Femtoscopic correlation between D^0 meson and charged hadrons in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV at STAR

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  - Femtoscopic correlation
- Experiment
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  - D^0 reconstruction
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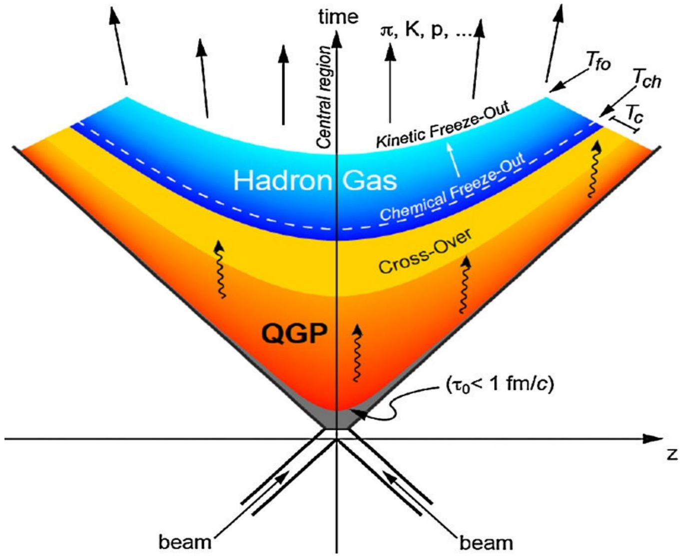
- Summary

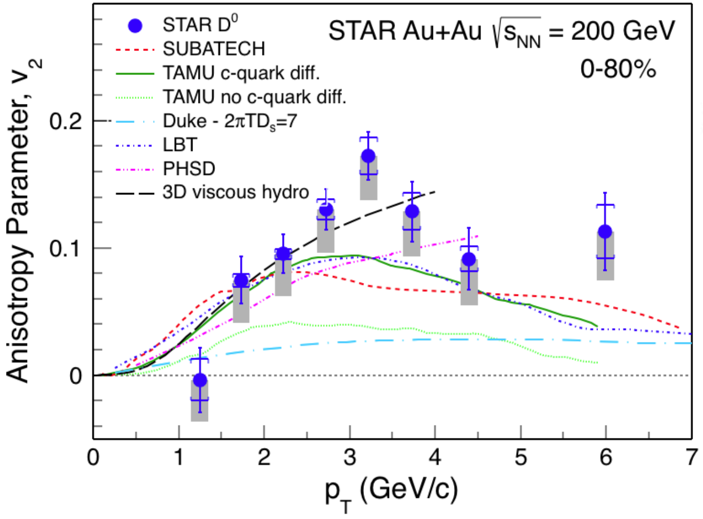
Motivation

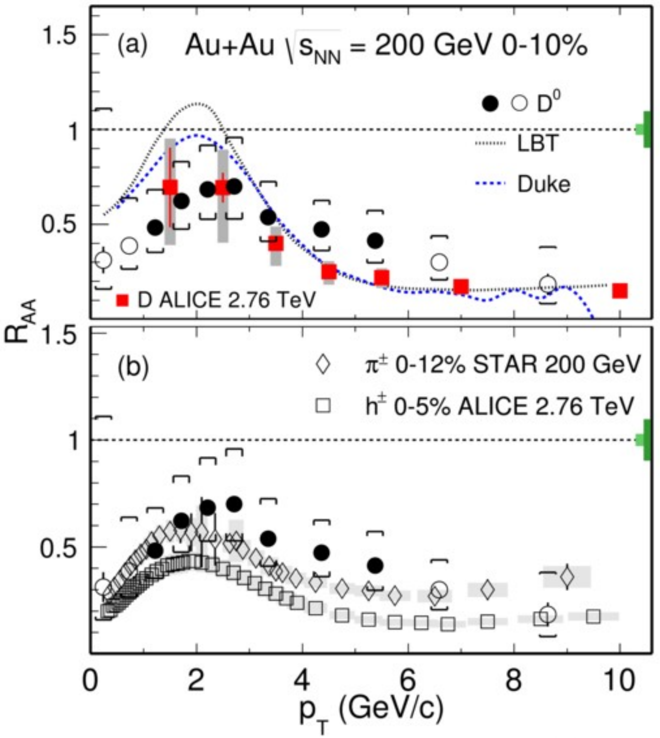
- Heavy quarks (c and b) produced early in collisions → useful to probe all stages of heavy-ion collisions
- Suppression of D^0 meson at high p_T and significant D^0 elliptic flow observed in heavy-ion collisions at RHIC
  - Strong interaction of charm with quark-gluon plasma
- **New measurements** to constrain different models and gain further insights to QGP properties



