# In-Medium Nucleon Structure and Fragmentation

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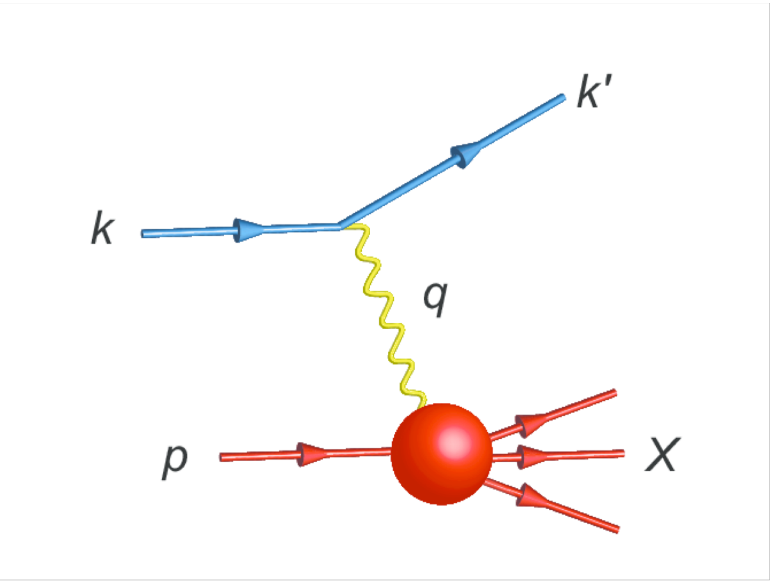
# Outline

- Medium Effect In Inclusive DIS
- Medium Effect In SIDIS
- pA Drell-Yan Process
- Summary

# Medium Effect In Inclusive DIS




$$q = l - l' \qquad Q^2 = -q^2 = 4E_l E_{l'} \sin^2 \theta/2$$

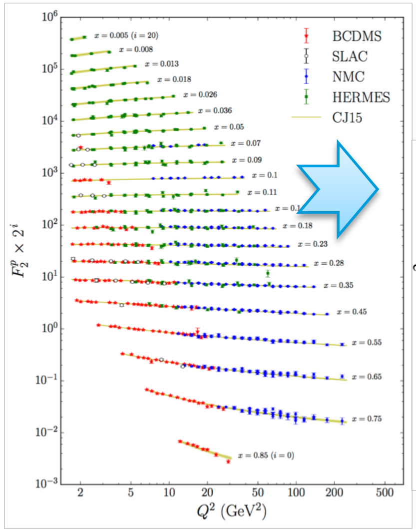
$$x_B = \frac{Q^2}{2M\nu} = \frac{q \cdot P}{M} \qquad y = \frac{E_l - E_{l'}}{E_l} = \frac{q \cdot P}{l \cdot P}$$

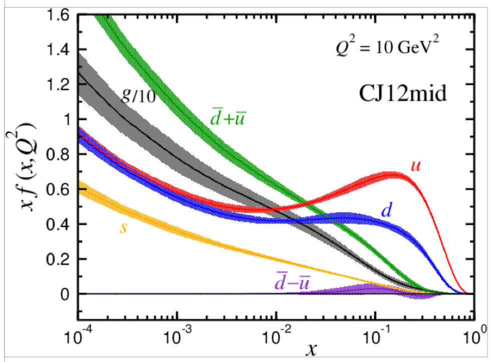
# PDF in Inclusive DIS

➢ Nucleons vs in Nuclei:

- Inclusive DIS accesses PDFs:

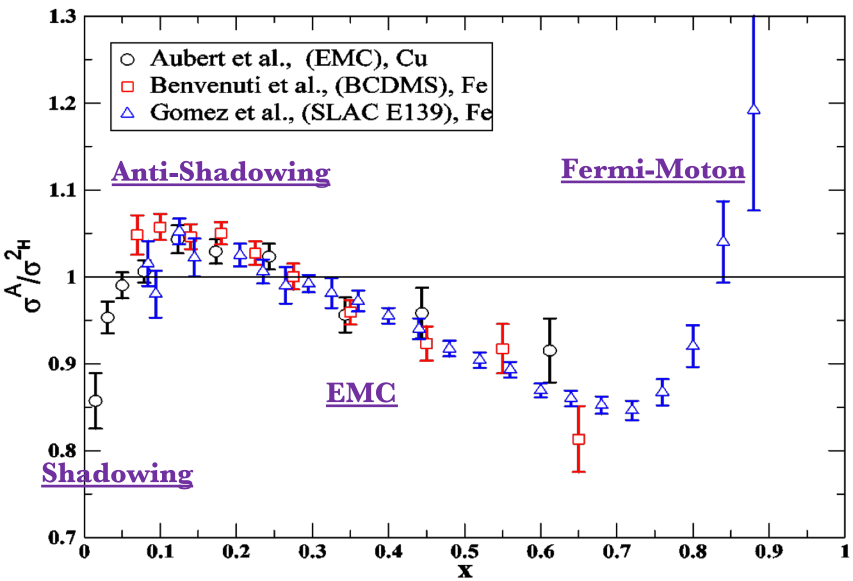
$$\frac{d\sigma}{dxdQ^2} = \frac{2\pi\alpha^2}{(x_B s)^2} \frac{1-y+\frac{y^2}{2}}{y^2} \sum_q e_q^2 f_1^q(x) \quad F_2^N(x) = x\sum_q e_q^2 q(x)$$




✓ Many decades of measurement w/ eDIS, pp
✓ Nuclear effects corrected for effective-"free" neutrons (BoNUS/BoNUS12, MARATHON, PVDIS, …)

- **Interesting features when using nuclei**

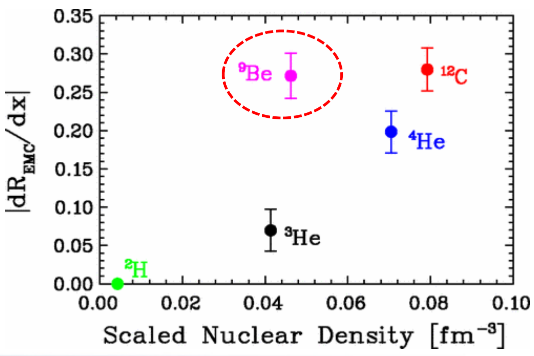


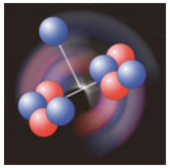

*Modified parton structure?*

$$R(x) = \frac{\sigma_{DIS}^A}{\sigma_{DIS}^D} \propto \frac{F_2^A}{F_2^D} = \frac{\sum_q e_q^2 q^A(x/y) \otimes f_q^A(y)}{\sum_q e_q^2 q^D(x/y) \otimes f_q^D(y)}$$

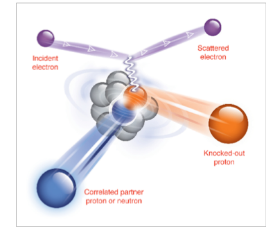
*Nuclear medium correction?*

Local-effect?

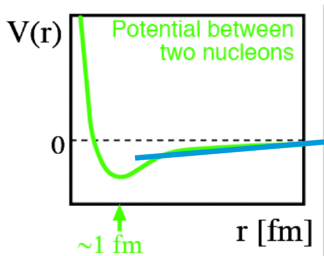


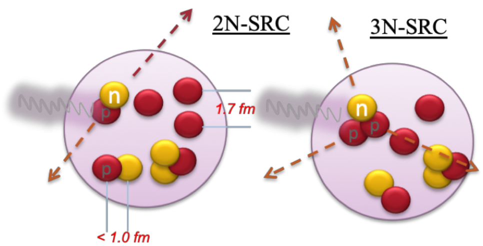



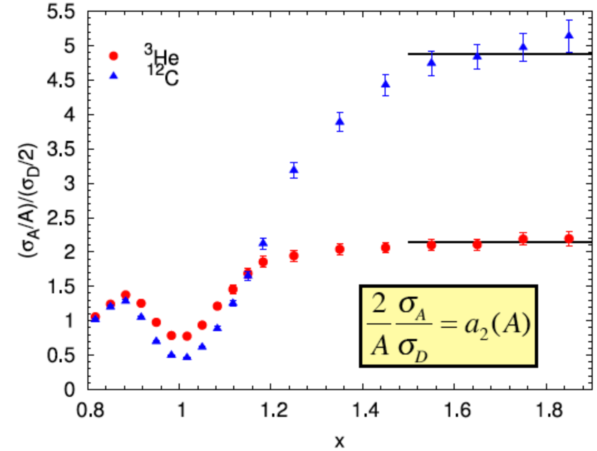
# PDF in Inclusive DIS




- EMC Effect vs. SRC Effect:
  - **Short-Range Correlations (SRC):** Nucleons largely overlapped (high-density); each carry large momenta (high-virtuality) ; small total momentum



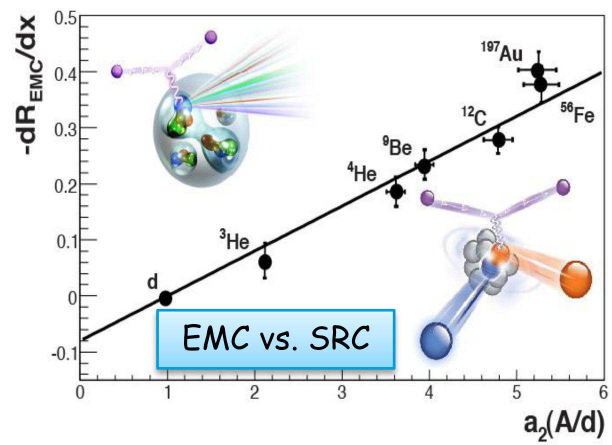




  - 2N-SRC and 3N-SRC in nuclei are similar to $^2$D and $^3$He ($^3$H)
    Inclusive QE XS ratios reveal a scaling behavior x in (1.3<x<2.0)

  - Surprising similar A-dependence with EMC
    - ✓ EMC vs SRC provide a way to understand the partonic picture in NN-interaction
      Many new JLab@12GeV experiments

      **High virtuality?**
      EMC effect driven by virtuality of nucleon

      **Local Density?**
      EMC effect driven by local density

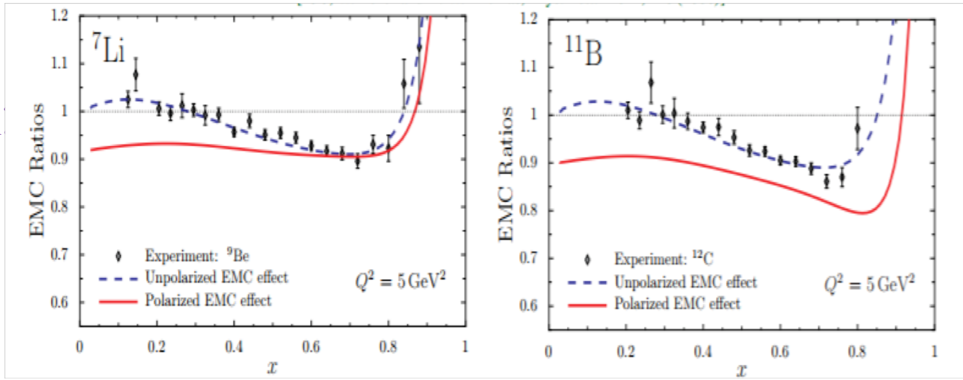



L. Weinstein et al, PRL 106, 052301 (2011)
J. Arrington et al., PRC 86, 065204 (2012)
O. Hen et al, PRC 85, 047301 (2012)

# Medium Effect in Inclusive DIS

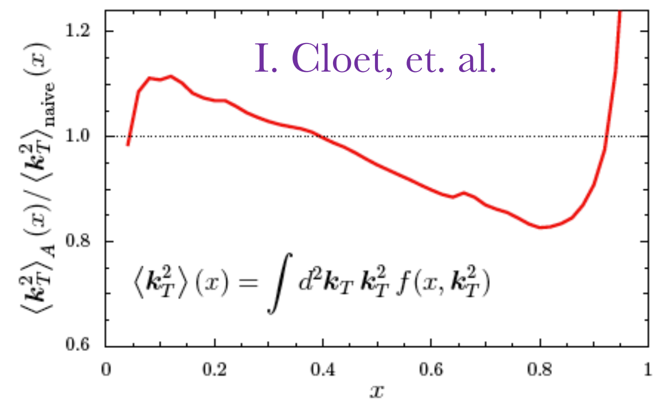
➤ What more we can learn?:

- ✓ The flavor-dependent medium effect:
  Stronger medium effect on u- then d-quark
  Medium effect in sea-quarks?




- Medium effect in Helicity-PDF $g_1(x)$
  CLAS12 new experiment with polarized Li[7]
  I. Cloet, PRL 95, 052302, 2005); PLB 642, 210(2006)

- Medium effect in Transversity-PDF $h_1(x)$?
  $g_1(x)$ has stronger medium effect than $f_1(x)$, how about $h_1(x)$?



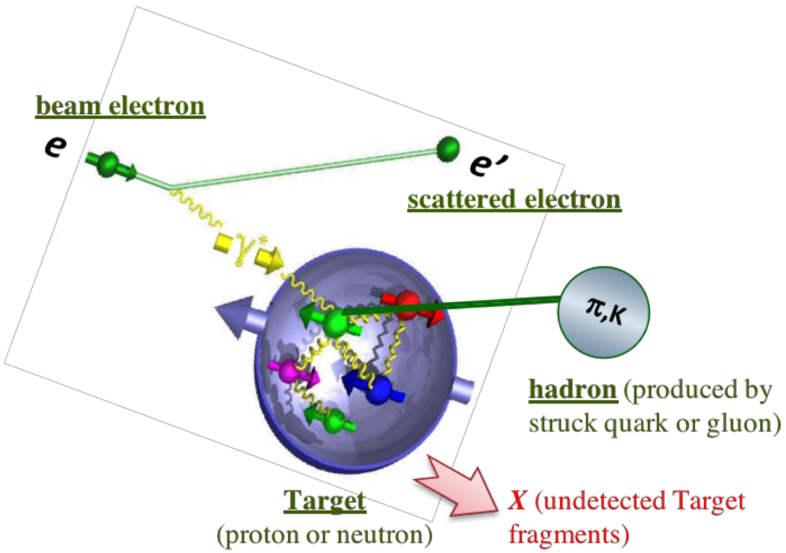

- ✓ Medium effect on the transverse direction?
  Maybe the reason that we still don't understand the
  EMC effect is because we only look at 1D-PDF?

