Recent measurements of hyperon-hyperon correlations in the STAR experiment

Moe Isshiki
For the STAR Collaboration

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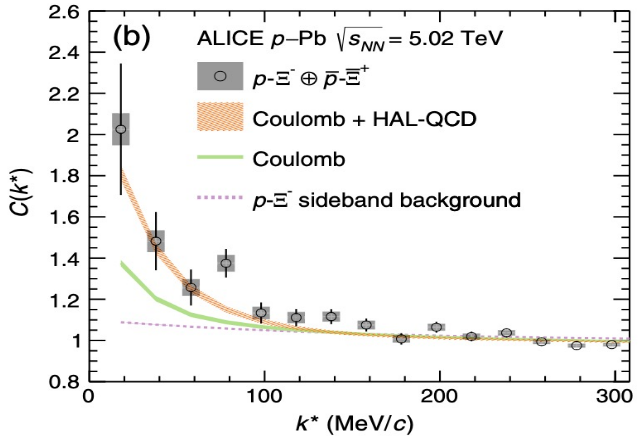
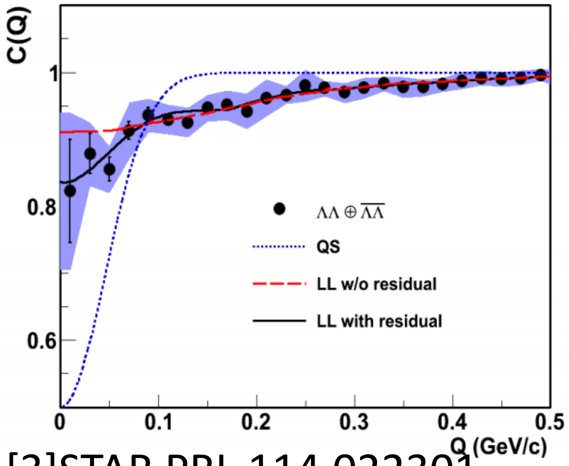
Physics Motivation

- 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.



[1]ALICE PRL.123,112002

- 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].

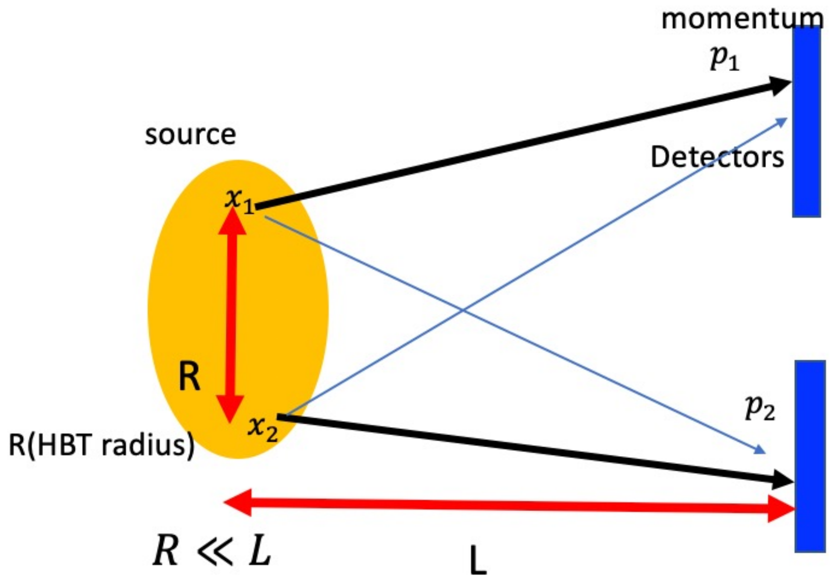


[3]STAR PRL.114.022301

- In this study, p-Ξ, Λ,-Λ, and Ξ-Ξ correlations are studied at Au+Au $\sqrt{s_{NN}}$ = 200 GeV.
- p-d correlation is studied using Fixed target measurement $\sqrt{s_{NN}}$ = 3 GeV.

