

Exclusive Measurement of Single-Proton Strength in Quasi-Elastic $^{12}\text{C}(p, 2p)^{11}\text{B}$ at High Momentum Transfer

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PPIHE, Jun 4, 2026



Short-Range Correlations (SRCs) – close proximity nucleon pairs

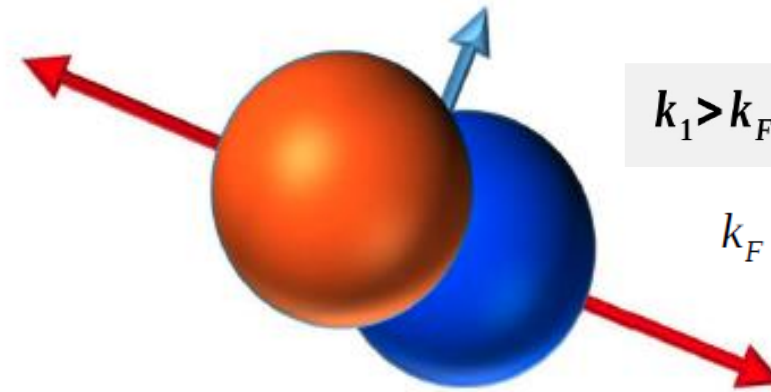
Short-range, short-lived,
highly correlated nucleon pairs

$r \sim R$



Position-space

High momentum of correlated
nucleons, low pair momentum

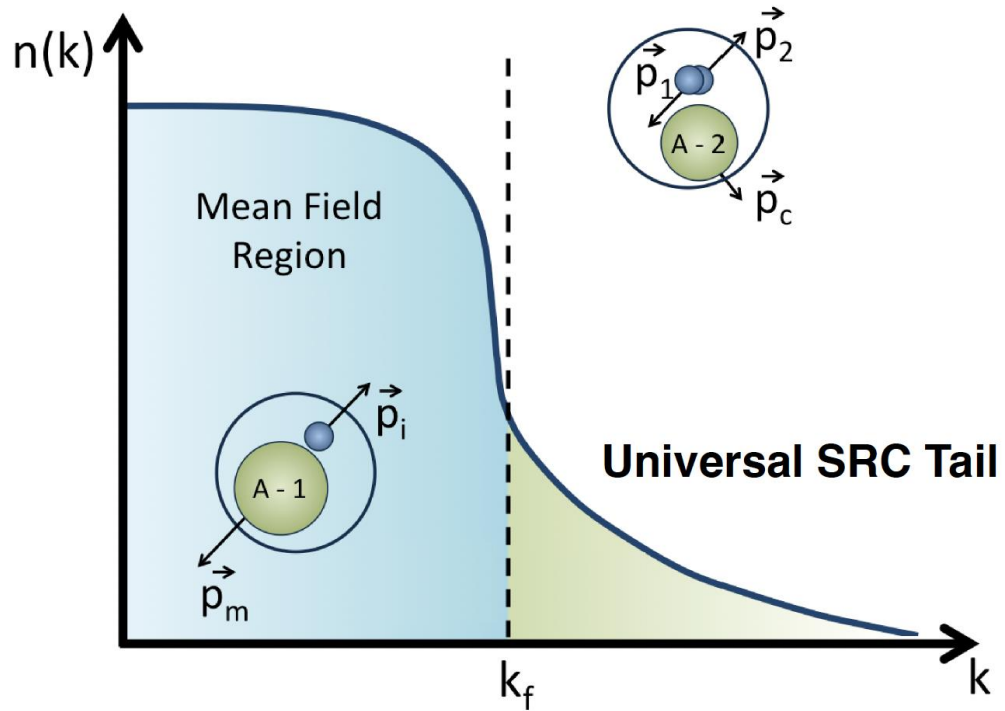
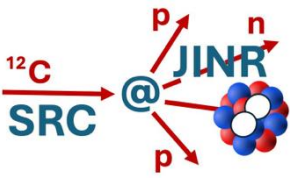


$$k_1 > k_F \quad k_2 > k_F \quad k_1 \simeq k_2$$

$$k_F \approx 250 \text{ MeV}/c$$

Momentum-space

Why studying SRC is important?



Almost all nucleons above k_f belong to SRC

~80% of kinetic energy in heavy nuclei is carried by SRC

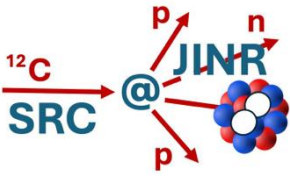
Dense nuclear matter --> neutron stars

Reveal intermediate- and short-range nuclear forces

Probes new physics beyond nucleonic description

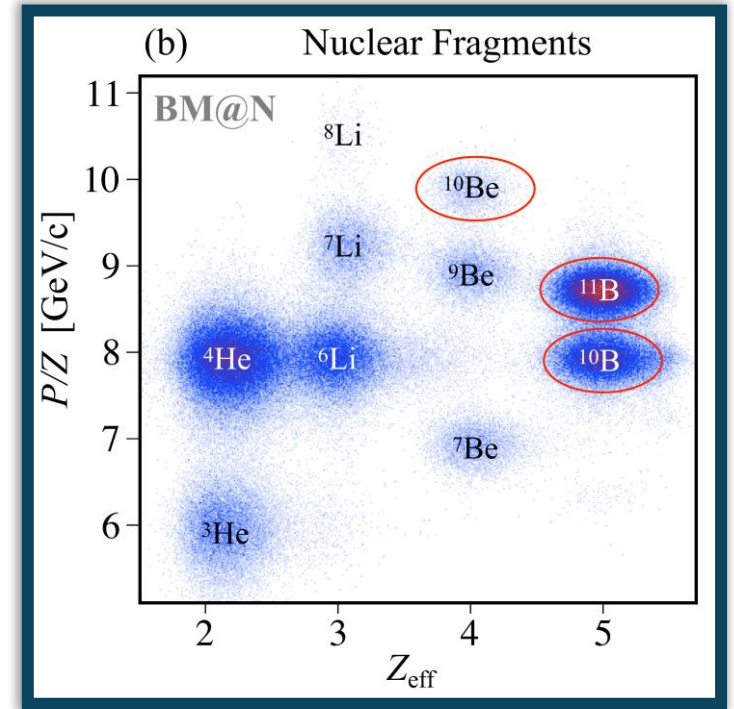
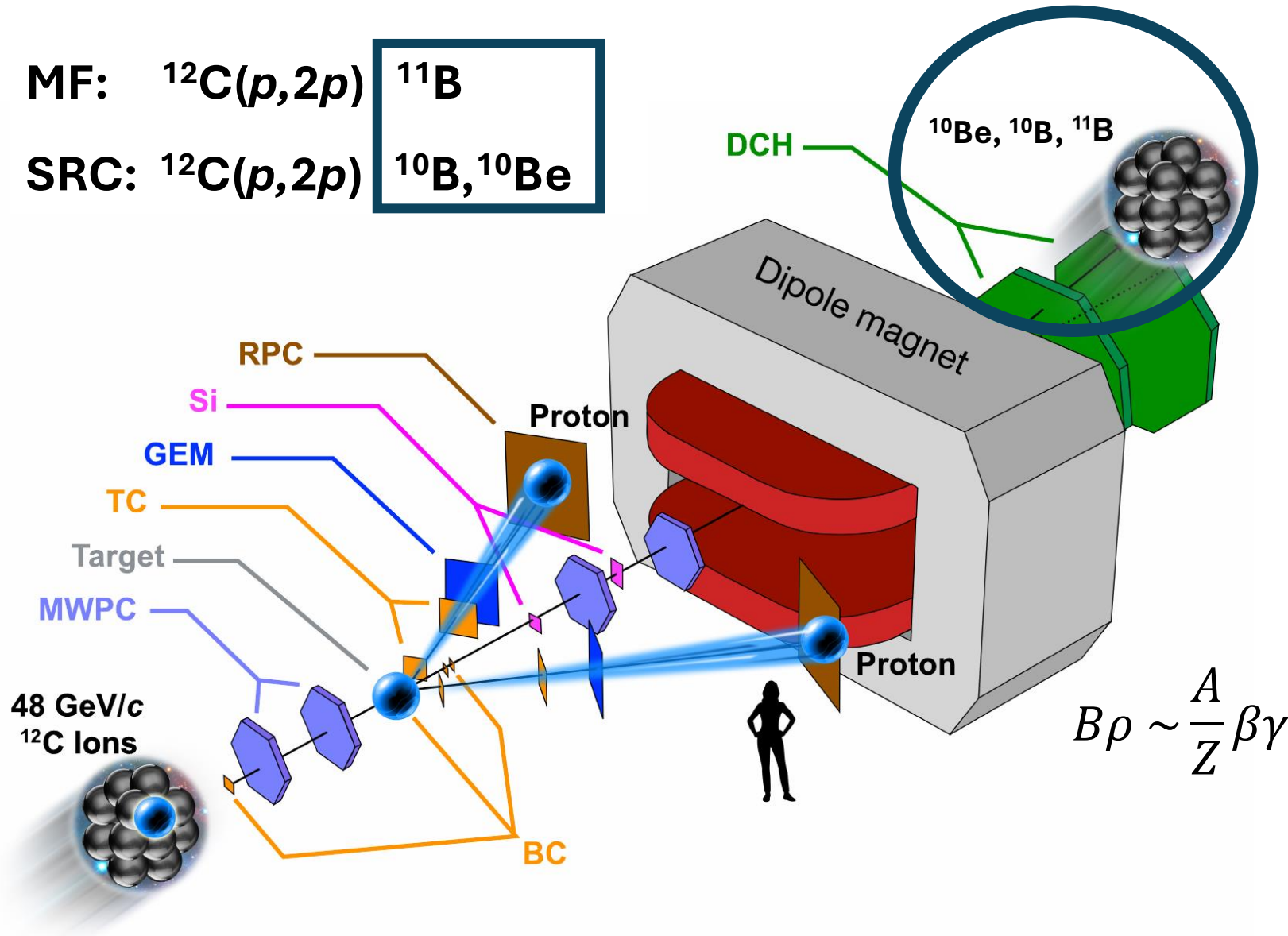
Bridge nuclear structure, QCD-based nuclear interactions and astrophysical phenomena

