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

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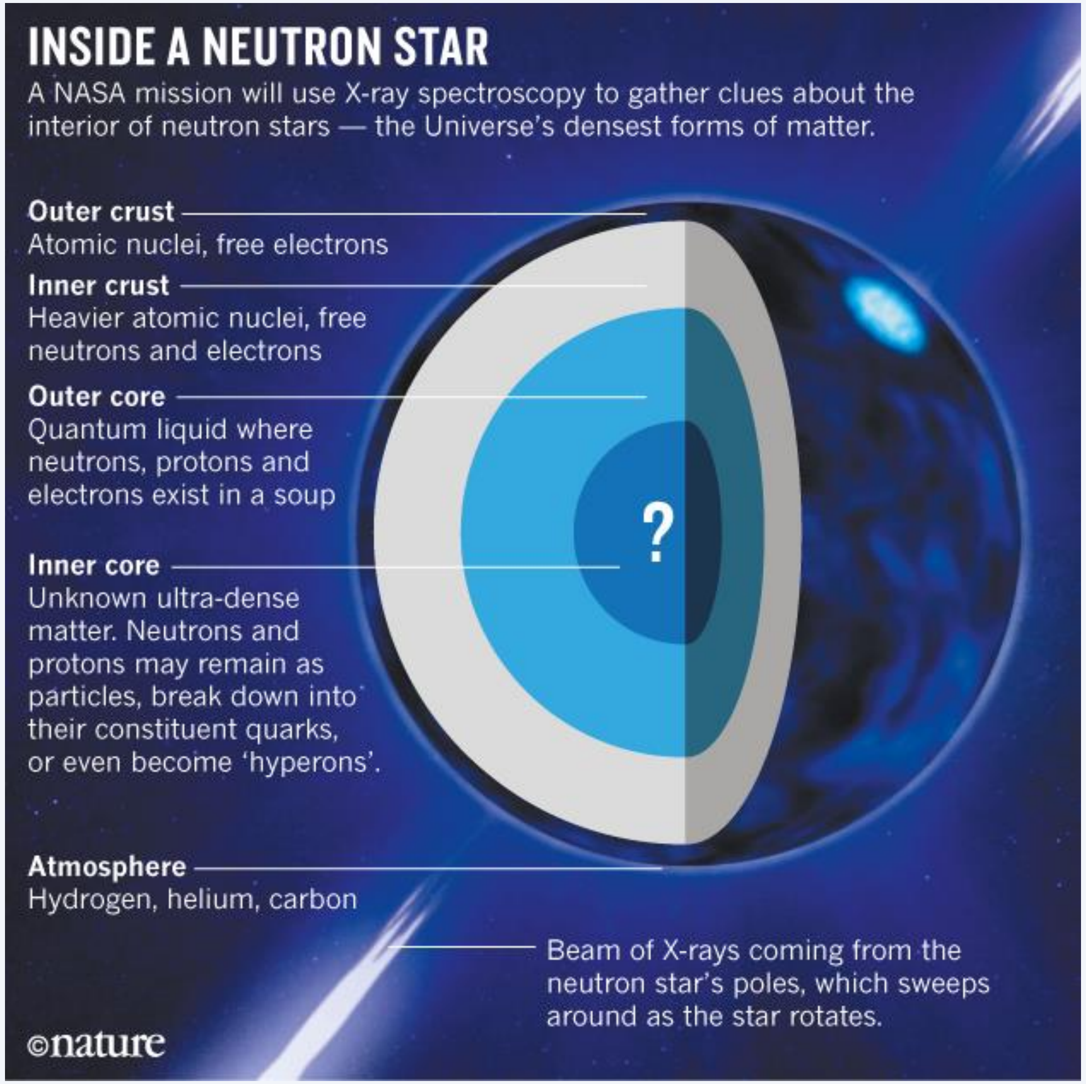
for the STAR collaboration

Tsinghua University

2023.11.10

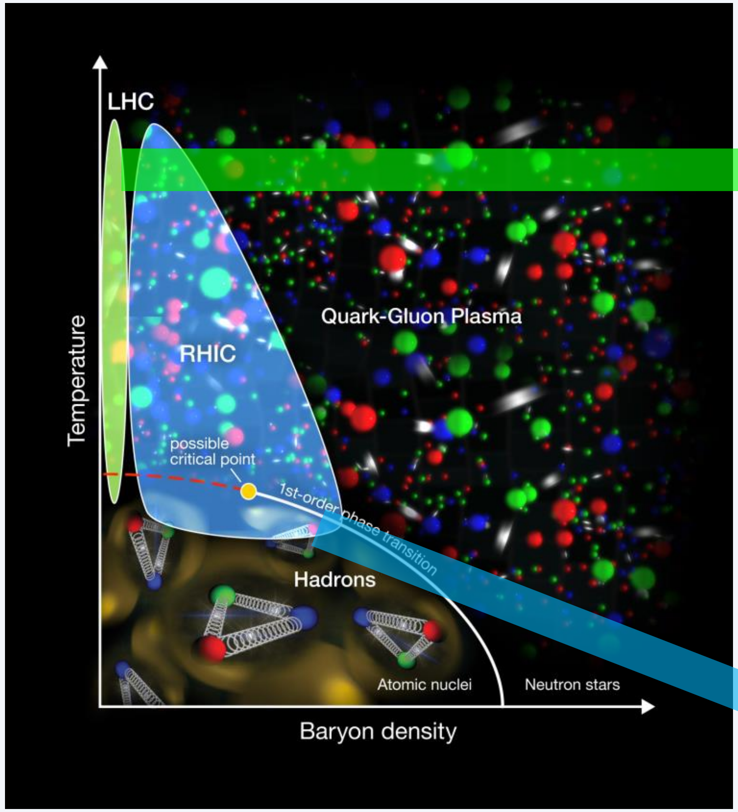
Supported in part by U.S. DEPARTMENT OF ENERGY

QCD Dense Matter & Nucleon-Nucleon/Hyperon Interactions



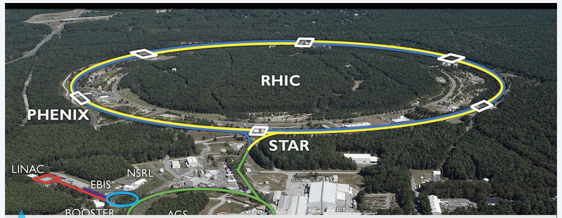
Credit: Source: Adapted from NASA Goddard SVS
Nature volume 546, page18 (2017)

