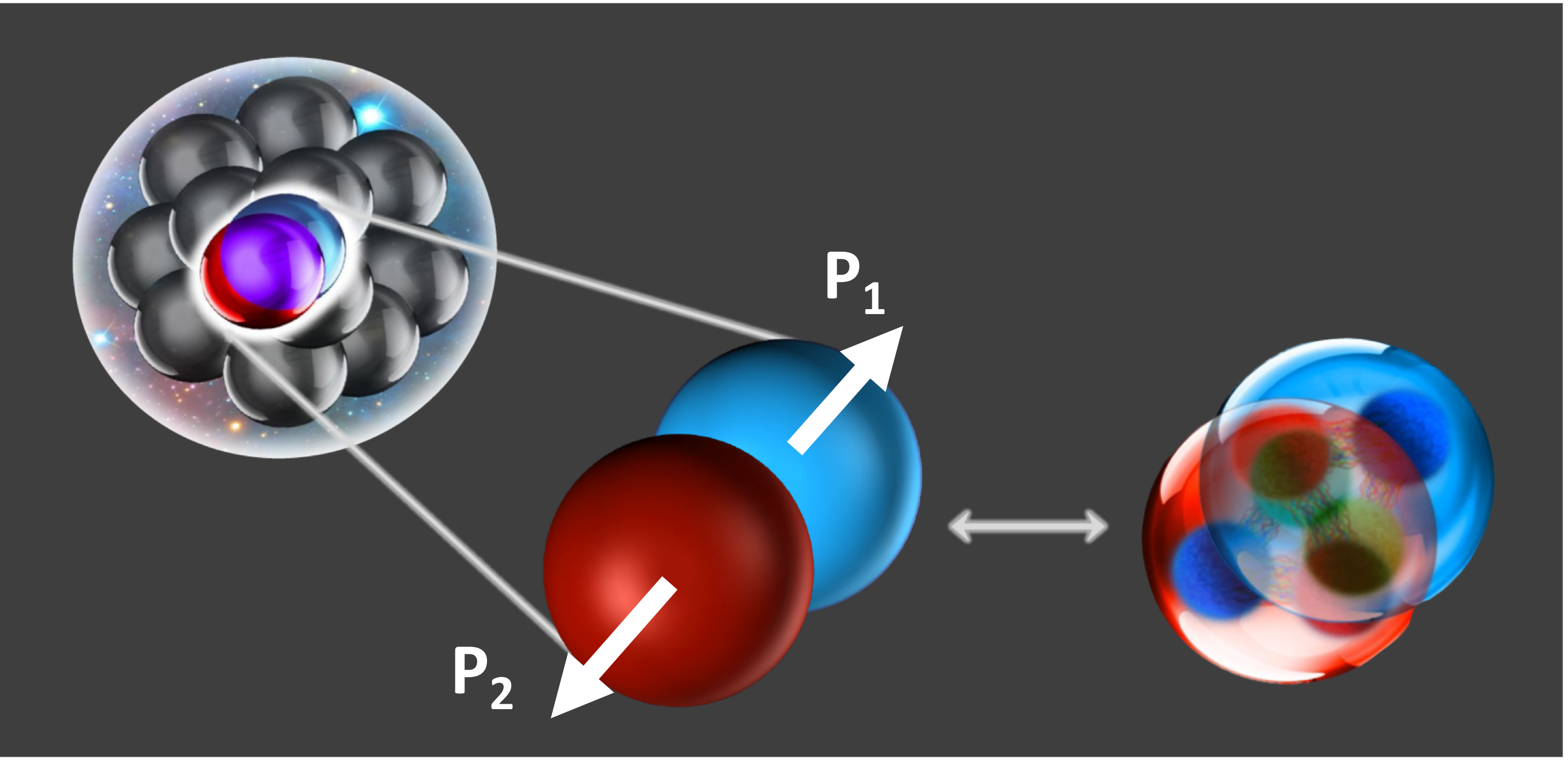
Experimental study of cold dense nuclear matter

Maria Patsyuk (JINR)

INFINUM 2023

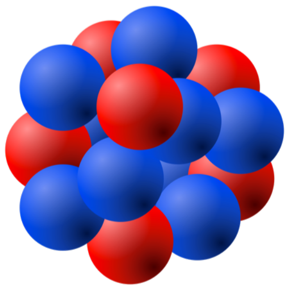
Short-Range Correlations (SRCs) – local nuclear density fluctuations by close proximity nucleon pairs



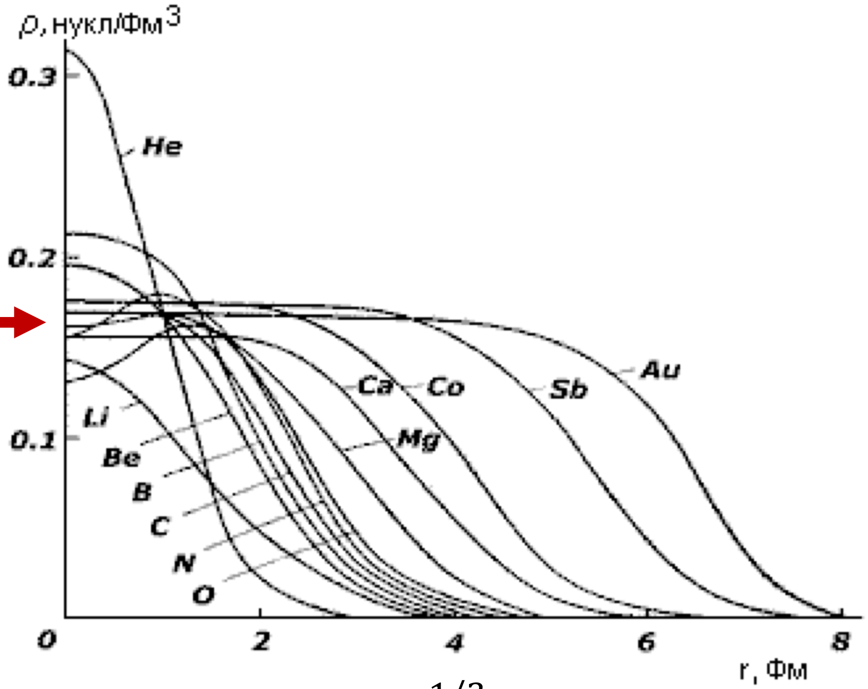
Momentum space: high relative and low c.m. momenta, compared to the Fermi momentum (kF)

$P_1 > p_F$ $P_2 > p_F$ $P_1 \sim P_2$

$p_F \sim 250$ MeV/c



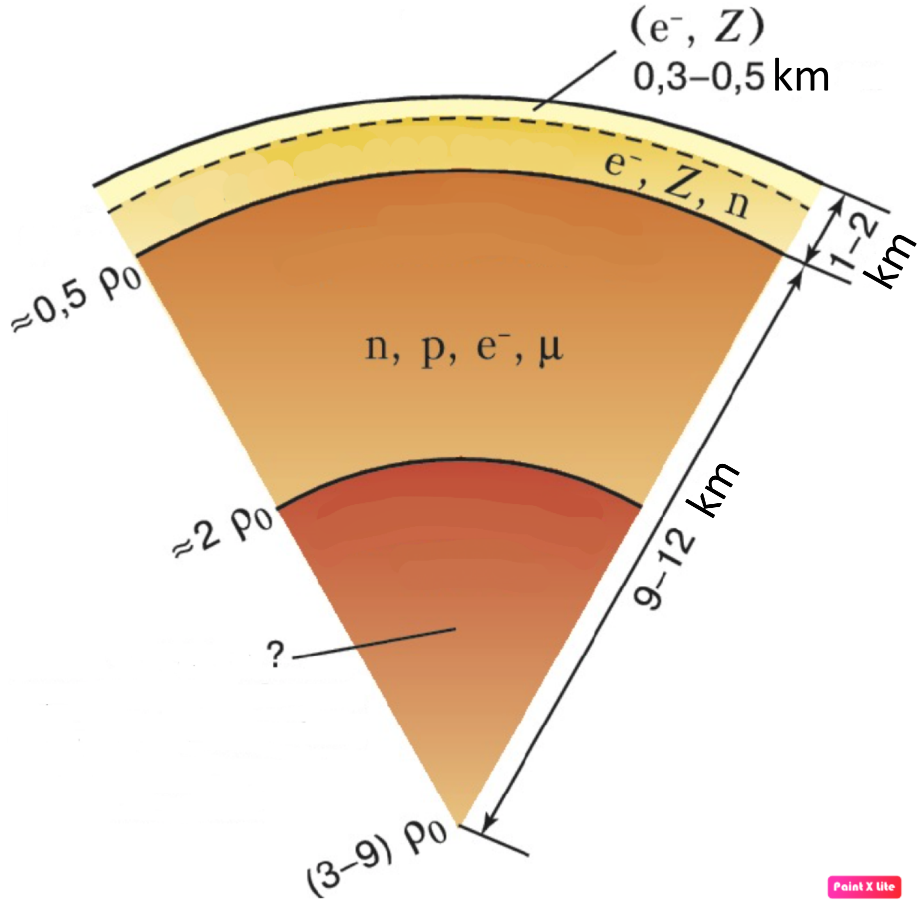
Nucleus is the densest matter on Earth



$\rho_0 = 0.17$ nucleons/fm^3

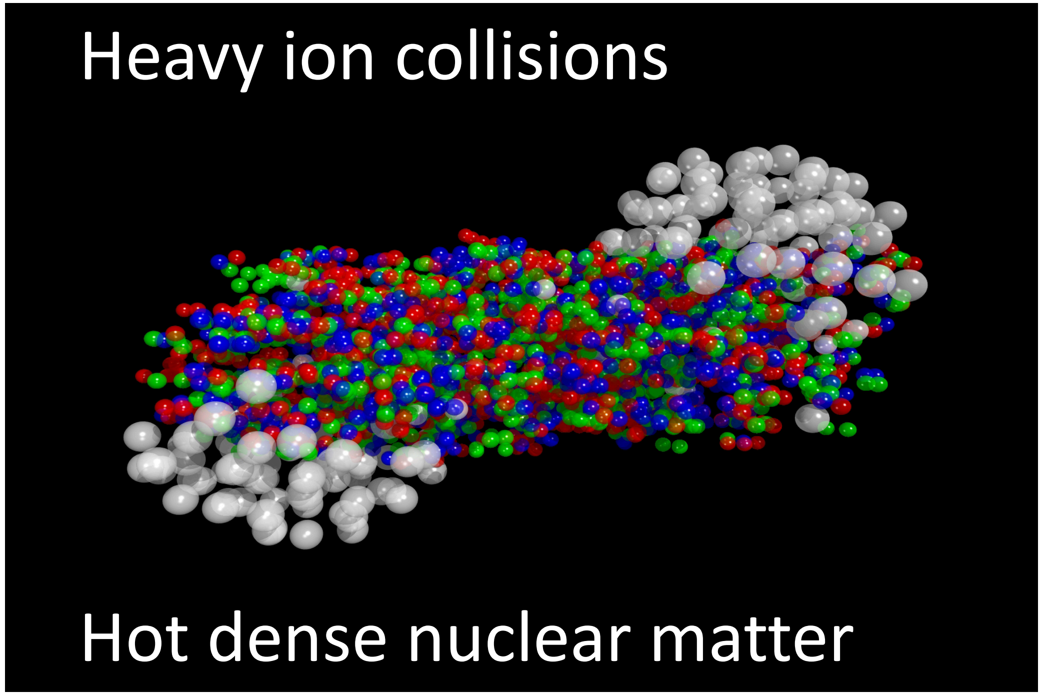
r $= 1.3\, A^{1/3}$

Internal structure of a neutron star



Even denser nuclear systems exist in nature – e.g. neutron stars

Densest nuclear matter in the lab



SRC – short-lived density fluctuations

$\rho = (2-5)\rho_0$

20% of nucleons

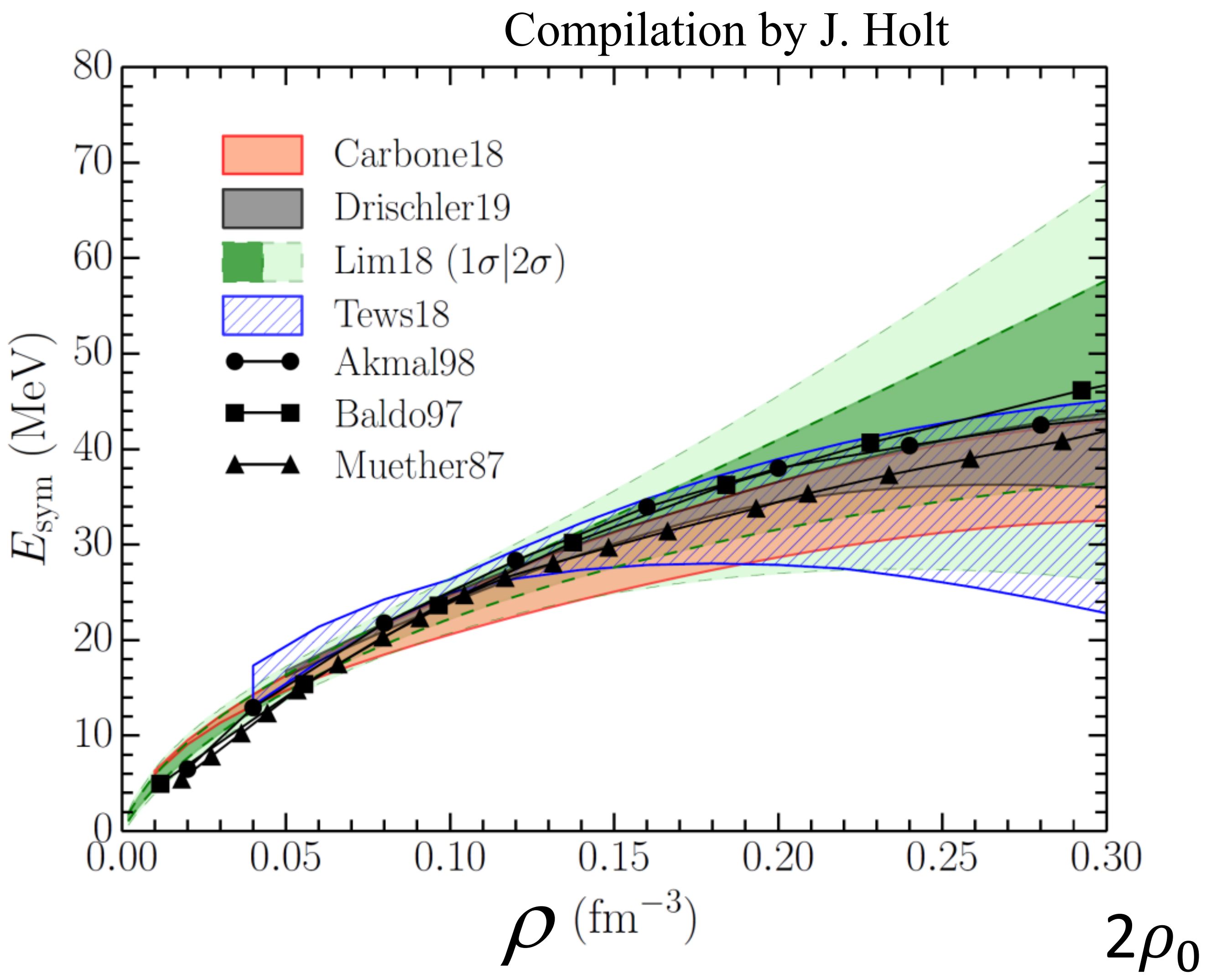
Cold dense nuclear matter

SRC is a key to understand:

1. E_{sym} which is important for neutron stars' EOS

2. NN-interactions at short distances

3. Parton distribution functions

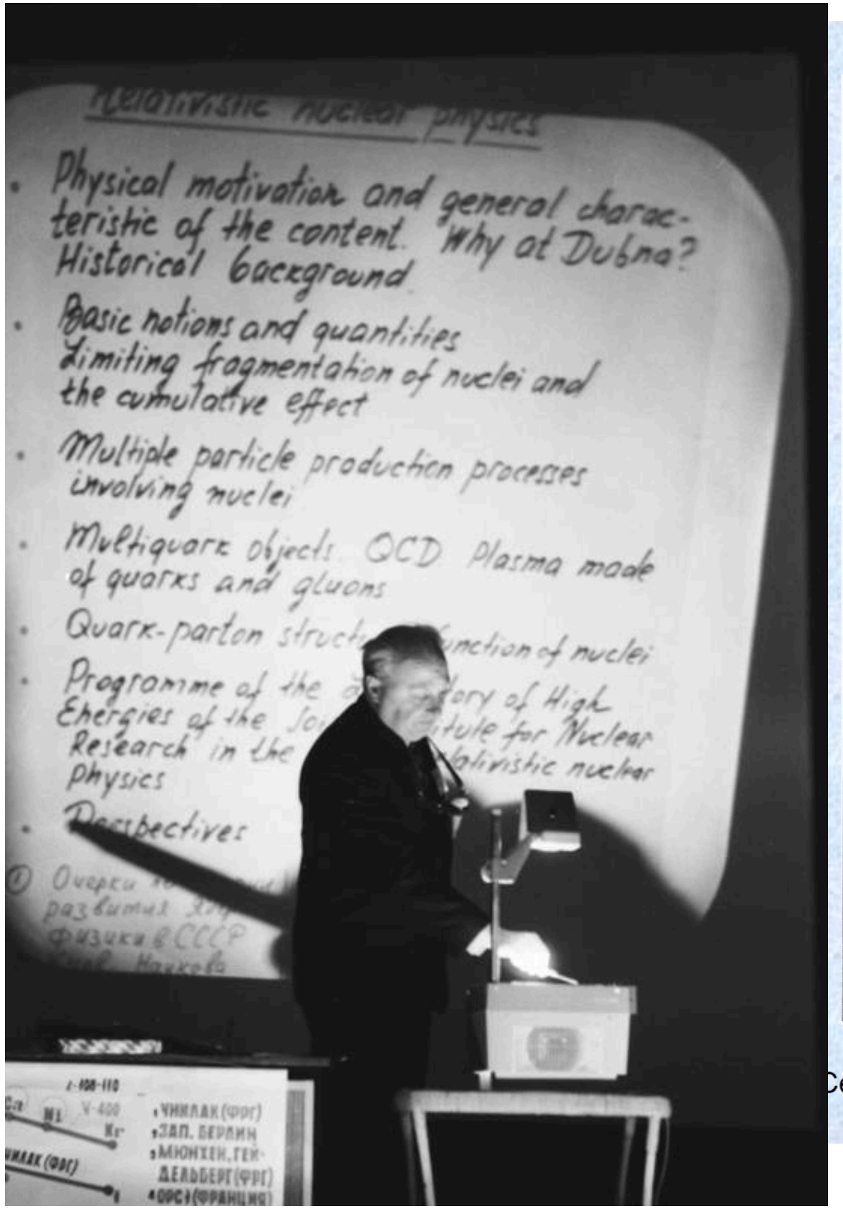


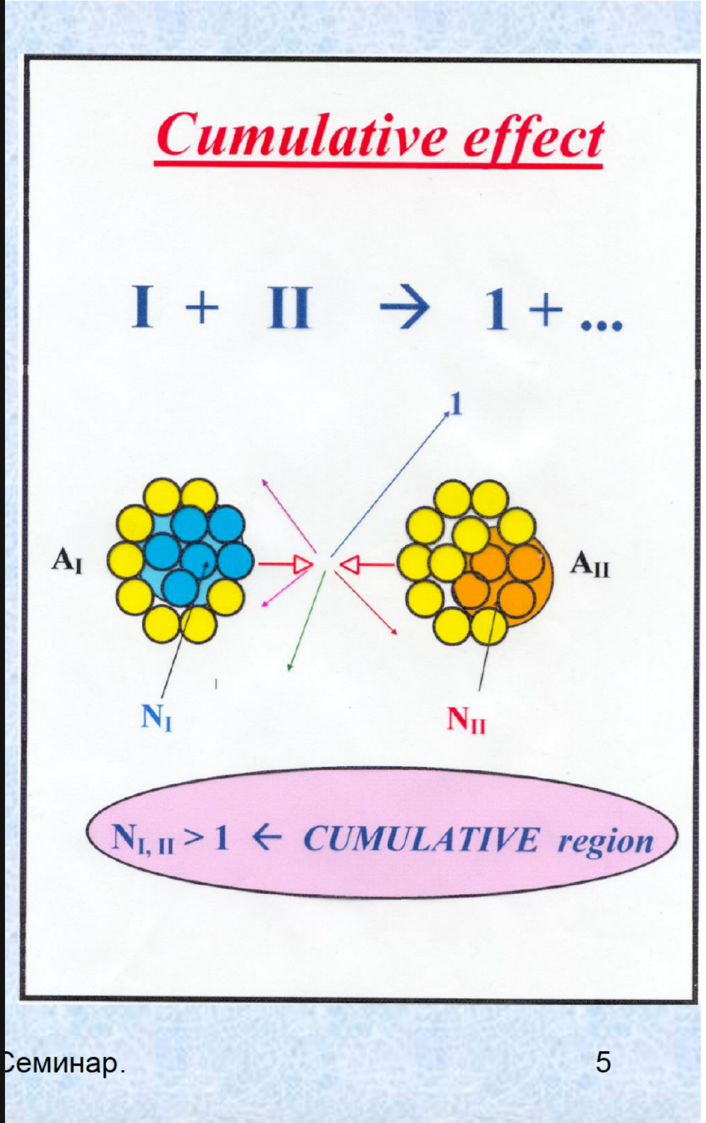
SRC historically connected to JINR

G.A. Leksin
D.I. Blokhintsev
A.V. Efremov
V.V. Burov
V.K. Lukyanov
A.I. Titov
A.M. Baldin…

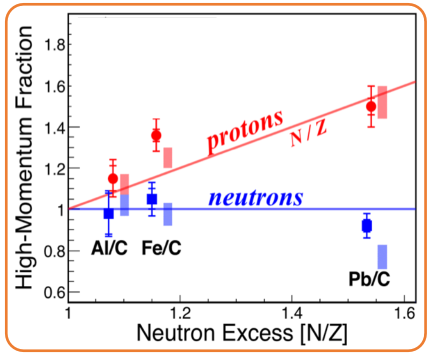
fluctuons

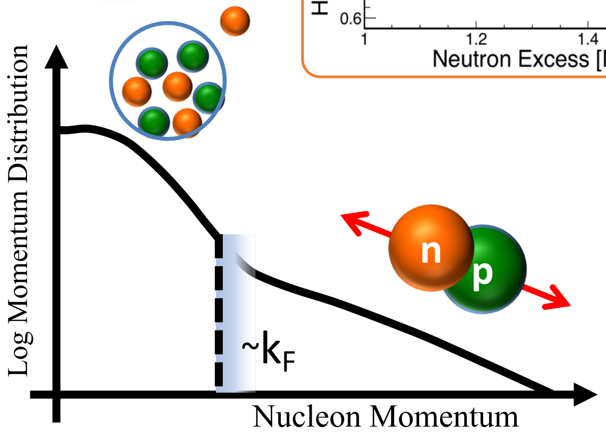
cumulative effect





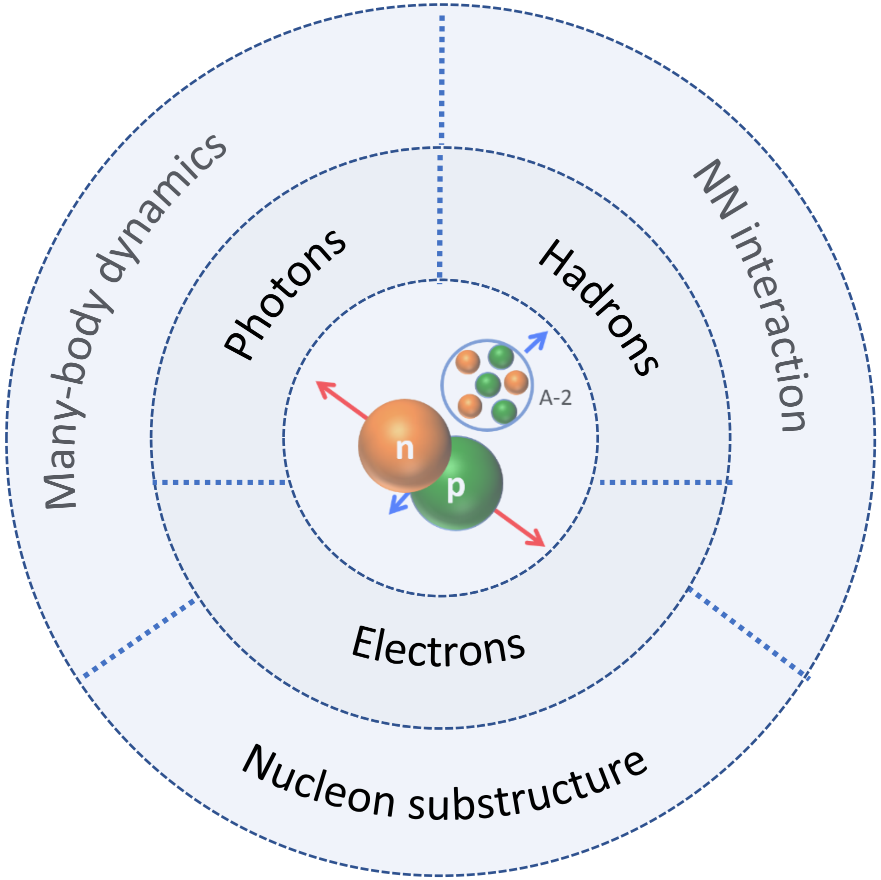
SRC studies relevant for many fields

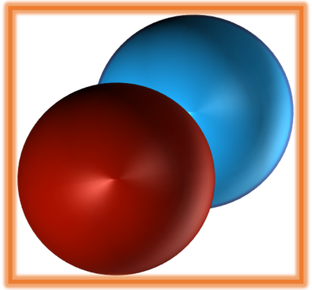




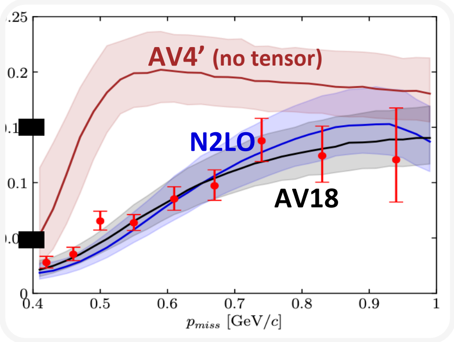
Nature ’18
Phys. Rev. Lett. ‘18
Phys. Lett. B ‘18a
Phys. Lett. B ’18b

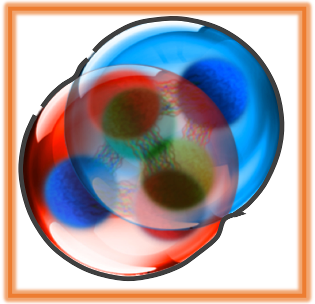
Phys. Rev. Lett. ’19
Phys. Lett. B ’19
Nature Phys. ’21a
Nature Phys. ’21b

