Grant 18-02-40046

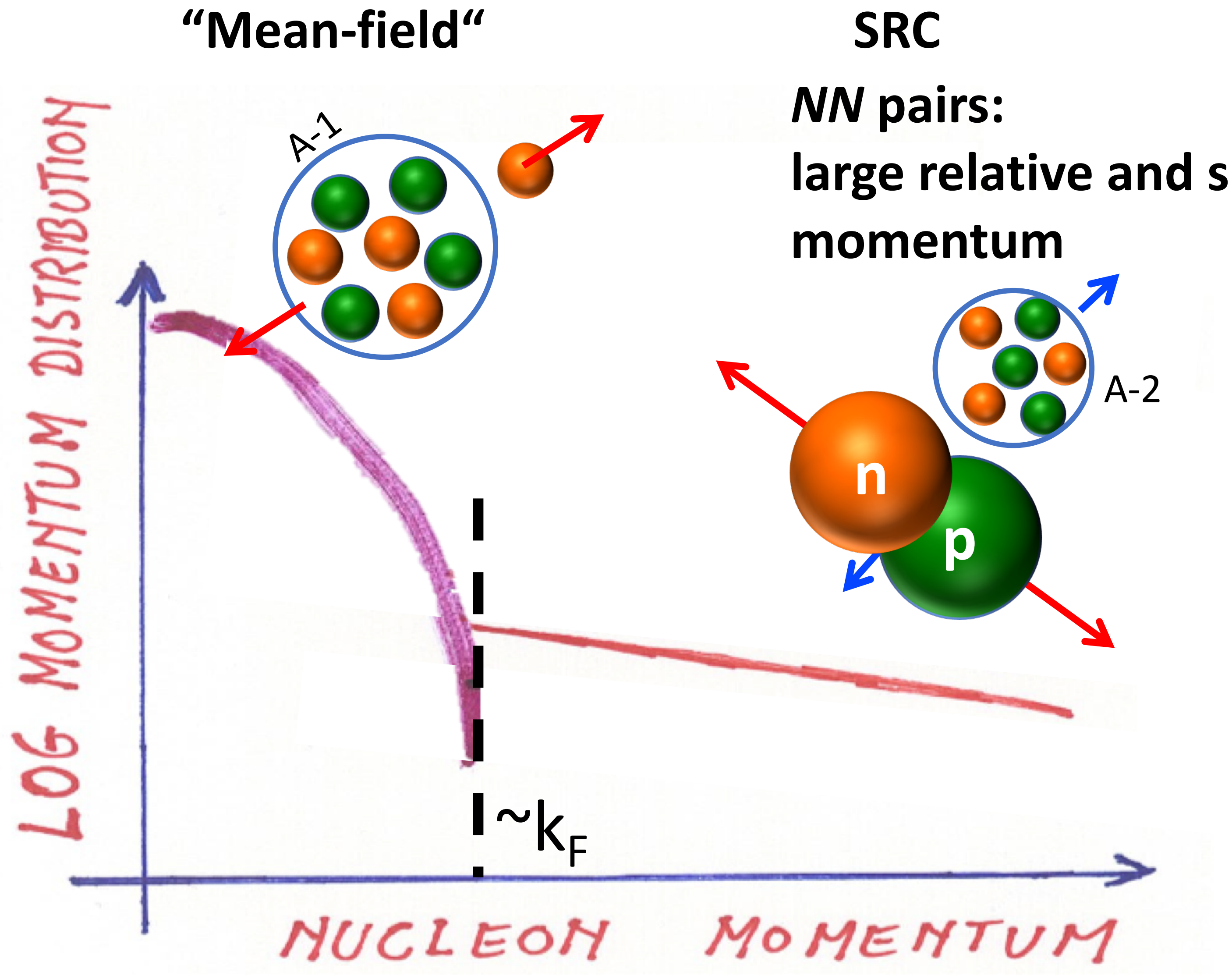
BM@N data analysis aimed at studying SRC pairs:

one-step single nucleon knockout measurement in inverse kinematics with a 48 GeV/c ^{12}C beam

Maria Patsyuk

RFBR Grant Review
October 2020

Short Range Correlations (SRCs)



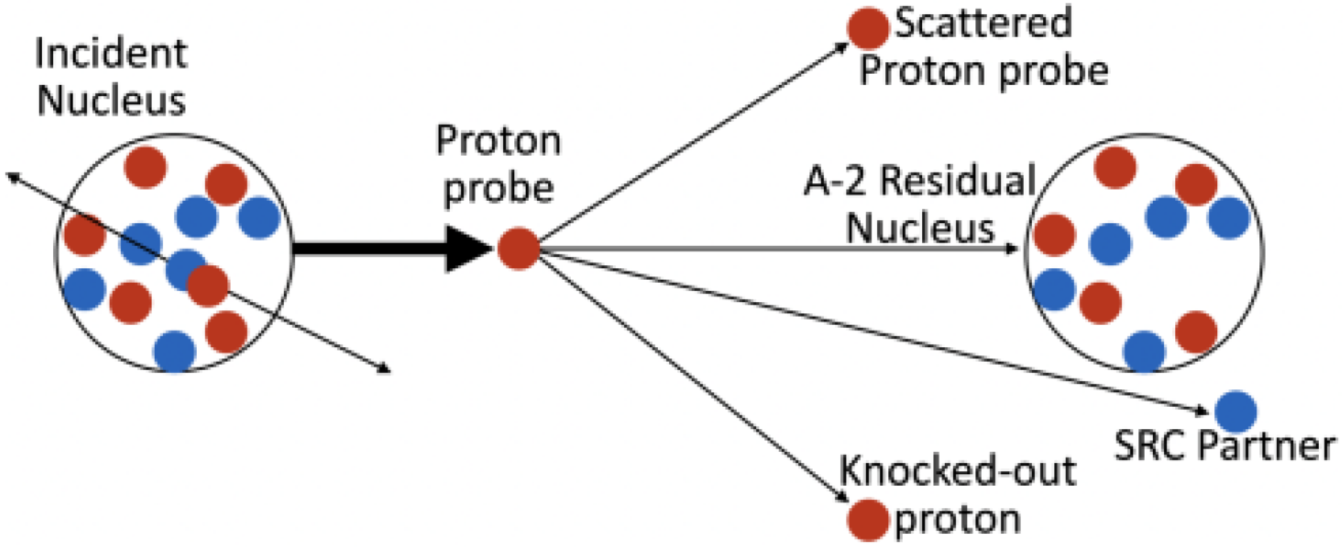
***NN* pairs:**
large relative and small c.m. momentum

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

Quasi-free (p,2p) scattering at BM@N

Inverse kinematics with a detection of A-2 system:

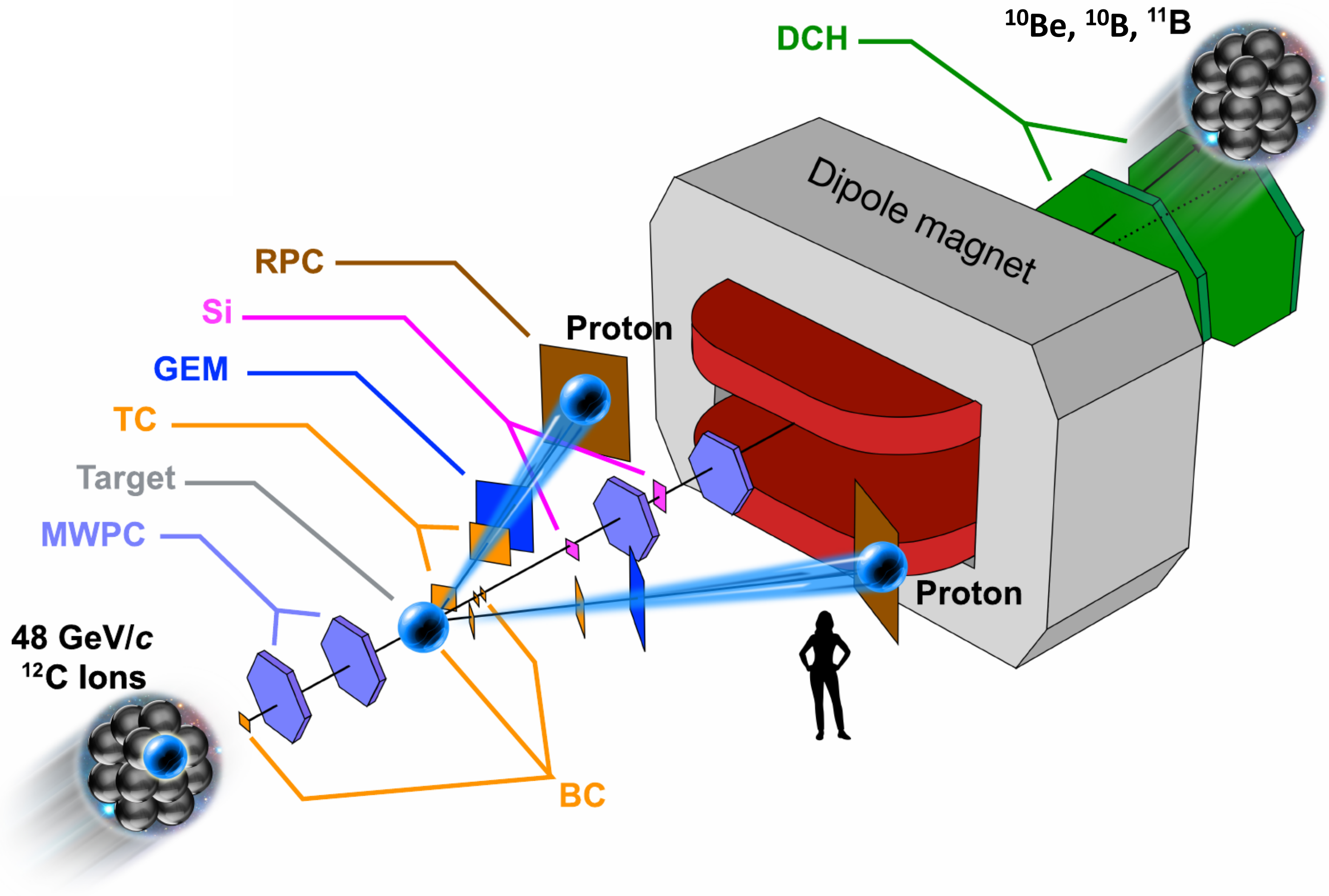
- High cross section compared to e-scattering
- Suppressing ISI/FSI using fragment tagging **and accessing the ground state distribution of nucleons in ^{12}C**
- Access to neutron-rich/exotic unstable nuclei (impossible with a fixed target)



Pilot experiment at BM@N in 2018

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

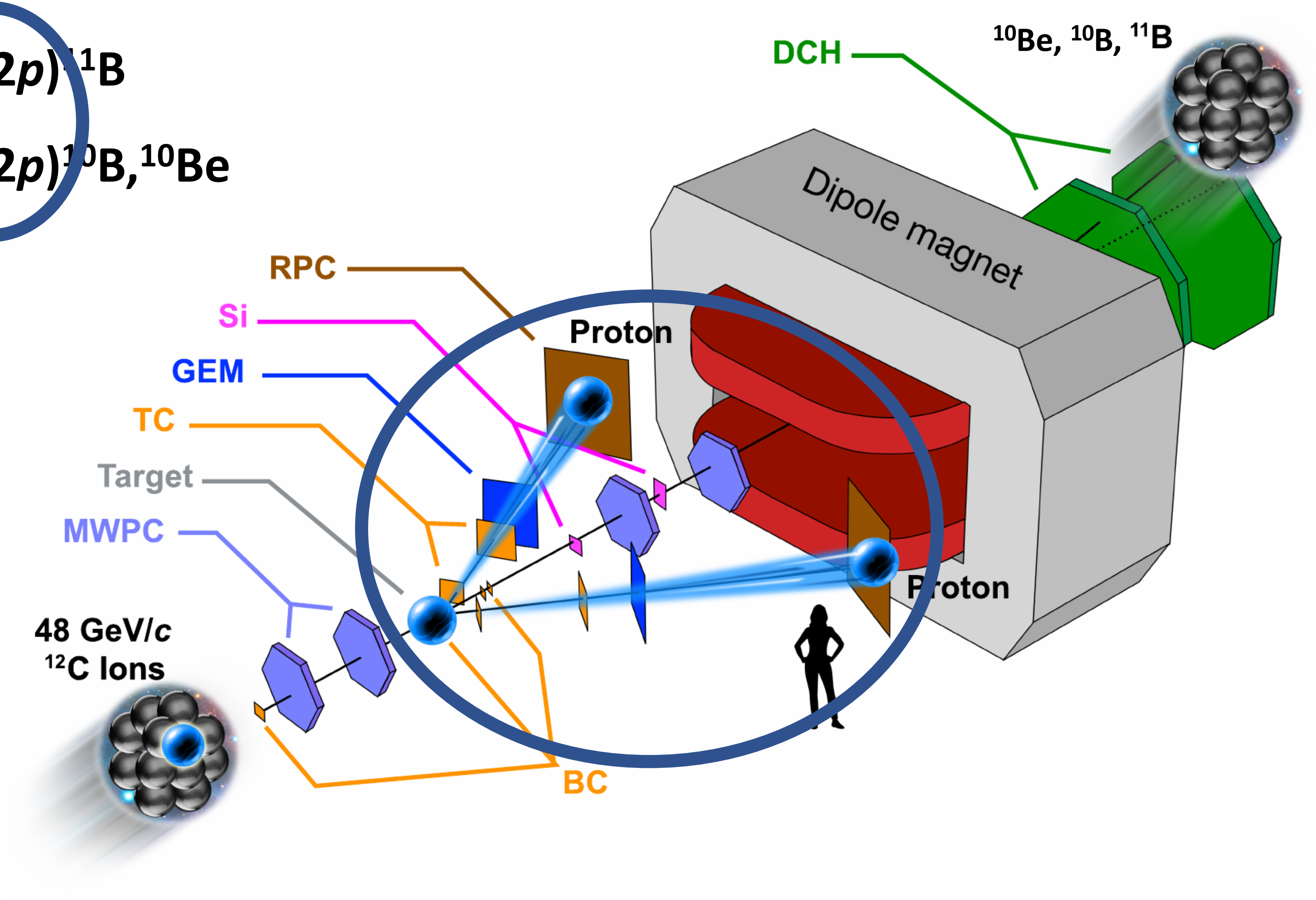
SRC: $^{12}C(p,2p)^{10}B,^{10}Be$



Quasi-free (p,2p) scattering

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

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



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

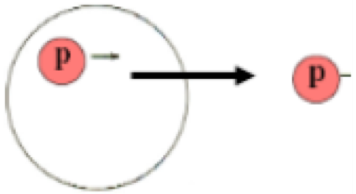
Remove a single nucleon:

~90° c.m. scattering

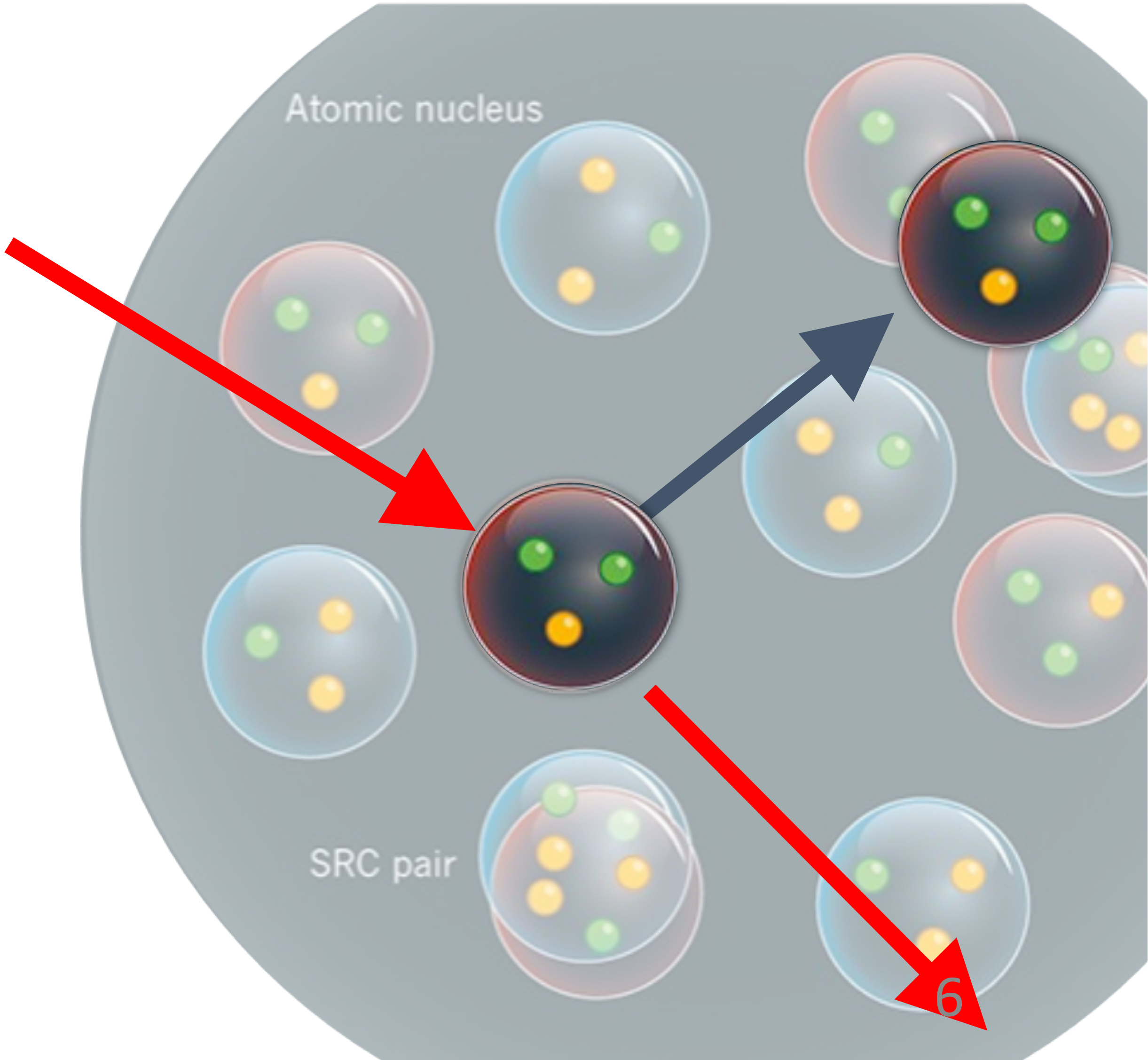
→ Reconstruct initial nucleon momentum p_{miss} from scattered particles