- ❖ 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



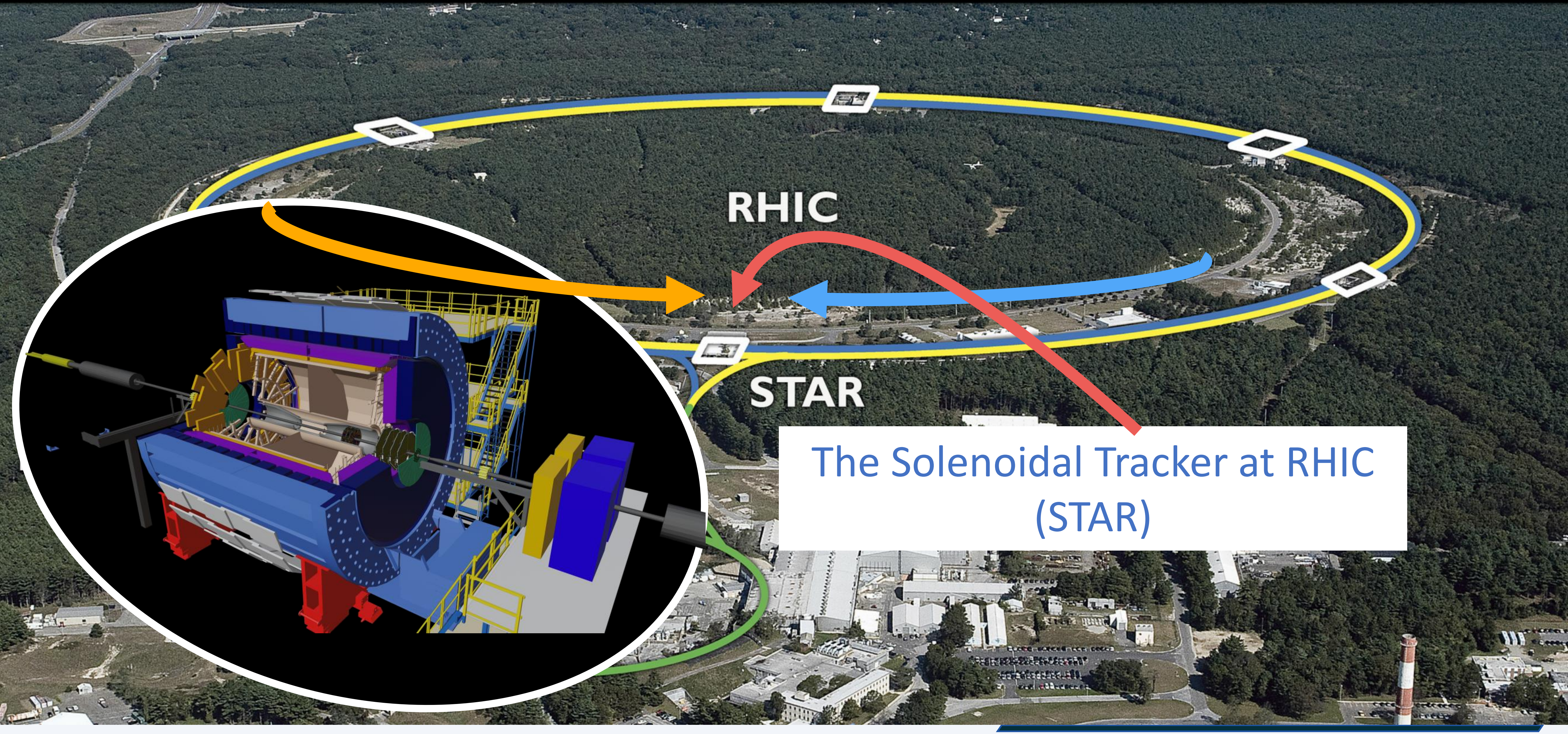
https://www.bnl.gov/newsroom/news.php?a=219079

The Large Hadron Collider (LHC)



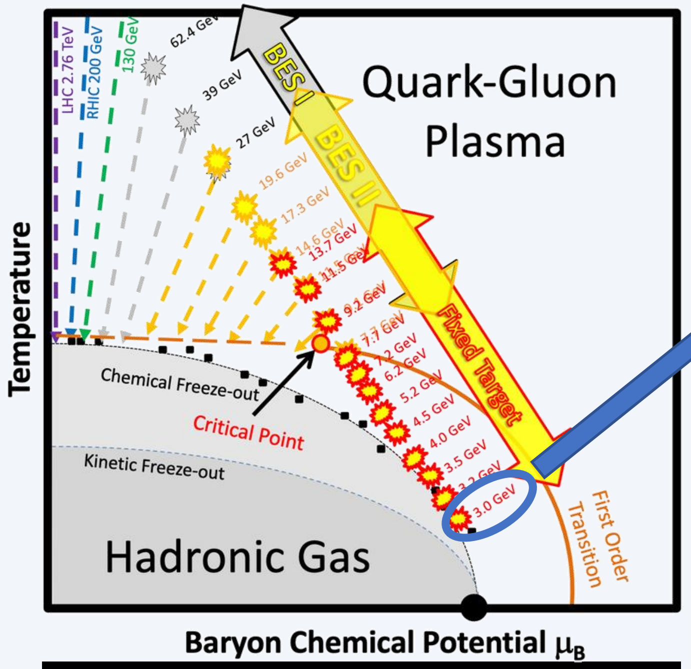
Relativistic Heavy Ion Collider (RHIC)

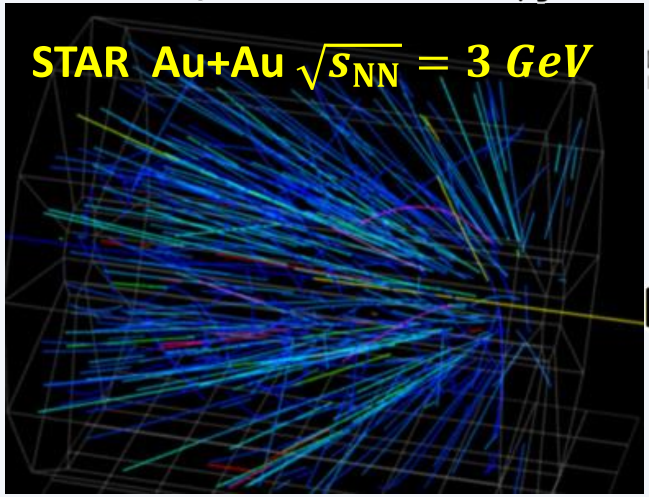
STAR Detector



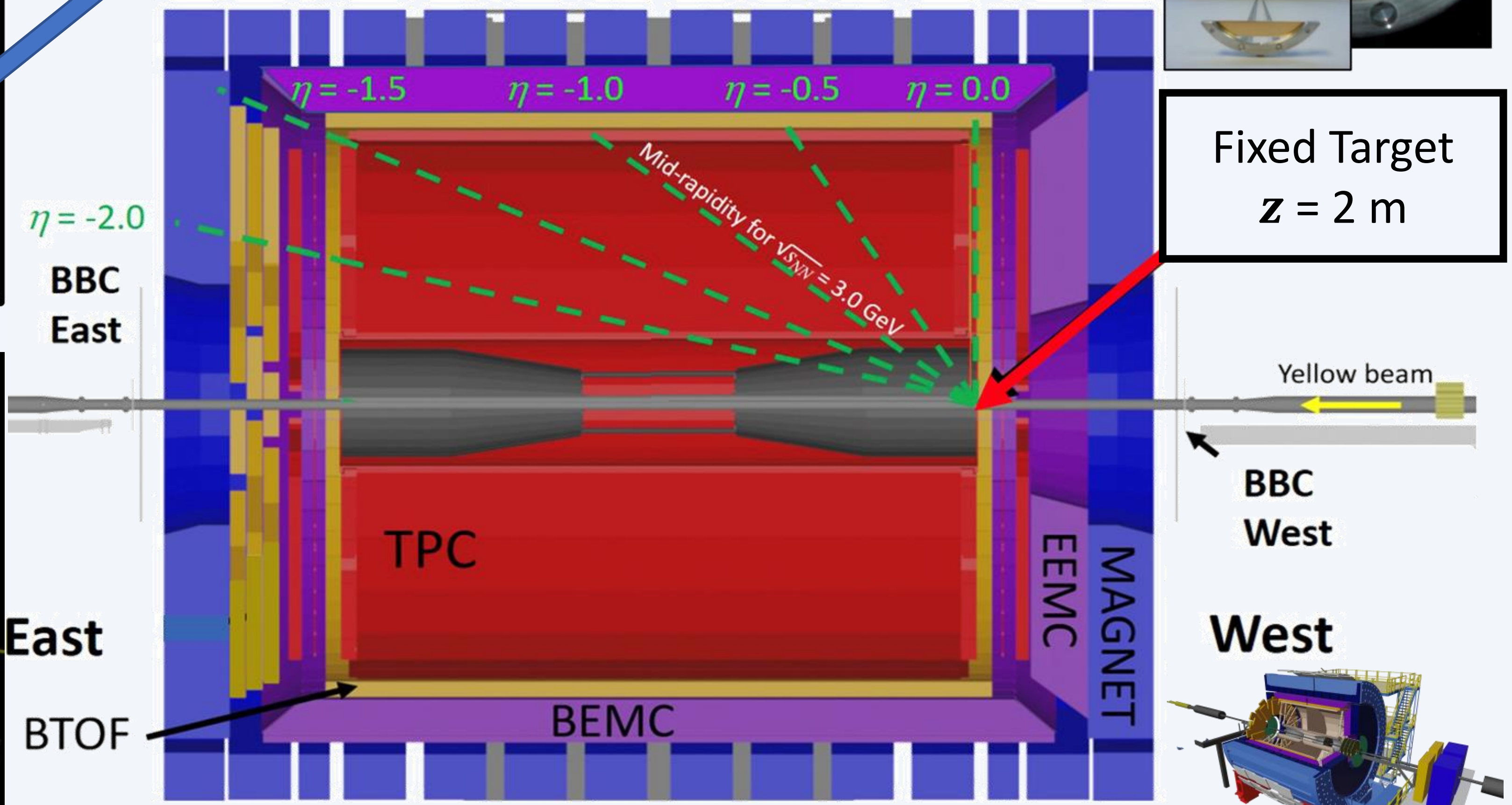
The Solenoidal Tracker at RHIC (STAR)

