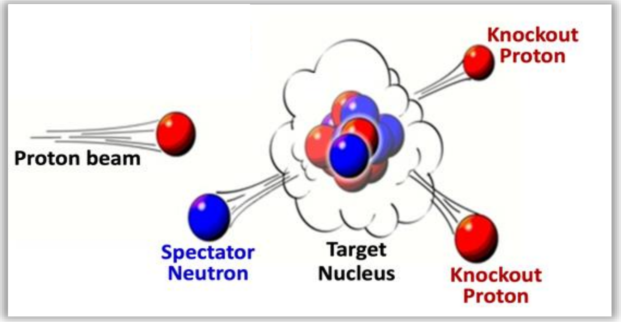
SRC studies in inverse kinematics

Julian Kahlbow

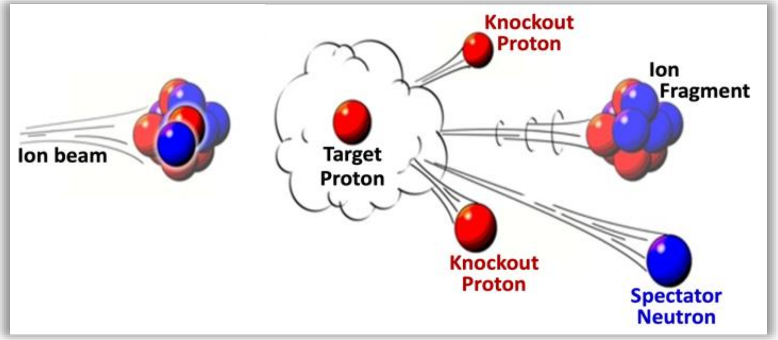
ECT* Workshop
July 20, 2023

Flipping reaction kinematics provides powerful access to SRCs!

nuclear target
and p or e^- beam



(radioactive) ion beam
hitting hadronic probe



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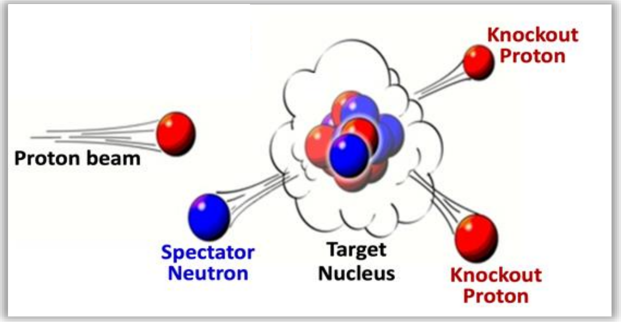

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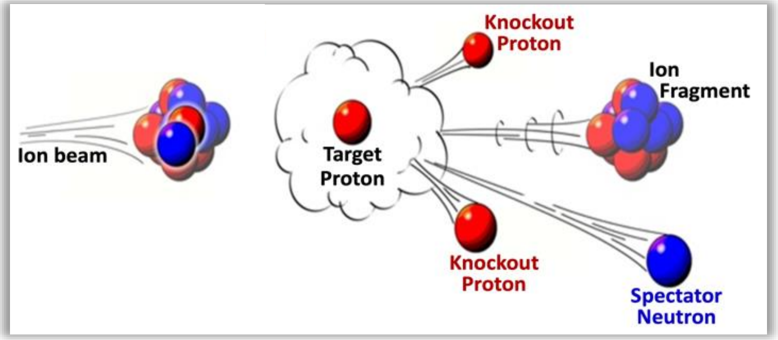

1. **Inverse kinematics: nuclear structure using hadronic probes**
2. **SRCs in neutron-rich environments**

Flipping reaction kinematics provides powerful access to SRCs!

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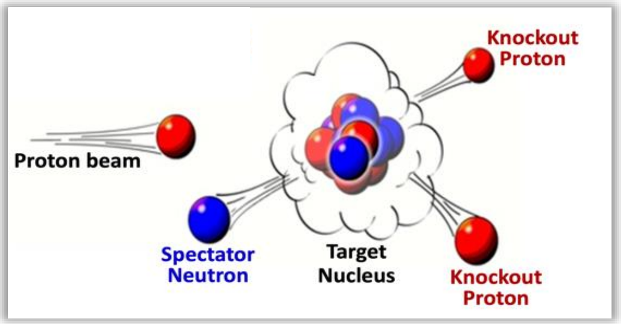

(radioactive) ion beam
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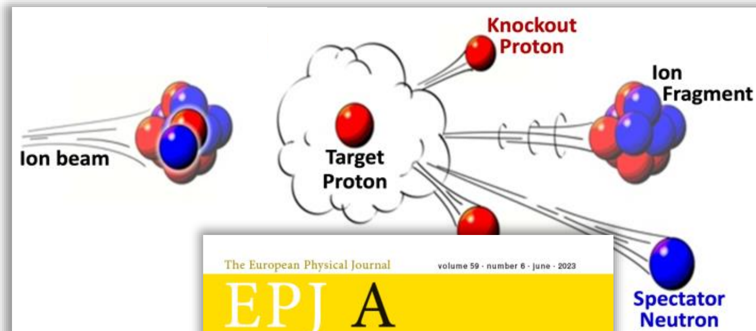
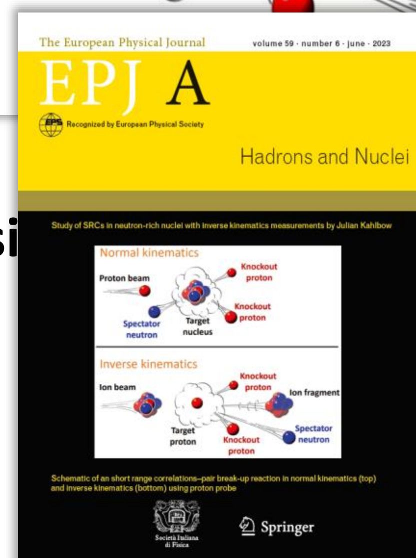
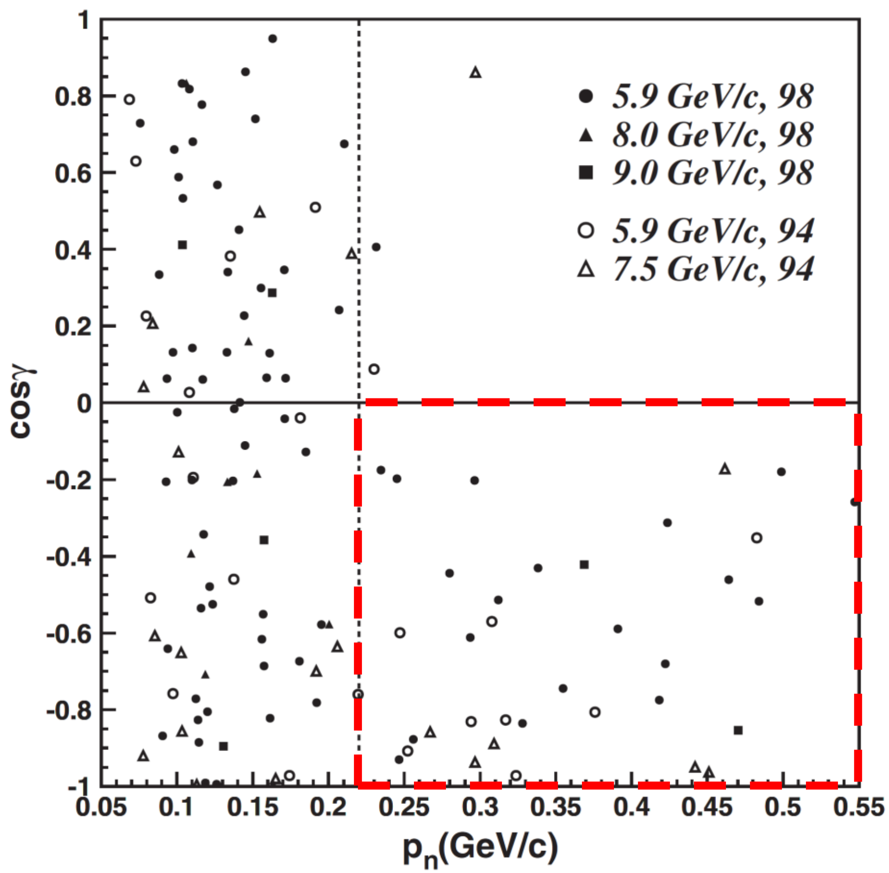




1. **Inverse kinematics: nuclear structure usi** … **es**
2. **SRCs in neutron-rich environments**

One of the first SRC experiments:



p(^{12}C,X)2pn at EVA/BNL

→ correlated high-momentum nucleon pairs

→ np pair dominance

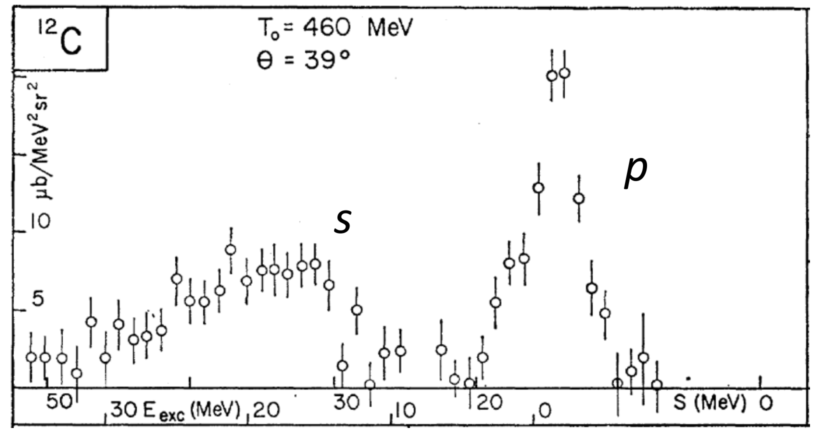
A. Tang et al., PRL 90 (2003)
E. Piasetzky et al., PRL 97 (2006)

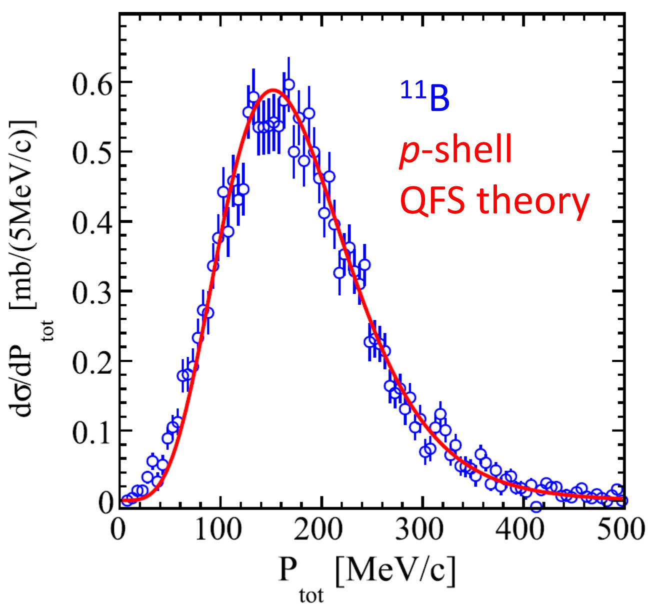
Quasi-free scattering to study nuclear structure

$^{12}C(p,2p)$:

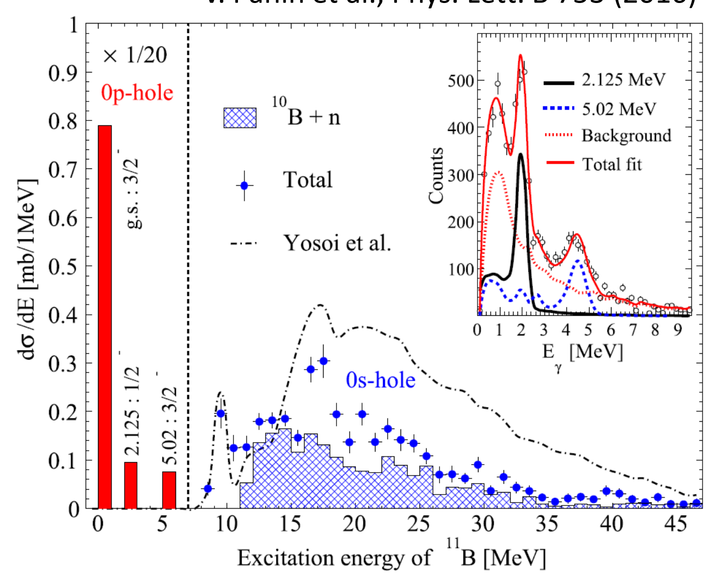
- shell structure
- momentum distributions

G. Jacob, Th. A. Maris, Rev. of Mod. Phys. 38 (1966)



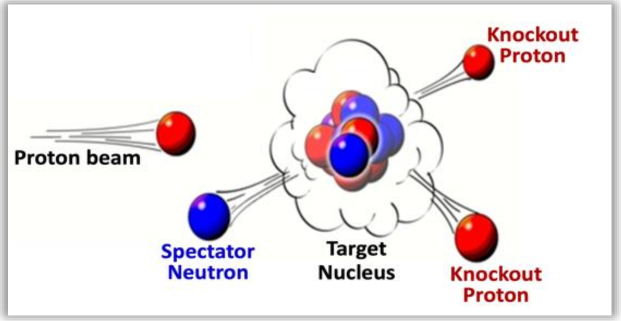


V. Panin et al., Phys. Lett. B 753 (2016)

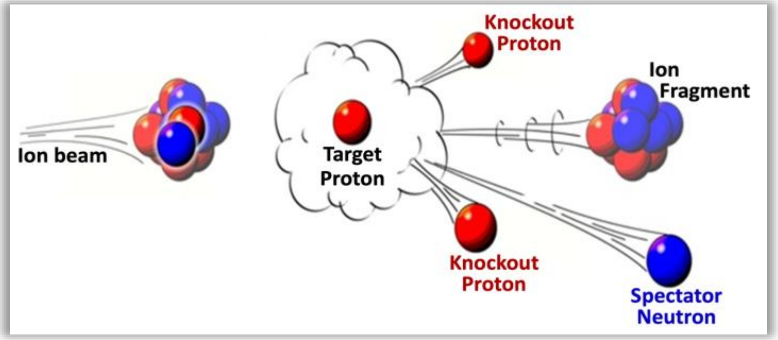


Advantages of inverse kinematics experiments

nuclear target
and p or e^- beam



(radioactive) ion beam
hitting hadronic probe



fully exclusive measurement: measure momenta of *all* emerging particles + Lorentz boost

Advantages of inverse kinematics experiments

nuclear target
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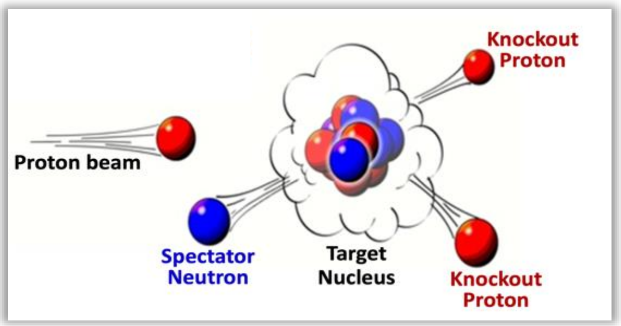

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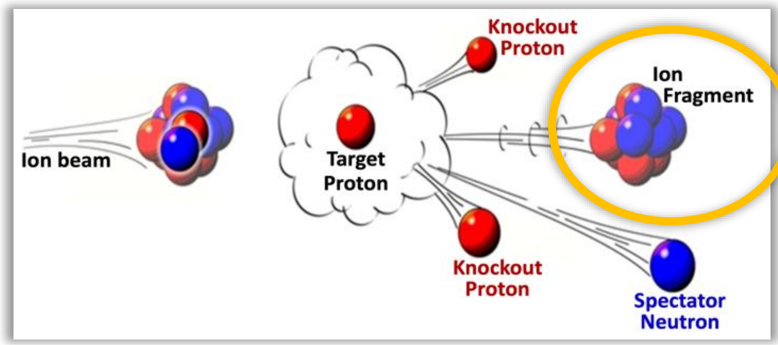


fully exclusive measurement: measure momenta of *all* emerging particles + Lorentz boost

Disadvantages: In-medium effects

Incoming proton and outgoing protons interact with other nucleons
(**initial and final state interactions**)

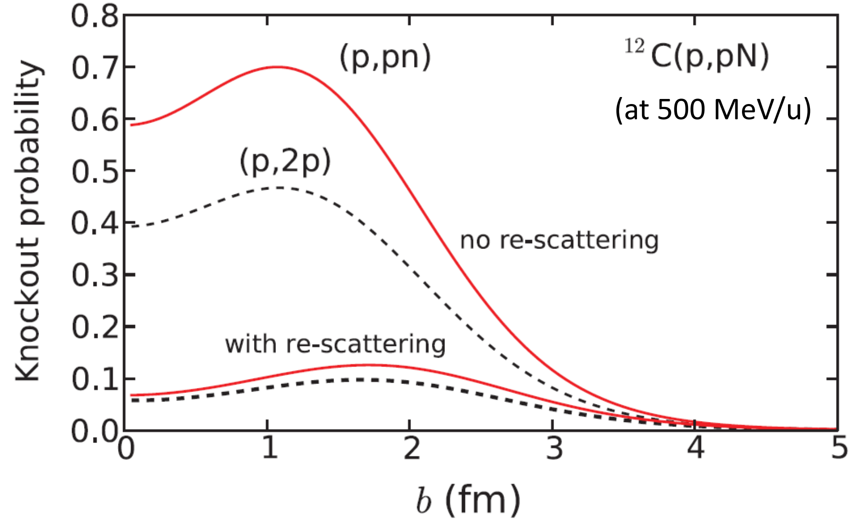
→ disturb initial momentum reconstruction

