Production of Unstable Light Nuclei in Au+Au Collisions at $\sqrt{s_{NN}}$ = 3 GeV with the STAR Detector

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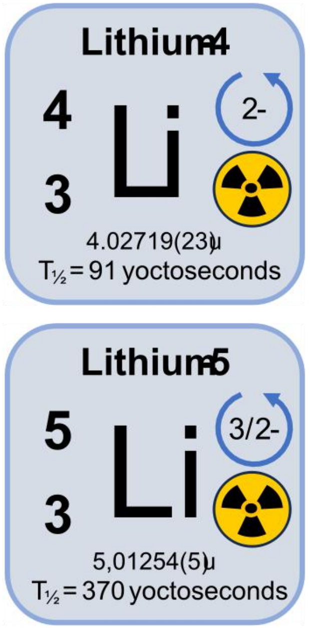
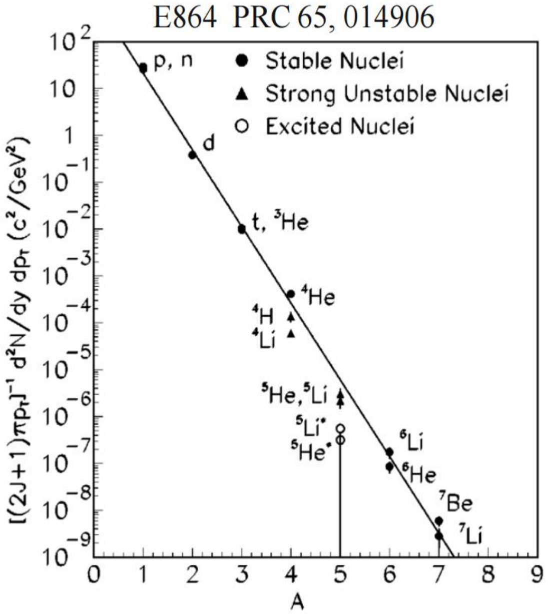
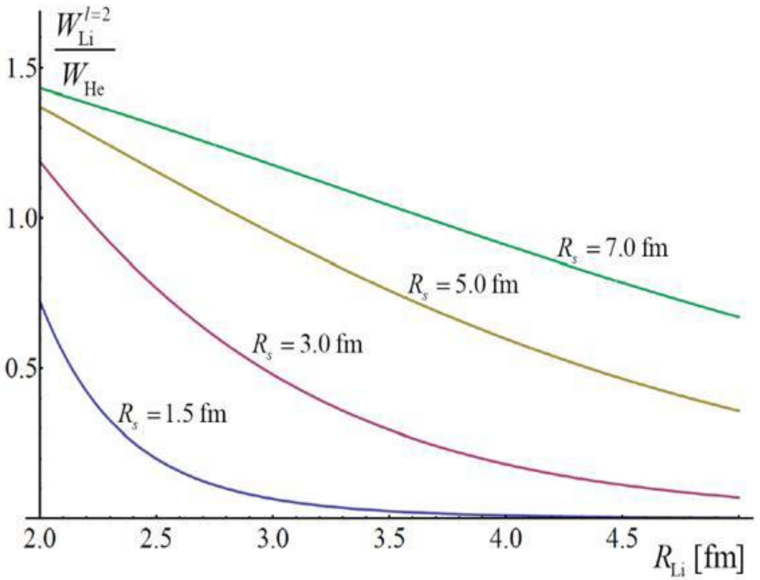
Motivation

1. Present systematic studies of light nuclei production at $\sqrt{s_{NN}}$ = 3 GeV, extending published results on stable light nuclei (*STAR Collaboration*, *Physical Review C 110, 054911 (2024)*).
2. To further understand the production mechanisms of light nuclei.
   Thermal production v.s. coalescence v.s. other possible mechanisms.
3. Unstable light nuclei will decay, which allows us to measure their polarization.
   This analysis will be the basis of polarization measurement.