Pilot experiment in 2018



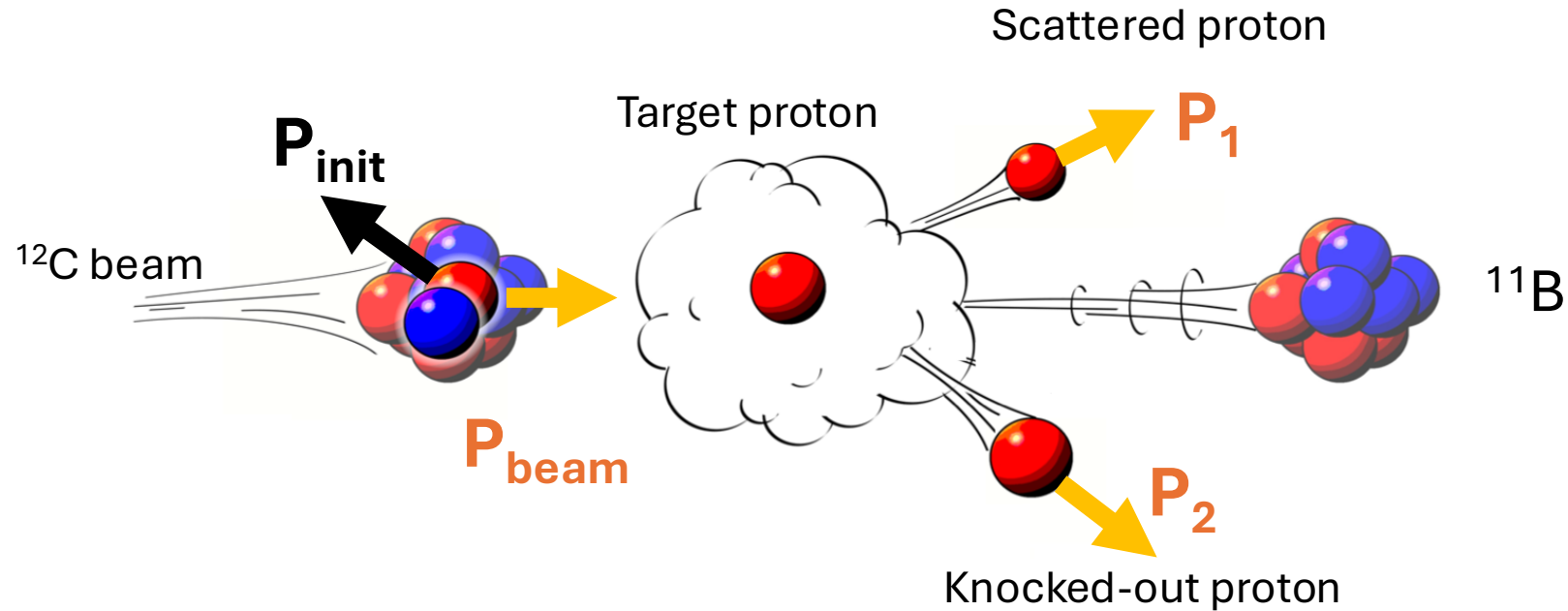
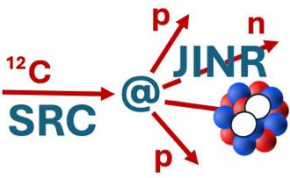
MF: $^{12}\text{C}(p,2p)^{11}\text{B}$

SRC: $^{12}\text{C}(p,2p)^{10}\text{B}, ^{10}\text{Be}$



$$B\rho \sim \frac{A}{Z} \beta\gamma$$

Quasi-free (p,2p) scattering in inverse kinematics



Reconstruct initial nucleon momentum P_{miss} from scattered particles

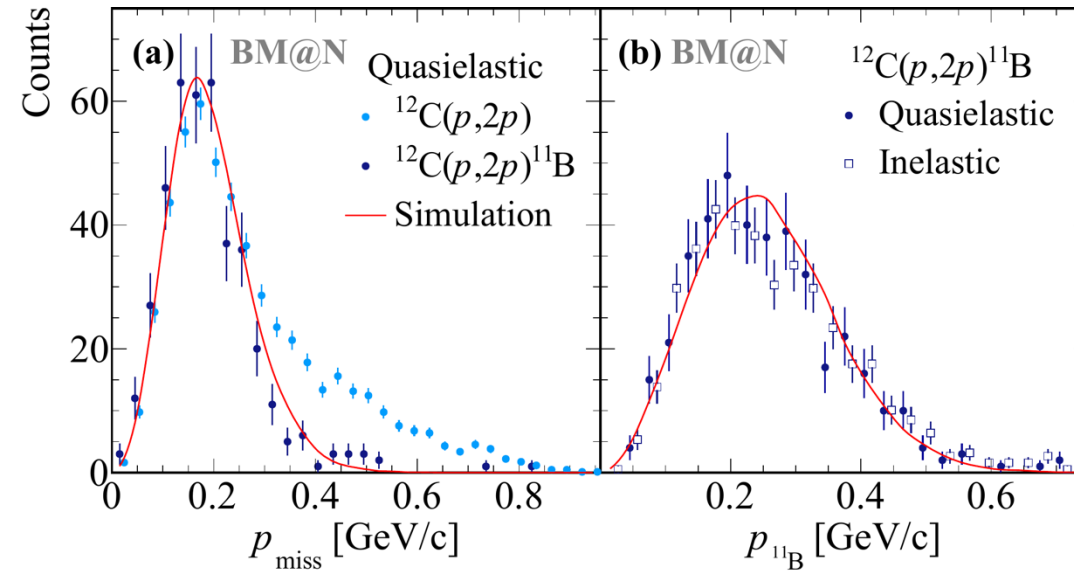
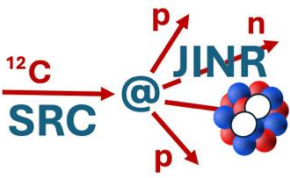
with no ISI/FSI $P_{\text{miss}} = P_{\text{init}}$

$$P_{\text{miss}} = P_1 + P_2 - P_{\text{beam}}$$

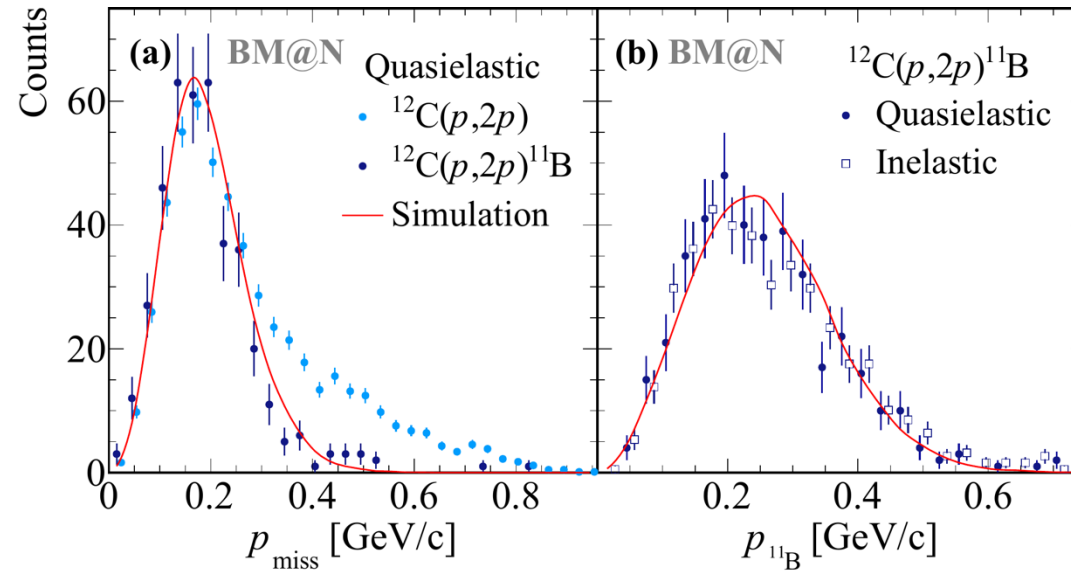
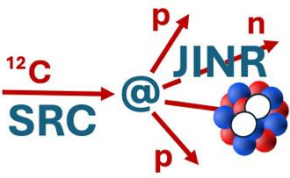
$$M_{\text{miss}}^2 = P_{\text{miss}}^2$$

$$\vec{p}_{\text{miss}} = -\vec{p}_{11\text{B}}$$

First SRC experiment at BM@N in 2018

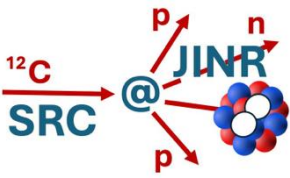


First SRC experiment at BM@N in 2018



Analysis of QE $^{12}\text{C}(p,2p)^{11}\text{B}$ established **suppressed rescattering in ISI/FSI**,
but no absolute cross section determined

