



Measurements of p- Λ and d- Λ correlations in 3 GeV Au+Au collisions at STAR

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for the STAR collaboration
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QCD Dense Matter & Nucleon-Nucleon/Hyperon Interactions

INSIDE A NEUTRON STAR

A NASA mission will use X-ray spectroscopy to gather clues about the interior of neutron stars — the Universe's densest forms of matter.

Outer crust

Atomic nuclei, free electrons

Inner crust

Heavier atomic nuclei, free neutrons and electrons

Outer core

Quantum liquid where neutrons, protons and electrons exist in a soup

Inner core

Unknown ultra-dense matter. Neutrons and protons may remain as particles, break down into their constituent quarks, or even become 'hyperons'.

Atmosphere

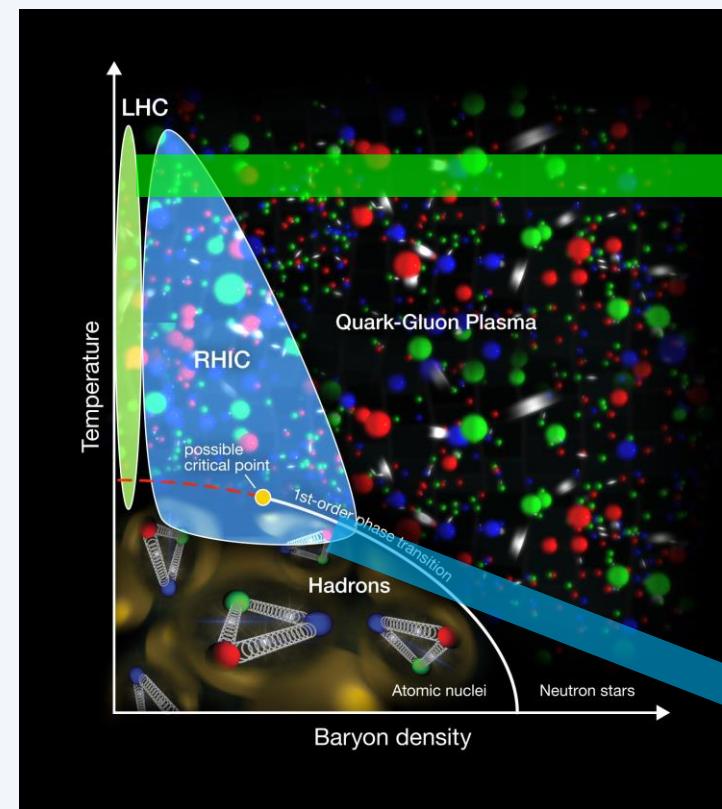
Hydrogen, helium, carbon

Beam of X-rays coming from the neutron star's poles, which sweeps around as the star rotates.

©nature

Credit: Source: Adapted from NASA Goddard SVS
Nature volume 546, page18 (2017)

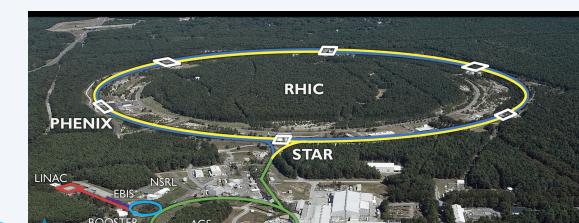
- ❖ Heavy ion collisions – laboratory for dense QCD matter
- ❖ Role of Nucleon-Nucleon (N-N) and Hyperon-Nucleon (Y-N) interactions in the Equation-of-State



<https://www.bnl.gov/newsroom/news.php?a=219079>

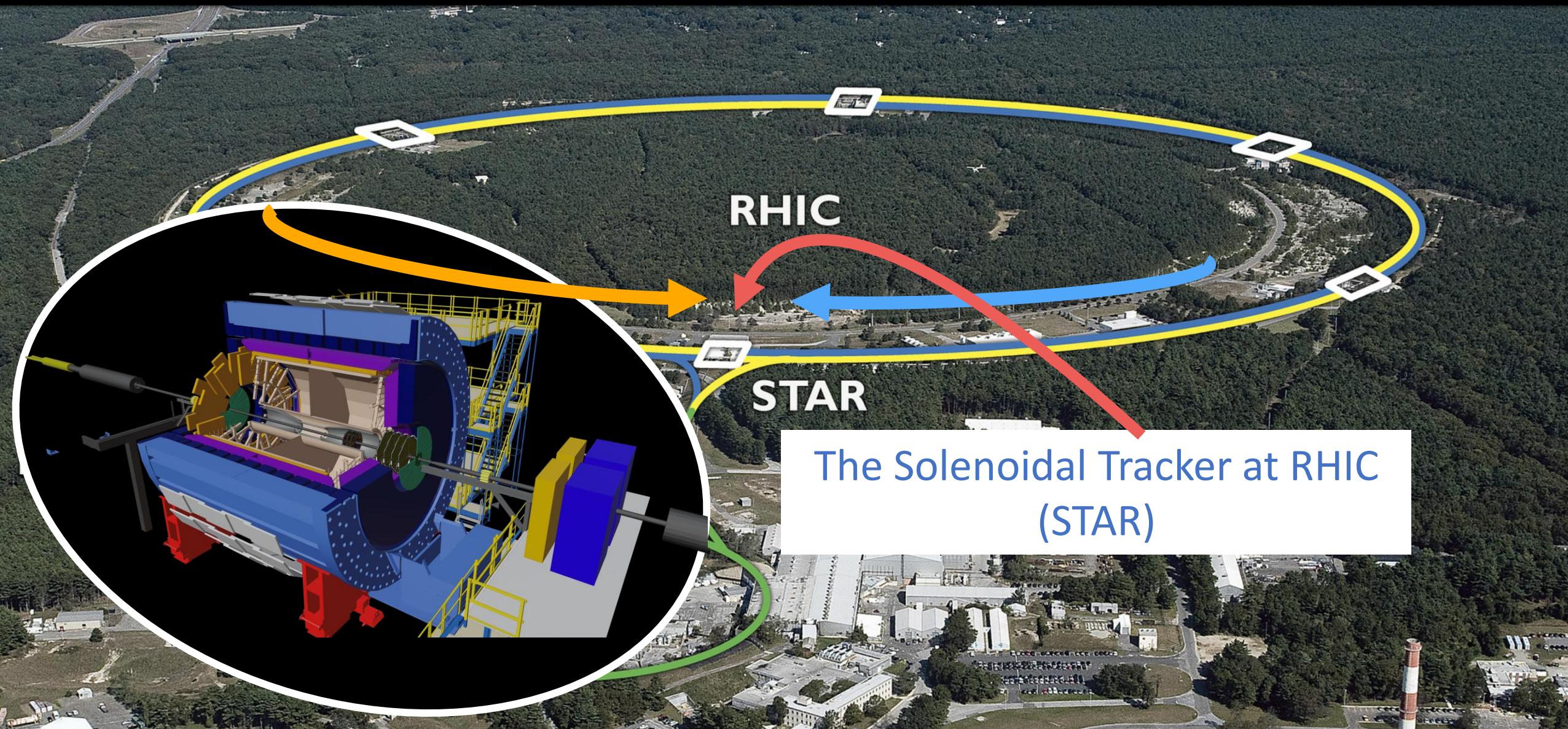


The Large Hadron Collider (LHC)

