Study Quark Structures with eA Scattering at 22GeV

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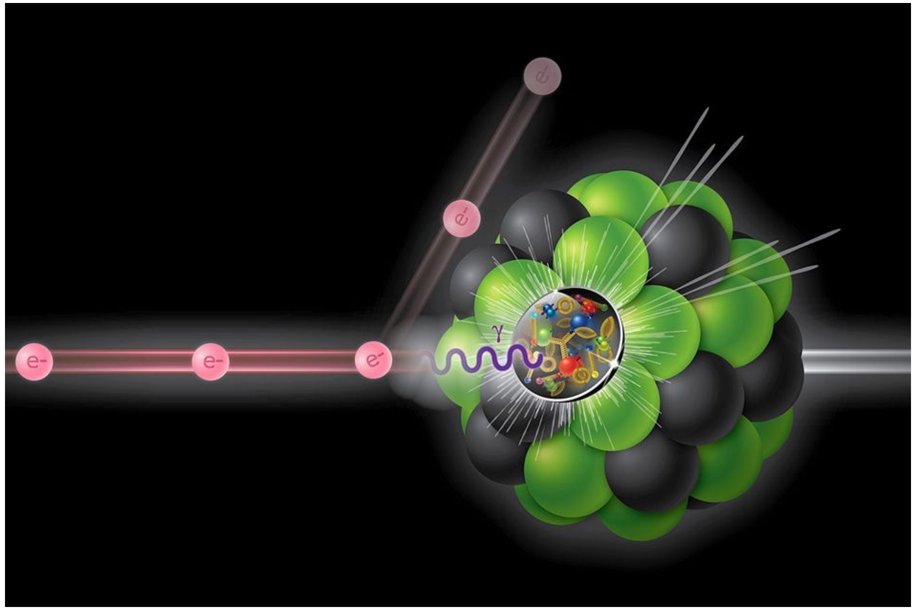
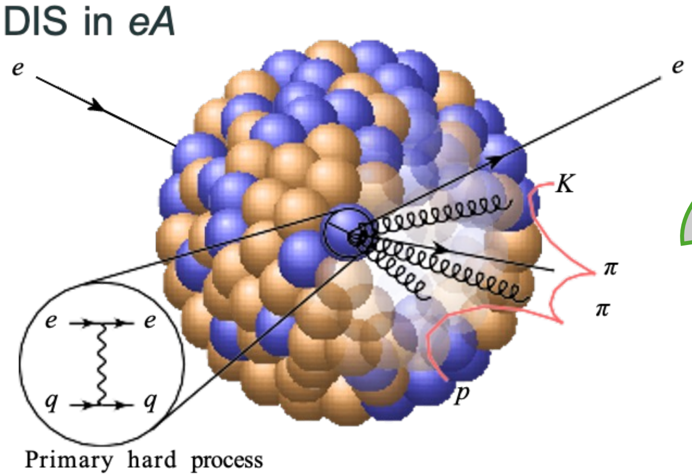
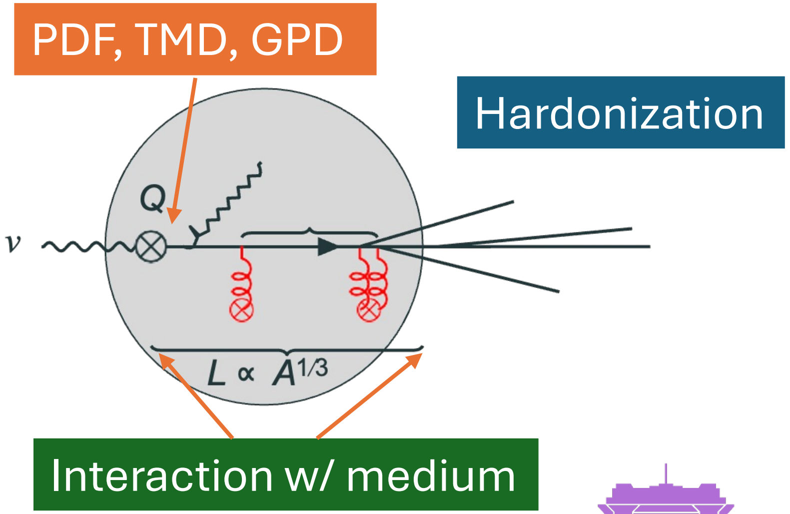
Eletron-Nucleus Scattering

- Quasi-elastic scattering of nucleons in nuclei
  - ✓ Nuclear Strucutre, NN-interaction, SRC,…
- Deep-Inelastic scattering (DIS) of nucleons in nuclei
  - ✓ Patron distributions in nuclei vs free
  - ✓ Confiment & Hadronization
- Measurements
  - ✓ Inclusive DIS, PVDIS, Nucleon-tagging DIS
  - ✓ Exclusive Reactions
  - ✓ Flavor-tagging Semi-Inclusive DIS (SIDIS)
    - ✓ Multiple hadron final states: π , $K, p, \bar{p}, \Lambda, \bar{\Lambda}$, …





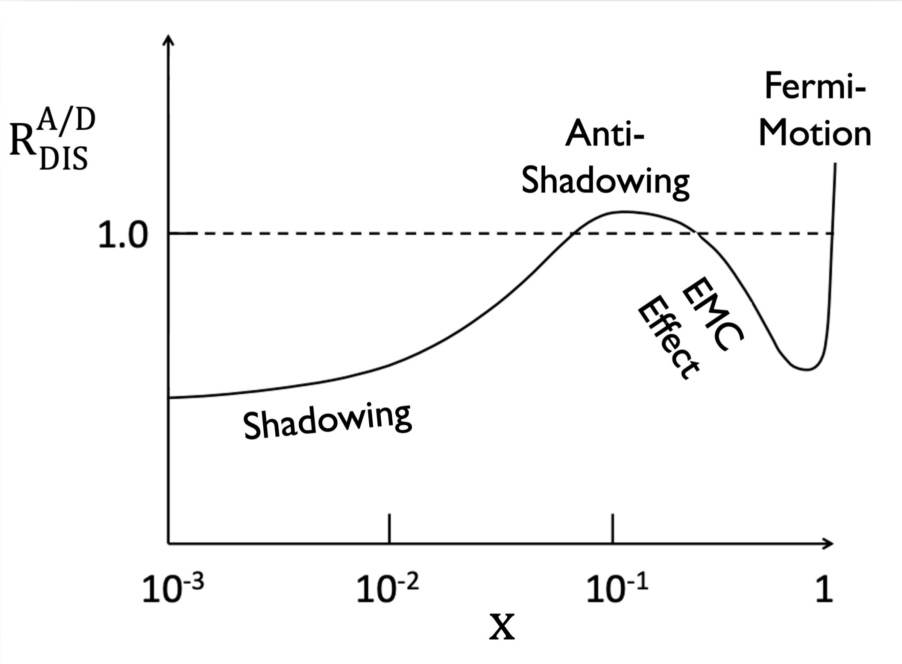

PDF, TMD, GPD

Hardonization

Interaction w/ medium

Partons in Nuclei

- Four Regions



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

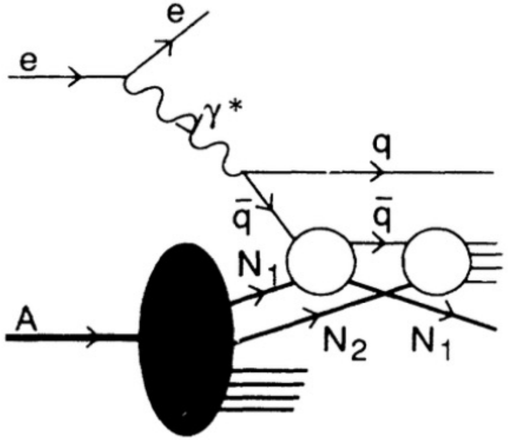
☐ **Fermi-Motion**:

- ✓ Bound nucleons moving in nuclear medium (offshell, smearing, …)
- ✓ Recent discussion on A=2,3

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

☐ **Shadowing:**

- ✓ multiple-scattering (diffractive)
- ✓ models various (especially when treating along w/ anti-shadowing & EMC)



☐ **EMC**

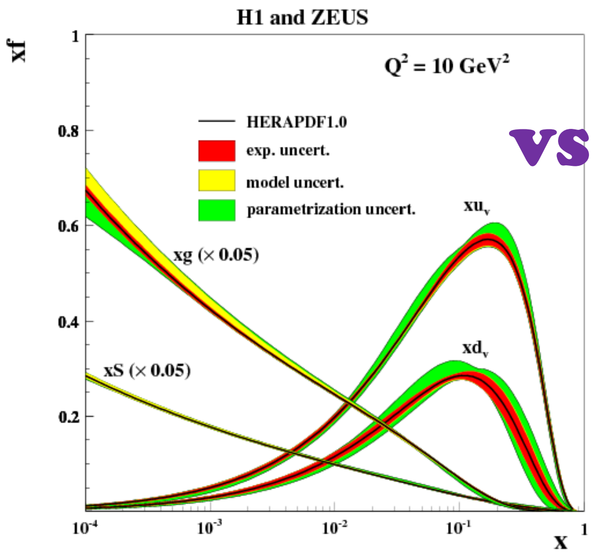
- Flavor dependent?
- Connected to SRC?

☐ **Anti-Shadowing**

- Not seen in sea quarks? Strong flavor dependence?
- May only exists in σ_L^{DIS} →gluons only?

Partons in Nuclei

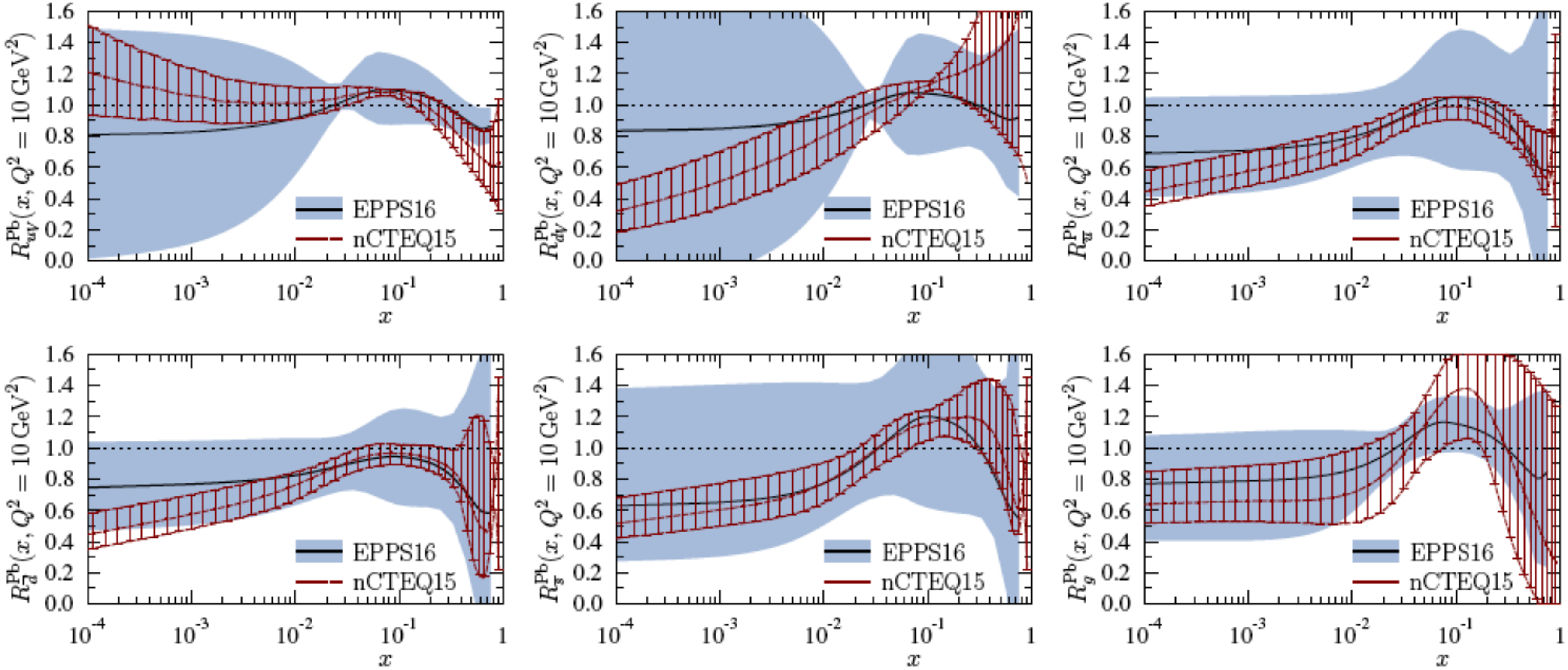
- High Precision Nuclear PDF are needed!
  - ☐ Data unprecise; Limited A-coverage;
  - ☐ Many assumption made in global fit (e.g., flavor-independence, isospin-symmetry)
  - ☐ **Electron-Nuleus (eA) Scattering w/ JLab 11GeV & 22GeV**



Free nucleon PDF

vs

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



Measurements

- eA-SIDIS in Simplified Pictures

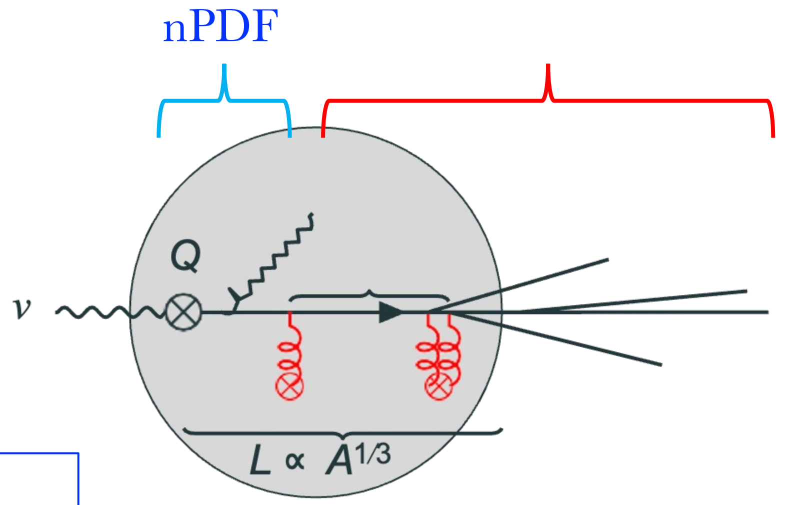
☐ Colinear & Leading-Order

Nuclear Fragmentation Function (nFF)

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

Nuclear PDF (nPDF)

$$\boxed{u_A = \frac{Z\tilde{u} + N\tilde{d}}{A}, d_A = \frac{Z\tilde{d} + N\tilde{u}}{A}, s_A = s,}$$



☐ Super-Ratio of Multiplicities:

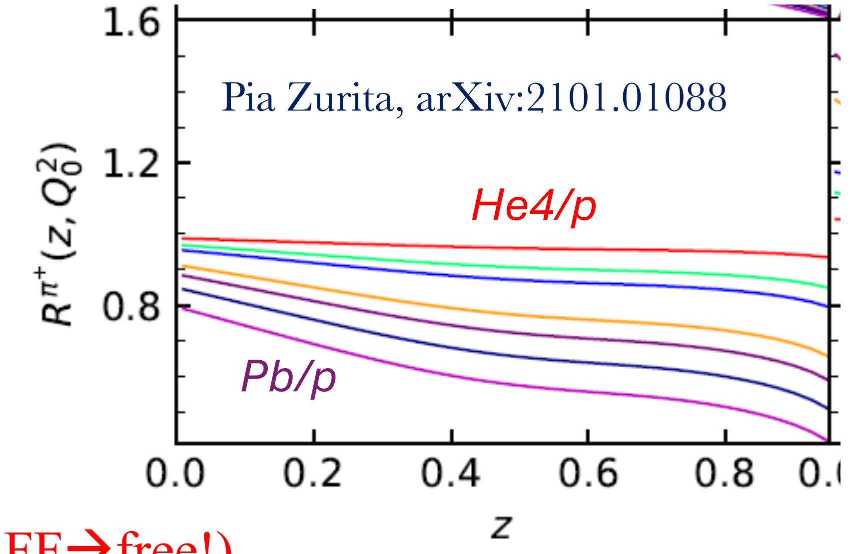
$$R_A(x_B, Q^2, z_h) = \frac{\frac{d\sigma_{eA\to h}}{dx_B dQ^2 dz_h} \Big/ \frac{d\sigma_{eA}}{dx_B dQ^2}}{\frac{d\sigma_{ed,ep\to h}}{dx_B dQ^2 dz_h} \Big/ \frac{d\sigma_{ed,ep}}{dx_B dQ^2}}.$$

$$R_A^{h^+/h^-} = R_A^{h^+} / R_A^{h^-}$$

☐ Super Ratio of Charge Difference:

$$R_{A/D}^{\pi^+-\pi^-}(x, z, Q^2) = \frac{N_A^{\pi^+} - N_A^{\pi^-}}{N_D^{\pi^+} - N_D^{\pi^-}}$$

nFF Ratios



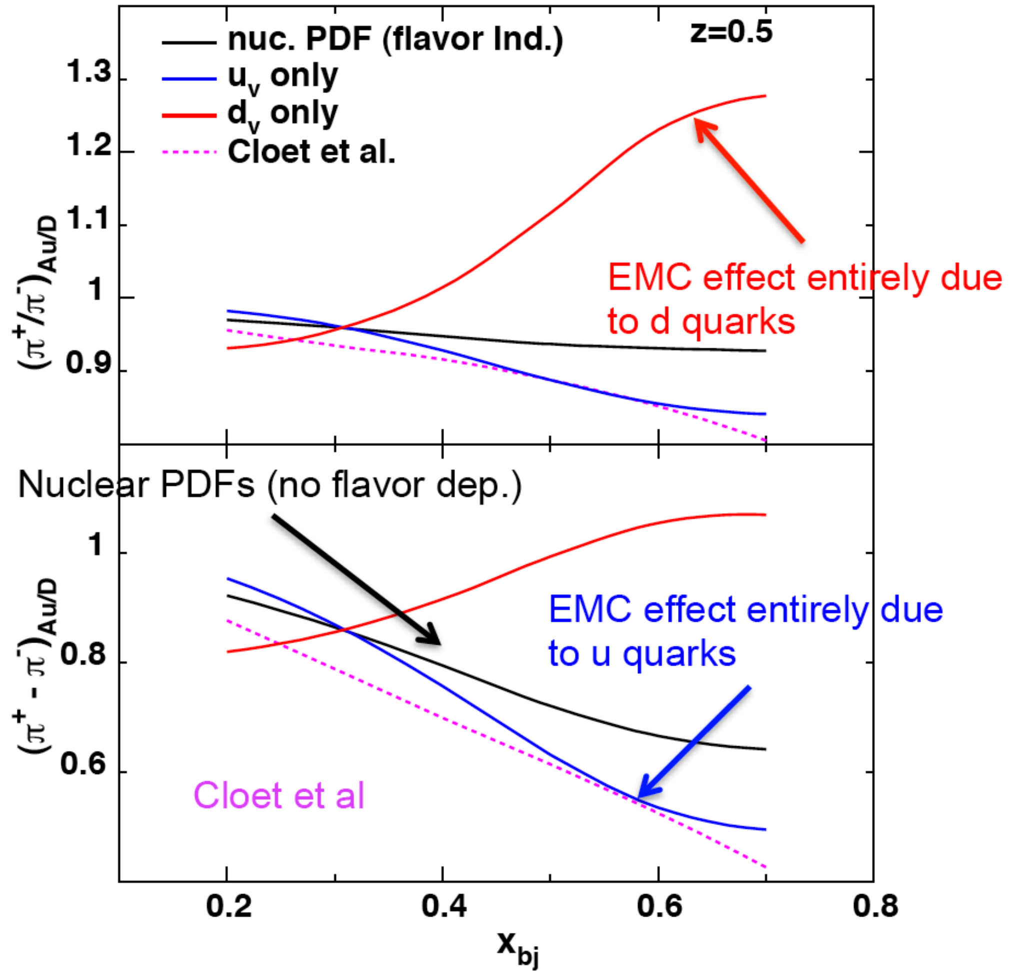
Pia Zurita, arXiv:2101.01088

☐ At low energy, FFs are also significantly modified in heavy nuclei

- ✓ At high energy, however, quarks likely hadronized in vacuum (nFF→free!)

Semi-Inclusive DIS (SIDIS)

- SIDIS in eA:
  - ☐ EMC signals magnified in Super ratios
  - ☐ Stronger flavor-dependence seen in different hadrons-productions

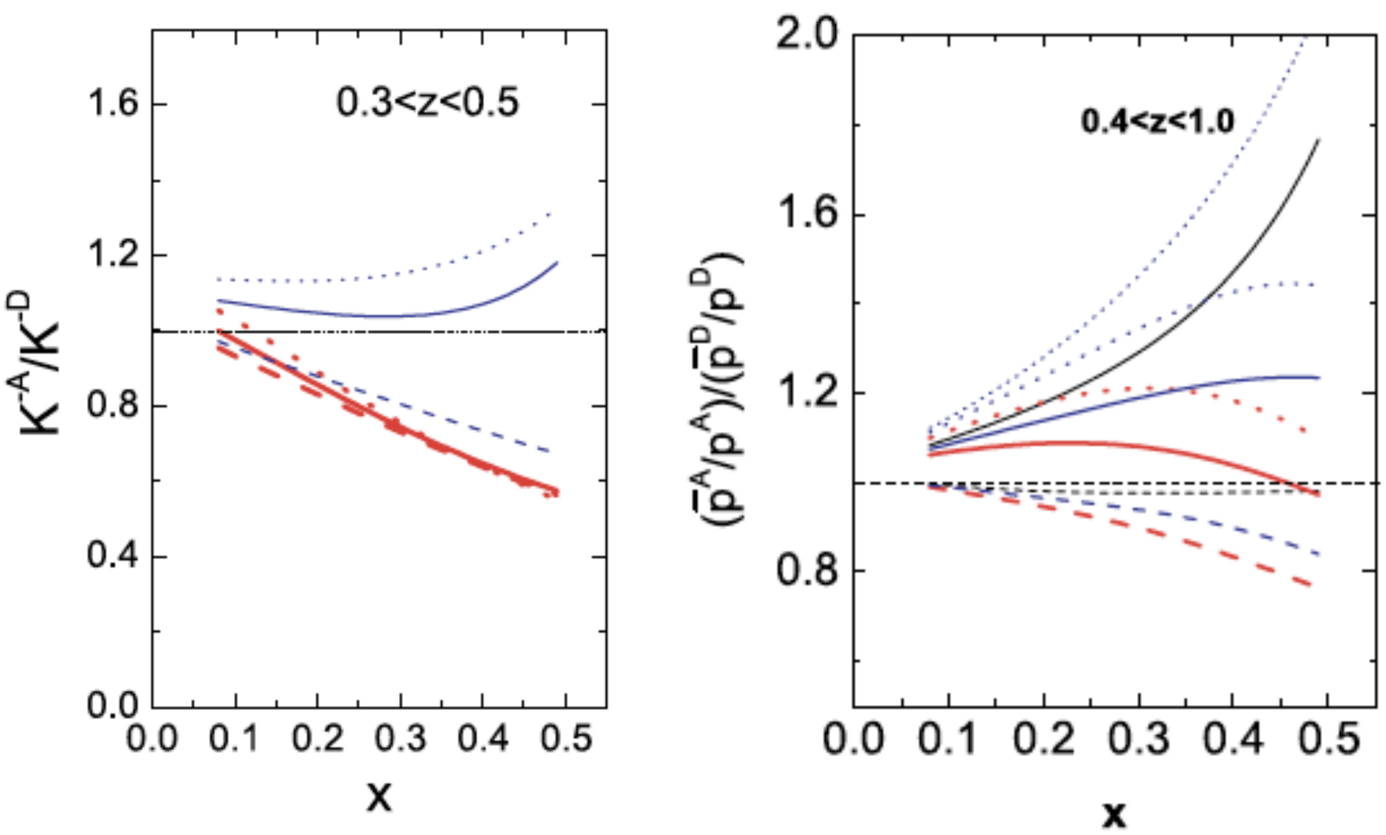


EMC effect entirely due to d quarks

Nuclear PDFs (no flavor dep.)

EMC effect entirely due to u quarks

Cloet et al



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

Semi-Inclusive DIS (SIDIS)

➢C12-21-004 Experiment

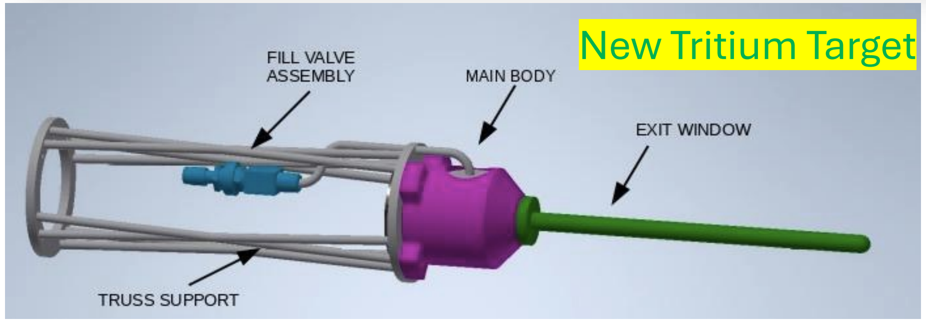
SIDIS Measurement of A=3 Nuclei with CLAS12 in Hall-B

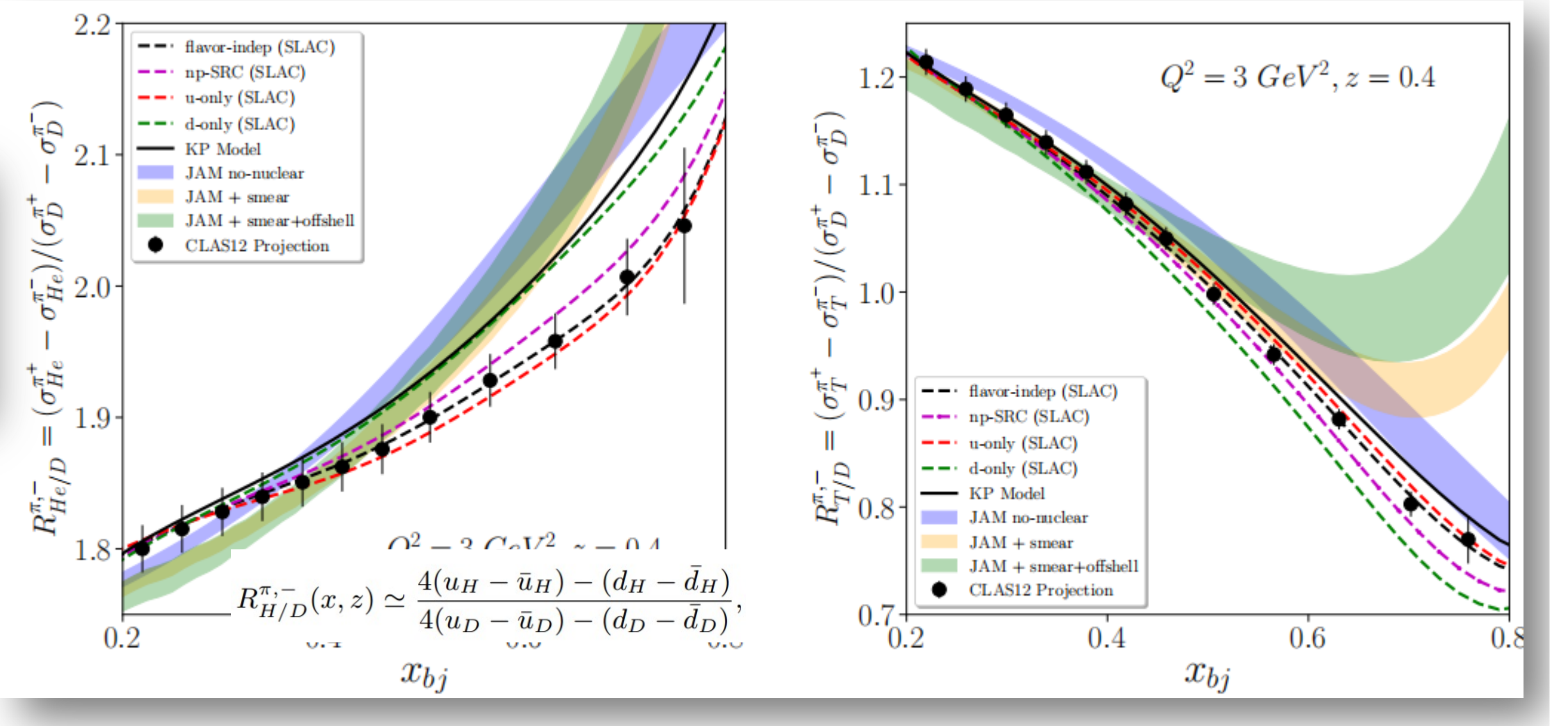
Conditionally approved in PAC49

On behalf of the spokespeople:

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

and the CLAS Collaboration





❑ Targets: D2/H3/He3 with 10.6 GeV unpolarized beam

- ✓ New Tritium target system (same as 2nd Tritium-SRC)
- ✓ Standard CLAS12 setup
- ✓ Detecting electrons, pions and kaons

❑ “Conditionally” approved

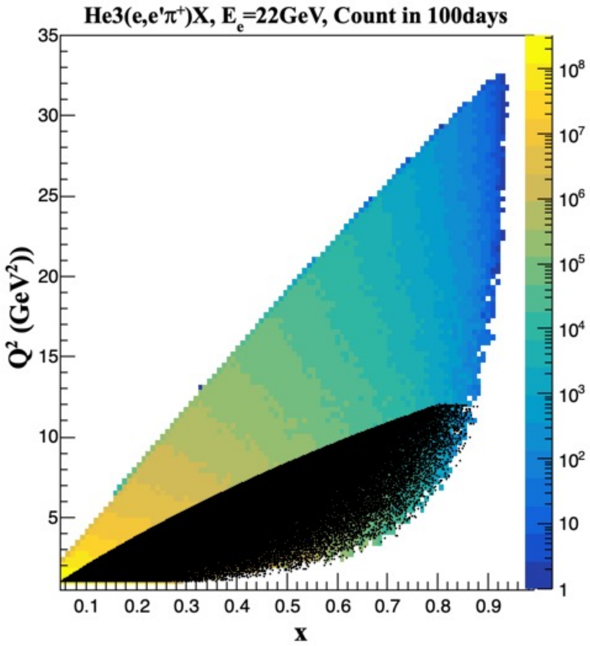
- ▪ Seek theorists' input
- ▪ Projections on A=3 nTMD+nFF

