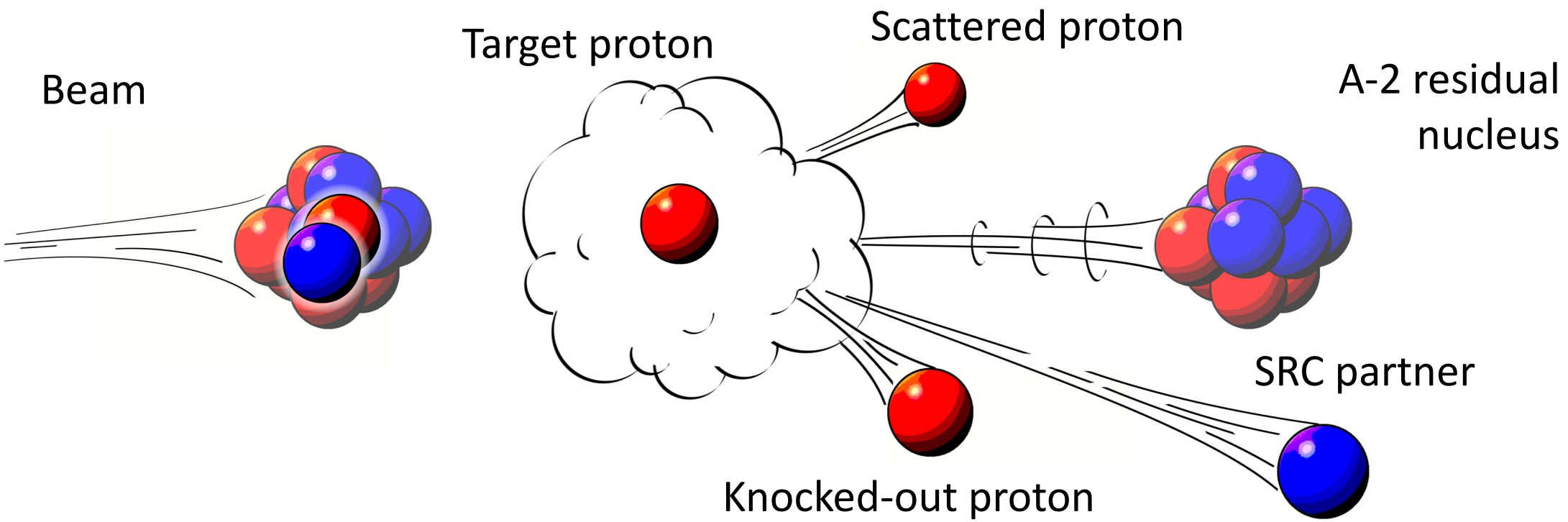
The Transparent Nucleus

Inverse kinematics nucleon-knockout measurement with a 48 GeV/c ^{12}C beam

Maria Patsyuk

SRC/EMC Workshop at MIT
March 2021

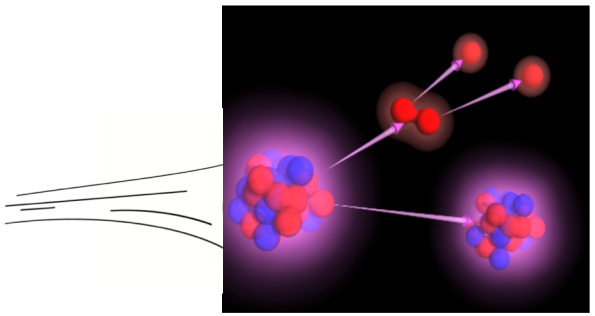
Today: Results from 1st SRC Studies in Inverse Kinematic



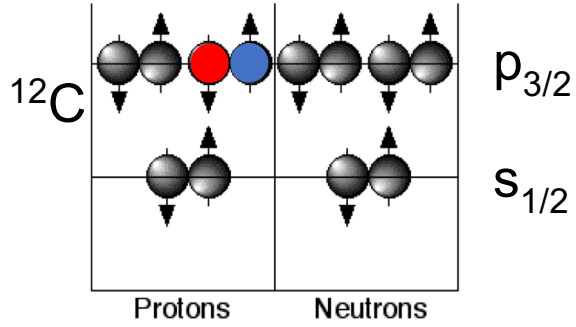
Nature Physics (in print)
[arXiv:2102.02626]

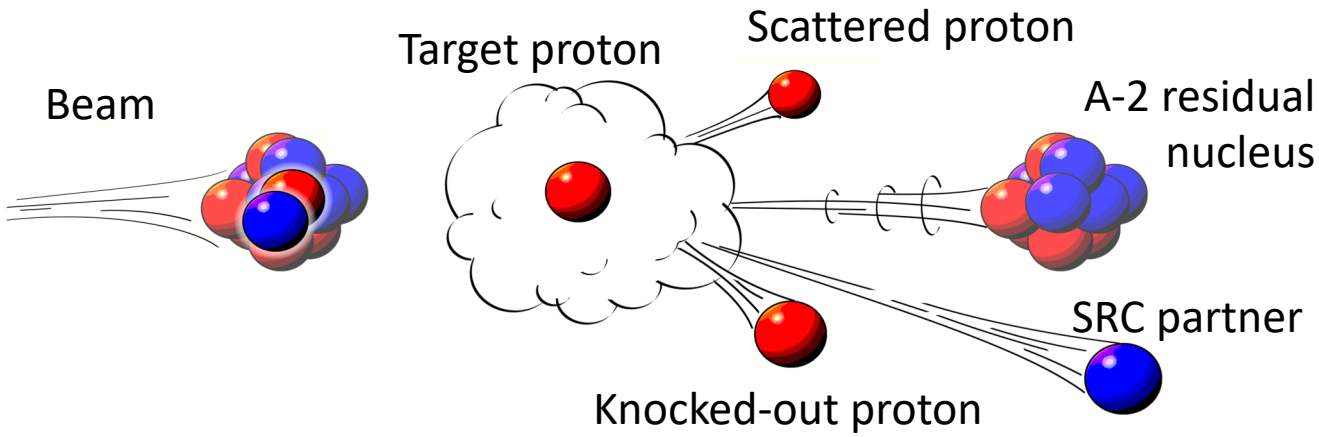
Enables Cutting-edge SRC Studies:

(1) SRC in radioactive nuclei



(2) SRC formation Mechanisms



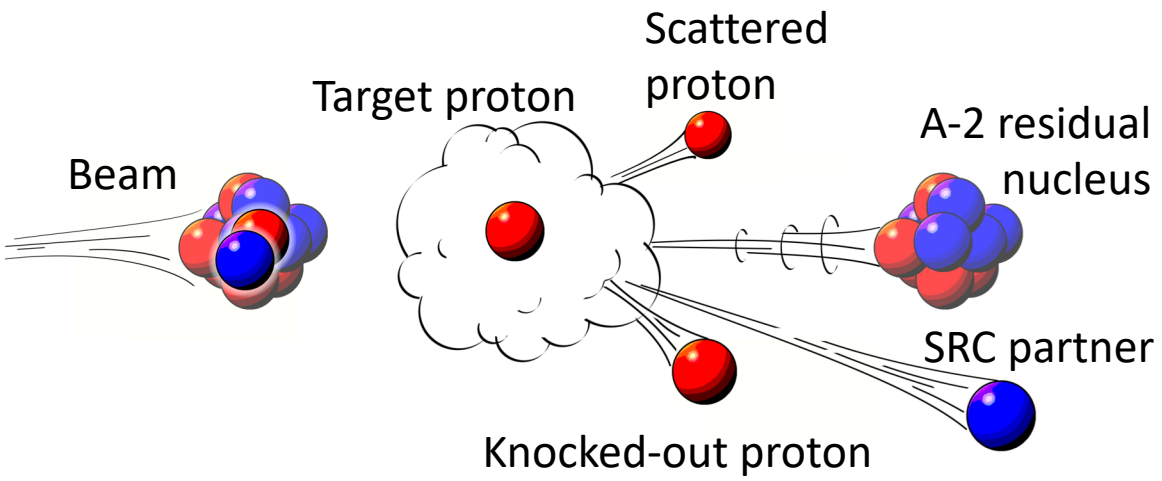


Inverse Kinematics == Hadron probes

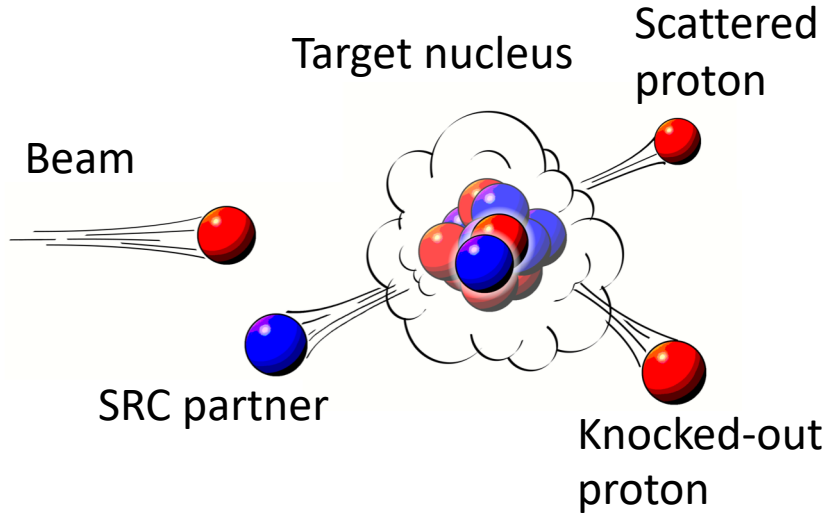
High cross-section compared to electrons
(especially important for unstable beams)

Increased ISI/FSI challenges data interpretation

Inverse kinematics



Direct kinematics



SRC at BM@N: proof of principles in 2018

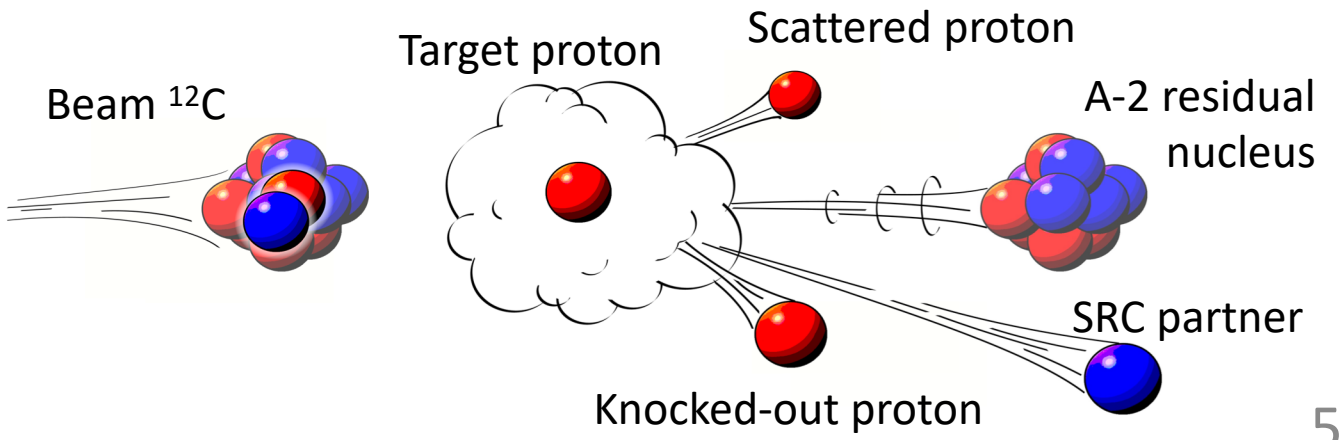
Took advantage of high cross-section compared to e^-

Used kinematically complete measurement to achieve better resolution

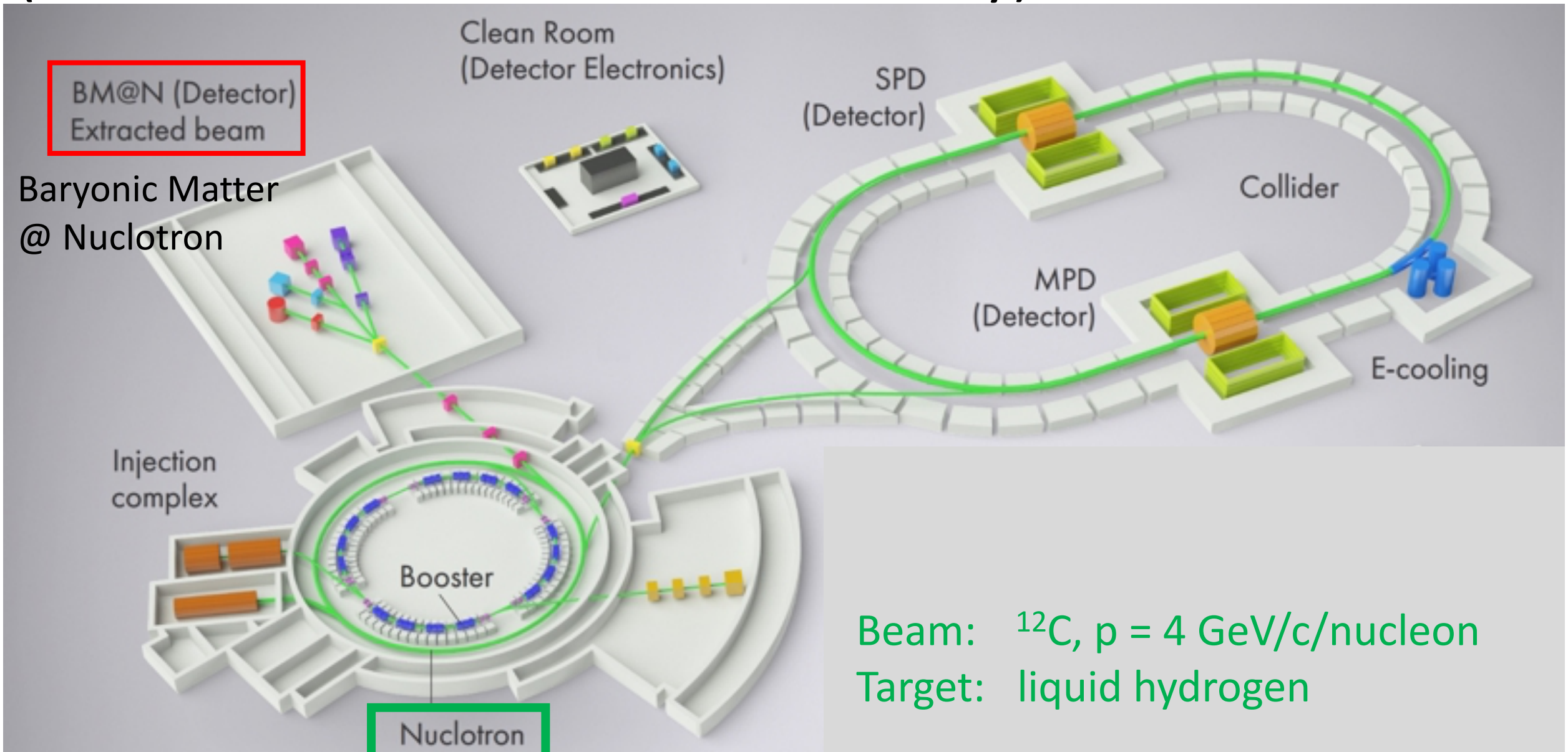
Fragment tagging suppress ISI/FSI → access to ground state properties

Identified SRC in inverse kinematics → measured properties of the nuclear remnant

Observed fragmentation pattern



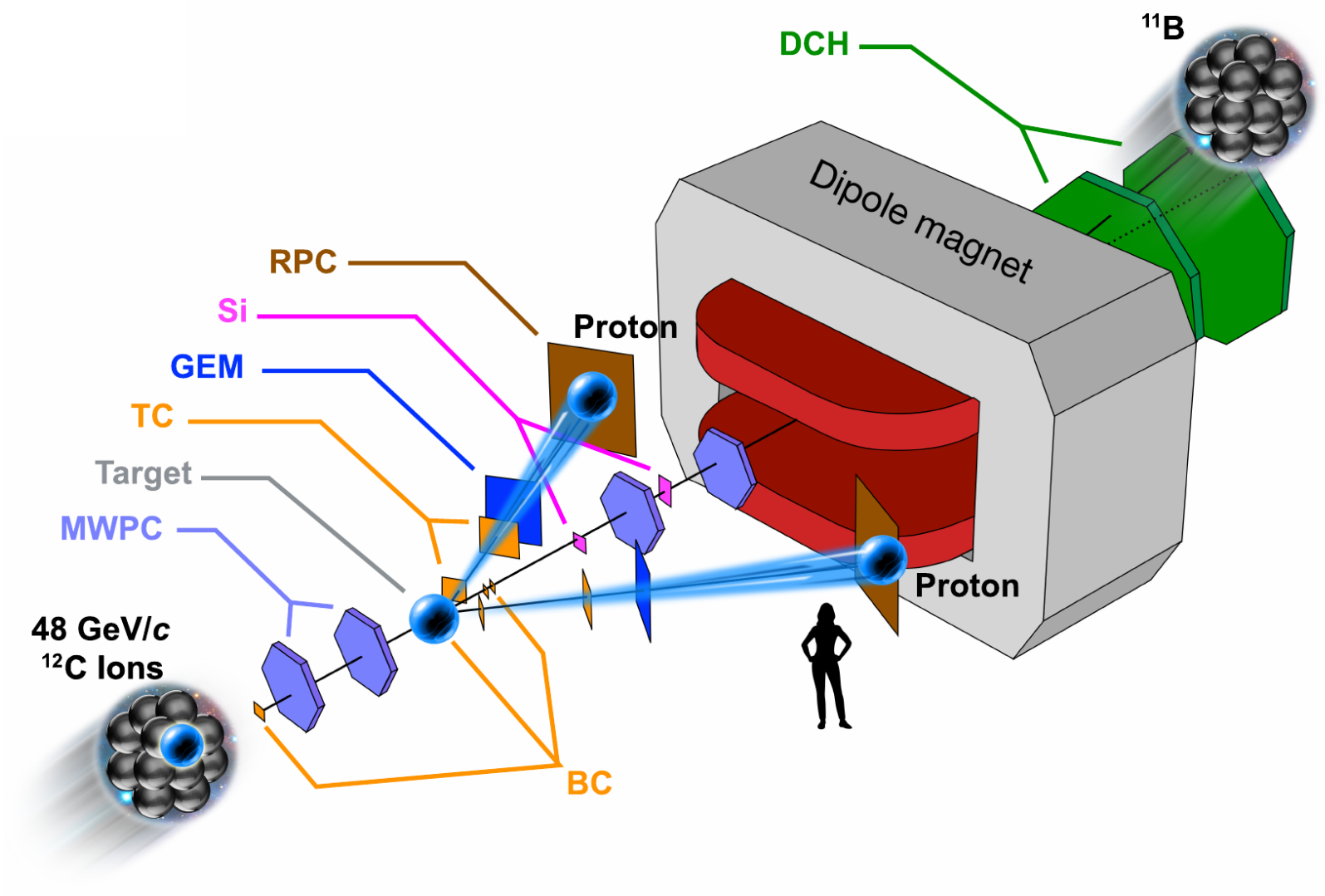
High-energy ion beam @ NICA (Nuclotron-based Ion Collider fAcility)

