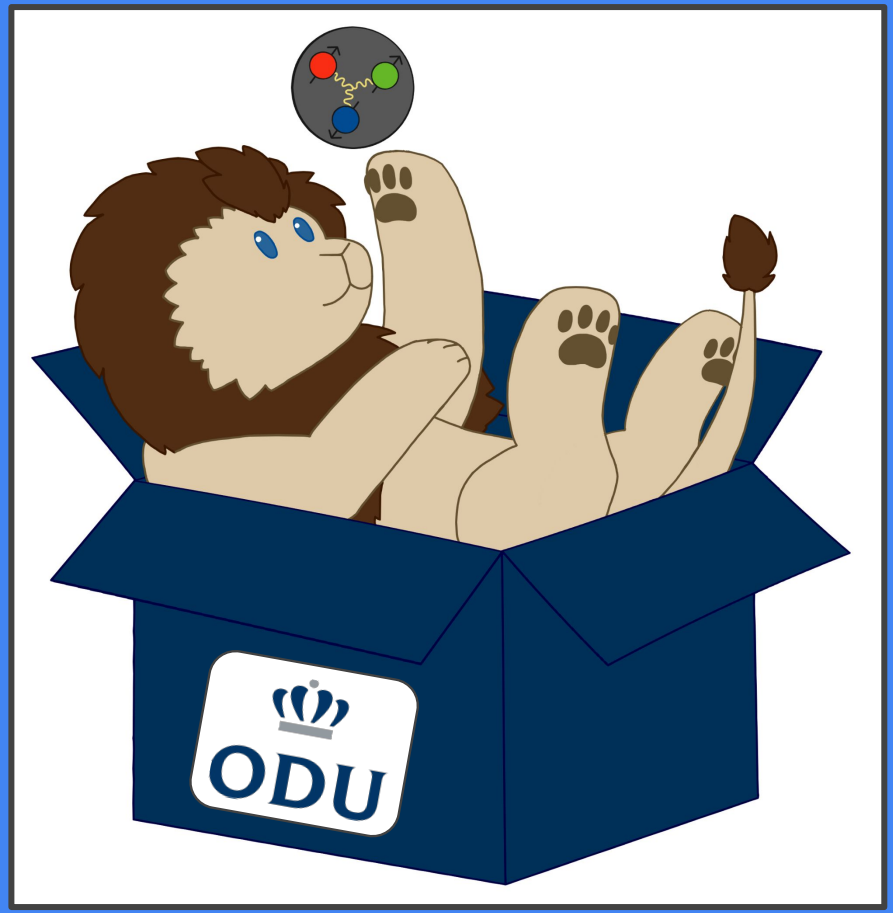
More Than Just the Proton

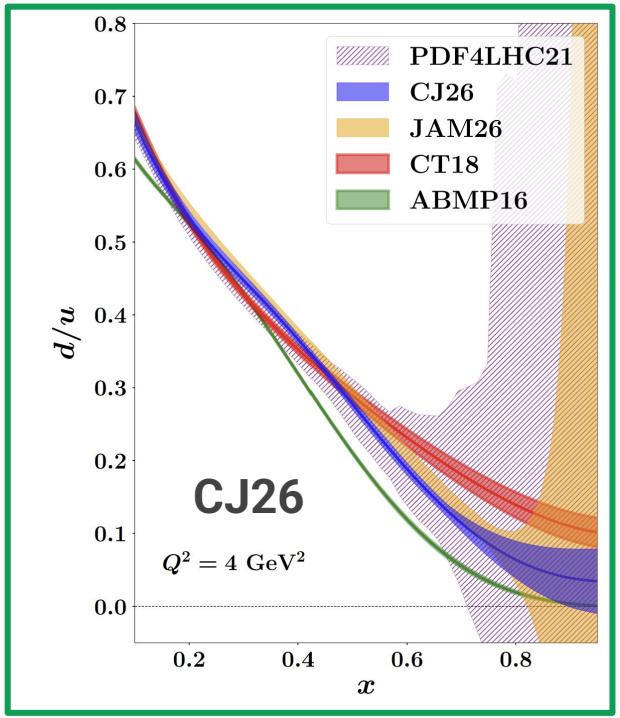
Darren W. Upton (he/they)

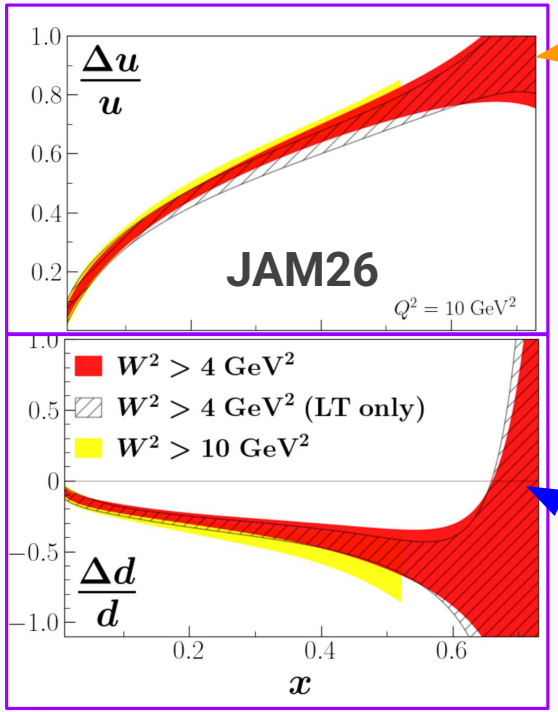
18 Nov 2026



Holy Grail of Large *x* Physics

- PDFs of valence u & d -> carry nucleon's quantum numbers
- Flavor separation of unpol & pol requires data on pro & "neu"



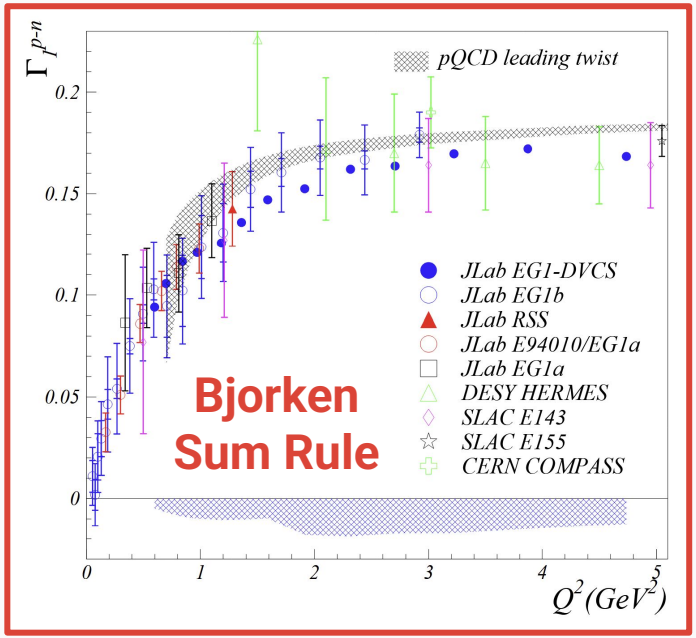


Continue to 1??

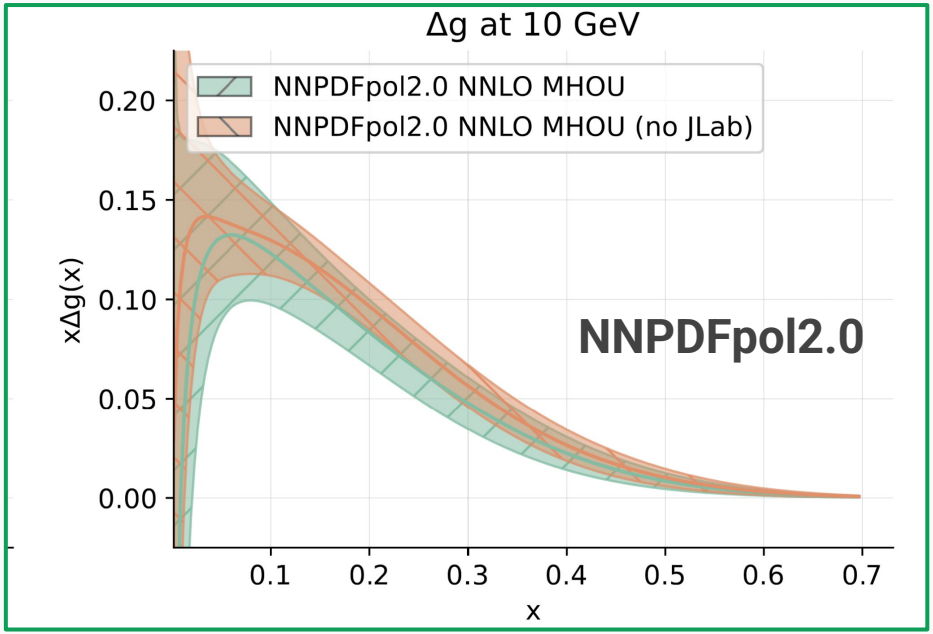
Turn Over??

Historical Importance of CLAS

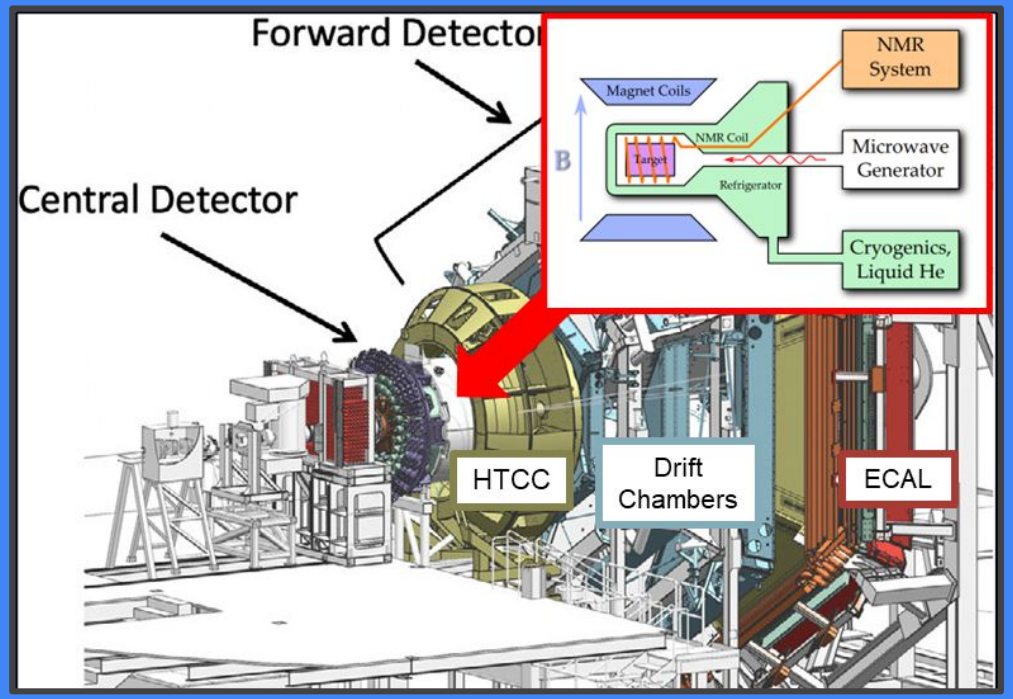
- Large converge of $g_1(x,Q^2)$ -> mapping sum rules & constraining Δg



A. Deur et al (2014)



RG - C Inclusive Analysis



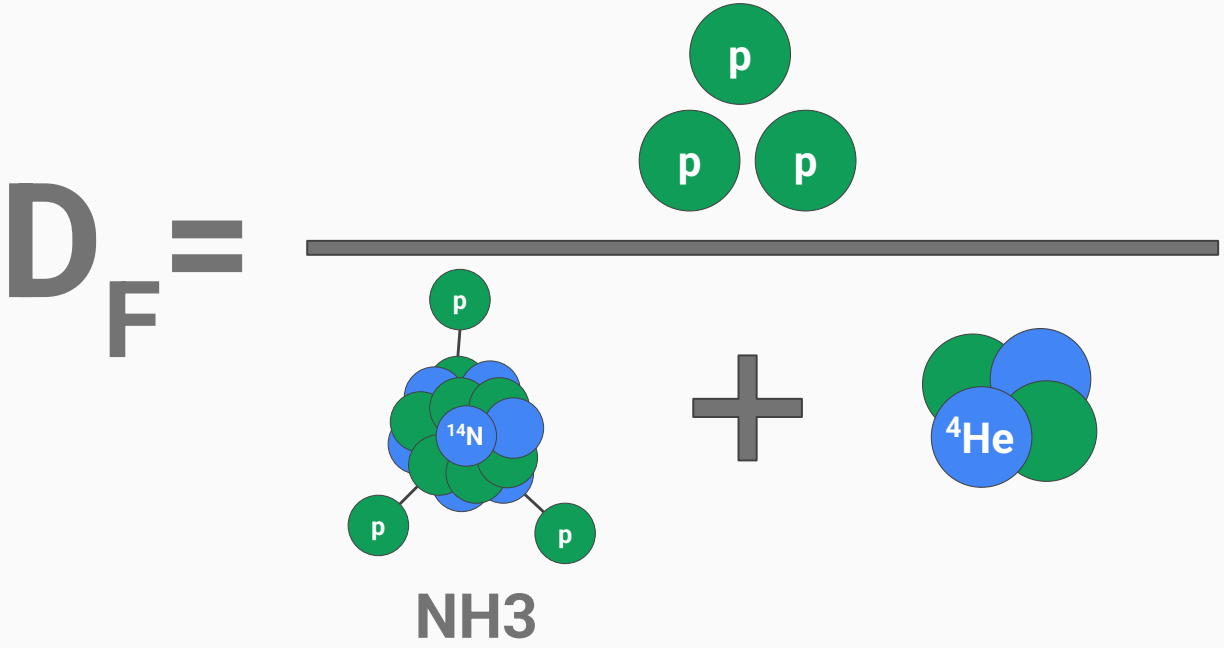
Constructing the Double-Spin Asymmetry

- "Raw Asymmetry" - Asym between +/- helicity states norm by Faraday cup*
- ***Main*** Correction Factors
  - Dilution Factor D_F - Fraction of events from hydrogen in target
  - Beam & Target Polarization $P_b P_t$

$$A_{||} = \frac{\sigma^{\downarrow\uparrow} - \sigma^{\uparrow\uparrow}}{\sigma^{\downarrow\uparrow} + \sigma^{\uparrow\uparrow}} = \frac{1}{D_F P_b P_t} \frac{n^- - n^+}{n^- + n^+}$$

