SQM 2024
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Measurements of p-Ξ^- Correlation Function in $\sqrt{s_{NN}}$ = 200 GeV Isobar (Zr+Zr and Ru+Ru) and Au+Au Collisions with the STAR Detector

Boyang Fu

for the STAR collaboration

Central China Normal University

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U.S. DEPARTMENT OF ENERGY | Office of Science

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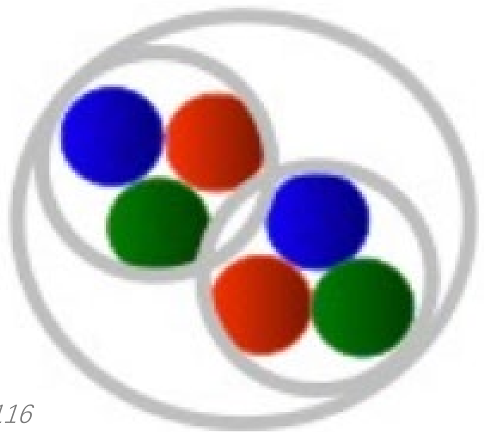
Outline

- ☆ Motivation
- ☆ Two-particle Correlations
- ☆ The STAR Experiment
- ☆ Data Analysis and L-L Fits
- ☆ Results
- ☆ Summary

Motivation

- Why study p-Ξ⁻(n-Ξ⁻) correlations ?
  - Important to study the Hyperon-nucleon interactions and explore the inner structure of the neturon star.
  - Related to the possible existence of H-dibaryon in S=-2 sector.
- Lattice QCD potentials (HAL-QCD Collaboration) – Predicted an attractive interaction in p-Ξ⁻ and it is observed in p−Pb and p−p collisions at ALICE.

Hexaquark
Baryon-Baryon molecule



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Nucl. Phys. A 998 (2020) 121737
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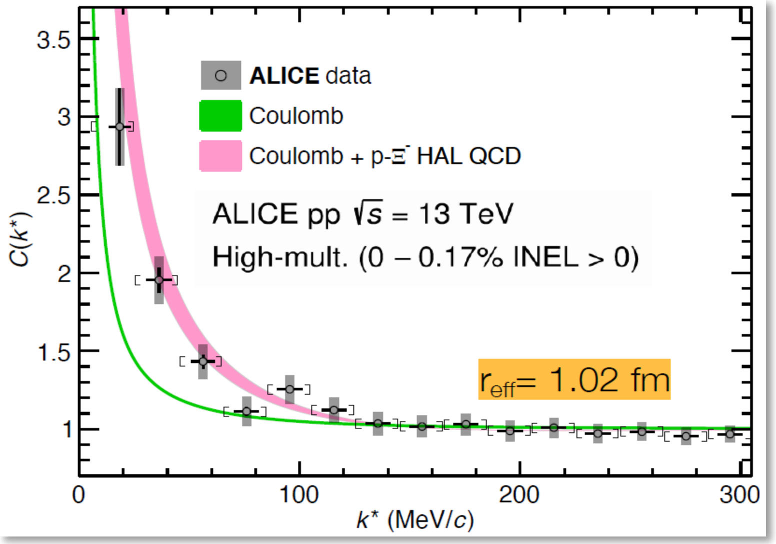
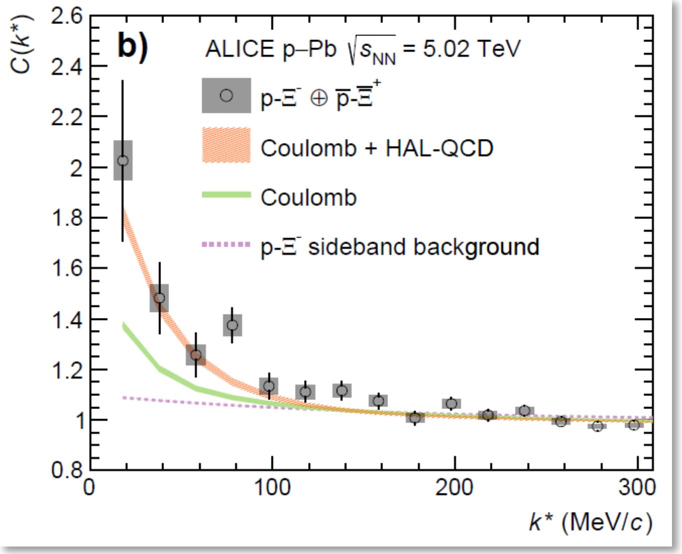


Nature 588(2020) 233



Phys. Rev. Lett. 123, 112002

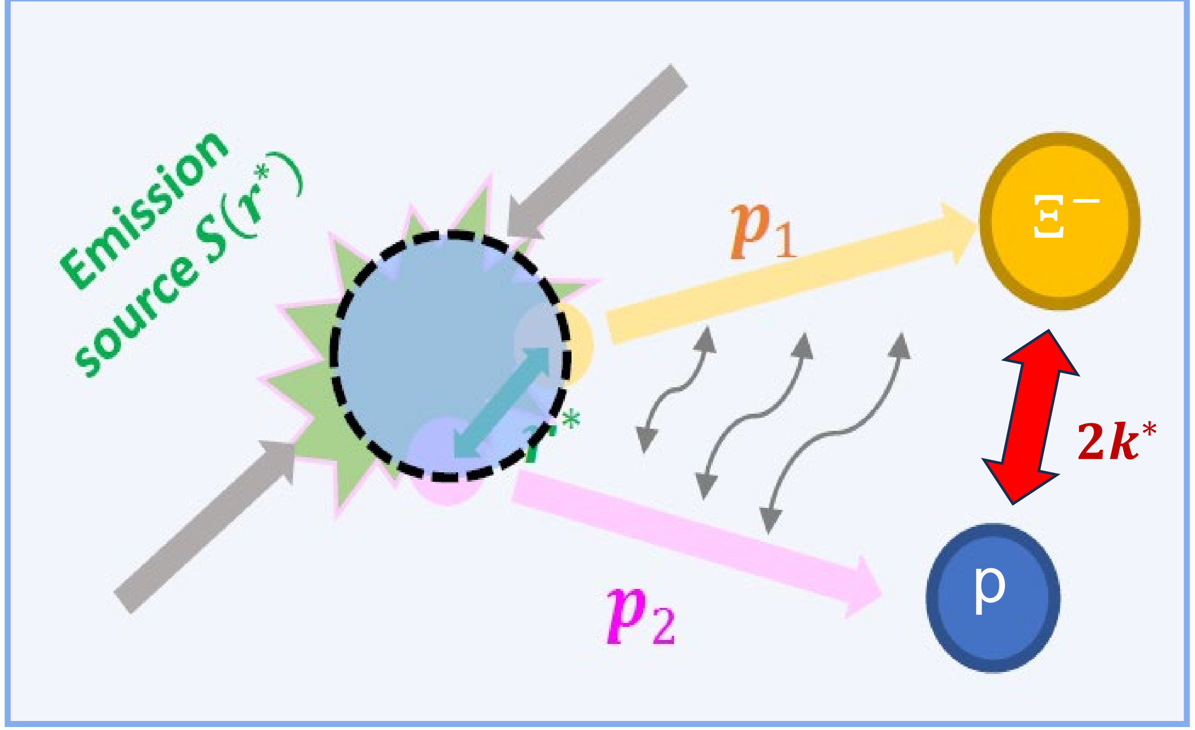
Two-Particle Correlations

Statistical

Momentum correlation function:

$$C(p_1, p_2) = \frac{P(p_1, p_2)}{P(p_1) \cdot P(p_2)}$$

Single-particle momentum



Modeling

Approximating the emission process
And the momenta of the particles:

$$C(k^*) = \int d^3r^* S(r^*) |\Psi(r^*, k^*)|^2$$

Pair Source Function — Pair Wave function

$$\Psi(r^*, k^*) \propto (QS, Coul, SI)$$

Experimental

Observable:

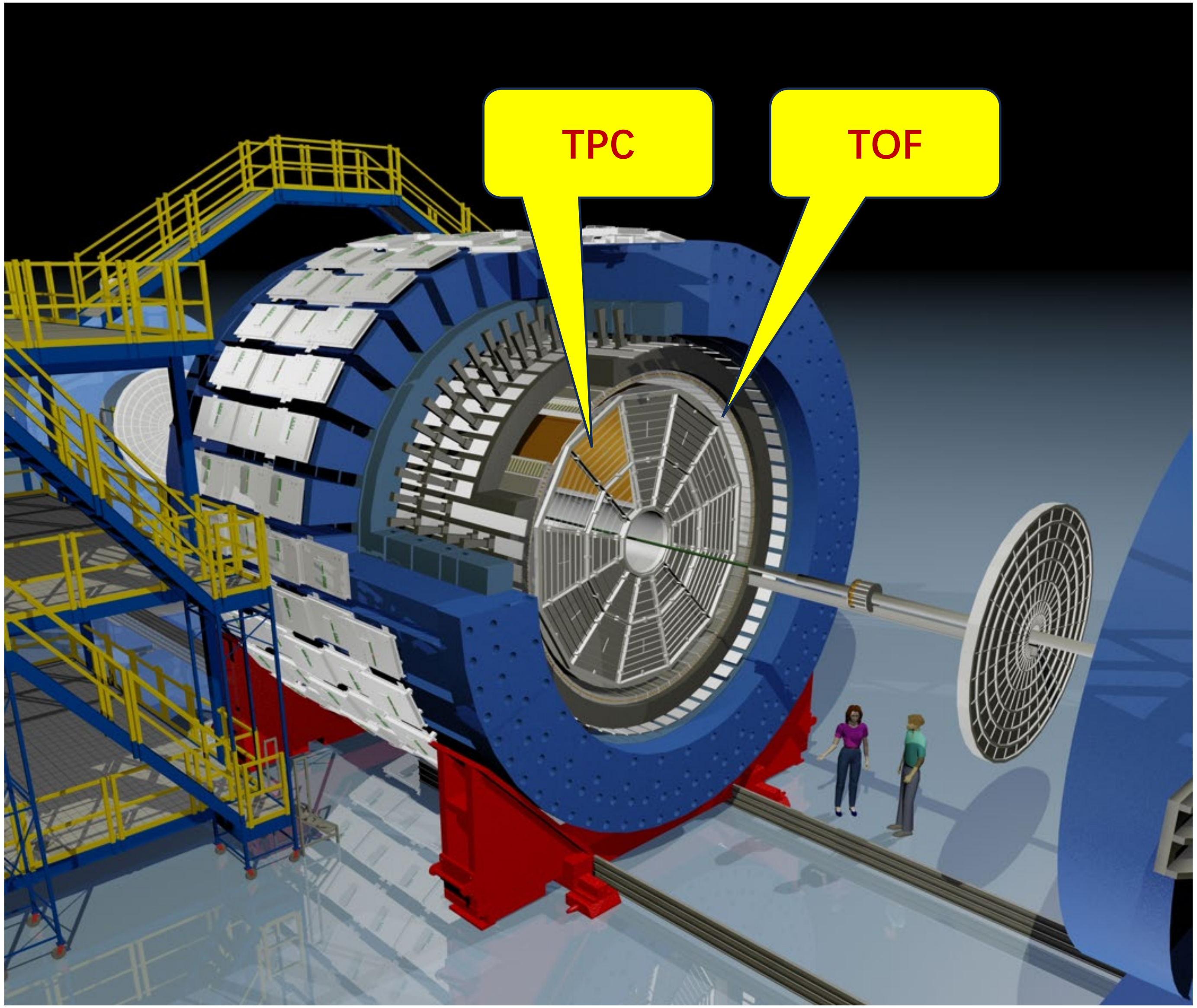
$$C(k^*) = \mathcal{N} \frac{N_{same}(k^*)}{N_{mixed}(k^*)}$$

Normalization factor — Signal — Background

k^* : relative momentum in the pair rest frame (PRF)
r^*: relative distance in PRF

R. Lednicky, et al. Sov.J.Nucl.Phys.35(1982)770
L. Michael, et al. Ann.Rev.Nucl.Part.Sci. 55 (2005) 357-402
J. Haidenbauer, Phys.Rev.C 102 (2020) 3, 034001

STAR Detector



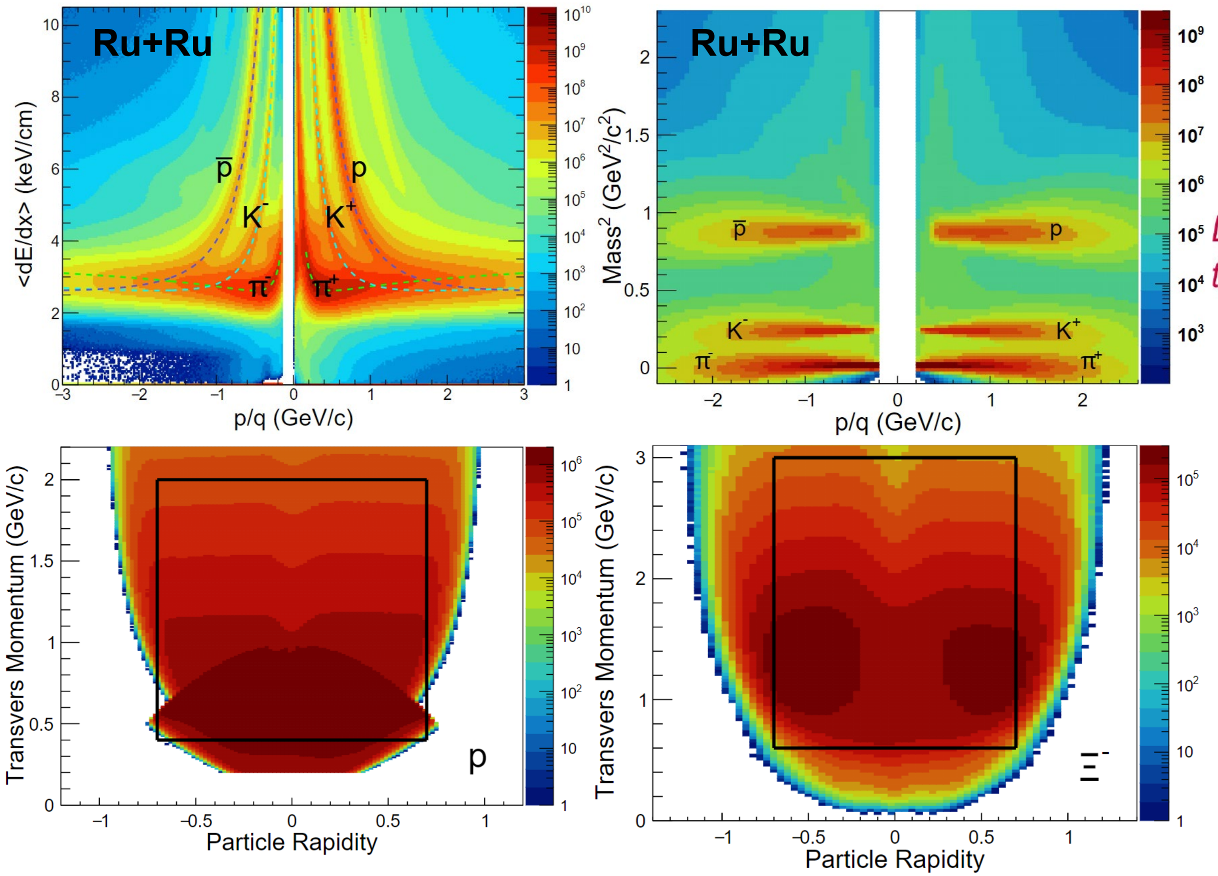
Time Projection Chamber (TPC)

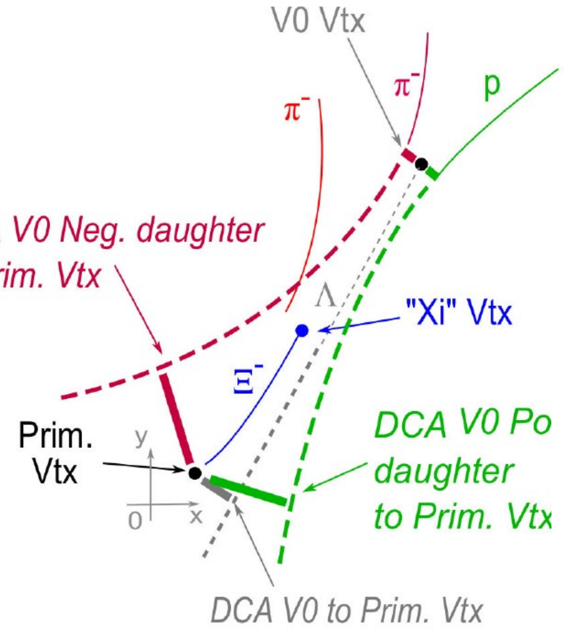
- ✓ Charged particle tracking
- ✓ Momentum reconstruction
- ✓ Particle identification from ionization energy loss (dE/dx)
- ✓ Pseudorapidity coverage $|\eta|$ < 1.0

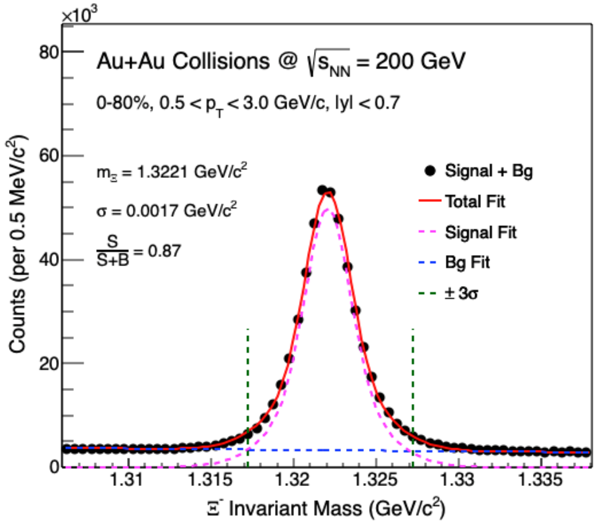
Time-of-Flight (TOF)

