PR12-21-004: SIDIS Measurement of A=3 Nuclei with CLAS12 in Hall-B

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On behalf of the spokespeople:

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and the CLAS Collaboration

清華大學

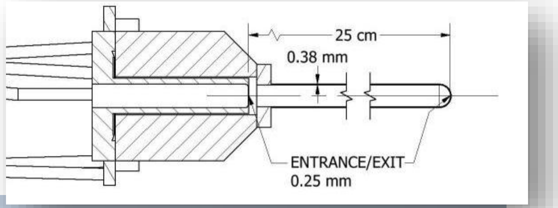
Tsinghua University

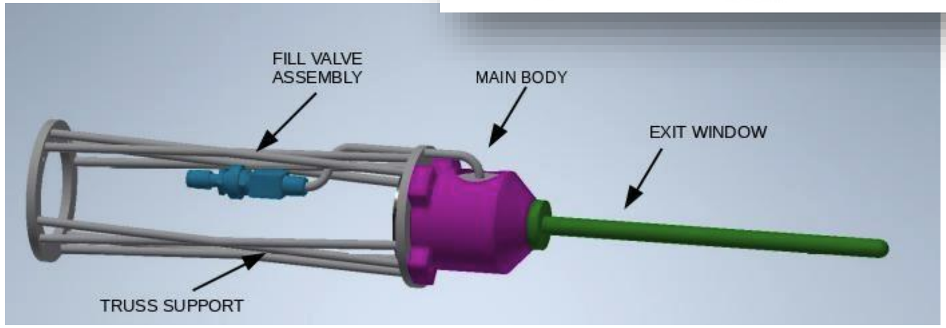
07/19/2021, PAC49 Meeting

Tritium is Back!

➢ New Tritium-Targets in Hall-B:

- ❖ Approved E12-20-005 at 6.6 GeV w/ CLAS12 (Tritium-SRC)
- ❖ New Target-System design for D2, H3 and He3





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 Tritium/He3 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)

    This proposal
  - DVCS
    - Neutron-GPD (incoherence)
    - Nuclear-GPD (nGPD)) in A=3 (coherence)
  - More?
  - Same beam time, same measurements, plentiful physics topics!

SIDIS with A=3

➢ Standard CLAS12 Setup:

- ❖ Same target system as E12-20-005 (Tritium-SRC)

- ❖ Beam-Time request:

Target:	^{2}D	^{3}He	^{3}H	Total
Measurement Days (10.6 GeV)	10	20	20	50
Calibration: Luminosity, dummy, H				5
Target Changes				2
Torus polarity reversals				1
			Total at 10.6 GeV:	58

- ❖ Error budget: overall 1% point to point

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

- ❖ Detected scattered electrons and pions (also kaons w/ RICH)
  - Flip the Torus field often to minimize the different acceptance of +/- charged particles

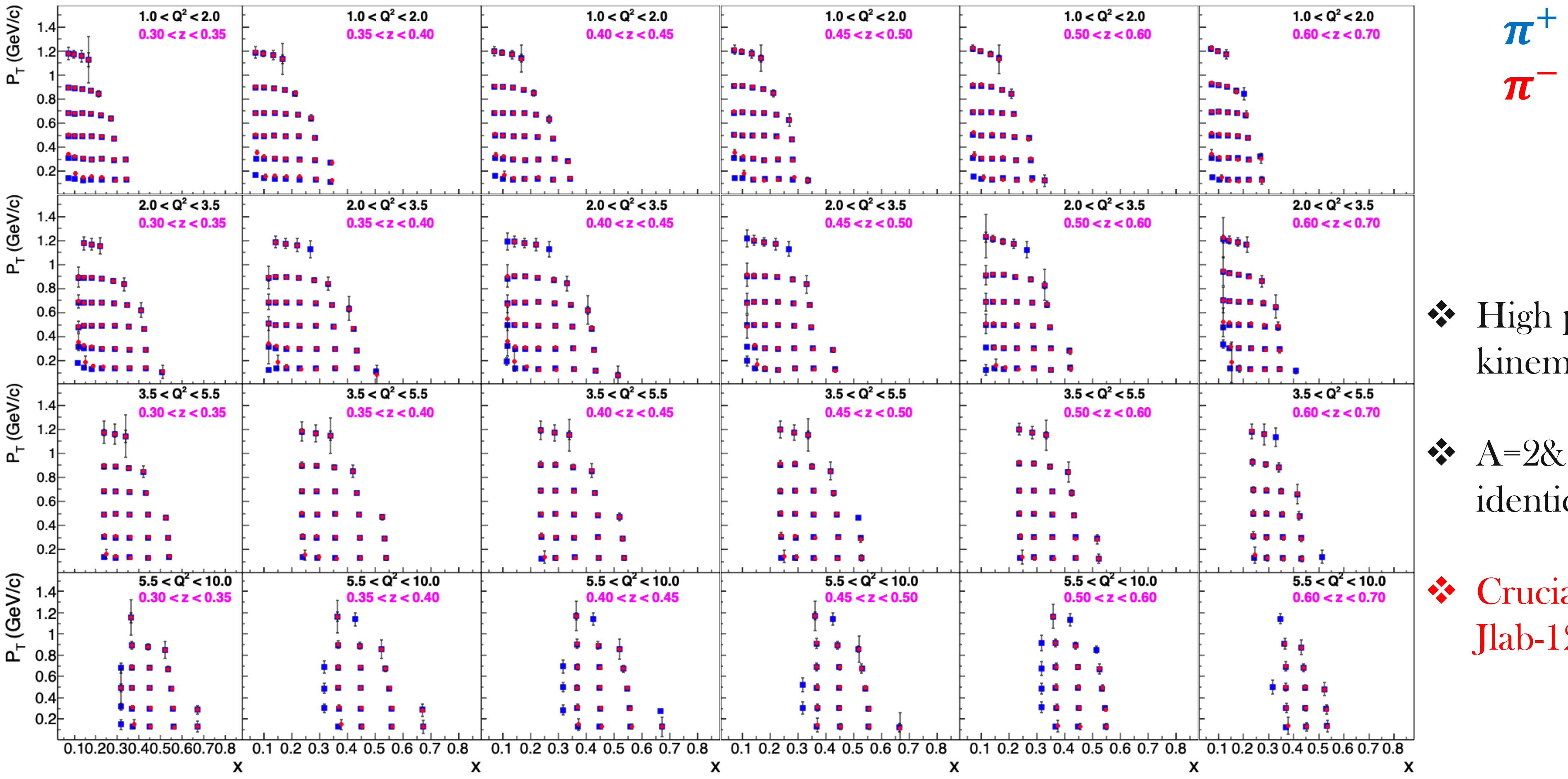
- ❖ Kinematic cuts: $Q^2 > 1$ GeV^2 , $W^2 > 4$ GeV, $0.1 < y < 0.85$, $0.3 < z < 0.7$

- ❖ Bin the data in 4D (Q^2, x, z, P_T)

- ❖ Observables: SIDIS cross-sections and ratios

Pion Projection

➤ Projected Results of A=3 in SIDIS: Pion Data 4D Binning



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

SIDIS with A=3

➢ Nature Fit for Jlab 12GeV:

❖ Major goal of Jlab 12GeV: 3D structure of nucleons and nuclei

❑ 3D structure of the hadrons ("free" nucleons)
- H2 as protons, D2 & He3 as effective neutrons
- PDF, d/u at high-x
- 3D TMD, GPD,

❑ Hadrons and cold nuclear matter
- Nuclear structure, NN interaction
- Nuclear-PDF, EMC effect
- Hadronization

❑ Gaps: 3D structure of nuclei?
- Nuclear corrections in D2 & He3
- Flavor-Dependent EMC effect
- nTMD, nFF and nGPD

Bob Mckeown, 48 PAC Report, Aug 10th, 2020

12 GeV Experiments by PAC Days (status at May 1st)

Topic	Hall A	Hall B	Hall C	Hall D	Total
Hadron spectra as probes of QCD	0	219	11	540	770
Transverse structure of the hadrons	150.5	85	146	25	406.5
Longitudinal structure of the hadrons	19	230	211	0	460
3D structure of the hadrons	359	872	196	0	1427
Hadrons and cold nuclear matter	220	275	205	15	715
Low-energy tests of the Standard Model and Fundamental Symmetries	547	180	0	79	806
Total Days	1295.5	1861.0	769.0	659	4584.5
Total Days - (includes MOLLER)	821.5	1861	769	659	4110.5
Total Approved Run Group Days (includes SoLID)	1295.5	1026	726	459	3506.5
Total Approved Run Group Days (includes MOLLER)	821.5	1026	726	459	3032.5
Total Days Completed	240.5	283	159.0	184	866.5
Total Days Remaining	581	743	567	235	2166

+167 (PAC) days completed in FY20 to date

A DECADE OF EXCELLENT SCIENCE!