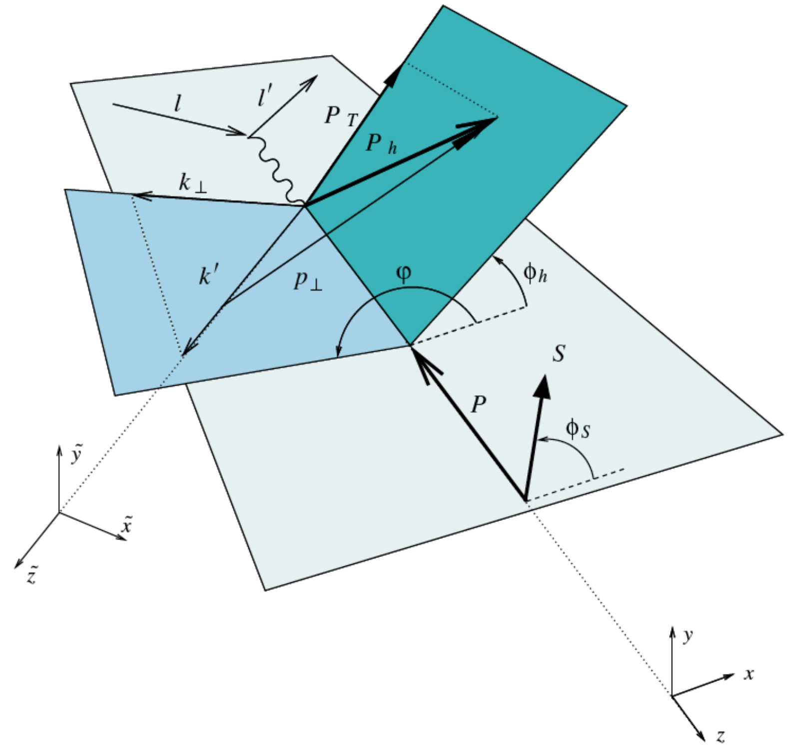
- ✓ 3D structure of nucleons in nuclei (Nuclear TMD/GPD, Nuclear Fragmentation-Function)?

❖ Would be very difficult, especially w/ polarized nuclear targets
❖ Higher-Twist effects in nuclear

✓ **Possible in new measurements on SIDIS/Drell-Yan w/ nuclei**

# Medium Effect In SIDIS

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$$x_B = \frac{Q^2}{2M\nu} = \frac{q\cdot P}{M} \qquad y = \frac{E_l - E_{l'}}{E_l} = \frac{q\cdot P}{l\cdot P} \qquad z = \frac{P\cdot P_h}{P\cdot q}$$

$$P_T = \frac{p\cdot P_h}{\left|q^2\right|} = p_{h\perp}$$

Quark's final transverse momentum (before hadronized)

Quark's intrinsic transverse momentum

$$\boxed{\vec{p}_\perp = \vec{P}_T - z_h \vec{k}_\perp}$$

Out-going Hadron's transverse momentum

# SIDIS with Nucleons

- Some unpolarized LO formulism:

Unpolarized fragmentation functions (FF)

  - Unpolarized SIDIS cross section at LO:

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

  - Ignore heavy quarks and make few assumptions:

$$u_n(x) \to d_p(x) = d(x)$$
$$d_n(x) \to u_p(x) = u(x)$$
$$\bar{d}_n(x) \to \bar{u}_p(x) = \bar{u}(x)$$
$$\bar{u}_n(x) \to \bar{d}_p(x) = \bar{d}(x)$$

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

  - Useful observables for pion production :

Yield, XS

$$R_{p/n}^{\pi^+-\pi^-} = \frac{N_p^{\pi^+} - N_p^{\pi^-}}{N_n^{\pi^+} - N_n^{\pi^-}} = \frac{4[u(x)-\bar{u}(x)]-[d(x)-\bar{d}(x)]}{4[d(x)-\bar{d}(x)]-[u(x)-\bar{u}(x)]}$$

$$R_{p/n}^{\pi^++\pi^-} = \frac{N_p^{\pi^+} + N_p^{\pi^-}}{N_n^{\pi^+} + N_n^{\pi^-}} = \frac{4[u(x)+\bar{u}(x)]+[d(x)+\bar{d}(x)]}{4[d(x)+\bar{d}(x)]+[u(x)+\bar{u}(x)]}$$

Sensitive to "pure" PDF

Ignore strangeness

$$r_p^{\pi^+/\pi^-} = \frac{N_p^{\pi^+}}{N_p^{\pi^-}} = \frac{4u(x)D^{fav} + 4\bar{u}(x)D^{unf} + d(x)D^{unf} + \bar{d}(x)D^{fav}}{4u(x)D^{unf} + 4\bar{u}(x)D^{fav} + d(x)D^{fav} + \bar{d}(x)D^{unf}}$$

$$r_n^{\pi^+/\pi^-} = \frac{N_n^{\pi^+}}{N_n^{\pi^-}} = \frac{4d(x)D^{fav} + 4\bar{d}(x)D^{unf} + u(x)D^{unf} + \bar{u}(x)D^{fav}}{4d(x)D^{unf} + 4\bar{d}(x)D^{fav} + u(x)D^{fav} + \bar{u}(x)D^{unf}}$$

Partially sensitive to PDF (experimental advantage, less NLO effect)

$$M_{p,n}^{\pi}(x,z) = \frac{N_{p,n}^{\pi^+} + N_{p,n}^{\pi^-}}{N_{p,n}} \propto (D^{fav} + D^{unf})$$

Sensitive to "pure" FF

  - In kaon production:

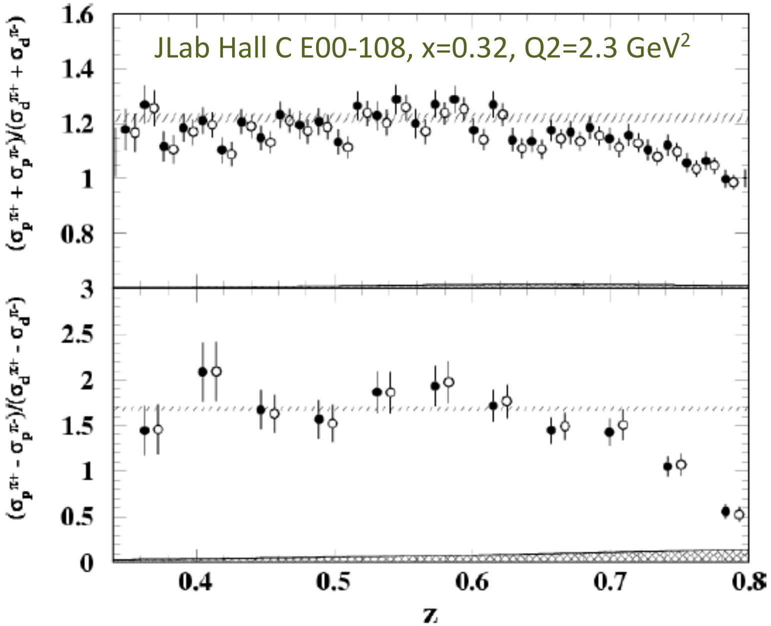
$$R_{pn}^{K^+-K^-} = \frac{N_p^{K^+} - N_p^{K^-}}{N_n^{K^+} - N_n^{K^-}} = \frac{4[u(x)-\bar{u}(x)]-[s(x)-\bar{s}(x)]}{4[d(x)-\bar{d}(x)]-[s(x)-\bar{s}(x)]}$$

**Note**: Simplified for proof of principle; Global analysis needed!

# SIDIS with Nucleons

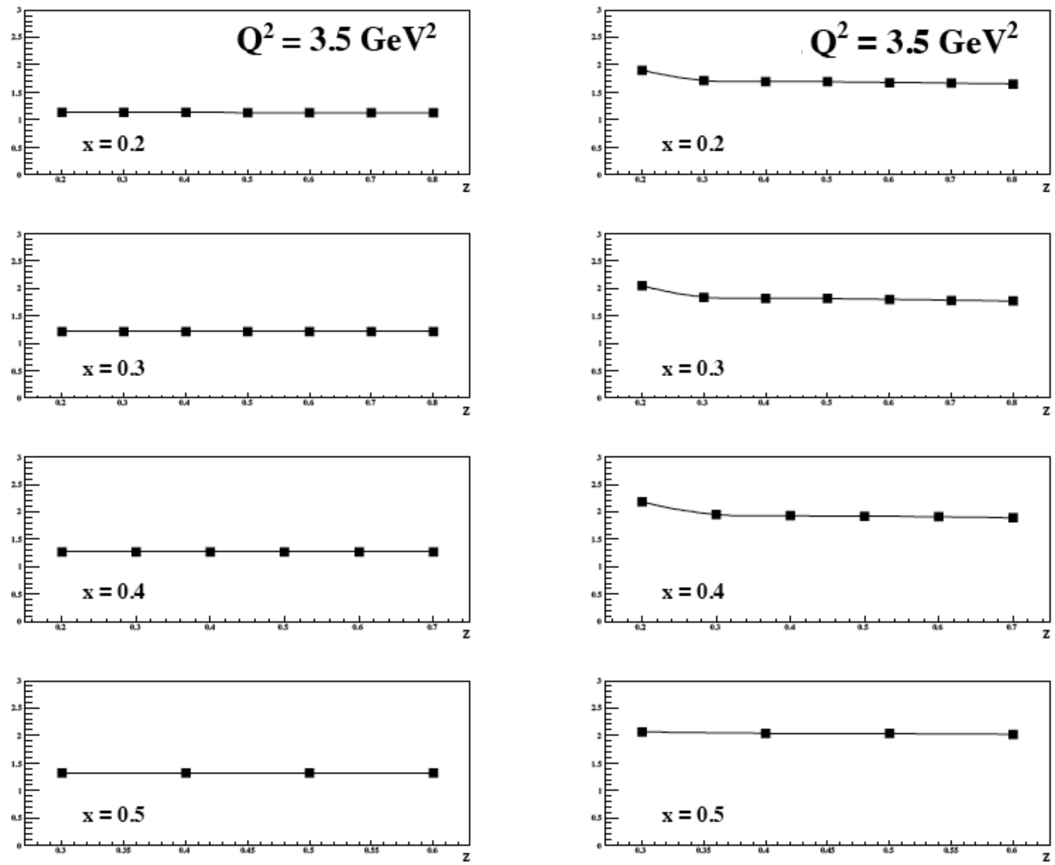
- Some unpolarized LO formulism:

❖ Supported by Hall-C data




❖ Check NLO in Monte-Carlo

$$\frac{\sigma_p^{\pi^+} + \sigma_p^{\pi^-}}{\sigma_d^{\pi^+} + \sigma_d^{\pi^-}} \qquad \frac{\sigma_p^{\pi^+} - \sigma_p^{\pi^-}}{\sigma_d^{\pi^+} - \sigma_d^{\pi^-}}$$

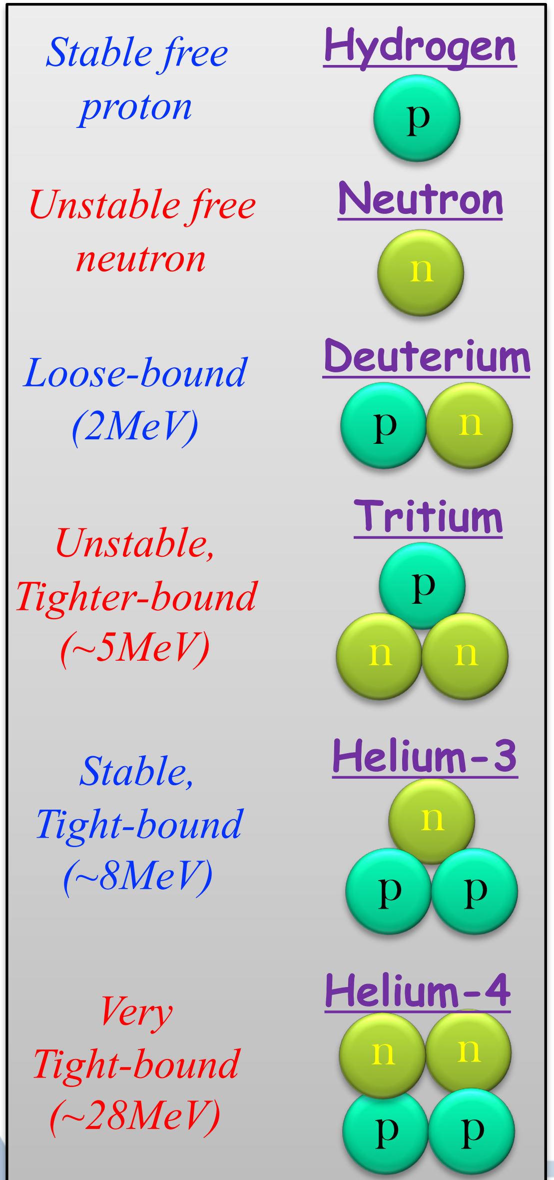



❖ Good enough to motivate the initial study of SIDIS w/ nuclei

Courtesy to X-D. Jiang

# SIDIS with Light Nuclei

- Tritium and He3:




- Free-proton available, but need Deuteron as effective neutron

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

*Spectral functions (calculable)*

*"dressed" nucleons (but close to free)*

**Medium-Effect:** Fermi-motion, binding, off-shell, **medium-modification**, …

- $^3$H & $^3$He:

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

- ✓ Spectral functions in A=3 nuclei are precisely calculable
- ✓ Correction becomes small (sometimes ignored) in ratios
- ✓ Medium-modification effect is similar and small at high-x

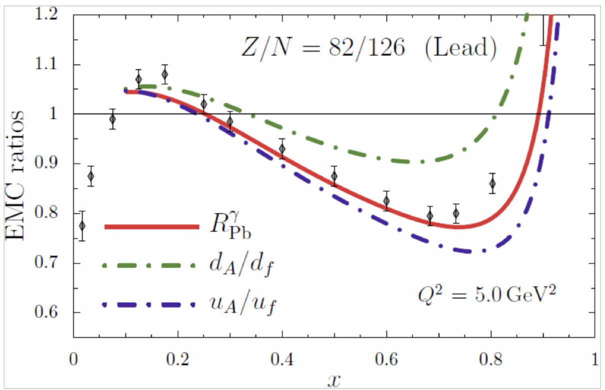
- $^3$H & $^3$He can be used as effective "free-nucleons" or as well-controlled nuclear medium

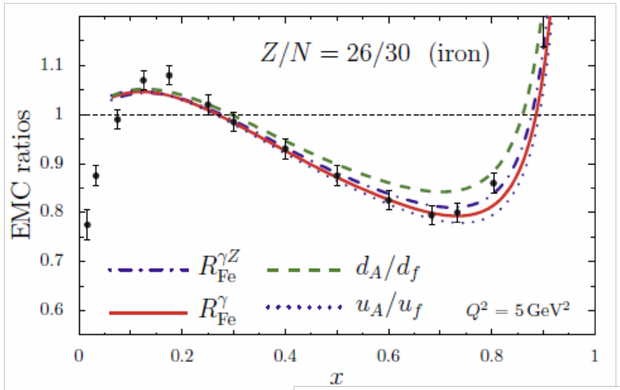
- Better to study medium effect in these lightly bound nuclei before getting into **REAL** nuclei (He4 and above) → A bridge to the free-world!

# SIDIS with Light Nuclei

- Tritium and He3 as well-controlled nuclear medium:
  - Study flavor-dependent EMC effect

In $Z \neq N$, different medium effect on u- and u- quark ? I. Cloet, et al, PRL 109, 182301 (2012); PRL 102, 252301 (2009)]

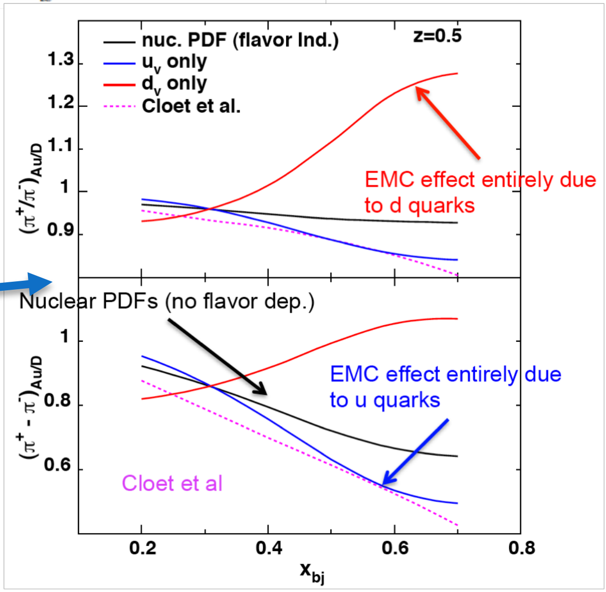



- A power probe with $^3$H (Z/N=1/2) and $^3$He (Z/N=2):
  - ✓ If N>Z, u-quark is more "bound" → $^3$H
  - ✓ If N<Z, d-quark is more "bound" → $^3$He
- Systematic measurement w/ $^1$H, $^2$D and $^3$He&$^3$He

$$R^{\pi^+-\pi^-}_{A/D}(x,z,p_T) = \frac{N_A^{\pi^+}-N_A^{\pi^-}}{N_D^{\pi^+}-N_D^{\pi^-}} = \frac{1}{3}\frac{(4Z-N)u_v^A-(Z-4N)d_v^A}{u_v^D+d_v^D}\cdot\frac{D_A^{fav}-D_A^{unfav}}{D_D^{fav}-D_D^{unfav}}$$

If not cancelled, we can exam their z-dependence!




- Would also measure the $p_T$-dependence
- Important input for SIDIS w/ polarized D2 and He3 as effect neutrons!

# SIDIS with Light Nuclei

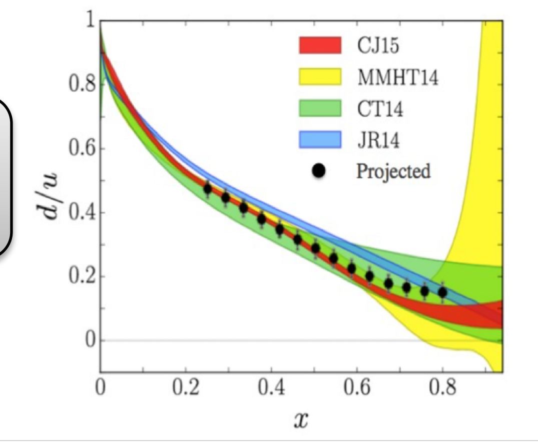
- Tritium and He3 as "free"-nucleons:

  - MARATHON experiment

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

Super-Ratio in EMC (DIS)

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




  - SIDIS w/ $^3$H & $^3$He → direct flavor tagging of "free" nucleon PDF

$$U^{^3He} = U^{^3H} = U^{A=3} \simeq 2u(x) + d(x) \qquad S^{^3He} = S^{^3H} = S^{A=3} \simeq 3s(x)$$

$$R_A^{\pi^+-\pi^-}|_{A=3} = \frac{N^{\pi^+}_{^3He} - N^{\pi^-}_{^3He}}{N^{\pi^+}_{^3H} - N^{\pi^-}_{^3H}} = \frac{4U_v^A(x) - D_v^A(x)}{4D_v^A(x) - U_v^A(x)}|_{A=3}$$

Fragmentation function cancelled if A-dependence!

$$\frac{D_v^A}{U_v^A}|_{A=3} = \frac{D^A(x) - \bar{D}^A(x)}{U^A(x) - \bar{U}^A(x)} = \frac{4 + R_A^{\pi^+-\pi^-}}{1 + 4R_A^{\pi^+-\pi^-}}|_{A=3}$$

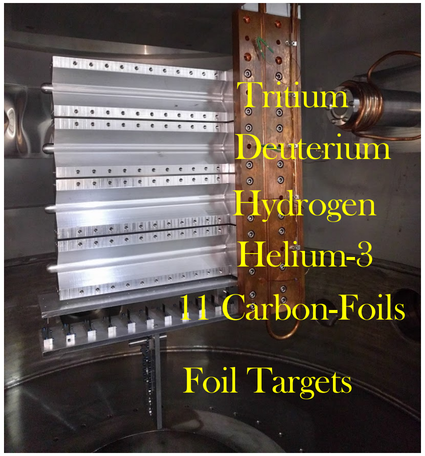
$$R_A^{K^+-K^-}|_{A=3} = \frac{N^{K^+}_{^3He} - N^{K^-}_{^3He}}{N^{K^+}_{^3H} - N^{K^-}_{^3H}} = \frac{4U_v^A(x) - [S^A(x) - \bar{S}^A(x)]}{4D_v^A(x) - [S^A(x) - \bar{S}^A(x)]}$$

Equal if strangeness symmetry!
***A way to test $s = \bar{s}$ assumption?***
But probably not at large x

  - Flavor dependence of Fragmentation function:

❖ **If extending into dependence in ($Q^2$, x, z, $p_T$), test the factorization in SIDIS**

# SIDIS with Light Nuclei




- New Tritium Experiments:
  - Tritium was successfully used in the Hall-A Tritium Run-Group (2018)
    MARATHON, (e,e')-SRC, (e,e'p)-SRC, (e,e'K) Λnn-Hypernucleus)
  - A second Tritium experimental Run-Group is under discussion
    - ✓ The Tritium Run-Group experiments were very successfully
    - ✓ Tritium Target System worked as expected
    - ✓ Still plenty of physics can do with Tritium

**Few ideas are under development:**

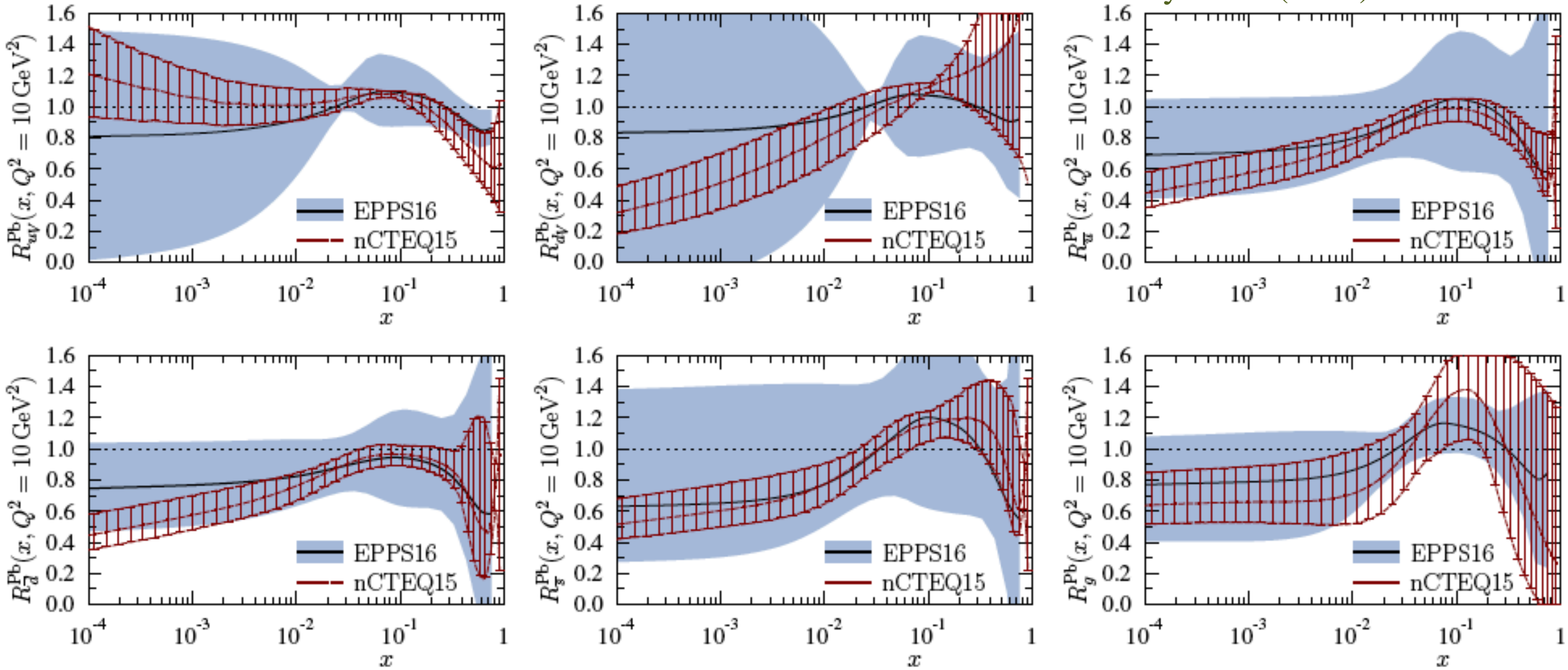
- Semi-Inclusive Deep Inelastic Scattering (SIDIS)
- Coherence/Incoherence DVCS→ Nuclear-GPD, Neutron-GPD
- (e, e'D) → Few body force, Deuteron Form Factors
- (e, e' pN) Triple-Coincident SRC
- Tritium/He-3 Radii
- More?

