筑波大学
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Measurements of Λ-Λ and Ξ-Ξ Correlations in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV at RHIC-STAR

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ATHIC 2021

2021/11/09

STAR

Supported in part by
U.S. DEPARTMENT OF ENERGY

Physics Motivation

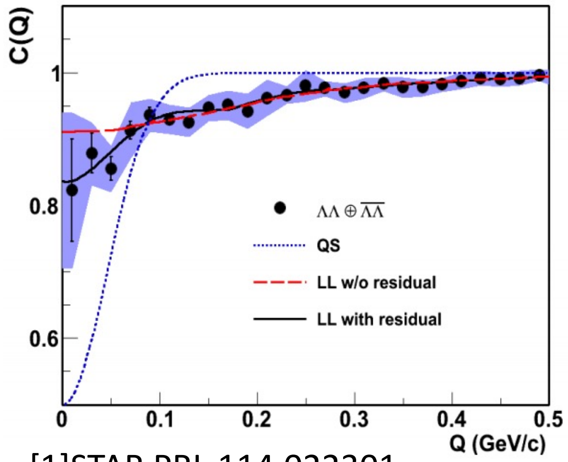
- Inside the neutron star, there are many hyperon particles (baryons containing strange quarks).

  Understanding the interaction between hyperon particles is very important for elucidating the internal structure of neutron stars including the equation of state.

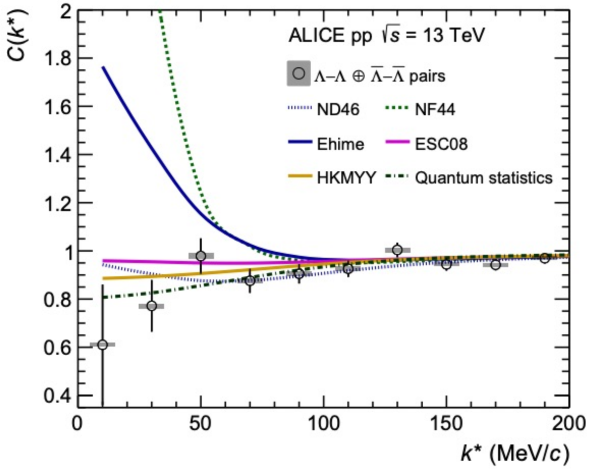
- It has recently been reported that hyperons could be in deeply bound state or shallow bound state or unbound with attractive interactions.

- Various hadrons including hyperons are abundantly produced in HIC.
- In STAR and ALICE, the anti-correlation of Λ-Λ was observed in Au+Au and p+p (p+Pb) collisions with large uncertainty[1][2].

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

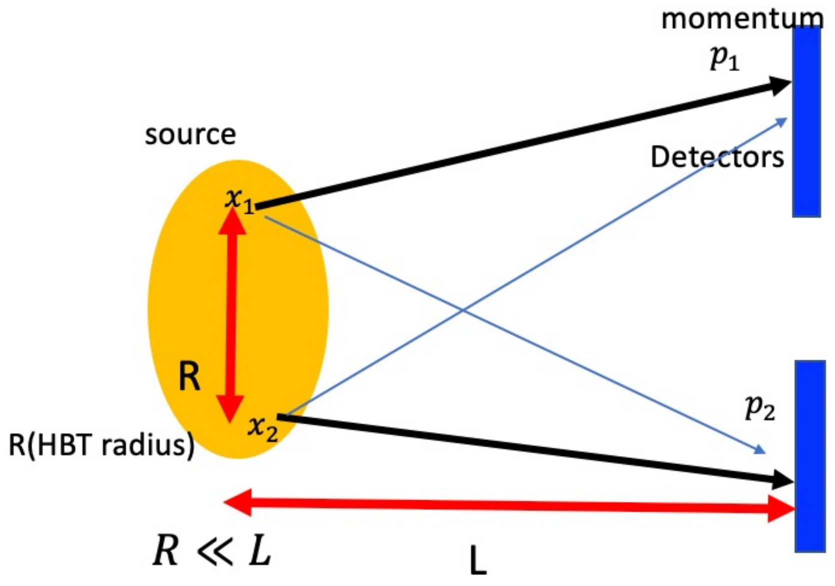


[1]STAR PRL.114.022301



[2]ALICE Phys. Lett. B 797 (2019) 134822

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[1].

