First measurement of heavy flavour femtoscopy using D^0 mesons and charged hadrons in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV by STAR

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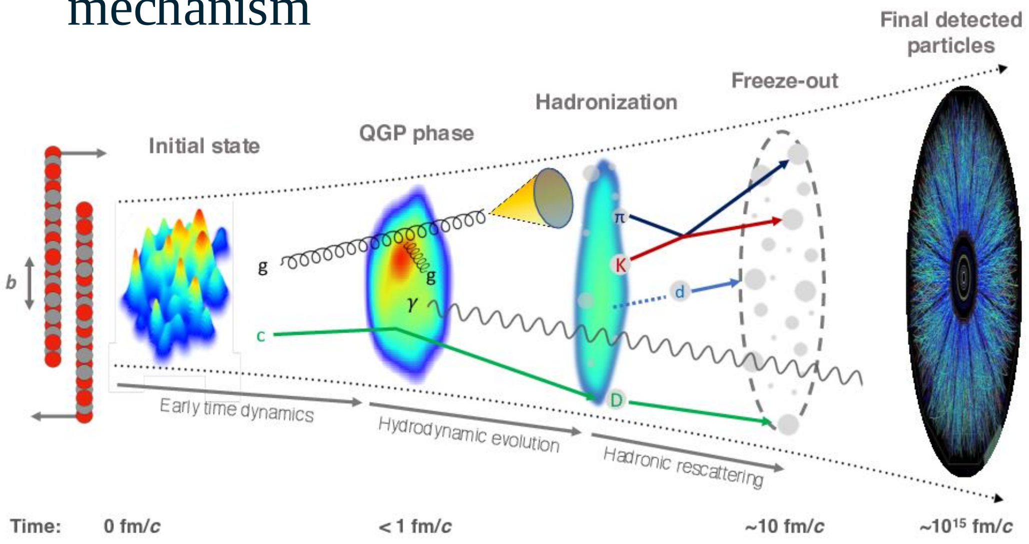
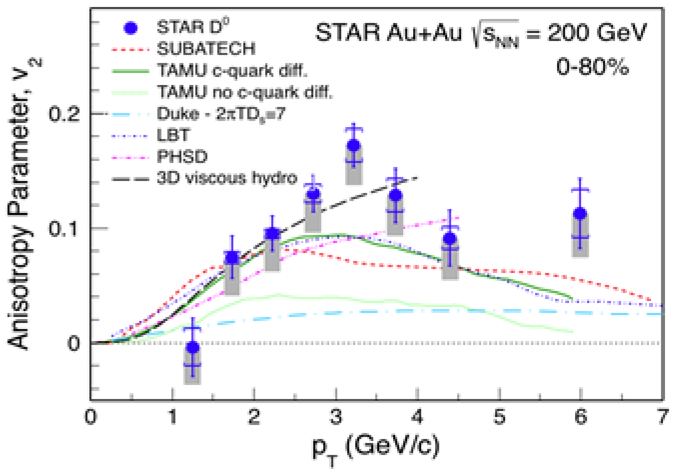
Motivation – $c/\bar{c}$ interactions with QGP

- Heavy quarks are produced early in the collisions → good probes to study all stages of the heavy-ion collisions
- Observation in heavy-ion collisions at RHIC: significant D^0 elliptic flow and suppression at high p_T
- Strong interaction of charm quarks with the quark-gluon plasma and their thermalisation
- New observables to constrain different models and understand production mechanism



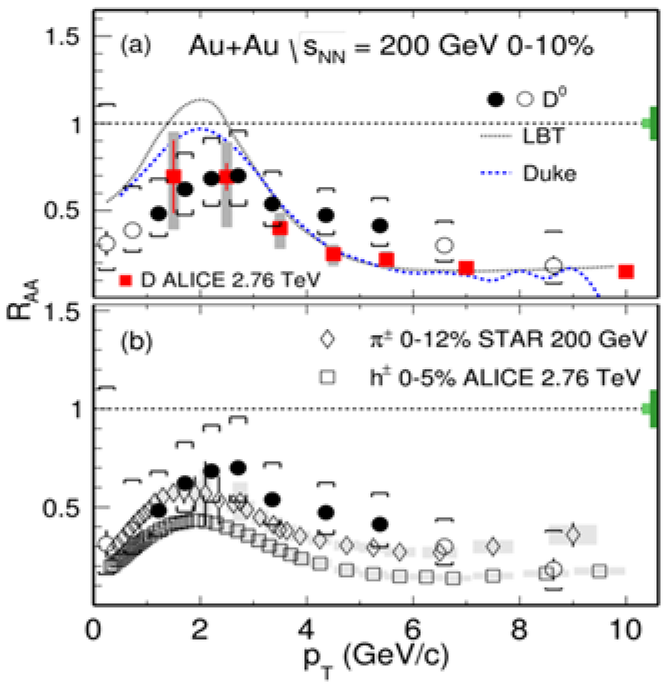
Stages of heavy-ion collisions

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



D^0 anisotropy vs. transverse momentum

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



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

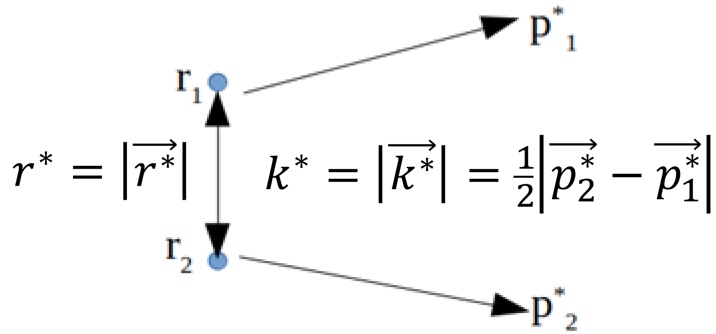
Femtoscopic correlation

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

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

$S(r^*)$: Source emission function

$\Psi(\overrightarrow{k^*}, \overrightarrow{r^*})$: Pair wave function



Femtoscopic correlations, $\overrightarrow{k^*}$ and $\overrightarrow{r^*}$ (relative separation vector)

- ➢ Femtoscopic Correlation → QS + FSI
  - ➢ Quantum Statistics [QS]: Bose-Einstein and Fermi-Dirac
  - ➢ Final-State-Interaction [FSI]: Strong and Coulomb interactions
  - ➢ **Only strong interaction contributes to $D^0/\overline{D^0}$-$h^{\pm}$ femtoscopy**

Femtoscopy and interaction parameters

The Lednicky–Lyuboshitz analytical model connects the two-particle correlation function with the particle emission source size (r_0) and the s-wave strong interaction scattering amplitudes ($f^S(k^*)$):

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

where for a given total spin S (S = 0 or S = 1):

- $\Re f^S(k^*)$, $\Im f^S(k^*)$ – real and imaginary part of the scattering amplitude for singlet or triplet state,
- ρ_S – the fraction of pairs with a given spin S (ρ_0 = ¼ and ρ_1 = ¾),
- d_0^S – the effective radius of the strong interaction,

$$Q = 2k^*, \quad F_1(z) = \int_0^z dx\, e^{x^2 - z^2}/z, \quad F_2(z) = (1 - e^{-z^2})/z \qquad (3)$$