Dilution Factor Basics

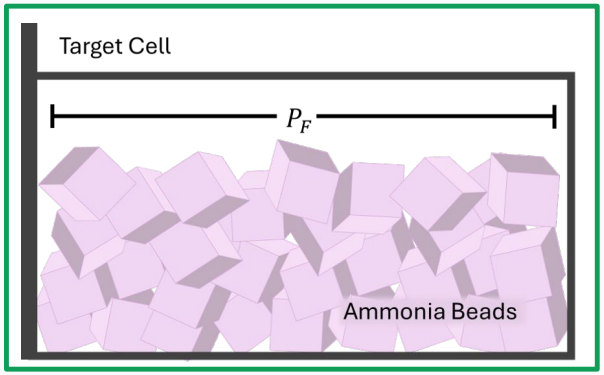
- Fraction of events from hydrogen in ammonia (NH3/ND3) targets
- Very naïvely $D_F \sim 3/17$ & $D_F \sim 6/20$ but only ~25% accurate

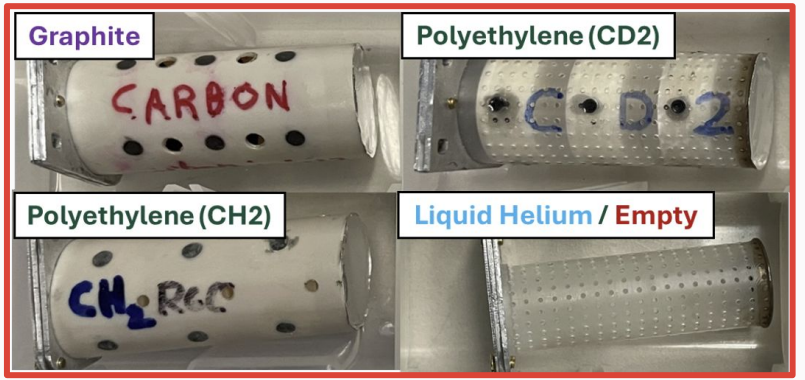


Dilution Factor from Data

- Extract using combination of ammonia & background targets

$$D_F(x, Q^2) = \frac{(n_A - n_{MT})(n_{CH} + An_C + Bn_{MT} + Cn_F)}{n_A(n_{CH} + Dn_C + En_{MT} + Fn_F)}$$



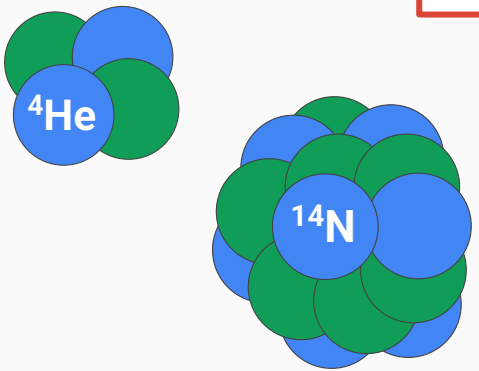


Modeling Target with Event Generator

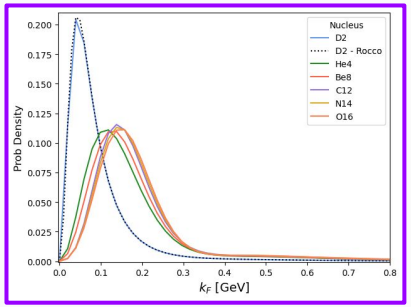
- "Build" targets out of unpol Δσ with nuclear effects
- Account for target geometry & include radiative effects

$$N_{NH_3} \propto l_A \rho_A (\Delta\sigma_H + \Delta\sigma_{N_{14}}) + (L - l_A)\rho_{He}\Delta\sigma_{He} + l_F \rho_F \Delta\sigma_F$$

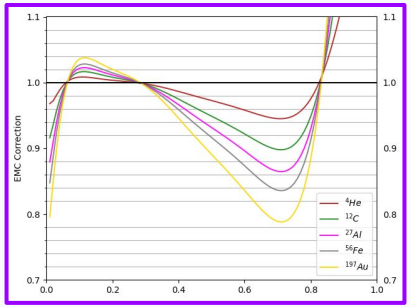
$$\Delta\sigma^N(x, Q^2) = \sigma_{Mott}\left[\frac{1}{\nu}F_2^N + \frac{2}{M}\tan^2(\theta/2)F_1^N\right]$$



Fermi Motion

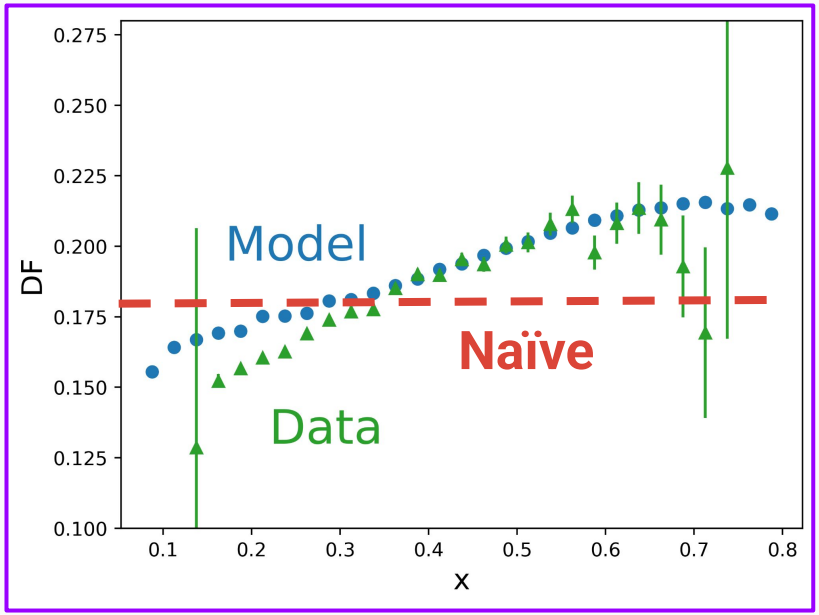


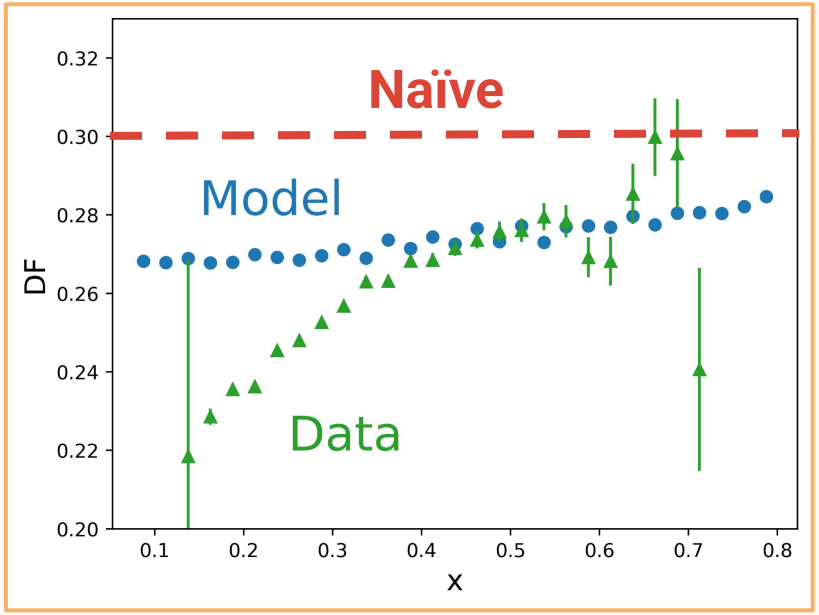
EMC Ratio



Comparison of Data & Model Dilution Factors

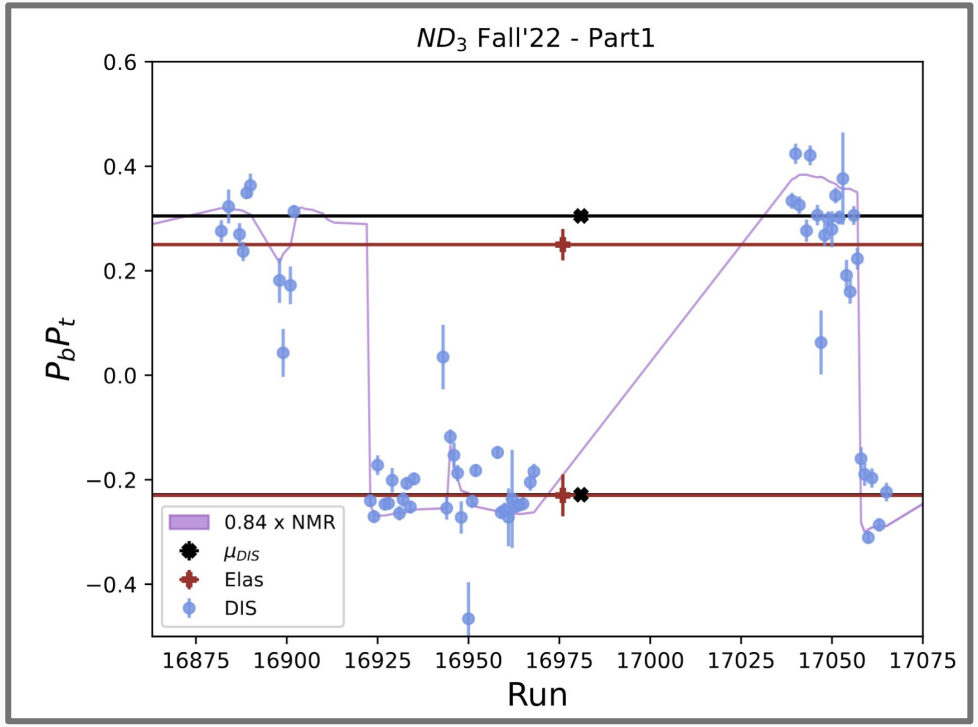
- Disagreement at small *x* for proton & especially deuteron





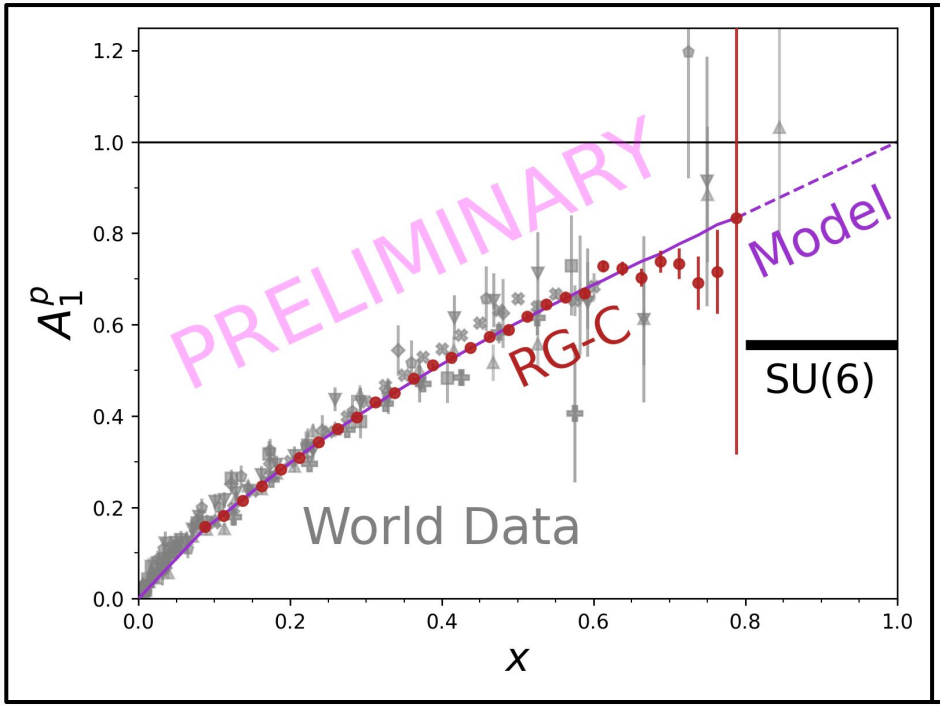
Polarization Term

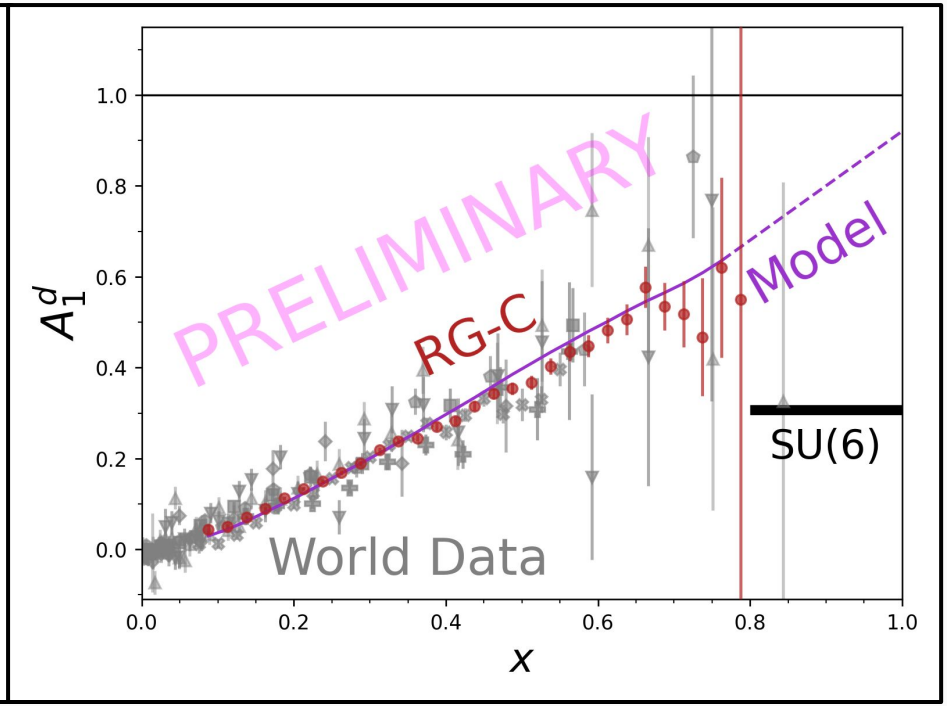
- Estimate with NMR x beam polarimeter & measure with scattering
- Use DIS for precise run-by-run results then normalize with elastics