3 Jefferson La

❖ A=3: a natural bridge between free-nucleons to heavy nuclei!

SIDIS with A=3

➢ SIDIS Measurements w/ Nucleons & Nuclei:

❖ Unpolarized SIDIS Cross Section (Factorization, LO, P_T integrated):

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

Free or Nuclear PDF (nPDF)

Free or Nuclear Fragmentation Function

- **Potential:**
  - Sensitive to flavor-contents
    - By detecting different hadron types
  - Access 3D info
    - By measuring P_T distributions
- **Challenges:**
  - Common for all SIDIS:
    - Factorization Regions, FF poorly known, Theoretical Corrections
  - Additions for Nuclei-SIDIS:
    - Nuclear structure, Hadronization

❖ Key: take advantage of the Potential while minimizing the Challenges

❖ Heavier nuclei more challenges

❖ Need close collaboration with theorists in global analysis

SIDIS with A=3

➢ Tritium and Helium-3:

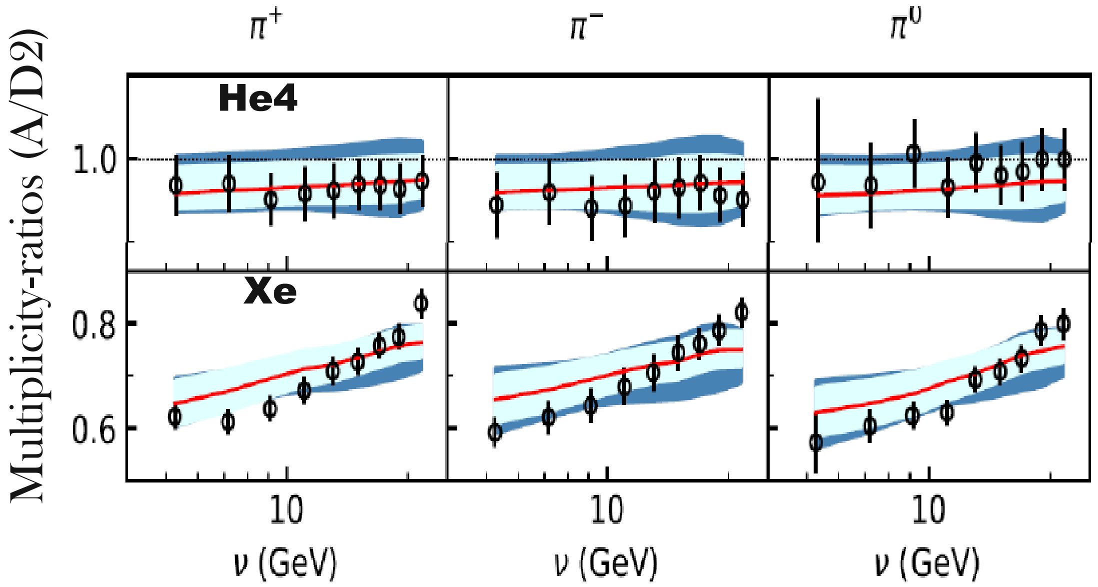
- Along with all Jlab SIDIS experiments w/ nucleons, A=3 measurement helps resolving common challenges

- Complementary to and extension of other efforts, such as MARATHON and Ca-Isotopes

- Minimize Challenges w/ A=3:
  - ✓ Precise nuclear calculations
  - ✓ Small hadronization effects
  - ✓ Fragmentation functions
    - Expected small & similar nuclear effect (also D2)
  - ✓ Many theoretical corrections are similar

- Unique advantage with mirror nuclei: SIDIS cross-section ratios

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



SIDIS with A=3

➢ Proof of Principle: SIDIS cross-section at LO

❖ SIDIS cross section at LO:

$$\frac{d\sigma_A^h}{dx dQ^2 dz} = \frac{4\pi\alpha^2 s}{Q^4}\left(1 - y + \frac{y^2}{2}\right)\sum_q e_q^2 f_1^{A,q}(x) \cdot D_{A,q}^h(z),$$

Simplify the FFs:

$$D_u^{\pi^+} = D_d^{\pi^+} = D_d^{\pi^-} = D_{\bar{u}}^{\pi^-} \equiv D^{\text{fav}},$$
$$D_d^{\pi^+} = D_{\bar{u}}^{\pi^+} = D_u^{\pi^-} = D_{\bar{d}}^{\pi^-} \equiv D^{\text{unfav}},$$

❖ XS-Sum and XS-Difference between $\pi^+$and π^- :

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

❖ Super-Ratios between two nuclei:

$$R_{A_1/A_2}^{\pi,\pm}(x,z) = \frac{(\sigma_{A_1}^{\pi^+} \pm \sigma_{A_1}^{\pi^-})/A_1}{(\sigma_{A_2}^{\pi^+} \pm \sigma_{A_2}^{\pi^-})/A_2}$$
$$= \frac{4(u_{A_1} \pm \bar{u}_{A_1}) \pm (d_{A_1} \pm \bar{d}_{A_1})}{4(u_{A_2} \pm \bar{u}_{A_2}) \pm (d_{A_2} \pm \bar{d}_{A_2})} \cdot \frac{D_{A_1}^{fav} \pm D_{A_1}^{unfav}}{D_{A_2}^{fav} \pm D_{A_2}^{unfav}} = A_{A_1/A_2}^{\pi,\pm}(x) \cdot B_{A_1/A_2}^{\pi,\pm}(z),$$

❖ Similar and small nFF for D2, H3 (“T”) and He3 (“H”): $B_{A_1/A_2}^{\pi,\pm} \cong 1$

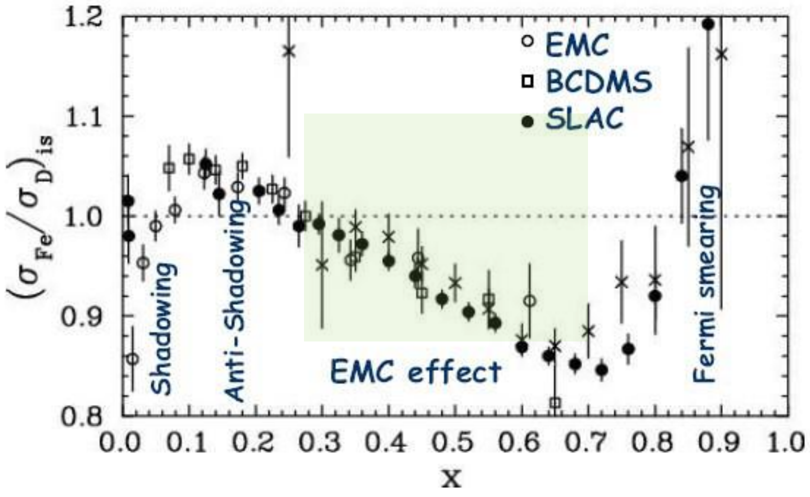
- ✓ Can also be independently measured (SIDIS multiplicity ratio)

❖ Global analysis to obtain medium effect on the u- and d-quark PDFs and FFs!

