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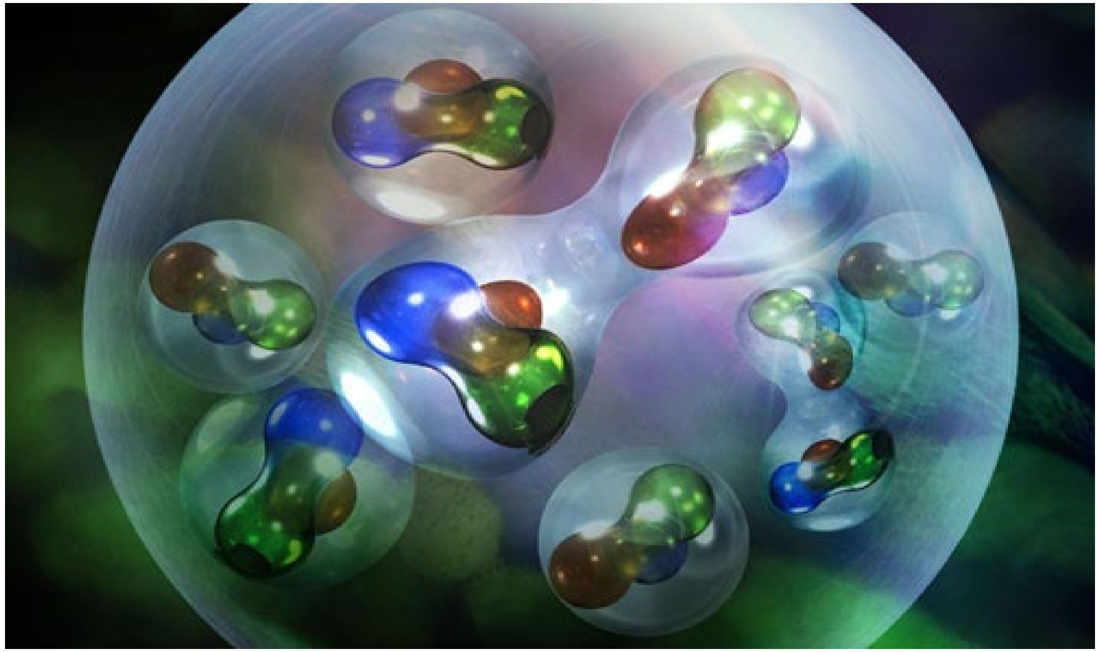
PVEMC experiment with SoLID: Flavor dependence of the EMC effect

John Arrington, LBL



INT workshop on Parity-violation and other EW physics at JLab12 and beyond, June 30, 2022

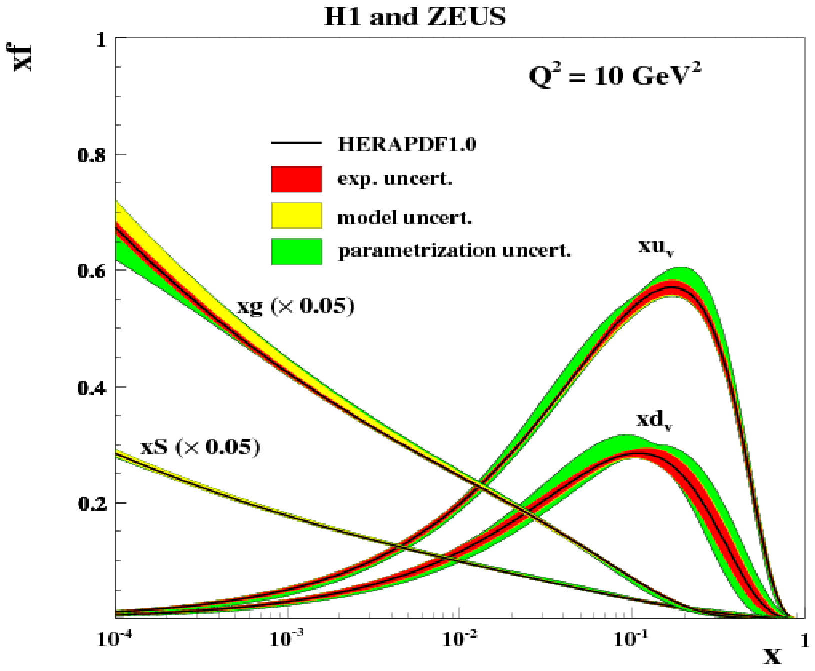
Quark distributions in nuclei: EMC effect

- Deeply-inelastic scattering (DIS) measures structure function $F_2(x)$
  - x = quark longitudinal momentum fraction
  - $F_2(x)$ related to parton momentum distributions (pdfs)

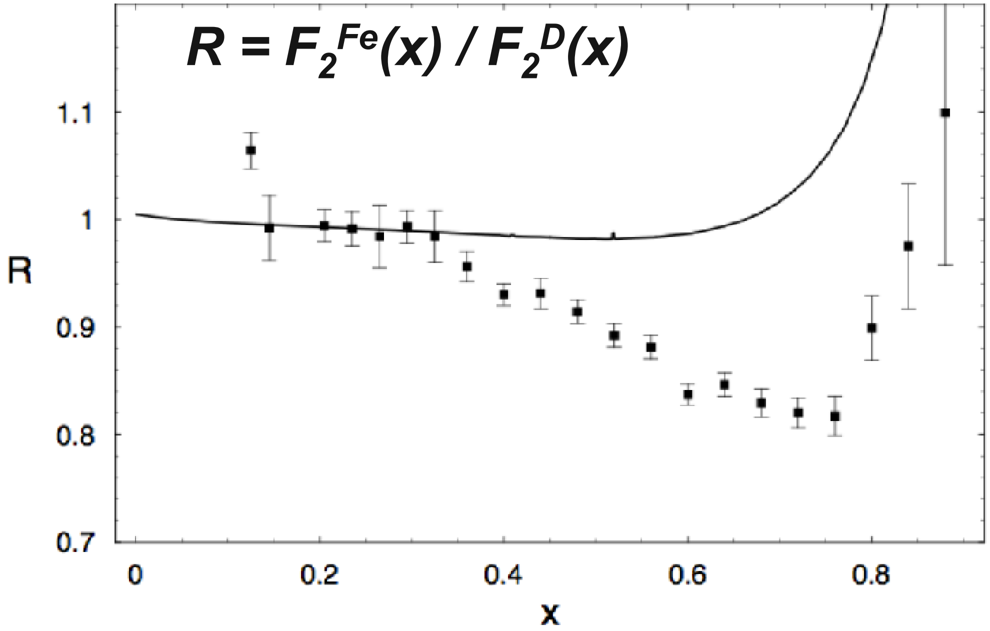
$$F_2(x) \sim \sum e_i^2\, q_i(x) \qquad i = up, down, strange\ldots$$

- Nuclear binding << energy scales of probe, proton/neutron excitations

Expected $F_2^A(x) \approx Z\, F_2^p(x) + N\, F_2^n(x)$ (deviations from Fermi smearing at very large x)



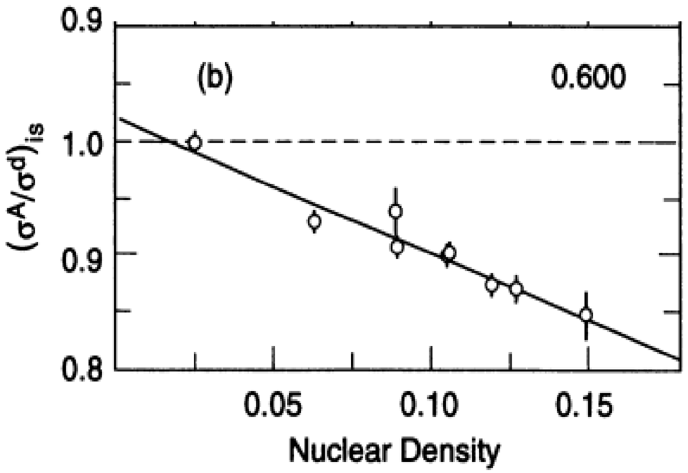
J. J. Aubert, et al., PLB 123, 275 (1983)