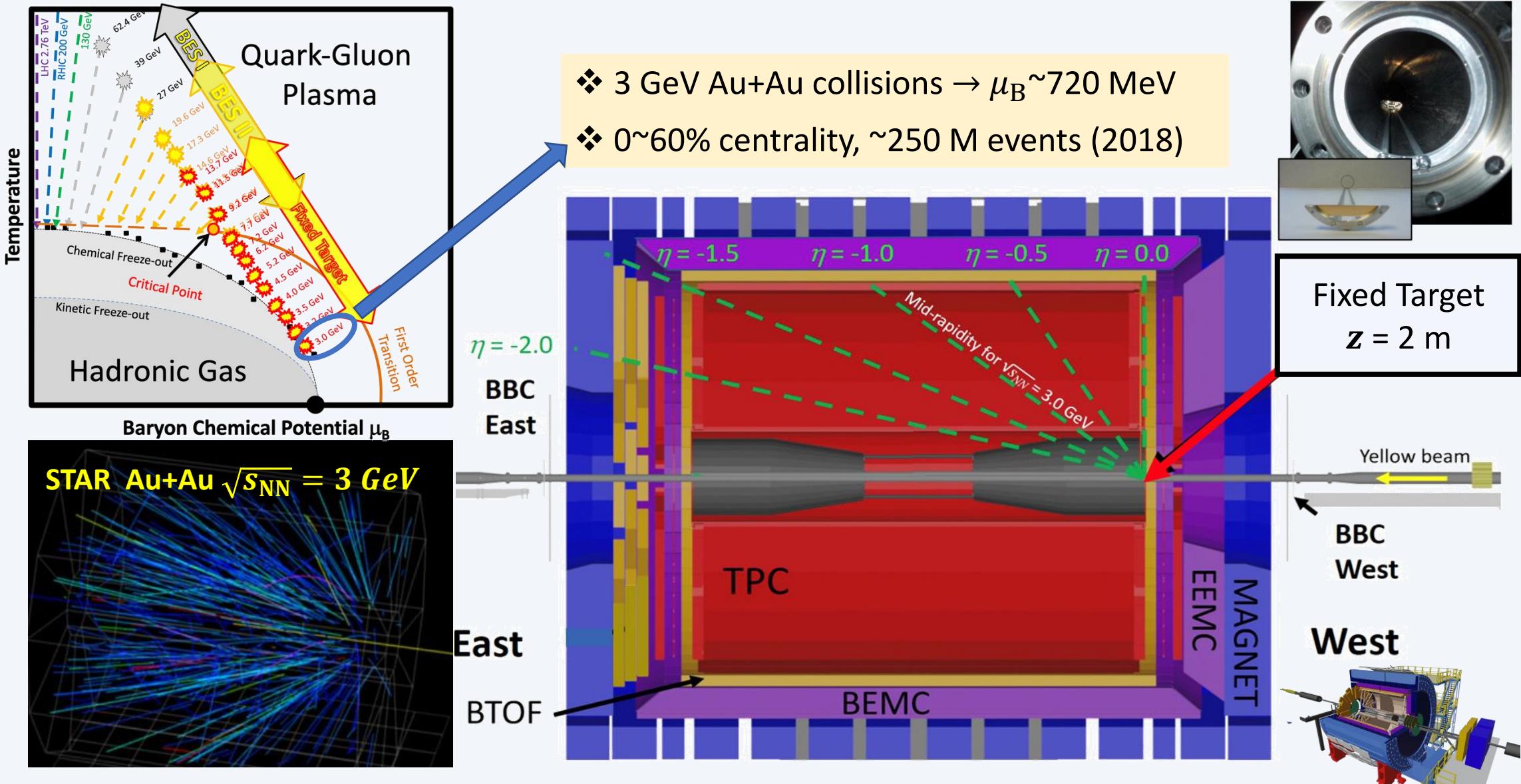


Relativistic Heavy Ion Collider (RHIC)

STAR Detector



Beam Energy Scan – II & Fixed Target Setup



Baryon Correlation Function (CF)

Momentum correlation function:

$$C(\mathbf{p}_1, \mathbf{p}_2) \equiv \frac{P(\mathbf{p}_1, \mathbf{p}_2)}{P(\mathbf{p}_1) \cdot P(\mathbf{p}_2)}$$

Single-particle momentum

Statistical

Approximating the emission process and the momenta of the particles:

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

Modeling

Distribution of the relative distance of particle pair

Relative wave function of the particle pair

Experimental

$$C(k^*) = \mathcal{N} \frac{A(k^*)}{B(k^*)}$$

Signal

Background

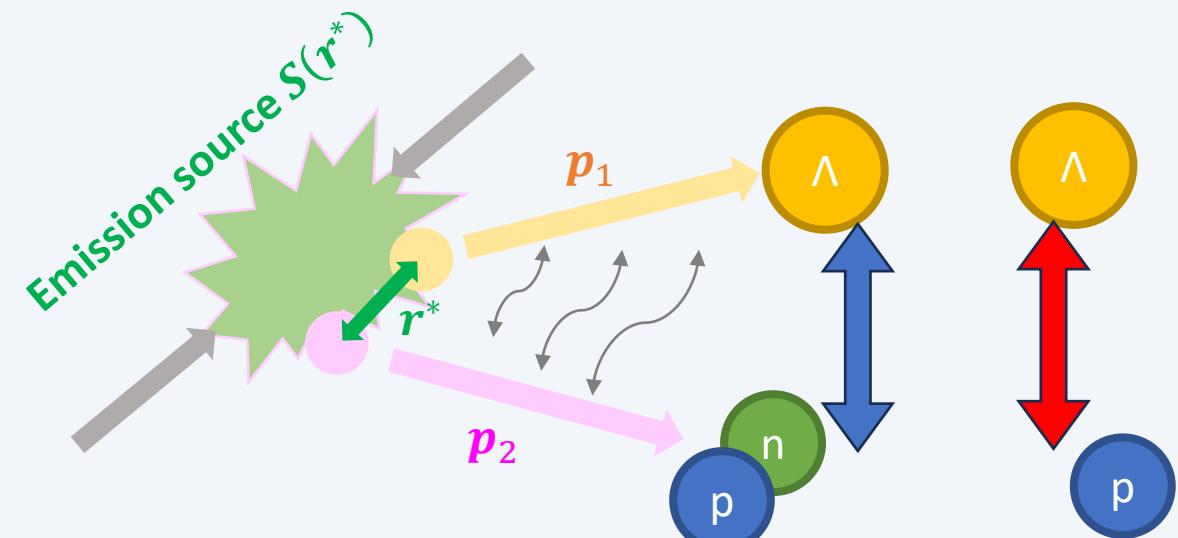
Normalization factor

k^* : particle momentum in the pair rest frame

R. Lednický, 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



❖ Space and time evolution of particle-emitting source

❖ Final state interactions

p- Λ & d- Λ correlations:

N(-N)-Y interactions / hypernuclei structure

Methodology

Experimental

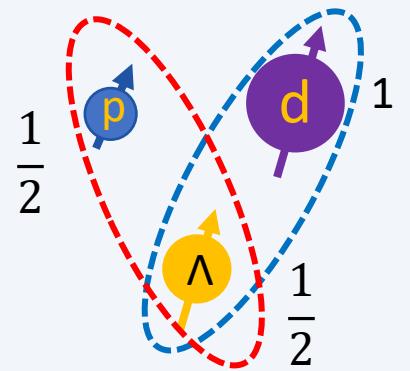
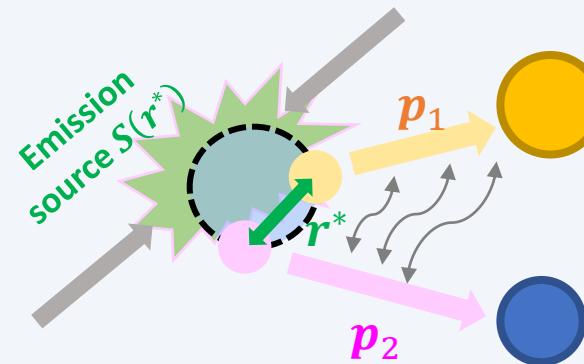
$$C(k^*) = \mathcal{N} \frac{A(k^*)}{B(k^*)}$$

Same events
Mixed events

Normalization factor

Corrections on:

- ❖ Purity
- ❖ Weak decays
- ❖ Track splitting & merging
- ❖ Momentum resolution



| | | |
|---------------|-------------|-----|
| Singlet State | 1S_0 | (S) |
| Triplet State | 3S_1 | (T) |
| Doublet State | $^2S_{1/2}$ | (D) |
| Quartet State | $^4S_{3/2}$ | (Q) |

Physics Image Extraction

Formalism with
Lednicky-Lyuboshitz
(L-L) approach

R_G : spherical Gaussian source of pairs
 f_0 : scattering length
 d_0 : effective range

Major assumptions:

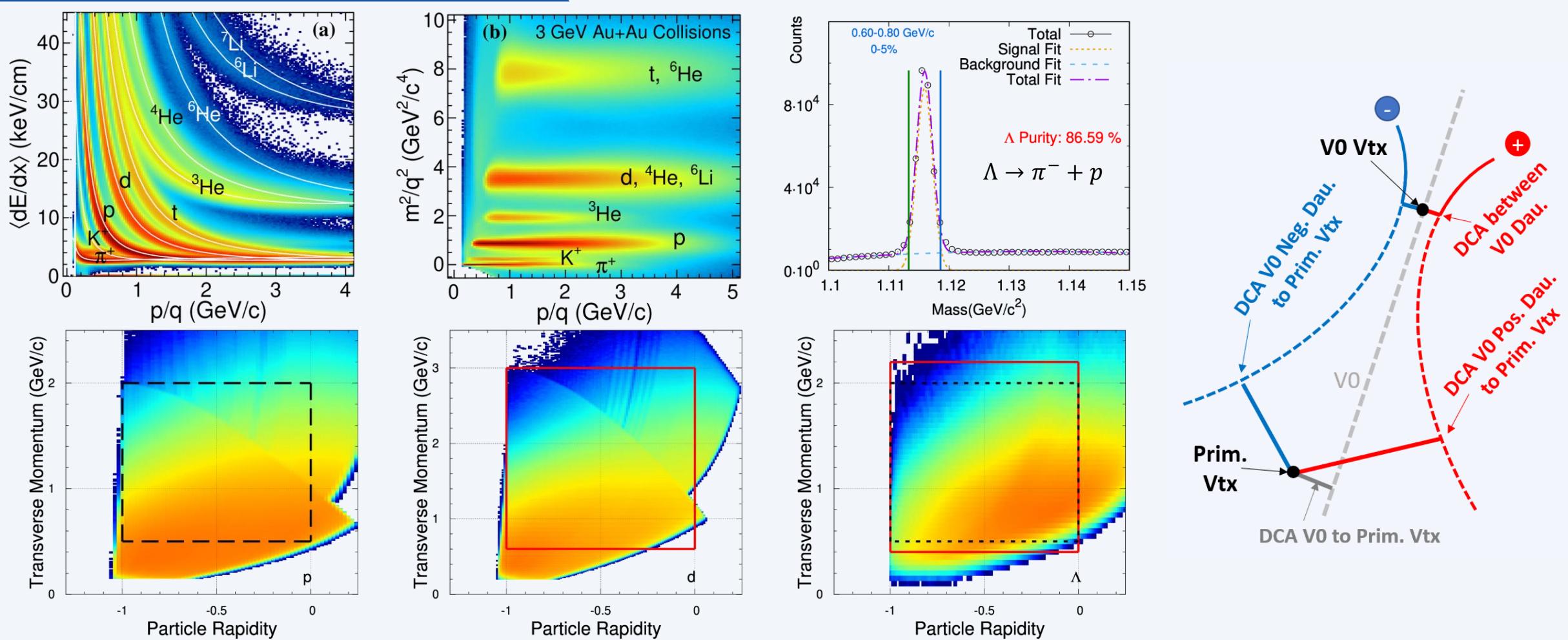
- ❖ Smoothness approximation for source function
- ❖ Effective range expansion for $\Psi(\mathbf{r}^*, \mathbf{k}^*)$
- ❖ Static and spherical Gaussian source
 - Single particle source: $S_i(x_i, p_i^*)$
 - Pair source (radius R_G): $S(x, p^*) \propto e^{-x^2/2R_G^2} \delta(t - t_0)$
- ❖ Approximate the wave function by its asymptotic form

$$C(\mathbf{k}^*) \approx 1 + \frac{|f(k)|^2}{2R_G^2} F(d_0) + \frac{2\text{Re}f(k)}{\sqrt{\pi}R_G} F_1(2kR) - \frac{\text{Im}f(k)}{R_G} F_2(2kR_G)$$