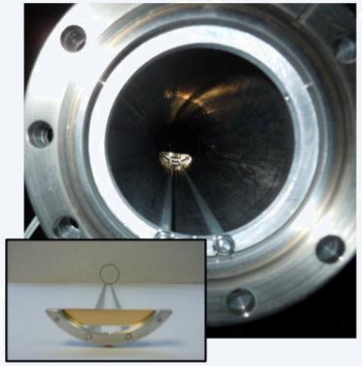
Beam Energy Scan – II & Fixed Target Setup





- 3 GeV Au+Au collisions → μ_B~720 MeV
- 0~60% centrality, ~250 M events (2018)





Fixed Target
z = 2 m

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

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

Experimental

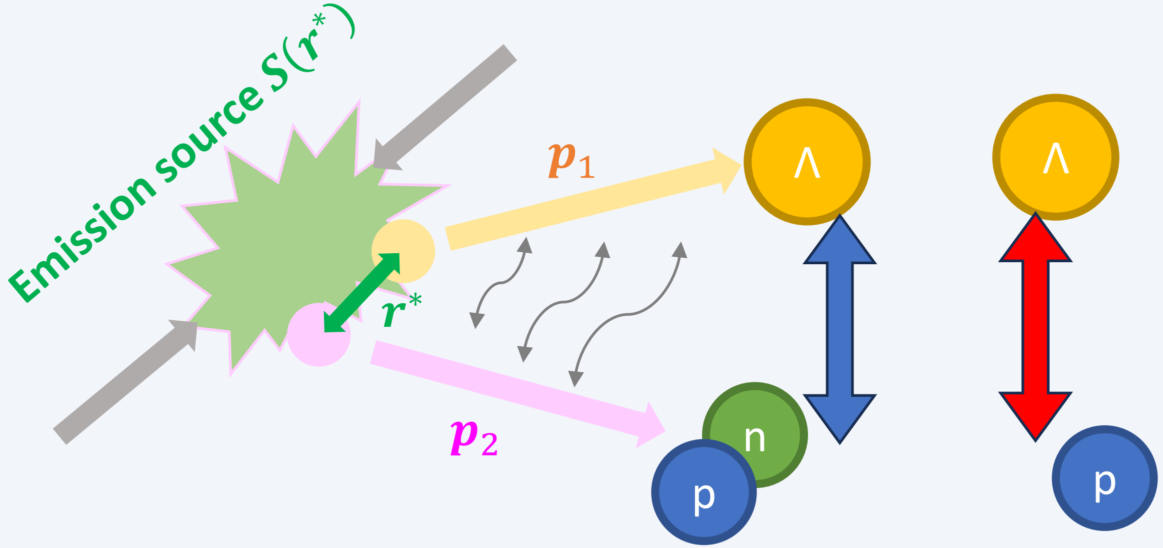
$$C(k^*) = \mathcal{N} \frac{A(k^*)}{B(k^*)}$$

Signal

Background

Normalization factor

k^*: particle momentum in the pair rest frame



- **Space and time evolution of particle-emitting source**
- **Final state interactions**

  p-Λ & d-Λ correlations:

  N(-N)-Y interactions / hypernuclei structure

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

Methodology

Experimental

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

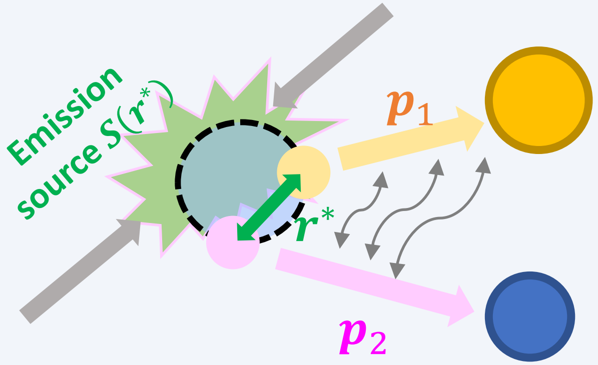
Same events

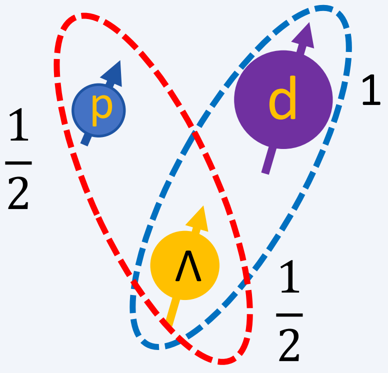
Mixed events

Normalization factor

Corrections on:

- Purity
- Feed-down effect
- 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

$\boldsymbol{R_G}$: spherical Gaussian source of pairs
$\boldsymbol{f_0}$: scattering length
$\boldsymbol{d_0}$: effective range

Major assumptions:

- Ignore multiplicity correlations and charge of source
- Smoothness approximation
- Effective range expansion for $\Psi(\boldsymbol{r}^*, \boldsymbol{k}^*)$
- Static and spherical Gaussian source
  - Single particle source: $S_i(x_i, p_i^*)$
  - Pair source (radius $\boldsymbol{R_G}$): $S(x, p^*) \propto e^{-x^2/4\boldsymbol{R_G}^2}\delta(t - t_0)$