Flavor-Dependence EMC Effect

➢ What causes the EMC Effect:

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



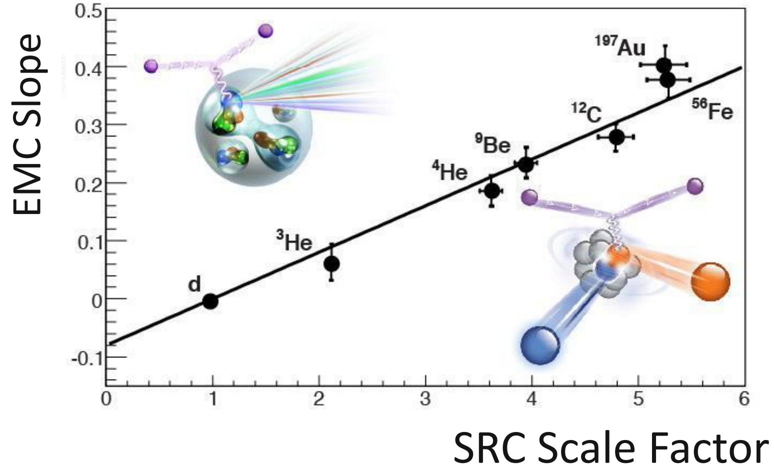
- Nucleon must be modified
- No accepted explanation

❖ EMC effect related to short range correlated (SRC) pairs:

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

SRC pairs

- Predominantly pn
- High relative momentum
- Overlapping?

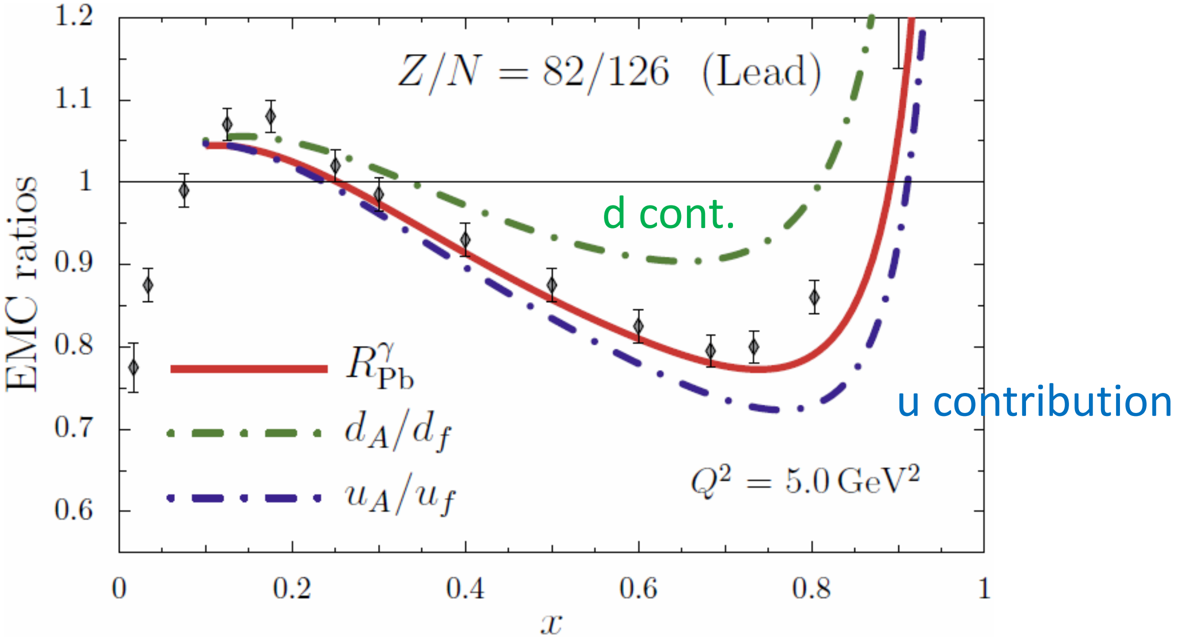


❖ Which nucleons are modified?

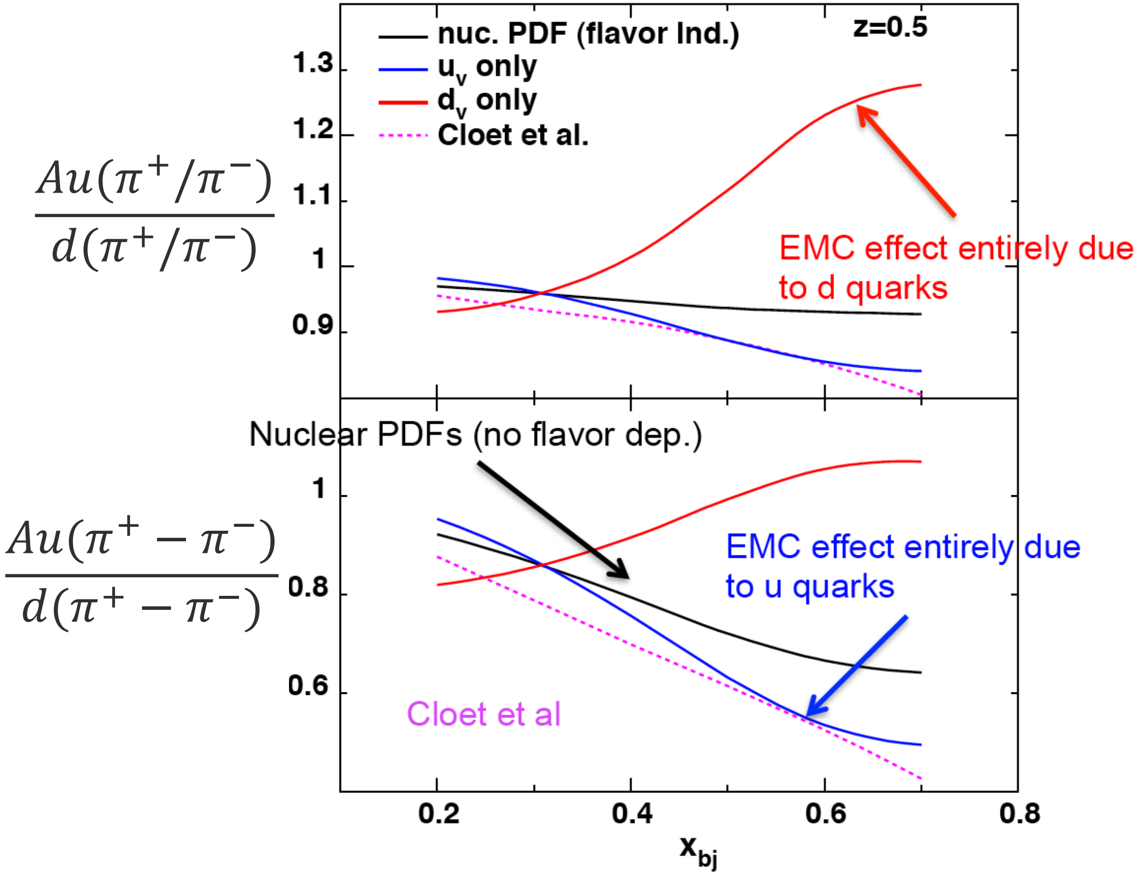
- All nucleons?
- Only SRC (pn) pairs?
- Flavor dependent?