$$\frac{1}{f(k)} \approx \frac{1}{f_0} + \frac{d_0 k^2}{2} - ik$$

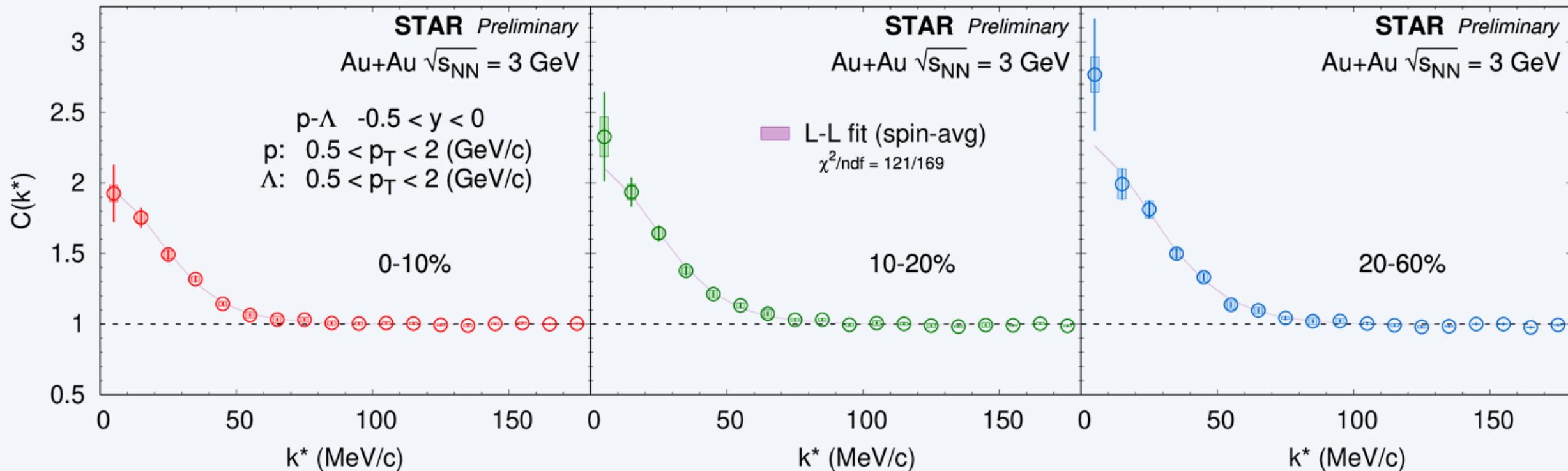
Different f_0 and d_0 for different spin states

Particle Identification & Reconstruction @ 3 GeV



- ❖ π^- , p, and d particles are identified by TPC and TOF
- ❖ A larger acceptance is used in d- Λ correlation measurement (red) due to statistics

p- Λ Correlation Measurement @ STAR



Corrections

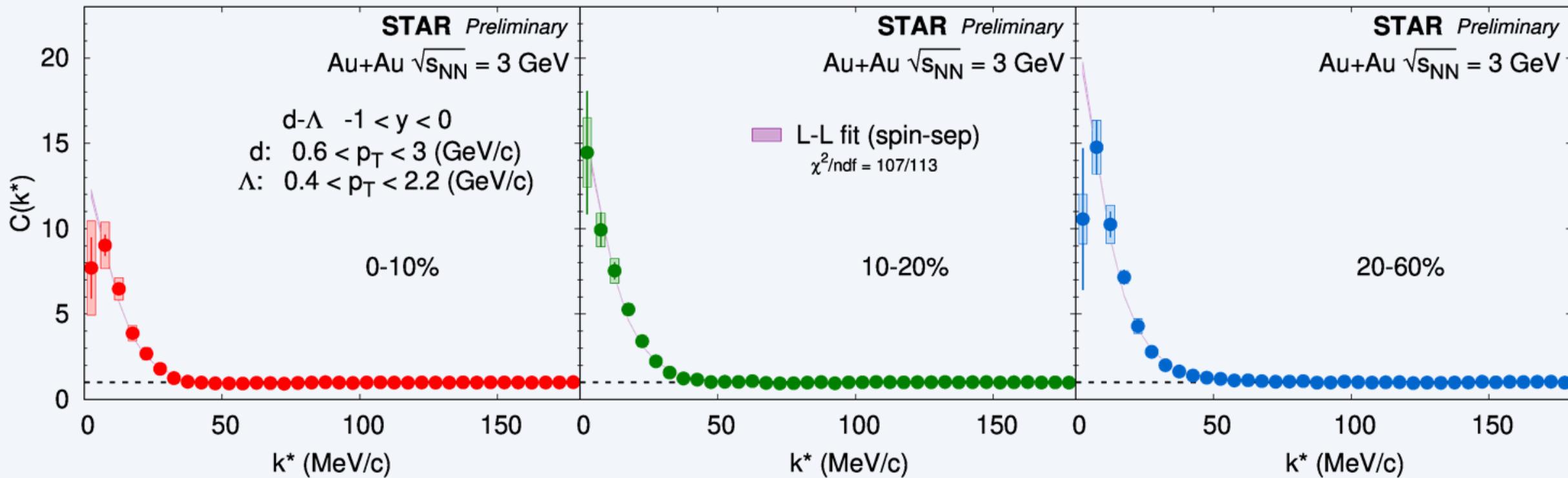
1. Purity correction
2. Λ feed-down correction
3. Track splitting & merging
4. Momentum smearing effect

- ❖ Simultaneous fit to data in different centralities/rapidity
 - ❖ R_G^i , spin-avg f_0 and d_0 with Lednicky-Lyuboshitz approach
- ❖ Spin-avg scattering length (f_0) and effective range (d_0):

$$f_0 = 2.32^{+0.12}_{-0.11} \text{ fm}$$

$$d_0 = 3.5^{+2.7}_{-1.3} \text{ fm}$$

d- Λ Correlation Measurement @ STAR



Corrections

1. Purity correction
2. Track splitting & merging

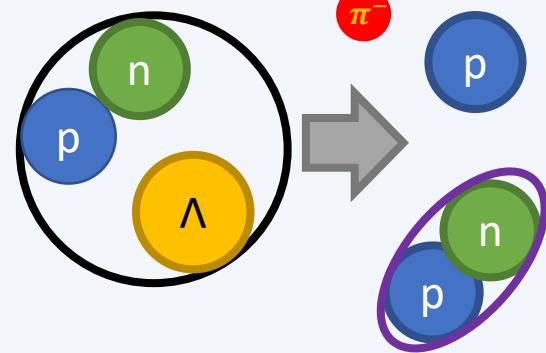
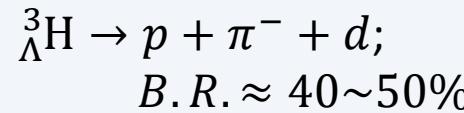
3. Contamination from
 ${}^3\text{H} \rightarrow \pi^- + p + d$ decay