SRC experiment in 2022

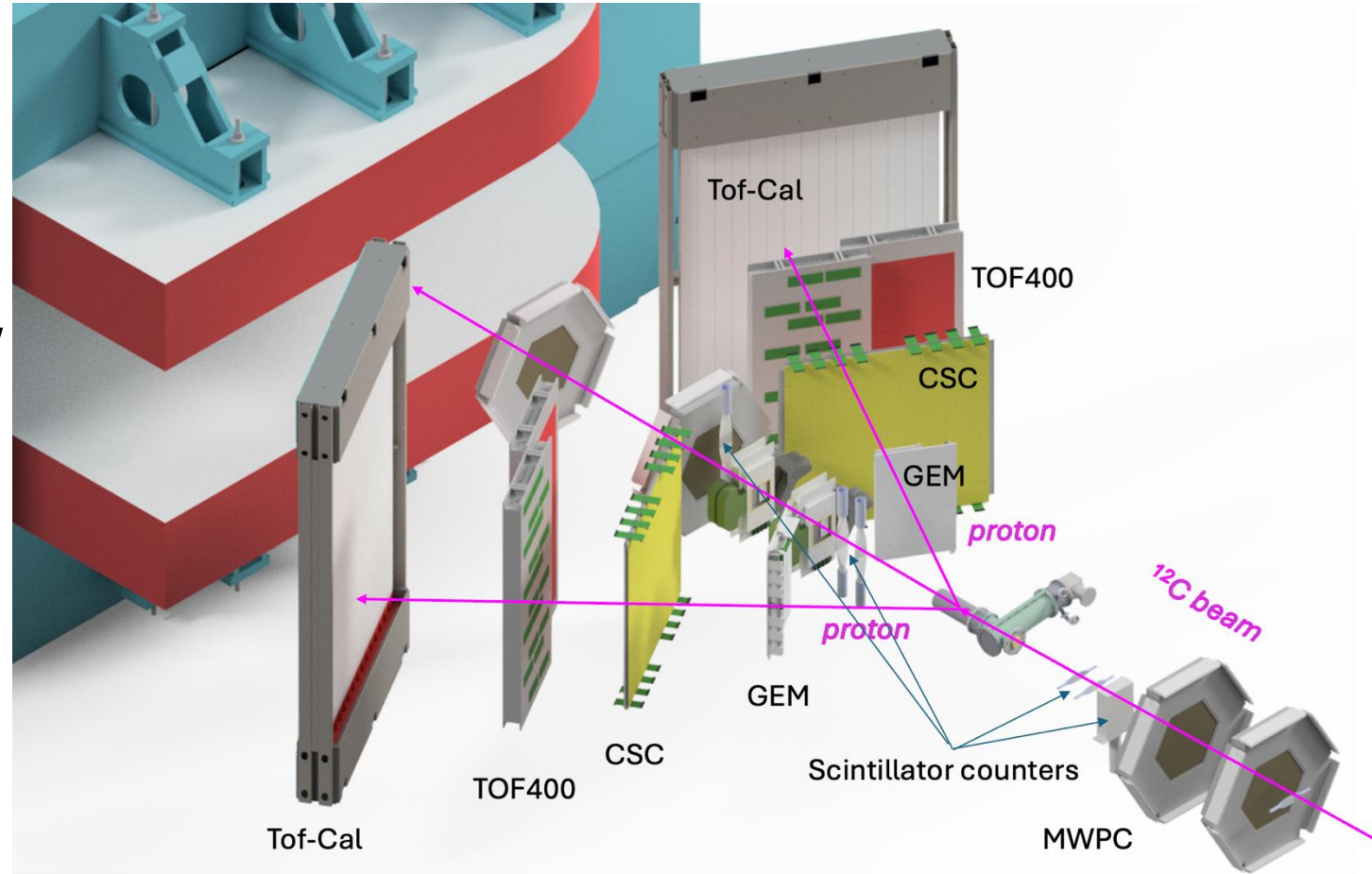


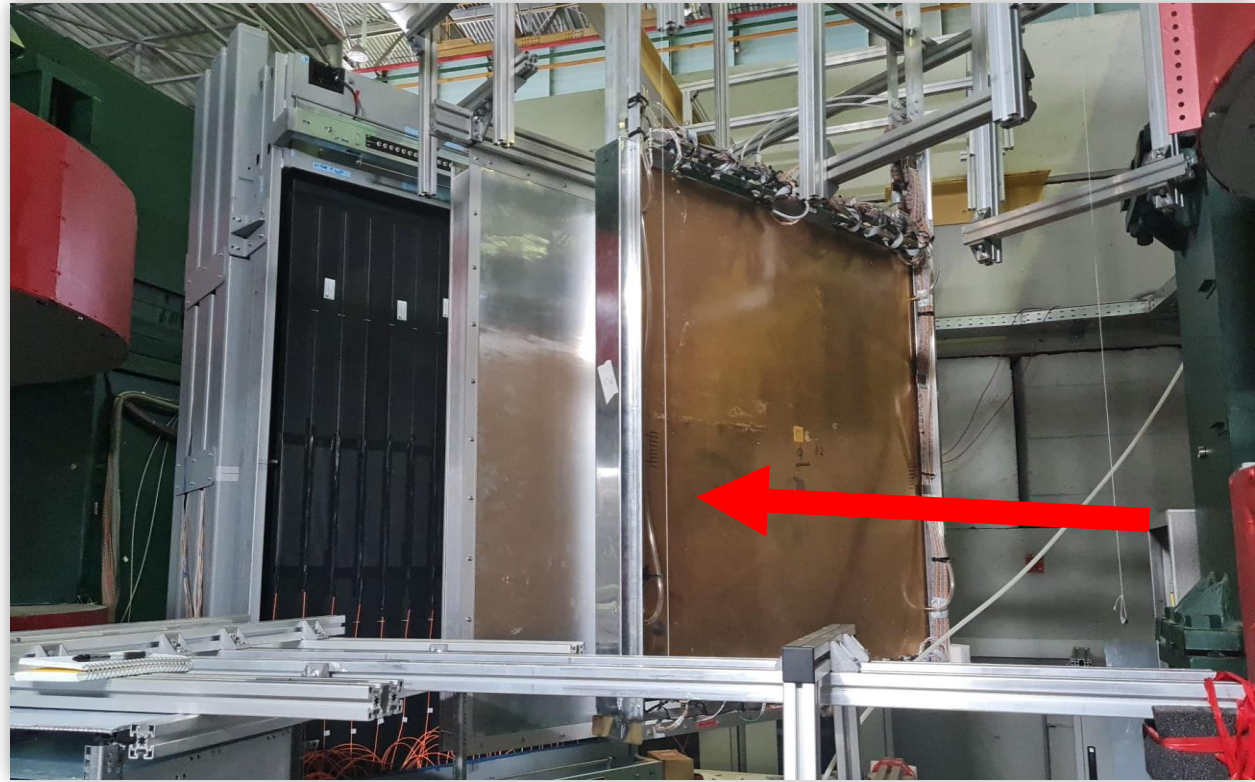
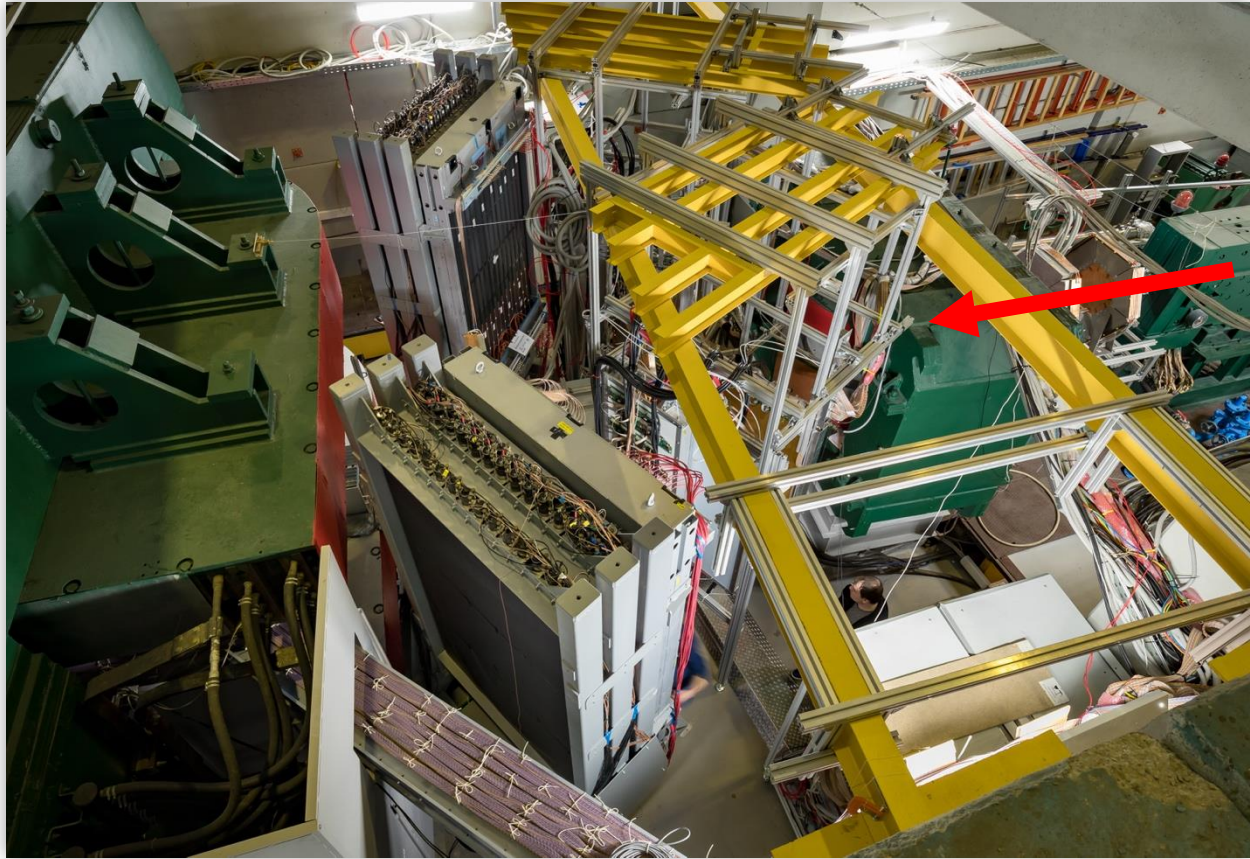
Main goal: reaction cross sections and fragmentation properties