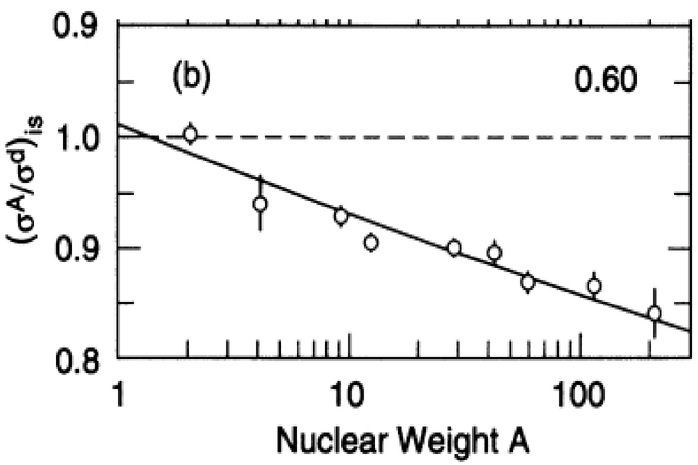


EMC effect: SLAC E139

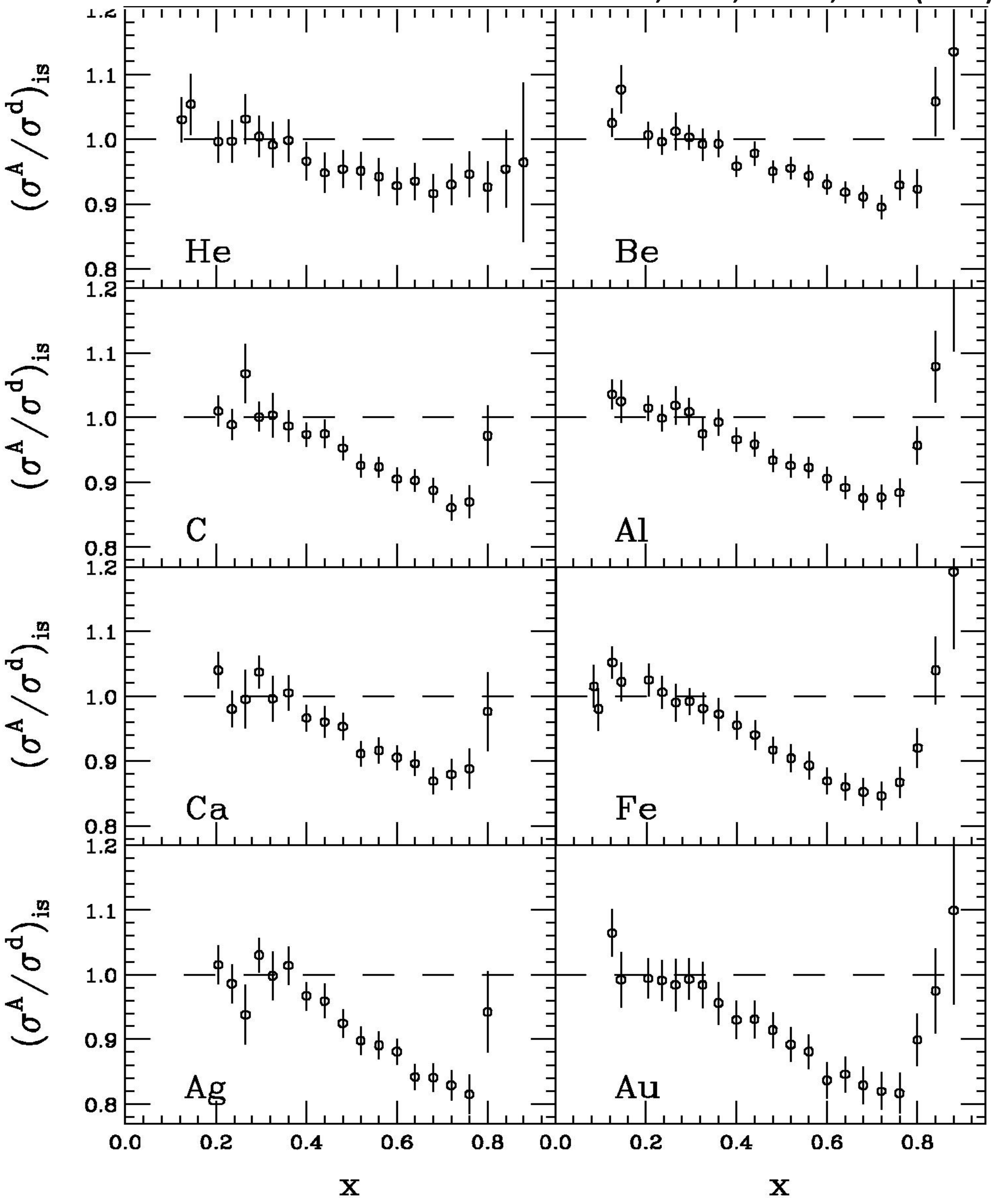
SLAC E139

- Most precise large-x data
- Nuclei from A=4 to 197
- Universal x-dependence
- Size depends weakly on A
  - Scales well with density or with A ($\sim A^{1/3}$)
  - Scales with density





J. Gomez, et al., PRD49, 4349 (1994)



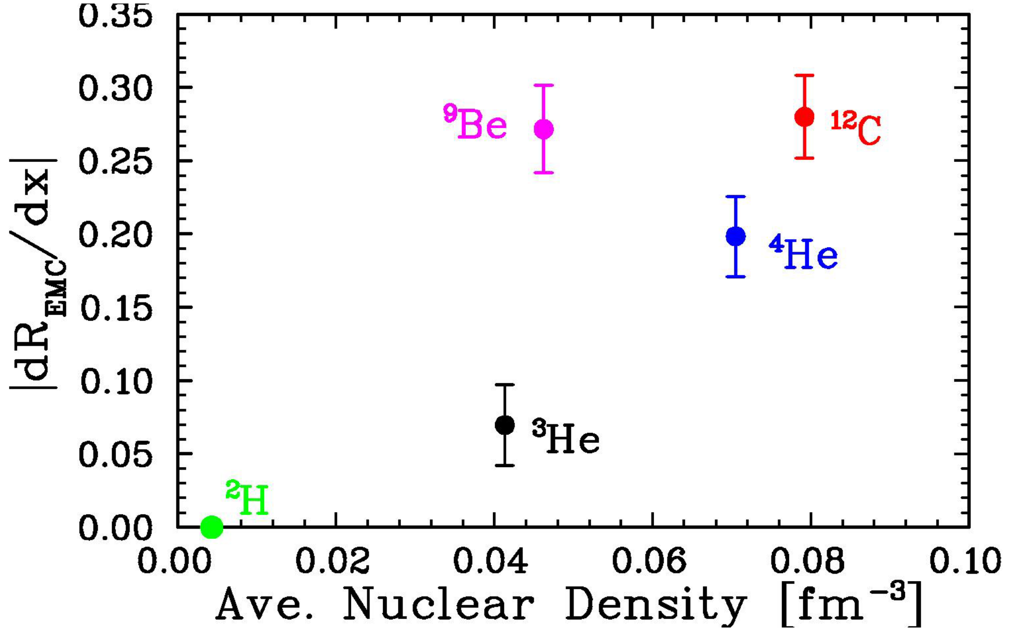
EMC effect in light nuclei

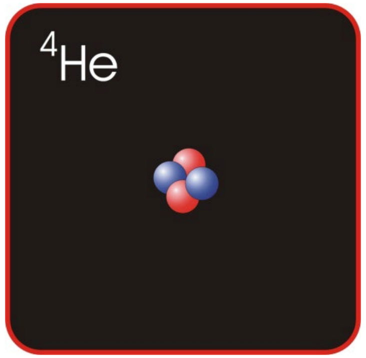
JLab E03-103: JA, D. Gaskell - spokespersons

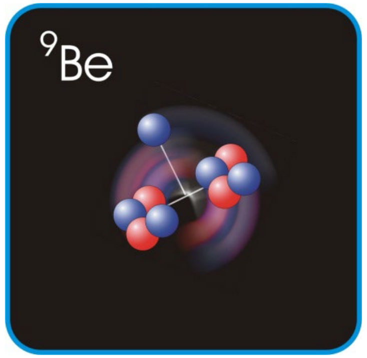
Measured EMC effect for ^{3}He, ^{4}He, ^{9}Be, ^{12}C, ^{63}Cu, ^{197}Au,

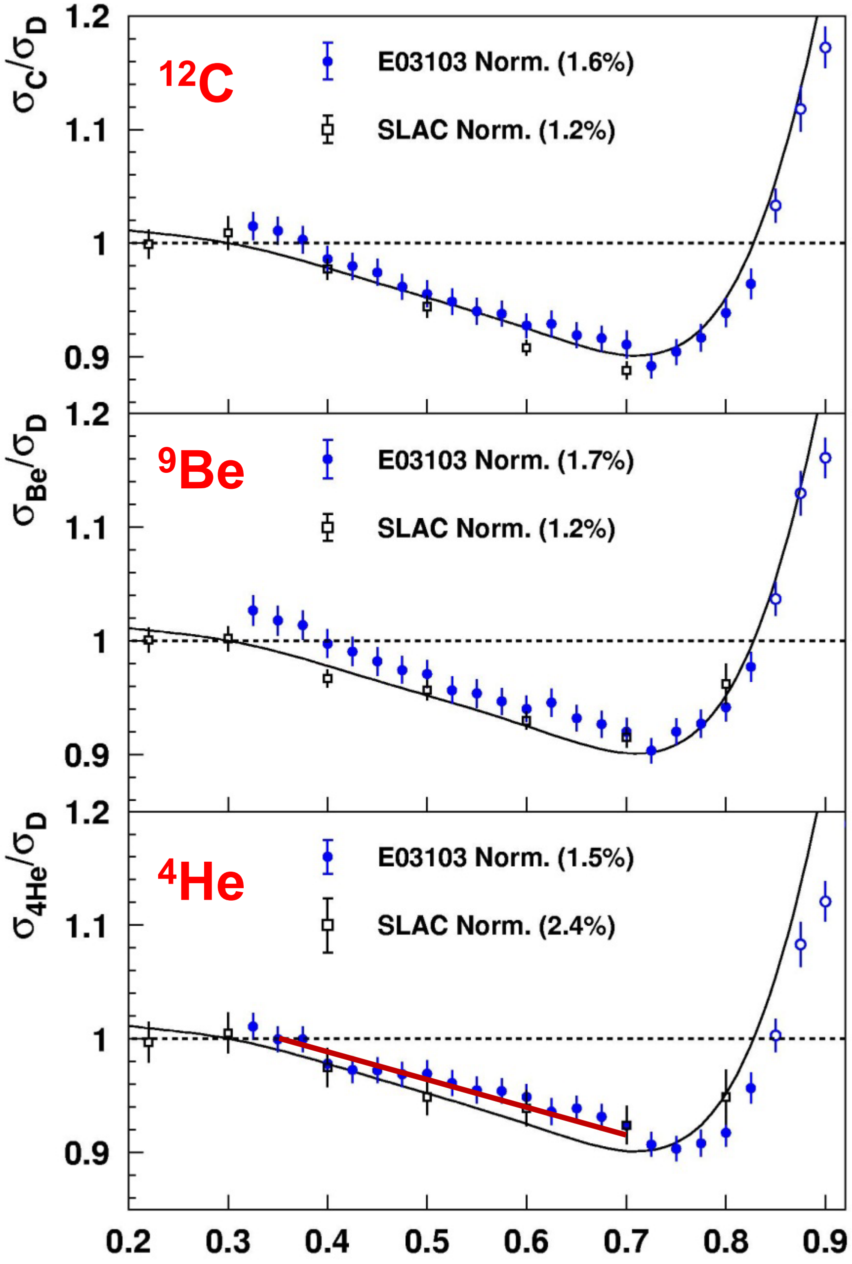
Consistent shape for all nuclei (Curve is SLAC fit for ^{12}C)