✓ Currently consider using CLAS12 but can be in Hall-C or SoLID (prefer)
✓ New Tritium target system design is ongoing

# SIDIS with Heavy Nuclei

- **Nuclear 3D Tomography:**
  - There are plenty rooms to improve the nPDF precision

Eur. Phys. J. C (2017) 77:163




- Much less knowledge about fragmentation function in medium (arxiv:1706.02859, also see Elke's talk)
- New data from eA and pA channels w/ wide range of nuclei are crucial
- SIDIS provides additional info on the transverse direction

# SIDIS with Heavy Nuclei

## ➢ Nuclear 3D Tomography:

- Learn the medium effect of PDF (aka, TMD) and FF in 3D using Hadronization data?

$$\frac{d\sigma^h}{dx\,dy\,dz\,d^2\mathbf{P_T}} = \frac{4\pi\alpha^2 s}{Q^4}\left(1-y+\frac{y^2}{2}\right)\sum_q e_q^2[f_1^q \otimes D_{1q}^h], \qquad [\ldots\otimes\ldots] = \int d^2p_T d^2k_T \delta^{(2)}\left(\mathbf{p_T} - \frac{\mathbf{P_T}}{z} - \mathbf{k_T}\right)[\ldots].$$

with Gaussian Ansatz: $f_q(x,k_\perp) = f_q(x)\frac{1}{\pi\langle k_\perp^2\rangle}e^{-k_\perp^2/\langle k_\perp^2\rangle}$ $\quad D_q^h(z,p_\perp) = D_q^h(z)\frac{1}{\pi\langle p_\perp^2\rangle}e^{-p_\perp^2/\langle p_\perp^2\rangle}$

- Again, define useful observables **but in 3D**:

Convolution instead of production!

$$R_{A/D}^{\pi^+ + \pi^-}(x,z,p_T) = \frac{N_A^{\pi^+} + N_A^{\pi^-}}{N_D^{\pi^+} + N_D^{\pi^-}} = A^+(x,p_T) \otimes B^+(z,p_T)$$

$$R_{A/D}^{\pi^+ - \pi^-}(x,z,p_T) = \frac{N_A^{\pi^+} - N_A^{\pi^-}}{N_D^{\pi^+} - N_D^{\pi^-}} = A(x,p_T) \otimes B(z,p_T)$$

"Pure" TMD term

$$A_{A/D}^+(x,p_T) = \frac{1}{5}\frac{(4Z+N)(u_A+\bar{u}_A)+(Z+4N)(d_A+\bar{d}_A)}{(u_D+\bar{u}_D)+(d_A+\bar{d}_A)}$$

$$A_{A/D}^-(x,p_T) = \frac{1}{3}\frac{(4Z-N)\cdot u_v^A - (Z-4N)\cdot d_v^A}{u_v^D + d_v^D}$$

"Pure" FF term

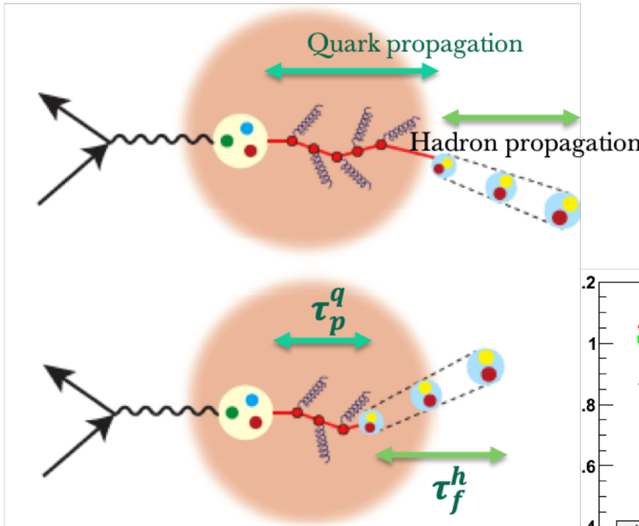
$$B_{A/D}^+(z,p_T) = \frac{D_A^{fav}+D_A^{unfav}}{D_D^{fav}+D_D^{unfav}} = \frac{M_A^\pi(z,p_T)}{M_D^\pi(z,p_T)} = \frac{(N_A^{\pi^+}+N_A^{\pi^-})/N_A}{(N_D^{\pi^+}+N_D^{\pi^-})/N_D}$$

$$B_{A/D}^-(z,p_T) = \frac{D_A^{fav}-D_A^{unfav}}{D_D^{fav}-D_D^{unfav}}$$

- To decouple "pure" TMD and FF terms, high luminosity and wide acceptance systems are needed!
  e.g., SoLID, CLAS12, EIC (similar experiment done in Hall-C, E12-09-004, w/o $p_T$ dependence)

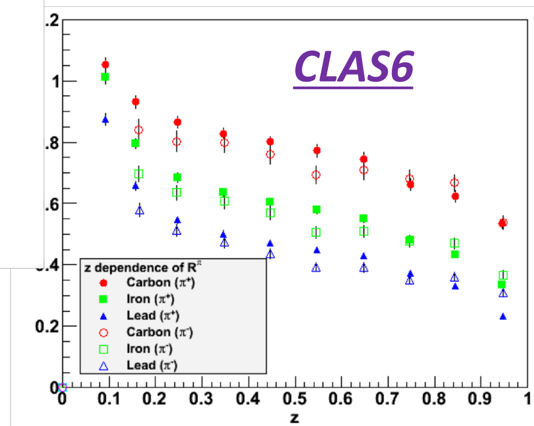
# SIDIS with Heavy Nuclei

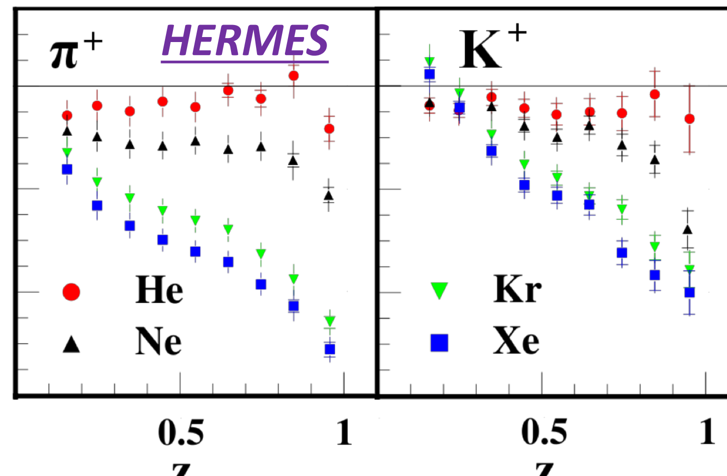
- Hadronization Physics:
  - Historically, we used the SIDIS w/ heavy nuclei to lean the Hadronization process in medium




Study in Hadronization Physics

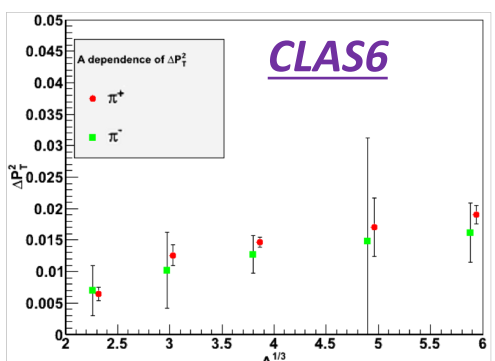
- Color confinement
- Parton energy loss in the medium
- Modification of the fragmentation functions in the medium
- Hadron/pre-hadron formation in the medium

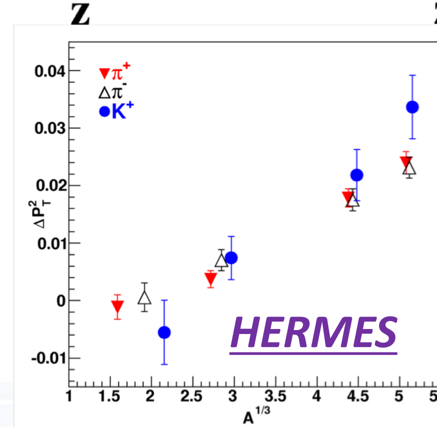



- $P_T$ broadening:

$$\Delta P_T^2 = \langle P_T^2 \rangle_A - \langle P_T^2 \rangle_D$$



# SIDIS with Heavy Nuclei

➢ Future Hadronization Experiments in Hall-B:

❖ A list of approved CLAS12 experiments (Run-Group B, D and E) to study Hadronization

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| E12-07-104 | Neutron magnetic form factor | Gilfoyle | A- | 30 | 90 | Neutron detector RICH (1 sector) Forward tagger | 11 | B K. Hafidi | liquid $D_2$ target |
| PR12-11-109 (a) | Dihadron DIS production | Avakian | - | - | | | | | |
| E12-09-007a | Study of partonic distributions in SIDIS kaon production | Hafidi | A- | 56 | | | | | |
| E12-09-008 | Boer-Mulders asymmetry in K SIDIS w/ H and D targets | Contalbrigo | A- | TBA | | | | | |
| E12-11-003 | DVCS on neutron target | Niccolai | A | 90 | | | | | |
| E12-06-106 | Color transparency in exclusive vector meson production | Hafidi | B+ | 60 | 60 | | 11 | D | Nuclear |
| E12-06-117 | Quark propagation and hadron formation | Brooks | A- | 60 | 60 | | 11 | E | Nuclear |

✓ Beam energy, E0 = 8.8 and 11 GeV

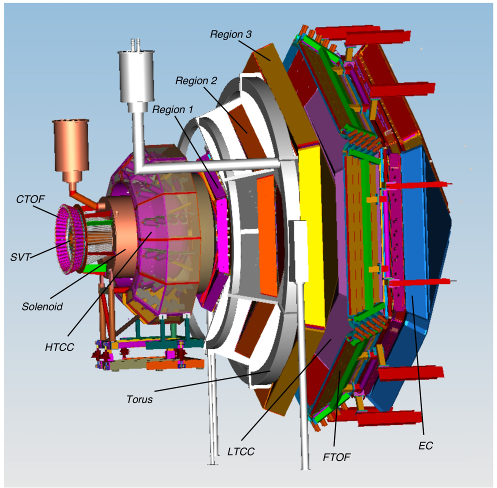
✓ Targets: H1, D2, C12, N14, Ar40, Fe56, Kr85, Sn119, Au197
(~80 days for gas targets, 10 days for solid targets)

✓ Hadrons: detecting all pions and kaons

✓ Acceptance (Gaps between six sectors) :
electrons: 6.5 < theta < 40 degrees, 0< phi < 360 *80%
hadrons: 5.0 < theta < 40 degrees, 0< phi < 360 *80%

✓ $10^{35}$ luminosity → Rates are good enough for 4D binning

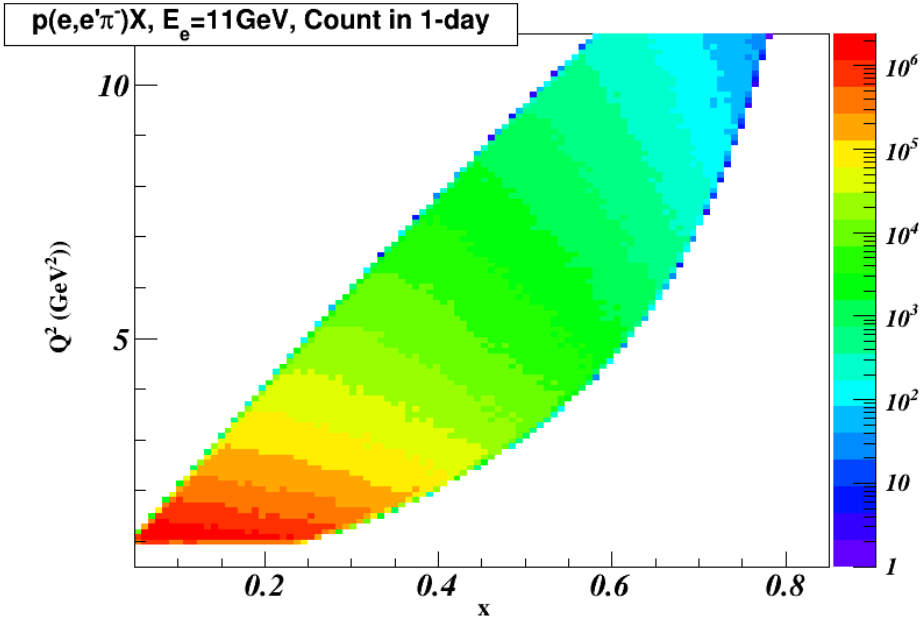
| Rate (KHz) | pi+ | pi- | K+ | K- |
|---|---|---|---|---|
| C12 | 1.16 | 0.43 | 0.34 | 0.16 |

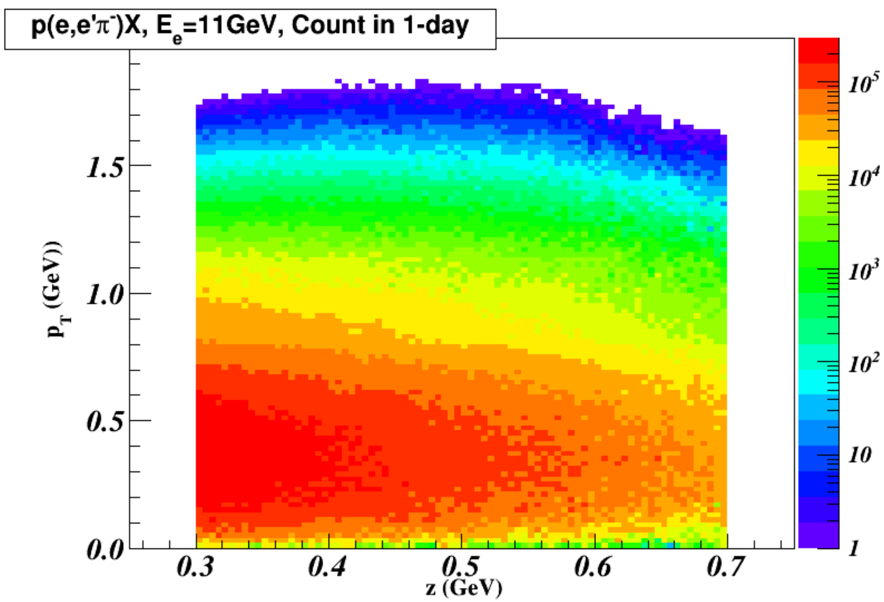



❖ **Perform a parallel analysis to extract 3D info of nuclei?**
(a developing effort by H. Avakian, D. Dutta, D. Gaskell, K. Hafidi, Z. Meziani, Z. Ye)

