



# Femtoscopic correlations between heavy & light flavor hadrons in heavy-ion collisions by STAR

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# Motivation: charm interaction with QGP

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

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

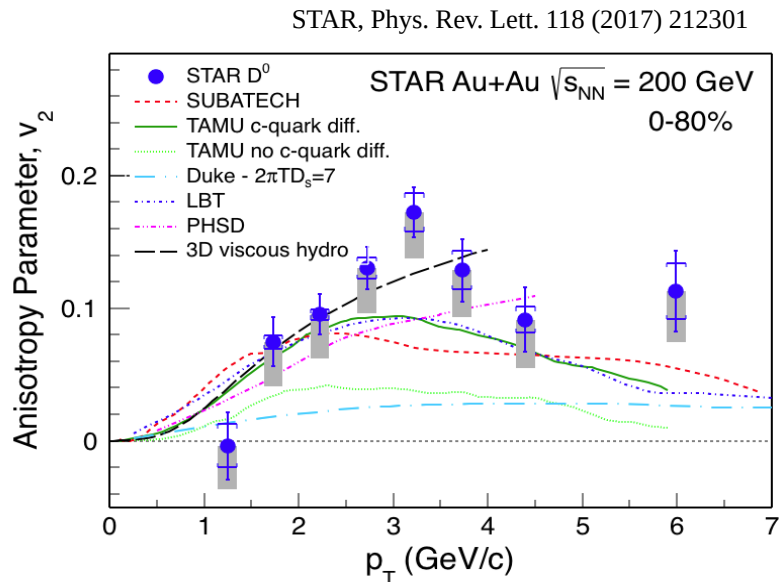


Figure 1:  $D^0$  anisotropy,  $v_2$  vs. transverse momentum,  $p_T$

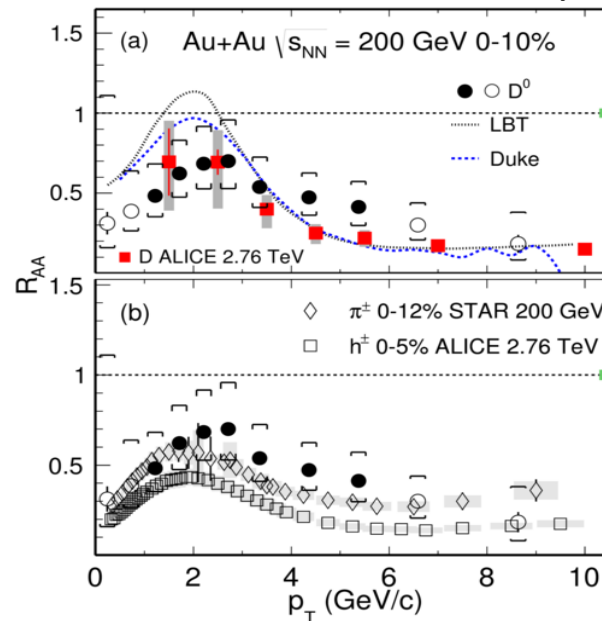


Figure 2: Nuclear modification factor,  $R_{AA}$  (a)  $D^0$ , (b)  $\pi^{+/-}$  &  $h^{+/-}$

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

Strong interaction of charm quarks with the quark-gluon plasma and their (partial) thermalization

- **New observables** to constrain different models and understand D-meson 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**
- **Strength of correlation function is inversely proportional to source radius**

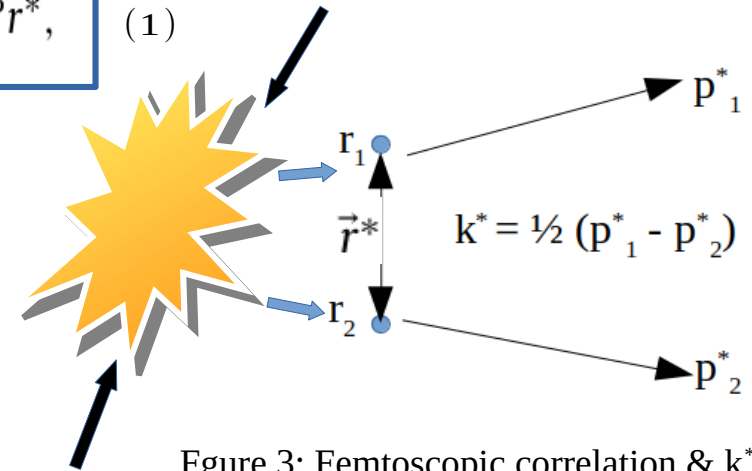


Figure 3: Femtoscopic correlation &  $k^*$  definition

M. Lisa, S. Pratt, R. Soltz, U. Wiedemann,  
Ann. Rev. Nucl. Part. Sci. 55 (2005) 357

# Femtoscscopy with $D^0$ meson

- Study femtoscopic correlations between  $D^0$ -hadron ( $D^0$ - $K^\pm$ ,  $\bar{D}^0$ - $K^\pm$ ,  $D^0$ - $\pi^\pm$ ,  $\bar{D}^0$ - $\pi^\pm$ ,  $D^0$ - $p^\pm$ ,  $\bar{D}^0$ - $p^\pm$ ) pairs at final-state of Heavy-Ion Collisions (HIC)
- Two-particle femtoscopic correlations provide information of interactions b/w the pairs. Also sensitive 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

