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

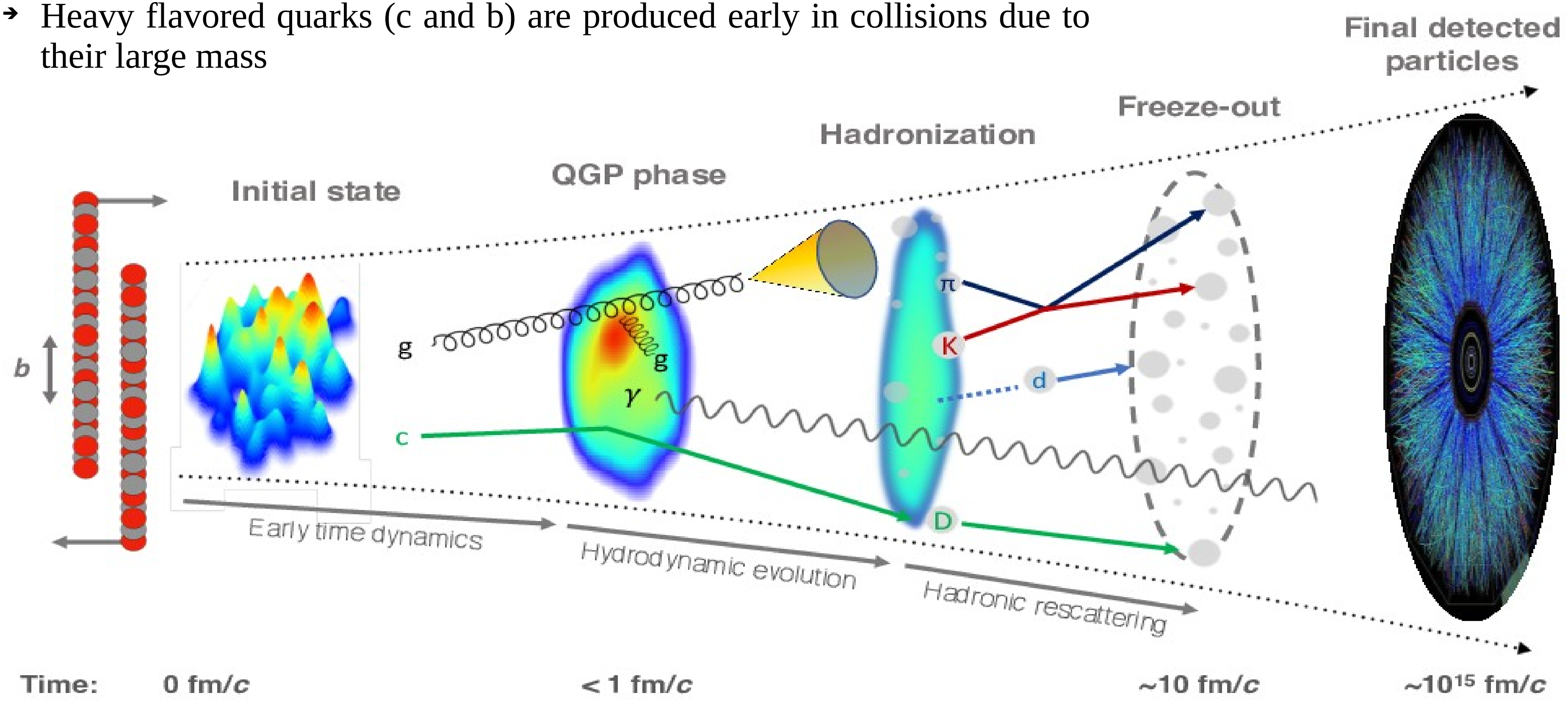


Figure 1: Evolution of heavy-ion collision

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

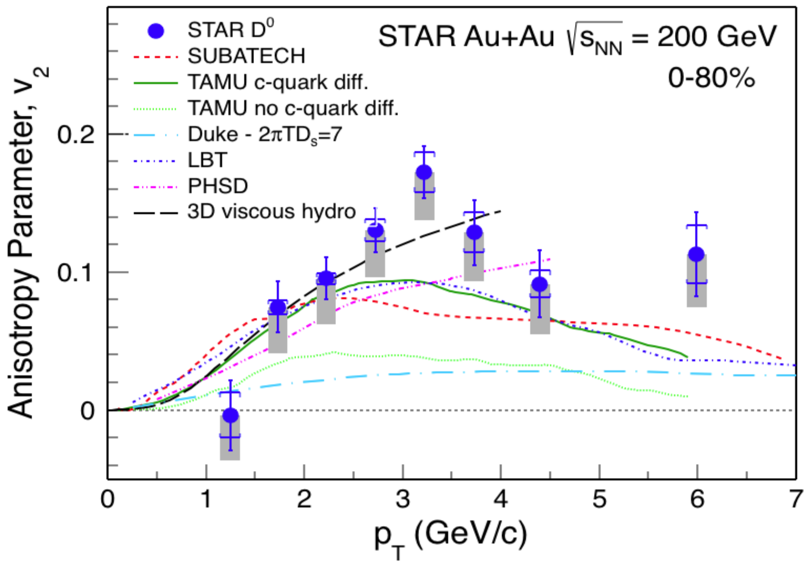


Figure 2: D^0 anisotropy vs. transverse momentum

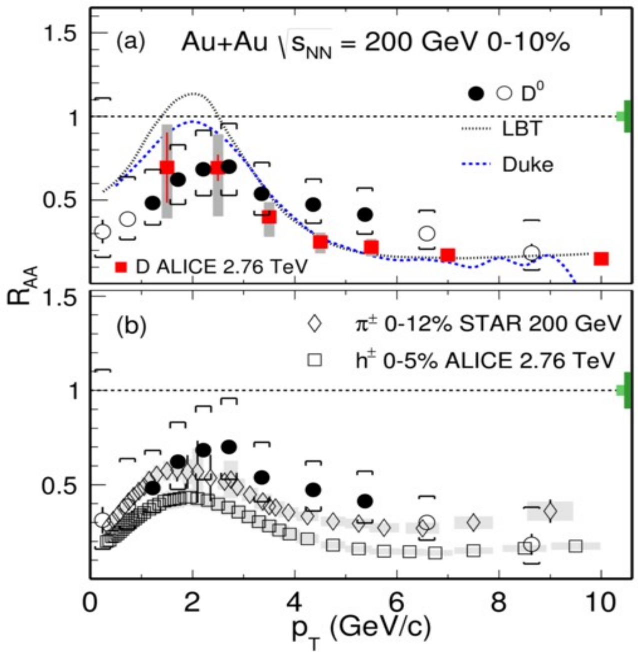


Figure 3: Nuclear modification factor, R_{AA} (a) D^0, (b) $\pi^{+/-}$ & $h^{+/-}$