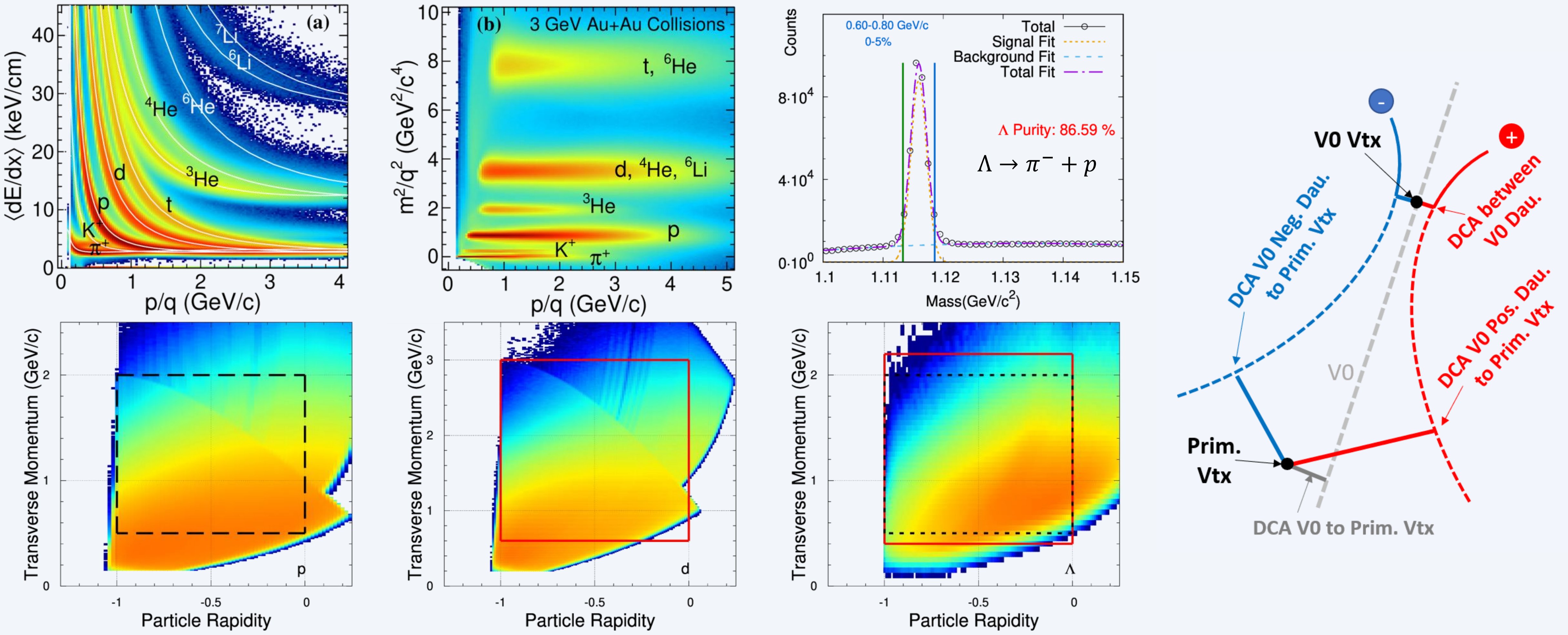
$$C(\boldsymbol{k}^*) \approx 1 + \frac{|f(k)|^2}{2\boldsymbol{R_G}^2}F(d_0) + \frac{2\mathrm{Re}f(k)}{\sqrt{\pi}\boldsymbol{R_G}}F_1(2kR) - \frac{\mathrm{Im}f(k)}{\boldsymbol{R_G}}F_2(2k\boldsymbol{R_G})$$

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

Different f_0 and d_0 for different spin states

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

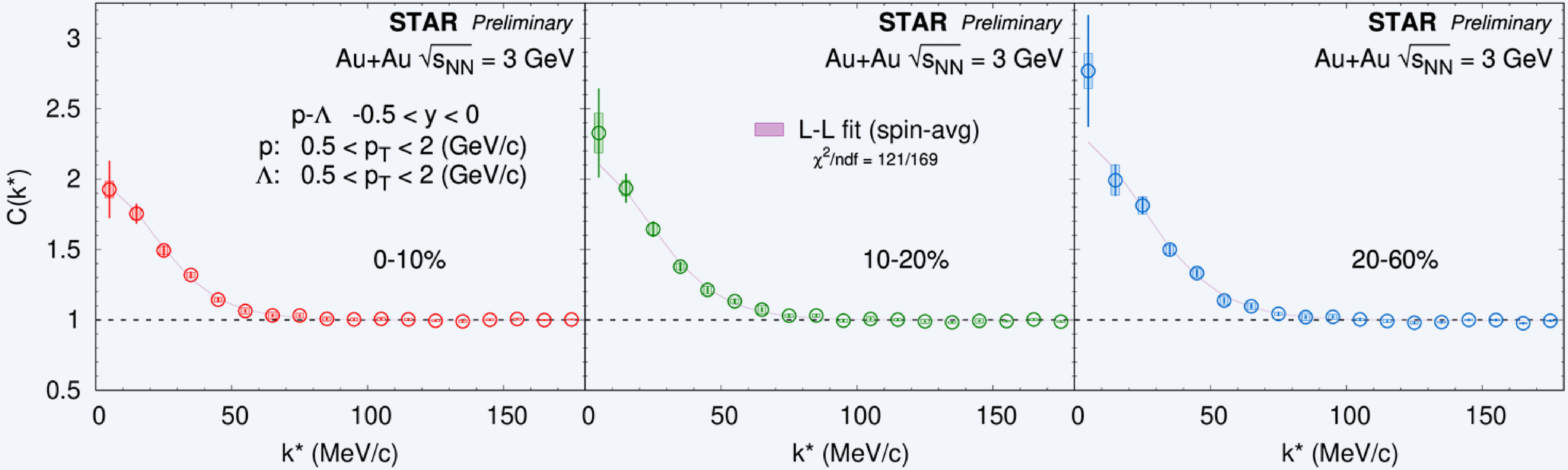
Particle Identification & Reconstruction @ 3 GeV



- 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

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

p-Λ Correlation Measurement @ STAR



Corrections

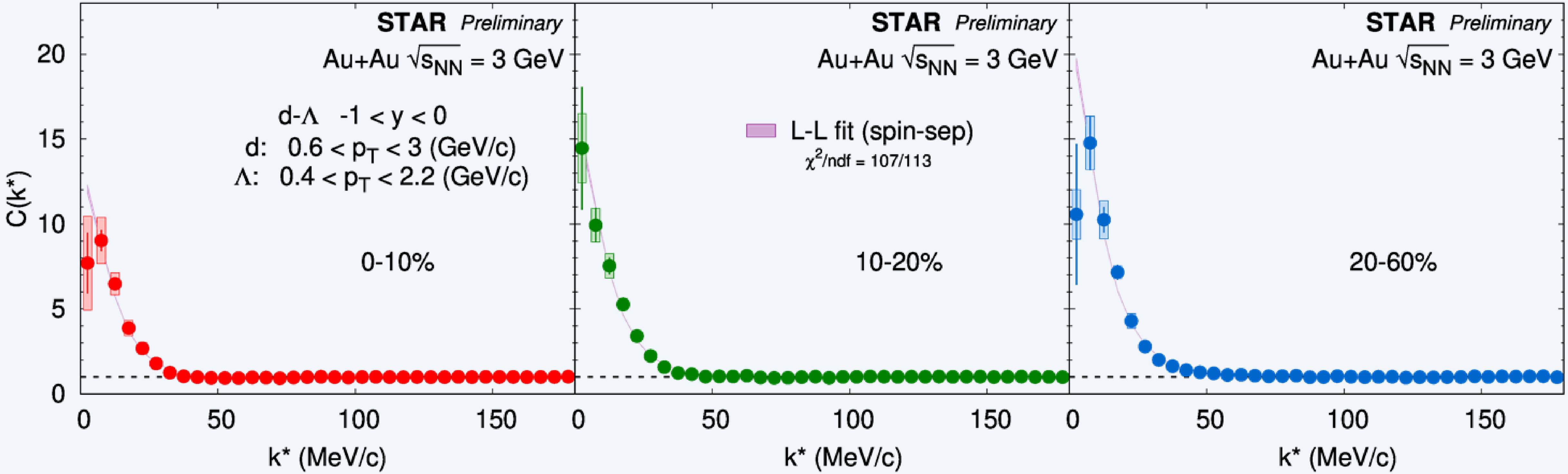
1. Purity correction
2. Λ feed-down correction
3. Track splitting & merging
4. Momentum smearing effect

