Short-Range Correlations Study at HIAF

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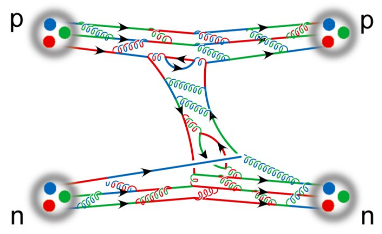
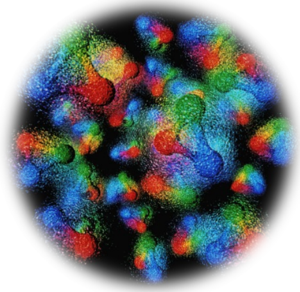
Huizhou, 2024-11-17

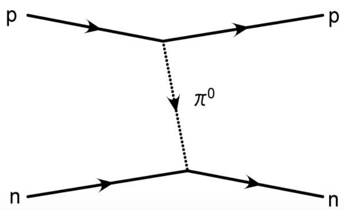
Short-Range Correlations

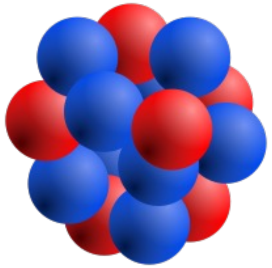
- Nuclear force is a strong force, but how it originates from QCD remaining largely unknown!



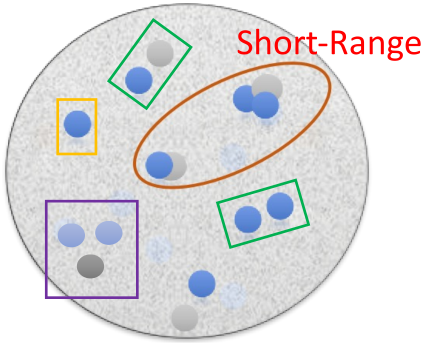


- Suprisedly, shell-models work very well
  - ✓ Sum of nucleon-nucleon(NN) Interactions → mean field
  - ✓ Nucleons are point-like; Force from pion-exchange
  - ✓ Modern NN potentials, e.g. AV18





$$V = \sum_i \bar{V}(i) + \sum_{i<j} V^{(2)}(i,j) + \sum_{i<j<k} V^{(3)}(i,j,k) + \dots$$

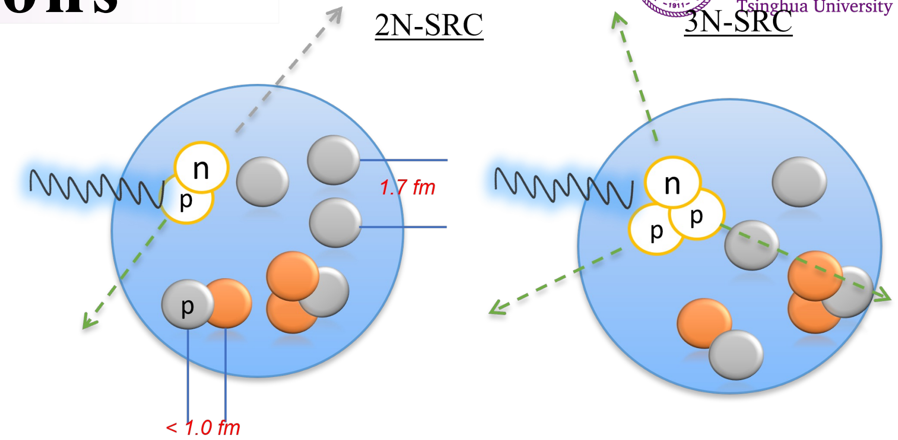


- NN terms fitted from data
- 3-body force poor known
- Short range (non-nucleonic)?

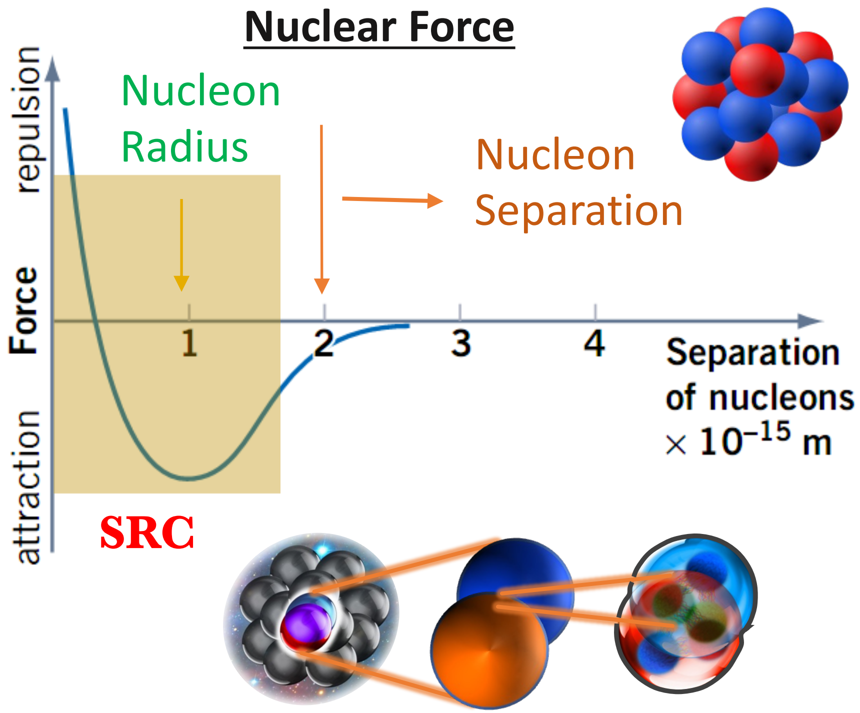
TABLE I. Argonne V18 spin-isospin operators in coordinate space.

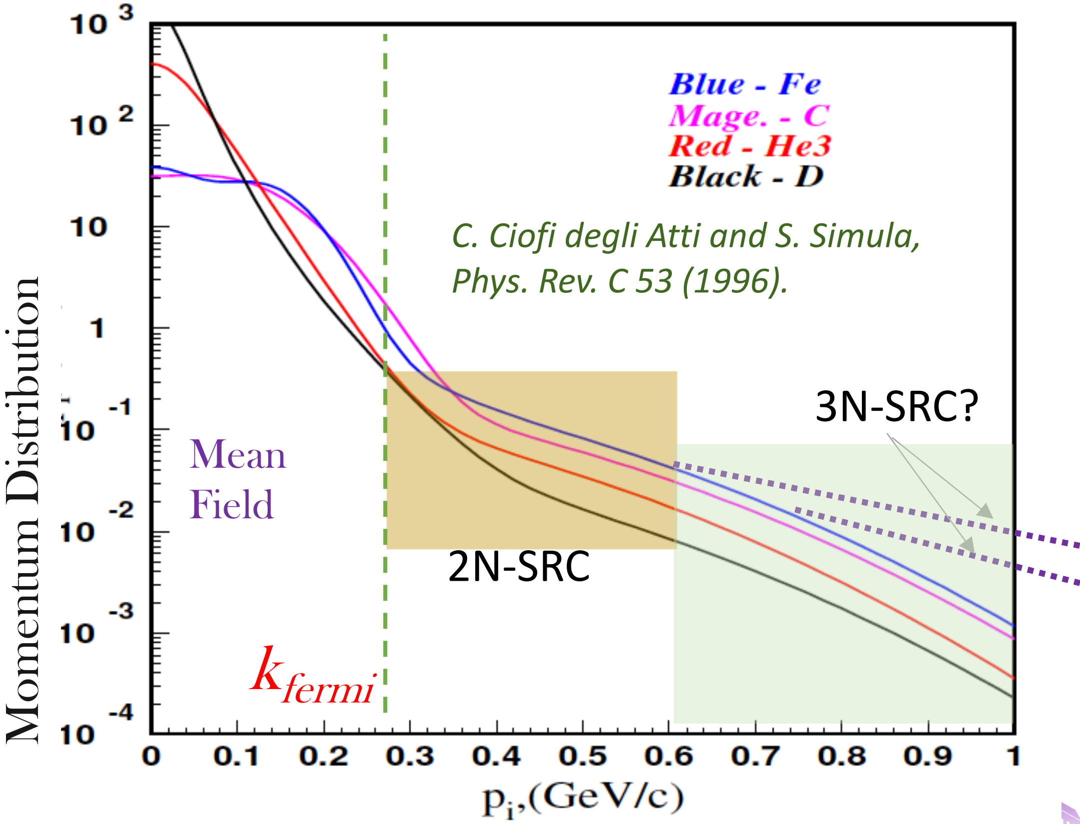
Term	Spin-isospin operator in r space
O_1	$\mathbf{I}$
O_2	$(\boldsymbol{\tau}_1\cdot\boldsymbol{\tau}_2)$
O_3	$(\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2)$,
O_4	$(\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2)(\boldsymbol{\tau}_1\cdot\boldsymbol{\tau}_2)$
O_5	$S_{12} = 3(\boldsymbol{\sigma}_1\cdot\hat{\mathbf{r}})(\boldsymbol{\sigma}_2\cdot\hat{\mathbf{r}}) - \boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2$
O_6	$S_{12}(\boldsymbol{\tau}_1\cdot\boldsymbol{\tau}_2)$,
O_7	$(\mathbf{L}\cdot\mathbf{S})$
O_8	$(\mathbf{L}\cdot\mathbf{S})(\boldsymbol{\tau}_1\cdot\boldsymbol{\tau}_2)$
O_9	$(\mathbf{L}\cdot\mathbf{L})$
O_{10}	$(\mathbf{L}\cdot\mathbf{L})(\boldsymbol{\tau}_1\cdot\boldsymbol{\tau}_2)$
O_{11}	$(\mathbf{L}\cdot\mathbf{L})(\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2)$
O_{12}	$(\mathbf{L}\cdot\mathbf{L})(\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2)(\boldsymbol{\tau}_1\cdot\boldsymbol{\tau}_2)$
O_{13}	$(\mathbf{L}\cdot\mathbf{S})^2$
O_{14}	$(\mathbf{L}\cdot\mathbf{S})^2(\boldsymbol{\tau}_1\cdot\boldsymbol{\tau}_2)$
O_{15}	$T_{12} = (3\tau_{1z}\tau_{2z} - \boldsymbol{\tau}\cdot\boldsymbol{\tau})$
O_{16}	$(\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2)T_{12}$
O_{17}	$S_{12}T_{12}$
O_{18}	$(\tau_{1z} + \tau_{2z})$

Short-Range Correlations



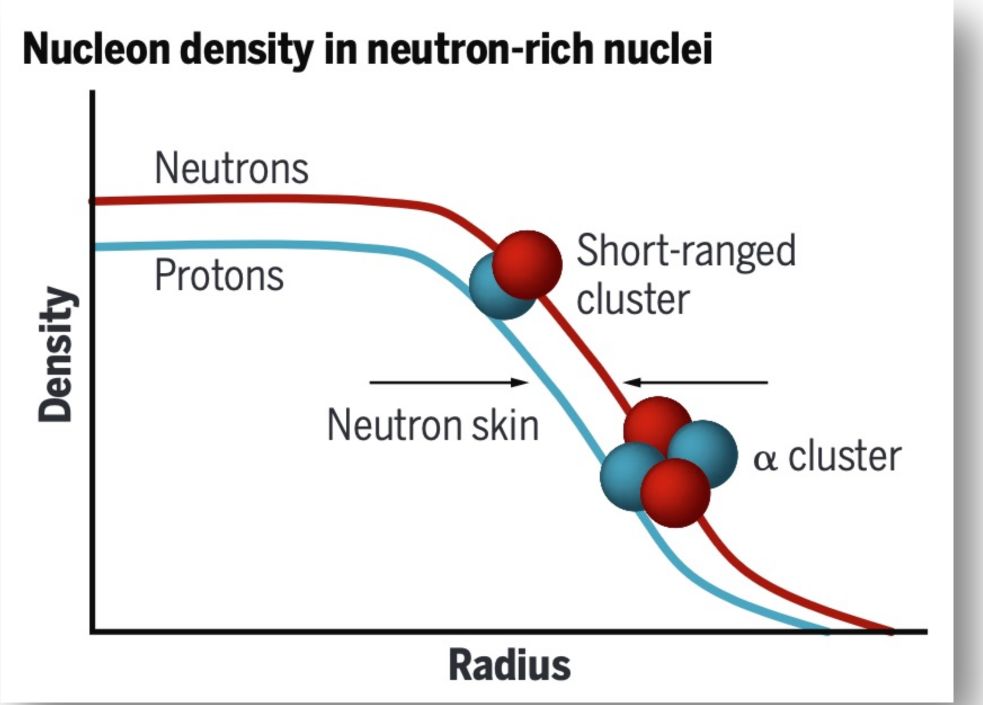
- 2 or more nucleons highly overlapped → high-density but cold!
- Nucleons carry high relative momenta (A-independent)
- Experimental signals:
  - ✓ Look for back-to-back nucleons after breaking up SRC





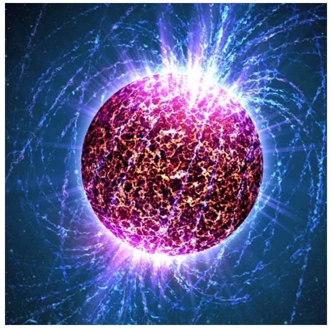
Why Study SRC?

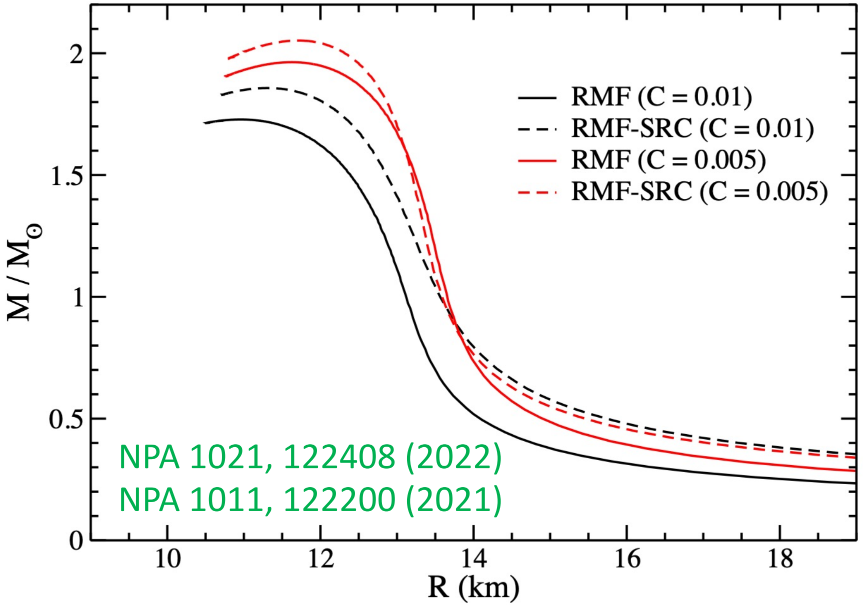
- ❑ Study extreme cases of NN & NNN forces → The origin of nuclear forces?
- ❑ Important in forming neutron-rich nuclei



Hen, Science 371, 232 (2021)

- ❑ Forming ultra-heavy neutron stars?