45 GeV/c ^{12}C beam momentum
(3.7 GeV/c/nucleon)

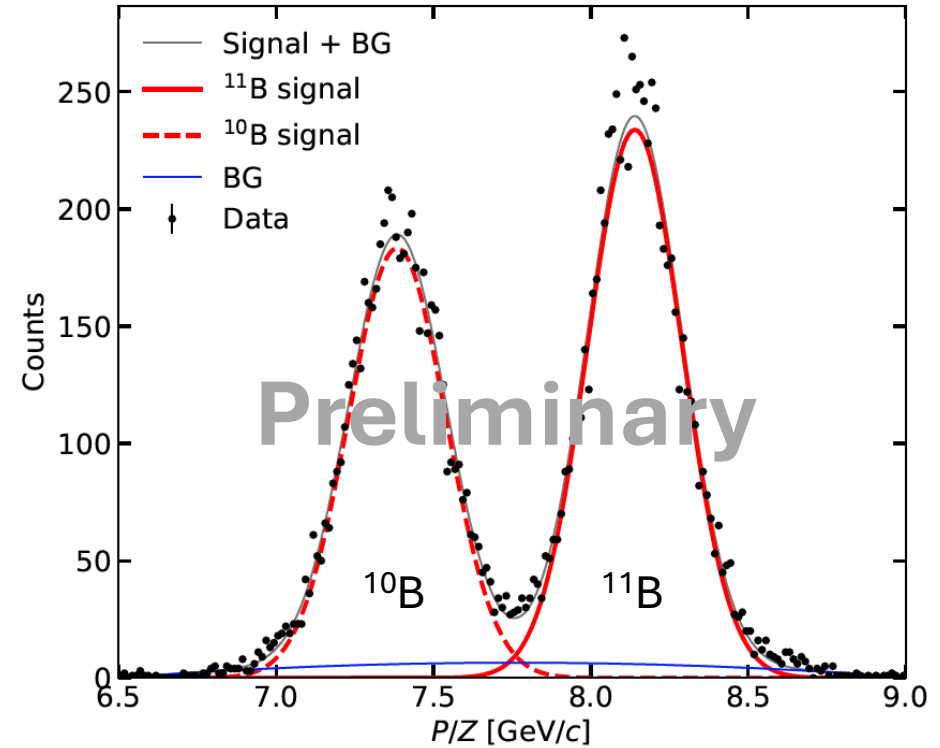
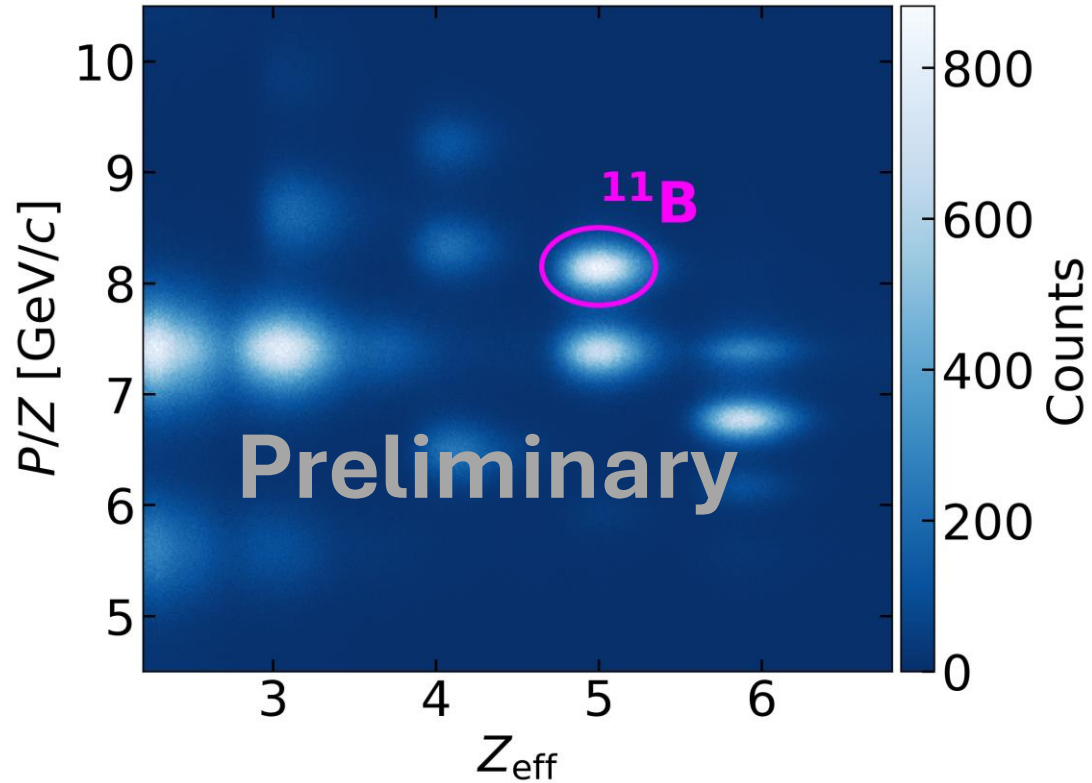
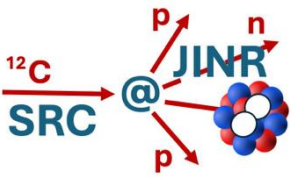
Improved experimental setup:

- New scintillator detectors: T0, BC, and SW
- 2 pairs of Si detectors
- TOF layer in arms
- Cathode Strip Chambers
- Laser calibration system
- Veto Box detector

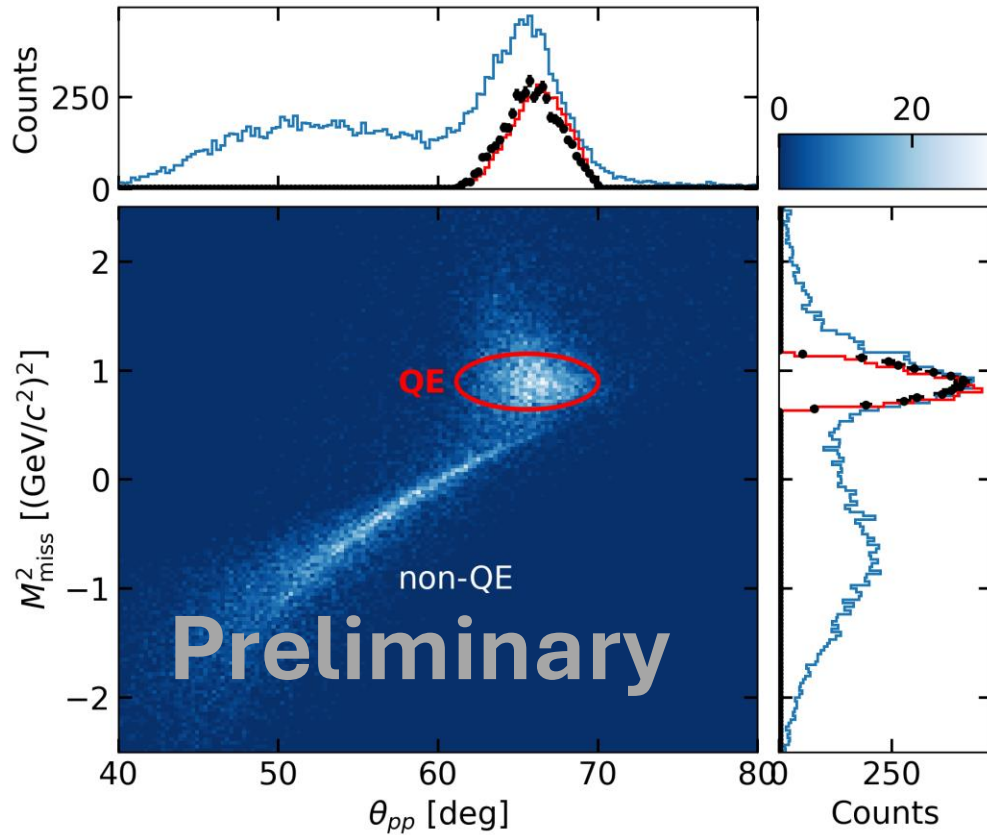
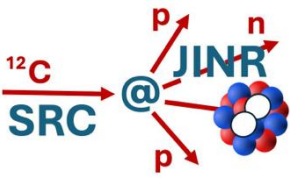