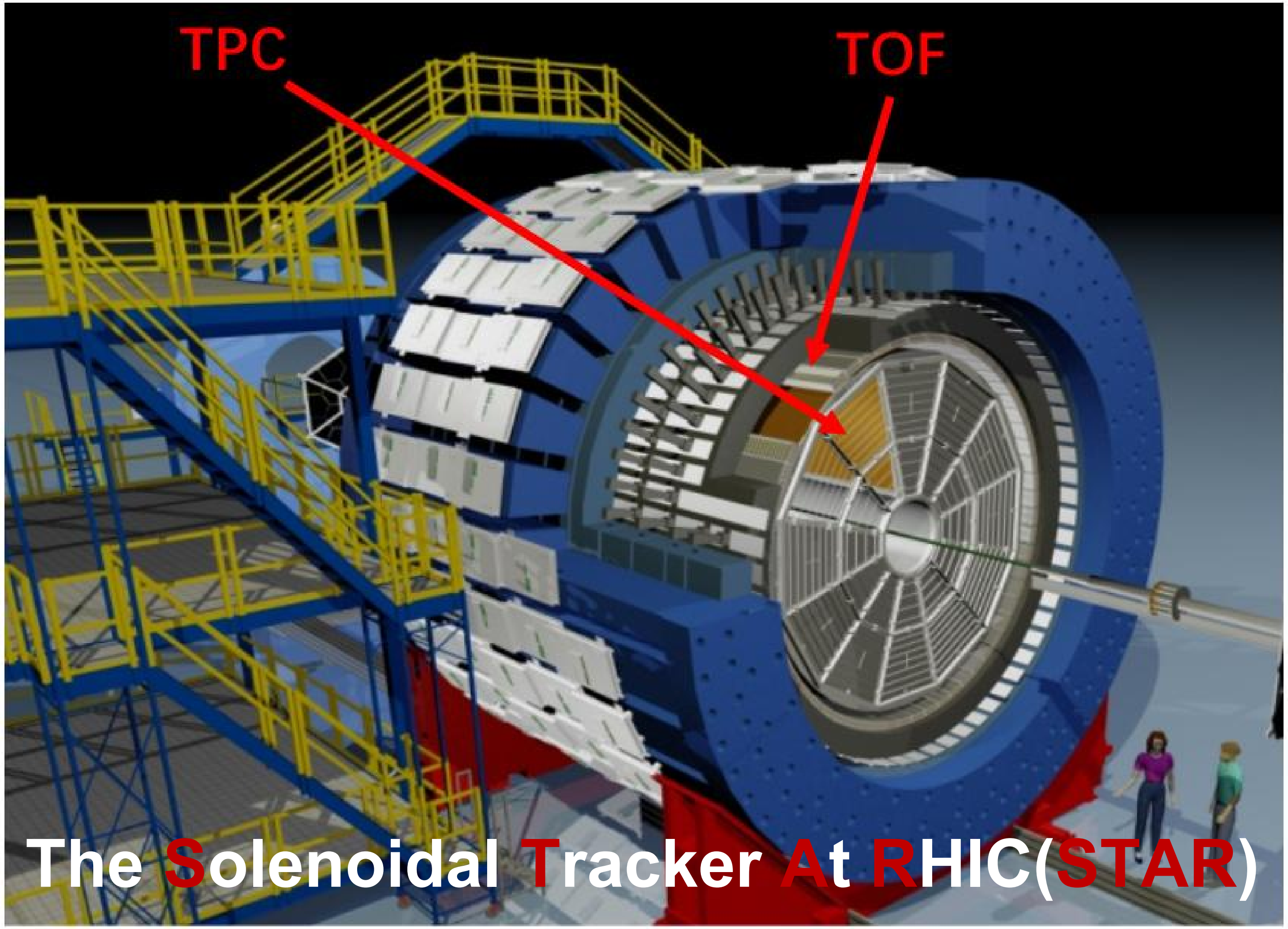


E864 Collaboration, PHYSICAL REVIEW C 65, 014906



Sylwia Bazak et al. , Mod. Phys. Lett. A (2018) 1850142

STAR Detector and Data Sets



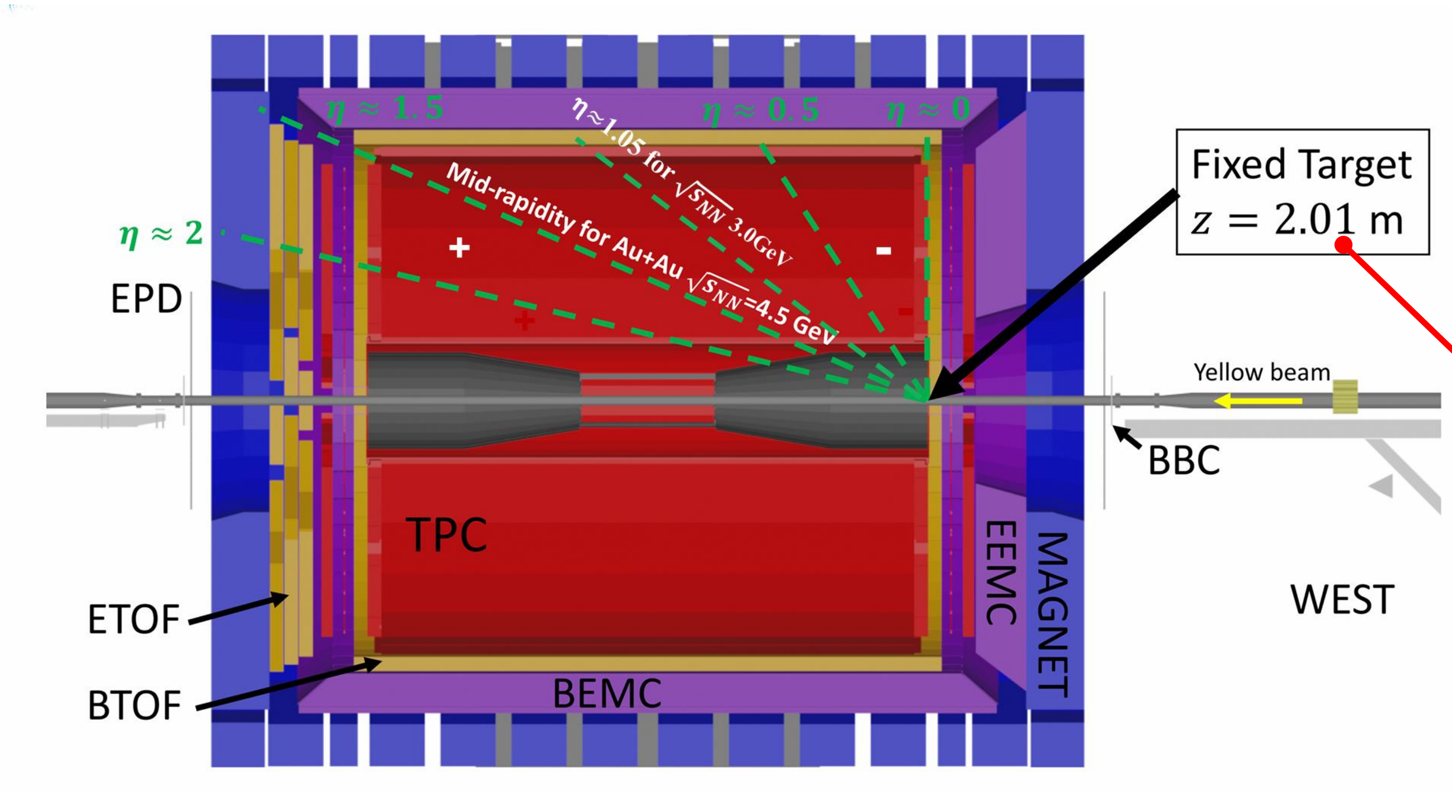
Time Projection Chamber (TPC)

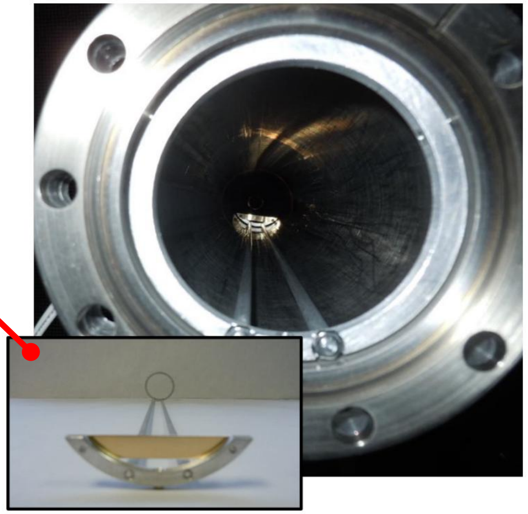
- Charged particle tracking
- Momentum reconstruction
- Particle identification from energy loss (dE/dx vs. p/q)

Time of Flight (TOF)

- Particle identification via m^2/q^2

STAR Detector and Data Sets



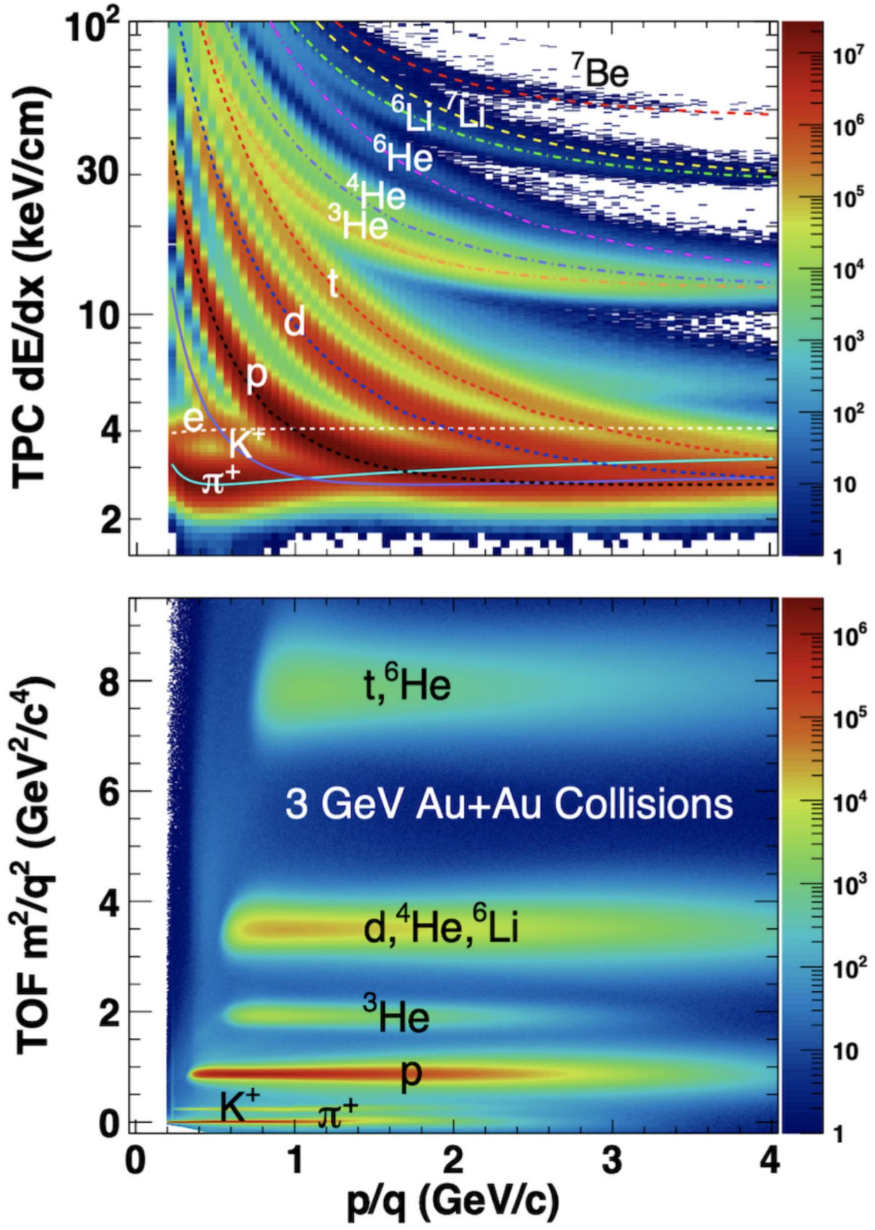


- Fixed Target Setup at STAR
- Au + Au $\sqrt{s_{NN}}$ = 3 GeV collected in 2018
- ~ 240M Events