Theory

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

r: relative distance (of pair)

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

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

Experiment

$$C(Q_{inv}) = \frac{A(Q_{inv})}{B(Q_{inv})}$$

A: actual pairs from same events

B: background pairs from mixed events

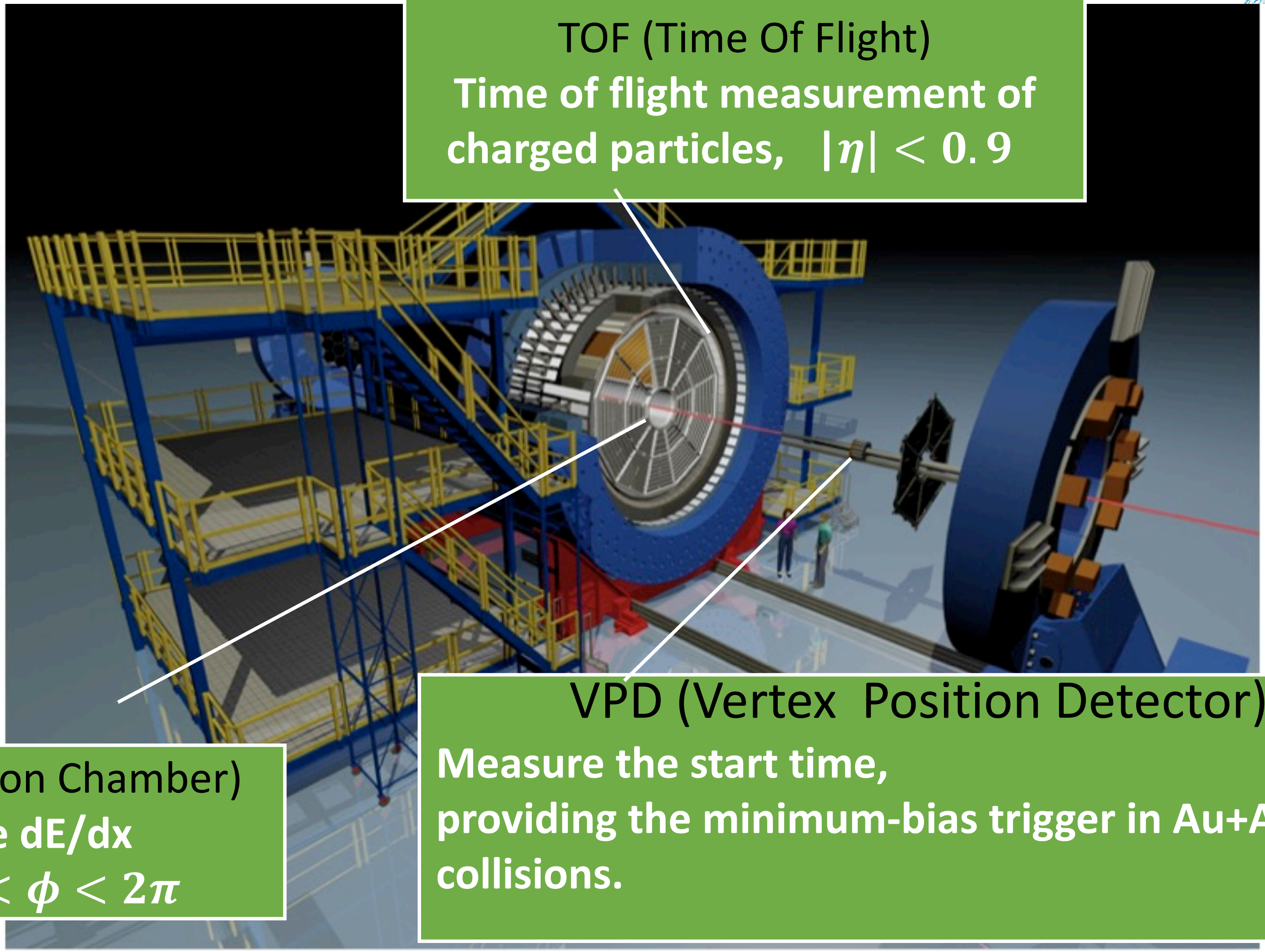
[1] M. Lisa et al., Ann.Rev.Nucl.Part.Sci.55(2005)357

STAR detectors

Data Set

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

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



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.

