Measurements of d-Λ correlations from STAR

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for the STAR collaboration

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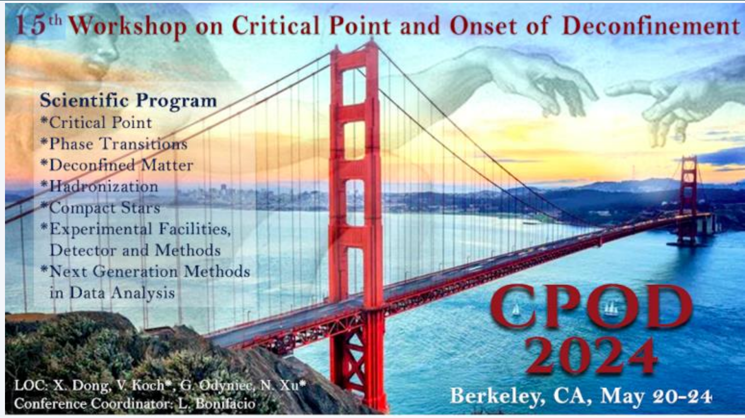


STAR

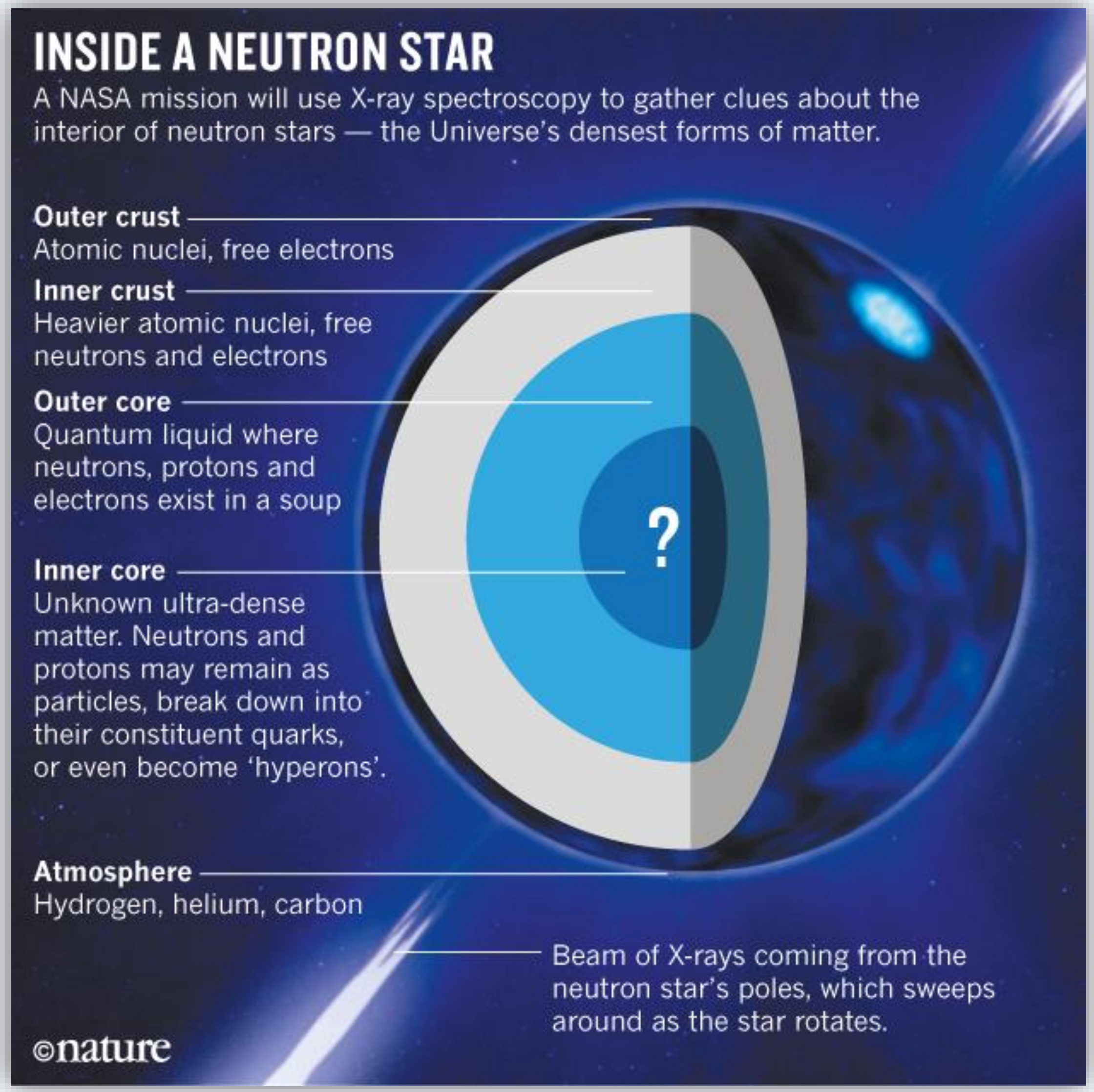
Supported in part by U.S. DEPARTMENT OF ENERGY

2024.05.22

Outlines

- Introductions & Lednicky-Lyuboshitz (L-L) approach
- Particle identification
- p-Λ & d-Λ correlation function
  - Source size with L-L approach
  - Correlation function & spin states
  - Scatterings length (f_0) and effective range (d_0)
  - Λ separation energy of ${}^{3}_{\Lambda}\mathrm{H}$
- Summary & Outlooks

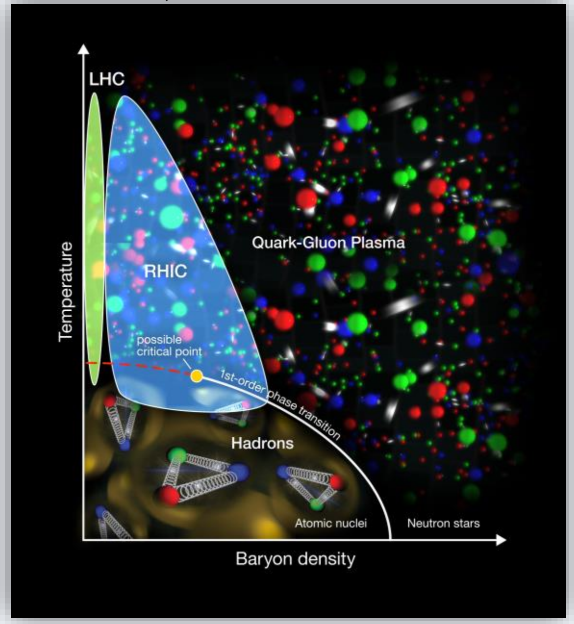
QCD Dense Matter & Nucleon-Nucleon/Hyperon Interactions



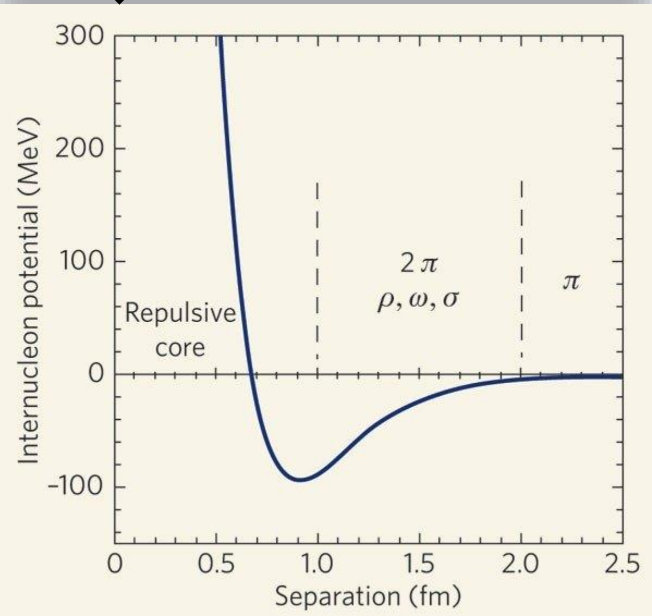
Credit: Source: Adapted from NASA Goddard SVS
Nature volume 546, page18 (2017)

State of Matters → **Interaction of Matters**

Phase diagram



Nuclear potential



- ❖ Structure of nuclear and hyper-nuclei 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
https://www.quora.com/What-does-the-potential-function-for-the-strong-nuclear-force-look-like

Low–E scattering experiment & Effective Range Expansion

Low energy elastic scatterings:

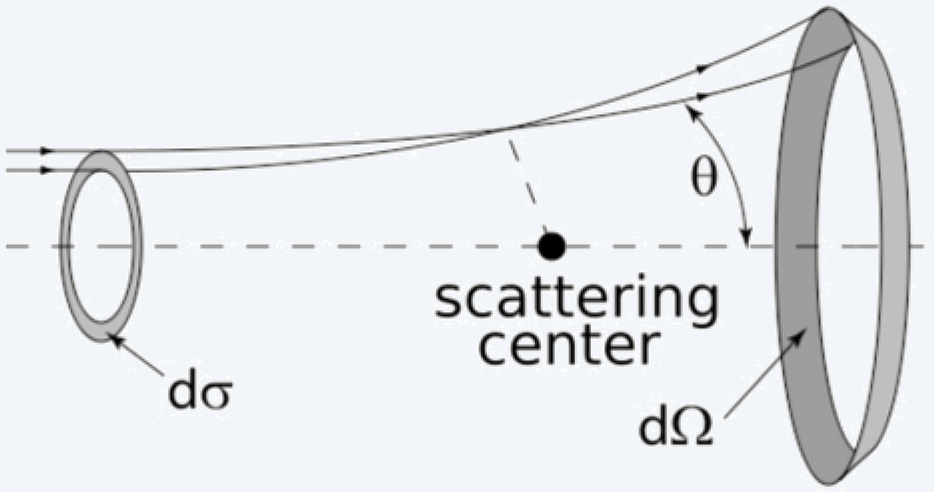
$$k\cot\big(\delta(k)\big) = -\frac{1}{a} + \frac{1}{2} r_0 k^2 + O(k^4)$$