- ✓ Particle identification m^2
- ✓ Pseudorapidity coverage $|\eta|$ < 0.9

Particle Identification & Reconstruction







$$\Lambda(\bar{\Lambda}) \rightarrow p(\bar{p}) + \pi^-(\pi^+), 63.9\%$$

$$\Xi^-(\bar{\Xi}^+) \rightarrow \Lambda(\bar{\Lambda}) + \pi^-(\pi^+), 99.887\%$$

- ☆ p, π^- particles are identified by TPC and TOF
- ☆ Reconstruct $\Xi^-(\bar{\Xi}^+)$ via helix swimming method

Phys. Rev. C 102 (2020) 34909

Two-track Effects

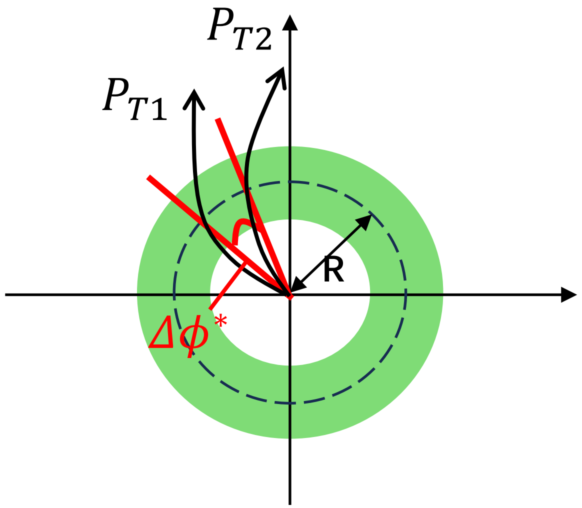
Track merging & splitting: track vs. track from $\Xi^-(\bar{\Xi}^+)$ decay

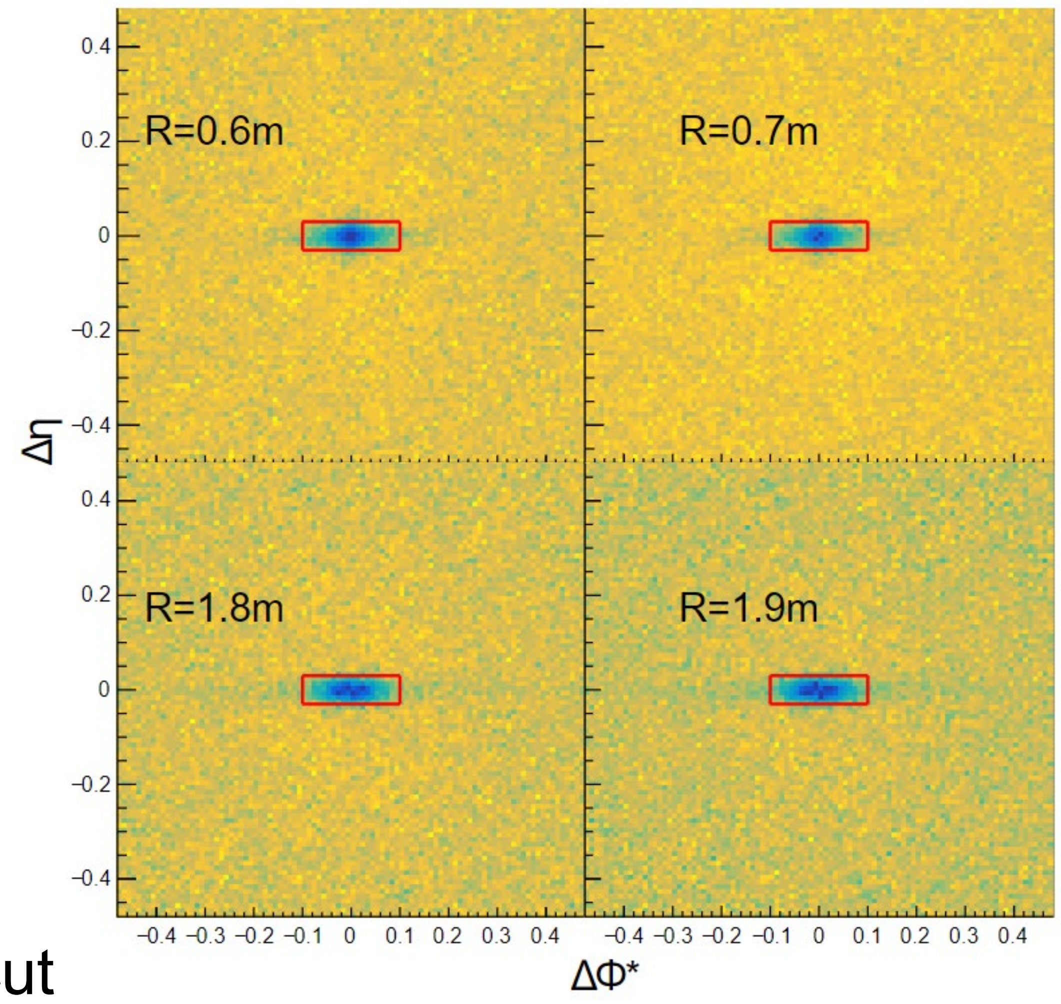
$$\Delta\phi^* = \phi_1 - \phi_2 + sin^{-1}\left(\frac{0.3B_Z R}{2p_{T_1}}\right) - sin^{-1}\left(\frac{0.3B_Z R}{2p_{T_2}}\right)$$

$B_Z = 0.5[\mathrm{T}]$ R : transverse distance from vertex position

TPC region(0.6m<R<1.9m)

p_T: transverse momentum





☆ The effect can be removed by $\Delta\Phi^*$ and $\Delta\eta$ cut

Additional Effects

$$C(k^*) = 1 + \lambda_{genuine}\left(C_{genuine}(k^*) - 1\right) + \lambda_{residual}(C_{residual}(k^*) - 1) + \lambda_{mis-id}(C_{mis-id}(k^*) - 1)$$

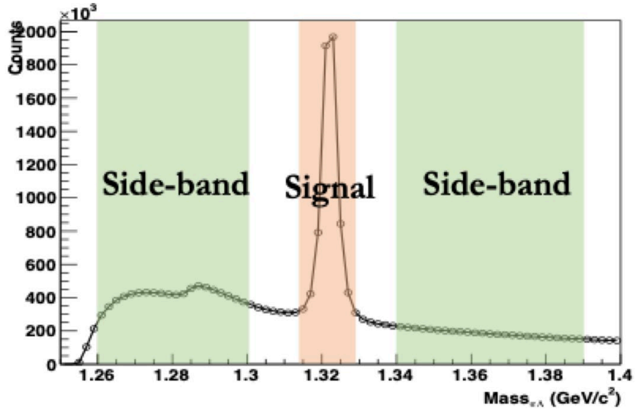
We want this | Background

1. Background correction (~1%):

$$\lambda_{mis-id} = (1 - pur_{proton} \times pur_{\Xi^-}) \times fra_{proton} \times fra_{\Xi^-}$$

☆Estimate mis-id correlation via side-band method

◎|Invmass – pdgmass| > 5σ



2. Residual correction (~3%):

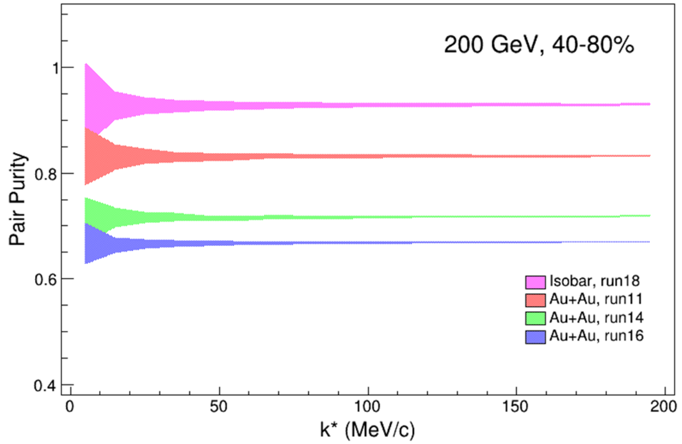
$$\lambda_{residual} = (1 - pur_{\Xi^-})$$