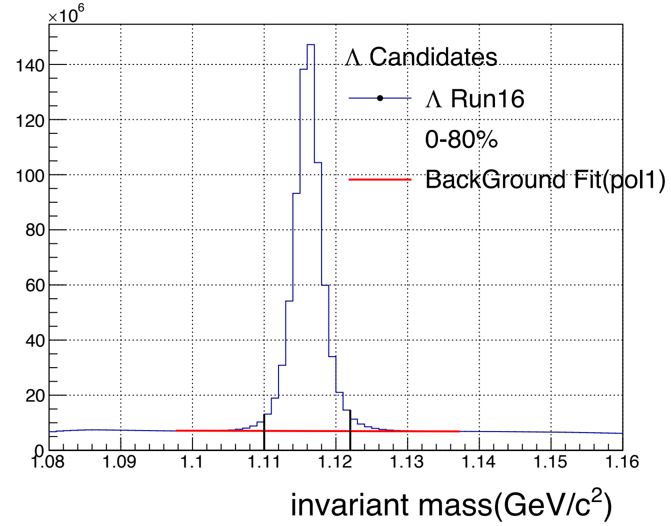
Reconstruction of Λ and Ξ

	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)

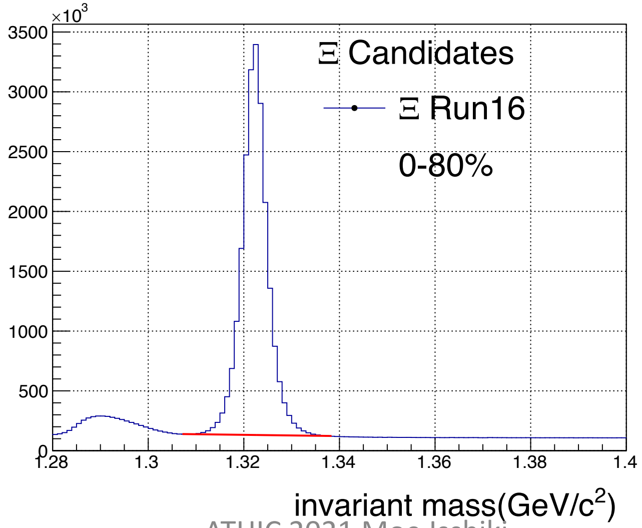
- KFParticle package was used.
  KFParticle is based on Kalman filter.
  [1] Kisel (CBM Collaboration), J. Phys. Conf. Ser.1070, 012015 (2018).
- Very good Purity for Λ(~88%) and Ξ(~90%).

Invariant mass

Λ



Ξ



Daughter particle selection for Λ and Ξ

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

For proton
- $|\ n_{\sigma,p}\ | < 3$
- 0.5 < 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 as follows,

$$C_{true}(q) = \frac{C_{measured}(q) - 1}{P(q)} + 1$$

Residual correlation from background pairs is also studied as follows,

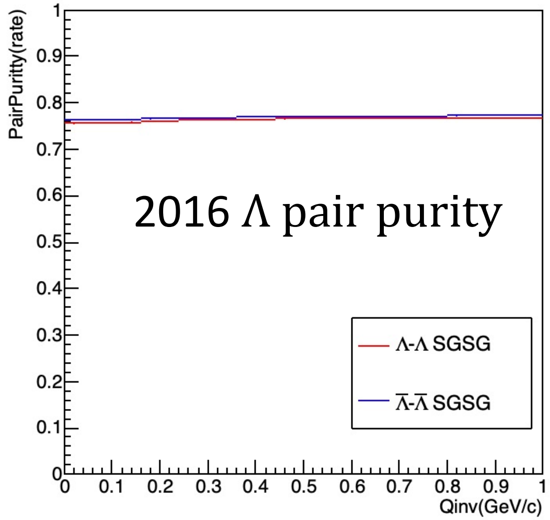
$$C_{res.true}(q) = \frac{1}{P_{SGSG}(q)}\{(C_{measured}(q) - 1) - 2 * (P_{SGBG}(q))(C_{SGBG}(q) - 1) - P_{BGBG}(q) * (C_{BGBG}(q) - 1)\} + 1$$

$C_{measured}(q)$:measured correlation functon

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

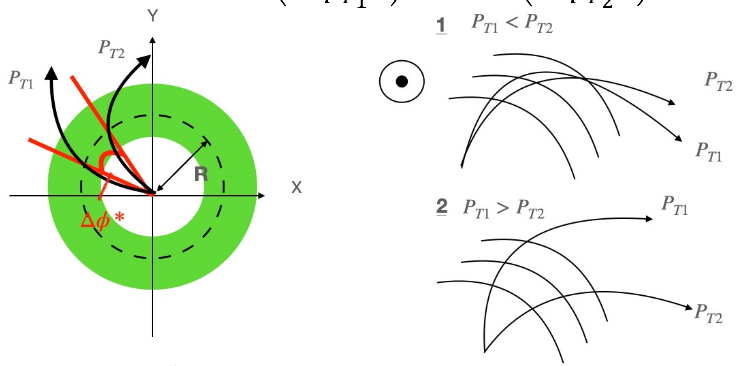
$P_{SGBG}(q)$: pair fraction of signal-background pairs
$P_{BGBG}(q)$: pair fraction of background-background pairs

- the residual correlation was found to be almost negligible on C(q).