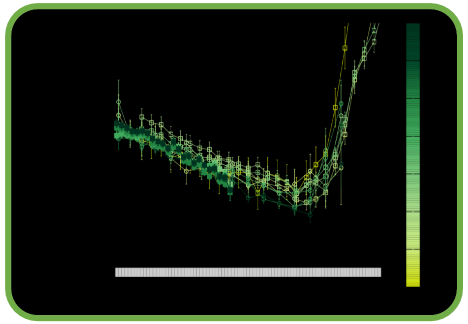




Nature ’20
Phys. Rev. Lett. ’20
Phys. Lett. B ‘20
Phys. Lett. B ‘21

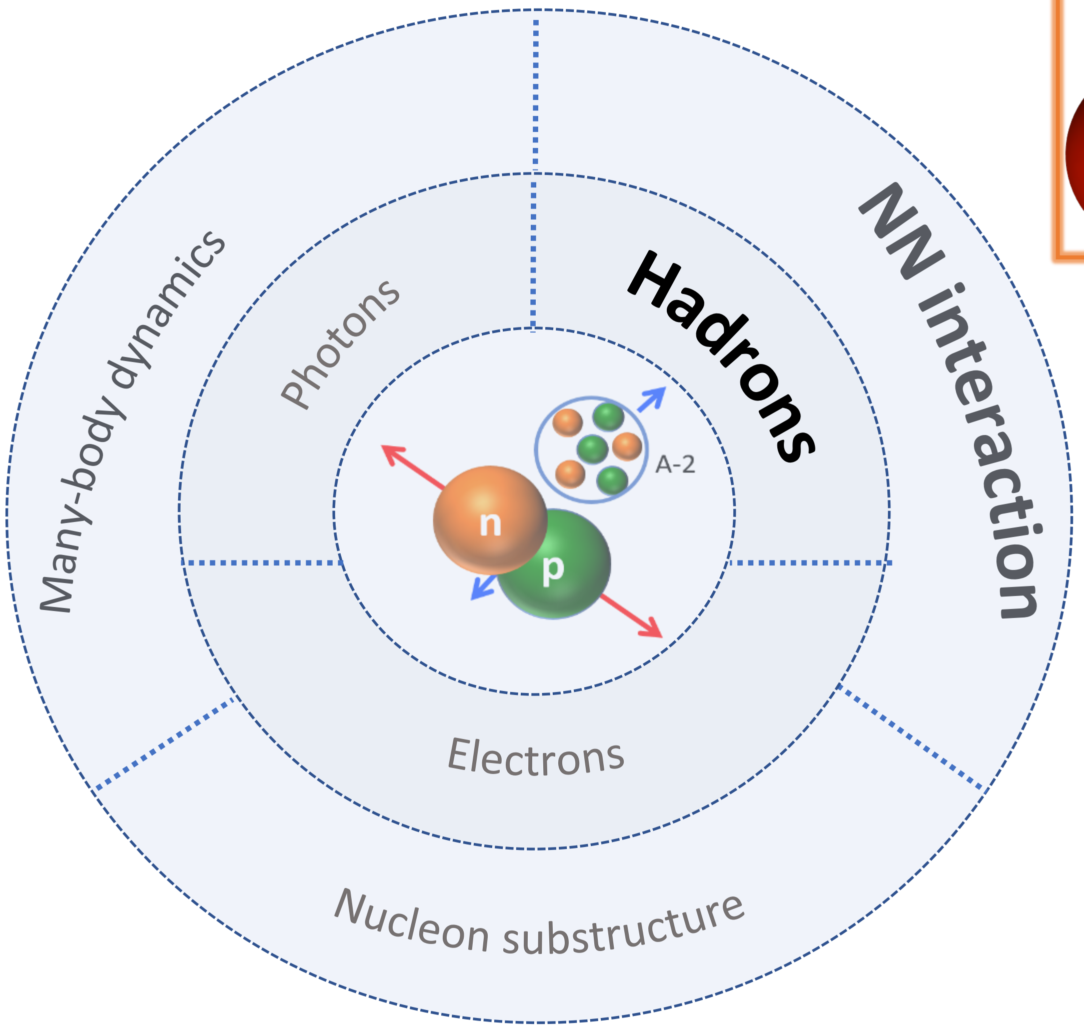


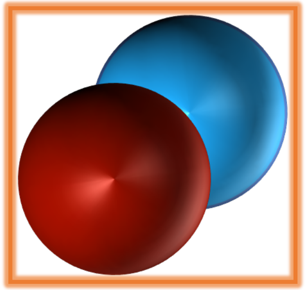




Nature ’19
Phys. Rev. Lett. ’20
Phys. Rev. Research ‘21

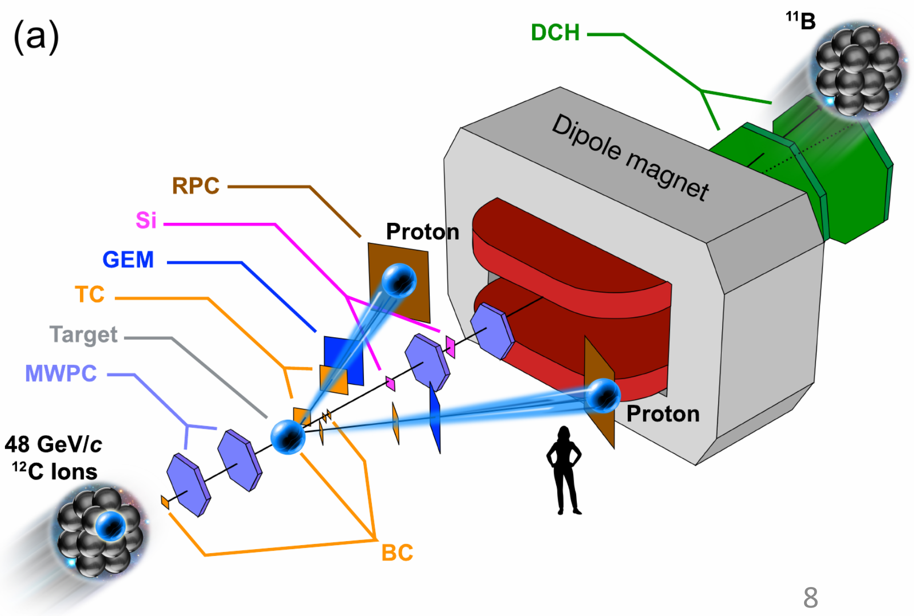
SRC @ JINR



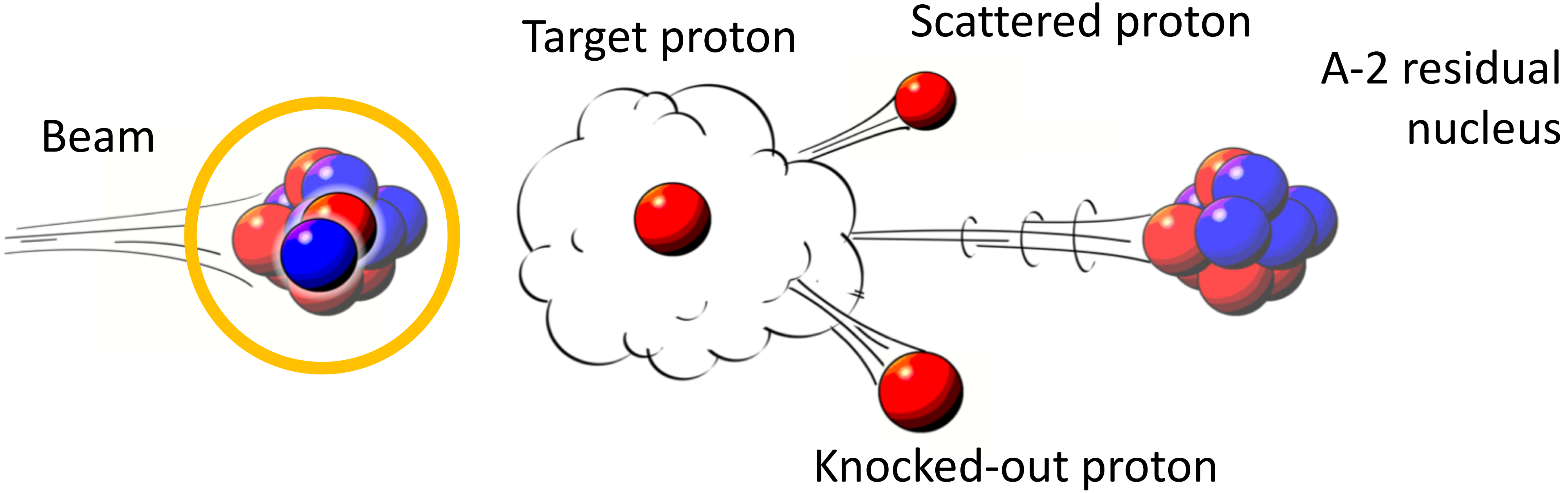


BM@N at Nuclotron

2018 and 2022 experiments

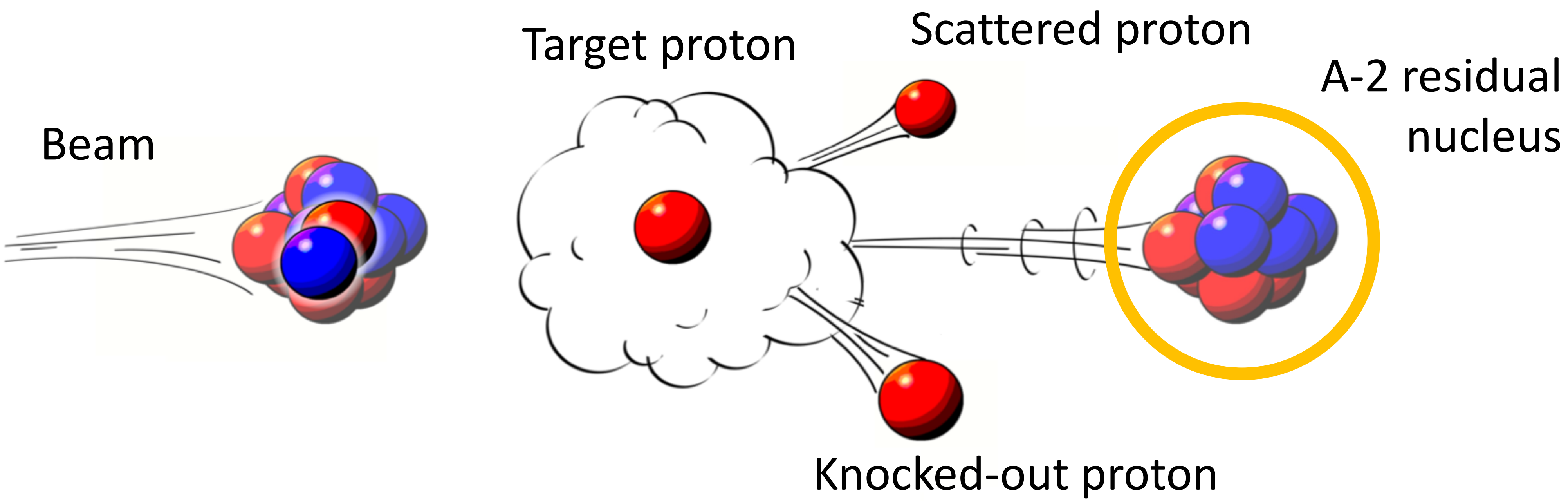


Quasi-free (p,2p) scattering in **inverse kinematics**



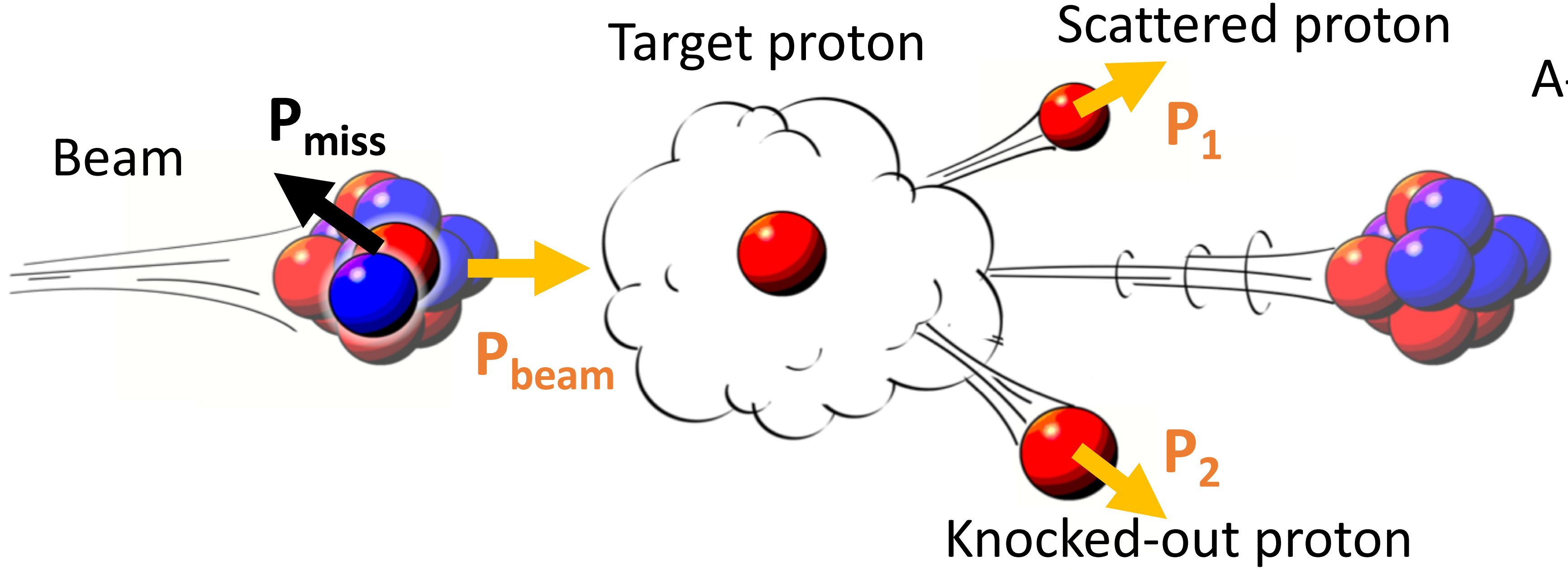
- Access to neutron-rich/exotic unstable nuclei (impossible with a fixed target)
- High cross section compared to e-scattering

Quasi-free (p,2p) scattering: **detection A-2**



Suppressing ISI/FSI using fragment tagging **and accessing the ground state distribution of nucleons in ^{12}C**

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



Reconstruct initial nucleon momentum $\mathbf{P_{miss}}$ from scattered particles

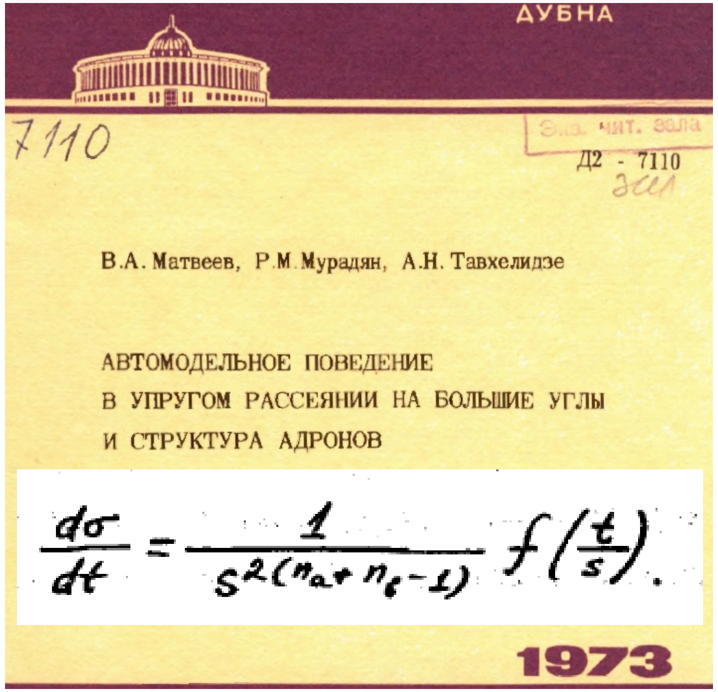
$$\mathbf{P_{miss}} = P_1 + P_2 - P_{beam}$$