Quantify EMC effect using the slope in the linear region (0.35<x<0.7)









EMC effect grows with density except for ^{9}Be – low **average** density but significant alpha clustering

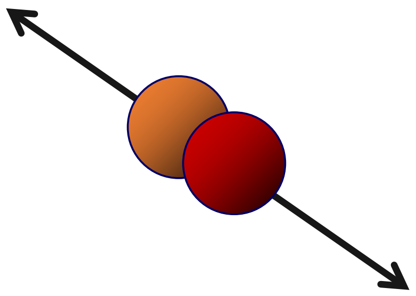
K. Arai, et al., PRC54, 132 (1996)

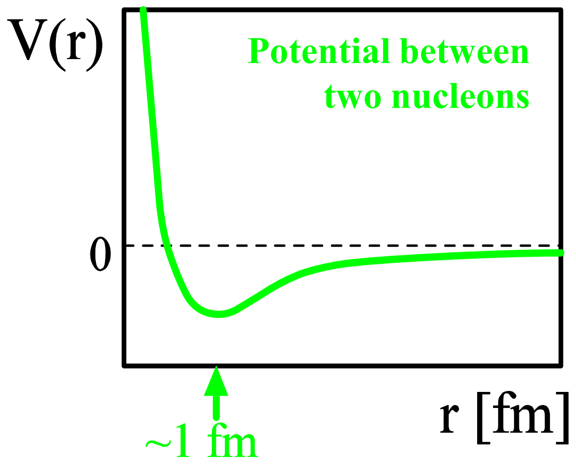
J.Seely, et al., PRL103, 202301 (2009) x

Nuclear structure ←→ Quark effects?

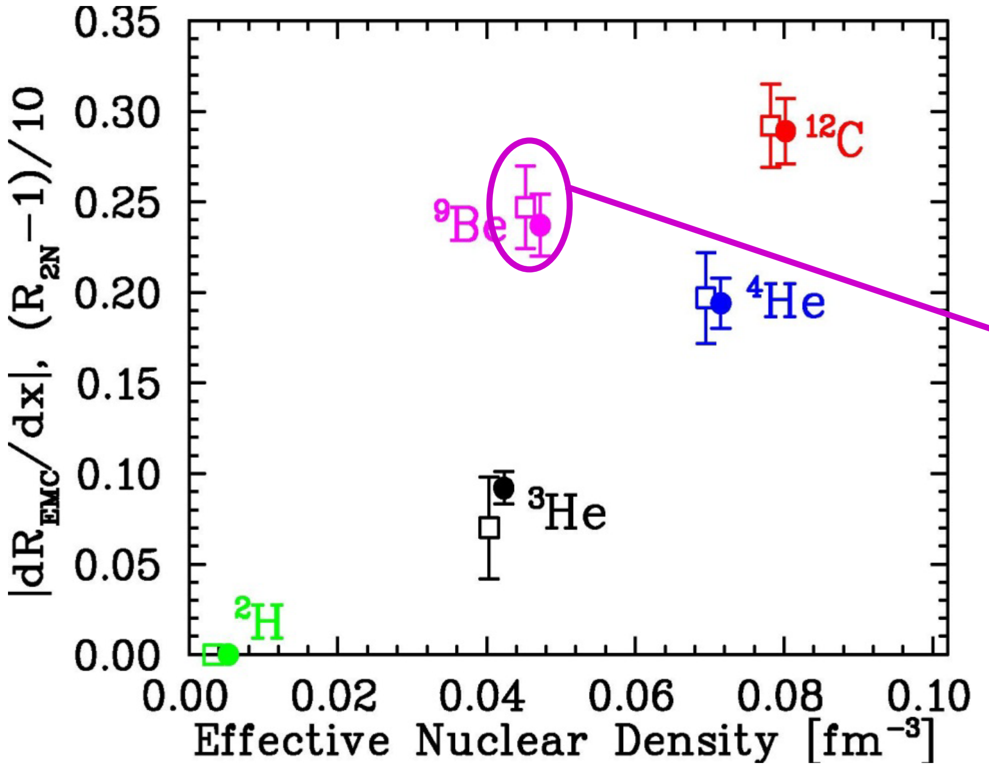
- **Data on light nuclei suggest importance of 'local density'**
  - Shows connection to detailed nuclear structure, clustering effects
  - Intriguing observation, but microscopic explanation not yet clear

- **Can we study these high-density structures directly?**
  - Short-range correlation (SRC) measurements are meant to probe such high-density configurations
    - Aim is to **study** contribution of high density configurations
    - The experiments **measure** high momentum nucleons





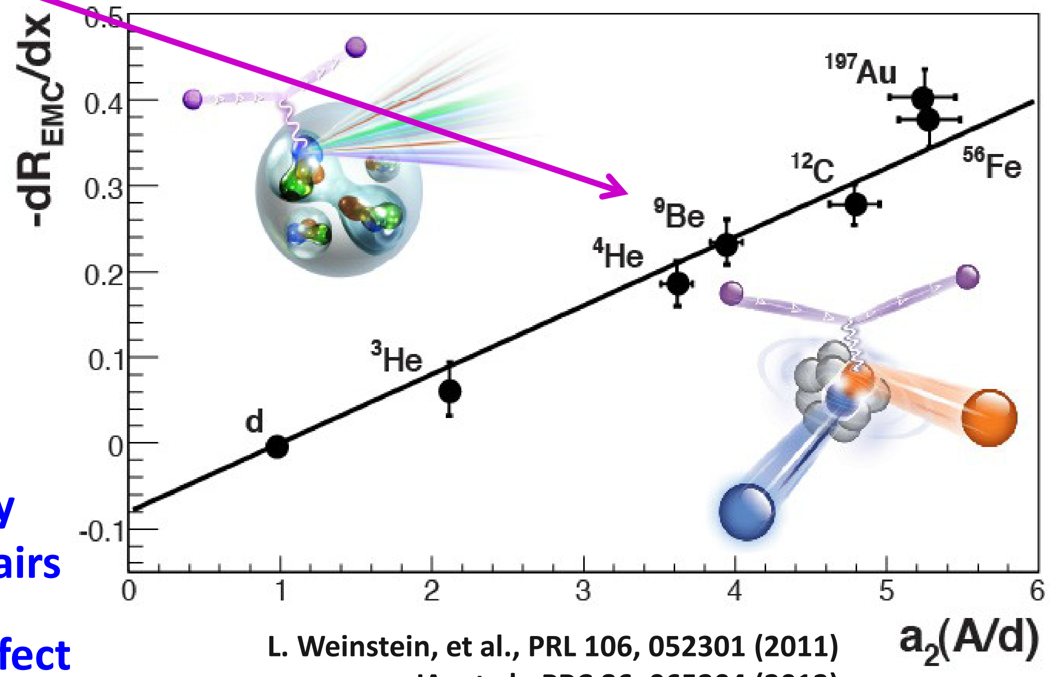
EMC–SRC correlation



J. Seely, et al., PRL103, 202301 (2009) – EMC
N. Fomin, et al., PRL 108, 092052 (2012) – SRCs

SRCs are mainly np – does SRC isospin dependence lead to flavor dependence of the EMC effect?

Do SRCs and EMC effect share a common origin, or do SRCs generate the EMC effect?