Preliminary Results for A_1 of Proton & Deuteron

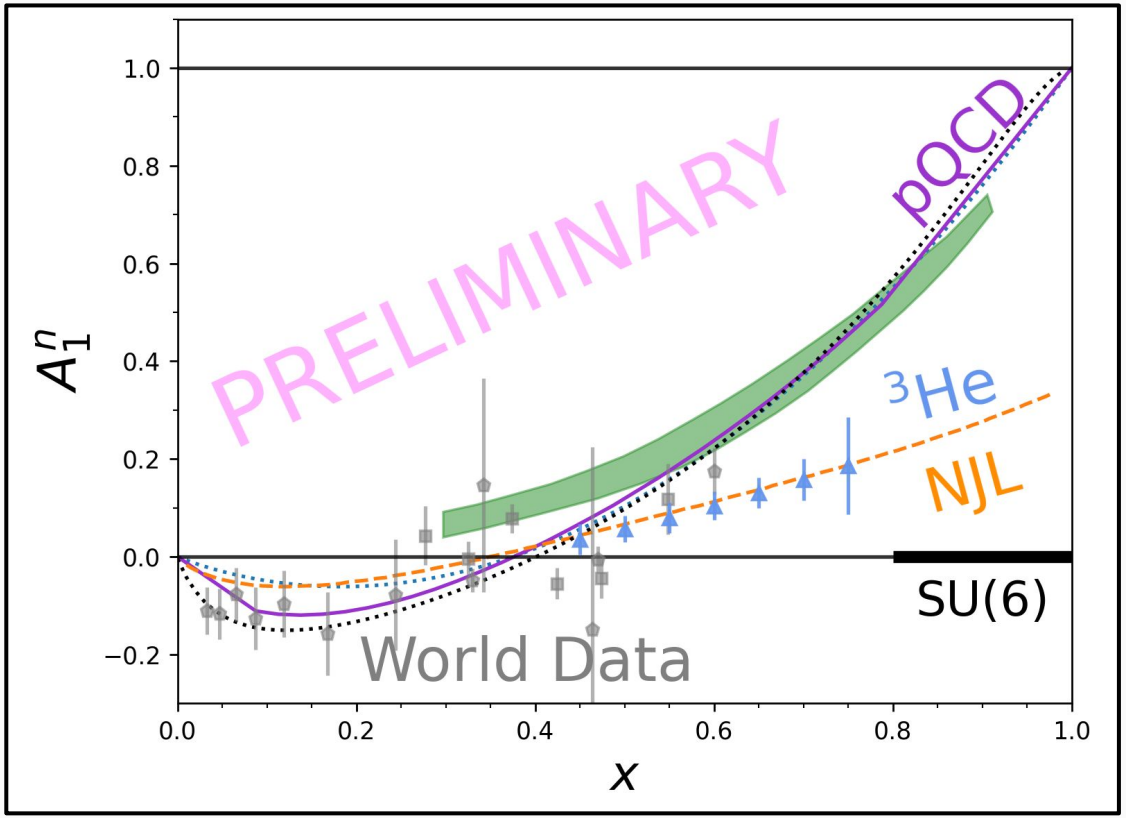
- RG-C (stats) disagree with SU(6) & possibly hint ***$A_1(x->1)->1$***





Current State for A_1 of the Neutron

^{3}He deviates from $A_1(x->1)->1$



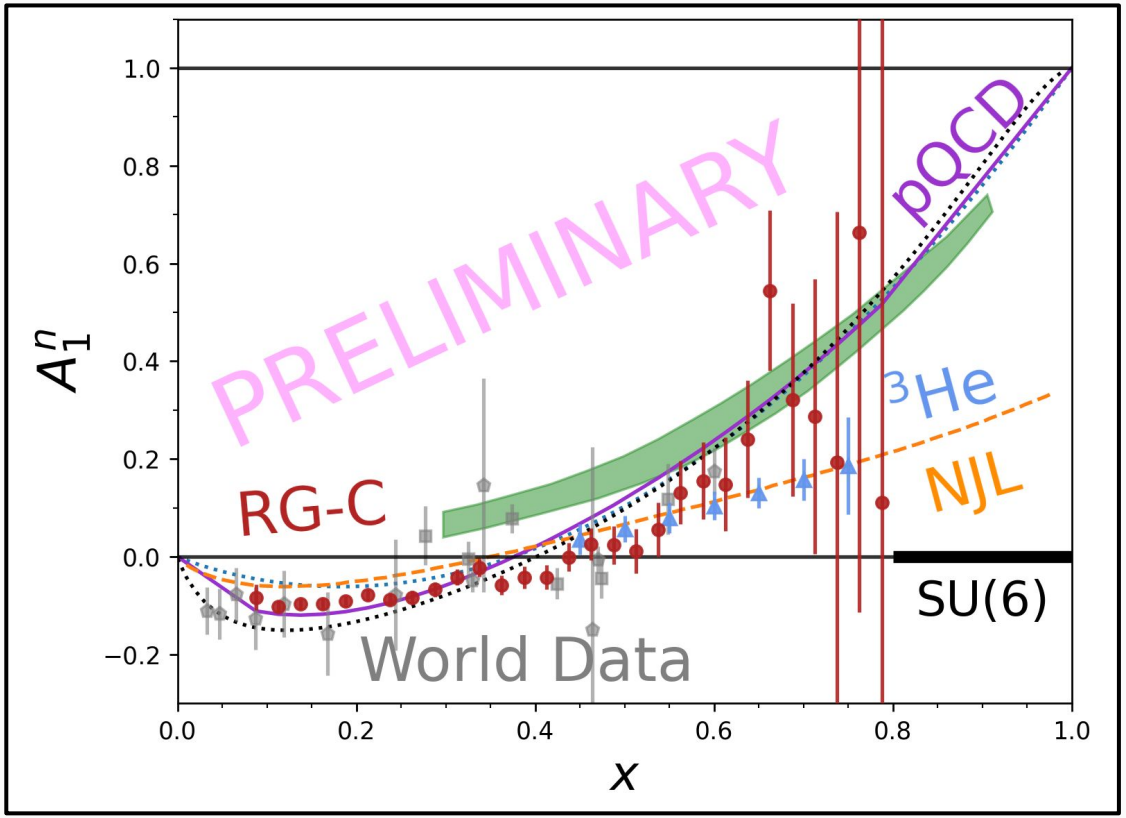
Very Preliminary Results for A_1 of the Neutron

Naïve Correction

$$A_1^n = \frac{1}{F_2^n}\left(\tilde{A}_1^d F_2^d - A_1^p F_2^p\right)$$

^{3}He deviates from $A_1(x\to 1)\to 1$

RG-C inconclusive for $A_1(x\to 1)$



Super Preliminary Quark Distribution Extractions

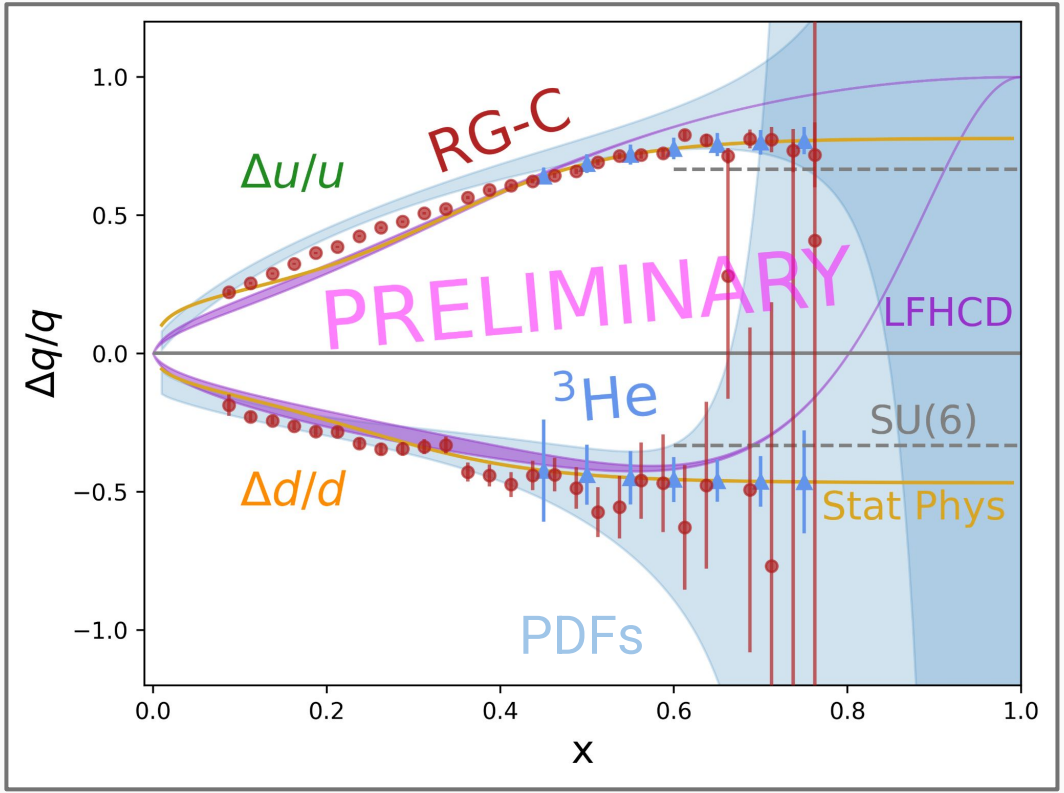
Flattening for ***Δu/u < 1***

No clear ***Δd/d*** flip

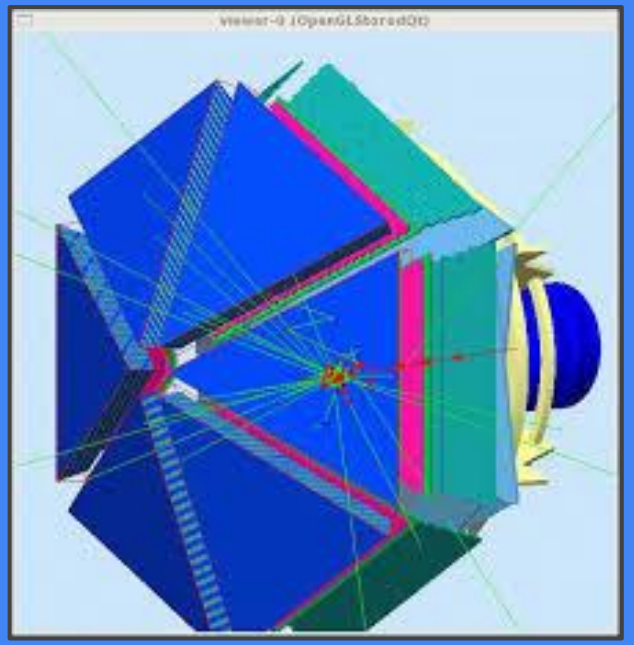
$$\frac{\Delta d + \Delta \bar{d}}{d + \bar{d}} = -\frac{1}{15}\frac{g_1^p}{F_1^p}\left(1 + \frac{4}{R^{du}}\right) + \frac{4}{15}\frac{g_1^n}{F_1^n}\left(4 + \frac{1}{R^{du}}\right)$$

$$\frac{\Delta u + \Delta \bar{u}}{u + \bar{u}} = \frac{4}{15}\frac{g_1^p}{F_1^p}\left(4 + R^{du}\right) - \frac{1}{15}\frac{g_1^n}{F_1^n}\left(1 + 4R^{du}\right)$$

R^{du} from JAM26

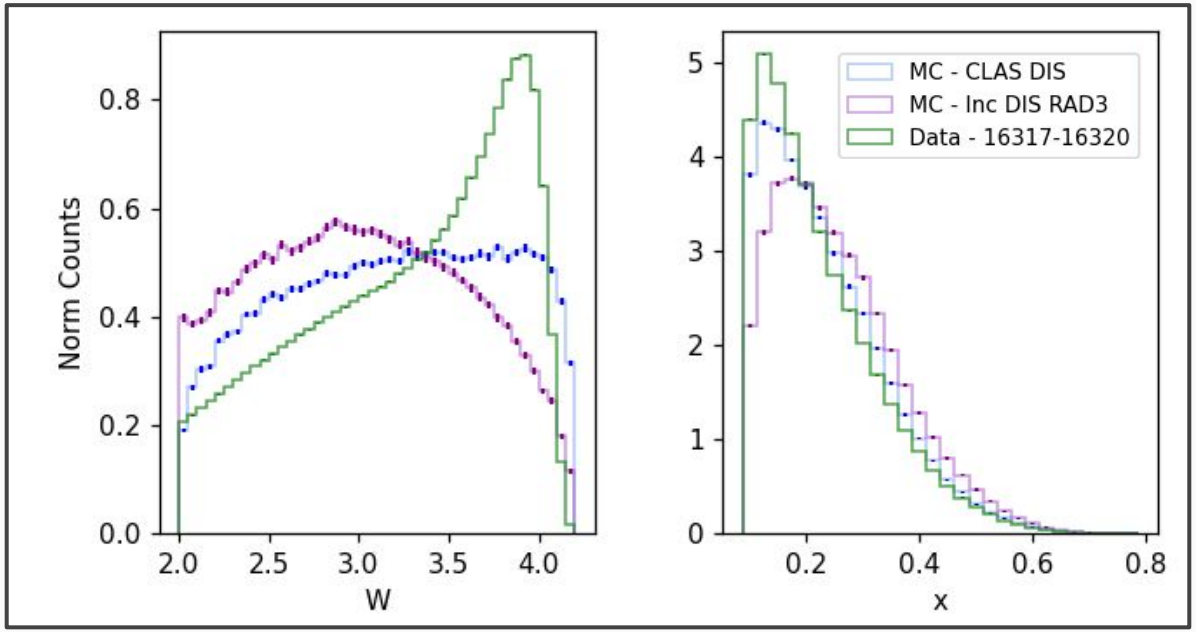


Moving Towards Full Monte Carlo



Existing CLAS12 Monte Carlo (MC) Simulation

- Poor agreement between NH_3 data & MC (only pro & deu)
- Fermi smearing is necessary but not sufficient



Monte Carlo Requirements for Inclusive

- **Need to simulate all targets over entire kinematic space**
- Requirements:
  - GEMC compatible event generator
  - Polarized & Nuclear models
  - Radiative effects