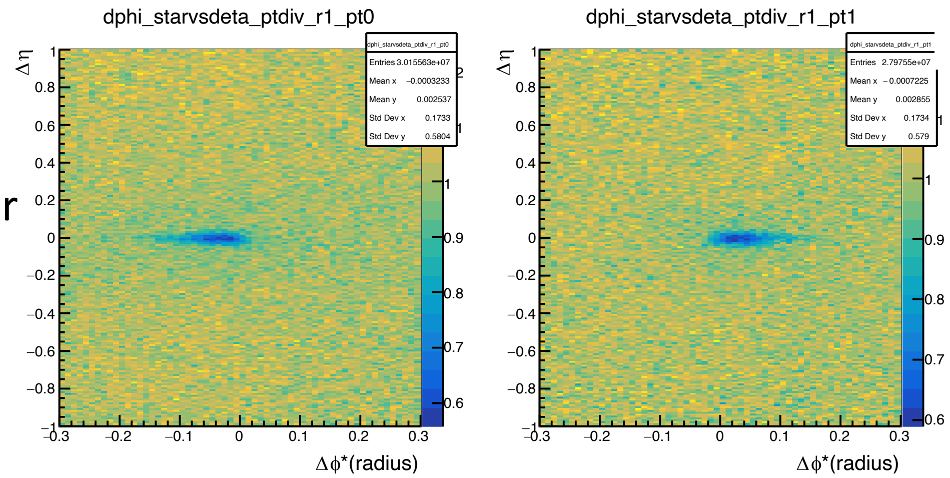
Pair inefficiency and daughter sharing removal

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

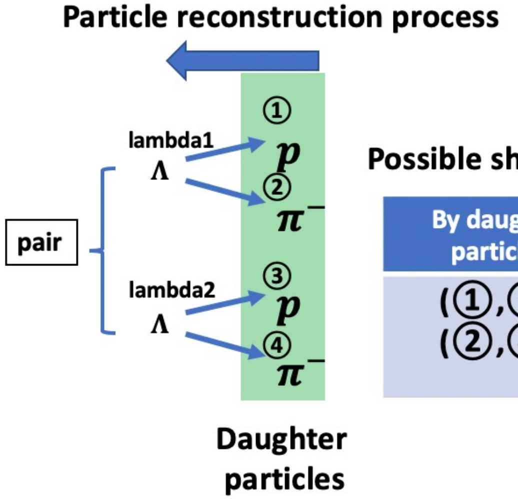


$p_{T_1} < p_{T_2}$ $p_{T_1} > p_{T_2}$

daughter $p - p$



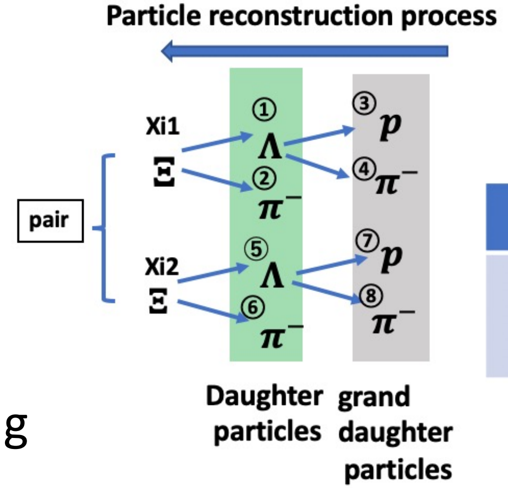
➢ Pair inefficient region was removed considering B-field, particle charge, and p_T.



