筑波大学
University of Tsukuba

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Measurements of p-Ξ, Λ-Λ, and Ξ-Ξ Correlation in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV at RHIC-STAR

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For the STAR Collaboration

SQM 2021

STAR

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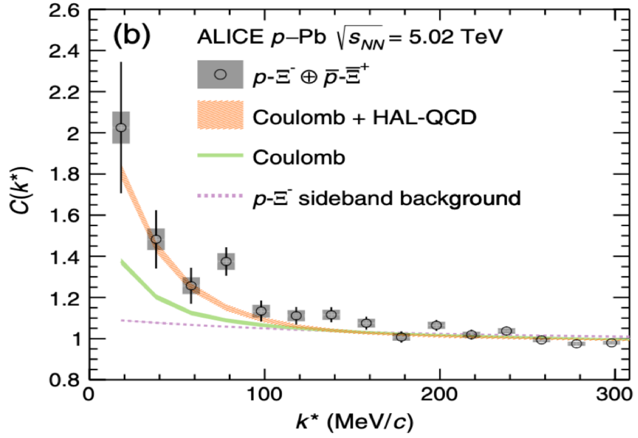
Physics Motivation

- Hyperon-Hyperon (Y-Y) and Hyperon-Nucleon (Y-N) interactions are important for study of 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) ?

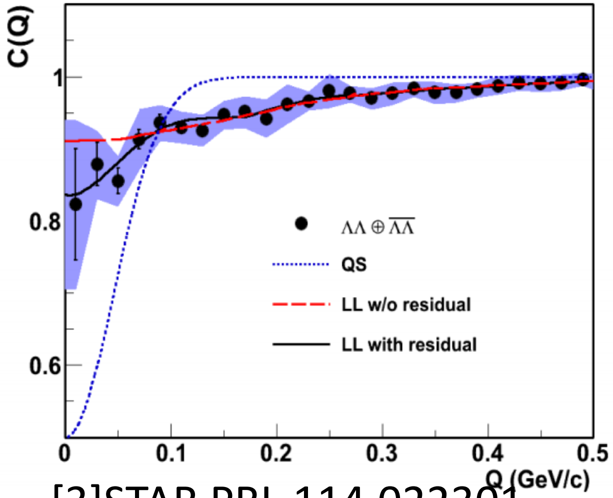
- Various hadrons including hyperons are abundantly produced in HIC.

- In ALICE, the attractive interaction of p−Ξ was observed in p+p and p+Pb collisions[1,2].
- In STAR, the anti-correlation of Λ-Λ was observed in Au+Au collisions with large uncertainty[3].

- In this study, p-Ξ, Λ-Λ, and Ξ-Ξ correlations are studied at Au+Au $\sqrt{s_{NN}}$ = 200 GeV.



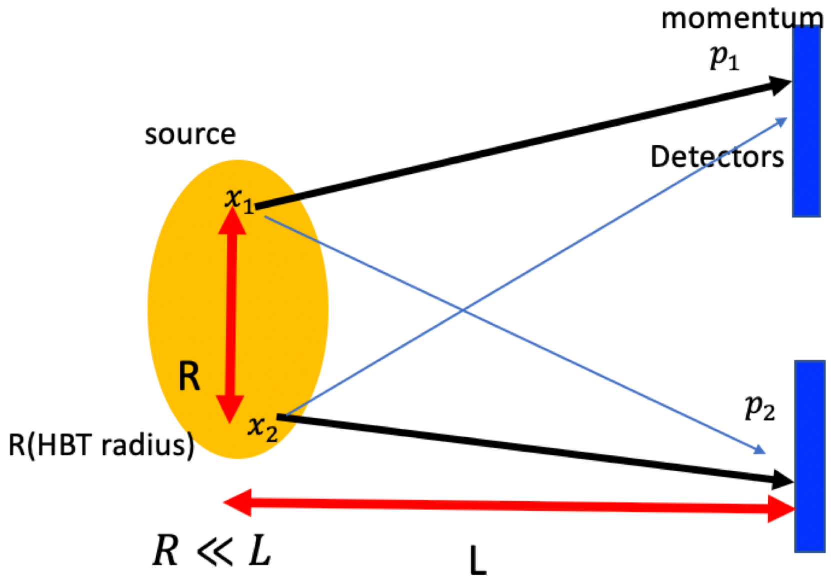
[1]ALICE PRL.123,112002



[3]STAR PRL.114.022301

[2]S. Acharya et al., Nature 588, 232 (2020)

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

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

r: relative distance (of pair)

