Recent Femtoscopy Measurements from STAR Experiment

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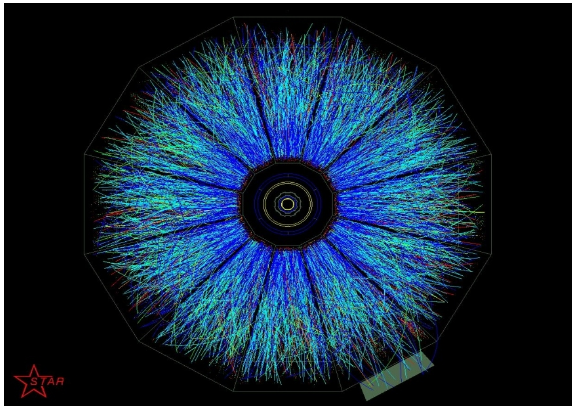
Indian Institute of Technology Patna, India



Outline:

- Introduction
- Experimental Set up
- Recent measurements:

  Baryon-Baryon

  - $\Lambda-\Lambda$ correlations
  - proton - Ξ correlations
  - proton - Ω correlations
  - $\Xi-\Xi$ correlations

  Meson-Meson

  - K^0_s - K^0_s correlations

  Light nuclei

  - Proton - Deuteron, Deuteron - Deuteron Correlations

- Summary

Hypernuclear Interactions

- Hypernuclear interactions are of fundamental interest in Nuclear Physics and Astrophysics

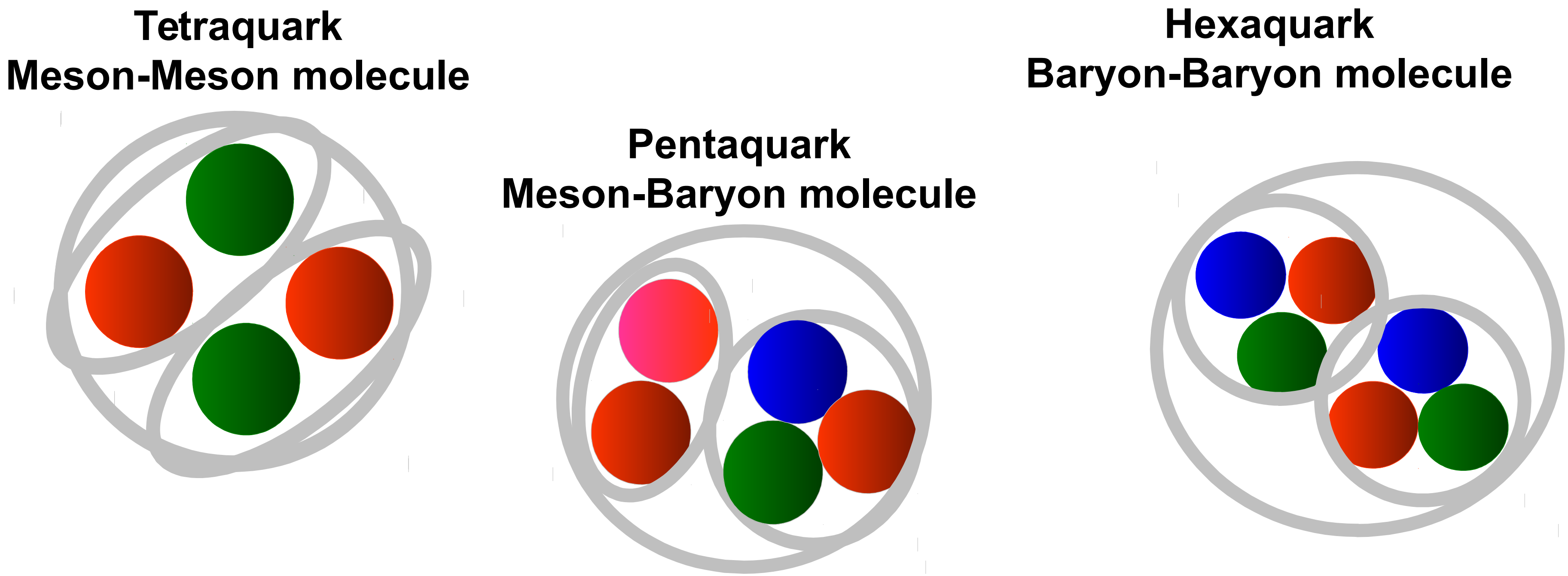
- Hypernuclear interactions - hyperon puzzle in Neutron stars

- Understanding production and the structure of hypernuclei

- Exotic hadrons (tetraquarks, pentaquark, dibaryons) – long standing challenge in hadron physics

Exotic Hadrons

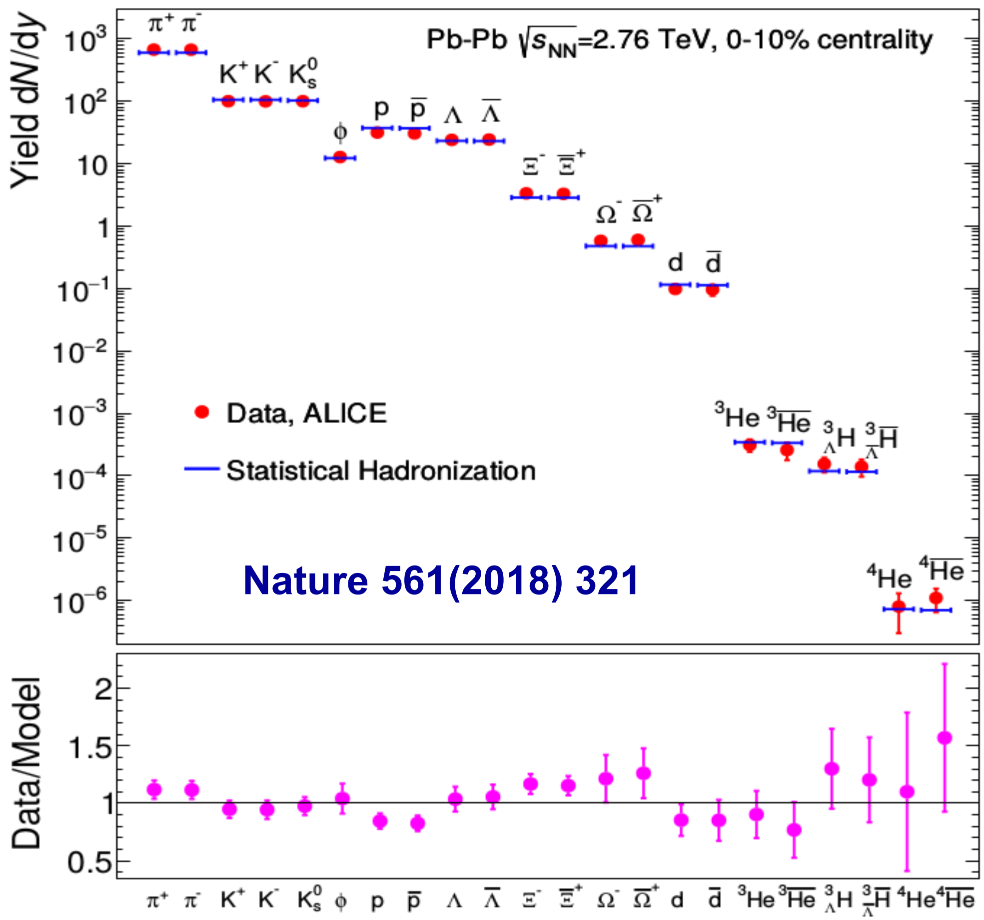
- **Within Standard Model, baryons are made up of 3 quarks and mesons are made up of a pair of quark-antiquark**
- **1977: using the Quark Bag Model, Jaffe predicted H-dibaryon made of six quarks (uuddss)** (Phys. Rev. Lett. 38,195 (1977); 38, 617(E)(1977))
- **Exotic hadrons – long standing challenge in hadron physics**

