Differential measurements of the particle-emitting source via proton-proton femtoscopy in pp and Pb-Pb collisions in LHC Run 3 with ALICE

Romanenko G. (University and INFN Bologna)

on behalf of the ALICE Collaboration

CosmicAntiNuclei

European Research Council
Established by the European Commission

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

Istituto Nazionale di Fisica Nucleare
Sezione di Bologna

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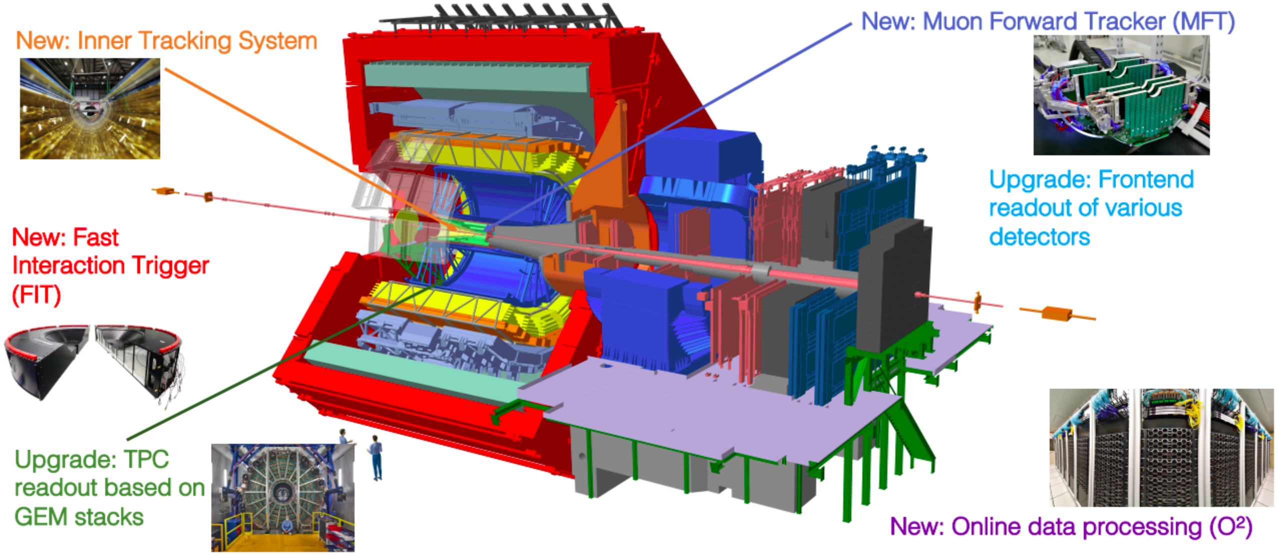
ALICE detector

ALICE detector scheme and Run 3 upgrades



A Large Ion Collider Experiment (ALICE):

- one of the main LHC experiments
- designed for studying ultrarelatevistic heavy-ion collisions (HIC)
- excellent tracking capabilities in high multiplicity events

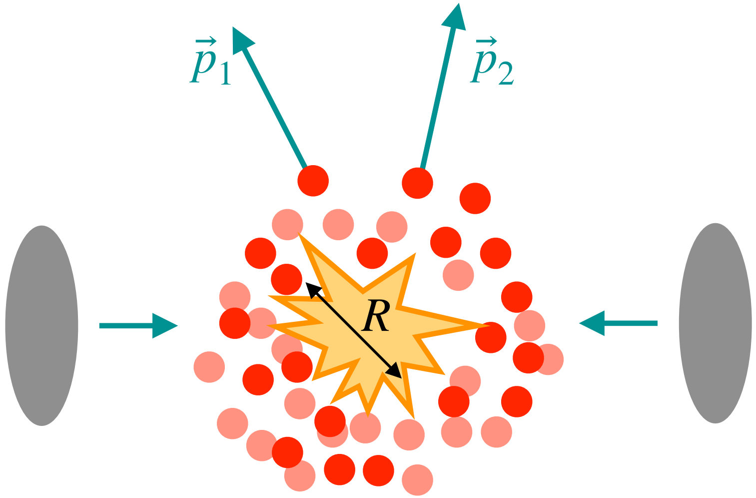
Main tracking detectors:

- Inner Tracking System (ITS)
- Time Projection Chamber (TPC)

Main Particle Identification (PID) detectors:

- TPC
- Time-Of-Flight (TOF)

Femtoscopy: motivation



Knowing that particles interact with each other during system's evolution, one can access **its properties** by measuring particle **correlations in the final state**.

Femtoscopy uses correlations in momenta which makes it an **excellent tool** for studying systems created in heavy-ion collisions since momentum is a quantity that we can measure.

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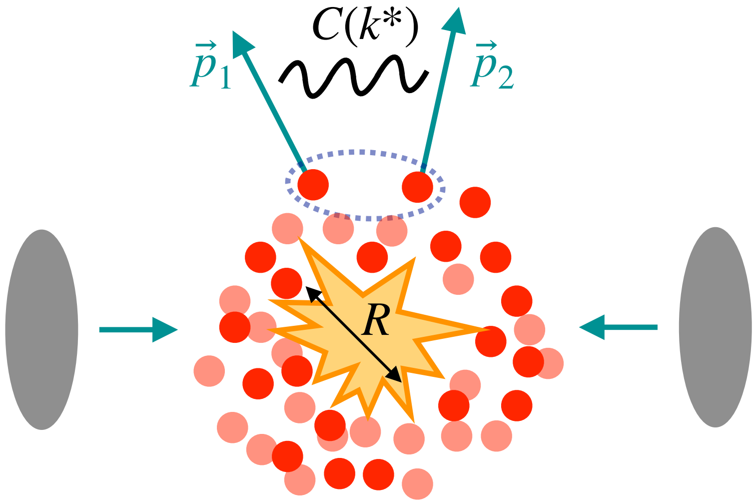

$$2k^* = |\vec{p}_1 - \vec{p}_2|$$

rel. momentum of a pair in its centre of mass (or PRF — Pair Rest Frame)

Knowing that particles interact with each other during system's evolution, one can access **its properties** by measuring particle **correlations in the final state.**

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Thus, measuring **relative momentum distribution of pairs from the same event** $\mathbf{S}(k^*)$ one obtains the signal, and by dividing it for **mixed event distribution** $\mathbf{B}(k^*)$ (where any correlation is absent), one obtains the **femtoscopic correlation function**:

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

N — normalisation

Femtoscopy: motivation

Theoretical description of the **femtoscopic correlation function** is given by the Koonin-Pratt equation:

$$\mathbf{C_{th}(k^*, R)} = \int d^3\mathbf{r^*}\ \mathbf{S(r^*, R)} \cdot \left|\mathbf{\Psi(r^*, k^*)}\right|^2$$

M. Lisa et al., Ann.Rev.Nucl.Part.Sci.55:357-402(2005)

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macroscopic level

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2. Extracting R and **studying its dynamics:**
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   - **transverse pair momentum k_T dependence**
3. etc.

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2. Extracting parameters of the interaction — e.g. effective range parameters (*see Maximilian's talk at 09:21 10 July*)
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ALICE

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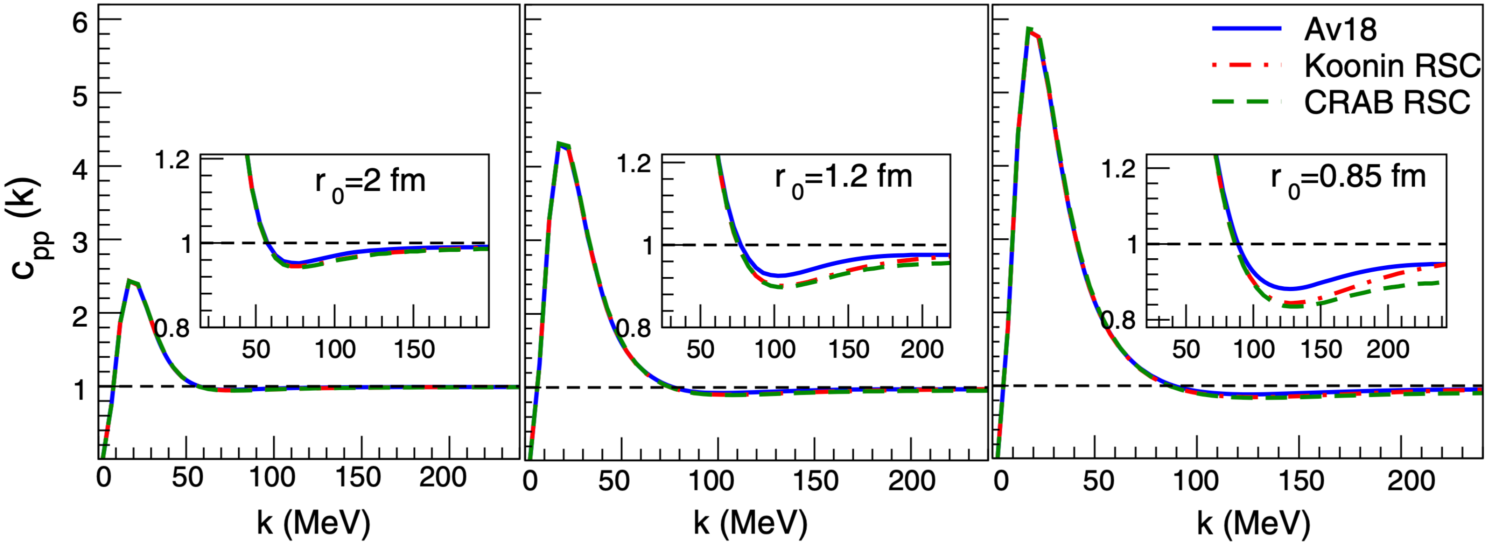
p-p femto in “small” systems: motivation

Protons are the most abundant hadrons produced in the collision for which taking into account the **strong interaction is crucial** (not dominant for pion and kaon pairs).