→ extra excitations of the nucleus (break fragment apart)

→ eject additional particles (pions, …)

→ attenuation

T. Aumann, C.A. Bertulani, J. Ryckebusch, Phys. Rev. C 88 (2013)



L. Frankfurt, M. Strikman, M. Zhalov, PLB 503 (2001).
S. Stevens et al., PLB 777 (2018).

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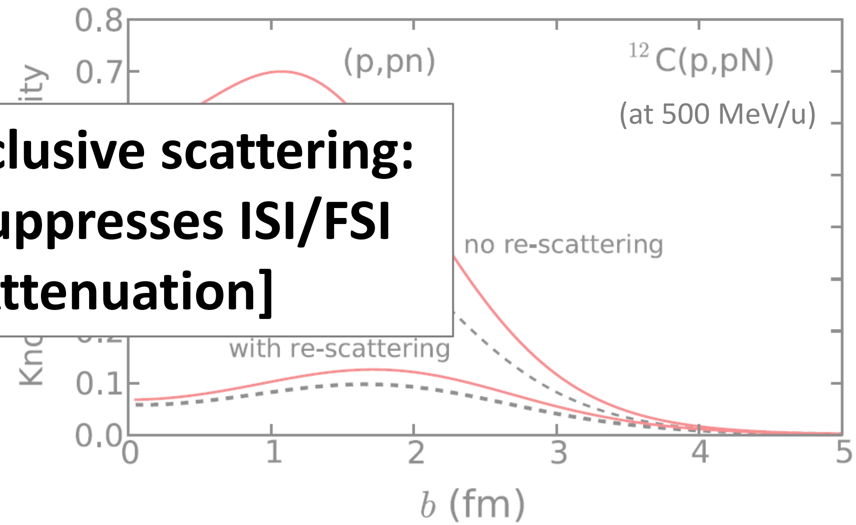
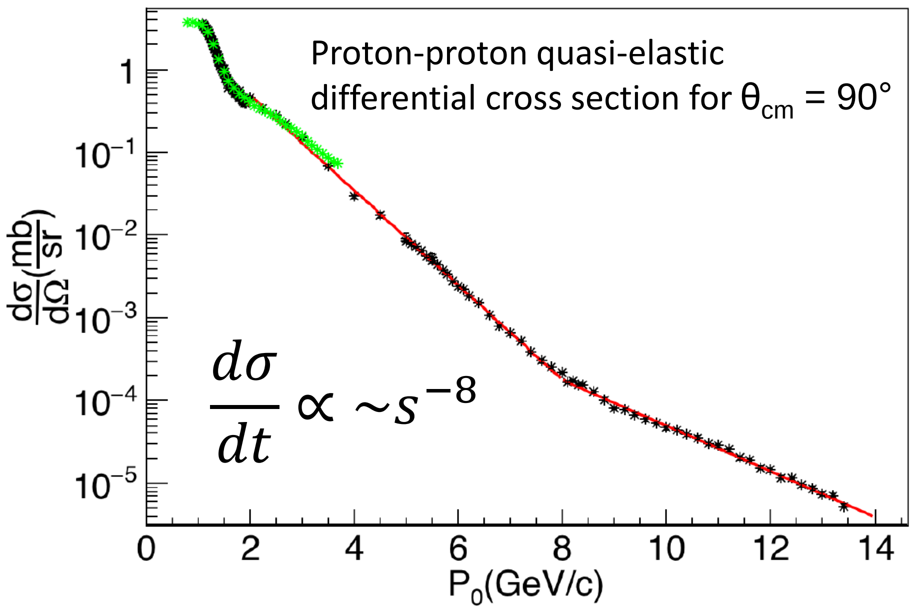


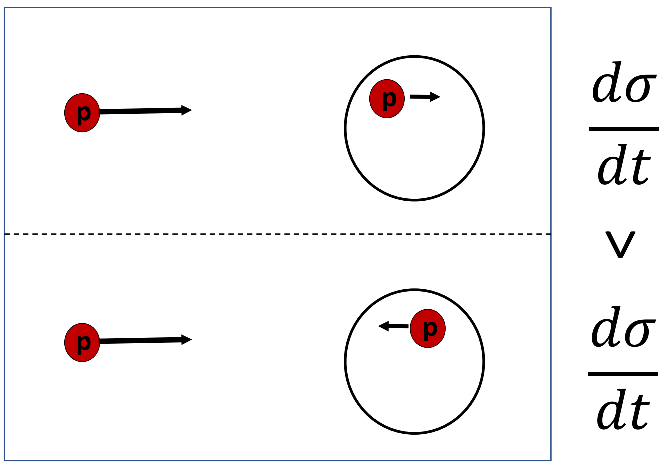
**We proof in fully exclusive scattering:
fragment tagging suppresses ISI/FSI
[Distortion + Attenuation]**

L. Frankfurt, M. Strikman, M. Zhalov, PLB 503 (2001).
S. Stevens et al., PLB 777 (2018).

Quasi-free scattering at high energies



``Selective Attention``



+ large energy and momentum transfer

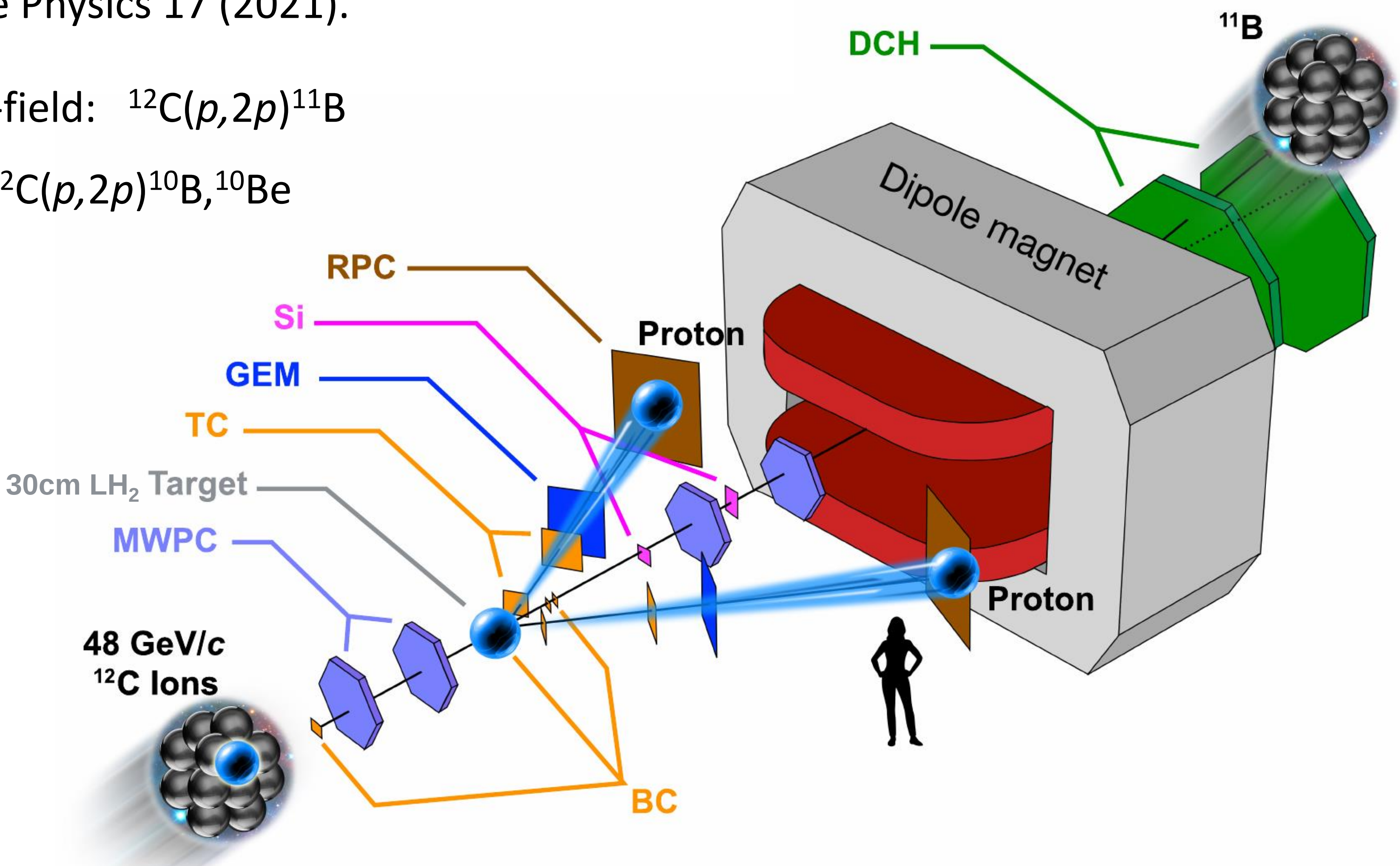
→ impulse & spectator approximation (~ adiabatic process)
→ multiple scattering well described by Glauber theory

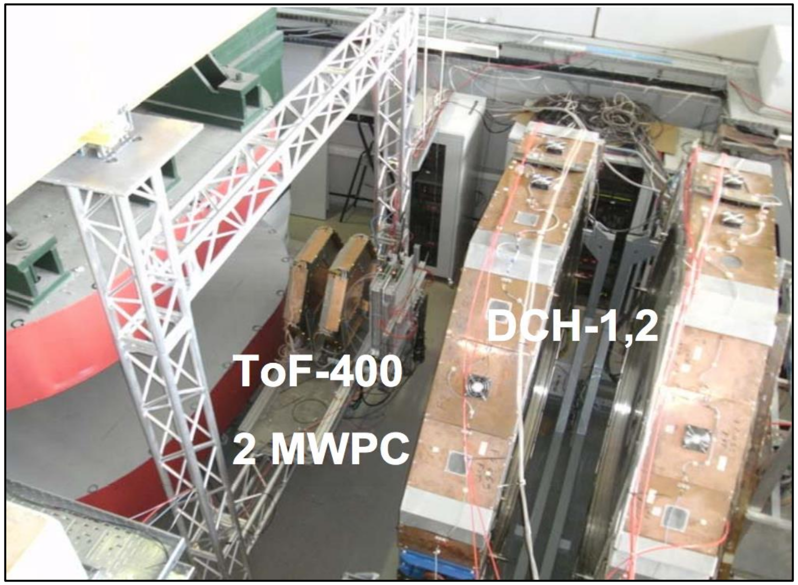
Experiment at BM@N Setup (JINR)

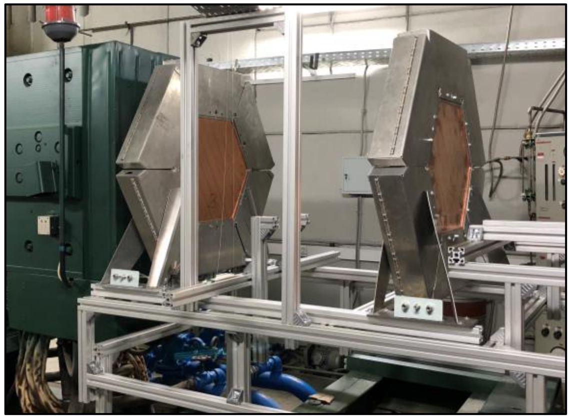
M. Patsyuk, JK et al. (BM@N), Nature Physics 17 (2021).

