Heavy-flavor femtoscopy in Au+Au collisions @ $\sqrt{s_{NN}}$ = 200 GeV at STAR

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Fitting C(k*) data for D-π pairs

- ✔ Fitting approach: LL, fixed scattering length (f_0)
- ✔ Results of χ^2/NDF vs R for different interaction parameters
- ✔ Results for probability vs R for different interaction parameters
- ✔ Estimation of the lower limit on R and systematic unc. on this value
- ✔ Plots with fits for low R

Analysis Information

- Dataset: Au+Au, $\sqrt{s_{NN}}$ = 200 GeV
- Year: 2014
- Centrality: 0-80%
- Good events: 490 M

Event cuts

- $|V_z| < 6.0$ cm.
- $|V_z - V_z^{VPD}| < 3.0$ cm.
- $|V_x| > 1.0e^{-5}$ cm.
- $|V_y| > 1.0e^{-5}$ cm.
- $\sqrt{[(V_x)^2 + (V_y)^2]} <= 2.0$
- Centrality = 0-80%

Track cuts

- $p_T > 0.5$ GeV/c
- $|dca| > 0.0050$ cm.
- nHitsFit >= 20
- $|\eta| <= 1.0$

PID cuts for Pions & Kaons

- $|n\sigma_\pi| < 3.0$
- $|n\sigma_K| < 2.0$
- $|n\sigma_p| < 2.0$
- $|\frac{1}{\beta} - \frac{1}{\beta_\Pi}| < 0.03$
- $|\frac{1}{\beta} - \frac{1}{\beta_K}| < 0.03$
- $|\frac{1}{\beta} - \frac{1}{\beta_p}| < 0.03$
- $\frac{nHitsFit}{nHitsFitMax} > 0.51$

Approach: by fixing parameters

The Lednicky–Lyuboshitz analytical model connects the correlation function with final-state strong interaction parameters

$$C(k^*) = 1 + \sum_S \rho_s \left[\frac{1}{2}\left|\frac{f^S(k^*)}{r_0}\right|^2 \left(1-\frac{d_0^S}{2\sqrt{\pi}\, r_0}\right) + \frac{2\Re(f^S)(k^*)}{\sqrt{\pi}\, r_0} F_1(Q r_0) - \frac{\Im(f^S k^*)}{r_0} F_2(Q r_0)\right] \qquad (1)$$

where , $f^s(k^*)$ is scattering length, d_0^S is effective radius for total spin s (s = 0 or s = 1) state

ρ_s is fraction of pairs with a given spin s (ρ_0 = ¼ and ρ_1 = ¾)

$$Q = 2k^*, \quad F_1(z) = \int_0^z dx\, e^{x^2 - z^2}/z, \quad F_2(z) = (1 - e^{-z^2})/z$$

This model assumes, average separation vector $(\vec{r}^*)$ from eq. (1), follows Gaussian distribution

$$dN^3/d^3r^* \quad e^{-r^{*2}/4r_0^2} \qquad (2)$$

where, r_0 is the effective radius of the correlated source

STAR, Phys. Rev. C 74 (2006) 064906

Fixed parameters:

All 5 parameters are unknown. By fixing all, we performed χ^2 test to P of χ^2 test to check lower limit on source radius

$Re(d_0)$ & $Im(d_0)$ = 0 (acc. to zero effective range approximation)

$Re(f_0)$ & $Im(f_0)$ = fixed (acc. to theory models used by ALICE)

r_0 = fixed (varies from 0.5 fm to 6 fm)

Motivation & list of fixed parameter

ALICE, Phys. Rev. D 110, 032004 (2024)

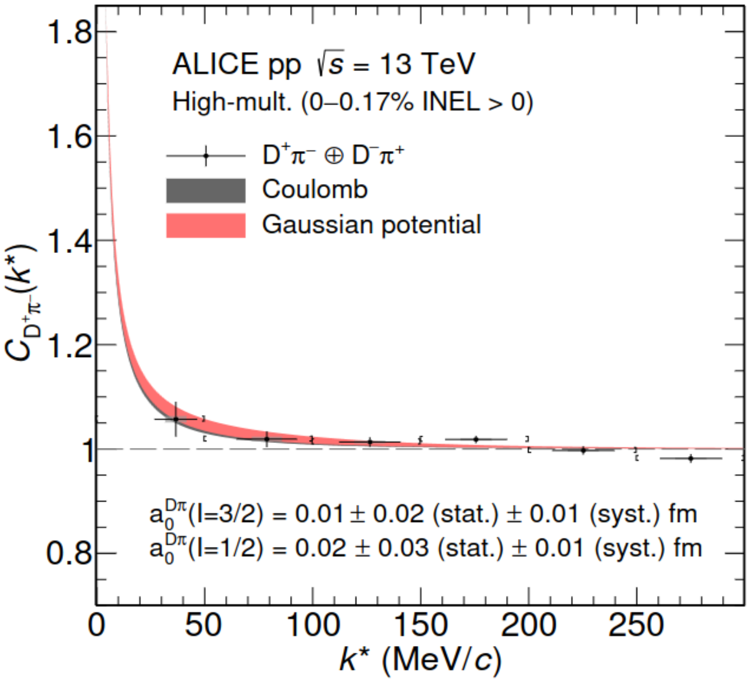
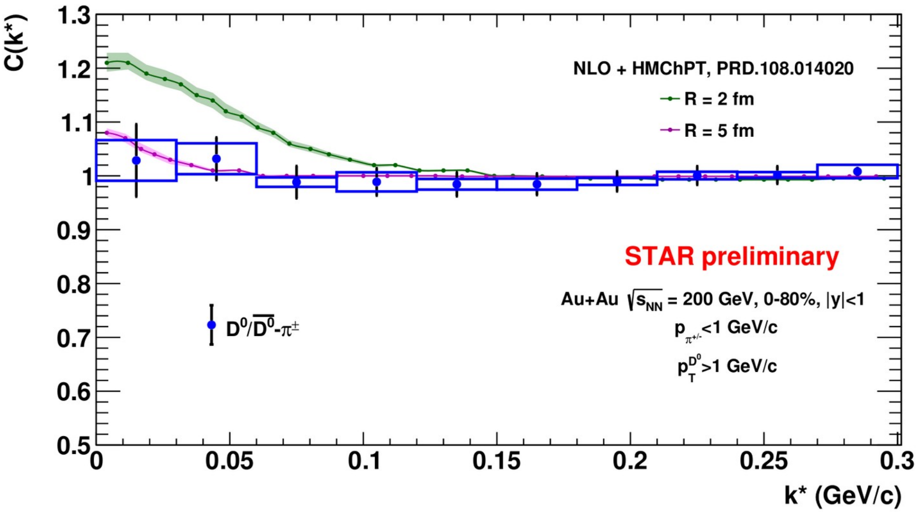


TABLE IV. Scattering lengths of the available theoretical models for the $D\pi$ interactions. The values are reported separately for the different isospin states.