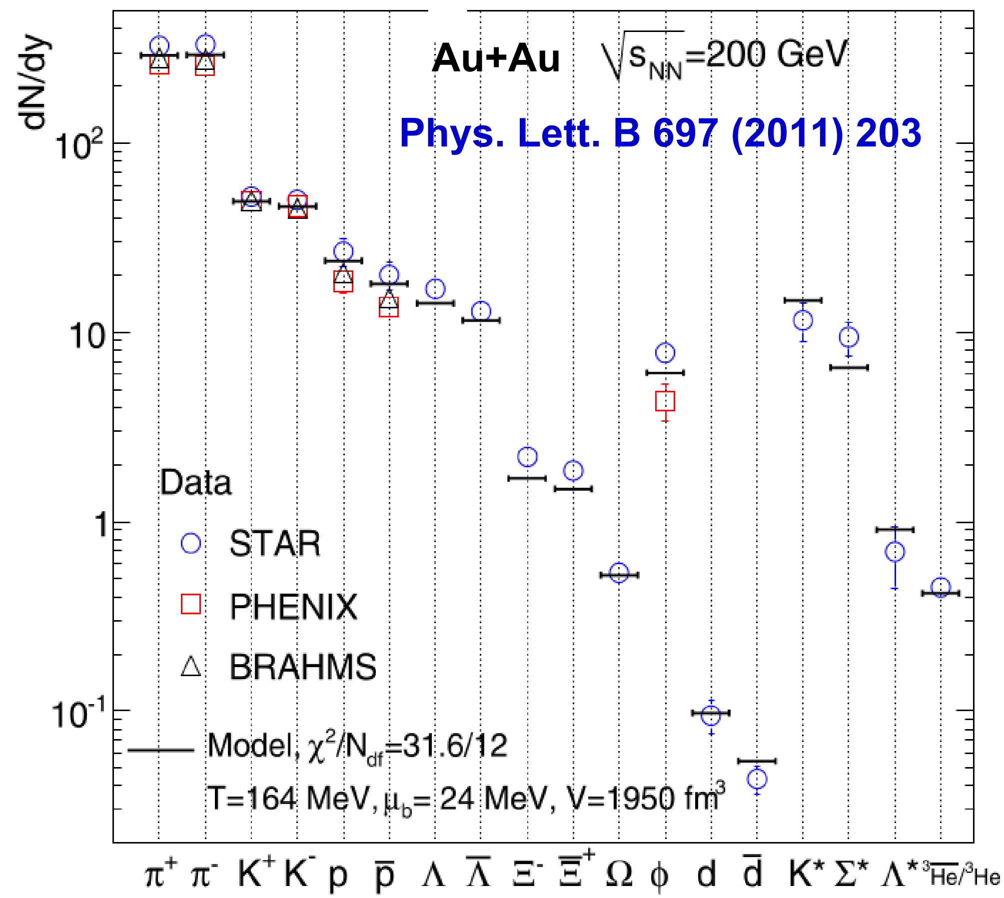


Hadrons in HIC

- Hot and dense, strongly interacting partonic matter

- Comparable number of hadrons are produced in HIC





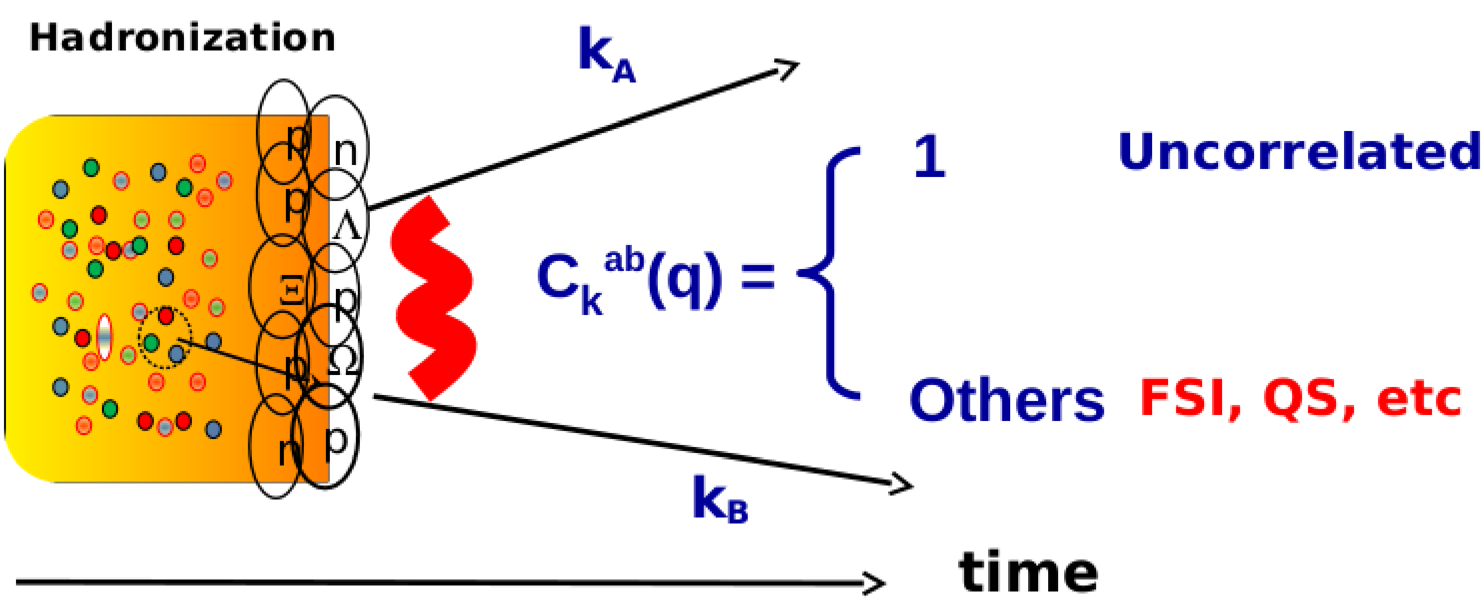
Two-particle Correlation Function

Femtoscopy: Probe the spatial and temporal extent of particle emitting source

$$C_{\vec{K}}^{ab}(\vec{q}) = \frac{d^6N^{ab}/(dp_a^3 dp_b^3)}{(d^3N^a/dp_a^3)/(d^3N^b/dp_b^3)} = \int d^3\vec{r'} \cdot S_{\vec{K}}^{ab}(\vec{r'}) \cdot \left|f(\vec{q},\vec{r'})\right|^2$$

S(r') $\rightarrow$ normalized separation distribution

f(q, r') $\rightarrow$ two-particle wave function, where
(Quantum statistics (QS), FSI: Coulomb int., Strong int.)



Two-particle Correlation Function

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S(r') → normalized separation distribution

f(q, r') → two-particle wave function, where
(Quantum statistics (QS), FSI: Coulomb int., Strong int.)

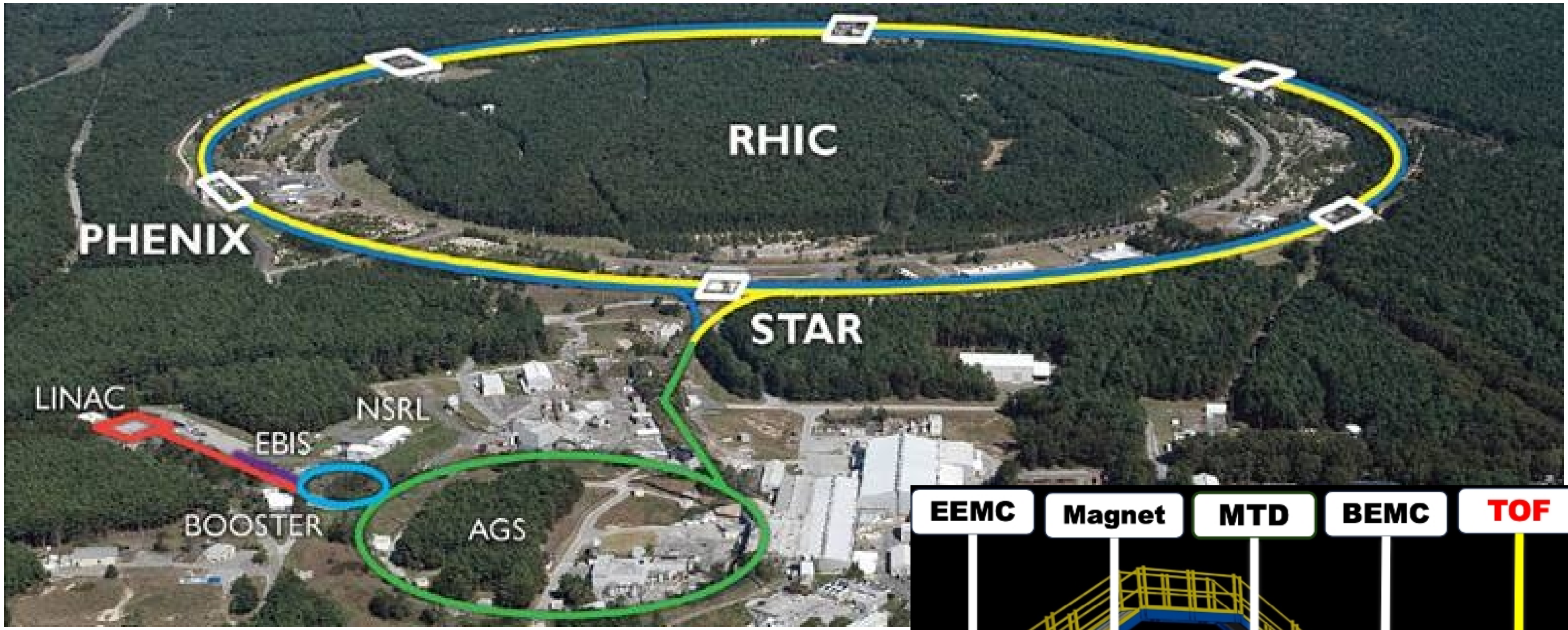
Standard procedure:

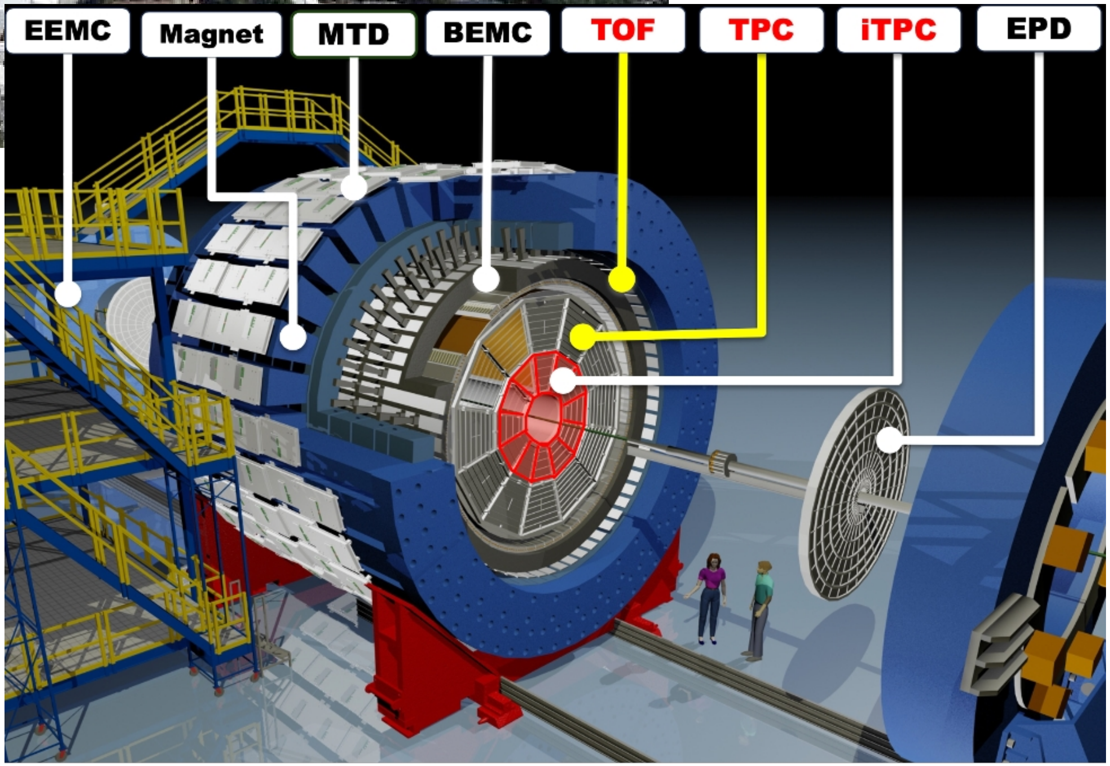
$$C^{ab}_{\vec{K}}(\vec{k}^*) = \int d^3\vec{r} \cdot S^{ab}_{\vec{K}}(\vec{r'}) \cdot |f(\vec{k}^*,\vec{r'})|^2$$

Reversed procedure:

$$C^{ab}_{\vec{K}}(\vec{k}^*) = \int d^3\vec{r} \cdot S^{ab}_{\vec{K}}(\vec{r'}) \cdot |f(\vec{k}^*,\vec{r'})|^2$$

STAR Experiment at RHIC





Relativistic Heavy Ion Collider (RHIC)

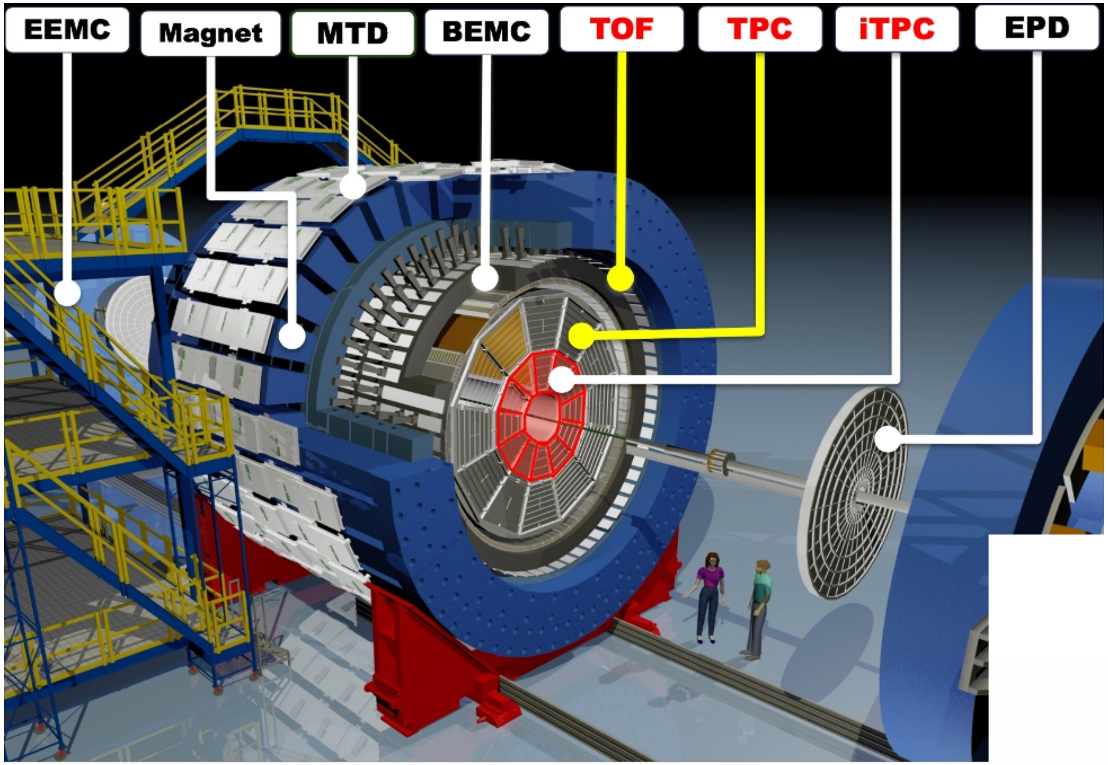
Brookhaven National Laboratory, Upton

→ Au+Au, p+p, d+Au, Zr+Zr, Ru+Ru ..