☆ Main residual correlation comes from:

$$p\Xi^-(1530) \rightarrow p\Xi^-, \quad \Lambda\Xi^- \rightarrow p\Xi^-$$

3. Pair Purity correction:

$$\text{Pair purity} = pur_{proton} \times pur_{\Xi^-}$$



4. Feed-down correction:

$$\lambda_{genuine} = pur_{proton} \times pur_{\Xi^-} \times fra_{proton} \times fra_{\Xi^-}$$

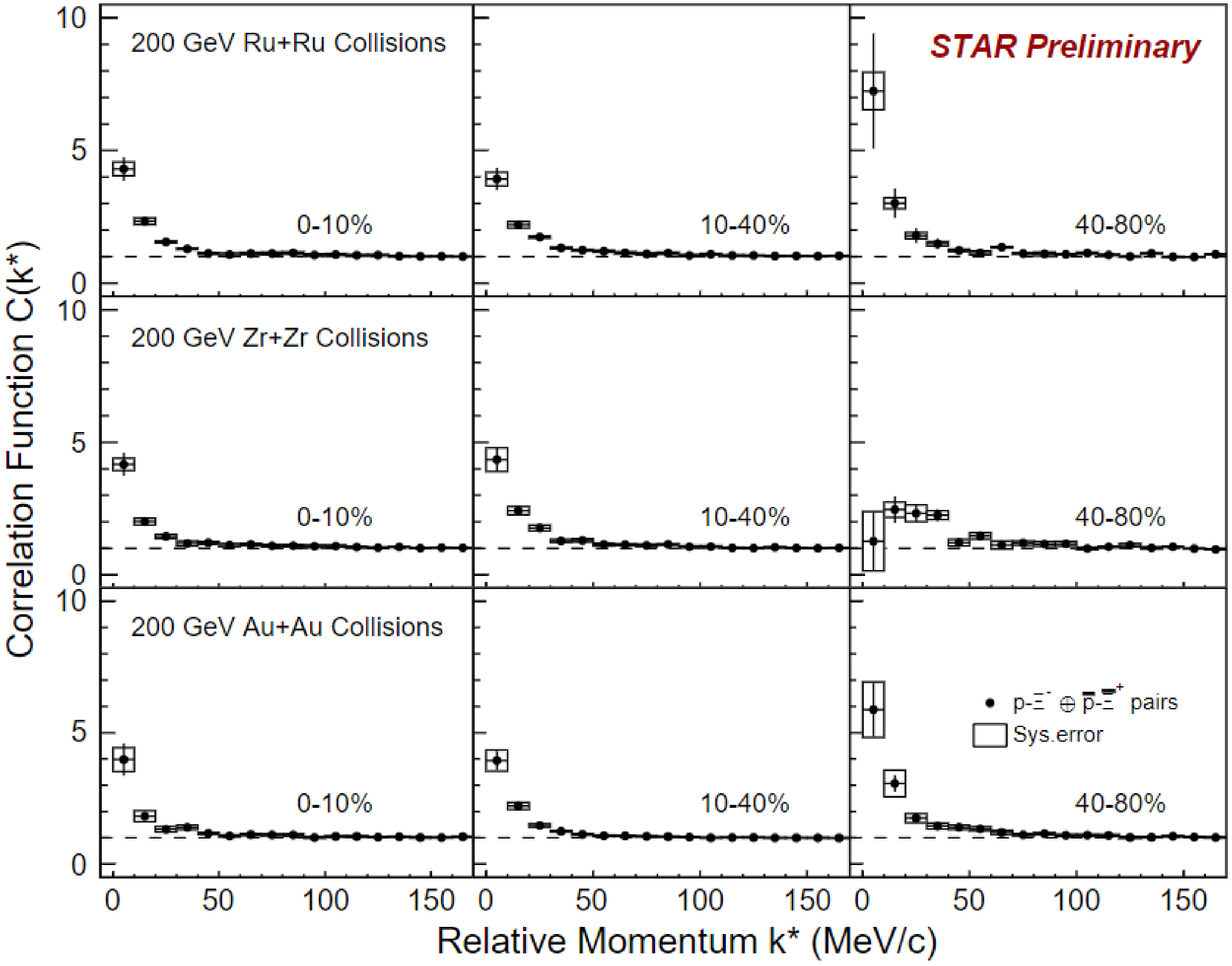
☆ For proton:

◎ Data-driven feed-down study in each collision

☆ For Ξ^-:

◎ Therminator2 model

Results: p-Ξ^- Correlation Functions



☆ CFs show enhancement at low k*

➔ More pronounced in peripheral collisions

Lednicky-Lyuboshitz Model

☆ In p-Ξ^- correlation, two spin states appear:

$$C_{p-\Xi} = \frac{1}{4}C_{S=0,singlet} + \frac{3}{4}C_{S=1,triplet}$$

☆ Correlation function:

$$C(\boldsymbol{k}^*) = \int d^3r^* S(\boldsymbol{r}^*)|\Psi\ (\boldsymbol{r}^*, \boldsymbol{k}^*)|^2$$

☆ Scattering amplitude (include Coulomb):

$$f_0(k^*) = [\frac{1}{f_0} + \frac{1}{2}d_0 k^{*2} - \frac{2}{a_c}h(\eta) - ik^* A_c(\eta)]^{-1}$$

$\boldsymbol{f_0}$: scattering length $\quad a_c$: Bohr radius $\quad \eta = (k^* a_c)^{-1}$

$\boldsymbol{d_0}$: effective range $\quad A_c, h$: Coulomb interaction

◎ Different spin state have different f_0 and d_0

◎ Different system have same f_0 and d_0

R. Lednicky, et al. Sov.J.Nucl.Phys.35(1982)770

Lednicky-Lyuboshitz Model

☆ In p-Ξ^- correlation, two spin states appear:

$$C_{p-\Xi} = \frac{1}{4}C_{S=0,singlet} + \frac{3}{4}C_{S=1,triplet}$$

Total spin	Baryon pair	a_0 (fm)	$r_{\rm eff}$ (fm)
$J=0$	$p\Xi^-$	$-1.25(0.03)(^{+0.12}_{-0.00}) - i2.00(0.40)(^{+0.16}_{-0.31})$	$3.7(0.3)(^{+0.0}_{-0.1}) - i2.4(0.2)(^{+0.1}_{-0.3})$
	$n\Xi^0$	$-2.76(0.63)(^{+0.33}_{-0.66}) - i0.15(0.12)(^{+0.00}_{-0.03})$	$1.5(0.3)(^{+0.0}_{-0.1}) - i0.1(0.0)(^{+0.0}_{-0.0})$
	$\Lambda\Lambda$	$-0.99(0.30)(^{+0.00}_{-0.17})$	$4.9(0.70)(^{+0.1}_{-0.5})$
$J=1$	$p\Xi^-$	$-0.47(0.08)(^{+0.11}_{-0.09}) - i0.0(0.00)(^{+0.00}_{-0.00})$	$6.7(0.7)(^{+1.4}_{-0.9}) + i0.0(0.1)(^{+0.0}_{-0.0})$
	$n\Xi^0$	$-0.47(0.08)(^{+0.11}_{-0.09})$	$6.8(0.7)(^{+1.4}_{-0.9})$

$$f_0 = -a_0, \; d_0 = r_{eff}$$

☆ Spin averaged method: does not distinguish between spin states (have same CF)

$$f_0^{ave} = \frac{1}{4}f_{0,singlet} + \frac{3}{4}f_{0,triplet} = 0.66^{+0.11}_{-0.07}$$

$$d_0^{ave} = \frac{1}{4}d_{0,singlet} + \frac{3}{4}d_{0,triplet} = 5.95^{+1.05}_{-0.71}$$

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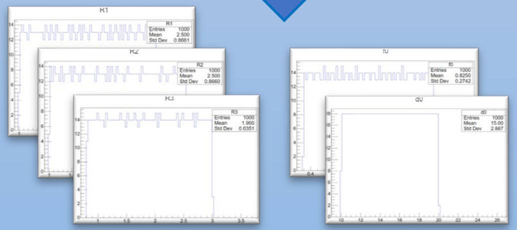
Bayesian Analysis Method

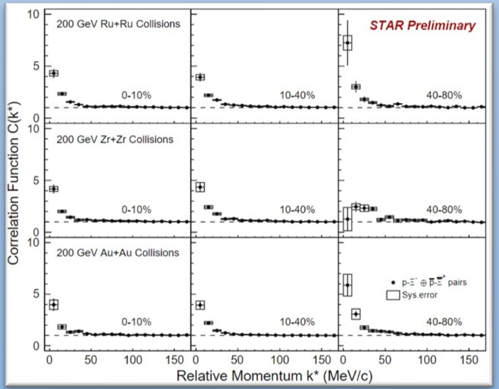
1st Step — Sample Input

- $R_1 = [R_{1min}, R_{1max}]$
- $R_2 = [R_{2min}, R_{2max}]$
- $R_3 = [R_{3min}, R_{3max}]$
- $f_0 = [0.3, 1.2]$
- $d_0 = [0, 20]$