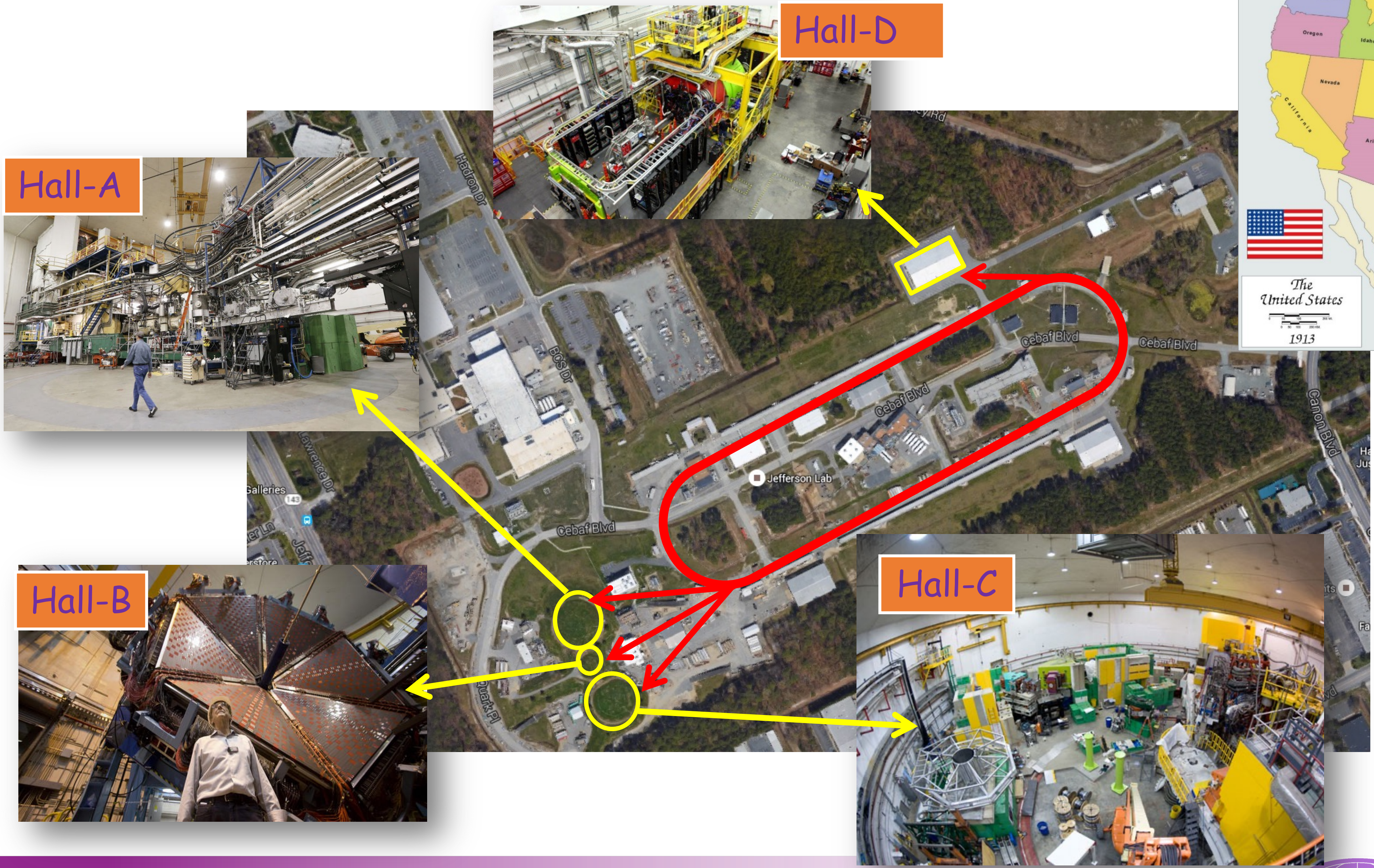
NPA 1021, 122408 (2022)
NPA 1011, 122200 (2021)

- ❑ SRC in the mass matrix for neutrino-less double beta decay?

Wang, Zhao, Meng, arXiv: 2304.12009, Song, Yao, Ring, Meng, Phys. Rev. C **95**, 024305

Measuring SRC w/ eA

- Thomas Jefferson Lab



Jefferson Lab
Thomas Jefferson National Accelerator Facility

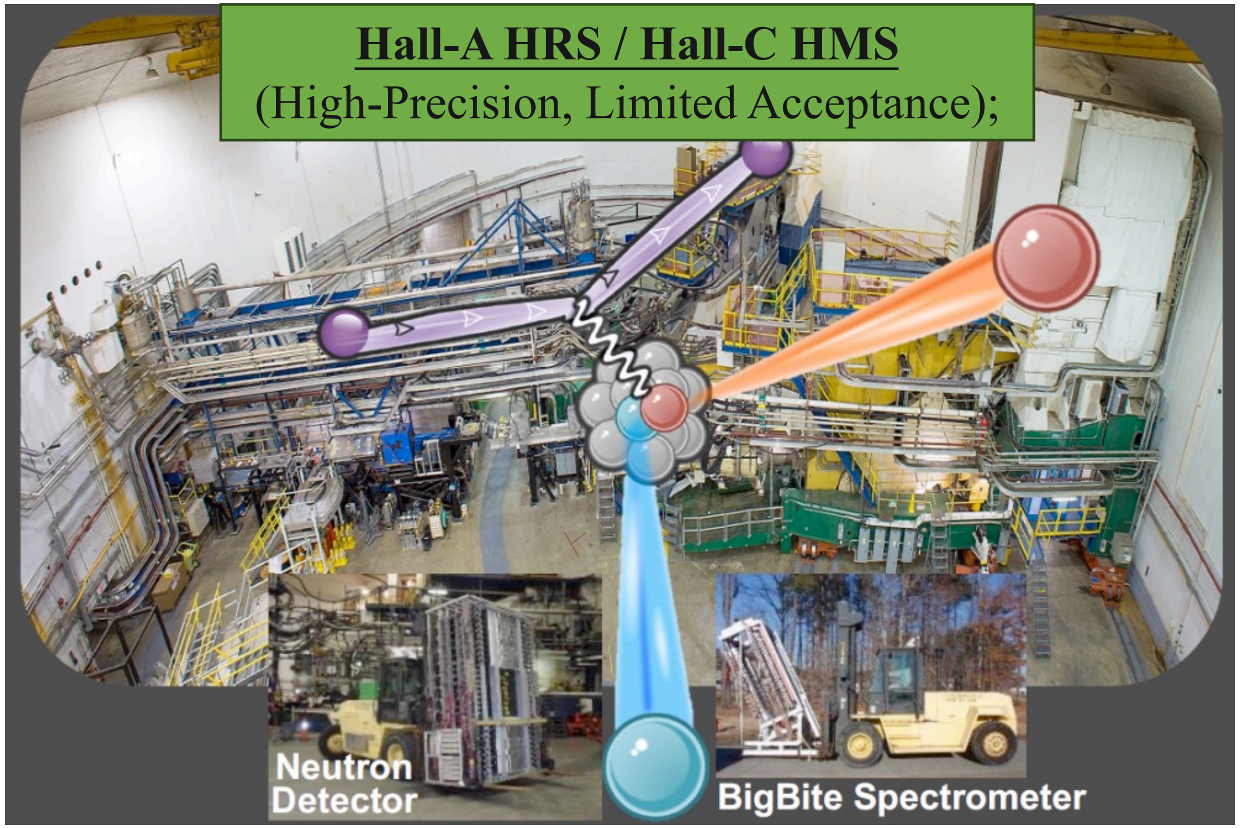
U.S. DEPARTMENT OF ENERGY

Detector Systems

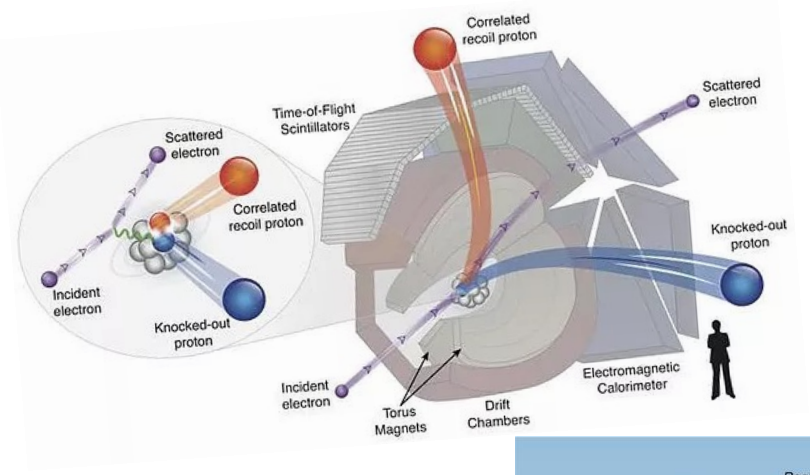
Hall-B CLAS6/CLAS12
(Low-Precision, Full Acceptation)

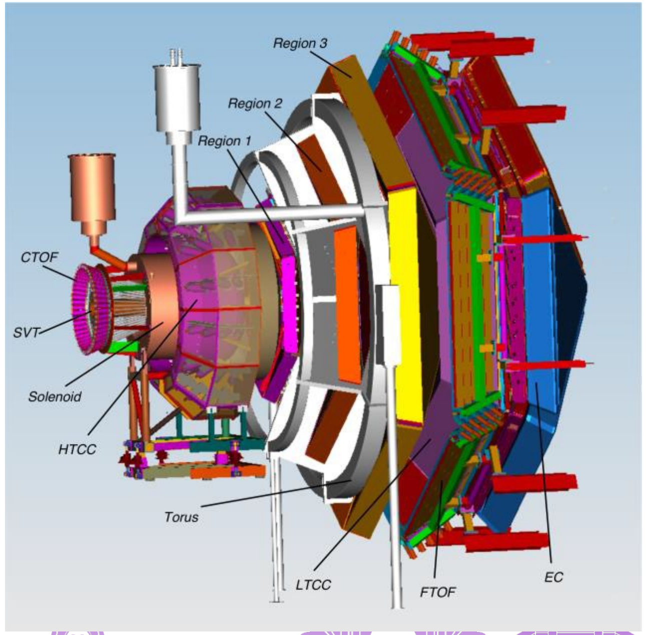
❑ Precision vs Acceptance

Hall-A HRS / Hall-C HMS
(High-Precision, Limited Acceptance);



Add third-arm to detector p/n

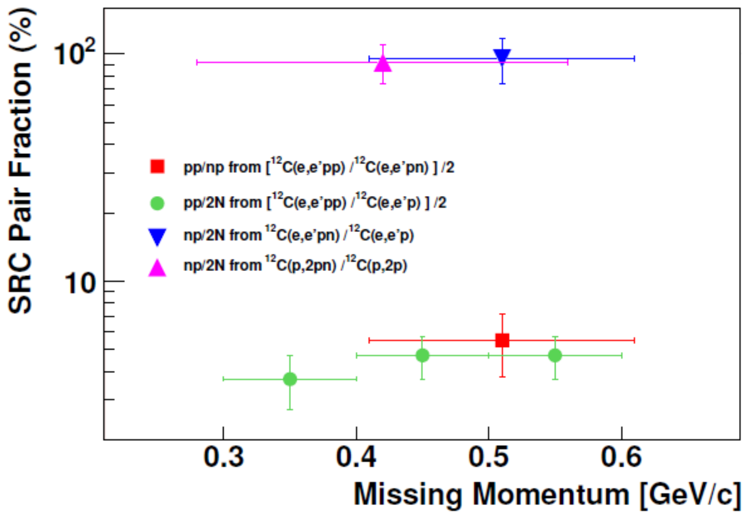




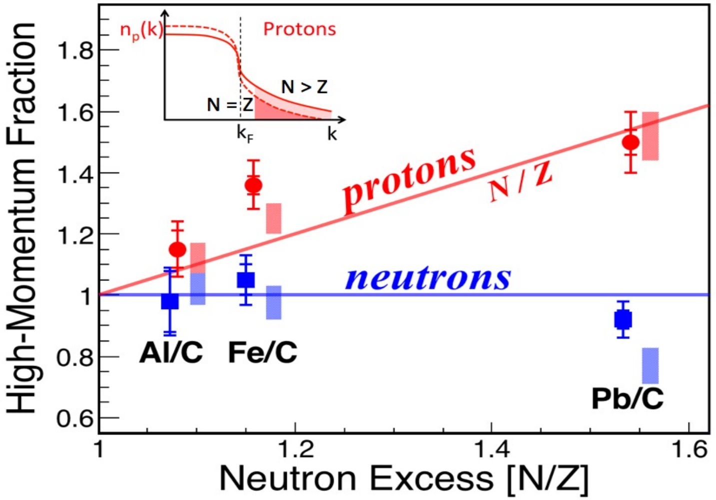
Isospin-Dependence in Exclusive Method

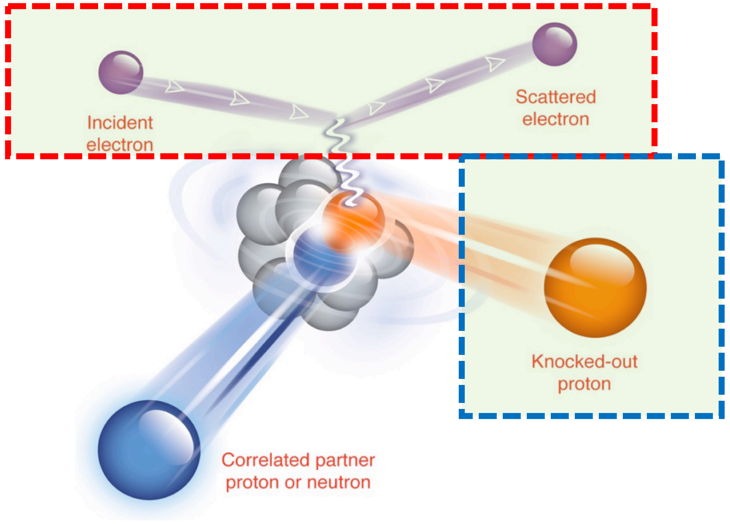
- Exclusively count np-/pp-/nn-SRC pairs → np make up 90% of SRC pairs

R. Subedi, et al, Science 320 1476 (2008)

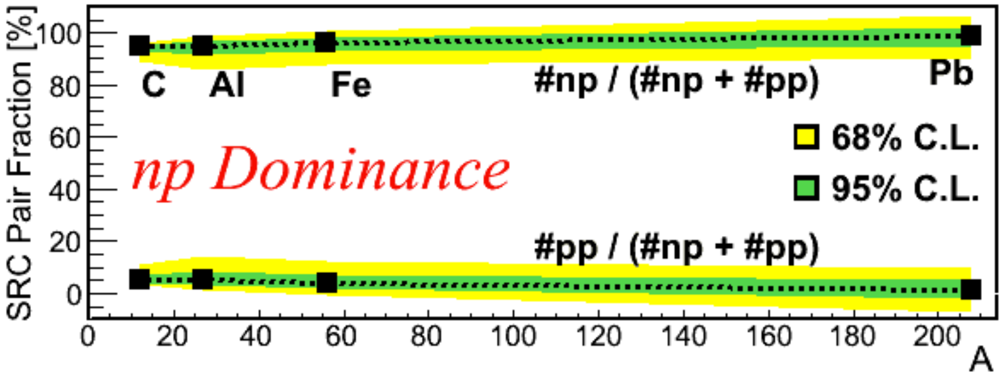


proton "speed up" with neutron excess





- Similar np-dominances in heavy nuclei → universality?



O. Hen et al., Science (2014), M. Duer et. al., Nature (2018) , B. Schmookler et. al. Nature (2019), A. Schmidt et. al Nature (2020) + many others

Isospin-Dependence in Inclusive Method

- Using Tritium and Helium-3 isotopes (E12-11-112)

E12-11-112 (Inclusive SRC)

- Study Isospin Effect in 2N-SRC and 3N-SRC
- Measure GMn at small Q^2

Spokespeople: J. Arrington, D. Day, D. Higinbotham, P. Solgignon*, Z. Ye

PhD Students: Shujie Li, Nathaly Santiesteban (UNH)

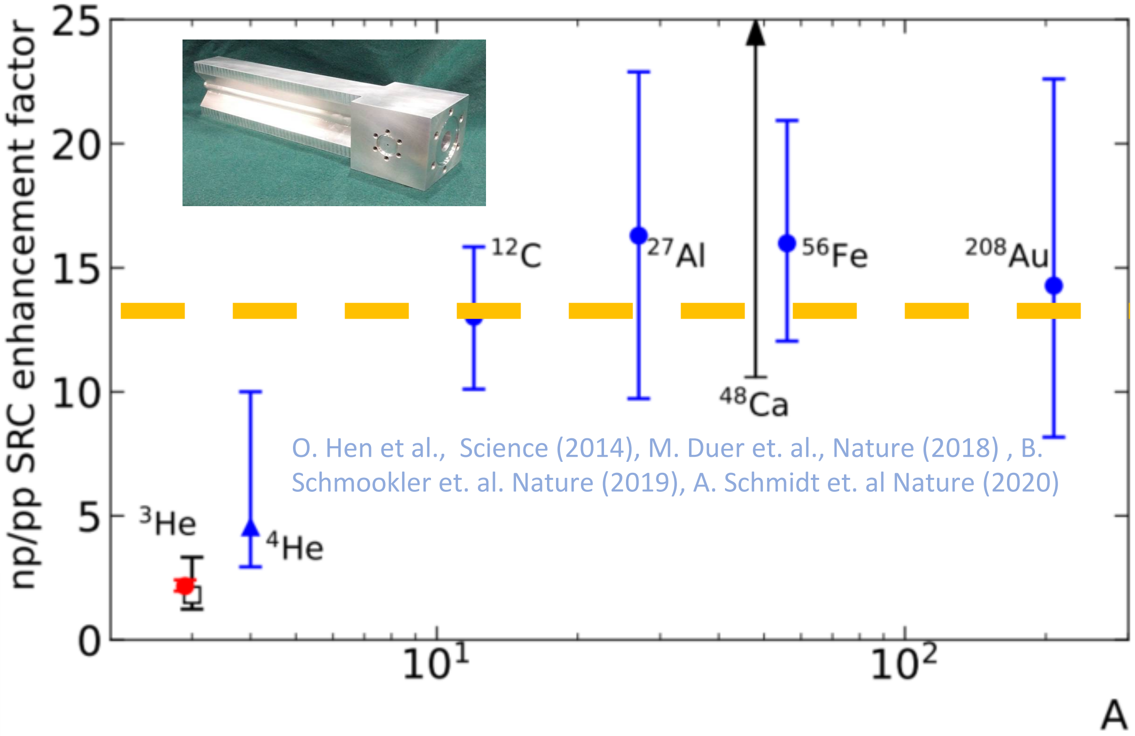
$$\frac{\sigma_{H3}}{\sigma_{He3}} = \frac{2R_{pp/np} + 1 + \frac{\sigma_{ep}}{\sigma_{en}}}{(2R_{pp/np}+1)\frac{\sigma_{ep}}{\sigma_{en}} + 1} \Rightarrow R_{pp/np} = \frac{\left(1+\frac{\sigma_{ep}}{\sigma_{en}}\right)\left(1-\frac{\sigma_{H3}}{\sigma_{He3}}\right)}{2\left(\frac{\sigma_{H3}}{\sigma_{He3}}\cdot\frac{\sigma_{ep}}{\sigma_{en}}-1\right)}$$

- x10 precisions of isospin-study vs. exclusive study
- Small np-dominances in A=3 nuclei → Why?