→ Beam Energy Scan Program I, II

$\sqrt{s_{NN}}$ = 3.0 - 200 GeV

STAR Experiment (Fixed Target) at RHIC



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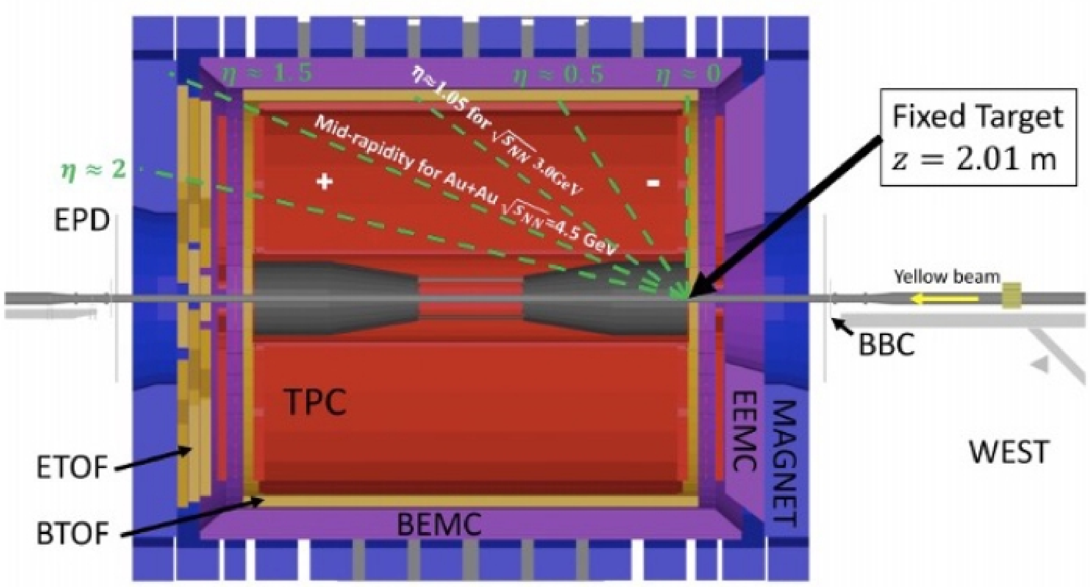
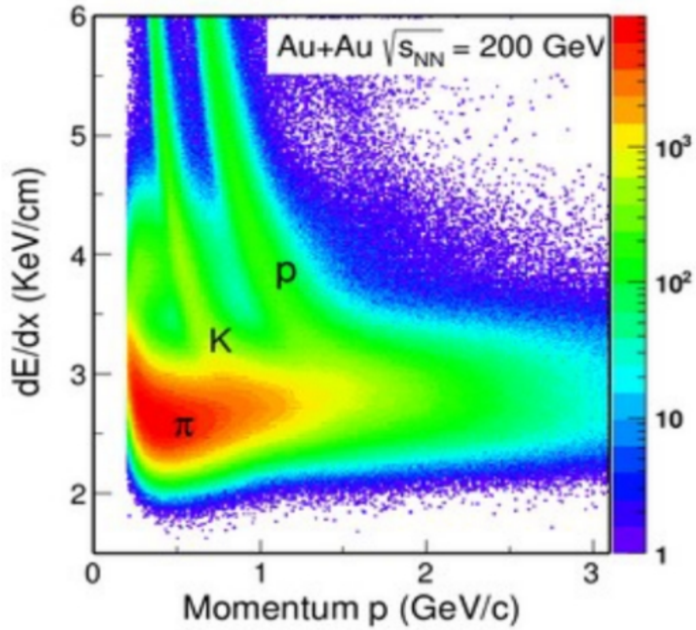
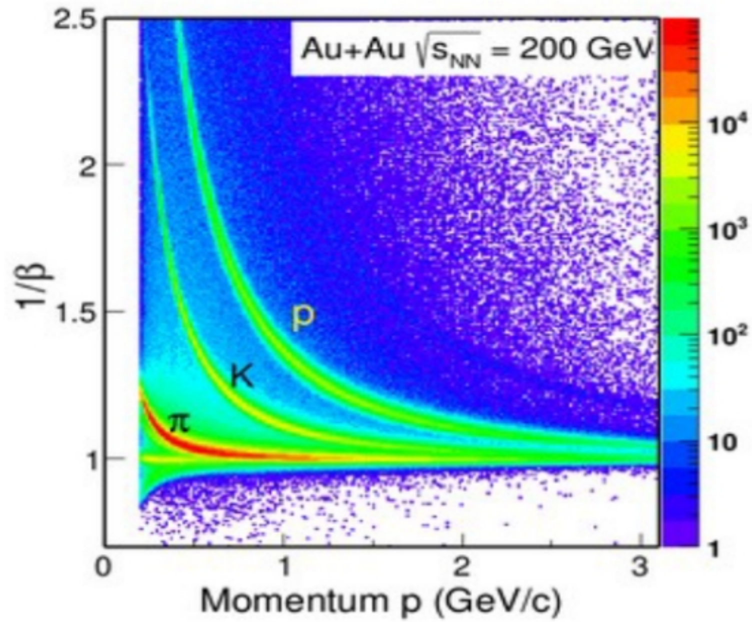
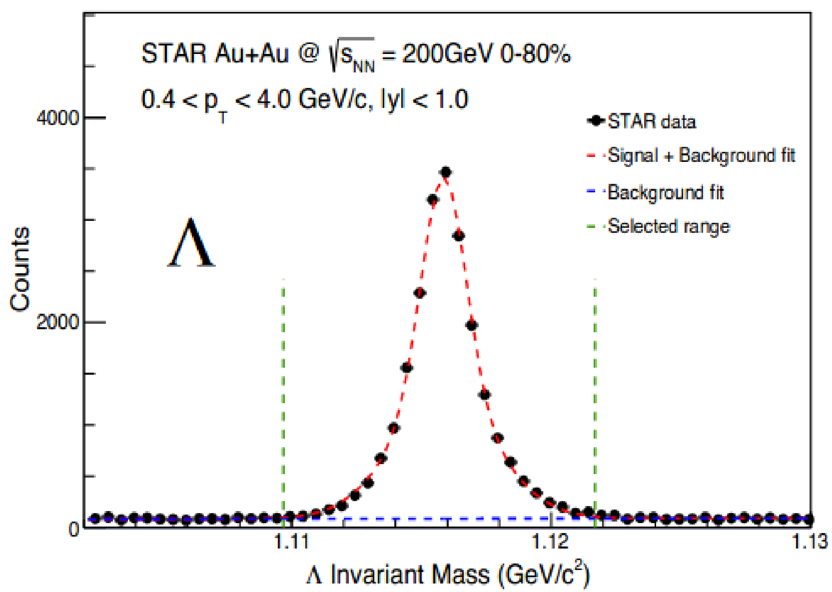
STAR Fixed-target Experiment Setup