[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

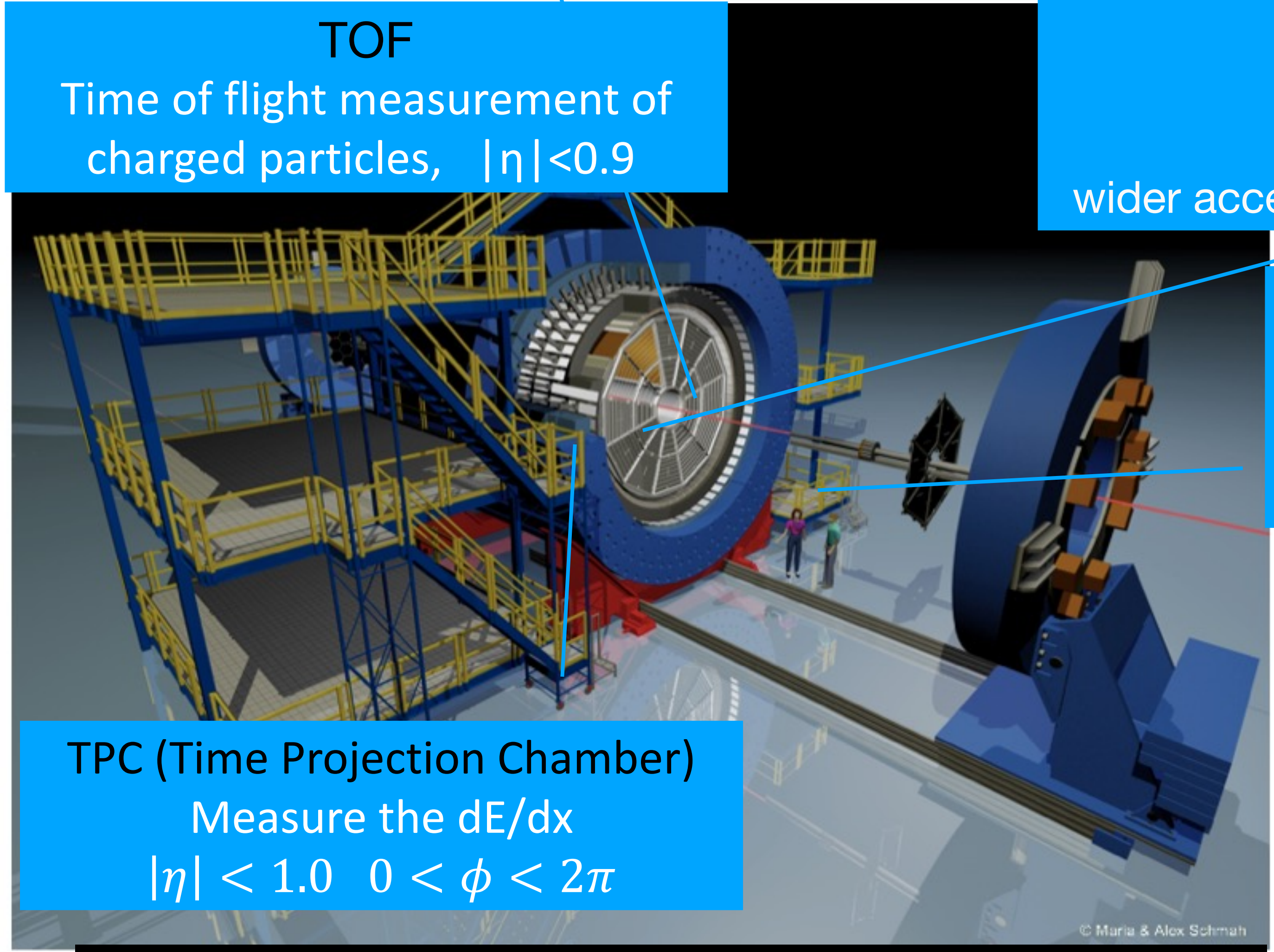
Experiment

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

A: actual pairs from same events

B: background pairs from mixed events

STAR detectors



TOF
Time of flight measurement of charged particles, |η|<0.9

iTPC
Upgraded
Better resolution
wider acceptance |η|<1.0 -> |η|<1.5

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

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

The high-precision tracking system, Large acceptance

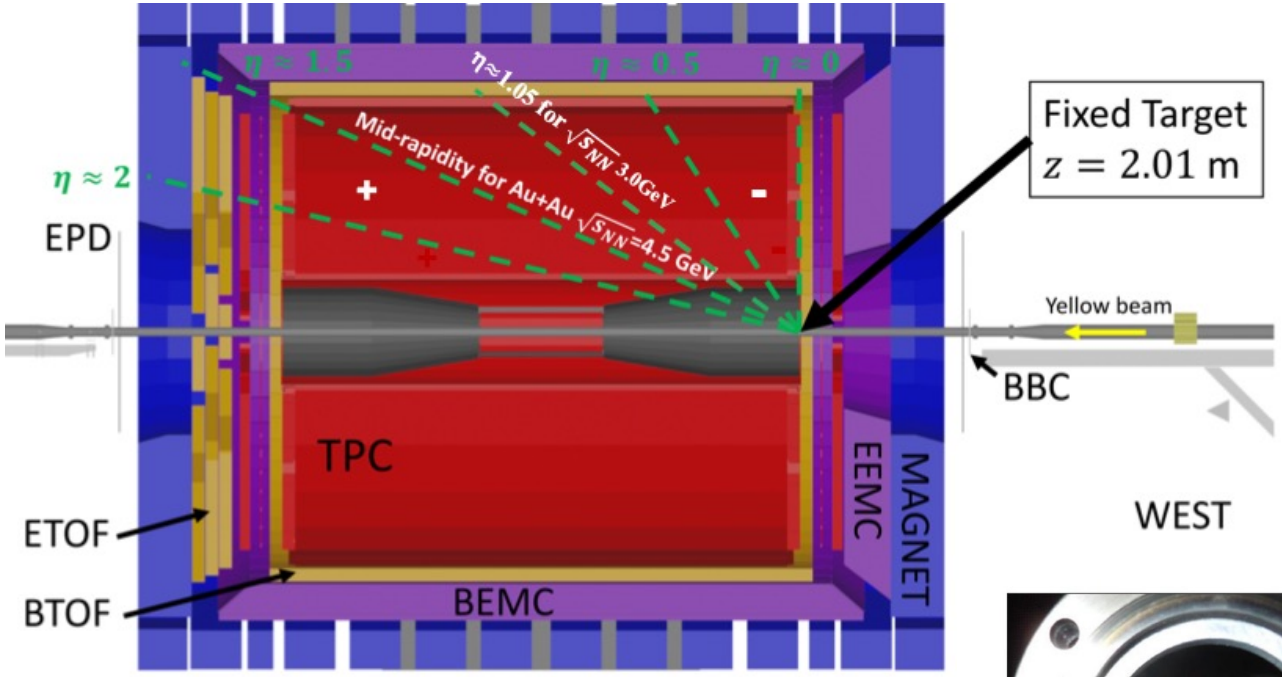
Data Set

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

Au+Au $\sqrt{s_{NN}} = 3$ GeV (Fixed target)

	p-Ξ	p-d	Λ-Λ and Ξ-Ξ
Run year	2010, 2011, 2014	2018(FXT)	2011, 2014, 2016

FXT target set up in STAR

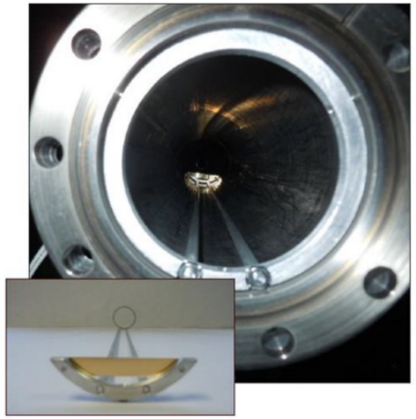


A gold fixed target is inserted in the beam pipe.

The target is located 210cm from the collision point.

TPC reconstraction acceptantce : -2 < η < 0

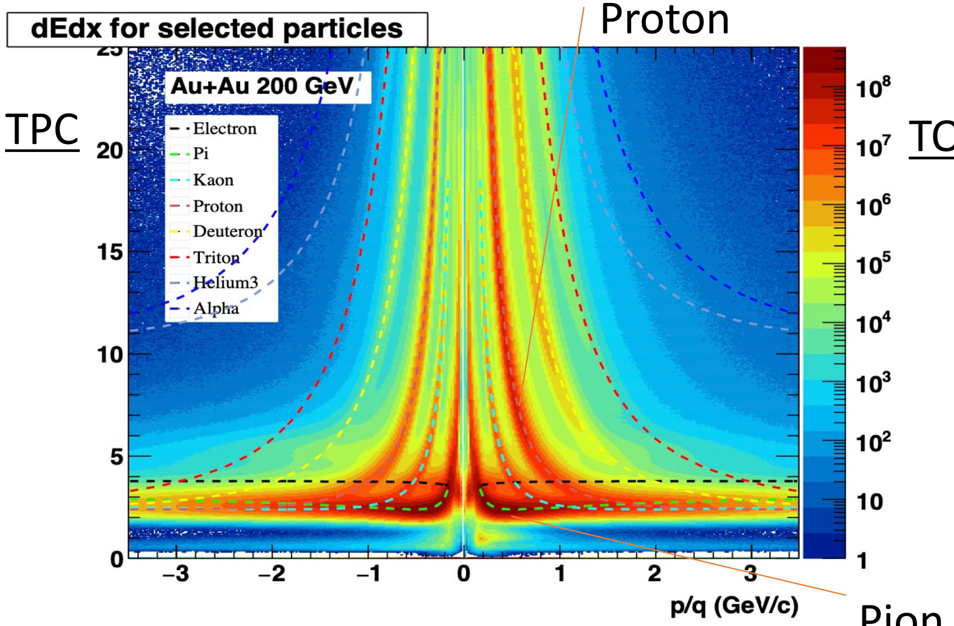
Target :Au



TPC & TOF PID

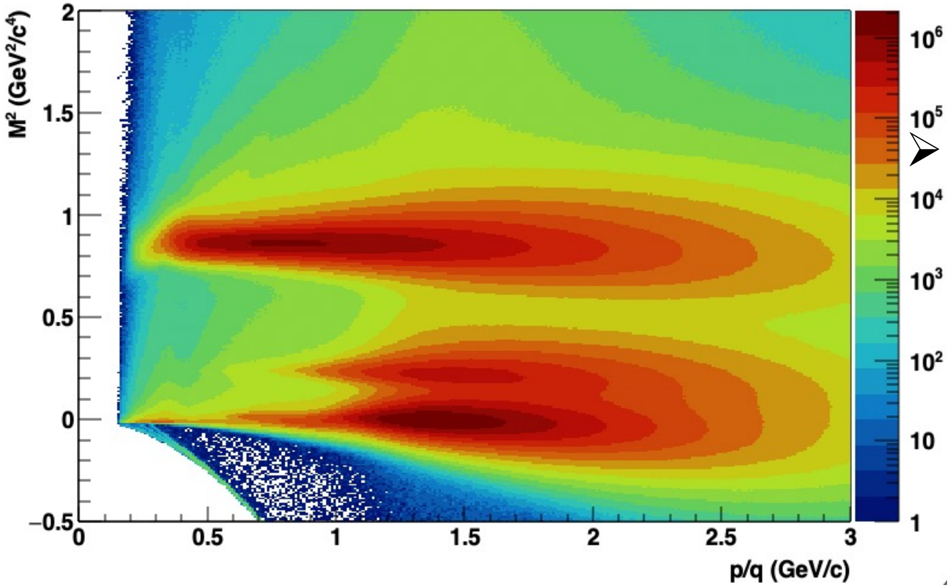
Particle identification based on dE/dx and time-of-flight