~ 90° c.m. scattering

Elastic (pp,pp) scattering near 90°

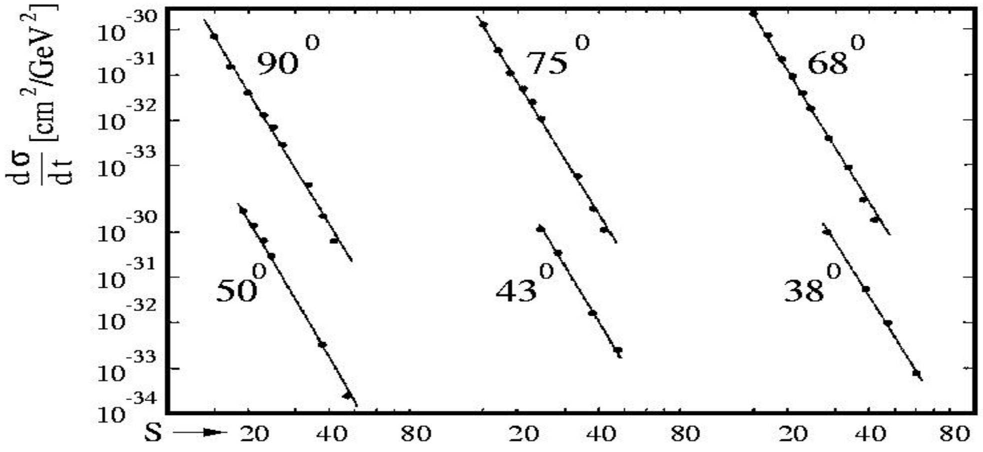
Automodel behavior

Constituent counting rules

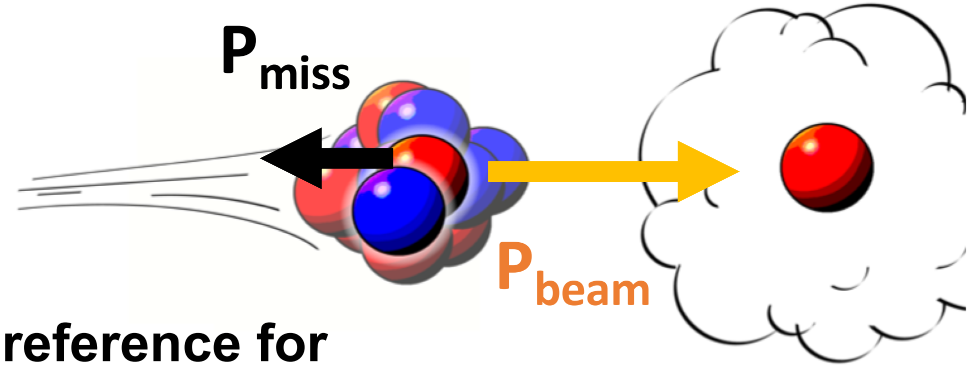


$$\frac{d\sigma}{dt} = \frac{1}{s^{2(n_a+n_b-1)}} f\left(\frac{t}{s}\right).$$

LETTERE AL NUOVO CIMENTO VOL. 7, N. 15 11 Agosto 1973



$$\frac{d\sigma}{dt} \propto s^{-10}$$

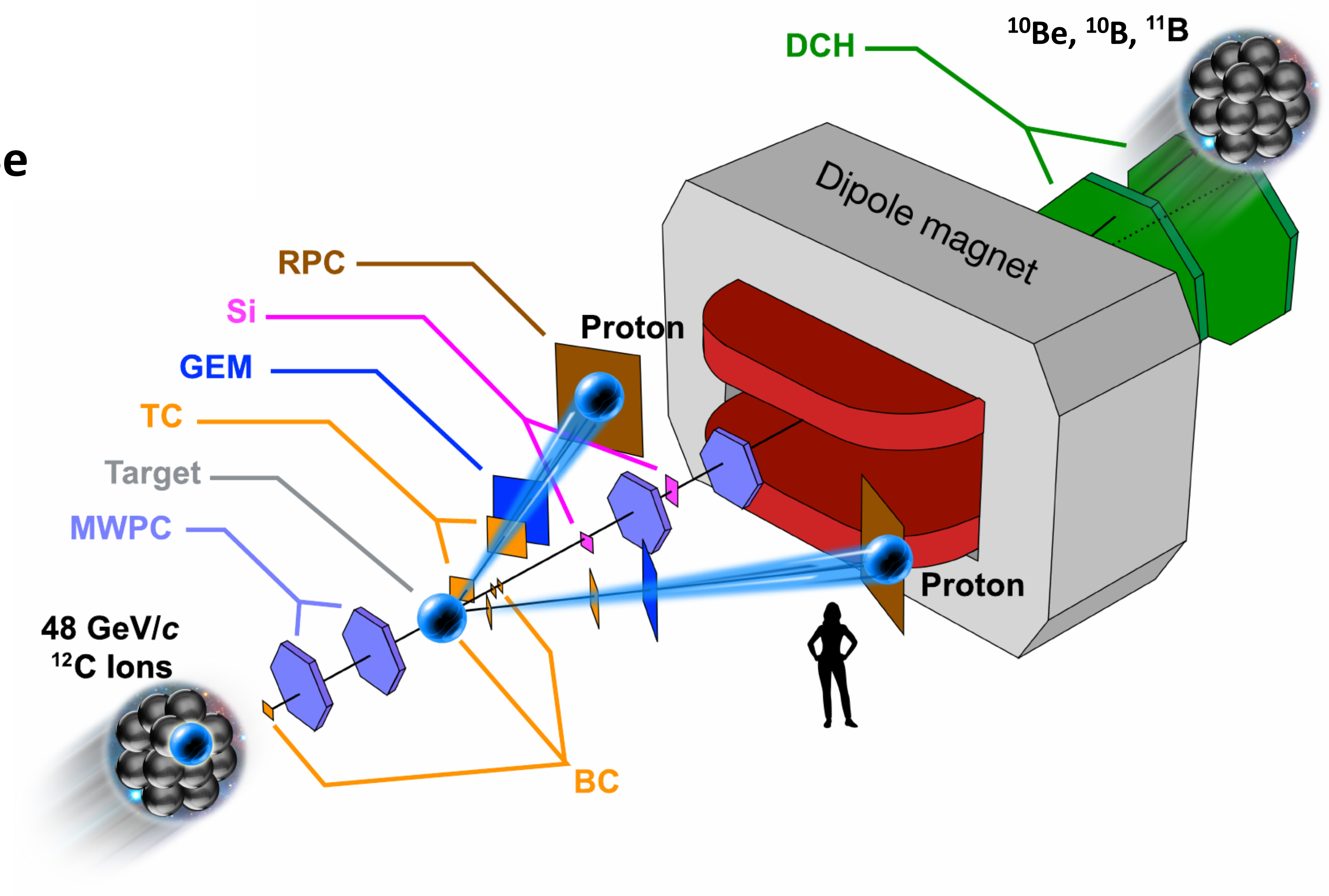


QE pp scattering have a very strong preference for reacting with high-momentum nuclear protons (lower s).

Pilot experiment at BM@N in 2018

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

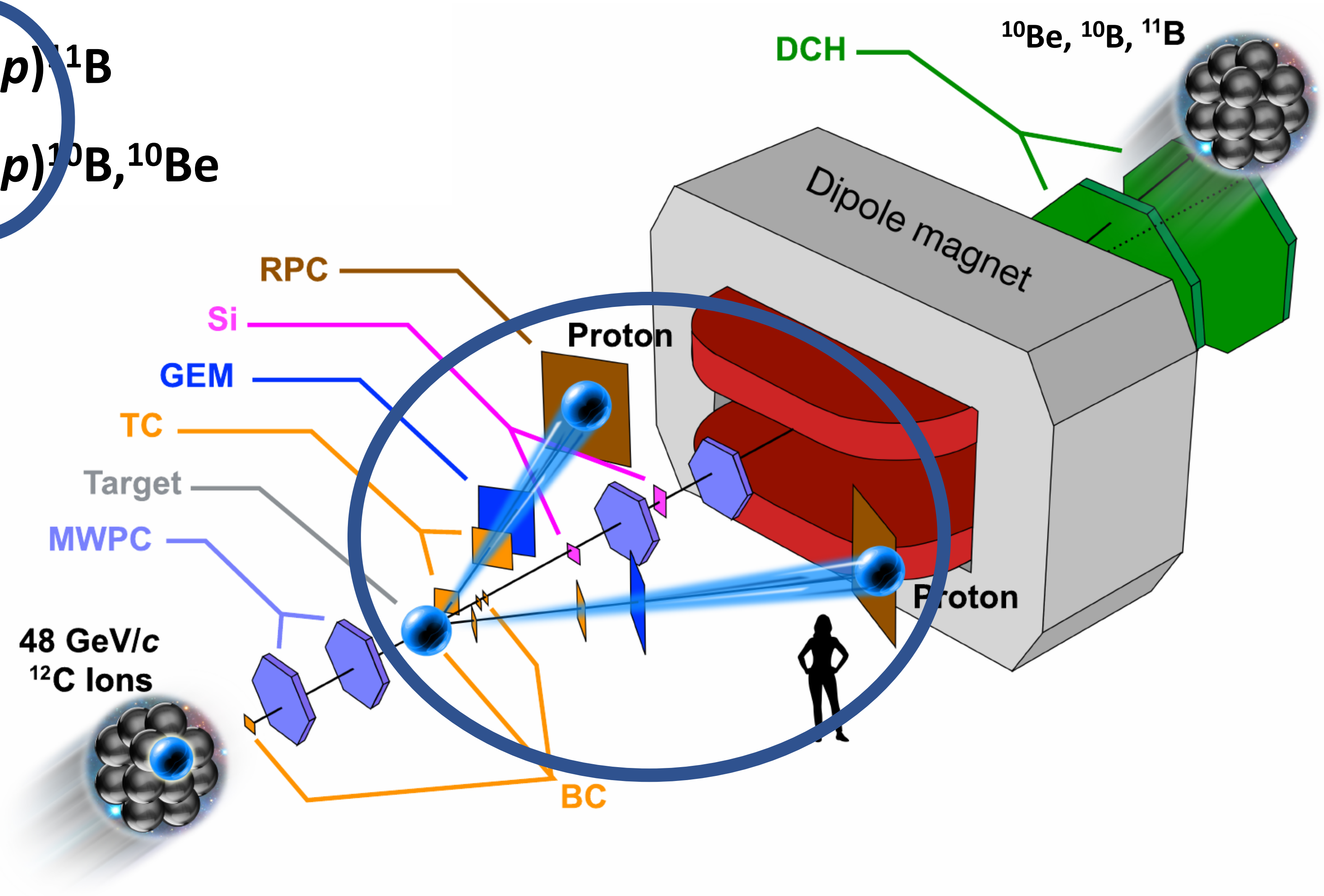
SRC: $^{12}C(p,2p)^{10}B,^{10}Be$



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

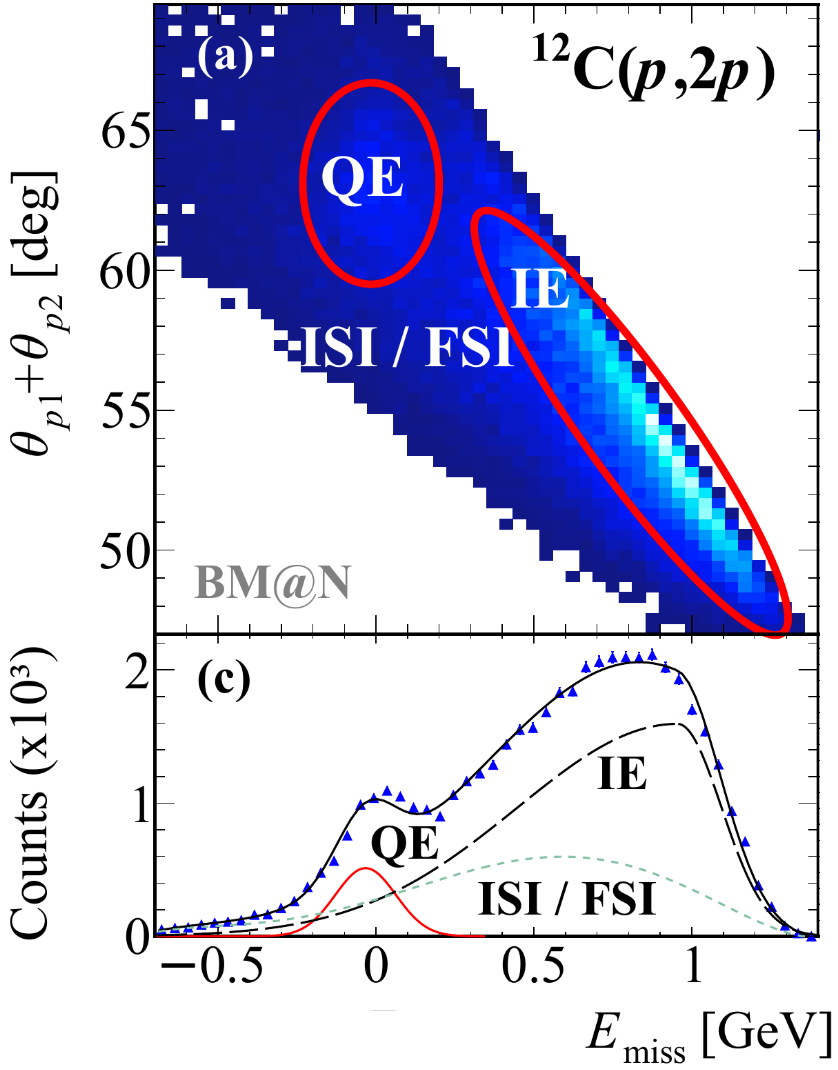
MF: $^{12}C(p,2p)^{11}B$

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



Single proton knockout

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

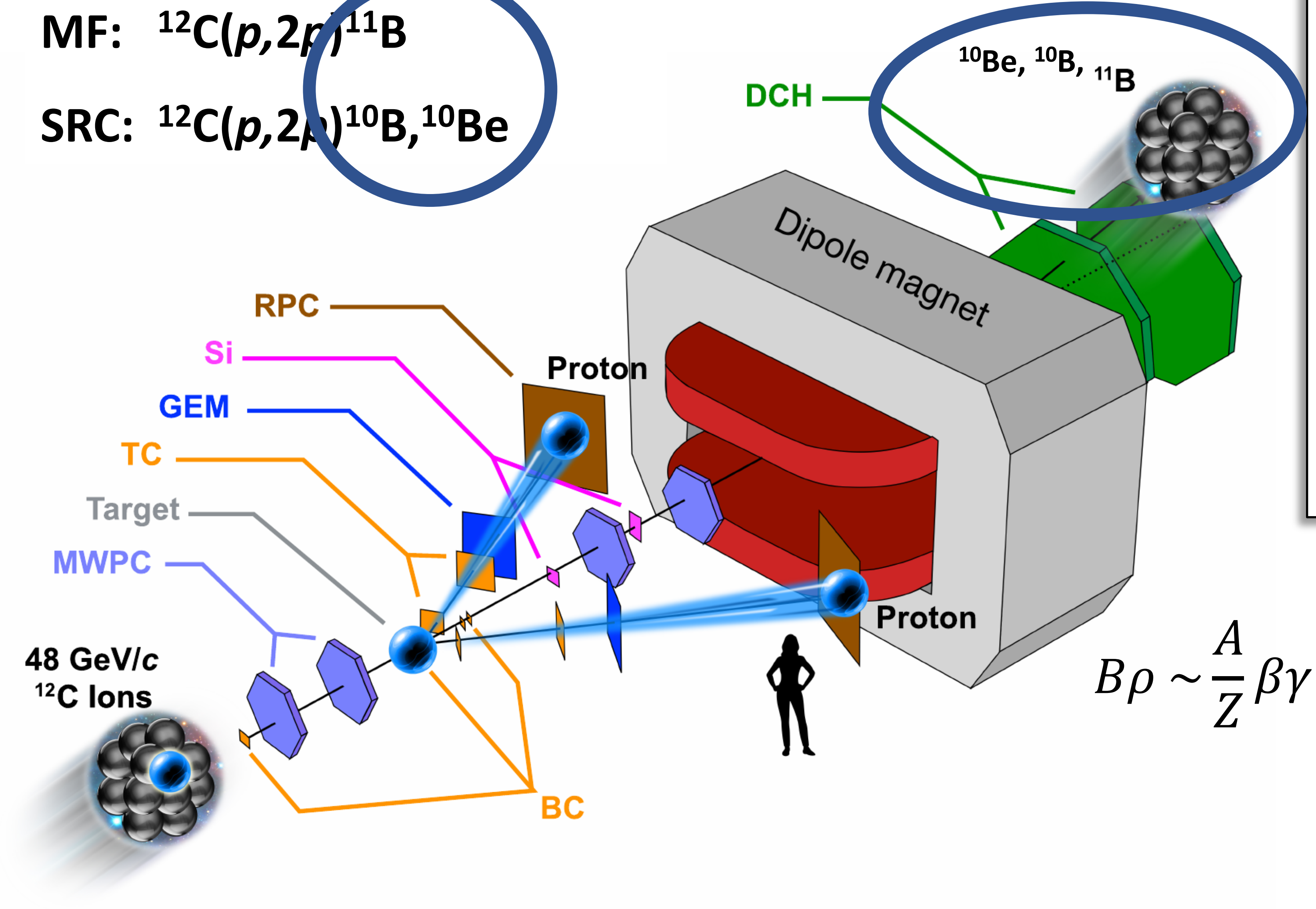


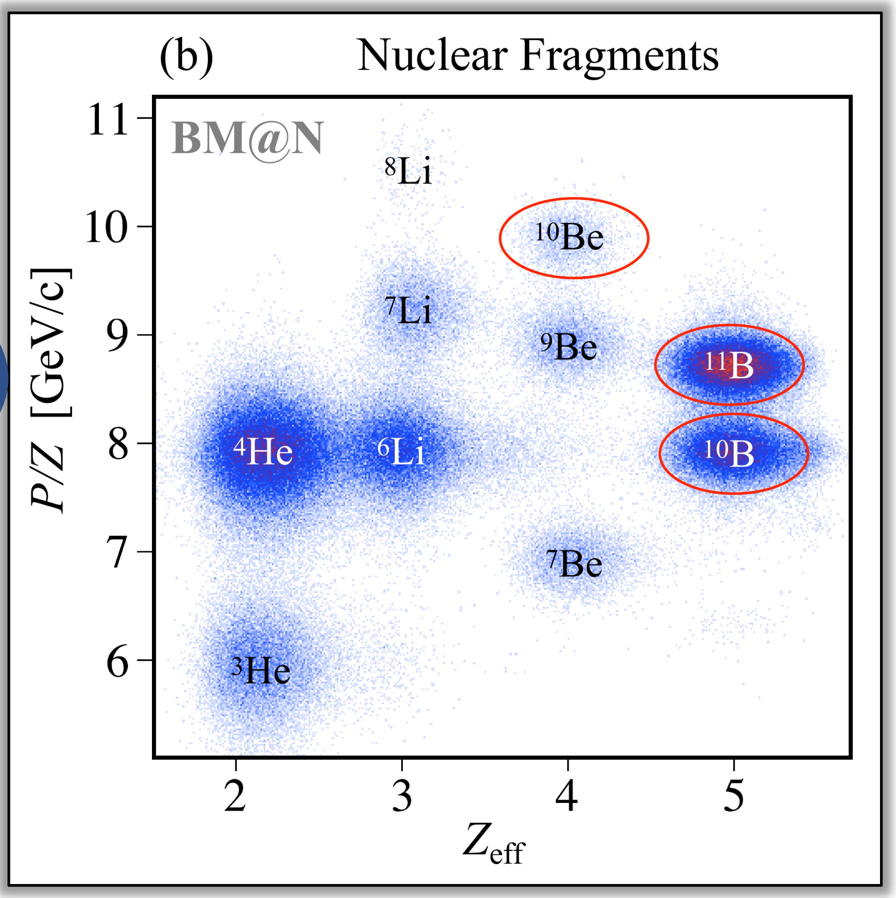
contaminated by
inelastic scattering (IE)
and ISI / FSI