Possible sharing pairs

By daughter particles
(①,③) (②,④)

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



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 Λ-Λ

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

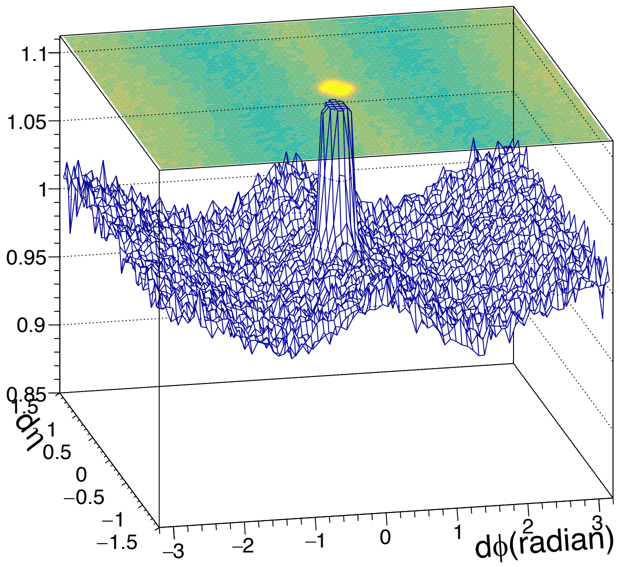
$\Delta\eta = \eta_2 - \eta_1$

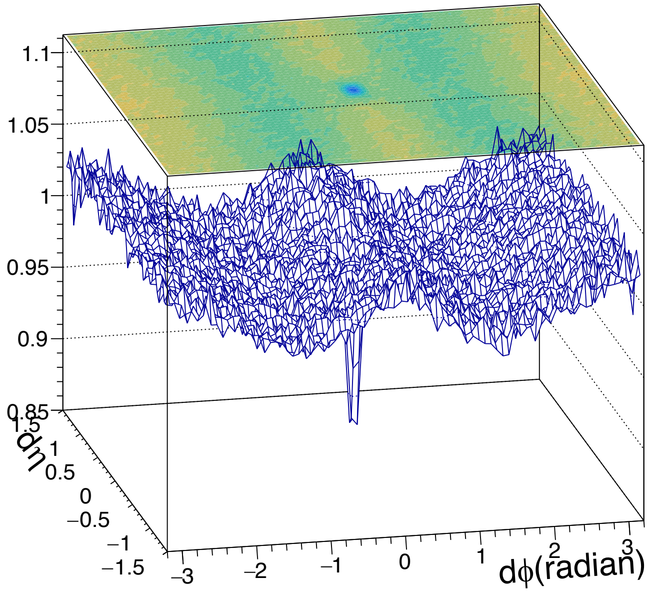
$\Delta\phi = \phi_2 - \phi_1$

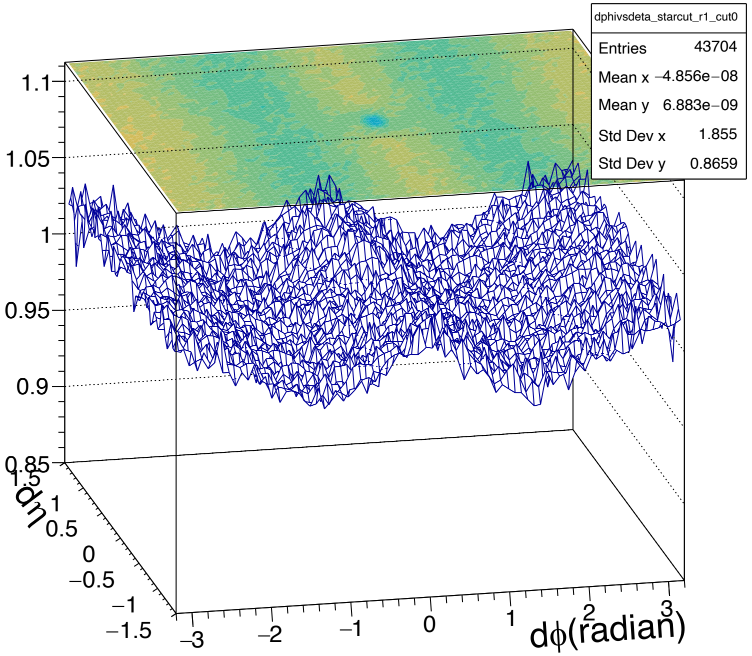
Y=yield of pairs

Before/After the tracks which shared the daughter particles were removed

Pair inefficiency due to track crossing was removed







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

Coulomb interaction

- Coulomb wave function was used for the calculation.