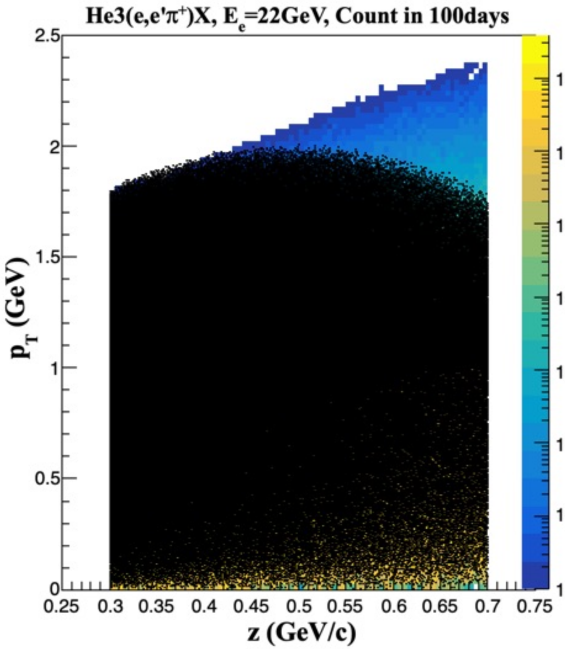
❑ **Physics Topics:**

- ✓ Flavor-Dependent EMC
- ✓ Hadronization in light Nuclei
- ✓ TMD and FF in A=3
- ✓ Bonus： GPD in A=3

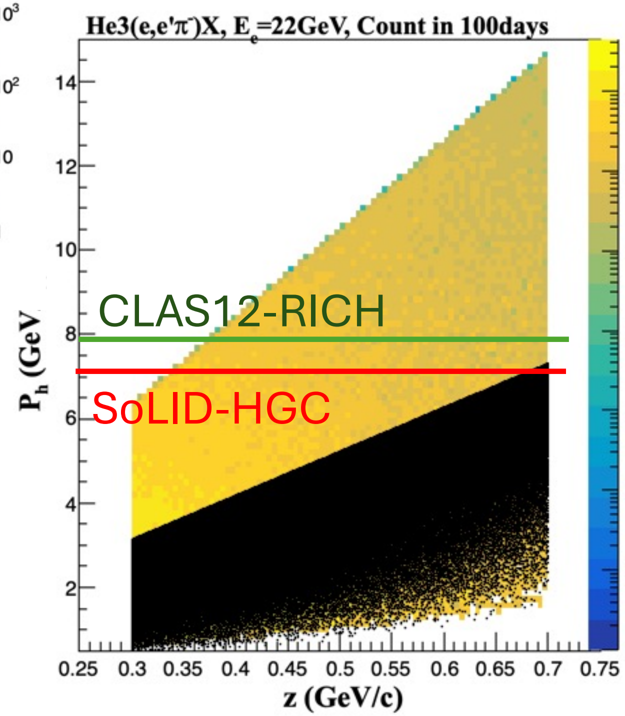
eA-SIDIS @ 22GeV

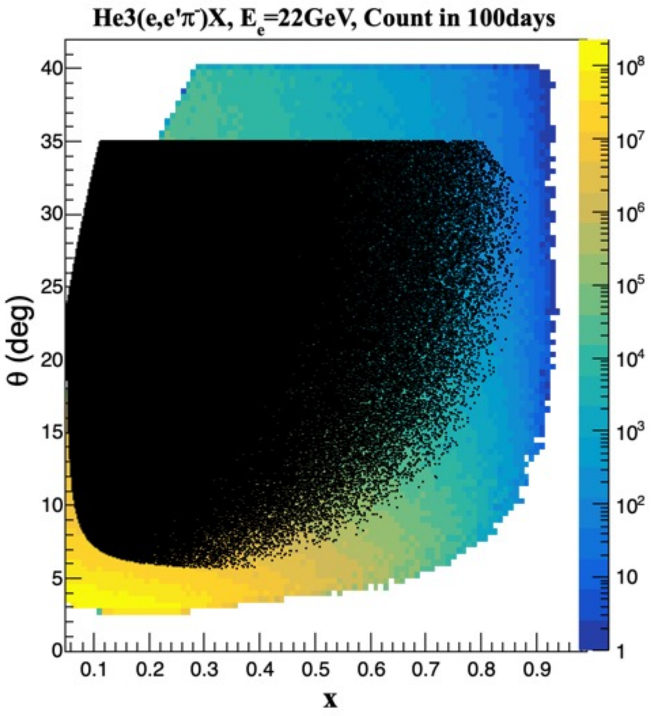
- ➢Larger Phase-Space + Kaon/Proton/Lambda Production





Back dots→11GeV
Color dots→22GeV

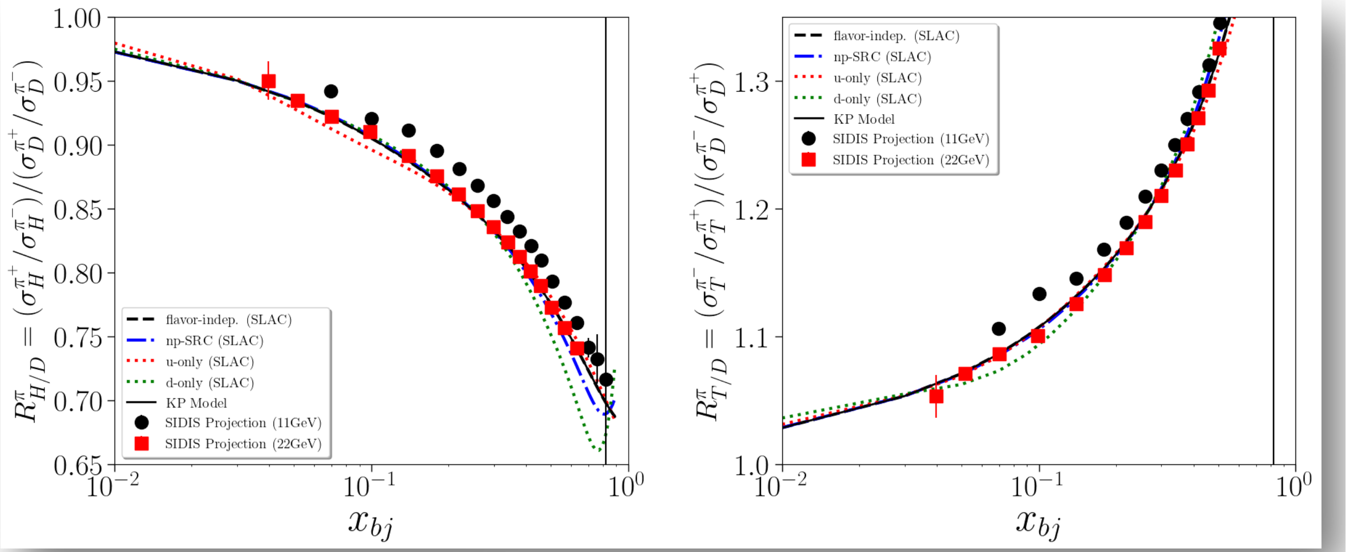




- ☐ Assuming updated CLAS12/SoLID detectors cover the entire acceptance

eA-SIDIS @ 22GeV

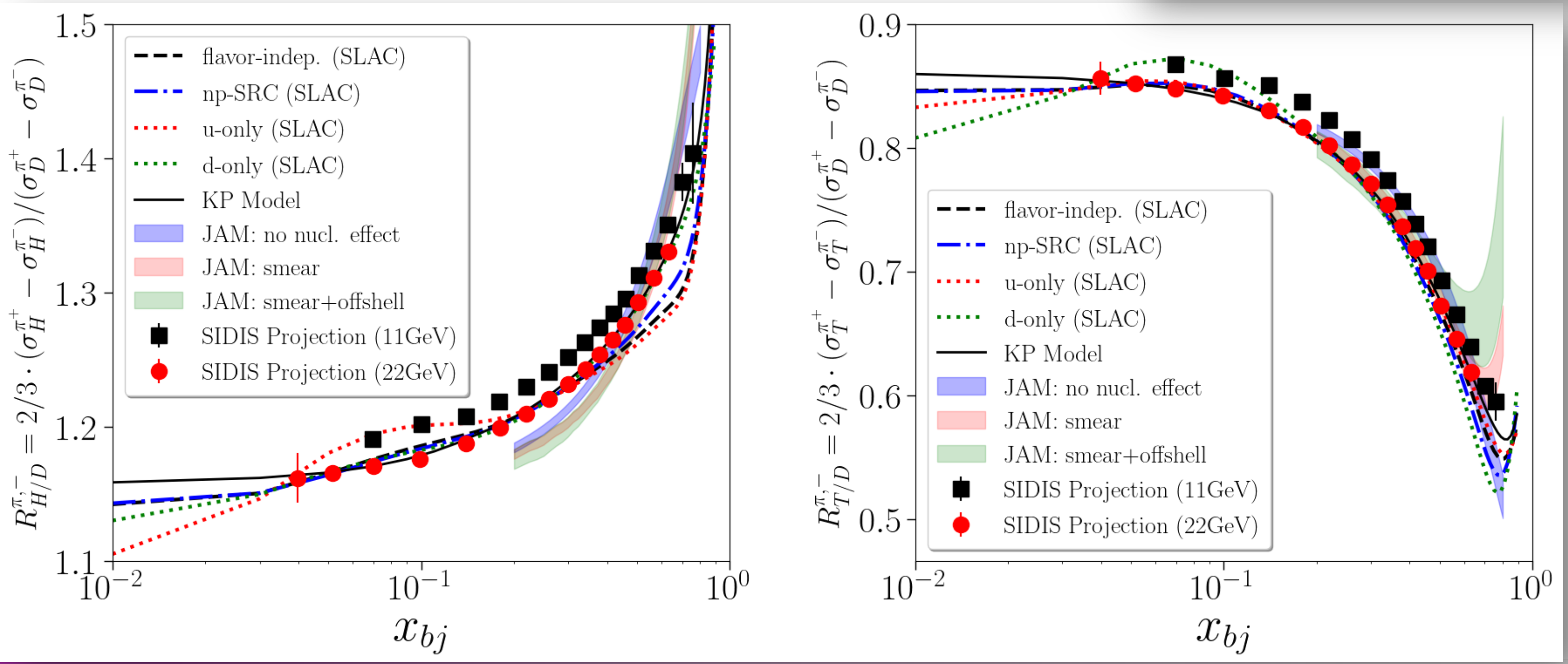
- eA SIDIS w/ mutiple Hadron-Production
  - ☐ Fully decouple flavor-dependent EMC & Antishadowing in A=3



0.3<z<0.4

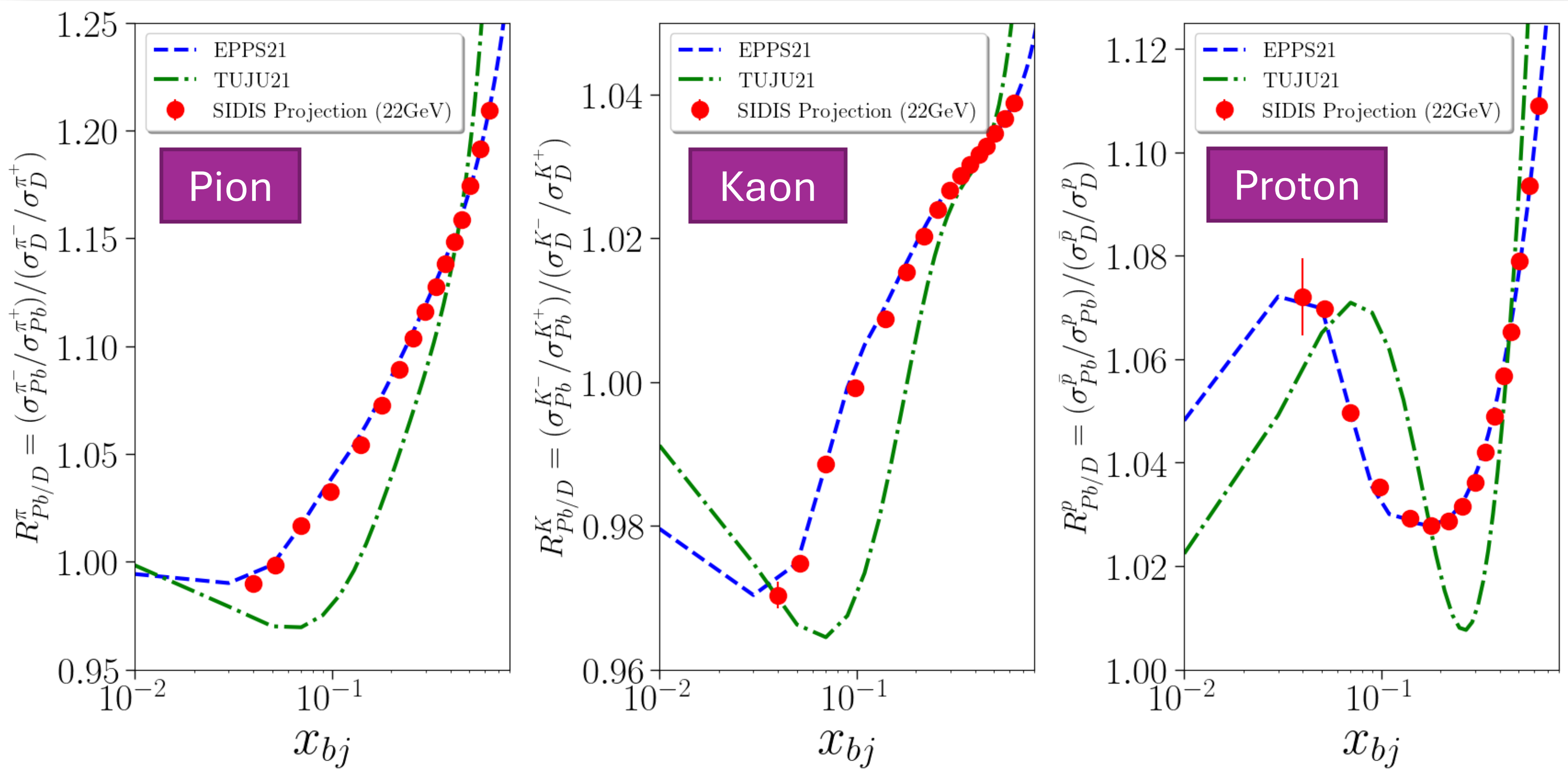
Pion

Log-scale

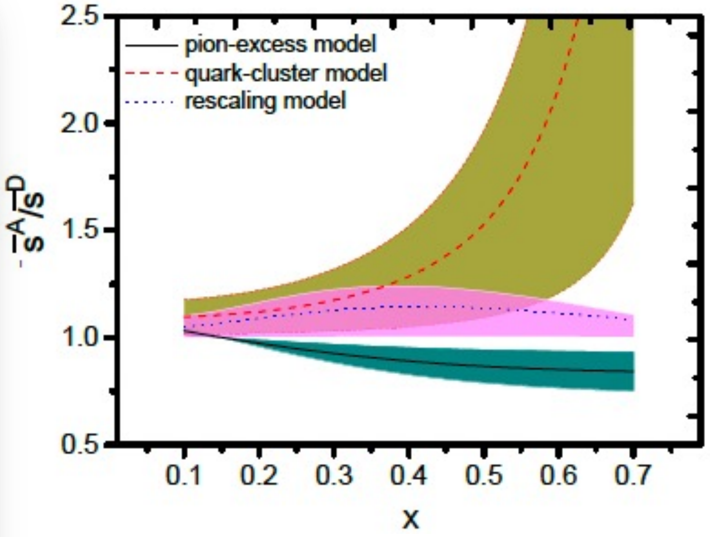


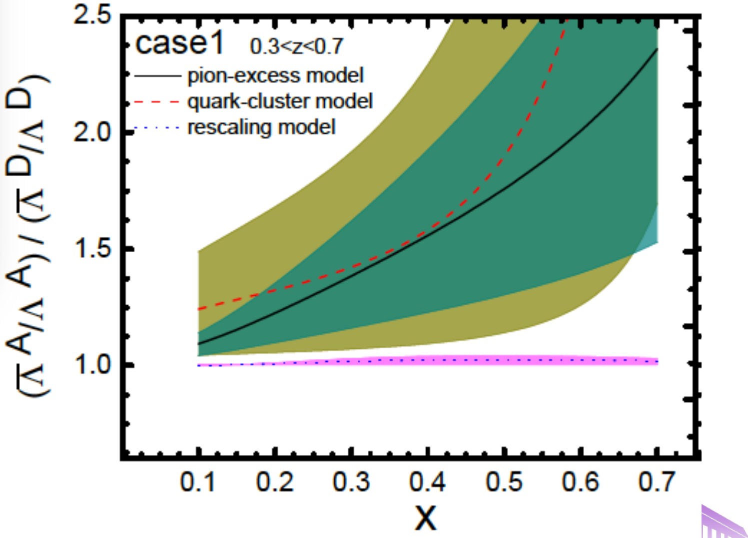
eA-SIDIS @ 22GeV

- ➢eA SIDIS w/ mutiple Hadron-Production
  - ❑ From light to heavy nulcei



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



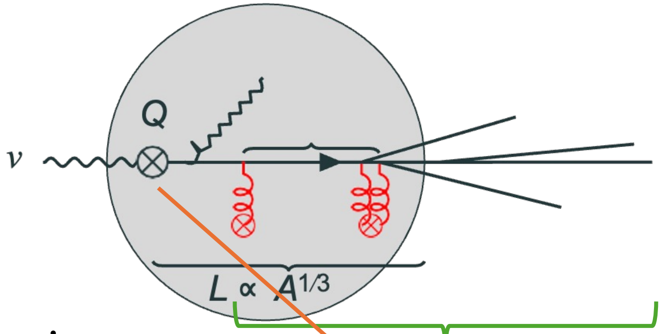


- ❑ EMC & Antishadowing in strange-quarks via Lambda-Production? (ongoing projection)

eA-SIDIS @ 22GeV

- More advanced theoretical treatments

Weiyao Ke, Ivan Vitev, Phys. Lett. B 854 (2024) 138751



☐ SIDIS cross-section:

$$\frac{d\sigma_{eA\to h}}{dx_B dQ^2 dz_h} = \frac{2\pi\alpha_e^2}{Q^4}\sum_{i,j} e_q^2 \left\{ \left\{ f_{j/A} \otimes C_{ij} \right\}_{x_B} \otimes d_{h/i} \right\}_{z_h},$$

nPDF/nTMD

Hard coefficient function

nFF

- nPDF from global fit (e.g. EPPS21-NLO)
- Hadron coefficient function calculable
- Special treament of DGLAP evolution in medium for FF (no nFF needed in this model):

$$\text{nFF} = \text{M} \otimes \boldsymbol{FF}$$

Medium effect (calc+fit)