TPC



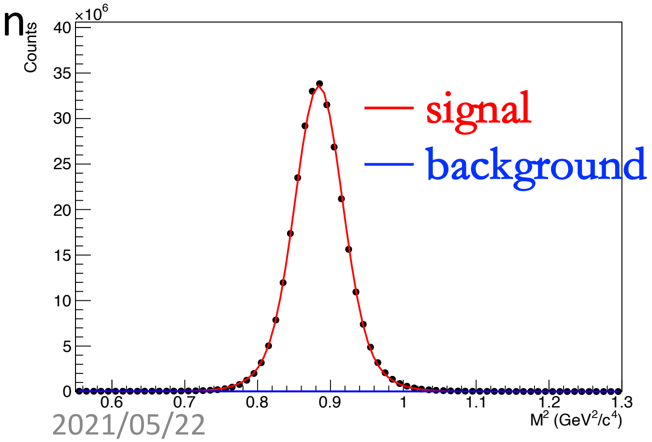
Proton, 200 GeV, Run11 0.5-0.7 GeV/c

TOF



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

proton



-proton selection

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

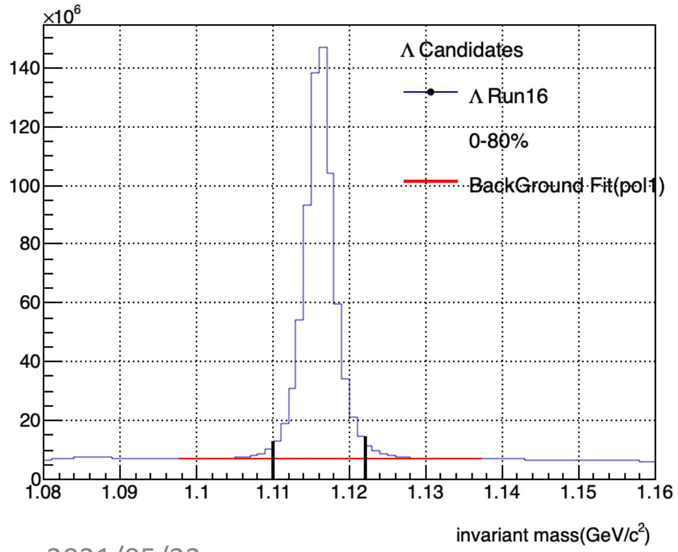
Reconstruction of Λ and Ξ

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

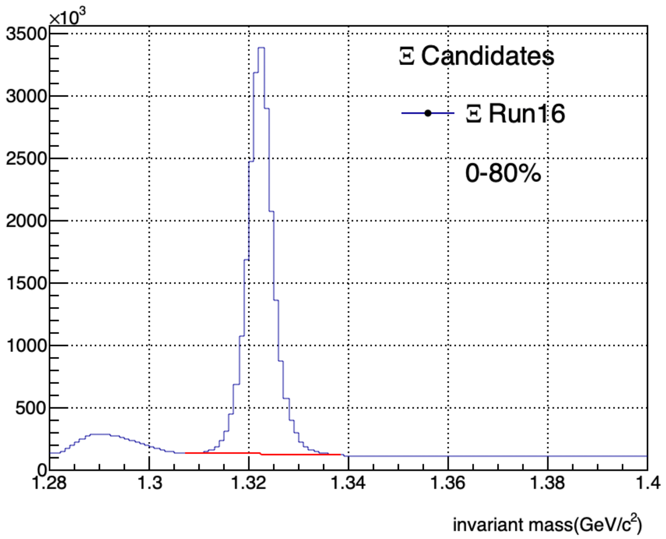
- KFParticle package was used.
  KFParticle is based on Kalman filter.
- Very good Purity for Λ(~88%) and Ξ(~90%).

Invariant mass

Λ



Ξ



Daughter particle selection for Λ and Ξ

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

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

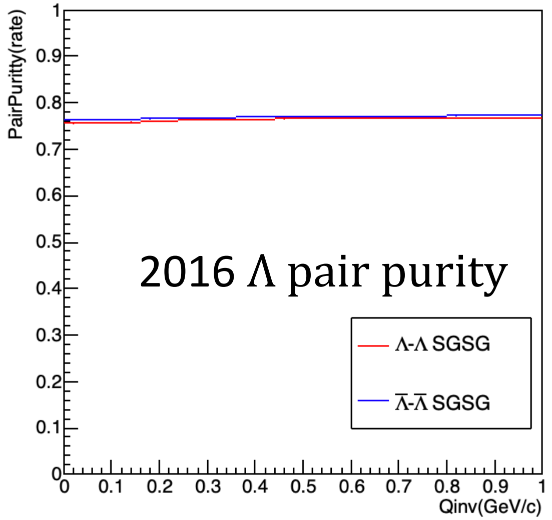
Correlation function is corrected for pair purity and feed-down as follows

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

$P(q)$: 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)



2016 Λ pair purity

Residual correlation from background pairs is also studied.

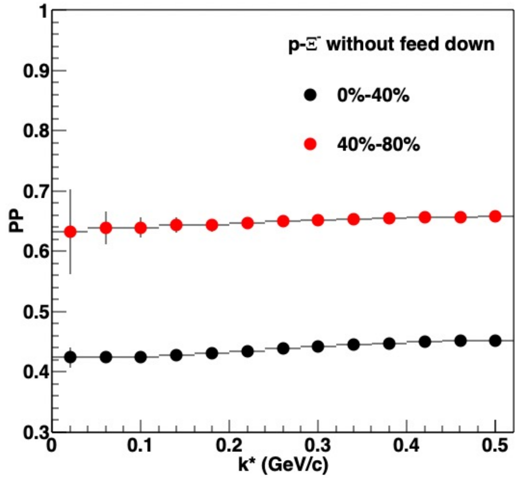
- Used for Λ-Λ and Ξ-Ξ study

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

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

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

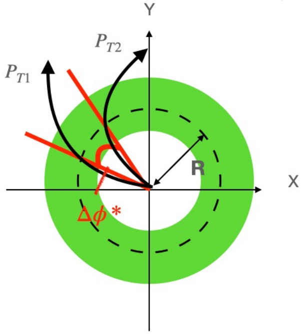
- ➢ the residual correlation was almost <u>negligible</u> on C(q).



