Short-range correlations in stable and asymmetric nuclei investigated at R³B

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Short-range correlations

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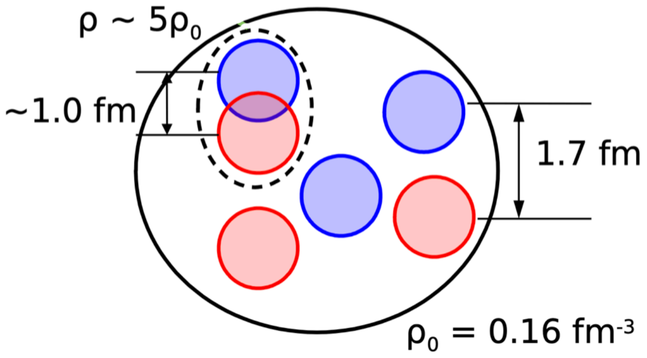
SHORT-RANGE CORRELATIONS

- **< 1 fm** distance.
- **Hard repulsive core** of the NN interaction.
- Study the in-medium and with **large N/Z asymmetry**.
- **This work.**



Data
SRC sim

Short-range correlations

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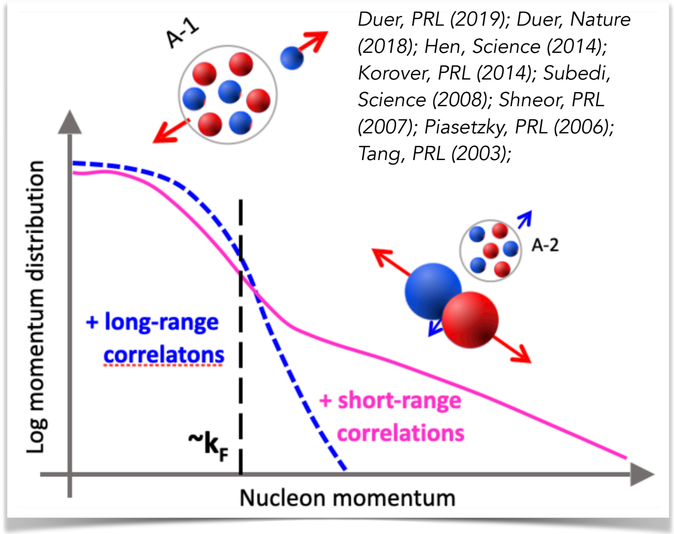
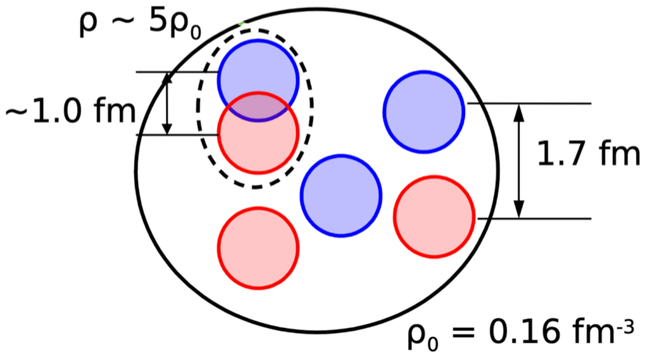
- **High relative momentum and low centre of mass (c.m.) momentum pairs;**
  - **Dominance of p-n** over p-p SRC pairs;
  - **pp/pn ratio** does not change with A;
  - The fraction of high momentum protons **increases with N/Z**.
- **Generalized Contact Formalism (GCF):**
  - **Model tuned for SRC:** nuclear wave function as a product of a short-distance and mean-field term.

R.Weiss , N. Barnea. Phys. Rev. C, 96:041303 (2017).



Duer, PRL (2019); Duer, Nature (2018); Hen, Science (2014); Korover, PRL (2014); Subedi, Science (2008); Shneor, PRL (2007); Piasetzky, PRL (2006); Tang, PRL (2003);



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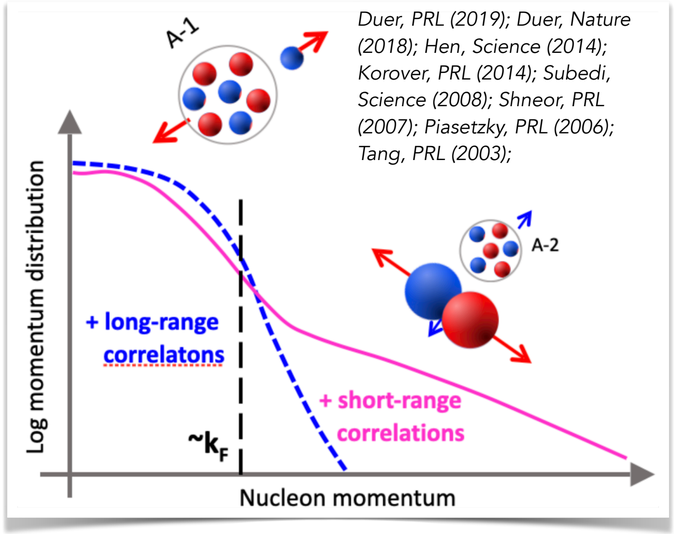

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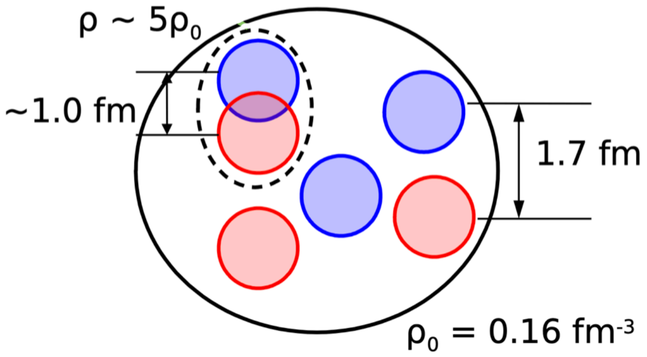
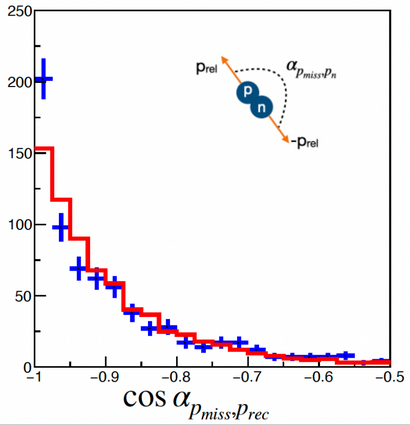
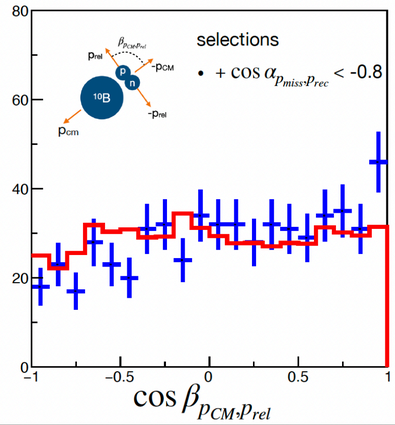






Data
SRC sim

GOALS

- **SRC measurement with high statistics** in ^{12}C at 1.25 GeV/u.
- **First measurement of SRC in radioactive nuclei (^{16}C).**
- **SRC quantum number measurement** through **final state selectivity.**

R^3B Setup

Experiment location:

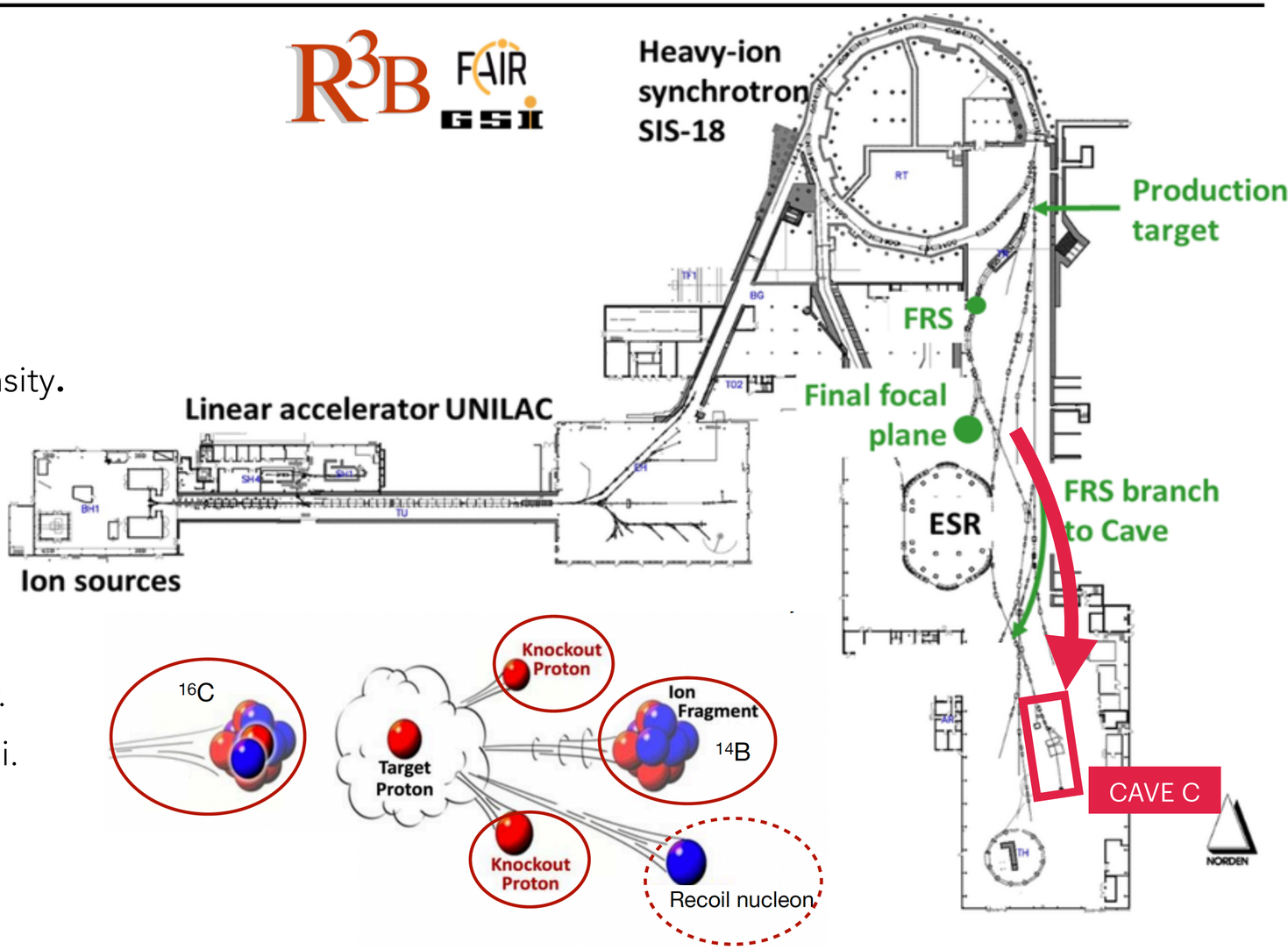
- **FAIR GSI,** Darmstadt, Germany;

Beam Setup for Experiment:

1. **UNILAC:** stable isotopes up to 11.4 AMeV.
   - **Primary beam of ^{12}C, 1.25 GeV/u, $5 \cdot 10^5$ pps** intensity**.**
   - **Primary beam ^{18}O.**

2. **SIS 18 Synchrotron:** beams up to 1 GeV/u.
3. **FRS:** secondary radioactive beams:
   1. Secondary ^{16}C beam, 1.25 GeV/u, 10^5 pps intensity.
   2. Magnetic rigidity (Bρ): 17.63 Tm for A/Z ≈ 2.5 nuclei.

4. **Cave C:** Inverse kinematic reaction.



R^3B Setup

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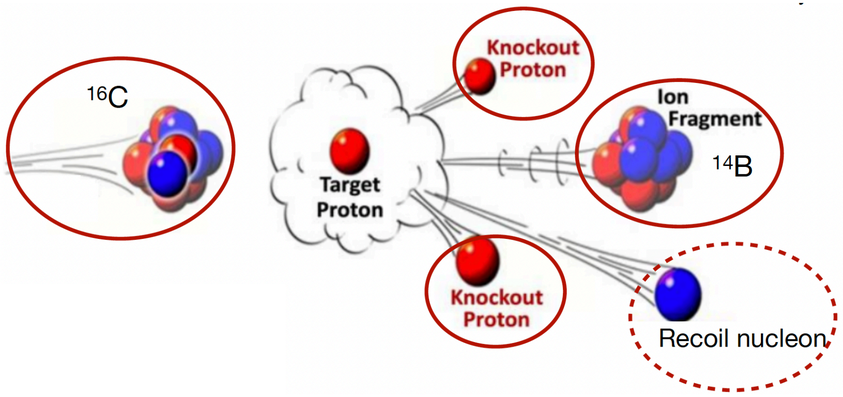


pn pairs

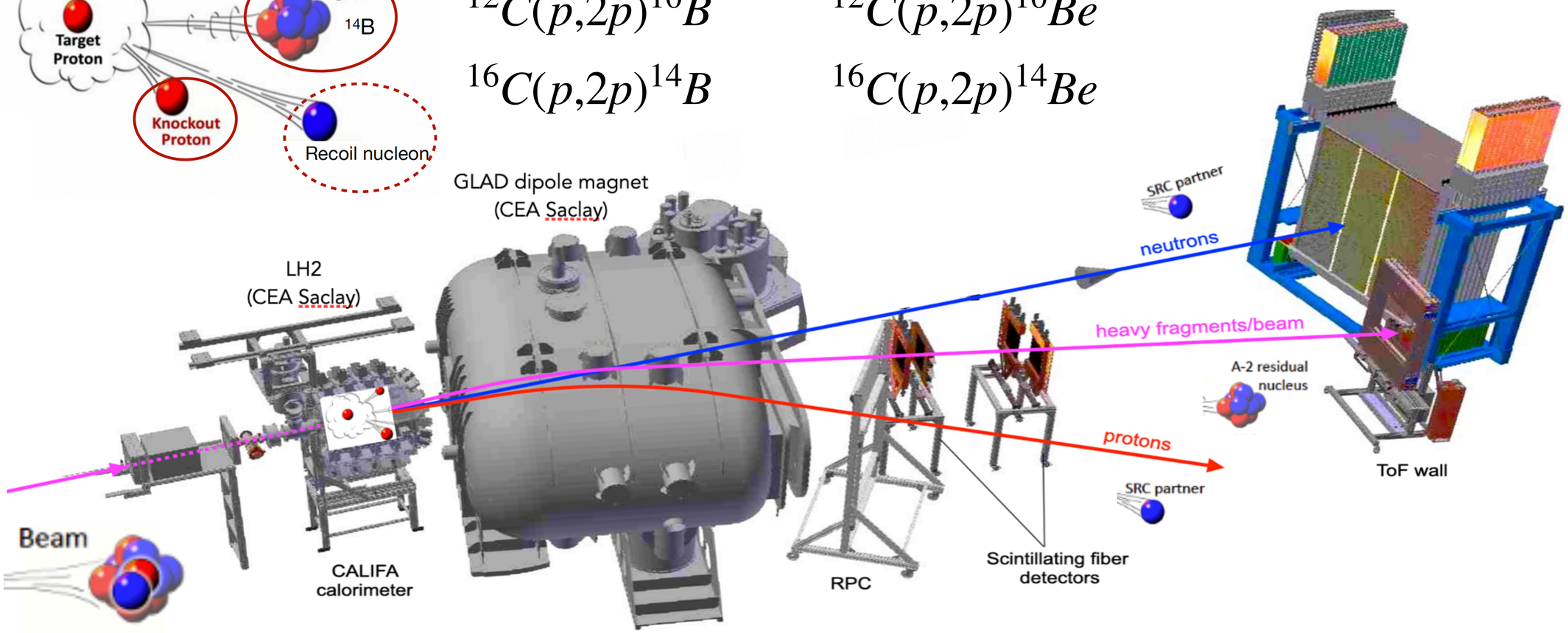
$^{12}C(p,2p)^{10}B$

$^{16}C(p,2p)^{14}B$

pp pairs

$^{12}C(p,2p)^{10}Be$

$^{16}C(p,2p)^{14}Be$



Simulation guided SRC selection

SRC signal

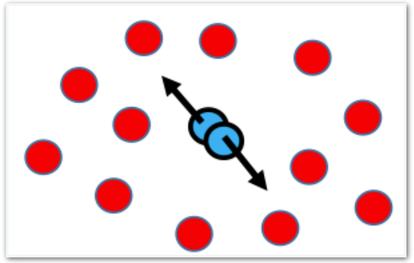
SRC signature modeled with Generalized Contact Formalism (GCF):

