The XXIXth International Conference On Ultrarelativstic Nucleus-Nucleus Collisions

Femtoscopy of Proton, Light nuclei, and Strange hadrons in Au+Au Collisions at STAR

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QUARK MATTER KRAKÓW 2022

Outline

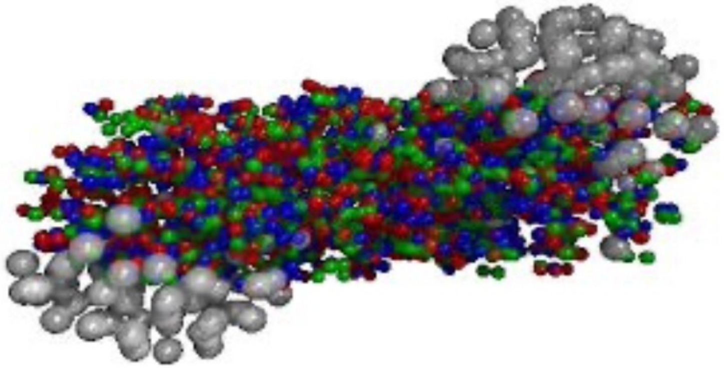
1. Introduction
2. STAR Experiment & Datasets
3. Results
   1) Meson-Meson Correlation Function (K_s^0-K_s^0)
   2) Baryon-Baryon Correlation Function (p-p, p-Ξ^-)
   3) Light Nuclei Correlation Function (p-d, d-d)
4. Summary & Outlook

Introduction

Two-particle correlations at small relative momenta contain information about the space-time characteristics of the emitting source and final-state interaction effects

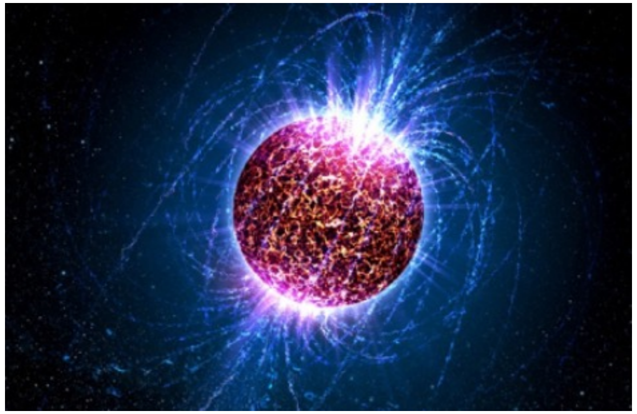
1. Meson-Meson Interaction -> neutral kaons correlation

1) Kaon can provide complementary information to pions
2) Kaon correlation measurement offers space-time evolution involving strangeness



2. Baryon-Baryon Interaction -> p-p and p-Ξ^- correlations

1) p-p interaction can be used as baseline for other systems
2) Hyperon-Nucleon(Y-N) & Hyperon-Hyperon(Y-Y) interaction: Important for understanding the inner structure of compact stars and the formation of bound states

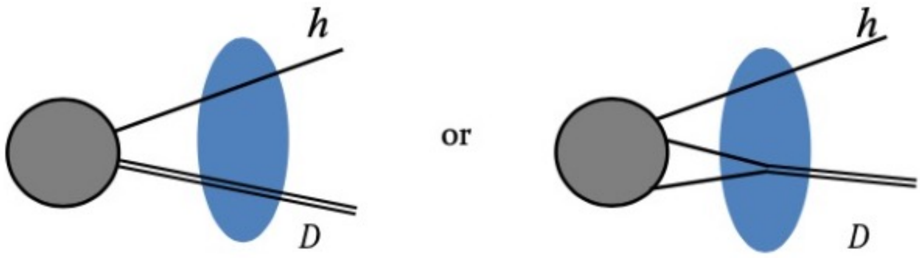


LonardoniD,LovatoA,GandolfiS,PederivaF.Phys.Rev.Lett.114:092301(2015)

Two-particle correlations at small relative momenta contain information about the space-time characteristics of the emitting source and final-state interactions effects

3 . Light Nuclei Correlation -> p-d, d-d correlations

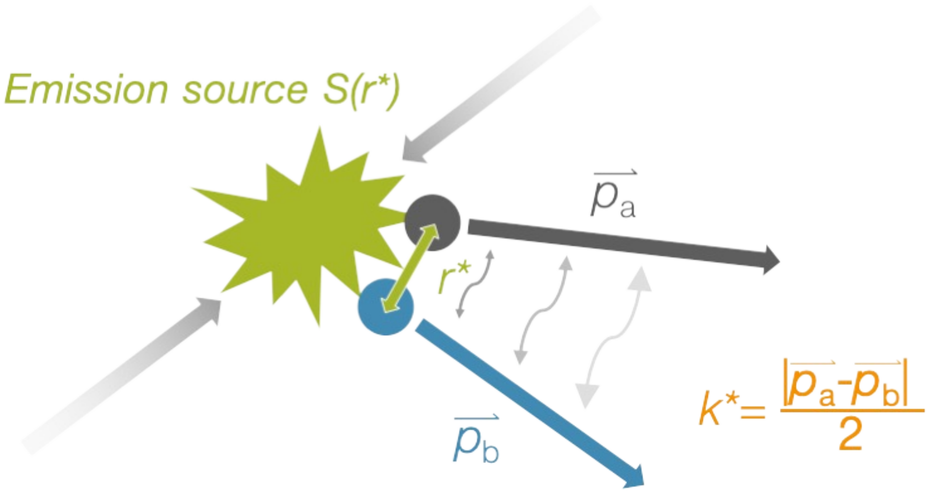
1) A systematic measurement of p-p, p-d, and d-d correlation functions may tell us whether deuterons are directly emitted from the fireball or formed due to final-state interactions
2) A large amount of light nuclei produced at 3 GeV -> Allowing precision measurements



Direct production　　　Coalescence

St. Mrówczyński and P. Słoń, Acta Physica Polonica B 51, 1739 (2020)
St. Mrówczyński and P. Słoń, Physical Review C 104, 024909 (2021)

Analysis Method : Femtoscopy



- ✓ **Femtoscopy (HIC) is inspired by Hanbury Brown and Twiss interferometry method (Astronomy)[1]**
- ✓ **Study the spatial and temporal extent of emission source**
  - **Quantum Statistics (Fermi-Dirac, Bose-Einstein)**
  - **Final-state Interactions (Coulomb, Strong)**
  - **Collision Dynamics**