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

Selection of high momentum:

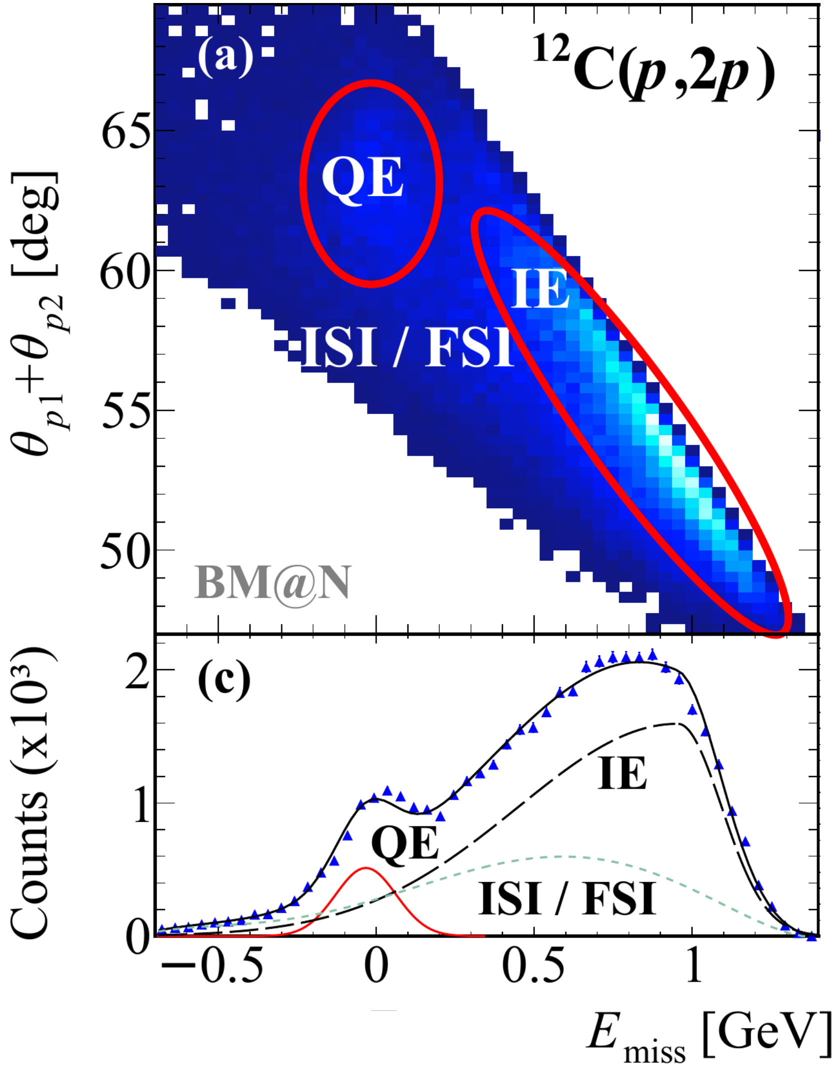


$$\frac{d\sigma}{dt} \propto s^{-8}$$ (at our energies)



Single proton knockout

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

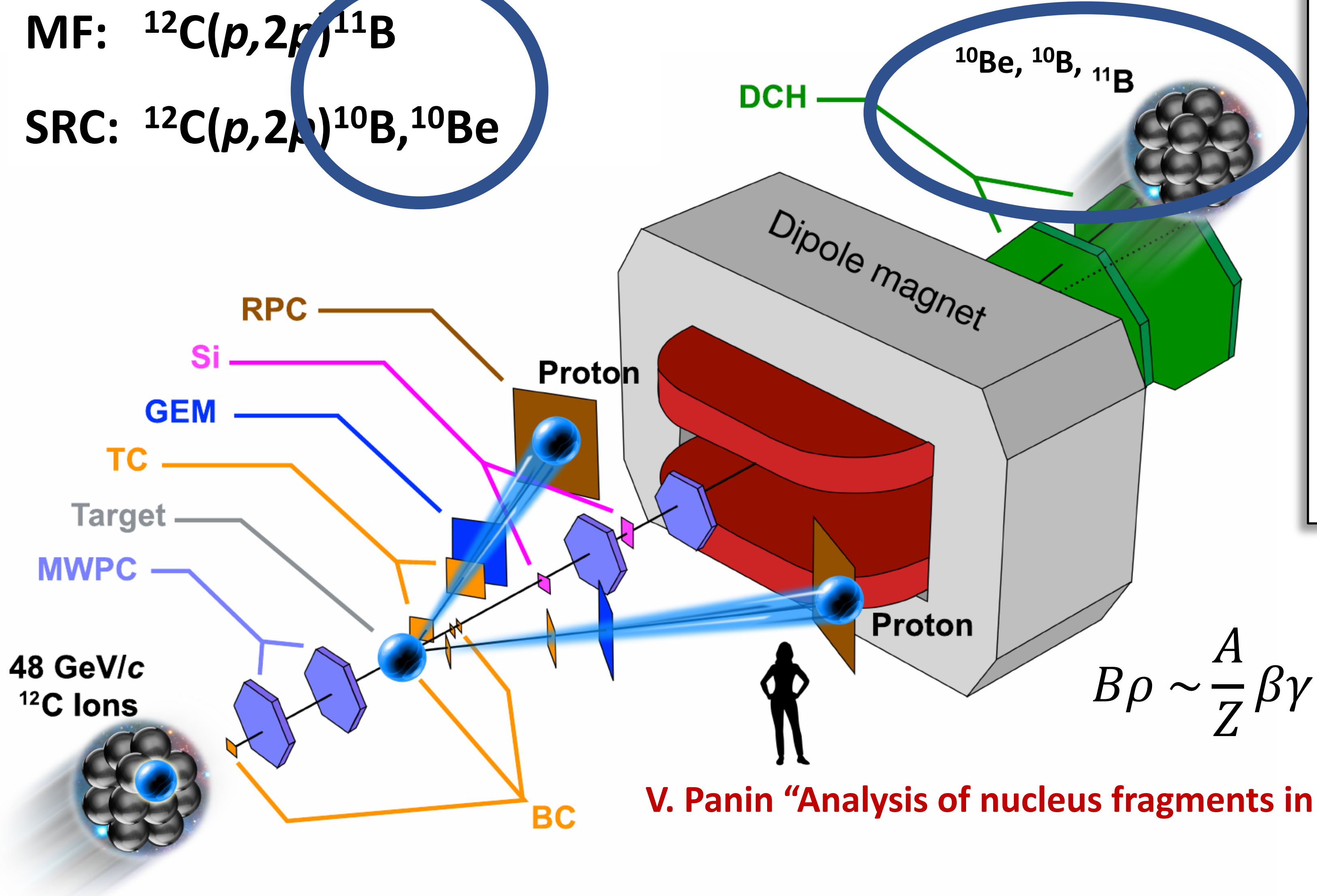


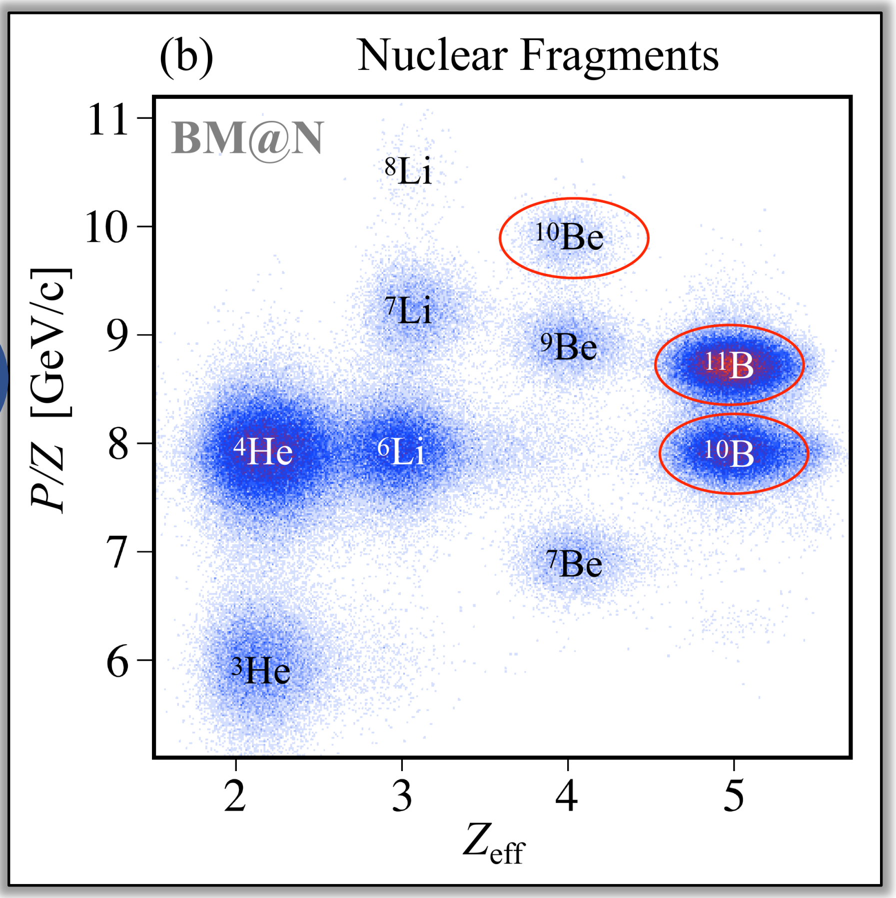
contaminated by inelastic scattering (IE) and ISI / FSI

Heavy-fragment identification

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

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

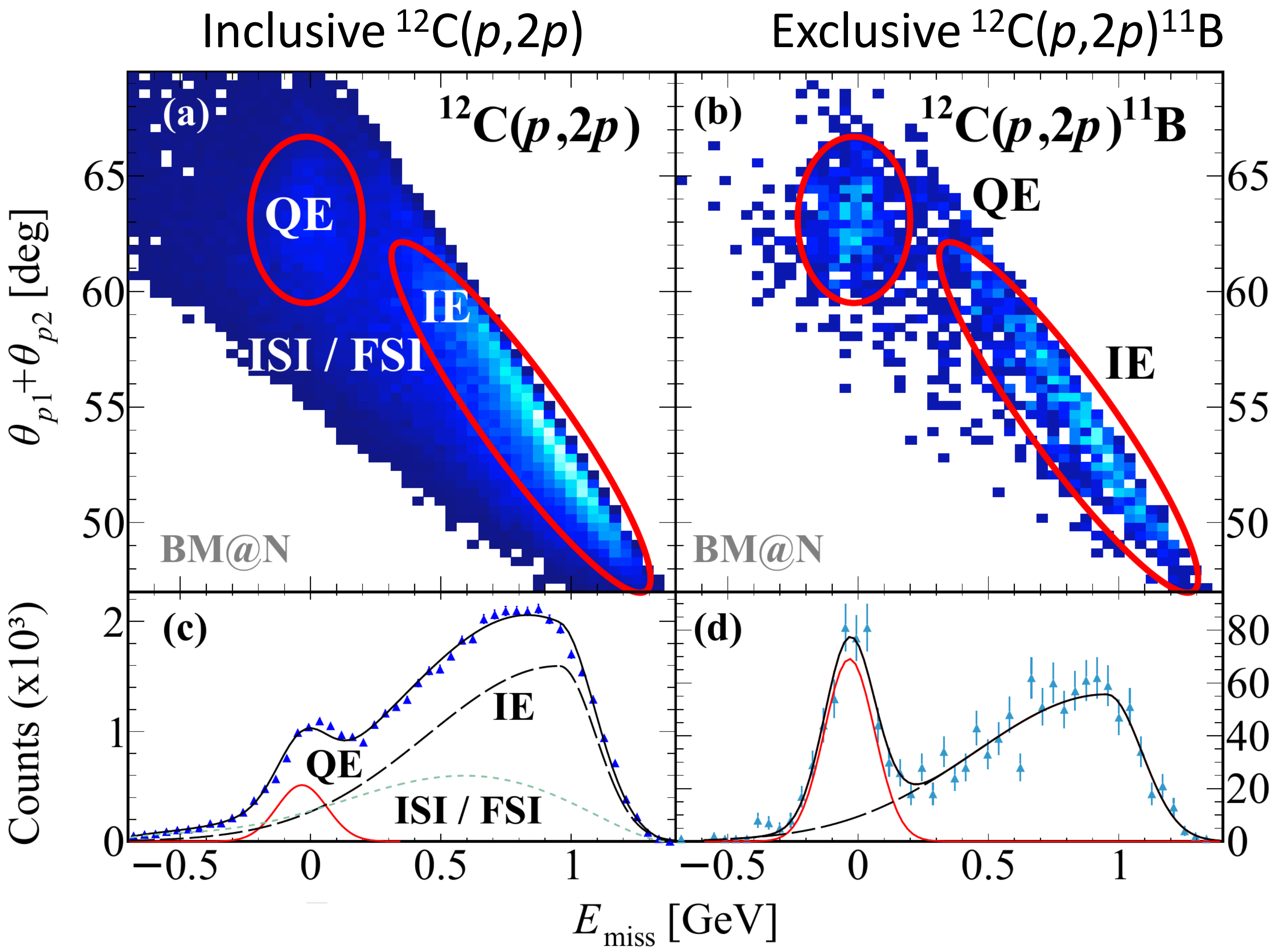




$$B\rho \sim \frac{A}{Z}\beta\gamma$$

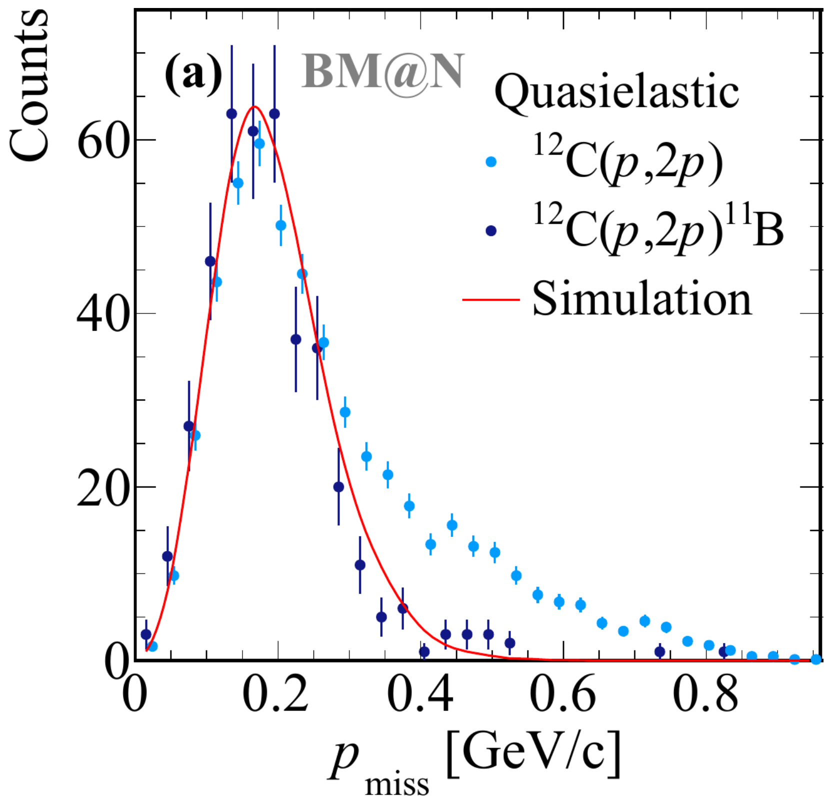
V. Panin "Analysis of nucleus fragments in SRC run with BM@N setup" Oct 22, 15:10

Single proton knockout



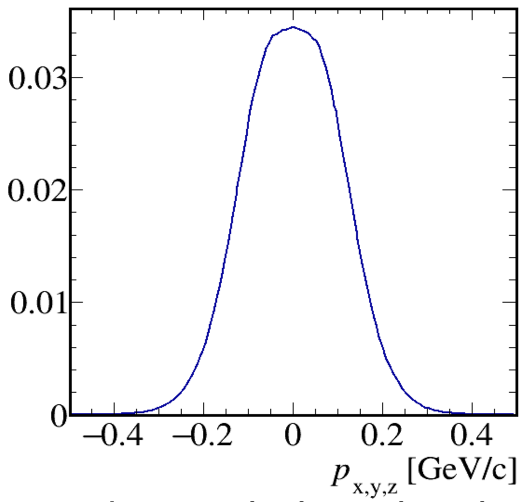
- **fragment tagging removes ISI / FSI**
- select **quasi-elastic scattering (bound ^{11}B)** under large momentum transfer