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

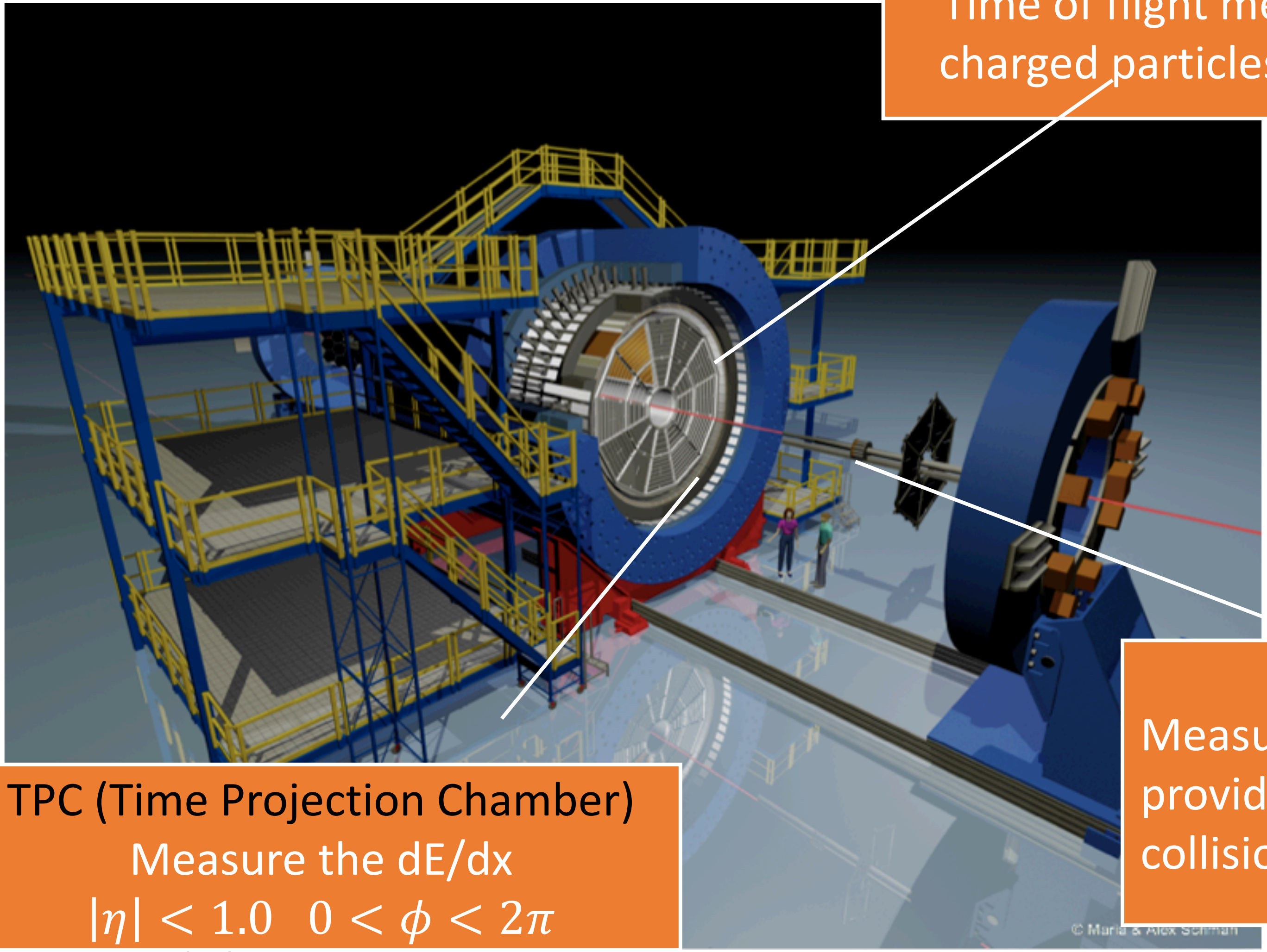
$s(r)$ source function $\psi(q,r)$: wave function of two-particles

Experiment

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

A: actual pairs from same events
B: background pairs from mixed events

STAR detectors



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

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

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

Data Set

Au+Au $\sqrt{s_{NN}} = 200$ GeV

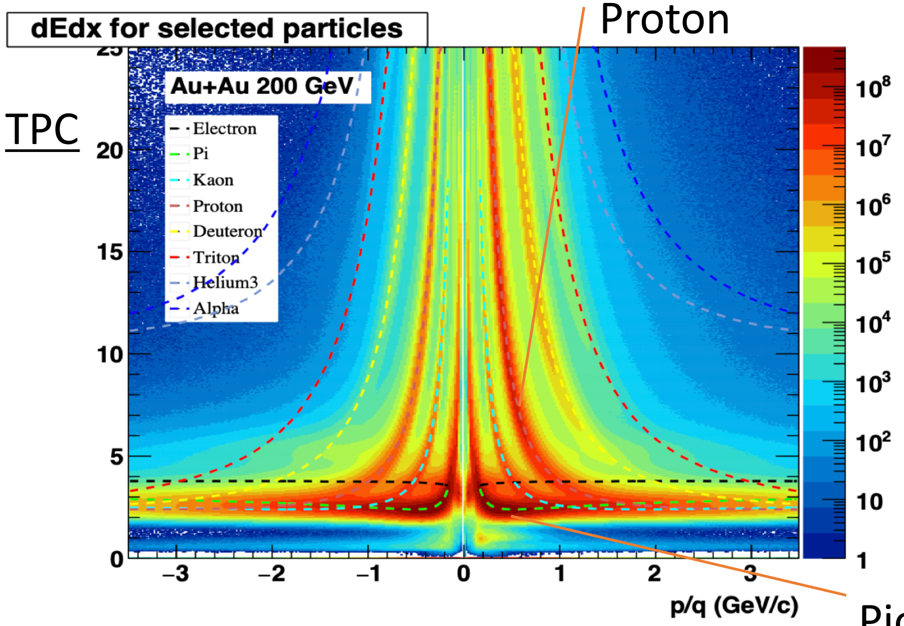
	p-Ξ	Λ-Λ and Ξ-Ξ
Run year	2010, 2011, 2014	2011, 2014, 2016
Total events	1.5billion	2.8billion

