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

Approved C2 by PAC50

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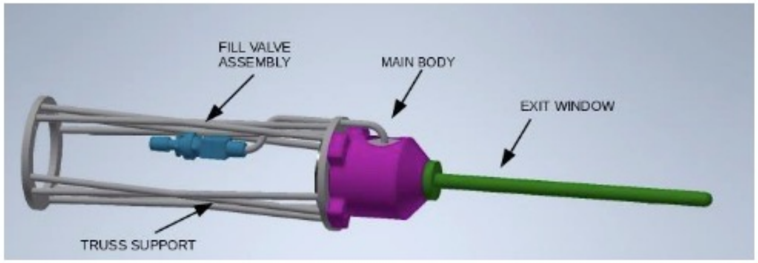
and the CLAS Collaboration

3/13/26 CLAS meeting

SIDIS with A=3 (C12-21-004)

➢ Proposed SIDIS Measurement:

- Standard CLAS12 w/ new Tritium-Target
  - ✓ Same target system for approved E12-20-005@6.6GV
  - ✓ 10.6GeV



- 50+8 days of beam time requested
- Observables: unpolarized (e,e'$\pi^{\pm}$) & (e,e'$K^{\pm}$) SIDIS cross-sections and ratios
- Main goals:
  - ✓ Flavor-dependence of the EMC effect
  - ✓ Test high-x nuclear corrections
  - ✓ Medium effect on nuclear TMDs & Fragmentation Functions
  - ✓ Medium effect in Strangeness

SIDIS with A=3 (C12-21-004)

- Conditionally approved (C2):

> **PAC50 Summary:** The proposal has the potential to address the fundamental question of the origin of the EMC effect. The physics programme is very rich, but the extraction of the underlying physics observables is very challenging. The PAC strongly encourages the proponents to provide more convincing arguments for the impact of the proposed measurements.

- Very positive PAC50-TAC reports:

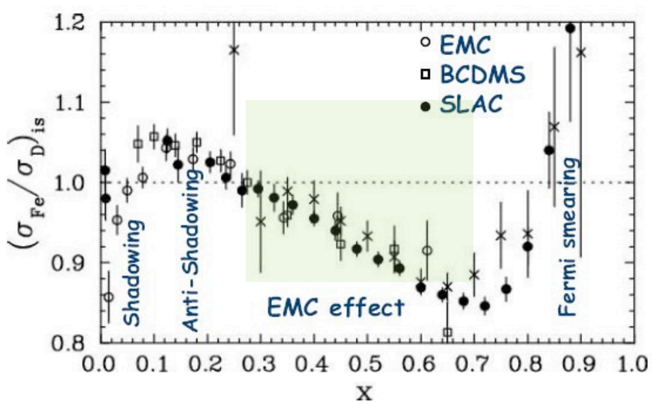
> **Theory:**
> "… The revised proposal has taken into account the suggestions made in PAC49, …."

> **Experiment:**
> "There are no technical issues with running the experiment in Hall-B other than safe handling of the tritium target ..."

Flavor-Dependent EMC Effect

The EMC Effect:

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

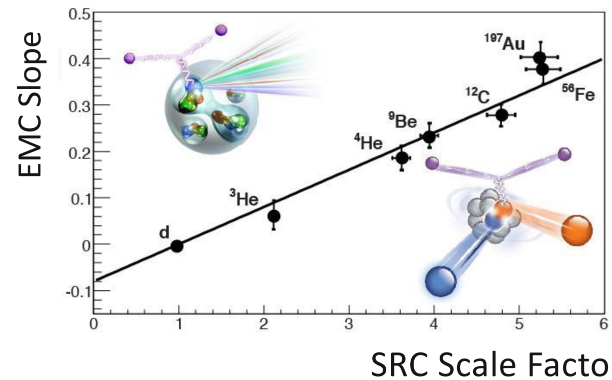


- Nucleons must be modified
- No accepted explanation

❖ 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?



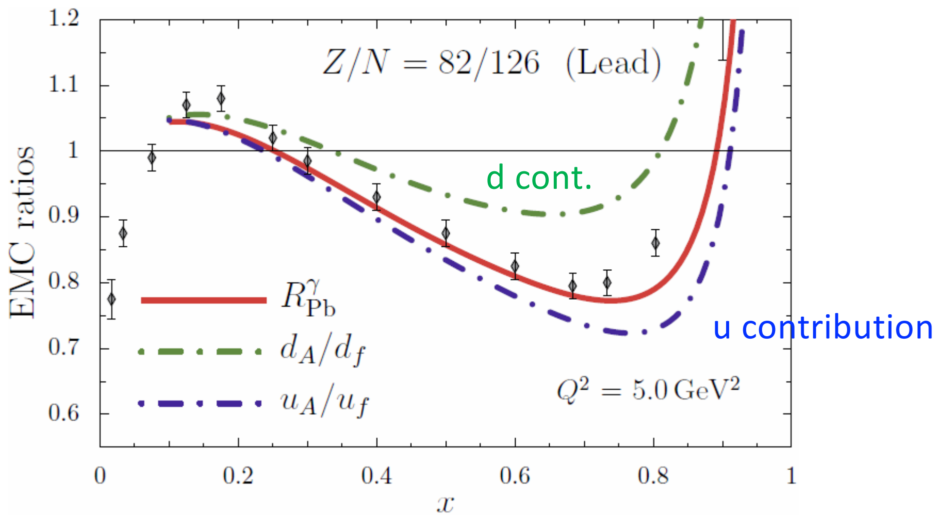
❖ Which nucleons are modified?
- All nucleons?
- Only SRC (pn) pairs?
- Flavor dependent?