Initial proton momentum



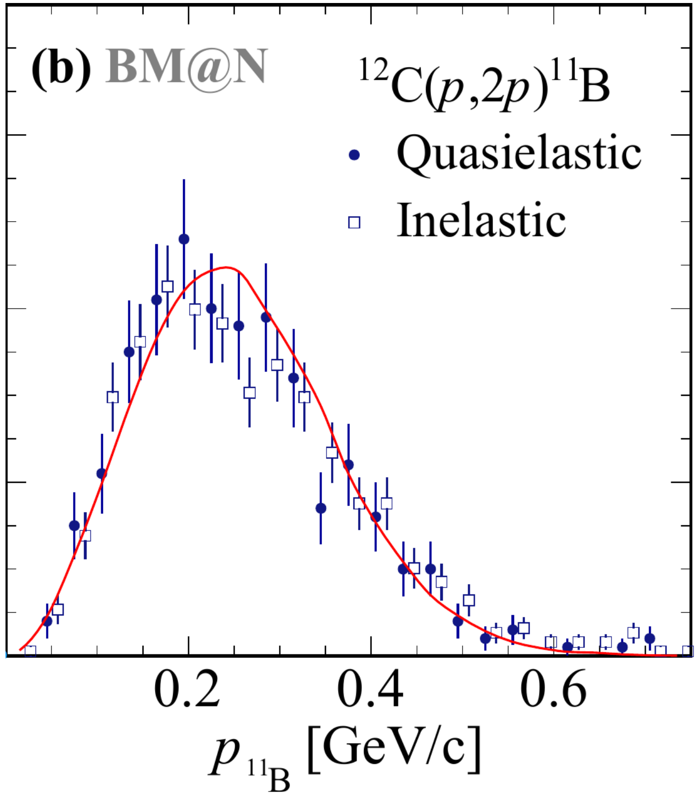
High momentum tail – ISI/FSI

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



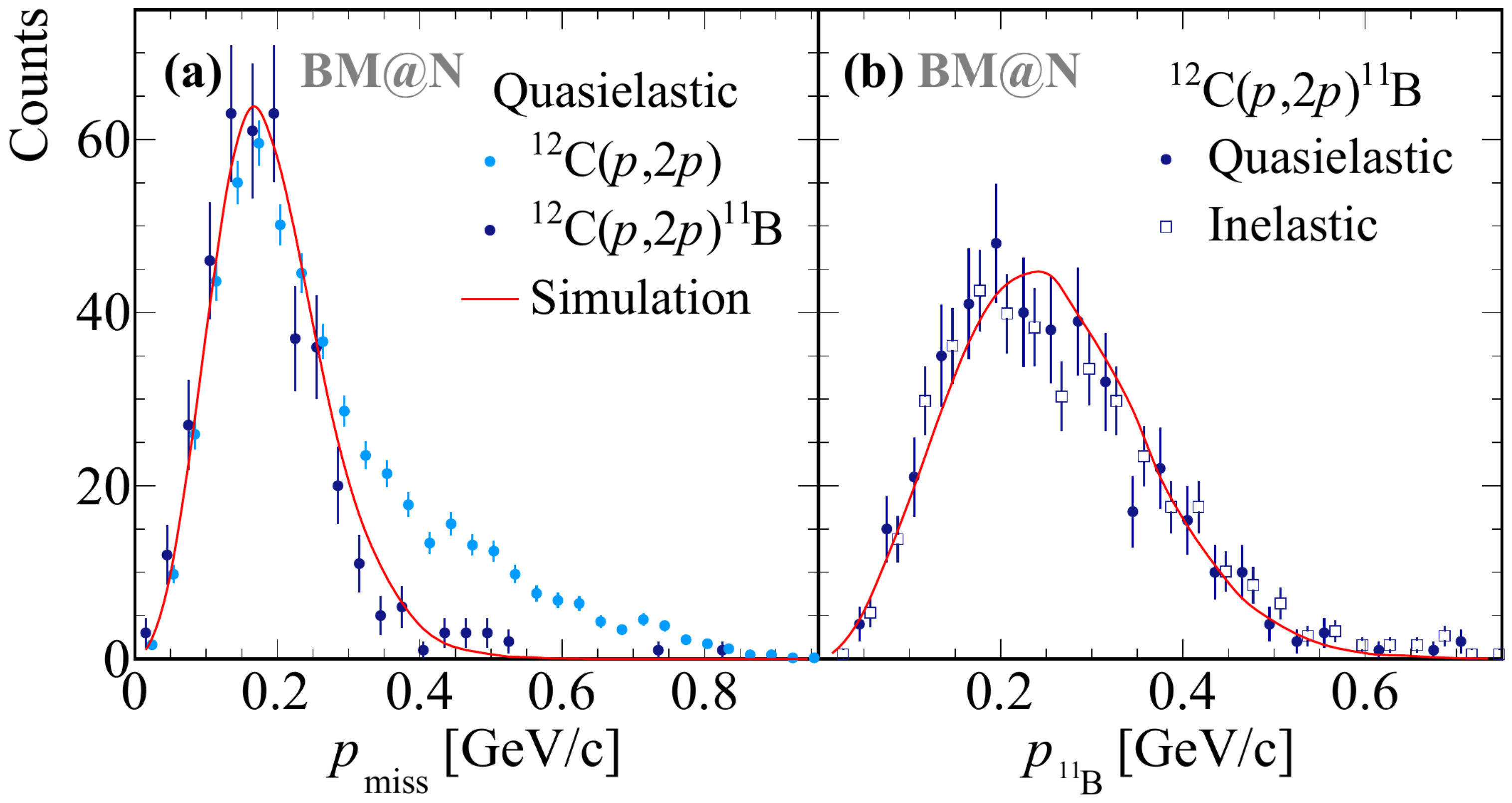
T. Aumann, C. Bertulani, and J. Ryckebusch, Phys. Rev. C 88 (2013)

Recoil fragment momentum



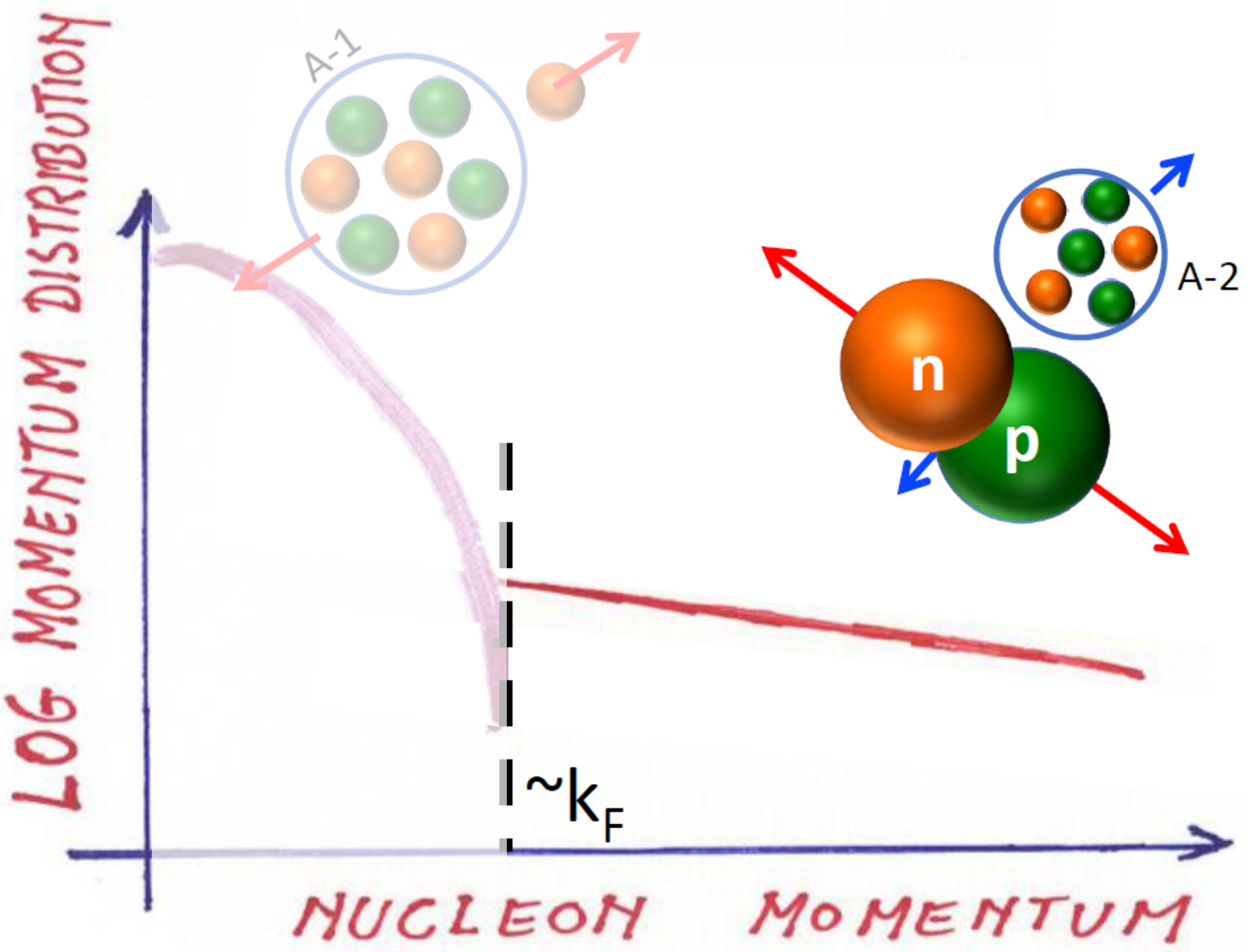
Fragment not impacted by proton multiple scattering → fragment tagging selects **quasi-free unperturbed single-step reactions**

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



We show that for the first time we can probe a single–step knockout reaction

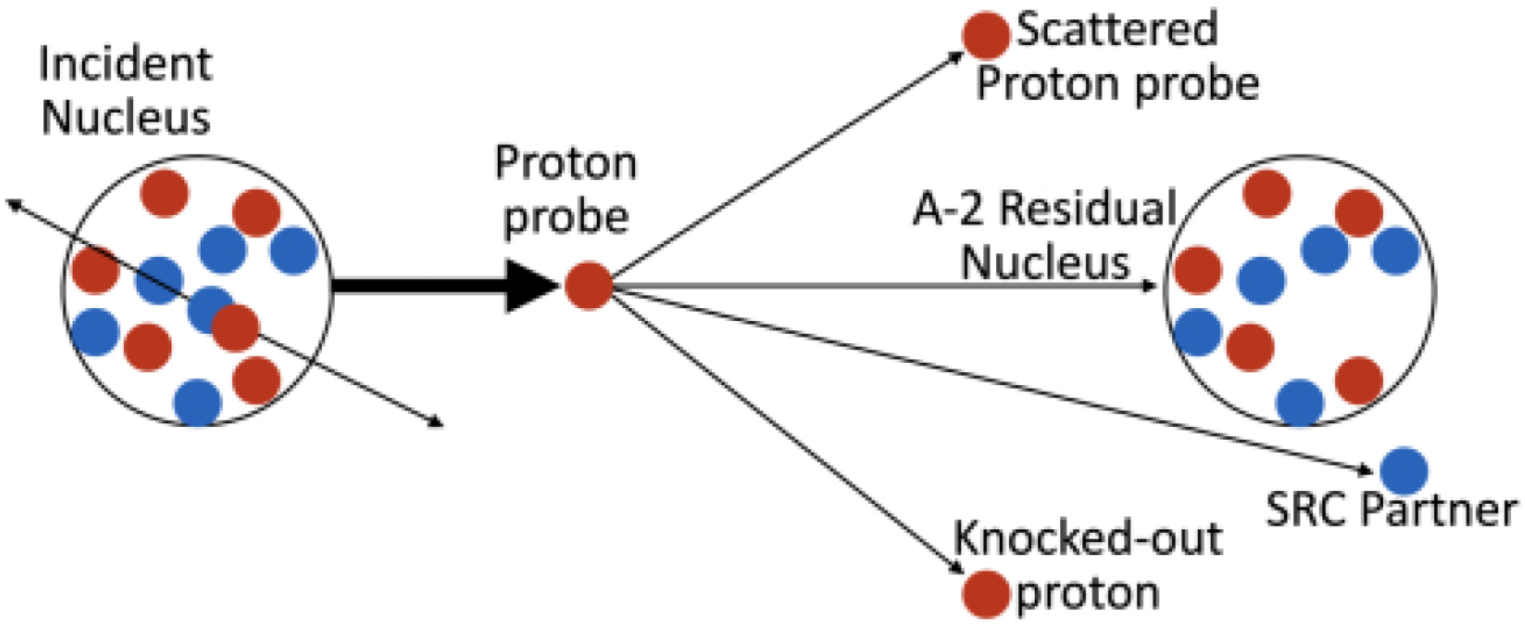
First study of SRCs in inverse kinematics



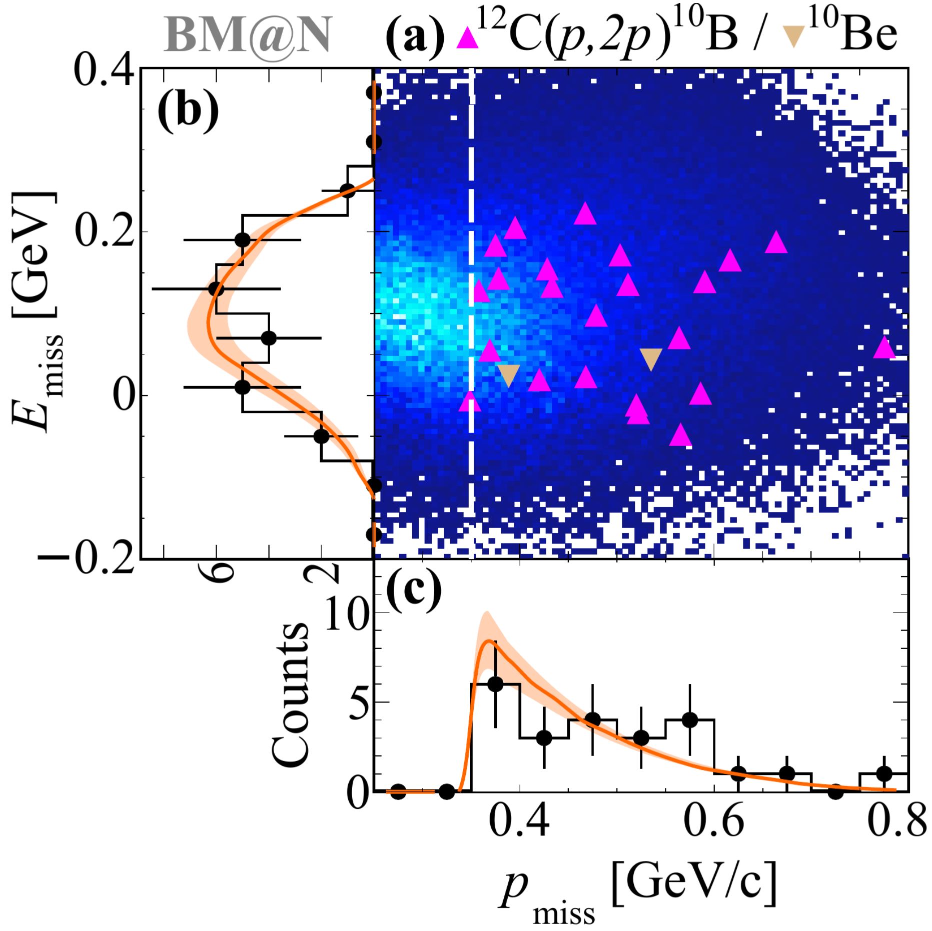
Hard breakup of SRC pairs

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

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



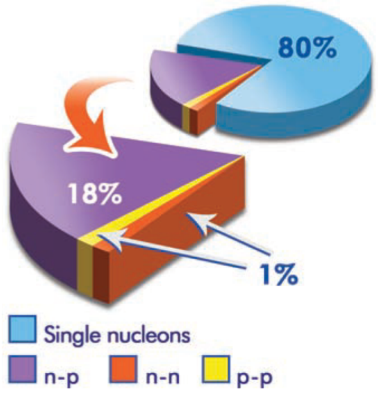
Identifying SRCs



+ proton-proton opening angle
(guided by simulation)

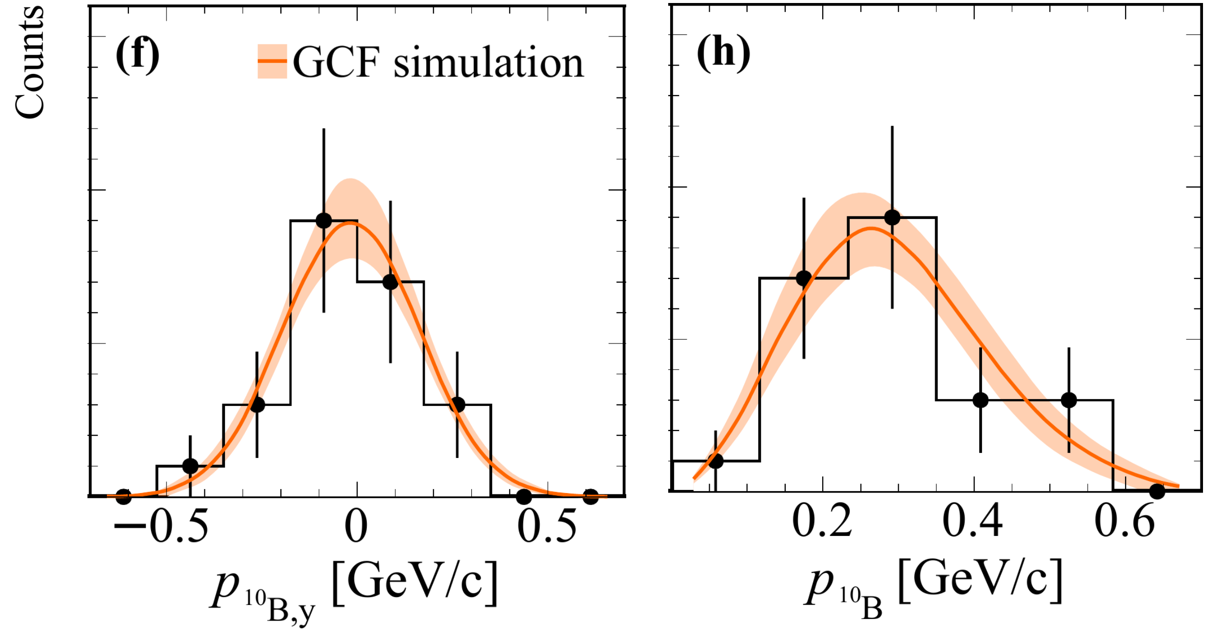
23 np pairs
2 pp pair

-> *np* dominance



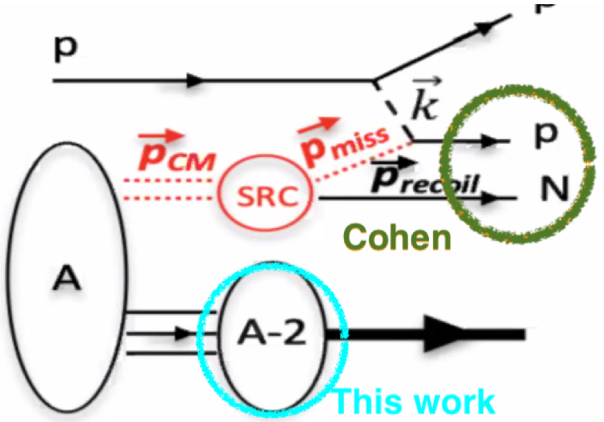
R. Subedi et al., **Science** 320 (2008)