TPC & TOF PID

Particle identification based on dE/dx and time-of-flight

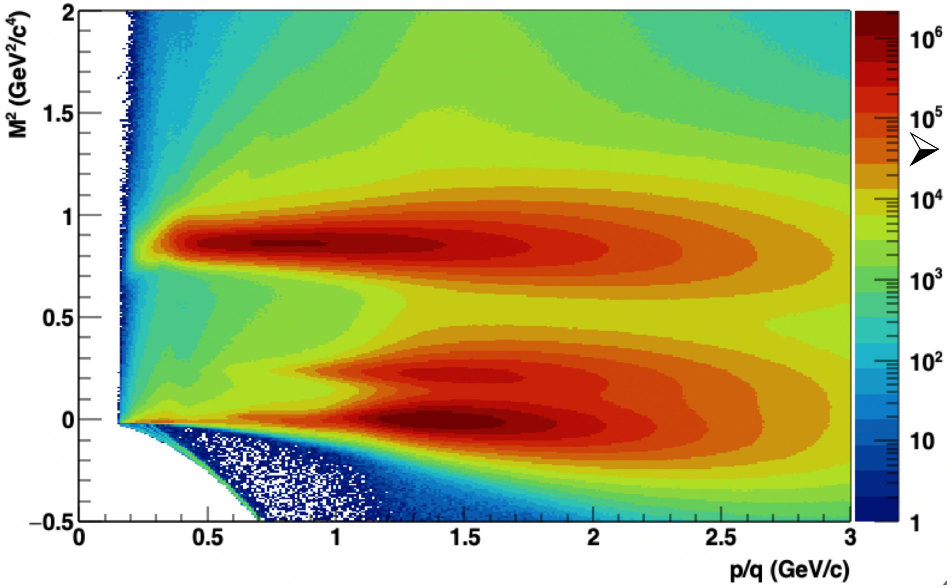
TPC

Proton



Pion

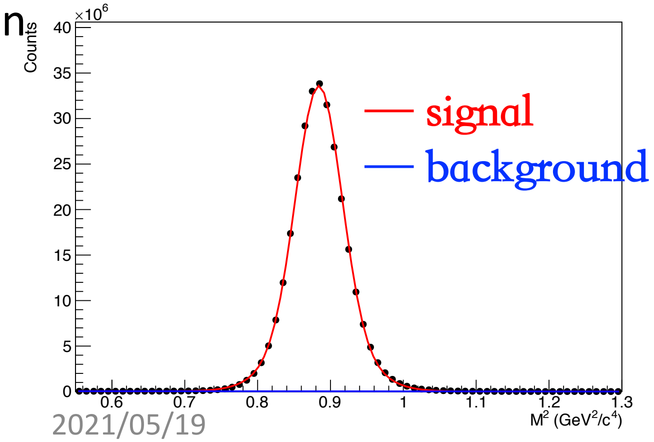
TOF



- ➢ Separation of pions and protons up to p = 3 GeV/c

Proton, 200 GeV, Run11 0.5-0.7 GeV/c

proton



-proton selection

- ➢ $|n_{\sigma,p}| < 2$
- ➢ $0.75 < \text{Mass}^2 < 1.15 (\text{GeV}/c^2)^2$
- ➢ $0.5 < p_T < 2.5$ GeV/c
- ➢ $|y| < 1.0$

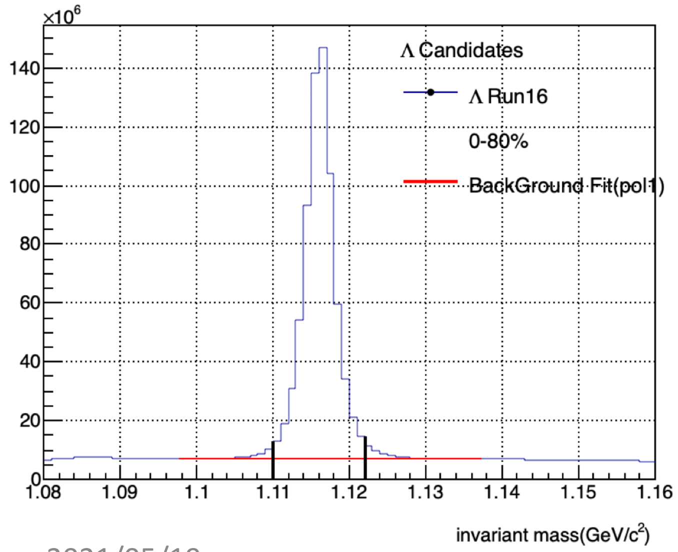
Reconstruction of Λ and Ξ

	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)
$\Xi\ (dss)$ $\bar{\Xi}$	$\Xi -> \Lambda + \pi^+$ $\bar{\Xi} -> \bar{\Lambda} + \pi^-$ (99.87%)	1.32171 (GeV/c^2)

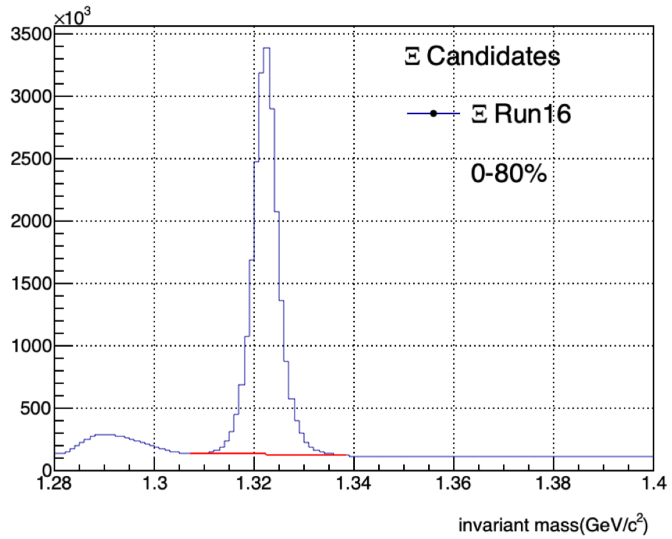
- KFParticle package was used.
  KFParticle is based on Kalman filter.
- Very good Purity for Λ(~88%) and Ξ(~90%).

Invariant mass

Λ



Ξ



Daughter particle selection for Λ and Ξ

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

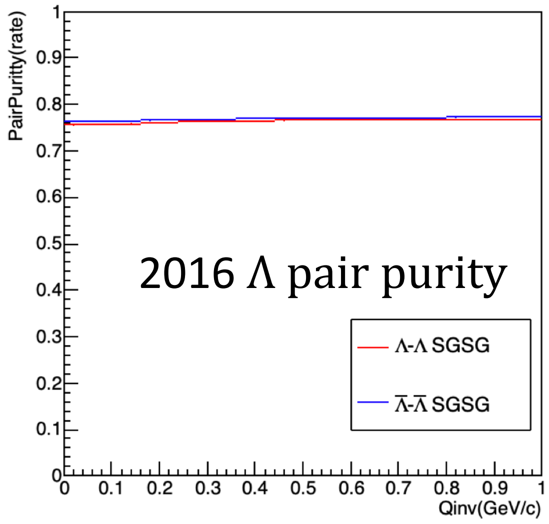
For proton
- $|\ n_{\sigma,p}\ | < 3$
- $0.5 < \mathrm{Mass}^2 < 1.5\ (\mathrm{GeV}/c^2)^2$

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

Purity Correction

Correlation function is corrected for pair purity and feed-down as follows

$$C_{true}(q) = \frac{C_{measure}(q) - 1}{P(q) * F} + 1$$



$\boldsymbol{P(q)}$: **pair purity as a function of q**

F: Fraction of primary to inclusive particles

F(p)=0.6 - 0.7, F(Ξ^-) =0.438 (from Therminator2 model)

Residual correlation from background pairs is also studied.