# SIDIS with Heavy Nuclei

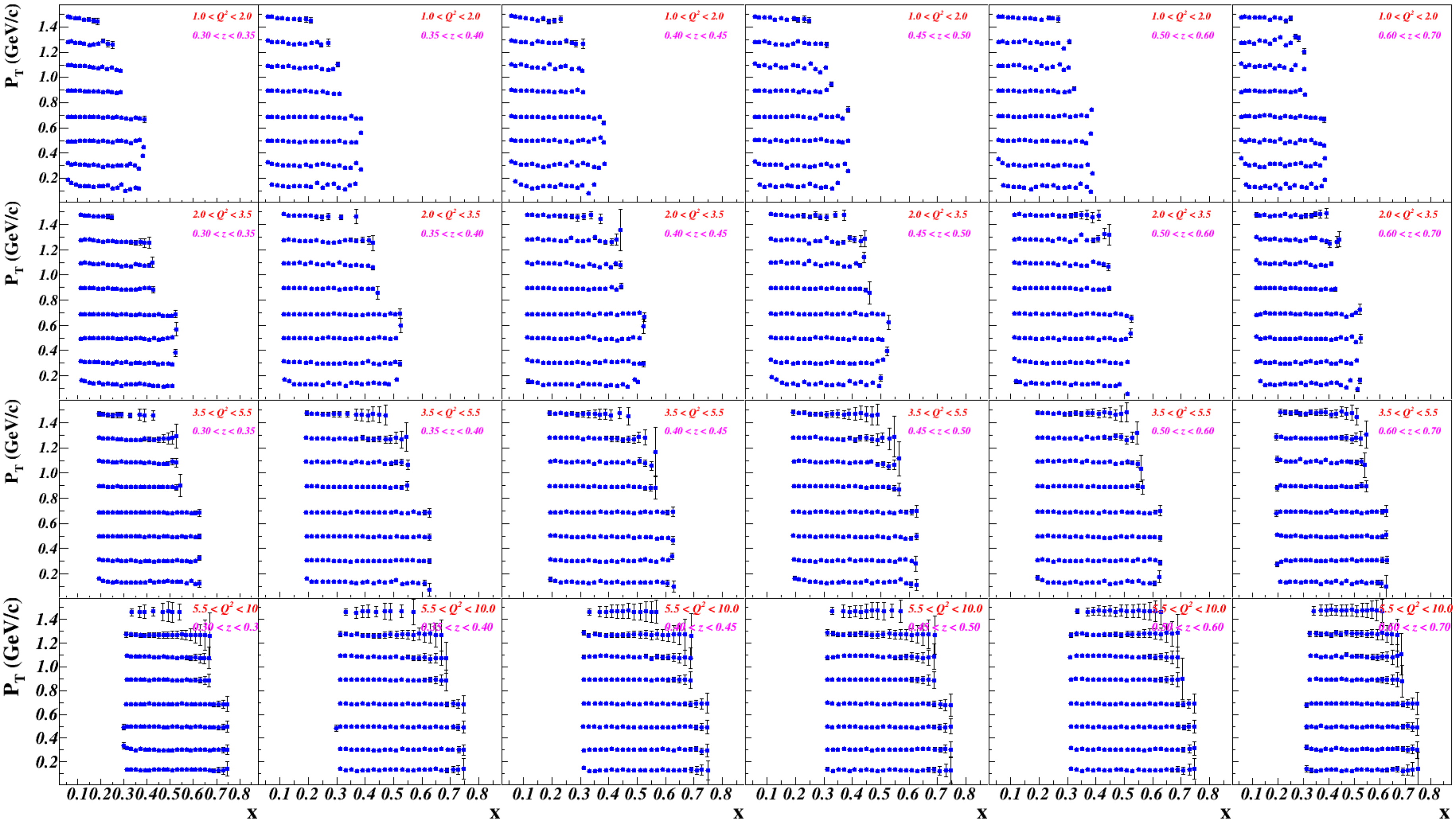
- **Nuclear 3D Tomography:**
  - CLAS12 Kinematic Coverage:



# SIDIS with Heavy Nuclei

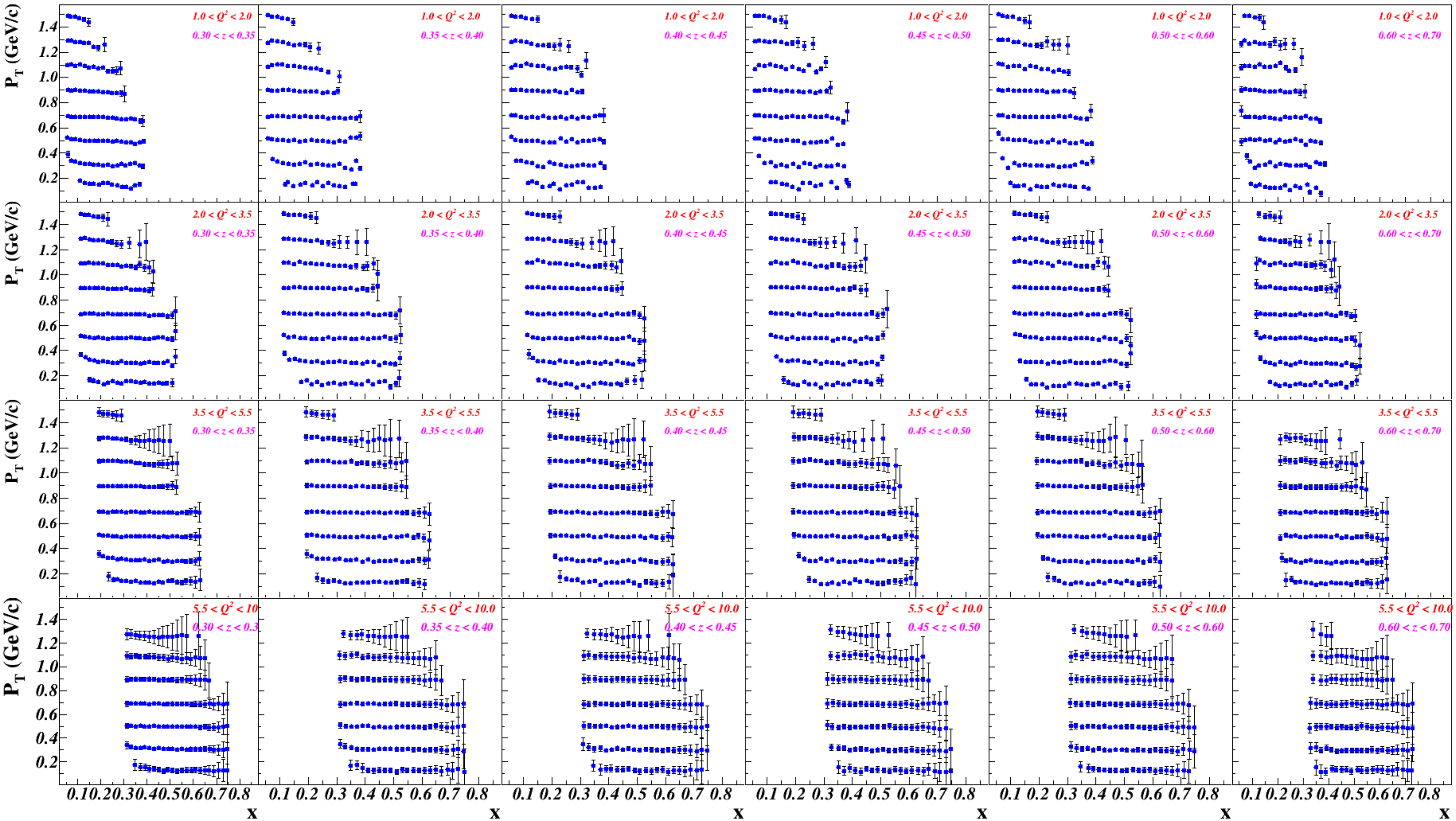
- **Nuclear 3D Tomography:**
  - CLAS12 Projected Data Coverage and Statistical Accuracy: $^{12}C(e,e'\pi^+)X$



# SIDIS with Heavy Nuclei

- Nuclear 3D Tomography:
  - CLAS12 Projected Data Coverage and Statistical Accuracy:

$^{12}C(e, e'K^-)X$



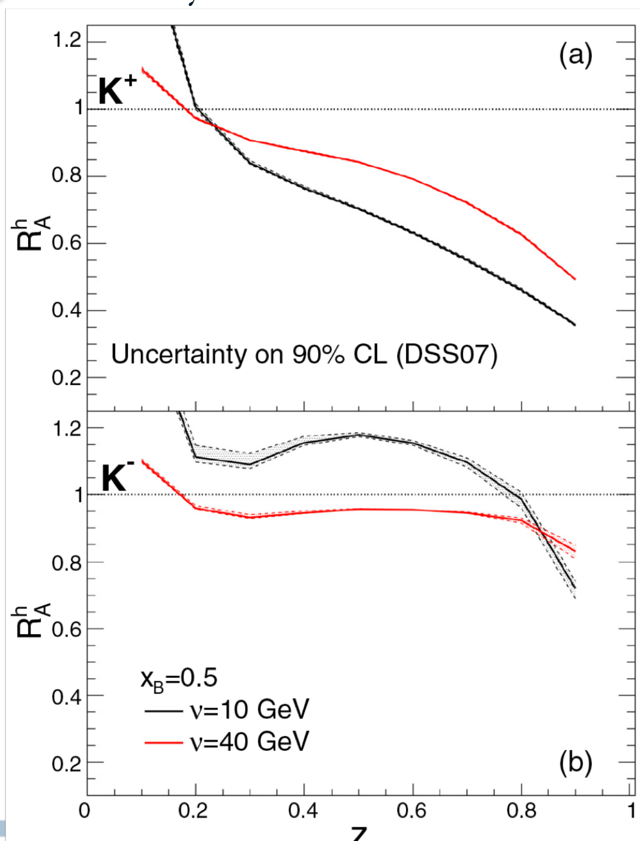
# SIDIS with Heavy Nuclei

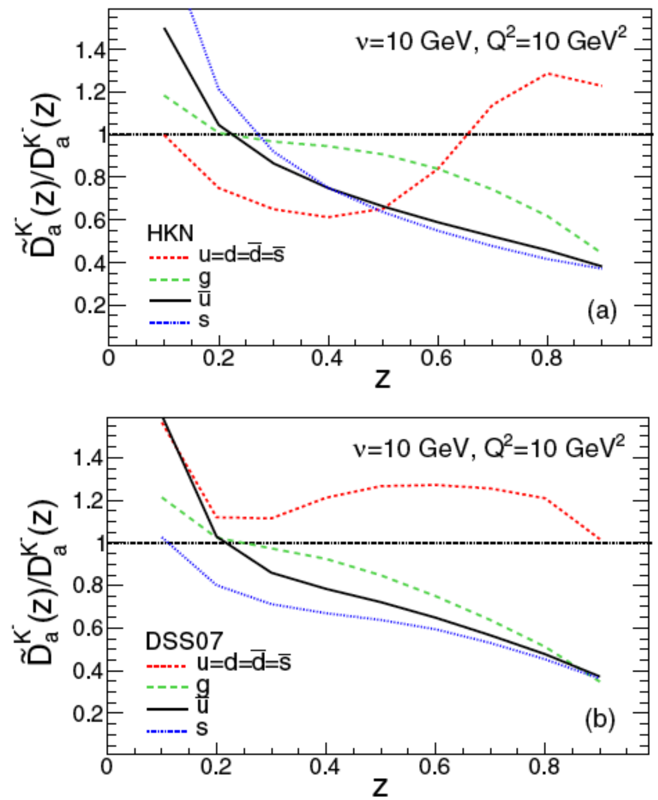
- **Nuclear 3D Tomography:**
  - 4D-binning ($Q^2$, x, z, $P_T$) in SIDIS for light and heavy nuclei
  - Study the A-dependence of PDF and PDF in medium

$$B^{h+}_{A/D}(z,p_T) = \frac{M^h_A(z,p_T)}{M^h_D(z,p_T)} = \frac{(N^{h+}_A + N^{h^-}_A)/N_A}{(N^{h^+}_D + N^{h^-}_D)/N_D}$$

$$R^{h^+ + h^-}_{A/D}(x,z,p_T) = \frac{N^{h^+}_A + N^{h^-}_A}{N^{h^+}_D + N^{h^-}_D} = A^{h+}(x,p_T) \otimes B^{h+}(z,p_T)$$

- Study Medium effect of FF




N Chang, et. al. PRC92, 055207 (2015)

W. Deng and X.-N Wang PRC 81, 024902 (2010)

# SIDIS with Heavy Nuclei

## Nuclear 3D Tomography:

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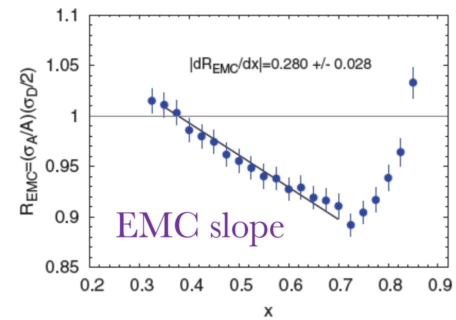
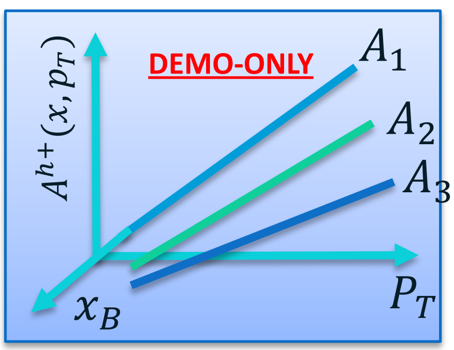
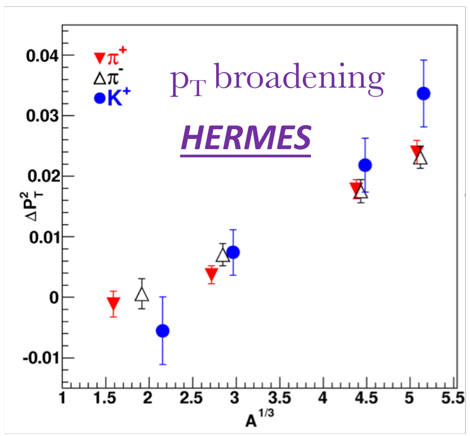
$$R^{h^+ + h^-}_{A/D}(x,z,p_T) = \frac{N^{h^+}_A + N^{h^-}_A}{N^{h^+}_D + N^{h^-}_D} = A^{h+}(x,p_T) \otimes B^{h+}(z,p_T)$$

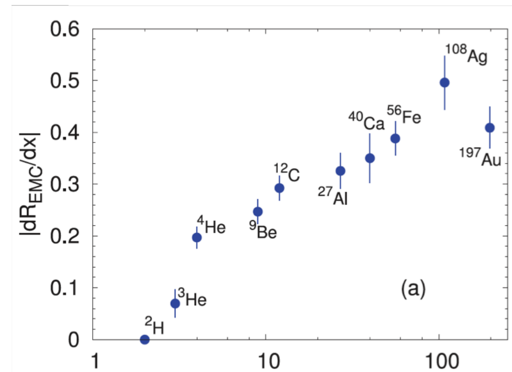



- ✓ A comprehensive way to study nuclear-effect in QCD
- ✓ Look at the $p_T$ dependence (not just broadening)




EMC ratio in 2D?