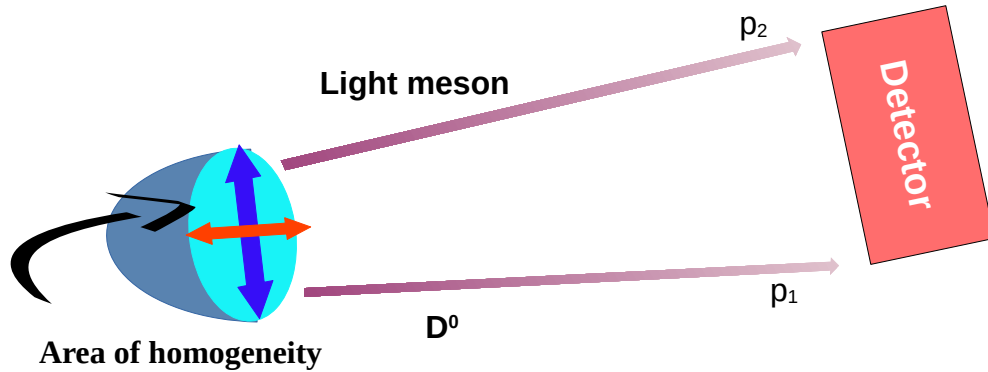


Figure 4: Homogeneity area of  $D^0$ -hadron at final-state of HIC

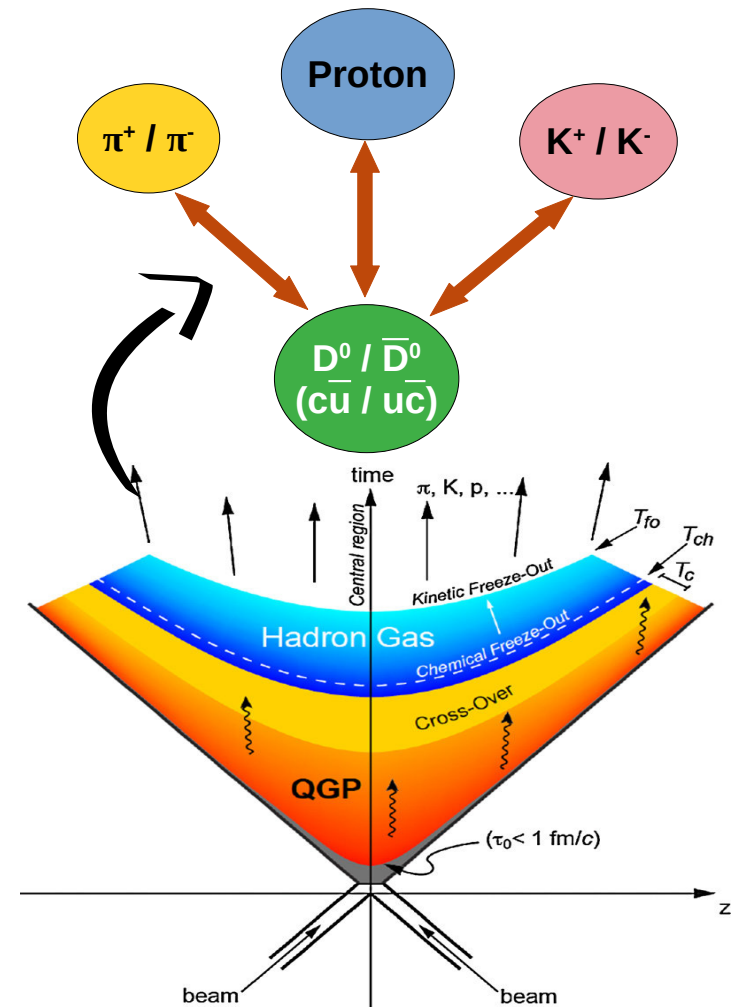


Figure 5:  $D^0/\bar{D}^0$  as a probe to study HIC

# Femtoscopia with $D^0$ meson

- Homogeneity length of  $D^0$ -hadron (ex.  $D^0$ - $\pi$ ) can be expressed as convolution of single-particle femtoscopic source radius of  $D^0$  and  $\pi$ , having Gaussian distributions [Adam Kisiel, Phys. Rev. C **81**, 064906 (2010)]

$$R_{D^0\pi} = \sqrt{R_{D^0}^2 + R_{\pi}^2} \quad (2)$$

- Eq. 2 can be reduced to eq. 3 to achieve femtoscopic source radius of  $D^0$

$$R_{D^0} = \sqrt{R_{D^0\pi}^2 - R_{\pi}^2} \quad (3)$$

where  $R_{D^0\pi}$ ,  $R_{D^0}$  and  $R_{\pi}$  are the femtoscopic source radius of  $D^0$ - $\pi$ ,  $D^0$  and  $\pi$ , respectively. Homogeneity length of identical hadrons ( $\pi$ , K or p) are well observed in previous studies.

- By providing new information about charm meson distribution at the freezeout, femtoscopia in HIC could help constrain models of charm quark propagation in partonic matter

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

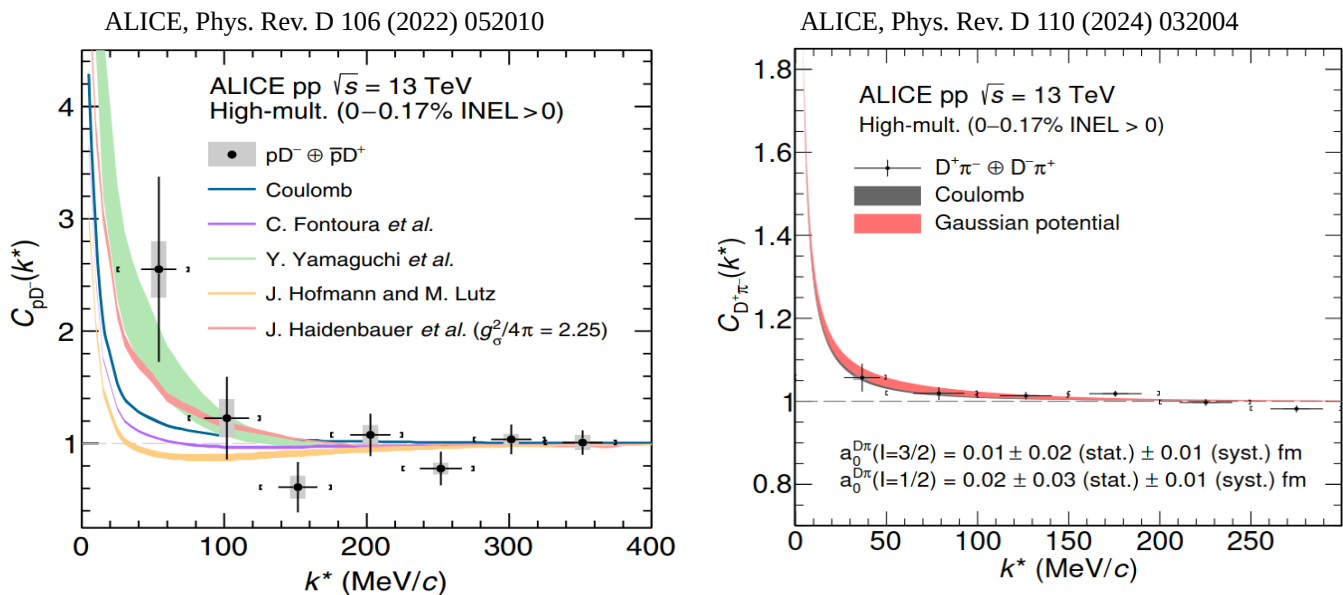
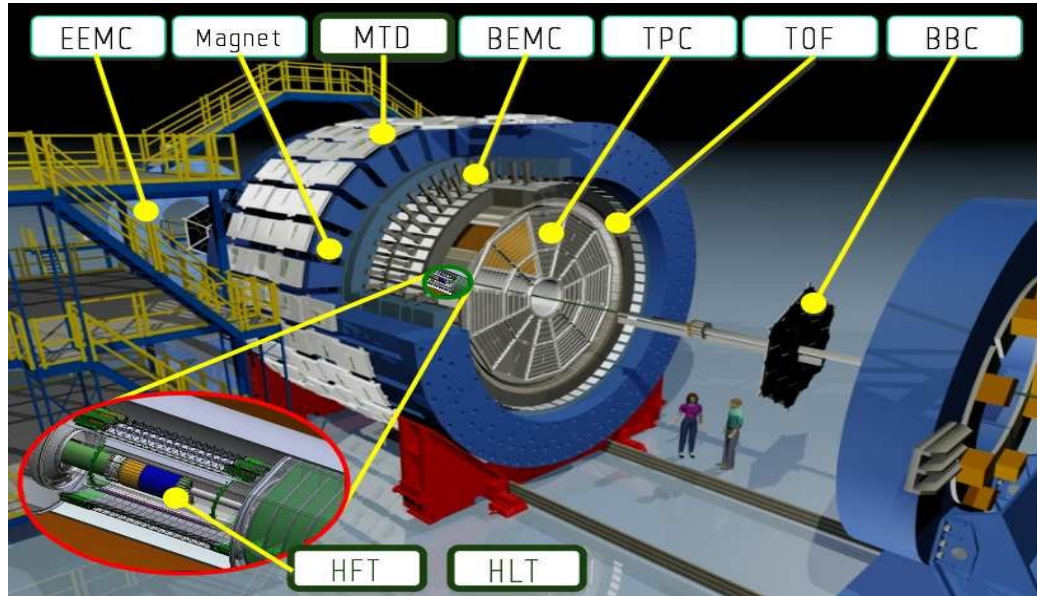