$\delta(k)$: phase shift

a: Fermi scattering length at zero energy

r_0: effective range

O: higher order contribution



H. A. Bethe, Phy. Rev. 76 (1949) 38

Cross section:

$$\lim_{k\to 0} \sigma_e = 4\pi a^2$$

Binding energy:

$$\frac{1}{a} = \gamma - \frac{1}{2} r_0 \gamma^2$$

- $\mathrm{B} = \frac{\gamma^2}{2\mu}$
- μ: reduced mass
- γ: binding momentum

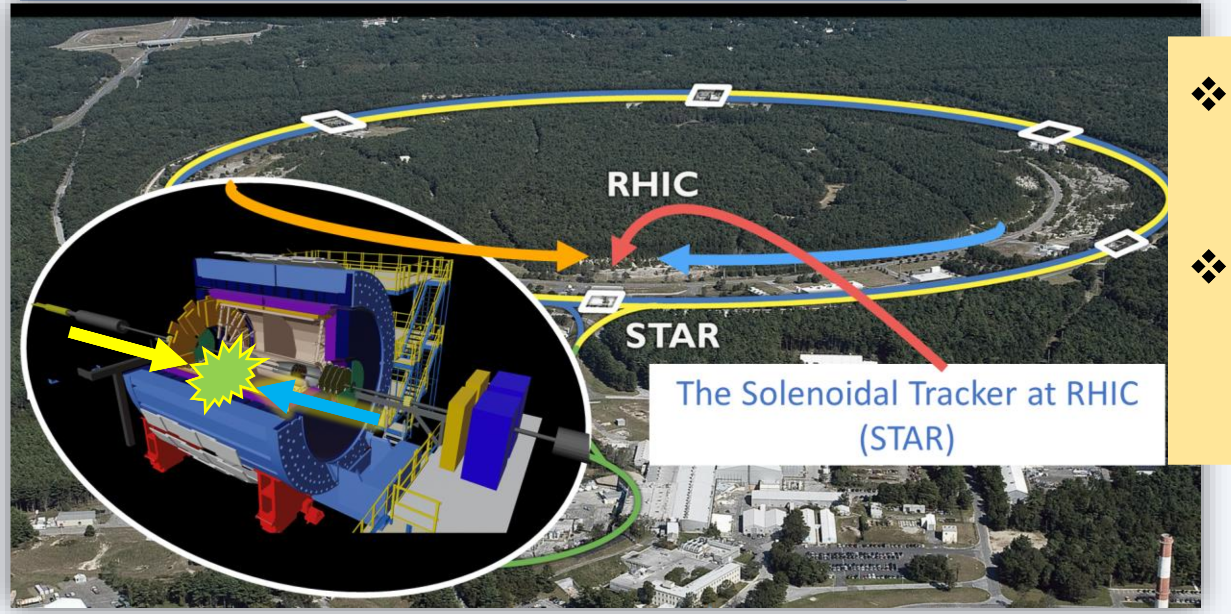
For the n-p scattering:

S_0:	$a = -23.714$ fm	$r_0 = 2.73$ fm
S_1:	$a = 5.425$ fm	$r_0 = 1.749$ fm

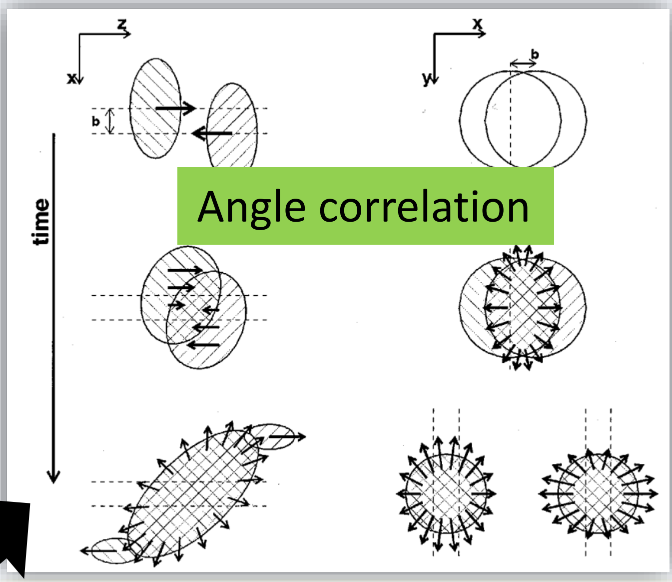
→ $\mathrm{B_d} = 2.2$ MeV

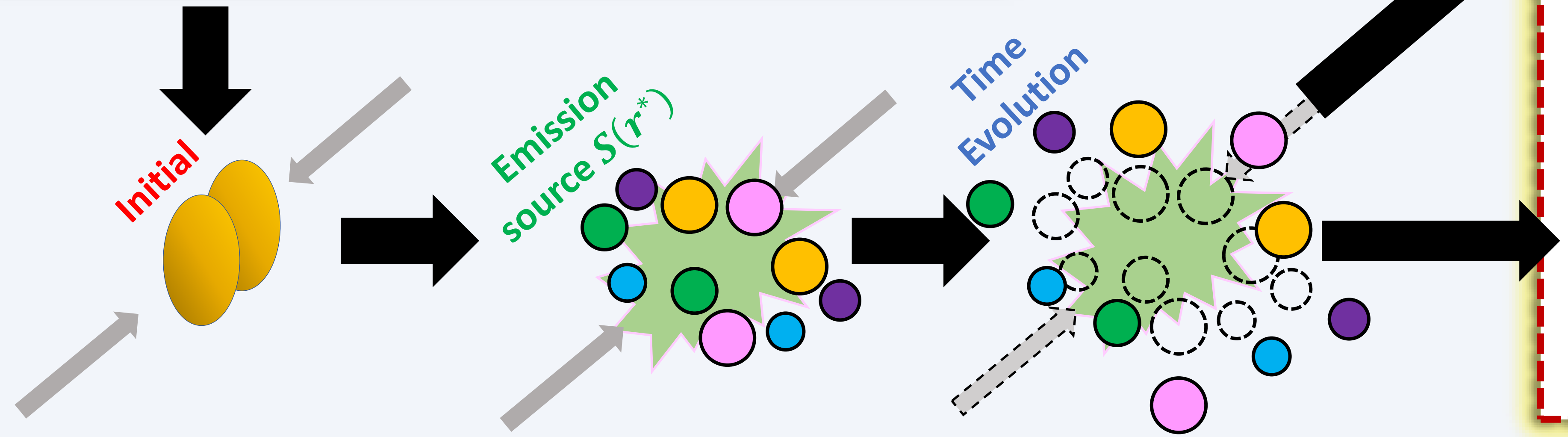
Heavy Ion Collision Experiment

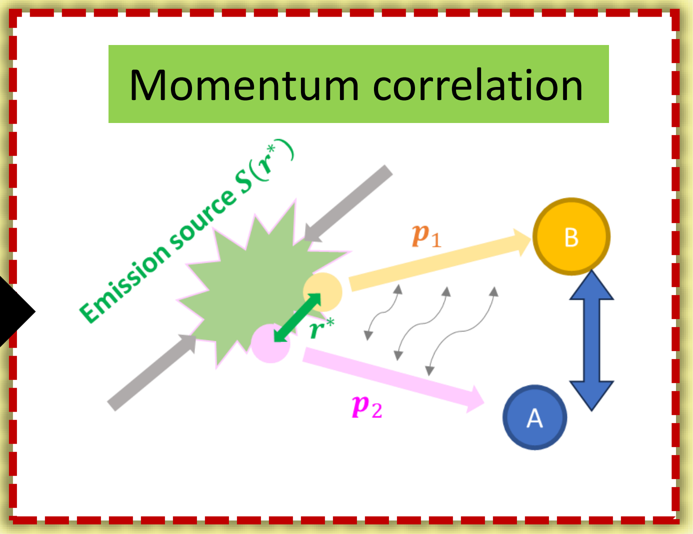
Annu. Rev. Nucl. Part. Sci. 1999.



- Space and time evolution of particle-emitting source
- Final state interactions
  - N(-N)-Y interactions
  - hypernuclei structure







Baryon Correlation Function (CF)

Statistical

Momentum correlation function:

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

Single-particle momentum

Experimental

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

$A(k^*)$: Same events

$B(k^*)$: Mixed events

$\mathcal{N}$: Normalization factor

k^*: particle momentum in the pair rest frame

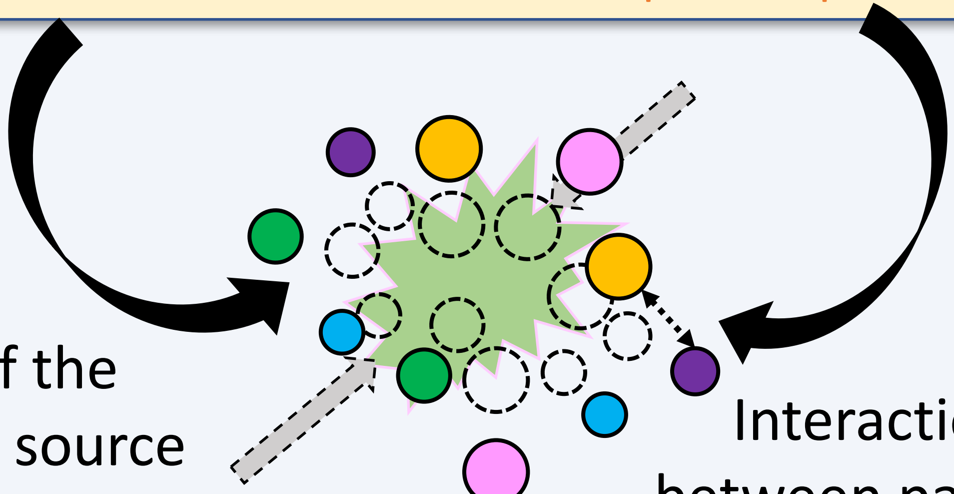
Modeling

Approximating the emission process and the momenta of the particles:

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

$S(\boldsymbol{r}^*)$: Distribution of the relative distance of particle pair

$|\Psi(\boldsymbol{r}^*, \boldsymbol{k}^*)|^2$: Relative wave function of the particle pair



Size of the emitting source

Interactions between particles

Lednicky-Lyuboshitz (L-L) Approach

R. Lednicky, et al. Sov.J.Nucl.Phys. 35 (1982) 770
J. Haidenbauer, Phys.Rev.C 102 (2020) 3, 034001
L. Fabbietti, et al., Ann.Rev.Nucl.Part.Sci. 71 (2021) 377-402
Michael Annan Lisa, et al., Ann.Rev.Nucl.Part.Sci. 55 (2005) 357-402