Symmetrized Coulomb wave function for 2 particles is given by,

$$\Psi_{c.sym}(\vec{q},\vec{r}) = \frac{1}{\sqrt{2}}(\Psi_c(\vec{q},\vec{r}) + \Psi_c(\vec{q},-\vec{r}))$$

r:relative distance

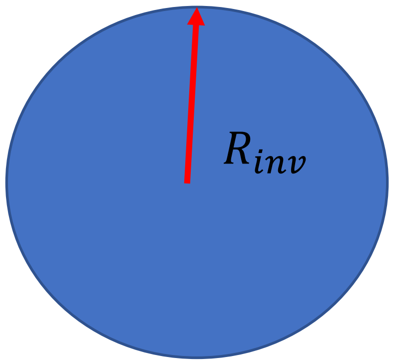
The Coulomb interaction is calculated as

$$F_c = \frac{P_c(\overrightarrow{p_1},\overrightarrow{p_2})}{P_{12}(\overrightarrow{p_1},\overrightarrow{p_2})}$$

$$P_c(\overrightarrow{p_1},\overrightarrow{p_2}) = \int d^3r\rho(\vec{r})\,|\Psi_{c.sym}|^2$$

ρ(r) is the spatial distribution of the relative distance between two particles

The source distribution is assumed to be Gaussian with input sorce size R_{inv}.



gauss

Coulomb interaction

Ξ-Ξ and Ξ̄-Ξ̄ correaltions include the Coulomb effect.

- The source is generated according to a Gaussian distribution and the Coulomb interaction is calculated based on Coulomb wave function.

- It was found that the strength of Coulomb force does not greatly depend on the source size R_{inv}.

- The test for changing particle mass is shown in Fig. 2. The Coulomb strength is stronger in higher mass.

Fig. 1

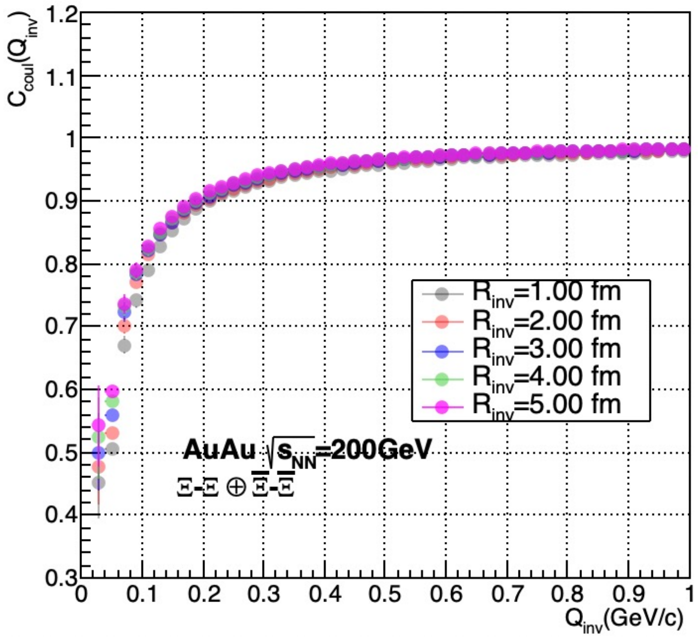
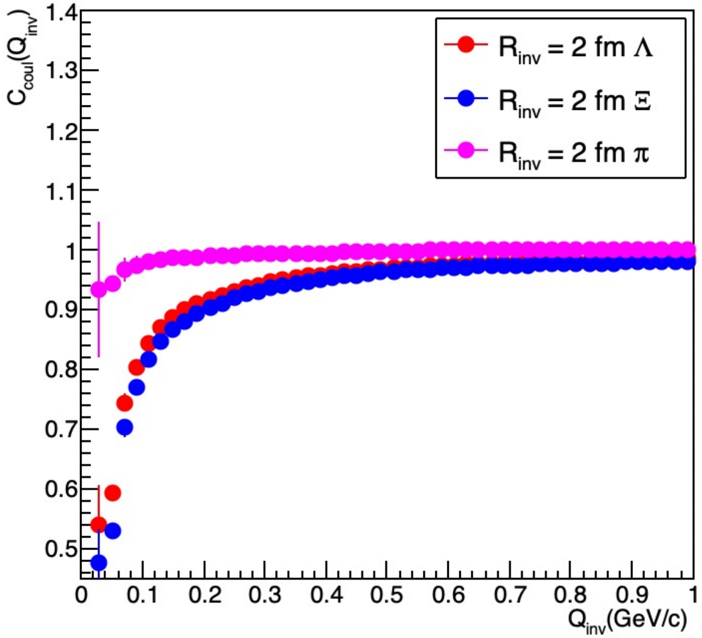
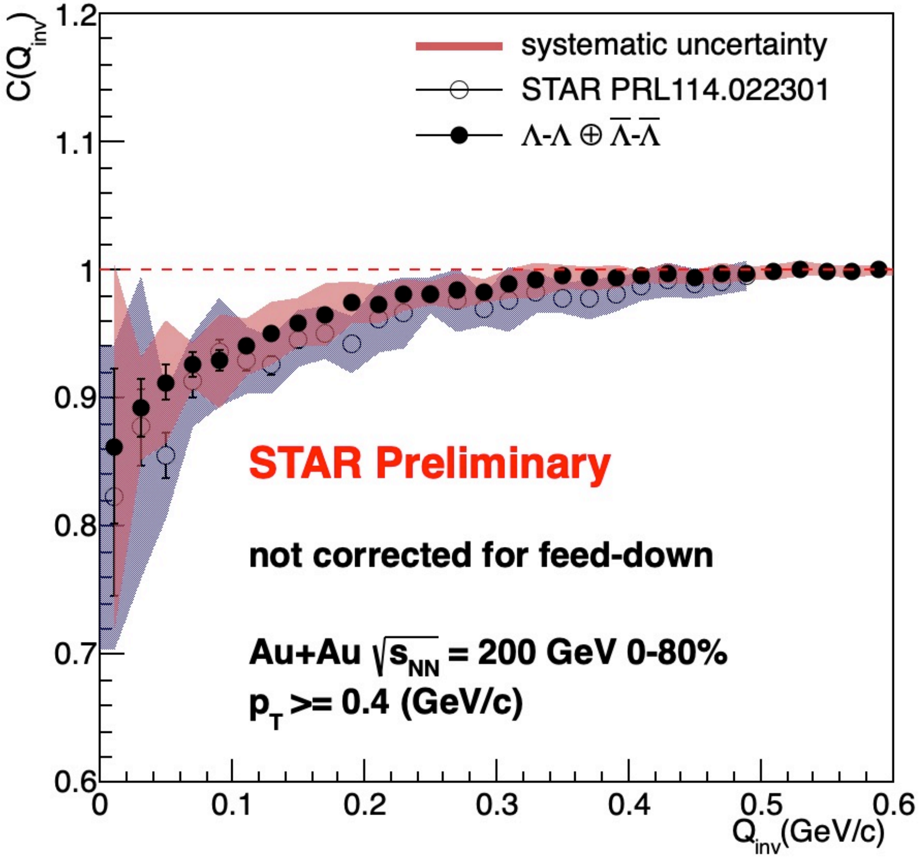


