Where are we in understanding parton distributions from the first principles?

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EIC + LaMET

The timing is just right to tackle the problem of hadron and nuclear structures.

LaMET

- Computing quasi-PDF with equal time quark bilnear matrix elements for proton states with large momenta

$$\widetilde{q}(x,\mu^2,P^z) \;\; = \;\; \int \frac{dz}{4\pi} e^{-ixzP^z} \left\langle P \left| \overline{\psi}(0)\lambda\cdot\gamma\Gamma\psi(z\lambda) \right| P \right\rangle$$

$$\lambda^\mu = (0,0,0,1)$$

- Factorization theorem: analogous to HQET: need power corrections & matching

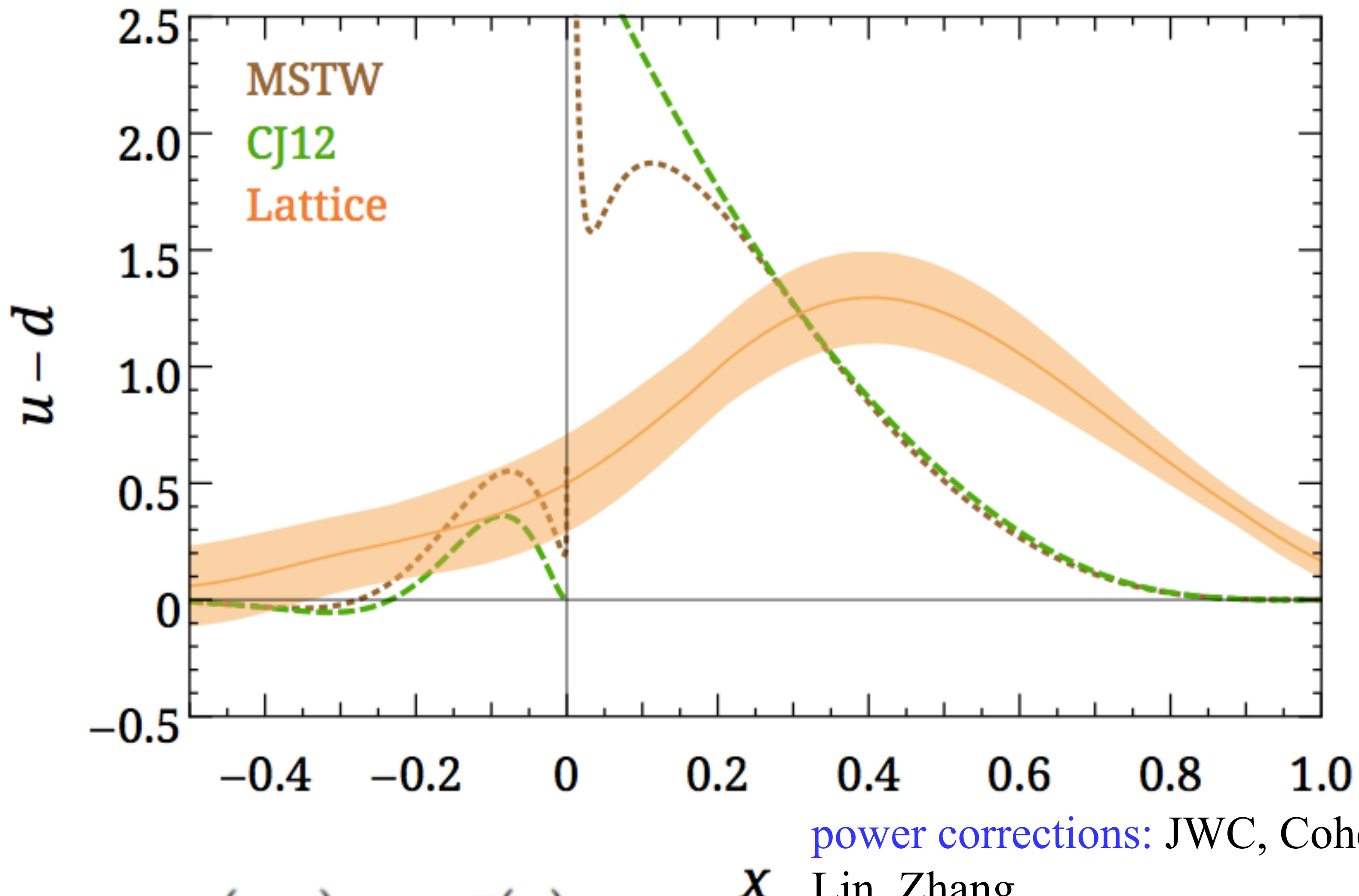
UV, PQCD

$$\tilde{q}(x,\Lambda,P_z) = \int \frac{dy}{|y|} Z\left(\frac{x}{y},\frac{\mu}{P_z},\frac{\Lambda}{P_z}\right) q(y,\mu) + \mathcal{O}\left(\frac{\Lambda^2_{\rm QCD}}{P_z^2},\frac{M^2}{P_z^2}\right) + \ldots .$$

LaMET 1.0

Proton Unpolarized PDF

LP3 (1402.1462)



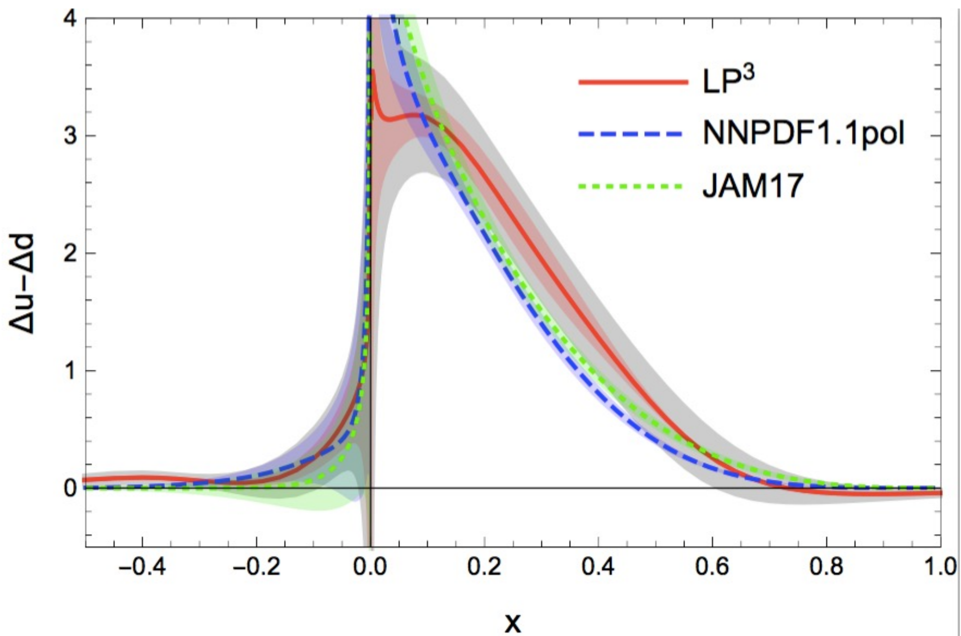
$q(-x) = -\bar{q}(x)$

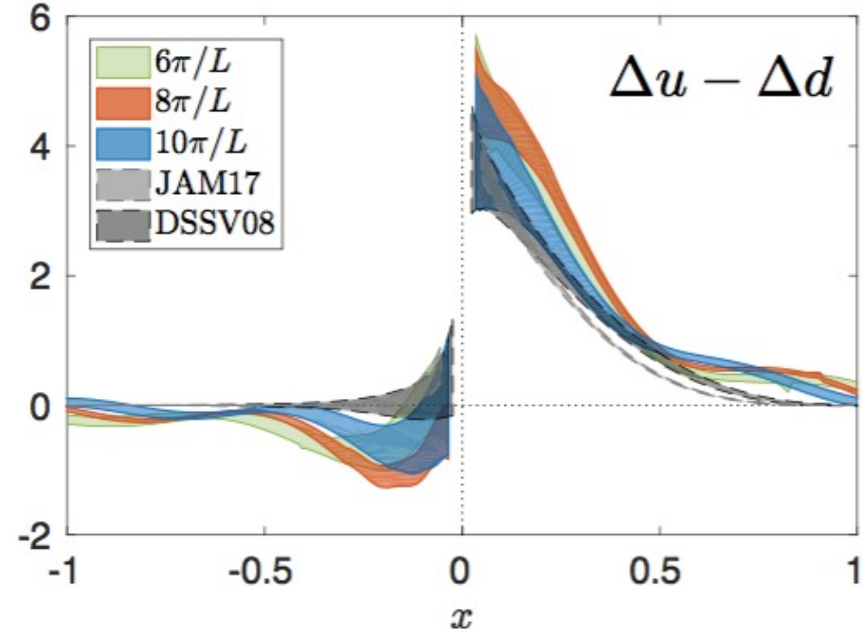
power corrections: JWC, Cohen, Ji, Lin, Zhang

matching: Xiong, Ji, Zhang, Zhao

LaMET 2.0

Proton Helicity PDF

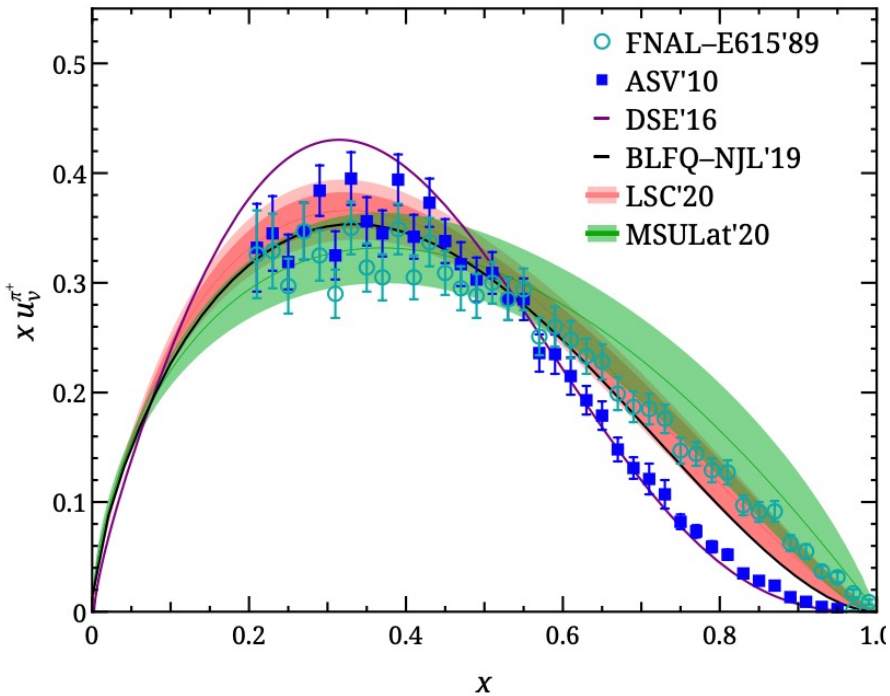


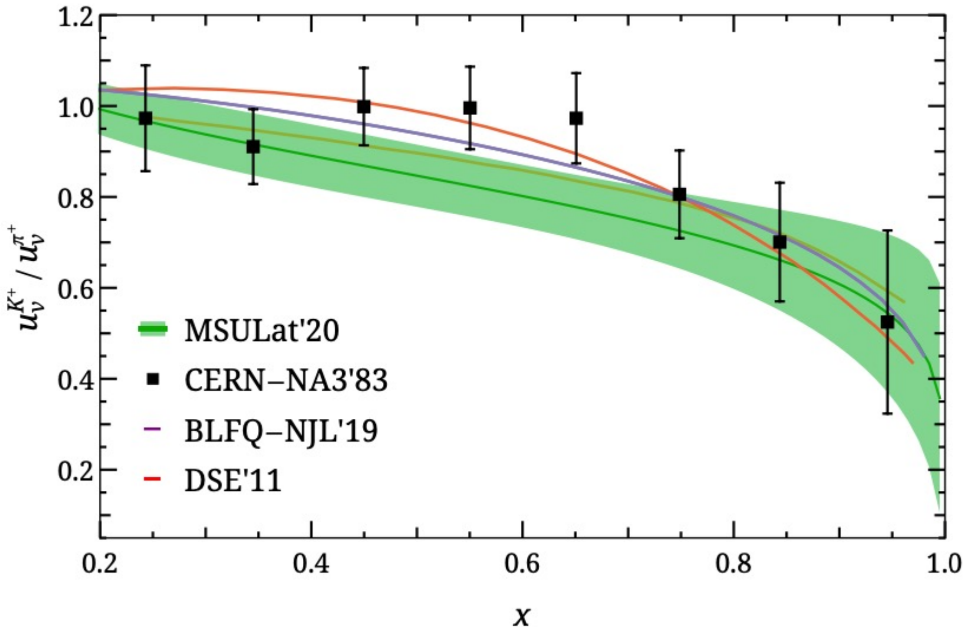


LP3(1807.07431,PRL) ETMC(1803.02685,PRL)

