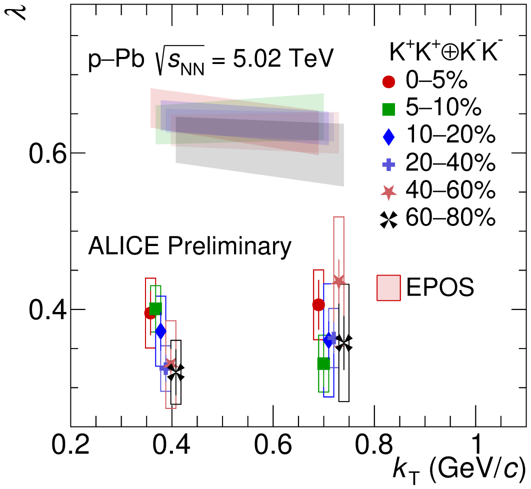
- Extracted λ parameters are nicely grouped and compatible between different centralities within uncertainties;
- No signs of k_T/centrality dependence;

Extracted λ parameters for kaons in p–Pb

Extracted from 1D fit for two different setups of k_T/centrality binning;



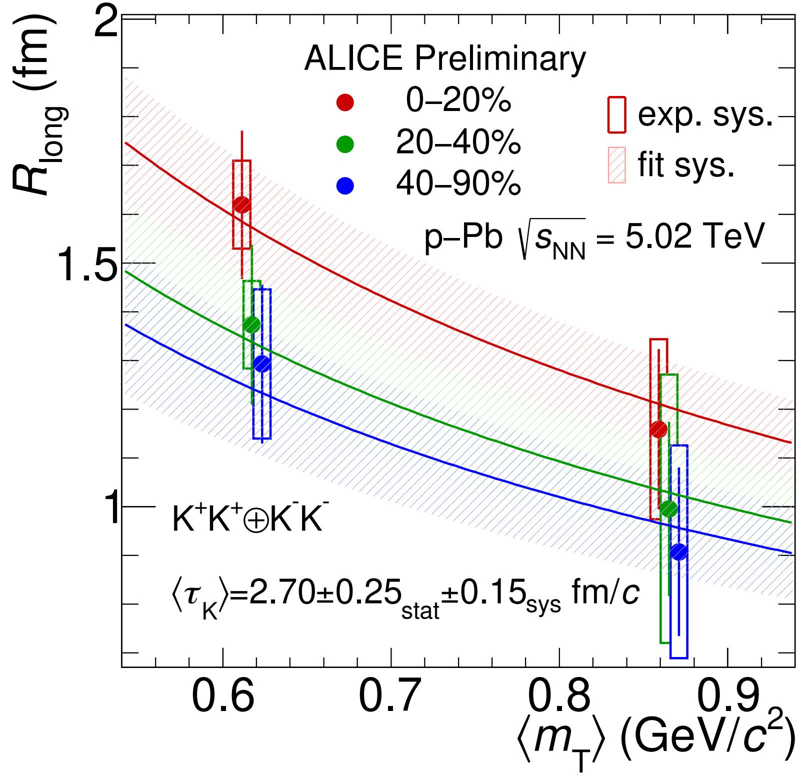
ALI-PREL-541066



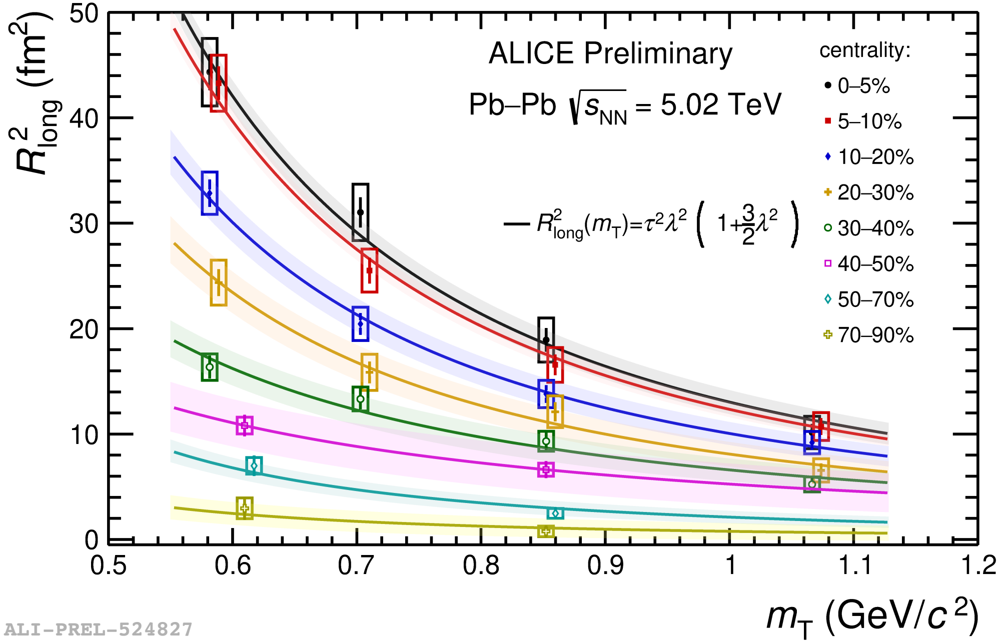
ALI-PREL-541074

- Extracted λ parameters are nicely grouped and compatible between different centralities within uncertainties;
- No signs of k_T/centrality dependence;
- EPOS overestimates λ → production of K from long-lived resonances like K* should probably be revised in the model