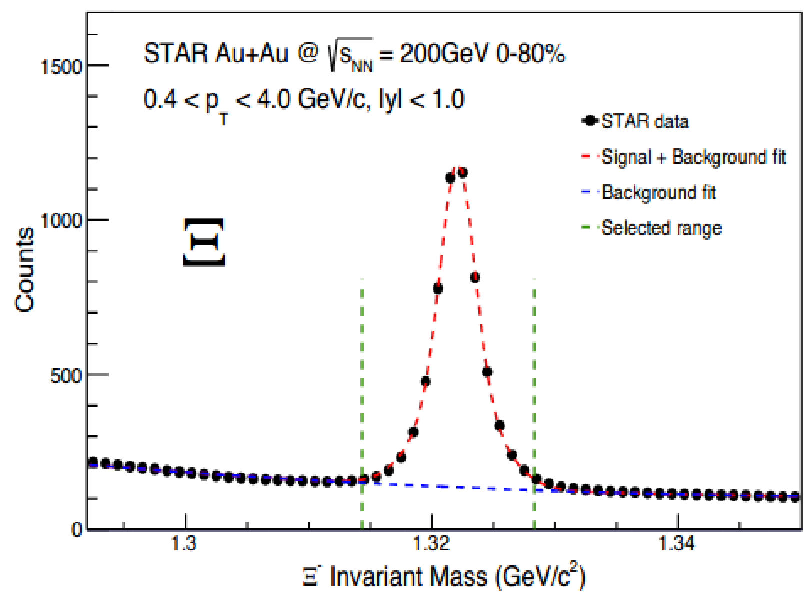


PID and Reconstruction @ 200 GeV



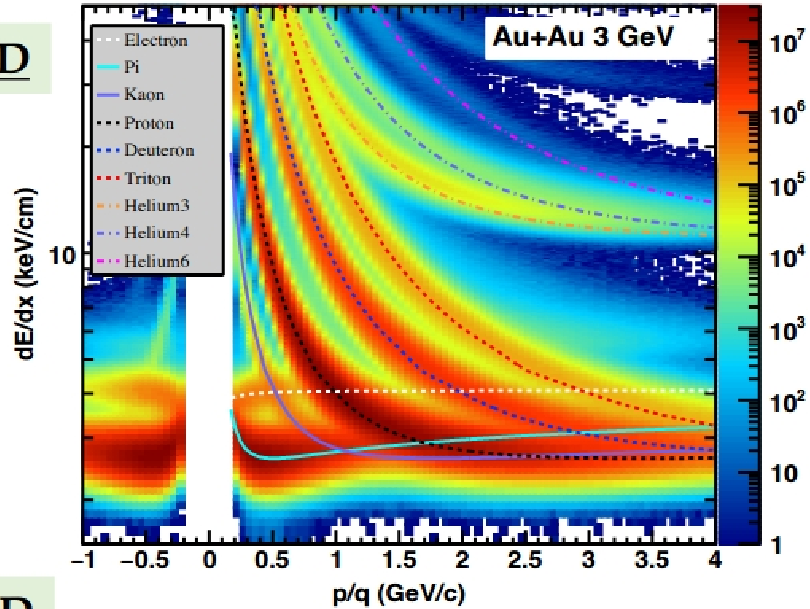




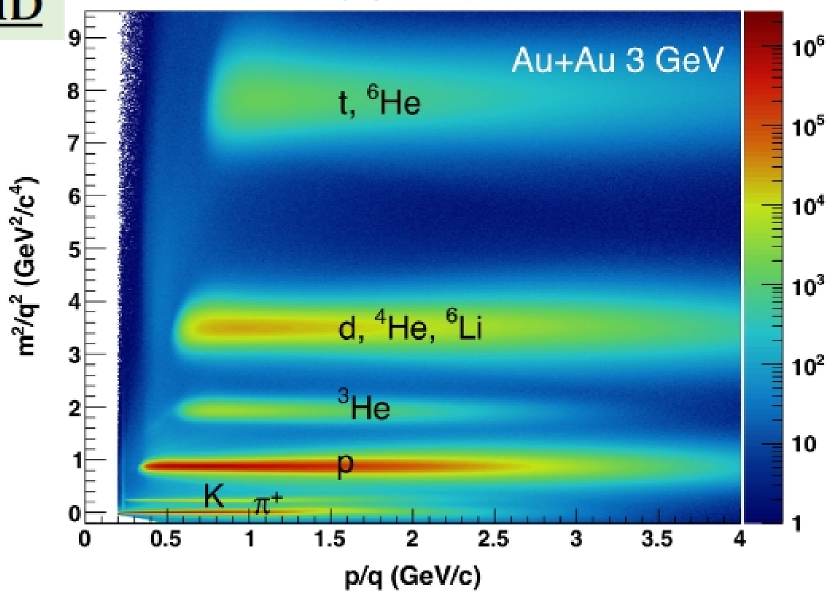


PID and Acceptance @ 3 GeV

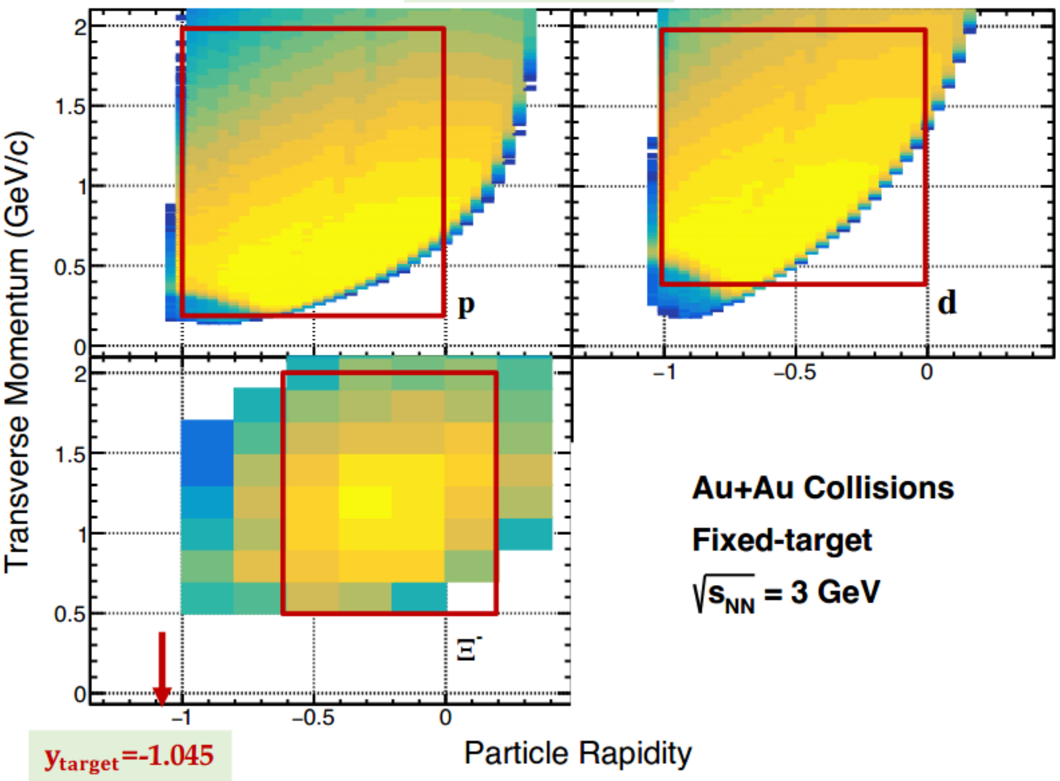
TPC PID



TOF PID



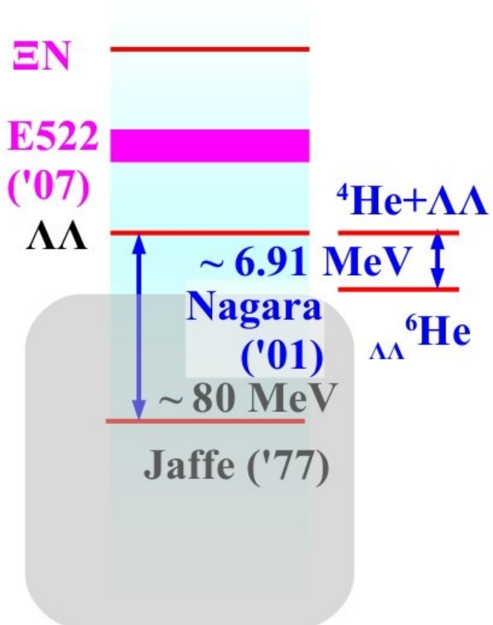
Acceptances



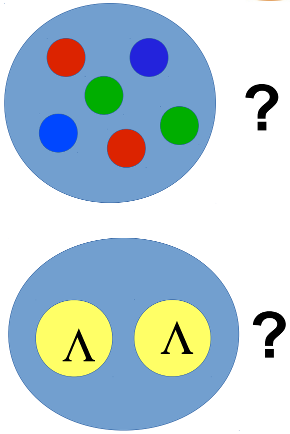
- p and d: Identified by TPC and TOF

ΛΛ Correlation Function

H-Dibaryon Properties : $J^{\pi} = 0^{+}$, mass : (1.9-2.8) GeV/c^2



$$\boxed{\psi(\mathrm{H}) = \sqrt{\frac{1}{8}}\psi(\Lambda\Lambda) + \sqrt{\frac{4}{8}}\psi(N\Xi) - \sqrt{\frac{3}{8}}\psi(\Sigma\Sigma)}$$



Lattice calculation – a bound state 20-50 MeV/c^2 (NPLQCD) or 13 MeV/c^2 (HALQCD)

Phys. Rev. Lett. 106 (2011) 162001, Phys. Rev. Lett. 106 (2011) 162002

- **Chiral extrapolation to physical pion mass leads to unbound H**

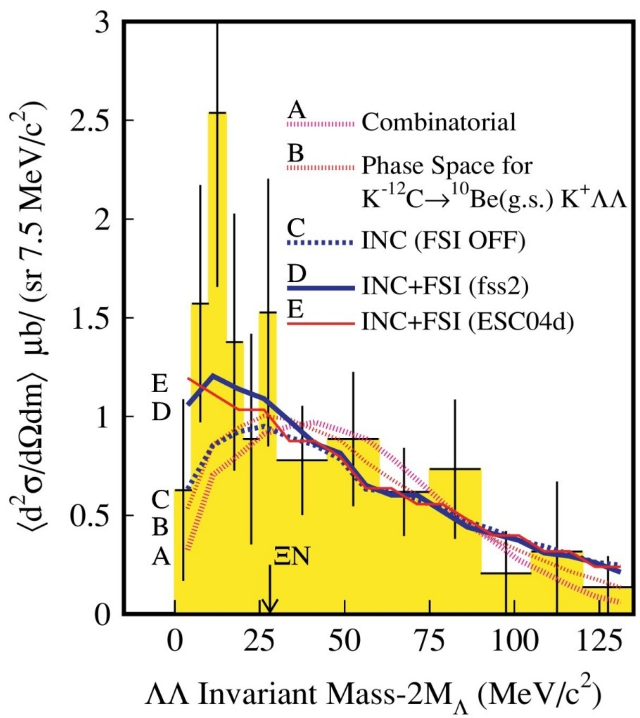
  Phys. Rev. Lett. 107 (2011) 092004, Phys. Lett. B 706 (2011) 100

- **Nagara event – Measurement of $_{\Lambda\Lambda}{}^{6}\mathrm{H} \rightarrow \Lambda\Lambda + {}^{4}\mathrm{He}$ (BE ~ 6.91 MeV)**

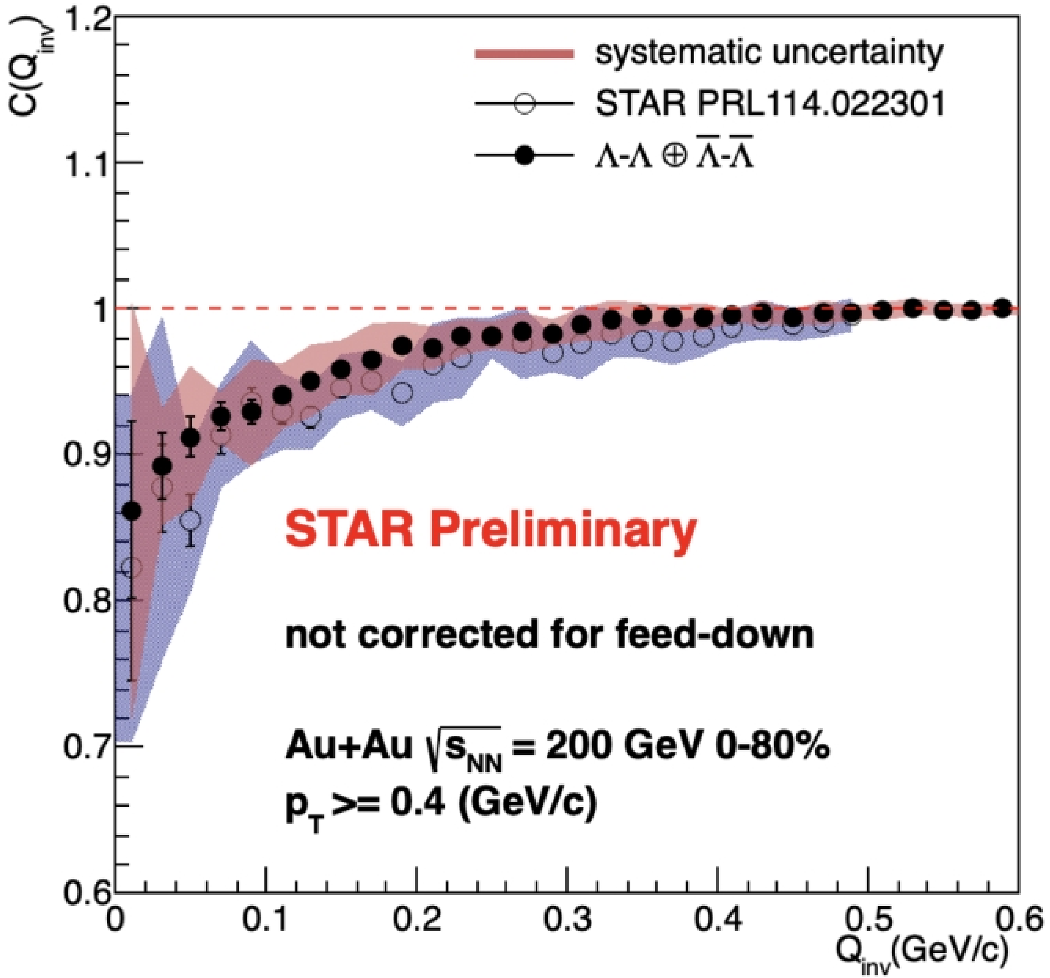
  Phys. Rev. Lett. 87 (2001) 212502

- **KEK-E522 observation of 2.6σ enhancement for ΛΛ invariant mass spectra – resonance!**
- **scattering length ($a_{\Lambda\Lambda}$) = $-0.10^{+0.45}_{-2.27} \pm 0.04$ fm – no/weakly bound H**