- 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):

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

R_G^i: source size in different centrality

d-Λ Correlation Measurement @ STAR



Corrections

1. Purity correction
2. Track splitting & merging
3. **Contamination from $^{3}_{\Lambda}H \rightarrow \pi^{-} + p + d$ 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^{i}_{G}, $f_0(D)$, $d_0(D)$, $f_0(Q)$, and $d_0(Q)$ with Lednicky-Lyuboshitz approach

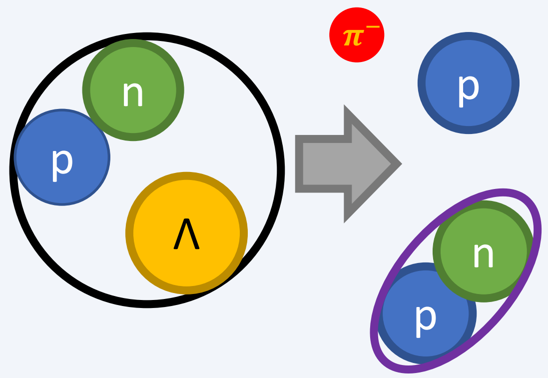
$f_0(D) = -20^{+3}_{-3}$ fm $\quad d_0(D) = 3^{+2}_{-1}$ fm

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

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

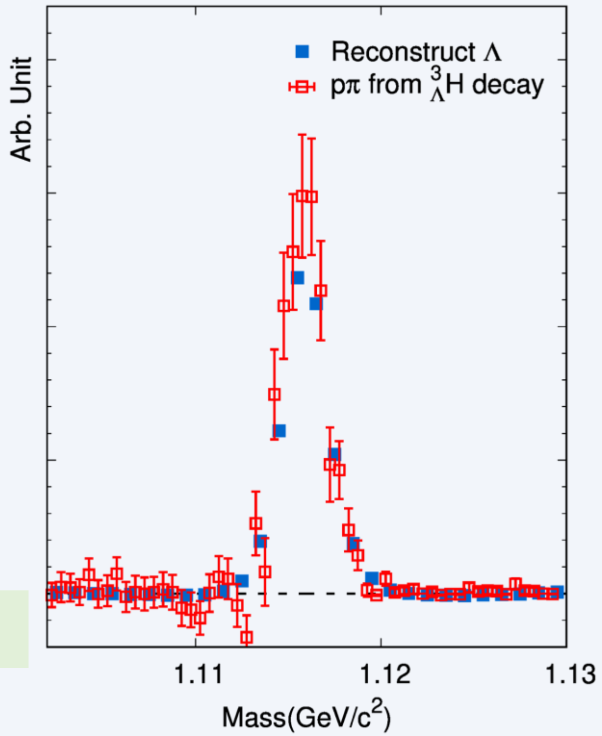
Contamination Correction from ${}^{3}_{\Lambda}\mathrm{H} \rightarrow p\pi^{-} + d$ Decay

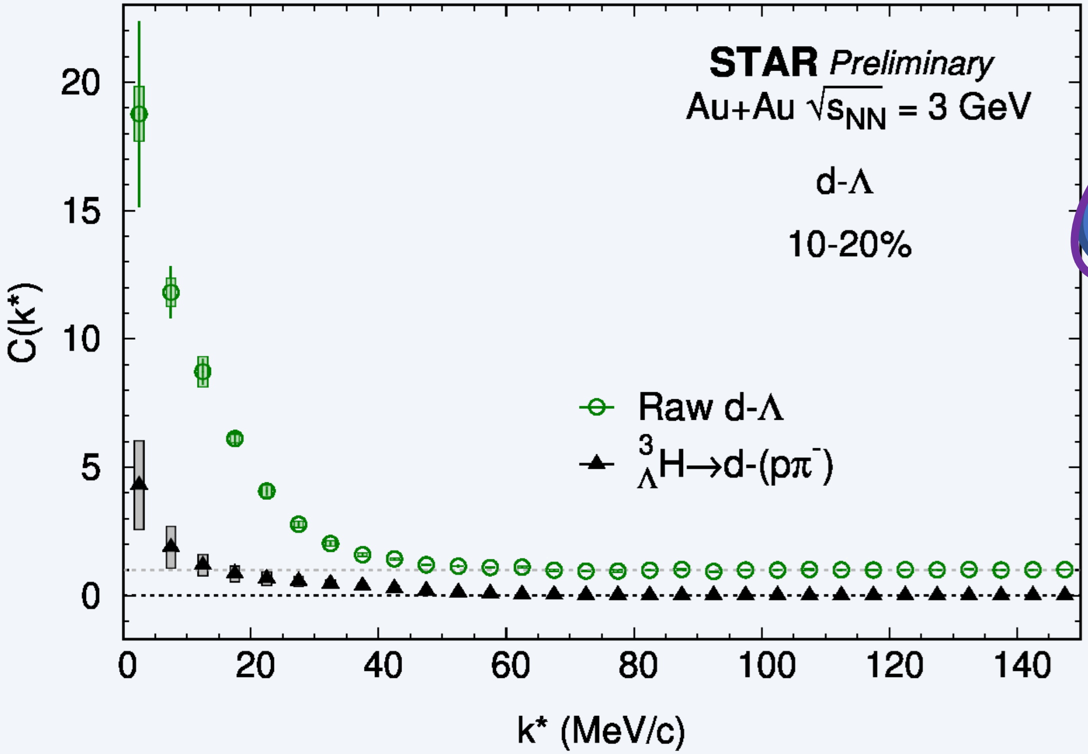
${}^{3}_{\Lambda}\mathrm{H} \rightarrow p + \pi^{-} + d;$
$B.R. \approx 40\sim50\%$