Mean-field: $^{12}C(p,2p)^{11}B$

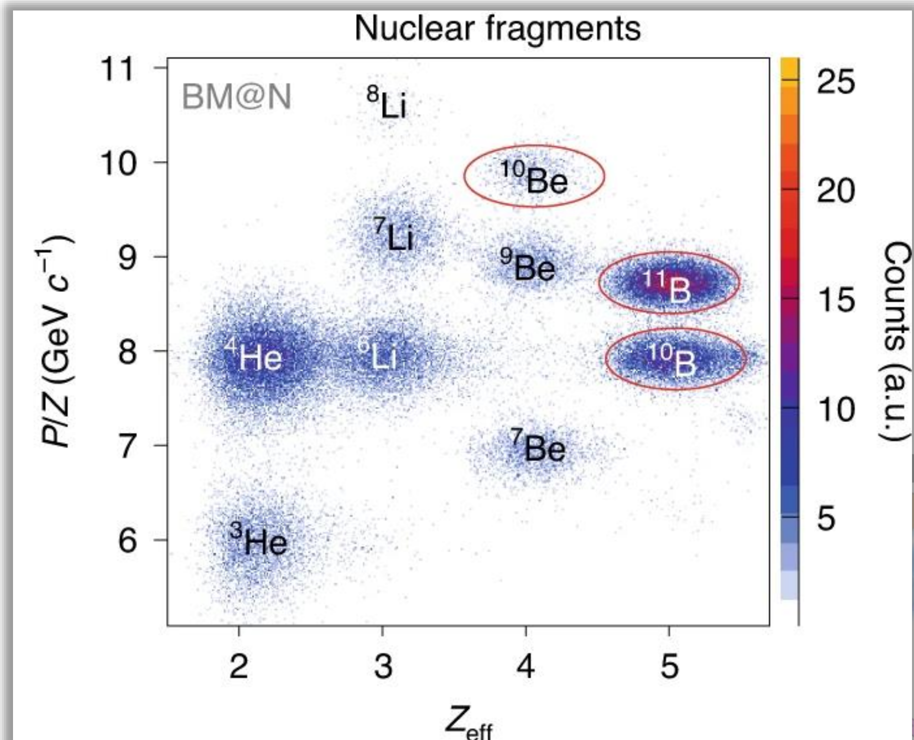
SRC: $^{12}C(p,2p)^{10}B,^{10}Be$

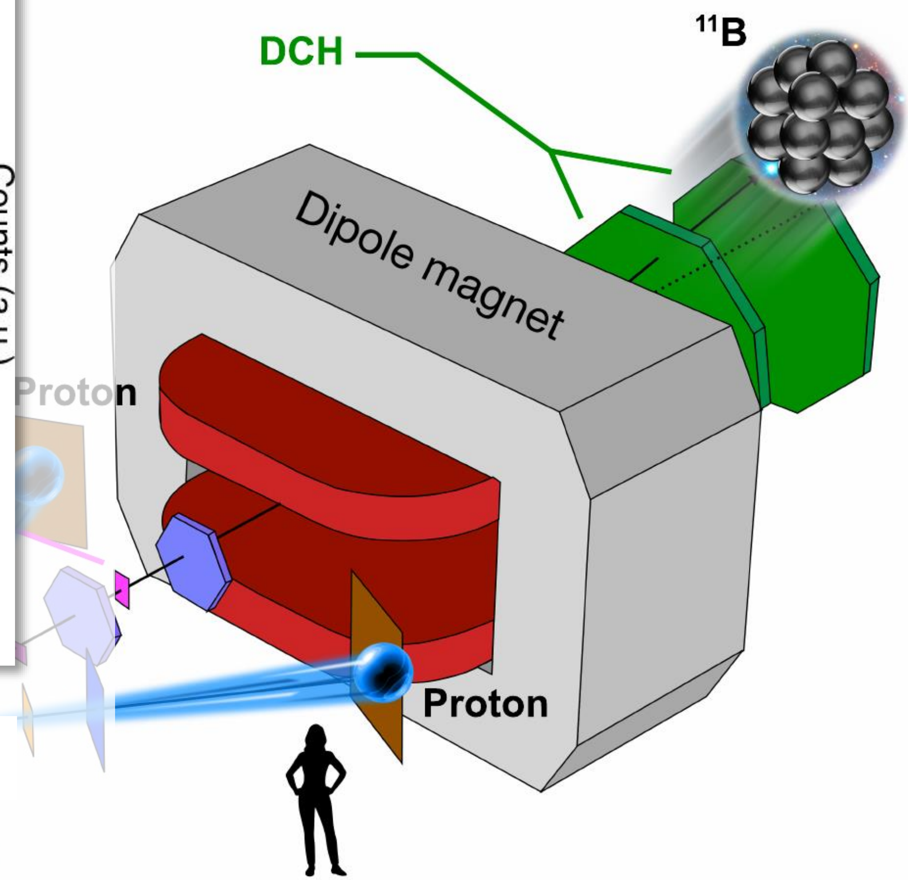



DCH-1,2
ToF-400
2 MWPC



Heavy-fragment identification: post-selection



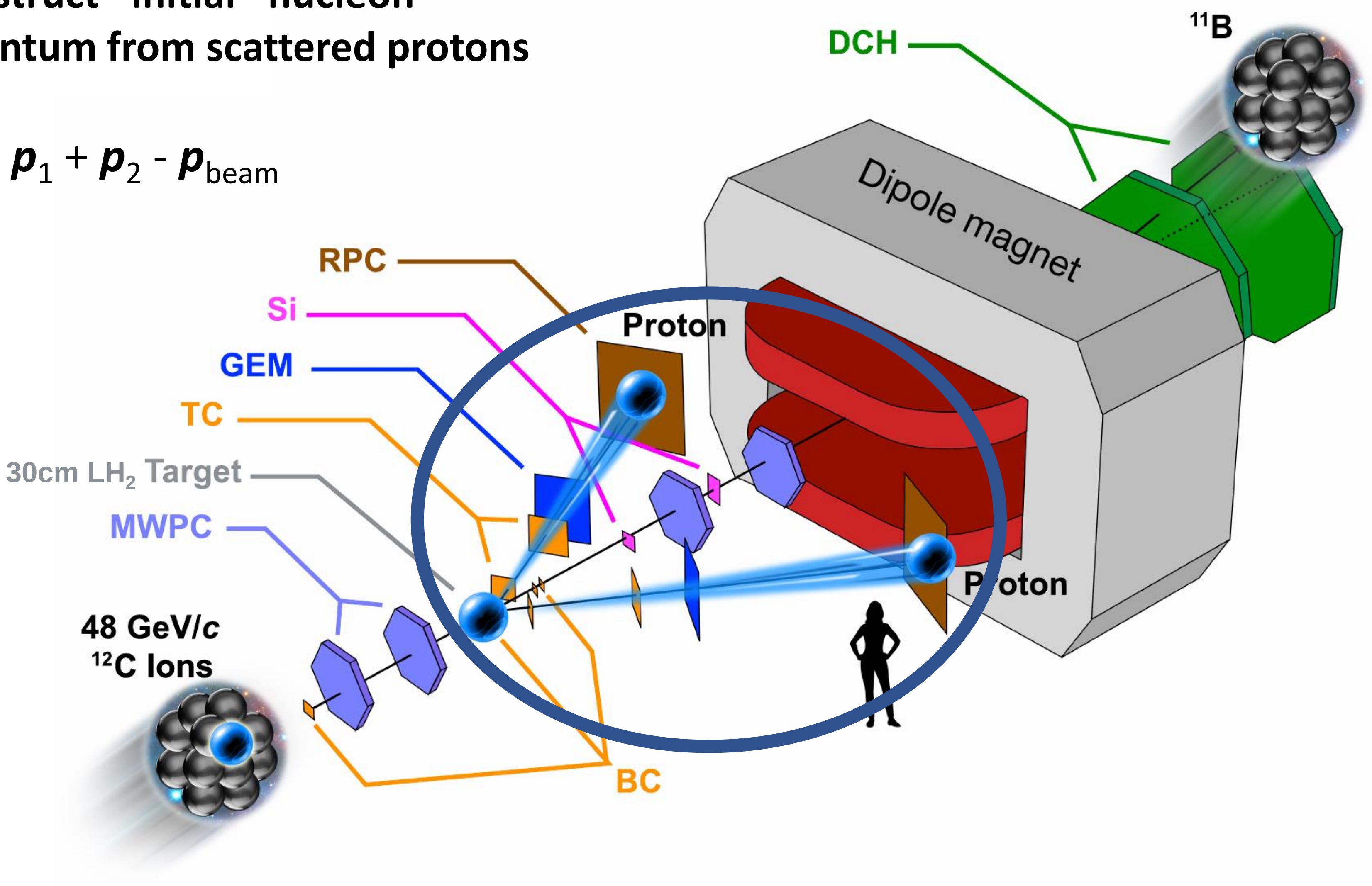


→ Break-up reactions of heavy fragment

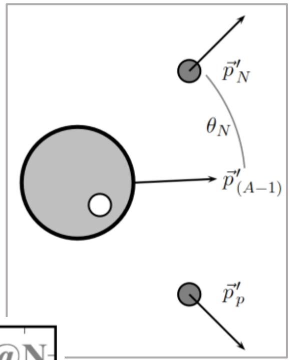
Quasi-free (p,2p) scattering

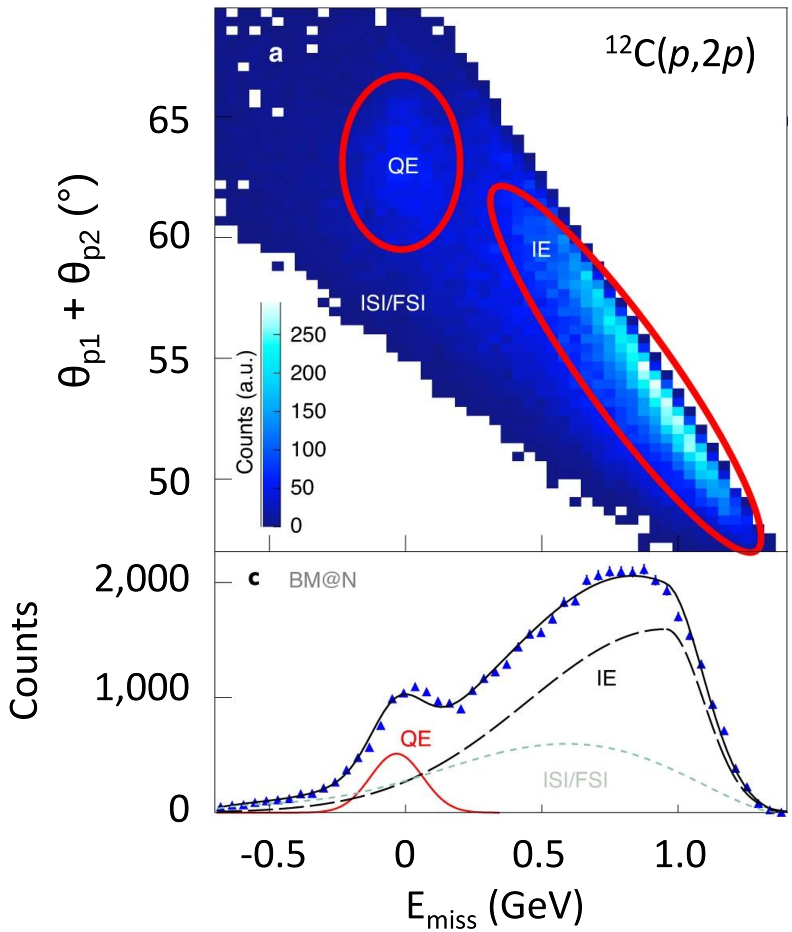
Reconstruct "initial" nucleon momentum from scattered protons

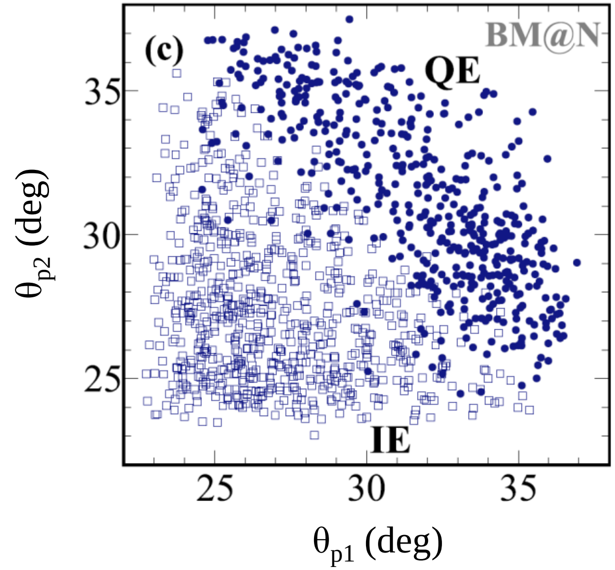
$\boldsymbol{p}_{\text{miss}} = \boldsymbol{p}_1 + \boldsymbol{p}_2 - \boldsymbol{p}_{\text{beam}}$



But: Is QE scattering free of FSI?



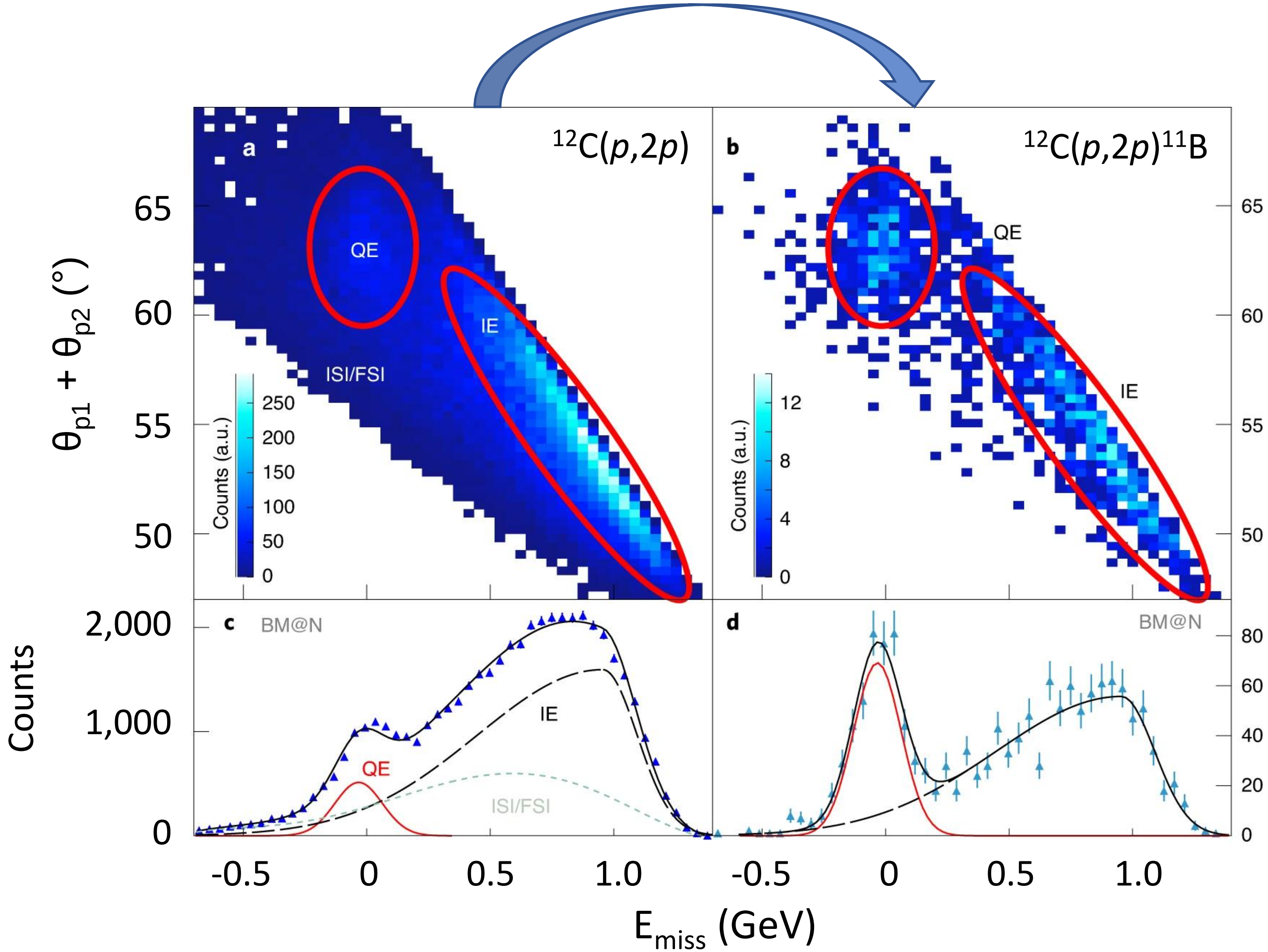




(p,2p) inclusive scattering dominated by inelastic scattering and initial/final state interactions

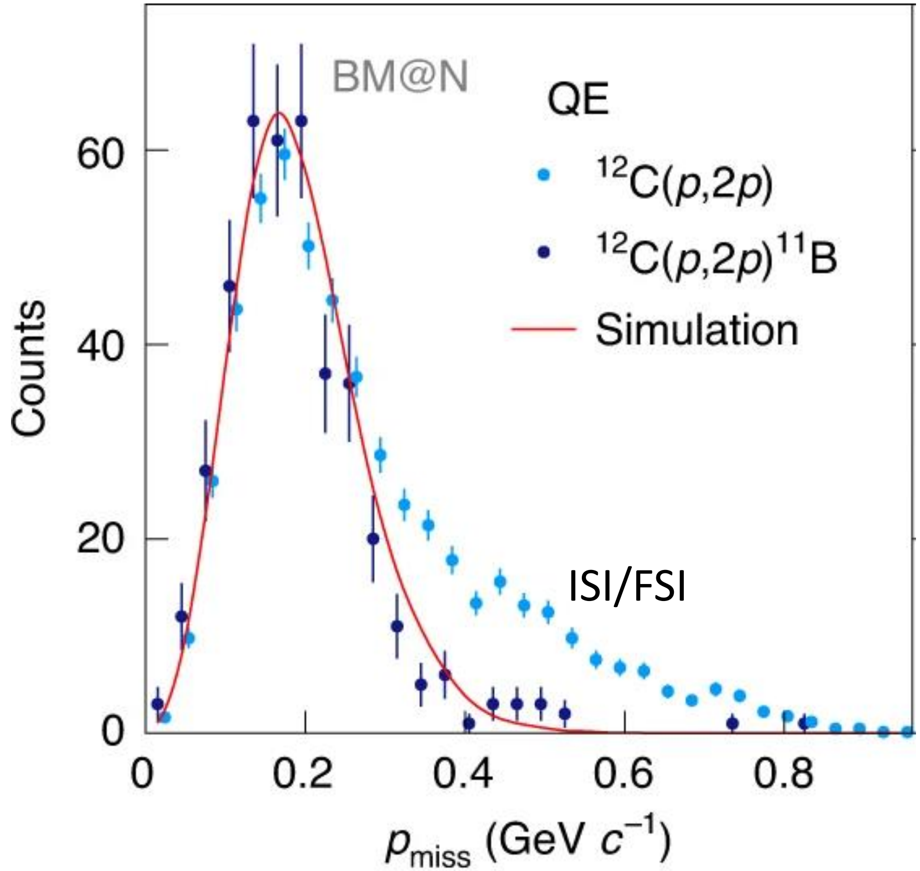
Reaction mechanism under control

Fragment tagging suppresses initial/final state interactions



Single-step nucleon knockout

Proton momentum distribution with fragment tagging to access ground-state distribution

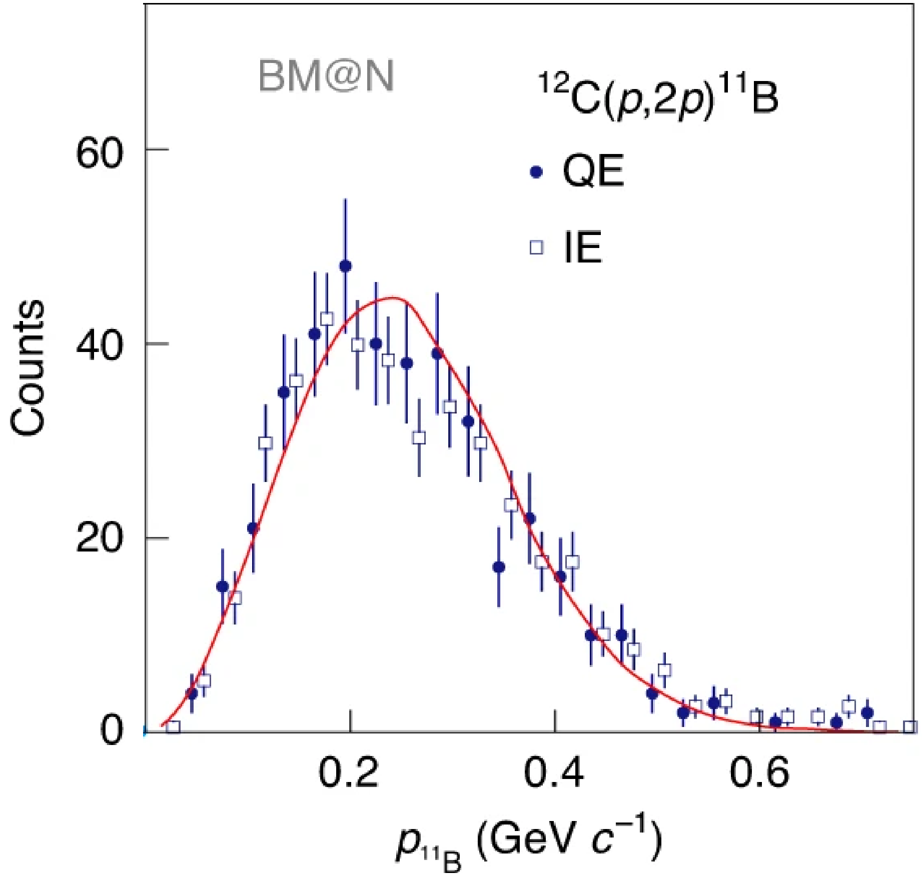


Calculation of QE (p,$2p$) scattering off p-shell nucleon in ^{12}C without ISI/FSI