Heavy-fragment identification

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

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

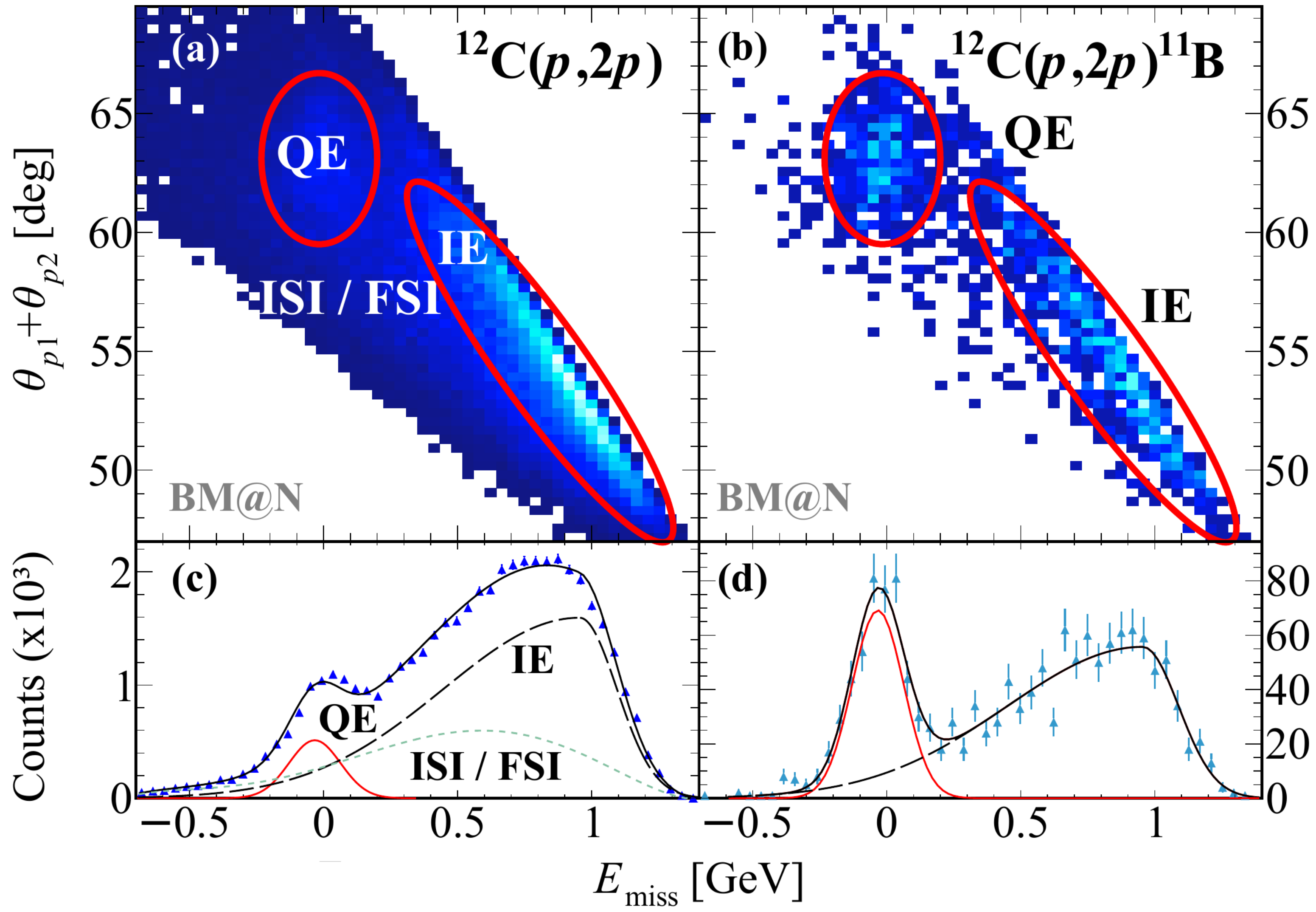




$$B\rho \sim \frac{A}{Z}\beta\gamma$$

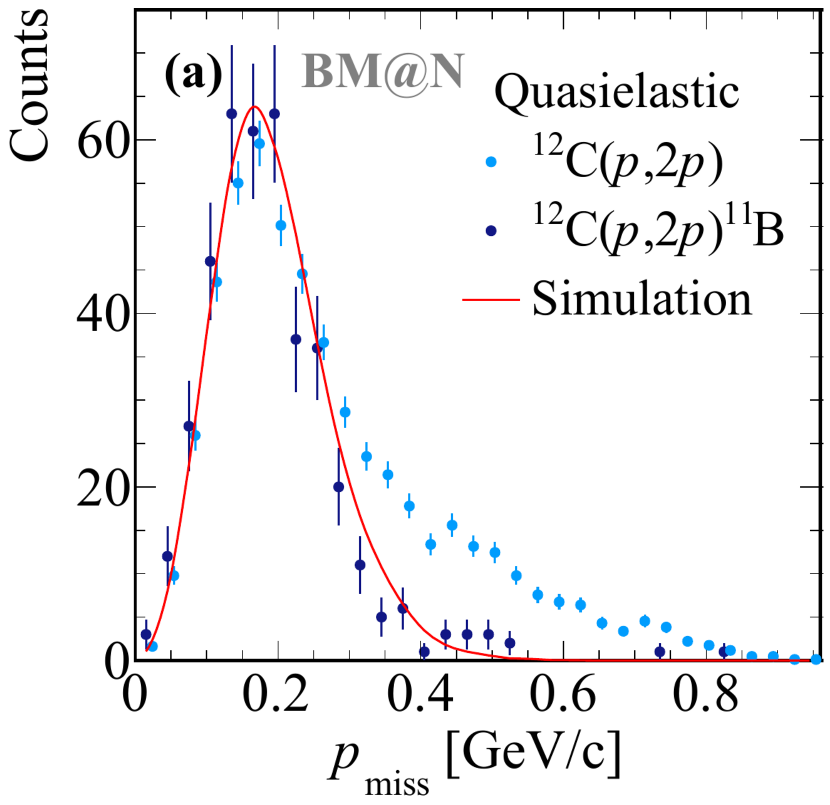
Single proton knockout

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



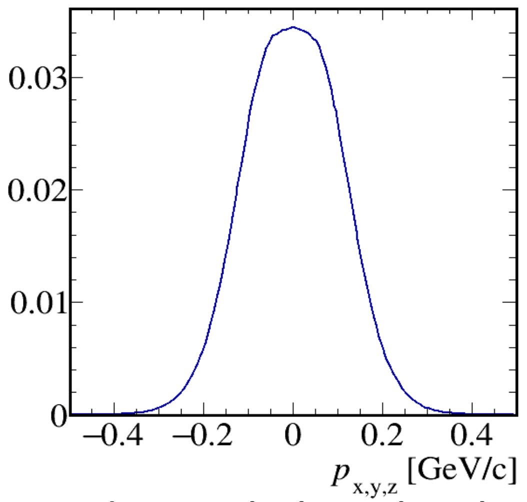
- **fragment tagging removes ISI / FSI**
- select **quasi-elastic scattering (bound ^{11}B)** under large momentum transfer

Initial proton momentum



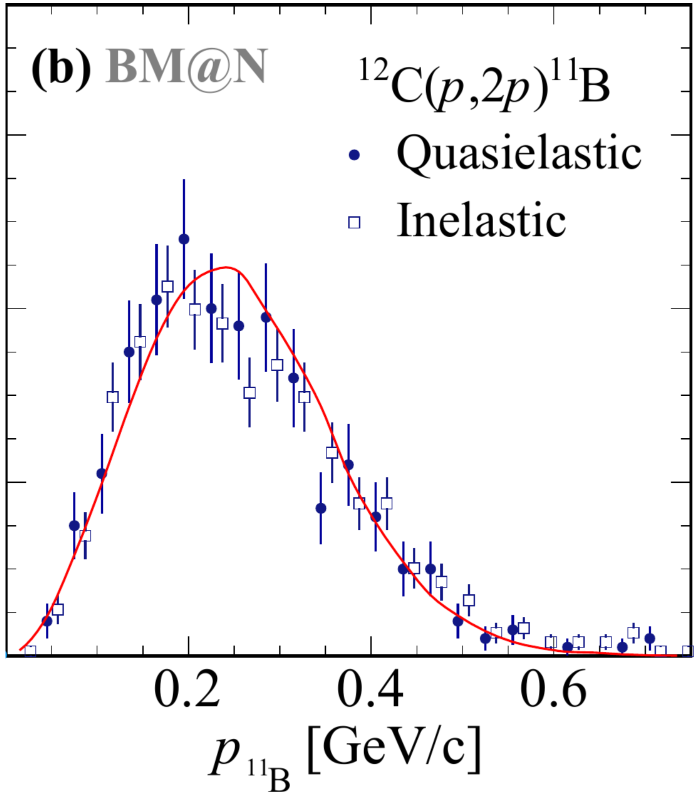
High momentum tail – ISI/FSI

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



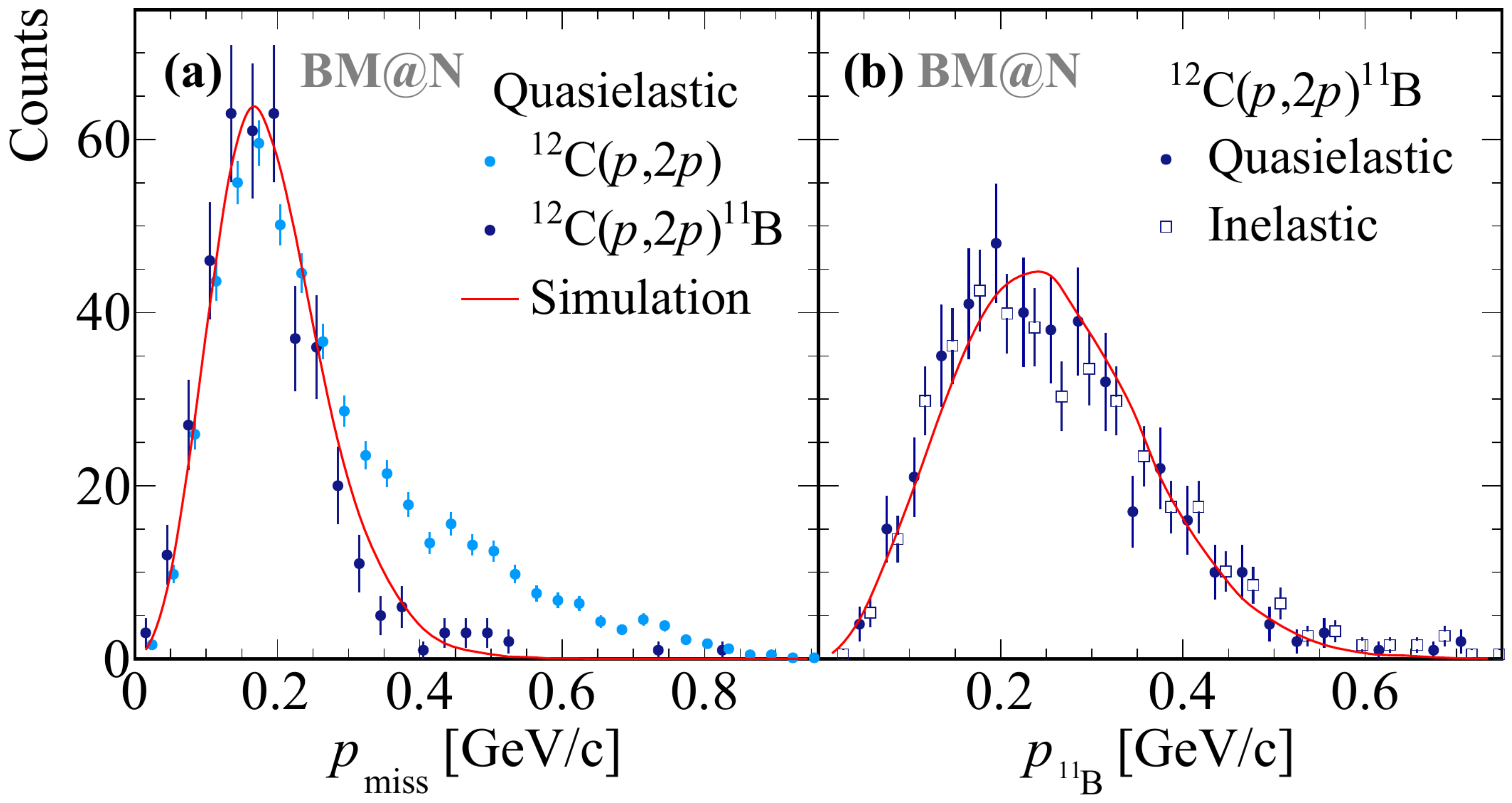
T. Aumann, C. Bertulani, and J. Ryckebusch, Phys. Rev. C 88 (2013)

Recoil fragment momentum



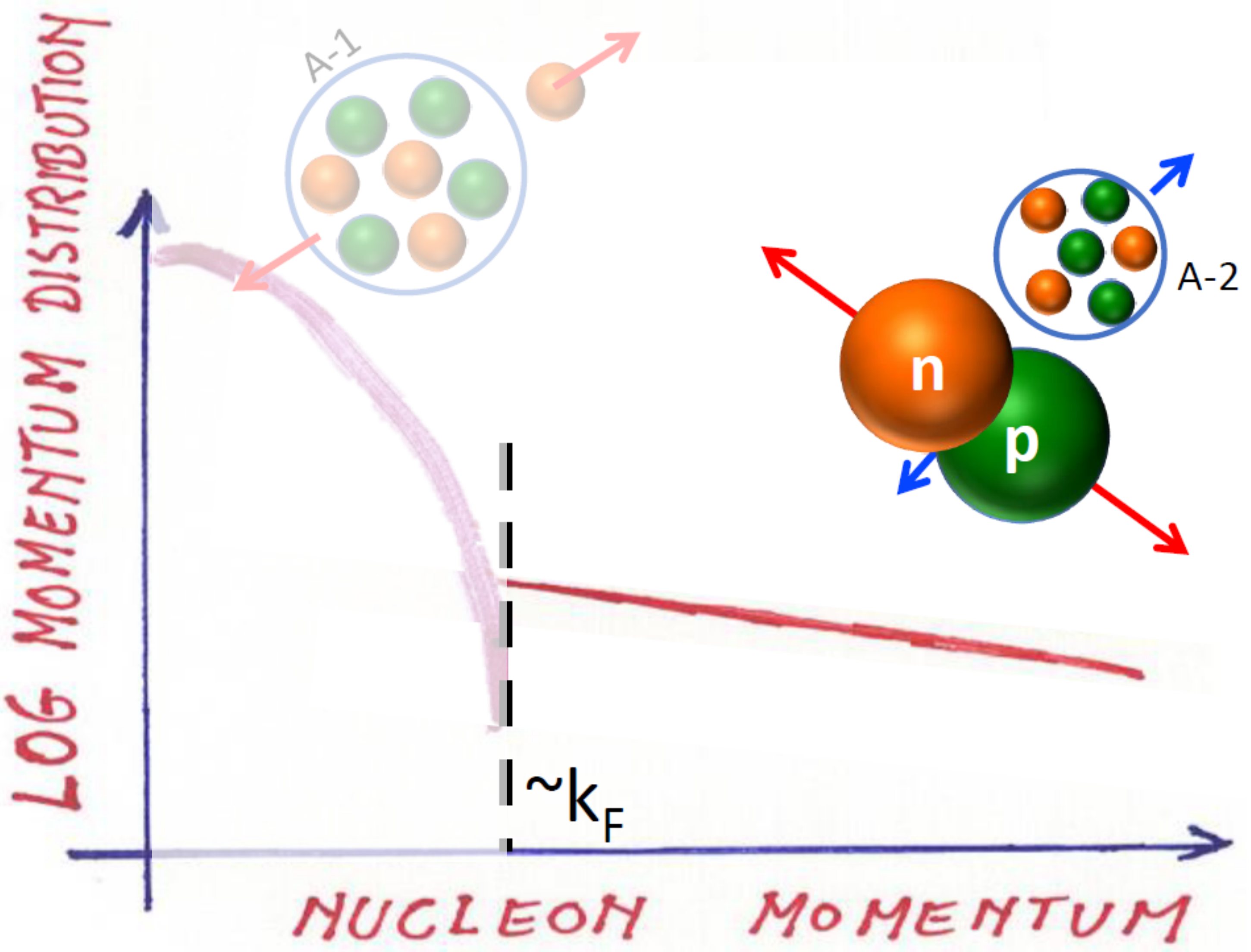
Fragment not impacted by proton multiple scattering → fragment tagging selects **quasi-free unperturbed single-step reactions**