✓ **Two-particle correlation function:**

Statistical | *Model* | *Experimental*

$$C(k^*) = \frac{\mathcal{P}(\vec{p}_a,\vec{p}_b)}{\mathcal{P}(\vec{p}_a)\mathcal{P}(\vec{p}_b)} = \int S(\vec{r})|\Psi(\vec{k}^*,\vec{r})|^2 d^3\vec{r} = \frac{N_{same}(k^*)}{N_{mixed}(k^*)}$$

- >1: Attraction
- =1: No Correlation
- <1: Replusion

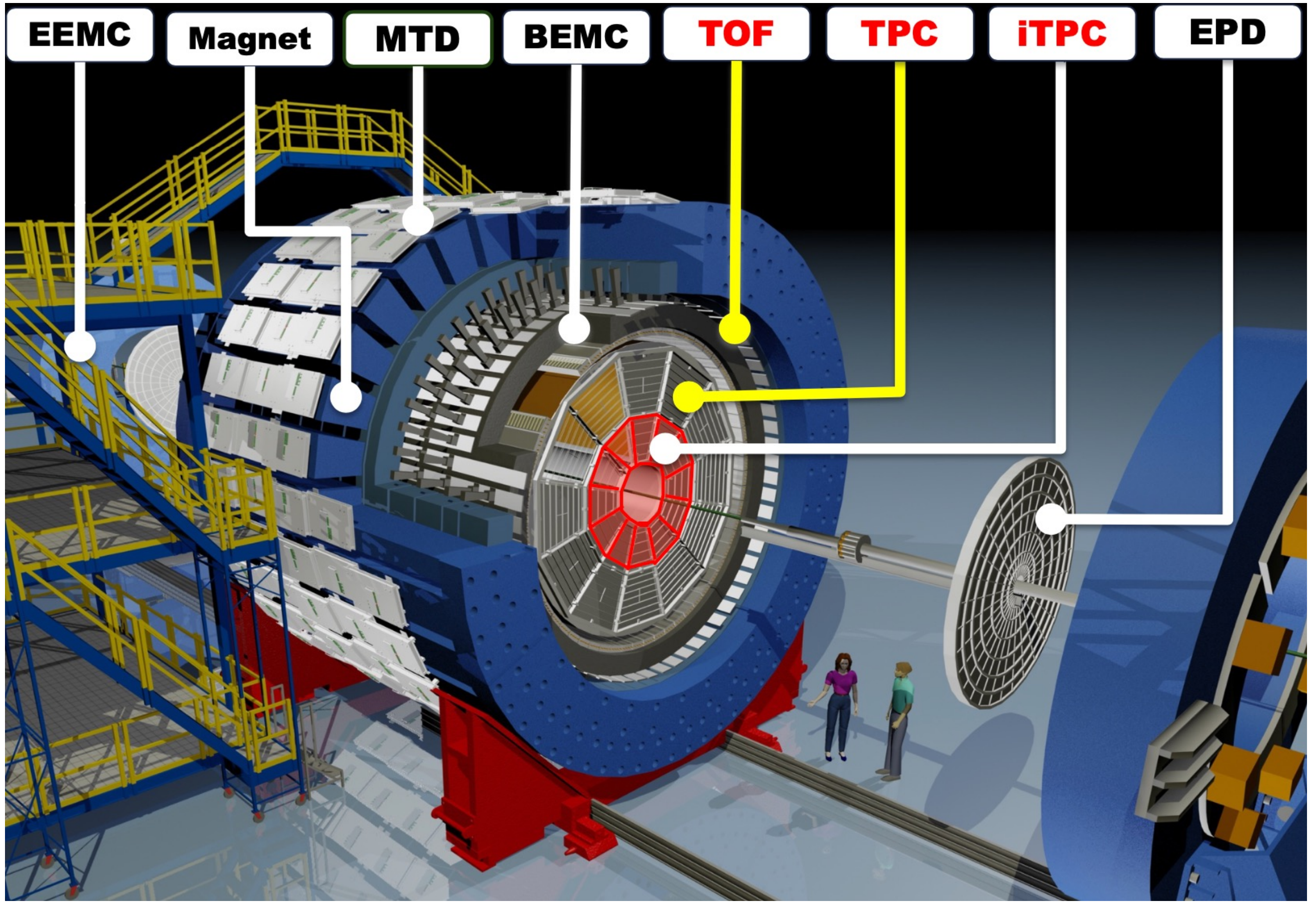
$\vec{p}_a$, $\vec{p}_b$: Single-particle momentum

$S(\vec{r})$: Source function
$\Psi(\vec{k}^*,\vec{r})$: Pair wave function
$k^* = \frac{1}{2}|\vec{p}_a - \vec{p}_b|$, relative momentum
$\vec{r}$: relative distance

$N_{same}(k^*)$: same event
$N_{mixed}(k^*)$: mixed event

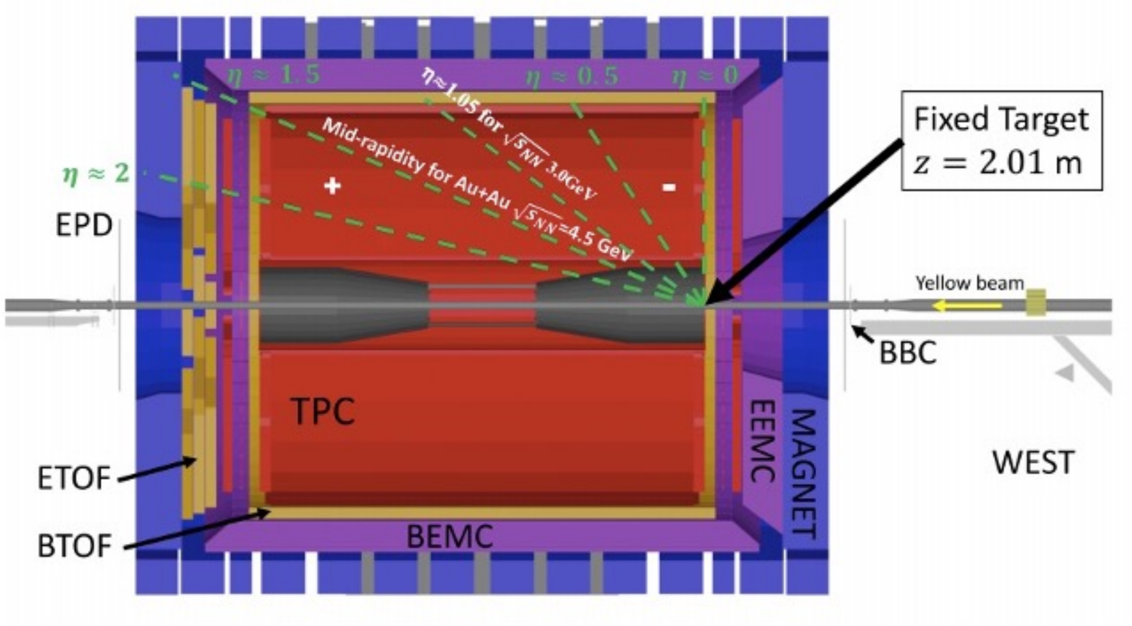
[1]*Nature 178 1046-1048(1956)*
[2]*ALICE Coll. Nature 588, 232–238 (2020)*