Stages of heavy-ion collisions

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

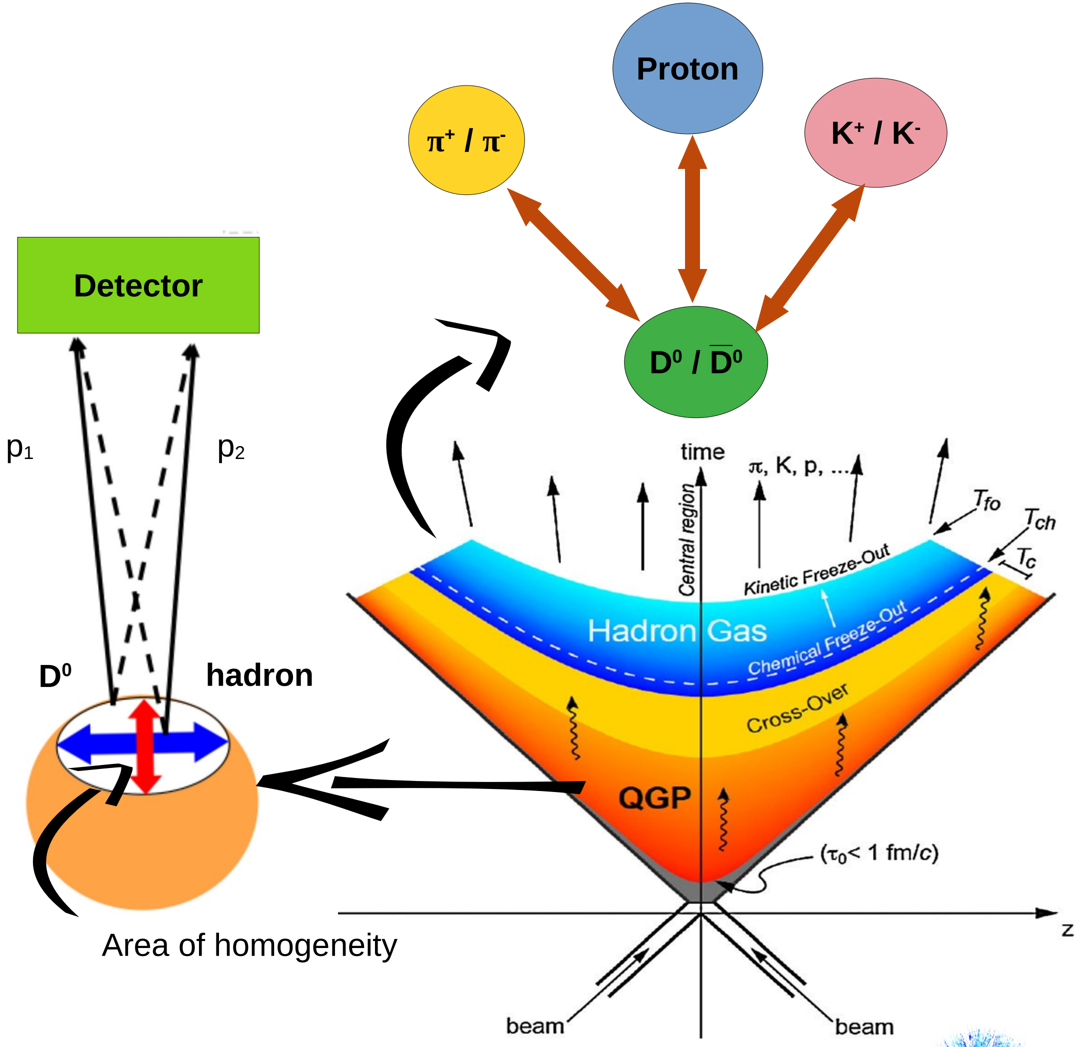




STAR, Phys. Rev. C 99 (2019) 34908

Motivation

- Femtoscopic correlations sensitive to the interactions in the final state as well as the extent of the region from which correlated particles are emitted
- '*Length of homogeneity*' or the average distance between emission points of D^0-hadron pair
- Can provide additional information about the correlation of hadrons and charmed mesons at the freeze-out



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

Femtoscopic correlation

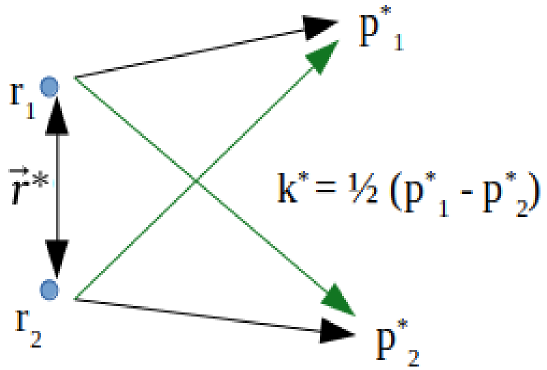
- Femtoscopic correlations are observed between pair of particles with low relative momentum
- It is measured as a function of the reduced momentum difference (k^*) of the pair of particles in rest frame

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

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

$\vec{r}^*$ $\longrightarrow$ relative separation vector (length of homogeneity)

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



Femtoscopic correlation & k^*

- Femtoscopic Correlation $\longrightarrow$ QS + FSI
  - Quantum Statistics [QS]: Bose-Einstein QS or Fermi-Dirac QS
  - Final-State-Interaction [FSI]: Strong & Coulomb interaction

Lednický–Lyuboshitz model

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

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

where, $Q = 2k^*$,

$$F_1(z) = \int_0^z dx\, e^{x^2 - z^2}/z$$

$$F_2(z) = (1 - e^{-z^2})/z.$$

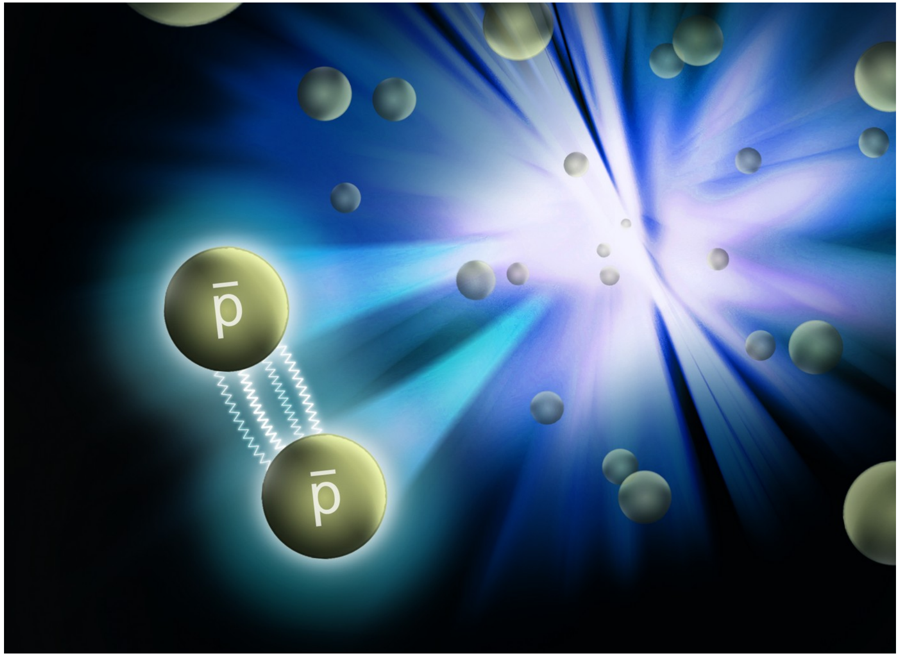
- This model assumes $\vec{r}^*$ (average separation vector) from eq. (1), follows Gaussian distribution