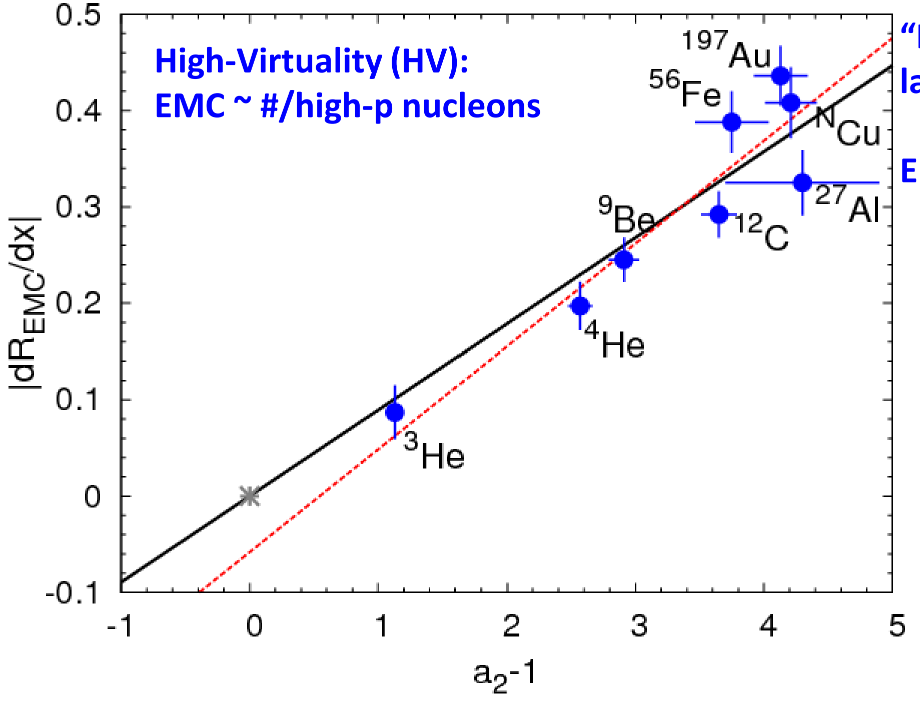
L. Weinstein, et al., PRL 106, 052301 (2011)
JA, et al., PRC 86, 065204 (2012)

In local-density (LD) picture, both SRCs and EMC effect driven by short-distance configurations, but SRCs generated only for np pairs

In high-virtuality (HV) picture, short distance → SRCs → EMC effect

Can we test/differentiate these pictures?

Two Hypotheses for EMC-SRC correlation



"HV": short-distance → SRCs, but large momenta in SRCs → EMC

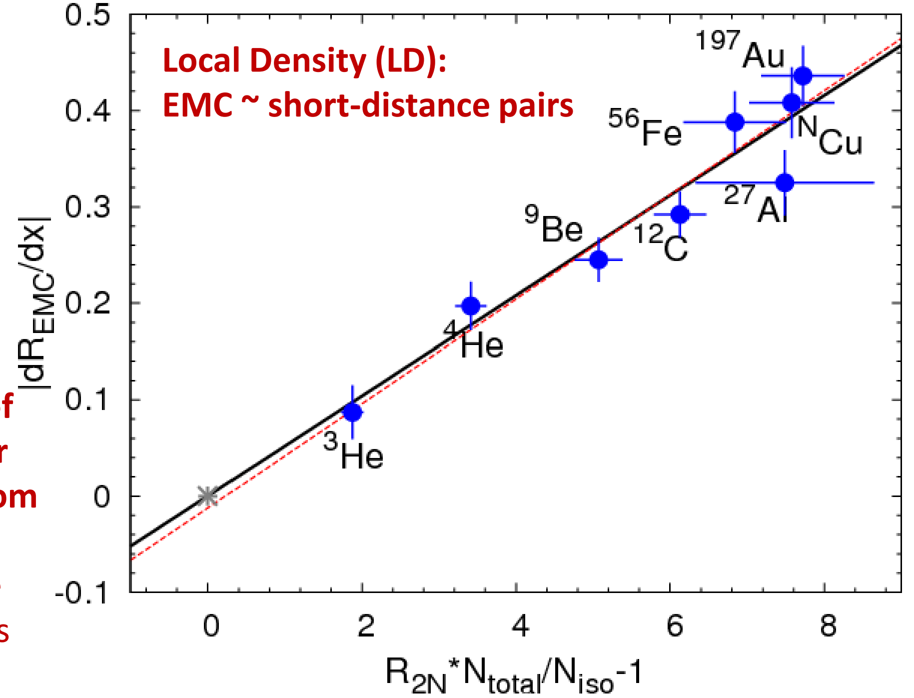
EMC ~ # of high-p nucleons ~ a2

"LD": short-distance → SRCs and EMC effect

a2 measures high-p contribution of np pairs. a2 has to be corrected for smearing of the pair and scaled from np to NN pairs.

Short-distance pairs assumed to be isospin-independent in this analysis

JA, et al., PRC 86 (2012) 065204



Hypothesis	Fit type	χ^2_ν	EMC(D)
High Virtuality	2-param No constraints	1.26	-0.058±0.036
High Virtuality	1-param	1.47	–
Local Density	2-param No constraints	(0.64) 0.84	-0.012±0.033
Local Density	1-param	(0.57) 0.74	–

"Local Density" (flavor-independent) model gives better correlation, better extrapolation to (known) deuteron values

Difference only at the 2σ level

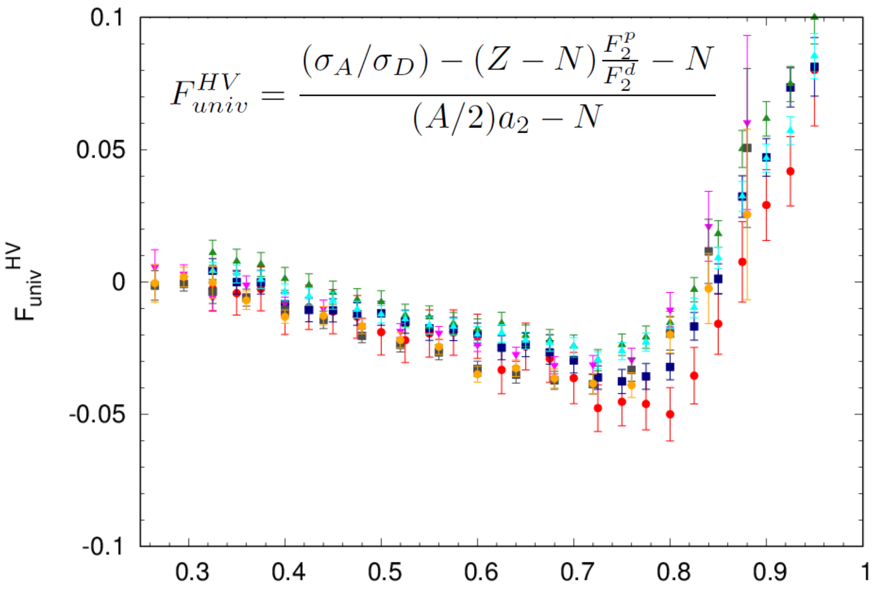
Similar analysis, looking at **“universal EMC effect”** extracted under similar assumptions:

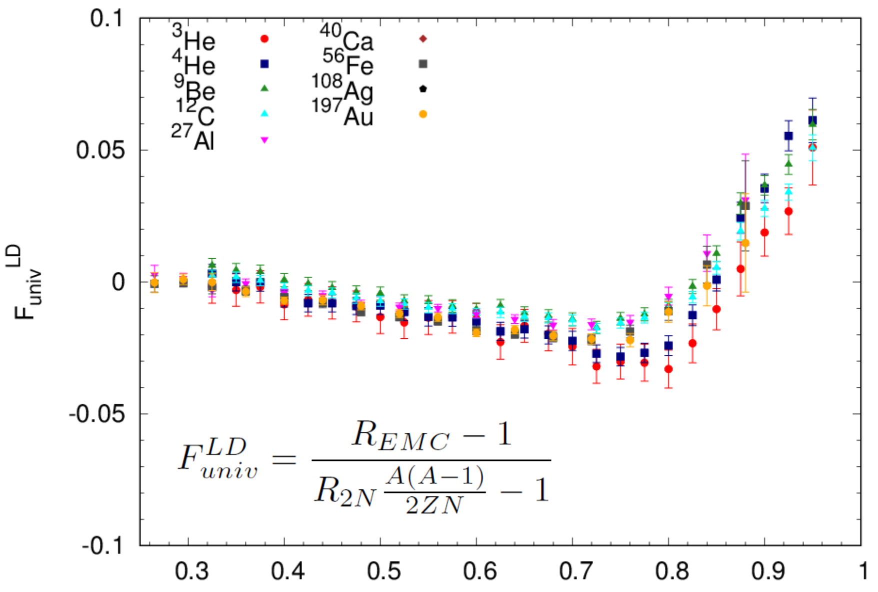
B. Schmookler, et al., Nature 566 (2019) 345

JA, N. Fomin, PRL 123 (2019) 042501

HV picture (left): EMC effect from np-SRC, yields specific flavor dependence

LD picture (right): Driven by short-distance pairs, assumed to be flavor independent