STAR Detector and Datasets



- Excellent Particle Identification
- Large, Uniform Acceptance at Mid-rapidity

STAR Fixed-target Experiment Setup

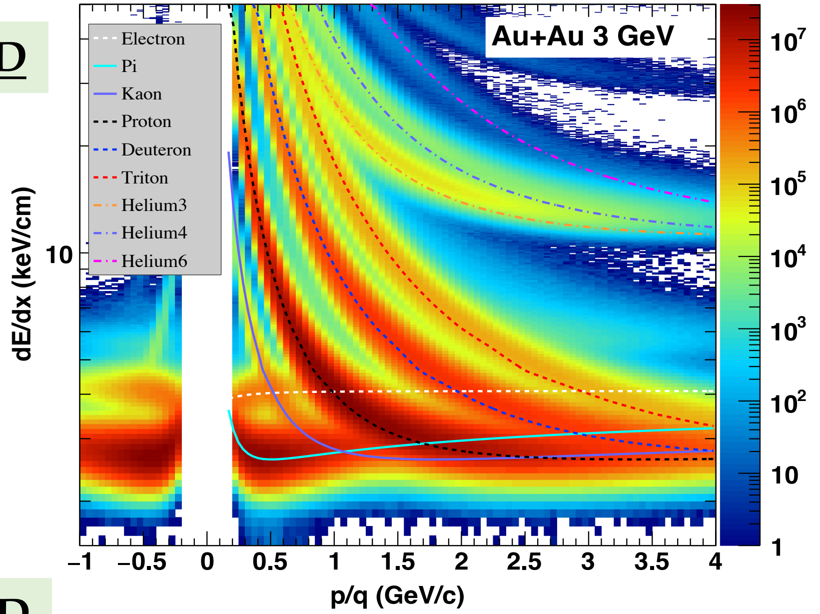


Datasets

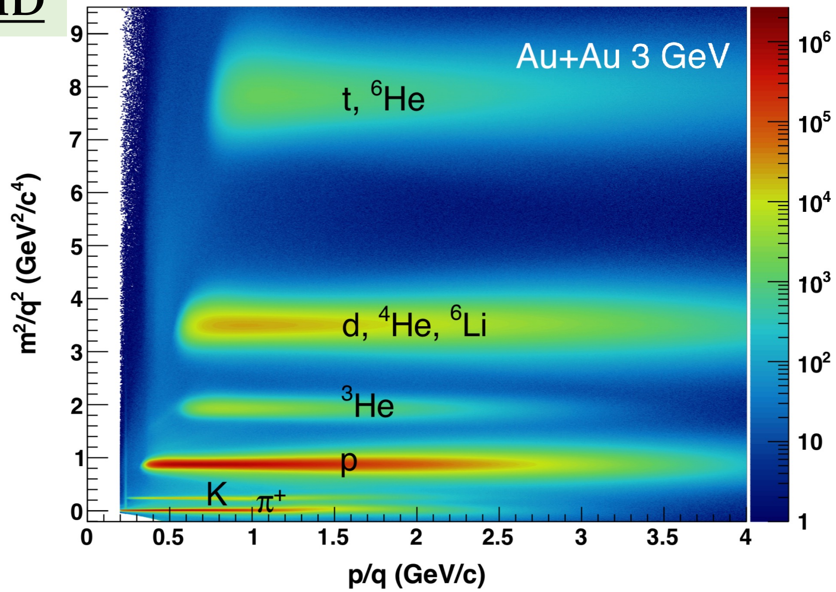
Energy $\sqrt{s_{NN}}$	Year	Mode	Statistics (M)
3 GeV	2018	Fixed-Target	~260
39 GeV	2010	Collider	~86
200 GeV	2010	Collider	~230