- Factorization of **SRC pair** and **A-2 system**.
- **High relative momentum** between the SRC pair nucleons.

$$\Psi(r_1, r_2, \dots, r_A) \xrightarrow{r_{12}\to 0} \varphi(\boldsymbol{r}) \times A\left(\boldsymbol{R}, \{\boldsymbol{r}_k\}_{k\neq 1,2}\right)$$

Universal function
(but depends on the potential)
Short-Range

Nucleus-dependent function
Mean-Field



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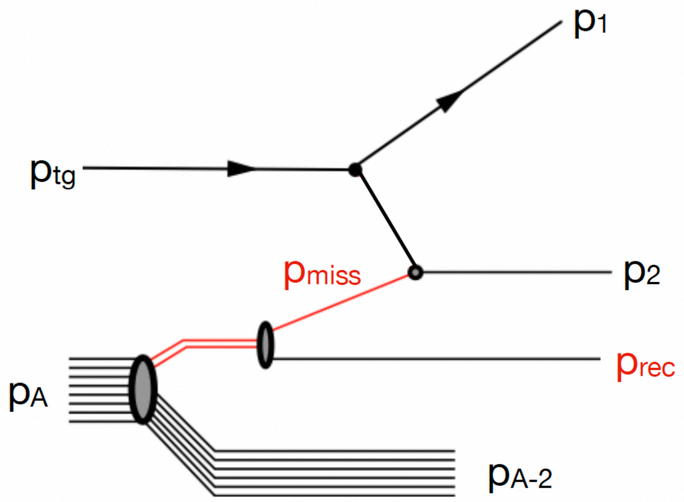
Background signal

Background modeled with QFS simulation:

- Mean-field proton scattering with **neutron evaporation**.
- $^{12}C(p,2p)^{11}B, ^{11}B^* -> ^{10}B + n$
- Neutron decay: realistic ^{11}B excitation energy spectrum.

SRC selection: Suppress mean-field and FSI



QE proton scattering benchmark: $^{12}C(p,2p)^{11}B$

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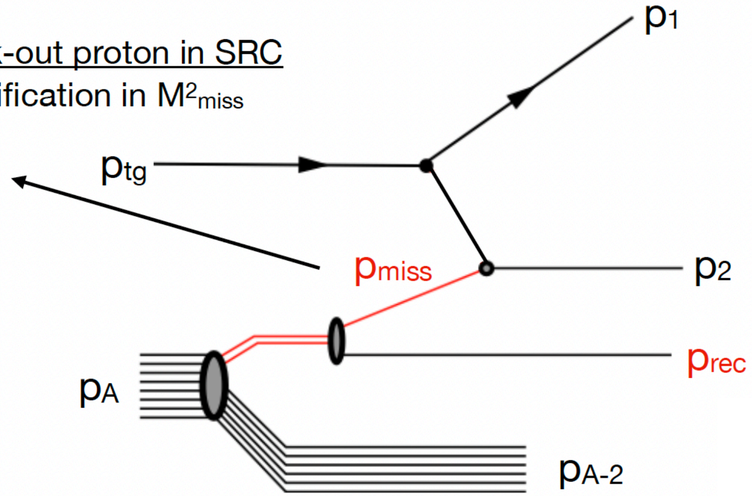
Initial state of knock-out proton in SRC
High p_{miss}; QE identification in M^2_{miss}
$p_{miss} = p_1 + p_2 - p_{tg}$

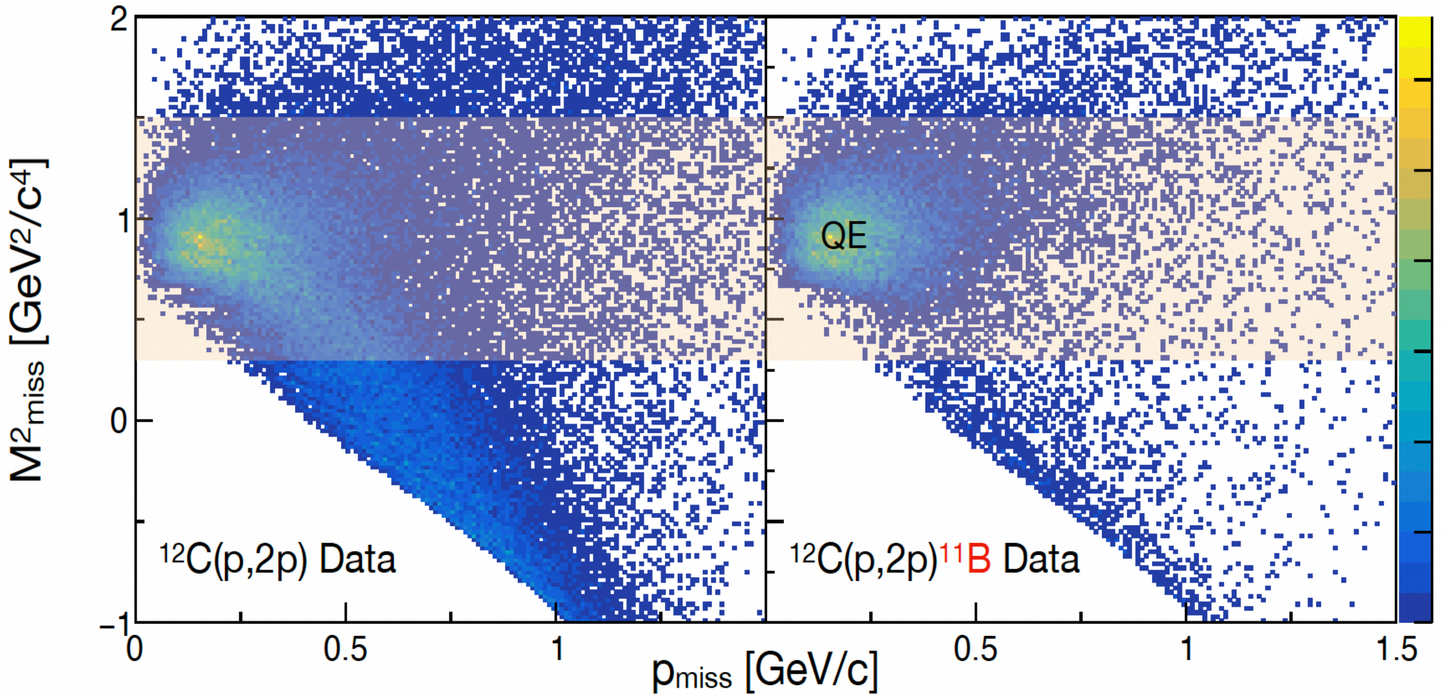


QFS

- **High-energy proton** hits a nucleus, knocking out one proton.
- **Minimal excitation of the remaining system.**
- Most energy and momentum transfer used to **remove one proton**.

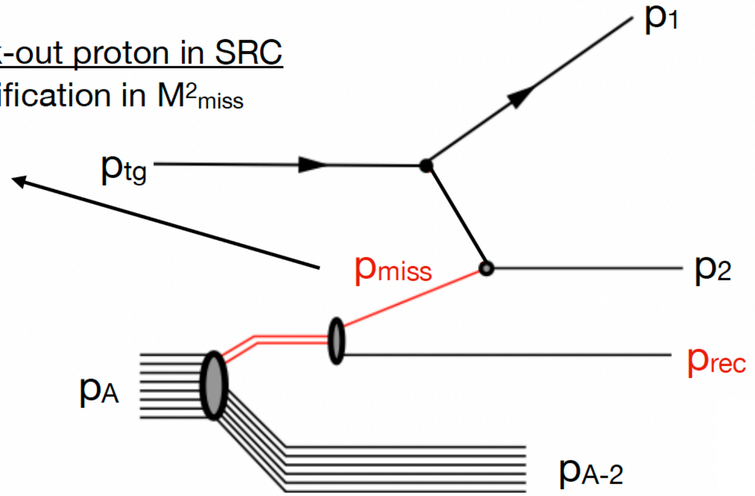
Selections:

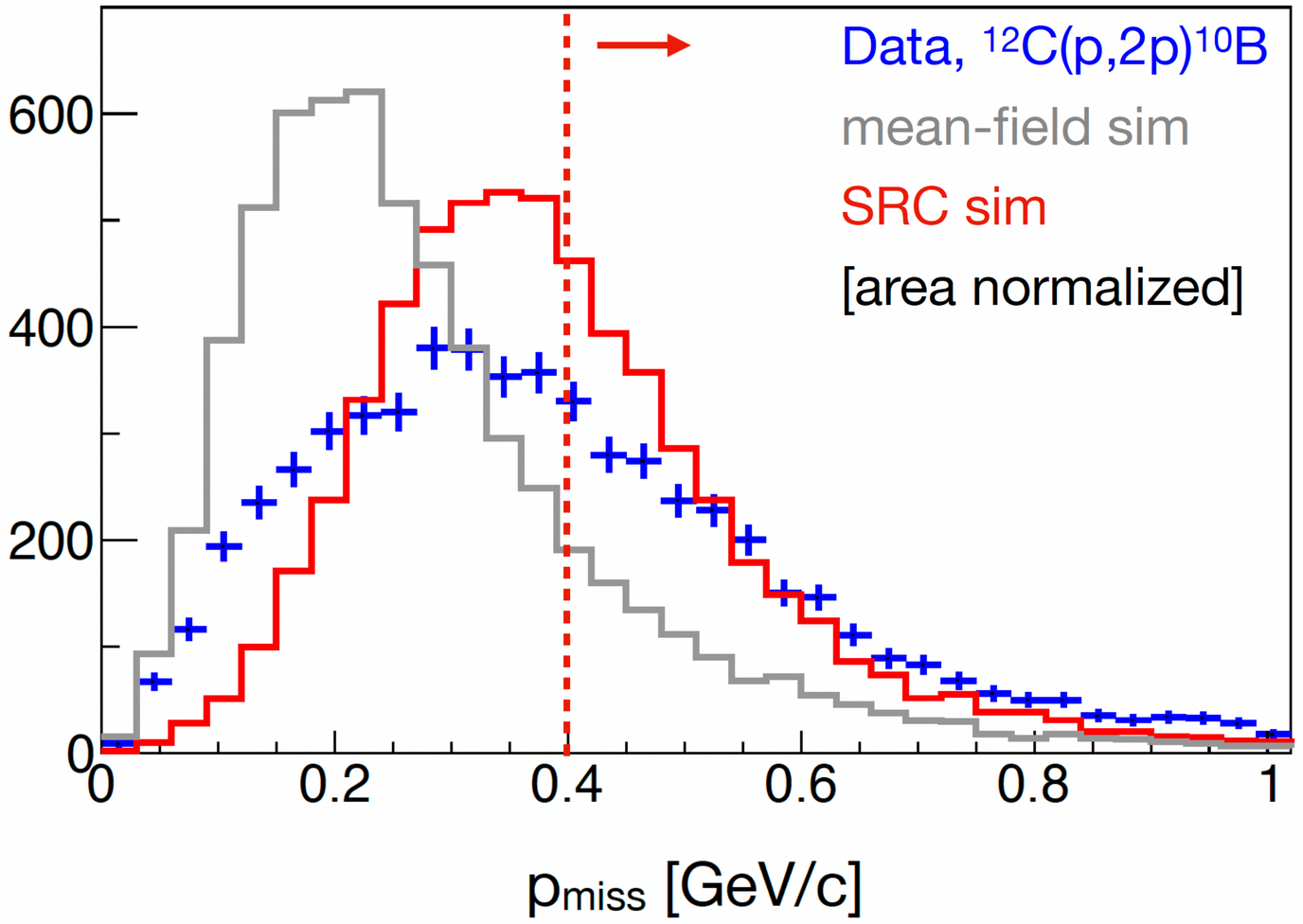
- (p,2p) tagging
- ^{11}B selection
- $|t|, |u| > 0.8\ GeV^2$



SRC selection: High missing momentum

Initial state of knock-out proton in SRC
High p_{miss}; QE identification in M^2_{miss}
$p_{miss} = p_1 + p_2 - p_{tg}$

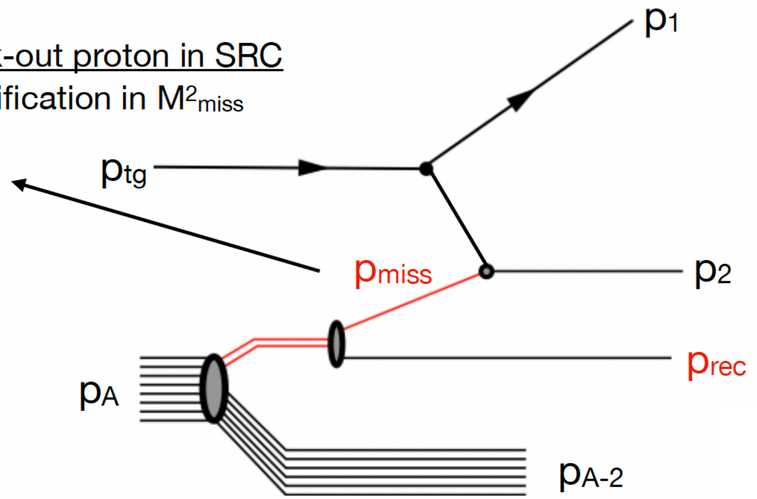




Selections:

- (p,2p) tagging
- ^{10}B selection
- $|t|, |u| > 0.8\ GeV^2$
- $0.3 < M^2_{miss} < 1.5\ GeV^2/c^4$

