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K^+K^- correlations in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV by ALICE at the LHC

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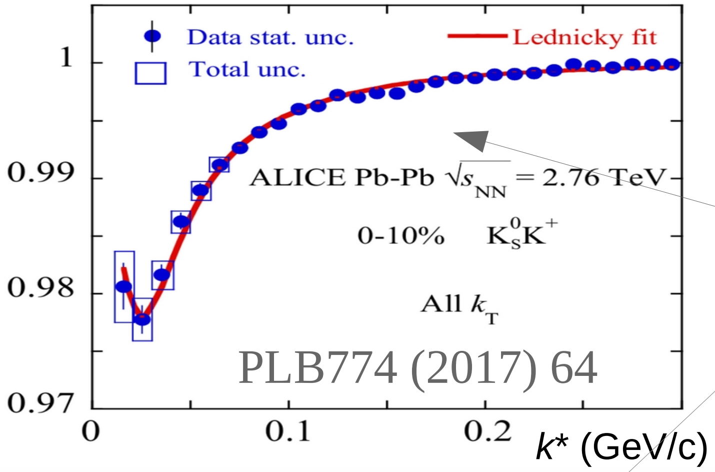
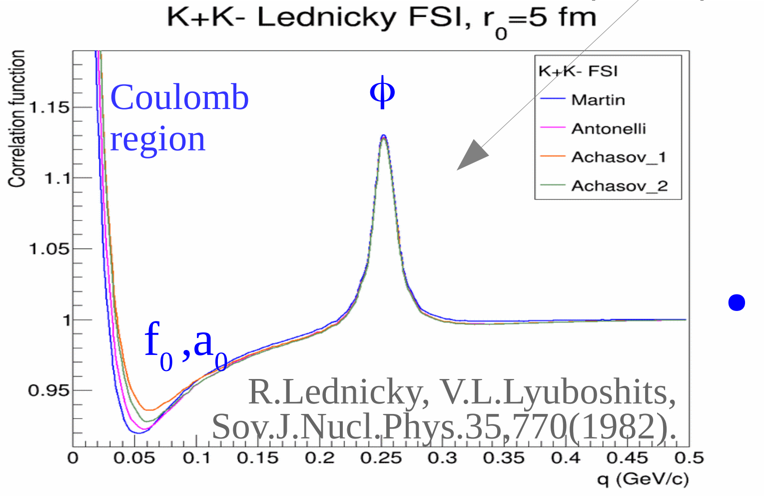
Outline:

- Motivation
- Formalism
- Data and PID, purity, momentum resolution
- Fit data with different models
- Conclusion

Motivation





- First measurement of K^+K^- at the LHC
- Constrain couplings and masses of $f_0(980)$ and $a_0(980)$: $K^0_SK^\pm$: strong FSI, $a_0(980)$ only [ALICE PLB774 (2017) 64]
- K^+K^-: s-wave strong FSI (both a_0 and f_0), p-wave FSI (ϕ meson) and Coulomb FSI [all sensitive to source size]

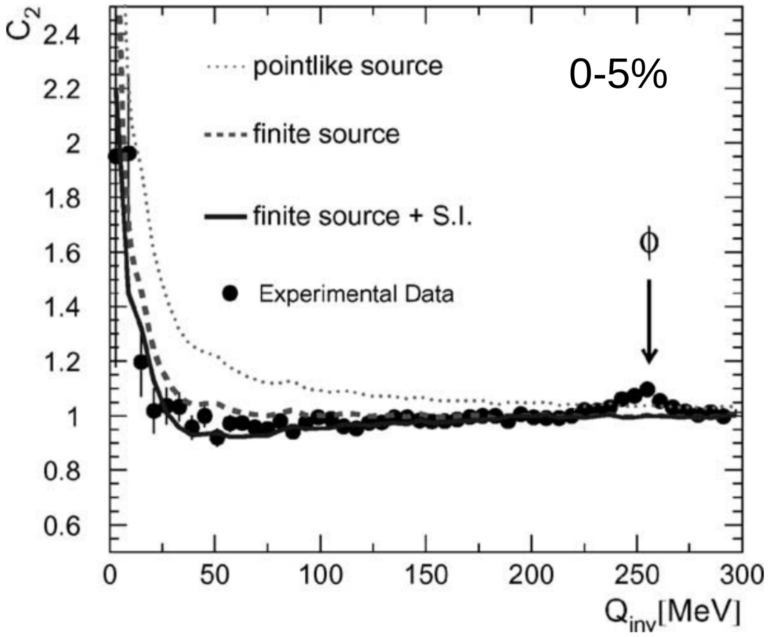
  a_0, f_0 couplings and masses: four model descriptions

  → a_0 couplings and mass were fixed from ALICE papers [PLB774 (2017) 64, PLB 790 (2019) 22]

  → are these a_0 values suitable for K^+K^-
- Cross-check of identical kaon ($K^\pm K^\pm$ and $K^0_SK^0_S$) results