Particle Identification

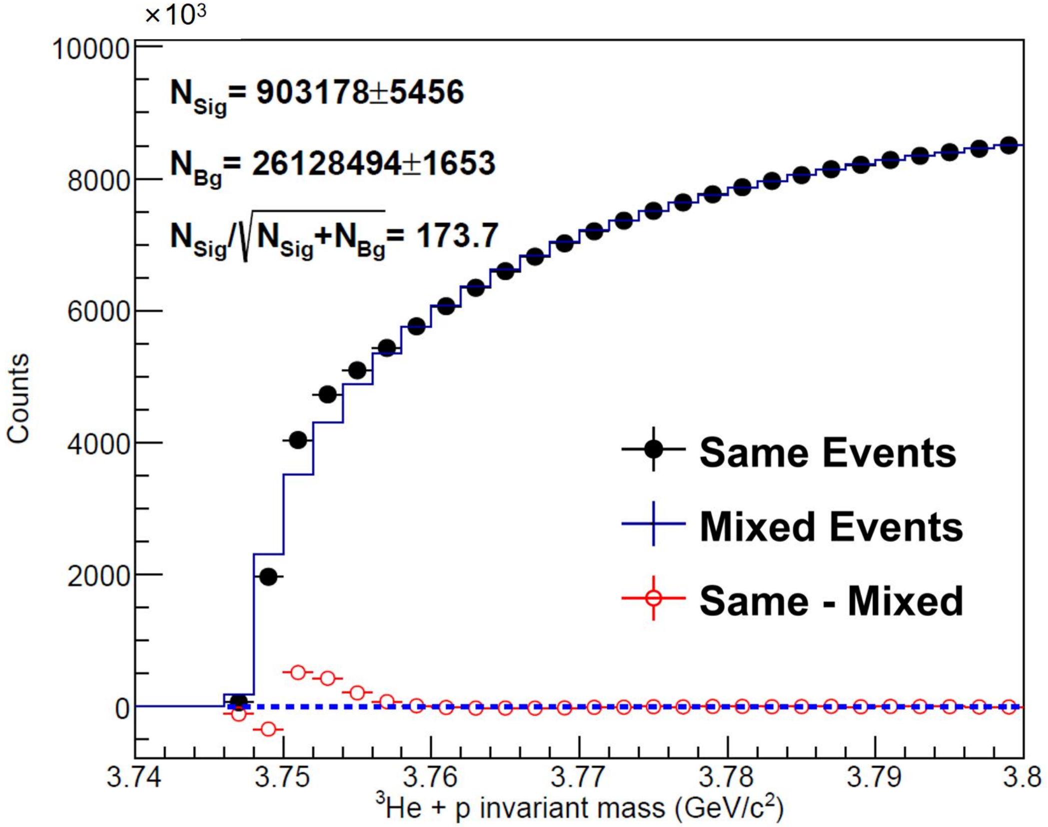
- ^4Li and ^5Li Reconstruction channels:
  - $^4Li \rightarrow {}^3He + p$ (B.R. = 100%)
  - $^5Li \rightarrow {}^4He + p$ (B.R. = 100%)

- Good particle identification capability based on TPC (dE/dx) and TOF (m^2/q^2) for charged particles: p, ^3He and ^4He.



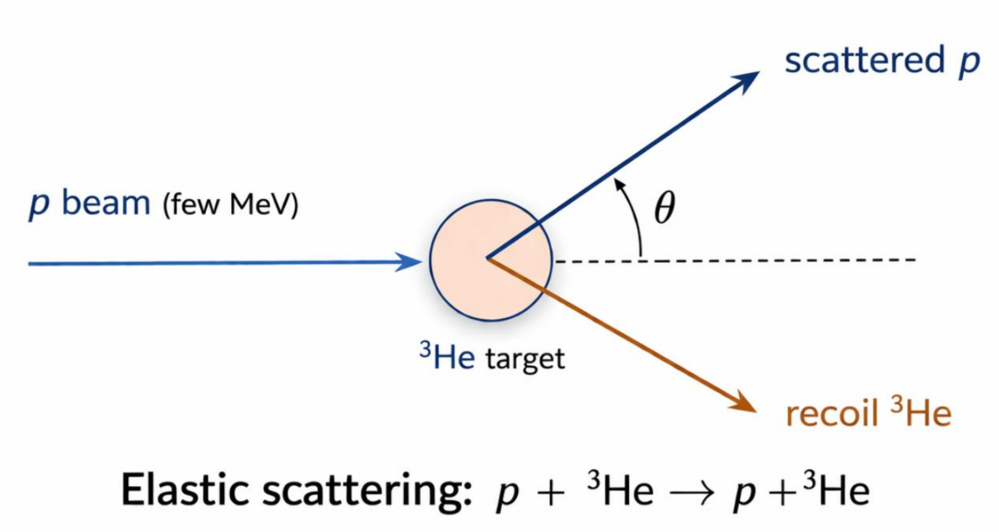
Background Handling

$^4Li \rightarrow {}^3He + p$



- The signal region is close to the threshold.
- Mixed-event (or rotation) background can lead to negative signal counts.
- The p-^{3}He corelation is mixed with ^{4}Li signal region.
- **The correlated background needs to be accounted.**

What is ^{4}Li? How was ^{4}Li first identified?



1. Measure the scattering cross-section, spin-related coefficients or polarization angle distribution. (Few MeV beam energy)

T. A. Tombrello, Physical Review Volume138， Number1B

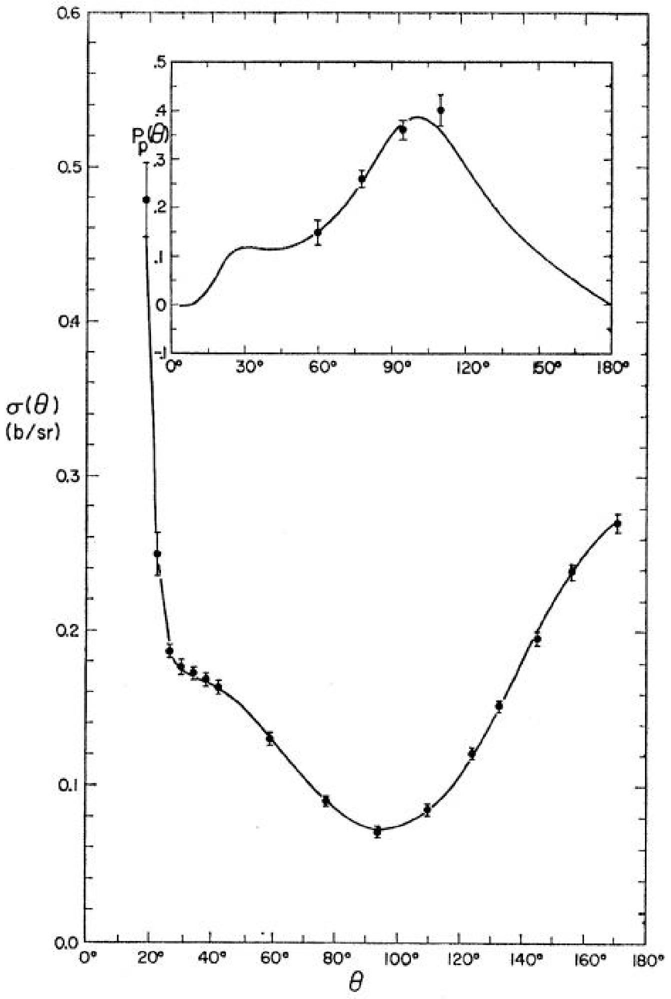


FIG. 5. The scattering and polarization data of Ref. 7 together with the fit corresponding to solution I at a proton energy of 4.00 MeV.