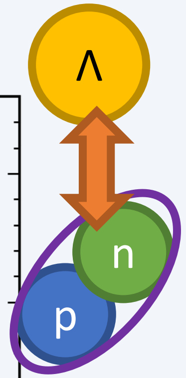


${}^{3}_{\Lambda}\mathrm{H} \nrightarrow \Lambda + d$

Violation of energy conservation





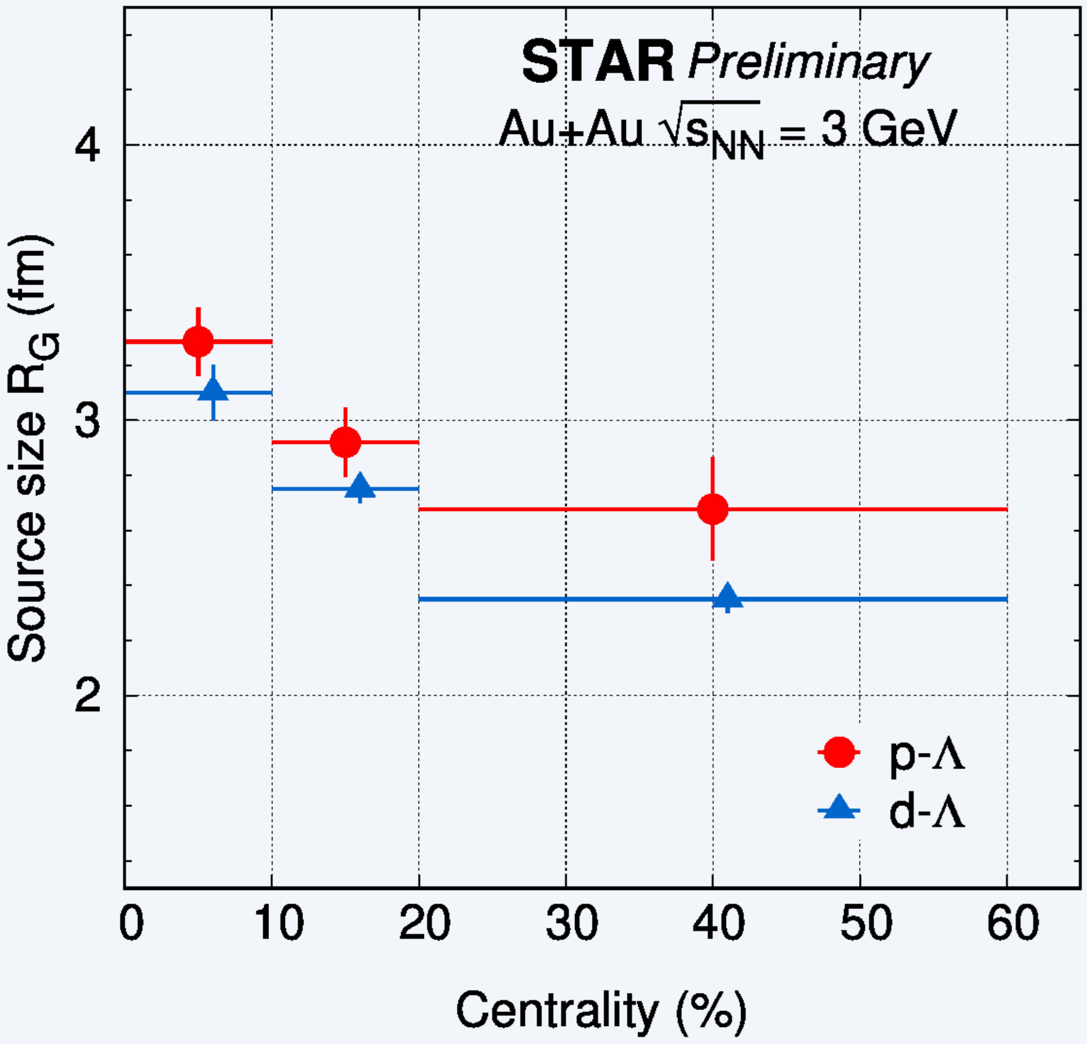


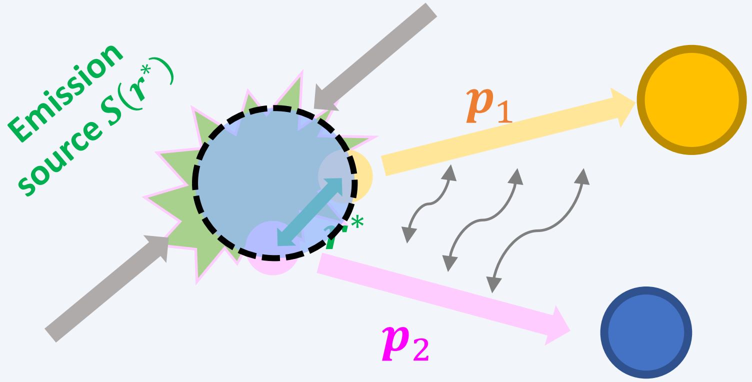
- The ${}^{3}_{\Lambda}\mathrm{H}$ decayed $p + \pi^{-}$ are **not experimentally distinguishable** with the reconstructed Λ
- $(p\pi^{-}) - d$ from ${}^{3}_{\Lambda}H$ will affect small k^{*} region

- 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

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

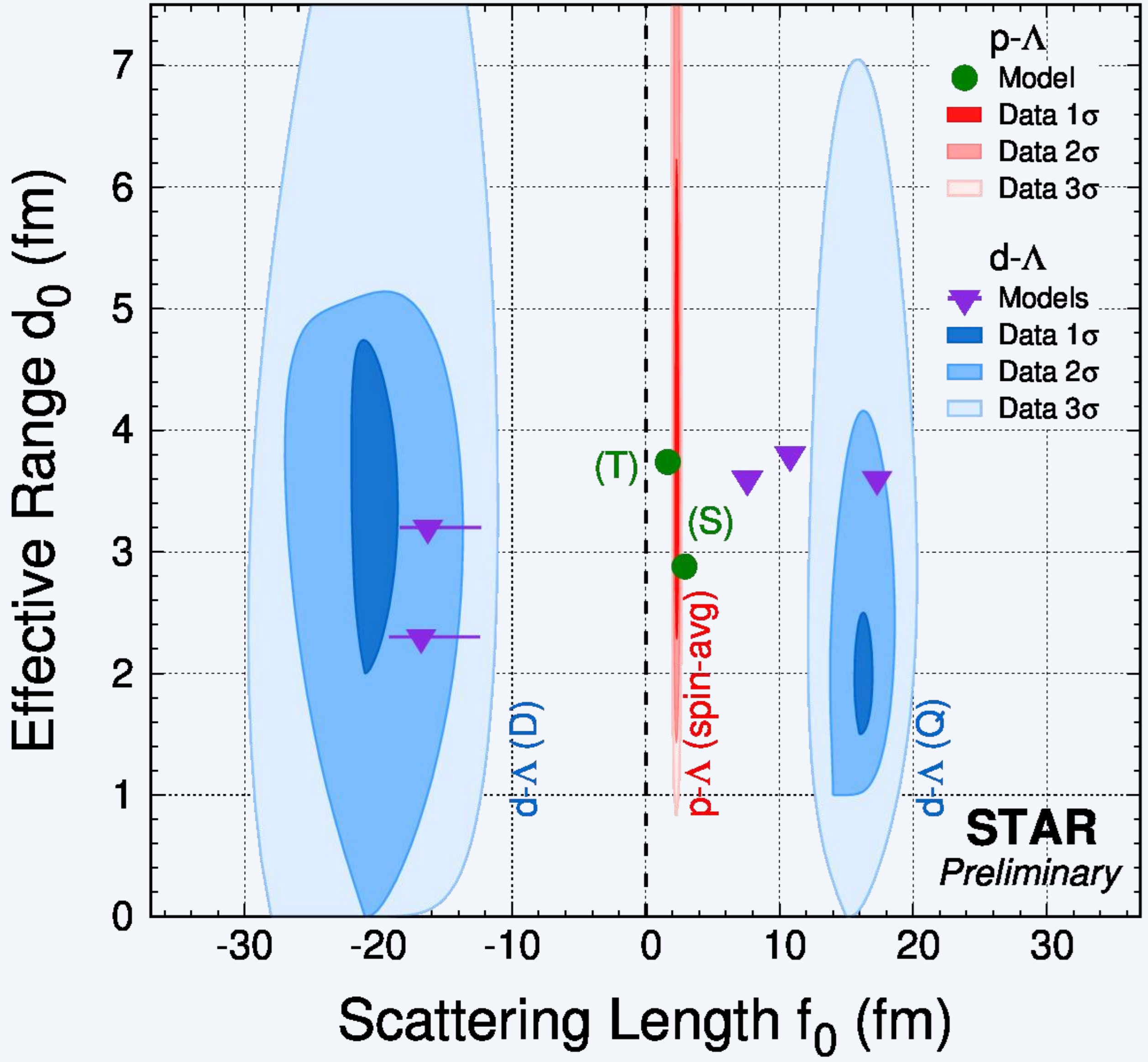
Source Size with L-L approach

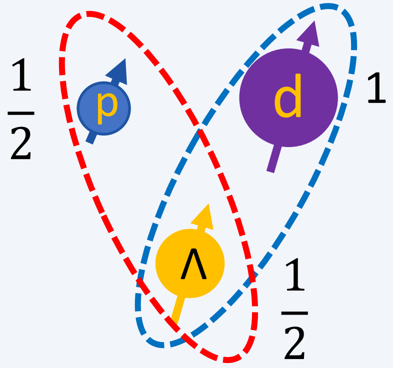




- R_G: **spherical Gaussian source of pairs** by Lednicky-Lyuboshits approach
- Separation of emission source from final state interaction
- Collision dynamics as expected:
  - $R_G^{central} > R_G^{peripheral}$
  - $R_G\ (p - \Lambda) > R_G\ (d - \Lambda)$