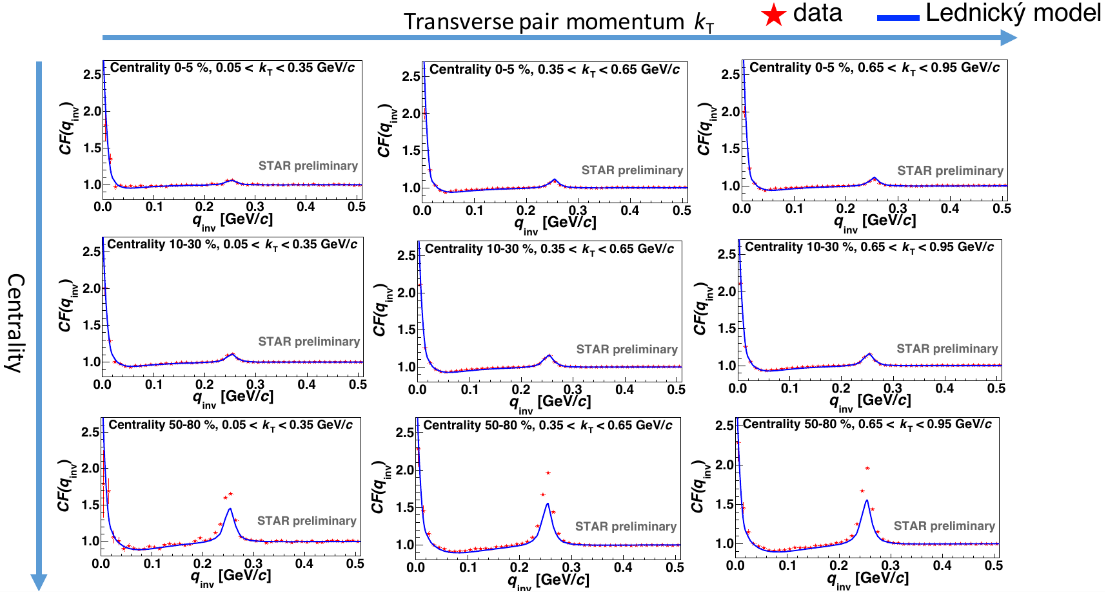
K^+K^- existing results

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^- 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 $f(k^*)$:

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

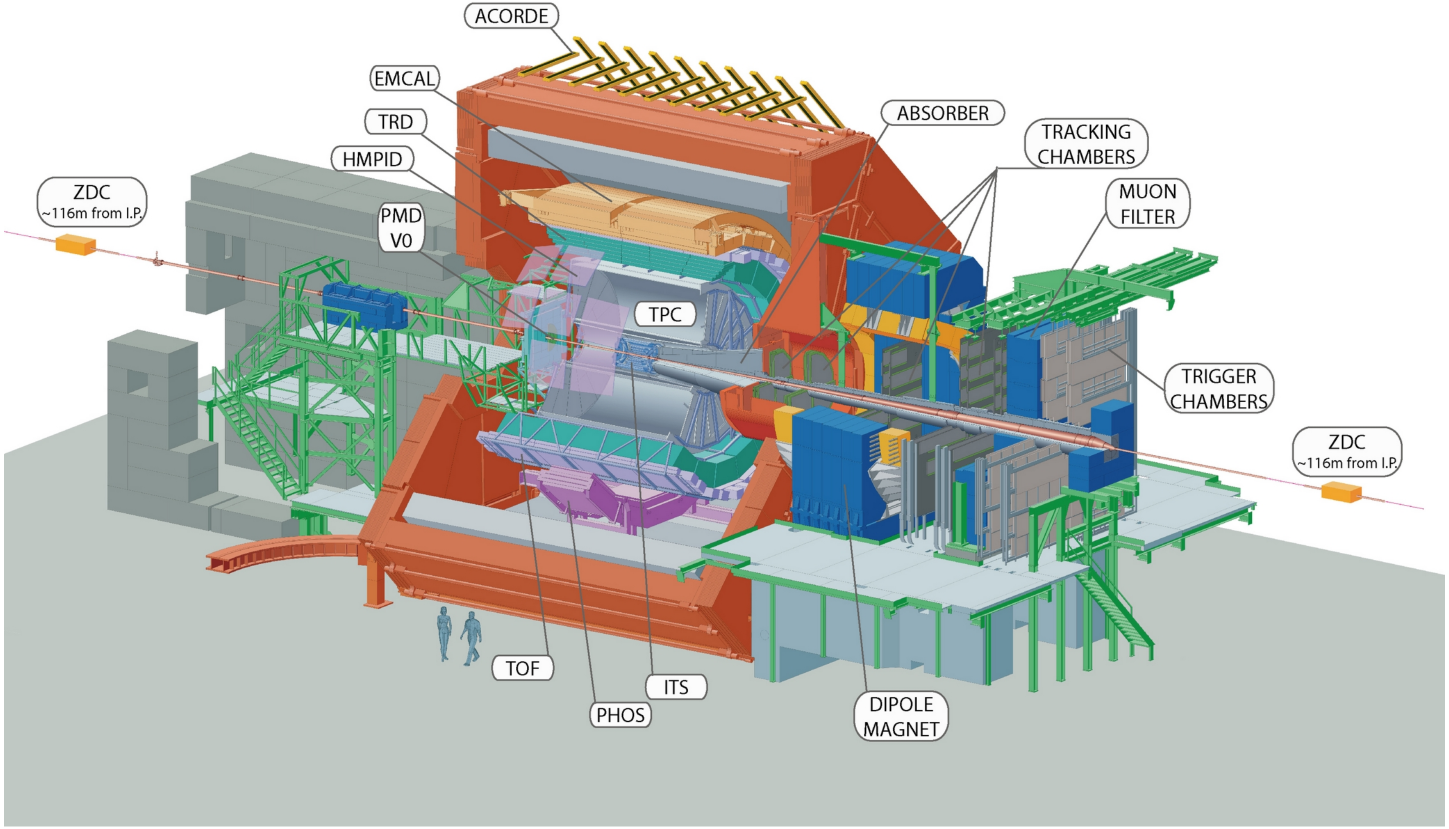
The p-wave strong interaction through ϕ meson resonance [R.Lednicky Part. Nucl. Letters 8(2011)965]:

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

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.