Particle Identification and Acceptance at $\sqrt{s_{NN}}$ = 3 GeV

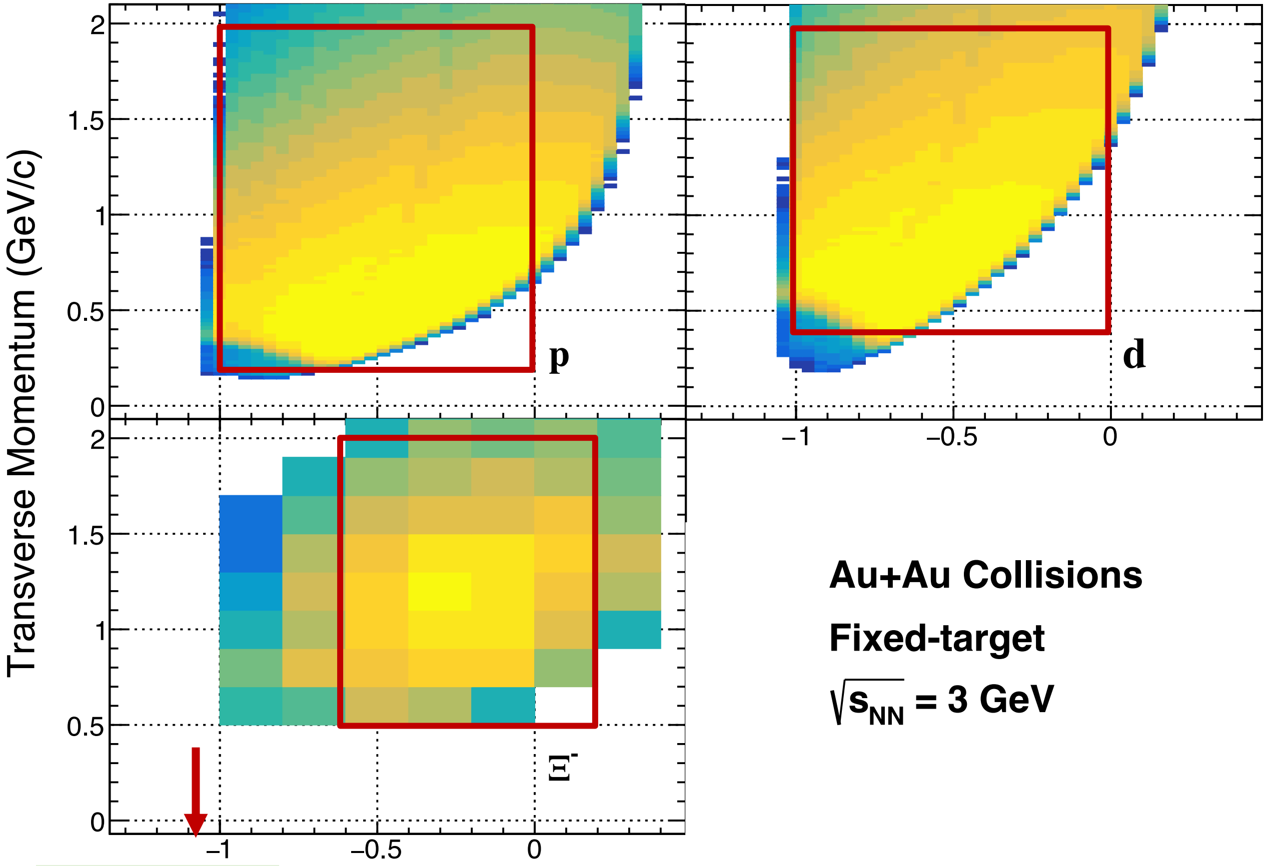
TPC PID



TOF PID



Acceptances



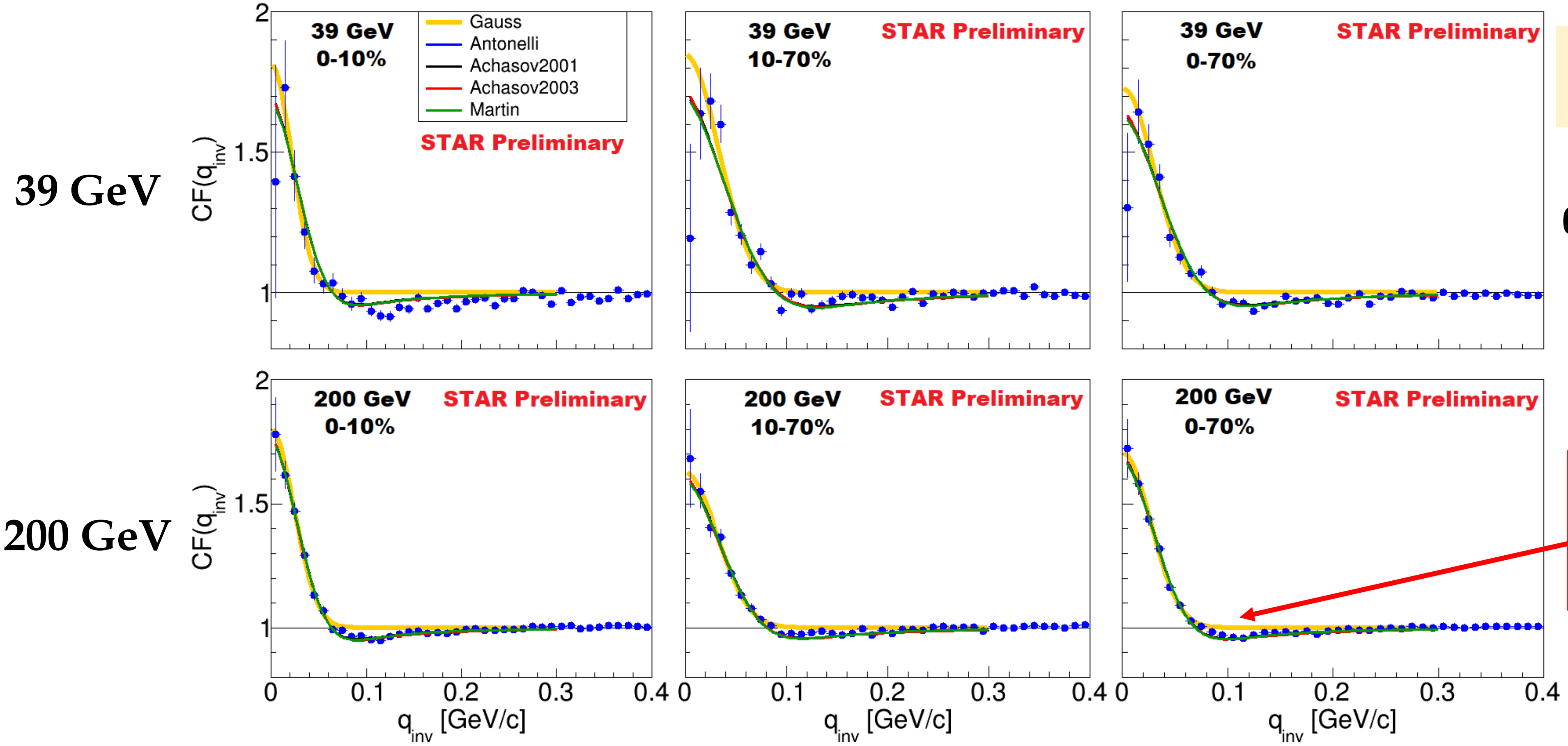
y_{target}=-1.045

Au+Au Collisions
Fixed-target
$\sqrt{s_{NN}}$ = 3 GeV

- p and d: Identified by TPC and TOF
- Ξ^- : Reconstructed via KFParticle Package
  - Ξ^- -> $\Lambda + \pi^-$ -> $p + \pi^- + \pi^-$, *b.r. 99.887%*

