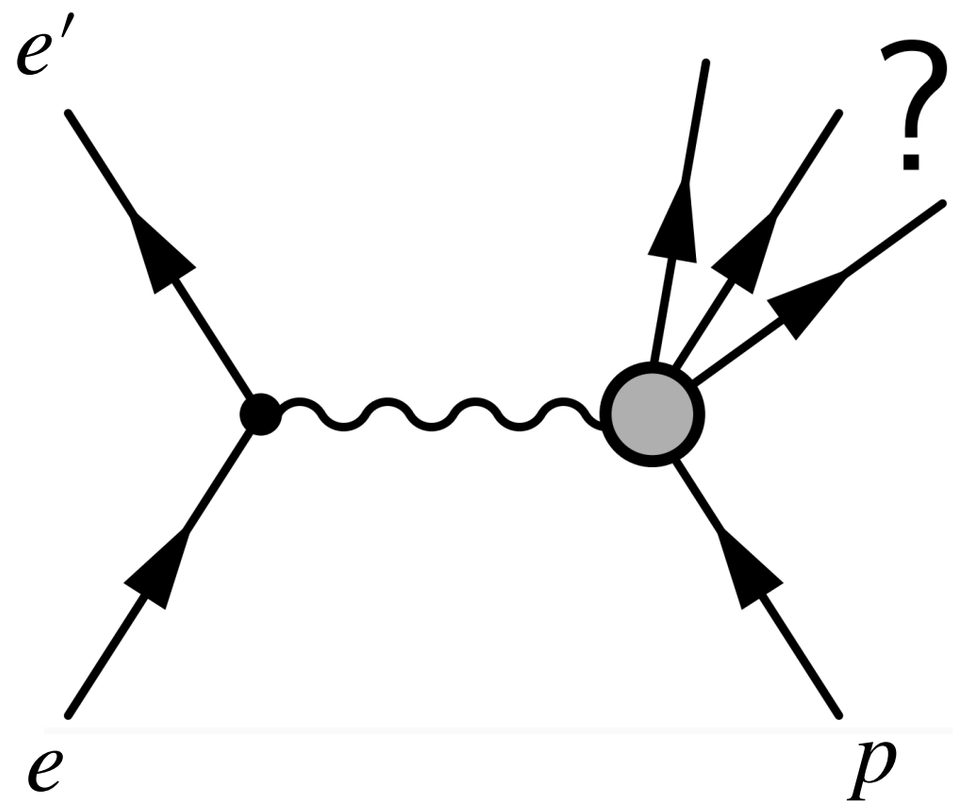
Bound **and** Free Nucleon Structure

Efrain Segarra

Jefferson Lab 2019 Users Organization
Annual Meeting

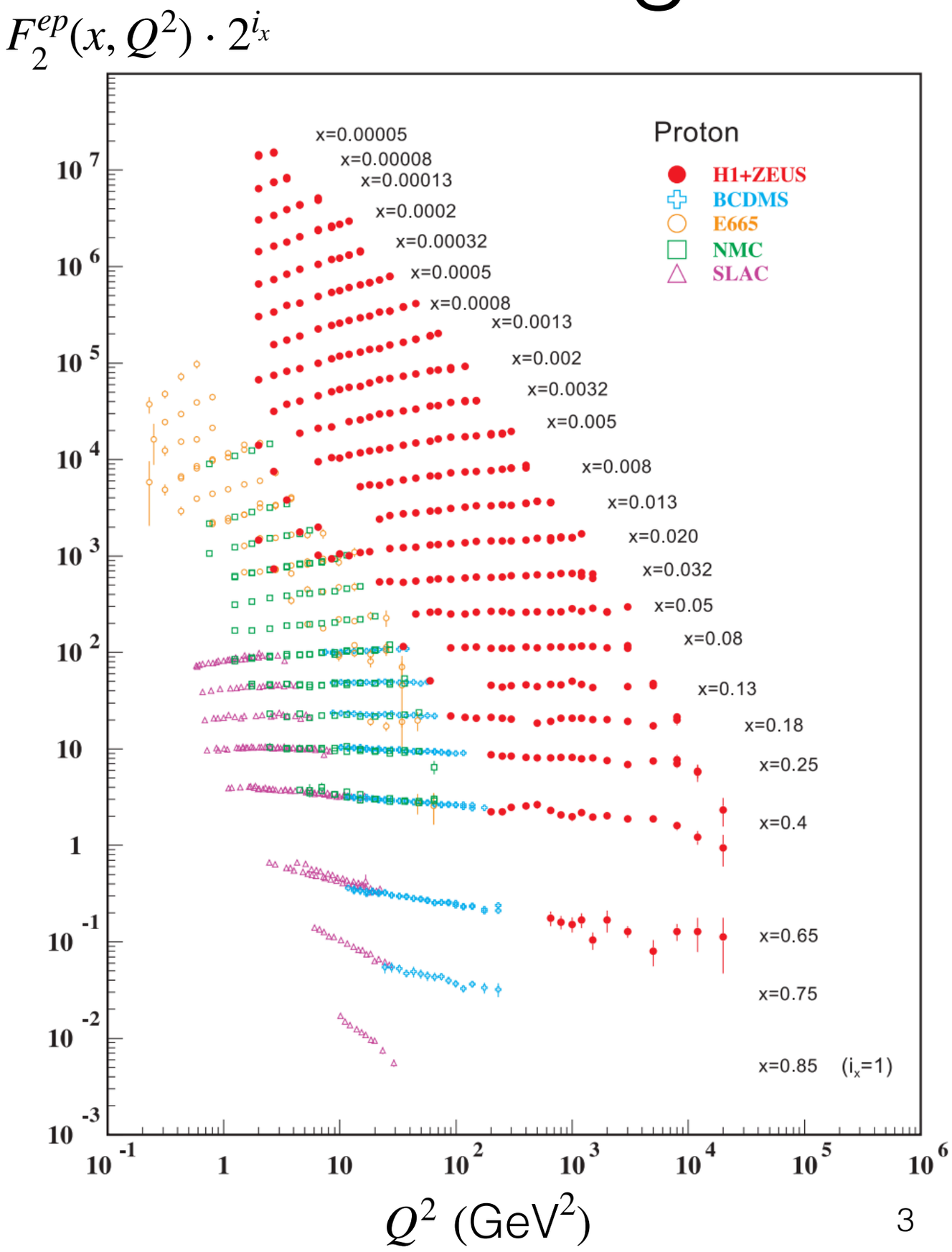
June 25, 2019

Structure Functions of a free proton

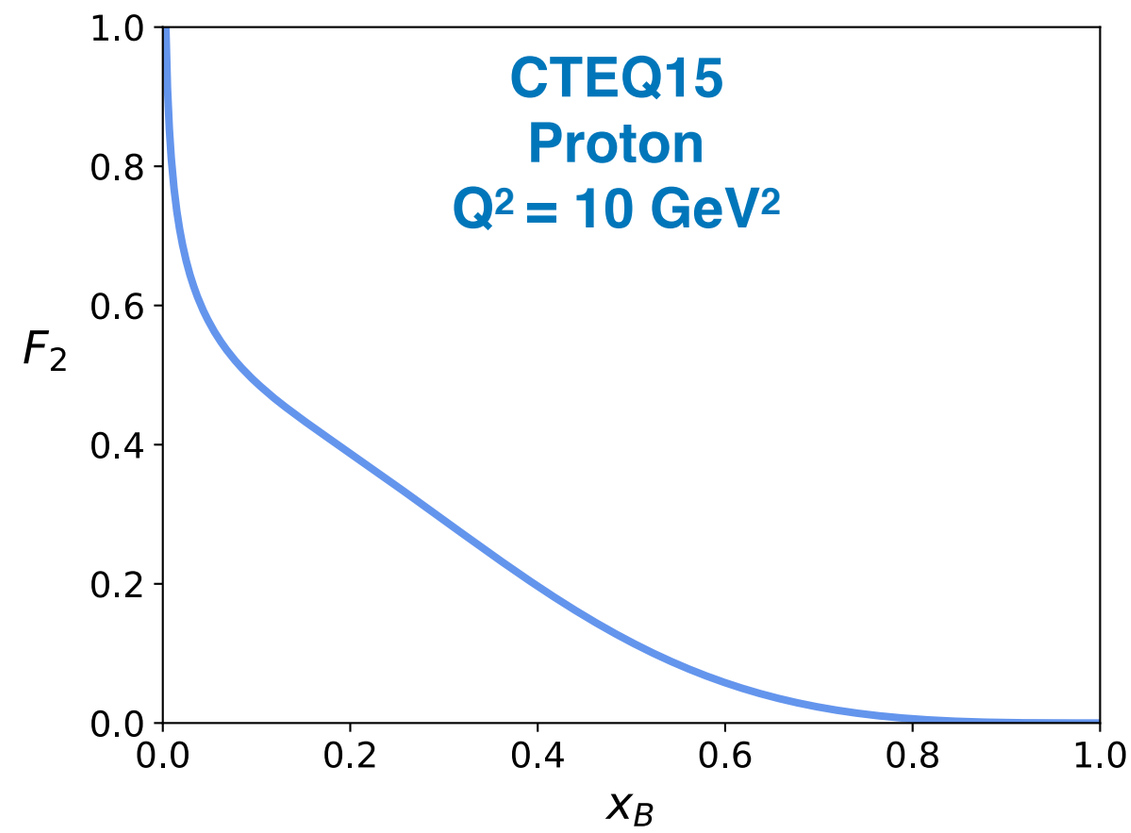


$$\frac{d\sigma}{dx dQ^2} = \frac{4\pi\alpha^2}{Q^4}\left[\left(1 - y - \frac{m_p^2 y^2}{Q^2}\right)\frac{F_2(x, Q^2)}{x} + y^2 F_1(x, Q^2)\right]$$

Getting F_2 of free proton



$$F_2 \rightarrow x \sum e_i^2 \left(q_i(x) + \bar{q}_i(x)\right)$$



What about the neutron structure F_2?

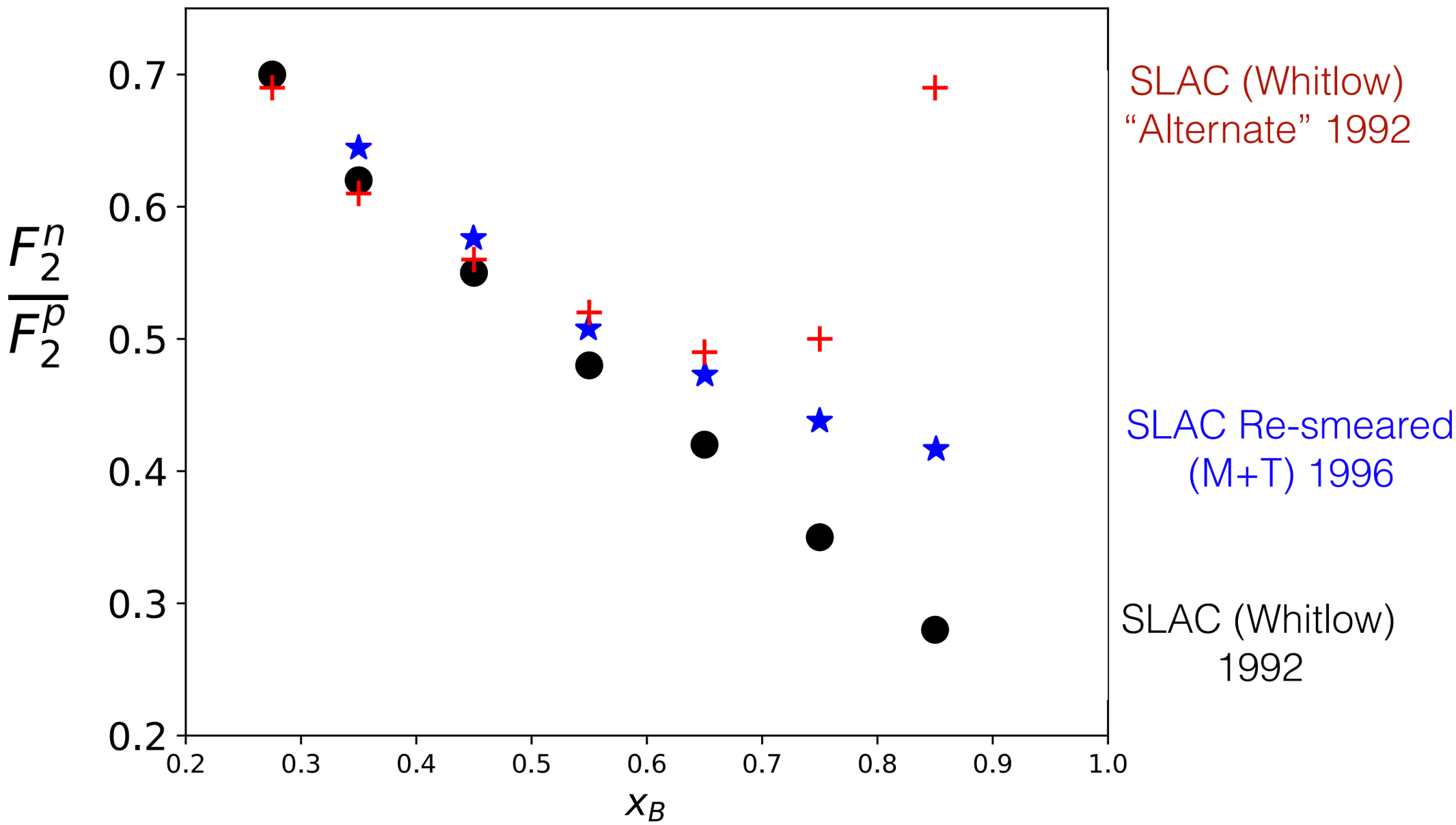
$$F_2^d \approx F_2^p + F_2^n$$

How to treat deuterium to get out neutron?

Smearing, off-shell, etc..

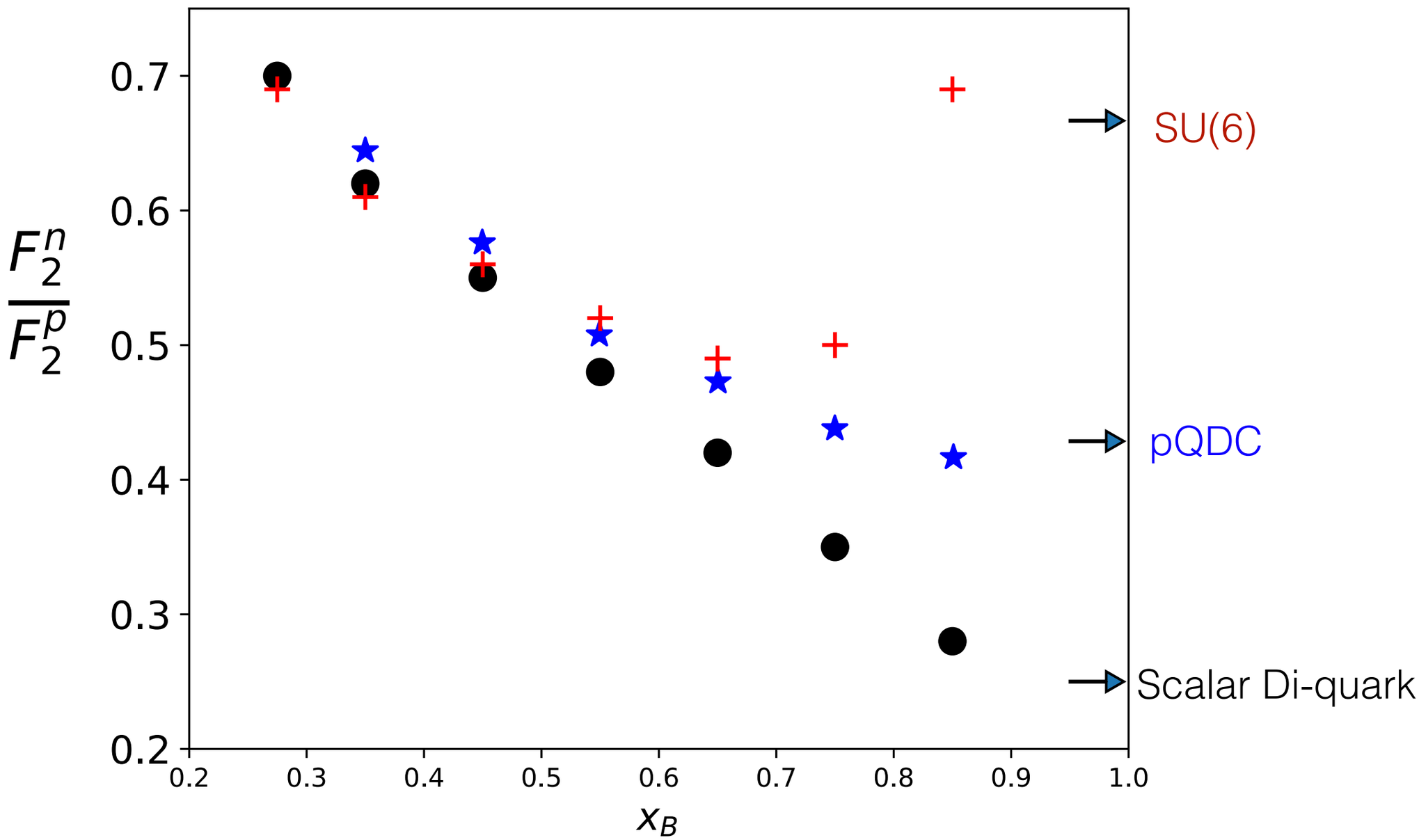
What about the neutron structure F_2?

$$F_2^d \approx F_2^p + F_2^n$$



Large-x informs us about valence nucleon structure

$$F_2^d \approx F_2^p + F_2^n$$

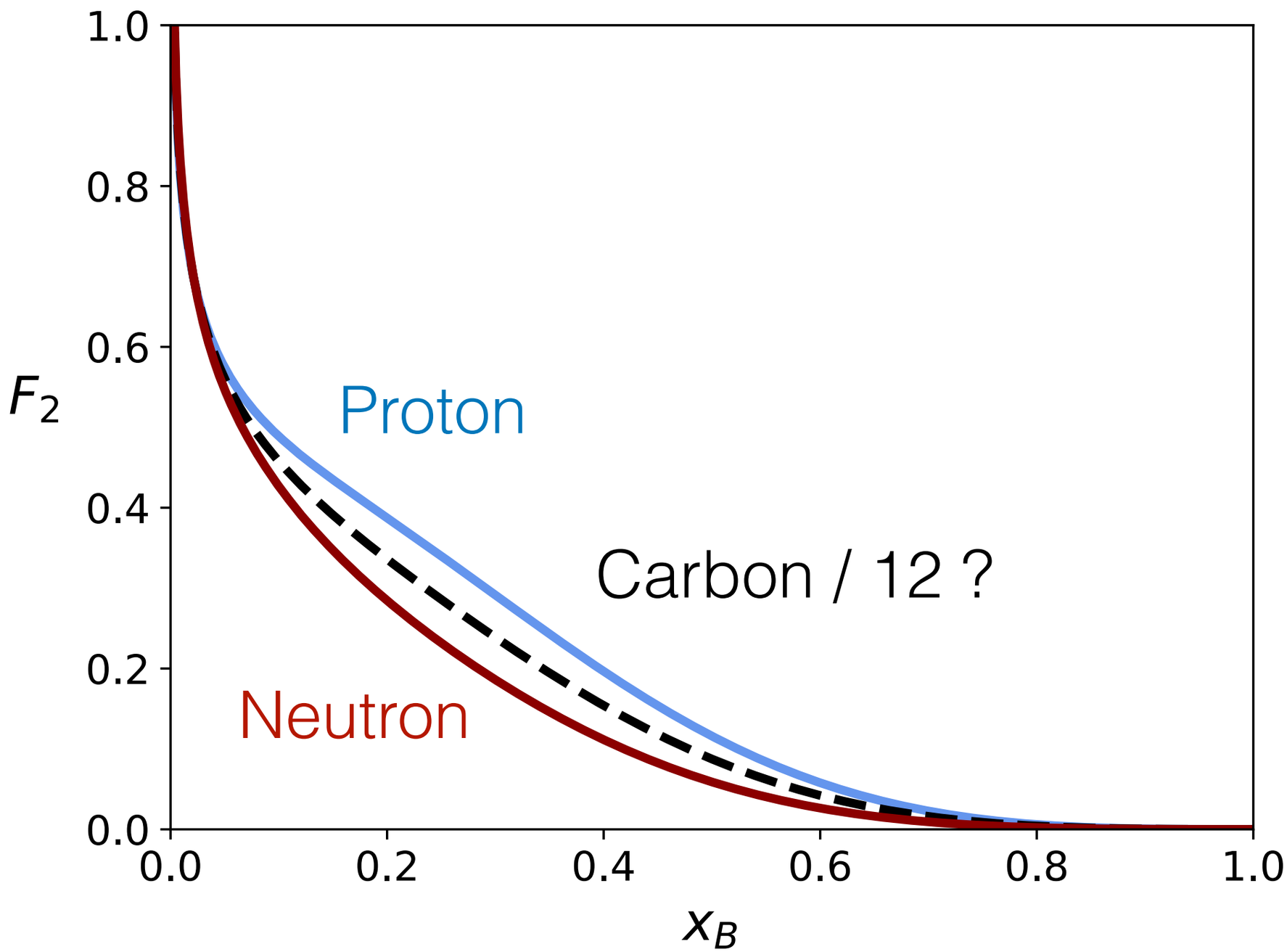


This has been an open question since 90's

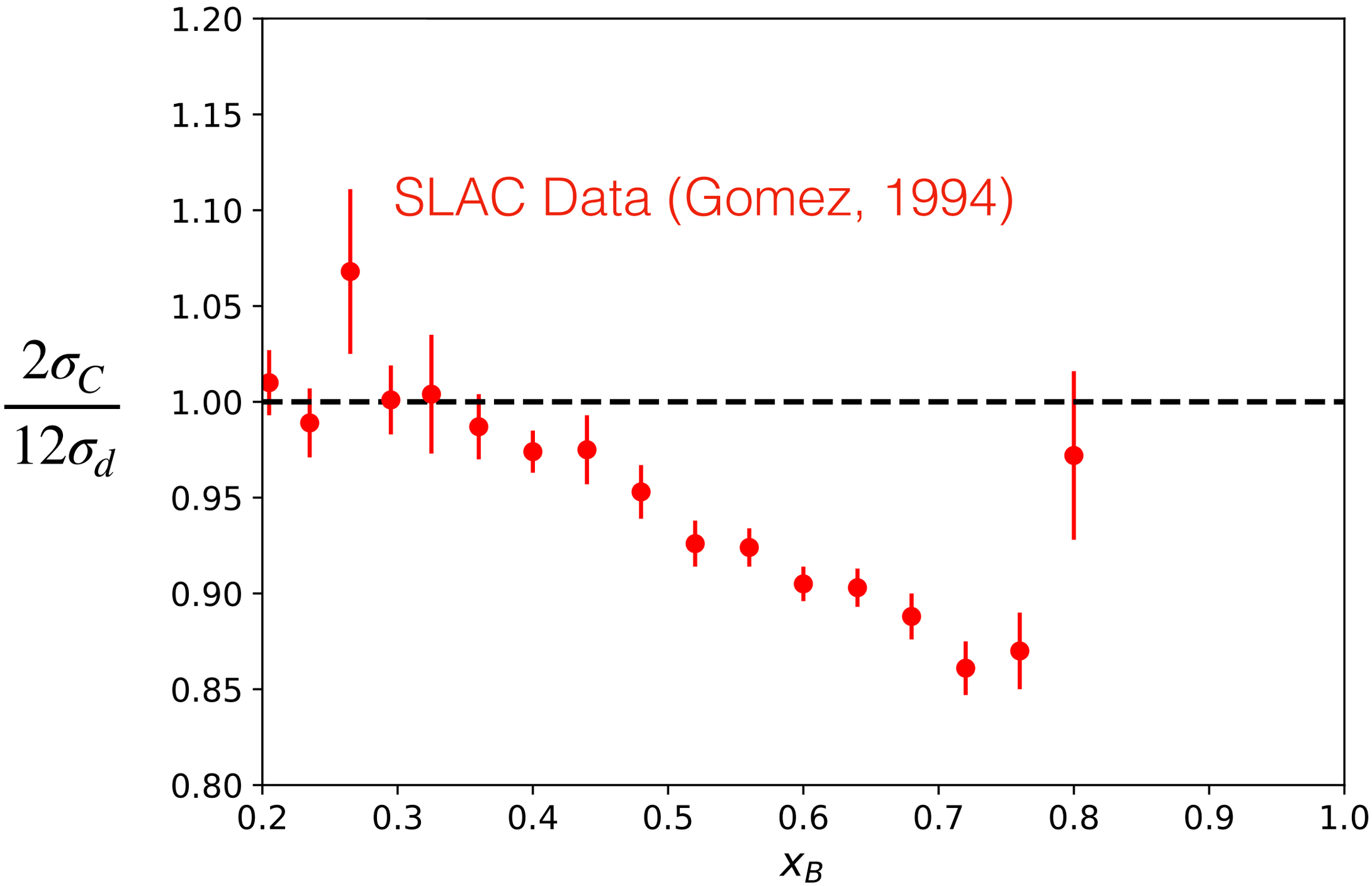
Using insight recently gained on origin on EMC effect, we propose another approach

