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Charged kaon femtoscopy with ALICE at the LHC

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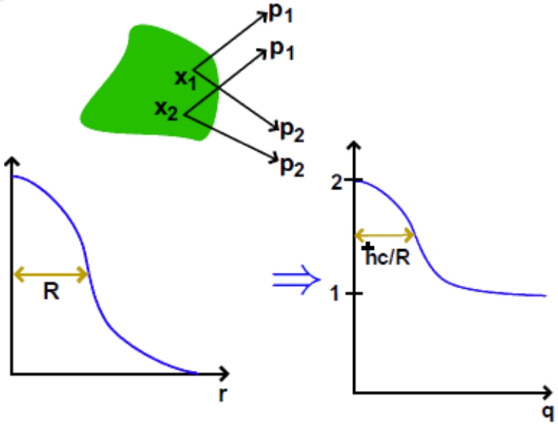
Outline

- Femtoscopy
- ALICE setup
- Kaon and pion in pp 13 TeV
- Kaon in p–Pb 5.02 TeV
- Non-identical kaons in Pb–Pb 2.76 TeV
- Summary

Femtoscopy



Correlation femtoscopy:

Measurement of space–time characteristics **R**, **cτ** of particle production using particle correlations due to the effects of quantum statistics (QS) and final–state interactions (FSI)

Two-particle correlation function:

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

experiment: $$C(q)=\frac{S(q)}{B(q)}, q=p_1-p_2$$ $S(q)$ – distribution of pair momentum difference from same event, $B(q)$ – reference distribution built by mixing different events

Parametrizations used:

1D CF:

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

R – Gaussian radius in PRF,

λ – correlation strength parameter

3D CF:

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

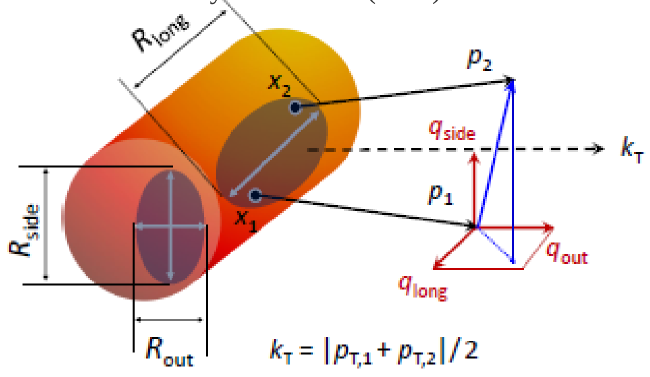
R and q are in Longitudinally Co-Moving Frame (**LCMS**)

long || beam; out || transverse pair velocity $\boldsymbol{v}_T$; side normal to out,long

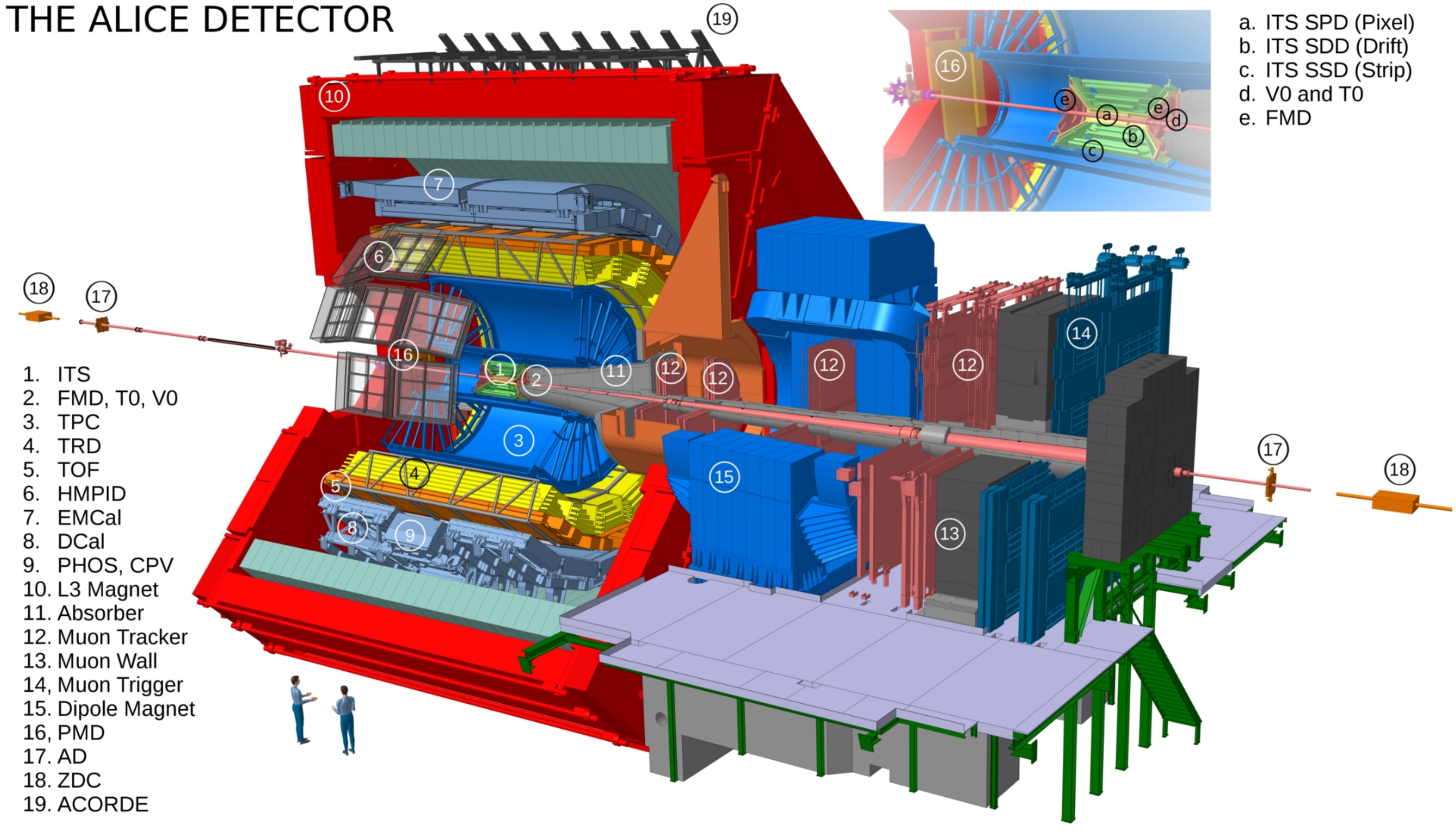
LCMS decomposition:

S. Pratt. Phys. Rev. D 33 (1986) 1314

G. Bertsch. Phys. Rev. C 37 (1988) 1896



ALICE setup

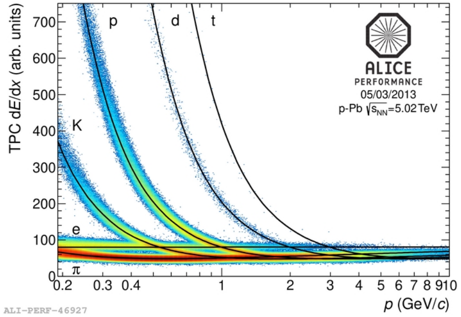


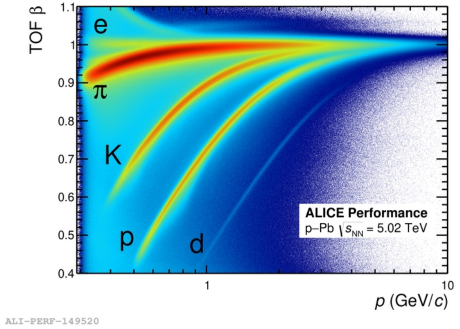
Tracking and vertexing
- Time Projection Chamber (TPC)

& Inner Tracking System (ITS)

Particle Identification
- TPC and Time of Flight (TOF)

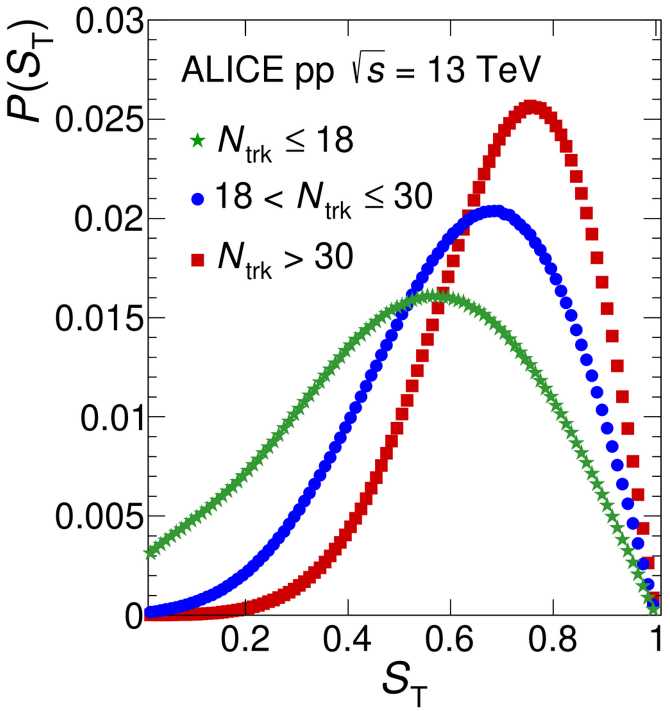
Centrality determination
- V0





π and K femtoscopy with event-shape selection

Femtoscopic correlations of identical charged pions and kaons
in pp collisions at $\sqrt{s}$=13 TeV with event-shape selection ALICE Collaboration, arXiv:2310.07509



ALI-PUB-562712

- Select jetty or spherical events
- S_T transverse sphericity

$$S_T = \frac{2\min(\lambda_1, \lambda_2)}{\lambda_1 + \lambda_2}$$

λ_1 and λ_2 are the eigenvalues of the matrix of p_T

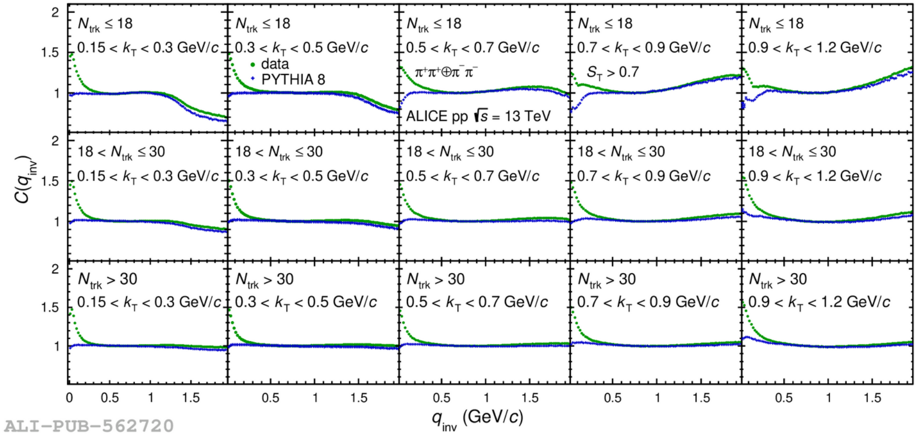
$$S_T = \frac{1}{\sum_i p_T^i} \sum_i \frac{1}{p_T^i} \begin{pmatrix} (p_x^i)^2 & p_x^i p_y^i \\ p_x^i p_y^i & (p_y^i)^2 \end{pmatrix}$$

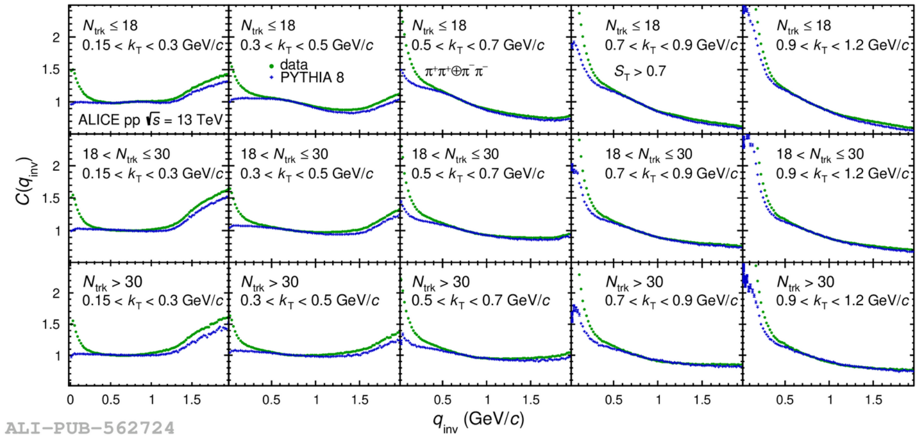
- $S_T \rightarrow 0$: a strongly elongated ellipse
- $S_T \rightarrow 1$: an isotropic source

