Femtoscopy of baryonic particles in heavy-ion collisions

TCHoU WorkShop

2022/03/24 (Thurs)

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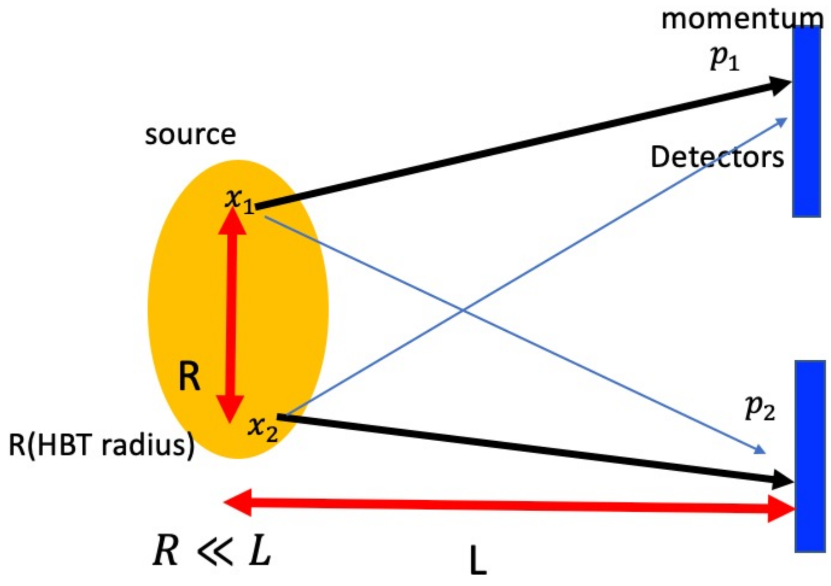
Baryon-Baryon interaction....

- Hyperon-Hyperon (Y-Y) and Hyperon-Nucleon (Y-N) interactions are important for studying exotic hadronic states such as H-dibaryon as well as to understand the Equation of State of neutron stars.
  - Possible bound state of Y-N and Y-Y (S=-2) ?
- Also, the identical baryon correlations such as proton-proton are good probe to see the FSI and QS interaction directly.

- Various hadrons including hyperons are abundantly produced in Heavy Ion Collisions.

Today, I will talk about ...
<u>In STAR,</u>
-The measurement of Λ-Λ in high precision in Au+Au collisions.
-The first measurement of Ξ-Ξ correlation function in Au+Au collisions.
- The first measurement of p$-\Xi$ in Au+Au collisions.
-The first measurement of proton-proton correlation function in $\sqrt{s_{NN}}$ = 3 GeV Au+Au FXT Collisions.
-The measurement of p-Ω correlation in Au+Au collisions.
<u>In ALICE,</u>
-The first measurements of p-K interaction in Pb+Pb collisions at $\sqrt{s_{NN}}$=5.02 TeV and ΛK interaction at $\sqrt{s_{NN}}$=2.76 TeV
-The measurements of p-Ξ and p-Ω interactions in Pb+Pb collisions at $\sqrt{s}$ = 13 TeV.

What's femtoscopy?



- Technique based on Bose-Einstein/Fermi-Dirac correlation has been used in heavy-ion collisions to probe the spatial and temporal extent of particle emitting source.
- Femtoscopic correlations arise due to **quantum statistical effects and final state (strong and Coulomb) interaction** (if present) at low relative momentum of two particles.

Theory

$$\boxed{C(q) = \int s(r)|\psi(q,r)|^2 dr^3}$$

r: relative distance (of pair)

q: relative momentum $q = \sqrt{{q_x}^2 + {q_y}^2 + {q_z}^2 - {E_0}^2}$

$s(r)$ source function $\psi(q,r)$: wave function of two-particles

Experiment

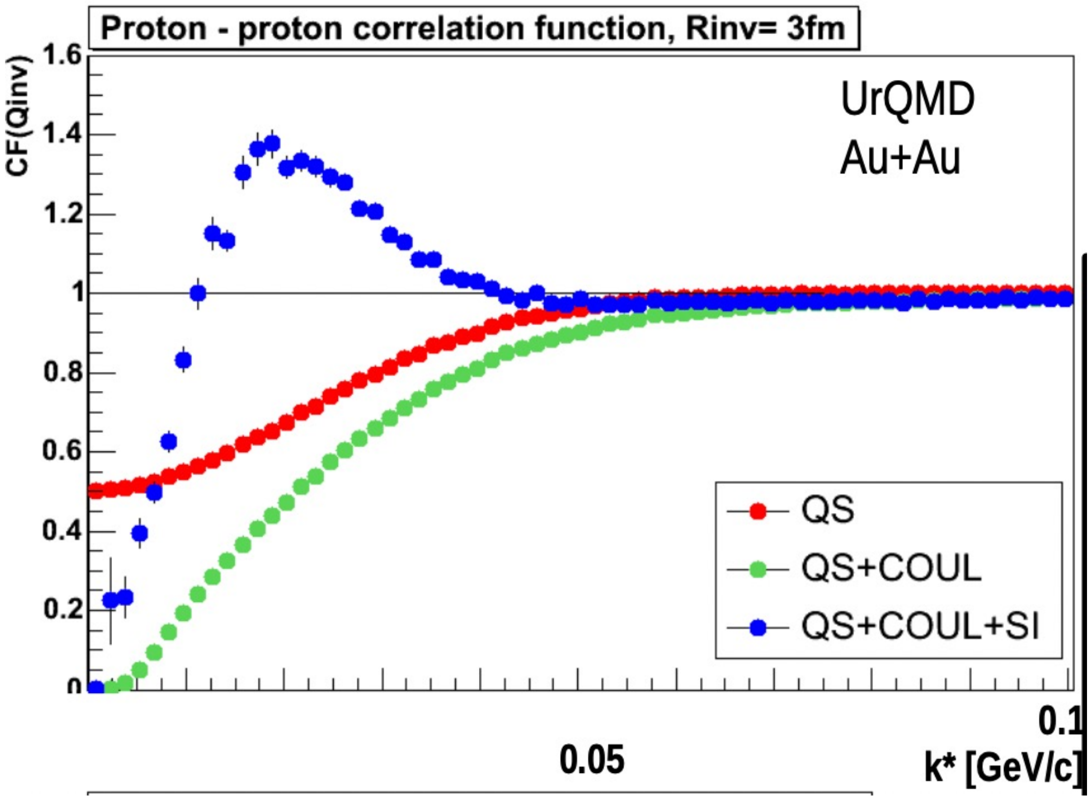
$$\boxed{C(q) = \frac{A(q)}{B(q)}}$$

A: actual pairs from same events

B: background pairs from mixed events

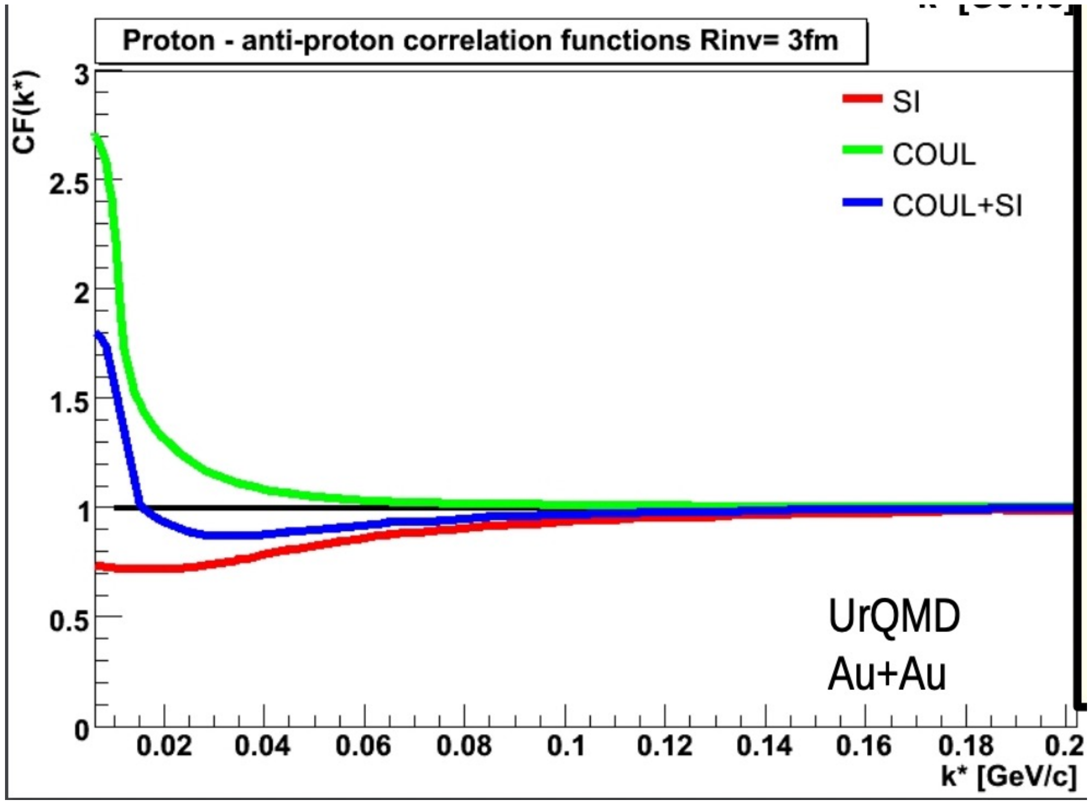
Contribution of Each interaction

Identical correlation



QS+FSI(Strong +Coulomb)

