Tsinghua University

MARATHON Experiment

Me**A**surement of the F_2^n/F_2^p, d/u **RA**tios and A=3 EMC Effect in Deep Inelastic Electron Scattering Off the **T**ritium and **H**elium Mirr**O**r **N**uclei.

Zhihong Ye

Department of Physics, Tsinghua University

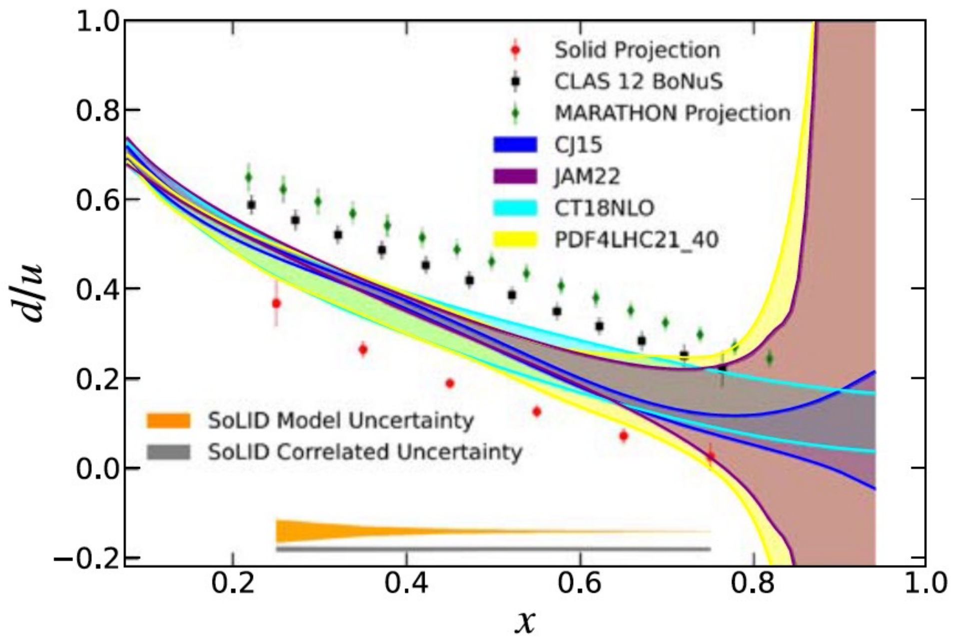
On behalf of the Tritium-MARATHON Collaboration

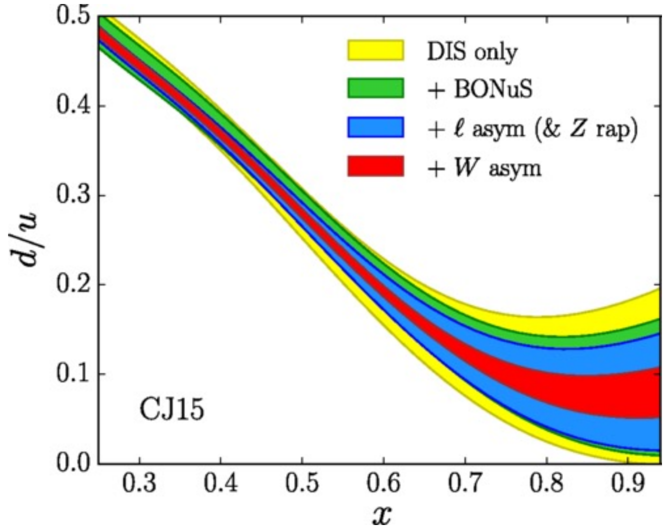
Strong QCD from Hadron Structure Experiments – VI, Nanjing University, 05/16/2024

Motivation

d/u ratios at high-x

- d/u drops to zero at x=1 but not the ratio
  - Different models, diff. predictions
  - Constrain QCD models for d/u
- CTEQ-JLab (CJ15), gave small errors
  - Including tagged-DIS, charged lepton and W boson asymmetry
    Loose kinematic cuts (Q^2>1.3GeV^2, W^2>3GeV^2)
  - New model-dependent corrections
  - ✓ New high-x DIS data are still essential





A. Accardi et. al. Phys. Rev. D 93, 114017 (2016).

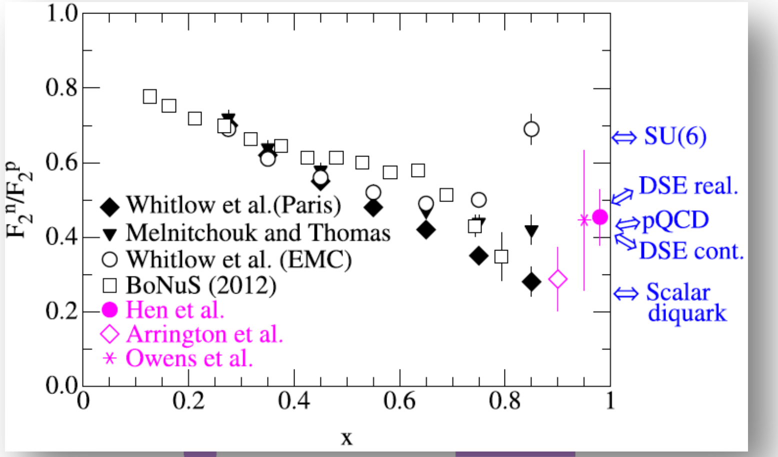
- Extracted from DIS:

$$\frac{F_2^n}{F_2^p} = \frac{[(u+\bar{u})+(s+\bar{s})]+4(d+\bar{d})}{4(u+\bar{u})+[(d+\bar{d})+(s+\bar{s})]}$$

$$\frac{1}{4} \leq \frac{F_2^n}{F_2^p} \leq 4$$

- Problem: No free stable neutrons!

C. Roberts, R. Holt, S. Schmidt, PLB 727 (2013) 249–254



Motivation

d/u ratios at high-x

- Deuteron as an "effective" neutron target:
  - Measure DIS w/ D2
  - Obtain nDIS after subtracting pDIS
  - Model corrections to nuclear effect

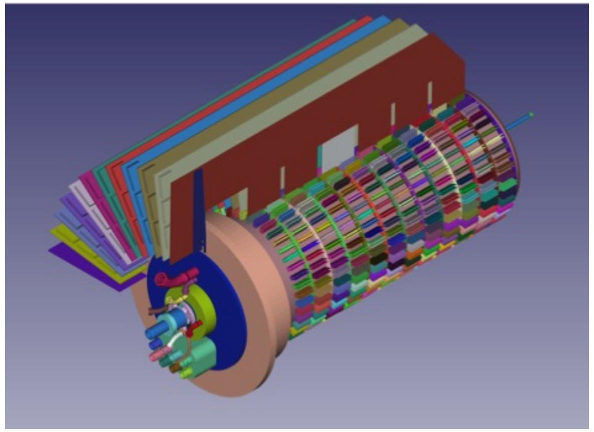
Spectral functions (fermi-motion)

$$F_D = F_{\tilde{p}} \otimes f_p^D + F_{\tilde{n}} \otimes f_n^D$$

Slightly "modified" nucleons
- Offshell
- Target Mass
- Higher Twists
- EMC ...

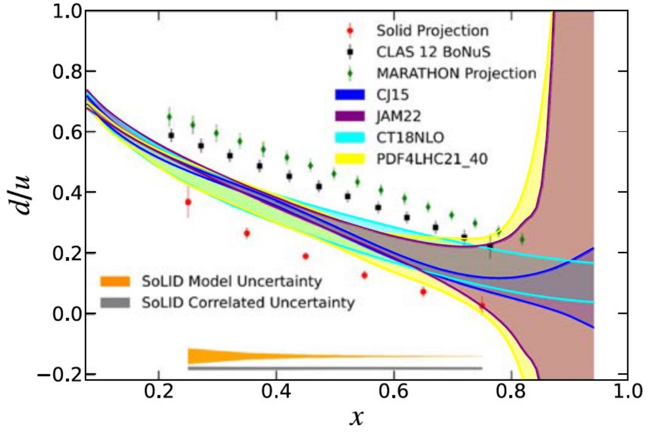
PRD 107, L051506 (2023)

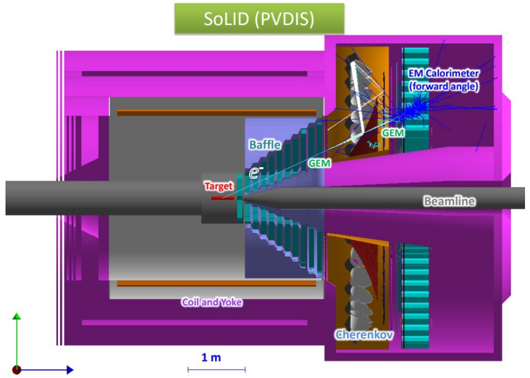
- Reduce the nuclear effect by spectator tagging, e.g. : BoNUS/BoNUS12/EIC
  - Statistical limit, FSI, efficiencies, phase-space…
  - Medium modification effects still exist



- PVDIS is less sensitive to the nuclear effect
  - Intensity hunger + large detector acceptance required

$$A_{LR}^p \sim -\frac{1}{4\pi\alpha}\frac{Q^2}{\upsilon^2}\left[\frac{12\, g_{AV}^{eu} - 6\, g_{AV}^{ed}\, d/u}{4 + d/u}\right]$$





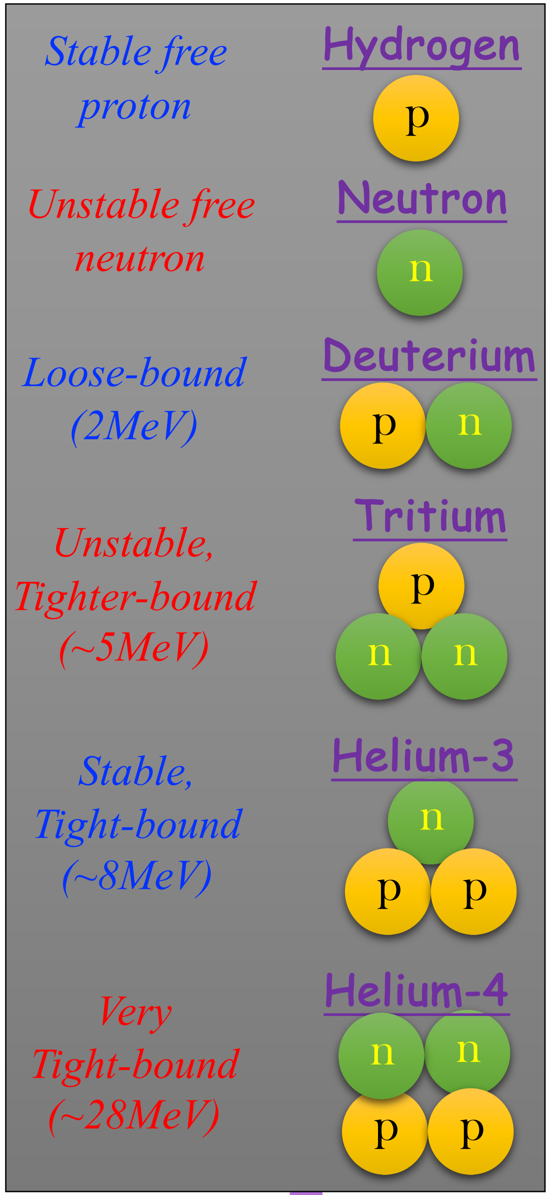
J. Phys. G: Nucl. Part. Phys. 50 (2023) 110501

Motivation

- **^{3}H & ^{3}He**
  - Deuteron as effective "free" neutron
  - Triton(^{3}H) and ^{3}He → the boundary of "quasi-free" and "real" nuclei

number of protons \ number of neutrons	0	1	2	3	4	5
4			Be6 5e-21 sec 6.01973	Be7 53.3 d 7.01693	Be8 8e-19 sec 8.00530	Be9 100% 9.01218
3		Li4 8e-23 sec 4.0272	Li5 3e-22 sec 5.0125	Li6 7.59% 6.01512	Li7 92.41% 7.01600	Li8 0.840 sec 8.0225
2		He3 0.000137% 3.01603	He4 99.999863% 4.00260	He5 7e-22 sec 5.0121	He6 0.807 sec 6.01889	He7 3e-21 sec 7.02803
1	H1 (p) 99.9885% 1.007825	H2 (D) 0.0115% 2.01410	H3 (T) 12.32 yr 3.01605	H4 8e-23 sec 4.0278	H5 v. short 5.035	H6 3e-22 sec 6.0449
0		n 10.25 min 1.008665				

Table of Light Nuclei



Motivation

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MARATHON Experiment

- In ^{3}H & ^{3}He: $F_{H3} = F_{\tilde{p}} \otimes f_p^{H3} + 2F_{\tilde{n}} \otimes f_n^{H3}$

  $F_{He3} = 2F_{\tilde{p}} \otimes f_p^{He3} + F_{\tilde{n}} \otimes f_n^{He3}$

- DIS cross section:

$$\sigma = \frac{4\alpha^2(E')^2}{Q^4}\cos^2(\frac{\theta}{2})F_2\left[\frac{1}{\nu} + \frac{(1+Q^2/\nu^2)}{xM(1+R)}\tan^2(\frac{\theta}{2})\right]$$

$$\frac{\sigma(^3\mathrm{H})}{\sigma(^3\mathrm{He})} = \frac{F_2(^3\mathrm{H})}{F_2(^3\mathrm{He})}$$

$R = \sigma_L/\sigma_T$

From other measurements

Super-Ratio in EMC (DIS)

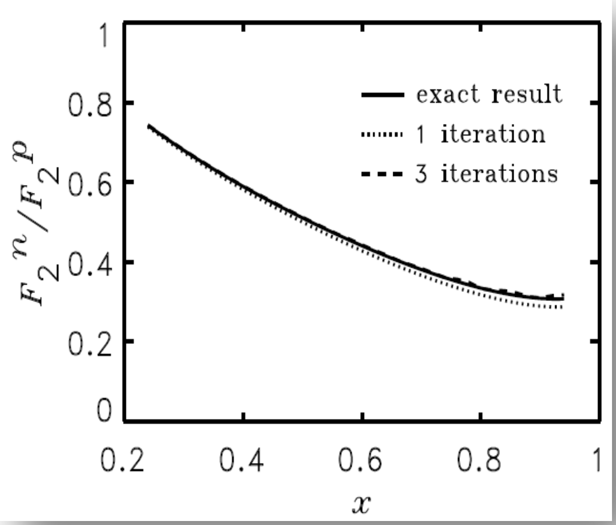
$R(3_{He}) = \frac{F_{3He}}{2F_p+F_n}$, $R(3_H) = \frac{F_{3H}}{F_p+2F_n}$ $\mathcal{R} = \frac{\mathrm{R}(3_{\mathrm{He}})}{\mathrm{R}(3_{\mathrm{H}})}$

$$\frac{F_2^n}{F_2^p} = \frac{2\mathcal{R} - F_2^{^3\mathrm{He}}/F_2^{^3\mathrm{H}}}{2F_2^{^3\mathrm{He}}/F_2^{^3\mathrm{H}} - \mathcal{R}}$$