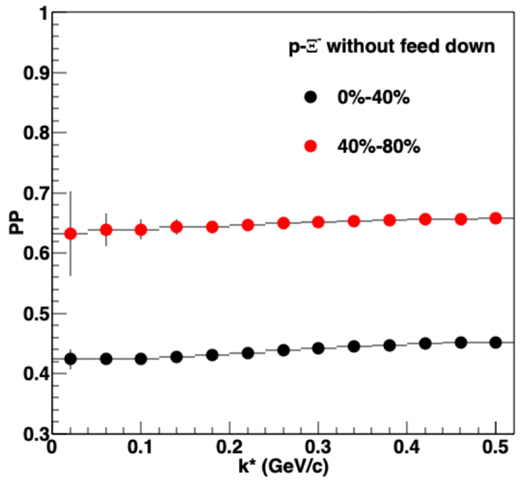
- Used for Λ-Λ and Ξ-Ξ study

$$C_{true}(q) = \frac{1}{P_{SGSG}(q)}\{(C_{measured}(q) - 1) - 2 * (P_{SGBG}(q))(C_{SGBG}(q) - 1) - P_{BGBG}(q) * (C_{BGBG}(q) - 1)\} + 1$$

$\boldsymbol{P_{SGBG}(q)}$: **pair fraction of signal-background pairs**

$\boldsymbol{P_{BGBG}(q)}$: **pair fraction of background-background pairs**

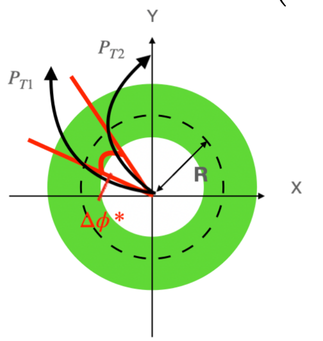
➢ the residual correlation was almost <u>negligible</u> on C(q).

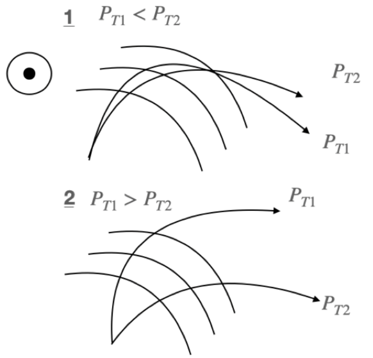


p-Ξ pair purity

Pair inefficiency and daughter sharing removal

$$\Delta\phi^* = \phi_1 - \phi_2 + \sin^{-1}\left(\frac{0.3eB_zR}{2p_{T_1}}\right) - \sin^{-1}\left(\frac{0.3eB_zR}{2p_{T_2}}\right)$$

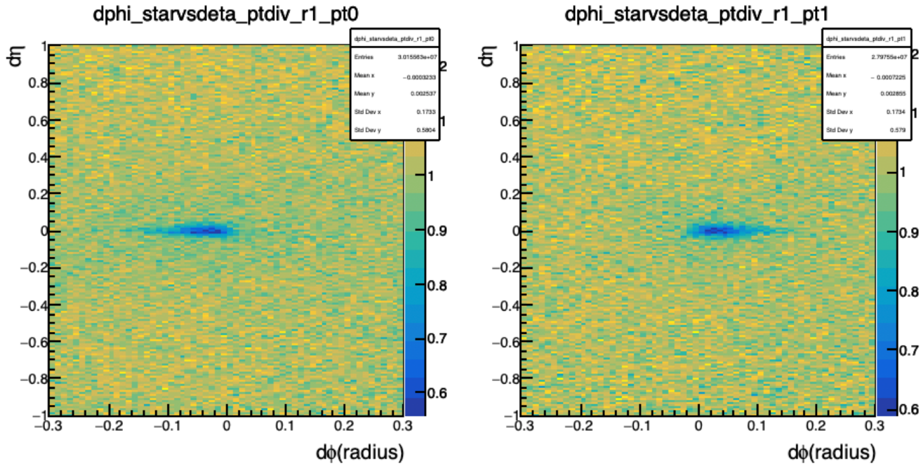




$p_{T_1} < p_{T_2}$ $\quad$ $p_{T_1} > p_{T_2}$

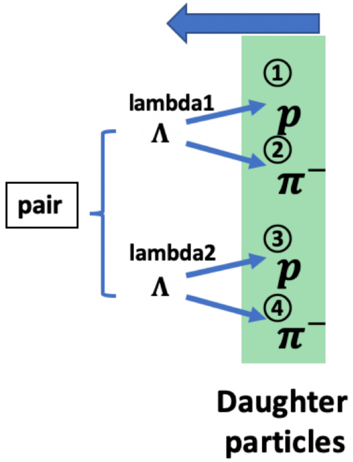
daughter

$p - p$



- Pair inefficient region was removed considering B-field, particle charge, and p_T.

Particle reconstruction process

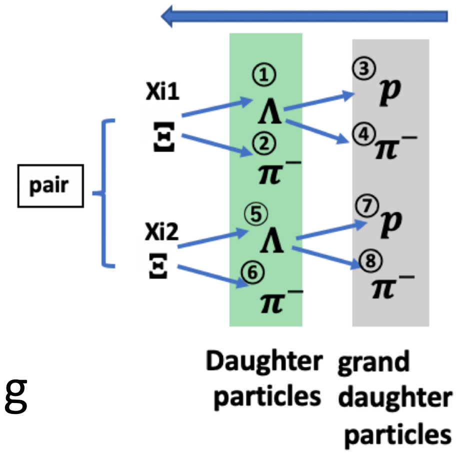


Possible sharing pairs

By daughter particles
(①,③) (②,④)

- Particles sharing their daughters with others are removed to avoid auto-correlation.

Particle reconstruction process



Possible sharing pairs

By daughter particles	By grand daughter particles
(②,⑥)	(②,⑧) (④,⑧) (④,⑥),(③,⑦) (③,⑧),(④,⑦)