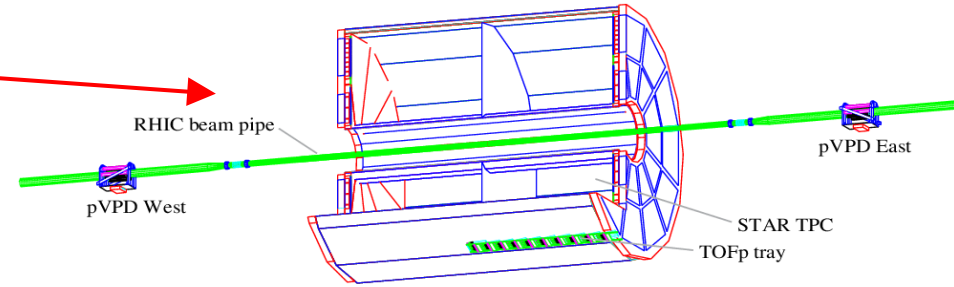
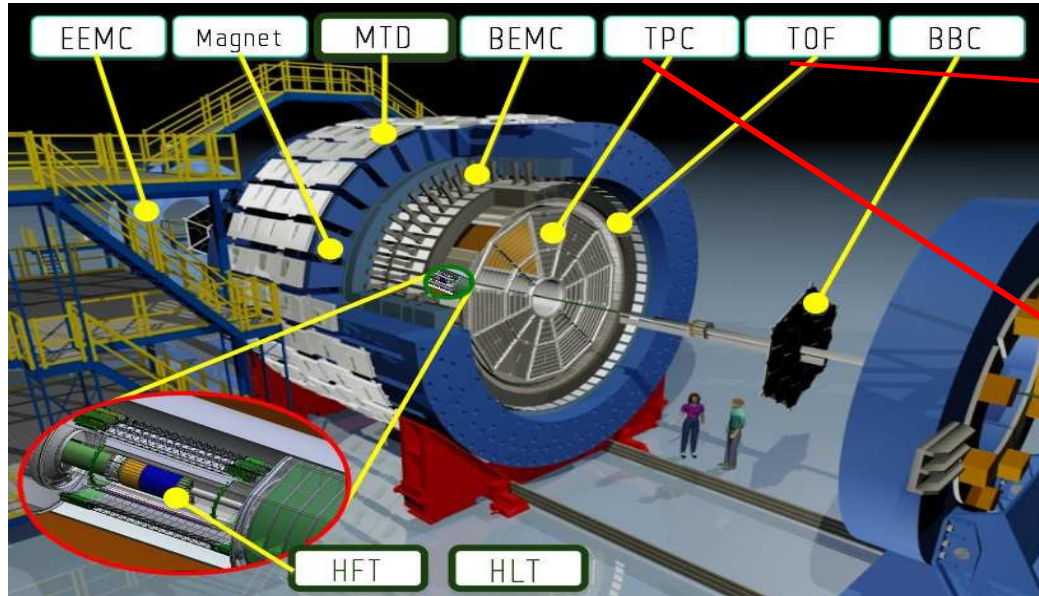
Figure 6:  $C(k^*)$  for (left)  $pD$  and (right)  $\pi D$  pairs and interaction behavior of  $D^\pm$  at final state

- First studies of D-hadron interactions in p-p collisions at  $\sqrt{s} = 13$  TeV by the ALICE experiment
- ALICE data for both p-D and D- $\pi$  pairs are compatible within  $(1.1 - 1.5)\sigma$  with the theory predictions obtained from the hypothesis of Coulomb only interaction
- Small values of  $a_{\pi D}$  (scattering length) → ALICE measurement suggests rescattering probability of charm mesons with light hadrons in the hadronic phase of heavy-ion collision is 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

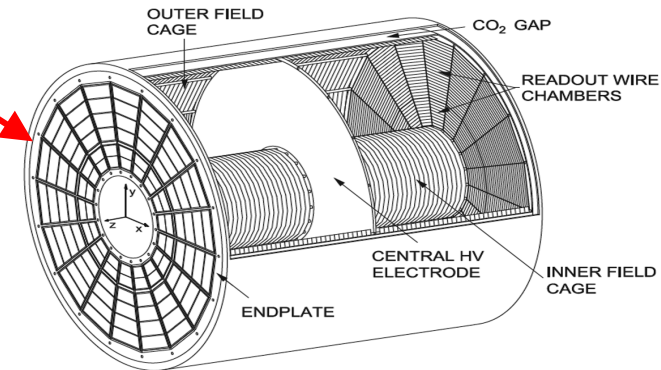
# STAR (Solenoidal Tracker At RHIC)



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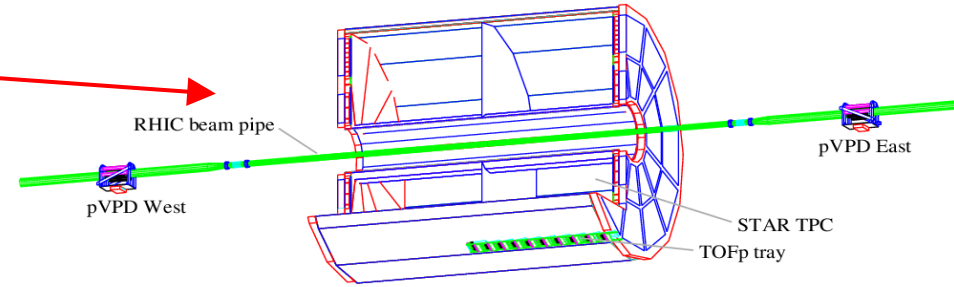
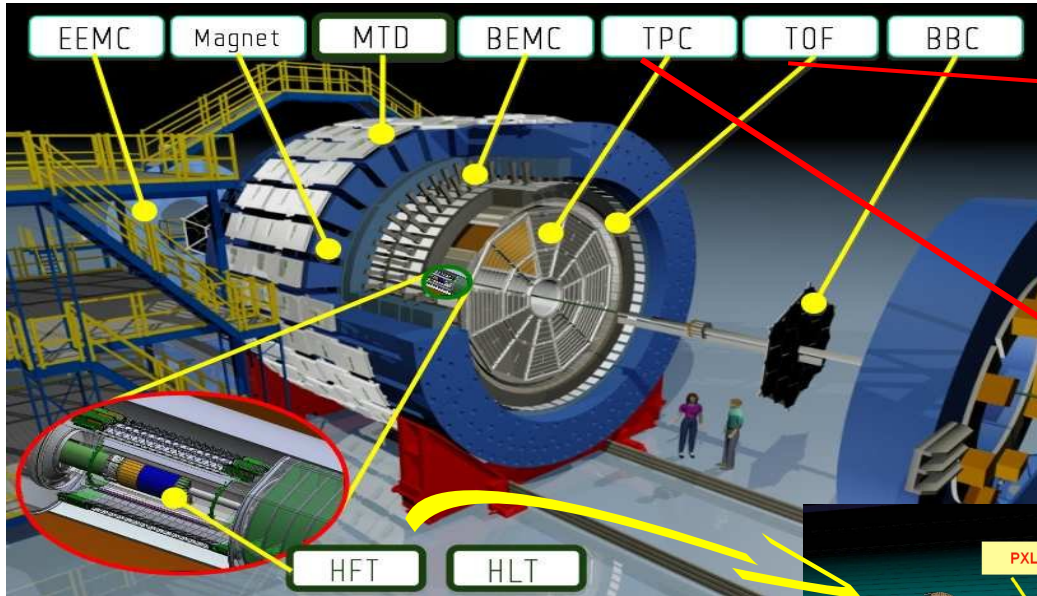
**TOF (Time of Flight)**