- Different source size → different signal

- **Different collision systems**

Mihaylov, D.L. et al., Eur. Phys. J. C 78, 394 (2018)

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macroscopic level

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Gaussian source: $S(r^*, R_{inv}) \sim exp(-\frac{r^{*2}}{4R_{inv}^2})$

QS + Coulomb + strong

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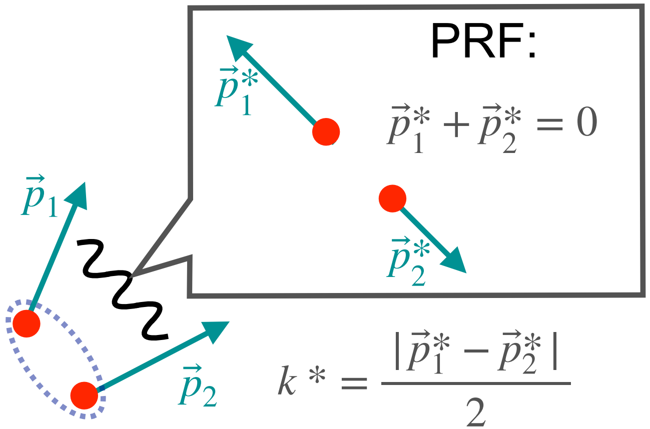
1D parametrisation of the experimental CF in Pair Rest Frame (PRF*):

$$C_{exp}(R_{inv}, k^*) = N\left[1 - \lambda\left(C_{th}(R_{inv}, k^*) - 1\right)\right]$$

λ — correlation strength

N — normalisation

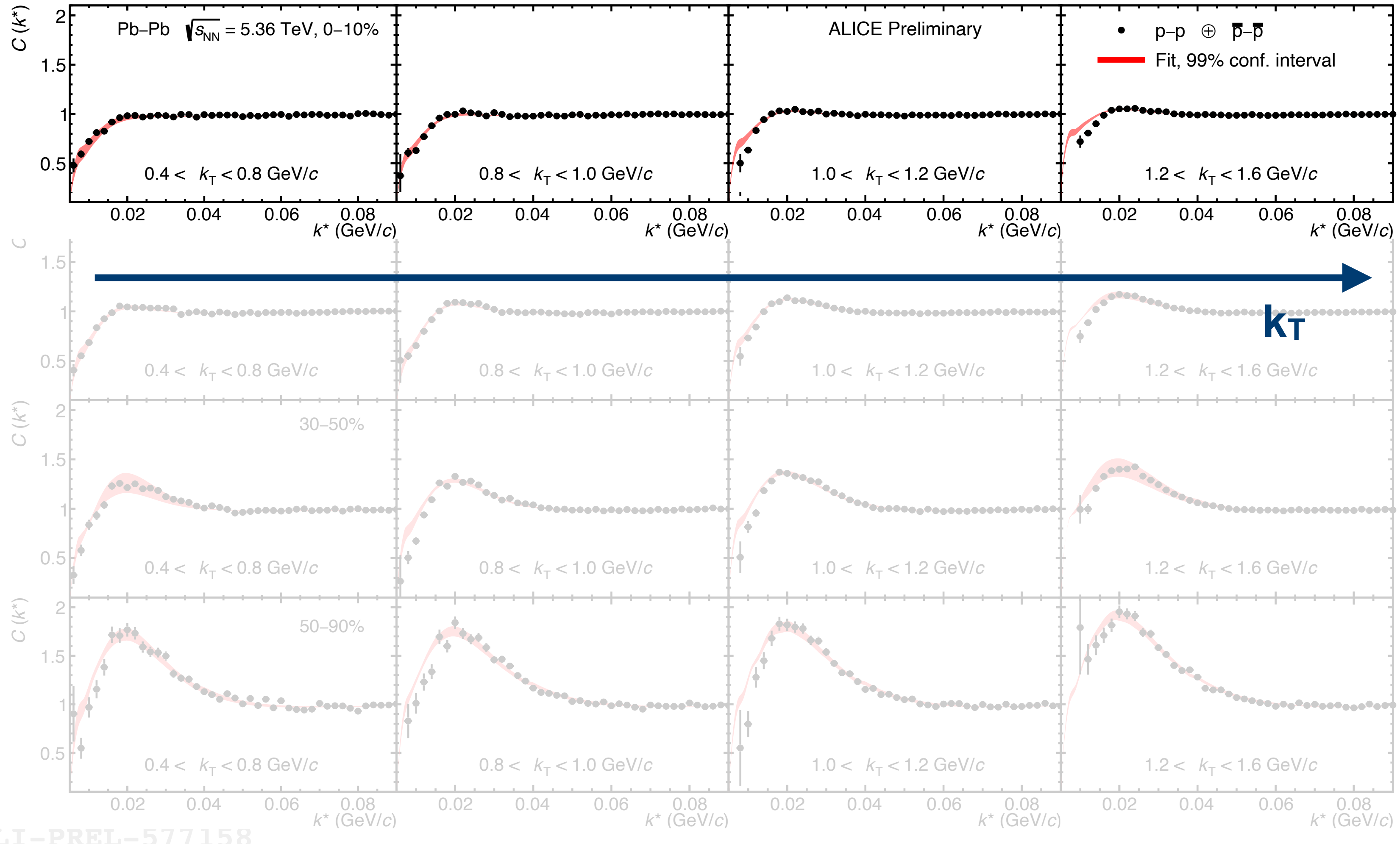
$\boldsymbol{R_{inv}}$ — 1D radius — corresponds to geometrical size of the source