Goal: constrain **high-*x***, low Q^2 free **and** bound nucleon structure **consistently** with **all** nuclear DIS and QE data

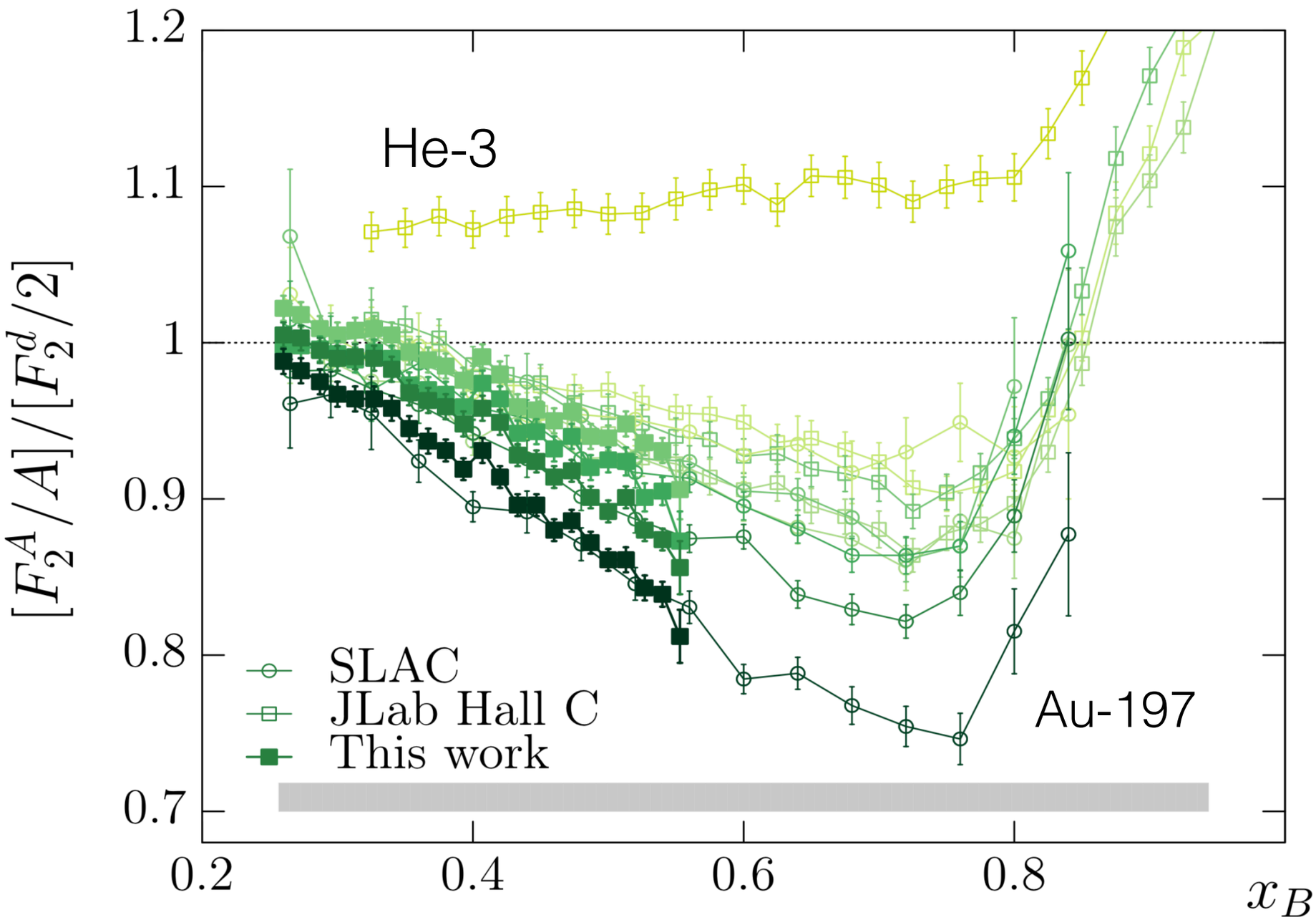
So what's the deal with bound nucleons?



EMC Effect

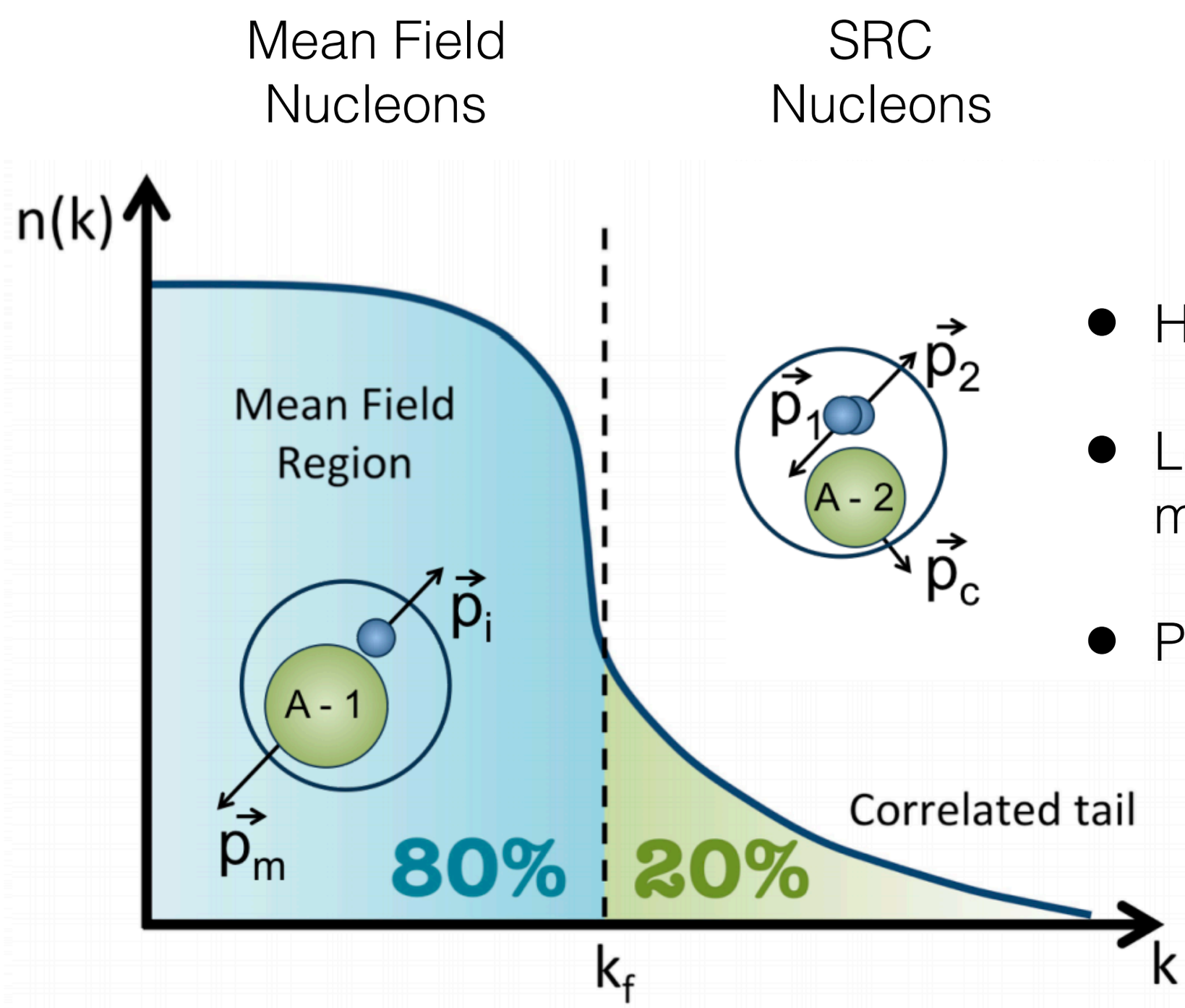

SLAC Data (Gomez, 1994)
$\frac{2\sigma_C}{12\sigma_d}$
1.20
1.15
1.10
1.05
1.00
0.95
0.90
0.85
0.80
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
x_B

EMC Effect — ***Nuclear*** Effect



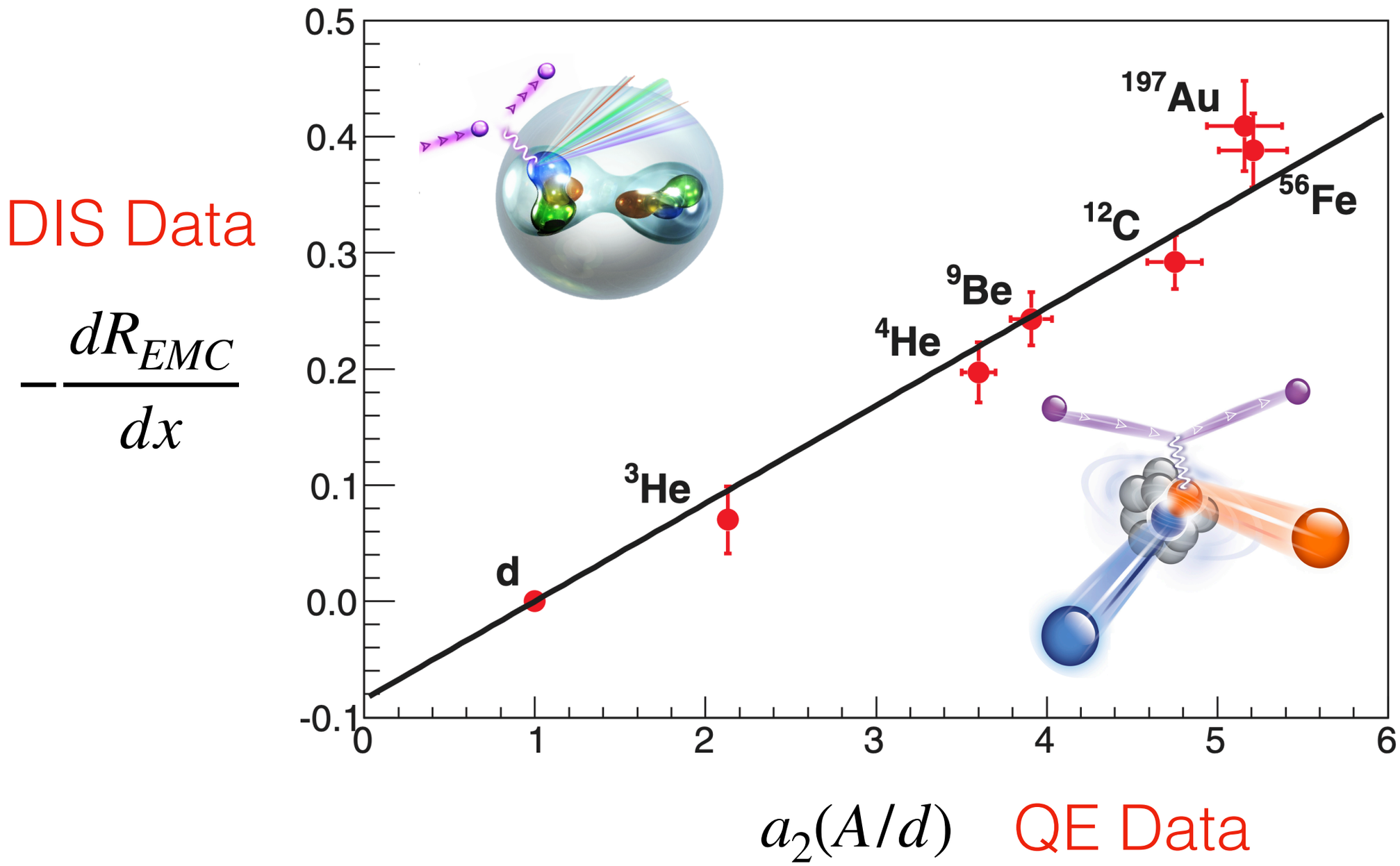
CLAS Collaboration, "Modified structure of protons and neutrons in correlated pairs", Nature 566 (2019) no.7744, 354-358

What else do we know about the nucleus?



- High relative mom.
- Low center-of-mass mom.
- Pairs np dominant

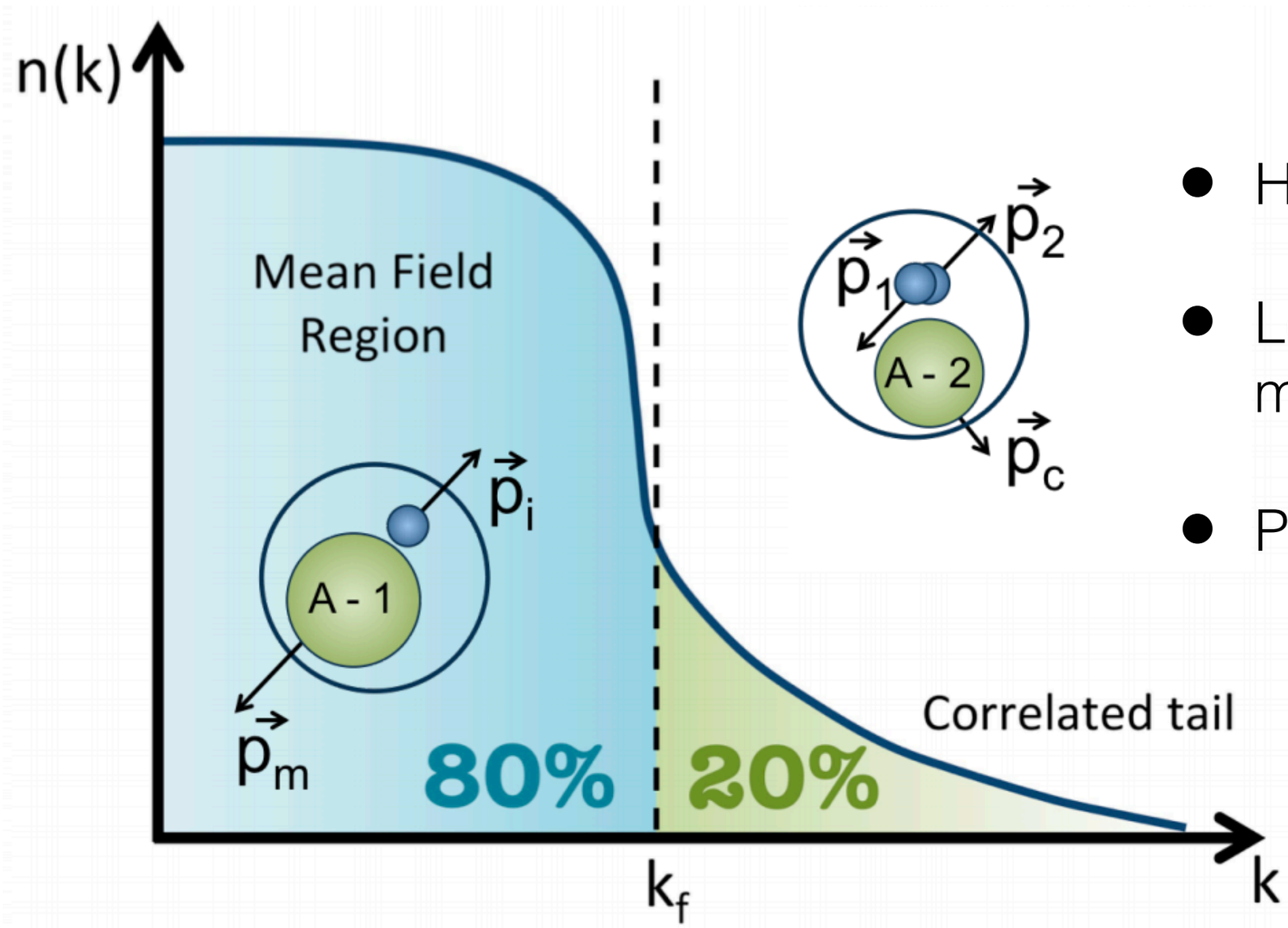
EMC slope tracks SRC pair density



O. Hen et al., "New data strengthen the connection between short range correlations and the EMC effect", Phys. Rev. C **85**, 047301 (2012)

"Bound" **"Free"** **"Modified"**

$$F_2^A = (Z - n_{SRC}^A)F_2^p + (N - n_{SRC}^A)F_2^n + n_{SRC}^A\left(F_2^{p*} + F_2^{n*}\right)$$



- High relative mom.
- Low center-of-mass mom.
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EMC-SRC hypothesis of universal modification

$$F_2^A = ZF_2^p + NF_2^n + n_{SRC}^A \left(\Delta F_2^p + \Delta F_2^n \right)$$

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$$F_2^d = F_2^p + F_2^n + n_{SRC}^d \left(\Delta F_2^p + \Delta F_2^n \right)$$

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$$F_2^d = F_2^p + F_2^n + n_{SRC}^d \left(\Delta F_2^p + \Delta F_2^n \right)$$

$$F_2^A = (Z - N)\, F_2^p + NF_2^d + \left(n_{SRC}^A - Nn_{SRC}^d \right) \left(\Delta F_2^p + \Delta F_2^n \right)$$

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Treat **all** bound nucleon structure **consistently** with **all** nuclear DIS and QE data

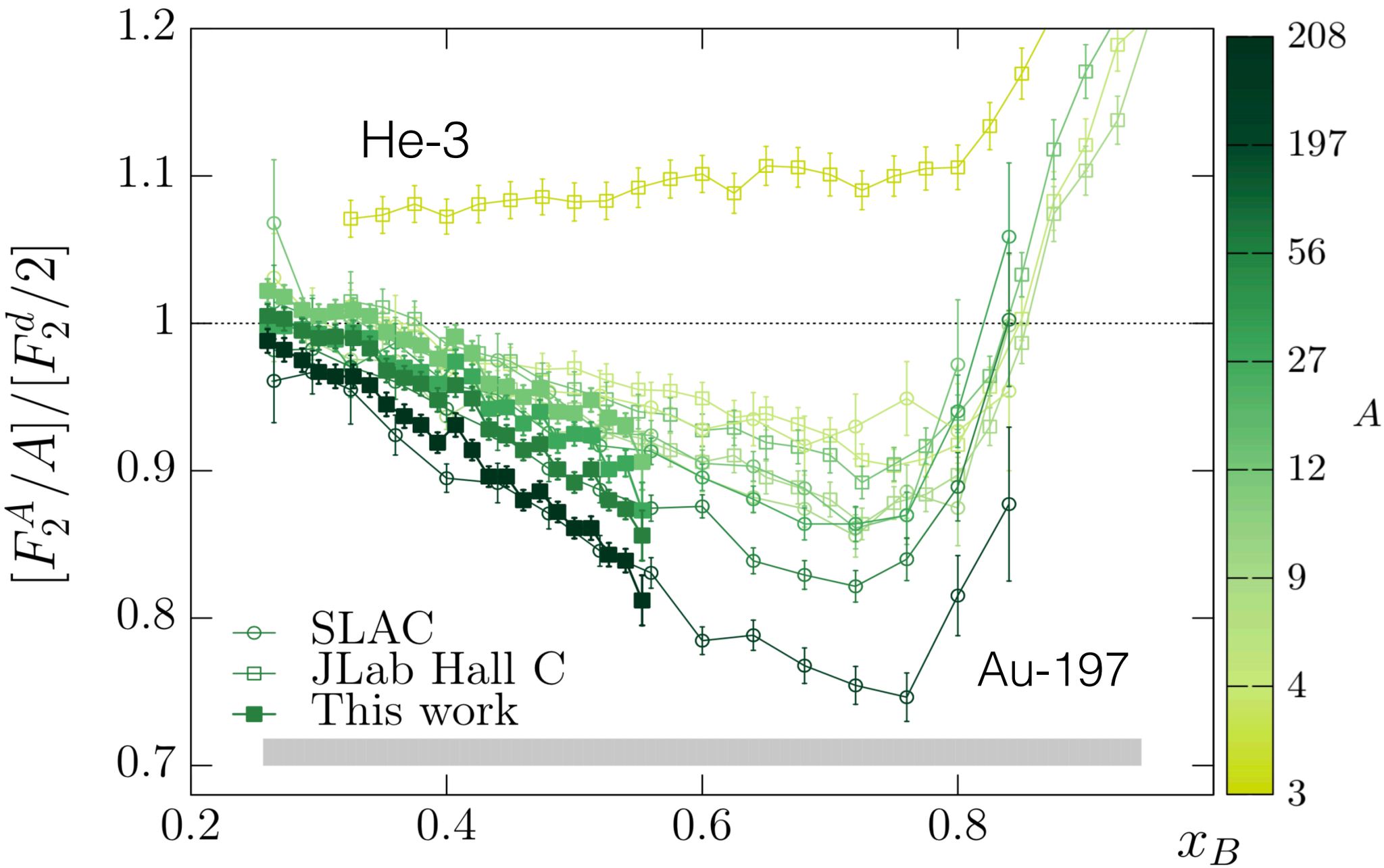
Universality Test

$$\frac{n_{SRC}^{d}}{F_2^d}\left(\Delta F_2^p + \Delta F_2^n\right) = \frac{\frac{F_2^A}{F_2^d} - (Z-N)\frac{F_2^p}{F_2^d} - N}{\frac{n_{SRC}^{A}}{n_{SRC}^{d}} - N}$$