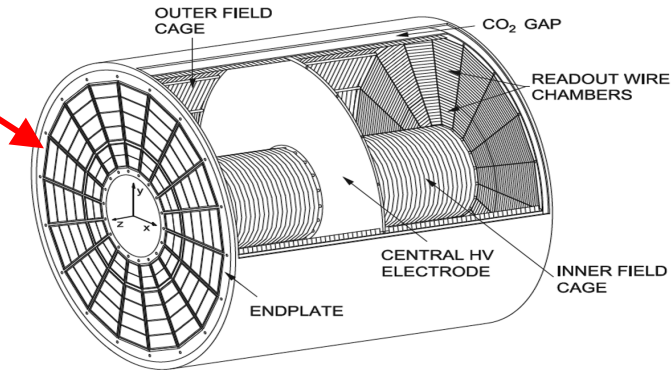
**TPC (Time Projection Chamber)**

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

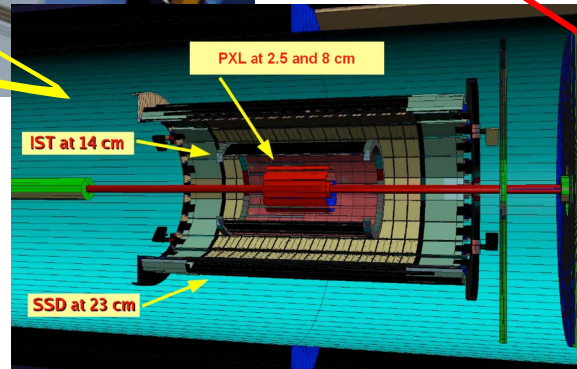
# STAR (Solenoidal Tracker At RHIC)



**TOF (Time of Flight)**



**TPC (Time Projection Chamber)**



**HFT (Heavy Flavor Tracker)**

- TOF: used for PID
- TPC: used for tracking and PID
- HFT (installed in 2014-2016): for  $D^0$  reconstruction which can discriminate secondary vertices from primary vertex with  $30 \mu\text{m}$  resolution

# Particle Identification (PID)

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

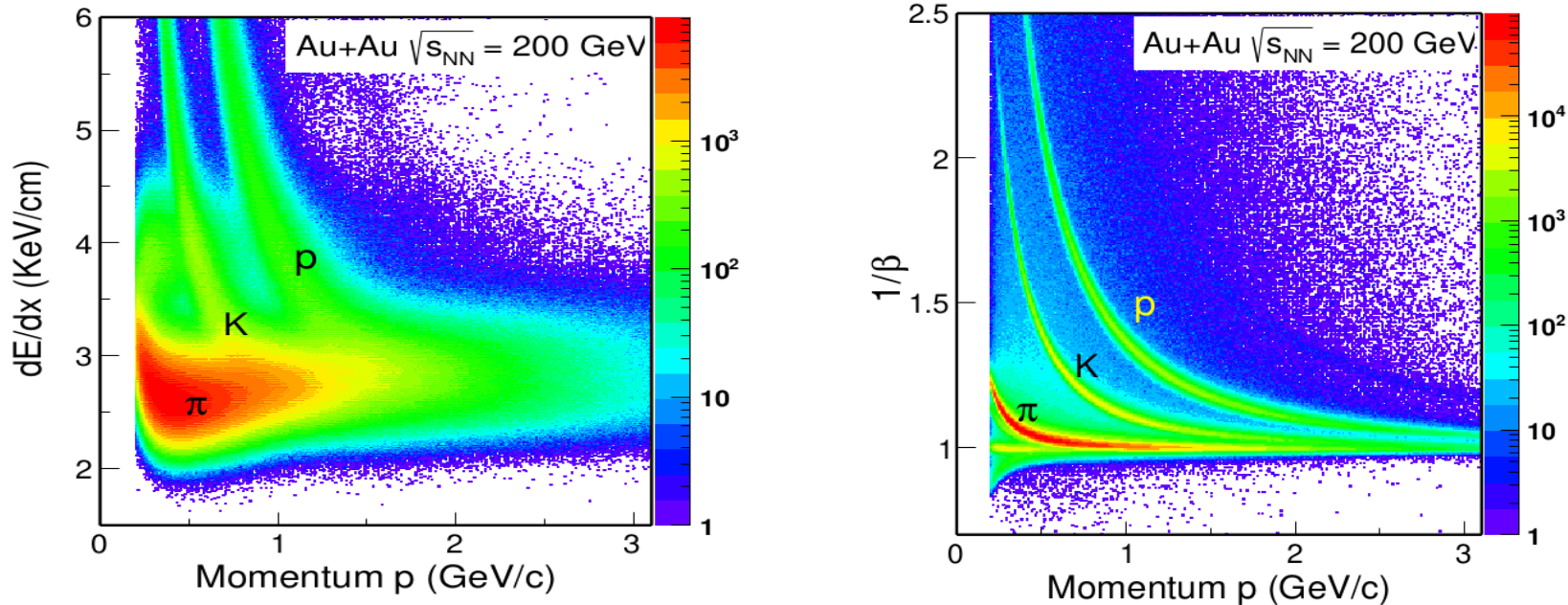
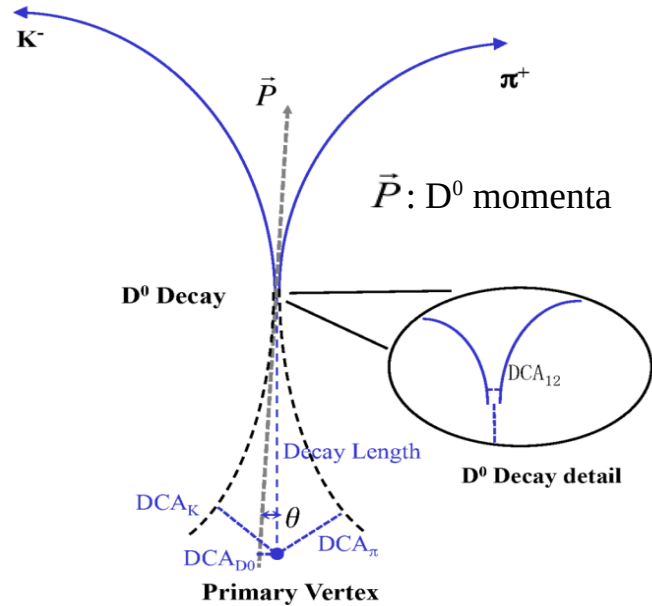


Figure 7: Particle identification using TPC (left) and TOF (right)

- $dE/dx$  bands for  $\pi$  and  $K$  overlap around  $p = 0.7$  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 is required