Article

Revealing the short-range structure of the ”mirror nuclei” ^{3}H and ^{3}He

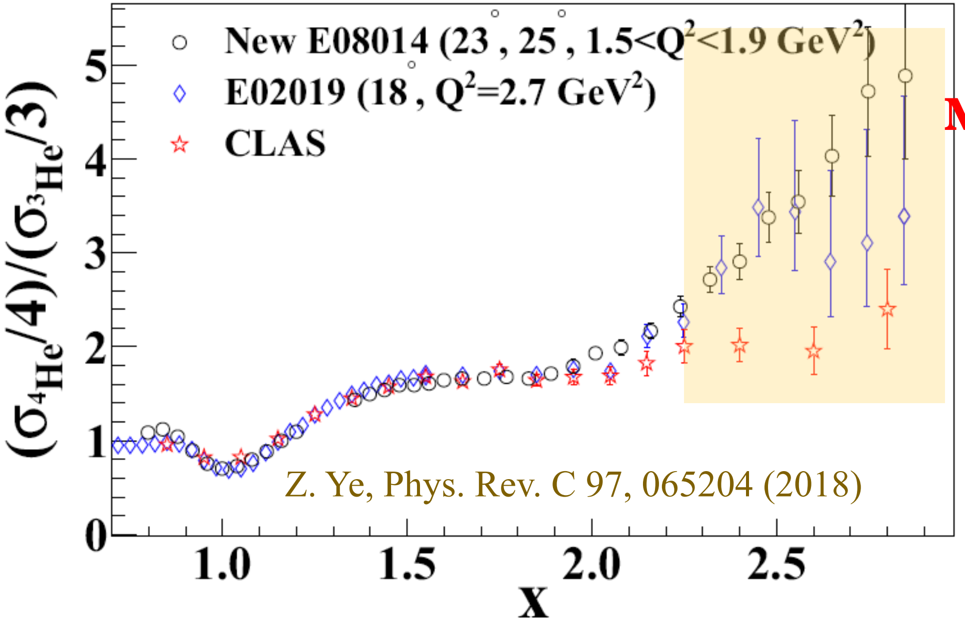
S. Li[1,2], R. Cruz-Torres[3,2], N. Santiesteban[1,3], Z. H. Ye[4,5] D. Abrams[6], S. Alsalmi[7,41],



3N-SRC

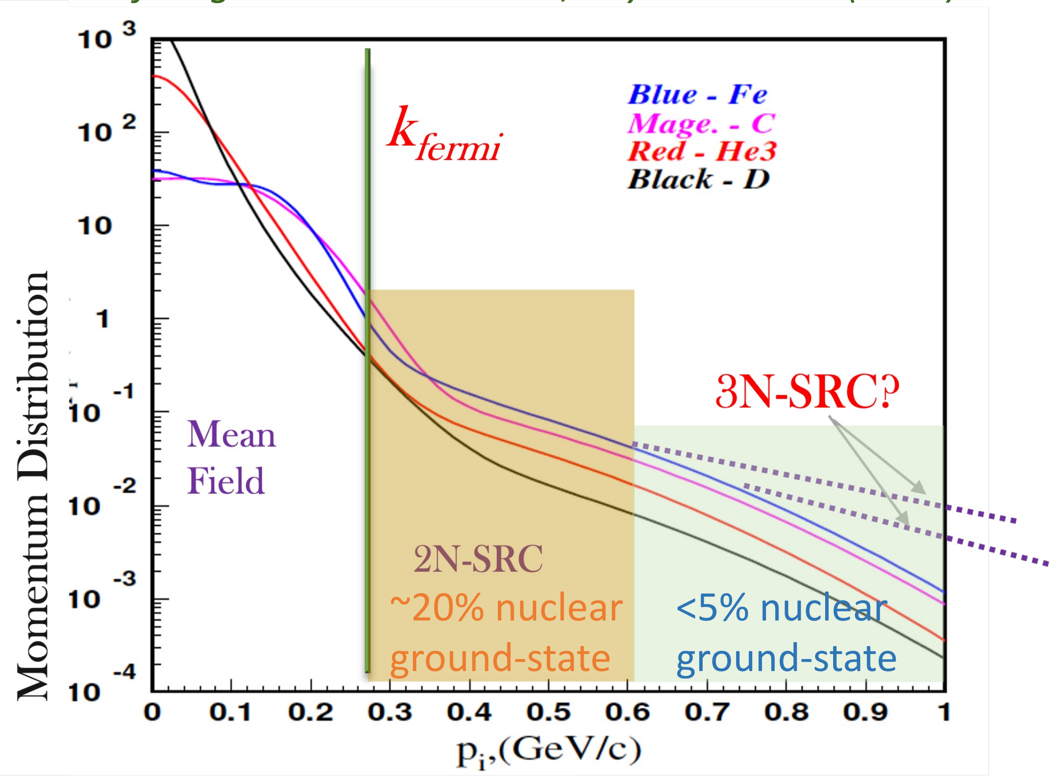
- Much higher relative momenta
- Much denser cluster (Neutron-Star, Nuclear Matter）
  - ➢ Bi-neutron-stars merger: neutron star > 2.4 solar mass
    → Short-Range 3-body force?
- Inclusive Measurement: XS links to the 3N-SRC tails

3N-SRC (2<x<3) $$a_3(A,{}^3He) = K \cdot \frac{3\sigma_A}{A\sigma_{{}^3He}}$$



Missing 3N-SRC?

C. Ciofi degli Atti and S. Simula, Phys. Rev. C 53 (1996).

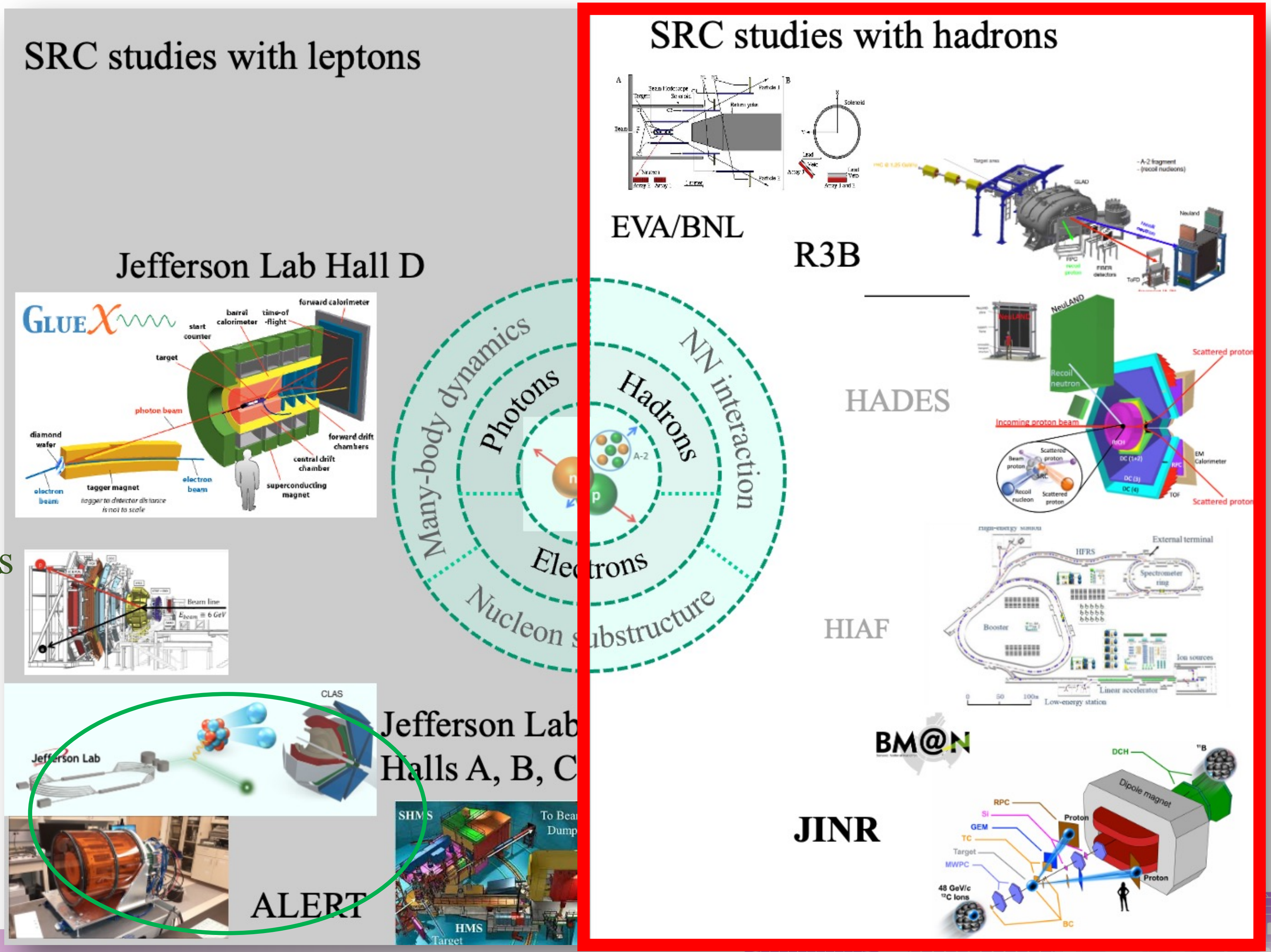


- CLAS result has big background
  Higinbotham & Hen, PRL 114,169201 2015)
- Q^2 too low to see 3N-SRC?
- Much bigger FSI?

"Muti-messenger" era

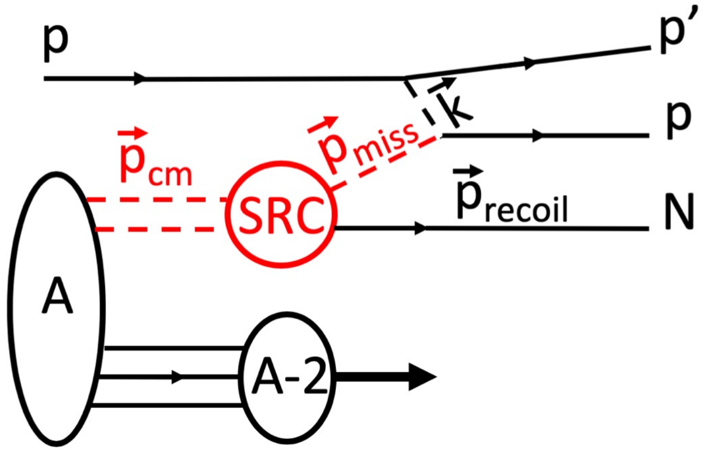
Precision Frontier!

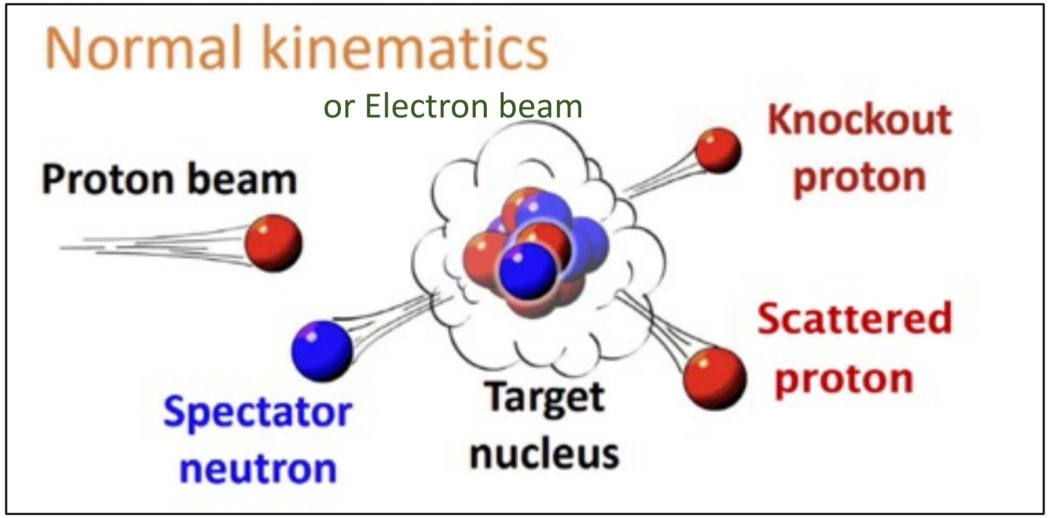
- ❑ QE cross drops significantly at high energy → not suitable measurements w/ EIC
- ❑ Real photon scattering in Hall-D (check universality)
- ❑ ALERT- SRC:
  - ✓ measure C.M motion of pairs (Mean-Field vs SRC)
  - ✓ Thesis student from THU
  - ✓ Run in April 2025

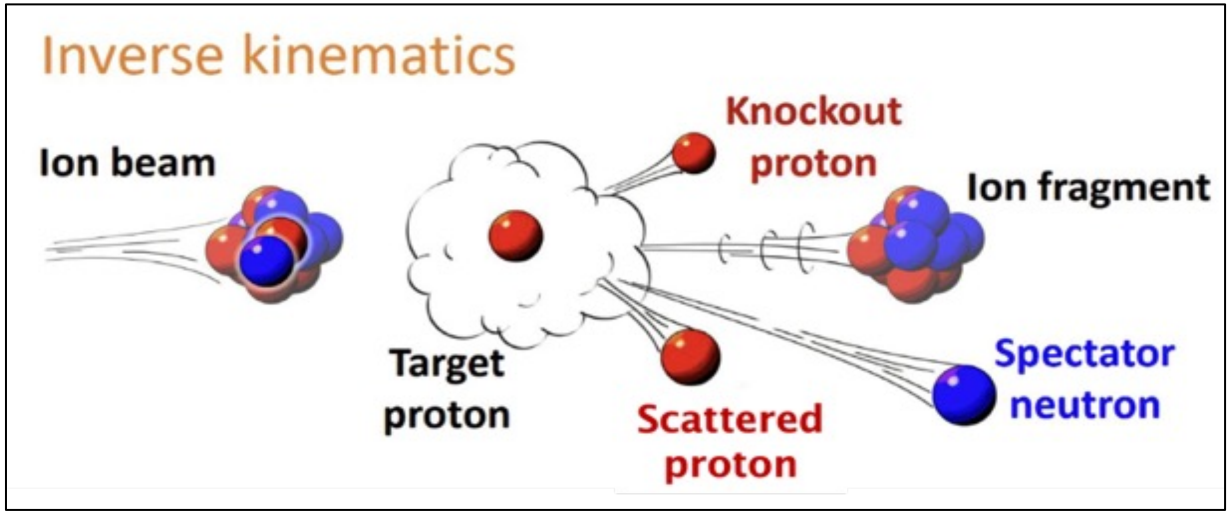


Measuring SRC w/ Inverse-pA

- Advantage vs eA Scattering
  - ✓ Bigger cross-sections → Precision and discovery
  - ✓ Easier detection of fragments → Suppress mean field contribution
  - ✓ Better controlled FSI → Reduce theoretical systematic errors
  - ✓ Secondary ion beams → Large asymmetric nuclei, radioactive isotopes