Modeling

Approximating the emission process and the momenta of the particles:

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

Distribution of the relative distance of particle pair — Relative wave function of the particle pair

Major Assumptions

Source

- ❖ Smoothness approximation for source function*
- ❖ Static and spherical Gaussian source
  - Single particle source: $S_i(x_i, p_i^*)$
  - Pair source (radius R_G): $S(x, p^*) \propto e^{-x^2/2R_G{}^2}\delta(t - t_0)$

Wave function

- ❖ S-wave scattering wave
- ❖ Effective range expansion for $\Psi(\boldsymbol{r}^*, \boldsymbol{k}^*)$
- ❖ Approximate the wave function by its asymptotic form

Gaussian source approximation:

$$S(\boldsymbol{r}^*) = (2\sqrt{\pi}R_G)^{-3} e^{-\boldsymbol{r}^{*2}/4R_G^2}$$

Scattering amplitude:

Consider only S-wave $\Psi(r^*) = e^{-i\boldsymbol{r}^*\cdot\boldsymbol{k}^*} + \frac{f(\boldsymbol{k}^*)}{\boldsymbol{r}^*} e^{i\boldsymbol{r}^*\cdot\boldsymbol{k}^*}$

$$f(\boldsymbol{k}^*) \approx \left(\frac{1}{\boldsymbol{f_0}} + \frac{\boldsymbol{d_0}\boldsymbol{k}^{*2}}{2} - i\boldsymbol{k}^*\right)^{-1}$$

Scattering length: $a \to -f_0$
Effective range: $r_0 \to d_0$

Lednicky-Lyuboshitz (L-L) approach

R_G : spherical Gaussian source of pairs

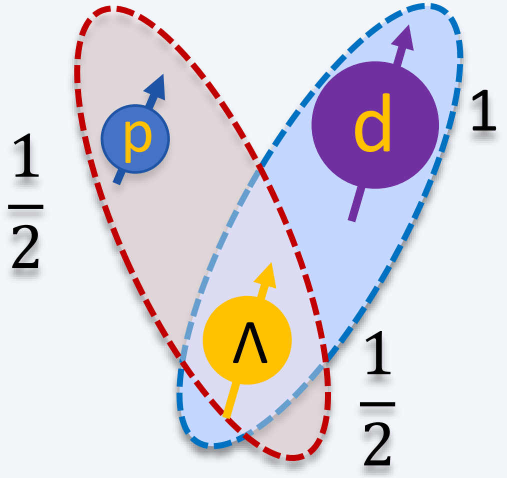
f_0 : scattering length

d_0 : effective range

*The smoothness approximation has been checked for expanding thermal sources, found to be very reasonable for large (RHIC-like) sources, but still questionable for smaller sources

Modeling with Separated Spin States

Singlet State	$^{1}S_0$	(S)
Triplet State	$^{3}S_1$	(T)



Doublet State	$^{2}S_{1/2}$	(D)
Quartet State	$^{4}S_{3/2}$	(Q)

Modeling

Approximating the emission process and the momenta of the particles:

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

Source — $S(\boldsymbol{r}^*)$; Wave function — $|\Psi(\boldsymbol{r}^*, \boldsymbol{k}^*)|^2$

Spin averaged

$|\Psi(\boldsymbol{r}^*, \boldsymbol{k}^*)|^2$ expanded with averaged parameters: $\overline{f_0}$ and $\overline{d_0}$

$$|\Psi(\boldsymbol{r}^*, \boldsymbol{k}^*)|^2 \rightarrow f_{S1}|\Psi_{S1}(\boldsymbol{r}^*, \boldsymbol{k}^*)|^2 + f_{S2}|\Psi_{S2}(\boldsymbol{r}^*, \boldsymbol{k}^*)|^2$$

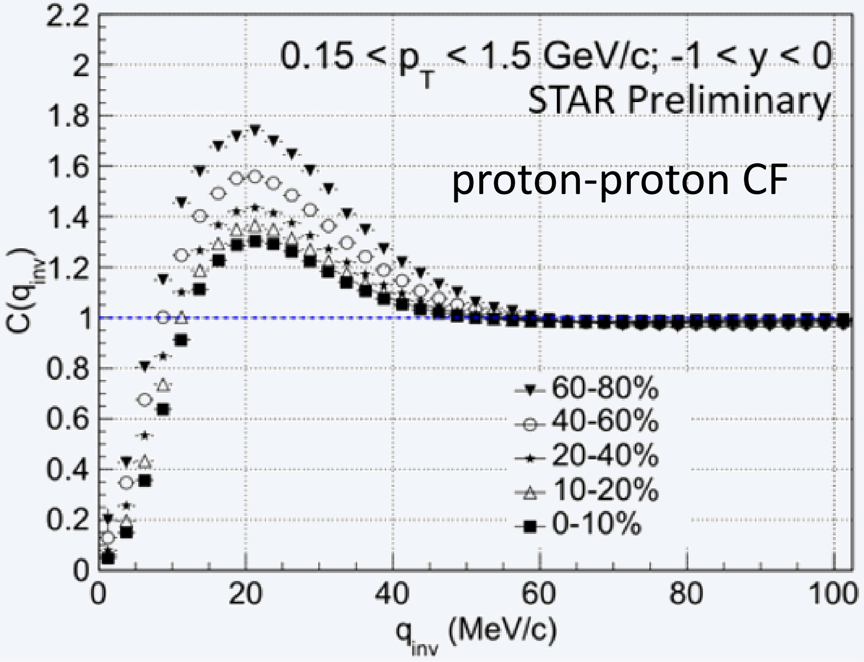
Spin separated

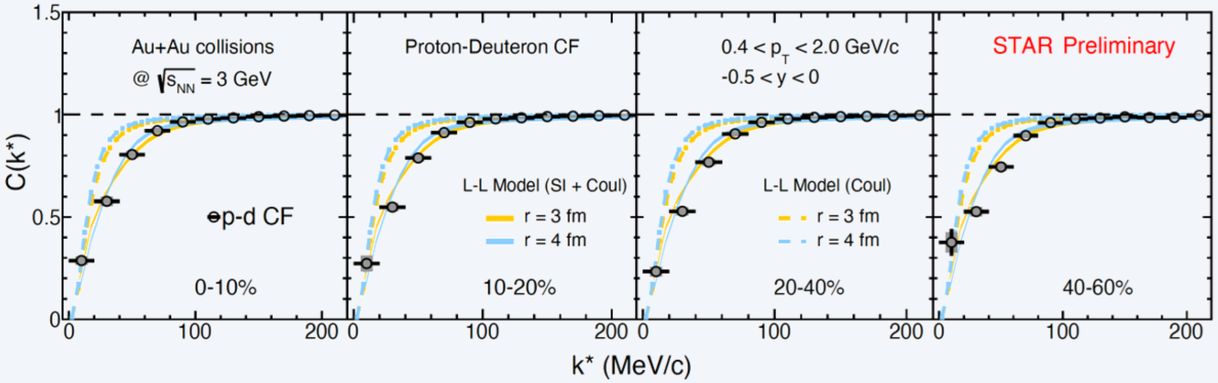
$$C(\boldsymbol{k}^*) = \int d^3r^* S(\boldsymbol{r}^*)\left(\frac{1}{3}\left|\Psi_{1/2}(\boldsymbol{r}^*, \boldsymbol{k}^*)\right|^2 + \frac{2}{3}\left|\Psi_{3/2}(\boldsymbol{r}^*, \boldsymbol{k}^*)\right|^2\right)$$

For separated spin states in d-Λ: $f_0(D)$, $d_0(D)$; $f_0(Q)$, $d_0(Q)$

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

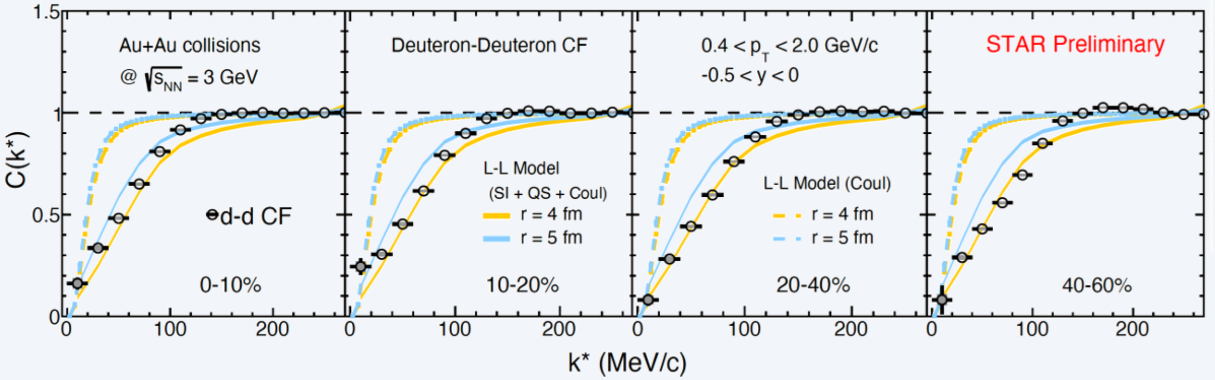
Correlation Function & Low-E Scattering Experiment





Consistent with L-L model with Coulomb + repulsive interaction

Models	p-d	f_0 (fm)	d_0 (fm)	d-d	f_0 (fm)
	Doublet	-2.73	2.27	Singlet	-10.2
	Quartet	-11.88	2.63	Quintet	-7.5