Universal modification function

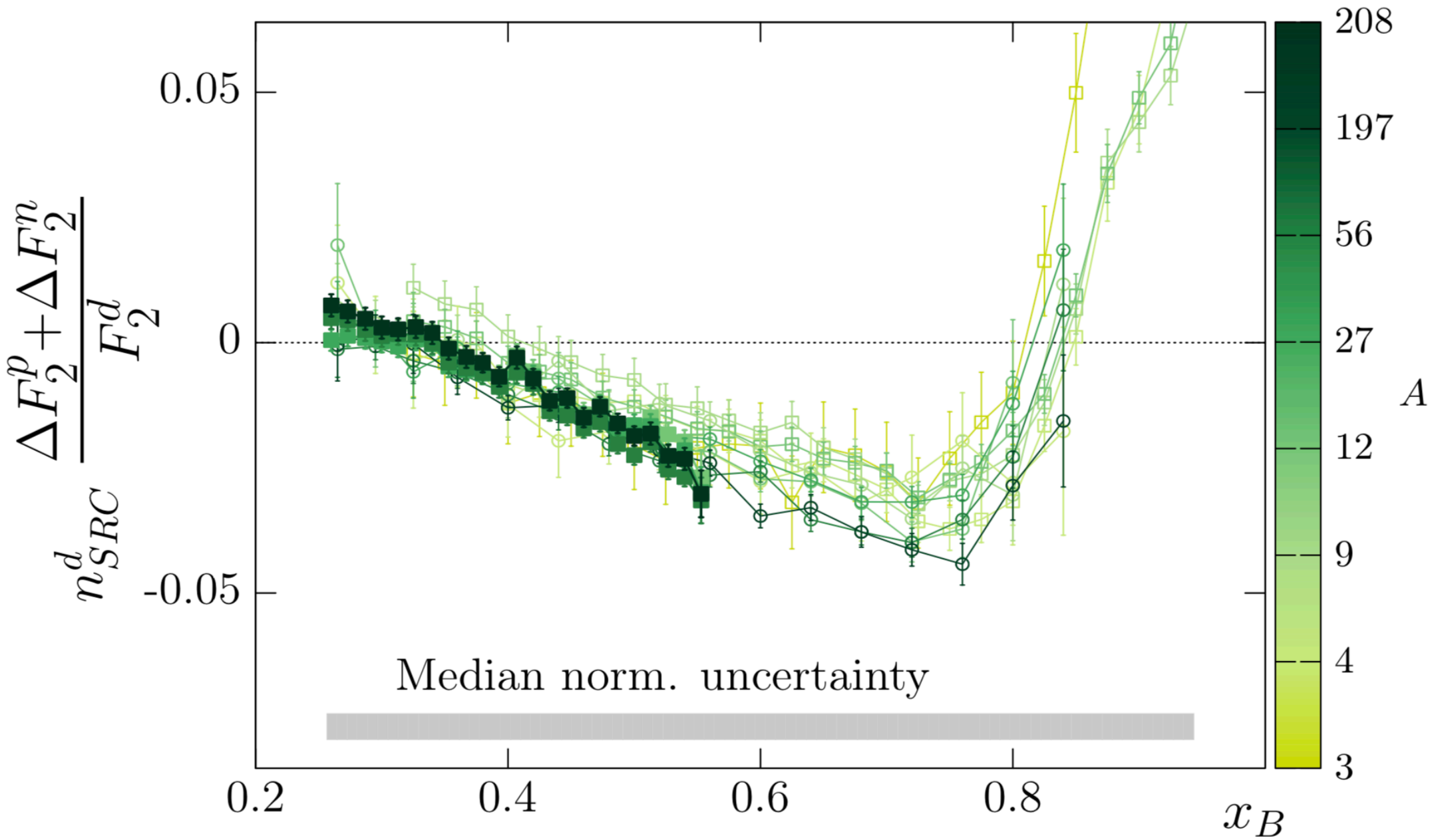
Nuclear-dependent

EMC data vary significantly for nuclei



CLAS Collaboration, "Modified structure of protons and neutrons in correlated pairs", Nature 566 (2019) no.7744, 354-358

But modification is universal



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Extract universal modification using Bayesian inference via Hamiltonian Markov Chain Monte Carlo

$$\frac{F_2^A}{F_2^d} = (Z-N)\frac{F_2^p}{F_2^d} + N + \left(\frac{n_{SRC}^A}{n_{SRC}^d} - N\right)\frac{n_{SRC}^d}{F_2^d}\left(\Delta F_2^p + \Delta F_2^n\right)$$

EMC data

Proton-Deuterium data

$\sim a_2(A/d)$

Universal modification function

Extract universal modification using Bayesian inference via Hamiltonian Markov Chain Monte Carlo

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EMC data

Proton-Deuterium data

$\sim a_2(A/d)$

Universal modification function

$x \in [0.08, 0.95]$ $Q^2 \in [2,15]$ GeV^2

^{3}He, ^{4}He, ^{9}Be, ^{12}C, ^{27}Al, ^{56}Fe, ^{197}Au, ^{208}Pb

(interested in moderate-to-high x ~ 0.2,0.95)

Extract universal modification using Bayesian inference via Hamiltonian Markov Chain Monte Carlo

$$\frac{F_2^A}{F_2^d} = (Z-N)\frac{F_2^p}{F_2^d} + N + \left(\frac{n_{SRC}^A}{n_{SRC}^d} - N\right)\frac{n_{SRC}^d}{F_2^d}\left(\Delta F_2^p + \Delta F_2^n\right)$$

EMC data

Proton-Deuterium data

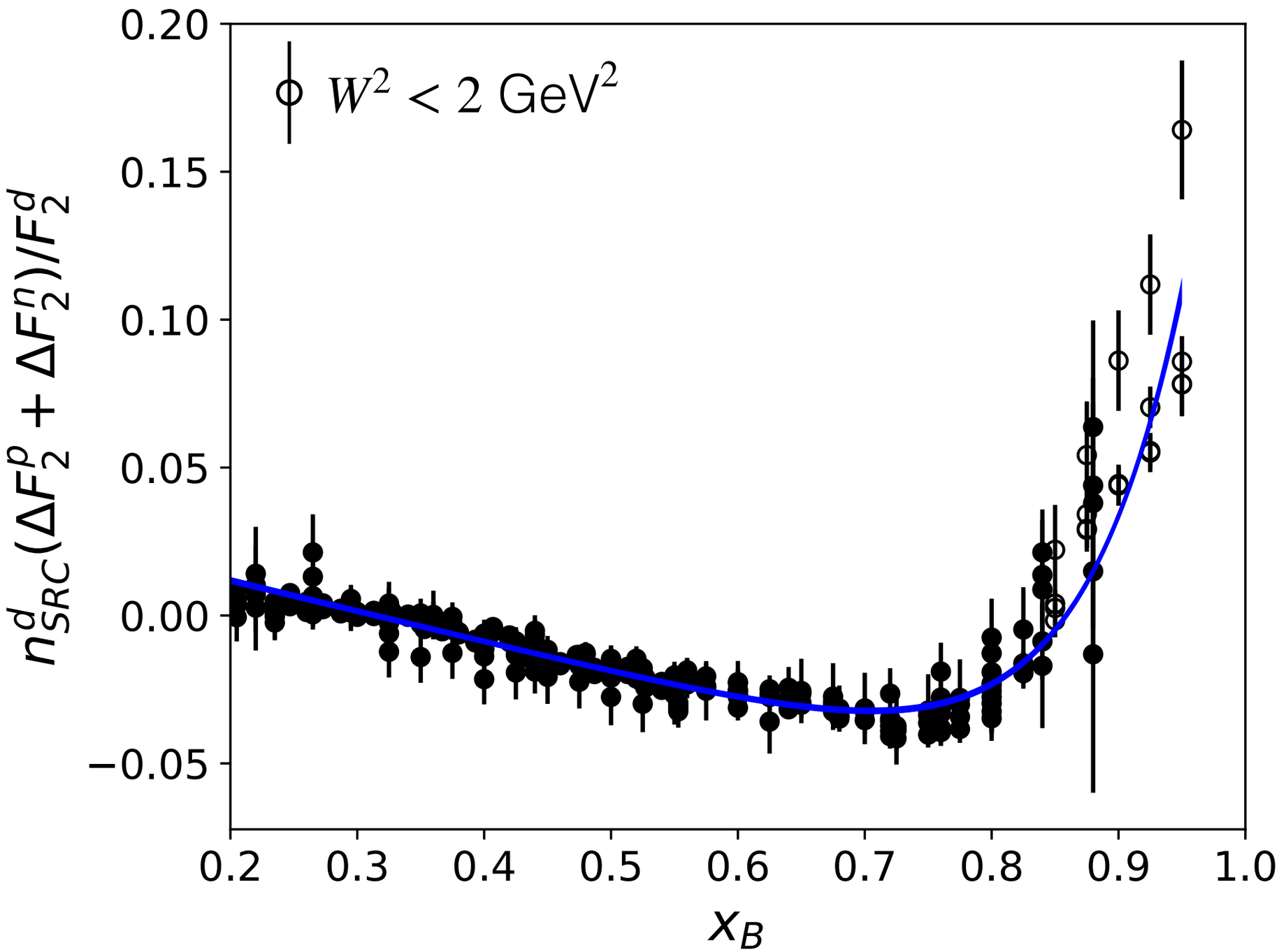
$\sim a_2(A/d)$

Universal modification function

Consistent, simultaneous global extraction of 31 model parameters sampled from joint-posterior distribution

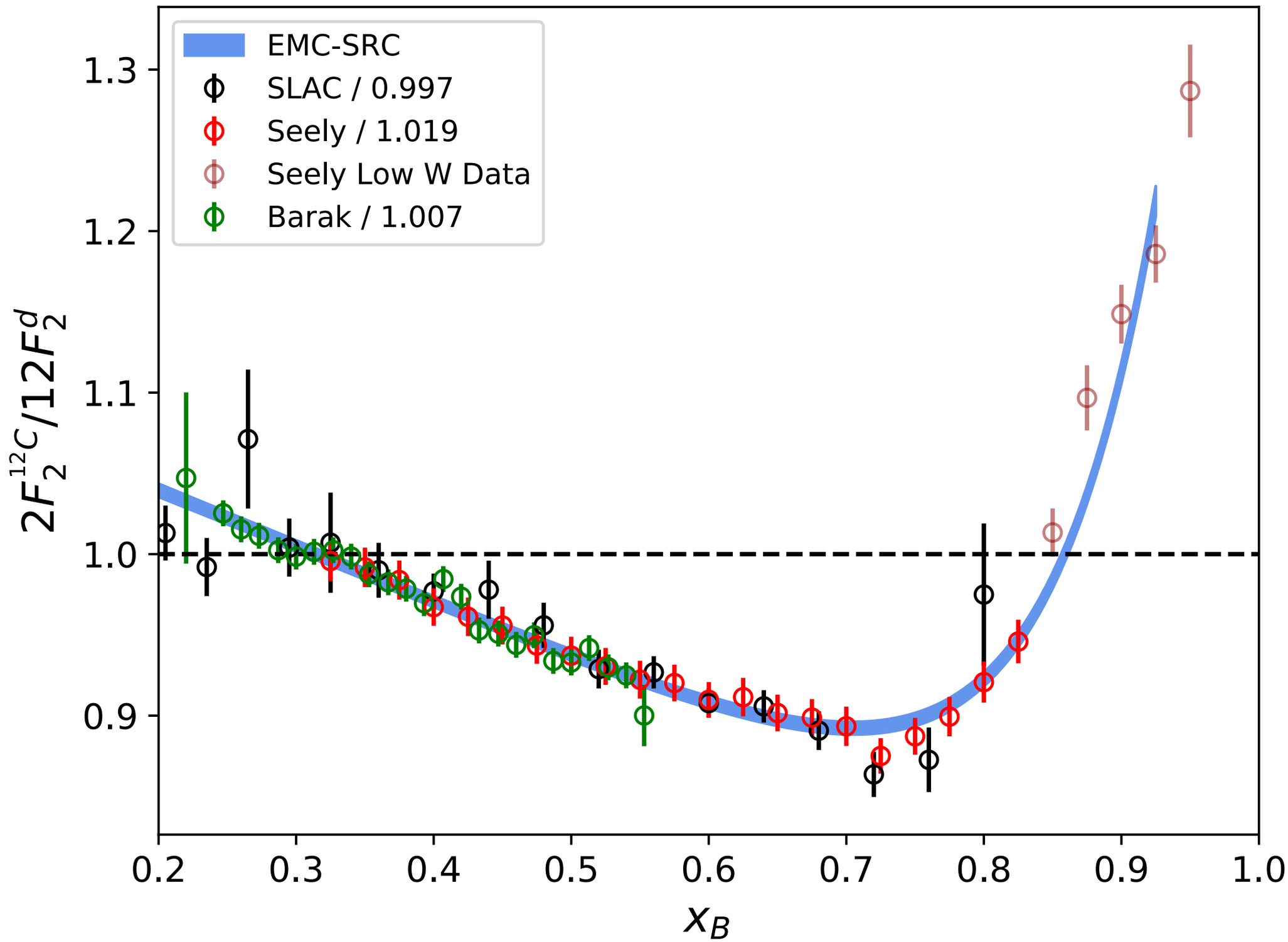
$f_{univ}(x)$ $R_{pd}(x)$ $\vec{s}_i$ $\vec{a}_2(A/d)$

Extract universal modification using Bayesian inference via Hamiltonian Markov Chain Monte Carlo



(All 31 model parameters simultaneously extracted from joint posterior)

Reproduce the data remarkably well



Extracting the free neutron structure F_2

$$F_2^d = F_2^p + F_2^n + n_{SRC}^d \left(\Delta F_2^p + \Delta F_2^n \right)$$

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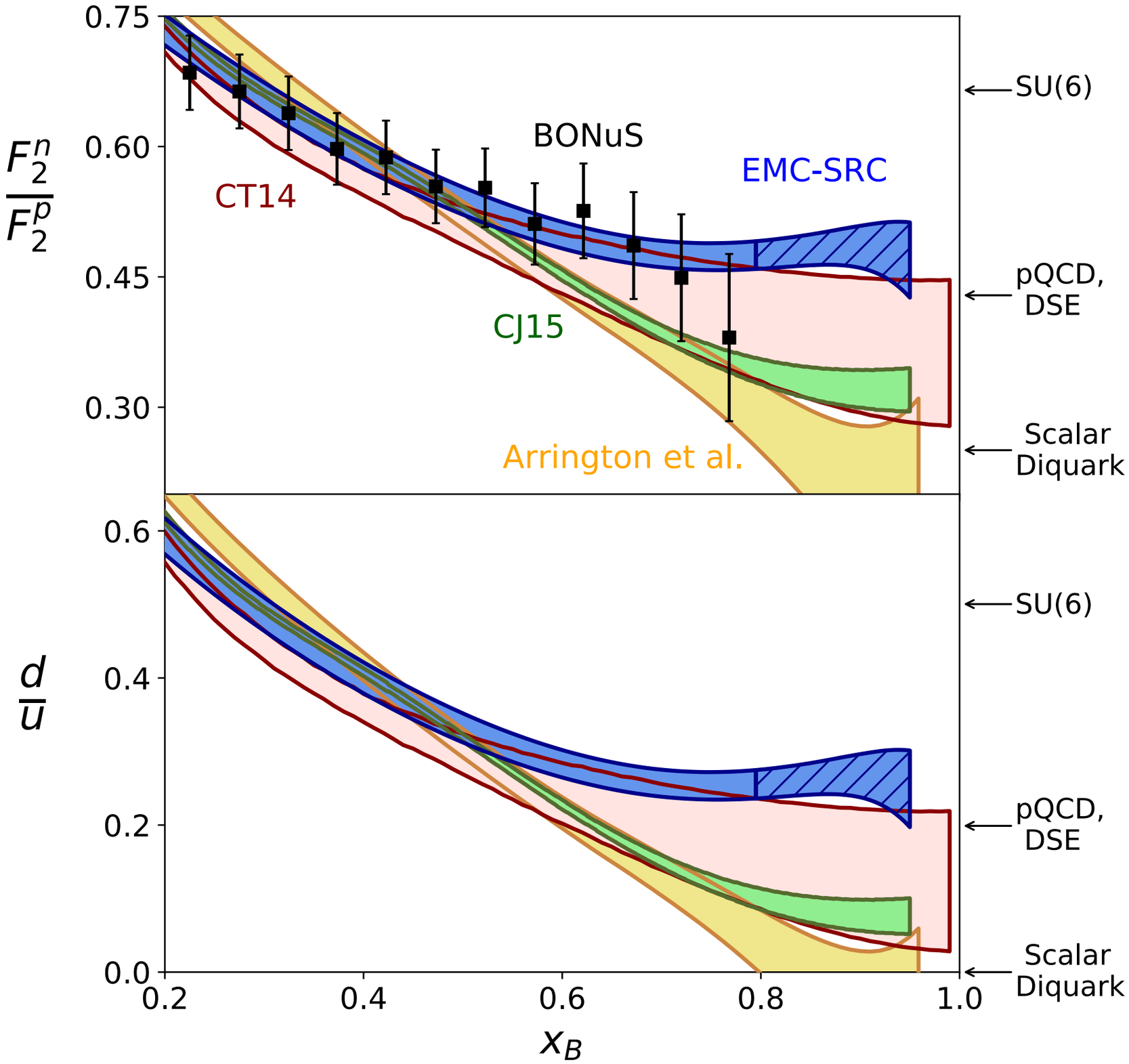


Our model goal:

Constrain **high-*x***, low Q^2 free **and** bound nucleon structure **consistently** with **all** nuclear DIS and QE data

Disadvantages:

Model-dependent extraction

How can we test this hypothesis with experiment

- MARATHON (Hall A)
- BAND (Hall B, RG-B)

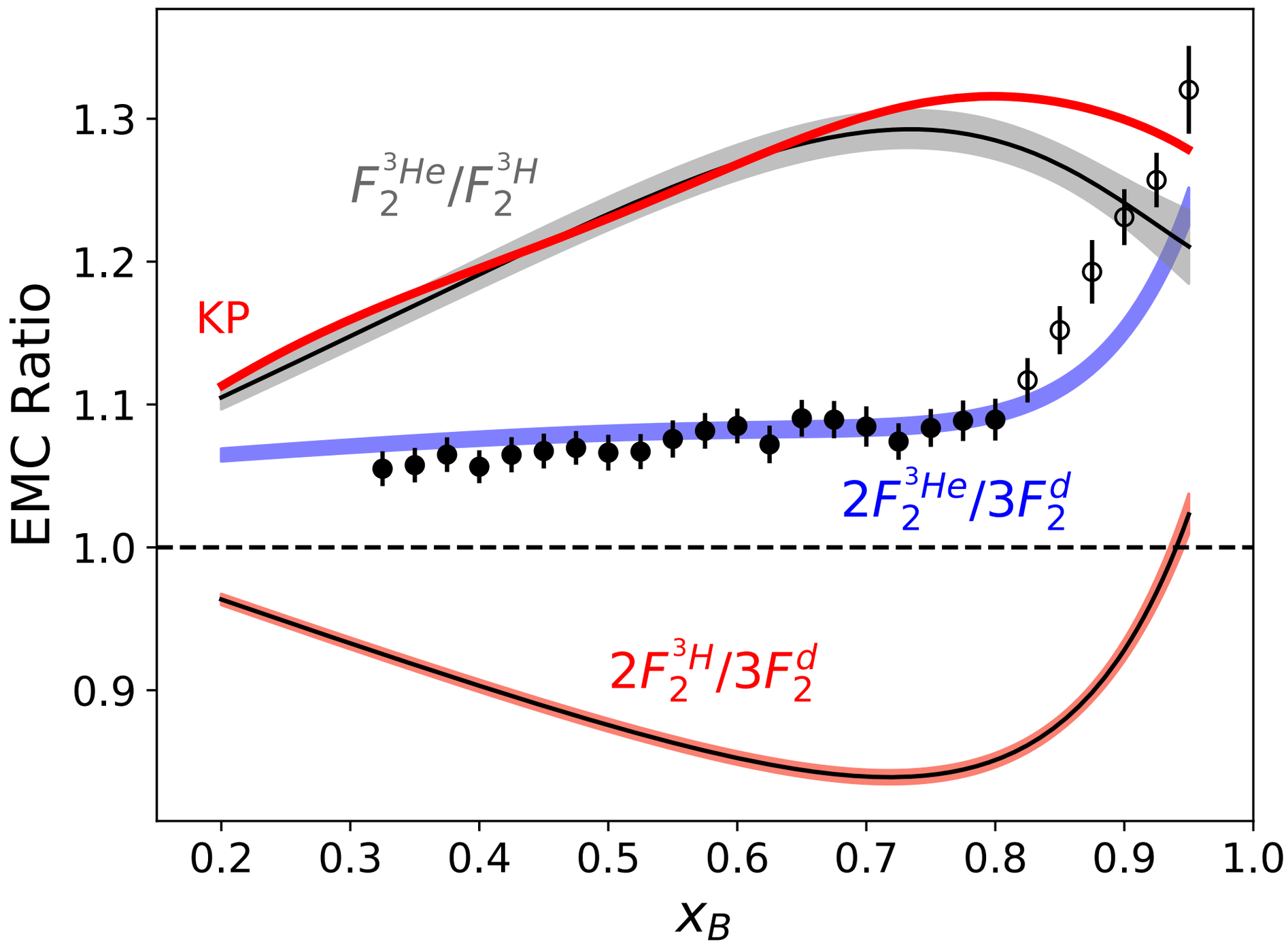
Checking extracted free neutron structure in A=3 nuclei

(MARATHON Experiment, Hall A)

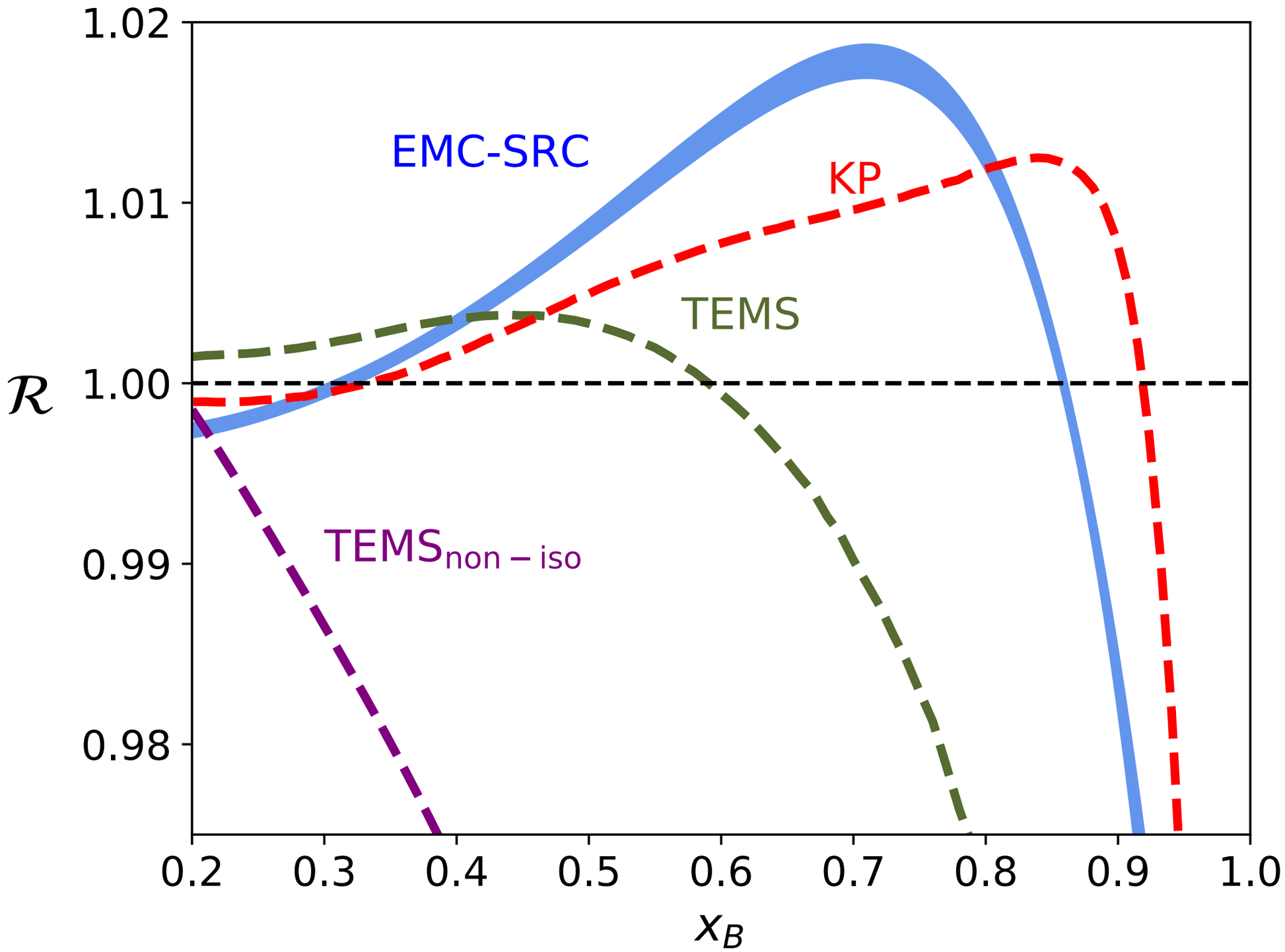
$$\frac{F_2^n}{F_2^p} = \frac{2\mathscr{R} - F_2^{^3He}/F_2^{^3H}}{2F_2^{^3He}/F_2^{^3H} - \mathscr{R}}$$

$$\mathscr{R} = \frac{F_2^{^3He}}{2F_2^p + F_2^n} \cdot \frac{F_2^p + 2F_2^n}{F_2^{^3H}}$$