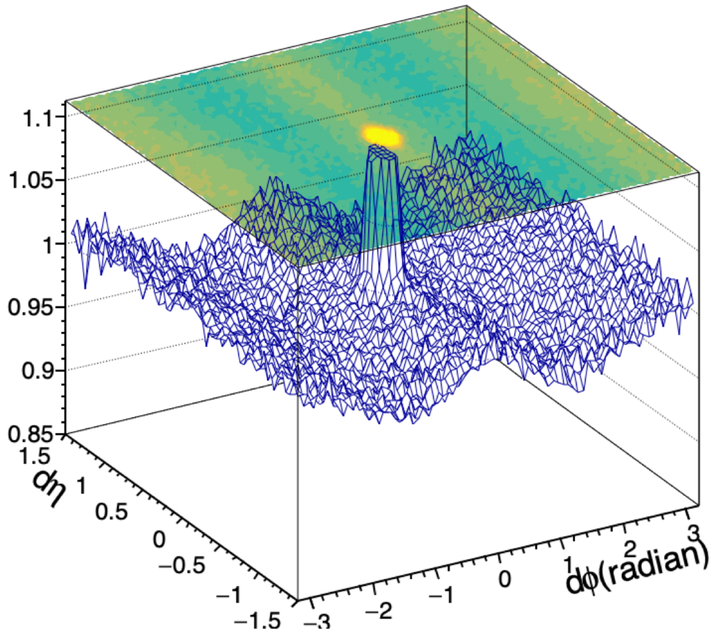
$\Delta\phi$ vs $\Delta\eta$ correlation function

$$C_2(\Delta\phi, \Delta\eta) = \frac{N_{mix}^{pair} Y_{real}(\Delta\phi, \Delta\eta)}{N_{real}^{pair} Y_{mix}(\Delta\phi, \Delta\eta)}$$

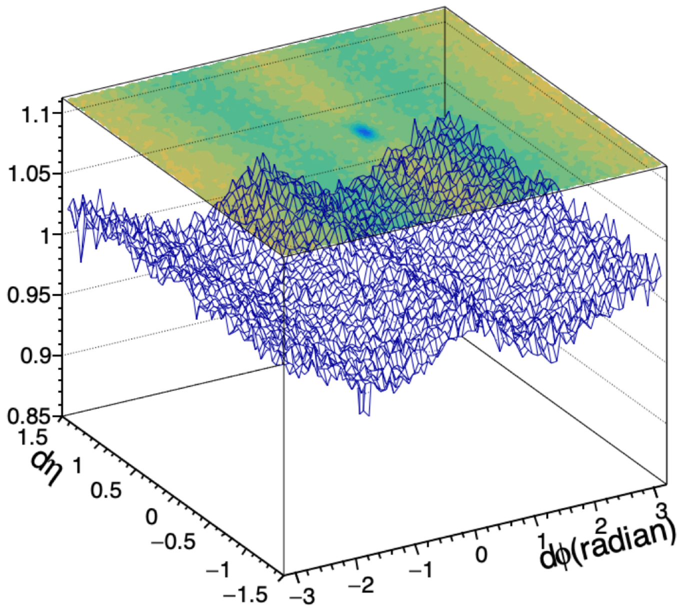
$\Delta\eta = \eta_2 - \eta_1$
$\Delta\phi = \phi_2 - \phi_1$

Y =yield of pairs

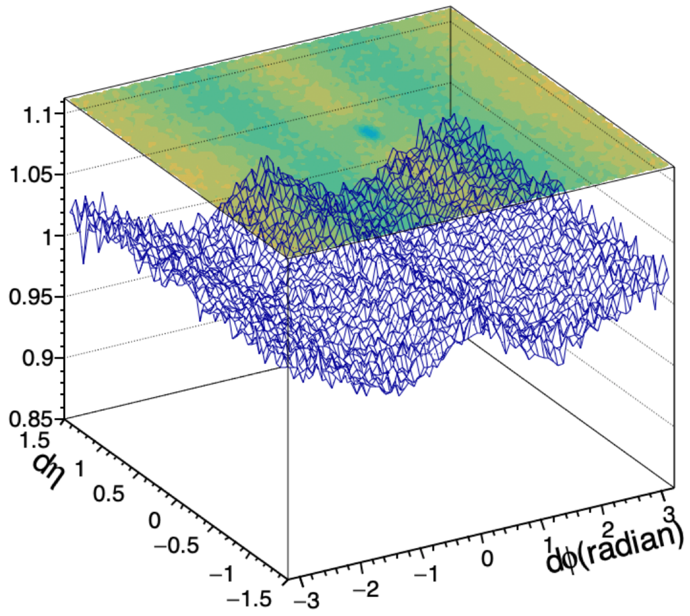
Before sharing cut Λ-Λ



After sharing cut Λ-Λ



After sharing cut Λ-Λ + pair cut($\Delta\phi^*$vs $\Delta\eta$)