Consistent with L-L model with Coulomb + QS + repulsive interaction

CF & low-E scattering results are consistent

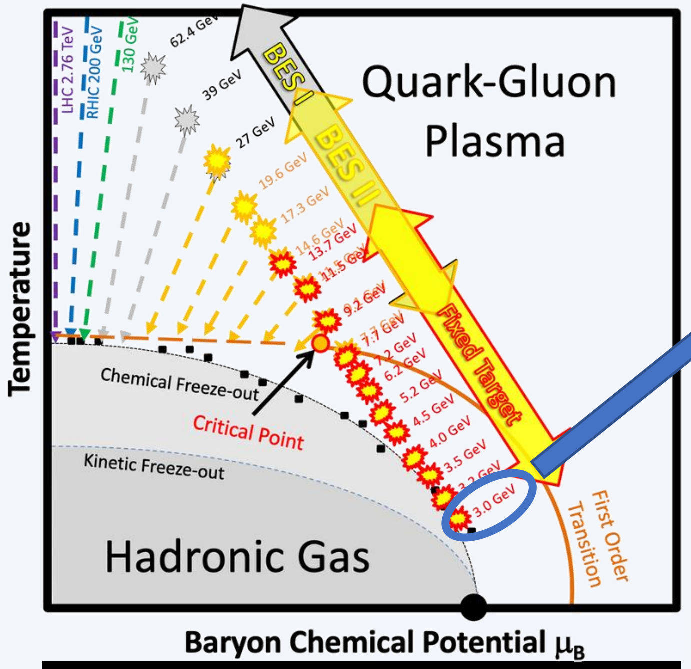
Correlation indicate strong interaction $f_0 \sim 7$ fm
Low-E experiment found $a = -7.806 \pm 0.003$ fm

A valid method to study the interaction between baryons

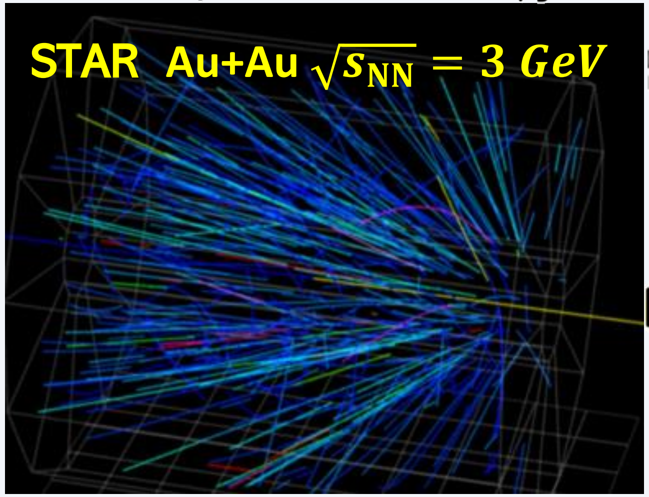
Ongoing studies @ STAR

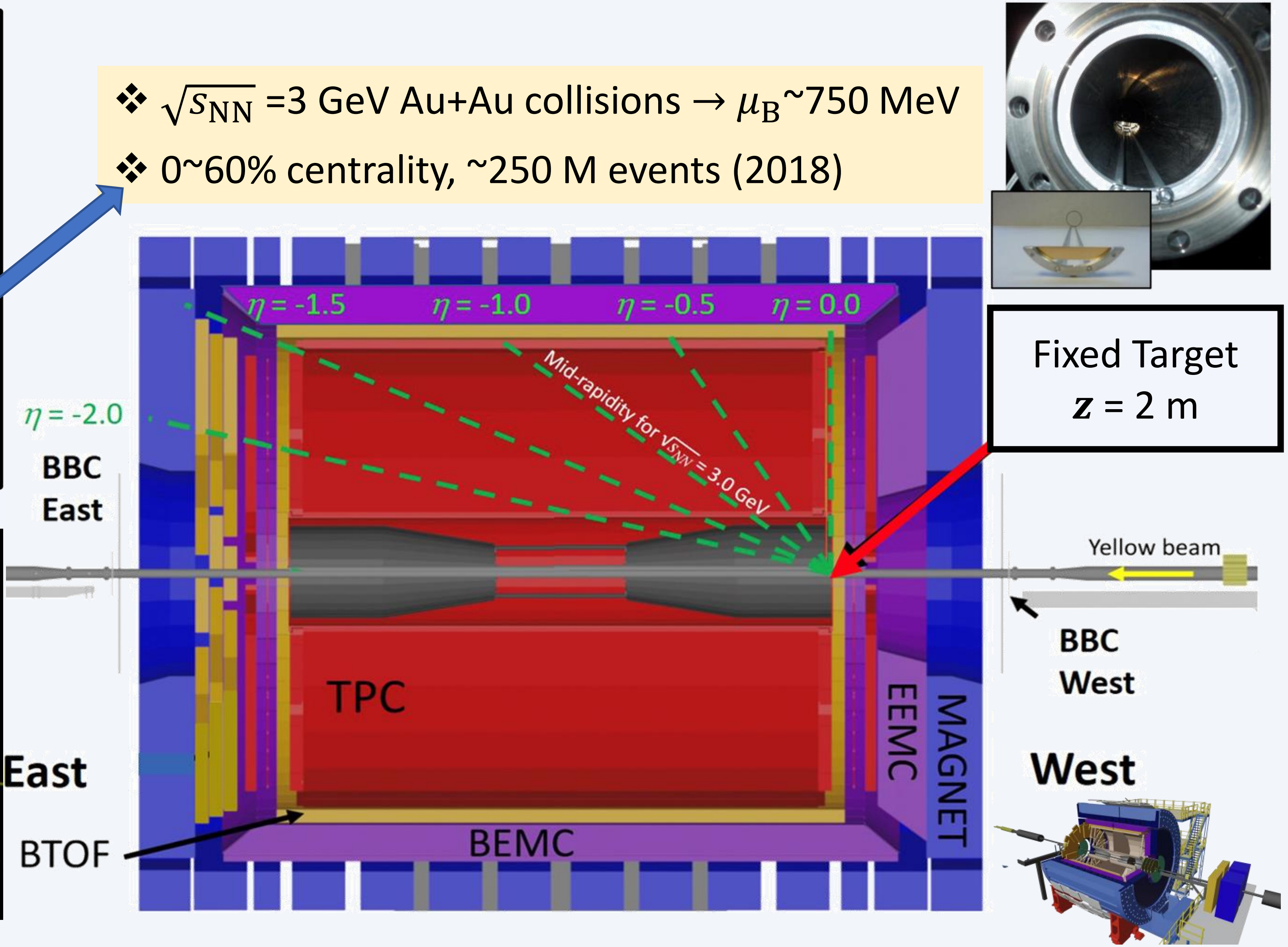
J. Arvieux, NPA 221 (1974) 253
I.N. Filikhin and S.L. Yakovlev, Phys. Atom. Nucl. 63 (2000) 55 / 216
Robert B. Wiringa, et. al, Phys.Rev.C 51 (1995) 38-51

Beam Energy Scan – II & Fixed Target Setup

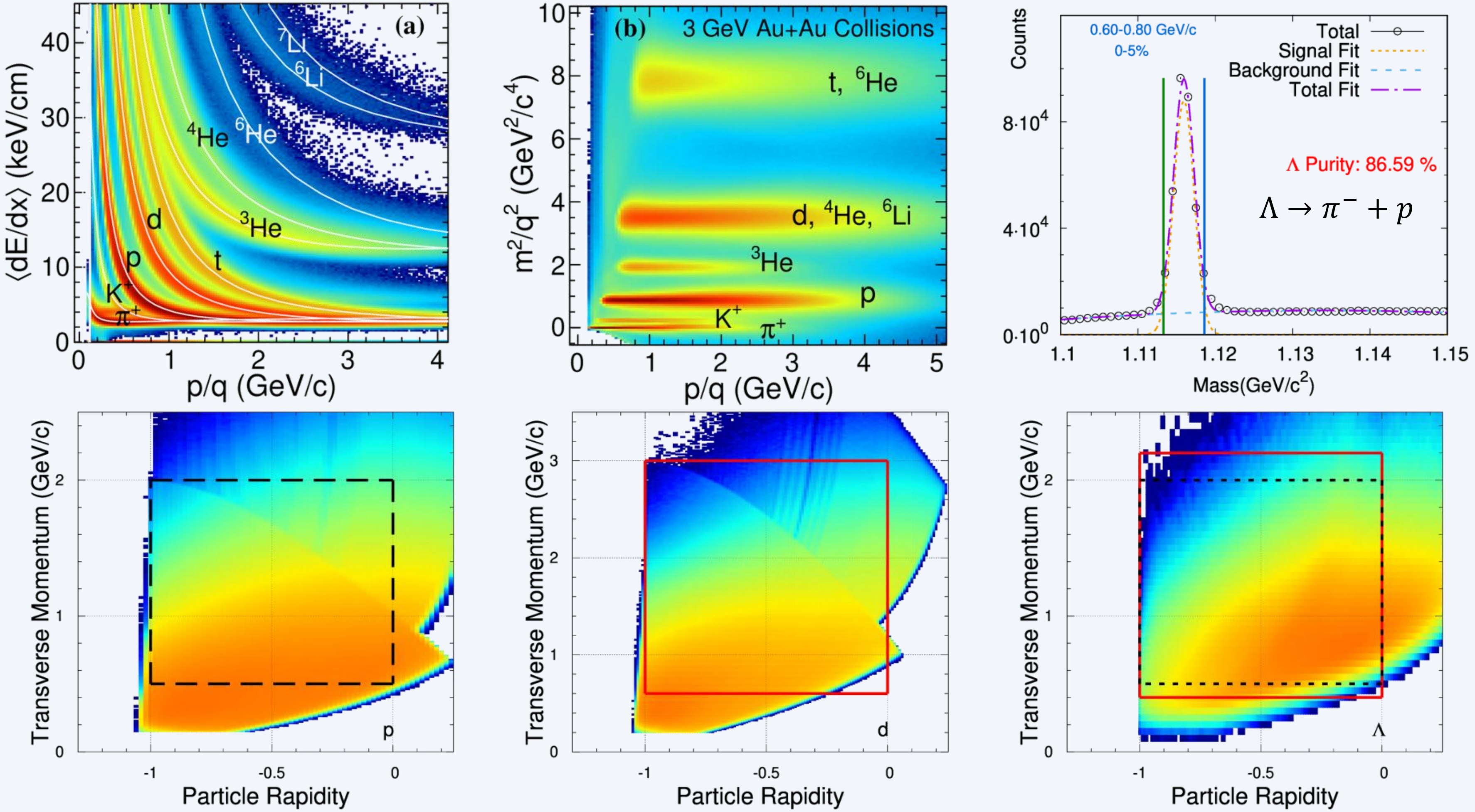


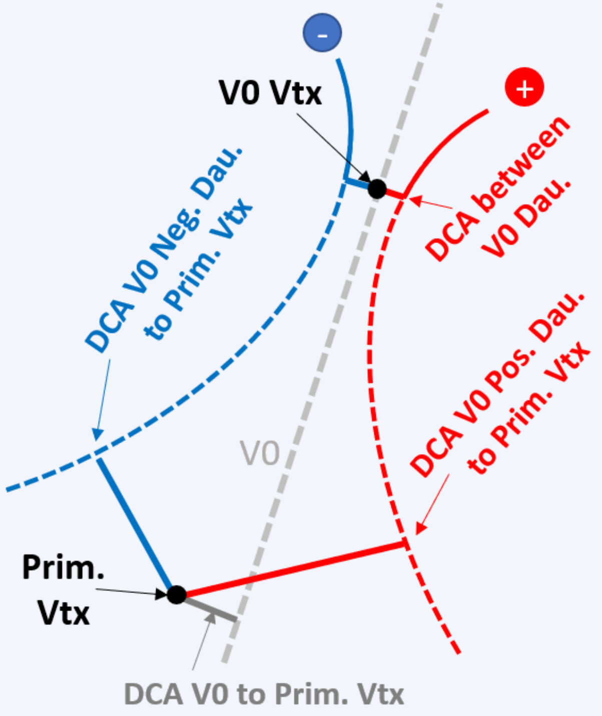
- $\sqrt{s_{NN}}$ =3 GeV Au+Au collisions → μ_B~750 MeV
- 0~60% centrality, ~250 M events (2018)