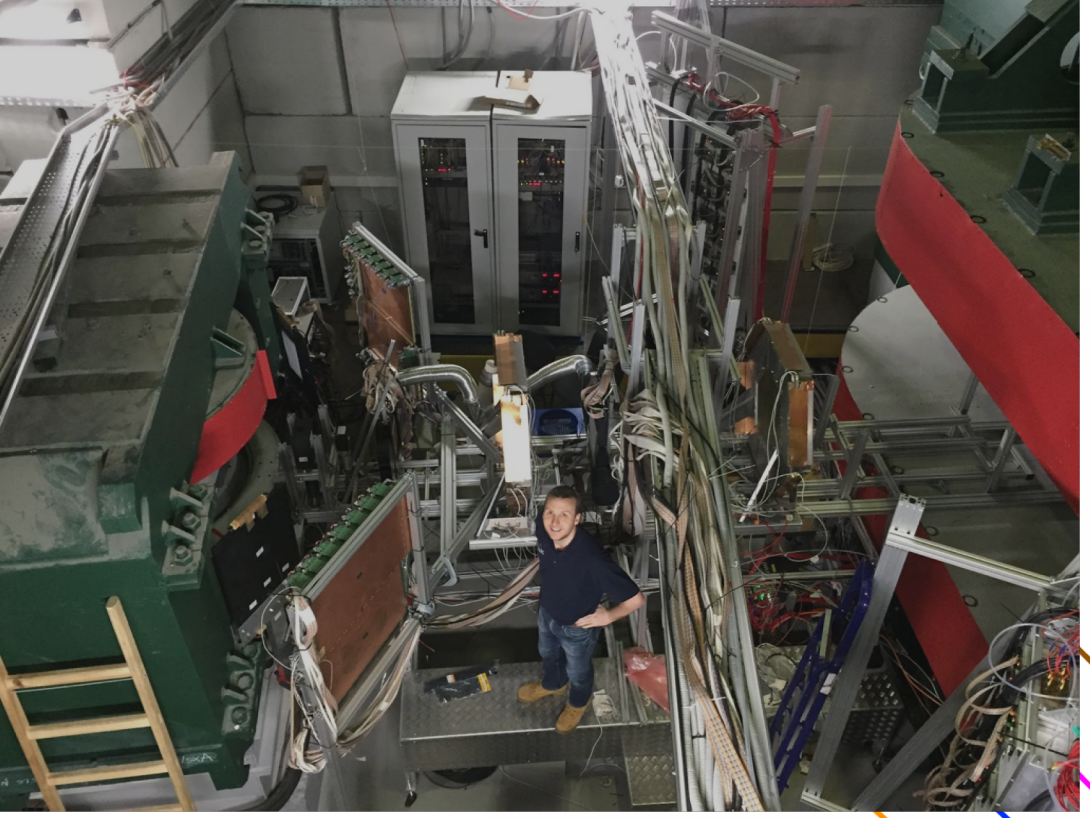


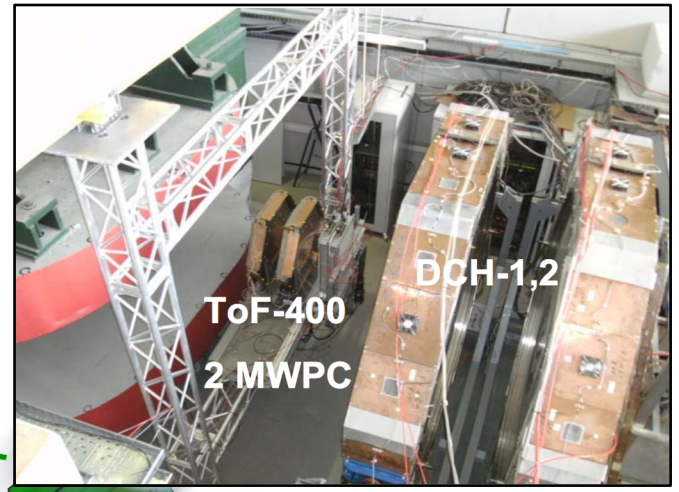
Beam: ^{12}C, p = 4 GeV/c/nucleon

Target: liquid hydrogen

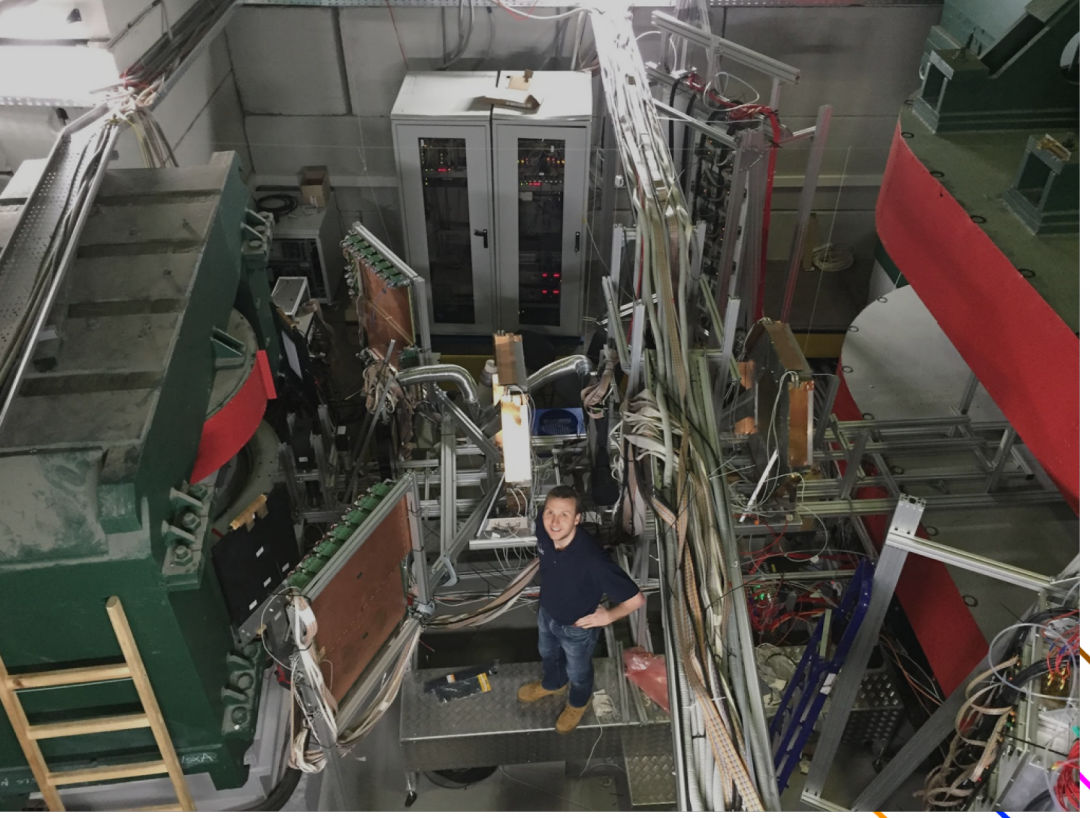
Experimental setup

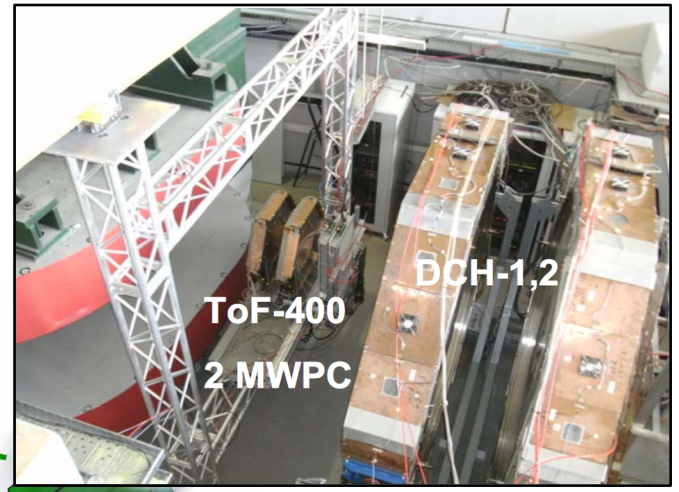





ToF-400
2 MWPC
DCH-1,2

DCH
Dipole magnet
Proton
Target
MWPC
Proton
BC





DCH

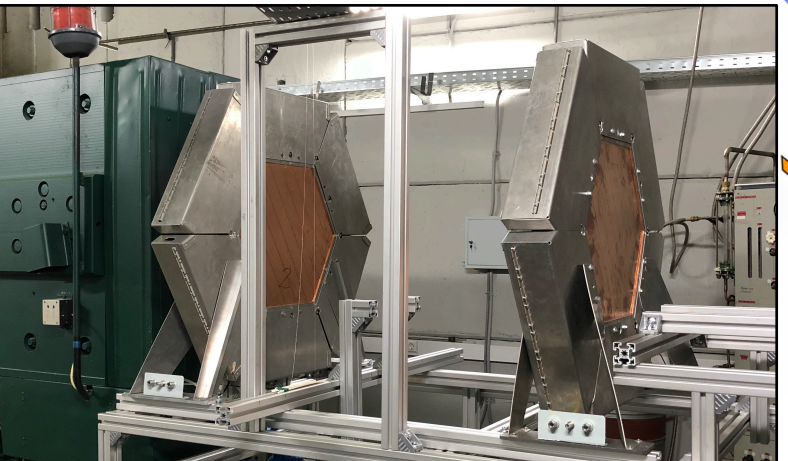
Dipole magnet

Proton

Target

MWPC

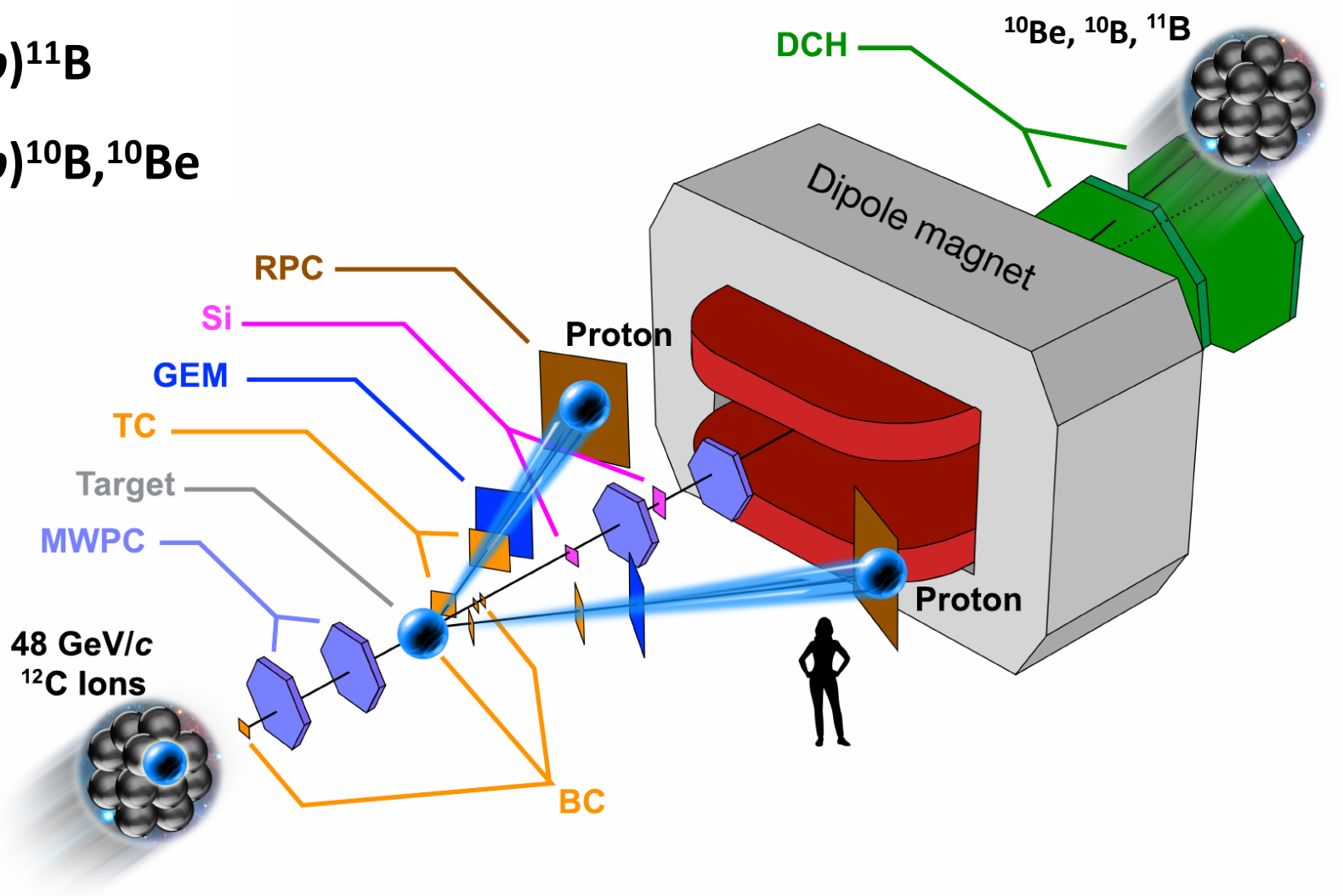
BC



Pilot experiment in 2018

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

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



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Quasi-free (*p*,2*p*) scattering

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

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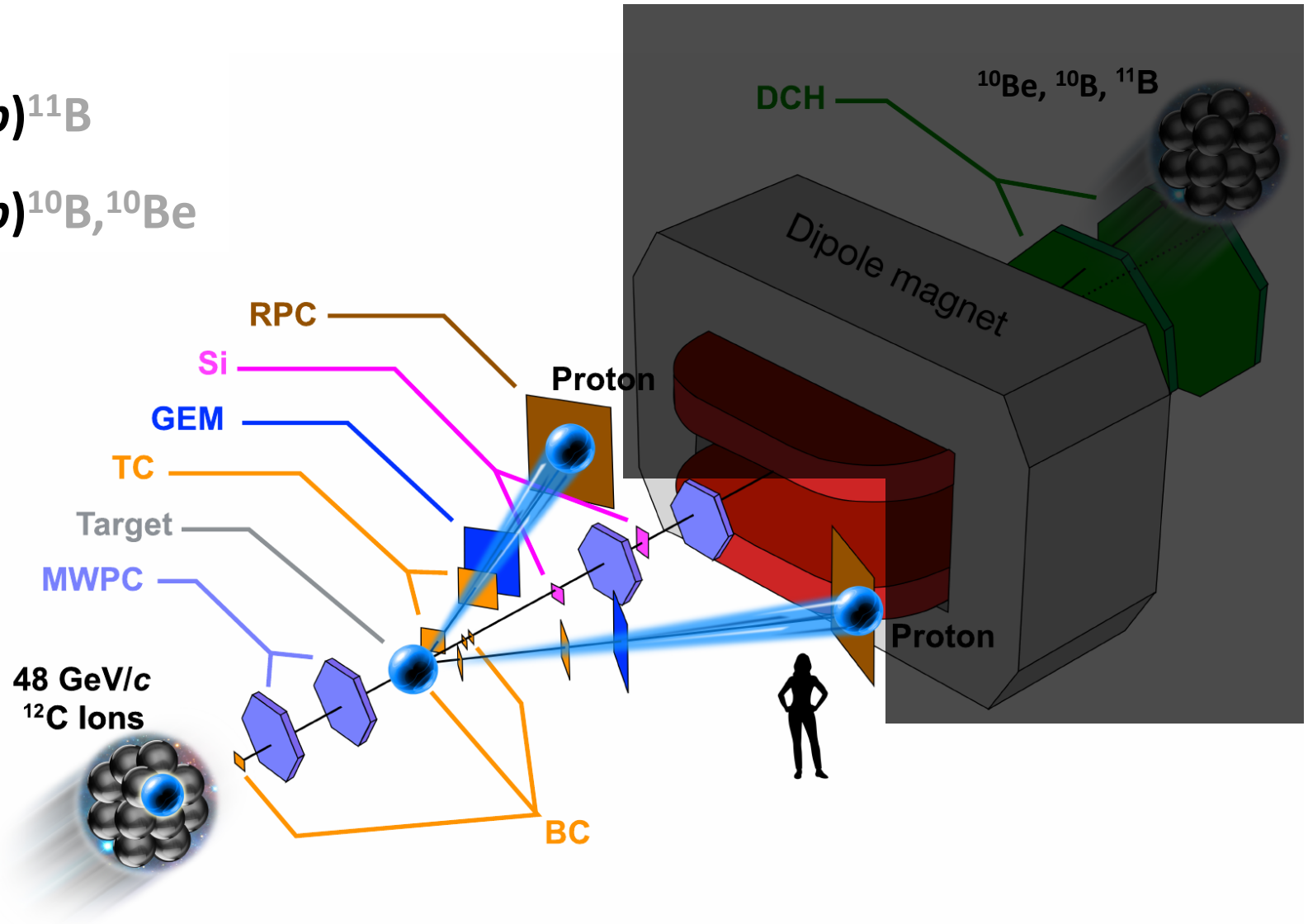


Nature Physics (in print)
[arXiv:2102.02626]

Quasi-free (*p*,2*p*) scattering: reaction mechanism

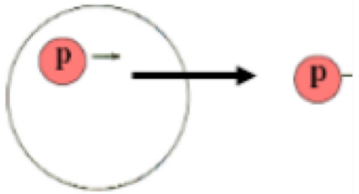
Remove a single nucleon:

~90° c.m. scattering

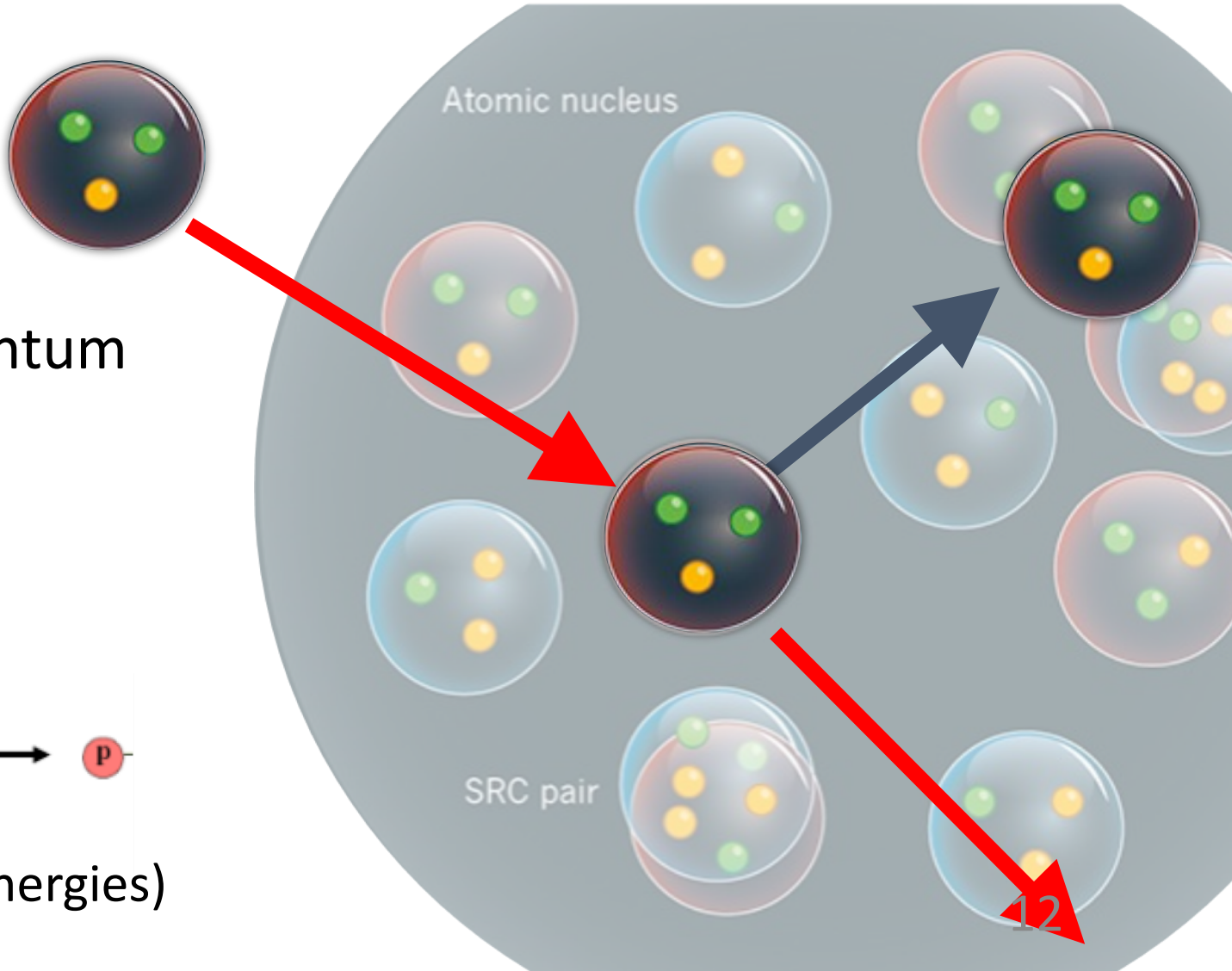
Reconstruct initial nucleon momentum p_{miss} from scattered particles

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

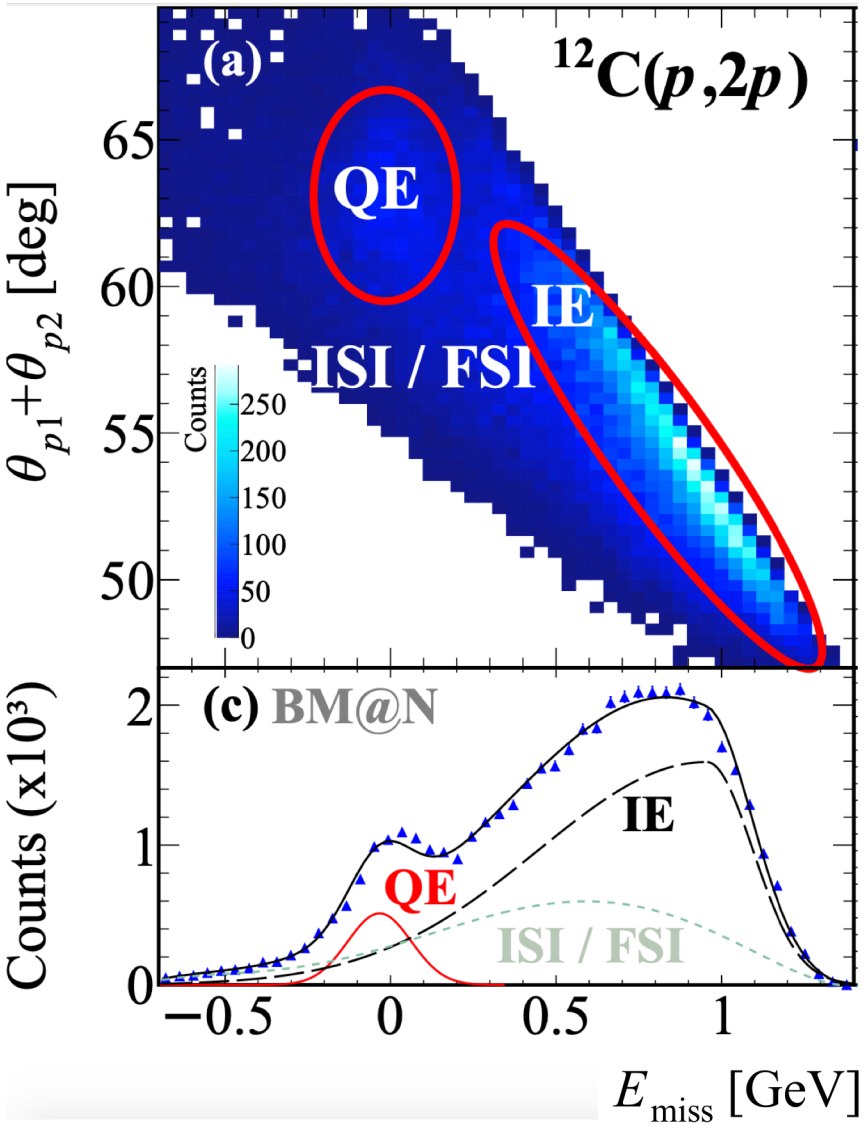
Selection of high momentum:



$$\frac{d\sigma}{dt} \propto s^{-8}$$ (at our energies)