Free FF (e.g. NNFF10lo)

Treament of DGLAP evoluation in medium:

$$F_{ij}^{1,L}(z) \equiv f_{j/A} \otimes zC_{ij}^{1,L}$$

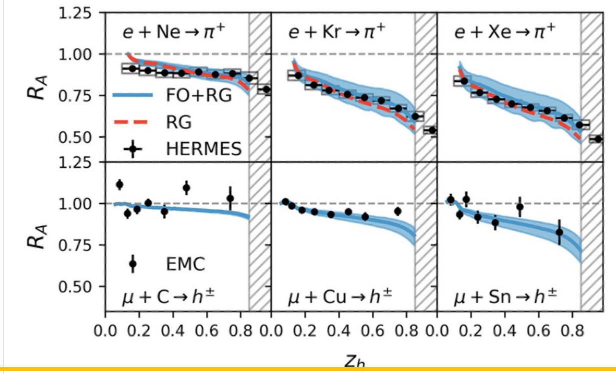
$$\frac{\partial F_f}{\partial \tau} = 2C_F\left(2C_A\frac{\partial}{\partial z} - \frac{2C_A + C_F}{z}\right)F_f + C_F\frac{F_g}{z},$$

$$\frac{\partial F_g}{\partial \tau} = \left(4C_A^2\frac{\partial}{\partial z} - \frac{2N_f C_F}{z}\right)F_g + 2C_F^2\sum_f\frac{F_f}{z},$$

$$\frac{\partial F_{\rm NS}(\tau, z)}{\partial \tau} = 2C_F\left(2C_A\frac{\partial}{\partial z} - \frac{2C_A + C_F}{z}\right)F_{\rm NS},$$

$$\tau(\mu_2^2) = \frac{B(w)\rho_G L}{8\nu/L}\frac{4\pi}{\beta_0}\left[\alpha_s(\mu_2^2) - \alpha_s\left(\frac{\chi(w)z\nu}{L}\right)\right],$$

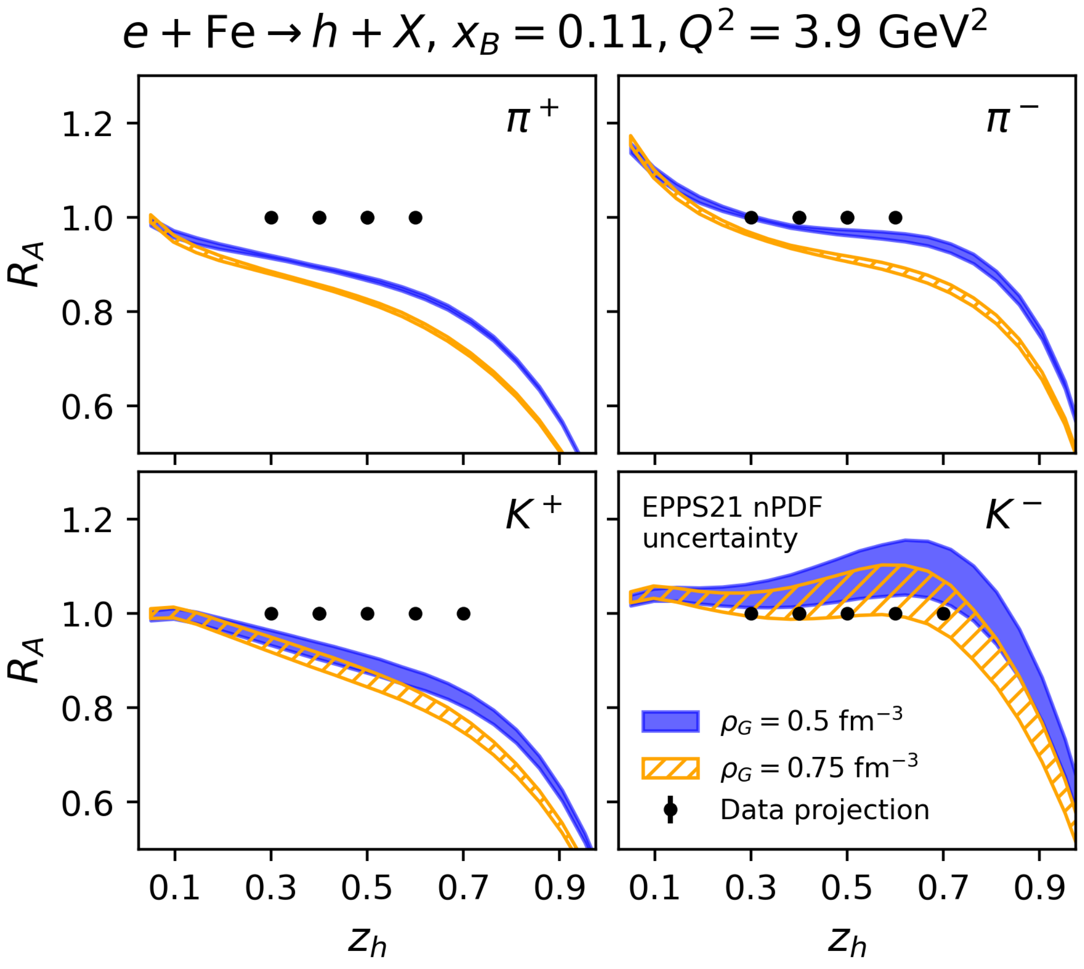
Effective Glauber gluon density (accounting coupling constants, color factors & density of scattering centers)→ Fit from HERMES data (0.4 fm^{-3})

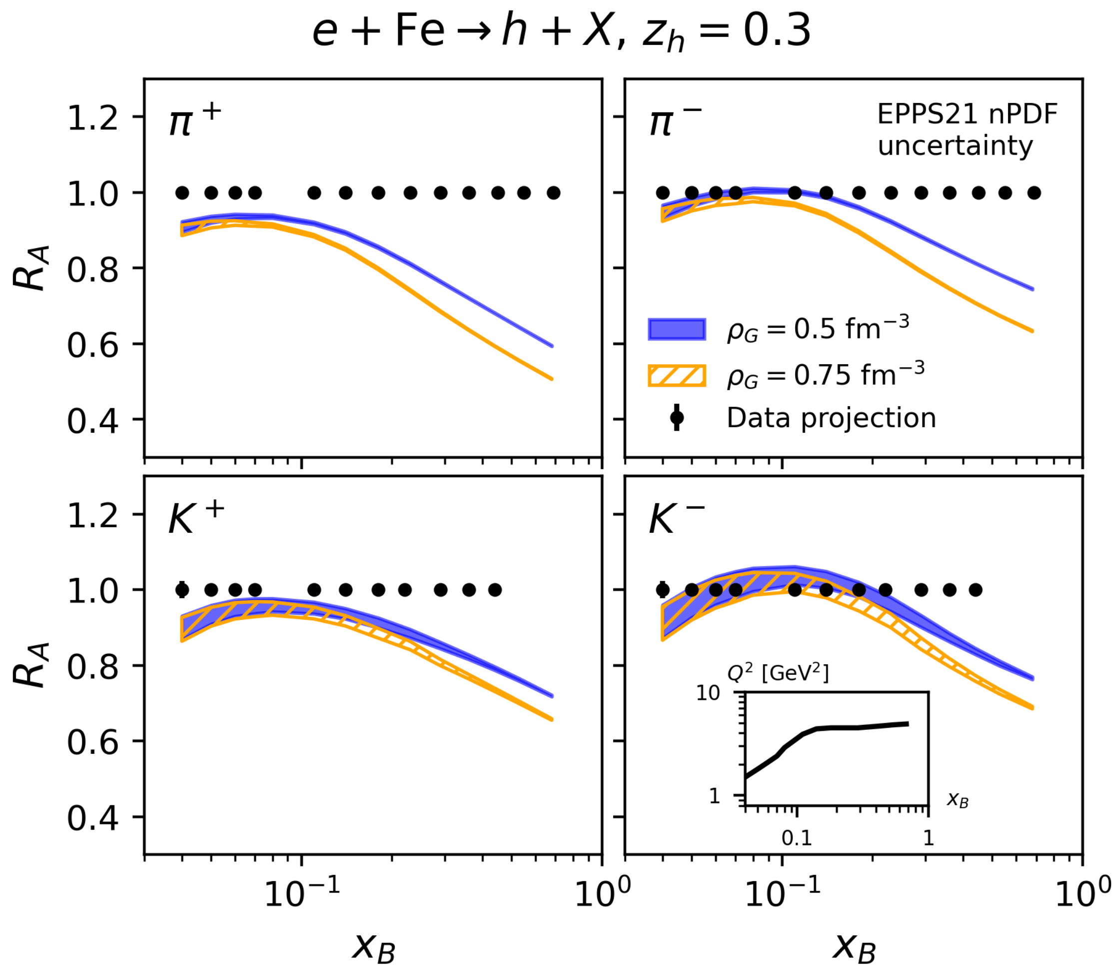


eA-SIDIS @ 22GeV

- Multiplicity ratios are senstitive to the medium effect (or nFF)
  - ✓ Study Pre-Hadronization and Hadronization
  - ✓ Expect great improvement w/ Kaon-SIDIS

$$R_A(x_B, Q^2, z_h) = \frac{\frac{d\sigma_{eA\to h}}{dx_B dQ^2 dz_h} \Big/ \frac{d\sigma_{eA}}{dx_B dQ^2}}{\frac{d\sigma_{ed,ep\to h}}{dx_B dQ^2 dz_h} \Big/ \frac{d\sigma_{ed,ep}}{dx_B dQ^2}}.$$