Flavor-Dependent EMC Effect

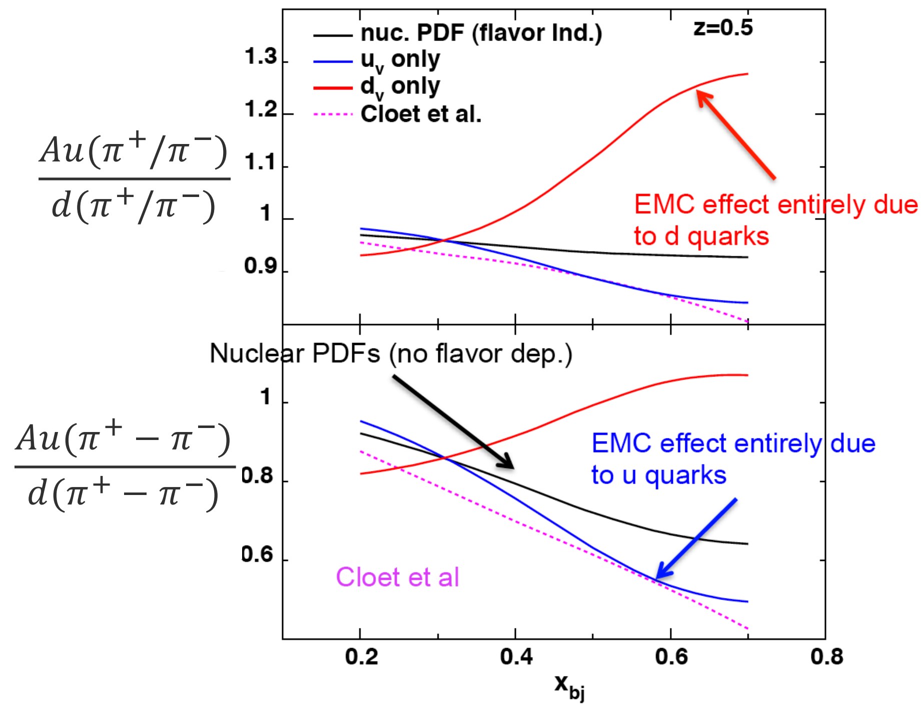
➢ **What causes the EMC Effect:**

❖ Gold nPDF model is flavor-dependent

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



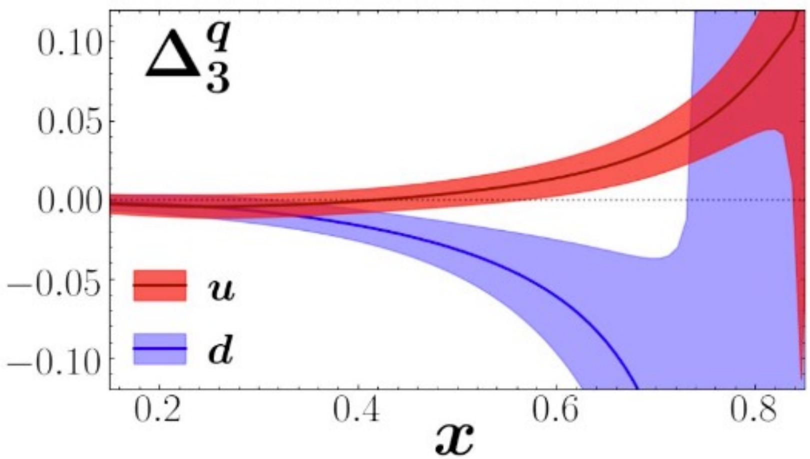
I. Cloet, et al, PRL 109, 182301 (2012); PRL 102, 252301 (2009)]



Motivation

➢ Flavor-Dependence of the EMC Effect:

❖ JAM suggests strong flavor-dependent effect in A=3:
- ✓ d_p-quark more modified in ^{3}H
- ✓ Much larger difference at x>0.6



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

$$\Delta_3^q \equiv \frac{q_{p/^3\mathrm{H}} - q_{p/^3\mathrm{He}}}{q_{p/^3\mathrm{H}} + q_{p/^3\mathrm{He}}} \neq 0$$

q = u or d

⇩

$$F_2^A \stackrel{?}{=} ZF_2^{p/A} + (A-Z)F_2^{n/A}$$

✓ Need independent verification!

SIDIS with A=3

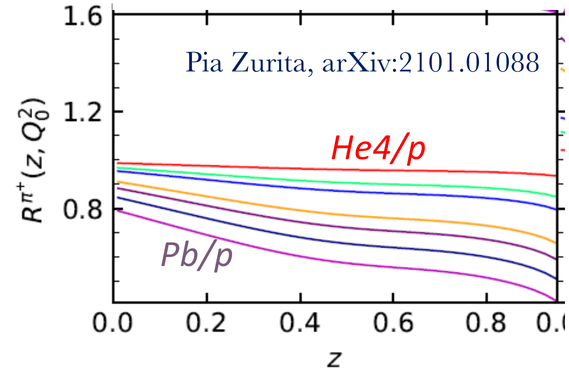
❖ Unpolarized SIDIS Cross Section (Factorization, LO, P_T integrated):

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

Free or Nuclear PDF (nPDF)

Free or Nuclear Fragmentation Function

nFF Ratios



❖ FFs are significantly modified in heavy nuclei

- Potential:
  - Sensitive to flavor
    - Detect π^+, π^-, K^+, K^-
  - Access 3D info via P_T distributions
- Challenges:
  - Common for all SIDIS:
    - Factorization Regions, FF poorly known, Theoretical Corrections
  - Nuclear-SIDIS:
    - Nuclear structure, Hadronization

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

❖ Light nuclei are easier

❖ Need close collaboration with theorists in global analysis

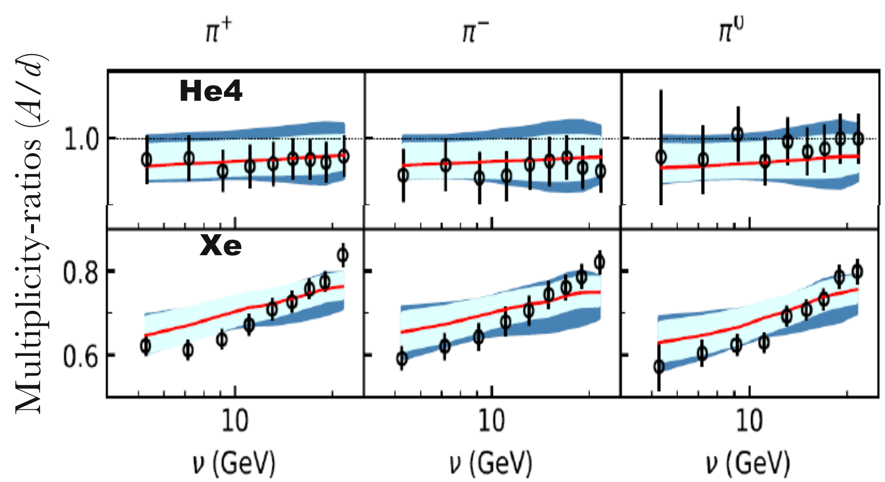
SIDIS with A=3

➢ Tritium and Helium-3:

❖ Minimize Challenges w/ A=3:

- ✓ Precise nuclear calculations
- ✓ Small hadronization effects
- ✓ Fragmentation functions
  - o Nuclear effects should be small and very similar
- ✓ Many theoretical corrections are similar

Small (~ 5% at high-z) effects in 4He nFF
Large effects in Xe nFF
(Pia Zurita, arXiv:2101.01088)



❖ Unique advantage with mirror nuclei: SIDIS cross-section ratios
❖ Help disentangle SIDS measurements with 3He as a neutron target
❖ Complementary to nuclear DIS (Marathon) and PVDIS

SIDIS with A=3

➢ SIDIS cross-section at LO

❖ SIDIS cross section at LO:

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

Simplify the FFs:

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

❖ Ratios:

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

Similar and small nuclear effects in nFF for d, 3He, 3H → $B_{A_1/A_2}^{\pi\pm} \approx 1$

❖ Most corrections cancel in ratios

❖Final results: Global analysis with theory to obtain u- and d-quark nPDFs and nFFs!

Motivation

➢ Proof of Principle: SIDIS cross-section at LO

✓ The ratios are uniquely sensitive to the PDFs (D=^{2}D, H = ^{3}He, T = ^{3}H):

^{3}He $$R^{\pi,-}_{H/D}(x,z) \simeq \frac{4(u_H - \bar{u}_H) - (d_H - \bar{d}_H)}{4(u_D - \bar{u}_D) - (d_D - \bar{d}_D)},$$

$$R^{\pi,-}_{T/D}(x,z) \simeq \frac{4(u_T - \bar{u}_T) - (d_T - \bar{d}_T)}{4(u_D - \bar{u}_D) - (d_D - \bar{d}_D)}$$ ^{3}H

Test these assumptions with other observables:

$$R^{\pi,+}_{A/D}(x,z) \stackrel{?}{=} R^{A}_{EMC} = \frac{2}{A}\frac{\sigma^{DIS}_A(x)}{\sigma^{DIS}_D(x)}$$

$$B^{\pi,+}_{A/D}(z) = \frac{M^{\pi+}_A + M^{\pi-}_A}{M^{\pi+}_D + M^{\pi-}_D}$$

SIDIS multiplicity ratios:

$$M^h(z) = \frac{\sigma_{SIDIS}}{\sigma_{DIS}}$$

Response to PAC50

Conditionally approved (C2) by PAC 50

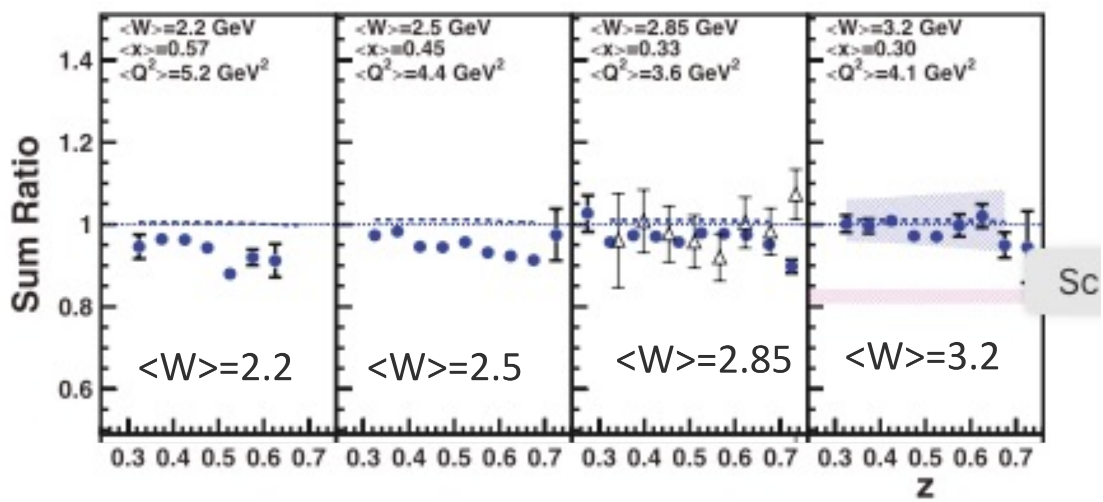
Issues: 1) The proposal does not sufficiently address the challenges in extracting PDFs from SIDIS measurements in JLab kinematics, which might be enhanced in nuclear targets. The proponents should understand what the contamination from target fragmentation is as a function of the W2-cut and study the impact of more stringent cuts on the precision and kinematic coverage in xB and Q2.

We now plot our results with cuts on W at 2, 2.5, and 2.7 GeV. We will compare results as a function of the W cut.

$$R_1(z) = \frac{M_{\rm d}^{\pi^+}(z) + M_{\rm d}^{\pi^-}(z)}{M_{\rm p}^{\pi^+}(z) + M_{\rm p}^{\pi^-}(z)} \stackrel{?}{=} 1$$

$$M = \frac{\sigma_{SIDIS}}{\sigma_{DIS}}$$

Bhatt, et al, PLB 865 (2025) 139485



Response to PAC50

Conditionally approved (C2) by PAC 50

Issues: 2) A closer interaction with theorists has started and should be further pursued. A NLO analysis of pseudo-data, using in-medium fragmentation functions, would better clarify what is the sensitivity of the proposed measurement. This analysis should account for any possible target fragmentation contribution in the extraction. To make a strong case for the measurement it is important to show the impact of different cuts and model assumptions on the physics goal, i.e., the flavor dependence of the EMC effect.

→ We are working with the JAM group to implement our simulated results in their fits to see how our data would constrain their models.