ALICE at the LHC



Tracking and vertex

- Time Projection Chamber (TPC)

& Inner Tracking System (ITS)

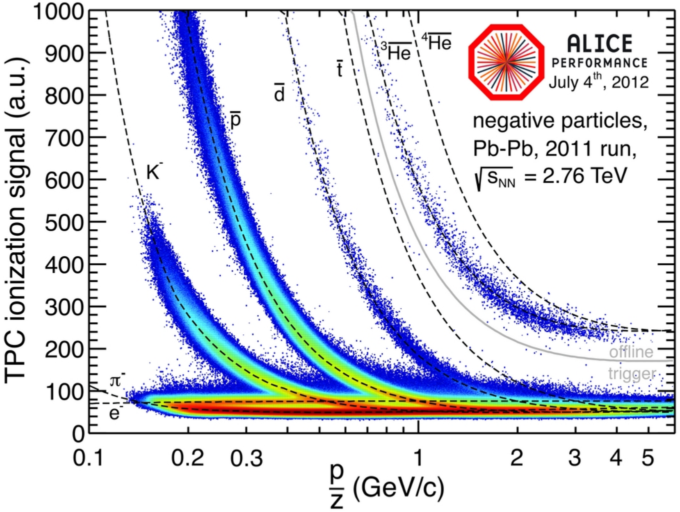
Particle Identification

- TPC and Time of Flight

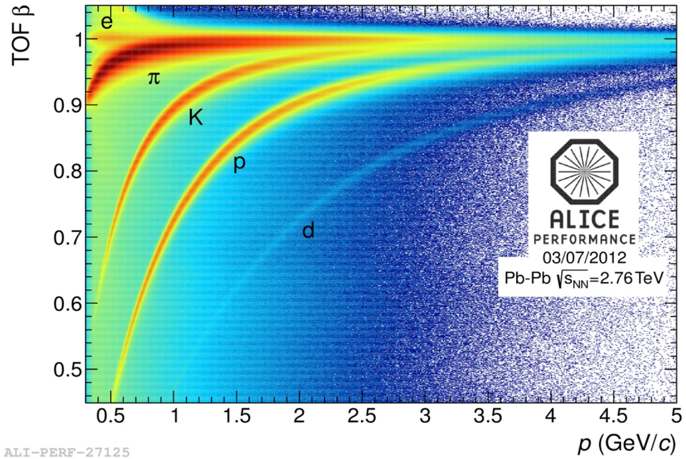
Centrality determination

- V0

Dataset and particle identification



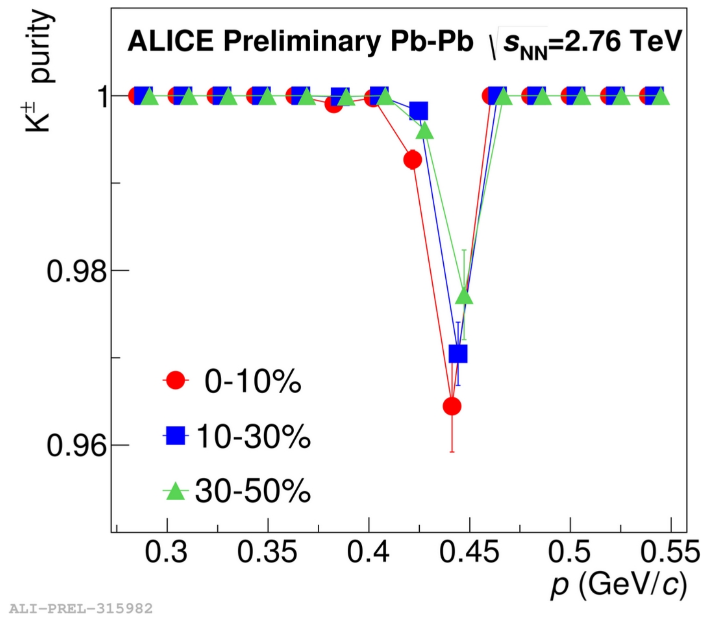
ALI-PERF-27141

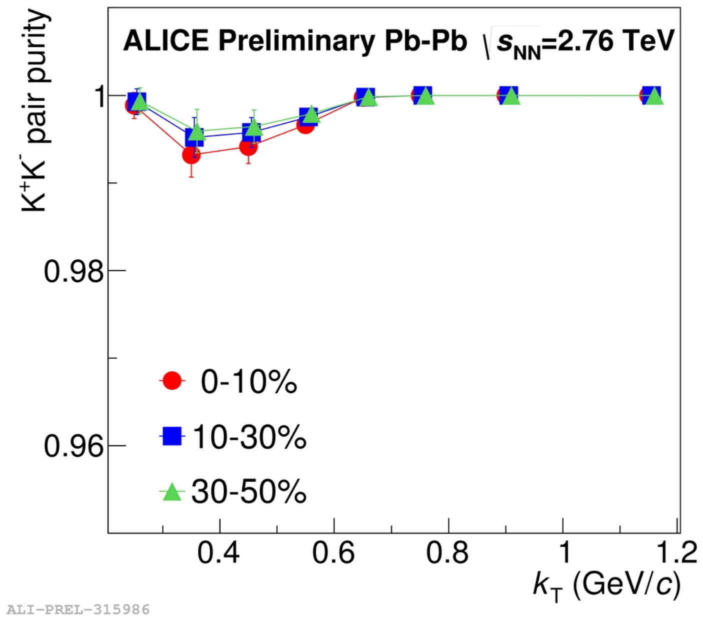


ALI-PERF-27125

- Data: 40 million events, the same as for $K^{\pm}K^{\pm}$ in Pb-Pb at 2.76 TeV [PRC 92 (2015) 054908]
- TPC: 2σ 0.2<p<0.4 GeV/c, 1σ 0.4<p<0.45 GeV/c
  TOF+TPC(3σ): 2σ 0.45<p<0.8 GeV/c, 1.5σ 0.8<p<1.0 GeV/c, 1.0σ 1.0<p<1.5 GeV/c
- Bins(24 CF): same as they were in $K^{\pm}K^{\pm}$ analysis
  k_T[8]: 0.2-0.3,...,1.0-1.3 GeV/c
  Centrality[3]: 0-10, 10-30, 30-50 %