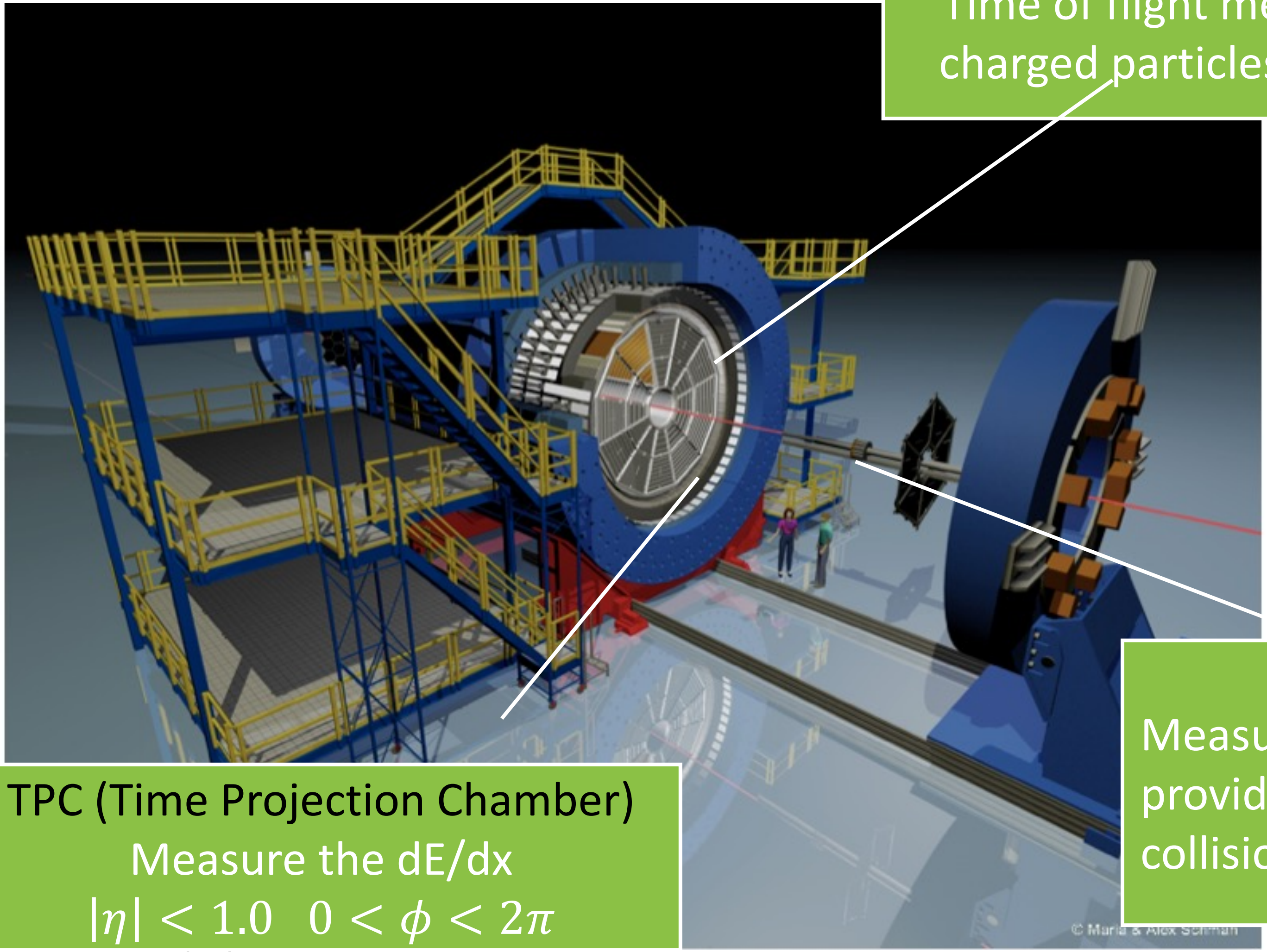
Non-identical correlation



FSI only

Hanna Zbroszczyk from STAR(WPCF2018)

STAR detectors

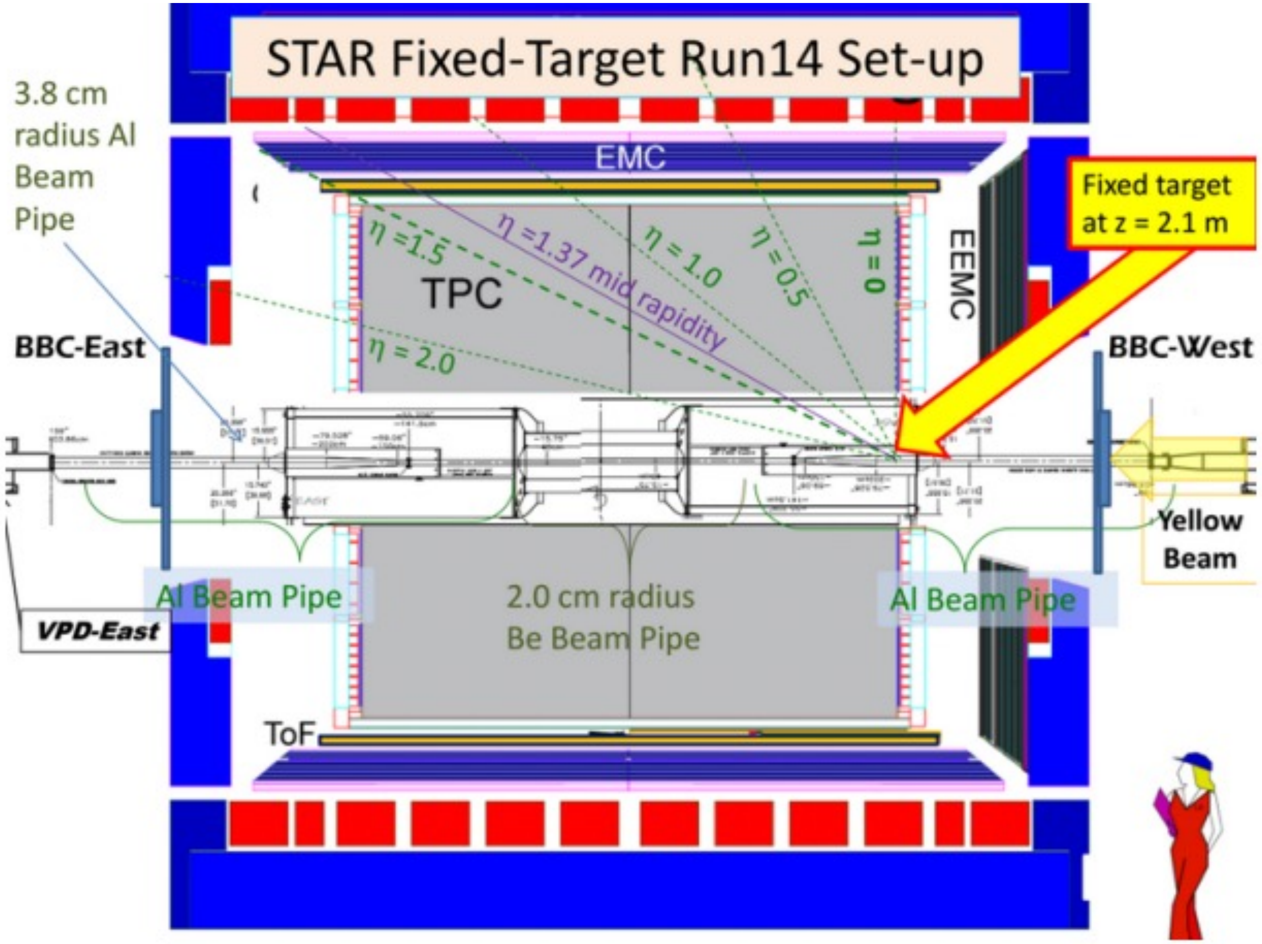


TOF (Time Of Flight)
Time of flight measurement of charged particles, $|\eta| < 0.9$

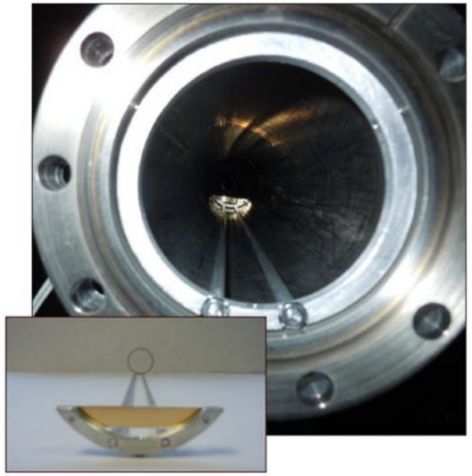
VPD (Vertex Position Detector)
Measure the event start time, providing the minimum-bias trigger in Au+Au collisions.