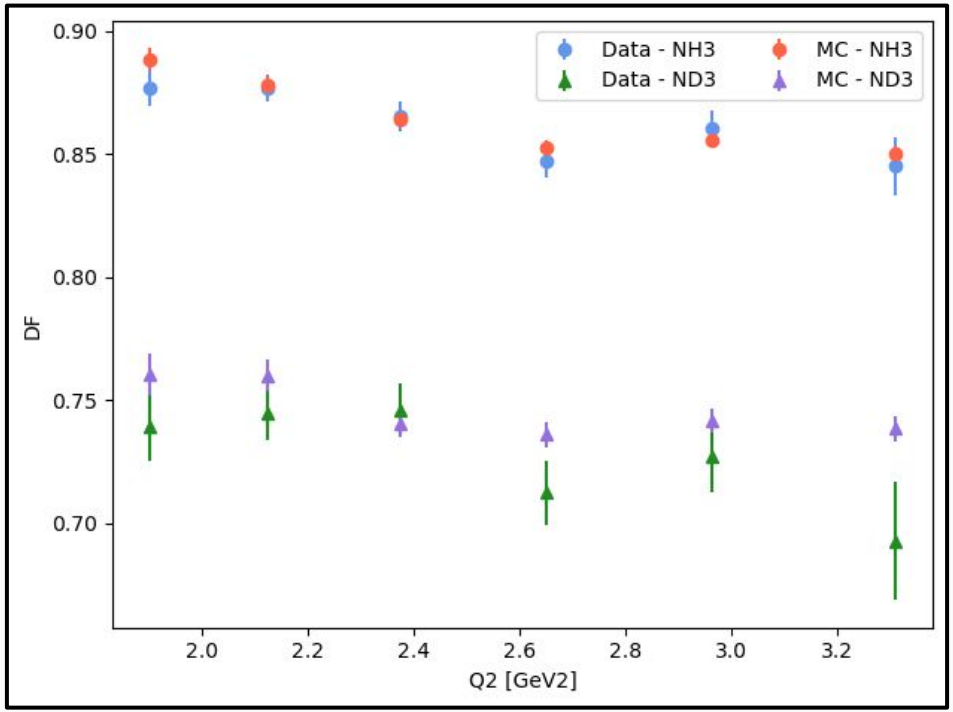
My DOE SCGSR Fellowship Project for 2027



Starting with (Quasi-)Elastics A(e,e'p')

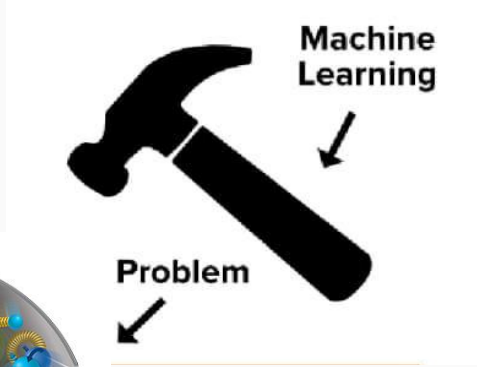
See back-ups for details

- Built QE event generator & simulated in GEMC
- Nice agreement between data & **MC**



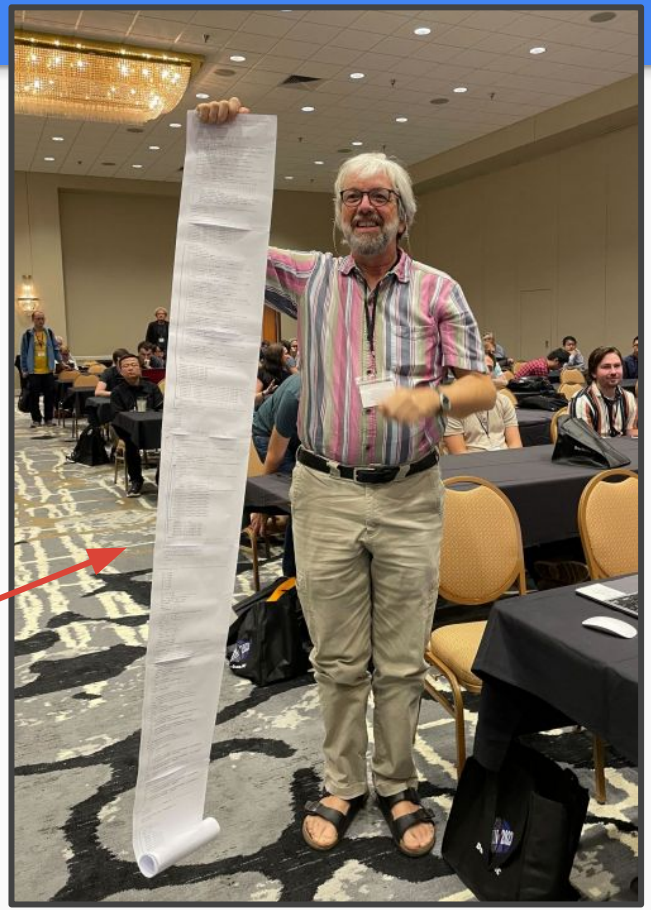
Using ML for Polarized Model

- Replace existing Fortran model with ML





Existing Model
(**SEK**)

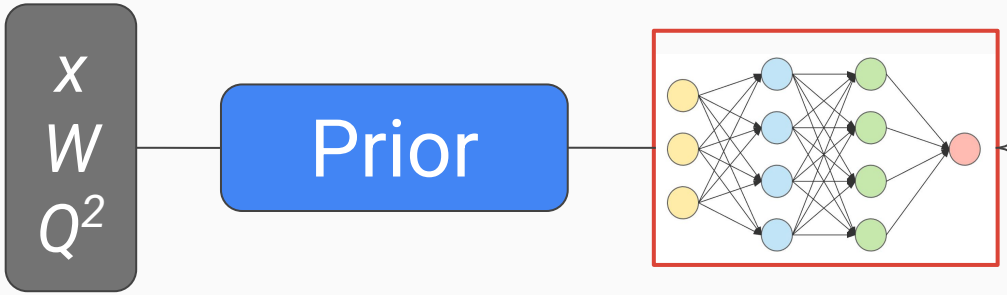


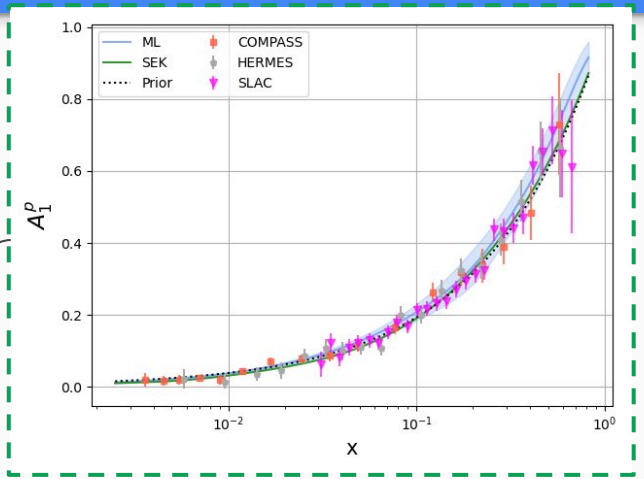
Sebastian **E**. **K**uhn

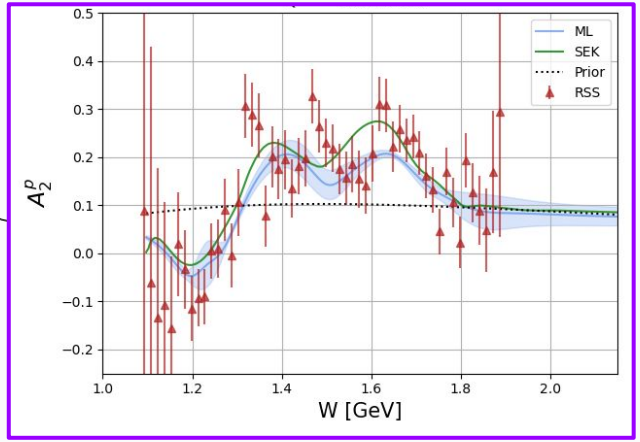
DNN Ensemble Fit of World SSF Data

See back-ups for details

Use physics priors modified by DNN to fit world data of A_1 & A_2 for p, d, & ^{3}He



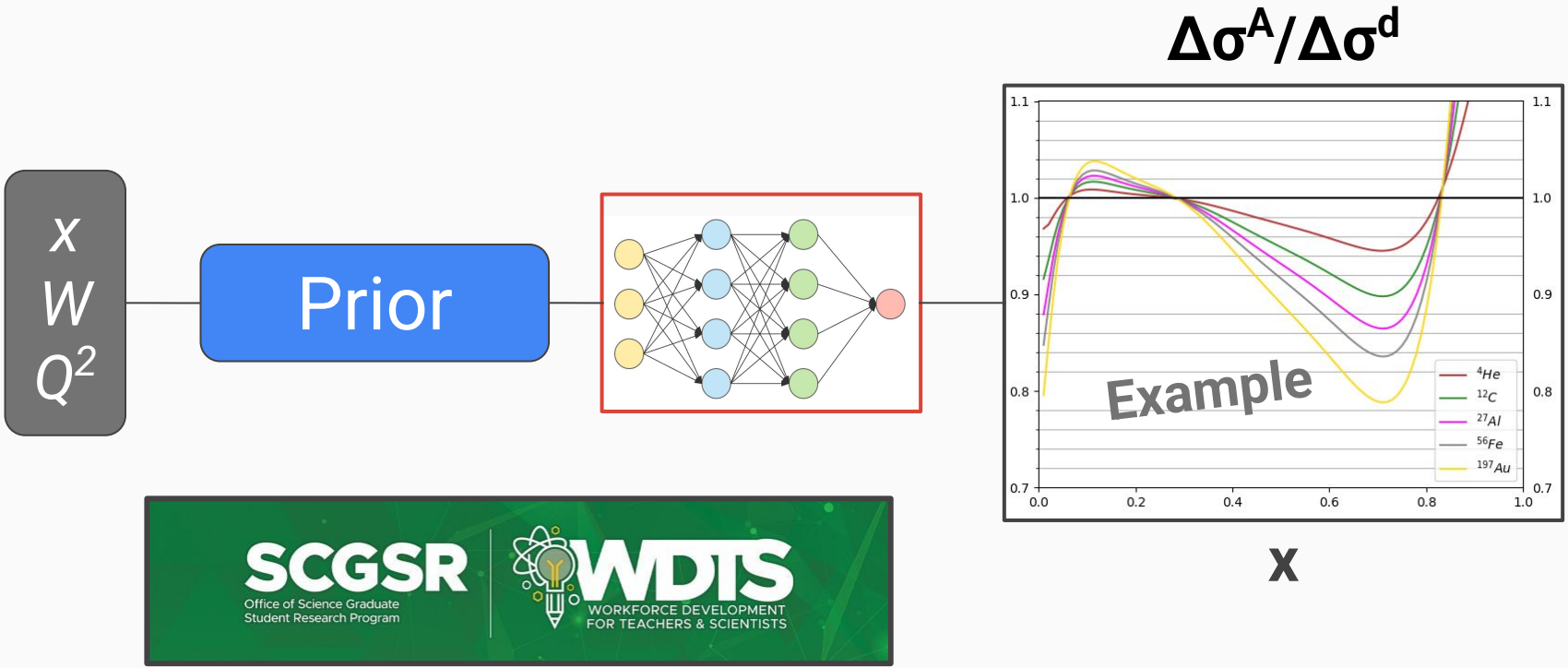




JSA Fellowship Project

Nuclear Model with DNNs

- Implement similar approach to fit **nuclear ratio**

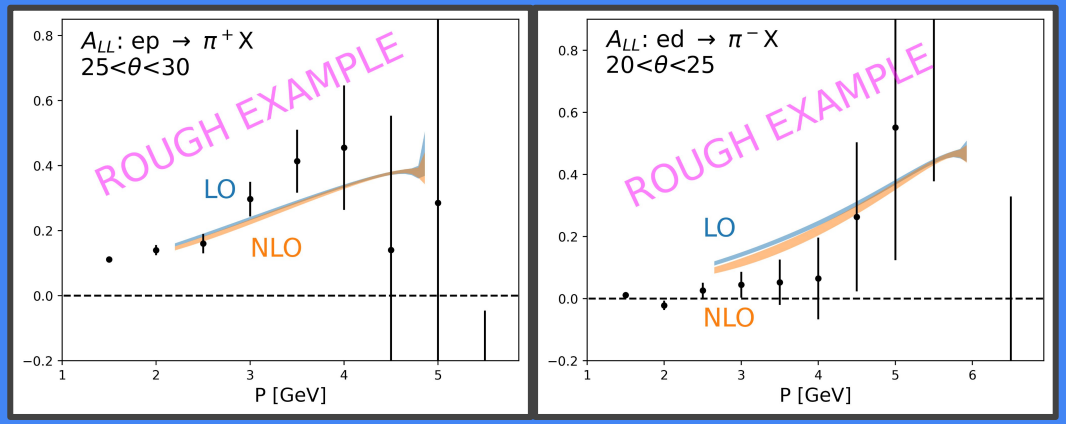


Future Analysis Topics

A_1 in Resonances



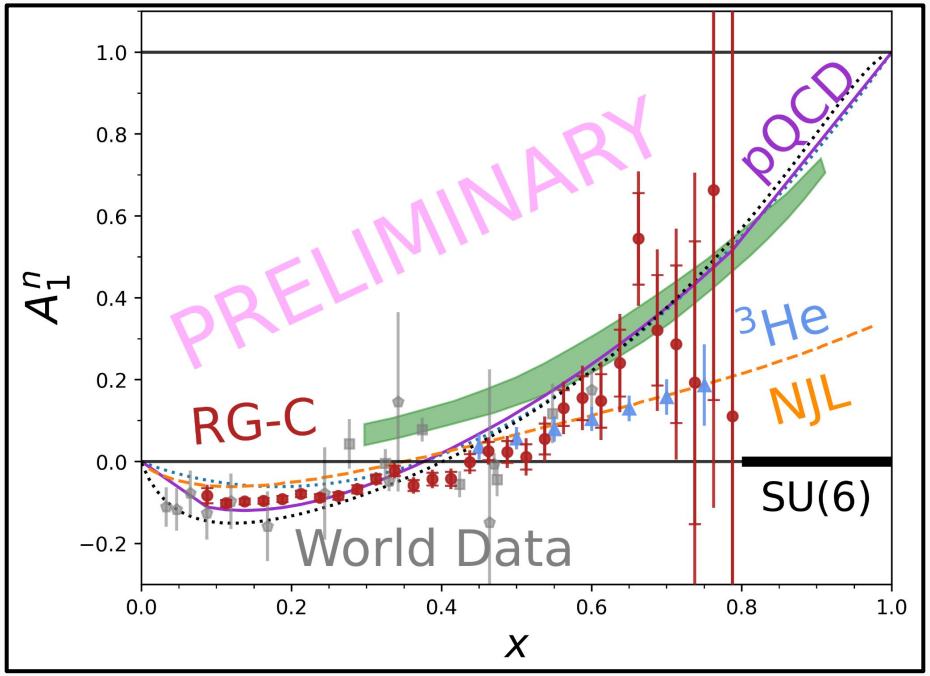
Inclusive ***Hadron*** Asyms ???