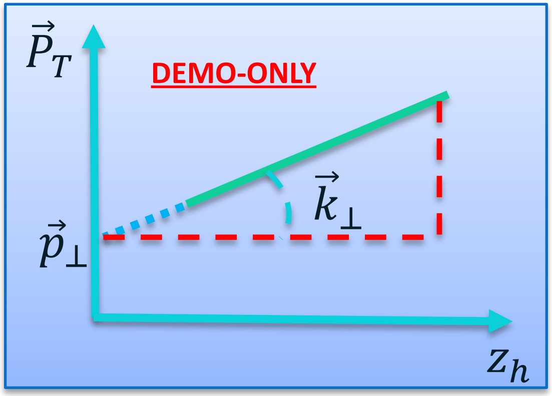
# SIDIS with Heavy Nuclei

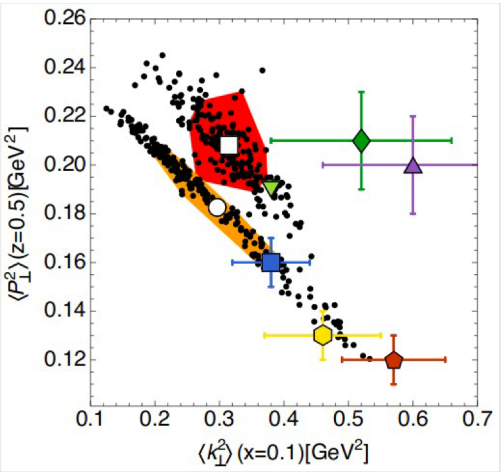
➢ **Nuclear 3D Tomography:**

❖ Possible to extraction of $\boldsymbol{k_\perp}$ ***and*** $\boldsymbol{p_\perp}$ distributions

$$\vec{P}_T = \vec{p}_\perp + z_h \vec{k}_\perp + O\left(\frac{k_\perp^2}{Q^2}\right), \qquad \langle P_T^2\rangle = \langle p_\perp^2\rangle + z_h^2\langle k_\perp^2\rangle$$

not 100% correct in full QCD but roughly hold (see Andrea's talk)



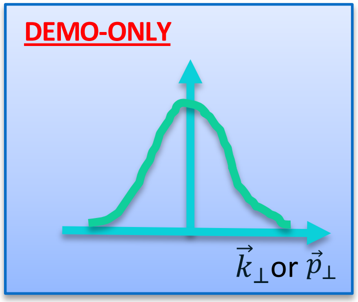




✓ Extrapolation to $z_h \rightarrow 0$ to extract the distributions of $\vec{p}_\perp$

✓ The slope gives the ("relative") distributions of $\vec{k}_\perp$

By comparing the distributions of extracted $\vec{p}_\perp$ and $\vec{k}_\perp$ in different nuclei:

- From $\vec{k}_\perp$ , does the quark shrink or enlarge when A is larger?
- From $\vec{p}_\perp$, does the quark shrink or enlarge after it is struck out?
- Is the Gaussian Ansatz hold for $\vec{p}_\perp$ and $\vec{k}_\perp$ in all nuclei?




- Extract relative change of 3D TMD/FF in nuclei from this technique?

# SIDIS with Heavy Nuclei

## ➢ Nuclear TMDs?:

- The unpolarized SIDIS cross section w/ additional azimuthal dependence:

$$\frac{d^5\sigma^{\ell p\to\ell hX}}{dx_B dQ^2 dz_h d^2\boldsymbol{P}_T} \simeq \sum_q \frac{2\pi\alpha^2 e_q^2}{Q^4} f_q(x_B) D_q^h(z_h)\left[1+(1-y)^2 - 4\frac{(2-y)\sqrt{1-y}\langle k_\perp^2\rangle z_h P_T}{\langle P_T^2\rangle Q}\cos\phi_h\right]\frac{1}{\pi\langle P_T^2\rangle} e^{-P_T^2/\langle P_T^2\rangle}$$

If we consider the Boer-Mulder Term (very small):

$$\frac{d^5\sigma^{\ell p\to\ell hX}}{dx_B dQ^2 dz_h d^2\boldsymbol{P}_T} = A + \underbrace{B\cos\phi_h}_{\text{Cahn}} + \underbrace{C\cos 2\phi_h}_{\text{Boer-Mulder}}$$

  - The $\cos(\phi_h)$ azimuthal dependence term:

$$\langle\cos\phi\rangle_{UU} = -\frac{|\vec{k}_\perp|}{Q}\frac{B(y)}{A(y)}\frac{x_B f^\perp(x_B,k_\perp)}{f_1(x_B,k_\perp)}$$

$$f_q^A(x,k_\perp) \approx \frac{A}{\pi(\alpha+\Delta_{2F})} f_q^N(x) e^{-\vec{k}_\perp^2/(\alpha+\Delta_{2F})},$$

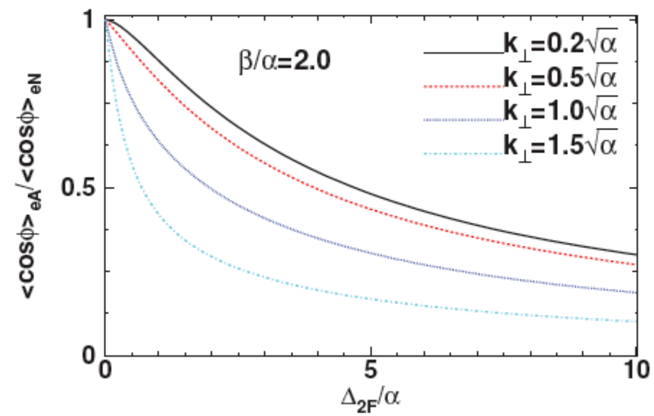
Twsist-3 $$f_{q\perp}^A(x,k_\perp) \approx \frac{A\beta}{\pi(\beta+\Delta_{2F})^2} f_{q\perp}^N(x) e^{-\vec{k}_\perp^2/(\beta+\Delta_{2F})}.$$

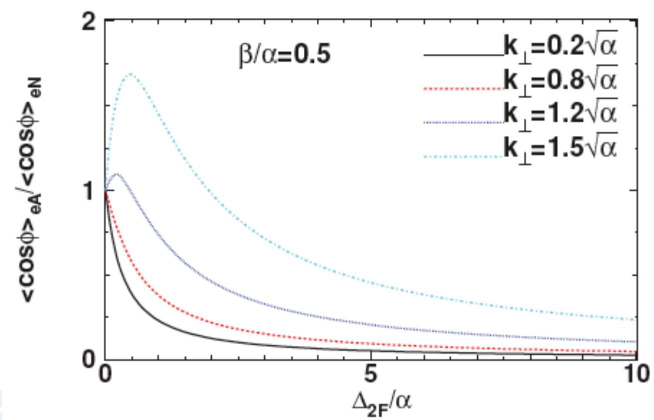
$p_T$ width

$$\frac{\langle\langle\cos\phi_h\rangle\rangle_{eA}}{\langle\langle\cos\phi_h\rangle\rangle_{eN}} = \sqrt{\frac{\beta z^2+\alpha_F}{(\beta+\Delta_{2F})z^2+\alpha_F}}.$$

broadening

Gao, Liang, Wang RPC 81, 065211 (2010)



# SIDIS with Heavy Nuclei

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- The $\cos(2\phi_h)$ dependence module gives the BM convoluted by Collins Fragmentations:

$$F_{UU,A}^{\cos(2\phi_h)}(x,z,p_T,Q^2) \propto \langle\cos(2\phi_h)\rangle_{UU,A} \propto h_{1,A}^{\perp}(x,k_\perp,Q^2) \otimes H_{1,A}^{\perp}(z,p_\perp,Q^2)$$

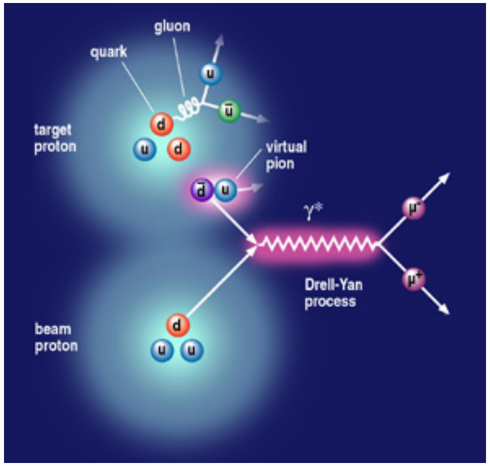
- In principle, we can study the medium effects of BM-TMD and Collins-FF at the same time!

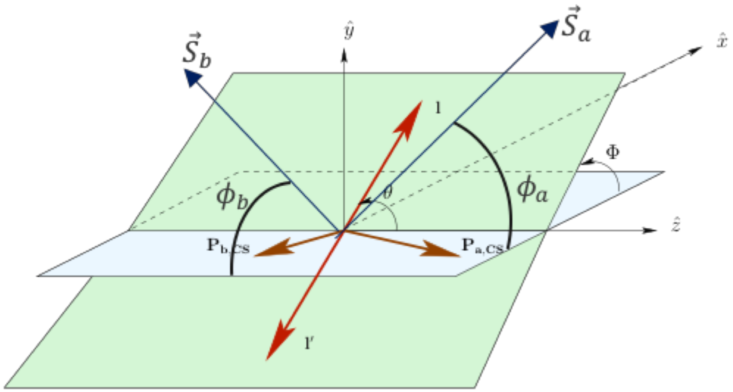
Very difficult! → Boer-Mulder is tiny; Cahn effect couples; radiative corrections …

❖ Polarized nuclear targets (up to Li7) could be used to study other nuclear TMD → Dilution is a pain!

❖ Directly probe the orbital angular momentum due to TMDs mixing in nuclei?
(Y.V. Kovchegov, M.D. Sievert, Nuclear Physics B 903 (2016) 164-203)

# pA Drell-Yan Process



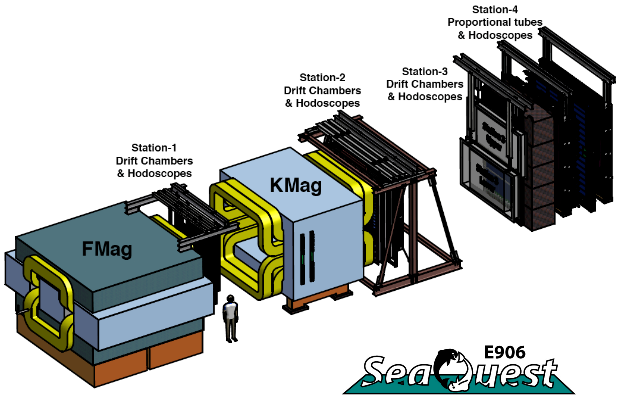



# pA Drell-Yan Process

- Study Medium Effect of Sea-Quark PDF:
  - DY get access to the initial-state information of the annihilated quark and anti-quark pair.
  - Unpolarized DY cross section is sensitive to sea-quark contents:

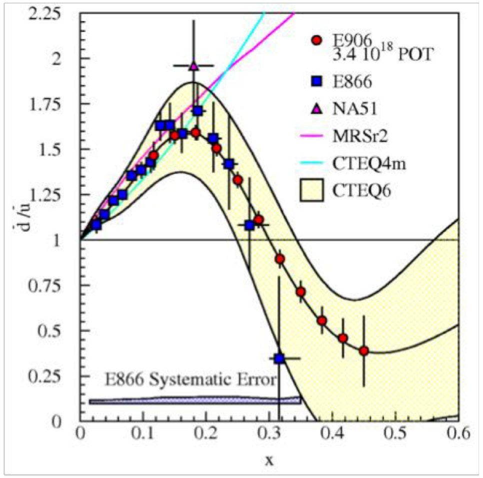
$$\frac{d^2\sigma}{dx_b\, dx_t} = \frac{4\pi\alpha^2}{9x_b\, x_t}\frac{1}{s}\sum_q e_q^2\left[\bar{q}_t(x_t)q_b(x_b) + q_t(x_t)\bar{q}_b(x_b)\right]$$

Small at selected region

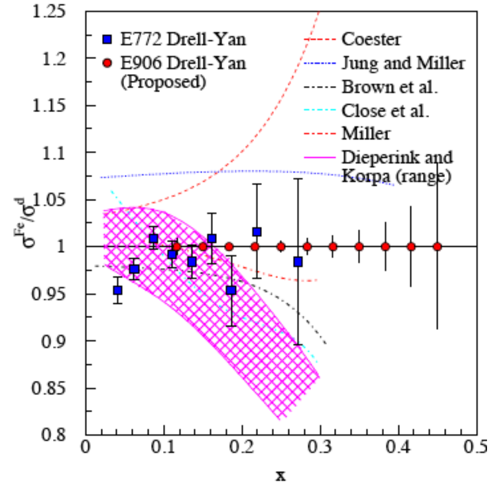



- SeaQuest experiment at Fermi-Lab aims to study $(\bar{d}/\bar{u})$ at moderate high-x:

$$\left.\frac{\sigma_{pd}}{2\sigma_{pp}}\right|_{x_1 \gg x_2} = \frac{1}{2}\left[1 + \frac{\bar{d}(x_2)}{\bar{u}(x_2)}\right]$$