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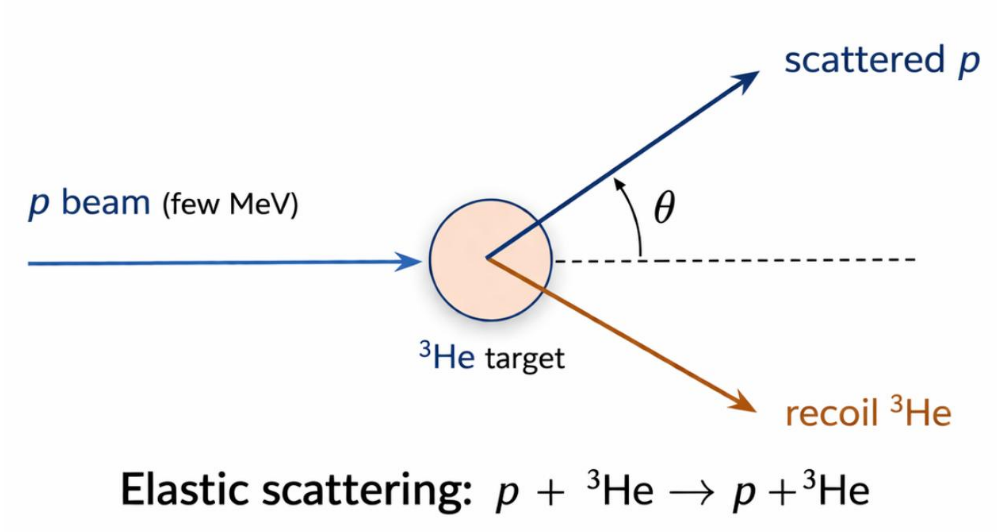
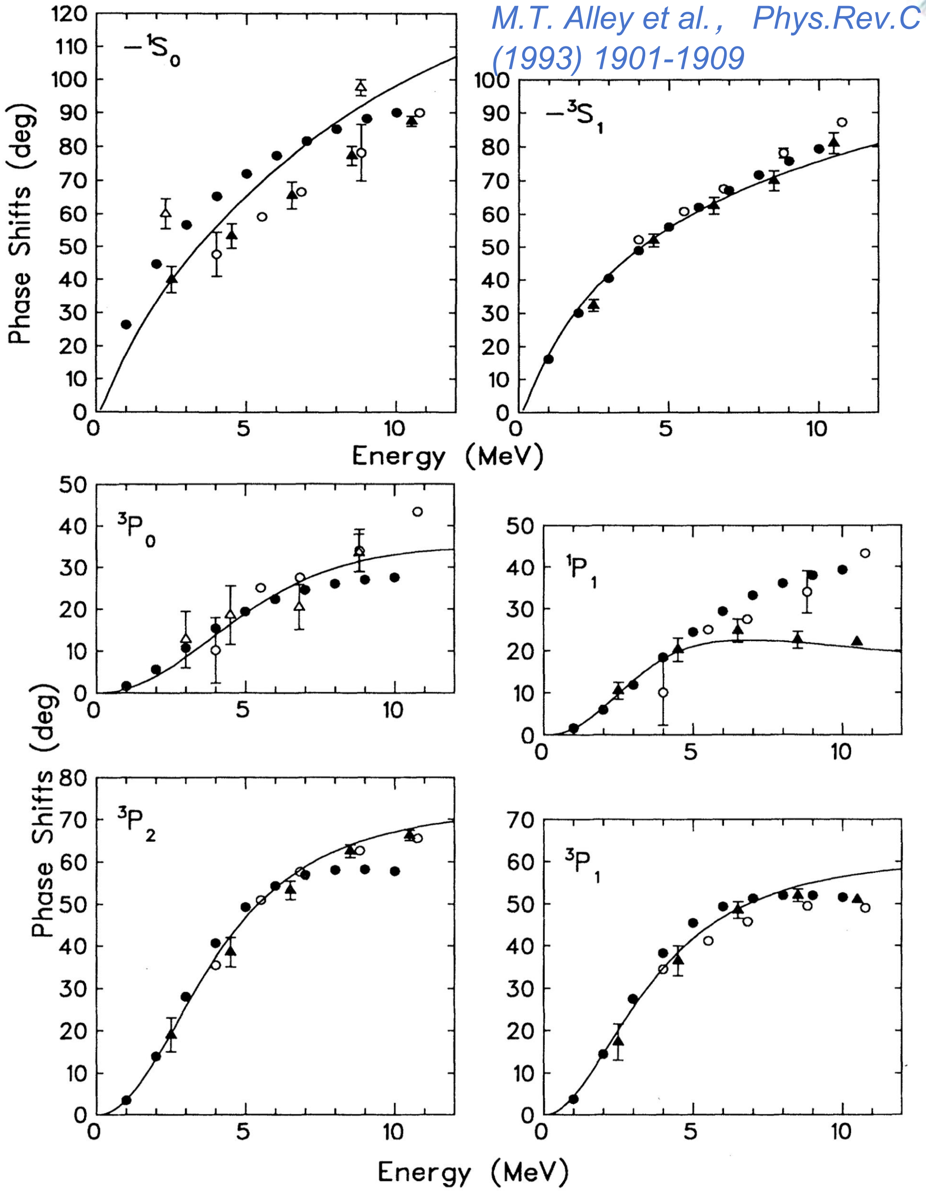


1. Measure the scattering cross-section, spin-related coefficients or polarization angle distribution. (Few MeV beam energy)
2. Phase-Shift analysis for each partial wave.



M.T. Alley et al., Phys.Rev.C 48 (1993) 1901-1909

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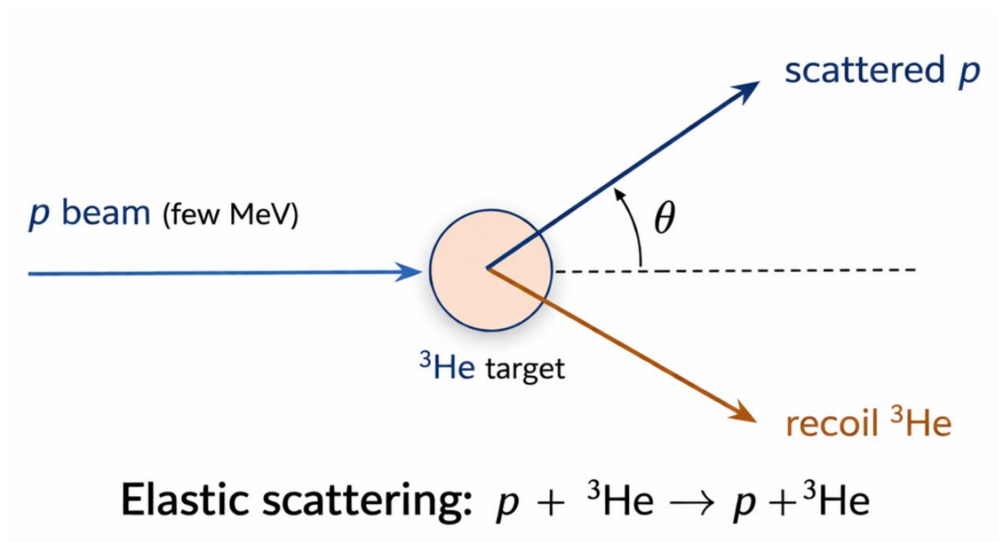
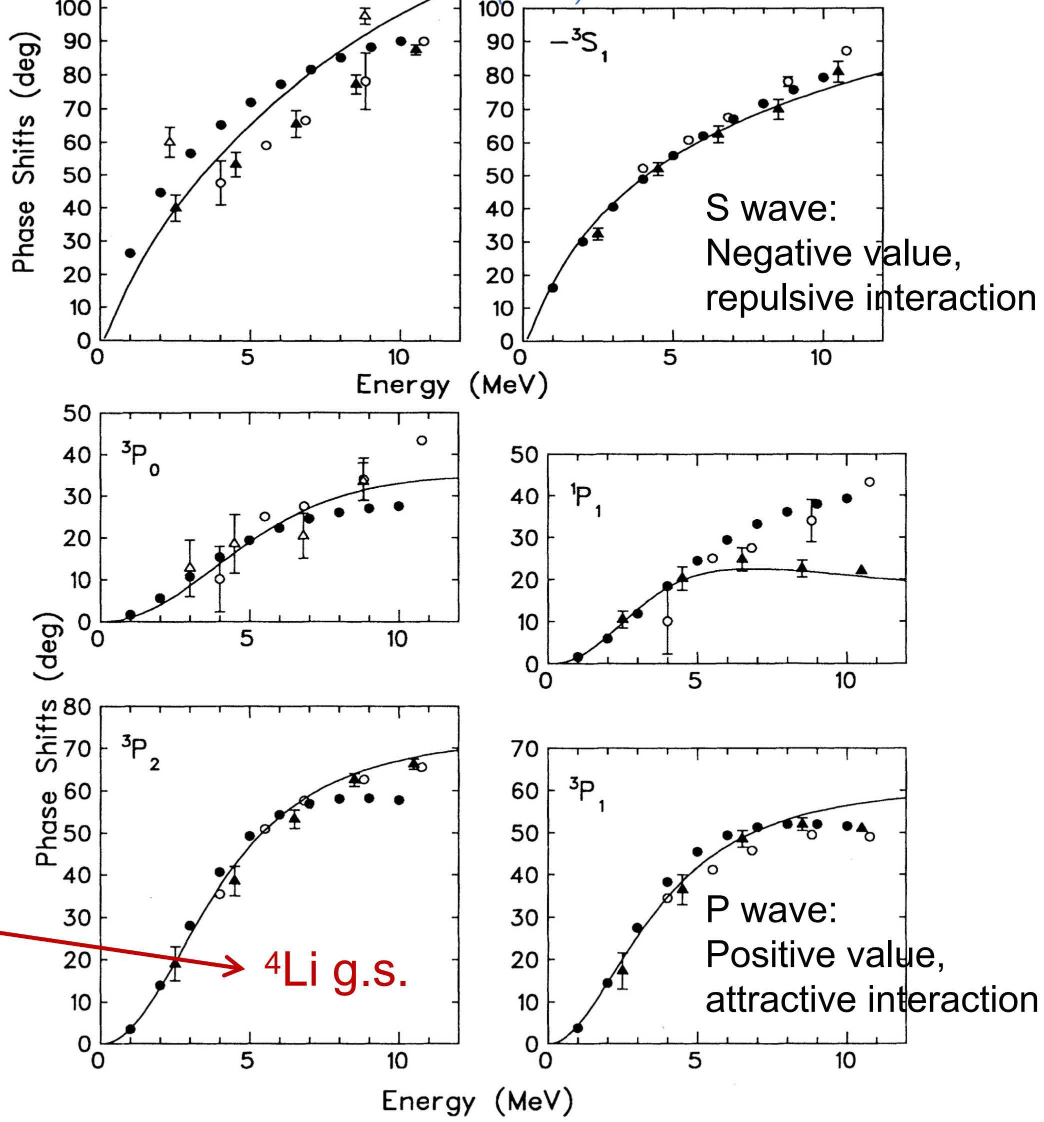