- 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

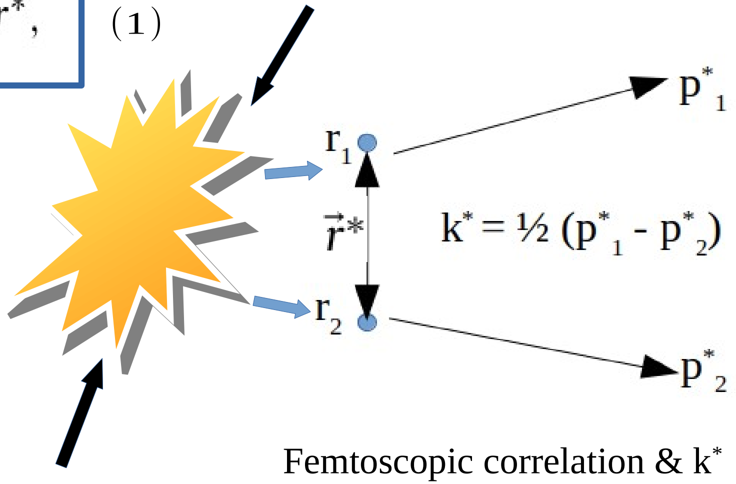
- Femtoscopic correlations are observed between pair of particles with low relative momentum
- Correlations are measured as a function of the reduced momentum difference (k^*) of the pair of particles in rest frame

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

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**

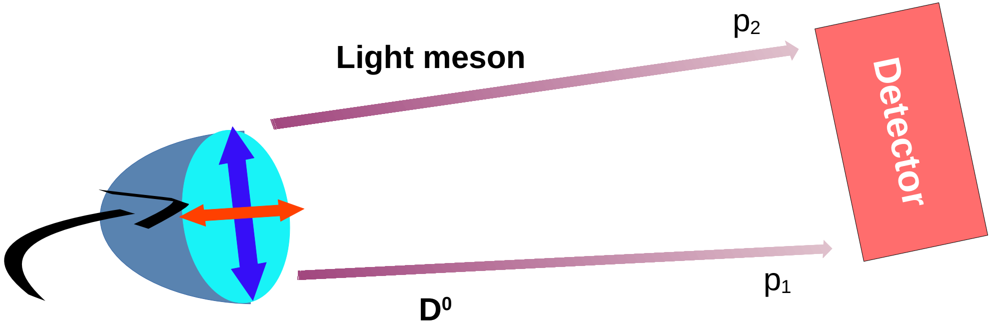
M. Lisa, S. Pratt, R. Soltz, U. Wiedemann, Annu. Rev. Nucl. Part. Sci. 2005.55:357-402