π and K correlation function

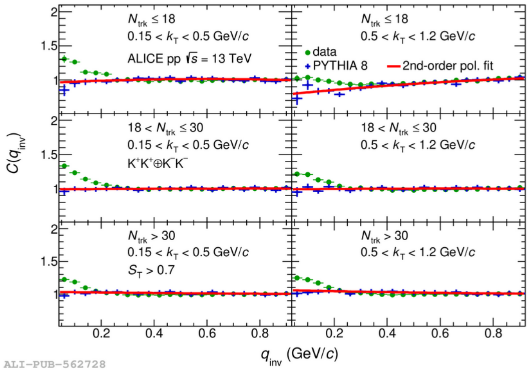
Spherical events

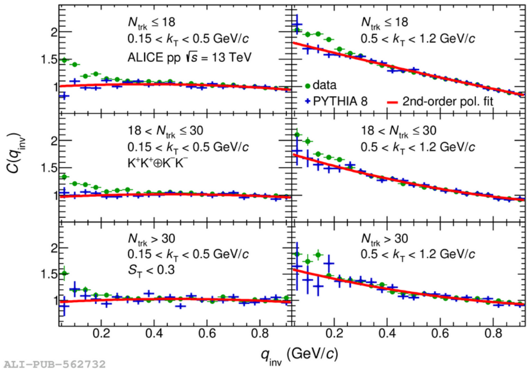
Jetty events





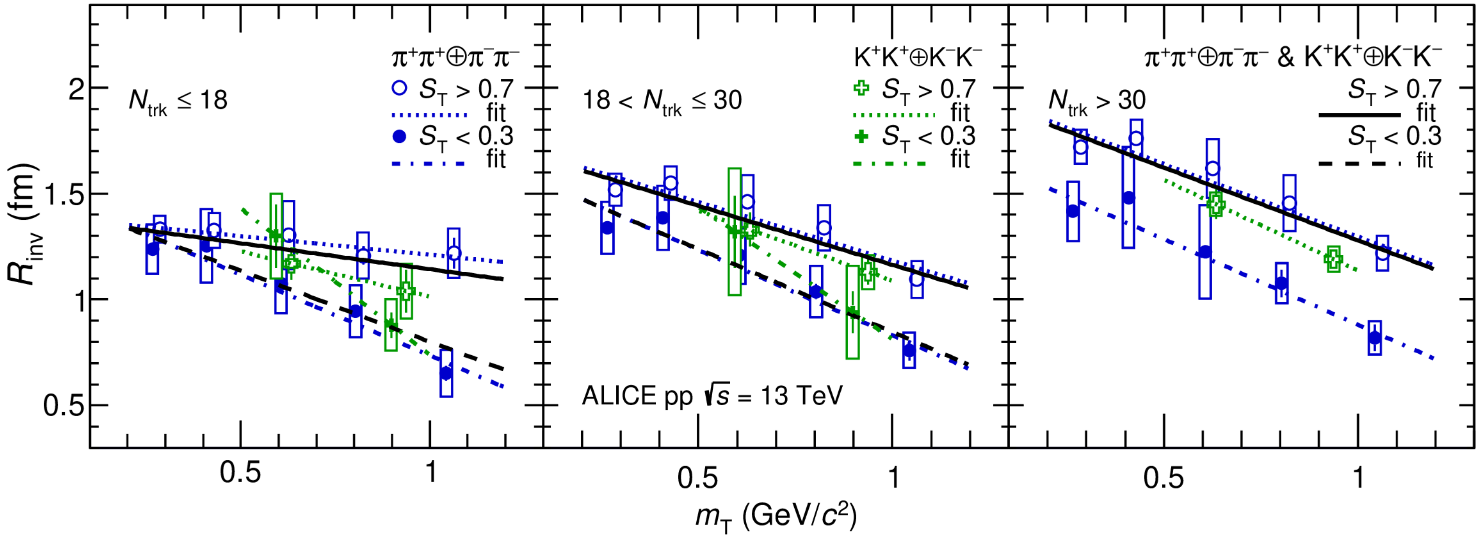
ππ





KK

π and K spherical and jetty radii

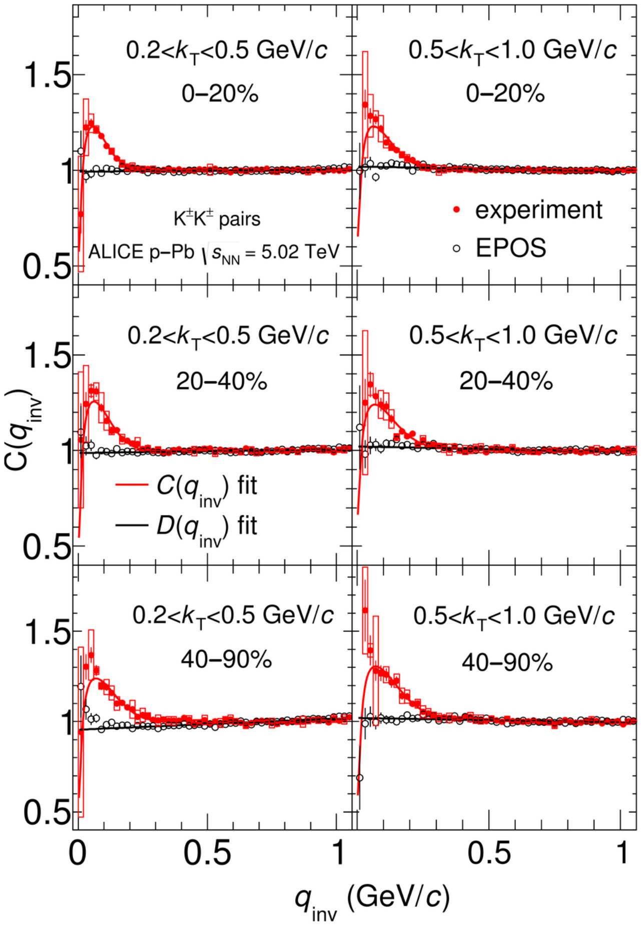


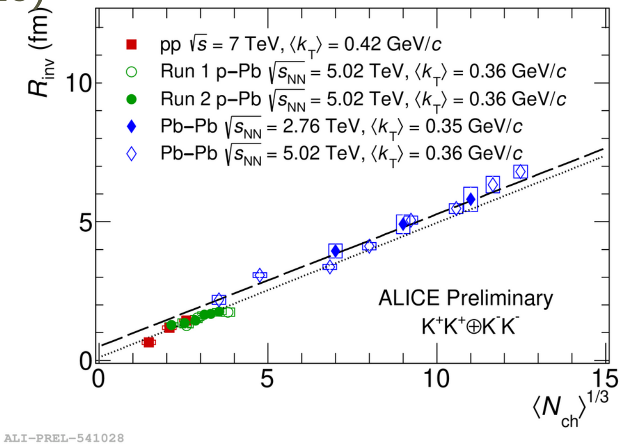
ALI-PUB-562752

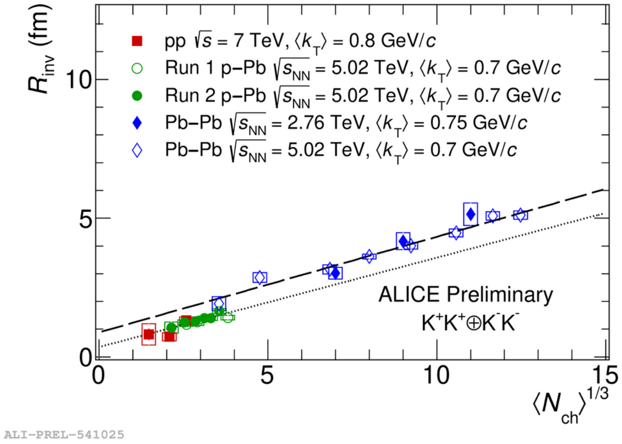
- π radii extracted for spherical events > those for jet-like events
- Both π and K R_{inv} demonstrate a decreasing trend with increasing m_T
- Spherical and jetty events m_T dependence is different

p–Pb $\sqrt{s_{NN}}$=5.02 TeV: 1D KK results

Phys. Rev. C 100, 024002 (2019)