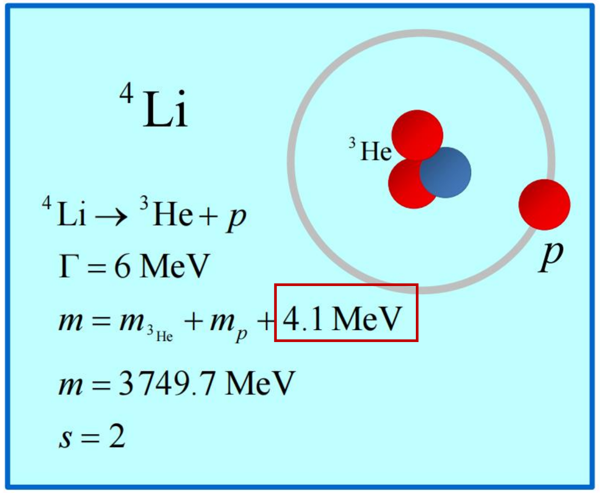
1. Measure the scattering cross-section, spin-related coefficients or polarization angle distribution. (Few MeV beam energy)
2. Phase-Shift analysis for each partial wave.
3. The phase shift of a specific partial wave shows a rapid change with energy, suggesting the existence of a resonance state here.

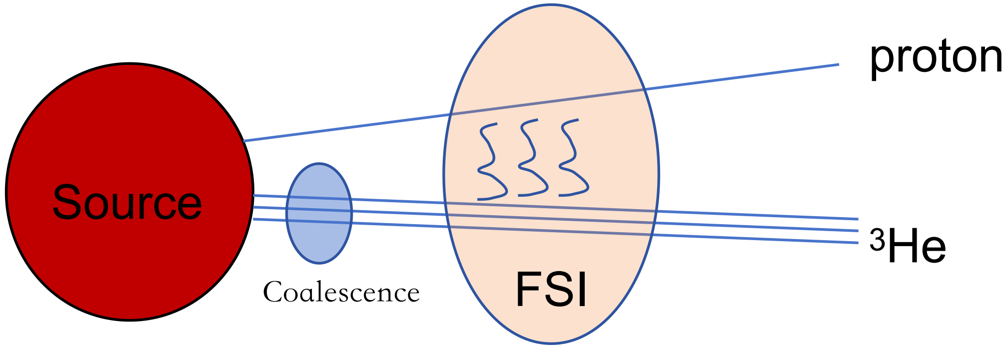
M.T. Alley et al., Phys.Rev.C 48 (1993) 1901-1909



Signal Extraction Technique

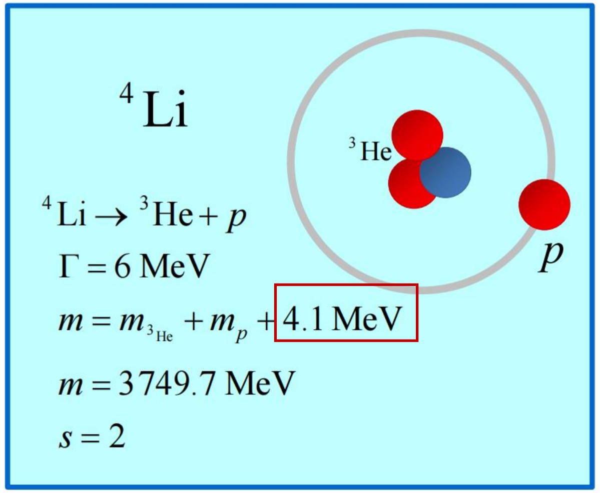
1. **The final-state interaction (FSI) of nuclear in HIC, corresponds to the low-energy nuclear scattering!**

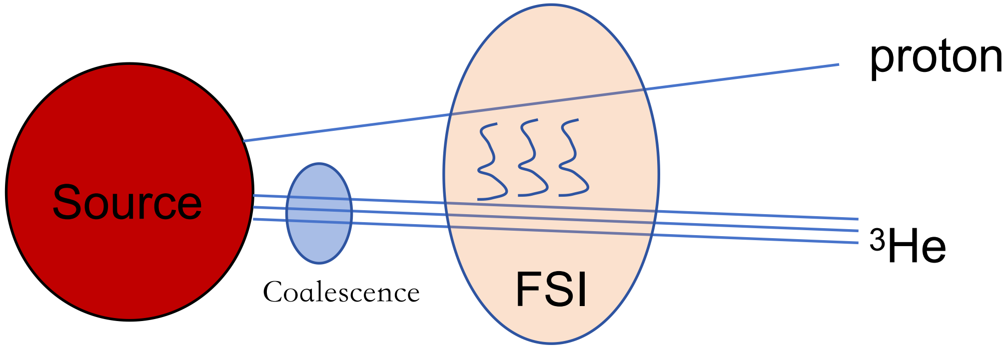




Signal Extraction Technique

1. **The final-state interaction (FSI) of nuclear in HIC, corresponds to the low-energy nuclear scattering!**
2. **$^3P_2$ wave of p-^{3}He is ^{4}Li**. Other partial-waves ($^3P_1$, $^3P_0$, $^1P_1$, $^1S_0$, $^3S_1$ ...) also contribute in the signal area.