A=3 Predictions for MARATHON



Super-ratio theoretical input



Model uncertainty in neutron structure F_2 from A=3 nuclei

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

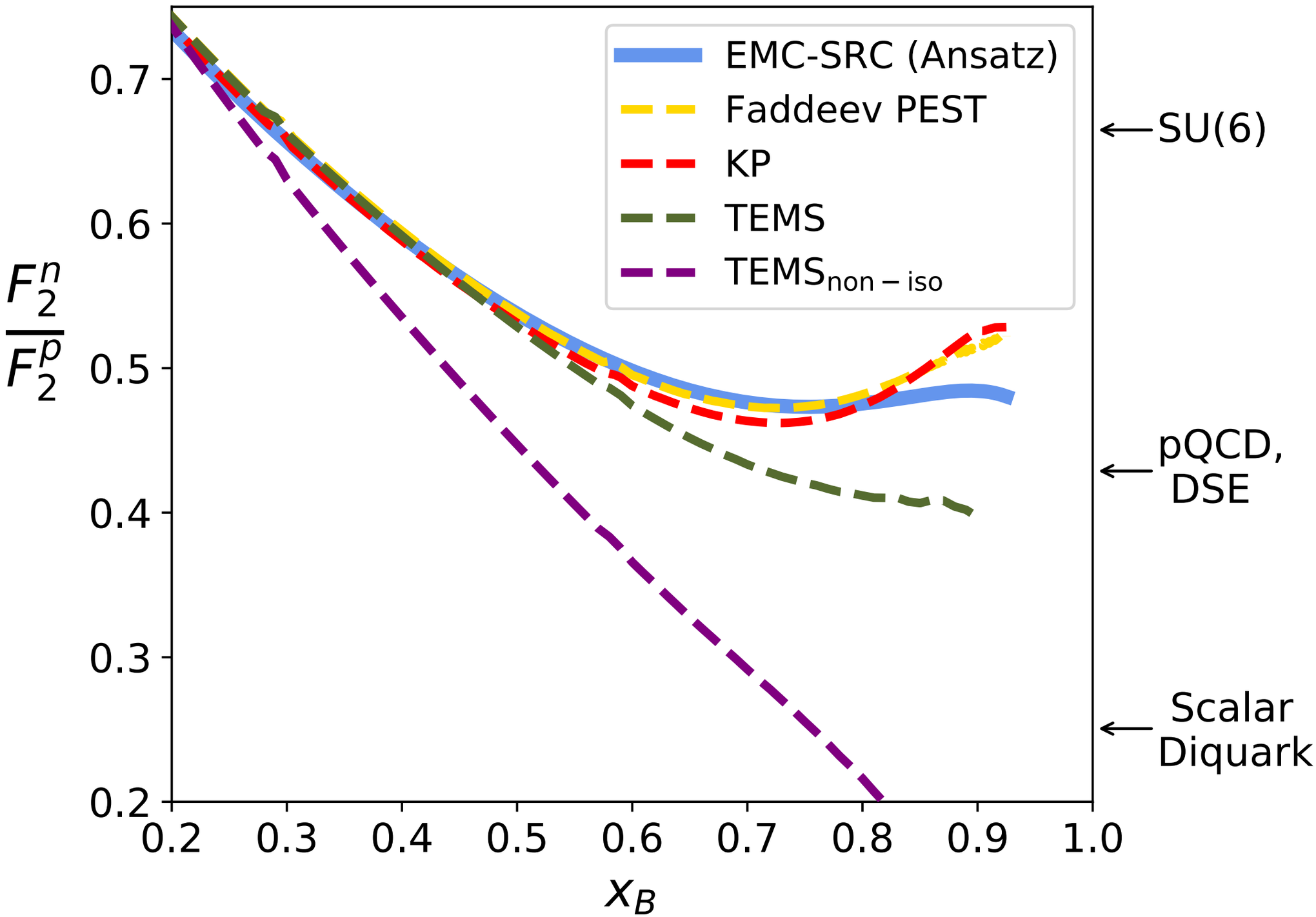
Assuming EMC ratio from one model

$$\mathscr{R} = \frac{F_2^{^3He}}{2F_2^p + F_2^n} \cdot \frac{F_2^p + 2F_2^n}{F_2^{^3H}}$$

With input of different super-ratios

Model uncertainty in neutron structure F_2 from A=3 nuclei

~10% uncertainty due to super-ratio model



Is modification really driven by nucleons in SRC states?

$$F_2^A = ZF_2^p + NF_2^n + n_{SRC}^A \left(\Delta F_2^p + \Delta F_2^n \right)$$

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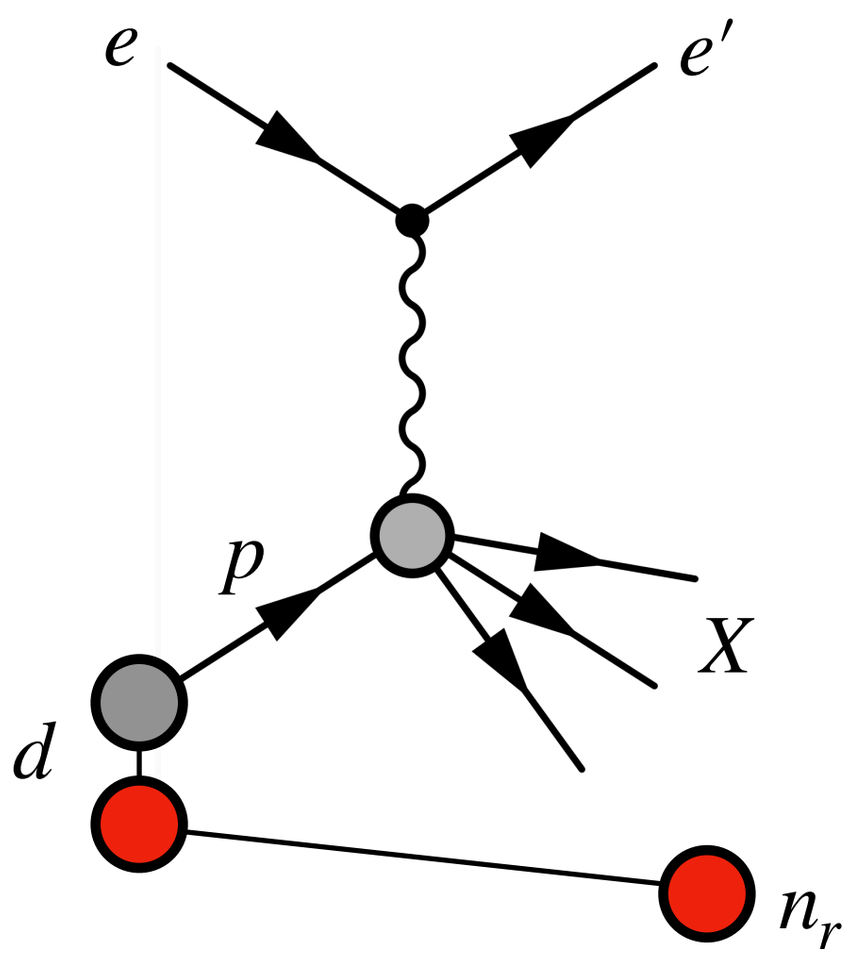
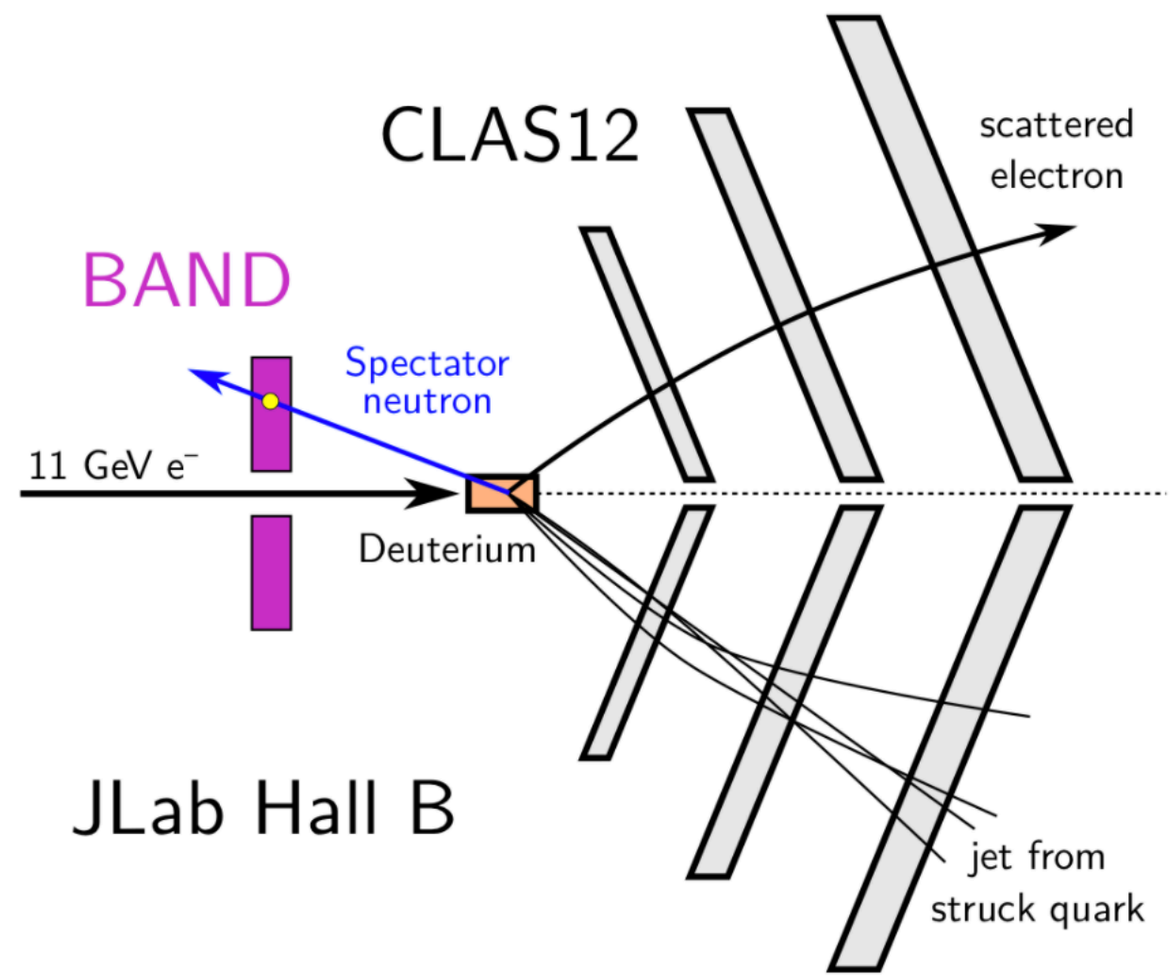
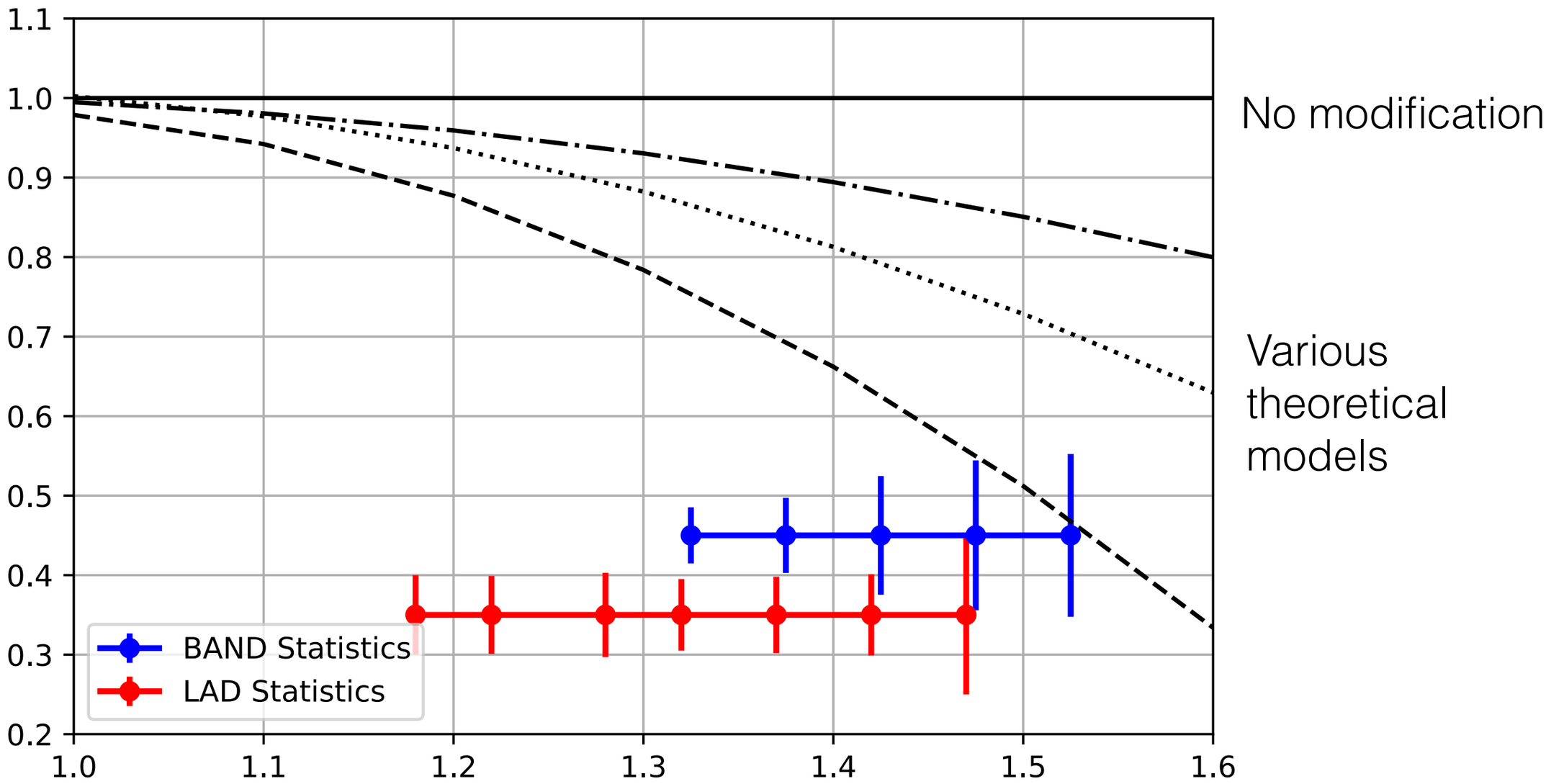
BAND Experiment in Hall B (RG-B)





Is modification really driven by nucleons in SRC states?

Bound F_2 / Free F_2 (measuring universal function)

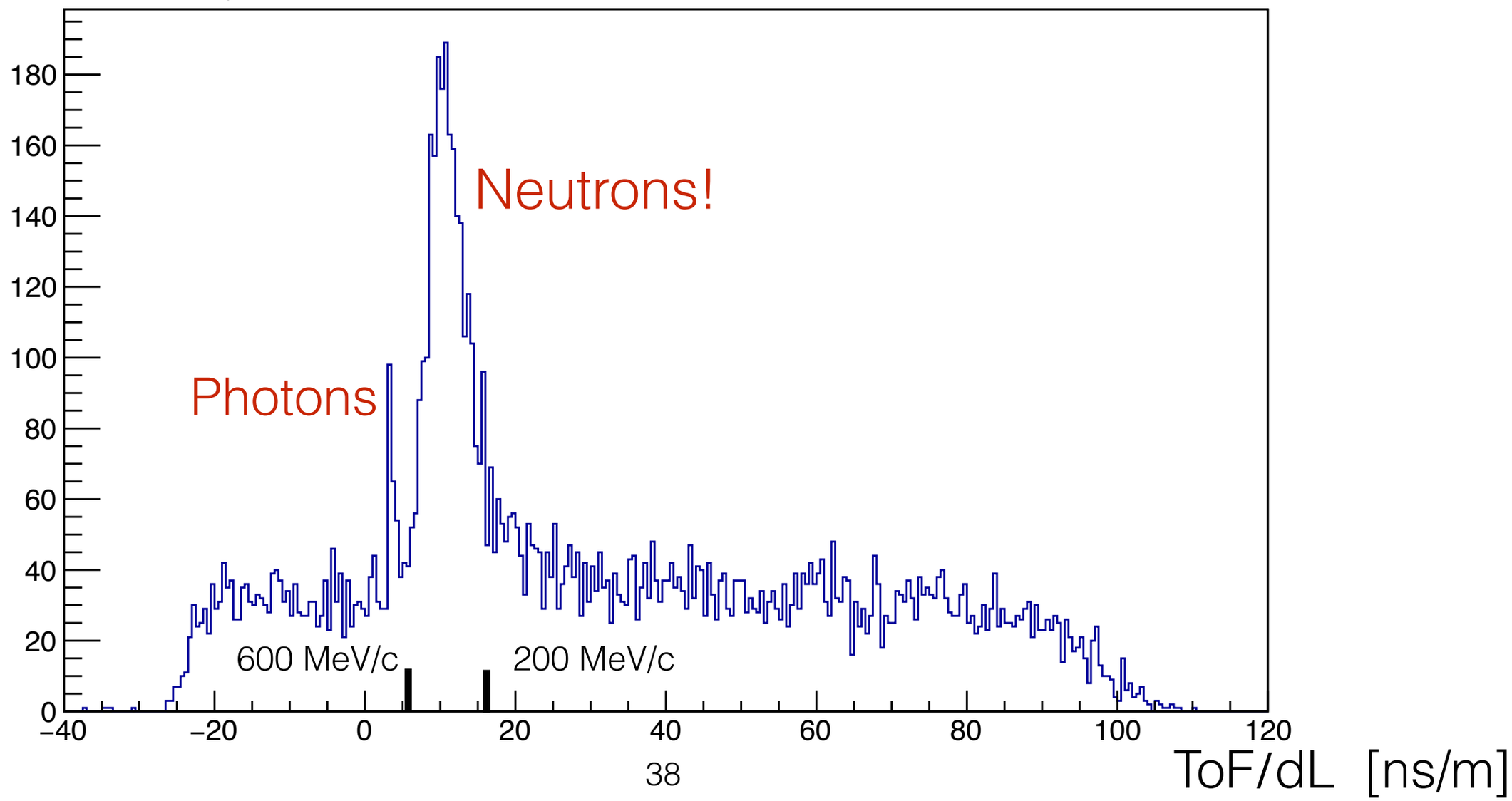


$\alpha_s = (E_s - p_s^z)/m_s$ (Virtuality)

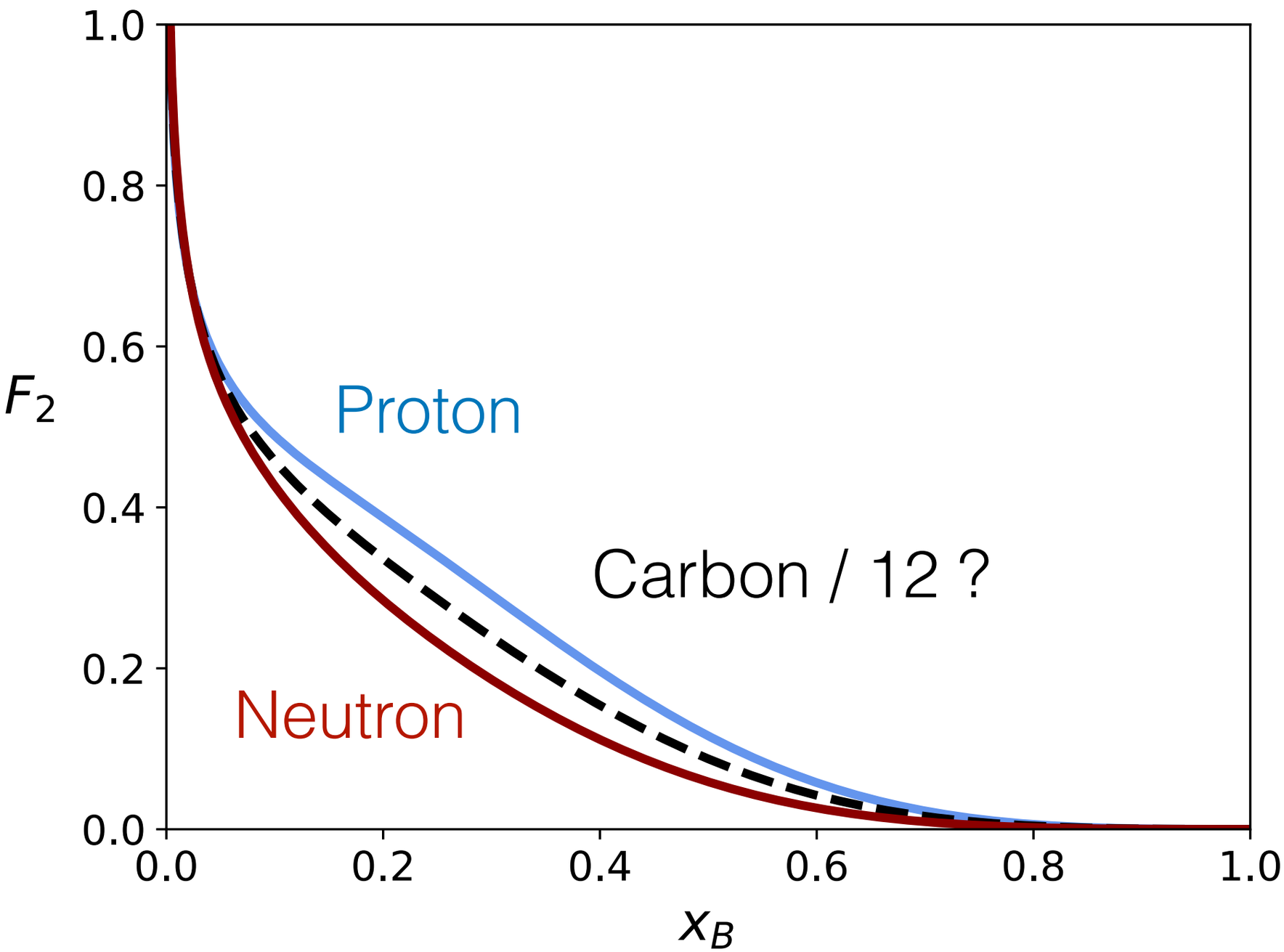
Status of BAND

- RG-B 50% complete
- New detector fully calibrated
- Building analysis framework in simulation
- CLAS cooking & calibration in progress

