Short-Range Correlations Study at HIAF

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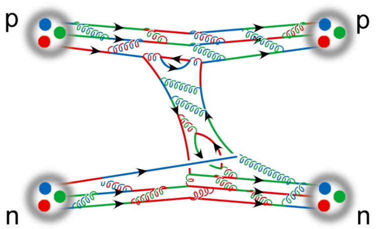
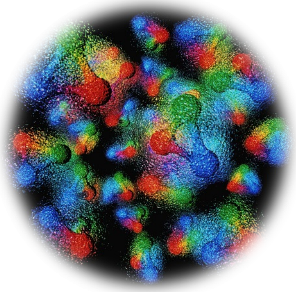
清華大學 Tsinghua University

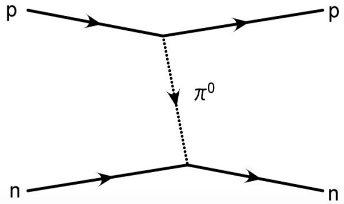
Nucleons in Nuclei

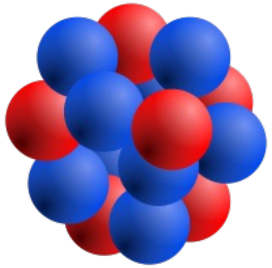
➢ Strong Force vs Nuclear Force





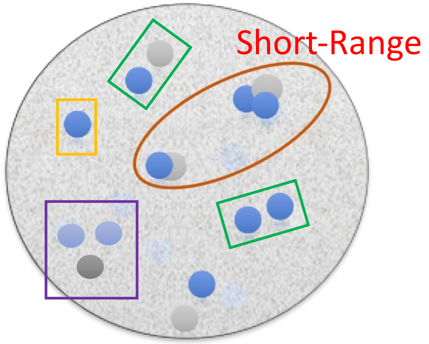
- ❑ Nuclear force is a "weak" strong force, but too complicated for QCD in description of Nuclei





- ❑ Suprisedly, shell-models work very well
  - ✓ Sum of nucleon-nucleon(NN) Interactions → mean field
  - ✓ Modern NN potentials, e.g. AV18

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



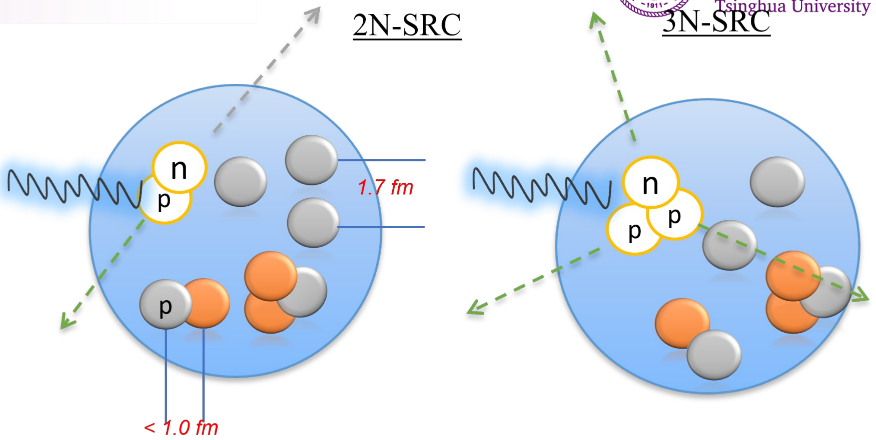
- NN terms fitted from data
- Too hard for NNN and beyond
- Short range part (non-nucleonic)?

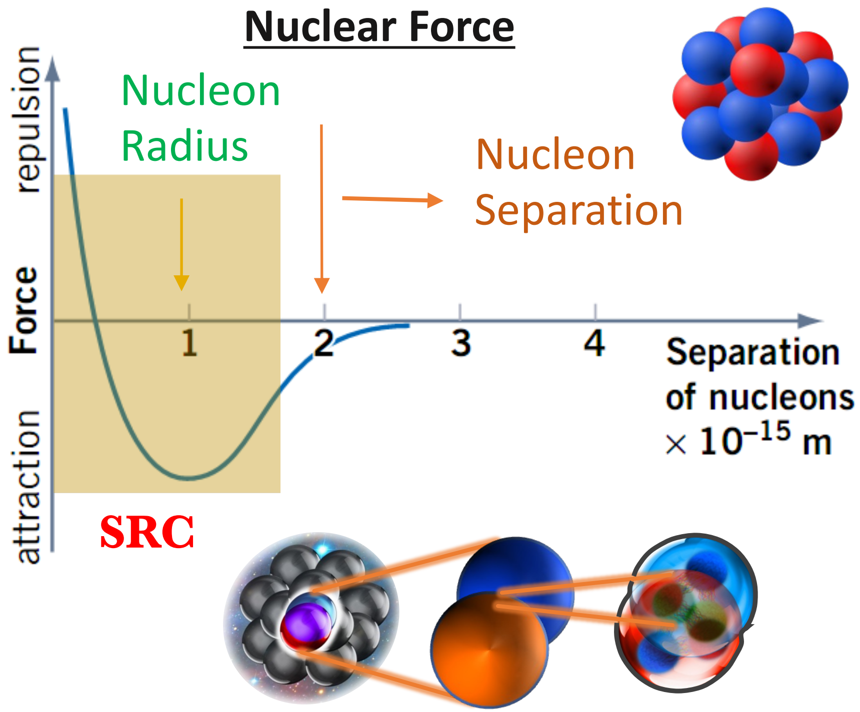
TABLE I. Argonne V18 spin-isospin operators in coordinate space.

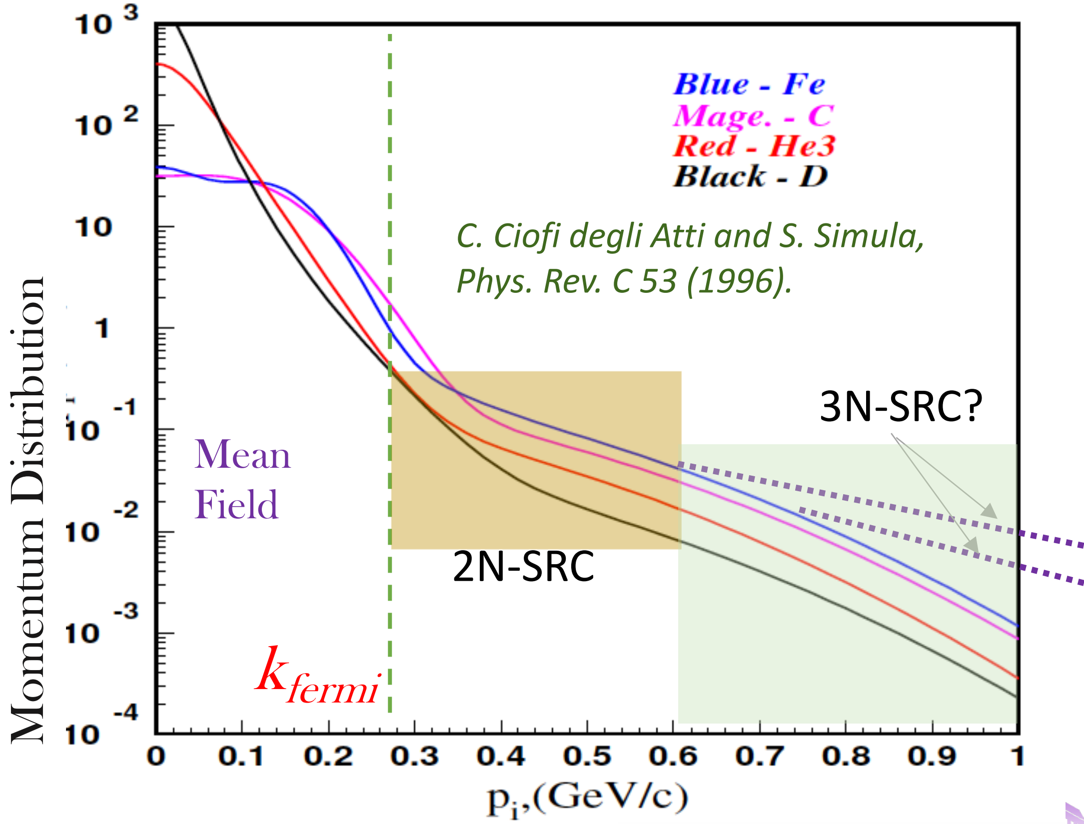
Term	Spin-isospin operator in r space
O_1	$\mathbf{I}$
O_2	$(\boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2)$
O_3	$(\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2)$,
O_4	$(\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2)(\boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2)$
O_5	$S_{12} = 3(\boldsymbol{\sigma}_1 \cdot \hat{\mathbf{r}})(\boldsymbol{\sigma}_2 \cdot \hat{\mathbf{r}}) - \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2$
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}	$(\tau_{1z} + \tau_{2z})$

Nucleons in Nuclei

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

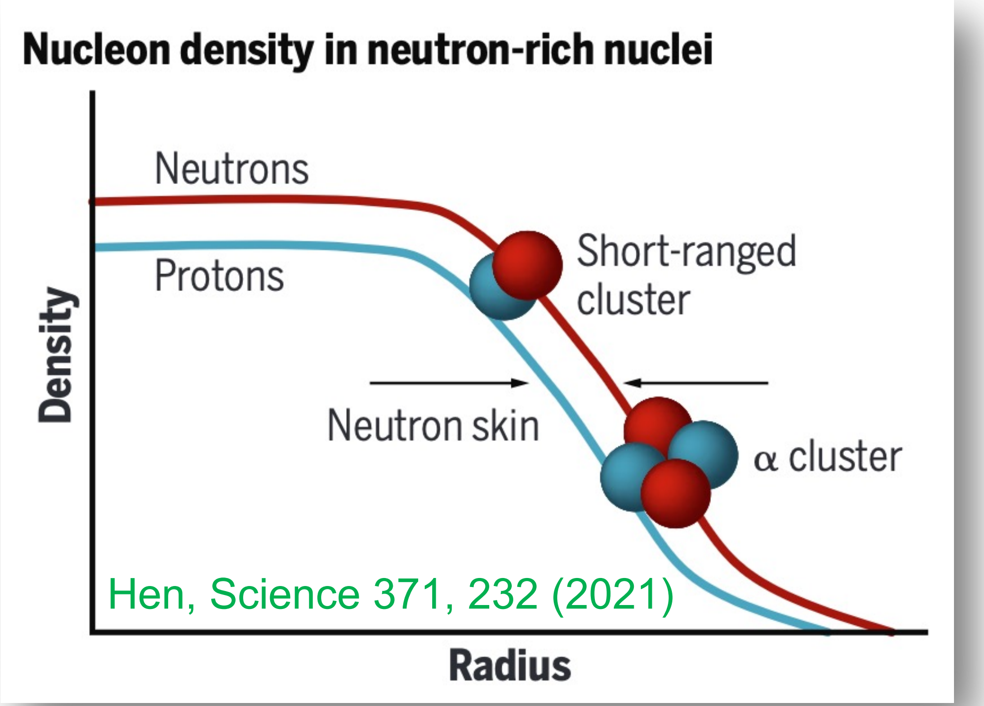




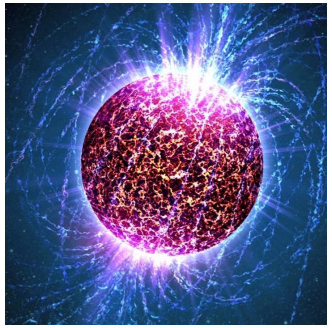


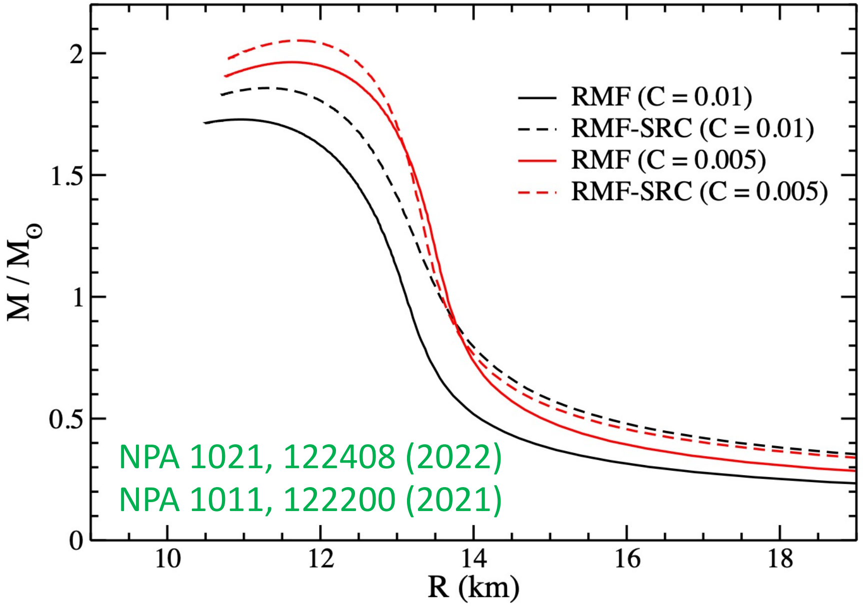
Nucleons in Nuclei

- **Studying SRC is important**
  - ❑ Short-Range forces are the extreme cases of NN & NNN forces
  - ❑ SRC could be important in forming neutron-rich nuclei



- ❑ SRC in forming ultra-heavy neutron stars?



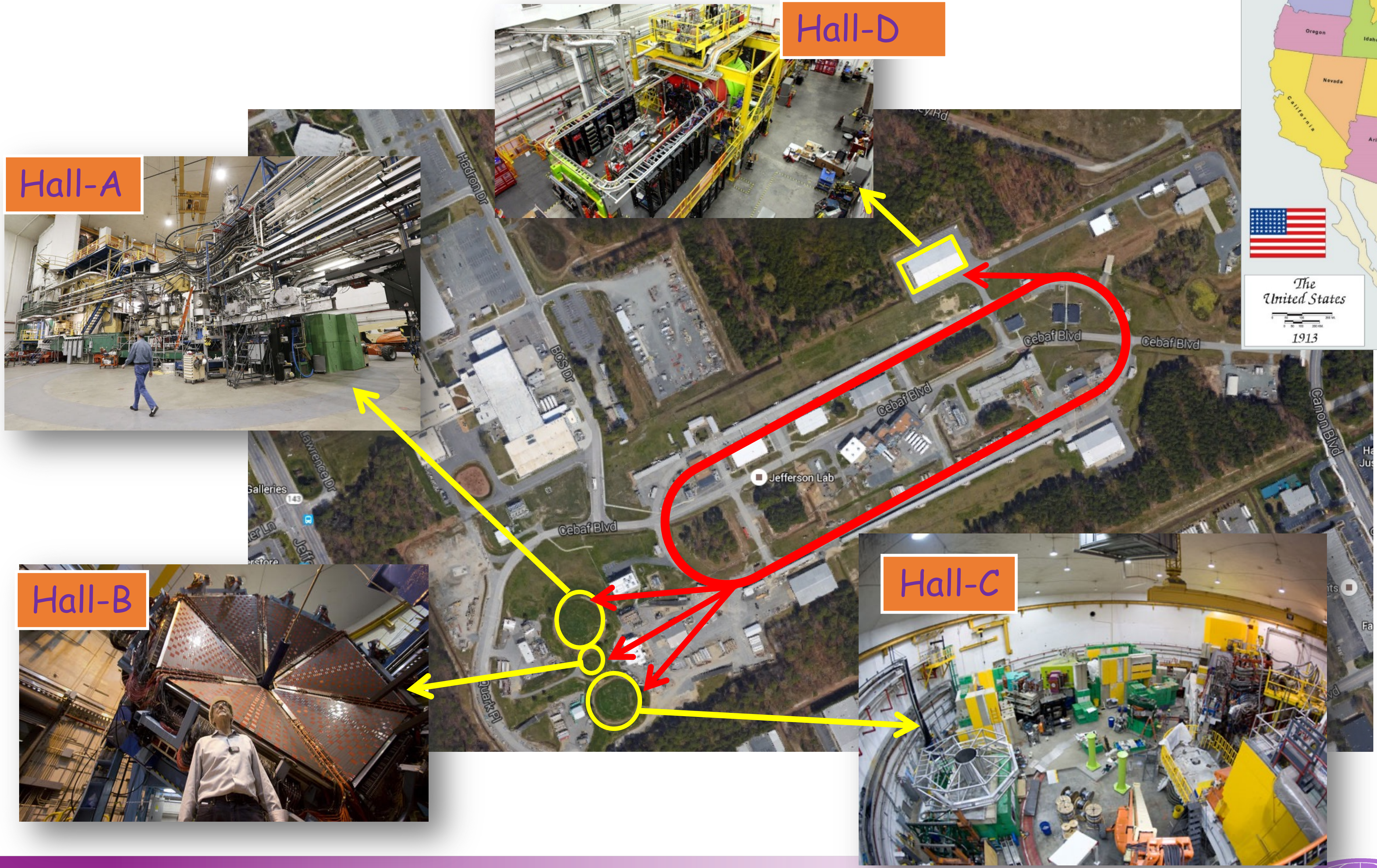


- ❑ SRC in the mass matrix for neutrino-less double beta decay?

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

Measuring SRC w/ eA

- Thomas Jefferson Lab



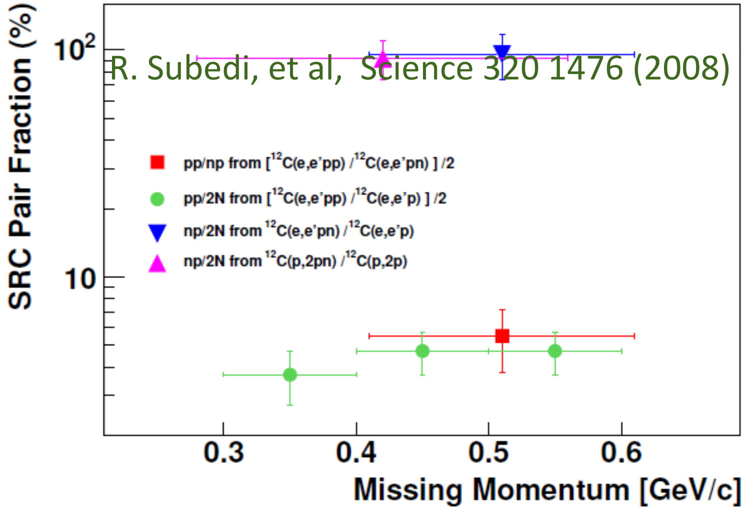
Jefferson Lab
Thomas Jefferson National Accelerator Facility

U.S. DEPARTMENT OF
ENERGY

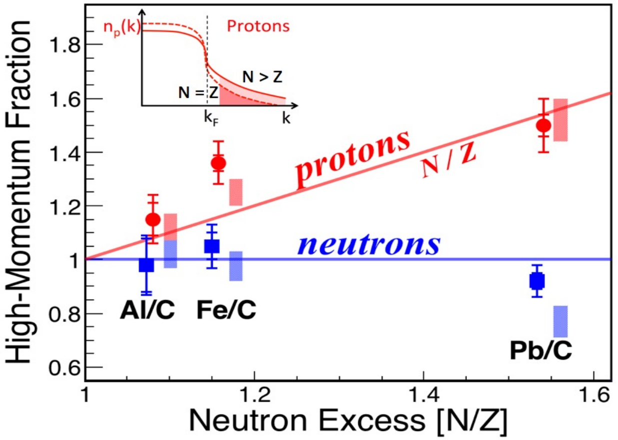
Measuring SRC w/ eA

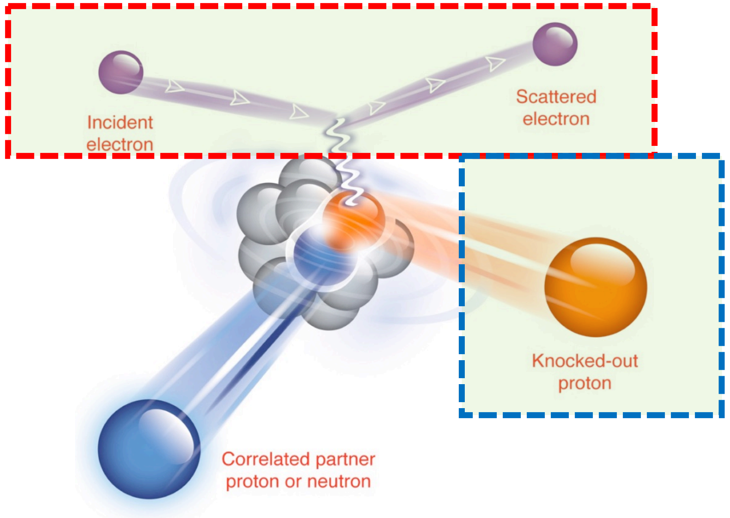
➢ Exclusive SRC Results

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



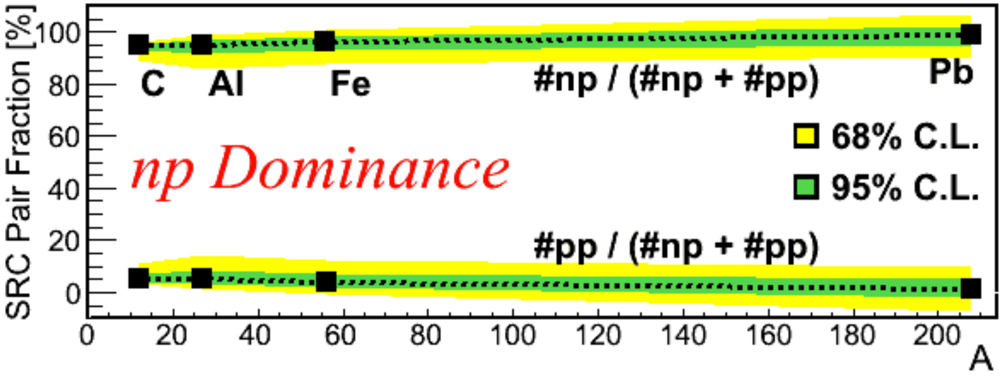
proton "speed up" with neutron excess





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

- ❑ Similar np-dominances in heavy nuclei → universality?