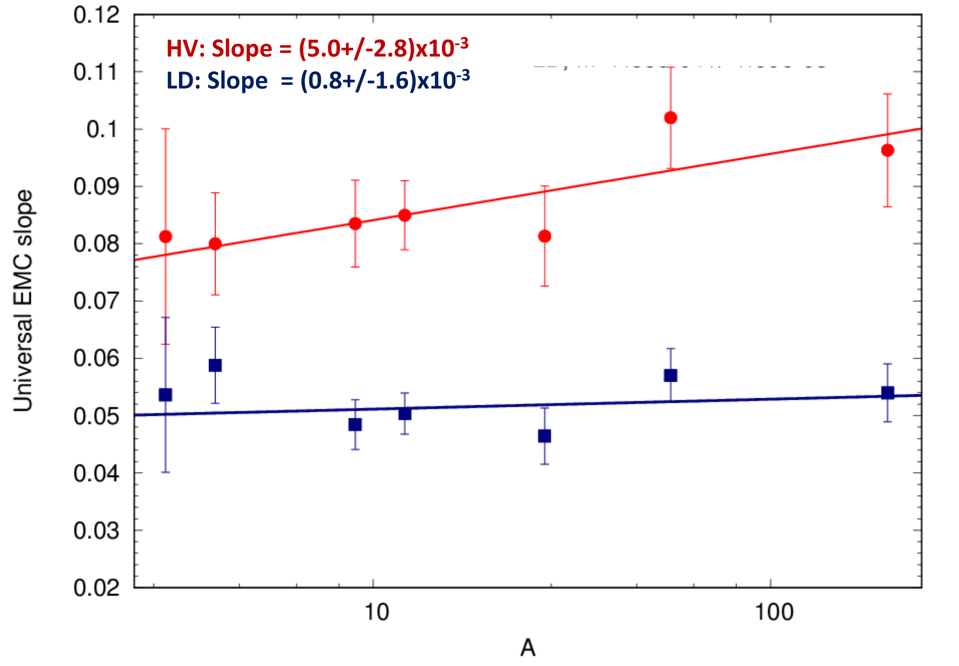


Both give reasonable description; slightly better for LD

Very different deuteron EMC effect for HV and LD

This approach is nearly identical to the previous analysis (looking at the quality of EMC-SRC correlation)

JA, N. Fomin, PRL 123 (2019) 042501



Flavor-dependent EMC effect?

- **Always assumed that EMC effect is identical for proton and neutron; becoming extremely hard to believe, at least for non-isoscalar nuclei**
  - **EMC-SRC correlation + n-p dominance of SRCs suggests enhanced EMC effect in minority nucleons**
    - In ^{3}H, np-dominance suggests single proton generates same high-momentum component as two neutrons –> larger proton EMC effect in 'high-virtuality' picture
  - **Neutron rich nuclei like ^{48}Ca, ^{208}Pb expected to have significant neutron skin; neutrons preferentially sit near the surface in lower density regions**
    - Larger proton EMC effect in 'local-density' picture
  - **Some calculations show difference for u-, d-quark as result of scalar and vector mean-field potentials in asymmetric nuclear matter**

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

- All show **enhanced EMC for minority nucleons**; size of effect varies factor of ~3
  - Flavor dependence of EMC effect provides new way to test models of nuclear effects
  - Modify nuclear pdfs in e-A and ν-A scattering; e-A, p-A, and A-A collisions

Flavor dependence?

There is reason to <u>expect</u> flavor-dependent EMC effect

- Calculations (CBT)
- EMC-SRC correlation
- Multiple predictions based on simple scaling models

It is critical that it be measured

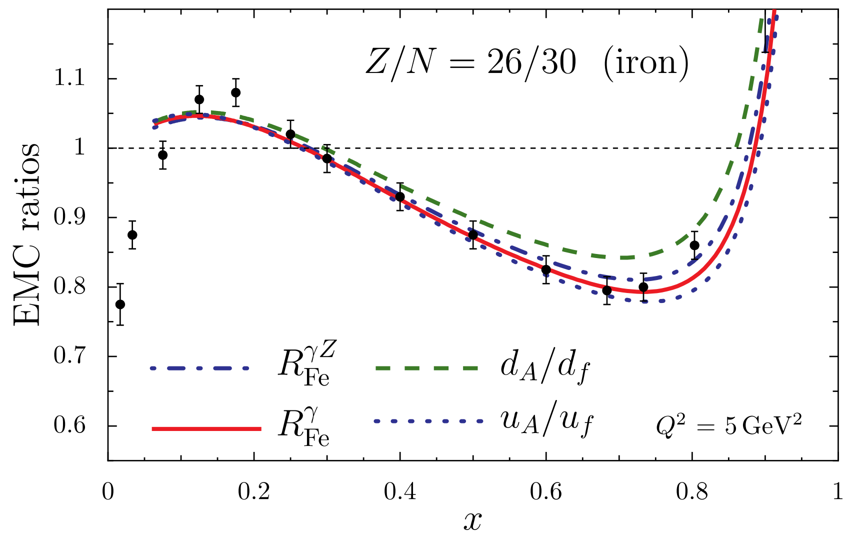
- Totally new information to help elucidate origin of the EMC effect
- Input to high-energy e-A, ν-A, p-A, and A-A measurements (polarized e-^{3}He)
- Modifies extraction of neutron structure from comparison of deuteron, proton

As of today, <u>no experimental indications</u> of a flavor dependence

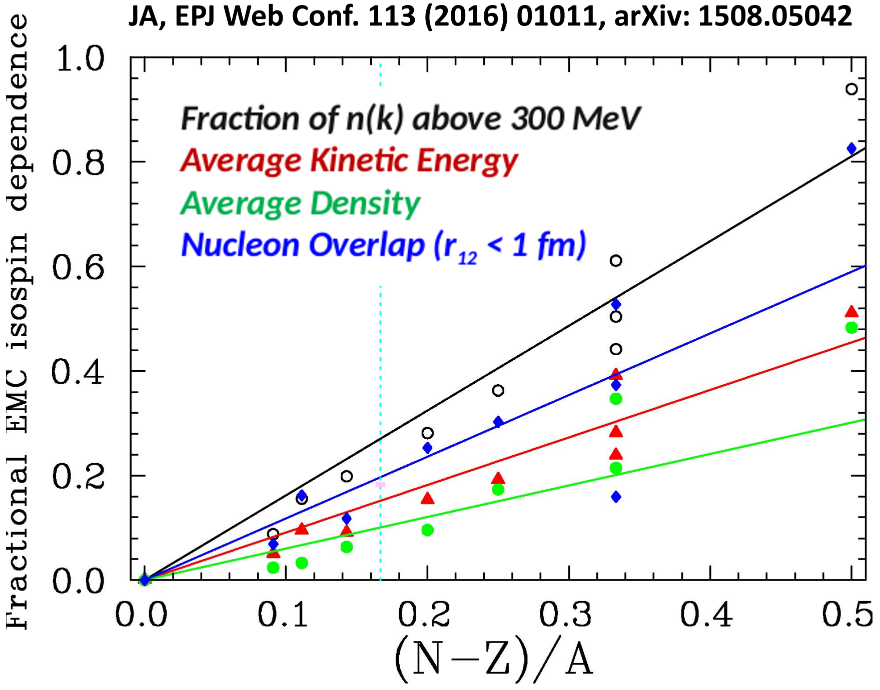
Estimates of flavor dependence?

- CBT calculation – mean-field model; impact of QCD scalar, vector fields modifies up, down quark differently
- Simple assumptions about underlying cause:
  - EMC scales with #/high-momentum nucleons, avg nucleon kinetic energy, amount of short-distance configurations
  - All can be calculated for p, n separately → isospin dependence
- “Extreme cases” – EMC is 100% up (or down) quarks
  - Not very realistic, but sometimes shown for other expts.
- pdf analyses
  - Tension between electron and neutrino data suggested possible flavor dependence, of a size similar to the CBT model
  - Recent updates comparing 3H/3He and 2H/1H DIS data also suggest possible flavor dependence

Cloët, Bentz, and Thomas, PRL 102, 252301 (2009)



JA, EPJ Web Conf. 113 (2016) 01011, arXiv: 1508.05042



SIDIS, D-Y measurements

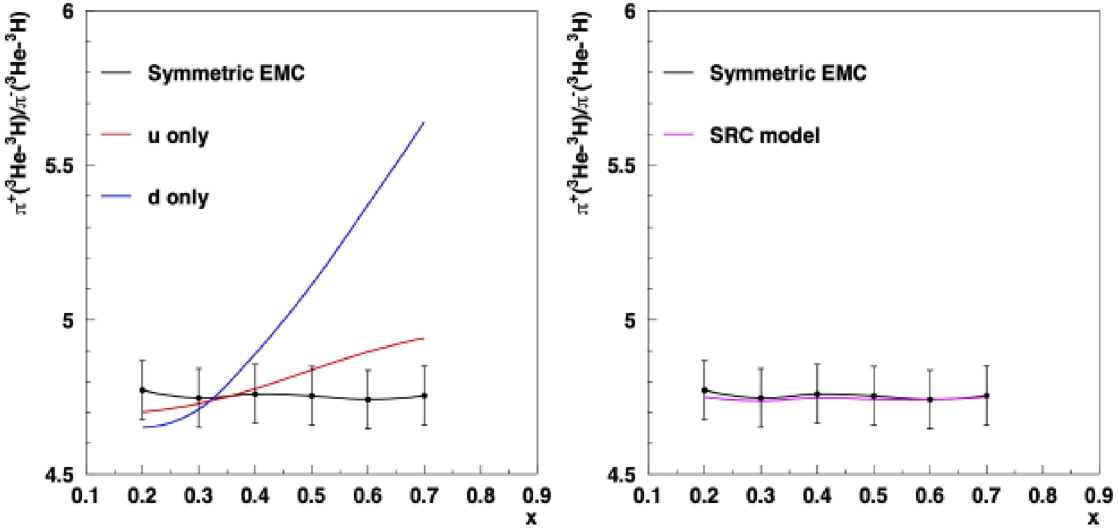
SIDIS projections: various target ratios for sums(differences) of pi+ and pi-