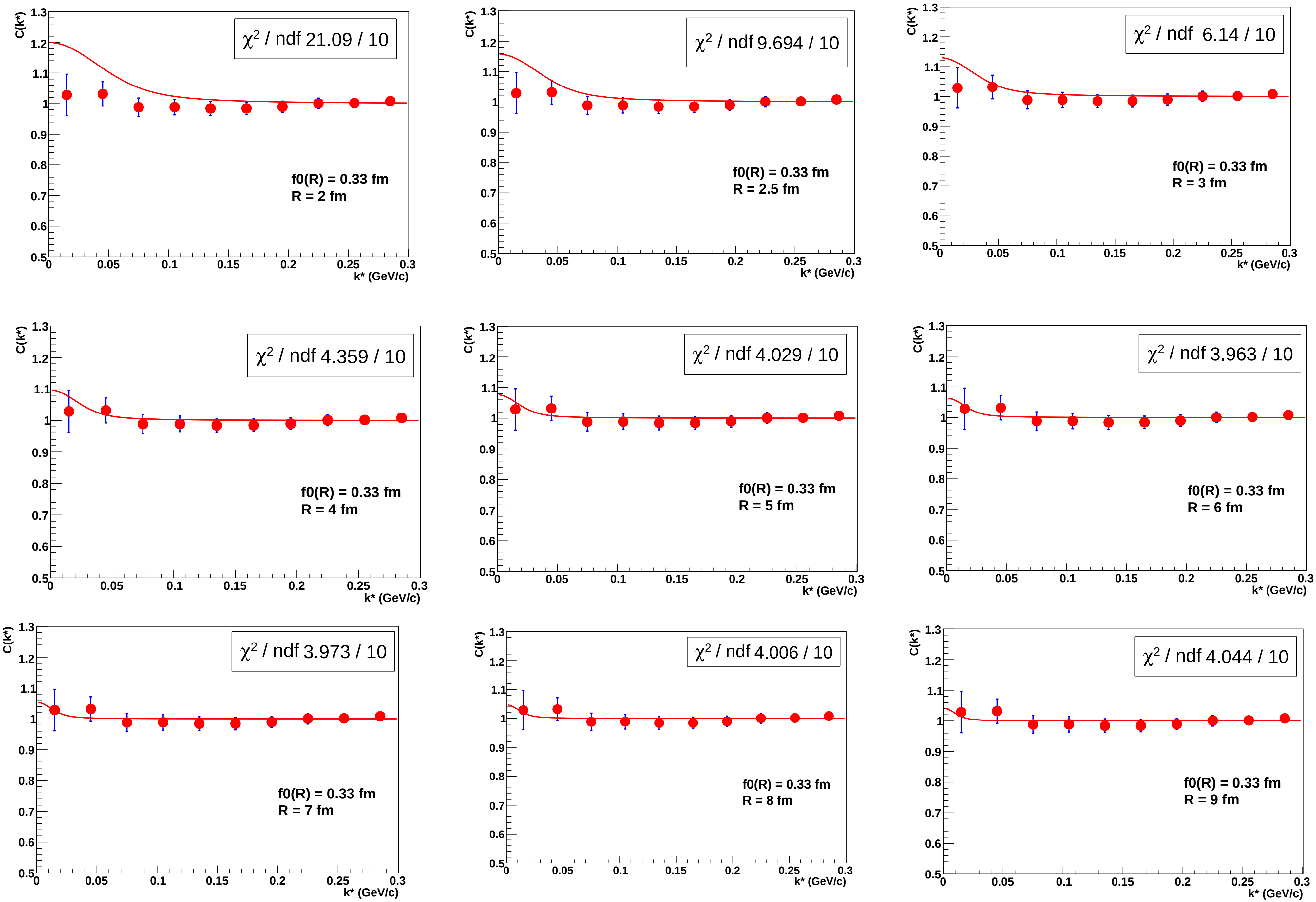
Model		a_0 (fm)	
		$D\pi(I = 3/2)$	$D\pi(I = 1/2)$
Liu *et al.* [89]		-0.100 ± 0.002	$0.37^{+0.03}_{-0.02}$
Guo *et al.* [90]		-0.11	0.33
Guo *et al.* [91]	Fit-1B	$-0.101^{+0.005}_{-0.003}$	$0.31^{+0.01}_{-0.01}$
	Fit-2B	$-0.099^{+0.003}_{-0.004}$	$0.34^{+0.00}_{-0.03}$
Huang *et al.* [92]		-0.06 ± 0.02	0.61 ± 0.11
Torres-Rincon *et al.* [93]		-0.101	0.423
		$D^*\pi(I = 3/2)$	$D^*\pi(I = 1/2)$
Liu *et al.* [94]		$-0.13 - 0.00036i$	$0.27 - 0.00036i$

Guo [90]: https://doi.org/10.1103/PhysRevD.98.014510

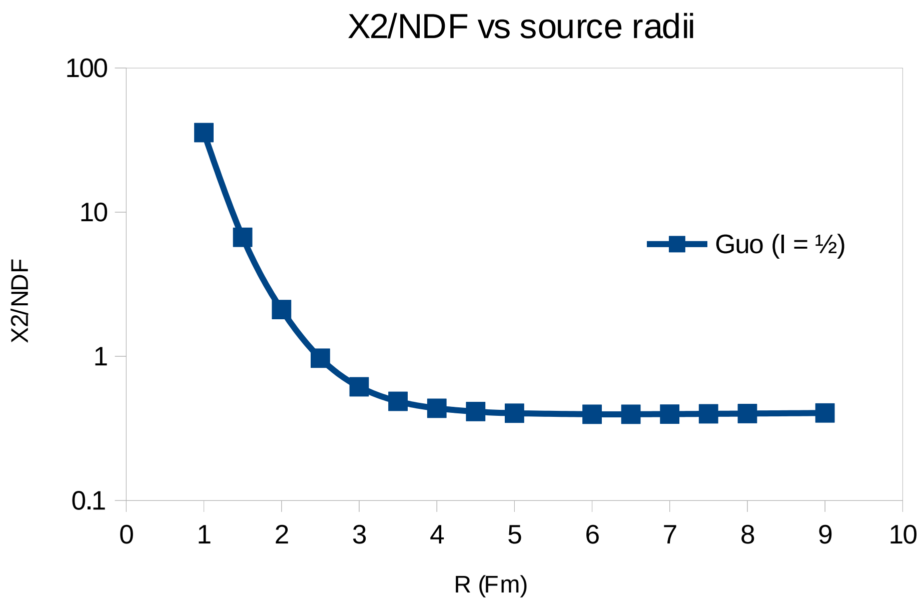


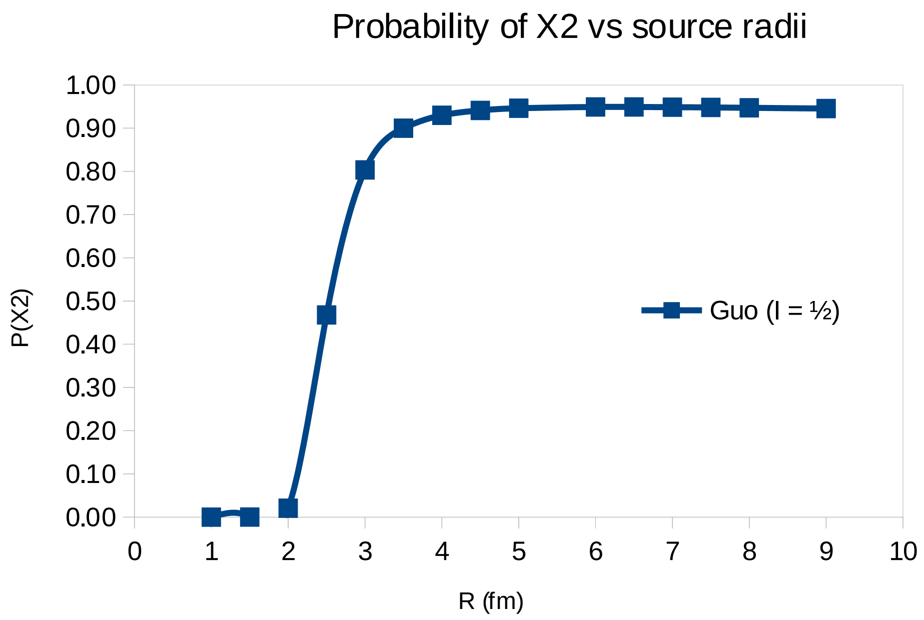
- Fits using scattering length (a_0) values from Guo et al. [90] will be reported here
- Due to lack of statistics, we can't extract interaction parameters from current data but can study the lower limit of source radii