TPC (Time Projection Chamber)
Measure the dE/dx
$|\eta| < 1.0 \quad 0 < \phi < 2\pi$

STAR FXT trarget program



- The RHIC-Beam Energy Scan Ⅱ (2019~) program covered the fixed target mode from 3.0 to 7.7 GeV.
- Put the gold target at 210cm from the interaction region of TPC.



J. Phys.: Conf. Ser. 742 012022

Lednicky Fit (femtoscopy fit)

$$C(Q)_{Lednicky} = N[1 + \lambda\left(\boxed{-\frac{1}{2}\exp(-r_0{}^2Q^2)} + \boxed{\frac{1}{4}\frac{|f(k)|^2}{r_0{}^2}\left(1 - \frac{1}{2\sqrt{\pi}}\frac{d_0}{r_0}\right) + \frac{Ref(k)}{\sqrt{\pi}r_0}F_1(Qr_0) - \frac{Imf(k)}{2r_0}F_2(Qr_0)}\right) + a_{res}\exp(-r_{res}{}^2Q^2)]$$

Quantum Statistic term

FSI(Final state interaction) term

Residual term
(introduced by STAR to account for residual effect)

$$k = \frac{Q}{2}, F_1(z) = \int_0^z \frac{e^{x^2-z^2}}{z}dx \ldots\ldots \text{Approximate formula} \quad F_1(z) \cong \frac{1}{z}(1 - e^{-z^2}),$$

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

N :Normalization factor

λ :chaotic parameter

f_0 : scattering length

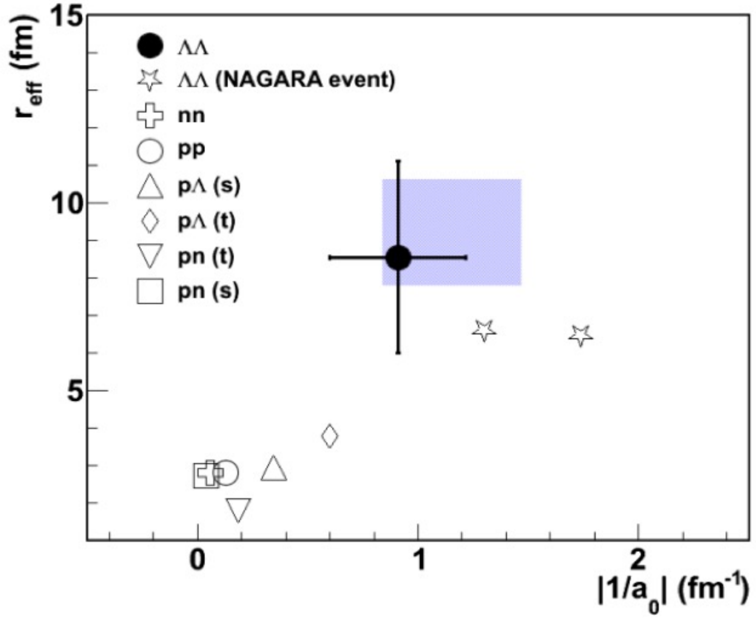
d_0 : effective range

Physical quantity to study a bound state

r_0 :source size

a_{res} : residual amplitude

r_{res} : width of the Gaussian



L. Adamczyk for the STAR Collaboration PhysRevLett.114.022301

Scattering Amplitude: $f(k) = (\frac{1}{f_0} + \frac{1}{2}d_0\, k^2 - ik)^{-1}$

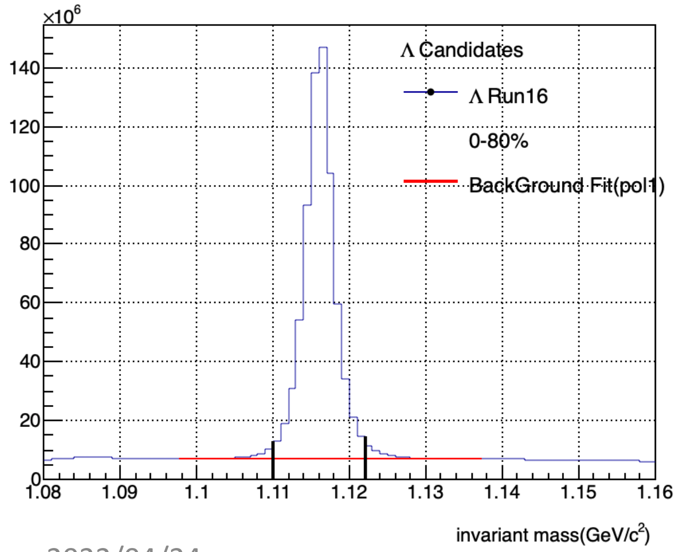
Reconstruction of Λ and Ξ

	Decay channel	Mass (from PDG 2018)
Λ (uds) $\bar{\Lambda}$	$\Lambda -> \pi^- + p$ $\bar{\Lambda} -> \pi^+ + \bar{p}$ (63.9%)	1.115683 (GeV/c^2)
Ξ (dss) $\bar{\Xi}$	$\Xi -> \Lambda + \pi^+$ $\bar{\Xi} -> \bar{\Lambda} + \pi^-$ (99.87%)	1.32171 (GeV/c^2)

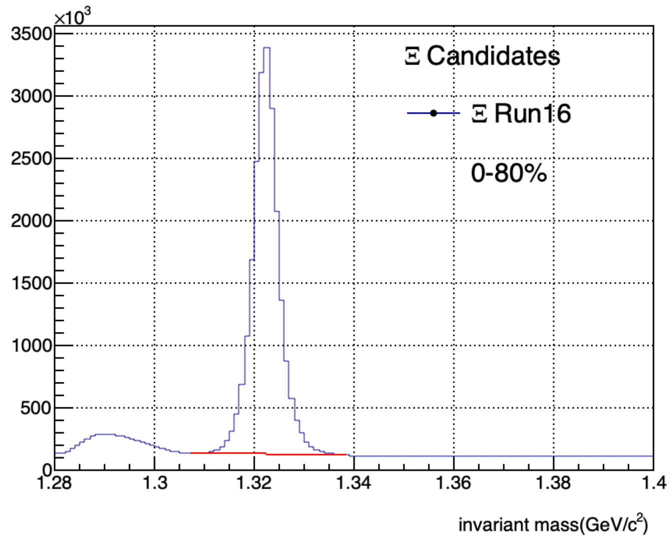
- KFParticle package was used.
  KFParticle is based on Kalman filter.
- Very good Purity for Λ(~88%) and Ξ(~90%).

Invariant mass

Λ



Ξ



Daughter particle selection for Λ and Ξ

For pion
- $|\,\mathrm{n}_{\sigma,\pi}\,| < 3$
- $-0.15 < \mathrm{Mass}^2 < 0.15\ (\mathrm{GeV}/c^2)^2$

For proton
- $|\,\mathrm{n}_{\sigma,\mathrm{p}}\,| < 3$
- $0.5 < \mathrm{Mass}^2 < 1.5\ (\mathrm{GeV}/c^2)^2$

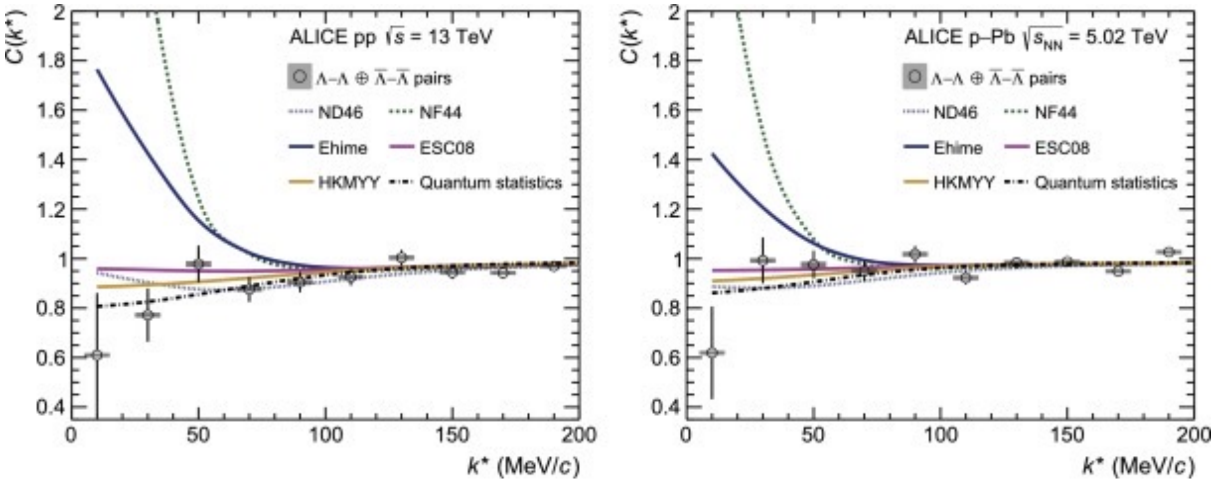
For Λ and Ξ
- $\mathrm{p_T} \geq 0.4\ \mathrm{GeV}/c$
- $|\mathrm{y}| < 1.0$