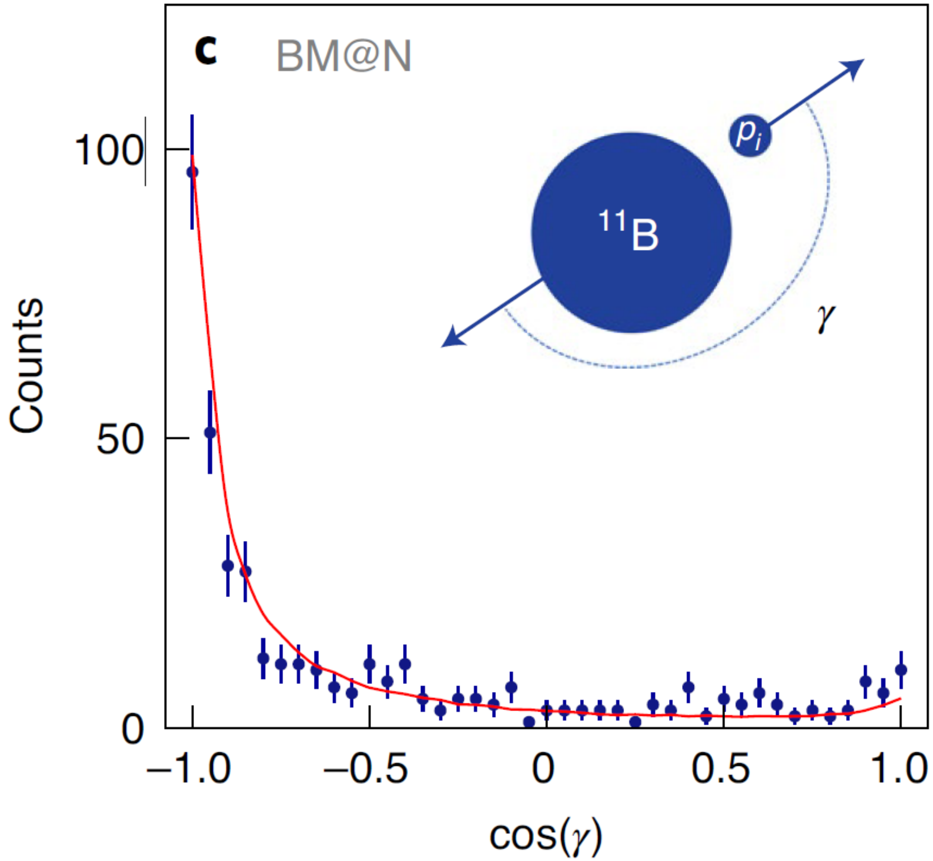
[T. Aumann, C.A. Bertulani, J. Ryckebusch, PRC 88 (2013).]

Fragment recoil momentum

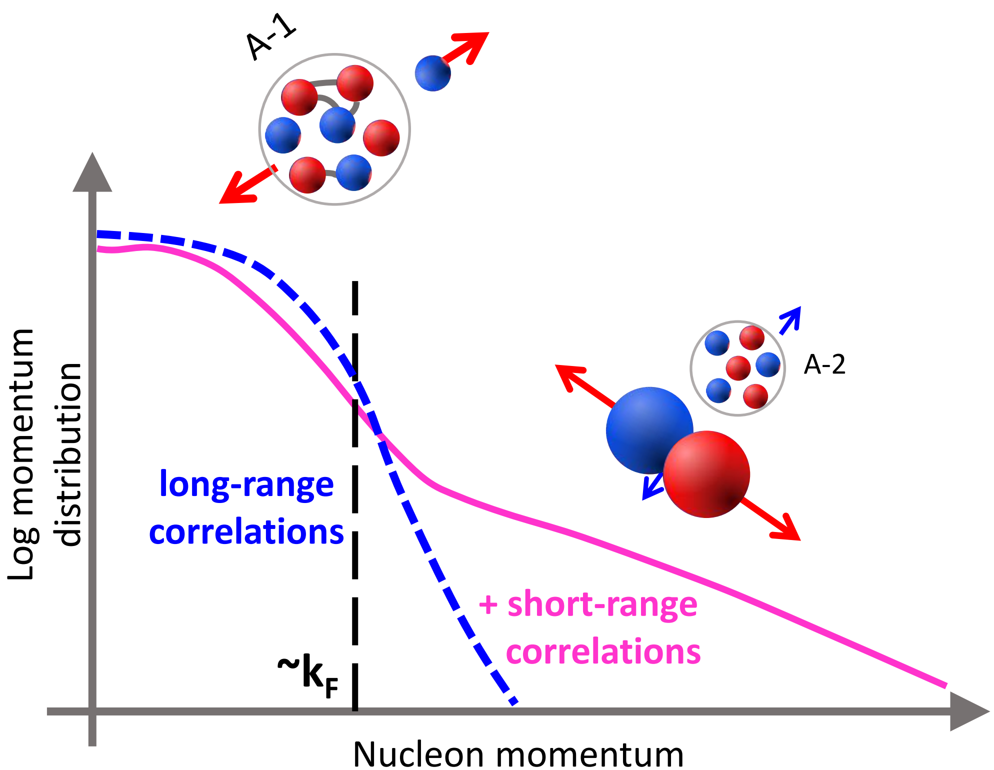
Fragment not impacted by inelastic scattering: adiabatic approximation holds $\boldsymbol{p}_{miss} = -\boldsymbol{p}_{A-1}$



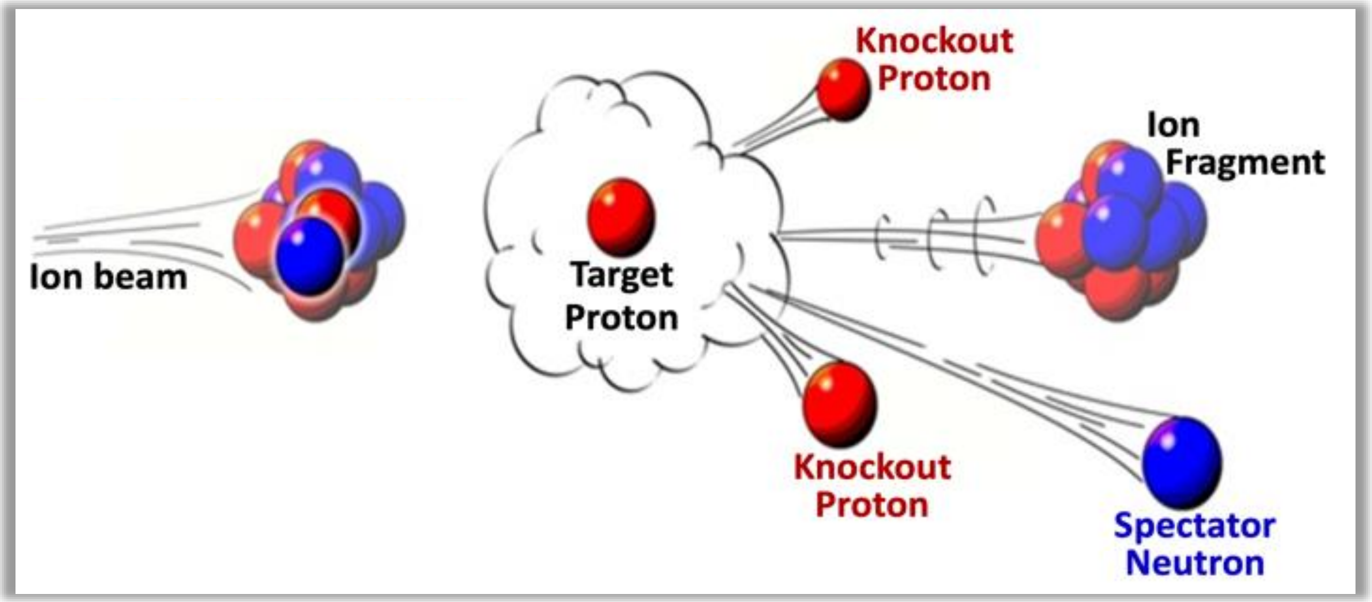
Fragment-proton correlation



Experiment in inverse kinematics at high energy with hadronic probe is a “clean” technique to study nuclear structure



SRC study in inverse kinematics



Measure:
- **scattered proton momenta**
- **fragment momentum**
- **recoil nucleon momentum**
- **final state / energy**

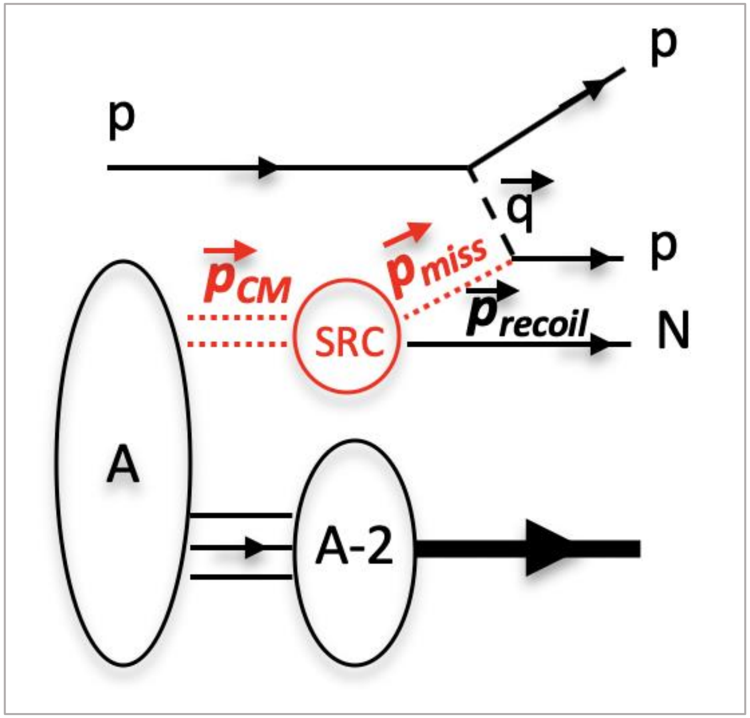
Extract:

p_{miss}
pair c.m.
factorization
pair ratios
spin, parity

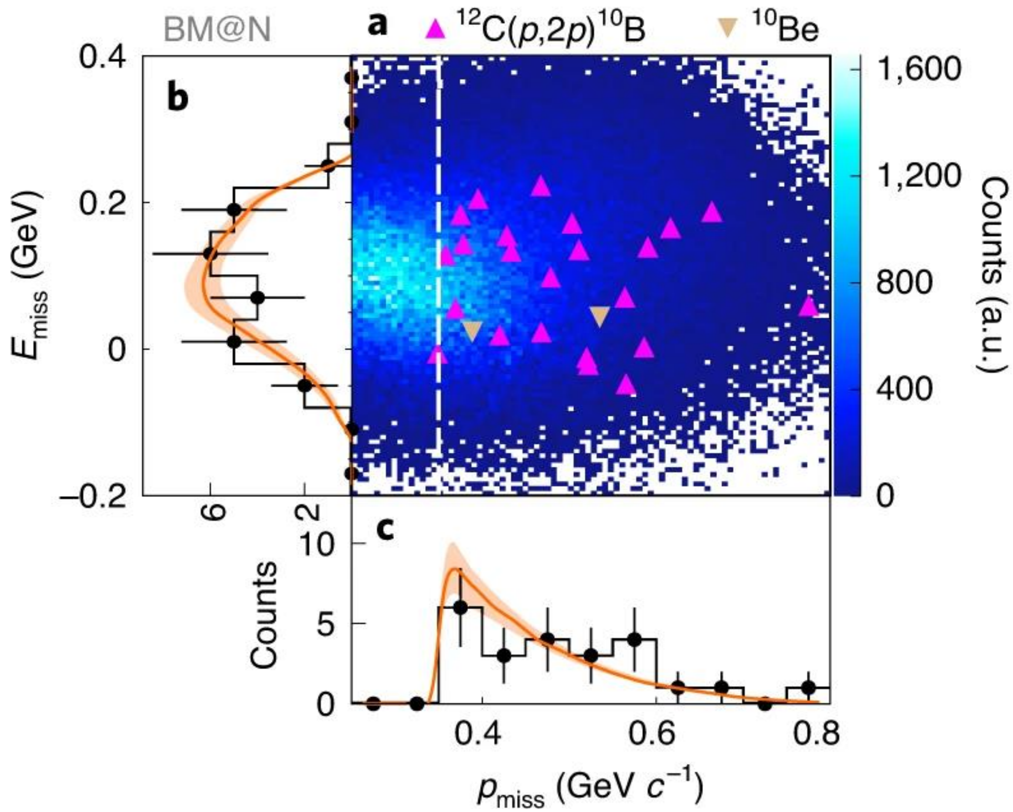
SRC breakup using hadronic probe

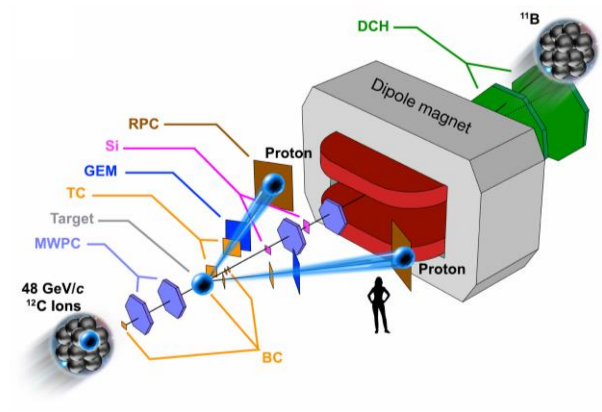
$$d\sigma \sim K \cdot \cancelto{\sigma_{pp}}{\sigma_{eN}} \cdot S(p_i, E_i)$$

$$S(p_i, E_i) \sim \sum_{\alpha} C^{A}_{\alpha,NN}(p_{cm}) \times |\tilde{\varphi}^{\alpha}_{NN}(|\vec{p}_{Rel}|)|^2$$



SRC identification





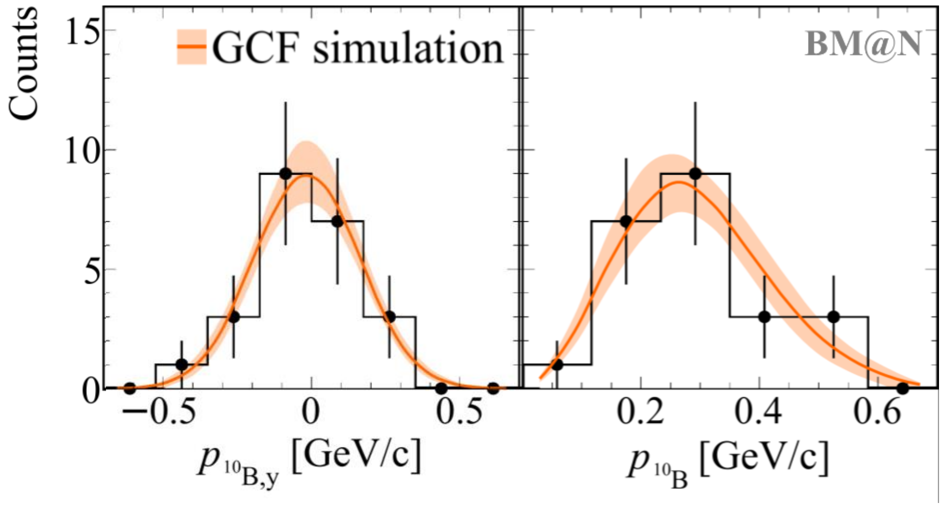
23 *np* pairs (^{10}B)
2 *pp* pairs (^{10}Be)
→ *np* dominance

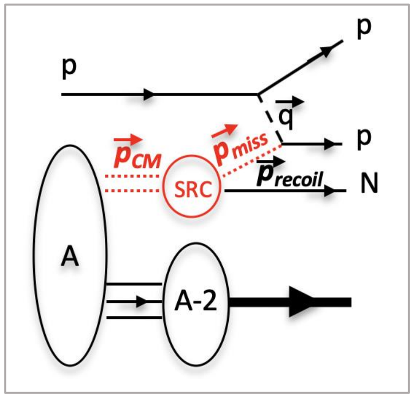
(guided by GCF)

+ opening angle > 63°, M^2_{miss} > 0.42 (GeV/c²)²

M. Patsyuk, JK et al. (BM@N), Nat. Phys. 17 (2021).

Fragment momentum = pair c.m. motion

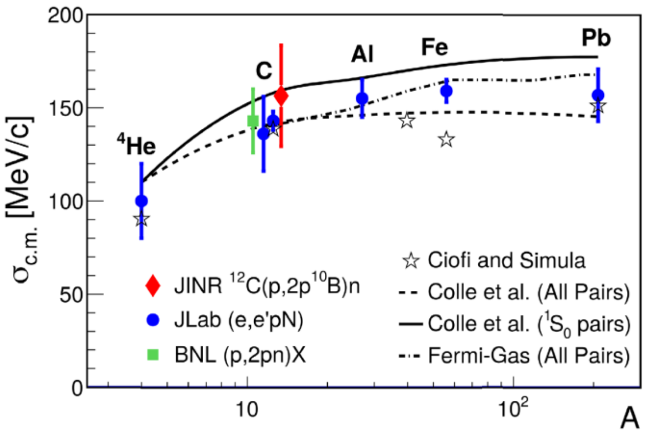




direct extraction:

σ = (156 ± 27) MeV/c

-> small c.m. momentum



SRC universality & scale separation

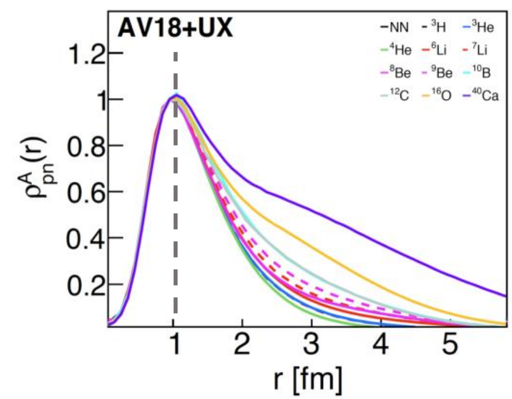
factorized **Generalized Contact Formalism** (GCF)

$$S(p_i, E_i) \sim \sum_{\alpha} C^{A}_{\alpha,NN}(p_{cm}) \times |\tilde{\varphi}^{\alpha}_{NN}(|\vec{p}_{Rel}|)|^2$$

universal

~ A-2 system
[number of pairs
small c.m. motion]

strongly
correlated pair
[universal 2-body]

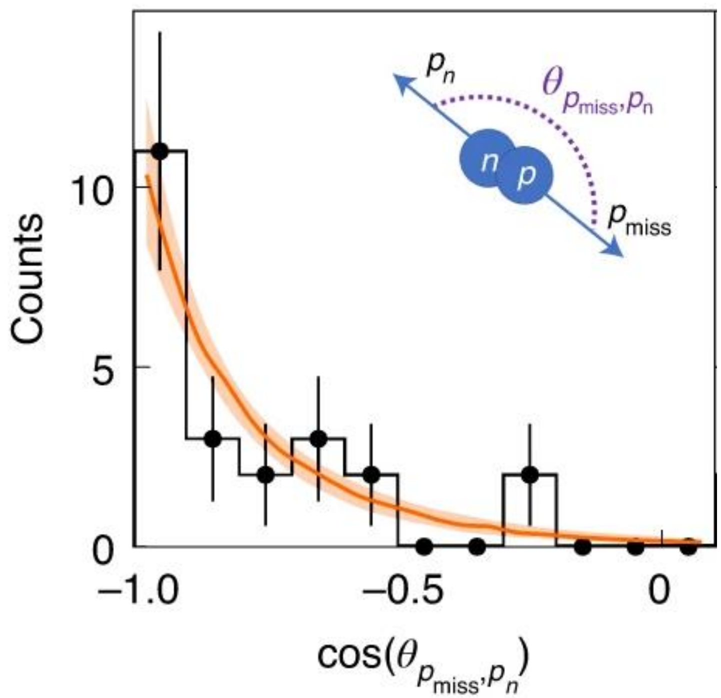


R. Cruz-Torres, D. Lonardoni, R. Weiss et al.,
Nature Physics 17 (2021).

Pair correlations

strongly correlated pair:
nucleon momentum not
balanced by *A-1*

NN back-to-back emission



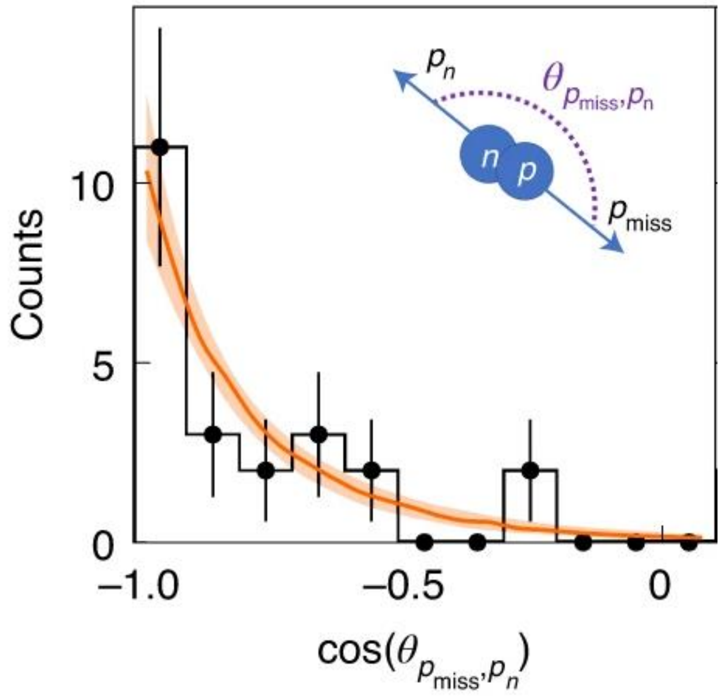
Pair correlations

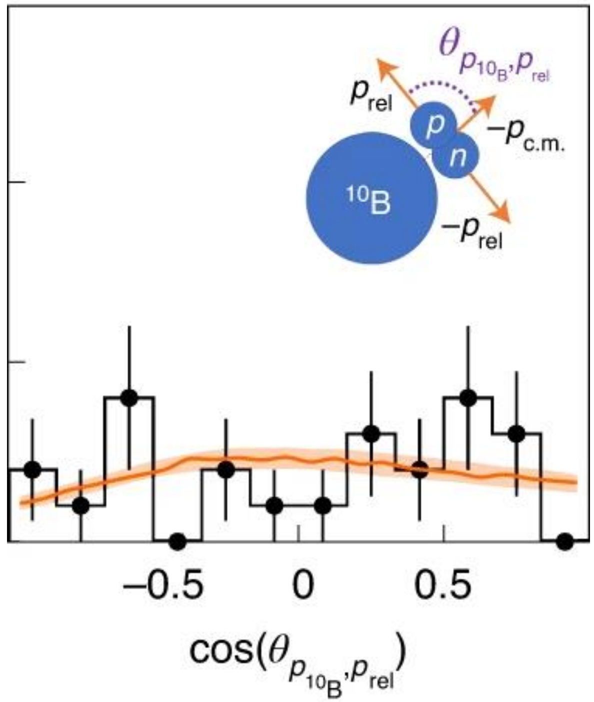
strongly correlated pair:
nucleon momentum not balanced by *A-1*

NN back-to-back emission

weak interaction between pair and A-2 spectator

→ Factorization measured directly



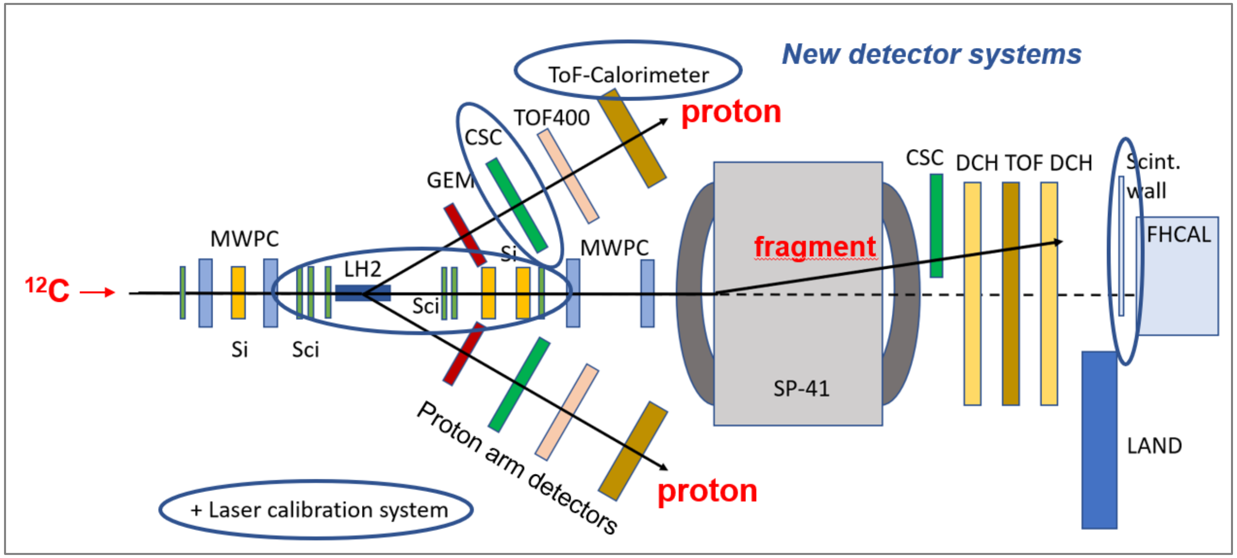


SRC in inverse kinematics:

Direct access to pair properties

Follow-up experiment at JINR

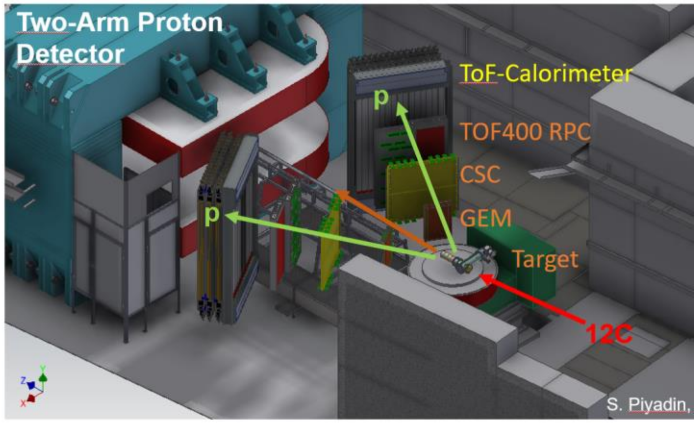
Goal: increase statistics for quantitative results



QFS:
- Absolute cross sections
- Quenching of spectroscopic strength

SRC:
- Recoil nucleon analysis
- SRC origin: fragment final states

Excursion: SRC experiment preparations at JINR 2022



MIT

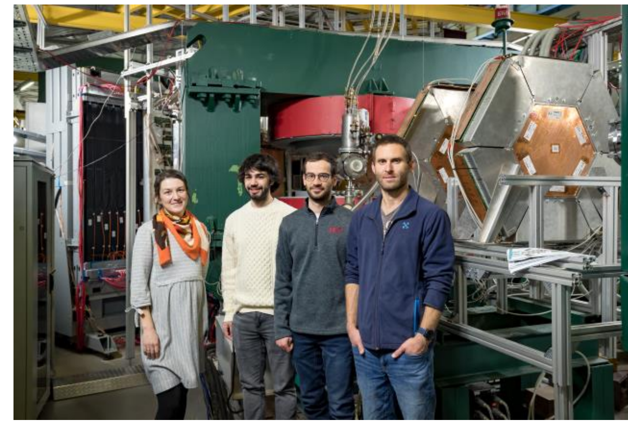
TEL AVIV UNIVERSITY

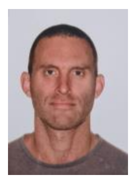
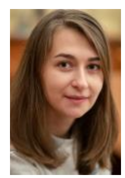
TECHNISCHE UNIVERSITÄT DARMSTADT

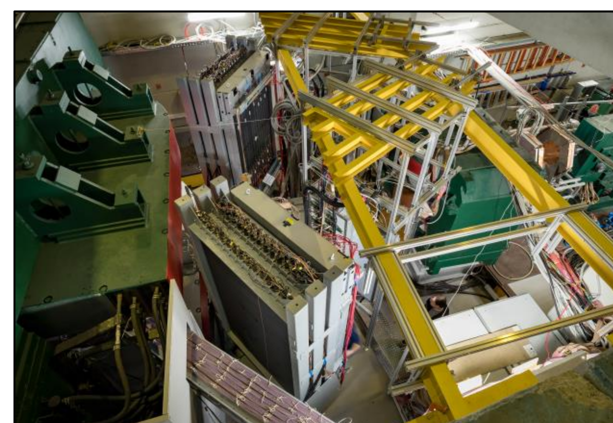
JINR

FAIR

GSI

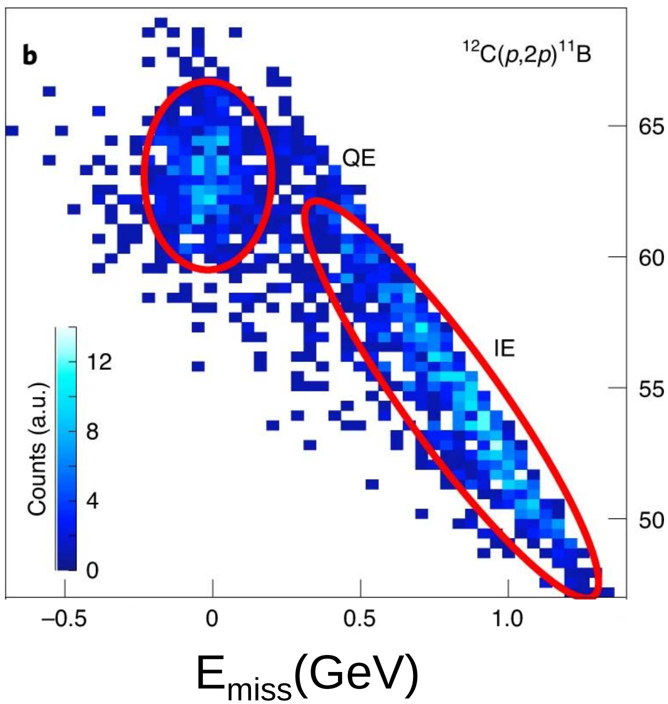


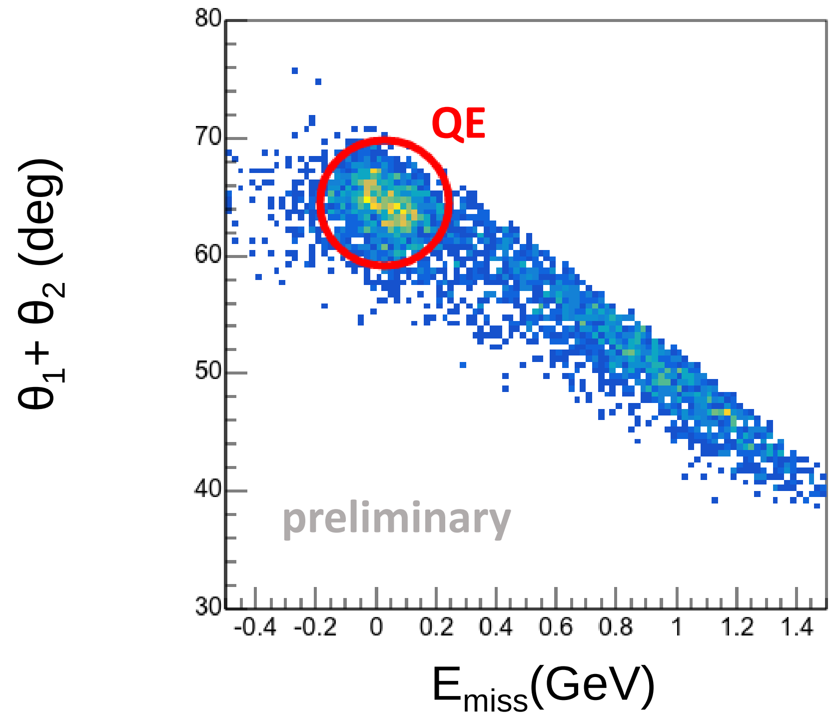


Quasi-elastic scattering

2018



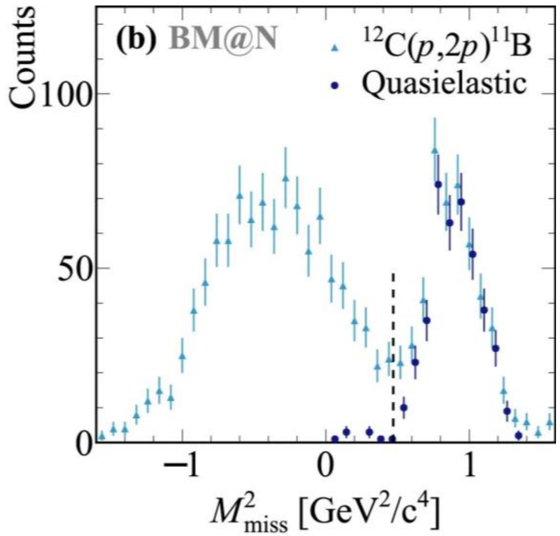
2022

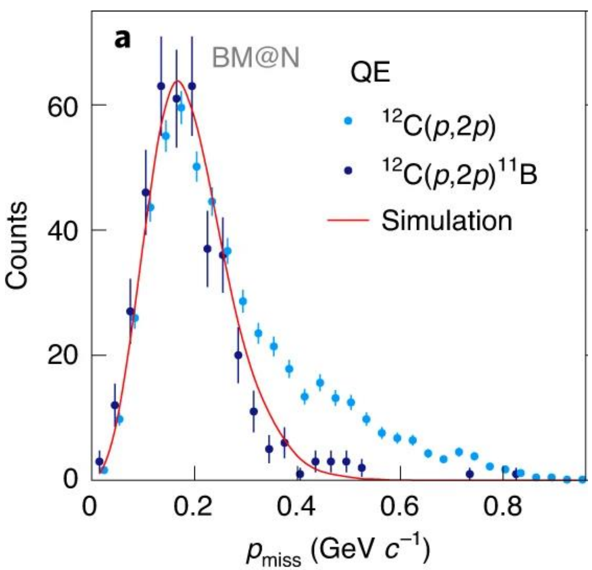


increased statistics (x3) + improved resolution

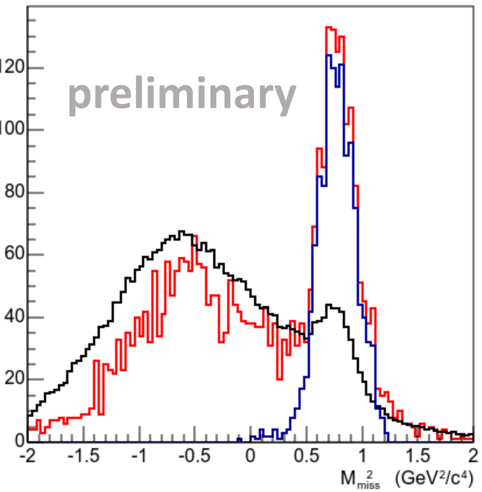
Quasi-elastic scattering

2018

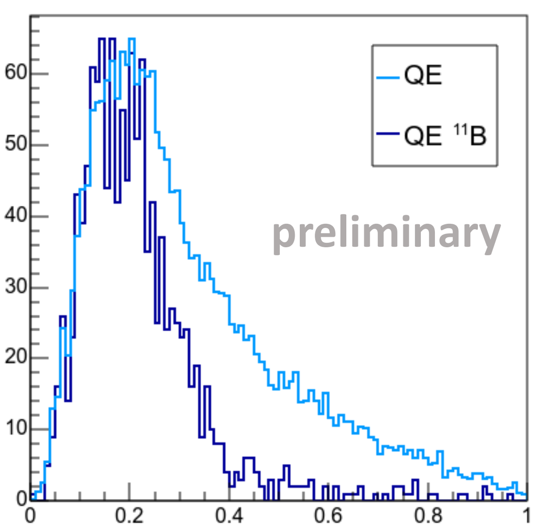




2022



M^2_{miss} (GeV^2/c^4)



p_{miss} (GeV/c)