Momentum smearing: Bali, Lang, Musch, Schafer
Factorization: Ma, Qiu; Izubuchi, Ji, Jin, Stewart, Zhao
Wilson line mass subtraction: JWC, Ji, Zhang
LPT: Ishikawa, Ma, Qiu, Yoshida; Xiong, Luu, Meissner; Constantinou et al.
Multiplicative renormalizability: Ji, Zhang, Zhao
NPR: RI/MOM: Yong, Stewart; Constantinou et al.; Ratio: Radyushkin

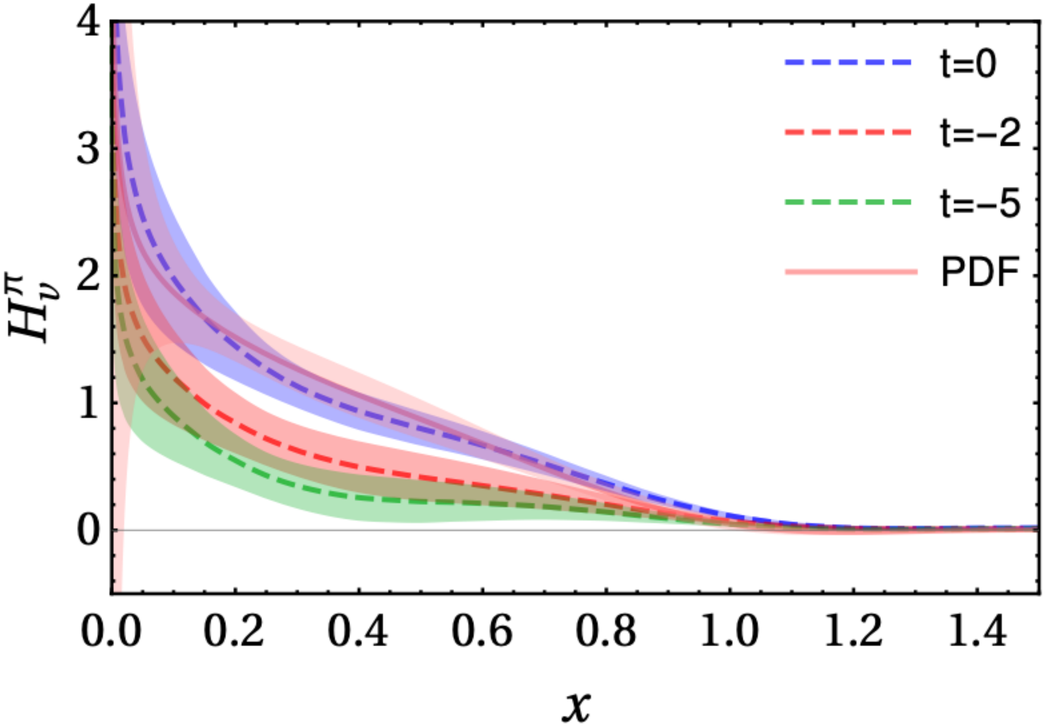
Meson Valence Quark Distributions





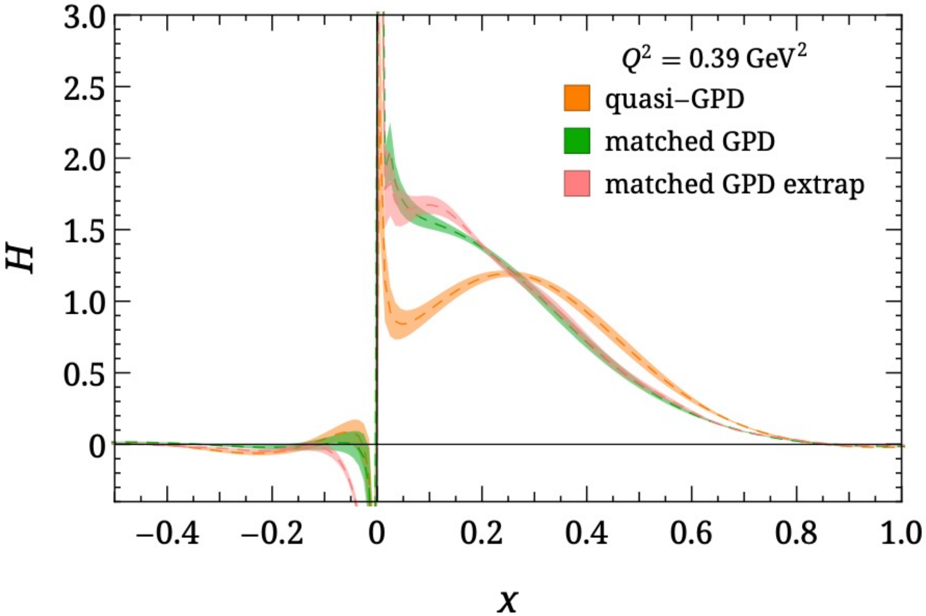
HW Lin, JWC, Z Fan, JH Zhang, R Zhang (2003.14128)

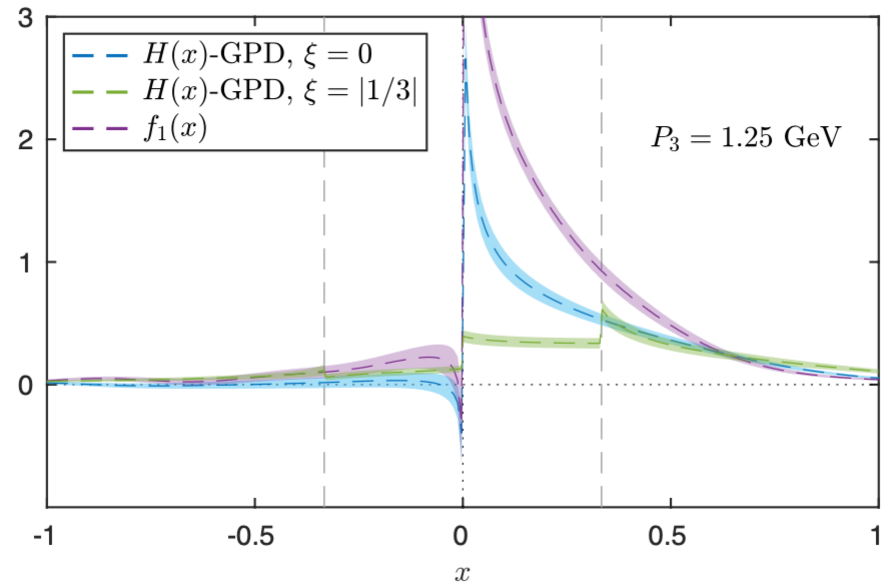
Pion Skewless Valance GPD



JWC, HW Lin, JH Zhang (1904.12376)