Extracting maximal emission time



ALI-PREL-540893



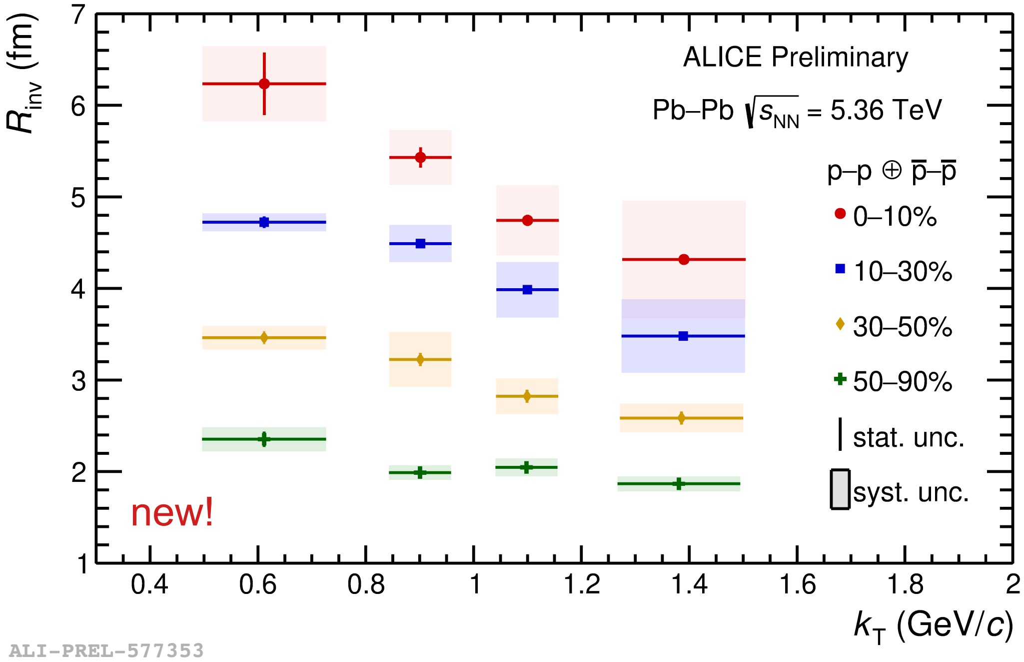
Extracting maximal emission time was performed by fitting m_T- dependent R^2_{long} with this formula:

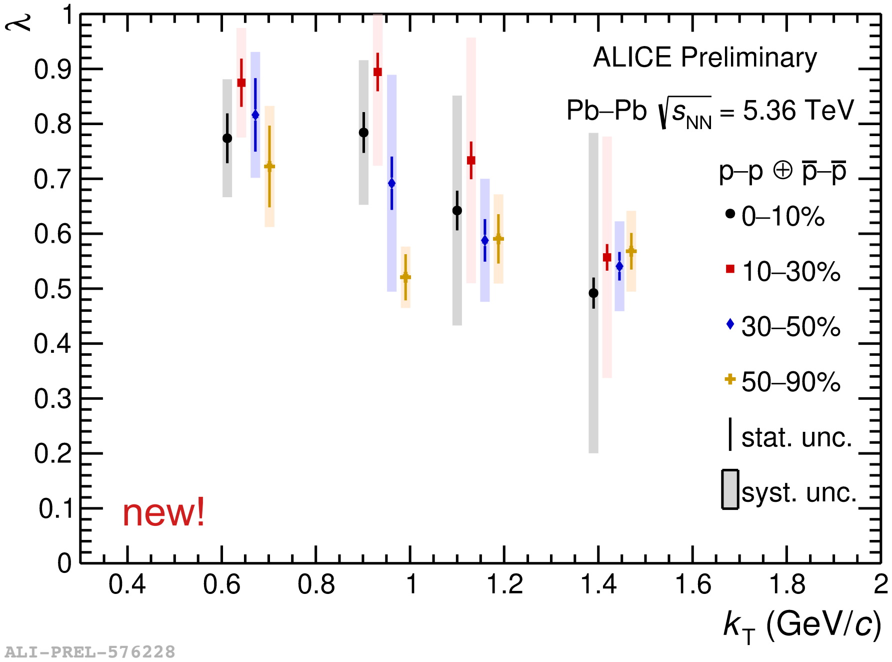
$$R^2_{long}(m_T) = \tau^2\lambda^2\left(1+\frac{3}{2}\lambda^2\right)$$

$$\lambda^2 = \frac{T}{m_T}\sqrt{1-\bar{v}_T^2}$$

More details: Shapoval, V.M., Adzhymambetov, M.D. & Sinyukov, Y.M., Eur. Phys. J. A 56, 260 (2020).