Flavor-Dependence EMC Effect

- What causes the 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)]



Flavor-Dependence EMC Effect

➢ Flavor-Dependent EMC Effect in A=3:

✓ The Super-Ratios are uniquely sensitive to the PDF-contribution:

$$R^{\pi,+}_{H/D}(x) \simeq \frac{4(u_H + \bar{u}_H) + (d_H + \bar{d}_H)}{5(u + \bar{u}) + 5(d + \bar{d})} \qquad R^{\pi,+}_{T/D}(x) \simeq \frac{4(u_T + \bar{u}_T) + (d_T + \bar{d}_T)}{5(u + \bar{u}) + 5(d + \bar{d})}$$

$$R^{\pi,-}_{H/D}(x) \simeq \frac{4(u_H - \bar{u}_H) - (d_H - \bar{d}_H)}{3(u - \bar{u}) + 3(d - \bar{d})} \qquad R^{\pi,-}_{T/D}(x) \simeq \frac{4(u_T - \bar{u}_T) - (d_T - \bar{d}_T)}{3(u - \bar{u}) + 3(d - \bar{d})}$$

- EMC effect on all nucleons:

$$u_{T,Adep} = \frac{\tilde{u} + 2\tilde{d}}{3}, \quad d_{T,Adep} = \frac{\tilde{d} + 2\tilde{u}}{3},$$
$$u_{H,Adep} = \frac{2\tilde{u} + \tilde{d}}{3}, \quad d_{H,Adep} = \frac{2\tilde{d} + \tilde{u}}{3},$$

- EMC effect only on SRC pairs

$$u_{T,SRC} = \frac{\tilde{u} + \tilde{d} + d}{3}, \quad d_{T,SRC} = \frac{\tilde{d} + \tilde{u} + u}{3},$$
$$u_{H,SRC} = \frac{\tilde{u} + \tilde{d} + u}{3}, \quad d_{H,SRC} = \frac{\tilde{d} + \tilde{u} + d}{3},$$

Flavor Dependent EMC Effect

➢ Projected Results of A=3 in SIDIS :

❖ This experiment is mostly data-driven (lack of existing theoretical predictions)

❖ More sophisticated theoretical predictions are underway:

- ✓ Chris Cocuzza, Nobuo Sato, Wally Melnitchouk, et.al (NLO SIDIS Structure-Functions based on arXiv:2104.06946)
- ✓ Pia Zurita, NLO SIDIS cross sections, based on arxiv:2101.01088
- ✓ Jennifer Rittenhouse West, et. al, based on diquark-models, arXiv:2009.06968, Nucl. Phys. A 1007:122134
- ✓ Ian Cloet, et. al. , flavor-dependence, nuclear effect on transverse directions

❖ Models used in this simulation:

- CJ15-LO as free-PDFs (no modification)
- KP Model calculated for MARATHON analysis (A-dependent, flavor-independent)
- SLAC-fit (Phys. Rev. D 49, 4348) + 5% correction to match the Hall-C He3 EMC data (A-dependence, flavor-independent)
- "Toy-Model" for the extreme case → the EMC effect due only to u- or d-quark (extreme flavor-dependent)

✓ 100% u-quark modification

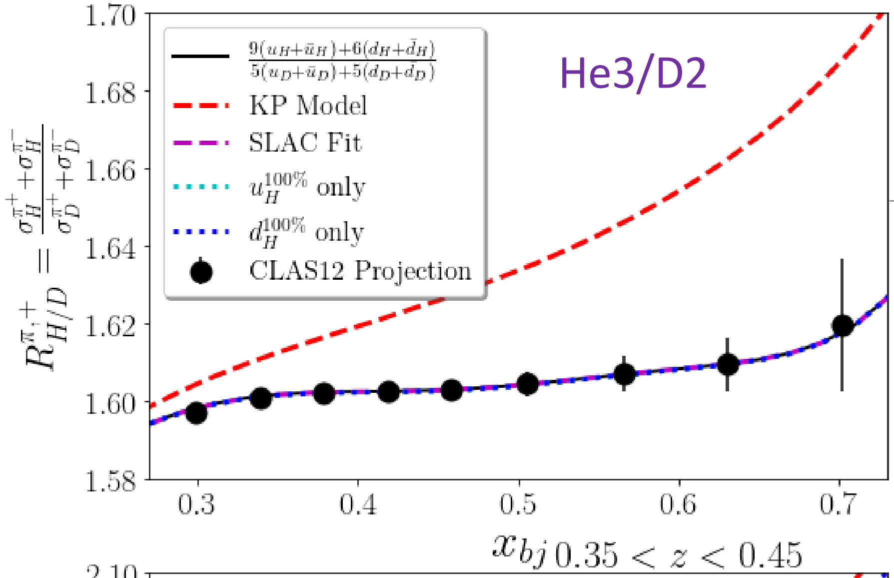
$$\begin{aligned} F_2^{A,SLAC} &= (Ze_u^2 + Ne_d^2)(u_{p,A}^{100\%} + \bar{u}) \\ &+ \ (Ze_d^2 + Ne_u^2)(d + \bar{d}) \\ &+ \ (Z+N)e_s^2(s+\bar{s}), \end{aligned}$$

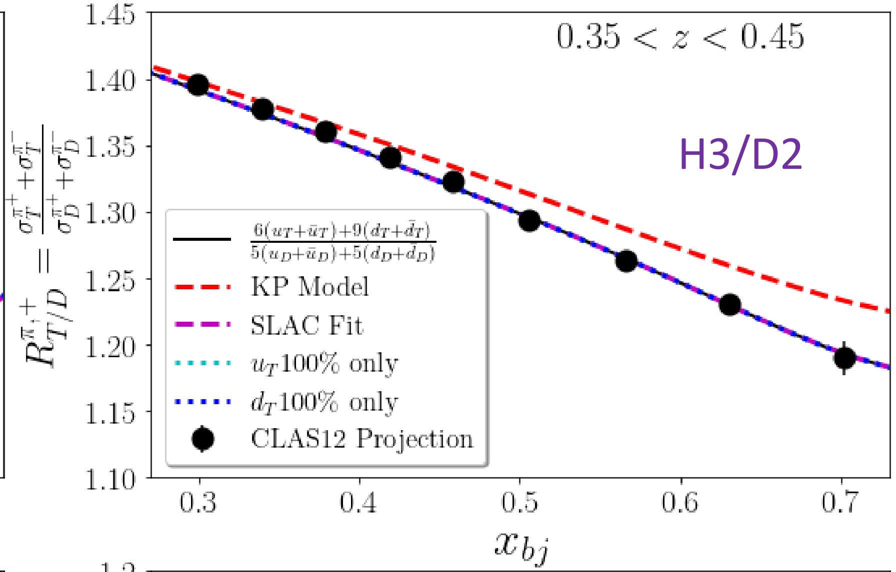
✓ 100% d-quark modification

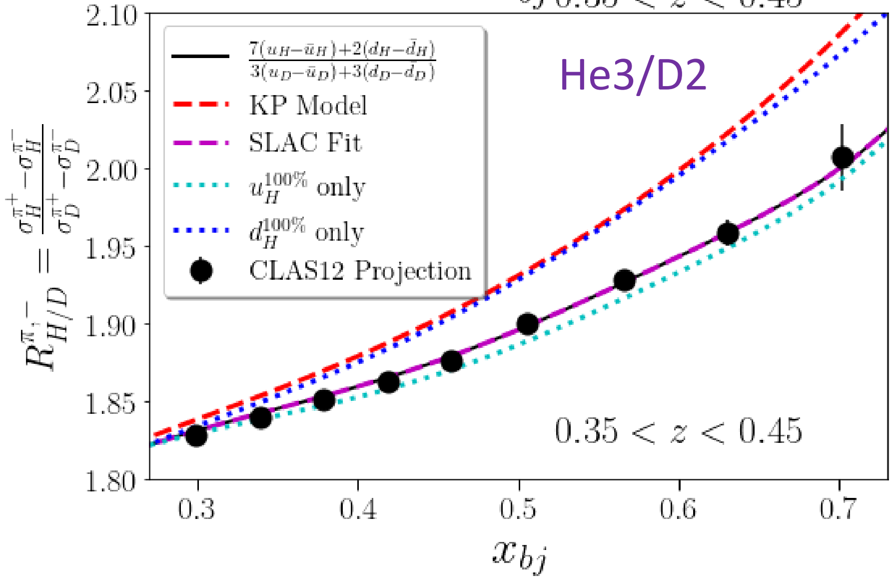
$$\begin{aligned} F_2^{A,SLAC} &= (Ze_d^2 + Ne_u^2)(d_{p,A}^{100\%} + \bar{d}) \\ &+ \ (Ze_u^2 + Ne_d^2)(u + \bar{u}) \\ &+ \ (Z+N)e_s^2(s+\bar{s}), \end{aligned}$$