$e + \mathrm{Fe} \to h + X$, $x_B = 0.11, Q^2 = 3.9$ GeV^2


$e + \mathrm{Fe} \to h + X$, $z_h = 0.3$

eA-SIDIS @ 22GeV

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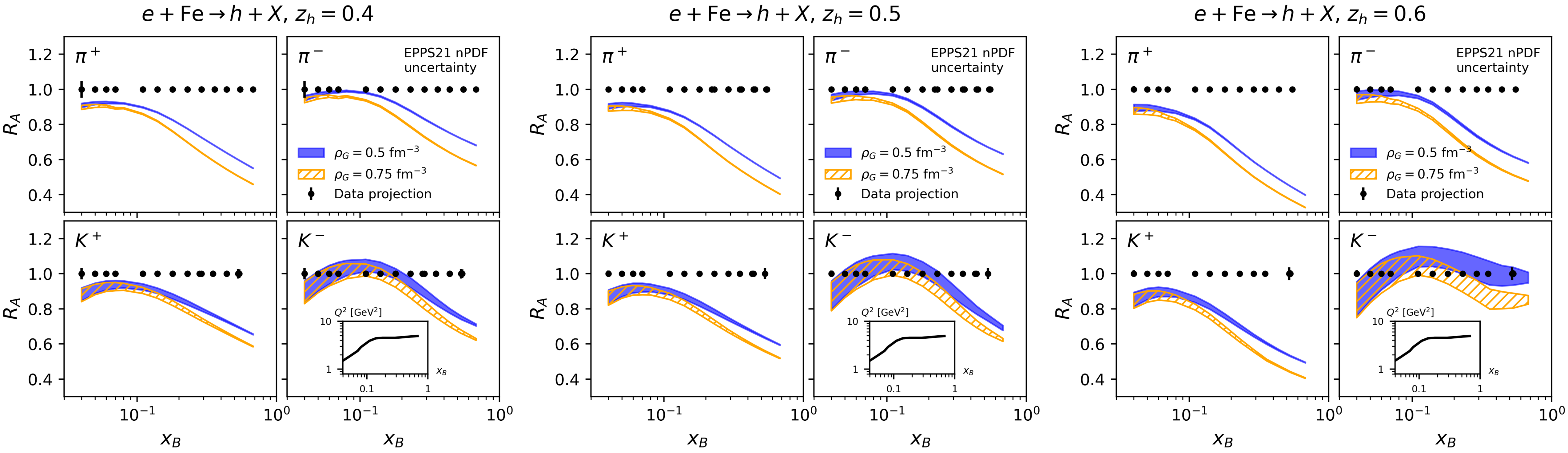
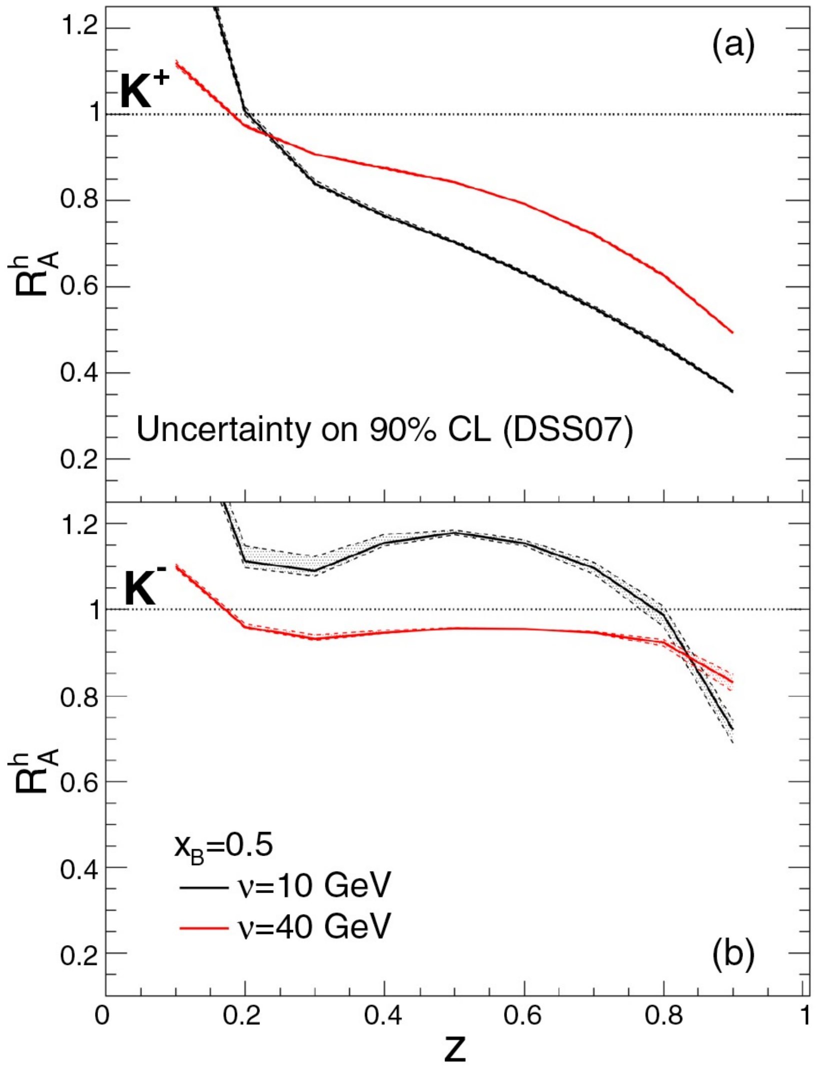
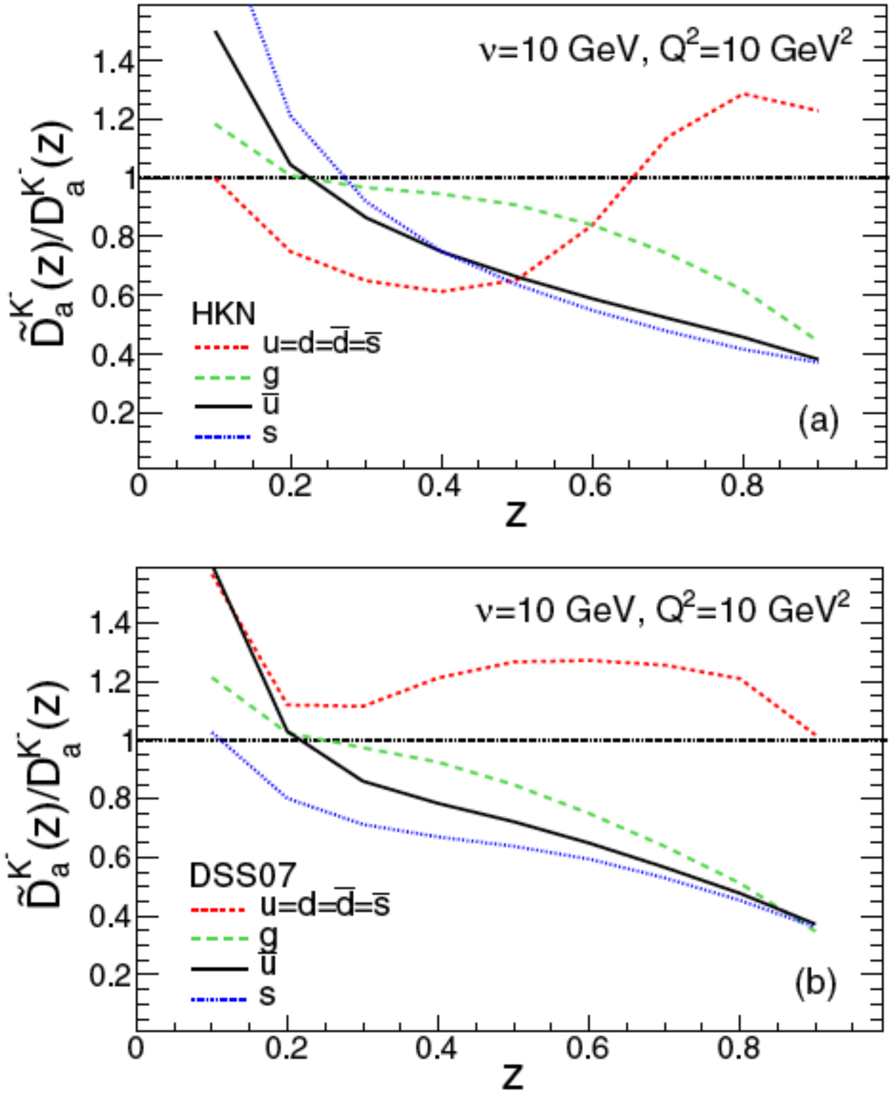


eA-SIDIS @ 22GeV

- Study flavor-dependence of Medium effect in nFF





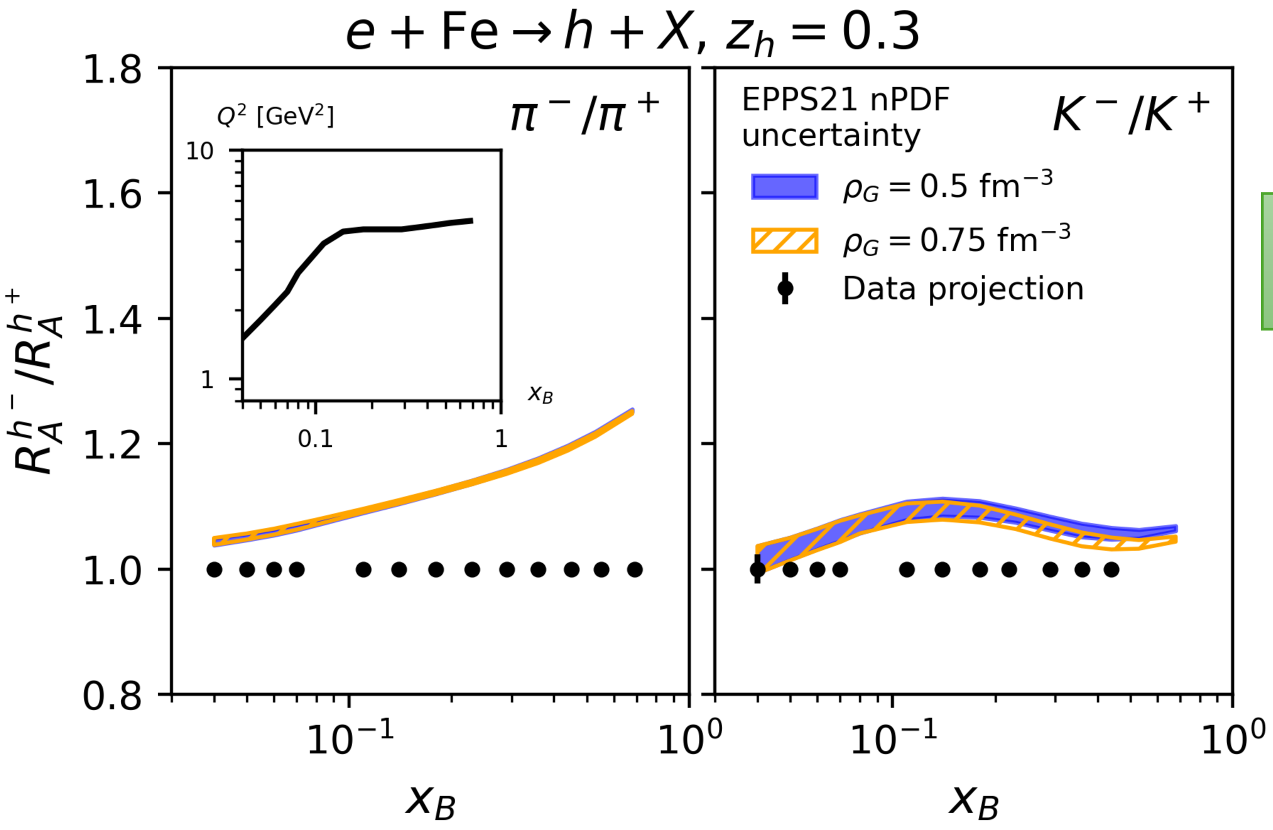
N Chang, et. al. PRC92, 055207 (2015)

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

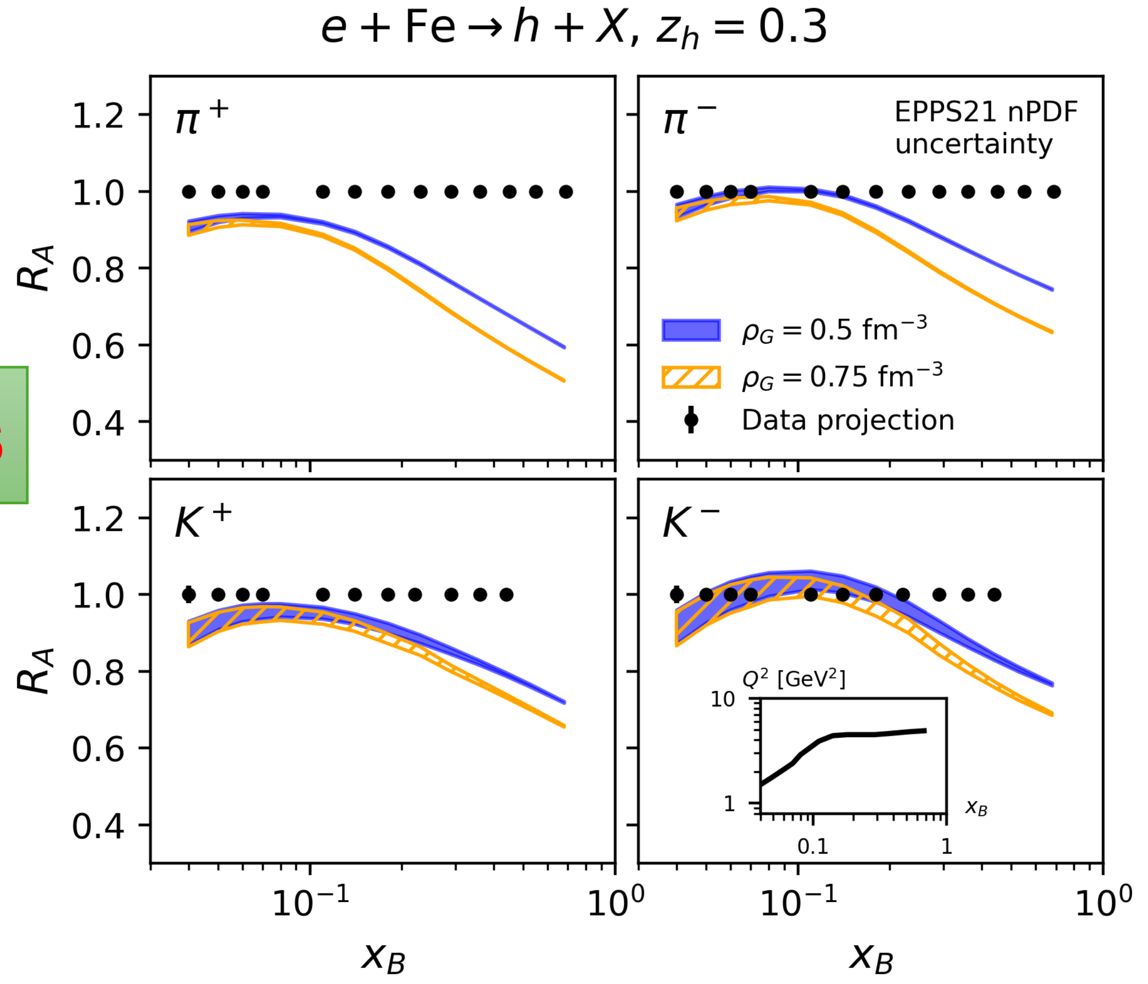
eA-SIDIS @ 22GeV

- Double ratio removes model-dependence of the medium effect in FF
  - ✓ More effective to extract nPDF from SIDIS
  - ✓ Flavor-seperation of nPDF in the anti-Shadowing & EMC region

$$R_A^{h^+/h^-} = R_A^{h^+} / R_A^{h^-}$$



VS



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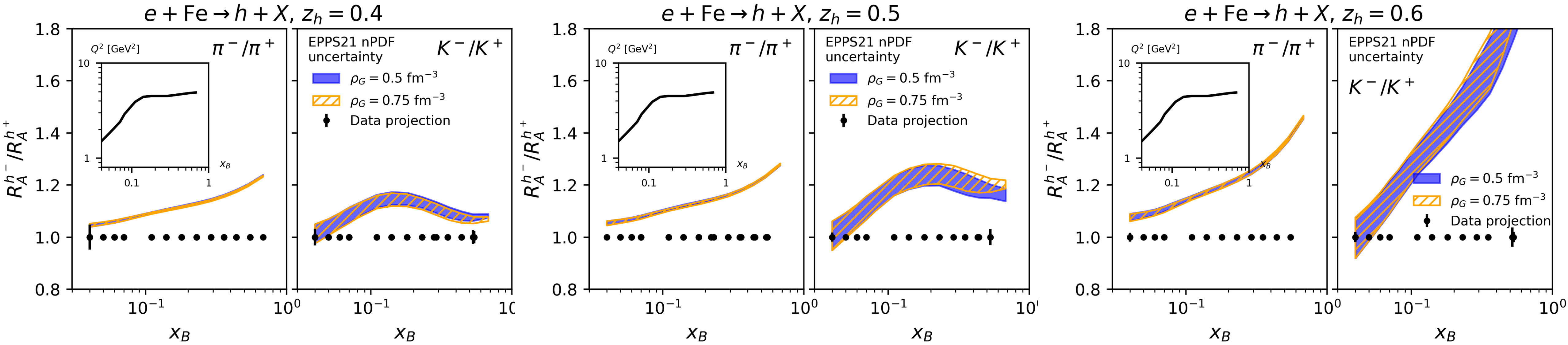


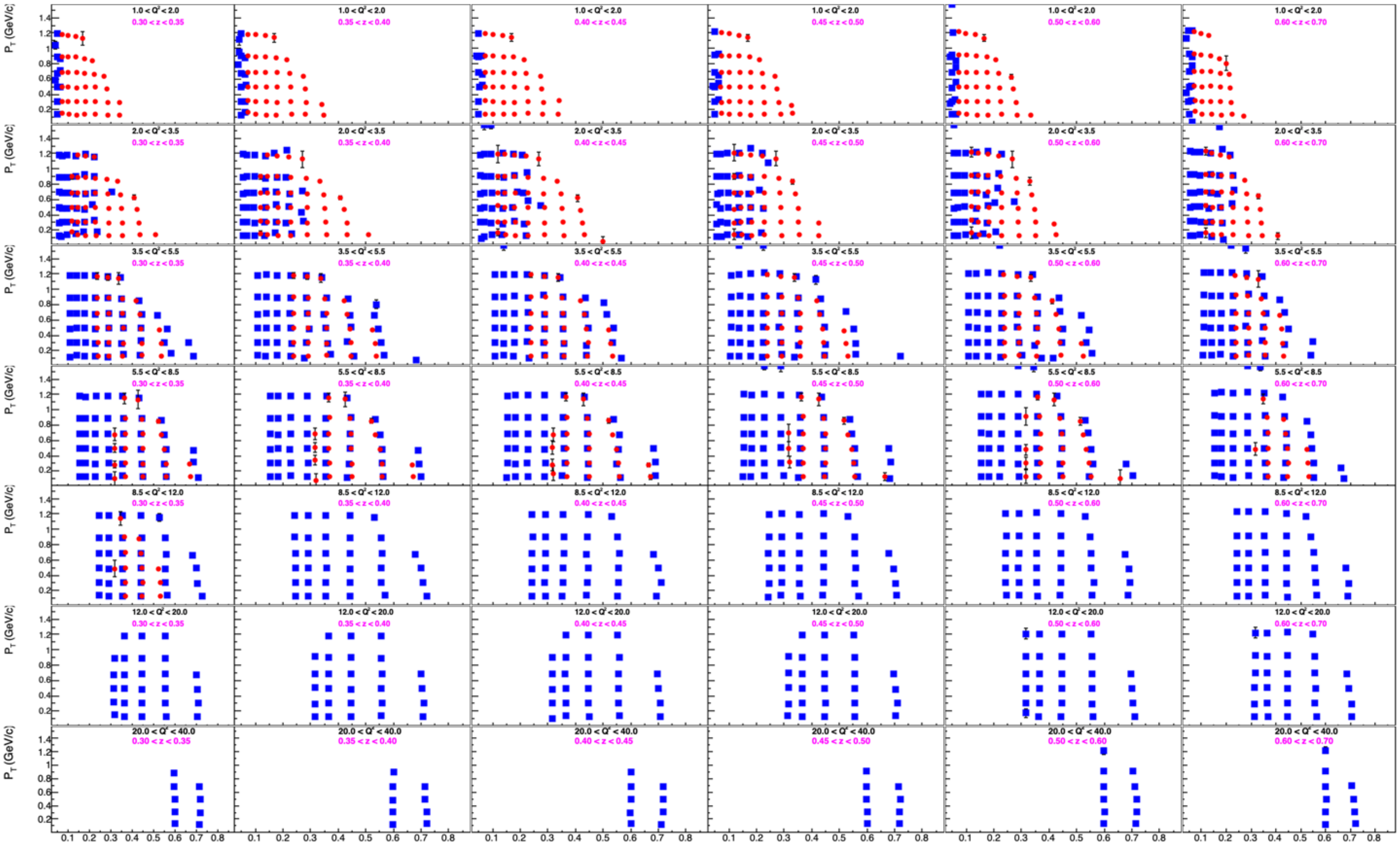
11GeV to 22GeV

- ➢ From 1D to 3D?