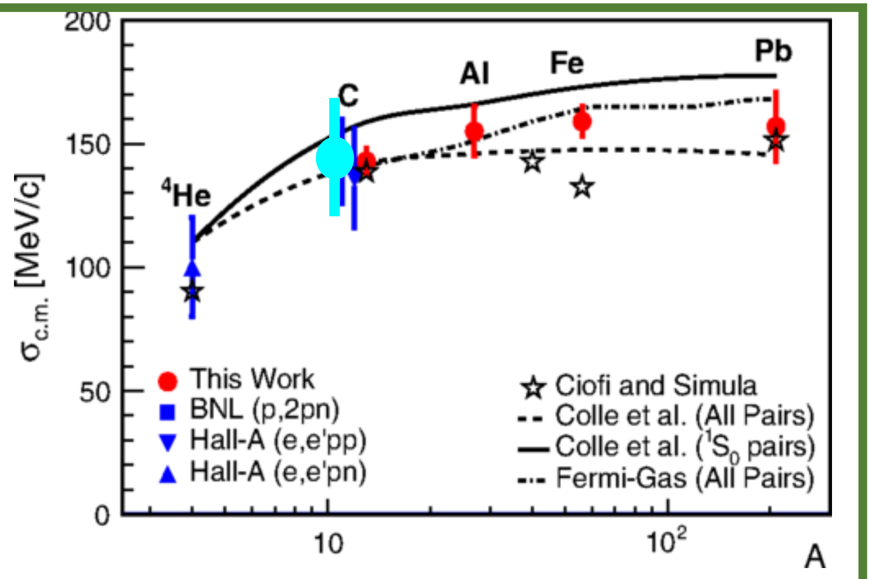
New observable: Fragment (SRC pair c.m.) momentum



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

-> small c.m. momentum





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

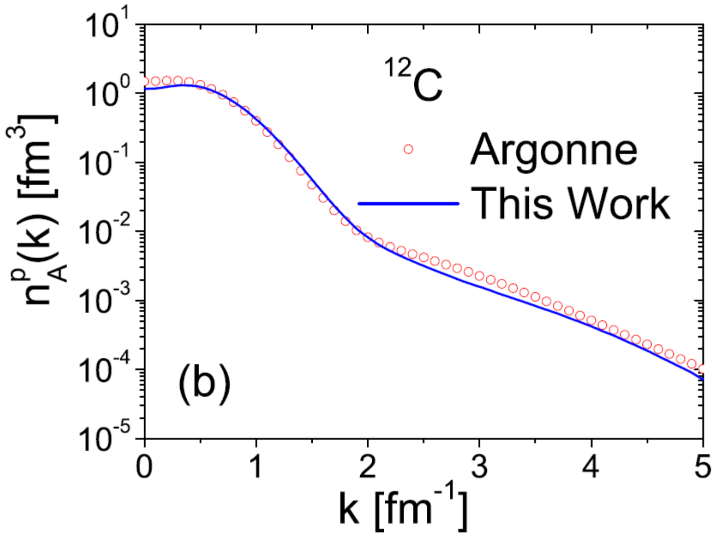
Scale separation in high-momentum regime

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)



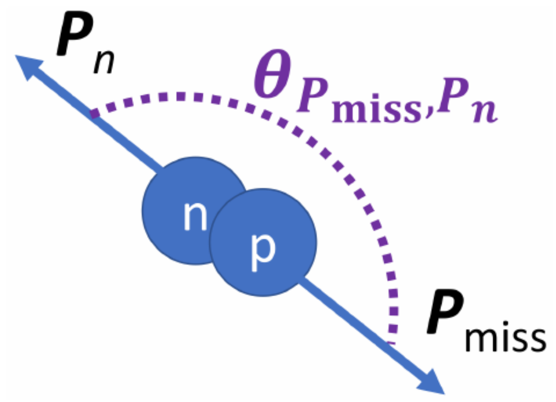
M. Alvioli, C. Ciofi degli Atti, H. Morita, Phys. Rev. C 94 (2016)

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

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

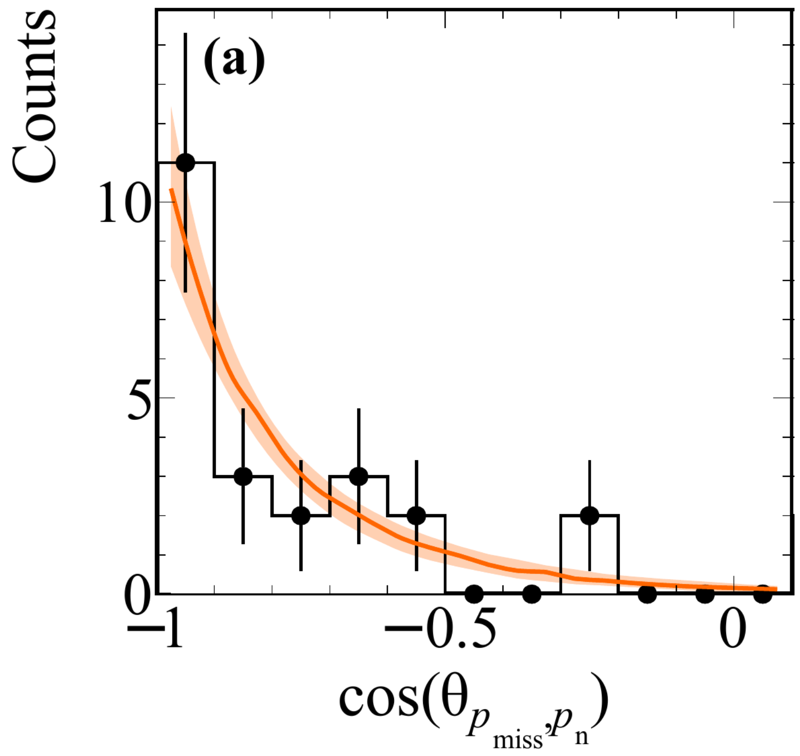
R. Weiss, B. Bazak, N. Barnea, Phys. Rev. C 92 (2015)
J.-W. Chen, W. Detmold, J. E. Lynn, A. Schwenk, PRL 119 (2017)
R. Weiss et al., Phys. Lett. B 780 (2018)

Strong pair correlation

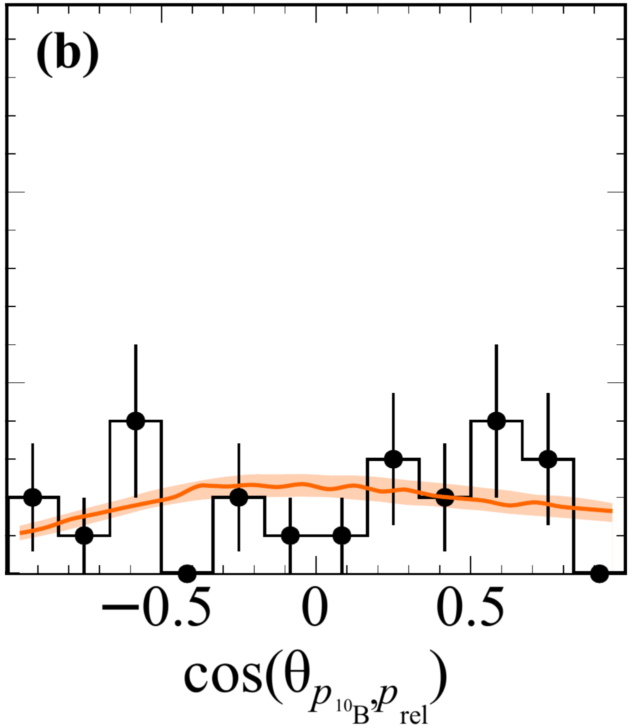


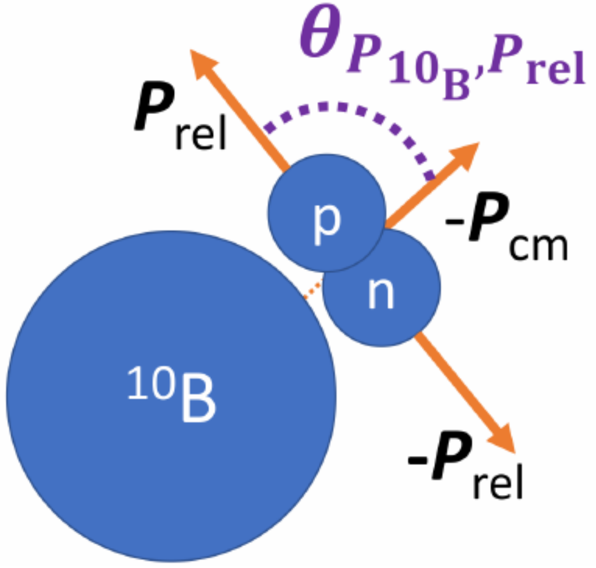
nucleon momentum not balanced by A-1

-> NN back-to-back emission



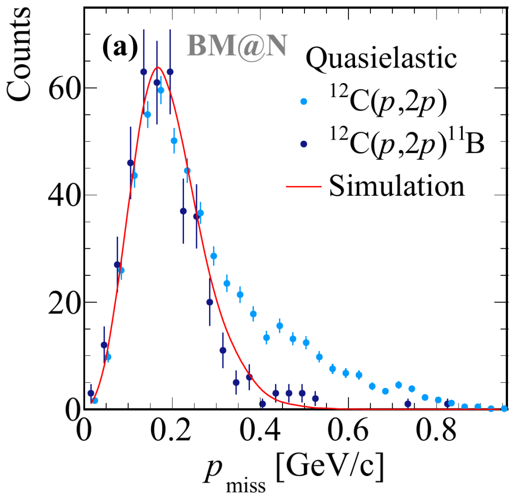
Experimental evidence for factorization



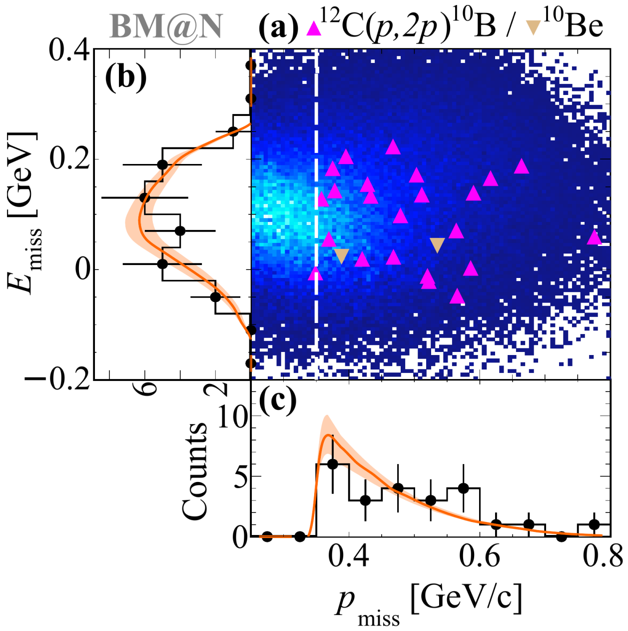


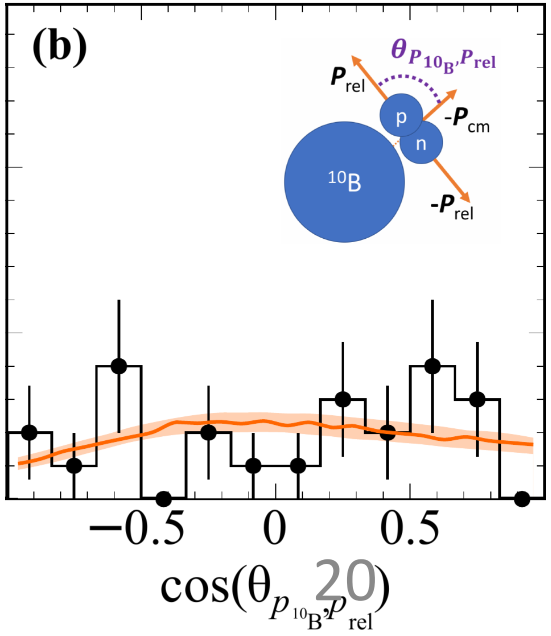
SRC studies in many-body dynamics entering new era

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



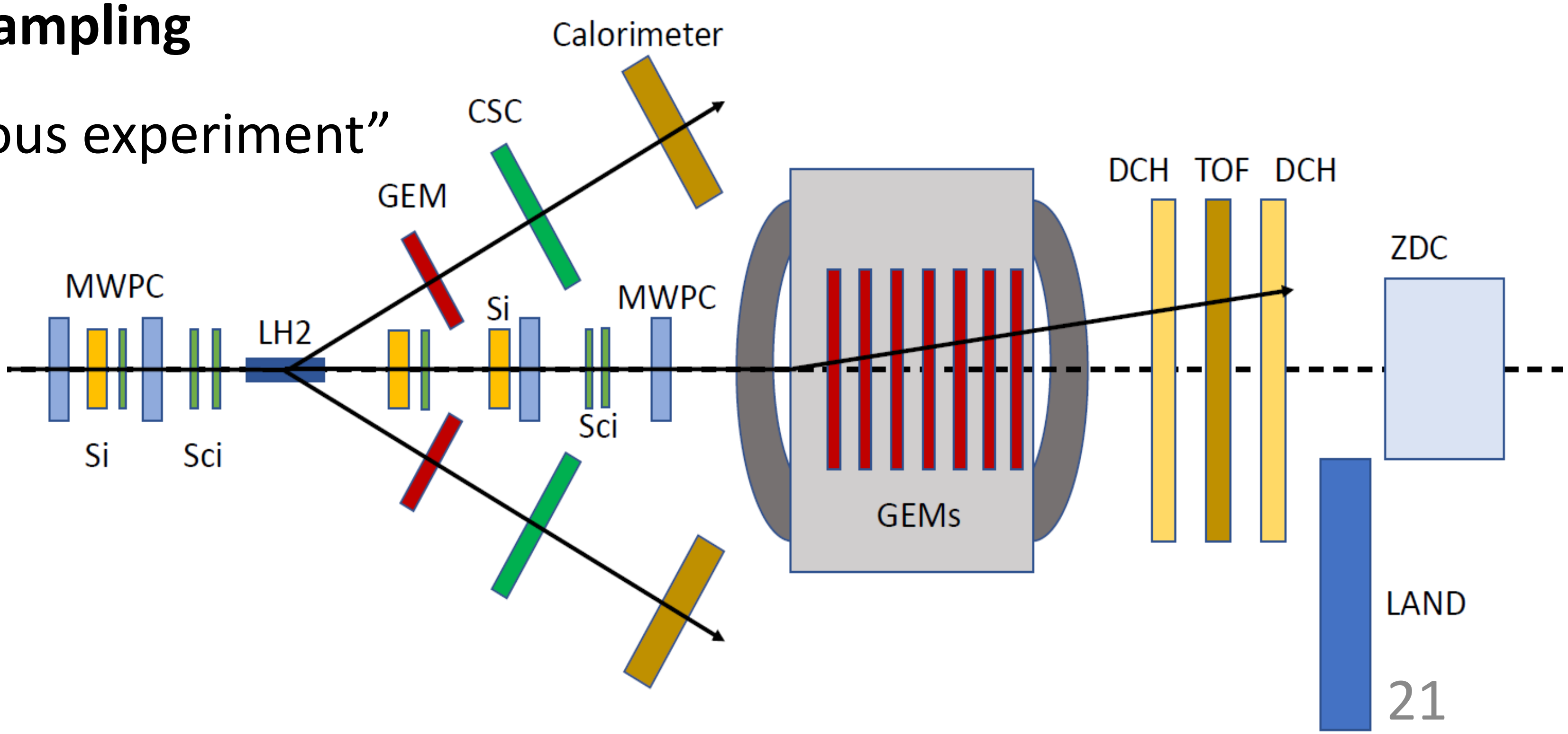
- **1st SRC experiment in inverse kinematics:**
  evidence for scale separation





Next measurement

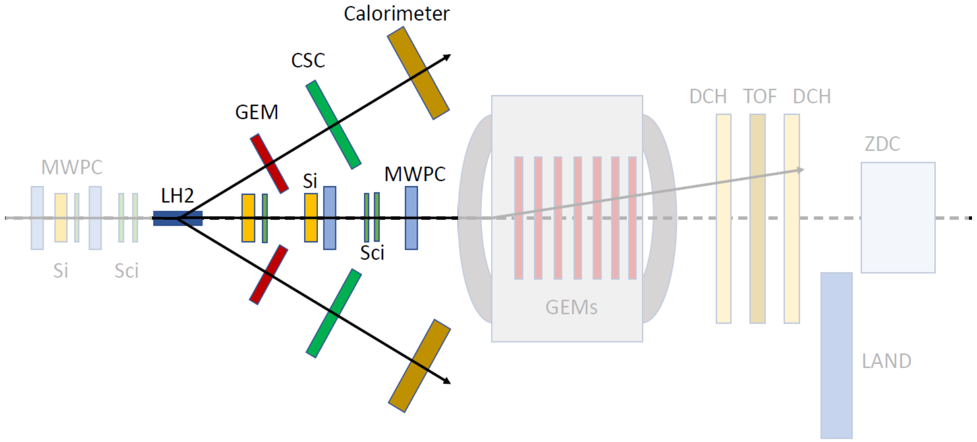
- **increase statistics** by order(s) of magnitude for detailed comparison with calculations
- improve detector resolutions
- employ multi-particle tracking
- **event selection: p/pion sampling**
- “learn lessons from previous experiment”