$$d^3N/d^3r^* \sim e^{-\mathbf{r}^{*2}/4r_0^2}, \quad (3)$$

where, r_0 is effective radius of the source

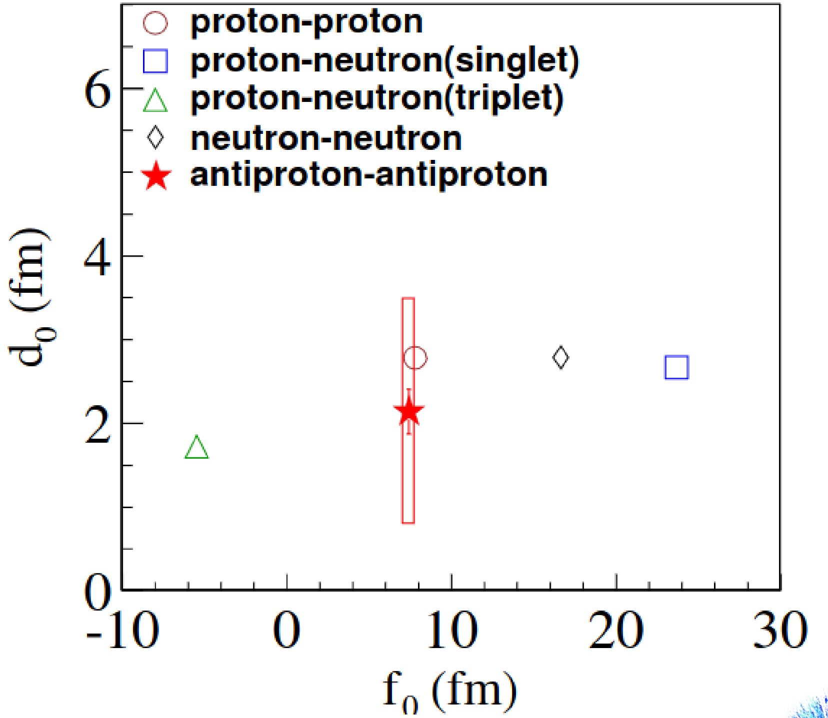
What can we learn from femtoscopy?

- **Parameters of final-state interactions**
- Example: **interaction between antiprotons is the same as between protons**



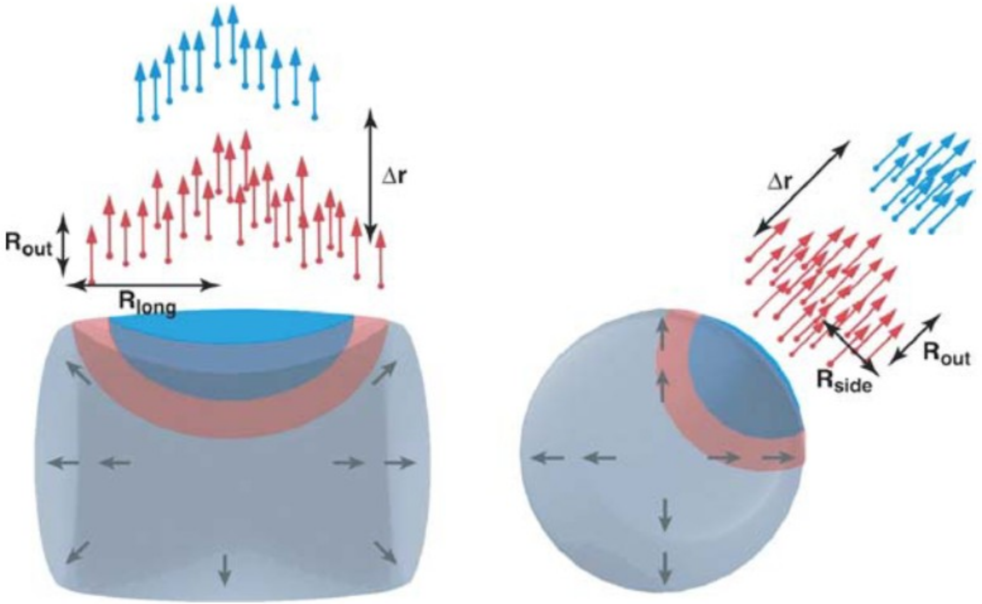
https://www.bnl.gov/newsroom/news.php?a=111786

STAR, Nature 527 (2015) 345



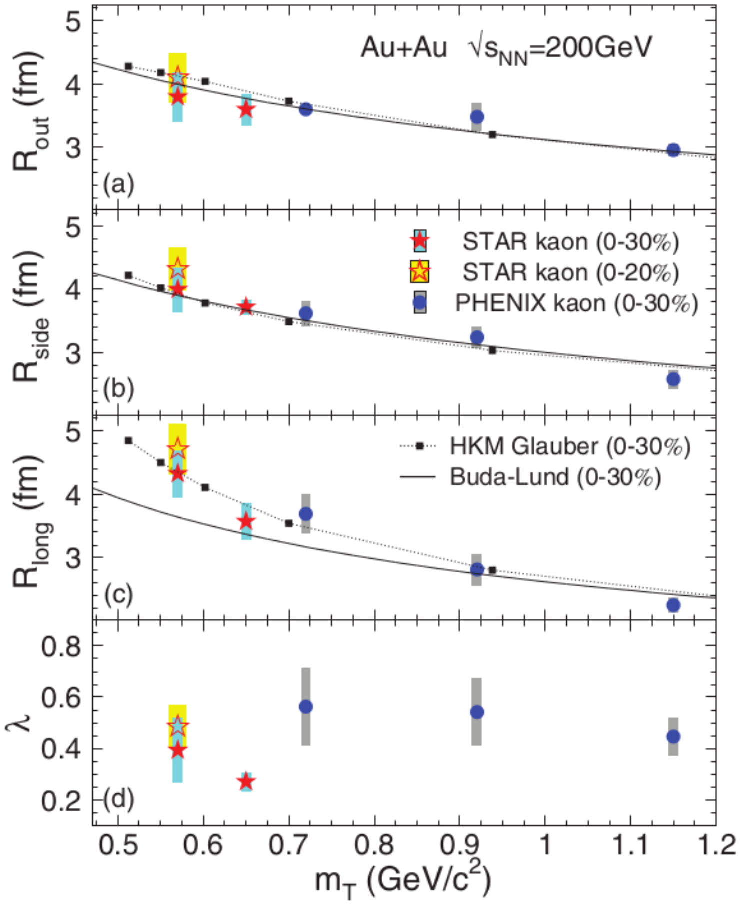
What can we learn from femtoscopy?

- **Properties of the nuclear medium**
- Example: The 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