SRC selection: On-shell recoil nucleon mass



Initial state of knock-out proton in SRC

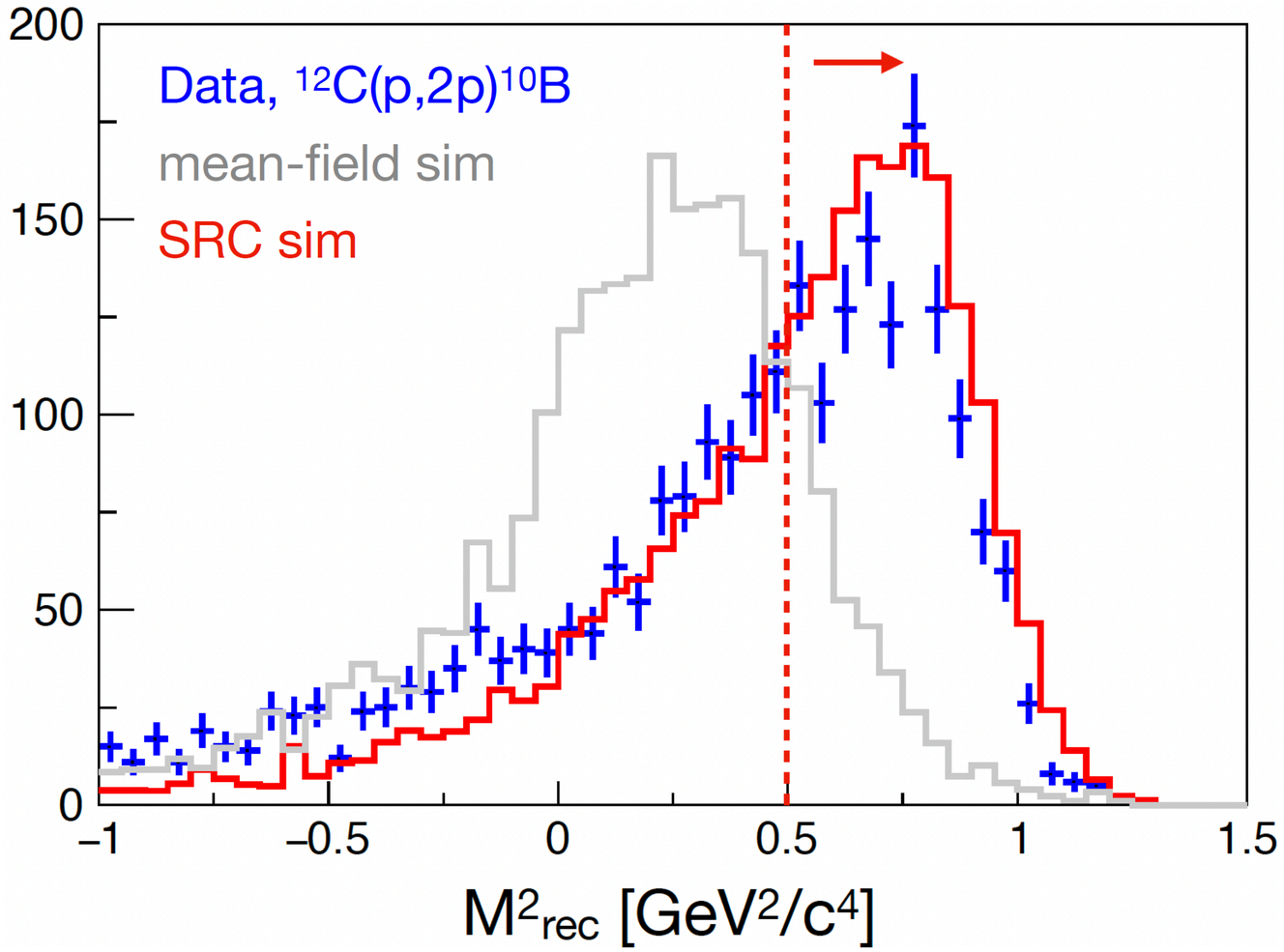
High p_{miss}; QE identification in M^2_{miss}

$p_{miss} = p_1 + p_2 - p_{tg}$

On-shell recoil nucleon

$p_{rec} = p_A + p_{tg} - p_1 - p_2 - p_{A-2}$

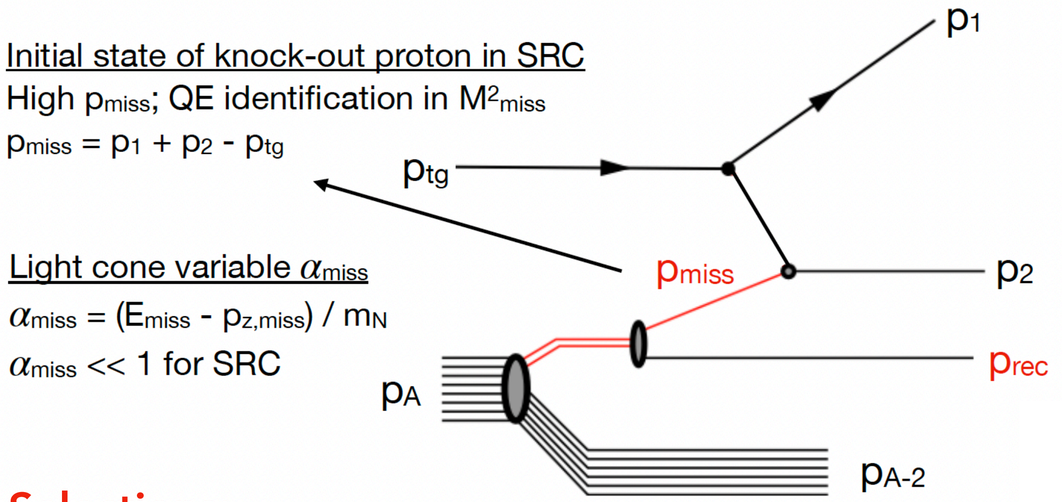
$M^2_{rec} = p^2_{rec}$



Selections:

- (p,2p) tagging
- ^{10}B selection
- $|t|, |u| > 0.8\ GeV^2$
- $0.3 < M^2_{miss} < 1.5\ GeV^2/c^4$
- $P_{miss} > 0.4\ GeV/c$

SRC selection: Light-cone variable



Initial state of knock-out proton in SRC

High p_{miss}; QE identification in M^2_{miss}

$p_{miss} = p_1 + p_2 - p_{tg}$

Light cone variable α_{miss}

$\alpha_{miss} = (E_{miss} - p_{z,miss}) / m_N$

$\alpha_{miss} << 1$ for SRC

Selections:

- (p,2p) tagging
- ^{10}B selection
- $|t|, |u| > 0.8\ GeV^2$
- $0.3 < M^2_{miss} < 1.5\ GeV^2/c^4$
- $P_{miss} > 0.4\ GeV/c$
- $0.5 < M^2_{rec} < 1.1\ GeV^2/c^4$

On-shell recoil nucleon

$p_{rec} = p_A + p_{tg} - p_1 - p_2 - p_{A-2}$

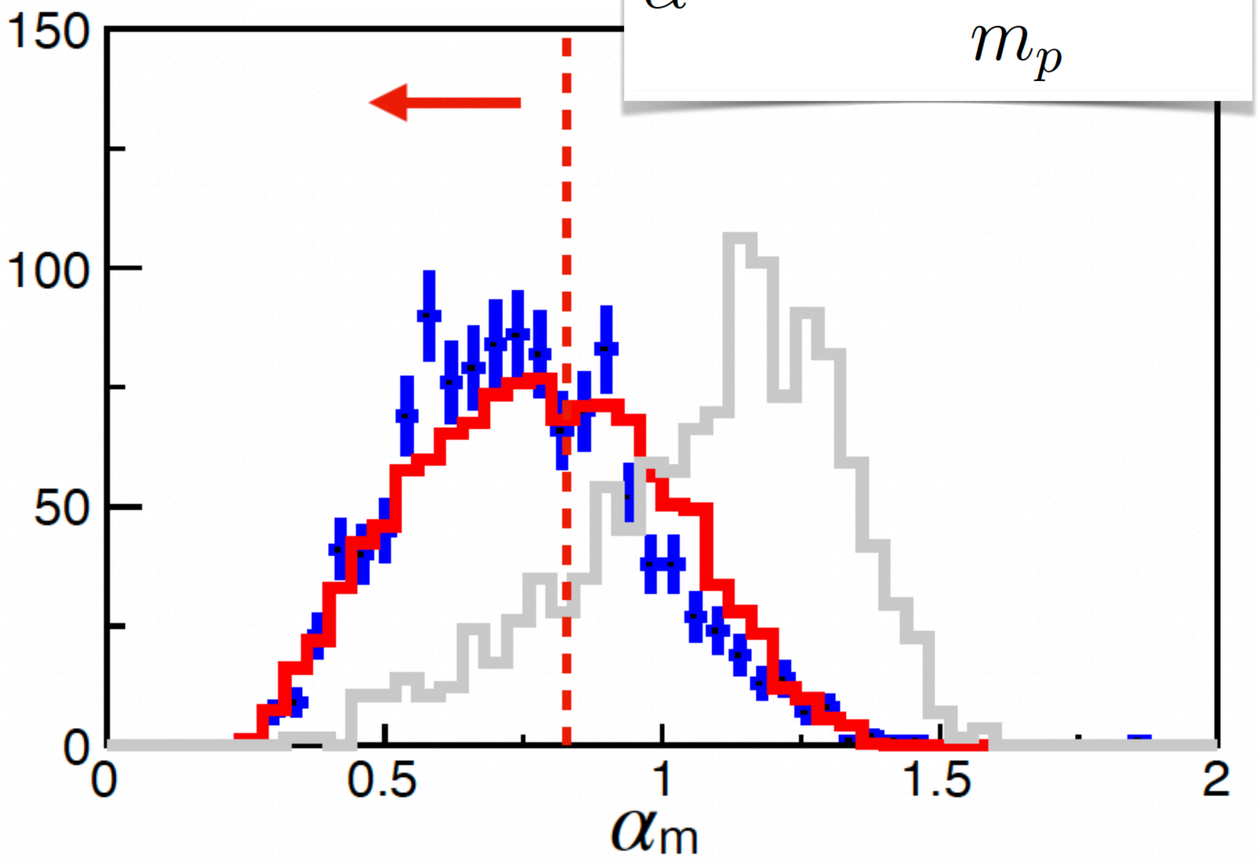
$M^2_{rec} = p^2_{rec}$

Data, $^{12}C(p,2p)^{10}B$

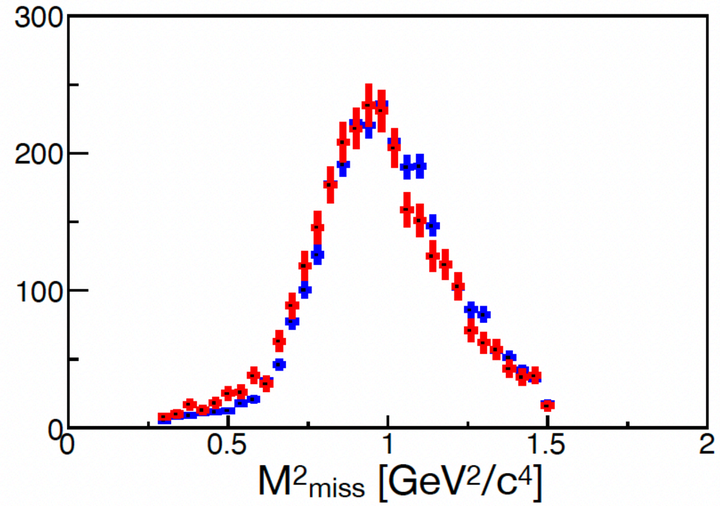
mean-field sim

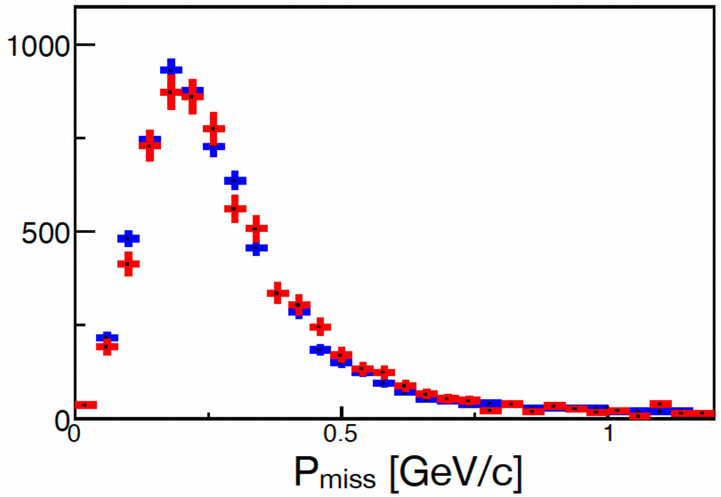
SRC sim

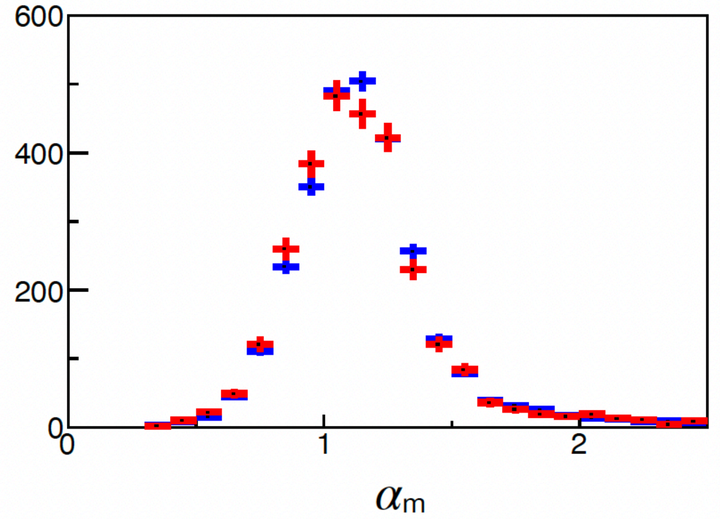
$$\alpha = \frac{E_{\mathrm{miss}} - p_{z,\mathrm{miss}}}{m_p}$$

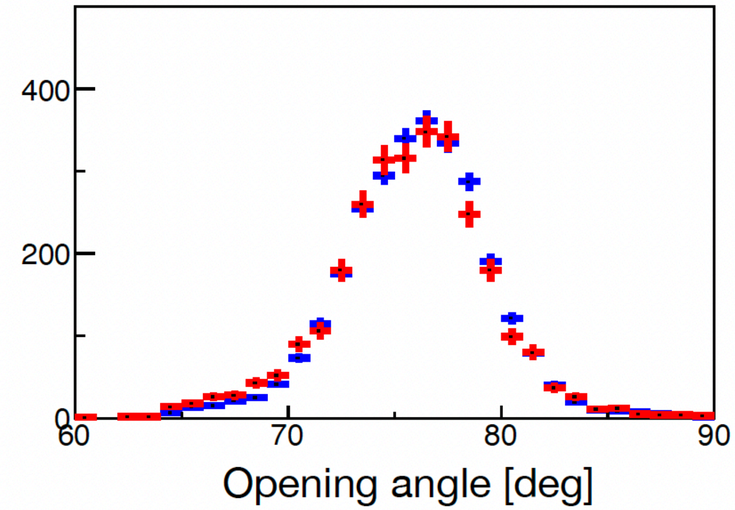


^{12}C as reference for ^{16}C









$^{16}C(p,2p)^{15}B$ Data

$^{12}C(p,2p)^{11}B$ Data

Selections:

- (p,2p) tagging
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- $0.3 < M^2_{miss} < 1.5\ GeV^2/c^4$

$^{10}B/^{10}Be$ channels: SRC signature

Data
mean-field sim
SRC sim
SRC + MF fit

Selections:

- (p,2p) tagging
- $^{10/14}B/Be$ selection
- $|t|, |u| > 0.8\ GeV^2$
- $0.3 < M^2_{miss} < 1.5\ GeV^2/c^4$
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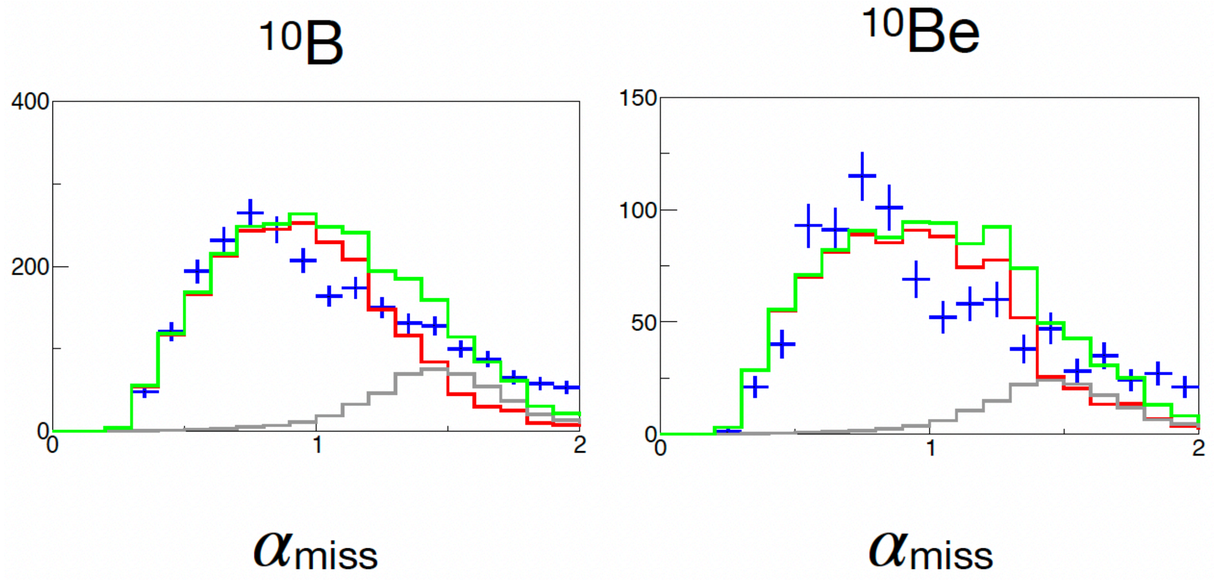