- ❑ Cautions:
  - Exclusive results are statistics limited
  - Mixed with mean-field and long-range NN signals
  - Complicated FSI corrections
  - Limited stable nuclei

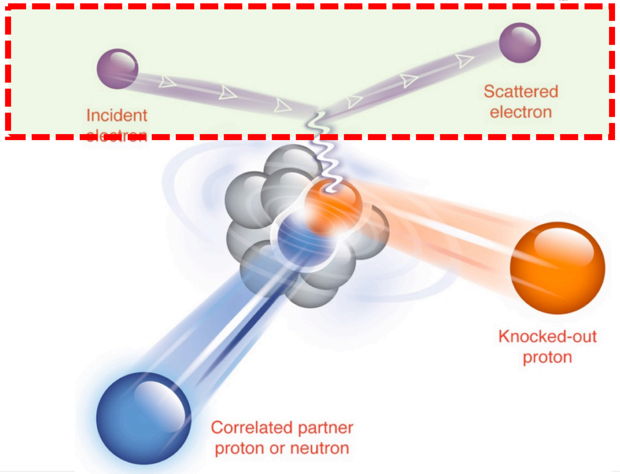
Measuring SRC w/ eA

- Inclusive SRC Measurements:
  - QES inclusive cross-sections:

Nucleon momentum distribution

$$\frac{d\sigma_{QE}}{dE'd\Omega}(Q^2, x_{bj}) = 2\pi\sigma_{eN}\int_{p_{min}}^{p_{max}} kdk \int_{E_s^{min}}^{E_s^{max}} S(k, E_s)dE_s$$

"links" to momentum distribution



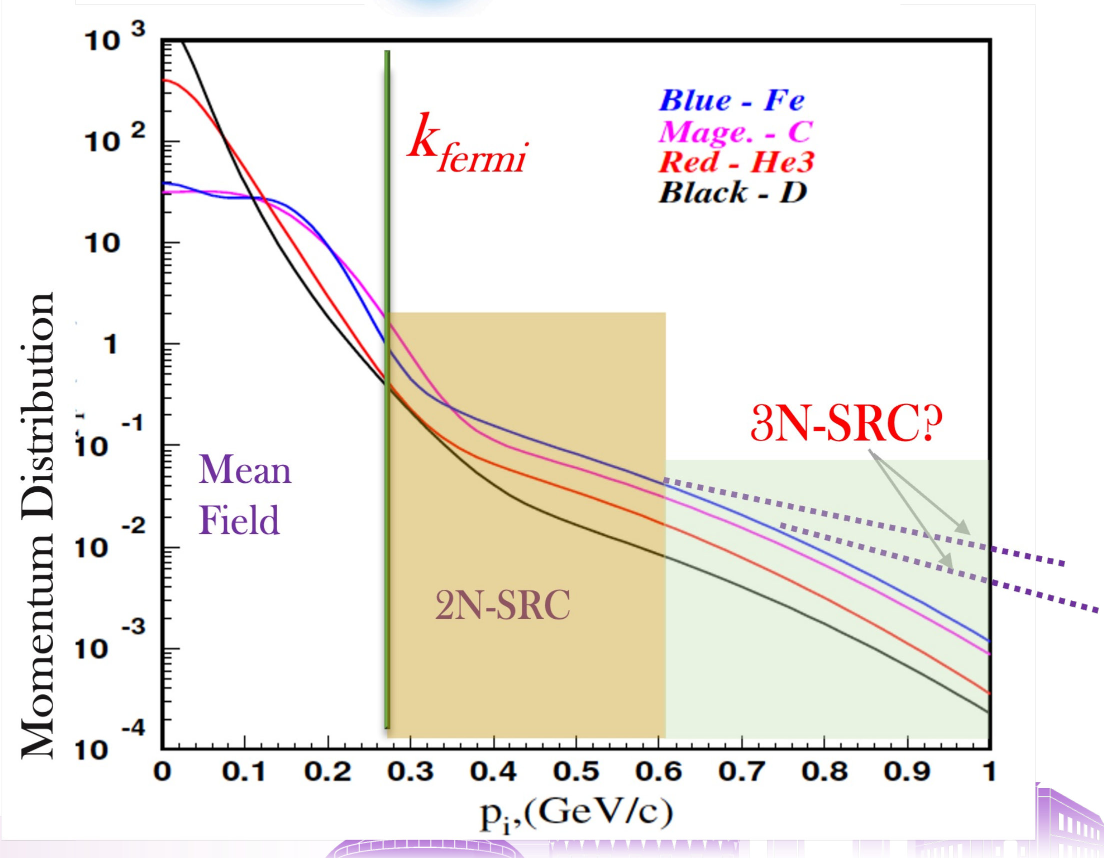
  - Heavy to light nuclei have similar high-P tails

    → look for a plateau

    ✓ 2N-SRC ($1.3<x_{bj}<2$): $a_2(A,D) = \frac{2}{A}\frac{\sigma_A(x,Q^2)}{\sigma_D(x,Q^2)}$,

    ✓ 3N-SRC ($2<x_{bj}<3$): $a_3(A,{}^3He) = \frac{3\sigma_A}{A\sigma_{^3He}}$

  - Inclusive vs Exclusive:
    - High precision, small FSI
    - Not direct probing np-SRC internal info



Measuring SRC w/ eA

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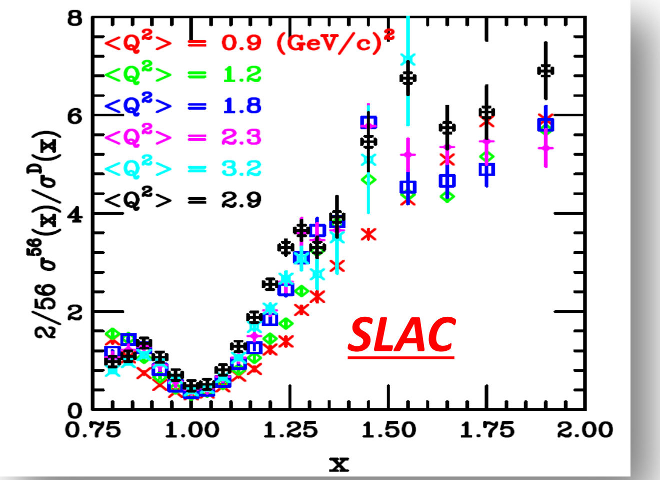
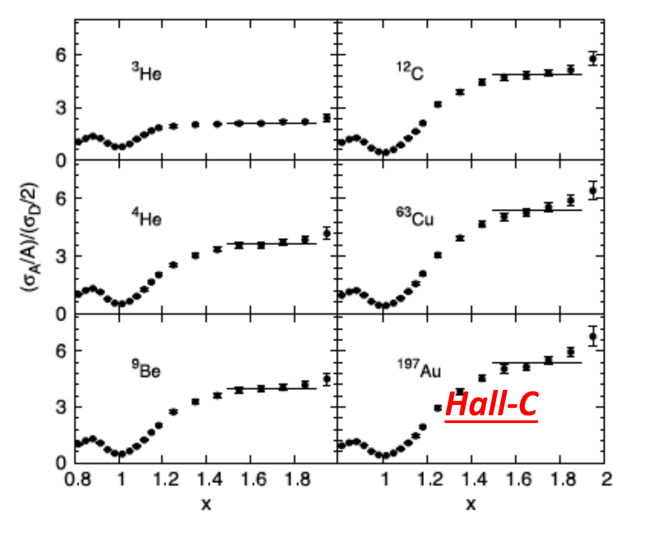
- 2N-SRC
  - ❑ SRC plateau at Q2>1.4GeV/c

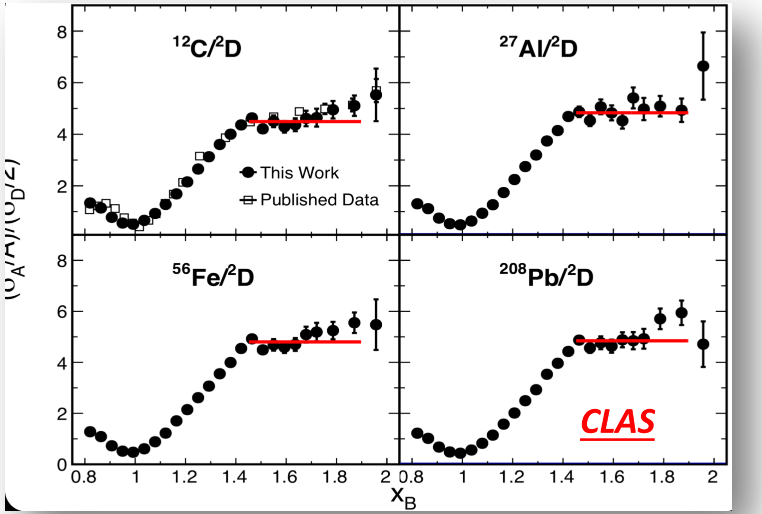


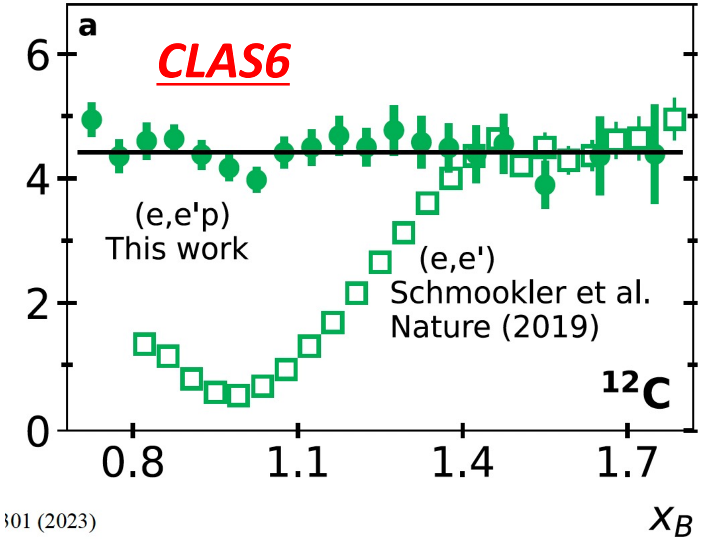
Frankfurt, Strikman, Day, Sargsian, PRC48, 2451 (1993)

N. Fomin *et al*, PRL 108,092502 (2012)



Schmookler et al., Nature (2019)



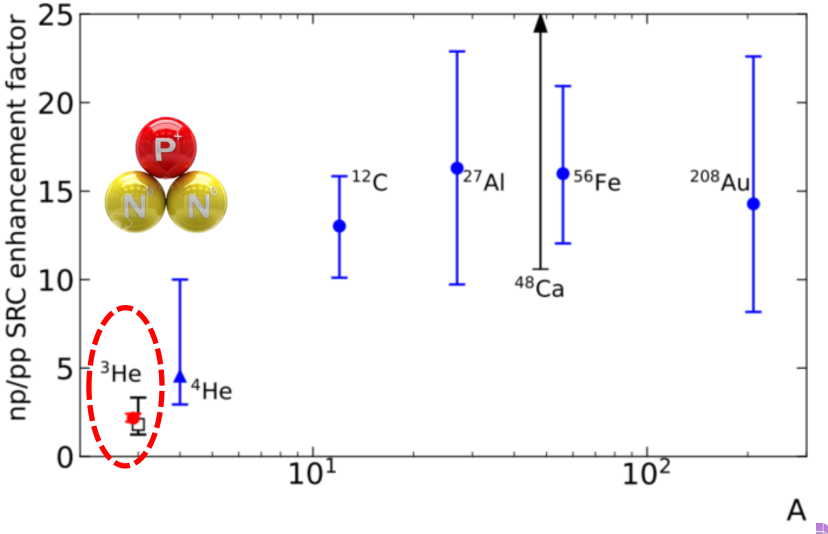


- ❑ Compared with exclusive SRC

  Korover and Denniston et al.,CLAS, PRC 107, L061301 (2023) 27

- ❑ Non-Universal in light nuclei?

  S. Li, R. Cruz-Torres, N. Santiesteban, Z. Ye, et. al, Nature, 2022, 609: 41



Measuring SRC w/ eA

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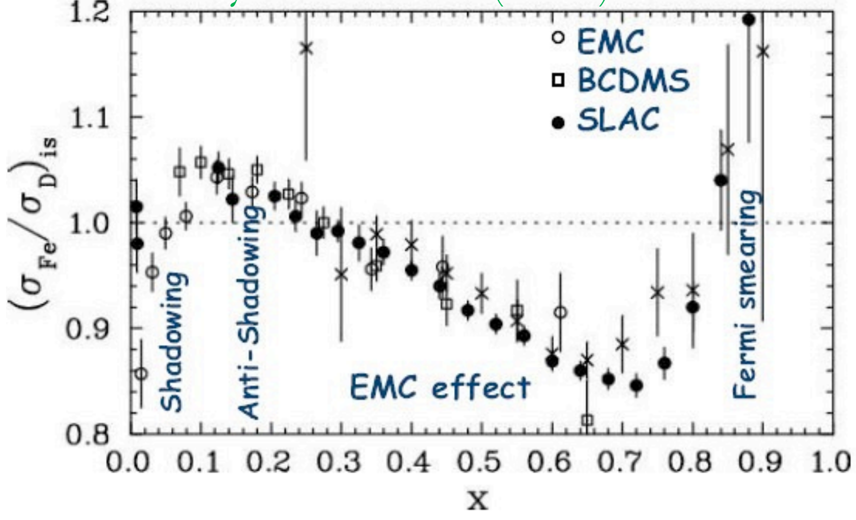
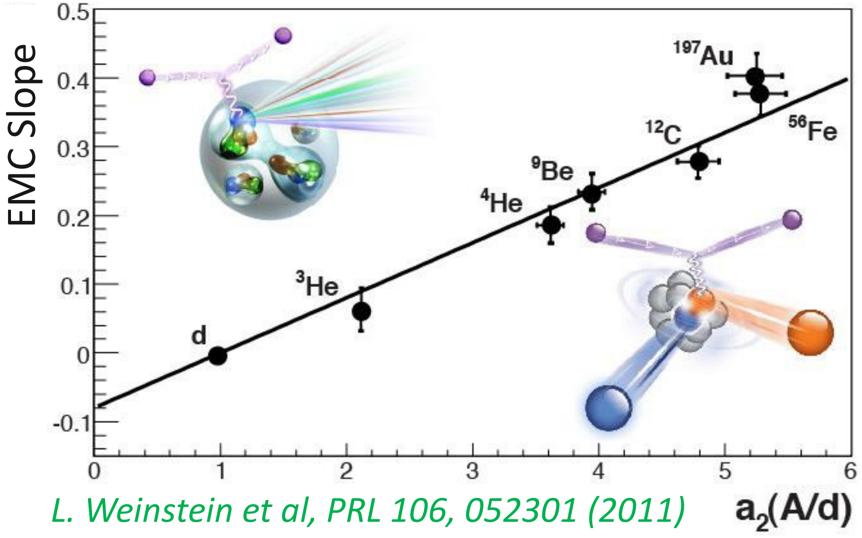
➢SRC vs EMC

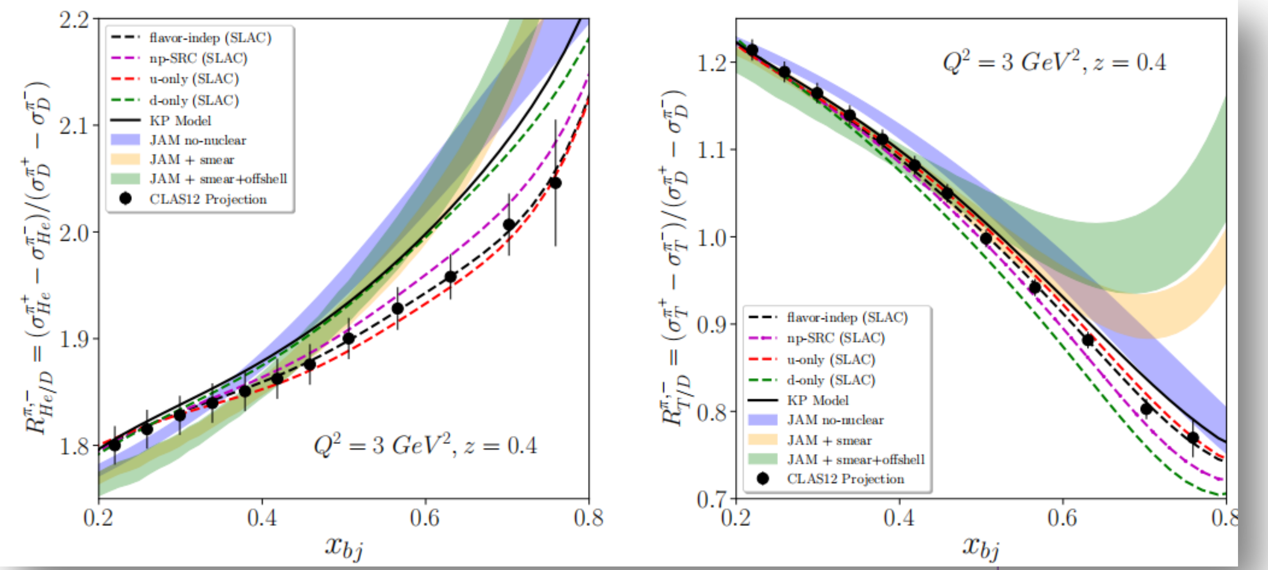
- ❑ EMC: Inclusive DIS A/D XS ratio drops linearly in 0.3<x<0.7
  - 40 years after discovery, still unknown!
- ❑ Connection with SRC?
  - Modification in all nucleons or partially?

Phys.Lett.B 123 (1983) 275-278

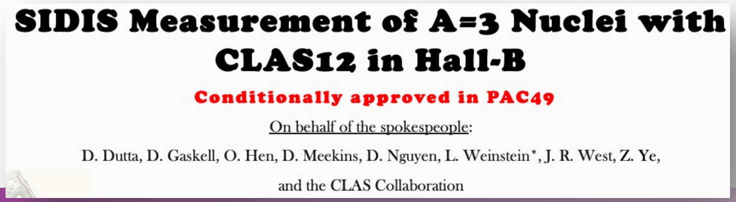




L. Weinstein et al, PRL 106, 052301 (2011)



- ❑ C12-21-004 w/ new Tritium target (+ 2nd Tritium-SRC)



SIDIS Measurement of A=3 Nuclei with CLAS12 in Hall-B

Conditionally approved in PAC49

On behalf of the spokespeople:

D. Dutta, D. Gaskell, O. Hen, D. Meekins, D. Nguyen, L. Weinstein*, J. R. West, Z. Ye,

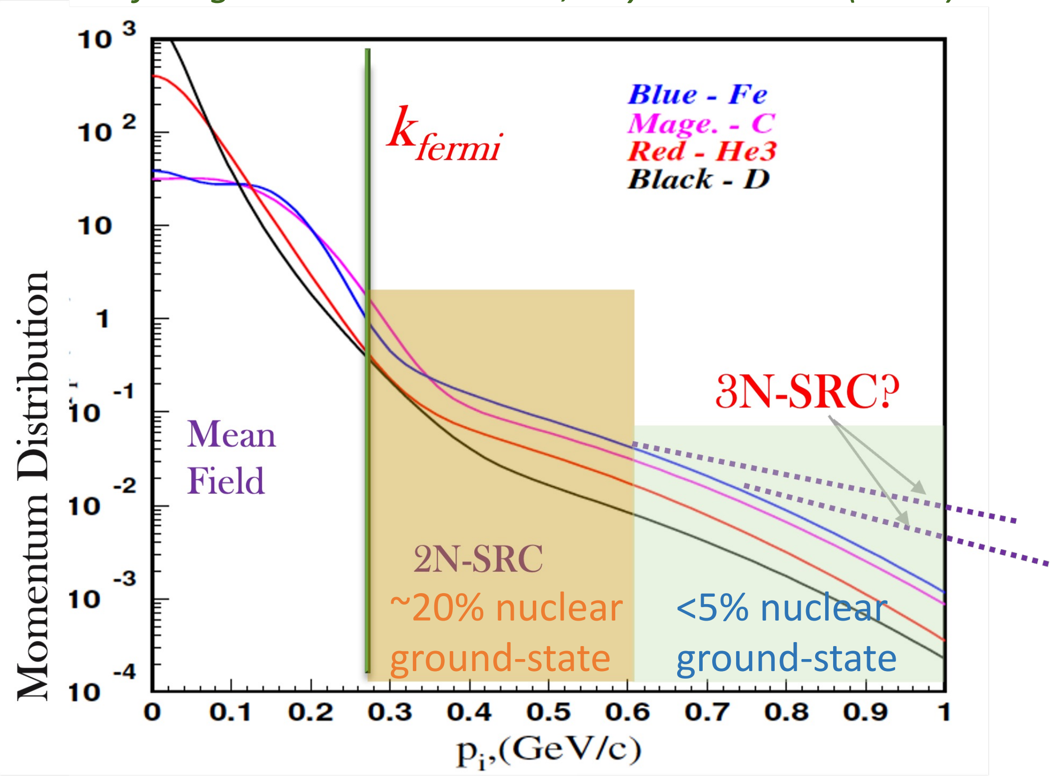
and the CLAS Collaboration

Measuring SRC w/ eA

- 3N-SRC
  - Much higher relative momenta
  - Much denser cluster (Neutron-Star, Nuclear Matter)

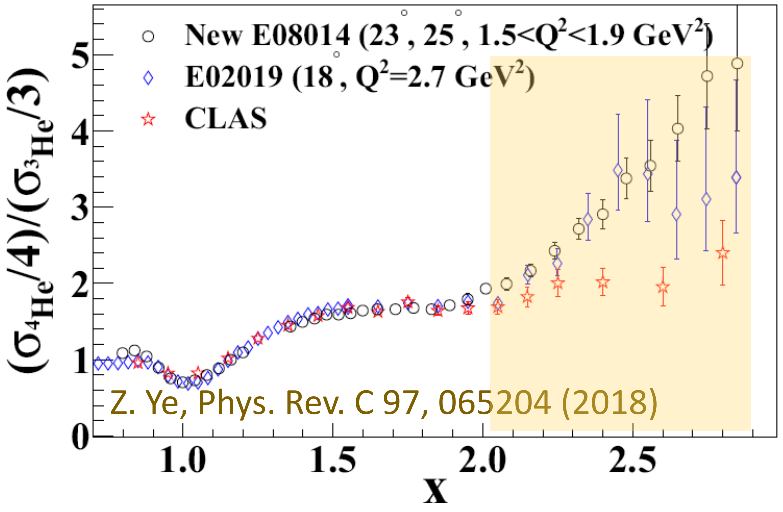
- Bi-neutron-stars merger: neutron star > 2.4 solar mass → Short-Range 3-body force?

