



Recent studies on heavy-flavor femtoscopy in heavy-ion collisions by STAR

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Heavy-flavors in Heavy-ion Collisions (HIC)

- Heavy flavored quarks (c and b) are produced early in collisions due to their large mass

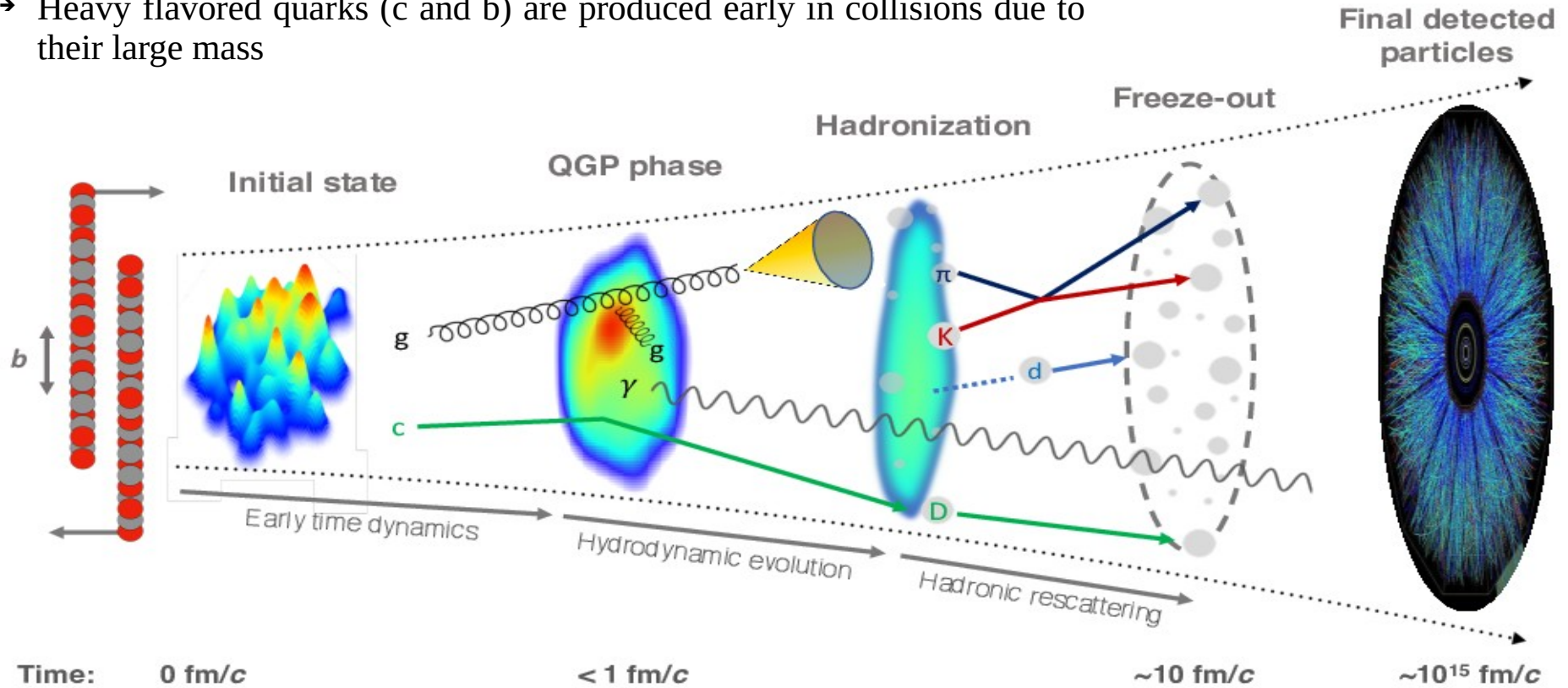


Figure 1: Evolution of heavy-ion collision

arXiv:2303.17254 [nucl-ex]

Motivation: charm interaction with QGP

- Significant D^0 elliptic flow and suppression of D^0 meson at high p_T are observed in heavy-ion reactions at RHIC

STAR, Phys. Rev. Lett. 118 (2017) 212301

STAR, Phys. Rev. C 99 (2019) 34908

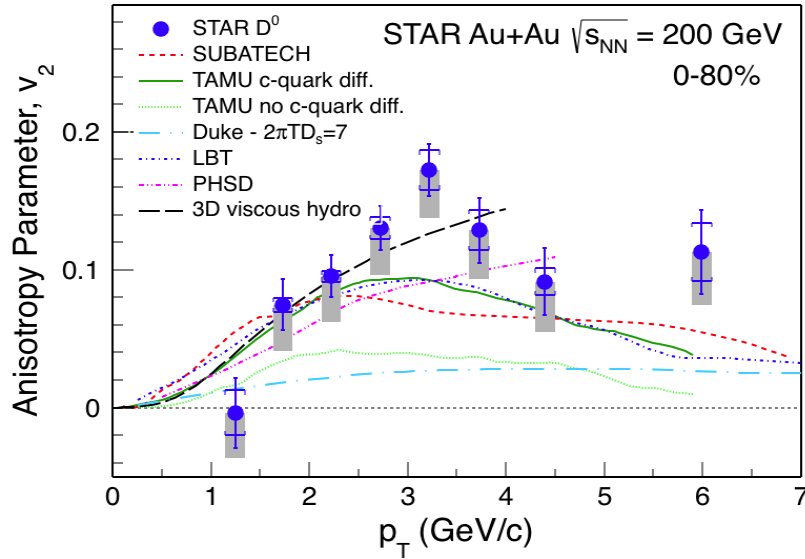


Figure 2: D^0 anisotropy vs. transverse momentum

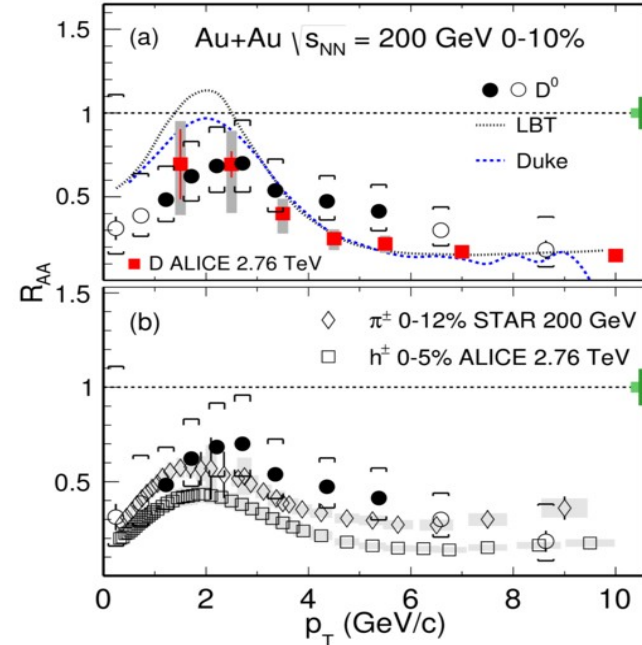


Figure 3: Nuclear modification factor, R_{AA} (a) D^0 , (b) $\pi^{+/-}$ & $h^{+/-}$

- Strong interaction of charm quarks with the quark-gluon plasma and their thermalization
- **New observables** to constrain different models and understand production mechanism

Femtoscopic correlation

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

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

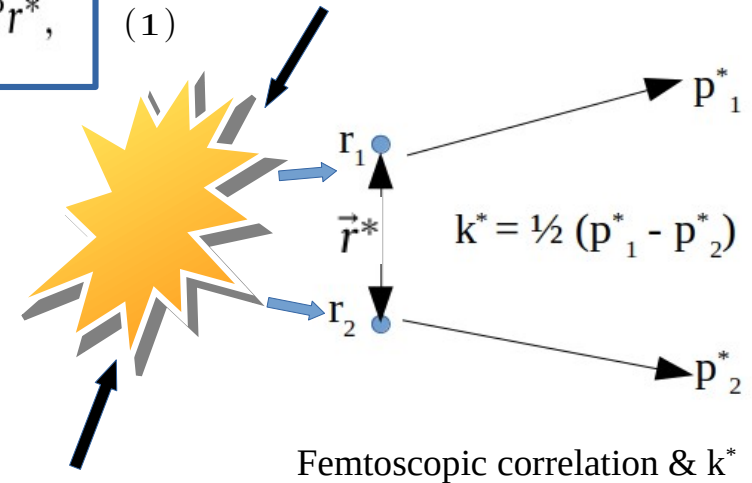
where, $S(\vec{r}^*) \rightarrow$ source emission function