^{14}Be channel: SRC signature

Data
mean-field sim
SRC sim
SRC + MF fit

Selections:

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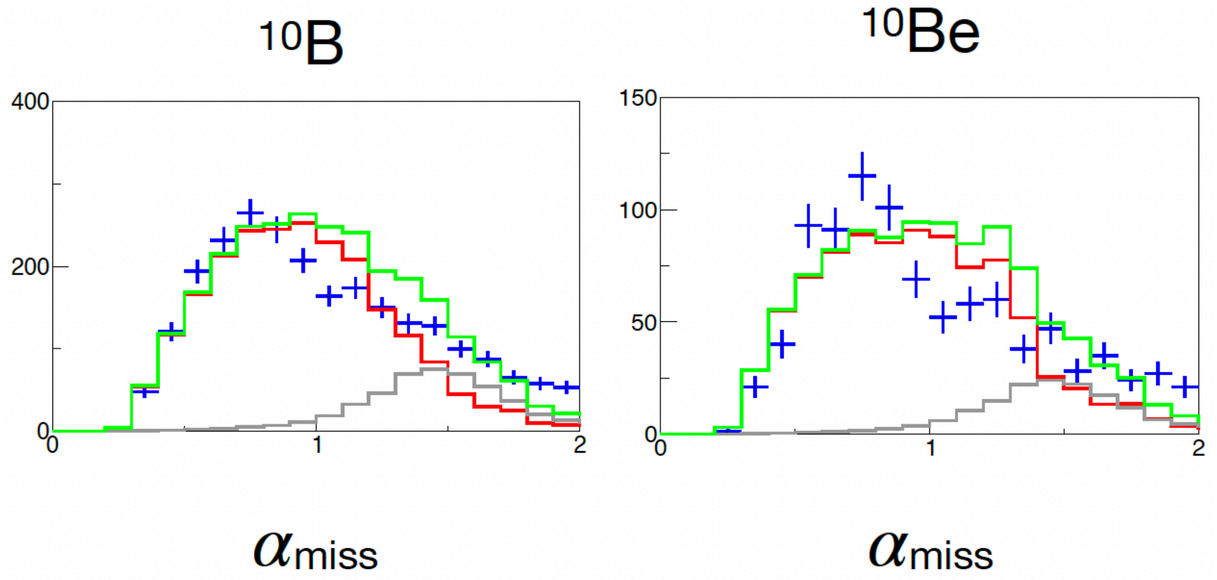

^{14}B channel: SRC suppression

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SRC sim
SRC + MF fit

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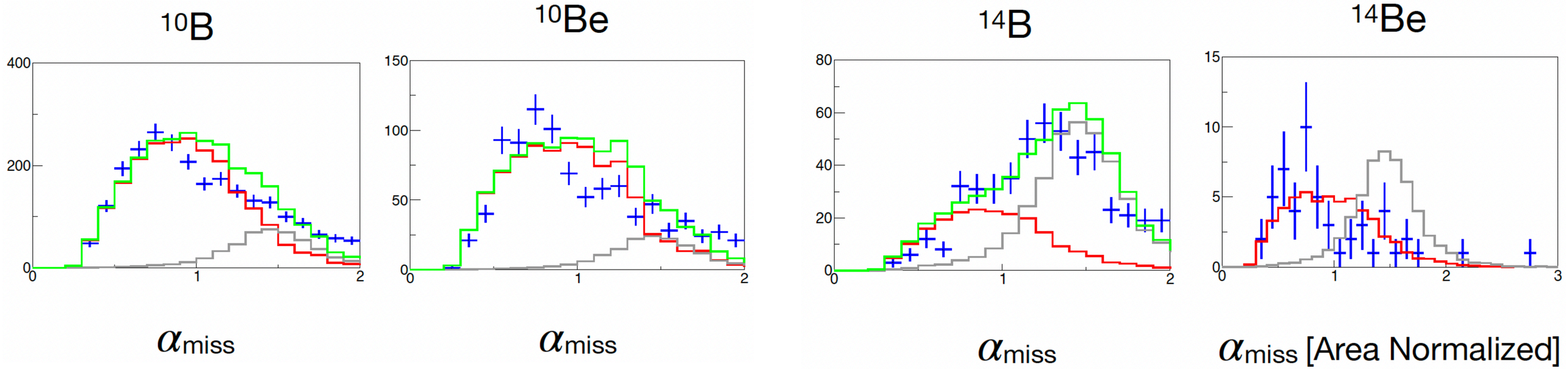
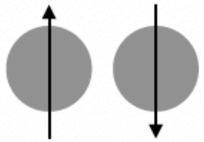


SRC final-state selectivity: Pair quantum numbers

SRC pp pair:  $T = 1$, $J^\pi = 0^+$

^{16}C - pp -> ^{14}Be

$J^\pi=0^+$ - $J^\pi=0^+$ -> $J^\pi=0^+$

Bound ground state allowed

E [MeV]	Jpi
0.0	0^+

SRC pn pair ~ deuteron: $T=0$, $J^\pi=1^+$

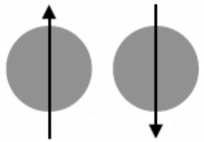
^{16}C - pn -> ^{14}B

$J^\pi=0^+$ - $J^\pi=1^+$ -> $J^\pi=1^+$

No known bound states with positive parity

E [MeV]	Jpi
0.0	2^-
0.74	(1^-)

SRC final-state selectivity: Pair quantum numbers

SRC pp pair: 

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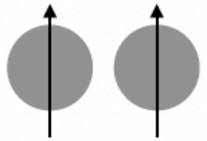
SRC pn pair ~ deuteron:



$T=0$

$J^\pi=1^+$

^{16}C - pp -> ^{14}Be

$J^\pi=0^+$ - $J^\pi=0^+$ -> $J^\pi=0^+$

^{16}C - pn -> ^{14}B

$J^\pi=0^+$ - $J^\pi=1^+$ -> $J^\pi=1^+$

Bound ground state allowed

E [MeV]	Jpi
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No known bound states with positive parity

E [MeV]	Jpi
0.0	2^-
0.74	(1^-)

$^{12}Be/^{13}B$ channels: SRC signature

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SRC sim
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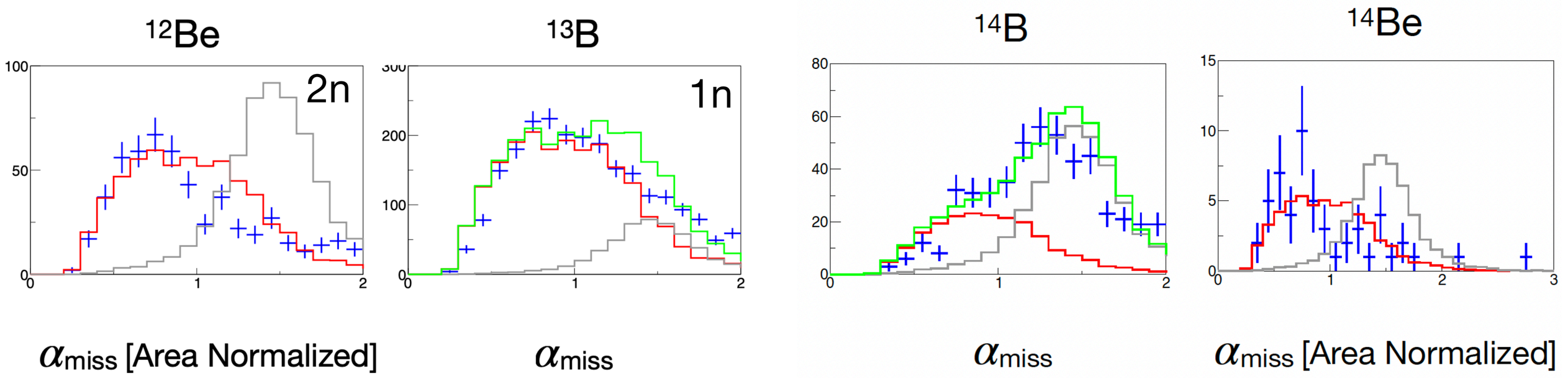
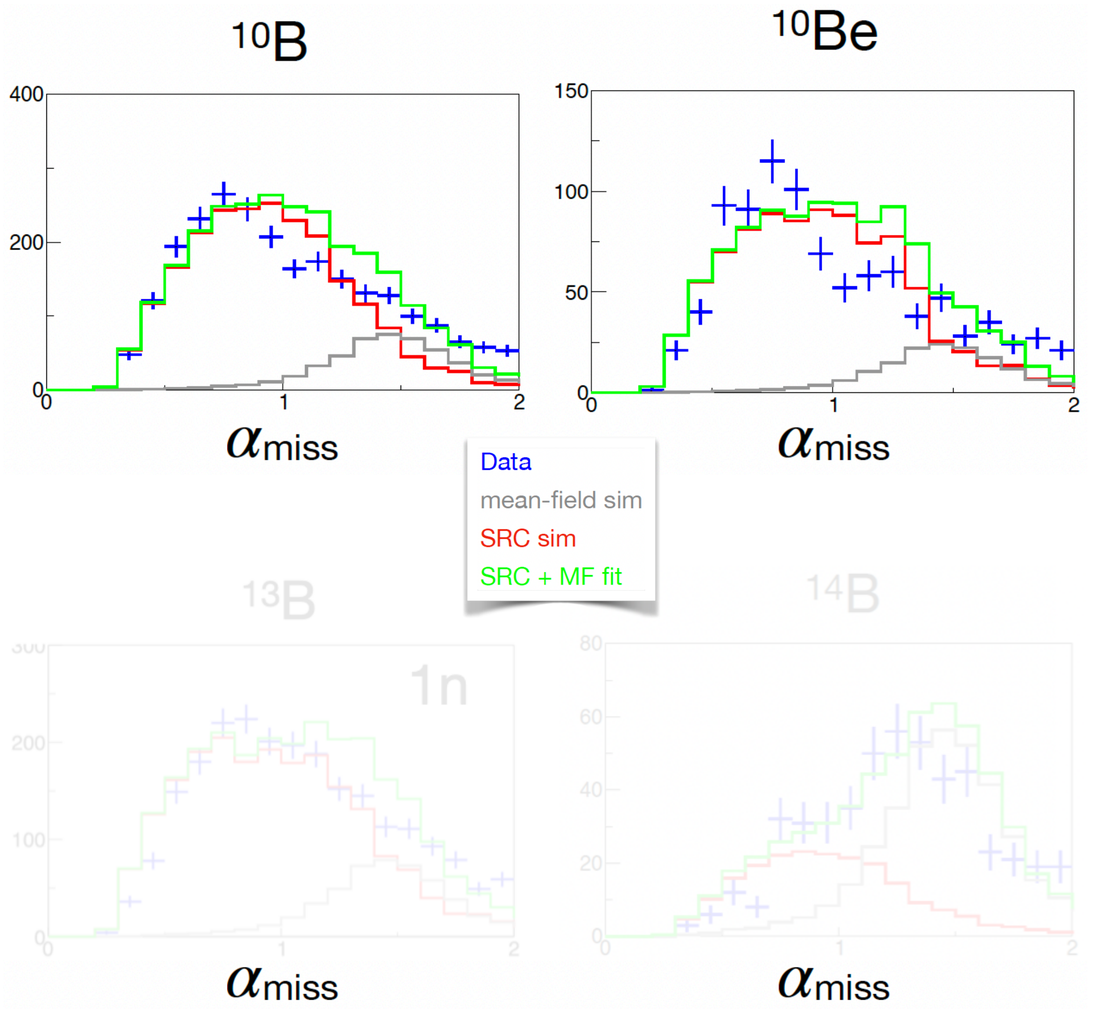
Investigate unbound systems



Conclusions

- Established a possible **method** to pin down SRC physics.
- **Measured a signal compatible with SRC physics** with high statistics at beam energy of 1.25 GeV/u in ^{12}C channel.
- First measurement of a signal compatible with **SRC in radioactive nuclei**.



Conclusions

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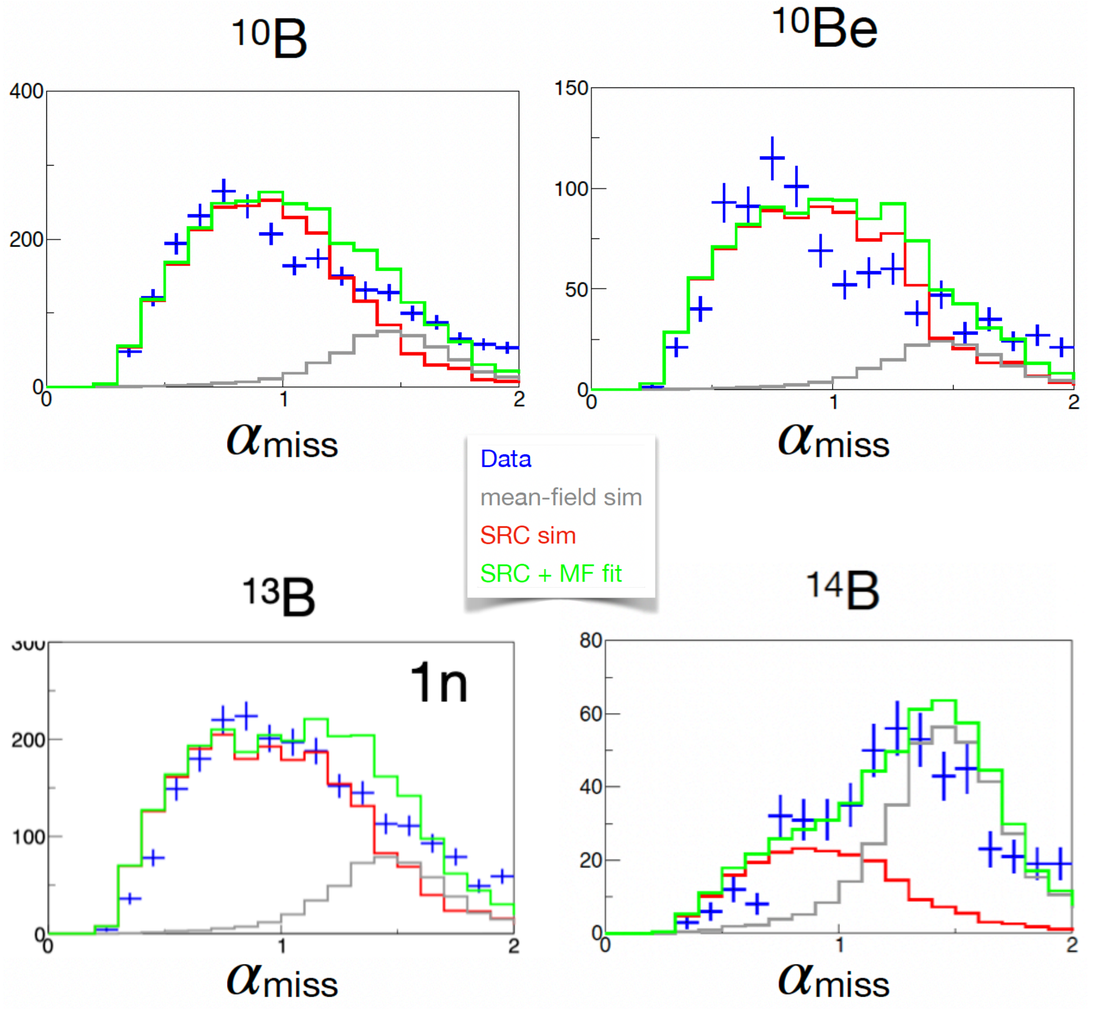
- **Measured a signal compatible with SRC physics** with high statistics at beam energy of 1.25 GeV/u in ^{12}C channel.
- First measurement of a signal compatible with **SRC in radioactive nuclei**.
- ^{14}B **SRC suppression** supported by final state selectivity (SRC Deuteron quantum numbers).
- SRC signal observed in **1n evaporation channel** ($^{13}B + 1n$).