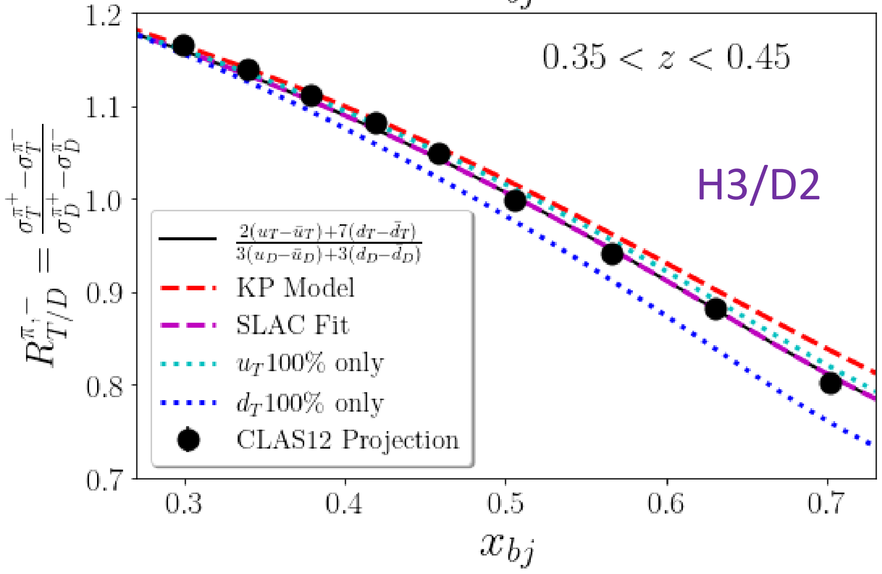
Flavor Dependent EMC Effect

➢ Projected Results of A=3 in SIDIS









❖ Integrating P_T and fix z-bins

❖ D2, H3 ("T") and He3 ("H")

❖ Statistical errors only

✓ EMC effect has a strong cancellation XS-Sum ratio(except KP-model)

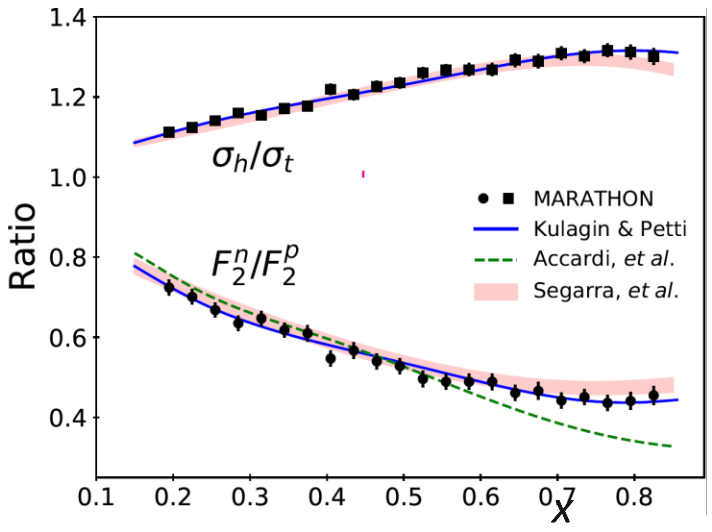
✓ Flavor-dependence sensitive to XS-Difference ratio

d/u from SIDIS

- New MARATHON Results
  - Assume small & similar nuclear effect in p and n

$$F_{H3} = F_{\tilde{p}} \otimes f_p^{H3} + 2F_{\tilde{n}} \otimes f_n^{H3}$$
$$F_{He3} = 2F_{\tilde{p}} \otimes f_p^{He3} + F_{\tilde{n}} \otimes f_n^{He3}$$

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



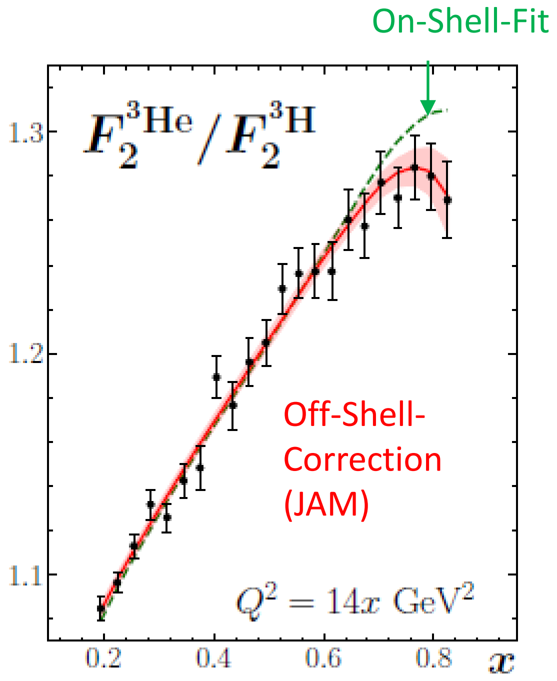
(arXiv:2104.05850)

Figure is replotted by T. Kutz using the same result

- Significant different nuclear effects and off-shell uncertainties for extracting d/u from the data

C. Cocuzza, et. al., arXiv:2104.06946v1

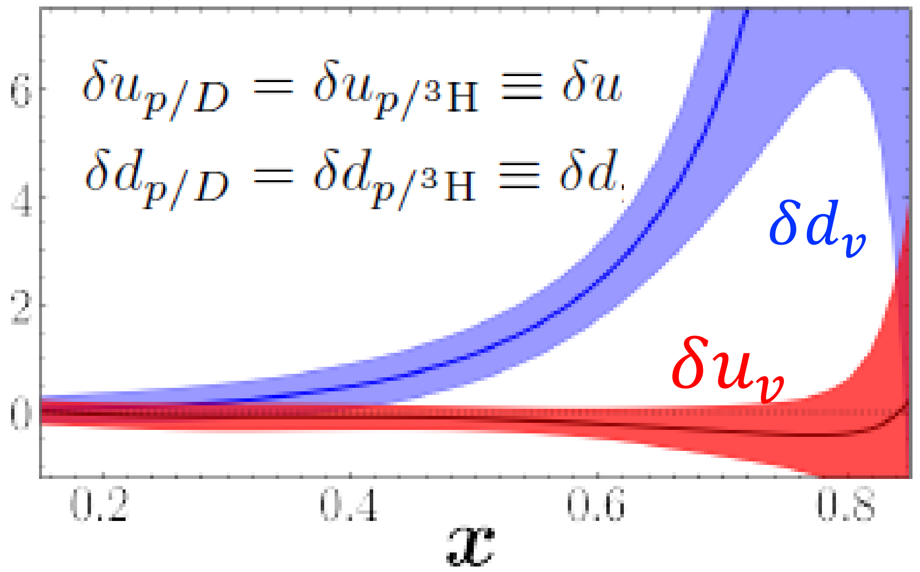
E.P. Segarra, et. al. Phys. Rev. Lett.124, 092002, arXiv:2104.07130v1