# Dataset and $D^0$ meson reconstruction

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



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

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

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

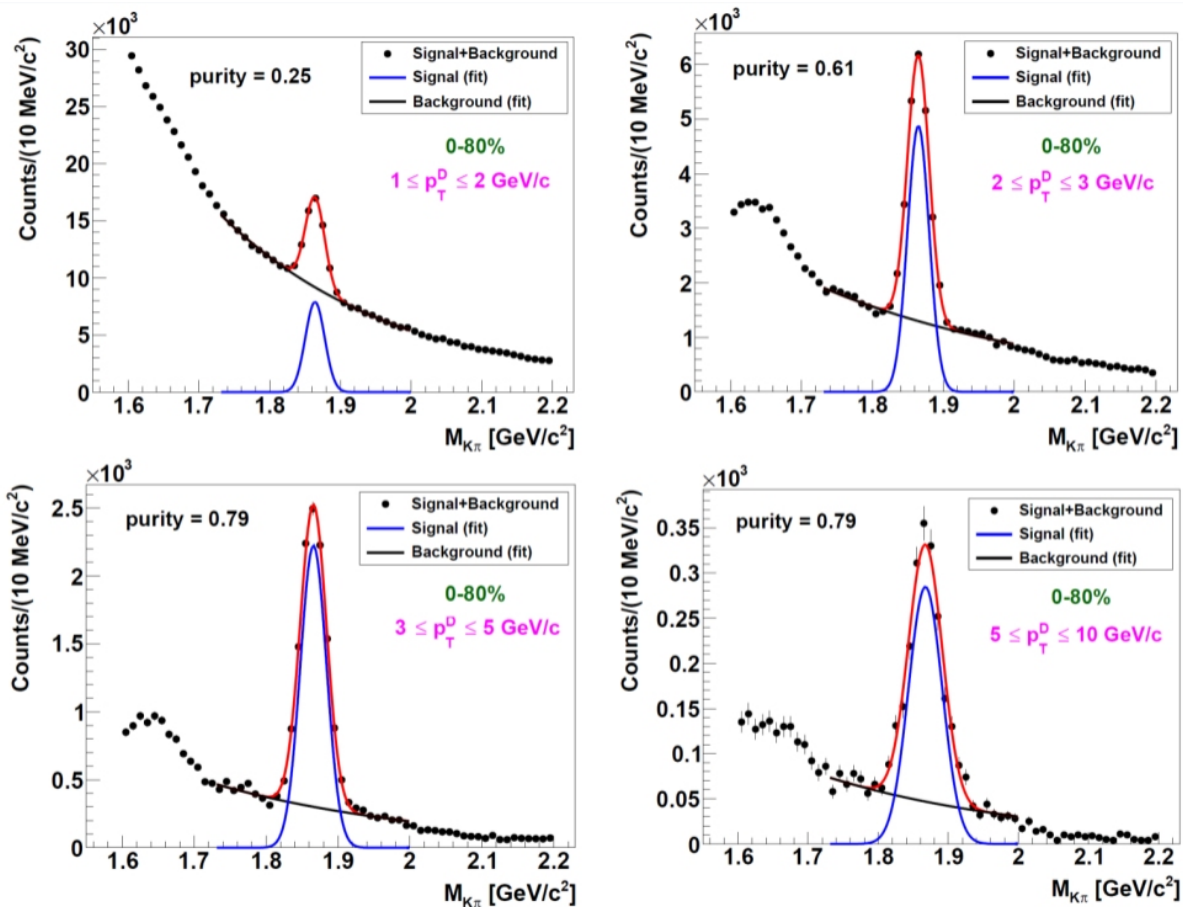
## Dataset:

- 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)  $K^-$  &  $\pi^+$  -  $DCA_{12}$
  - 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



- Invariant mass distribution of unlike-sign ( $K^-\pi^+$ ) pairs
- Invariant mass range for  $D^0$  signal: 1.82 – 1.91 GeV/c<sup>2</sup>
- $D^0$  signal and background are fitted with Gaussian and exponential functions, respectively
- $D^0$  purity: 
$$\frac{\text{Signal}}{\text{Signal} + \text{Background}}$$
- Higher  $D^0$  signal purity with increasing  $p_T$

Figure 8:  $p_T$  dependence of  $K\pi$  invariant mass distribution and  $D^0$  signal purity

# Correction of raw correlation function

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

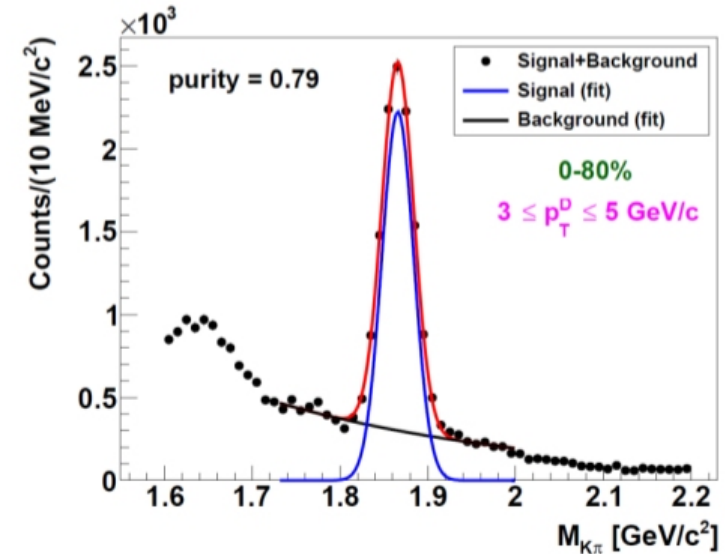
$A(\vec{k}^*)$  and  $B(\vec{k}^*) \rightarrow k^*$  distribution for correlated and uncorrelated pairs;  $\mathcal{N} \rightarrow$  normalization factor

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

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

→  $C_{\text{measured}}(k^*)$  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



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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  $\sim 37\%$ ,  $1 \text{ GeV}/c < p_T < 10 \text{ GeV}/c$
- 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

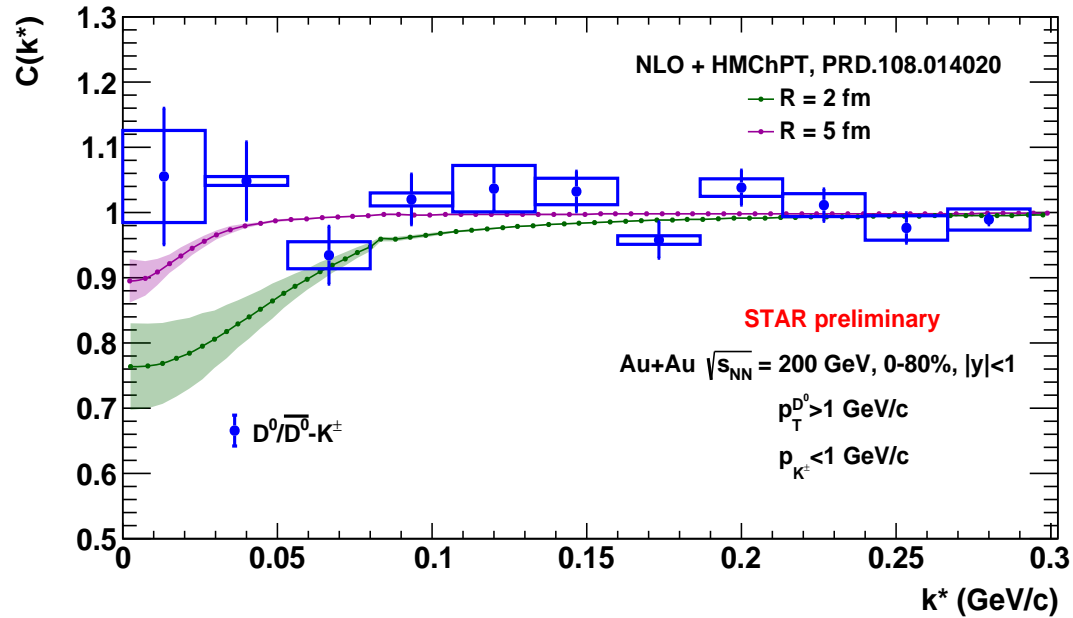


Figure 9:  $C(k^*)$  for  $D^0$ - $K$  pairs with systematic uncertainties (boxes) and theory predictions (bands) of  $C(k^*)$  for  $D^0$ - $K^+$  channel using source radii of 2 fm and 5 fm, respectively