\+ **Latin Hypercube Sampling**



2nd Step — Data Input

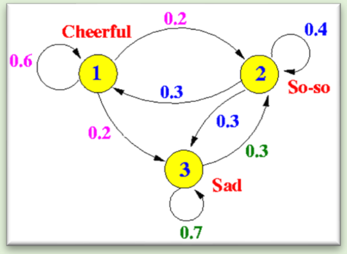


Compare with the samples and predict the parameter's value with error

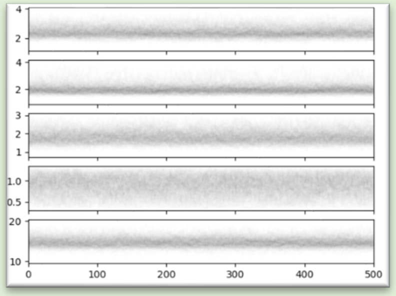
Study samples

3rd Step — Technique

MC MC
Markov Chain
Monte Carlo



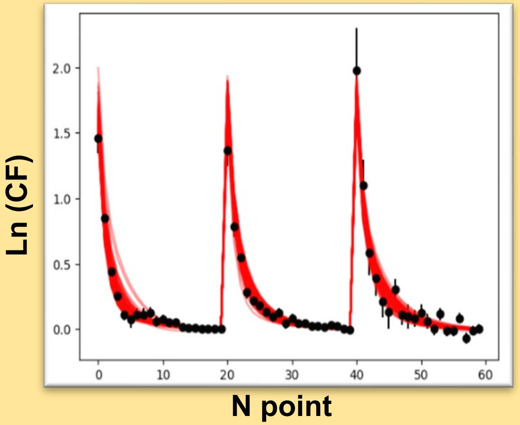
\+ **Gaussian Processes Regression**



\+ **Resampling**

N_{steps}~500
$N_{walkers}$~400
$N_{burnsteps}$~500

Results

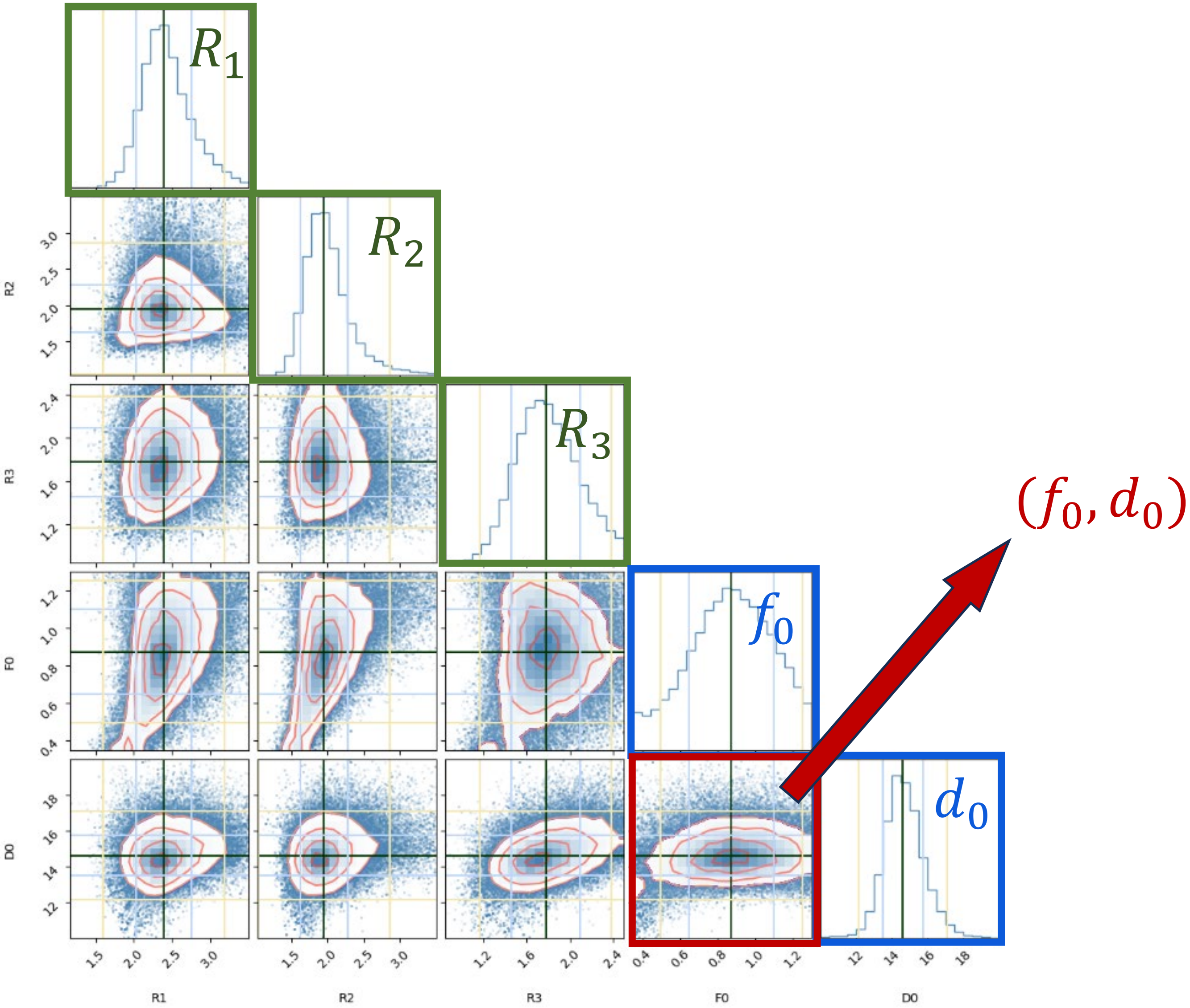


Steps = $N_{walkers} \times N_{burnsteps}$

	Value	Err_+	Err_-
R_1	2.39	0.36	0.27
R_2	1.95	0.33	0.24
R_3	1.78	0.32	0.27
f_0	0.87	0.23	0.24
d_0	14.63	1.12	0.97

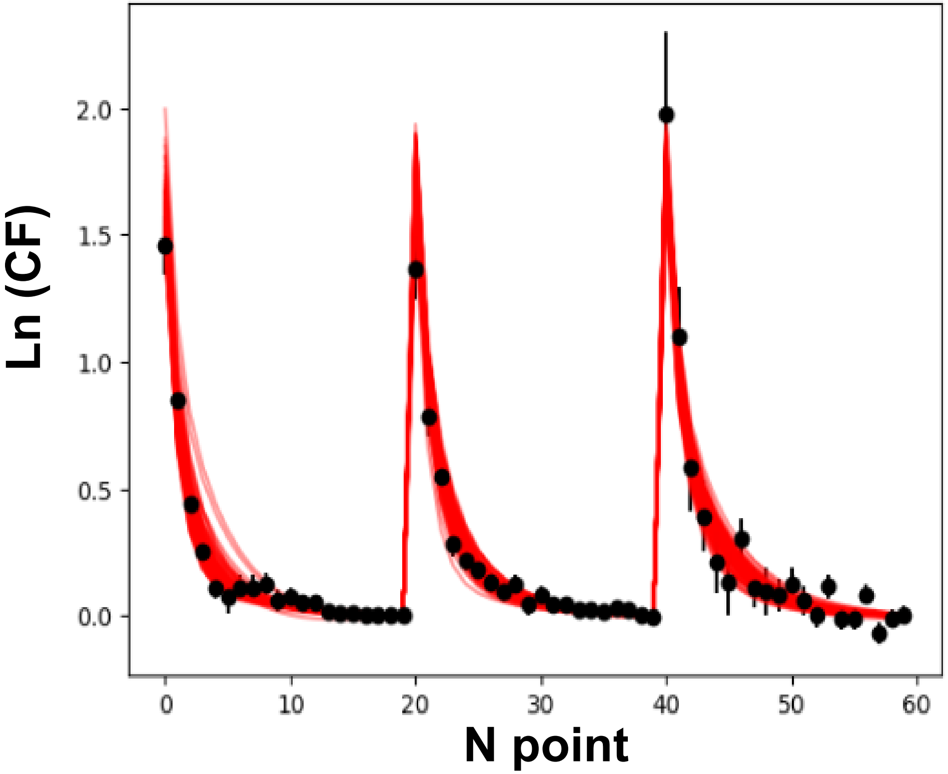
https://github.com/chunshen1987/bayesian_analysis
Phys. Lett. B 833 (2022) 137348