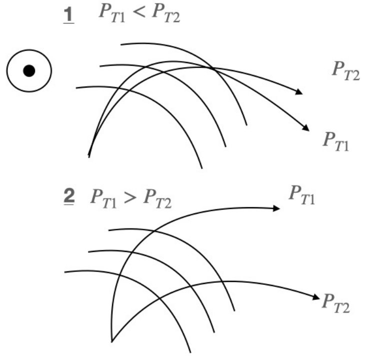
p-Ξ pair purity

Pair inefficiency and daughter sharing removal

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

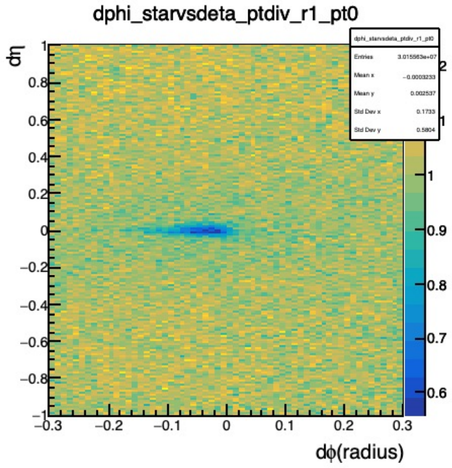


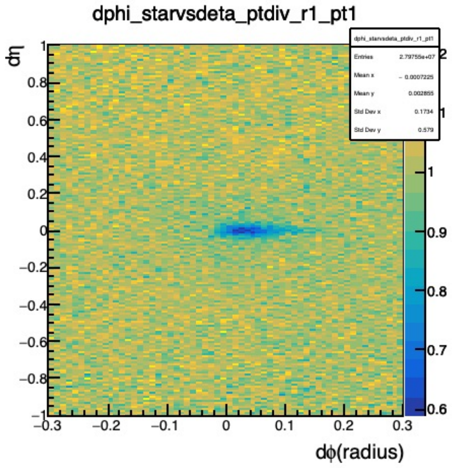
$p_{T_1} < p_{T_2}$



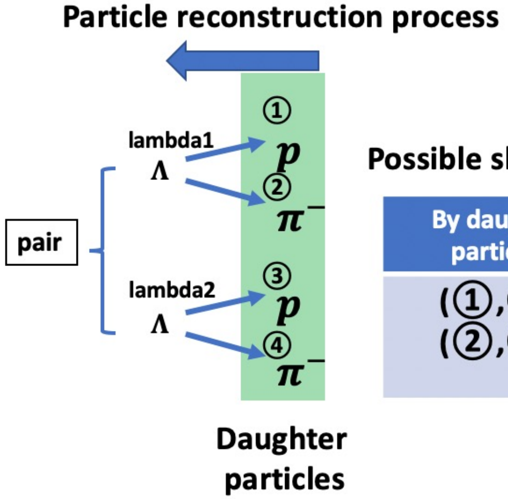
$p_{T_1} > p_{T_2}$

daughter
$p - p$





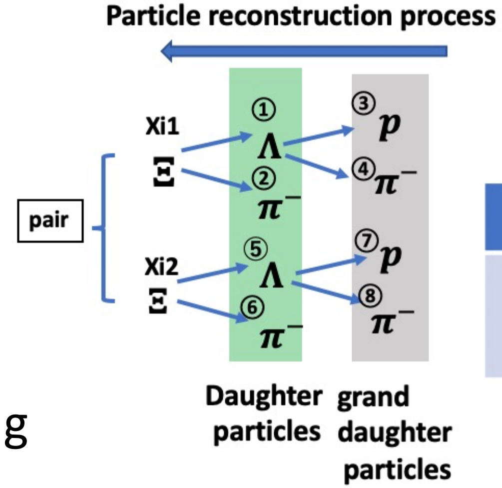
- Pair inefficient region was removed considering B-field, particle charge, and p_T.



Possible sharing pairs

By daughter particles
(①,③) (②,④)

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



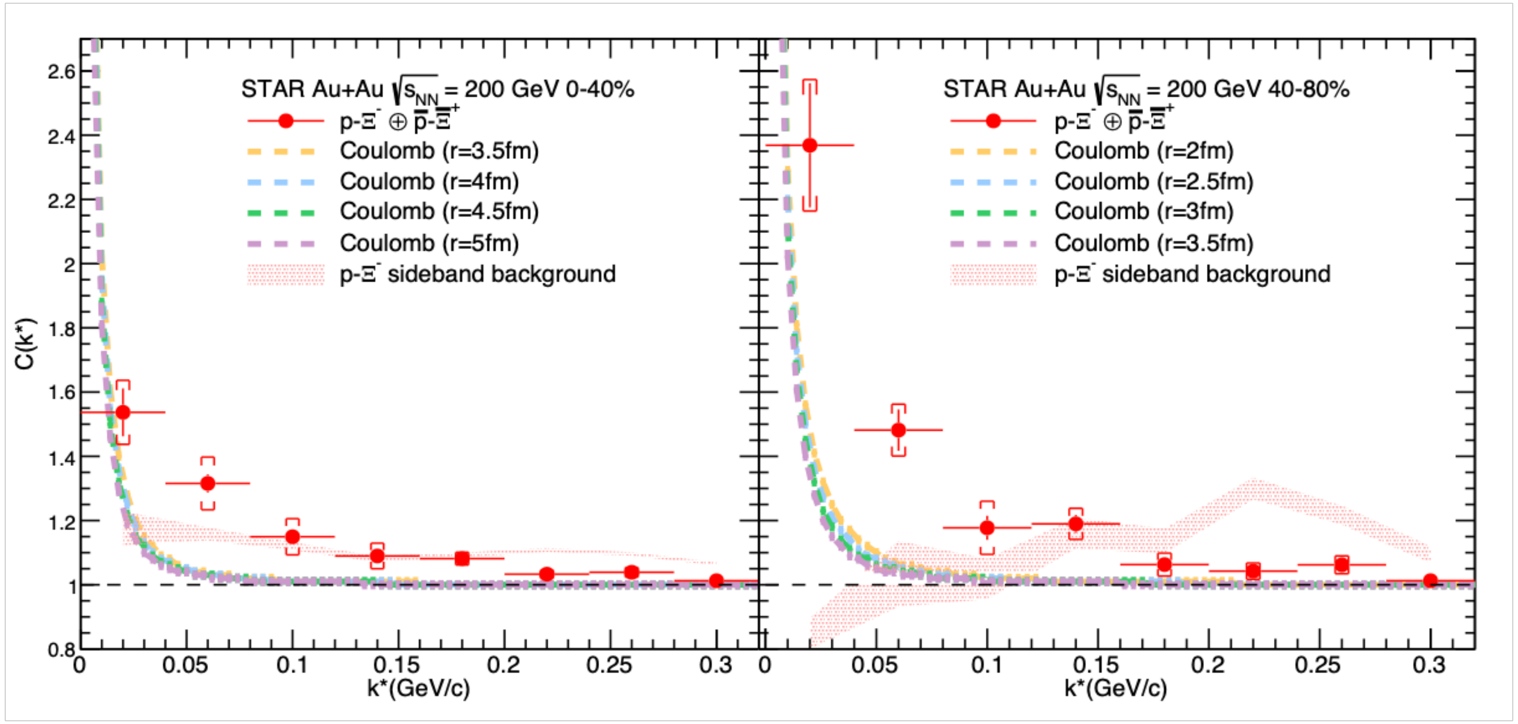
Possible sharing pairs

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

p-Ξ

p-Ξ correlation function

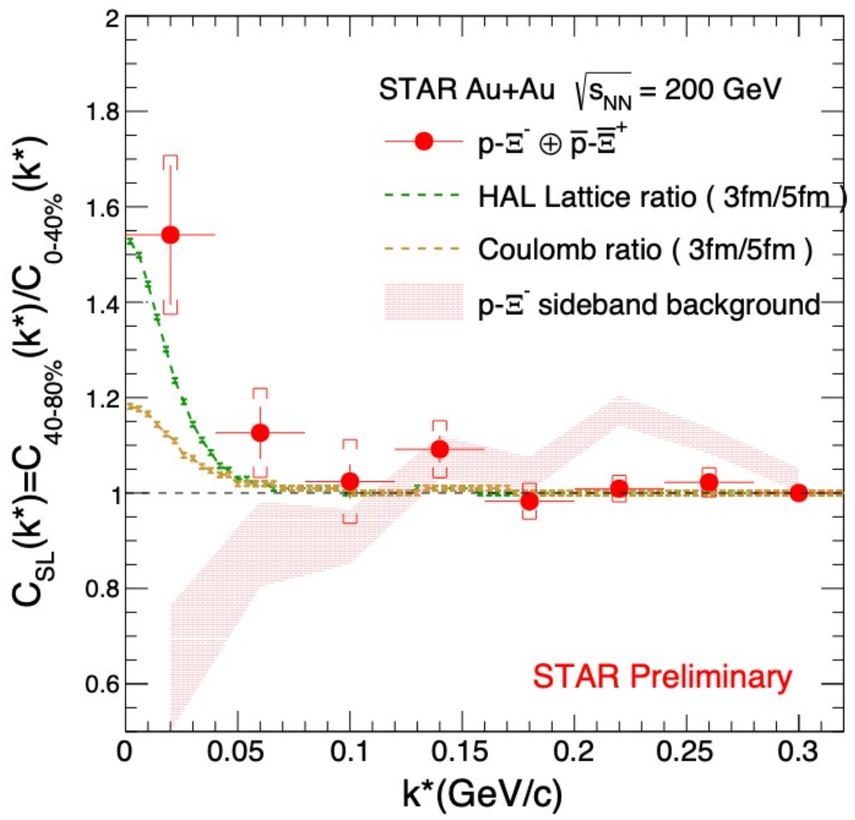
First measurement of p-Ξ correlation in Au+Au collisions at RHIC