- Which one is more modified: u or d quark?
- Different in A=3?

d/u from SIDIS

- Use H3 and He3 to extract nucleon-PDFs
  - Model predicts u and d-quark modified differently in H3 and He3



C. Cocuzza, et. al., arXiv:2104.06946v1

- SIDIS with A=3 provide a new way to measure d/u ratio
  - Assuming u (and d) modified similarly in A=3

$$R^{\pi;+}_{H/T} = \frac{9(\tilde{u}+\tilde{\bar{u}}) + 6(\tilde{d}+\tilde{\bar{d}})}{6(\tilde{u}+\tilde{\bar{u}}) + 9(\tilde{d}+\tilde{\bar{d}})},$$

$$R^{\pi;-}_{H/T} = \frac{7(\tilde{u}-\tilde{\bar{u}}) + 2(\tilde{d}-\tilde{\bar{d}})}{2(\tilde{u}-\tilde{\bar{u}}) + 7(\tilde{d}-\tilde{\bar{d}})},$$

$$\frac{\tilde{d}+\tilde{\bar{d}}}{\tilde{u}+\tilde{\bar{u}}} = \frac{9-6R^{\pi;+}_{H/T}}{9R^{\pi;+}_{H/T}-6}$$

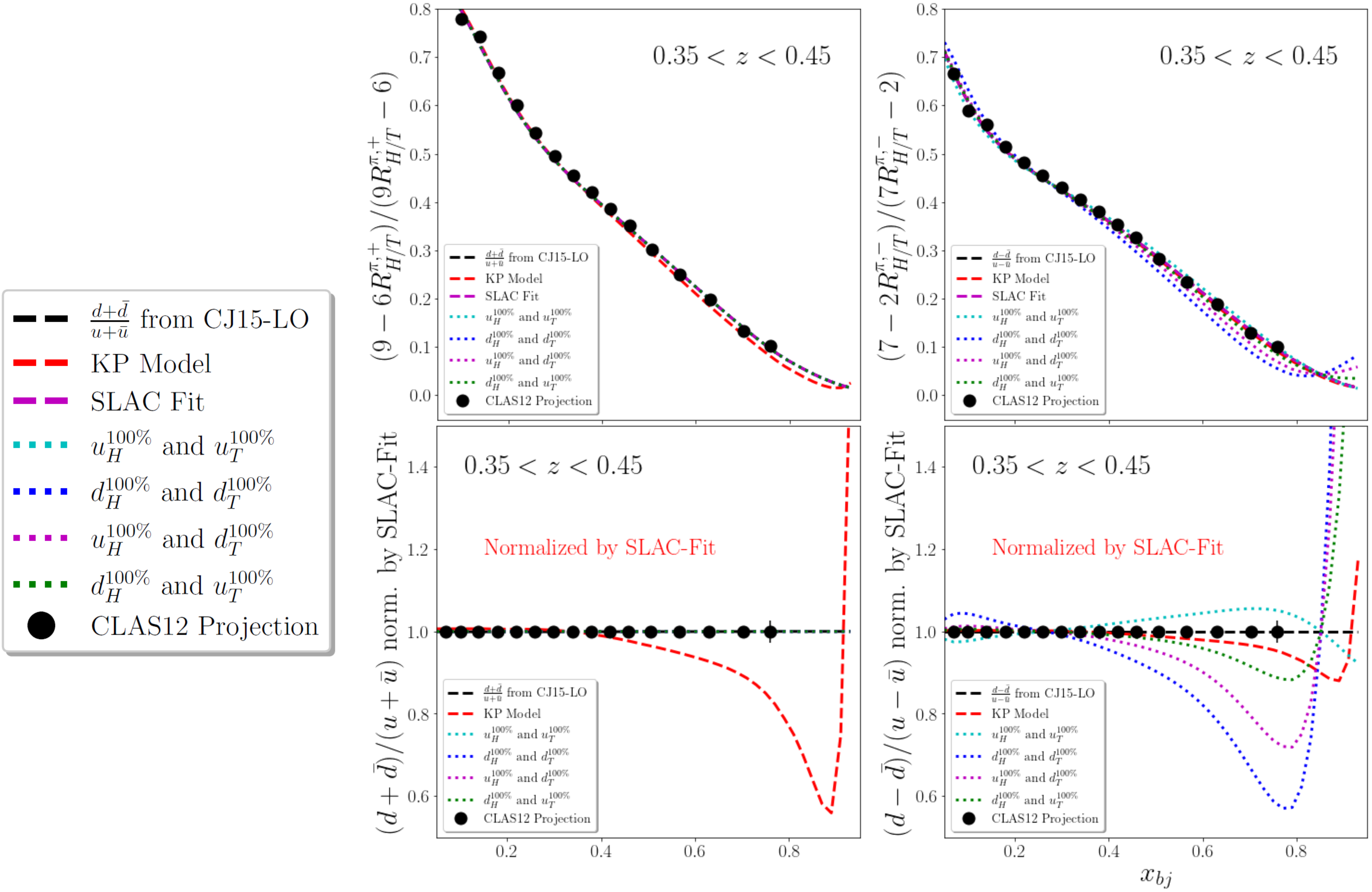
$$\frac{\tilde{d}-\tilde{\bar{d}}}{\tilde{u}-\tilde{\bar{u}}} = \frac{7-2R^{\pi;-}_{H/T}}{7R^{\pi;-}_{H/T}-2}.$$

at large-x

$$\frac{\tilde{d}}{\tilde{u}} \simeq \frac{9-6R^{\pi;+}_{H/T}}{9R^{\pi;+}_{H/T}-6} = \frac{7-2R^{\pi;-}_{H/T}}{7R^{\pi;-}_{H/T}-2},$$

d/u from SIDIS

- ➢ Use H3 and He3 to extract nucleon-PDFs



- ❖ Integrating P_T and fix z-bins
- ❖ D2, H3 (“T”) and He3 (“H”)
- ❖ Statistical errors only

✓ EMC effect has a strong cancellation XS-Sum ratio(except KP-model)

✓ Models w/ flavor-dependent EMC effect can be distinguished in the XS-Difference ratio

3D TMD/FF in A=3

➢ From 1D to 3D :

Unpolarized TMD *Unpolarized FF*

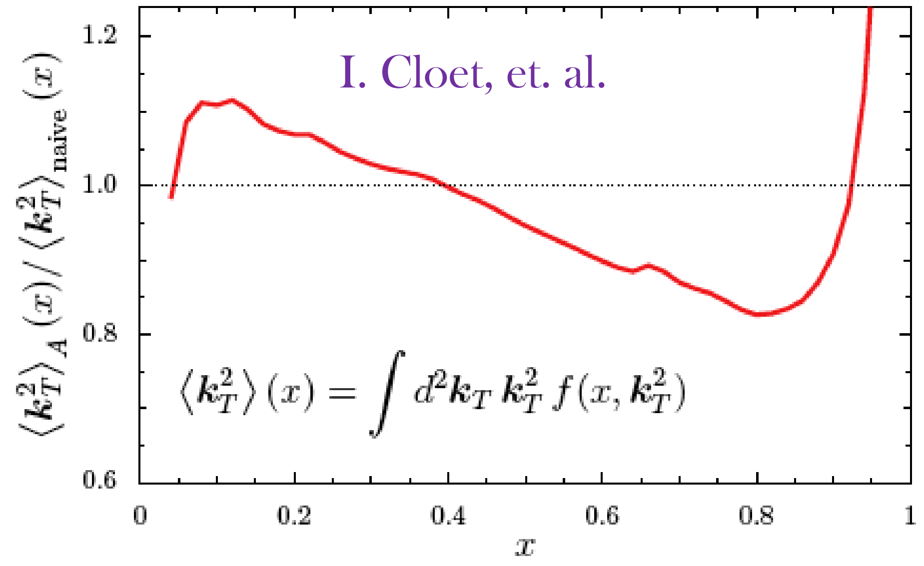
❖ The SIDIS SF with additional P_T dependence: $F_{UU}(x,z,P_T) = \sum_q e_q^2 [f_1^q(x,K_\perp) \otimes D_q^h(z,q_T)]$

❖ P_T is the only experimentally accessible quantity: $\vec{P}_T = z\vec{k}_\perp + \vec{q}_T + O(k_\perp^2/Q^2)$

❖ Gaussian ansatz are commonly used but imprecise → Actual P_T distribution needed!