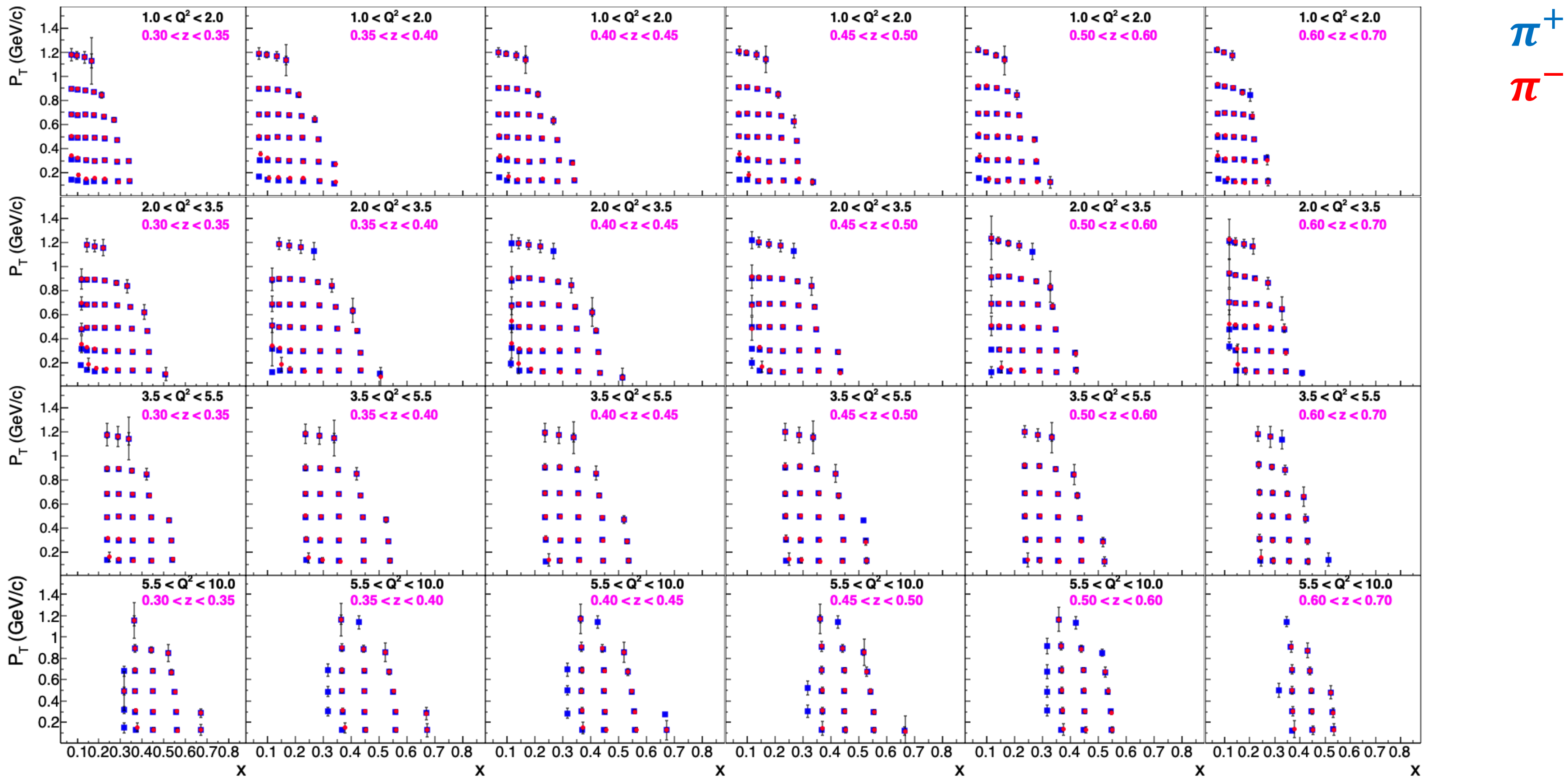
→ We are also working with other theorists to get updated calculations

3) The measurement of cross sections as a function of xB, Q2, z, and pT is strongly encouraged by the PAC, as it allows one to study the applicability of the SIDIS factorization formalism, and possibly to extract (nuclear) unpolarized PDFs, TMDs, and fragmentation functions.

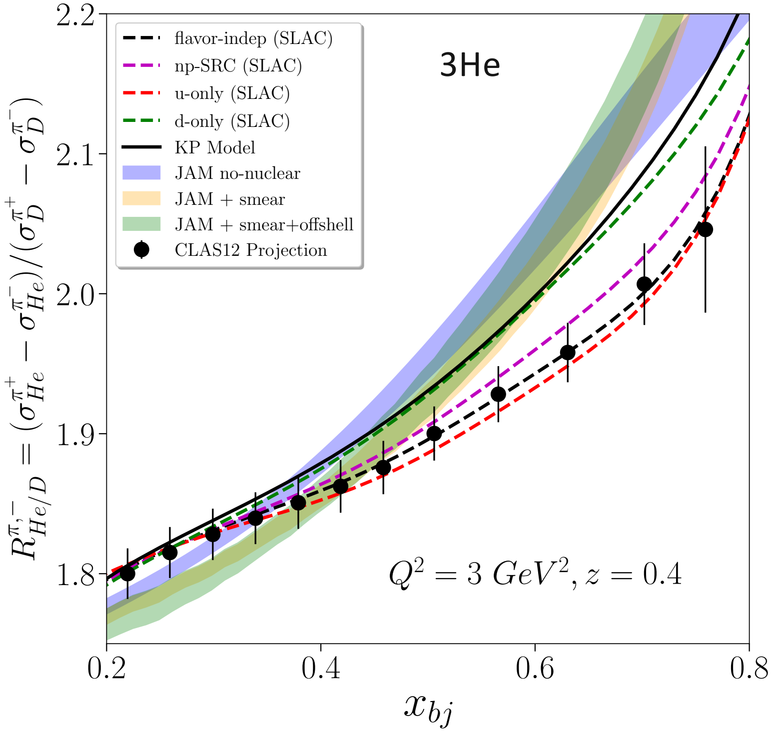
→ We will publish four-dimensional cross sections as a function of xB, Q2, z, and pT. This will be the primary input to theoretical and phenomenological models.