Single proton knockout

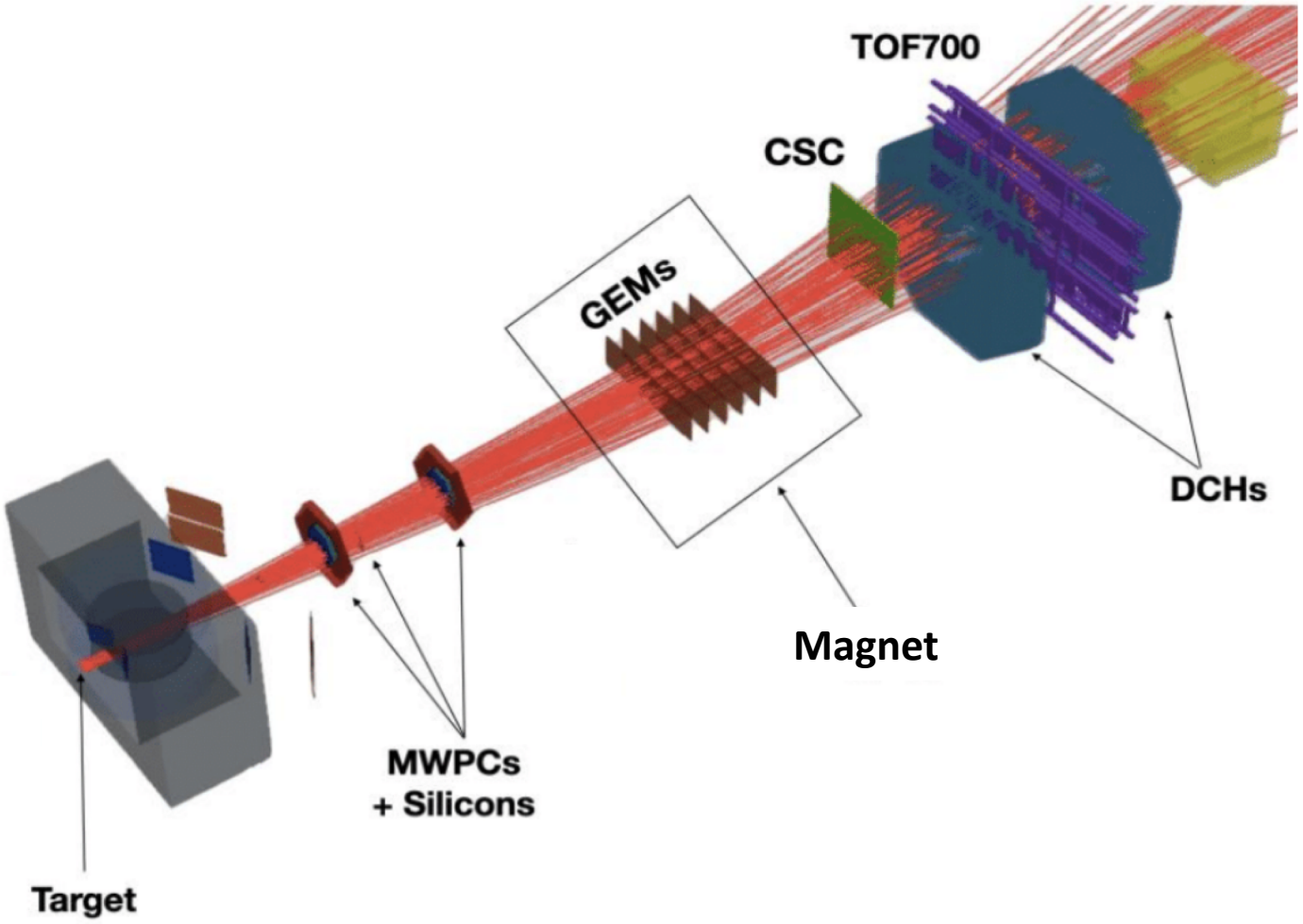


contaminated by inelastic scattering (IE) & ISI / FSI

$E_{miss} = m_p - e_{miss}$

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

Single proton knockout + Fragment Tagging



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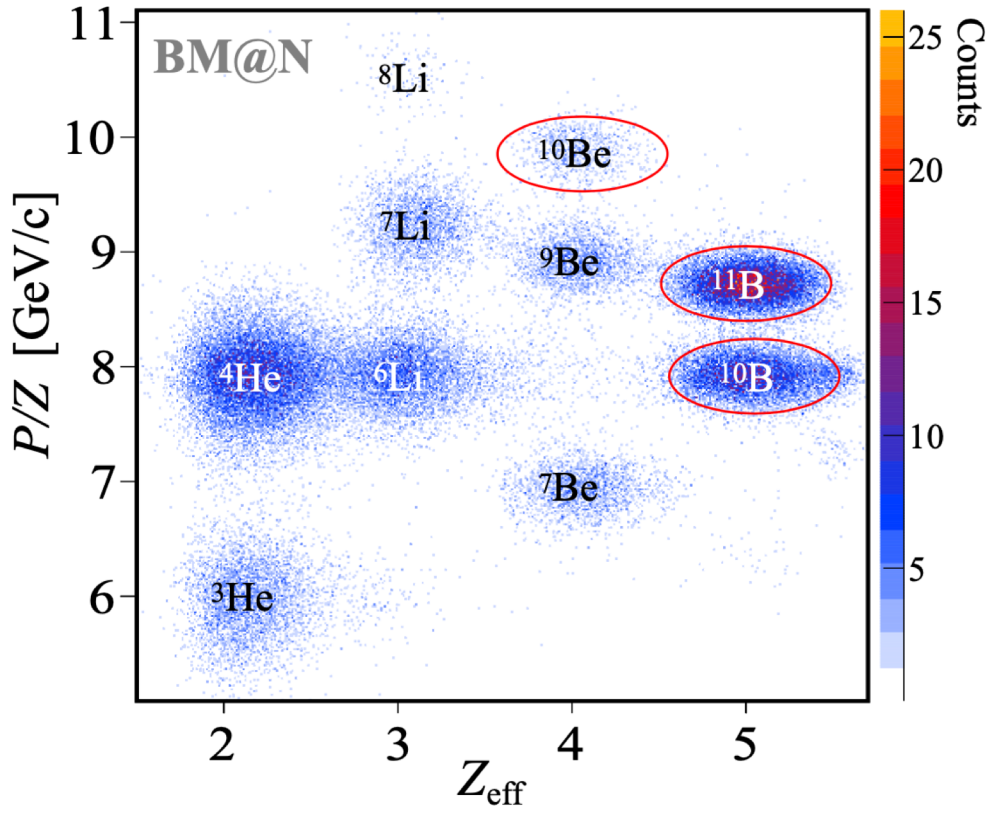
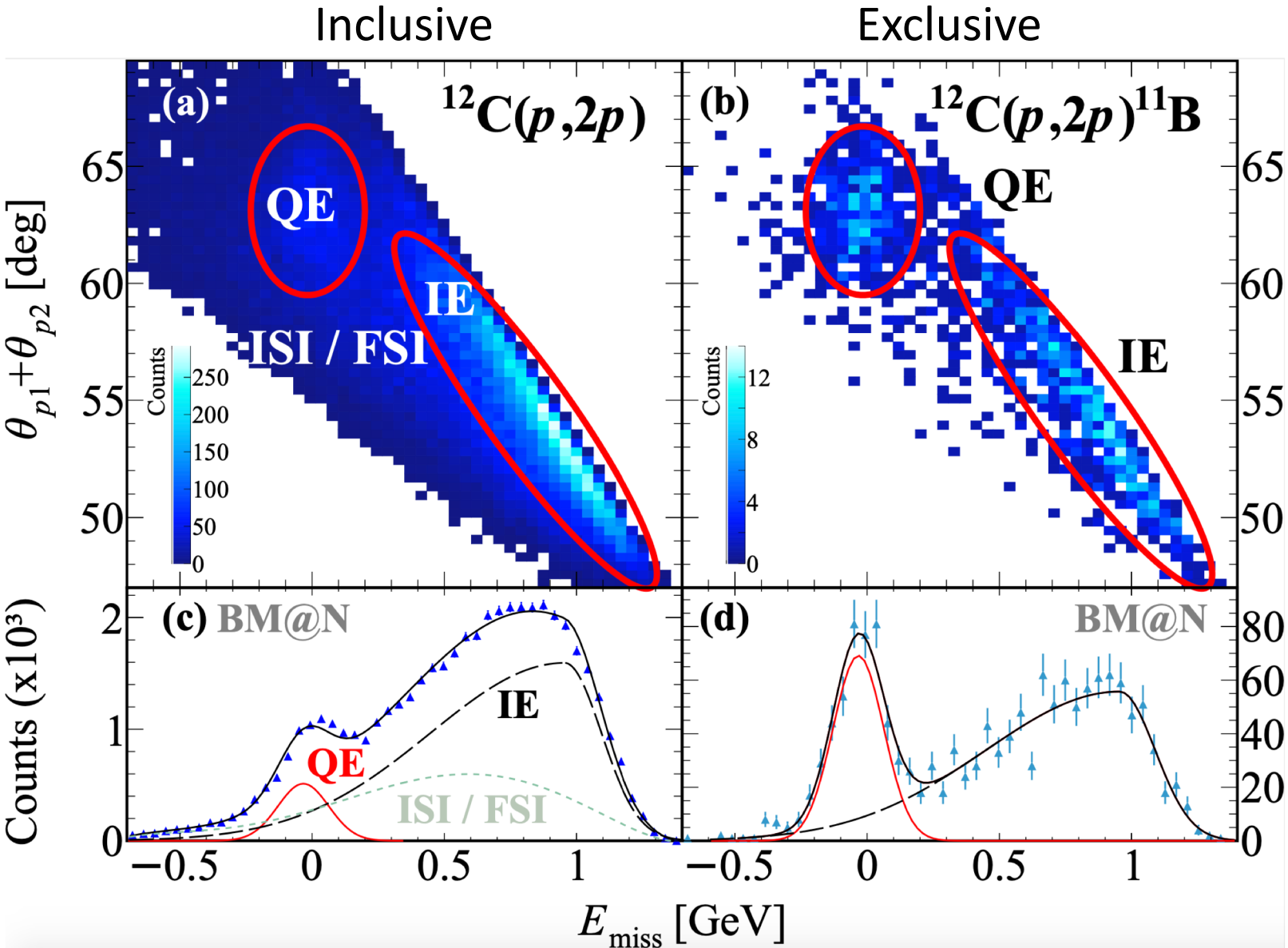
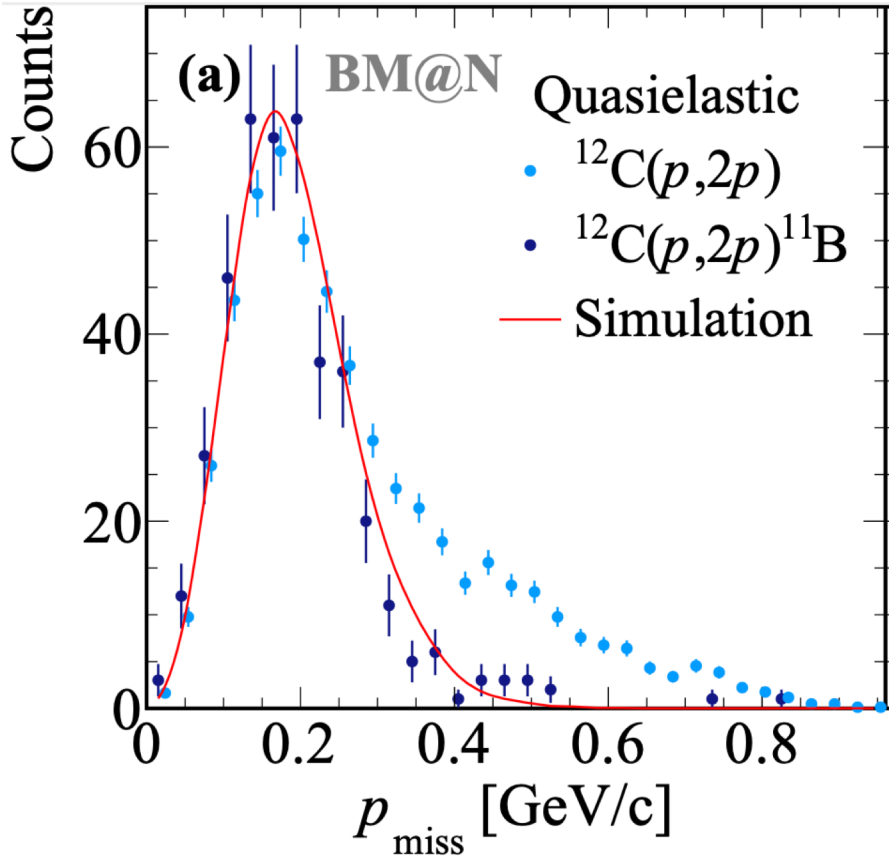


Single proton knockout + Fragment Tagging

- **fragment tagging removes ISI / FSI**
- selects **quasi-elastic scattering (bound ^{11}B)** @ large momentum transfer

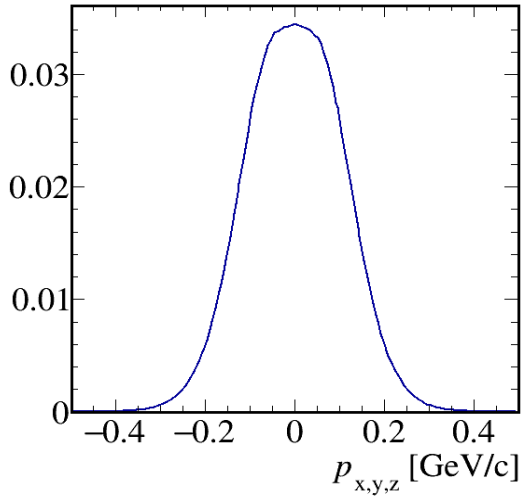


Initial proton momentum



High momentum tail – ISI/FSI

Calculation of QE (p, 2p) scattering off a p-shell nucleon in 12C **w/o ISI/FSI**

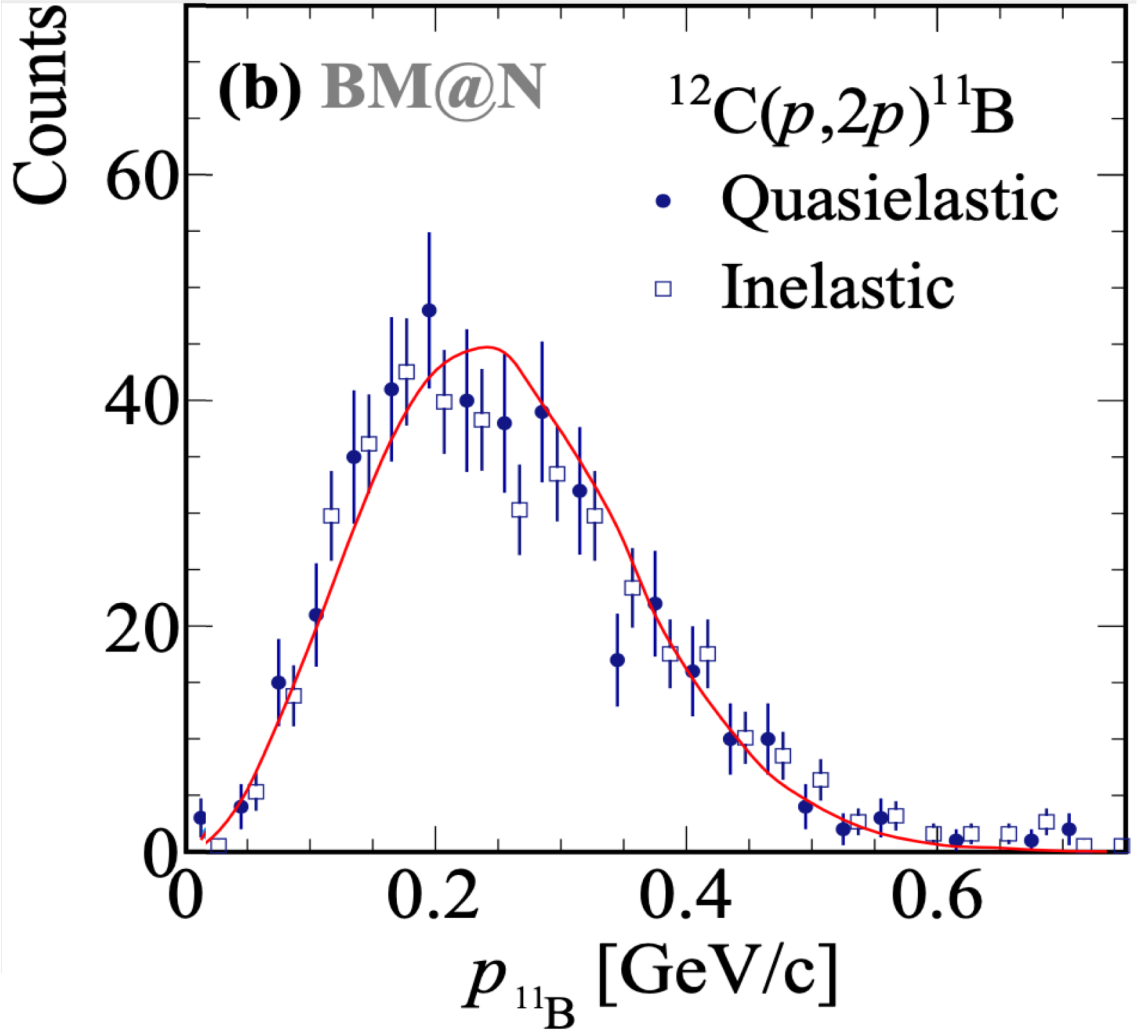


T. Aumann, C. Bertulani, and J. Ryckebusch, Phys. Rev. C 88 (2013)

Recoil fragment momentum

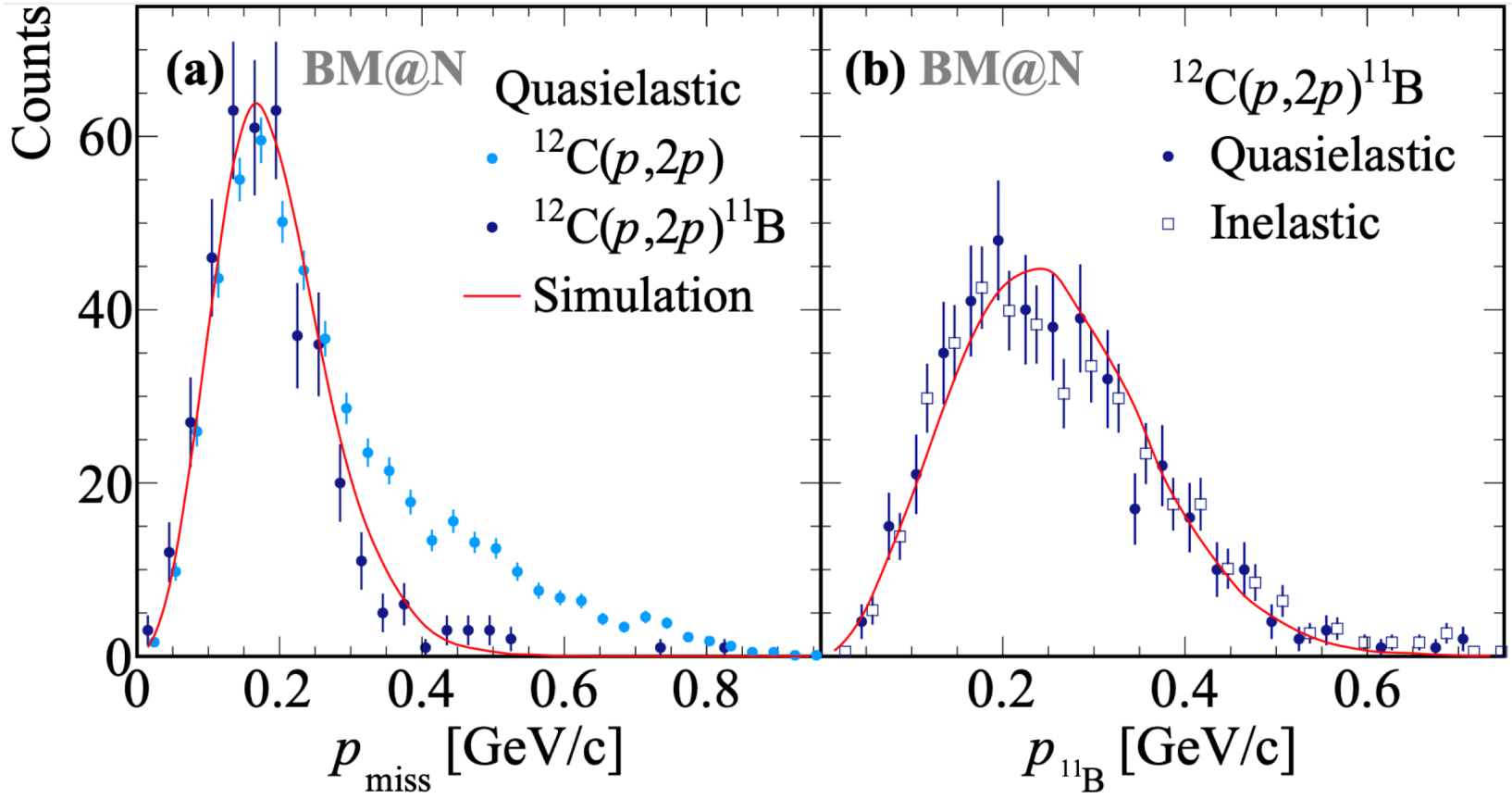
Fragment tagging selects **quasi-free unperturbed single-step reactions**

First direct comparison of QE and IE fragments

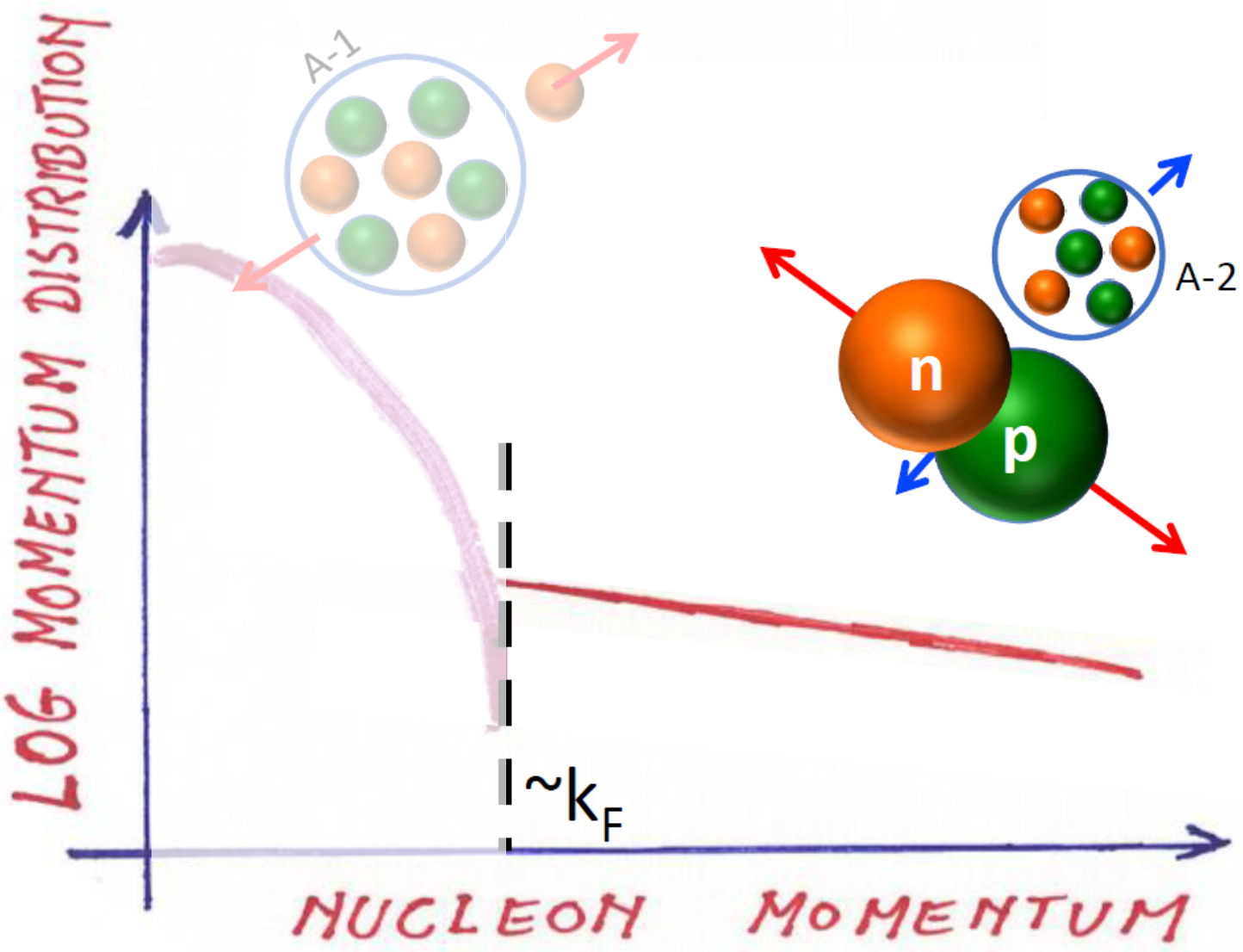


Access to ground-state properties of ^{12}C

Demonstration of single–step knockout reaction



First QE study of SRCs in inverse kinematics

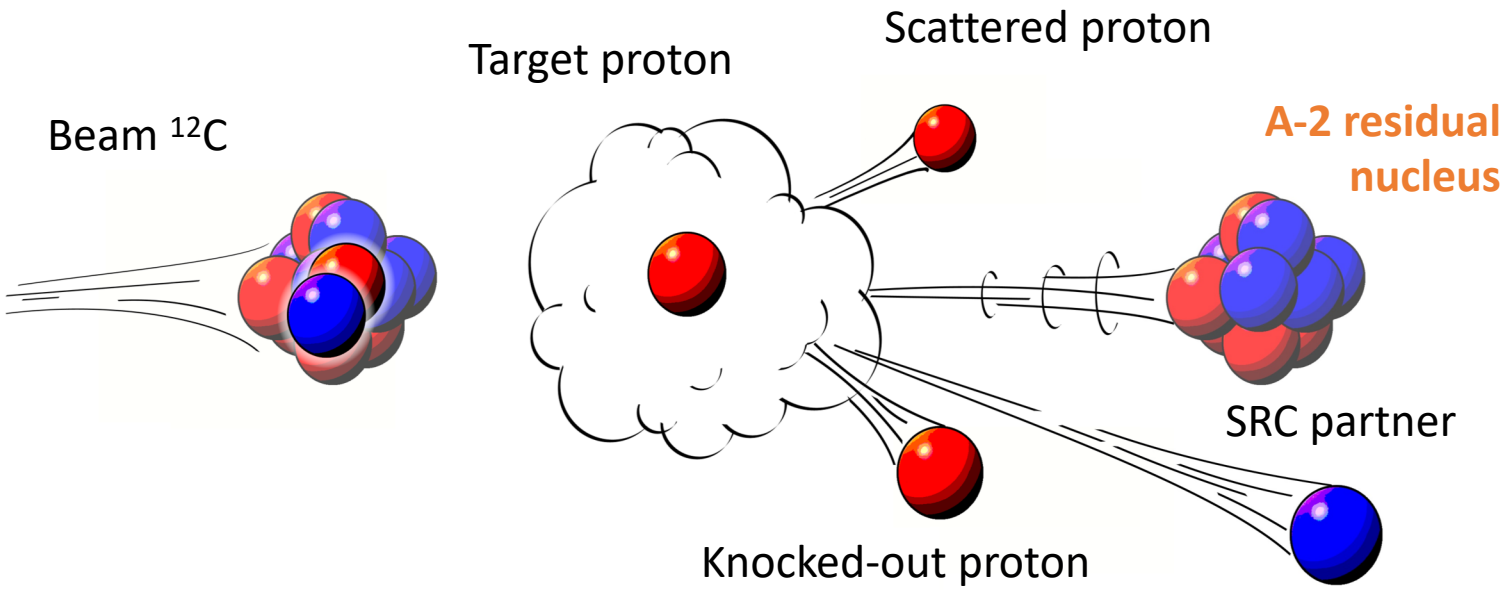


Hard breakup of SRC pairs

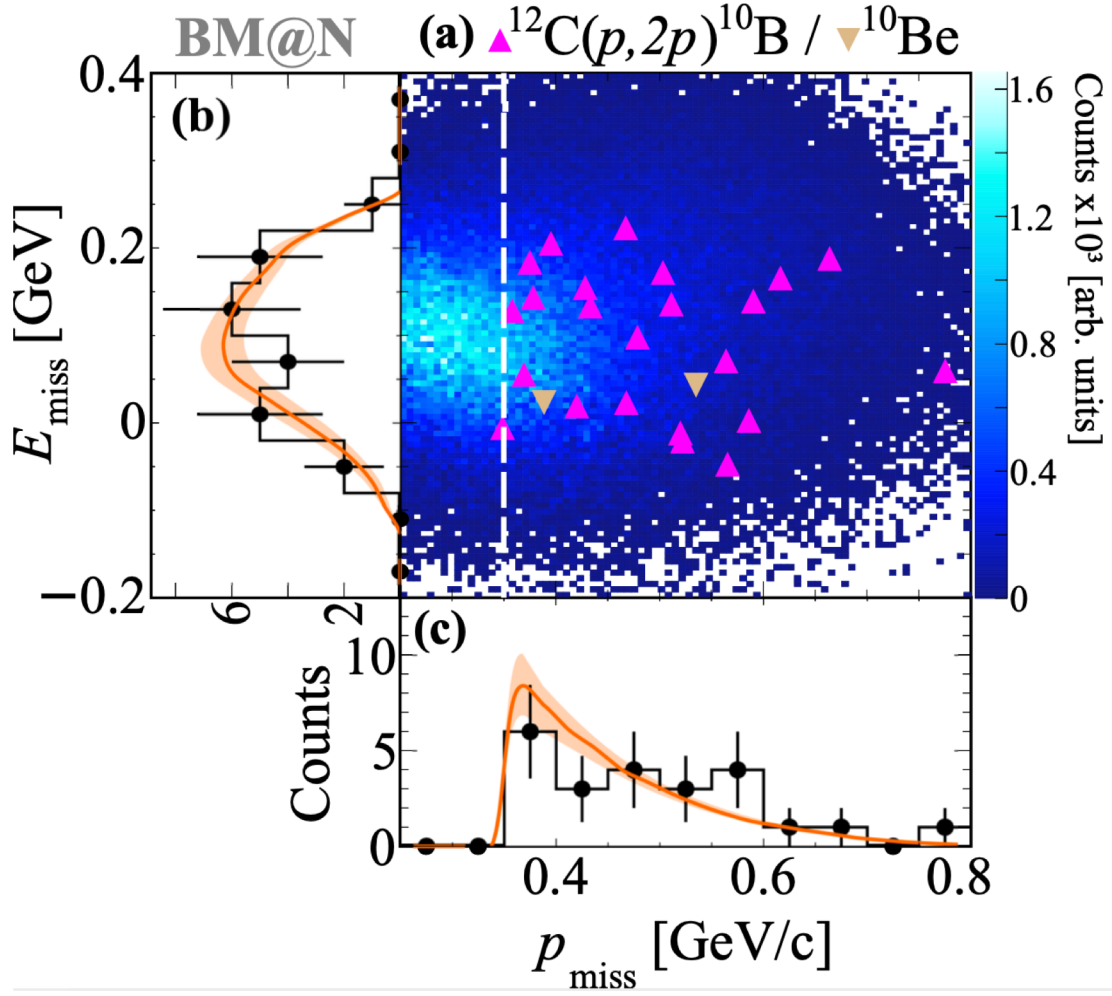
***np* pair:** $^{12}C(p,2p)$ **^{10}B**