Results

$K_s^0 K_s^0$ Femtoscopy in Au+Au Collisions at 39 GeV & 200 GeV



For details, see poster by Diana Pawłowska

$0.4 < p_T < 2.0$ GeV/c

$|y|<0.5$

FSI is needed to reproduce the dip structure

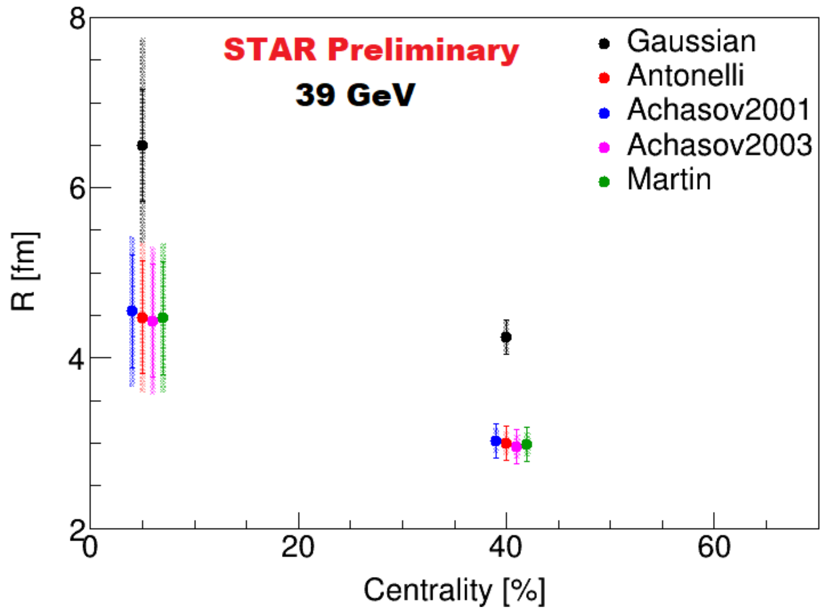
$q_{inv} = 2k^*$

- **Quantum statistics** correlation function (Gaussian) $CF(q_{inv}) = 1 + \lambda e^{[-R_{inv}^2 q_{inv}^2]}$
- Lednicky & Lyuboshitz model (QS + FSI)

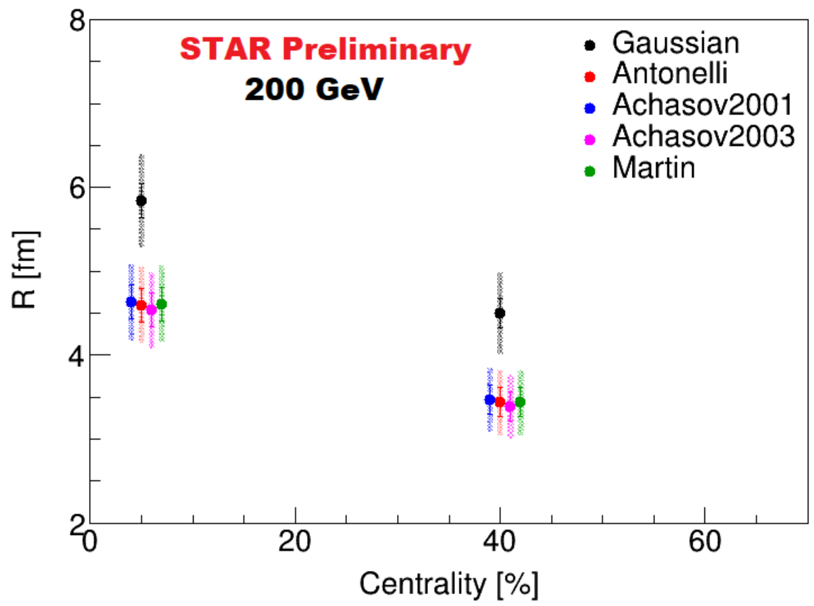
$$CF(q_{inv}) = 1 + \lambda\left(e^{[-R_{inv}^2 q_{inv}^2]} + \frac{1}{2}\left[\left|\frac{f(k^*)}{R_{inv}}\right|^2 + \frac{4\Re f(k^*)}{\sqrt{\pi}R_{inv}} F_1(q_{inv}R_{inv}) - \frac{2\Im f(k^*)}{\sqrt{\pi}R_{inv}} F_2(q_{inv}R_{inv})\right]\right)$$