Fig. 2



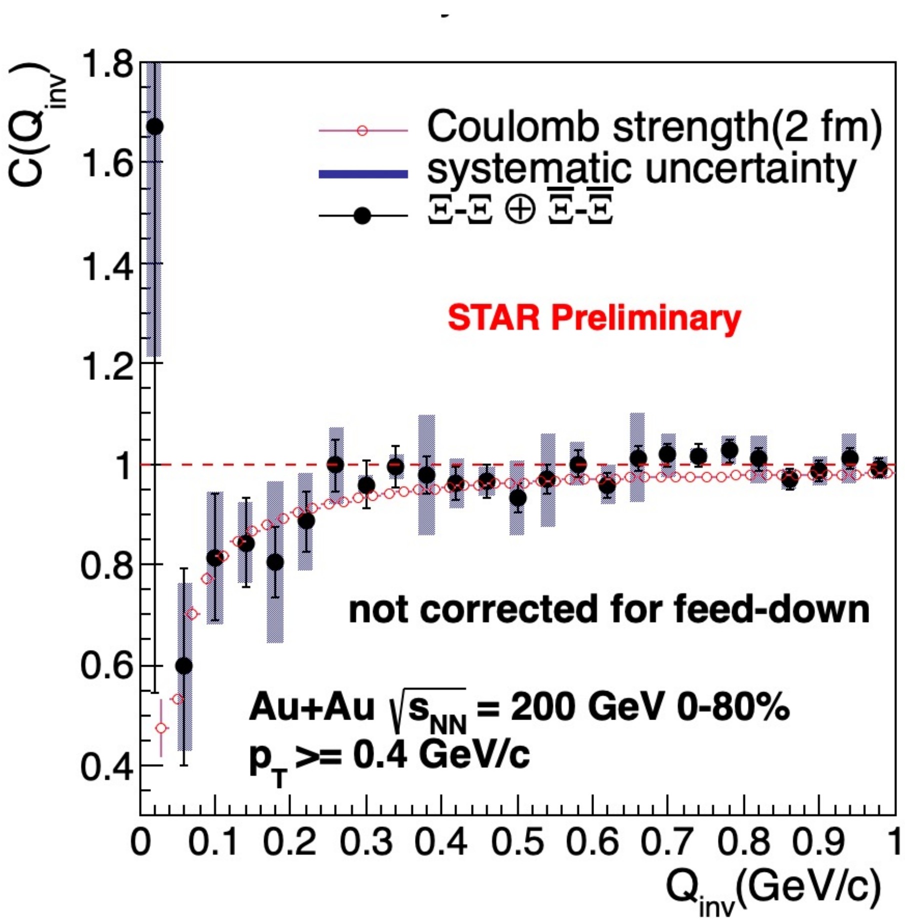
Λ-Λ correlation function



- 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}.