Guo (I = 1/2), Re(f_0) = 0.33 fm

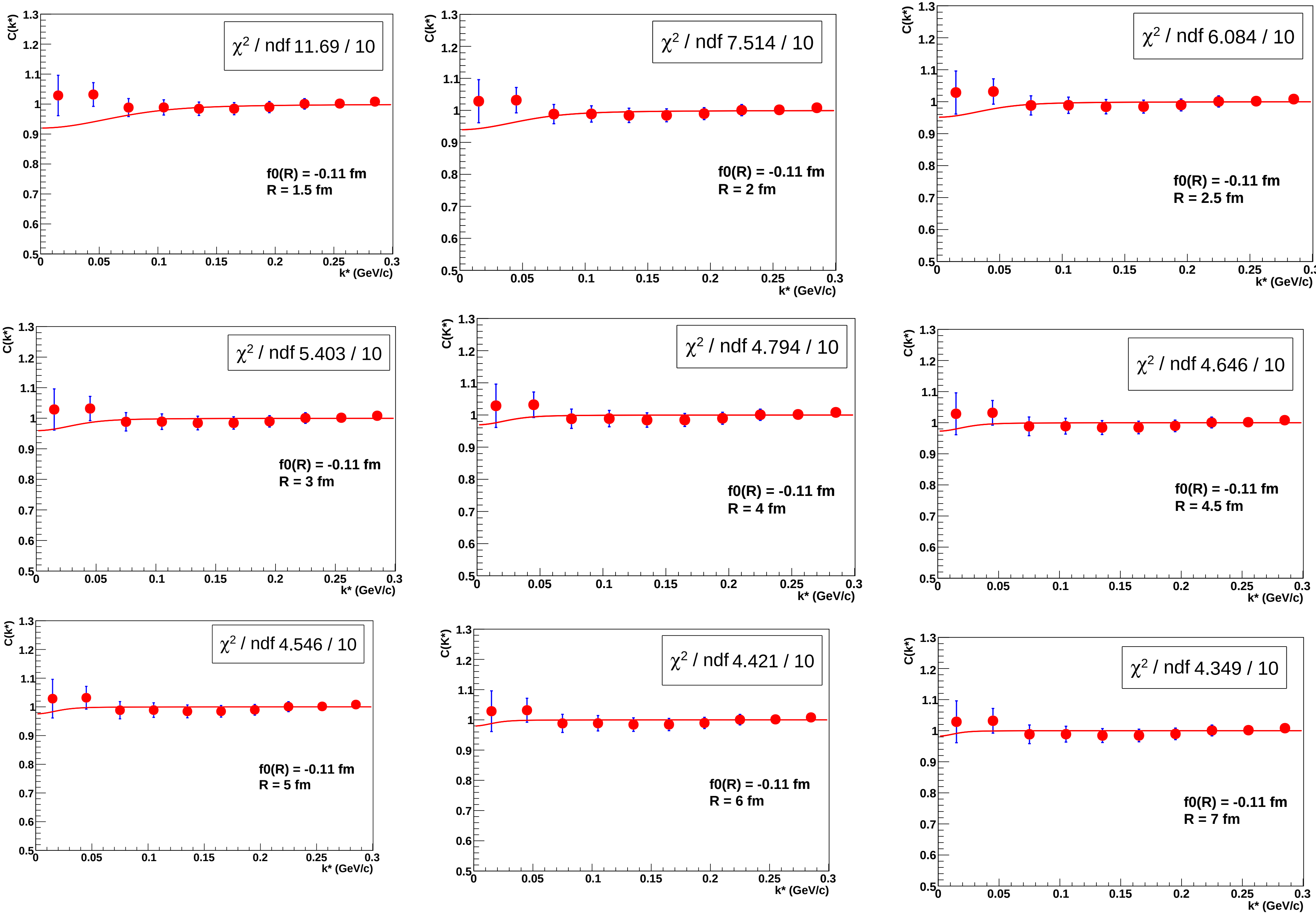


Guo (I = 1/2), Re(f_0) = 0.33 fm

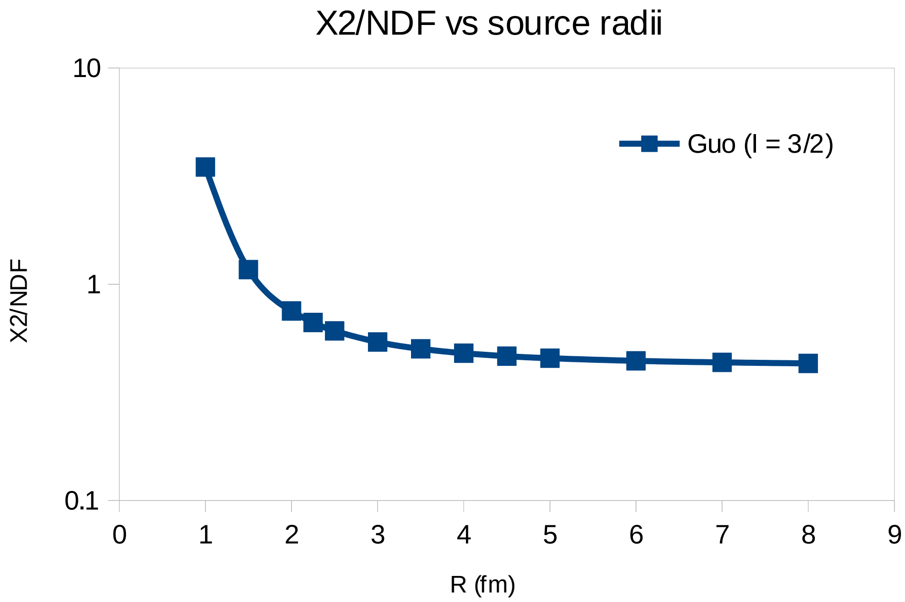


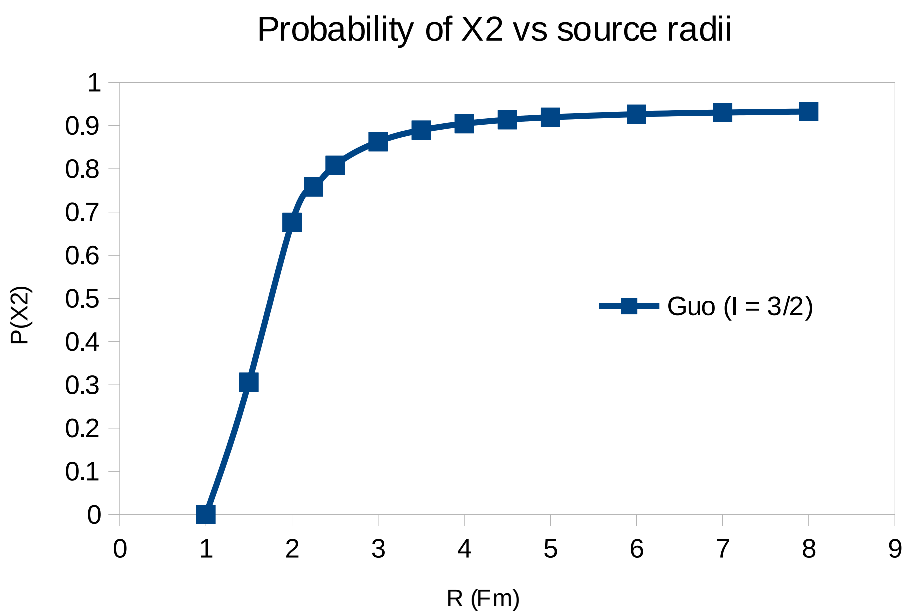


Guo (I = 3/2), Re(f_0) = -0.11 fm



Guo (I = 3/2), Re(f_0) = -0.11 fm





Summary

- From the studies with current set of parameters with CL 90%, acceptable value of D^0-π emission source radii is R > 1.5 fm
- Systematic studies using different set of fixed f_0 values could be helpful to make precise conclusion