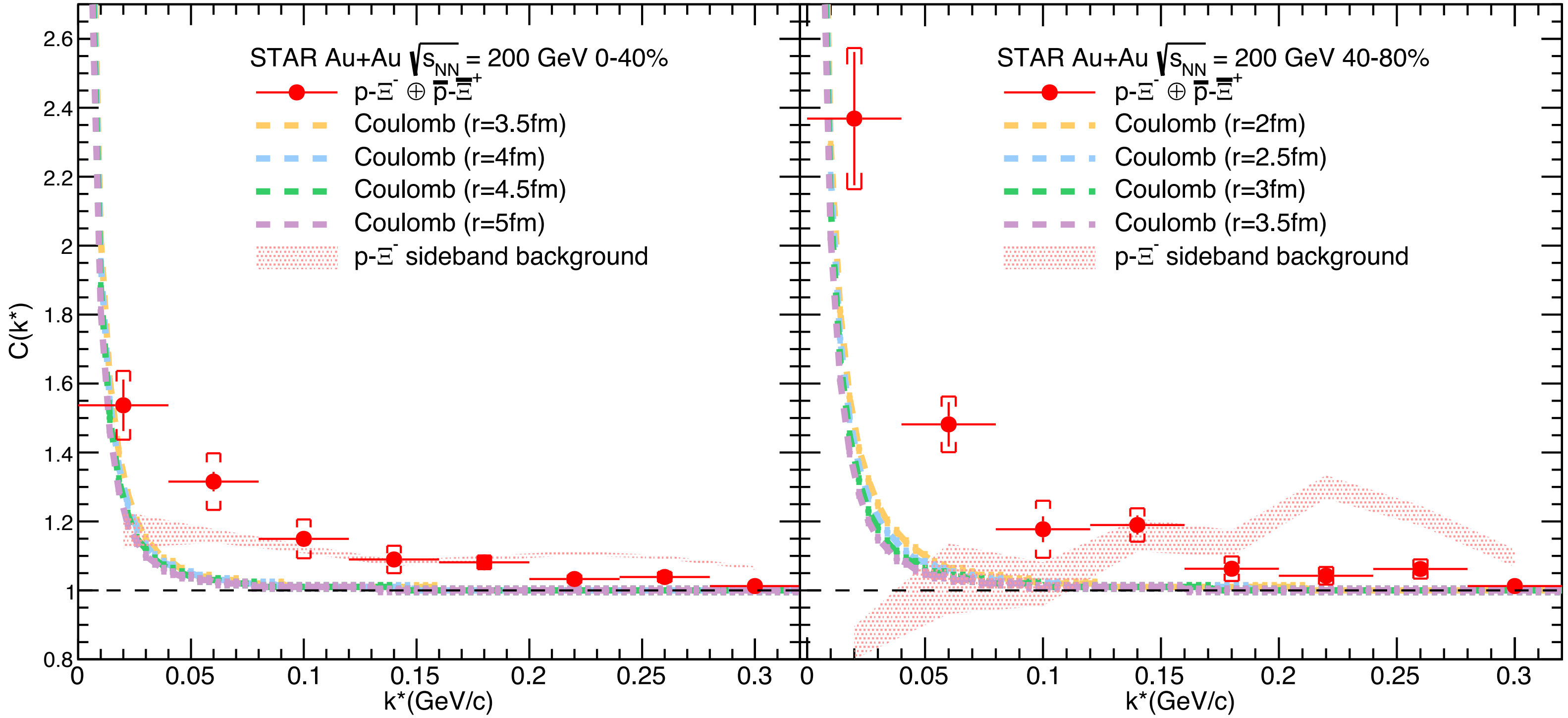


- The peak due to auto-correlation is gone after daughter sharing cut.
- The anti-correlation by detector inefficiency was largely mitigated.

p-Ξ

p-Ξ correlation function

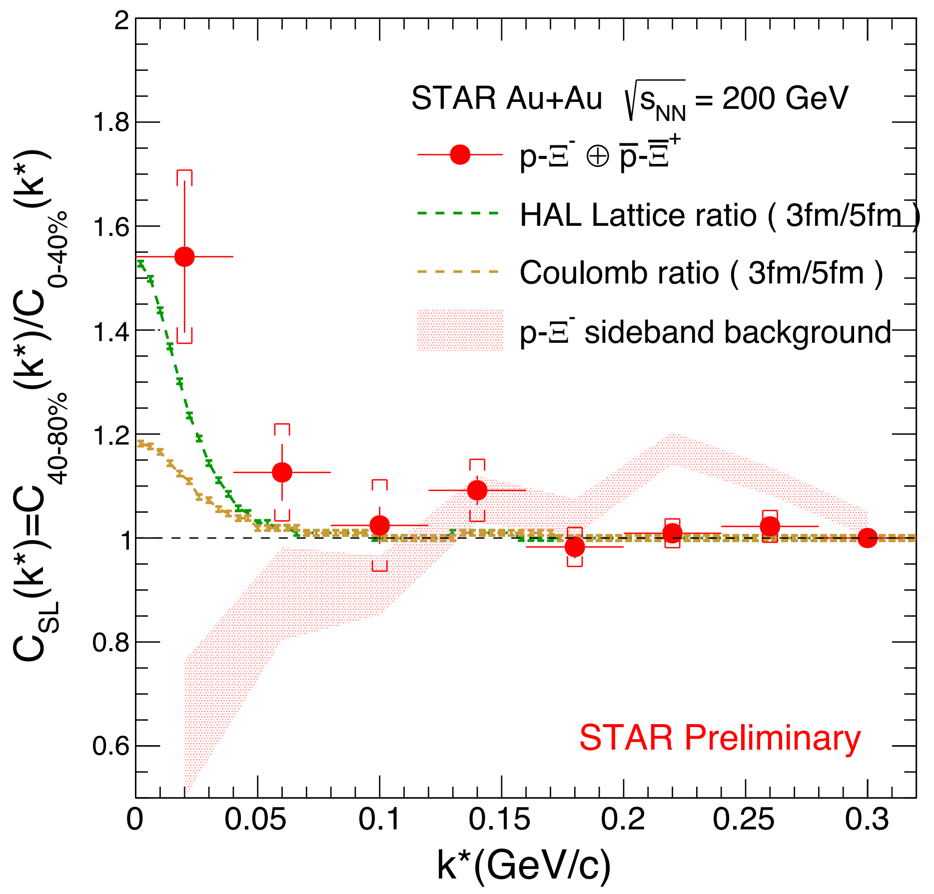
First measurement of p-Ξ correlation in Au+Au collisions at RHIC



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,

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

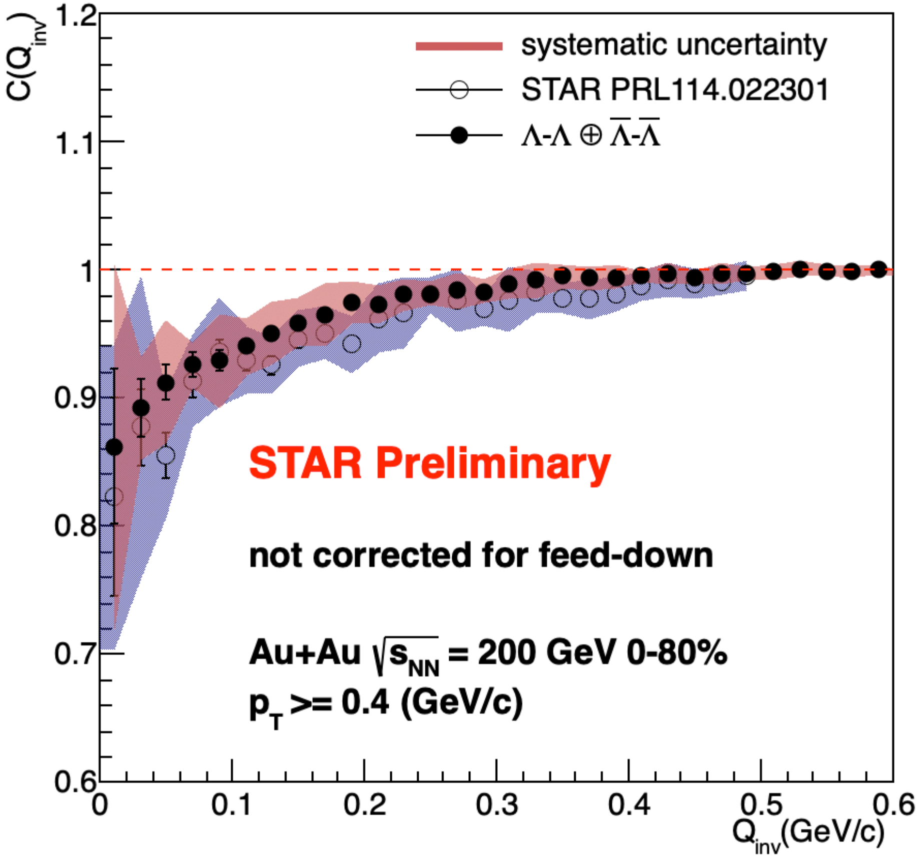
$C_{SL}(k^*)$ is more sensitive to strong interaction with largely canceled Coulomb interaction[1].

