清華大學物理系
TSINGHUA UNIVERSITY DEPARTMENT OF PHYSICS

Short-Range Correlations & Nuclear Medium Effects

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Exploring nuclear physics across energy scales

Peking University, 04/~~23~~/2024
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Nuclear Structure Across Energy Scales

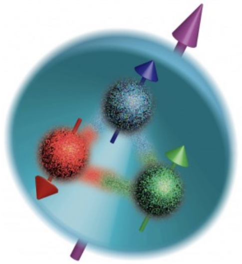
➢ Nucleon vs Nuclei

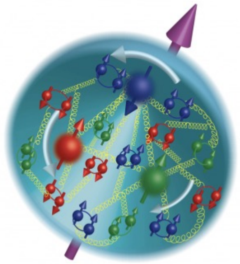
early 1900s

1970s

2015

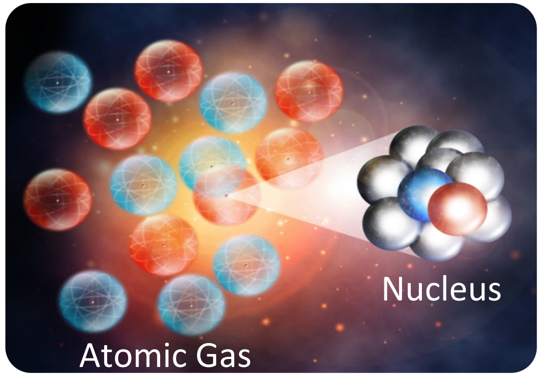
❑ Proton

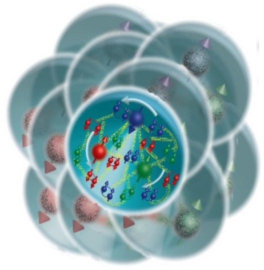


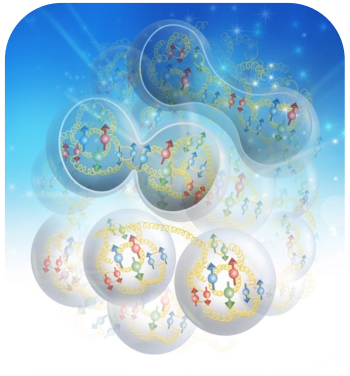


Complicated QCD dynamics

❑ Nucleus







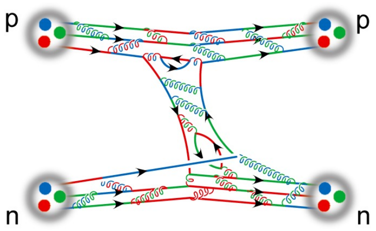
- ❑ How quarks and gluons participate in this process?
- ❑ Are free protons & nuctrons same as ones into nuclei?

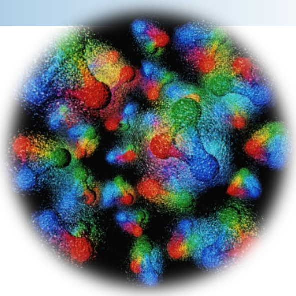
Spoil-alert: NO!

Nucleons in Nuclei

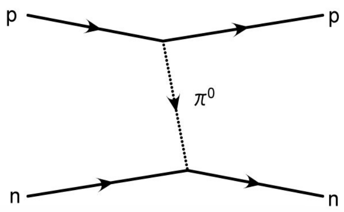
➢ Strong Force vs Nuclear Force

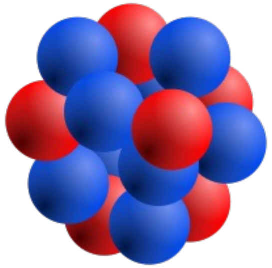
- ❑ Nuclear force is a "weak" strong force, but too complicated for QCD in description of Nuclei



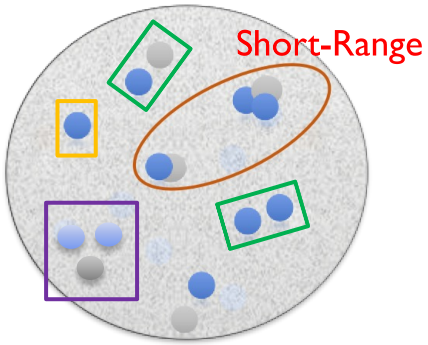


- ❑ Suprisedly, shell-models work very well
  - ✓ Sum of nucleon-nucleon(NN) Interactions → mean field
  - ✓ Modern NN potentials, e.g. AV18





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



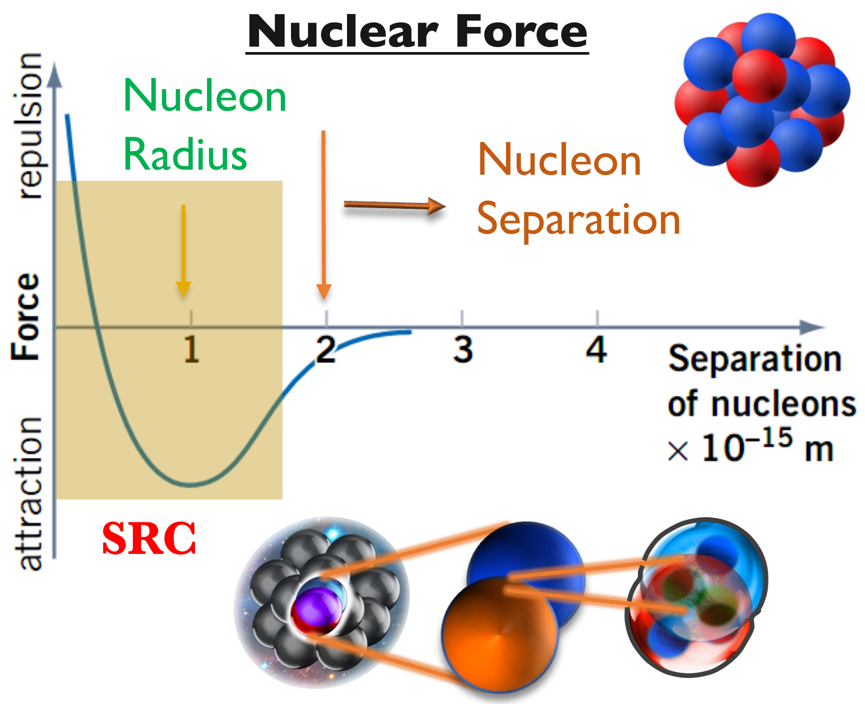
- NN terms fitted from data
- Too hard for NNN and beyond
- Short range part (non-nucleonic)?

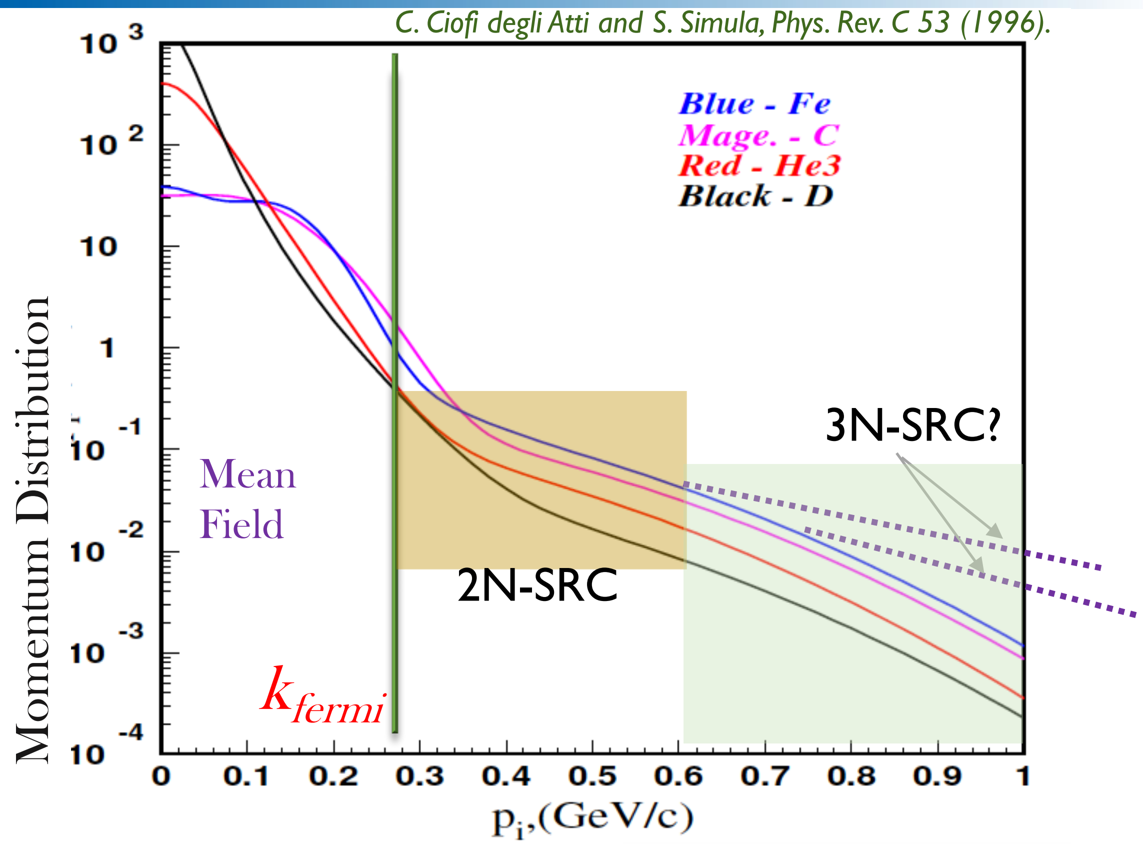
TABLE I. Argonne V18 spin-isospin operators in coordinate space.

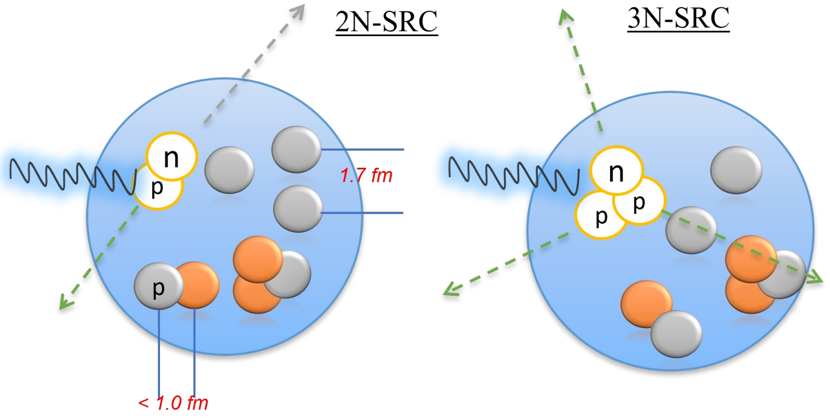
Term	Spin-isospin operator in r space
O_1	$\mathbf{I}$
O_2	$(\boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2)$
O_3	$(\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2)$,
O_4	$(\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2)(\boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2)$
O_5	$S_{12} = 3(\boldsymbol{\sigma}_1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



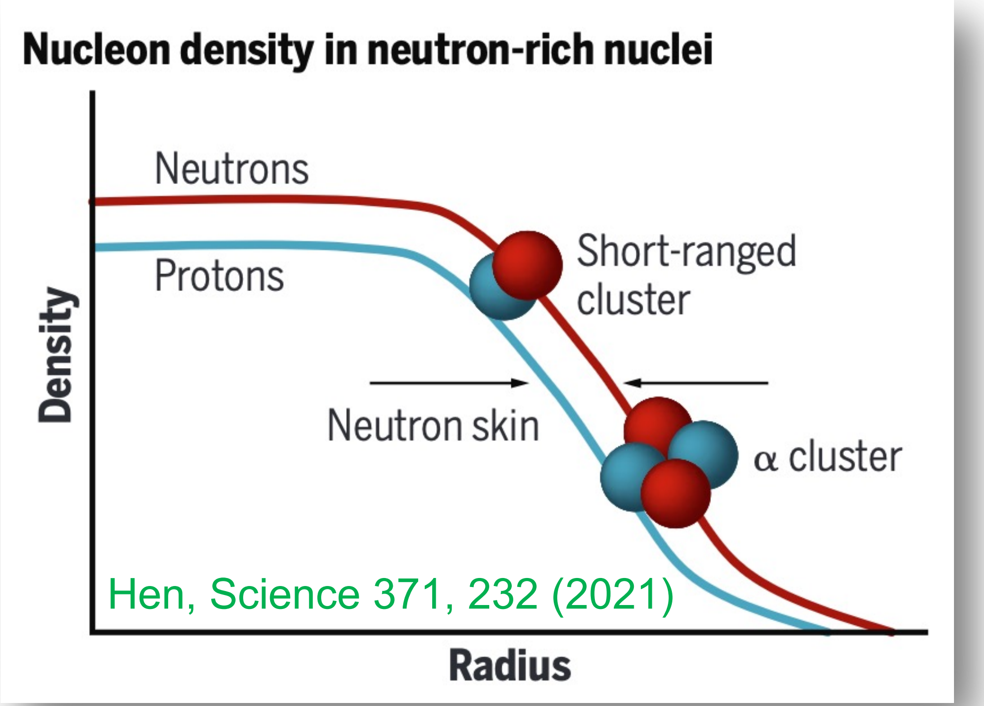




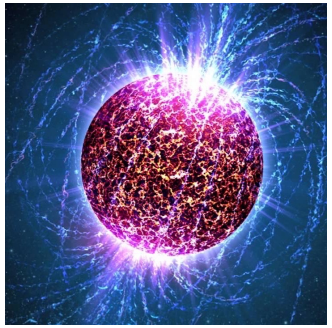
- 2 or more nucleons highly overlapped → high-density but cold!
- SRC nucleons carry high relative momenta (A-independent)
- Experimental signals:
  - ✓ Look for back-to-back nucleons after breaking up SRC

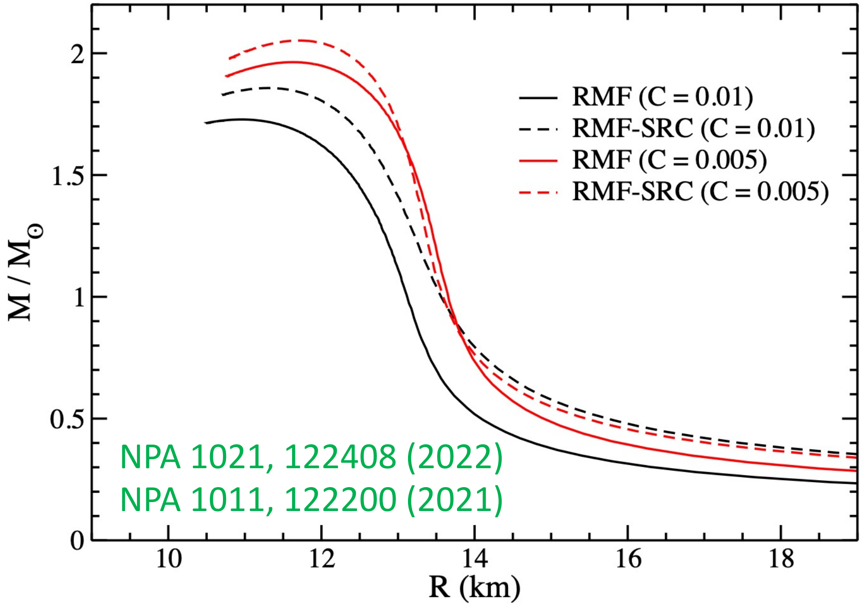
Nucleons in Nuclei

- 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

➢ Nucleus-scattering with high momenta

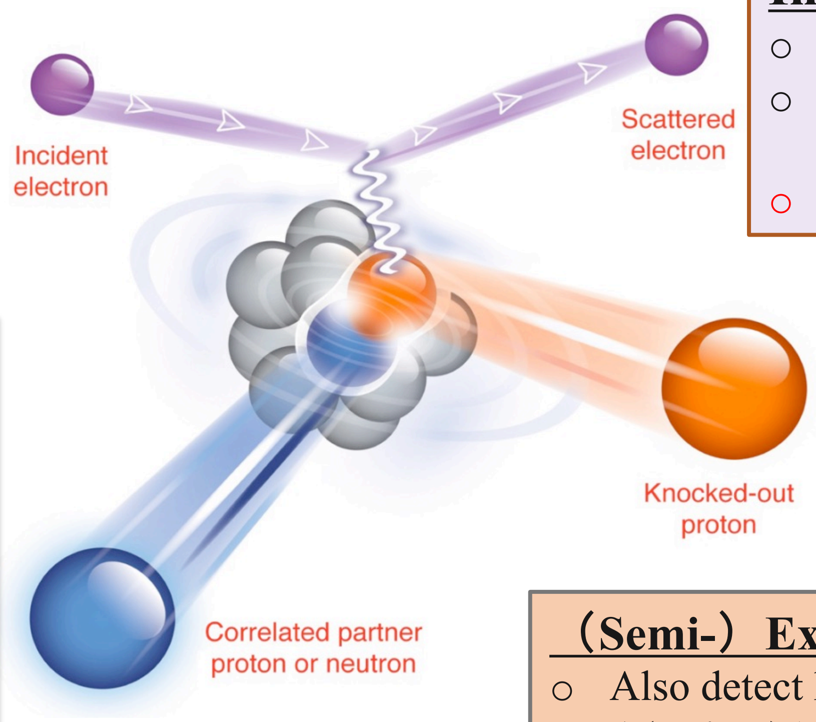
❑ **Quasi-Elastic Scattering (QES):** Knock out a nucleon but not breaking it

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:

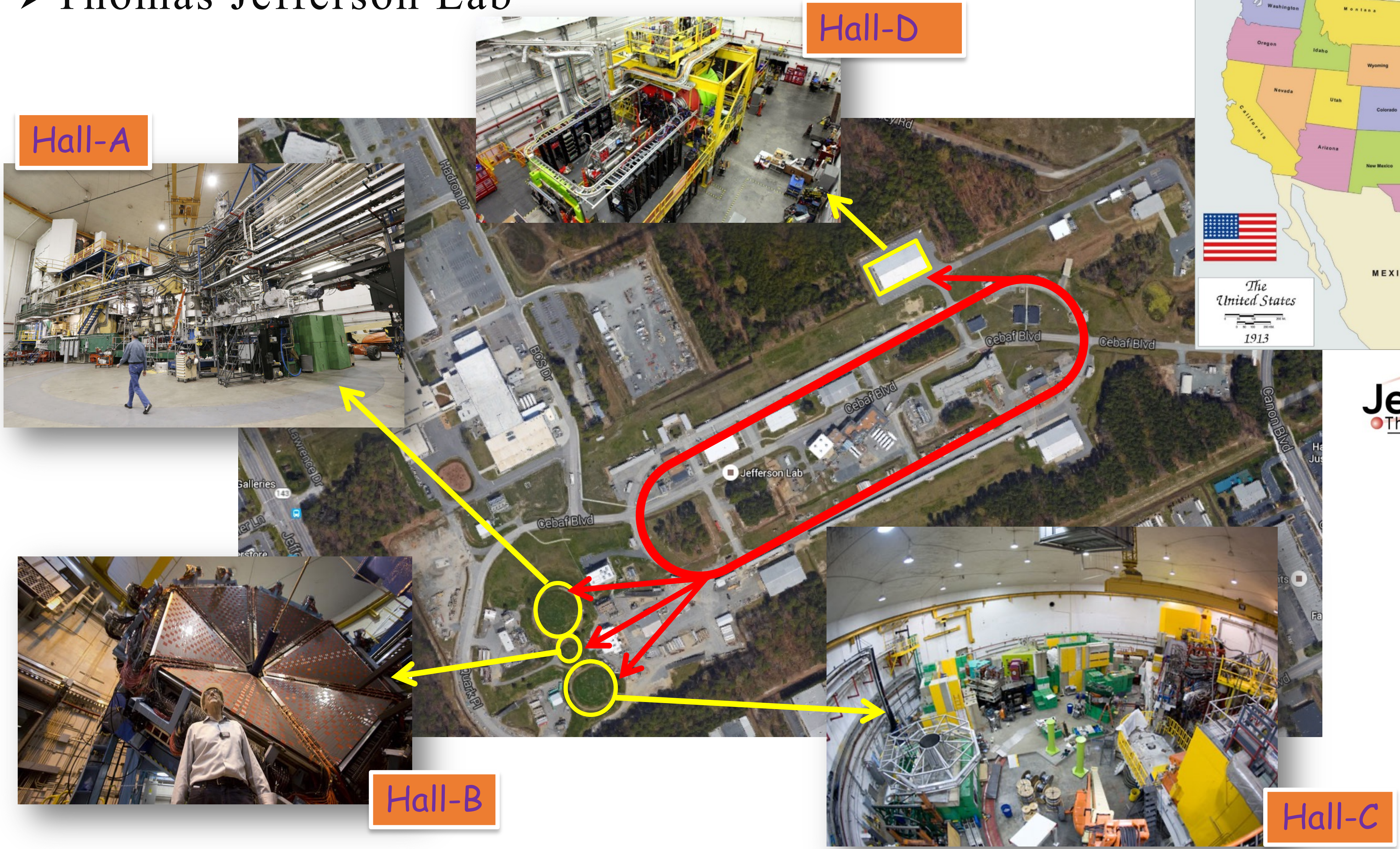
- Only detect scattered electrons, A(e,e')
- Measuring response of internal structure to the momentum-transfer
- **Less (not zero) Final State Interaction (FSI)**)

（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

- ➢Thomas Jefferson Lab



Jefferson Lab
Thomas Jefferson National Accelerator Facility

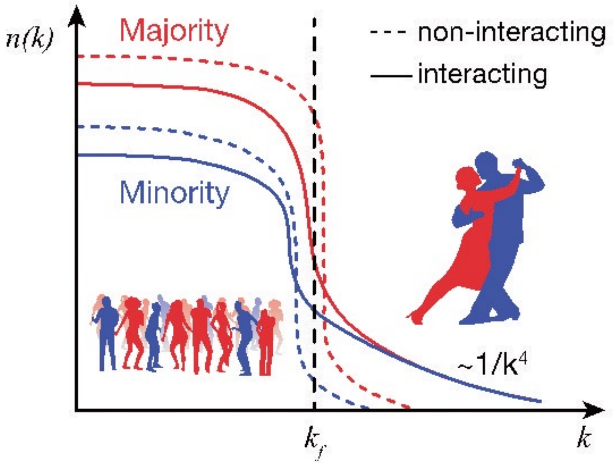
U.S. DEPARTMENT OF ENERGY

2N-SRC

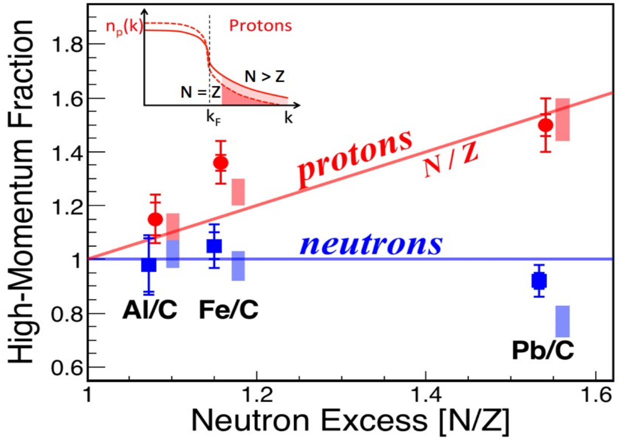
➢ Exclusive SRC Results

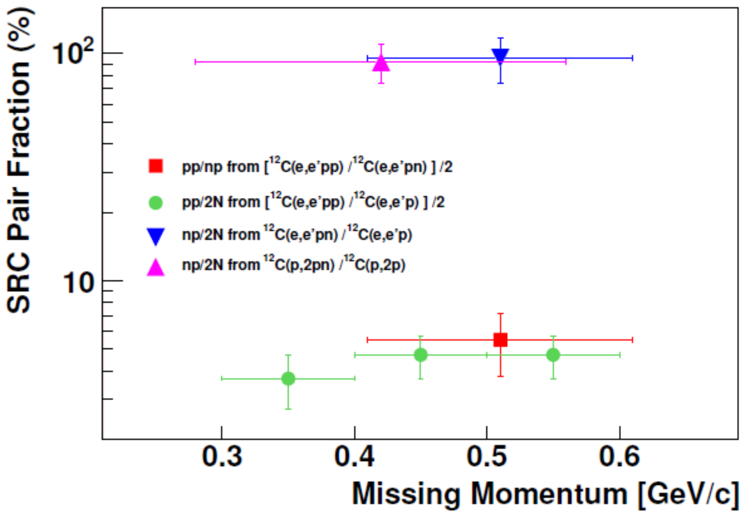
R. Subedi, et al, Science 320 1476 (2008)

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



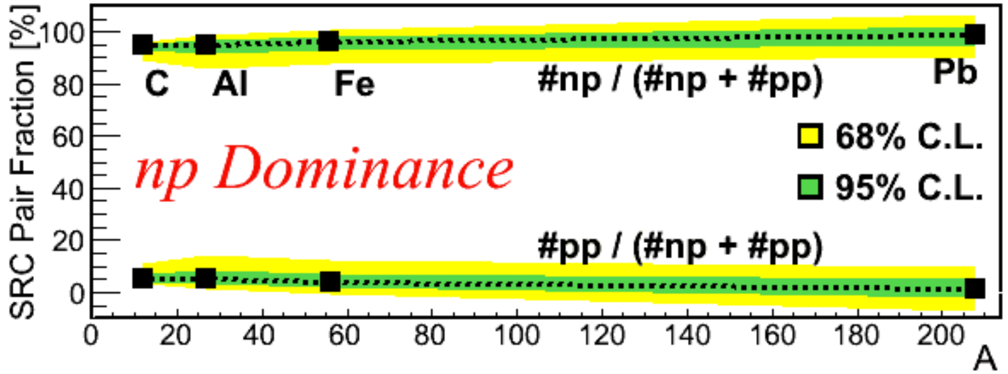
proton "speed up" with neutron excess





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 most of heavy nuclei → universality?