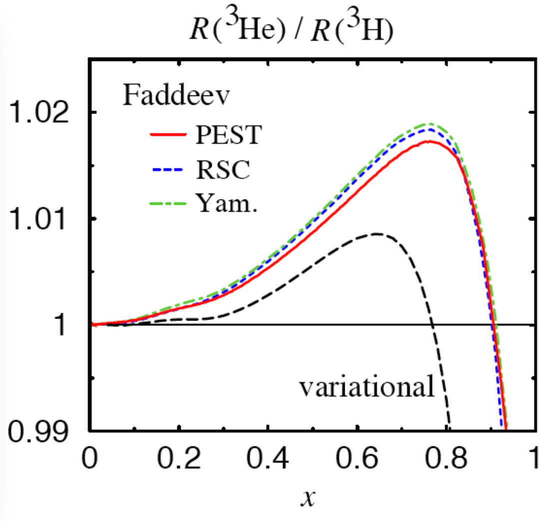
E12-10-103

Spokespeople: G (Makis) Petratos, J. Gomez, A. Katramatou, R. Holt (J. Arrington), D. Meekins, R. Ransome,

PhD Students: T. Hague, M. Mycz, T. Su (Kent), J. Bane (Tennessee) , Tyler Kutz (Stony Brooks), H. Liu (Columbia)



<2% effect between two nuclei



- Spectral functions in A=3 nuclei are similar & calculable
- Corrections become small (or cancelled) in ratios
- "EMC" effect *could be* similar and small at high-x (to measure)
- $\mathcal{R}$ to be initialized by a model, iterate w/ data

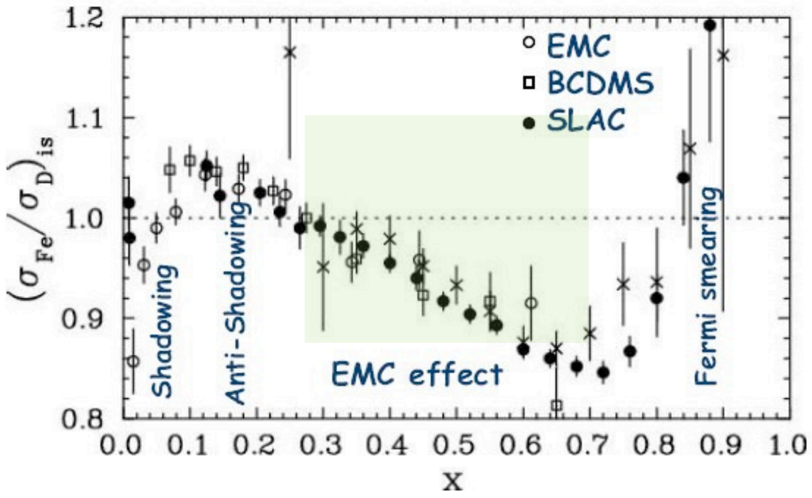
Afnan, et. al. PLB 493 36 (2000), PRC 035201 (2001), M. Sargsian PRC 66 024001 (2002)
Tropiano, et.al., PRC C 99, 035201 (2019), Alekhin et. al. PRC 107, L051506 (2023)

Motivation

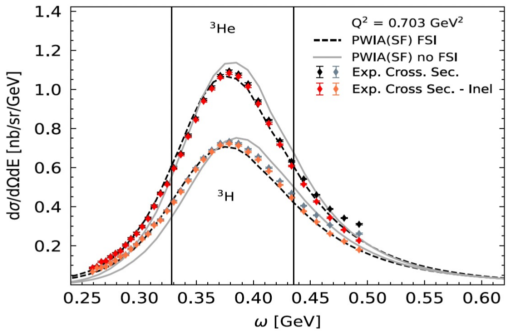
清華大學
Tsinghua University

■ MARATHON Experiment

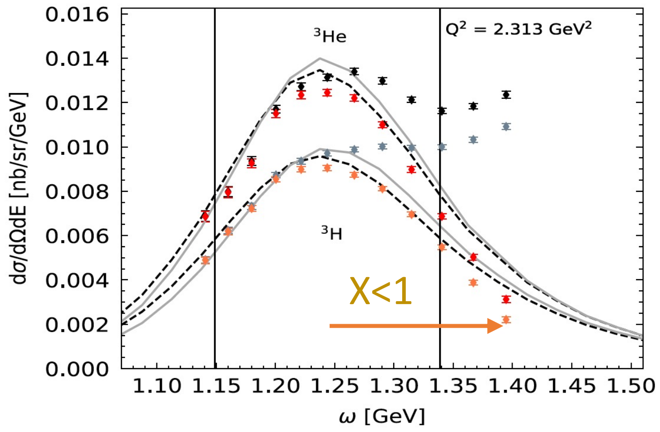
❖ **EMC Effect**: Per-nucleon DIS cross-section ratio between a nucleus-A to the deuteron decreases linearly in 0.3<x<0.7



- Nucleon must be modified
- No accepted explanation
- Isospin Dependence?

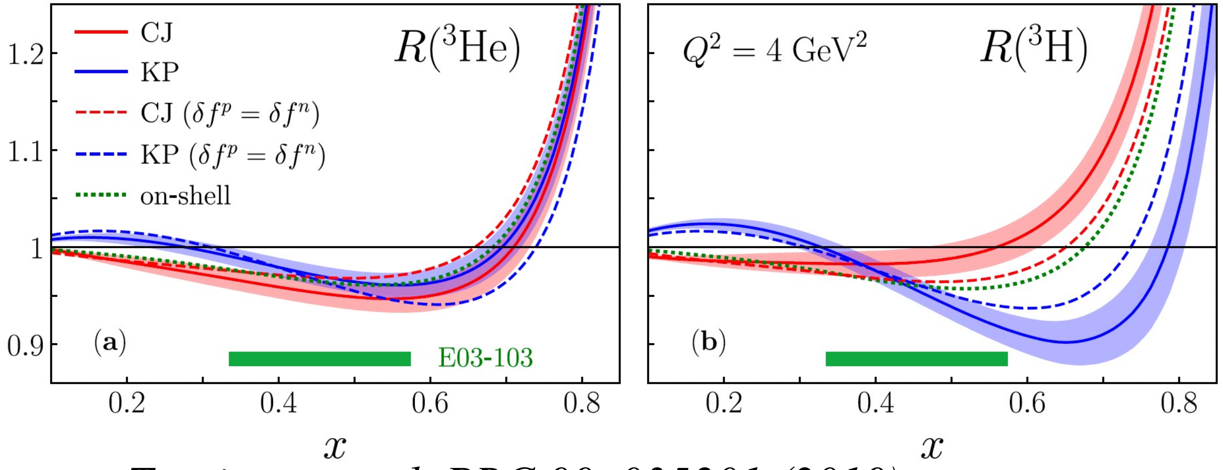


N. Santiesteban, PRL 132, 162501 (2024)



❖ Medium effect in A=3

- Fermi-motion (QE)
- Offshell effect
- High-Twist effects
- Quark modification (EMC Effect)?



Tropiano, et. al. PRC 99, 035201 (2019)

Tritium Target

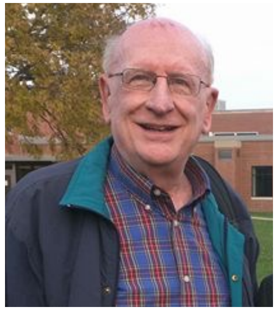
A 10-year effort!

- Allowed quantities have been dramatically reduced

Lab	Year	Quantity (kCi)	Thickness (g/cm²)	Current (µA)	Current x thickness (µA-g/cm²)
Stanford	1963	25	0.8	0.5	0.4
MIT-Bates	1982	180	0.3	20	6.0
Saskatoon	1985	3	0.02	30	0.6
JLab	**(2016)**	**1**	**0.08**	**20**	**1.6**

- Two big heroes :

Roy Holt (ANL)



Dave Meekins (JLab)

- Three Big Reviews (2010, 2015, 2016), Many tests
- Very detailed documentation of procedures of assembly, fill, transportation, storage, installation and operations
- Test the whole system during the Ar(e,e'p) Run in 2017

Tritium target technical reports

- Hall A Tritium Target System, D. Meekins *et al*, September, 2015
- A Tritium Gas Target for Jefferson Lab, R. J. Holt *et al*, July 13, 2015.
- Jefferson Lab Tritium Target Cell, D. Meekins, November 28, 2014
- Activation of a Tritium Target Cell, G. Kharashvili , June 25, 2014
- Thermomechanical Design of a Static Gas Target for Electron Accelerators, B. Brajuskovic et al., NIM A 729 (2013) 469.
- Absorption Risks for a Tritium Gas Target at Jefferson Lab, R. J. Holt, August 13, 2013.
- Beam-Induced and Tritium-Assisted Embrittlement of the Target Cell at JLab, **R. E. Ricker (NIST)**, R. J. Holt, D. Meekins, **B. Somerday (Sandia)**, March 4, 2013.
- Activation Analysis of a Tritium Target Cell for Jefferson Lab, R. J. Holt, D. Meekins, Oct. 23, 2012.
- Tritium Inhalation Risks for a Tritium Gas Target at Jefferson Lab, R. J. Holt, October 10, 2012.
- Tritium Permeability of the Al Target Cell, R. J. Holt, **R. E. Ricker (NIST)**, D. Meekins, July 10, 2012.
- Scattering Chamber Isolation for the JLab Tritium Target, T. O'Connor, March 29, 2012.
- Hydrogen Getter System for the JLab Tritium Target, T. O'Connor, W. Korsch, February 16, 2012.
- Tritium Gas Target Safety Operations Algorithm for Jefferson Lab, R. J. Holt, February 2, 2012.
- Tritium Gas Target Hazard Analysis for Jefferson Lab, E. Beise et al, January 18, 2012.
- Analysis of a Tritium Target Release at Jefferson Lab, **B. Napier (PNNL)**, R. J. Holt, January 10, 2012.
- Estimating the X-ray Dose Rate from the MARATHON Tritium Target, J. Singh, February 22, 2011.

Task force: R. J. Holt, A. Katramatou, W. Korsch, D. Meekins, T. O'Connor, G. Petratos, R. Ransome, J. Singh, P. Solvignon, B. Wojtsekhowki

Equipment Setup and Checklists

- TGT-PROC-17-001: Hall A and C Cryotarget Lifter Test and Certification
- TGT-PROC-17-005: HATT Tritium Exhaust System Configuration Verification
- TGT-PROC-17-008: Hall A CANS setup and test procedure for tritium mode
- TGT-PROC-17-009: HATT vacuum system exhaust verification checklist
- TGT-PROC-17-011: FSD Test/Verification Checklist
- TGT-PROC-17-014: Tritium alarm verification checklist

Cell Assembly

- TGT-PROC-17-004: HATT Tritium Cell Examination, Assembly, and Testing Procedure
- TGT-PROC-17-003: Cleaning Procedure for High Purity Fluid Service

Hall Access Procedures

- TGT-PROC-17-007: Hall A Truck Ramp Access for Tritium Mode

Installation/Removal

- TGT-PROC-17-002: Hall A Tritium Target Cell Installation
- TGT-PROC-17-006: Hall A Tritium Target Cell Removal
- TGT-PROC-17-015: Unpacking HATT cell from BTSP transfer to TSV
- TGT-PROC-17-016: Inspection of TSV prior to use
- TGT-PROC-18-003: Unpacking HATT cell from TSV transfer to BTSP

Operations

- TGT-PROC-17-010: HATT Operator Manual
- TGT-PROC-17-012: HATT commissioning - beam centering and checkout, ion chamber FSD calibration
- TGT-PROC-17-013: Hall A tritium target density study

Hall A Technical Procedures

- A-08-039-P: Installation Of Hall A Target Chamber Window Procedure
- A-17-001-P: Installation and Removal Of Platform On Pivot
- A-17-001-P: Valve actuator replacement
- A-17-003-P: Removal Of Hall A Target Chamber Window Assembly
- A-17-004-P: Collimator installation and removal

Operational Safety Procedures

- OSP for Cell Installation
- Unpack of BTSP
- Removal of Cell from Chamber
- Operation of the HATT

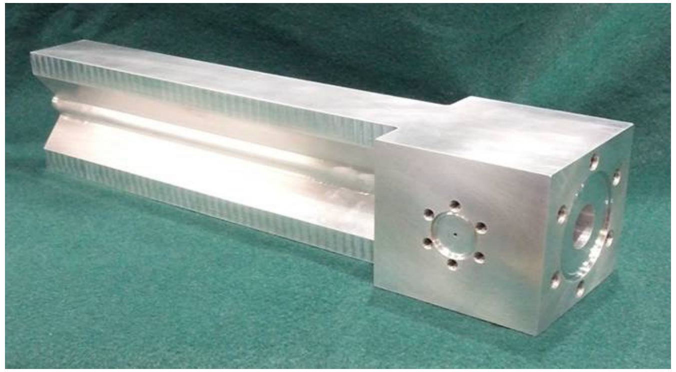
Manuals

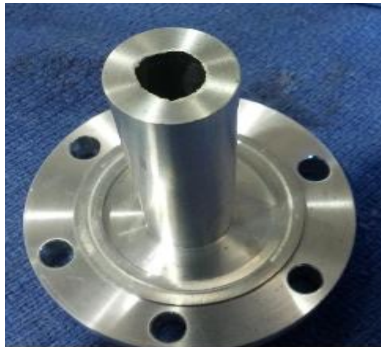
- Lakeshore 218 manual

Tritium Target

Target Cell:

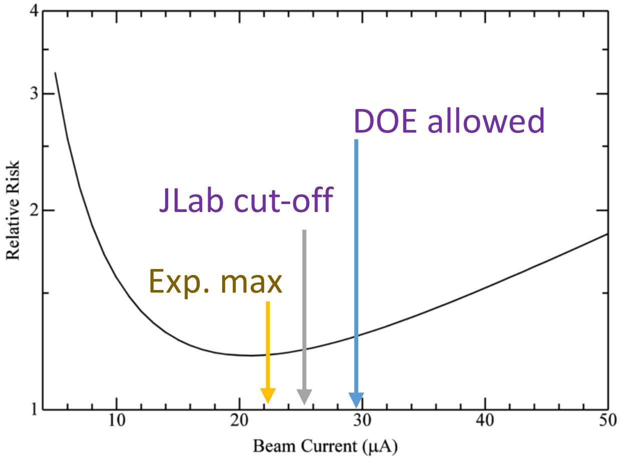
❖ Design and layout:

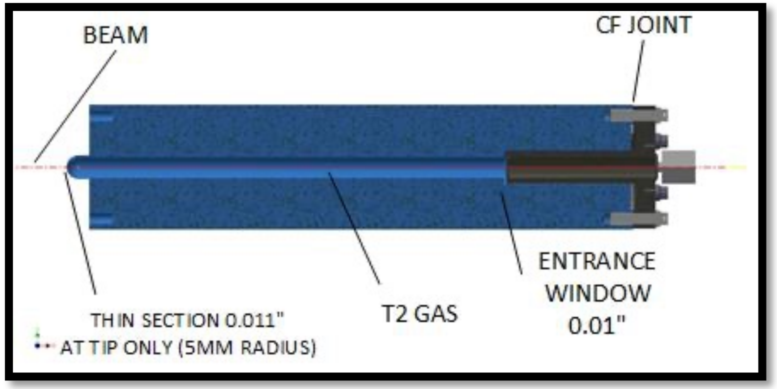




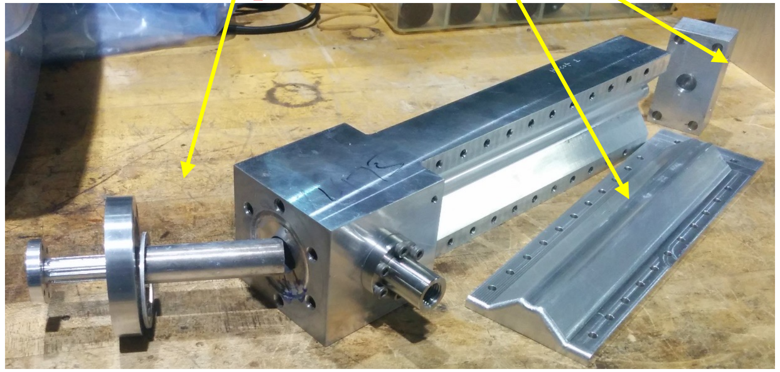
Tritium Specs:

- 1099 Ci
- 200 psia at room temperature
- Cool with 40K (from 15K helium-loop)
- Max Beam Current: 22.5 (~15W heat)





Extra protection when no in-used

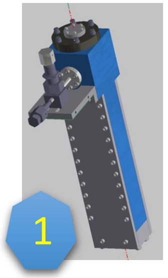


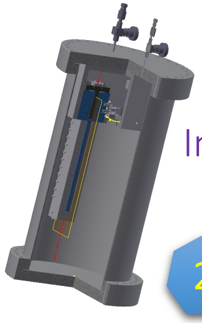
Tritium Target

■ Transportation and Installation

❖ Three-layer protection during transportation and storage

Tritium-cell

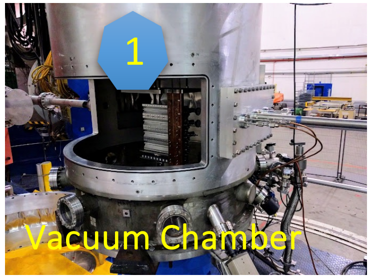


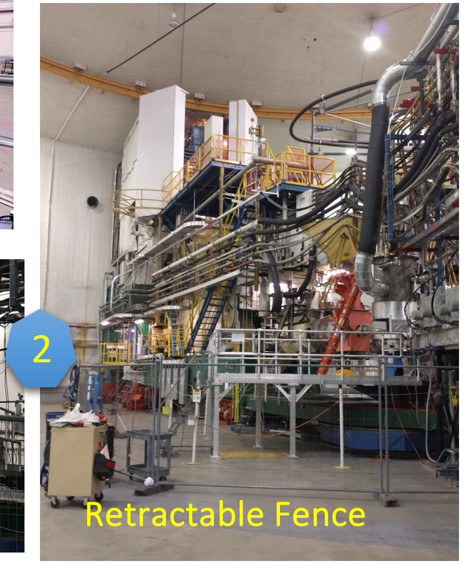


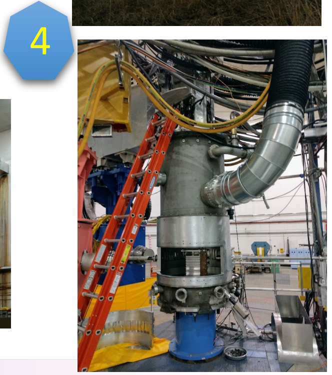
Intermediate Vessel

Military-Grade Container

❖ Three-layer protection during installation and in-use:







Last safty device to run Tritium!

Hall-A Tritium Experiments

From MARATHON to Four Experiments:

E12-10-103 (MARATHON)

- d/u Ratio at x→1
- EMC Effect

Spokespeople: G (Makis) Petratos, J. Gomez, A. Katramatou, R. Holt (J. Arrington), D. Meekins, R. Ransome,
PhD Students: T. Hague, M. Mycz, T. Su (Kent), J. Bane (Tennessee) Tyler Kutz (Stony Brooks), H. Liu (Columbia)

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)

E12-17-003 (Hypernucleus)

- Search for Lambda-N-N Hypernuclear

Spokespeople: F. Garibaldi, P. Markowitz, S. Nakamura, J. Reinhold, L. Tang, G. Urciuoli
PhD Student: Bishnu Pendey (Hampton)

E12-14-009 (Exclusive SRC)

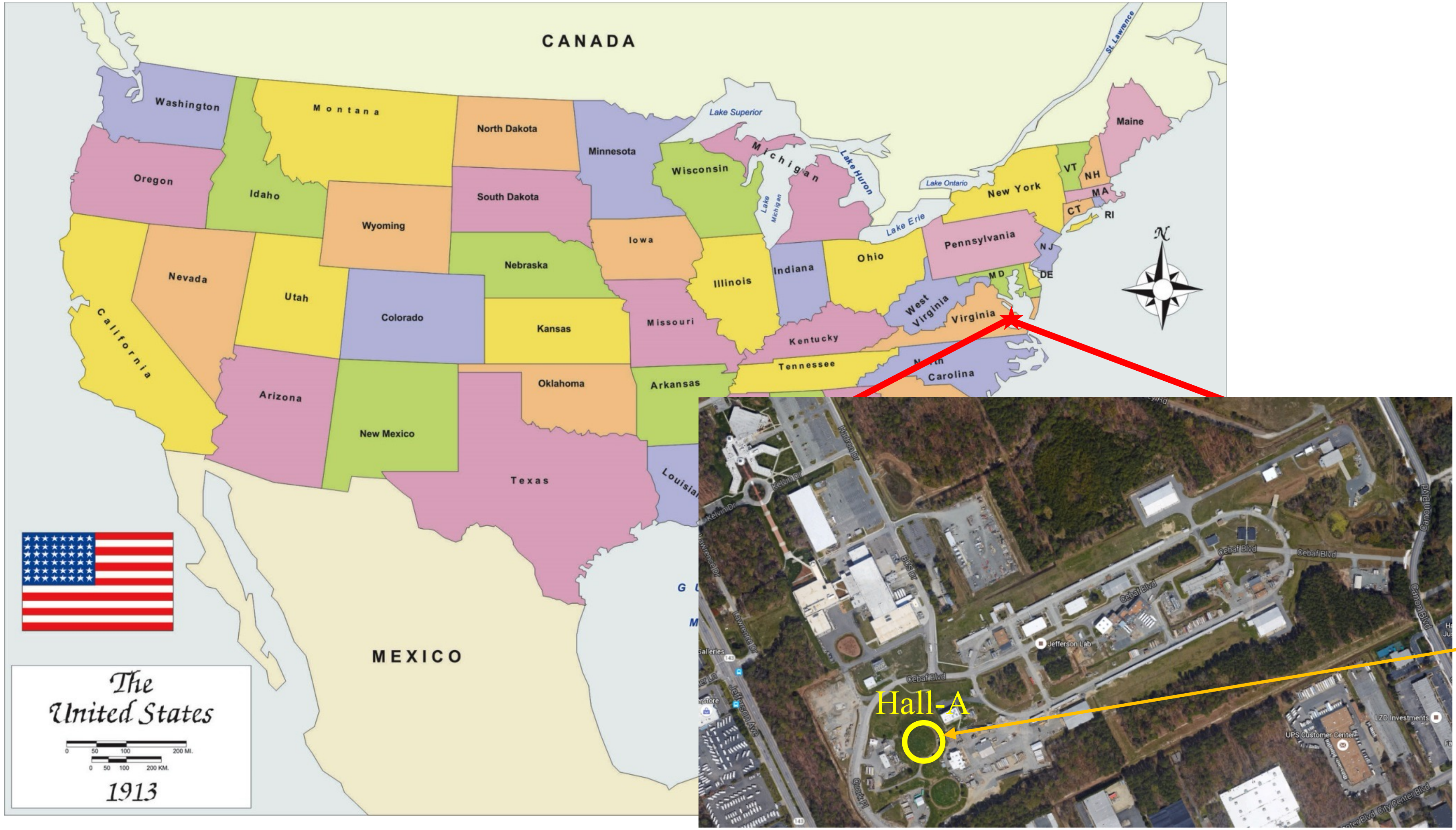
- Measure proton mom. dis. in ^{3}H & ^{3}He
- Verify in neutron-rich nuclei: $n_p(k)>n_n(k)$

Spokespeople: L. Weinstein, W. Boeglin, F. Hauenstein, O. Hen, S. Gilad
PhD Students: Reynier Cruz Torres (MIT)

Experimental Setup

■ Thomas Jefferson Lab

Located at Newport News, Virginia; Funded by Department of Energy; First operation in 1990s



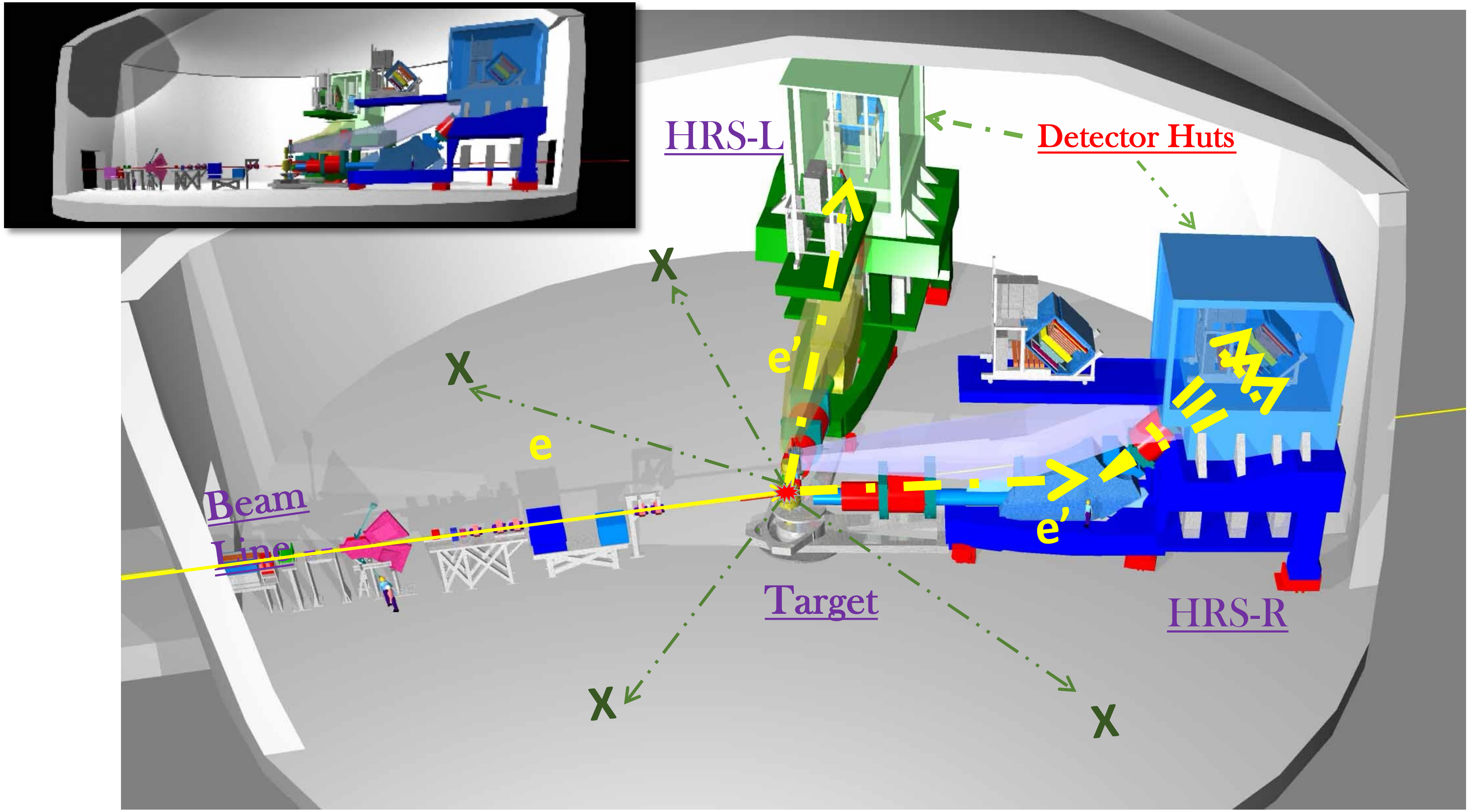
Jefferson Lab
Thomas Jefferson National Accelerator Facility

JSA

U.S. DEPARTMENT OF ENERGY

Experimental Setup

- Hall-A

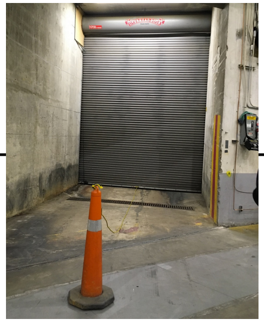


Inclusive Measurement (e, e')

Experimental Running

Tsinghua University

Road Map

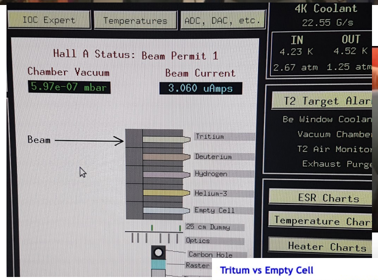


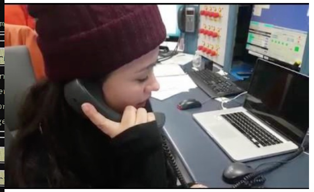
Beam on Tritium (12/15/2017, 6pm)

Ar-Run (Pre-Tritium)
Spring 2017

December-2017-Run

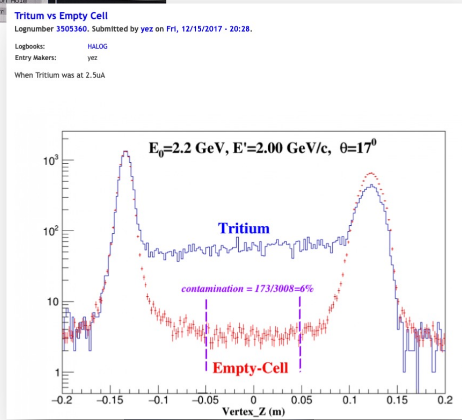
- CEBAF Started Oct. 2017
- CEBAF Tuning — Tritium Started 12/04/2017
- Attempt to get beam at any pass — First Tune-Beam 12/11/2017
- Commissioning, Inclusive SRC, 1st pass — First CW-Beam 12/13/2017, 10pm
- **Target-Motion Failed, Exp. Stopped 12/16/2017, 9pm**