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 $Q_{inv} < 0.25$ GeV/c.
  - qualitatively matched with coulomb strength accidentally.
  - 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 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 Ξ-Ξ correlations in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV and also revisited Λ-Λ correlations with high statistics data.

- **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 accidentally matched with Coulomb interaction. Likely that quantum statistics and strong interaction are canceled.

Outlook

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

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

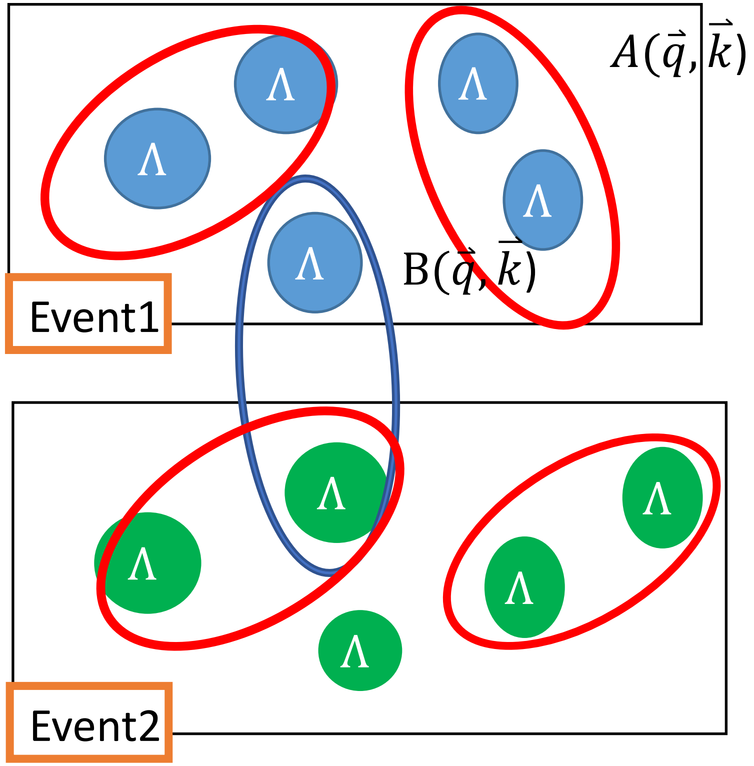
Event mixing method

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.

Event Mixing method



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)

$k = \frac{Q}{2}, F_1(z) = \int_0^z \frac{e^{x^2-z^2}}{z}dx$ …… 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

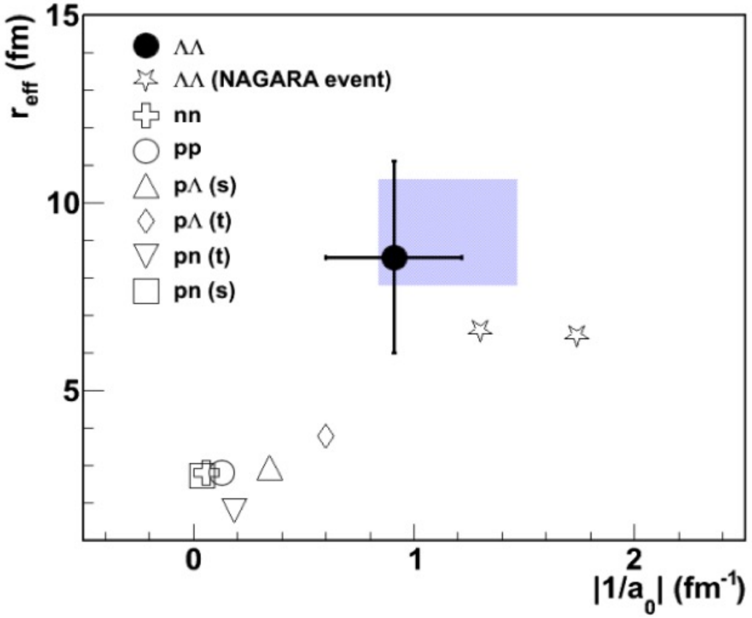
r_0 :source size

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