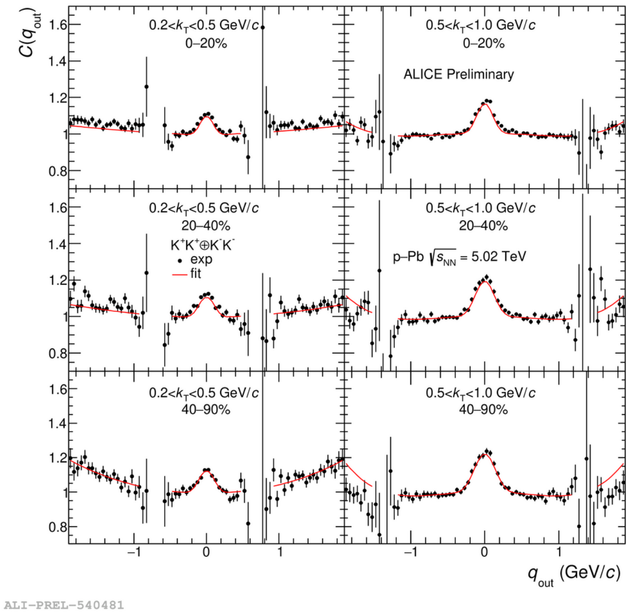
- E.g. of 1D CF fit by Bowler-Sinyukov (B-S) equation:

$$C(q_{inv}) = N \cdot [1 - \lambda + \lambda K(q_{inv}, R_{inv}) e^{-R_{inv}^2 q_{inv}^2}] \cdot D(q_{inv})$$

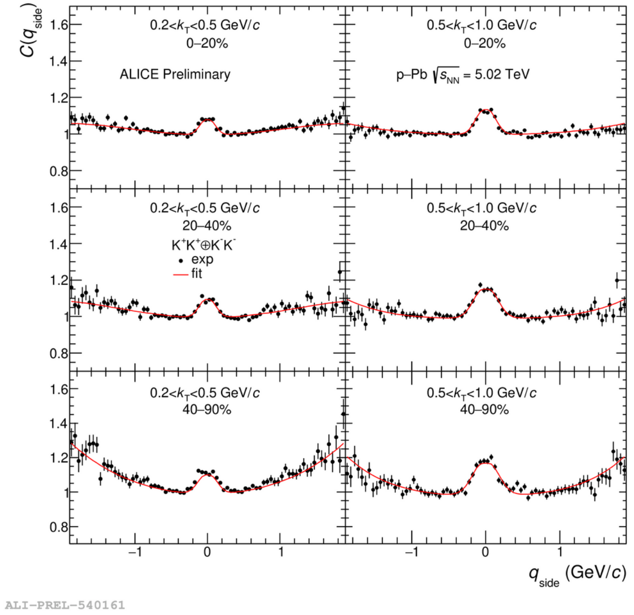
- R_{inv} vs $<N_{ch}>^{1/3}$ at low k_T
- R_{inv} vs $<N_{ch}>^{1/3}$ at high k_T
- Gap between Pb–Pb and pp+p–Pb
- Value of gap increases with increasing k_T

p–Pb $\sqrt{s_{NN}}$=5.02 TeV: 3D KK CF projections

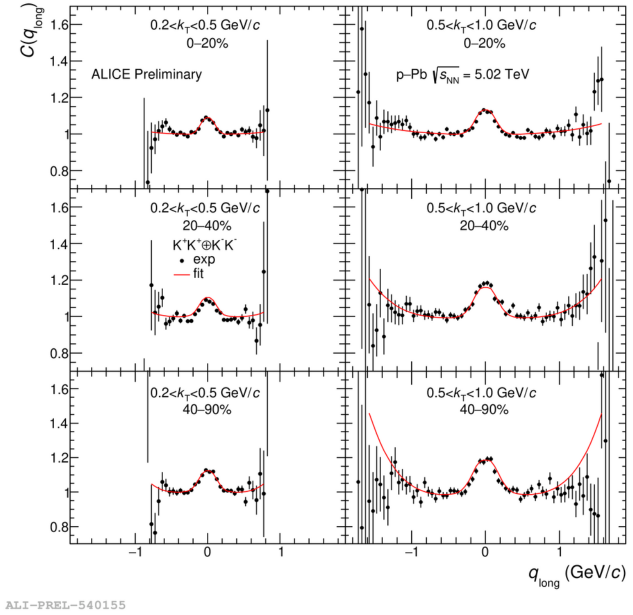
out



side



long

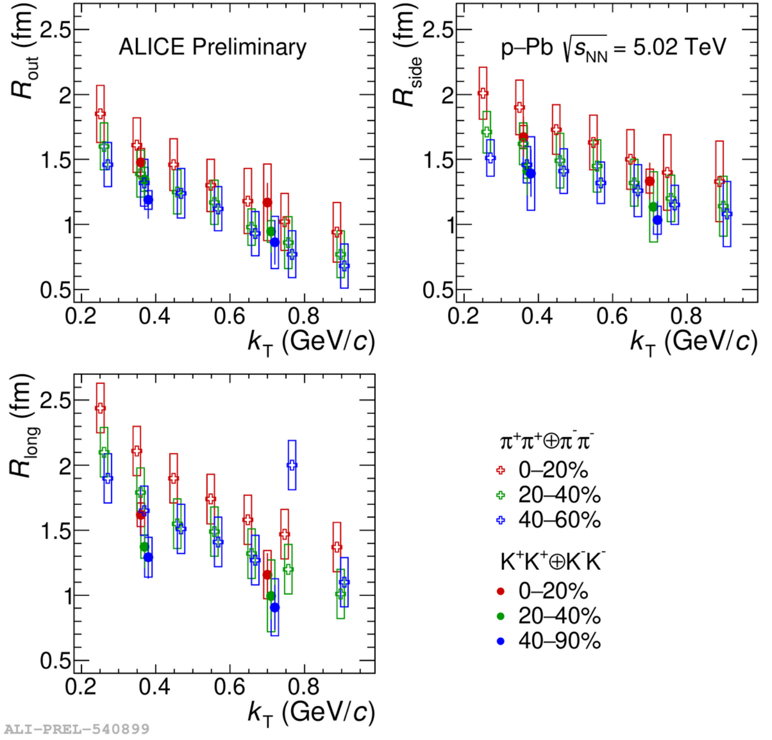


- E.g. of CF projection onto out-side-long axis in LCMS with fit B-S:

$$C(q_{out},q_{side},q_{long})=N[\lambda-1+\lambda K(R,q_{inv})e^{-R_{out}^2 q_{out}^2-R_{side}^2 q_{side}^2-R_{long}^2 q_{long}^2}]D(q_{out},q_{side},q_{long})$$