Spring-2018-Run

- Restarted 01/12/2018
- CEBAF
- MARATHON, 5th pass — First-Beam 01/14/2018
- Exclusive SRC, 2nd pass — Exp. Changed, Pass change 04/09/2017
- Inclusive-SRC, 1st pass — Exp. Changed, pass-change 05/03/2017
- Ended for Summer Shut-Down 05/06/2018
- Tritium-Cell Sent back



New
Tritium-Cell

Fall-2018-Run

- CEBAF Started Aug. 2018 (gave up early runs)
- CEBAF Tuning — Tritium Started 09/19/2018
- Inclusive SRC, 2nd pass — First-Beam 09/26/2018
- Elastic Attempt — Exp. Changed 10/24/2018
- Hypernucleus, 2nd pass — Exp. Started 10/26/2018
- Tritium Ended 11/20/2018

Already Published Results

Tsinghua University

Nuclear Inst. and Methods in Physics Research, A 940 (2019) 351–358

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

Density changes in low pressure gas targets for electron scattering experiments

S.N. Santiesteban [a], S. Alsalmi [b], D. Meekins [c], C. Ayerbe Gayoso [e], J. Bane [d], S. Barcus [e], J. Campbell [f], J. Castellanos [g], R. Cruz-Torres [h], H. Dai [i], T. Hague [b], F. Hauenstein [j]

PHYSICAL REVIEW LETTERS 124, 212501 (2020)

Editors' Suggestion

Probing Few-Body Nuclear Dynamics via ^{3}H and ^{3}He $(e,e'p)pn$ Cross-Section Measurements

R. Cruz-Torres,[1,*] D. Nguyen,[1,2,*] F. Hauenstein,[3] A. Schmidt,[1] S. Li,[4] D. Abrams,[5] H. Albataineh,[6] S. Alsalmi,[7]

PHYSICAL REVIEW LETTERS 132, 162501 (2024)

Novel Measurement of the Neutron Magnetic Form Factor from A = 3 Mirror Nuclei

S. N. Santiesteban,[1,*] S. Li,[1,2] D. Abrams,[3] S. Alsalmi,[4,5] D. Androic,[6] K. Aniol,[7] J. Arrington,[2,8] T. Averett,[9]

Physics Letters B 831 (2022) 137165

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Search for a bound di-neutron by comparing ^{3}He(e,e'p)d and ^{3}H(e,e'p)X measurements

D. Nguyen [a,b,1], C. Neuburger [c,1], R. Cruz-Torres [d,b], A. Schmidt [e,b], D.W. Higinbotham [a,*], J. Kahlbow [b,c], P. Monaghan [f], E. Piasetzky [c], O. Hen [b]

PHYSICAL REVIEW C 105, L051001 (2022)

Letter

Spectroscopic study of a possible Λnn resonance and a pair of ΣNN states using the $(e,e'K^+)$ reaction with a tritium target

B. Pandey,[1] L. Tang,[1,2,*] T. Gogami,[3,4] K. N. Suzuki,[4] K. Itabashi,[3] S. Nagao,[3] K. Okuyama,[3] S. N. Nakamura,[3] D. Abrams,[5]

arXiv: 2404.16235 (submitted)

Inclusive studies of two- and three-nucleon short-range correlations in ^{3}H and ^{3}He

S. Li,[1,2,*] S. N. Santiesteban,[1] J. Arrington,[2,3] R. Cruz-Torres,[4] L. Kurbany,[1] D. Abrams,[5]

PHYSICAL REVIEW LETTERS 128, 132003 (2022)

Measurement of the Nucleon F_2^n/F_2^p Structure Function Ratio by the Jefferson Lab MARATHON Tritium/Helium-3 Deep Inelastic Scattering Experiment

D. Abrams,[1] H. Albataineh,[2] B. S. Aljawrneh,[3] S. Alsalmi,[4,5] D. Androic,[6] K. Aniol,[7] W. Armstrong,[8] J. Arrington,[8,9]

arXiv: 2402.08199 (submitted)

A=3 (e,e') $x_B \geq 1$ cross-section ratios and the isospin structure of short-range correlations

A. Schmidt,[1] A. W. Denniston,[2] E. M. Seroka,[1] N. Barnea,[3] D.W. Higinbotham,[4] I. Korover,[5]

Physics Letters B 797 (2019) 134890

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Comparing proton momentum distributions in $A = 2$ and 3 nuclei via ^{2}H ^{3}H and ^{3}He $(e,e'p)$ measurements

Jefferson Lab Hall A Tritium Collaboration

R. Cruz-Torres [a], S. Li [b], F. Hauenstein [c], A. Schmidt [a], D. Nguyen [d], D. Abrams [d],

Article Nature 609, 41 (2022)

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],

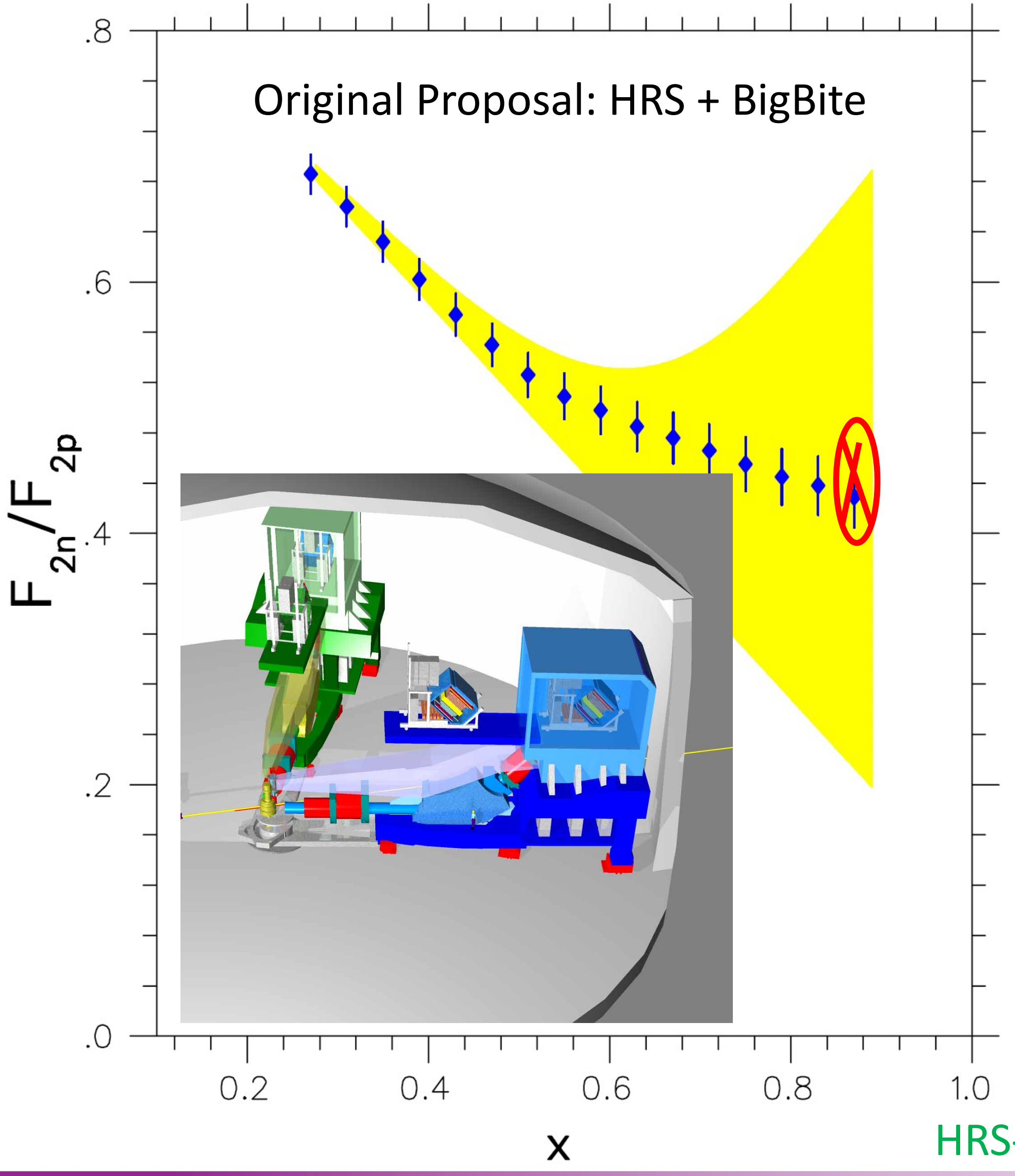
DRAFT ***** Measurement of the EMC Effect of Tritium and Helium-3 by the JLab MARATHON Experiment ***** DRAFT

D. Abrams,[1] H. Albataineh,[2] B. S. Aljawrneh,[3] S. Alsalmi,[4,5] D. Androic,[6] K. Aniol,[7] W. Armstrong,[8]

(in preparation)

Data Analysis

■ Kinematic Settings



HRS-R

Kin#	x_{bj} (x_{bj}^{avg})	W^2 (W^2_{avg})	Q^2	E'	θ
16	0.818 (0.774)	3.51 (4.17)	11.82	2.90	36.12
15	0.778 (0.737)	4.00 (4.60)	10.95	3.10	33.55
14	0.738 (0.703)	4.57 (5.08)	10.39	3.10	32.65
13	0.698 (0.668)	5.13 (5.57)	9.82	3.10	31.73
12	0.658 (0.632)	5.69 (6.07)	9.26	3.10	30.79
11	0.618 (0.595)	6.26 (6.60)	8.70	3.10	29.81
10	0.578 (0.558)	6.82 (7.12)	8.13	3.10	28.81
9	0.538 (0.520)	7.38 (7.65)	7.57	3.10	27.77
8	0.498 (0.482)	7.95 (8.18)	7.01	3.10	26.70
7	0.458 (0.444)	8.51 (8.71)	6.45	3.10	25.59
6	0.418 (0.406)	9.07 (9.25)	5.88	3.10	24.43
5	0.378 (0.367)	9.63 (9.79)	5.32	3.10	23.21
4	0.338 (0.329)	10.20 (10.34)	4.76	3.10	21.93
3	0.298 (0.290)	10.76 (10.88)	4.19	3.10	20.58
2	0.258 (0.250)	11.32 (11.43)	3.63	3.10	19.14
1	0.218 (0.211)	11.89 (11.98)	3.07	3.10	17.58

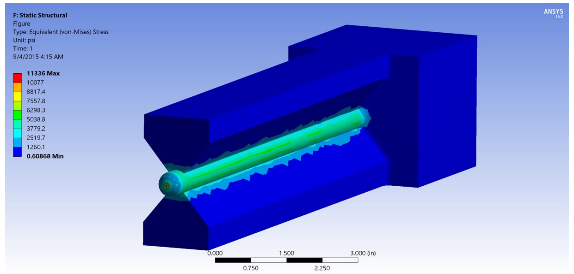
HRS-L

- ❑ Beam time cut by half
- ❑ BigBite wasn't avaiblable
- ❑ New experimental design with only HRSs
- ❑ x → 0.82 (W^2<=3.5 GeV^2)
- ❑ Drop x ~ 0.87

^1H & ^2D data

Data Analysis

Target Boiling Correction



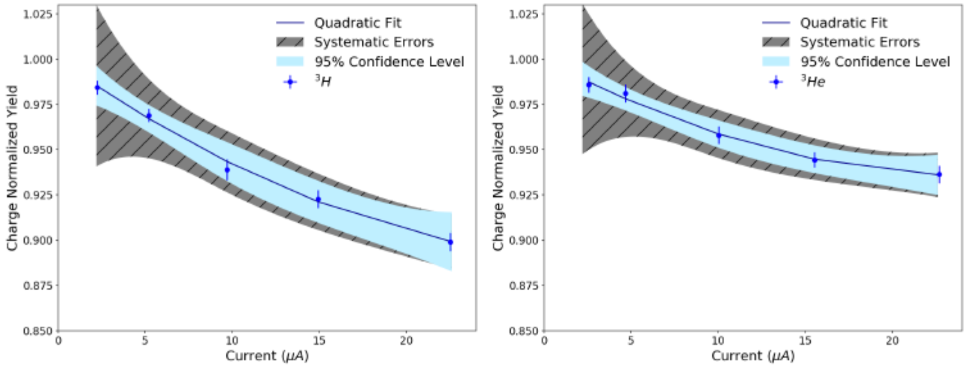
- Localized density fluctuation due to heat deposition from beam
- Different gas targets respond to beam variation differently

  → Affect measured quantities, like cross-section & ratio
- A boiling study was performed:
  - Measured normalized electron yields at 2.5uA, 5uA, 10uA, 15uA, 22.5uA

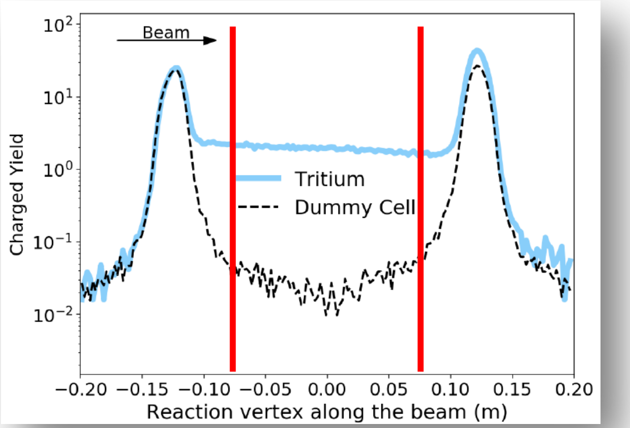
$$Y_{\text{norm}} = \frac{PS \cdot N}{Q \cdot \epsilon \cdot LT}$$

  - Fit yields vs current quadratically

$$f(I_{\text{beam}}) = a \cdot I_{\text{beam}}^2 + b \cdot I_{\text{beam}} + c$$



(a) ^{3}H Density Analysis. (b) ^{3}He Density Analysis.



- Apply boiling corrections to extracted yields and cross sections.