Phys. Rev. C 75 (2007) 022201 (R)



ΛΛ Correlation Function



An attractive interaction allows to describe both STAR and ALICE experiment data

STAR Collaboration, Phys. Rev. Lett. 114 (2015) 022301

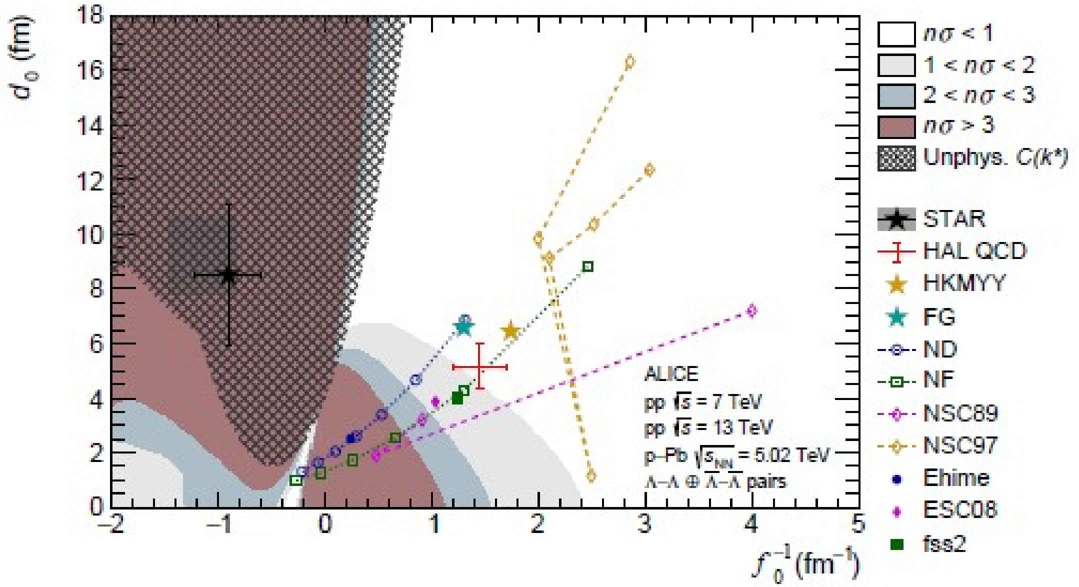
M. Isshiki, QM2022

ΛΛ Correlation Function

- The scattering length is constrained to $f_0^{-1} < 0.8\ \mathrm{fm}^{-1}$
- A shallow attractive potential is in good agreement with the experimental results
- The bindding energy,

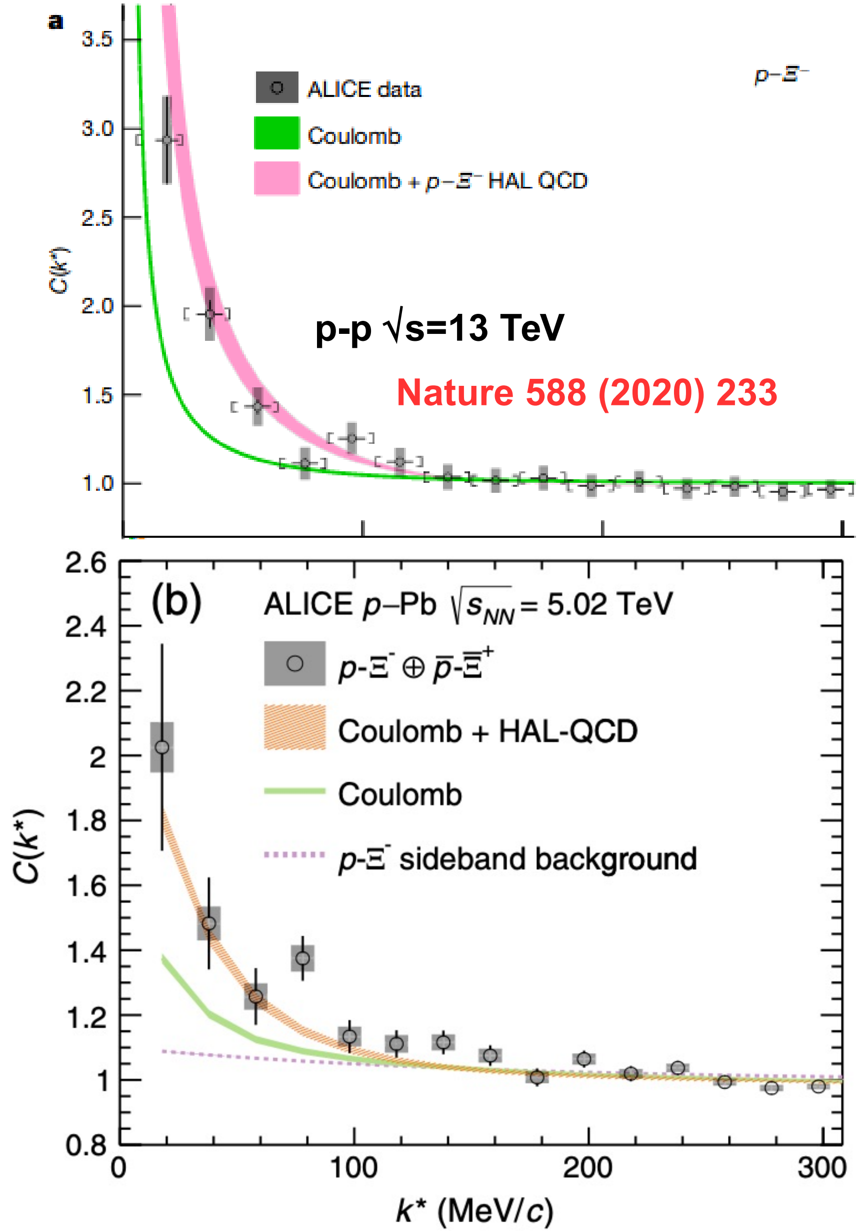
$$B_{\Lambda\Lambda} = 3.2^{+1.6}_{-2.4}(\mathrm{stat})^{+1.8}_{-1.0}(\mathrm{syst})\ \mathrm{MeV}$$

- Larger statistics data-sets at RHIC and LHC to yield a conclusive answer



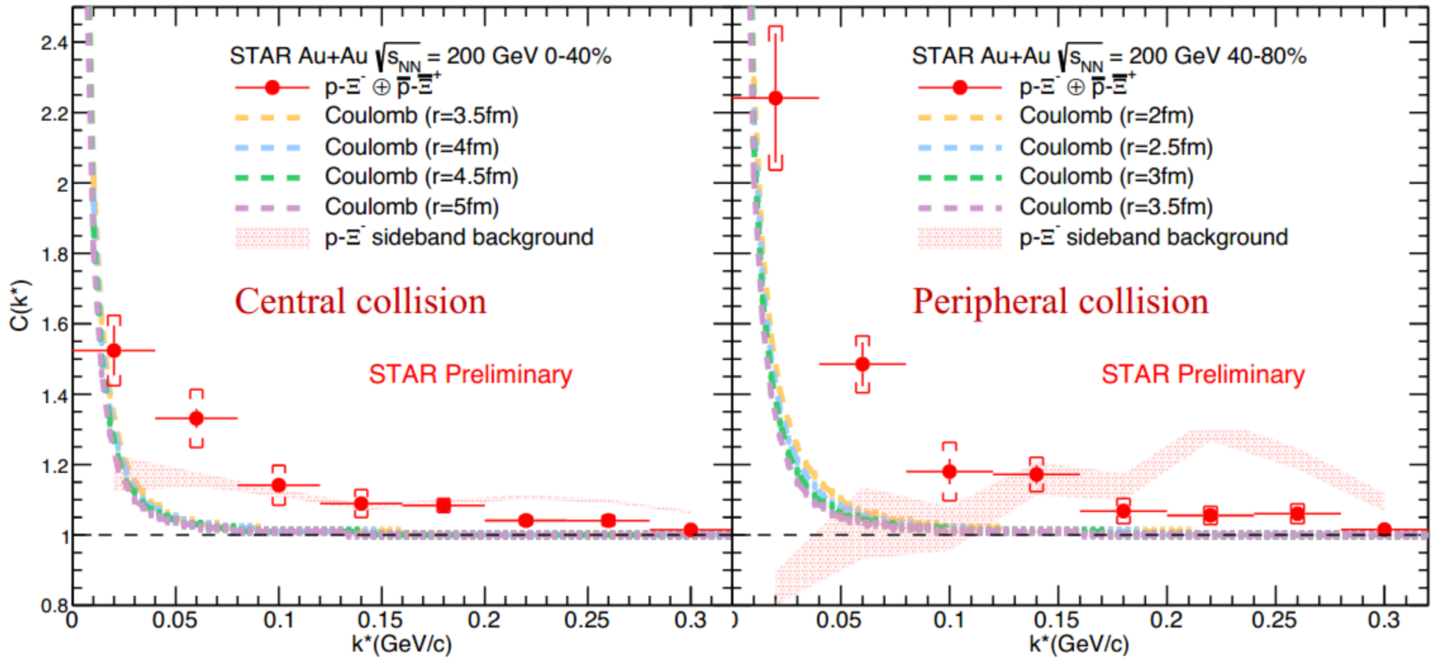
ALICE Collaboration, Phys. Lett. B 797 (2019) 134822

Proton-Ξ Correlation Function



- The measured p-Ξ correlation function show deviation from expection based on the Coulomb interactions.
- **An attractive p-Ξ strong interaction is observed.**
- The p-Ξ interactions from HAL-QCD collaboration are found to be consistent with the measurement.