- Fit function gives a good description for centrality(top to bottom) and k_T(let to right) bins

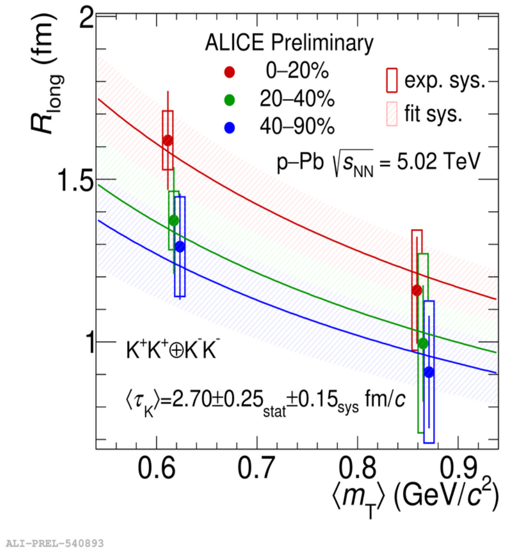
p–Pb $\sqrt{s_{NN}}$=5.02 TeV: 3D KK CF results

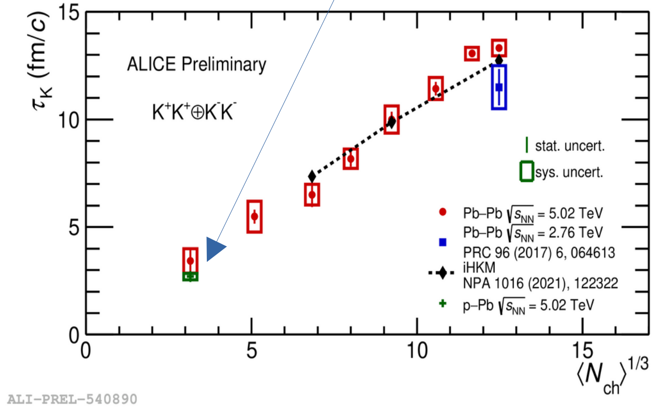


- Extract time of maximal emission τ
- m_T dependence of R^2_{long} as NPA 1016(2021)122322

$$R^2_{long} = \tau^2 \lambda^2 \left(1 + \frac{3}{2}\lambda^2\right), \ \lambda^2 = T / m_T \sqrt{1 - \bar{v}_T^2}$$

- p–Pb and very peripheral Pb–Pb results for τ are similar





- π results from ALICE Collaboration, PRC 91 (2015) 034906
- π and K results agree well

K^+K^- theoretical correlation function (formalism)

[R.Lednicky,V.Lyuboshitz Sov. J. Nucl. Phys. 35, 770 (1982), R.Lednicky Phys. Part. Nucl.40, pp.307(2009)]

The K^+K^- correlation function(CF) at given **k*** and 3-momentum **P**:

$$C_{sFSI}(\mathbf{k}^*,\mathbf{P}) = \int \mathrm{d}^3\mathbf{r}^* S^{\alpha}(\mathbf{r}^*,\mathbf{P}) \sum_{\alpha'} \left| \psi^{\alpha'\alpha}_{-\mathbf{k}^*}(\mathbf{r}^*) \right|^2 \quad (1)$$

Spatial separation: $S(\mathbf{r}^*) \sim exp(-\mathbf{r}^{*2}/4R^2)$

The s-wave scattering amplitude $f(k^*)$:

$$f_0(k^*) = \frac{\gamma_{f_0\to K+K-}}{m^2_{f_0} - s - i(\gamma_{f_0\to K+K-}k^* + \gamma_{f_0\to\pi\pi}k_{\pi\pi})} \quad \text{and} \quad f_1(k^*) = \frac{\gamma_{a_0\to K+K-}}{m^2_{a_0} - s - i(\gamma_{a_0\to K+K-}k^* + \gamma_{a_0\to\pi\eta}k_{\pi\eta})} \quad (2)$$

The p-wave strong interaction through ϕ meson resonance [R.Lednicky Part. Nucl. Letters 8(2011)965]:

$$C_{\phi}(p_1,p_2) = N^{-1}(p_1,p_2) \int d^3\mathbf{r} W_P(\mathbf{r},\mathbf{k}) \sum_{\alpha' m'} |\psi^{\alpha' m';\alpha}_{-\mathrm{k}}(\mathbf{r})|^2 \quad (3)$$

The total correlation function : $C_{FSI}(p_1,p_2) = 1 + C_{sFSI}(p_1,p_2) + N_1 C_{\phi\text{-}direct}(p_1,p_2) + N_2 C_{\phi}(p_1,p_2)$ (4)

$C_{\phi\text{-}direct}(p_1,p_2)$ is a non-relativistic Breit-Wigner function.

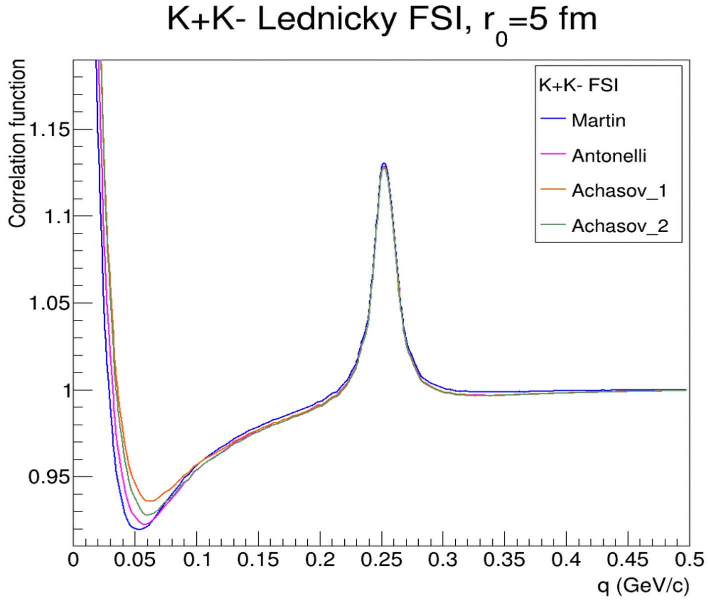
Pb–Pb $\sqrt{s_{NN}}$=2.76 TeV: K+K- fit

- $C(q) = Norm\cdot[1+\lambda\cdot C_{sFSI}(q,R) + \lambda_\phi\cdot C_\phi(q,M,\sigma))]$