❑ Cautions:

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

2N-SRC

➢ Inclusive SRC Measurements:

❑ QES inclusive cross-sections:

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

Nucleon momentum distribution

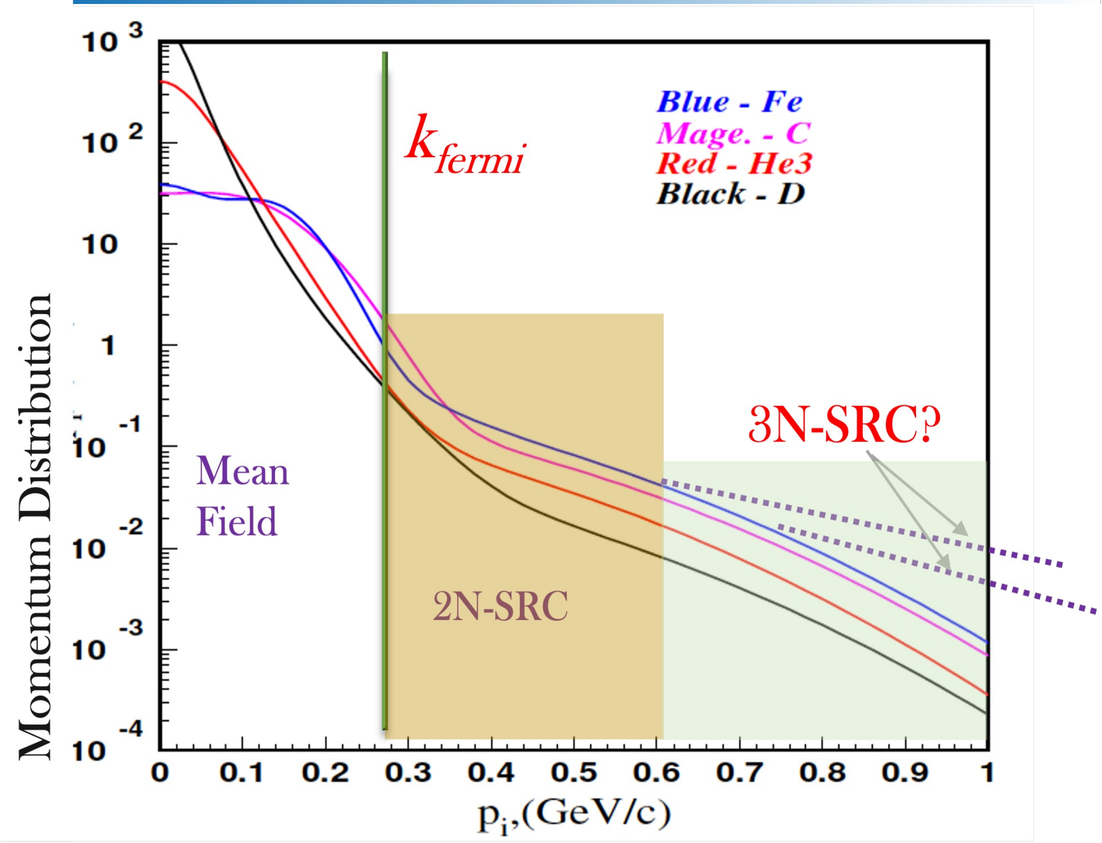
"links" to momentum distribution

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



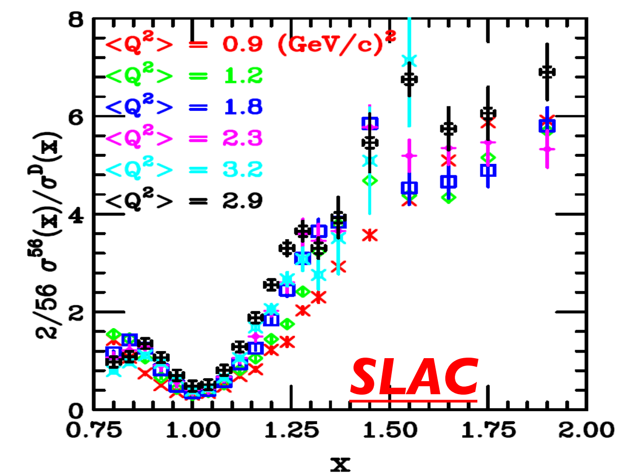
❑ Inclusive vs Exclusive:

- High precision, small FSI
- Not direct probing SRC internal info

2N-SRC

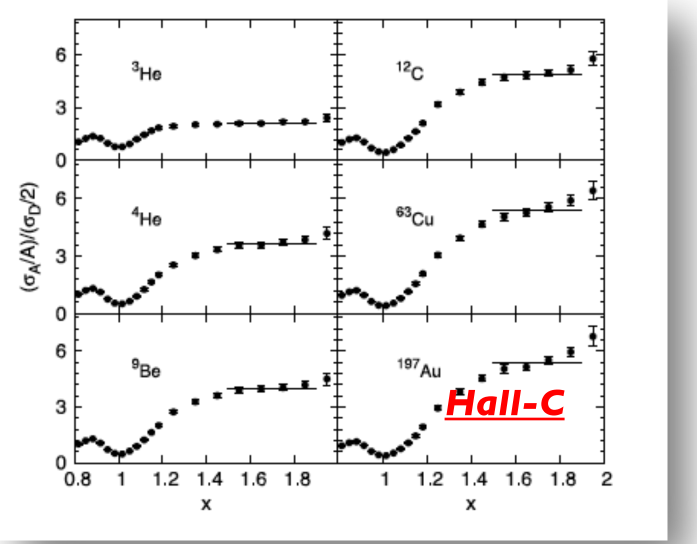
➢Inclusive SRC Results

- ❑ SRC plateau at Q2>1.4GeV/c

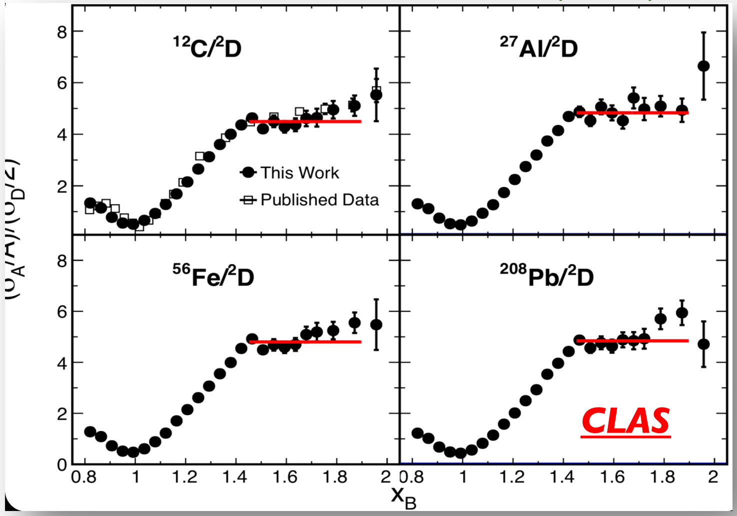


Frankfurt, Strikman, Day, Sargsian, PRC48, 2451 (1993)

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

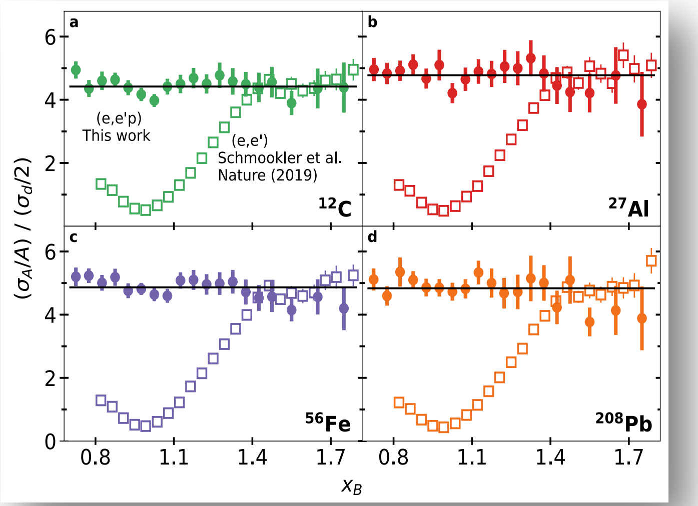


Schmookler et al., Nature (2019)

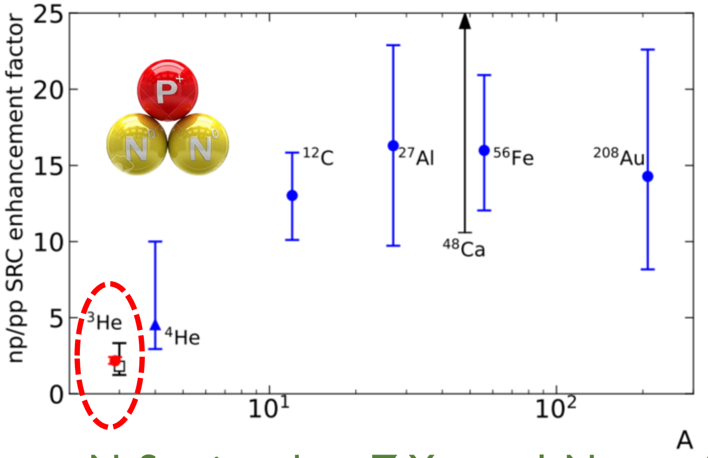


- ❑ Compared with exclusive SRC

Korover and Denniston et al.,CLAS, Submitted (2022)



- ❑ Non-Universal in light nuclei?



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

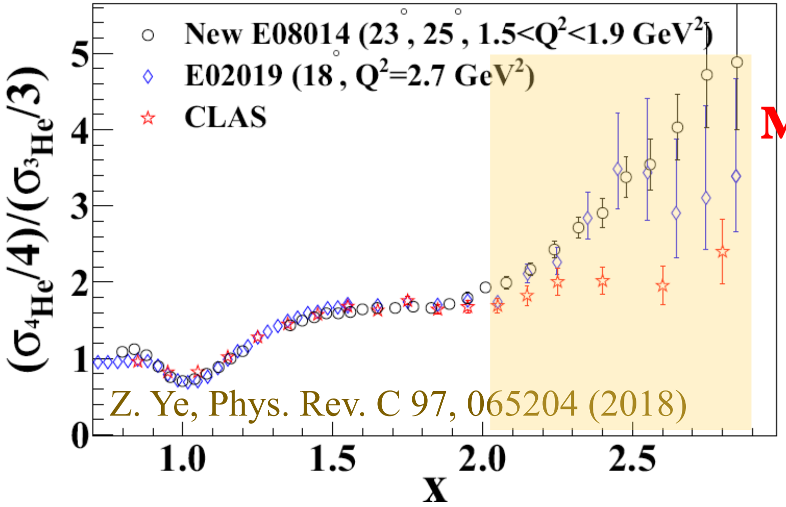
3N-SRC

➢A More Extreme Case

- ❑ 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?

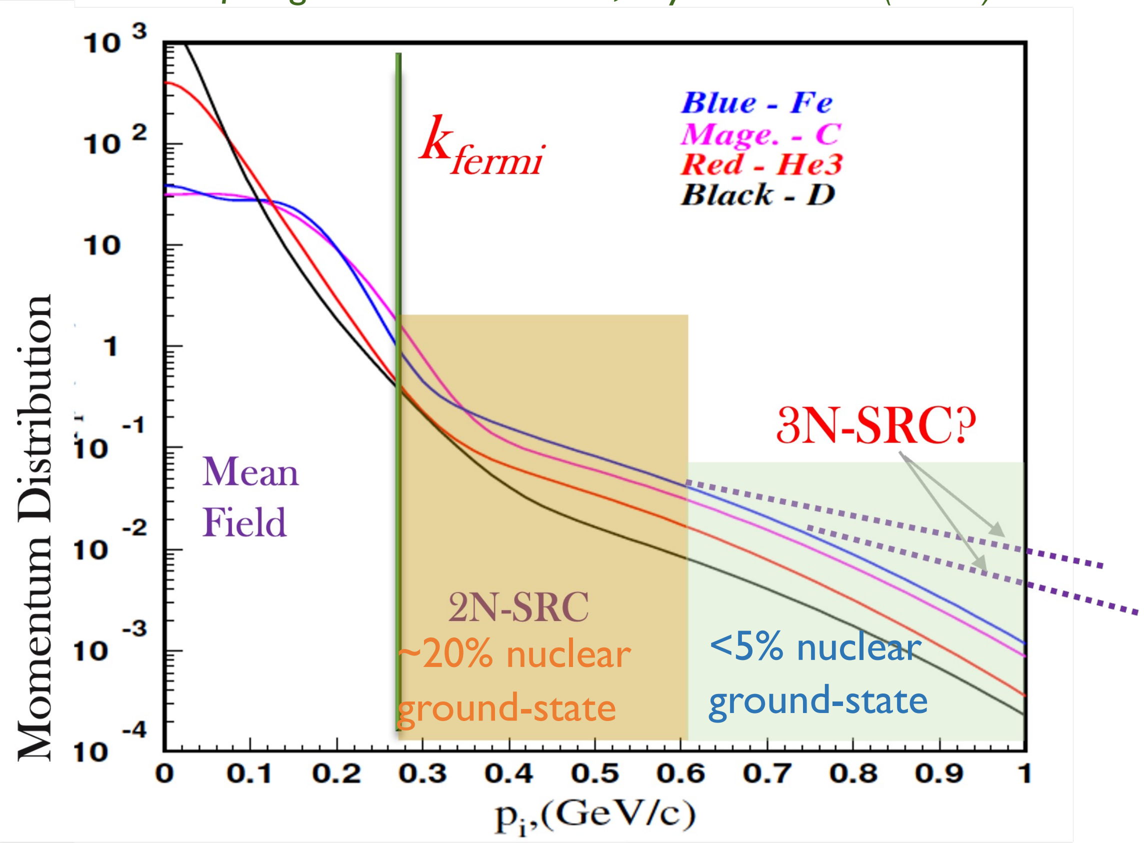
- ❑ Inclusive Measurement: XS links to the 3N-SRC tails

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



Missing 3N-SRC?

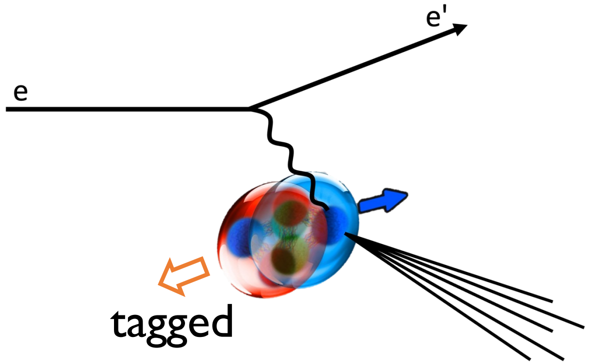
C. Ciofi degli Atti and S. Simula, Phys. Rev. C 53 (1996).

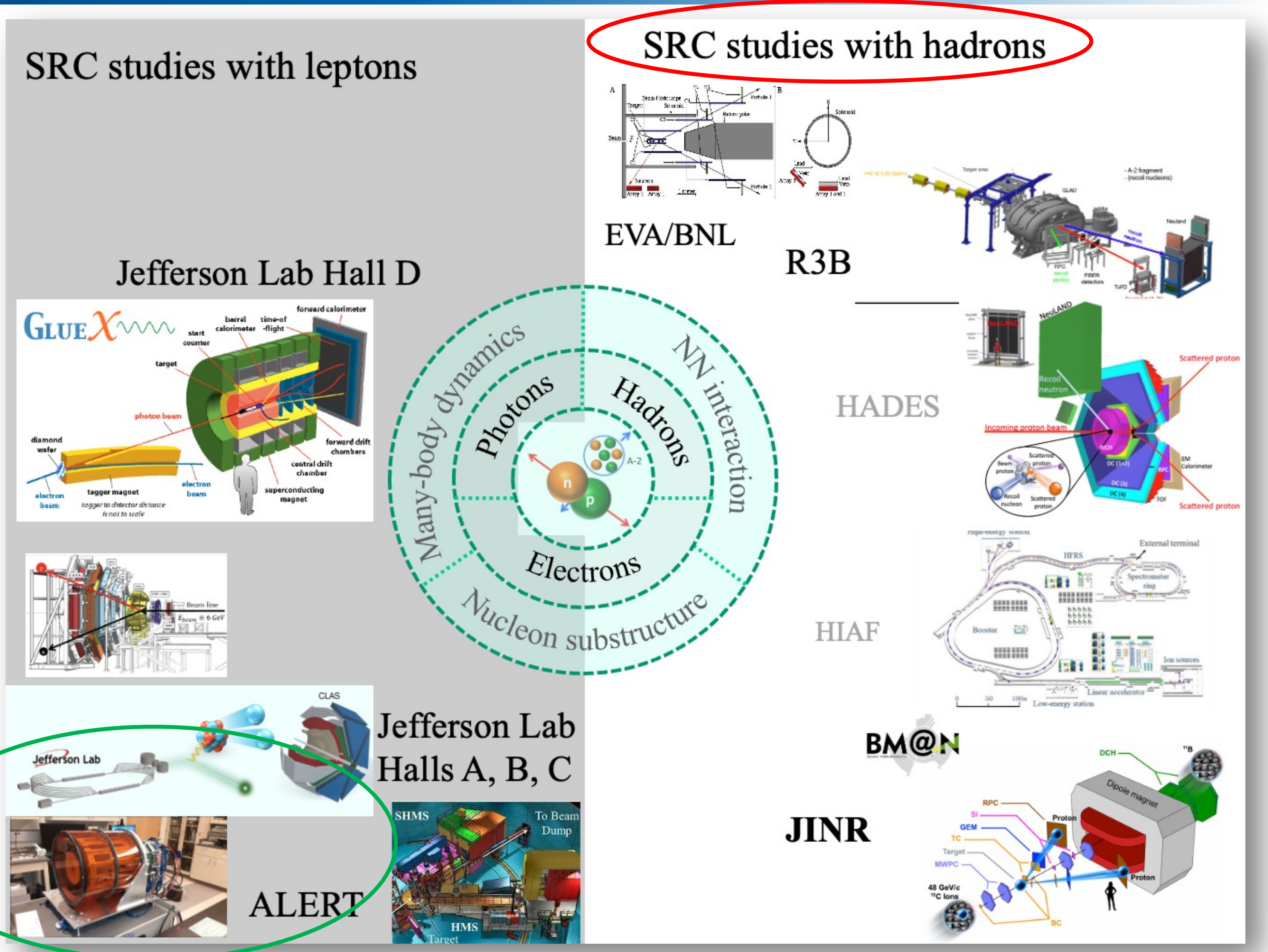


- ○ CLAS result has big background
  Higinbotham & Hen, PRL 114,169201 2015)
- ○ Q^2 too low to see 3N-SRC?
- ○ Much bigger FSI?

"Muti-messenger" era

- ❑ Upcoming Jlab RC Experiments:
  - ✓ ALERT- SRC： measure C.M motion of pairs (Mean-Field vs SRC)
  - ✓ Real photon scattering (check universality)
- ❑ Future EIC with much higher energy: SRC in J/Psi, tagged DIS



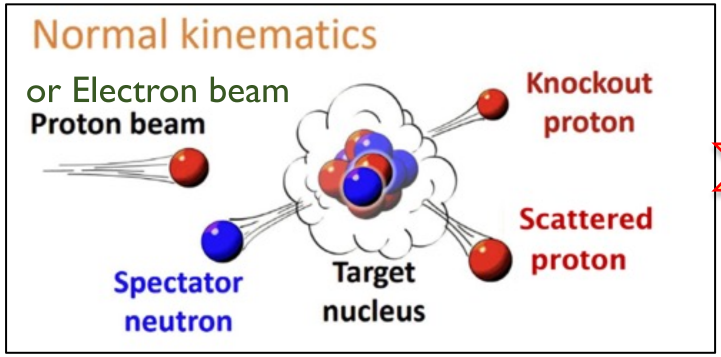


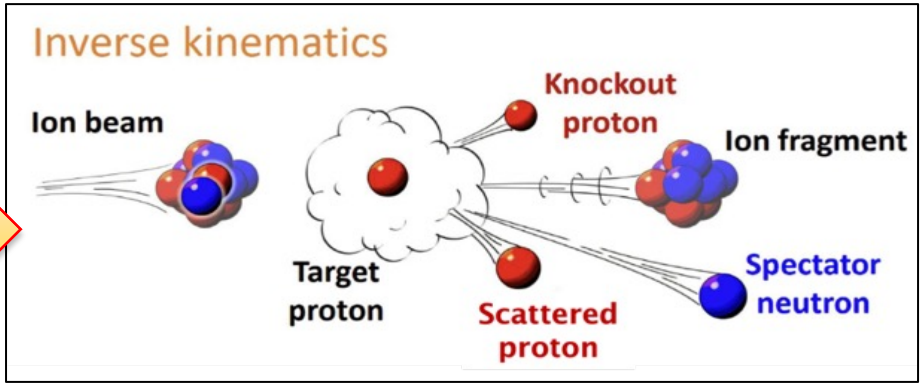
❑ Precision Frontier of SRC: pA reaction!

Inverse-pA Experiments

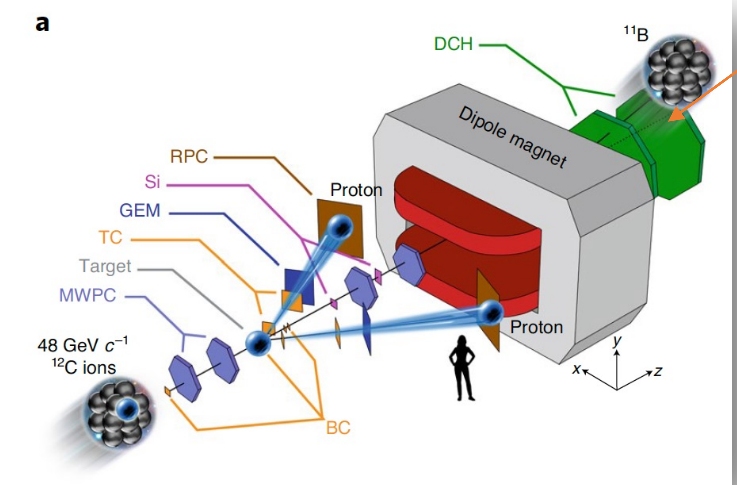
➢Dubna BM@N SRC Experiments

- ❑ Bigger cross-sections in pA collision vs eA
- ❑ Inverse pA: Easier detection and better controlled FSI
- ❑ Pioneer experiment at BM@N





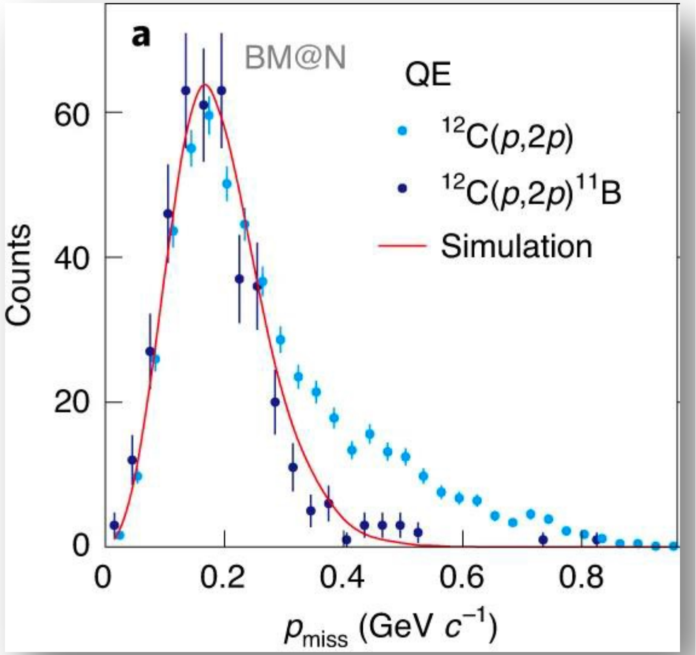
23 np pairs , 2 pp pairs



- Test run in 2018, results publised

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

- Full run in 2022; data-analysis ongoing (JINR, MIT, Tel Aviv, Tsinghua)