S. Santiesteban, et. al., NIM (2019) 06 025

^{3}H Fit Parameters		^{3}H Correlation Factors	
a	$(1.06 \pm 0.36) \times 10^{-4}$	C(a, b)	−0.974
b	$(-6.8 \pm 0.89) \times 10^{-3}$	C(b, c)	−0.888
c	1. + / − 0.003	C(a, c)	0.801
^{3}He Fit Parameters		^{3}He Correlation Factors	
a	$(1.04 \pm 0.25) \times 10^{-4}$	C(a, b)	−0.973
b	$(-5.1 \pm 0.64) \times 10^{-3}$	C(b, c)	−0.879
c	1 ± 0.003	C(a, c)	0.779

Data Analysis

Trtium Decay Evaluation

- Tritium decays into He3, w/ half-live-time: $t_{1/2} = \ln(2)\tau = (4500 \pm 8)$ days
- The contents of Tritium and He3 when filling the cell (Oct 2017) were given:

$$\eta_T^0 = (0.077 \pm 0.001)\ \mathrm{g\ cm^{-2}} \qquad \eta_{He}^0 = (2.26 \pm 0.452) \times 10^{-5}\ \mathrm{g\ cm^{-2}}$$

- w/ known time spent at JLab, the updated densities were:

$$n_T \equiv n_T(t) = n_T^0\ e^{-t/\tau} \qquad n_{He} \equiv n_{He}(t) = n_{He}^0 + n_T^0(1 - e^{-t/\tau})$$

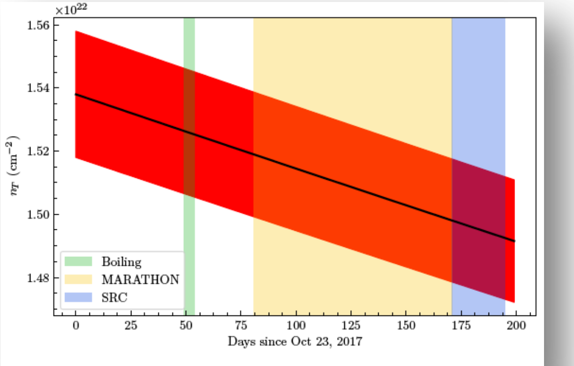


Figure 1: Number density of ^{3}H

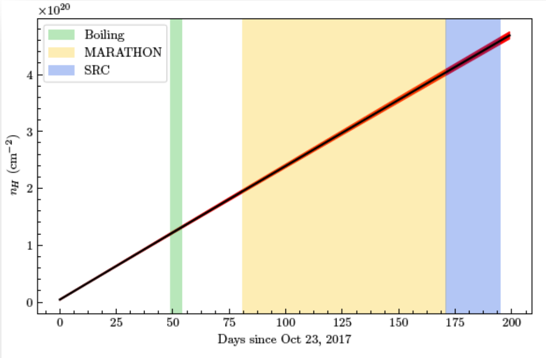


Figure 2: Number density of ^{3}He

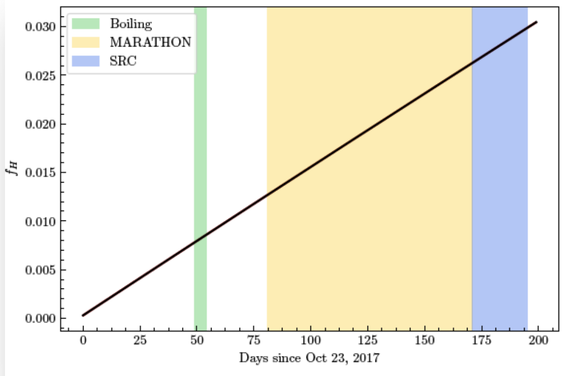
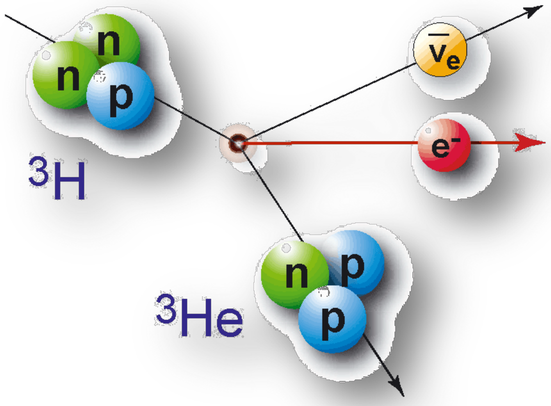


Figure 3: Helium fraction $n_H/(n_{tot})$



- Tritium measurement have to be corrected for Helium-3 contaminations

$$Y_T = Y_{raw}\left(\frac{Q_{tot}}{Q_{tot} - \langle f_{He} \rangle}\right) - Y_{He}\left(\frac{\langle f_{He} \rangle}{Q_{tot} - \langle f_{He} \rangle}\right)$$

Y_{He} was obtained from the He3-cell runs

$$\langle f_{He} \rangle \equiv \sum_i Q_i f_{He_i} \qquad f_{He} \equiv f_{He}(t) = \frac{n_{He}}{n_T + n_{He}} = \frac{n_{He}}{n_{tot}}$$

Data Analysis

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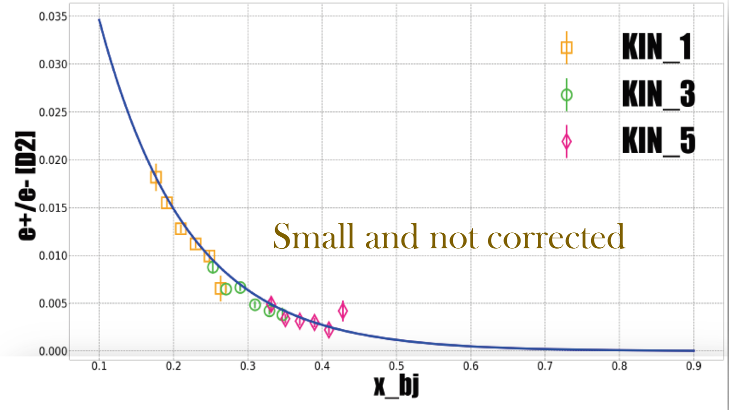
Background Evaluation

- Experimental observables: cross-section ratios
- Lots of systematic uncertainties are cancelled in the ratios
- However, the background won't!

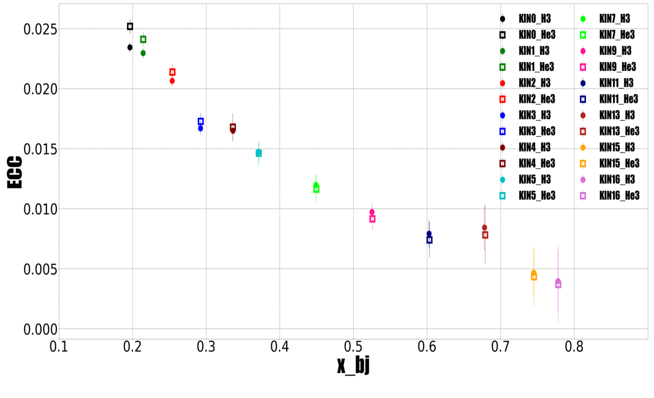
Major sources of background

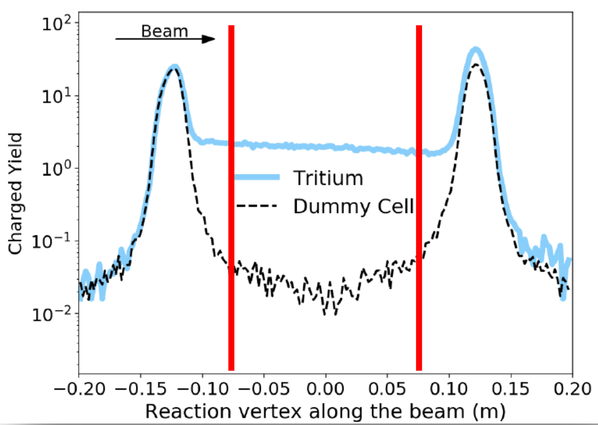
- Misidentified "electrons" → PID Study
- Electrons coming from endcaps → Target Vertex-Z Cuts
- Electrons coming from other reactions → Physics Quantities Cuts
- Secondary electrons → Optics Cuts & PID
- gamma->e^+e^- conversion → "Positron" Runs

- For MARATHON, a dedicated "Positron" runs at low-x (positive HRS-L)



- Endcap-contamination:
  - ✓ Empty-Target (or Dummy Foils) runs
  - ✓ An optimized Z-cuts





Data Analysis

Ratio Extractions

- Experimental yield: $Y(x) = \frac{N_{e'}}{N_e(\rho/A)_t L_t} C_{cor}$

$$C_{cor} = C_{det} C_{cdt} C_{den} C_{tec} C_{psp} C_{rad} C_{cde} C_{bin} C_{dth}$$

Dead time, End caps, Radiation, Bin Center, Detector Eff., Density (boiling), PID, Coulomb, ^{2}T-decay

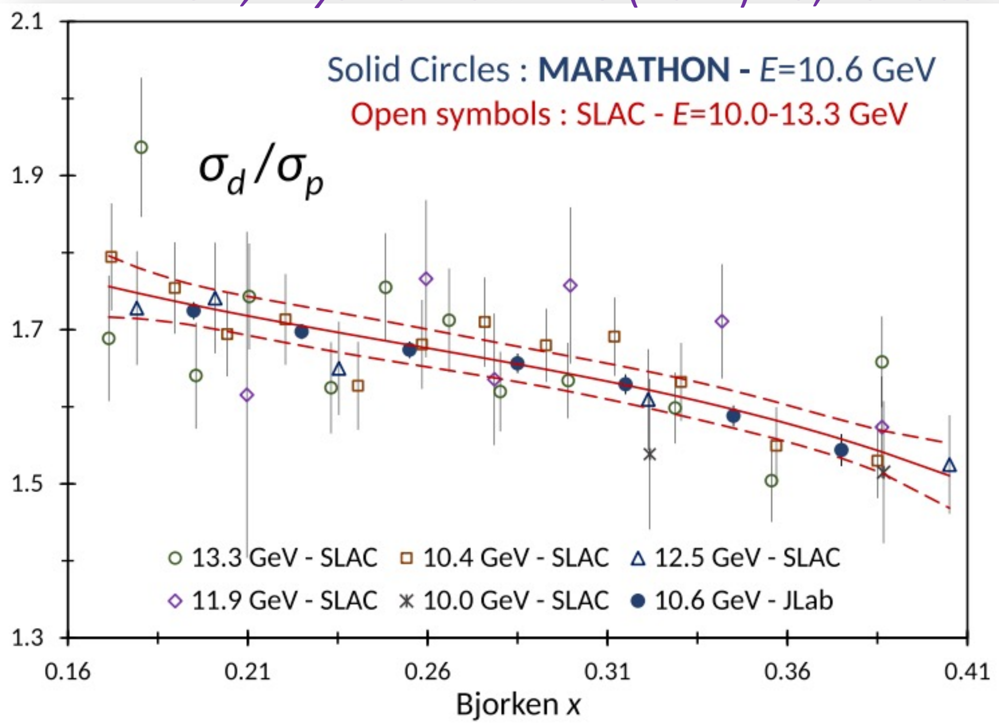
- Differential cross-sections: $\frac{d\sigma}{dE'd\Omega}(x) = Y(x)/(\Delta E \Delta \Omega)$

- Cross-section ratios→yield ratios: $\frac{\sigma_{A1}}{\sigma_{A2}} = \frac{Y_{A1}}{Y_{A2}}$

  ✓ Many experimental corrections cancelled
  ✓ Boiling effect corrected w/ syst. Err [0.1%~0.5%]
  ✓ Radiation and bin-centering corrections use KP models (model-dependent syst. Error [0.25%~0.45%])

  KP model: PRC82 054614 (2010), NPA765,126 (2006)

MARATHON, *Phys.Rev.Lett.* 128 (2022) 13, 132003



- Measured proton (p) and deutron (d) cross-section ratios:

$$F_2^n/F_2^p = (F_2^d/F_2^p)/R_d - 1$$

KP models

Agreed with SLAC and BoNUS data (overal systmatic check!)

Results & Discussion

■ Cross-Section & F2n/F2p Ratio:

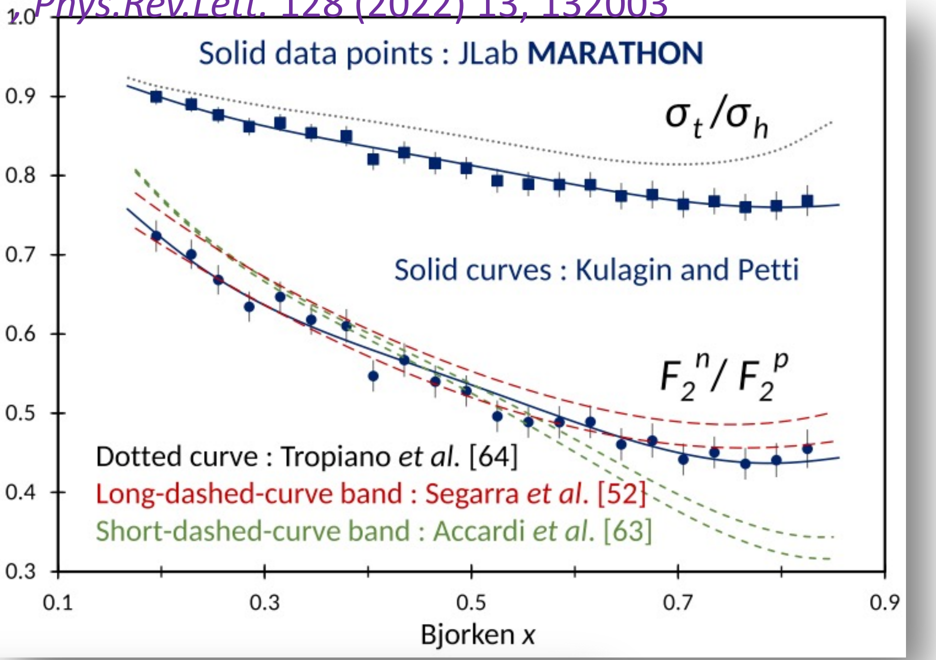
- A=3 Ratio: $\frac{\sigma_t}{\sigma_h} = \frac{Y_t}{Y_h} = \frac{F_2^t}{F_2^h}$ (model-independent!)

$$\frac{F_2^n}{F_2^p} = \frac{2\mathcal{R}_{ht} - F_2^h / F_2^t}{F_2^h / F_2^t - \mathcal{R}_{ht}}$$

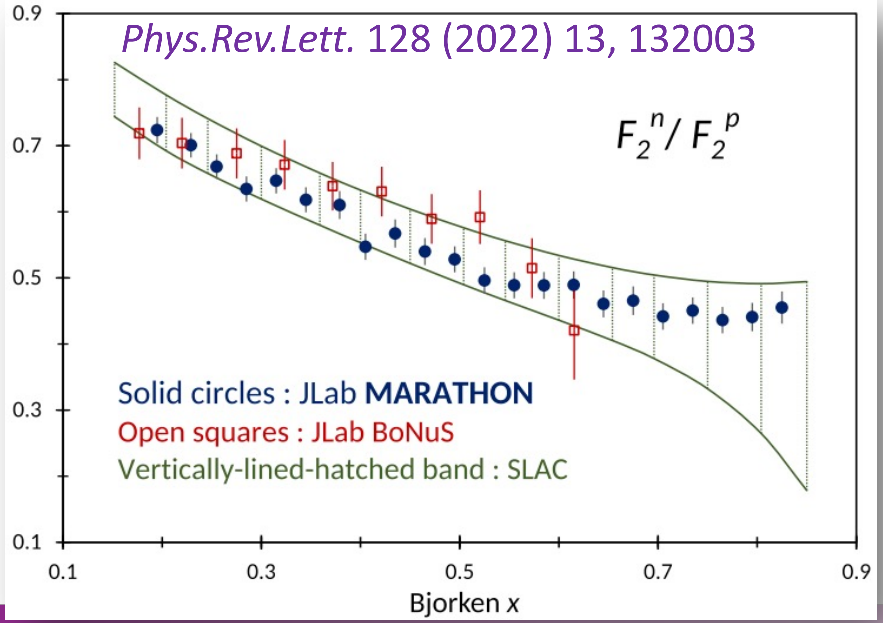
- KP-model used for $\mathcal{R}_{ht}$, syst. error estimated and included
- Good agreement; No iteration needed $\mathcal{R}_{ht}$