Back Up

Theory prediction of CF for Dπ channels

NLO + HMChPT: M. Albaladejo *et al.*, Phys. Rev. D 108, 014020

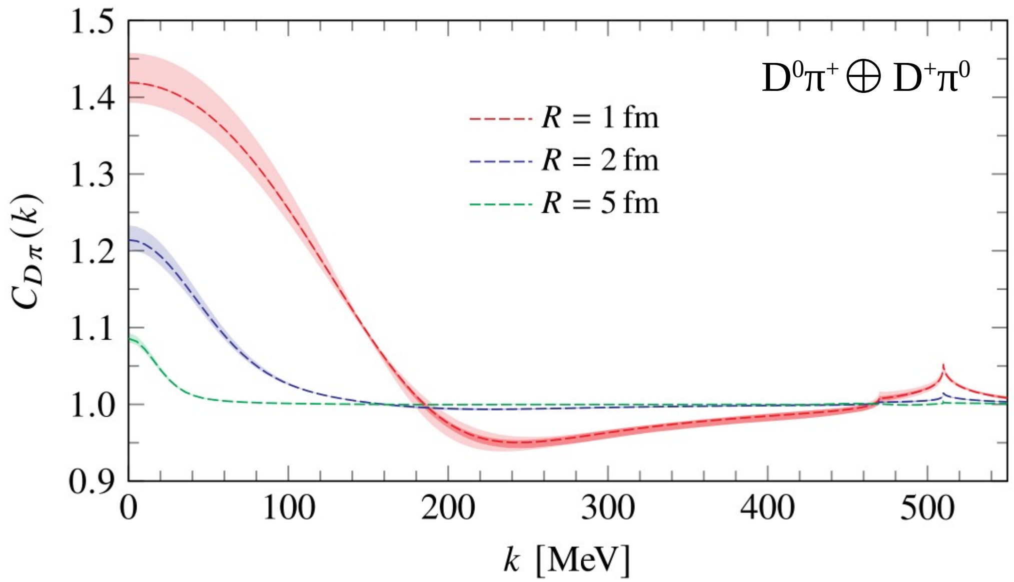


Figure: Correlation functions for Dπ channels predicted for R = 1, 2 and 5 fm sources represented by red, blue and green dashed lines respectively. Corresponding bands show uncertainties with 68% CL

- Interaction in I = 3/2 sector ($D^0\pi^-$) is weaker and repulsive

- Isospin combinations for $D\pi$ channels

$$C_{D^+\pi^0} = \frac{2}{3} C_{3/2}^{D\pi} + \frac{1}{3} C_{1/2}^{D\pi},$$

$$C_{D^0\pi^+} = \frac{1}{3} C_{3/2}^{D\pi} + \frac{2}{3} C_{1/2}^{D\pi},$$

$$C_{D^0\pi^-} = C_{3/2}^{D\pi},$$

- Predicted CF for $D^0\pi^+$ and $D^+\pi^0$ channels considered only I = ½ state
- Depletion at k ~ 215 MeV for R = 1 fm source, produce due to presence of the lightest D^*_0 state [$D^*_0(2135)$]
- For R = 2 fm and 5 fm sources, the minimum is present but diluted

Physics Goal

- Understand the interactions in the final state through two-particle (D^0-$K^\pm$, $\overline{D^0}$-$K^\pm$, D^0-$\pi^\pm$, $\overline{D^0}$-$\pi^\pm$, D^0-$p^\pm$, $\overline{D^0}$-$p^\pm$) femtoscopic correlations

- Femtoscopy is sensitive As well as to the extent of the region from which correlated particles are emitted

- Average distance between emission points of correlated pairs (D^0-hadron) is known as '*length of homogeneity*' or emission source radius (r_0) using LL model

- Theoretical inputs are required to connect the observed correlation functions and interaction parameters of charm and light quarks before hadronization

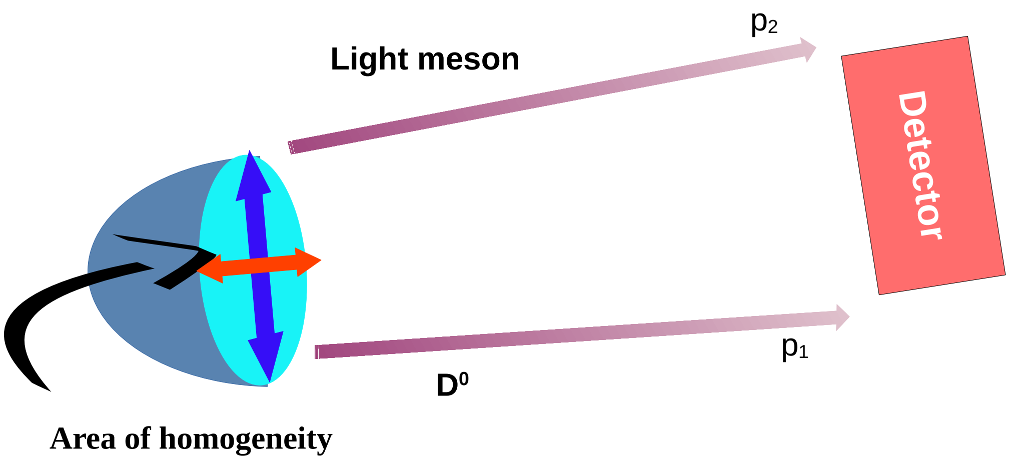


Figure 4: c/$\bar{c}$ as a probe of QGP medium and final-state interaction

Physics Motivation – Quark Gluon Plasma

- Heavy quarks (c and b) are produced early in collisions → useful to probe all stages of heavy-ion collisions
- Suppression of D^0 meson at high p_T and significant D^0 elliptic flow observed in heavy-ion reactions at RHIC
- Strong interaction of charm quarks with the quark-gluon plasma and its thermalization
- **New observables** to constrain different models and understand production mechanism