Details in the next page

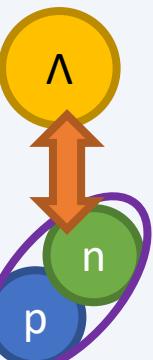
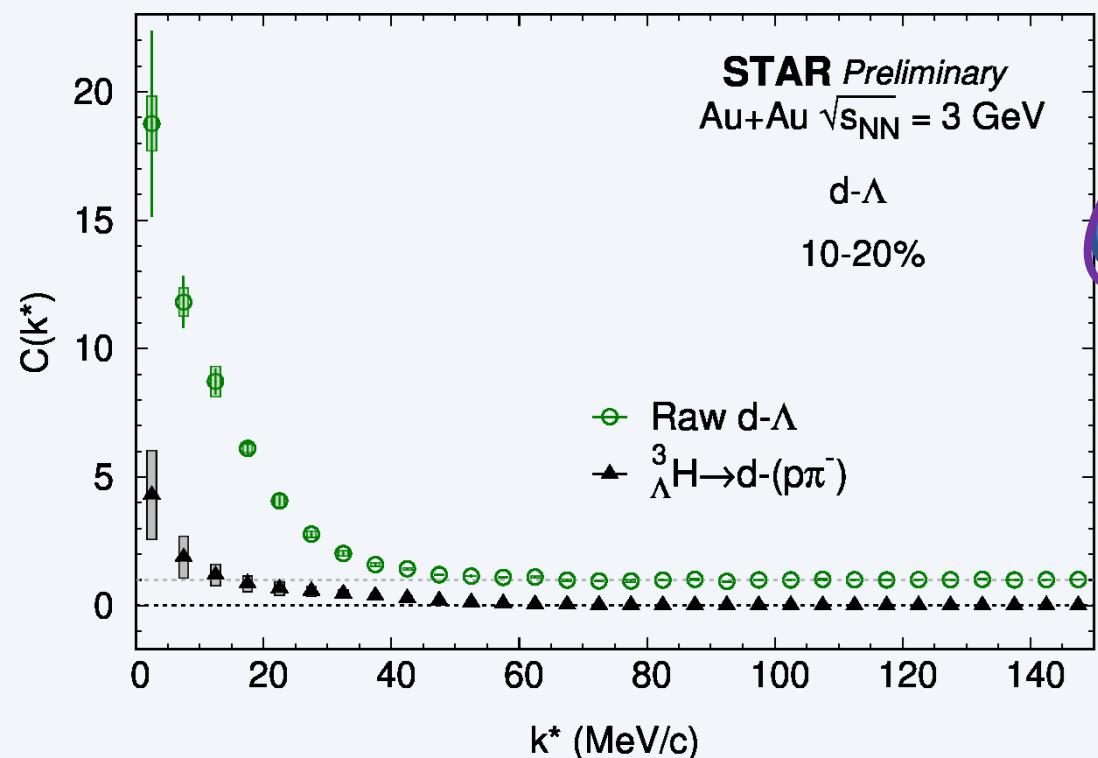
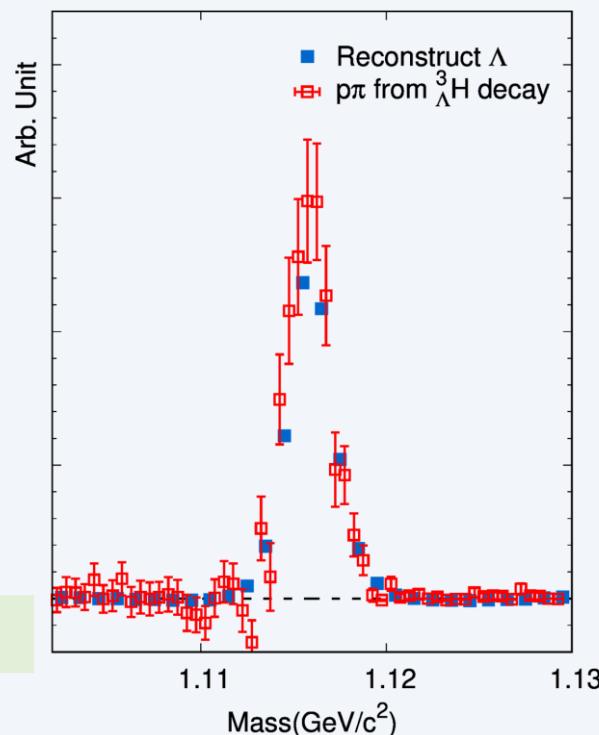
- ❖ First d- Λ correlation measurements in the heavy-ion collision experiment
 - ❖ Simultaneous fit to data in different centralities
 - ❖ $R_G^i, f_0(D), d_0(D), f_0(Q)$, and $d_0(Q)$ with Lednicky-Lyuboshitz approach
- | | |
|-----------------------------|---------------------------|
| $f_0(D) = -20^{+3}_{-3}$ fm | $d_0(D) = 3^{+2}_{-1}$ fm |
| $f_0(Q) = 16^{+2}_{-1}$ fm | $d_0(Q) = 2^{+1}_{-1}$ fm |

- ❖ Λ feed-down correction not applied due to unknown d- Σ/Ξ correlation
- ❖ Momentum smearing effect negligible

Contamination Correction from ${}^3_{\Lambda}\text{H} \rightarrow p\pi^- + d$ Decay



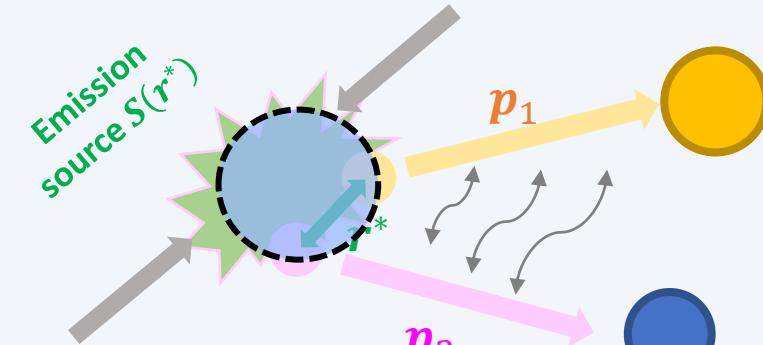
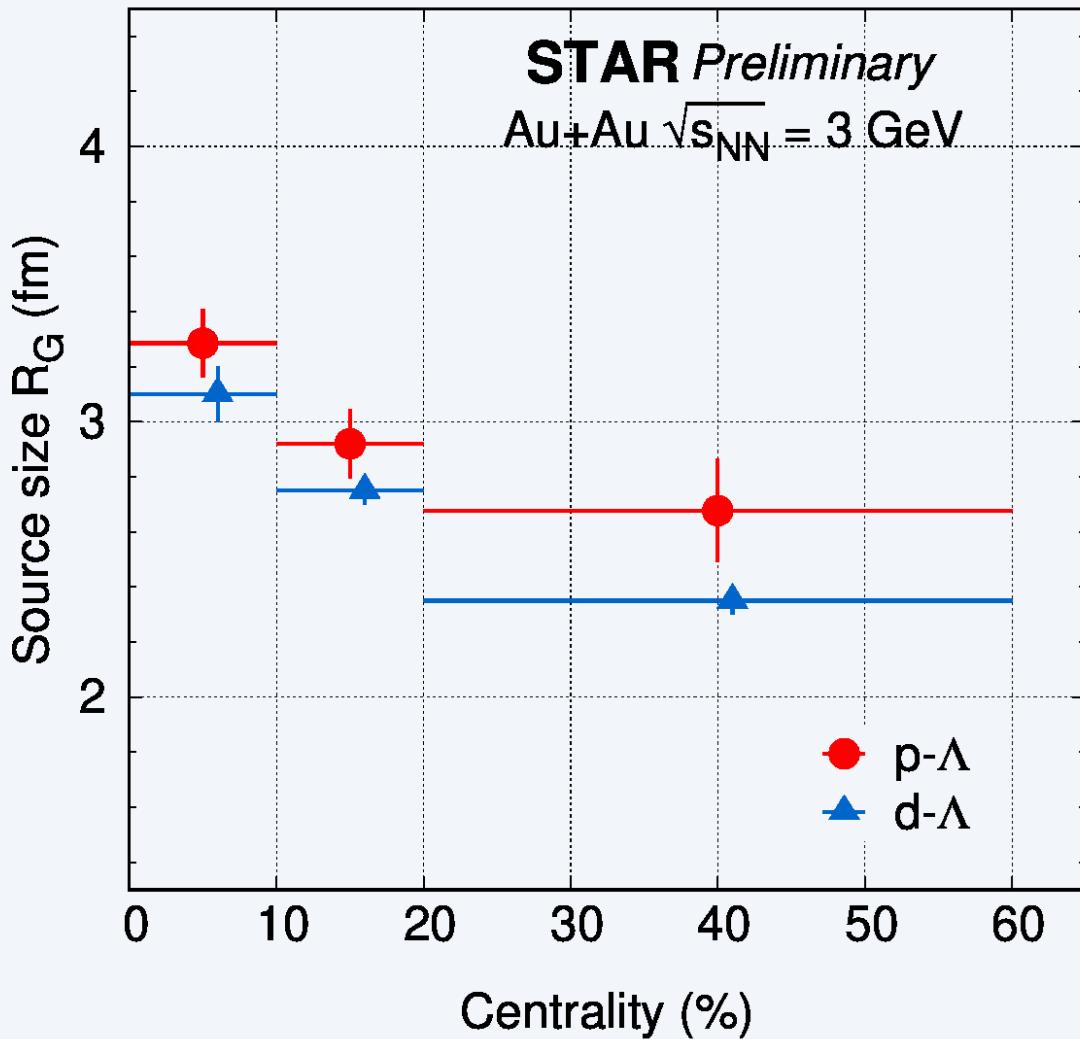
Violation of energy conservation