^{11}B fragment selection $^{12}\text{C}(p,2p)^{11}\text{B}$

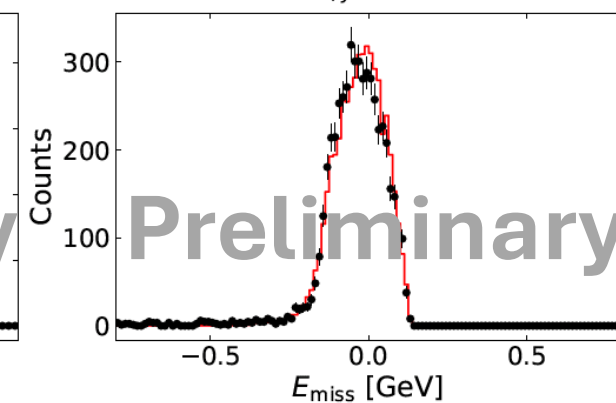
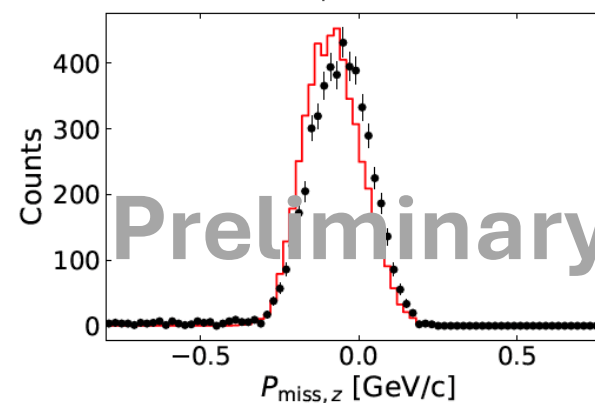
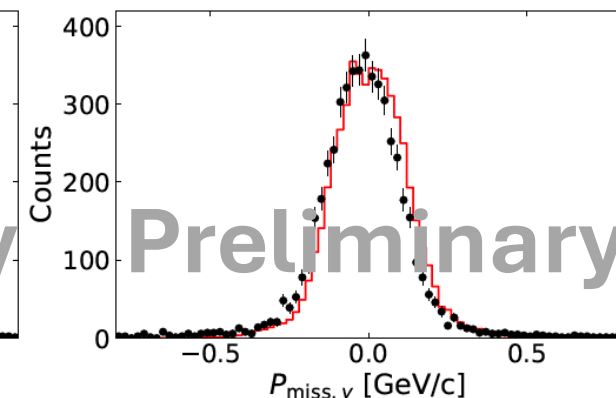
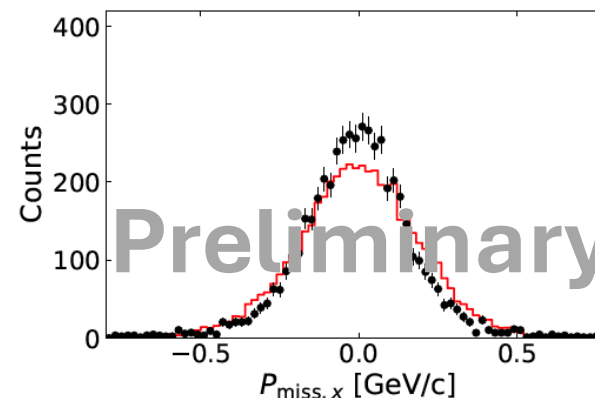
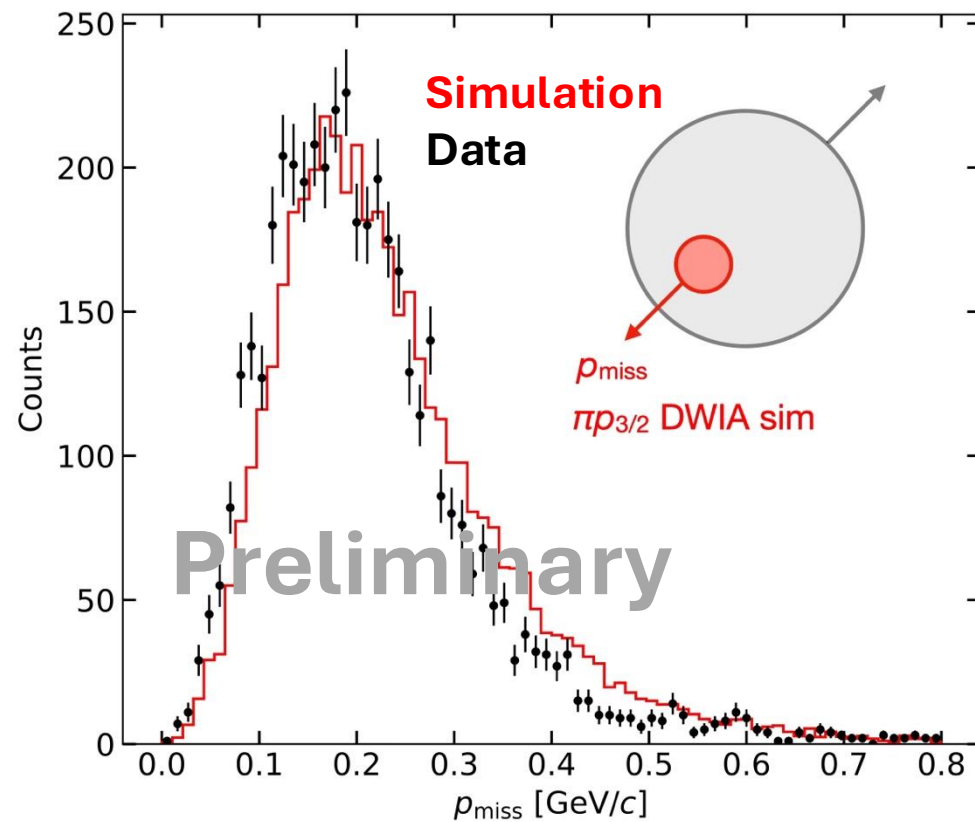
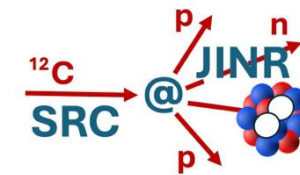


Quasi-Elastic identification $^{12}\text{C}(p,2p)^{11}\text{B}$

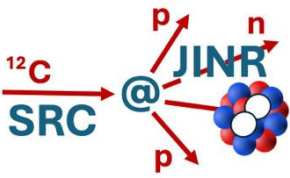


- Incoming ^{12}C , outgoing ^{11}B
- Two single tracks in the arms
- Reaction vertex within the target
- Velocity cut
- 2d cut: M_{miss}^2 vs. θ_{pp}

Missing momentum $P_{\text{miss}} = P_1 + P_2 - P_{\text{beam}}$



QE (p,2p) process at intermediate relativistic energies



Theory by Alexey Larionov and Yuri Uzikov, PRC 110 (2024)

Nuclear Structure

x

(p,2p)

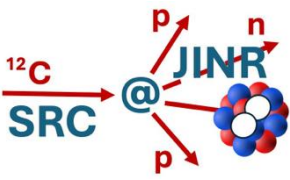
x

ISI/FSI

Translationally invariant
shell model
(here: HO WF)

Impulse
Approximation

Glauber
Calculation



Nuclear Structure

x (p,2p)

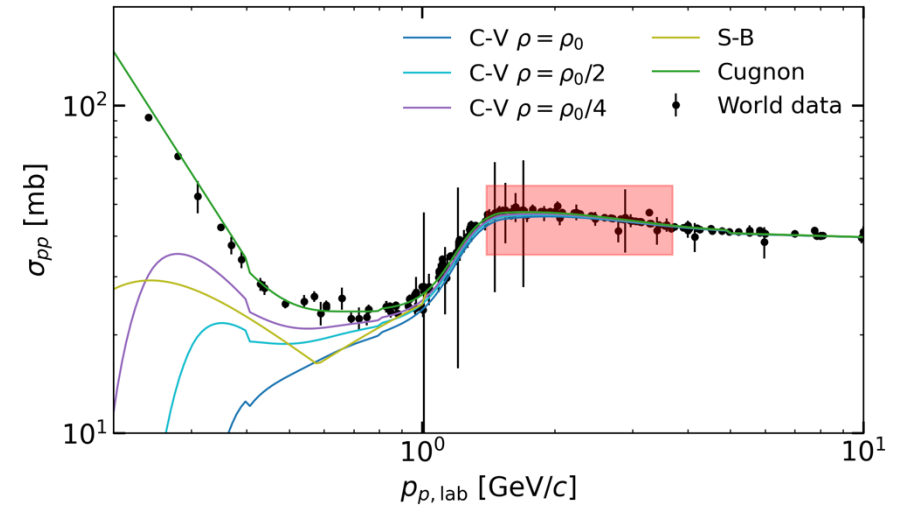
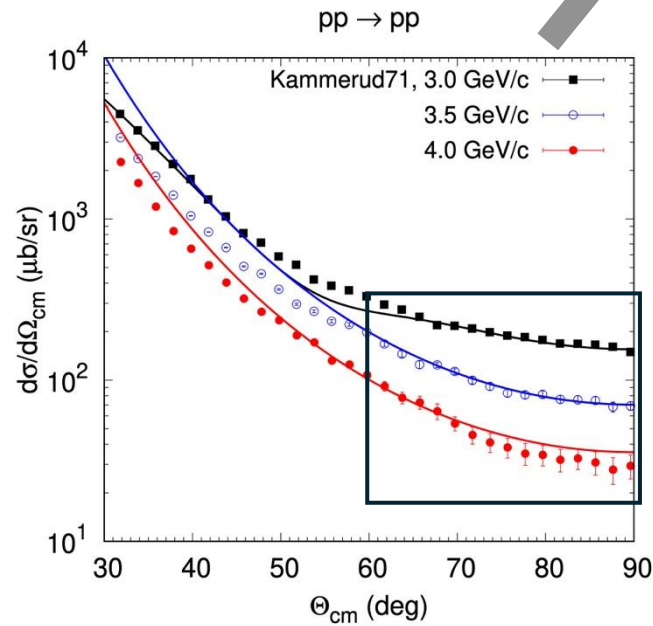
x

ISI/FSI

Translationally invariant shell model (here: HO WF)

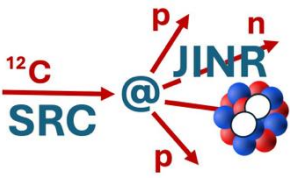
Impulse Approximation

Glauber Calculation



data - L. R. Workman et al. (Particle Data Group), PTEP 2022, 083C01 (2022)
J. Cugnon et al., Nucl. Instr. Meth. B 111, 215 (1996)
R. D. Smith and M. Bozoian, Phys. Rev. C 39 1751 (1989)
E. Clementel and C. Villi, Il Nuovo Climento 2, 176-179 (1955)

QE cross section



$$\sigma_{QE p} = \frac{N_{(p,2p)11B}(T)}{N_{12C}} \frac{1}{T} \cdot e^{\sigma_R T}$$

T – number of protons in the target
 σ_R - reaction cross section

Corrections:

Beam-trigger corrections

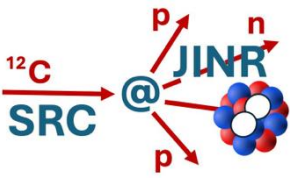
Fragment

tracking efficiency
P/Z cut and background
Z cut

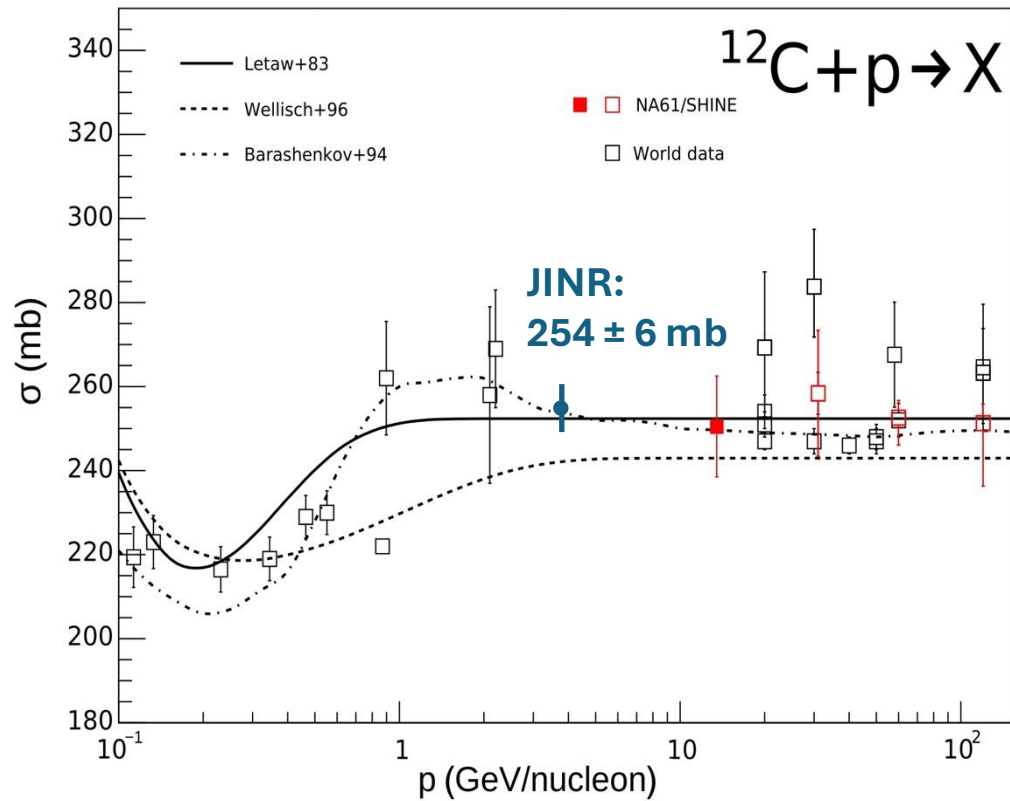
(p,2p)