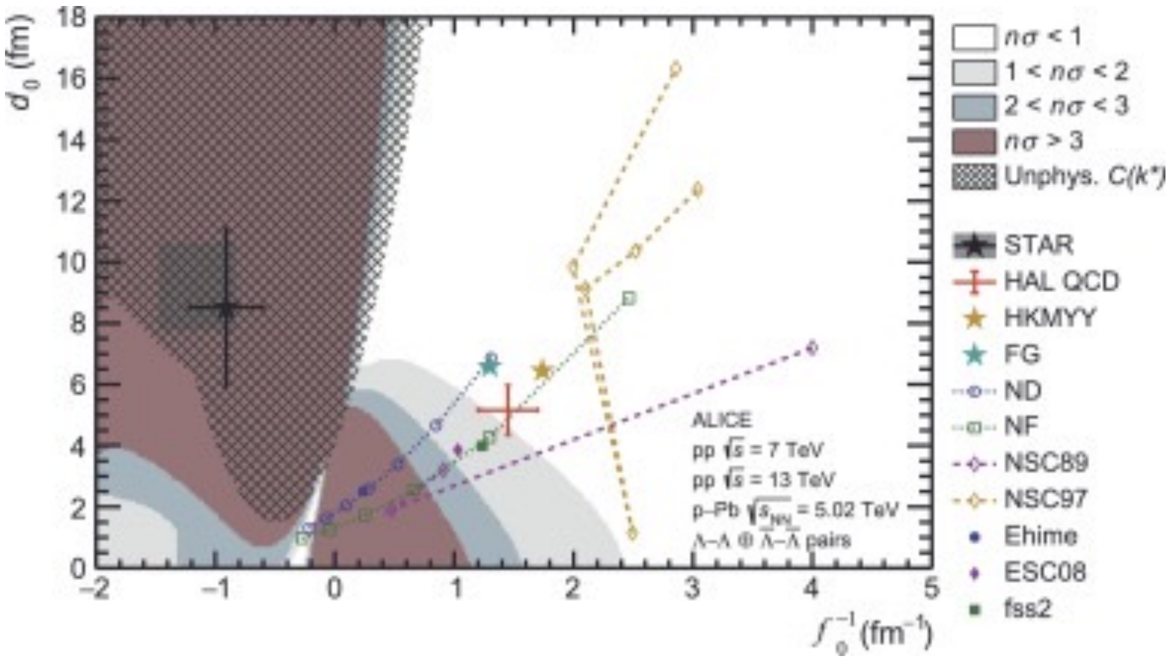
Result

Scattering parameters of $\Lambda\Lambda$

Phys. Lett. B 797 (2019) 134822

From ALICE's result..





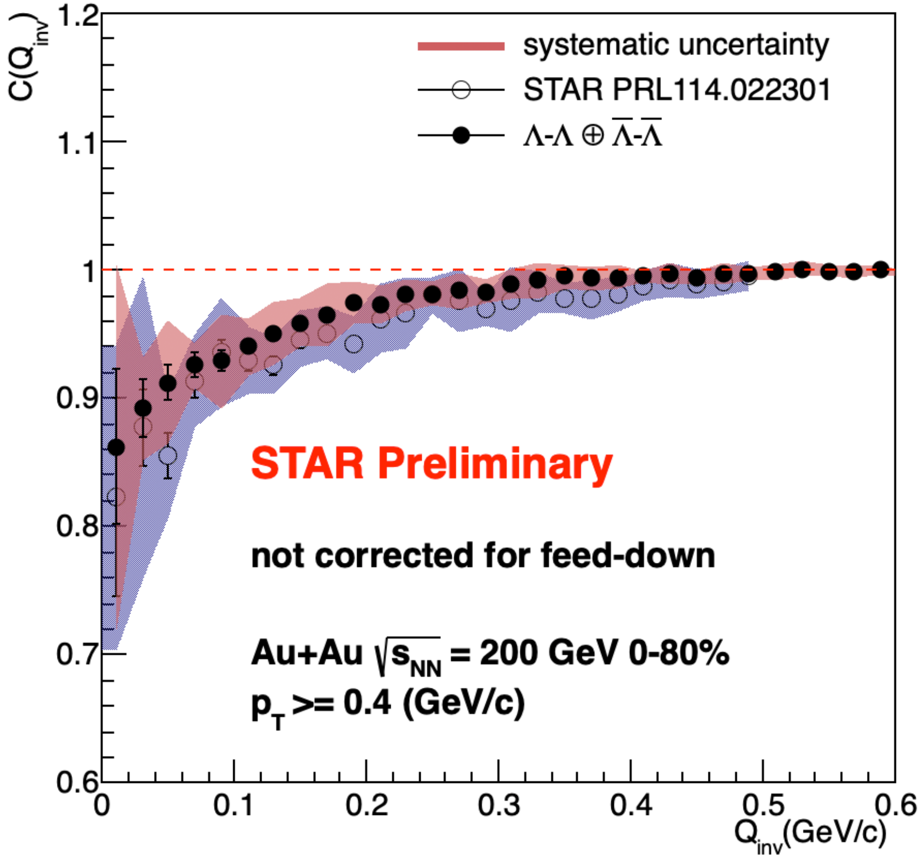
- The HAL QCD from lattice calculation and HKMYY and FG models from hypernuclei data match with ALICE's exclusion plot's region of 1 sigma.

- Previous STAR data is in the unphysical region.

The STAR and ALICE's result is different largely.
This might be due to feed-down contribution in STAR result.
The paramter is very unstable….

We revisit Λ-Λ correlation with high statistics data.

Λ-Λ correlation function



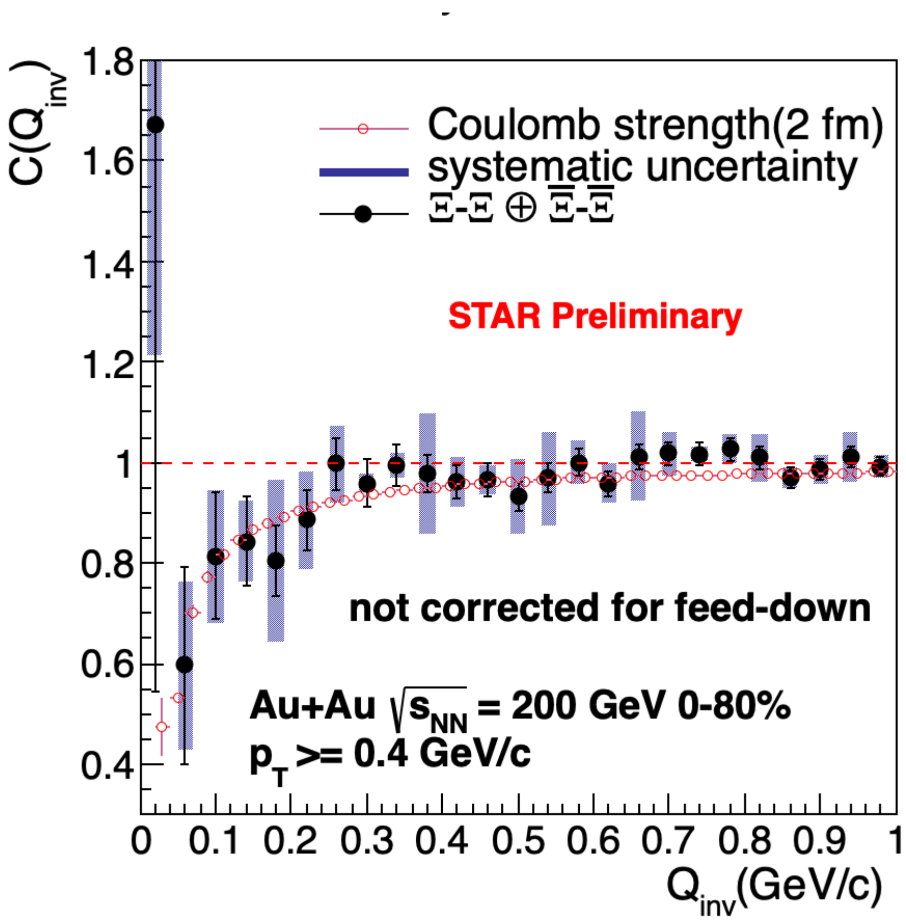
- New result with high statistics data ~4 times larger than that in previous study.
  - Not corrected for feed-down yet.