C12-Pion-SIDIS Projection

- • 11GeV
- ■ 22GeV

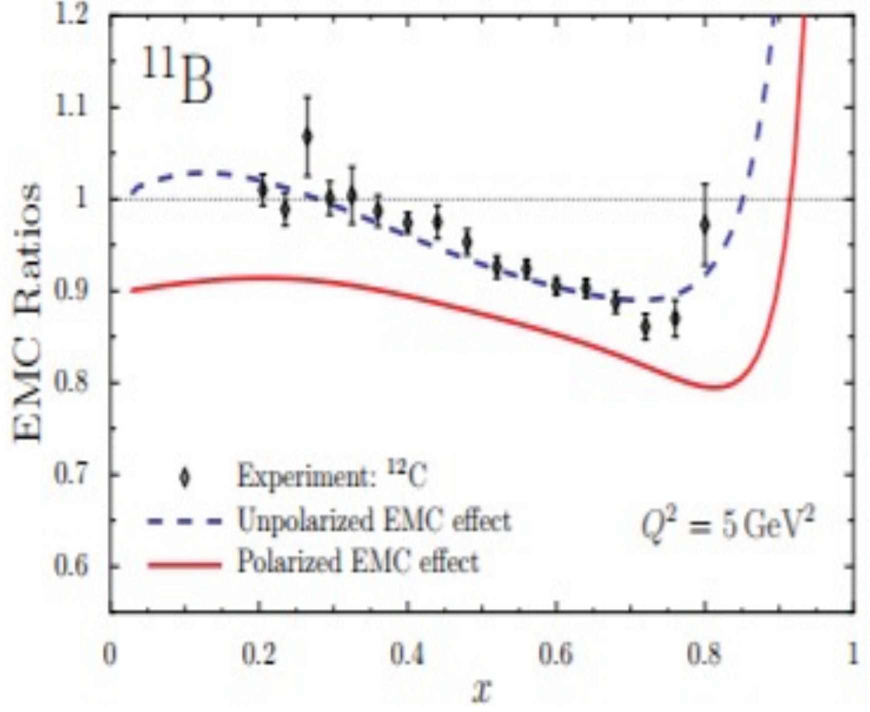
→4π-detector (CLAS12 & SoLID)
→Lumi~10^{35}cm^{-2}s^{-1},
→100-days



11GeV to 22GeV

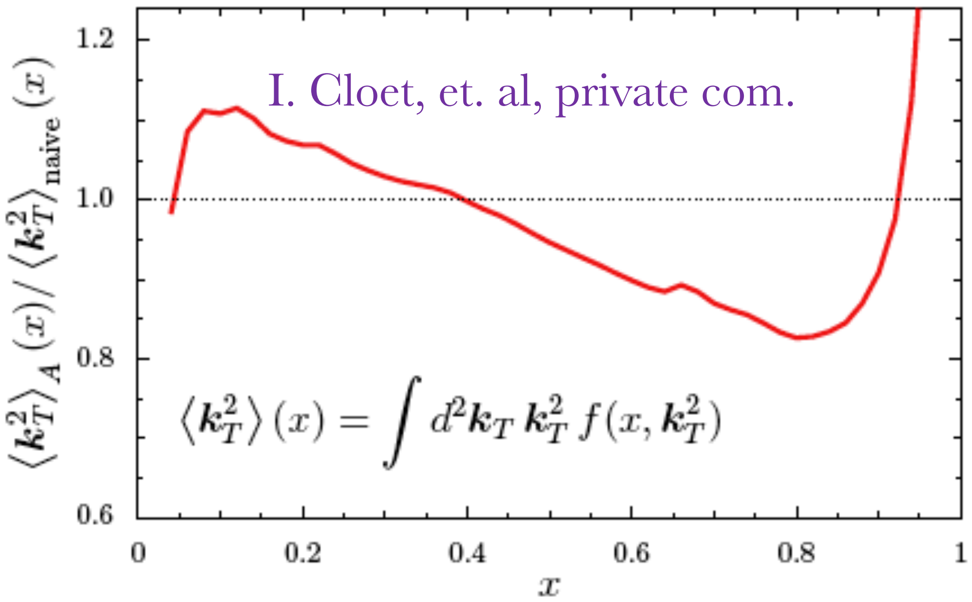
➢ From 1D to 3D?

- ❑ Models suggest polarized PDFs in Nuclei are modified!
  - Modification of quark-spin in nuclei?



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

See Ian Cloet's talk today



- ❑ Transverse momentum distributions also likely modified
- ❑ However, heavy nuclei are unlikely to be polarized!

11GeV to 22GeV

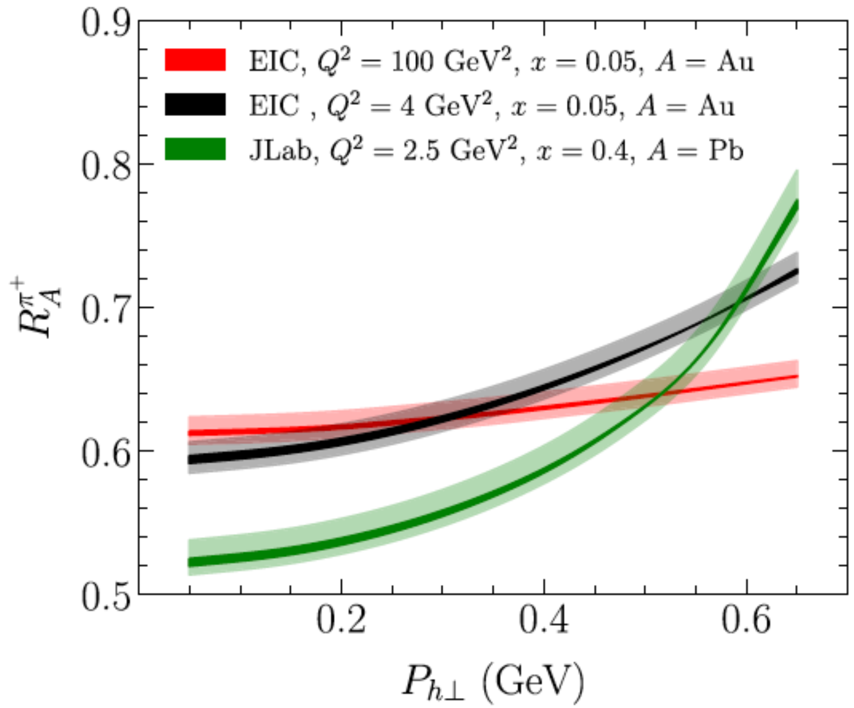
- From 1D to 3D?

❑ To fully understand EMC effect → Nuclear effect in 3D!

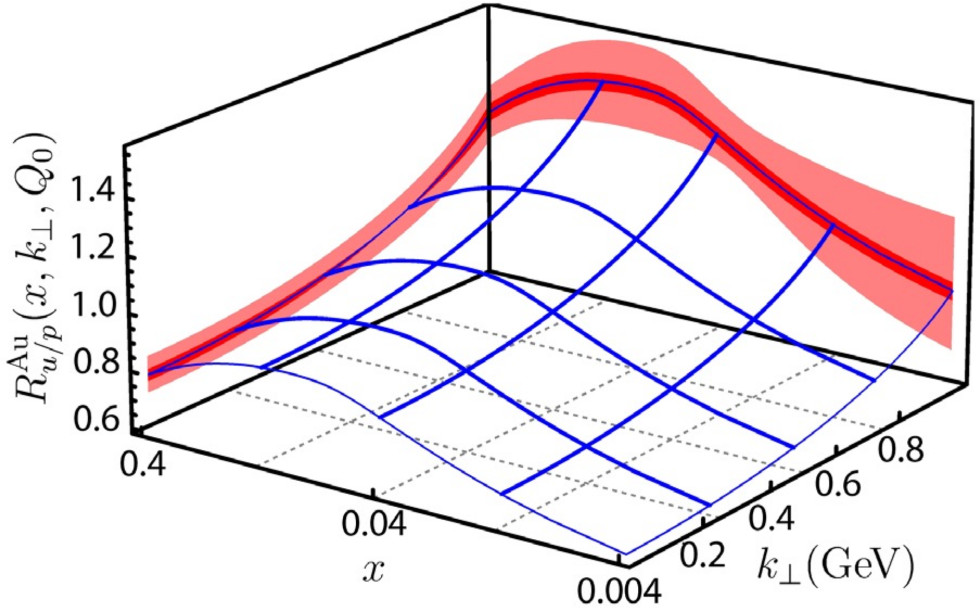
$$F_{UU}(x,z,P_T) = \sum_q e_q^2[f_1^q(x,K_\perp)\otimes D_q^h(z,q_T)]$$

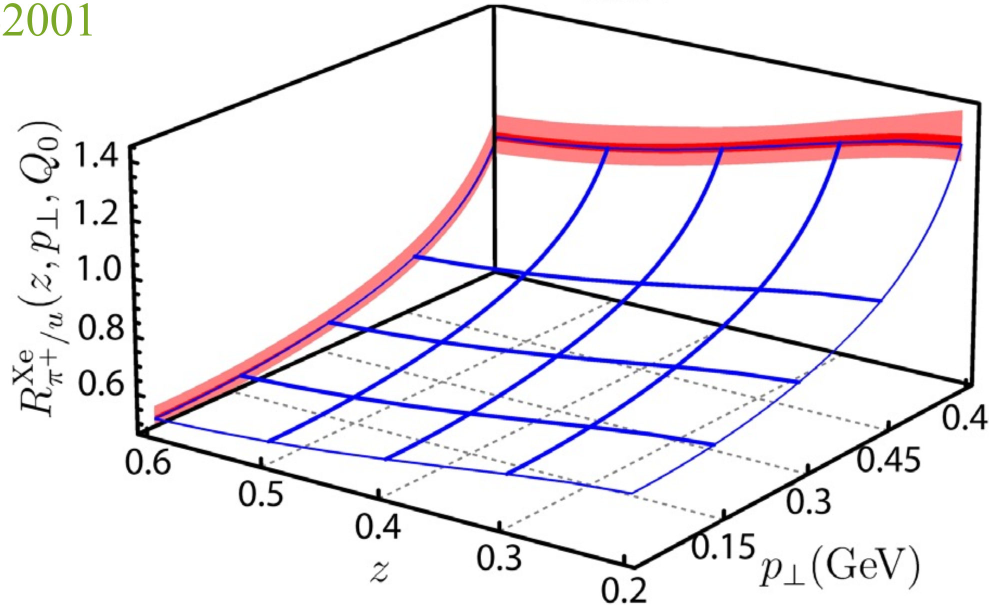
Unpolarized TMD *Unpolarized FF*

❑ First global analysis of nTMD



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





❑ Projections @Jlab w/ 11&22GeV on going

11GeV to 22GeV

- From 1D to 3D?
  - ☐ The unpolarized SIDIS cross section w/ additional azimuthal dependence:

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

$$= A + \underset{\text{Cahn}}{B\cos\phi_h} + \underset{\text{Boer-Mulder}}{C\cos 2\phi_h}$$

  - ☐ If we consider the Boer-Mulder Term
    - Study A-dependence of the $\cos(\phi_h)$ azimuthal term:

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

Twsist-3

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

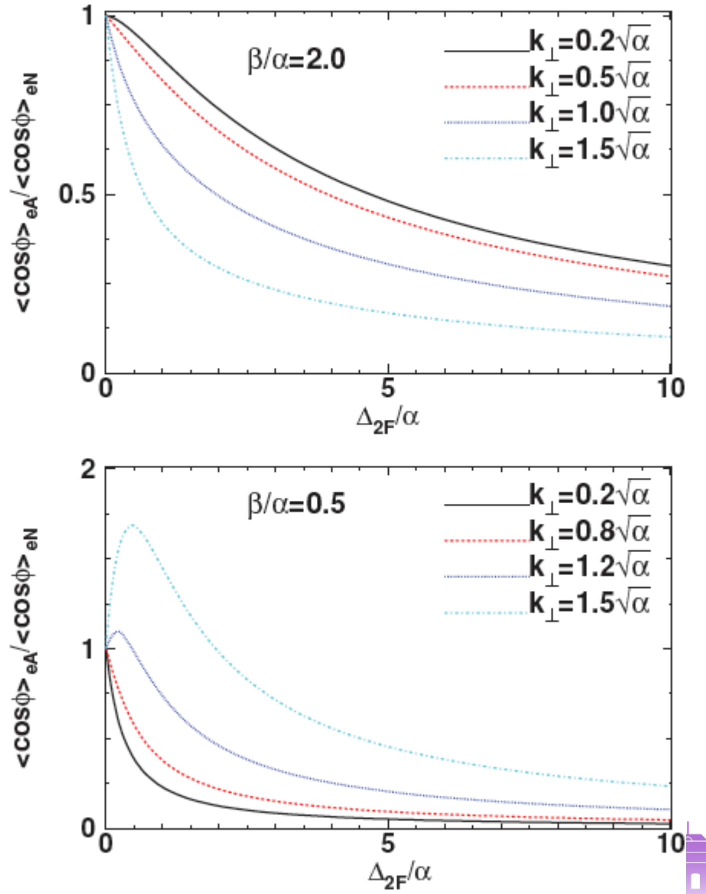
$$f_{q\perp}^A(x,k_\perp) \approx \frac{A\beta}{\pi(\beta+\Delta_{2F})^2} f_{q\perp}^N(x) e^{-\vec{k}_\perp^2/(\beta+\Delta_{2F})}.$$

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)