  $C_{sFSI}(q,R)$ - Lednicky model

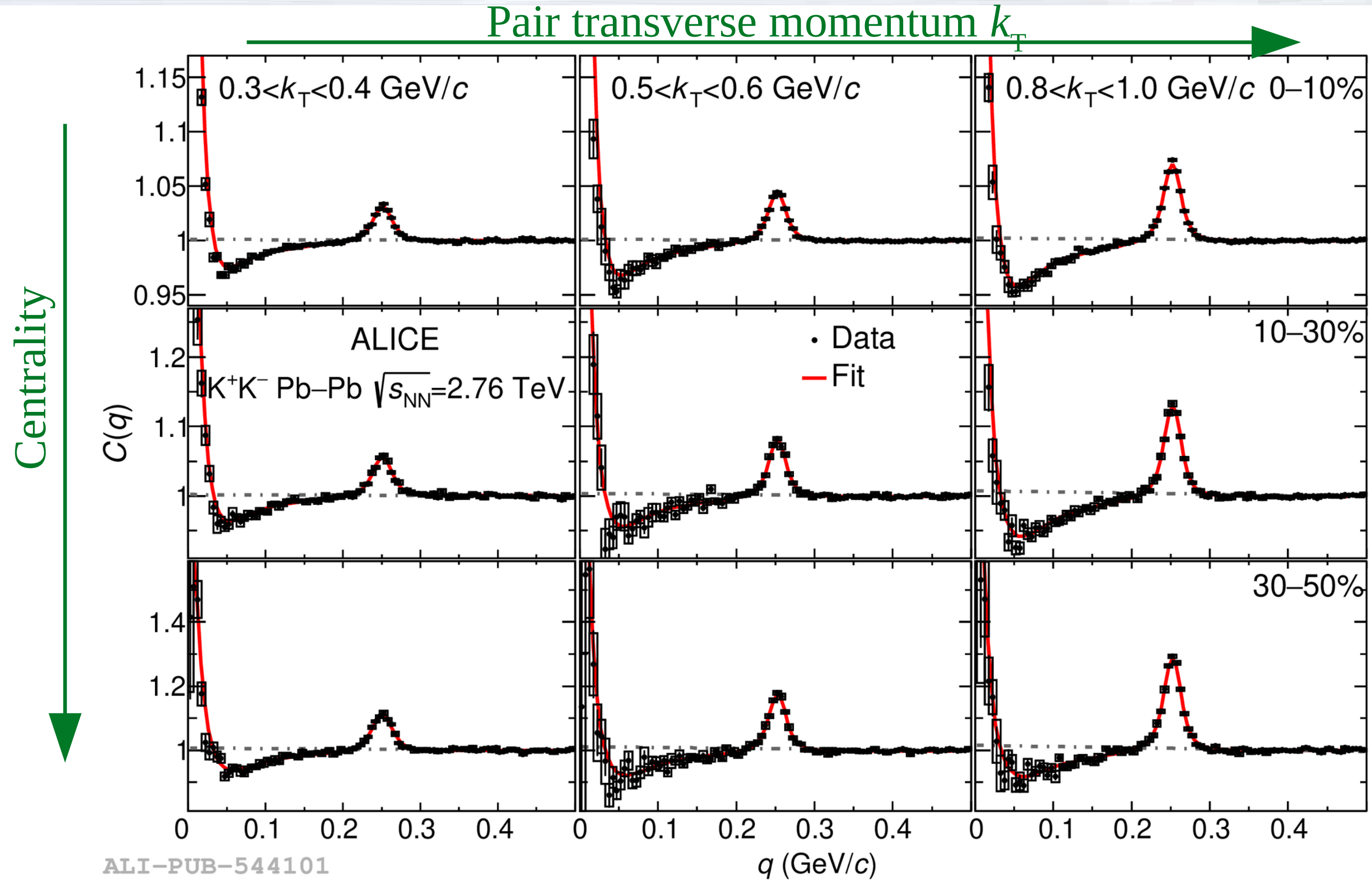
  $C_\phi(q,M,\sigma)$ - Breit-Wigner Γ_ϕ=4.25MeV

- a_0 parameters fixed from Achasov[2] [ALICE PLB774 (2017) 64, PLB 790 (2019) 22]
- f_0 mass and coupling parameters are free



The masses (a_0 and f_0) and coupling parameters							
Model	m_{f0}^2	m_{a0}^2	$\gamma_{f0\to K+K-}$	$\gamma_{f0\to\pi\pi}$	$\gamma_{a0\to K+K-}$	$\gamma_{a0\to\pi\eta}$	
Martin	.9565	.9487	.792	.199	.333	.222	NPB 121 (1977) 514
Antonelli	.9467	.9698	2.763	.5283	.4038	.3711	hep-ex/0209069
Achasov[1]	.9920	.9841	1.305	.2684	.5555	.4401	PRD 63(2001) 094007
Achasov[2]	.9920	1.0060	1.305	.2684	.8365	.4580	PRD 68(2003) 014006

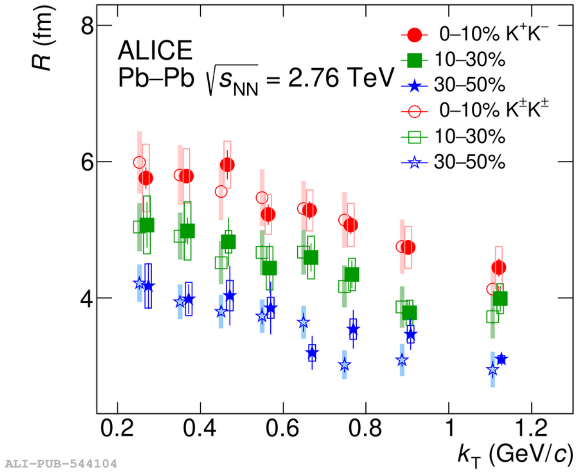
Pb–Pb $\sqrt{s_{NN}}$=2.76 TeV: K+K- CF

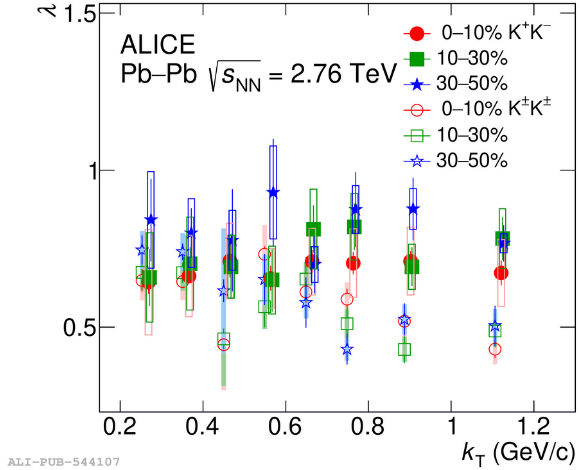


ALICE Collaboration,
Phys. Rev. C107 (2023) 054904

Fit function gives a good description for centrality(top to bottom) and k_T(let to right) bins