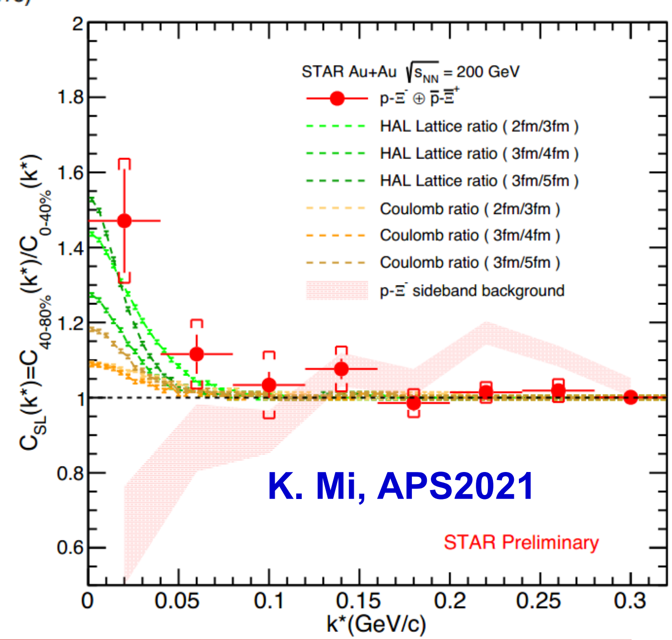
Proton-Ξ Correlation Function



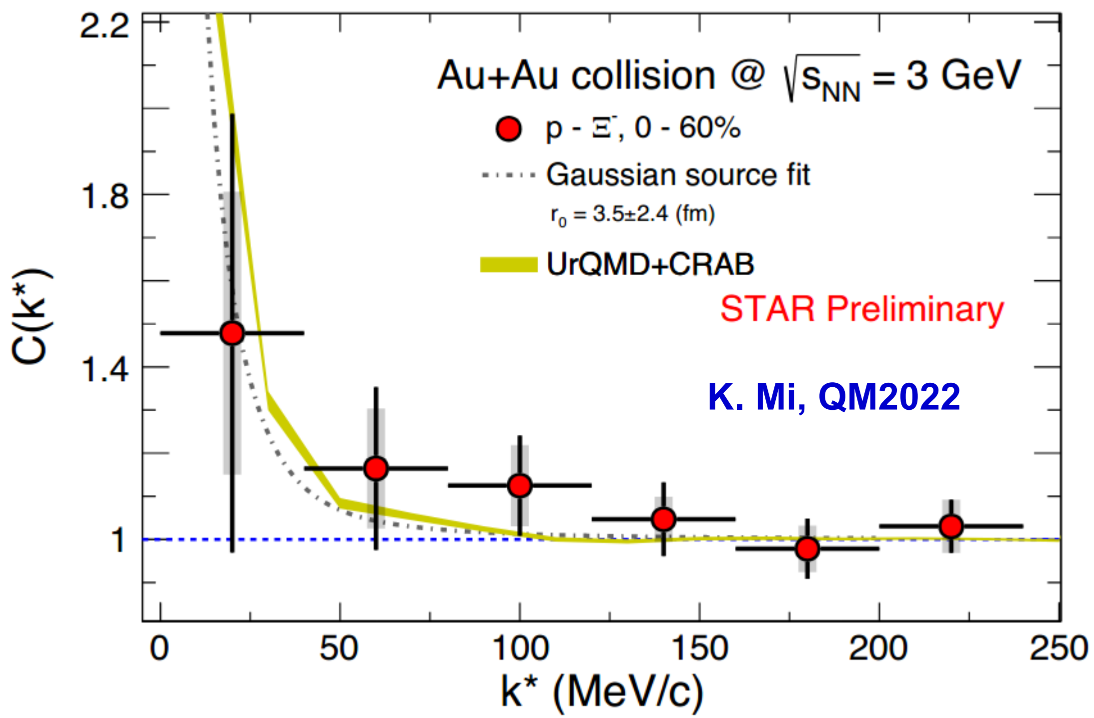
- **The measured p-Ξ correlation function show deviation from expection based on the Coulomb interactions.**

- **An attractive p-Ξ strong interaction is observed.**

- **The ratio of p-Ξ correlation function for the perpheral to central collisions is consistent with the p-Ξ interactions from HAL-QCD collaboration.**



Proton-Ξ Correlation Function



- First measurement of p-Ξ correlation function at 3 GeV.
- Enhancement at low k* seen at 3 GeV
- UrQMD + CRAB calculation is consistent with data

Exotic: NΩ-dibaryon (strangeness = -3)

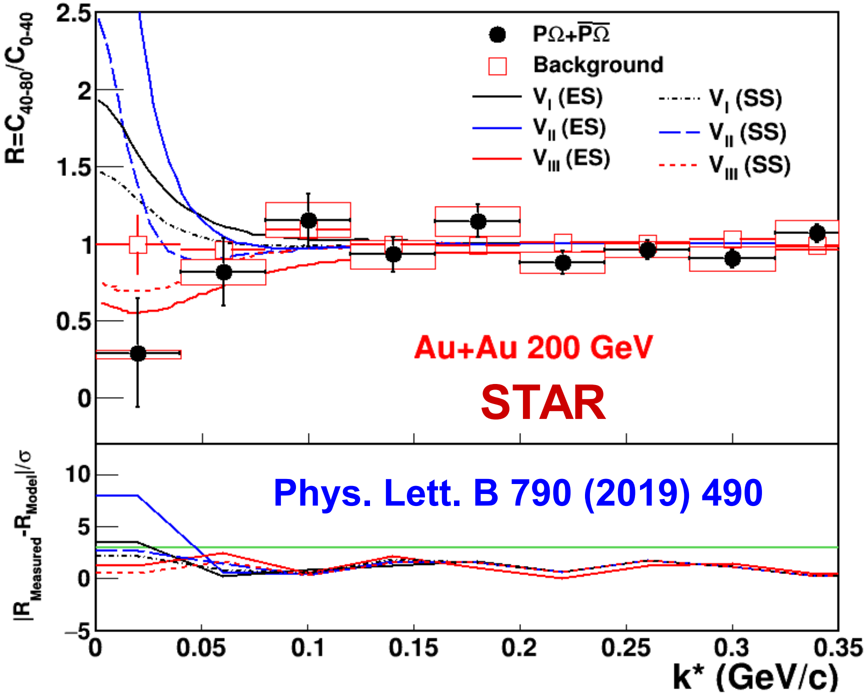
- **Nucleon-Ω (NΩ): A strangeness = -3 dibaryon is stable against strong decay**
  - T. Goldman et al., Phys. Rev. Lett. 59 (1987) 627, H. Pang et al., Phys. Rev. C69 (2004) 065207, H. Pang et al., Phys. Rev. C70 (2004) 035204.
- **Many calculations based on coupled channel and lattice QCD predict a bound state for NΩ** (PRC 83(2011)015202, PRC 92 (2015) 065202, NPA 928 (2014) 89)

	Scattering length (a_0) fm	Effective range (r_{eff}) fm	BE (sc) MeV	BE (cc) MeV
SU(2)	1.87	0.87	23.2	19.6
SU(3)	-4.23	2.1	ub	ub
QDCSM	2.58	0.9	8.1	7.3
HALQCD	$1.28+0.13^{0.14}_{-0.15}$	$0.499+0.026^{0.029}_{-0.048}$	$18.9+5.0^{12.1}_{-1.8}$	

M. Chen et al., Phys. Rev. C 83 (2011) 015202,

HAL QCD Collaboration, Nucl. Phys. A 928 (2014) 89

Proton-Ω Correlation Function

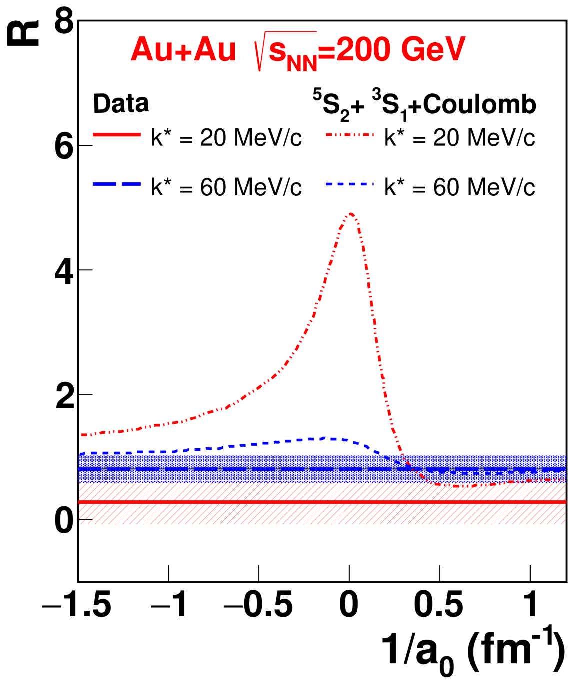


SS → Static source
ES → Expanding source
Background → Ω sideband is used
Boxes → systematic uncertainty

Spin-2 PΩ potentials	V_I	V_{II}	V_{III}
Binding energy E_B (MeV)	-	6.3	26.9
Scattering length a_0 (fm)	-1.12	5.79	1.29
Effective range r_{eff} (fm)	1.16	0.96	0.65

✓ The ratio of correlation function for the small (peripheral collisions) to large (central collisions) system is smaller than unity at low relative moment.

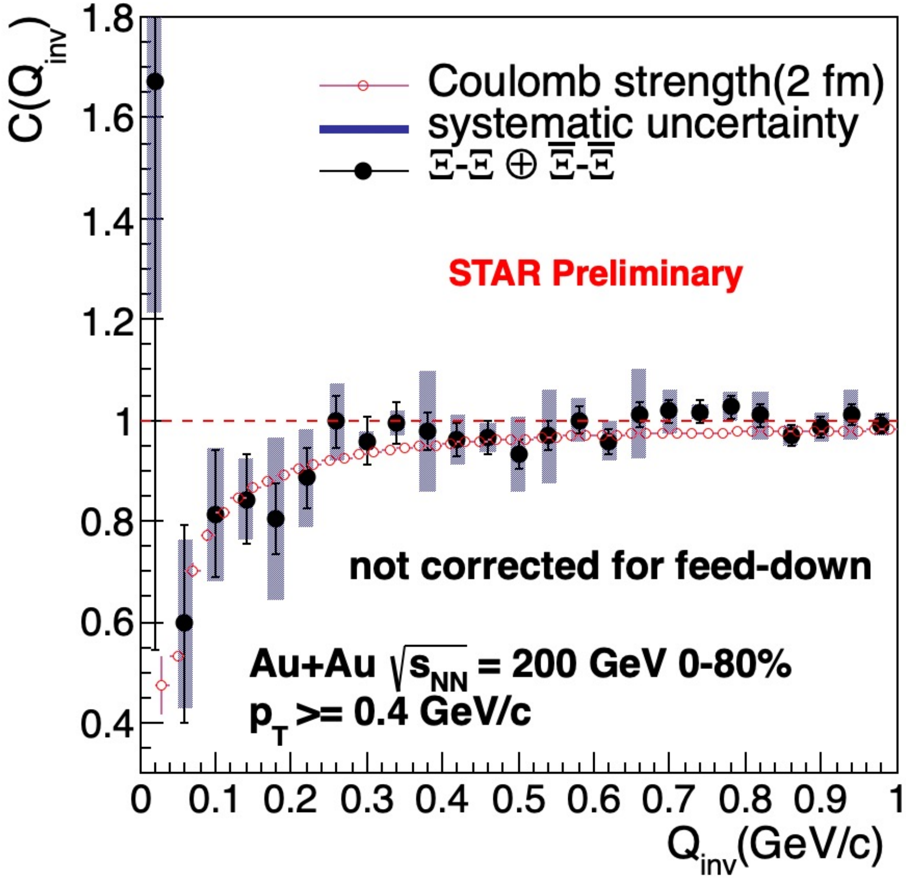
✓ **Measurement supports the existence of a deeply bound state decaying into the proton Ω final state.**