$$k^* = \frac{|\vec{p}_1^* - \vec{p}_2^*|}{2}$$

Proton CFs in Pb–Pb at 5.36 TeV

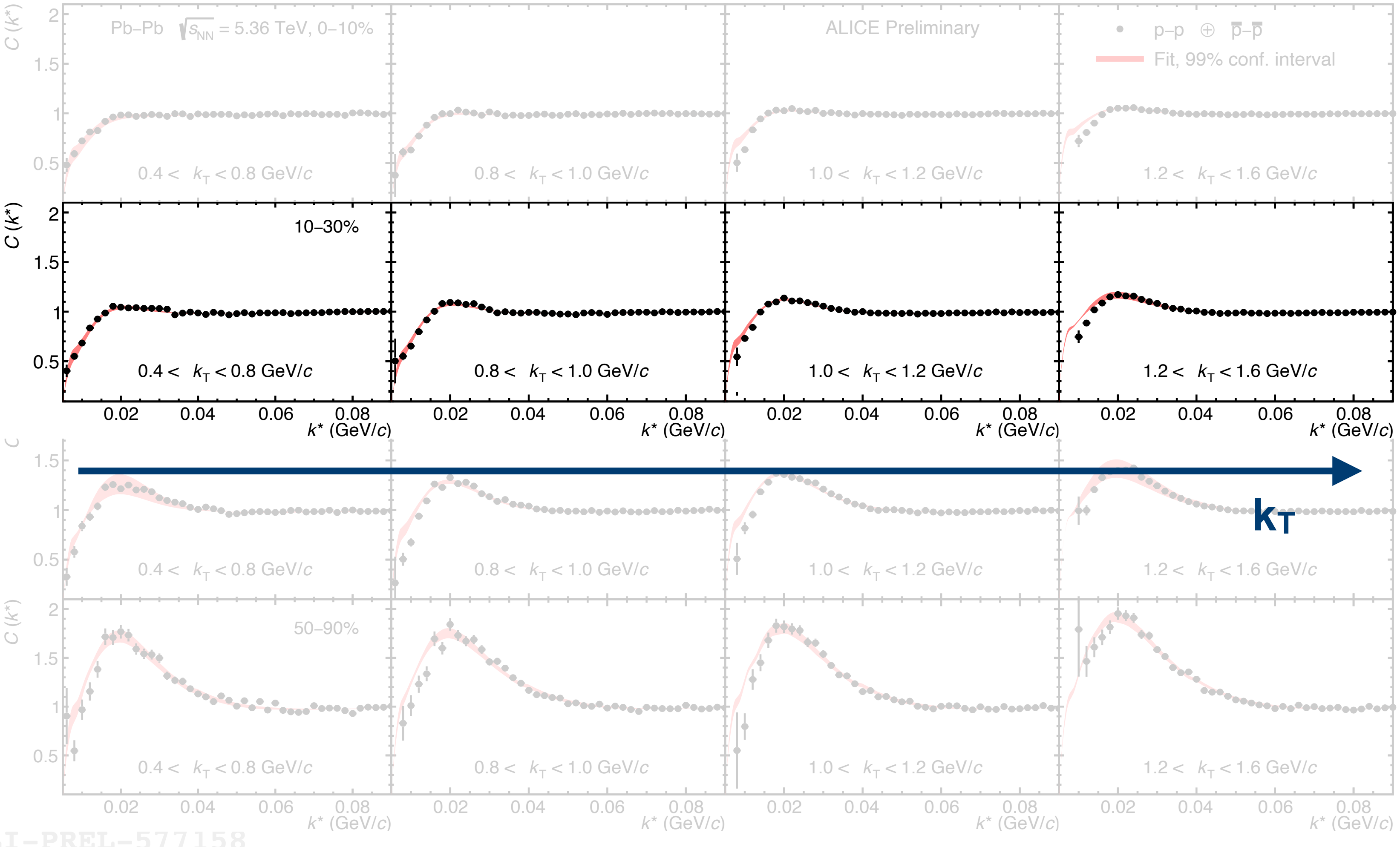
0-10%



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

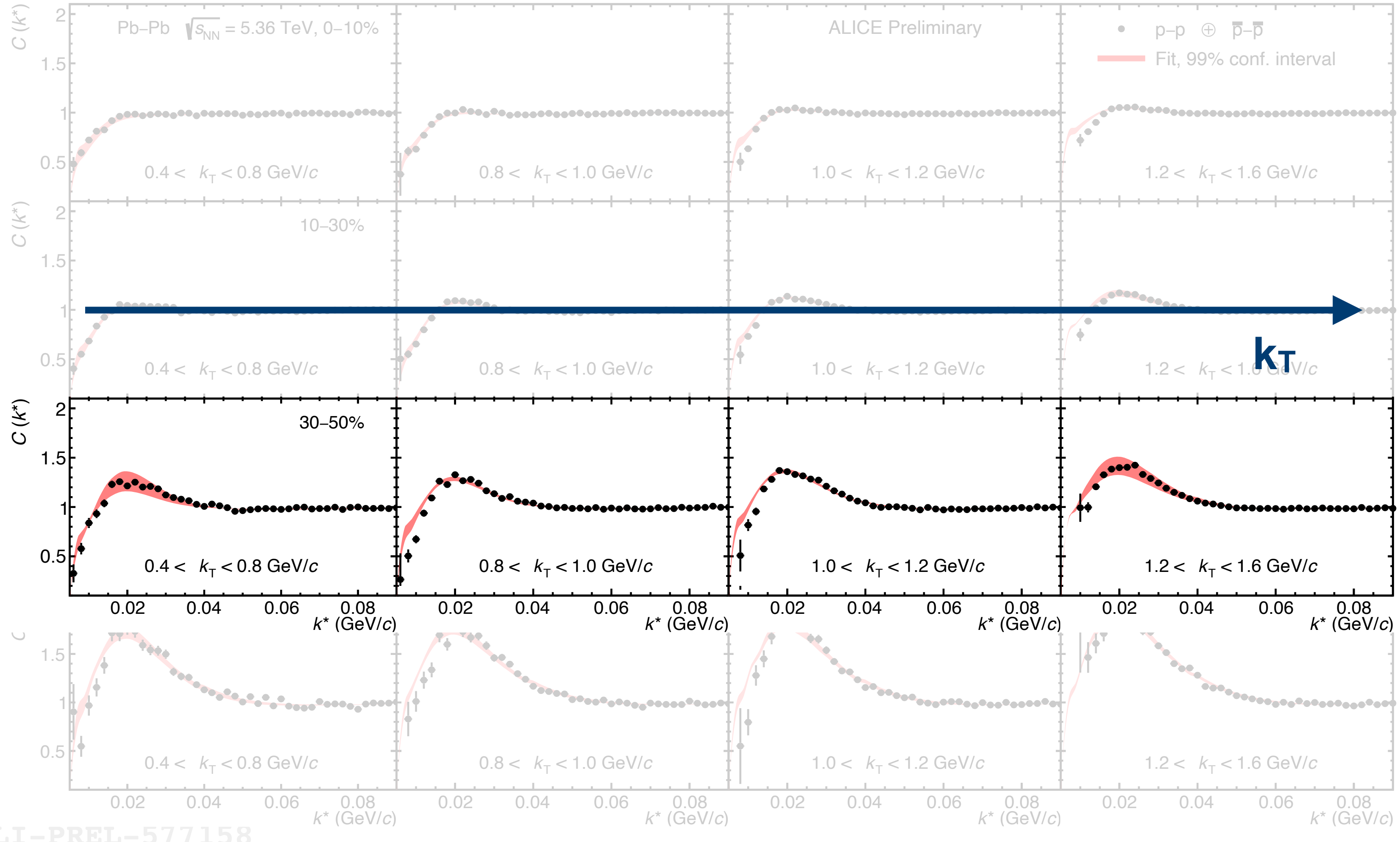
Proton CFs in Pb–Pb at 5.36 TeV

10-30%



Proton CFs in Pb–Pb at 5.36 TeV

30-50%



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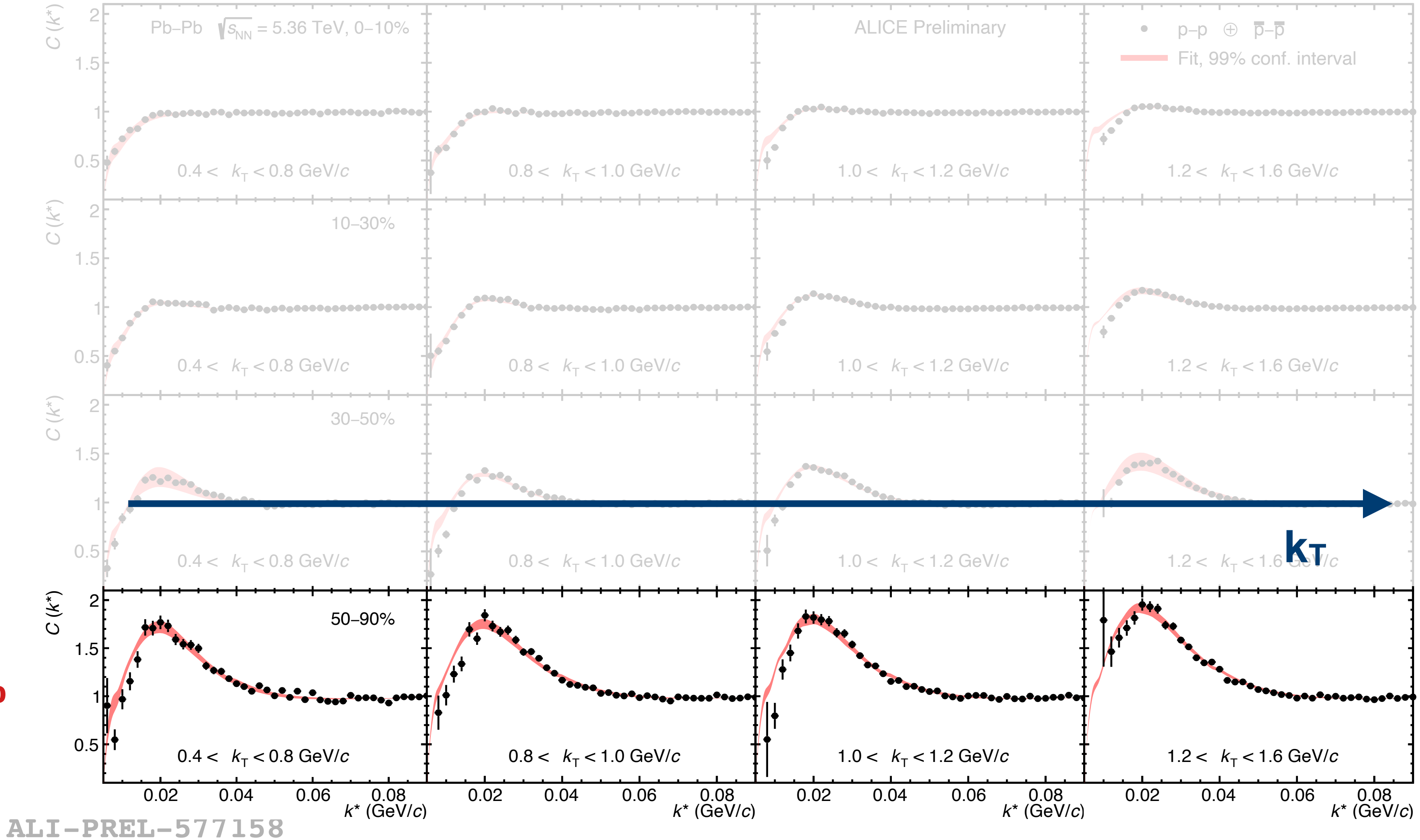
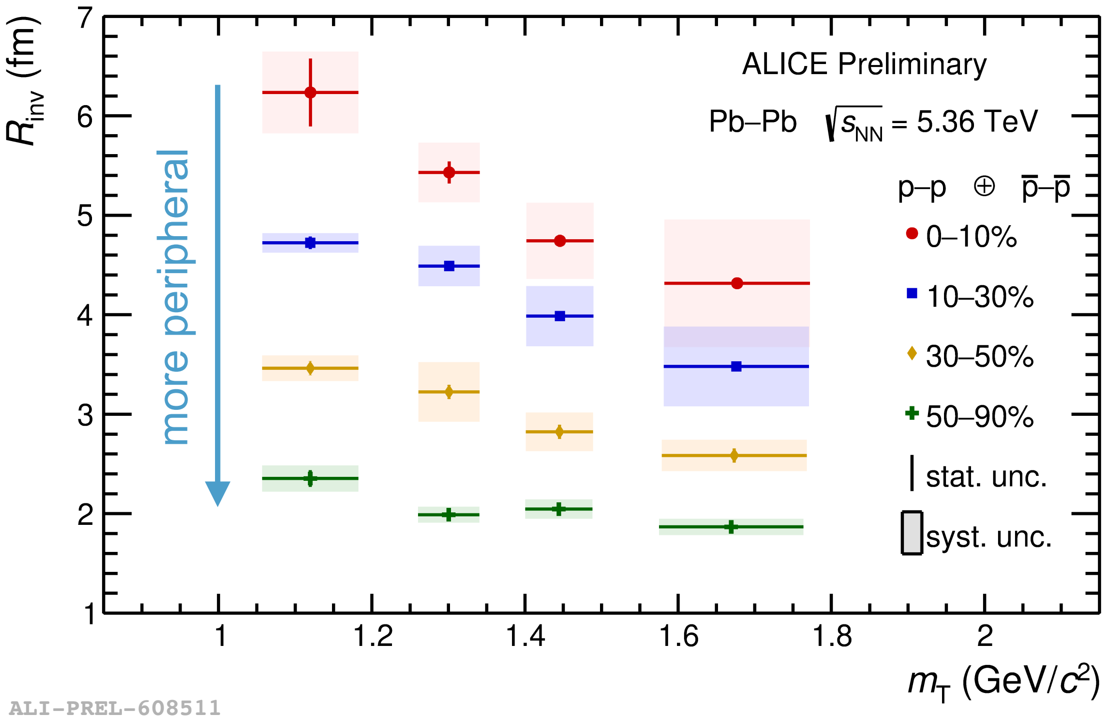