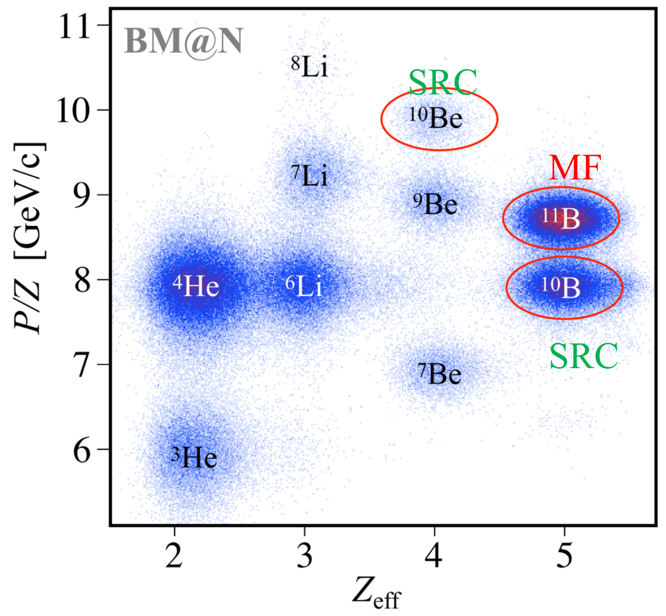


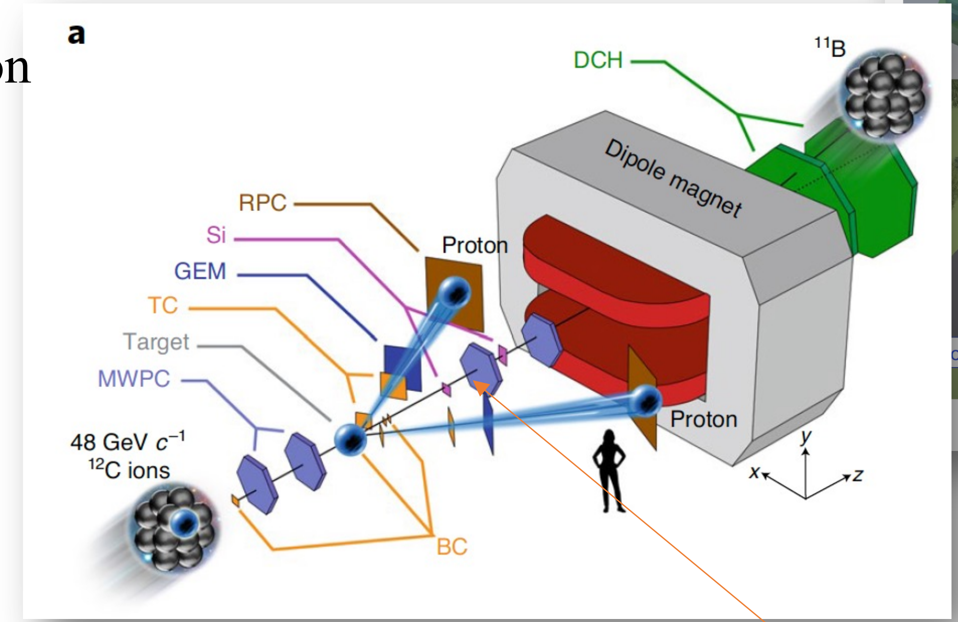


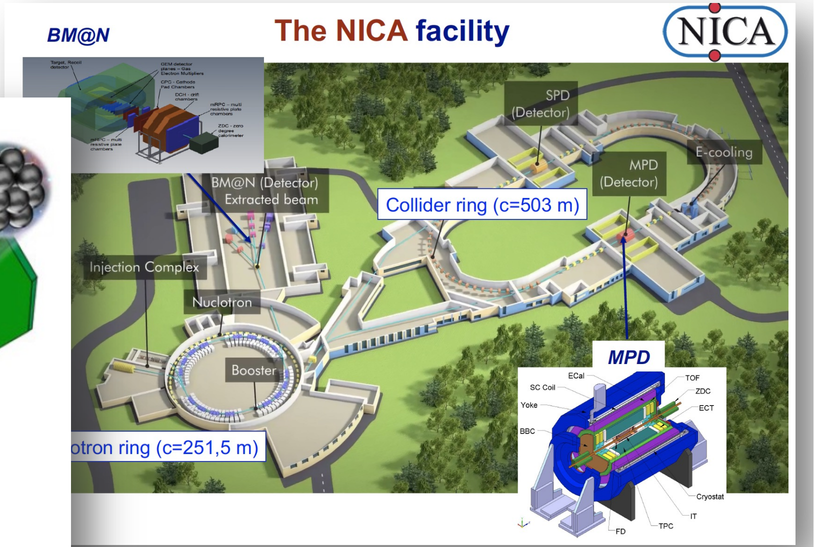
First Atemp at JINR BM@N

❑ Pioneer run in BM@N in 2018

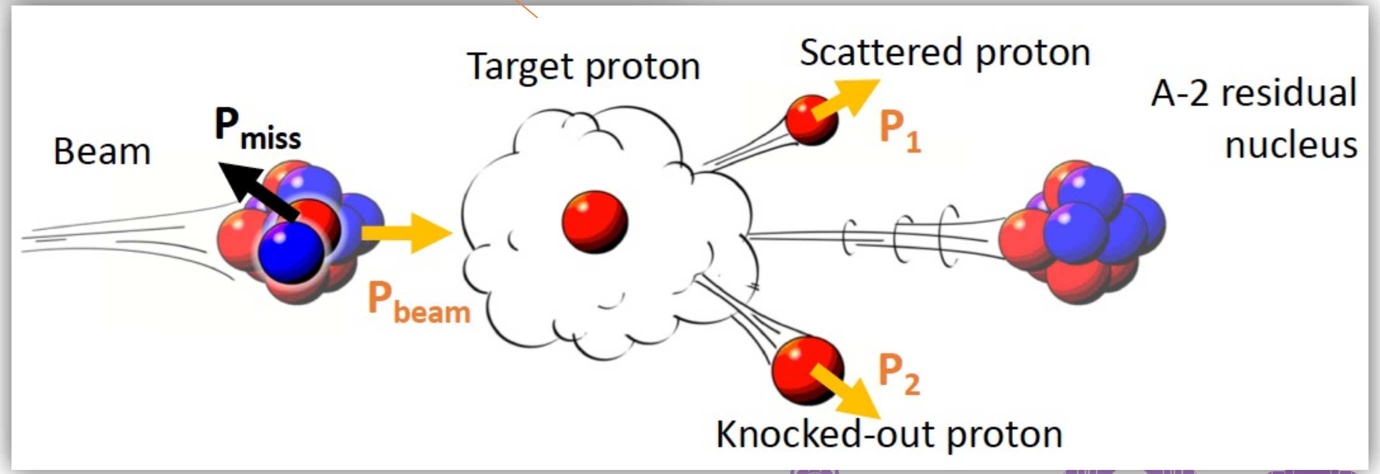
- ^{12}C beam, 3.5 – 4 GeV/c/nucleon
- Identify fragments:







M. Patsyuk et al. Nature Physics 17, 693 (2021)



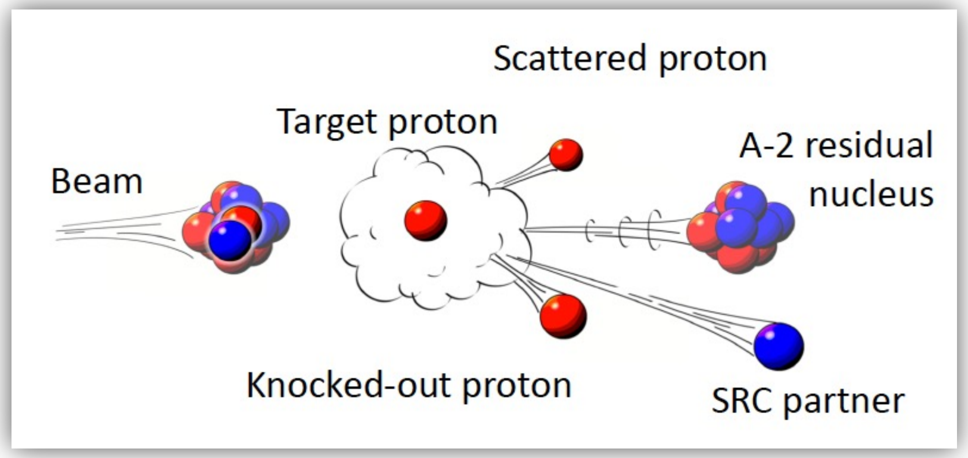
- Detection of two outgoing nucleons
- Reconstruct initial nucleon momentum:

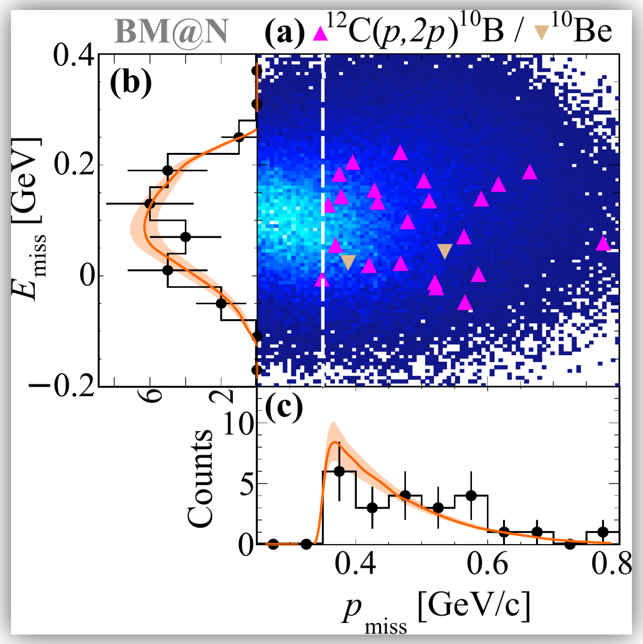
$$P_{miss} = P_1 + P_2 - P_{beam}$$

First Atemp at JINR BM@N

❑ Selection of 2N-SRC Pairs

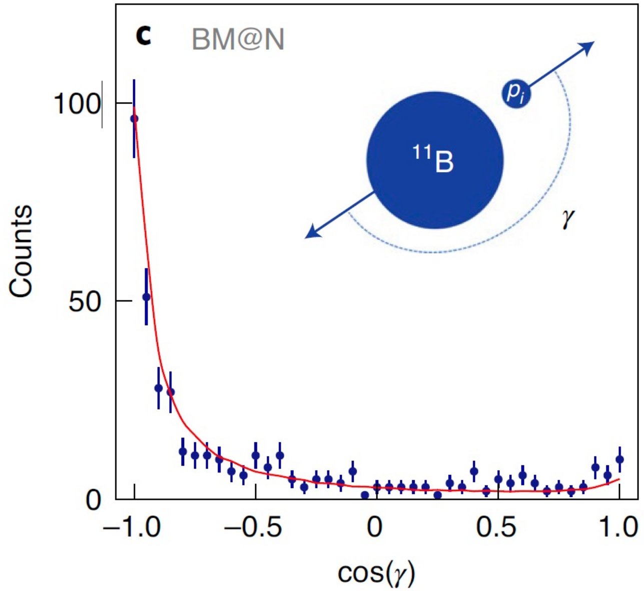
np pair: $^{12}C(p,2p)\ ^{10}B$
pp pair: $^{12}C(p,2p)\ ^{10}Be$





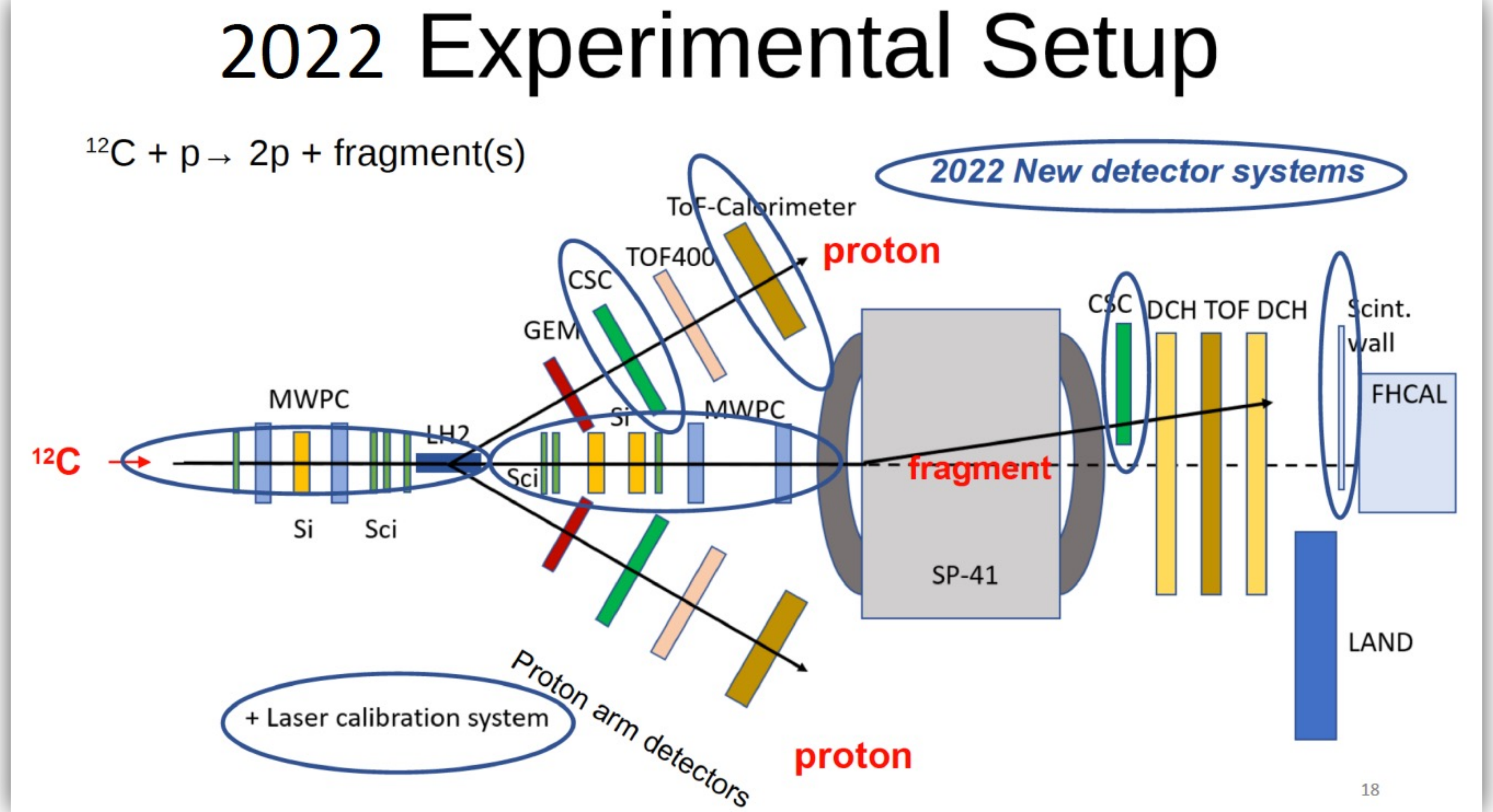
M. Patsyuk et al. Nature Physics 17, 693 (2021)

23 np & 2 pp SRC-pairs



Full BM@N SRC Run

- ❑ 2018 run firstly demonstrated advantage of inverse-pA reaction in SRC study
  M. Patsyuk et al. Nature Physics 17, 693 (2021)
- ❑ 2022 run completed
  - ✓ JINR,GSI, MIT, Tel Aviv, Tsinghua …
  - ✓ Improve statics x100
  - ✓ Detection of n & p recoils
  - ✓ Multi-fragment reconstruction
  - ✓ Absolute cross-section

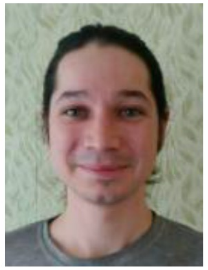


Full BM@N SRC Run

Tsinghua University

- Data under analysis by:

Göran Johansson (TAU)



Timur Atovuallev (JINR)

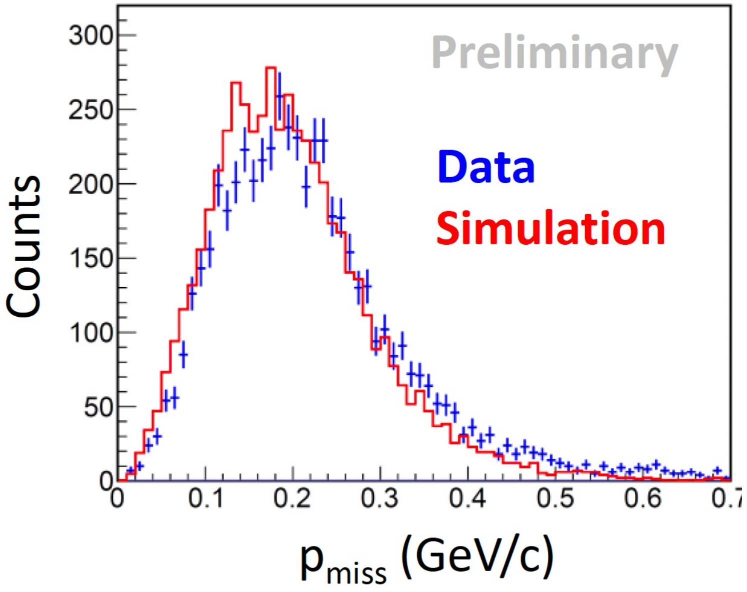
Sergey Nepochatykh (JINR)