New (non-magnetic) calorimeter

Sandwich like structure of Sci – Fe – Sci (~ 150 x 230 x 25 cm^3)

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

The grant objectives

Analysis of the reactions at high momentum transfer and high initial momentum of the struck nucleon: ^{12}C + p --> ^{11}B + pp, ^{12}C + p --> ^{10}B + pp + X, ^{12}C + p --> ^{10}Be + pp + X, ^{12}C + p --> ^{10}B + np + X, ^{12}C + p --> ^{10}B + pp + n, ^{12}C + p --> ^{10}Be + pp + p, ^{12}C + p --> ^{10}B + np + p

1. Calibration and alignment of subsystems
2. Signal correlations between subsystems
3. Reconstruction of the interaction vertex
4. Reconstruction of p_{miss}
5. Corrections for acceptance, efficiency and other detector effects
6. Inclusive quasi-elastic scattering on a single nucleon in inverse kinematics
7. Inclusive spectra of protons and neutrons with large momenta
8. Comparison of results with models, other experimental data and theoretical calculations
    1. Calculate spectroscopic factors
    2. Calculate amplitude of p<NN> -> p NN
    3. Propagation of the initial proton and final state particles through the nuclear medium

first measurement of SRCs in inverse kinematics - established the factorization theorem

Achievements

1. Identification of a quasi-elastic (QE) scattering reaction $^{12}C(p, 2p)^{11}B$

2. first measurement of SRCs in inverse kinematics - established the factorization theorem

3. Theoretical calculations

Yu. N. Uzikov "QE knockout of nucleon from SRC pair in $^{12}C(p,2pN)^{10}A$" Oct 22, 15:30

Achievements of my group

1. Reconstruction, alignment, simulation of MWPC and Si
2. Matching MWPC-Si and Upstream tracks
3. Reconstruction, simulation tuning of DCH
4. TOF400 calibration and reconstruction of the vertex
5. TOF700 calibration
6. Charge calibration
7. Simulation studies using DCM-SMM generator
8. Global tracking, new tracking inside the magnet
9. New vertex finder

S. Merts "Global track and vertex reco in SRC and argon beam at BM@N" Oct 22, 14:50

Plans for 2021

1. Analysis of multitrack events
2. Analysis of reactions with recoil neutrons
3. Theoretical calculations:

Calculation of differential cross sections of the reactions $^{12}C(p,2p)^{11}B$, $^{12}C(p,2pN)^{10}A$ and pp/pn ratio in kinematics of the BM@N SRC experiment within the developed in 2019-2020 microscopic model with accounting for absorptions effects and spectroscopic factors for NN pairs and comparison the results with data.

4. Construction of fast TOF calorimeter, new T0 and veto box detectors, and beam counters
5. Experimental setup optimization

Plans for my group for 2021

1. Analysis of multitrack events
2. Preparation for the next run in 2021:
    1. Simulations helping to finalize the design of the setup
    2. Manufacturing, tests of scintillator beam counters
    3. Simulations to find the optimal design of the new calorimeter
    4. Setting up the detectors in the hall, new frame for the calorimeter

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

Status of the theoretical work

Courtesy of Yu. N. Uzikov

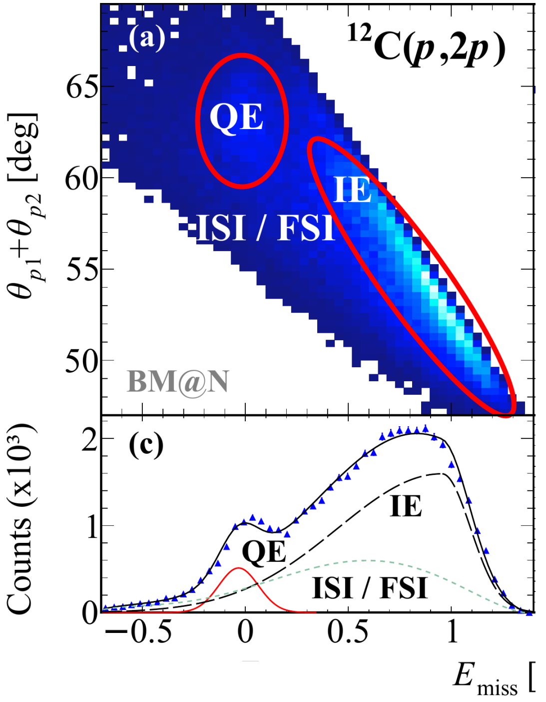
CONCLUSION

- Translationally-invariant shell model (TISM) applied for S_A^x and $n_{cm}(k_{cm})$ of the deuterons in the ^{12}C works reasonable well for the $^{12}C(p,pd)^{10}B$ reaction at 670 MeV with transition to the g.s. of ^{10}B (s^4p^6) and its excited states $E_B^* > 20$ MeV (s^2p^8).
- TISM can be applied to BM@N data on quasi-elastic knok-out of nucleon from SRC NN pairs from the ^{12}C in exclusive reaction $^{12}C + p \to p + p + N +^{10} B$
- The corresponding formalism is developed in the plane-wave approximation taking into account relativistic effects in the $p + < NN > \to p + N + N$ within the LFD approach.
- pp/pn ratio obtained within TISM is in agreement with the data.
- Observed in $^{12}C(e,epp)^{10}B$ S-wave $k_{c.m.}$ momentum distribution is a puzzle for TISM. Corresponding measurements of $^{12}C(p,pd)^{10}B$ at BM@N conditions for $s^4p^6$and s^2p^8 will be very important.

Cuts applied

QE events have additionally

2 sigma cuts



Incoming ^{12}C

Good reaction vertex (dZ = 4 cm)

Velocity cut in the arms

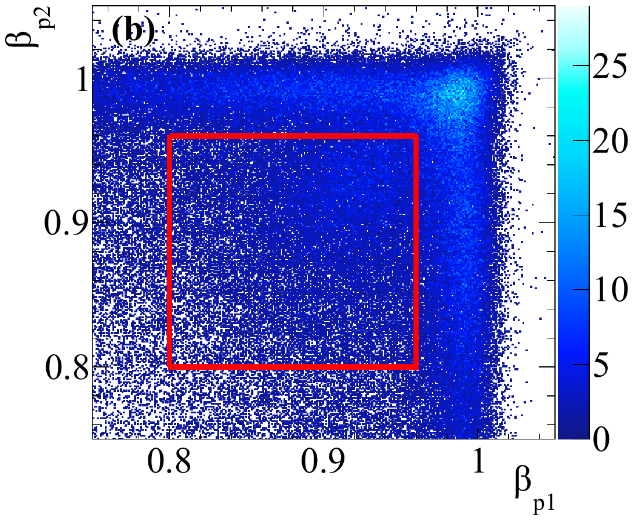
$M_{miss} > 0.47$ GeV^2/c^4

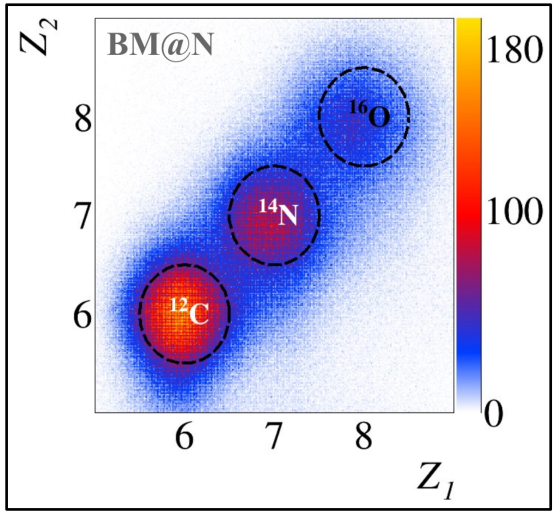
SRC events have additionally

$P_{miss} > 350$ MeV/c

pp angle > 60 degrees

-110 MeV < E_{miss} < 240 MeV





New LH_2 Target

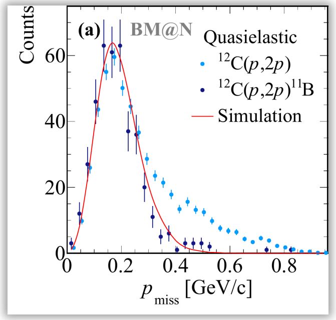
- The target group is developing a new LH2 target with the same parameters (D = 6 cm, length = 30 cm)
- Target will be inside the SP-57 magnet gap to gain acceptance for the arms
- Veto box around target: thin scintillator detectors

The team

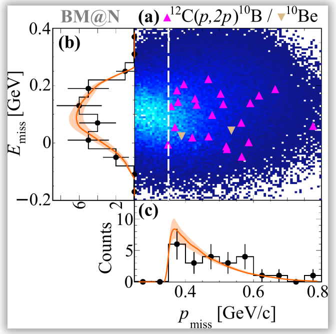
Local team	SRC international team
Timur Atovullaev	Julian Kahlbow
Nikolay Voytishin	Valerii Panin
Vasilisa Lenivenko	Eli Piasetzky
Mikhail Rumyantsev	Or Hen
Sergey Merts	Goran Johansson
Yuri Petukhov	Efrain Segarra
Vladimir Palichik	George Laskaris
Yuri Uzikov	

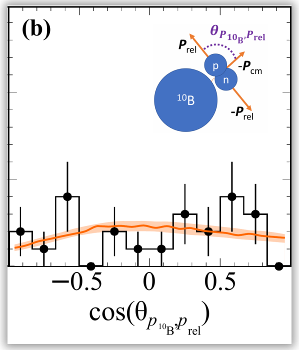
SRC studies in many-body dynamics entering new era

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

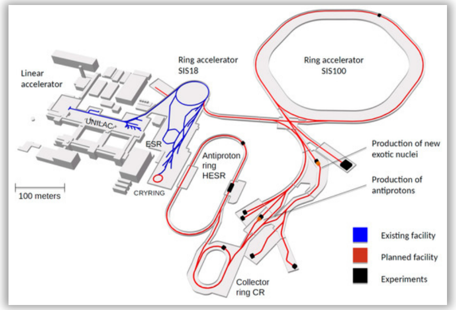


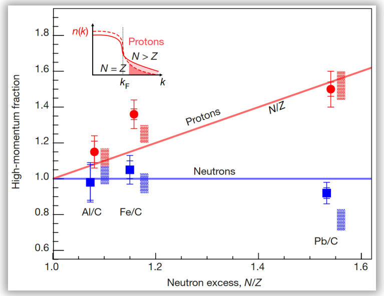
- **1st SRC experiment in inverse kinematics:**
  evidence for scale separation



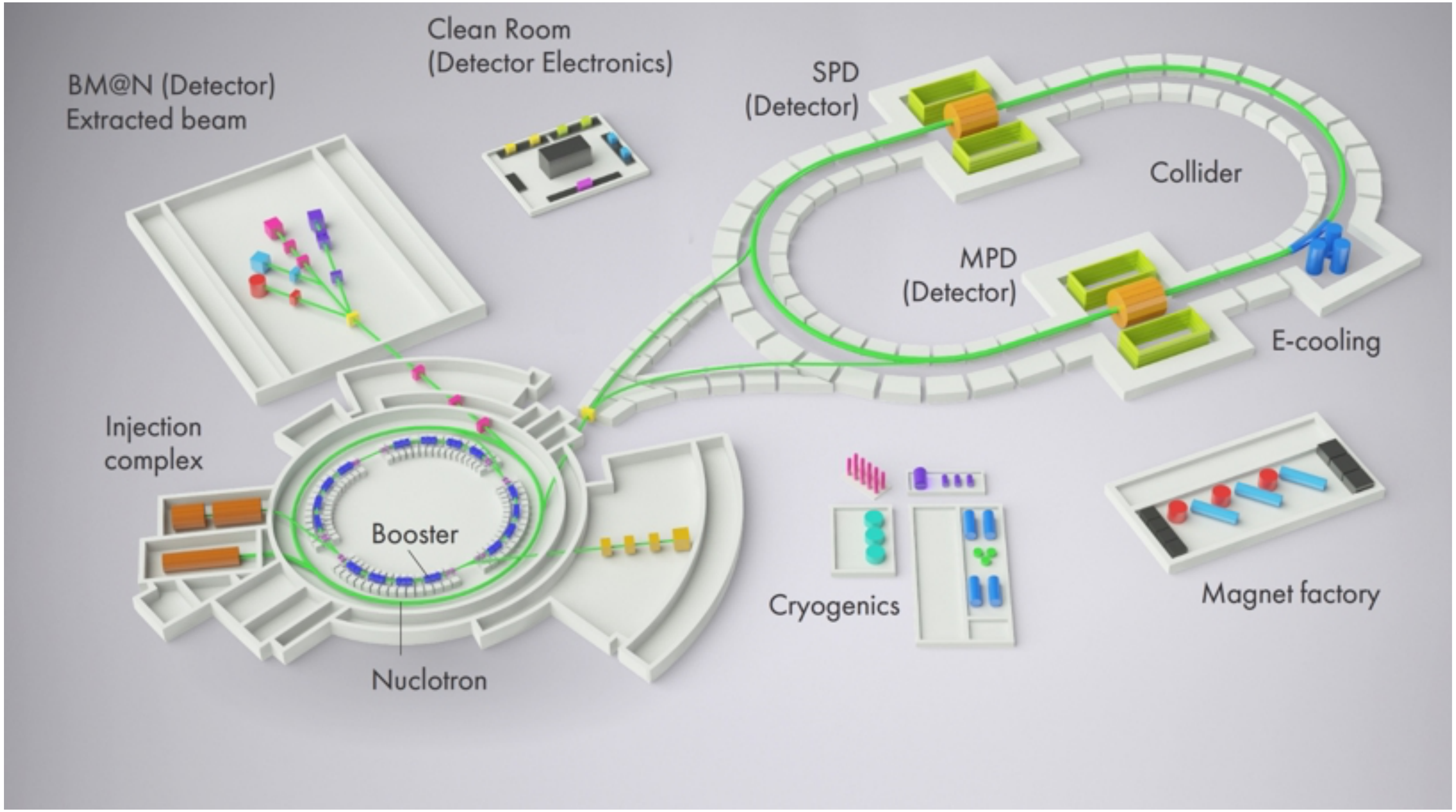


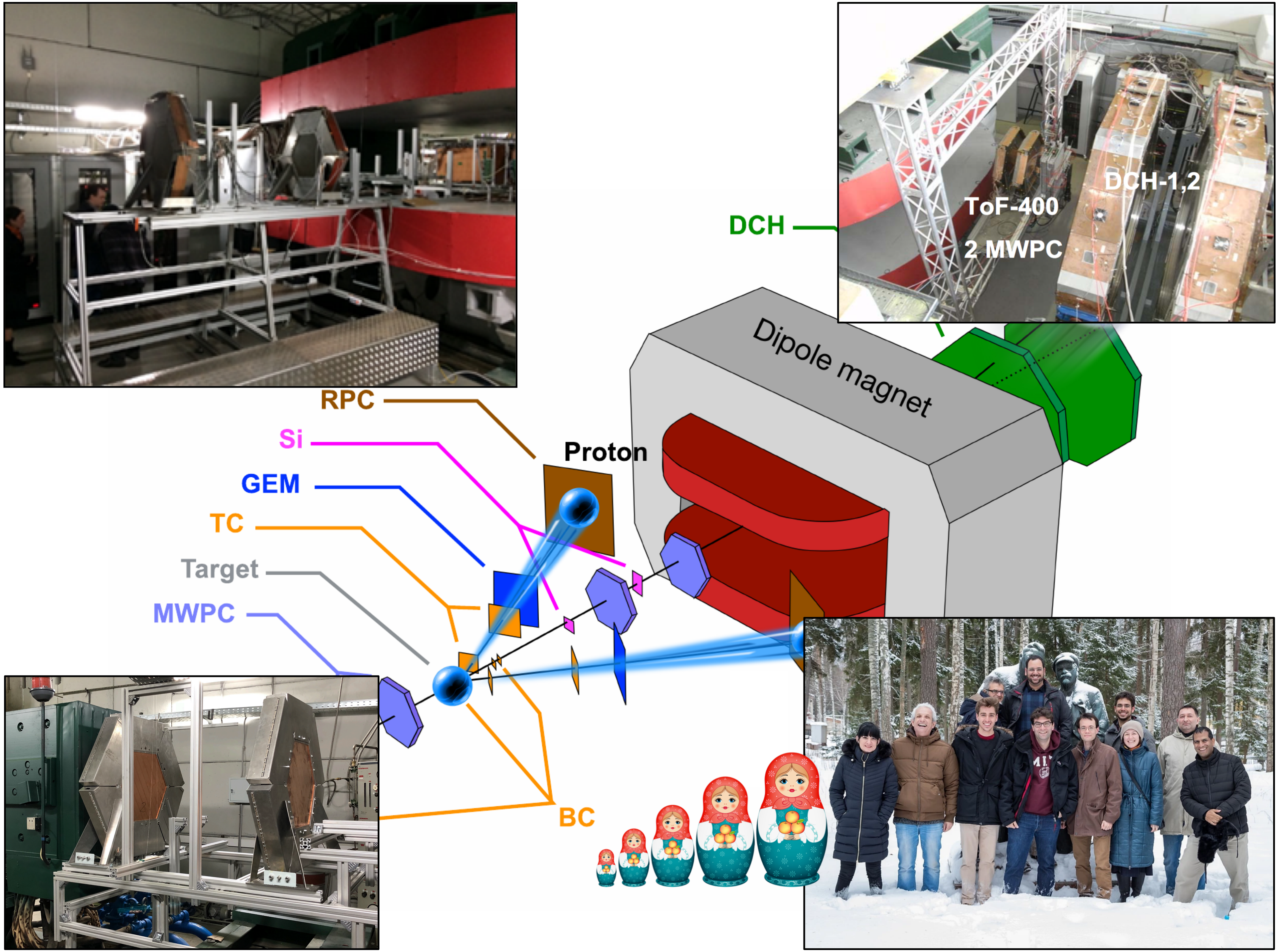
- **Merge Radioactive Beam and SRC physics:**
  Cold dense asymmetric nuclear matter