$^1S_0 + {}^3S_1 + {}^1P_1 + {}^3P_1 + {}^3P_0 + {}^3P_2(^4\text{Li g.s}) + ...$

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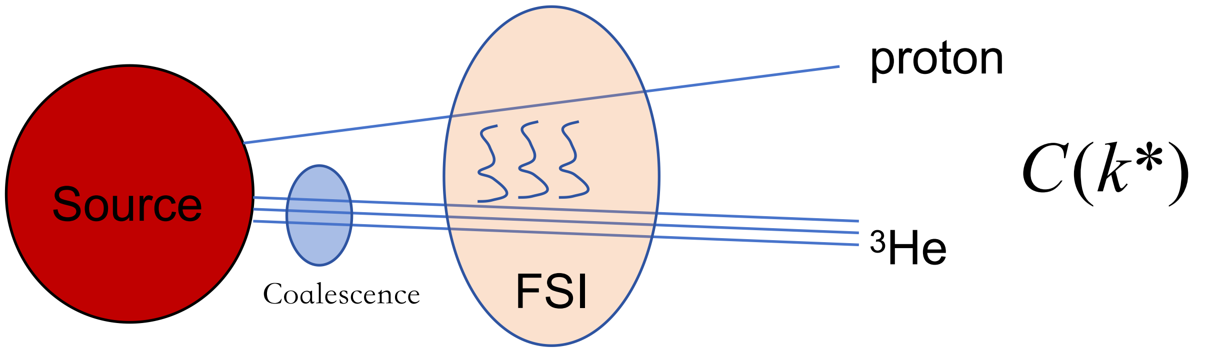
3. Correlation function C(k*) can be used to describe this FSI.

Definition of the correlation function C(k*)

$$C(k^*) = \frac{P(\vec{p}_1, \vec{p}_2)}{P(\vec{p}_1)P(\vec{p}_2)} = \boxed{\frac{N_{foreground}(k^*)}{N_{background}(k^*)}}$$

experimental

- P: The probability of observing particles with given momenta.
- k*: Relative momentum of the daughter particles in rest frame of particle pair.



$^1S_0+^3S_1+^1P_1+^3P_1+^3P_0+$**$^3P_2$(^{4}Li g.s)**+...

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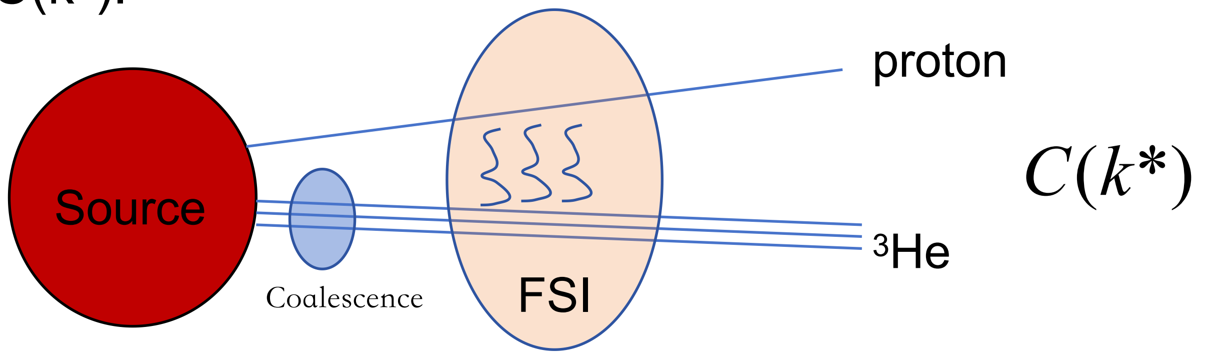
3. Correlation function C(k*) can be used to describe this FSI.
4. Lednicky-Lyuboshitz(LL) model is used to fit C(k*).

LL model：

- Wave function: $\psi(\vec{k}^*, \vec{r}) = \psi_{ingoing} + f \cdot \psi_{outgoing}$
- Source function：$S(\vec{r})$
- Scattering amplitude：f
- Koonin-Pratt equation：$C(\vec{k}^*) = \int d^3 r S(\vec{r}) \left|\psi(\vec{k}^*, \vec{r})\right|^2$



$^1S_0 + {^3S_1} + {^1P_1} + {^3P_1} + {^3P_0} +$ **$^3P_2$(^{4}Li g.s)**+...

Signal Extraction Technique

Three assumptions of LL model:

1. Asymptotic wave function: Confluent Hypergeometric function+ f*Coulomb wave function (The solution of the Schrödinger equation under the Coulomb potential)
2. Gaussian Source.
3. **Partial-wave scattering amplitude (f):**

Yu.V. Orlov, Nuclear Physics A 1004(2020) 122060

$$\widetilde{f}_l^{NC}(k) = \frac{1}{C_l^2 k(\cot\delta_l - i)}$$

phase-shift data

For any partial wave

l=0, even-order Taylor expansion →

$$\widetilde{f}_0^{NC} = \left[\frac{1}{a_0} + \frac{1}{2} d_0 k^2 - 2k\eta H(\eta) - ikC_0^2(\eta)\right]^{-1}$$

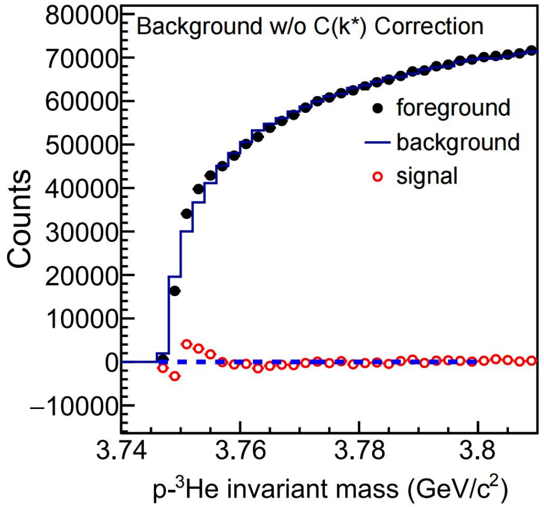
Only for S wave

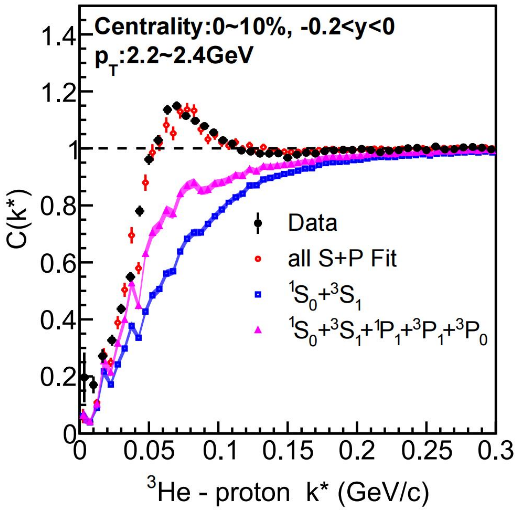
p-^{3}He: $C = n * \left(\frac{1}{4} C(^1S_0) + \frac{3}{4} C(^3S_1)\right) + (1-n) * \left(\frac{3}{12} C(^1P_1) + \frac{1}{12} C(^3P_0) + \frac{3}{12} C(^3P_1) + \frac{5}{12} C(^3P_2)\right)$

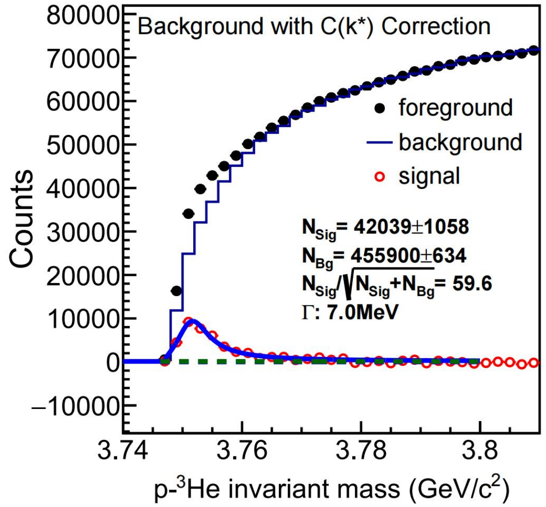
p-^{4}He: $C = n * C(S) + (1-n) * \left(\frac{1}{3} C(P_{1/2}) + \frac{2}{3} C(P_{3/2})\right)$

- n is fraction of the S wave, Gauss Source size R_g, both are determined by fitting the experimental data.
- Spin degeneracy factor $\frac{(2S+1)}{(2s_1+1)(2s_2+1)} \cdot \frac{(2J+1)}{(2L+1)(2S+1)}$