- ❖ The ${}^3_{\Lambda}\text{H}$ decayed $p + \pi^-$ are **not experimentally distinguishable** with the reconstructed Λ
- ❖ $(p\pi^-) - d$ from ${}^3_{\Lambda}\text{H}$ will affect small k^* region

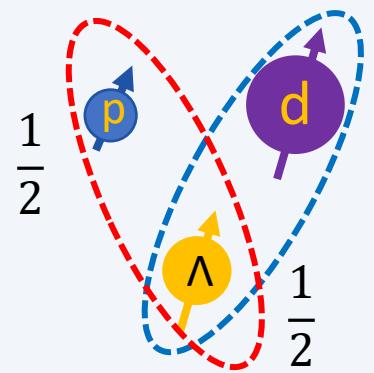
- ❖ Simulation based on STAR ${}^3_{\Lambda}\text{H}$ yield measurement:
4~8% of d- Λ entries from ${}^3_{\Lambda}\text{H}$ decay at $k^* < 100 \text{ MeV}/c$ in 10~20% centrality
- ❖ Contamination subtracted from inclusive d- Λ correlation

Source Size with L-L approach



- ❖ R_G : **spherical Gaussian source of pairs** by Lednicky-Lyuboshits approach
- ❖ Separation of emission source from final state interaction
- ❖ Collision dynamics as expected:
 - ❖ $R_G^{\text{central}} > R_G^{\text{peripheral}}$
 - ❖ $R_G(p - \Lambda) > R_G(d - \Lambda)$