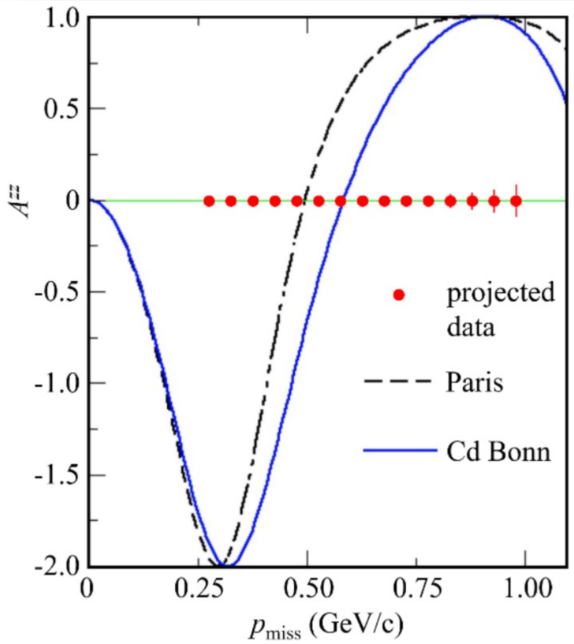


Inverse-pA Experiments

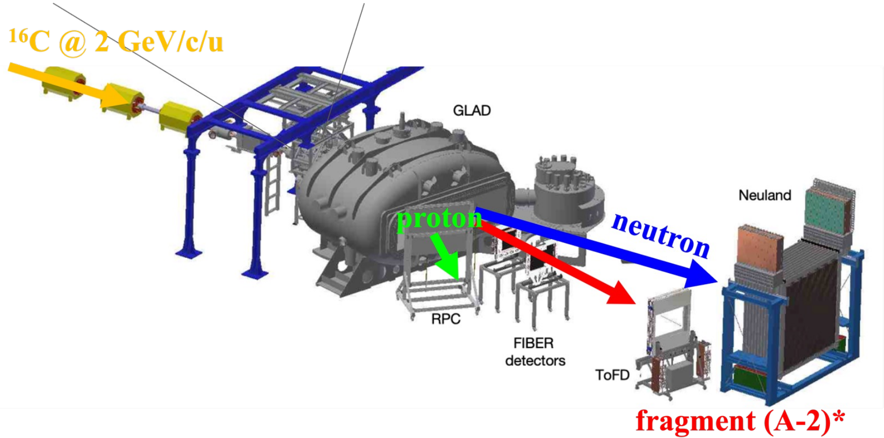
➢Other ongoing/future Experiments

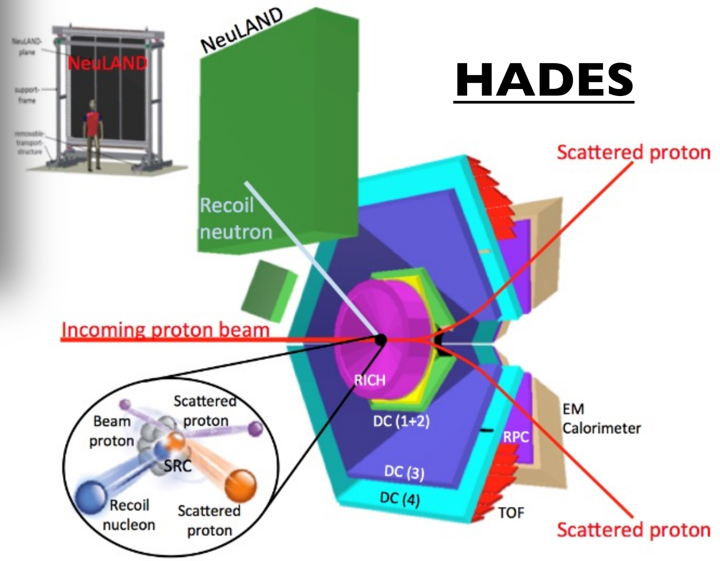
- ❑ 3rd Gen experiment in HyperNIS@Dubna: non-nucleonic d.o.f in Deutron (Tel Aviv, FIU, MIT, ODU, PSU, BNU, Tsinghua)

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



- ❑ 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)

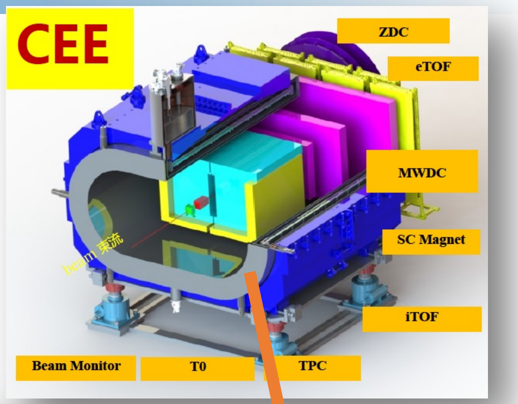
- ❑ Tensor-Force Projects （RIKEN, CSR@IMP, GSI ...）

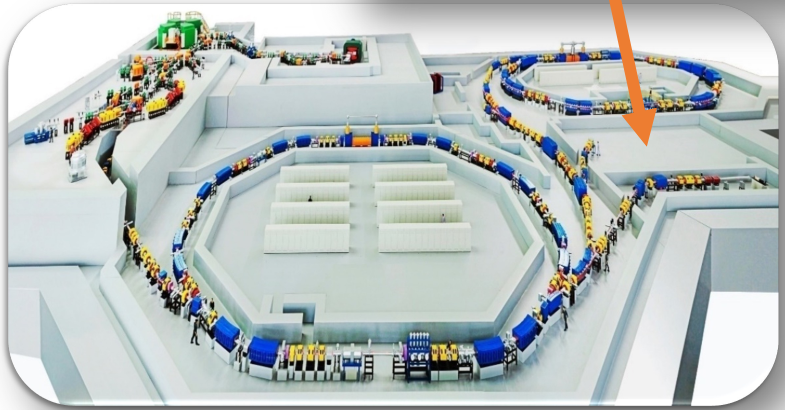
Inverse-pA Experiments

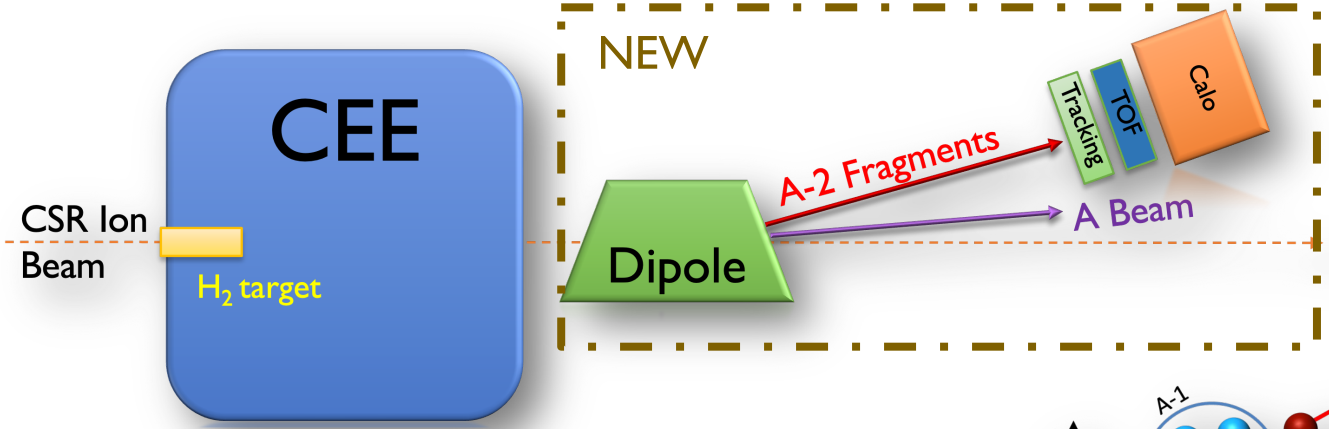
➢ CEE@HIRFL-CSR

- ❑ Using current CEE design for measuring protons
- ❑ A-2 fragments are measured by a new magnet + ZDC

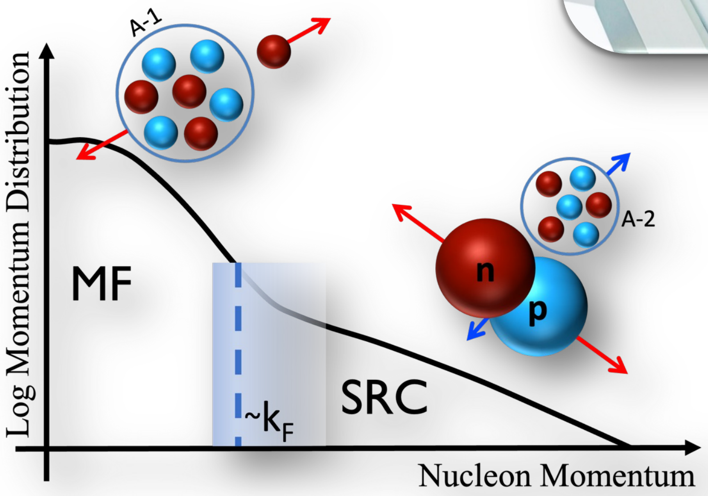
HIRFL-CSR beam
- P： 2.8 GeV
- $^{12}C^{+}$： 1 GeV/u
- $^{238}U^{+}$： 0.5 GeV/u







- ❑ Goals:
  - ✓ Define MF & SRC transition regions
  - ✓ Check FSI corrections
- ❑ Simulation ongoing

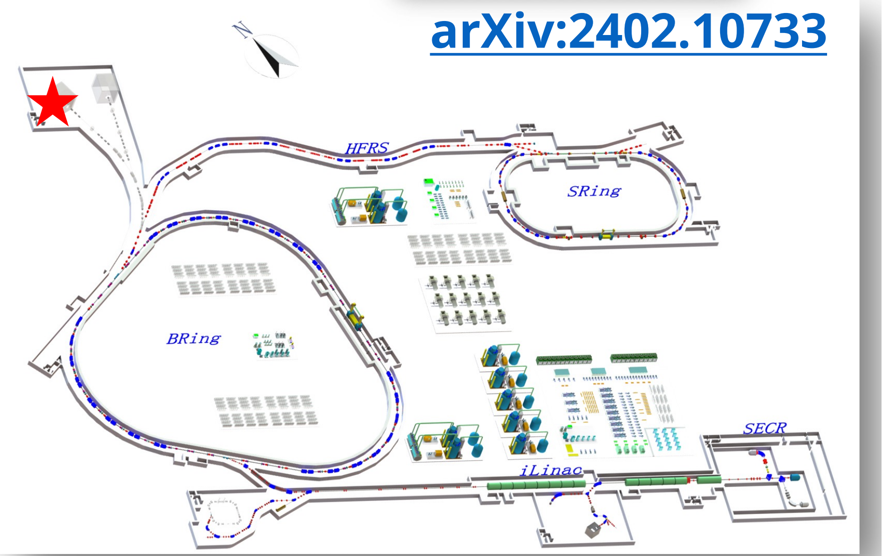


arXiv:2402.10733

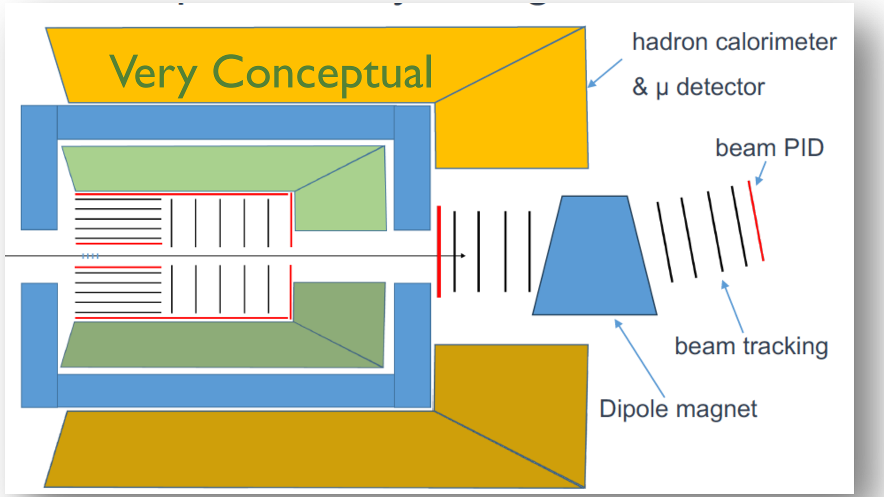
Inverse-pA Experiments

- HIAF-High-Energy Station
  - HIAF construction to be completed in 2025：
    - C12, E=51 GeV/c (4.25GeV/c/u) → similar to NICA
    - $1.8x10^{12}$pps (fast extr.), $4.5x10^{11}$pps (slow extr.) vs. $3.5x10^{4}$ pps at JINR
    - Liquid hydrogen target (under development by Hongna Liu from BNU (0.073g/cm3 x 15cm)
    - Total Luminosity = $3x10^{35}$ cm^{-2} s^{-1} (slow ext)

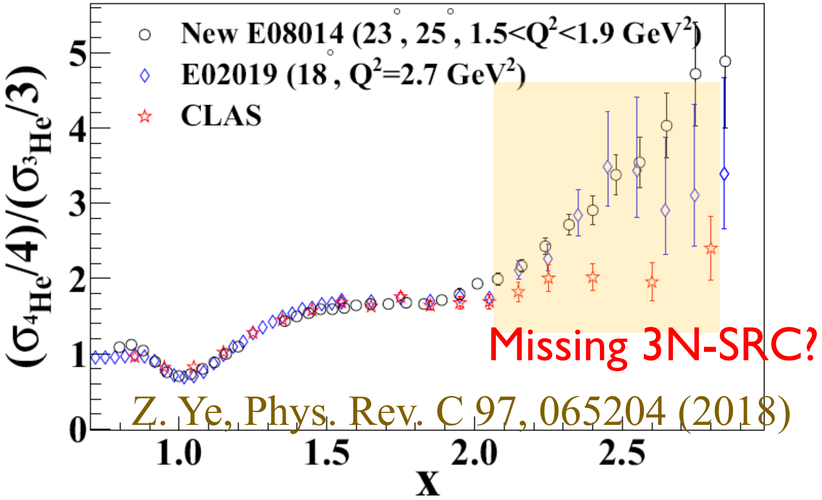
arXiv:2402.10733



- **New concept:** a general-purpose full acceptance detector: Heavy-Ion, Hypernuclei, **SRC**, …



- Most idea place for searching 3N-SRC signals
- Precision frontier for SRC for the first time
- Key challenges: Target + DAQ

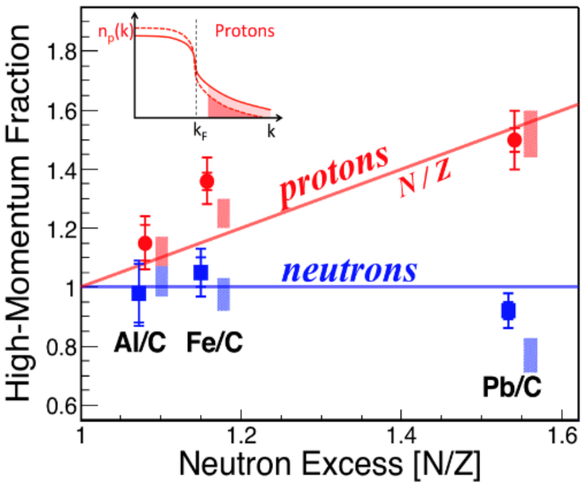


Inverse-pA Experiments

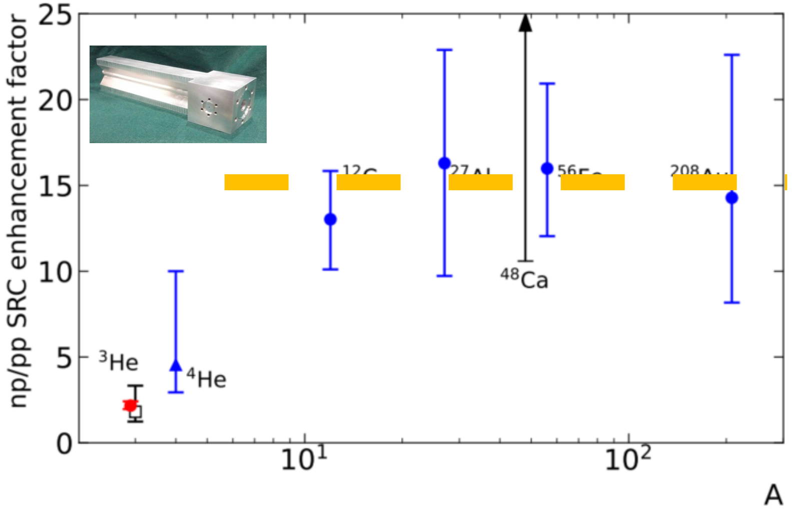
➢ HIAF-HFRS:

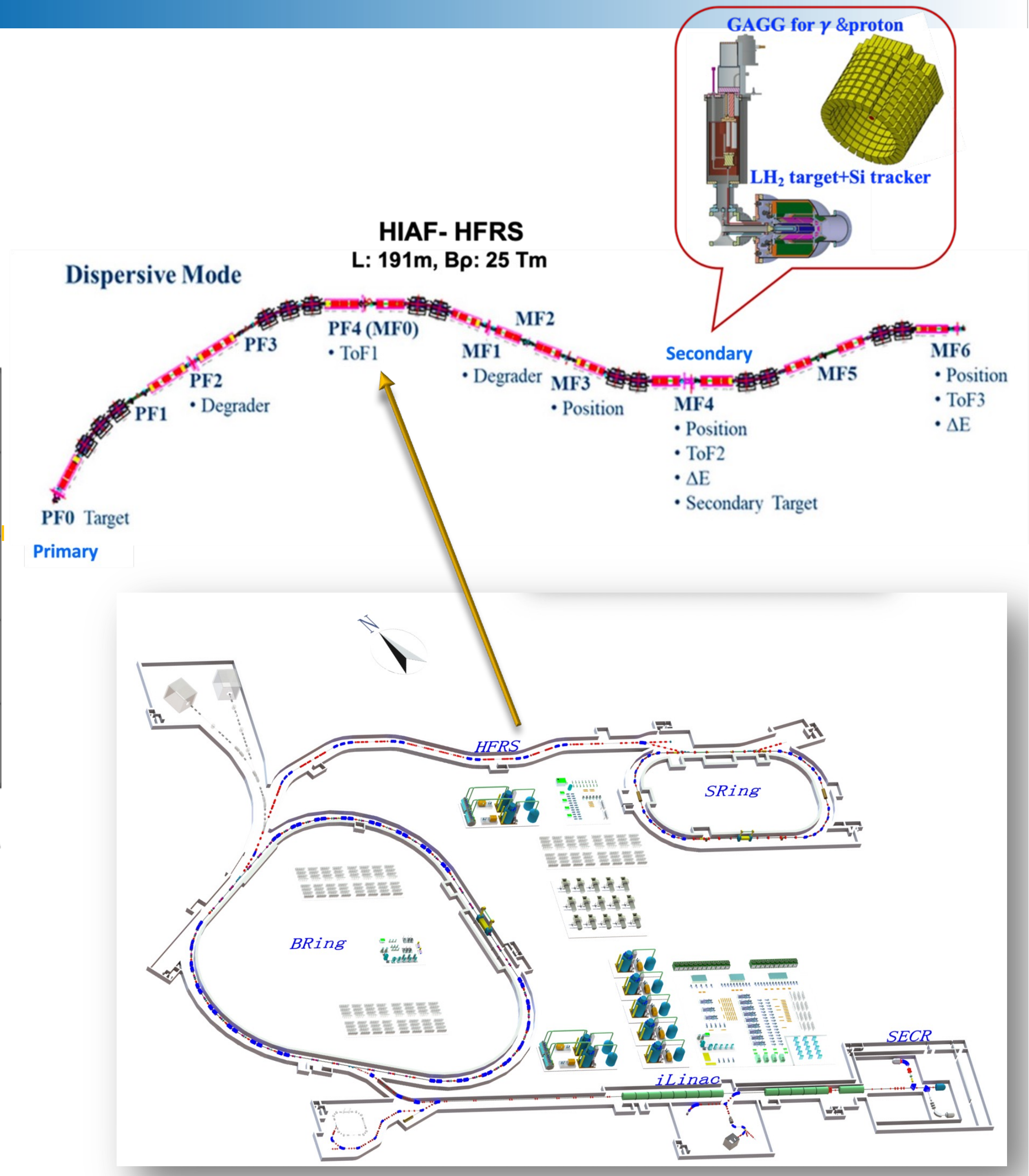
- ❑ Study 2N-SRC w/ radioactive isotopes from HFRS
  - ✓ Wide range of asymmetric nuclei vs fixed target exp.

Nature, 560 (2018) 617-621.



S Nature, 2022, 609: 41





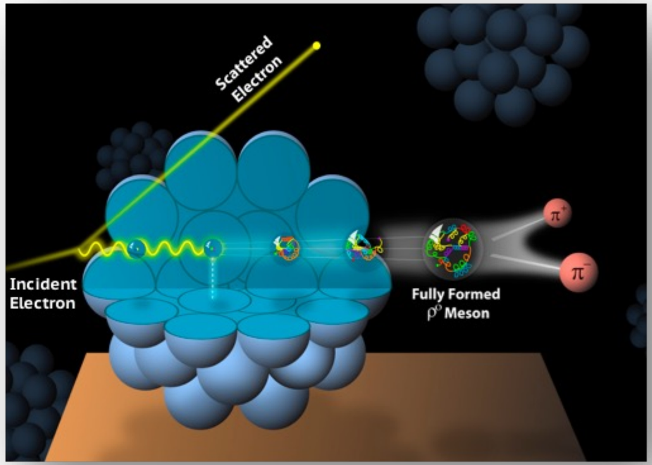
arXiv:2402.10733

- ❑ NSFC-ISF Joint Fund approved（2024～2026）
  - ▪ Tel Aviv, MIT, BNU, Tsinghua
  - ▪ Analyze NICA & GSI data
  - ▪ Simulation of SRC study at CEE@HIRFL and HIAF

First SRC Workshop in China

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

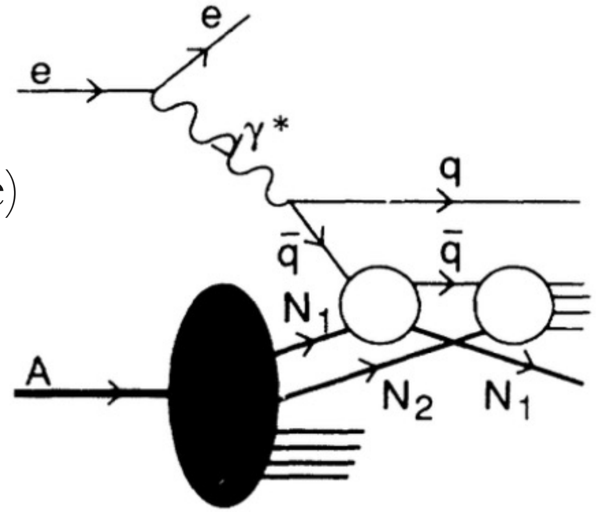
➢ Quarks in bound protons are modified!

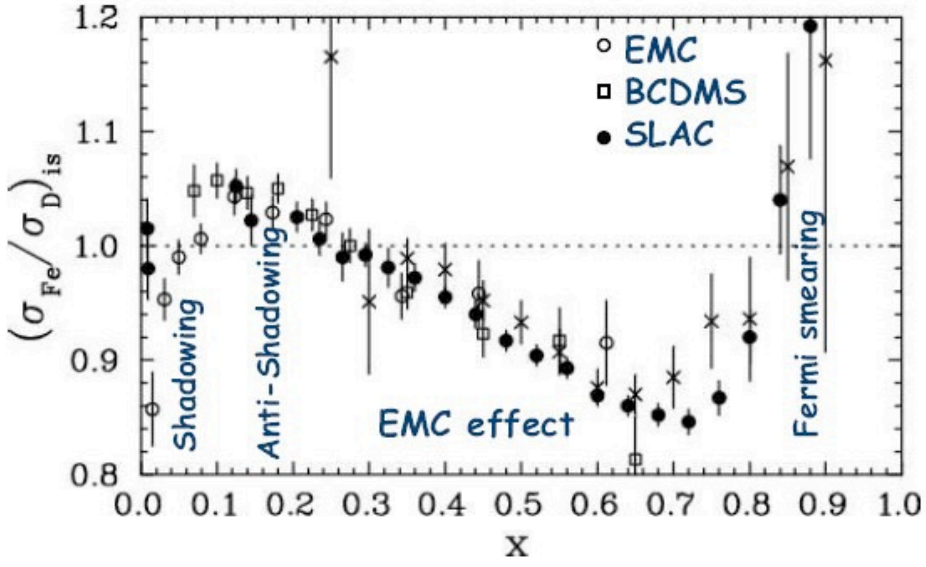


❖ **Fermi Motion:**
- ✓ Bound nucleons are moving
- ✓ Hard to calculate, even in A=2,3

Alekhin, Kulagin, Petti, PRD 96, 054005 (2017)
C. Cocuzza, et. al., PRL 127, 242001
Segarra et. al. PRL 124, 092002 (2020)

❖ **Shadowing:**
- ✓ Final state particles after DIS rescattered with residuals (diffractive)
- ✓ Many models works





❖ **Anti-Shadowing?**

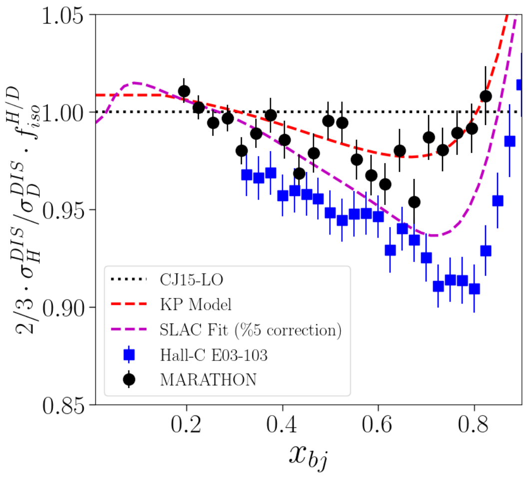
❖ **EMC? ?**

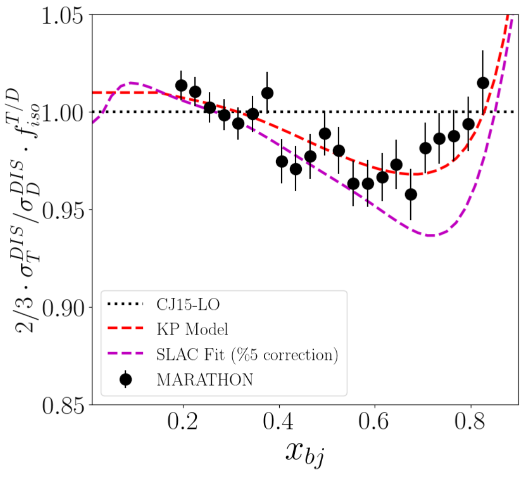
Geesaman, Saito, Thomas, Ann. Rev. Nucl. Part. Sci.45, 337 (1995)
Norton, Rept.Prog.Phys. 66 (2003) 1253-1297

Quarks in Nuclei

➢ EMC Effect:

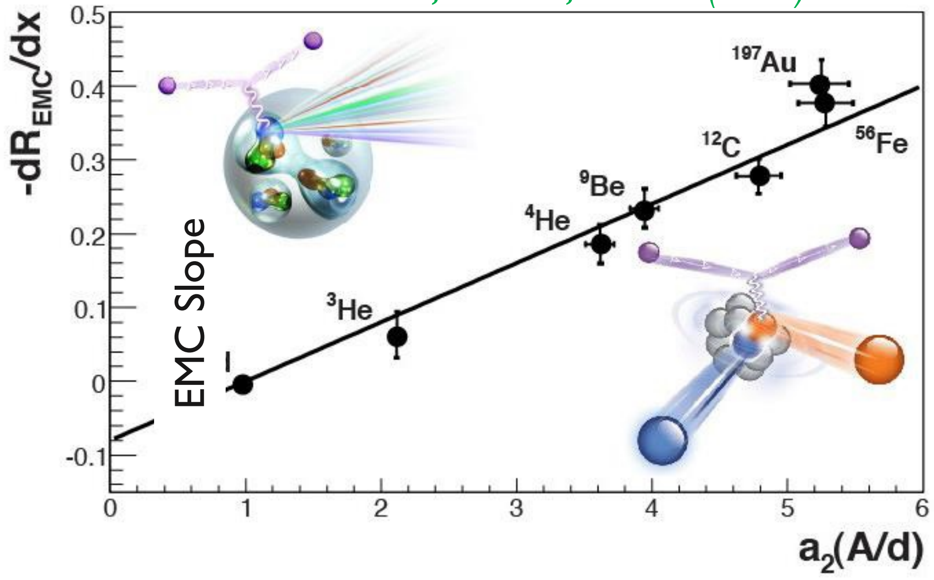
- ❑ EMC: Inclusive DIS cross-section ratio of A to D drops linearly in 0.3<x<0.7
  Phys.Lett.B 123 (1983) 275-278
- ❑ Even modified in A=3 (likely D2 as well)



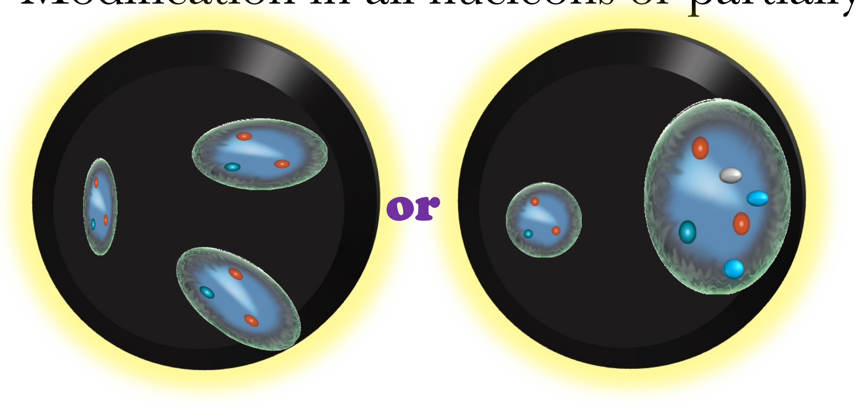


- ❑ 40 years after discovery, still unknown!
- ❑ Every Model is Cool!
  - ✓ Rescaling of quark & gluon sizes
  - ✓ Mean-Field (MIT bag, NJL …)
  - ✓ Multi-quark clusters (6-quark bag)

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

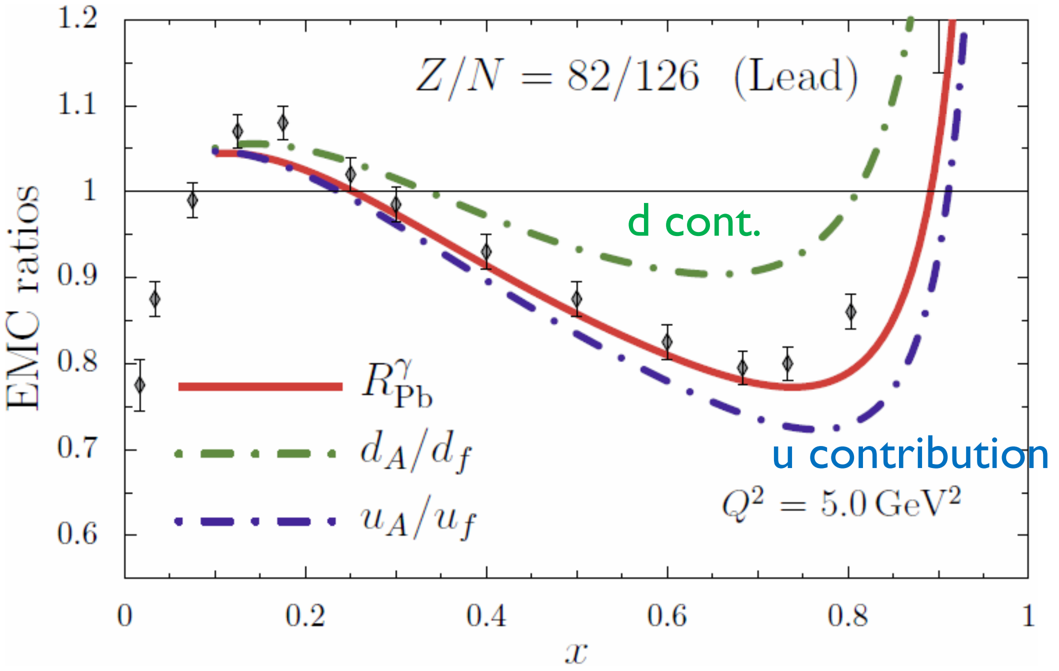


- ❑ Connection with SRC?
  - ▪ Modification in all nucleons or partially?

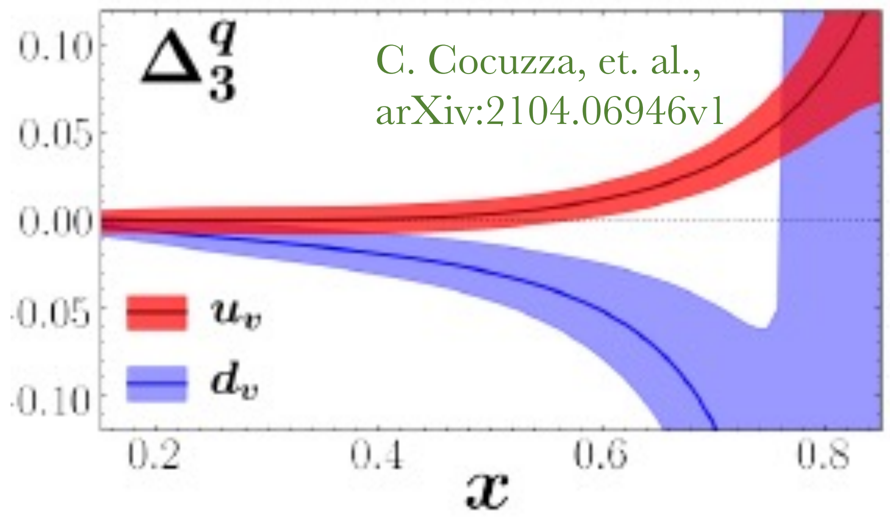


Quarks in Nuclei

- EMC Effect:
  - Several models predict flavor-dependence
    - ✓ If N>Z, u-quark is more "bound"
    - ✓ If N<Z, d-quark is more "bound"



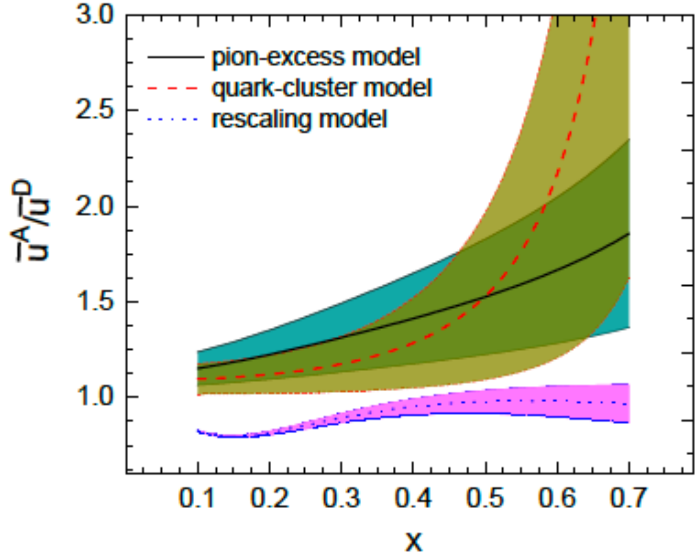
I. Cloet, et al,
PRL 109, 182301 (2012)
PRL 102, 252301 (2009)



- Jlab JAM model predicts u & d-quarks in H3 & He3 are modified very differently

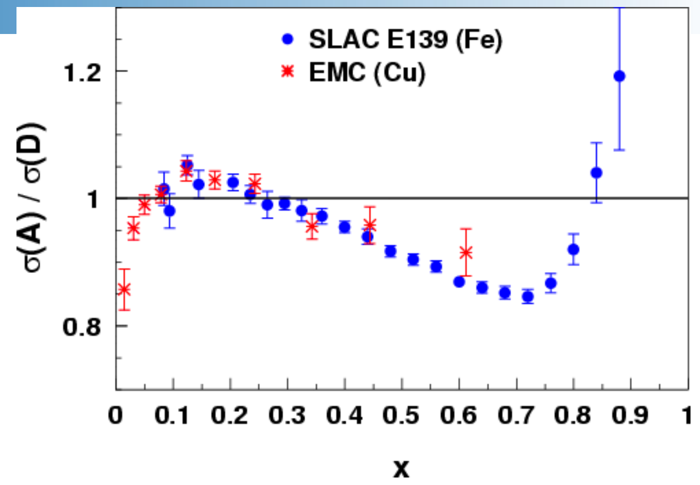
- EMC effect in sea quark?

C. Gong, B.Q. Ma,
Phys.Rev.C 97 (2018) 6, 065207



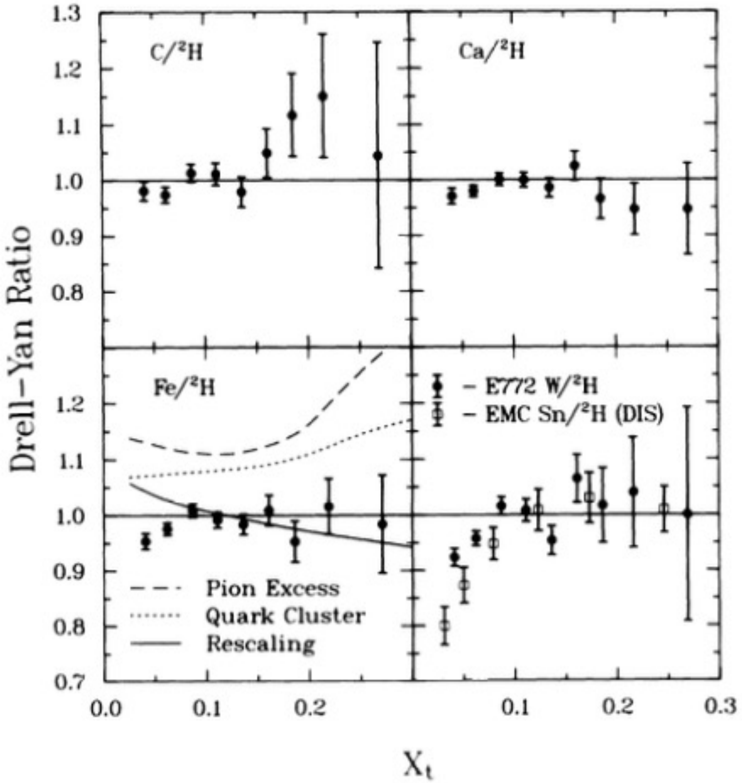
Quarks in Nuclei

- Anti-Shadowing
  - ❑ Origin still unknown
    - EMC + shadowing doesn't make up by anti-shadowing
  - ❑ Many models but can't explain both shadowing & anti-shadowing
    - Deffractive process (multiple-scattering)?
    - Rescaling (enlarged confiment sizes)?
    - 6-quark bag?
    - …
  - ❑ Contamin more interesting phyiscs?
    - Link to how strong-force leaks into nuclear force?



❑ No anti-shadowing seen in sea quark?

Drell-Yan, E772, PRL. 64 (1990) 2479-2482

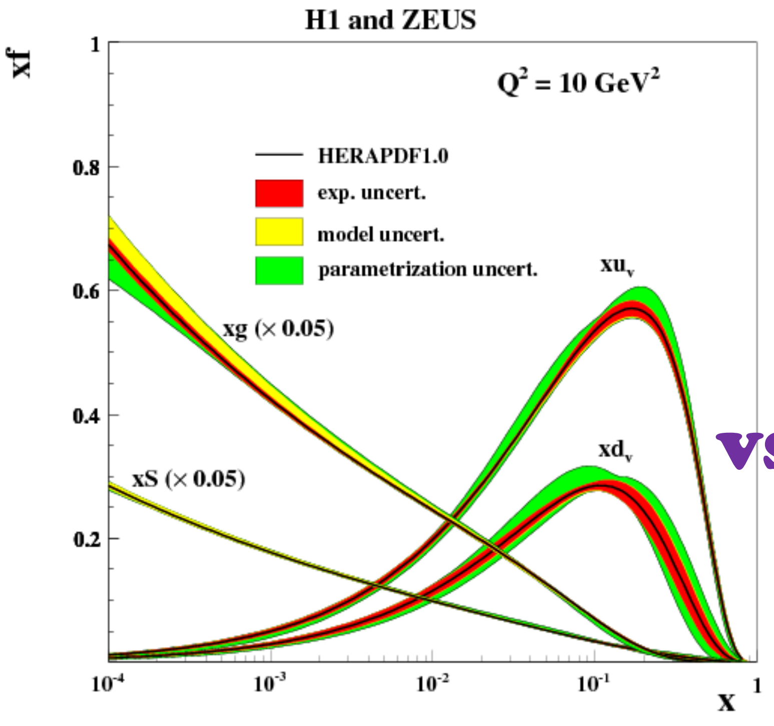


❑ Maybe only gluons carry anti-shadowing?

Frankfurt, Guzey, Strikeman PRC 95 055208 (2017),
Guzey, et.al, PRC86,045201 (2012)

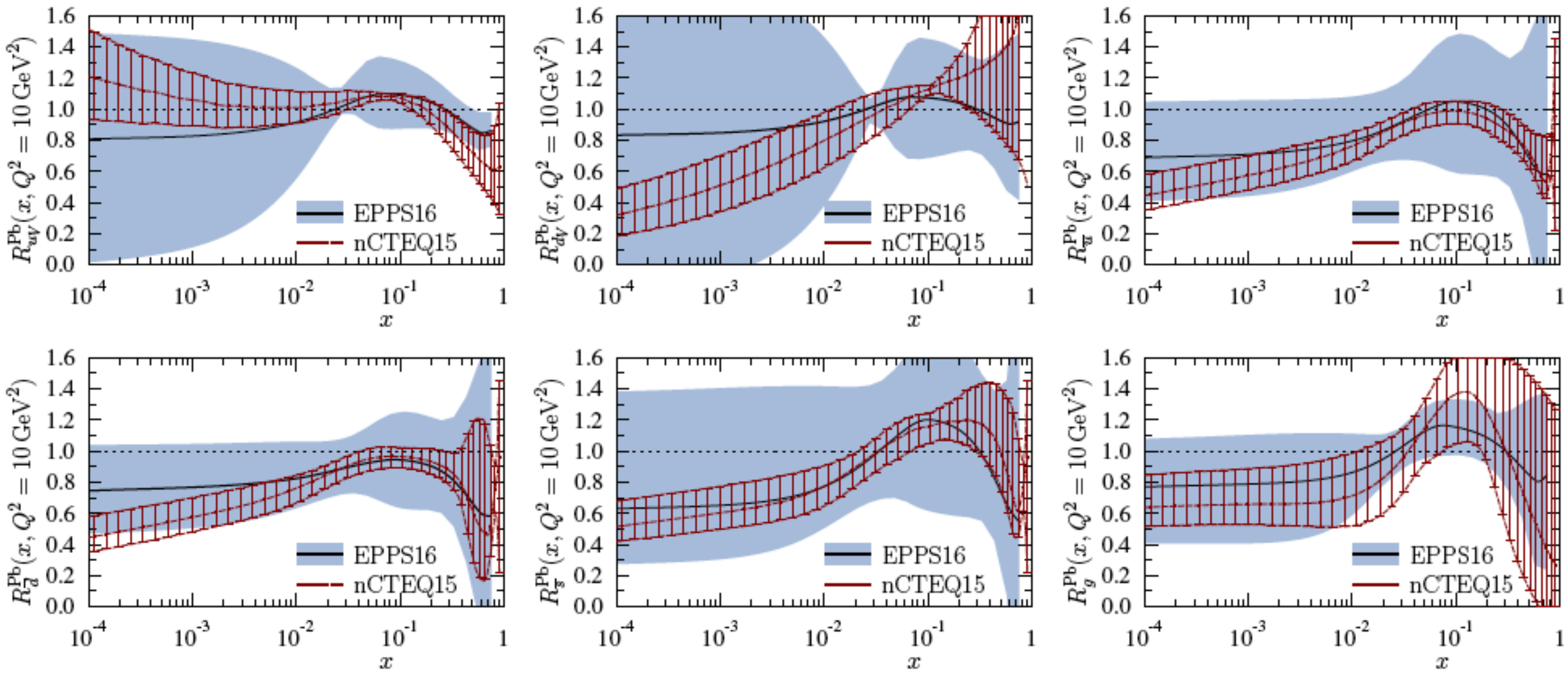
Measuring Medium Effect

- Parton-Distribution Functions in Nuclei (nPDF)
  - Limited eA or pA data; limited measured nuclei (Z~N) unprecise;
  - nPDFs extractions rely on many assumptions, e.g. flavor-independence, isospin-symmetry



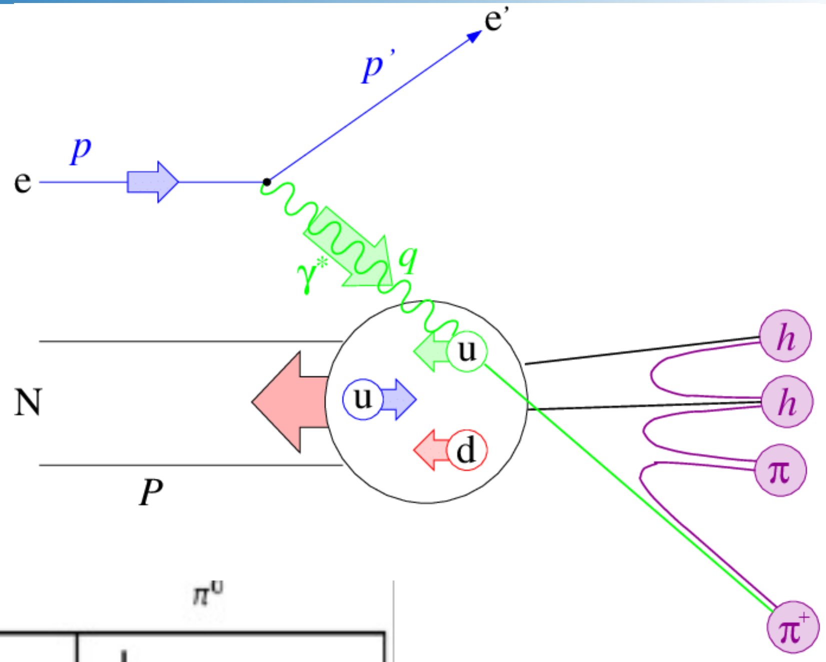
Free nucleon PDF

vs



EPPS16 Nuclear PDF   Eur. Phys. J. C (2017) 77:163

- Semi-Inclusive DIS (SIDIS) in eA :



- SIDIS: Detect both scattered electrons and hadrons

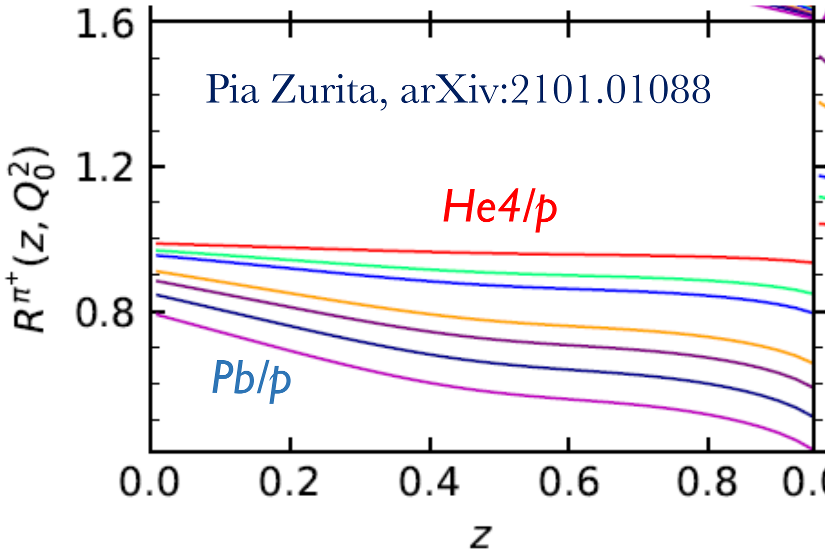
$$\frac{d\sigma^h}{dxdydz} = \frac{4\pi\alpha^2 s}{Q^4}\left(1 - y + \frac{y^2}{2}\right)\sum_q e_q^2 [f_1^q(x)] \cdot [D_q^h(z)]$$

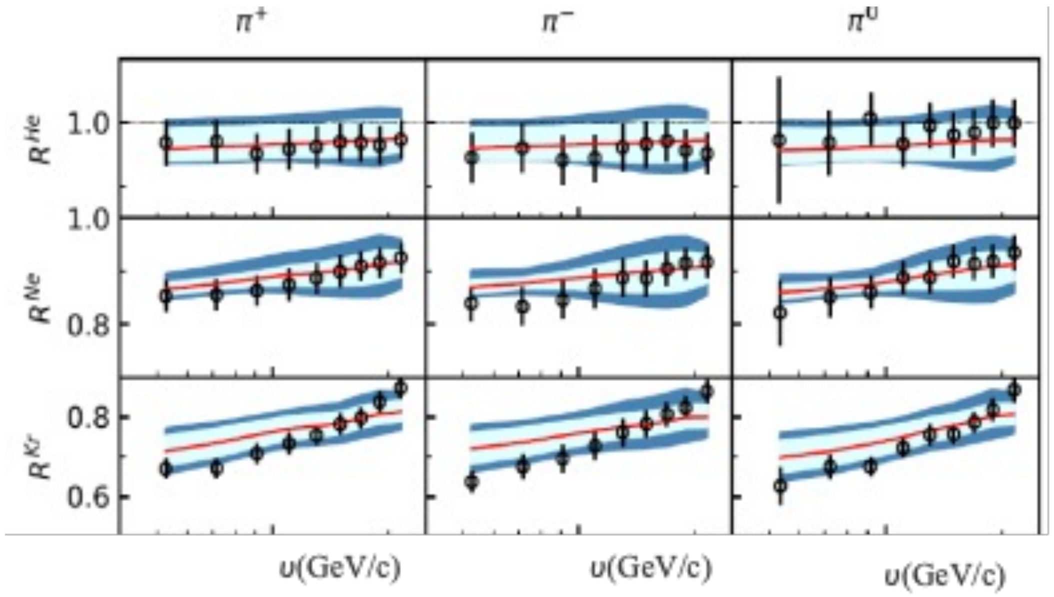
Nuclear PDF (nPDF)

Nuclear Fragmentation Function (nFF)

- nFFs are also modified

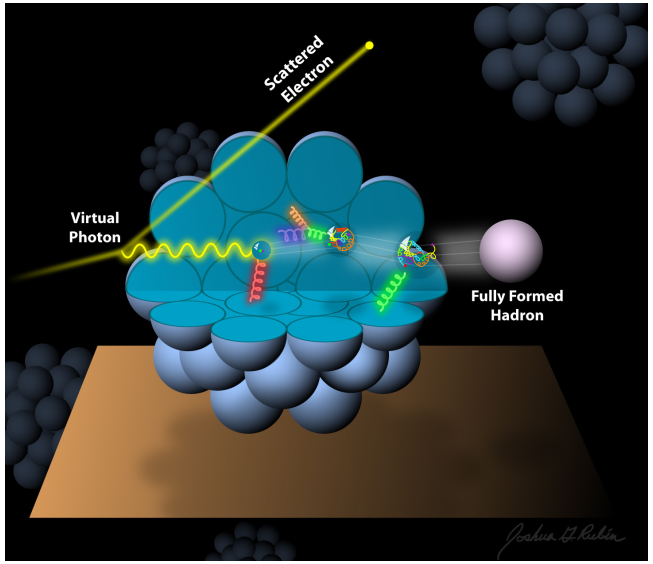
nFF Ratios



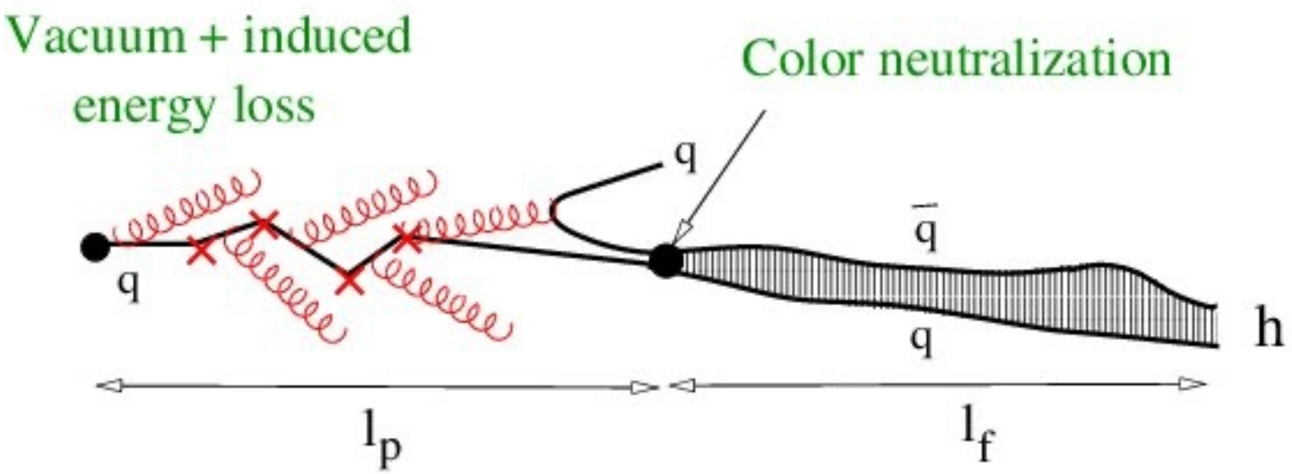


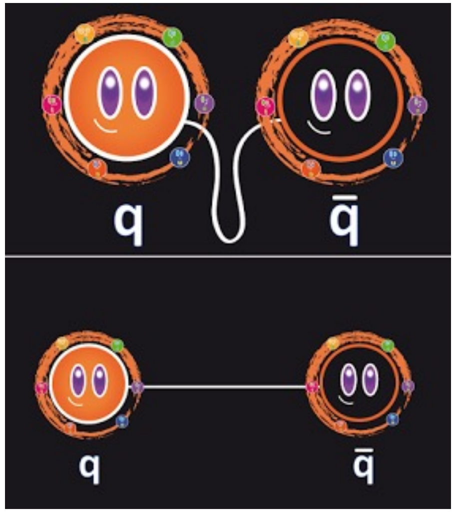
Measuring Medium Effect

➢ Hadronization



- ❑ Struct quark has to hadronized
- ❑ Nuclei as a QCD Lab:
  - with different sizes of nuclei, structs quark hadronized in medium or vacuum
- ❑ Hadronization of a quark in space (vacuum & medium) and time