- $C(k^*)$  measured for mixture of  $D^0$ - $K^+$ ,  $D^0$ - $K^-$ ,  $\bar{D}^0$ - $K^+$  and  $\bar{D}^0$ - $K^-$  with  $p_K < 1$  GeV/c and  $D^0 p_T > 1$  GeV/c
- Theory predictions are provided 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 are consistent with theoretical model prediction with emission source size of 5 fm or larger within uncertainty

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

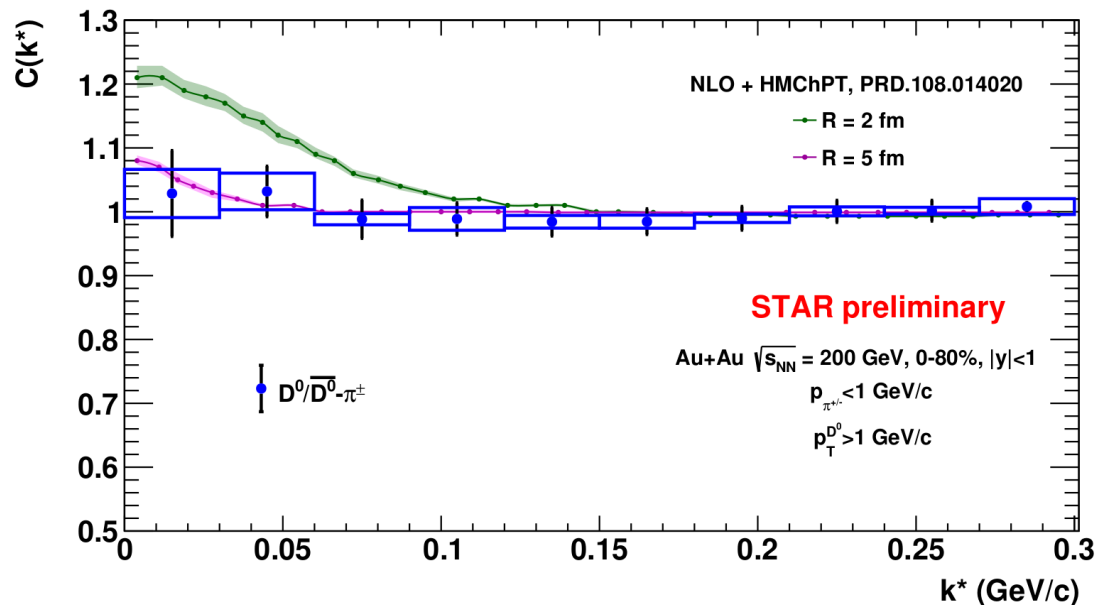


Figure 10:  $C(k^*)$  for  $D^0$ - $\pi$  pairs with systematic uncertainties (boxes) and theory predictions (bands) of  $C(k^*)$  for  $D$ - $\pi$  channel using source radii of 2 fm and 5 fm, respectively

- $C(k^*)$  measured for mixture of  $D^0$ - $\pi^+$ ,  $D^0$ - $\pi^-$ ,  $\bar{D}^0$ - $\pi^+$  and  $\bar{D}^0$ - $\pi^-$  with  $p_\pi < 1$  GeV/c and  $D^0 p_T > 1$  GeV/c
- Theory calculations for  $D^0$ - $\pi^+$  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: $D^0/\bar{D}^0$ - $p^{+/-}$ correlation

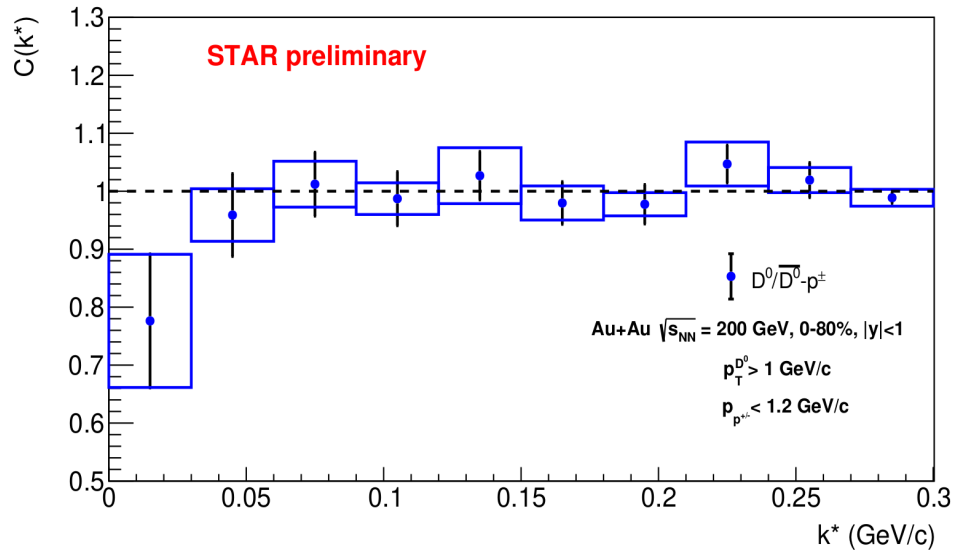


Figure 11:  $C(k^*)$  for  $D^0$ - $p$  pairs with systematic uncertainties (blue box)

→  $C(k^*)$  contains mixture of  $D^0$ - $p^+$ ,  $D^0$ - $p^-$ ,  $\bar{D}^0$ - $p^+$  and  $\bar{D}^0$ - $p^-$  with  $p_p < 1.2$  GeV/c and  $D^0 p_T > 1$  GeV/c

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

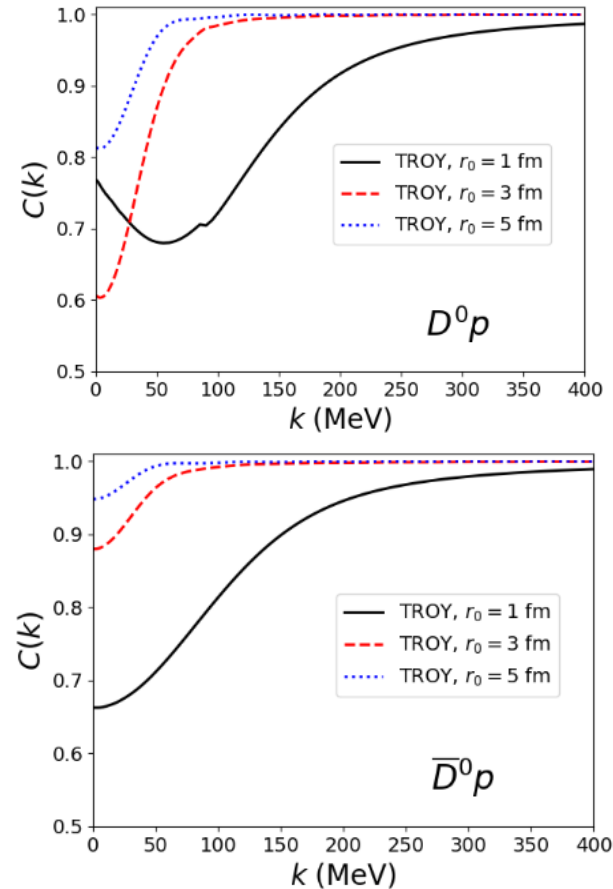
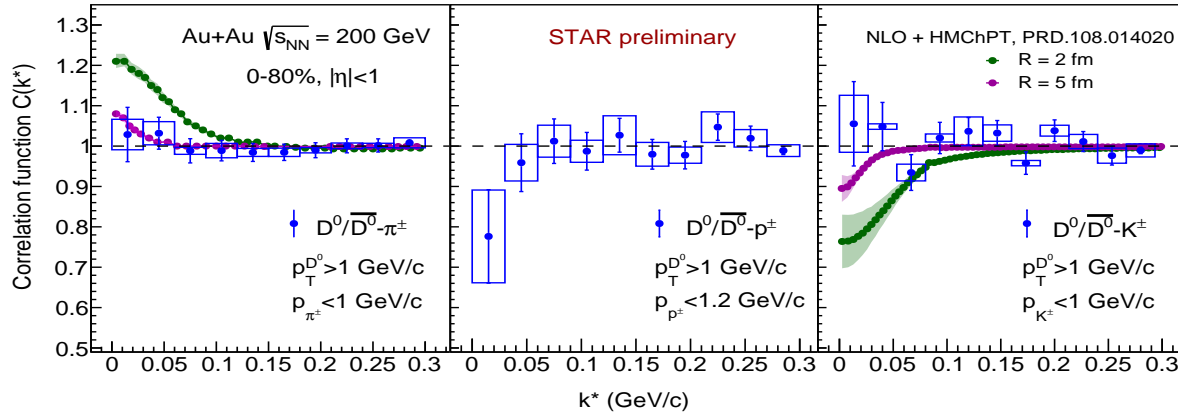