***pp* pair:** $^{12}C(p,2p)$ **^{10}Be**

A-2



Identifying SRCs



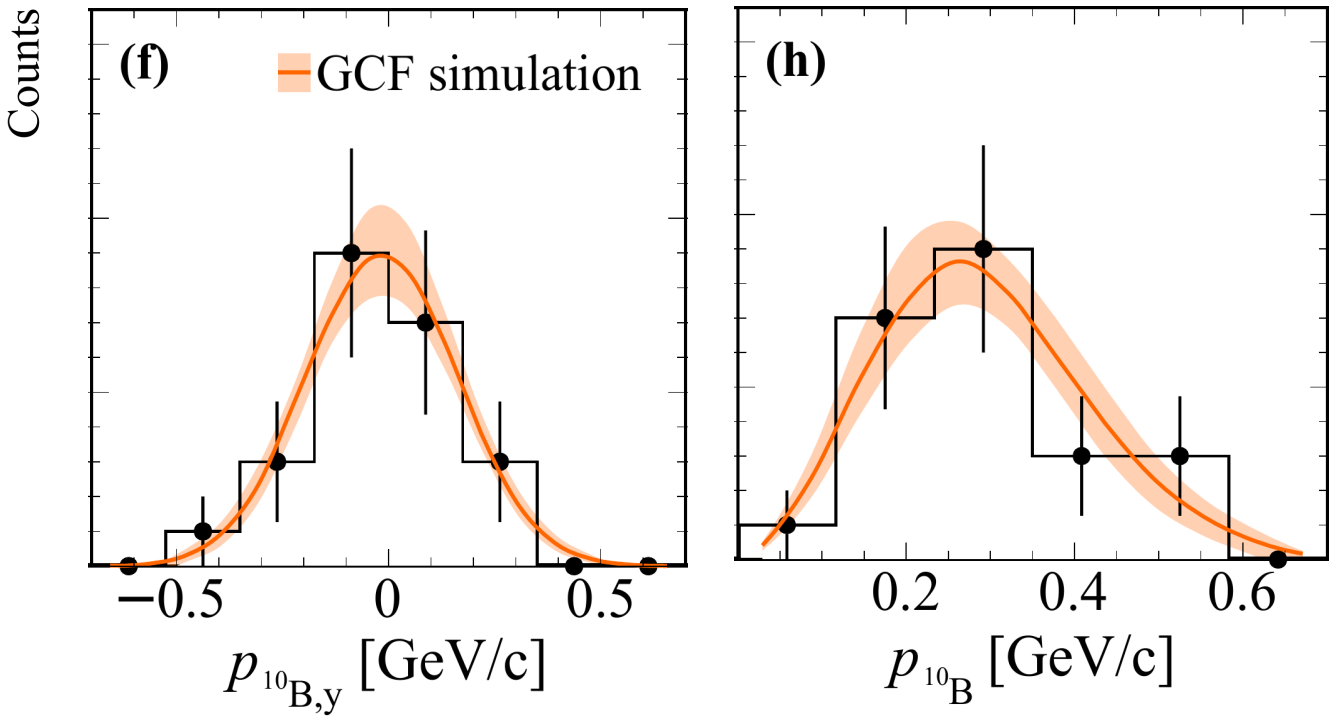
23 np pairs
2 pp pair

-> *np* dominance

+ (p,2p) opening angle
(guided by Generalised Contact Formalism)

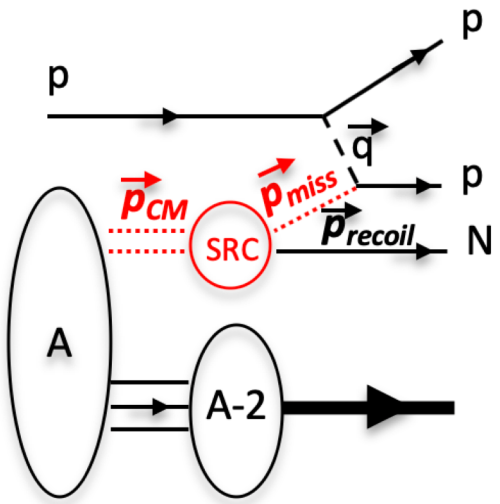
* A. Schmidt et al., Nature 578 (2020)
R. Cruz-Torres, D. Lonardoni et al., Nature Physics (2020)
J.R. Pybus et al., PLB 805 (2020)

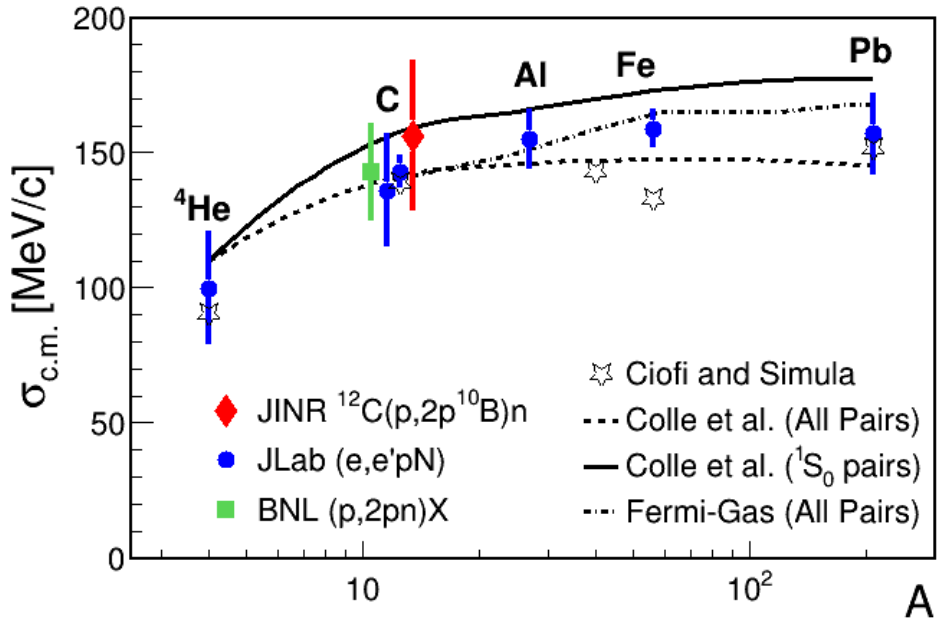
First direct measurement of fragment (SRC pair c.m.) momentum



direct extraction: **σ = (156 ± 27) MeV/c**

-> small c.m. momentum



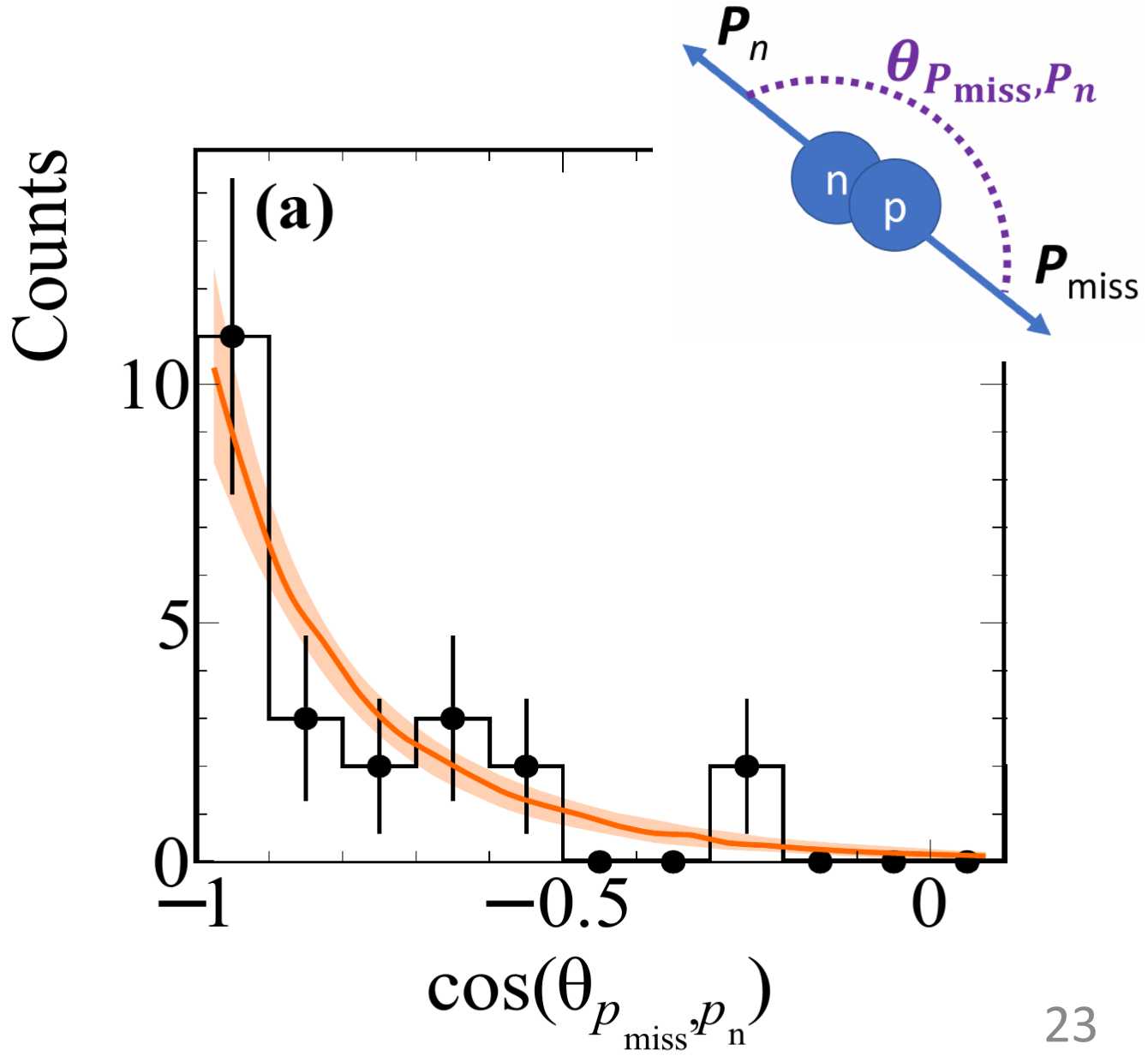


E.O. Cohen et al., Phys. Rev. Lett. 121 (2018)

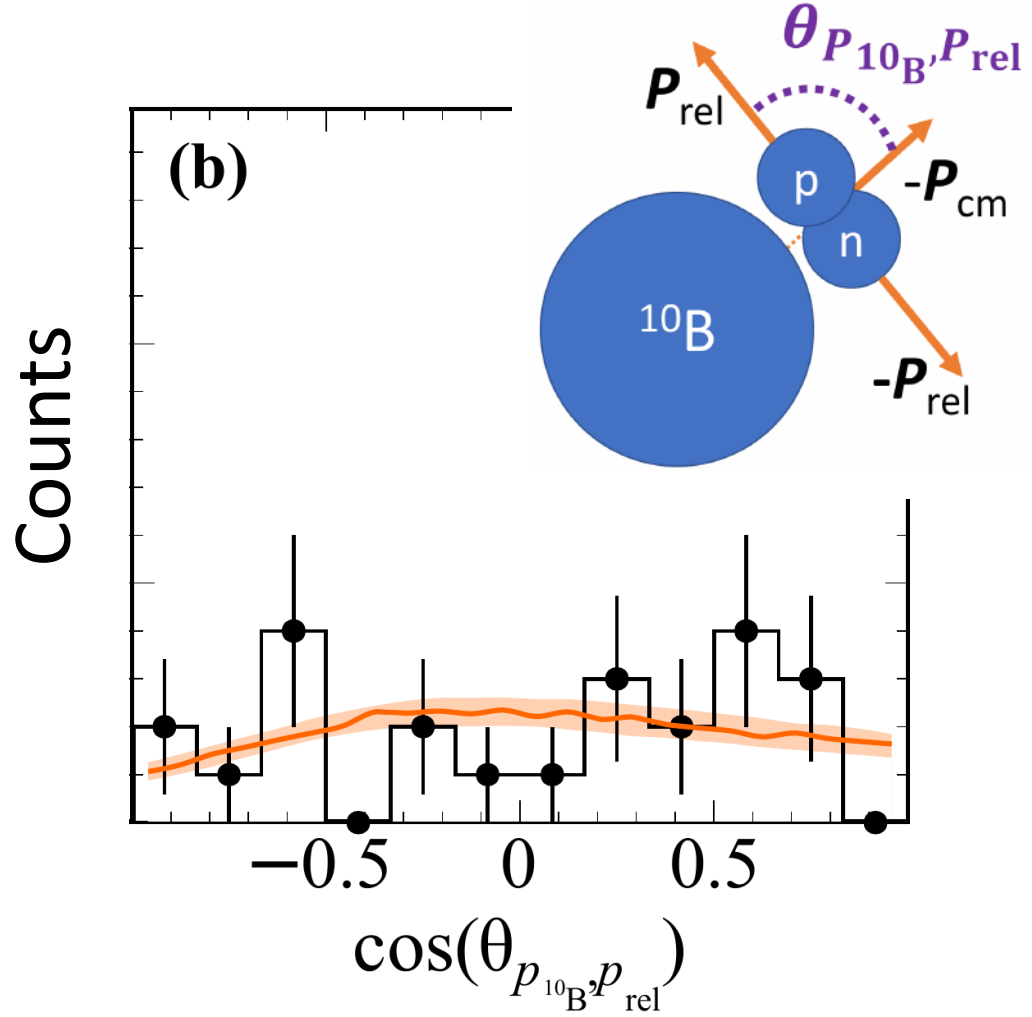
Strong pair correlation

NN back-to-back emission

nucleon momentum not balanced by A-1



Experimental evidence for factorization between pair and A-2



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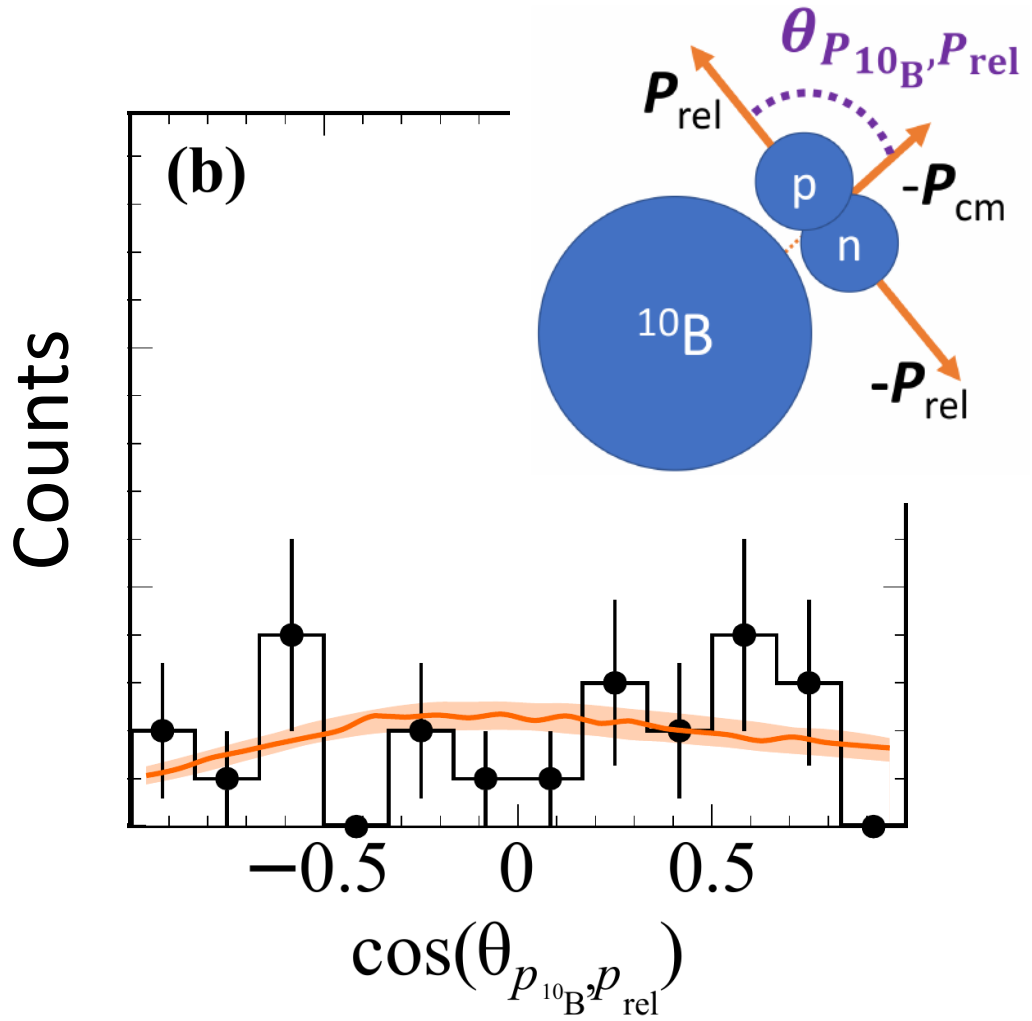


$$f_{SRC}(p_{rel}, p_{c.m.}, \theta_{rel,c.m.})$$

$$\approx C(p_{c.m.}) \times \varphi(p_{rel})$$

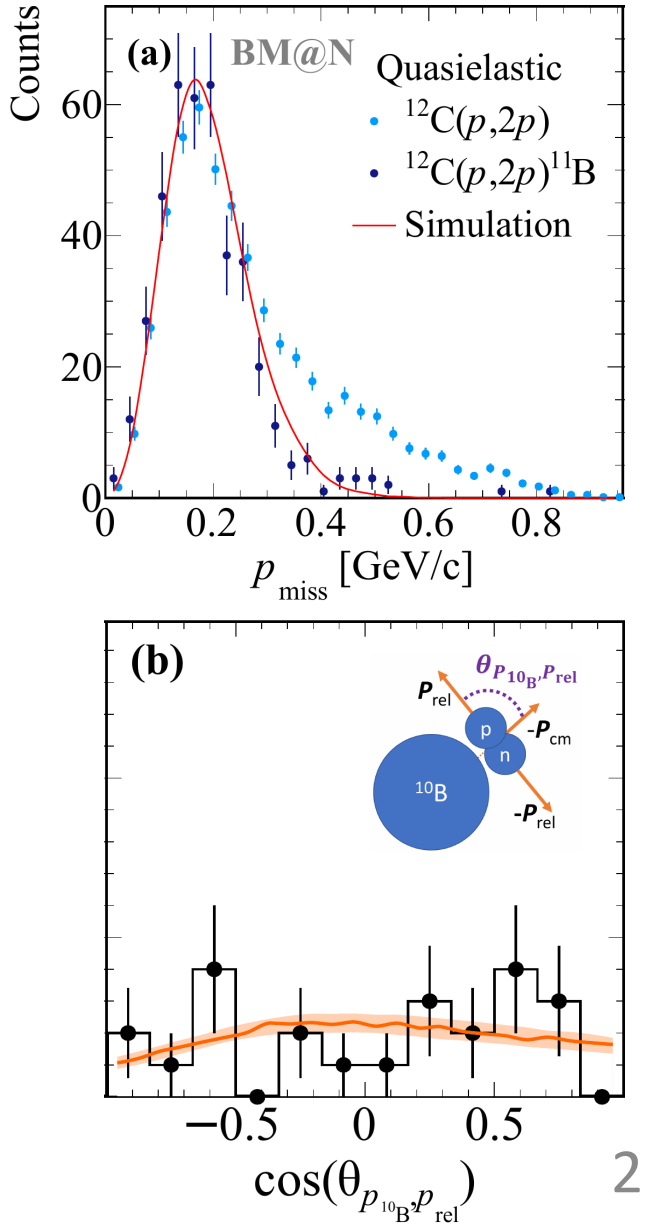
FACTORIZATION!