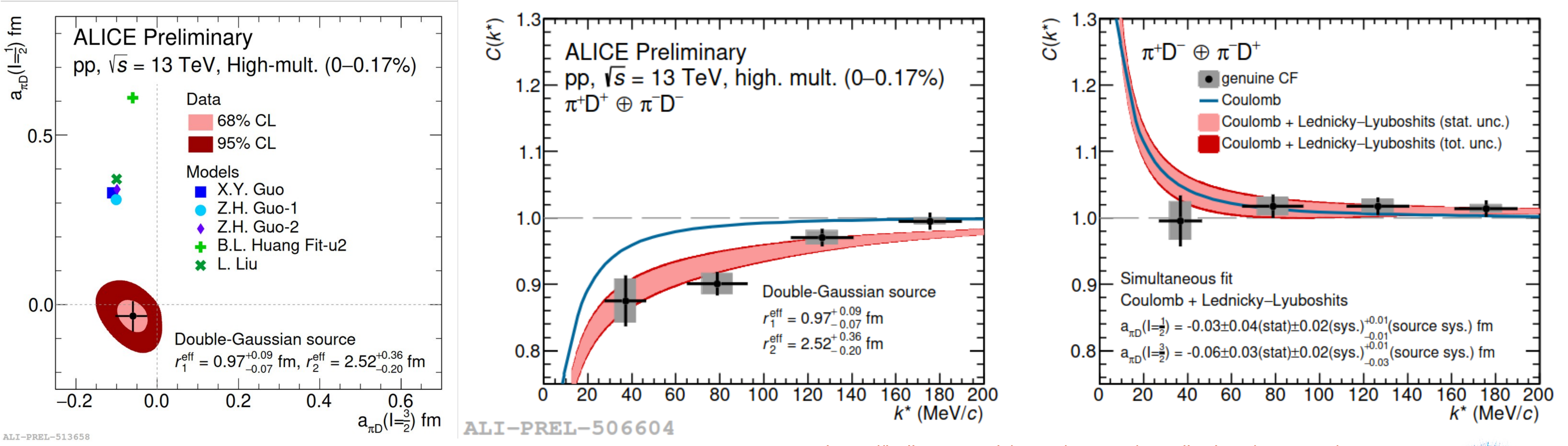
HKM - hydrokinetic model



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

What do we know already about D-hadron femtoscopy?

- First studies of D-hadron interactions in pp by the ALICE experiment
  - Search for new molecular states
  - Measurement of scattering lengths of interactions between charm mesons and light hadrons
- **Small values found suggest small role of D meson re-scattering in the hadronic phase of heavy-ion collisions**

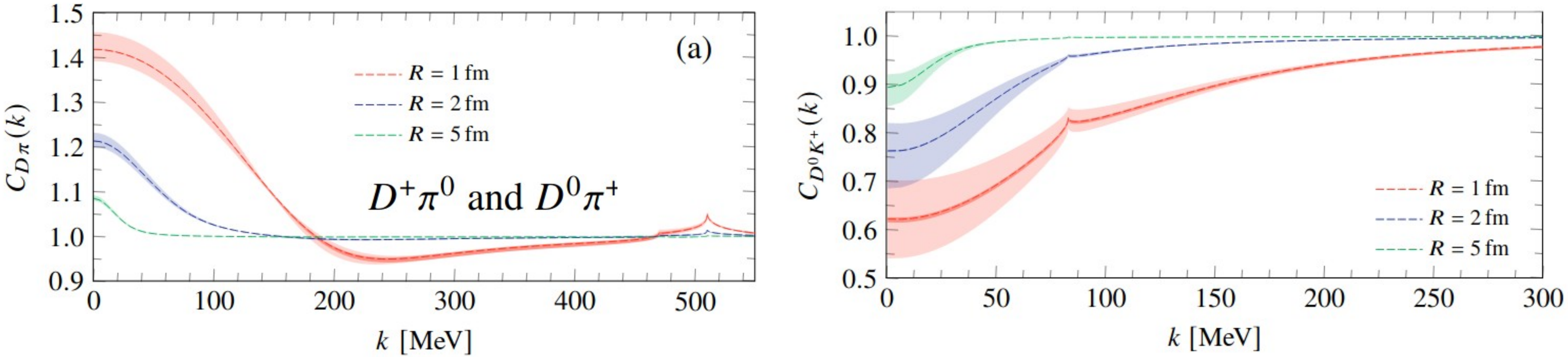


QM 2022: https://indico.cern.ch/event/895086/contributions/4715876/

What can we expect?

- D^0-Kaon and D^0-pion femtoscopic correlation function:

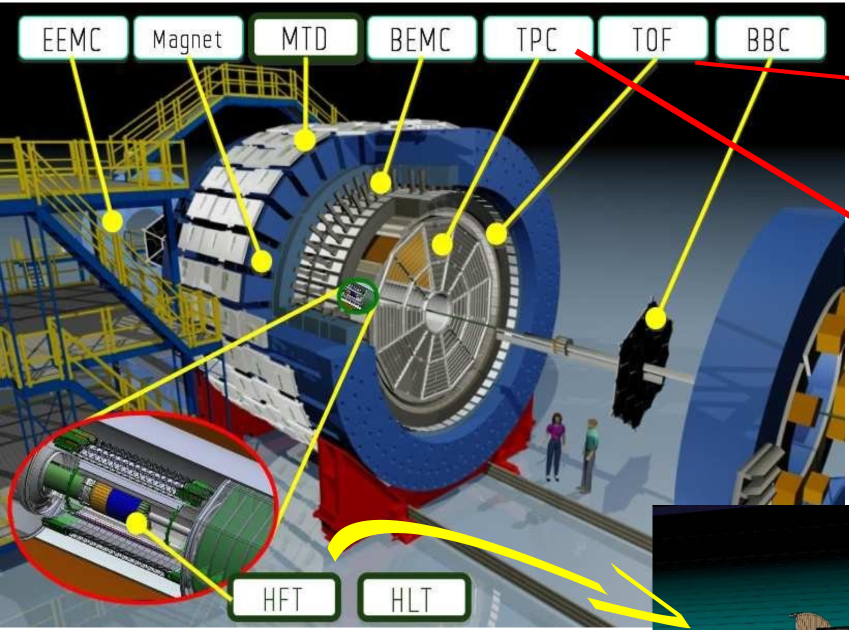
  The larger the source size, the smaller the correlation effect



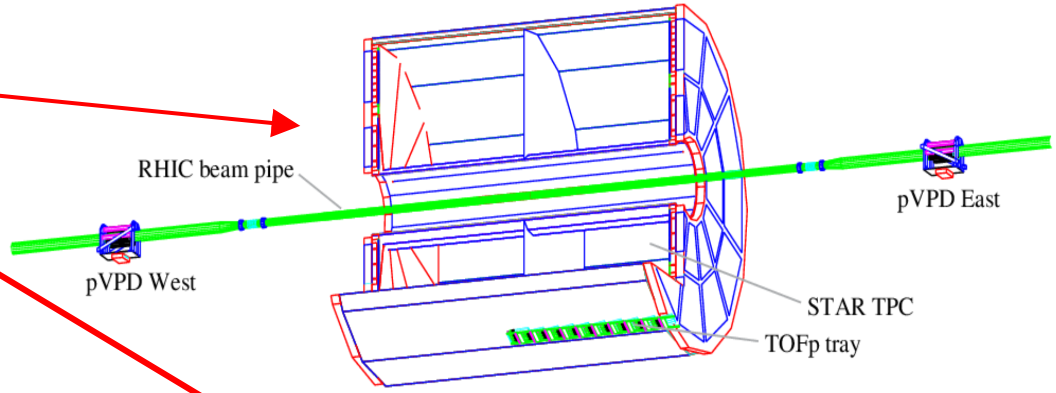
M. Albaladejo , J. Nieves, E. Ruiz Arriola, arXiv:2304.03107v1

