# 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

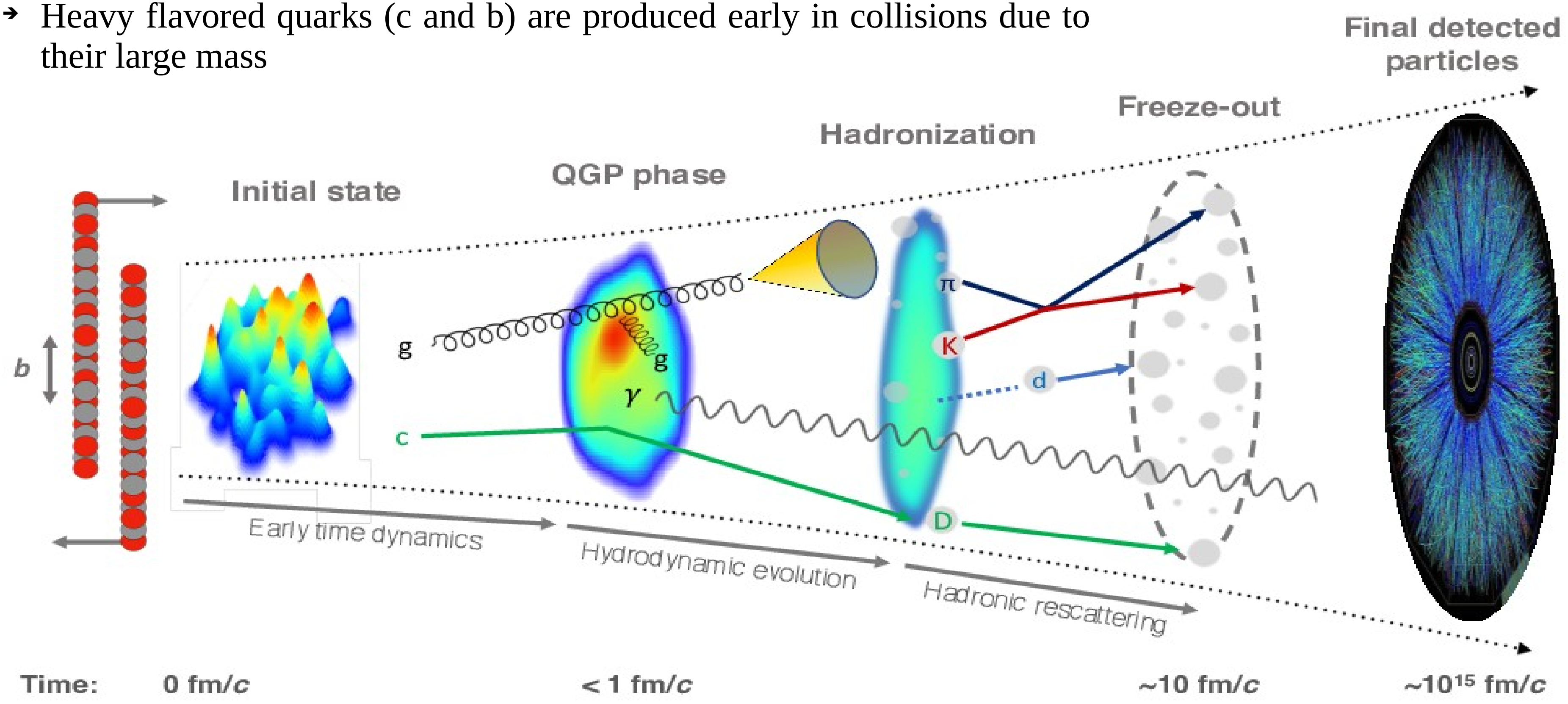



Figure 1: Evolution of heavy-ion collision

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

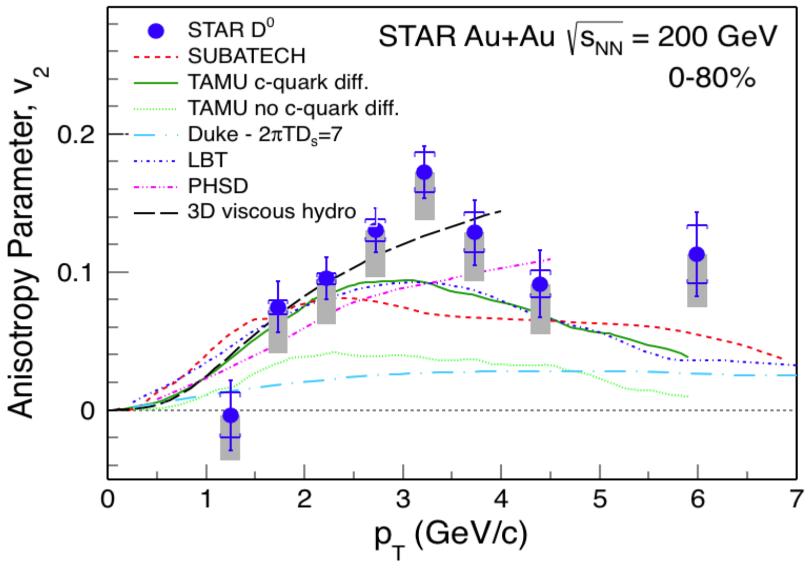



Figure 2: $D^0$ anisotropy vs. transverse momentum

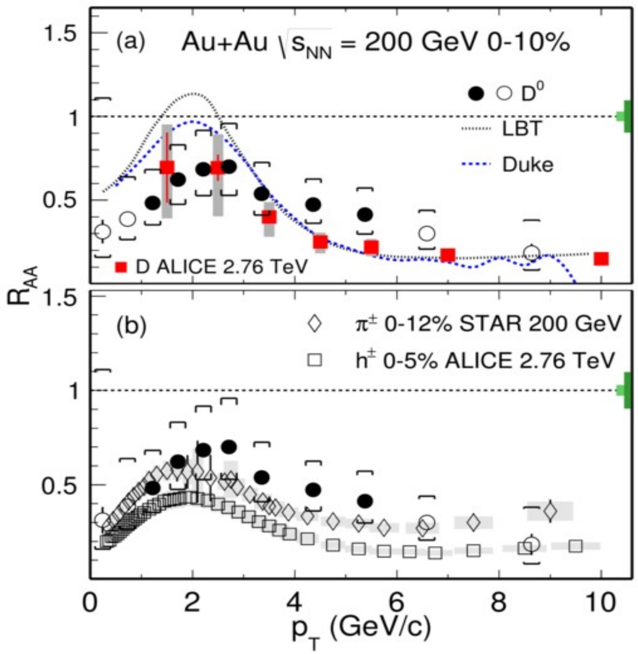


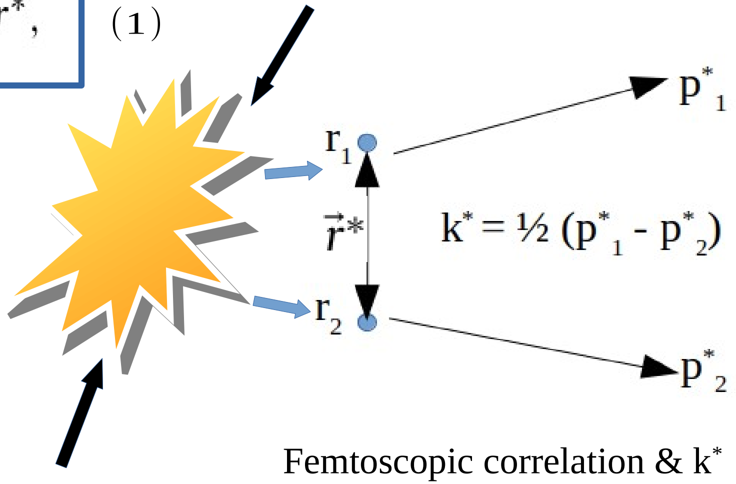

Figure 3: Nuclear modification factor, $R_{AA}$ (a) $D^0$, (b) $\pi^{+/-}$ & $h^{+/-}$

- 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

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



Femtoscopic correlation & $k^*$

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

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

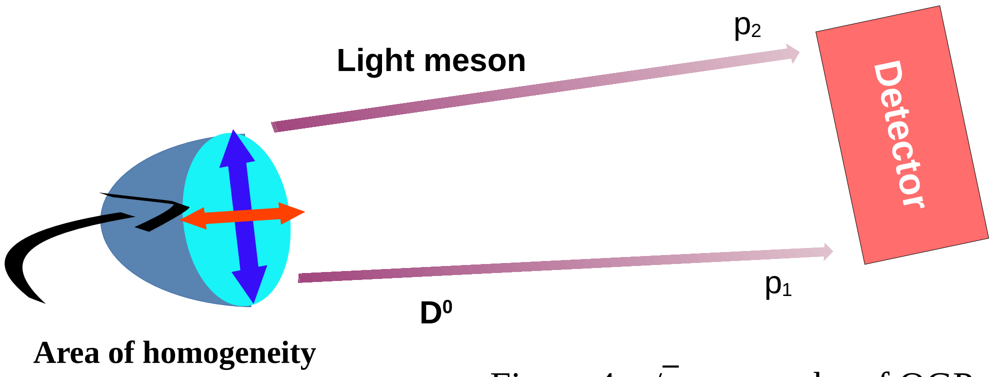