- w/ heavy nuclei, can also study sea-quark EMC effect which has not been carefully studied experimentally



# pA Drell-Yan Process

- Nuclear TMD In Drell-Yan:

  - Sensitivity w/ different polarization in pp Drell-Yan:
    - Boer-Mulders TMD from DY with unpolarized target: $$\nu = \frac{2F_{UU}^{cos2\phi}}{F_{UU}^{1} + F_{UU}^{2}} \propto \frac{h_1^{\perp q}(x_b) \cdot h_1^{\perp,\bar{q}}(x_t)}{f_1^{q}(x_b) \cdot f_1^{\bar{q}}(x_t)}$$
    - Sivers TMD from DY with transversely polarized targets: $$A_{UT}^{sin\phi_S} = \frac{F_{UT}^{sin\phi_S}}{F_{UU}^{1} + F_{UU}^{2}} \propto \frac{f_1^{q}(x_b) \cdot f_{1T}^{\perp,\bar{q}}(x_t)}{f_1^{q}(x_b) \cdot f_1^{\bar{q}}(x_t)}$$
    - Sivers TMD from DY with transversely polarized beam: $$A_{TU}^{sin\phi_S} \propto \frac{f_1^{\bar{q}}(x_b) \cdot f_{1T}^{\perp q}(x_t)}{f_1^{q}(x_b) \cdot f_1^{\bar{q}}(x_t)}$$

  - Sensitivity w/ different polarization in pA Drell-Yan:

$$A_{UU}(p + A \to l^+ + \bar{l}^- + X) \rightarrow \nu(\boldsymbol{A}) = \frac{2F_{UU}^{cos2\phi}}{F_{UU}^{1} + F_{UU}^{2}} \propto \frac{h_1^{\perp q}(x_b) \cdot h_1^{\perp,\bar{q}}(x_t, A)}{f_1^{q}(x_b) \cdot f_1^{\bar{q}}(x_t, A)}$$

Sensitive to ***sea-quarks*** Boer-Mulders TMDs in nuclei

$$A_{TU}(p^{\uparrow\downarrow} + A \to l^+ + \bar{l}^- + X) \rightarrow A_{TU}^{sin\phi_S} \propto \frac{f_1^{\bar{q}}(x_b) \cdot f_{1T}^{\perp q}(x_t, A)}{f_1^{q}(x_b) \cdot f_1^{\bar{q}}(x_t, A)}$$

Sensitive to ***valance-quarks*** sivers TMDs in heavy nuclei

- Polarized DY with polarized anti-proton beam would be ideal to study nuclear TMD since a quark-TMD is convoluted with an anti-quark TMD (no nuclear-FF involved!)

- **Drawback:** Low rates, limited acceptance, low-luminosity w/ polarized anti-proton

# Medium Modification in SIDIS

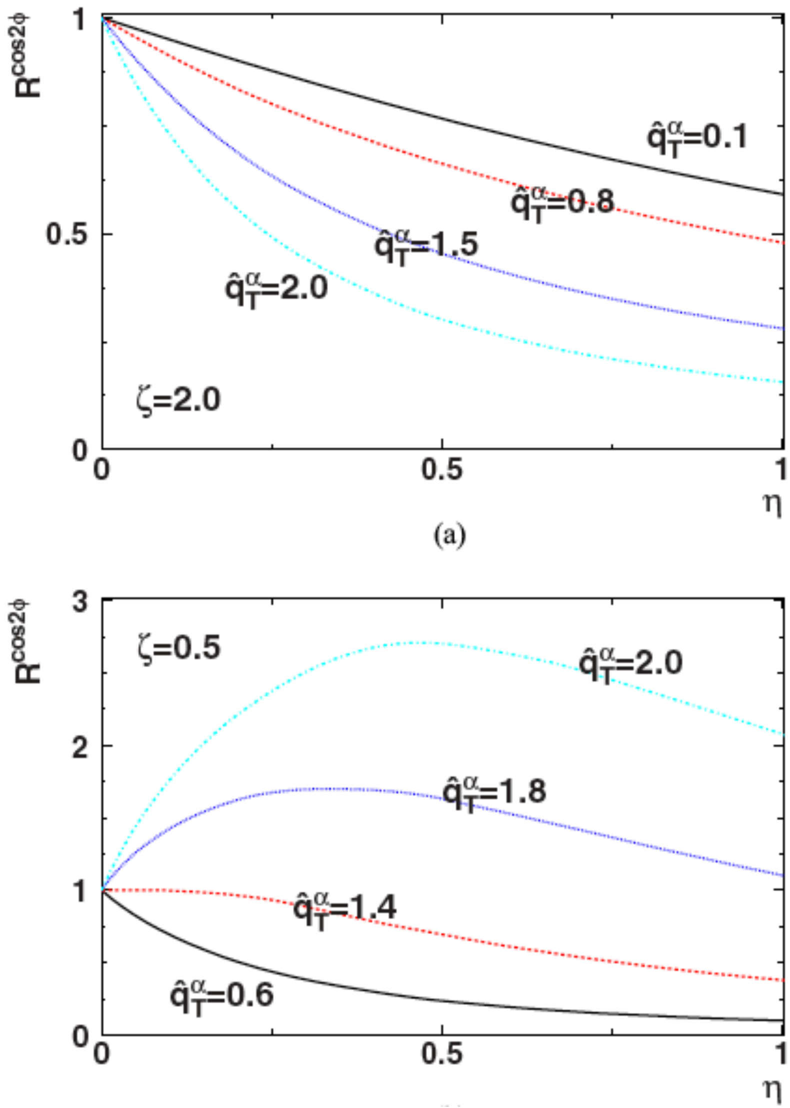
- Nuclear TMD In Drell-Yan:

Nuclear Boer-Mulder TMD in unpolarized Drell-Yan:

$$R^{\cos 2\phi} \equiv \frac{A_{NA}^{\cos 2\phi}}{A_{NN}^{\cos 2\phi}} = \frac{2\alpha + \Delta_{2F}}{2\alpha}\left(\frac{2\beta}{2\beta + \Delta_{2F}}\right)^3 \times e^{\frac{(\alpha-\beta)(2\alpha+2\beta+\Delta_{2F})\Delta_{2F}}{2\alpha\beta(2\alpha+\Delta_{2F})(2\beta+\Delta_{2F})}\vec{q}_T{}^2}.$$

$$\eta \equiv \Delta_{2F}/2\alpha, \quad \hat{q}_T^\alpha \equiv |\vec{q}_T|/\sqrt{2\alpha}, \quad \zeta \equiv \beta/\alpha$$

L. Chen, J. Gao, and Z. Liang,
PHYSICAL REVIEW C 81, 065211 (2010)



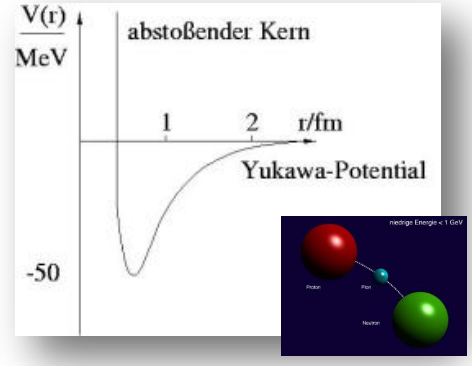
# Summary

- How partonic structure differ in nucleons and in nuclei needs more studies
- Detailed study w/ inclusive DIS → EMC effect and correlation with SRC
- Origin of EMC effect is not understood;

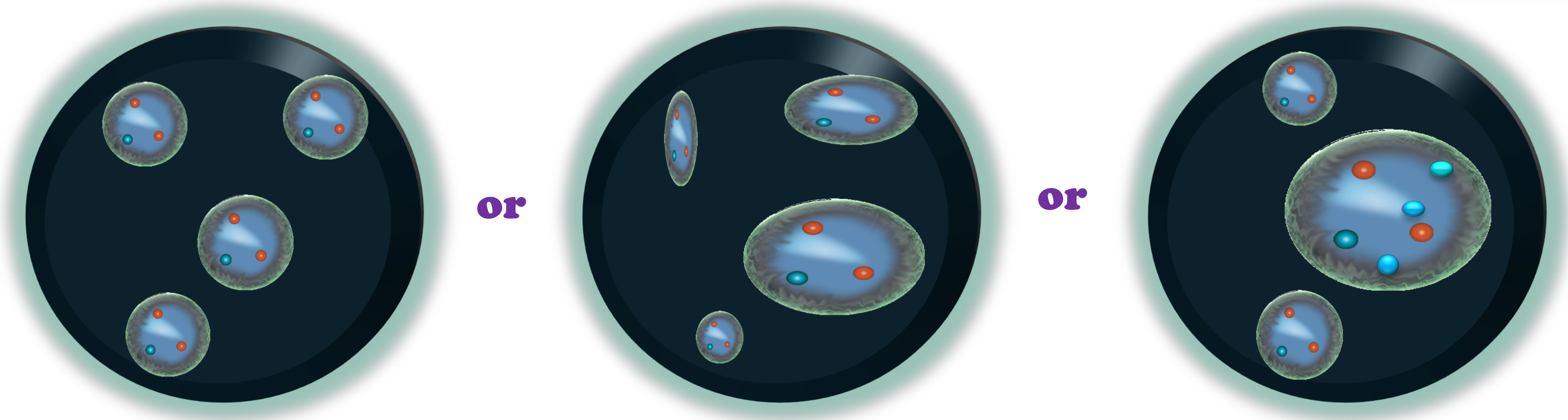
  Flavor-dependence EMC effect? Medium effect in sea-quarks?
- SIDIS w/ light and heavy nuclei provides more info about the medium modification in nuclear structure → medium modified PDF/TMD and FF
- Drell-Yan w/ heavy nuclei measures pure medium effect of PDF/TMD
- Near future JLab 12GeV eA experiments will provide high precision SIDIS data w/ 4D binning
- EIC eA program can push the study of medium effect into the sea-quark and gluon regions.

# Backup Slides

# Nucleons in a Nucleus




- Interesting Facts:
  - ✓ Quarks & Gluons → Nucleons → Nuclei
  - ✓ Quarks & Gluons move extremely fast inside Nucleon, but don't escape!
  - ✓ NN-Interaction is strong-interaction, but much weaker
  - ✓ NN-interactions don't need partons (pion-exchange)!




Not Modified? Modified in Mean-Field? Modified in Cluster?

- 50+ years old questions but yet to be answered:
  - How are protons and neutrons bounded together into nuclei?
  - Bounded protons and neutrons are really different from free ones?

*Original from the same mechanism?*

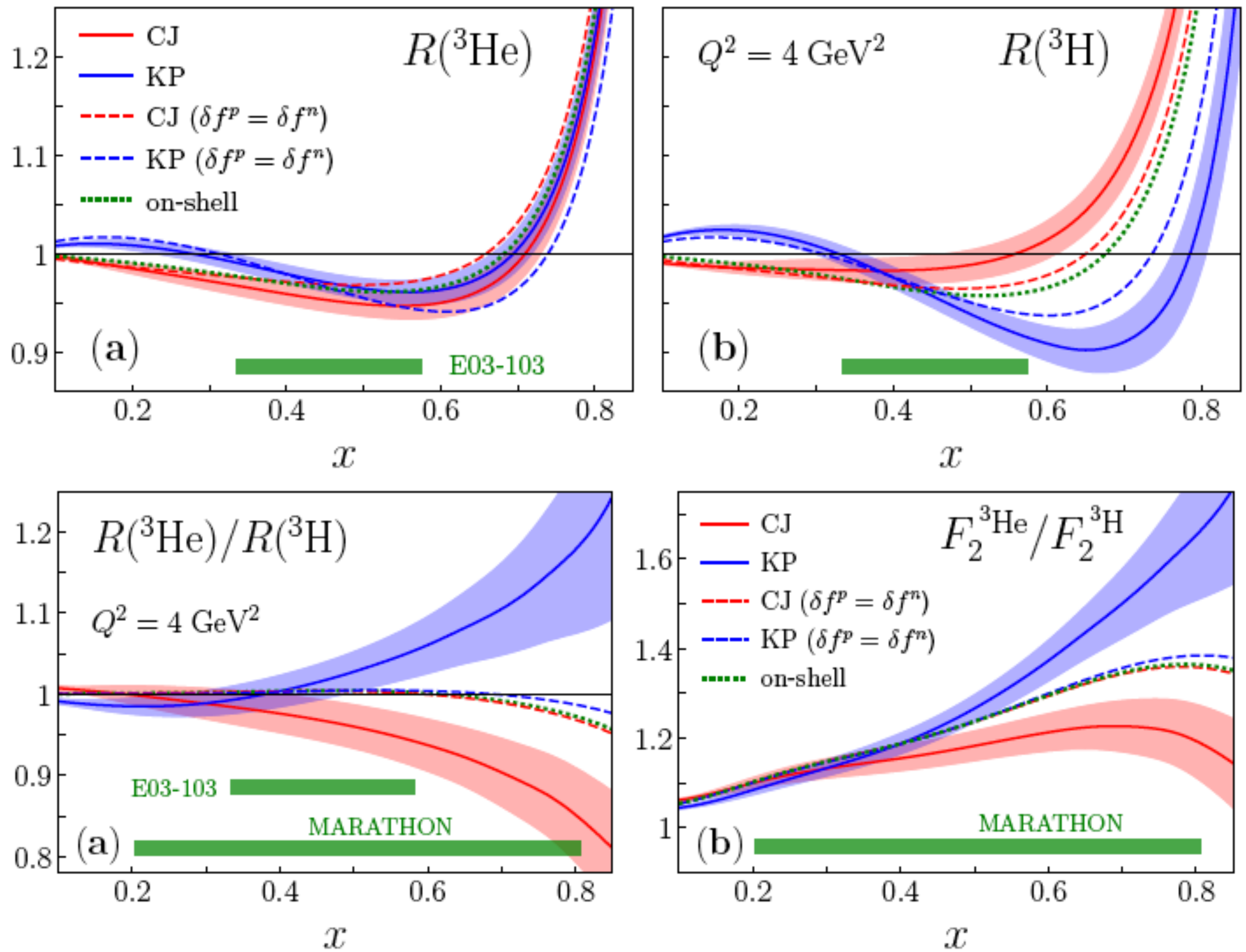
- May require another 50+ years of works both theoretically and experimentally!