50-90%

Proton 1D radii in Pb–Pb at 5.36 TeV



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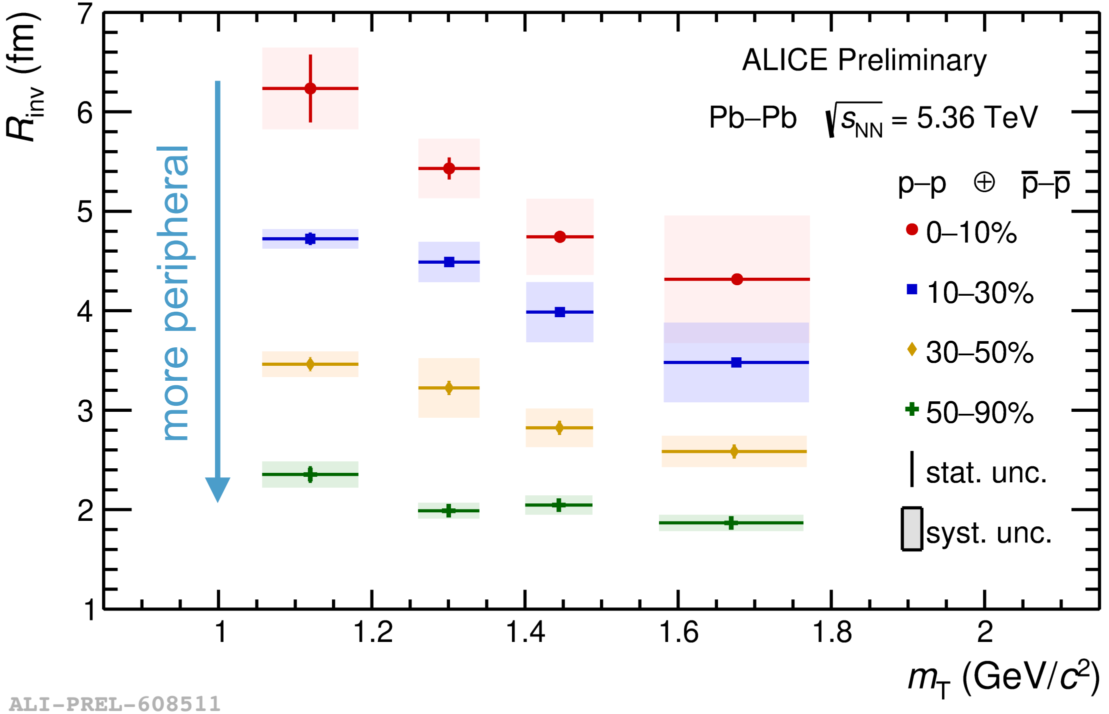
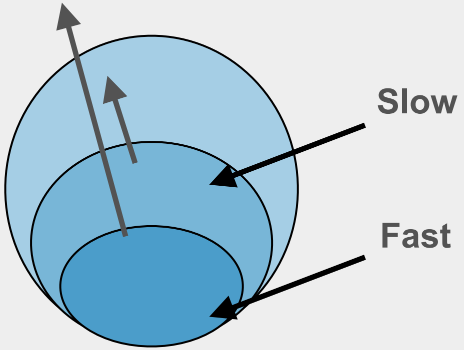


ALI-PREL-608511

Radial expansion of the source → coordinate-momentum correlation

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



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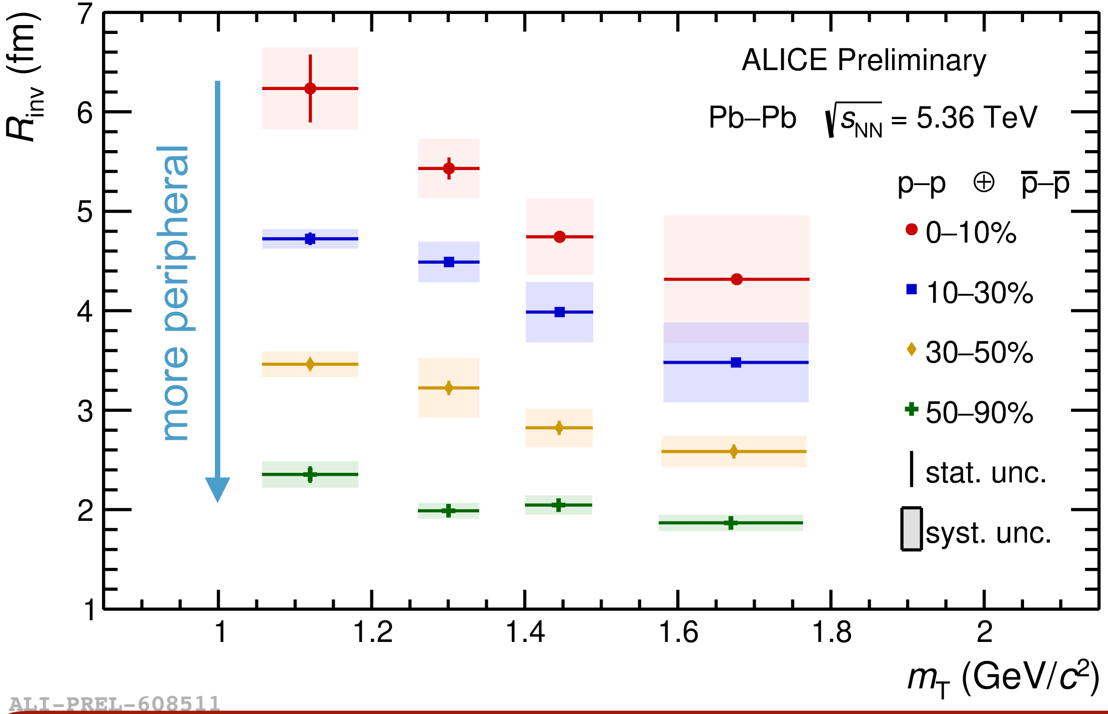