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



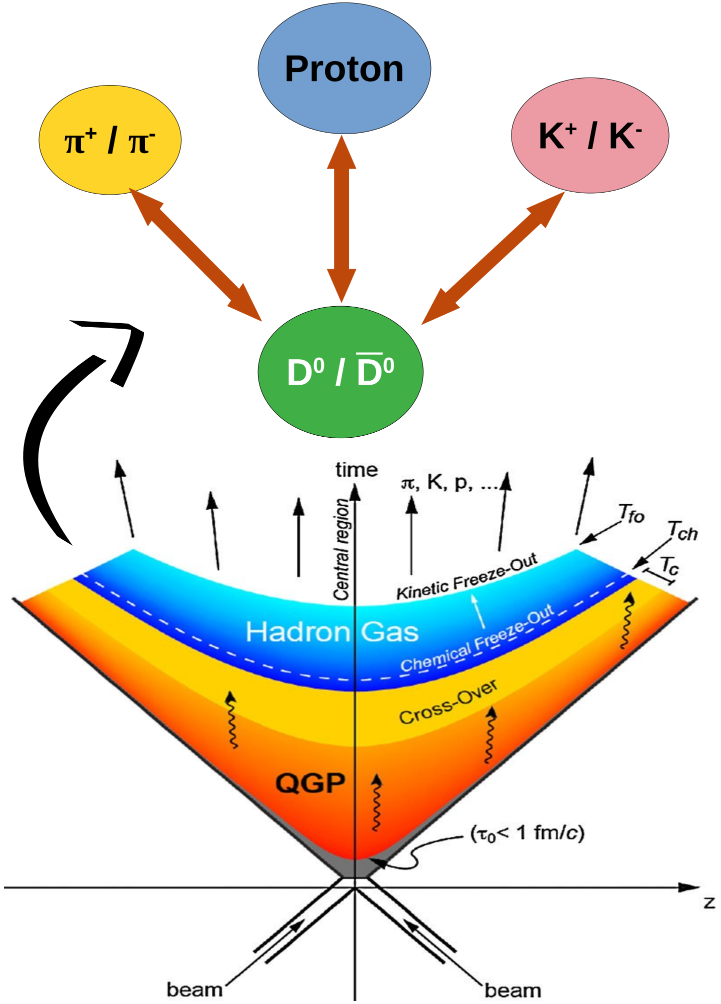


Figure 4: $c/\bar{c}$ as a probe of QGP medium and final-state interaction

Extraction of interaction parameters

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

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

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

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

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

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

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

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

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

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

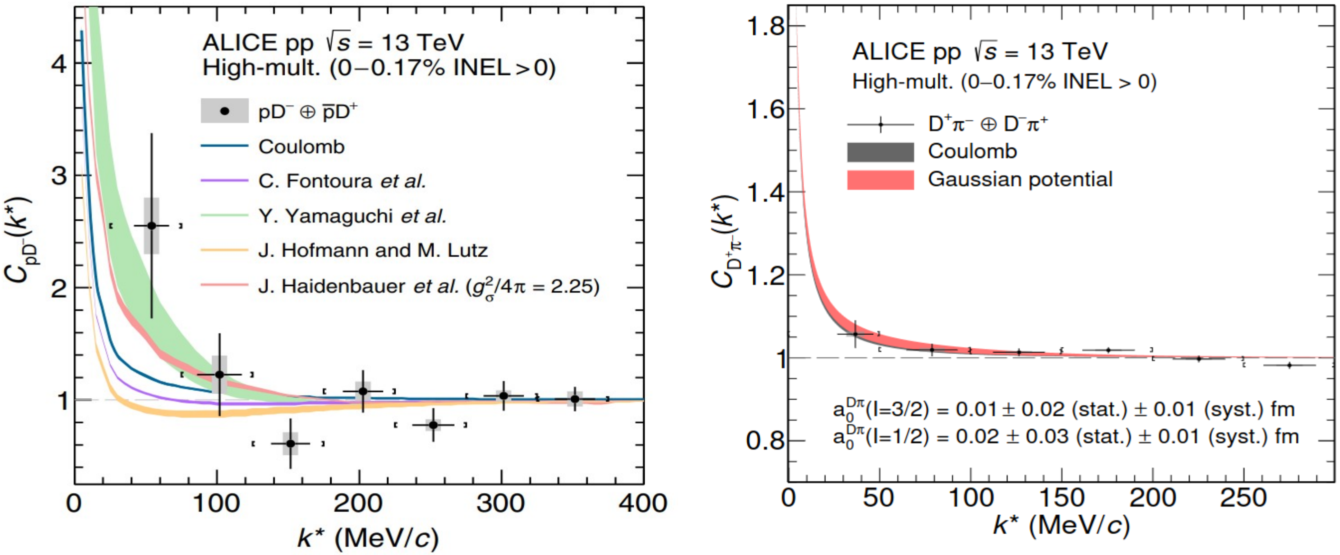
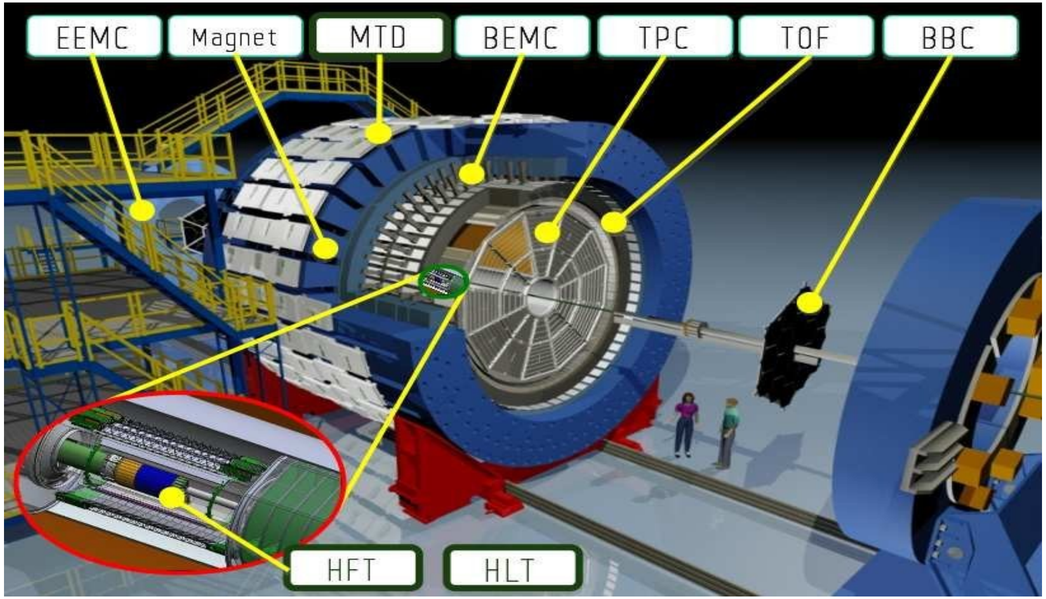


Figure 5: C(k*) for (left) pD and (right) πD pairs and interaction behavior of $D^{\pm}$ at final state

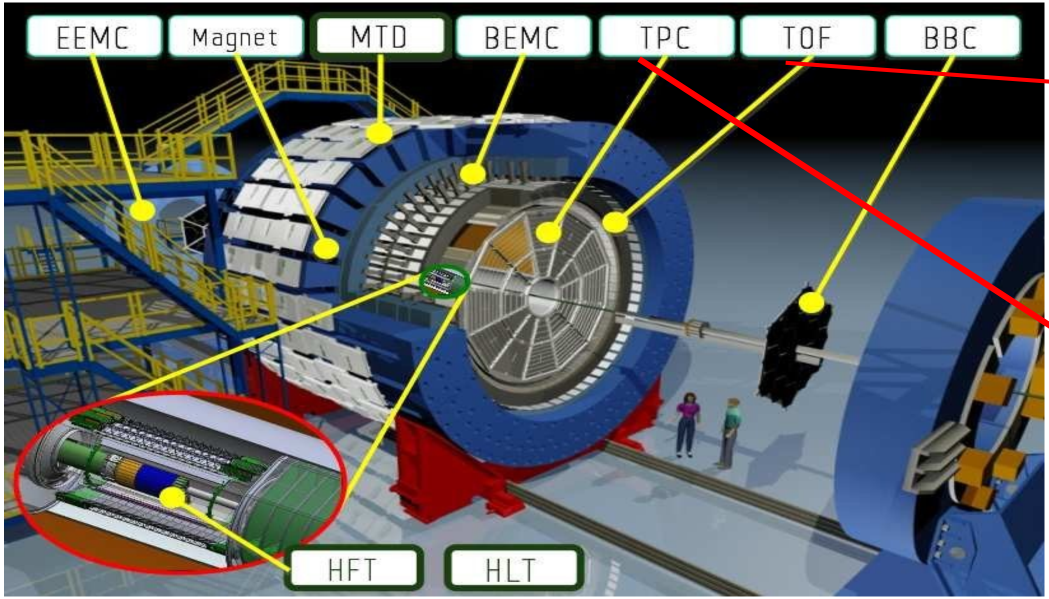
- First studies of D-hadron interactions in pp collisions at √s = 13 TeV by the ALICE experiment
- ALICE data for both p-D and D-π pairs are compatible within (1.1 – 1.5)σ with the theory predictions obtained from the hypothesis of Coulomb only interaction