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

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

❖ Successfully separate two spin states in d-Λ

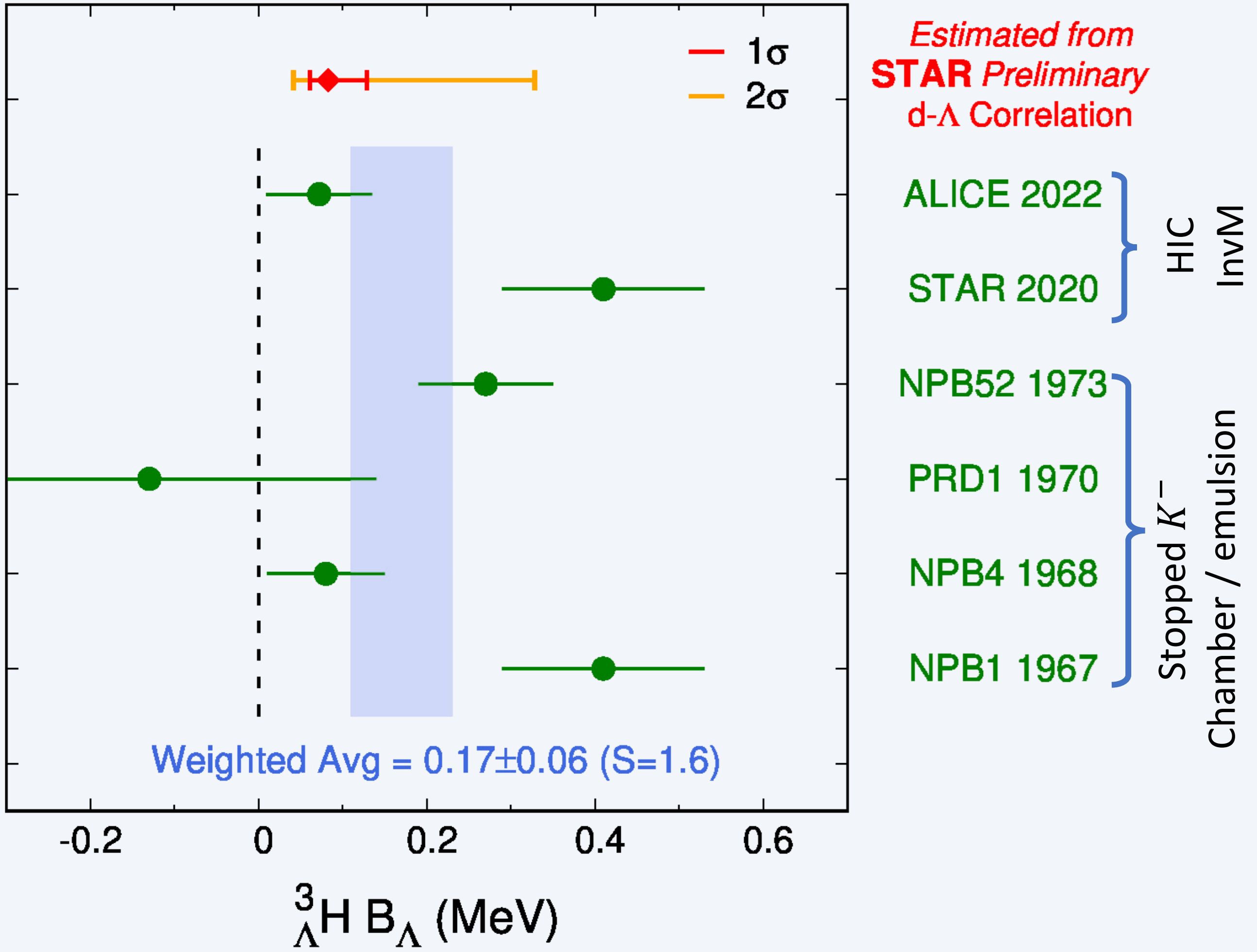
$f_0(D) = -20^{+3}_{-3}$ fm $\qquad d_0(D) = 3^{+2}_{-1}$ fm

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

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

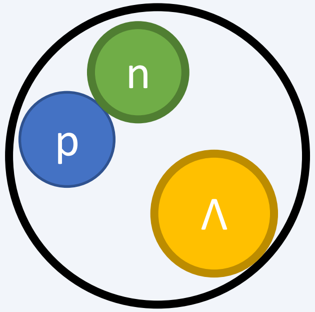
H. W. Hammer, Nucl. Phys. A 705 (2002) 173
F. Wang, et al. Phys.Rev.Lett. 83 (1999) 3138
M. Schäfer, et al. Phys.Lett.B 808 (2020) 135614
A. Cobis, et al. J. Phys. G 23 (1997) 401
G. Alexander, et al. Phys. Rev. 173 (1968) 1452
J. Haidenbauer, Phys.Rev.C 102 (2020) 3, 034001
J. Haidenbauer, et al. Nucl.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

❖ ${}^{3}_{\Lambda}H$ $B_{\Lambda} = [0.04, 0.33]$ (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

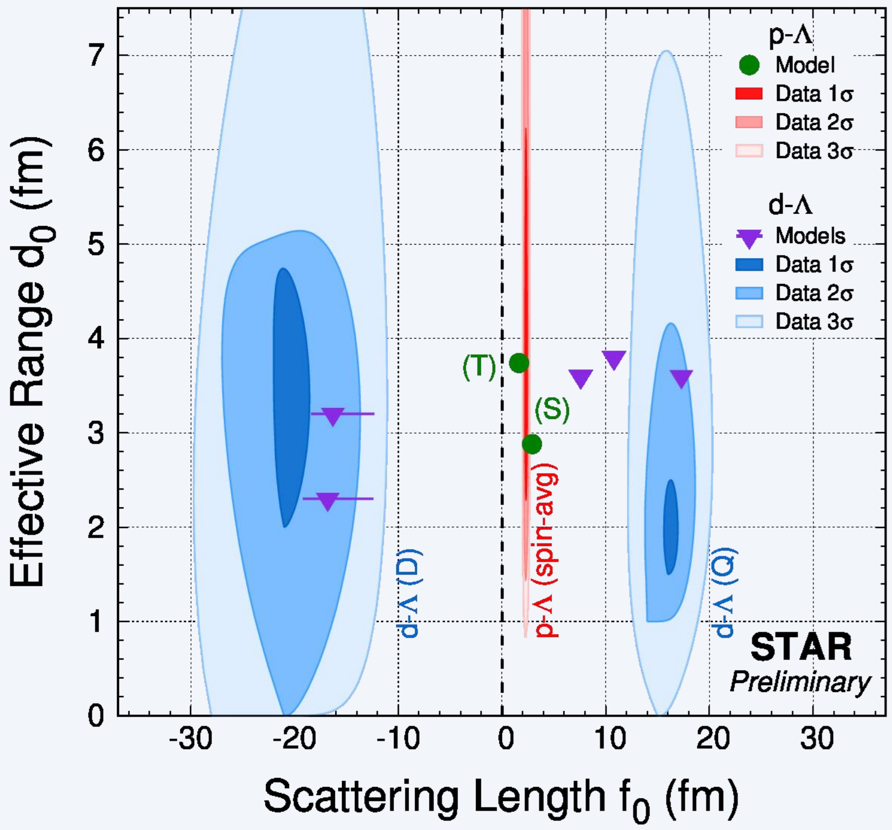
- **The first d-Λ correlation function measurements in heavy-ion collisions**
- **New p-Λ correlation function measurements with 3 GeV Au+Au collisions**
- **Successfully separated emission source size from final state interactions in p-Λ & d-Λ correlation functions**