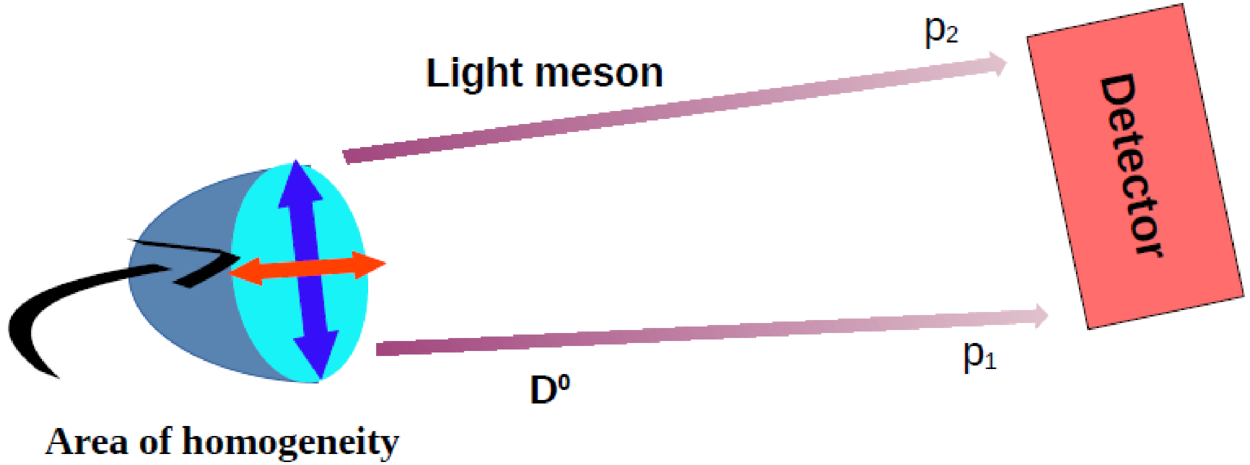
This model assumes an average separation vector ($\overrightarrow{r^*}$) from eq. (1), follows Gaussian distribution:

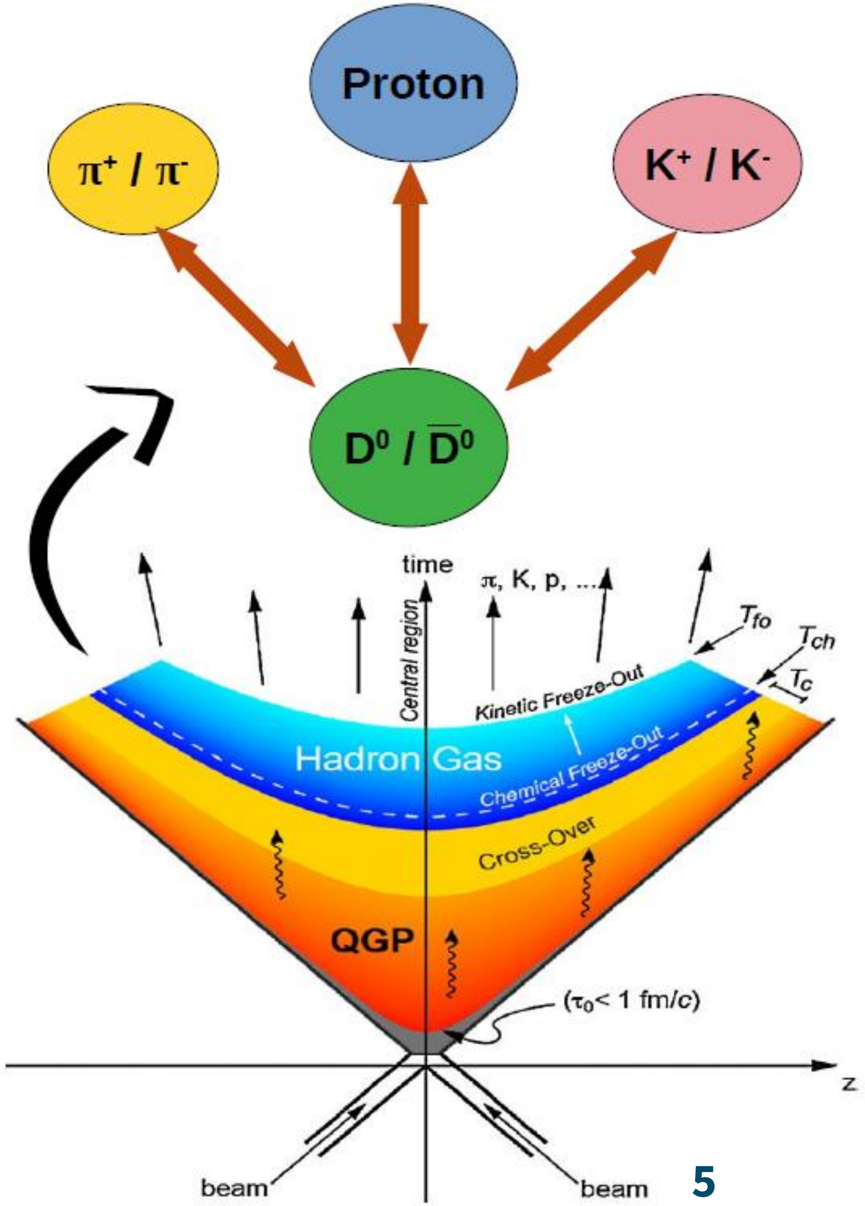
$$dN^3/d^3r^* \quad e^{-r^{*2}/4r_0^2} \qquad (4)$$

where r_0 is the effective radius of the correlated source.

Learning outcomes

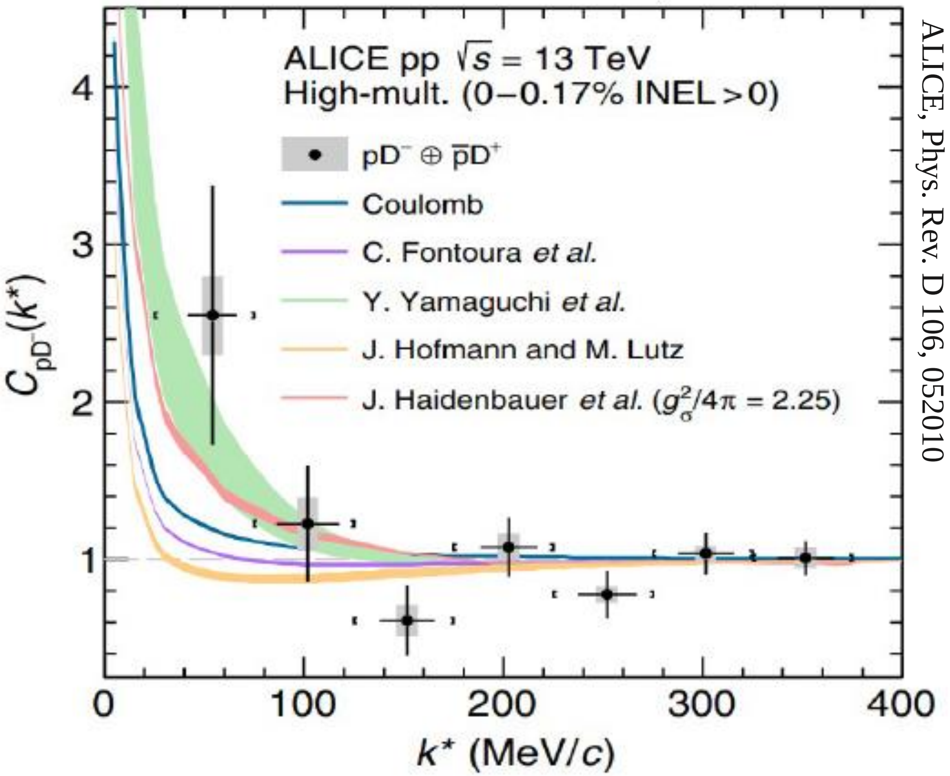
- Two-particle femtoscopic correlations are sensitive to the interactions in the final state as well as to the extent of the region from which correlated particles are emitted
- Average distance between emission points of correlated pairs (D^0-hadron) is known as the 'length of homogeneity'
- Femtoscopy may provide additional information about the correlation between charmed mesons and light mesons at the freeze-out