SRC studies in many-body dynamics entering new era

- "Transparent" nucleus:
  Extract ground-state distributions in strongly interacting many-body system with fragment tagging (suppress ISI/FSI)

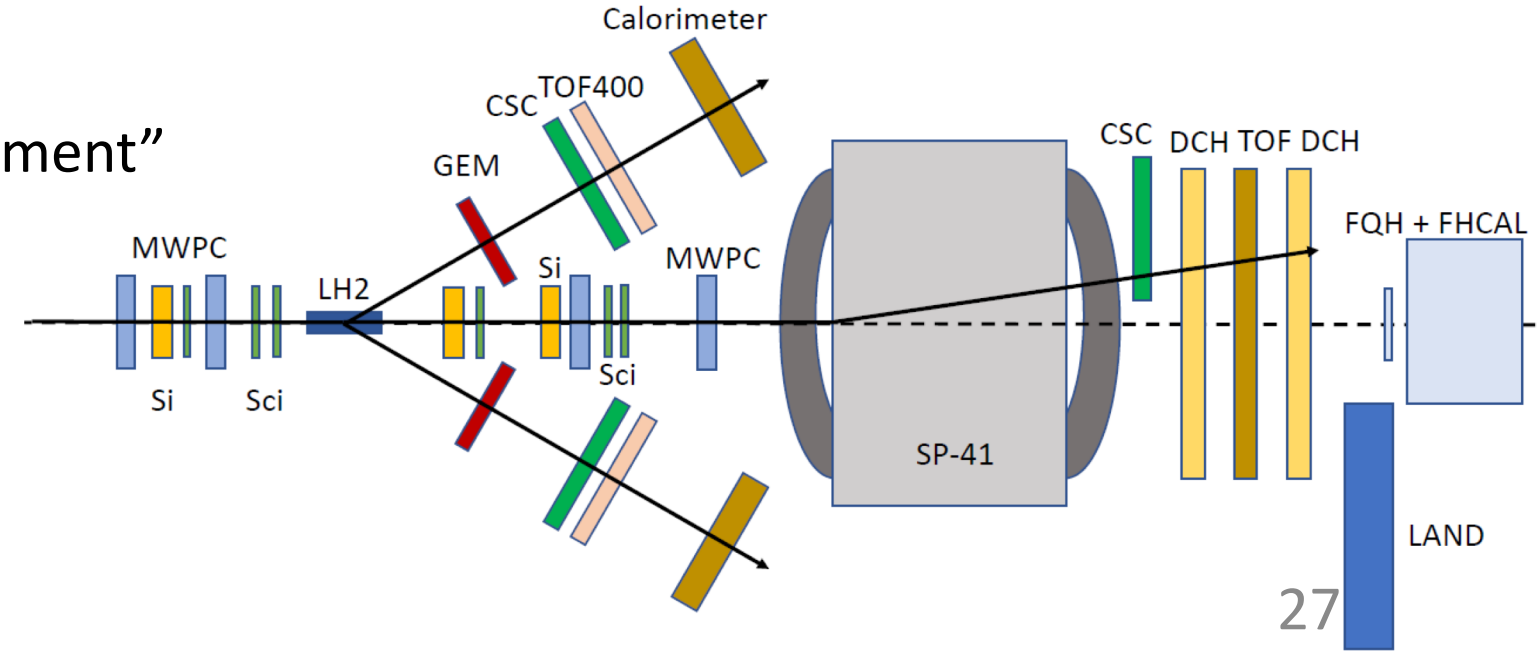
- 1st SRC experiment in inverse kinematics:
  evidence for scale separation

- Merge radioactive beam and SRC physics:
  2021: ^{12}C high statistics run at BM@N (JINR)
  2022: ^{16}C run at R^{3}B (GSI/FAIR)



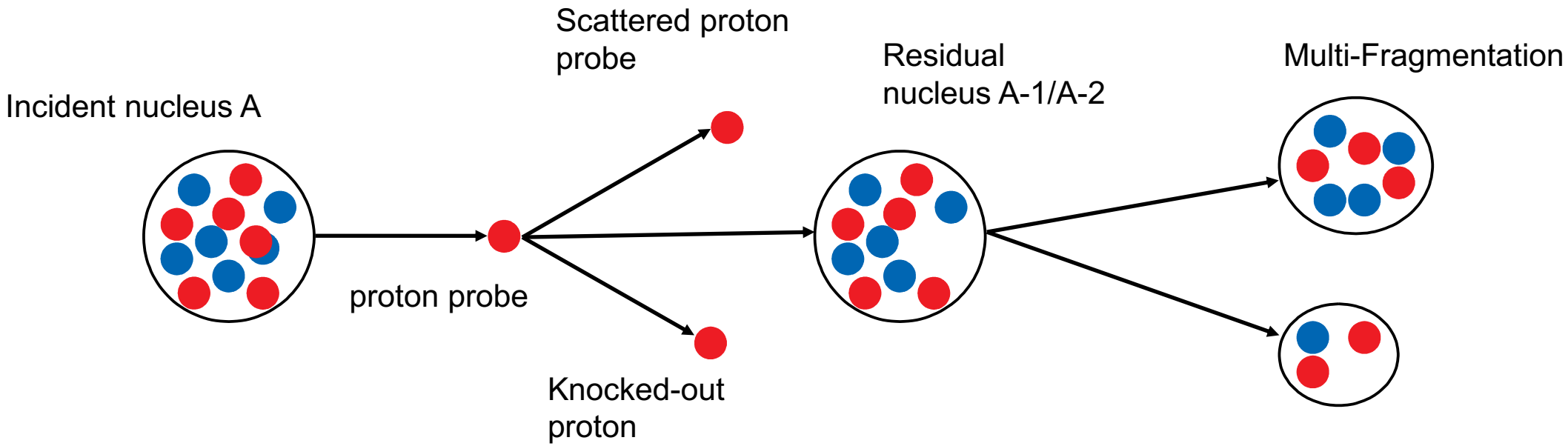
Next measurement (Fall ’21)

- **increase statistics** by order(s) of magnitude for detailed comparison with calculations
- improve detector resolutions
- absolute cross section measurement
- **employ multi-particle tracking**
- **event selection: p/pion sampling**
- “learn lessons from previous experiment”



Analysis of Multi-Fragment Emission

Göran Johansson, Tel-Aviv University



Motivation: Extract momentum distribution of deeply bound nucleons in unstable nuclei.

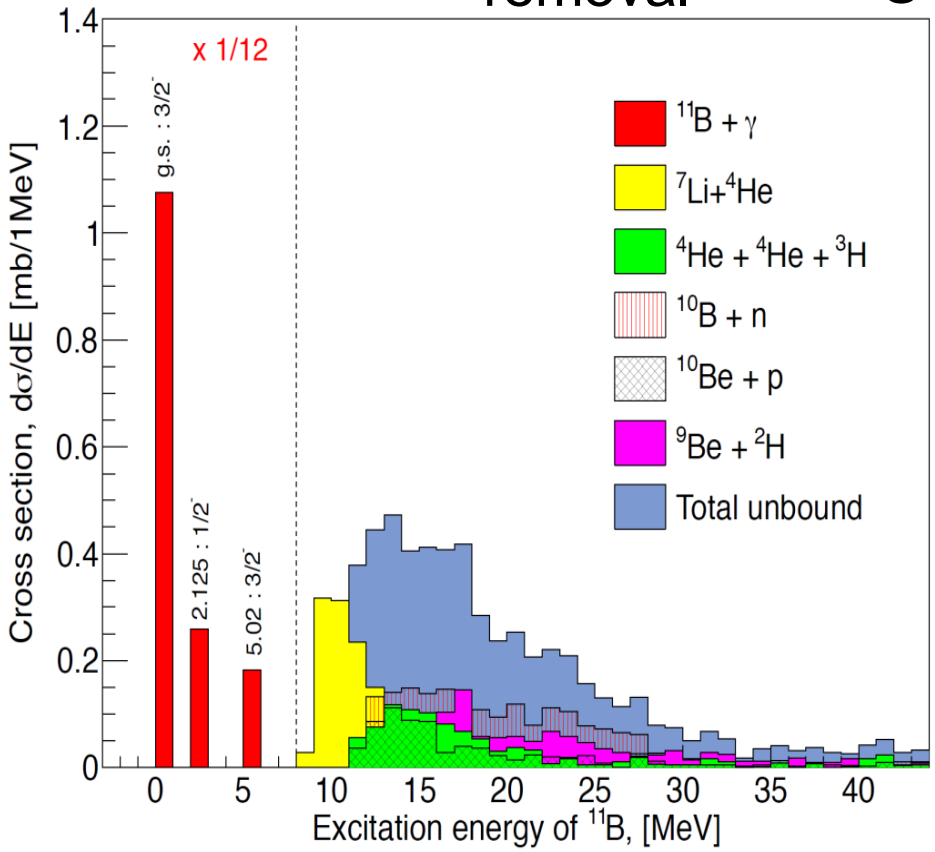
$^{12}C(p, 2p)X$

p-shell knockout ↔ single fragment

s-shell knockout ↔ more than one fragment

p-shell removal

s-shell removal



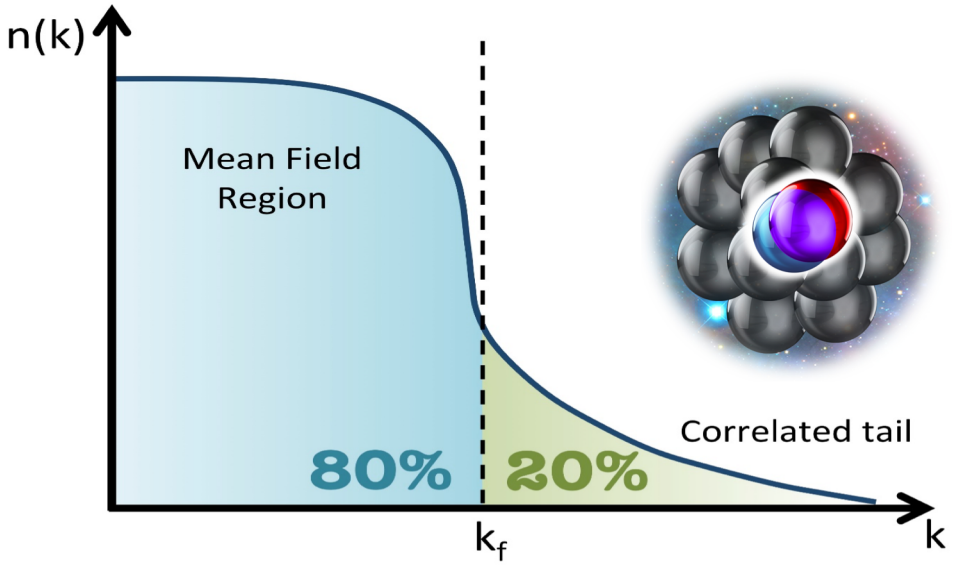
R^3B (GSI): ^{12}C at 0.95 GeV/c/u

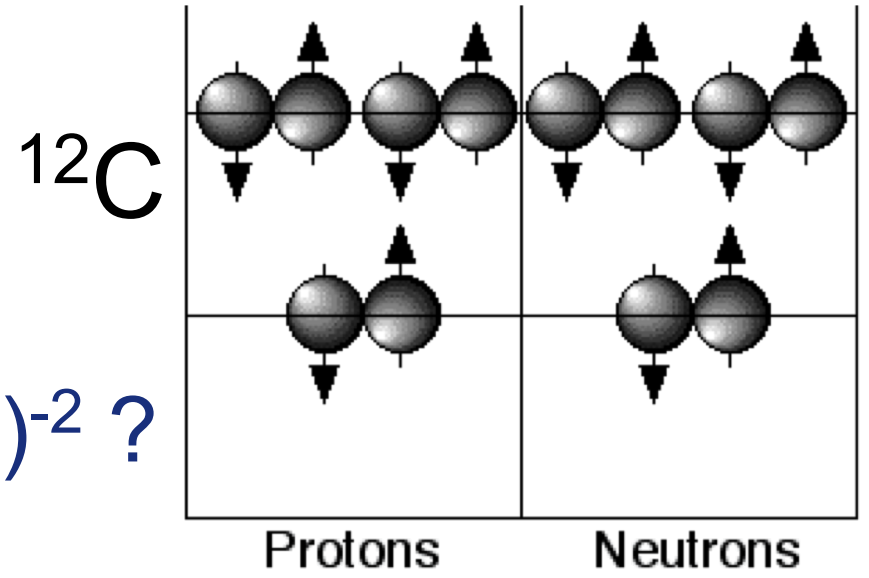
V. Panin et al., Phys. Lett. B 753 (2016).

V. Panin, Ph.D. Thesis, 2012.

Motivation:

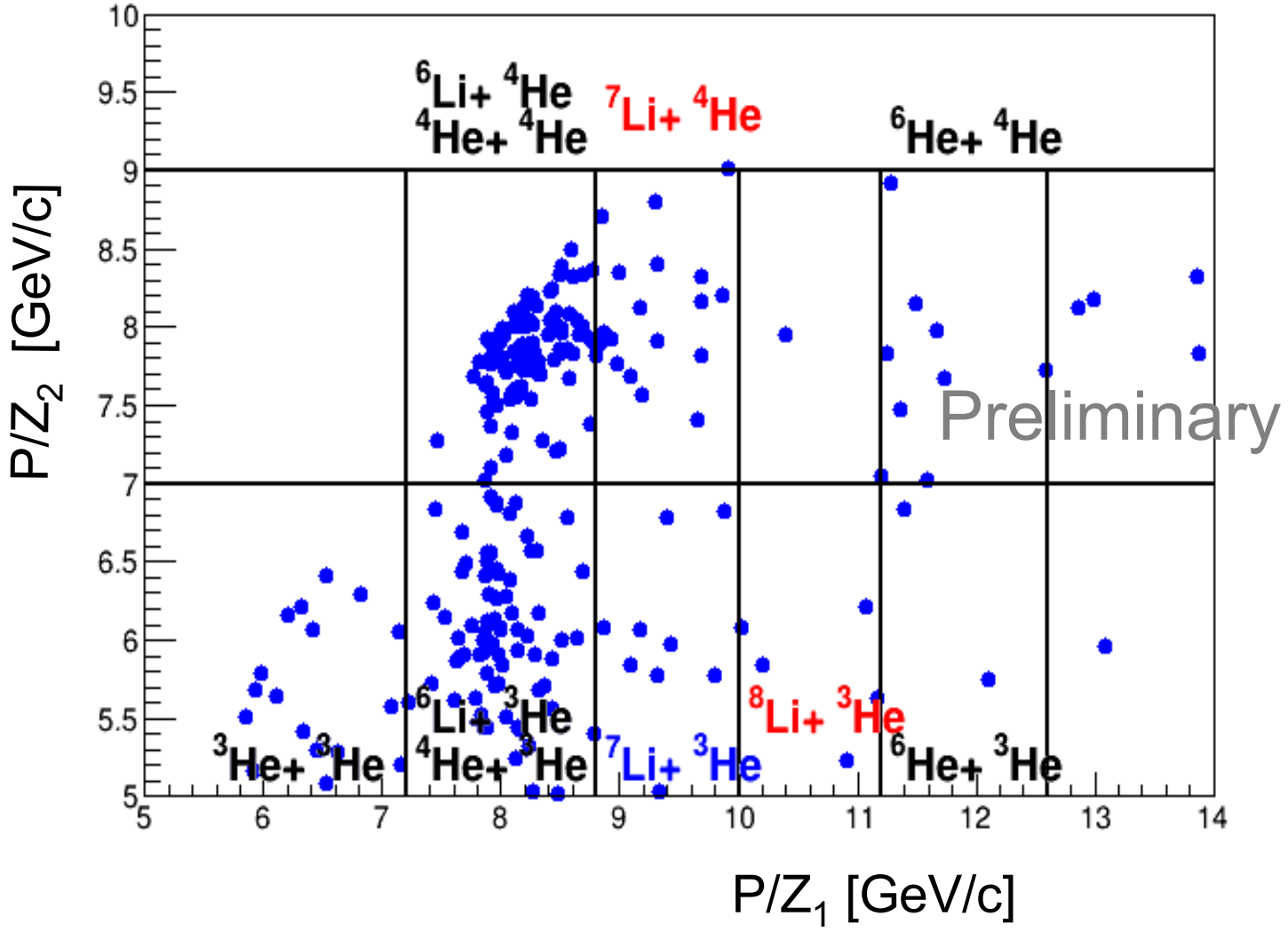
From what shells nucleons in Short Range Correlated (SRC) pairs originate?





- What SRC pairs are: $(p)^{-2}$, $(ps)^{-1}$, $(s)^{-2}$?

^{12}C(p, 2p) with Two Fragments



Exclusive 2 heavy tracks ($A_1 + A_2 = {}^{11}$B)

w/o correction for acceptance and efficiency

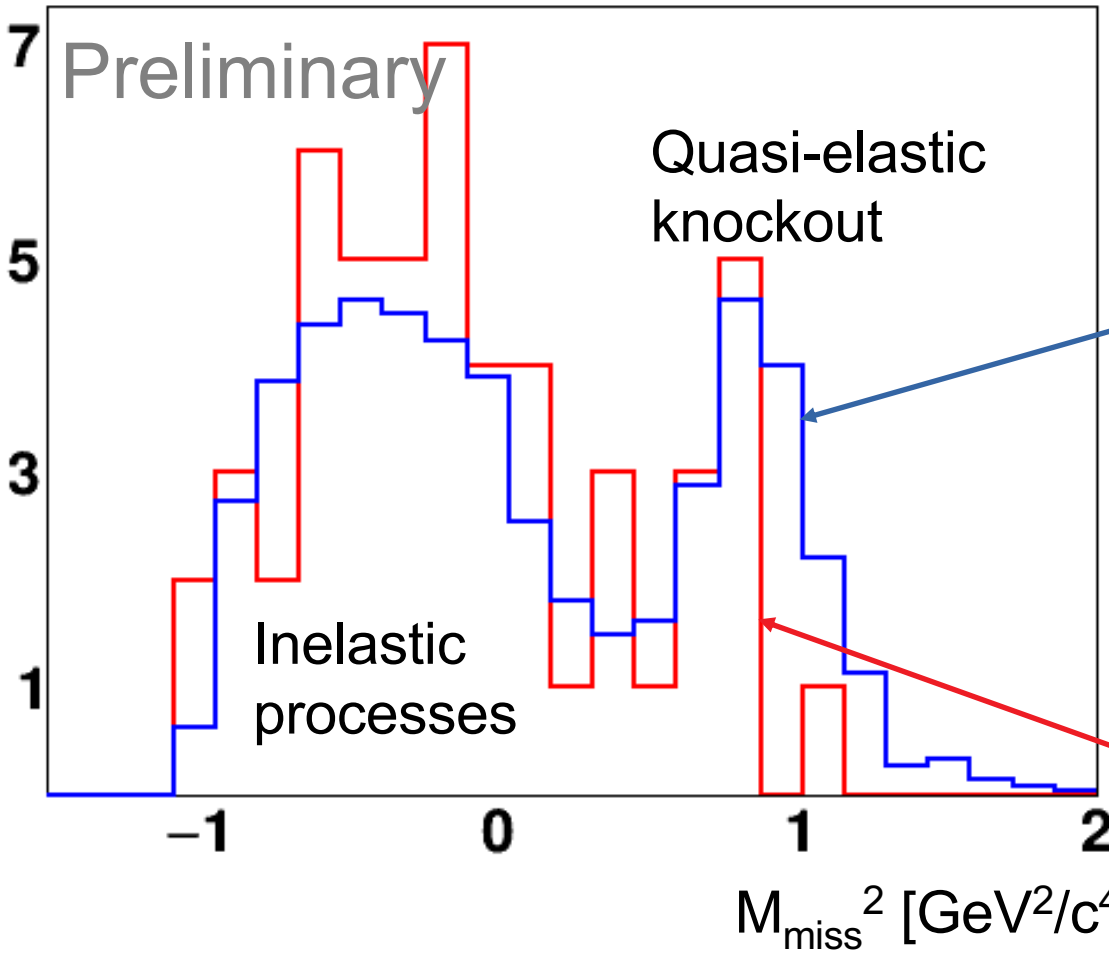
Preliminary Results: JINR 2018

$$p^{\mu}_{miss} = p^{\mu}_{1} + p^{\mu}_{2} - p^{\mu}_{target}$$

$$E_{miss} = m_{p} - e_{miss}$$

$$M^{2}_{miss} = E^{2}_{miss} - \vec{p}^{2}_{miss}$$

^{12}C rest frame



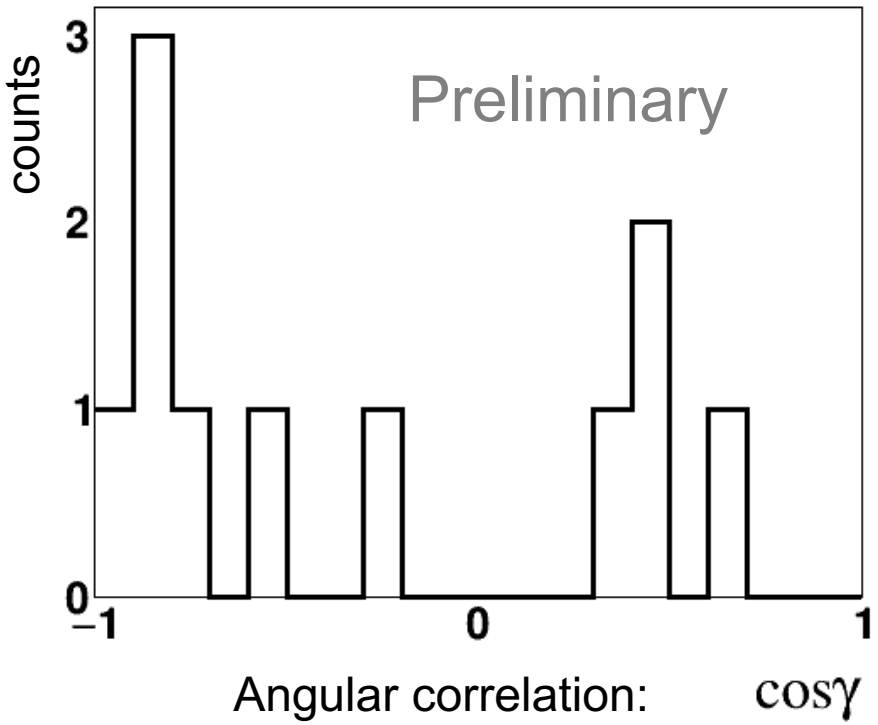
^{12}C(p, 2p)^{11}B

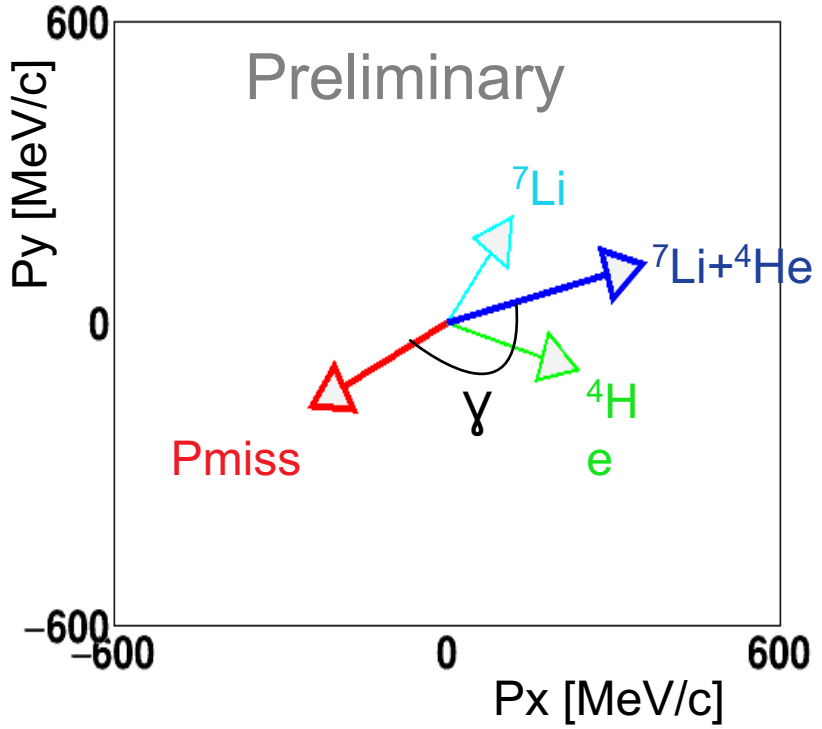
Removal of a proton from p-shell (scaled)

Removal of a proton from s-shell

^{12}C(p, 2p)^{7}Li+^{4}He

$^{12}C(p, 2p)^{7}Li+^{4}He$






JINR


BM@N
Baryonic Matter at Nuclotron


Hen Lab
Laboratory for Nuclear Science @ MIT


TEL AVIV UNIVERSITY
אוניברסיטת תל אביב


DE LA RECHERCHE À L'INDUSTRIE
cea


TECHNISCHE
UNIVERSITÄT
DARMSTADT


MIT


GSI

Cuts applied

Incoming ^{12}C

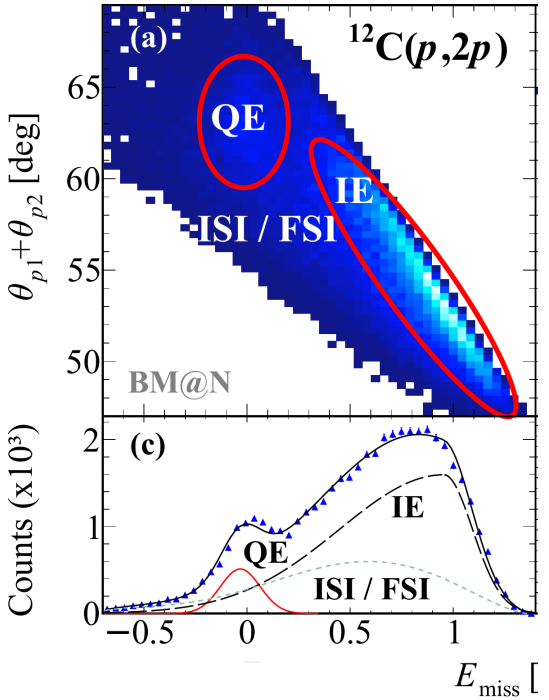
Good reaction vertex (dZ = 4 cm)