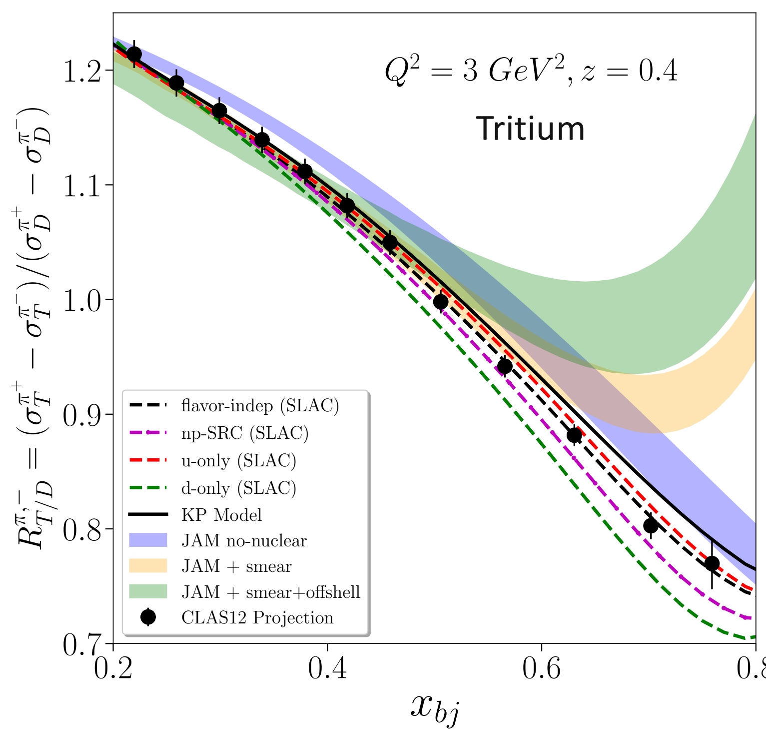
Excellent statistics, kinematic reach

➢ **Projected Results of 3He SIDIS: Pion Data 4D Binning**



2022 Projected results (W>2 cut)



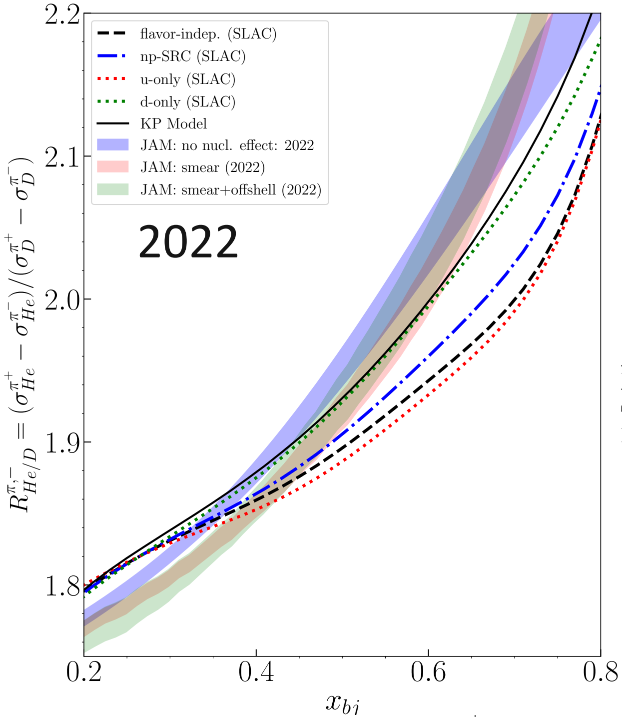


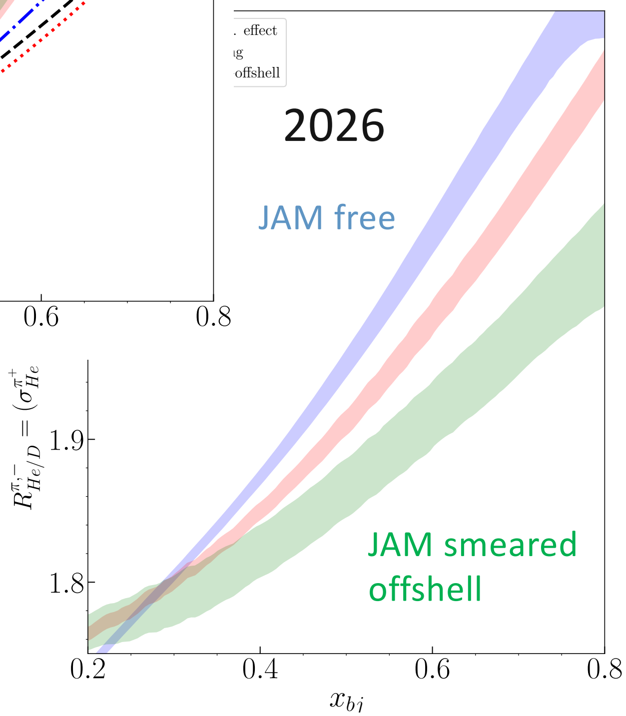
Dashed – different SLAC models (flavor-indep, np-SRC, u-only, d-only)
Solid – Kulagin and Petti

New JAM Results

$$R = \frac{\sigma_3^{\pi+} - \sigma_3^{\pi-}}{\sigma_d^{\pi+} - \sigma_d^{\pi-}}$$