K^+K^- purity

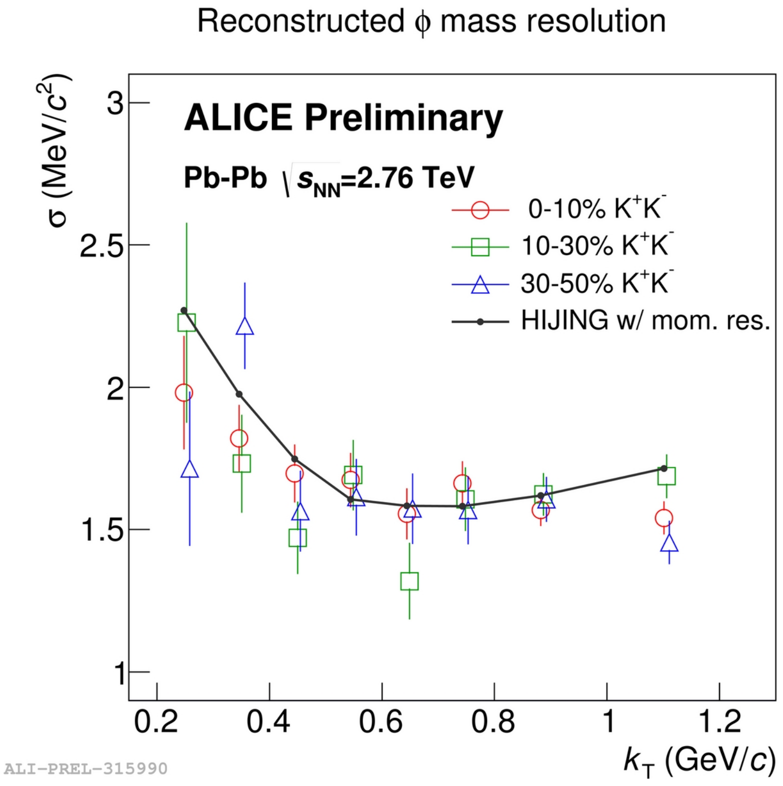




- The obtained purity decreases with increasing centrality.
- The single kaon purity is higher than 96%

- PairPurity(k_T) = SinglePurity(p_1) • SinglePurity(p_2)
- $k_T = |p_{T,1} + p_{T,2}|/2$
- The value of the pair purity is higher than 99% for K^+K^- pairs.

Momentum resolution(MR) with MC:



- The finite track momentum resolution smears the relative momentum correlation function.
- Correlation function smeared by MR:

$$C(Q_{rec}) = \frac{\sum_{Q_{true}} C(Q_{true}) M(Q_{true}, Q_{rec})}{\sum_{Q_{true}} M(Q_{true}, Q_{rec})}$$

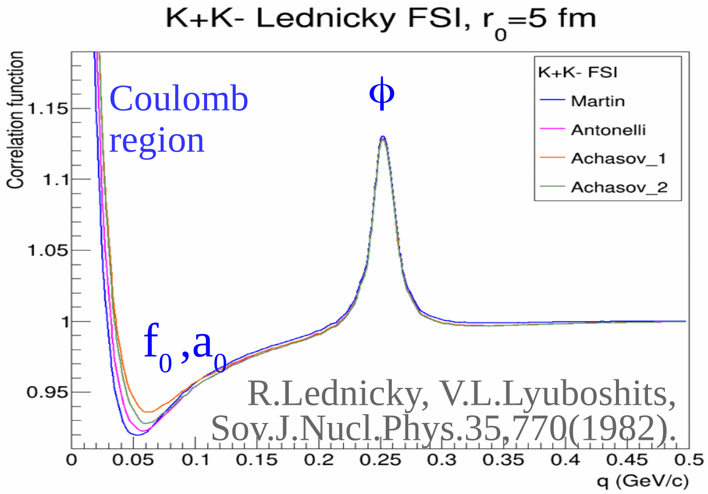
- $M(Q_{true}, Q_{rec})$ – HIJING[PRD 44,3501,1991]+GEANT
- Cross-check MR using ϕ peak in K^+K^- CF
- ϕ peak is fitted with the convolution of a non-relativistic Breit-Wigner peak and a Gaussian [PRC 91(2015)024609]
- The mass resolutions obtained from the two methods are in agreement