$K_s^0 K_s^0$ Femtoscopy in Au+Au Collisions at 39 GeV & 200 GeV

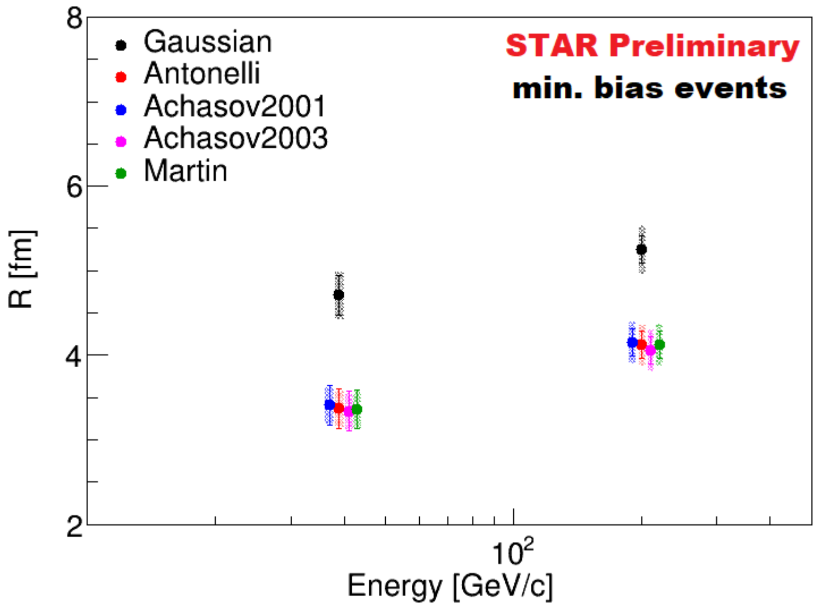
39 GeV



200 GeV



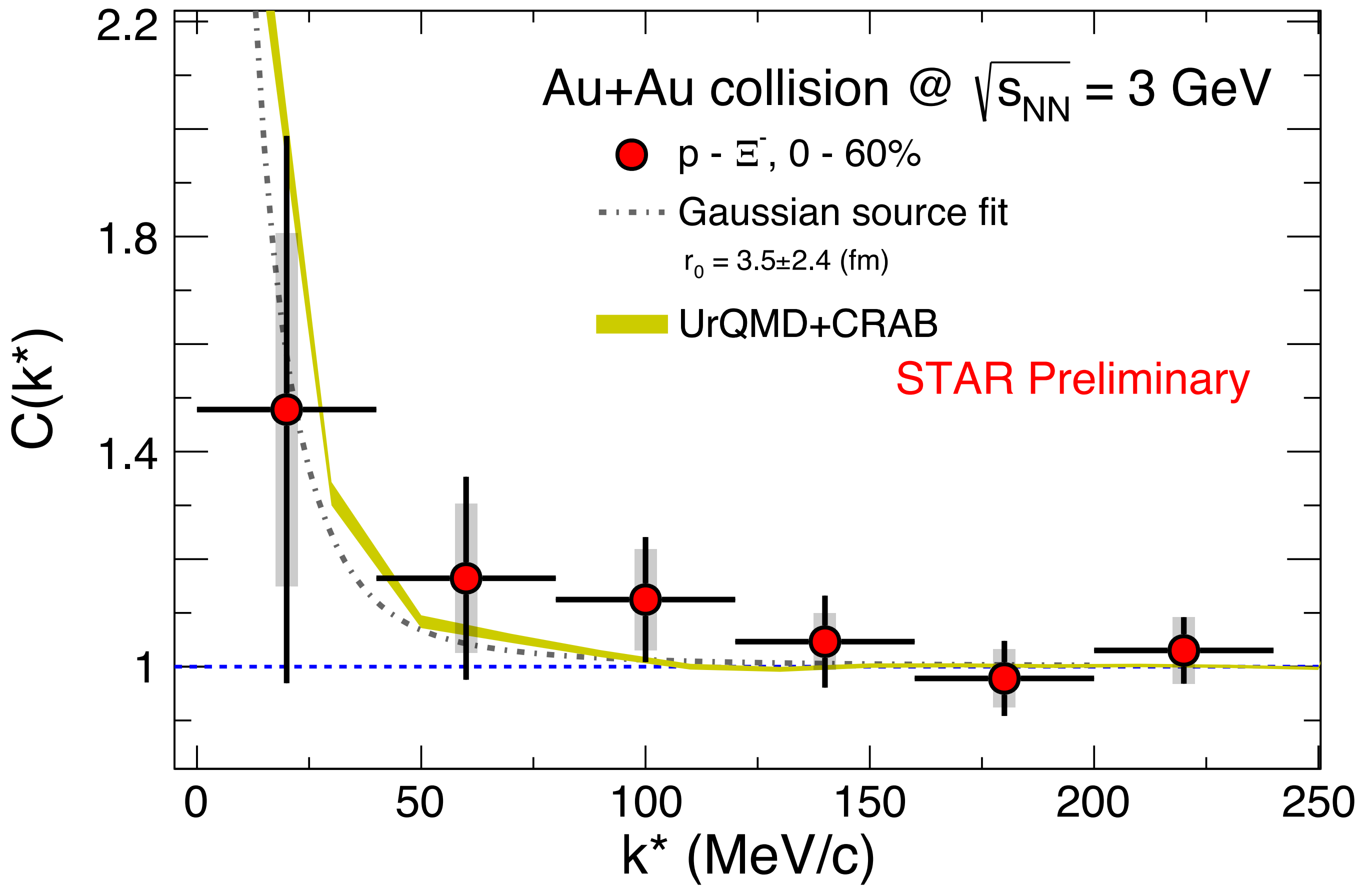
Energy dependence



1. **Centrality dependence:** $R_{0-10\%} > R_{10-70\%}$
2. **Energy dependence:** $R_{200GeV} > R_{39GeV}$
3. **Significant difference in radii between QS and Lednicky & Lyuboshitz models ➡ Final state interactions**

Antonelli: eConf C020620, THAT06 (2002)
Achasov2001: Phys. Rev. D 63, 094007 (2001)
Achasov2003: Phys. Rev. D 68, 014006 (2003)
Martin: Nucl. Phys. B 121, 514–530 (1977)