$\Psi(\vec{k}^*, \vec{r}^*) \rightarrow$ pair wave function

- Femtoscopic Correlation ──► 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**

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



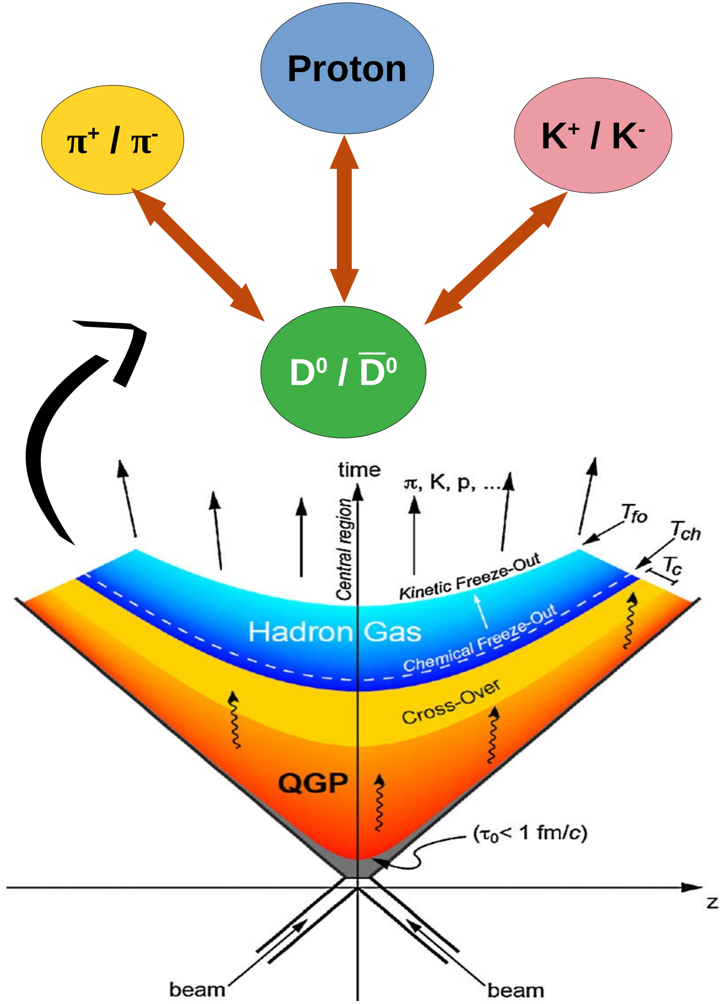




Figure 4: $c/\bar{c}$ as a probe of QGP medium and final-state interaction

# Extraction of interaction parameters

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

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

where , $f^s(k^*)$ is the scattering length, $d_0^s$ is effective range for singlet (s = 0) or triplet (s = 1) state

$\rho_s$ is fraction of pairs with a given spin s ($\rho_0$ = ¼ and $\rho_1$ = 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

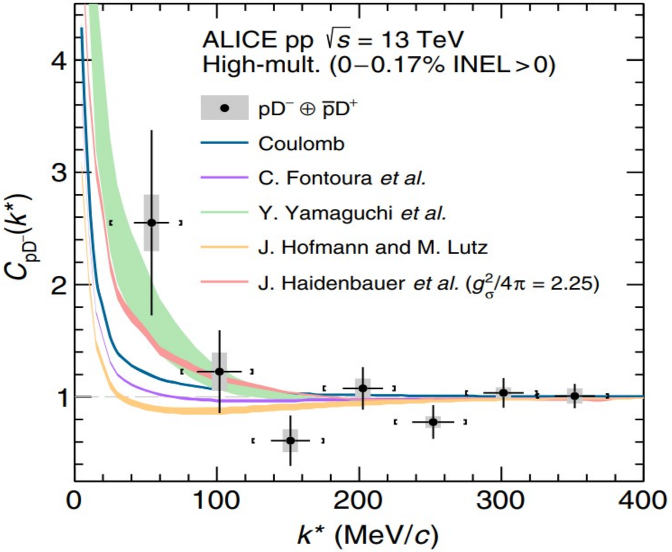
$$dN^3/d^3r^* \quad e^{-r^{*2}/4r_0^2} \qquad (3)$$