$\vec{r}^* \rightarrow$ relative separation vector

$\Psi(\vec{k}^*, \vec{r}^*) \rightarrow$ pair wave function

- Femtoscopic Correlation \longrightarrow QS + FSI

- Quantum Statistics [QS]: Bose-Einstein / Fermi-Dirac
- Final-State-Interaction [FSI]: Strong & Coulomb interaction
- **Only strong interaction contributes to D^0/\bar{D}^0 - h^\pm femtoscopy**



M. Lisa, S. Pratt, R. Soltz, U. Wiedemann, Annu. Rev. Nucl. Part. Sci. 2005.55:357-402

Physics outcomes

- Two-particle femtoscopic correlations are sensitive to the interactions in the final state 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*'
- Femtoscopy may provide additional information about the correlation between charmed mesons and light mesons at the freeze-out

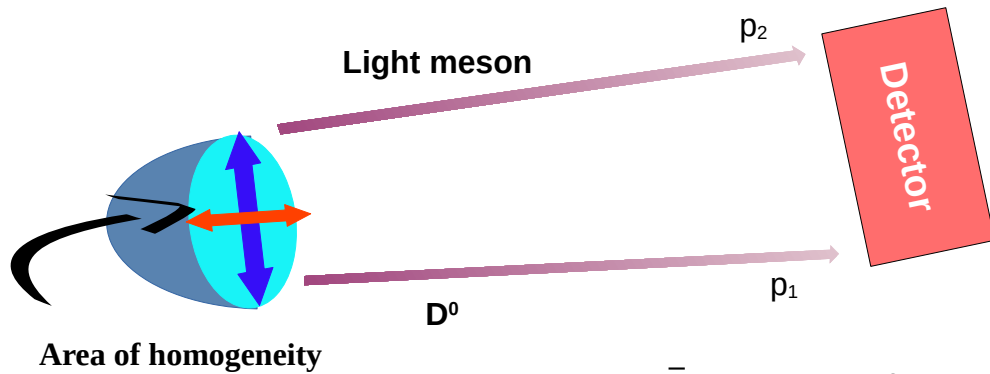
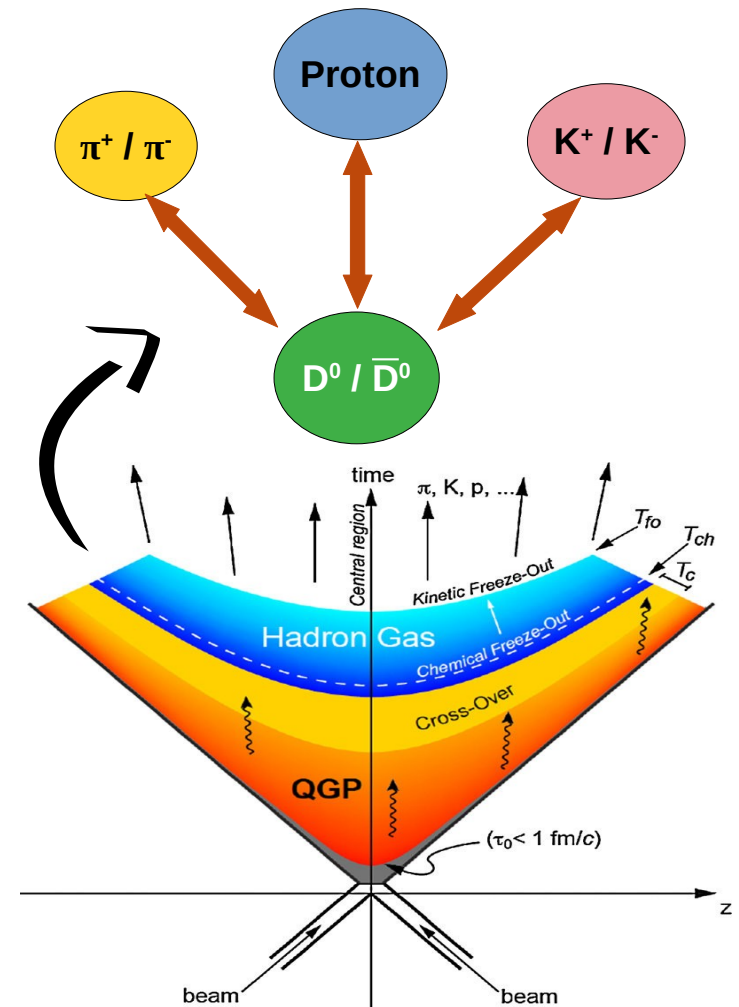


Figure 4: c/\bar{c} as a probe of QGP medium and final-state interaction



Extraction of interaction parameters

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

$$C(k^*) = 1 + \sum_s \rho_s \left[\frac{1}{2} \left| \frac{f^s(k^*)}{r_0} \right|^2 \left(1 - \frac{d_0^s}{2\sqrt{\pi}r_0} \right) + \frac{2\Re(f^s(k^*))}{\sqrt{\pi}r_0} F_1(Qr_0) - \frac{\Im(f^s k^*)}{r_0} F_2(Qr_0) \right] \quad (1)$$

where, $f^s(k^*)$ is the scattering amplitude for singlet ($s = 0$) or triplet ($s = 1$) state

ρ_s is fraction of pairs with a given spin s ($\rho_0 = 1/4$ and $\rho_1 = 3/4$)

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

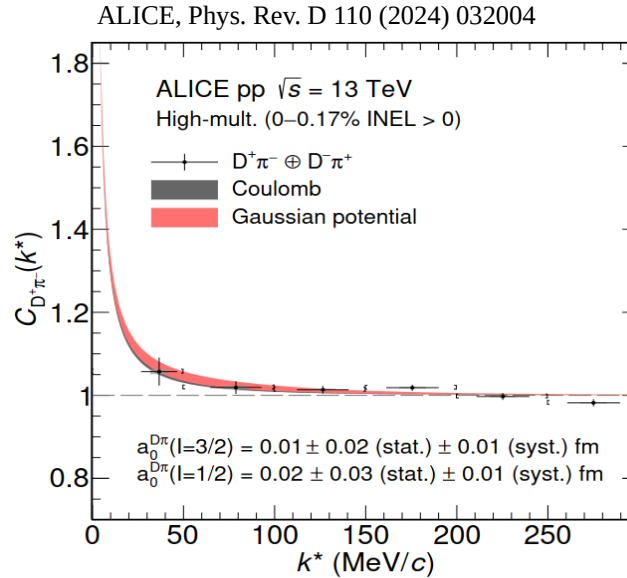
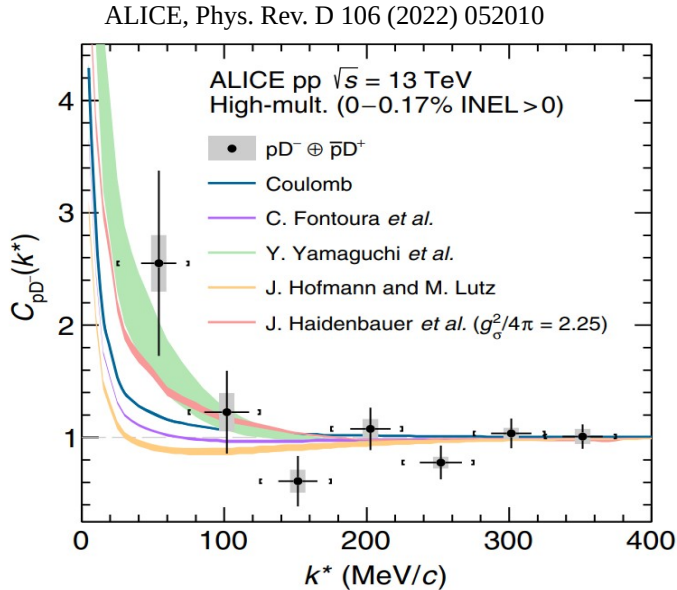
This model assumes, average separation vector (\vec{r}^*) from eq. (1), follows Gaussian distribution