Bayesian Analysis Method



☆ All contours show the converged results

☆ The contour shows 3σ range of the predicted value



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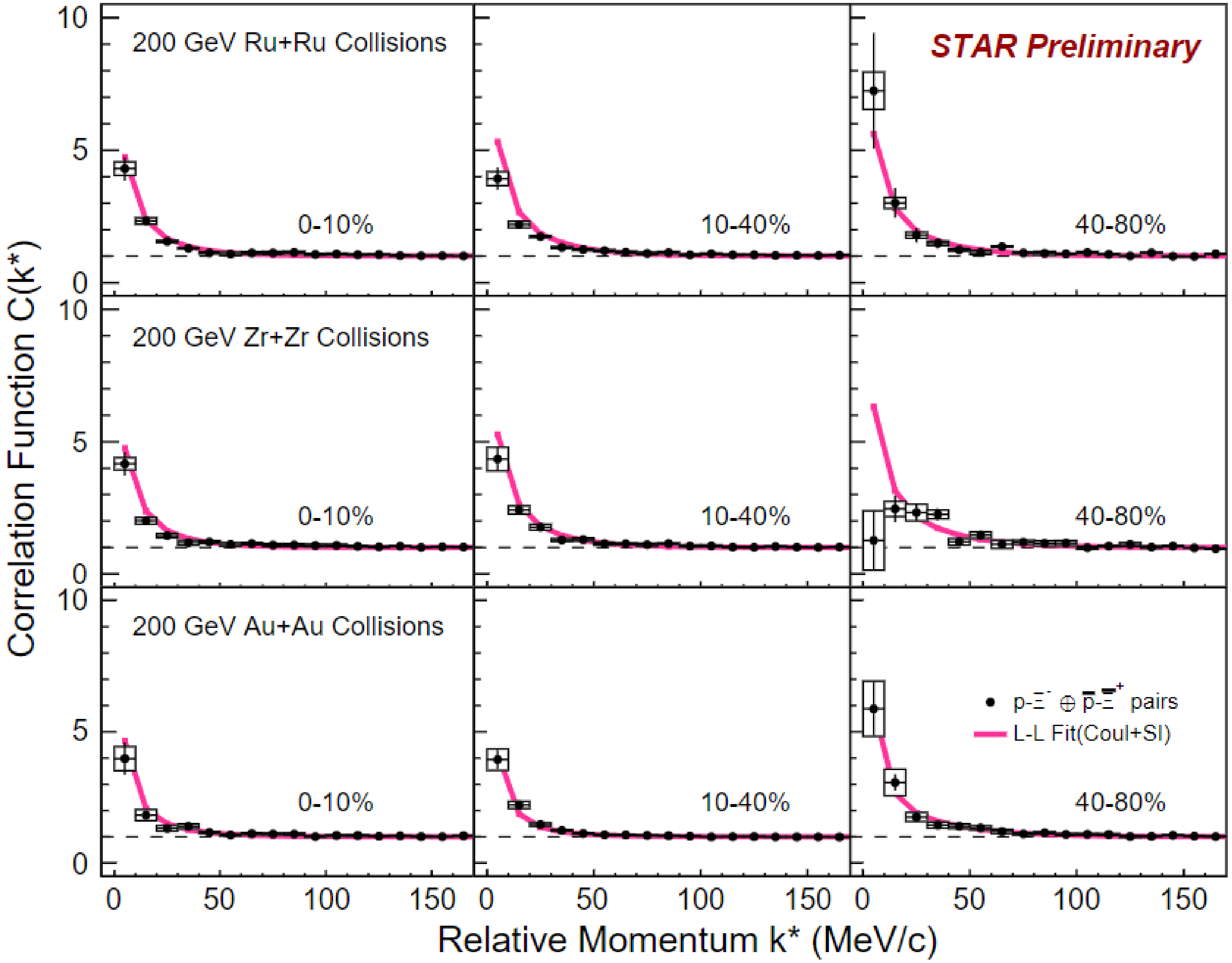
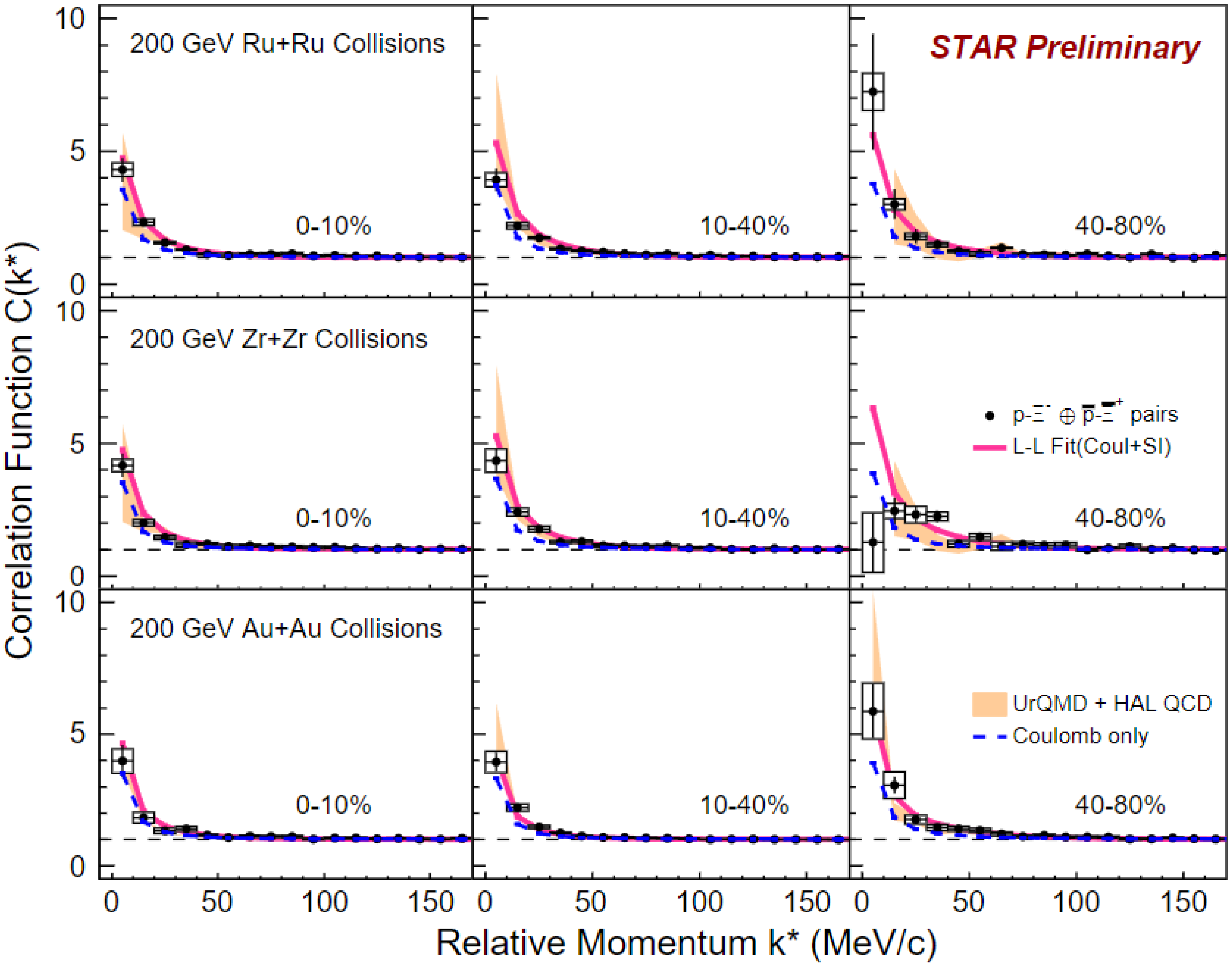
Results: p-Ξ^- Correlation Functions



☆ Simultaneously fit with L-L function for different centralities in each collision system to extract R_G, f_0 and d_0 by Bayesian method

Results: p-Ξ^- Correlation Functions



☆ Simultaneously fit with L-L function for different centralities in each collision system to extract R_G, f_0 and d_0 by Bayesian method

☆ UrQMD + HAL QCD model is consistent with data

◎ Particle phase space provided by UrQMD
◎ Interaction potential provided by HALQCD