where, $r_0$ is the effective radius of the correlated source

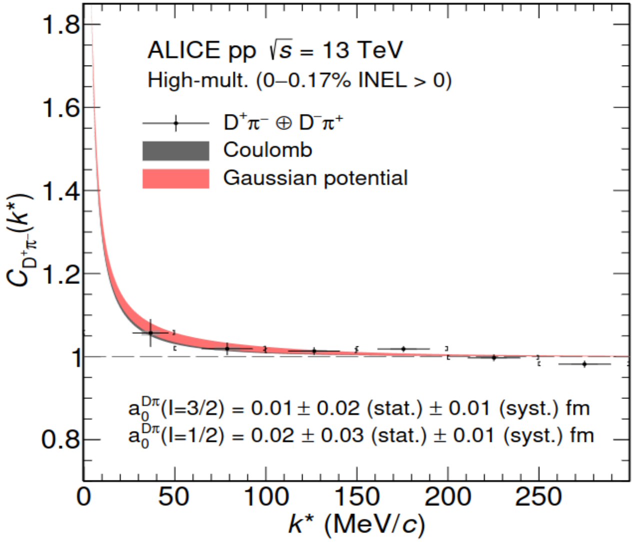
STAR, Phys. Rev. C 74 (2006) 064906

# D-hadron femtoscopy in p-p system at LHC

ALICE, Phys. Rev. D 106 (2022) 052010




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

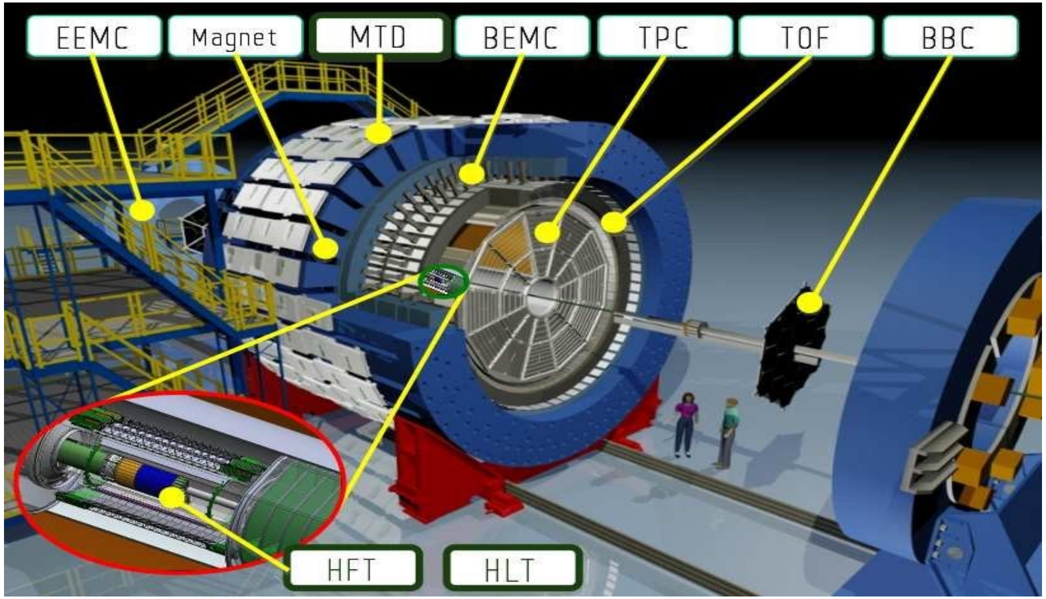



- First studies of D-hadron interactions in pp collisions at $\sqrt{s}$ = 13 TeV by the ALICE experiment
- ALICE data for both p-D and D-π pairs are compatible within (1.1 – 1.5)σ with the theory predictions obtained from the hypothesis of Coulomb only interaction

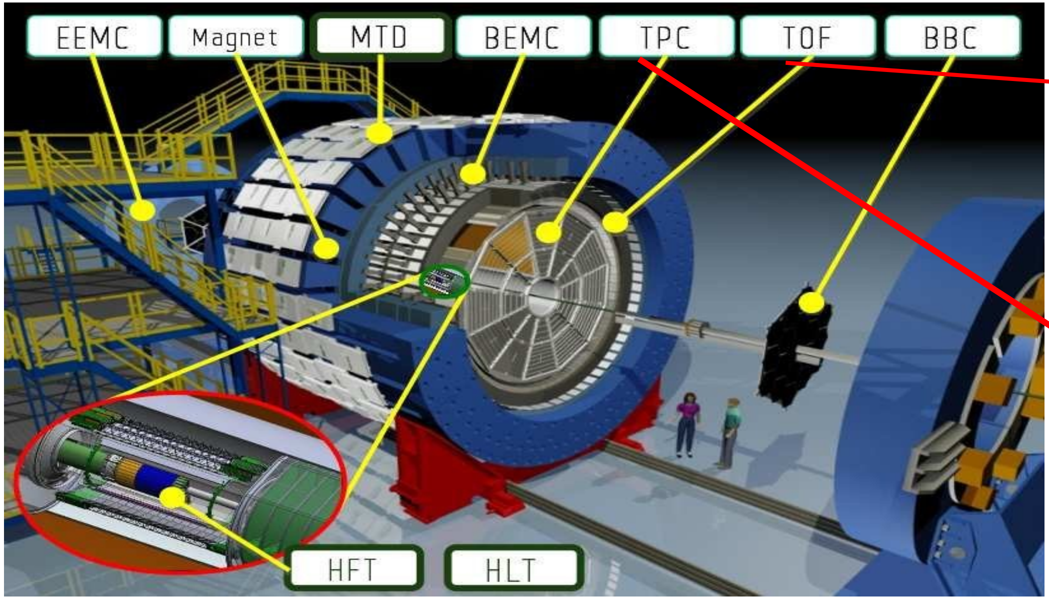
Figure 5: C(k*) for (left) pD and (right) πD pairs and interaction behavior of $D^{\pm}$ at final state

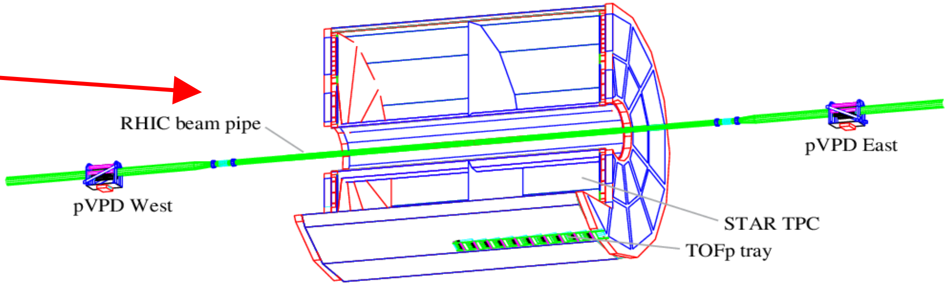
- Small values of $a_{\pi D}$ (scattering length) → ALICE measurement suggests strong interactions in the hadronic phase of heavy-ion collision are small (parameters are consistent with 0)
- Possiblity to learn something new about nuclear medium or QGP by measuring the source size or length of homogeneity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