Nucleon GPD at Physical Pion Mass



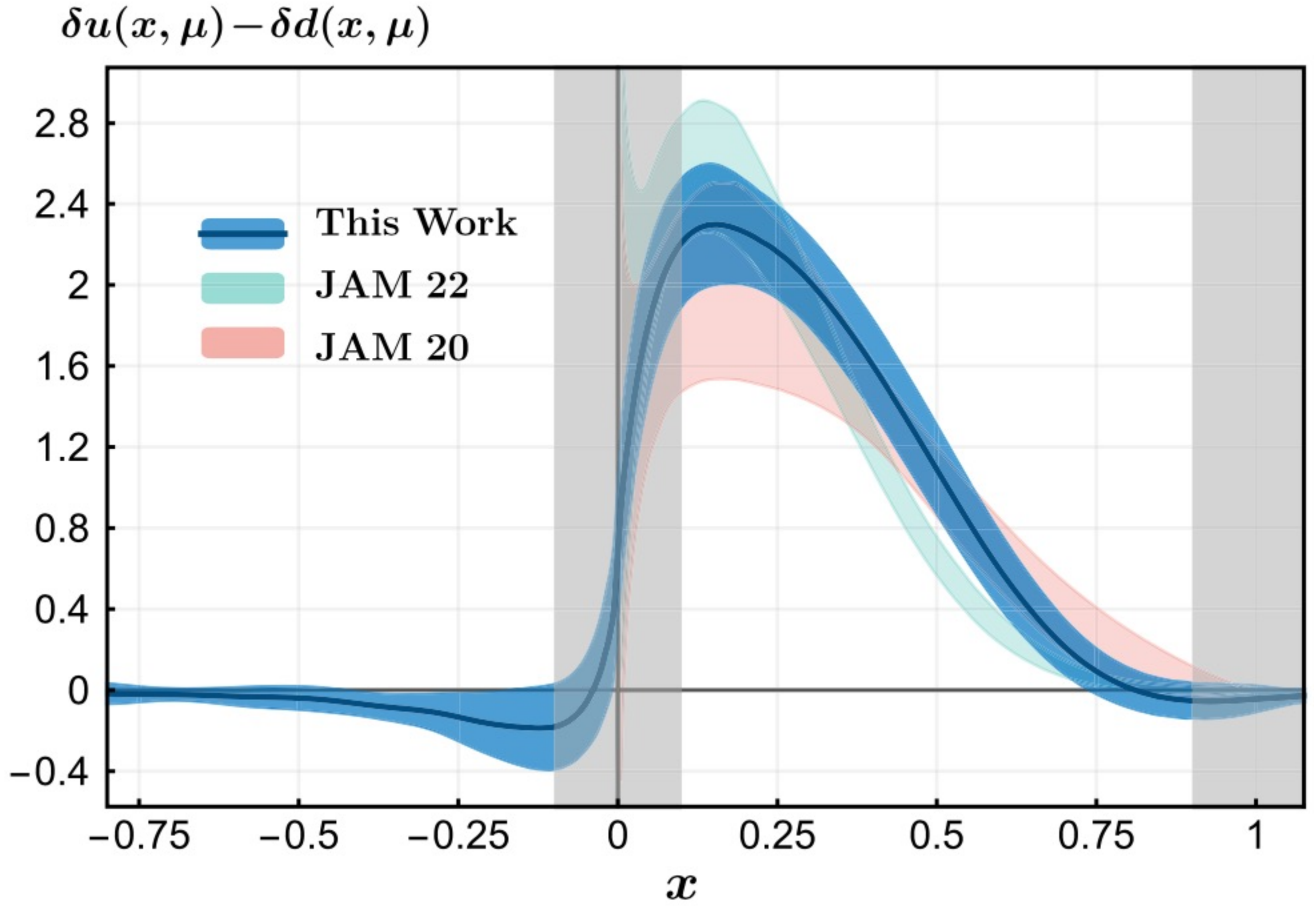


HW Lin (2008.12474, PRL)
M_pi =140 MeV

ETMC (2008.10573, PRL)
M_pi = 260 MeV

LaMET 3.0

Proton Transversity PDF in the Continuum and Physical Mass Limit

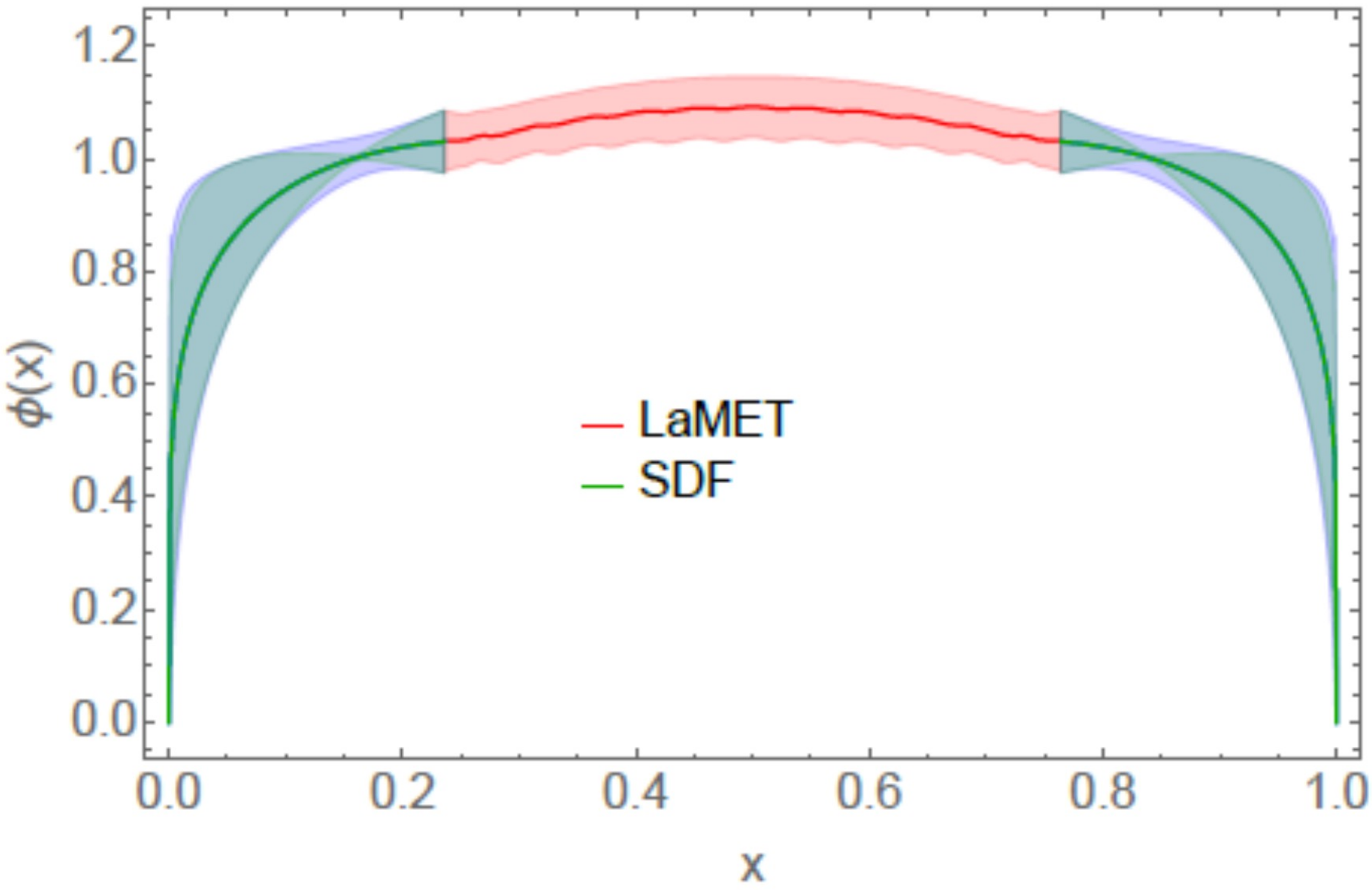


Yao, Walter, JWC, et al. (LPC), PRL 2023

Renormalon: Braun, Vladimirov, Zhang

Hybrid renormalization: Ji, Liu, Schäfer, Wang, Yang, Zhang, Zhao

Pion Distribution Amplitude

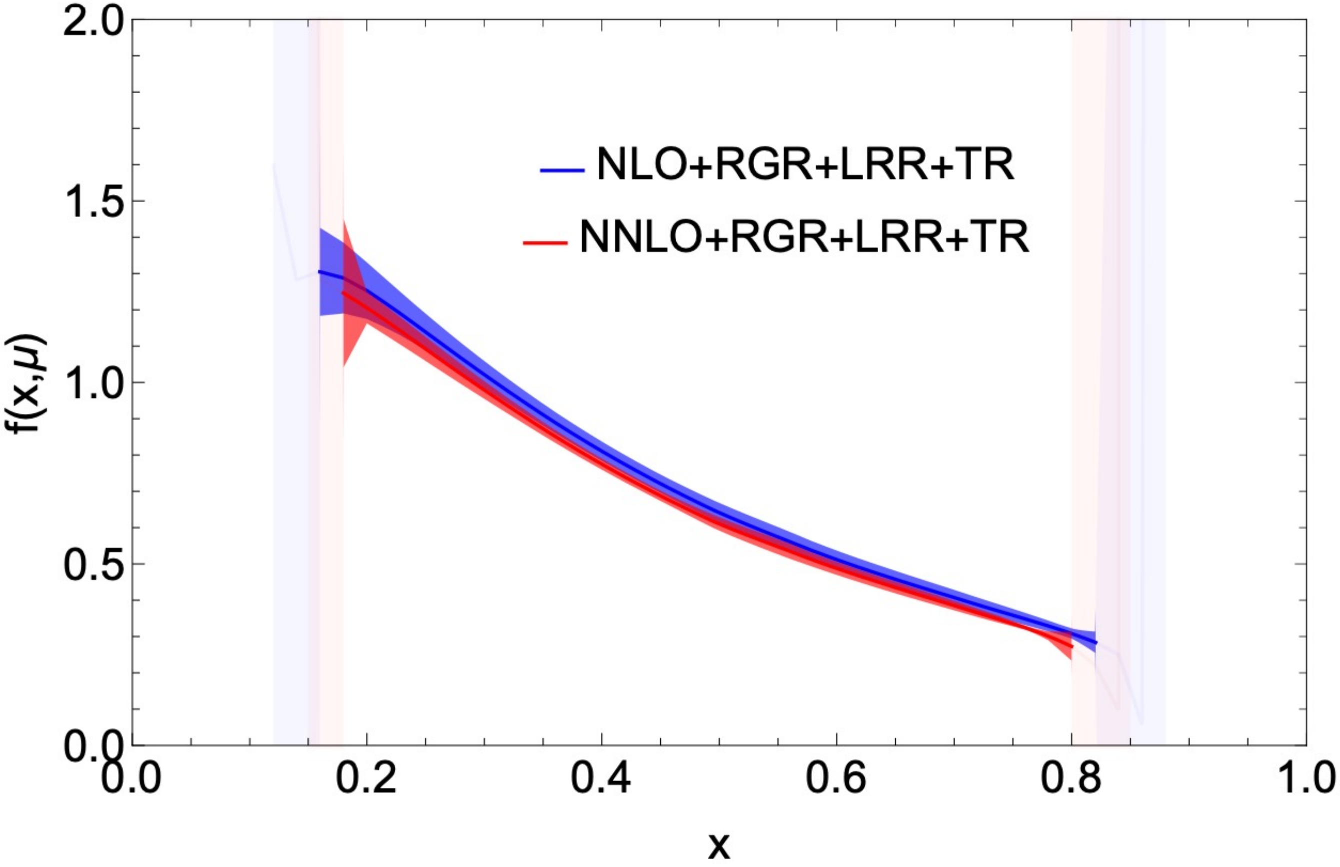


J. Holligan et al 2301.10372

Most recent developments

- Precision frontier: NNLO matching, Resummations, no Wilson line, Lanczos (D. Hackett, M. Wagman), high precision gauge fixing (YB Yang)
- Higher dimensional frontier: TMD, GPD
- Flavor frontier? gluon, u+d, s, c, b(?)

Resummations



Xiangdong Ji, Yizhuang Liu, Yushan Su, Rui Zhang (2410.12910)

NNLO kernel: ZY Li, YQ Ma, JW.Qiu; LB Chen, W Wang, R Zhu

Resummations: RGR: ln(x) powers; TR: ln(1-x) powers; LRR: leading renormalon

Nuclear Parton Distributions?