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

where, r_0 is the effective radius of the correlated source

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

D-hadron femtoscopy in p-p system at LHC

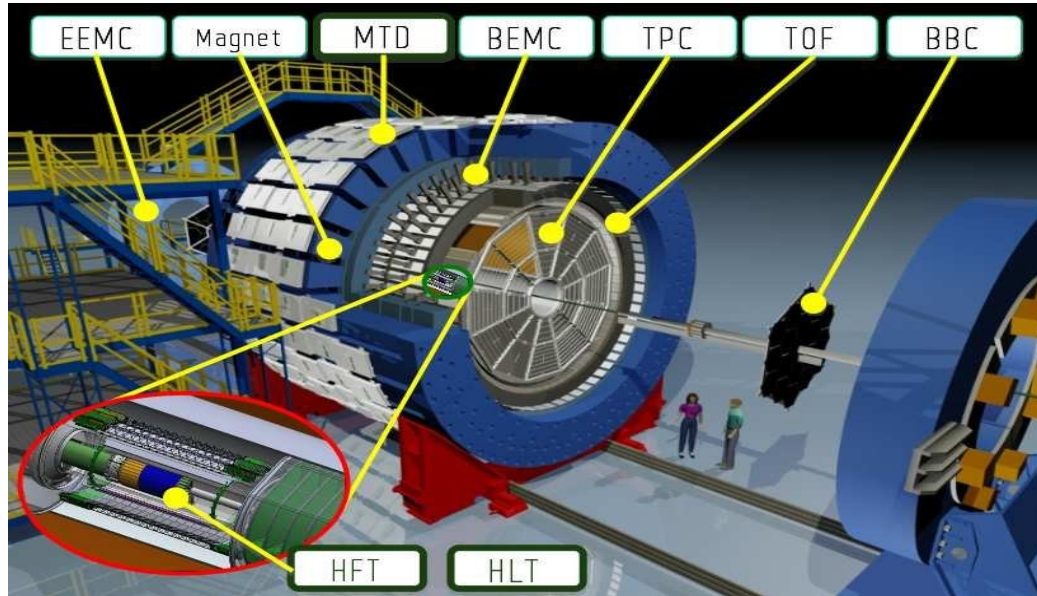


- First studies of D-hadron interactions in pp collisions at $\sqrt{s} = 13$ TeV by the ALICE experiment
- ALICE data for both p-D and D- π pairs are compatible within $(1.1 - 1.5)\sigma$ with the theory predictions obtained from the hypothesis of Coulomb only interaction

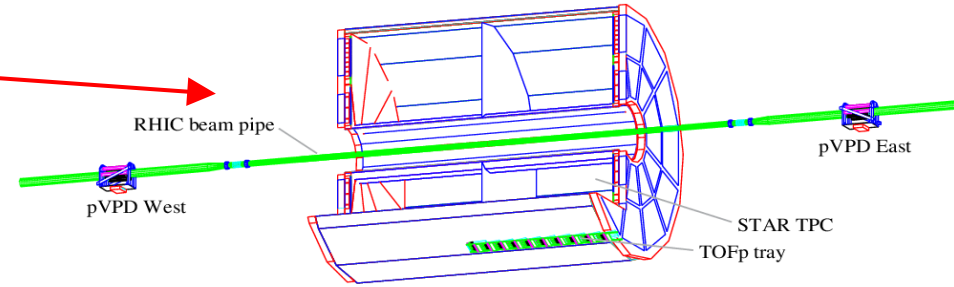
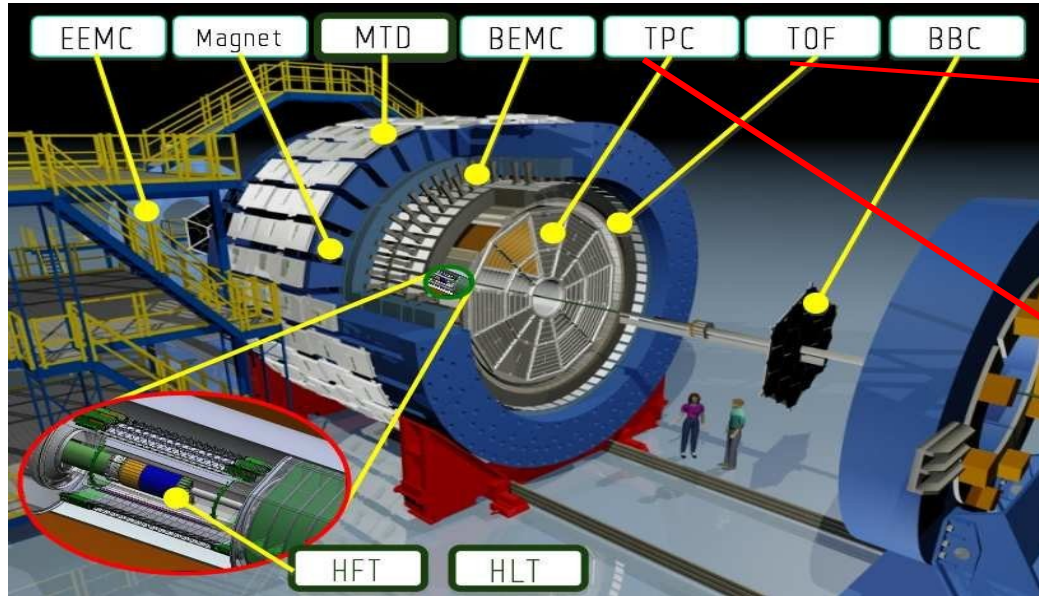
Figure 5: $C(k^*)$ for (left) pD and (right) π D pairs and interaction behavior of D^\pm at final state

- Small values of $a_{\pi D}$ (scattering length) → ALICE measurement suggests strong interactions in the hadronic phase of heavy-ion collision are small (parameters are consistent with 0)
- Possibility to learn something new about nuclear medium or QGP by measuring the source size or length of homogeneity in Au+Au system

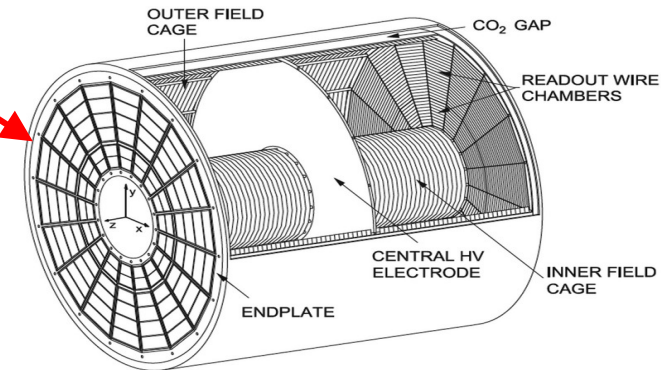
STAR (Solenoidal Tracker At RHIC)



STAR (Solenoidal Tracker At RHIC)



TOF (Time of Flight)

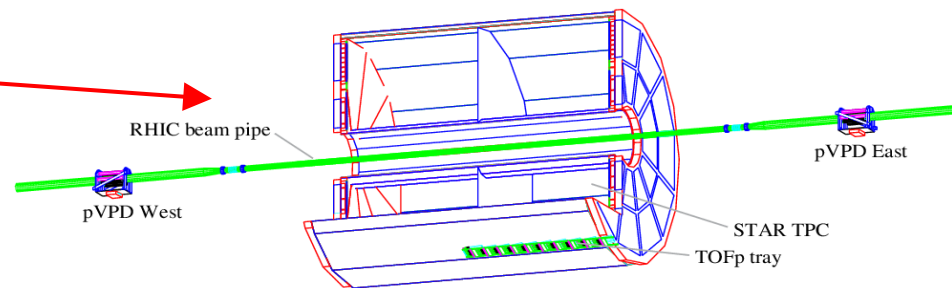
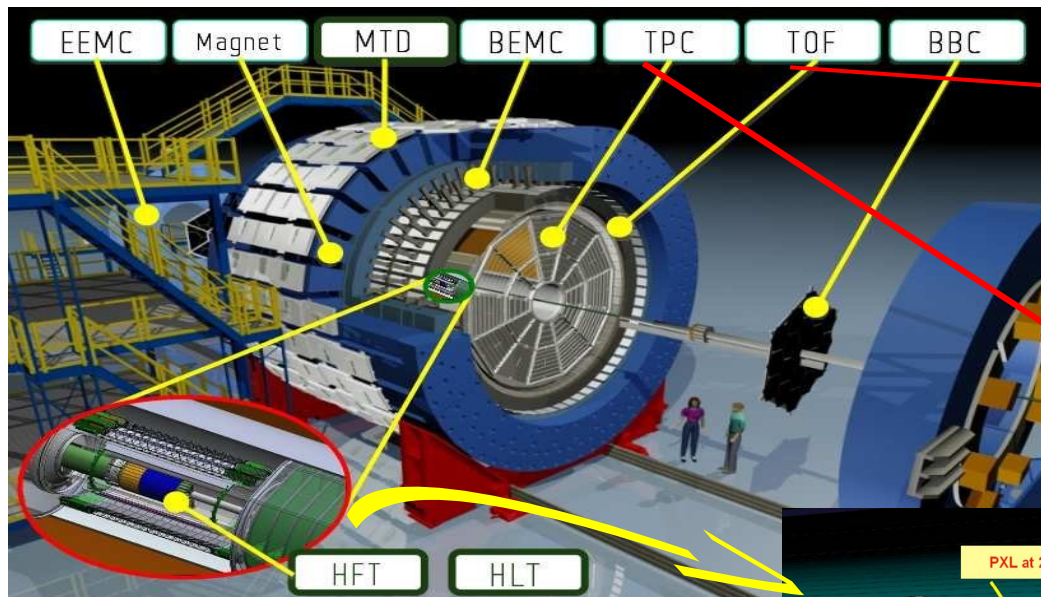