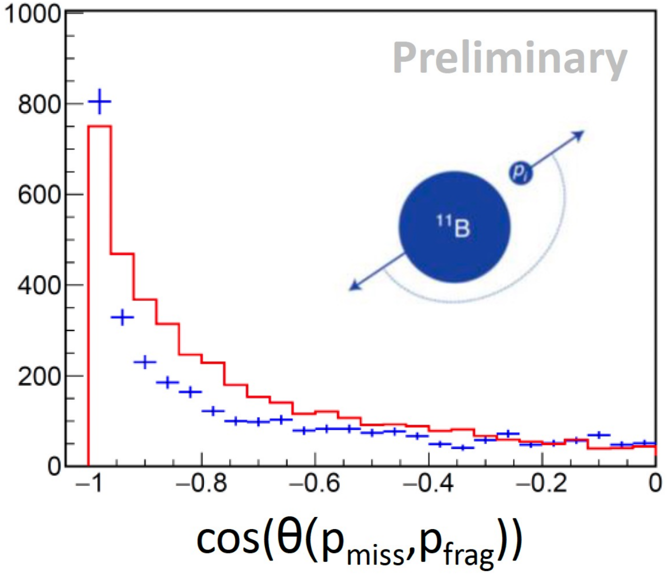
Yaopeng Zhang (Tsinghua U)

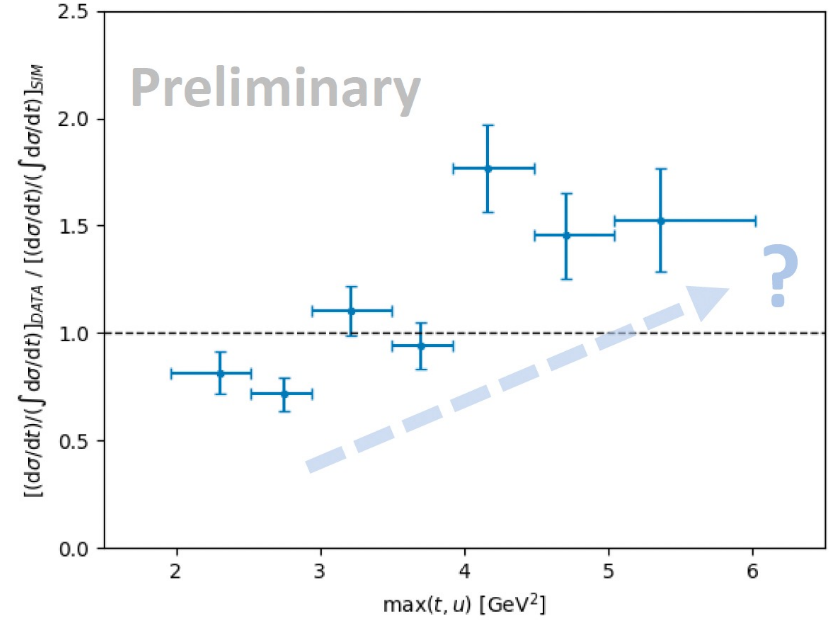
Vasilisa Lenivenko (JINR)

Maria Patsyuk (JINR)

Julian Kahlbow (MIT)





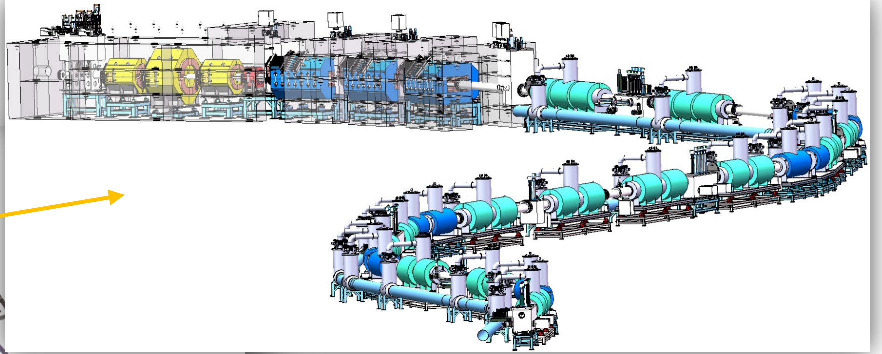


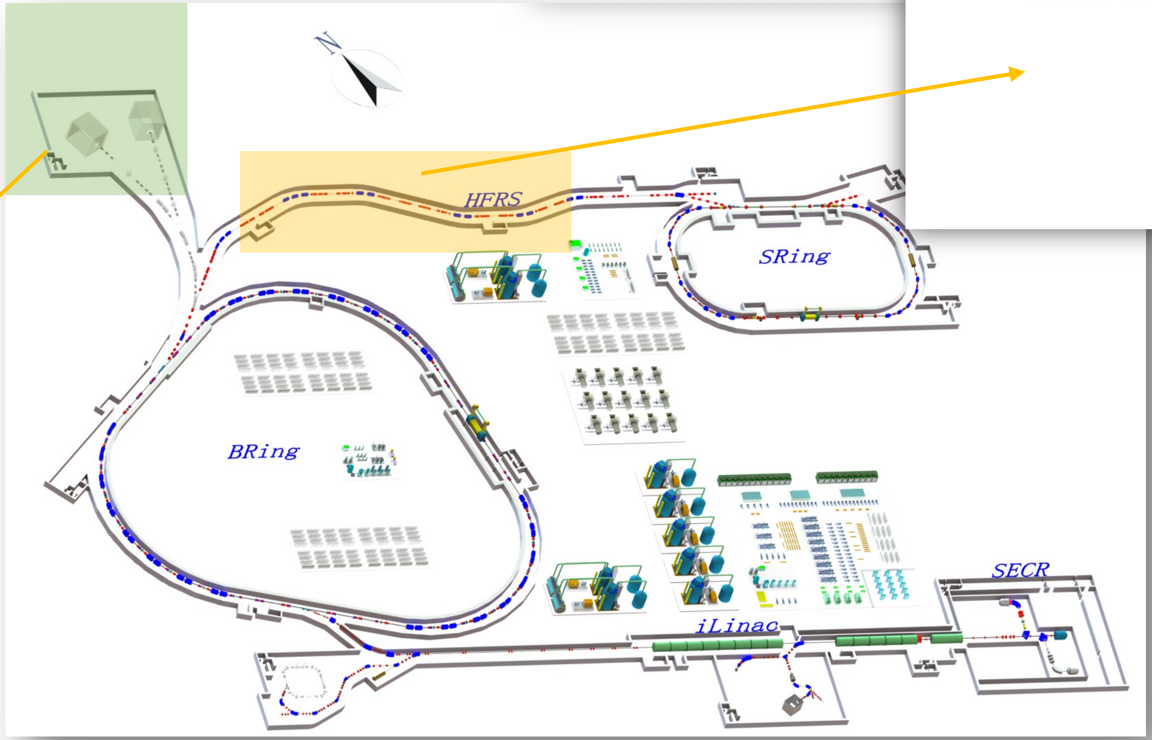
- ✓ X10 more statistics vs 2018 run
- ✓ First extraction of absolute XS

Measuring SRC @HIAF

Tsinghua University

- HIAF construction to be completed in 2025:
  - C12, E=51 GeV/c (4.25GeV/c/u) → similar to NICA
  - 1.8×10^{12}pps (fast extr.), 4.5×10^{11}pps (slow extr.) vs. 3.5×10^{4} pps at JINR



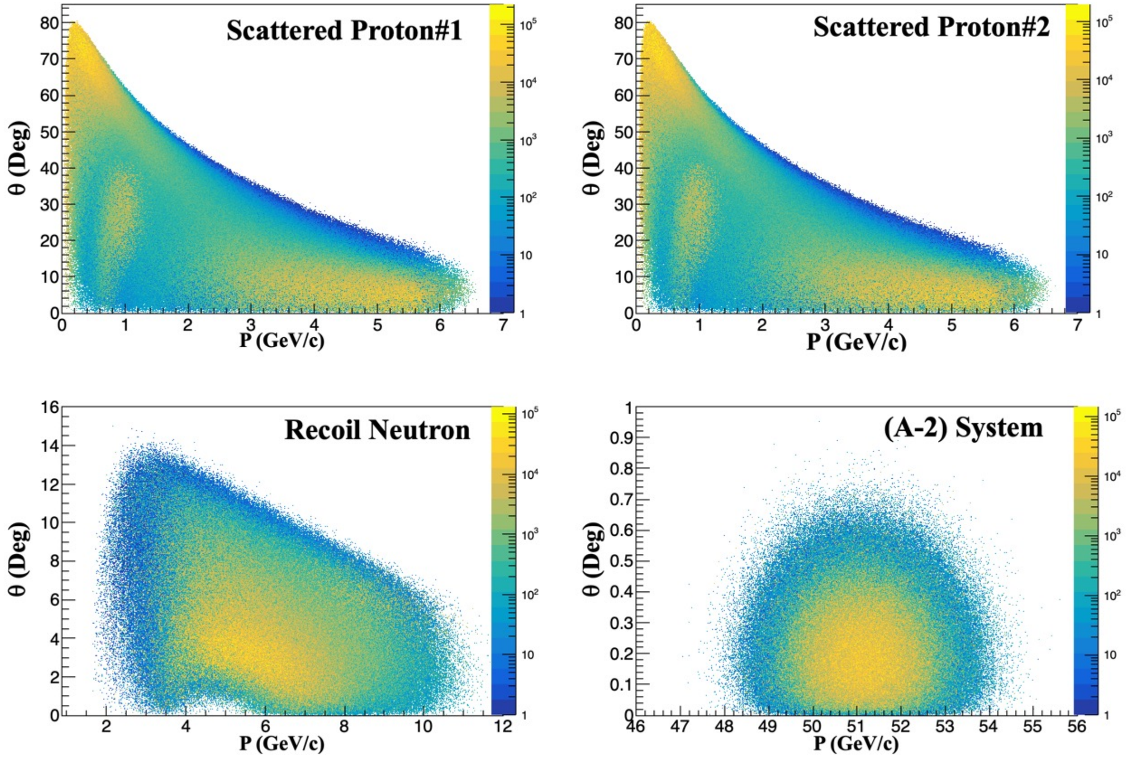


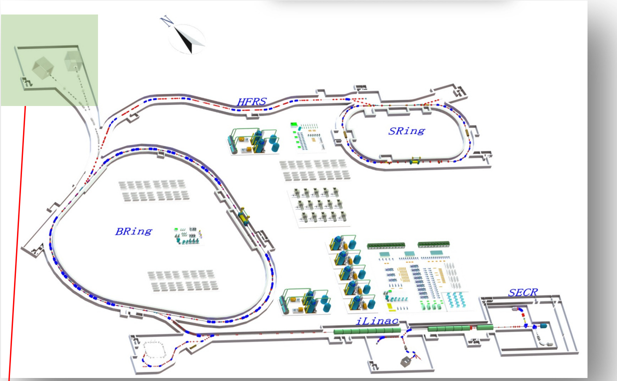
High-Energy Station (HES):
- CEE+, CHNS, …
- A general-purpose full acceptance detector?

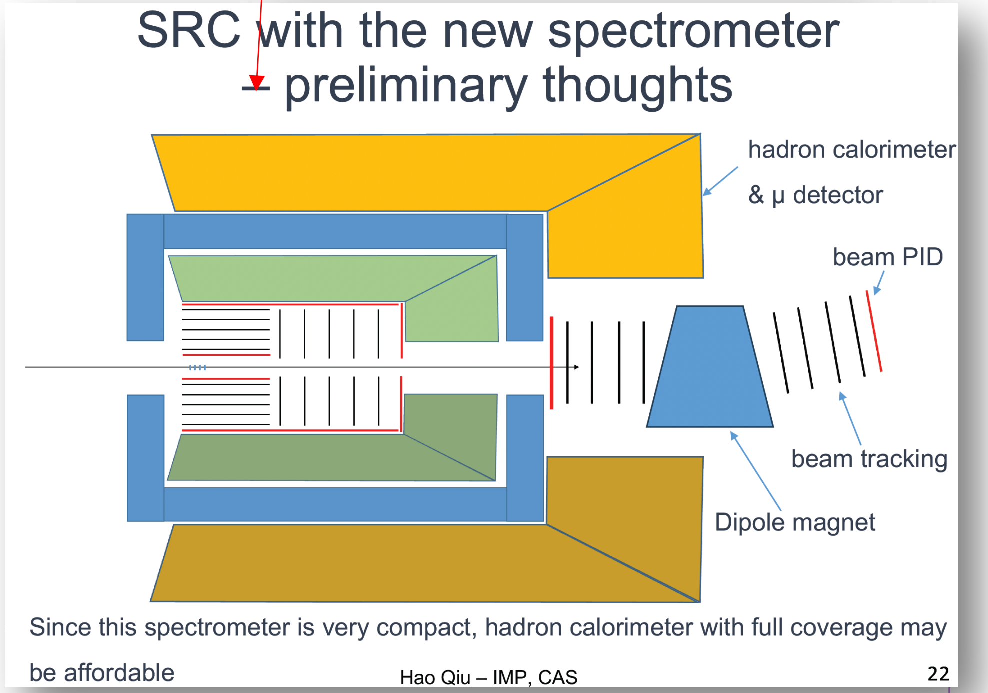
High Energy Fragment Separator (HFRS):
- Secondary radioactive beam

Measuring SRC @HIAF-HES

- Precision frontier for SRC in HES:
  - Mapping 2N-SRC at all kinematic
  - Search 3N-SRC







Measuring SRC @HIAF-HES

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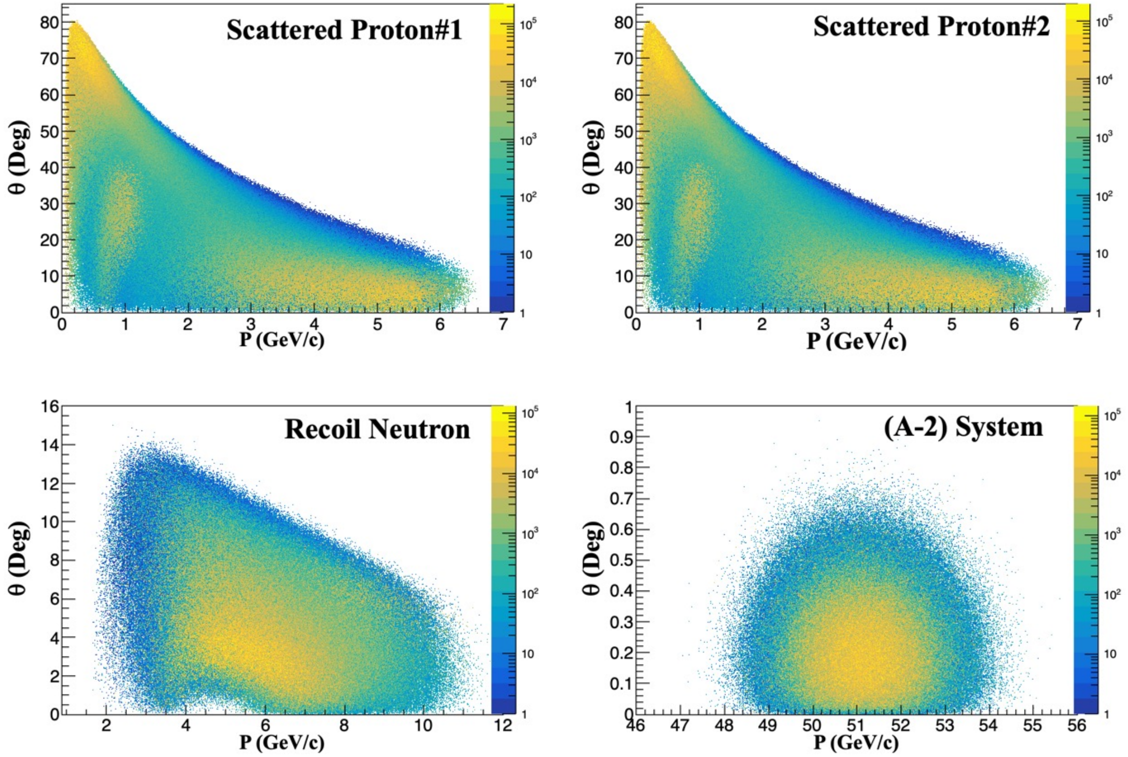
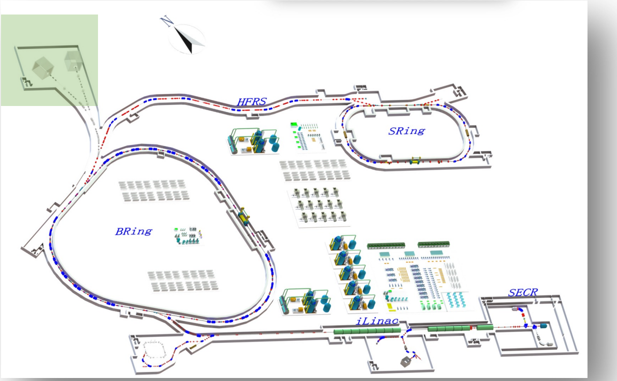
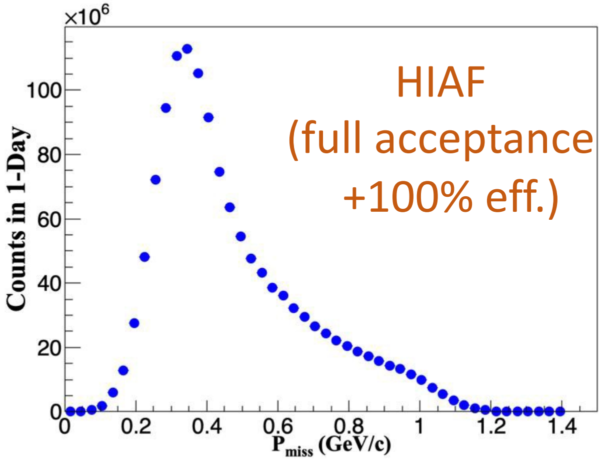