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



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

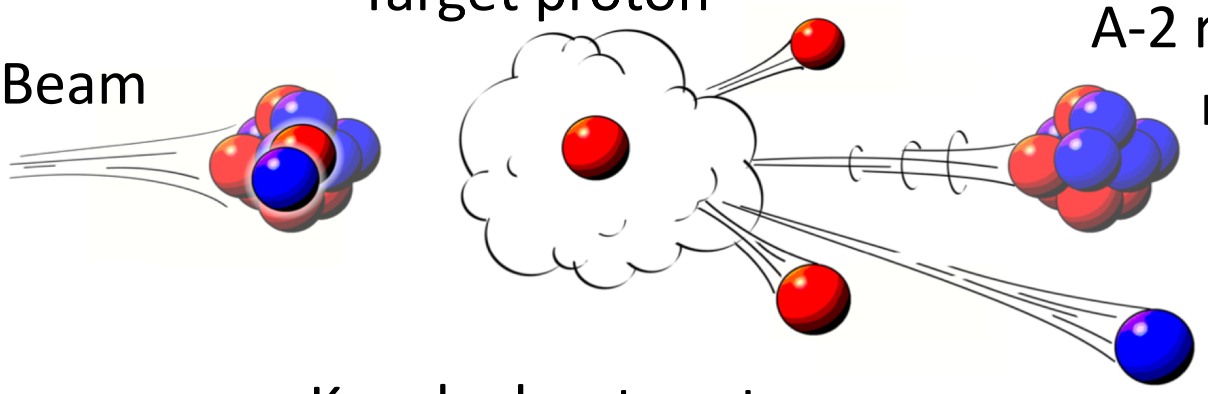
First study of SRCs in inverse kinematics



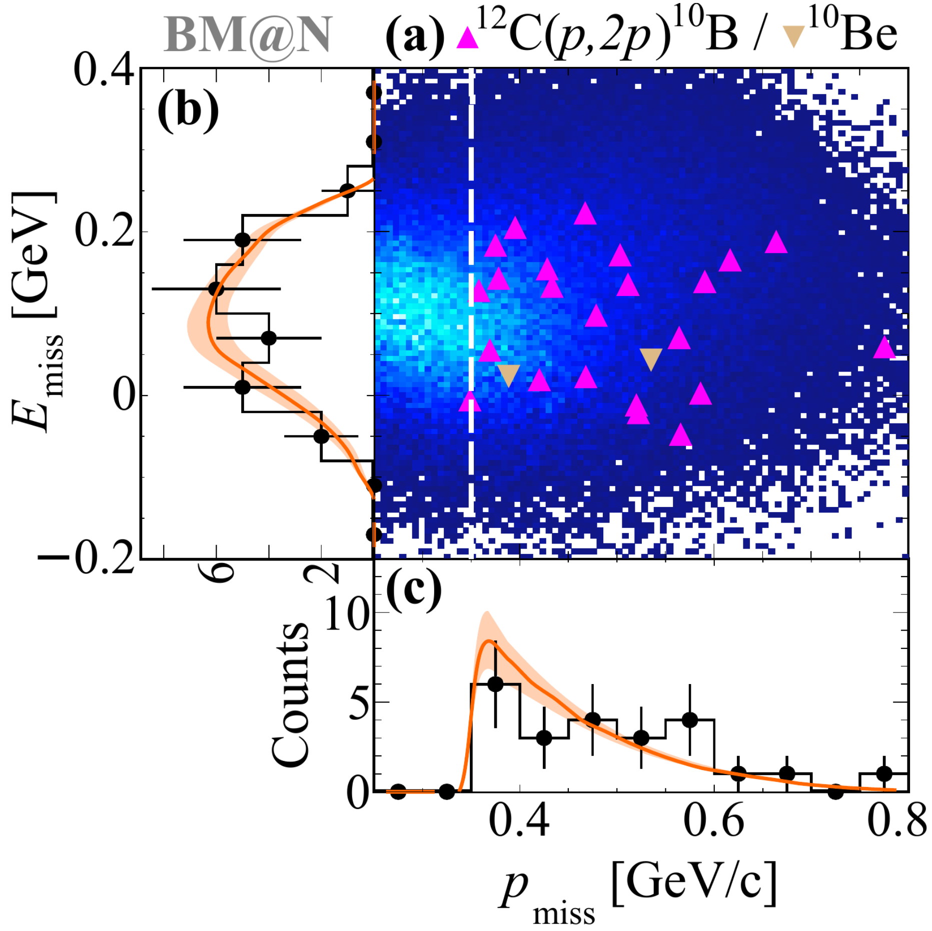
Hard breakup of SRC pairs

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

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



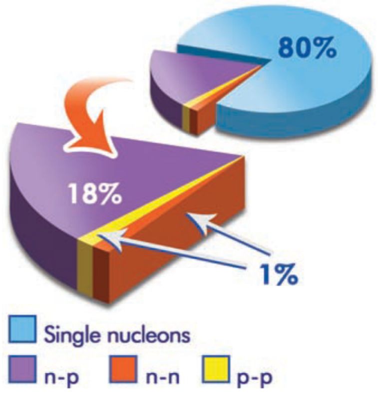
Identifying SRCs



+ proton-proton opening angle
(guided by simulation)

23 np SRC-pairs
2 pp SRC-pairs

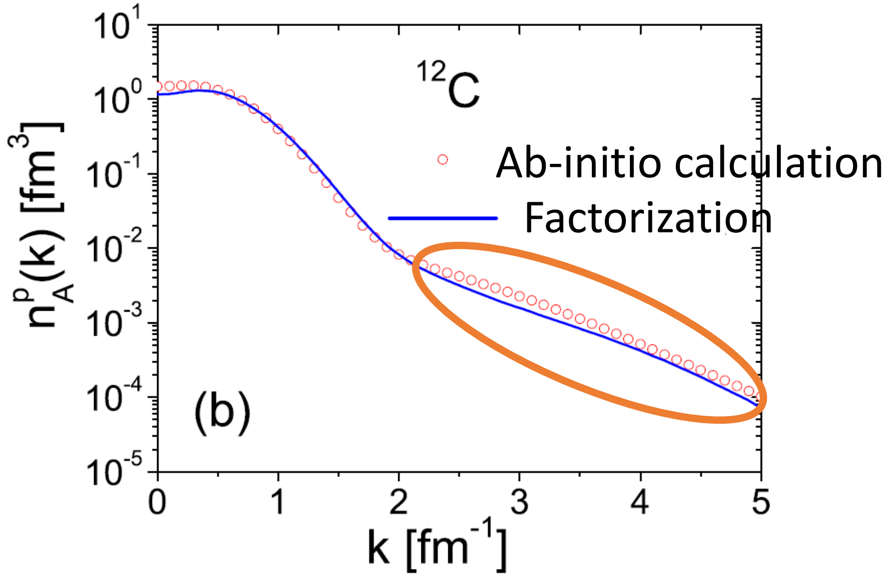
-> *np* dominance



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

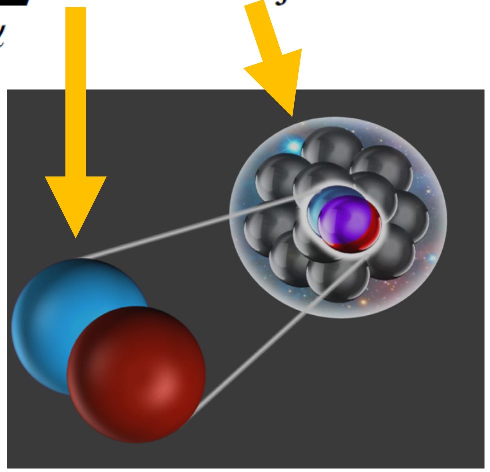
Scale separation in high-momentum regime

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



nuclear wave function can be factorized

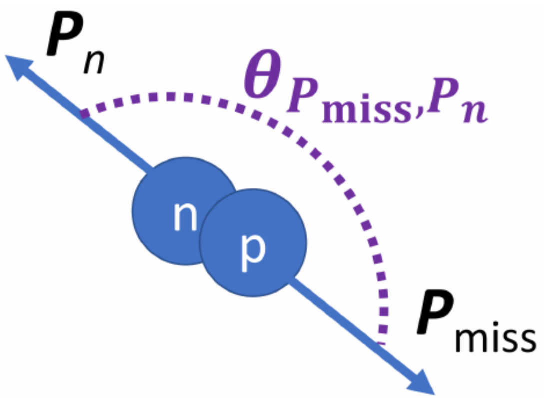
$$\Psi \xrightarrow{r_{ij}\to 0} \sum_{\alpha} \varphi_\alpha(\boldsymbol{r}_{ij}) A_{ij}^{\alpha}(\boldsymbol{R}_{ij}, \{\boldsymbol{r}\}_{k\neq ij})$$



applied in Generalized Contact Formalism

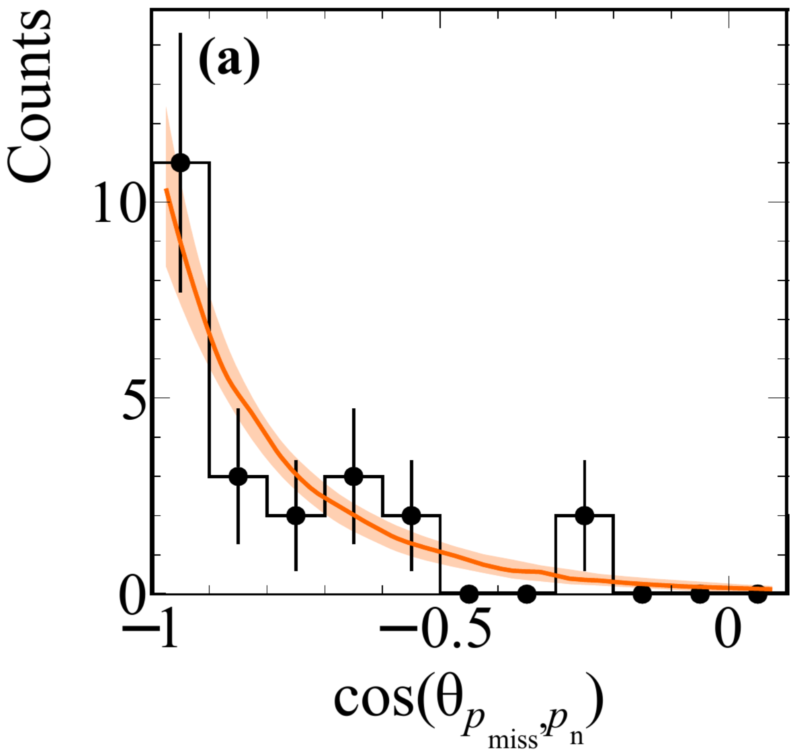
R. Cruz-Torres et al., Nature Physics (2020)
R. Weiss, B. Bazak, N. Barnea, Phys. Rev. C 92 (2015)
J.-W. Chen, W. Detmold, J. E. Lynn, A. Schwenk, PRL 119 (2017)
R. Weiss et al., Phys. Lett. B 780 (2018)