TPC (Time Projection Chamber)

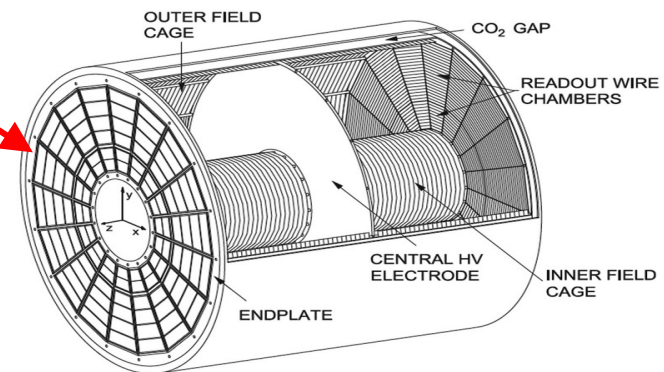
→ TOF: used for PID

→ TPC: used for tracking and PID

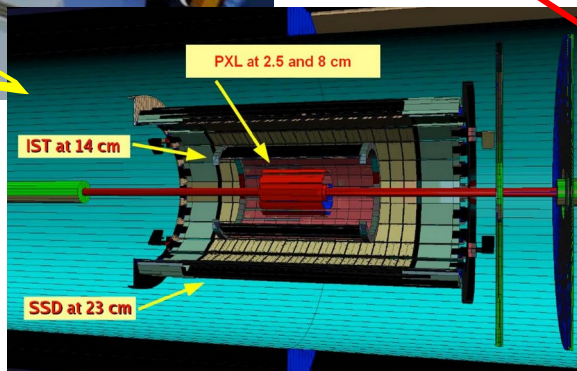
STAR (Solenoidal Tracker At RHIC)



TOF (Time of Flight)



TPC (Time Projection Chamber)



HFT (Heavy Flavor Tracker)

- TOF: used for PID
- TPC: used for tracking and PID
- HFT: used for D^0 reconstruction which can discriminate secondary vertices from PV by $DCA < 150 \mu\text{m}$

Particle Identification (PID)

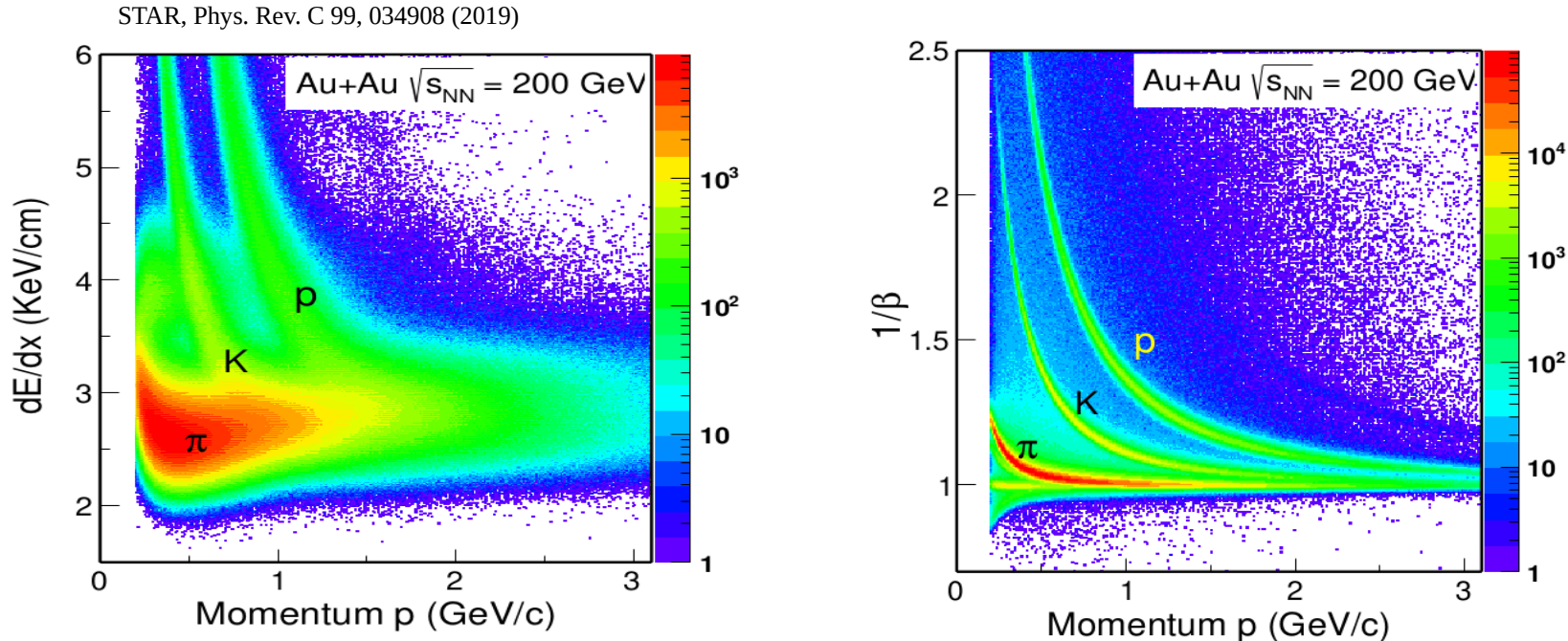
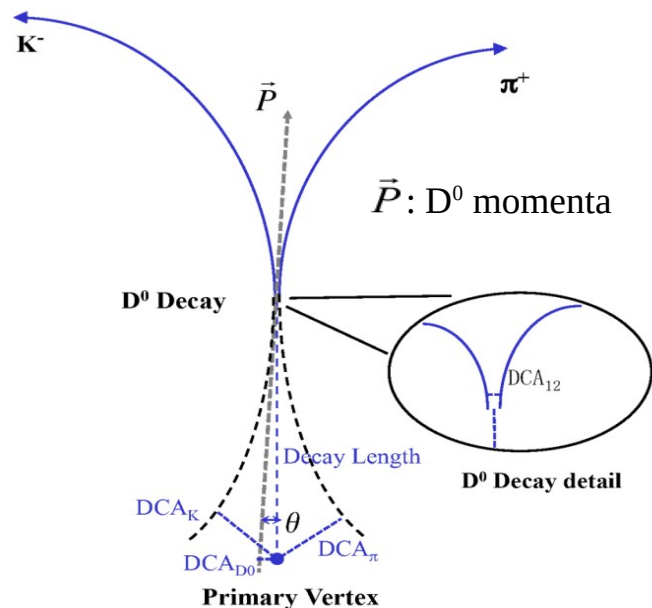


Figure 6: Particle identification using TPC (left) and TOF (right)

- dE/dx bands for π and K overlap around 0.7 GeV/c; K and p bands overlap beyond 1.2 GeV/c
- To distinguish between π , K and p at higher momenta (> 0.7 GeV/c), TOF information was required