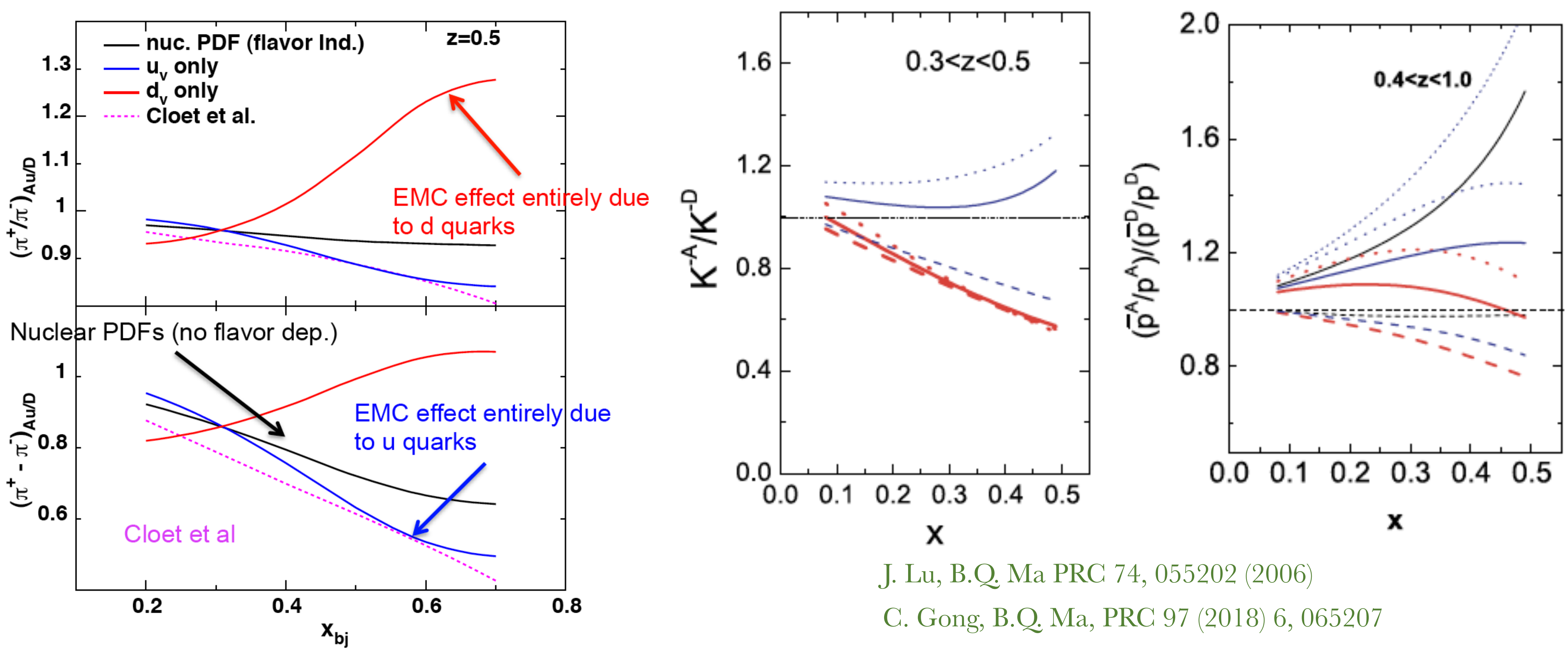




- ❑ Color Confinement
- ❑ CLAS12 SIDIS experiments w/ heavy nuclei recently completed

Measuring Medium Effect

- Flavor-Dependence EMC effects:
  - Models predict different quarks are modified differently
  - SIDIS super-ratio observables are sensitive to flavor-dependent



J. Lu, B.Q. Ma PRC 74, 055202 (2006)

C. Gong, B.Q. Ma, PRC 97 (2018) 6, 065207

Measuring Medium Effect

➢SIDIS w/ Light Nuclei:Experiment

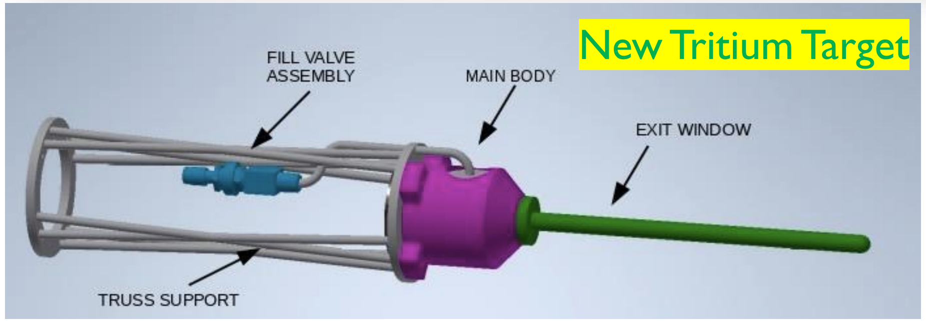
SIDIS Measurement of A=3 Nuclei with CLAS12 in Hall-B

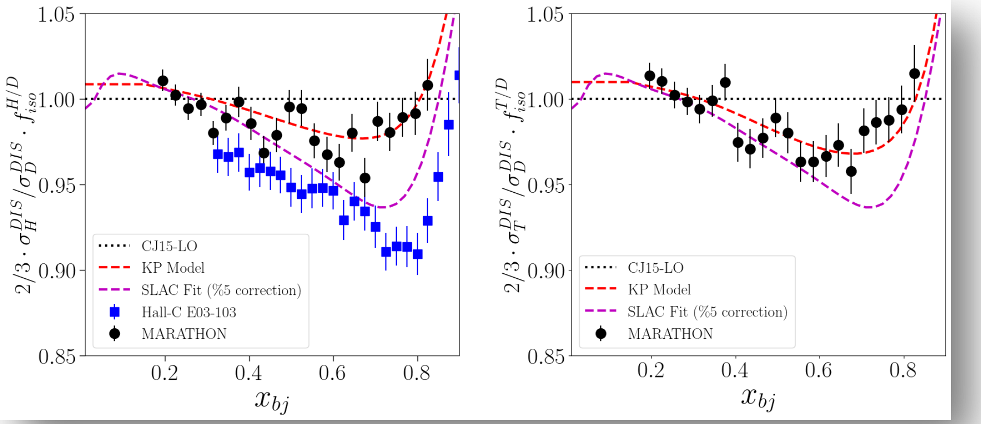
Conditionally approved in PAC49

On behalf of the spokespeople:

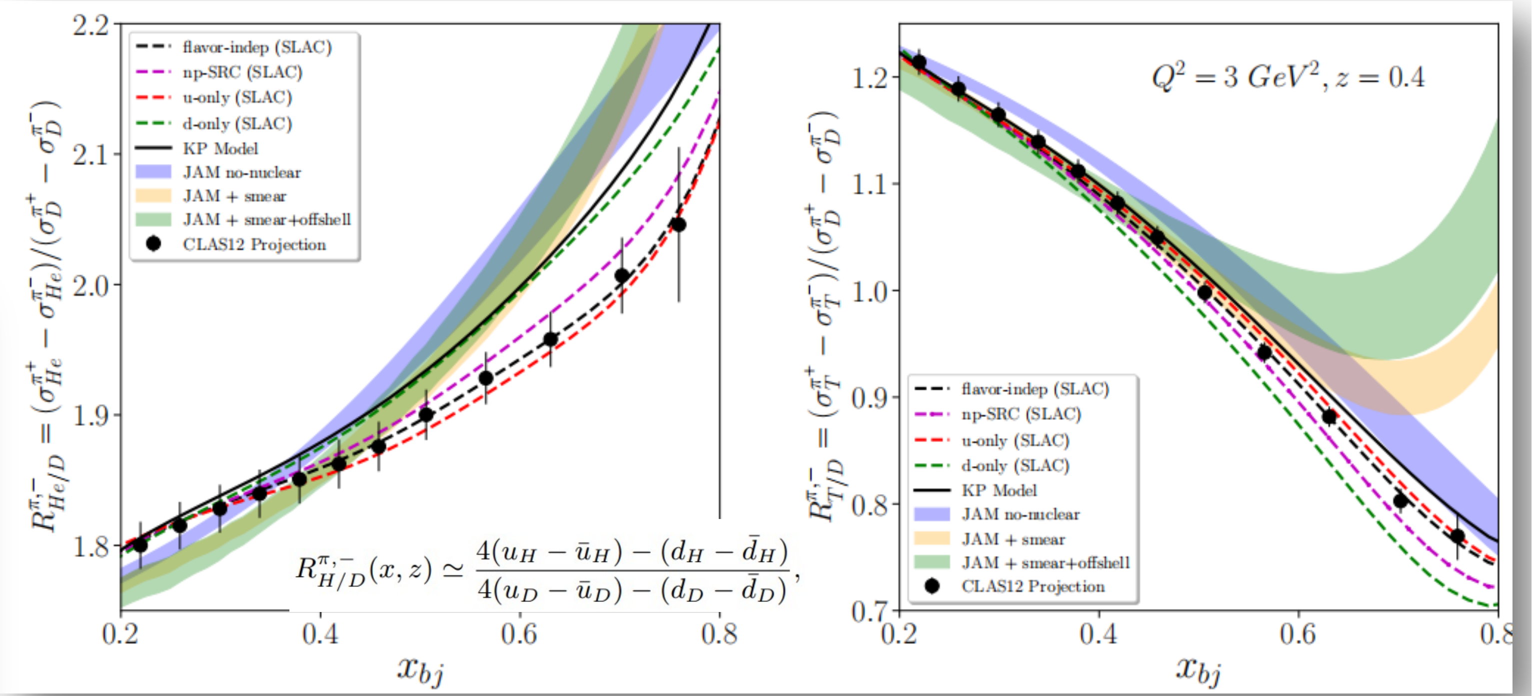
D. Dutta, D. Gaskell, O. Hen, D. Meekins, D. Nguyen, L. Weinstein*, J. R. West, Z. Ye,

and the CLAS Collaboration





- ❑ C12-21-004 Experiment : SIDIS w/10.6 GeV unpolarized beam
  - ✓ New Tritium target system (same as 2nd Tritium-SRC)
  - ✓ Detecting pions and kaons to decouple u, d, s
  - ✓ nFFs likely same in D2, He3 and Tritium



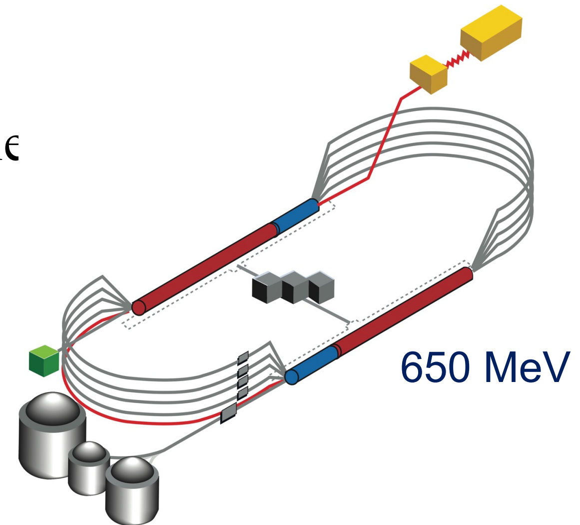
Measuring Medium Effect

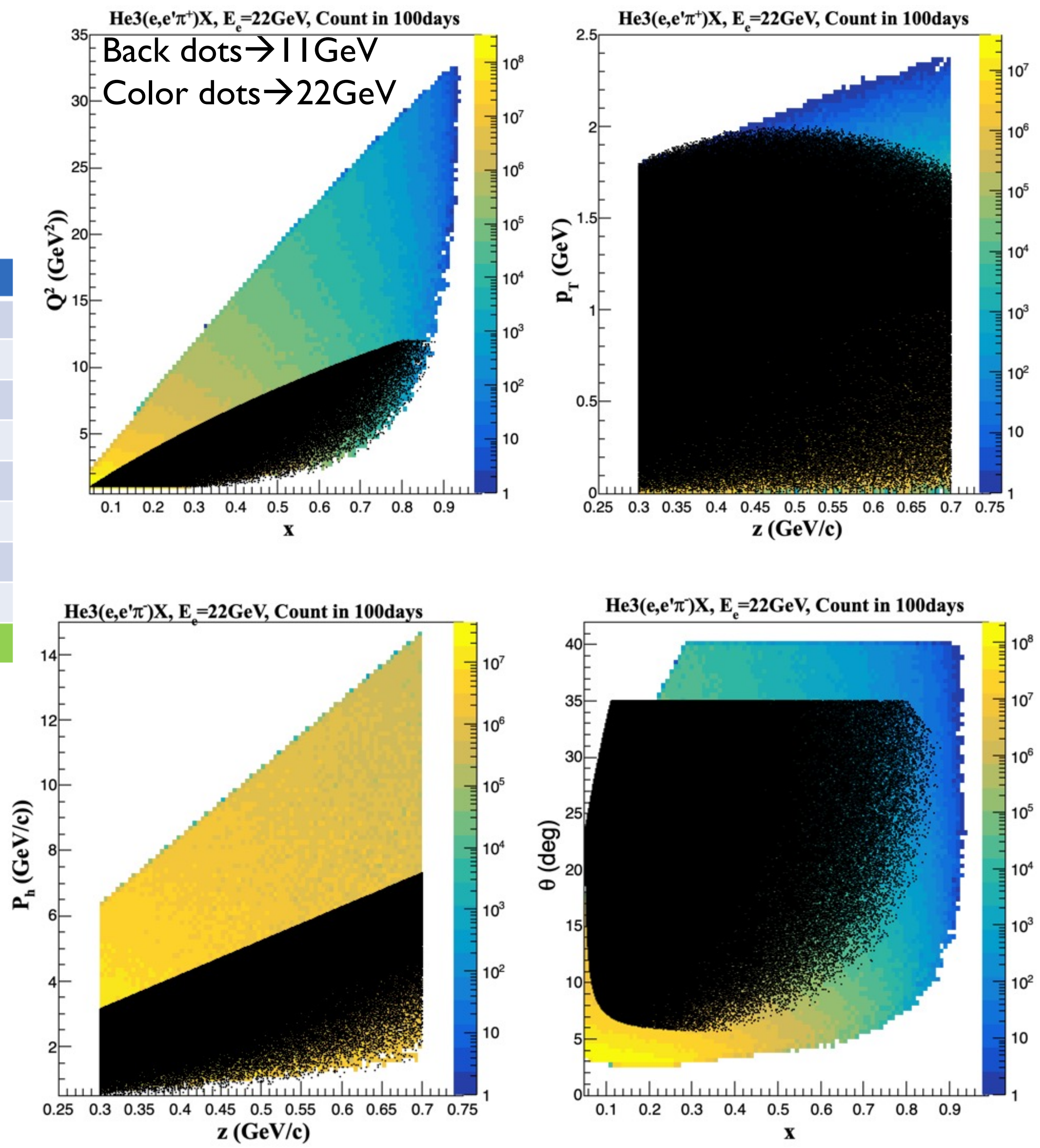
➢ From Valance to Sea

- ❑ Jlab seeks for energy upgarde from 11GeV to 22GeV
- ❑ 2023 Long-Range Plan https://indico.jlab.org/event/677/

	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41
Moller (funded)																		
SoLID (science rev)																		
Positron Source Dev																		
Pre-Project Dev																		
Upgrade Phase 1																		
Transport comm/e+																		
Upgrade Phase 2																		
CEBAF Up																		

- ❑ Use more powerful cavitie
- ❑ Add a whole new pass

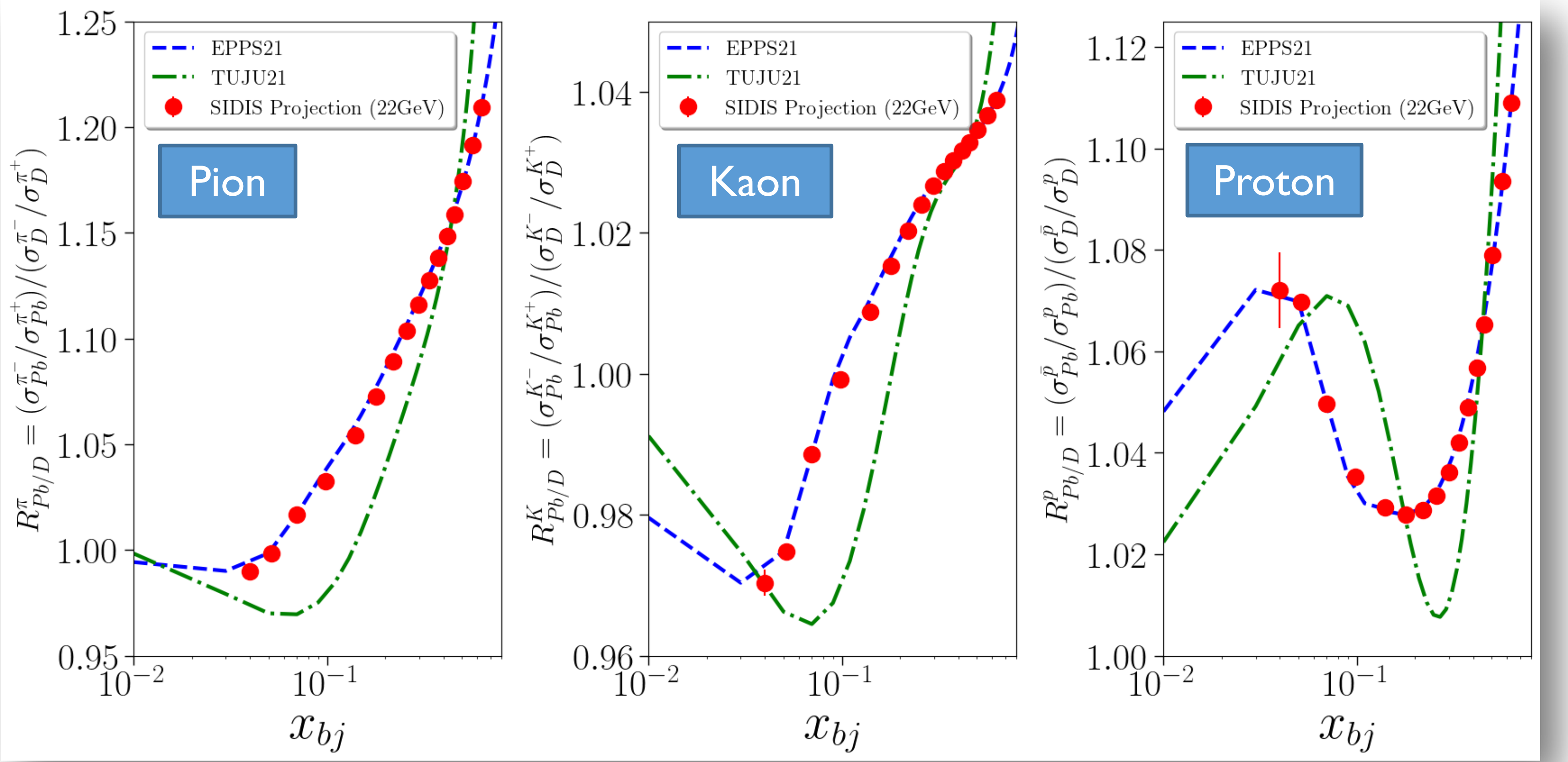




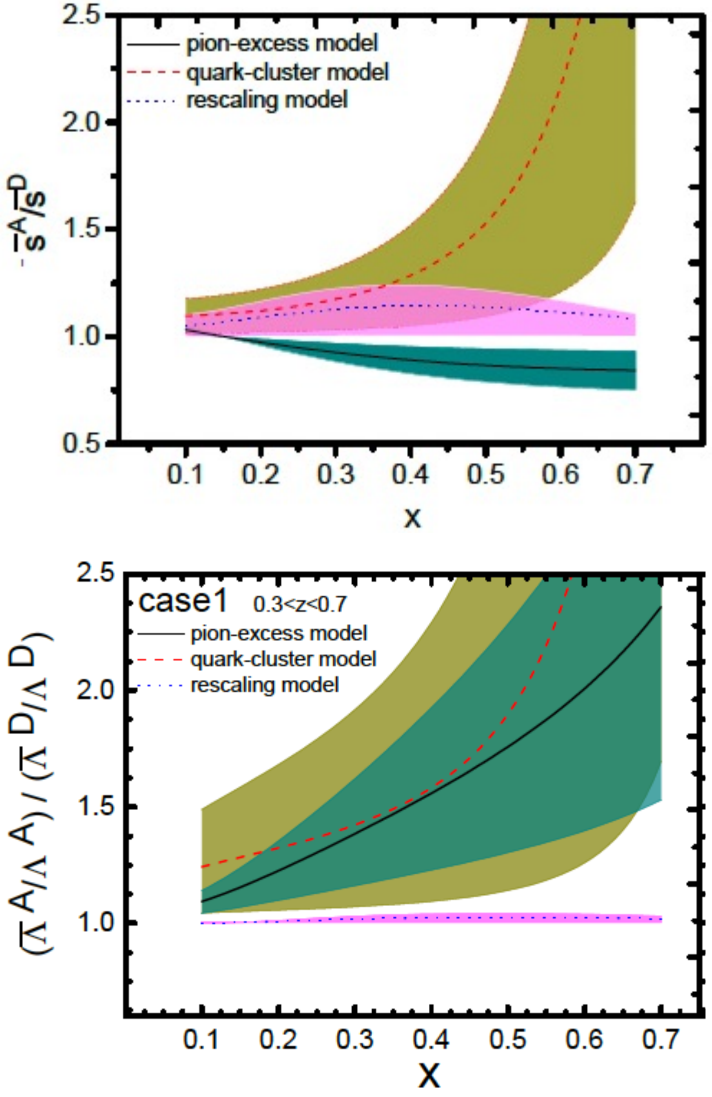
Measuring Medium Effect

➢eA SIDIS w/ mutiple Hadron-Production

- ❑ Focus on study anti-shadowing effect of sea quarks in heavy nuclei



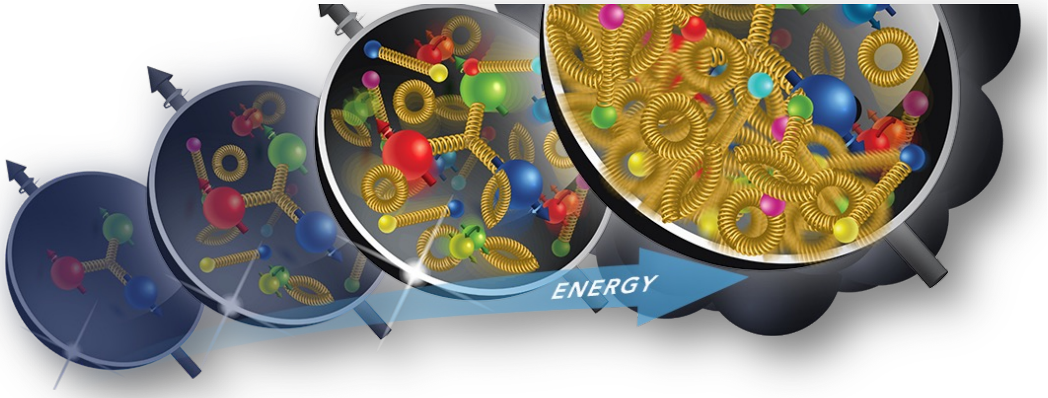
C. Gong, B.Q. Ma,
PRC 97 (2018) 6, 065207

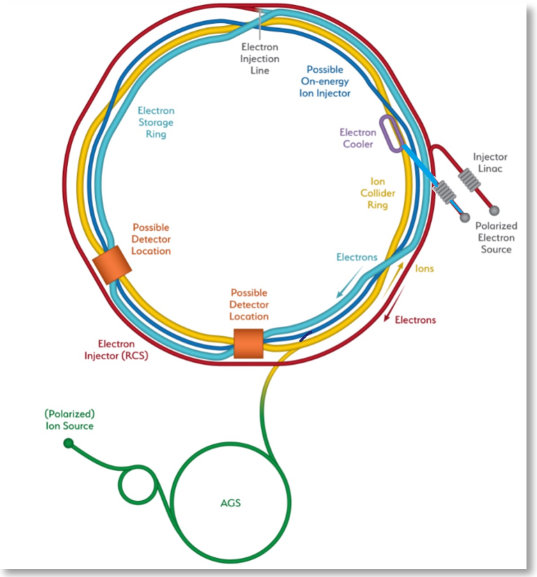


- ❑ Measurement of strange-quark's unseen EMC & Antishadowing

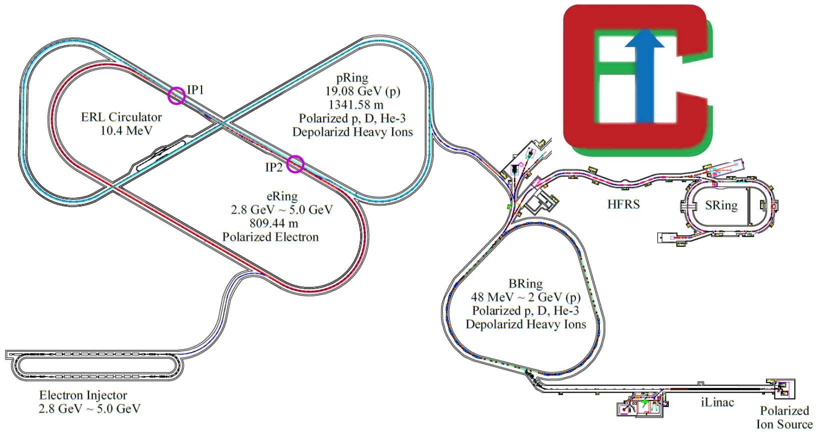
Measuring Medium Effect

- Electron-Ion Collider (EIC)
  - New facilities: US-EIC (eRIHC) & China-EIC (EicC)
  - SIDIS w/ $\pi, K, J/\psi$... to fully decouple all quark's flavors
  - Sea-quarks and gluons' anti-shadowing and shadowing effect