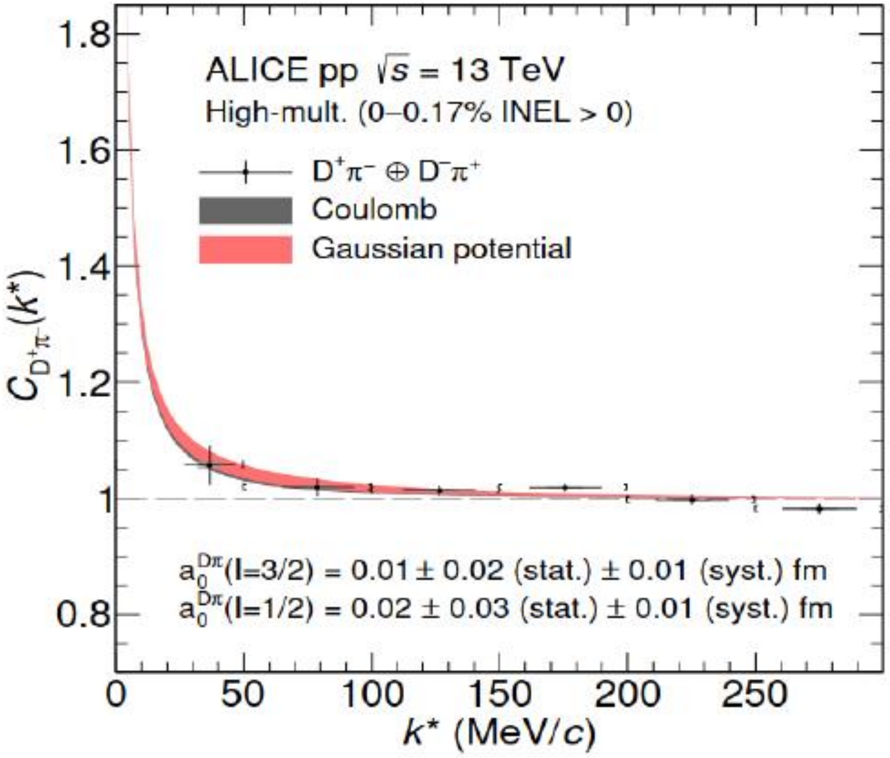


Final-state interaction

- 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 $a_0^{D\pi}$ (scattering length) → ALICE measurement suggests small strong interactions in the hadronic phase of heavy-ion collision (parameters are consistent with 0)

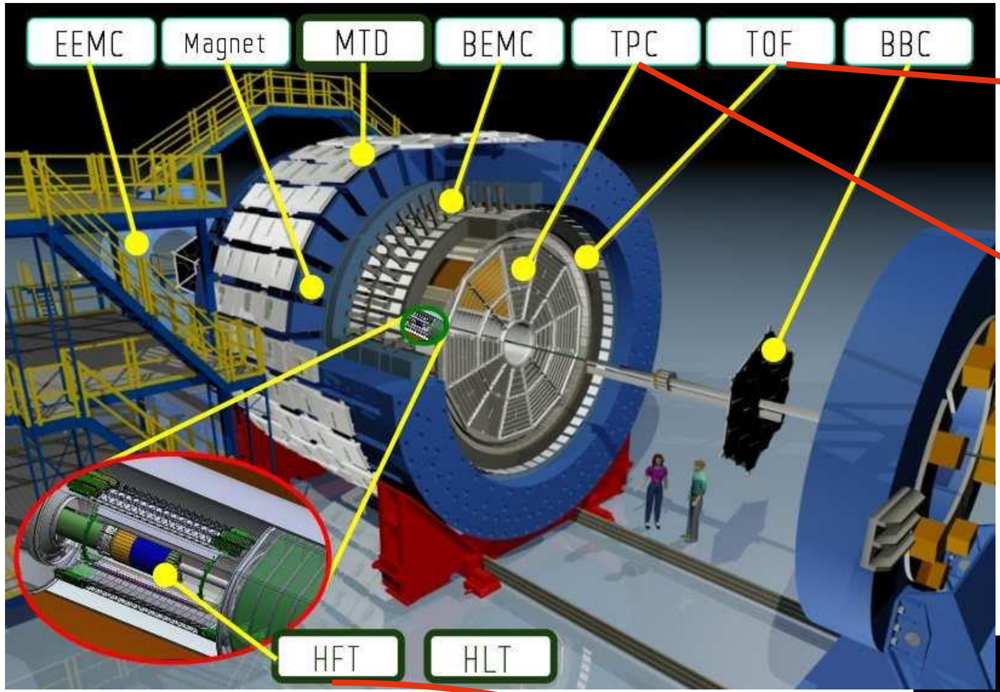


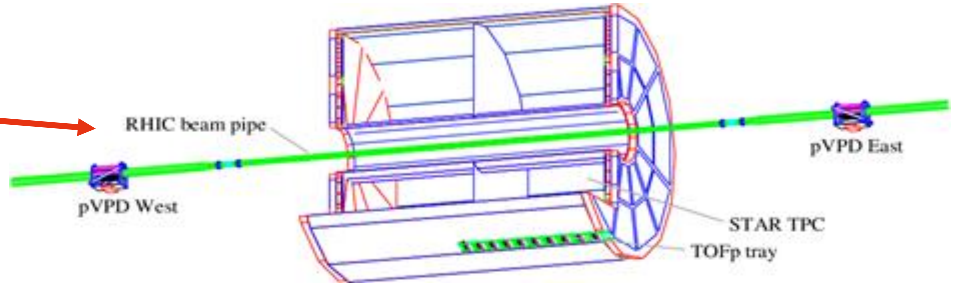
ALICE, Phys. Rev. D 106, 052010



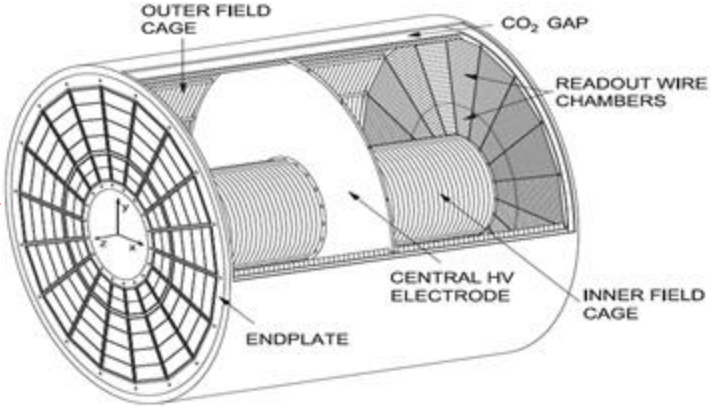
ALICE, https://doi.org/10.48550/arXiv.2401.13541

STAR (Solenoidal Tracker At RHIC)



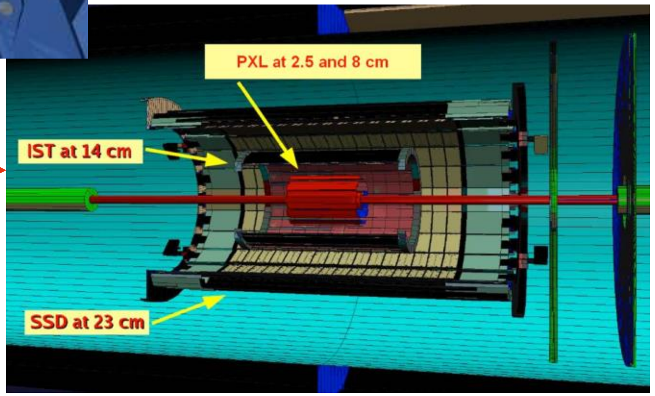


TOF (Time of Flight)



TPC (Time Projection Chamber)