# SIDIS with Light Nuclei

- Tritium and He3 as well-controlled nuclear medium:
  - Tritium and Helium-3 Medium Effect are similar at moderate x

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

Tropiano, Ethier, Melnitchouk, Sato, arXiv:1811.07668



# SIDIS with Heavy Nuclei

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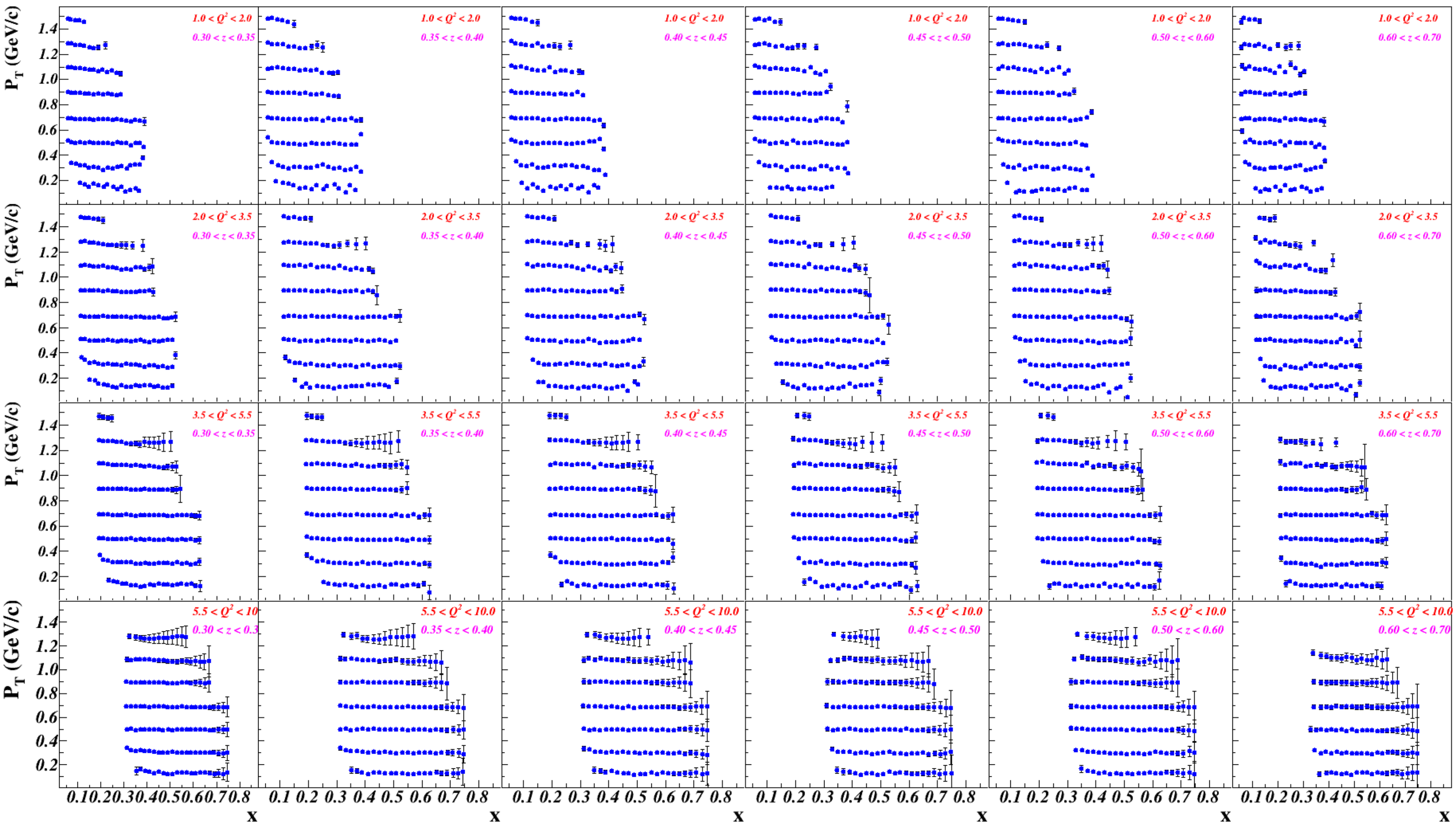
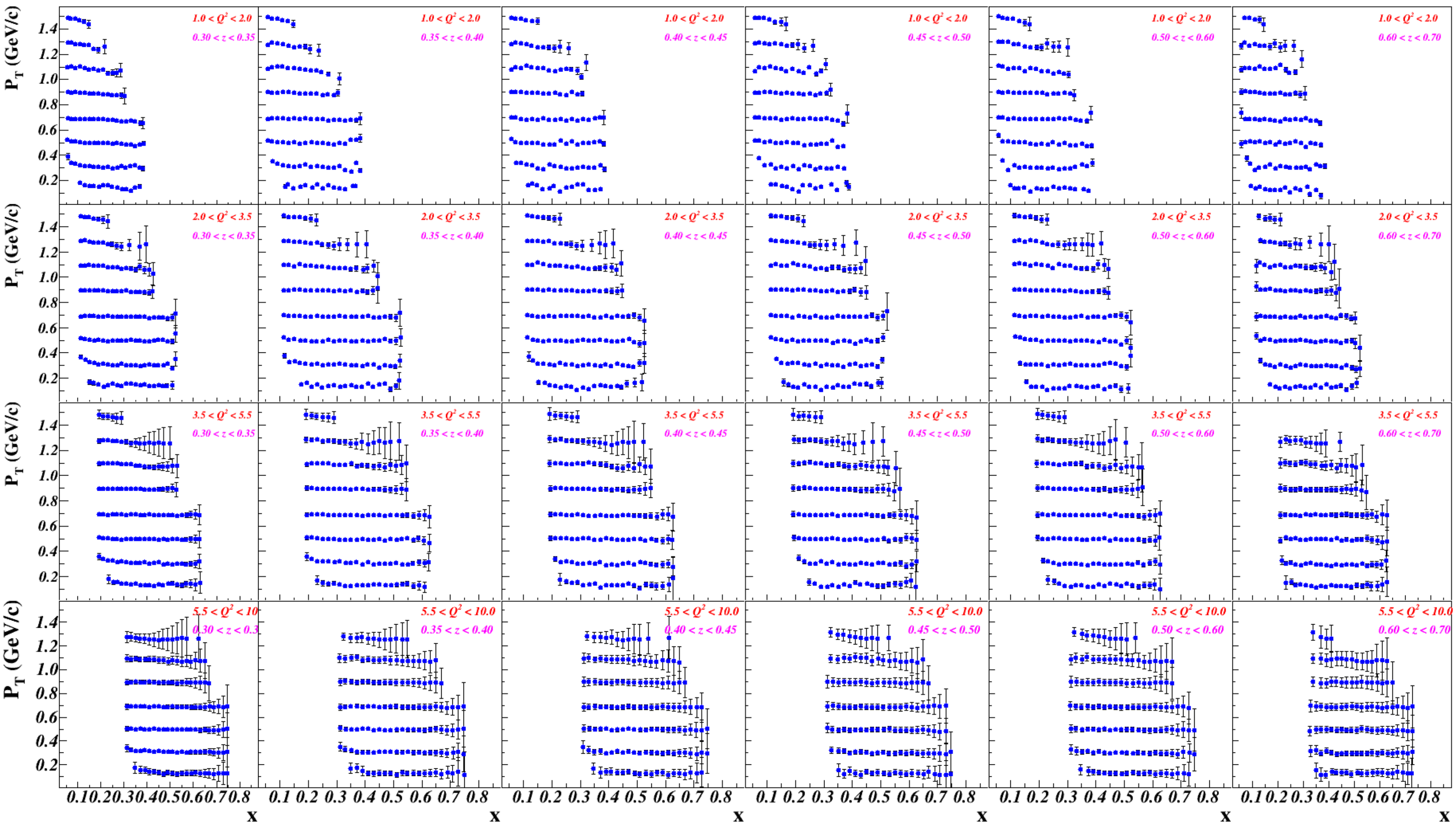
❖ CLAS12 Projected Data Coverage and Statistical Accuracy: $^{12}C(e, e'\pi^{-})X$



# SIDIS with Heavy Nuclei

- Nuclear 3D Tomography:
  - CLAS12 Projected Data Coverage and Statistical Accuracy: $^{12}C(e, e'K^+)X$



# New Study with CLAS12

- Simulation Study:

- Beam energy, E0 = 8.8 and 11 GeV
- Targets:

  a) D2 (totally 90 PAC days, plus approved E12-11-003 and other CLAS12 Run-Group B experiments)

  b) H1, D2, C12, Fe56, Sn119 (totally 60 PAC days, with 40+ days of production data taken, together with approved E12-06-106)

  c) N14, Ar40, Kr85, Au197 (totally 60 PAC days, assuming 10 days for each target, together with approved E12-06-117)

- Hadrons: detecting all pions and kaons

| Rate (KHz) | pi+ | pi- | K+ | K- |
|---|---|---|---|---|
| C12 | 1.16 | 0.43 | 0.34 | 0.16 |

- Acceptance:

  electrons: 6.5 < theta < 40 degrees, 0< phi < 360 *80% (Gaps between six sectors)

  hadrons: 5.0 < theta < 40 degrees, 0< phi < 360 *80% (Gaps between six sectors)

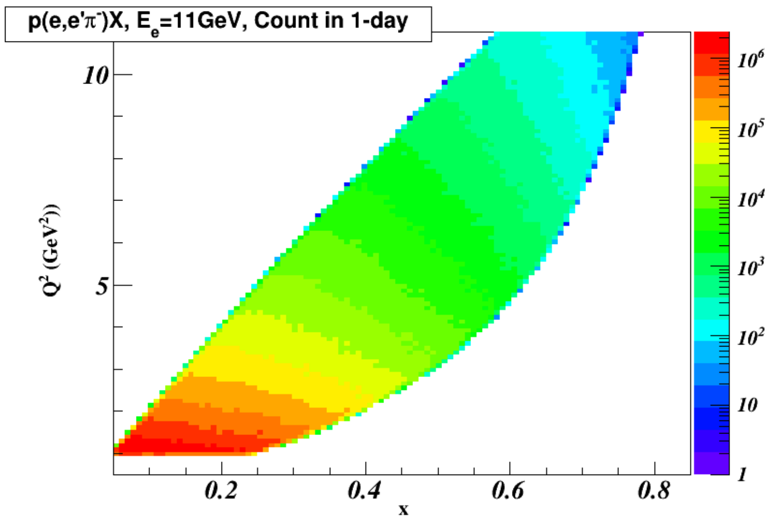
- Using unpolarized SIDIS generator developed for SoLID to generate MC events

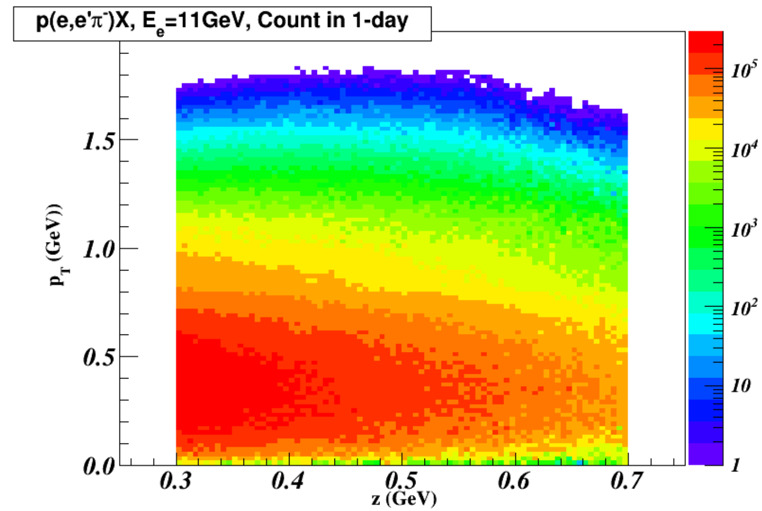
- Using CLAS12-FastMC to build in the CLAS12 acceptance; Assuming 85% totally detector efficiency

- Using the maximum CLAS12 luminosity (1e35/A cm-2 s-1, note: scaled by the nuclear number A)

# New Study with CLAS12

➢ Binning of MC Data (Binning method as demo):




- Bin the Q2 and z first, by defining the following boundaries:

  $Q^2[5] = [1.0,\ 2.0, 3.5, 5.5, 10.0]\ GeV^2, \qquad z[7] = [0.3, 0.35, 0.4, 0.45, 0.5, 0.6, 0.7]$

- Further bin the data on pT and x:

  $p_T[\leq 9] = [0.0, 0.2, 0.4, 0.6, 0.8, 1.0, 1.2, 1.4, 1.6] GeV/c$

  Note: merge a bin to its larger bins until the total events >= 1e5 (before binning on x)

  $x_B[N]$ = [from 0.0 to 1.0, step=0.02], increase the step size if the total events in the bin is <1e4

- Projected results (see plots on next few slides):
  a) Choose C12 target as examples (other targets should have similar statistical budges)
  b) Each projected data file has the detected hadron (pi+,pi-, K+, K-), and in which (Q2, z) bin
  c) Statistical error delta_stat = 1./sqrt(N_exp_count)
  d) No central values of any observables. Need theoretical inputs