# ***STAR* (Solenoidal Tracker At RHIC)**

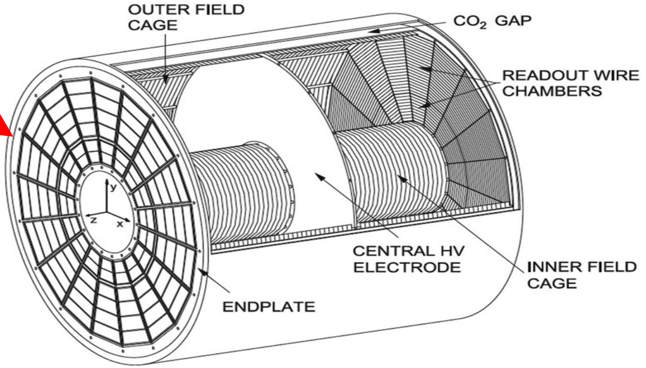


# STAR (Solenoidal Tracker At RHIC)



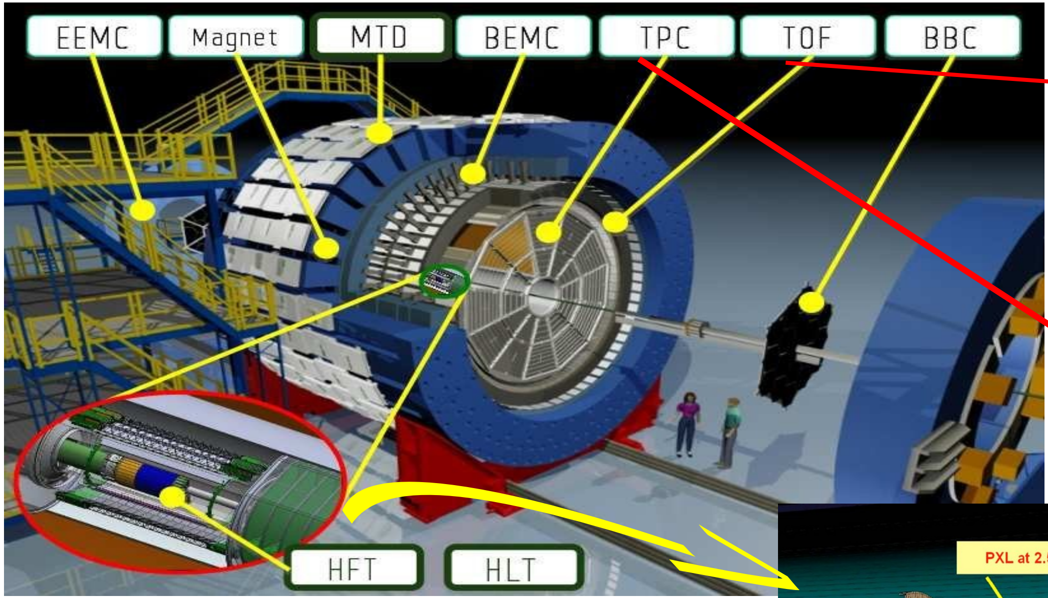

**TOF (Time of Flight)**

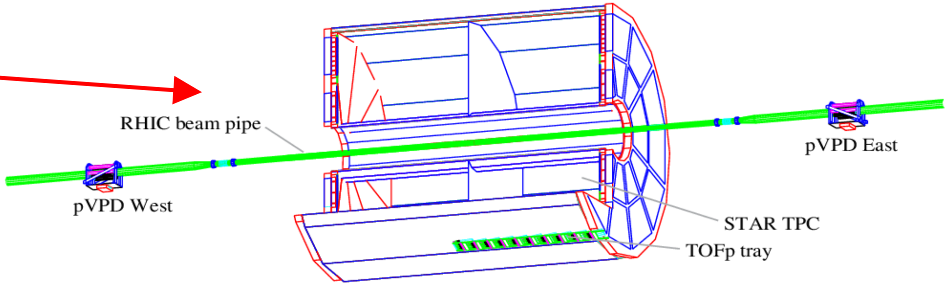



**TPC (Time Projection Chamber)**

- TOF: used for PID
- TPC: used for tracking and PID

# *STAR (Solenoidal Tracker At RHIC)*

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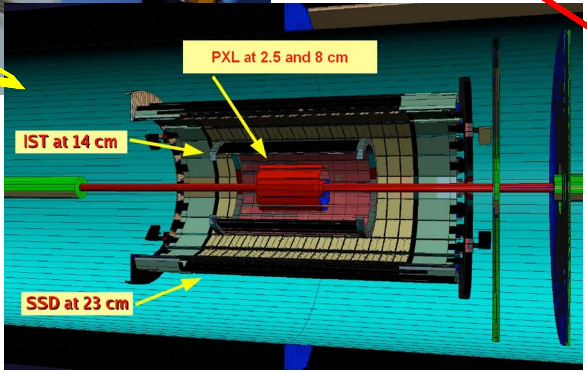
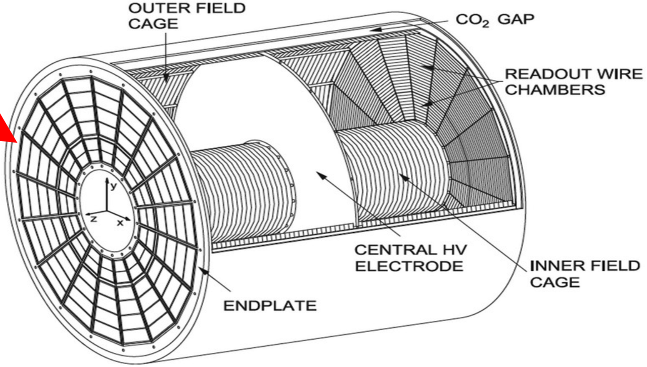