- **How to interpret the source size R results for heavy-ion collisions?**
- **Large source size → thermalization of charm quarks with the QGP medium (?)**
- **Small source size → information about the in-medium charm interaction and screening length for strong interactions (?)**
- **One needs calculation for C(k*) from models that include details of charm in-medium interaction**

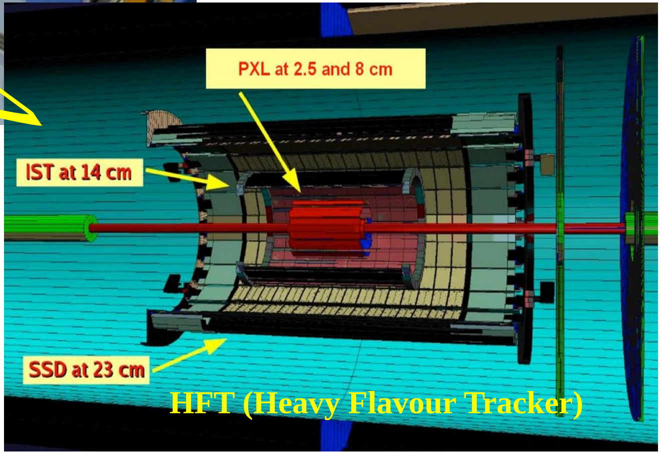
STAR (Solenoidal Tracker At RHIC)

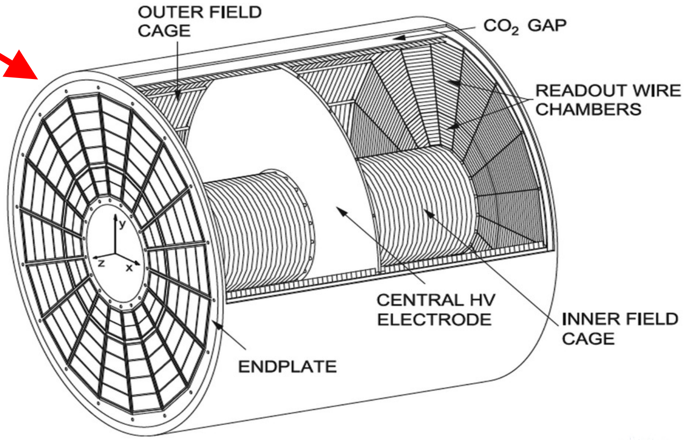


STAR detector system



TOF (Time of Flight)



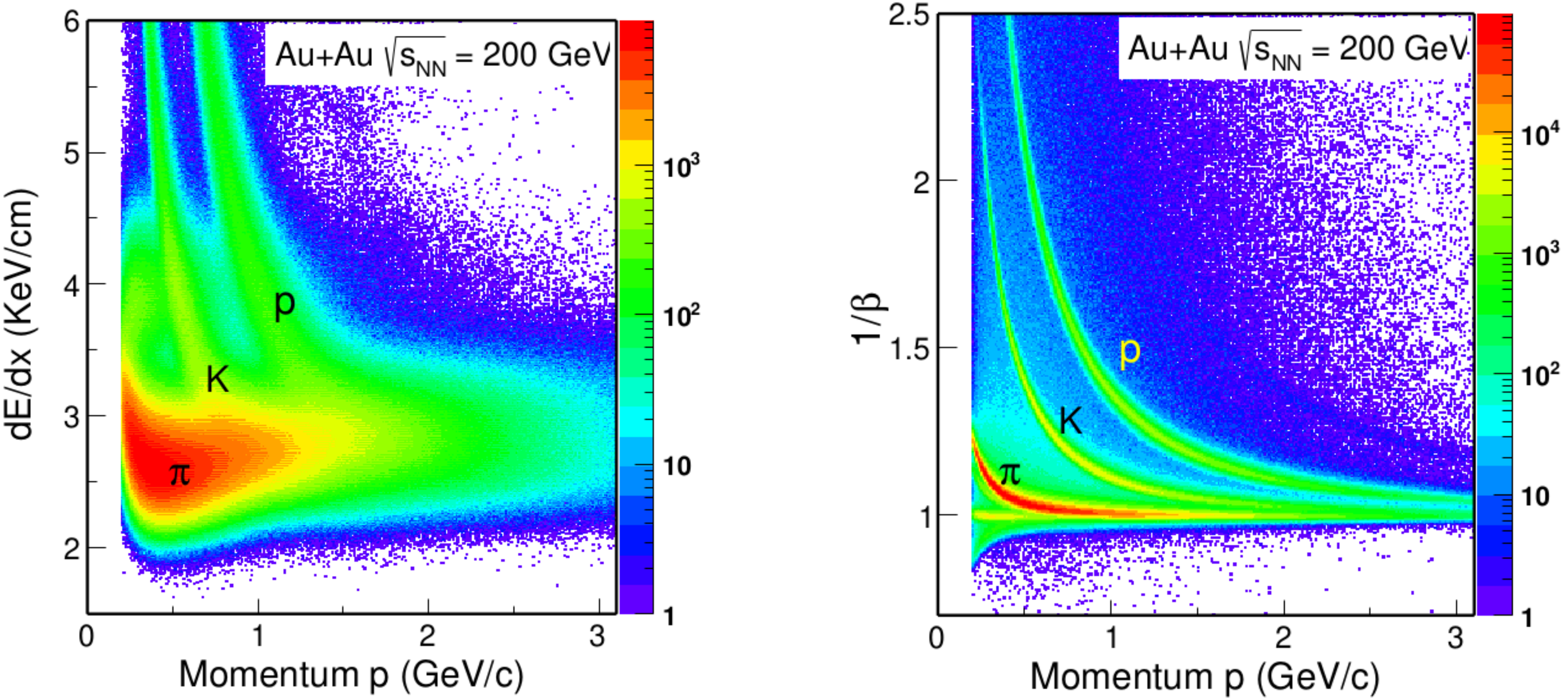


TPC (Time Projection Chamber)

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

Particle Identification (PID)