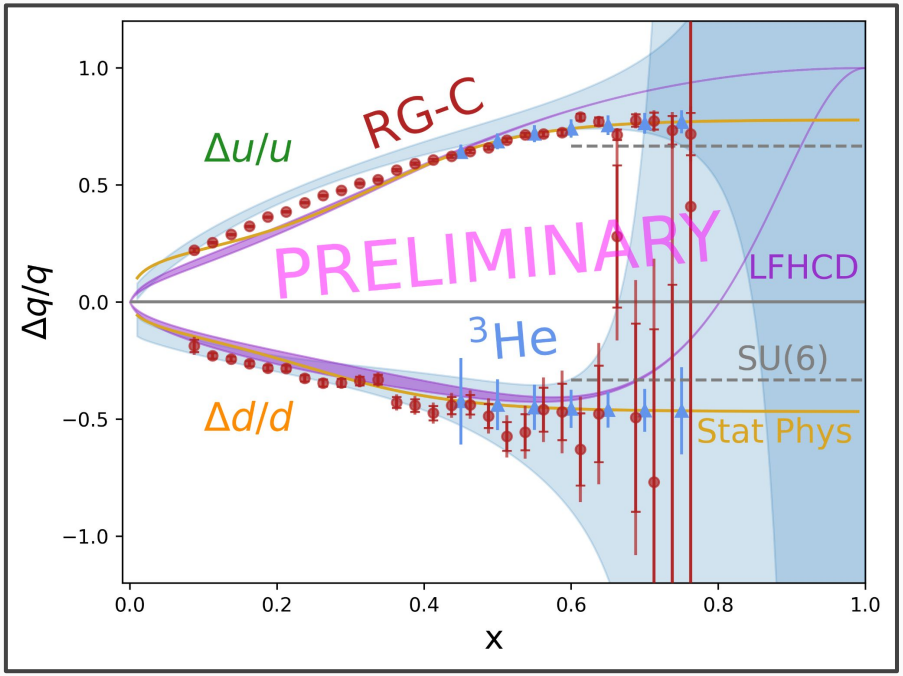


Predictions Courtesy of M. Schlegel

Closing Thoughts

- Finalize data analysis & perform data-MC comparison
- Prepare for RG-C II (see projections below)





Acknowledgments

- ODU Nuclear Group - “Quarks” DOE Grant
- Jefferson Science Associates Graduate Fellowship
- ODU Graduate Summer Research Award

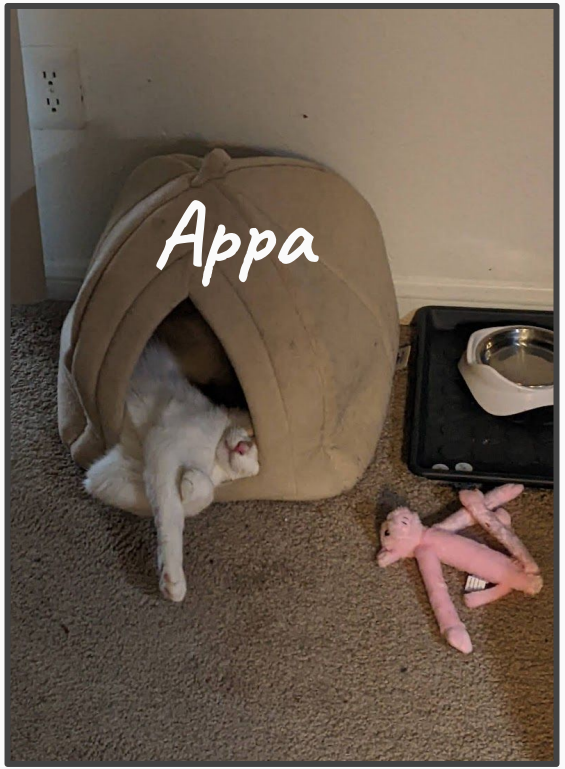


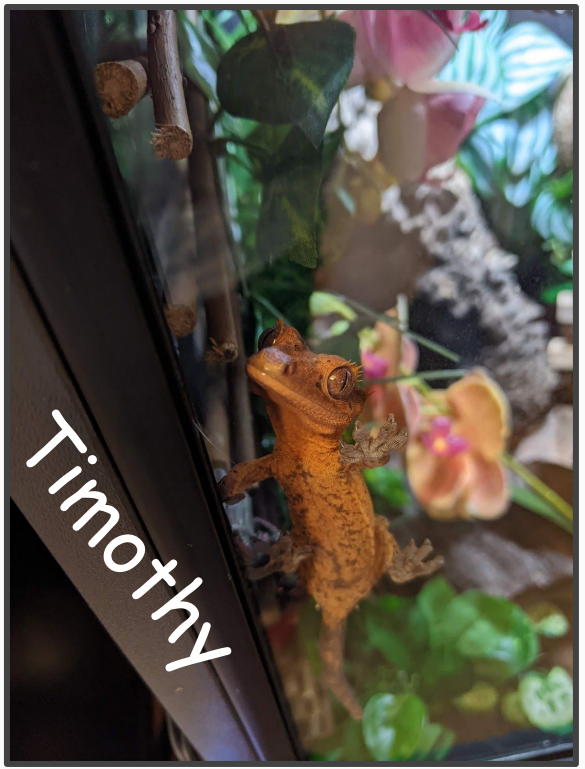




Questions/Comments



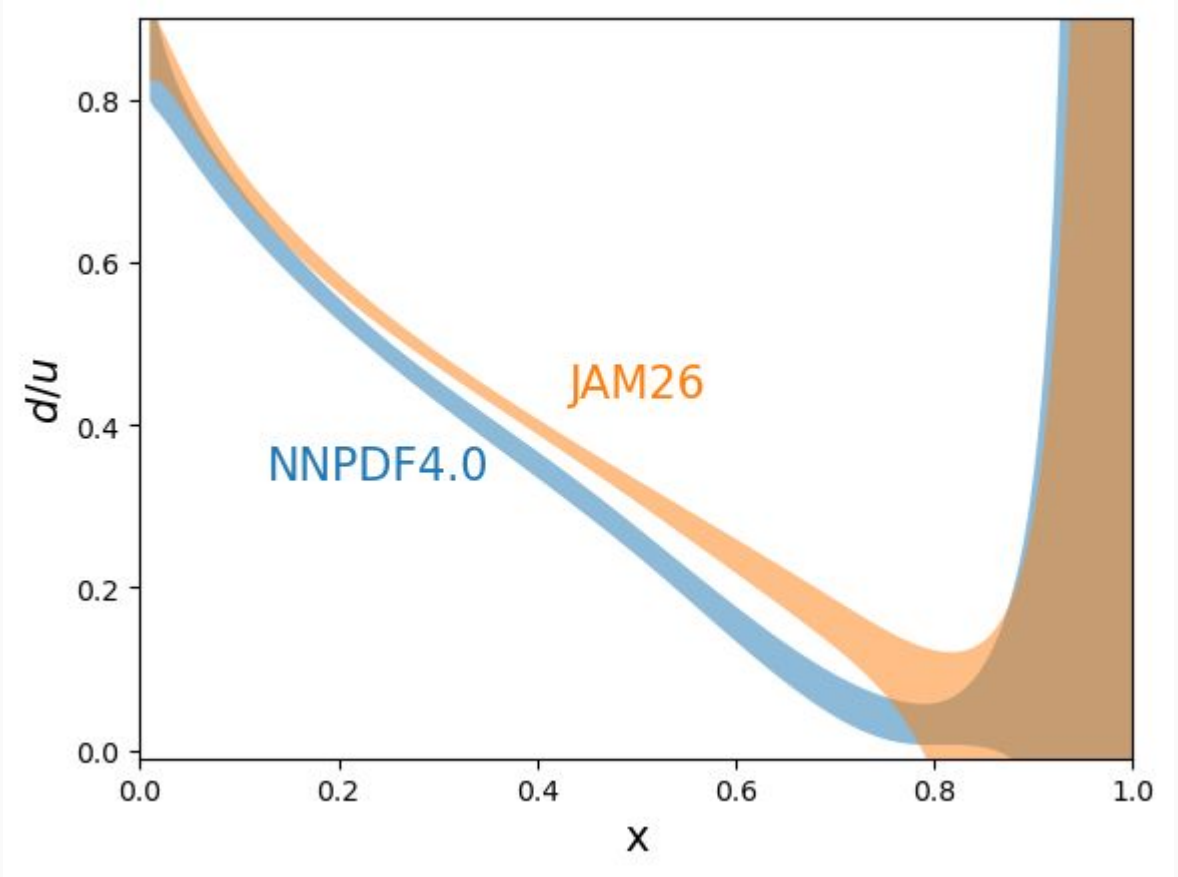




d/u PDFs

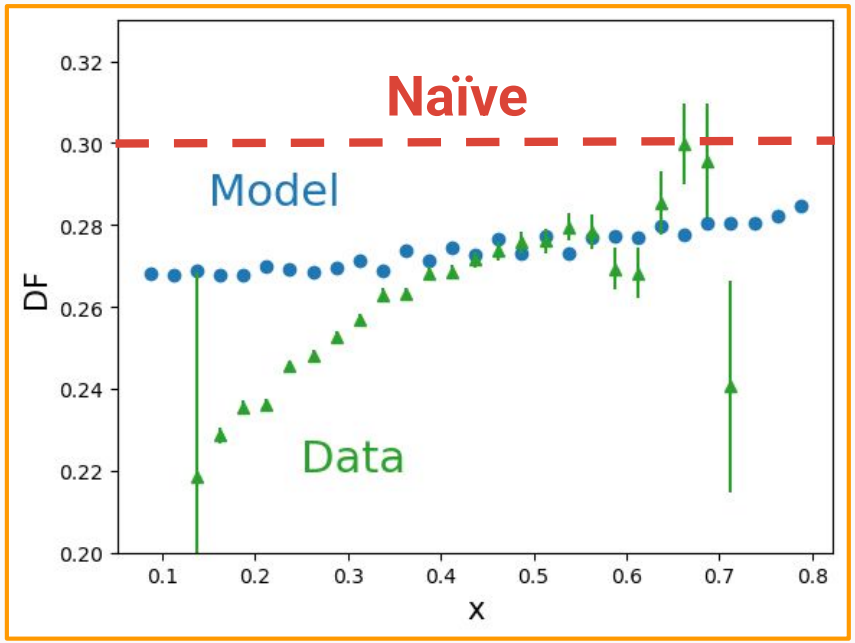
Needed for Δq/q results

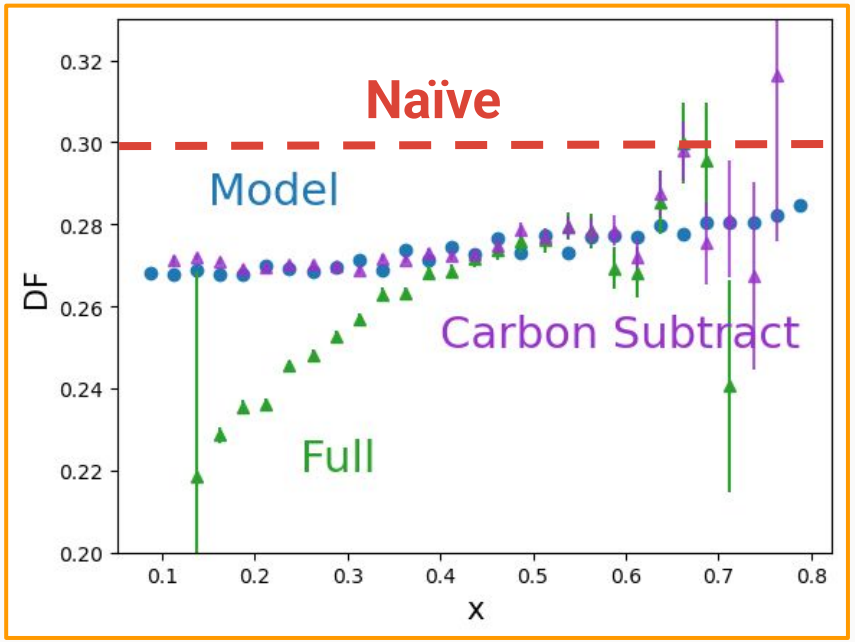
Using JAM26



Dilution Factor Compare

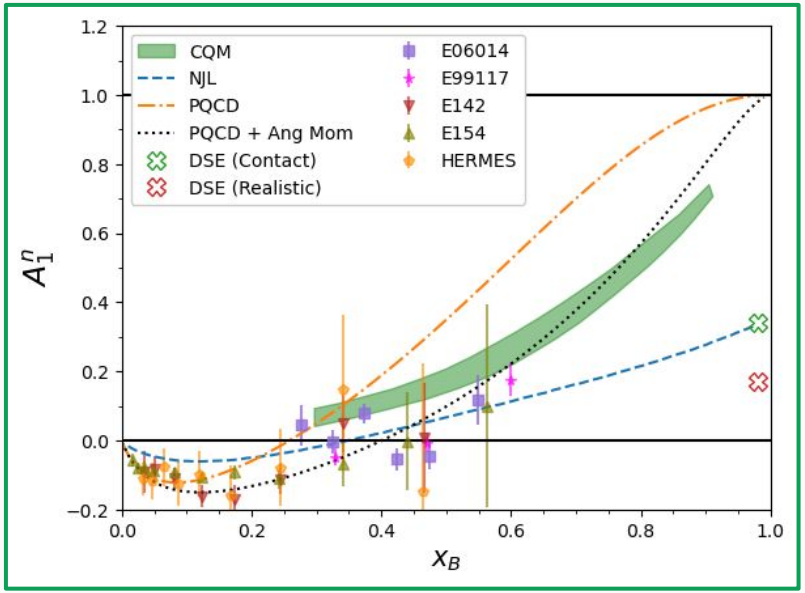
- Crude carbon subtraction agrees with model





What is Gained By Studying Everything?