Extracted λ for protons in Pb–Pb Run3



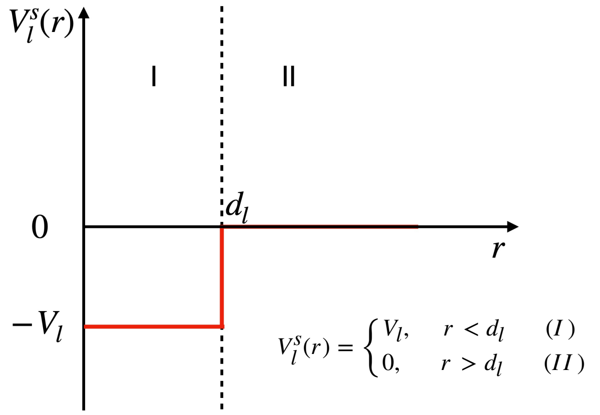


- Extracted λ parameters are nicely grouped and compatible between different centralities within uncertainties;
- No signs of k_T/centrality dependence for λ;

*k_T binning and errors along X axis for λ parameters are the same as for the radii, the points have been shifted for clarity.

Lednický-Lyuboshitz model with a box potential

Using partial wave expansion and solving the radial Schrodinger's equation with a simple box potential as strong (+Coulomb) one can obtain



$$\psi_{c+s}(k, r) = \frac{1}{r} \sum_{l=0}^{\infty} (2l+1)\, i^l e^{i\sigma_l}\, u_l(k, r)\, P_l(\cos\theta)$$

$$u_l(k, r) = \begin{cases} \frac{F_l(\tilde{\eta}_l, \tilde{k}_l r)}{F_l(\tilde{\eta}_l, \tilde{k}_l d)} \left(\frac{F_l(\eta, kd)}{k} + f_l(k) \left(G_l(\eta, kd) + i\, F_l(\eta, kd) \right) \right), & r < d \\ \left(\frac{F_l(\eta, \rho)}{k} + f_l(k) \left(G_l(\eta, \rho) + i\, F_l(\eta, \rho) \right) \right), & r \geq d \end{cases}$$

where $\tilde{k}_l = \sqrt{k^2 - \frac{2\mu}{\hbar^2} V_l}$, $\tilde{\eta}_l = \frac{1}{\tilde{k}_l a_B}$, $\tilde{\rho}_l = \tilde{k}_l r$ and $\tilde{\sigma}_l = arg\, \Gamma(l + 1 + i\tilde{\eta}_l)$

F_l and G_l — regular and irregular Coulomb functions

The potential parameters (depth and width) are obtained from the fit of the phase shifts with a formula coming from the matching conditions. Total WF for l=[0, 1]:

$$\psi(k, r) = \begin{cases} \sqrt{A_c(\eta)}\, e^{i\sigma_0} e^{i\vec{k}\vec{r}}\, {}_1F_1\left(-i\eta, 1, i(kr - \vec{k}\vec{r}) \right) + \sum_{l=0}^{n} (2l+1)\, i^l\, e^{i\sigma_l} \left[\frac{F_l(\tilde{\eta}_l, \tilde{k}_l r)}{F_l(\tilde{\eta}_l, \tilde{k}_l d)} \left(\frac{F_l(\eta, kd)}{kr} + f_l(k) \frac{G_l(\eta, kd) + i\, F_l(\eta, kd)}{r} \right) - \frac{F_l(\eta, \rho)}{kr} \right] P_l(cos\theta) & r < d \\ \sqrt{A_c(\eta)}\, e^{i\sigma_0} e^{i\vec{k}\vec{r}}\, {}_1F_1\left(-i\eta, 1, i(kr - \vec{k}\vec{r}) \right) + \sum_{l=0}^{n} (2l+1)\, i^l\, e^{i\sigma_l}\, f_l(k) \frac{G_l(\eta, \rho) + i\, F_l(\eta, \rho)}{r} P_l(cos\theta) & r \geq d \end{cases}$$

Theoretical femtoscopic CF

General expression:

$$C(k, R_{inv}) = \int d^3r \cdot S(r, R_{inv}) \cdot |\psi(\vec{k}, \vec{r})|^2$$

$\psi(\vec{k}, \vec{r})$ — solution to the Schrodinger's equation for a pair

$$S(r, R_{inv}) = \frac{1}{8\pi^{\frac{3}{2}} R_{inv}^3} exp(-\frac{r^2}{4R_{inv}^2})$$

— assuming Gaussian source

For a pair of protons with L=[0, 1]. Corresponding states: $^{2S+1}L_J : \quad {}^1s_0, \ {}^3p_0, \ {}^3p_1, \ {}^3p_2$

$$C_{pp}(k*, R_{inv}) = \frac{1}{2} \sum_{S=0}^{1} \frac{2S+1}{(2s_p+1)^2} \sum_{L, J} \omega_{LJ} \int d^3r \, S(r, R_{inv}) \, |\psi^S_{-\vec{k}}(\vec{r}) + (-1)^S \psi^S_{\vec{k}}(\vec{r})|^2$$

$$\omega_{LJ} = \frac{2J+1}{(2L+1)(2S+1)}$$