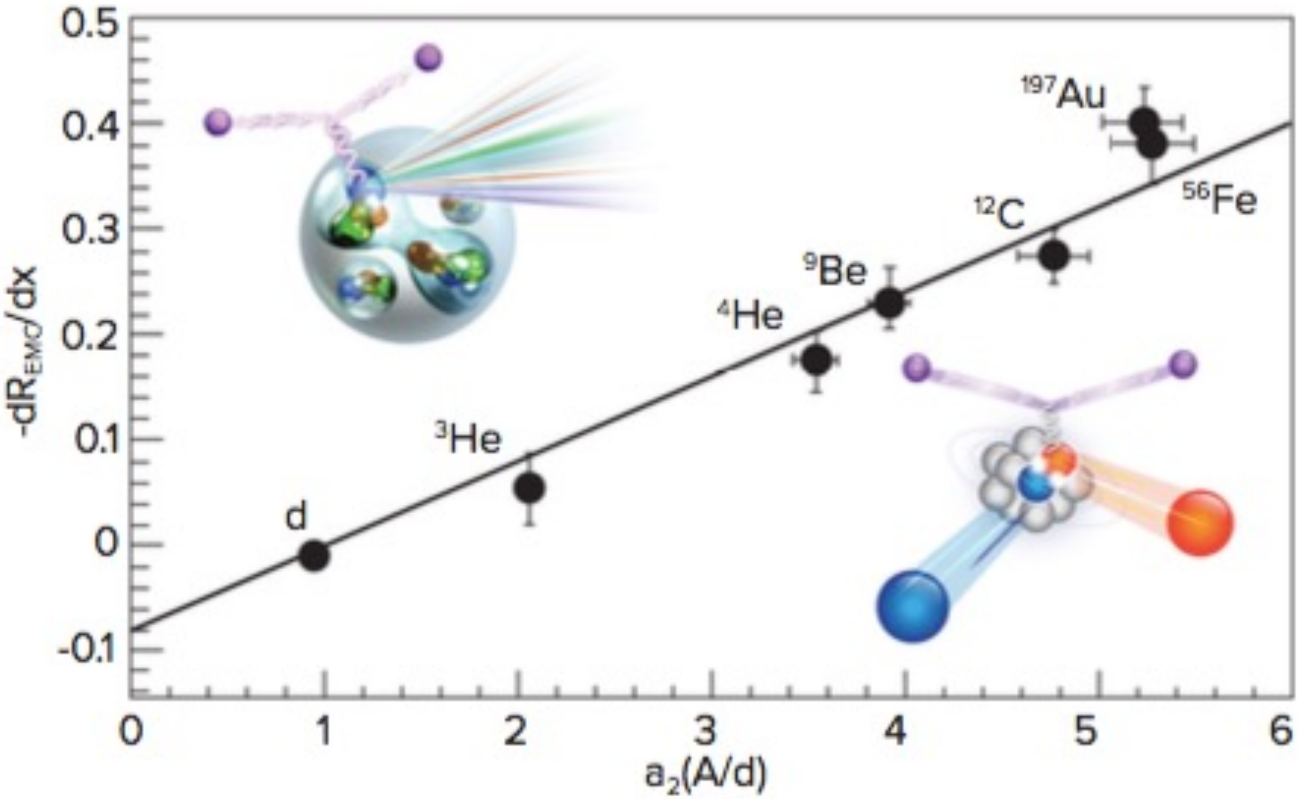
EMC/SRC Connections in EFT & QCD

w/ William Detmold, hep-ph/0412119, Phys.Lett. B625 (2005) 165

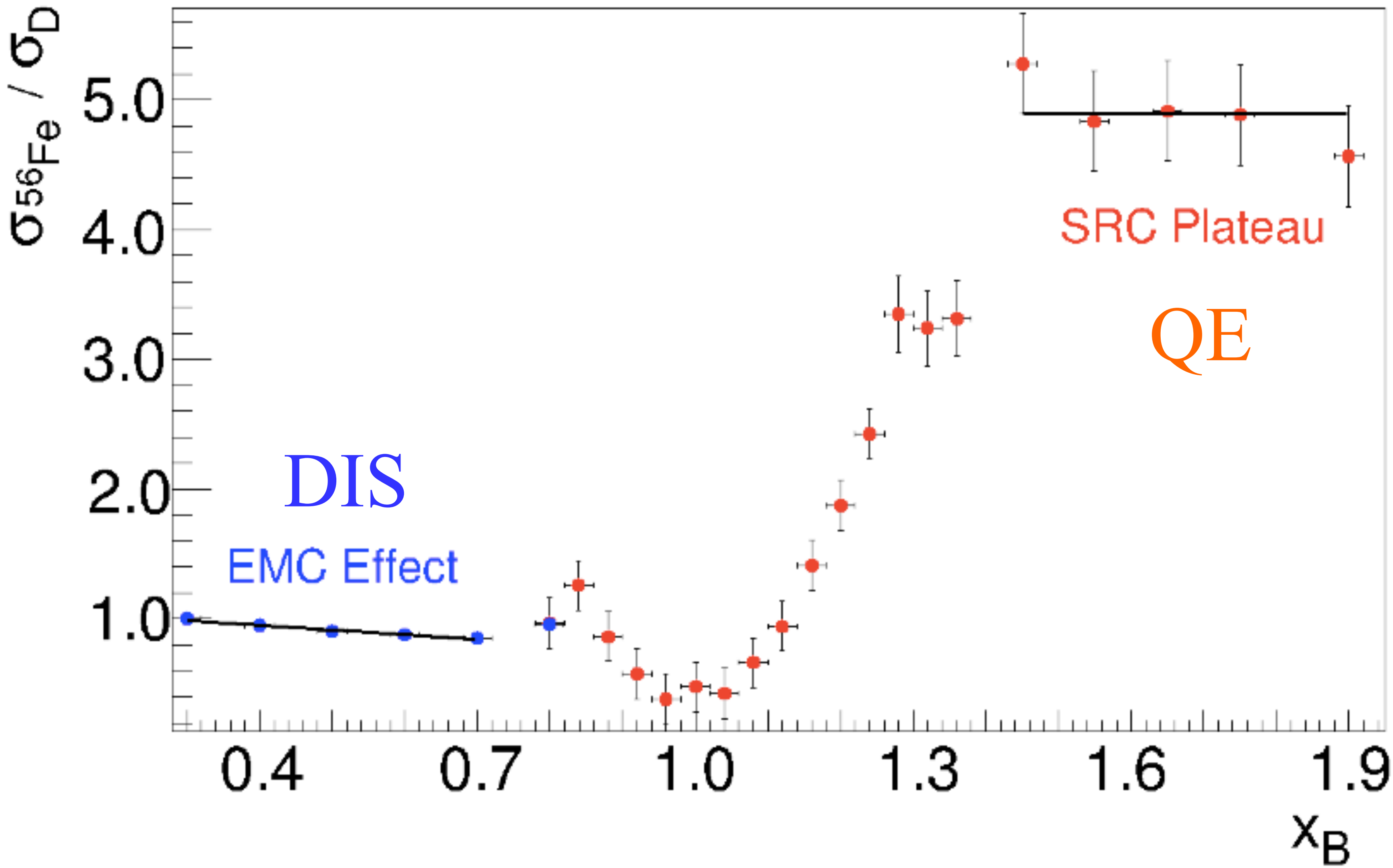
w/ William Detmold, Joel E. Lynn, Achim Schwenk,1607.03065, Phys. Rev. Lett. 119 (2017) 262502

w/ Lynn, Lonardoni, Carlson, Detmold, Gandolfi, Schwenk, J.Phys.G 47 (2020) 045109

An Astonishing Empirical Result!

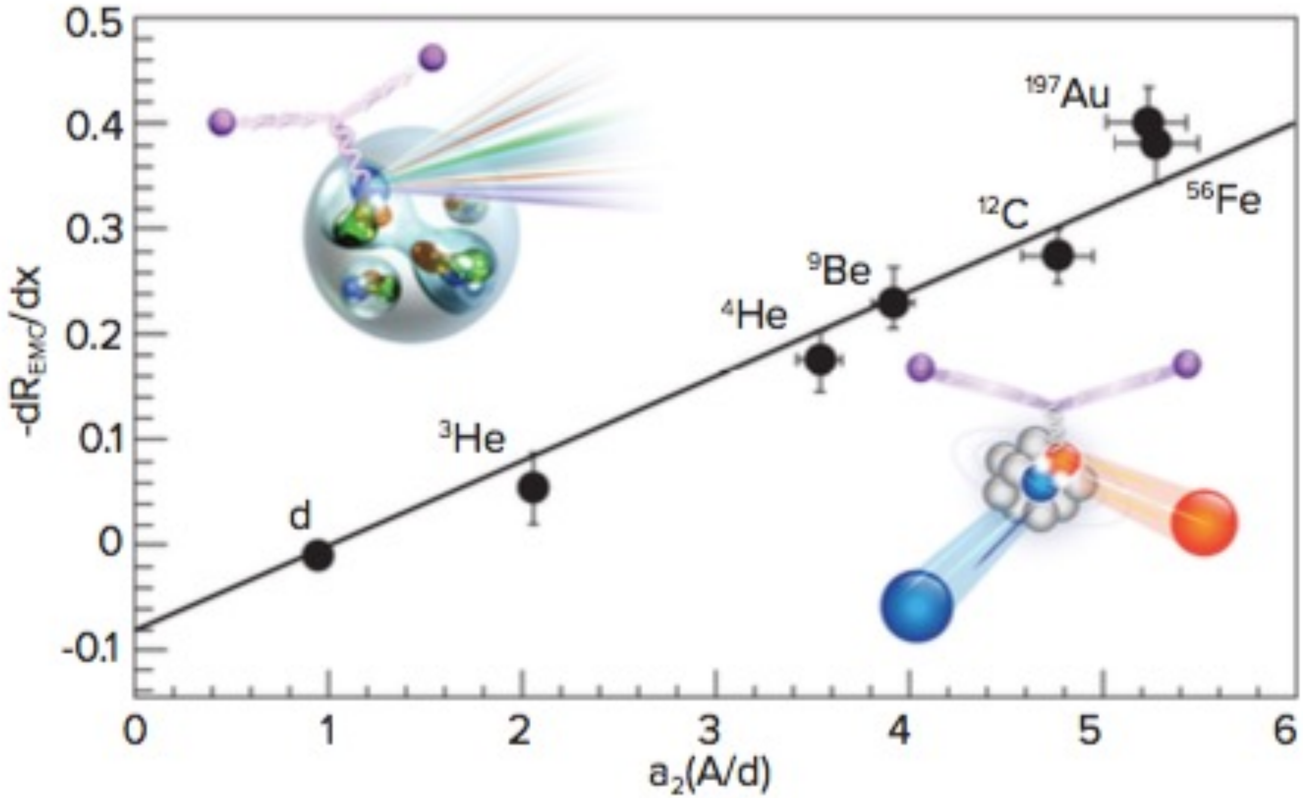


Weinstein et al., Phys. Rev. Lett.106, 052301 (2011)



Higinbotham, Miller, Hen, Rith, CERN Cour. 53N4 (2013) 24

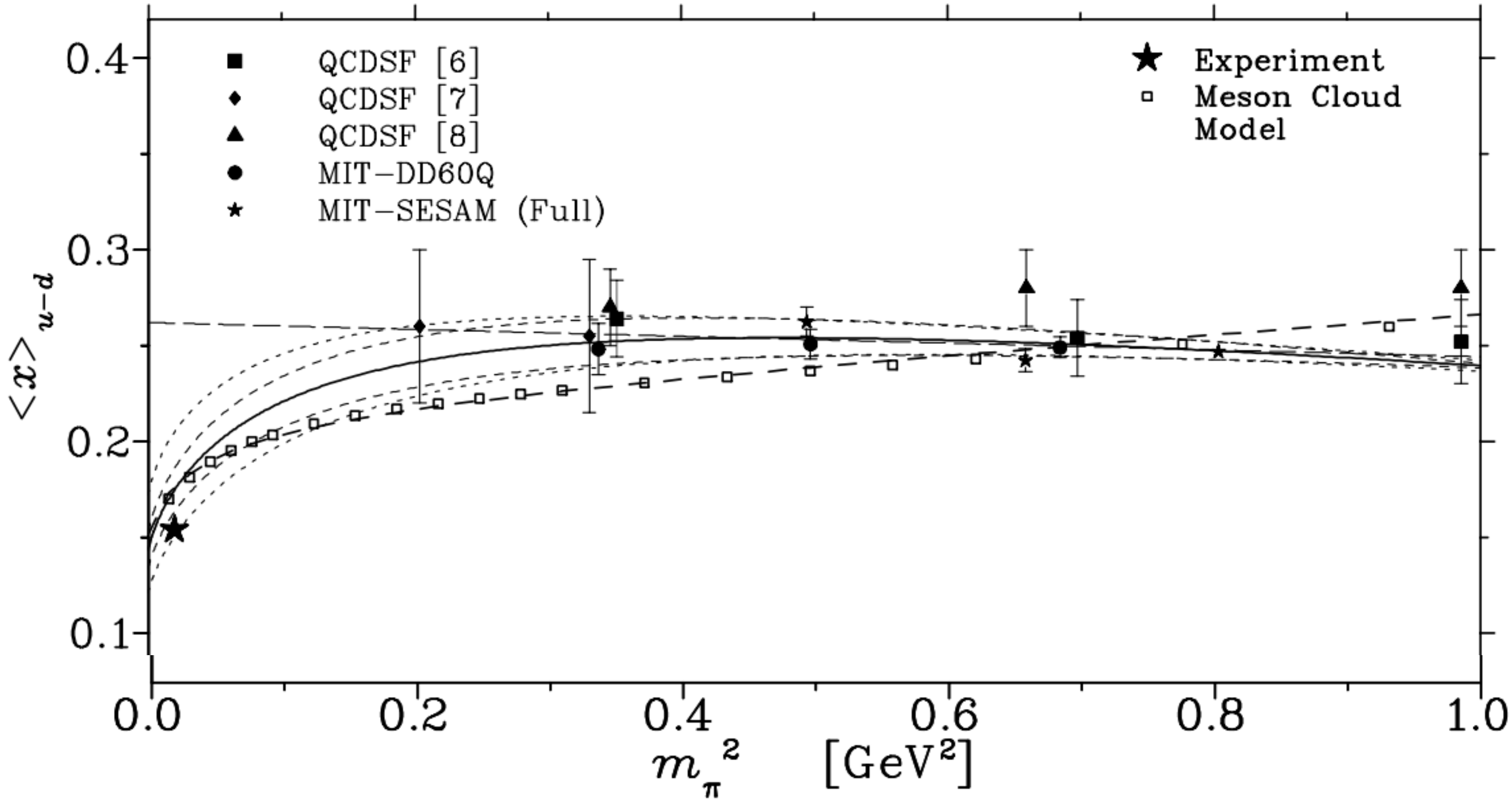
Promises from EFT



- EMC-SRC linear relation reproduced
- Some a_2 reproduced ab initioly
- Remaining problem: EMC slope from LQCD (only need deuteron)

No free parameters involved!