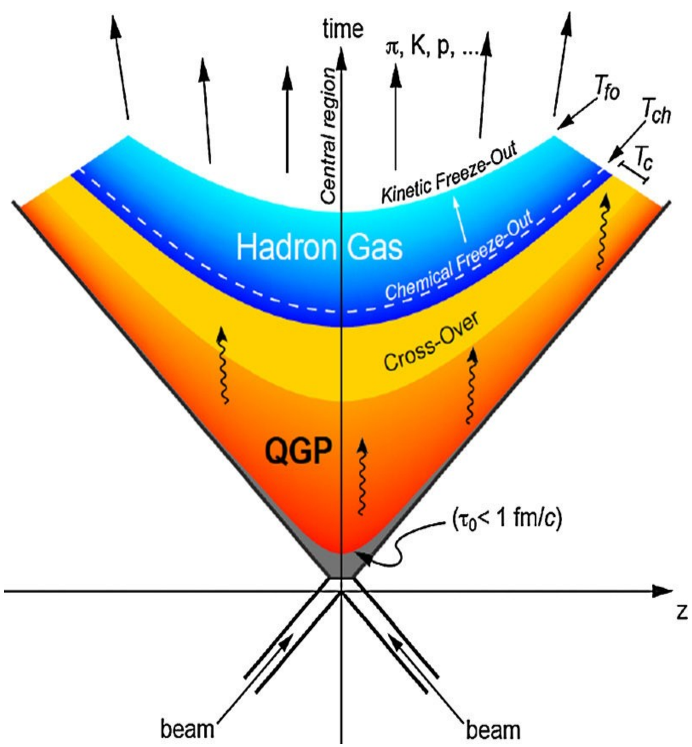


Figure 1: Stages of heavy-ion collisions

Phys. Rev. Lett. 118 (2017) 212301

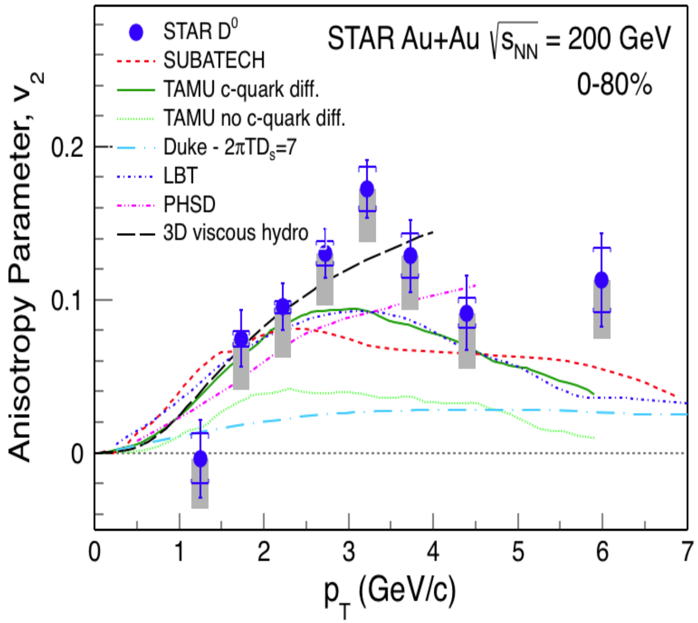


Figure 2: D^0 anisotropy Vs. transverse momentum

Phys. Rev. C 99 (2019) 34908

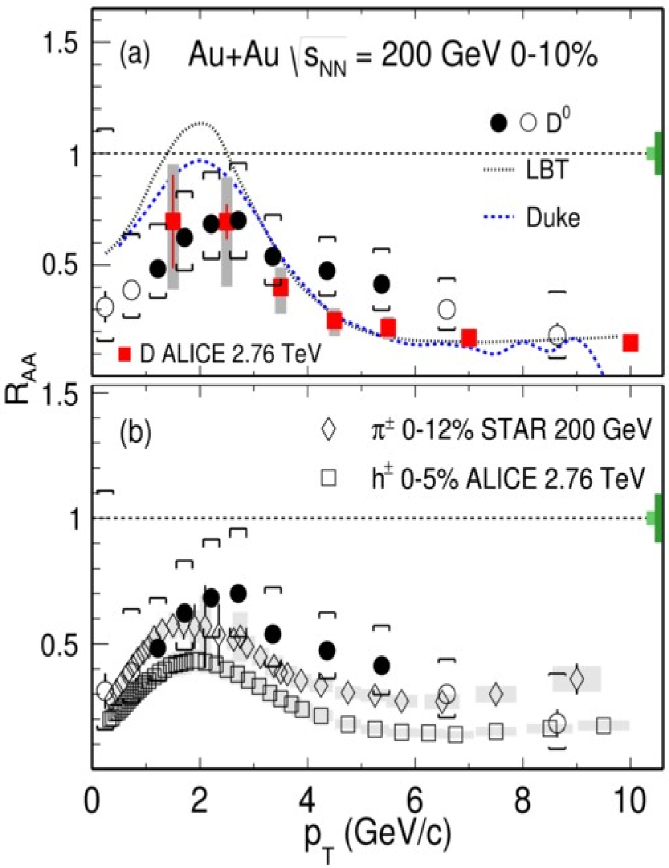


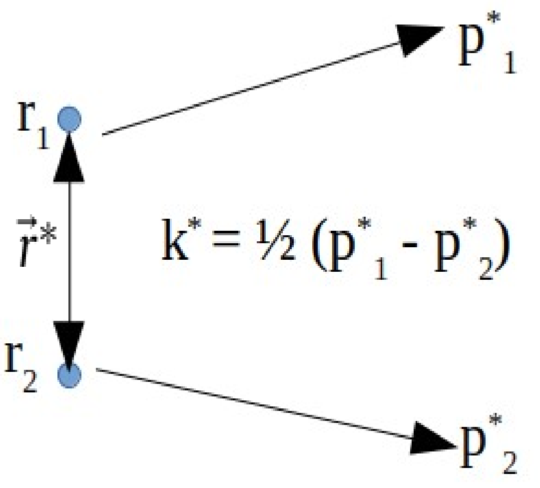
Figure 3: R_{AA} (a) D^0, (b) $\pi^{+/-}$ & $h^{+/-}$

Femtoscopic correlation

- Femtoscopic correlations are observed between pair of particles with low relative momentum
- It is measured as a function of the reduced momentum difference (k^*) of the pair of particles in rest frame

$$C(\vec{k}^*) = \int S(\vec{r}^*) \left|\Psi(\vec{k}^*, \vec{r}^*)\right|^2 d^3r^*, \qquad (1)$$

- where, $S(\vec{r}^*) \rightarrow$ source emission function
  $\vec{r}^* \rightarrow$ relative separation vector
  $\Psi(\vec{k}^*, \vec{r}^*) \rightarrow$ pair wave function



Femtoscopic correlation & k^*

- Femtoscopic Correlation ⟶ QS + FSI
  - Quantum Statistics [QS]: Bose-Einstein / Fermi-Dirac
  - Final-State-Interaction [FSI]: Strong & Coulomb interaction
  - **Only strong interaction contributes to $D^0/\overline{D}^0$-$h^{\pm}$ femtoscopy**
- Applied formula to measure correlation function $C(k^*)$ for $D^0/\overline{D}^0$ - $h^{+/-}$ pairs:

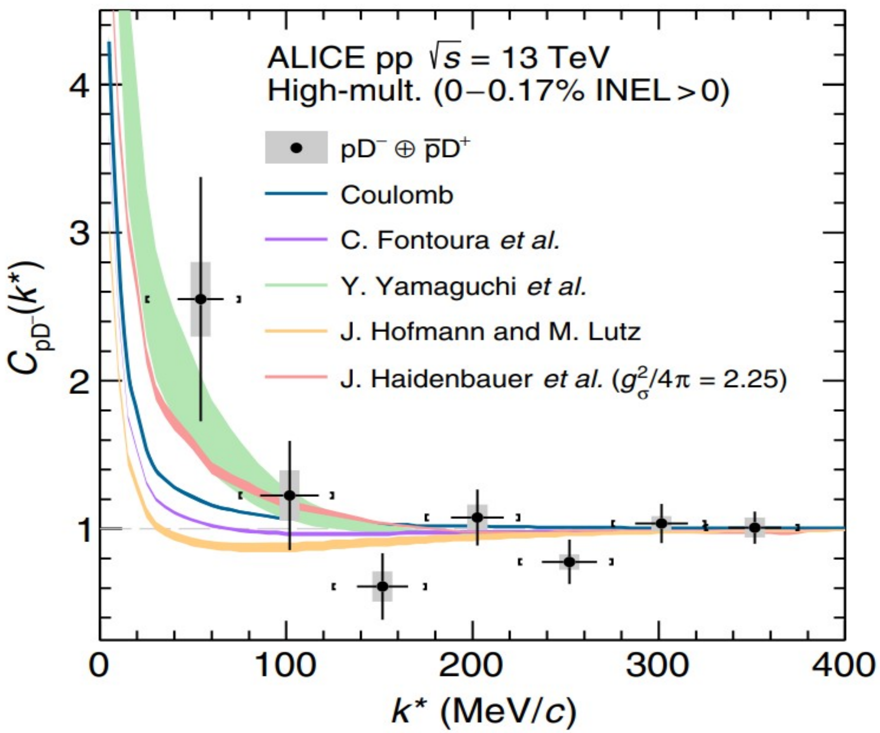
$$C(\vec{k}^*) = \mathcal{N} \frac{A(\vec{k}^*)}{B(\vec{k}^*)}. \qquad (2)$$

where $A(\vec{k}^*)$ and $B(\vec{k}^*)$ are k^* for correlated and uncorrelated pairs & $\mathcal{N}$ is normalization factor

Physics Motivation – Final State Interaction

- First studies of D-hadron interactions in pp at √s = 13 TeV by the ALICE experiment