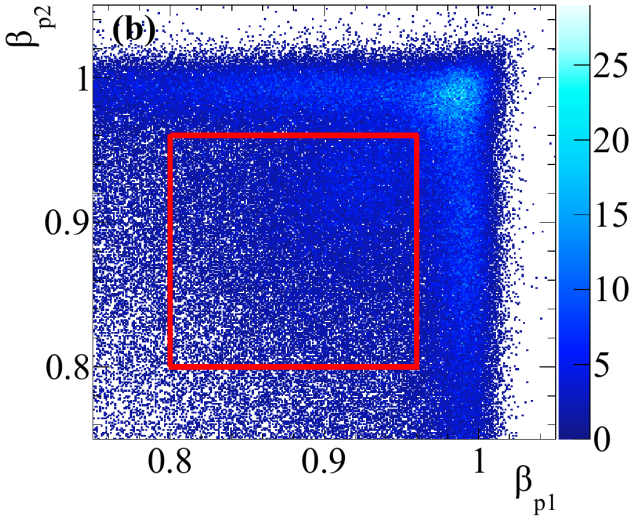
Velocity cut in the arms

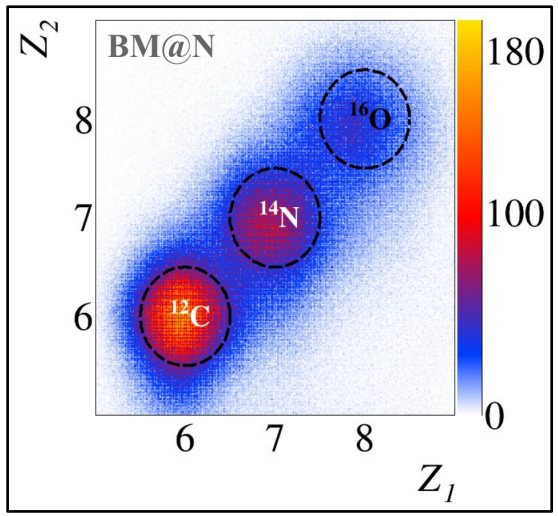
$M_{miss} > 0.47\ GeV^2/c^4$

QE events have additionally

2 sigma cuts







SRC events have additionally

$P_{miss} > 350$ MeV/c

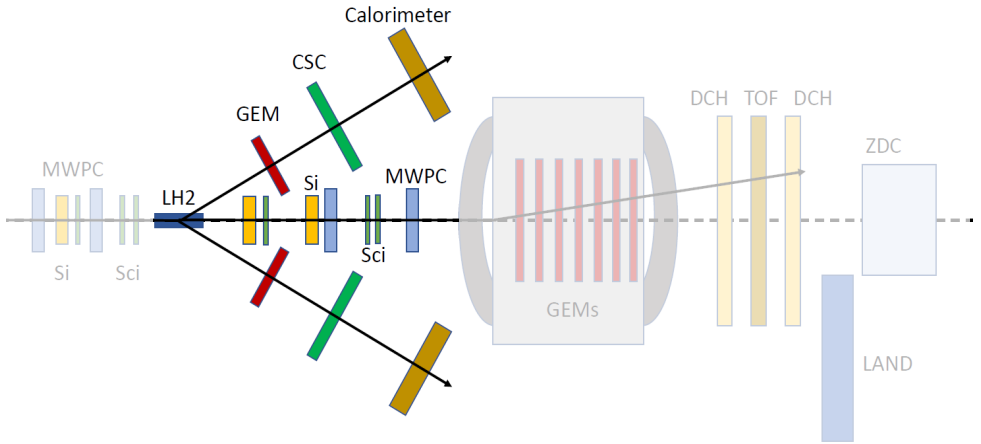
pp angle > 60 degrees

-110 MeV < E_{miss} < 240 MeV

New (non-magnetic) calorimeter

Sandwich like structure of Sci – Fe – Sci (~ 150 x 230 x 25 cm³)

1. Sci layer
High-performance Sci. bars (~25 each arm)
Sci + PMT Tests to reach <70ps ToF resolution



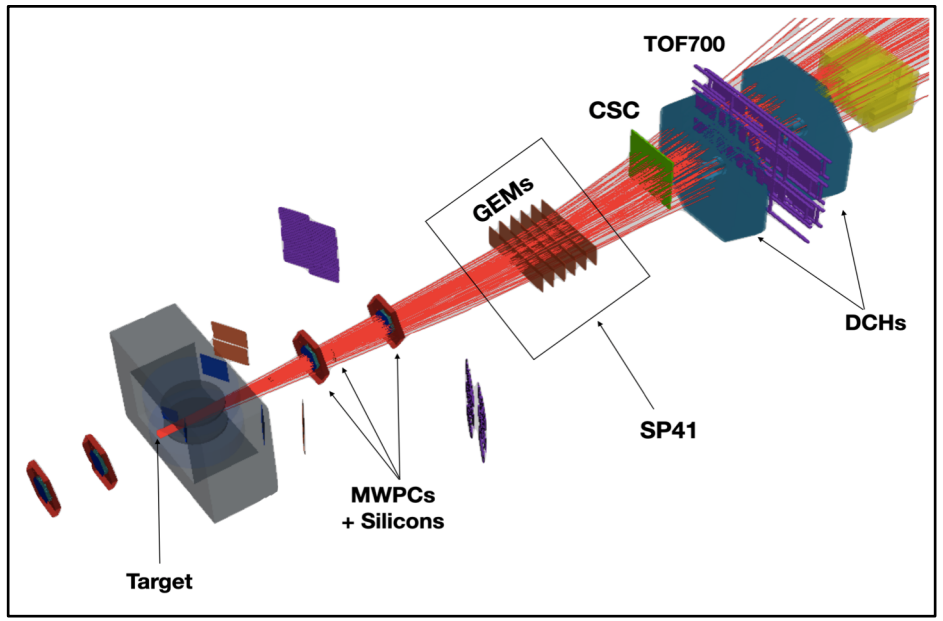
2. Fe layer ~10 cm
to be optimized to achieve strong p-pion separation

3. Sci layer for dE
- determine number of initial p and pions
- in statistical approach: pion contribution is small and can be subtracted in p_{miss} distribution

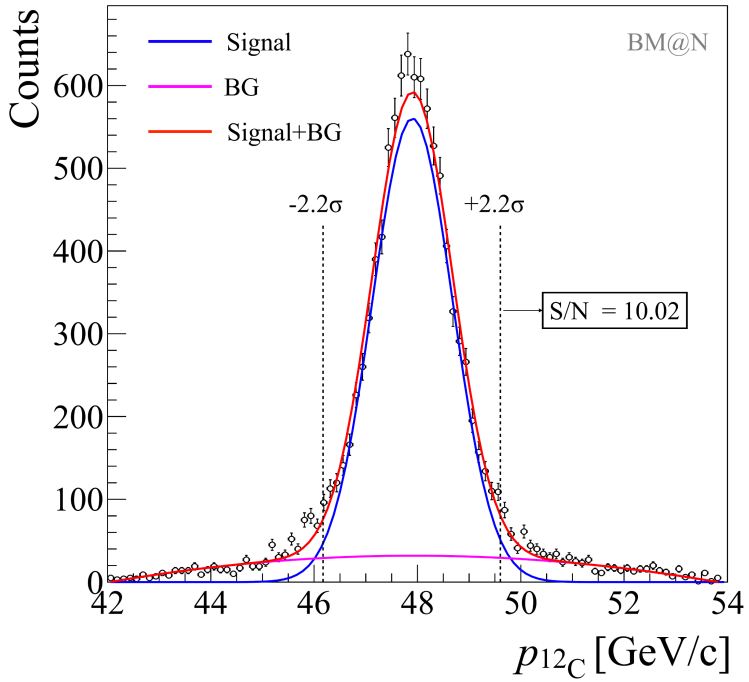
Fragment momentum

Simulation-based multi-dimensional fit

$P/Z = f(\boldsymbol{x}_{MWPC}, \alpha_{MWPC}, \boldsymbol{x}_{DCH}, \alpha_{DCH})$



Momentum resolution unreacted ^{12}C beam:
d*p*/*p* = 1.6% (σ)



New LH_2 Target

- The target group is developing a new LH2 target with the same parameters (D = 6 cm, length = 30 cm)
- Target will be inside the SP-57 magnet gap to gain acceptance for the arms
- Veto box around target: thin scintillator detectors

Scale separation in high-momentum regime

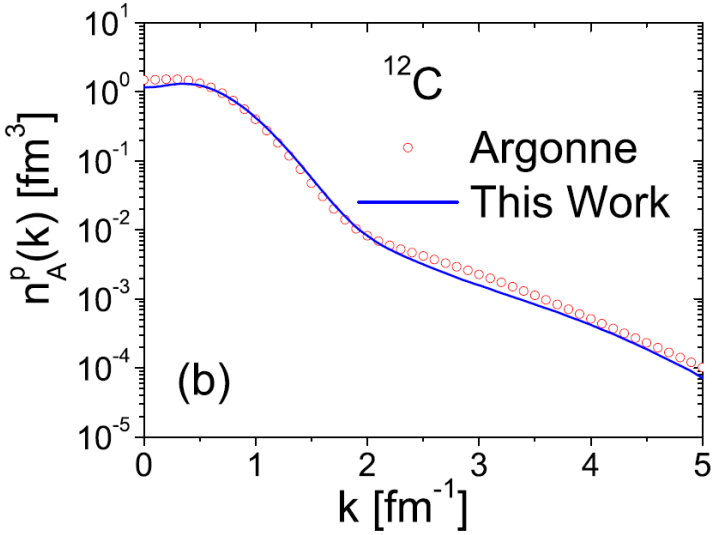
SRC: *universal* high-momentum tail

-> nuclear wave function factorizes into 2-body and *A*-2 systems

$$\Psi \xrightarrow{r_{ij}\to 0} \sum_{\alpha} \varphi_{\alpha}(\boldsymbol{r}_{ij}) A_{ij}^{\alpha}(\boldsymbol{R}_{ij}, \{\boldsymbol{r}\}_{k\neq ij})$$

(universal two-nucleon momentum distributions, *A*-independent)

- found also in *ab-initio* EFTs,
- applied in Generalized Contact Formalism



M. Alvioli, C. Ciofi degli Atti, H. Morita, Phys. Rev. C 94 (2016)

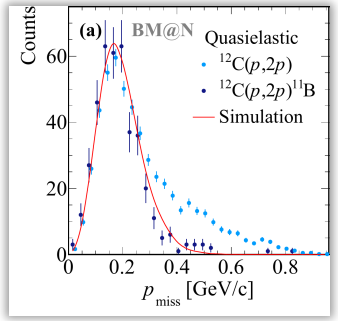
R. Cruz-Torres et al., Nature Physics (2020)
R. Weiss, B. Bazak, N. Barnea, Phys. Rev. C 92 (2015)
J.-W. Chen, W. Detmold, J. E. Lynn, A. Schwenk, PRL 119 (2017)
R. Weiss et al., Phys. Lett. B 780 (2018)

The team

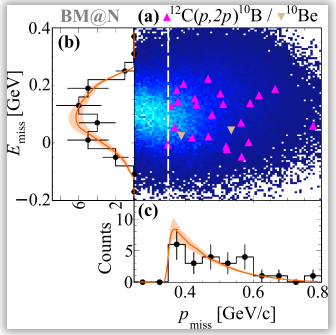
Local team	SRC international team
Timur Atovullaev	Julian Kahlbow
Nikolay Voytishin	Valerii Panin
Vasilisa Lenivenko	Eli Piasetzky
Mikhail Rumyantsev	Or Hen
Sergey Merts	Goran Johansson
Yuri Petukhov	Efrain Segarra
Vladimir Palichik	George Laskaris
Yuri Uzikov	Meytal Duer

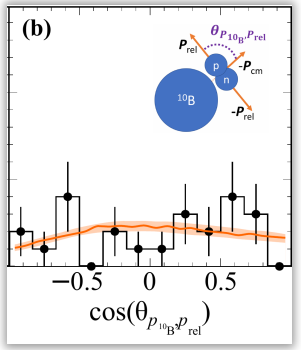
SRC studies in many-body dynamics entering new era

- **“Tranparent“ nucleus:**
  Extract ground-state distributions in strongly interacting many-body system with fragment tagging (suppress ISI/FSI)

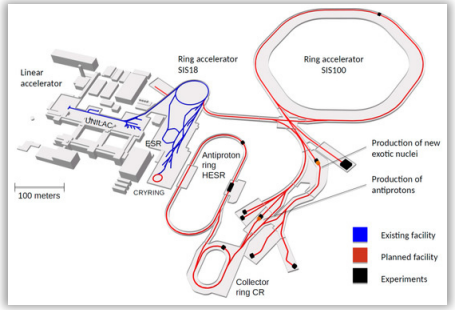


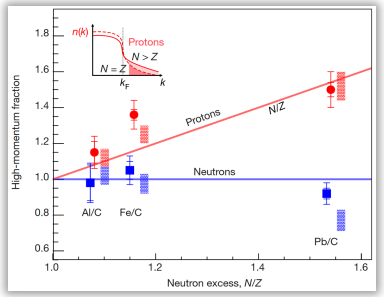
- **1st SRC experiment in inverse kinematics: evidence for scale separation**



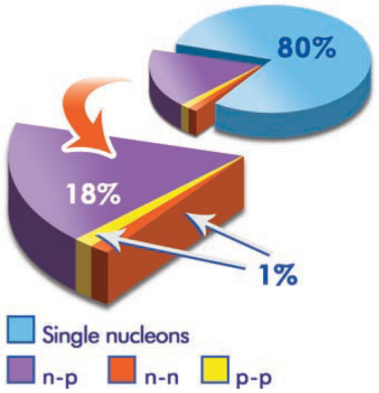


- **Merge Radioactive Beam and SRC physics:**
  Cold dense asymmetric nuclear matter



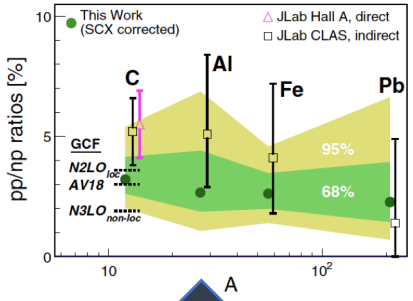


SRCs across the scales



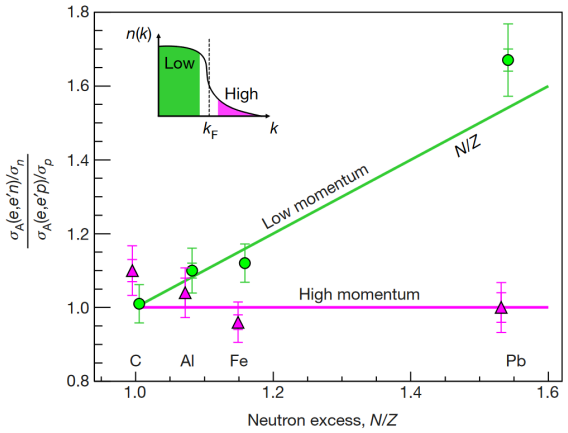
R. Subedi et al., **Science** 320 (2008)

pp/pn CONSTANT

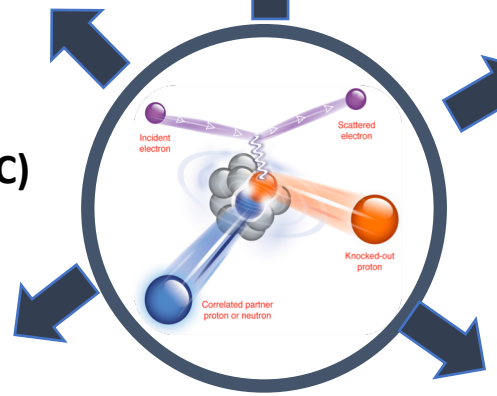


M. Duer et al., **PRL** 122 (2019)

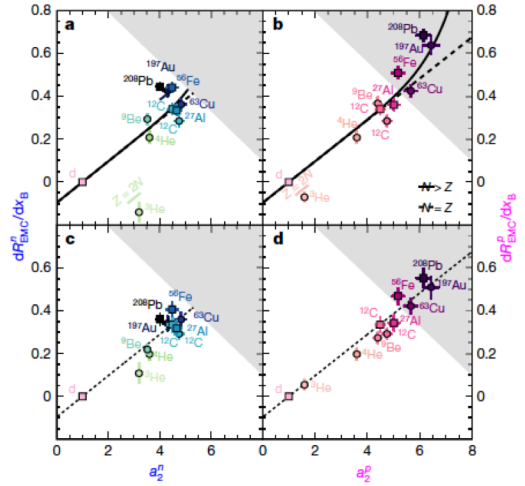
#SRC-protons = #SRC-neutrons



M. Duer et al., **Nature** 560 (2018)

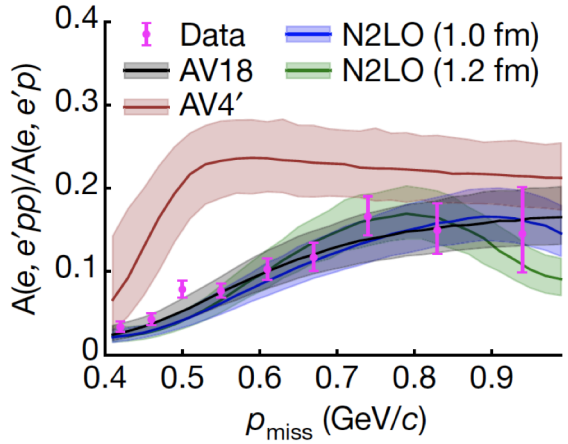


NUCLEON MODIFICATION (~EMC)



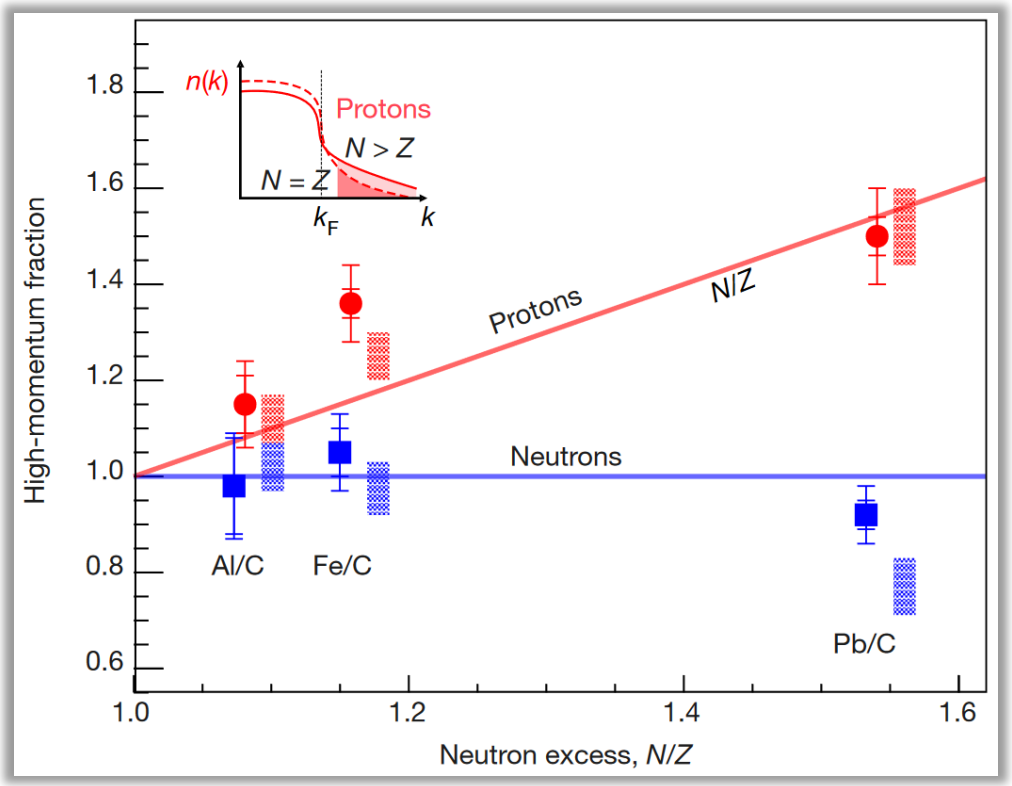
B. Schmookler et al., **Nature** 566 (2019)

SENSITIVE TO *NN* INTERACTION



A. Schmidt et al., **Nature** 578 (2020)

What do excess neutrons do?



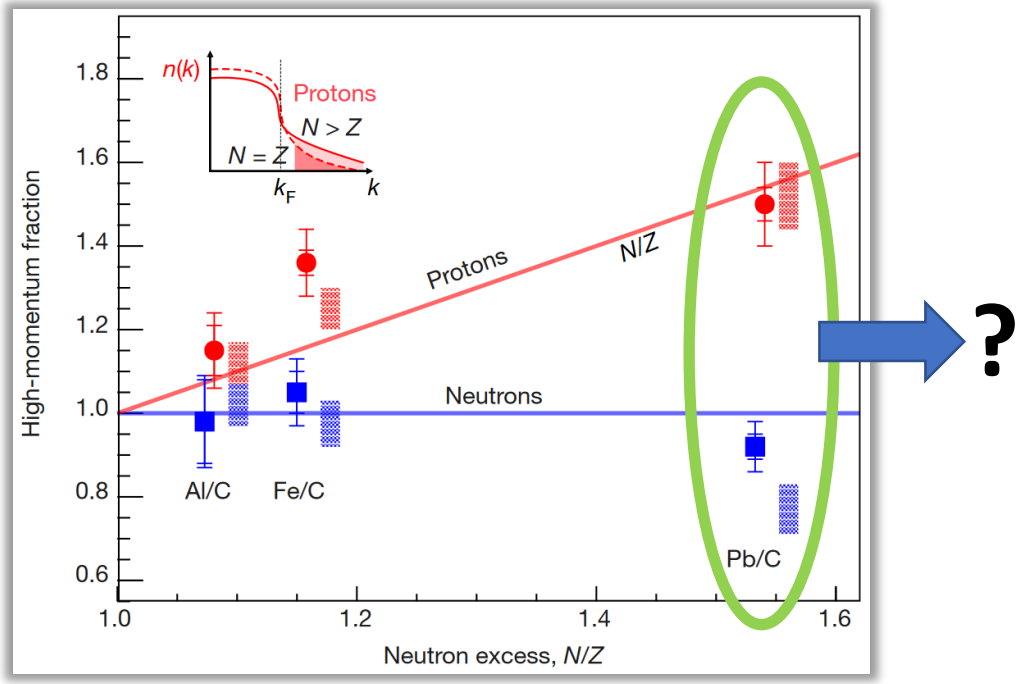
Fraction of correlated protons / neutrons grow / saturate with neutron excess

-> protons "speed up"

M. Duer (CLAS Collaboration), **Nature** 560 (2018)

What do excess neutrons do?

Heavy-to-light ratio:
Impact of nuclear effects?



?