Detector and tracking efficiency
QE false positive
MRPC acceptance

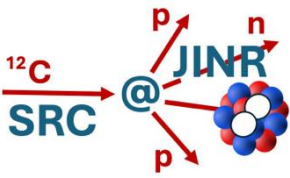
Cross-section benchmarking



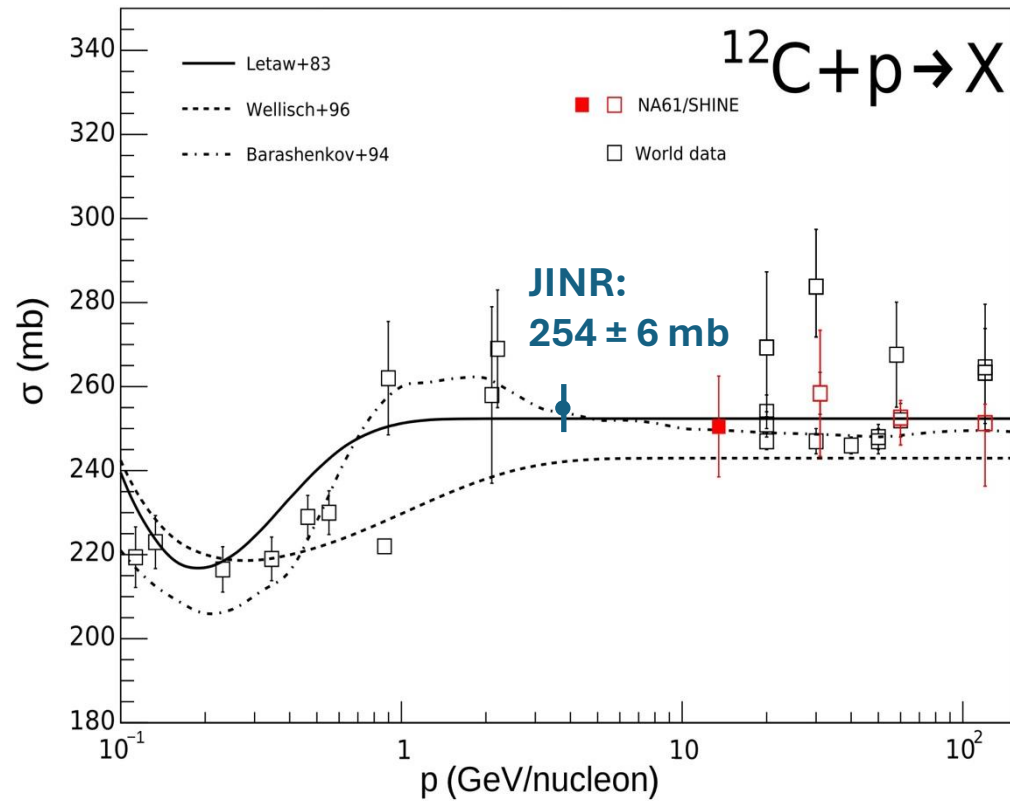
Interaction cross section: $^{12}\text{C} \rightarrow X$



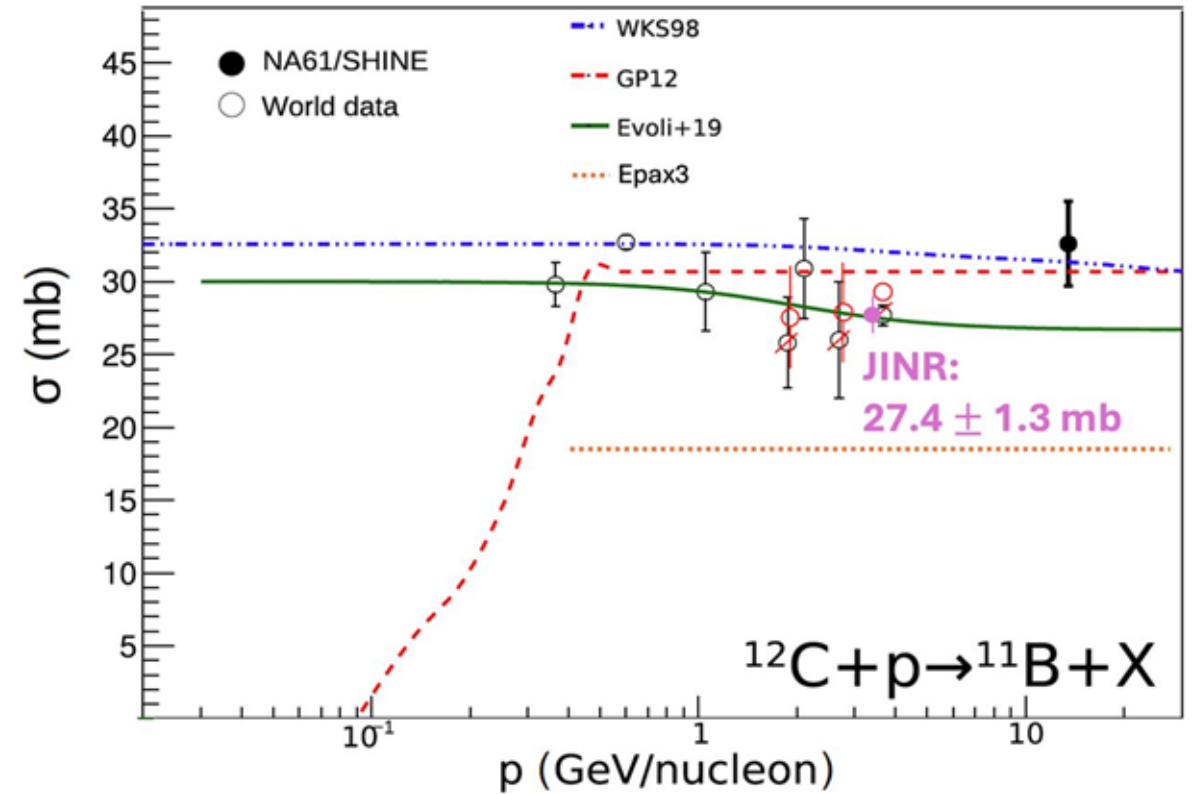
Cross-section benchmarking



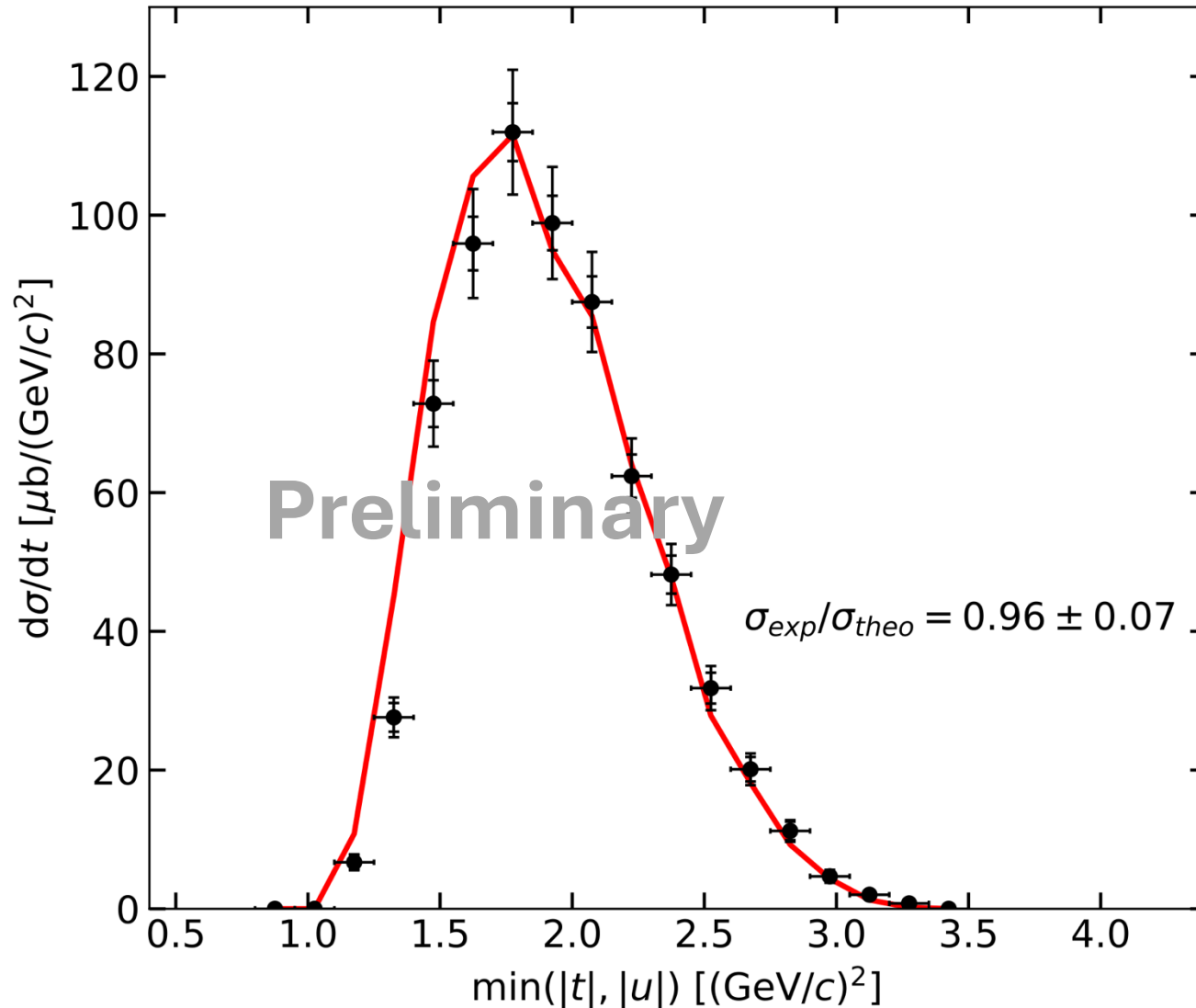
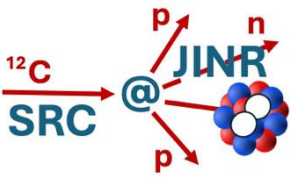
Interaction cross section: $^{12}\text{C} \rightarrow \text{X}$