Acknowledgements

A. Lagni (TUDa), H. Qi (MIT), M. Xarepe (LIP), A. Corsi (CEA/IRFU), O. Hen (MIT), J. Kahlbow (LBL)

Backup Slides

Backup Slides: SRC

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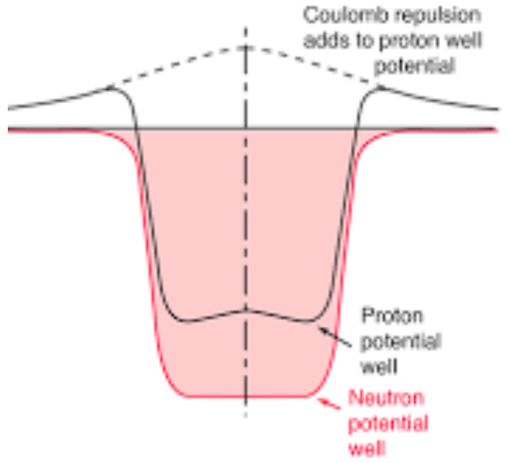
- Composed of **protons** and **neutrons** **(nucleons)** bound by the **strong nuclear force.**
- Nucleons are bound in a **self-consistent potential well** created by the collective interactions of all nucleons.
- **Complex many-body system of interacting nucleons.**
- Nucleon motion within the nucleus is governed by the **Schrödinger equation.**

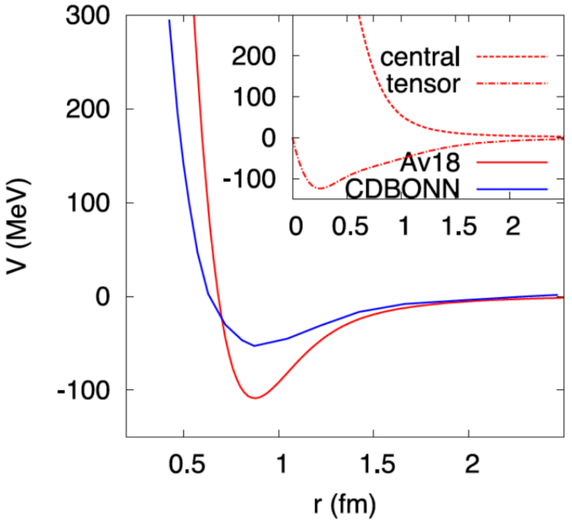


Analytical solutions for the dynamics of such systems, starting from individual particle interactions, are generally unattainable.

Short-Range part of NN interaction makes many-body problem difficult to solve.

Nuclear Models

- **Energy Density Functional (EDF), Empirical Shell Model, Collective Model, Ab Initio Models…**



Backup Slides: IPM

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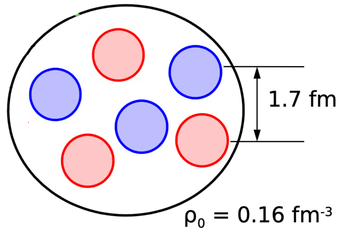
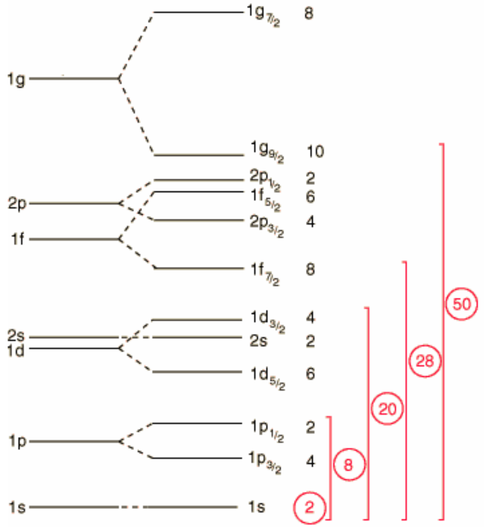
INDEPENDENT PARTICLES



- Nucleons **move independently in well-defined quantum orbits**;
- **Reduce the nuclear many-body problem** to a much simpler one-body one.

$$H = T + \sum_{i<j=1}^{A} V_{2N}(i,j) + \sum_{i<j<k=1}^{A} V_{3N}(i,j,k) + \ldots \quad \Rightarrow \quad H = T + \sum_{i=1}^{A} V(i)$$

2-body 3-body



Fermi Gas Model:

- Nucleons fill energy levels up to the Fermi energy (E_F).
- Key parameters:
  - **Fermi momentum:** $p_F \approx 250$ MeV/c
  - **Average nucleons distance:** d ≈ 2 fm
  - **Average nuclear density:** $\rho_0 \approx 0.16\ nucleons/fm^3$

Nuclear Shell Model:

- **Spherical Harmonic Oscillator (SHO)** and **Spin-orbit interaction** lifts degeneracy, explaining "magic" numbers (e.g., 2, 8, 20...).

Backup Slides: SRC

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Independent-Particle Model:

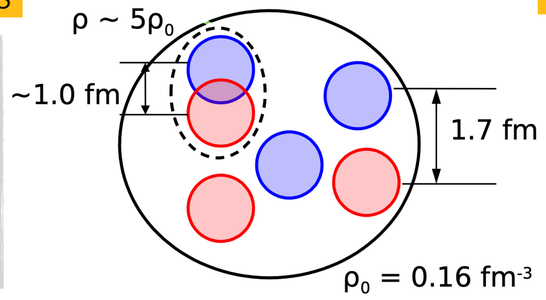
- **Successfully predicts many nuclear properties** (spins, parities, ground-state energies, excitation spectra).
- **Fail to account for high-momentum nucleons.**

Nucleon-Nucleon (NN) correlations modify the pure independent-particle picture.

30% – 40% of nucleons are involved in LRC and SRC configurations.

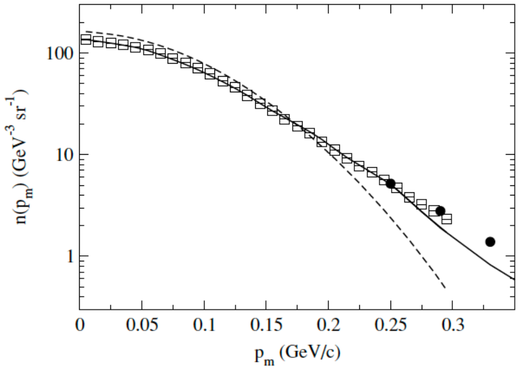
SHORT-RANGE CORRELATIONS

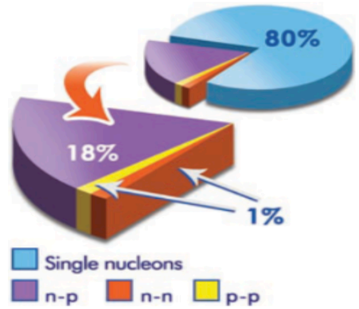
- **<1fm** distance.
- Related to the **hard repulsive core** of the NN interaction.
- Important to **characterise them in-medium and with large N/Z asymmetry.**
- **This experiment.**

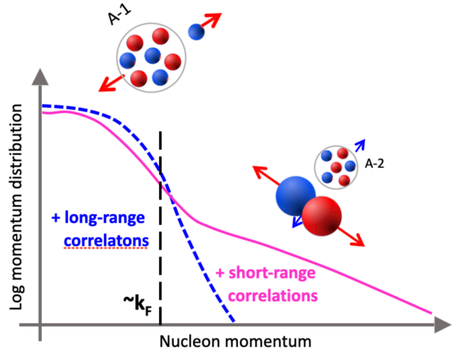


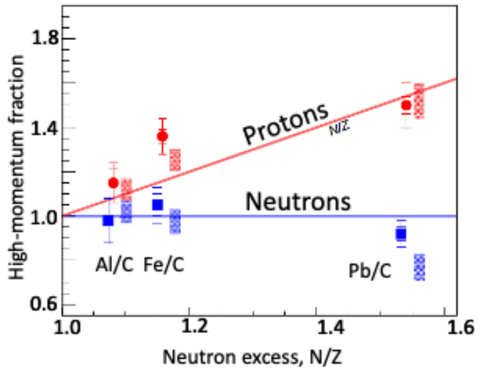
LONG-RANGE CORRELATIONS

- **Several fm** distance.
- Pairing and particle-vibration coupling.
- **Low-energy** structure experiment.

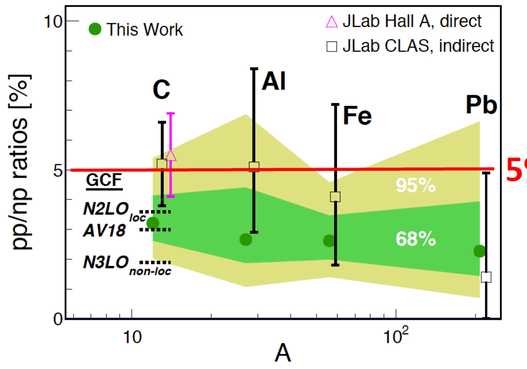








np Dominance

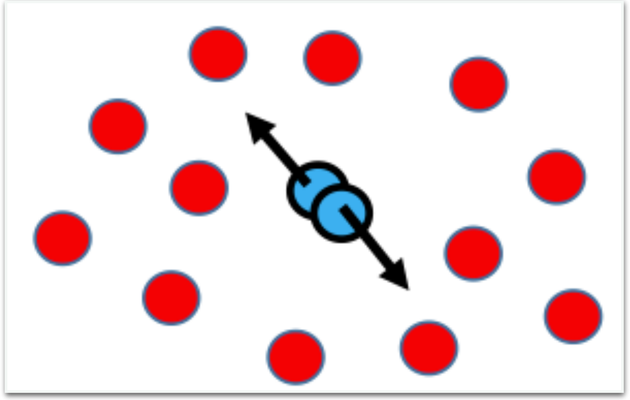


Backup Slides: GCF

$$\Psi(r_1, r_2, \ldots, r_A) \xrightarrow{r_{12}\to 0} \varphi(\boldsymbol{r}) \times A\left(\boldsymbol{R}, \{\boldsymbol{r}_k\}_{k\neq 1,2}\right)$$

Universal function
(but depends on the potential)
Short-Range

Nucleus-dependent function
Mean-Field



$$\frac{d^8\sigma}{d\Omega_e d^3 p_{CM} d\Omega_{rel} dk_{rel}} \propto \sigma_{eN} \sum_{\alpha} C_\alpha \left|\phi_\alpha(k_{rel})\right|^2 n_\alpha(p_{CM})$$

PWIA Cross-section

Mean-Field

Nuclear Contacts C_α

Short-Range

Center-of-Mass momentum distribution $n_\alpha(p_{CM})$

Relative momentum Wave Function $\phi_\alpha(k_{rel})$

Backup Slides: Resolution

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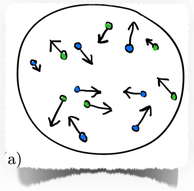
Observables vs Interpretation:

- **GCF** reproduces SRC observables with simpler calculations.
- **Different models (GCF, SM)** provide **different interpretation** of the same observable (e.g. cross-sections).

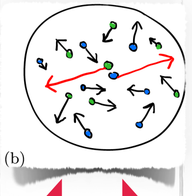
Resolution Conflict: RG connect low- and high-resolution interpretations, revealing how SRC physics manifests across scales.

Low Scale Resolution vs High Scale Resolution



- **Large length scale** or **low energy probe**.
- **Wave function approach the IPM one.**
- Related Models:
  - **Shell Model**
  - **Ab initio methods.**

LR

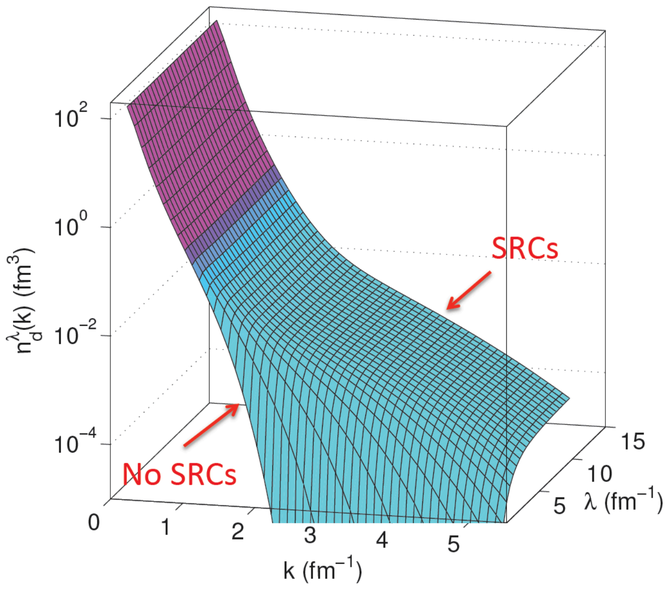


UNITARY TRANSFORMATION

- **Small length scale or high energy probe.**
- **Wave function manifest SRC component.**
- Related Models:
  - **GCF.**