Strong pair correlation

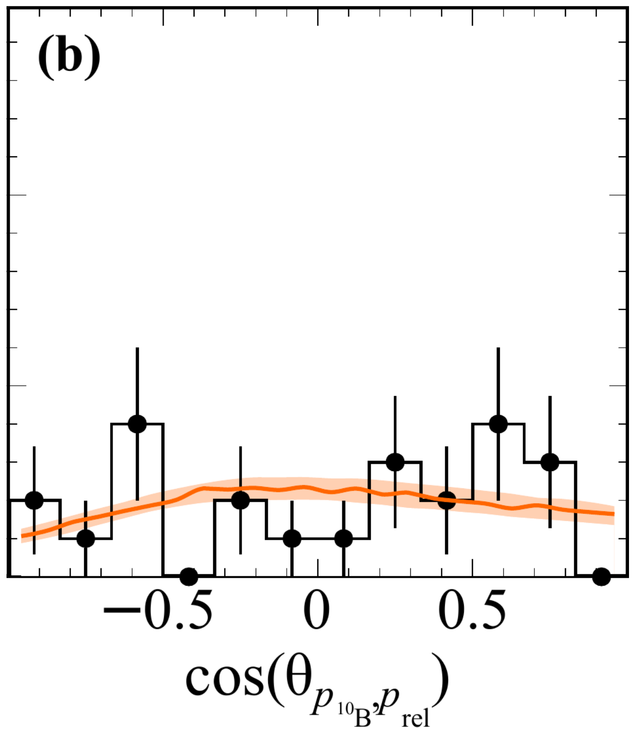


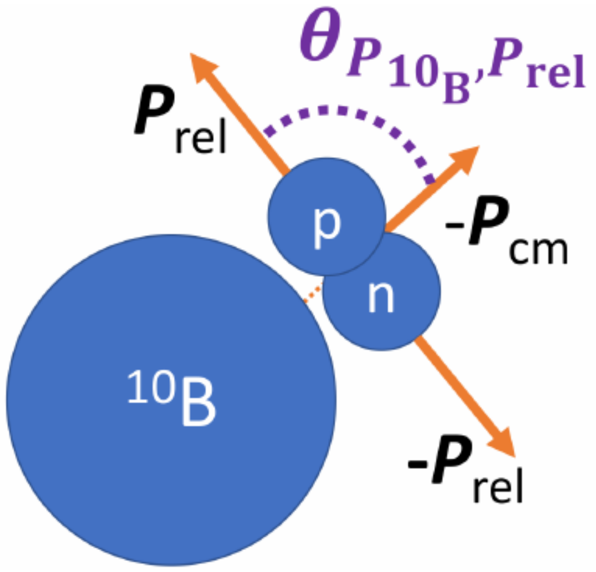
nucleon momentum not balanced by A-1

-> NN back-to-back emission

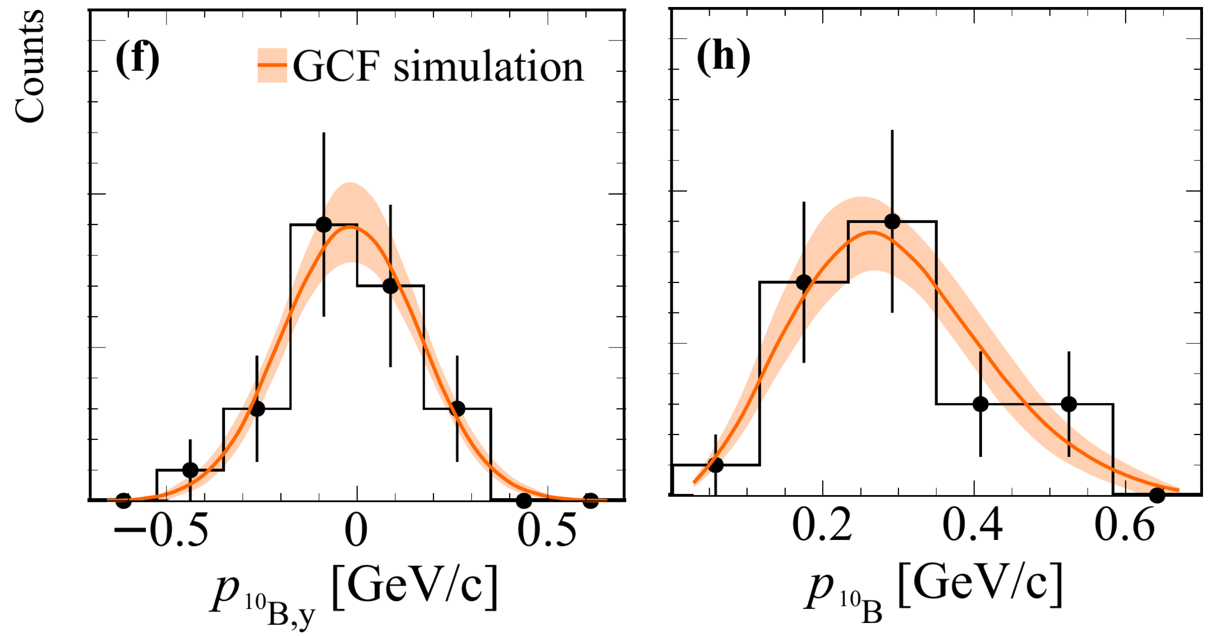


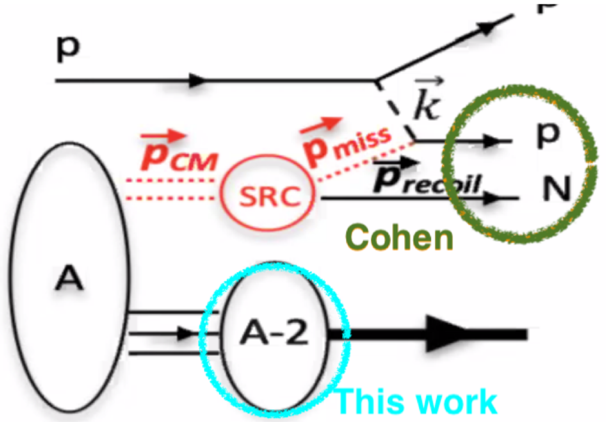
Experimental evidence for factorization

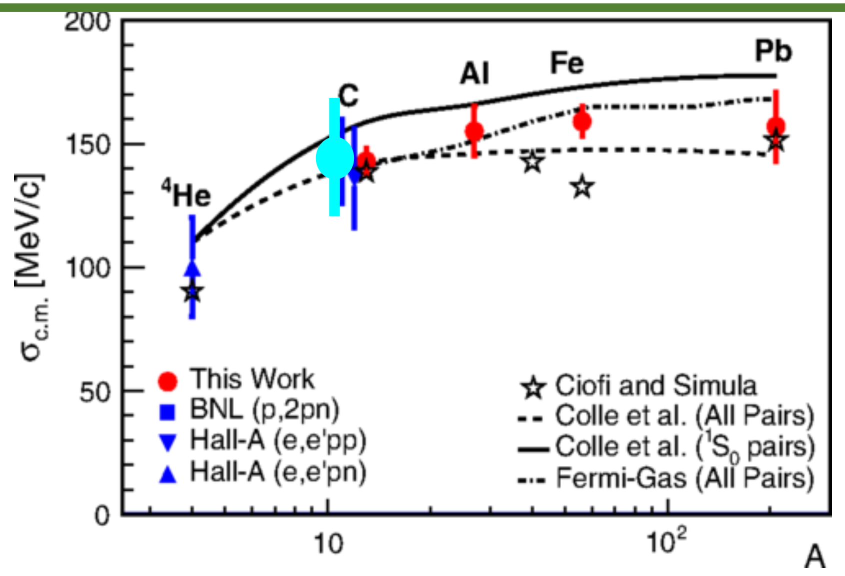




New observable: Fragment (SRC pair c.m.) momentum







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

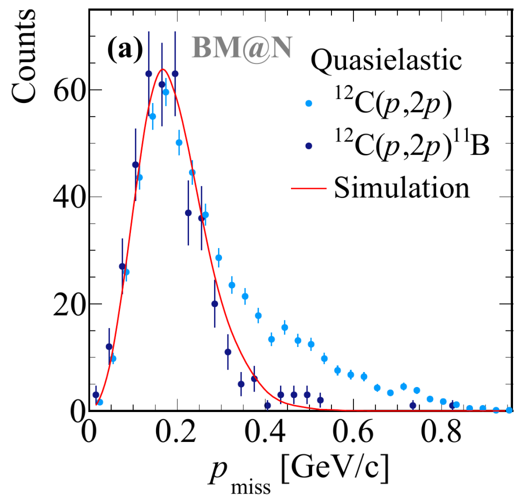
direct extraction: **σ = (156 ± 27) MeV/c**

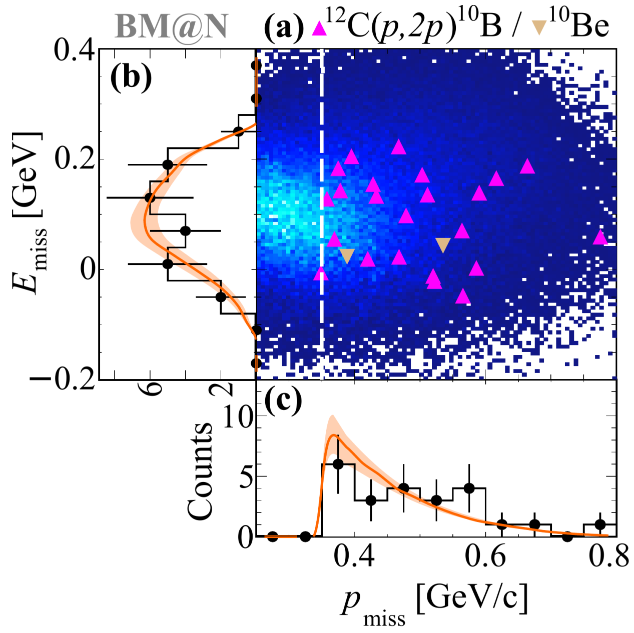
-> small c.m. momentum

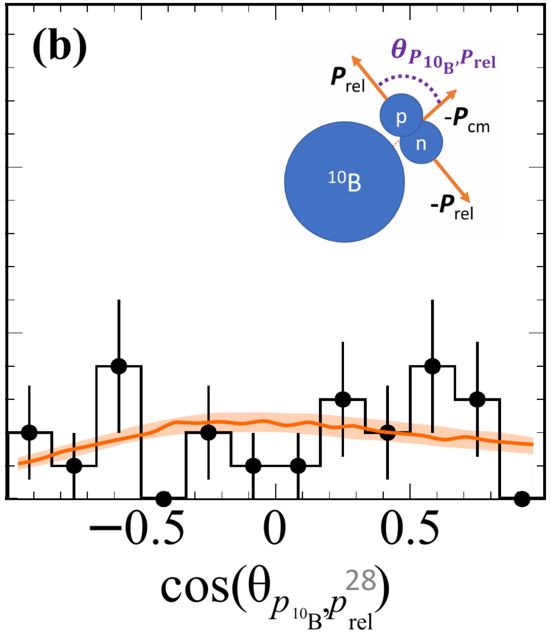
SRC studies in many-body dynamics entering new era

- **“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



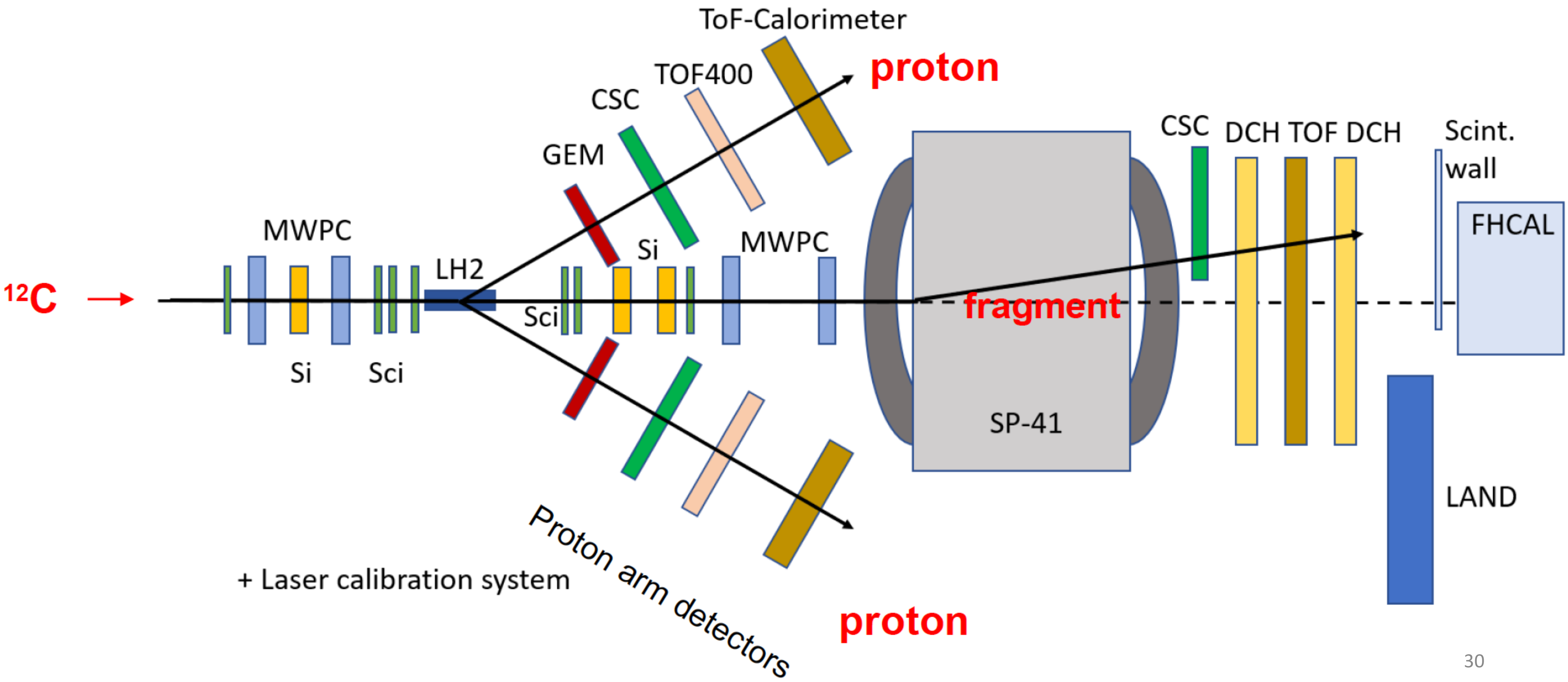




	QE (p, 2p) knockout	SRC
2018	Post selection suppresses distortion	• np-dominance • Scale separation (factorization) All at low statistics
2022	• Absolute cross section • Quenching • Attenuation All at high momentum transfer	• Improve statistics • Detect recoil n/p • Multi-fragment reconstruction • Fragment distribution → "SRC origin" → SRC pairs are $(2p)^{-1}$ $(1p1s)^{-1}$ $(2s)^{-1}$

Experimental Setup

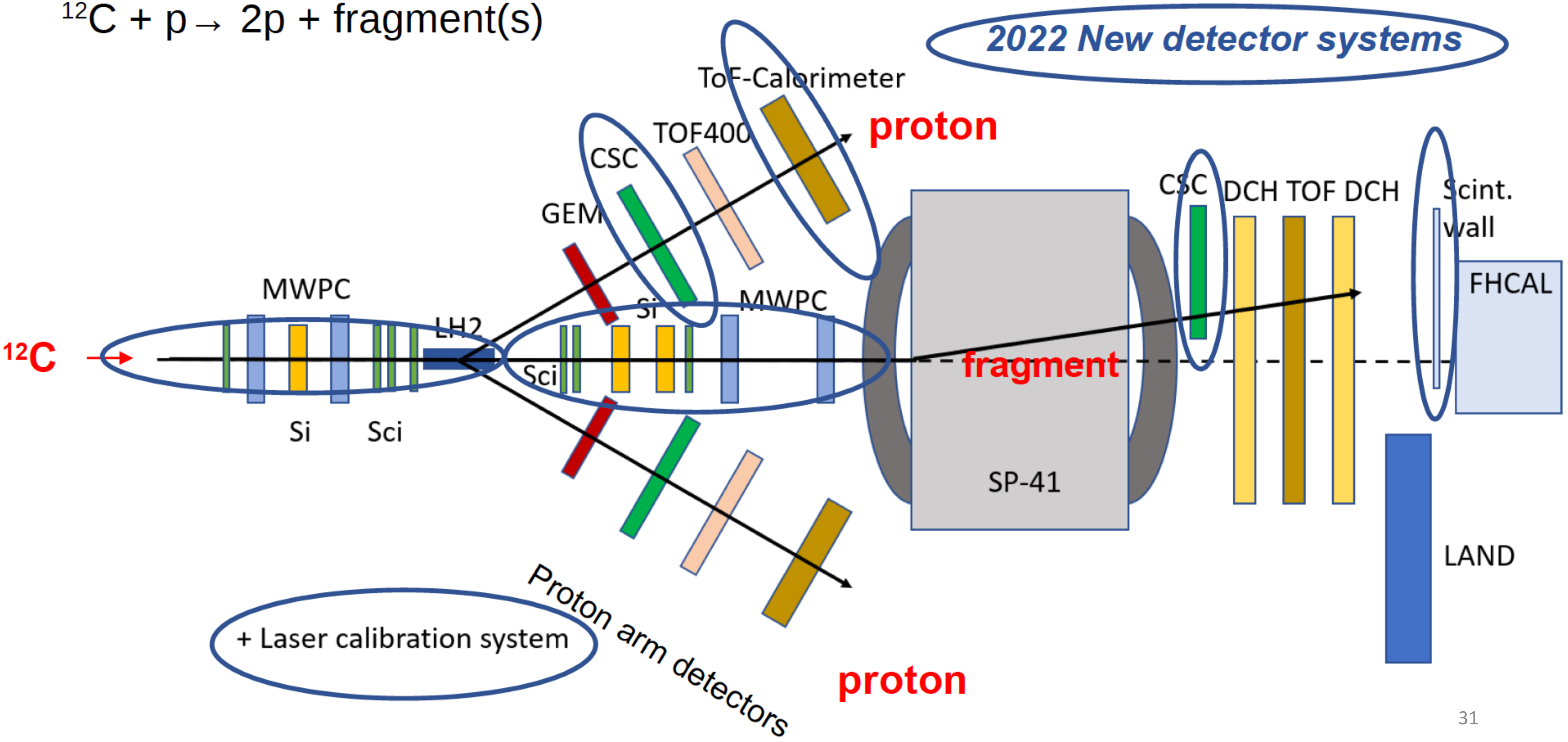
$^{12}C + p \rightarrow 2p$ + fragment(s)