Lattice Moments (Local Twist-2 Matrix Elements) in LQCD



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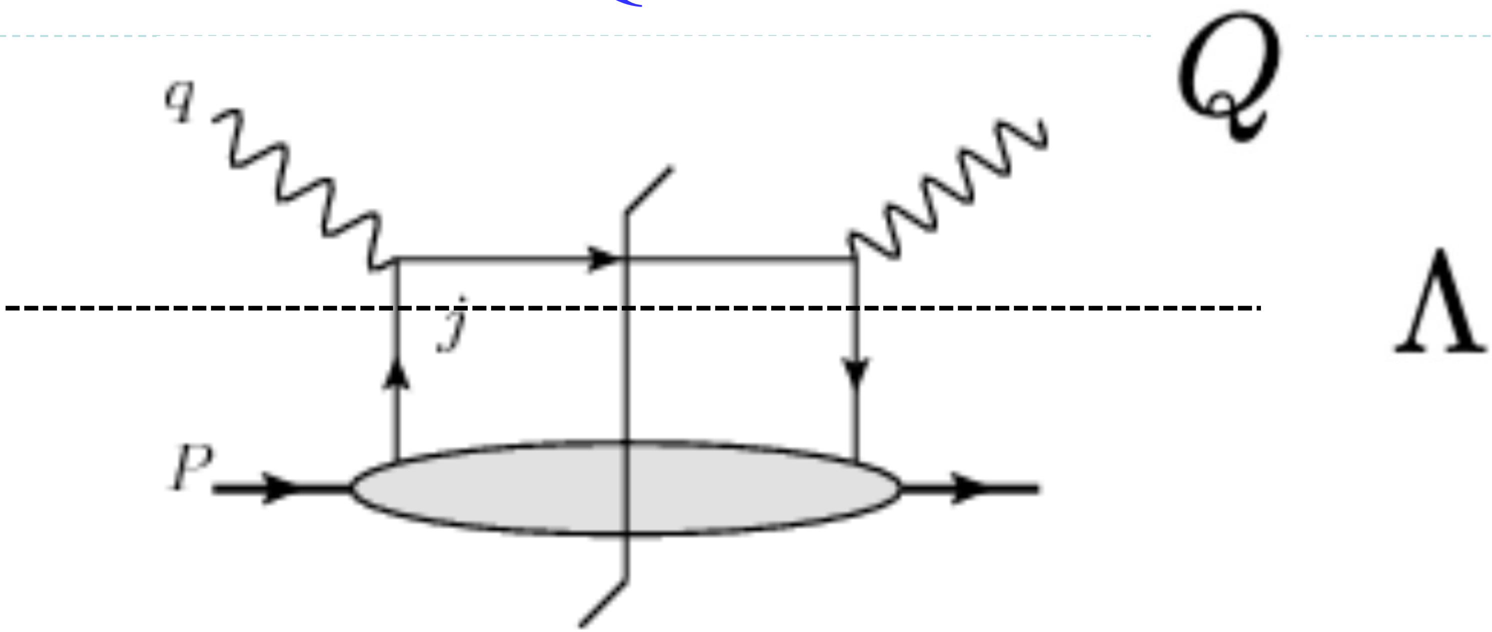
Detmold, Melnitchouk, Negele, Renner,Thomas, Phys.Rev.Lett.87:172001,2001

Parton Distribution Function (PDF) in QCD



The struck parton moves on a light cone at the leading order in the twist-expansion:

$$\Lambda/Q \ll 1$$

Further Separate the Pion Mass Scale

$$Q \gg \Lambda \gg P \sim m_\pi$$

- Double expansion:
  Twist expansion in Λ/Q (PQCD)
  Chiral expansion in $\epsilon \sim P/\Lambda \sim 0.2-0.3$ (ChPT)

JWC, Ji, Phys. Lett. B523 (2001) 107
Phys.Rev.Lett. 87 (2001) 152002
Phys.Rev.Lett. 88 (2002) 052003
JWC, Stewart, Phys.Rev.Lett. 92 (2004) 202001
Arndt, Savage, Nucl.Phys. A697 (2002) 429

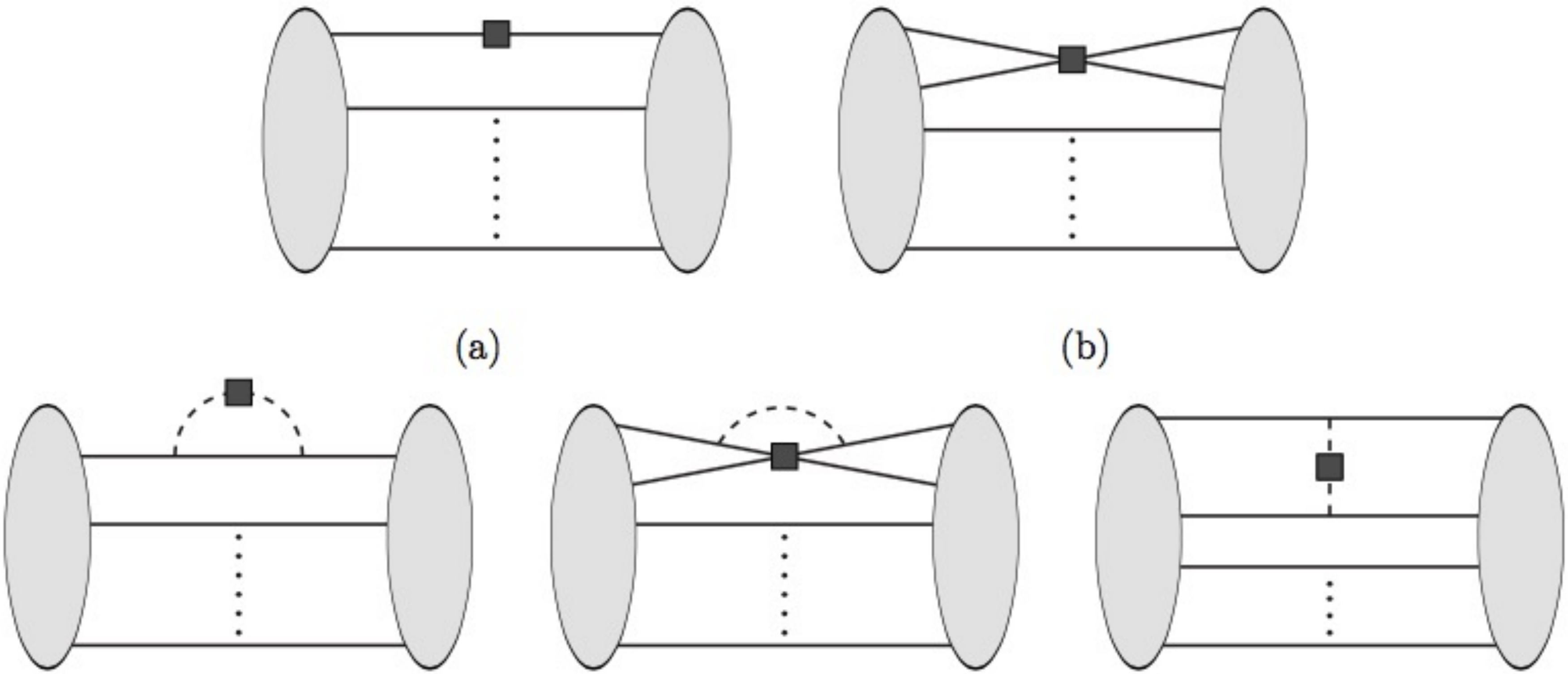
EMC Effect in EFT (JWC, Detmold, 2005)

Twist-2 operator matching (isoscalar):

$$\mathcal{O}^{\mu_0 \cdots \mu_n} = \bar{q}\gamma^{(\mu_0} iD^{\mu_1} \cdots iD^{\mu_n)} q,$$

$$\mathcal{O}^{\mu_0 \cdots \mu_n} \to \langle x^n \rangle_N M^n v^{(\mu_0} \cdots v^{\mu_n)} N^\dagger N \left[1 + \alpha_n N^\dagger N\right]$$
$$+ \langle x^n \rangle_\pi \pi^\alpha i\partial^{(\mu_0} \cdots i\partial^{\mu_n)} \pi^\alpha + \ldots,$$

Using large Nc counting



(a) (b) (c) (d) (e)

$$g_2(A,\Lambda) = \frac{1}{A}\langle A|\left(N^\dagger N\right)^2|A\rangle_\Lambda,$$

Factorization
Implies prediction power!