Pb–Pb $\sqrt{s_{NN}}$=2.76 TeV: results





$f_0(980)$ [j] $I^G(J^{PC}) = 0^+(0^{++})$

Mass $m = 990 \pm 20$ MeV
Full width $\Gamma = 10$ to 100 MeV

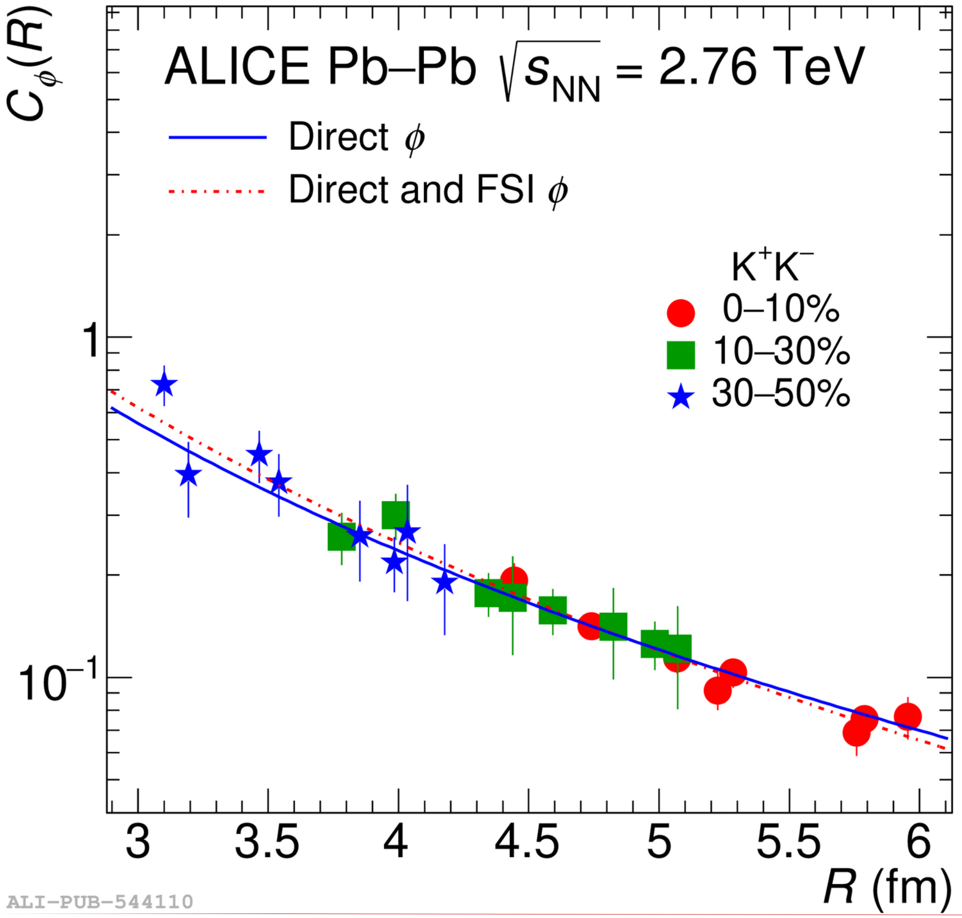
Particle Data Group

$f_0(980)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\pi\pi$	dominant	476
$K\overline{K}$	seen	36
$\gamma\gamma$	seen	495

- Radii are in agreement within errors
- λ of K^+K^- tend to be larger than for λ of $K^\pm K^\pm$
  ALICE Collaboration, Phys. Rev. C107 (2023) 054904
- $f_0(980)$ mass, width and couplings parameters:
- M_{f0} = 967 ± 3 ± 7 MeV/c^2
- Γ_{f0}= 43.81 ± 8.76 ± 6.90 MeV/c^2
- $\gamma_{f0\to\pi\pi}$ = 0.089 ± 0.0178 ±0.026 GeV
- $\gamma_{f0\to K+K-}$= 0.34 ± 0.068 ± 0.101 GeV

Pb–Pb $\sqrt{s_{NN}}$=2.76 TeV: ϕ peak value

ALICE Collaboration, Phys. Rev. C107 (2023) 054904



- ϕ peak height (corrected for λ and MR):

$$C_\phi = CF\left(q=\sqrt{M_\phi^2 - 4m_K^2}\right) - 1$$

- ϕ peak: direct production and FSI K^+K^-
- Direct=const/R^3
- FSI=const·exp(-$\mathbf{b}^2 k_0^2 R^2$)/R^3 , k_0=126 MeV/c
- $C_\phi = a_{dir} \cdot C_{dir} + a_{FSI} \cdot C_{FSI}$
- Red curve fit → a_{dir} =0.75, a_{FSI}=0.25
- FSI fraction could be estimated
- Lack of statistic → difficult to distinguish between direct and FSI contribution

Summary

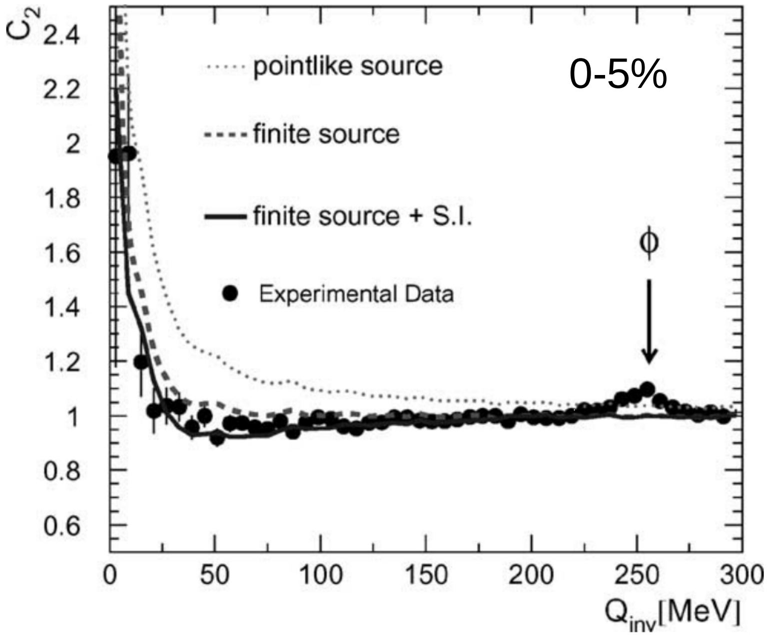
- CF $\pi^{\pm}\pi^{\pm}$ and $K^{\pm}K^{\pm}$ in pp at $\sqrt{s}$ = 13 TeV were measured;
  - CF classified via global event-shape variable, S_T;
  - Spherical CF cleared of mini-jets; Jet CF shows significant mini-jet effects;
  - The $\pi^{\pm}\pi^{\pm}$ radii for spherical events are larger than for jet events;
- CF $K^{\pm}K^{\pm}$ 1D+3D in p–Pb at $\sqrt{s_{NN}}$=5.02 TeV were measured;
  - 1D R vs N_{ch} for p–Pb and pp are in agreement and different from Pb–Pb;
  - 3D out-side-long $K^{\pm}K^{\pm}$ and $\pi^{\pm}\pi^{\pm}$ radii coincide within errors;
  - maximal emission time τ_K was extracted and is close to one at very peripheral Pb–Pb;
- CF K+K- Pb–Pb at $\sqrt{s_{NN}}$=2.76 TeV were measured;
  - For the first time the K^+K^- correlation functions were fitted with free f_0(980) mass, width with restriction on radii to be close to the corresponding identical $K^{\pm}K^{\pm}$;
  - The measured width of the f_0(980) is 43.81 ± 8.76(stat) ± 6.90(sys) MeV/c^2 and mass is 967 ± 3(stat) ± 7(sys) MeV/c^2 which do not contradict the PDG data.