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,

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

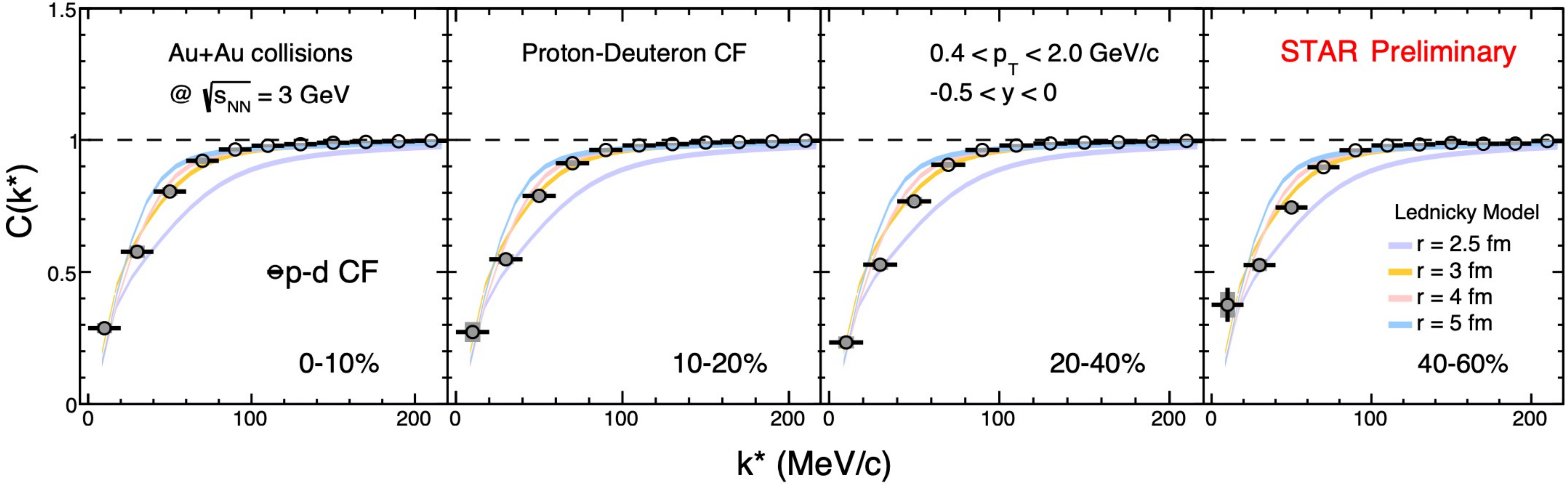
$C_{SL}(k^*)$ is more sensitive to strong interaction with largely canceled Coulomb interaction[1].

- 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

p-d

p-d interaction (FXT = 3 GeV)

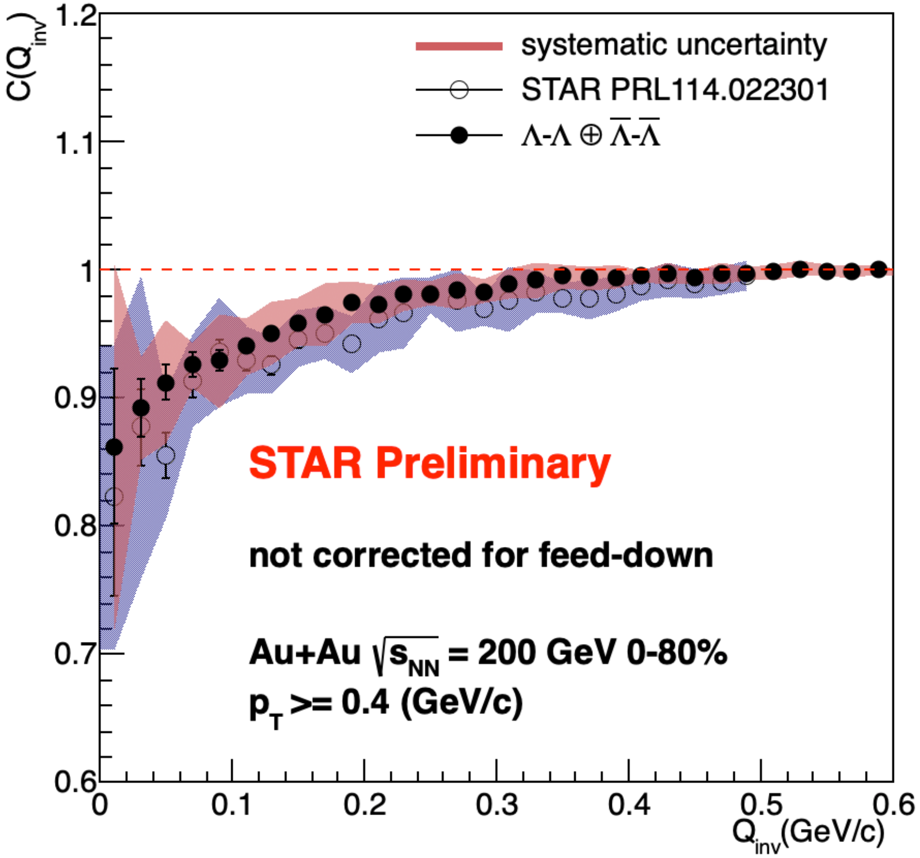


- The first measurement of deuteron-proton interaction in STAR.
- Clear depletion at small k* range is seen.
- The Lednicky model[1,2] of spherical source size with r = 3-4 fm is consistent with data.

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

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.

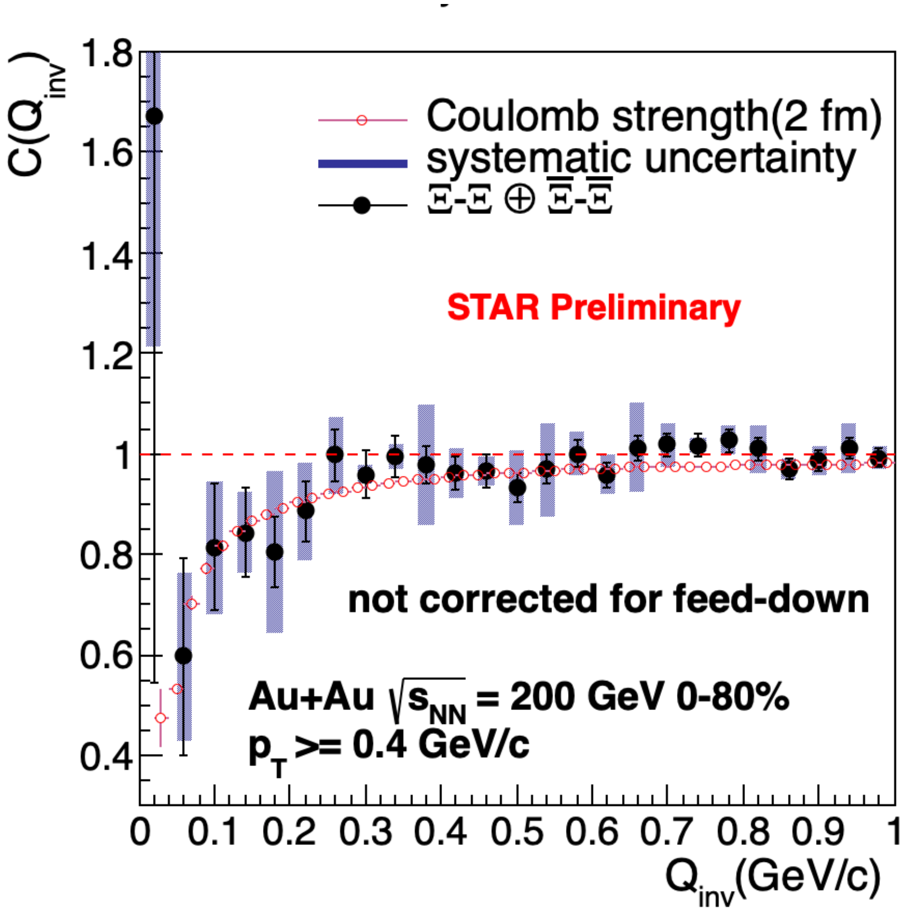
- Anti-correlation of Λ-Λ is observed in Au+Au at $\sqrt{s_{NN}}$ = 200 GeV.