K. Morita et al., Phys. Rev. C 94, 031901 (2016)

Ξ–Ξ Correlation Function

M. Isshiki, QM2022



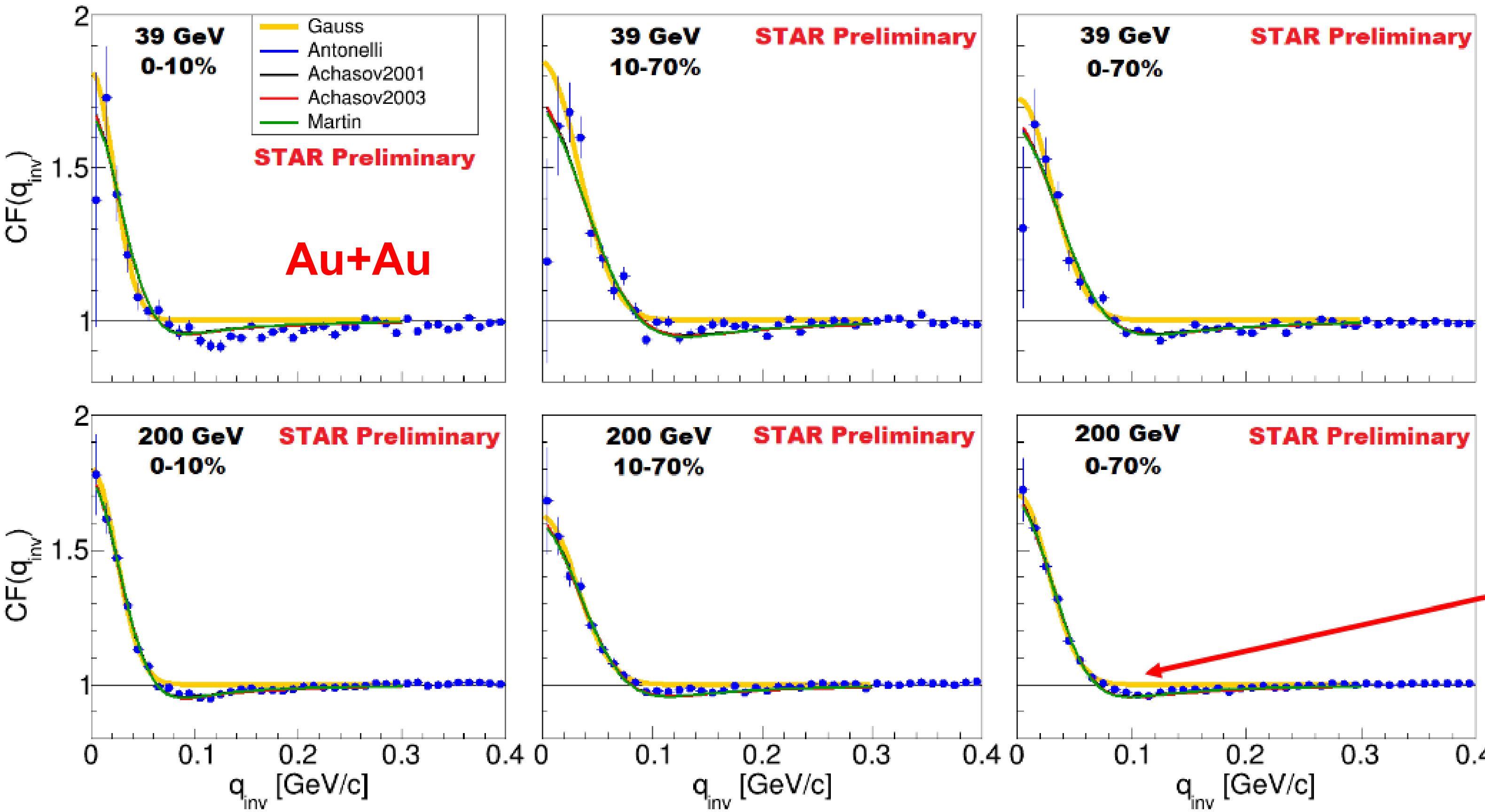
- **Lattice QCD/chiral EFT calculations indicate an attractive interaction, but not strong enough to form a bound state.**

- **The result shows anti-correlation at Q_{inv}< 0.25 GeV/c.**

  - qualitatively matches with coulomb strength.

  - to cancel quantum statistics (negative correlation), strong interaction needs to be positive correlation.

K^0_s - K^0_s Correlation Function



$0.4 < p_T < 2.0$ GeV/c
$|y| < 0.5$

FSI is needed to reproduce the dip structure

$q_{inv} = 2k^*$

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

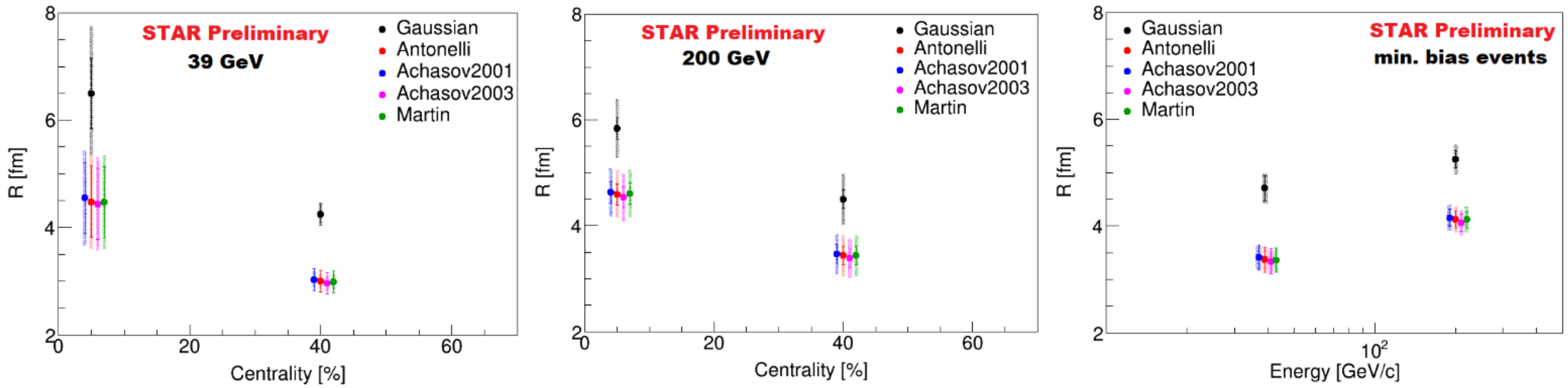
$$\boxed{CF(q_{inv}) = 1 + \lambda\left(e^{[-R_{inv}^2 q_{inv}^2]} + \frac{1}{2}\left[\left|\frac{f(k^*)}{R_{inv}}\right|^2 + \frac{4\Re f(k^*)}{\sqrt{\pi}R_{inv}} F_1(q_{inv}R_{inv}) - \frac{2\Im f(k^*)}{\sqrt{\pi}R_{inv}} F_2(q_{inv}R_{inv})\right]\right)}$$

$K^0_s - K^0_s$ Correlation Function

Centrality dependence: $R_{0-10\%} > R_{10-70\%}$

Energy dependence: $R_{200GeV} > R_{39GeV}$

Significant difference in radii between QS and Lednicky & Lyuboshitz models ➡ Final state interactions



Light Nuclei Correlation Function

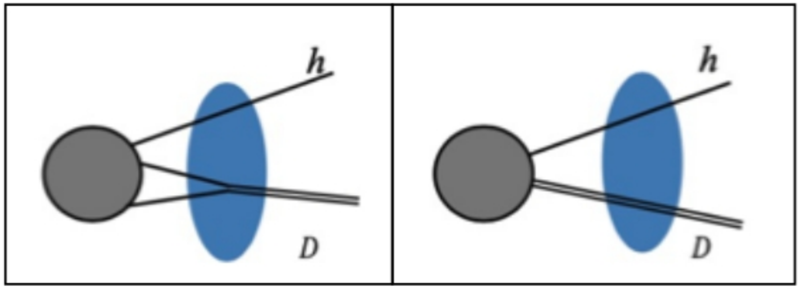
Proposed mechanism of light nuclei formation:

- Coalescense : final – state interaction
- Thermal: Produced directly from fireball

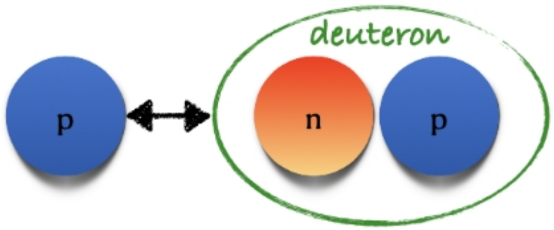
A systematic measurements of light nuclei femtoscopy

- **Help investigate formation mechanism**

Serves as indirect approach to study three-body and four body interactions



Coalescence   Direct production



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

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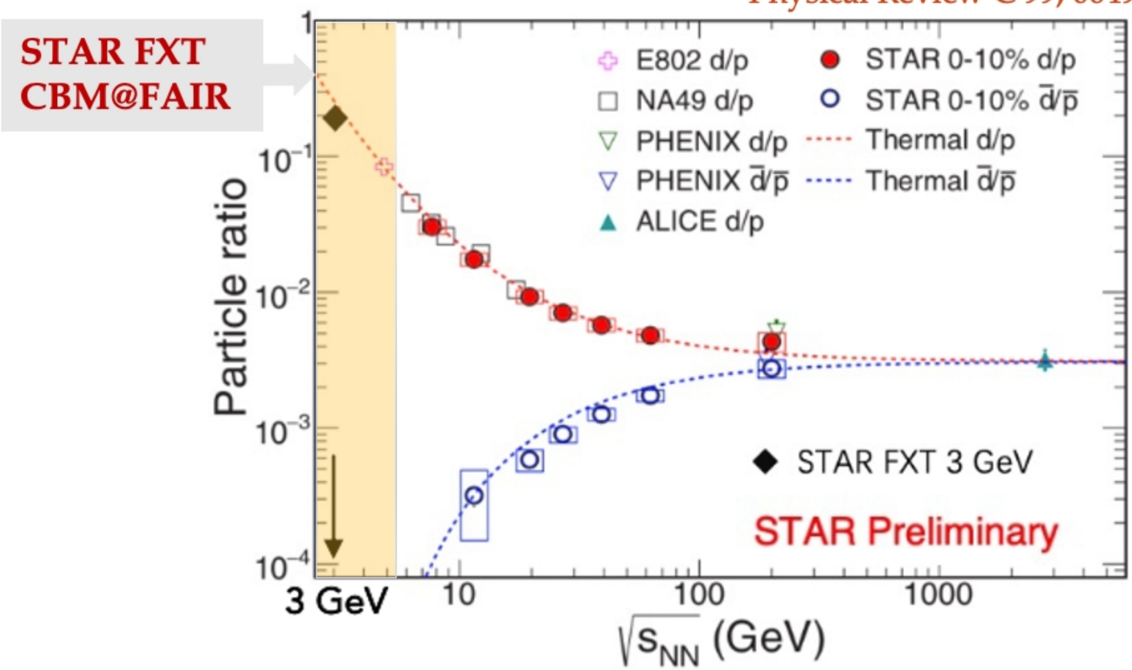
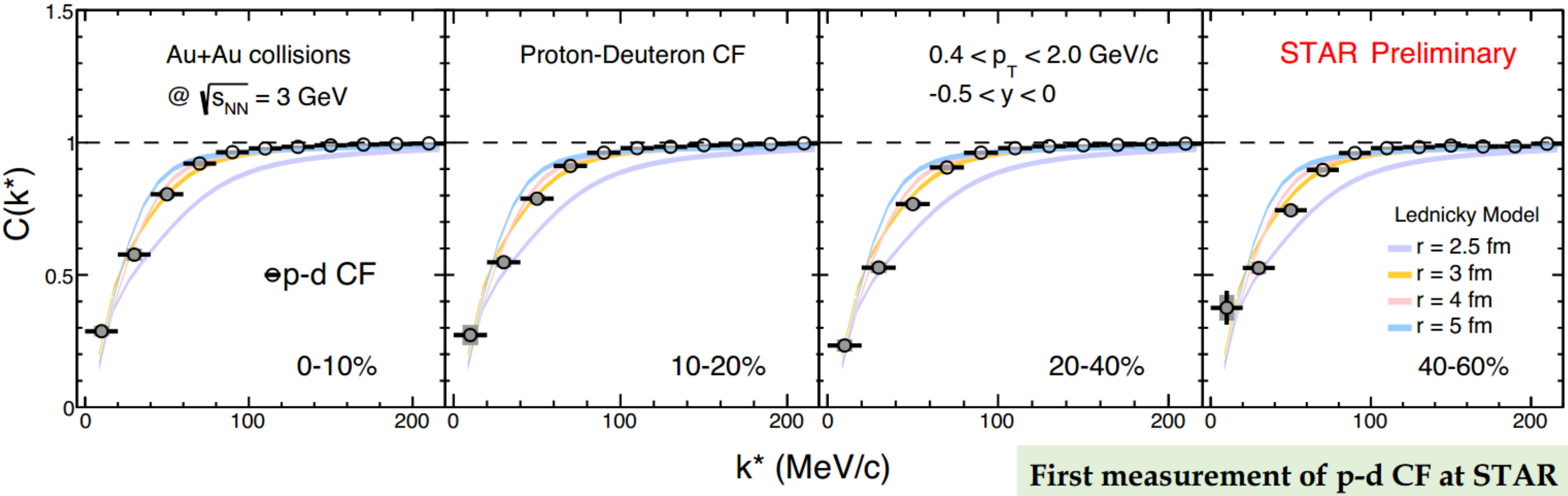
Large amount of light nuclei produced at 3 GeV, allowing precision measurements