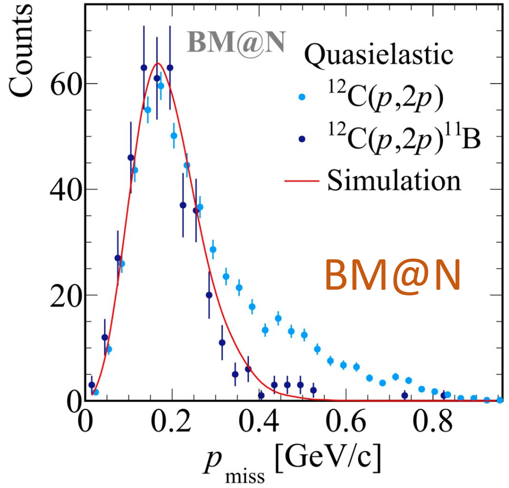


- Monte-Carlo Simulation ($^{12}C^{6+}$ at 51GeV/c)

1-day @ (4.5~18)x10^{11}pps

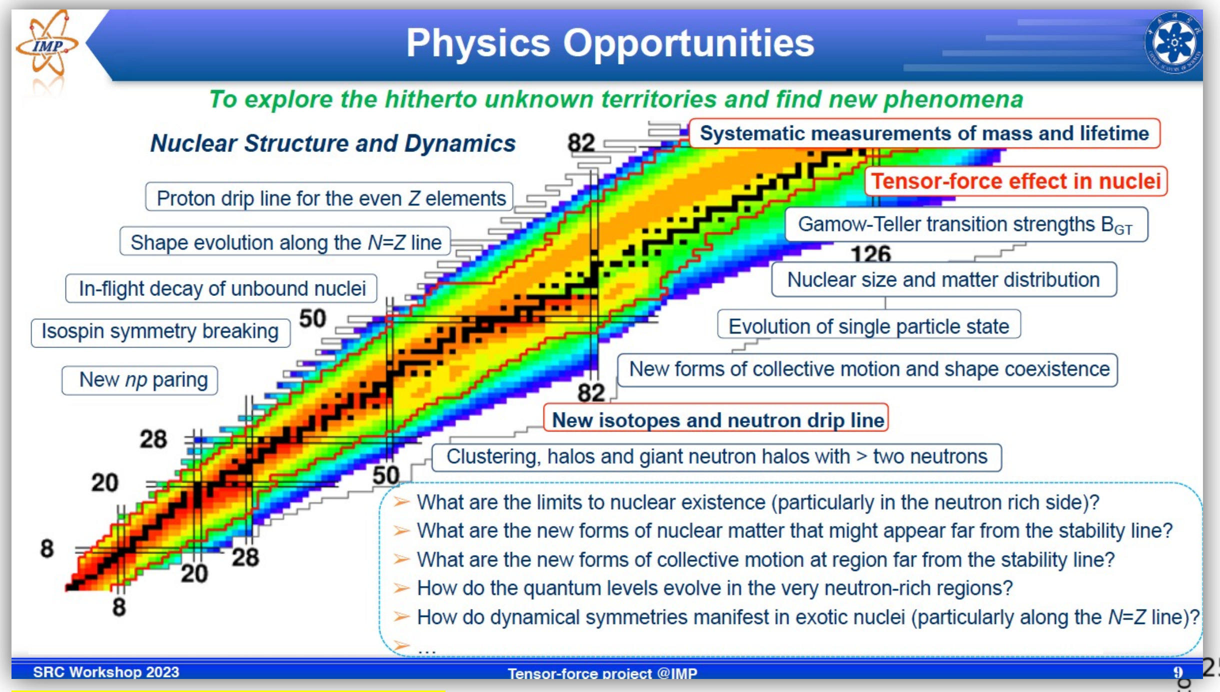


2-week @ 3.5x10^{4}pps



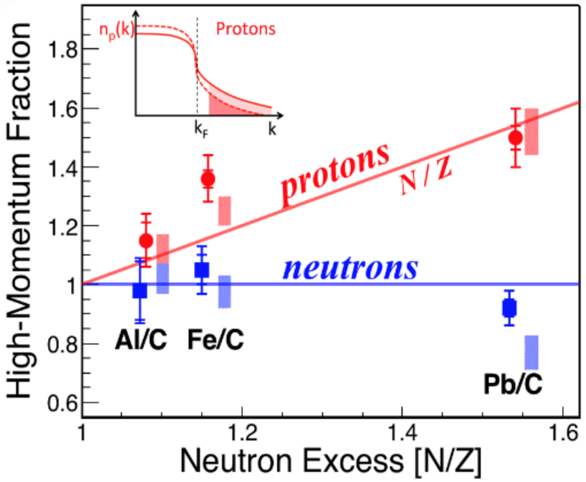
SRC Study @HIAF-HFRS

- ❑ Radioactive ion beams are produced at HFRS



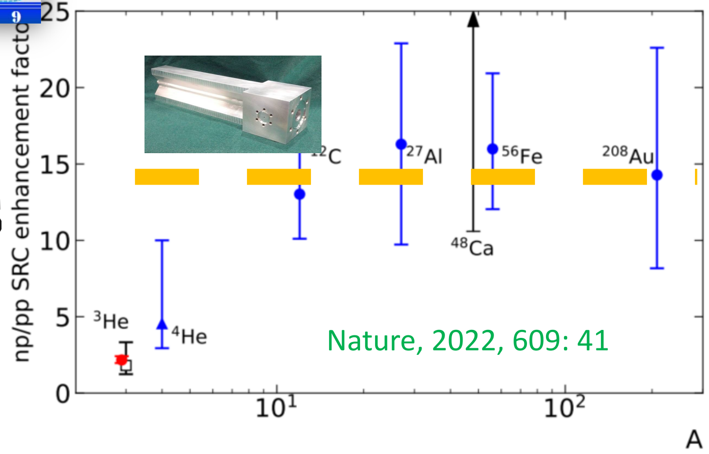
by Hooi-Jin Ong@IMP

Maximum rigidity	25 Tm
Resolving power	800, 700, 1100
Momentum acceptance	± 2.0%
Angular acceptance	± 30 mrad (x) ± 15 mrad (y)
Beam size	± 1 mm (x) ± 2 mm (y)
Total length	192 m



Nature, 560 (2018) 617-621.

- ❑ Study 2N-SRC w/ radioactive isotopes from HFRS
  - ✓ Survive light to large neutron-rich nuclei
  - ✓ Cannot be done in fixed target experiments



First SRC Workshop in China

- Link：https://indico.impcas.ac.cn/e/src
- Recording：https://cloud.tsinghua.edu.cn/d/0cdcfe10e90046d49f4b/

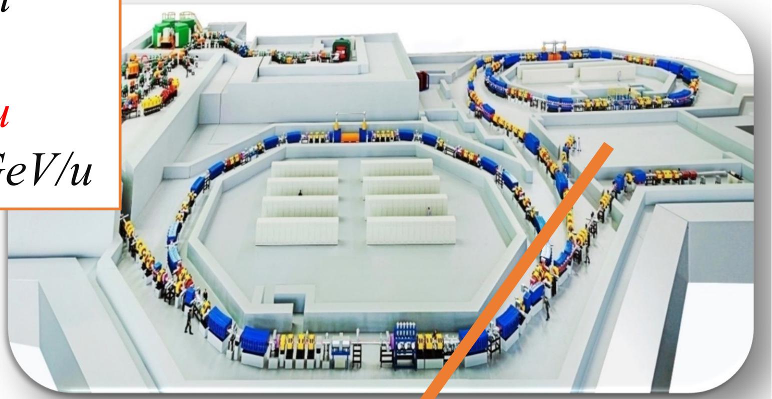
SRC Physics @ HIRFL-CEE

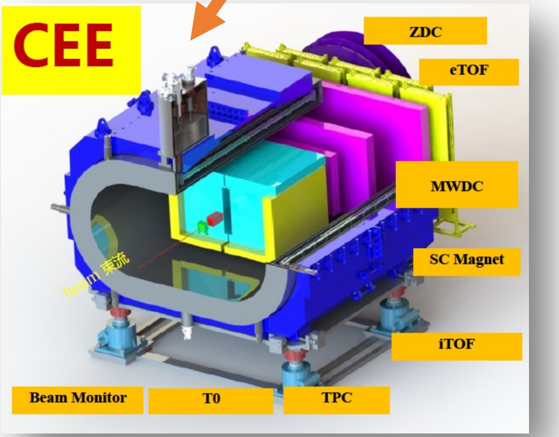
Tsinghua University

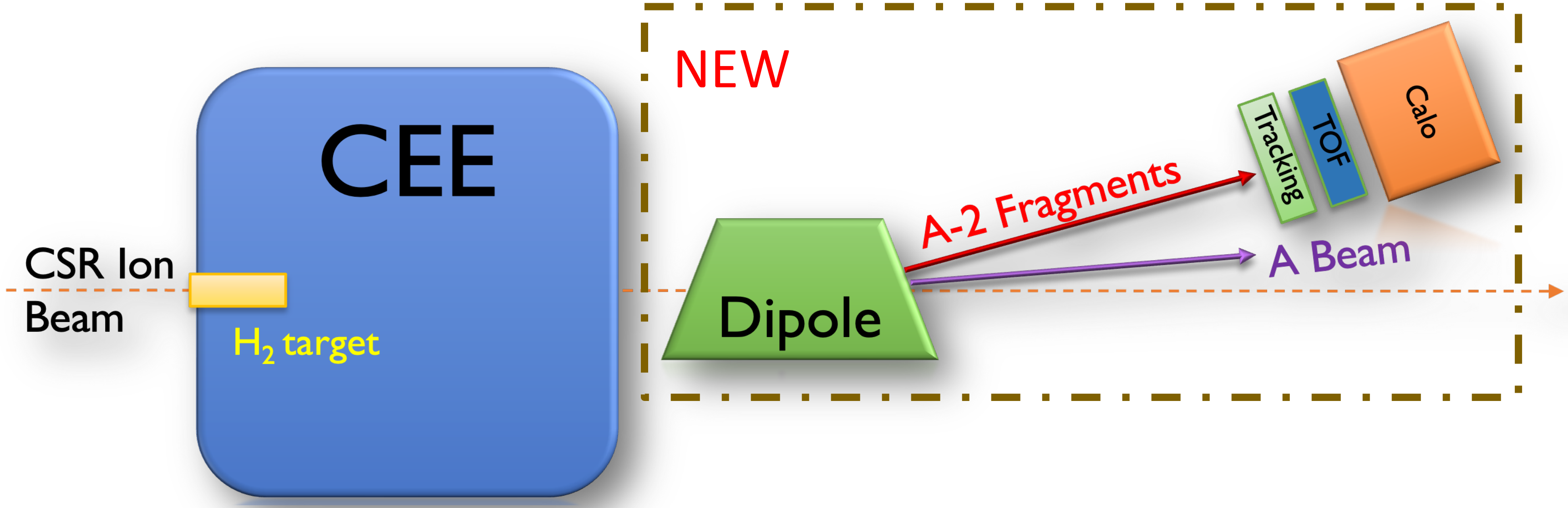
- Using CEE w/ additional changes/upgrades:
  - ✓ Liquid hydrogen (LH2) target
  - ✓ Replace ZDC w/ a new detectors for nuclear fragments
  - ✓ A new dipole?
  - ✓ Neutron wall?

HIRFL-CSR beam

- *P: 2.8 GeV*
- *$^{12}C^{+}$: 1 GeV/u*
- *$^{238}U^{+}$: 0.5 GeV/u*



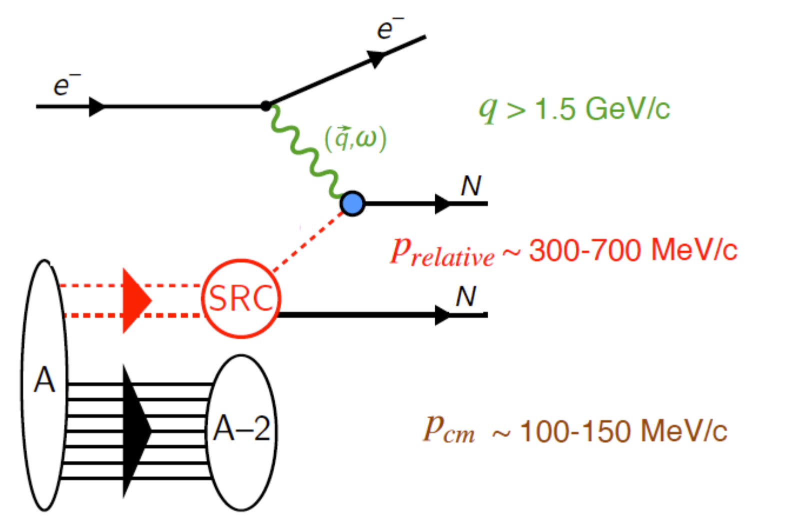




SRC Physics @ HIRFL-CEE

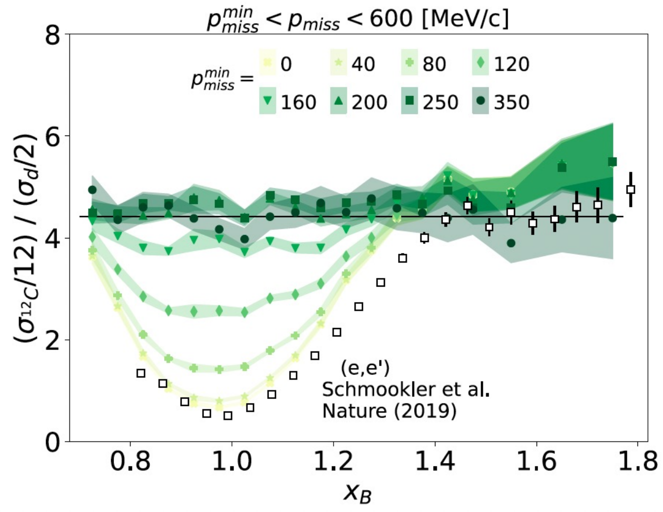
- ❑ Goals:
  - ✓ Precision nuclear wave functions
  - ✓ Cleanly define MF & SRC transition regions for the first time

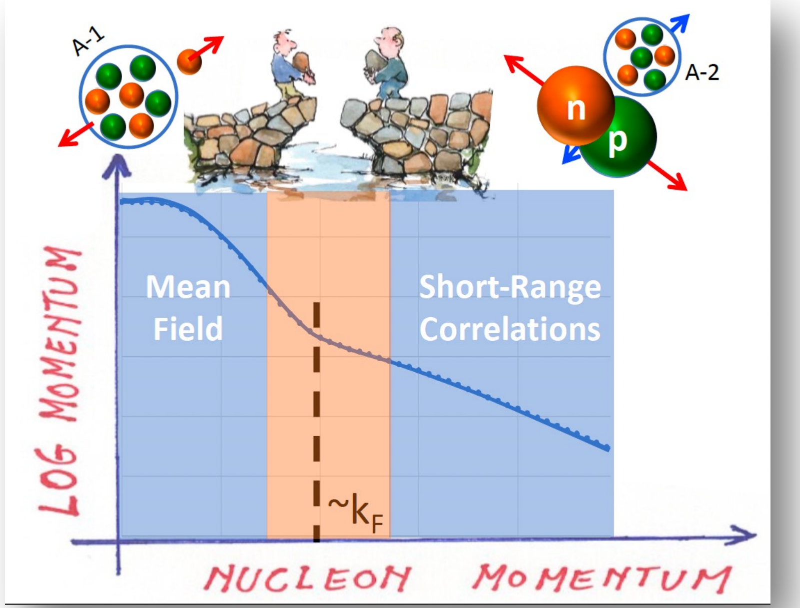
Scale Separation: $q \gg p_{relative} \gg p_{cm}$