Summary

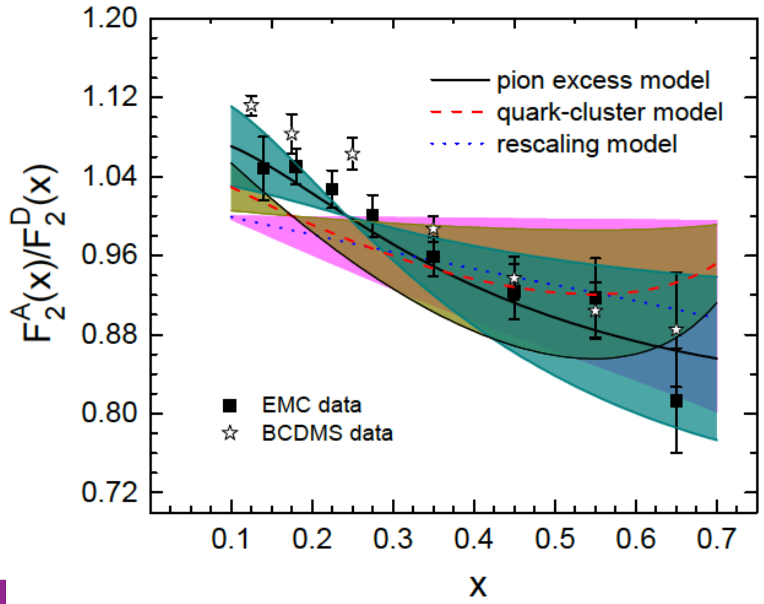
- Origins of EMC and anti-shadowing effects are still largely unknown
    - Flavor-dependence of u and d?
    - Effects in sea & gluon?
- Poor experimental precision (mostly inclusive-DIS)
- SIDIS with multiple hadron-production at Jlab 22 GeV
    - Phase-space, fragmentation regions, corrections
    - Pions, kaons, proton and lambda production →Flavor-tagging
    - Measuring in 3D: nPDF → nTMD & nFF & nGPD
    - Need to acquire SIDIS w/ A=3 using 11GeV, then move to heavier targets & 22GeV

Backup

Partons in Nuclei

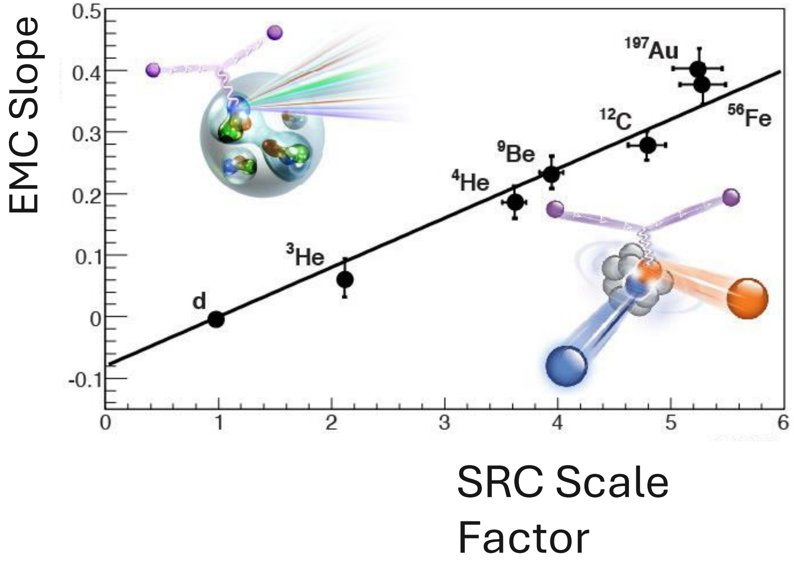
- EMC Effect:
  - ☐ EMC: The ratio of inclusive DIS cross-section between a nucleus-A to the deuteron drops linearly in 0.3<x<0.7

    Phys.Lett.B 123 (1983) 275-278
  - ☐ Modeling:
    - ✓ Rescaling of quark & gluon sizes
    - ✓ Mean-Field (MIT bag, NJL …)
    - ✓ Multi-quark clusters (6-quark bag)



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

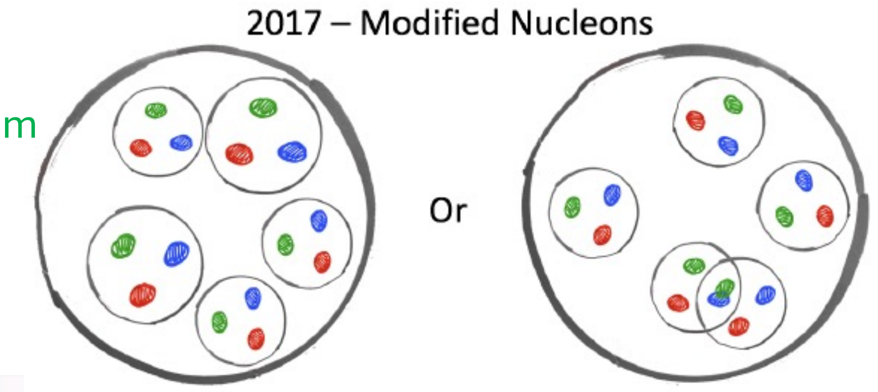
- ☐ Related to short range correlated (SRC) pairs:



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

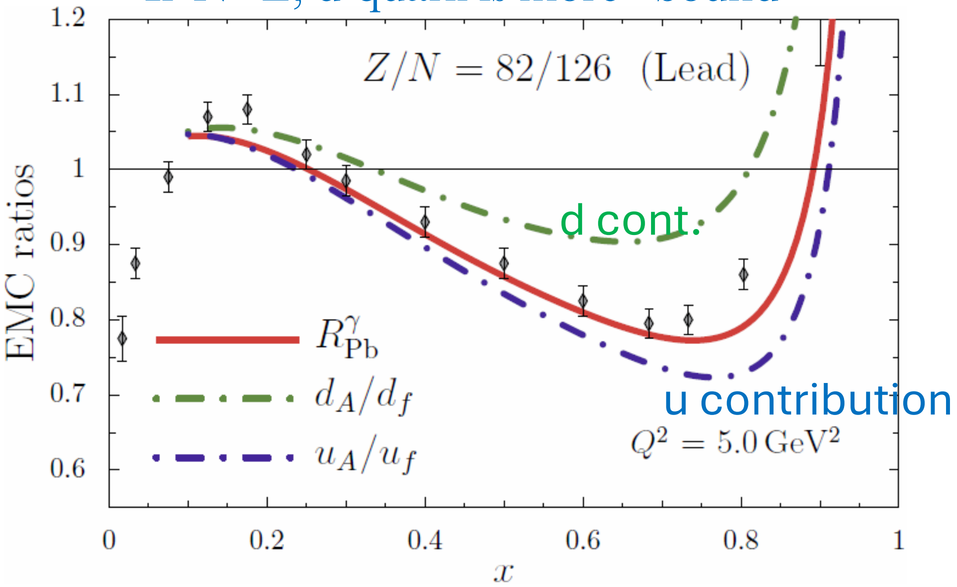
- ☐ Which nucleons are modified?

Drawing stealed from G. Miller

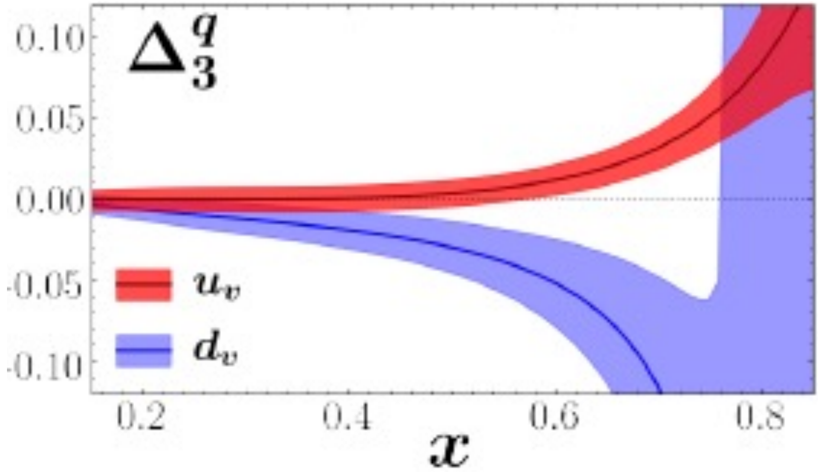


Partons in Nuclei

- Flavor-Dependence EMC Effect?
  - ☐ Mean-field model indicates flavor-dependence
    - ✓ If N>Z, u-quark is more "bound"
    - ✓ If N<Z, d-quark is more "bound"

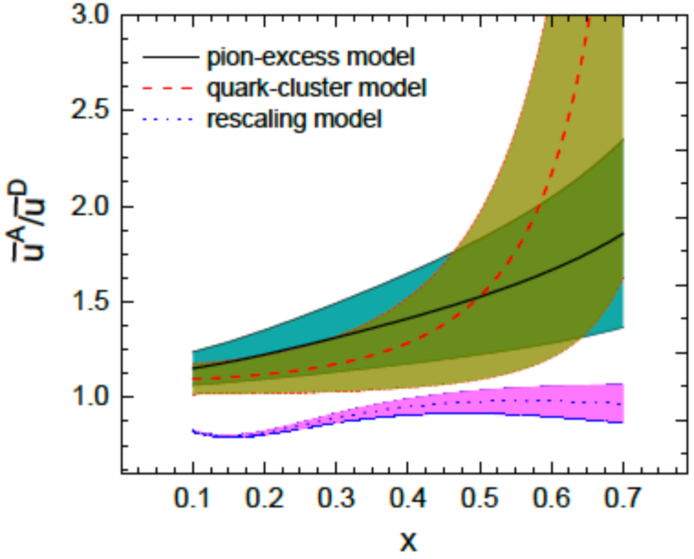


I. Cloet, et al, PRL 109, 182301 (2012)
PRL 102, 252301 (2009)



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

- ☐ JAM Model predicts u and d-quark modified differently in H3 and He3



- ☐ EMC effect in sea-quarks (unseen experimentally)?

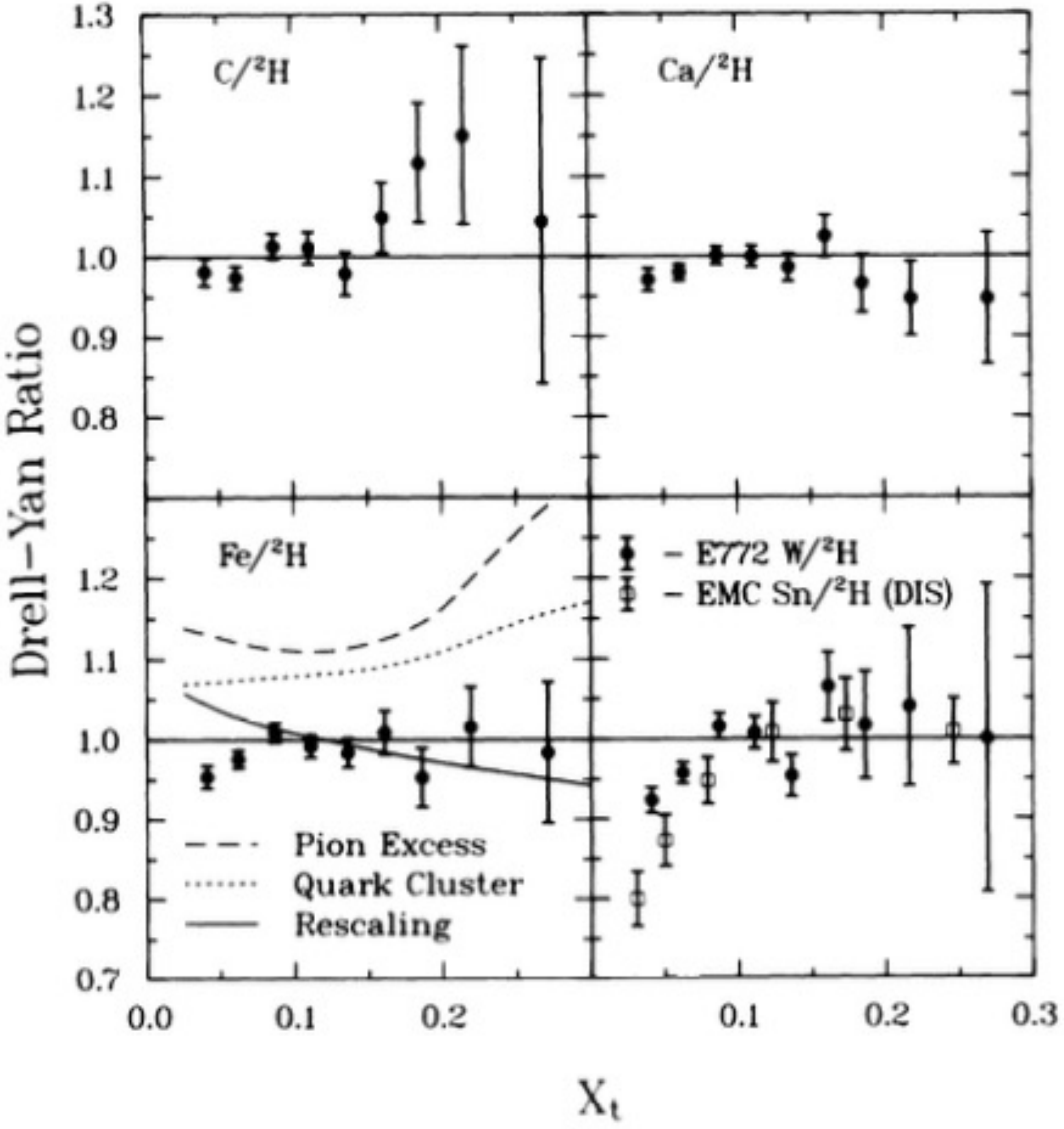
C. Gong, B.Q. Ma, Phys.Rev.C 97 (2018) 6, 065207

Partons in Nuclei

- Anti-Shadowing
  - ☐ Poorly known
  - ☐ May have richer physics info
    - connection with nuclear force?
  - ☐ Unsettled theoretical explanations
    - Deffractive process (multiple-scattering)?
    - Rescaling (enlarged confiment sizes)?
    - 6-quark bag?
    - …
  - ☐ "No" anti-shadowing in sea quarks
    - Strong flavor-dependence?

      Drell-Yan, E772, PRL. 64 (1990) 2479-2482
  - ☐ May only exists in σ_L^{DIS} →gluons only?