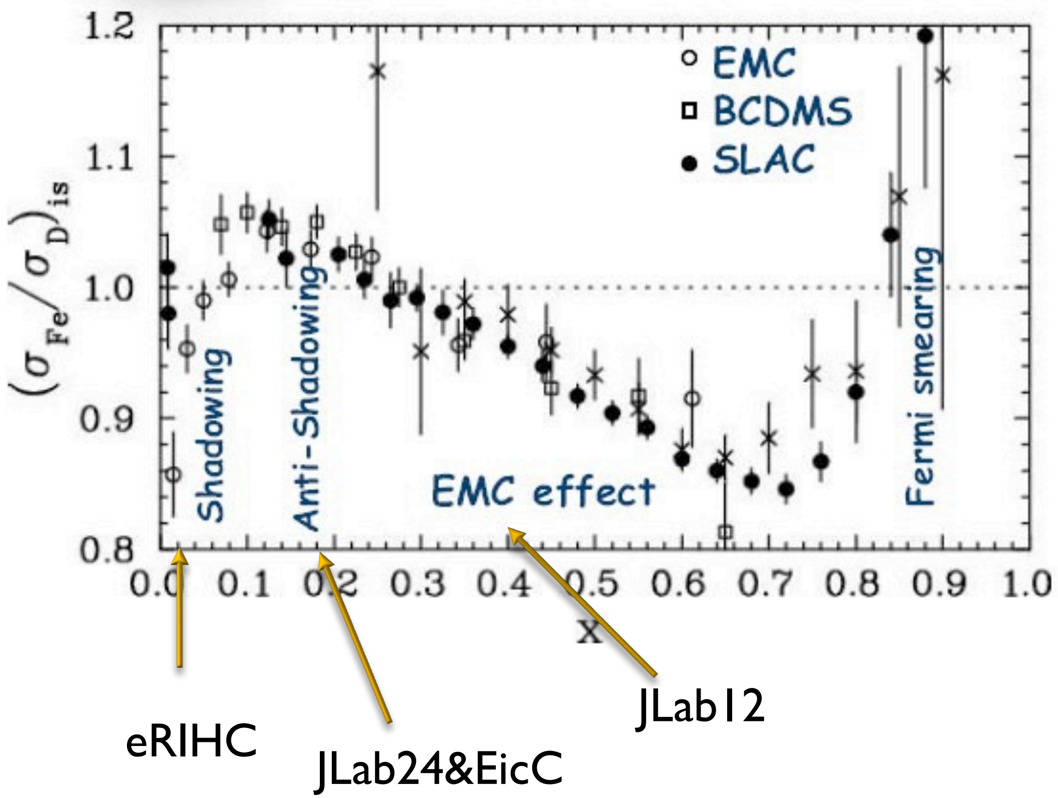




eRIHC@BNL



EicC@HIAF



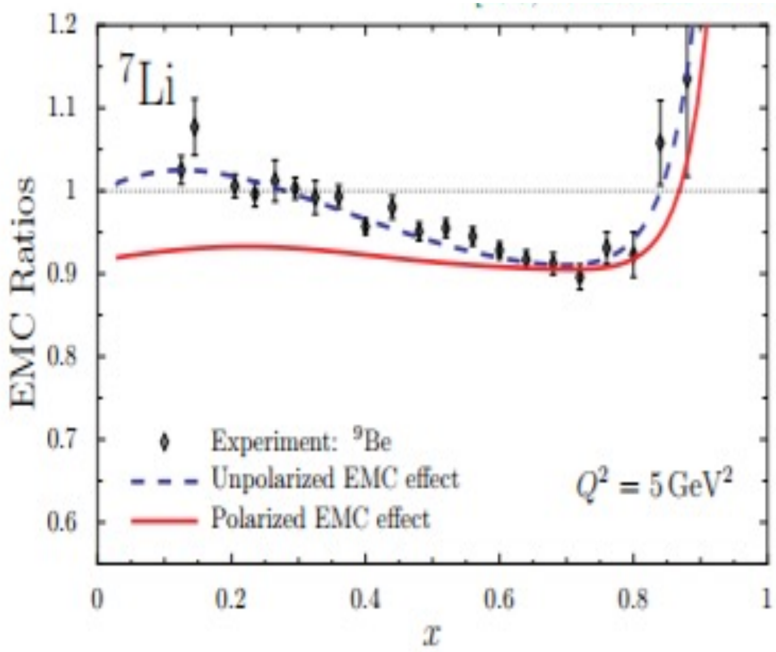
Measuring Medium Effect

➢ From 1D to 3D

❑ Polarized PDF (g_1) could be modified more significantly

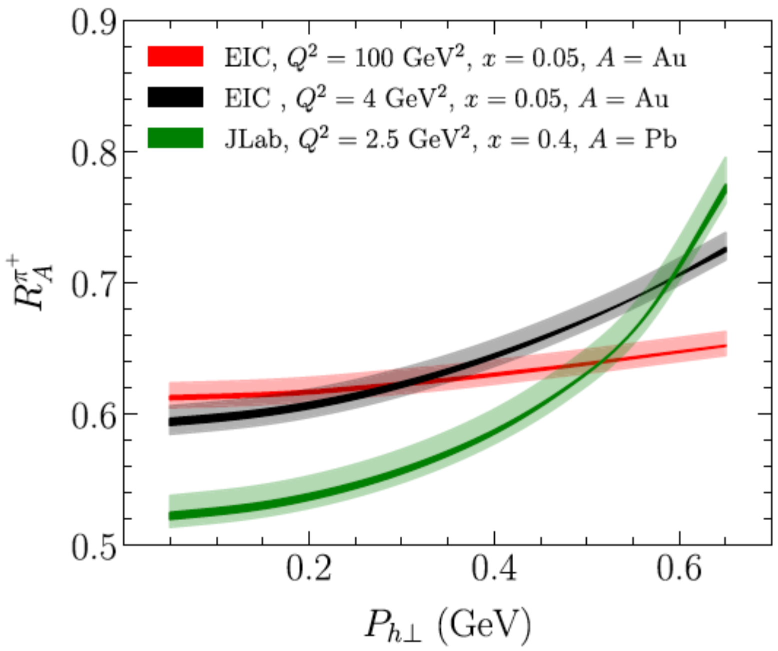
I. Cloet, PRL 95, 052302, 2005); PLB 642, 210(2006)

I. Cloet, PRL 95, 052302, 2005); PLB 642, 210(2006)

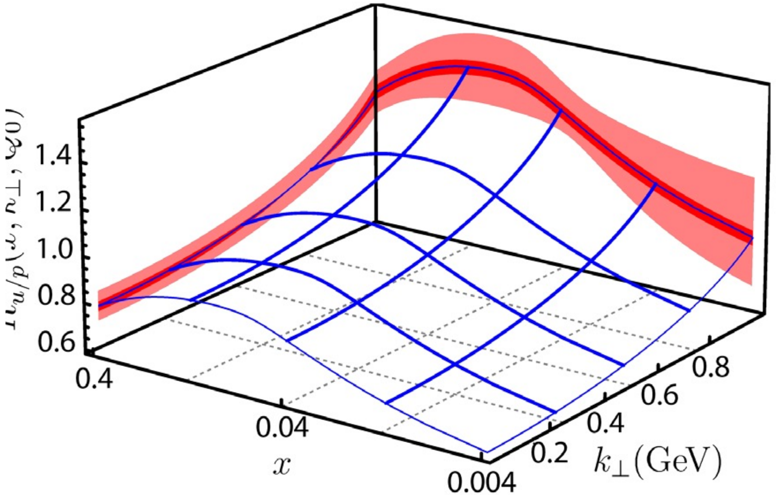


❑ First global analysis of nTMD

- See Hongxi Xing's talk on Tuesday afternoon



M. Alrashed et. al.
PRL 129 (2022) 24, 242001



❑ EicC & EIC: SIDIS w/ polarized light nuclei

$$\sigma_{SIDIS} = \sum_q e_q^2 [f_1^q(x, K_\perp) \otimes D_q^h(z, q_T)]$$

Unpolarized FF

Unpolarized TMD

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 Dubna & GSI & CEE@HIRFL, future high-precision study with HIAF

- EMC Effect: Modification of quark's distributions in nuclei → No good explanation yet
- Strong connection between the SRC and EMC → a way to solve 40-year-old puzzle?
- Jlab-12GeV & 22 GeV, US-EIC and EicC will systematically study EMC vs SRC, anti-shadowing, shadowing effects in valance & sea quarks & gluons.

❖ Bridging the gap between nuclear-structure and nucleon-structure!

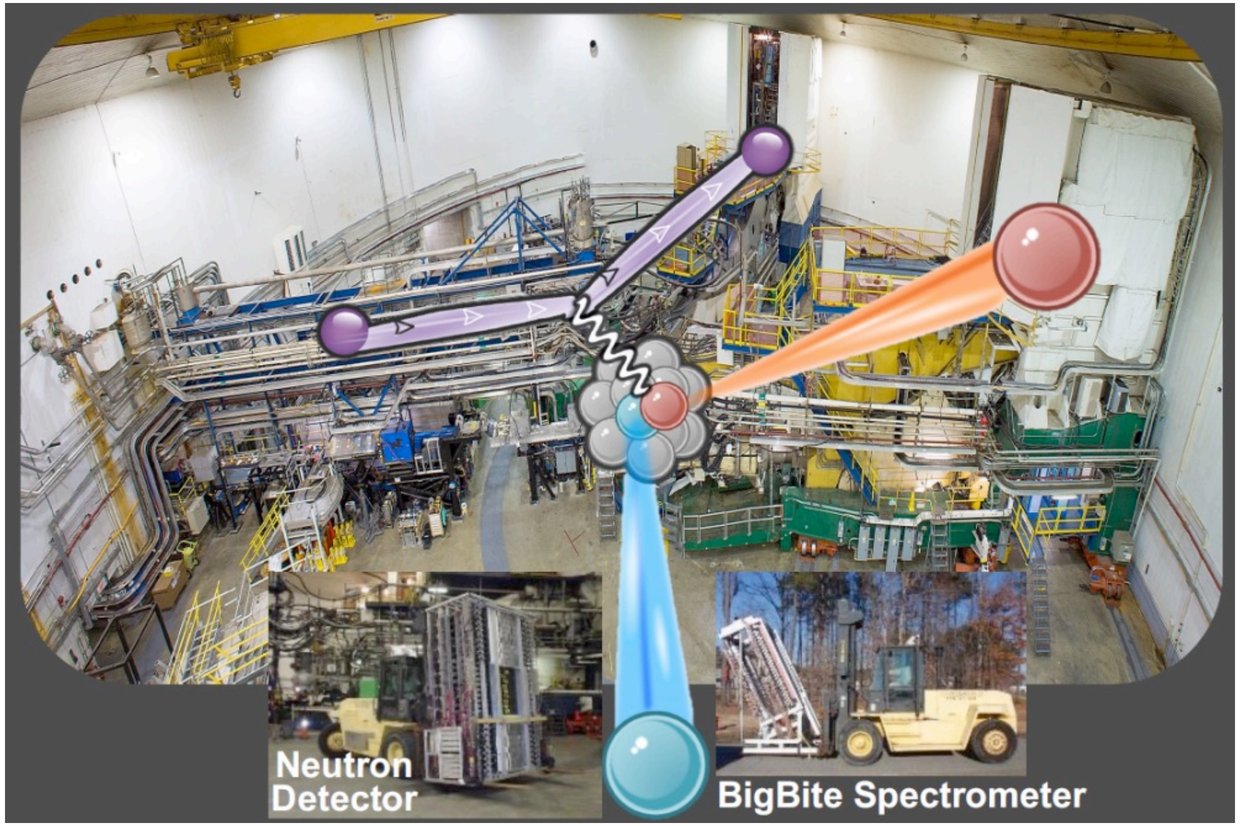
Backup Slides

Measuring SRC

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

Hall-A HRS / Hall-C HMS

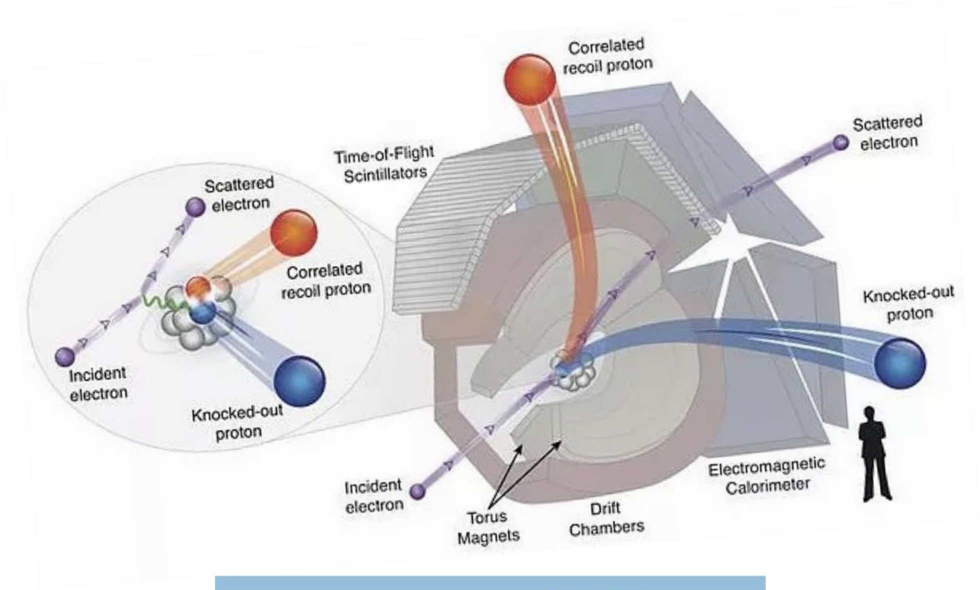
(High-Precision, Limited Acceptance);

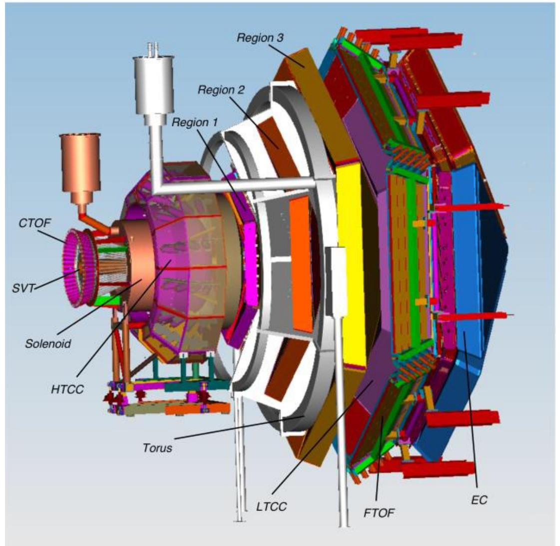


Add third-arm to detector p/n

Hall-B CLAS6/CLAS12

(Low-Precision, Full Acceptation)





➢ Isospin Dependence

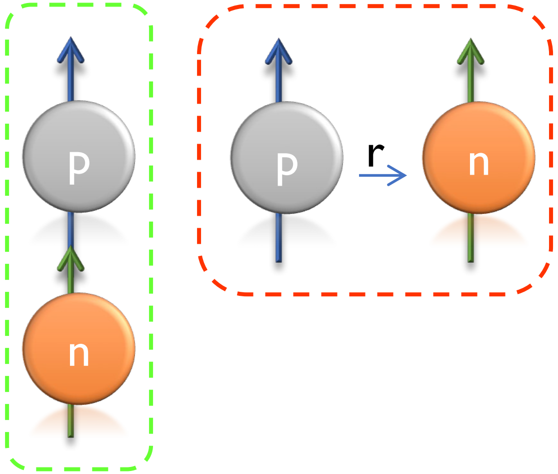
❑ Tensor Force is strongly abtractive

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

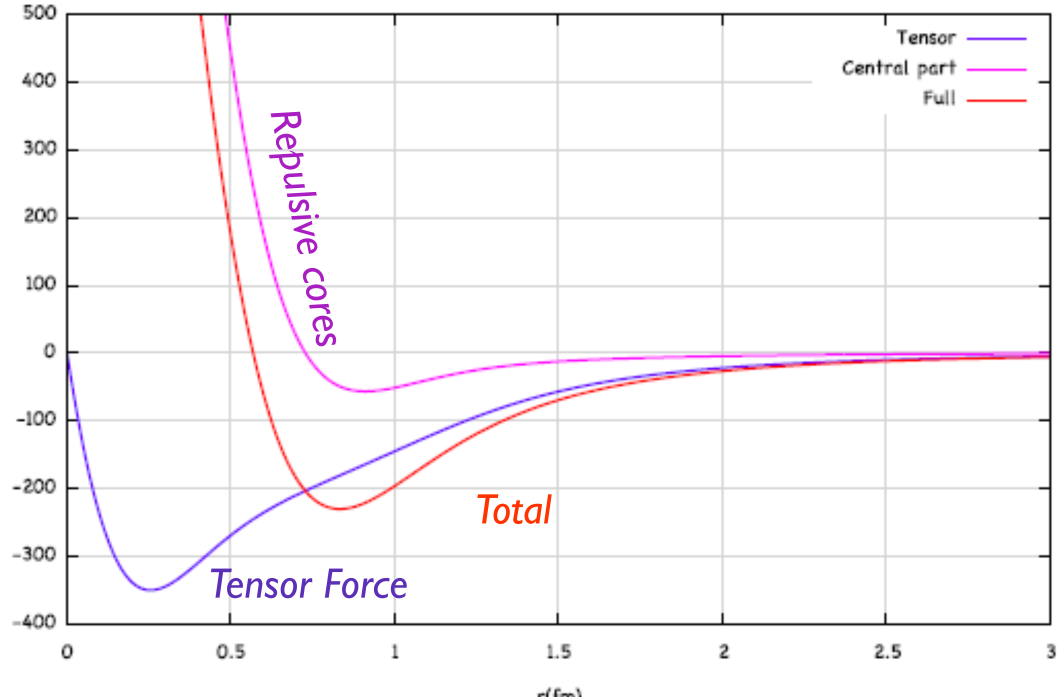
$= -3\ \sigma_1\sigma_2$

Attractive

$==0 \rightarrow$ *Repulsive*



NN Interaction Forces



❑ Tensor force favor neutron-proton pairs

Proton → T= 1/2, Neutron→ T= -1/2

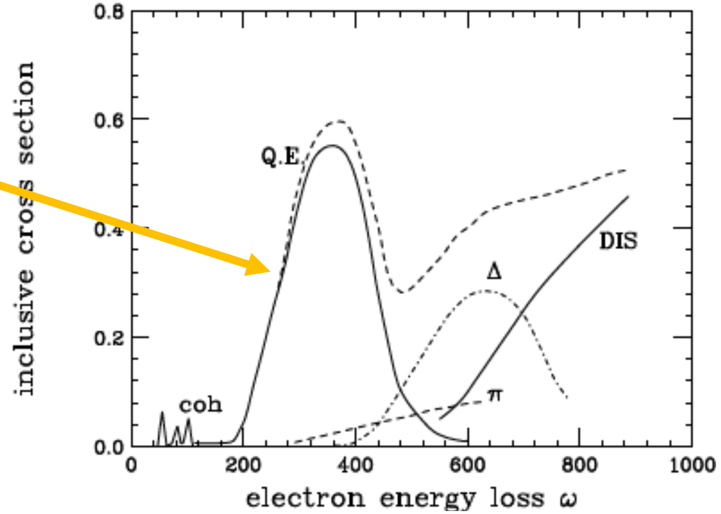
Isospin Singlet: T = 0, n-p pairs ✓ *Stable! due to Pauli Principle*

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

Measuring SRC

➢SRC Event Selection

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

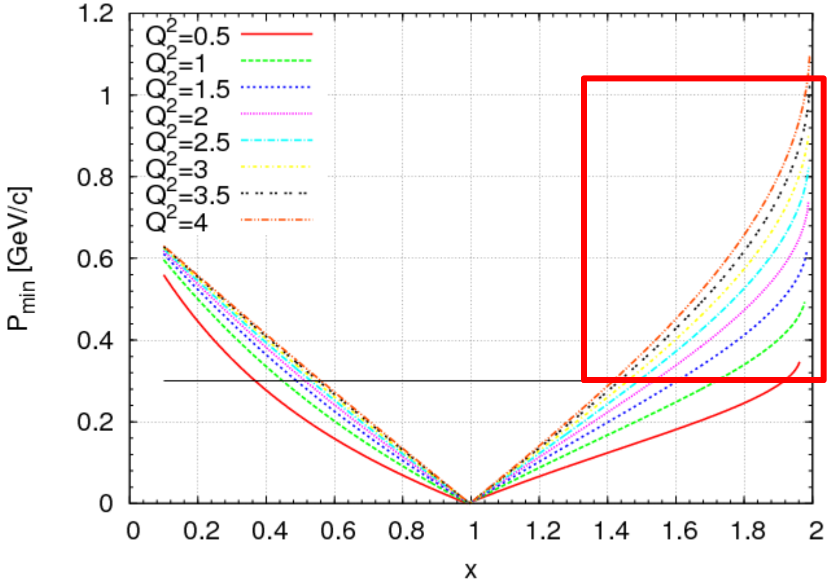


- ❑ Conditions： Knock-out nucleons, initial and final nuclear systems both in ground state → QES tail on the low-E side
- ❑ Quantities：

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

  Four Momentum Transfer: $Q^2 = 4E_0 E' sin^2(\theta/2)$

- ❑ 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

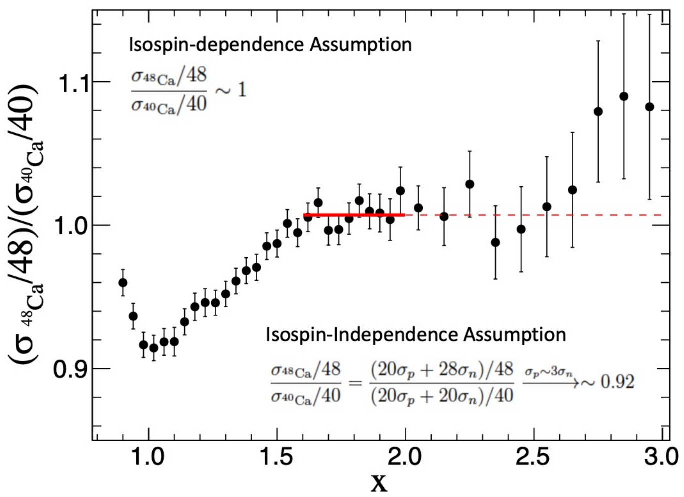
2N-SRC

➢ Isospin Dependence in Inclusive SRC

- Use asymmetric isotopes: **e.g. Ca48/Ca40**
  - 2N-SRC (n-p dominate): $R = \dfrac{\sigma_{Ca48}/48}{\sigma_{Ca40}/40} = \dfrac{(20\times 28)/48}{(20\times 20)/40} \longrightarrow 1.17$
  - Mixed (80% Mean-Field + 20% SRC): $R \approx 1.0$

M. Vanhalst, et. al., PRC 84, 031302 (2011), PRC 86, 044619 (2012)

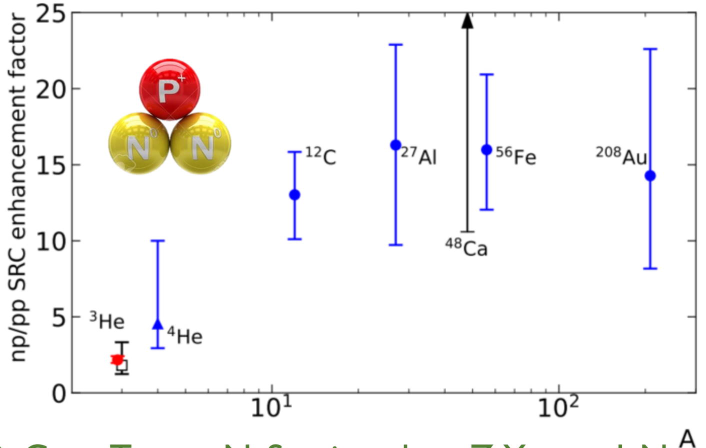
D. Nguyen, Z.Ye, et al, PRC **102**, 064004 (2020)



- H3 & He3 Mirror Nuclei (E12-11-112)

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

- 10 times precision vs Exclusive-SRC (E12-14-009)
- More precise than heavy-nuclei results
- A=3 reveal less np-Dominate!
- Different few-body forces in light nuclei vs heavy ones?



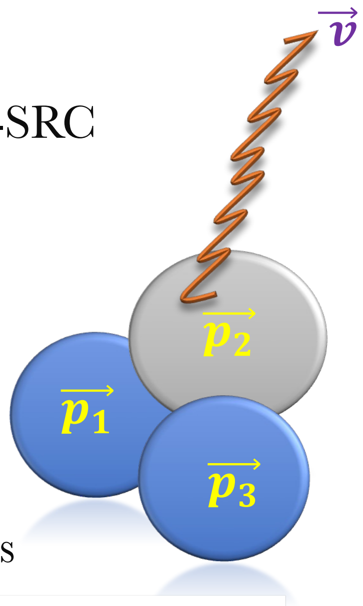
S. Li, R. Cruz-Torres, N. Santiesteban, Z.Ye, et. al, Nature, 2022, 609: 41

- A universal SRC feature for all nuclei?