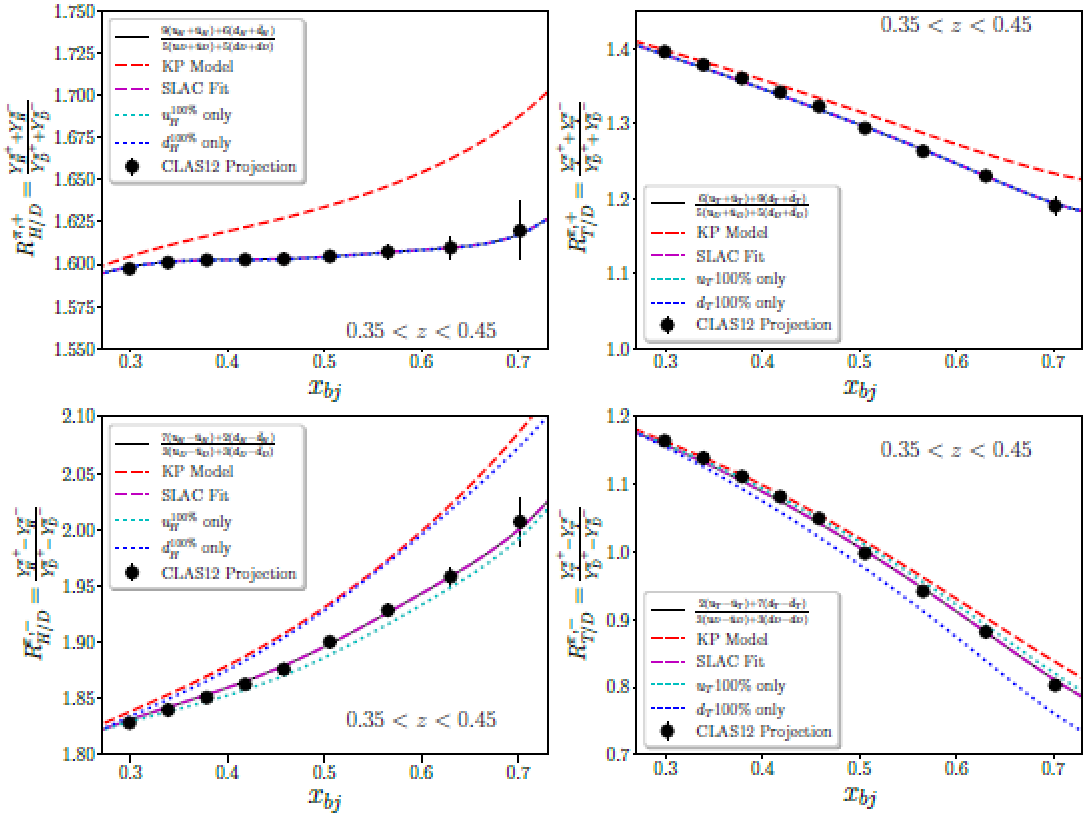
TOP: Symmetric EMC effect and "SRC" model (flavor dependence driven by SRC isospin structure) nearly indistinguishable - Large signal only when the EMC effect is d-quark only

BOTTOM: Only "KP" and "d-quark only" models give effects above few percent. Other cases are at most 1-2% effects (systematics limited)

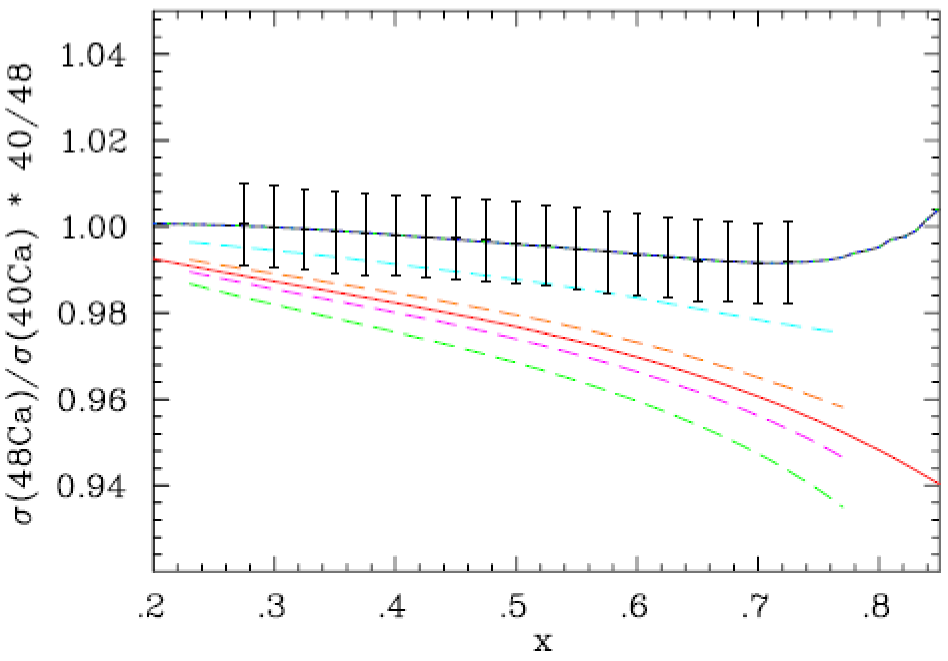
"KP" refers to the Kulagin-Petti calculation, but isn't consistent with KP. It reproduces the KP EMC effect for 3H and 3He, but applies this as a flavor-independent EMC effect for the SIDIS calculation.

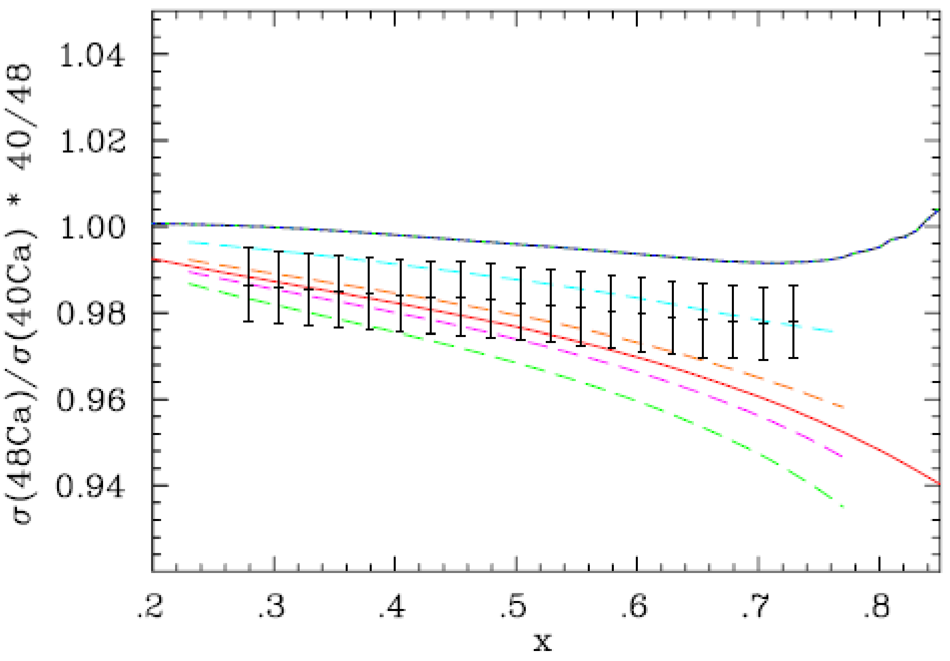
Drell-Yan: AMBER plans pi+ and pi- D-Y, which is sensitive to flavor dependent EMC effect. But data limited to x<0.34;





48Ca/40Ca comparison to models/projections





Left: comparison to various models

2.1σ deviation from CBT (red line)