❖ 4D(Q2, x, z, pT) SIDIS data using A=3 mirror nuclei

- ✓ P_T distributions for u and d in A=3
- ✓ Unpolarized TMDs and FFs in A=3
- ✓ Factorization Theorem in light nuclei
- ✓ Hadron Attenuation in light-nuclei
- ✓ Medium-modification effects in the transverse directions



❖ A more comprehensive way of study the nuclear effect in 3D!

Kaon Measurement

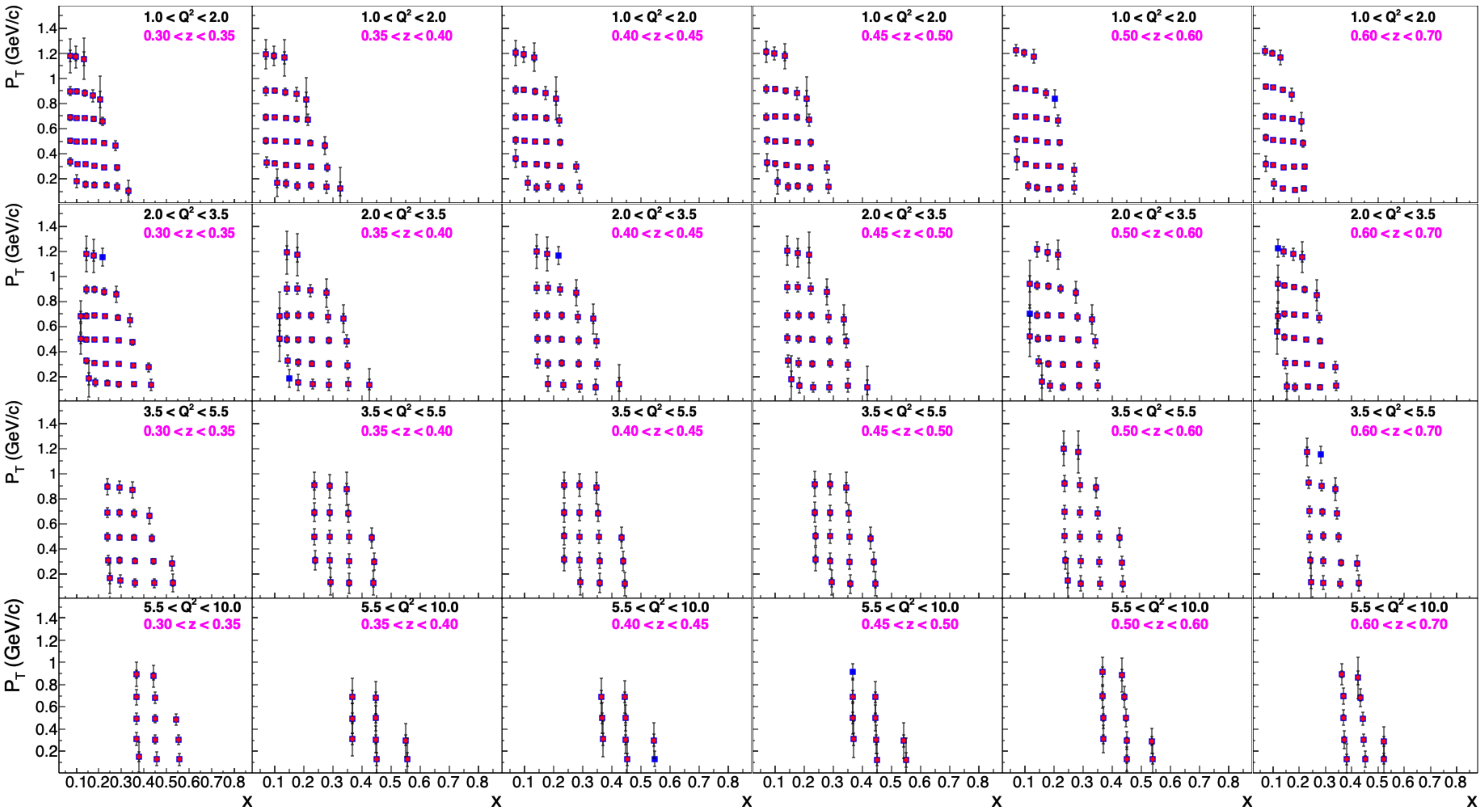
- Additional Channel: Kaon production in SIDIS with H3 and He3:
  - Probe the unobserved possible medium effect in strangeness

$$R^{K,\pm}_{A_1/A_2}(x,z) = \frac{(\sigma^{K^+}_{A_1} \pm \sigma^{K^-}_{A_1})/A_1}{(\sigma^{K^+}_{A_2} \pm \sigma^{K^-}_{A_2})/A_2}$$

  - Measure *s*-PDF in A=3 and nuclear modification effect
  - Extract 3D strangeness TMD and FFs
  - A secondary goal of this proposal:
    - ✓ One RICH sector installed (more planned)
    - ✓ Sophisticated global analysis needed (w/ pion data)
    - ✓ Great inputs for future EIC

Kaon Measurement

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



K+

K-

Assumes 6 RICH sectors

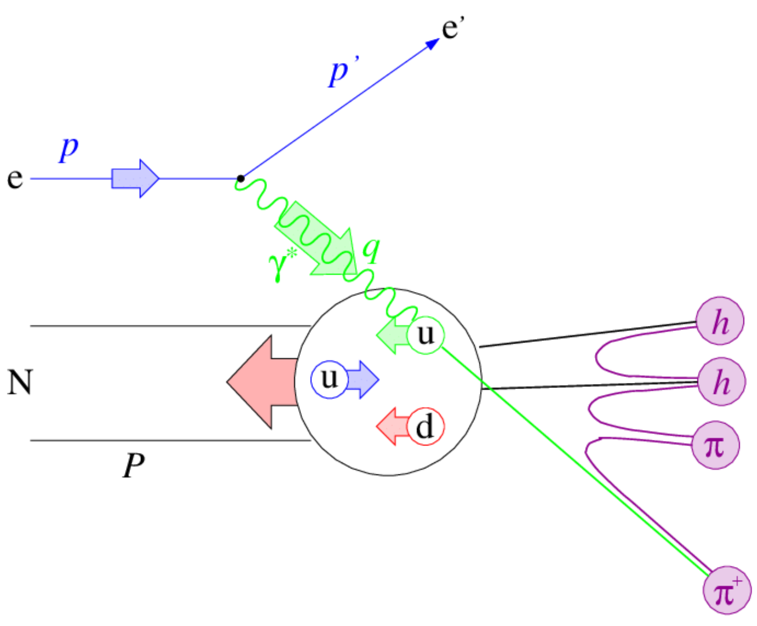
Summary

- Tritium is back → Maximize its usefulness
- The experiment:
  - 10.6 GeV, Standard CLAS12 setup
  - Measure SIDIS ratios of $(e, e'\pi^+)$ and $(e, e'\pi^-)$
  - Targets: D2, H3 and He3
    - Use approved CLAS12 Tritium-SRC target system
  - Measure $(e, e'K^+)$ and $(e, e'K^-)$ using the RICH when available
- The physics:
  - ✓ Resolve flavor-dependent EMC effect
  - ✓ Provide inputs to extract d/u ratio
  - ✓ Measure unpolarized TMDs and FFs, and their nuclear effects in 3D
  - ✓ Explore strangeness
- Data driven → Exploit new observables and new target technologies to resolve important questions
  - ✓ Ongoing theoretical support
  - ✓ Potential several other parallel physics topics (e.g. A=3 DVCS)
- Bridge between nucleons-3D and nuclear-3D structures
- Great input for future EIC