- Anti-correlation of Λ-Λ is observed in Au+Au at $\sqrt{s_{NN}}$ = 200 GeV.

  - New result with better precision is consistent with previous result within systematic uncertainty.

  - There is a long tail of residual correlation in high Q_{inv}.

Ξ-Ξ correlation function

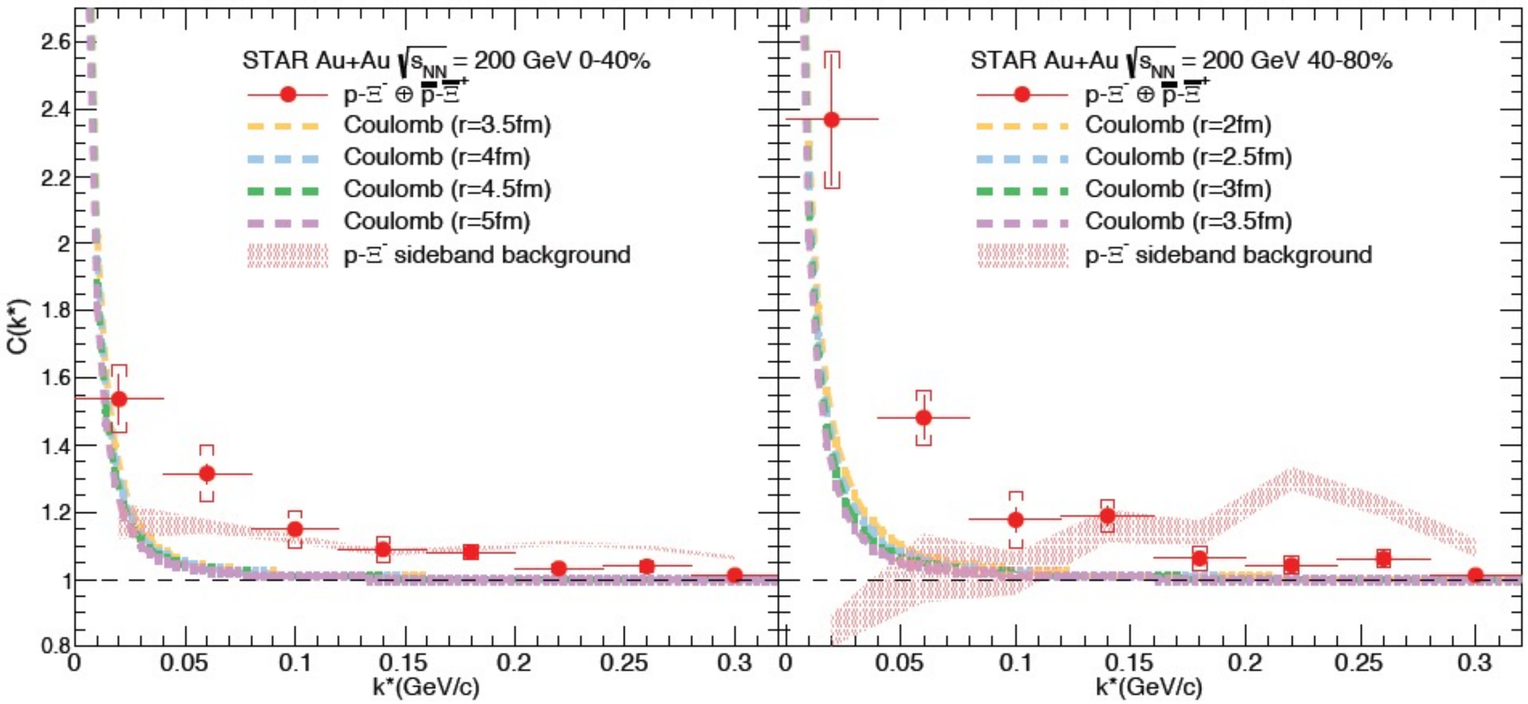


- First measurement of Ξ-Ξ correlation in Au+Au collisions.
- Lattice QCD/chiral EFT calculations indicate an attractive interaction, but not strong enough to form a bound state [1,2].
- The result shows anti-correlation at $Q_{inv} < 0.25\ \mathrm{GeV/c}$.
  - qualitatively matched with coulomb strength.
  - to cancel quantum statistics (negative correlation), strong interaction needs to be positive correlation.
- Feed-down needs to be evaluated and Lednicky- Lyuboshitz fit will be performed for further discussion.
- More events will be taken in 2023(~10B) and 2025(~10B).

[1] J. Haidenbauer et al., Eur. Phys. J. A 51: 17 (2015)
[2] T,Doi et al., EPJ Web Conf. 175 (2018) 05009

p-Ξ correlation function

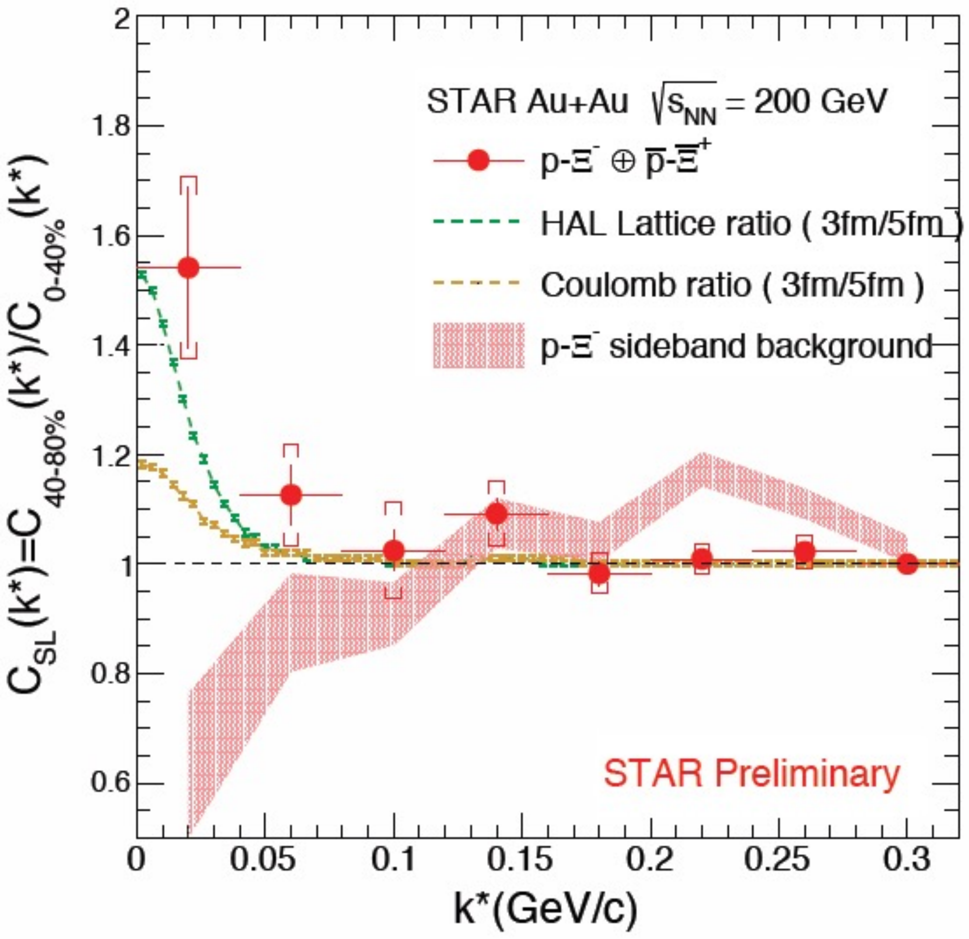
First measurement of p-Ξ correlation in Au+Au collisions at RHIC



k^*: half of relative momentum in pair rest frame

- Feed-down is corrected using Theminator2 model, but residual correlation is not corrected yet.
- p-Ξ correlation shows enhancement above Coulomb interaction
  ->Hints presence of strong interaction, and can not be described by sideband background.
- Sensitive to system size, more attractive in peripheral collisions (smaller collision system).