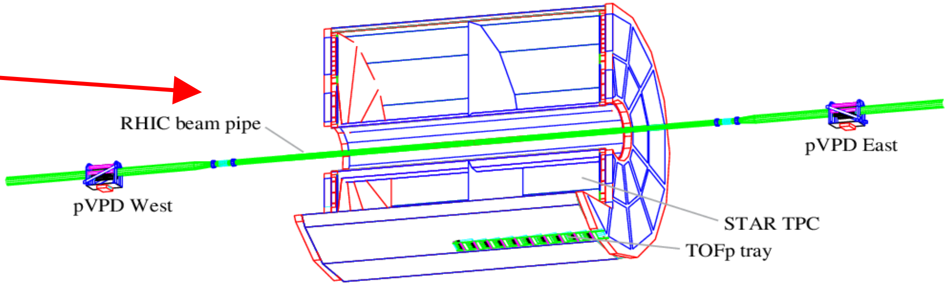
- Small values of $a_{\pi D}$ (scattering length) → ALICE measurement suggests strong interactions in the hadronic phase of heavy-ion collision are small (parameters are consistent with 0)
- Possiblity to learn something new about nuclear medium or QGP by measuring the source size or length of homogeneity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

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

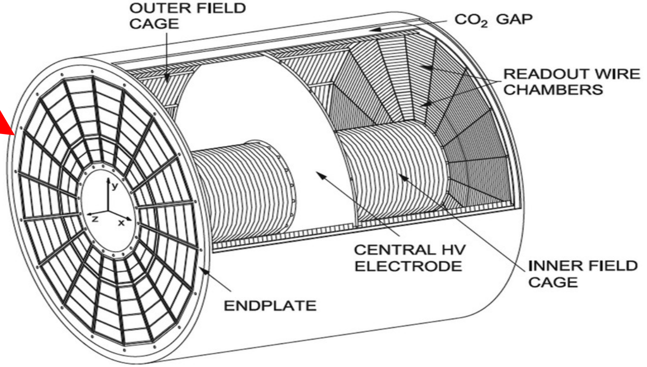


STAR (Solenoidal Tracker At RHIC)





TOF (Time of Flight)



TPC (Time Projection Chamber)

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

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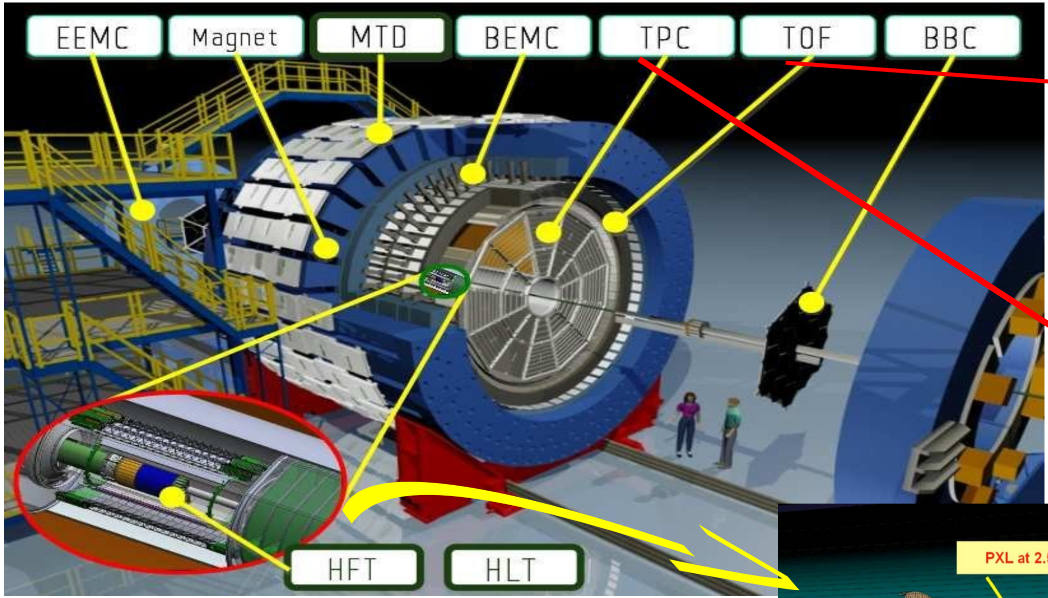

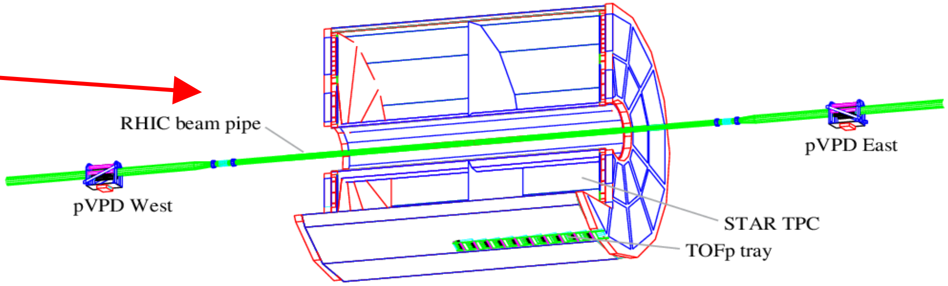

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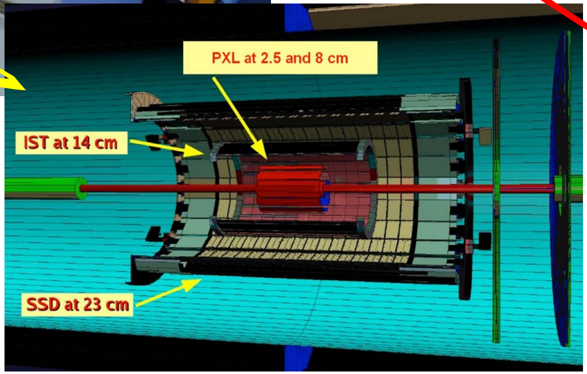
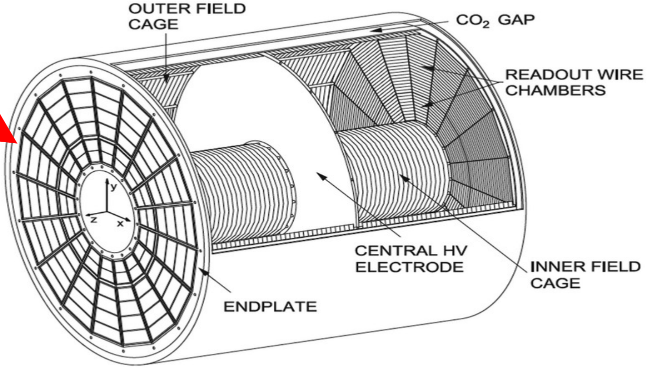


HFT (Heavy Flavor Tracker)



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 μm

Particle Identification (PID)