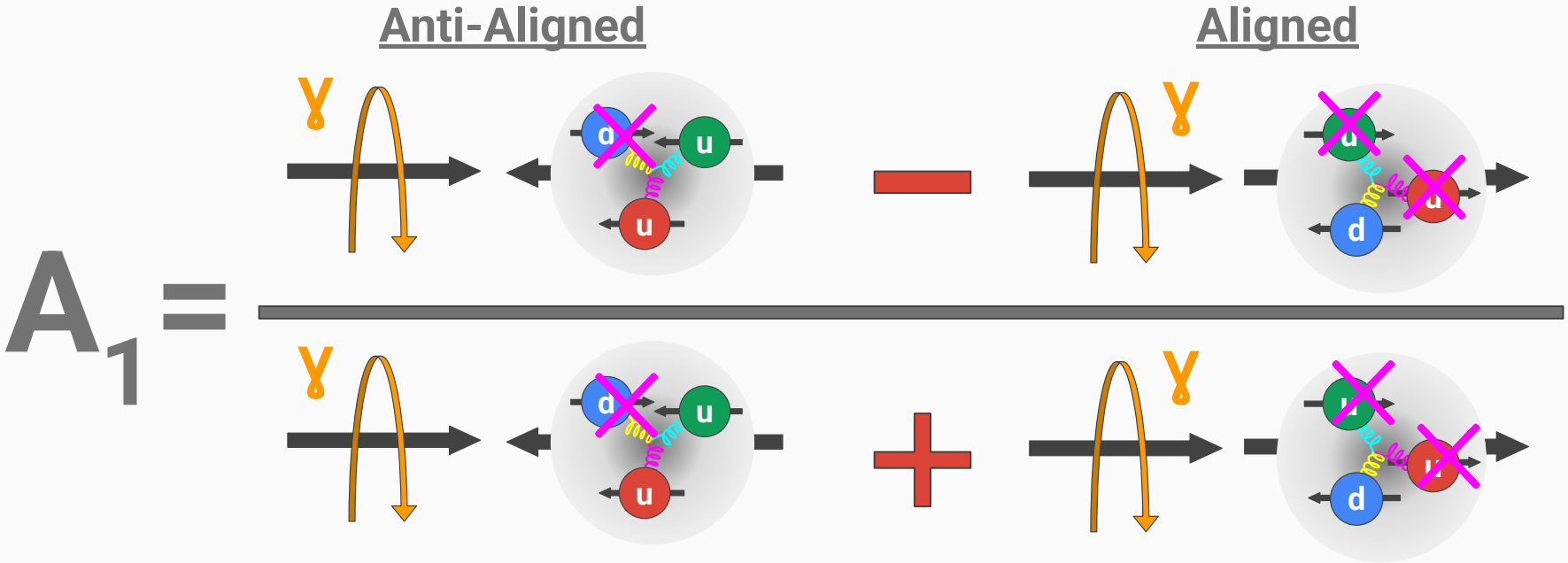
- Check theoretical predictions for $A_1(x->1)$



D. Flay et al. PRD 94, 052003 (2016)

First Virtual Photon Asymmetry

- Photoabsorption disfavors helicity aligned configurations

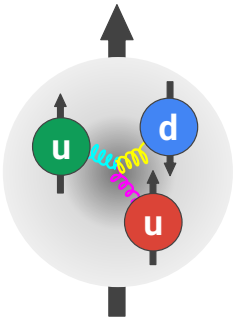


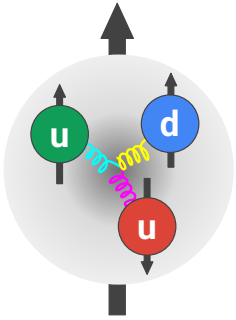
Naïve Quark Model SU(6) Prediction

- Taking wf into account **A1p=5/9 & A1n=0**

$$A_1 \sim \frac{g_1}{F_1} \approx \frac{\sum_q e_q^2 \Delta f_q}{\sum_q e_q^2 f_q}$$

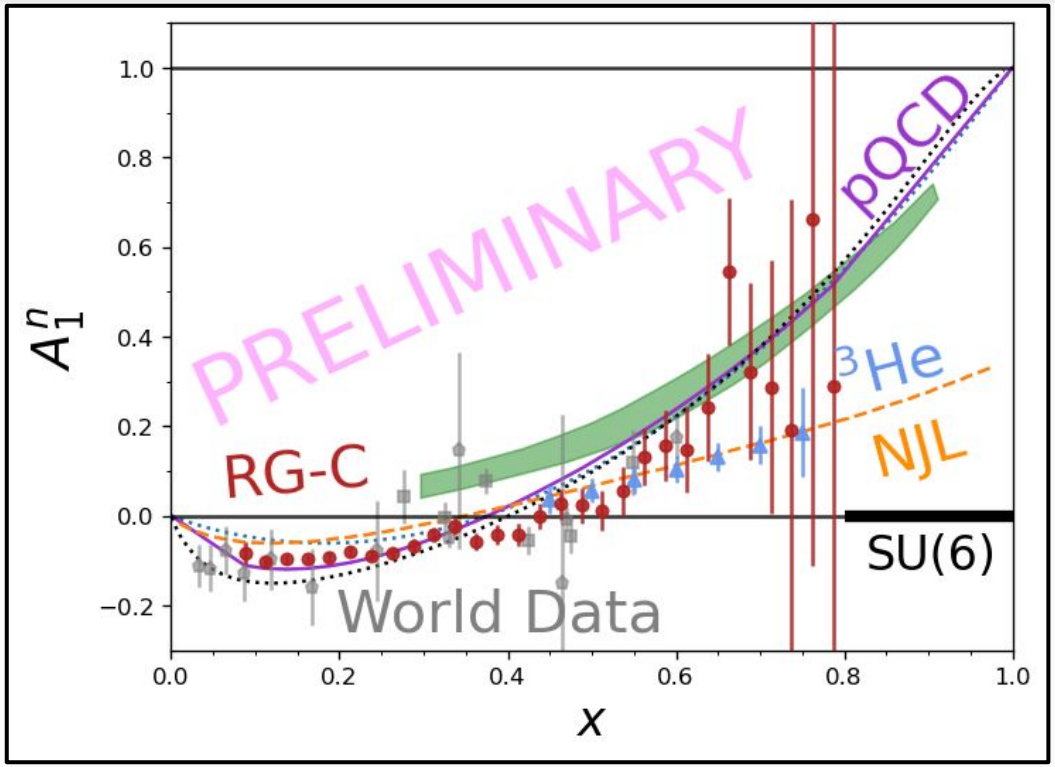
Proton

$$\frac{2}{3}$$ 

$$+ \frac{1}{3}$$ 

Very Preliminary Results for A_1 of the Neutron

Using More stats will help resolve large-x behavior of A1n

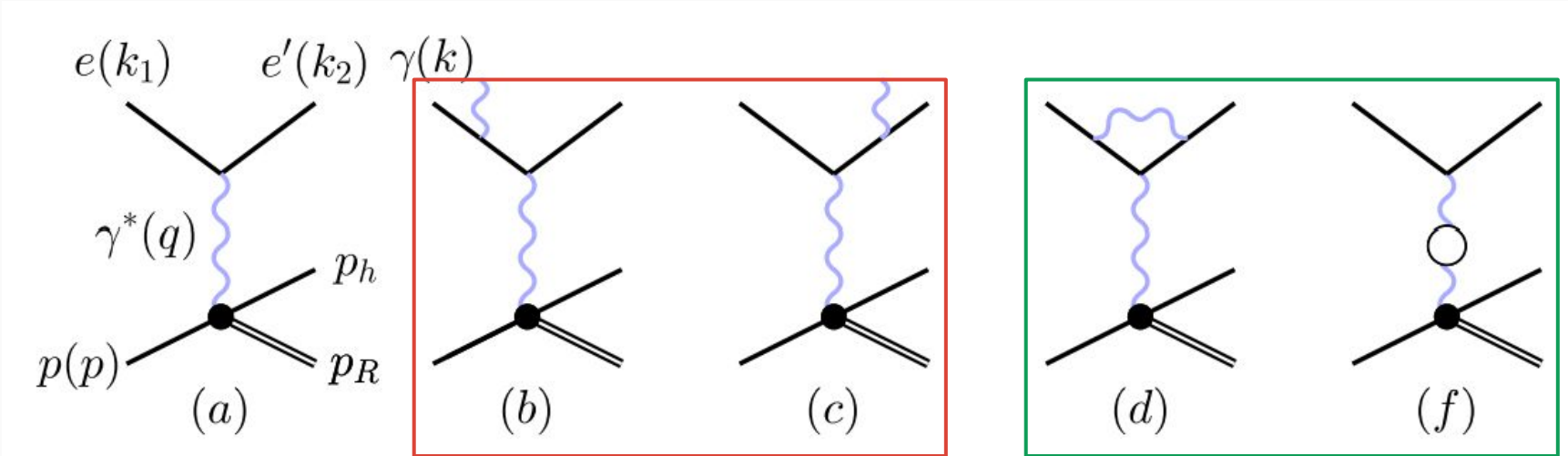


Naïve Correction

$$A_1^n = \frac{1}{F_2^n}\left(\tilde{A}_1^d F_2^d - A_1^p F_2^p\right) \quad \text{where} \quad \tilde{A}_1^d = \frac{A_1^d}{1 - 1.5\omega_D} \approx \frac{A_1^d}{0.92}$$

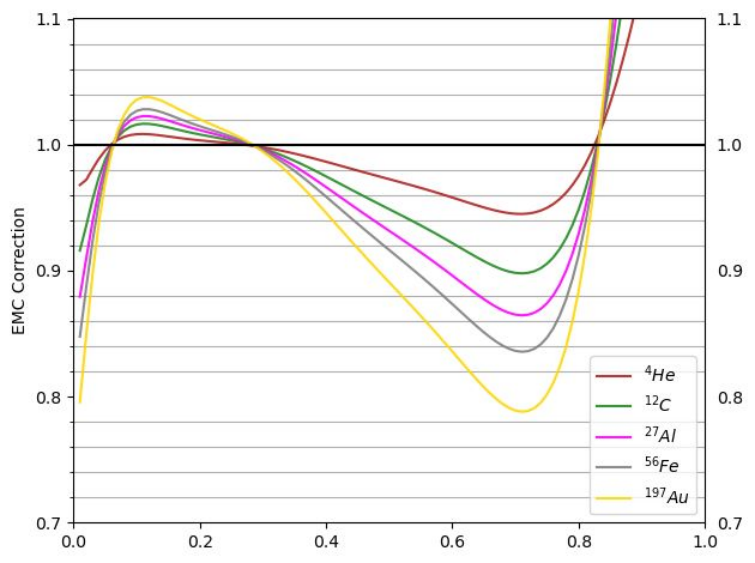
Radiative Effects

- Bremsstrahlung - Energy loss from photon
  - Initial & Final (pre/post scattering)
  - Includes external and internal pieces
- Vertex Corrections - Higher-order diagrams, etc
  - Needs more work



Nuclear Corrections

- Use EMC fit from SLAC
- Use smearing from F1F2-21(Hall C)



$$\tilde{F}^A(W^2,Q^2) \propto \int_{W'^2_{min}}^{W'^2_{max}} dx' \Big(ZF^p(x',Q^2) + (A-Z)F^n(x',Q^2) \Big)\ f(x',Q^2)$$

ı function that encodes the weight at a given value of the dummy variable x'. T
:mined by

$$(W'_i)^2 = W^2 + n_\sigma k_F |\vec{q}| - 2E_s(\nu + M)$$

^{2}, thus the minimum and maximum values of W'^2 are set by the number of stan

Bosted and Mamyan choose a 3-σ cutoff with a convolution grid of 100 points

$$(W'_i)^2 = W^2 + \xi_i k_F |\vec{q}| - 2E_s(\nu + M)$$

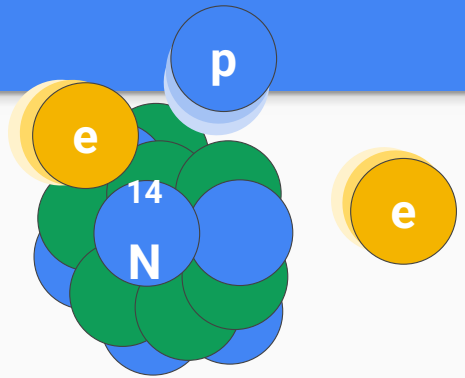
$$\xi_i = -3 + 6(i-1)/98 \quad \& \quad f_i = 0.0245 e^{-\xi_i^2/2}$$

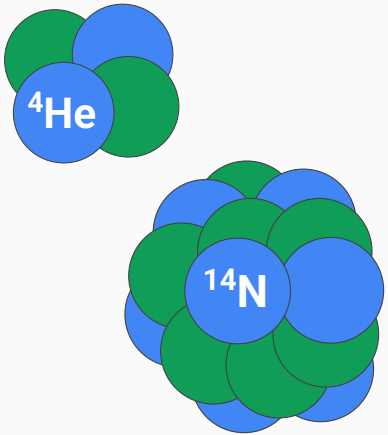
in the weight function f_i is a normalization factor. They then use these to coı
a

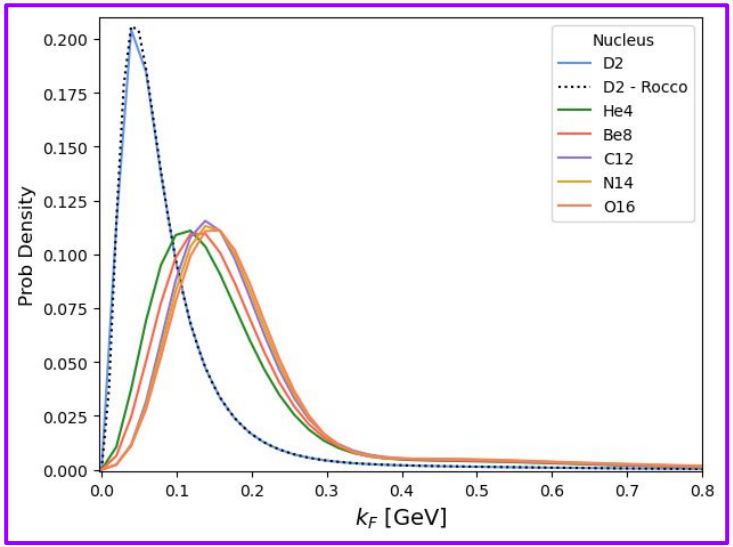
$$\tilde{F}^A(W^2,Q^2) \propto \sum f_i \left[ZF^p(W'_i) + (A-Z)F^n(W'_i) \right]$$

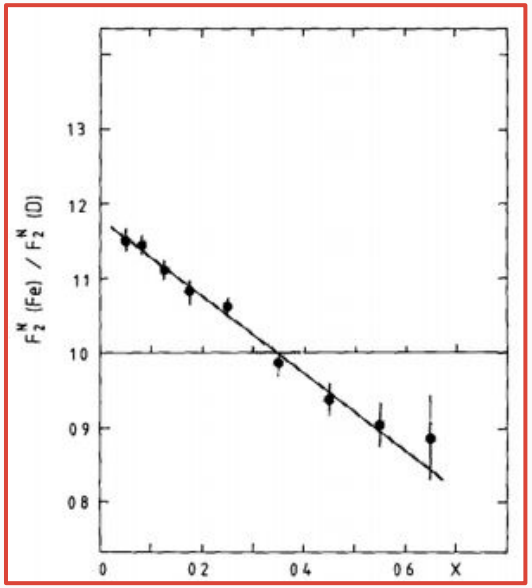
What's so Complicated?