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



- 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?

- 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

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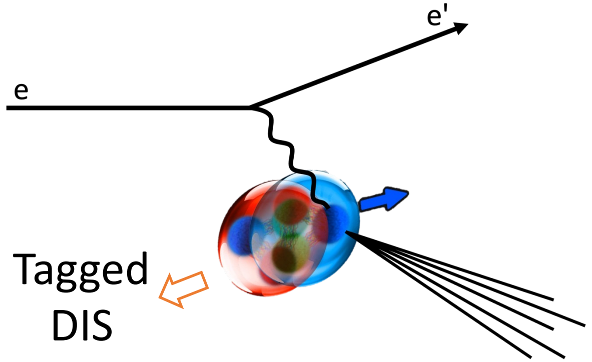
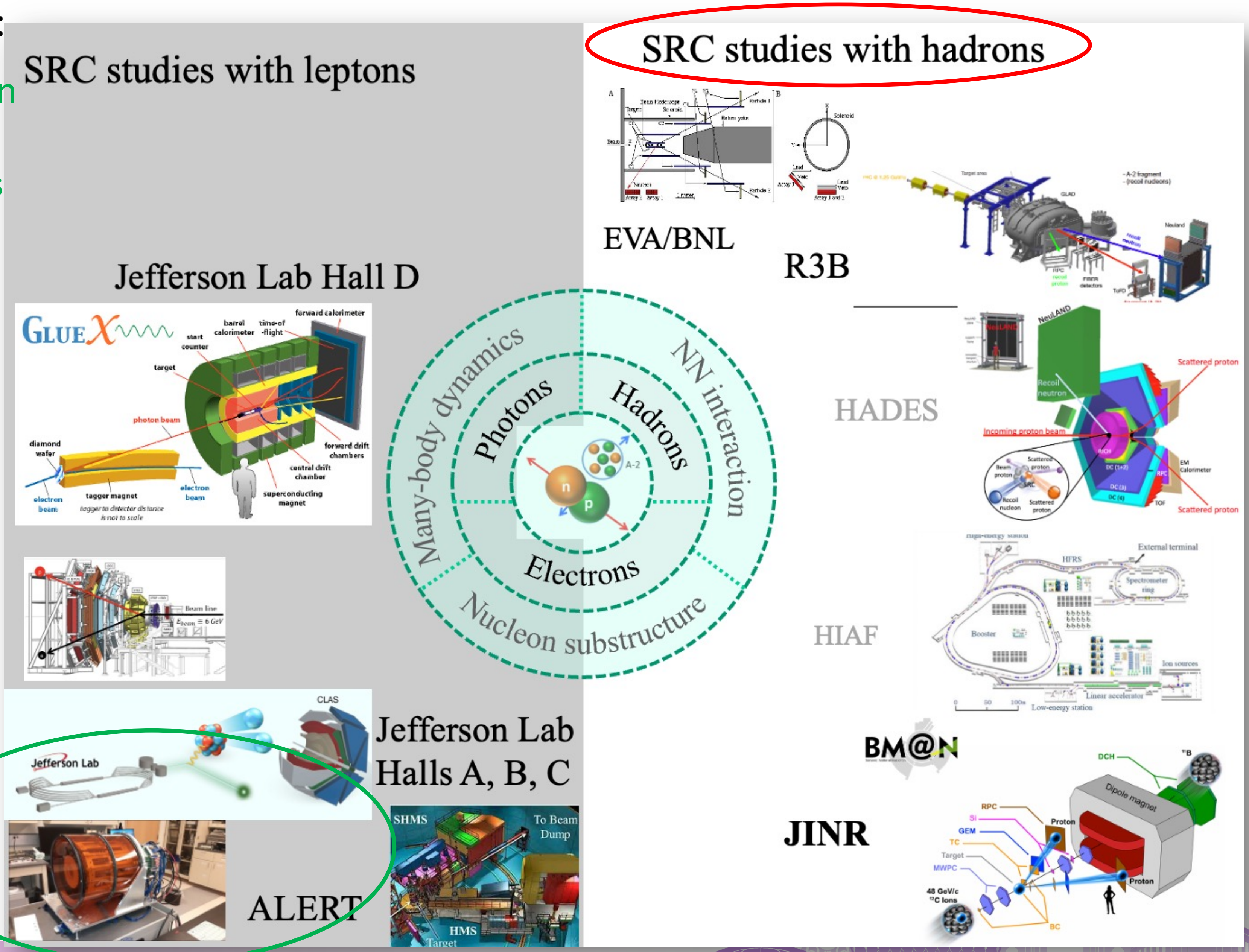
- Upcoming Jlab RC Experiments:
  - ALERT- SRC： measure C.M motion of pairs (Mean-Field vs SRC)
    - (THU) Haojie Zhang’s Ph.D thesis experiment
  - Real photon scattering (check universality)
  - Future EIC with much higher energy: SRC in J/Psi, tagged DIS

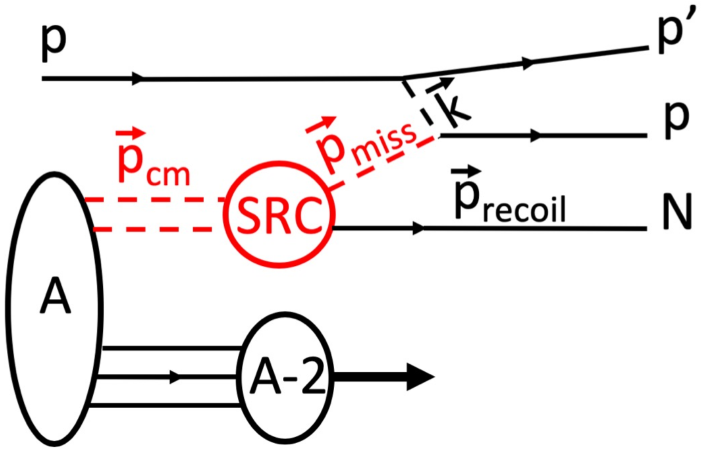


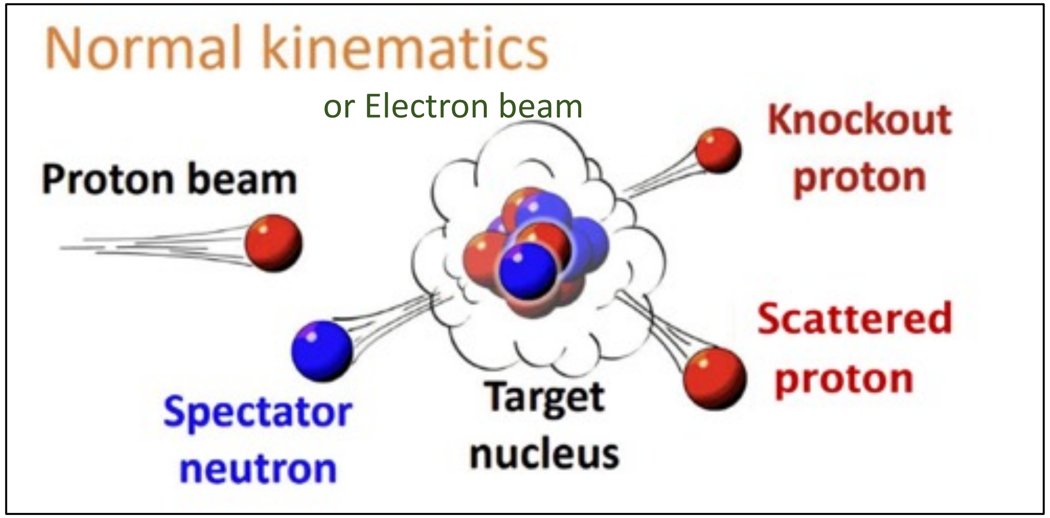
- Precision Frontier of SRC: pA reaction → next

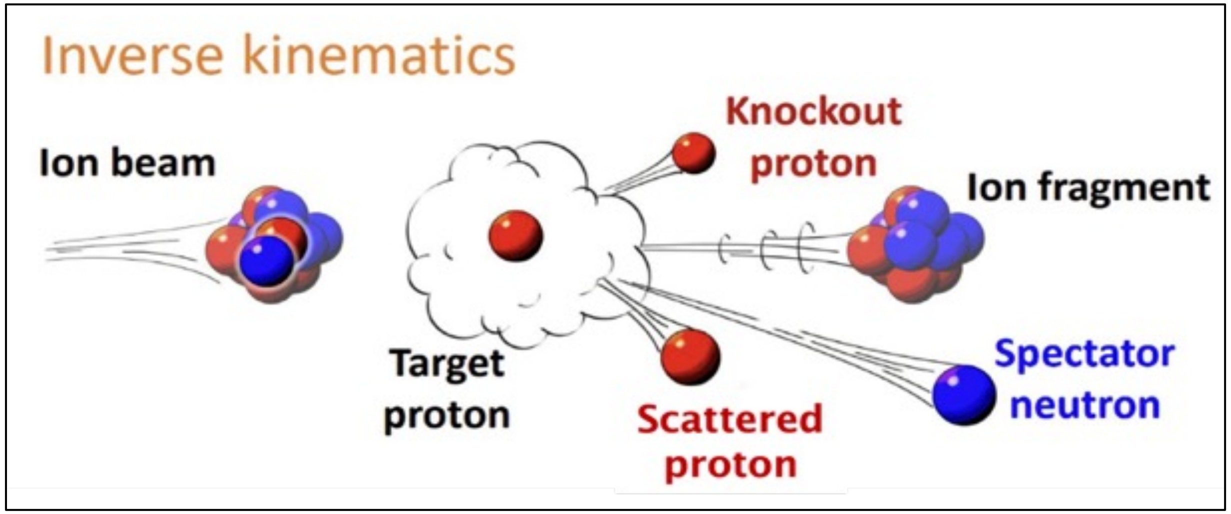


Measuring SRC w/ Inverse-pA

- 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





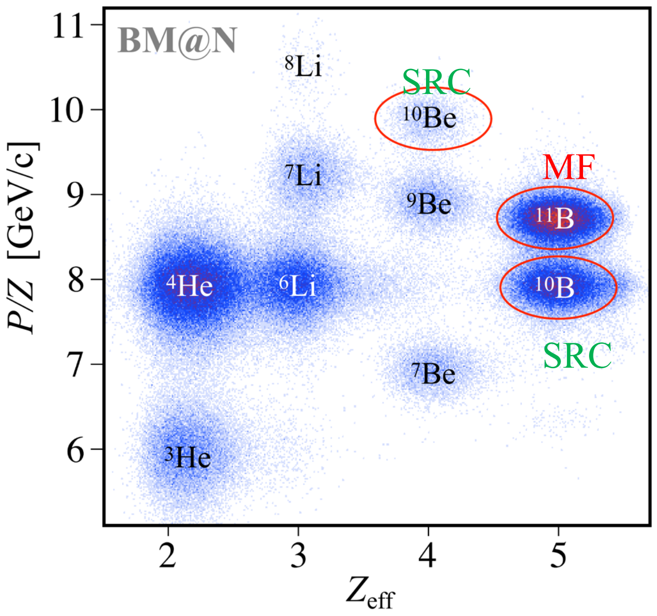


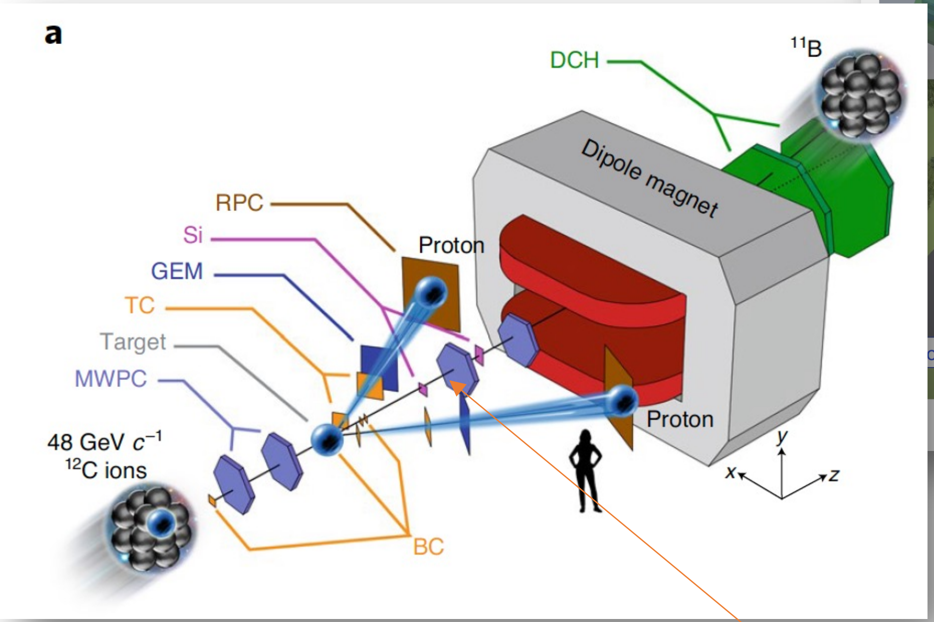
Measuring SRC w/ Inverse-pA

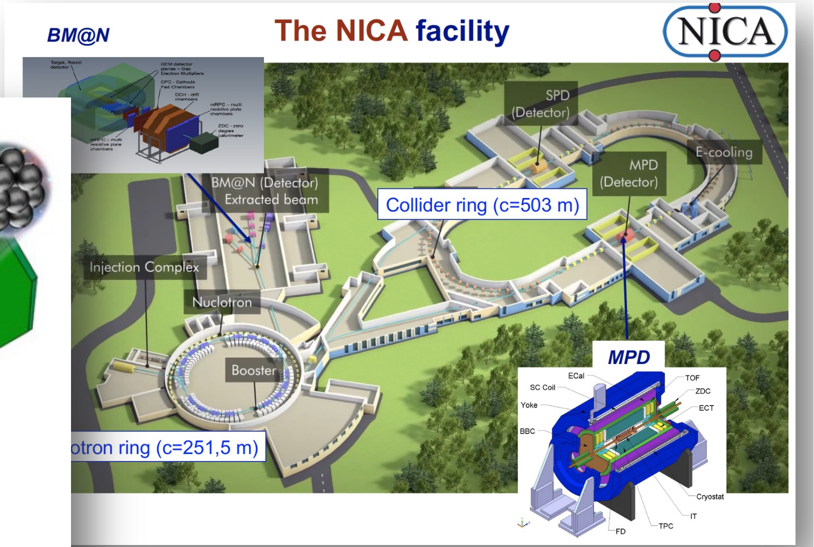
➢ JINR BM@N SRC Experiments

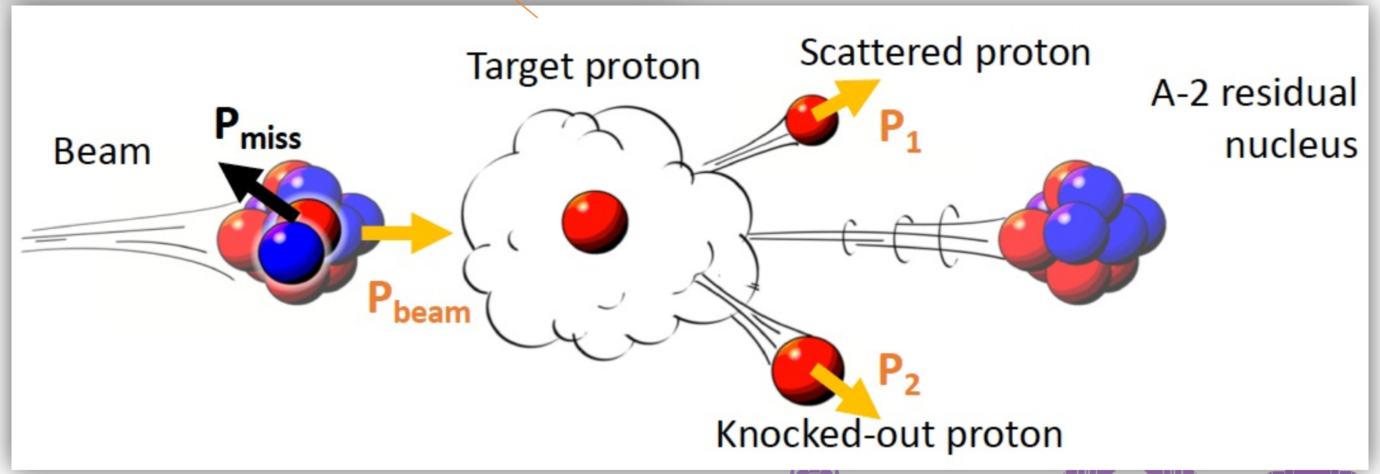
❑ Pioneer experiment at BM@N

- Test run in 2018, results publised
- ^{12}C beam, 3.5 – 4 GeV/c/nucleon
- Identify fragments:









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

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

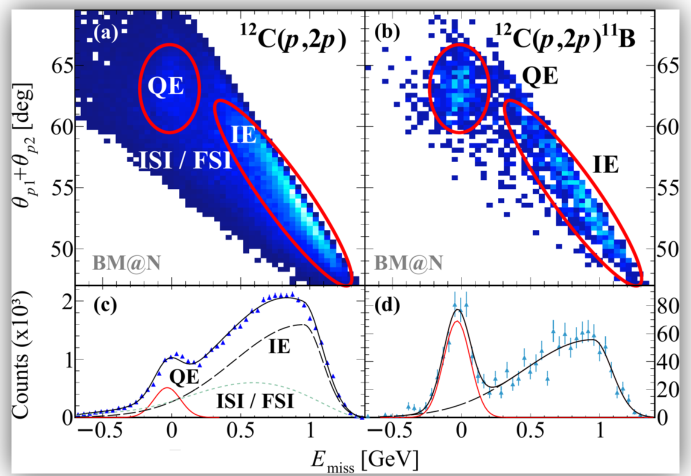
M. Patsyuk et al. Nature Physics 17, 693 (2021)

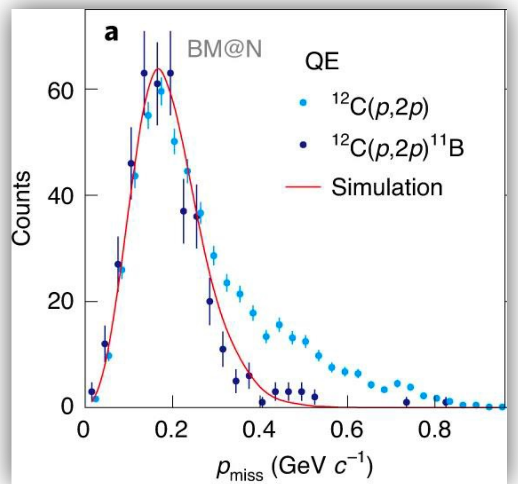
Measuring SRC w/ Inverse-pA

➢ JINR BM@N SRC Experiments

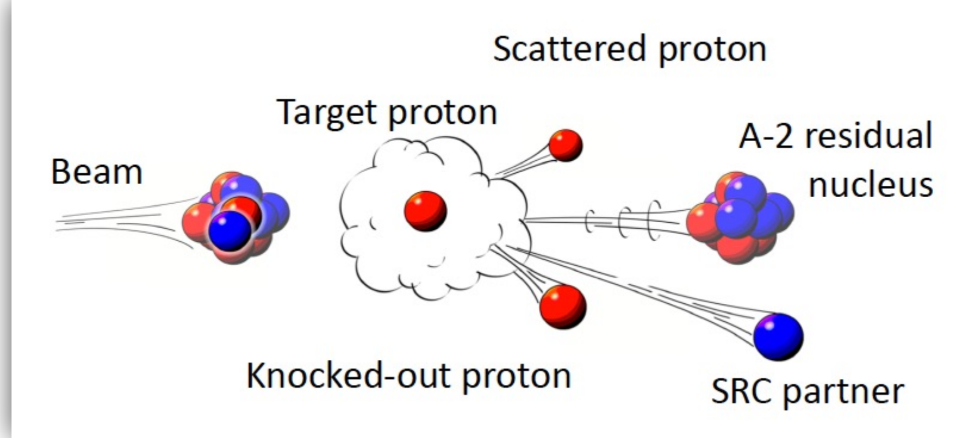
❑ Single nucleon quasi-free knock-out

- Select bound ^{11}B
- Large momentum tails mixed with SRC w/o tagging ^{11}B → Suppress Initial-&Final-State Interaction