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

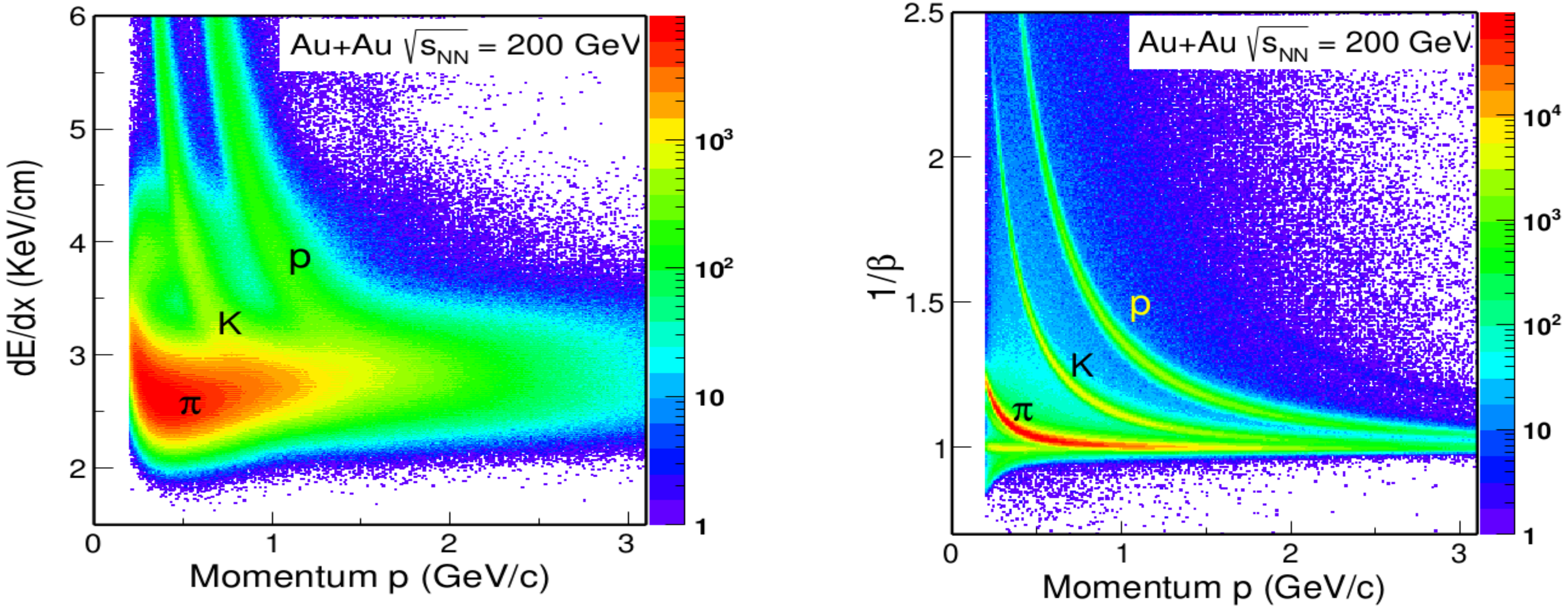
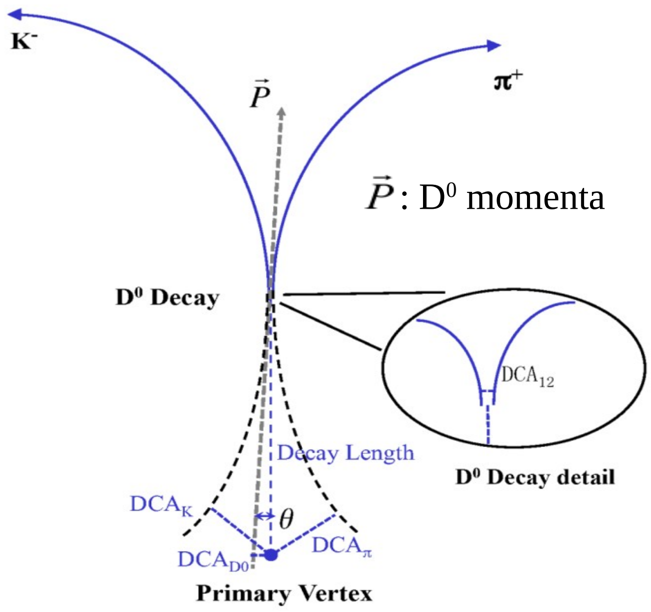


Figure 6: Particle identification using TPC (left) and TOF (right)

- 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)



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

$1.6 < D^0$ 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^- & 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