Quasi-elastic scattering

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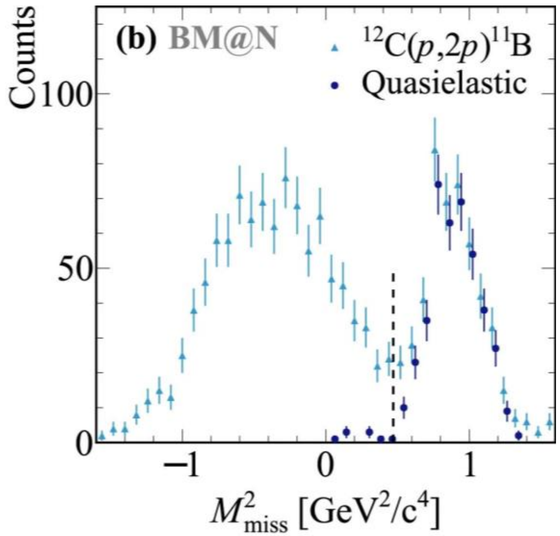
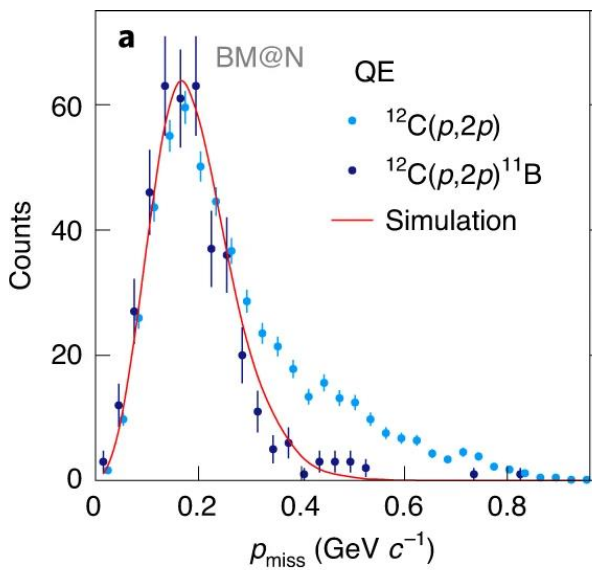
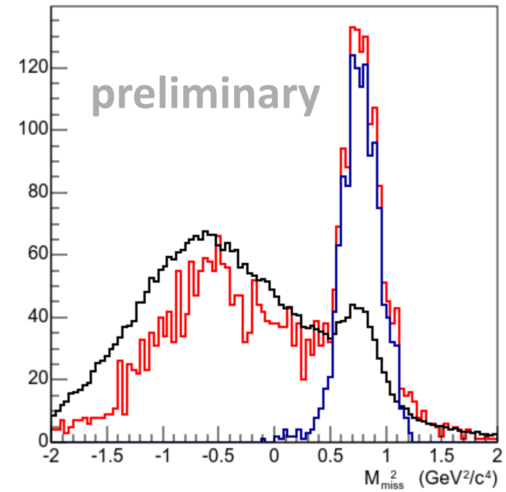


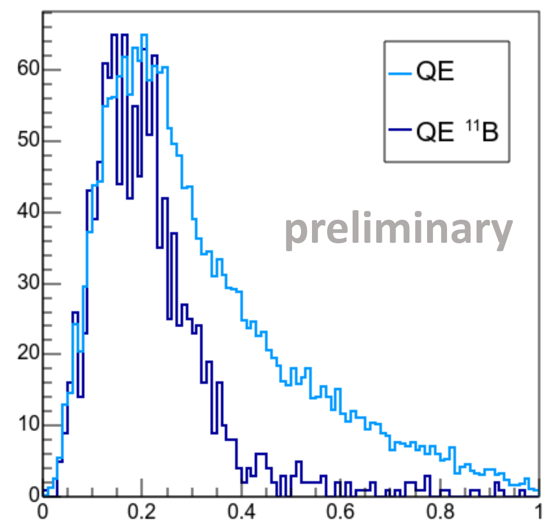


Stay tuned for SRC results!

2022



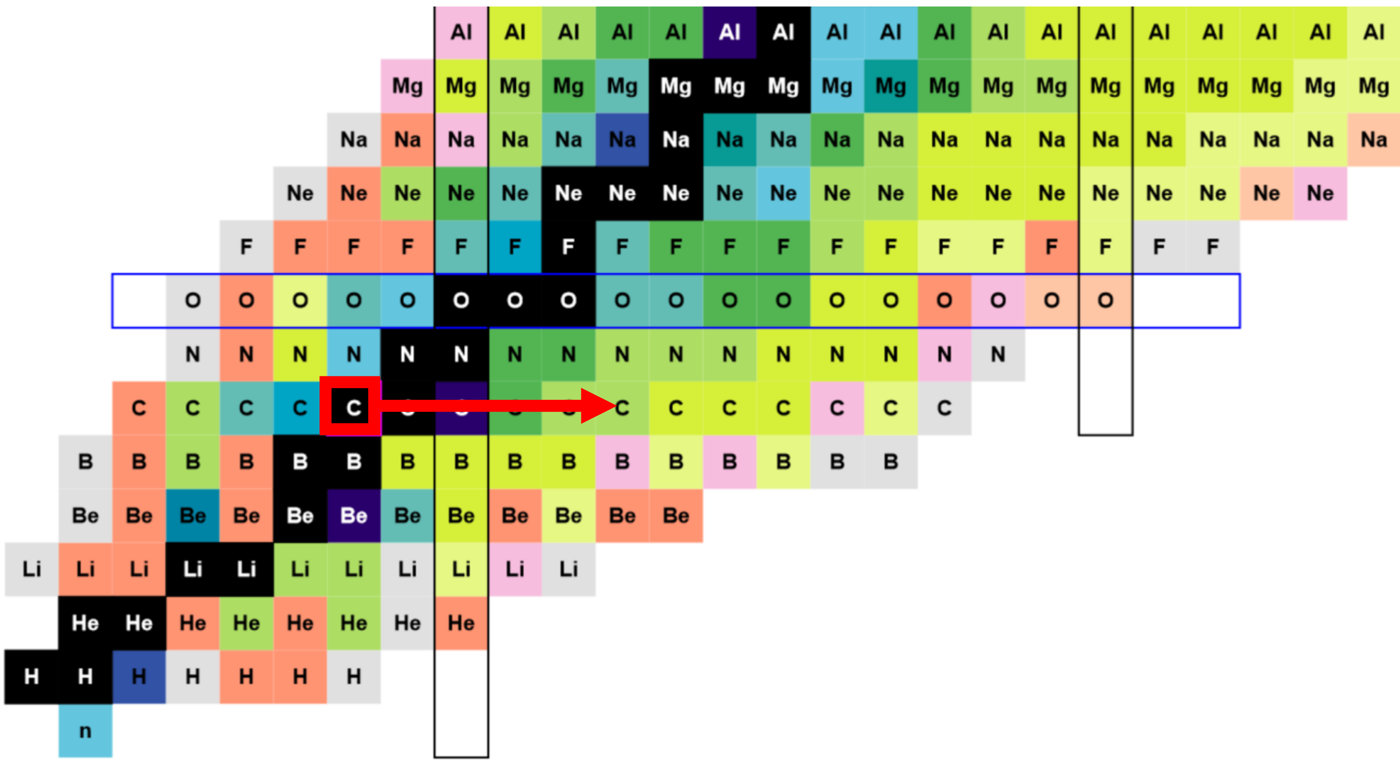
M^2_{miss} (GeV^2/c^4)



p_{miss} (GeV/c)

SRCs in neutron-rich nuclei

Short-lived (~ms) nuclei become accessible in inverse kinematics



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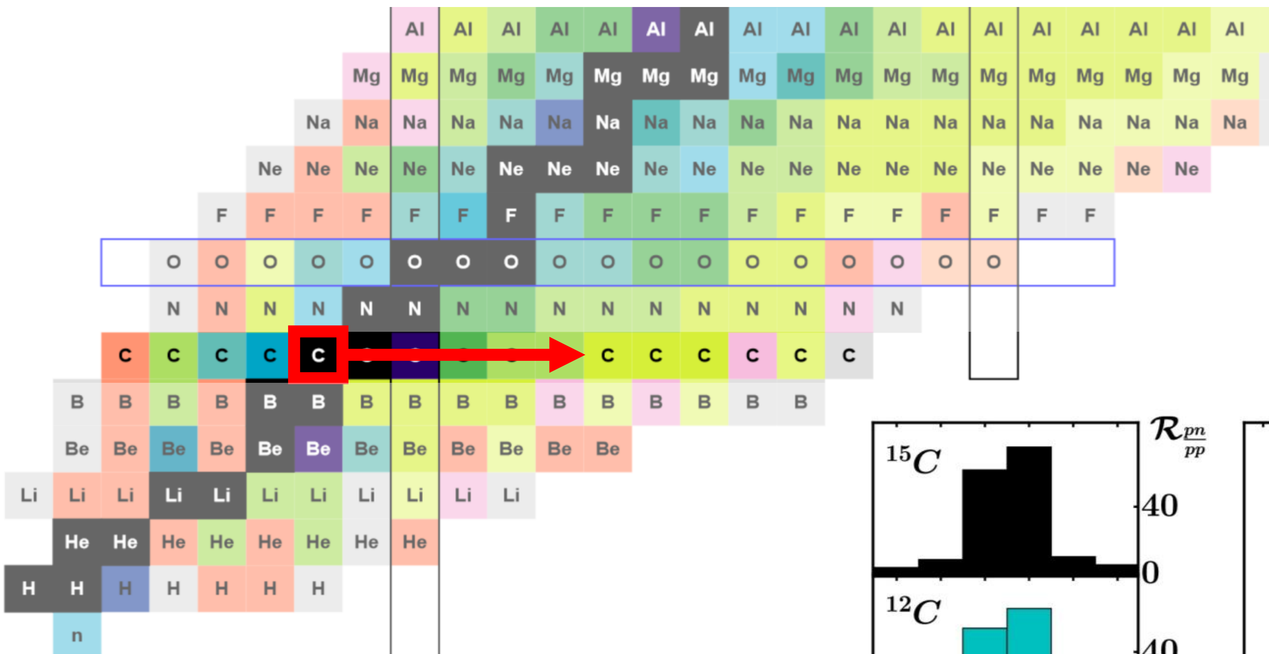
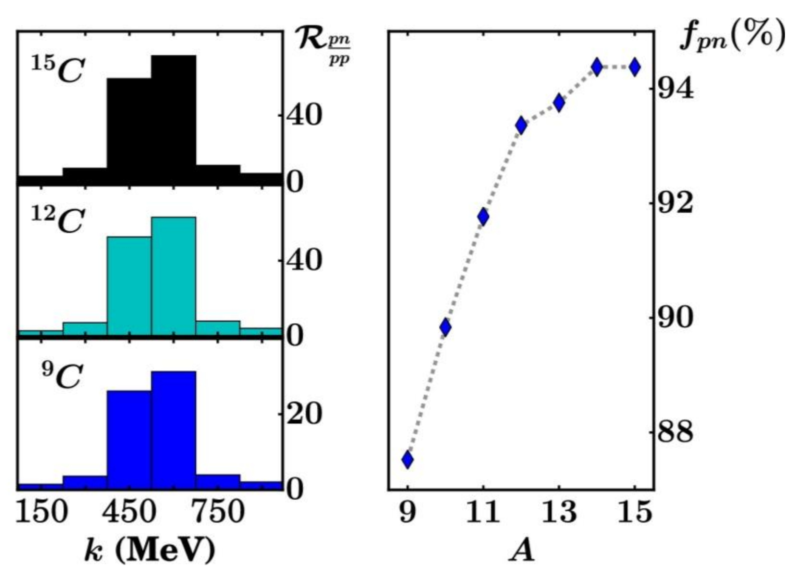
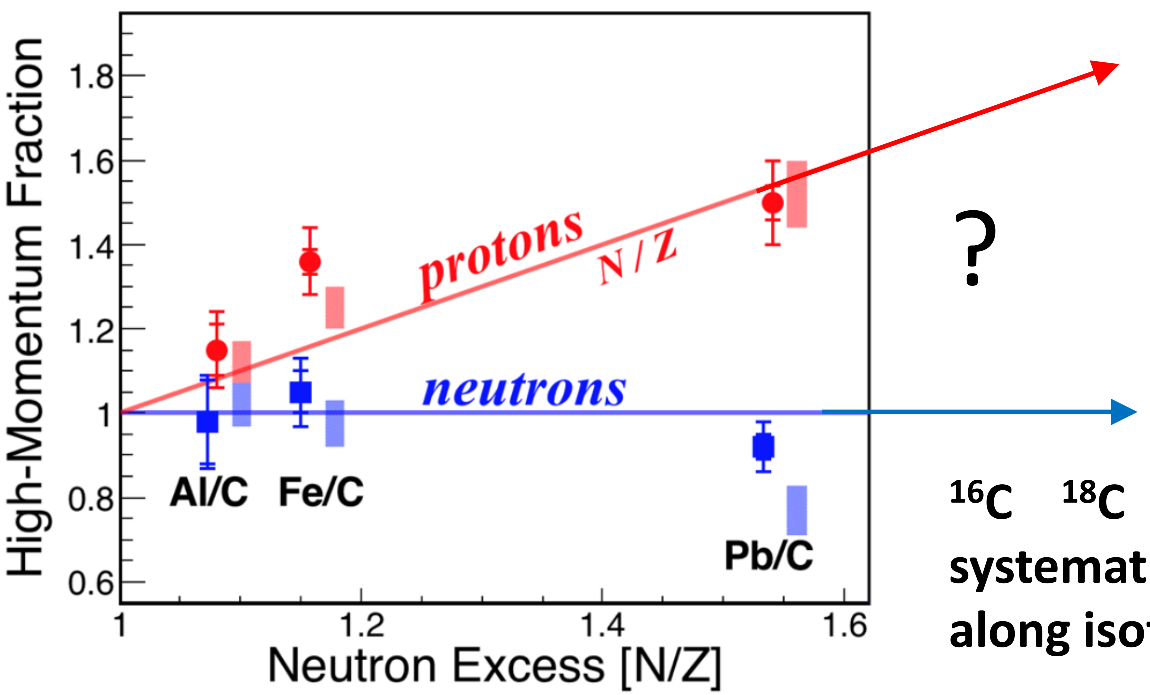




S. Stevens, J. Ryckebusch, W. Cosyn, A. Waets,
PLB 777 (2018).

Neutron-rich nuclei: towards cold dense nuclear matter

Neutron Star:
- **high density**
- **N/Z~20**



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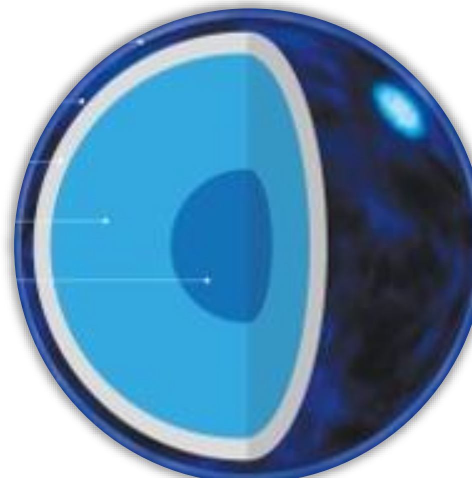