**HFT (Heavy Flavor Tracker)**




**TPC (Time Projection Chamber)**

- 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 $\mu$m

# Particle Identification (PID)

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

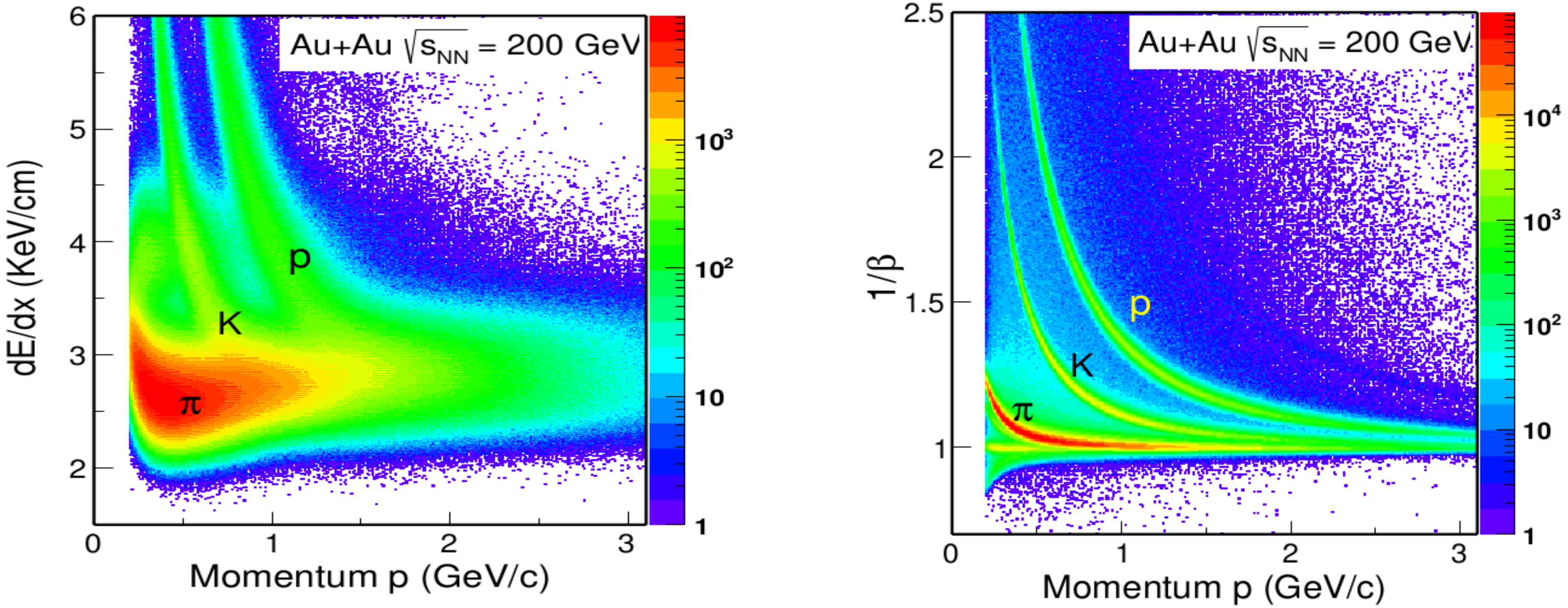
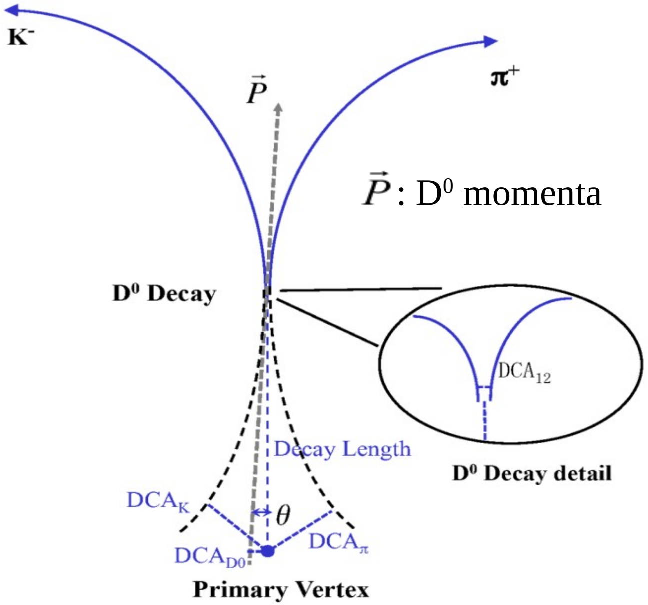



Figure 6: Particle identification using TPC (left) and TOF (right)

- dE/dx bands for $\pi$ and $K$ overlap around 0.7 GeV/c; $K$ and $p$ bands overlap beyond 1.2 GeV/c
- To distinguish between $\pi$, $K$ 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)




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

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

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

## 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) $K^-$ & $\pi^+$ - $DCA_{12}$
  - b) $\pi^+$ & PV - $DCA_\pi$
  - c) $K^-$ & PV - $DCA_K$
  - d) $D^0$ & PV - $DCA_{D0}$
- $\theta$ - angle between $\vec{P}$ & decay length