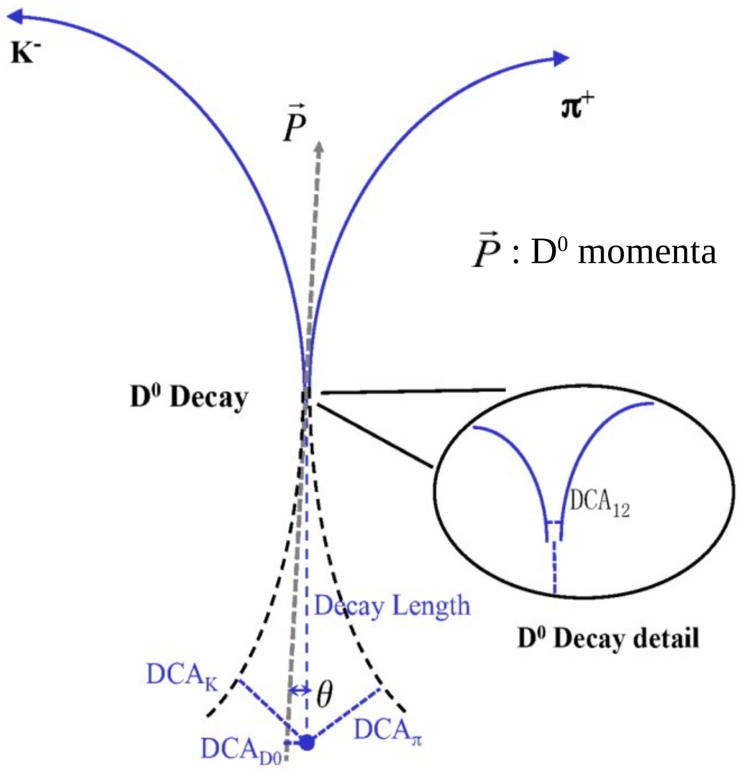
STAR, PRC 99, 034908 (2019)



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

Reconstruction of D^0 meson

STAR, PRC 99, 034908 (2019)



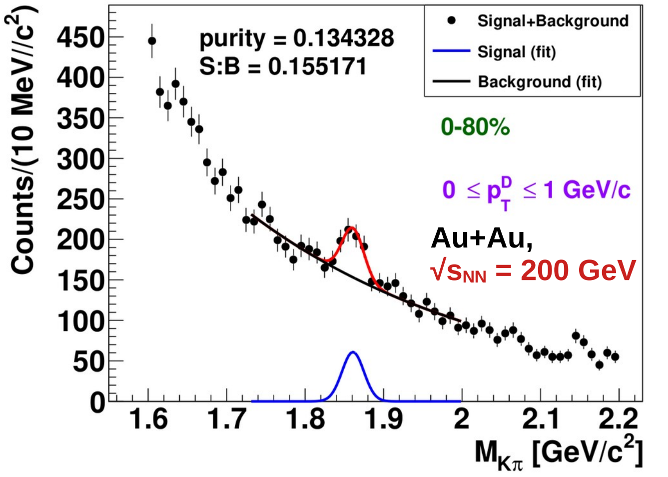
D^0 reconstruction

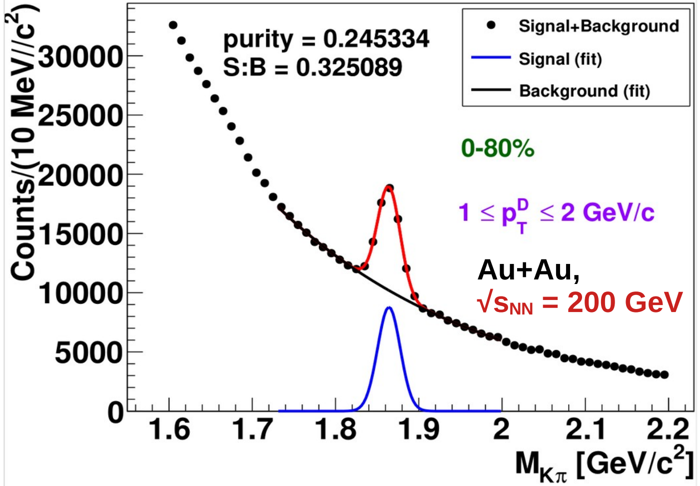
Topological selection cuts for D^0 reconstruction:

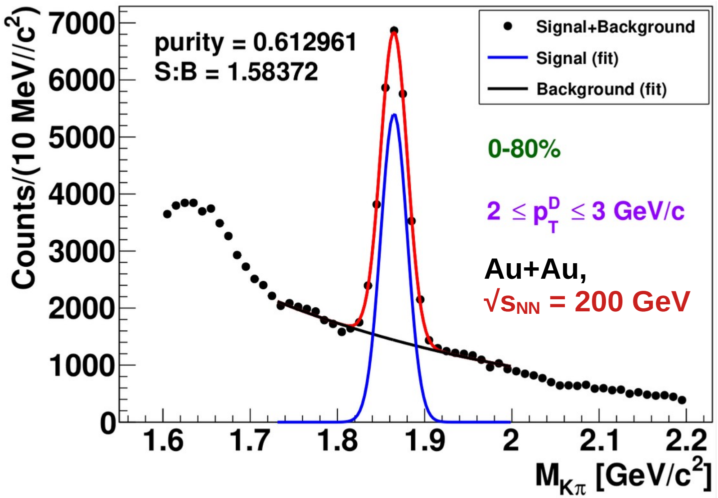
- Decay length - distance between decay vertex and primary vertex (PV)
- Distance of Closest Approach (DCA) between:
  - a) K^- & π^+ - DCA_{12}
  - b) π^+ & PV - DCA_π
  - c) K^- & PV - DCA_K
  - d) D^0 & PV - DCA_{D0}
- θ - angle between $\vec{P}$ & decay length