p-Ξ correlation function



$C(k^*)$ ratio of small to large systems,

$$C_{SL}(k^*) = \frac{C(k^*)_{40-80\%}}{C(k^*)_{0-40\%}}$$

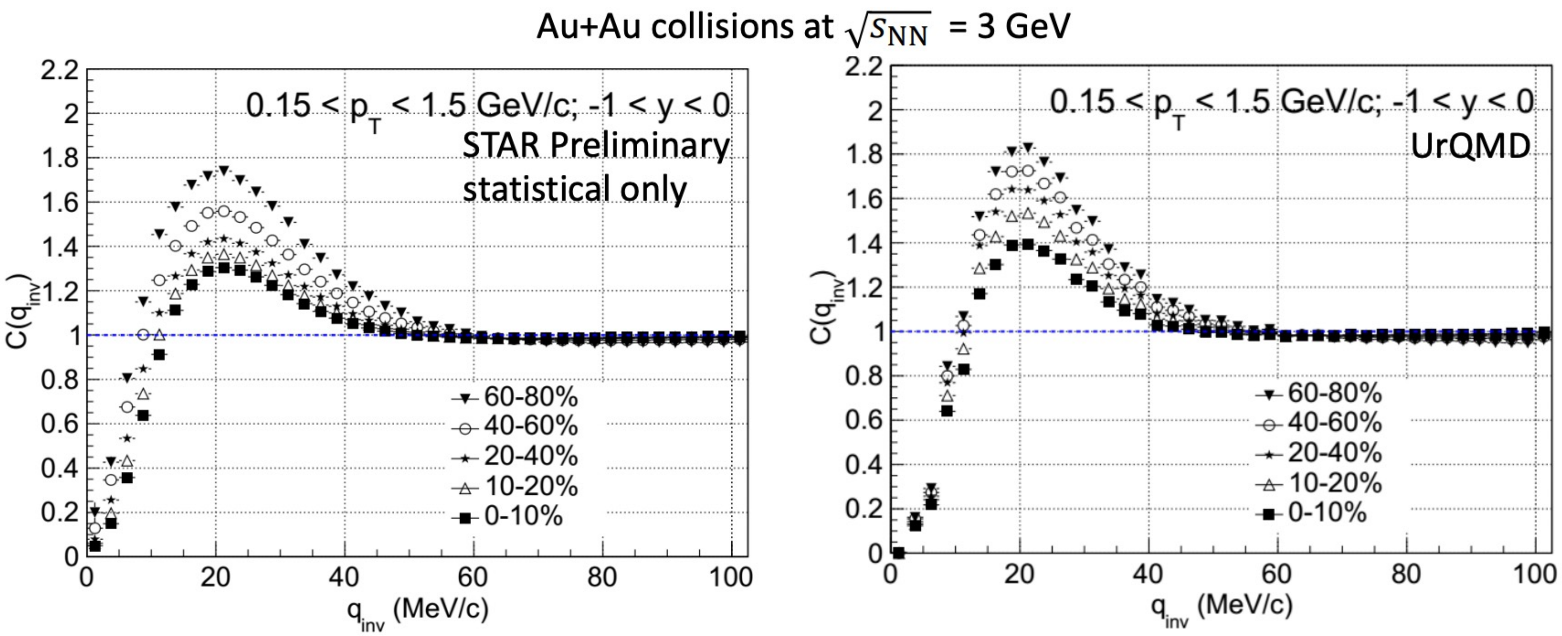
$C_{SL}(k^*)$ is more sensitive to strong interaction with largely canceled Coulomb interaction[1].

- Below k^* = 0.1 GeV/c, the signal is enhanced beyond the Coulomb interaction and background.
- Similar to lattice QCD calculation [2] which suggests an attractive strong interaction between p and Ξ^-.

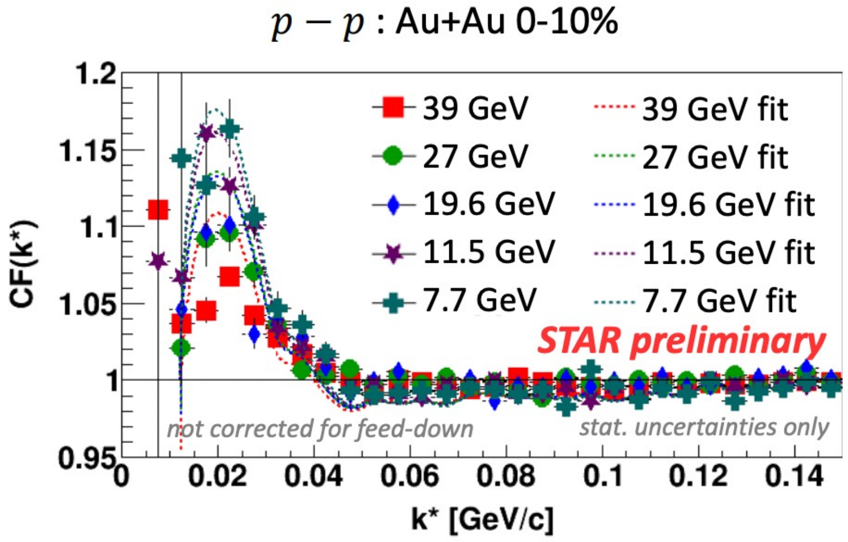
[1] K. Morita et al, Phys. Rev. C94(2016) 031901
[2] T.Hatsuda Nuclear Physics A 967 (2017) 856–859

proton-proton correlation at 3GeV FXT

Centralrity dependence



Chuan Fu, QPT 2021(STAR)



- Significant centrality dependence is observed.
- Large correlation in lower collision energy.

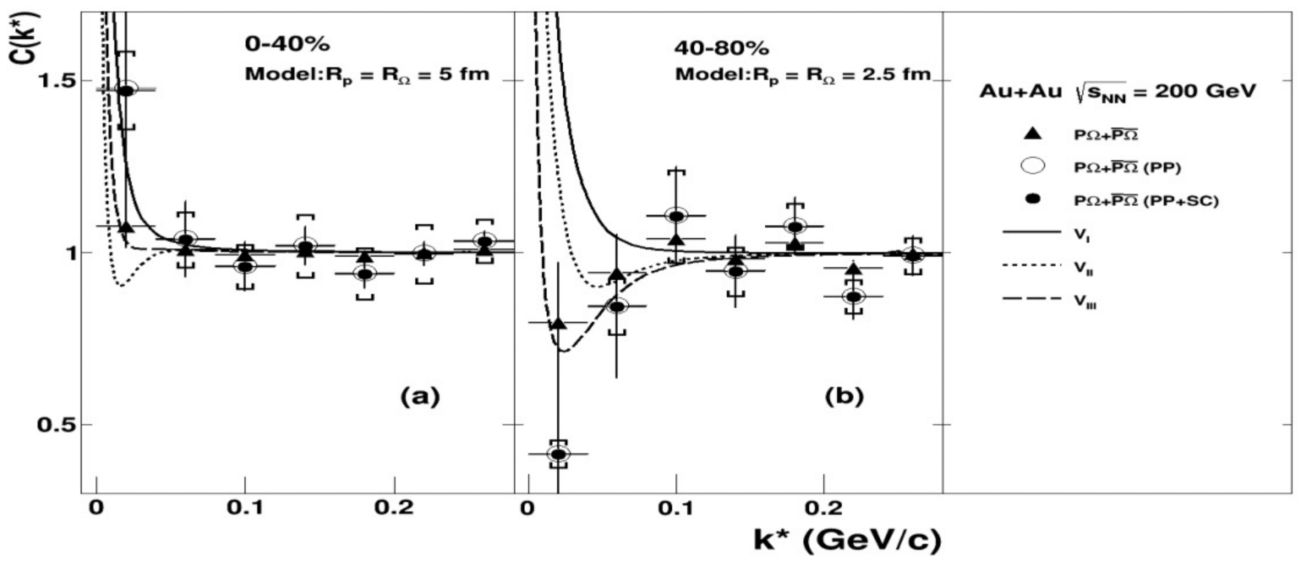
- The data is very similar to the UrQMD model.