  - 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



- 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

Momentum resolution study test

Correction formula for momentum resolution

Phys. Rev. C **71**, 044906 (2005)

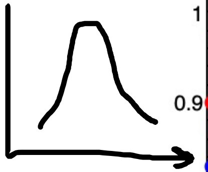
$$C(\vec{q}) = \frac{A(\vec{p_1},\vec{p_2})}{B(\vec{p_1},\vec{p_2})} K_{momentum}(\vec{q}). \qquad K_{momentum}(\vec{q}) = \frac{C(\overrightarrow{q_{ideal}})}{C(\overrightarrow{q_{smear}})} = \frac{\frac{A(\overrightarrow{p_{1ideal}},\overrightarrow{p_{2ideal}})}{B(\overrightarrow{p_{1ideal}},\overrightarrow{p_{2ideal}})}}{\frac{A(\overrightarrow{p_{1seamr}},\overrightarrow{p_{2smear}})}{B(\overrightarrow{p_{1smear}},\overrightarrow{p_{2smear}})}}$$

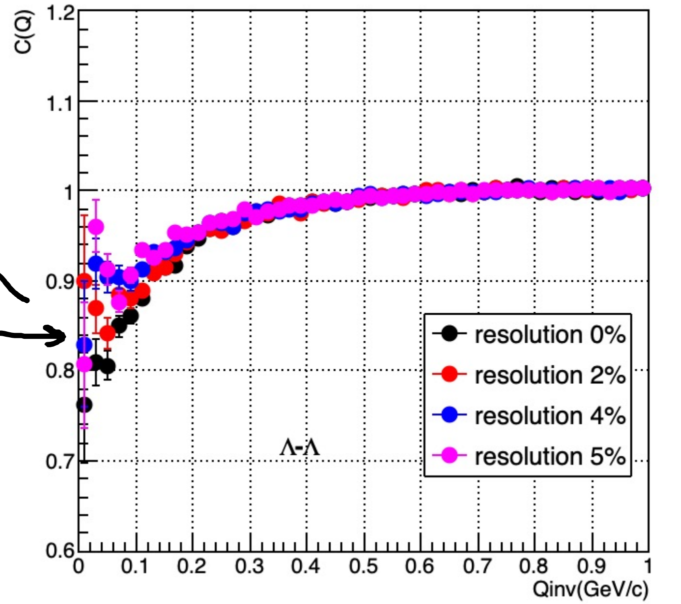
lambda

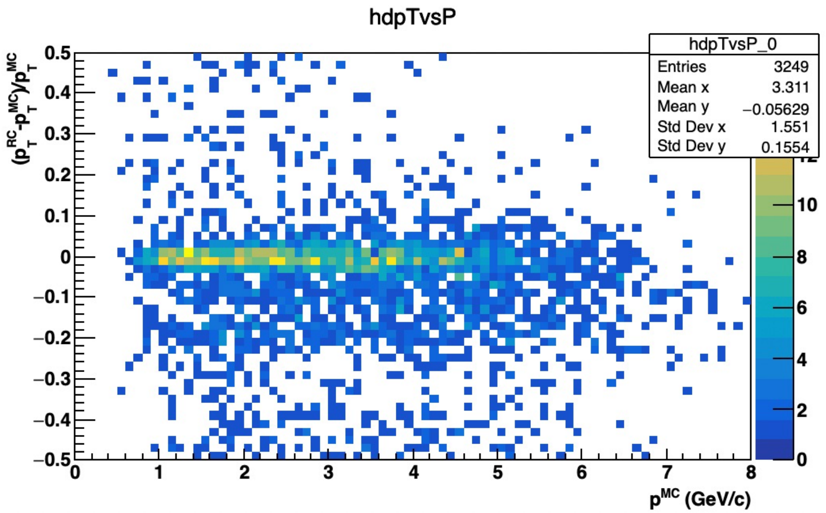
$\vec{p}$ . .

$\vec{p}+\Delta\vec{p}$

Gauss(0~5%)