Input for 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

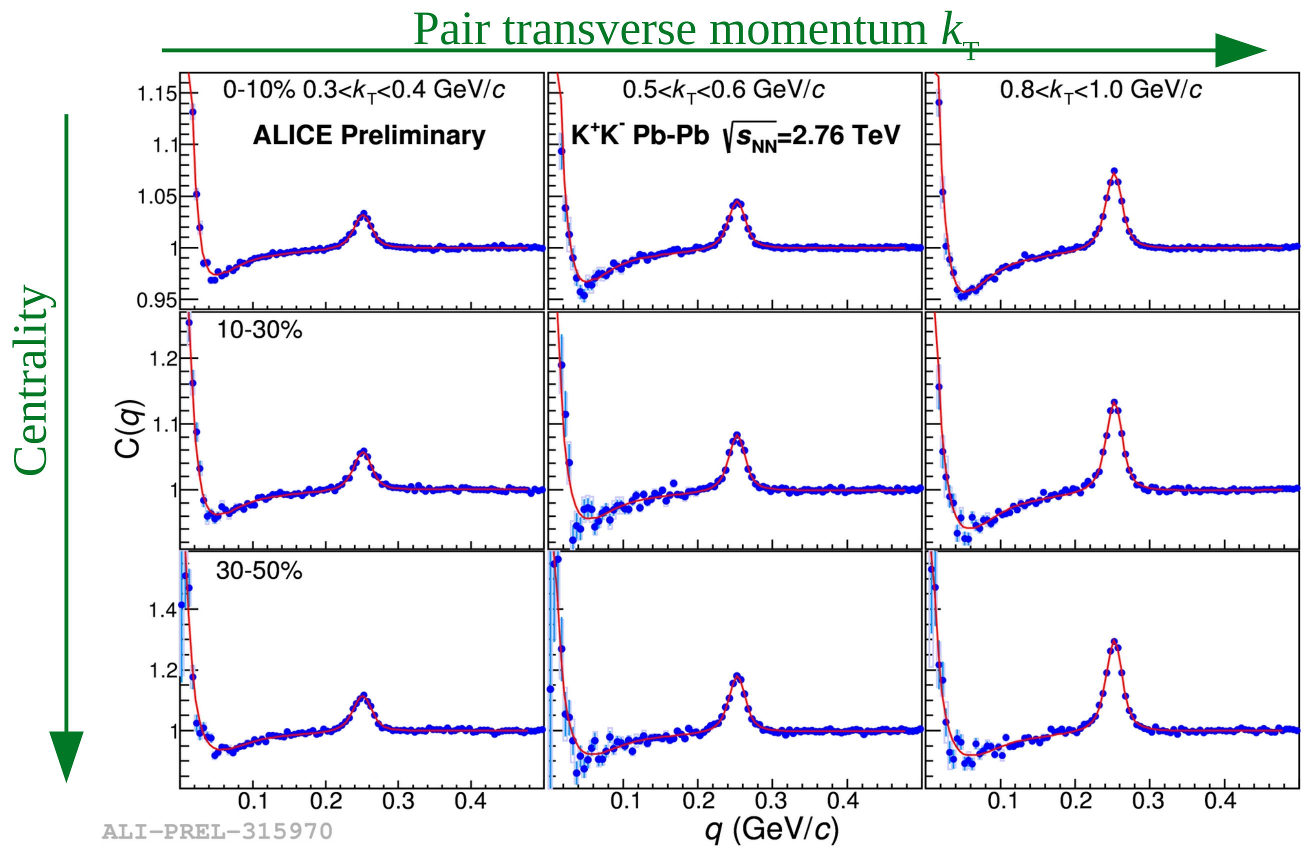
  $C_\phi(q,M,\sigma)$ - Breit-Wigner Γ_ϕ=4.25MeV



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

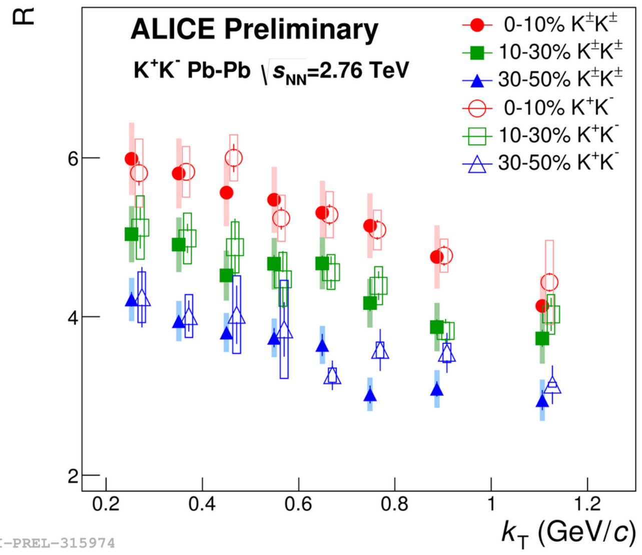
The masses (a_0 and f_0) and coupling parameters							
Model	m_{f0}^2	m_{a0}^2	$\gamma_{f0\to K+K-}$	$\gamma_{f0\to\pi\pi}$	$\gamma_{a0\to K+K-}$	$\gamma_{a0\to\pi\eta}$	
Martin	.9565	.9487	.792	.199	.333	.222	NPB 121 (1977) 514
Antonelli	.9467	.9698	2.763	.5283	.4038	.3711	hep-ex/0209069
Achasov[1]	.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

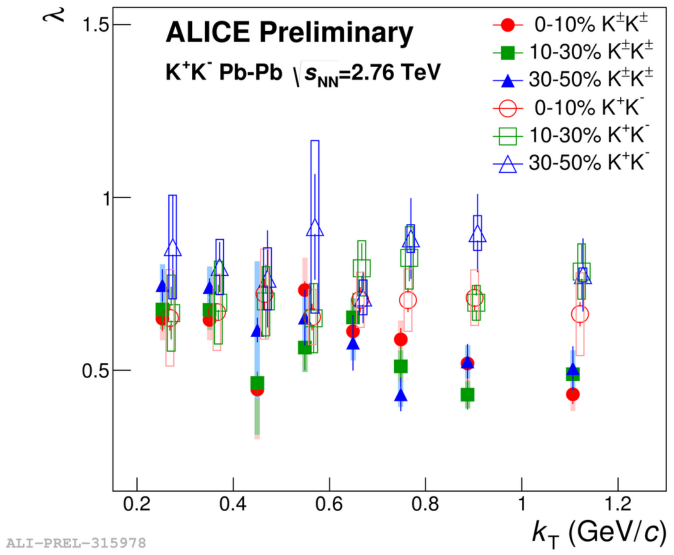
Correlation functions fitted by FSI with new f_0 parameters



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

Comparison radii and λ of K^+K^- and $K^\pm K^\pm$





- Radii are in agreement within errors
- λ of K^+K^- tend to be larger than for λ of $K^\pm K^\pm$ (possible due to FSI slightly underestimate)
- New preliminary $f_0(980)$ couplings and mass parameters:

$\gamma_{f0\to K+K-}$=0.31 ± 0.062 ± 0.092 GeV

$\gamma_{f0\to \pi\pi}$=0.081 ± 0.0162 ± 0.024 GeV

M_{f0} = 0.972 ± 0.003 ± 0.005 GeV/c^2

What does the PDG say? And what about ALICE measurements?