# $D^0$ invariant mass & signal purity

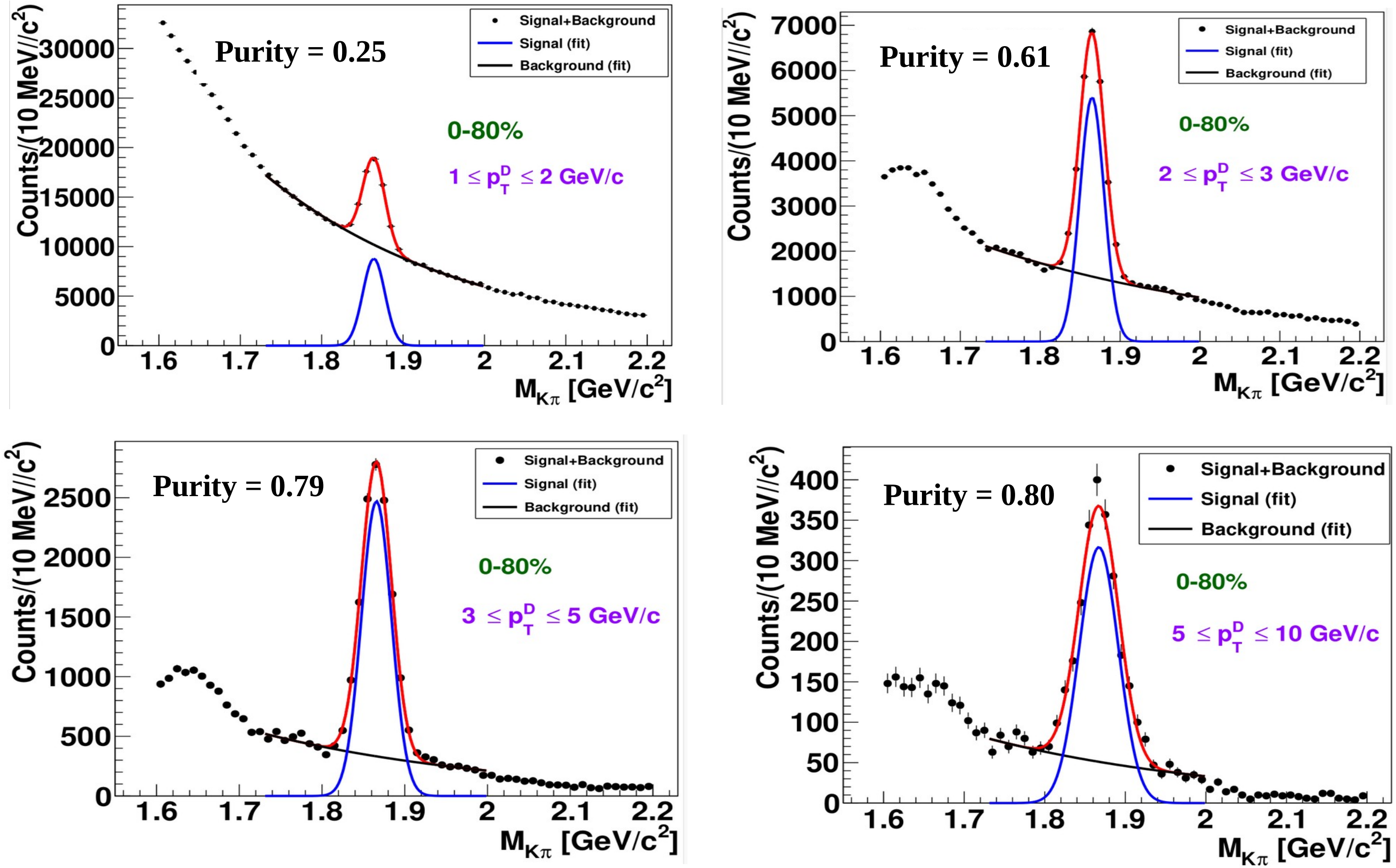



Figure 7: $p_T$ dependence of $K\pi$ invariant mass distribution and $D^0$ signal purity

- Invariant mass distribution of unlike-sign ($K^-\pi^+$) pairs
- 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: $$\frac{Signal}{(Signal + Background)}$$
- Higher $D^0$ signal purity with increasing $p_T$ bin

# Correction of raw correlation function

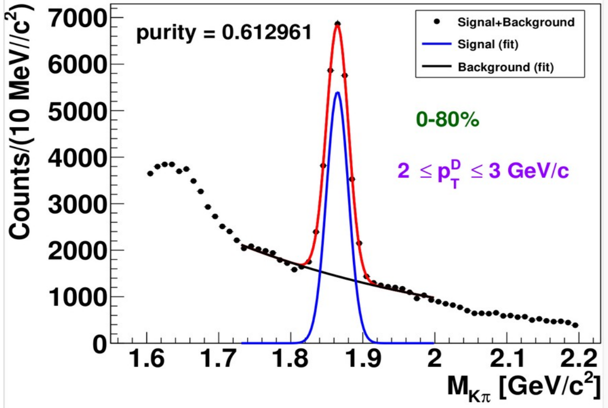
- Correlation function C(k*) for $D^0/\overline{D}^0$ - $h^{+/-}$ pairs: $$C(\vec{k}^*) = \mathcal{N}\frac{A(\vec{k}^*)}{B(\vec{k}^*)}. \quad (4)$$

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

- Pair-purity corrected correlation function: $$C^{corr}_{measured}(k^*) = \frac{C_{measured}(k^*) - 1}{\text{PairPurity}} + 1, \quad (5)$$

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

- $C_{measured}(k^*)$ is the raw correlation function calculated using Eq. (4)
- $D^0$-hadron pair purity correction is required to remove the contribution from combinatorial background under $D^0$ signal peak



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- $C_{\text{measured}}(k^*)$ is the raw correlation function calculated using Eq. (4)
- $D^0$-hadron pair purity correction is required to remove the contribution from combinatorial background under $D^0$ signal peak
- Average $D^0$ purity ~ 37%, 1 GeV/c < $p_T$ < 10 GeV/c
- Kaon purity ~ (97 ± 3 (syst.))%, $p_K$ < 1 GeV/c
- Pion purity ~ (99.5 ± 0.5 (syst.))%, $p_\pi$ < 1 GeV/c
- Proton purity ~ (99.5 ± 0.5 (syst.))%, $p_p$ < 1.2 GeV/c

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

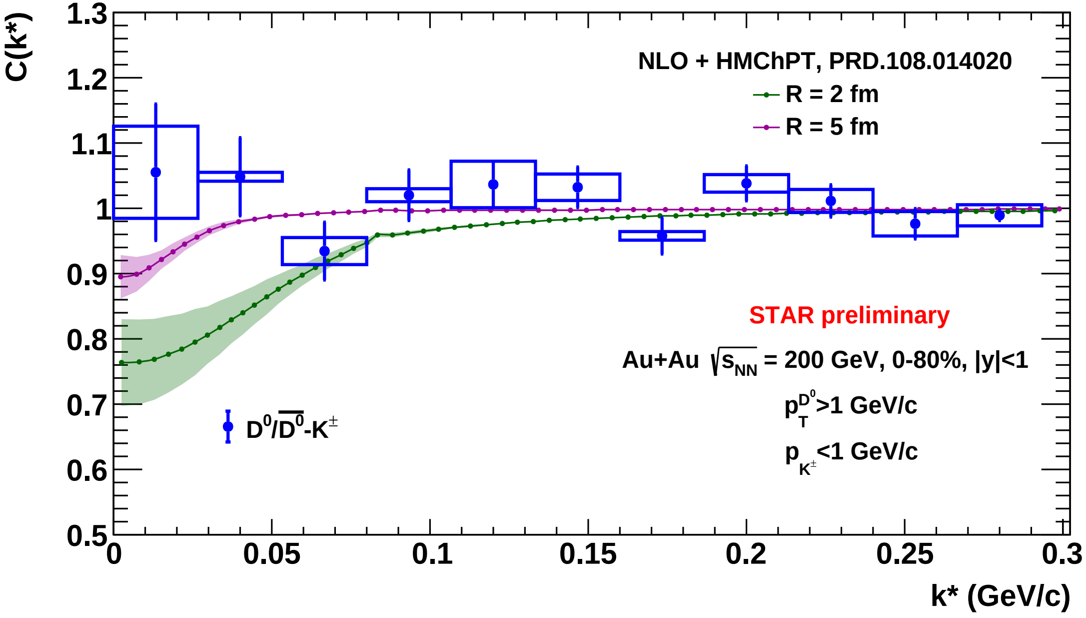


Figure 8: C(k*) for $D^0$-K pairs with systematic uncertainties (boxes). Green and pink bands are theory predictions of C(k*) for $D^0$-$K^+$ channel using source radii of 2 fm and 5 fm respectively

- C(k*) measured for $D^0$-$K^+$, $D^0$-$K^-$, $\overline{D}^0$-$K^+$ and $\overline{D}^0$-$K^-$ 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 $D_{S0}^*(2317)^\pm$ (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: $D^0/\overline{D}^0$-$\pi^{+/-}$ correlation