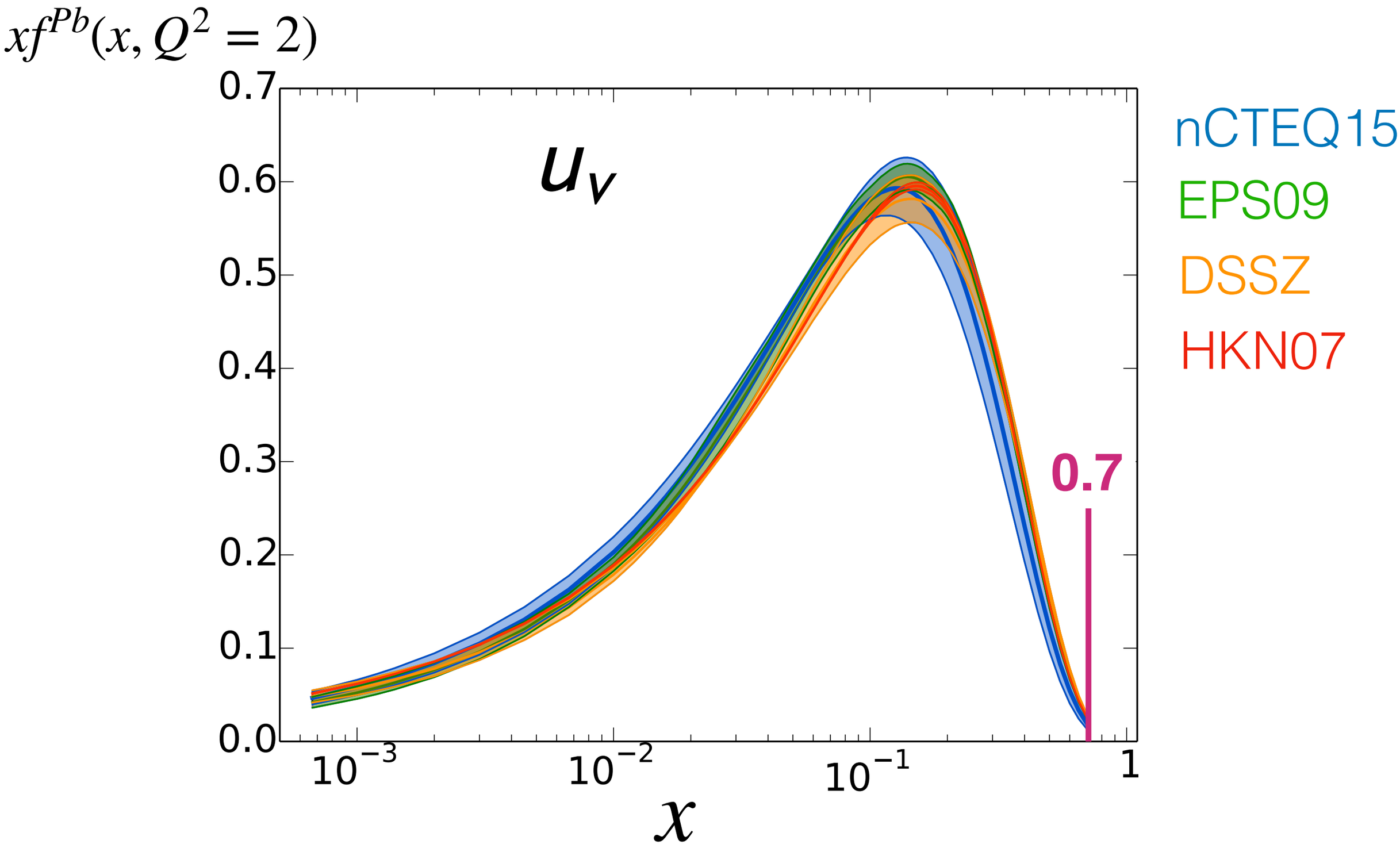
One full day @ 50nA, W>2.2 GeV, Q^2>2, x~0.3,BAND neutral hits



Path towards extracting bound nuclear PDFs



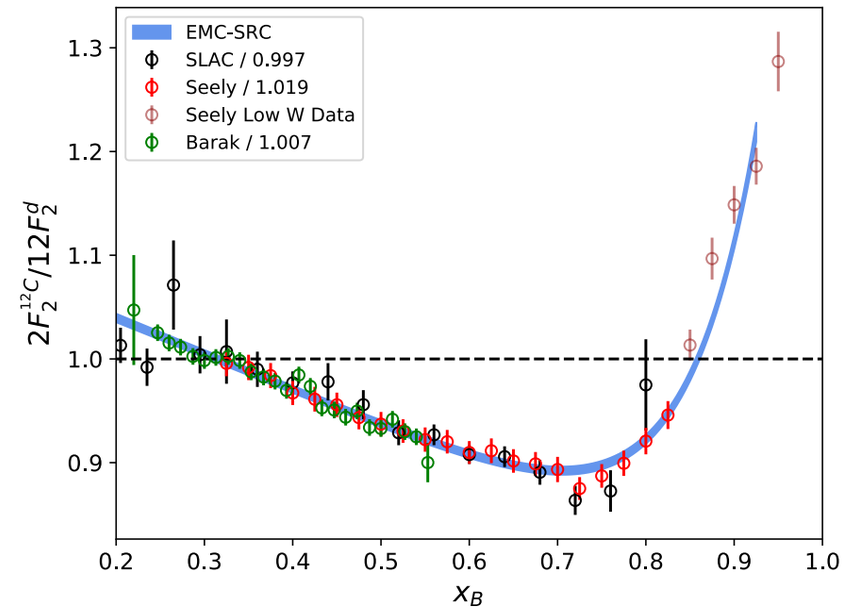
Bound nuclear PDFs for low Q^2, high x

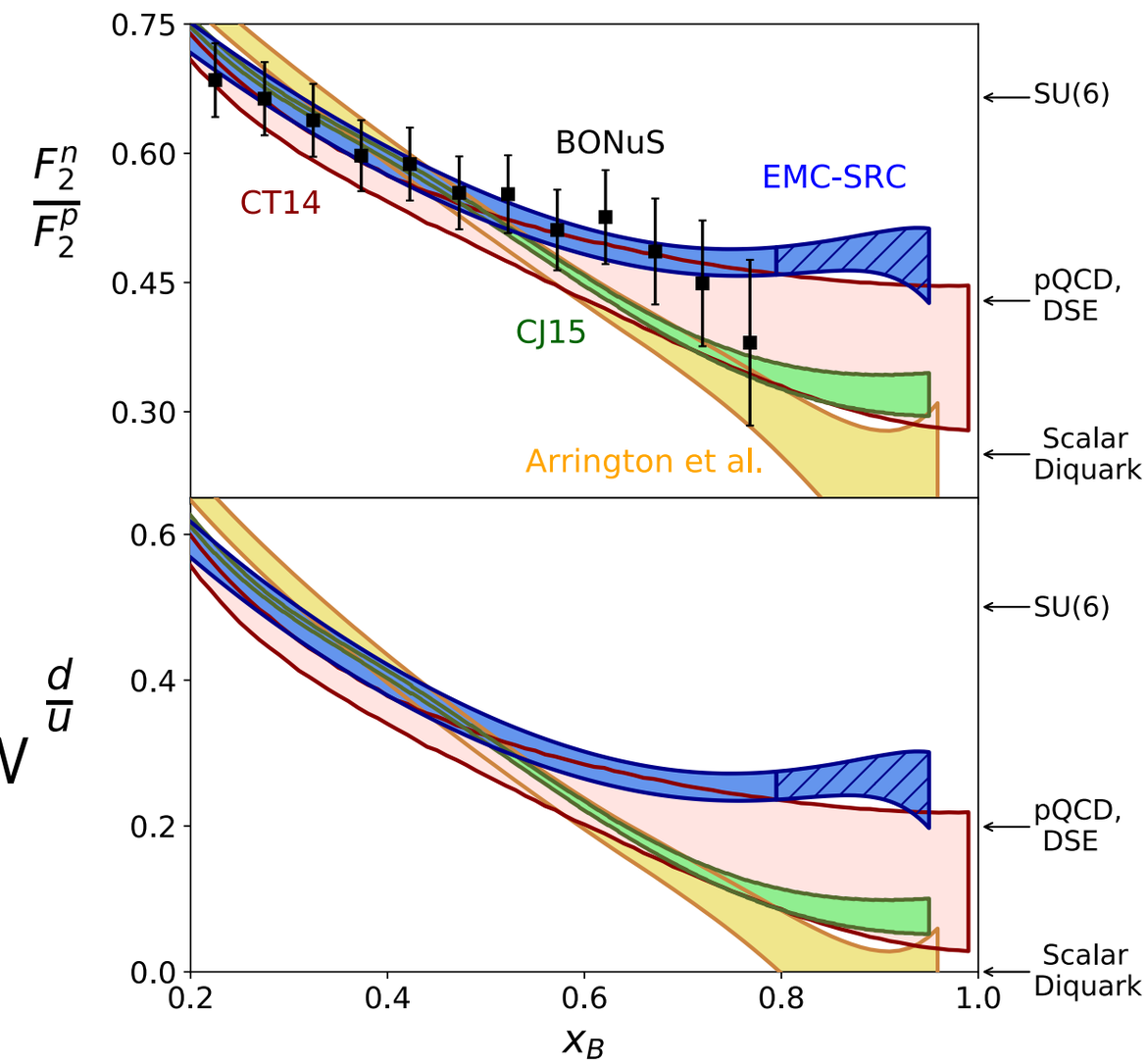


(Collaborative work with Fred Olness, Thia Keppel, Karol Kovarik, and many more)

On the path to understanding bound nucleon structure

- New method of extraction to consistently explain free and bound nucleon structure
- Predictive power for MARATHON
- Validating model assumptions with BAND
- Bound nuclear PDFs for low Q^2, high x





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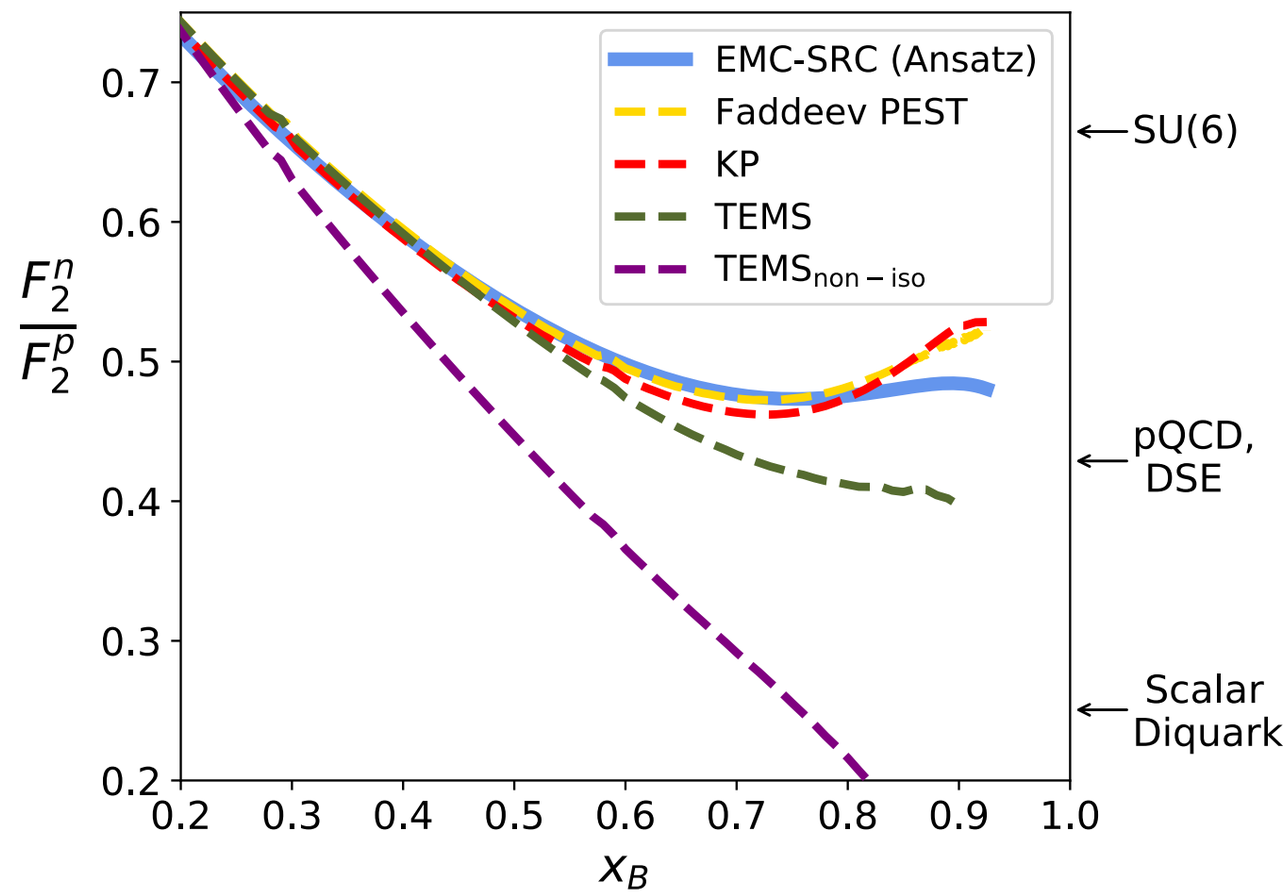

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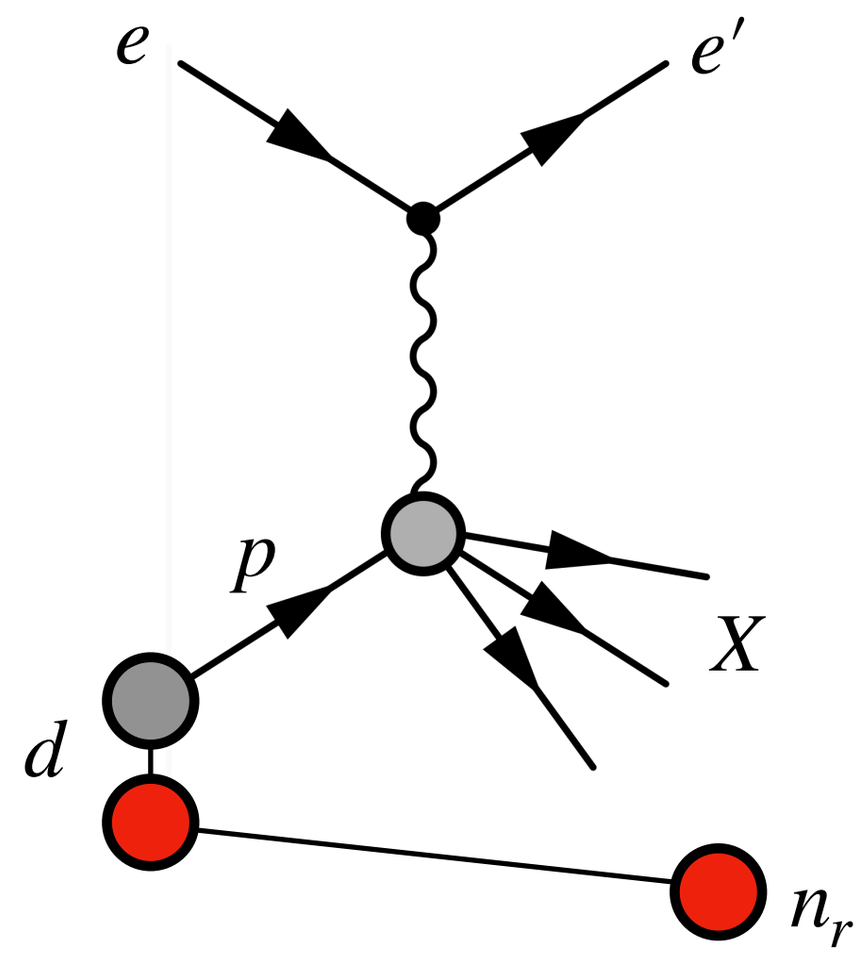

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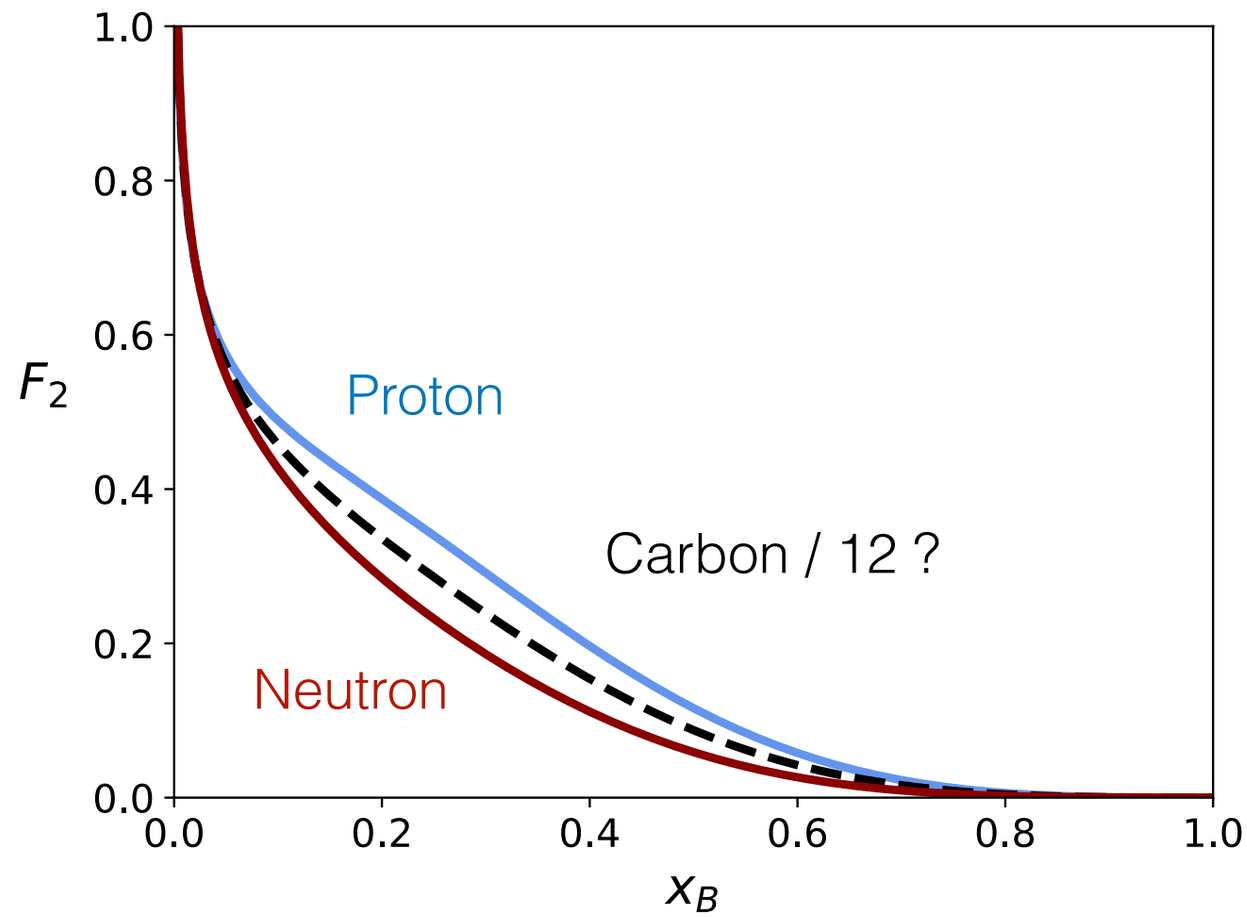


Thanks! Questions?

Efrain Segarra

Jefferson Lab 2019 Users Organization
Annual Meeting

June 25, 2019

Back up

Parameterization Form

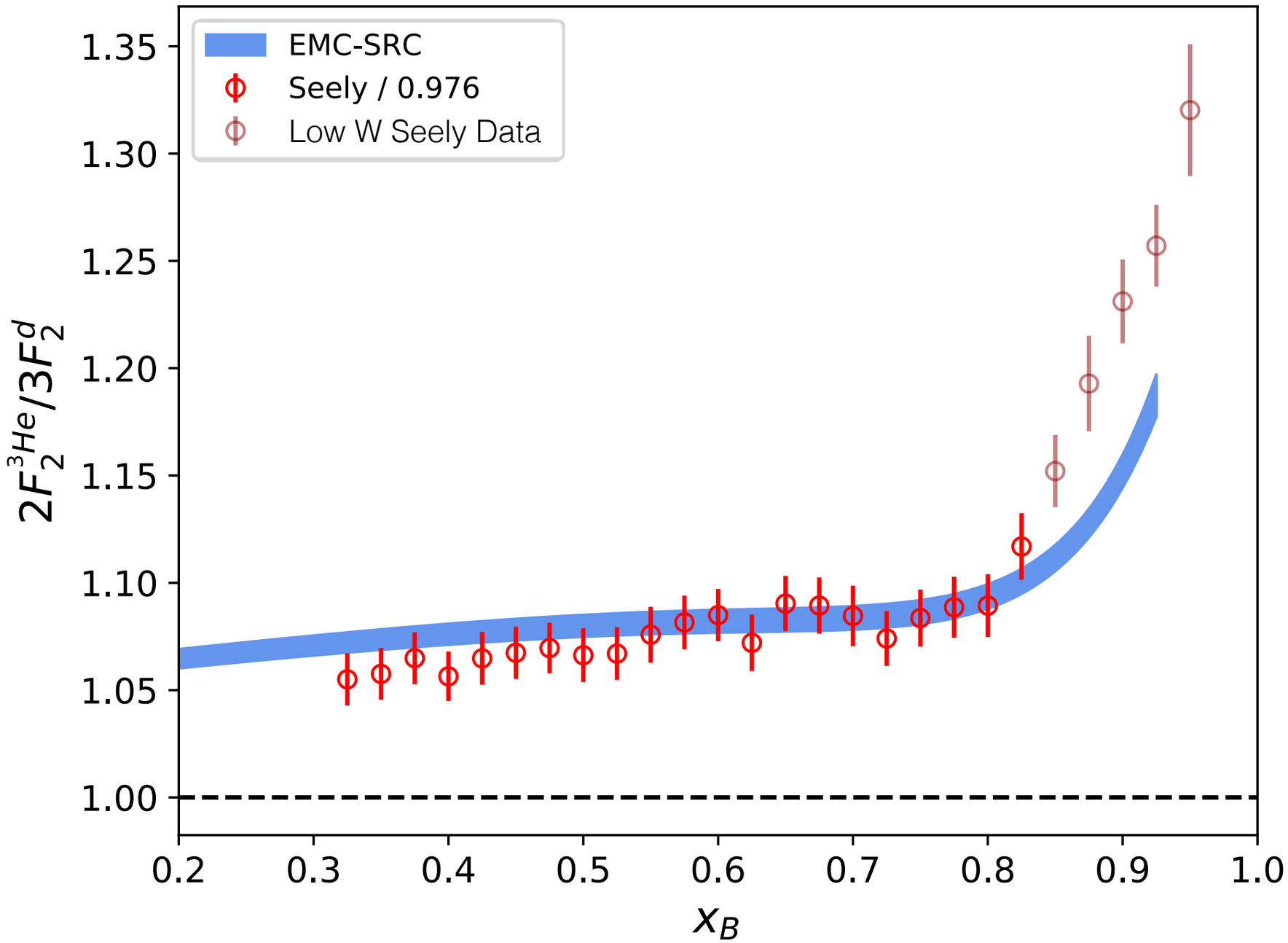
$$\frac{n_{SRC}^{d}}{F_2^d}\left(\Delta F_2^p + \Delta F_2^n\right) = \alpha + \beta x + \gamma e^{(1-x)\delta}$$