^{16}C ^{18}C ^{20}C
systematic studies along isotopic chains

Neutron-rich nuclei: towards cold dense nuclear matter

Neutron Star:
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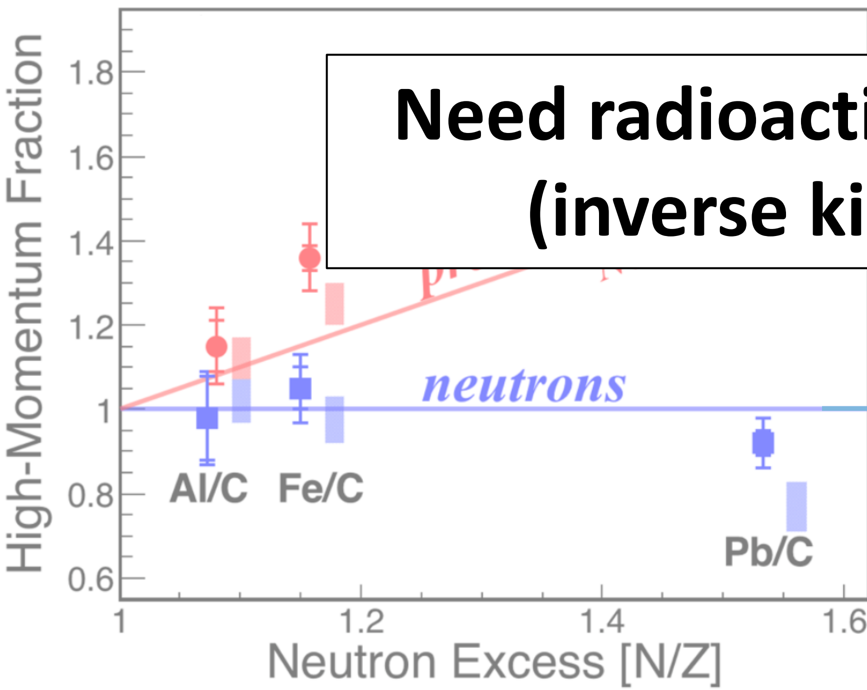
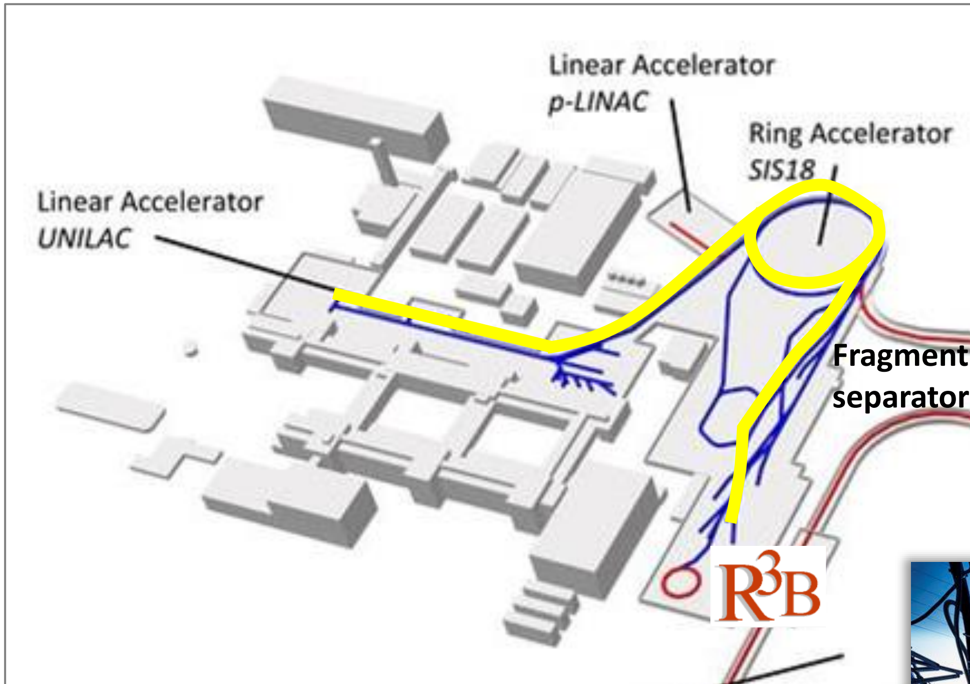


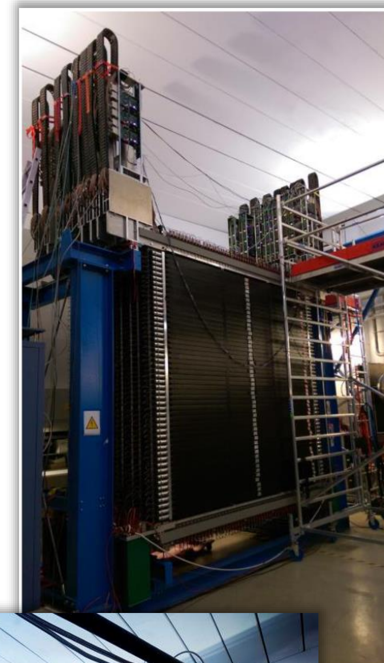
Need radioactive-ion beams (inverse kinematics)

^{16}C ^{18}C ^{20}C

systematic studies along isotopic chains

R3B @ FAIR GSI



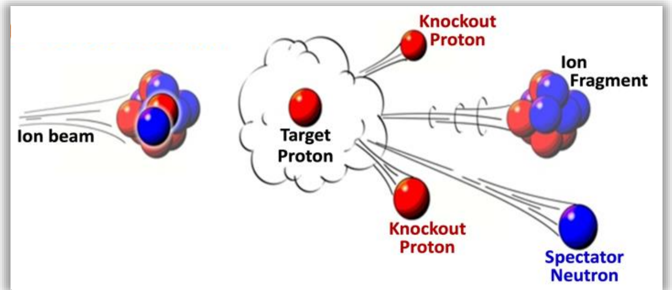


O. Hen + A. Corsi

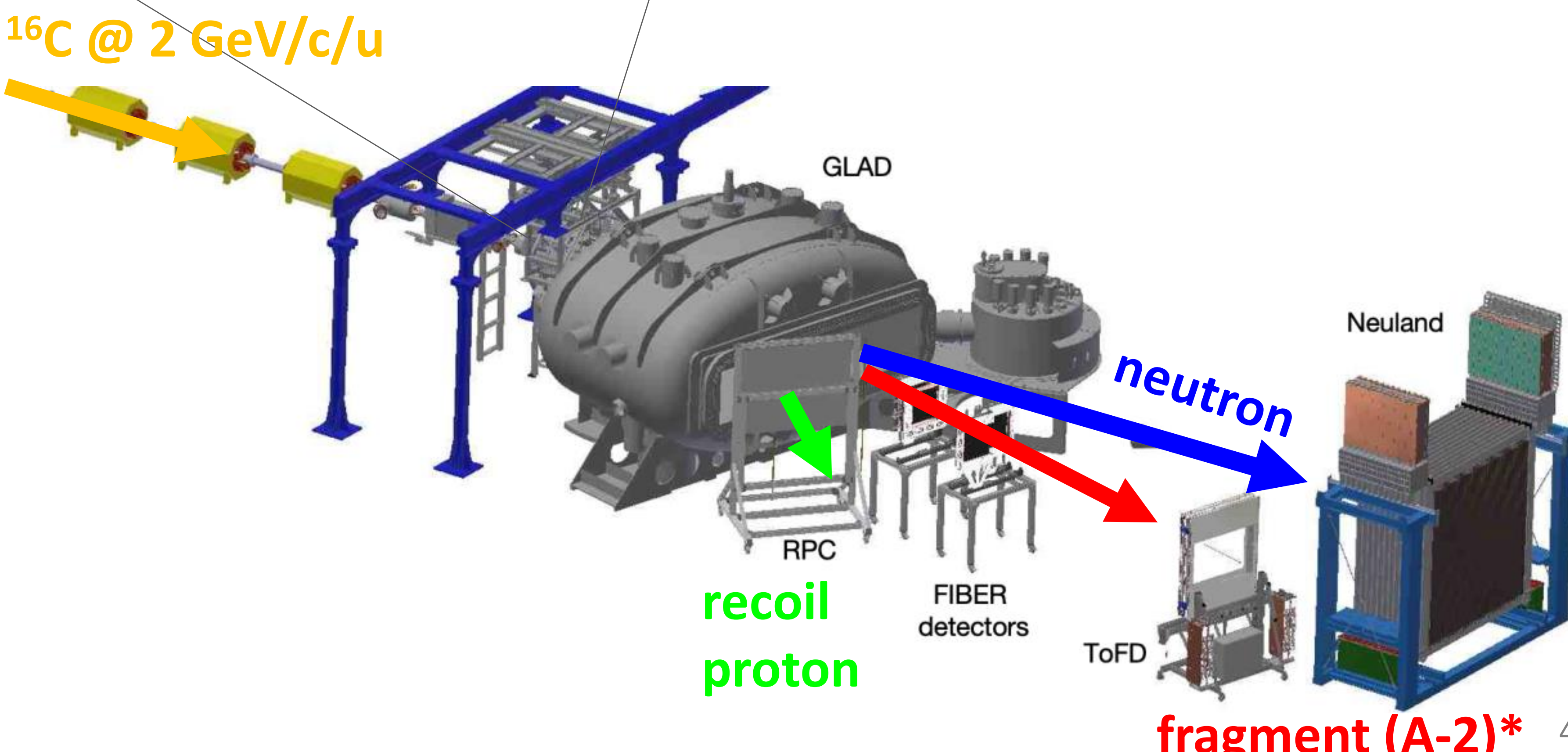
TECHNISCHE UNIVERSITÄT DARMSTADT

TEL AVIV UNIVERSITY

SRC studies in ^{16}C at R³B (GSI-FAIR)

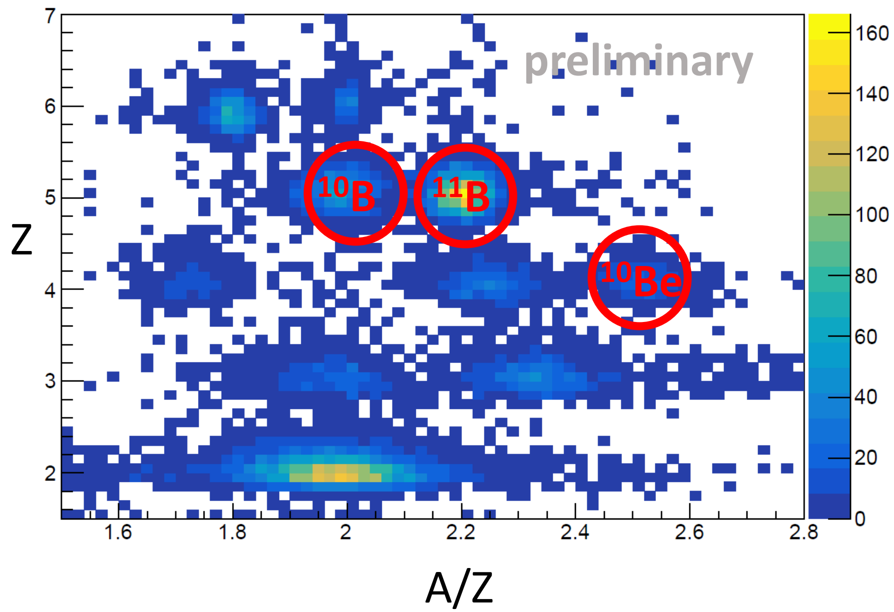


- SRC properties in 1st radioactive nucleus
- fully exclusive ^{16}C(p,2pN)A-2* measurement
- establish lower limit in momentum transfer