$$q_A(x)/A = q_N(x) + g_2(A,\Lambda)\tilde{q}_2(x,\Lambda)$$

1-body op. 2-body op. determined by deuteron

EFT predicts EMC $R_A(x) - 1 = f(A)\phi(x$

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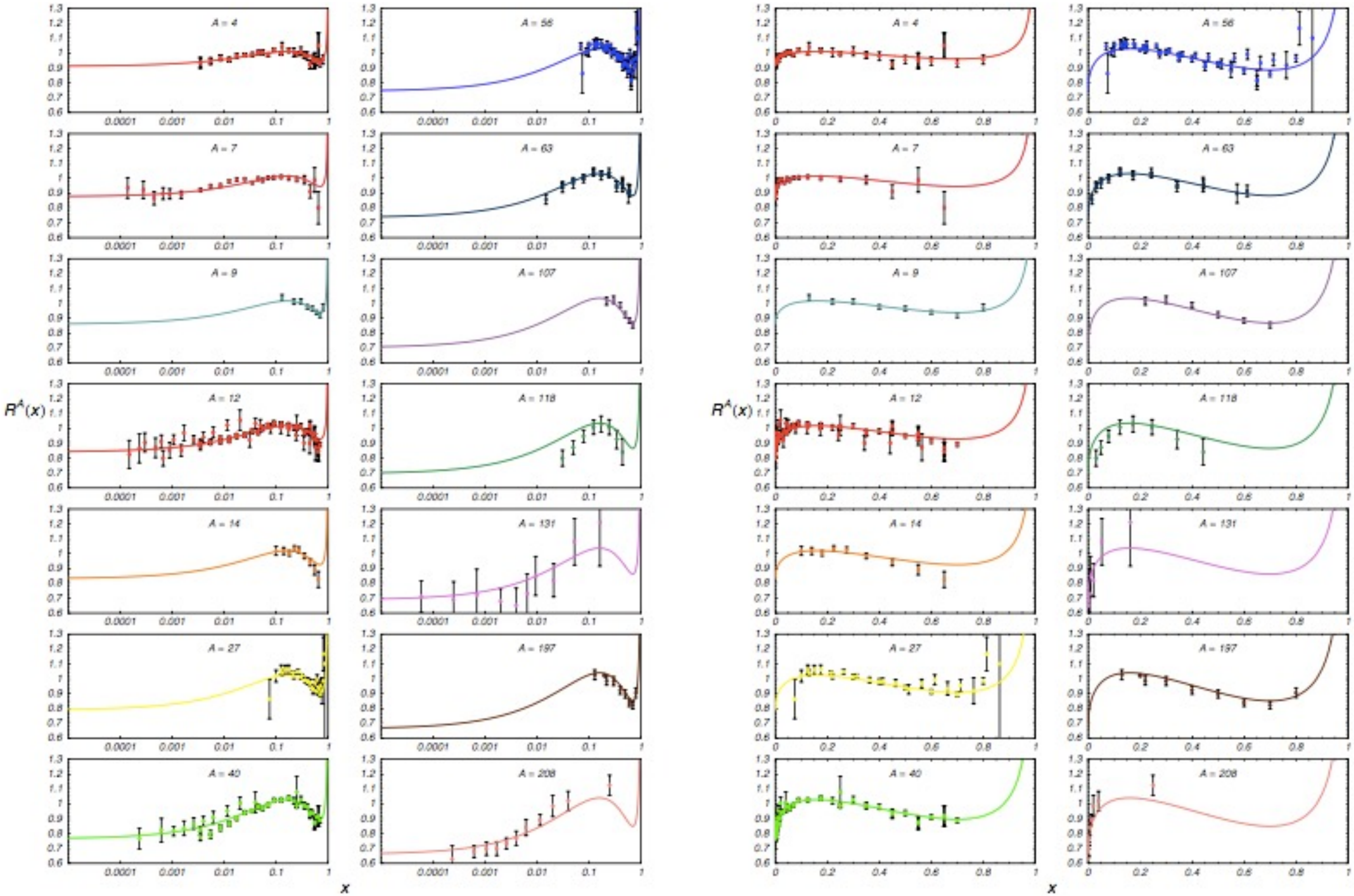
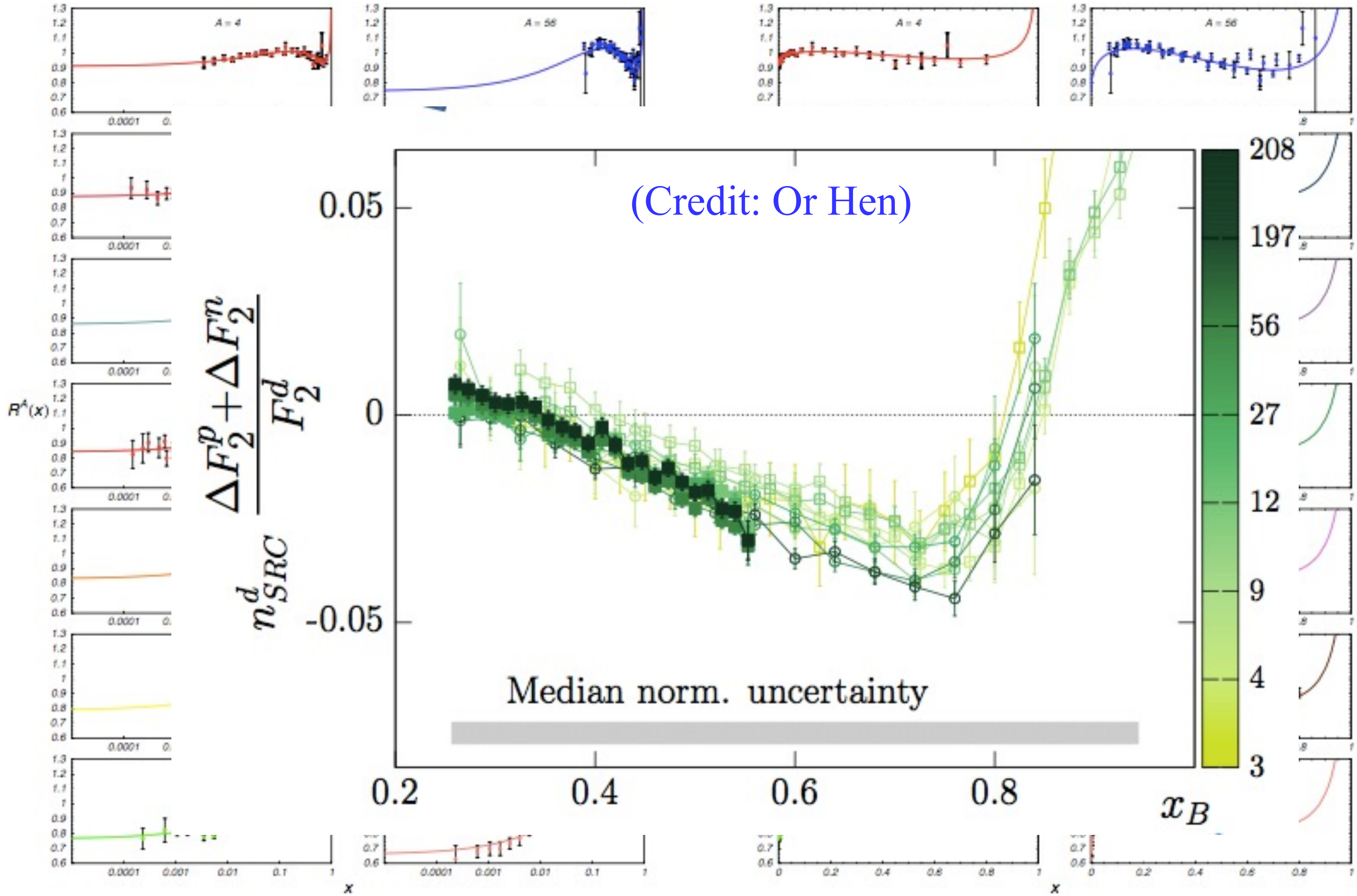
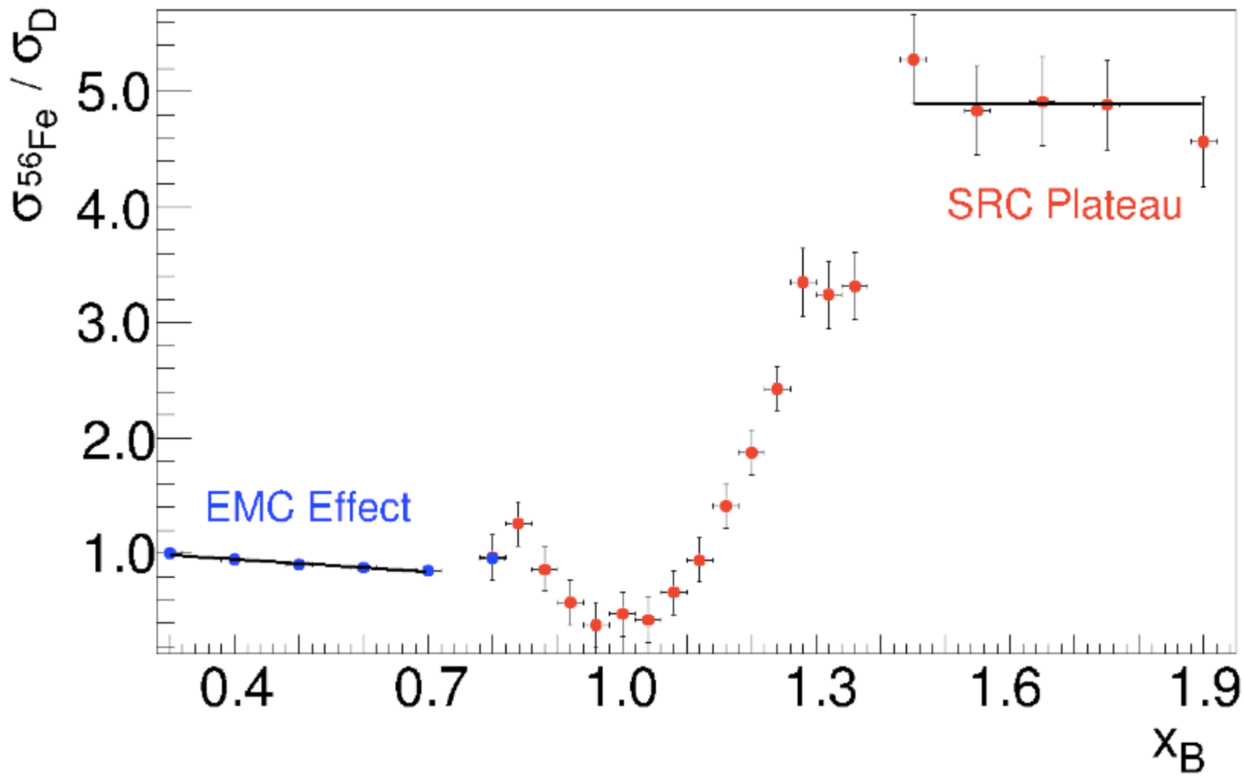


EFT predicts EMC $R_A(x) - 1 = f(A)\phi(x)$



SRC scaling factor (same in QE)



$$q_A(x)/A = q_N(x) + g_2(A,\Lambda)\tilde{q}_2(x,\Lambda) \qquad q_N(x>1)=0$$

Indept of scheme & scale!

$$a_2(A, x>1) = \frac{2q_A(x)}{Aq_d(x)} = \frac{g_2(A,\Lambda)\tilde{q}_2(x,\Lambda)}{g_2(2,\Lambda)\tilde{q}_2(x,\Lambda)} = \frac{g_2(A,\Lambda)}{g_2(2,\Lambda)}$$

a_2: scheme and scale independent

Ratio of LOW energy quantities:

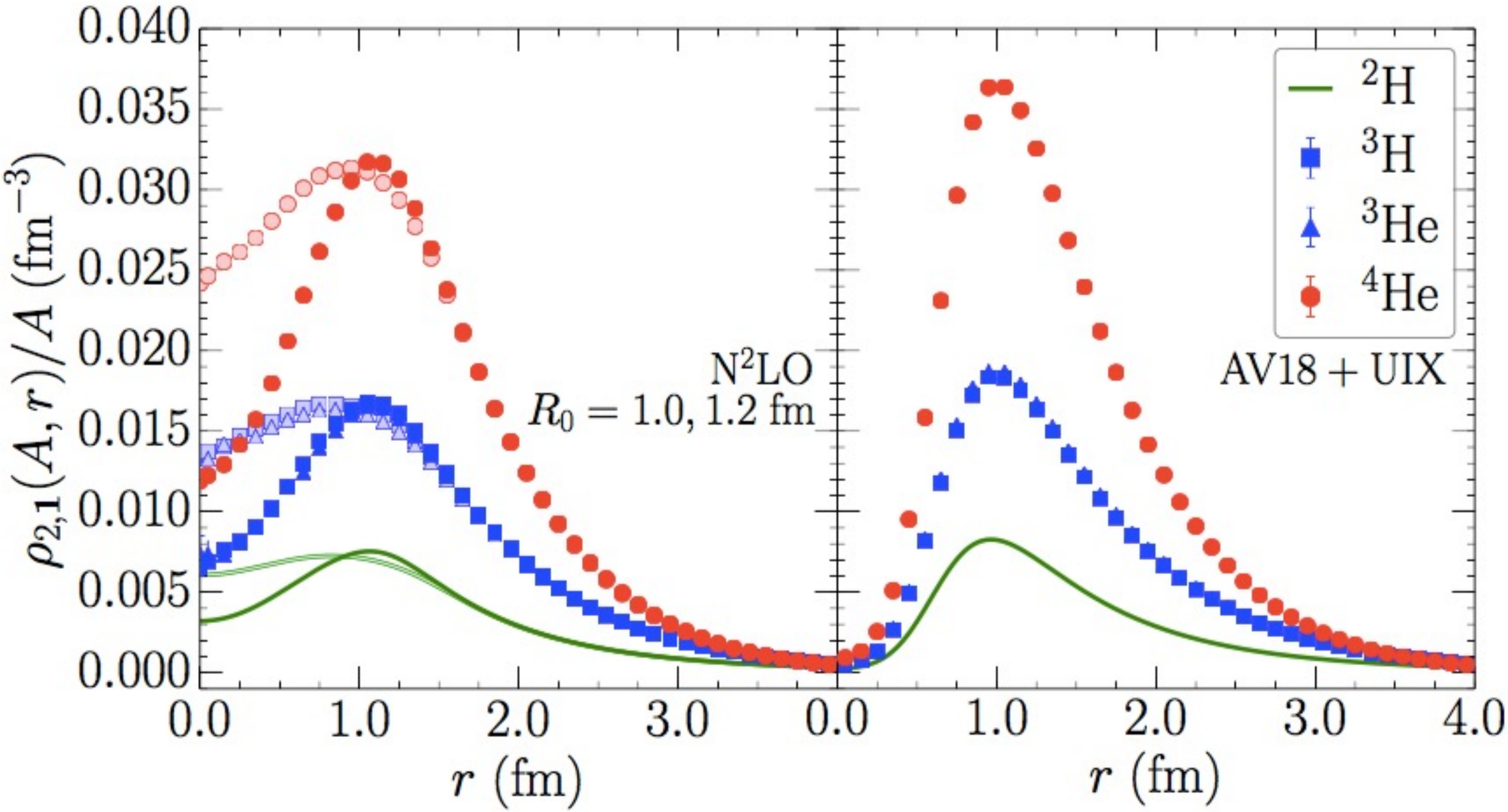
$$a_2(A, x > 1) = \frac{g_2(A, \Lambda)}{g_2(2, \Lambda)}.$$

$$g_2(A, \Lambda) = \frac{1}{A} \langle A | \left(N^\dagger N\right)^2 | A \rangle_\Lambda,$$