$f_0(980)$ [j]

$I^G(J^{PC}) = 0^+(0^{++})$

Mass $m = 990 \pm 20$ MeV

Full width $\Gamma = 10$ to 100 MeV

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

Present analysis(preliminary):

- Mass is $M_{f0} = 972 \pm 3(stat) \pm 5(sys)$ MeV/c^2
- $\Gamma_{f0} = \gamma_{f0\rightarrow\pi\pi} \bullet k_{\pi\pi}/m_{f0} = 39.7 \pm 7.94(stat) \pm 11.8(sys)$ MeV
- The measured width and mass of the $f_0(980)$ is close to the PDG result

Conclusions

- The ALICE experimental data on the non-identical K^+K^- correlation were presented

- The pair purity of K^+K^- was better than 99 %
- The smearing matrix was used to take into account momentum resolution

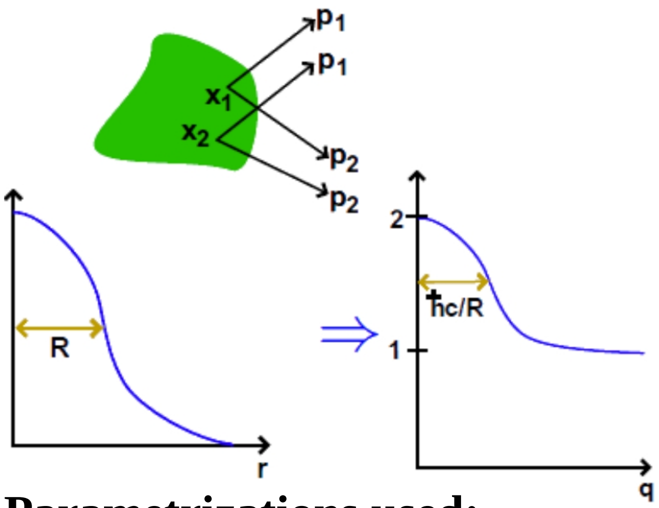
- For the first time the K^+K^- correlation functions were fitted with free $f_0(980)$ mass and couplings and with restriction on radii to be close to the corresponding identical $K^{\pm}K^{\pm}$

- The measured preliminary width of the $f_0(980)$ is 39.7 ± 7.94(stat) ± 11.8(sys) MeV and mass is 972 ± 3(stat) ± 5(sys) MeV/c^2 which do not contradict the PDG data

Thank you very much for your attention !!!

Backup slides

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:

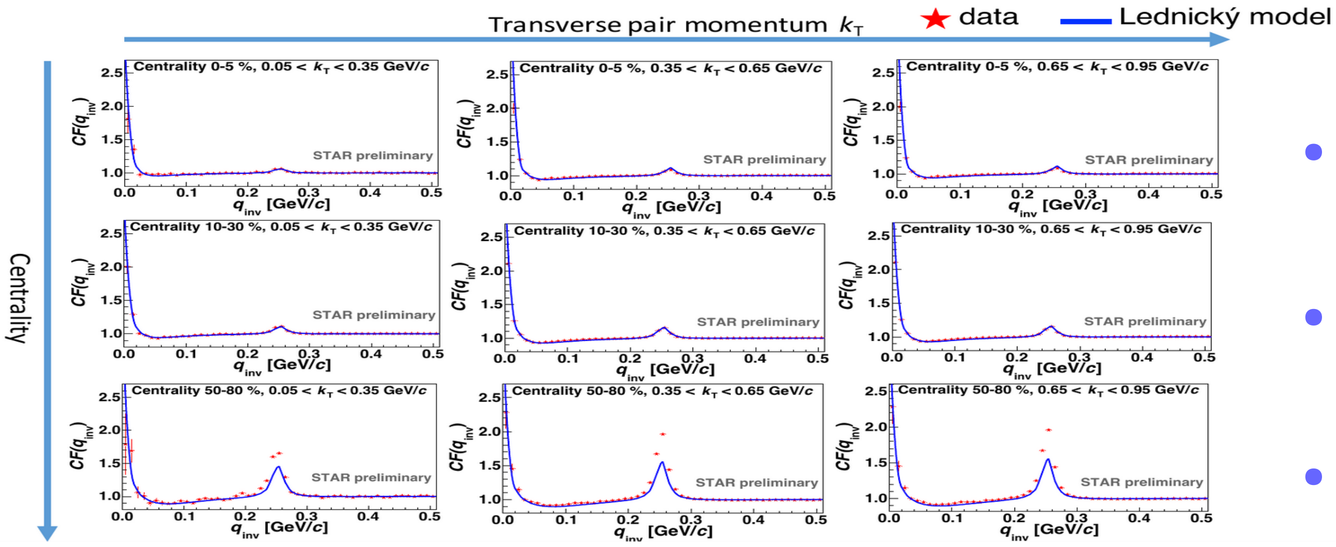
1D CF: $$C(q_{inv})=1+\lambda e^{-R^2 q_{inv}^2}$$

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

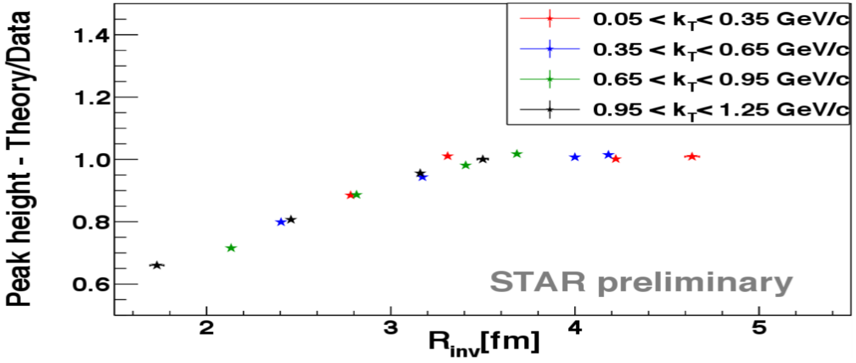
K^+K^- existing results: STAR



- 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

New and previous mass and couplings f_0(980):