Dataset and D^0 meson reconstruction

STAR, Phys. Rev. C 99, 034908 (2019)



$$c\tau \approx 123 \mu\text{m}$$

$$1.6 < D^0 \text{ mass window} < 2.2 \text{ GeV}/c^2$$

$D^0 \rightarrow$ *mixture of $D^0 (K^-\pi^+)$ and $\bar{D}^0 (K^+\pi^-)$*

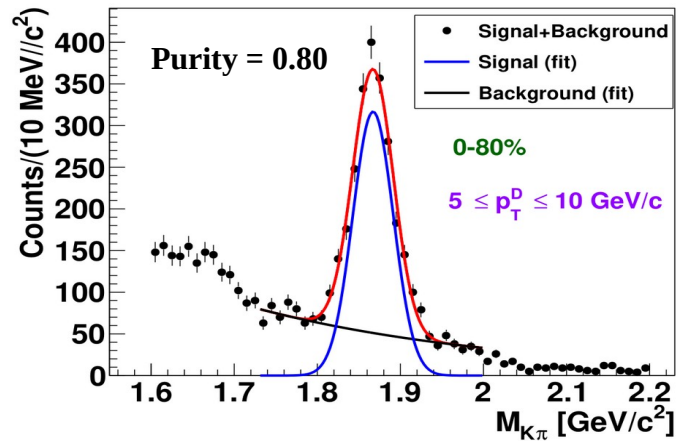
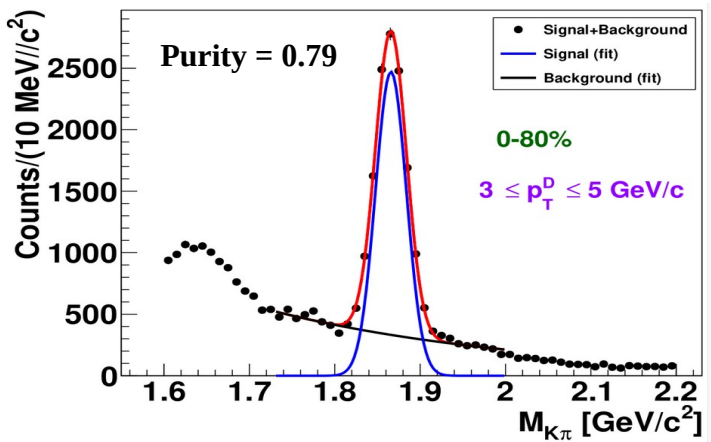
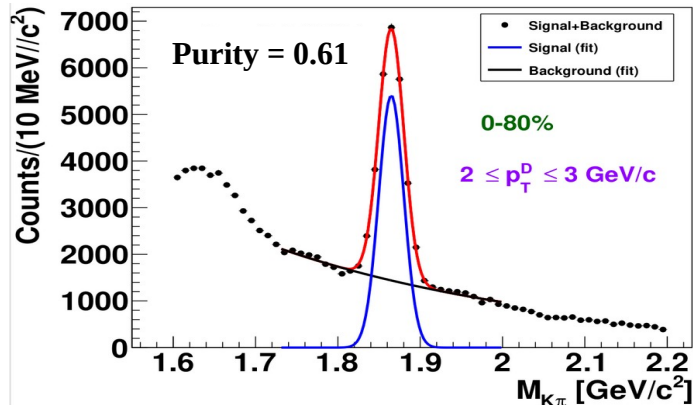
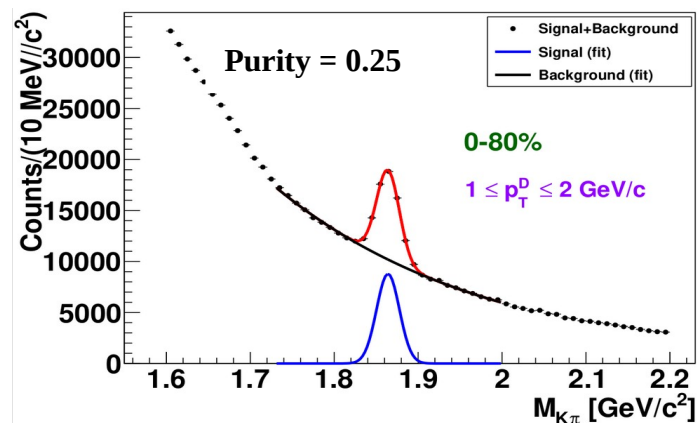
Dataset:

- Au+Au, 200 GeV, collected in Run 2014
- Trigger: Minimum bias
- Centrality: 0 – 80%
- 490 M good minimum bias events

D^0 reconstruction:

- 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

D^0 invariant mass & signal purity



- Unlike-sign ($K\pi^+$) pairs from SE construct 'signal'
- Invariant mass range for D^0 signal: 1.82 – 1.91 GeV/c^2
- D^0 signal and background are fitted with respectively Gaussian and exponential function
- D^0 purity:
$$\frac{\text{Signal}}{(\text{Signal} + \text{Background})}$$
- Higher D^0 signal purity with increasing p_T bin

Figure 7: p_T dependence of $K\pi$ invariant mass distribution and D^0 signal purity



Correction of raw correlation function

→ Correlation function $C(\vec{k}^*)$ for $D^0/\bar{D}^0 - h^{+/-}$ pairs:
$$C(\vec{k}^*) = \mathcal{N} \frac{A(\vec{k}^*)}{B(\vec{k}^*)}. \quad (3)$$

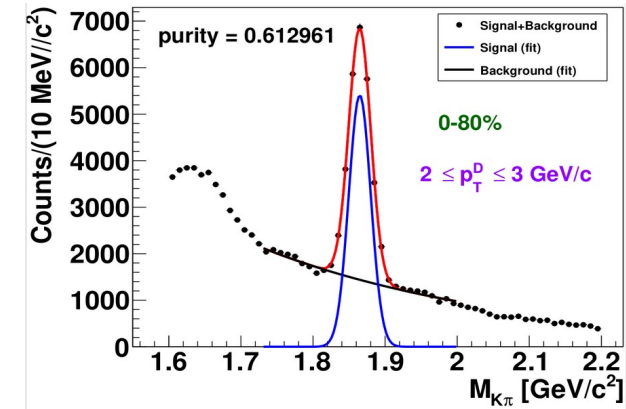
$A(\vec{k}^*)$ and $B(\vec{k}^*) \rightarrow k^*$ distribution for correlated and uncorrelated pairs; $\mathcal{N} \rightarrow$ normalization factor

→ Pair-purity corrected correlation function:
$$C_{\text{measured}}^{\text{corr}}(k^*) = \frac{C_{\text{measured}}(k^*) - 1}{\text{PairPurity}} + 1, \quad (4)$$

where $\text{PairPurity} = \mathbf{D^0 \text{ purity}} * \mathbf{hadron \text{ purity}}$

→ $C_{\text{measured}}(k^*)$ is the raw correlation function calculated using Eq. (3)

→ D^0 -hadron pair purity correction is required to remove the contribution from combinatorial background (D^0 candidates reconstructed from like-sign $K\pi$ pairs within selected mass range)



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- D^0 -hadron pair purity correction is required to remove the contribution from combinatorial background (D^0 candidates reconstructed from like-sign $K\pi$ pairs within selected mass range)
- Average D^0 purity $\sim 37\%$, $1 \text{ GeV}/c < p_T < 10 \text{ GeV}/c$
- Kaon purity $\sim (97 \pm 3 \text{ (syst.)})\%$, $p_K < 1 \text{ GeV}/c$
- Pion purity $\sim (99.5 \pm 0.5 \text{ (syst.)})\%$, $p_\pi < 1 \text{ GeV}/c$
- Proton purity $\sim (99.5 \pm 0.5 \text{ (syst.)})\%$, $p_p < 1.2 \text{ GeV}/c$