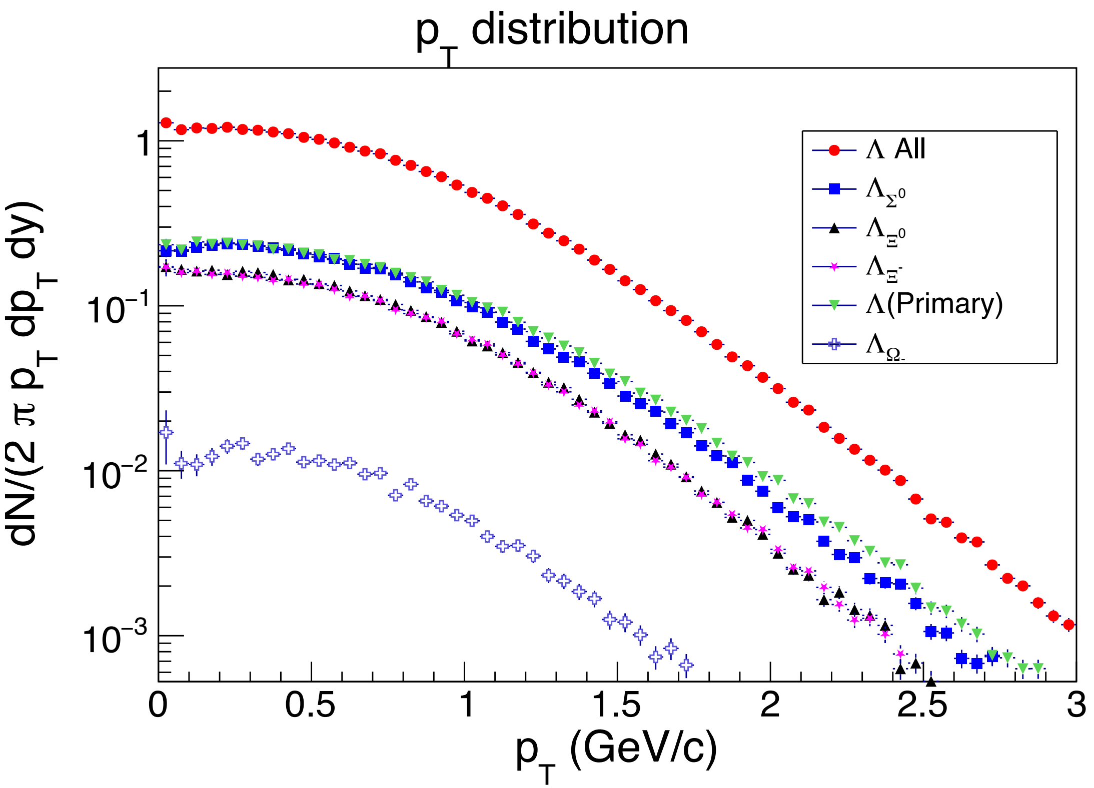


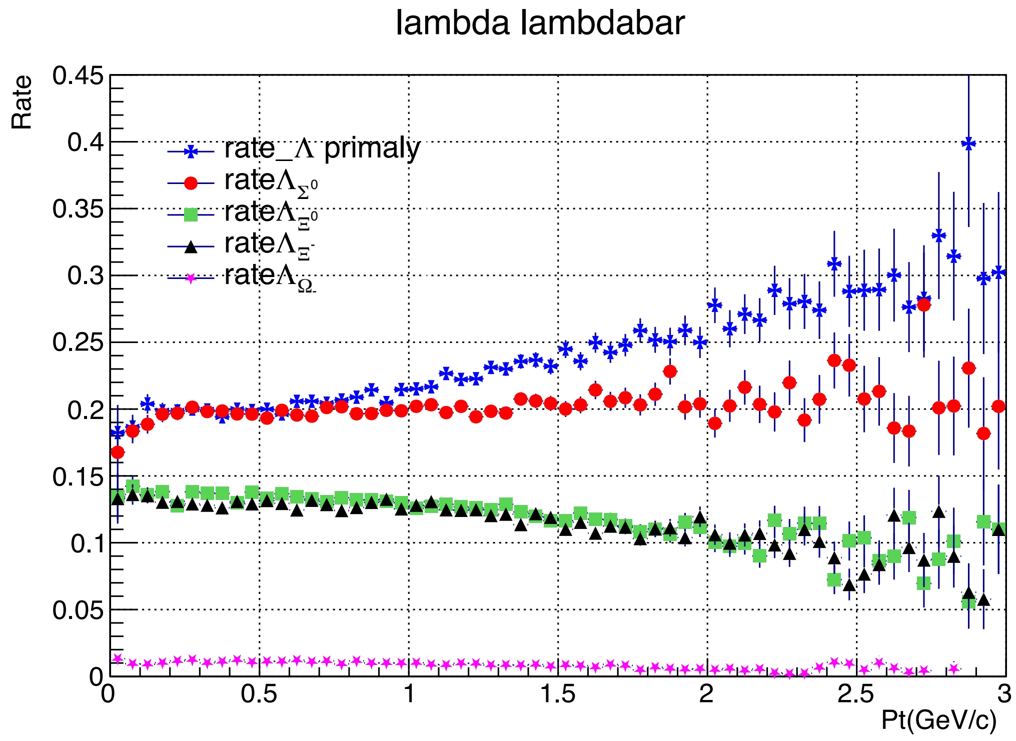
Momentum resolution effect put by hand was tested.

- Smearing effect is seen at low Q
- Need to apply the correction with actual resolution.

Λ feed-down

Feeddown effects was estimated by therminator2





- The largest contribution is Λ decaying from Σ_0.
- Λ_{Ω_0} ratio is 1/100 for all lambdas.
- Primary lambda is only ~20%!
- Kinematic cuts used in the analysis need to be included.

Primary Ξ is ~50%
(including strong decays)

Summary & Outlook

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

  - Attractive interaction is observed in 200 GeV.

  - $\mathrm{C}(k^{*})$ 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^{-}.
- **p-d correlation**

  -Clear depletion at small k* range is seen in data.
- Λ-Λ **correlation function**

  - New result with high statistics data is consistent with previous result.
- Ξ-Ξ **correlation**

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

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).

Back up

Momentum resolution study test

Correction formula for momentum resolution

$$C(\vec{q}) = \frac{A(\vec{p_1},\vec{p_2})}{B(\vec{p_1},\vec{p_2})} K_{momentum}(\vec{q}). \qquad K_{momentum}(\vec{q}) = \frac{C(\overrightarrow{q_{ideal}})}{C(\overrightarrow{q_{smear}})} = \frac{\dfrac{A(\overrightarrow{p_{1ideal}},\overrightarrow{p_{2ideal}})}{B(\overrightarrow{p_{1ideal}},\overrightarrow{p_{2ideal}})}}{\dfrac{A(\overrightarrow{p_{1seamr}},\overrightarrow{p_{2smear}})}{B(\overrightarrow{p_{1smear}},\overrightarrow{p_{2smear}})}}$$

Phys. Rev. C **71**, 044906 (2005)

How to make the C(q_{smear}) for the test

1.. Phi ,eta ,pt are taken from Run14 for example as ideal distribution.

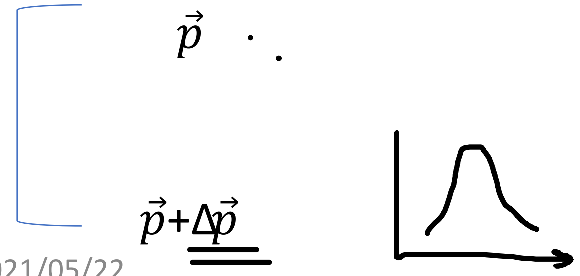
2. Smearing (phi, eta pt) by the random number fllowing Gaussian.

3. change the gausian width from 0% to 5%.

4.Take the correlation function using $A(\overrightarrow{p_{1seamr}},\overrightarrow{p_{2smear}})$ and $B(\overrightarrow{p_{1smear}},\overrightarrow{p_{2smear}})$

5. Compare the $C(\overrightarrow{q_{ideal}})$ and $C(\overrightarrow{q_{smear}})$.

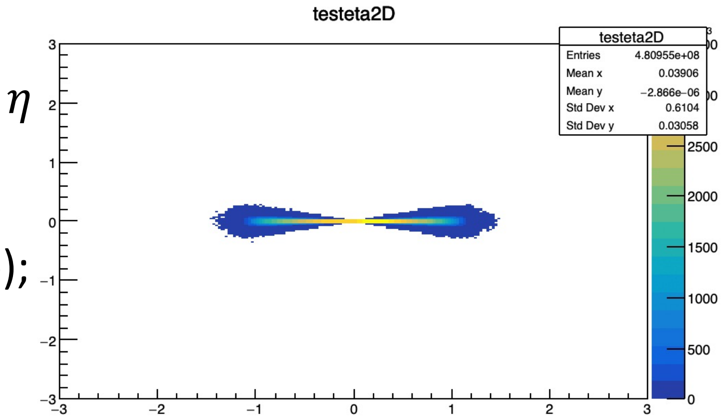
lambda



Gauss(0~5%)

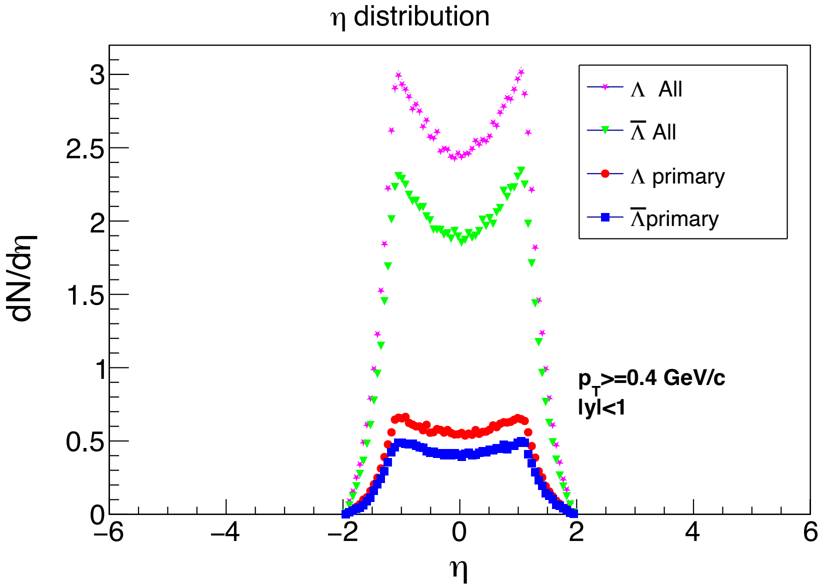
For example…
float rephi = phi+ fabs(phi)*gRandom->Gaus(0,reso);