- **Nuclear modification to nucleons inside nuclei!**
  - Fermi motion, EMC effect, FSI, MEC…



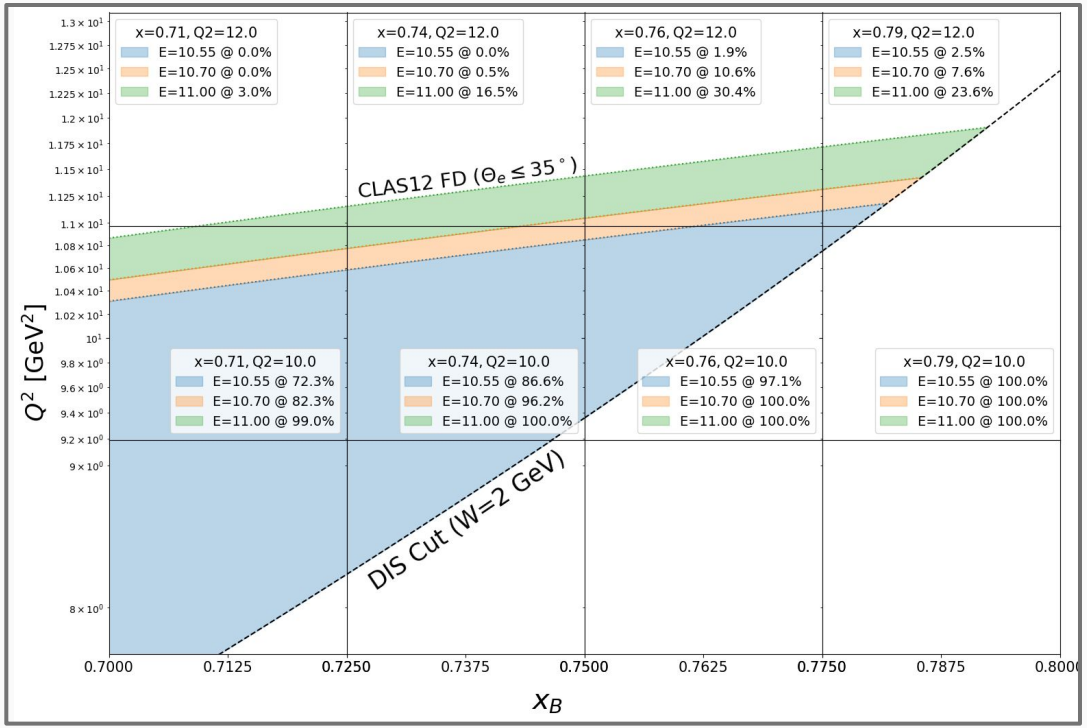






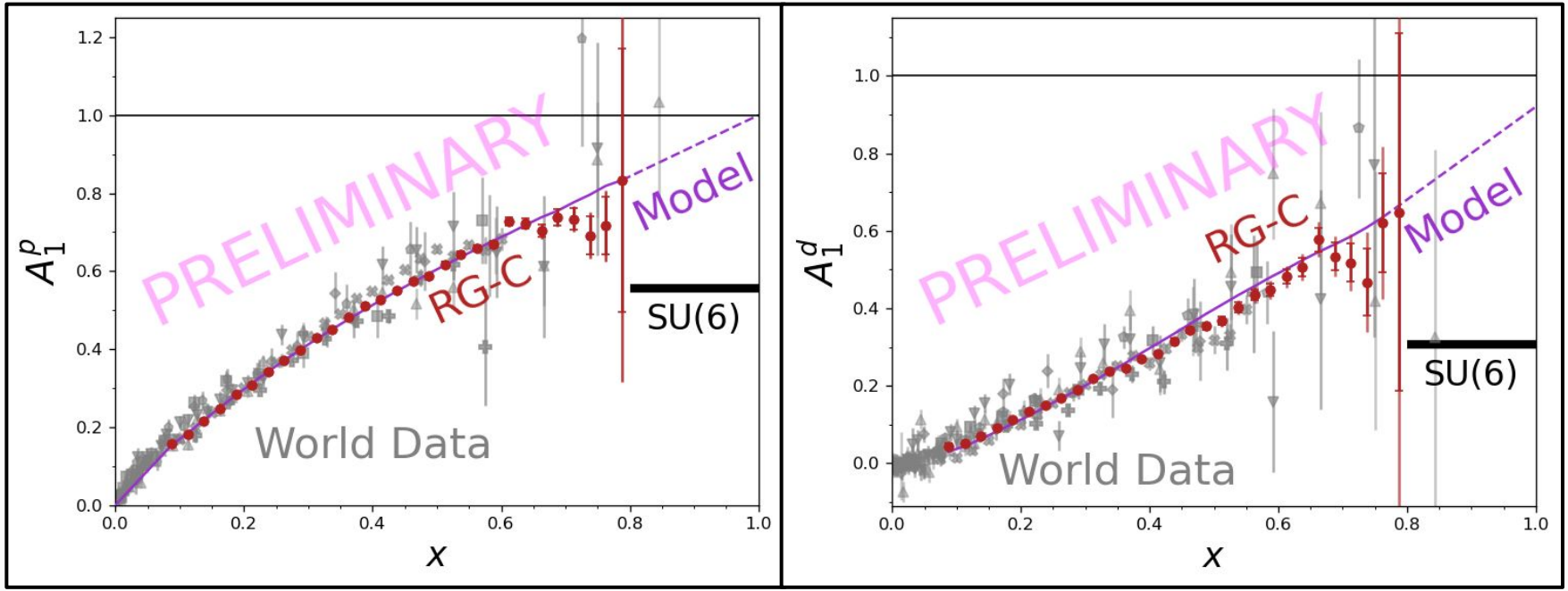
RG-C Part II

- Focus on ND3 with combination of improvements
  - Target Pol 25% -> 30%
  - Current 4nA -> 6 nA
  - Energy 10.5 -> 10.7 GeV

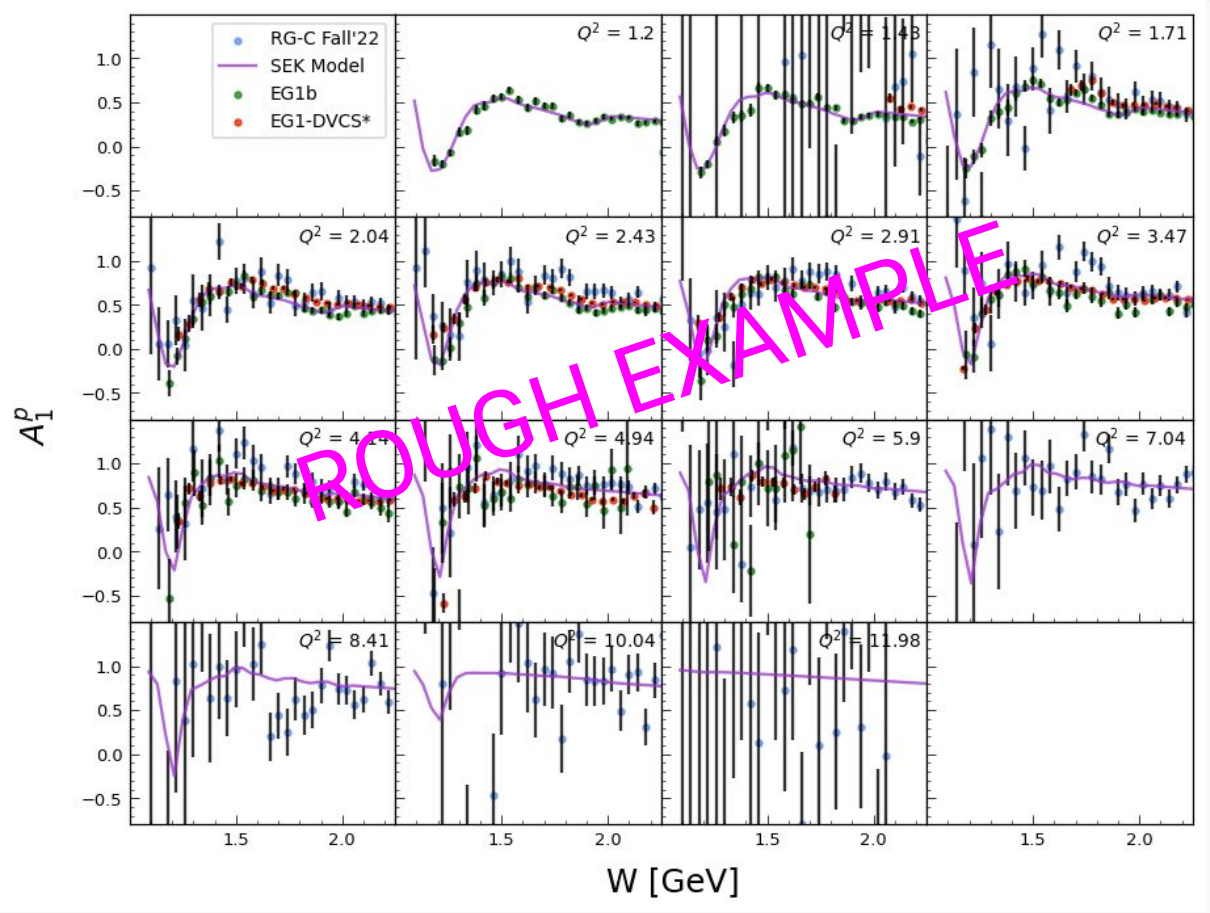


Preliminary Results for A_1 of Proton & Deuteron

- RG-C stats dramatically improves world data & disagrees with SU(6)
- Outer bars show current stats & inner with RG-C II



Example for Resonances - Small Sample of Fall 2022



QE Event Gen

Event Generator for e, A -> e', p/n, (A-1)

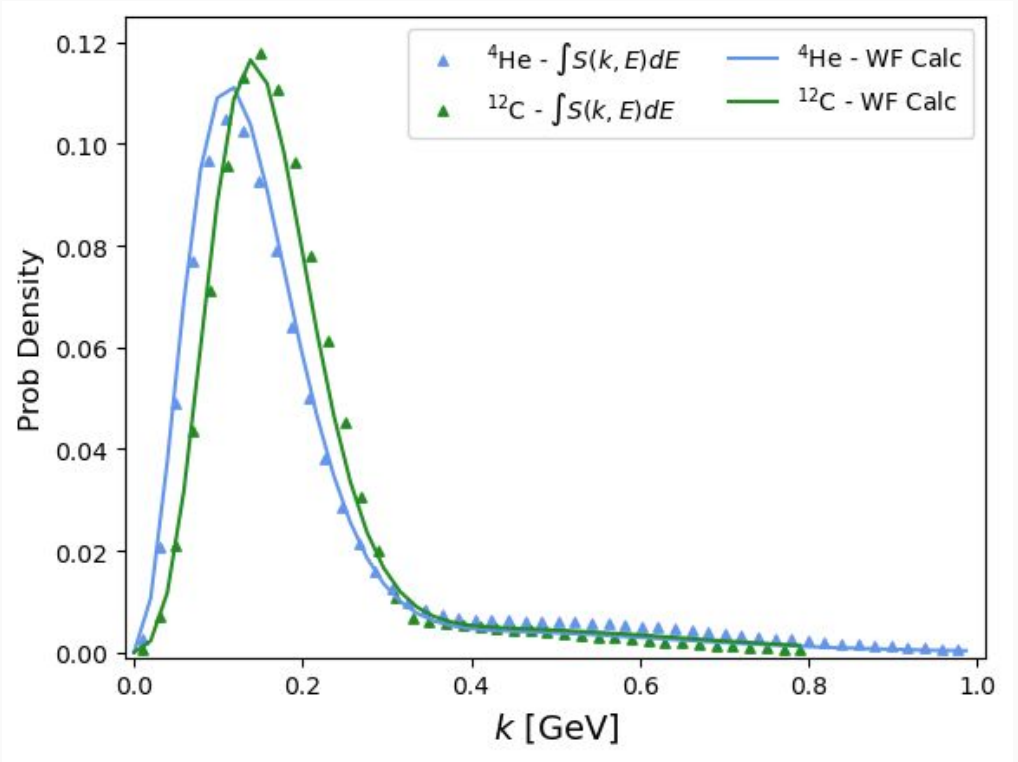
- Event generator for elastic/QE (e,e'p')
- Generate ***θ*** then solve for E' with energy & momentum constraints
  - On-shell required for initial nucleus, final p/n, & (A-1); **not pre-struck nucleon**
  - Requires initial nucleon momentum & nuclear excitation energy
  - Use CS weighting for events

$$E + M_A = E' + E'_f + E'_{A-1}$$

$$k = k' + p_f + P_{A-1}$$

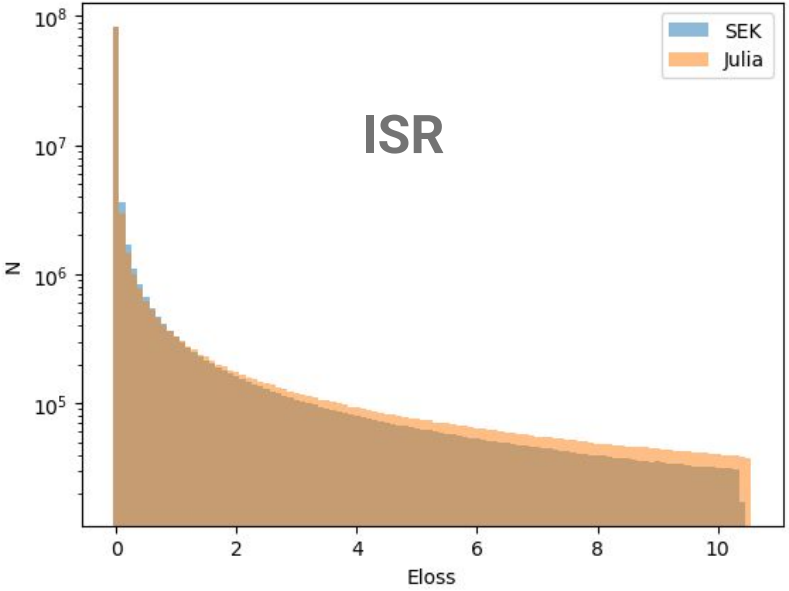
WF Calcs vs SFs

- Agree up to small shift & relative strength of tail to peak



Bremsstrahlung Radiation

- Using framework shown in neutrino event gen by J. Vidal et al
- Includes external and internal parts
- Similar to approach by Sebastian*



$$G = \frac{g(\Delta E_\gamma)^{g-1}}{E_{max}^g - (\Delta E_m)^g}$$

$$g = bt + \lambda$$

$$\lambda = \frac{\alpha}{\pi}\left[\ln\left(\frac{4|\vec{k}|^2}{m^2}\right) + 2\ln\left(\frac{|\vec{k}|}{|\vec{k'}|}\right) - 1\right] \simeq \frac{\alpha}{\pi}\left[\ln\left(\frac{4|\vec{k}|^2}{m^2}\right) - 1\right]$$