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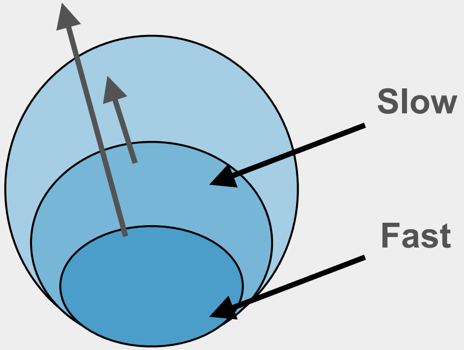
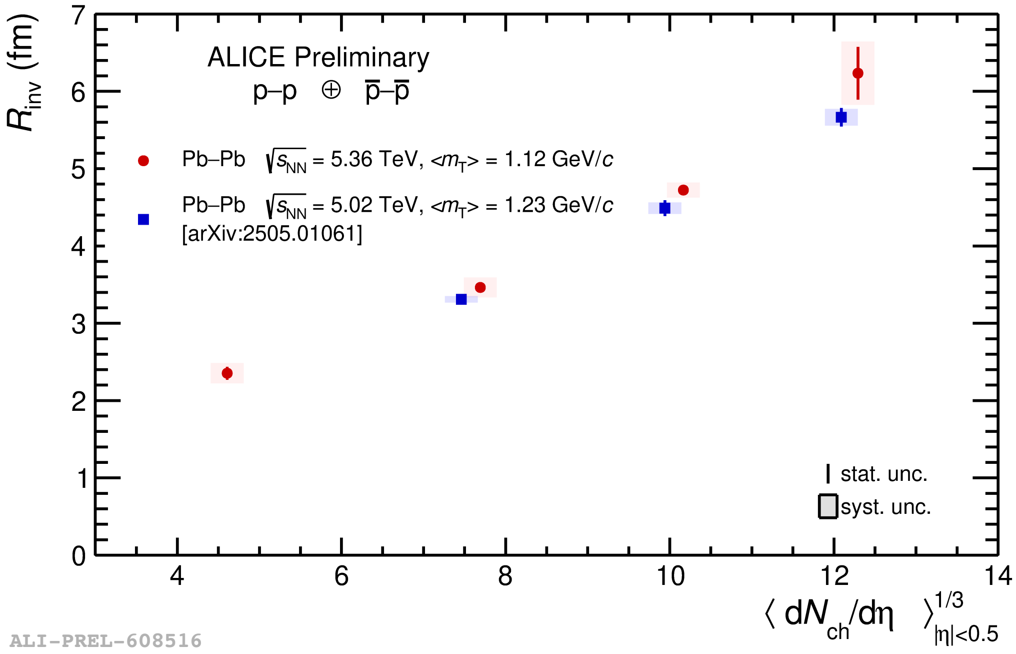
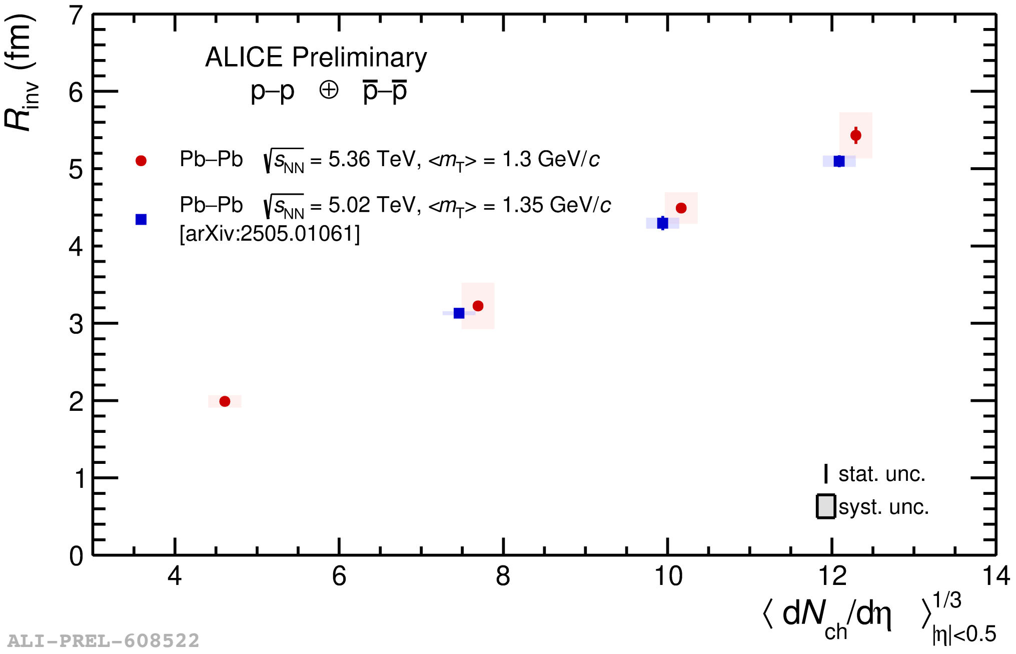


- Proton radii exhibit the dynamics that is typical for heavy-ion collisions
- Smaller effective size for more peripheral events
- R_{inv} decreases with increasing m_T → collective (radial) flow — “explosive” behaviour (weaker for more peripheral)

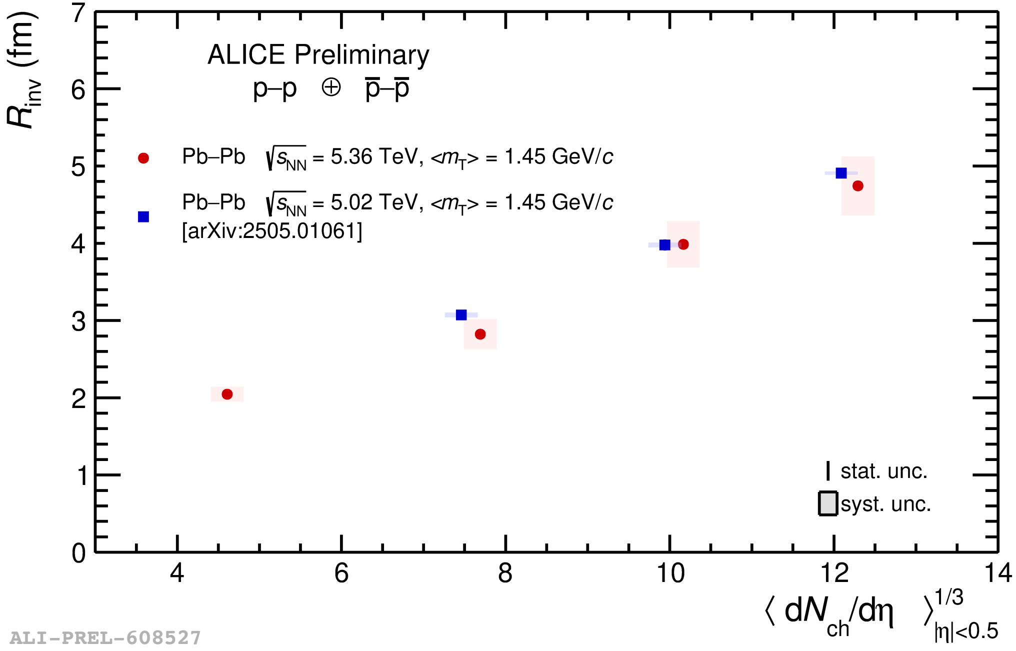
Proton 1D radii: comparison with Run 2 (1/2)

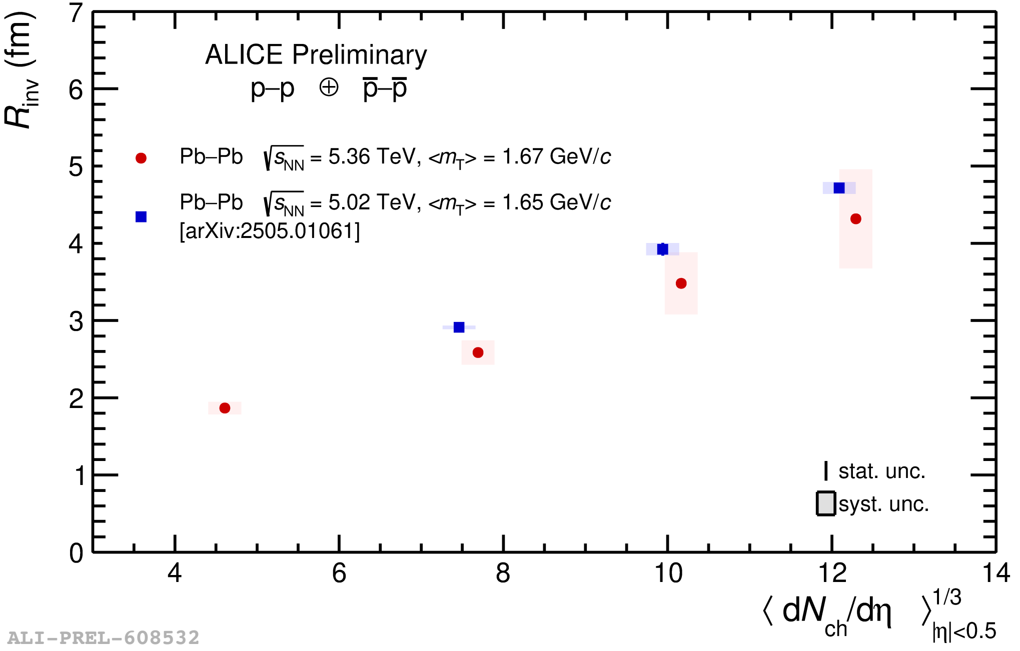




- The new Run 3 results (red) are consistent with Run 2 data (blue)
- More peripheral events are accessed w.r.t. Run 2
- More improvements for Run 3 is expected