Figure 12: Source radii dependence of  $C(k)$  for  $D^0$ - $p$  &  $\bar{D}^0$ - $p$

<https://arxiv.org/pdf/2507.07864>

# Summary

- D-meson femtoscopy is applicable to probe the interaction behavior of charmed hadron and the phase space geometry of emission source
- Correlation studies between  $D^0/\bar{D}^0$  and charged hadrons provide consistent results with no significant correlations. STAR data are in agreement with theory predictions of large emission source size ( $\sim 5$  fm or larger)



## Future plan:

- Source radius calculation using Lednicky–Lyuboshitz model
- Achieve the homogeneity length of  $D^0$



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# Freeze-out dynamics

## → Properties of nuclear medium

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

### → Local thermal equilibrium

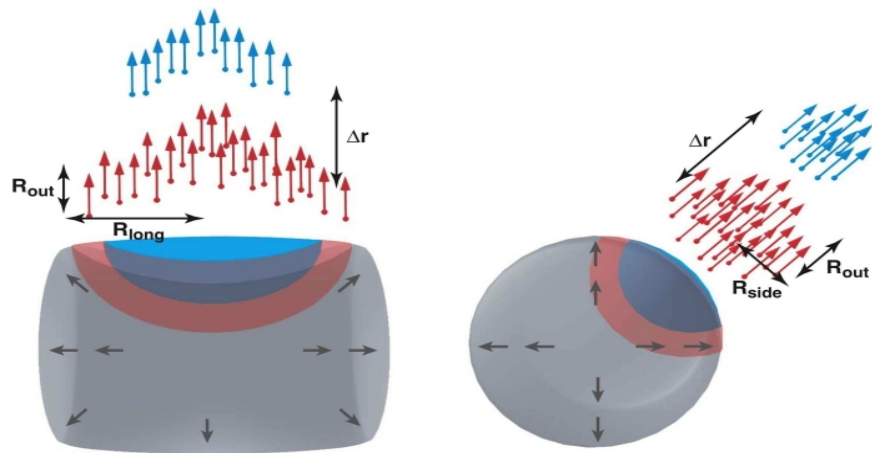


Figure 6: Emission source phase-space

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

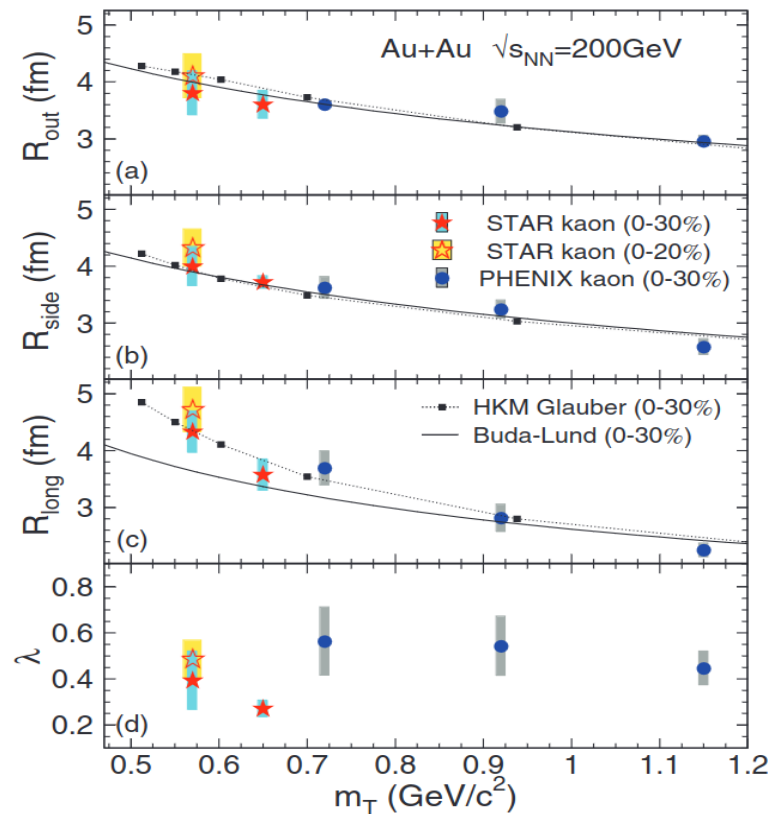


Figure:  $m_T$  dependence of 3-D source size using Kaon femtoscopy

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

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

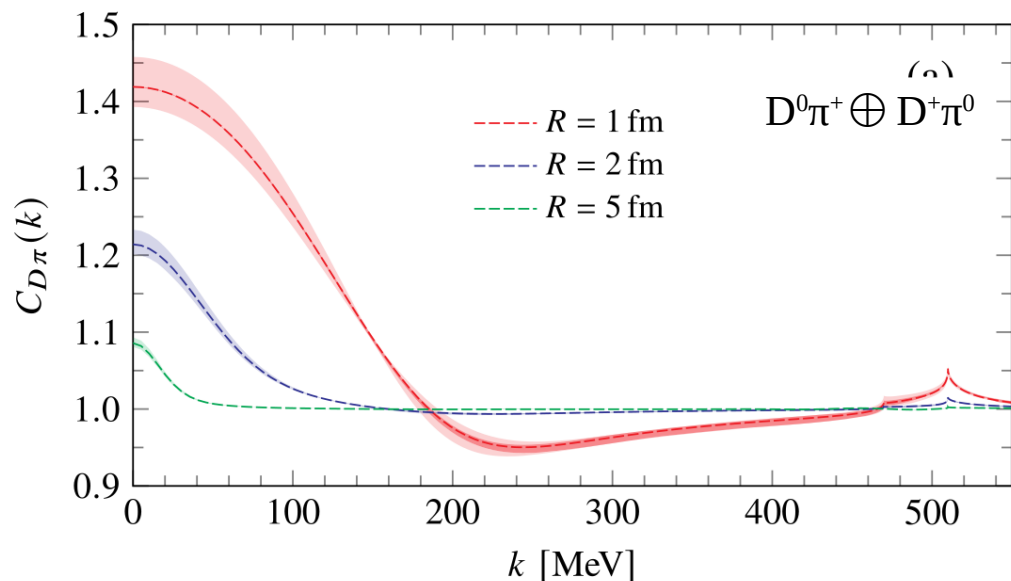


Figure: Correlation functions for  $D\pi$  channels predicted for  $R = 1, 2$  and  $5$  fm sources represented by red, blue and green dashed lines respectively. Corresponding bands show uncertainties with 68% CL