Universal modification function

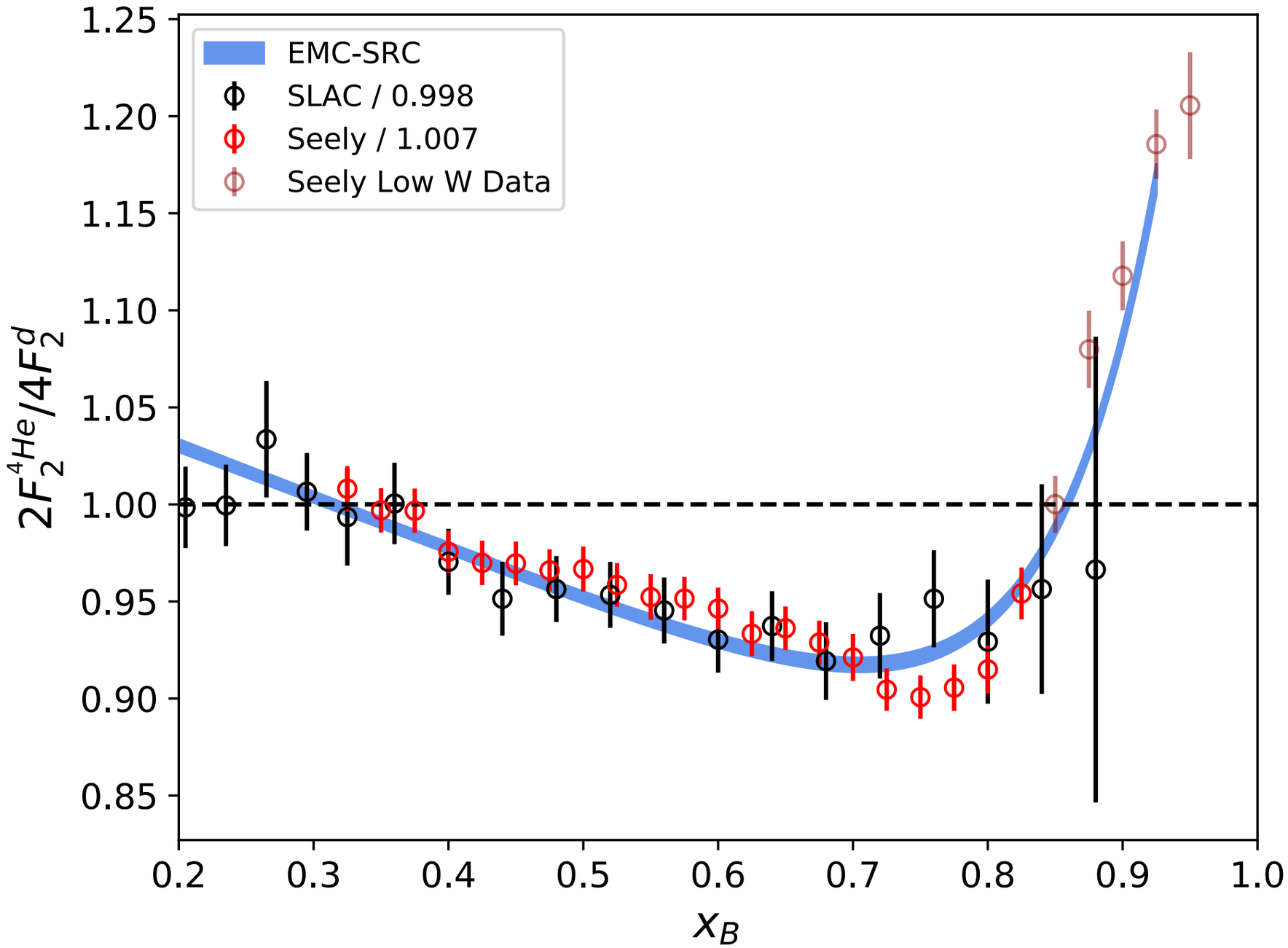
$$\frac{F_2^p}{F_2^d} = \alpha_d + \beta_d x + \gamma_d e^{(1-x)\delta_d}$$