Proton 1D radii: comparison with Run 2 (2/2)





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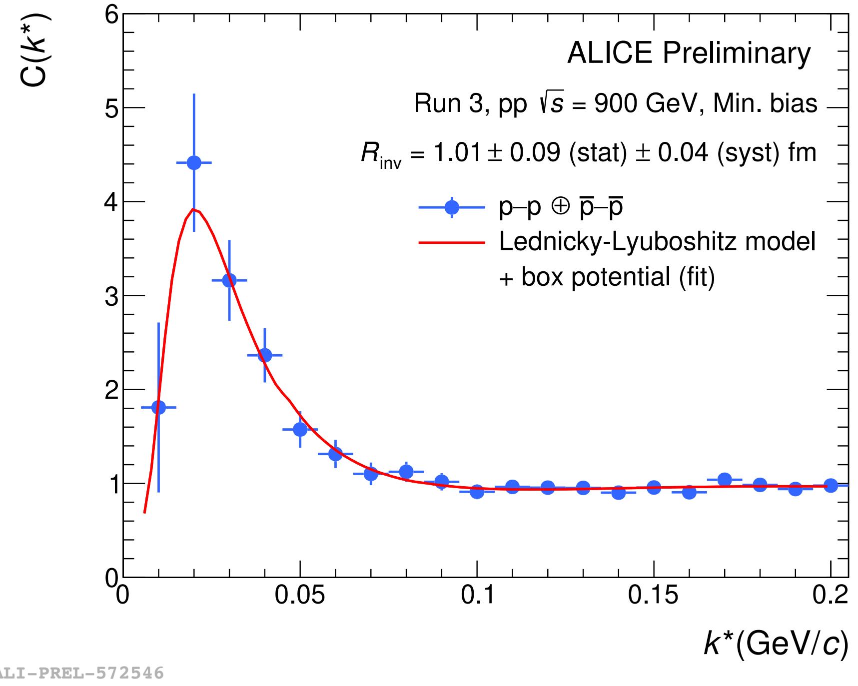
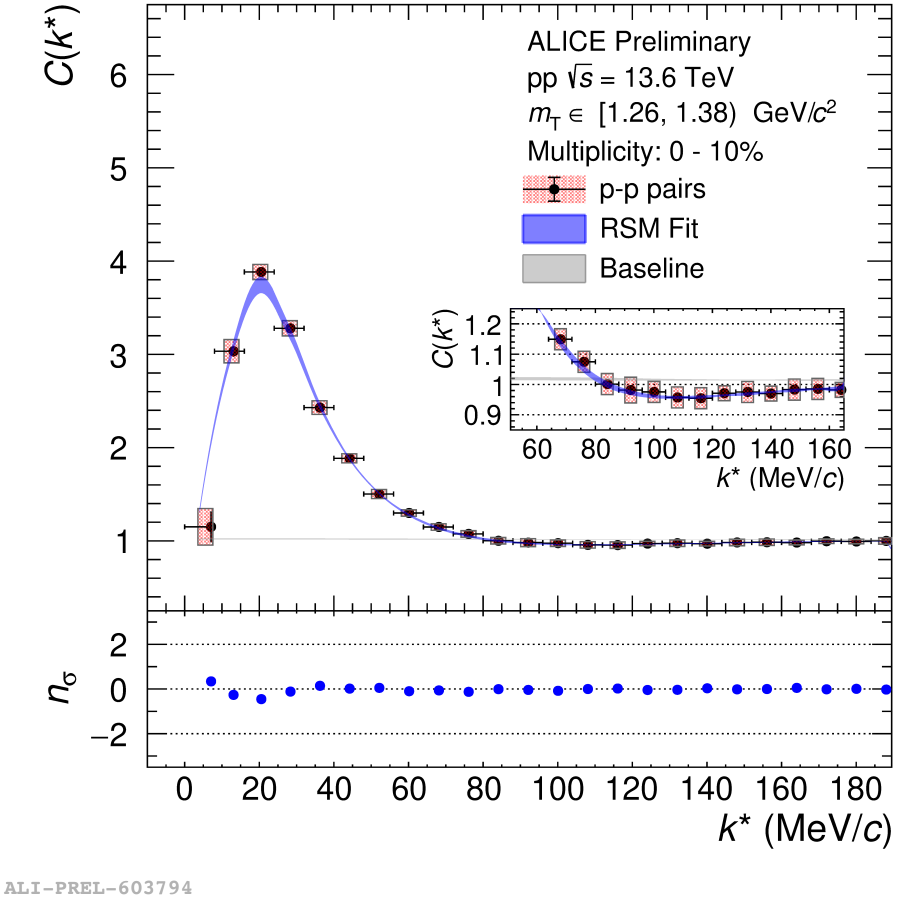
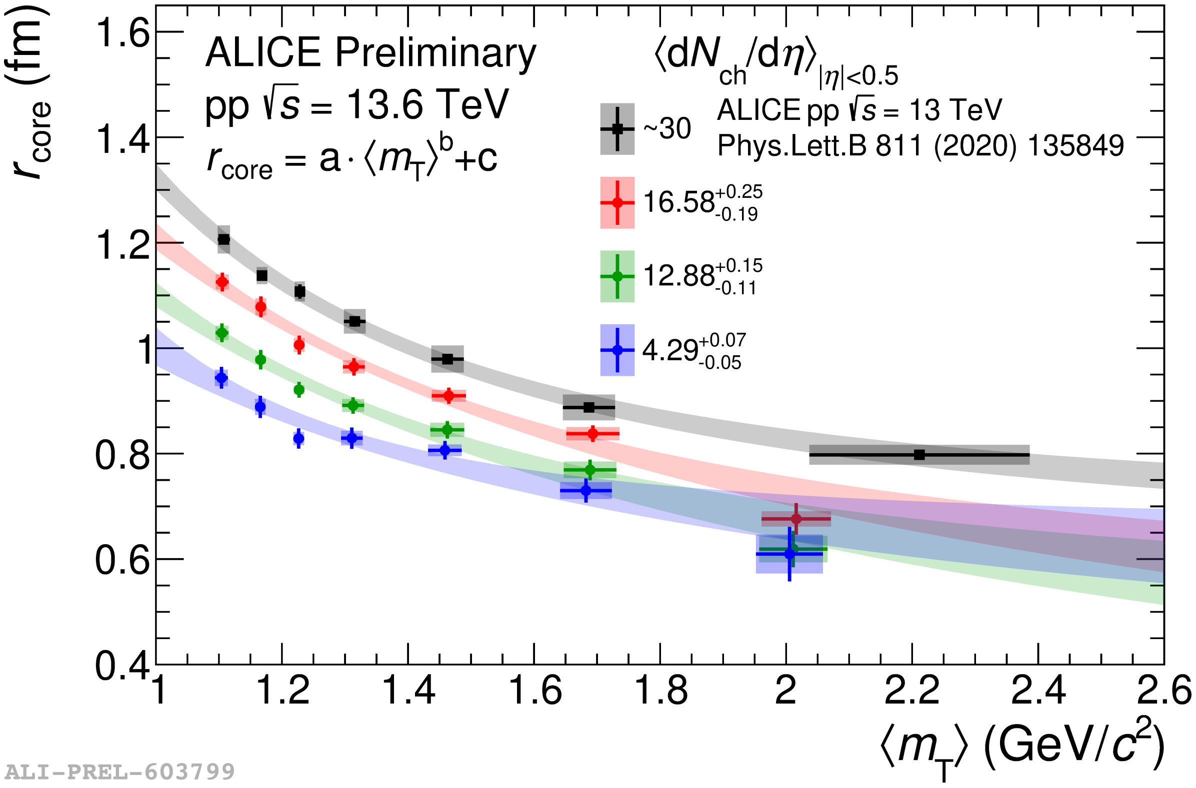
Proton CFs in pp collisions





- Femtoscopic CF at the lowest LHC energy is obtained
- Data from pp at 13.6 TeV have more statistics and can provide more precise and detailed measurements