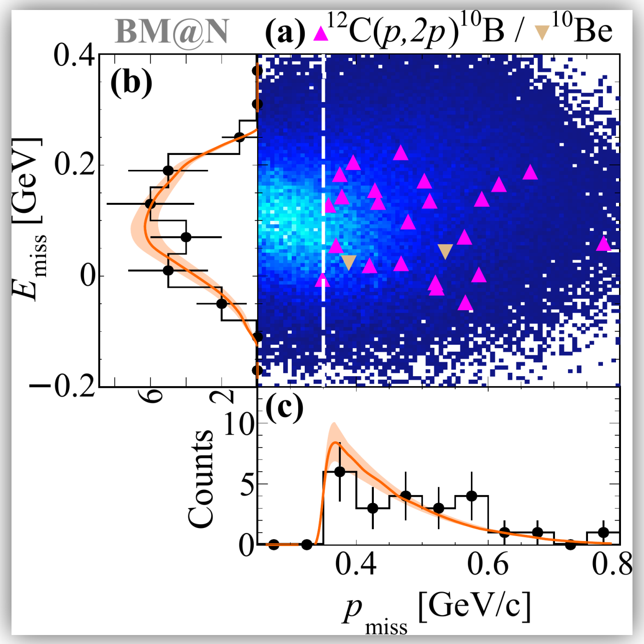




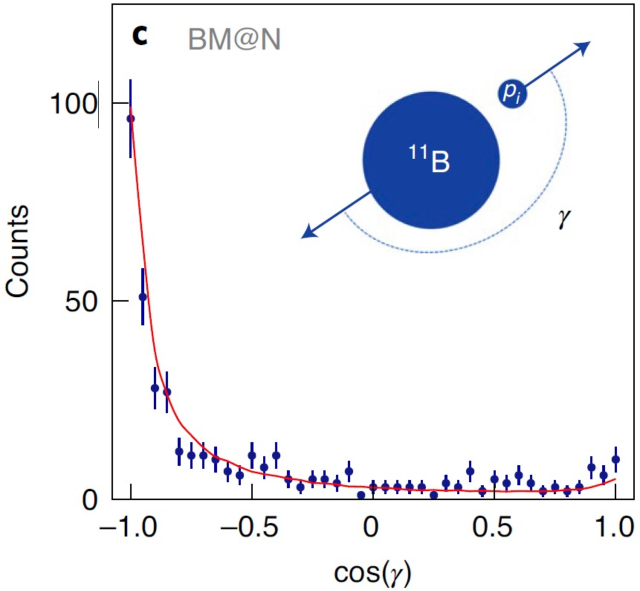
❑ Selection of 2N-SRC Pairs



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



23 np & 2 pp SRC-pairs



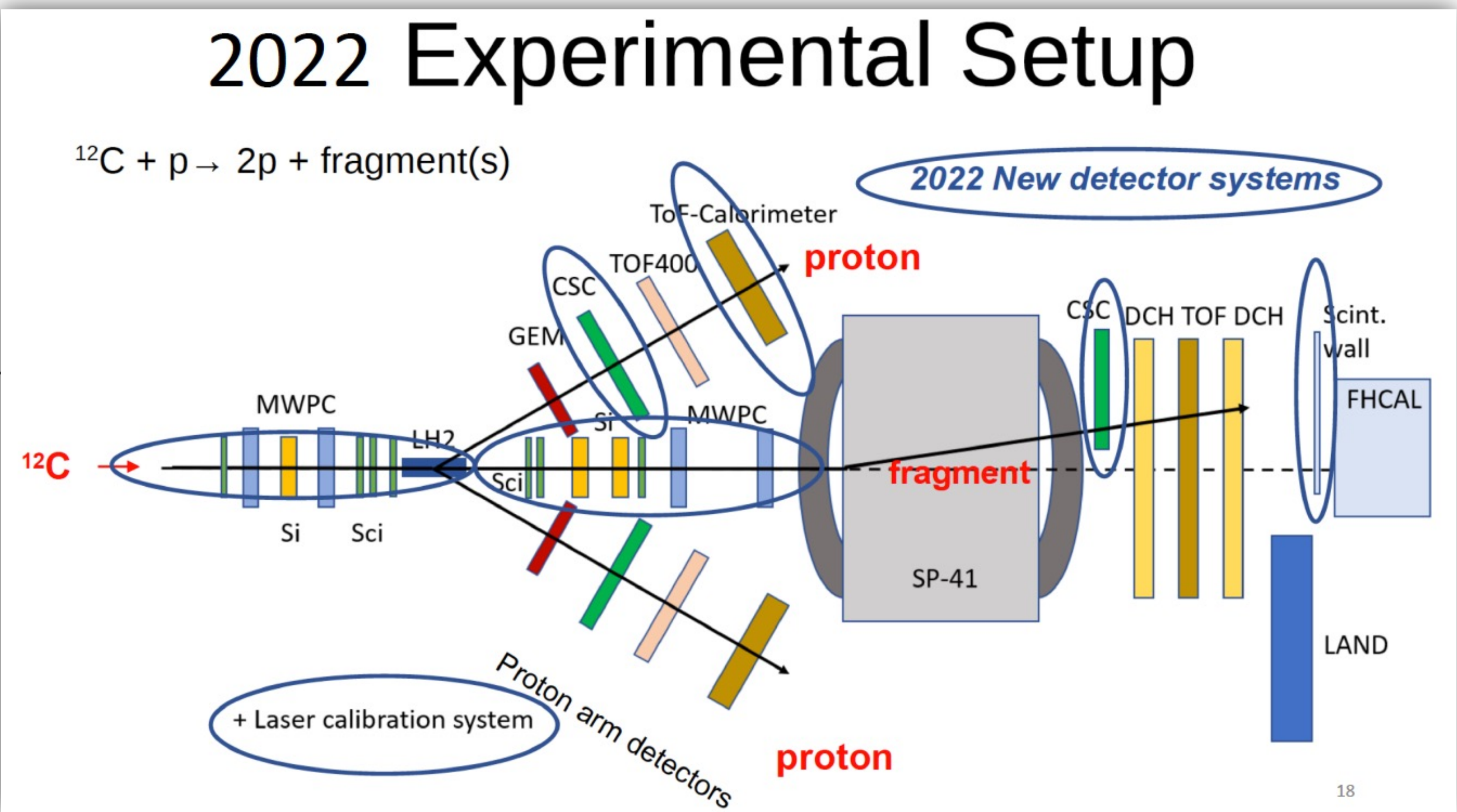
M. Patsyuk et al. Nature Physics 17, 693 (2021)

Measuring SRC w/ Inverse-pA

➢ JINR BM@N SRC Experiments

- ❑ 2018 run firstly demonstrated advantage of inverse-pA reaction in SRC study

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



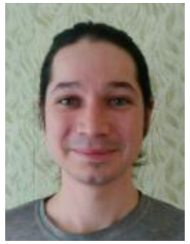
- ❑ 2022 run completed
  - ✓ JINR, GSI, MIT, Tel Aviv, Tsinghua …
  - ✓ Improve statics x100
  - ✓ Detection of n & p recoils
  - ✓ Multi-fragment reconstruction
  - ✓ Absolute cross-section (in preparing)

Measuring SRC w/ Inverse-pA

Tsinghua University

- JINR BM@N SRC Experiments
  - Preliminary results of 2022 run, under analysis by:

Göran Johansson (TAU)



Timur Atovuallev (JINR)

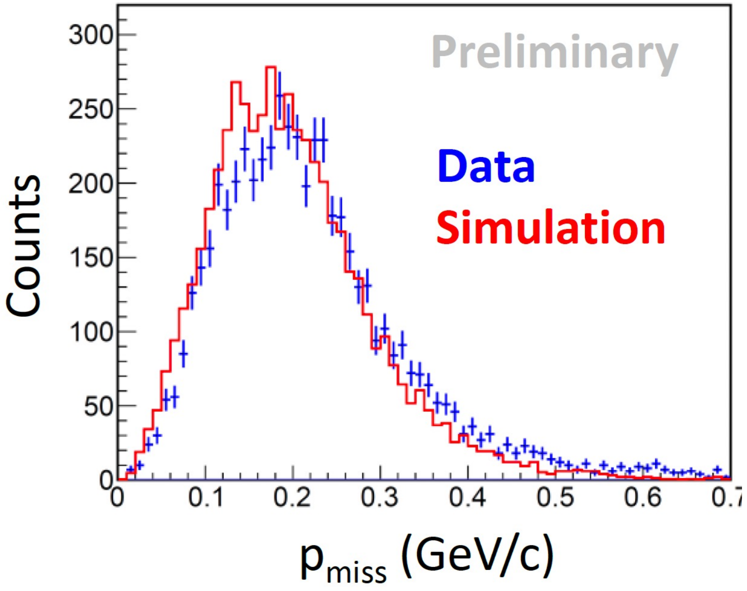
Sergey Nepochatykh (JINR)

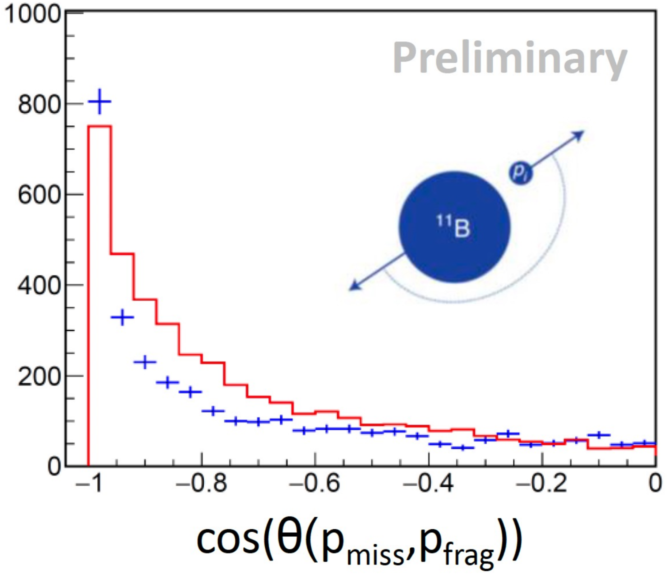
Yaopeng Zhang (Tsinghua U)

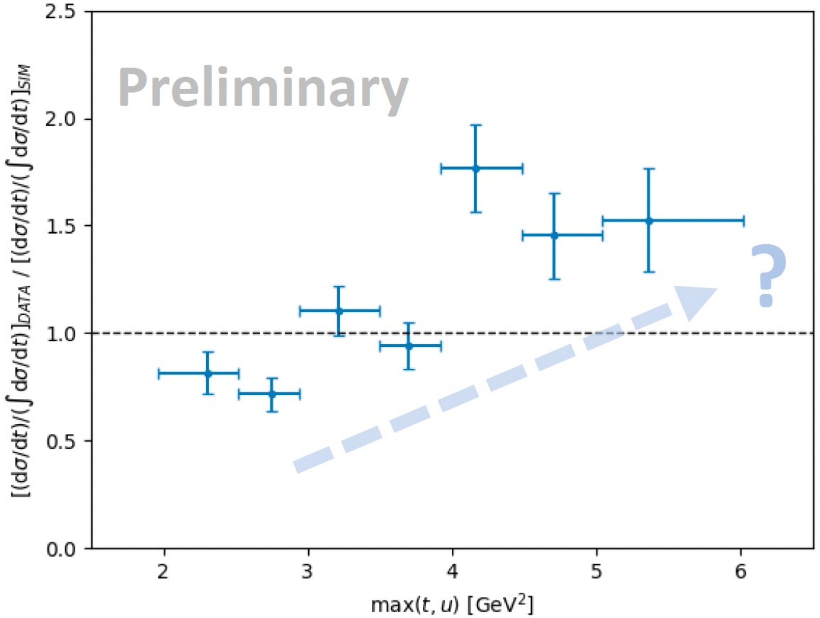
Vasilisa Lenivenko (JINR)

Maria Patsyuk (JINR)

Julian Kahlbow (MIT)





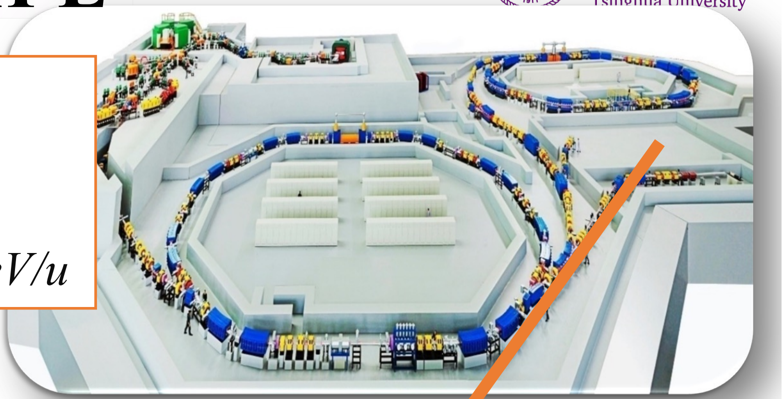


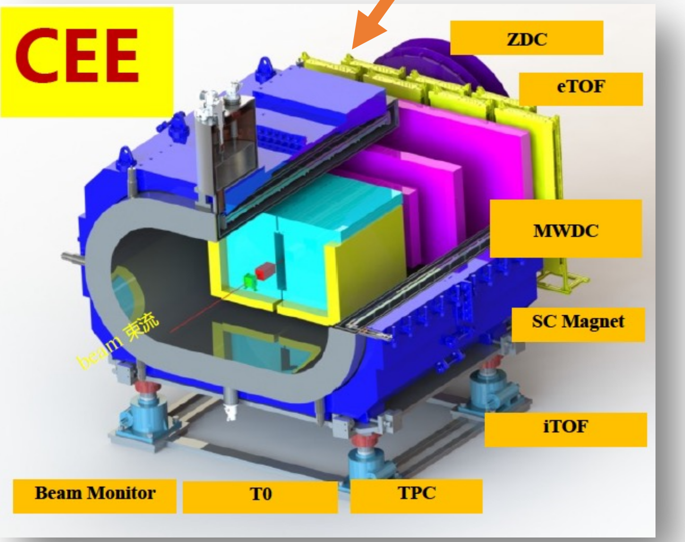
- ✓ X10 more statistics vs 2018 run
- ✓ First extraction of absolute XS

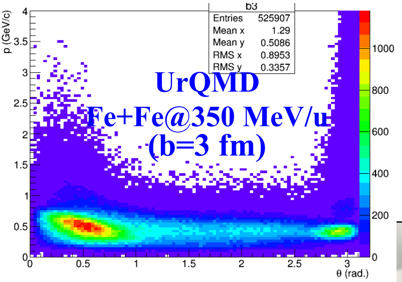
Measuring SRC w/ CEE@HIRFL

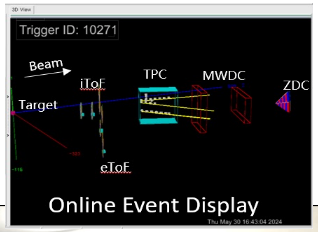
- CEE@HIRFL-CSR
  - HIRFL-CSR comparable with GSI:
    - ✓ 1.0GeV/u @10^5pps vs 1.25GeV/u@1×10^5pps
  - CSR External-Target Experiment (CEE):
    - ✓ Physics Goals: QCD phase boundary at low T, nuclear E.O.S. at $\rho>2\rho_0$ regime, Interplay with Neutron Star Physics
    - ✓ Expected to commission in early 2025

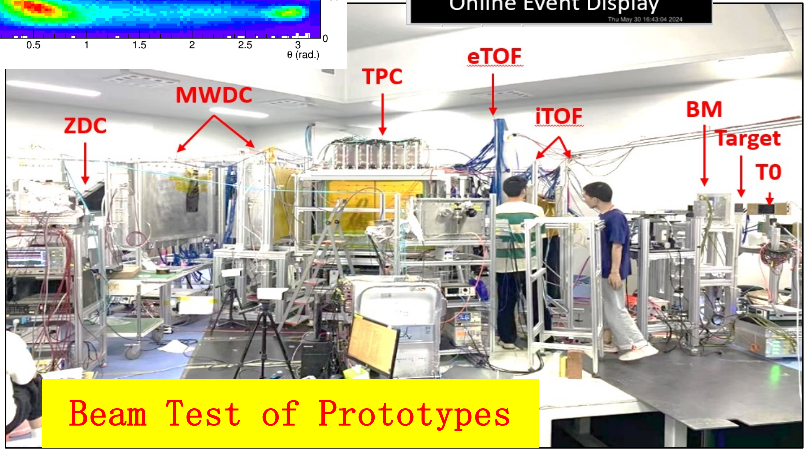
HIRFL-CSR beam
- *P: 2.8 GeV*
- *$^{12}C^+$: 1 GeV/u*
- *$^{238}U^+$: 0.5 GeV/u*

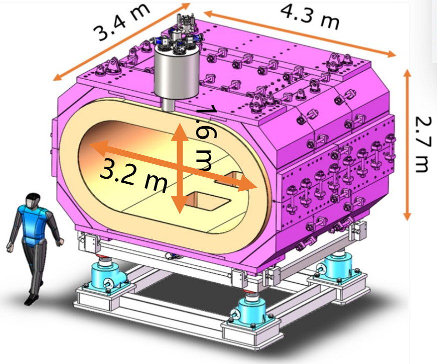












- $\Delta p/p$: ≤5%, $\Delta t/t$: ≤50ps
- Max. Rate: 10 kHz
- Proton acceptance: ~85%

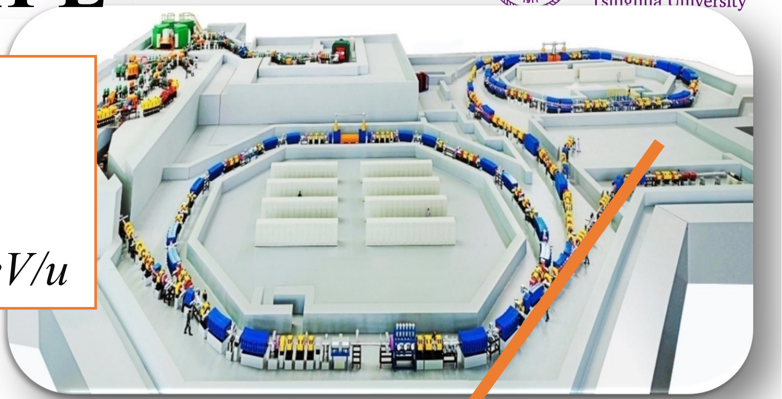
Measuring SRC w/ CEE@HIRFL

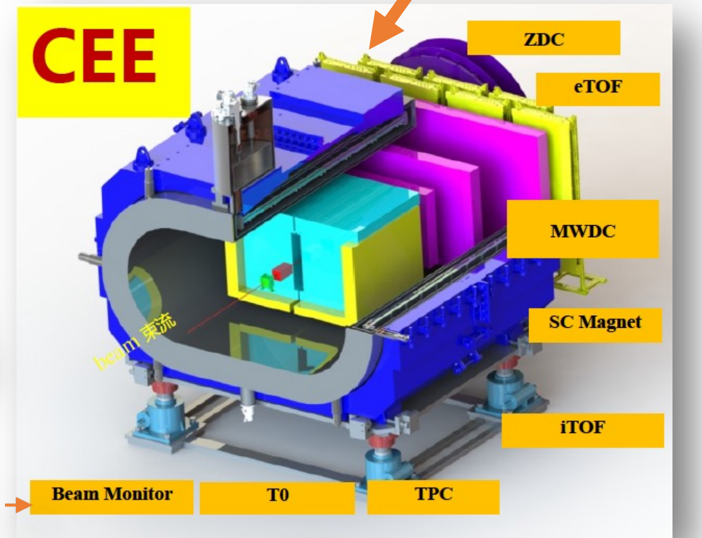
➢ CEE@HIRFL-CSR

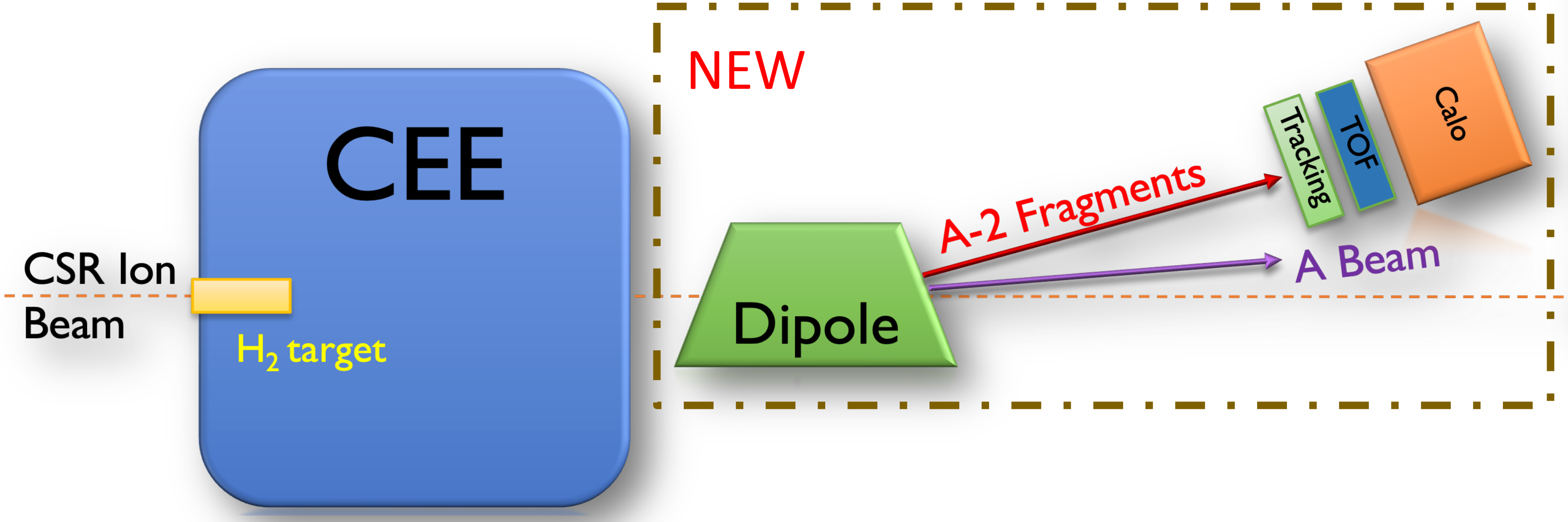
- ❑ HIRFL-CSR comparable with GSI:
  - ✓ 1.0GeV/u @10^5pps vs 1.25GeV/u@1×10^5pps

- ❑ Using CEE w/ additional changes:
  - ✓ Liquid hydrogen (LH2) target
  - ✓ Replace ZDC w/ a new detectors for A-2 fragments
  - ✓ Possibly a new dipole