Phys. Rev. D 106, 052010



https://doi.org/10.48550/arXiv.2401.13541

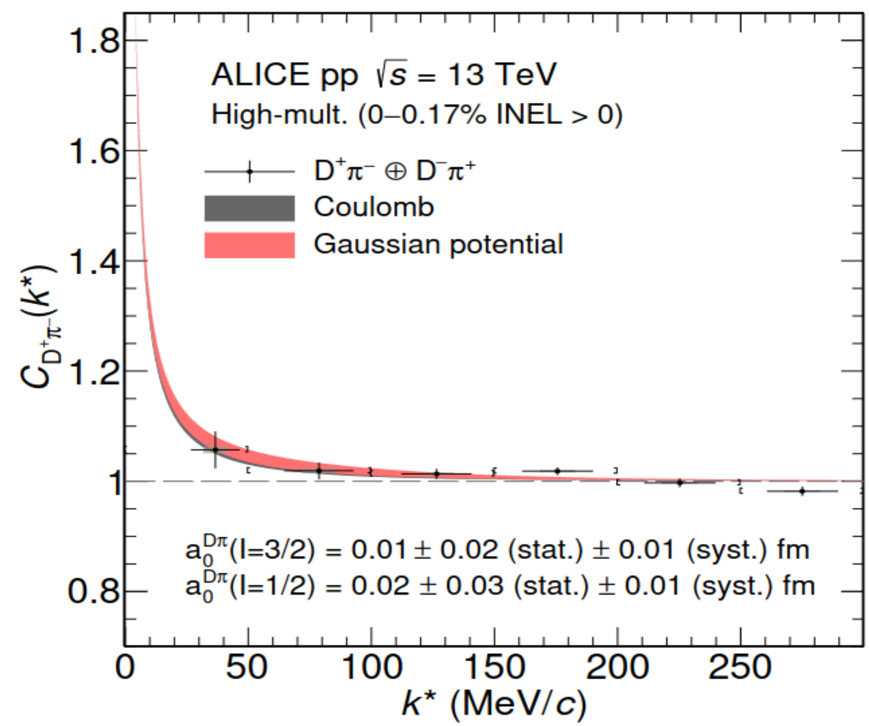
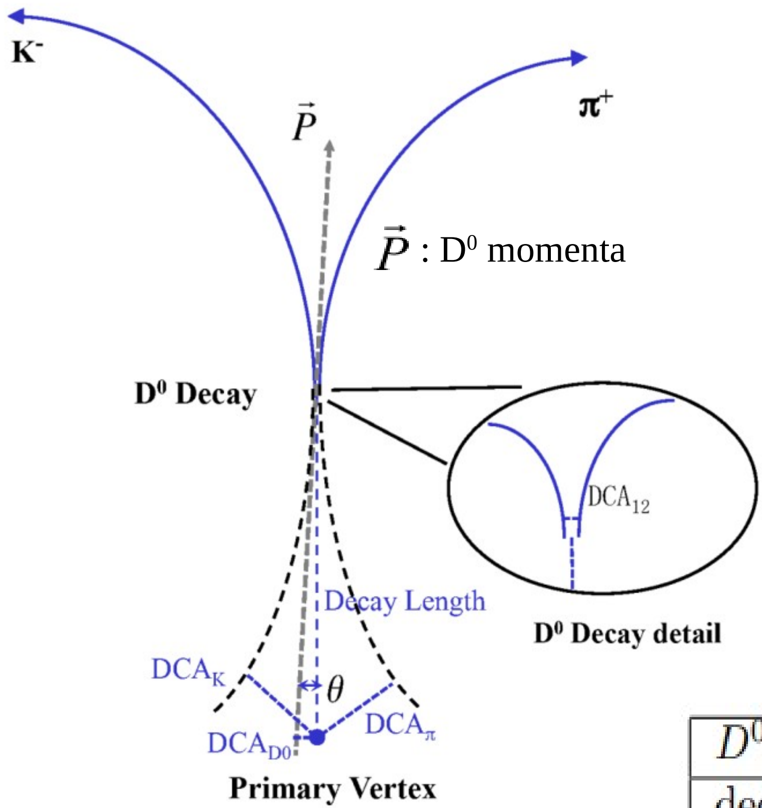


Figure 7: Interaction behavior of $D^{\pm}$ at final state

- CF data for pD^- and $\bar{p}D^+$ pairs are compatible within (1.1 – 1.5)σ with theory predictions obtained from the hypothesis of Coulomb only interaction
- Small values of $a_{\pi D}$ (scattering length) → small role of D meson re-scattering in the hadronic phase of heavy-ion collisions

Reconstruction of D^0 meson

Ref. - STAR: Phys. Rev. C 99, 034908 (2019)



$c\tau \approx 123\ \mu m$

$1.6 <$ D^0 mass < 2.2 GeV/c^2

- Decay length - distance between decay vertex and primary vertex (PV)
- Distance of Closest Approach (DCA) between:
  - a) K^- & π^+ - DCA_{12}
  - b) π^+ & PV - DCA_π
  - c) K^- & PV - DCA_K
  - d) D^0 & PV - DCA_{D0}
- θ - angle between $\vec{P}$ & decay length
- Here $D^0 \rightarrow$ ***mixture of D^0 ($K^-\pi^+$) and $\overline{D}^0$ ($K^+\pi^-$)***

Topological selection criteria:

D^0 p_T (GeV/c)	$0-1$	1-2	2-3	3-5	5-10
decay length (μm) >	145	181	212	247	259
DCA between 2 daughters (μm) <	84	66	57	50	60
DCA between D^0 and PV (μm) <	61	49	38	38	40
DCA between π and PV (μm) >	110	111	86	81	62
DCA between K and PV (μm) >	103	91	95	79	58
pointing angle cos (θ) >	0.99	0.99	0.99	0.99	0.99

p_T dependence of D^0 signal & its purity (Run 2014)