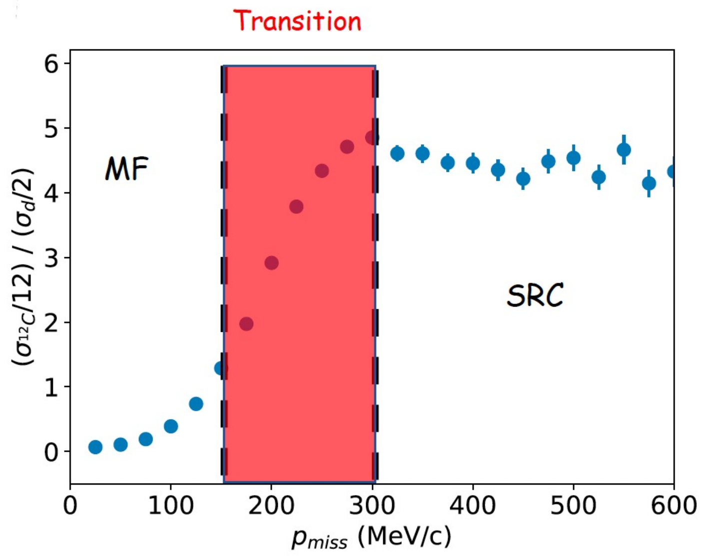


PRC 92 (2015), PLB 780 (2018), PLB 791 (2019), PLB 792 (2019), JPG 47 (2020), Nature Physics 17 (2021), PRC 104 (2021), PRC 53 (1996), PRL 119 (2017)

Korover PRC 107, L061301 (2023)





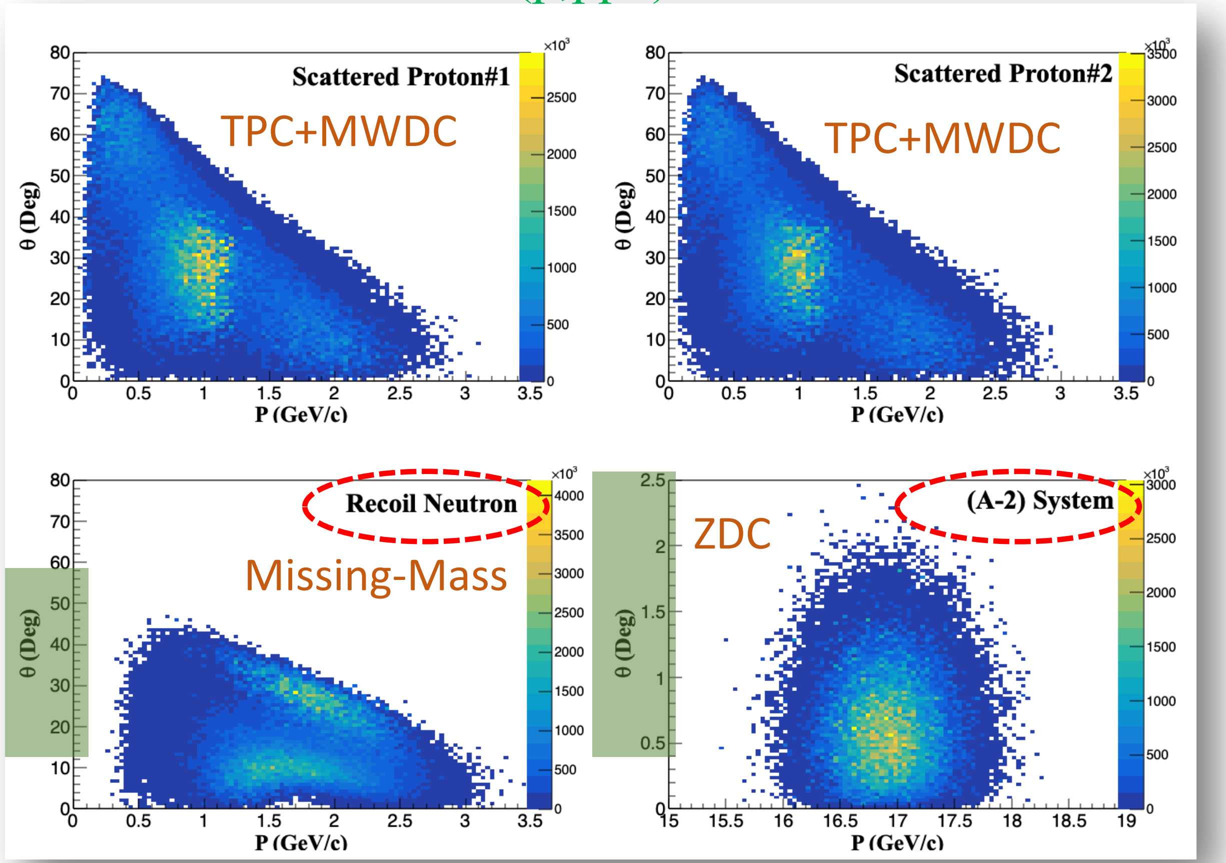


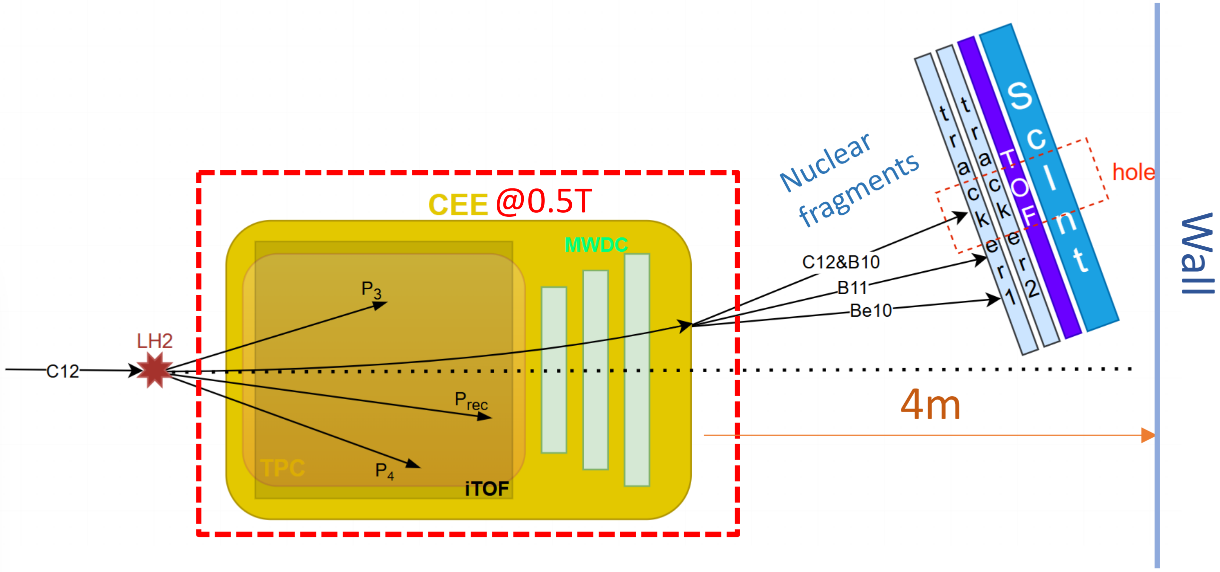
✓ IMPORTANT: a 30MeV/c missing-momentum resolution is key to understand transcition from Mean-Field to SRC

Proton Detection

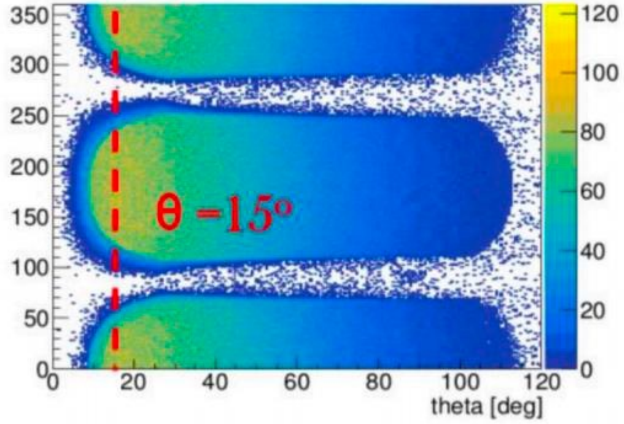
- ❑ Monte-Carlo simulation of SRC w/ CEE@HIRFL
- ❑ Protons are within existing CEE detectors

$^{12}C^{+}$ (p,ppn)$^{10}B^{+}$

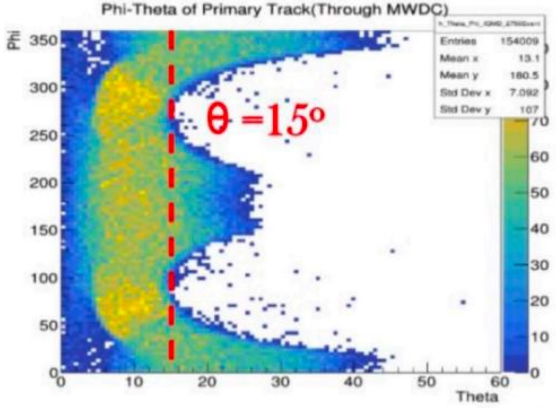




CEE-TPC

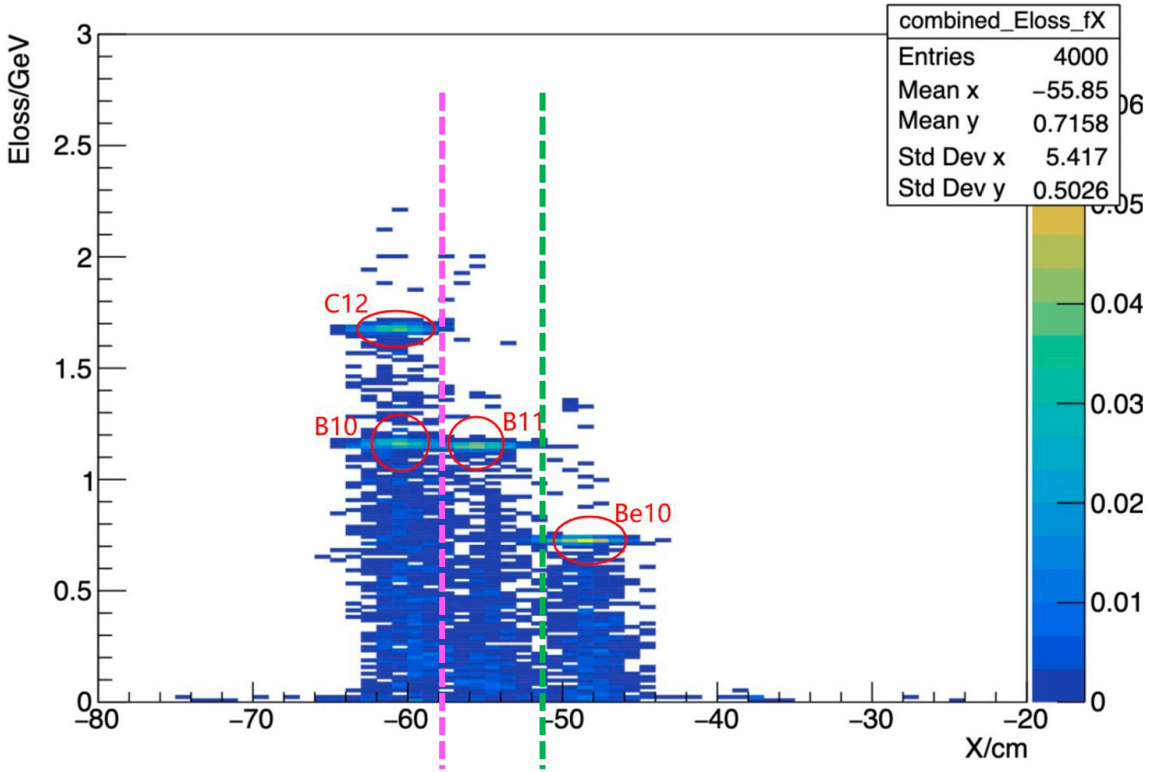


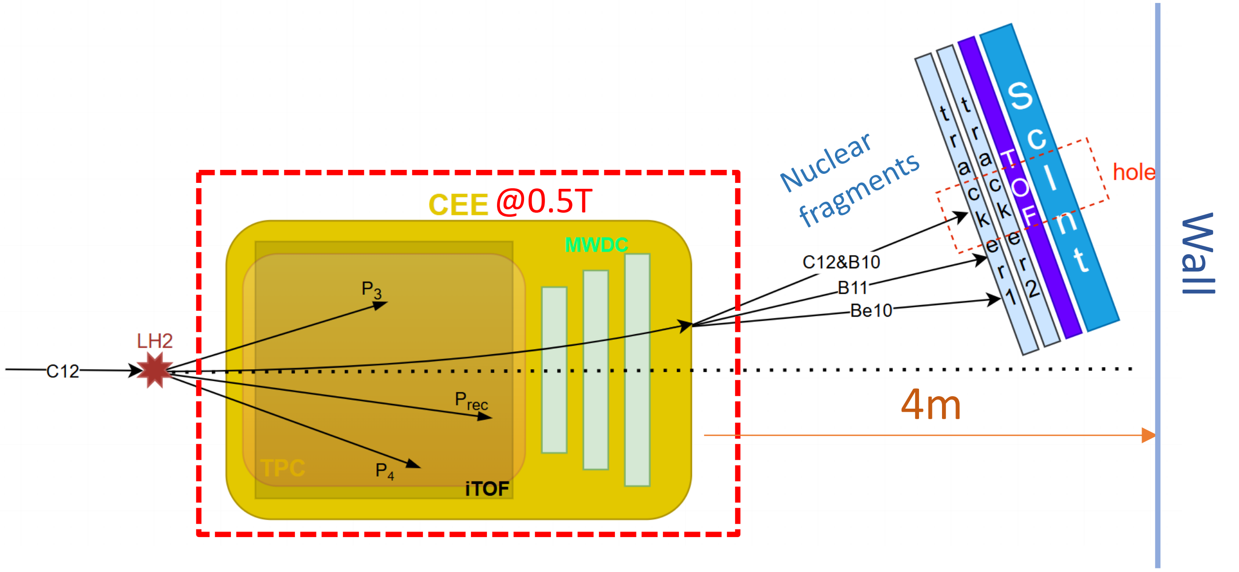
CEE-MWDC



Fragment Detection

- ❑ Fragment detection w/ standard CEE setup
  - ✓ Fragment-Detector at 4m downstream
  - ✓ Same magnetic field as 0.5T



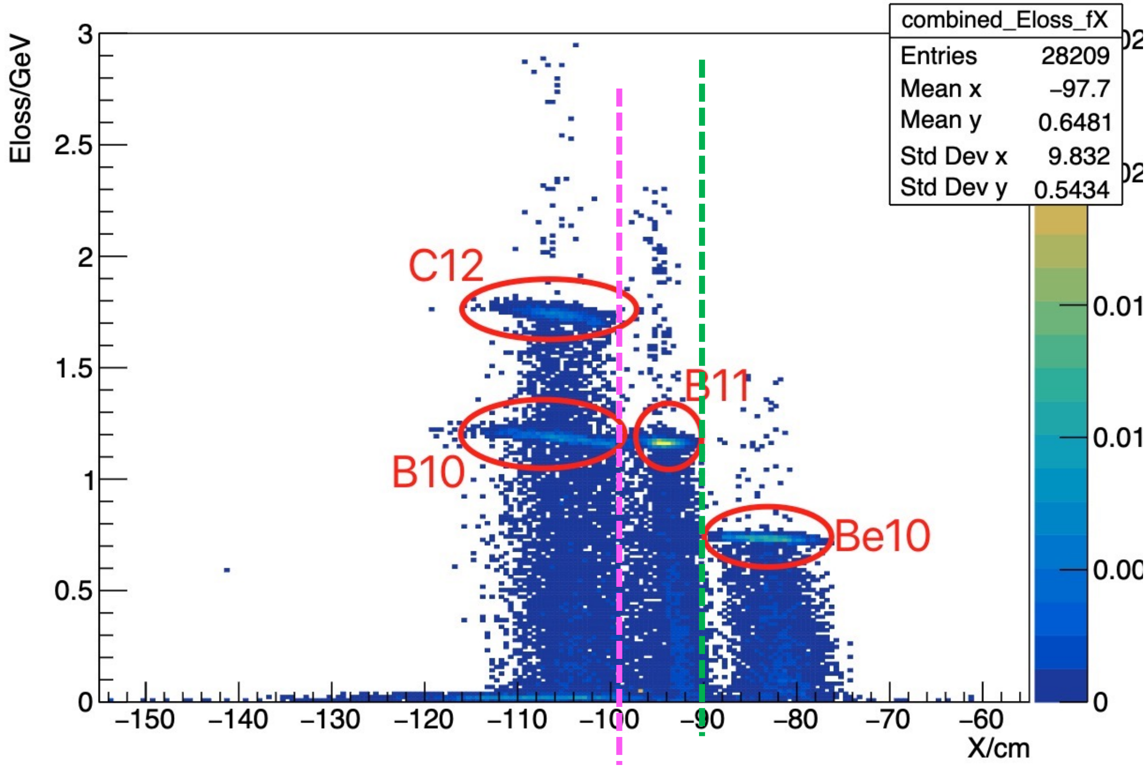


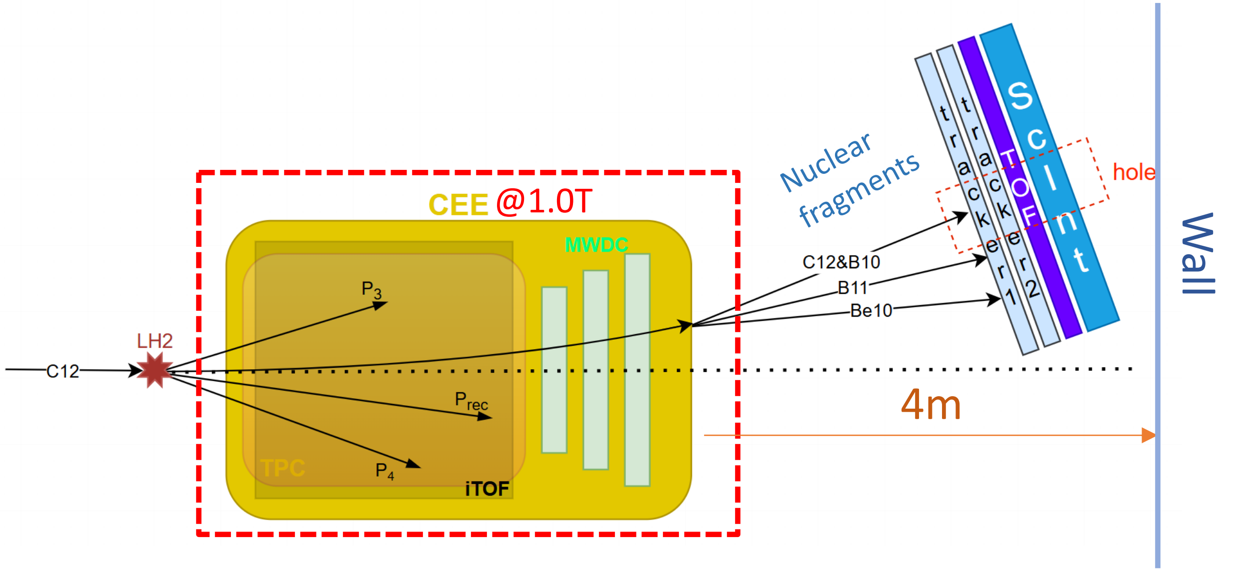
- ❑ Not yet considered:
  - Detector resolution & efficiencies
  - Background