Thank you for your attention!

Slides in trunk

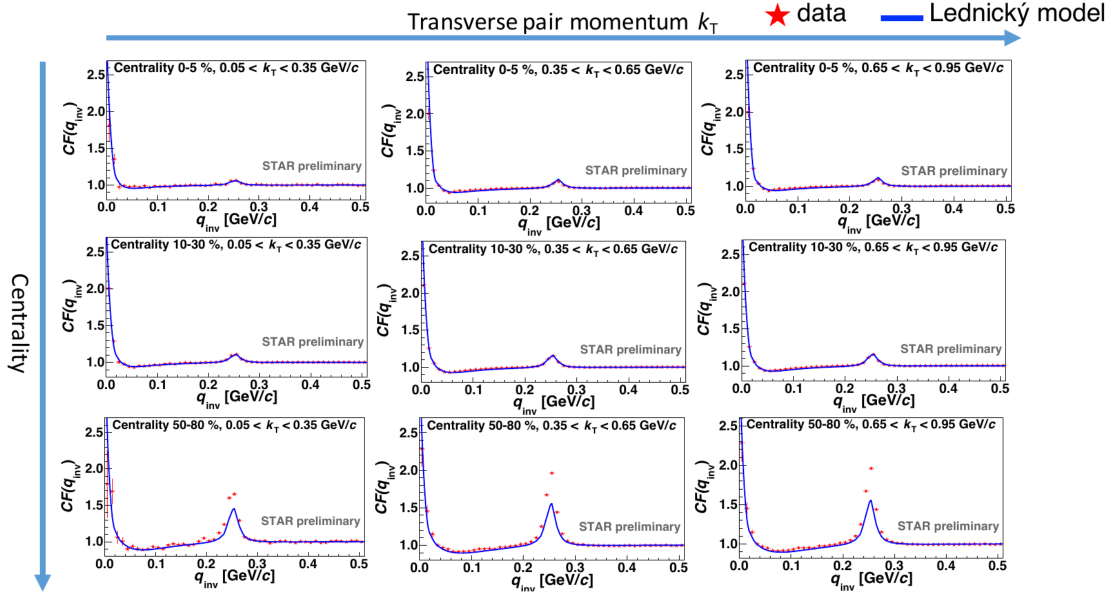
K^+K^- existing results

NA49 Pb-Pb 158 GeV [PLB 557(2003)157]



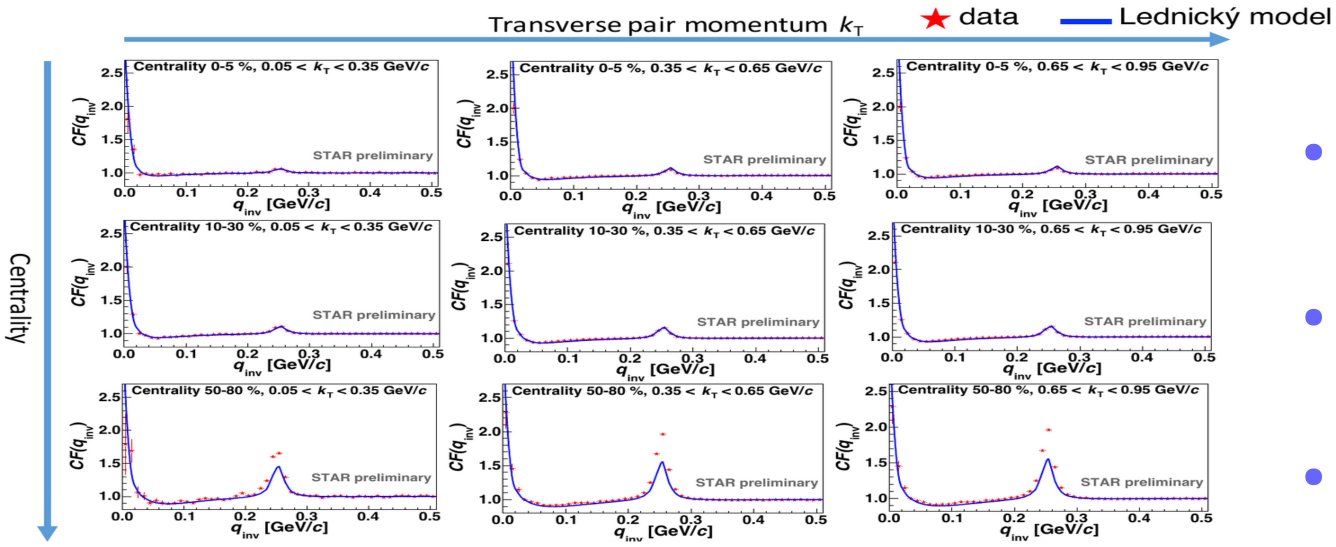
- Coulomb stays above data
- Dip at Q_{inv}~50-150 due to strong interaction
- Strong and Coulomb FSI does good job

STAR AuAu 200 GeV [WPCF 2017, J. Lidrych]



- No fit, comparison with Lednický model
- Data is described qualitatively for large source
- Phi production mechanism is not taken into account

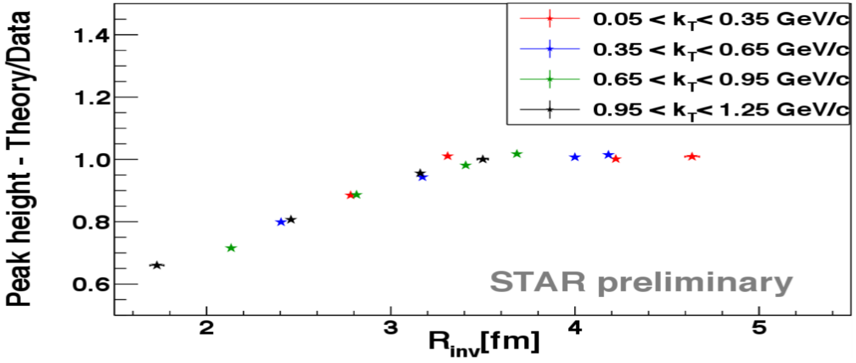
K^+K^- existing results: STAR



- K^+K^- in AuAu at $\sqrt{s_{NN}}$=200 GeV [WPCF 2017, Jindřich Lidrych]
- CF=(CF^{theor}-1)·λ+1 (no fit) CF^{theor} → Lednický model
- Data is described qualitatively for large source

Observations:

- The model underpredicts the strength of the correlation functions in the region of resonance with decreasing R_{inv}
- Model *fails* for smaller system (~3fm and smaller)



- Does not take into account ϕ production mechanism