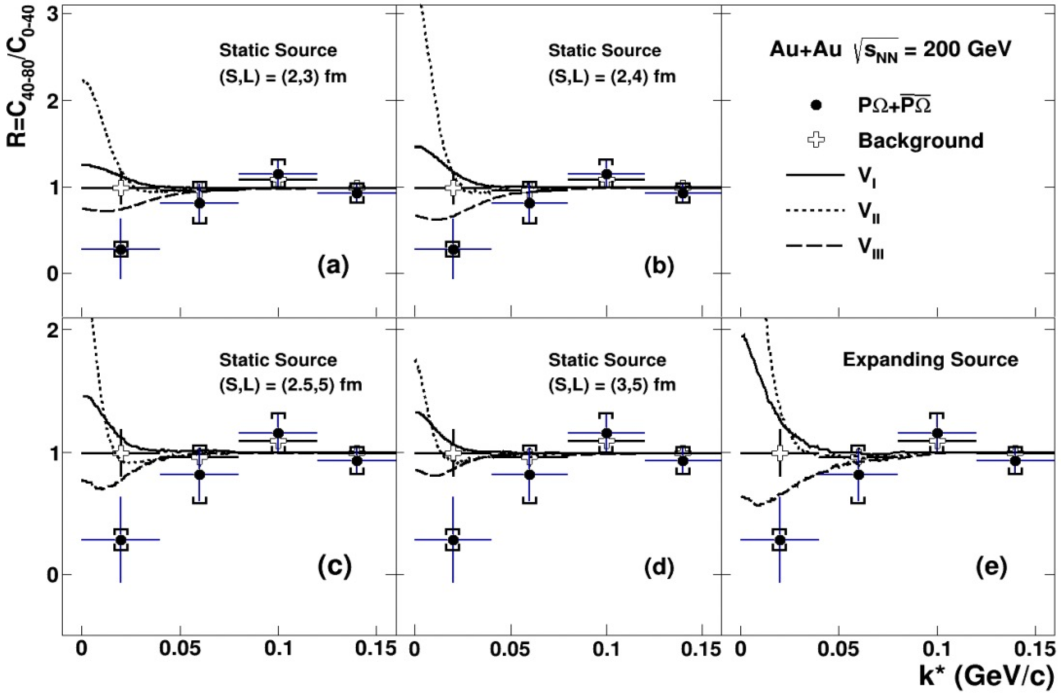
STAR Sebastian Siejka QuarkMatter2018

Nucl. Phys. A 982 (2019), 359-362

proton-Ω correlation

STAR, arXiv:1808.02511





In 40~80% centrality, enhancement due to Coulomb interaction is not visible.

<u>discussing about bound state….</u>

Models from lattice QCD

VⅠ:without bound state

VⅡ:shallow bound state

VⅢ:deep bound state

It's difficult which one is the best fit
->more statistics needed…

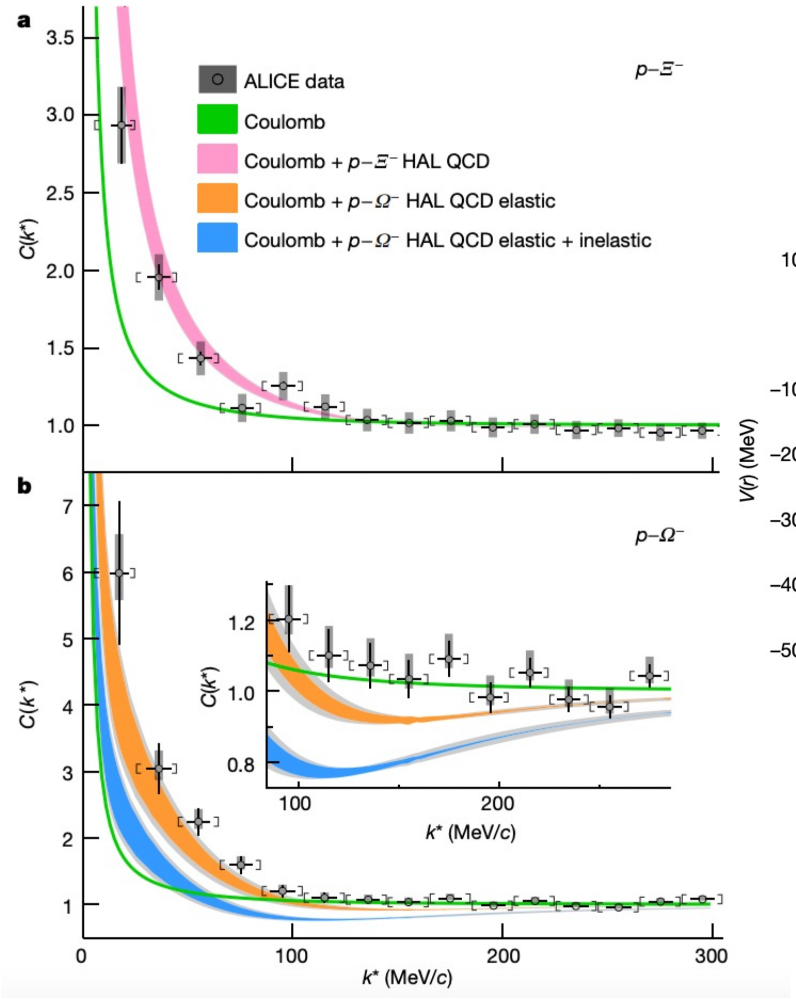
- potentials VI and VII are 3σ larger than the data at k^* = 20 MeV/c.
- VIII with expanding source and static source are within 1σ of the data at k^* = 20 MeV/c.

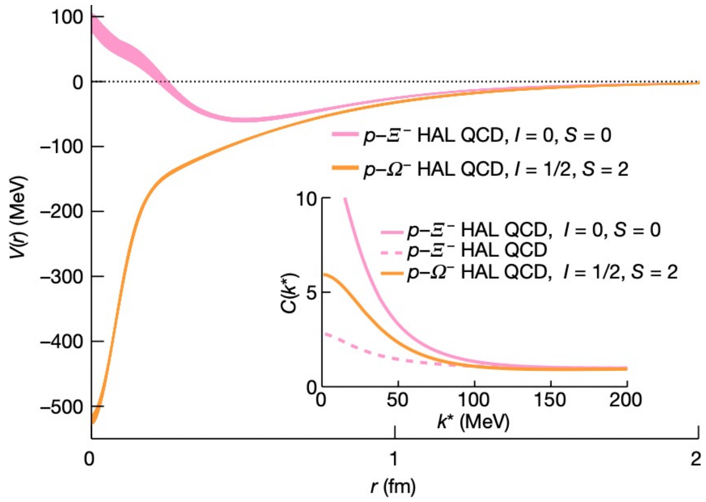
Deep bound state???

p-Ξ and p-Ω correlations from ALICE

Nature **volume 588**, pages232–238 (2020)

High multiplicity p-p collisions at $\sqrt{s} = 13$ TeV.





- p-Ξ and p-Ω were measured with good precision and have attractive interactions.

<u>Comparison with HAL QCD</u>

- p-Ω correlation is twice bigger than p-Ξ. This caused by the large difference in the strong attractive interaction predicted the calculations by the HAL QCD

- The depletion around k*= 150 MeV/c in HAL QCD model caused by the p-Ω bound state.

→the data is not matched…
There is no bound state of p-Ω ???