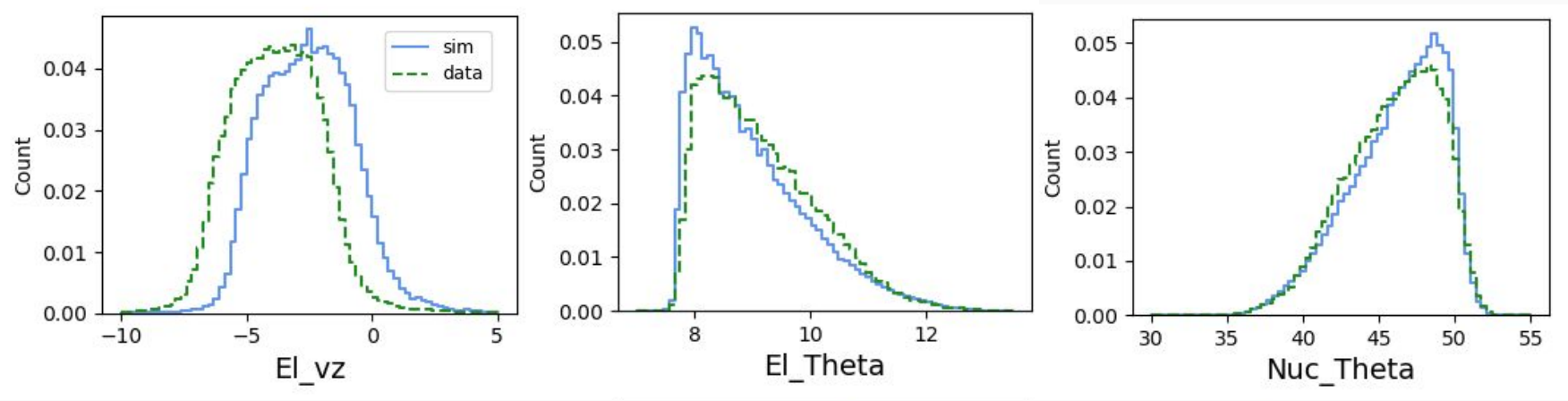
$$b = \frac{1}{9}\left(12 + \frac{Z+1}{ZL_1 + L_2}\right)$$

$$L_1 = \ln(184.15) - \frac{1}{3}\ln(Z) \quad \& \quad L_2 = \ln(1194) - \frac{2}{3}\ln(Z)$$

$$\lambda' = \simeq \frac{\alpha}{\pi}\left[\ln\left(\frac{4|\vec{k}|^2}{m^2}\right) - 1 + 2\ln\left(\frac{1-\cos\theta}{2}\right)\right]$$

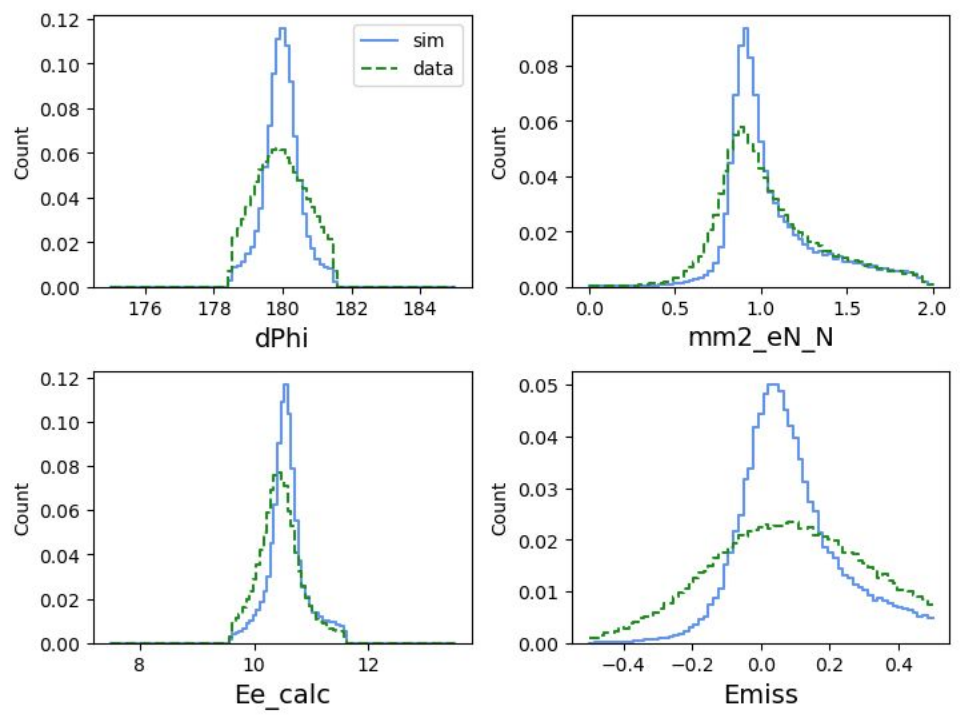
Reconstructed Distributions - NH3 & Pseudo NH3

- Used wrong vz distribution for Summer ‘22
  - Accidentally used dist from Spring ‘23 (might need to fix)
- Small shifts in reconstructed θ



Kinematic Distributions - NH3 & Pseudo NH3

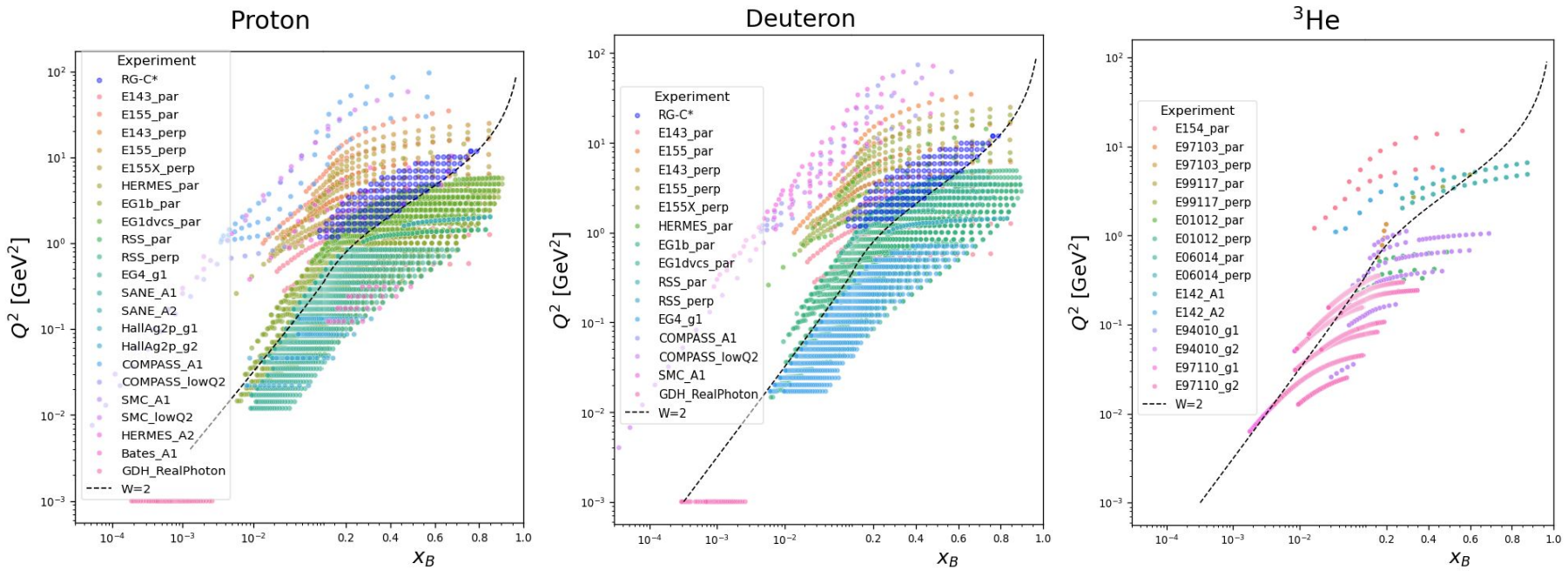
- GEMC distributions are sharper than data with some slight shifts
  - Proton part of MC NH3 seems too sharp



ML Fits

World Data

- Wealth of data but sparse & non-uniform precision (>50 sets)
- Combination of data for proton, ^{2}H, & ^{3}He from many experiments



Simultaneous Fits of A_1 & A_2 in Global Analysis

- Experiments measure asymmetries $A_{\parallel}$ & $A_{\perp}$
  - into virtual photon asymmetries A_1 & A_2
- SimultFit of proton and neutron A_1 & A_2
  - Leverage kinematic factors, constraints, & sum rules
  - Use nuclear corrections for deuteron and ^{3}He

Measurements →

$$A_{\parallel} = D(A_1 + \eta A_2),$$
$$A_{\perp} = d(A_2 - \zeta A_1),$$

“Full Smearing” Framework

- Using Weak Binding Approximation framework
- Using inelastic and elastic smearing

$$F_2^A(x,Q^2) = (f_0^{p/A} \otimes F_2^p) + (f_0^{n/A} \otimes F_2^n)$$

$$(f_0^{N/A} \otimes F_2^N)(x,Q^2) = \int_x^{M_A/M_N} dy f_0^{N/A}(y,\gamma) F_2^N\left(\frac{x}{y}, Q^2\right)$$

Penalties - Bounds on A1 & A2

- Hard Bounds (Heavy penalty)
  - Positivity Constraint: $|A1| \leq 1$ & $|A2| < \sqrt{R}$
  - Soffer Bound: $|A2| < \sqrt{R*(1+A1)/2}$
- Soft Bounds (Light/Moderate penalty)
  - BC Sum Rule (including elastic contribution)
  - Real Photon Limit: $A2(Q2=0)=0$
  - $A1(W<\pi$ thresh$)=1$
- Additional Bounds
  - GDH Sum Rule (anchor Q2=0)
  - Bjorken Sum Rule
  - $A2(Q2\to\infty)\to 0$???
  - Use Regge to bound $x<<1$

ML Structure - Details

- Resonances - Sum over BW's w/ NN corrections
  - List of resonances and widths from unpolarized fits
  - Asym = (BW + NN(W) mod) x (1+NN-Q2-evol)
    - Each res gets W-mod and Q2-evol
- Inelas - Only uses x, Q2 inputs
  - $A1p \sim x^{0.72}$ (1 + NN-mod-evol)
  - $A1p \sim (1/.6)(x-0.4)x^{0.72}$ (1 + NN)
  - $A2 \sim A2^{WW}$(1 + NN)
    - $A2^{WW}$ is analytically determined because of explicit A1p/n

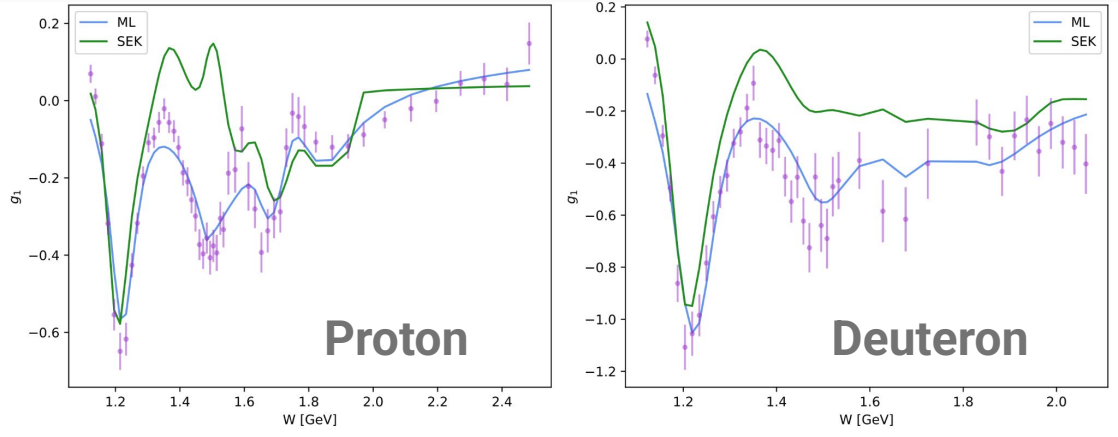
```
resonances = [
    #1.232, 1.440, 1.520, 1.535, 1.620, 1.650, 1.680, 1.720
    {"name": "Delta1232", "M0": 1.232, "G0": 0.117, "A0":-0.7},
    {"name": "N1440",     "M0": 1.430, "G0": 0.350, "A0":-0.07},
    {"name": "N1520",     "M0": 1.515, "G0": 0.115, "A0":-0.07},
    {"name": "N1535",     "M0": 1.535, "G0": 0.150, "A0":-0.07},
    {"name": "N1620",     "M0": 1.630, "G0": 0.140, "A0":-0.03},
    {"name": "N1650",     "M0": 1.655, "G0": 0.140, "A0":-0.03},
    {"name": "N1675",     "M0": 1.655, "G0": 0.150, "A0":-0.03},
    {"name": "N1680",     "M0": 1.685, "G0": 0.130, "A0":-0.03},
    {"name": "Delta1700", "M0": 1.700, "G0": 0.293, "A0":-0.03},
    {"name": "N1710",     "M0": 1.710, "G0": 0.100, "A0":-0.03},
    {"name": "N1720",     "M0": 1.748, "G0": 0.114, "A0":-0.03},
    {"name": "Np1720",    "M0": 1.725, "G0": 0.120, "A0":-0.03},

    {"name": "dip_1850",  "M0": 1.850, "G0": 0.2, "A0":-0.1},
```

ML Results - Low Q^2

- Good improvements over existing fits (new data & ML flexibility)
- Better matching of Res then transition between Res & Inelastic

Real Photon Data



EG4 Proton Data