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

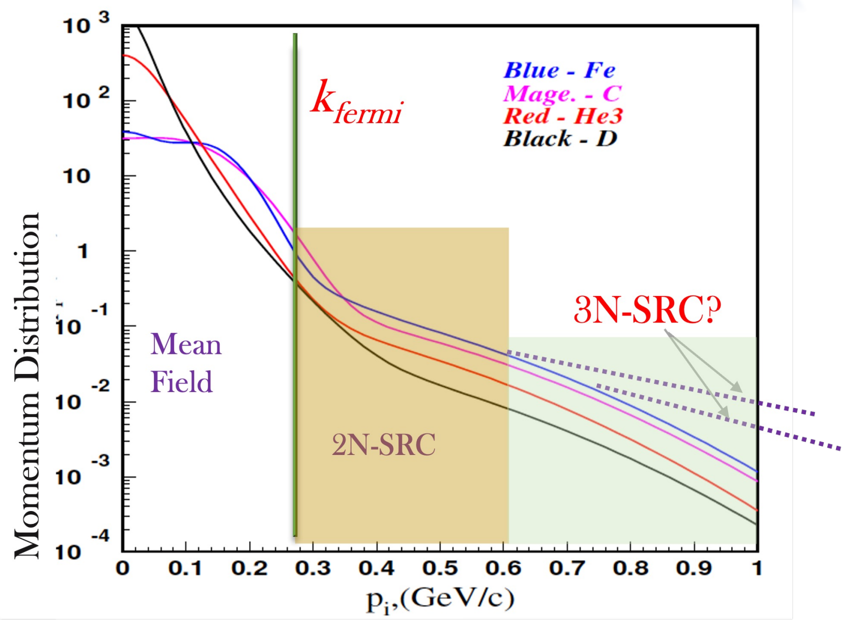


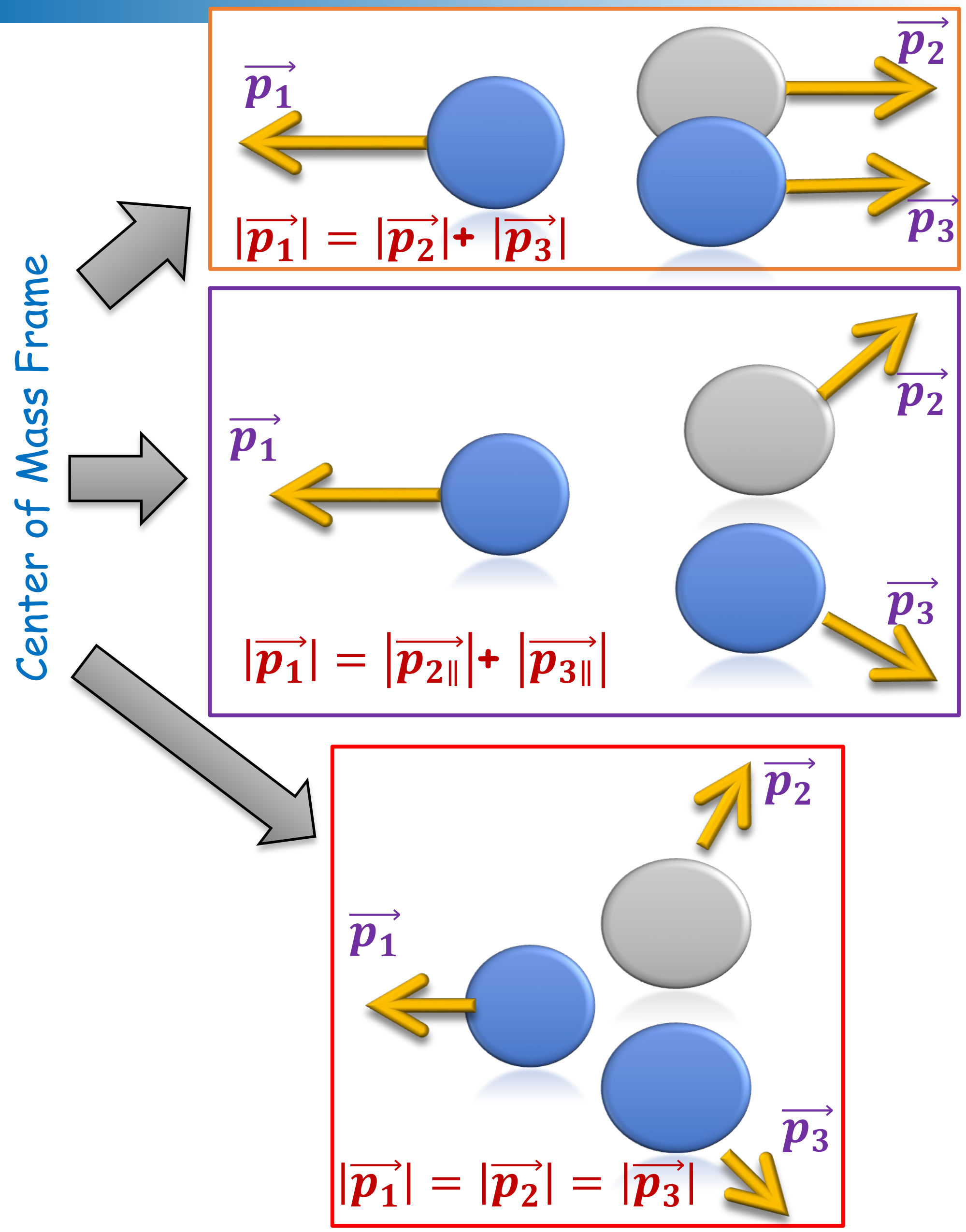
- ❑ Inclusive Measurement: XS links to the 3N-SRC tails

3N-SRC (2<x<3)

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

- ○ **2nd plateau?**

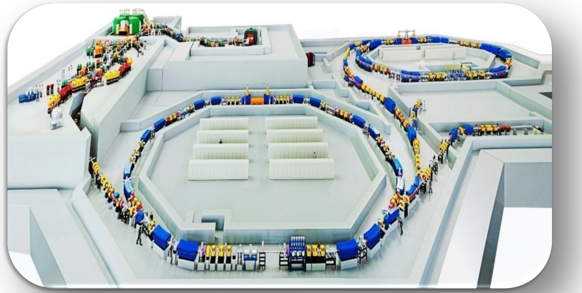


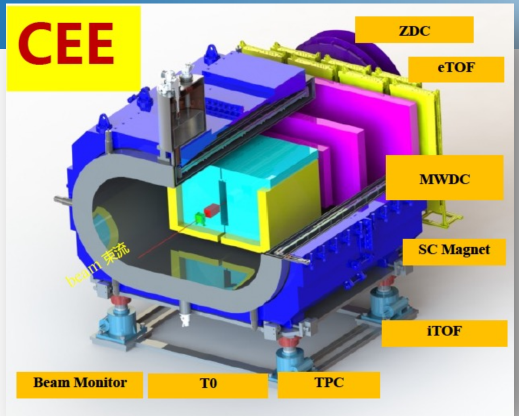


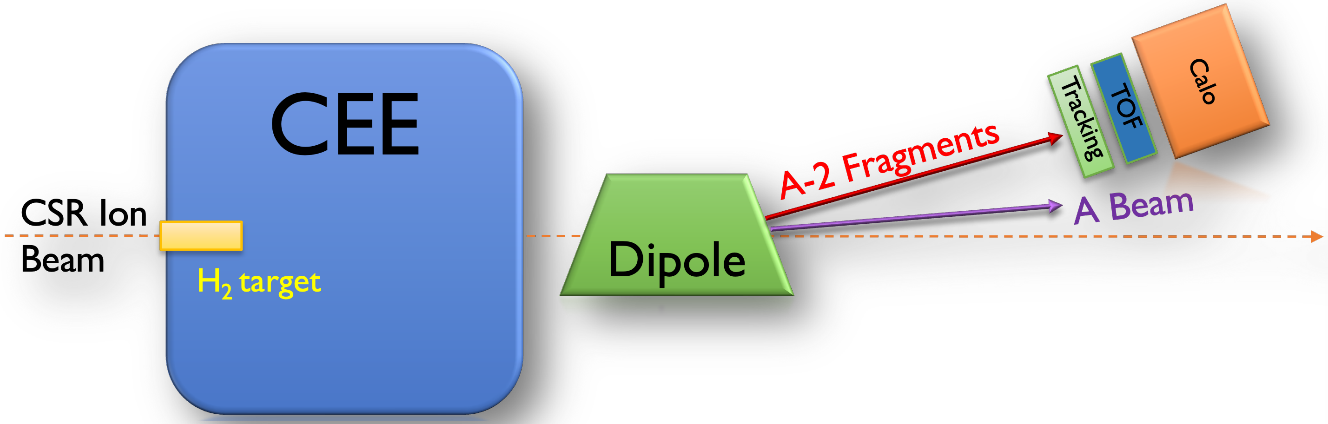
SRC@CEE

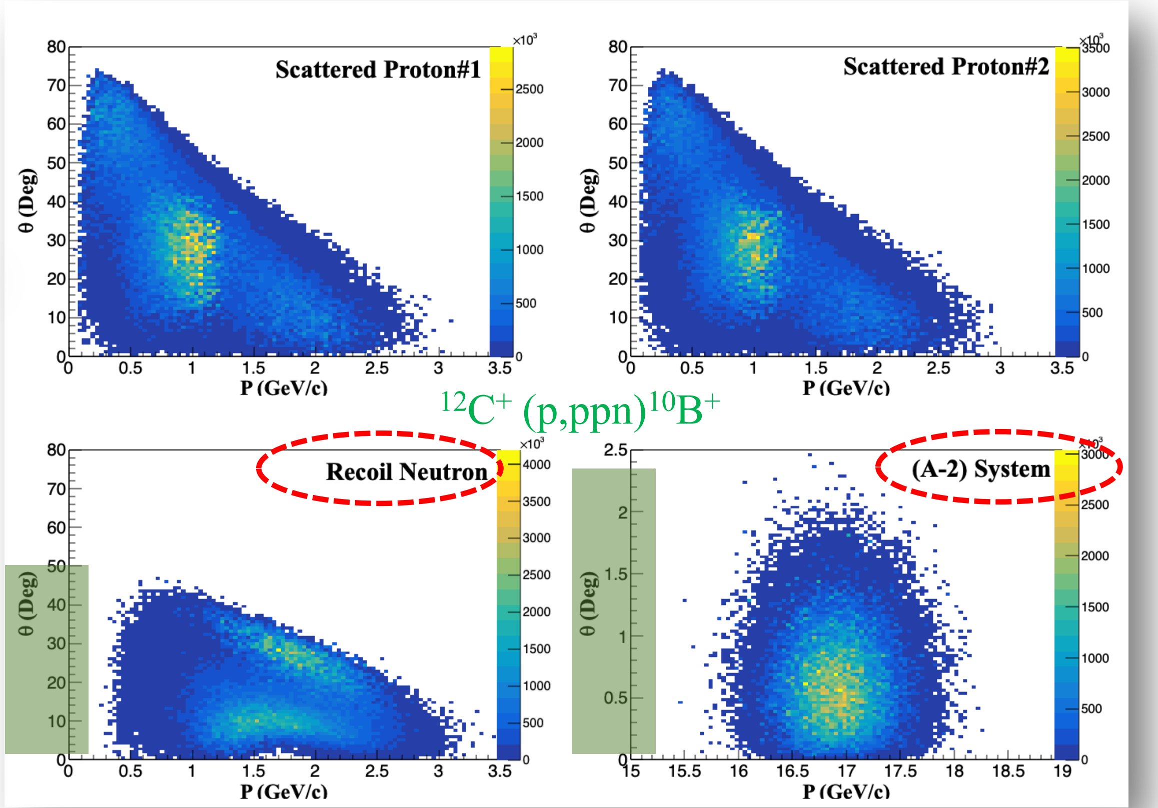
- CEE@HIRFL-CSR

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





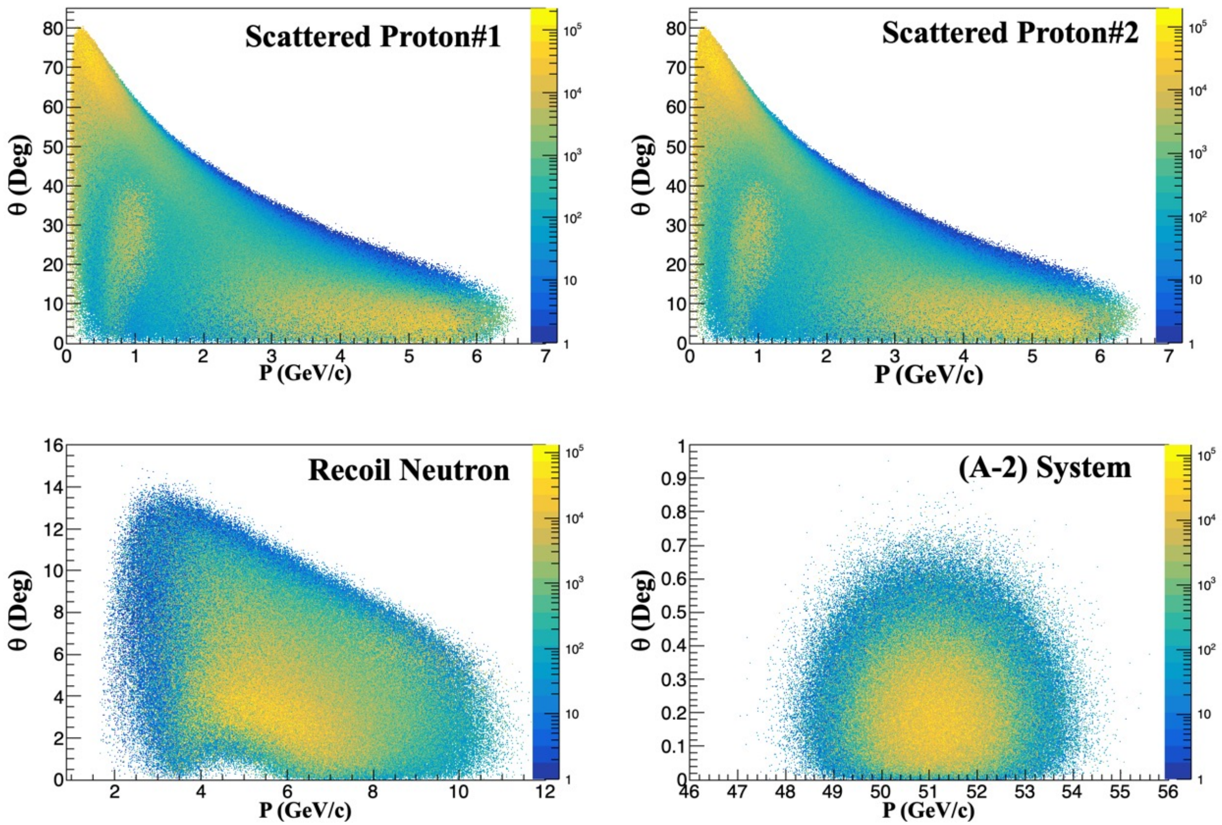


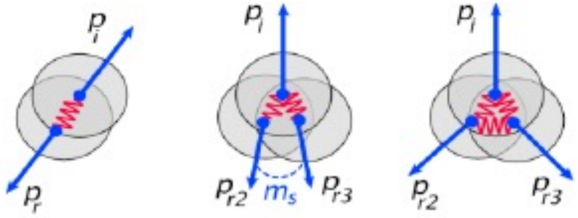


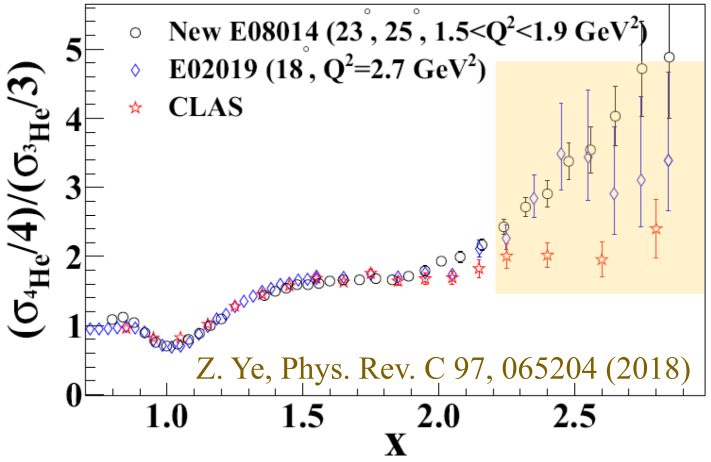
- SRC@CEE Simulation Ongoing

➢ High-Energy Station

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



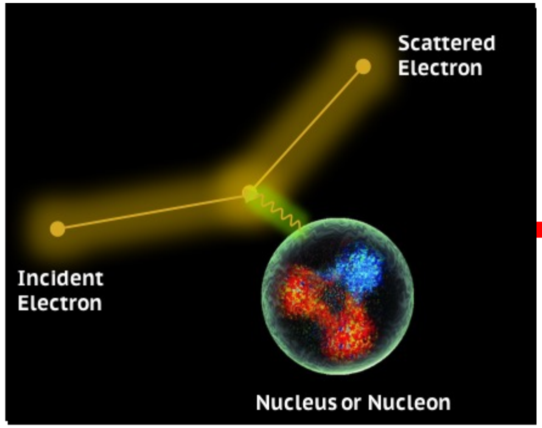


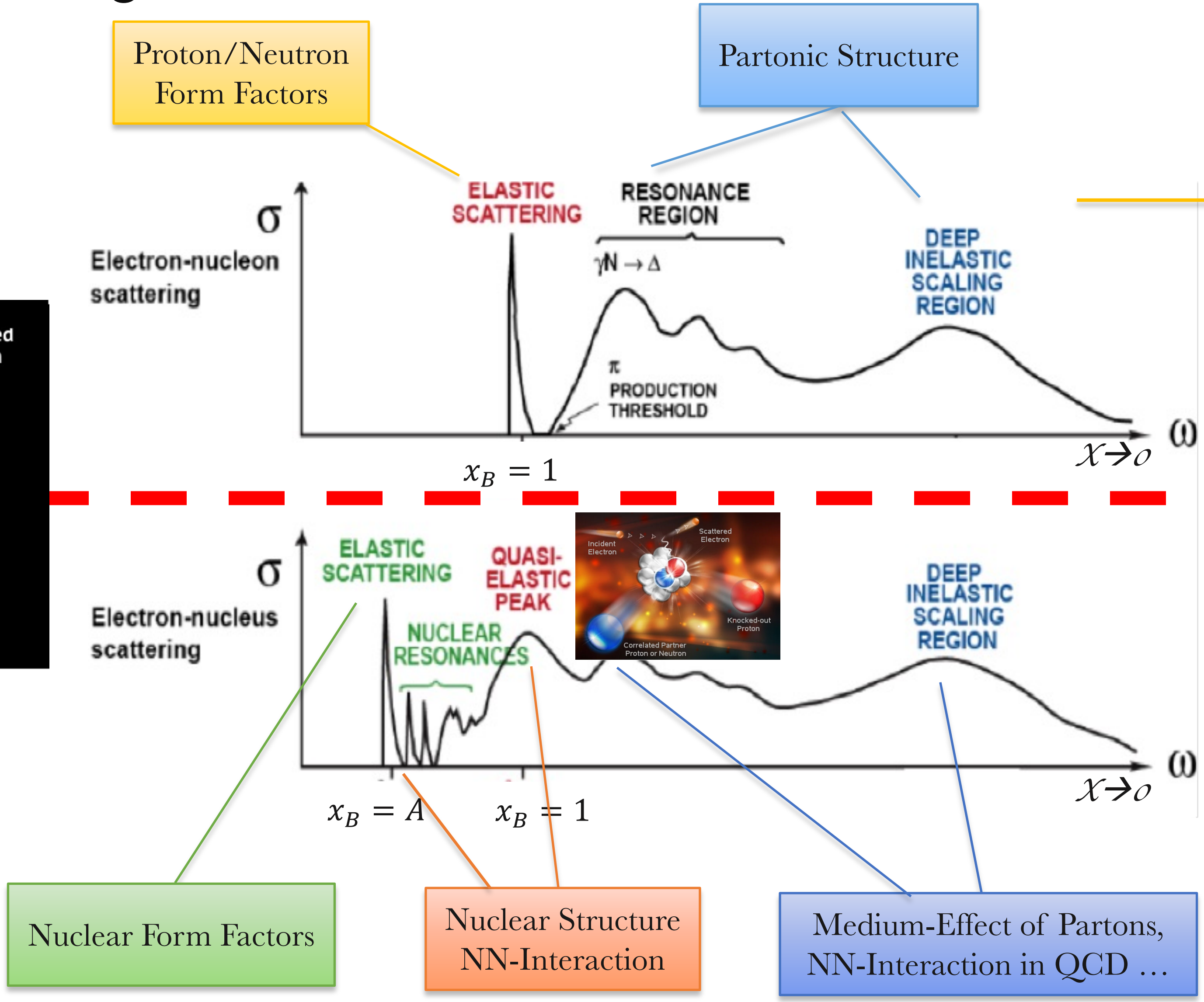


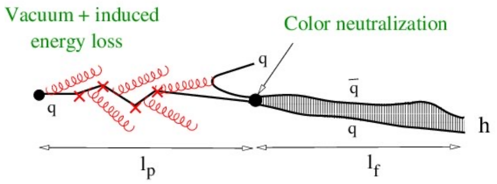
- ❑ Challenges：
  - Detector efficiency at small angles
  - Beam quality (energy, position, current …)
  - Target performance at high luminosity
  - FEE, DAQ

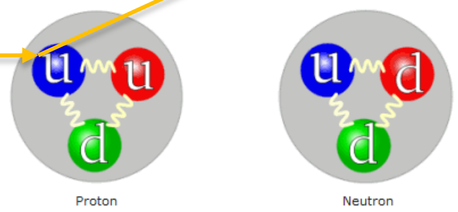
Quarks in Nuclei

➢eP vs eA scattering:

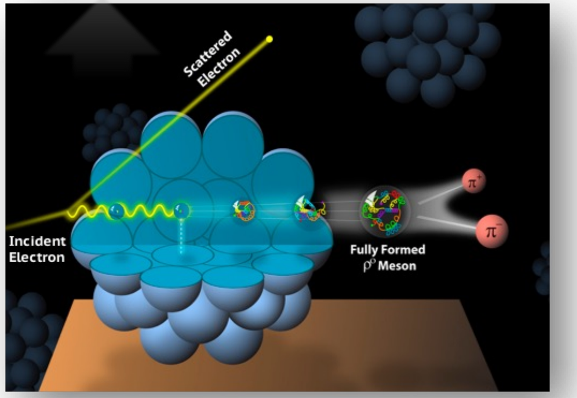








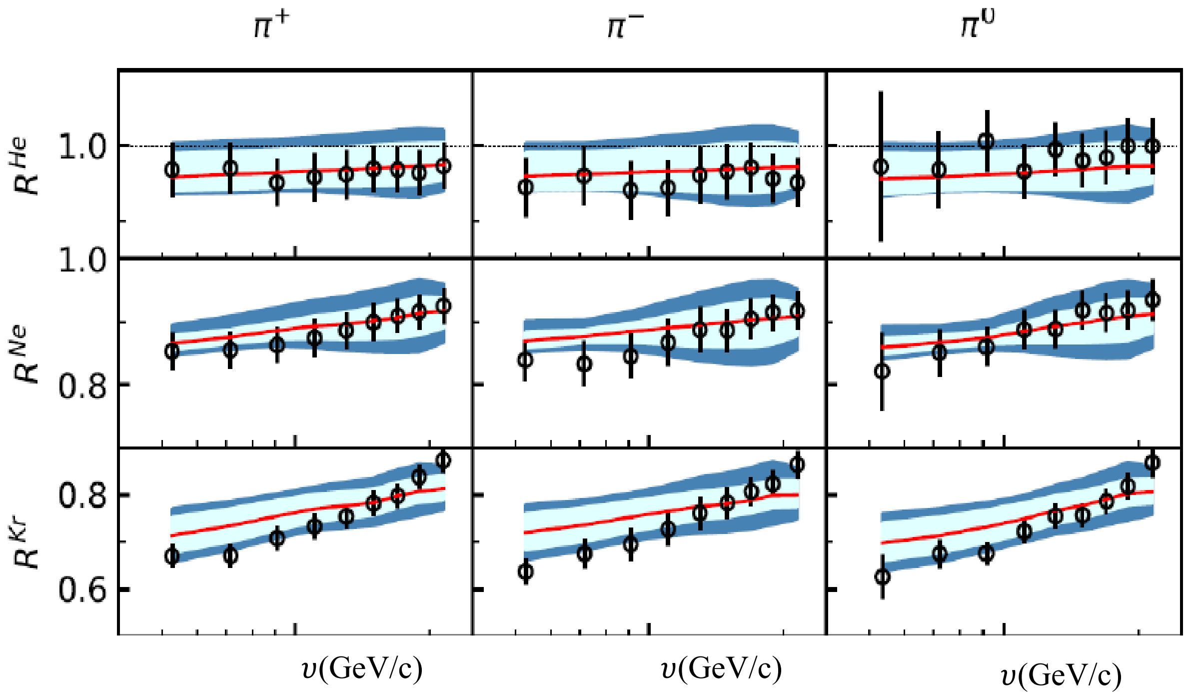
Quarks in free proton vs. Nucleon?