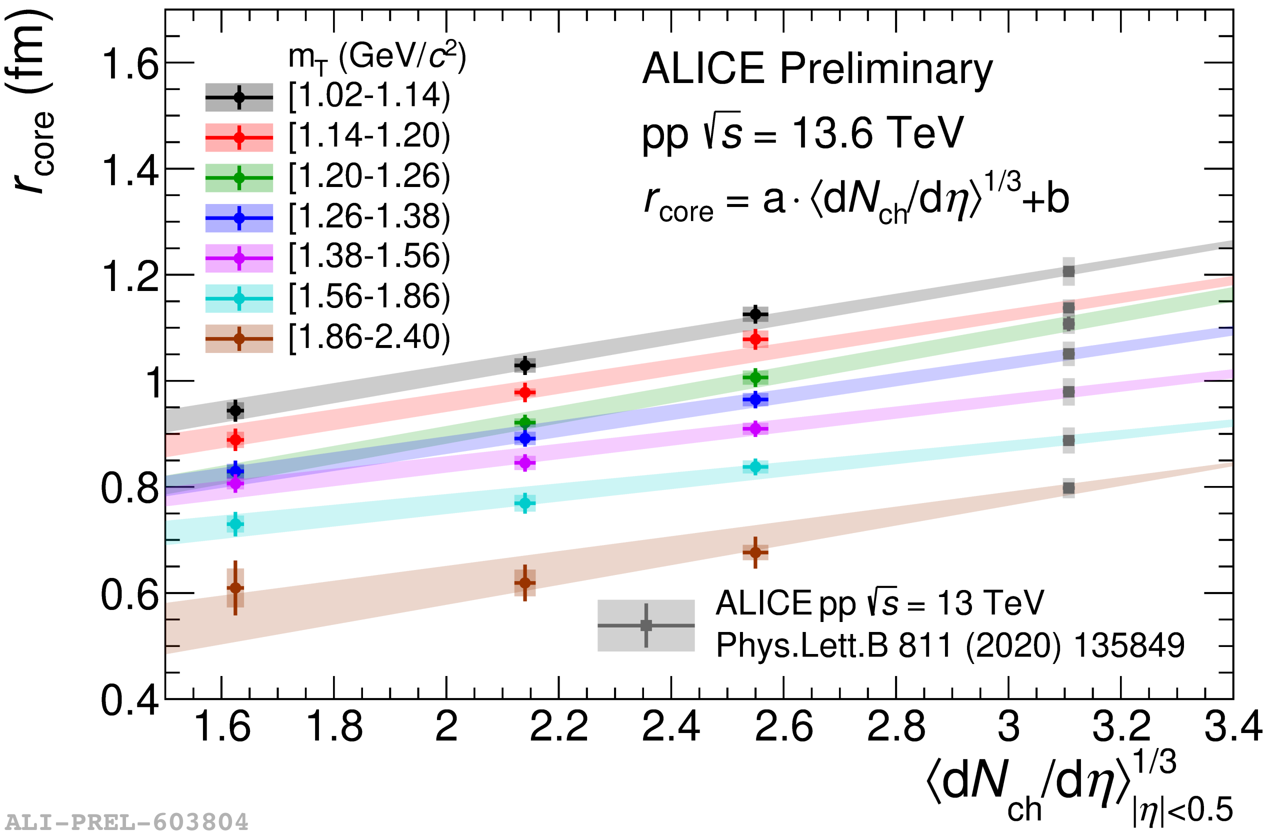
Proton 1D radii in pp at 13.6 TeV



- Scaling with multiplicity — smaller effective source size for events with lower mult.
- m_T dependence — manifestation of a similar “explosive” behaviour as in HIC?
- Source size saturates with increasing m_T

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

Proton 1D radii in pp at 13.6 TeV



ALI-PREL-603804

The extracted radii vs. the cube root of charged particle multiplicity density $< dN_{ch}/d\eta >^{1/3}_{|\eta|<0.5}$ exhibit the linear scaling prediction

(M. Lisa et al., Ann.Rev.Nucl.Part.Sci.55:357-402(2005))

Summary

- **Femtoscopy is a useful tool for studying heavy-ion collision physics on both macro- and microscopic levels**
- **Pb—Pb at 5.36 TeV results:**
  - Proton radii demonstrate the dynamics typical for heavy-ion collisions → radial expansion;
  - New Run 3 results are in a good agreement with Run 2 ones;
- **pp at 13.6 TeV results:**
  - Opportunity to check different strong potential models;
  - m_T dependence — manifestation of a similar “explosive” behaviour as in HIC?
  - The extracted radii seem to follow linear scaling with the cube root of charged particle multiplicity density

Don't miss other ALICE's femto results!

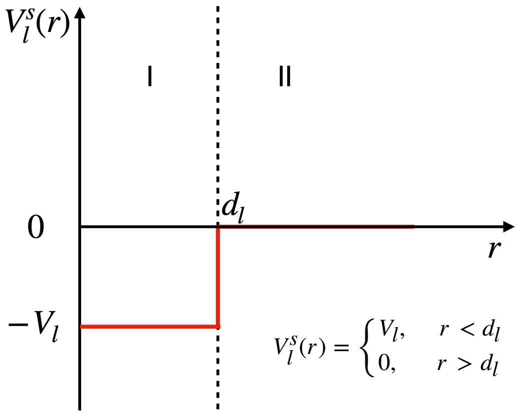
- **Investigating excited N states via the measurement of ρ^0-p final-state interaction with ALICE, Maximilian Korwieser, T05 at 09:21 on 10 July**

- **Accessing Three-Body Dynamics with p–d and Λ–d Correlations in pp Collisions at 13.6 TeV with ALICE, Anton Albert Riedel, Poster session T05 at 18:23 on 9 July**

Backup slides

EFT approach 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



$$V_l^s(r) = \begin{cases} V_l, & r < d_l \quad (I) \\ 0, & r > d_l \quad (II) \end{cases}$$

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

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

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

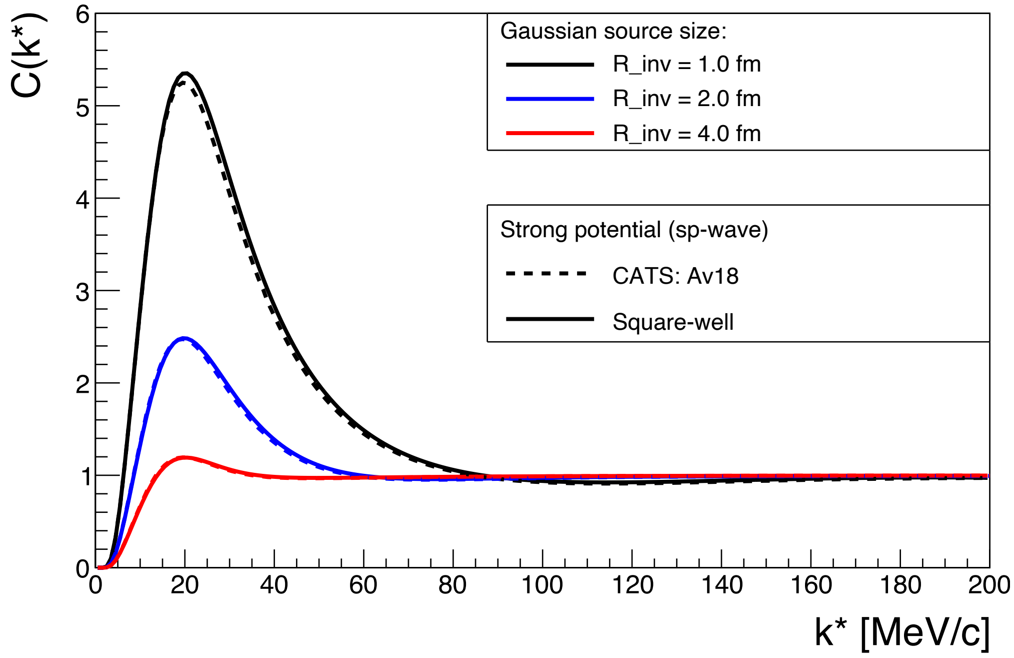
$$S(r, R_{inv}) = \frac{1}{8\pi^{\frac{3}{2}} R_{inv}^3} exp(-\frac{r^2}{4R_{inv}^2})$$ — assuming Gaussian source

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

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

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

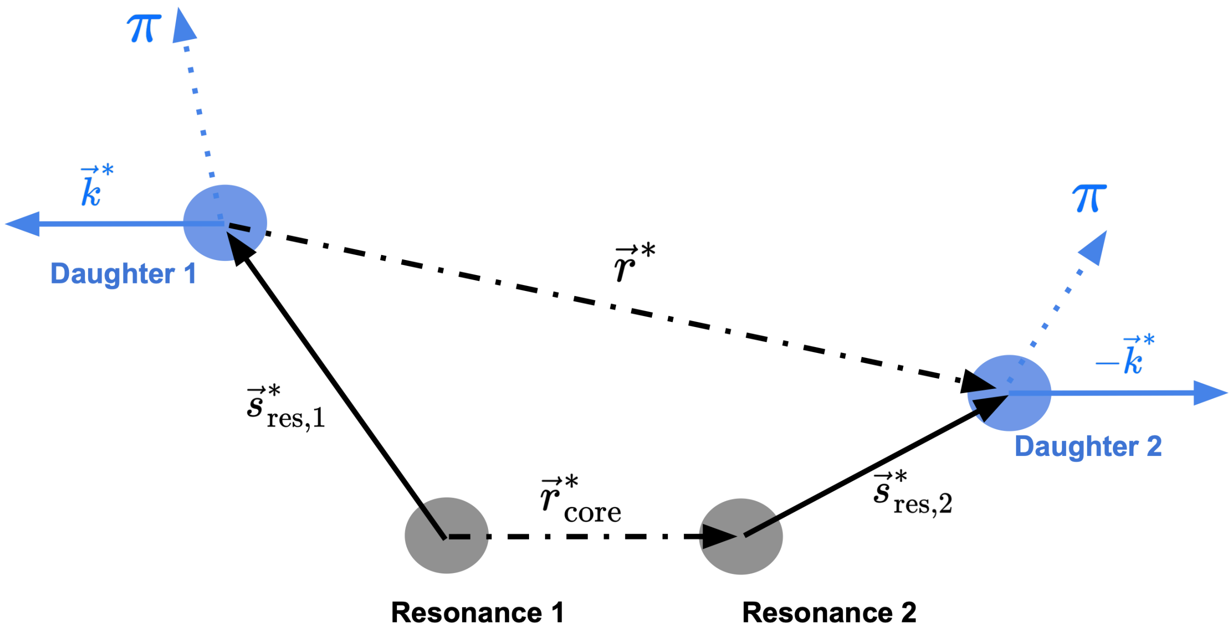
Comparing different approaches



- **Square-well** analytical approach results in **close** CFs w.r.t. exact calculations* for such an advanced strong potential model as **Argonne v18**.