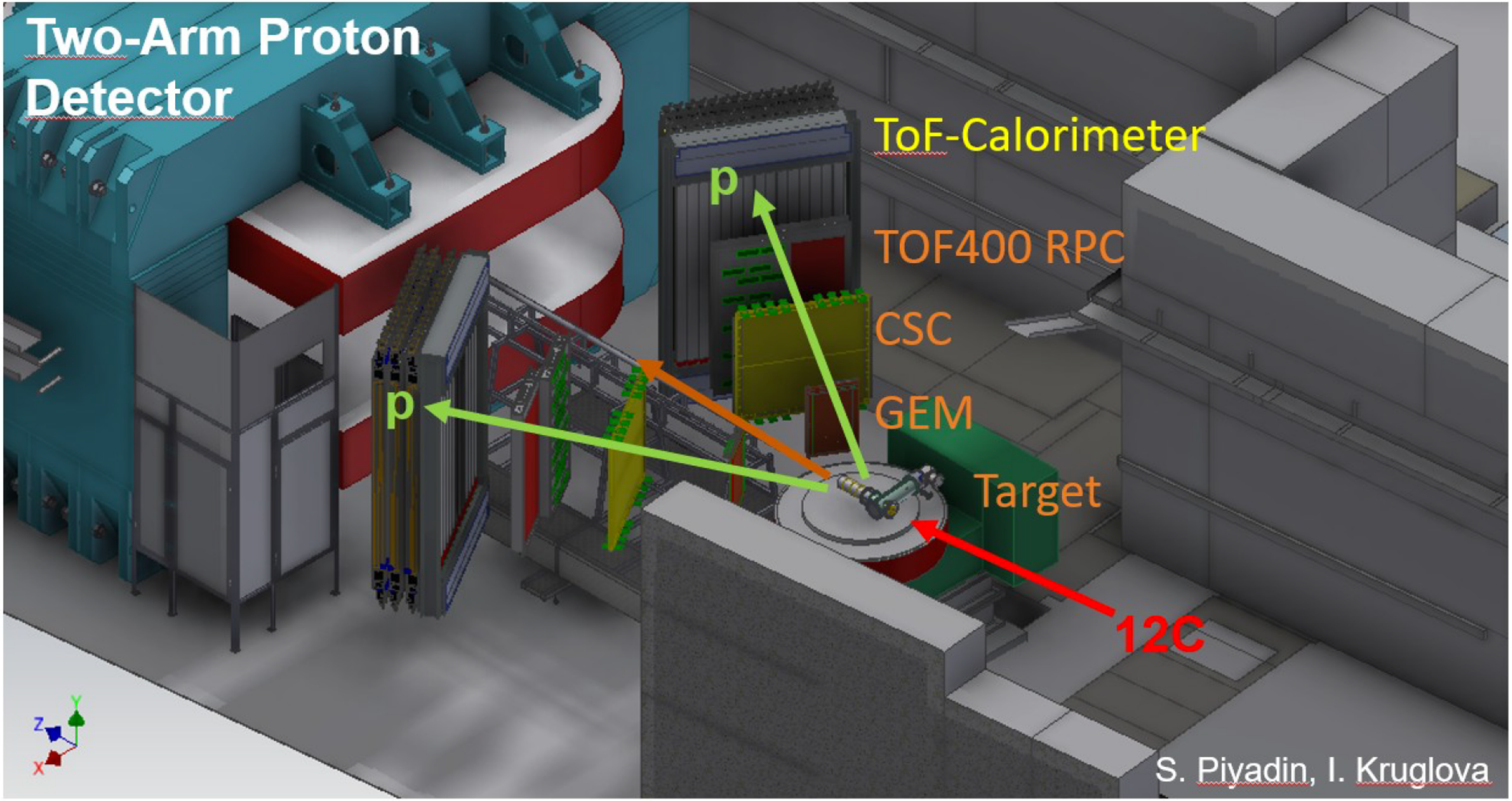


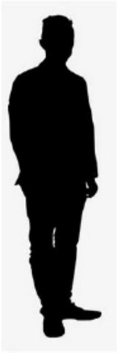
+ Laser calibration system

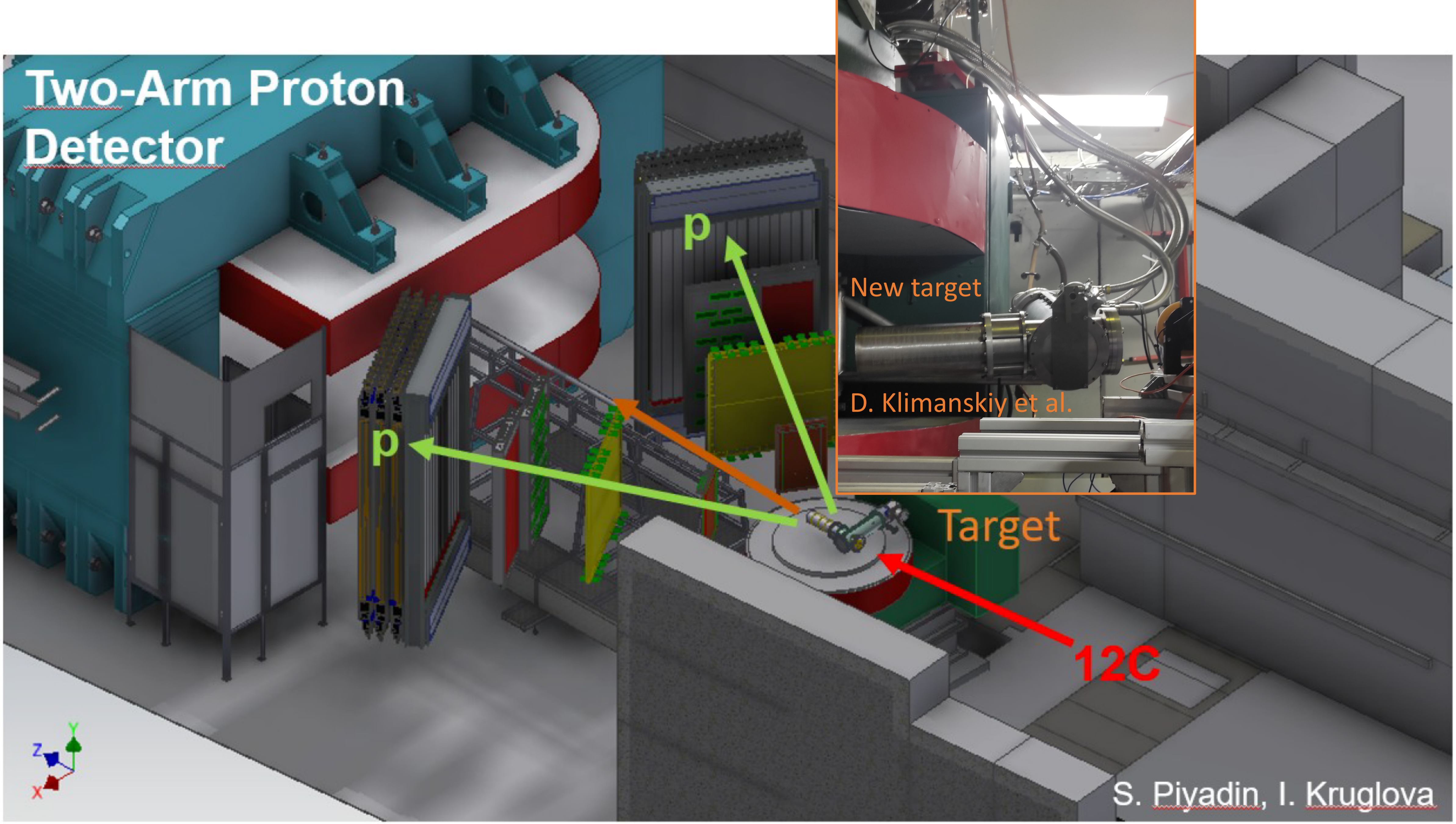
Experimental Setup

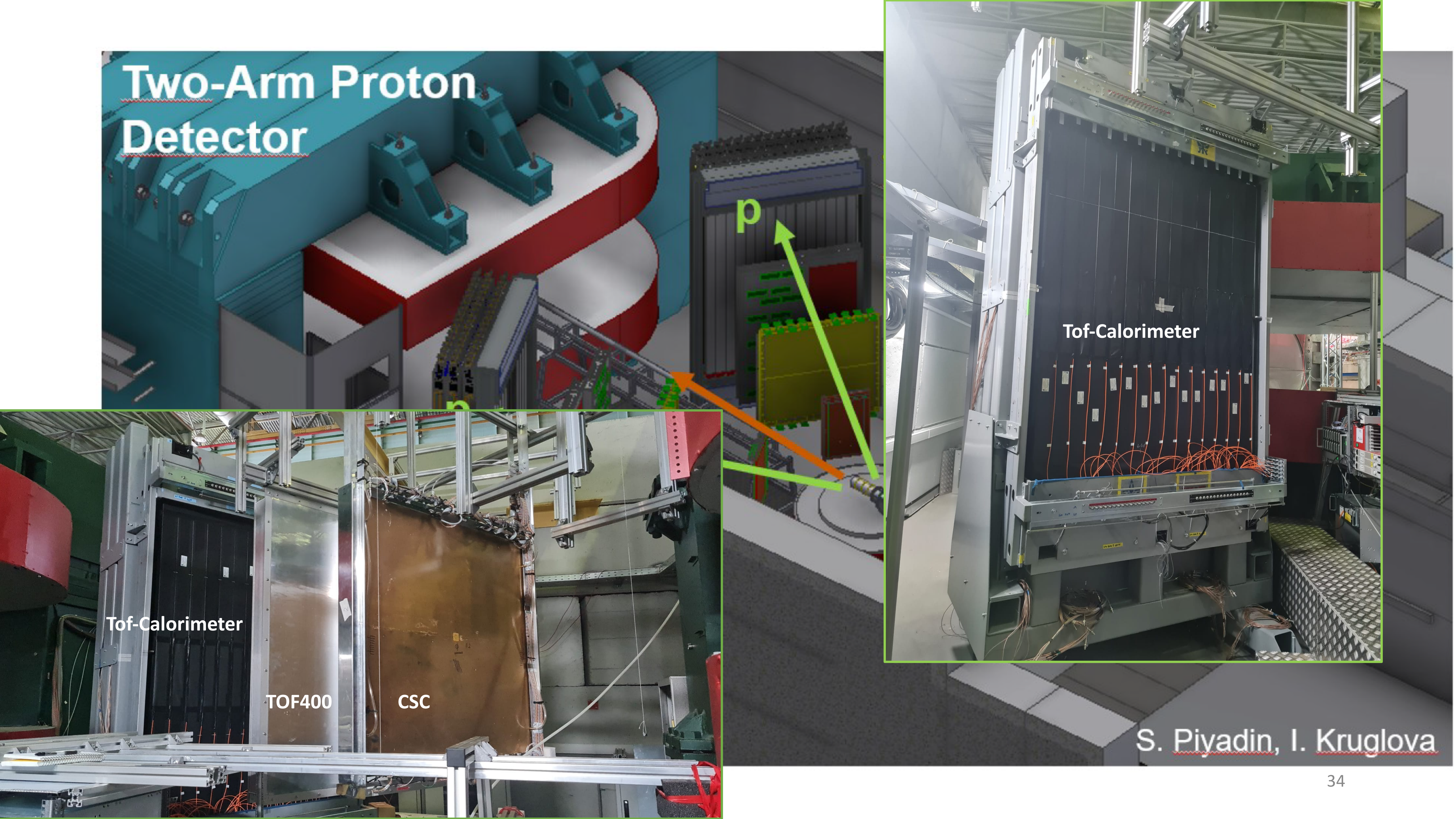
$^{12}C + p \rightarrow 2p + \text{fragment(s)}$




Two-Arm Proton Detector
ToF-Calorimeter
TOF400 RPC
CSC
GEM
Target
p
p
12C
S. Piyadin, I. Kruglova

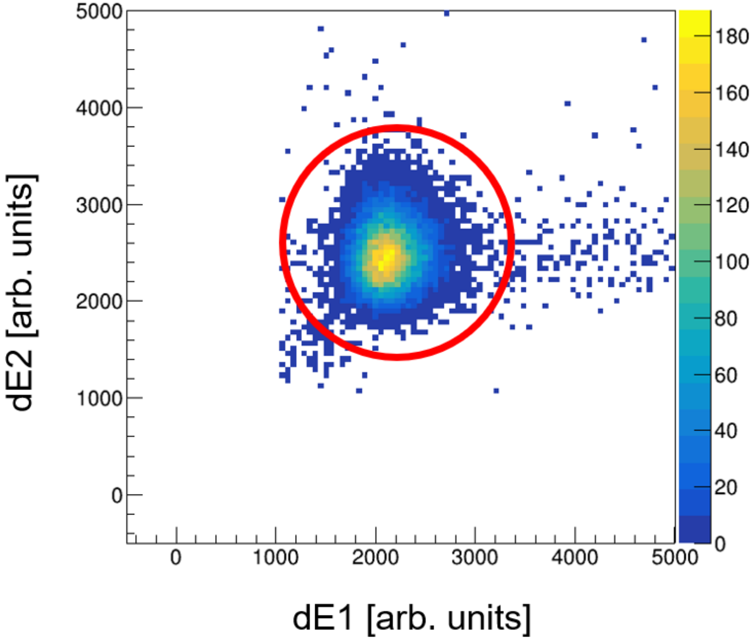



Two-Arm Proton Detector
p
p
New target
D. Klimanskiy et al.
Target
12C
S. Piyadin, I. Kruglova

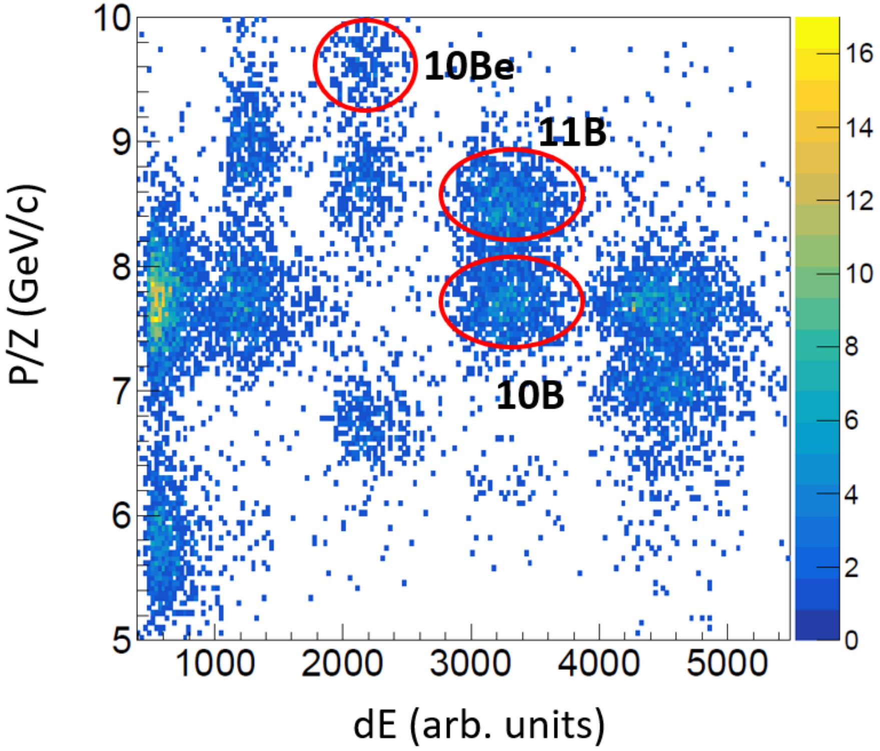

Two-Arm Proton Detector
p
Tof-Calorimeter
Tof-Calorimeter
TOF400
CSC
S. Piyadin, I. Kruglova

Analysis Status

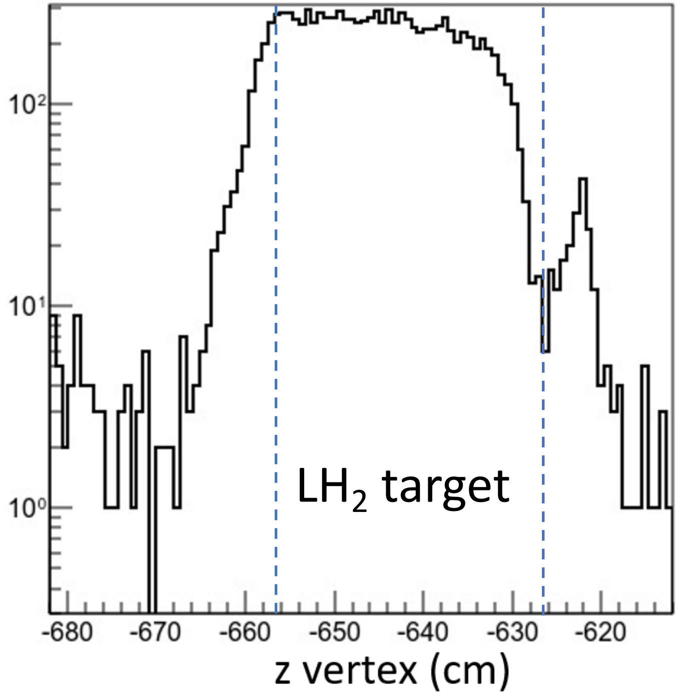
inc. beam - pure ^{12}C



Fragment ID



Reaction vertex reconstructed



Next: proton ID + momentum -> $^{12}C(p,2p)$ quasi-elastic

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Thanks!