- **Normalization**: To match the F_2^n / F_2^p at $x = 0.31$, a factor of 1.025 +/- 0.007 normalization applied to all σ_h/σ_t ratios

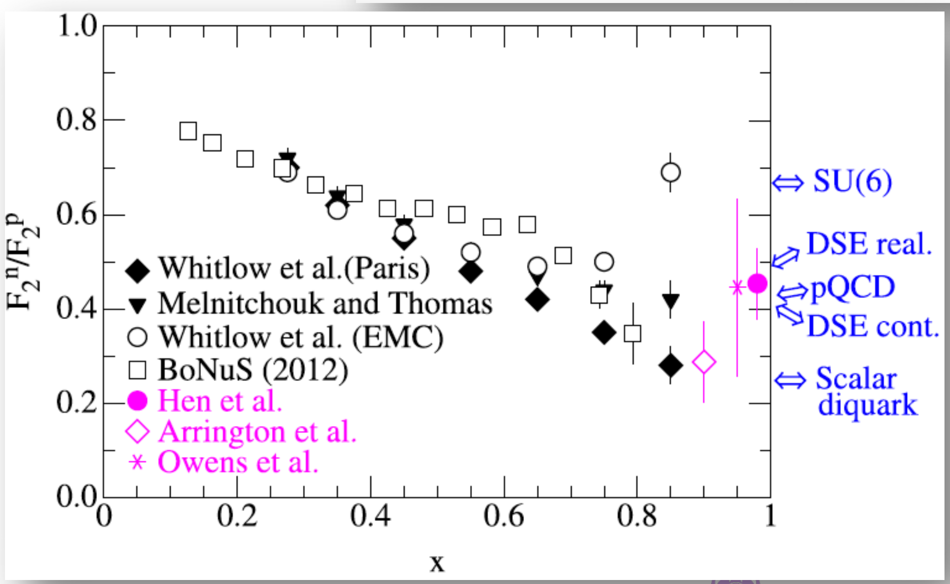
Phys.Rev.Lett. 128 (2022) 13, 132003



Phys.Rev.Lett. 128 (2022) 13, 132003



VS



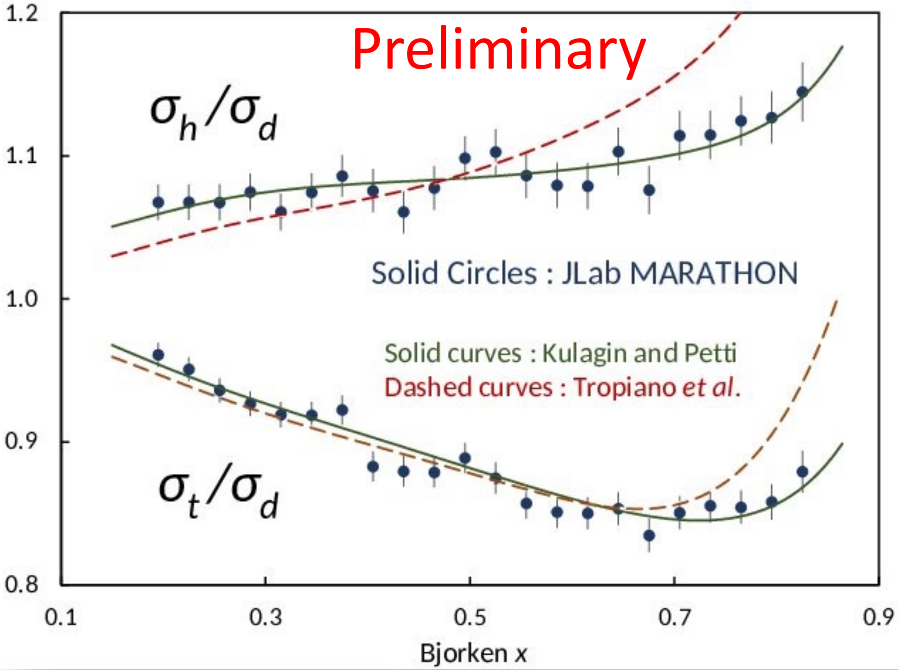
Results & Discussion

EMC Effect in A=3 (Preliminary):

- Identical to extract Deutron (d) yields (model-independent):

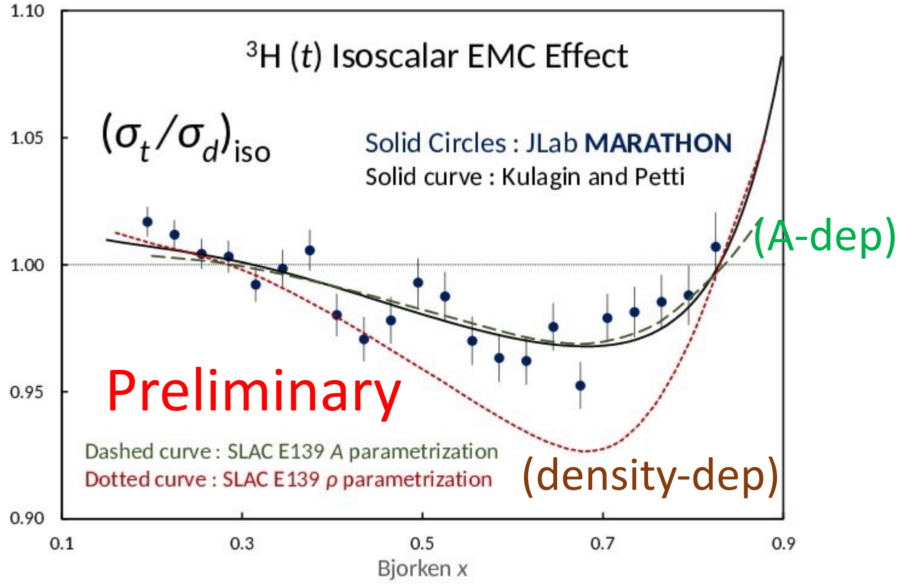
$$\frac{\sigma_h}{\sigma_d} = \frac{Y_h}{Y_d}, \frac{\sigma_t}{\sigma_d} = \frac{Y_t}{Y_d}$$

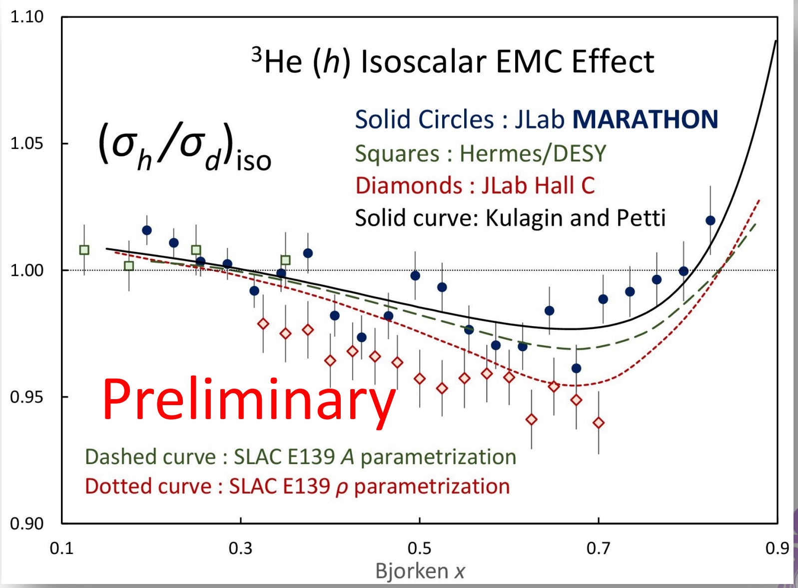
- Normalized $\sigma h/\sigma_d$ ratios w/ 1.021+/-0.005 and σ_t/σ_d ratios w/ 0.996 +/- 0.005



- Isocaler EMC ratios (corrected with KP-model):

$$(\sigma_h/\sigma_d)_{IS} = \frac{1}{2}\left[\sigma_h/\sigma_d + \mathcal{R}_{ht}(\sigma_t/\sigma_d)\right],$$
$$(\sigma_t/\sigma_d)_{IS} = \frac{1}{2}\left[\sigma_t/\sigma_d + (\sigma_h/\sigma_d)/\mathcal{R}_{ht}\right],$$





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New Efforts outside the MARATHON Collaboration

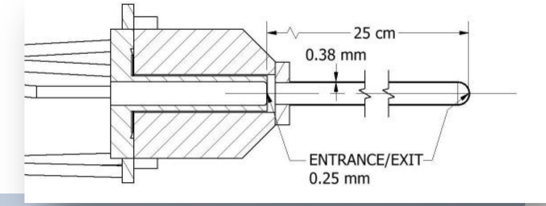
Second Tritium Run-Group

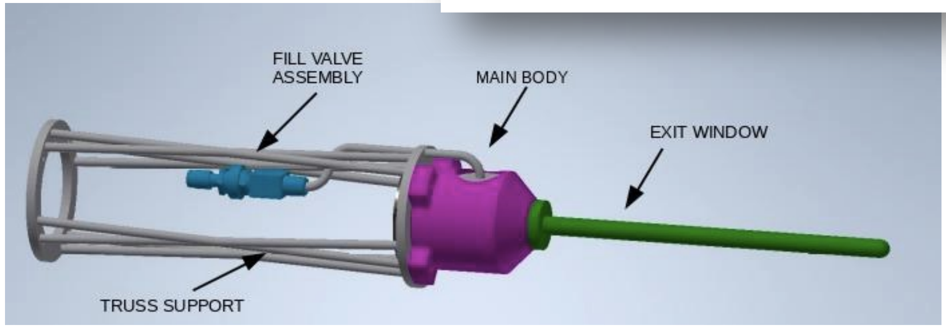
➢ New Tritium-Targets in Hall-B:

- ❖ Approved E12-20-005 at 6.6 GeV w/ CLAS12 (Tritium-SRC)
- ❖ New Target-System design for ^{2}D, ^{3}H and ^{3}He

Material	Tritium	Al Windows	Be Window	Total
Length(g/cm^2)	0.085	0.21	0.037	0.33
Luminosity	3.54×10^{34}	8.42×10^{34}	1.54×10^{34}	1.35×10^{35}

maximum luminosity





- ❖ Lifetime opportunity → What more we can do?
- ❖ DIS with ^{3}H/^{3}He Mirror Nuclei using 10.6 GeV electron beam
  - SIDIS
    - ✓ Nuclear PDF in A=3, Flavor-Dependent EMC Effect
    - ✓ Nuclear-TMD (nTMD) and Nuclear-Fragmentation Function (nFF)
  - DVCS/DVMP
    - Neutron-GPD (incoherence)
    - Nuclear-GPD (nGPD)) in A=3 (coherence)
  - More?

- Plentiful other physics topics!

C12-21-004:

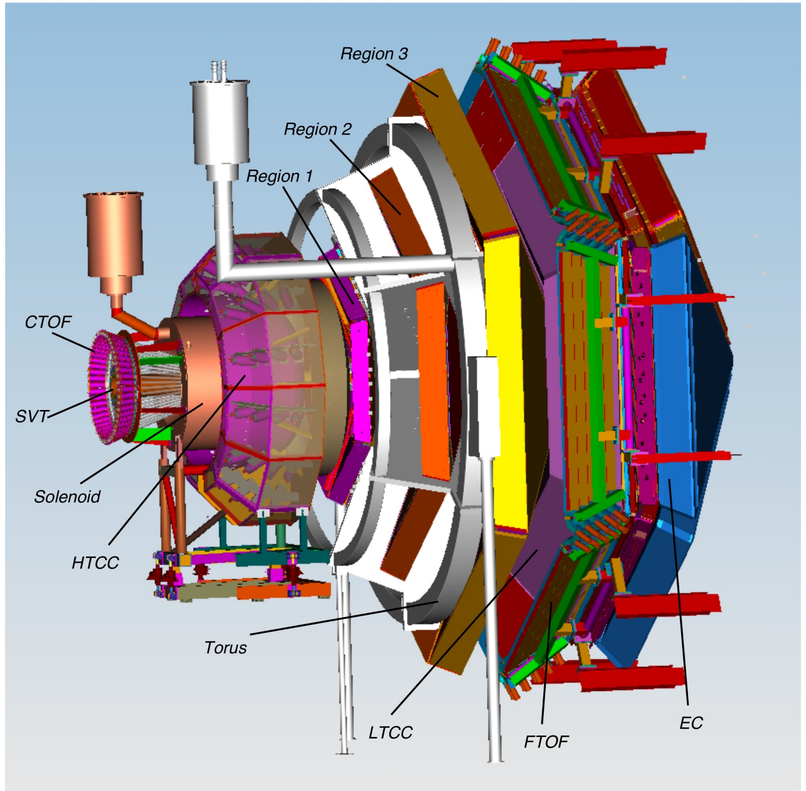
- Conditionally approved in PAC49
- Spokespeople: D. Dutta, D. Gaskell, O. Hen, D. Meekins, D. Nguyen, L. Weinstein, J. R. West, Z. Ye
- arXiv: 2202.09696

Second Tritium Run-Group

➢ Proposed SIDIS Measurement (C12-21-004):

- Same new Tritium target system
- Standard CLAS12
- 50+8 days of beam time requested
- Detected electrons, pions and maybe kaons w/ RICH)
  - Flip the Torus field often to minimize the different acceptance of +/- charged particles
- SIDIS Kinematic cuts:
  $Q^2 > 1$ GeV^2 , $W^2 > 4$ GeV, $0.1 < y < 0.85$, $0.3 < z < 0.7$
- Bin the data in 4D (Q^2, x, z, P_T)
- Error budget: overall 1% point to point

	Sectors	Tracking	Vertex	Fiducial	Acceptance
Uncertainty (%)	0.34	0.13	0.16	0.41	0.1



Tritium-SIDIS (C12-21-004)

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➢ Proposed SIDIS Measurement:

- ☐ Observables→ unpolarized SIDIS cross-sections

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

Free or Nuclear PDF (nPDF)

Free or Nuclear Fragmentation Function (nFF)