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



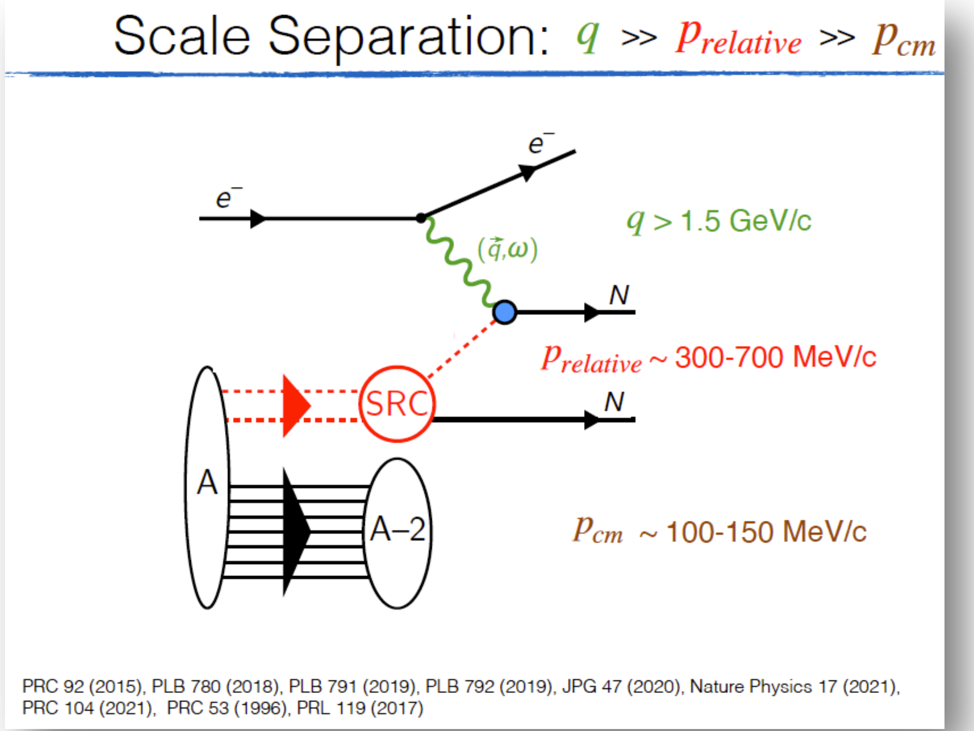


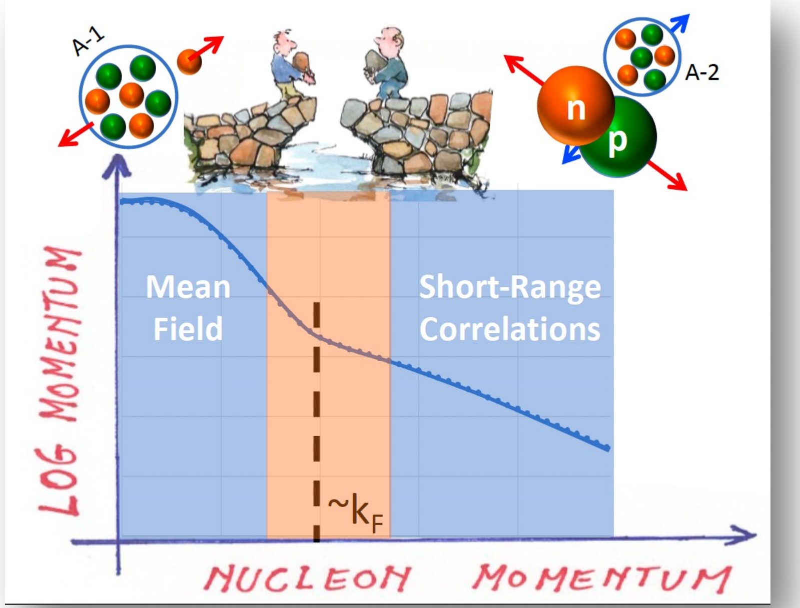


- $\Delta p/p$: ≤5%, $\Delta t/t$: ≤50ps
- Max. Rate: 10 kHz
- Proton acceptance: ~85%

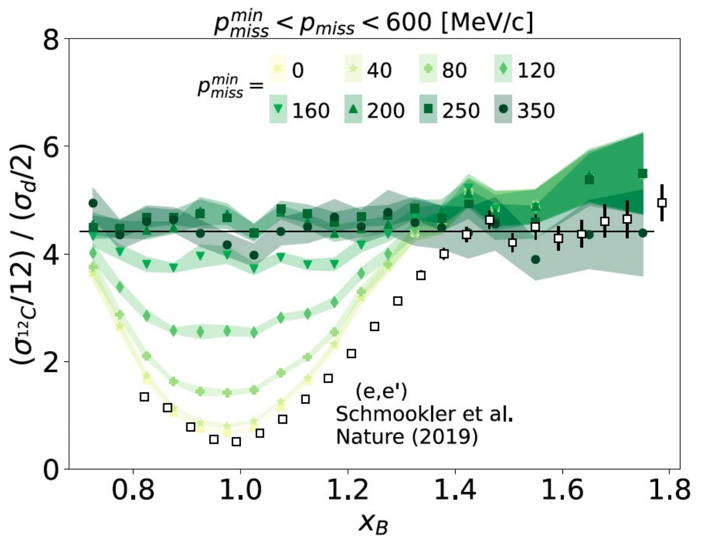
Measuring SRC w/ CEE@HIRFL

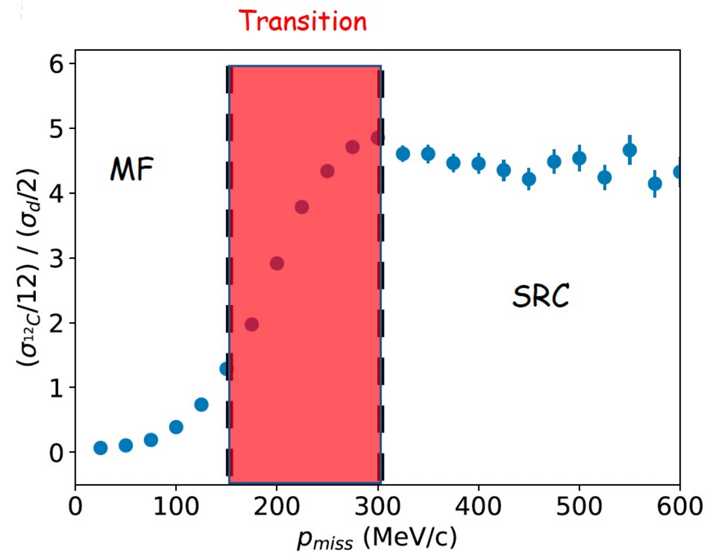
- CEE@HIRFL-CSR
  - Goals:
    - ✓ Precision nuclear wave functions
    - ✓ Define MF & SRC transition regions
    - ✓ Check FSI corrections
    - ✓ Other quasi-free knockout & pickup reactions





Korover PRC 107, L061301 (2023)

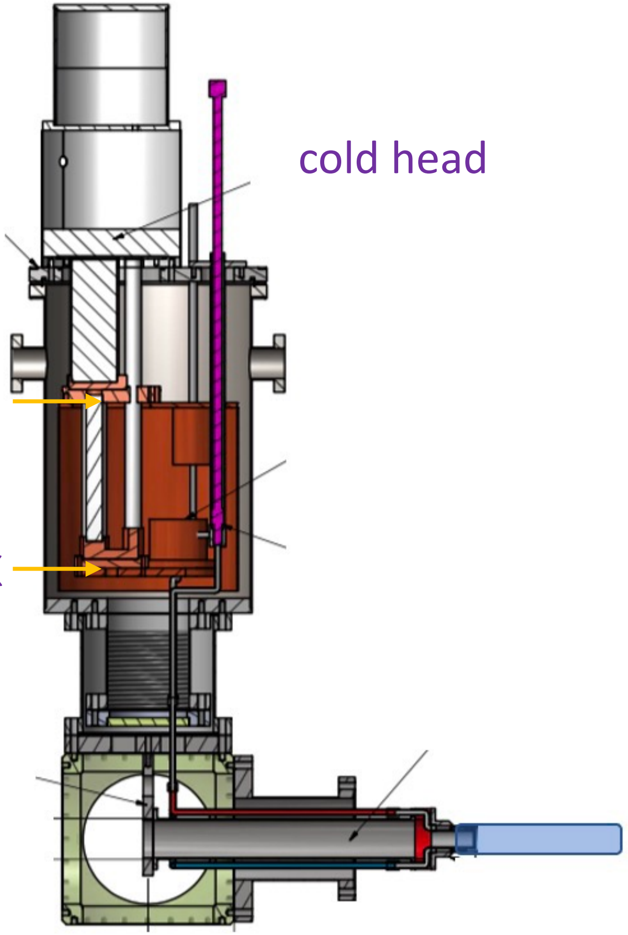


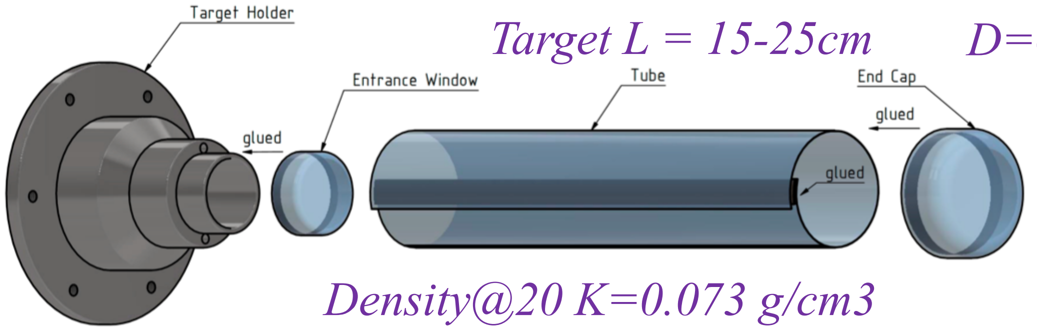


Measuring SRC w/ CEE@HIRFL

- LH2 Target:
  - Under development by Hongna Liu, Beijing Normal University (BNU)

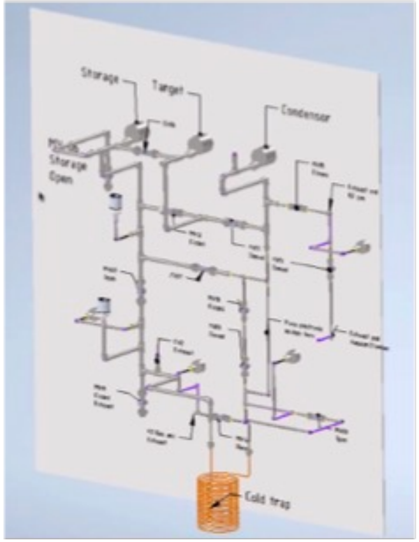
Target Chamber&Cooling



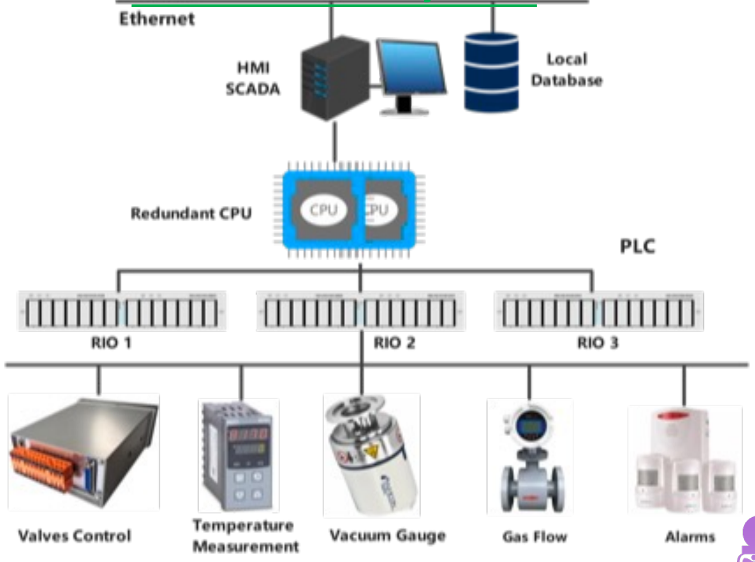


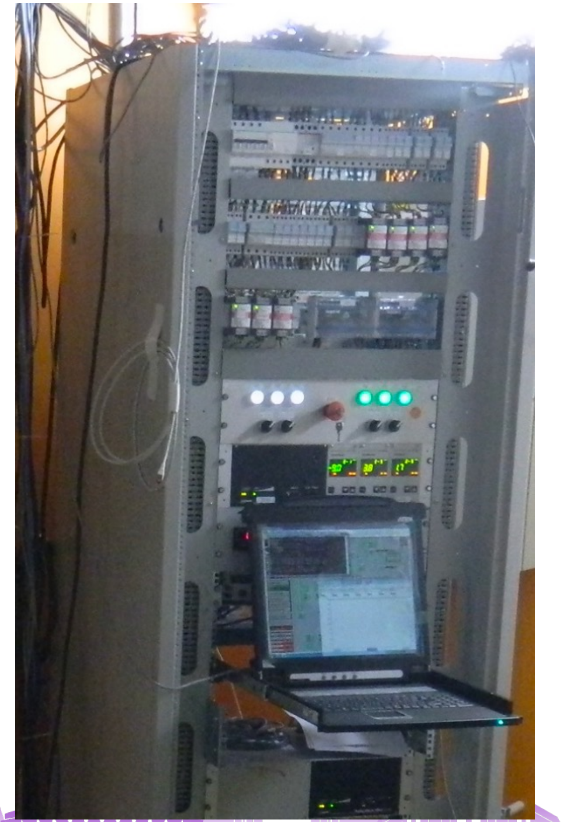
Target L = 15-25cm *D=0.52cm*

Density@20 K=0.073 g/cm3



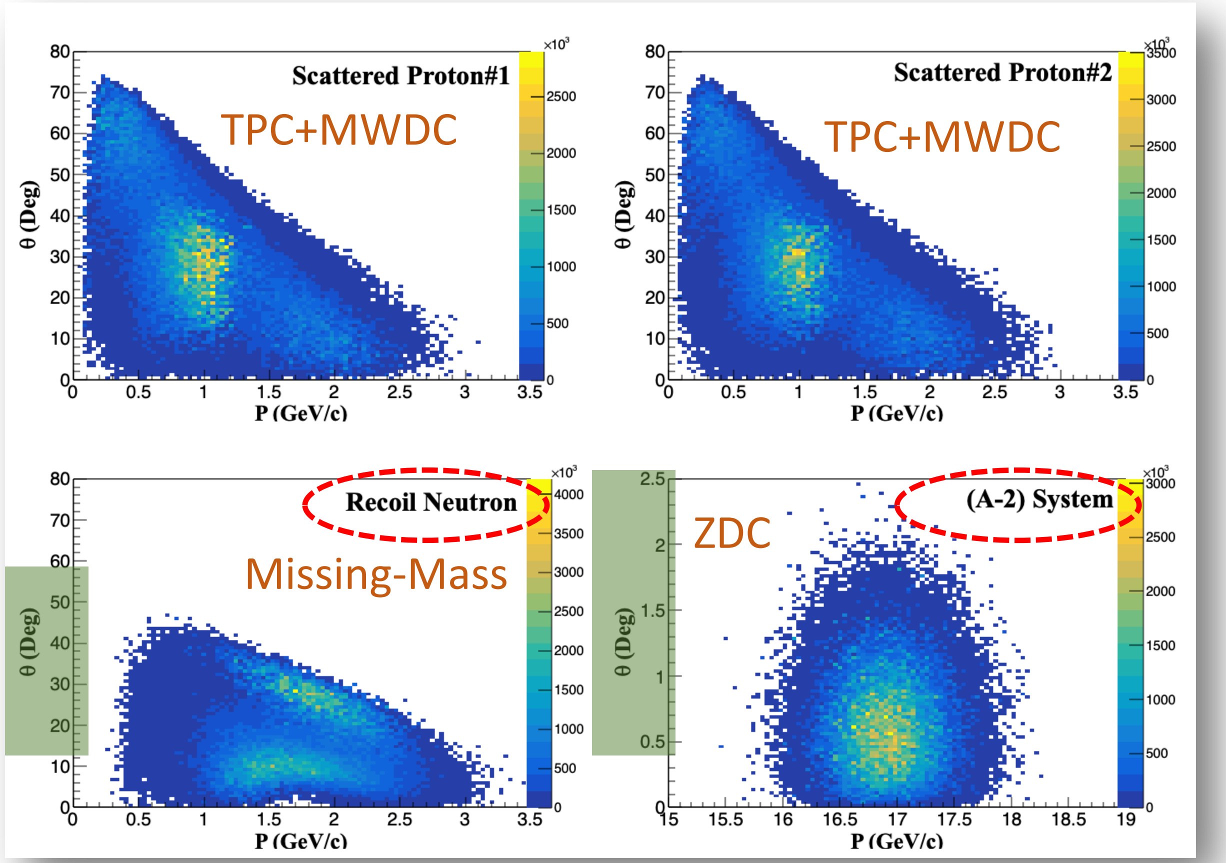
Slow Control System



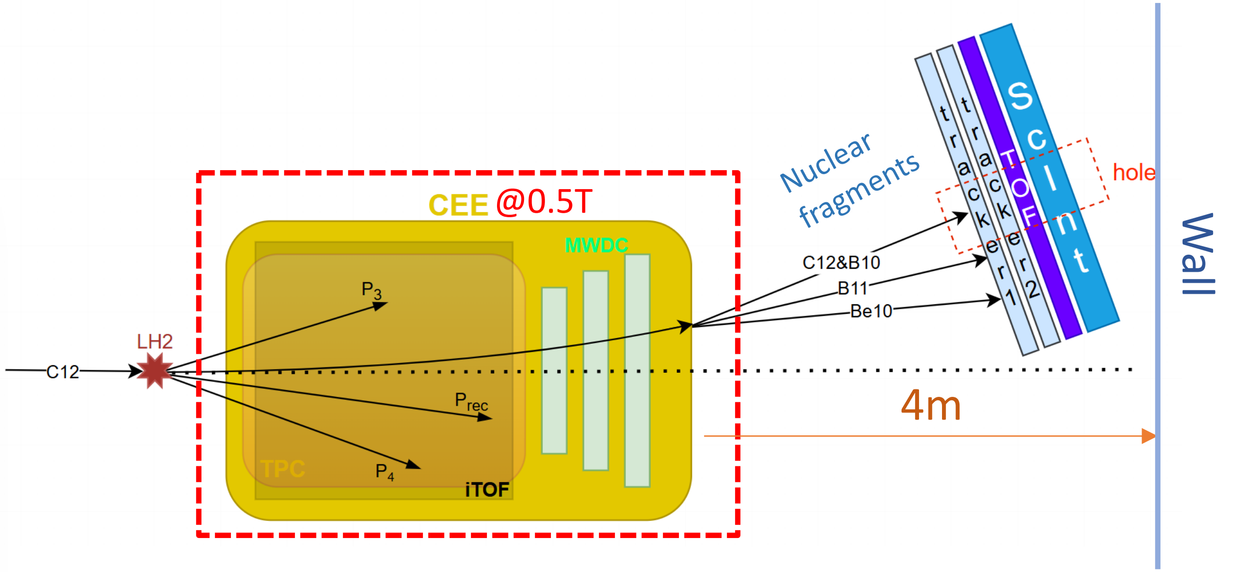


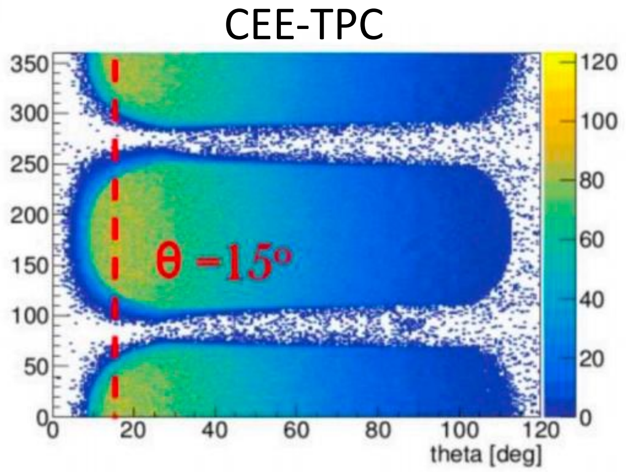
Measuring SRC w/ CEE@HIRFL

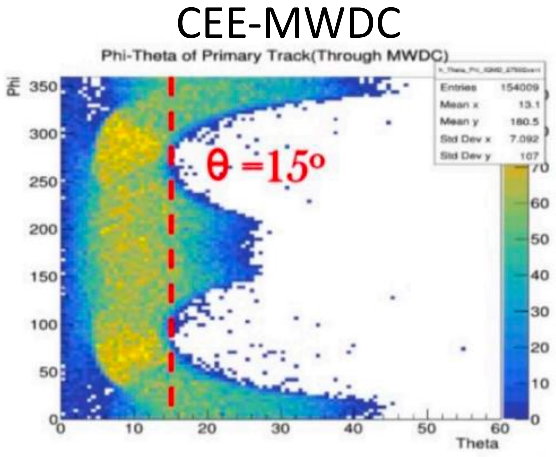
- CEE@HIRFL-CSR
  - Monte-Carlo simulation of SRC w/ CEE@HIRFL