Proton-Ξ^- Femtoscopy in Au+Au Collisions at 3 GeV

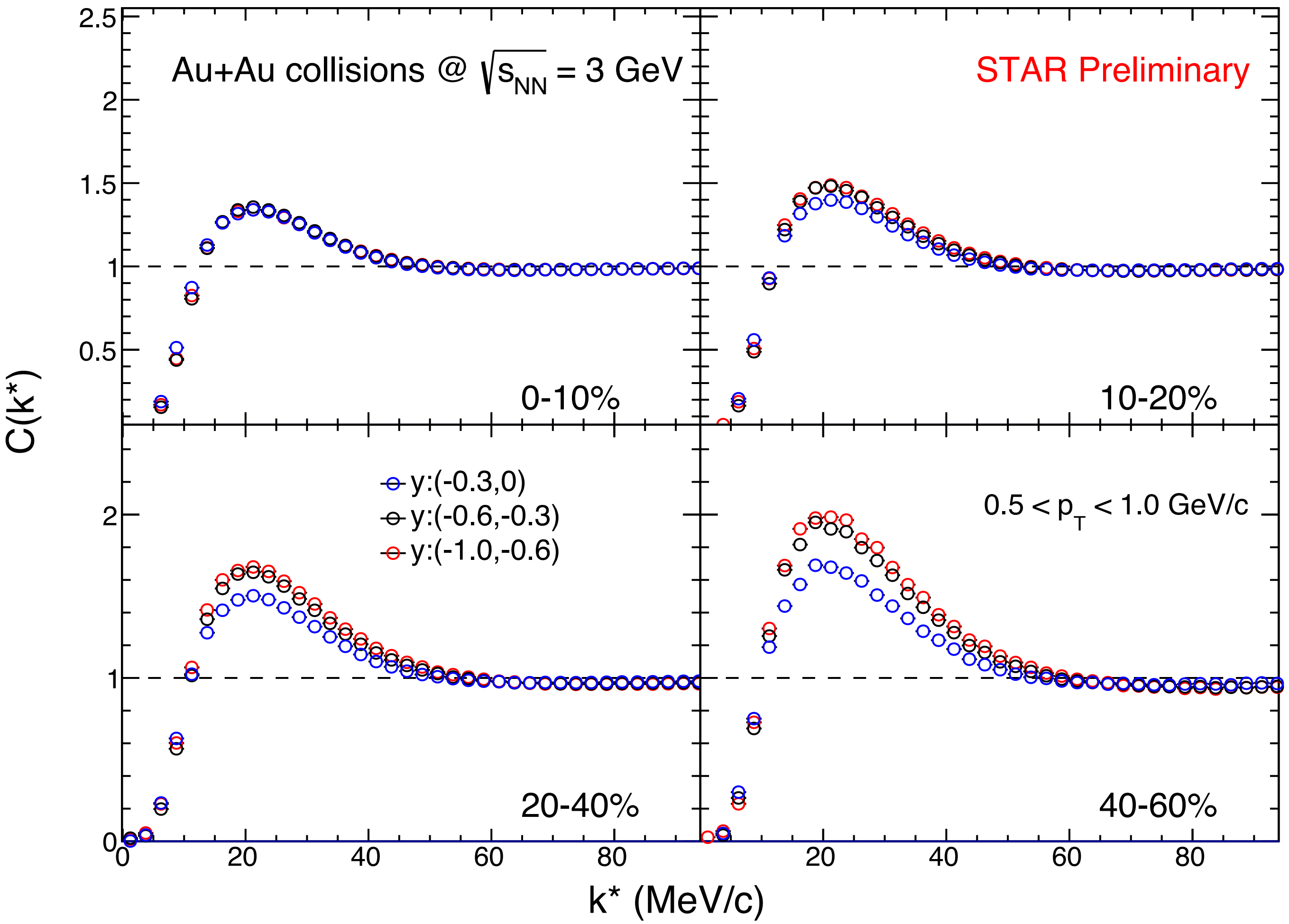


1. **Large uncertainties due to limited proton-Ξ^- pairs at low energy**
2. **Modelled by hadronic transport model UrQMD + an afterburner, model results show a similar trend as data**

For details, see poster by Zhi Qin

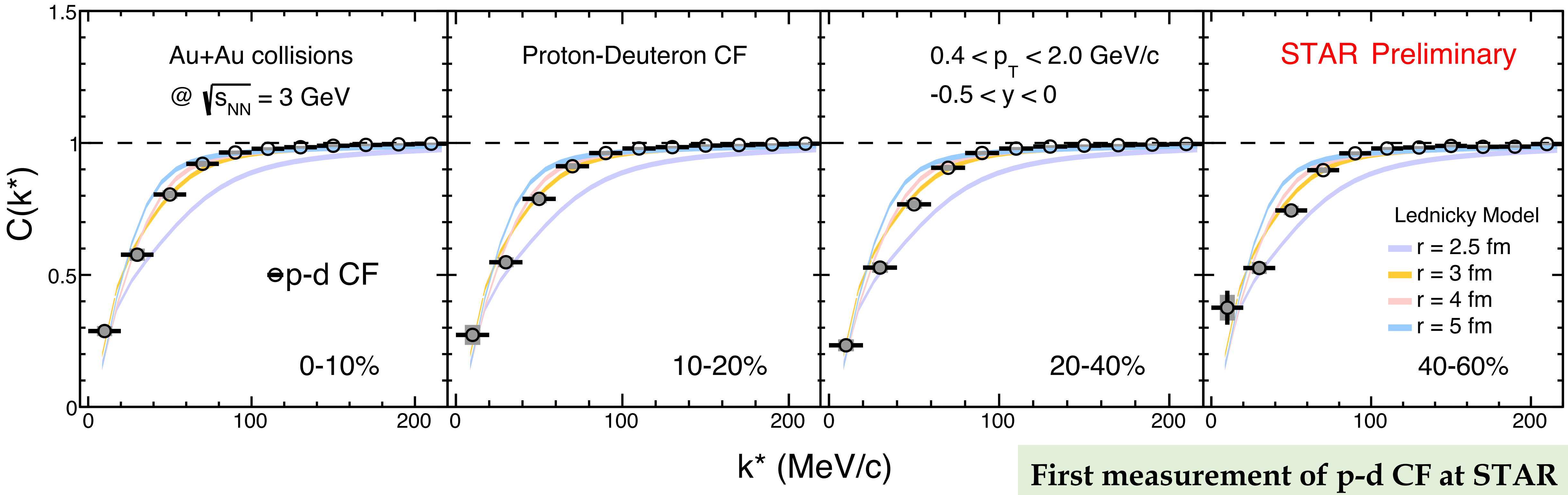
CARB: https://web.pa.msu.edu/people/pratts/freecodes/crab/home.html

Proton-Proton Femtoscopy in Au+Au Collisions at 3 GeV



1. **Clear centrality dependence seen -> Smaller source size in peripheral collisions**
2. **More siginificant rapidity dependence in peripheral collisions**