- ☐ Super-ratios of charge-sum &-difference:

$$(\sigma_A^{\pi^+} \pm \sigma_A^{\pi^-})/A \propto [4(u_A \pm \bar{u}_A) \pm (d_A \pm \bar{d}_A)] \cdot [D_A^+ \pm D_A^-],$$

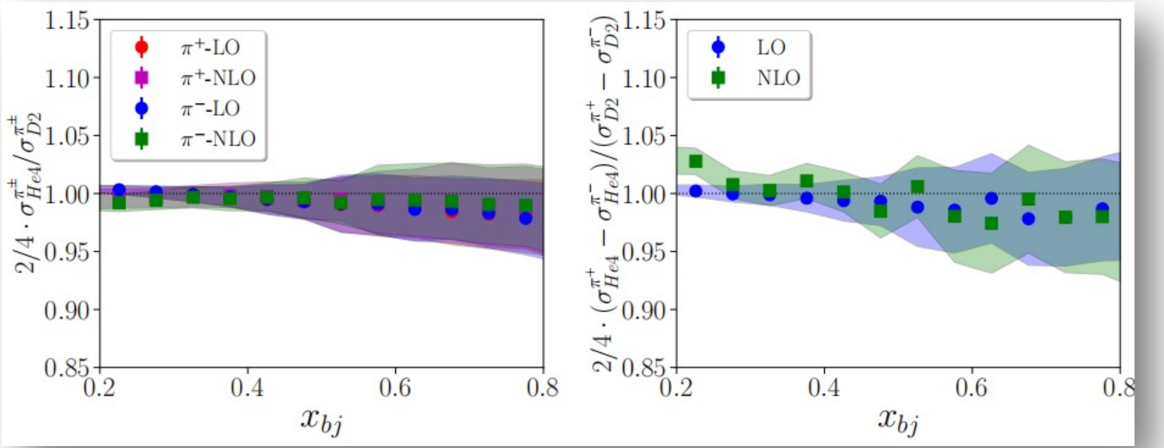
$$R^{\pi,\pm}_{A_1/A_2}(x,z) \simeq \frac{(\sigma_{A_1}^{\pi^+} \pm \sigma_{A_1}^{\pi^-})/A_1}{(\sigma_{A_2}^{\pi^+} \pm \sigma_{A_2}^{\pi^-})/A_2} \simeq \frac{4(u_{A_1} \pm \bar{u}_{A_1}) \pm (d_{A_1} \pm \bar{d}_{A_1})}{4(u_{A_2} \pm \bar{u}_{A_2}) \pm (d_{A_2} \pm \bar{d}_{A_2})} \cdot B^{\pm}_{A_1/A_2}(z),$$

- ☐ nFF parts most cancelled:

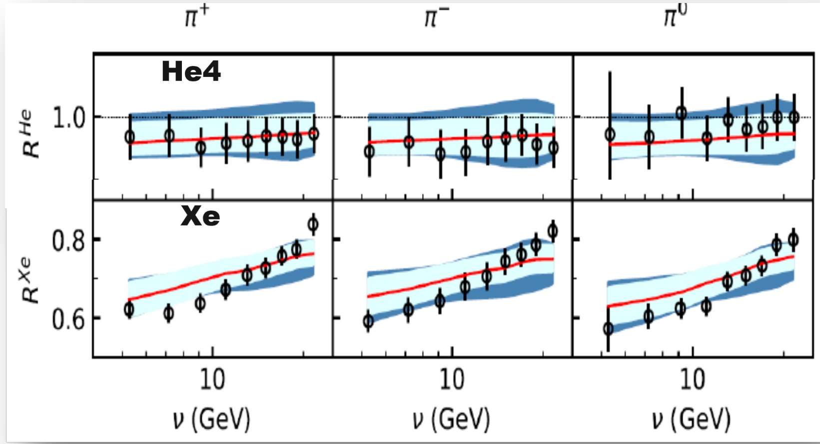
$$B^{\pi,\pm}_{H/T}(z) \simeq B^{\pi,\pm}_{H/D}(z) \simeq B^{\pi,\pm}_{T/D}(z) \simeq 1$$

D->^{2}D, T→^{3}H, H→^{3}He

✓ LO approximation seems effective



arXiv: 2202.09696



✓ He4's nFFs have small medium effects (~ 5% at high-z), (Pia Zurita, arXiv:2101.01088)

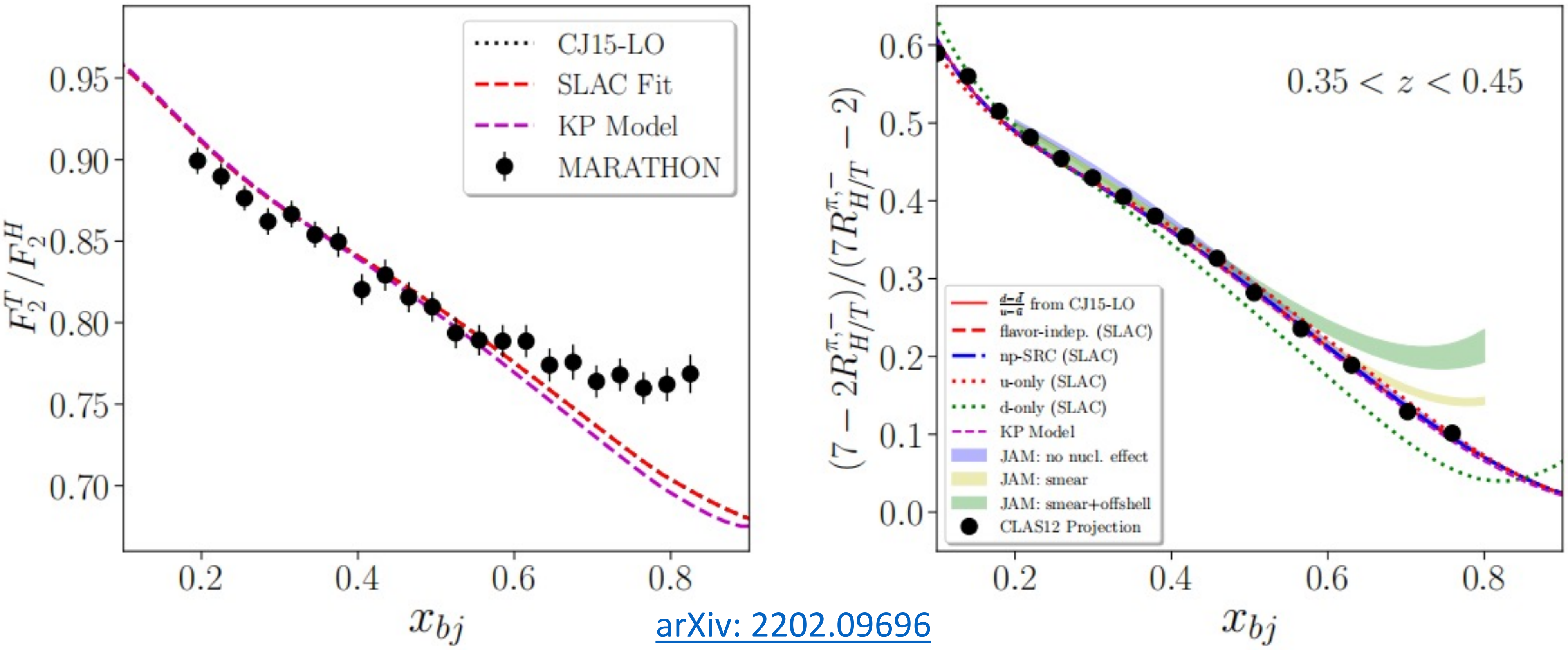
✓ nFF of D, T & H have smaller medium effects and similar

Tritium-SIDIS (C12-21-004)

➢ Verify "d/u" with A=3

- Model-independently measure nuclear-effects of d/u w/ A=3 at high-x

$$R^{\pi,-}_{H/T} = \frac{(\sigma^{\pi^+}_H - \sigma^{\pi^-}_H)}{(\sigma^{\pi^+}_T - \sigma^{\pi^-}_T)} \simeq \frac{4u_H - d_H}{4u_T - d_T} \quad \Rightarrow \quad \frac{\tilde{d}}{\tilde{u}} \simeq \frac{7 - 2R^{\pi,-}_{H/T}}{7R^{\pi,-}_{H/T} - 2}$$



arXiv: 2202.09696

Tritium-SIDIS (C12-21-004)

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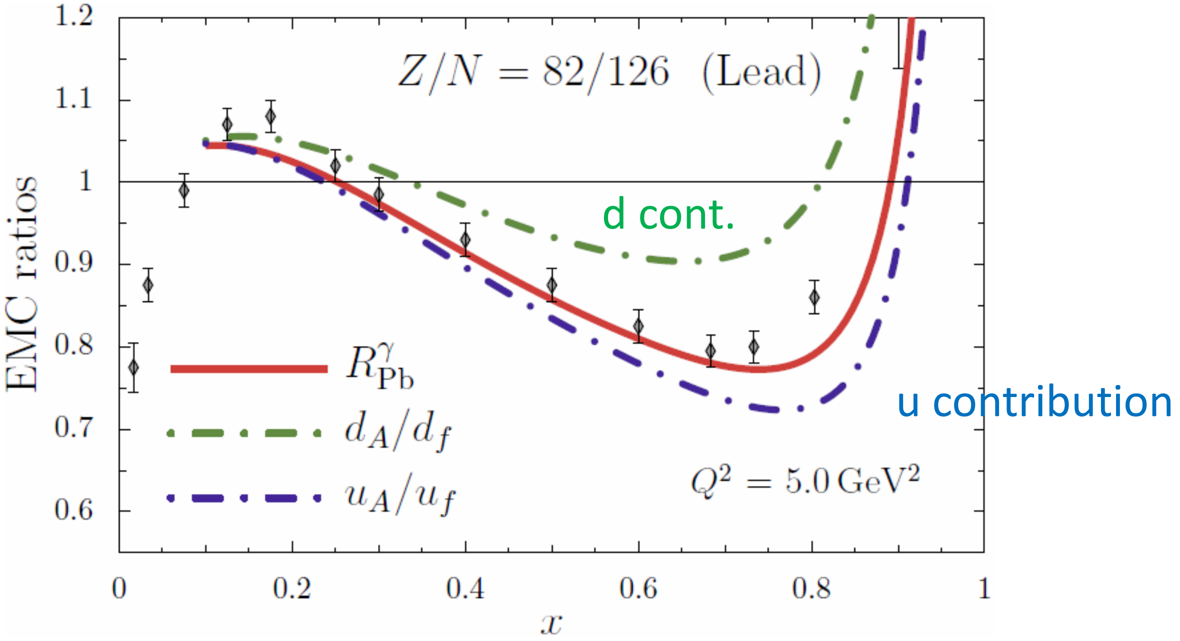
➢ Flavor-Dependent EMC Effect

❖ Gold nPDF model is flavor-dependent

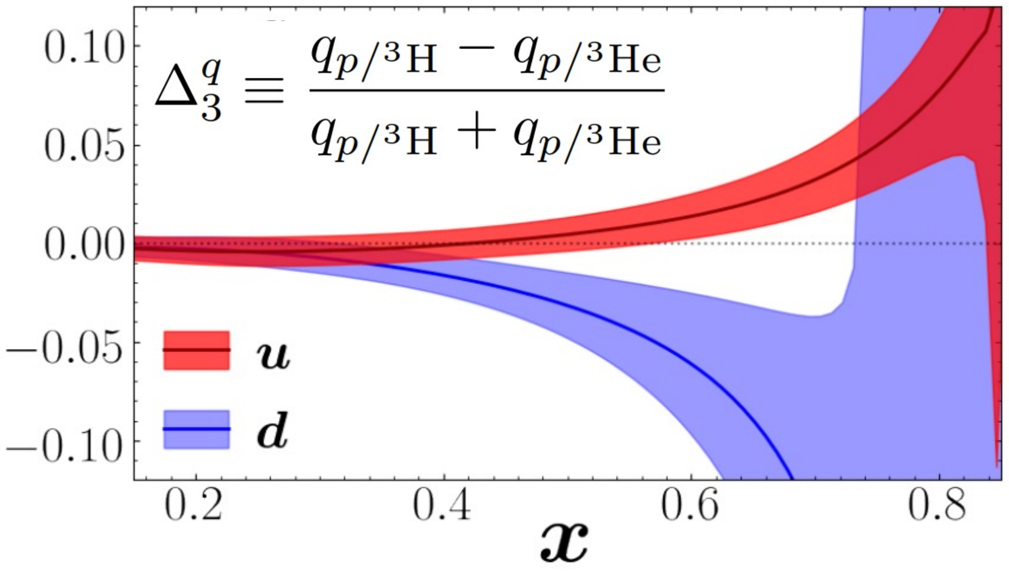
- ✓ If N>Z, u-quark is more modified
- ✓ If N<Z, d-quark is more modified



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

❖ JAM predicts strong isovector effect in A=3:

- ✓ stronger d_p-quark modified in ^3H
- ✓ stronger u_n-quark modification in ^3He

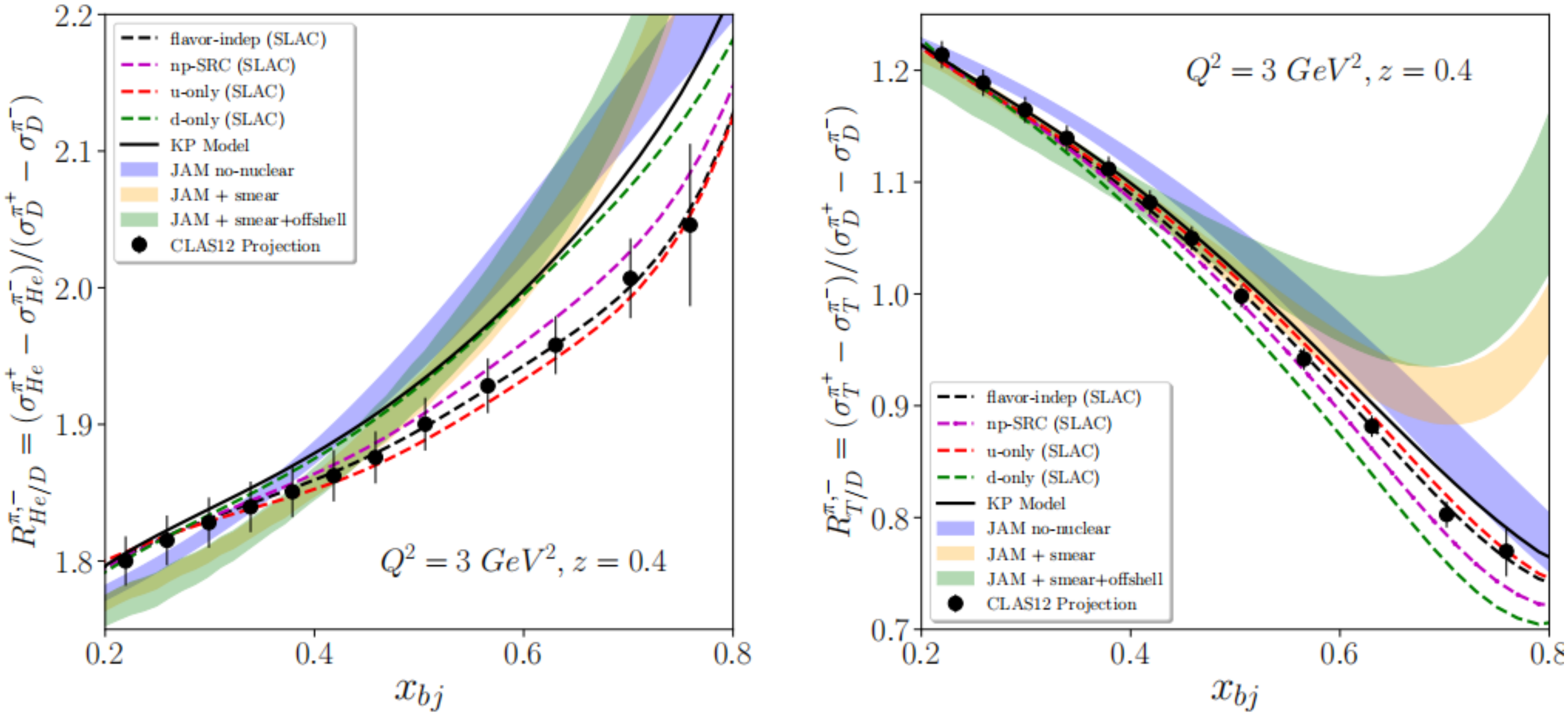


C. Cocuzza, et. al., Phys. Rev. Lett. 127, 242001

Tritium-SIDIS (C12-21-004)

➢ Flavor-Dependent EMC Effect

■ Precisely probe u- and d-quark EMC effect!