Particle Identification & Reconstruction @ 3 GeV

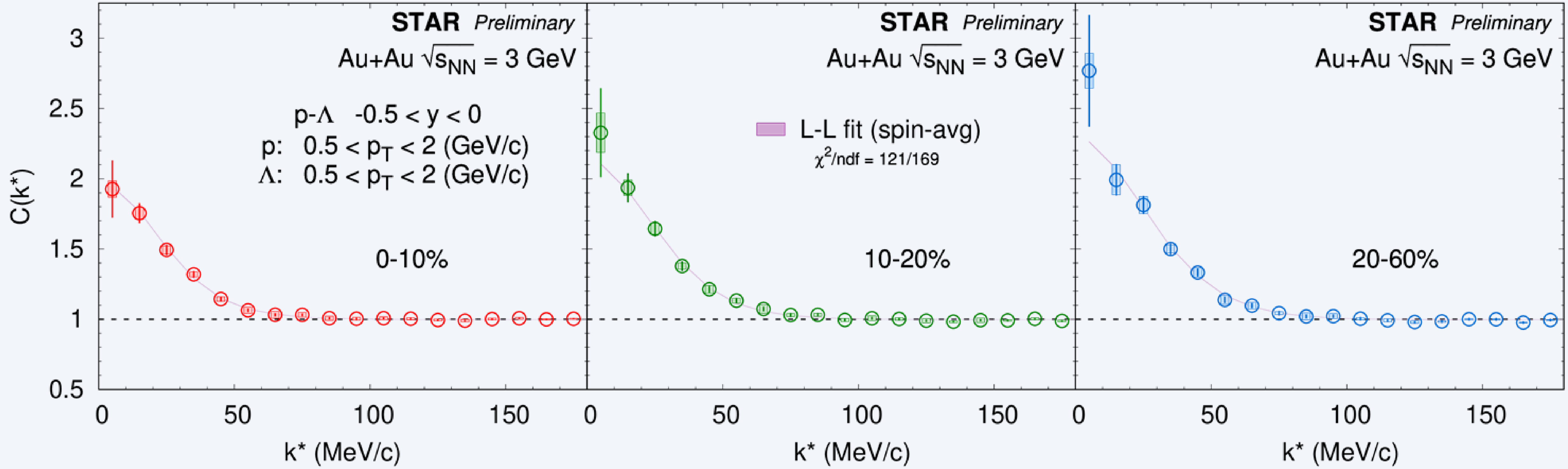




- ❖ π^-, p, and d particles are identified by TPC and TOF
- ❖ A larger p_T range is used in d-Λ correlation measurement (red) due to statistics

STAR. Phys. Lett. B 827 (2022) 136941

p-Λ Correlation Measurement @ STAR



Corrections

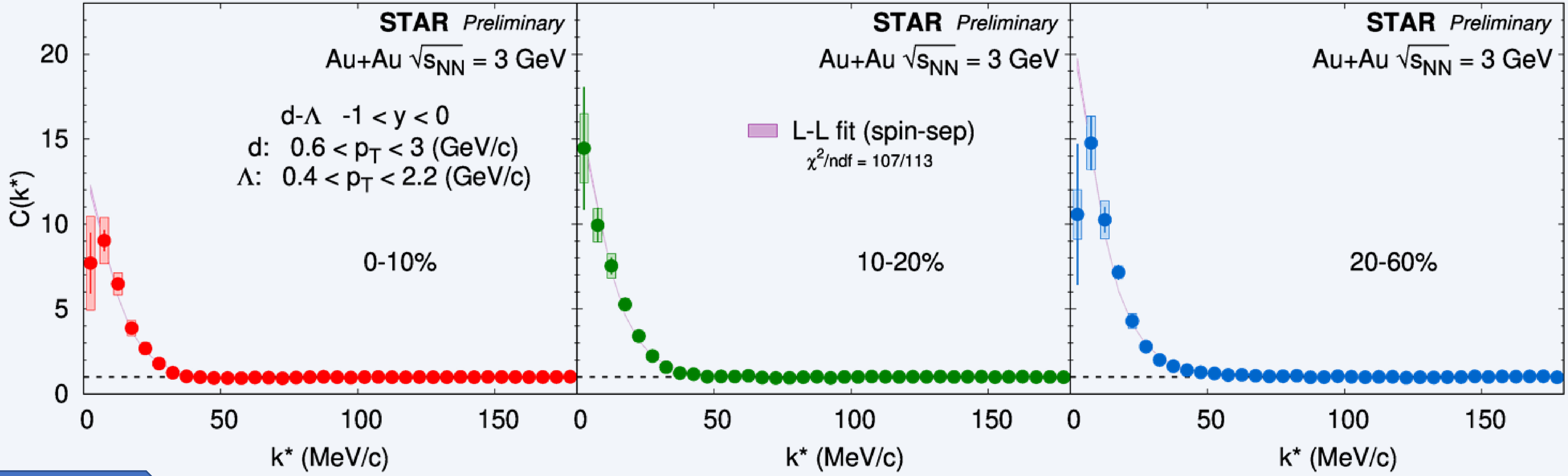
1. Purity correction
2. Λ feed-down correction
3. Track splitting & merging
4. Momentum smearing effect

- 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):

$$f_0 = 2.32^{+0.12}_{-0.11}\ \text{fm} \qquad d_0 = 3.5^{+2.7}_{-1.3}\ \text{fm}$$

R_G^i: source size in different centrality

d-Λ Correlation Measurement @ STAR



Corrections

1. Purity correction
2. Track splitting & merging
3. **Contamination from $^{3}_{\Lambda}\mathrm{H} \rightarrow \pi^- + p + d$ decay**

- **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

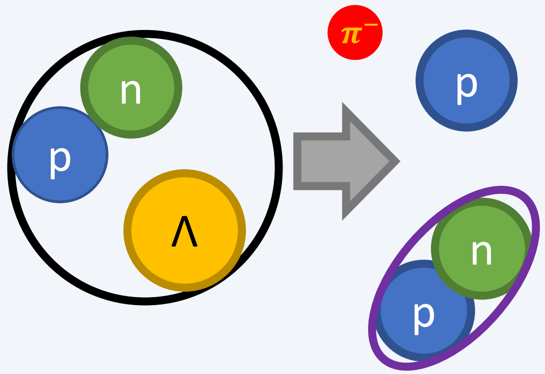
$f_0(Q) = 16^{+2}_{-1}$ fm $d_0(Q) = 2^{+1}_{-1}$ fm

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

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

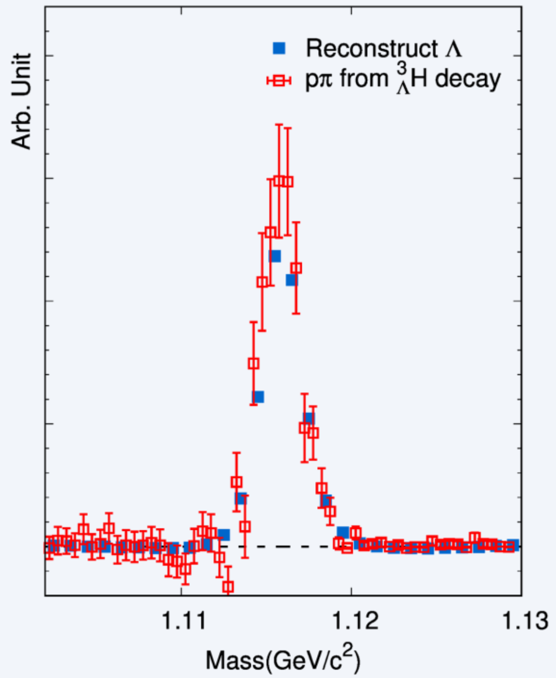
${}^{3}_{\Lambda}\mathrm{H} \rightarrow p + \pi^{-} + d;$