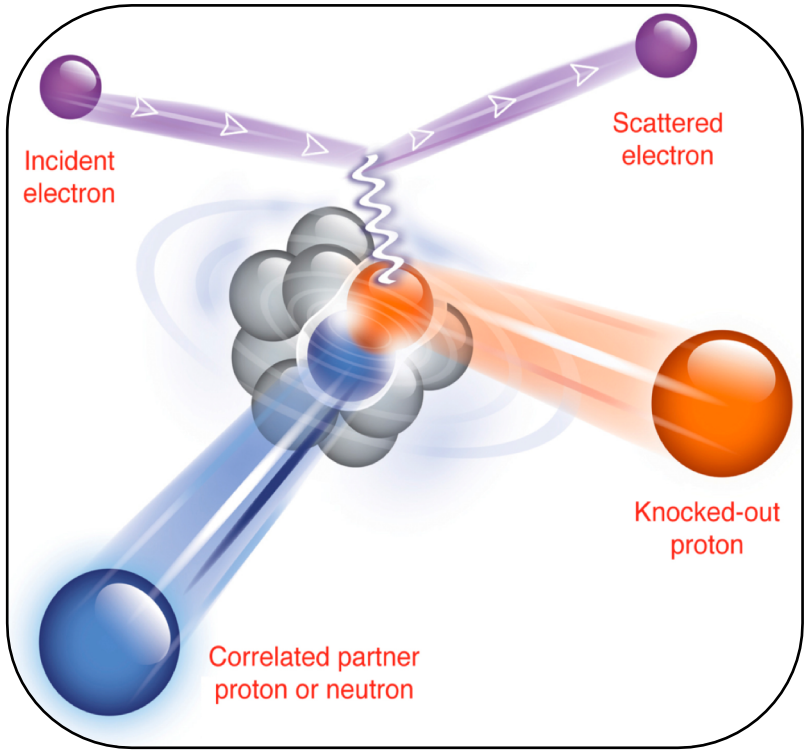
Limitations (e^- scattering)

- Stable targets
- N/Z < ~1.5
- N/Z grows with mass

M. Duer (CLAS Collaboration), **Nature** 560 (2018)

Probing SRCs in normal kinematics

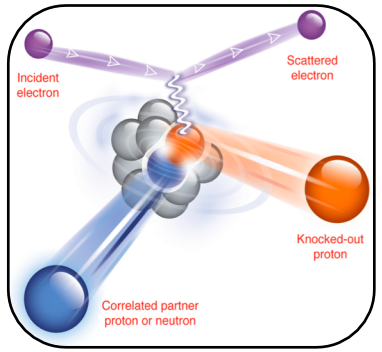
“Normal“ kinematics



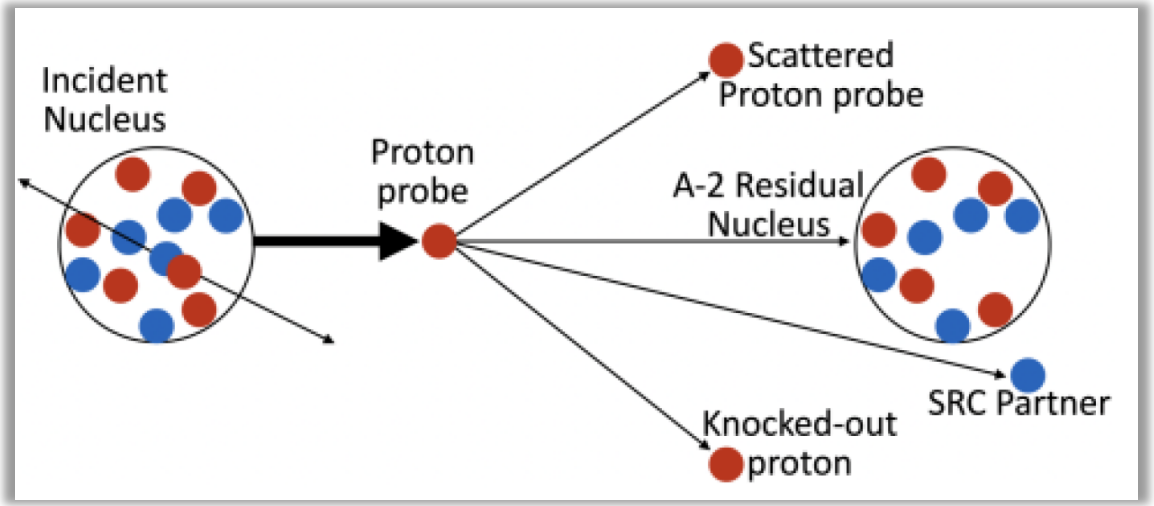
High-energy electromagnetic probe

Probing SRCs in inverse kinematics

Normal kinematics



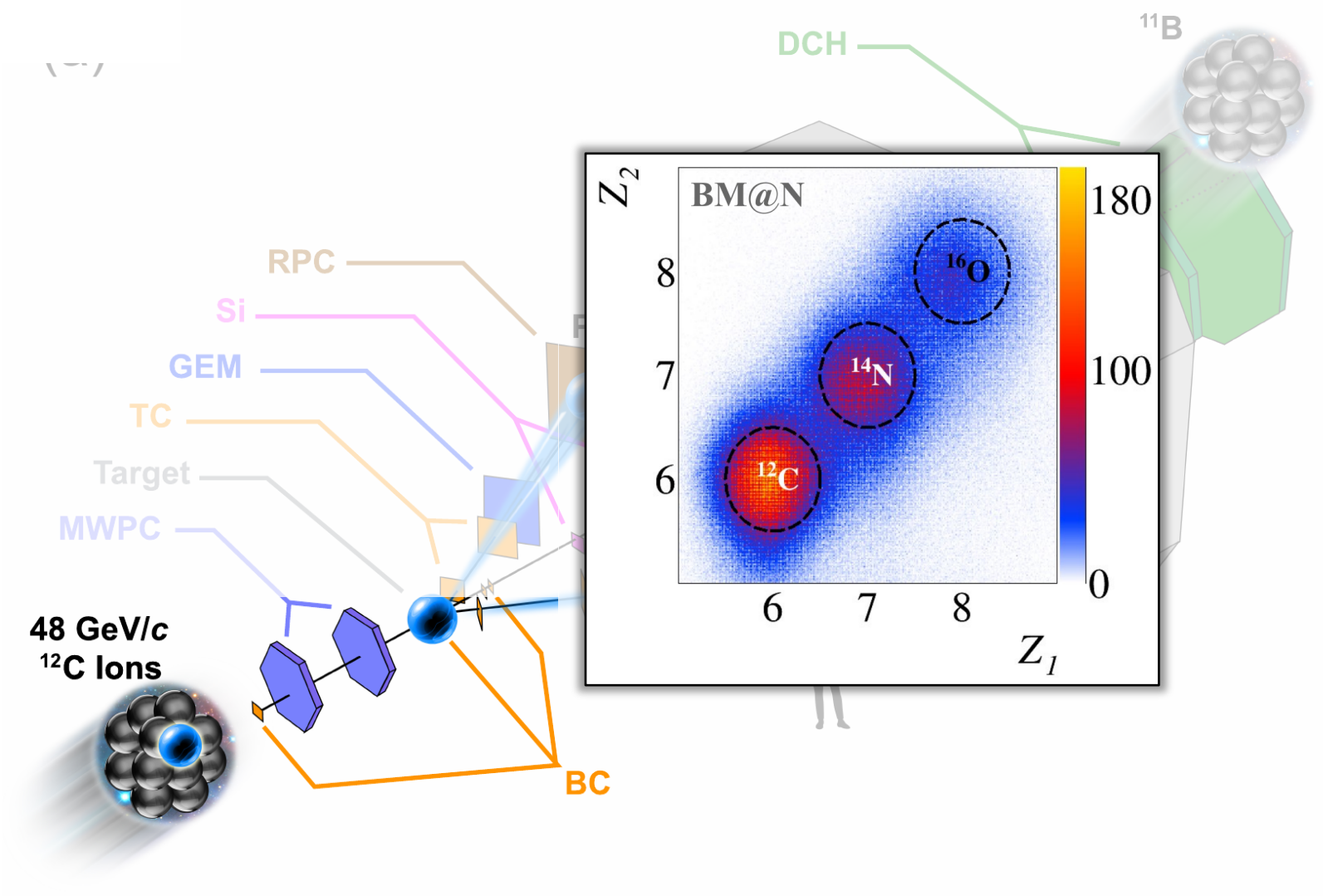
Reaction: *A* (*p*,2*pN*) *A*-2



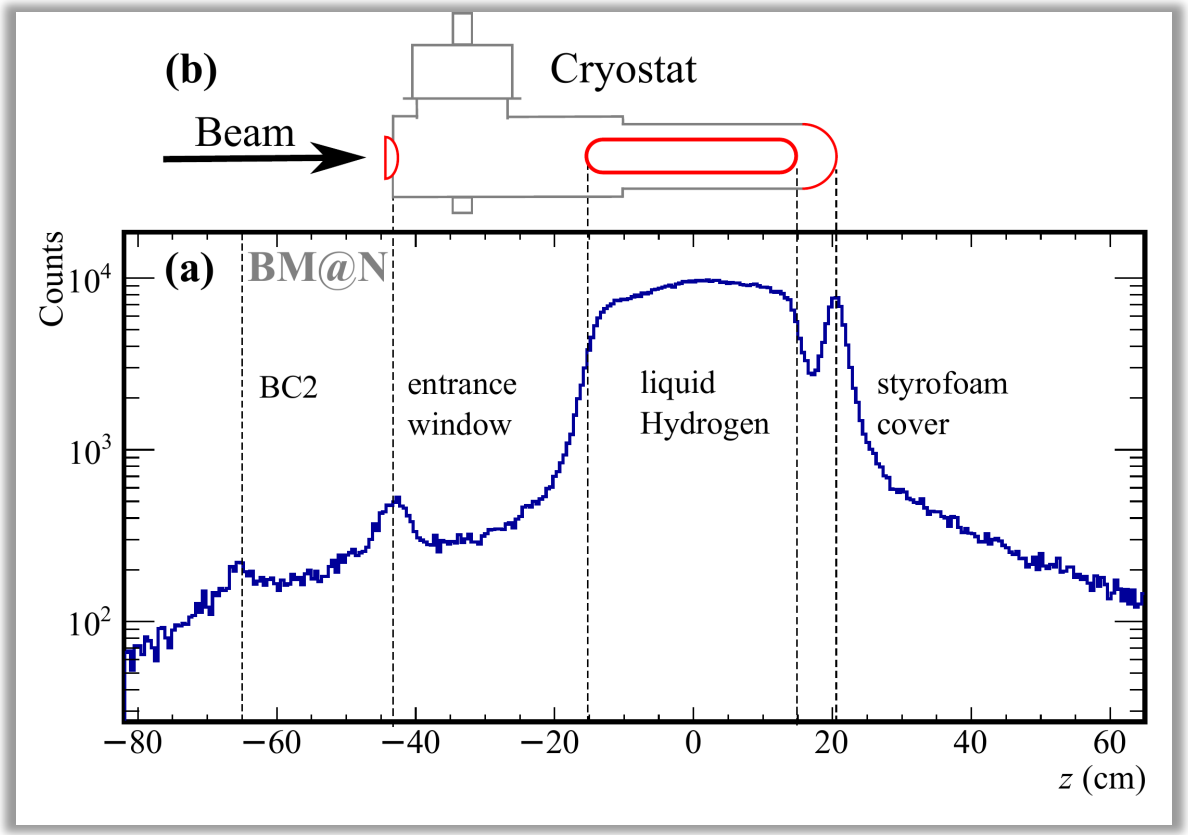
<u>Inverse kinematics</u>

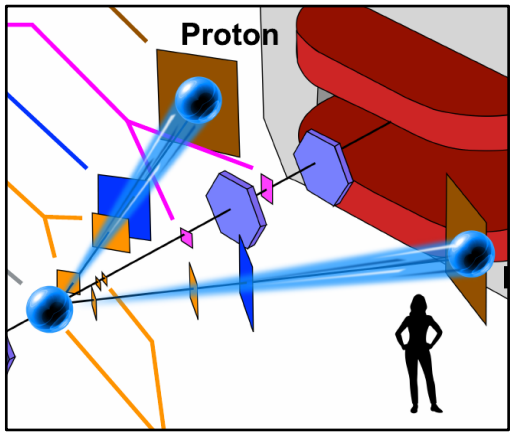
- ✓ p_{miss}, p_{recoil}
- ✓ fragment ID + p_{A-2}
- ✓ direct p_{CM}
- ✓ exotic nuclei

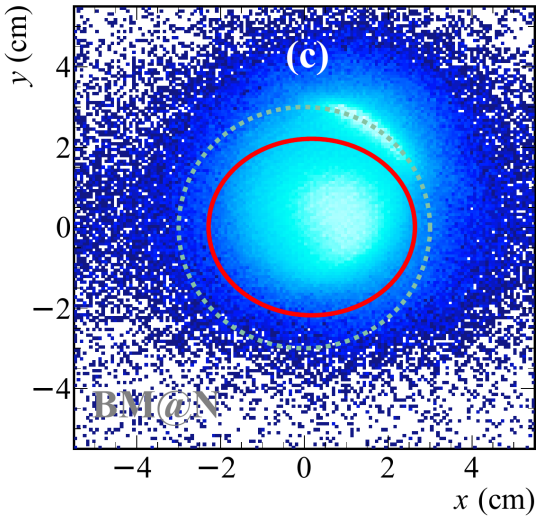
Incoming-beam identification



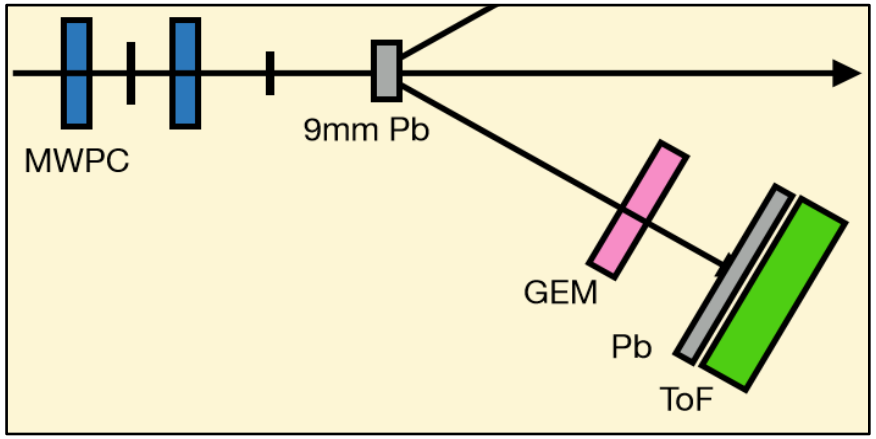
Proton vertex



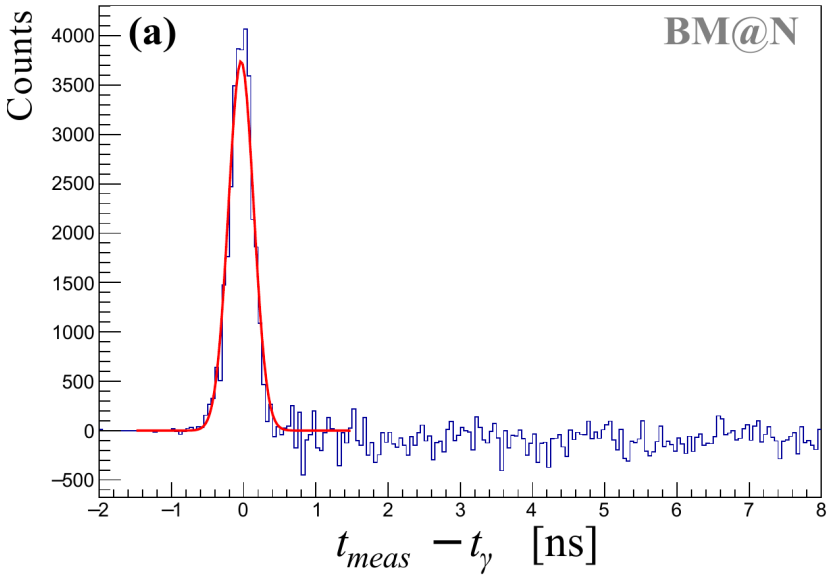


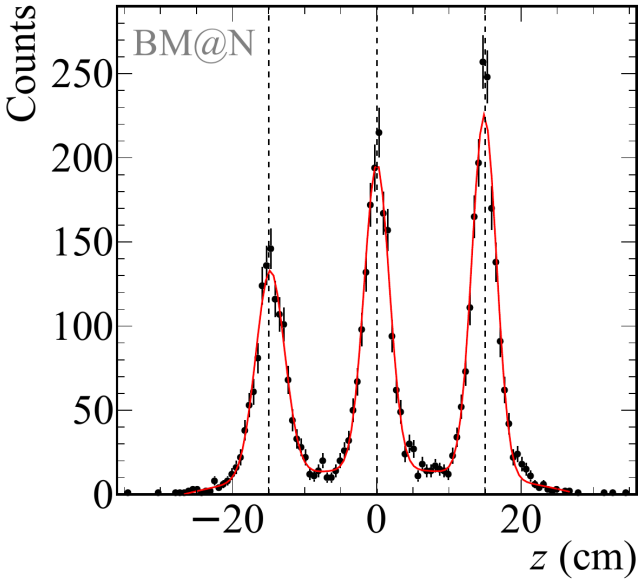


Two-Arm Spectrometer

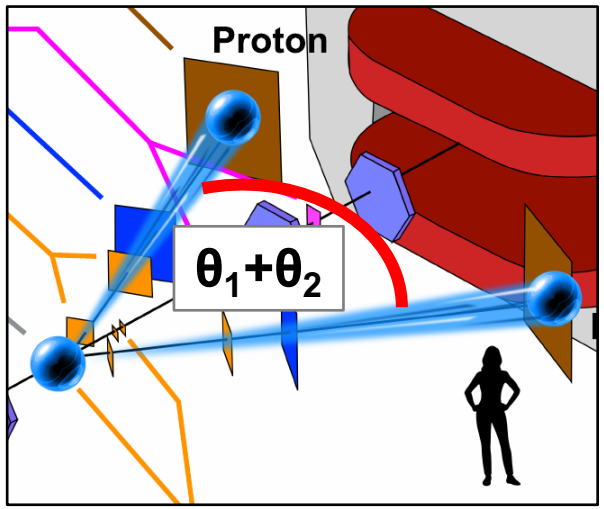


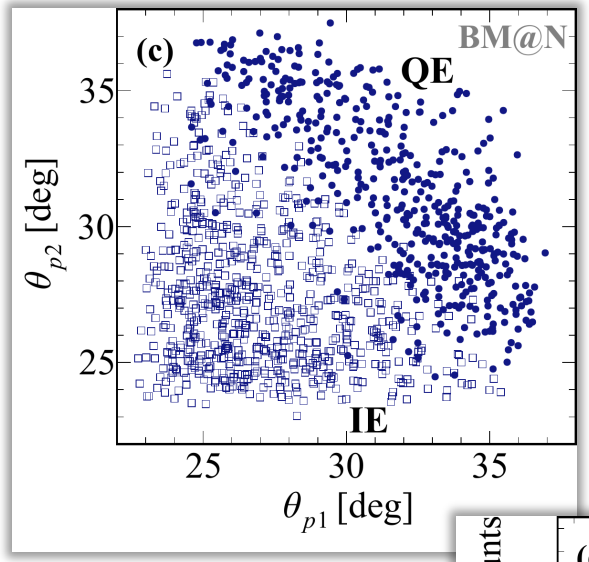
Position and Time calibration with single+multi foil Pb target



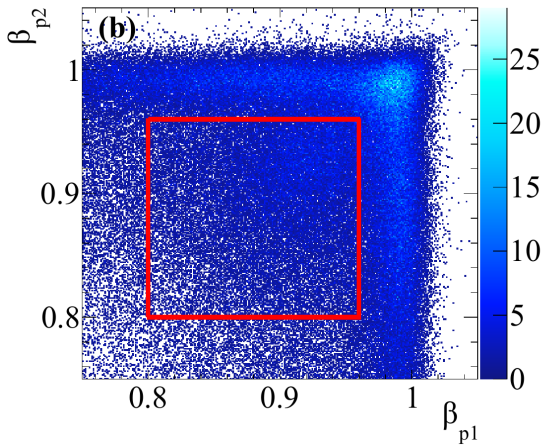


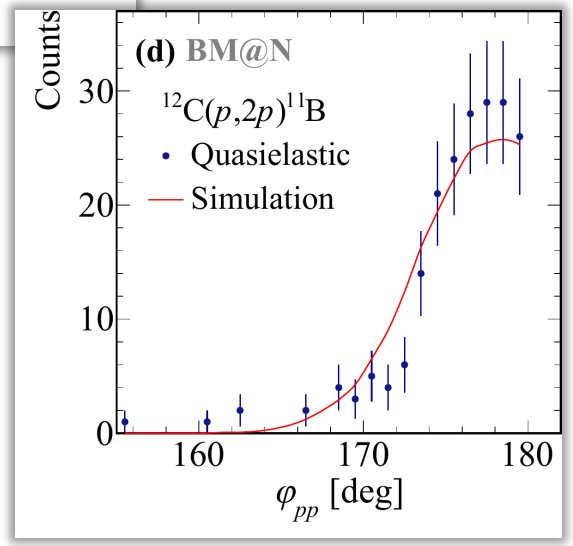
QFS angular correlations





Pion rejection

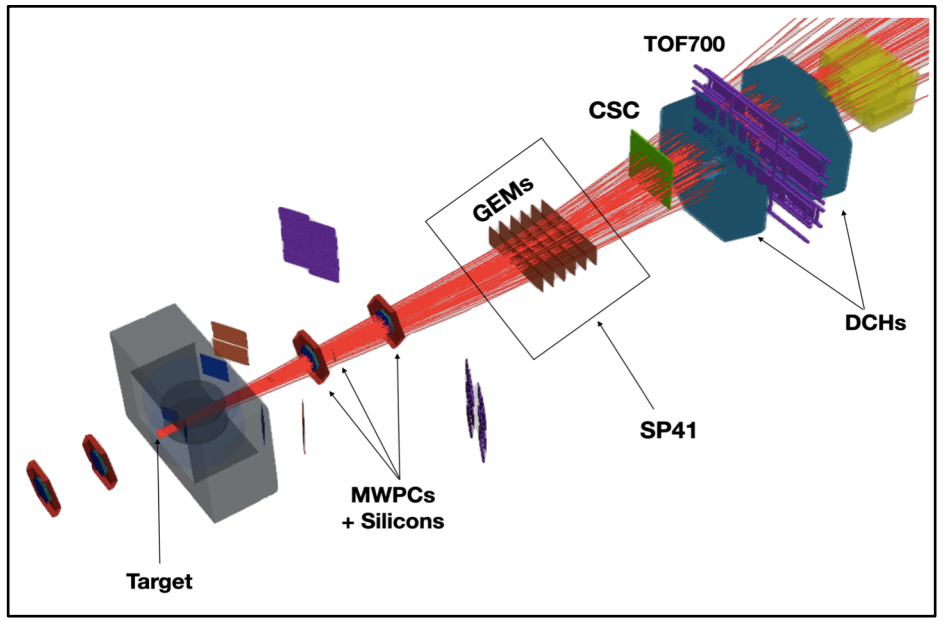




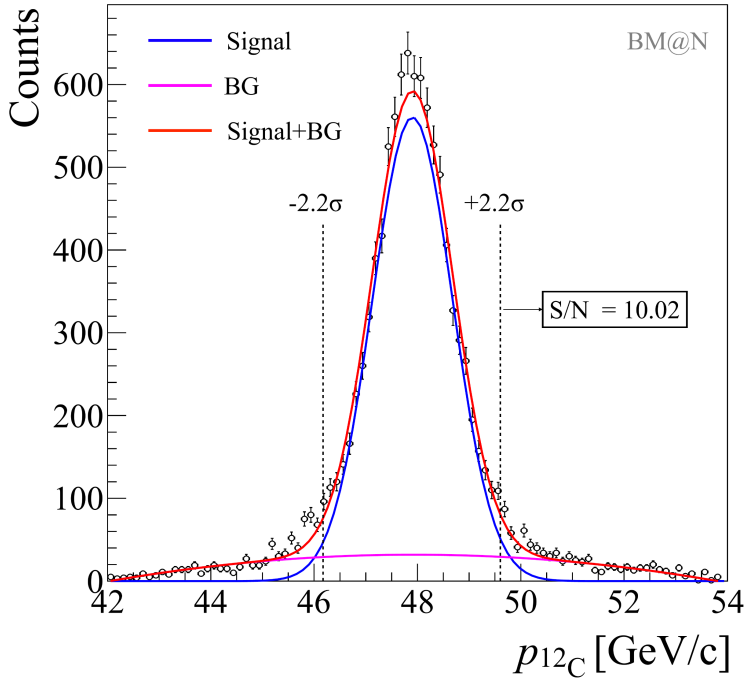
Fragment momentum

Simulation-based multi-dimensional fit

$P/Z = f(\boldsymbol{x}_{MWPC}, \alpha_{MWPC}, \boldsymbol{x}_{DCH}, \alpha_{DCH})$

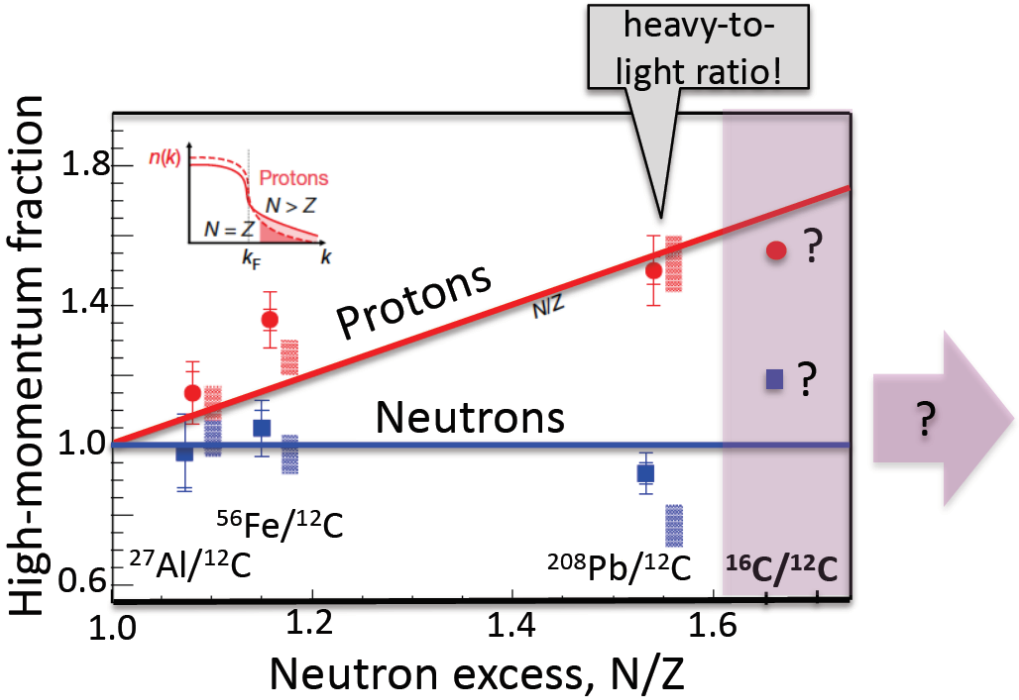


Momentum resolution unreacted ^{12}C beam:
dp/p = 1.6% (σ)

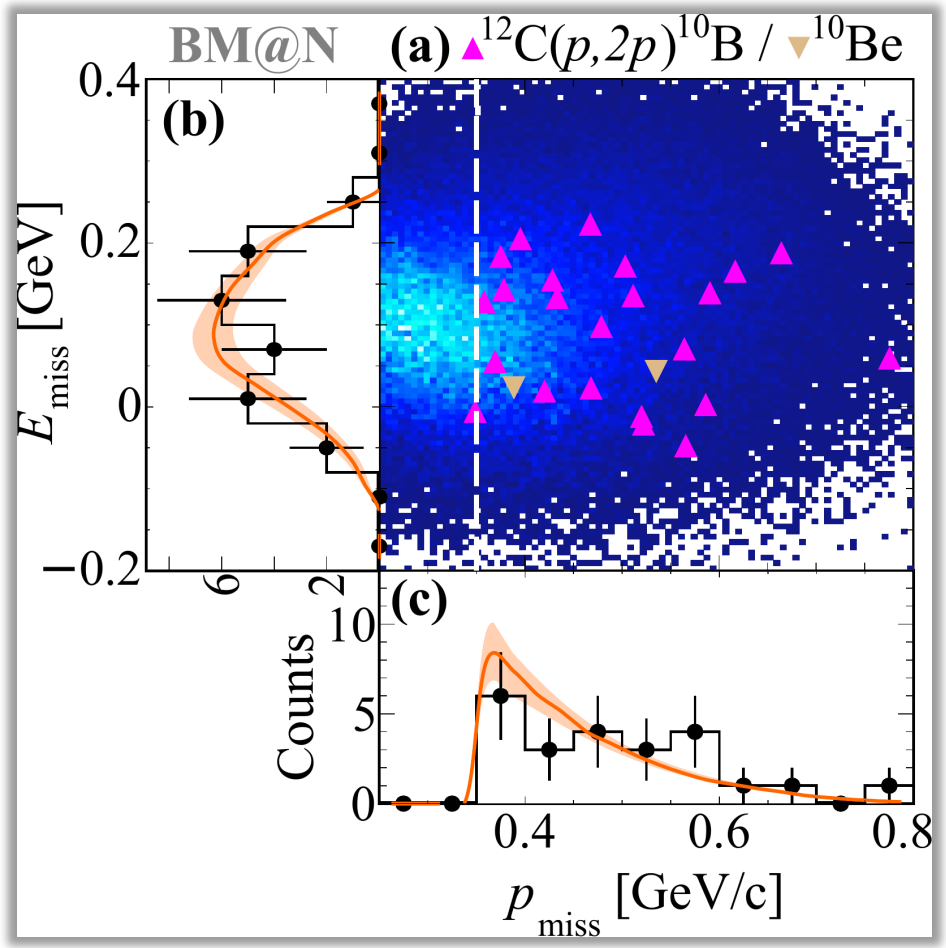


Outlook

SRC pairing in asymmetric systems



Identifying SRCs



+ proton-proton opening angle

23 np pairs
2 pp pair

-> *np* dominance

1. **^{11}B + FSI nucleon knockout?**
   Result in #^{10}B ~ ^{10}Be due to similar *np* / *pp* cross section.
2. **QE mean-field with excited ^{11}B?**
   Estimated maximal contribution of 3 (^{10}B) and 1 (^{10}Be) events.