Signal Extraction Technique





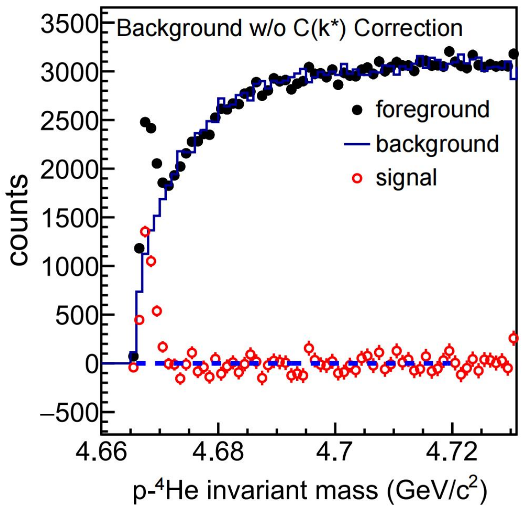


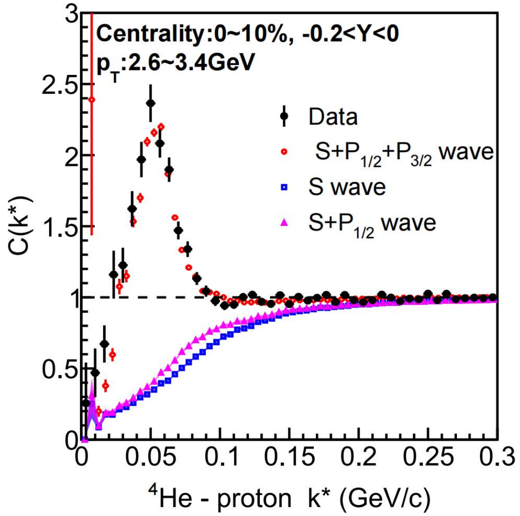
$$d^{sill}(E) = \frac{2E}{\pi} \frac{\sqrt{E^2 - E_{th}^2}\,\tilde{\Gamma}}{(E^2 - M^2)^2 + (E^2 - E_{th}^2)\tilde{\Gamma}^2} \theta(E - E_{th})$$

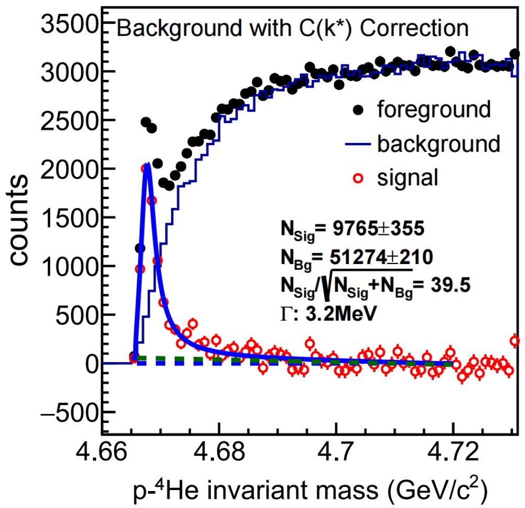
$$\tilde{\Gamma} = \frac{\Gamma M}{\sqrt{M^2 - E_{th}^2}}$$

- The blue line shows the fit using the Sill function

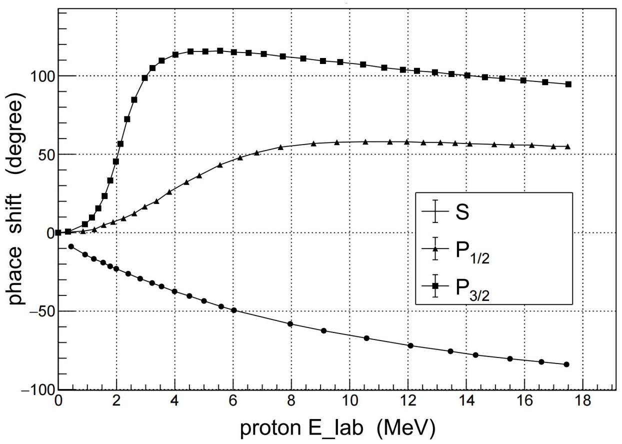
Francesco Giacosa et al., Eur. Phys. J. A (2020) 56:193