Interaction cross section: $^{12}\text{C} \rightarrow ^{11}\text{B}$



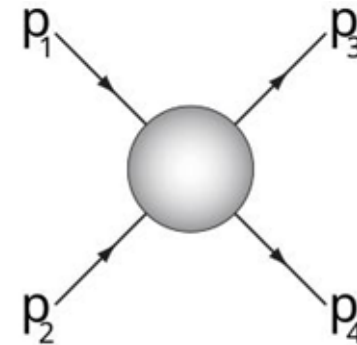
QE cross-section $^{12}\text{C}(p,2p)^{11}\text{B}$



pp-scattering:

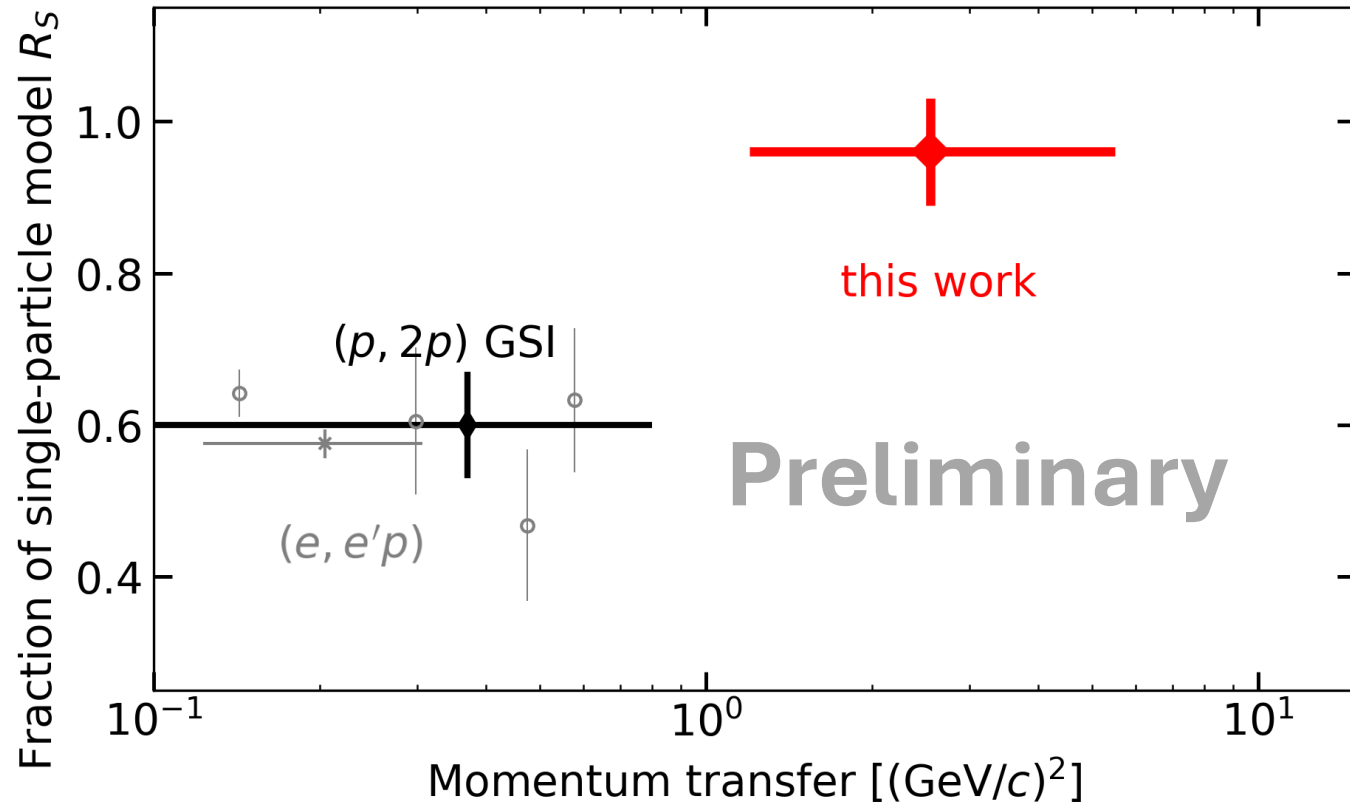
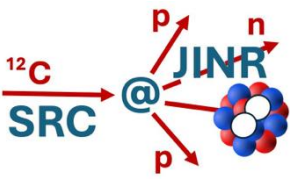
$$t = (P_1 - P_3)^2 = (P_2 - P_4)^2$$

$$u = (P_1 - P_4)^2 = (P_2 - P_3)^2$$

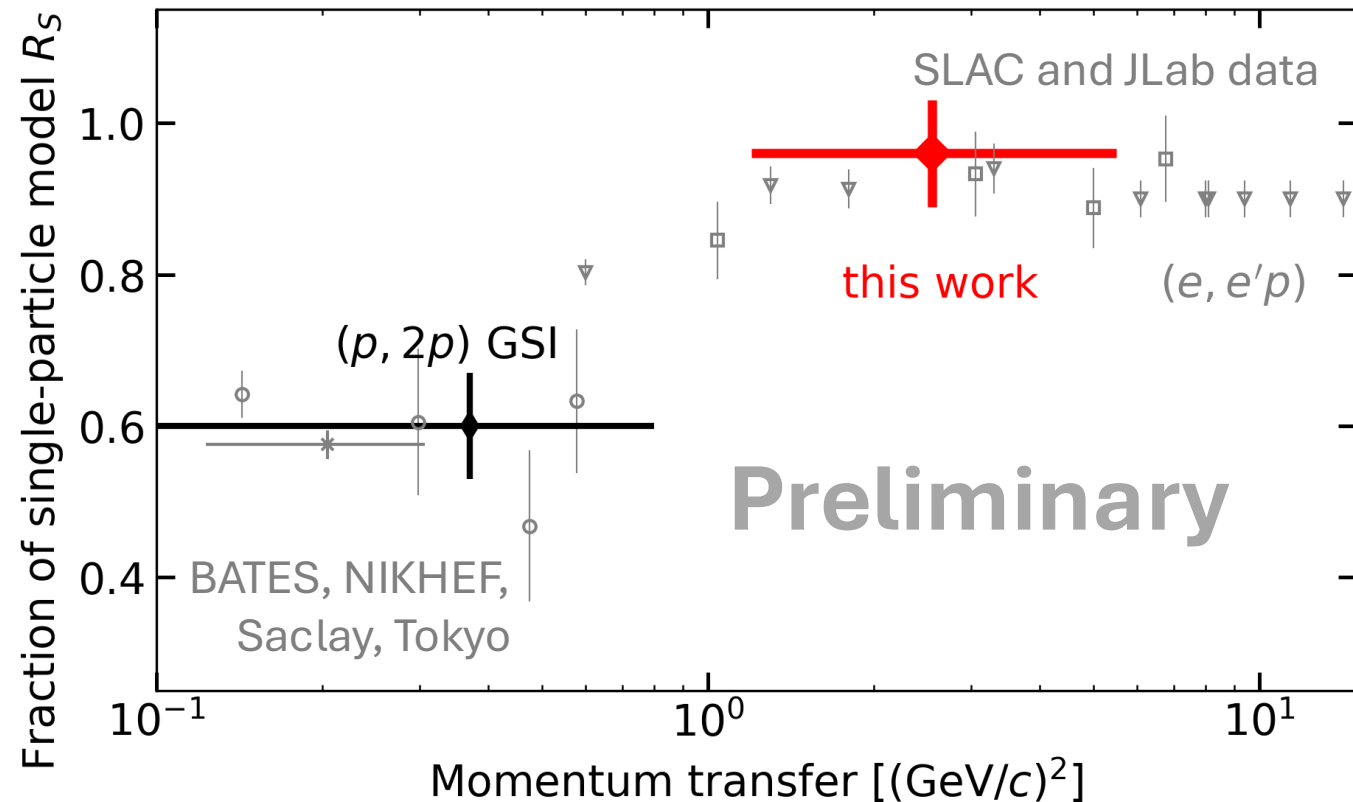
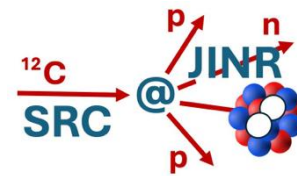


$$R_s = \frac{\sigma_{exp}}{\sigma_{theory}} = 0.96 \pm 0.07$$

^{12}C spectroscopic strength: scale dependence

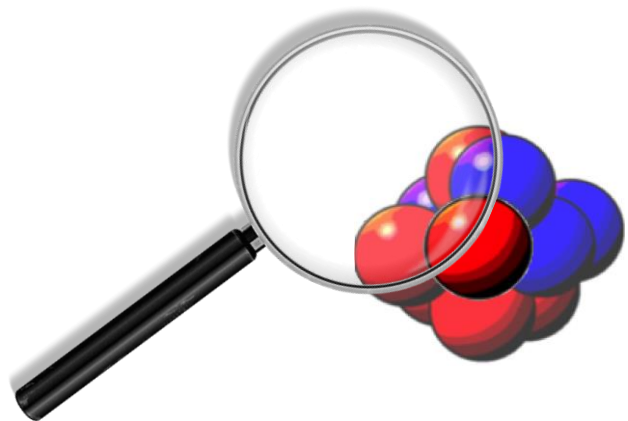
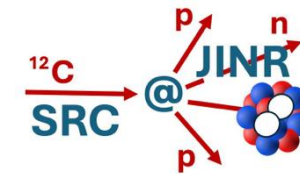