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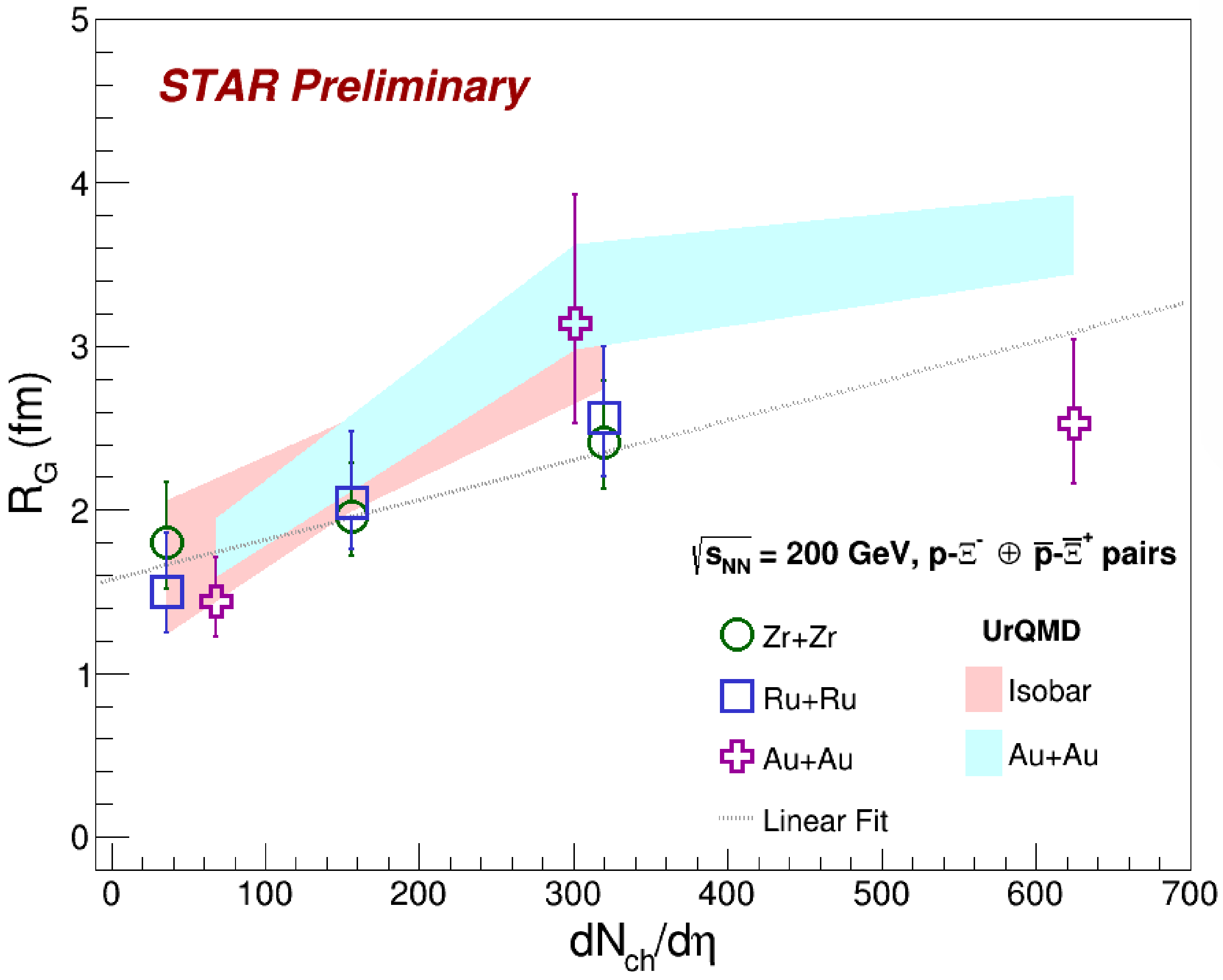
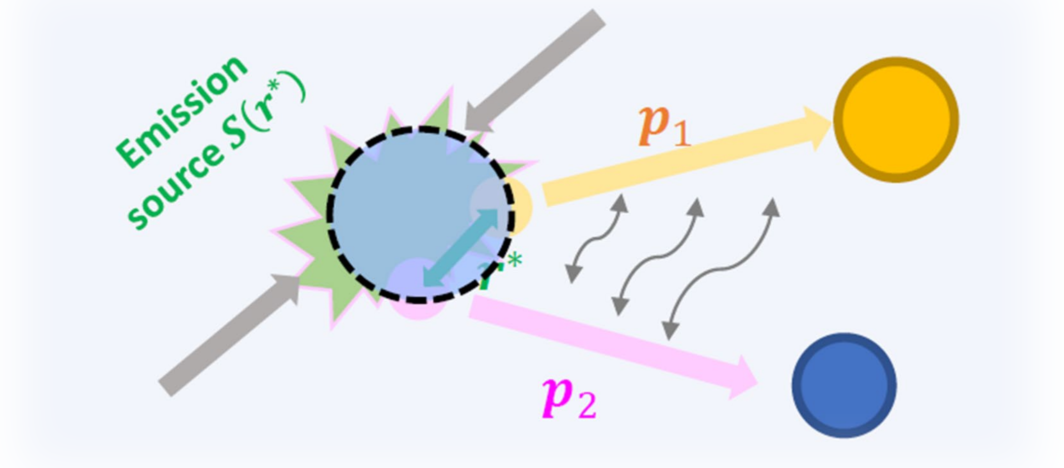
M. Bleicher et al., J. Phys. G 25, 1859 (1999)

Results: Source Size





☆ R_G: Spherical Gaussian source

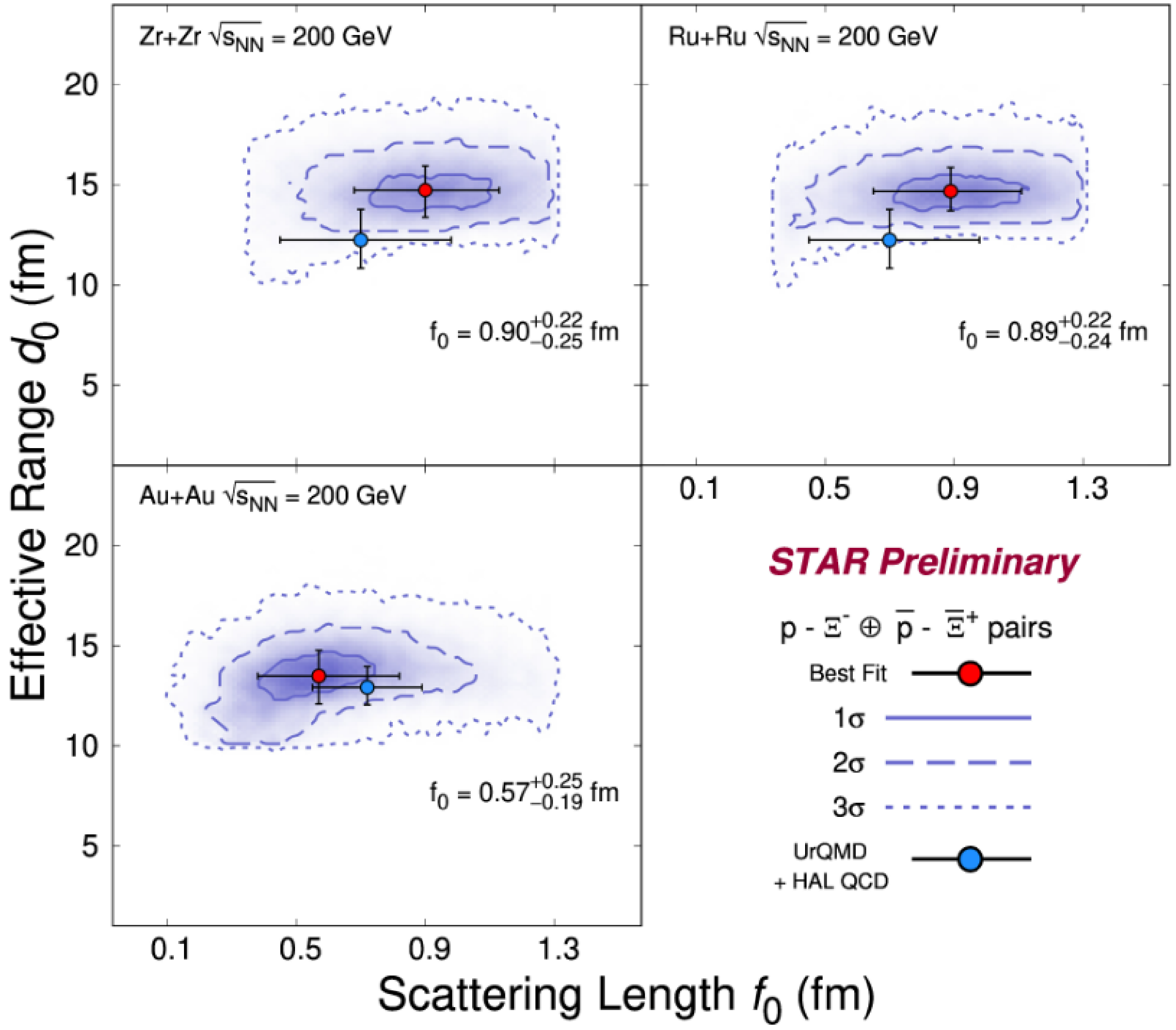
☆ Centrality dependence: $R_G^{central} > R_G^{peripheral}$

☆ R_G increase as charged multiplicity increase for these collisions

*Linear fit with all points

PHYSICAL REVIEW C 79, 034909 (2009)