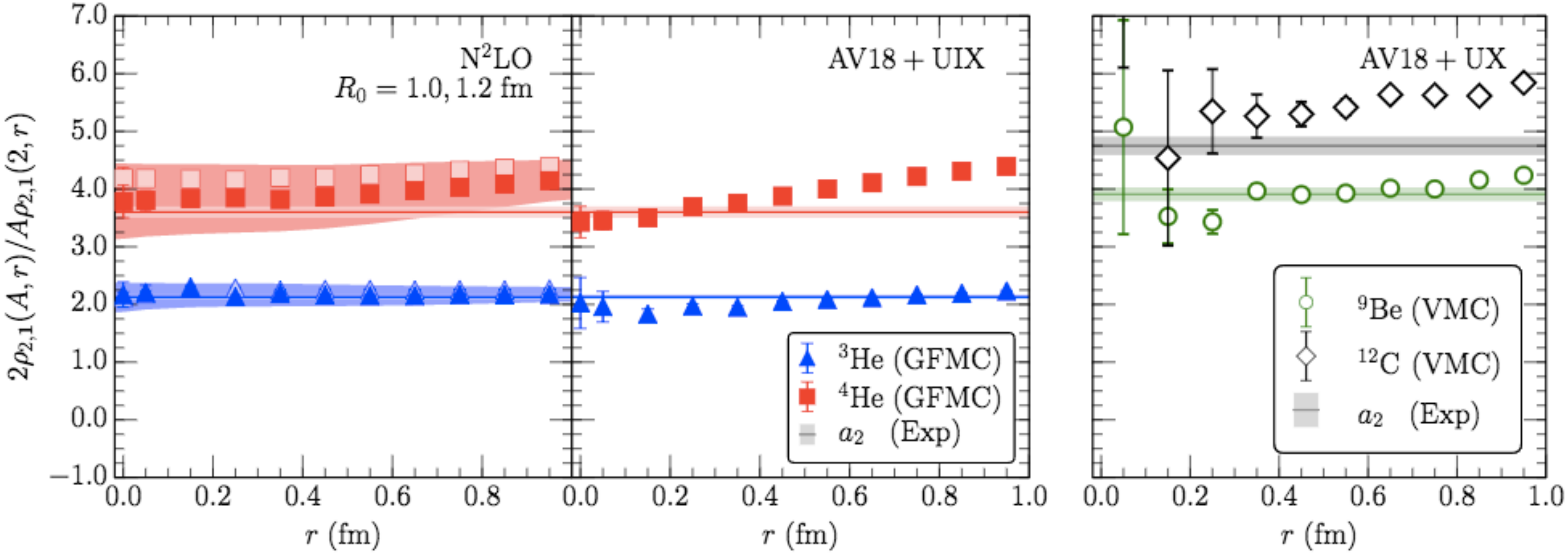
$$= \rho_{2,\mathbf{1}}(A, r = 0)/A$$

$$\rho_{2,\mathbf{1}}(A, r) = \frac{1}{4\pi r^2} \left\langle \Psi_0 \middle| \sum_{i<j}^{A} \delta(r - |\mathbf{r}_i - \mathbf{r}_j|) \middle| \Psi_0 \right\rangle$$

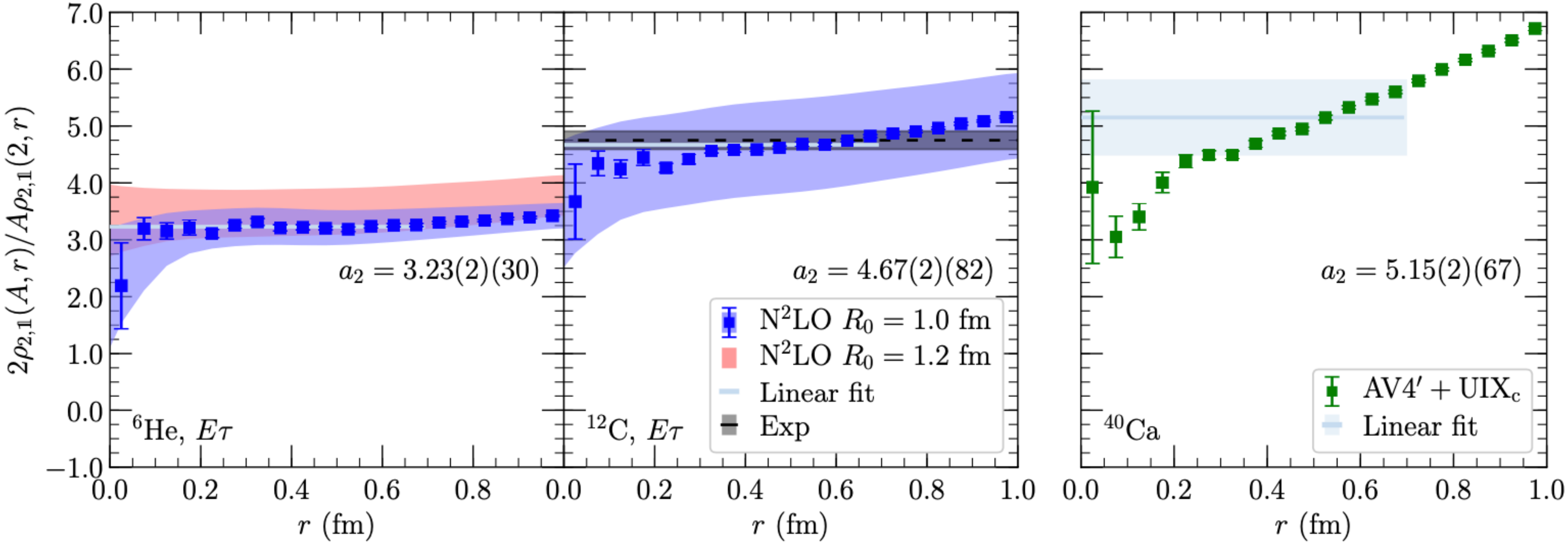
$\rho_{2,1}(A,r)/A$: scheme and scale DEPENDENT



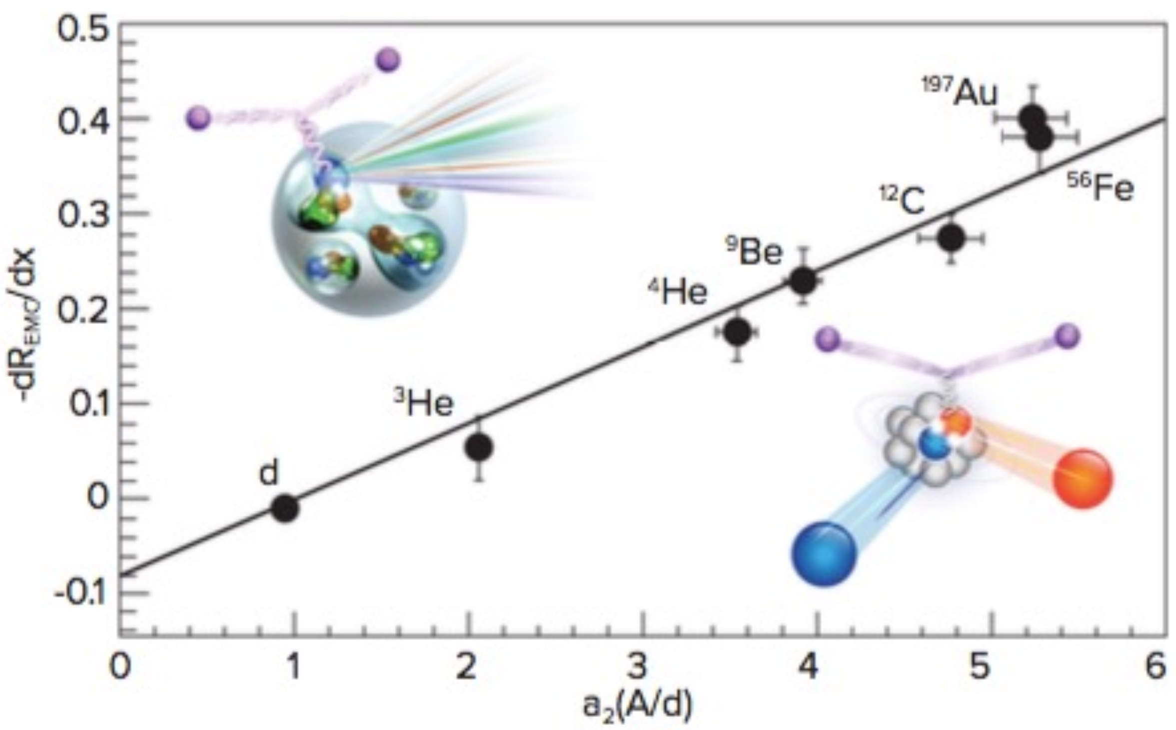
a_2: scheme and scale independent



a_2: scheme and scale independent



Towards a parameter free understanding



- EMC-SRC linear relation reproduced
- Some a_2 reproduced ab initioly
  - Remaining problem: EMC slope from LQCD (only need deuteron) ⇒ LaMET!

- EMC-SRC linear relation: a simple and elegant empirical result, might one day be explained in first principles (QCD and its EFT) with no free parameter!

- Possible applications:

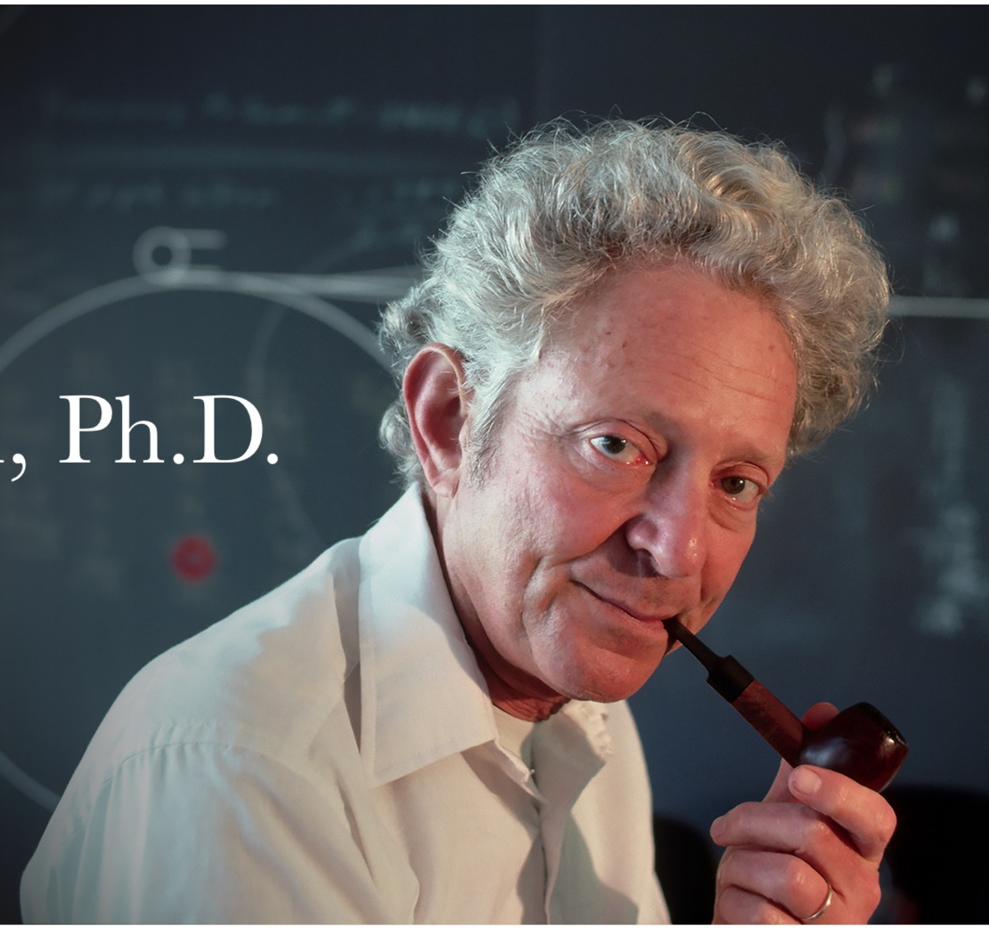
(a) ν-A inclusive scattering for long baseline exp.