^{12}C spectroscopic strength: scale dependence



- L. Lapikas et al., Phys. Rev. C 61, 064325 (2000)
- D. Bhetuwal et al. (Hall C), Phys. Rev. Lett. 126, 082301 (2021)
- N. Makins et al., Phys. Rev. Lett. 72, 1986 (1994)
- D. Abbott et al., Phys. Rev. Lett. 80, 5072 (1998)
- P. E. Ulmer et al., Phys. Rev. Lett. 59, 2259 (1987)
- L. B. Weinstein et al., Phys. Rev. Lett. 64, 1646 (1990)
- K. Garrow et al., Phys. Rev. C 66, 044613 (2002)
- V. Panin et al., Phys. Lett. B 753, 204 (2016)

Summary

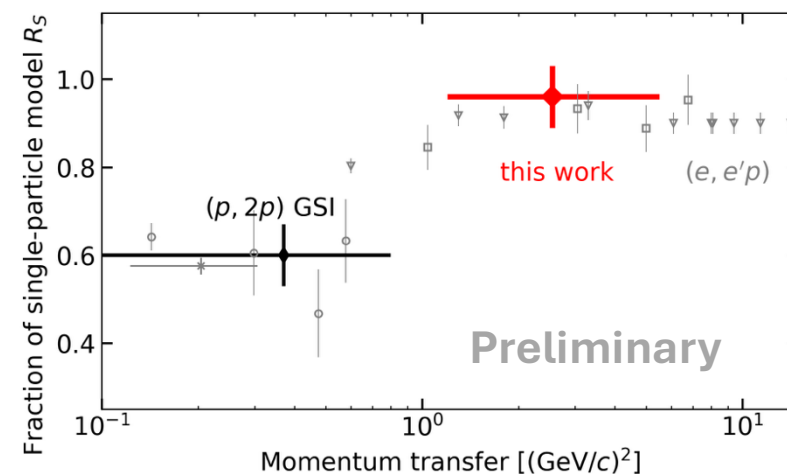


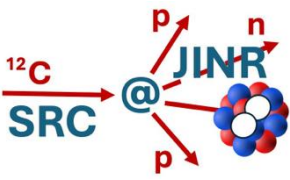
^{12}C spectroscopic strength is scale dependent

“Unquenching” \rightarrow Universal, resolution-dependent restoration of the single-particle picture

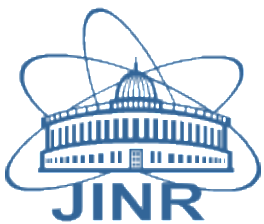
Favorable kinematics:

- High energy \rightarrow ISI/FSI in Glauber approach
- High momentum \rightarrow resolution scale

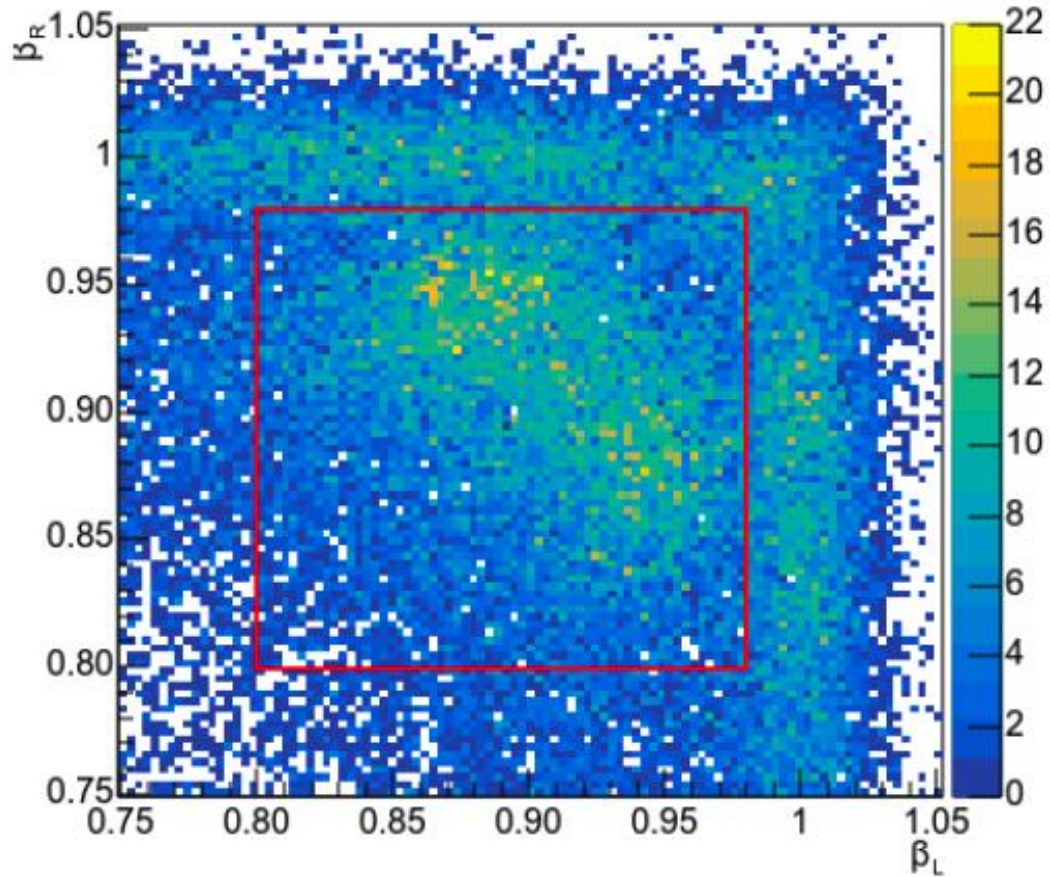




Thank you!



ToF in the arms and proton identification



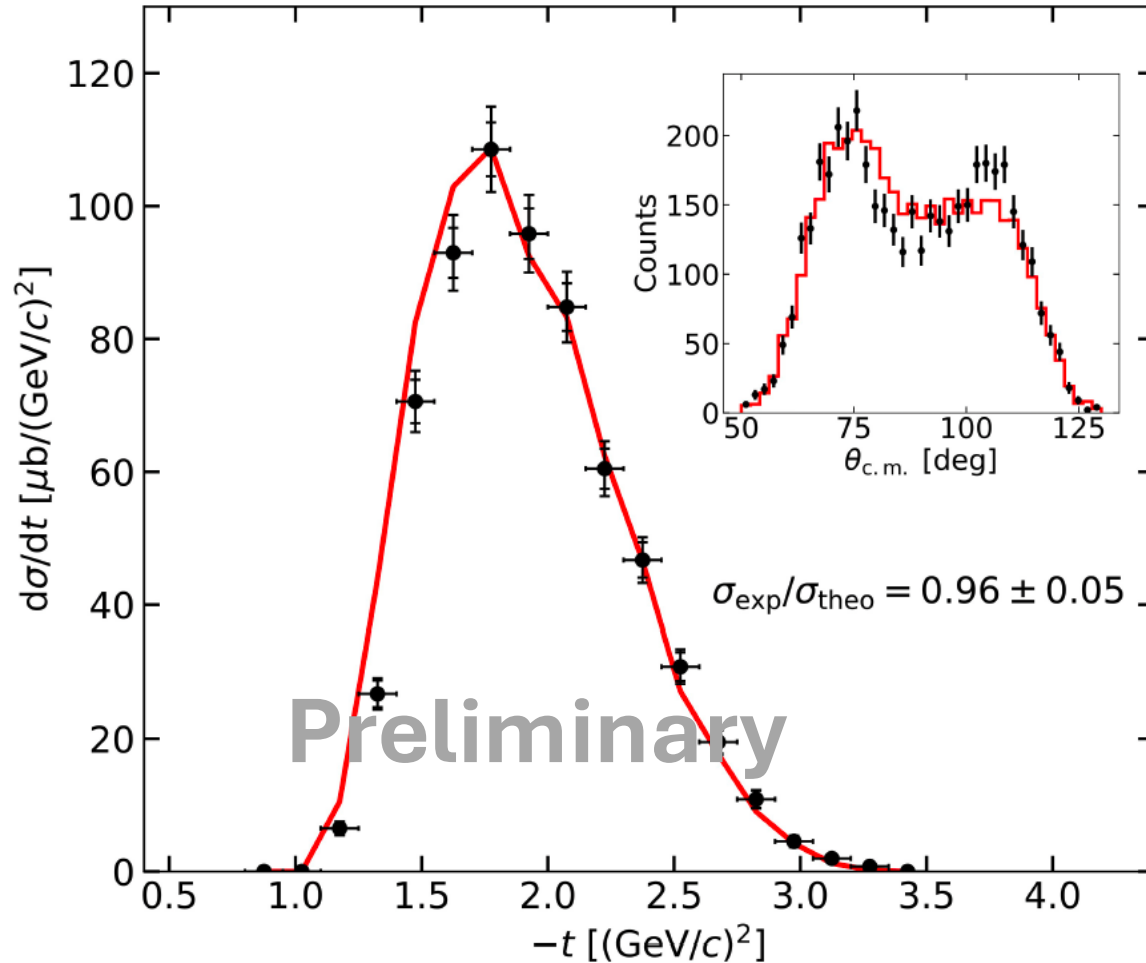
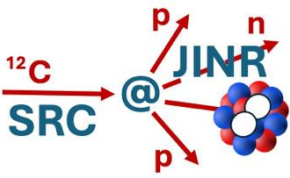
ToF resolution is 170 ps

The total momentum resolution is 150 MeV/c →

Pmiss resolution of 55 MeV/c

The resolution is extracted for QE events in comparison to simulation

QE cross-section $^{12}\text{C}(p,2p)^{11}\text{B}$



pp-scattering:

$$t = (P_1 - P_3)^2 = (P_2 - P_4)^2$$

$$u = (P_1 - P_4)^2 = (P_2 - P_3)^2$$