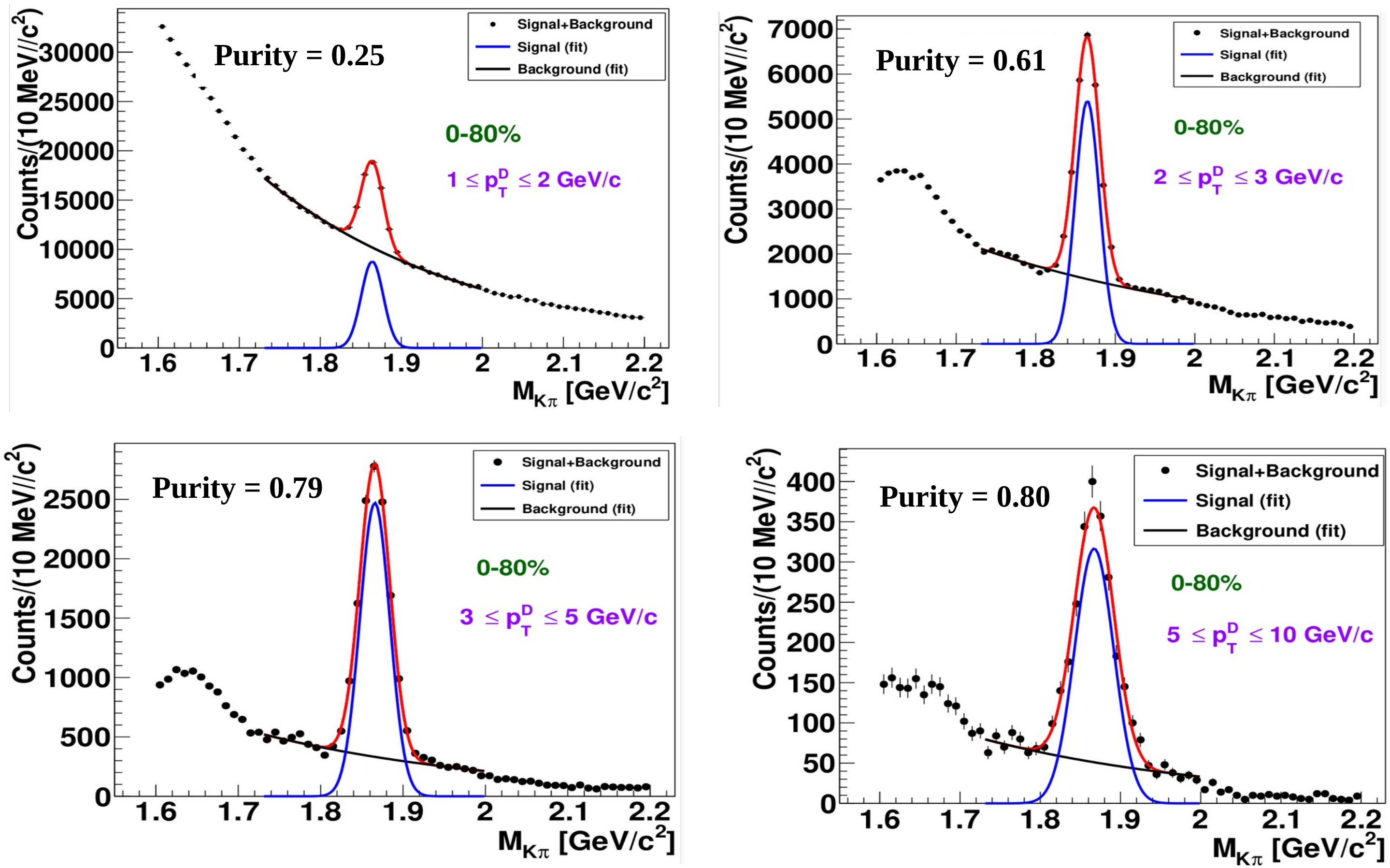


Figure 7: p_T dependence of $K\pi$ invariant mass distribution and D^0 signal purity

- 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: $$\frac{Signal}{(Signal + Background)}$$
- Higher D^0 signal purity with increasing p_T bin

Correction of raw correlation function

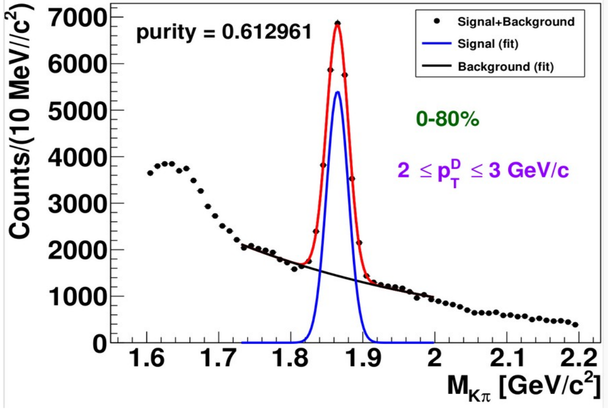
- Correlation function C(k*) for $D^0/\overline{D}^0$ - $h^{+/-}$ pairs: $$C(\vec{k}^*) = \mathcal{N}\frac{A(\vec{k}^*)}{B(\vec{k}^*)}. \qquad (3)$$

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

- Pair-purity corrected correlation function: $$C^{\rm corr}_{\rm measured}(k^*) = \frac{C_{\rm measured}(k^*) - 1}{\rm PairPurity} + 1, \qquad (4)$$

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

- $C_{\rm measured}(k^*)$ 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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- 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_π < 1 GeV/c
- Proton purity ~ (99.5 ± 0.5 (syst.))%, p_p < 1.2 GeV/c

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

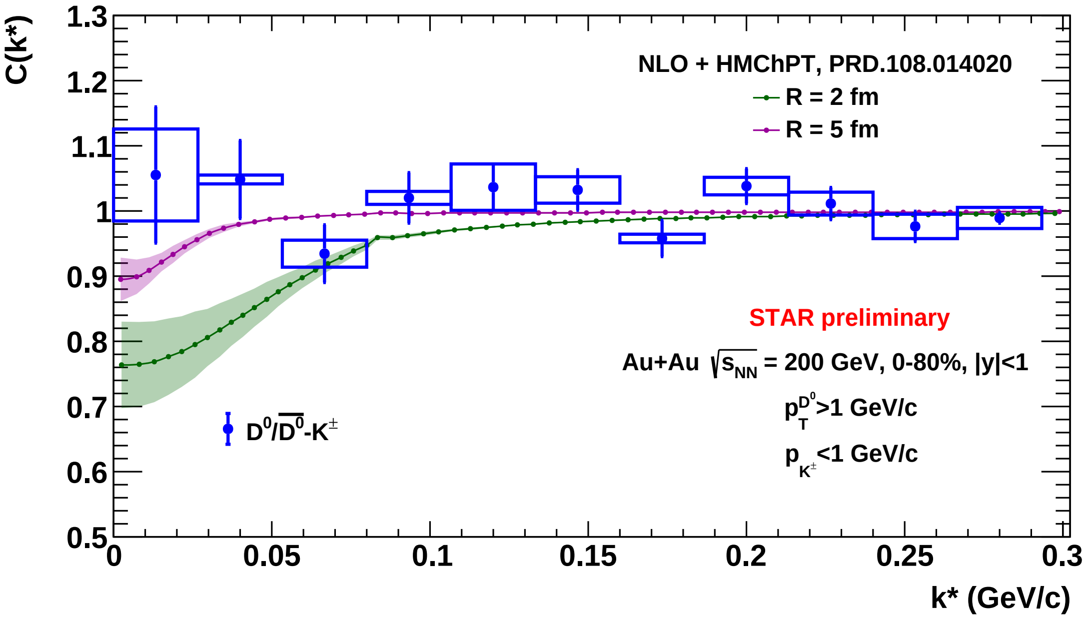

Figure 8: $C(k^*)$ for D^0-K pairs with systematic uncertainties (boxes). Green and pink bands are theory predictions of $C(k^*)$ for D^0-K^+ channel using source radii of 2 fm and 5 fm respectively