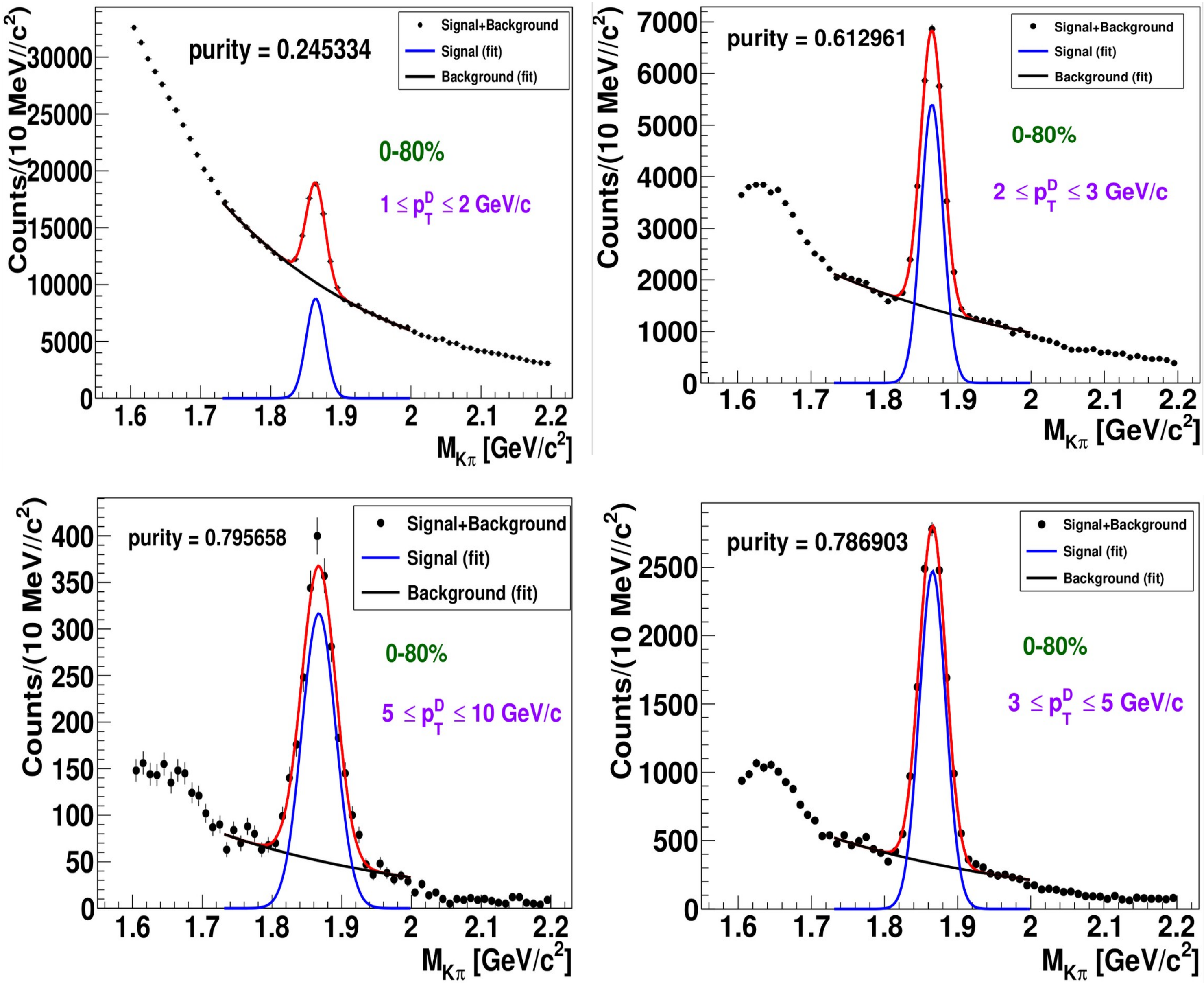


Figure 9: Kπ invariant mass distribution

- D^0 invariant mass range:

  1.82 – 1.91 GeV/c^2
- Standard topological cuts used for D^0 reconstruction
- D^0 purity:

$$\frac{signal}{(signal + background)}$$

- Good S/B ratio for D^0 signal p_T > 1 GeV/c

Particle Identification (PID)

Ref. - STAR: Phys. Rev. C 99, 034908 (2019)

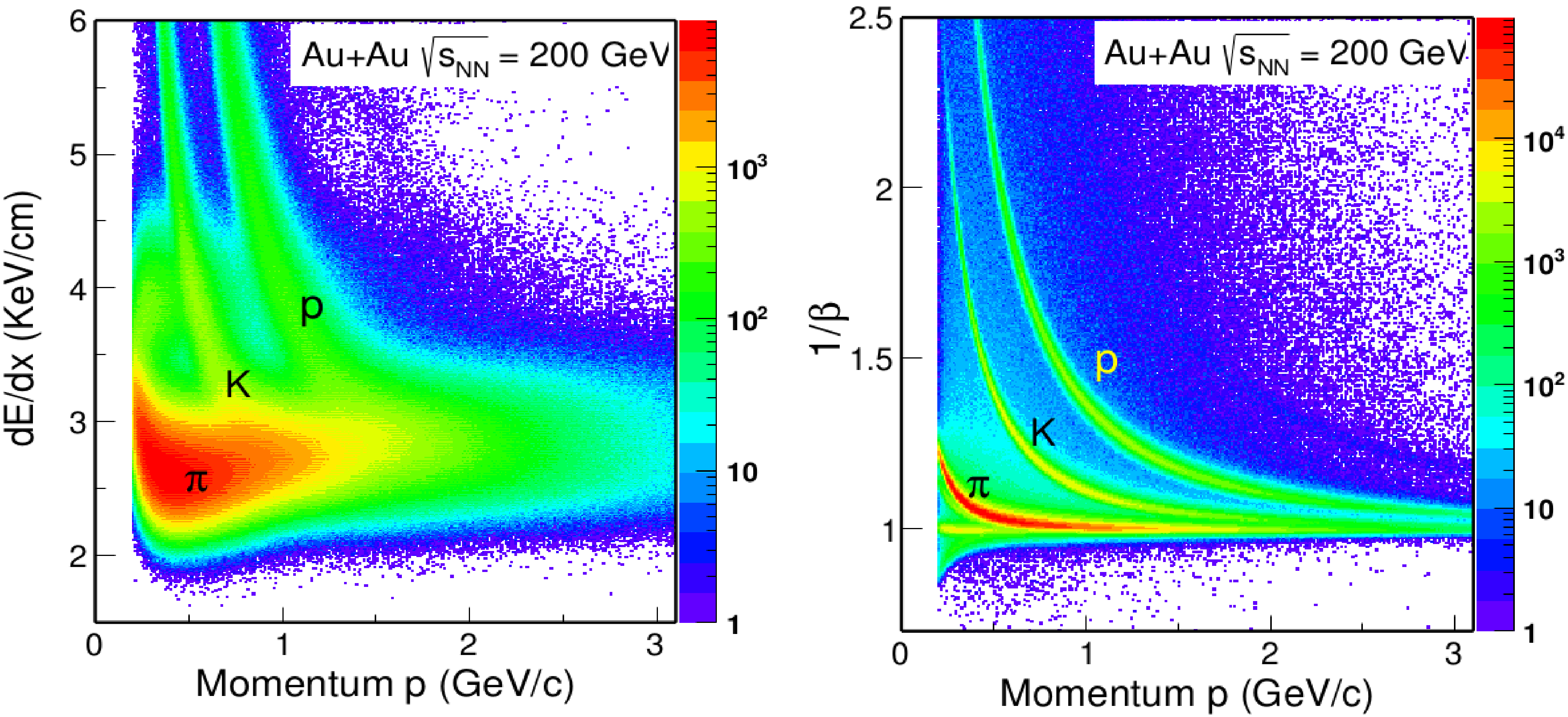


Figure 8: Particle identification using TPC (left) and TOF (right)

- dE/dx bands for π and K overlap around 0.7 GeV/c
- To distinguish between π and K at lower momenta (< 1 GeV/c), TOF info was required

Correction of detector effects

1. Self correlation: Possible correlation between D^0 candidates and their daughters were removed

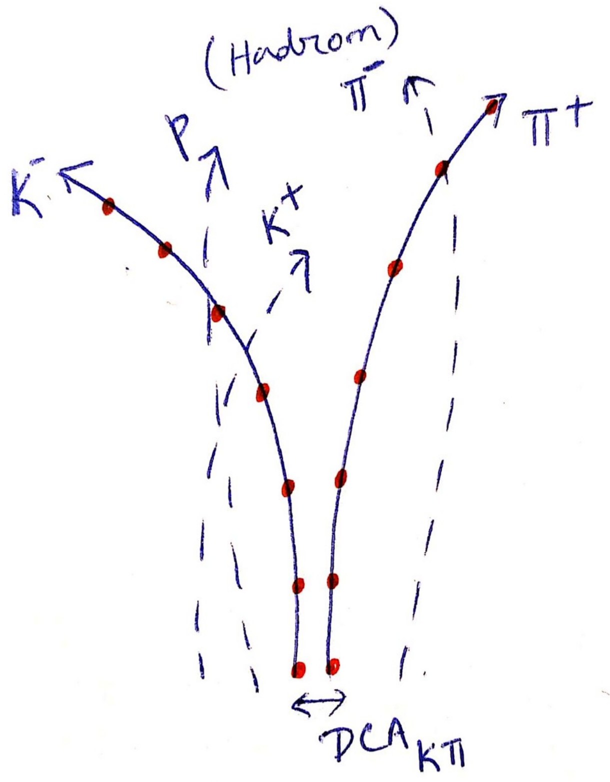
Hadron (chosen for pairing with D^0) track id ≠ Track id of D^0 (π^+K^-)

2. Track splitting: Track splitting causes an enhancement of pairs at low relative pair momentum k^*. This enhancement is created by a single track reconstructed as two tracks, with similar momenta. Track splitting mostly affects identical particle combinations (here, $\pi_D^0 - \pi$ and $K_D^0 - K$), as one track may leave a hit in a single pad-row. Due to shifts of pad-rows, it can be registered twice. In order to remove split tracks, we applied following condition.