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

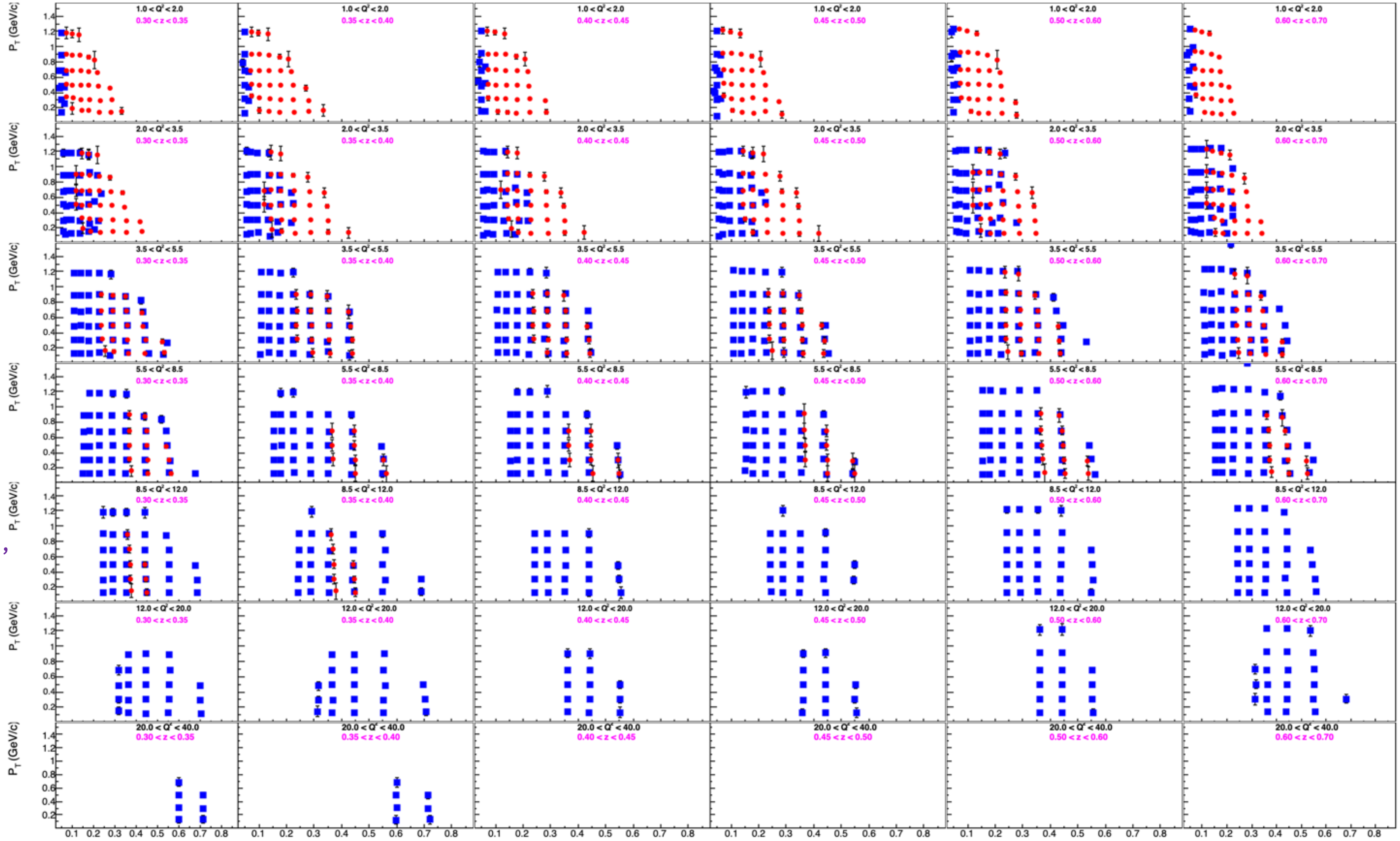


eA-SIDIS @ 22GeV

Kaon-SIDIS Projection

- ● 11GeV
- ■ 22GeV

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



eA-SIDIS @ 22GeV

Proton-SIDIS Projection

● Proton

■ Anti-Proton

→4π-detector (CLAS12 & SoLID)

→Lumi~$10^{35}cm^{-2}s^{-1}$,

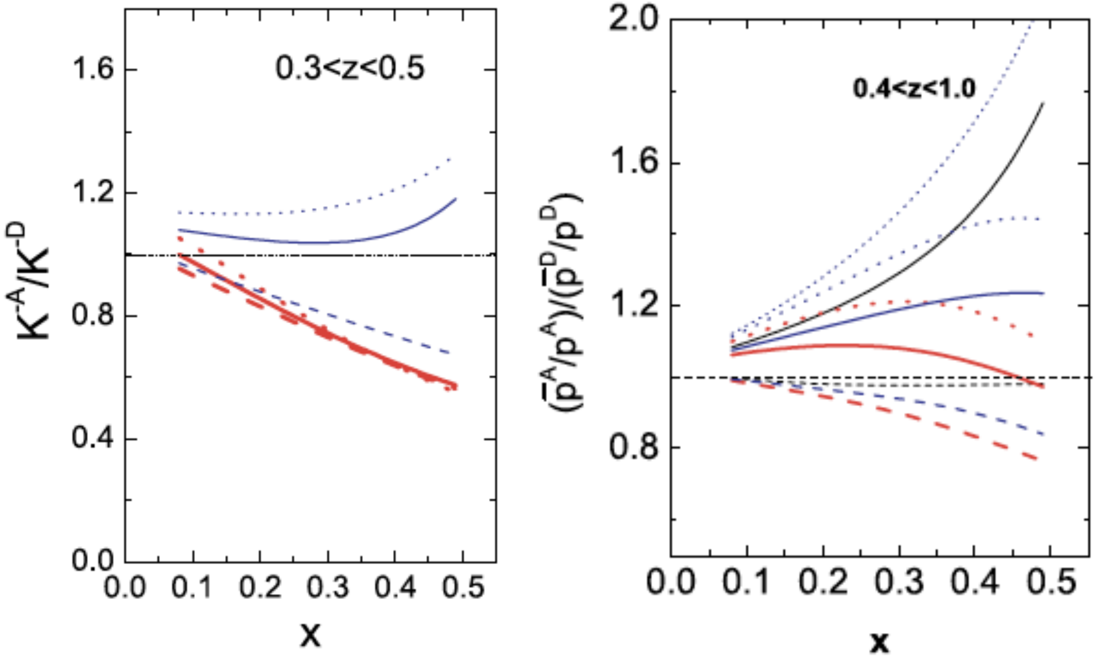
→100-days

11GeV to 22GeV

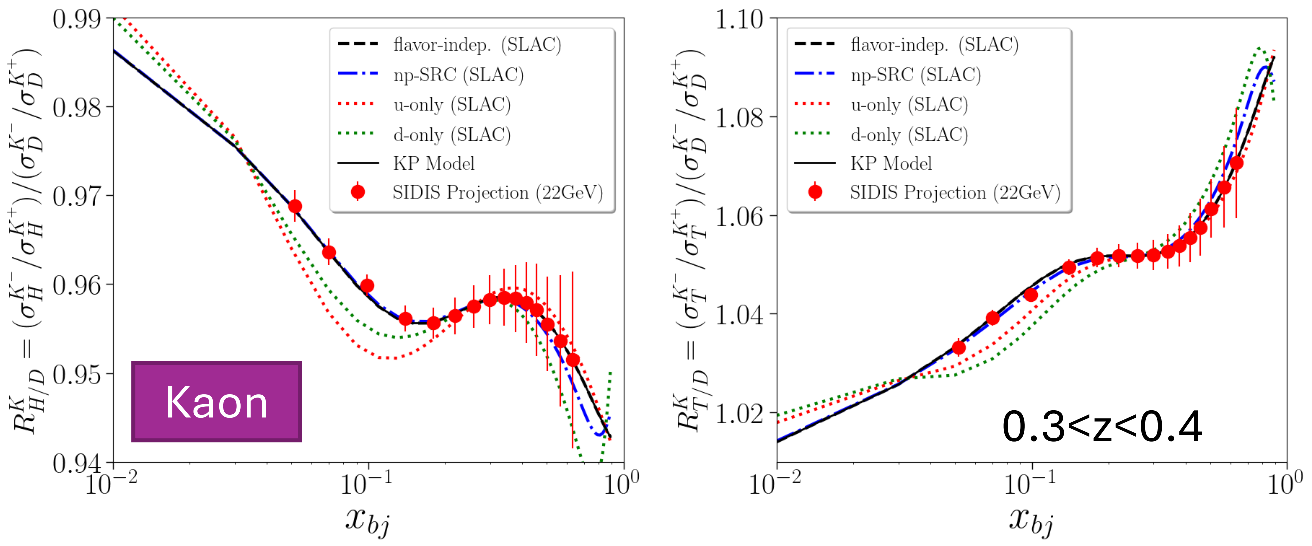
- eA SIDIS w/ mutiple Hadron-Production

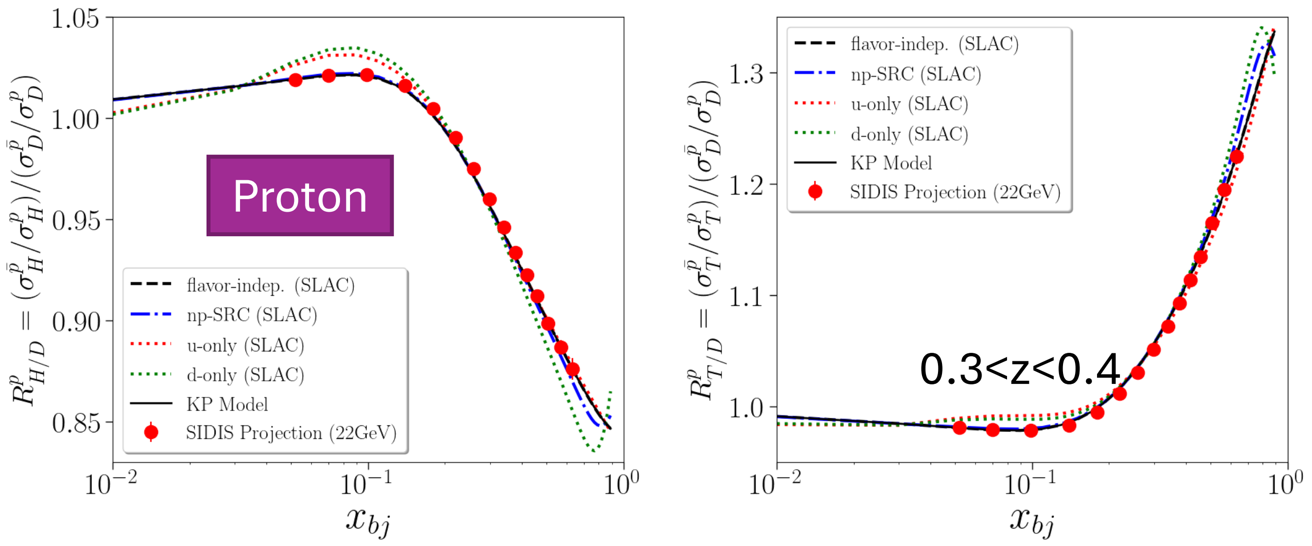
  ❑ Fully decouple flavor-dependent EMC & Antishadowing in A=3

  ❑ To do: implement more theoretical predictions



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





11GeV to 22GeV

- From 1D to 3D?

  - ☐ The SIDIS SF with additional P_T dependence:

Unpolarized TMD

Unpolarized FF

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

  - ☐ 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:
    - ▪ P_T Broadening to Actual distribution → Precision needed!

  - ☐ 4D(Q2, x, z, P_T) SIDIS data off nuclei with multiple hadron states
    - ✓ Decouple P_T distributions for individual flavor
    - ✓ Access unpolarized nTMDs and nFFs
    - ✓ Study Hadron Attenuation in light-nuclei
    - ✓ Medium-modification effects in the transverse directions

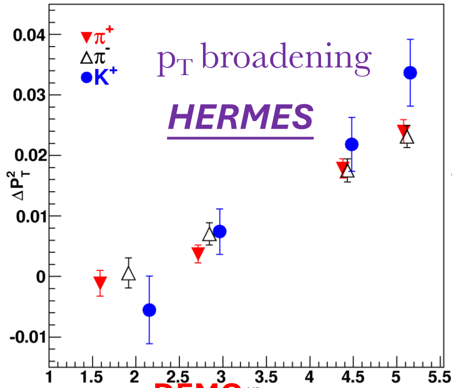
SIDIS with Heavy Nuclei

➢ 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

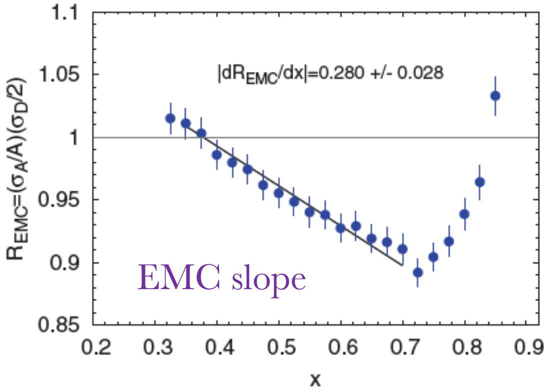
$$B^{h+}_{A/D}(z,p_T) = \frac{M_A^h(z,p_T)}{M_D^h(z,p_T)} = \frac{(N_A^{h+}+N_A^{h-})/N_A}{(N_D^{h+}+N_D^{h-})/N_D}$$

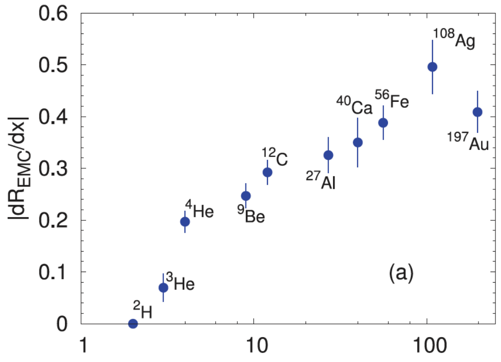
$$R^{h^+ + h^-}_{A/D}(x,z,p_T) = \frac{N_A^{h^+}+N_A^{h^-}}{N_D^{h^+}+N_D^{h^-}} = A^{h+}(x,p_T)\otimes B^{h+}(z,p_T)$$

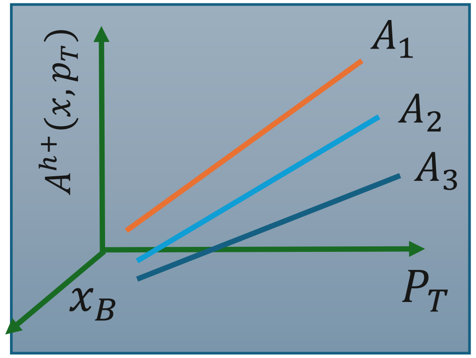


DEMQ-ONLY

- ❖ Look at the p_T dependence (not just broadening)







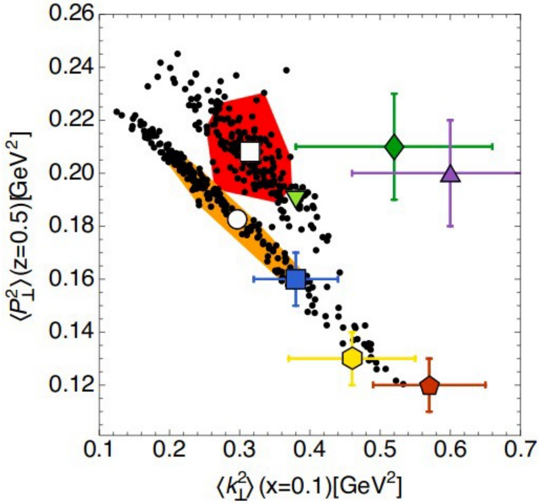
EMC ratio in 2D?

✓ A comprehensive way to study nuclear-effect in QCD

SIDIS with Heavy Nuclei

➢ Nuclear 3D Tomography:

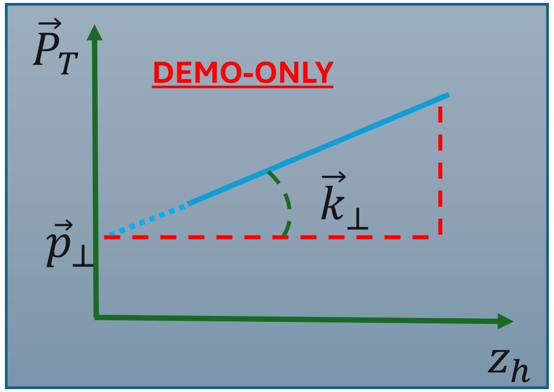
$\langle P_T^2 \rangle = \langle p_\perp^2 \rangle + z_h^2 \langle k_\perp^2 \rangle$



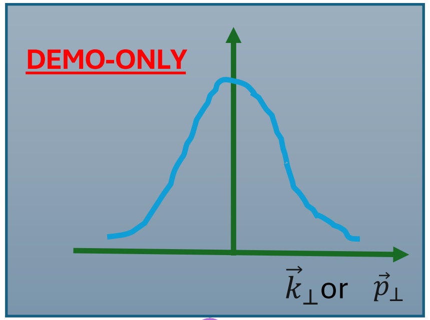
- ❖ Possible to extraction of ***k***$_\perp$ ***and p***$_\perp$ distributions:

$\vec{P}_T = \vec{p}_\perp + z_h \vec{k}_\perp + O(\frac{k_\perp^2}{Q^2})$, not 100% correct in full QCD but roughly hold

- ✓ Extrapolation to z_h→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?



THANKS!

清華大學
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