The masses (a_0 and f_0) and coupling parameters							
Model	m_{f0}^2	m_{a0}^2	$\gamma_{f0 \to K+K-}$	$\gamma_{f0 \to \pi\pi}$	$\gamma_{a0 \to K+K-}$	$\gamma_{a0 \to \pi\eta}$	$\Gamma_{f0}=\gamma_{f0 \to \pi\pi} k_{\pi\pi}/m_{f0}$
Martin	.9565	.9487	.792	.199	.333	.222	97
Antonelli	.9467	.9698	2.763	.5283	.4038	.3711	258
Achasov1	.9920	.9841	1.305	.2684	.5555	.4401	131
Achasov2	.9920	1.0060	1.305	.2684	.8365	.4580	131
ALICE	.945	1.0060	0.31	.081	.8365	.4580	40

Uncertainties for models are about 10-15% for couplings and 3-5% for masses

- New values of f_0 mass is close to Martin, Antonelli and Achasov results. But new couplings are smaller.
- The ratio $\gamma_{f0 \to K+K-}/\gamma_{f0 \to \pi\pi}$ is about 4-5 for all results
- ALICE $\gamma_{f0 \to K+K-}/\gamma_{f0 \to \pi\pi} \sim 4$.

K+K- theoretical correlation function (formalism) I

[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 at given **k*** and 3-momentum **P** as

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

where α means K^+K^- and summing over intermediate channels α'=K^+K^-,$K^0\overline{K^0}$

Assume a spherically symmetric Gaussian distribution of the particle emitter spatial separation **r*** in the PRF with size R

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

A stationary solution of the scattering problem at large distances has the asymptotic form of a superposition of a plane wave and an outgoing spherical wave:

$$\Psi_{-\vec{k}^*}(\vec{r^*}) = e^{-i\vec{k^*}\vec{r^*}} + f(\vec{k^*})\frac{e^{ik^*r^*}}{r^*}$$

The s-wave K+ K− scattering amplitude *f(k*)* is dominated by the near threshold s-wave isoscalar f_0 (980) and isovector a_0 (980) resonances characterized by their masses and respective couplings.

Total amplitude could be written as: $f(k^*) = \frac{[f_0(k^*) + f_1(k^*)]}{2}$, where amplitude for *I=0* and *I=1*:

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

where $s = 4(m_K^2 + k^{*2})$, m_{a0} , m_{f0} are the masses of the a0 and f0 and $k_{\pi\eta}$, $k_{\pi\pi}$ the momenta in the secondary decay

The general form of the strong FSI part (the s-wave scattering only) of the K+K- correlation function is:

$$C(q) = 1 + \lambda \left[\frac{1}{2} \left| \frac{f(q/2)}{R} \right|^2 + \frac{2\Re f(q/2)}{\sqrt{\pi}R} F_1(qR) - \frac{\Im f(q/2)}{R} F_2(qR) \right]$$

$$F_1(z) \equiv \int_0^z dx \frac{e^{x^2-z^2}}{z}, \quad F_2(z) \equiv \frac{1-e^{-z^2}}{z}$$

K+K- theoretical correlation function (formalism) II

The wave function of K+K− with the Coulomb interaction may be written (see Appendix in Sov. J. Nucl. Phys. 35, 770 (1982)) :

$$\Psi_{-\vec{k}^*}(\vec{r}^*) = \sqrt{Ac(\eta)}e^{\delta_c}\left[e^{-i\vec{k}^*\vec{r}^*/2}F(-i\eta,1,i\xi) + f_c(k^*)\frac{\tilde{G}(\rho,\eta)}{|\vec{r}^*|}\right]$$

where A_c is Gamov factor $A_c = 2\pi\eta[exp(2\pi\eta - 1)]^{-1}$, $\eta=1/(k^* a_c)$, $a_c=1/(\mu z_1 z_2 e^2)$ Bohr radius

The corresponding effective amplitude (renormalized by Coulomb interaction):

$$f_c(k^*) = \left[\frac{1}{f} - ik^* A_c(\eta) - \frac{2}{a_c}h(\eta)\right]^{-1}$$

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

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

The emission function with possible position-momentum (***rk)*** correlation:

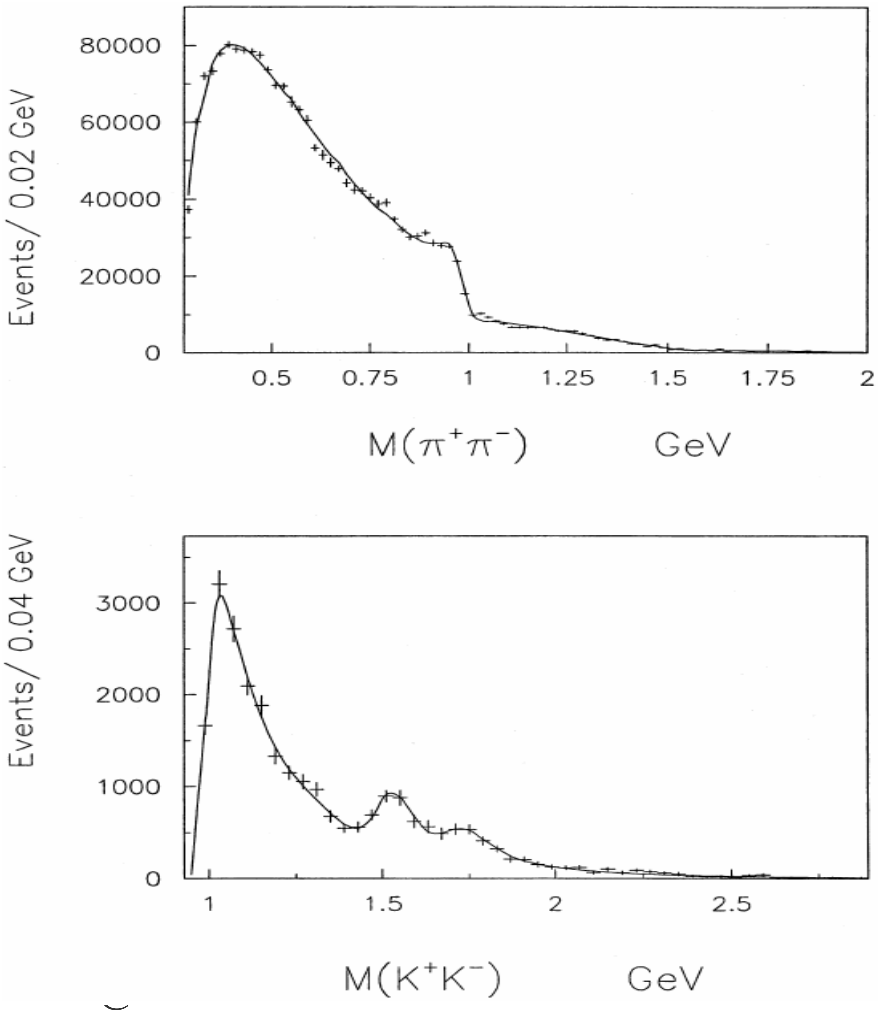
$$W_P(\mathbf{r},\mathbf{k}) = exp\left(-\frac{r^2}{4R^2} + b\mathbf{r}\mathbf{k}\right) \qquad N(p_1,p_2) = 8\pi^{3/2}R^3 exp(b^2k^2R^2) \qquad N(p_1,p_2) = \int d^3\mathbf{r}W_P(\mathbf{r},\mathbf{k})$$

The height of CF at Φ meson peak position $\Delta CF \sim 1/R^3$

The total correlation function is defined as a sum : $C_{FSI}(p_1,p_2) = 1+C_{sFSI}(p_1,p_2) + N_1C_{\Phi\text{-}direct}(p_1,p_2) + N_2C_\Phi(p_1,p_2)$, $C_{\Phi\text{-}direct}(p_1,p_2)$ is a non-relativistic Breit-Wigner function.

“Direct” Φ mesons are all phi mesons before last interaction (all stages of reaction including hadron cascade).

WA102 Collaboration [Physics Letters B 462 (1999) 462–470]
A coupled channel analysis of the centrally produced K+K- and π+π- final state



In this present paper we use the Flatté formula [6] to describe the $f_0(980)$, this is referred to as Method I. For the $\pi^+\pi^-$channel the Breit-Wigner has the form:

$$BW(M_{\pi\pi}) = \frac{m_0\sqrt{\Gamma_i}\sqrt{\Gamma_\pi}}{m_0^2 - m^2 - im_0(\Gamma_\pi + \Gamma_K)}$$

and in the K^+K^-channel the Breit-Wigner has the form:

$$BW(M_{KK}) = \frac{m_0\sqrt{\Gamma_i}\sqrt{\Gamma_K}}{m_0^2 - m^2 - im_0(\Gamma_\pi + \Gamma_K)}$$

where Γ_i is absorbed into the intensity of the resonance. Γ_π and Γ_K describe the partial widths of the resonance to decay to $\pi\pi$ and $K\overline{K}$ and are given by

$$\Gamma_\pi = g_\pi(m^2/4 - m_\pi^2)^{1/2}$$

$$\Gamma_K = g_k/2\left[(m^2/4 - m_{K^+}^2)^{1/2} + (m^2/4 - m_{K^0}^2)^{1/2}\right]$$

The f_0(980) couplings: g_π=0.19±0.03±0.04 g_K=0.40±0.04±0.04

These values best relate to Martin's model[NPB121(1977)514]:
g_π=0.199±0.014 g_K=0.792±0.099

Position-momentum correlations

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Femtoscopic Correlations and Final State Resonance Formation[1, 2]

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Abstract—The correlation femtoscopy formalism including resonance formation due to the final state interaction and its applicability conditions are discussed. The example calculations of $\pi^+\Xi^-$ and K^+K^- correlation functions are done with the account of $\Xi^*(1530)$ and $\phi(1020)$ resonances, respectively. It is shown that in these calculations the usual form of the smoothness approximation should be substituted by a more general one. A strong sensitivity of resonance formation in the final state to the position-momentum correlations at particle freeze-out is demonstrated.

$W_P(\mathbf{r},\mathbf{k}) \sim \exp[-r^2/4r_0^2 + \mathbf{bkr}]$; r-k correlation may result from the collective flows and resonance decays. CF suppressed by a factor $W_P(\mathbf{0},\mathbf{k}) \sim \exp[-\mathbf{b}^2 r_0^2 k^2]$

One can estimate **b** from experimental phi-meson peak in K+K- correlation function.

The peak height decreases with the increasing centrality in qualitative agreement with the inverse volume($\mathbf{r_0^{-3}}$) dependence.

Does the r-k correlation help to understand the ALICE data?

Φ peak value ($\Delta R=CF(m_\Phi)-1$) according to $W_P(\mathbf{r},\mathbf{k})$ space distribution with r_0=5fm. Simple Gaussian emmision function(b=0) leads to everestimates the peak value. Factor b~0.12 is sufficent to describe NA49 data on K+K- in PbPb at 158GeV.