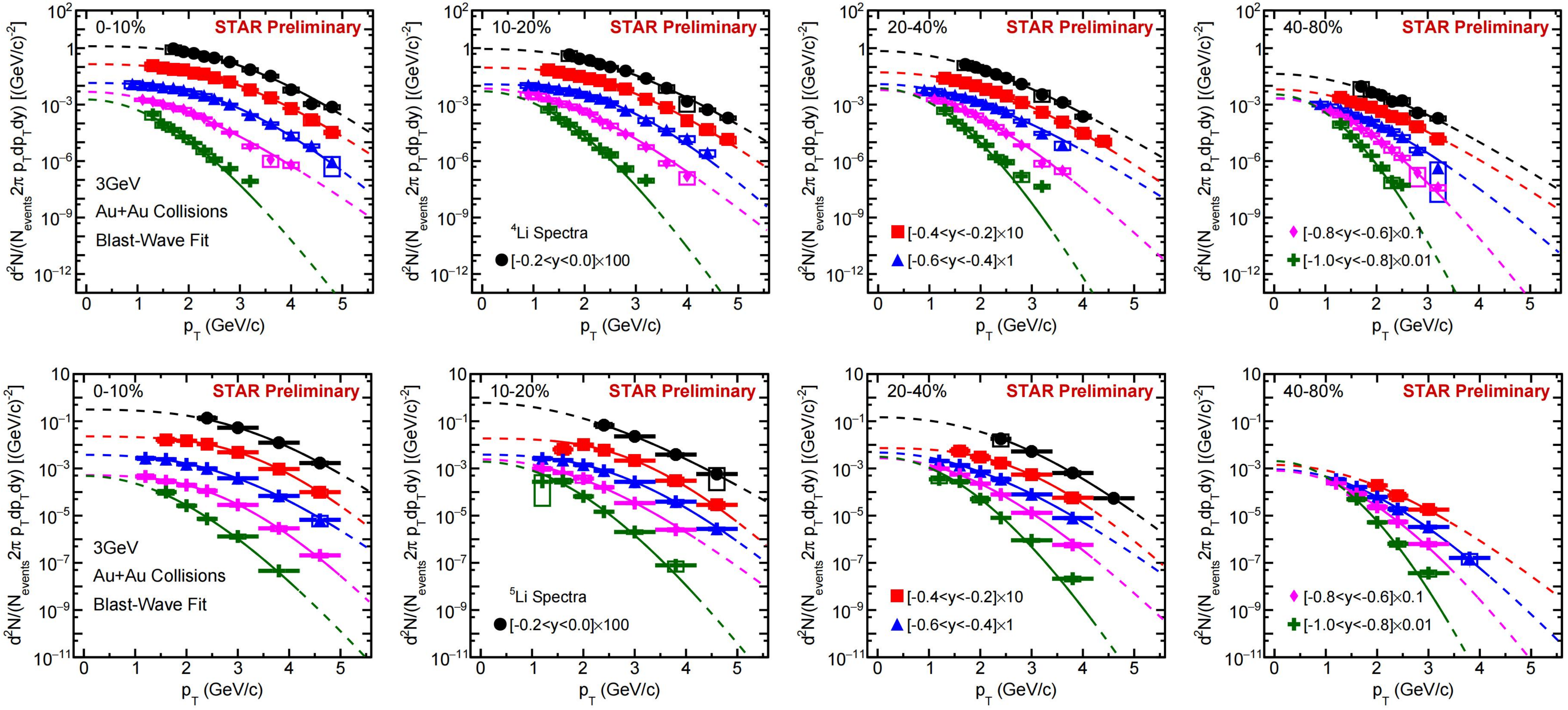




P. Schwandt et al., Nuclear Physics A163 (1971) 432-448



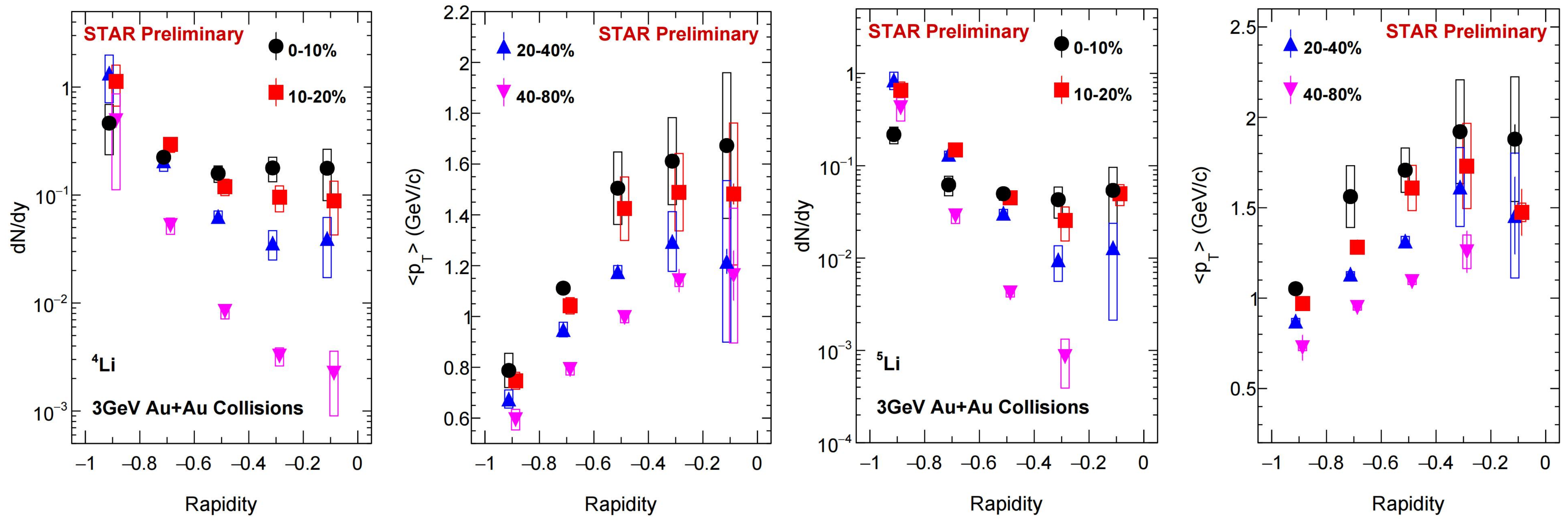
p_T Spectra



$$\frac{1}{2\pi p_T}\frac{d^2N}{dp_T dy} \propto \int_0^R r dr m_T I_0\left(\frac{p_T \sinh\rho}{T}\right) K_1\left(\frac{m_T \cosh\rho}{T}\right)$$

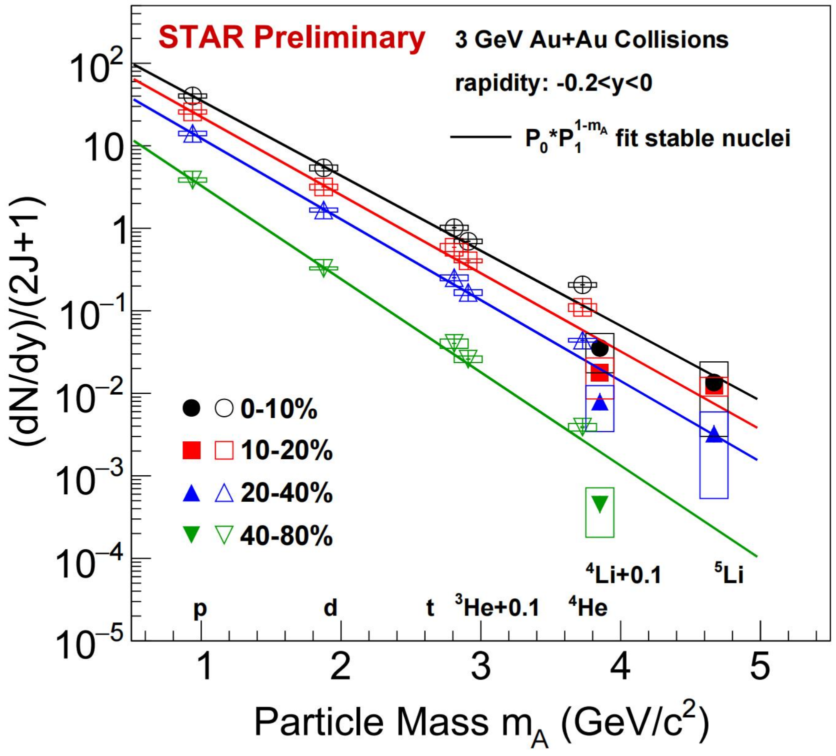
- Efficiencies are obtained using Monte Carlo simulations embedded to data.

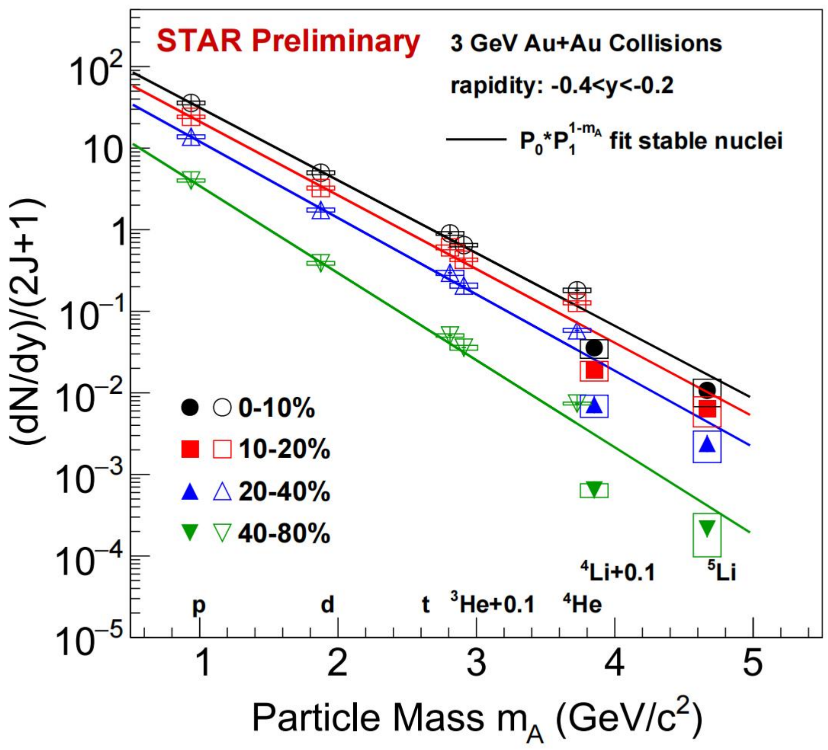
dN/dy Yield and mean p_T



- The trend of yield and mean p_T as function of rapidity is similar to that of stable light nuclei.

dN/dy Yield and mean p_T





- The baseline was obtained by fitting the stable light nucleus yields with an exponential function.
- The yield of ^{4}Li is significantly lower than the baseline in midrapidity.

stable light nuclei data： STAR Collaboration, PHYSICAL REVIEW C 110, 054911 (2024)

- Production mechanism of unstable light nuclei: **it is influenced not only by the mass number A, but also by the partial-wave scattering cross sections of its constituents.**

$$\sigma_l(E) = \frac{4\pi(2l+1)}{k^2}\sin^2(\delta_l(E))$$

p-^{3}He $\sigma(^3P_2)$ < p-^{4}He $\sigma(P_{3/2})$

Summary and Outlook

Summary:

1. First measurement of unstable light nuclei (^{4}Li and ^{5}Li) yield in Au+Au at $\sqrt{s_{NN}}$ = 3 GeV with STAR.
2. A new method to extract near-threshold resonance signals. Partial wave method+phase-shift data + Lednicky–Lyuboshitz model.
3. ^{4}Li yield (over 2J+1) is significantly lower than that of ^{4}He, which implies that the production mechanisms may be different.

Outlook:

1. Systematic study of energy dependence.
2. Extension to flow and polarization measurements.

Thanks for your attention!