➢Hadronization in Nuclei

- ❑ Start with light nuclei， e.g. D2， He3 and H3:
  - ✓ Calculable nuclear structure (mean-field)
  - ✓ EMC Effect small but can be measured
  - ✓ Small hadronization effect (mostly in vacuum)
  - ✓ Modification of FFs are small and similar

(Pia Zurita, arXiv:2101.01088)



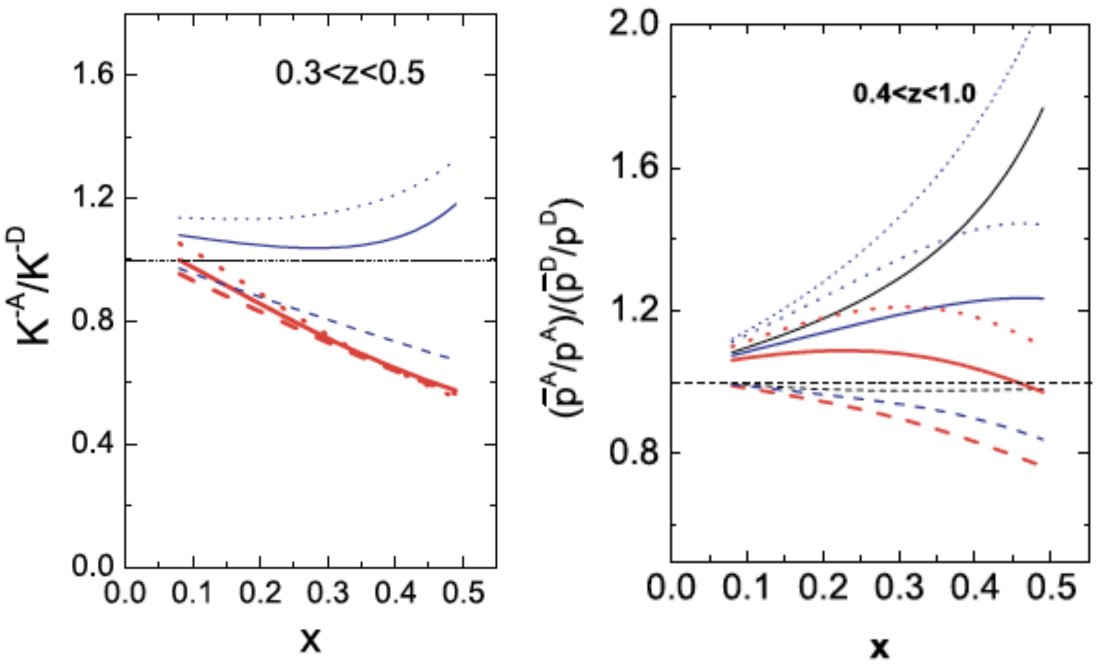
Small (~ 5% at high-z) effects on He4's nFFs
→ Safe to ignore medium effect of nFF in A=2, 3

❑ Systematically study D2， He3 & H3 is the first step to bridge between free-nucleons and heavy nuclei!

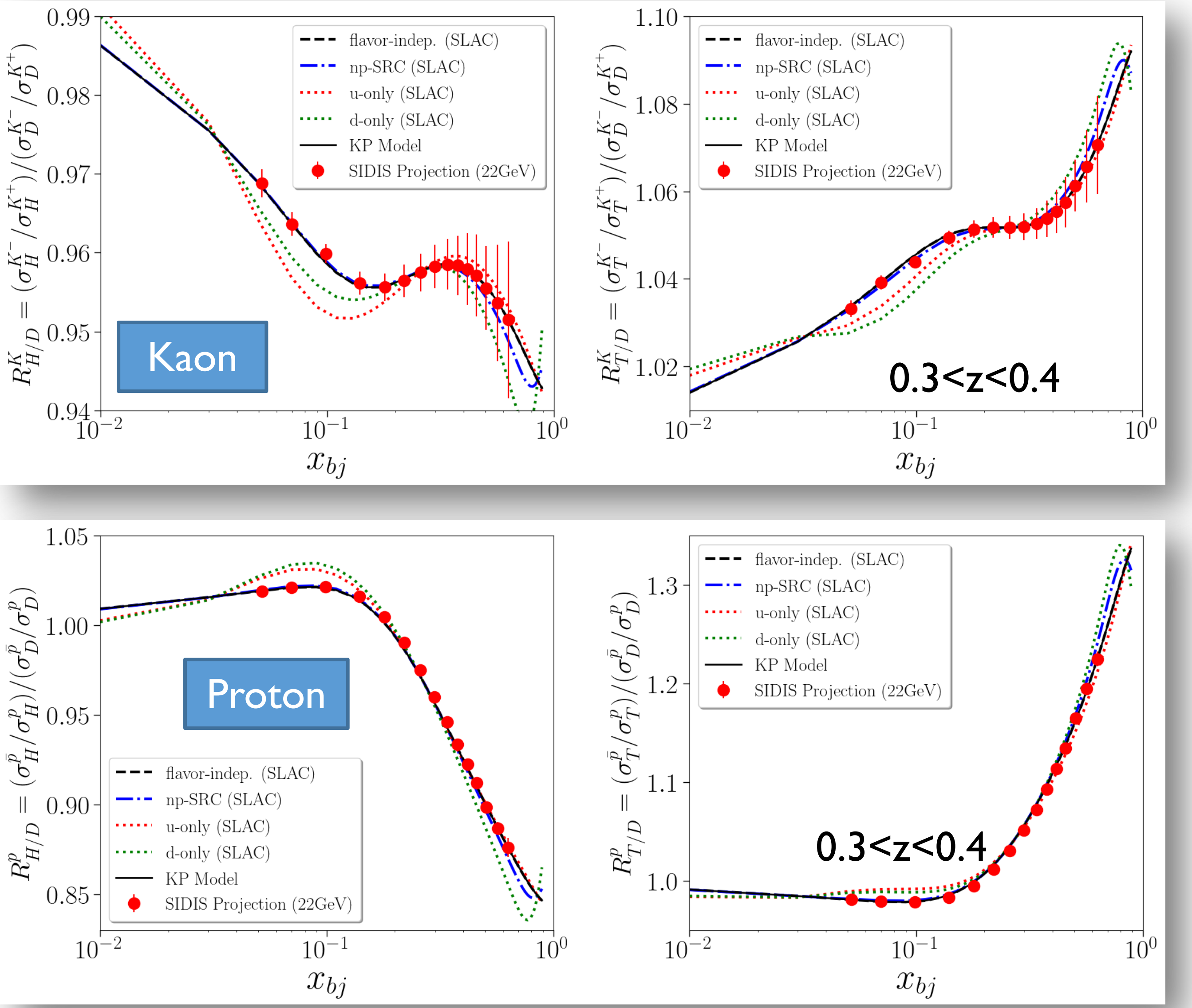
Jlab 22GeV Energy Upgrade Plan

➢eA SIDIS w/ mutiple Hadron-Production

- ❑ Use A=3 isotopes to fully decouple EMC & Antishadowing in u, d, and s



J. Lu, B.Q. Ma PRC 74, 055202 (2006)



Jlab 22GeV Energy Upgrade Plan

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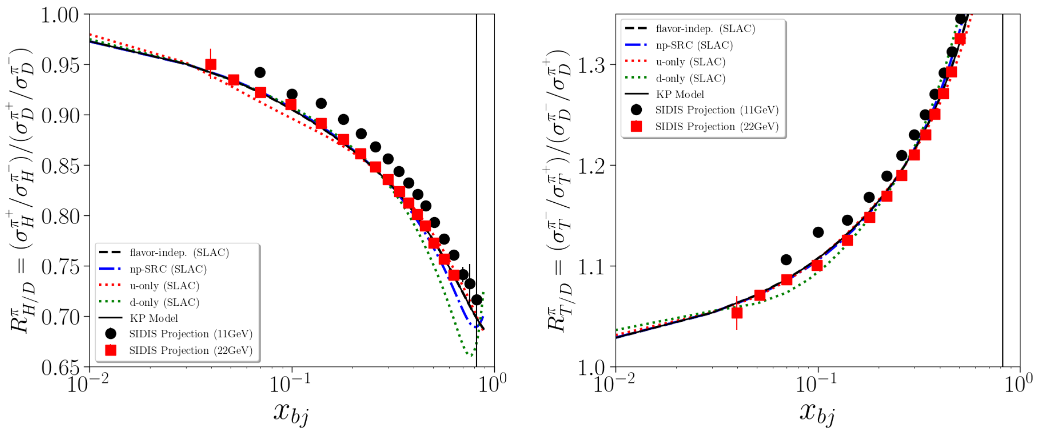
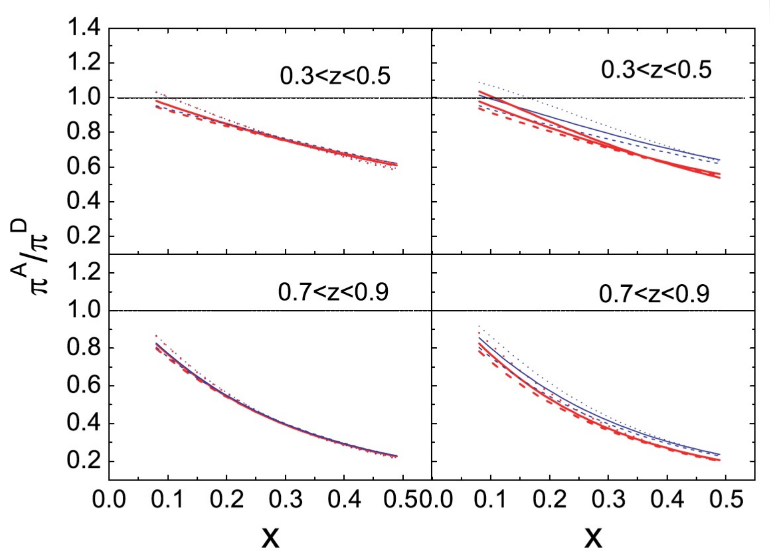
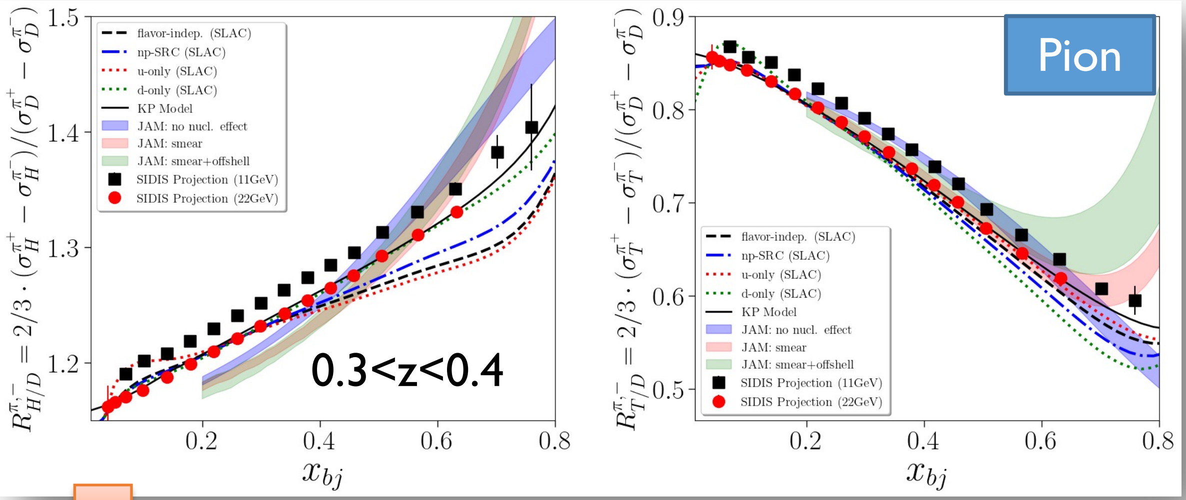
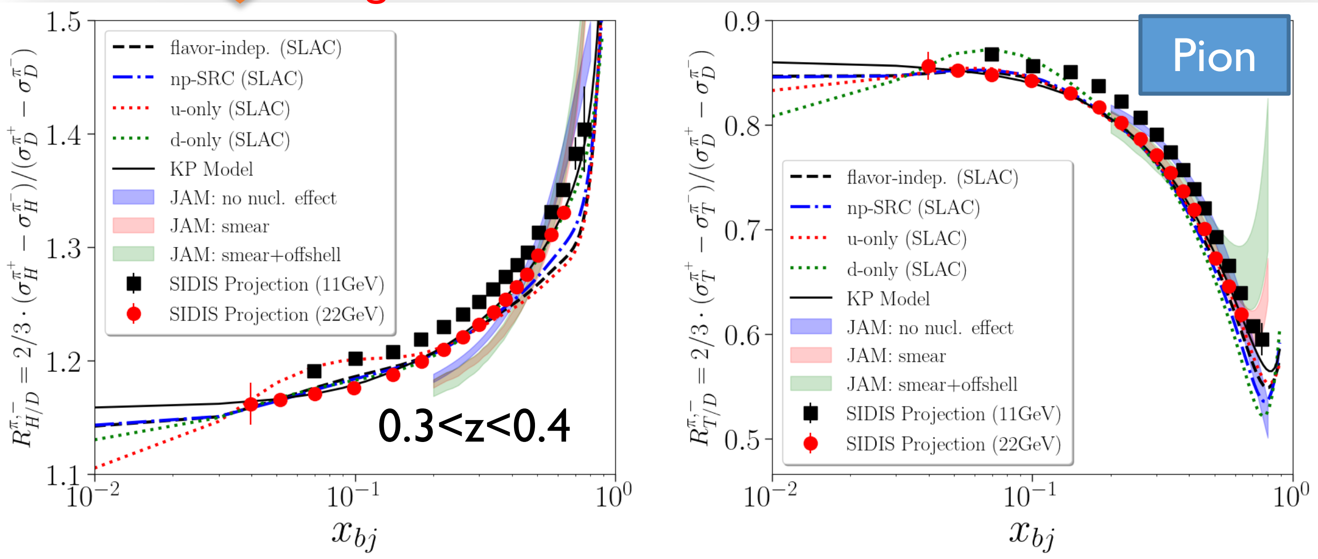




J. Lu, B.Q. Ma
PRC 74, 055202 (2006)



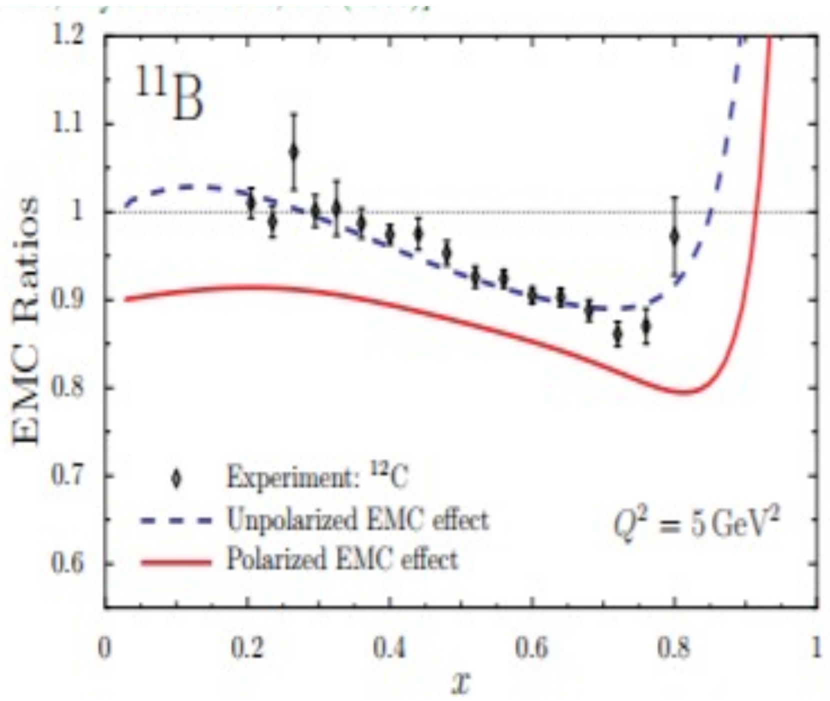
Log-scale



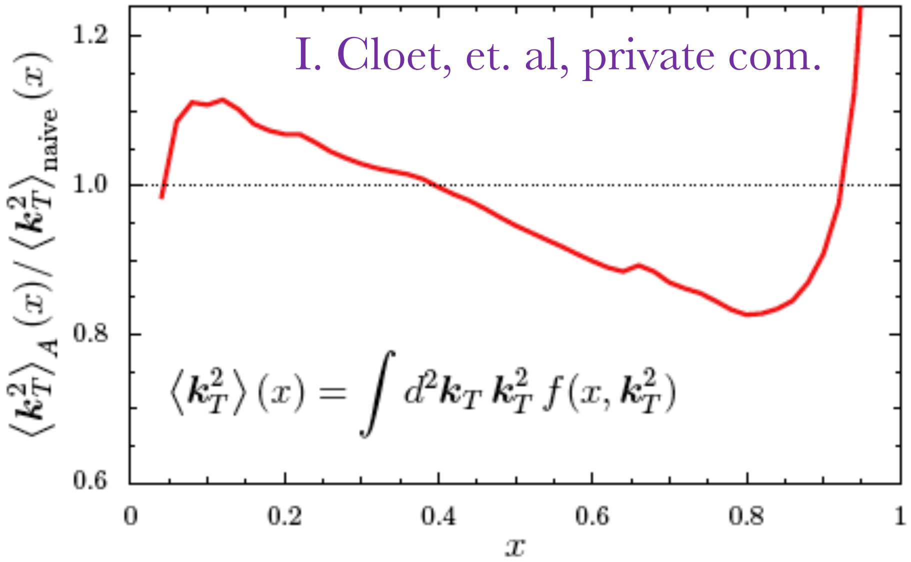
Quarks in Nuclei

➢ From 1D to 3D

- ❑ Strong EMC effect in the polarized PDF (helicity functions)?
  - Modification of quark-spin in nuclei?



I. Cloet, PRL 95, 052302, 2005); PLB 642, 210(2006)



- ❑ Transverse direction also modified (nuclear TMD)

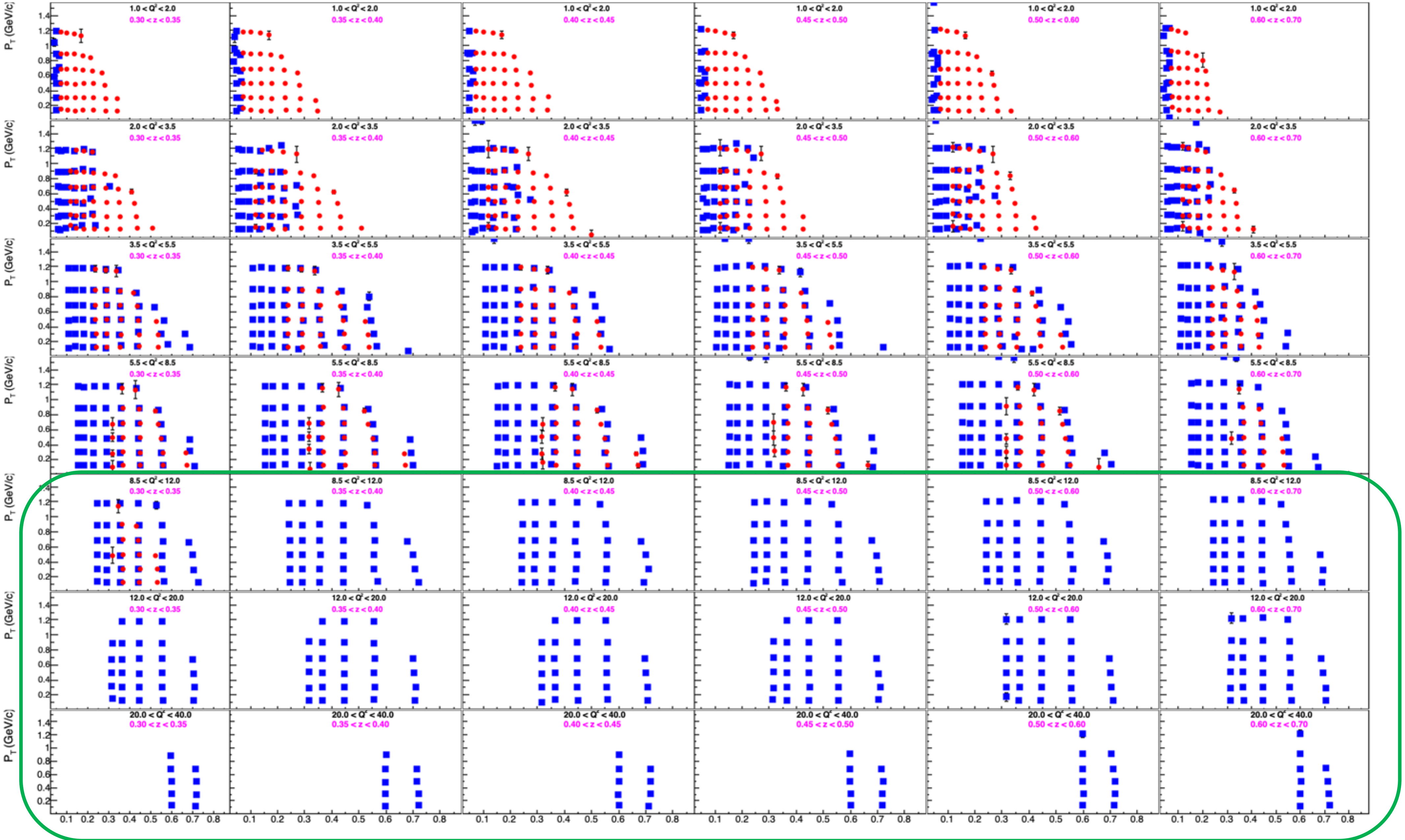
- ❑ Fully solve EMC puzzle → Study nuclei in 3D
  - ✓ Measure SIDIS with pT distributions

$$F_{UU}(x,z,P_T) = \sum_q e_q^2 [f_1^q(x,K_\perp) \otimes D_q^h(z,q_T)]$$

Unpolarized TMD *Unpolarized FF*

Jlab 22GeV Energy Upgrade Plan

Pion-SIDIS Projection



- 11GeV
- 22GeV

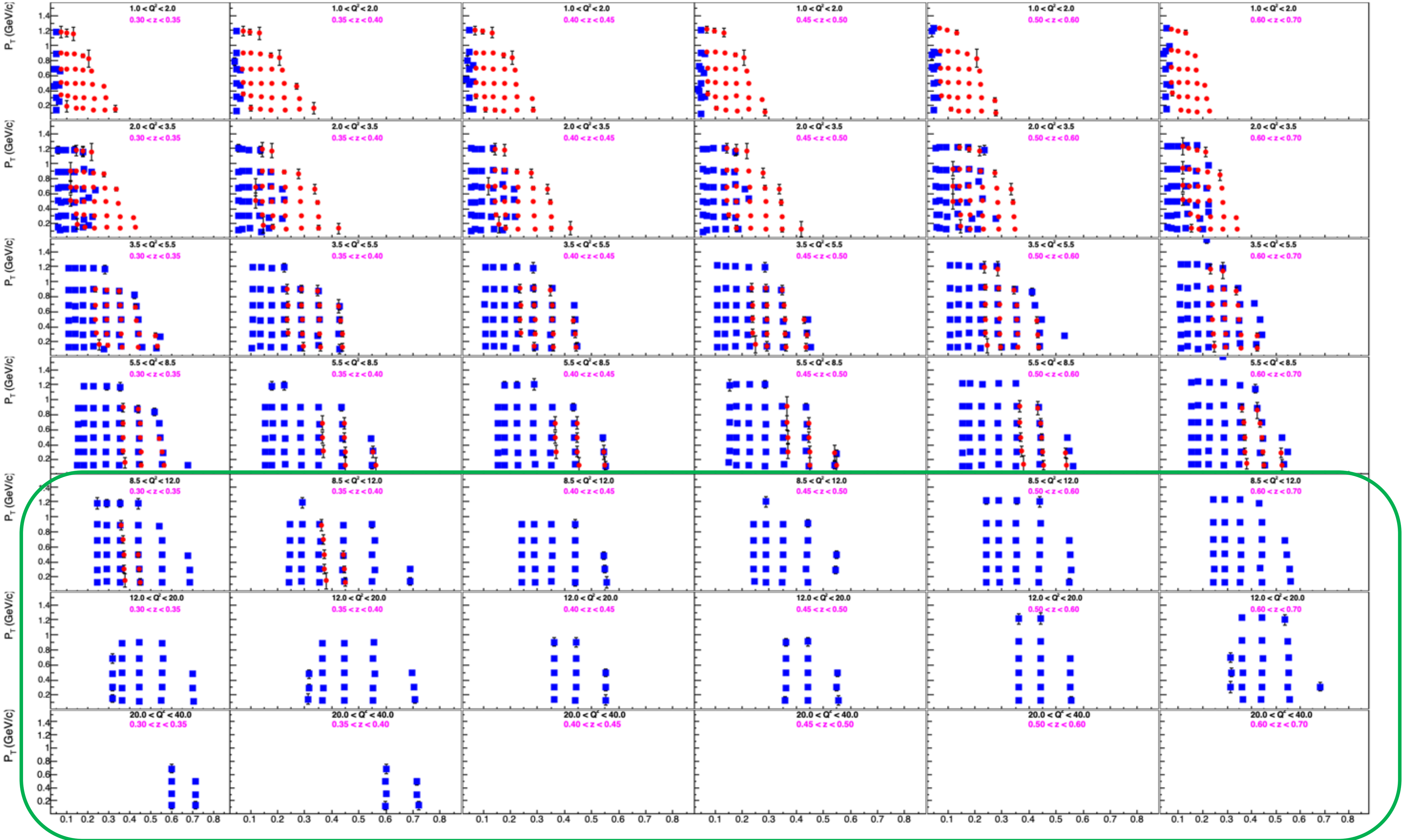
→4π-detector (CLAS12 & SoLID)
→Lumi~10^{35}cm^{-2}s^{-1},
→100-days

Jlab 22GeV Energy Upgrade Plan

Kaon-SIDIS Projection

- 11GeV
- 22GeV

→4π-detector (CLAS12 & SoLID)
→Lumi~10^{35}cm^{-2}s^{-1},
→100-days



Jlab 22GeV Energy Upgrade Plan

Proton-SIDIS Projection

- Proton
- Anti-Proton

→4π-detector (CLAS12 & SoLID)
→Lumi~$10^{35}cm^{-2}s^{-1}$,
→100-days