Data-Points: SIDIS MC events with CLAS12 acceptance, standard SIDIS cuts, one z-bin (0.35 < z < 0.45). 1% point-to-point systematic + statistical errors

arXiv: 2202.09696

Tritium-SIDIS (C12-21-004)

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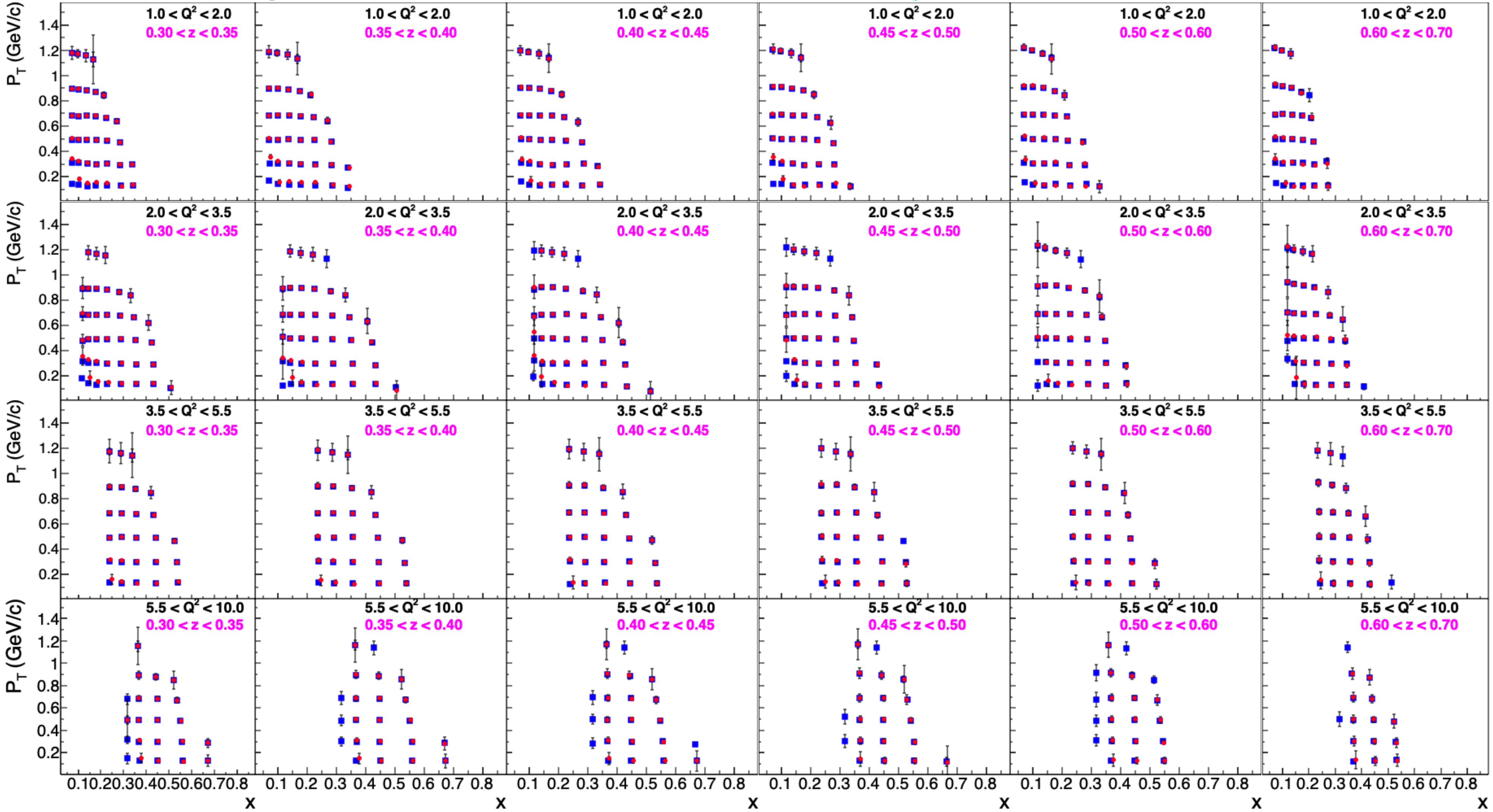
➢ 3D Image of A=3: Pion Data 4D Binning



π^+

π^-

- ❖ High precision, wide kinematic coverage
- ❖ A=2&3 data almost identical
- ❖ Crucial and unique to Jlab-12GeV programs

Summary

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- d/u PDF (or F_2^n/F_2^p) ratio at x→1 provides constrains to QCD model predictionss
- Lack of free neutron DIS data, need tagged ^{2}D-DIS, PVDIS
- A=3 isotope (Tritium & He3) provides a new way to measure F_2^n/F_2^p
- Precision measurements of nuclear effects in A=3
- Experiment done in 2018, F_2^n/F_2^p result published, EMC results to be submitted for publication
- New Tritium experiment w/ SIDIS measure flavor-dependent EMC effect and more

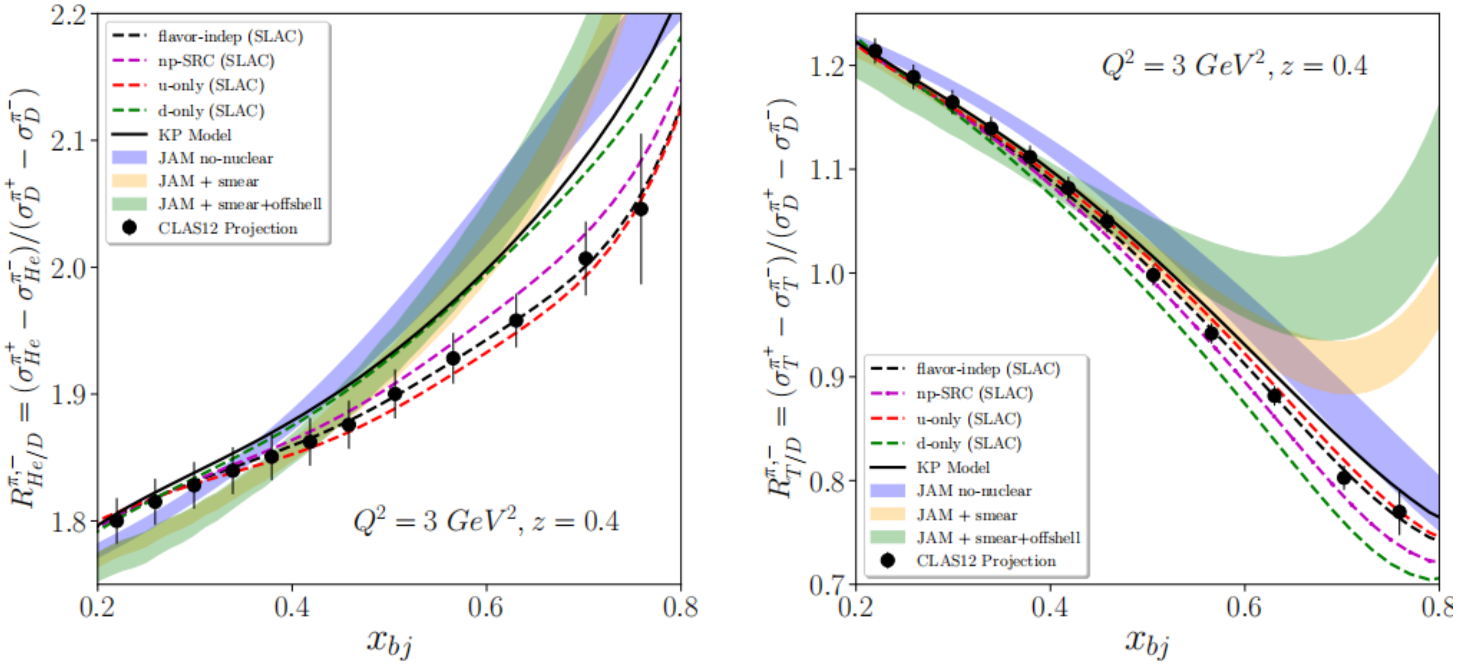
Backup

Tritium-SIDIS (C12-21-004)

➢ Flavor-Dependent EMC Effect

■ Updated Projections

→ precisely probe u- and d-quark EMC effect!



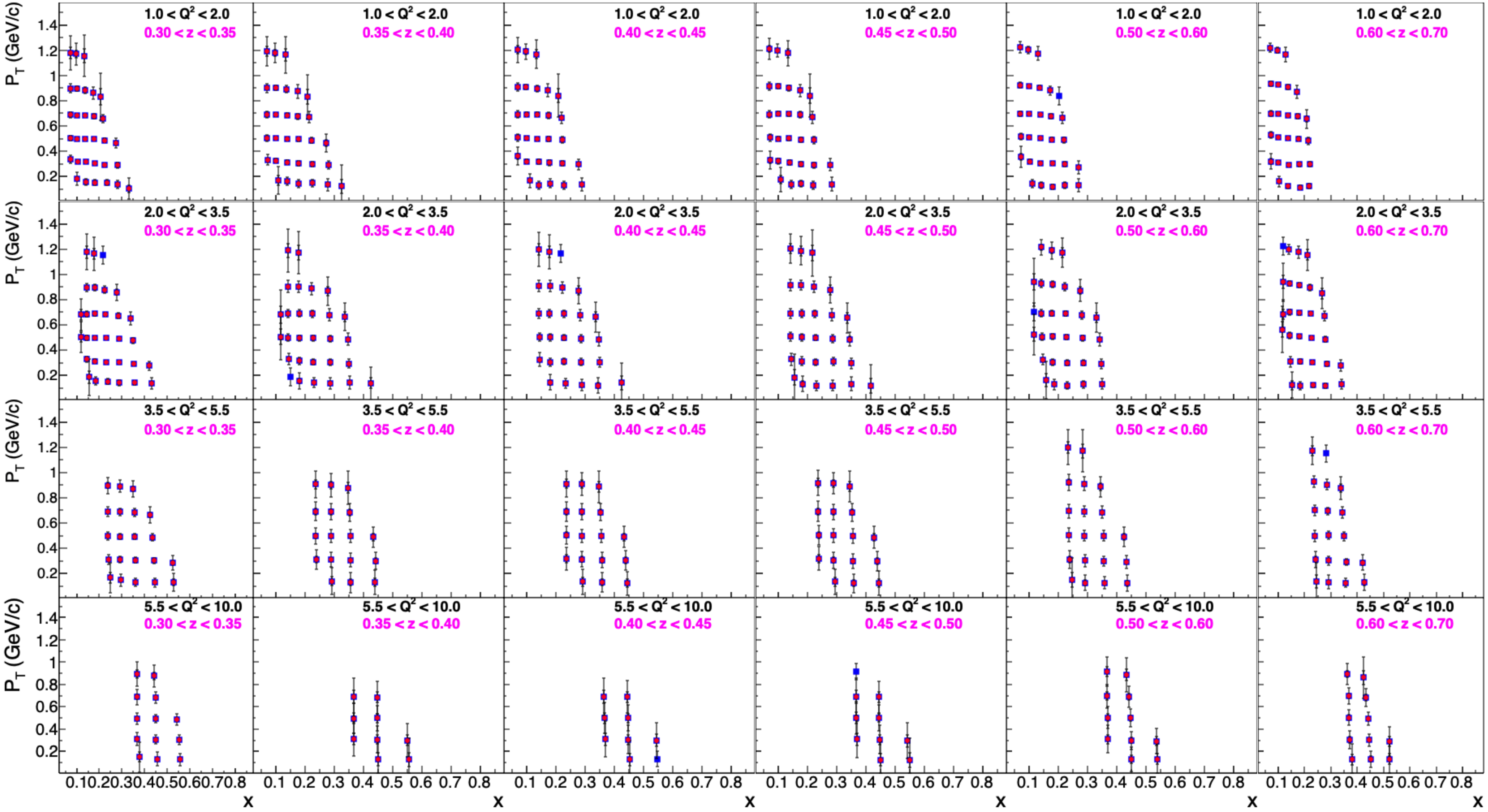
Data-Points: SIDIS MC events with CLAS12 acceptance, standard SIDIS cuts, one z-bin ($0.35 < z < 0.45$). 1% point-to-point systematic + statistical errors

Model Explanation:

- **SLAC**: fit from SLAC data (Phys. Rev. D 49, 4348)
  - ✓ **Flavor-indep**: flavor-independent
  - ✓ **np-SRC**: toy-model; only quarks in np-SRC pairs are modified
  - ✓ **u(d)-only**: toy-model, only u-quarks (or d-quark) are modified
- **KP Model**: theoretical calculation of A=3 with nuclear corrections used in MARATHON (Kulagin & Petti, Nuclear Physics A 765 (2006) 126–187)
- **JAM**: JAM global analysis (C. Cocuzza, et. al., Phys. Rev. Lett. 127, 242001)
  - ✓ "no-nuclear": no nuclear-correction included
  - ✓ "smear": Fermi-smearing turns on
  - ✓ "smear+offshell": Fermi-smearing and off-shell effect both turn on

Tritium-SIDIS (C12-21-004)

➢ Projected Results of A=3 in SIDIS: Kaon Data 4D Binning



K+

K-

Assumes 6 RICH sectors

清華大學
Tsinghua University