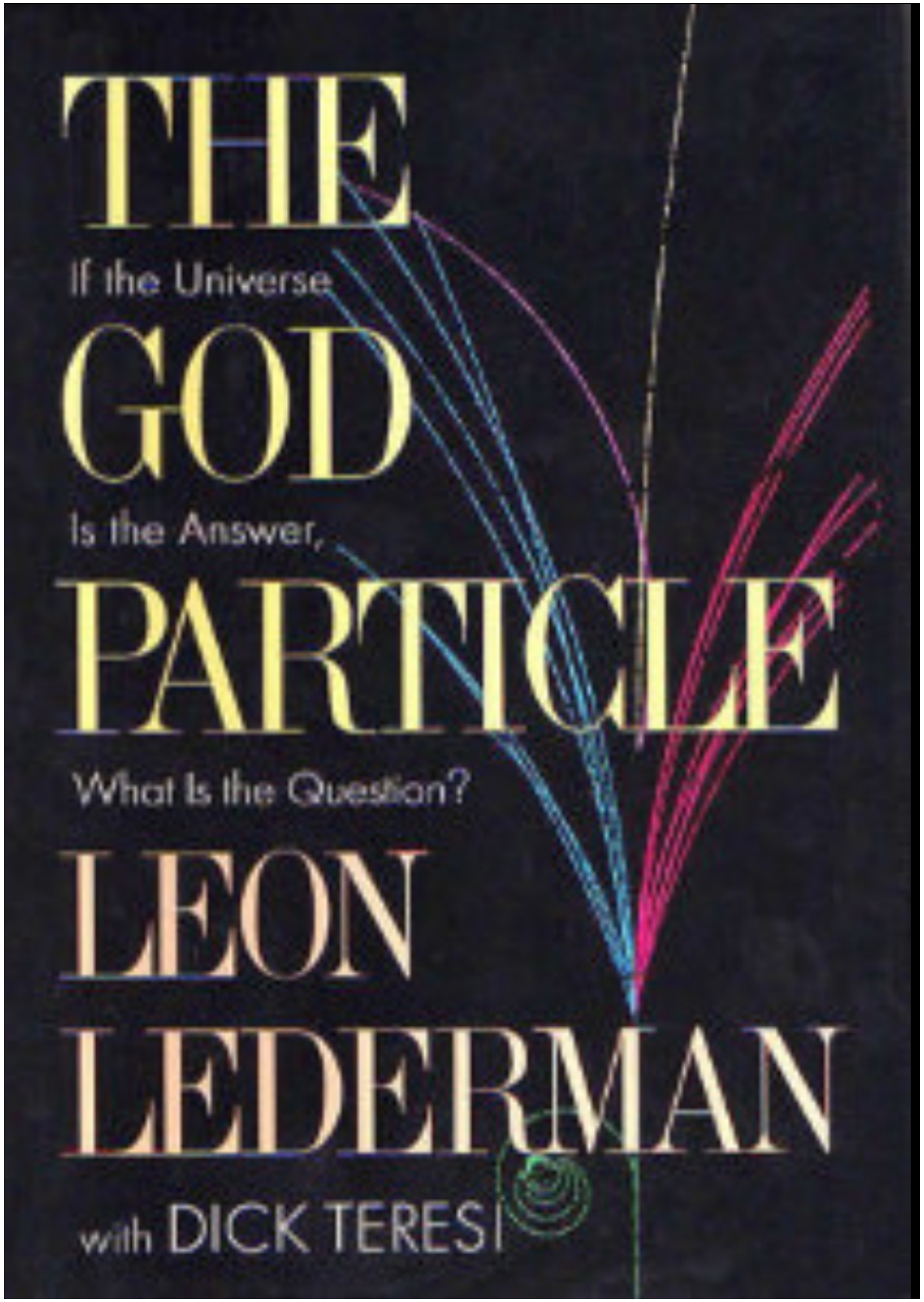
(b) 3D imagining of nuclear PDFs?

‹ ALL ACHIEVERS

Leon Lederman, Ph.D.

Nobel Prize in Physics





The God Particle:

If the Universe Is the Answer,

What Is the Question?

An Ultimate Question in Science

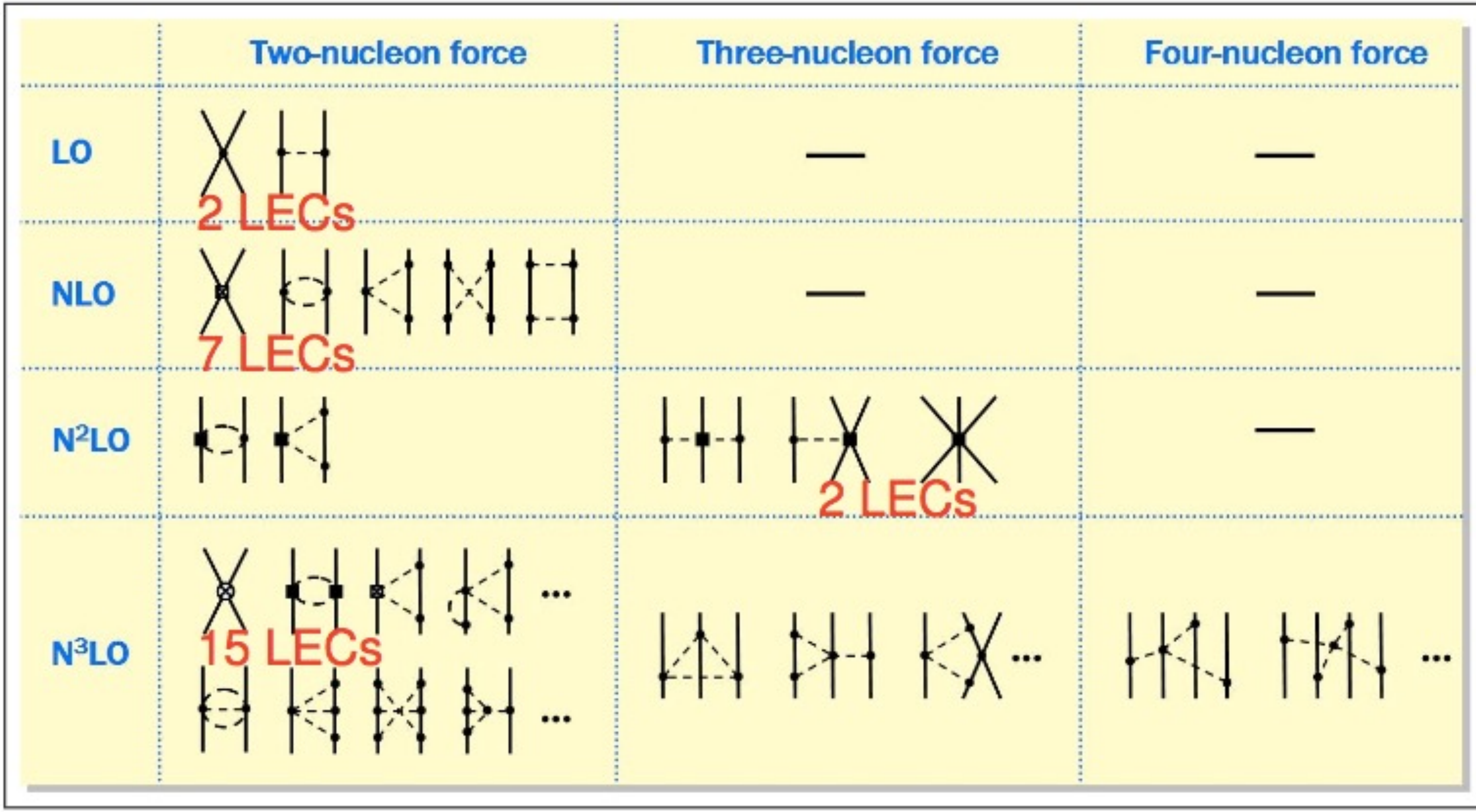
Life = Physical Laws ?

And We Are All in the Pursuit towards Answering this Question!

Thank you very much!

Backup

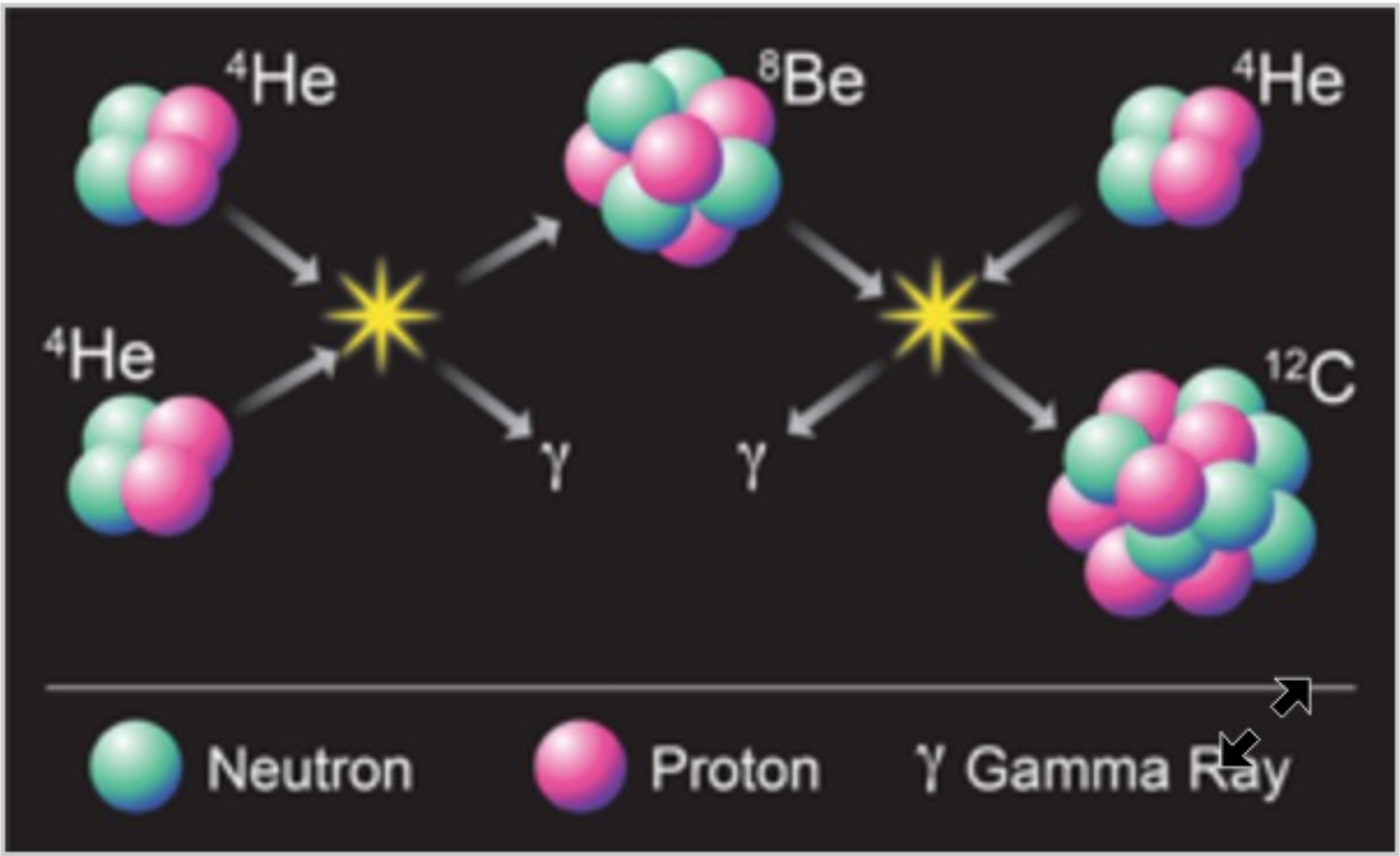
Applying ChPT to nuclear systems (Weinberg)



Credit: U-G Meissner

Hoyle State Obtained

Epelbaum, Krebs, Lee, Meißner, Phys. Rev. Lett. 106, 192501 (2011)



Credit: Carin Cain

No Wilson Line

(Xiang Gao, Wei-Yang Liu, Yong Zhao)

Boosting brings the equal time correlator

$$\tilde{h}(z, P^z, \mu) = \frac{1}{2P^t} \langle P| \bar{\psi}(z) \gamma^t \psi(0) \Big|_{\vec{\nabla}\cdot\vec{A}=0} |P\rangle$$

in Coulomb gauge w/o Wilson line towards the light cone correlator

$$h(\lambda, \mu) = \frac{1}{2P^+} \langle P| \bar{\psi}(\xi^-) W(\xi^-, 0) \gamma^+ \psi(0) |P\rangle$$

w/ Wilson line