Correlation Function & Spin States

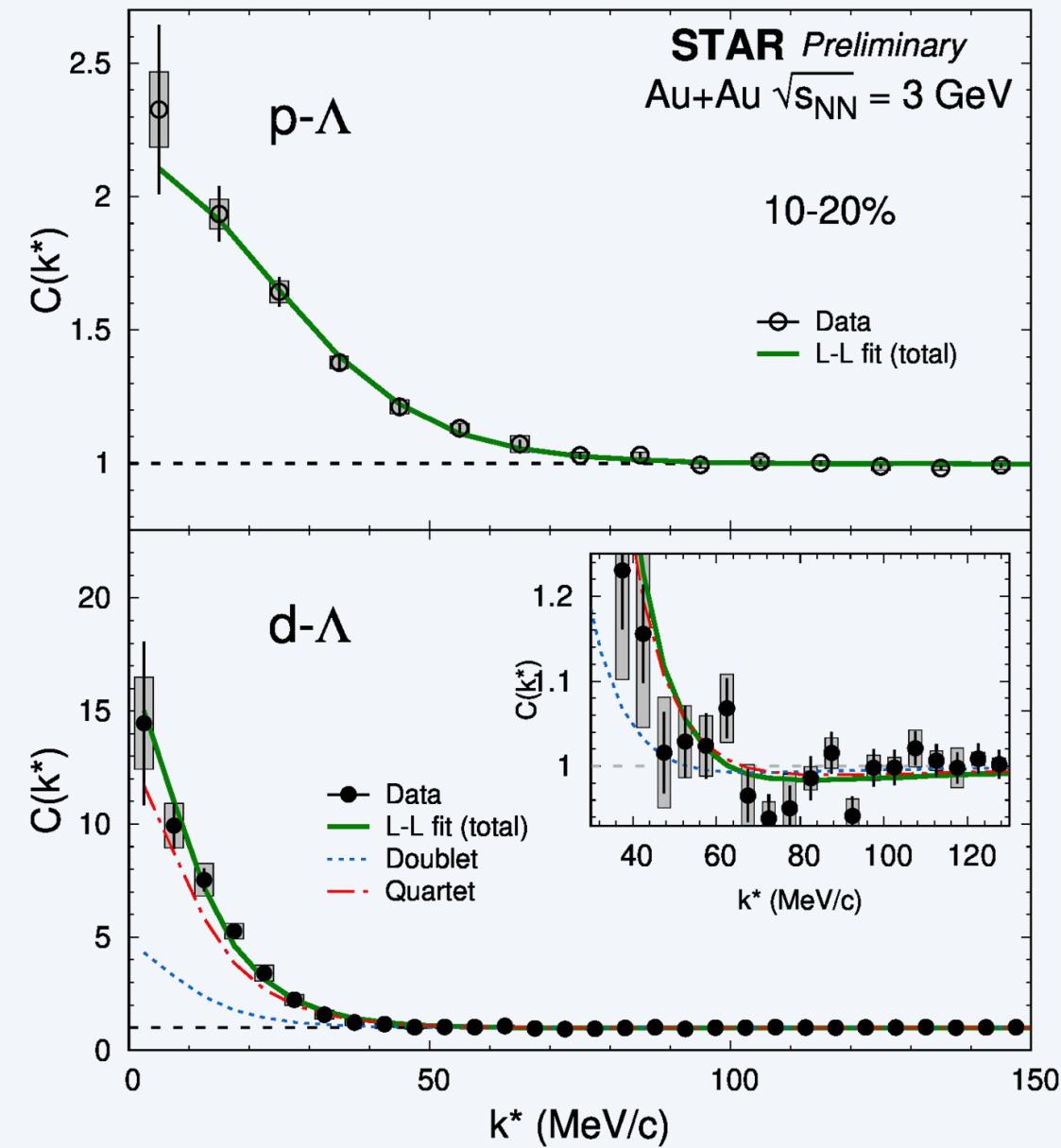


| | | |
|---------------|-------------|-----|
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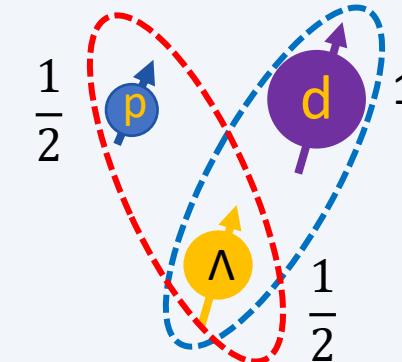
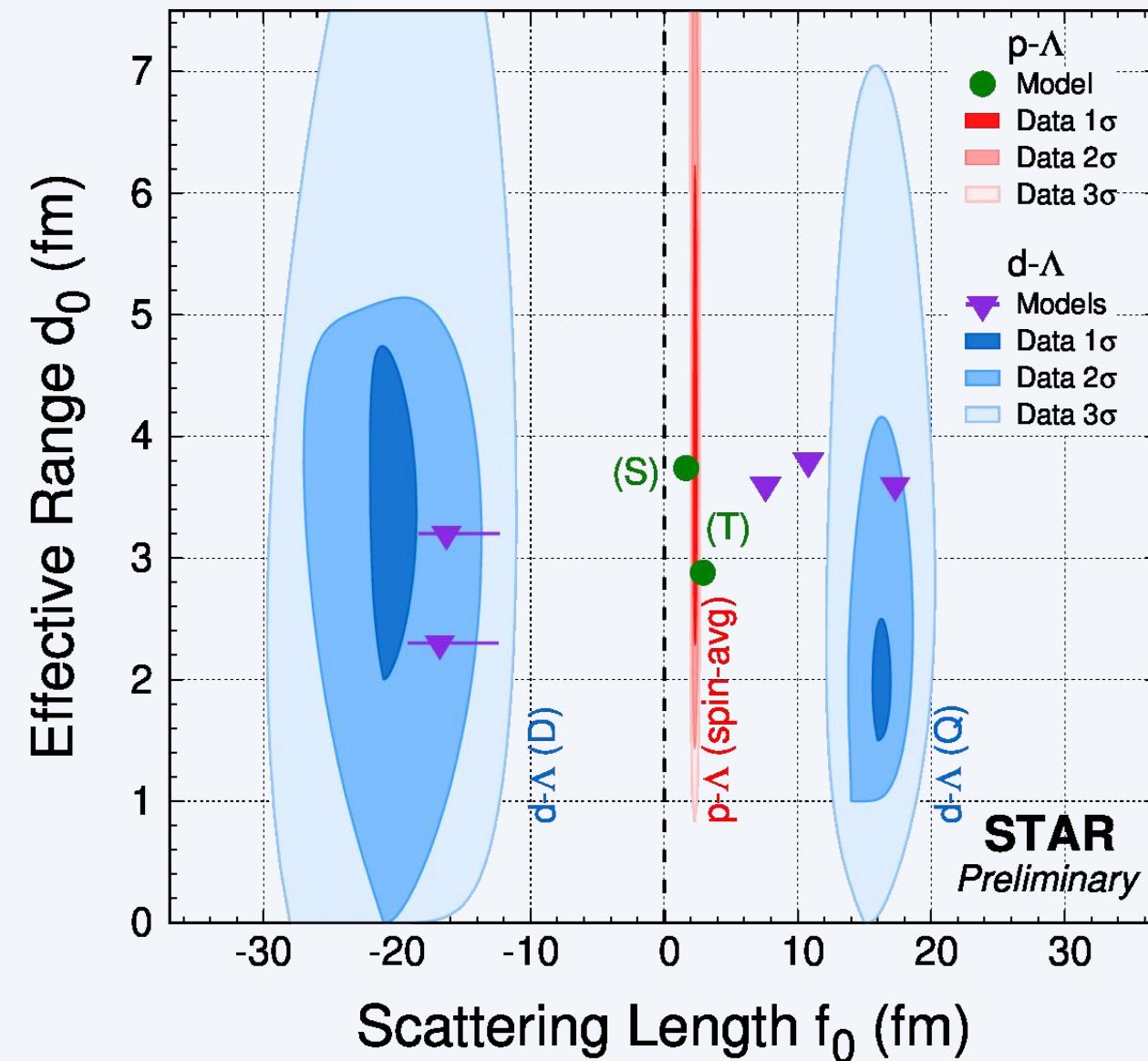
p- Λ : $|\psi(r, k)|^2 \rightarrow \frac{1}{4}|\psi_0(r, k)|^2 + \frac{3}{4}|\psi_1(r, k)|^2$

d- Λ : $|\psi(r, k)|^2 \rightarrow \frac{1}{3}|\psi_{1/2}(r, k)|^2 + \frac{2}{3}|\psi_{3/2}(r, k)|^2$

- Different spin states with different f_0 and d_0 parameters
- p- Λ correlation:** current statistics is not enough to separate two spin states \rightarrow spin-averaged fit
- d- Λ correlation:** very different f_0 for (D) and (Q) are predicted \rightarrow **Spin-separated fit**



Scatterings Length (f_0) and Effective Range (d_0)



$$\frac{1}{f(k)} \approx \frac{1}{f_0} + \frac{d_0 k^2}{2} - ik$$

❖ The constraint of the effective range (d_0) is weaker

- ❖ The measurement is done at freeze-out
- ❖ Spin-avg for f_0 & d_0 p- Λ system

$$f_0 = 2.32^{+0.12}_{-0.11} \text{ fm}$$

$$d_0 = 3.5^{+2.7}_{-1.3} \text{ fm}$$

- ❖ Successfully separate two spin states in d- Λ

$$f_0(\text{D}) = -20^{+3}_{-3} \text{ fm}$$

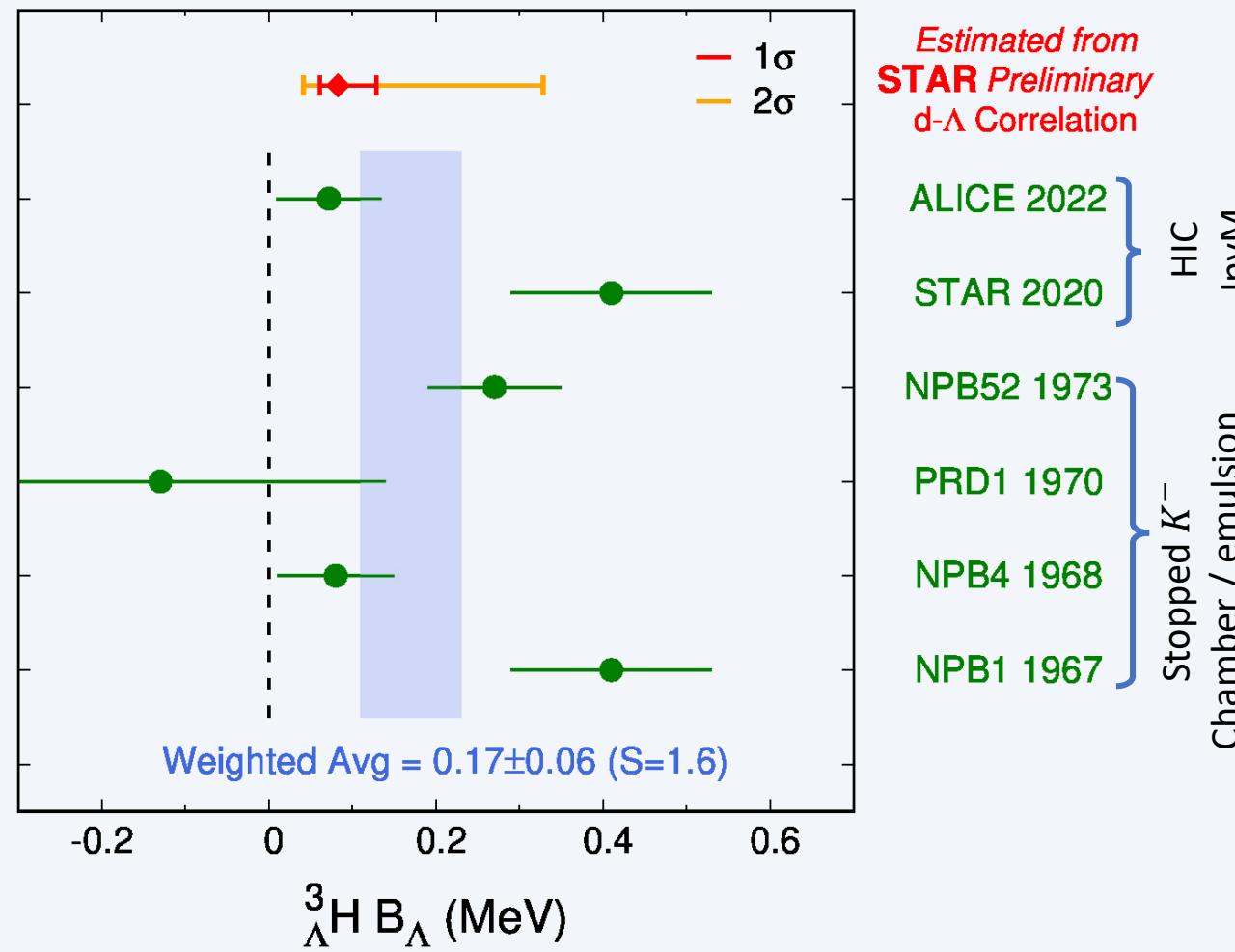
$$d_0(\text{D}) = 3^{+2}_{-1} \text{ fm}$$