Scale separation in high-momentum regime

$$n^{A}_{\alpha,NN}(Q,q) = \tilde{C}^{A}_{\alpha,NN}(Q) \times |\tilde{\varphi}^{\alpha}_{NN}(q)|^2$$

universal

small c.m. motion ~ A-2

strongly correlated pair [universal 2-body]

t distance]

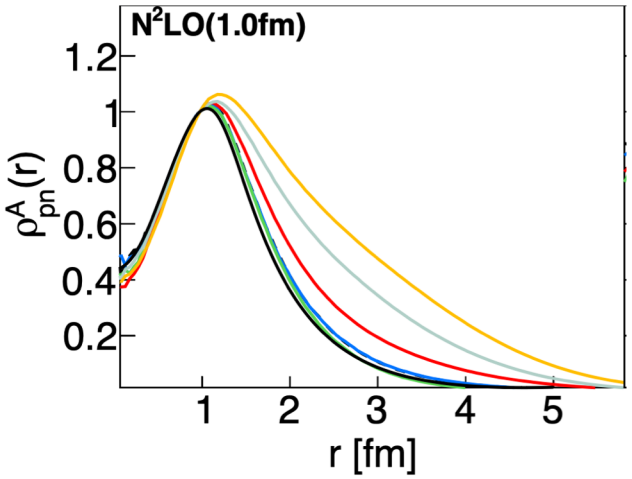
rmalism

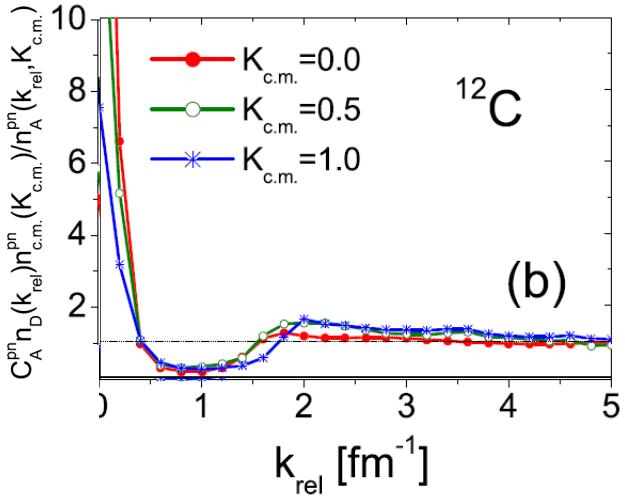
Factorization of a SRC distribution function:

$$f(p_{rel}, p_{c.m.}, \theta_{rel,c.m.}) \approx C(p_{c.m.}) \times \varphi(p_{rel})$$

Experimental evidence:
distributions are independent of $\theta_{rel,c.m.}$.

R. Cruz-Torres, D. Lonardoni et al., Nature Physics (2020)

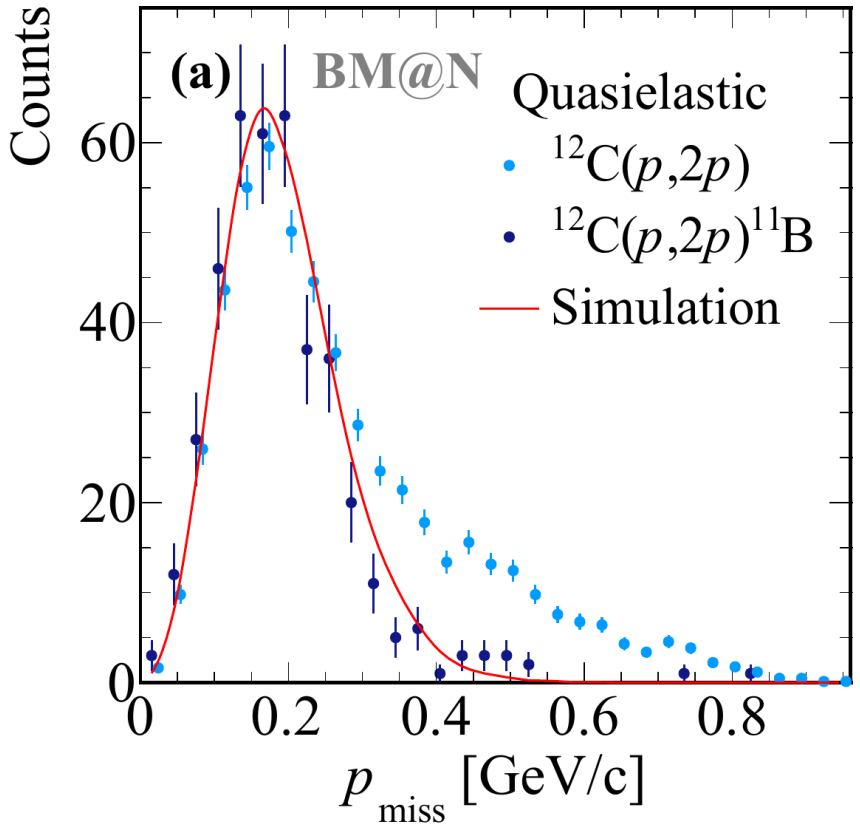




M. Alvioli, C. Ciofi degli Atti, H. Morita, Phys. Rev. C 94 (2016)

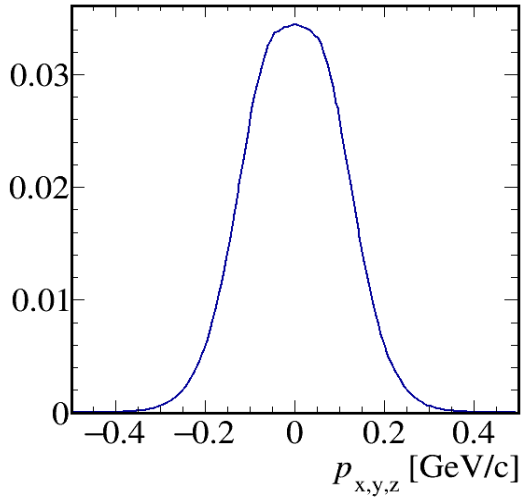
Reconstructed initial momentum

Fragment tagging suppresses ISI / FSI



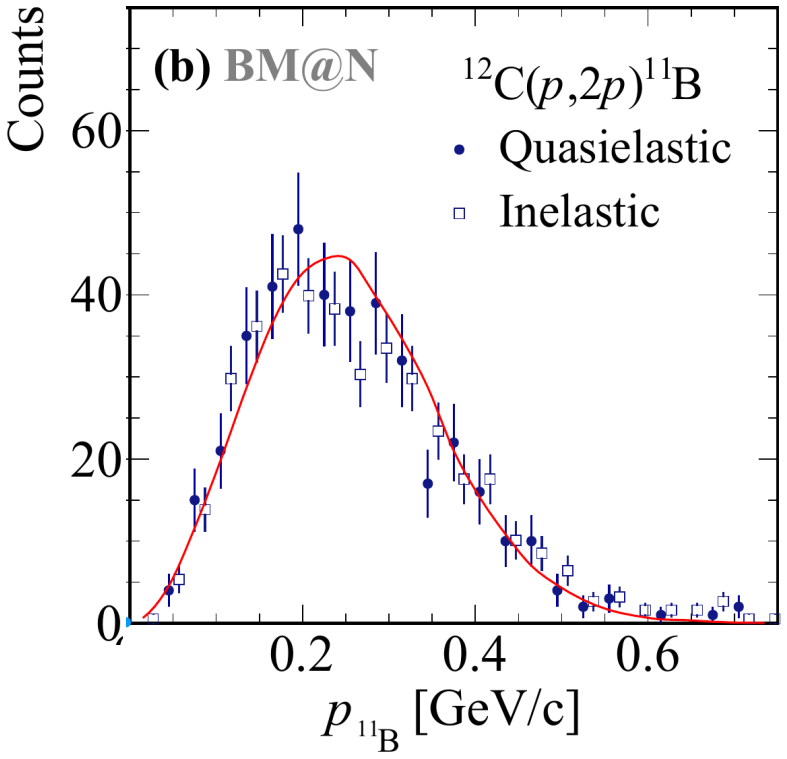
Simulation input:

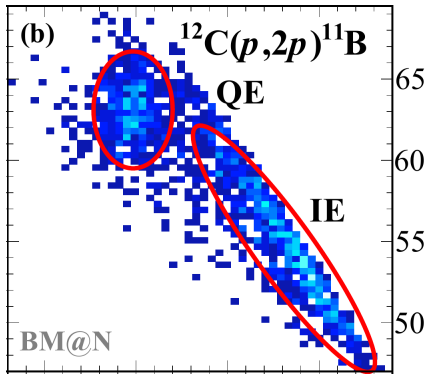
^{12}C $p_{3/2}$ shell distribution w/o FSI



Fragment recoil momentum

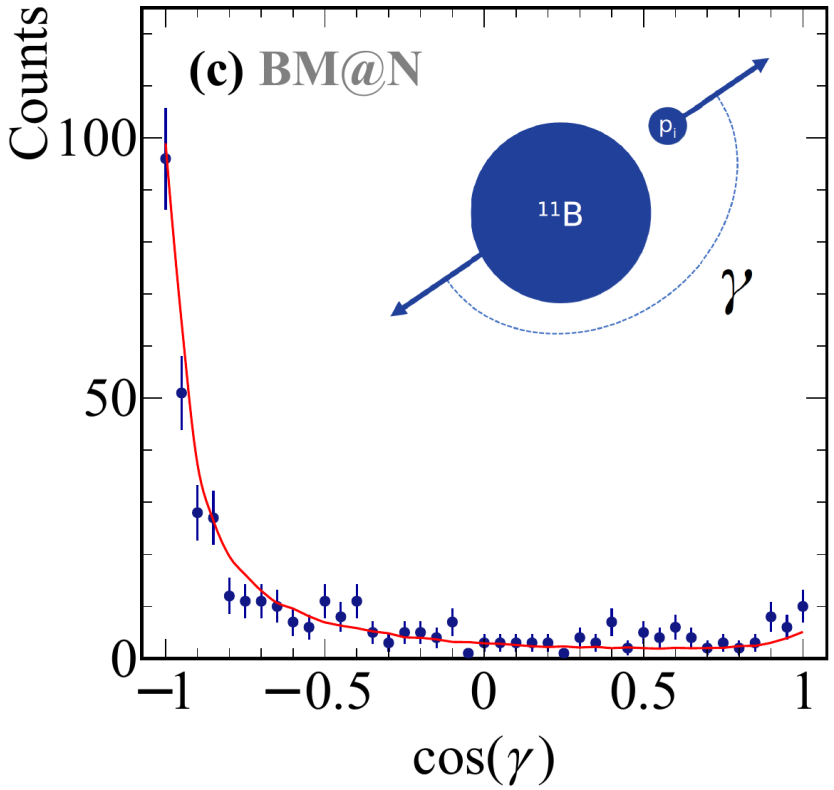
- **Fragment not impacted by ISI / FSI: reconstruct p_{miss}**
- **Adiabatic approximation holds $p_{miss} = -p_{A-1}$**



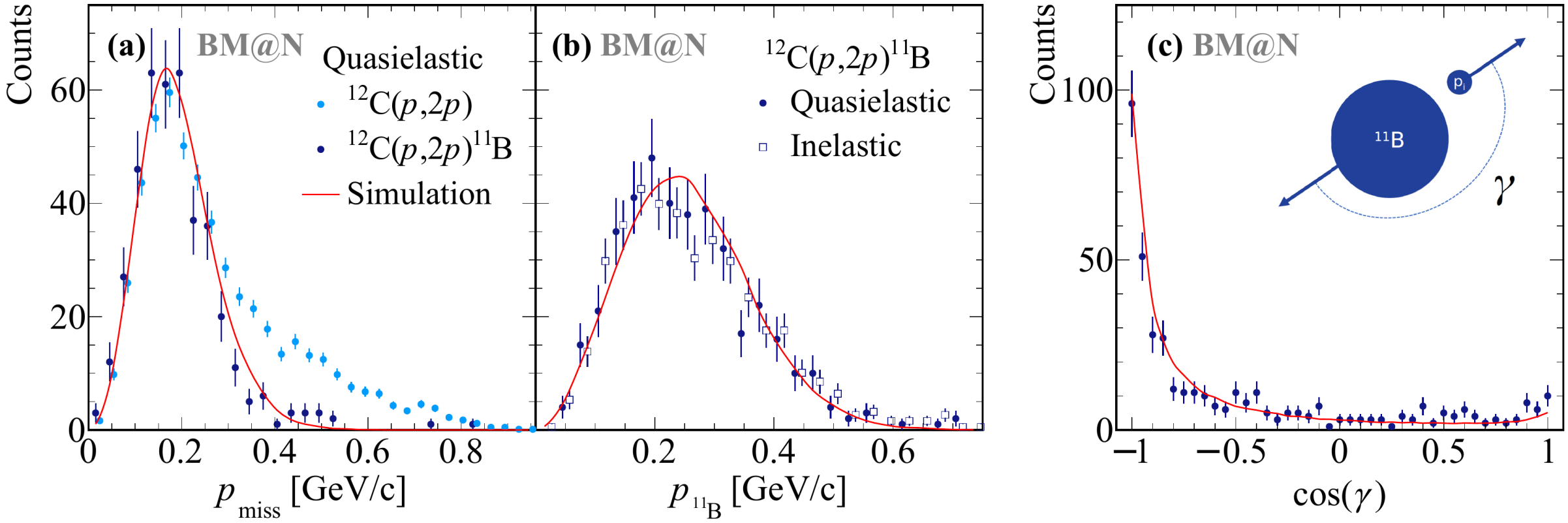


P_{miss} balances the recoil fragment momentum

Another indication that the reaction is quasi-elastic



Access to ground-state properties of 12C

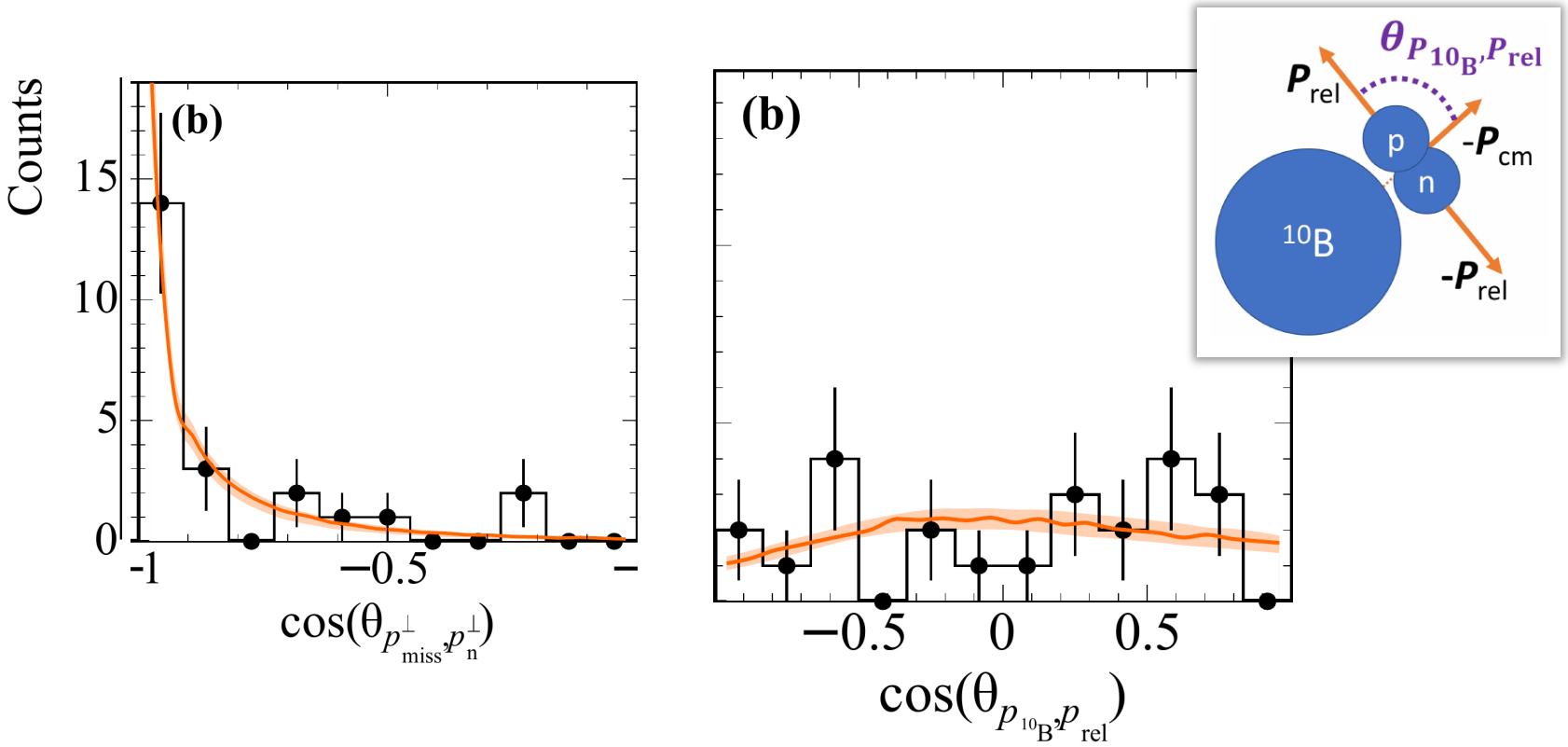


Single-step nucleon knockout

Transparent part of the reaction

Strong vs. weak interaction

Scale separation:
Evidence for factorization between pair and *A-2* !

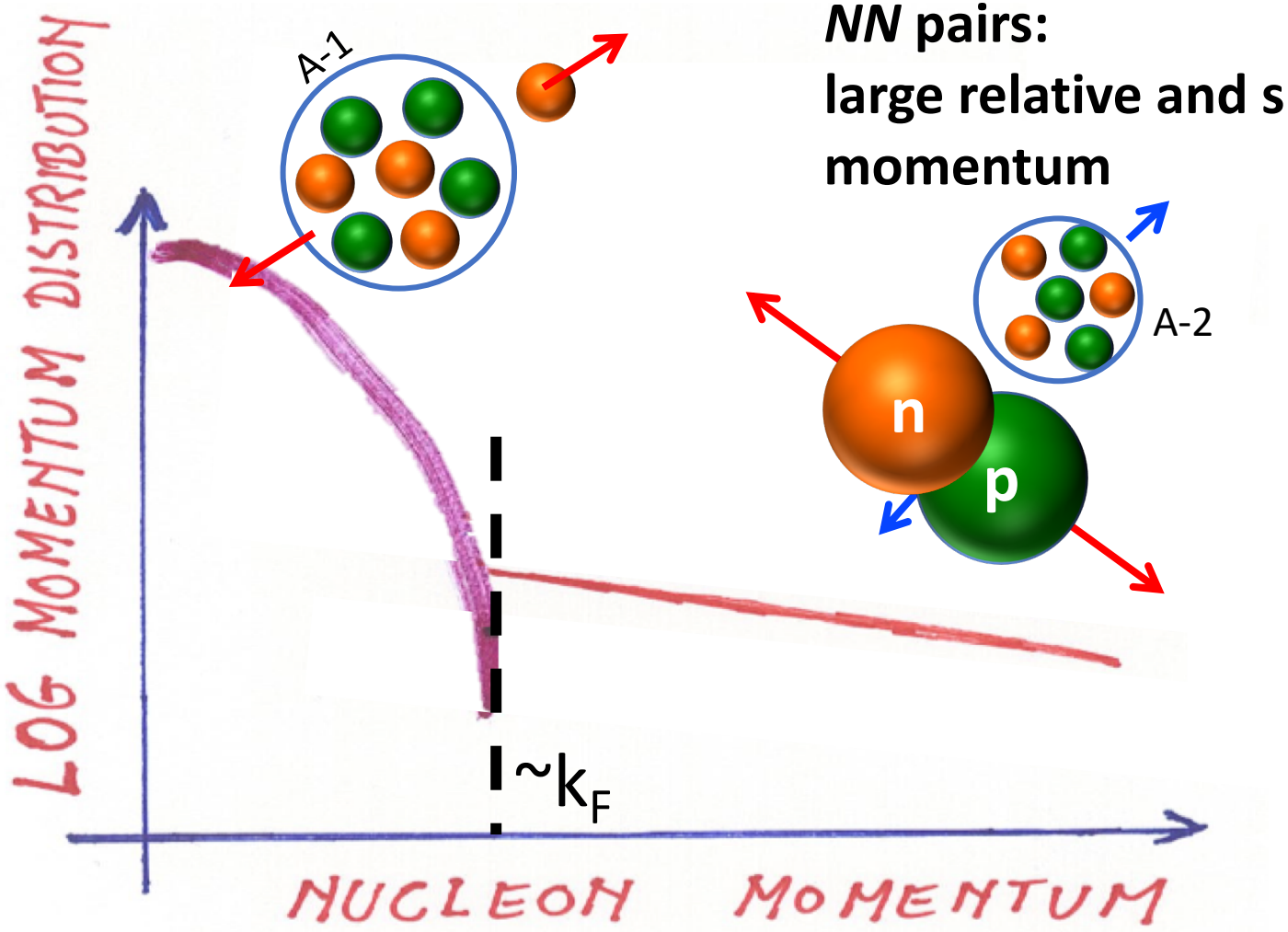


Short Range Correlations (SRCs)

“Mean-field“

SRC

***NN* pairs:**
large relative and small c.m. momentum



R. Subedi et al.
“Probing Cold Dense Nuclear Matter”
Science 320, 1426 (2008).