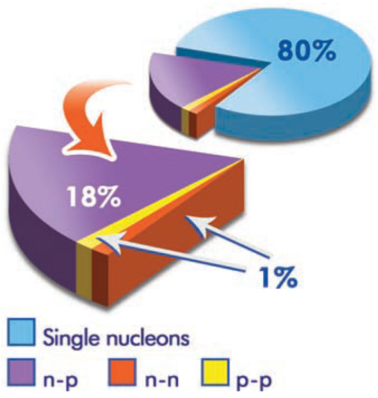
High-energy ion beam @ JINR Nuclotron





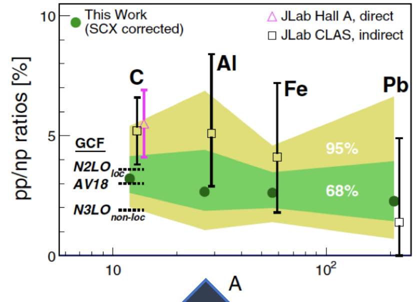
DCH-1,2
ToF-400
2 MWPC
DCH
Dipole magnet
RPC
Si
GEM
TC
Target
MWPC
Proton
BC

SRCs across the scales



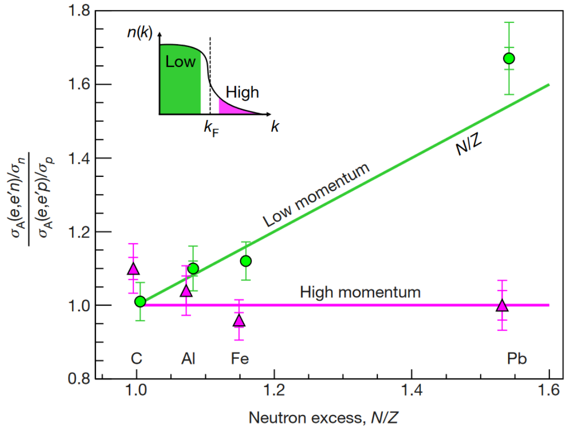
R. Subedi et al., **Science** 320 (2008)

pp/pn CONSTANT

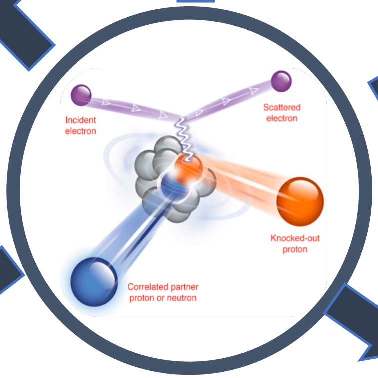


M. Duer et al., **PRL** 122 (2019)

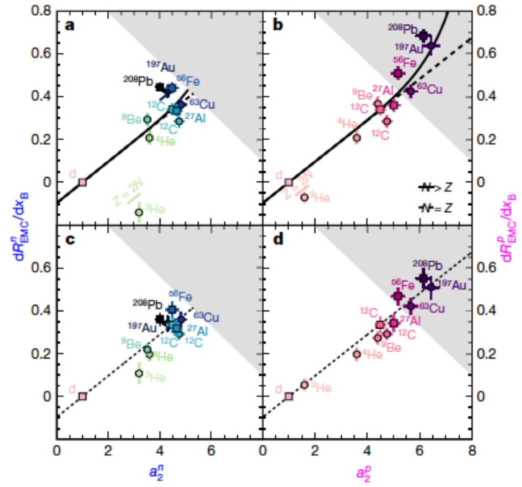
#SRC-protons = #SRC-neutrons



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

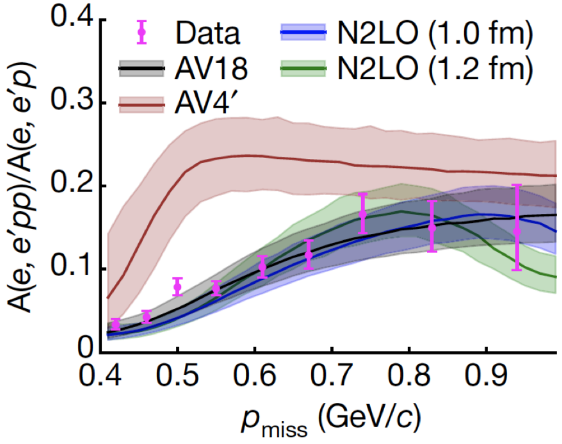


NUCLEON MODIFICATION (~EMC)



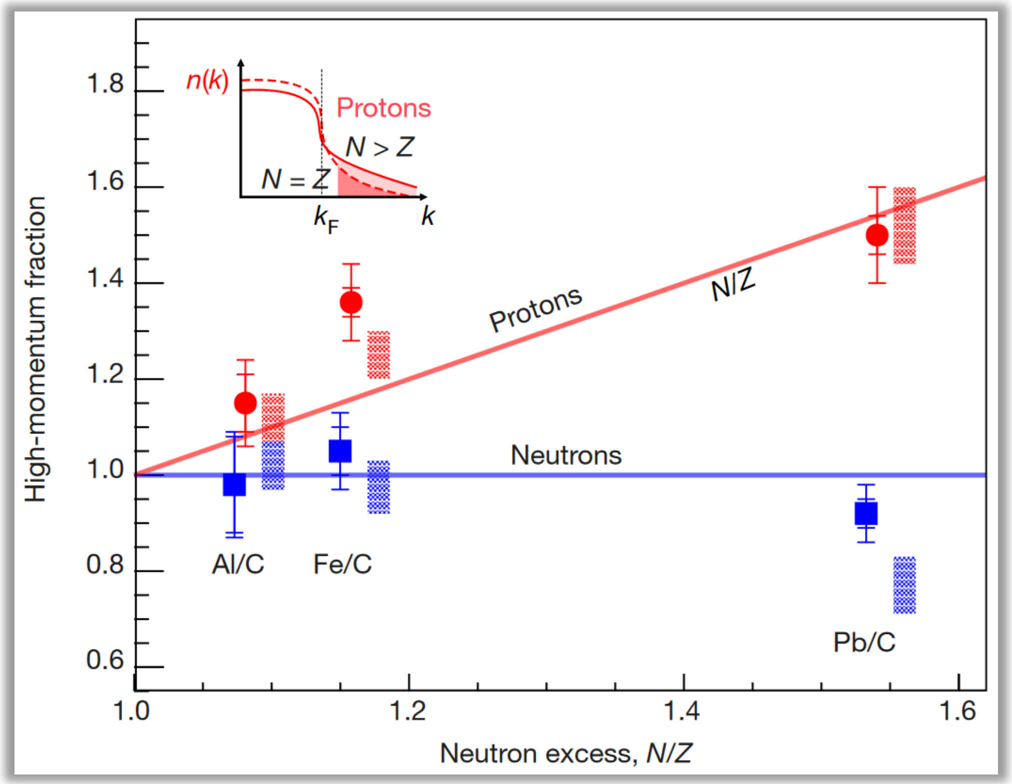
B. Schmookler et al., **Nature** 566 (2019)

SENSITIVE TO *NN* INTERACTION



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

What do excess neutrons do?



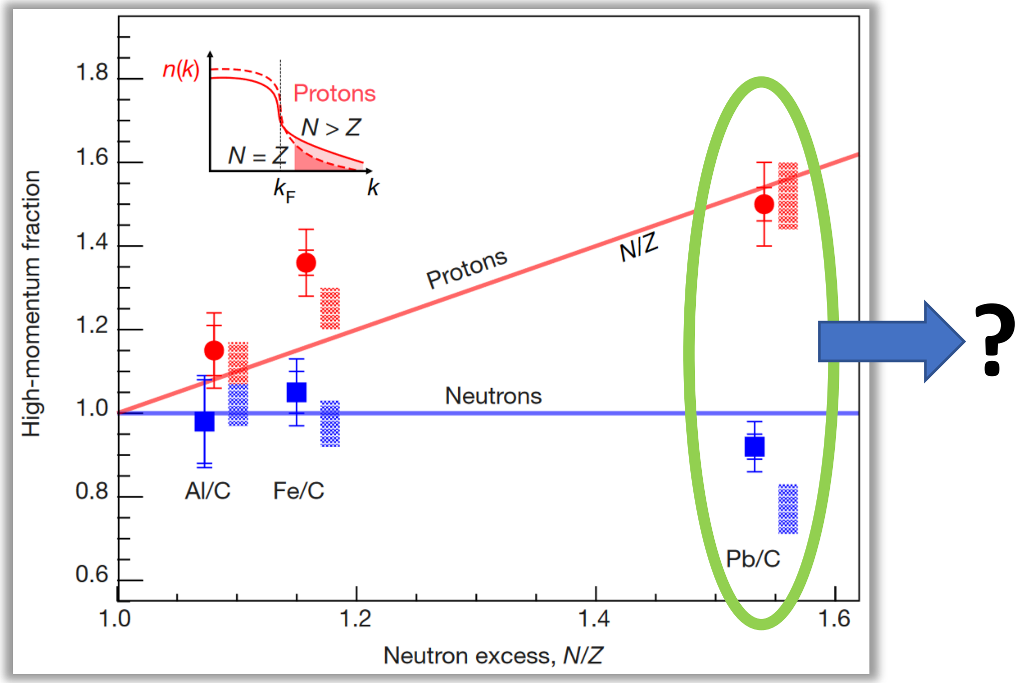
Fraction of correlated protons / neutrons grow / saturate with neutron excess

-> protons "speed up"

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

What do excess neutrons do?

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



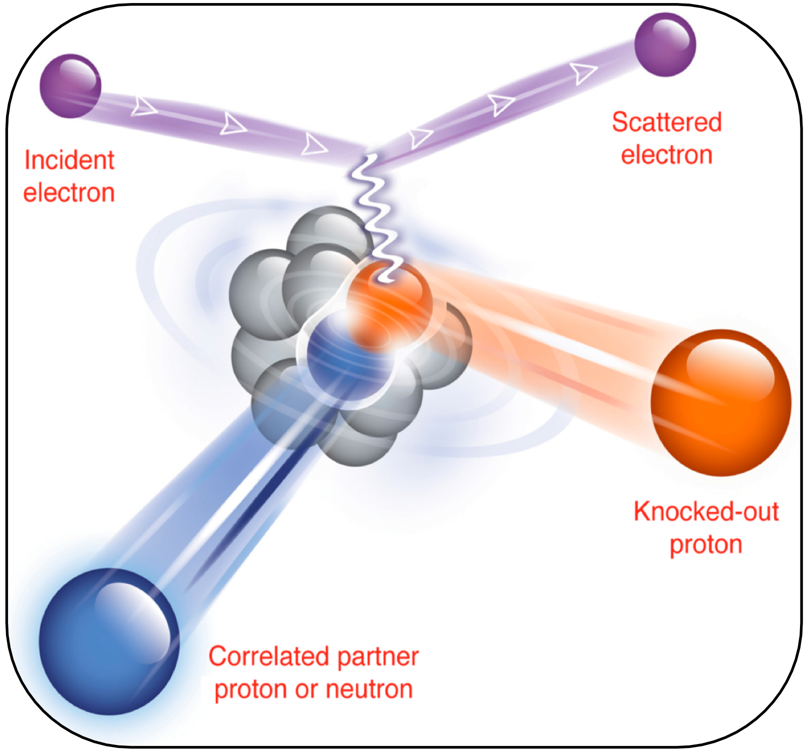
Limitations (e⁻ scattering)