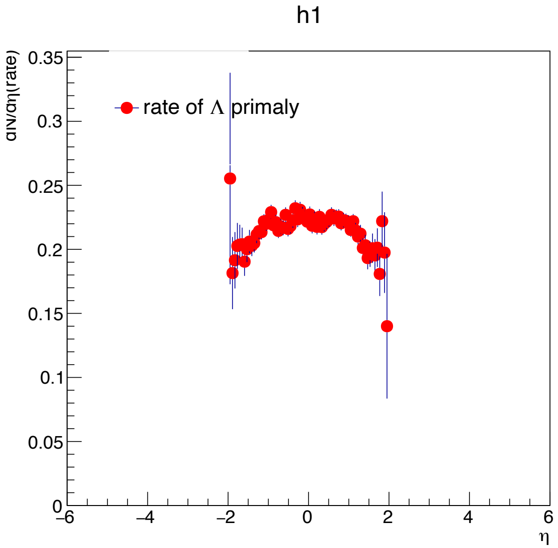
$\eta_{smr} - \eta$



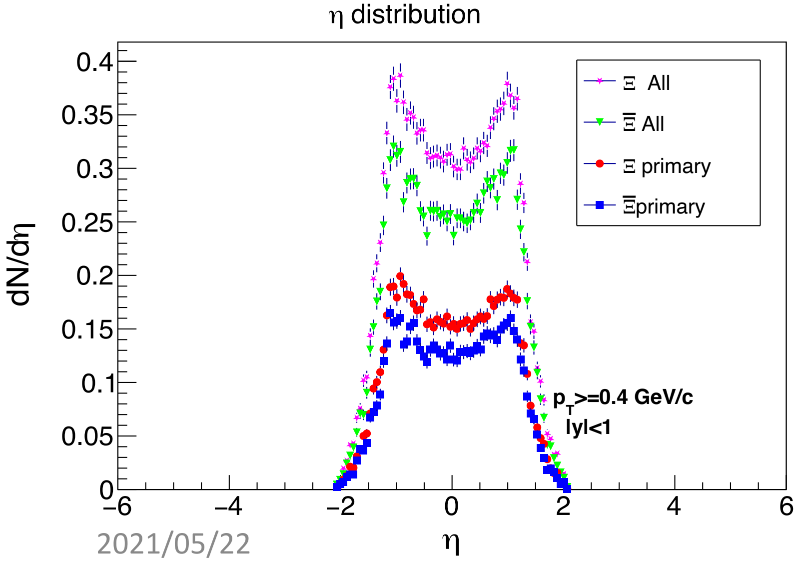
η

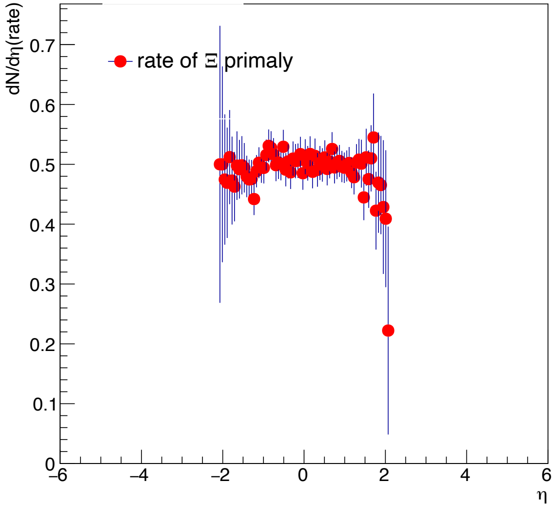
The primary paritcle ratio of Λ andΞ





The ratio of primary lambda is almost 20%~





The ratio of primary Xi is almost 50%~.

Therminator2 simulation

Motivation

- Estimate the feed-down contribution from other hyperons.

Therminator2

- Monte Carlo Event generator based on the thermal model of particle production.
  - The input of freeze-out hypersurface and expansion velocity from hydrodynamic code.
  - Subsequent space-time evolution and hadronic cascade.

- Successfully reproducing RHIC Au+Au 200 GeV and LHC Pb+Pb Collision at 5.5 TeV.
- Analysis of femtoscopic correlation.

M.Chojnacki et.al,arXiv:1102.0273

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)
- $\vec{q} = \overrightarrow{p_1} - \overrightarrow{p_2}$-- Relative momentum of 2 particles
- $\vec{k} = \frac{(\overrightarrow{p_1}+\overrightarrow{p_2})}{2}$ - The average values of 2 particles momentums

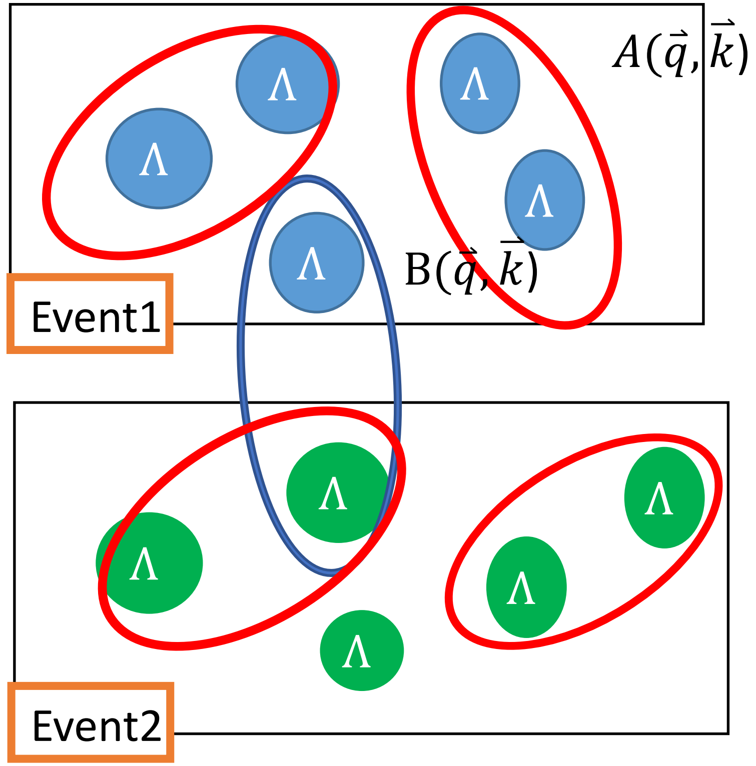
correlation function $C(\vec{q},\vec{k}) = \frac{A(\vec{q},\vec{k})}{B(\vec{q},\vec{k})}$

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

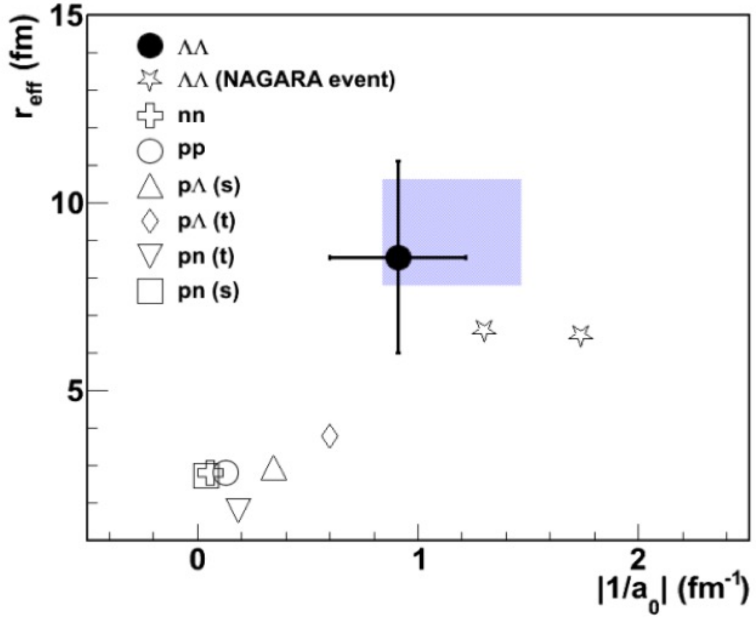
d_0 : effective range

Physical quantity to study a bound state

r_0 :source size

a_{res} : residual amplitude

r_{res} : width of the Gaussian



L. Adamczyk for the STAR Collaboration PhysRevLett.114.022301

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

Fitting method: ROOT default fitting(minimization)