HR

R. J. Furnstahl, arXiv:1309.5771v1, (2023)



Backup Slides: DUBNA

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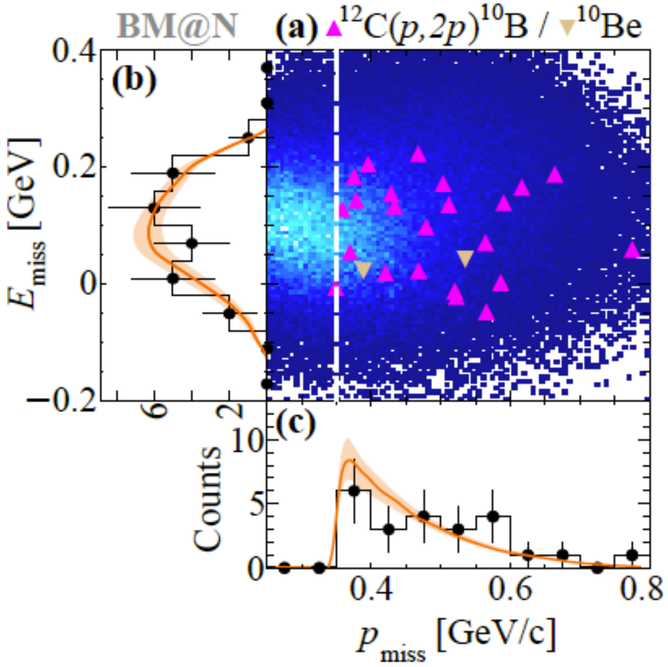
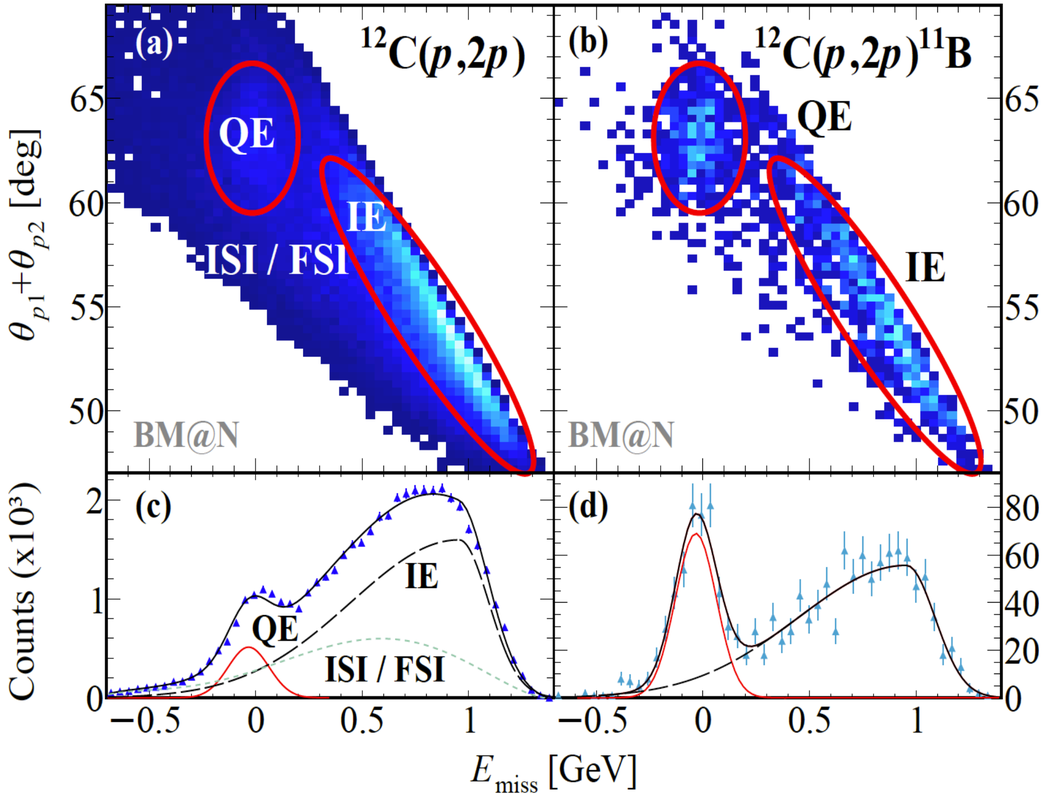
QFS analysis for ^{12}C

- (p,2p) kinematics investigation with selection on ^{11}B;
- Kinematical selection for FSI rejection.
- A-2 fragment selection to infer SRC.





M.Patsyuk,Nature Physics, volume 17, pages 693–699 (2021)

Backup Slides: Motivations

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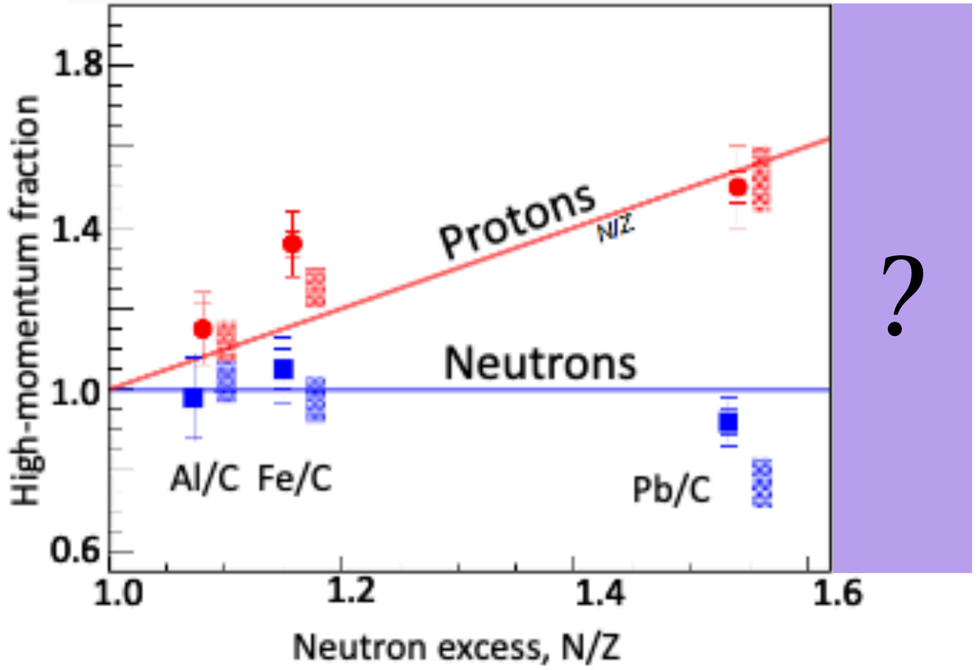
Motivations R^3B Experiment

- Investigate **SRC in N-rich environment**;
- Existing trend based on a **few points**;
- **Mass and N/Z excess cannot be disentangled** with stable nuclei.
- Possible interference from **nuclear structure effect** (open/closed shell);

- **New measurement at N/Z = 1.67 (^{16}C), above the largest available N/Z and at a much smaller mass.**



Adapted from M. Duer et al. (CLAS Collaboration), Nature, 560:617, 2018.

Backup Slides: CALIFA

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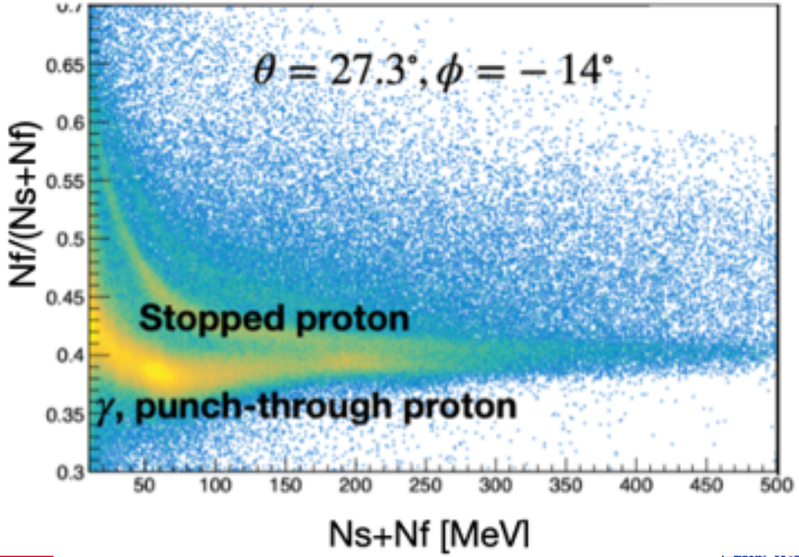
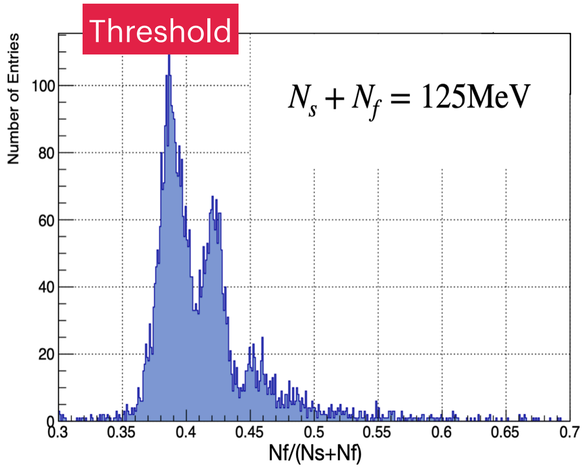
Proton identification:

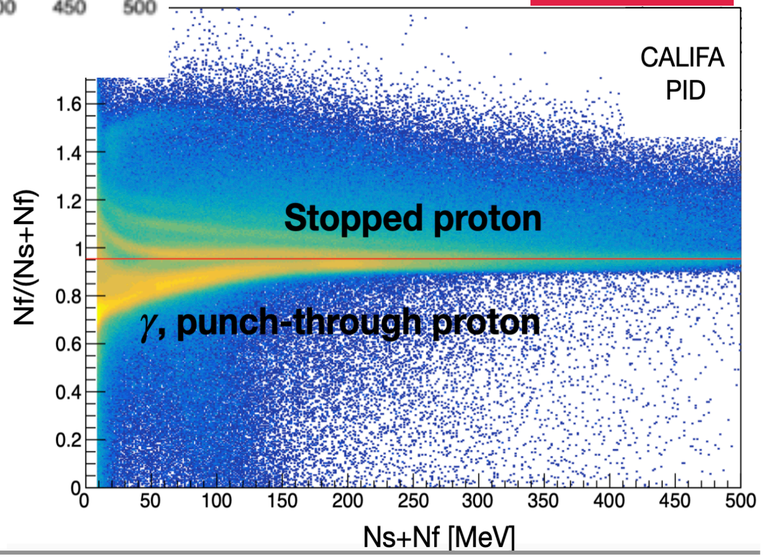
- Traditional PID uses fast (N_f) and slow (N_s) signals component to distinguish neutrons, protons, and heavier isotopes.
- New PID method **separates stopped and punch-through protons without saturation**.
- **Thresholds** are defined to distinguish stopped from punch-through protons.



Threshold



Identification



Courtesy H. Qi

Backup Slides: MDF

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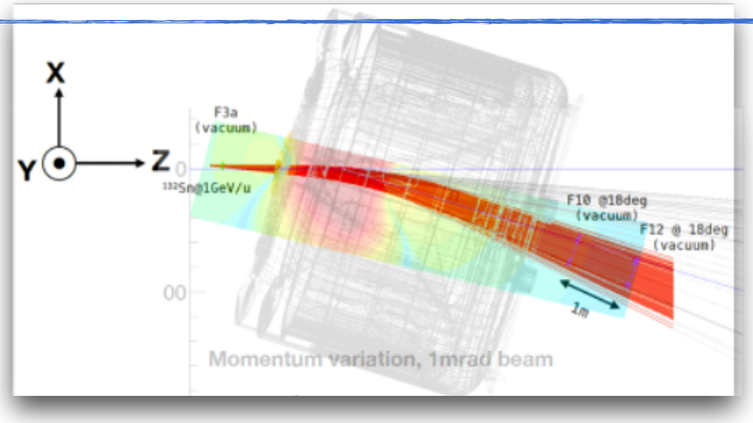
Extracting momentum information of forward-focused fragments by tracking trought GLAD

MDF Tracking:

- **The trajectory of charged particles is bent** in the GLAD magnet according to their magnetic rigidity.
- **Goal**: Determine the fragment's total **momentum** by analyzing their trajectory.
- Train MDF on **simulated Data**.



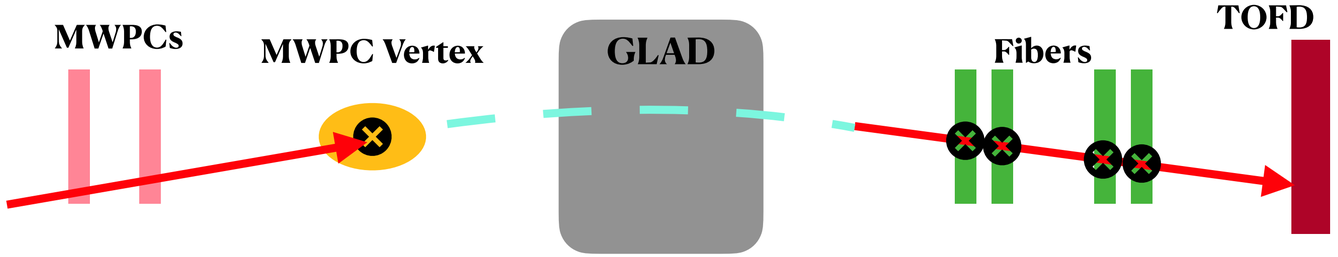
General Concept:

- P (e.g., P/Z, trajectory length) depends on N observables (x1,...,xN).
- **Create a training sample** of M events: (xj, Pj, Ej).
- xj are the N observables, Pj is the known value, Ej is the known error.
- TMultiDimFit class finds the parameterization.

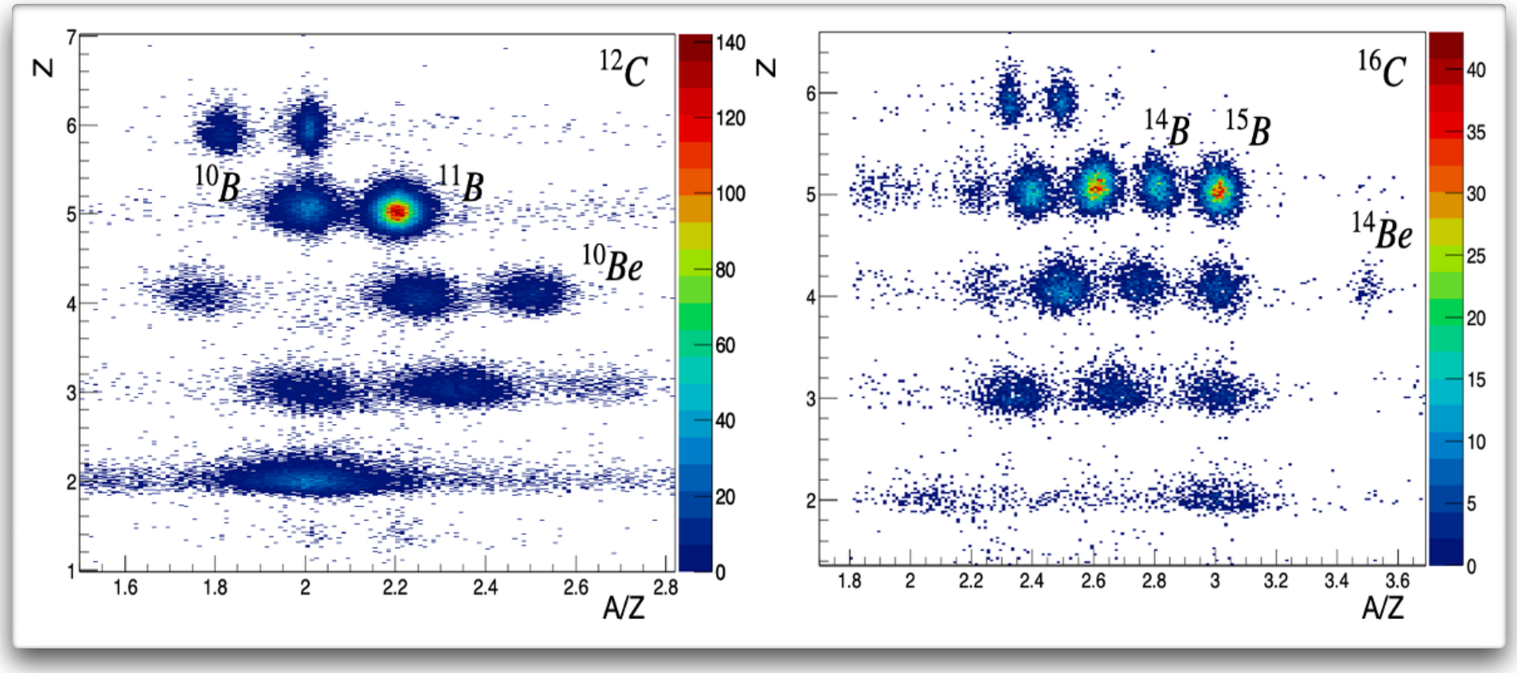
$$P_p(\mathbf{x}) = \sum_{l=1}^{L} c_l \prod_{i=1}^{N} p_{li}(x_i) = \sum_{l=1}^{L} c_l F_l(\mathbf{x})$$

such that $S = \sum_{j=1}^{M} (P_j - P_p(\mathbf{x}_j))^2$ is minimal

Backup Slides: PID



$$P/Z_{MDF} = (X_0, Y_0, Z_0, TX_0, X_1, Y_1, Z_1, TX_1, TY_1)$$



Backup Slides: FSI-IE

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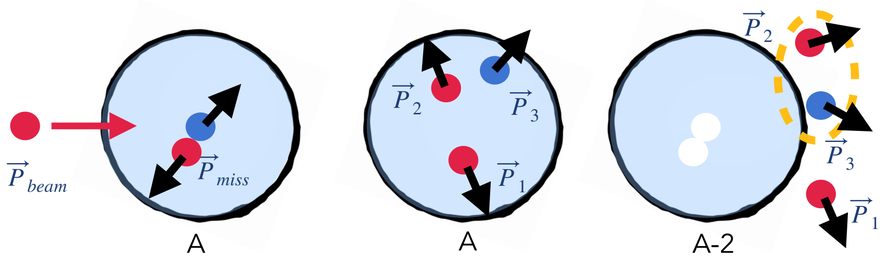
Challenges:
- **Final State Interactions** (**FSI**) and **Inelastic Events** (**IE**) mimic SRC signals.