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

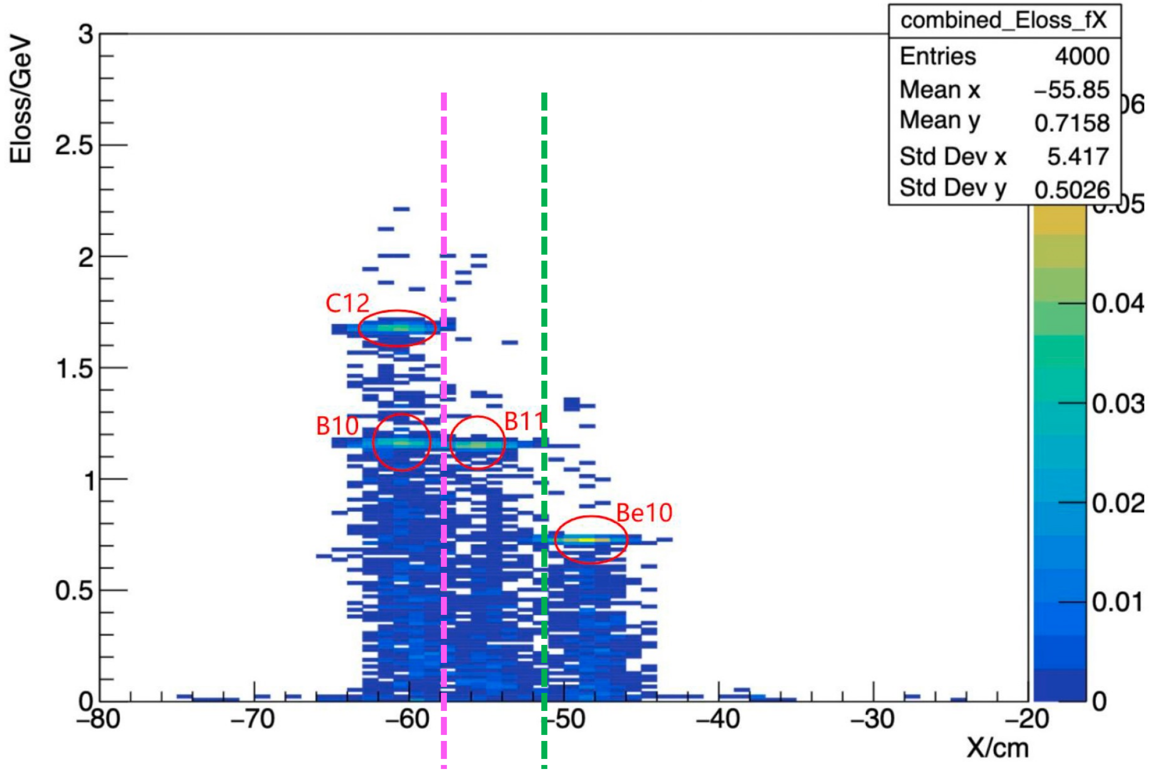


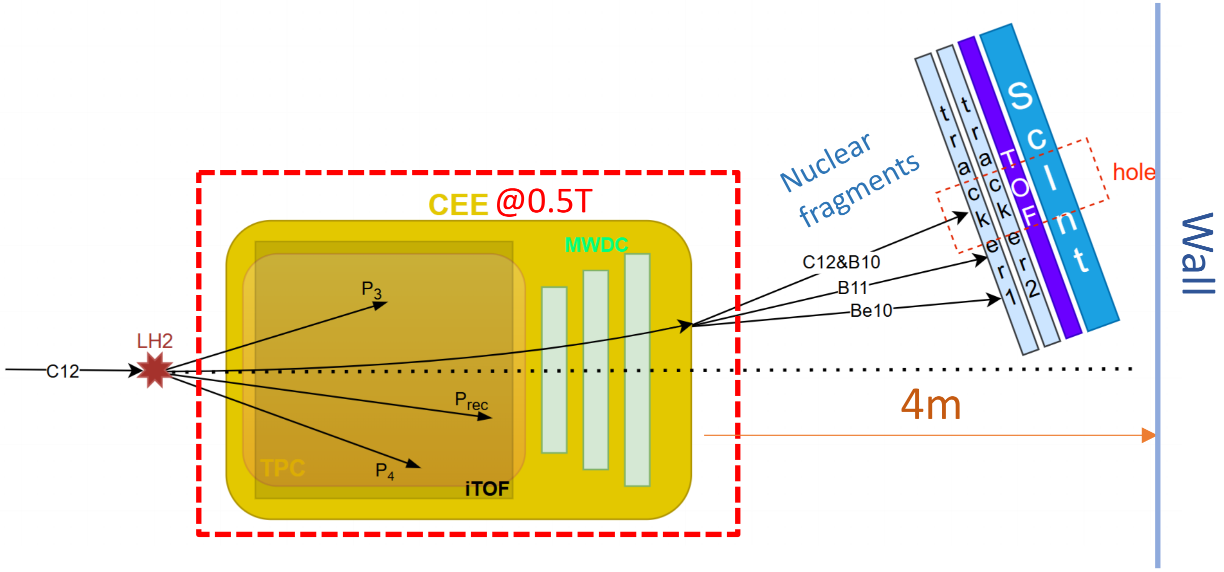




Measuring SRC w/ CEE@HIRFL

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



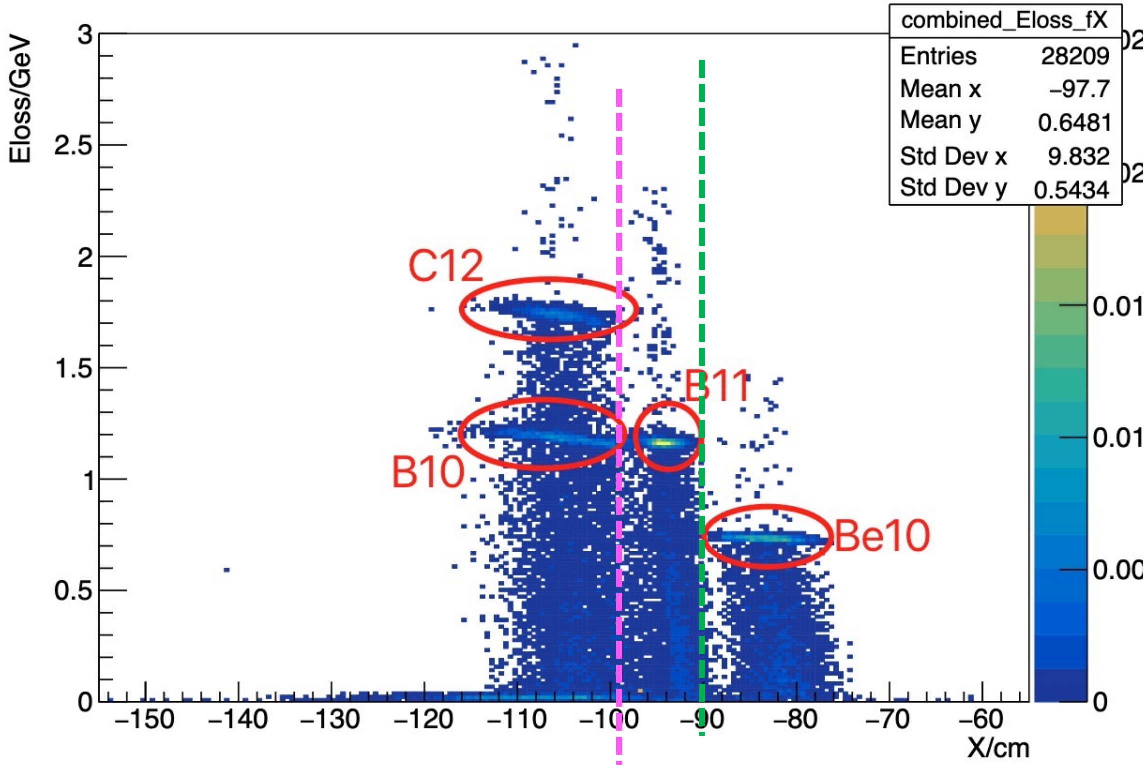


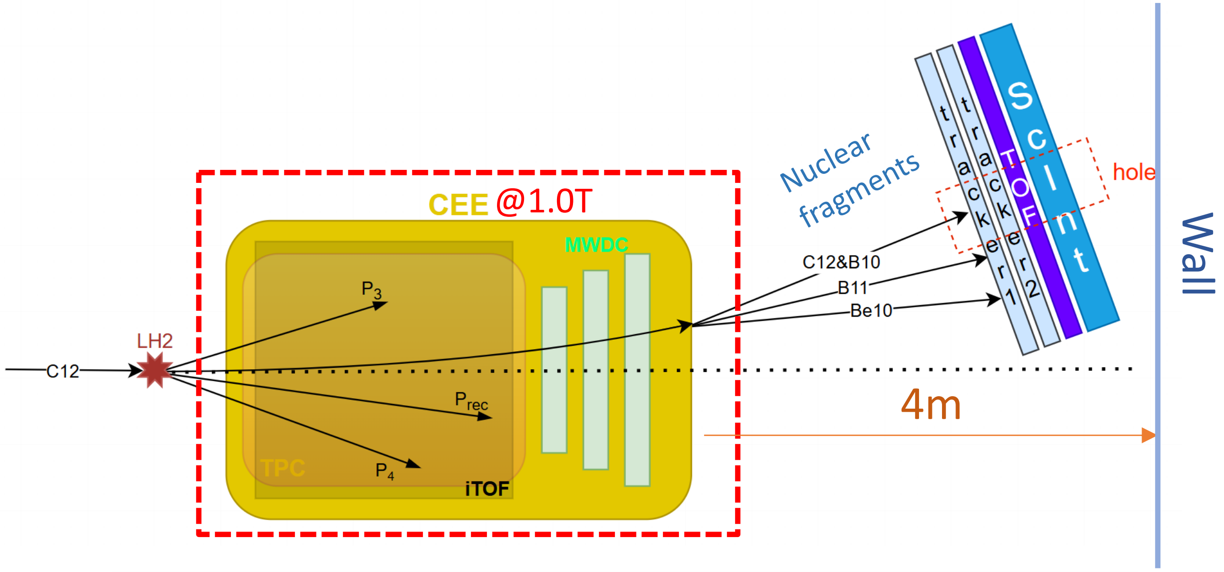
❑ Not yet considered:

- Detector resolution & efficiencies
- Background

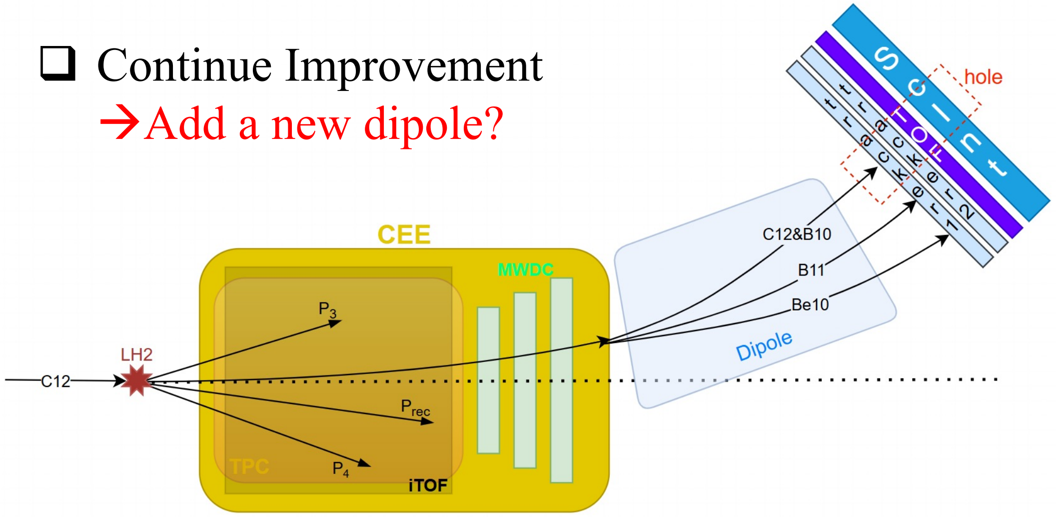
Measuring SRC w/ CEE@HIRFL

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



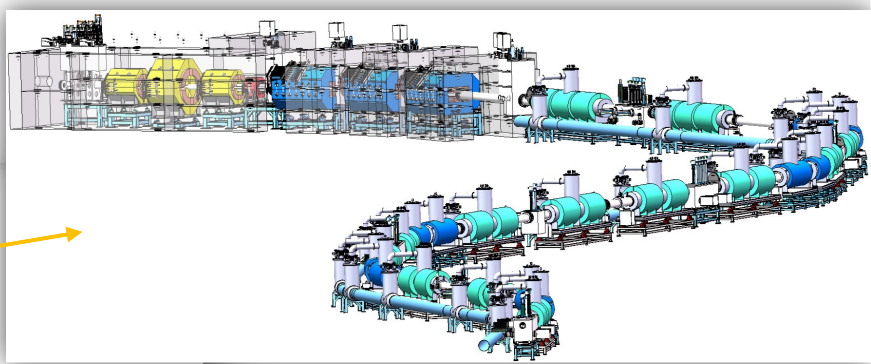


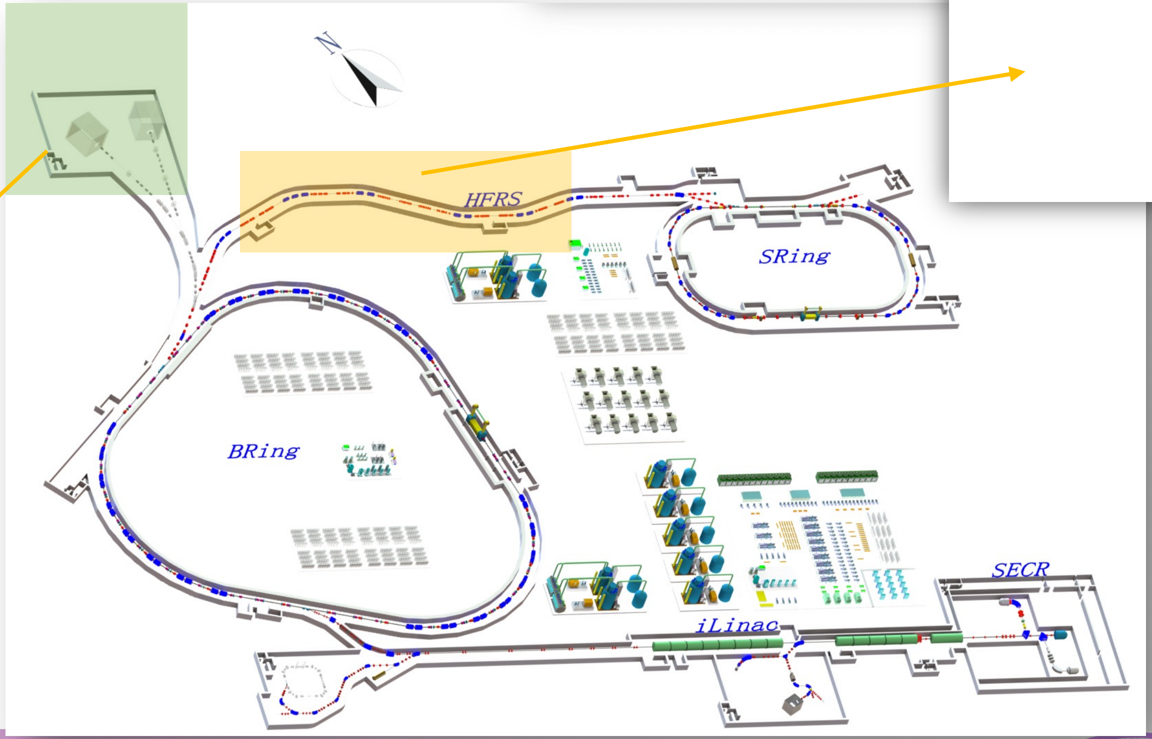
- Continue Improvement
  →Add a new dipole?



Measuring SRC @HIAF

- HIAF-High-Energy Station
  - HIAF construction to be completed in 2025 (see Dr. He Zhao's talk on Aug. 5th)：
    - 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
    - LH2 = 0.073g/cm3 x 15cm
    - Total Luminosity = 3×10^{35} cm^{-2} s^{-1} (slow ext)



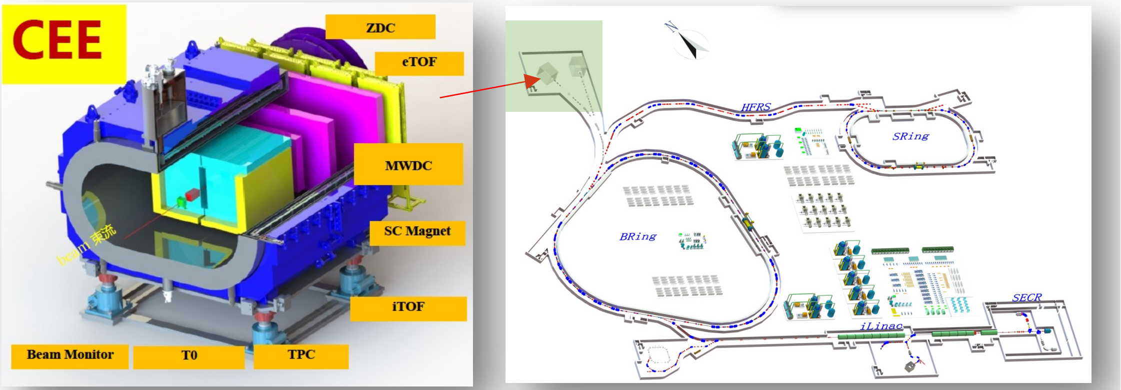


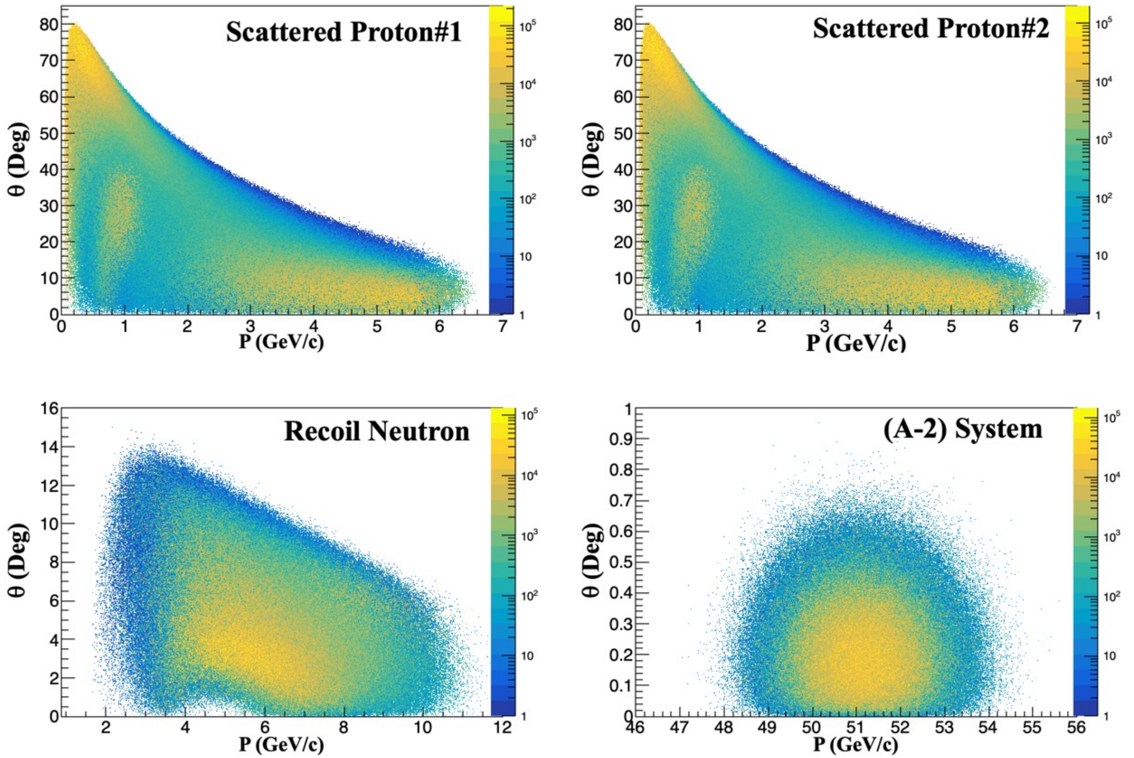
High-Energy Station (HES):
- CEE+, CHNS, ...
- A general-purpose full acceptance detector?

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

Measuring SRC @HIAF

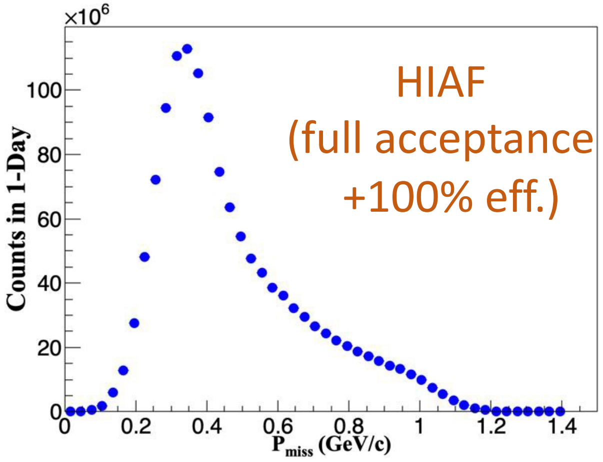
- HIAF-High-Energy Station
  - Precision frontier for SRC in HES:
    - Mapping 2N-SRC at all kinematic
    - Search 3N-SRC



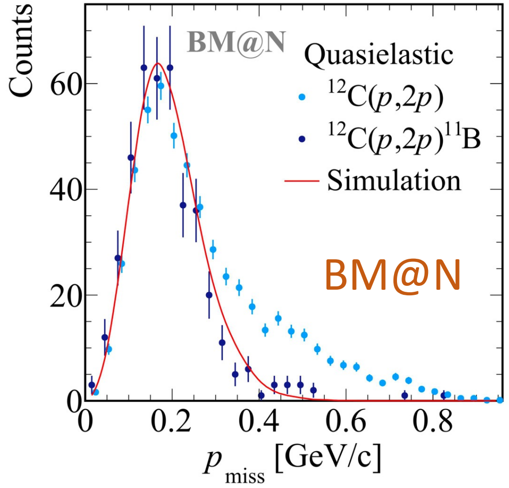


- Monte-Carlo Simulation ($^{12}C^{6+}$ at 51GeV/c)