**Mihaylov, D.L. et al., Eur. Phys. J. C 78, 394 (2018)*

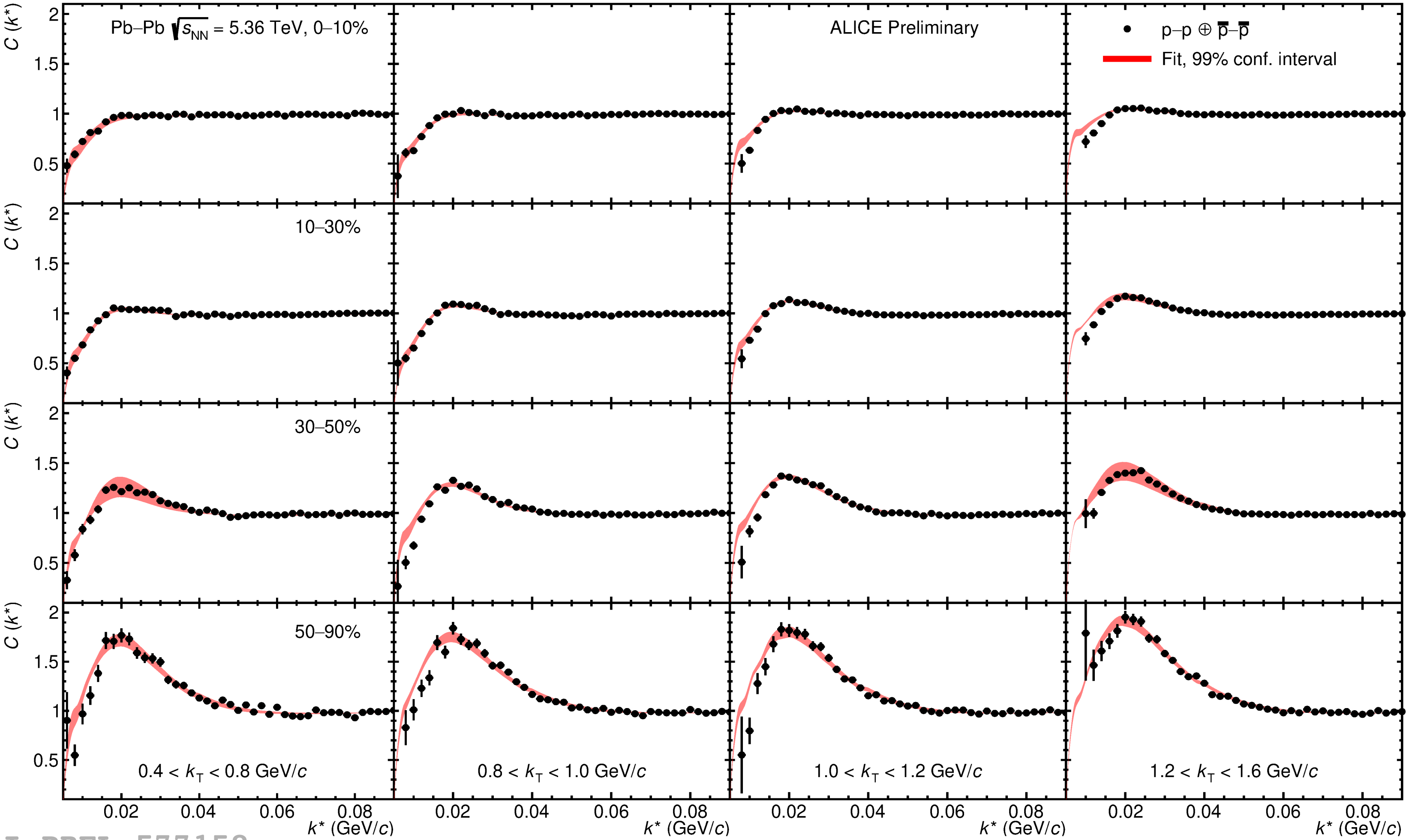
Resonance source model



Modelling the resonance decays to apply a source size correction since there is always a part of protons coming not primarily from the "source" but as product of resonance decays

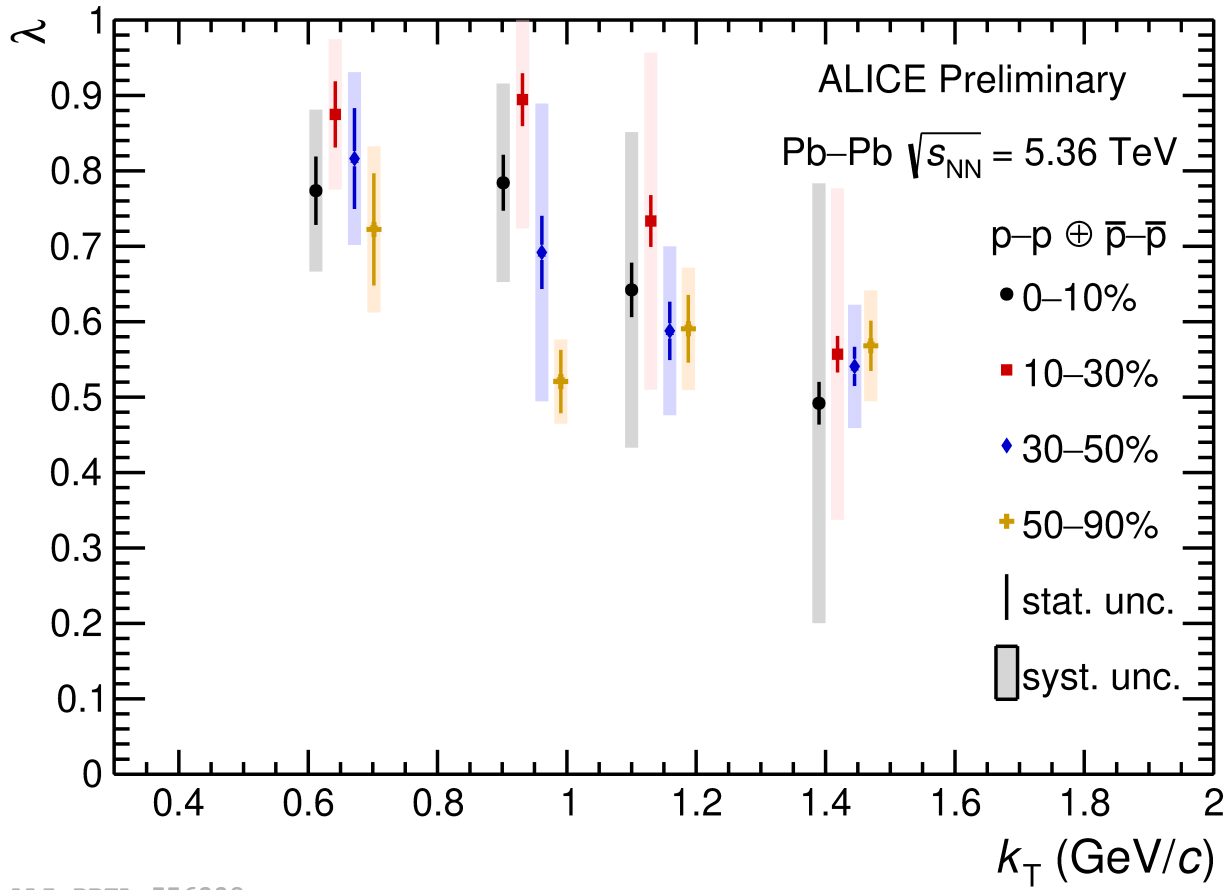
ALICE, Phys. Lett. B 811 (2020) 135849

Proton CFs in Pb–Pb at 5.36 TeV



ALI-PREL-577158

Proton 1D lambdas in Pb–Pb at 5.36 TeV



ALI-PREL-576228

- The extracted λ parameters are consistent throughout all the centrality bins
- The decreasing trend with increasing the k_T is caused by decrease in purity

*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.