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

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

Probing SRCs in normal kinematics

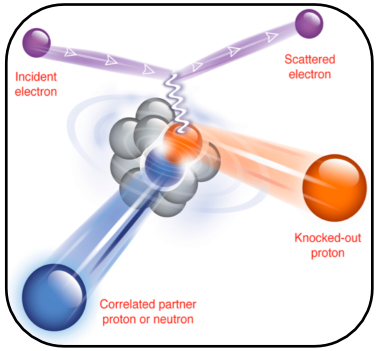
“Normal“ kinematics



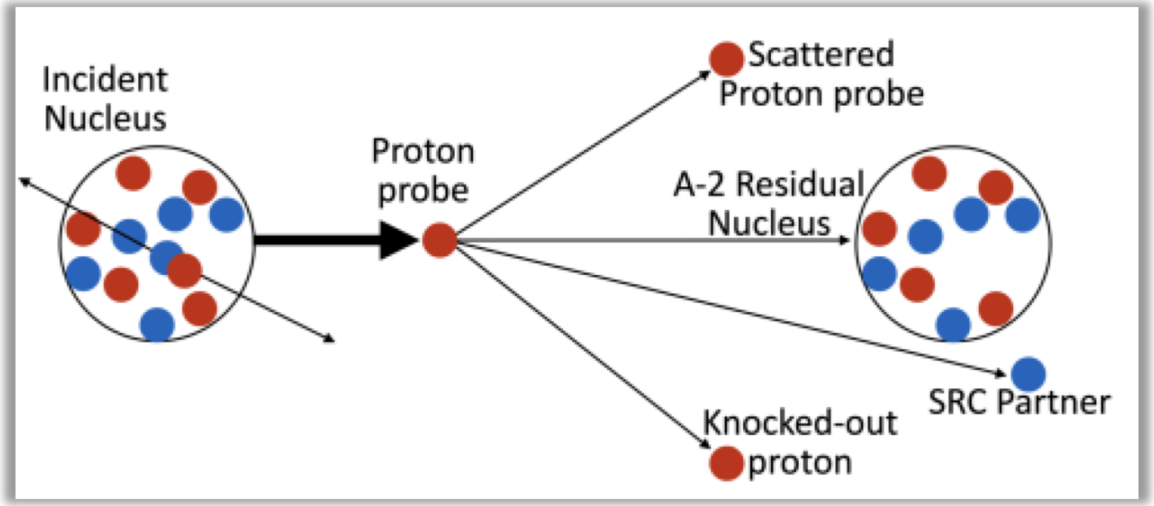
High-energy electromagnetic probe

Probing SRCs in inverse kinematics

Normal kinematics



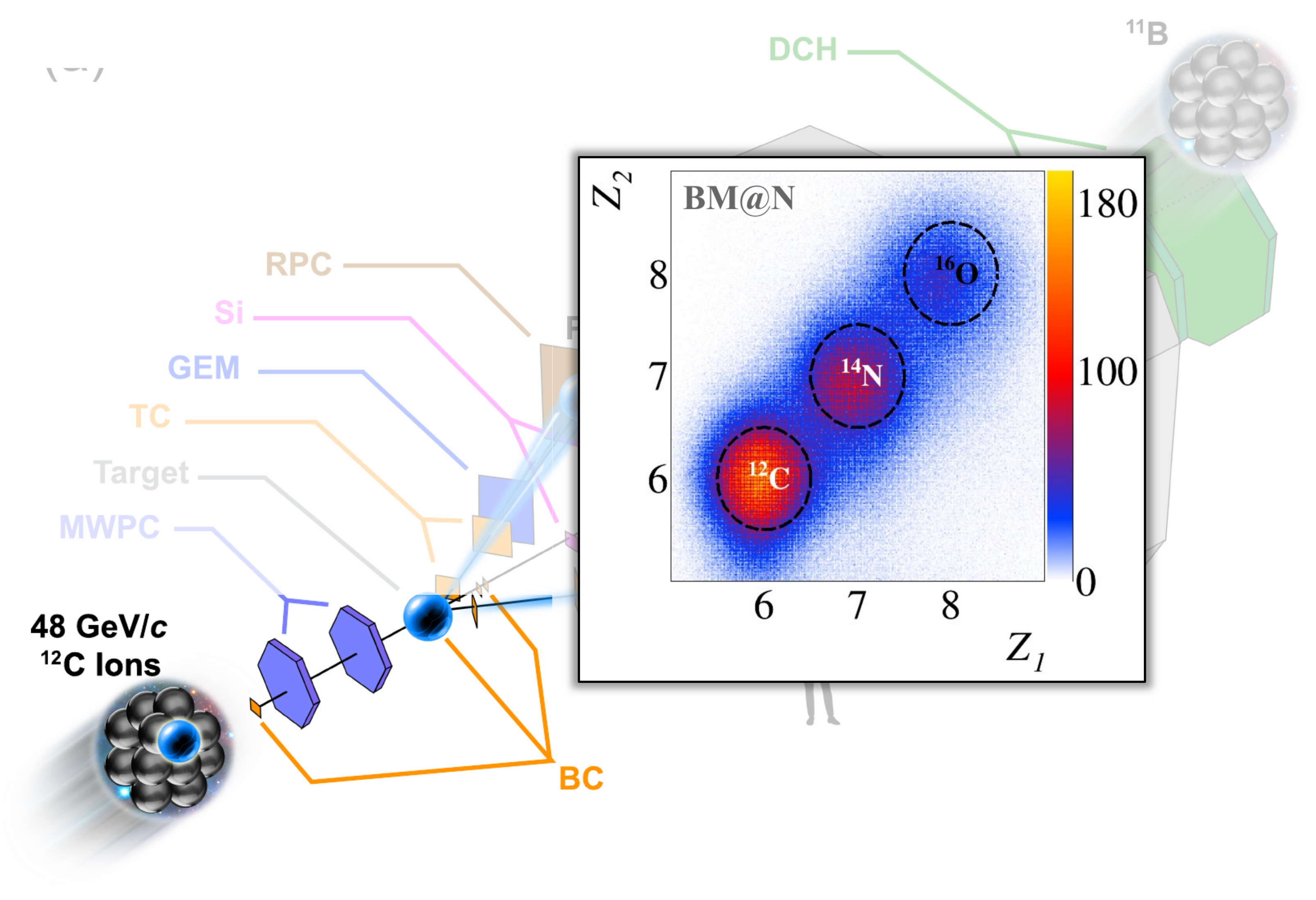
Reaction: ***A* (*p*,2*pN*) *A*-2**



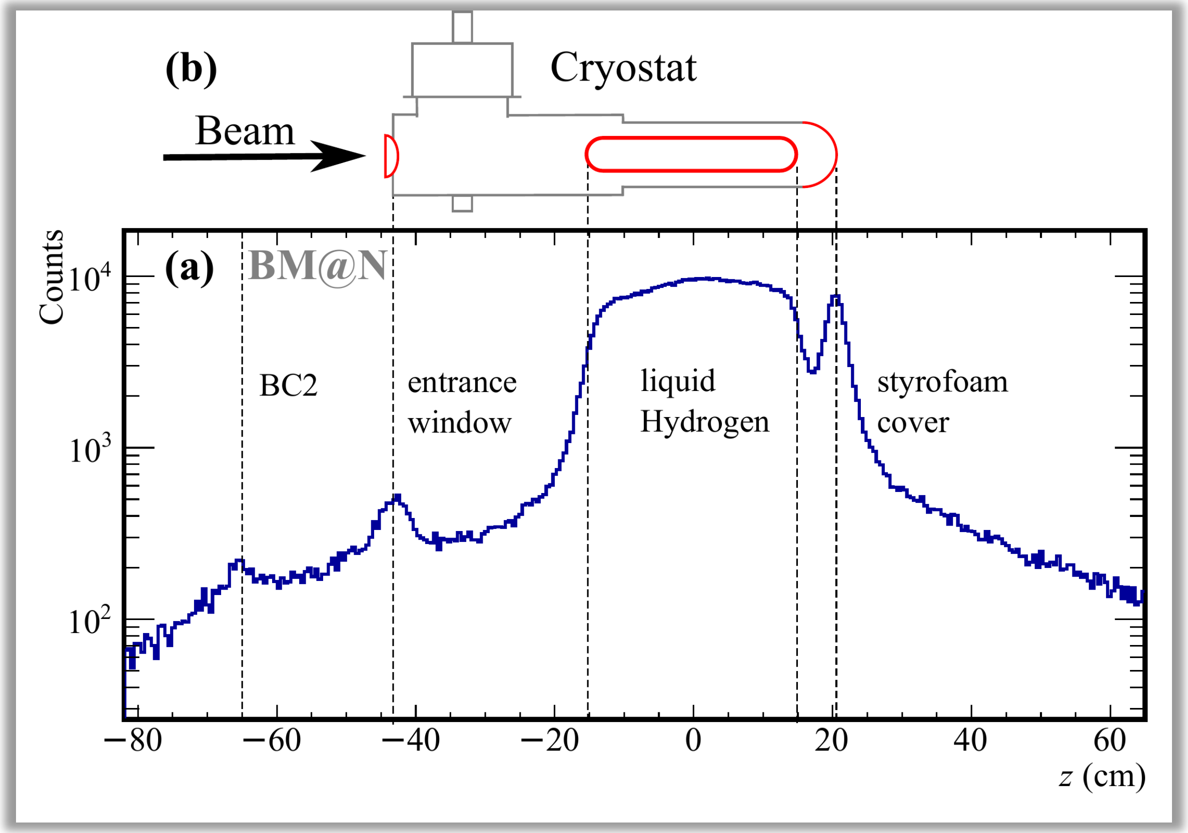
<u>Inverse kinematics</u>

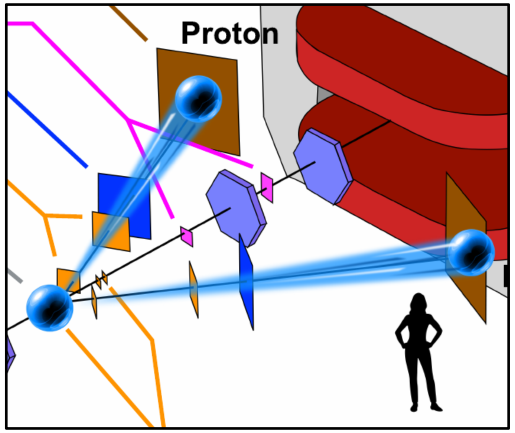
- ✓ p_{miss}, p_{recoil}
- ✓ fragment ID + $p_{A\text{-}2}$
- ✓ direct p_{CM}
- ✓ exotic nuclei

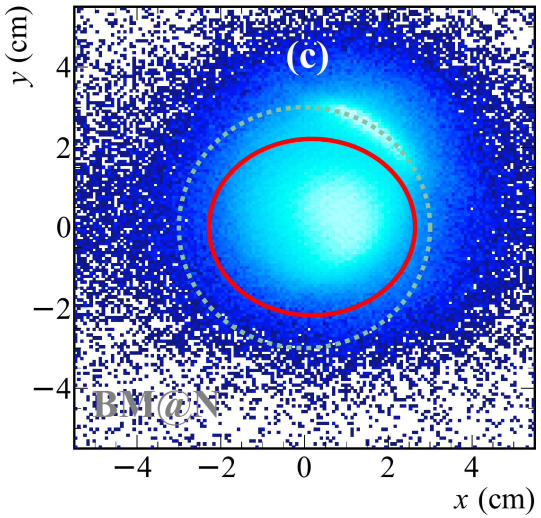
Incoming-beam identification



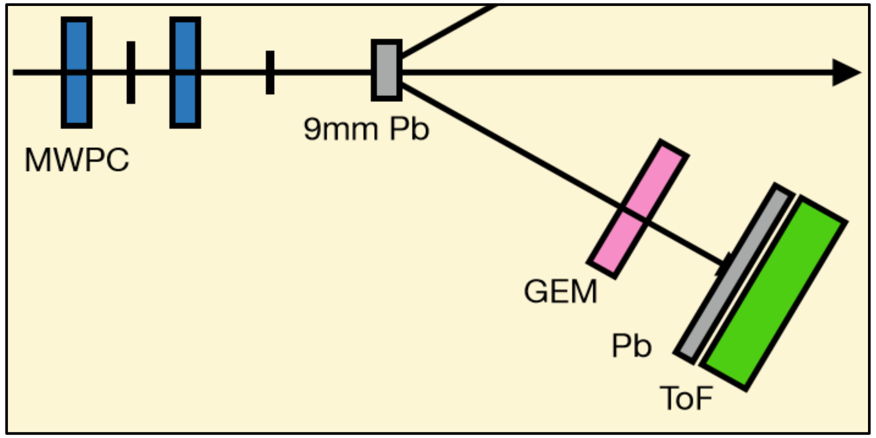
Proton vertex



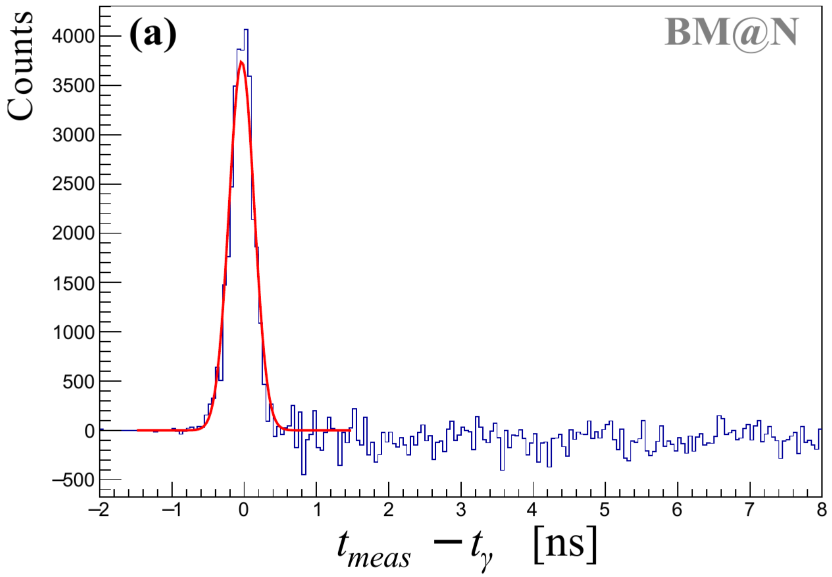


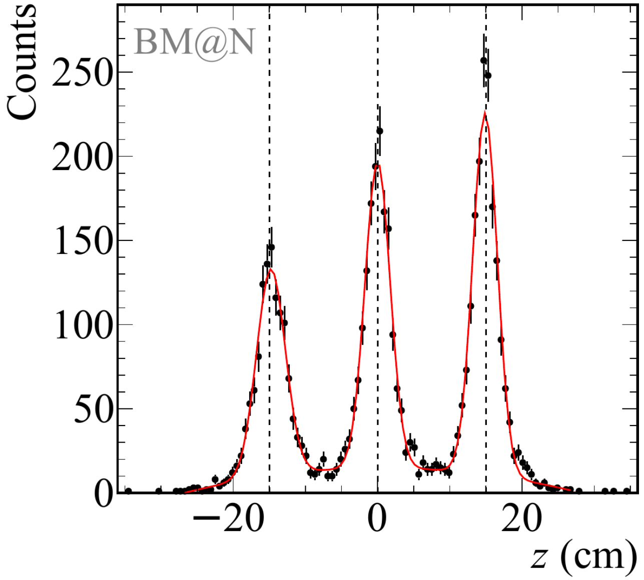


Two-Arm Spectrometer

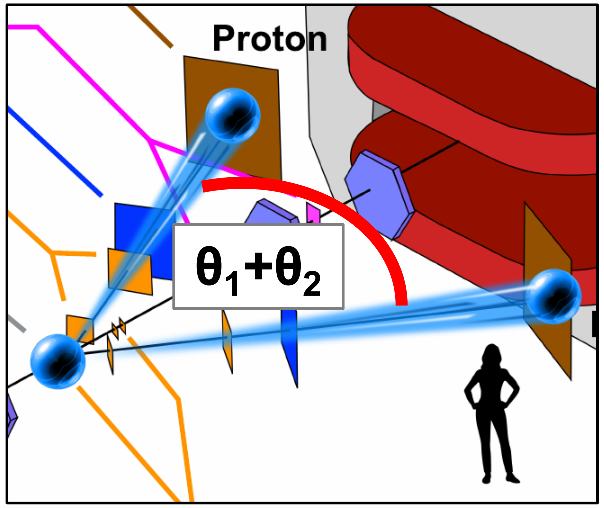


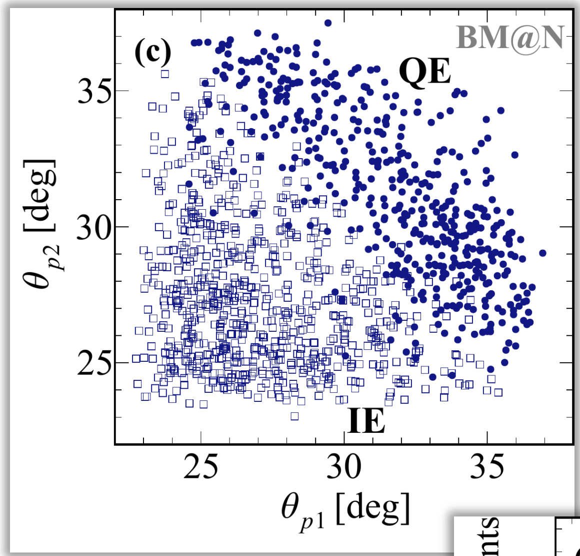
Position and Time calibration with single+multi foil Pb target



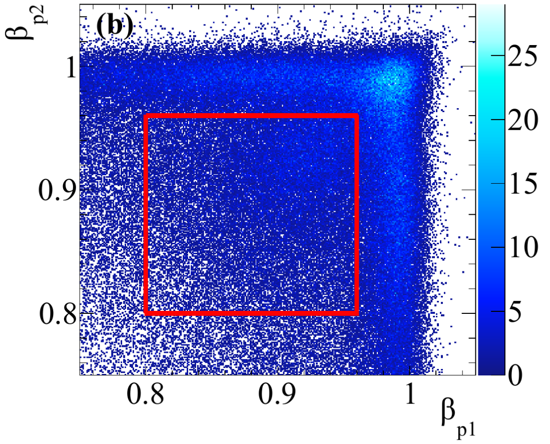


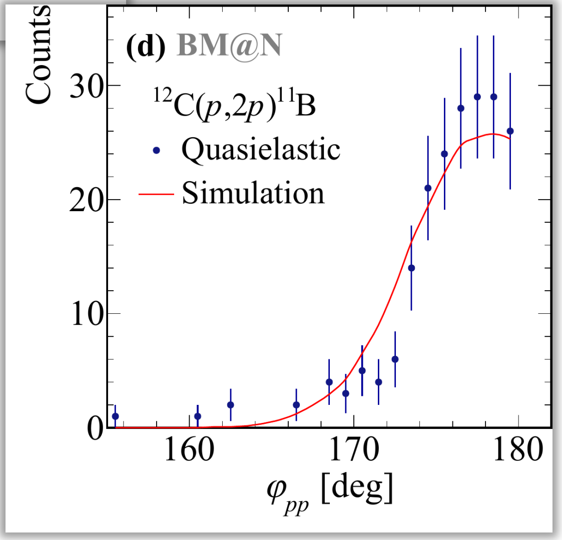
QFS angular correlations





Pion rejection

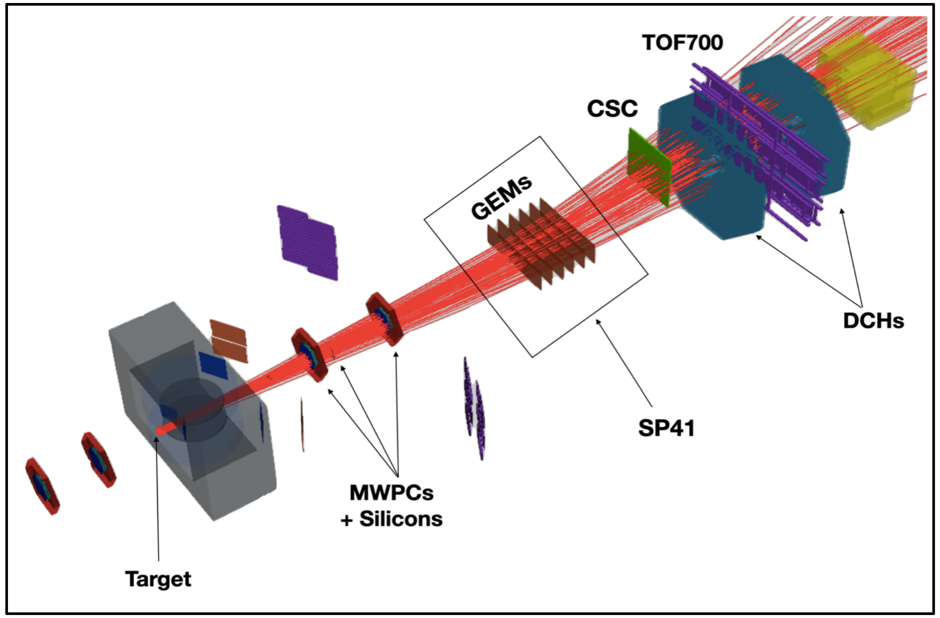




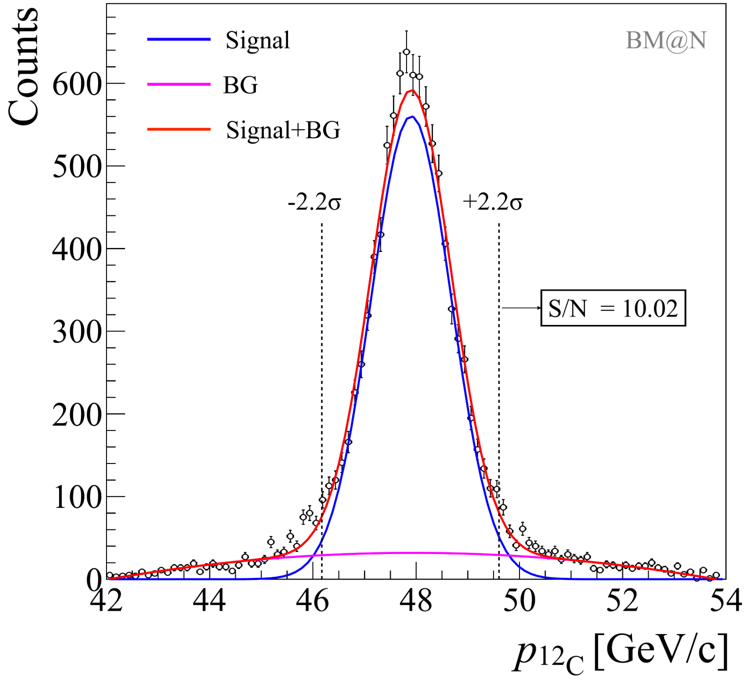
Fragment momentum

Simulation-based multi-dimensional fit

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

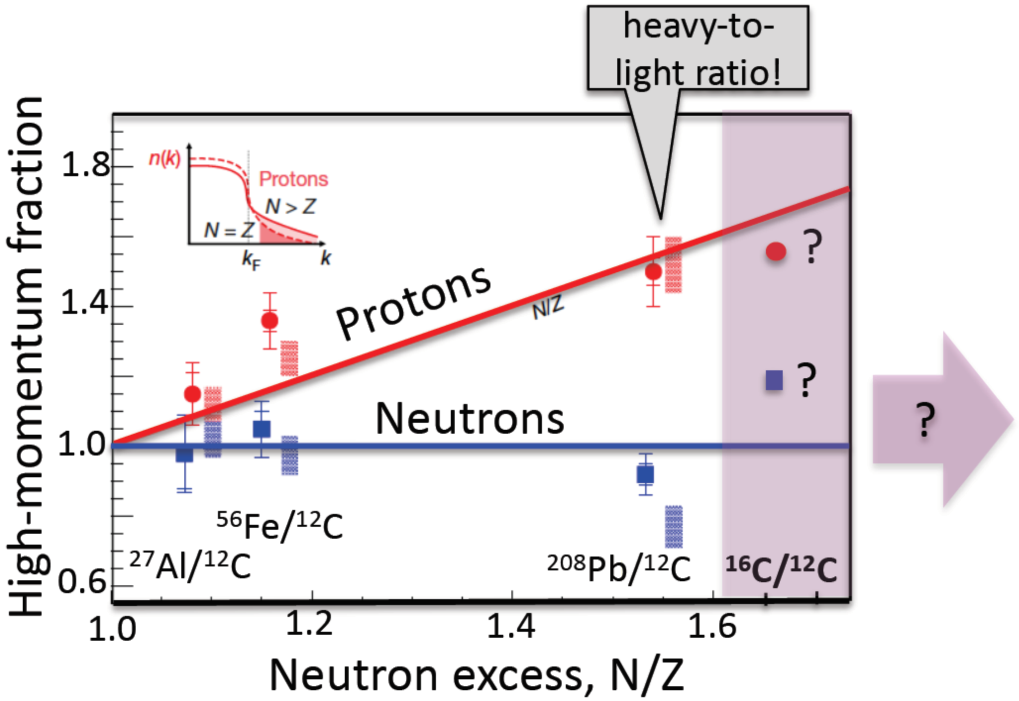


Momentum resolution unreacted ^{12}C beam:
d*p*/*p* = 1.6% (σ)