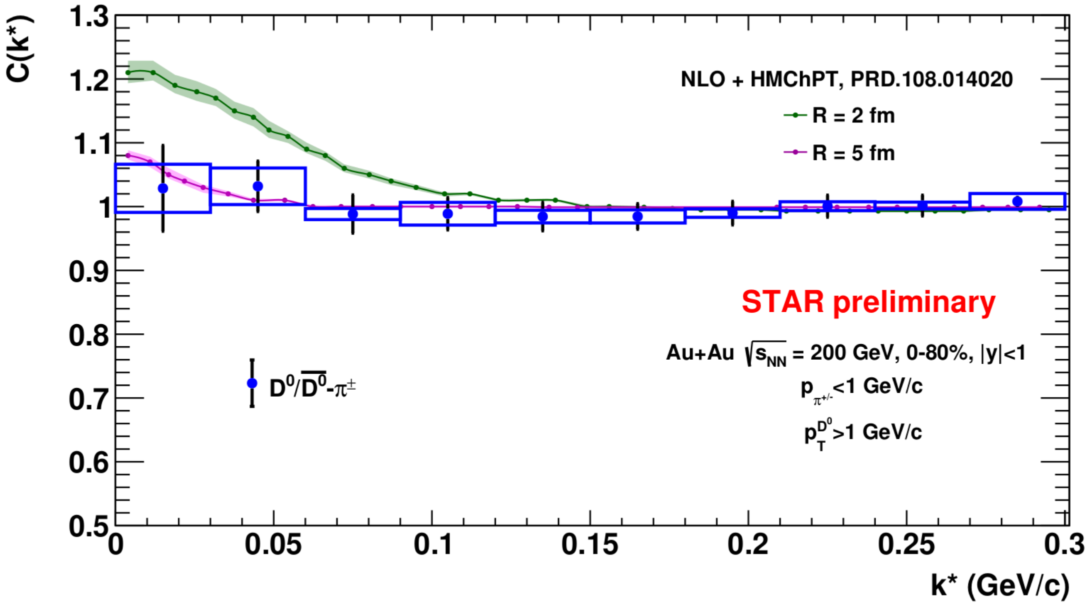


Figure 9: C(k*) for $D^0$-π pairs with systematic uncertainties (boxes). Green and pink bands are theory predictions of C(k*) for D-π channel using source radii of 2 fm and 5 fm respectively

- C(k*) calculated for $D^0$-$\pi^+$, $D^0$-$\pi^-$, $\overline{D}^0$-$\pi^+$ and $\overline{D}^0$-$\pi^-$ with π momentum < 1 GeV/c and $D^0$ $p_T$ > 1 GeV/c
- Theory calculations consist of $D^0$-$\pi^+$ and $D^+$-$\pi^0$ 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

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# *Results: $D^0/\overline{D}^0$-$p^{+/-}$ correlation*

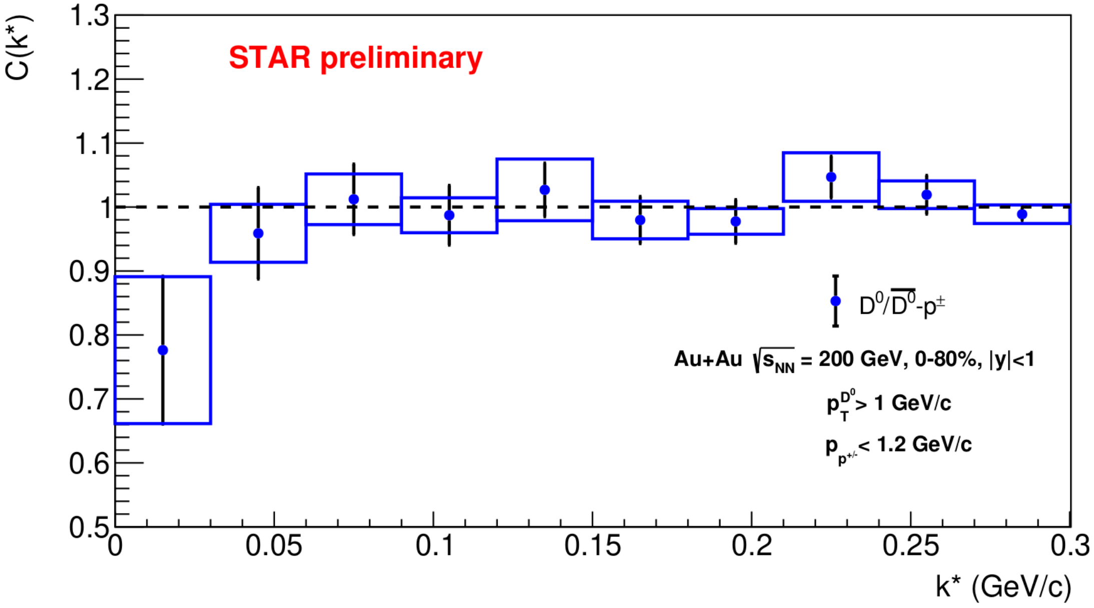



Figure 10: C(k*) for $D^0$-p pairs with systematic uncertainties (blue brackets)