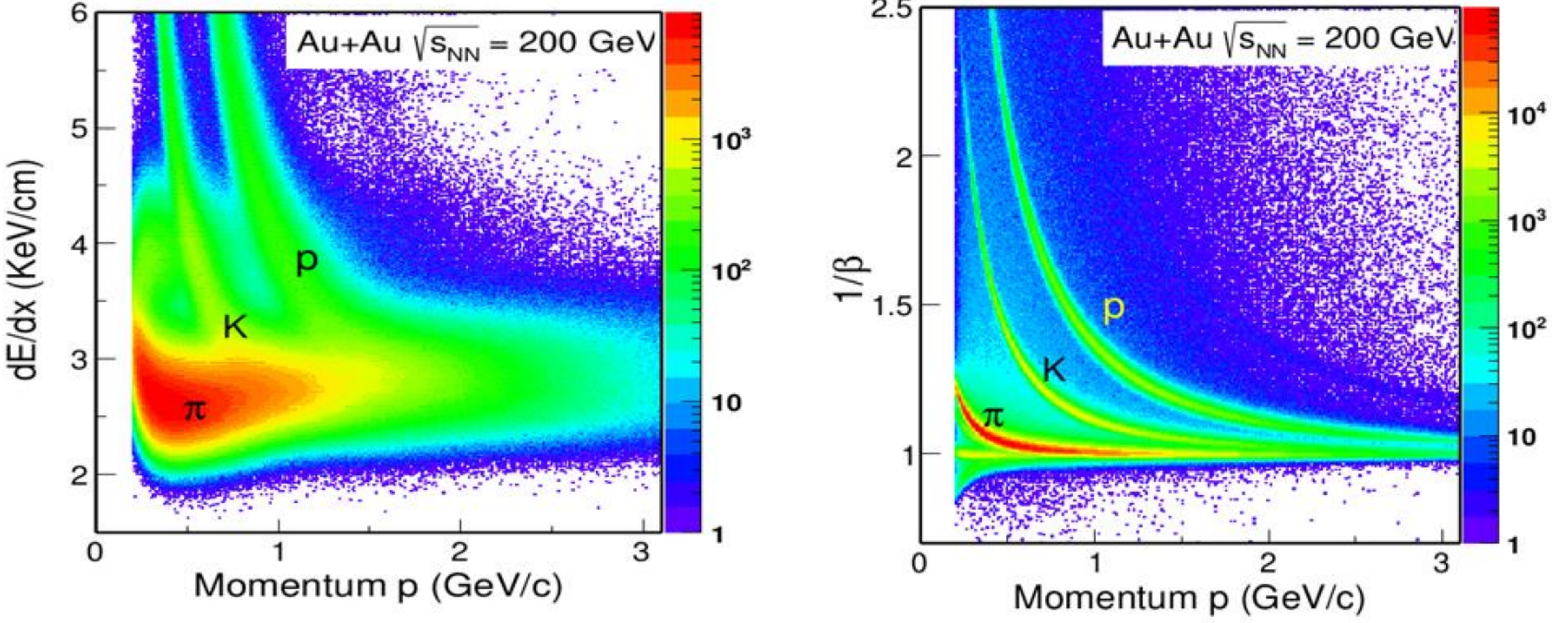
- TOF – used for PID
- TPC – used for tracking and PID
- HFT – used for D^0 reconstruction



HFT (Heavy Flavor Tracker)

Particle Identification (PID)

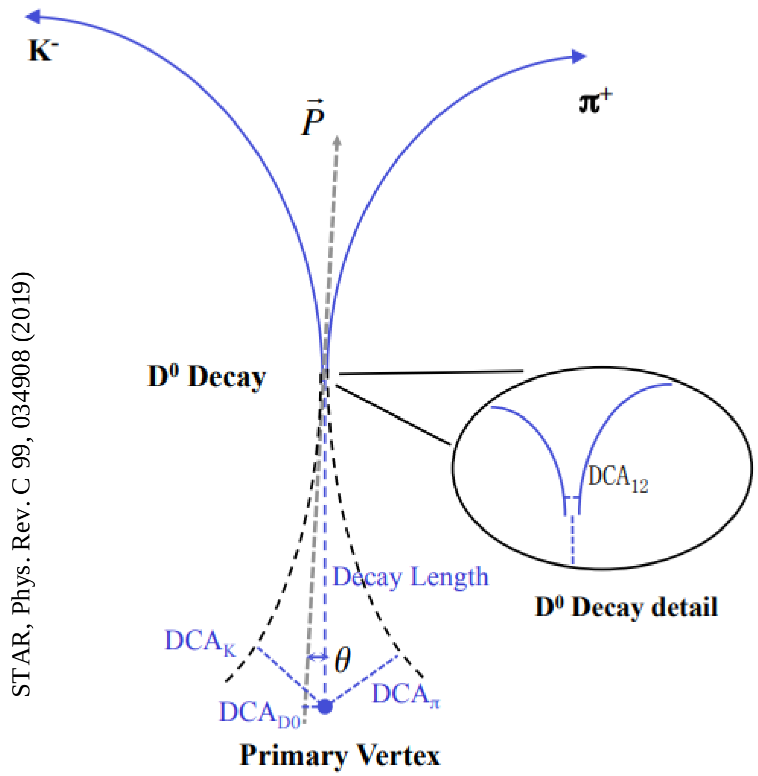
STAR, Phys. Rev. C 99, 034908 (2019)



Particle identification using TPC (left) and TOF (right)

- The 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



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

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

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

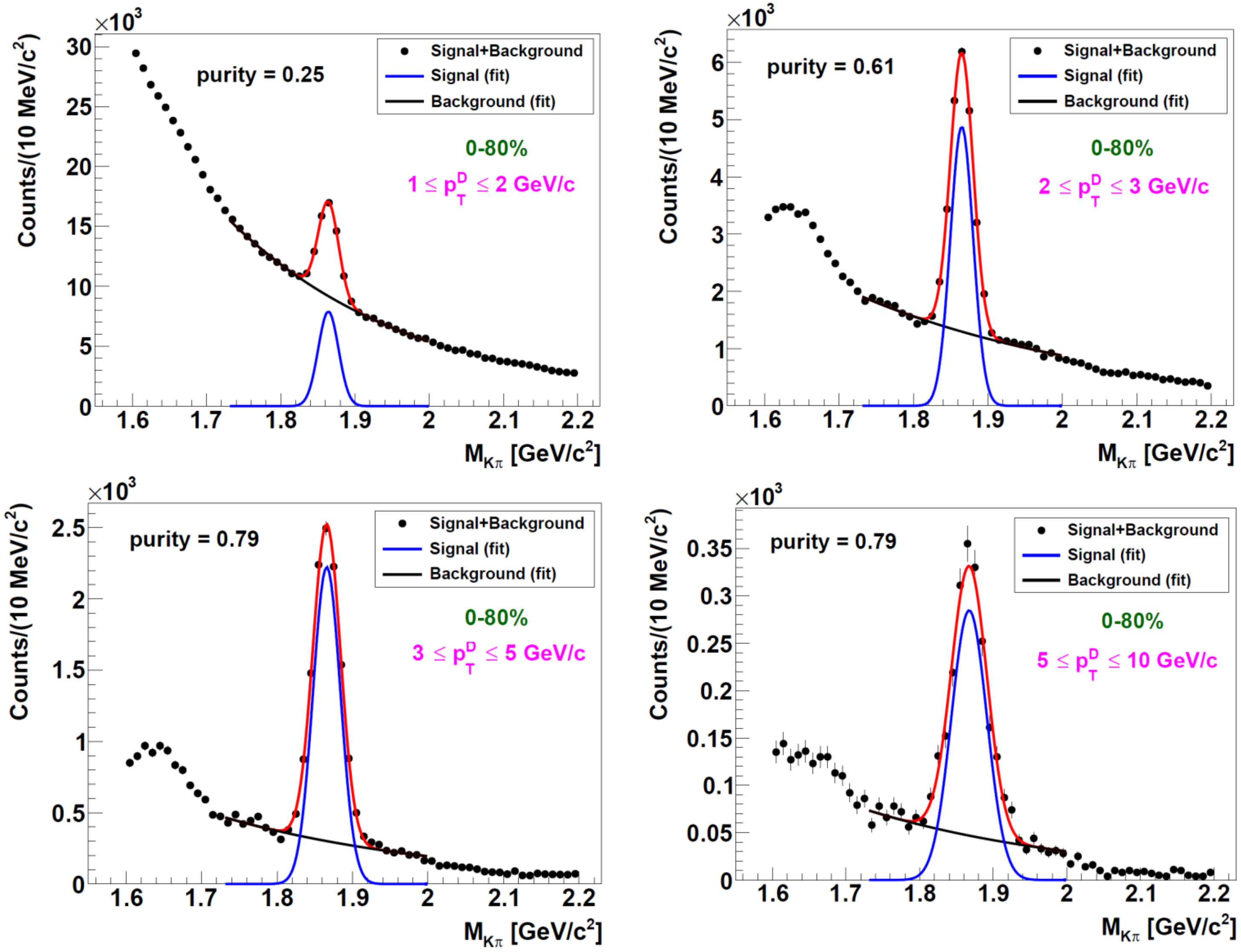
Dataset:

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

D^0 reconstruction:

- Decay length – distance between decay vertex and primary vertex (PV)
- DCA – Distance of Closest Approach between:
  - K & π - DCA_{12}
  - π & PV – DCA_π
  - K & PV – DCA_K
  - D^0 & PV - DCA_{D0}
- θ - the angle between the D^0 momentum vector ($\vec{P}$) and the decay length

D^0 invariant mass and signal purity



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

- Unlike-sign ($K^-\pi^+$) pairs from SE construct ‘signal’
- Like-sign ($K^-\pi^-$ and $K^+\pi^+$) pairs from SE and unlike-sign $K\pi$ pairs from ME represent ‘background’
- Invariant mass range for D^0 signal: 1.82 – 1.91 GeV/c^2
- D^0 purity:

$$\frac{Signal}{Signal + Background}$$

- Higher D^0 signal purity with increasing p_T bin
- Good S/B ratio for D^0 signal $p_T > 1$ GeV/c

Correction of raw correlation function

- Correlation function $C(k^*)$ for $D^0/\overline{D^0}$-$h^{\pm}$ pairs: $$C(k^*) = N\frac{A(k^*)}{B(k^*)} \quad (5)$$

  where:
  - $A(k^*), B(k^*)$ - k* distribution for correlated and uncorrelated pairs,
  - N – normalization factor.

- Pair-purity corrected correlation function:

$$C^{corr}_{measured}(k^*) = \frac{C_{measured}(k^*)-1}{PairPurity} + 1 \quad (6)$$

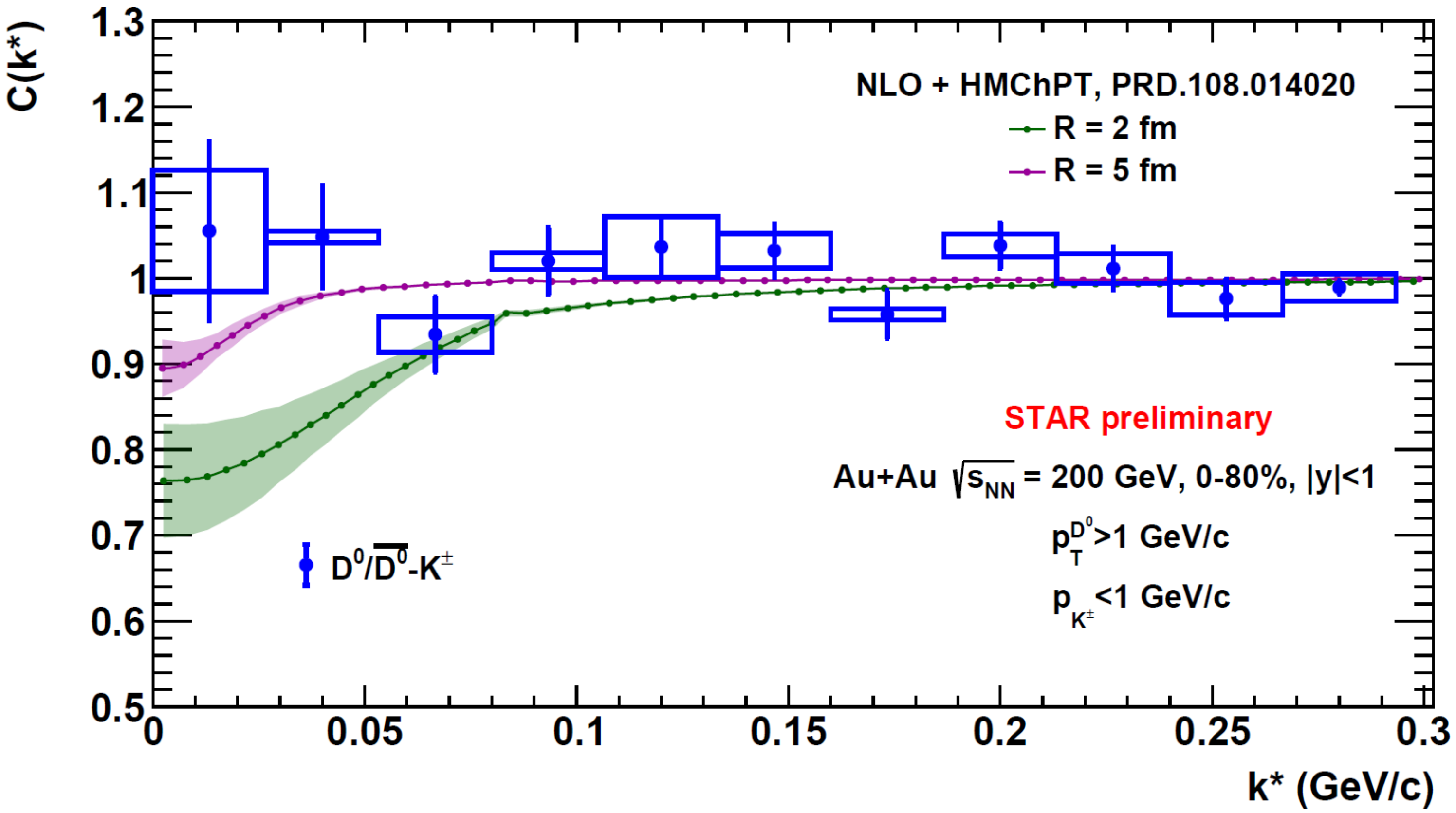
  where:
  - $C_{measured}(k^*)$ - the raw correlations function calculated using Eq. (5),
  - PairPurity = D^0 purity * hadron purity.

D^0 purity	Kaon purity	Proton purity	Pion purity
~ 37% 1 GeV/c < p_T < 10 GeV/c	(97 ± 3 (syst.))% p_K < 1 GeV/c	(99.5 ± 0.5 (syst.))% p_p < 1.2 GeV/c	(99.5 ± 0.5 (syst.))% p_π < 1 GeV/c

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

- Comparison to theory predictions of $C(k^*)$ for the D^0-K^+ channel: next-to-leading order (NLO) + Heavy Meson Chiral Perturbation Theory (HMChPT) scheme (green and pink bands are for radii of 2 fm and 5 fm, respectively)

- The STAR data shows no significant correlations
- The data is consistent with theoretical model predictions with an emission source size of 5 fm or larger