Results: D^0/\bar{D}^0 - $K^{+/-}$ correlation

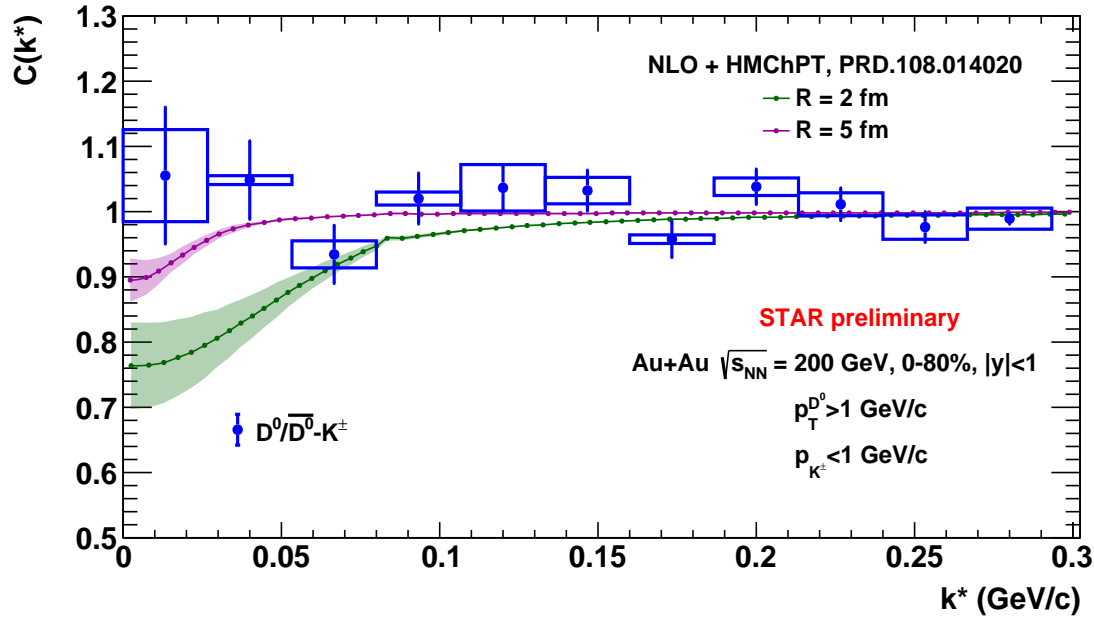


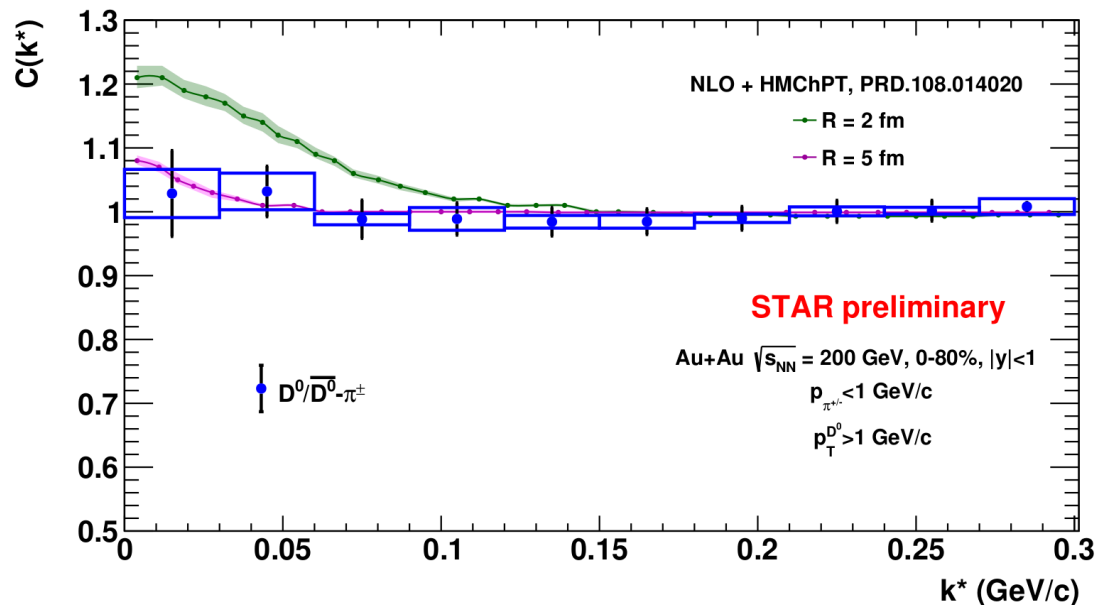
Figure 8: $C(k^*)$ for D^0 - K pairs with systematic uncertainties (boxes). Green and pink bands are theory predictions of $C(k^*)$ for D^0 - K^+ channel using source radii of 2 fm and 5 fm respectively

- $C(k^*)$ measured for D^0 - K^+ , D^0 - K^- , \bar{D}^0 - K^+ and \bar{D}^0 - K^- with kaon momentum < 1 GeV/c and D^0 $p_T > 1$ GeV/c
- Theory predictions are estimated for D^0 - K^+ channel using next-to-leading order (NLO) - Heavy Meson Chiral Perturbation Theory (HMChPT) scheme
- Resonance effect of $D_{S_0}^*(2317)^\pm$ (DK bound state) is NOT visible due to large source size or large experimental uncertainties

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

→ STAR data shows no significant correlations, but the data consistent with theoretical model prediction with emission source size of 5 fm within uncertainty

Results: D^0/\bar{D}^0 - $\pi^{+/-}$ correlation



- $C(k^*)$ calculated for D^0 - π^+ , D^0 - π^- , \bar{D}^0 - π^+ and \bar{D}^0 - π^- with π momentum < 1 GeV/c and D^0 $p_T > 1$ GeV/c
- Theory calculations consist of D^0 - π^+ and D^+ - π^0 channels using next-to-leading order (NLO) - Heavy Meson Chiral Perturbation Theory (HMChPT) scheme

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

Figure 9: $C(k^*)$ for D^0 - π pairs with systematic uncertainties (boxes). Green and pink bands are theory predictions of $C(k^*)$ for D - π channel using source radii of 2 fm and 5 fm respectively

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Results: D^0/\bar{D}^0 - $p^{+/-}$ correlation

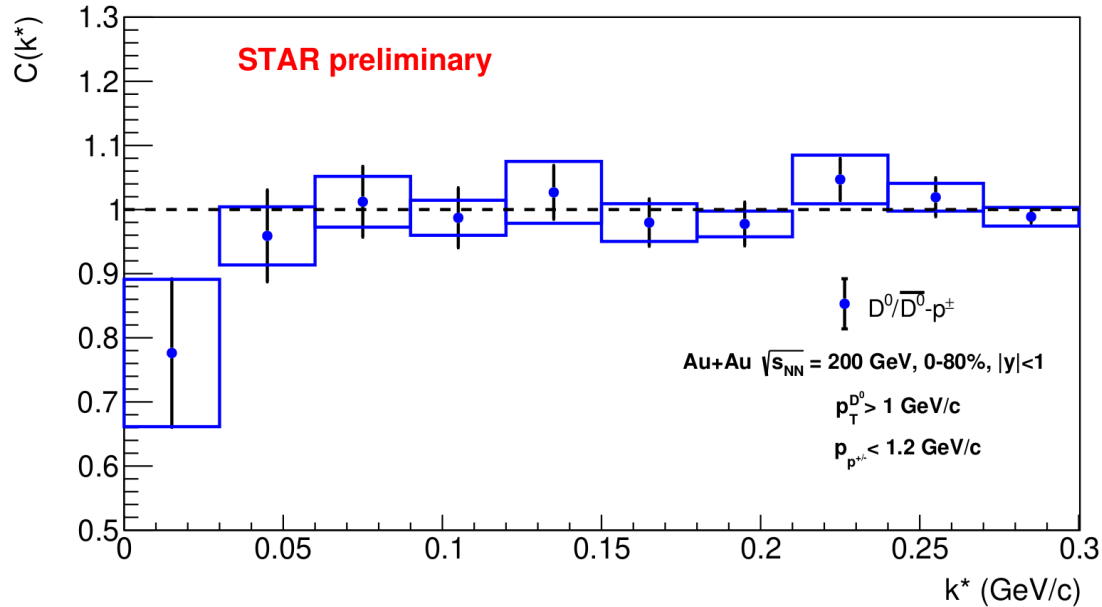


Figure 10: $C(k^*)$ for D^0 - p pairs with systematic uncertainties (blue brackets)

- $C(k^*)$ contains D^0 - p^+ , D^0 - p^- , \bar{D}^0 - p^+ and \bar{D}^0 - p^- with proton momentum < 1.2 GeV/c and $D^0 p_T > 1$ GeV/c
- No theory prediction available

Predictions?