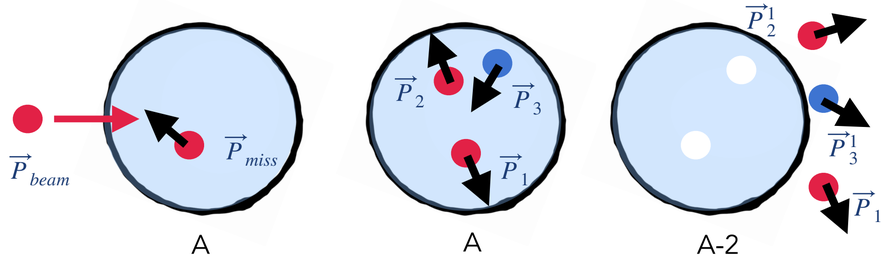
FSI:
- Secondary interaction alters energy and angles or may cause **nucleon emission**.
- **Single charge exchange** (SCX) rescattering in charge.

IE:
- Energy is absorbed by the nucleons and/or nucleus.
- Production of excited nuclear states, multi-particle emission, or nuclear fragmentation.

SRC:

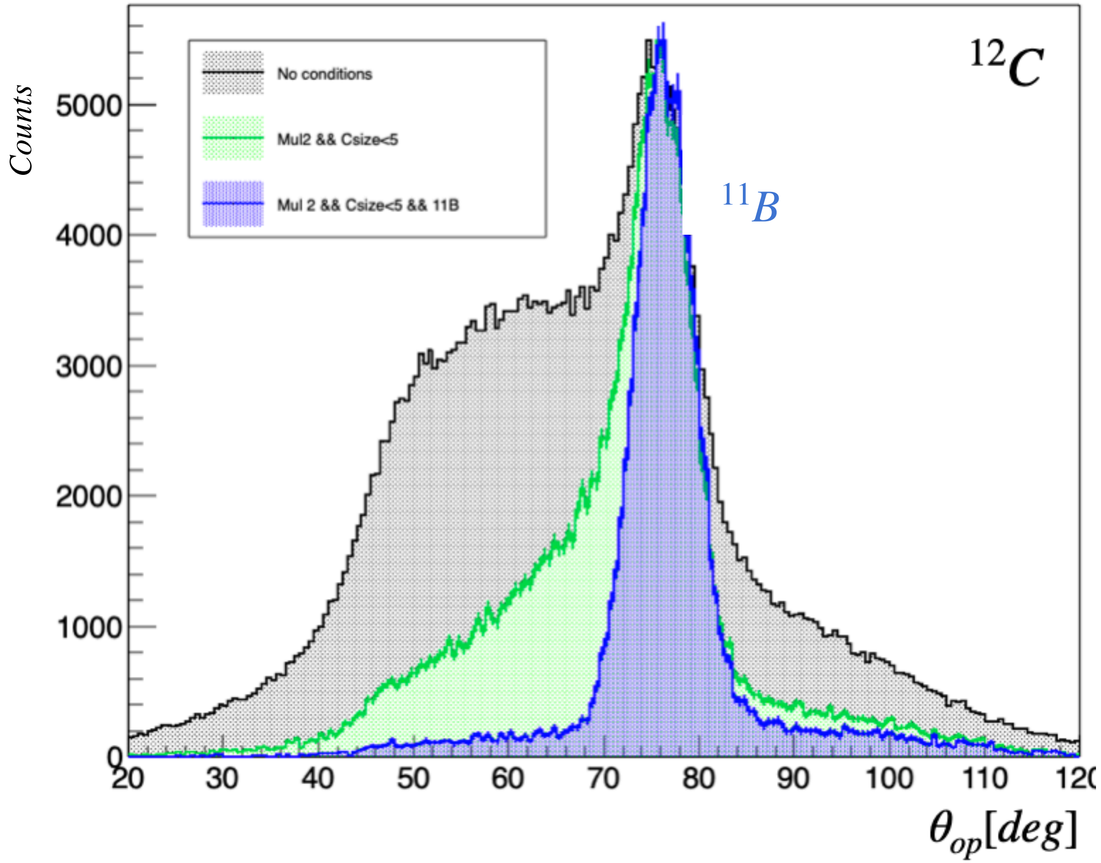


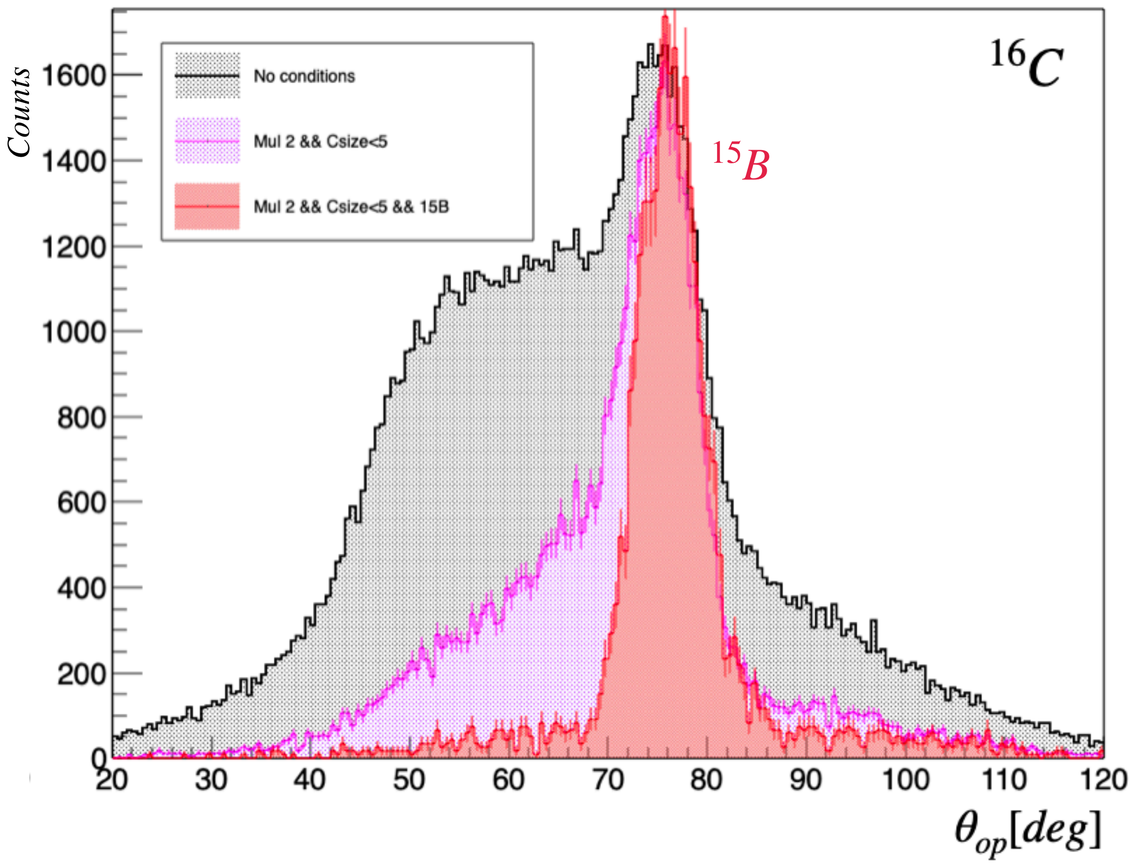
n
p
p



n
p
p

Backup Slides: A-1





Backup Slides: SRC

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- $^{12/16}C(p,2pN)A-2$
- **QFS conditions.**
- **A-2 fragment selection.**
- **High missing momentum ($P_{miss} > 0.4\ GeV/c$).**
- **Recoil n/p momentum (mom cons).**

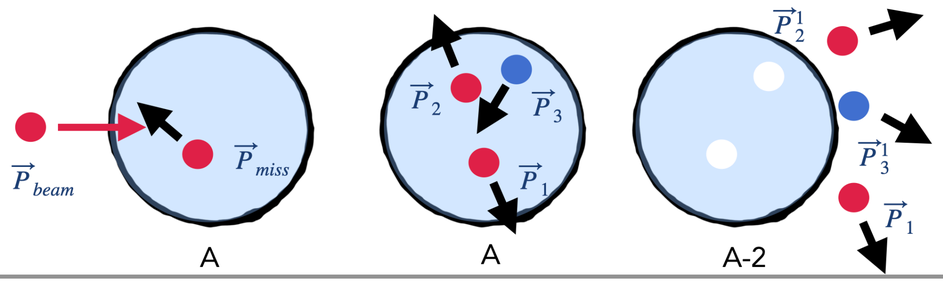
- Recoil n/p momentum reconstructed via **momentum conservation.**
- **Opening angle** between P_{miss} and the recoil nucleons momentum;
- SRC pair nucleons emitted **back to back** in the initial state;
- Unique feature of **SRC ?**

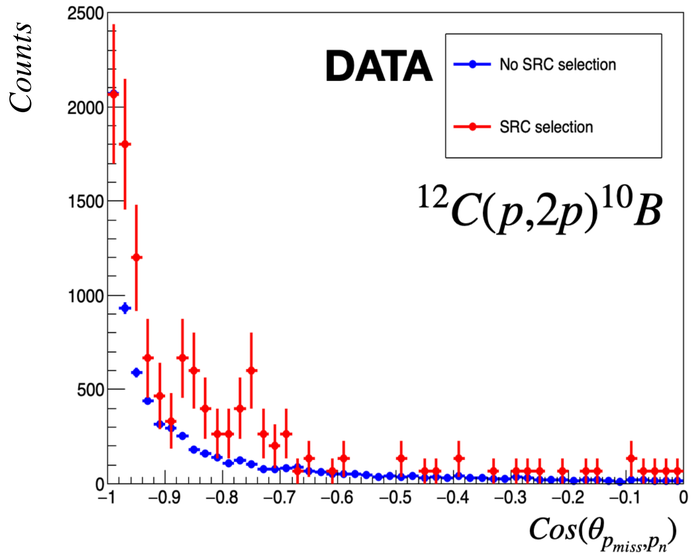
$$\vec{P}_{miss} = (\vec{P}_2 - \vec{P}_2^{\,1}) - \vec{P}_3^{\,1} - \vec{P}_F$$

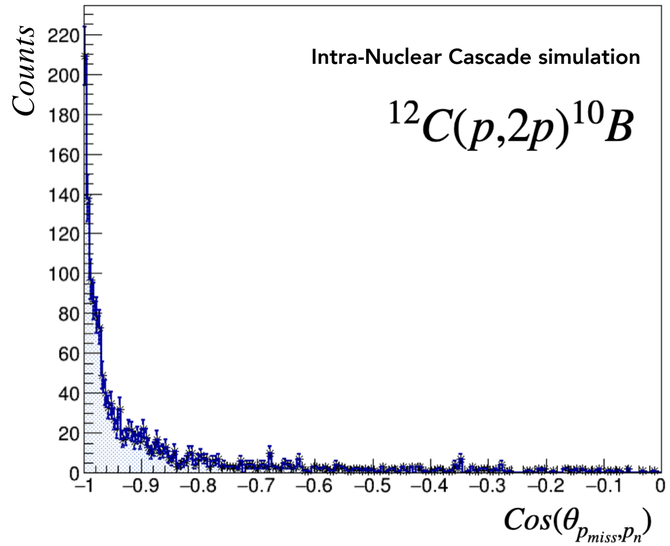
$\vec{P}_2 - \vec{P}_2^{\,1} \rightarrow 0$ (High E), $\vec{P}_F \rightarrow 0$

Discussion with JC. David

$$\vec{P}_{miss} \propto -\vec{P}_3^{\,1}$$







Backup Slides: SRC

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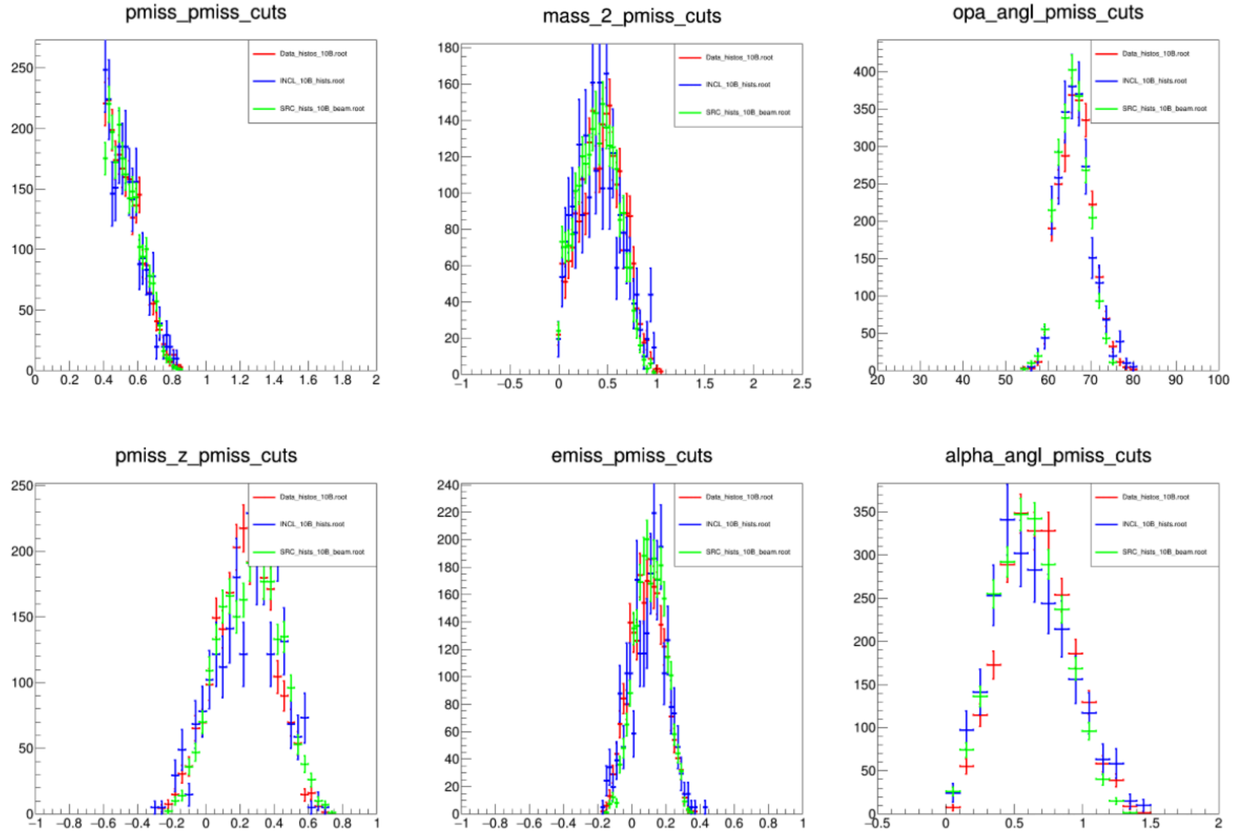
$^{12}C(p,2p)\ ^{10}B$ with QE + pmiss selection