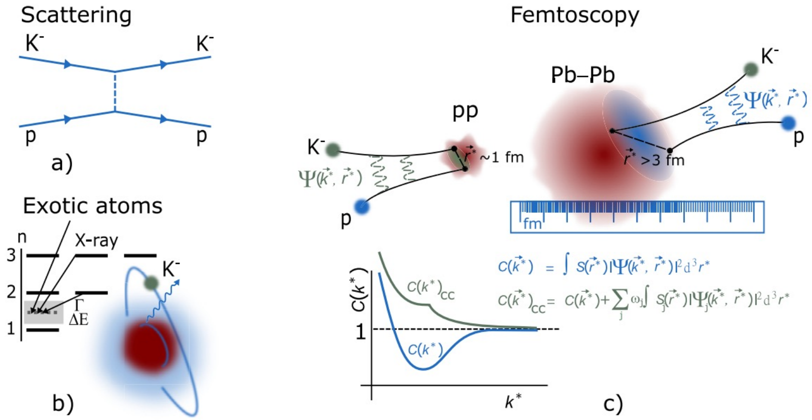
+α

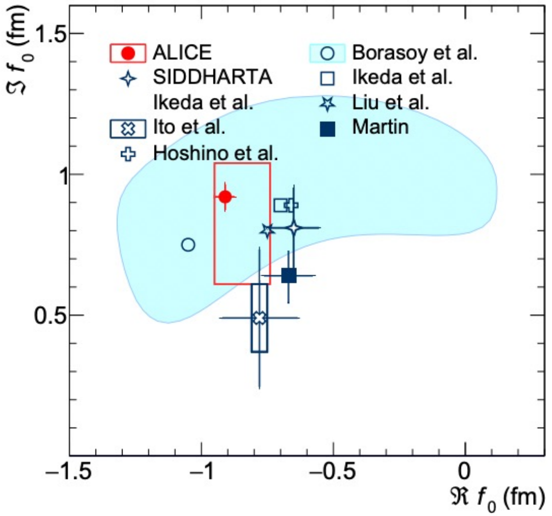
Recent study of hadron correlations

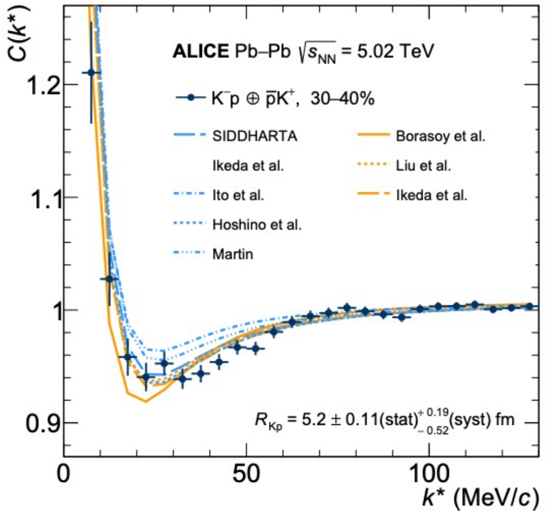
p-K Correlation function

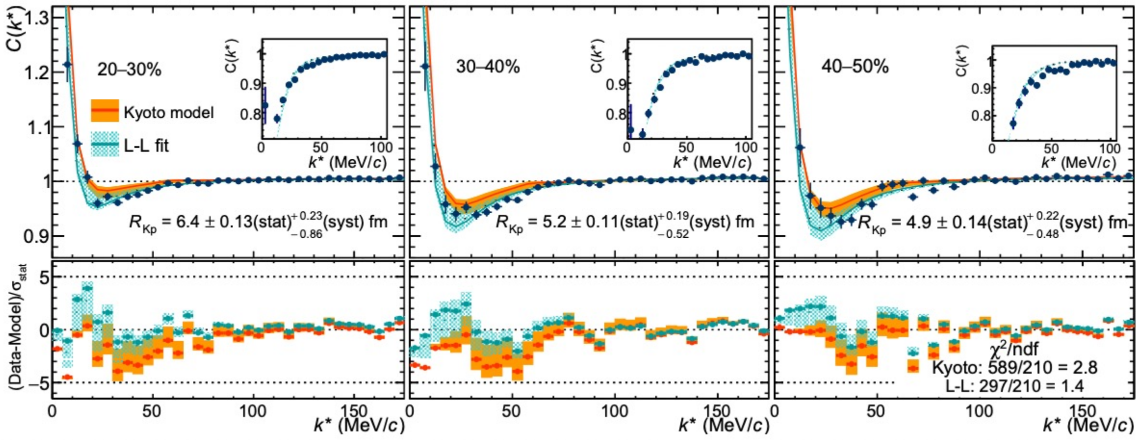
ALICE, Phys. Lett. B 822 (2021) 136708

The first mesurement of p-K in Pb-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV









ALICE Phys. Lett. B 822 (2021) 136708

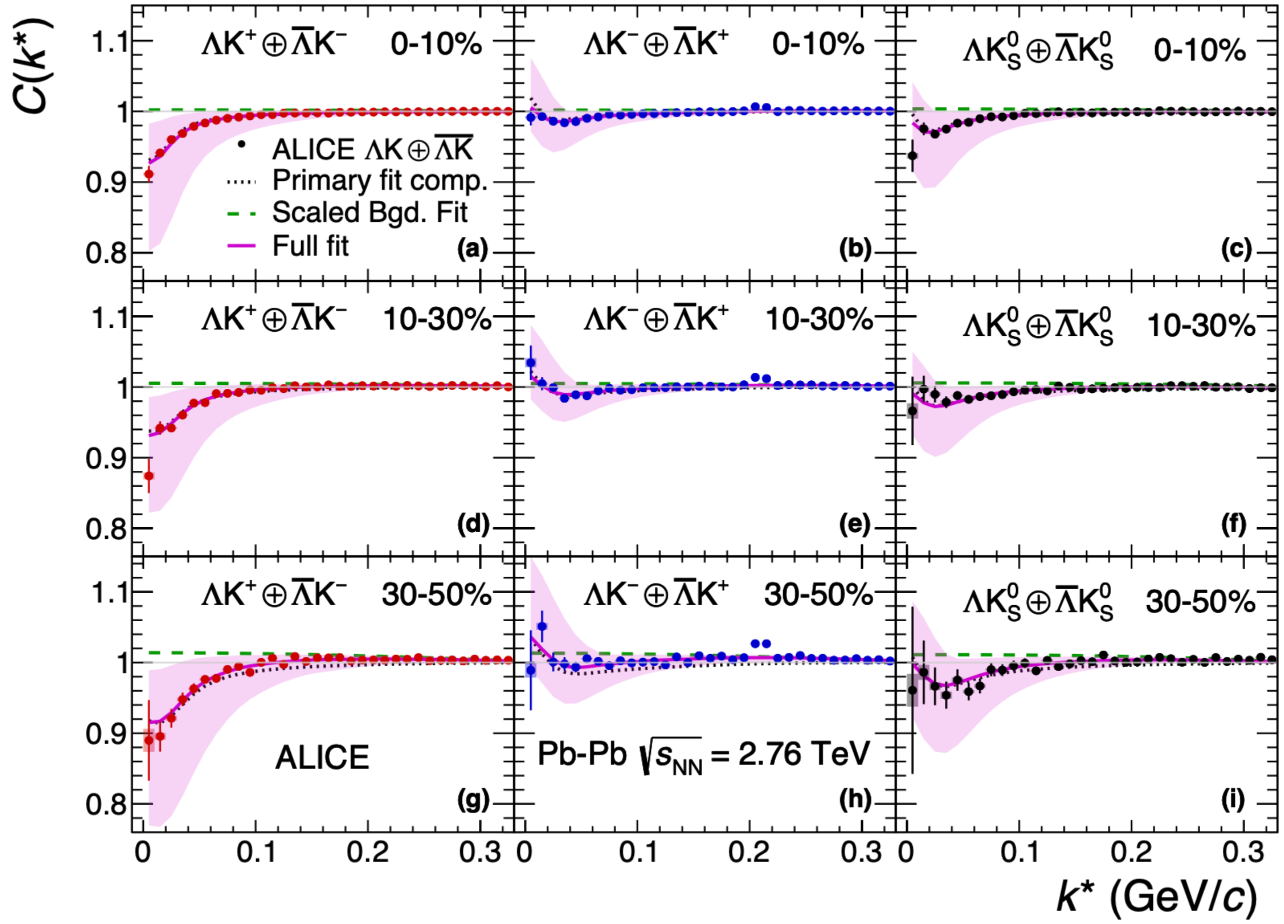
There are attractive Coulomb interactions in low k^*.

- In 20 < k^* < 50MeV/c, the repulsive strong interaction in more peripheral (small system), it's stronger

- The result is consistent with result from scattering and exotic kaonic atom experiments and model calculations.

Λ-K Correlation Function

ALICE,Phys. Rev. C 103, 055201 (2021)



The first mesurements of Λ-K correlations.

dotted curve…the primary (ΛK) contribution to the fit
dashed curve…the non-femtoscopic background
solid curve …the final fit

$$\boxed{C_{\mathrm{Fit}}(k^*_{\mathrm{Rec}}) = \mathcal{N} \times F_{\mathrm{Bgd}}(k^*_{\mathrm{Rec}}) \times C'_{\mathrm{Fit}}(k^*_{\mathrm{Rec}}),}$$

- primary ΛK component(dot curve) have the largest differences between solid curve in the 30–50%.

The contribution from non-femtoscopic background is biggest in 30-50%.

ΛK+…..replusive interaction
ΛK-……attractive interaction
ΛK_0^S….attractive interaction

Caused by the different quark-antiquark interactions or from different net strangeness

Summary

Recently, new results of baryon-baryon correlations were reported in the STAR.

- Λ-Λ **correlation function**
  - New result with high statistics data is consistent with previous result.
  - Anti-correlation is observed.
- Ξ-Ξ **correlation function**
  - Anti-correlation seems to be observed for the first time, which is almost matched with Coulomb interaction. It seems that quantum statistics and strong interaction are canceled.
- p-Ξ **correlation**
  - Attractive interaction is observed.
  - Similar to lattice QCD calculation which suggests an attractive strong interaction between p and Ξ^-.
- **p-p correlation**
  - Attractive interaction is also observed in the 3 GeV FXT.
  - There is clear energy dependence.
- **p-Ω correlation**
  - Deep bound state ??

ALICE's result

- p-Ξ and p-Ω correlations are attractive interactions.
- p-K is matched with the results scattering and exotic kaonic atom experiments.

Future plans

For Λ-Λ and Ξ-Ξ correlation,

-Apply the feed-down effect and momentum resolution corrections to the correlation functions.
-Fit the correlation functions using models including different interaction mechanisms to understand hyperons.
-More events of Au+Au $\sqrt{s_{\mathrm{NN}}}$ = 200 GeV will be taken in 2023(10B~events) and 2025(10B~events).

For other Correlations,
From STAR,
-Study on p-Λ in $\sqrt{s_{\mathrm{NN}}} = $ 3GeV the Fixed target and 19.6 GeV will be reported in QM2022.
-The proton-light-nuclei correlation in Fixed target will be reported in QM2022.
$-\Lambda$-$\overline{\Lambda}$ and Ξ-$\overline{\Xi}$ correlation functions are ongoing.
-If more statistics…. the Ω-Ω study is coming????A new study about most strangeness barons (di-omega).