- We do not observe significant correlations between D^0 - p pairs
- Suggesting large emission source size

Analytical fit using Lednicky–Lyuboshitz

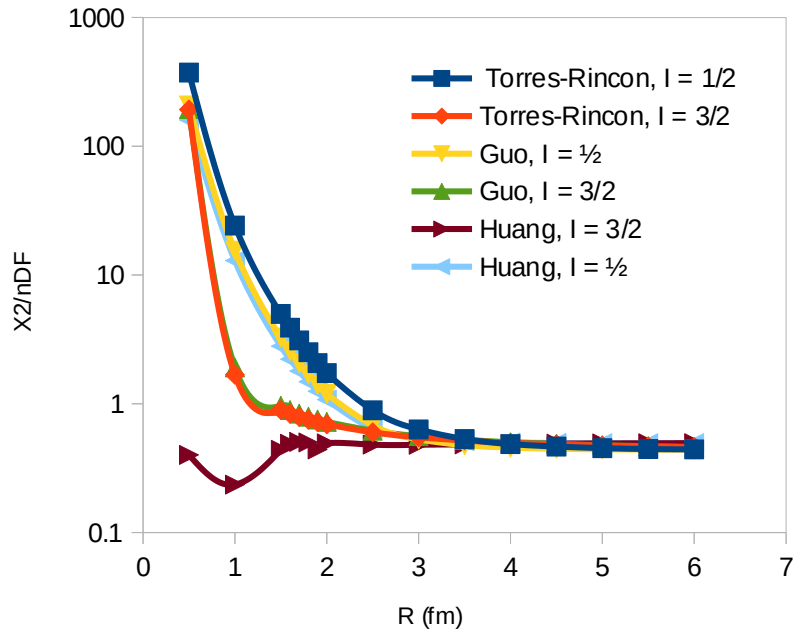


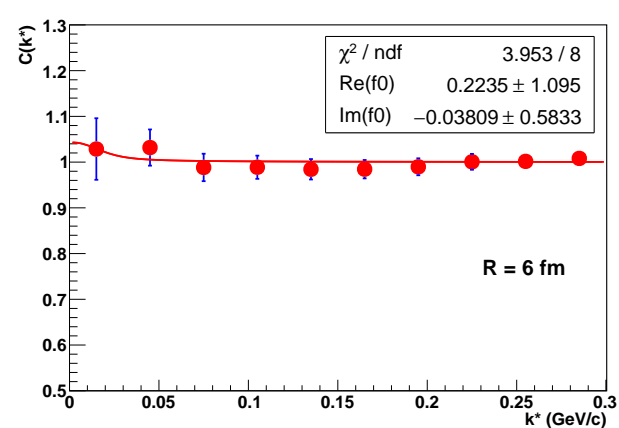
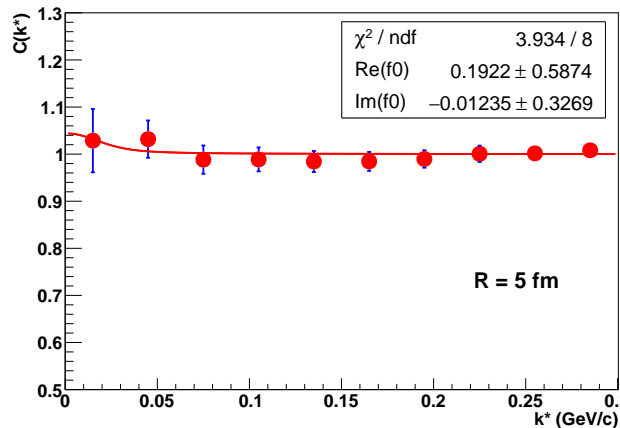
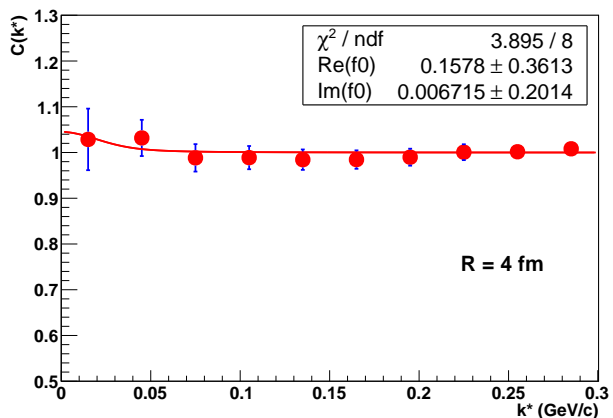
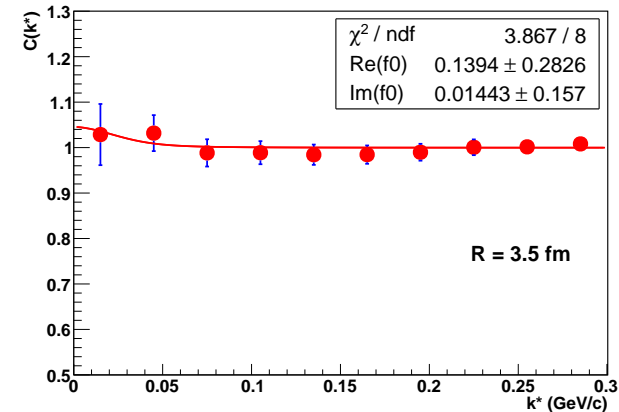
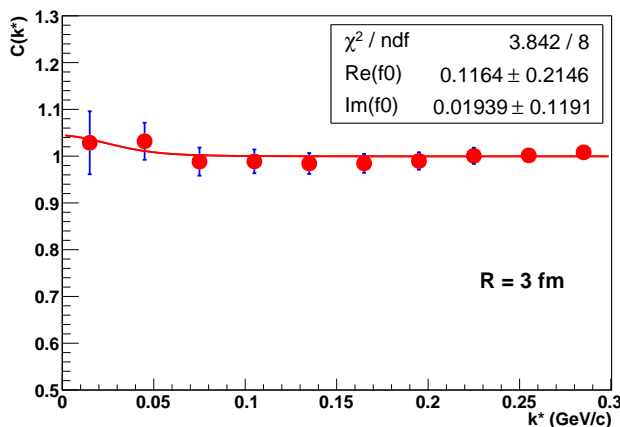
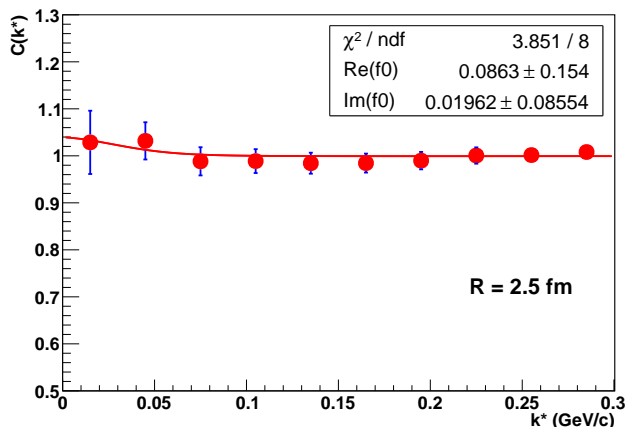
Fig 11: χ^2/nDF vs source radii (R) for $D^0\text{-}\pi$

D- π	
Theory model	Scattering length (fm)
Torres-Rincon, $I = 1/2$	0.423
Torres-Rincon, $I = 3/2$	-0.101
Guo, $I = 1/2$	0.33
Guo, $I = 3/2$	-0.11
Huang, $I = 1/2$	-0.61 ± 0.11
Huang, $I = 3/2$	-0.06 ± 0.02

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

From probability distribution of χ^2 , $D^0\text{-}\pi$ emission source radii should be larger than 2 fm

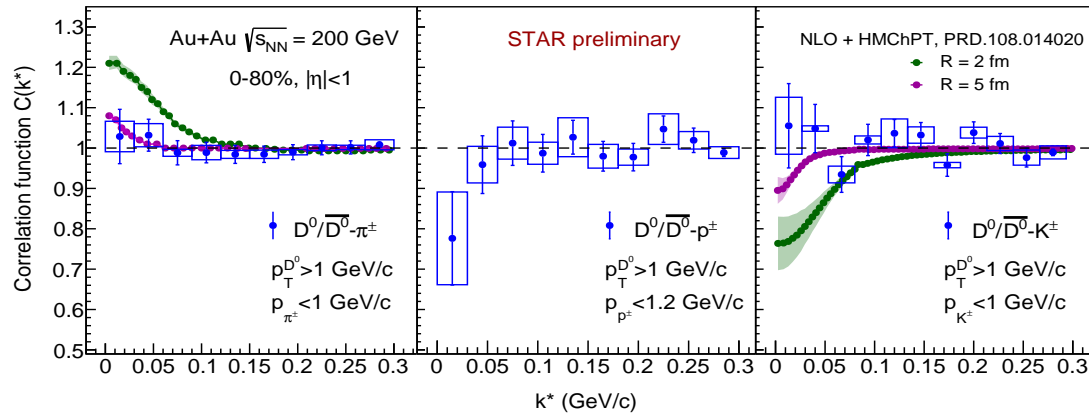
Scattering length with variation of source radii



Shows small scattering length (D- π) as expected

Summary & future plans

- D-meson femtoscopy is applicable to probe the interaction behavior of charmed hadron and the phase space geometry of emission source
- Correlation studies between D^0 and charged hadrons, provide consistent results with no significant correlation and large emission source size (~ 5 fm or larger)



Even though current statistical precision is not sufficient to make decisive conclusions but good prospects for improving precision of the measurement

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



Thank you!