2.9σ deviation if quadruple proposed statistics

Right: Same, but with 1-sigma normalization shift

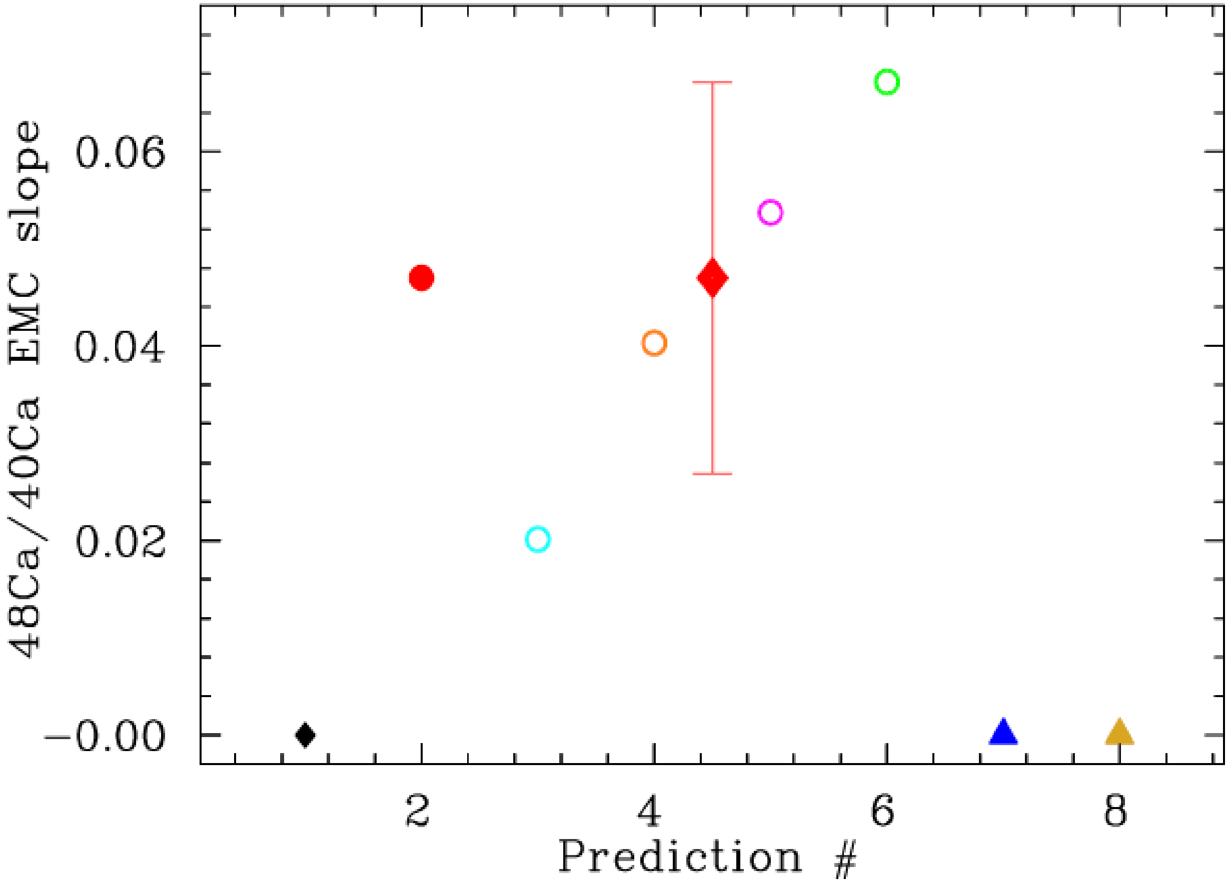
1.7σ deviation from CBT

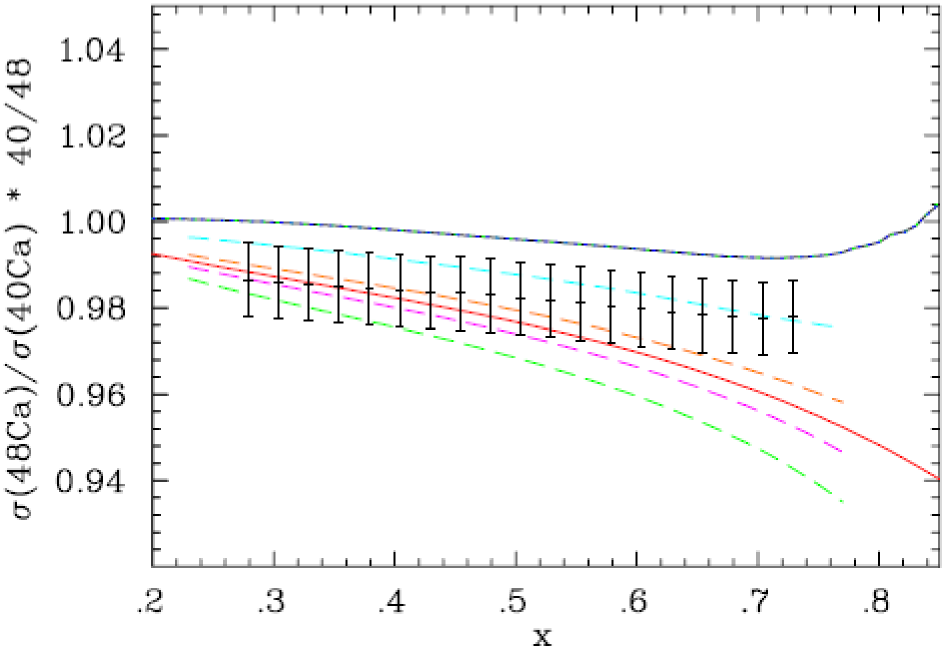
2.3σ deviation with quadrupled statistics

$>3\sigma$ sensitivity ONLY for largest (green) curve (assuming 4x the proposed statistics)

Limited “yes-no” sensitivity for flavor dependence, ~2σ between largest and smallest effects

48Ca/40Ca comparison to models/projections





Right: Same, but with 1-sigma normalization shift

1.7σ deviation from CBT

2.3σ deviation with quadrupled statistics

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Limited “yes-no” sensitivity for flavor dependence, ~2σ between largest and smallest effects

Flavor dependence - PVEMC

PVEMC on 48Ca

- Photon-Z interference / photon-squared
- Flavor-independent EMC effect → all pdfs rescaled same way, cancels in ratio
- Flavor-dependent EMC gives enhanced impact from d-quarks in numerator (weak vs EM charge)

$$A_{PV} = -\frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\left[a_1(x) + \frac{1-(1-y)^2}{1+(1-y)^2}a_3(x)\right]$$

Suppressed

Expanding about u_A=d_A limit, neglecting sea quarks:

$$a_1(x) \approx \frac{9}{5} - 4\sin^2\theta_W - \frac{12}{25}\frac{u_A^+ - d_A^+}{u_A^+ + d_A^+} \qquad q^\pm = q(x) \pm \bar{q}(x)$$

PVDIS sensitive to difference in up and down quark distributions in nuclei

PVEMC proposal - SoLID detector

JA, R. Beminiwattha, D. Gaskell, J. Mammei, and P. E. Reimer - spokespersons

Proposal submitted to PAC50

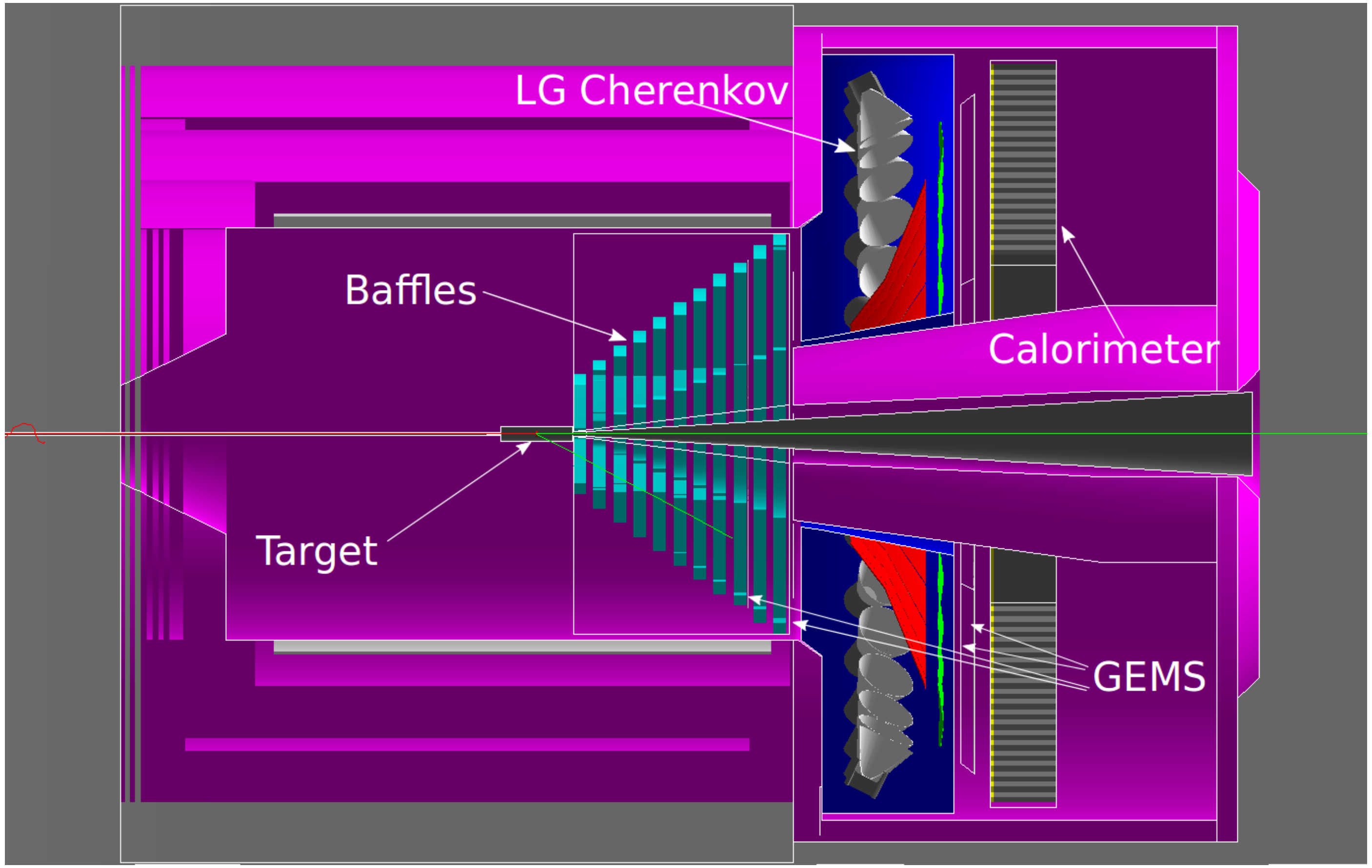
Uses SOLID in PVDIS configuration

→ Identical spectrometer/detector configuration as PVDIS (baffles, etc.)