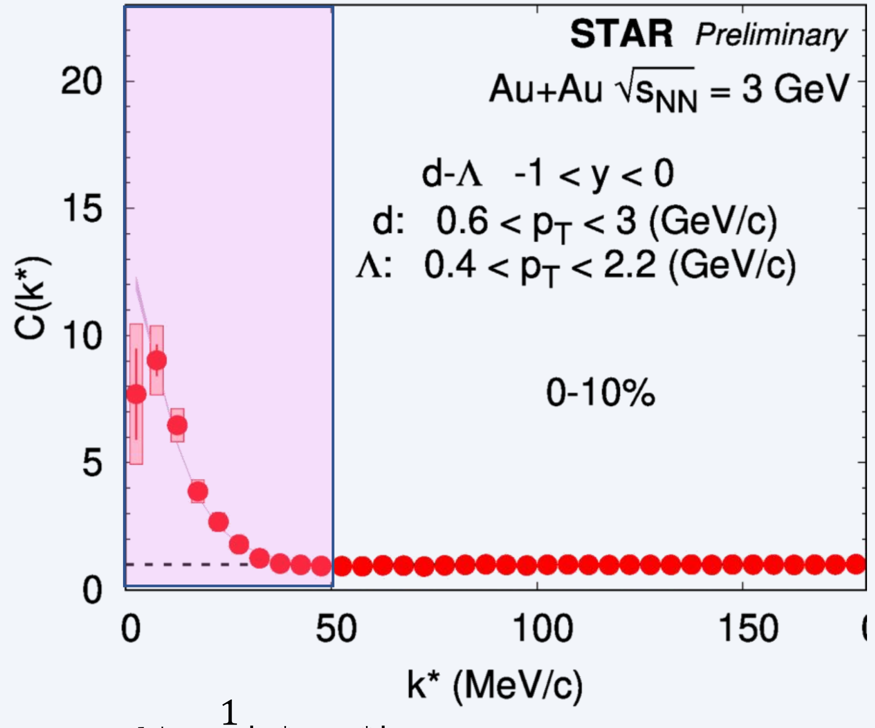
$B.R. \approx 40\sim50\%$



${}^{3}_{\Lambda}\mathrm{H} \not\rightarrow \Lambda + d$

Violation of energy conservation





$$k^* = \frac{1}{2}|\mathrm{p}_1^* - \mathrm{p}_2^*|$$

$$p_1 = \frac{\sqrt{(M^2 + m_1^2 - m_2^2)^2 - 4M^2 m_1^2}}{2M},$$

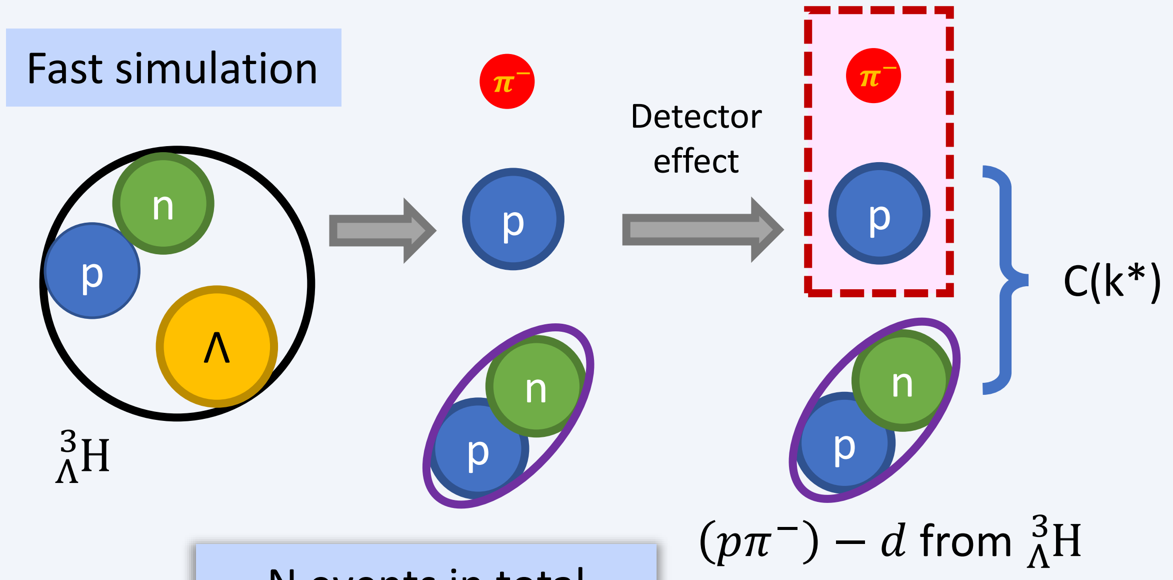
$$p_2 = \frac{\sqrt{(M^2 + m_2^2 - m_1^2)^2 - 4M^2 m_2^2}}{2M}.$$

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

p ≈ 20 MeV/c ⇒ k* ≈ 20 MeV/c

STAR, Phys.Rev.Lett. 128 (2022) 20, 202301
H. Kamada, et al. Phys.Rev.C 57 (1998) 1595