No. of hit points / Max no. of hit points > 0.51

Possible detector effects

3. Track merging:



Merging of tracks inside TPC

Approach 1:

- **δr(i) < mean TPC distance separation → 'merged' hits**
- δr(i) - distance between TPC hits of two tracks
- Pair of tracks with fraction of merged hits > 5% were removed as 'merged tracks'
- The technique was adopted from HBT approach

Approach 2:

- **δr(i) < threshold → 'merged' hits**

Approach 3:

- **SE/ME of Δη vs Δϕ distribution** → no dip around 0 → negligible effect of merged tracks

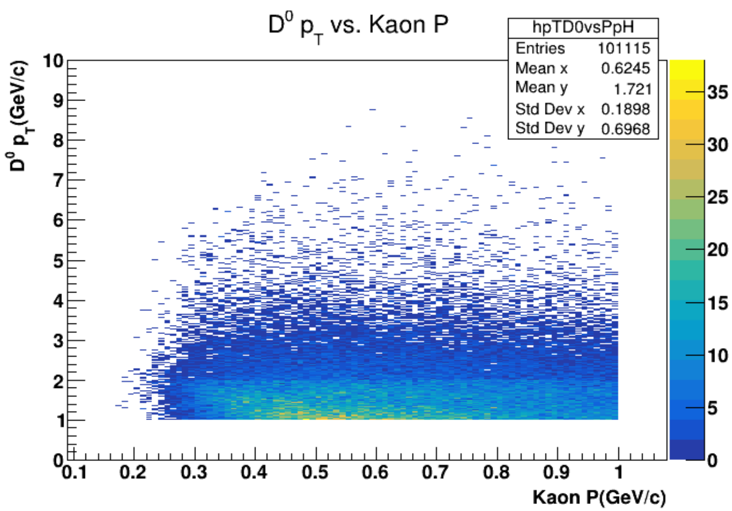
- **With variation of merging cuts → Negligible effect on correlation value, no correction applied**

Corrections & Systematic Uncertainties

Pair-purity corrected correlation function:

$$C^{\mathrm{corr}}_{\mathrm{measured}}(k^*) = \frac{C_{\mathrm{measured}}(k^*) - 1}{\mathrm{PairPurity}} + 1,$$

where PairPurity = **D^0 purity** * **hadron purity**



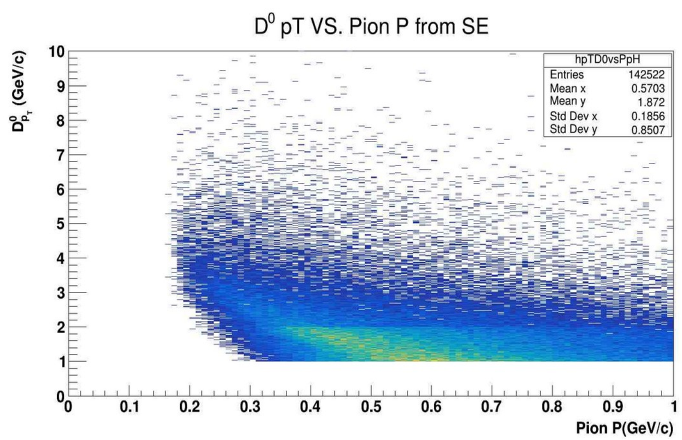


Figure 10: Momentum distribution of D^0 - K and D^0 - π

- Mean K and π momentum: <p> ≈ 0.62 GeV/c and 0.57 GeV/c
- Due to overlap with other hadrons, K and π with p < 1 GeV/c were considered
- Kaon purity ~ (97 ± 3(syst.))%
- Pion purity ~ (99 ± 0.5 (syst.))%
- Proton purity ~ (99 ± 0.5 (syst.))%

Estimation of systematic uncertainties:

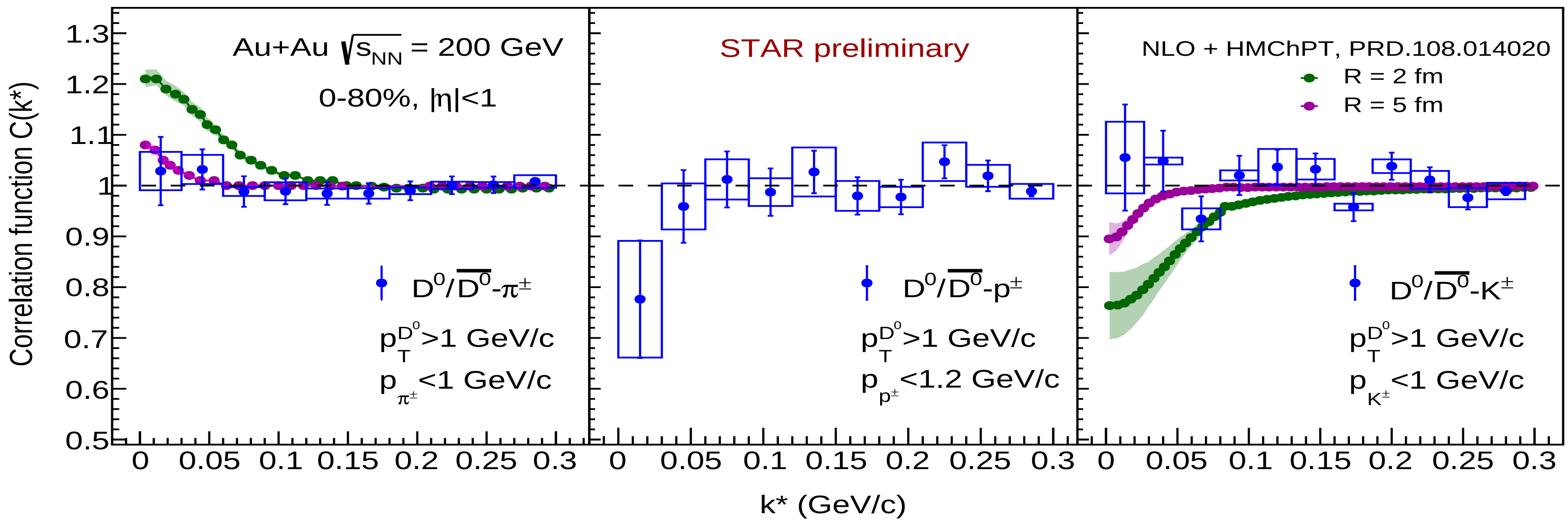
I. Variation of D^0 reconstruction criteria

II. Variation of D^0 invariant mass window

III. Uncertainty from D^0-h pair-purity correction

Correlation functions using Run 2014 data

NLO + HMChPT, Phys. Rev. D 108, 014020



$C(k^*)$ for D^0-K pairs with systematic uncertainties (boxes). Green and pink bands are theory predictions of $C(k^*)$ for D^0-K^+ channel using source radii of 5 fm and 2 fm respectively

- $C(k^*)$ calculated with *K* and *π* momentum < 1 GeV/c, *p* momentum < 1.2 GeV/c and D^0 p_T > 1 GeV/c
- Ref. CF estimated for D^0-K^+ using next-to-leading order (NLO) - Heavy Meson Chiral Perturbation Theory (HMChPT) scheme
- STAR data shows **no significant correlations**, but the data also consistent with theoretical model predictions with **emission source size of 5 fm or larger**
- Resonance effect of D_{S0}^* $(2317)^\pm$ state is NOT visible due to large source size or large experimental uncertainties