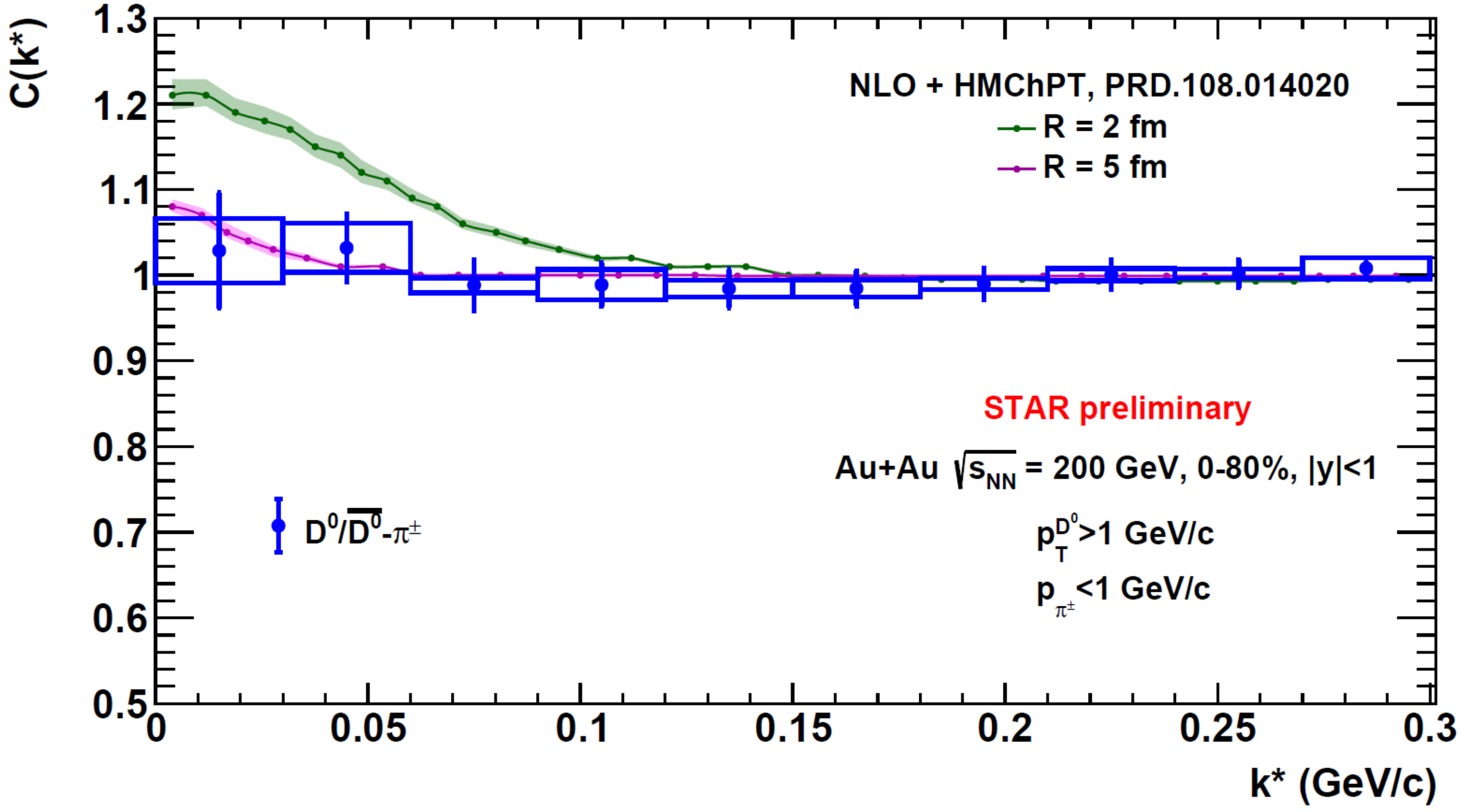
NLO + HMChPT: M. Albaladejo *et al.*, Phys. Rev. D 108, 014020

- Resonance effect of $D_{S0}^*(2317)^{\pm}$ state is NOT visible (large source size or large experimental uncertainties)

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

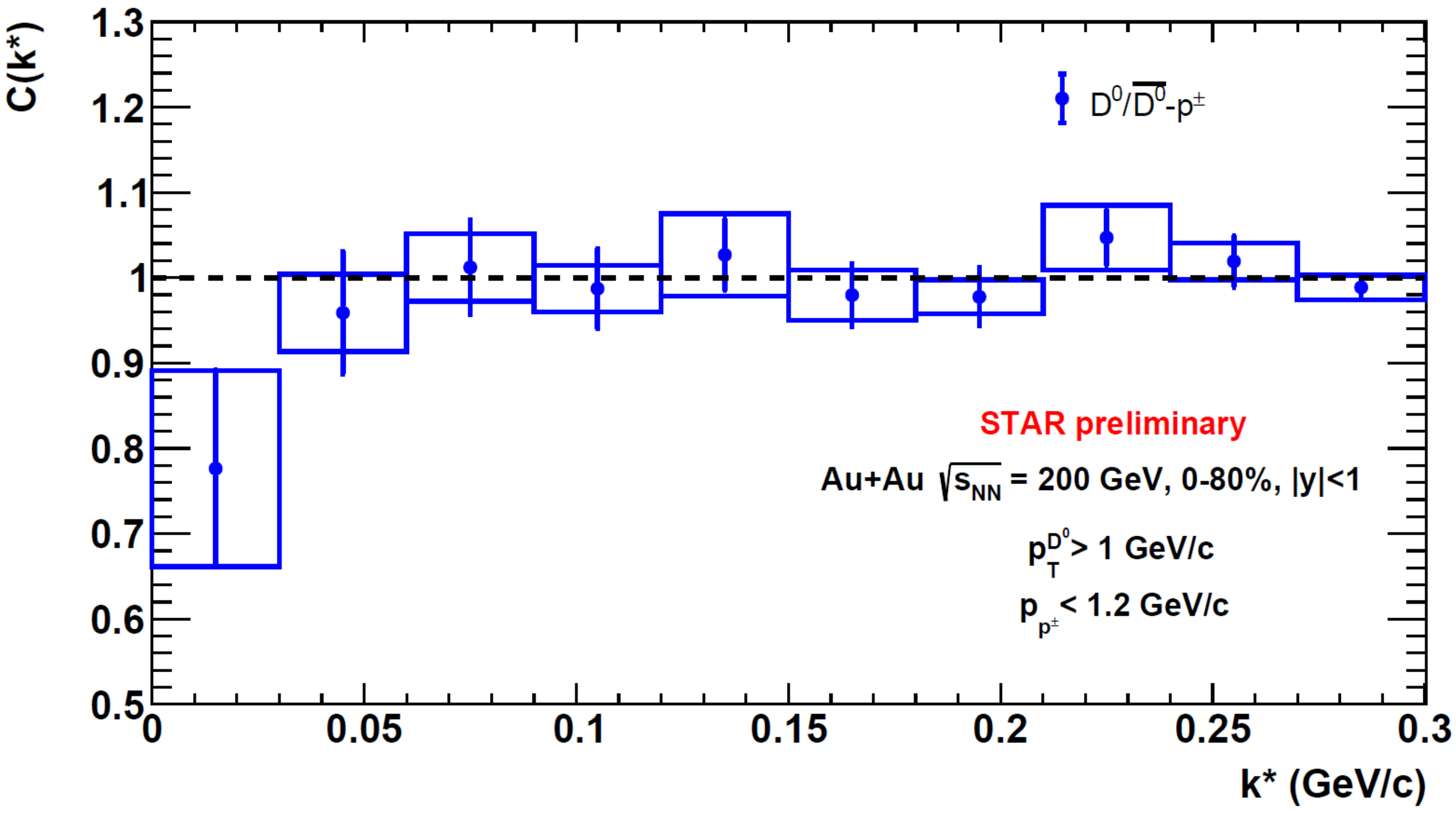
- Comparison to theory calculations of C(k*) for the D^0-π channel: next-to-leading order (NLO) + Heavy Meson Chiral Perturbation Theory (HMChPT) scheme (green and pink bands are for radii of 2 fm and 5 fm, respectively)

- We do not observe significant correlations
- The STAR data is consistent with theoretical model predictions with an emission source size of 5 fm or larger



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

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



- We do not observe significant correlations between $D^0/\overline{D^0} - p^{\pm}$ pairs
- Suggesting large emission source size
- Theoretical predictions are needed

Summary & future plans

- D-meson femtoscopy is applicable to probe the interaction behaviour of charmed hadrons and the phase space geometry of the emission source
- Correlation studies between D^0-K and D^0-π pairs provide consistent results with no significant correlation and are consistent with large emission source size (~ 5 fm)
- Current statistical precision is not sufficient to make decisive conclusions, however more data are available
- Model study (ex. Lednický–Lyuboshitz) is on the plan to extract interaction parameters and emission source size
- Theoretical inputs are required to connect the observed correlation functions and interaction parameters of charm and light quarks before hadronization