Physical Review C 99, 064905 (2019)



Proton-Deuteron Correlation Function

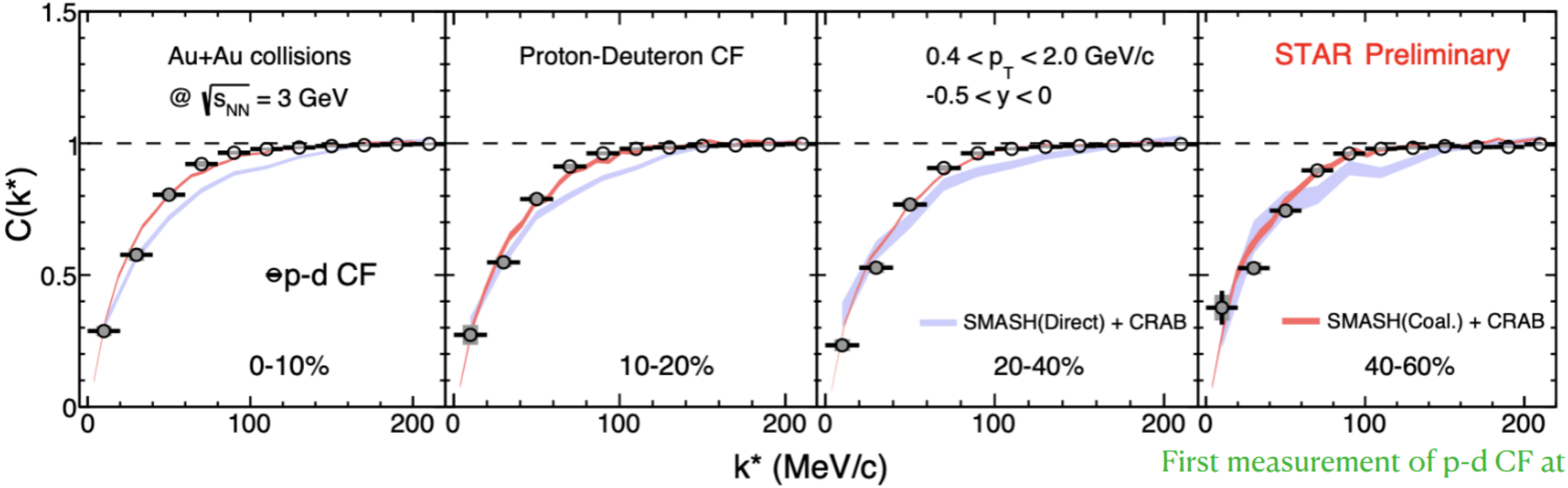


First measurement of p-d CF at STAR

- Clear depletion at small k* range seen in data
- Data compared with Lednicky&Lyuboshitz model
- Deuterons are treated as point-like particle
- A spherical source size with = 3 - 4 fm is consistent with data

Proton-Deuteron Correlation Function

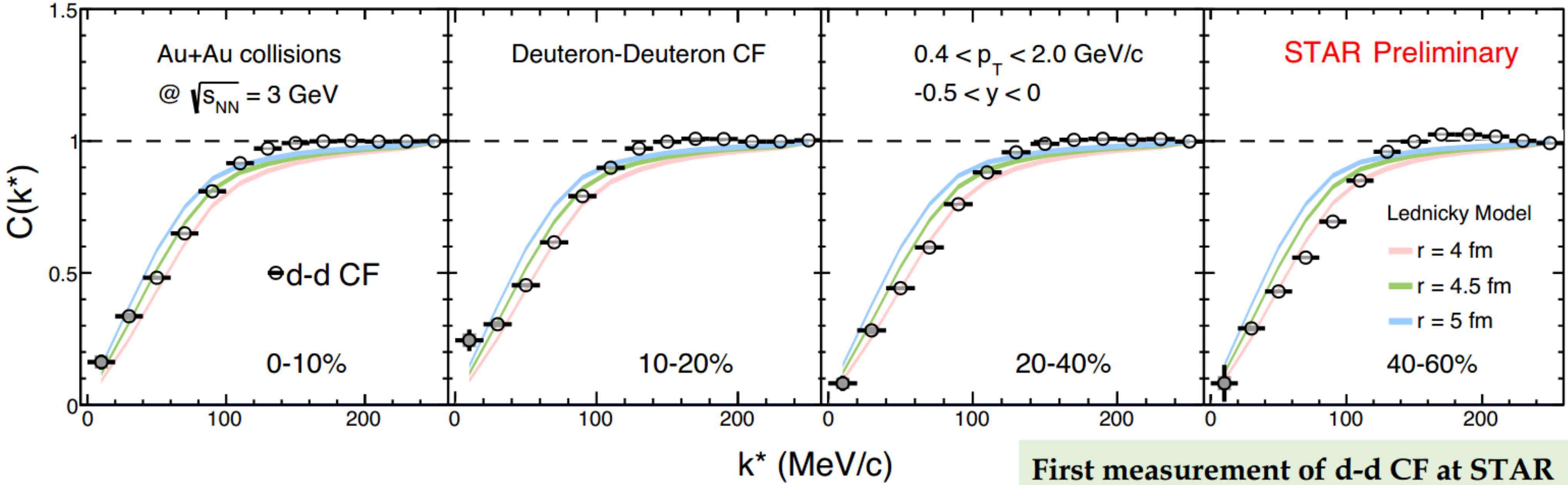
Quark Matter 2022



First measurement of p-d CF at STAR

- **Compared with SMASH + Correlation After burner (CRAB) model**
- **CF calculated with coalescence of deuterons is in better agreement with data**
- **Support the deuteron formation at 3 GeV is dominated by coalescence**

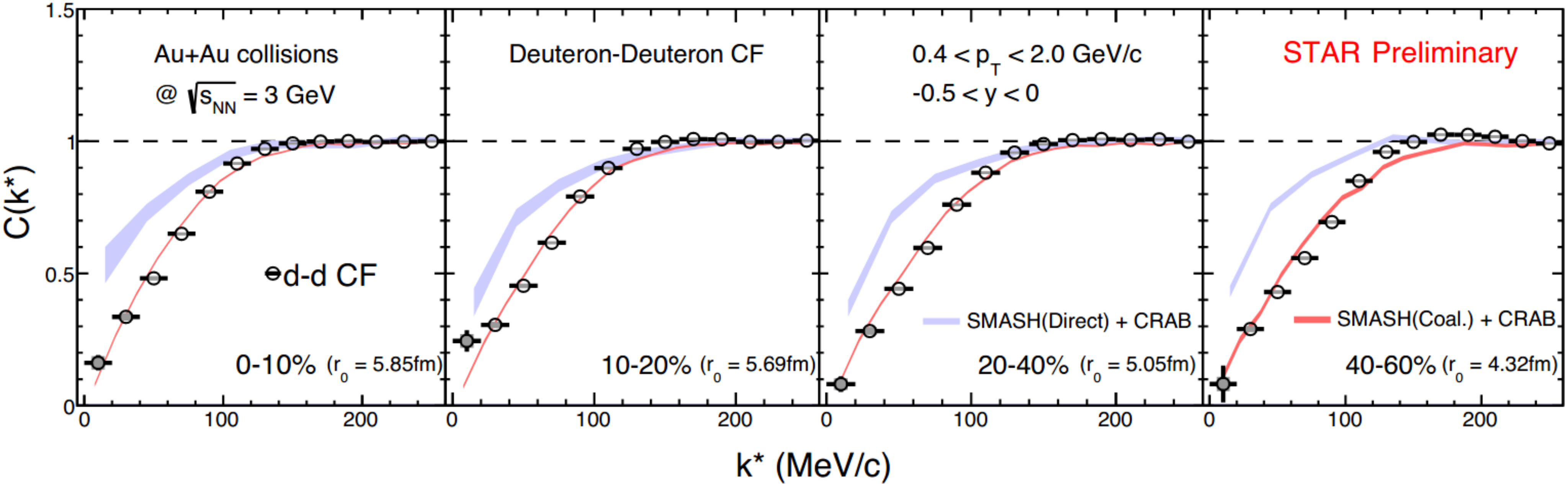
Deuteron-Deuteron Correlation Function



First measurement of d-d CF at STAR

- **Clear depletion at small k* range seen in data**
- **Data compared with Lednicky&Lyuboshitz model**
- **A spherical source size with r = 4 - 5 fm is consistent with data ⇒ Larger than p-d correlation function**

Deuteron-Deuteron Correlation Function



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Summary

- **The femtoscopy measurements from heavy-ion collisions provides a unique opportunity to explore strong interactions and search for exotics.**
- **More precise femtoscopy results with large statistics in BES-II program coming soon ! (light nuclei, many body, exotica ...)**
- **The upcoming Run for Au+Au at 200 GeV in 2023 and 2025 at RHIC will allow us to significantly improve the precision of the measurements.**

Thank you!

Hadronic molecules suggested by CFs

- Ωp and $K^- p$
  - **Bound states are expected.**
    Dalitz, Tuan ('59); Akaishi, Yamazamki ('02); Goldman+('87); Oka ('88); Etminan+[HAL QCD] ('14); Iritani+[HAL QCD]('19).
  - **Dip is expected at R ~ $|a_0|$** *Morita+('16,'20); Kamiya+('20); Haidenbauer('18)*
  - **Data support the existence of a BS.**