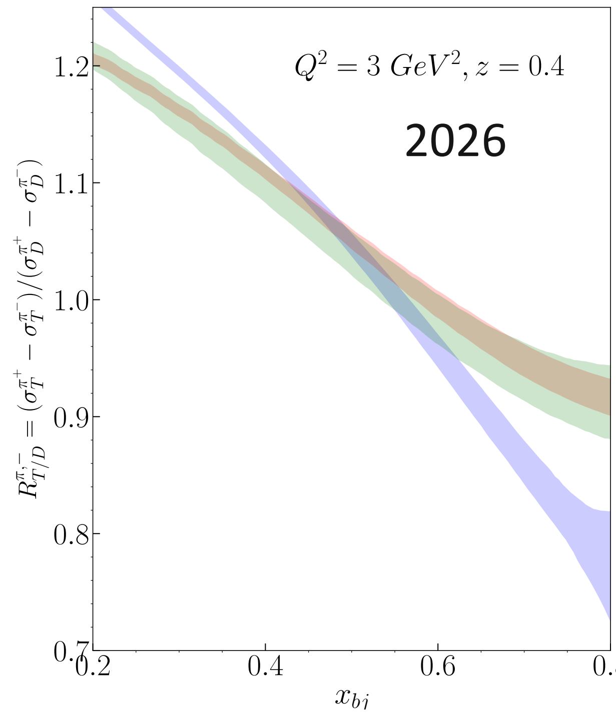
^{3}He

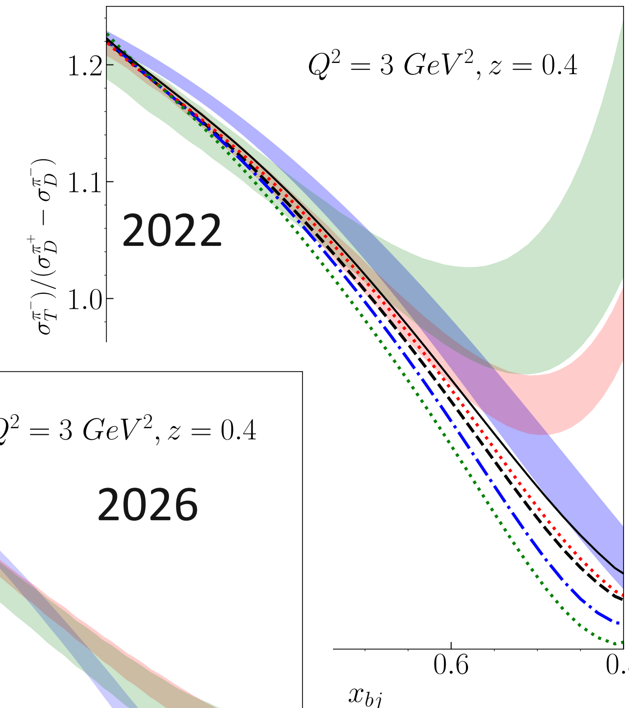


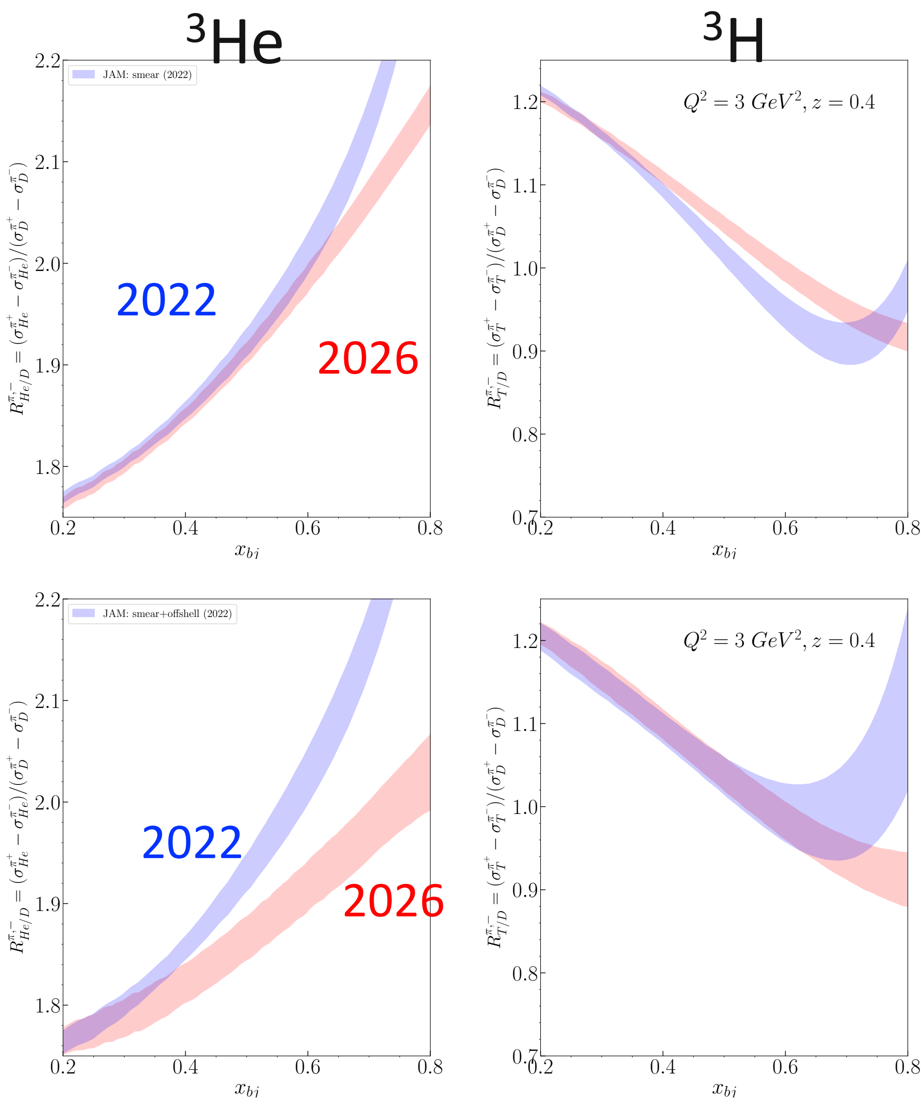


JAM smeared

^{3}H







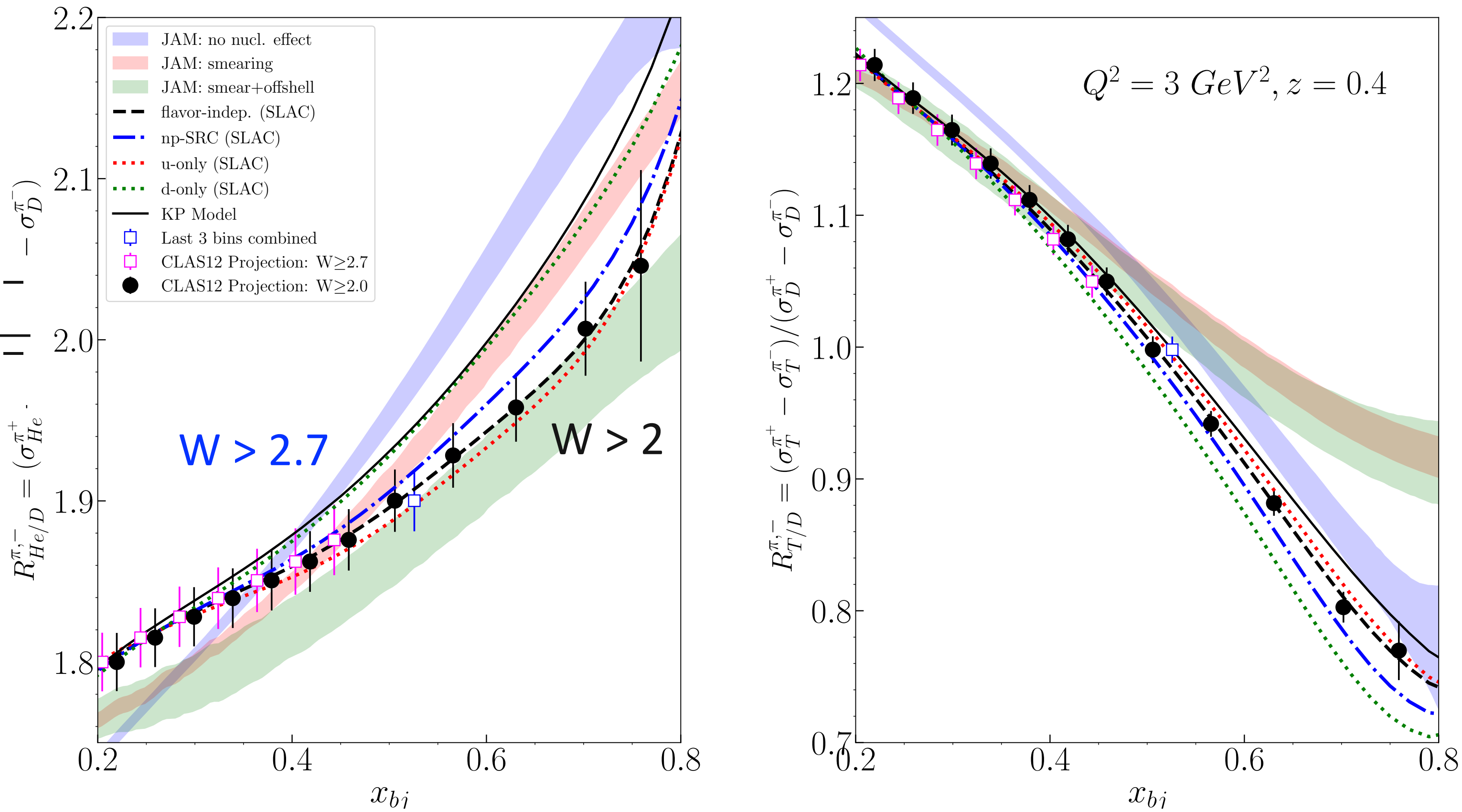
Updated JAM smearing

Updated JAM smearing and offshell effects

Projected Results

$$R = \frac{\sigma_3^{\pi+} - \sigma_3^{\pi-}}{\sigma_d^{\pi+} - \sigma_d^{\pi-}}$$

^{3}He ^{3}H



Summary

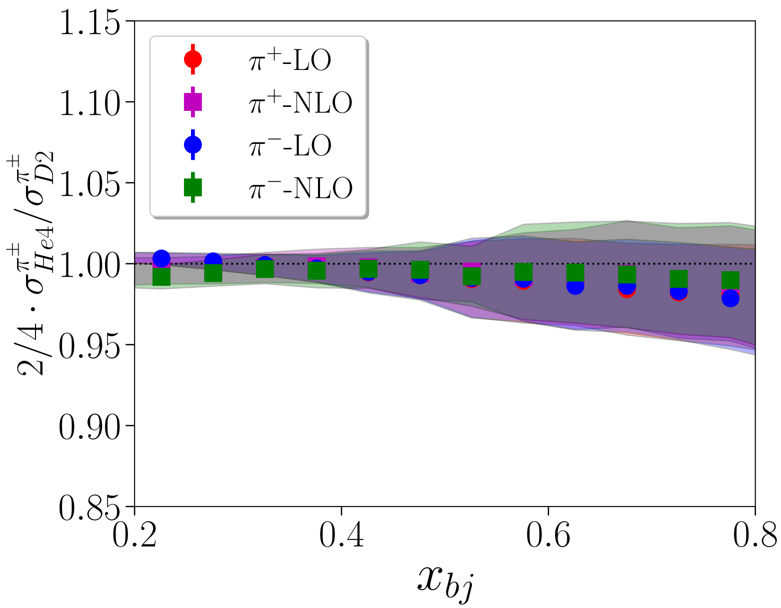
- ➢ Tritium is back → Maximize its usefulness!
- ➢ The physics:
  - ✓ Resolve flavor-dependent EMC effect
  - ✓ Test nuclear correction at high x
  - ✓ Measure medium effects on TMDs and FFs
  - ✓ Explore medium effects on strangeness
- ✓ Ongoing theoretical support
  - ✓ New JAM calculations
  - ✓ Implementing our simulation “data” in JAM to see impact
  - ✓ Large change in JAM from 2022 to 2026 implies large sensitivity
- ➢ Will request full approval