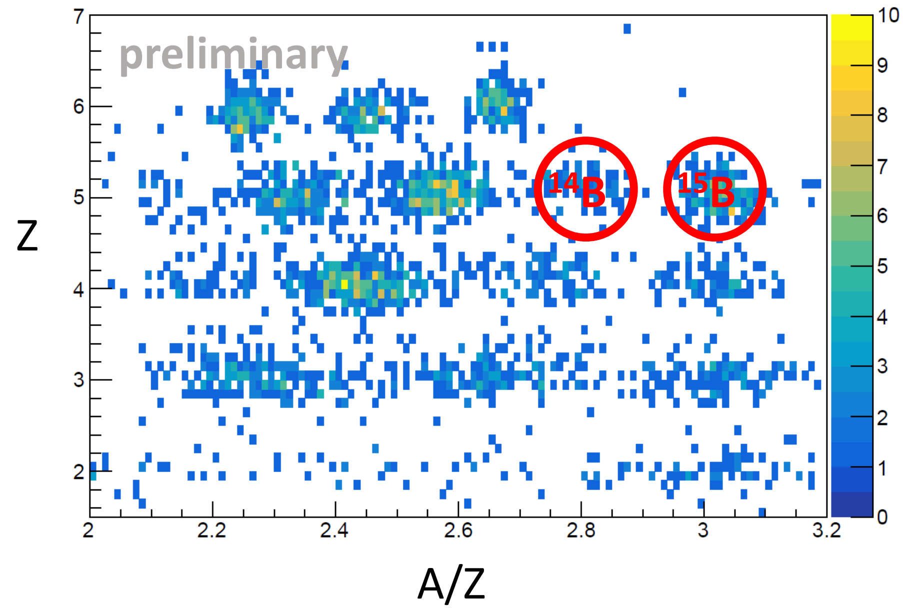


Final-state tagging

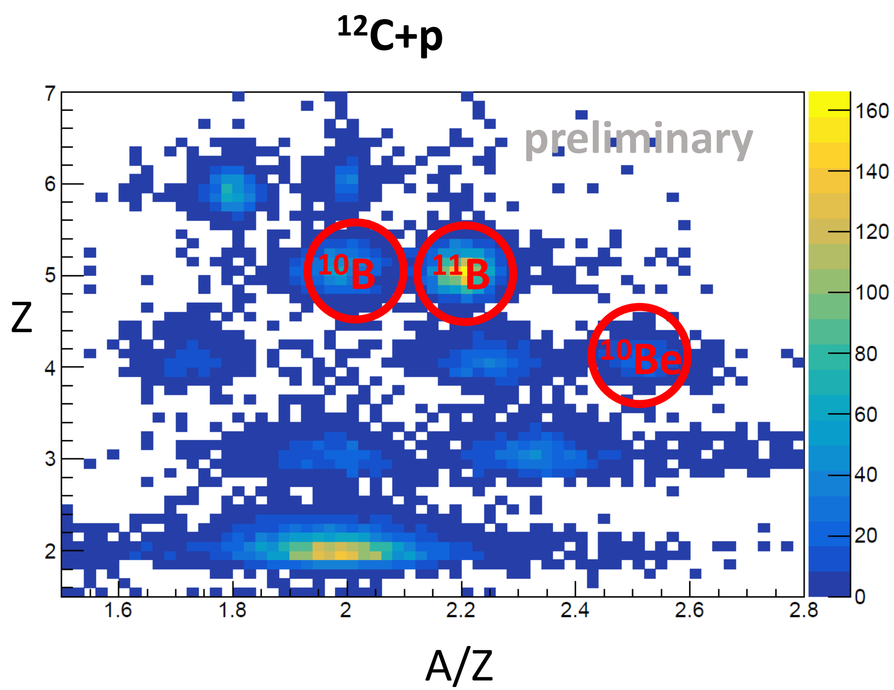
^{12}C+p

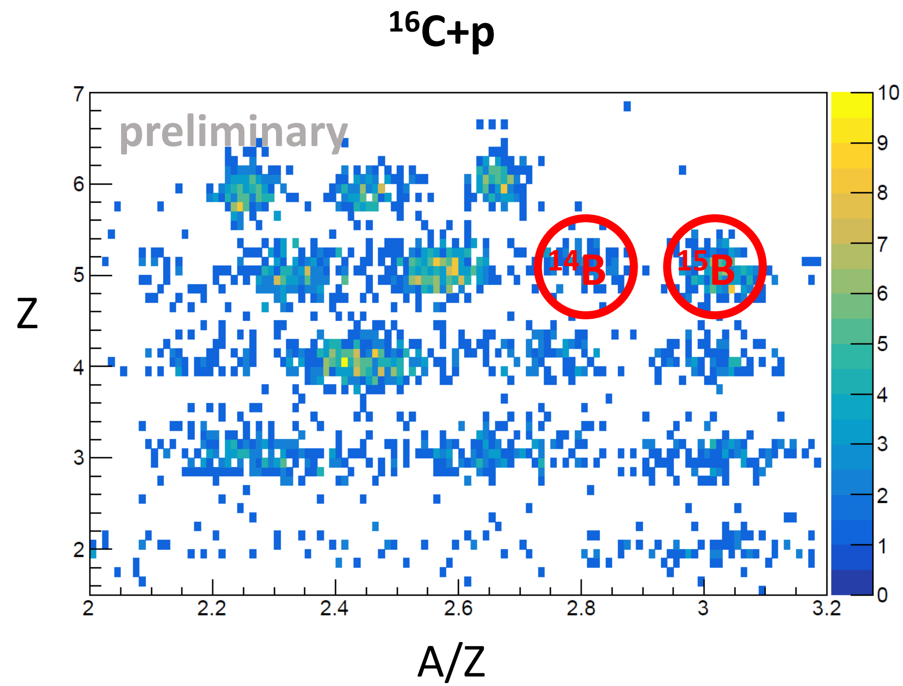


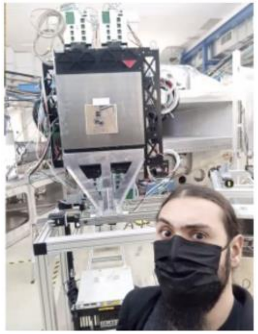
^{16}C+p

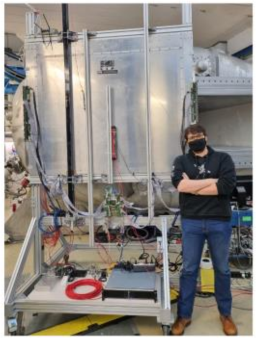


Final-state tagging

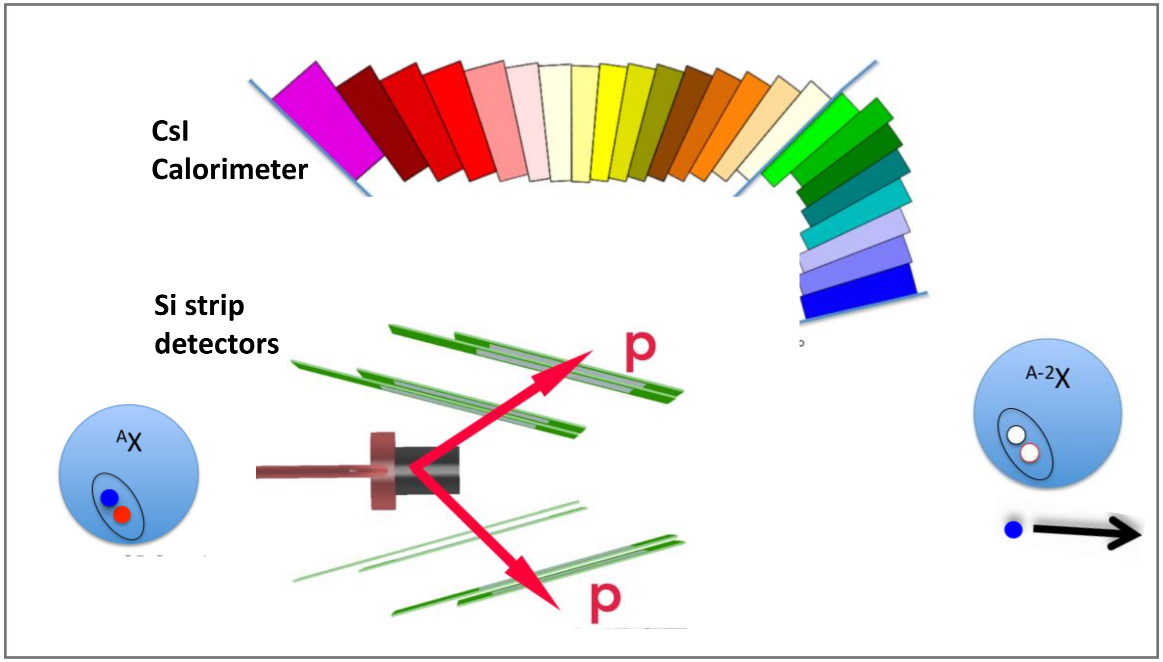




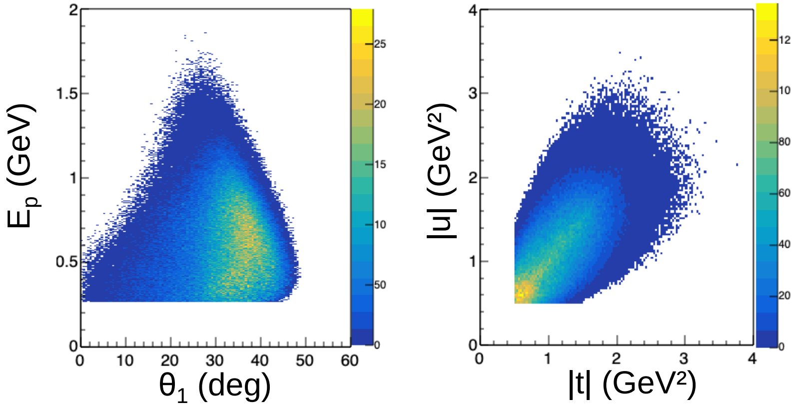


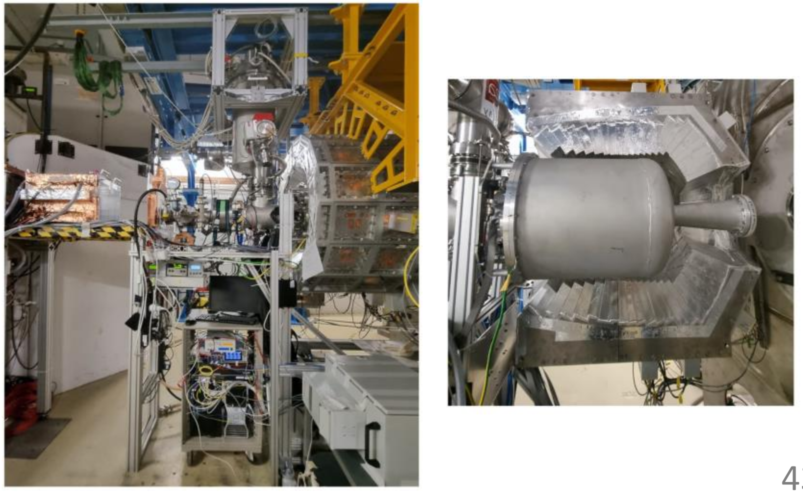


(p,2p) Reconstruction



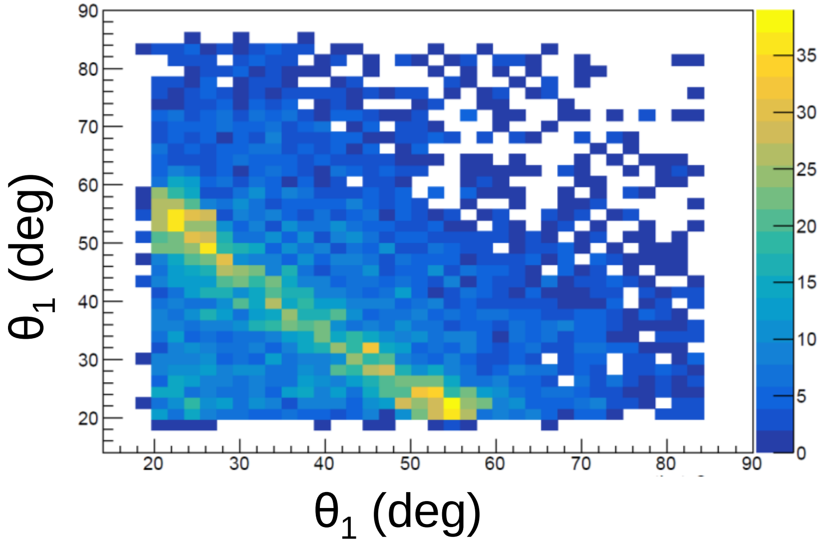
Simulation



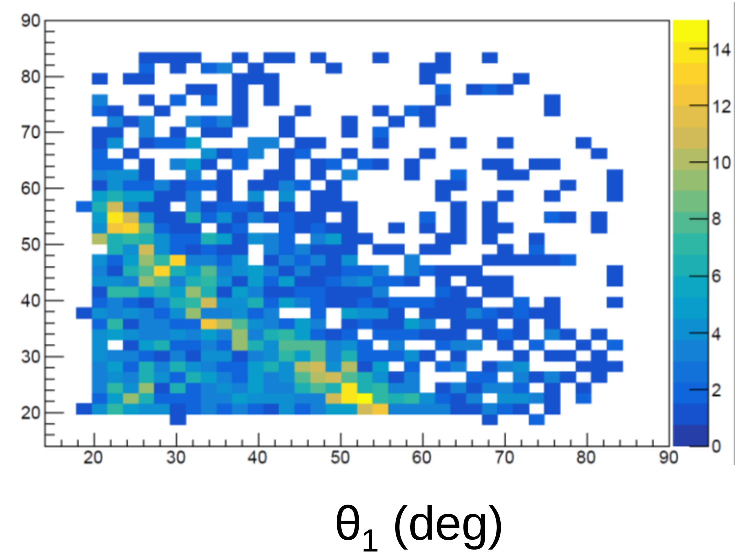


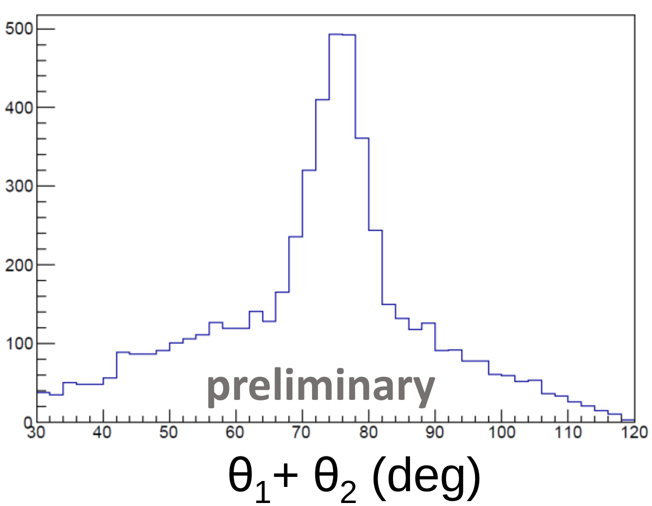
Quasi-elastic scattering

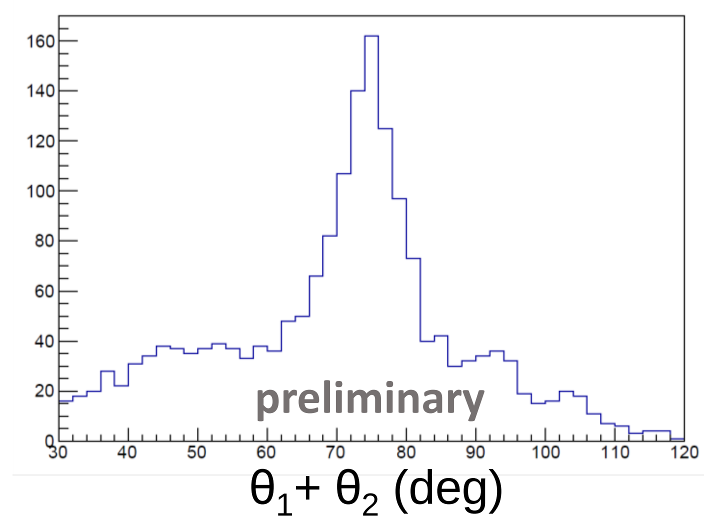
$^{12}C(p,2p)\,^{11}B$



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







Quasi-elastic scattering

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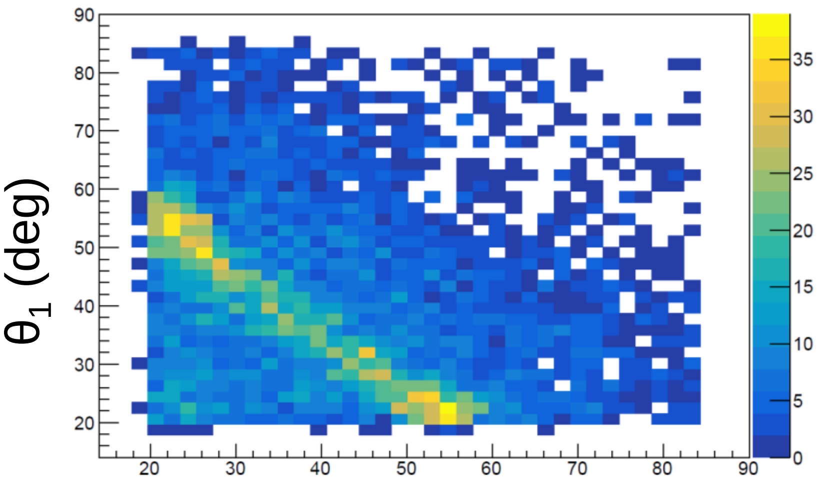
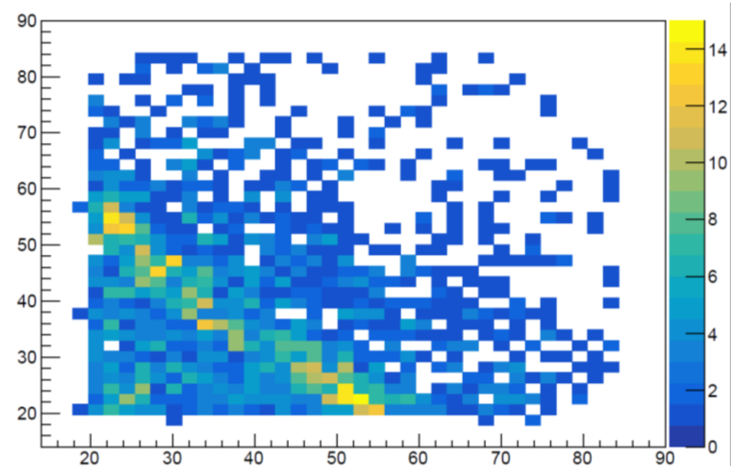


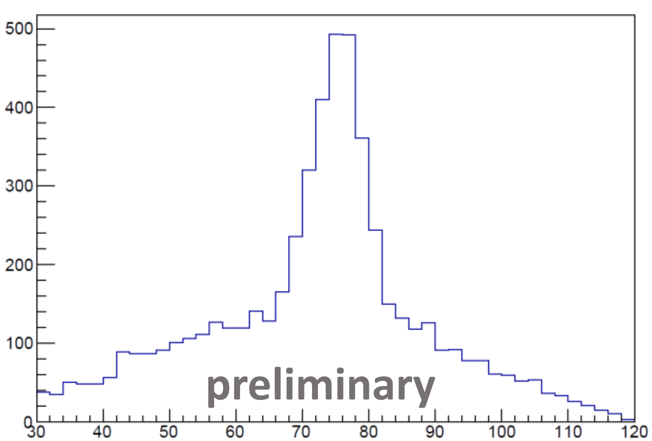
θ1 (deg)

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

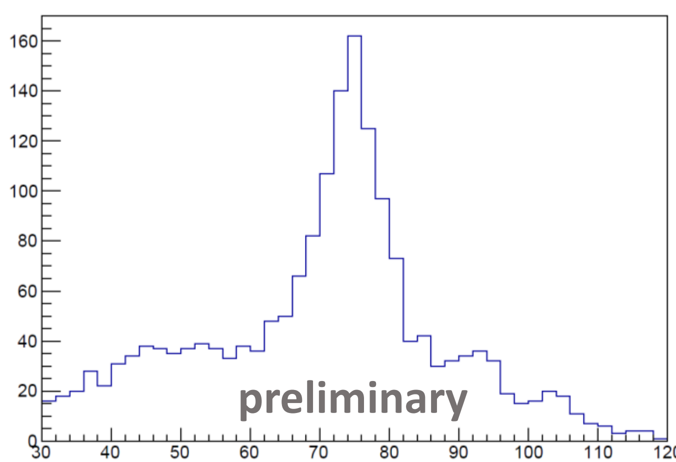


θ1 (deg)

Next steps: SRC ID

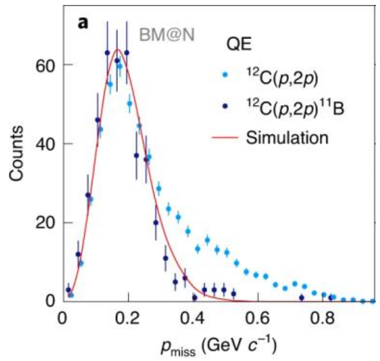


θ1+ θ2 (deg)

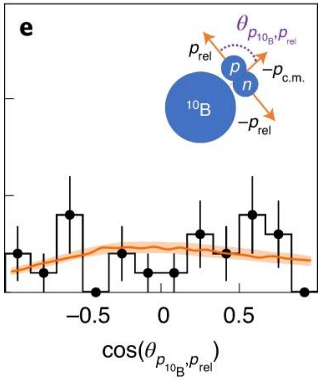


θ1+ θ2 (deg)

I. **How to study nuclear ground-state distributions**:
Inverse kinematics to suppress quantum-mechanical interference in (p,2*p*) reactions



II. **Study of SRCs with hadronic probes**:
1st SRC experiment in inverse kinematics
with access to new observables -> probe universality



III. **Study of cold dense nuclear matter**:
New pathway for SRC studies
with radioactive nuclei