- $C(k^*)$ 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

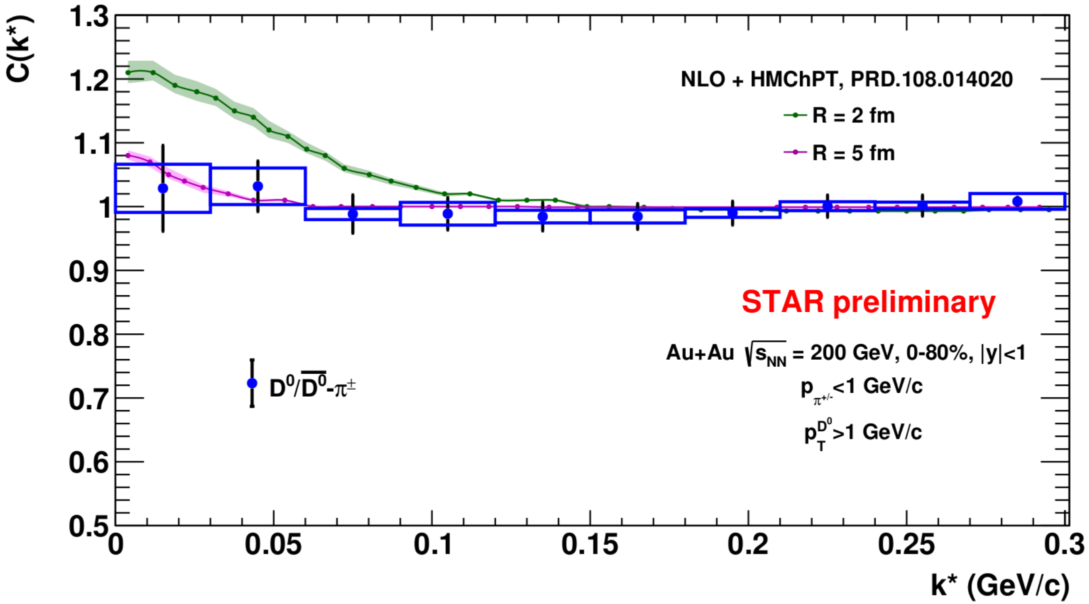

Figure 9: $C(k^*)$ for D^0-π pairs with systematic uncertainties (boxes). Green and pink bands are theory predictions of $C(k^*)$ for D-π channel using source radii of 2 fm and 5 fm respectively

- $C(k^*)$ calculated for D^0-π^+, D^0-π^-, $\overline{D}^0$-π^+ and $\overline{D}^0$-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

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

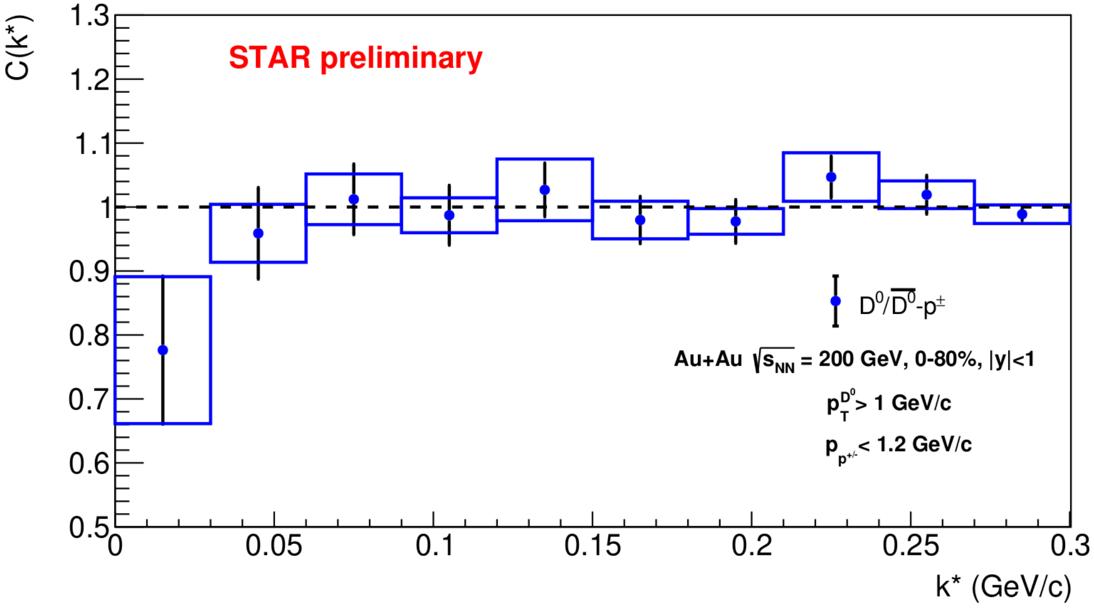


Figure 10: $C(k^*)$ for D^0-p pairs with systematic uncertainties (blue brackets)

- $C(k^*)$ 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

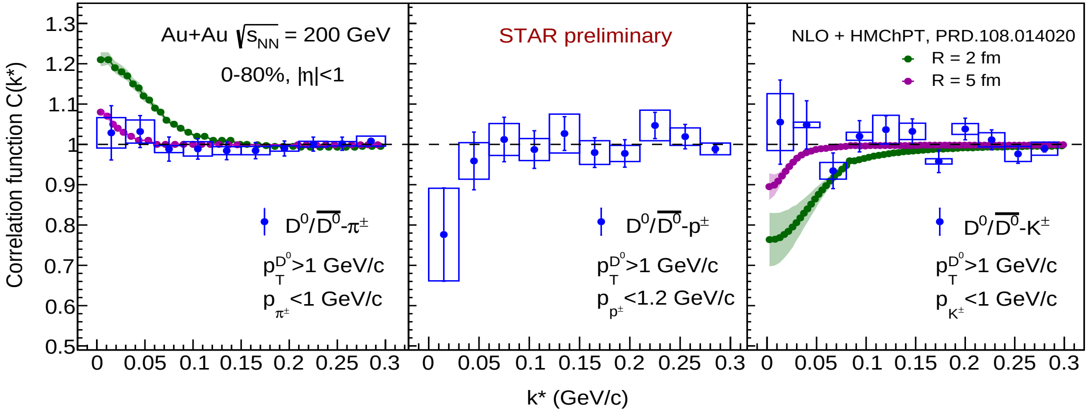
Predictions?