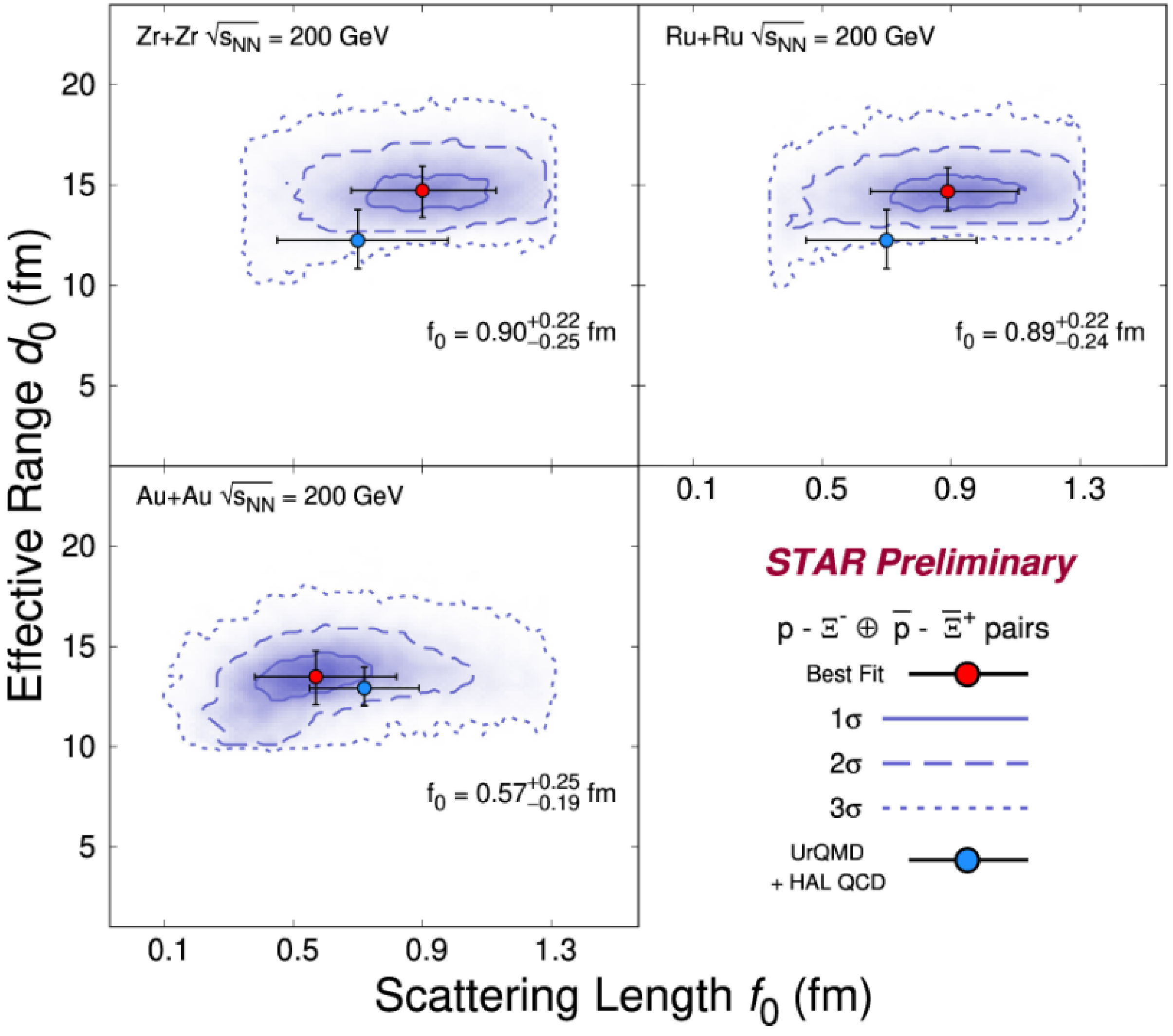
Results: Strong Interaction Parameters



- ☆ First experimental measurements in heavy-ion collisions of strong interaction parameters in p-Ξ^- pairs
- ☆ f_0 and d_0 are consistent with those extracted from UrQMD + HAL QCD model within 1sigma

*Edge of f_0 - d_0 contours are shown with Bezier smooth to improve the visibility

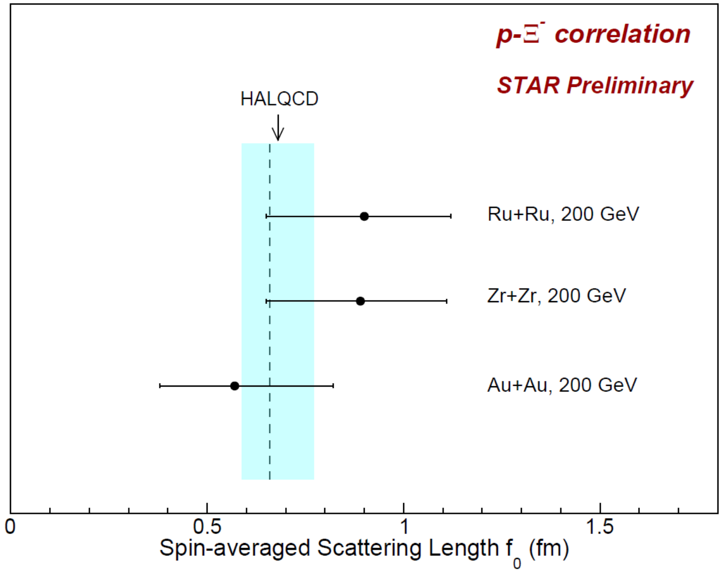
Results: Strong Interaction Parameters



☆ First experimental measurements in heavy-ion collisions of strong interaction parameters in p-Ξ^- pairs

☆ f_0 and d_0 are consistent with those extracted from UrQMD + HAL QCD model within 1sigma

☆ The f_0 measured from isobar (Zr+Zr and Ru+Ru) and Au+Au collisions are consistent with the prediction of HAL QCD



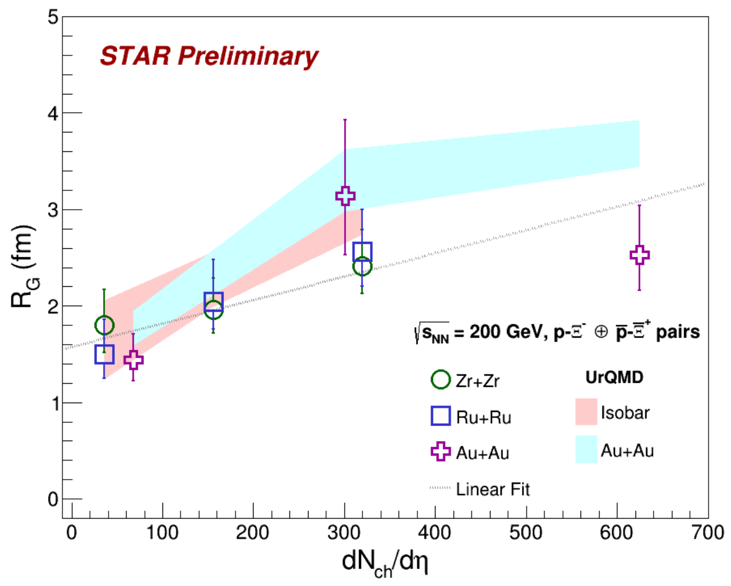
*Edge of f_0 - d_0 contours are shown with Bezier smooth to improve the visibility

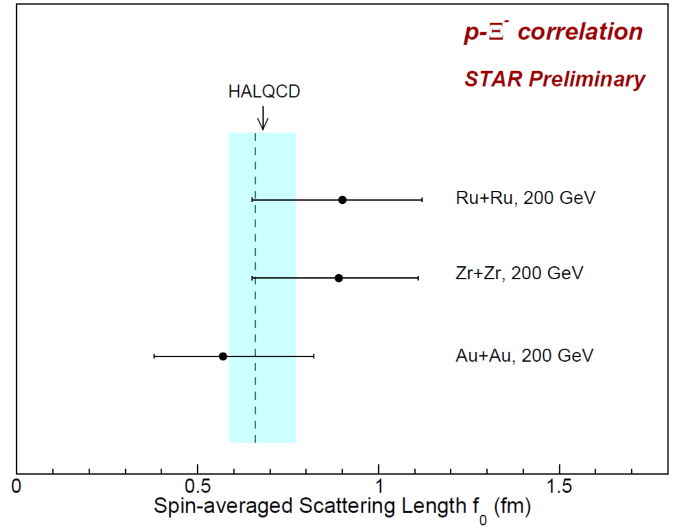
Summary

- ☆ Systematical measurements of p-Ξ^- correlation functions in isobar (Zr+Zr and Ru+Ru) and Au+Au collisions at 200 GeV at STAR

- ☆ The extracted source radii increase as charged multiplicity increase for different collisions

- ☆ **The first experimental measurements of strong interaction parameters (f_0, d_0) in p-Ξ^- pairs**
  - ◎ The f_0 is consistent with HAL QCD predictions within 1σ
  - ◎ Experimental evidence of shallow attractive interaction in p-Ξ^- pairs





Thank you !

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SQM2024, June 5th 2024, Starsbourg

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