Proton-to-deuterium ratio

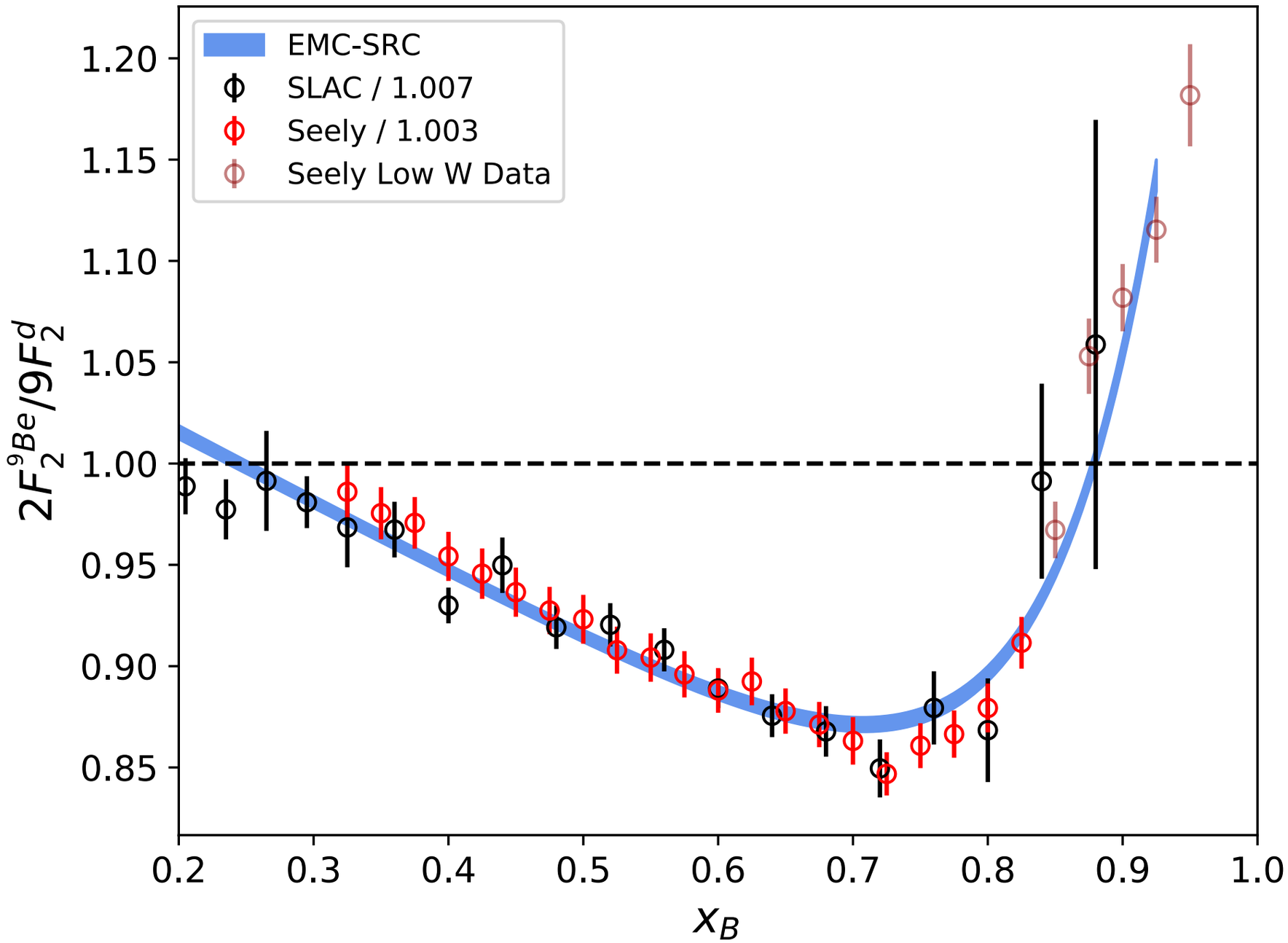
EMC Ratio: He-3



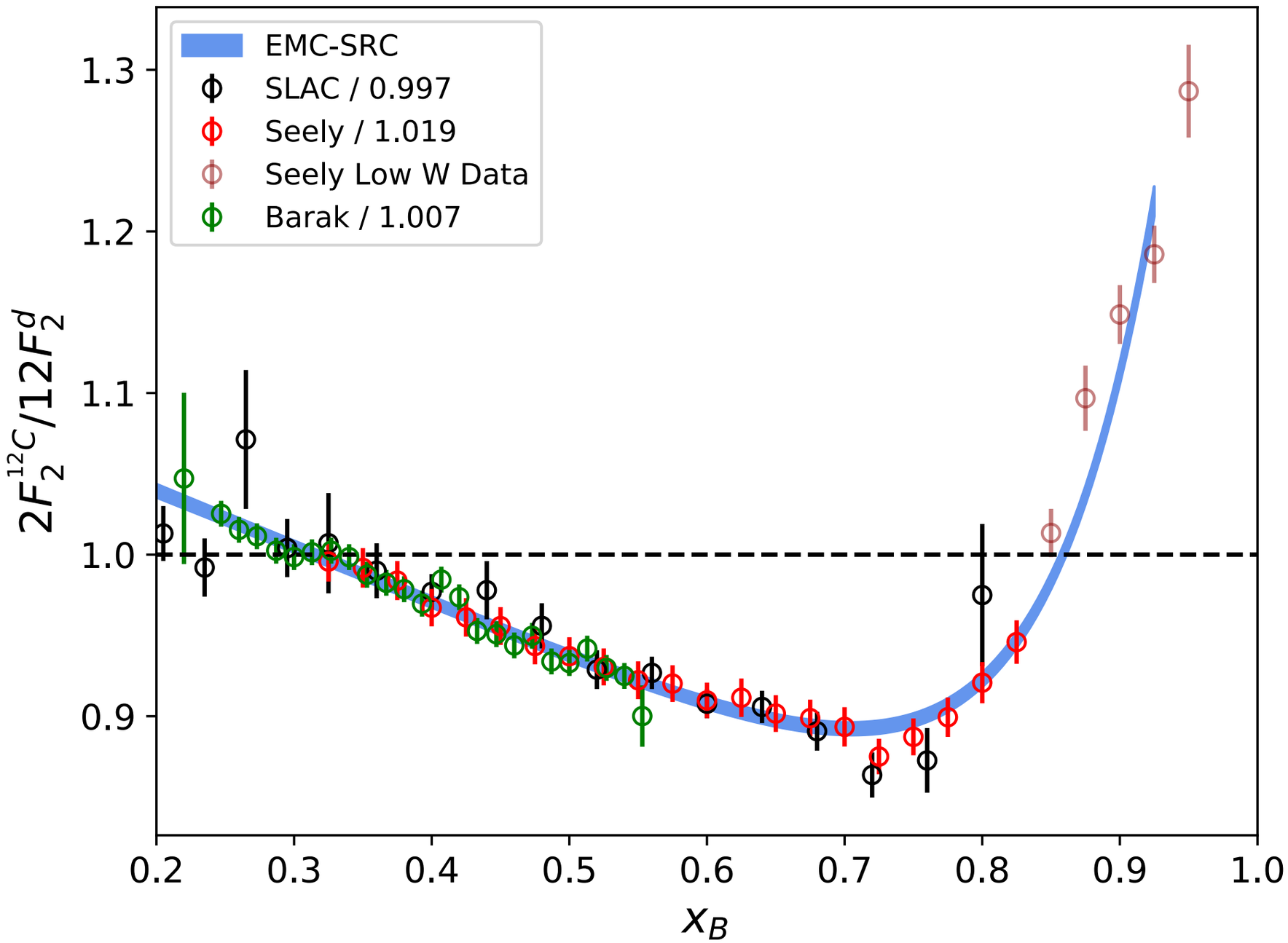
EMC Ratio: He-4



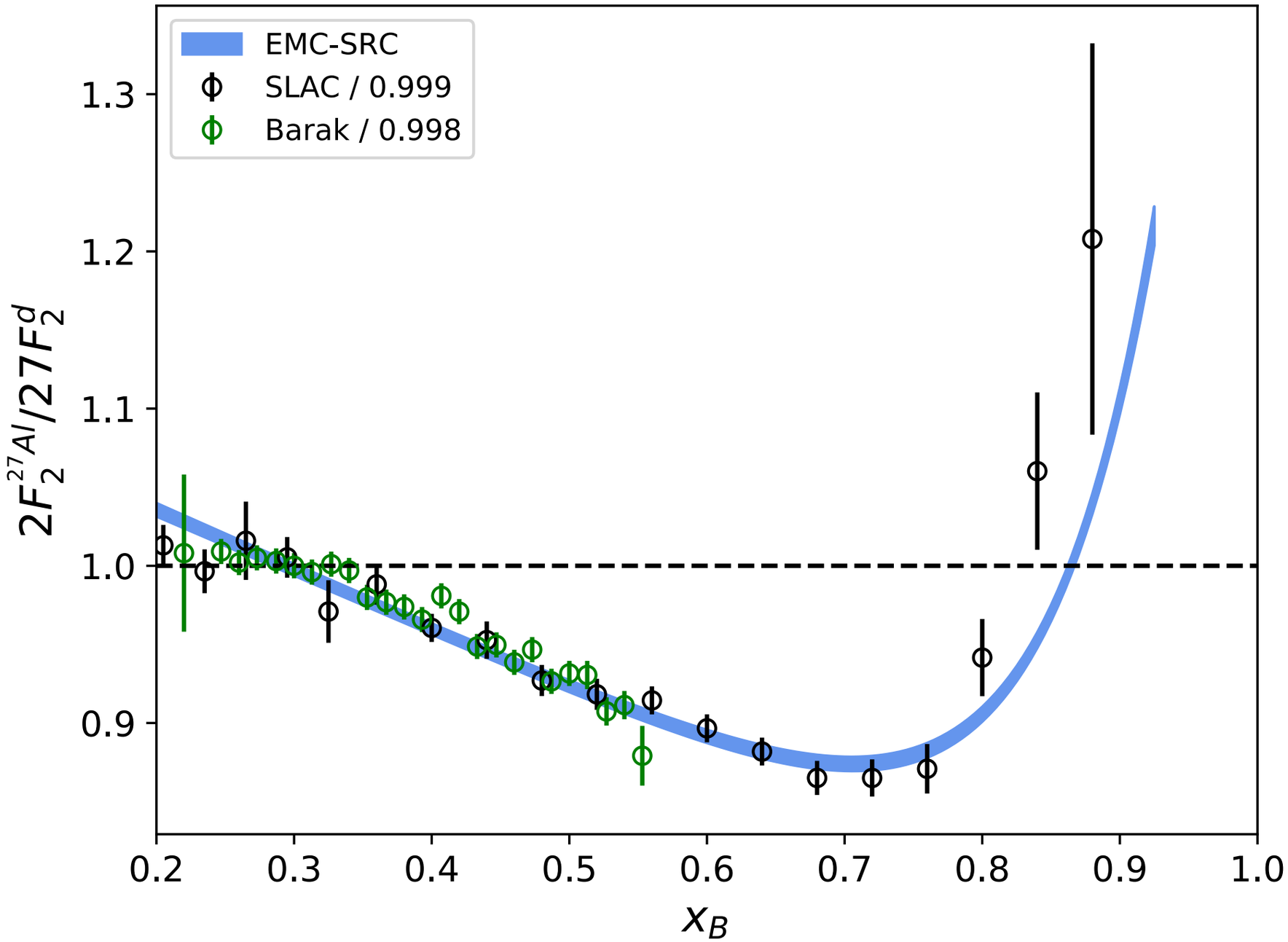
EMC Ratio: Be-9



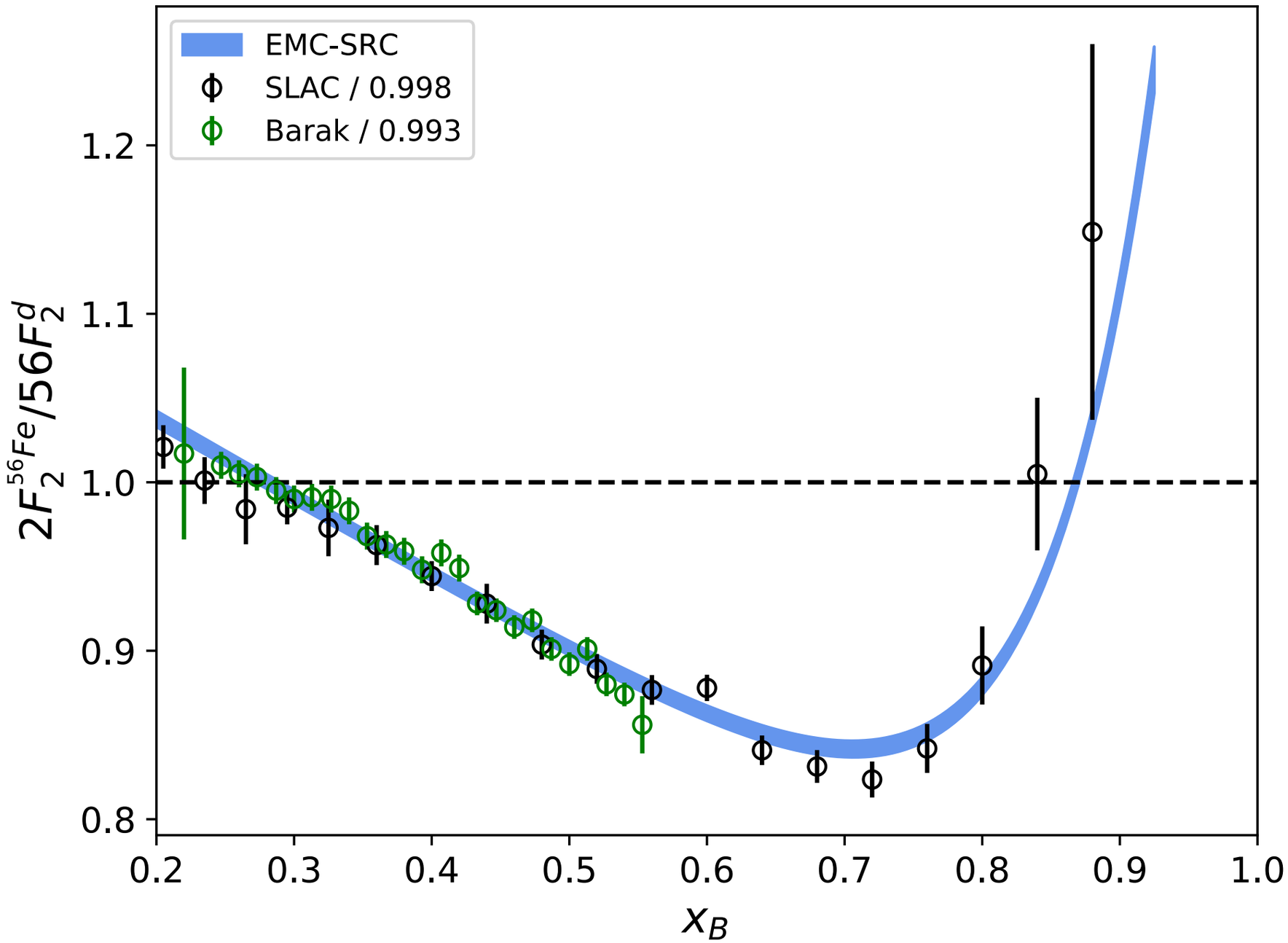
EMC Ratio: C-12



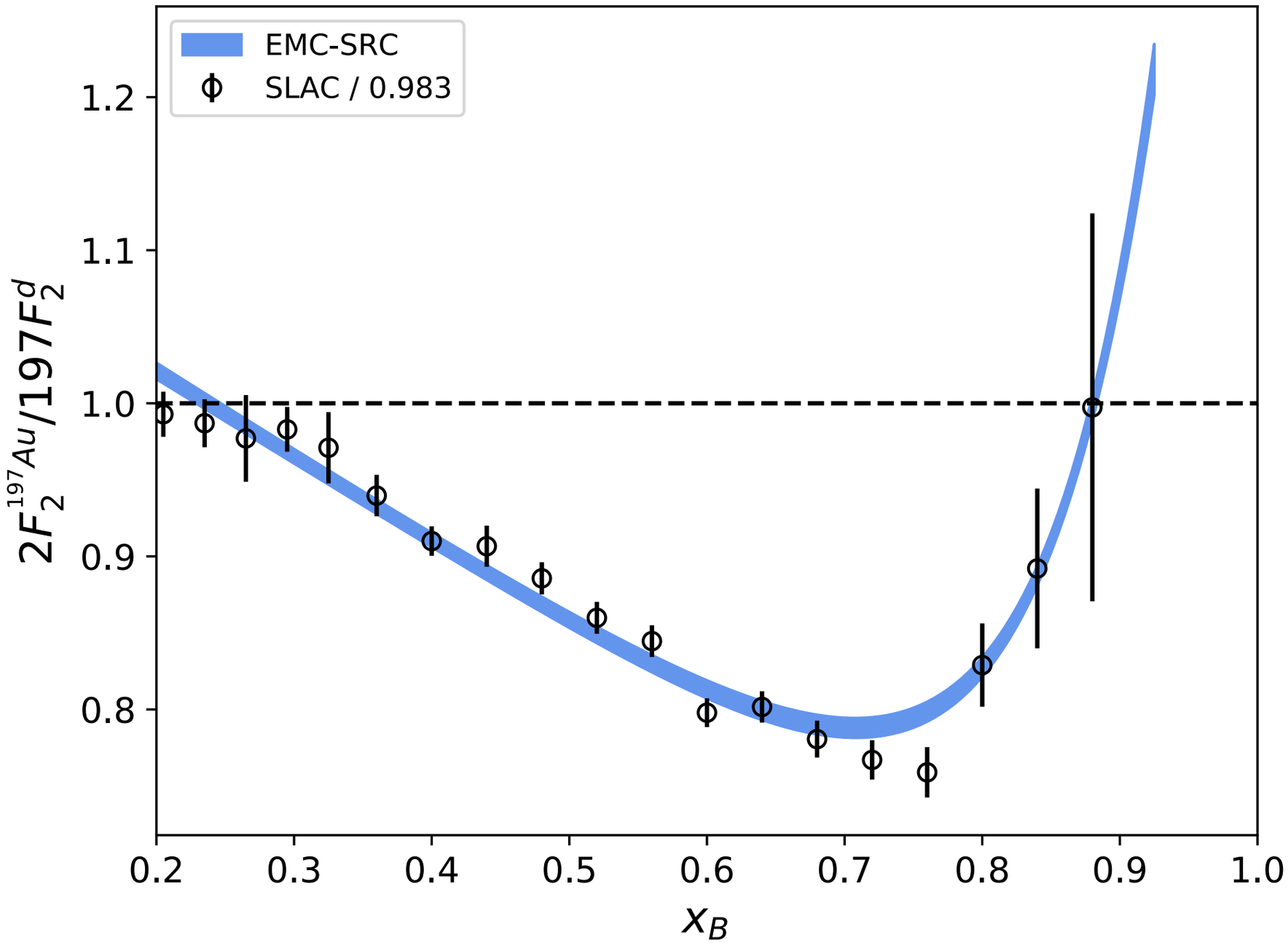
EMC Ratio: Al-27



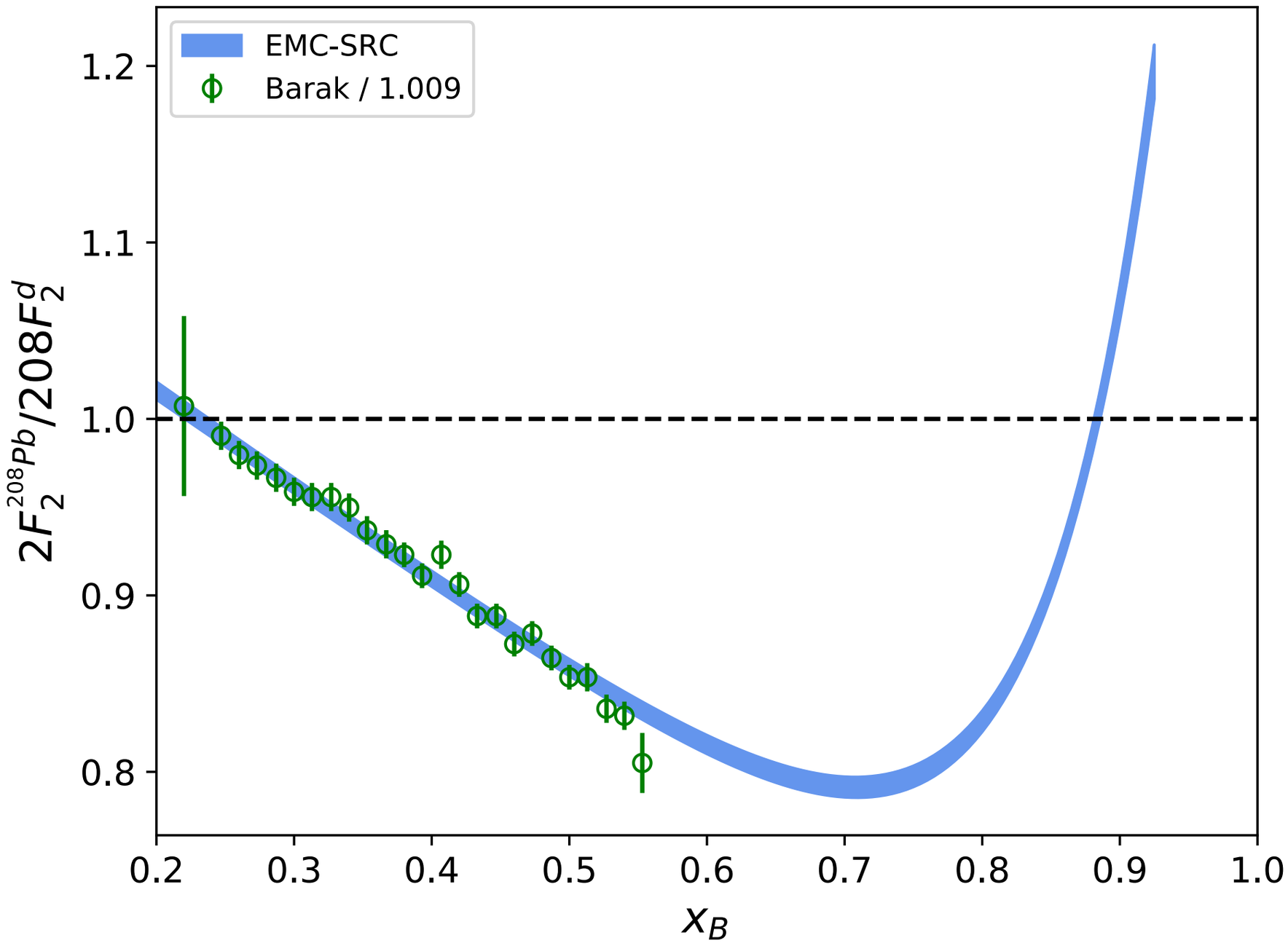
EMC Ratio: Fe-56



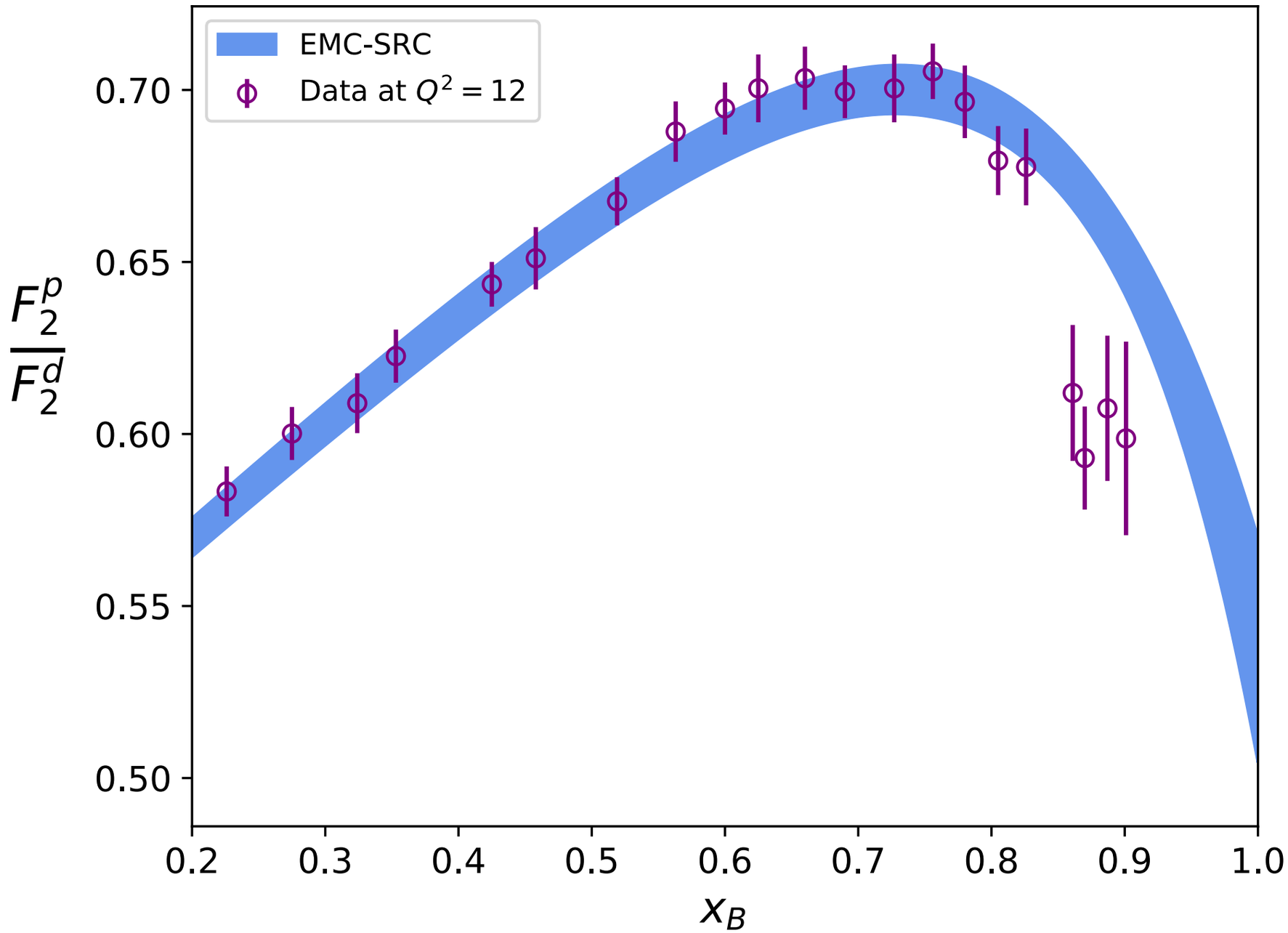
EMC Ratio: Au-197



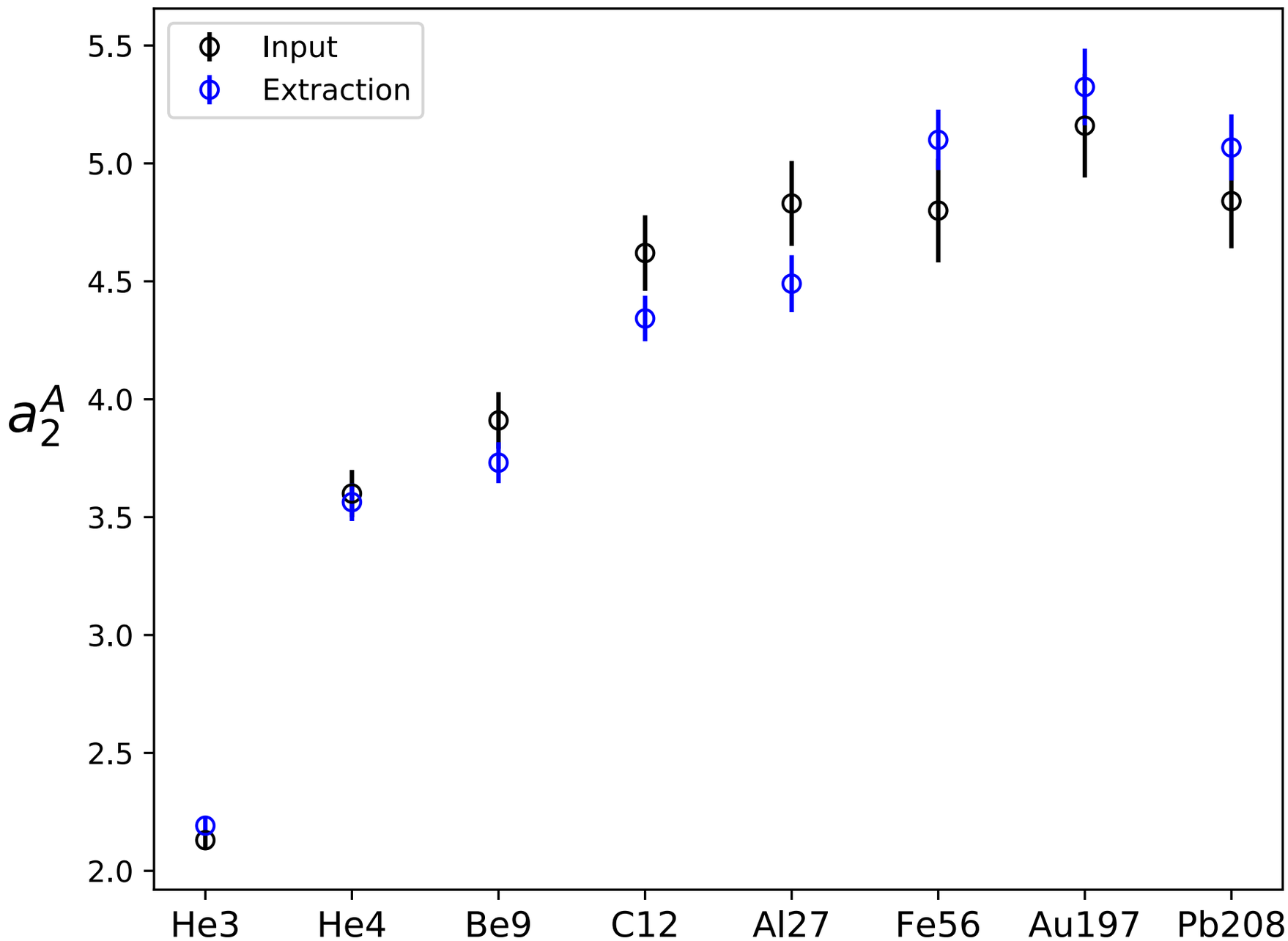
EMC Ratio: Pb-208



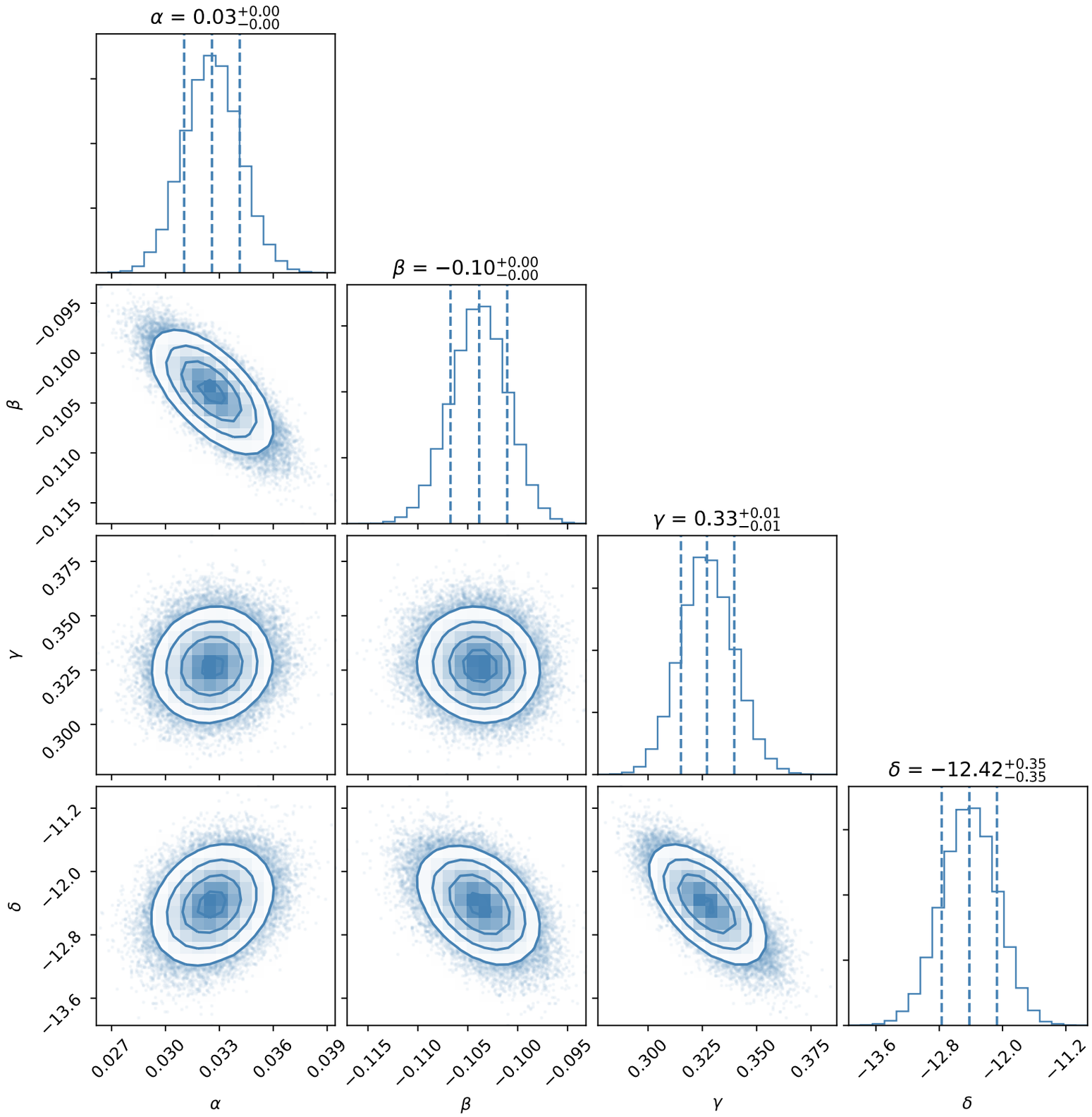
Proton-to-deuterium ratio



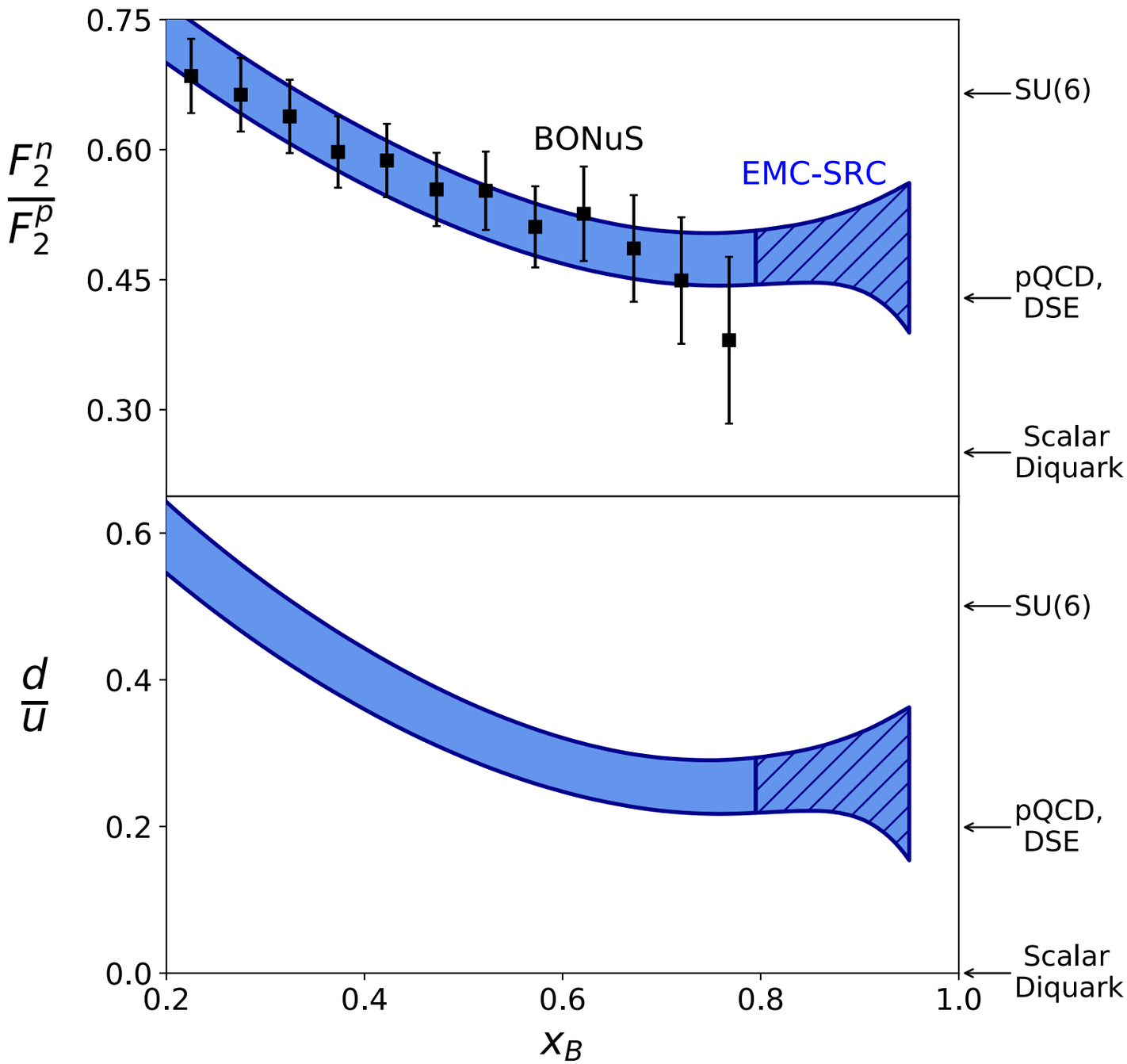
SRC Pair Density



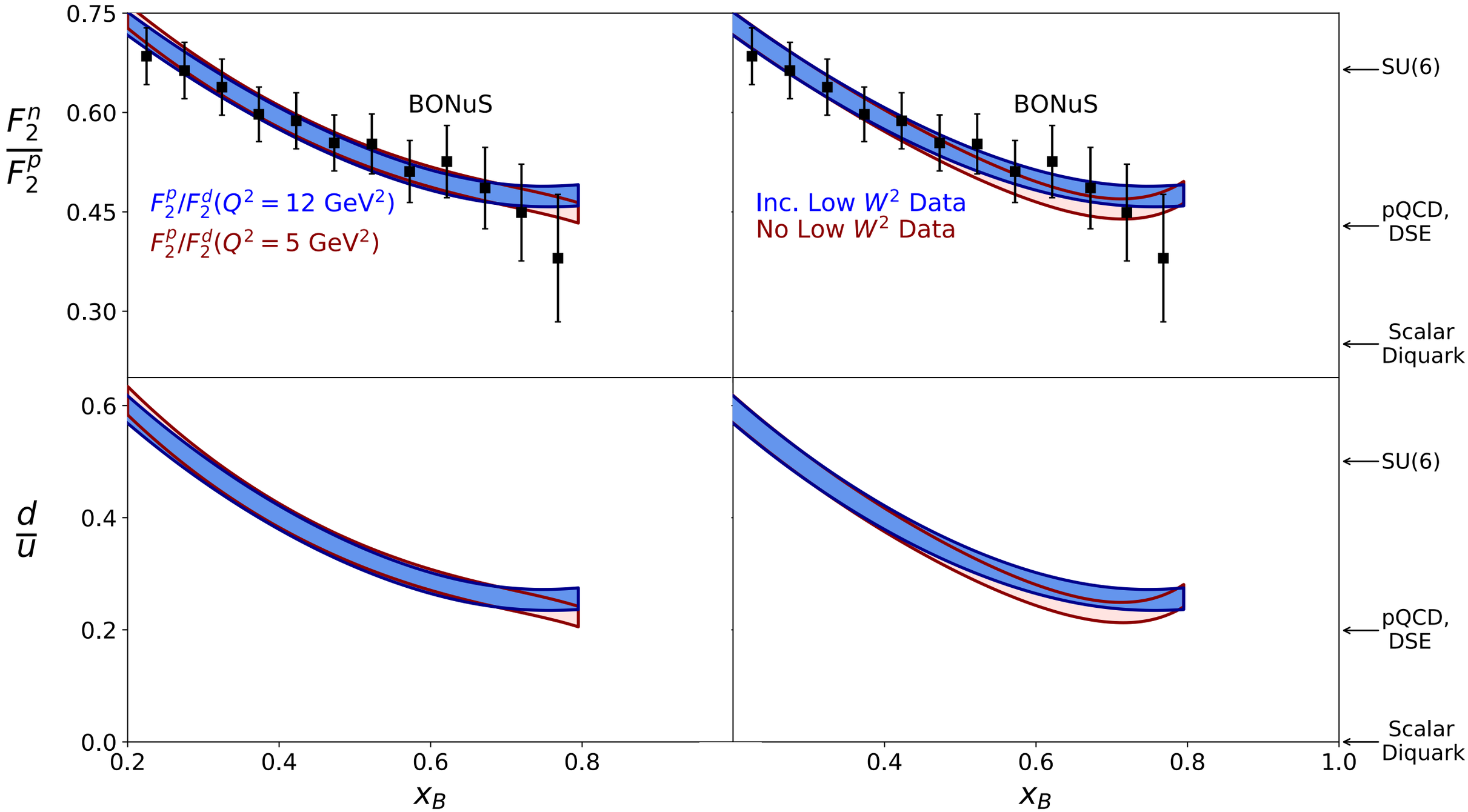
Partial Parameter Correlation



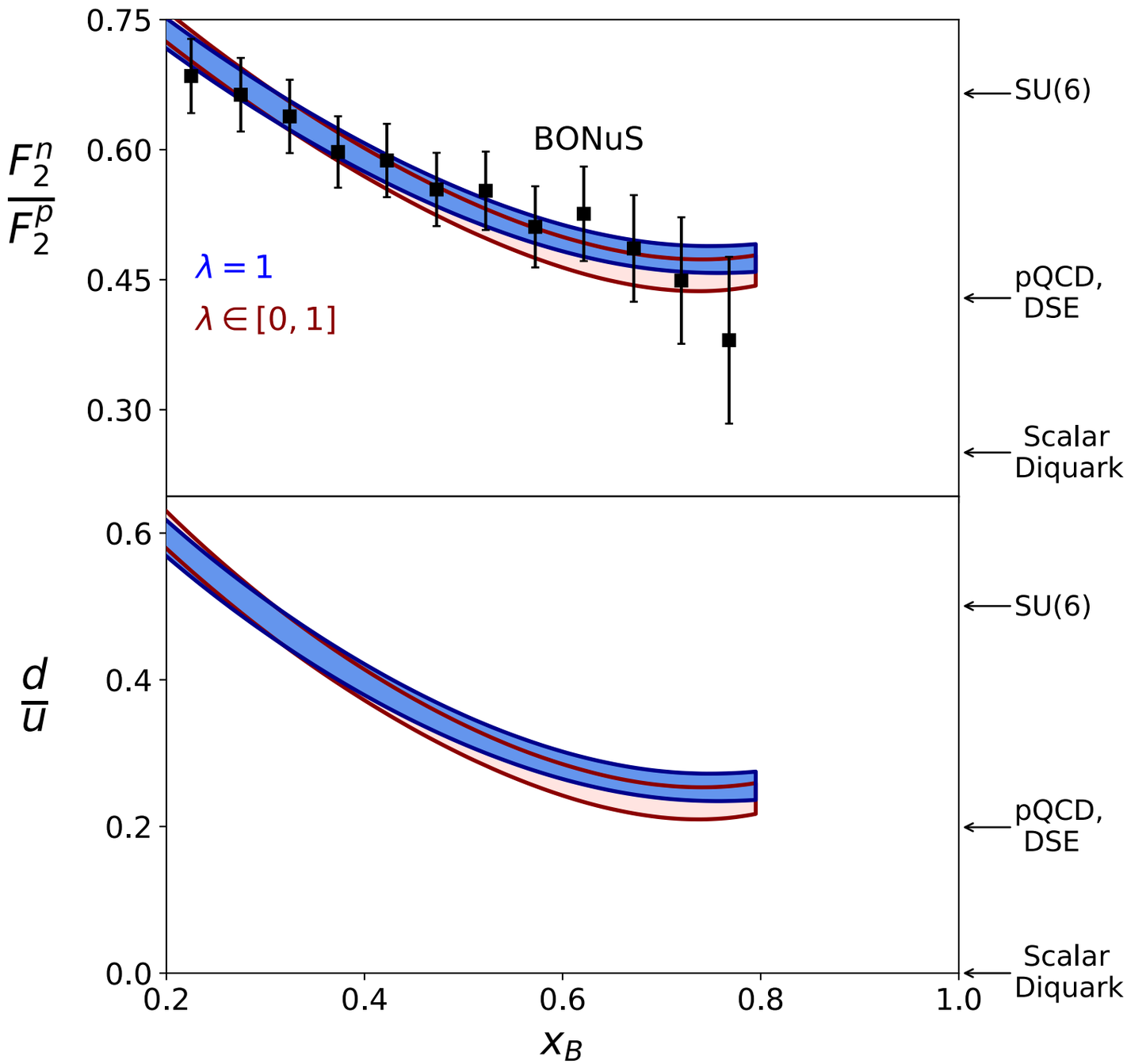
95% Posterior Samples



Sensitivity Checks: Q^2 and W^2

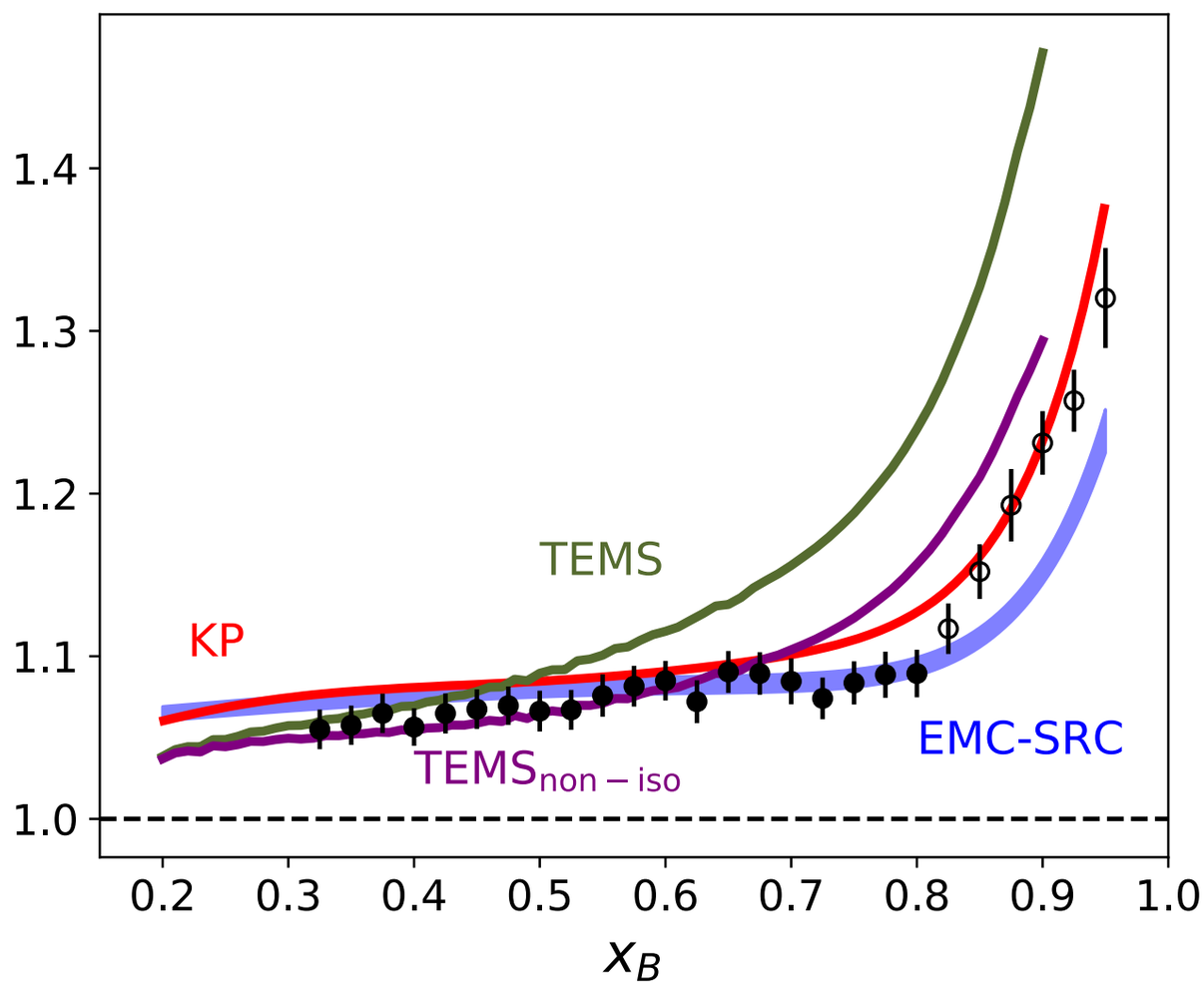


Sensitivity Checks: Deuterium Modification

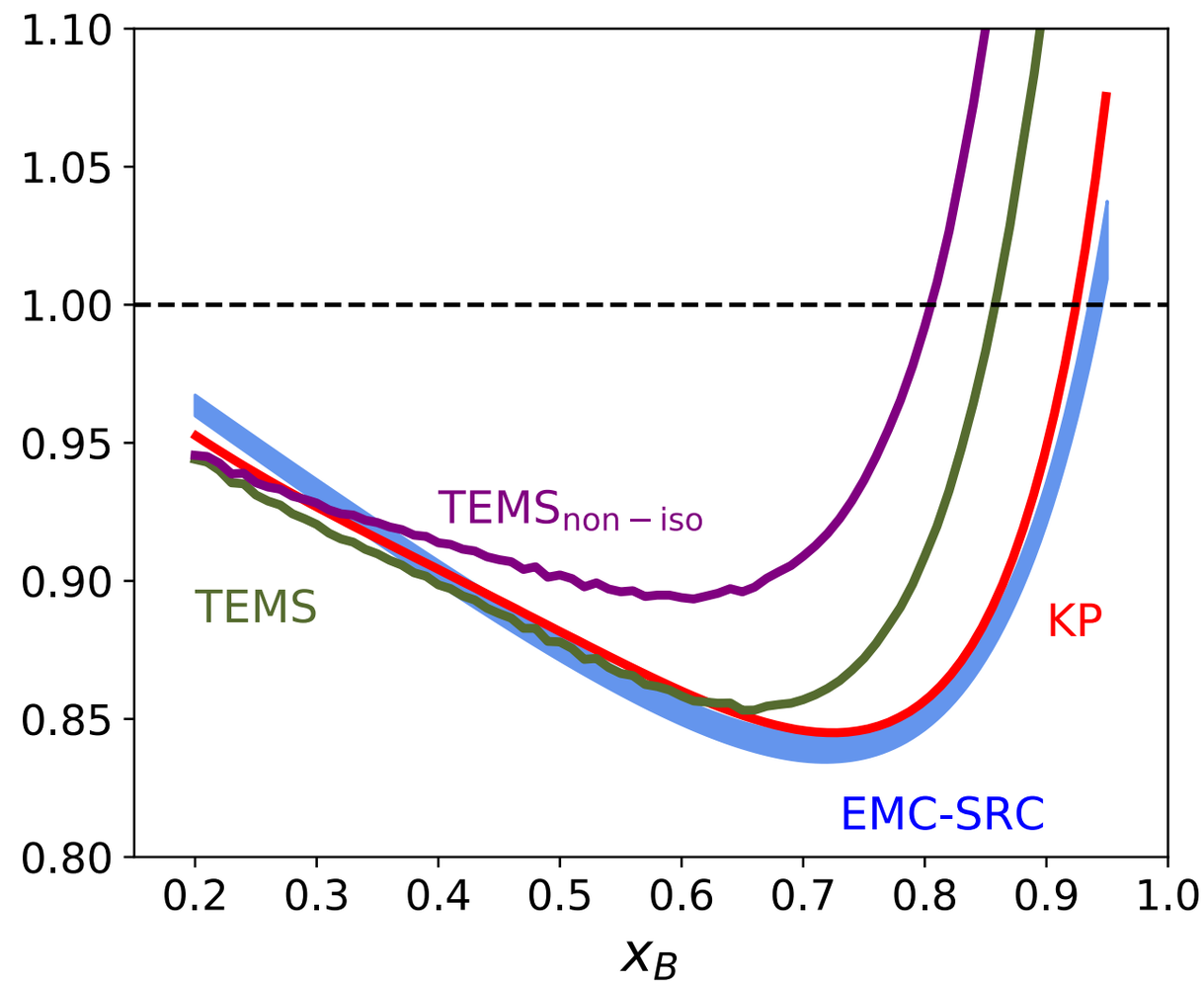


EMC A=3 Ratio

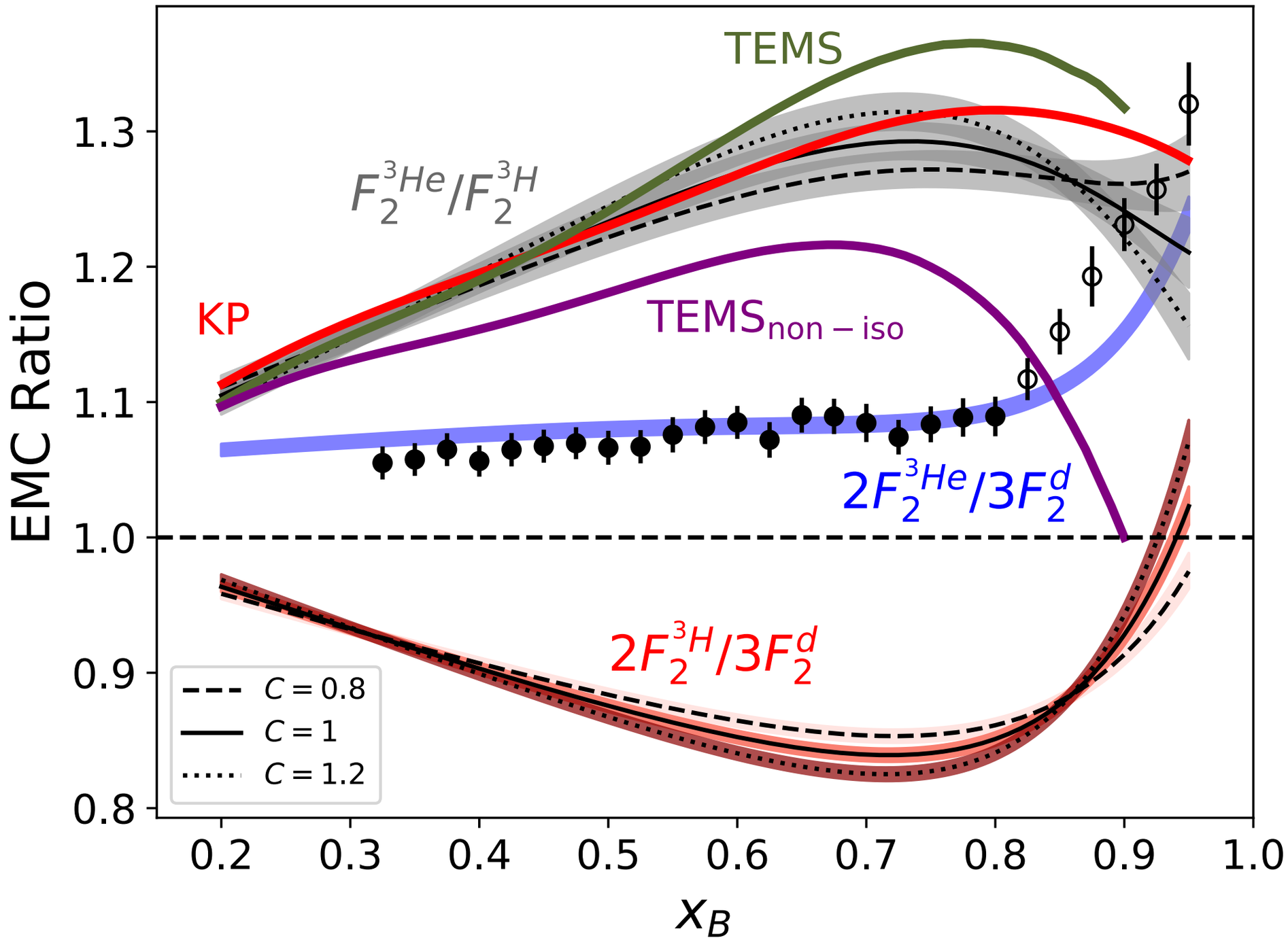