- 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

Λ-Λ and Ξ-Ξ

Λ-Λ correlation function

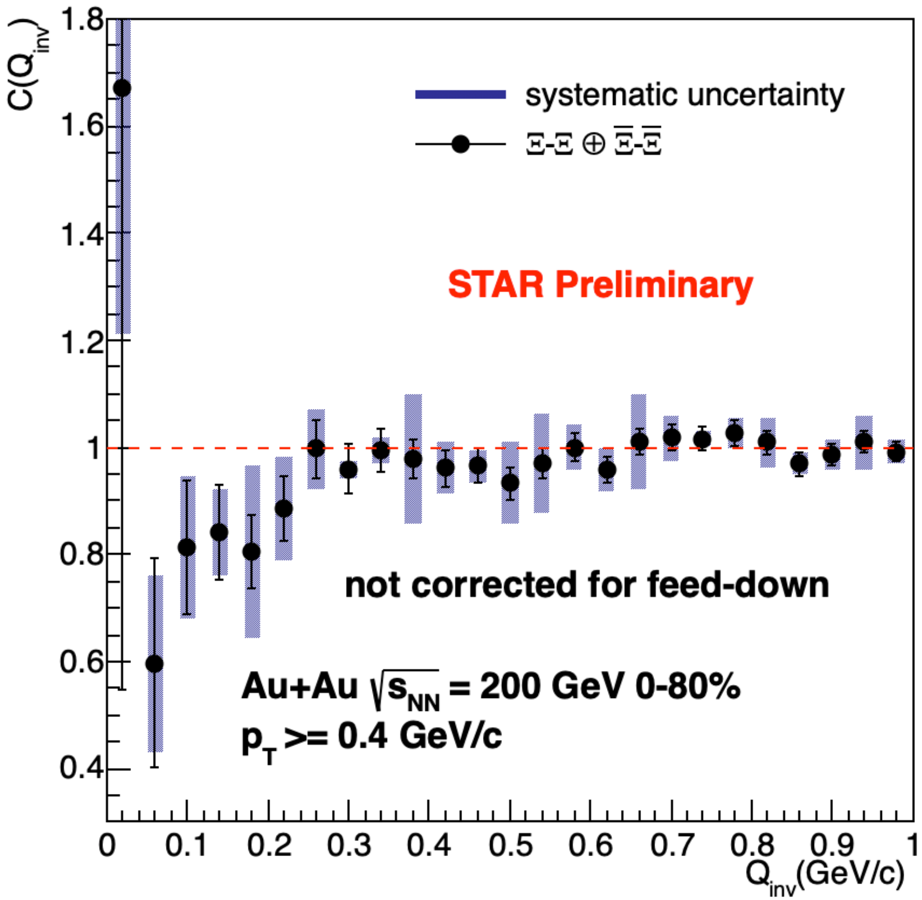


- New result with high statistics data ~4 times larger than that in previous study.
  - Not corrected for feed-down.

- 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}.

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

Ξ-Ξ correlation function



- <u>First measurement</u> 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 $Q_{inv} < 0.25$ GeV/c.
  - combination of quantum statistics, strong interaction, and Coulomb interaction.
- Feed-down and Coulomb effects need to be evaluated for further discussion.
- More events will be taken in 2023 and 2025.

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

Summary

- We presented the first measurements of p-Ξ and Ξ-Ξ correlations in Au+Au collisions at 200 GeV and also revisited Λ-Λ correlations with high statistics data.
- p-Ξ **correlation**

  - Attractive interaction is observed.

  - $C(k^*)$ ratio between peripheral and central collisions, $C_{SL}(k^*)$, is enhanced above the Coulomb interaction.

  - Similar to lattice QCD calculation which suggests an attractive strong interaction between p and Ξ^-.
- Λ-Λ **correlation function**

  - New result with high statistics data is consistent with previous result.

  - Anti-correlation is observed.
- Ξ-Ξ **correlation**

  - Anti-correlation seems to be observed for the first time.

<u>Outlook</u>

- Feed-down and possible residual correlation are being studied.
- Extraction of the scattering parameters with Lednicky- Lyuboshitz model is ongoing (scattering length, effective range).

Back up

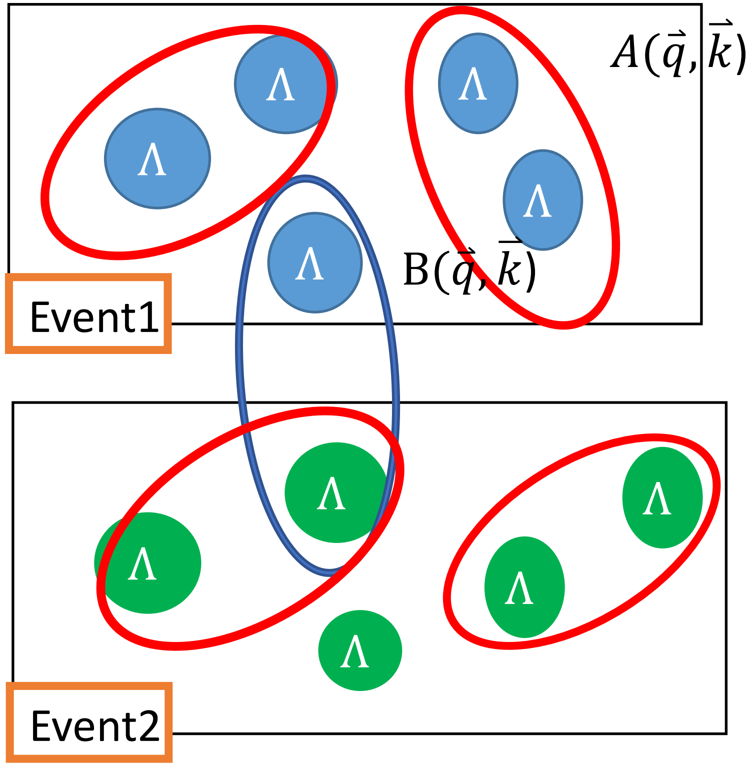
2 particle correlation analysis

Analysis

- $A(\vec{q}, \vec{k})$ ------- distribution of pairs (same events)
- $B(\vec{q}, \vec{k})$ ------- distribution of Back ground pairs (mix events)
- $\vec{q} = \vec{p_1} - \vec{p_2}$-- Relative momentum of 2 particles
- $\vec{k} = \frac{(\vec{p_1} + \vec{p_2})}{2}$ - The average values of 2 particles momentums