BACKUP

SIDIS with A=3

- SIDIS w/ Nucleons:



$$x_B = \frac{Q^2}{2M\nu} = \frac{q \cdot P}{M} \qquad z = \frac{E_h}{n} = \frac{P \times P_h}{P \times q}$$

$$y = \frac{n}{E_l} = \frac{q \times P}{l \times P} \qquad P_T = \frac{p \cdot P_h}{|q^2|} = p_{h\perp}$$

❖ Unpolarized SIDIS Cross Section (Factorization, LO, P_T integrated):

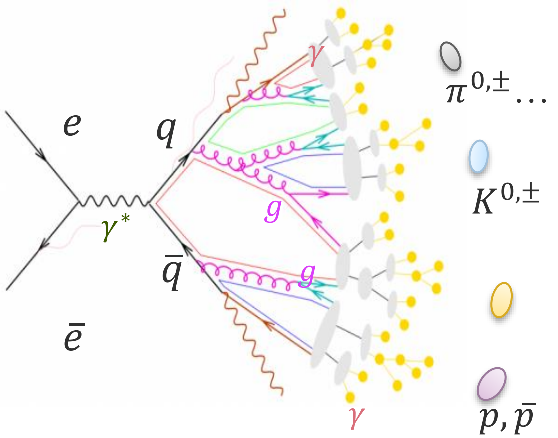
$$\frac{d\sigma^h}{dxdydz} = \frac{4\pi\alpha^2 s}{Q^4}\left(1 - y + \frac{y^2}{2}\right)\sum_q e_q^2 [f_1^q(x) \cdot D_q^h(z)]$$

PDF (from DIS) — Fragmentation Function

❖ Fragmentation Functions (FF):

- How quarks become hadrons
- Normally obtained from $e + e^- \longrightarrow h^\pm + X$
- Also from SIDIS multiplicity:

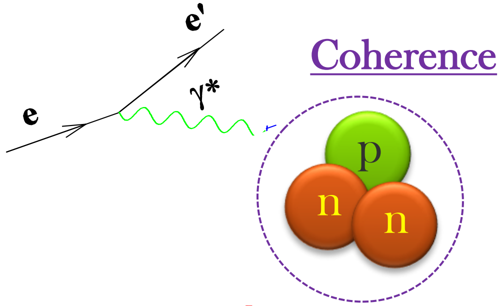
$$M^h(Q^2, z) = \frac{\sigma_{SIDIS}}{\sigma_{DIS}} = \frac{\sum_q e_q^2 f_1^q(Q^2, x) \cdot D_q^h(Q^2, z)}{\sum_q e_q^2 f_1^q(Q^2, x)}$$



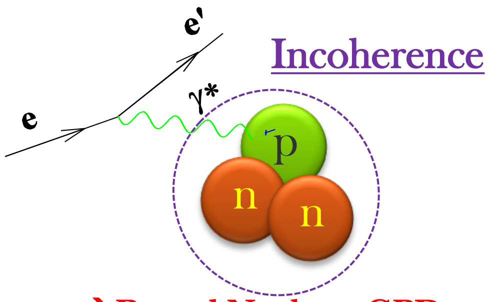
- Relatively poorly known.

The Proposed Measurement

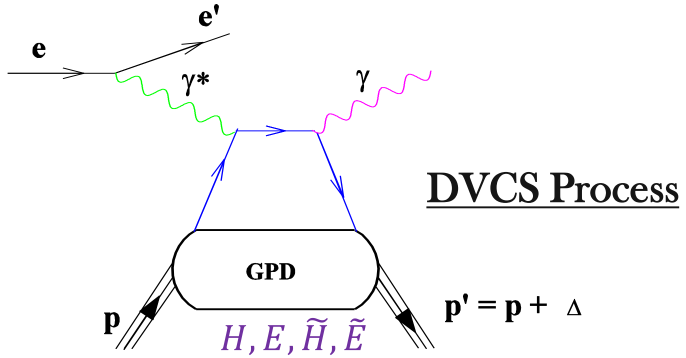
- Parasitic Run: DVCS measurement on H3 and He3:
  - DVCS off He3 and H3 (4 GPD for spin ½ targets):



→Nuclear-GPD



→Bound Nucleon-GPD

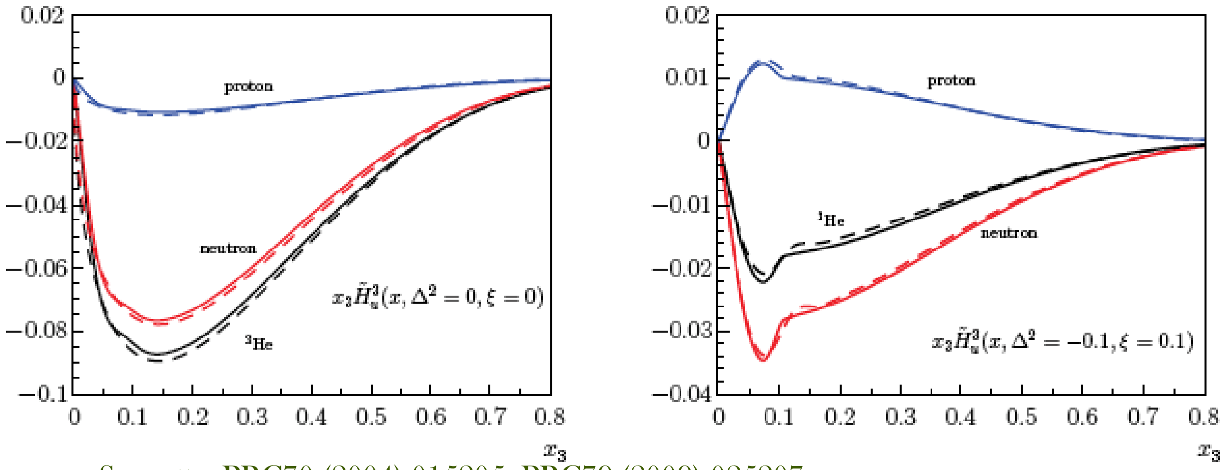


$$H_q^A(x,\xi,\Delta^2) \simeq \sum_N \int \frac{d\bar{z}}{\bar{z}} h_N^A(\bar{z},\xi,\Delta^2) H_q^N\left(\frac{x}{\bar{z}},\frac{\xi}{\bar{z}},\Delta^2\right)$$

  - Advantage of using DVCS off He3 & H3:
    - ✓ Neutron-contribution dominates in He3-GPDs
    - ✓ Sensitive to GPD-E (orbital angular momentum)
    - ✓ Use H3 to isolate pure neutron/proton contributions
    - ✓ Get access to the flavor-dependence GPDs

$$H_u^{He3} = H_d^{H3}$$

    - ✓ Medium Modification Effect in GPDs



Scopetta, PRC70 (2004) 015205; PRC79 (2009) 025207;
Rinadli and Scopetta, PRC87 (2013) 035208; arXiv:1401.1350 (2014)

- In collaboration with Silvia Nicolai, Alex Camsonne to explore this run-group proposal
- Welcome new collaborators
- Strong theory support needed!