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

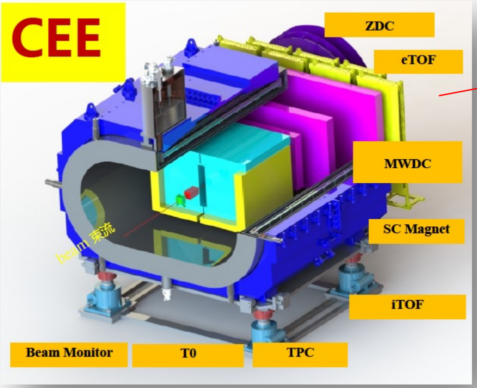


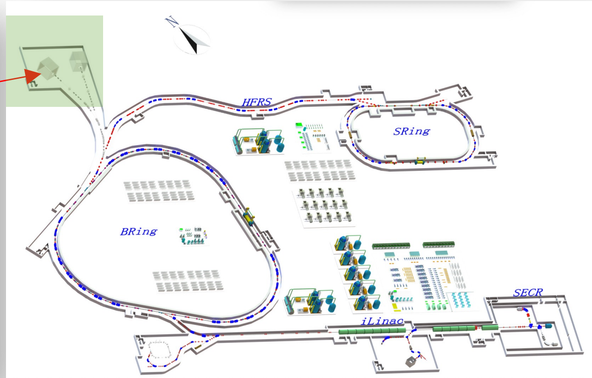
2-week @ 3.5x10^{4}pps

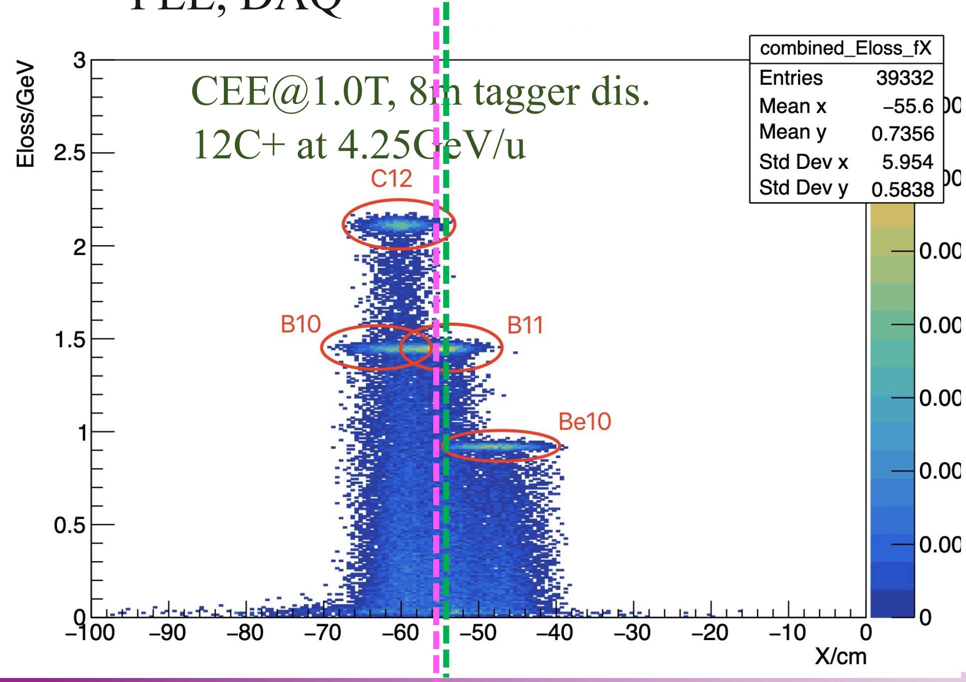


Measuring SRC @HIAF

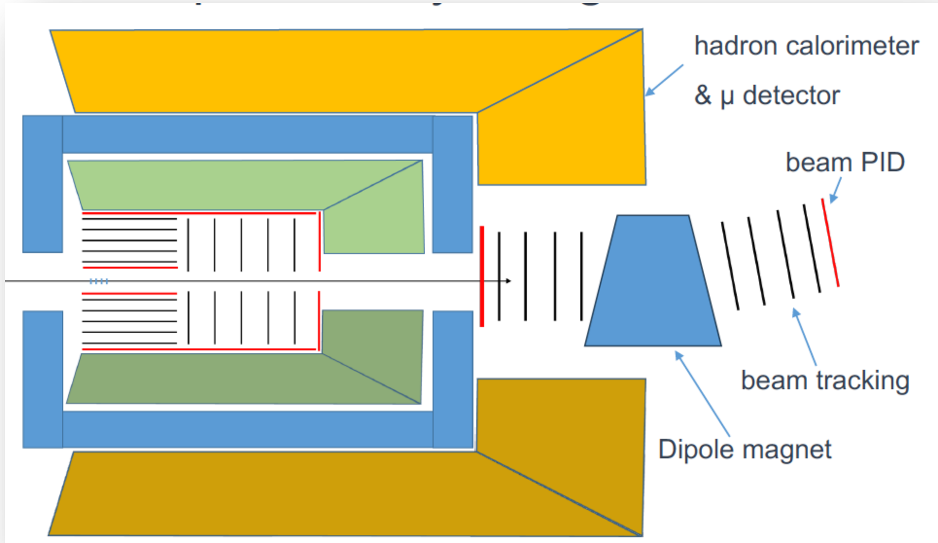
- HIAF-High-Energy Station
  - Precision frontier for SRC in HES：
    - Mapping 2N-SRC at all kinematic
    - Search 3N-SRC
  - **Challenges：**
    - CEE@1.0T won’t easily separate C12 and fragments
    - LH2 Target at high luminosity
    - FEE, DAQ







- A brand new detector?

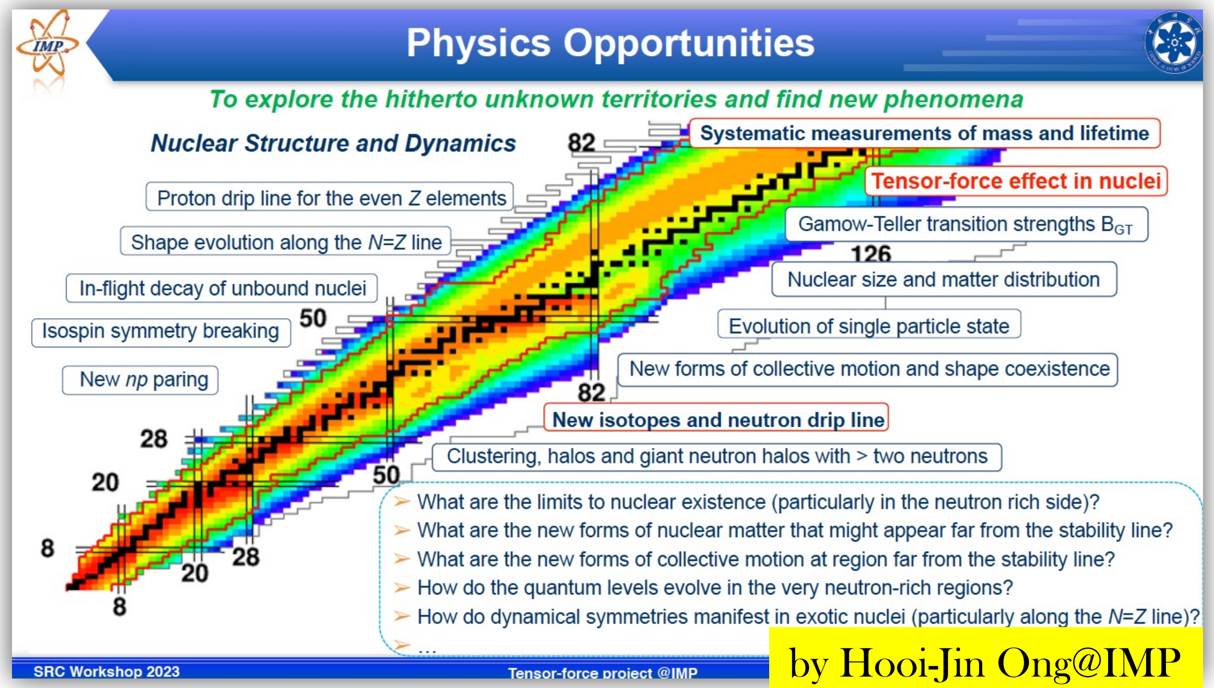


Measuring SRC @HIAF

Tsinghua University

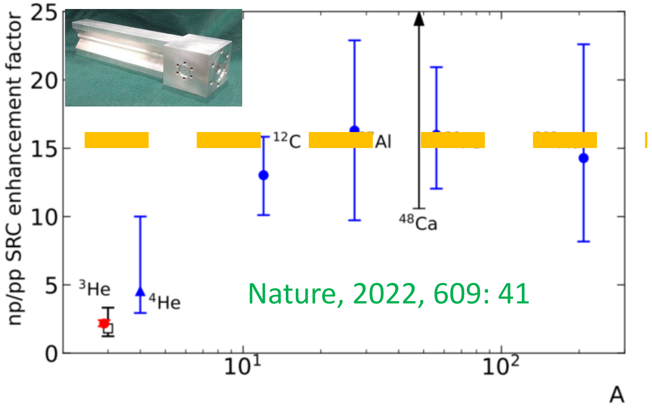
- HIAF-HFRS
  - Radioactive ion beams are produced at HFRS

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

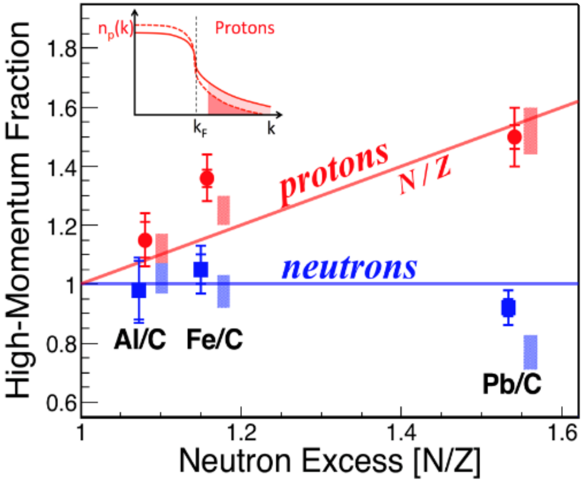


by Hooi-Jin Ong@IMP

- Study 2N-SRC w/ radioactive isotopes from HFRS
  - ✓ Neutron-rich nuclei vs fixed "isoscaler" nuclei



Nature, 2022, 609: 41



Nature, 560 (2018) 617-621.

Summary

- ➢ SRC allows fully studies of nuclear force, quark & gluon in nuclei, 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 & CEE@HIRFL,
- ➢ Precision frontier SRC study with HIAF → more simulation and optimization on ongoing!

- ❑ Most of simulation works done by TMEG undergraduate Haocen Zhao, & also graduate: Haojie Zhang, Yaopeng Zhang
- ❑ In close 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

Backup Slides

Measuring SRC

- Nucleus-scattering with high momenta

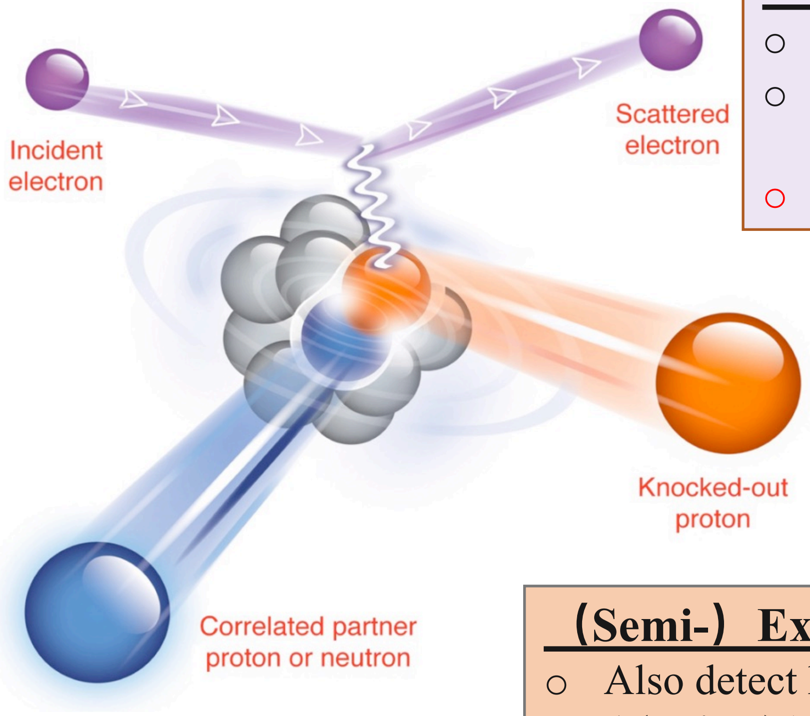
❑ **Quasi-Elastic Scattering (QES):** Knock out a nucleon but not breaking it

Beam Particle:

- Electron
  - Pro: Precise, low background
  - Con: small cross-section （EM)
- Proton:
  - Pro: large cross-section (Strong)
  - Con: Less precise, high background

"Target":

- Fixed (Gas, Liquid, Solid)
  - Pro: Luminosity=Density， most of stable nuclei (atoms) available
  - Con： Knocked-out nucleon, residuals hard to escape
- Ion Beam:
  - Pro: detector final state particles w/ high momenta
  - Con: Luminosity=current, limited ion beams



Inclusive Measurement:

- Only detect scattered electrons, A(e,e')
- Measuring response of internal structure to the momentum-transfer
- **Less (not zero) Final State Interaction (FSI)**

（Semi-） Exclusive Measurement :

- Also detect knocked-out high-momentum nucleon, A(e,e'pN)**A-2**
- Can detect paired nucleon in opposite direction
- Strong FSI (experimental & theory corrections)
- A-2 system in ground state

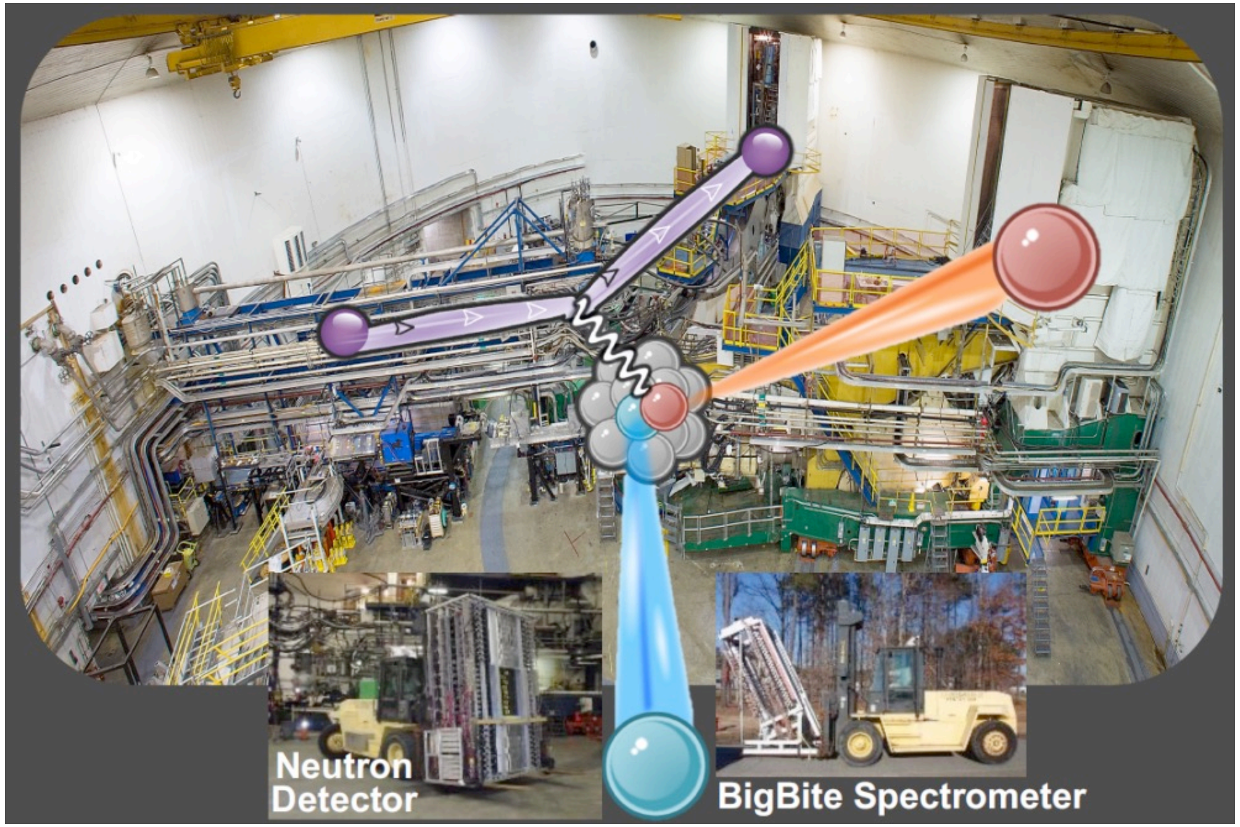
Measuring SRC w/ eA

Tsinghua University

- Two Types of Detector Systems
  - **SRC has small reaction rates → Precision vs. Coverage**

Hall-A HRS / Hall-C HMS

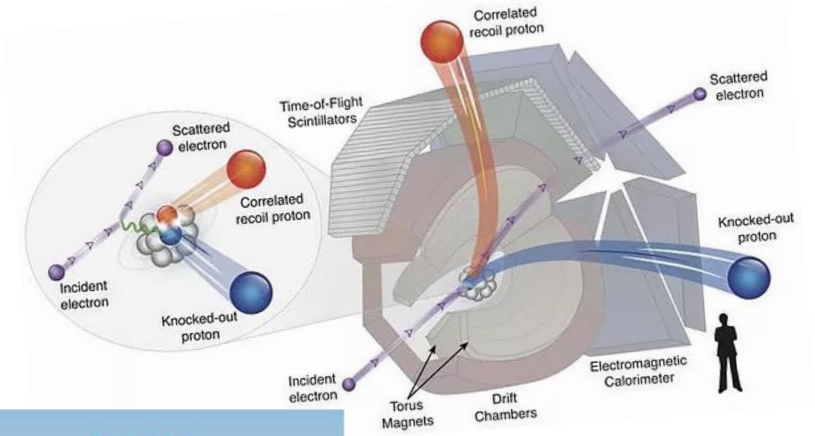
(High-Precision, Limited Acceptance);

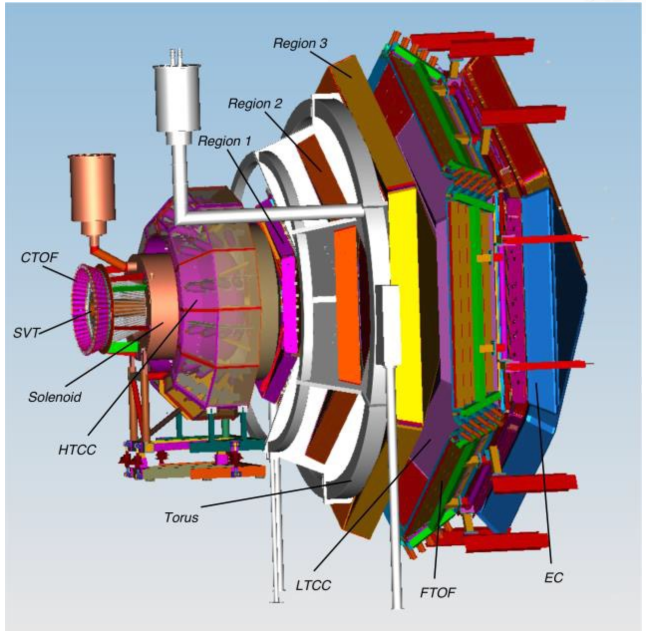


Add third-arm to detector p/n

Hall-B CLAS6/CLAS12

(Low-Precision, Full Acceptation)





Measuring SRC

- SRC Event Selection

  - ❑ Conditions： Knock-out nucleons, initial and final nuclear systems both in ground state → QES tail on the low-E side

  - ❑ Quantities：

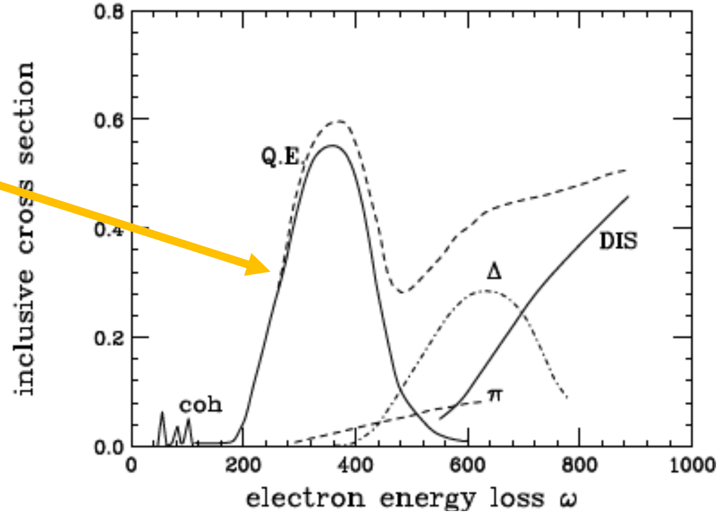
    Momentum Fractions: $x = \frac{Q^2}{2m_p v}$

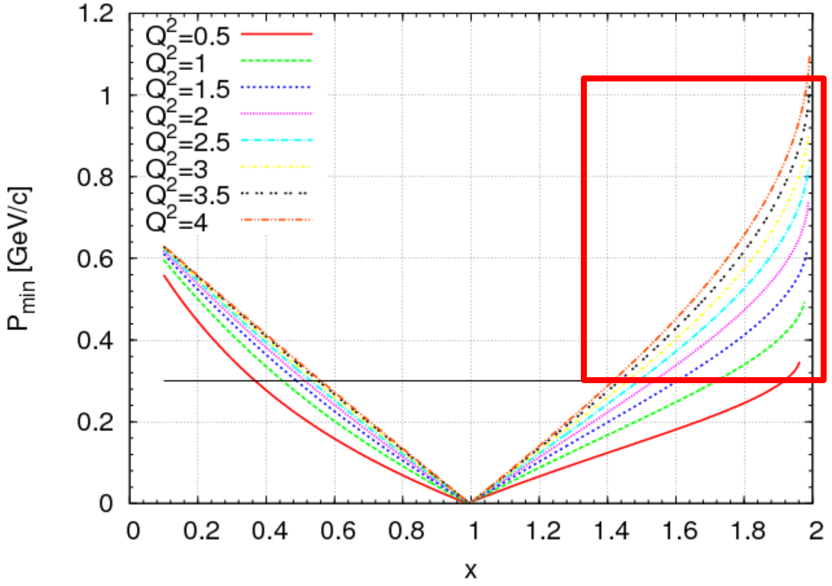
    Four Momentum Transfer: $Q^2 = 4E_0E'sin^2(\theta/2)$

  - ❑ Remove mean-field contribution → $k>k_{Fermi}$
    - ○ Directly measure high-P knock-out nucleons → strong FSI
    - ○ $1 < x < A$→"quark" takes addition momenta from nucleon-motion

  - ❑ Control FSI in semi-(exclusive) measurements (very hard!)：
    - ○ High-Q^2 to minimum the time of escaping→ less re-scattering
    - ○ Measure knocked out nucleons at special kinematics with min/max FSI
    - ○ Combine with theories models for additional corrections

Benhar, Day, Sick, Rev. Mod. Phys. 80, 189 (2008)





Measuring SRC w/ eA

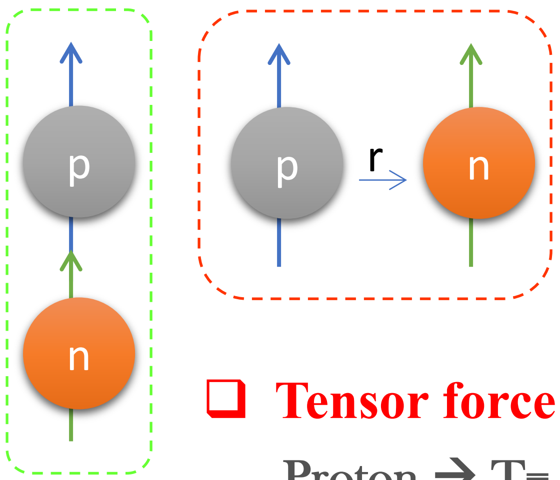
- Isospin Dependence
  - Tensor Force is strongly attractive