→ 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

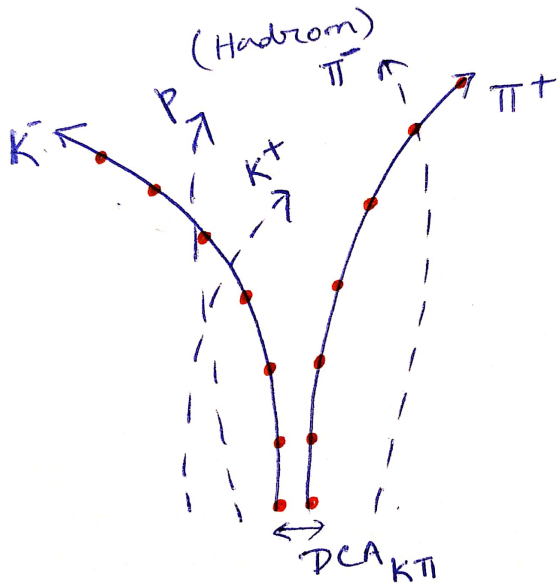
**Hadron (chosen for pairing with  $D^0$ ) track id  $\neq$  Track id of  $D^0$  ( $\pi^+K^-$ )**

**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:

- $\delta r(i) < \text{mean TPC distance separation}$  → '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.
- $\sqrt{[(V_x)^2 + (V_y)^2]} \leq 2.0$

## $D^0$ daughter track cuts

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

## Hadron selection cuts

- $p_T > 0.15$  GeV/c
- $|DCA| > 3.0$  cm.
- $n\text{HitsFit} \geq 20$
- $|\eta| \leq 1.0$

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

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

# Extraction of interaction parameters

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

$$C(k^*) = 1 + \sum_s \rho_s \left[ \frac{1}{2} \left| \frac{f^s(k^*)}{r_0} \right|^2 \left( 1 - \frac{d_0^s}{2\sqrt{\pi}r_0} \right) + \frac{2\Re(f^s(k^*))}{\sqrt{\pi}r_0} F_1(Qr_0) - \frac{\Im(f^s k^*)}{r_0} F_2(Qr_0) \right] \quad (6)$$

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  $s$  ( $\rho_0 = 1/4$  and  $\rho_1 = 3/4$ )

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

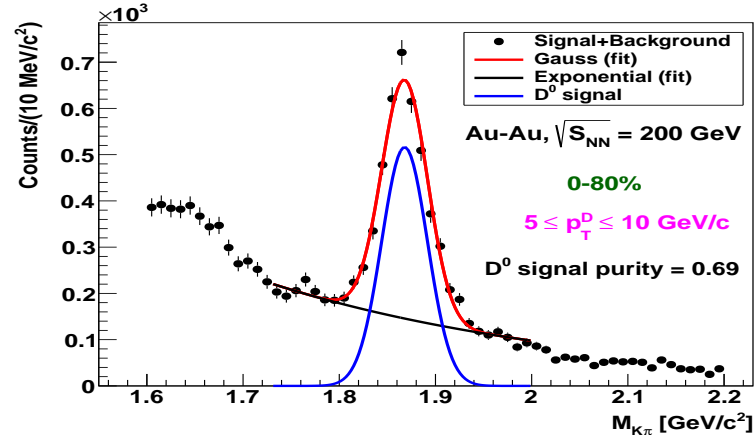
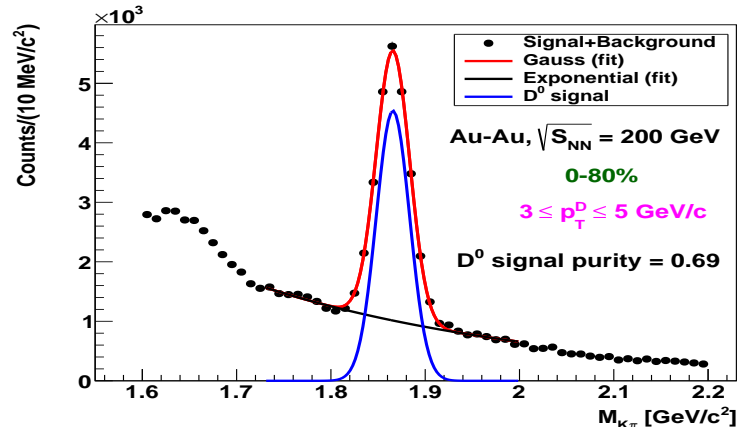
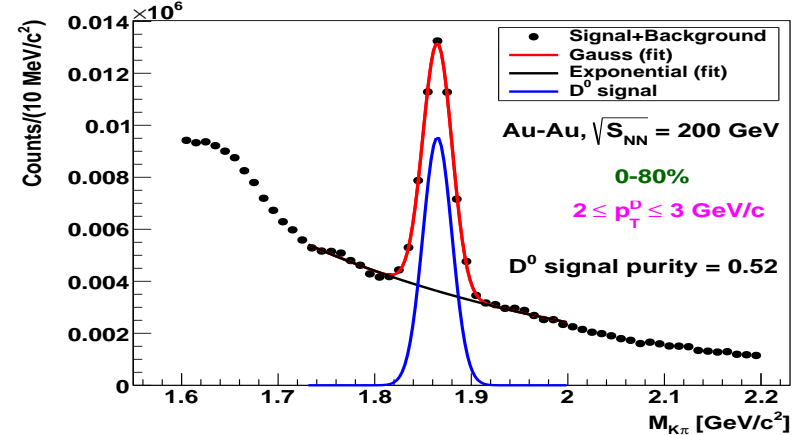
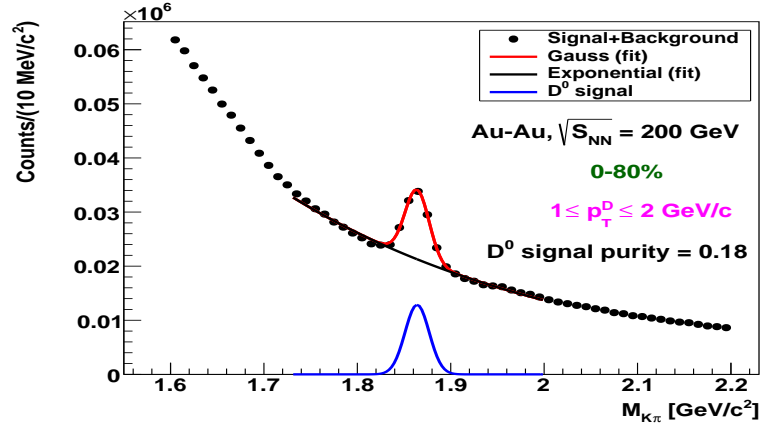
This model assumes, average separation vector ( $\vec{r}^*$ ) from eq. (1), follows Gaussian distribution

$$dN^3 / d^3 r^* e^{-r^{*2} / 4r_0^2} \quad (7)$$

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

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# $D^0$ signal with loose cut & its purity (Run 2014)



# $D^0$ signal with tight cut & its purity (Run 2014)