$$f_0(\text{Q}) = 16^{+2}_{-1} \text{ fm}$$

$$d_0(\text{Q}) = 2^{+1}_{-1} \text{ fm}$$

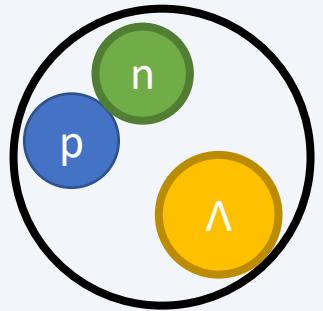
*Edge of d- Λ contours are shown with Bezier smooth to improve the visibility

${}^3_{\Lambda}\text{H}$ Binding Energy



${}^3_{\Lambda}\text{H}$ binding energy (B_{Λ}):

- ❖ Bethe formula from Effective Range Expansion (ERE) parameters $f_0(D)$ & $d_0(D)$



$$\frac{1}{-f_0} = \gamma - \frac{1}{2} d_0 \gamma^2$$

- ❖ $B_{\Lambda} = \frac{\gamma^2}{2\mu_{d\Lambda}}$
- ❖ $\mu_{d\Lambda}$: reduced mass
- ❖ γ : binding momentum

- ❖ ${}^3_{\Lambda}\text{H} B_{\Lambda} = [0.04, 0.33]$ (MeV) @ 95% CL
 - Consistent with the world average
 - ❖ A new way to constrain the ${}^3_{\Lambda}\text{H}$ structure

Summary and outlook

- ❖ The first d- Λ correlation function measurements in heavy-ion collisions
- ❖ New p- Λ correlation function measurements with 3 GeV Au+Au collisions
- ❖ Successfully separated emission source size from final state interactions in p- Λ & d- Λ correlation functions

1. $R_G^{\text{central}} > R_G^{\text{peripheral}}$ and $R_G(p - \Lambda) > R_G(d - \Lambda)$
2. p- Λ correlation spin-ave:

$$f_0 = 2.32^{+0.12}_{-0.11} \text{ fm}$$

$$d_0 = 3.5^{+2.7}_{-1.3} \text{ fm}$$

3. d- Λ correlation spin-sep:

$$f_0(D) = -20^{+3}_{-3} \text{ fm}$$

$$d_0(D) = 3^{+2}_{-1} \text{ fm}$$

$$f_0(Q) = 16^{+2}_{-1} \text{ fm}$$

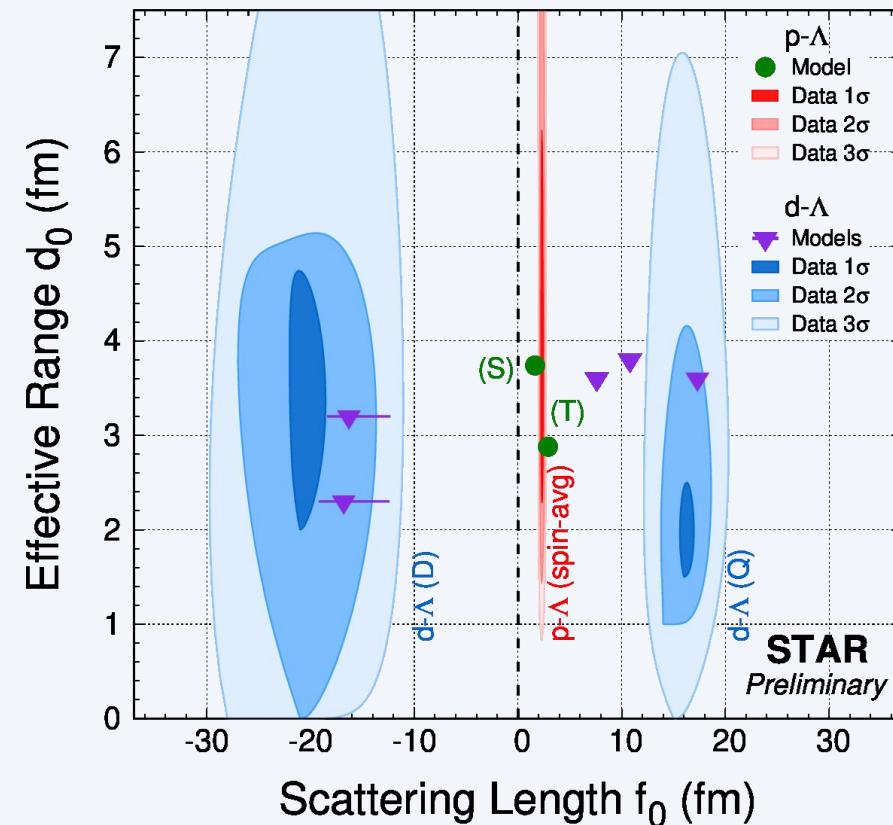
$$d_0(Q) = 2^{+1}_{-1} \text{ fm}$$

4. ${}^3\text{H} B_\Lambda = [0.04, 0.33] \text{ (MeV)}$ @ 95% CL from d- Λ correlation (D)

Outlook:

More than 10 times statistics from BES-II

- ❖ Emission source size vs. energy, rapidity...
- ❖ Baryon correlations with different species





Thank you!



Catania (Italy), November 6-10, 2023

2023.11.10



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