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

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

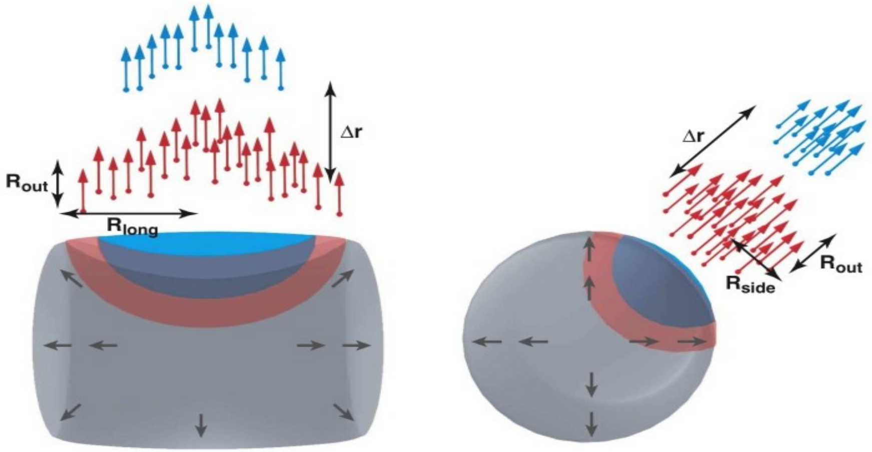


Figure 6: Emission source phase-space

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

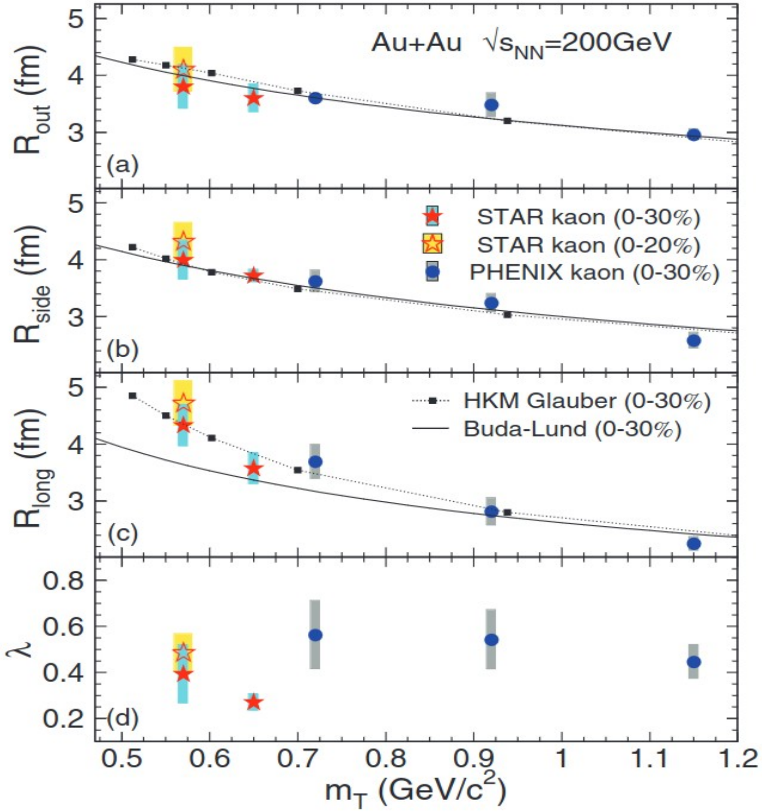


Figure: m_T dependence of 3-D source size using Kaon femtoscopy

Theory prediction of CF for $D\pi$ channels

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

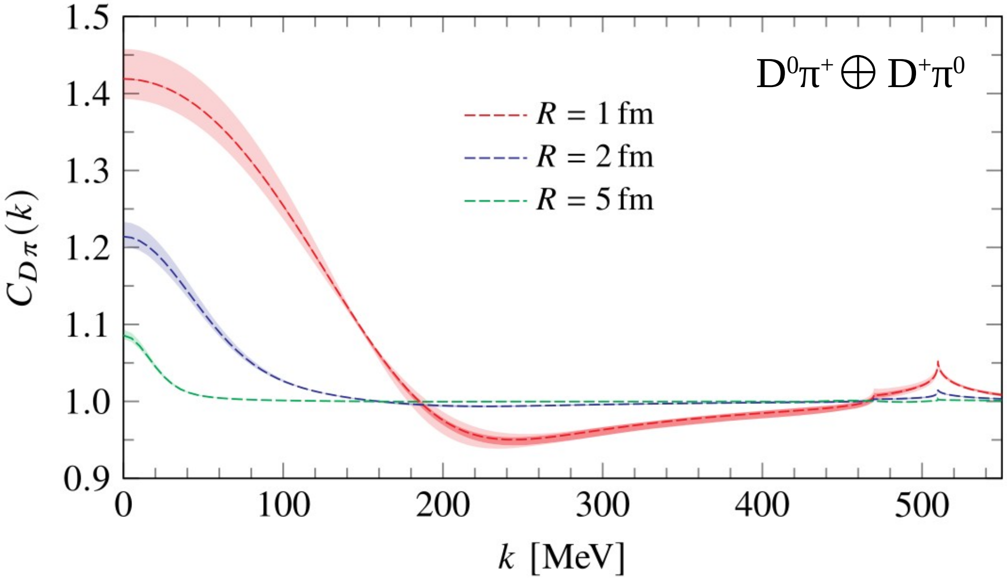


Figure: Correlation functions for $D\pi$ channels predicted for R = 1, 2 and 5 fm sources represented by red, blue and green dashed lines respectively. Corresponding bands show uncertainties with 68% CL

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

- Isospin combinations for $D\pi$ channels

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

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

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

- 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

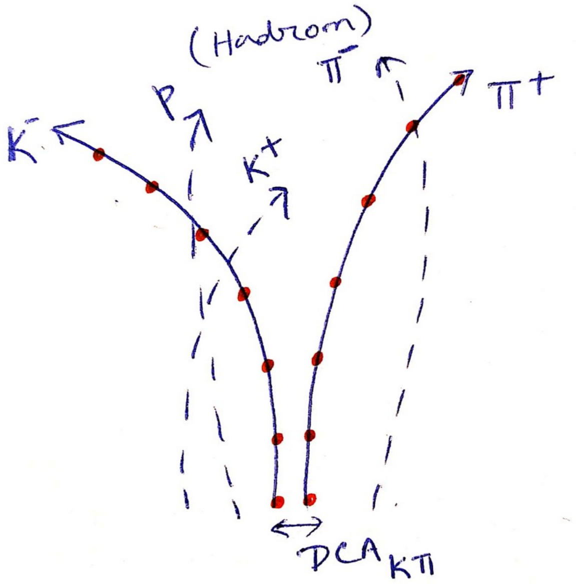
Hadron (chosen for pairing with D^0) track id ≠ Track id of D^0 (π^+K^-)

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**

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 π, K & p

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