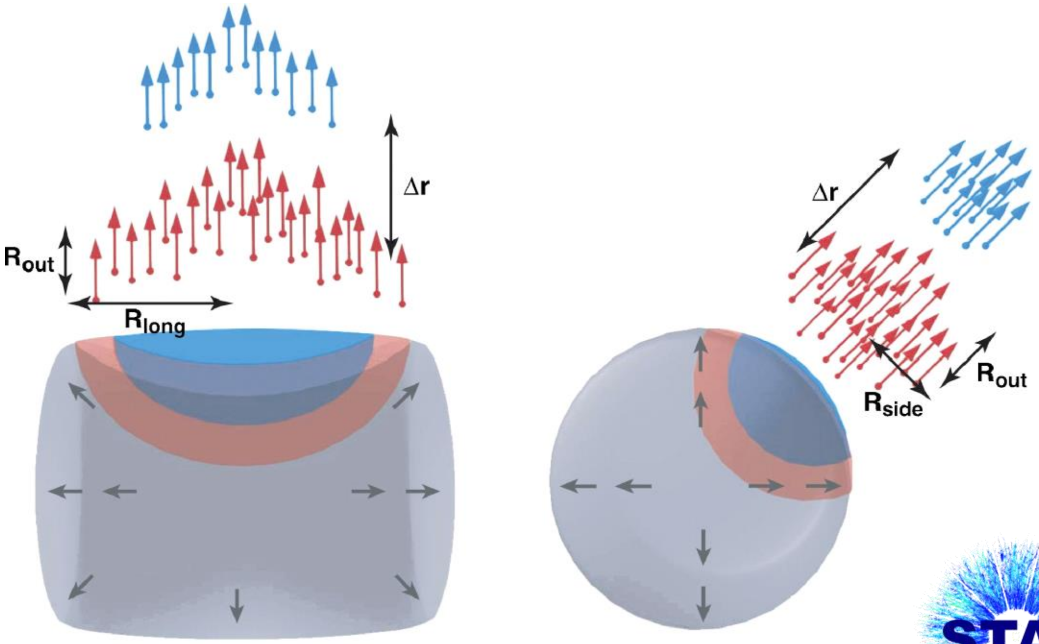
Thank you for your attention!

Backup

Freeze-out dynamics

- Properties of nuclear medium
  - Example – source size measured at RHIC with kaons compatible with model calculations employing hydrodynamics
  - Local thermal equilibrium

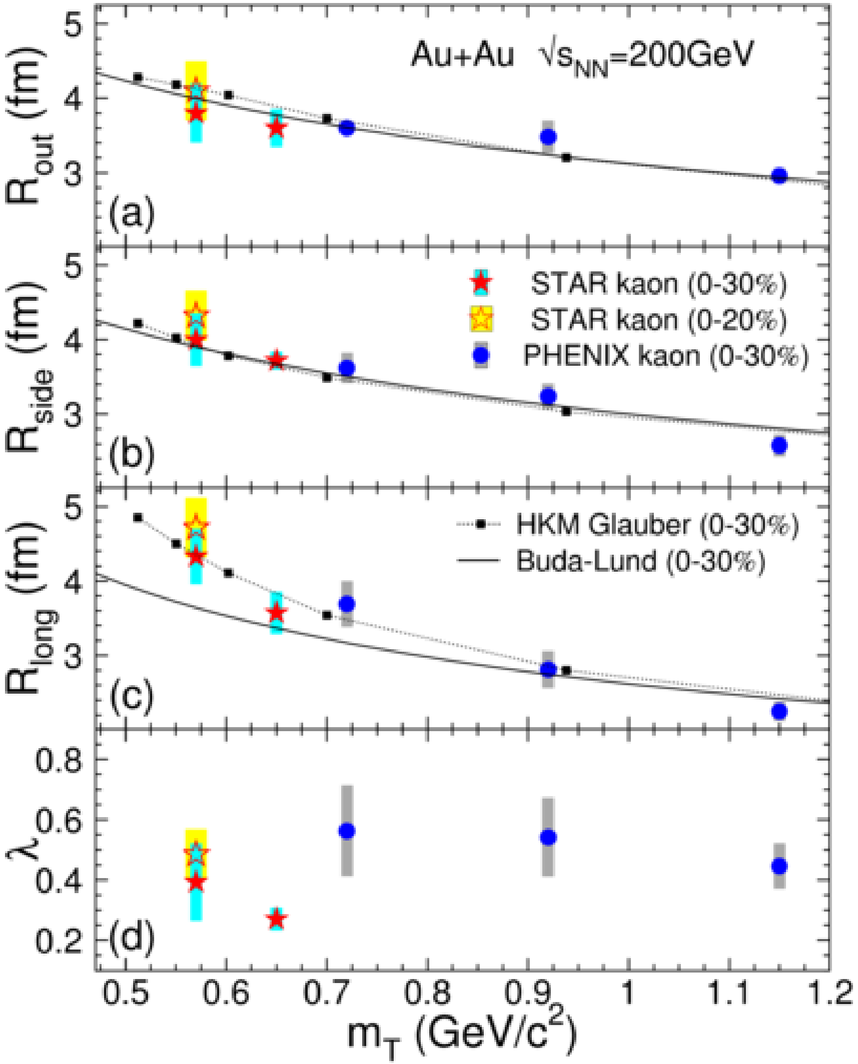
M. Lisa, S. Pratt, R. Soltz, U. Wiedemann, Annu. Rev. Nucl. Part. Sci. 2005.55:357-402



Emission source phase-space

HKM – Hydro Kinetic Model

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



The m_T dependence of 3-D source size using kaon femtoscopy

Theory predictions of CF for Dπ channels

- Isospin combinations for Dπ channels

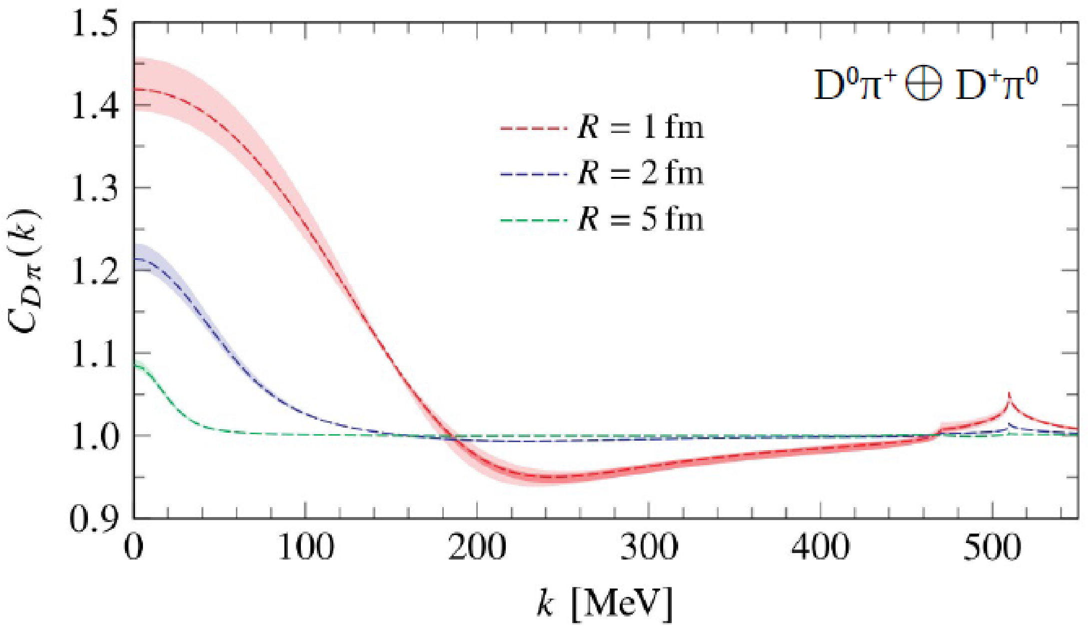
$$C_{D^+\pi^0} = \frac{2}{3} C^{D\pi}_{3/2} + \frac{1}{3} C^{D\pi}_{1/2},$$

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

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

- 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, produced due to the presence of the lightest D^*_0 state [$D^*_0(2135)$]
- For R = 2 fm and 5 fm sources, the minimum is present but diluted
- Interaction in I = 3/2 sector ($D^0\pi^-$) is weaker and repulsive.