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



N events in total

↓

Initial N*Yield*BR ${}^{3}_{\Lambda}\mathrm{H}$ in total

↓

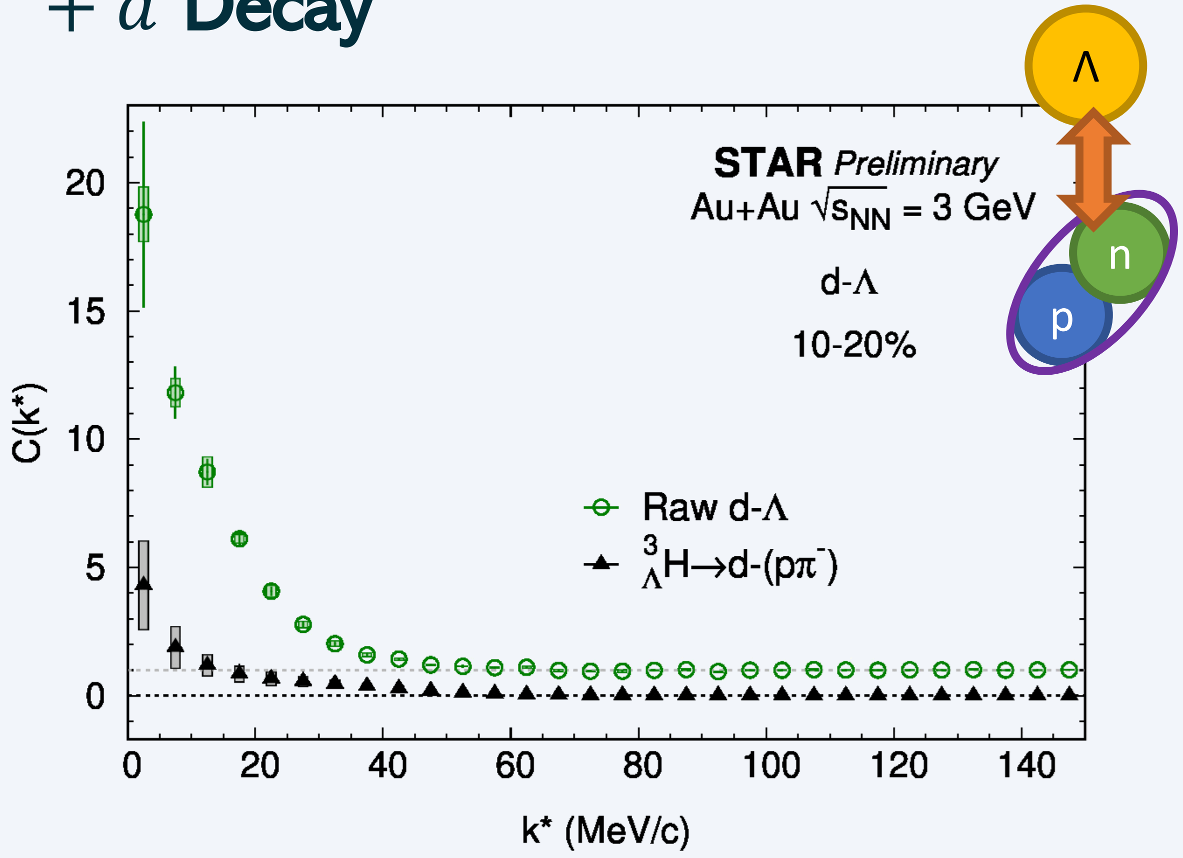
Apply different decay kinematics

↓

Detector effect, topological cuts, Acceptance cut…

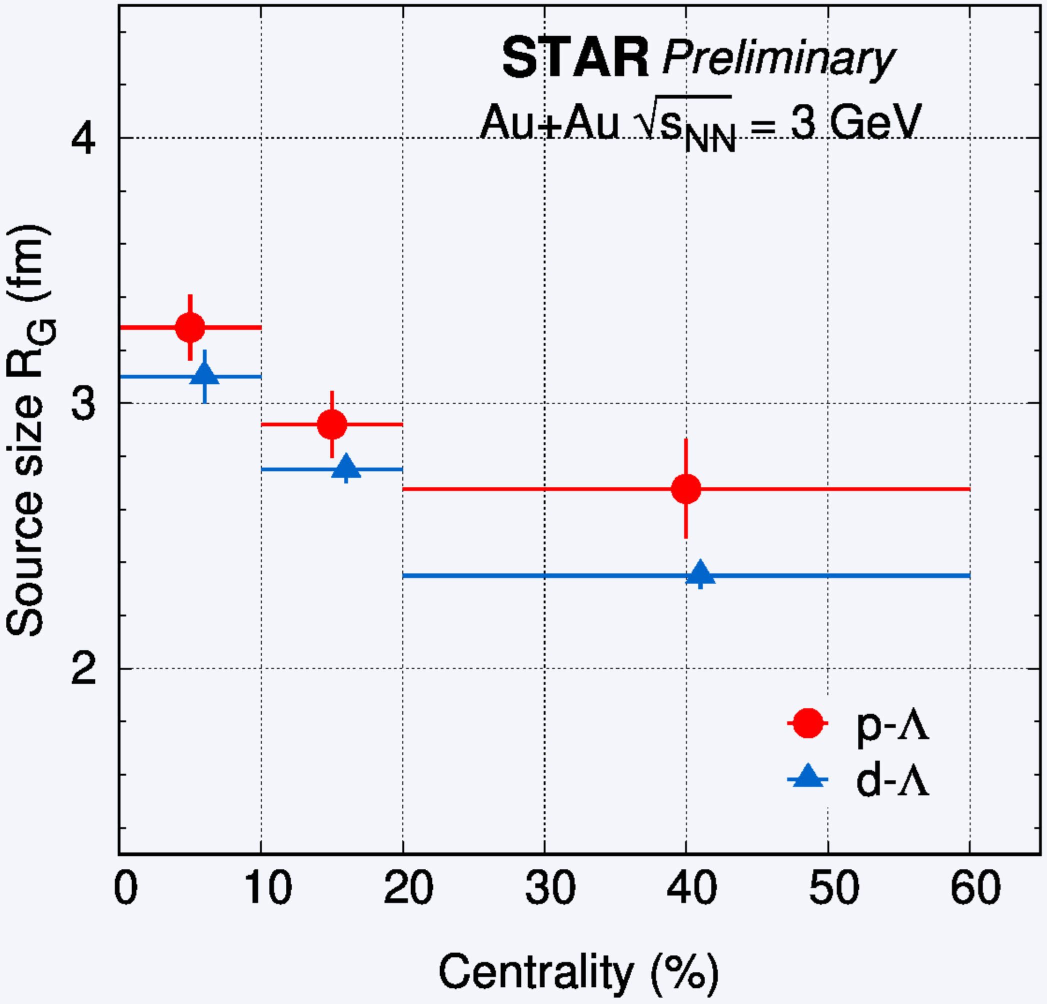
↓

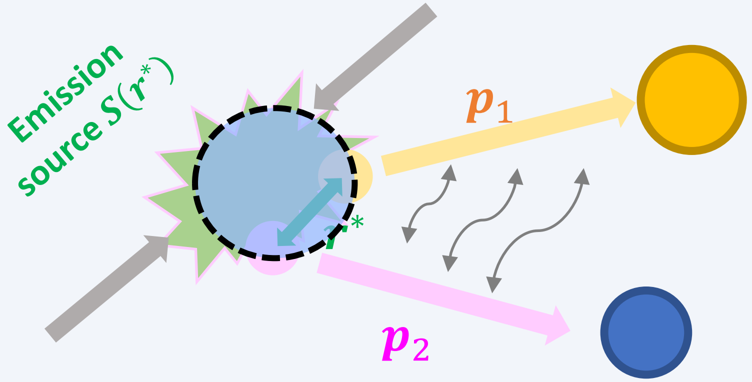
Normalize by the experimental mixed event



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

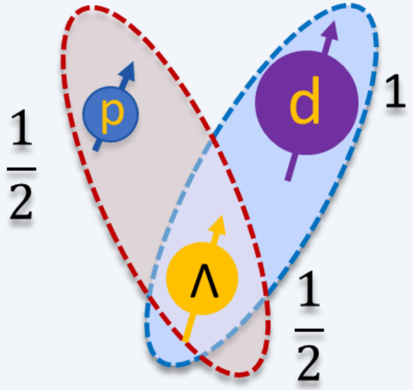
Source Size with L-L approach





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

Correlation Function & Spin States

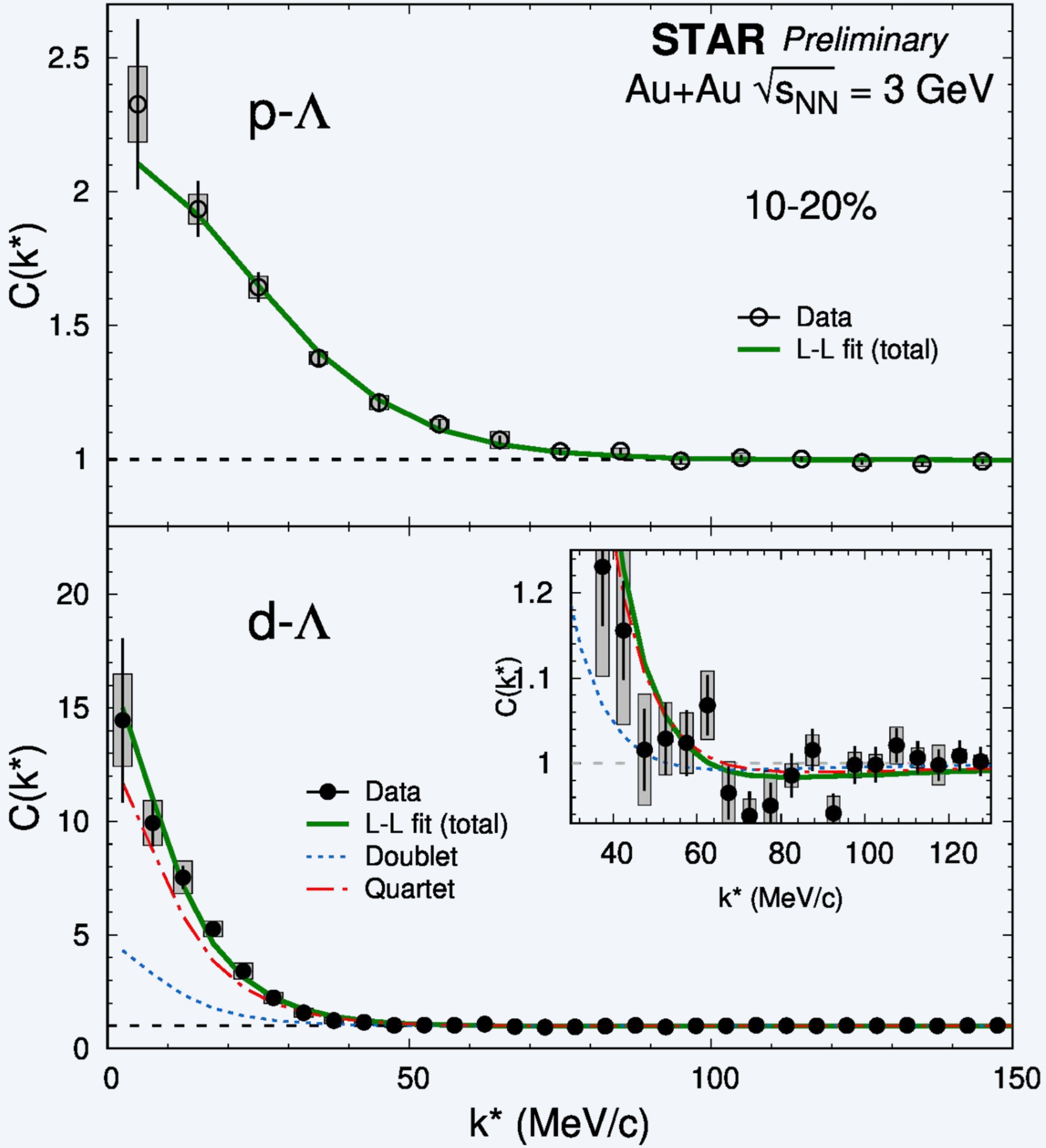


Singlet State	$^1S_0$	(S)
Triplet State	$^3S_1$	(T)

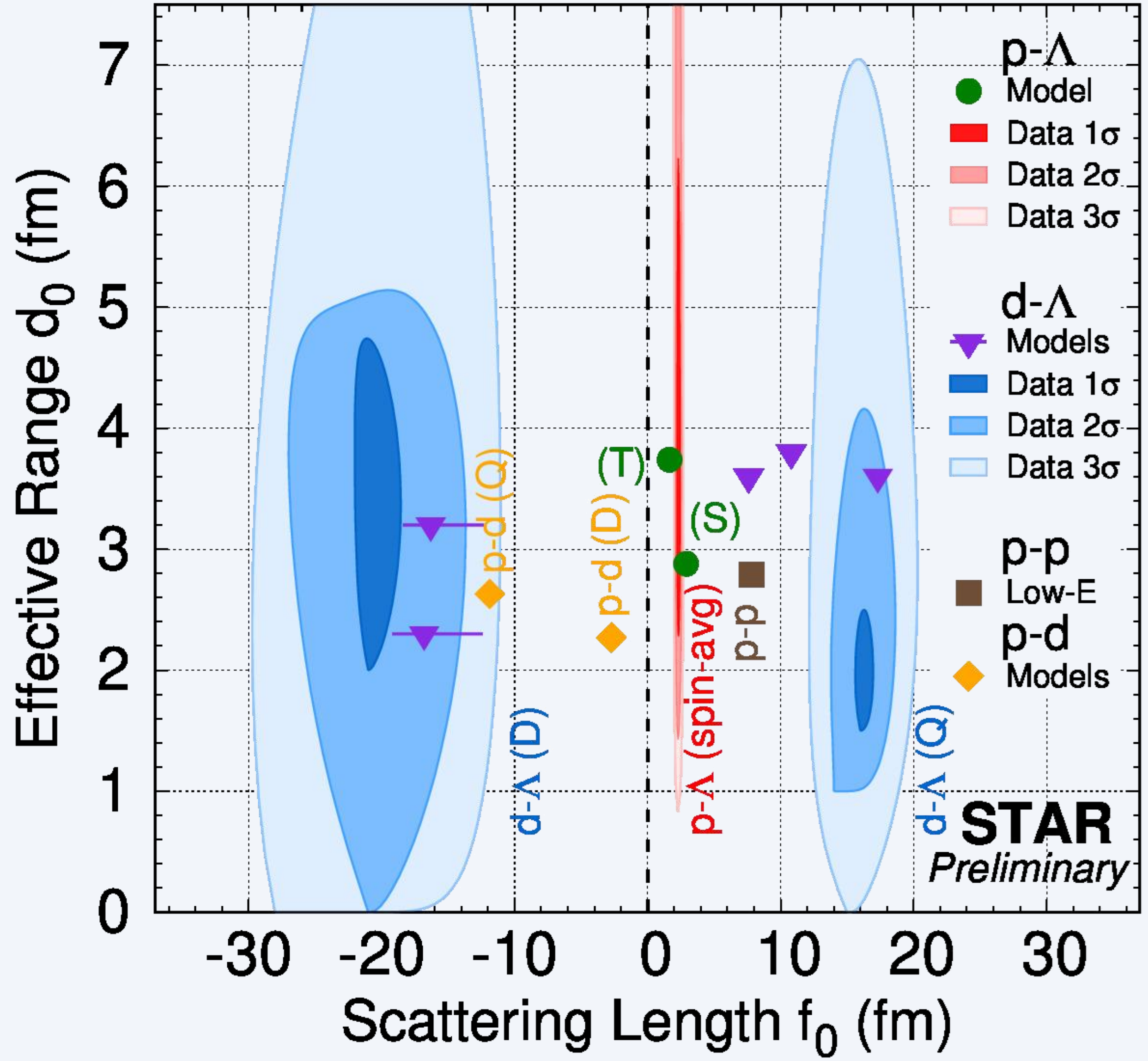
Doublet State	$^2S_{1/2}$	(D)
Quartet State	$^4S_{3/2}$	(Q)