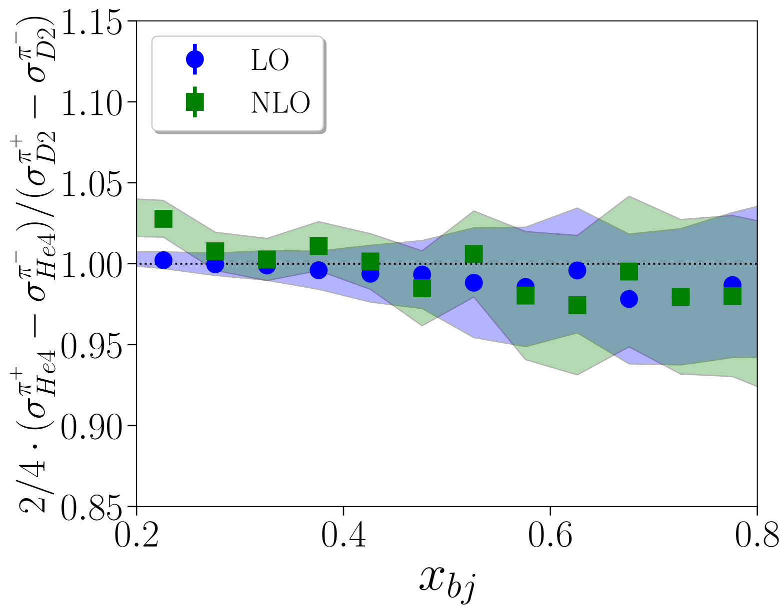
BACKUP

PAC Question

➢ **SIDIS cross-section: How good is LO?**

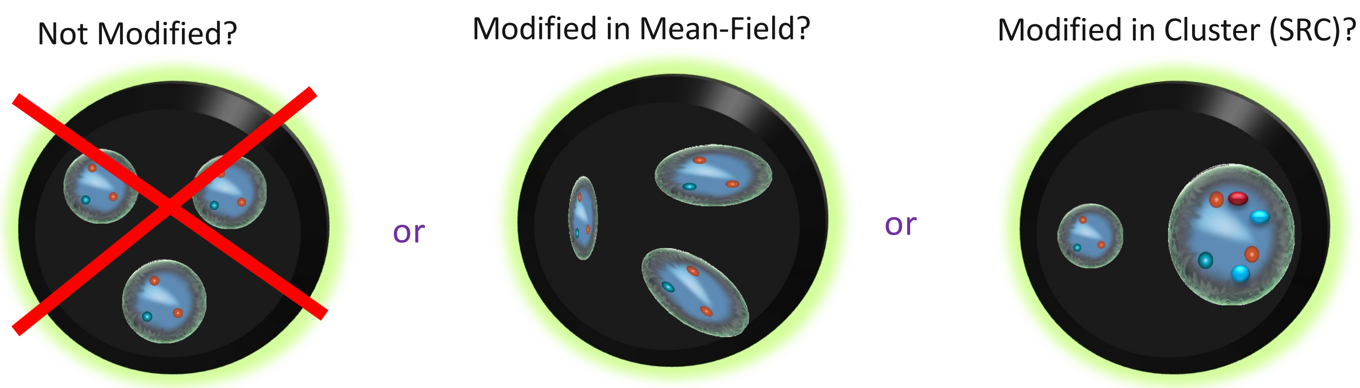
$$\frac{d\sigma_A^h}{dx dQ^2 dz} = \frac{4\pi\alpha^2 s}{Q^4}(1 - y + \frac{y^2}{2}) \sum_q e_q^2 f_1^{A,q}(x) \cdot D_{A,q}^h(z),$$





Motivations

➢ **Nucleons in a Nucleus**

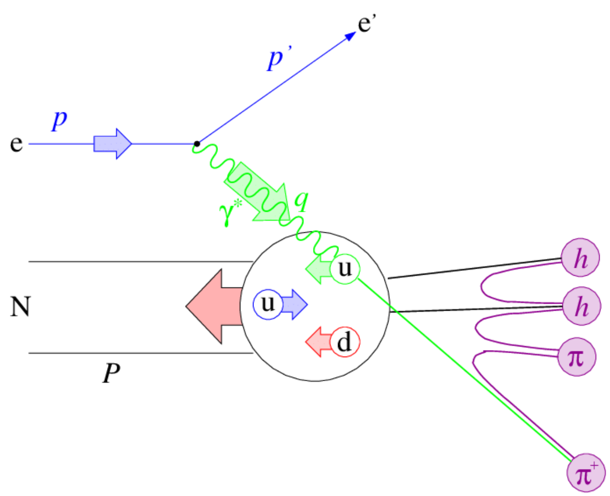


- EMC Effect: How nucleons modified?
- Which nucleons are modified?
- Modification to u- and d- quarks?
- Modification of transverse distributions (nuclear TMD)?

- 40 years of study→ No answers → Need new observables

SIDIS with A=3

➢ **SIDIS w/ Nucleons:**



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

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

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

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

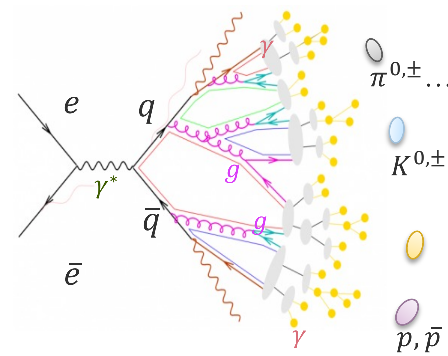
PDF (from DIS)

Fragmentation Function

❖ Fragmentation Functions (FF):

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

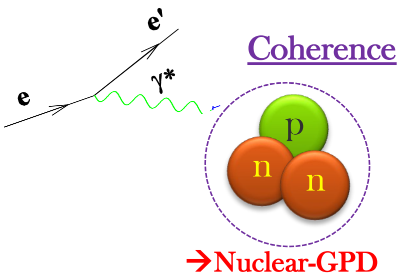
$$M^h(Q^2, z) = \frac{\sigma_{SIDIS}}{\sigma_{DIS}} = \frac{\sum_q e_q^2 f_1^q(Q^2, x) \cdot D_q^h(Q^2, z)}{\sum_q e_q^2 f_1^q(Q^2, x)}$$

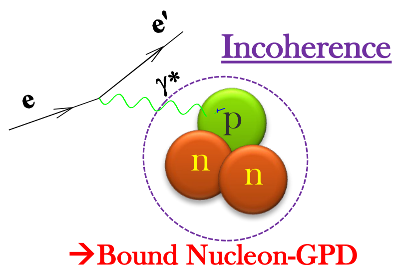


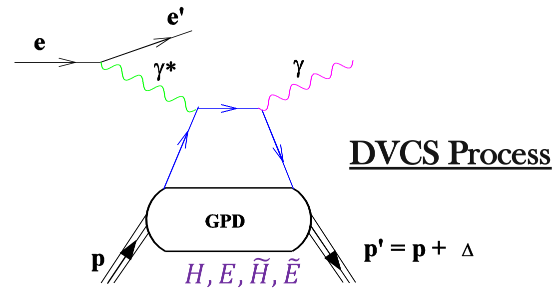
- Relatively poorly known.

The Proposed Measurement

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





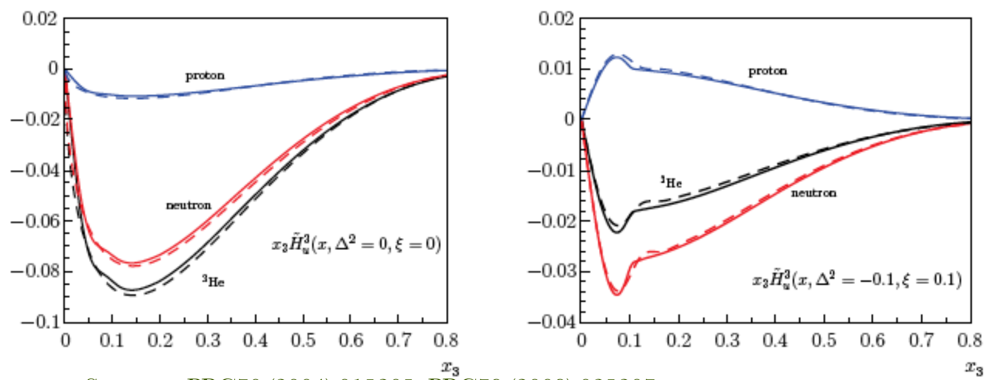


$$H_q^A(x,\xi,\Delta^2) \simeq \sum_N \int \frac{d\bar{z}}{\bar{z}} h_N^A(\bar{z},\xi,\Delta^2) H_q^N\left(\frac{x}{\bar{z}}, \frac{\xi}{\bar{z}}, \Delta^2\right)$$

  - ❖ 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!