Proton-Deuteron Femtoscopy in Au+Au Collisions at 3 GeV

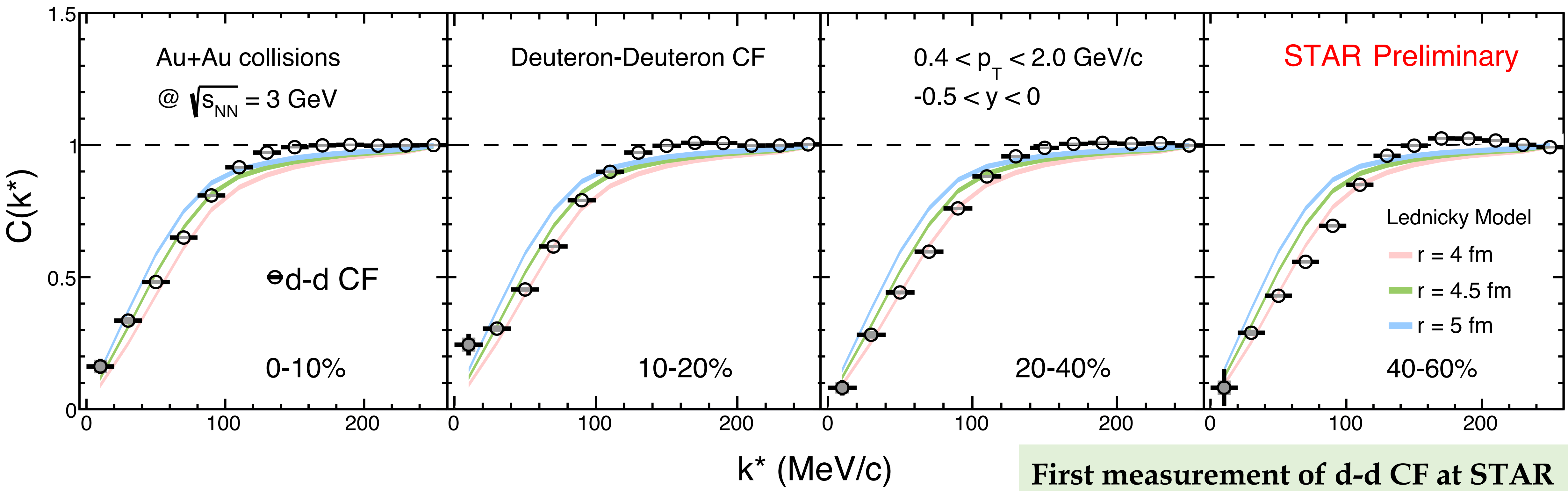


First measurement of p-d CF at STAR

1. **Clear depletion at small k* range seen in data**
2. **Data compared with Lednicky & Lyuboshitz model[1,2]**
   - ➢ **A spherical source size with r = 3-4 fm is consistent with data**

1.LednickýR,LyuboshitzV.Sov.J.Nucl.Phys.35:770(1982)
2.J. Arvieux, Nucl. Phys. A 221 (1974) 253–268

Deuteron-Deuteron Femtoscopy in Au+Au Collisions at 3 GeV

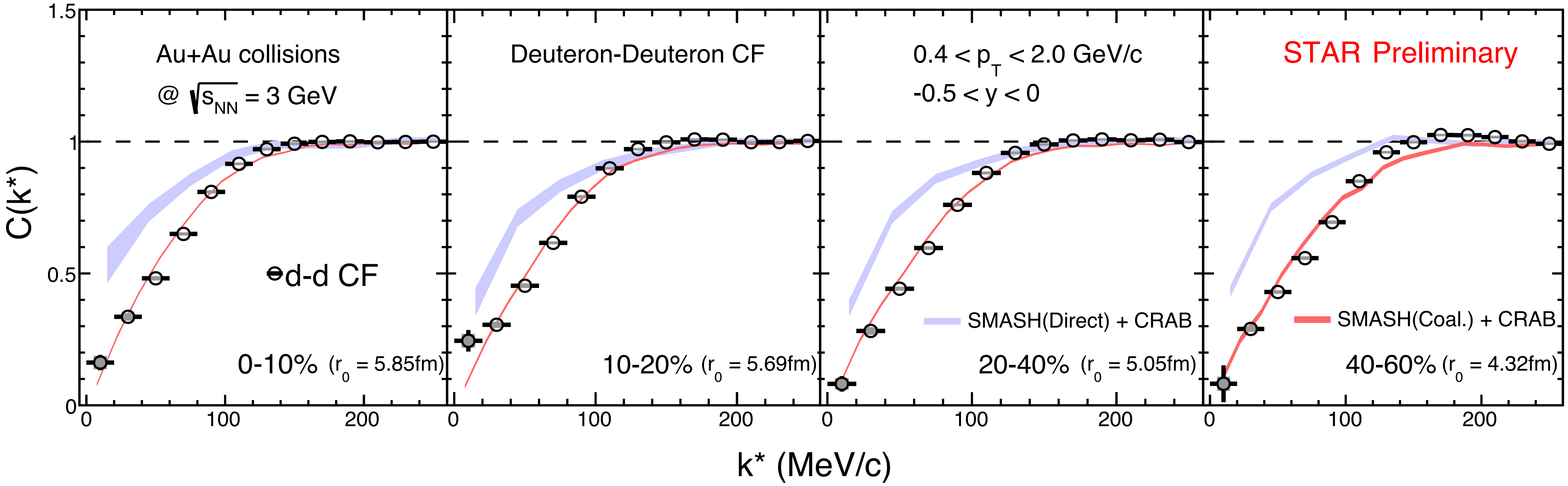


First measurement of d-d CF at STAR

1. **Clear depletion at small k* range seen in data**
2. **Data compared with Lednicky & Lyuboshitz model[1,2]**
   - **A spherical source size with r = 4-5 fm is consistent with data -> Larger than p-d**

1,I.N. Filikhin and S.L. Yakovlev, Phys. Atom. Nucl. 63, 55 (2000)
2,I.N. Filikhin and S.L. Yakovlev, Phys. Atom. Nucl. 63, 216 (2000)

Deuteron-Deuteron Femtoscopy in Au+Au Collisions at 3 GeV



1. **Compared with SMASH + Correlation after burner (CRAB) model**
2. **CF calculated with coalescence of deuterons is in better agreement with data**
   - ➢ **Support the deuteron formation at 3 GeV is dominated by coalescence**
3. **SMASH source size: 4.3 - 5.9 (fm) from peripheral to central collisions**

SMASH: J. Weil et al. Phys.Rev.C 94 (2016) 5, 054905
Coalescence: W.Zhao et al. Phys. Rev. C.98 (2018) 5,054905

Summary & Outlook

Summary

1. $K_s^0 K_s^0$ Correlation Function (39 GeV & 200 GeV)
   1) Significant difference in radii between QS and L&L models -> Final state interactions
2. Baryon-Baryon Correlation Function (3 GeV)
   1) Strong centrality dependence found in p-p CF -> Smaller source size in peripheral
   2) p-Ξ^-: UrQMD+Crab model result shows similar trend as data
3. Light Nuclei Correlation Function (3 GeV)
   1) First measurement of p-d and d-d correlation functions from STAR
   2) p-d and d-d CF qualitatively described by L&L model -> d-d has larger emission source size than p-d
   3) d-d CF described better by the model including coalescence

   ➡ Light nuclei are likely to be formed via coalescence

Outlook

➢ In the 2nd phase of BES, STAR has collected 10-20 times more data in Au+Au collisions at the energy range $\sqrt{s_{NN}}$ = 3 - 19.6 GeV. These data allow us to perform precision femtoscopy analysis.

Stay tuned for the RHIC BES-II !

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KRAKÓW, POLAND

Thank you for your attention!