$$\frac{2F_2^{3He}}{3F_2^d}$$



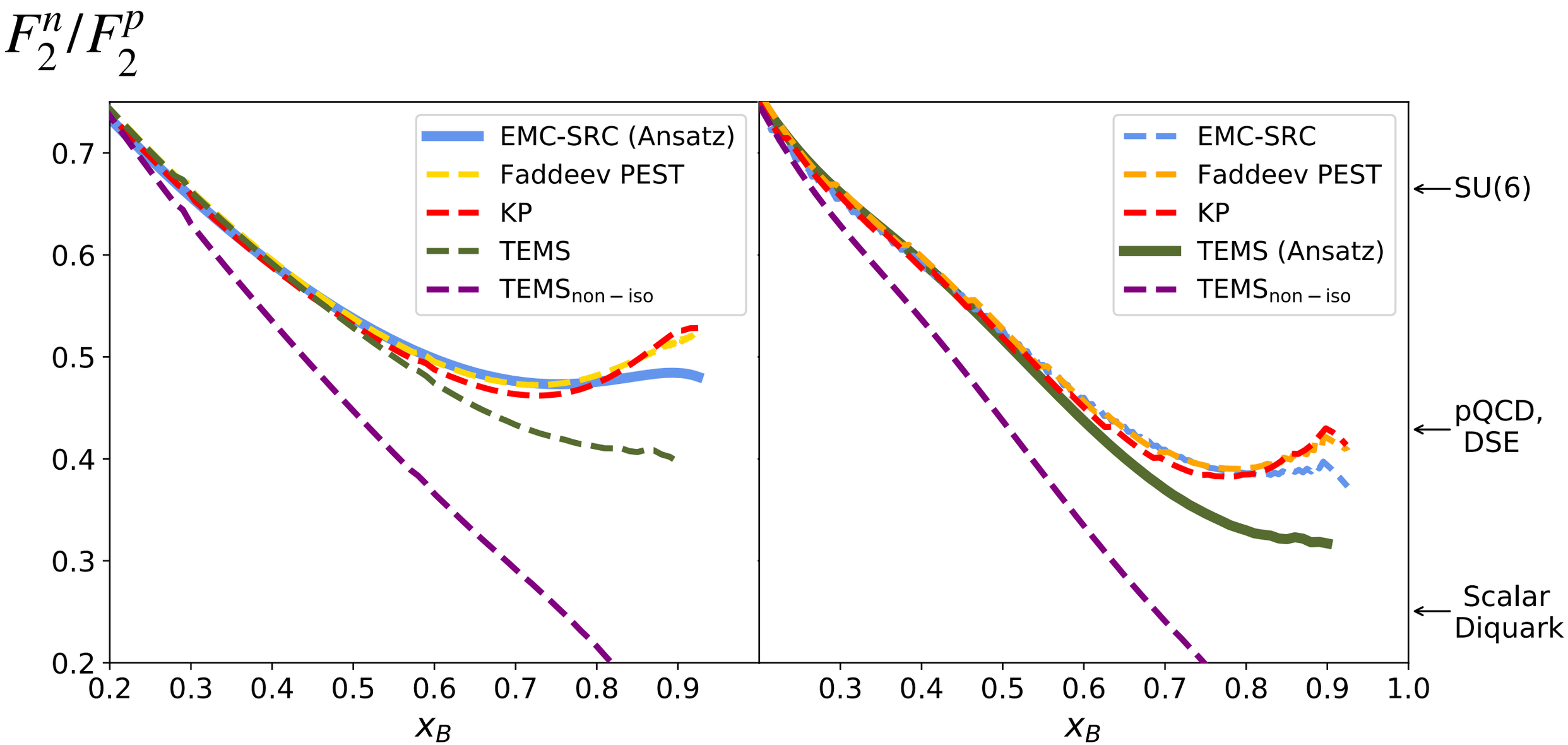
$$\frac{2F_2^{3H}}{3F_2^d}$$



A=3 Predictions for MARATHON



Model uncertainty in neutron structure function extraction



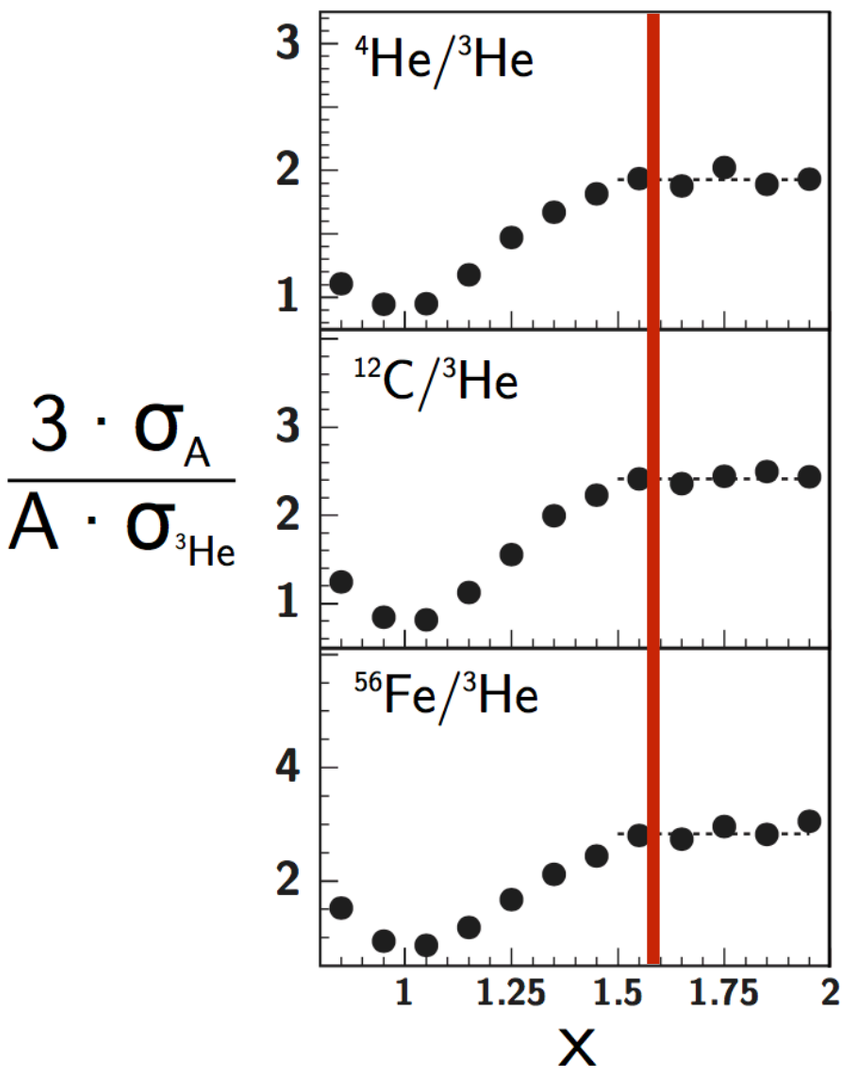
How can we disentangle iso-spin dependent modification

Not all pairs are np, and in asymmetric nuclei, our model is more complicated

$$F_2^A = (Z - n_{SRC}^A)F_2^p + (N - n_{SRC}^A)F_2^n + \ n_{SRC}^A \left(F_2^{p*} + F_2^{n*} \right)$$

Can start to disentangle this with SIDIS measurement on H3 and He-3 (LOI for Hall B)

Inclusive a2



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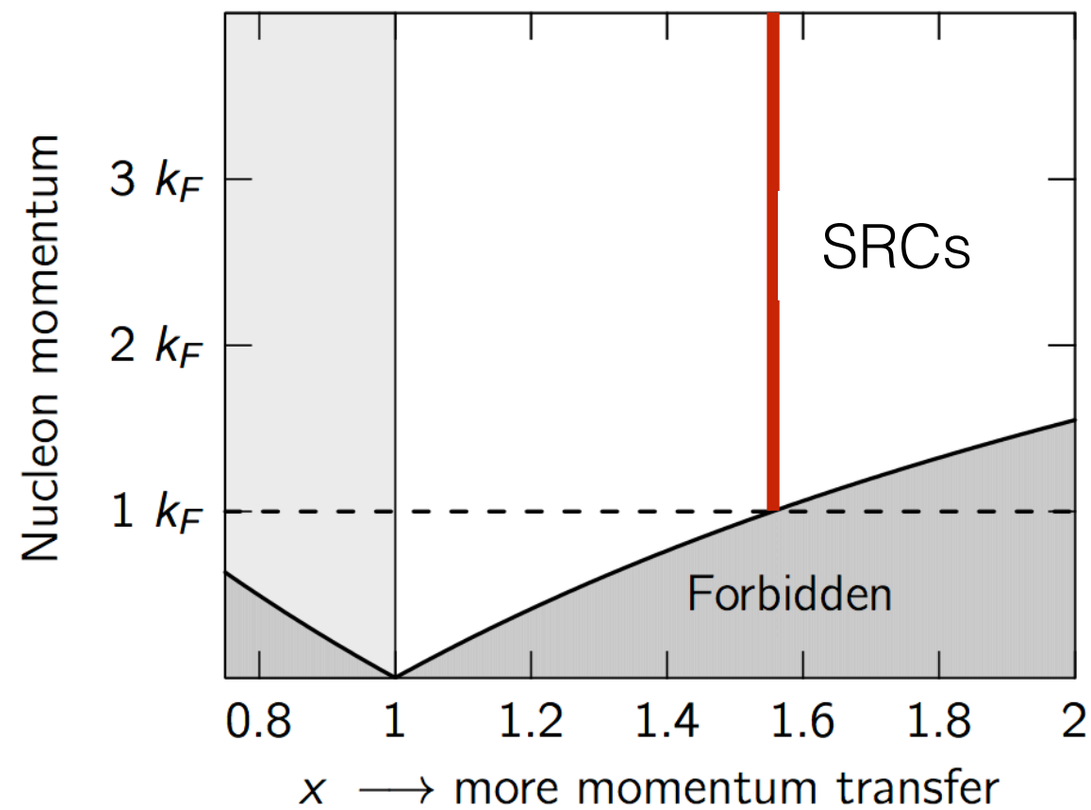

Scaling constant a_2:

$$\sigma_A = \mathbf{a_2} \times \frac{A}{2}\sigma_d$$

HV vs LD

$$F_{univ}^{LD} = \frac{R_{EMC} - 1}{R_{2N}\frac{A(A-1)}{2ZN} - 1}$$

- Only valid for symmetric nuclei
- Isospin correction factor inconsistent with LD model
- Combinatoric scaling of NN pairs inconsistent with QMC
- A-indepence slope over-fitting