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

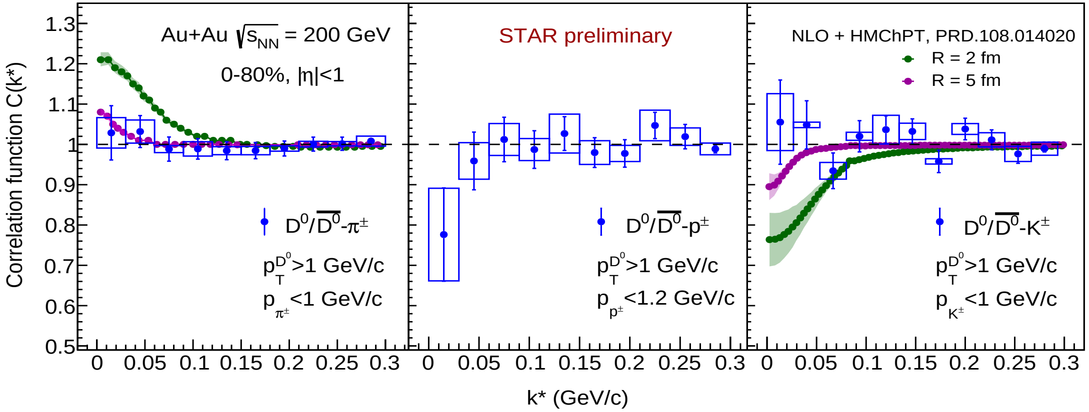
**Predictions?**

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

# 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

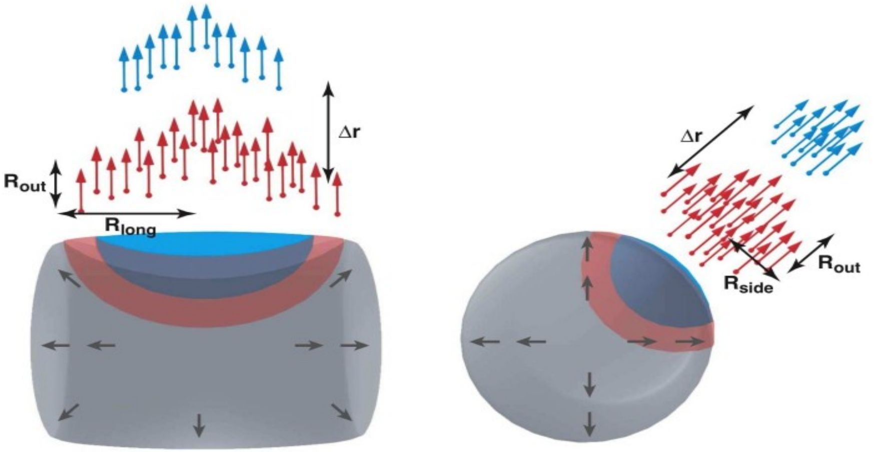



Figure 6: Emission source phase-space

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

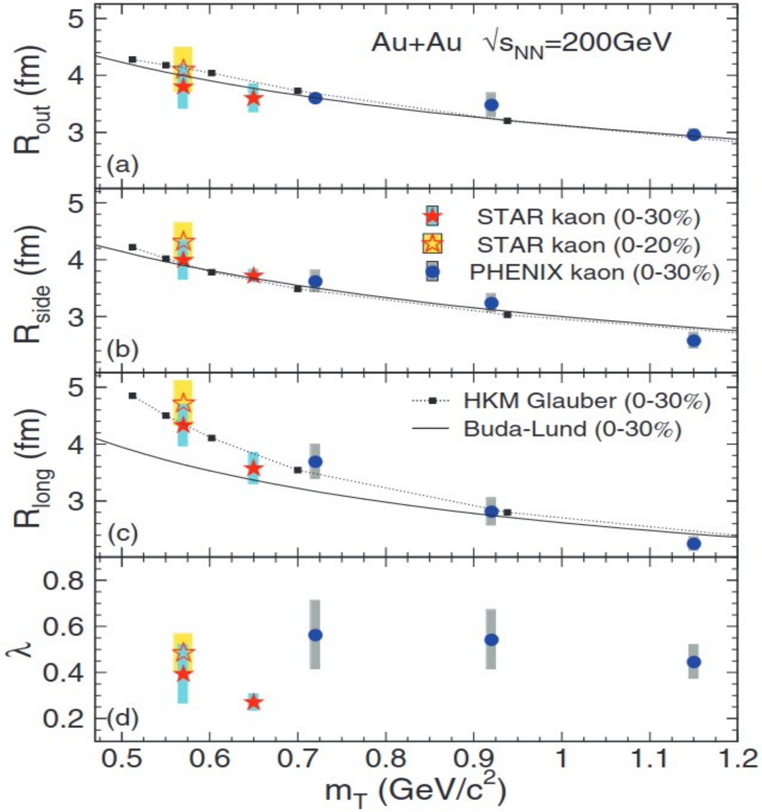



Figure: $m_T$ dependence of 3-D source size using Kaon femtoscopy

# Theory prediction of CF for $D\pi$ channels

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

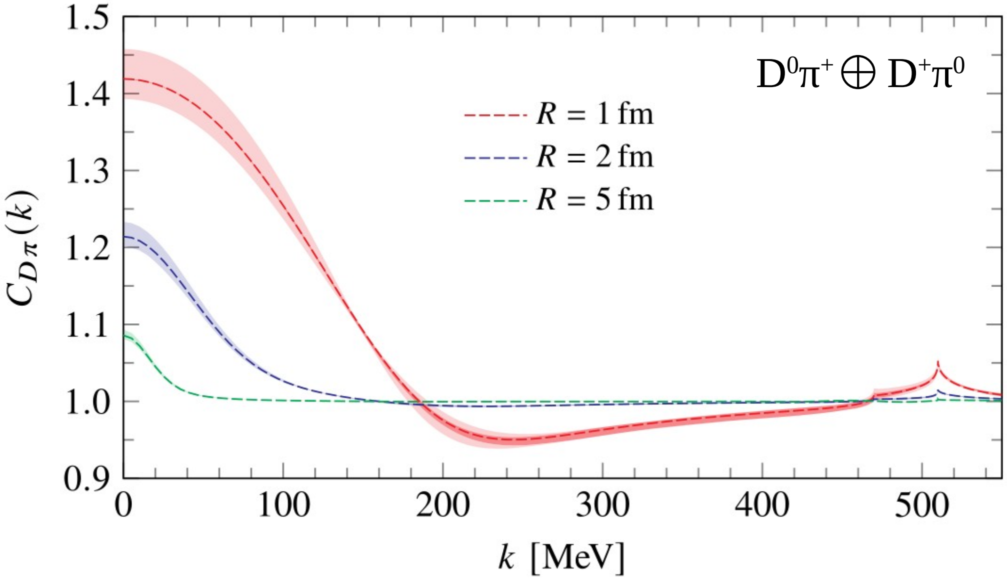



Figure: Correlation functions for Dπ channels predicted for R = 1, 2 and 5 fm sources represented by red, blue and green dashed lines respectively. Corresponding bands show uncertainties with 68% CL

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

- Isospin combinations for *Dπ* channels

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

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

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

- 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

# *Correction of detector effects*

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

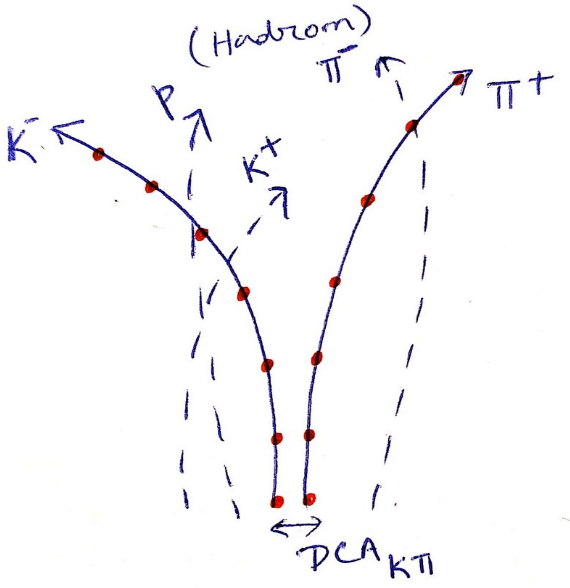
**Hadron (chosen for pairing with $D^0$) track id ≠ Track id of $D^0$ ($\pi^+K^-$)**

**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**

# Selection criteria

## 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.
- $\sqrt{[(V_x)^2 + (V_y)^2]} <= 2.0$

## Track cuts

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

## PID cuts for $\pi$, $K$ & $p$

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