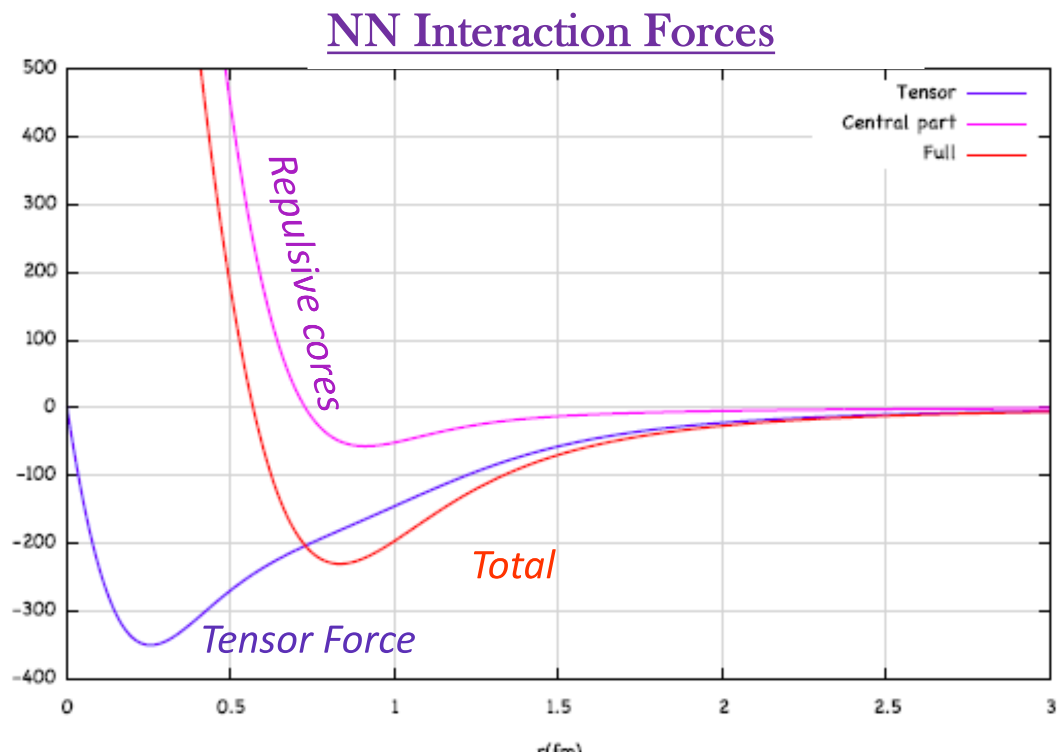
$$-S_{12} = -3(\vec{\sigma}_1 \cdot \hat{r})(\vec{\sigma}_2 \cdot \hat{r}) + (\vec{\sigma}_1 \cdot \vec{\sigma}_2)$$

= -3 $\sigma_1\sigma_2$

Attractive

==0 → *Repulsive*





- **Tensor force favor neutron-proton pairs**

Proton → T= 1/2, Neutron → T= -1/2

Isospin Singlet: T = 0, n-p pairs ✓ *Stable! due to Pauli Principle*

Isospin Triplet: T = 1, p-p (T_z=1), n-p (T_z=0), and n-n (T_z=-1)

3N-SRC

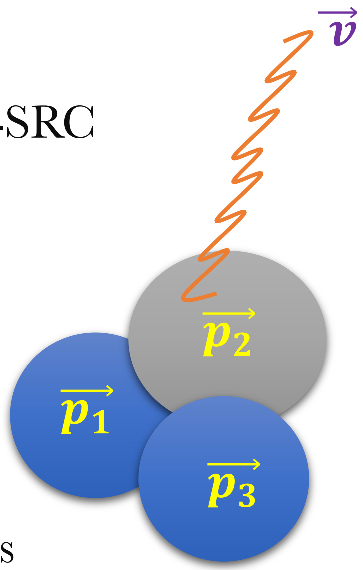
- Much Harder to Measure

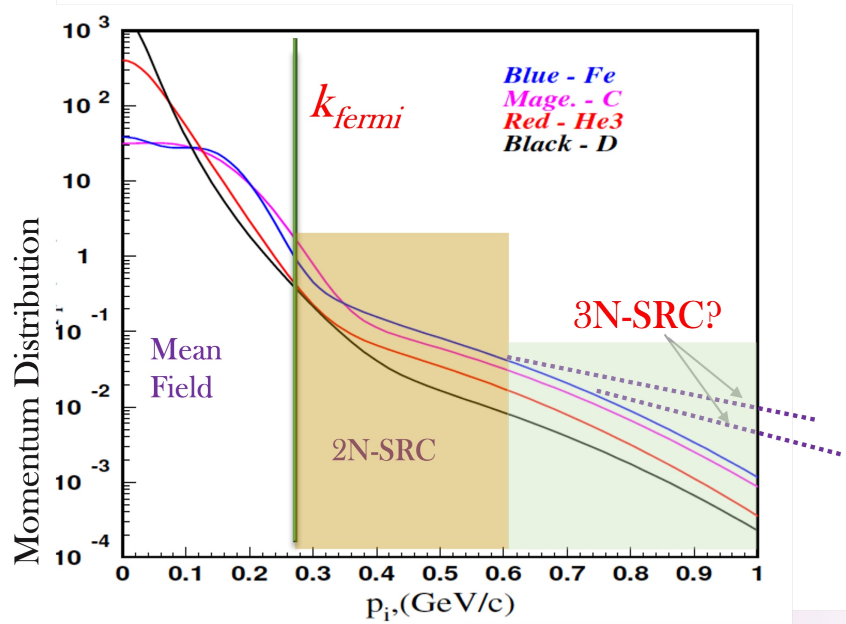
  - ❑ Many final-state combinations after breaking up 3N-SRC
  - ❑ Impossible w/ eA exclusive measurement→ need detect 3 high-P nucleons at all possible momenta
  - ❑ Inclusive Measurement: XS links to the 3N-SRC tails

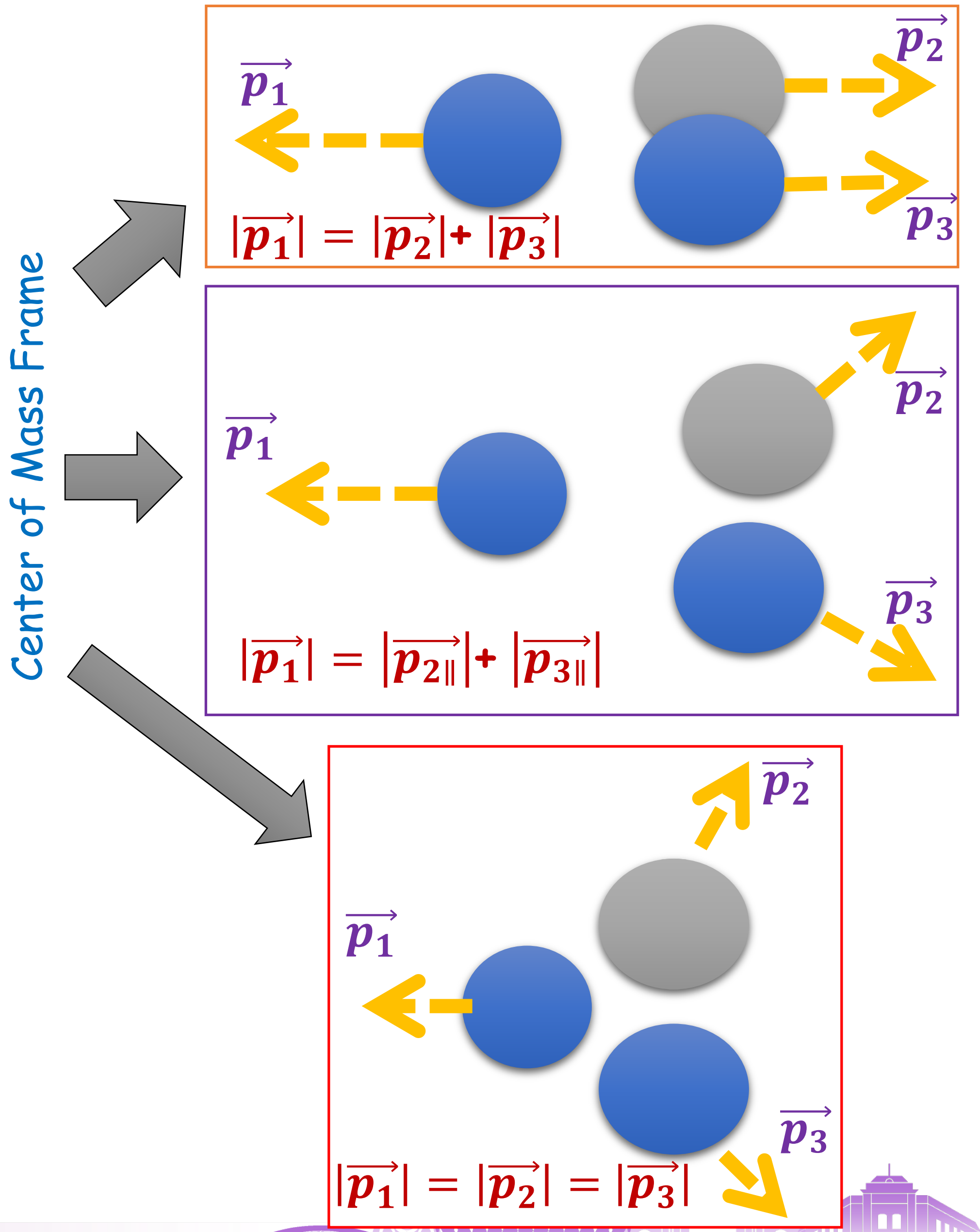
3N-SRC (2<x<3)

$$a_3(A,{}^3He) = K\cdot\frac{3\sigma_A}{A\sigma_{^3He}}$$

- **2nd plateau?**





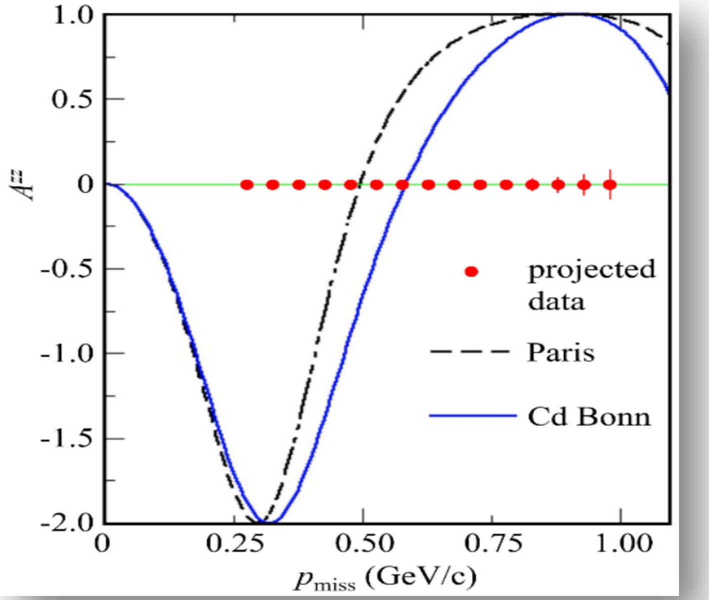


Measuring SRC w/ Inverse-pA

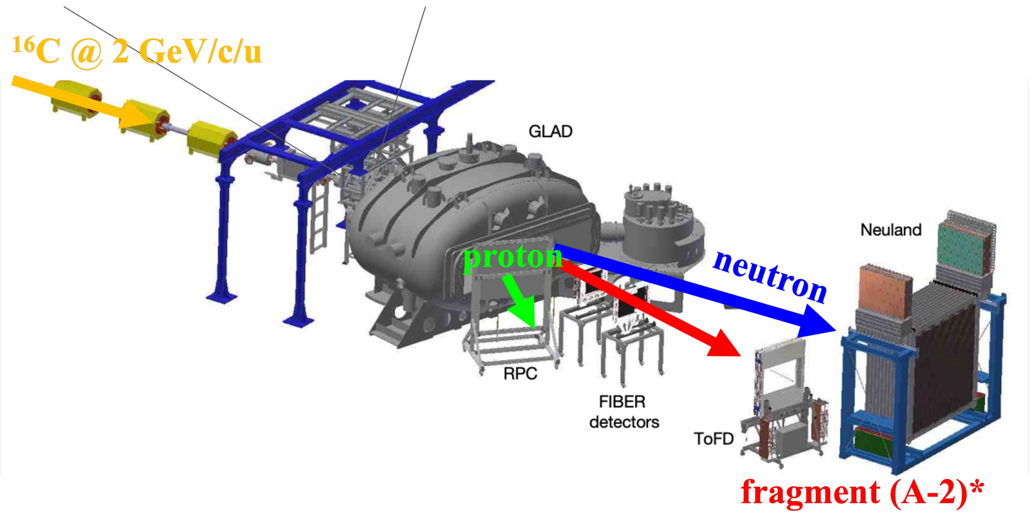
➢ Other ongoing/future Experiments

- ❑ 3rd Gen experiment in HyperNIS@JINR: non-nucleonic d.o.f in Deutron

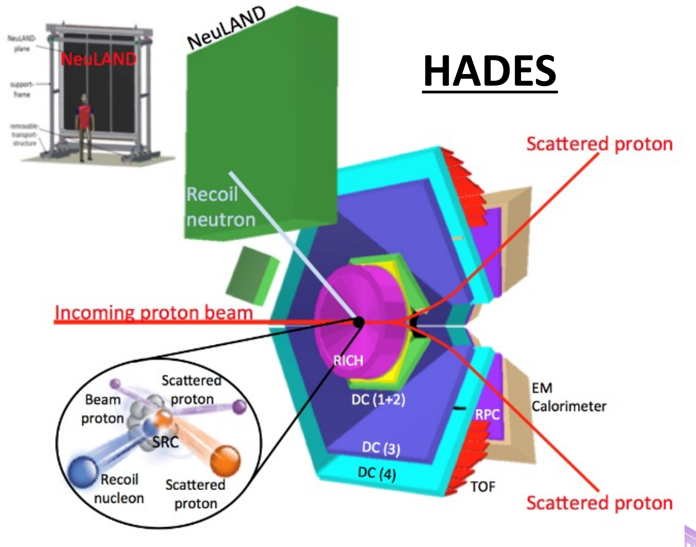
$$A_{zz} = \frac{(\sigma_- + \sigma_+ - 2\sigma_0)}{\sigma_{unpol}}$$



- ❑ SRC w/ rare radioactive isotope at R³B@GSI
  - ^{16}C(p,2pN)A-2* in 2022.
  - Future: ^{110,120,132}Sn (N/Z = 1.20, 1.40, 1.64)



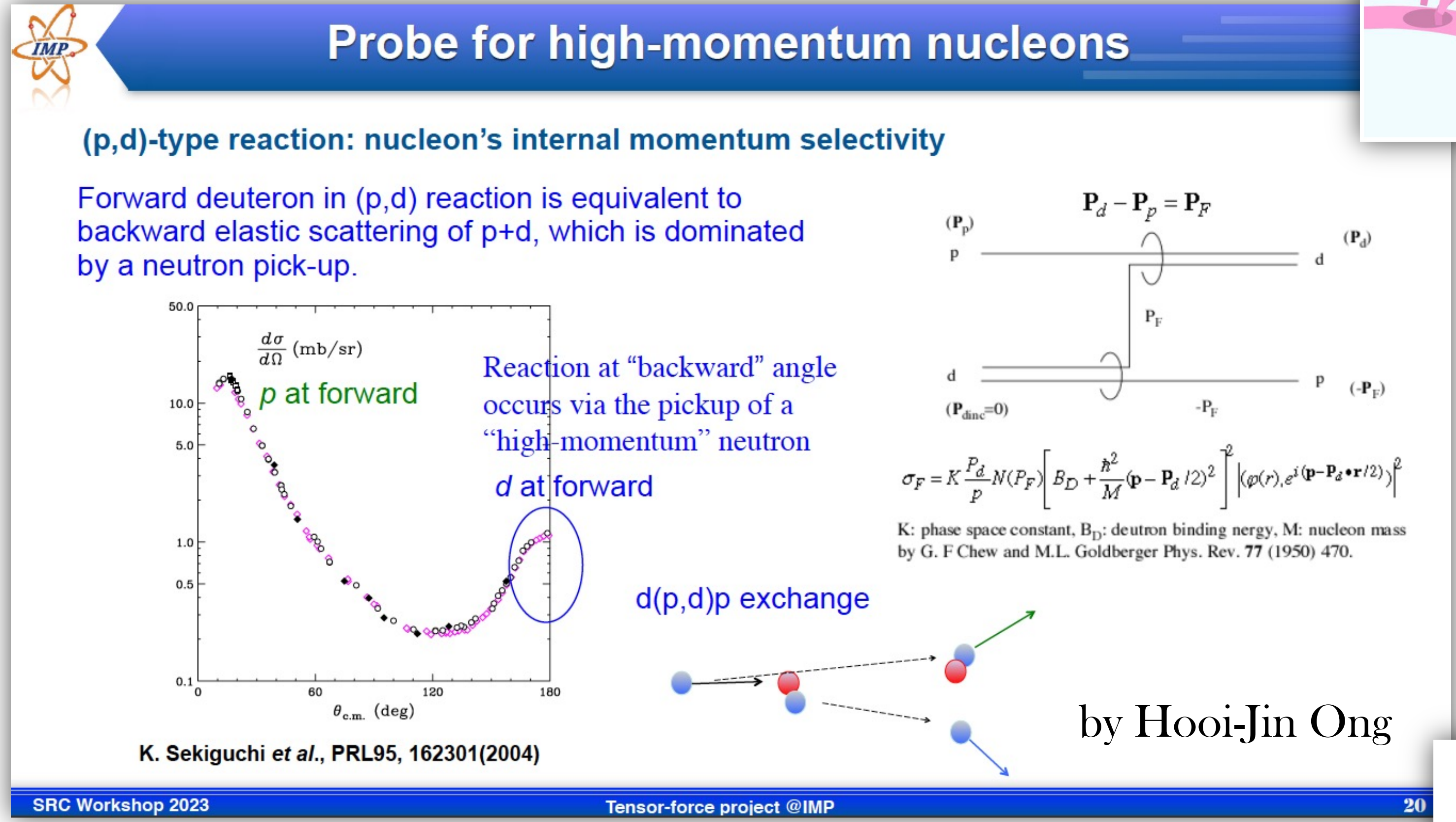
- ❑ SRC at HADES@GSI
  - 4.5GeV p on fixed nuclear targets
  - Search for 3N-SRC signals in A(p,2pNN)

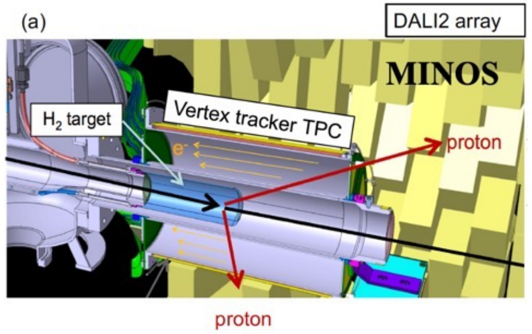


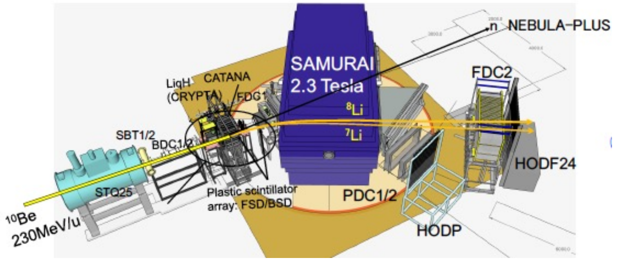
Measuring SRC w/ Inverse-pA

Tsinghua University

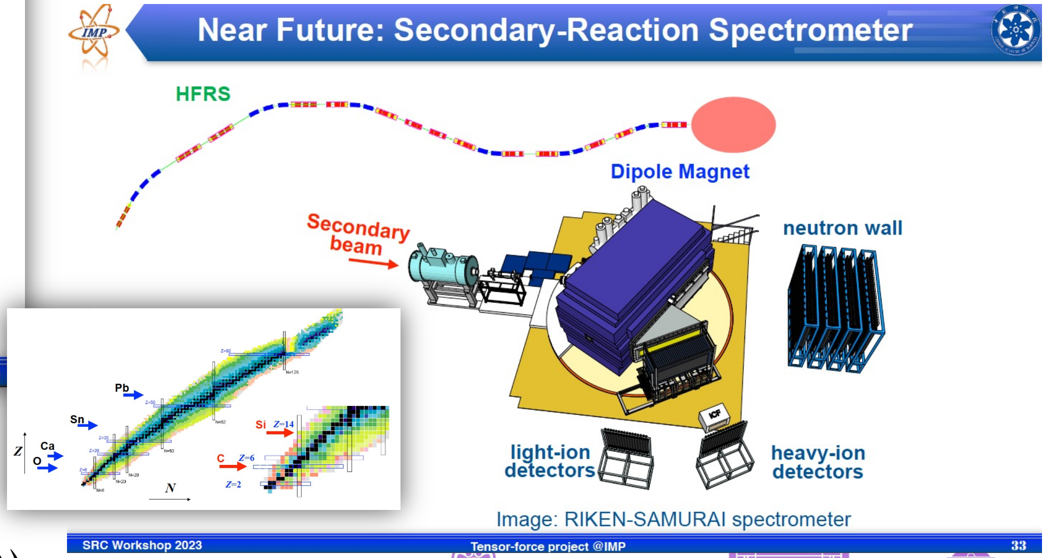
- Other ongoing/future Experiments
  - ❑ (p, d) pickup reaction (slides from Hooi-Jin Ong@IMP)







by Hooi-Jin Ong



- ❑ Bremsstrahlung γ generated from SRC (Y.H. Qin & Z.G. Xiao, Physics Letters B 850, 138514 (2024))