PVEMC measurement requires target with N ≠ Z and large EMC effect

→ ^{48}Ca satisfies both requirements with smaller radiation length than heavier targets (e.q., gold or lead)

→ Sufficient ^{48}Ca at JLab to provide 2.4 g/cm^2 thickness – modified target design; some processing of calcium may be required

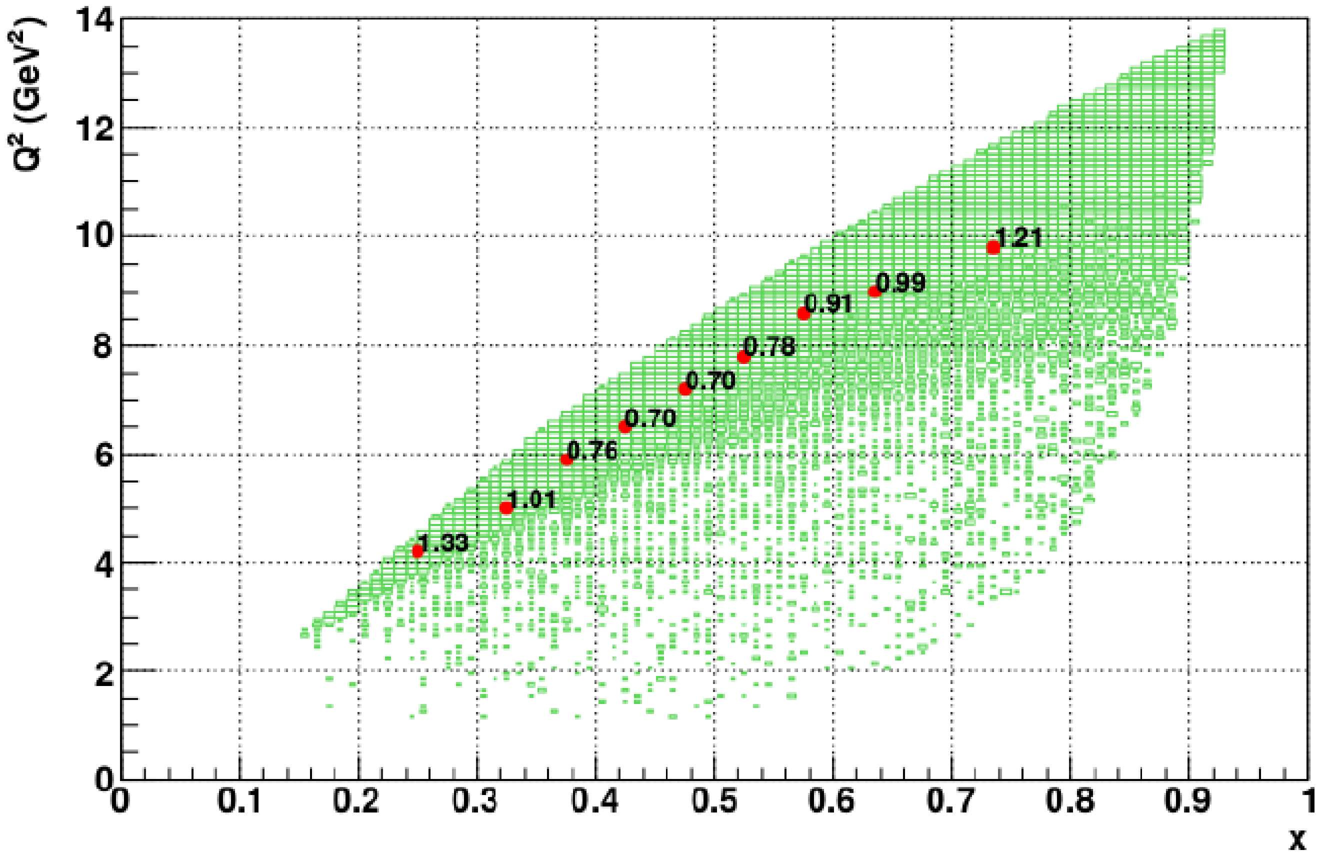


Kinematic coverage and projected precision

- Kinematics and statistics (%) for 68 days data taking shown on right

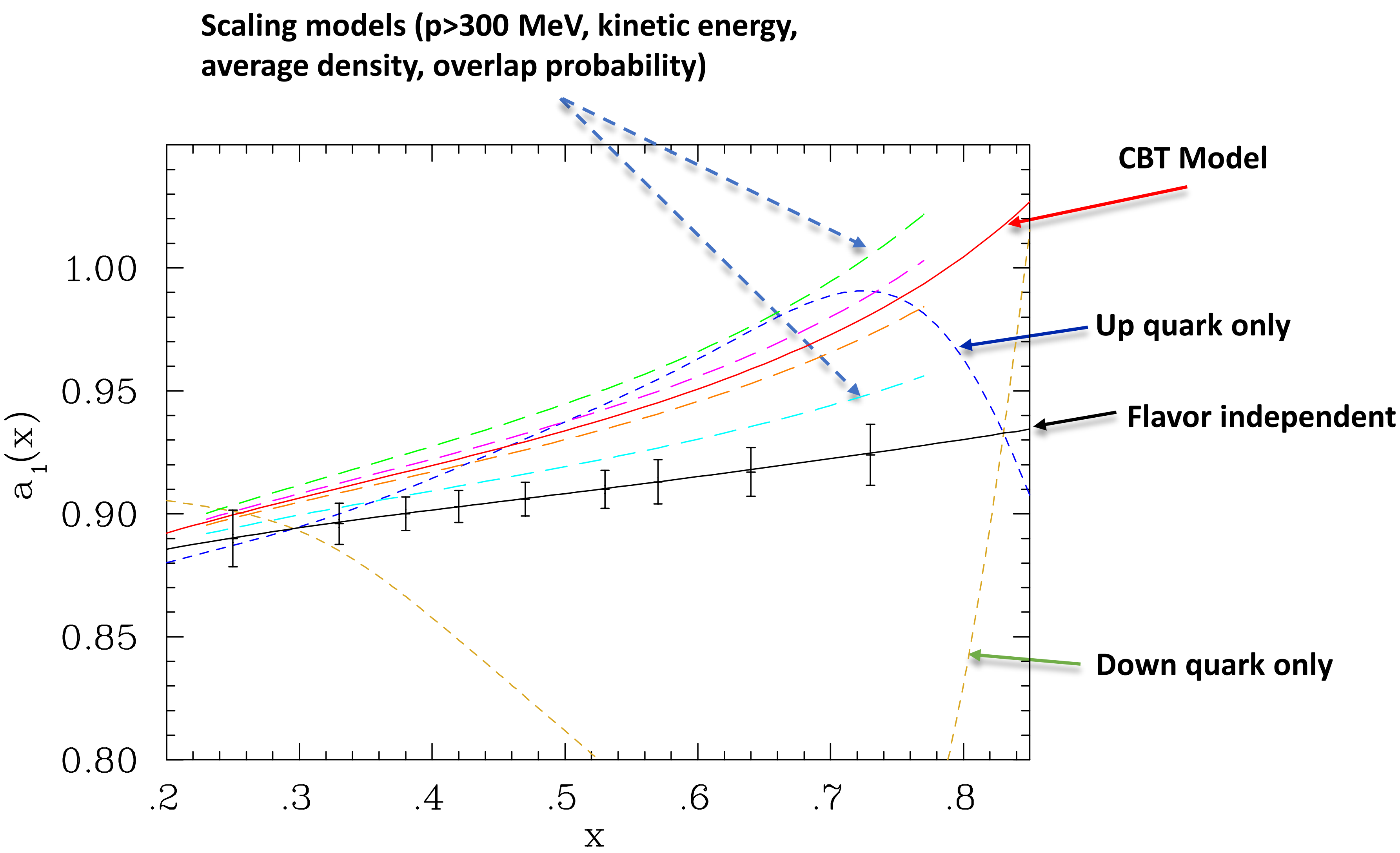
- Estimated systematics summarized below - includes experimental uncertainties AND model dependence associated with interpreting the data in terms of flavor dependence.

Effect	Uncertainty [%]
Polarimetry	0.4
$R^{\gamma Z}/R^{\gamma}$	0.2
Pions (bin-to-bin)	0.1-0.5
Charge-symmstric background	<0.1
Radiative Corrections (bin-to-bin)	0.5-0.1
Other corrections including CSV	0.2
pdf uncertainties	0.2
Total systematic	0.6-0.7
Statistics	0.7-1.3



0.4% normalization uncertainty (polarimetry)

Projections



Precision to differentiate models, set significant limit if results consistent with flavor-independent result

- **8σ sensitivity to CBT model** **(neglecting normalization); >6.5σ if you shift the data up by twice the scale uncertainty**
- **>3σ sensitivity to the smallest prediction** **(cyan curve)**
- **Smallest prediction (cyan) is ~8σ from largest (green), ~4.5σ from CBT**

Summary

- Despite renewed activity in recent years, no consensus on origin of the EMC effect; new observables required to provide more insight
- PVDIS offers a precise, interpretable measurement of possible flavor dependence of the EMC effect
- PR12-22-002: Measurement of PVDIS from 48Ca using SOLID apparatus
  - 83 days total (68 days production)
  - Will provide ~7σ test of CBT model, provide significant constraints on flavor dependence no matter what value is obtained
  - Several aspects less challenging than approved PVDIS on LD2 experiment: lower rates, no target boiling, shorter target (better control of acceptance and collimation)