Freeze-out dynamics

→ Properties of nuclear medium

Example – source size measured at RHIC with Kaons compatible with model calculations employing hydrodynamics

→ Local thermal equilibrium

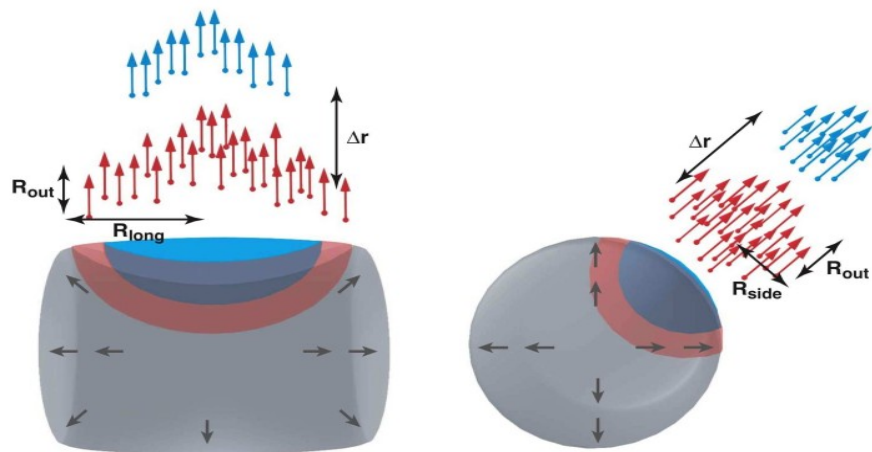


Figure 6: Emission source phase-space

M. Lisa, S. Pratt, R. Soltz, U. Wiedemann, Annu. Rev. Nucl. Part. Sci. 2005.55:357-402

STAR, Phys. Rev. C 88 (2013) 34906

HKM – Hydro Kinetic Model

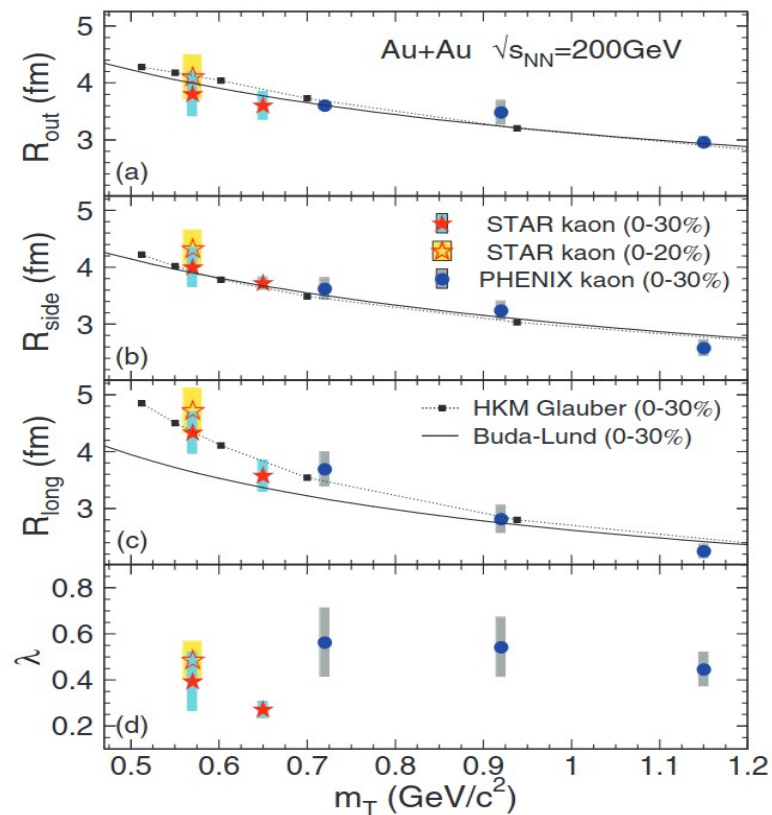


Figure: m_T dependence of 3-D source size using Kaon femtoscopy

Theory prediction of CF for $D\pi$ channels

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

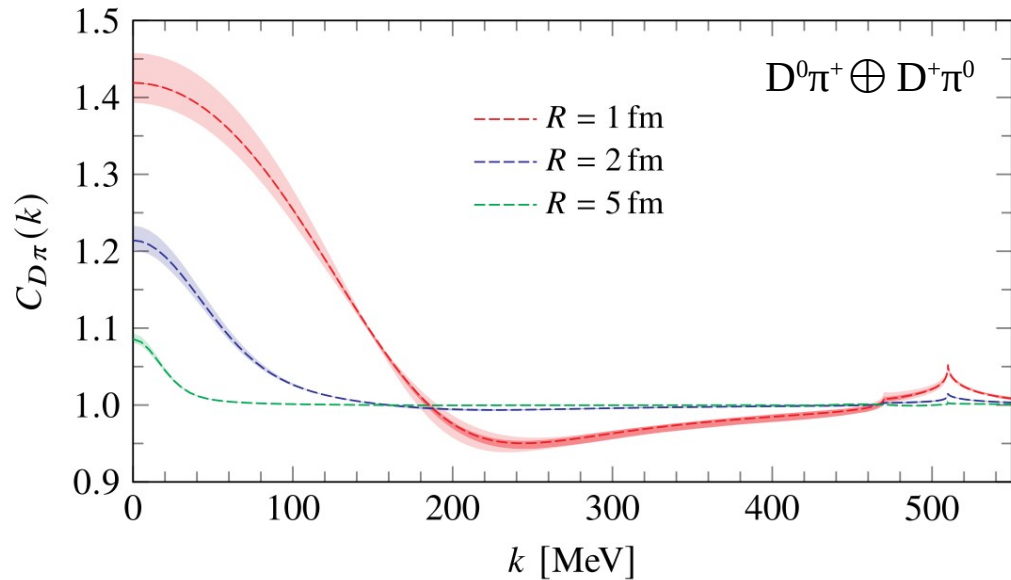


Figure: Correlation functions for $D\pi$ channels predicted for $R = 1, 2$ and 5 fm sources represented by red, blue and green dashed lines respectively. Corresponding bands show uncertainties with 68% CL

→ 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 $I = 1/2$ state

→ Depletion at $k \sim 215$ 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

Correction of detector effects

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

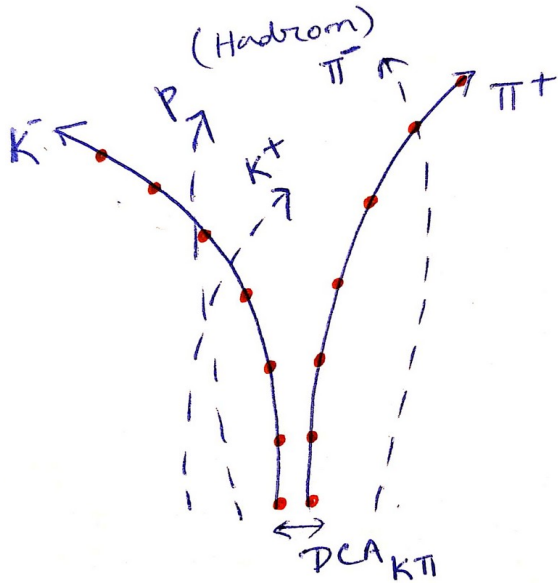
Hadron (chosen for pairing with D^0) track id \neq Track id of D^0 (π^+K^-)

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:

- $\delta r(i) < \text{mean TPC distance separation}$ → ‘merged’ hits
- $\delta r(i)$ - 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:

- $\delta r(i) < \text{threshold}$ → ‘merged’ hits

Approach 3:

- **SE/ME of $\Delta\eta$ vs $\Delta\phi$ distribution** → no dip around 0 → negligible effect of merged tracks
- **With variation of merging cuts → Negligible effect on correlation value, no correction applied**

Selection criteria

Event cuts

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

Track cuts

- $p_T > 0.5$ GeV/c
- $|dca| > 0.0050$ cm.
- $n\text{HitsFit} \geq 20$
- $|\eta| \leq 1.0$

PID cuts for π , K & p

- $|n\sigma_\pi| < 3.0$
- $|n\sigma_K| < 2.0$
- $|n\sigma_p| < 2.0$
- $|\frac{1}{\beta} - \frac{1}{\beta_\pi}| < 0.03$
- $|\frac{1}{\beta} - \frac{1}{\beta_K}| < 0.03$
- $|\frac{1}{\beta} - \frac{1}{\beta_p}| < 0.03$
- $\frac{n\text{HitsFit}}{n\text{HitsFitMax}} > 0.51$