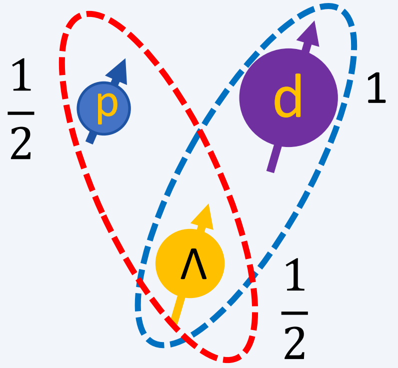
d-Λ: $|\psi(r,k)|^2 \rightarrow \frac{1}{3}\left|\psi_{1/2}(r,k)\right|^2 + \frac{2}{3}\left|\psi_{3/2}(r,k)\right|^2$

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



Scatterings Length (f_0) and Effective Range (d_0)





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

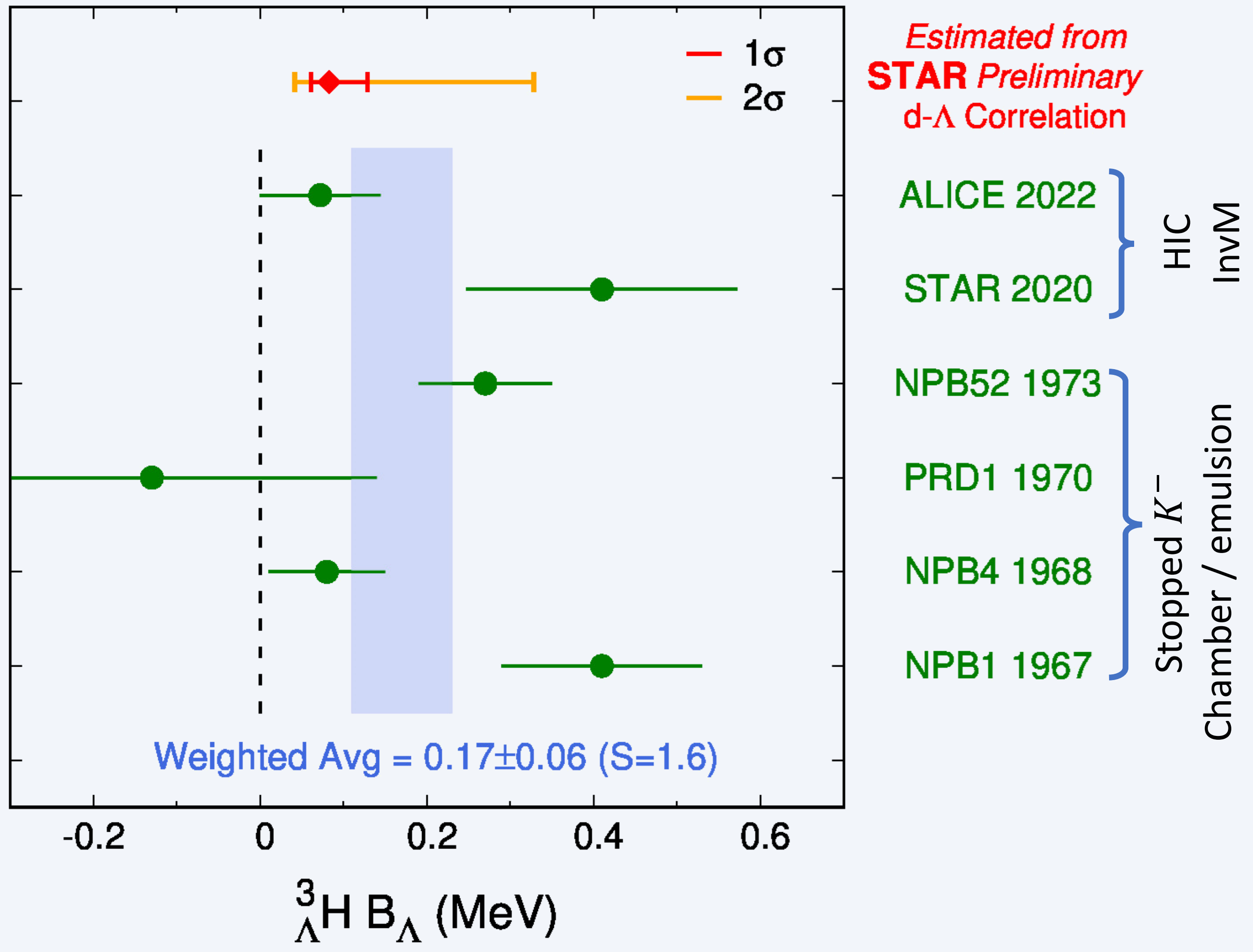
- The constraint on the effective range (d_0) is weaker

- The measurement is done at freeze-out
- Spin-avg for f_0 & d_0 p-Λ system
  $f_0 = 2.32^{+0.12}_{-0.11}$ fm $\quad d_0 = 3.5^{+2.7}_{-1.3}$ fm
- Successfully separate two spin states in d-Λ
  $f_0(\mathrm{D}) = -20^{+3}_{-3}$ fm $\quad d_0(\mathrm{D}) = 3^{+2}_{-1}$ fm
  $f_0(\mathrm{Q}) = 16^{+2}_{-1}$ fm $\quad d_0(\mathrm{Q}) = 2^{+1}_{-1}$ fm

- Constraint fit for d-Λ, require $f_0(\mathrm{D}) < 0$
- Edge of d-Λ contours are shown with Bezier smooth to improve the visibility

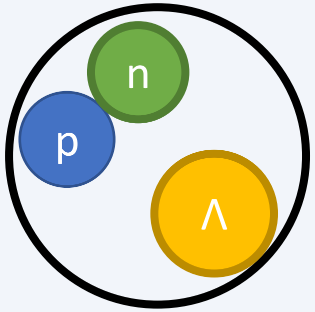
H. W. Hammer, Nucl. Phys. A 705 (2002) 173
F. Wang, et al. Phys.Rev.Lett. 83 (1999) 3138
M. Schäfer, et al. Phys.Lett.B 808 (2020) 135614
A. Cobis, et al. J. Phys. G 23 (1997) 401
G. Alexander, et al. Phys. Rev. 173 (1968) 1452
J. Haidenbauer, Phys.Rev.C 102 (2020) 3, 034001
J. Haidenbauer, et al. Nucl. Phys. A 915 (2013) 24

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



$^{3}_{\Lambda}$H binding energy (B_Λ):

❖ Bethe formula from Effective Range Expansion (ERE) parameters $f_0(\mathrm{D})$ & $d_0(\mathrm{D})$



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

❖ $B_\Lambda = \frac{\gamma^2}{2\mu_{d\Lambda}}$

❖ $\mu_{d\Lambda}$: reduced mass

❖ γ: binding momentum

❖ $^{3}_{\Lambda}\mathrm{H}\ B_\Lambda = [0.04, 0.33]$ (MeV) @ 95% CL
Consistent with the world average

❖ A new way to constrain the $^{3}_{\Lambda}$H structure

H. Bethe, Phys. Rev. 76, 38 (1949)

Summary and outlook

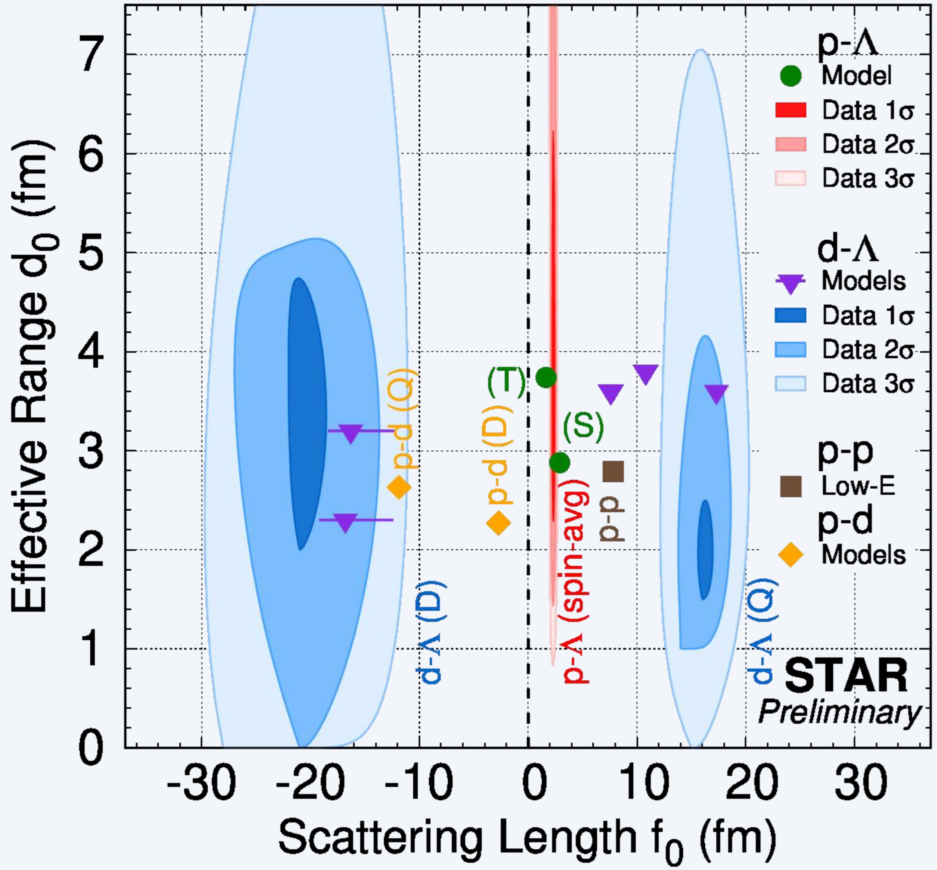
❖ **The first d-Λ correlation function measurements in heavy-ion collisions**

❖ **Successfully separated emission source size from final state interactions in d-Λ correlation functions**

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

   $\boldsymbol{f_0(D) = -20^{+3}_{-3}}$ **fm** $\boldsymbol{d_0(D) = 3^{+2}_{-1}}$ **fm**

   $\boldsymbol{f_0(Q) = 16^{+2}_{-1}}$ **fm** $\boldsymbol{d_0(Q) = 2^{+1}_{-1}}$ **fm**
3. ${}^{3}_{\Lambda}H\ B_\Lambda = [0.04, 0.33]\ (MeV)$ @ 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!

STAR

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