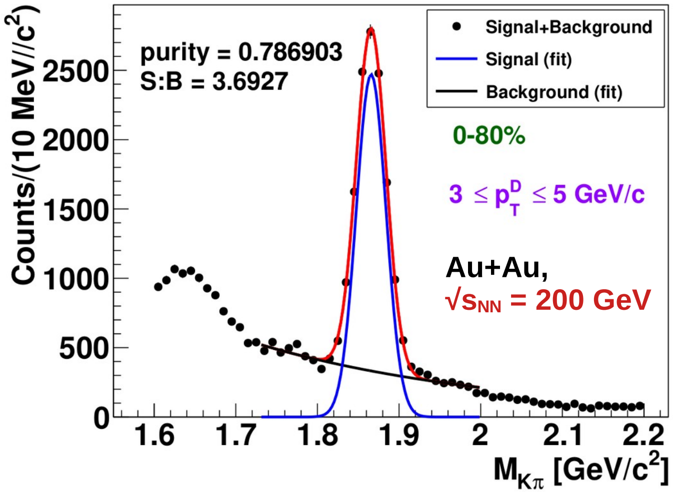
D^0 decay length ($c\tau$) ~ 123 μm

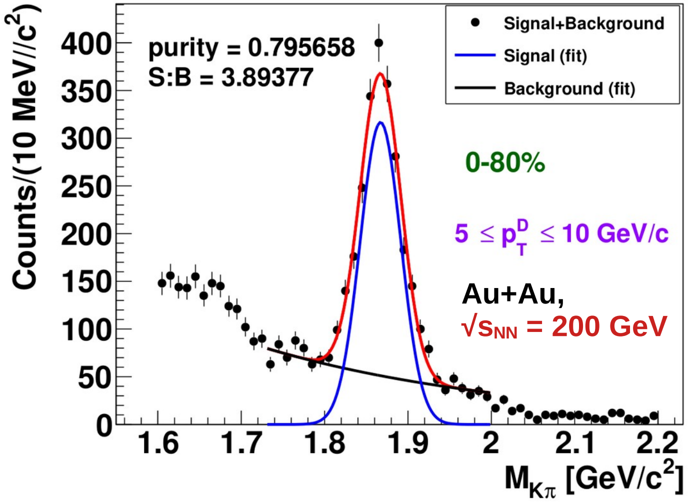
D^0 invariant mass: D^0 signal fit: Gaussian; BG fit: exponential











D^0 inv mass in different p_T intervals

- D^0 invariant mass range:
  1.82 – 1.91 GeV/c^2
- D^0 purity:
  signal / (signal + background)
- Very good signal/background ratio for p_T > 1 GeV/c

Experimental determination of correlation function

- Applied formula to measure correlation function $C(k^*)$ for D^0 - (π/p/K) pairs

$$C(\vec{k}^*) = \mathcal{N}\frac{A(\vec{k}^*)}{B(\vec{k}^*)}.$$

where, $A(\vec{k}^*)$ and $B(\vec{k}^*)$ $\rightarrow$ k^* distributions for correlated and uncorrelated pairs

$\mathcal{N}$ $\rightarrow$ normalization factor

- Event mixing technique to construct k^* distribution for uncorrelated pairs
- D^0 p_T range 1-10 GeV/c in 0-80% centrality range

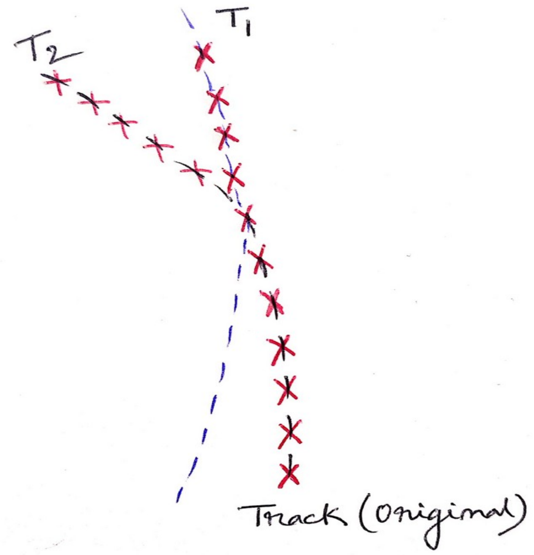
Experimental challenges

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 daughters (π and 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 for TPC tracks.

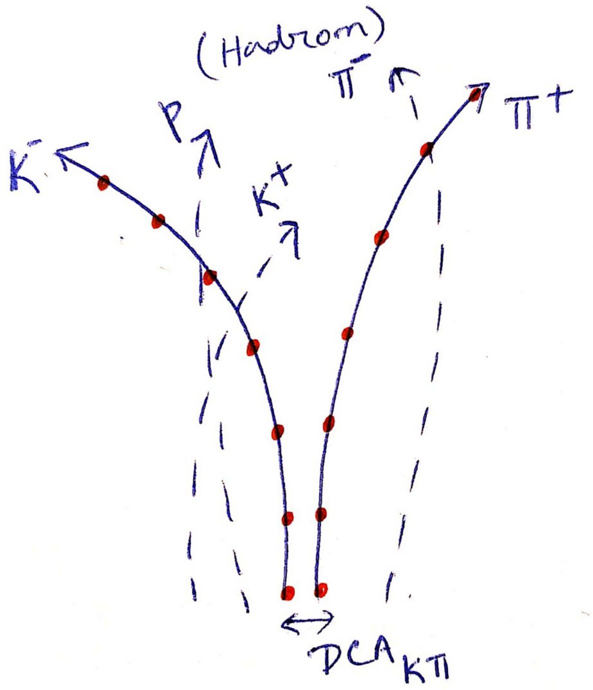
More than 51% of max. possible no. of TPC hits



Track splitting

Experimental challenges

3. Track merging:



Merging of tracks inside TPC

- Track merging causes a depletion of pairs at low relative momentum and appears when two tracks are registered as a single one
- The merging effect affects mostly non-identical particle combinations with opposite charges. Due to the magnetic field their curves go in opposite directions and if the angle between tracks is too small, they are treated as a single track
- **$\delta r(i)$ < mean TPC distance separation → 'merged' hits**
- $\delta r(i)$ - distance between TPC hits on two tracks
- Pair of tracks with fraction of merged hits > 5% were removed as 'merged tracks'

Summary & Future Plans

- First experimental analysis of D^0-hadron femtoscopy in Au+Au collisions at STAR is ongoing
- Model study (ex. Lednický–Lyuboshitz) is on the plan to extract interaction parameters, like emission source size
- This study can provide additional input on interactions of charm quarks within the QGP medium
- Model calculations needed that include details of charm interactions with the QGP for the interpretation of the results

Back Ups

Analysis cuts

Event cuts

- $|V_z| < 6.0$cm.
- $|V_z - V_z V_{pd}| < 3.0$cm.
- $|V_{x|} > 1.0$e-5 cm.
- $|V_y| > 1.0$e-5 cm.
- $\sqrt{[(V_x)^2 + (V_y)^2]} <= 2.0$
- Centrality = 0-80%

Track cuts

- p_T >0.5 GeV/c
- |dca_sign| >0.0050cm.
- nHitsFit >= 20
- |pseudorapidity| <=1.0