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



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.

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 the following condition:

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

Correction of detector effects

3. Track merging

Approach 1:

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

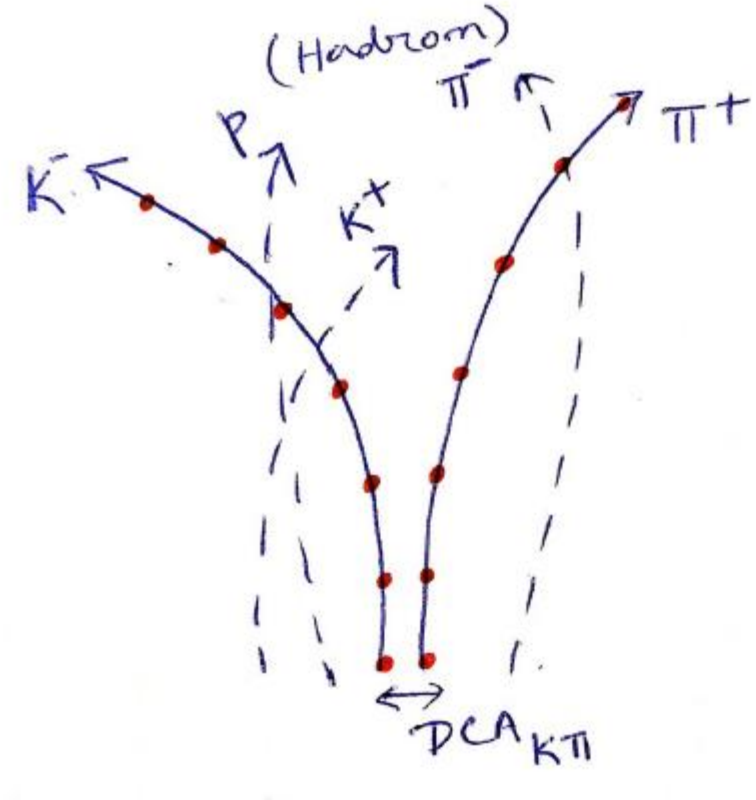
Approach 2:

- δr(i) < threshold → 'merged' hits

Approach 3:

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

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



Merging of tracks inside TPC

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

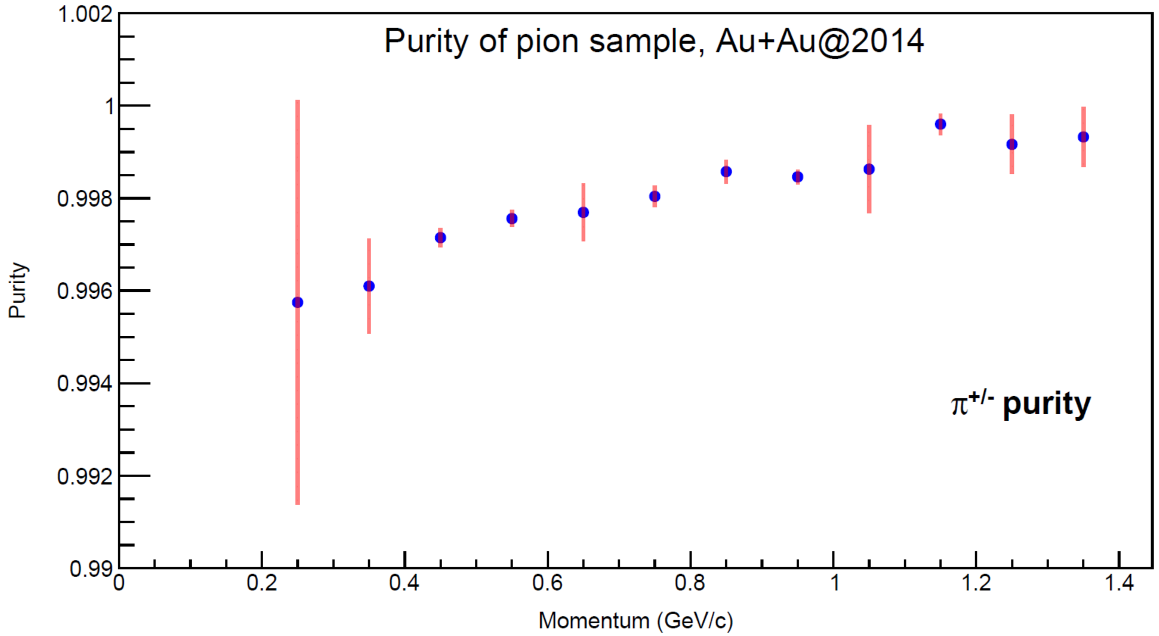
Track cuts

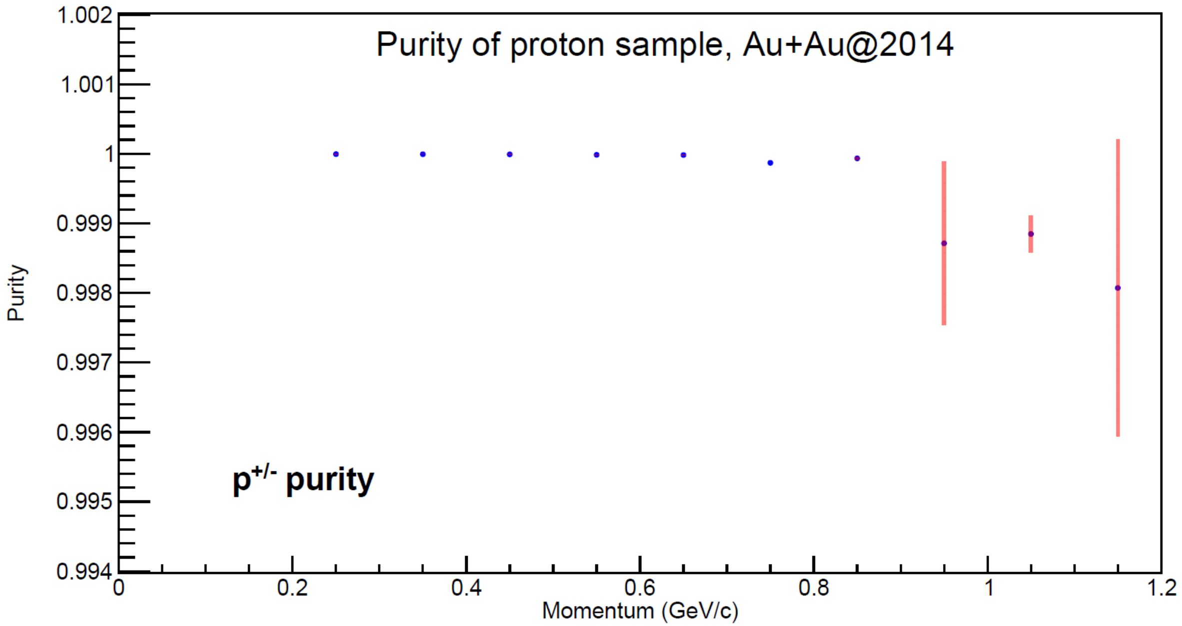
- $p_T > 0.5$ GeV/c
- $|dca| > 0.0050$ cm.
- nHitsFit >= 20
- $|\eta| <= 1.0$

PID cuts for π, K & p

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

Hadron purity distributions





Pion purity
$(99.5 \pm 0.5$ (syst.))%
$p_{\pi} < 1$ GeV/c

Proton purity
$(99.5 \pm 0.5$ (syst.))%
$p_{p} < 1.2$ GeV/c