Fragment Detection

Tsinghua University

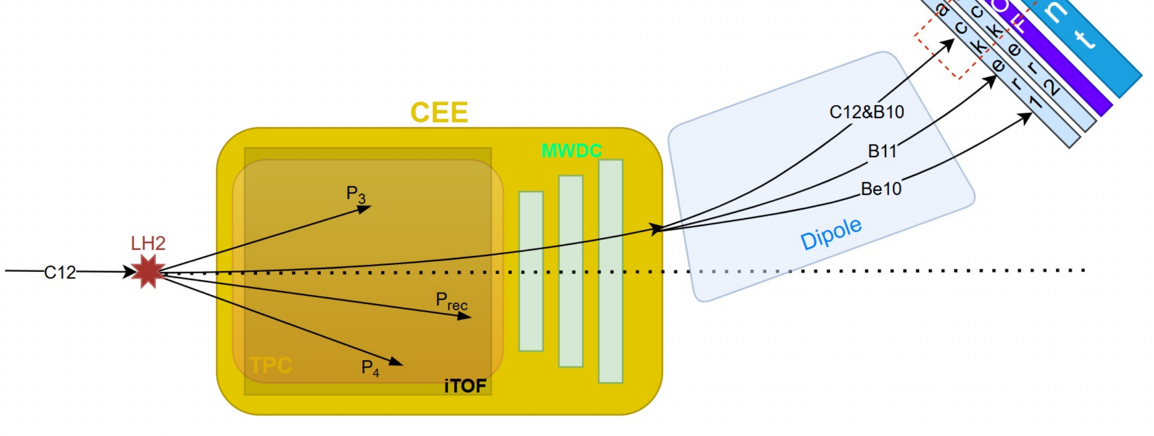
- ❑ Fragment detection w/ standard CEE setup
  - ✓ Fragment-Detector at 4m downstream
  - ✓ Increase magnetic field to 1.0T





❑ Continue Improvement

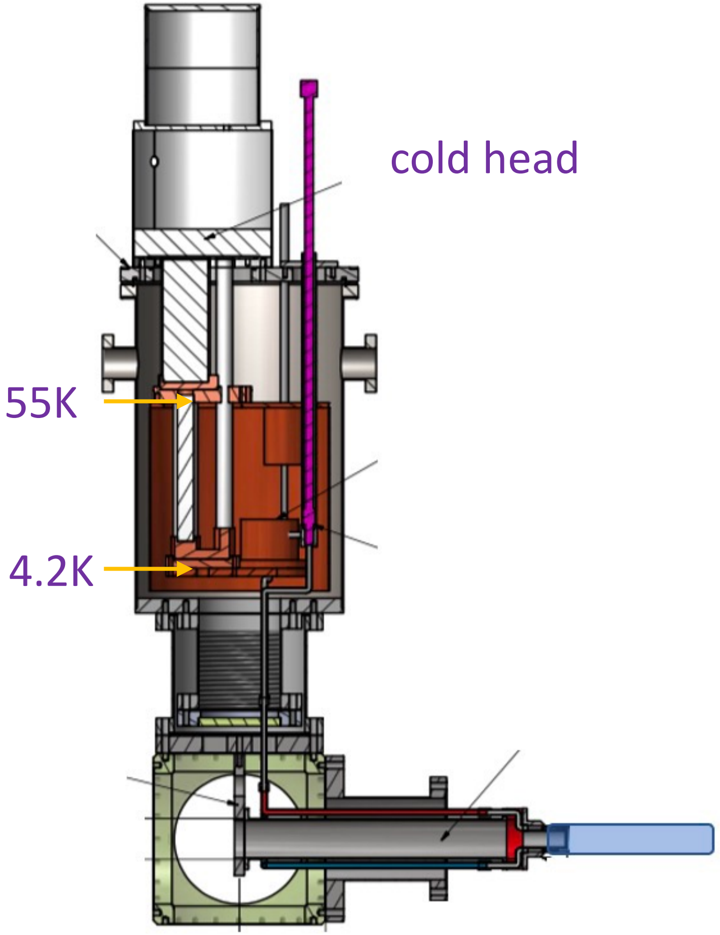
→Add a new dipole?



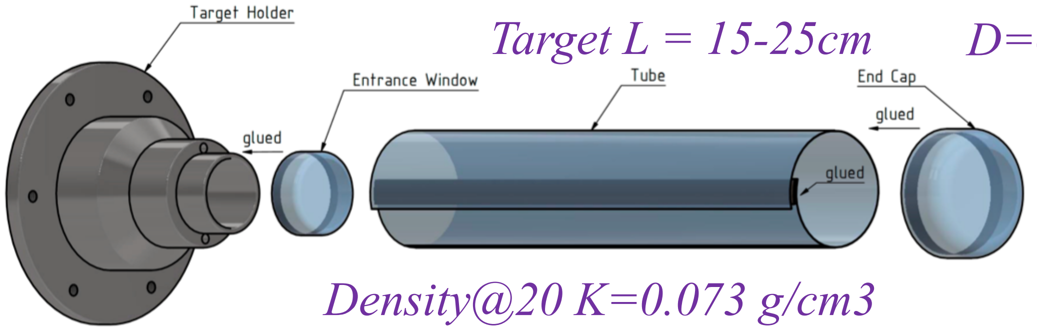
LH2 Target

- Under development by Hongna Liu, Beijing Normal University (BNU)

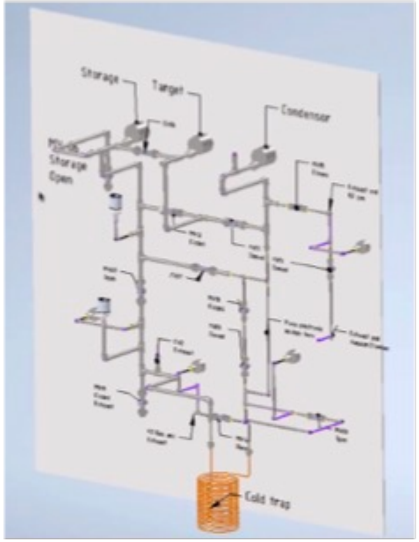
Target Chamber&Cooling



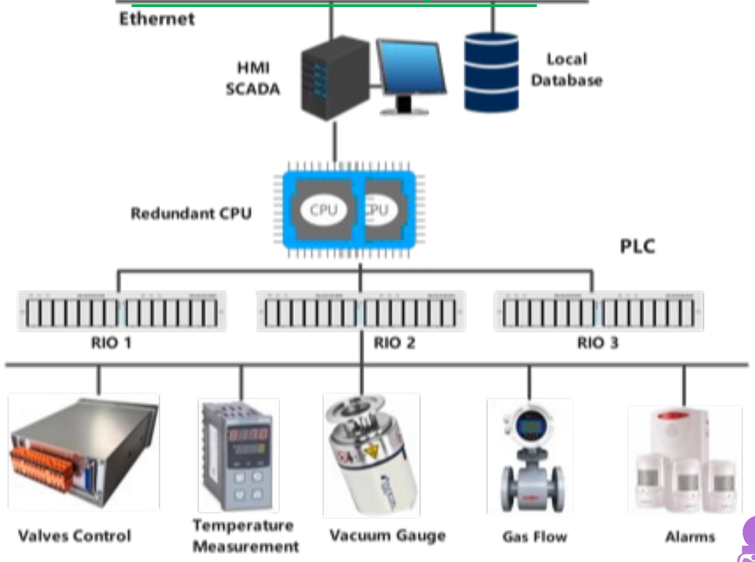
Target L = 15-25cm *D=0.52cm*

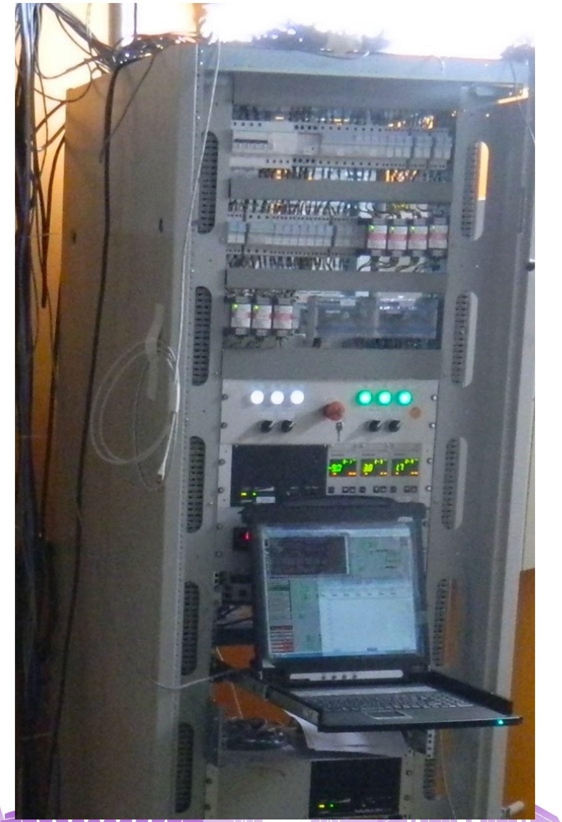


Density@20 K=0.073 g/cm3



Slow Control System

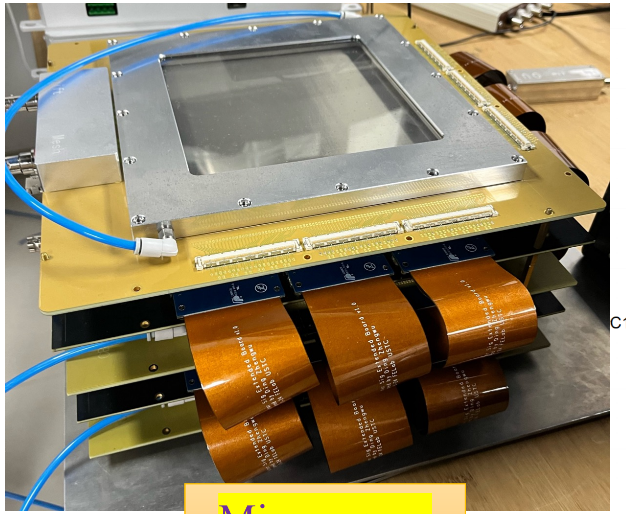




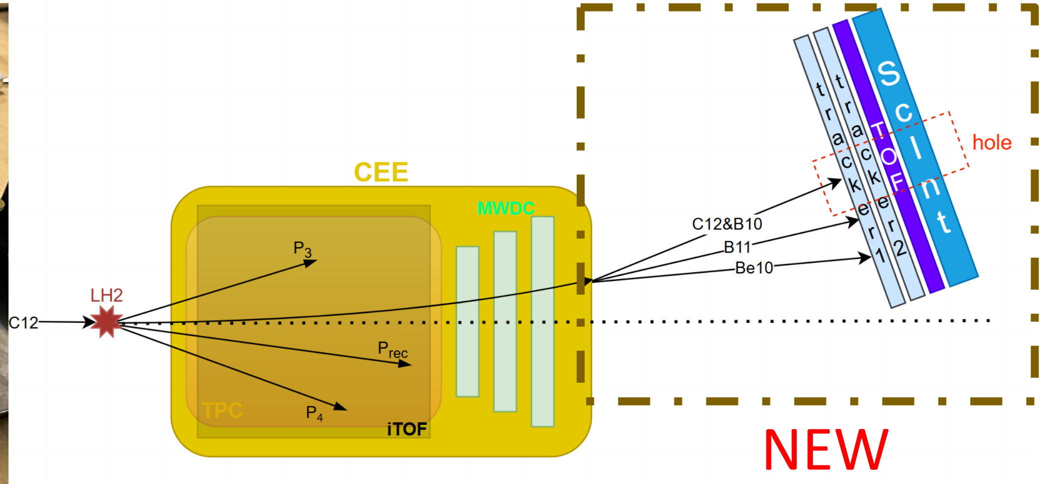
Detector R&D

Tsinghua University

- Fragment-Detectors:
  - mRPC-TOF
  - Micromegas trackers
  - Scintilators
  - Shashlyk-Ecal?
- All are available in Tsinghua

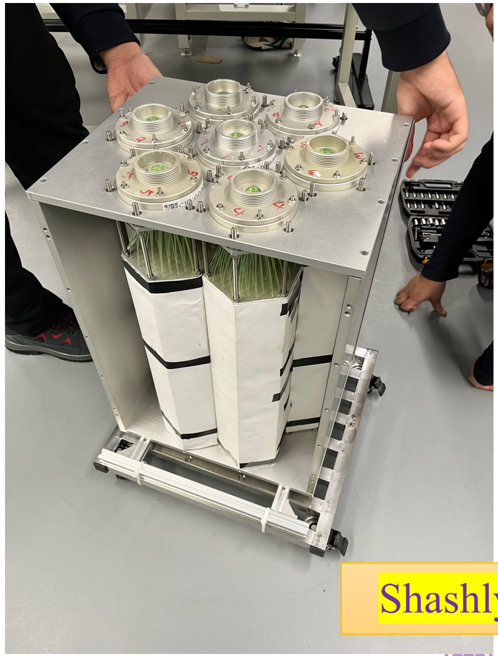


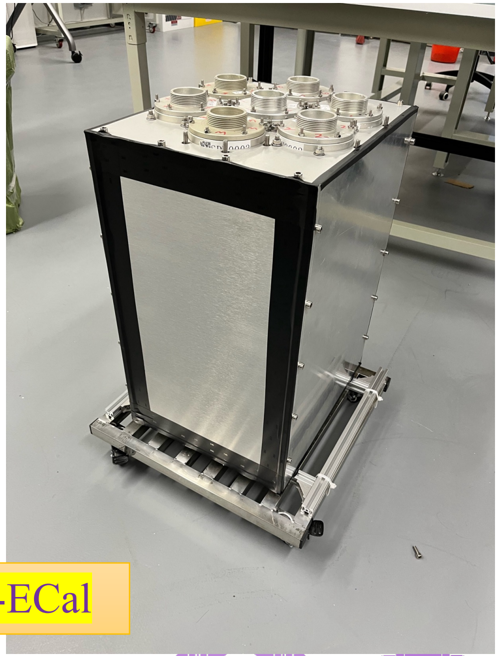
Micromegas



Sealed-mRPC

sMRPC at FermiLab (April 2022)





Shashlyk-ECal

Summary

- SRC allows studies of nuclear force, neutron stars, etc.
- 2N-SRC well studied (np-dominate); 3N-SRC remains unseen
- Inverse kinematic pA reaction → Precisely study SRC
- Initial exploration with JINR & GSI
- Precision frontier SRC study with HIAF
- Initial study in the existing CEE@HIRFL w/ small upgrades

❑ Collaboration with: Eli Piasetzky (Telv Aviv), Maria Patsyuk (Dubna), Hongna Liu (BNU), Or Hen&Julian Kahlbow & Hang Qi (MIT), Xionghong He & Hao Qiu & Yapeng Zhang (IMP), ...

✓ Supported by NSFC "Joint NSFC-ISF Research Grant" under funding#12361141822