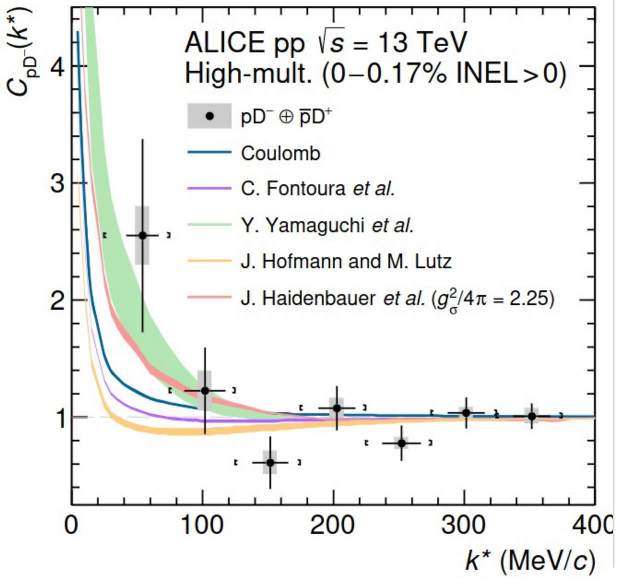
PID cuts for Pions, Kaons & Protons

- |nSigmaPion| < 3.0
- |nSigmaKaon| < 2.0 & |nSigmaProton| < 2.0
- |(1/beta) - (1/beta_{Pion})| < 0.03
- |(1/beta) - (1/beta_{Kaon})| < 0.03
- |(1/beta) - (1/beta_{Proton})| < 0.03

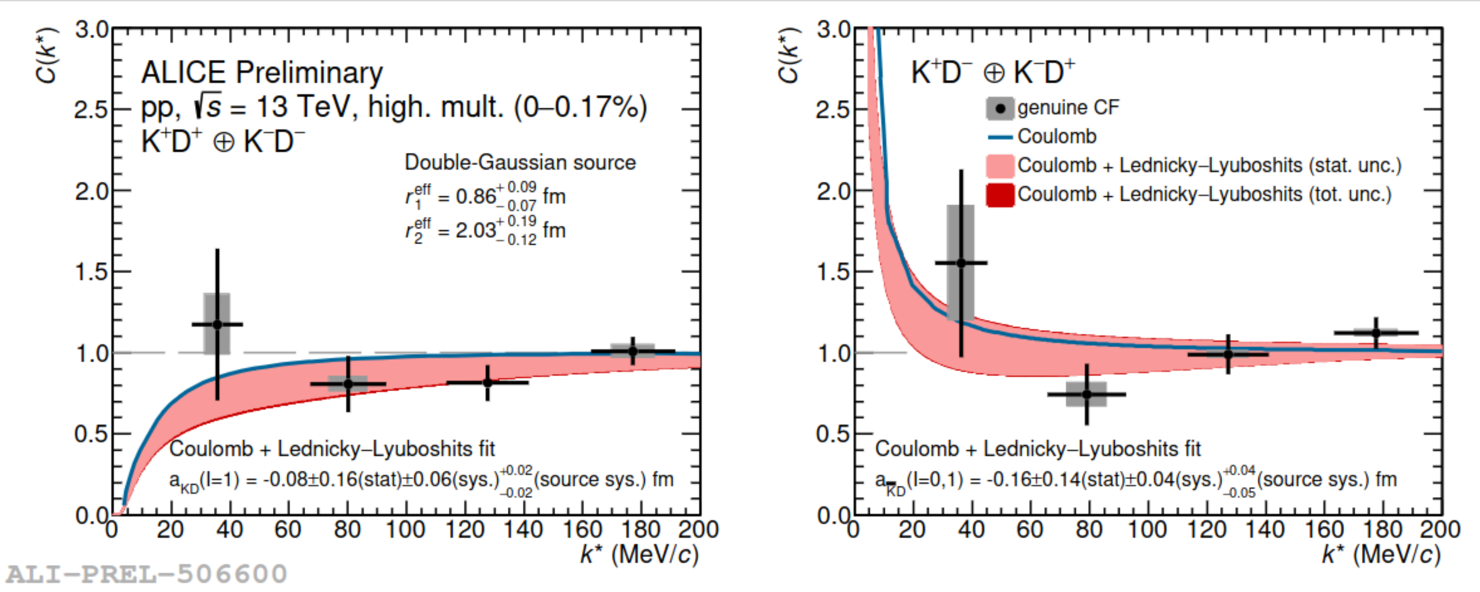
What do we know already about D-hadron femtoscopy?

- First studies of D-hadron interactions in p+p by the ALICE experiment

  Within sizable uncertainties:
- $D^{\pm}$-proton and $D^{\pm}$- Kaon: results compatible with Coulomb interaction only and with shallow attractive strong interaction



Phys.Rev.D 106 (2022) 052010

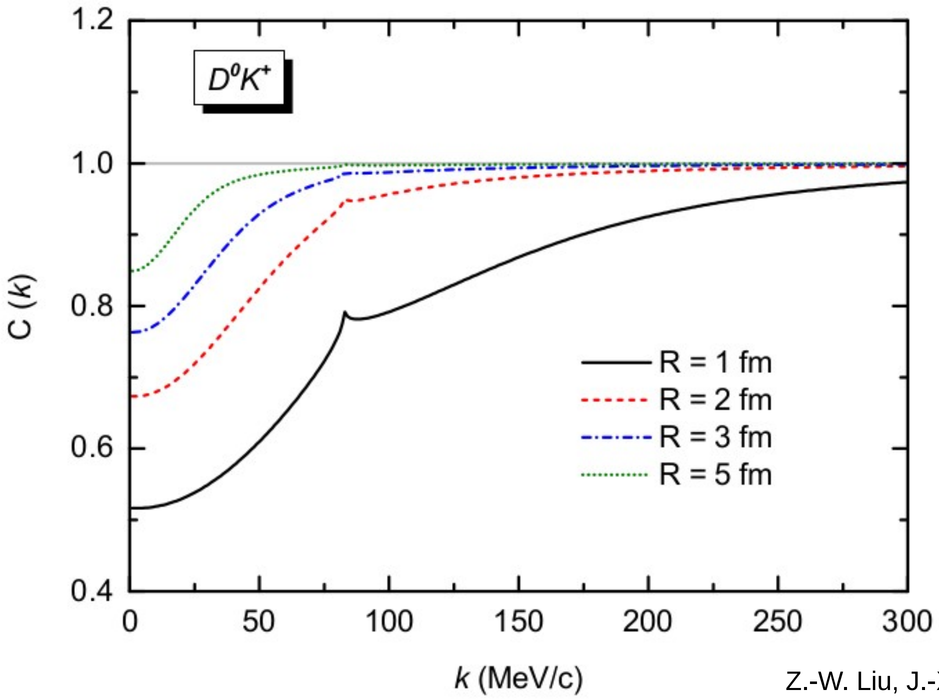


QM 2022: https://indico.cern.ch/event/895086/contributions/4715876/

What can we expect in heavy-ion collisions?

- D^0-Kaon and D^0-pion femtoscopic correlation function:

The larger the source size, the smaller the correlation effect



Z.-W. Liu, J.-X. Lu, L.-S. Geng, arXiv:2302.01046