correlation function $C(\vec{q}, \vec{k}) = \frac{A(\vec{q}, \vec{k})}{B(\vec{q}, \vec{k})}$

Event Mixing method



Event mixing method

mixed the events which close to Zvertex and centrality

- ➢ Real Event includes the physics correlation between 2 particles.
- ➢ Event mixing is used to make uncorrelated pairs as background.

Lednicky Fit

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

Quantum Statistic term

FSI(Final state interaction) term

Residual term

(introduced by STAR to account for residual effect)

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

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

N :Normalization factor

λ :chaotic parameter

f_0 : scattering length

d_0 : effective range

Physical quantity to study a bound state

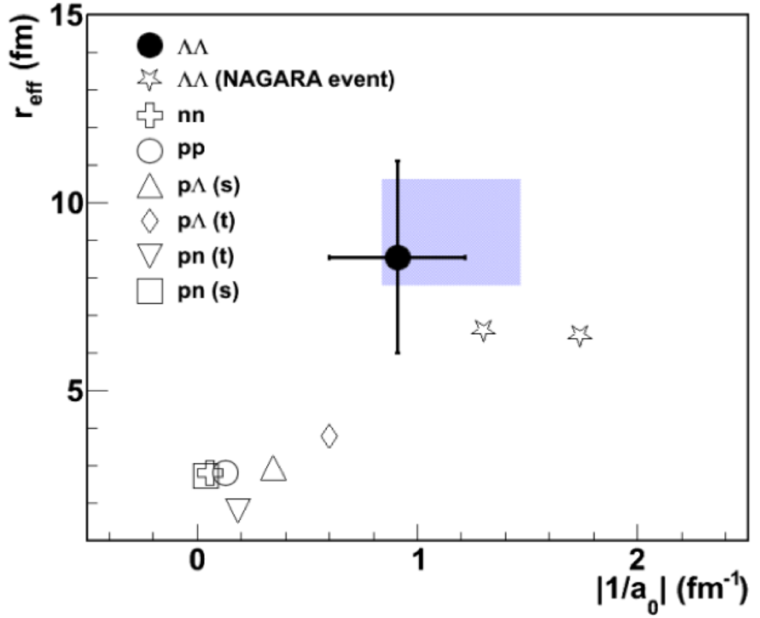
r_0 :source size

a_{res} : residual amplitude

r_{res} : width of the Gaussian

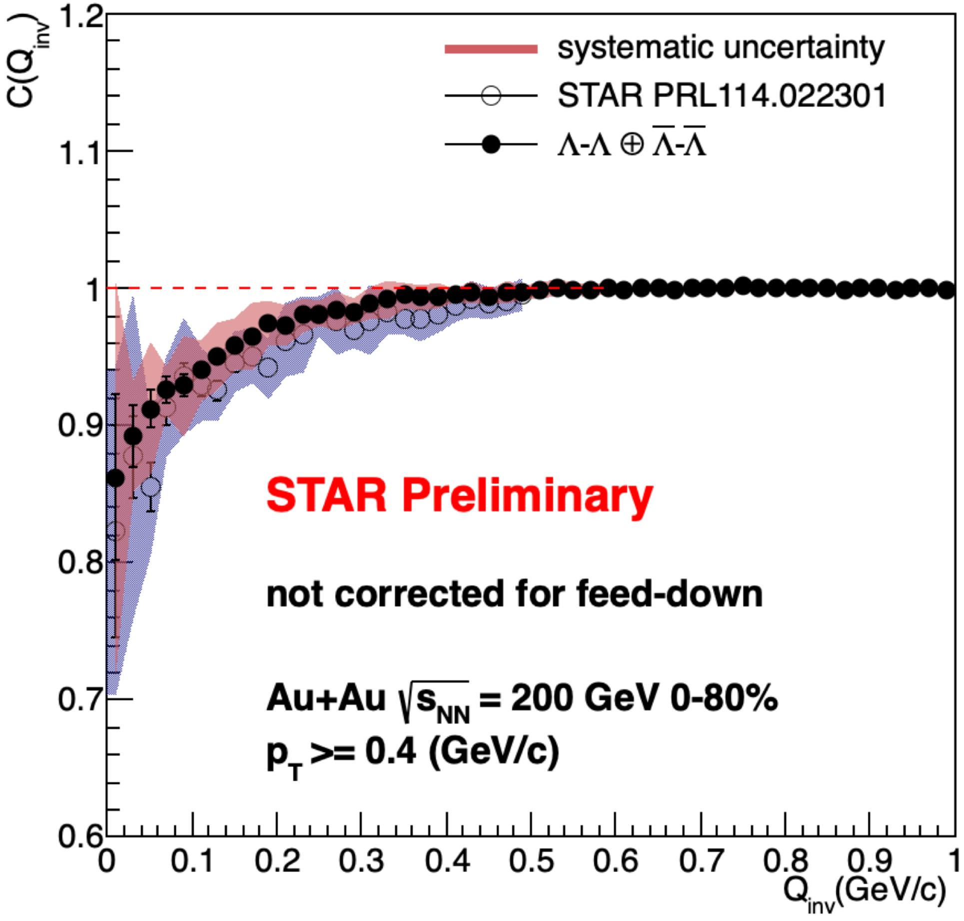
Scattering Amplitude:$f(k) = (\frac{1}{f_0} + \frac{1}{2}d_0\ k^2 - ik)^{-1}$

Fitting method: ROOT default fitting(minimization)



L. Adamczyk for the STAR Collaboration PhysRevLett.114.022301

Λ-Λ correlation function



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