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

   $\boldsymbol{f_0 = 2.32^{+0.12}_{-0.11}}$ **fm** $\boldsymbol{d_0 = 3.5^{+2.7}_{-1.3}}$ **fm**
3. 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**
4. ${}^3_\Lambda H\ B_\Lambda = [0.04, 0.33]\ (MeV)$ @ 95% CL from d-Λ correlation (D)



Outlook:

More than 10 times statistics from BES-II

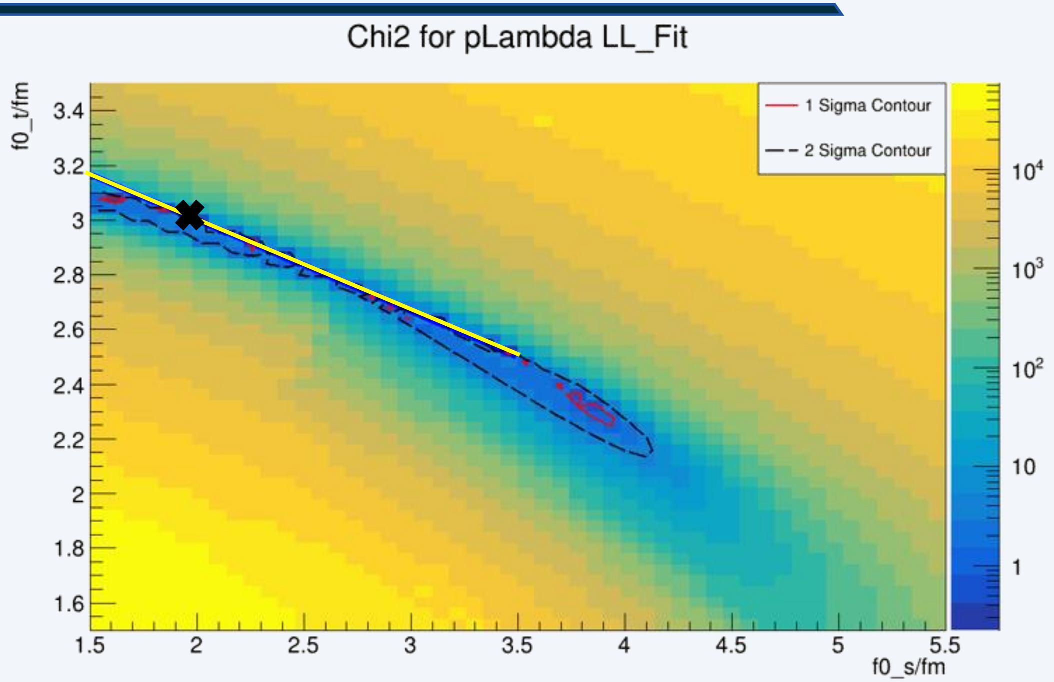
- Emission source size vs. energy, rapidity...
- Baryon correlations with different species

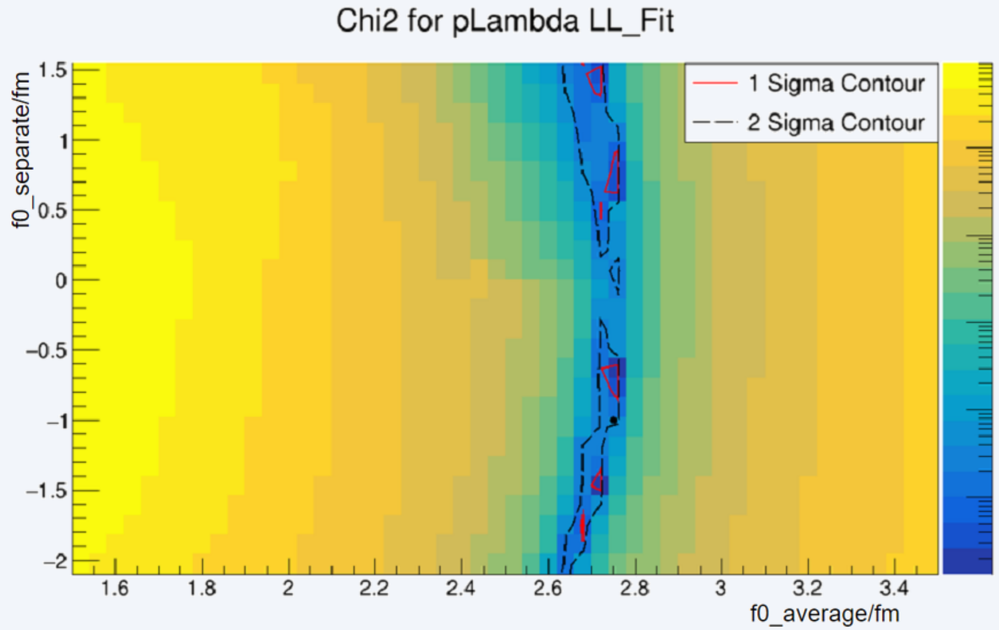
Thank you!

2023.11.10

Supported in part by U.S. DEPARTMENT OF ENERGY

Backup—Spin averaged f_0 , d_0 for $p\Lambda$





Input parameters(theoretically calculation):

$$r_G = 2.2\text{fm}$$
$$f_{0,s} = 2\text{fm},\ d_{0,s} = 2.46\text{fm}$$
$$f_{0,t} = 3\text{fm},\ d_{0,t} = 3.99\text{fm}$$

Yellow Straight Line(in top plot):

$$\frac{1}{4} f_{0,s} + \frac{3}{4} f_{0,t} = \frac{1}{4} \times 2\text{fm} + \frac{3}{4} \times 3\text{fm} = 2.75\text{fm}$$

So, theoretically we can't distinguish $f_0(d_0)$ of two spin from $p\Lambda$ CF theoretically

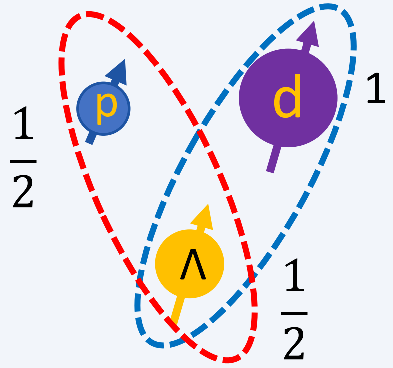
We can define:

$$f_{0,average} = \frac{1}{4} f_{0,s} + \frac{3}{4} f_{0,t}$$
$$f_{0,separate} = f_{0,s} - f_{0,t}$$

and get left plot, it shows that $f_{0,average}$ can be constrain well (~2.75fm), and no constrain for $f_{0,separate}$

So we use this spin-average spin definition to our data, and fix $f_{0,separate} = 0$

Backup— 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)

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

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

- ❖ 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**