INCL -> Blue

SRC -> Green

exp -> red



Event selection:

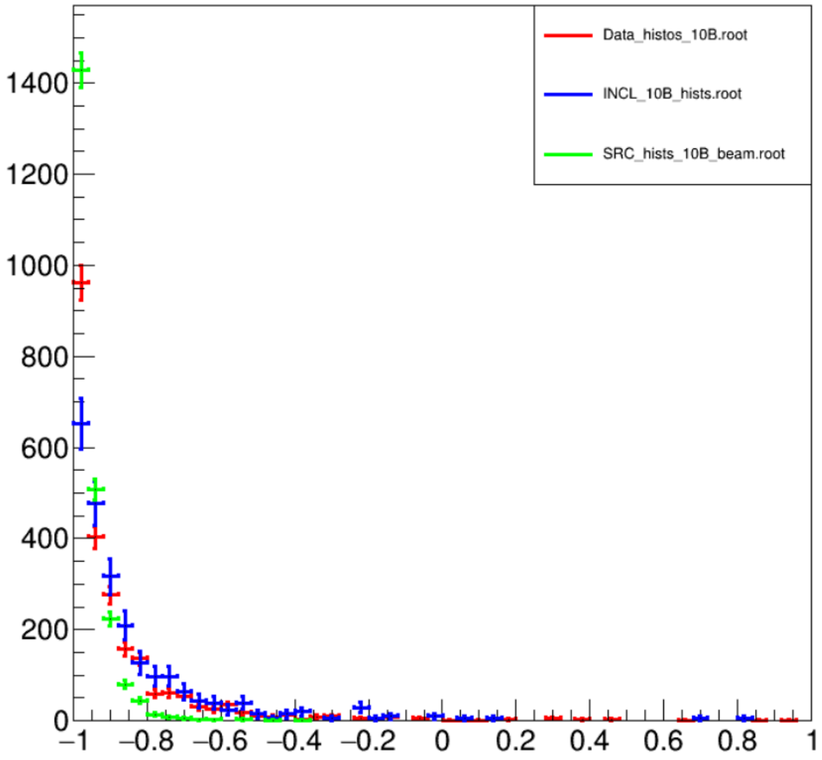
- (p,2p) selection
- $|t|, |u| > 0.8\ GeV^2$
- ^{10}B tagging
- Exclusive missing mass squared: $0 \sim 1.1\ GeV^2/c^4$
- Missing mass squared $> 0\ GeV^2/c^4$
- Missing momentum $> 0.4\ GeV/c$

Backup Slides: SRC

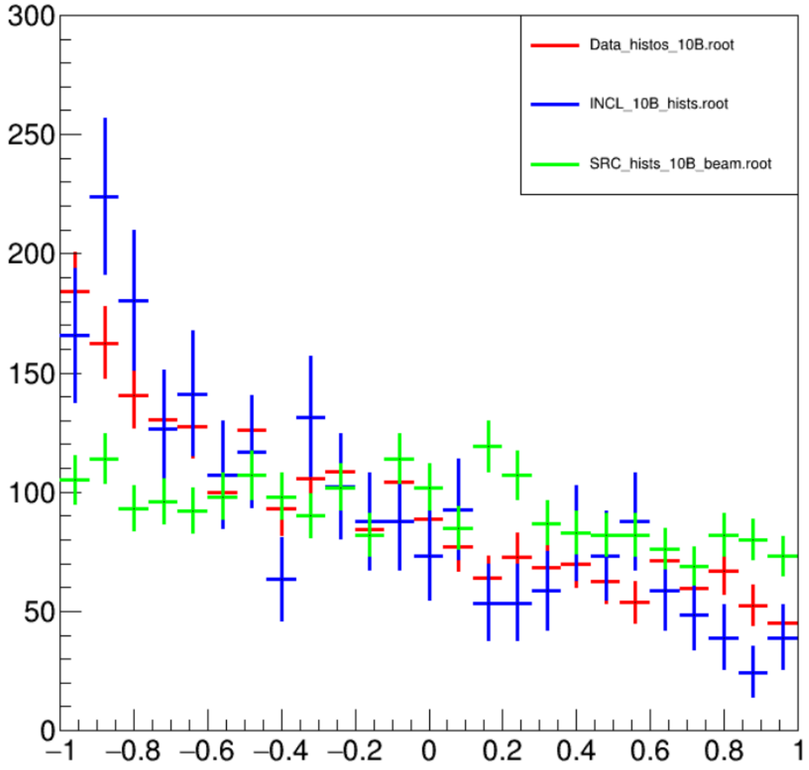
TECHNISCHE UNIVERSITÄT DARMSTADT

$^{12}C(p,2p)\ ^{10}B$ with QE + pmiss selection

pmiss_angl_pmiss_cuts



prel_angl_pmiss_cuts



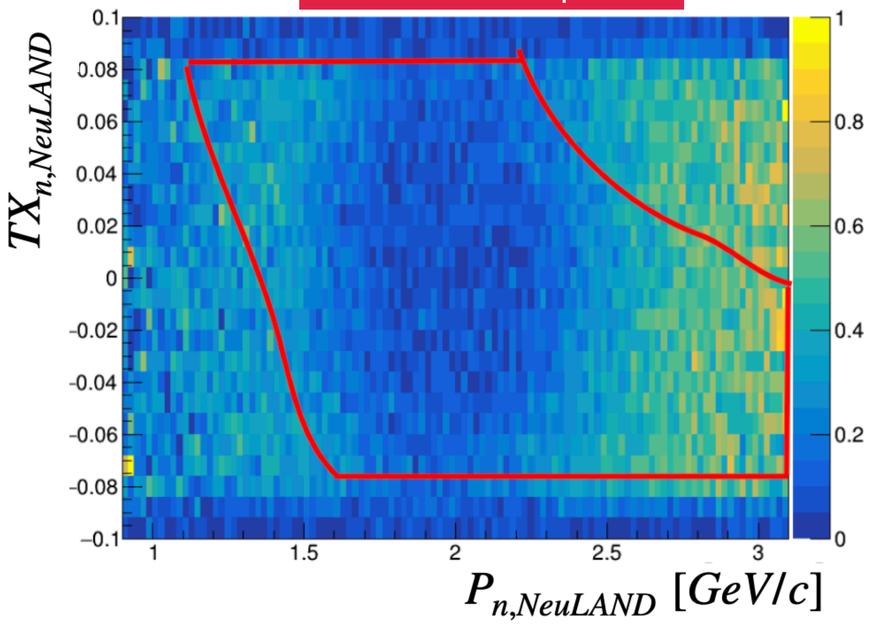
Backup Slides: Exclusive

TECHNISCHE UNIVERSITÄT DARMSTADT

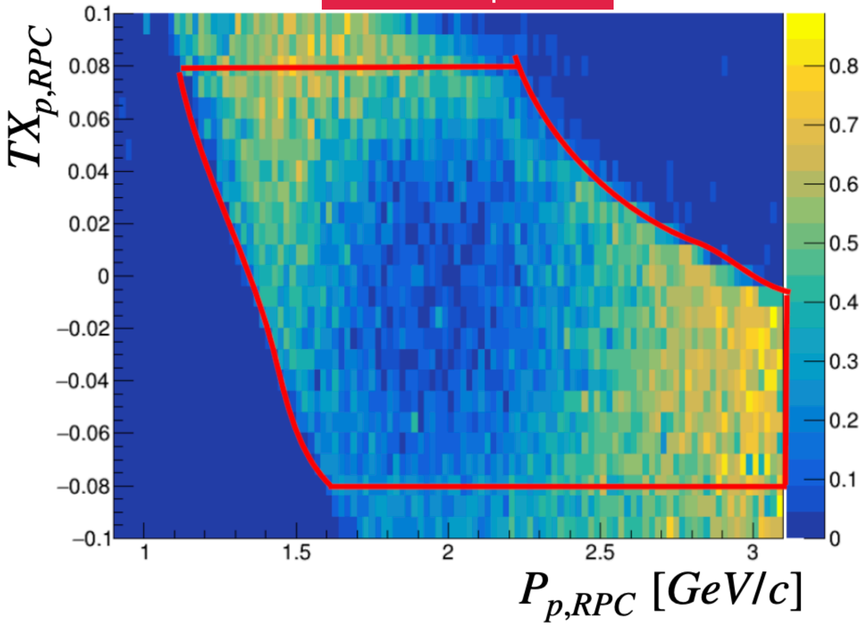
- $^{12/16}C(p,2pN)A-2$
- **QFS conditions.**
- **A-2 fragment selection.**
- **High missing momentum ($P_{miss} > 0.4\ GeV/c$).**
- **Recoil n/p momentum (direct).**

- Recoil n/p momentum **reconstructed directly.**
- **Common acceptance region.**
- **Small acceptance** for SRC events.
- **No statistics remained** after applying SRC selection conditions, indicating that **mean-field QE events dominate in this region.**

NeuLAND acceptance



RPC acceptance



Courtesy M. Xarepe

Backup Slides: Beam energy

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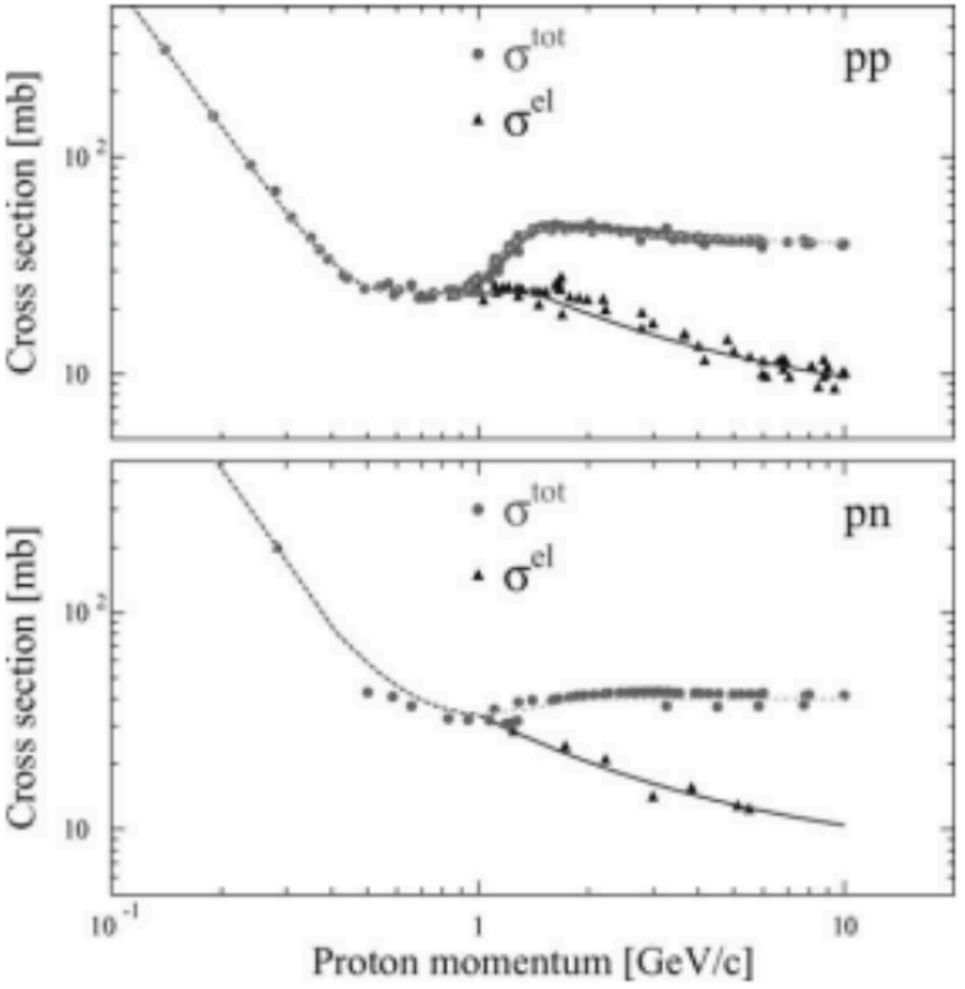
Beam energy

- SRC pair breakup cross-section trend **still not characterised.**
- **Previous experiment** performed at **higher beam energy (>3 GeV/u).**
- Ensures significant **energy transfer** for SRC pairs.
- **Simpler energy dependence** of rescattering cross-section (**Glauber approach**).
- 1.25 GeV/u **maximum energy** at R^3B.



Backup Slides: TRT

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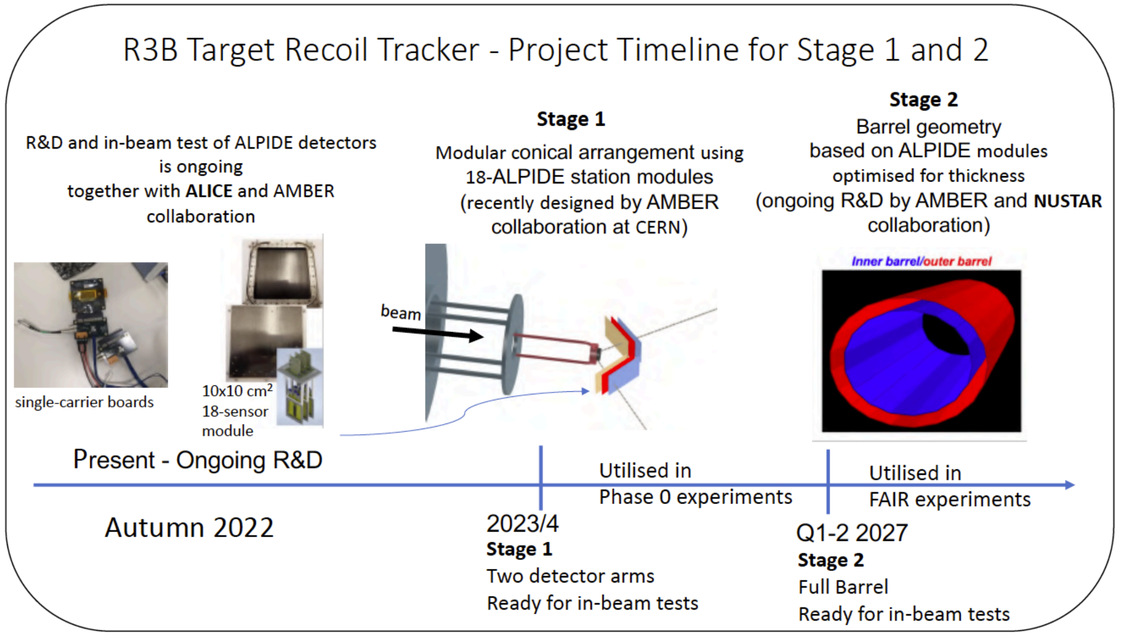
Rate Limitation

- $I_{beam} \approx 10^5\ pps$.
- **Multi-hit and pile up in several detectors**.
- **Heavy statistic reduction (20%)** selecting only 1 hit.
- **FOOT not ideal** at high trigger rate ($R_{trig} > 8\ kHz$).

New R^3B Target Recoil Tracker (TRT)

- Tracking **efficiency** ($\epsilon \approx 95\,\%$) **and resolution** ($R_{M_{miss}} \approx 3\ MeV$).
- **Higher rate capabilities** ($R_{trig} > 50\ kHz$), removing the rate bottleneck.



Far-Future Stage

A layer of fully flexible Silicon wafer (current R&D by ALICE) fitted inside the barrel geometry