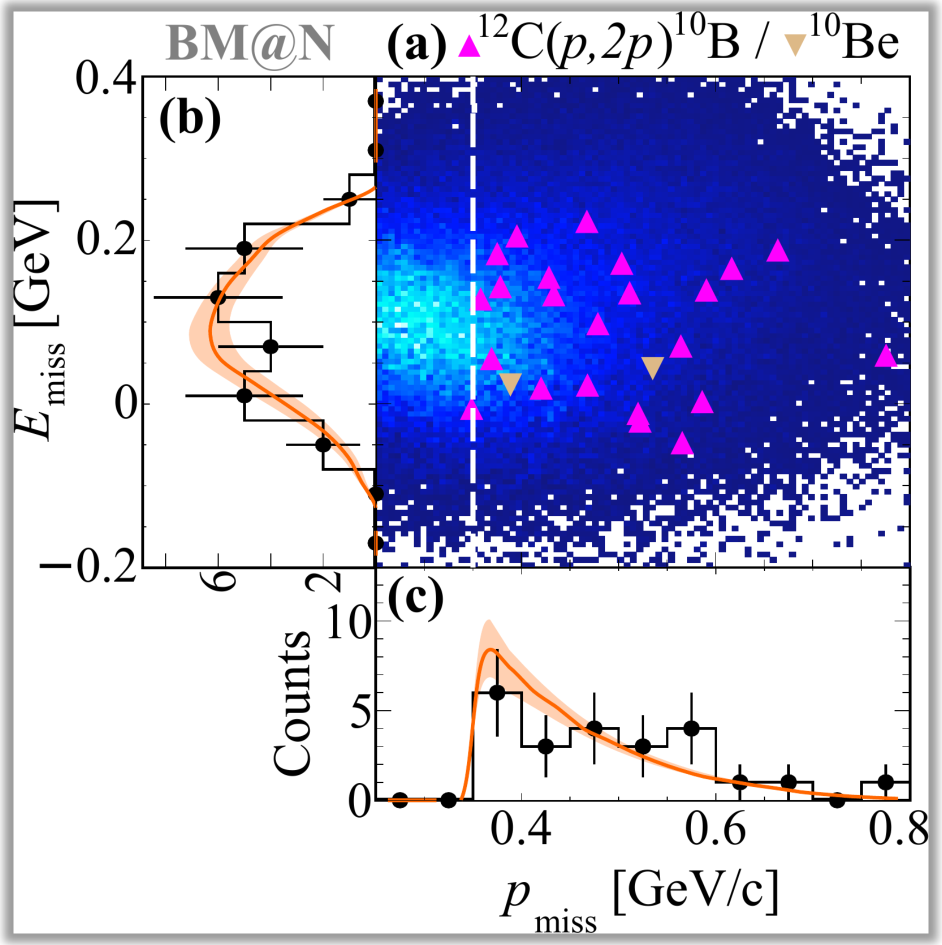


Outlook

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

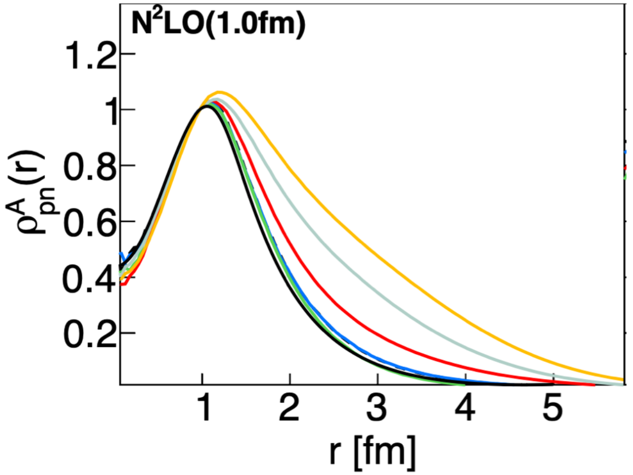
$$n^{A}_{\alpha,NN}(Q,q) = \tilde{C}^{A}_{\alpha,NN}(Q) \times |\tilde{\varphi}^{\alpha}_{NN}(q)|^2$$

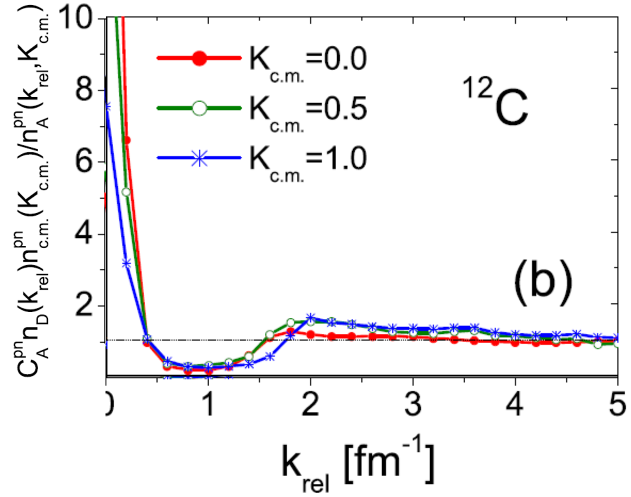
universal

small c.m. motion ~ A-2

strongly correlated pair [universal 2-body]

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





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

t distance]

Factorization of a SRC distribution function:

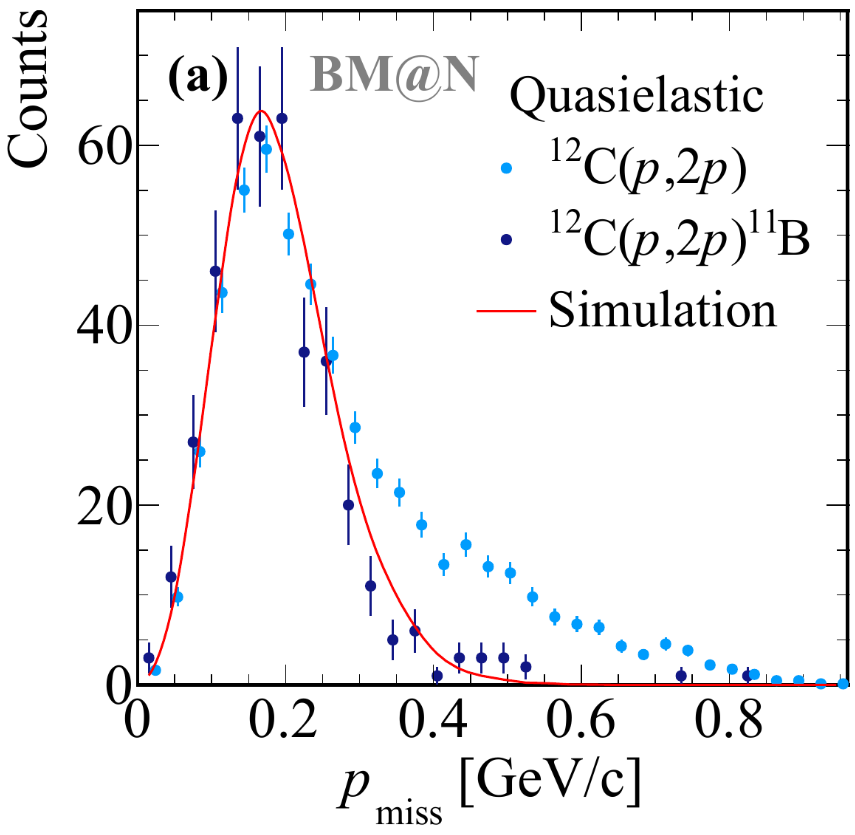
$f(p_{rel}, p_{c.m.}, \theta_{rel,c.m.}) \approx C(p_{c.m.}) \times \varphi(p_{rel})$

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

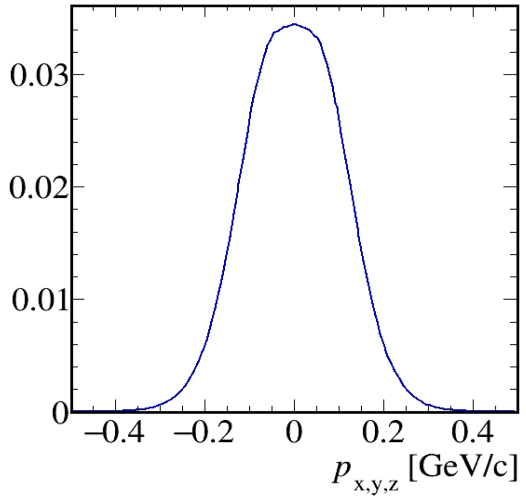
rmalism

Reconstructed initial momentum

Fragment tagging suppresses ISI / FSI

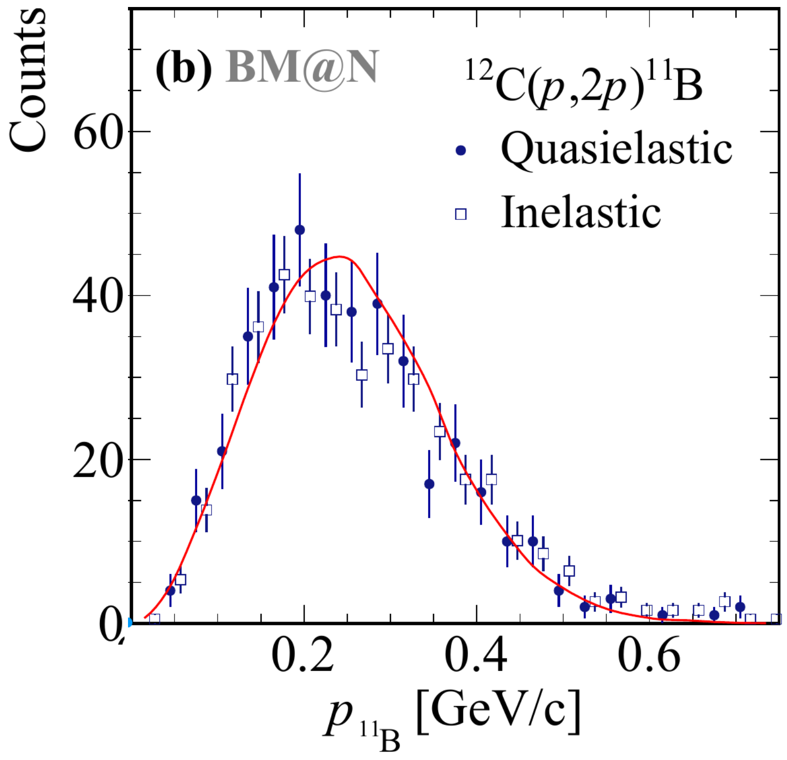


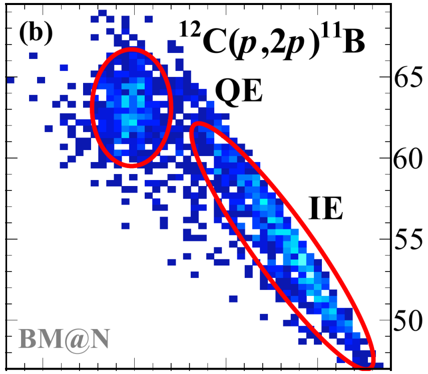
Simulation input:
^{12}C $p_{3/2}$ shell distribution w/o FSI



Fragment recoil momentum

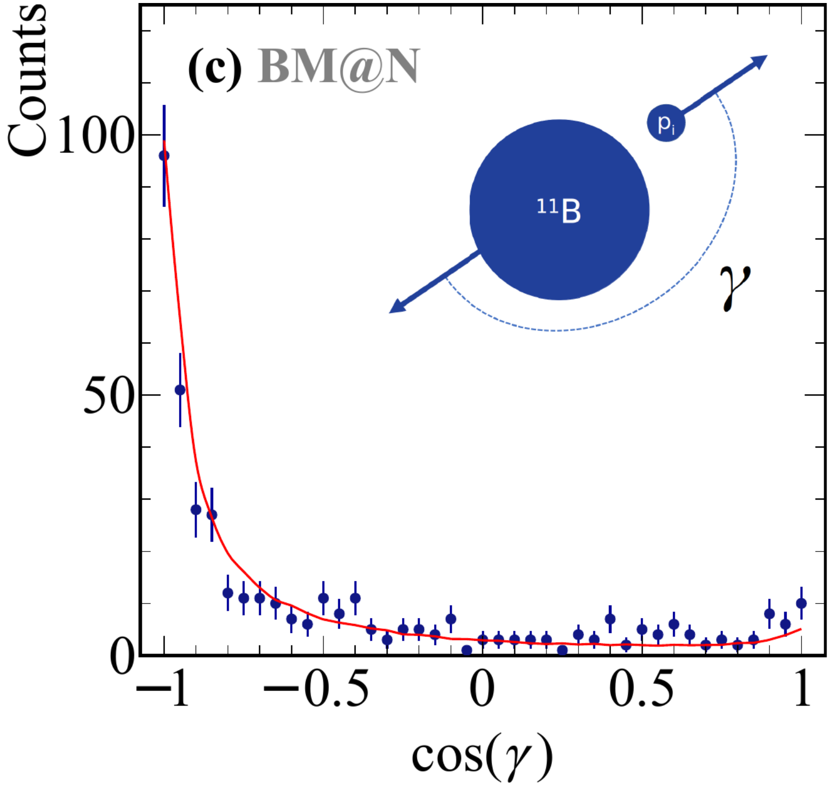
- **Fragment not impacted by ISI / FSI: reconstruct *p_{miss}***
- **Adiabatic approximation holds *p_{miss} = -p_{A-1}***



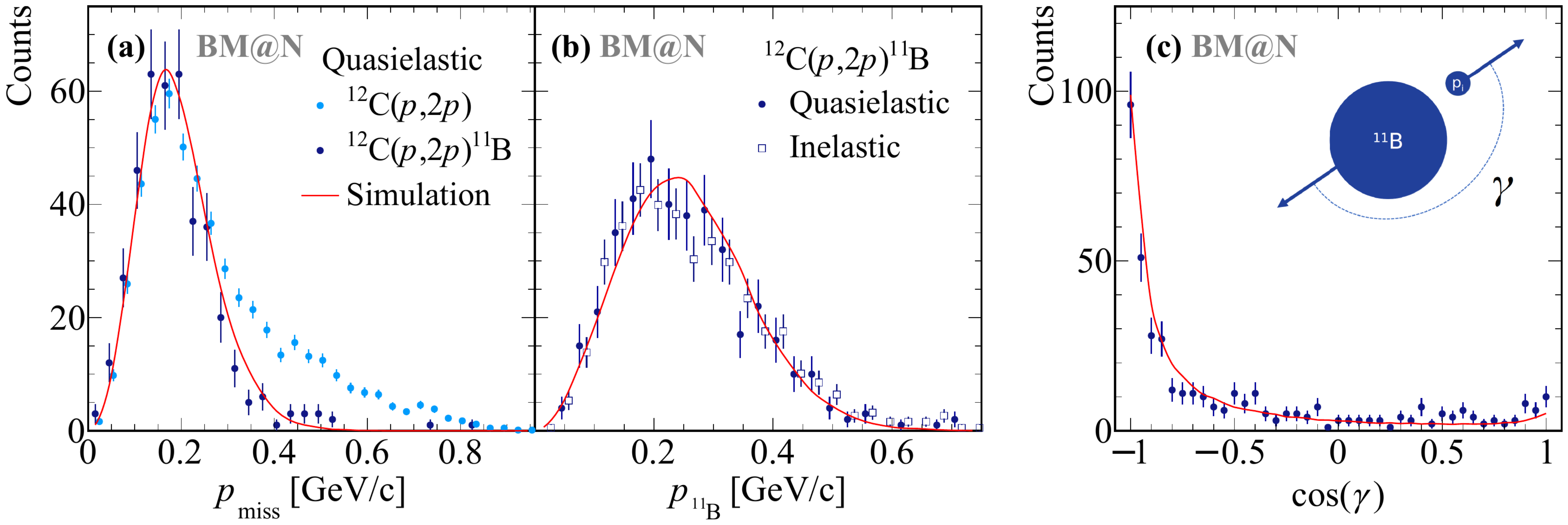


P_{miss} balances the recoil fragment momentum

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* !