Double-Spin Asymmetries for More Than Just the Proton

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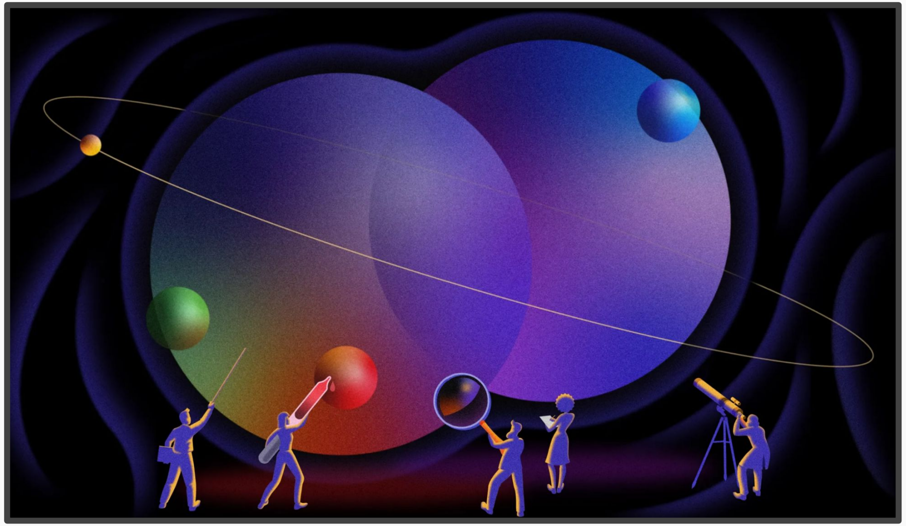
OLD DOMINION UNIVERSITY

There's More Than Just the Proton!

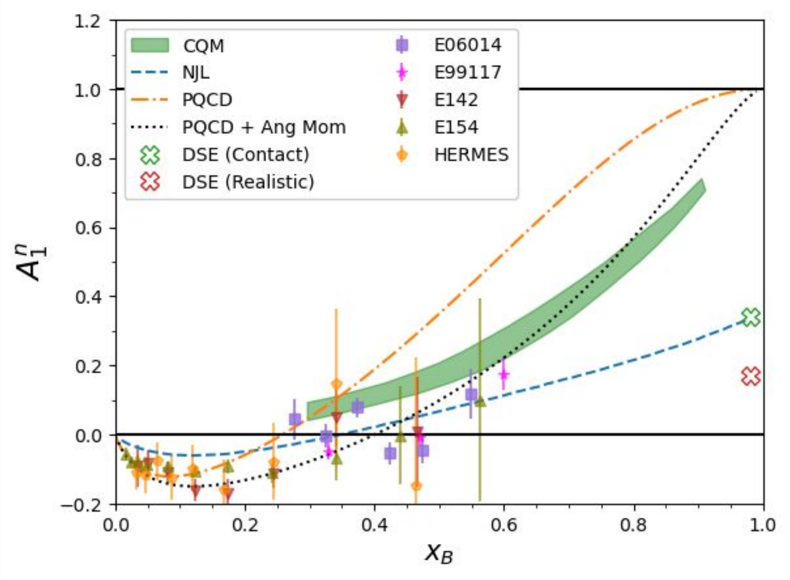
- What if you want to study the neutron?
  - Free neutron targets are a fairy tale
- BUT the deuteron is smallest nucleus
  - Study proton & deuteron to extract neutron



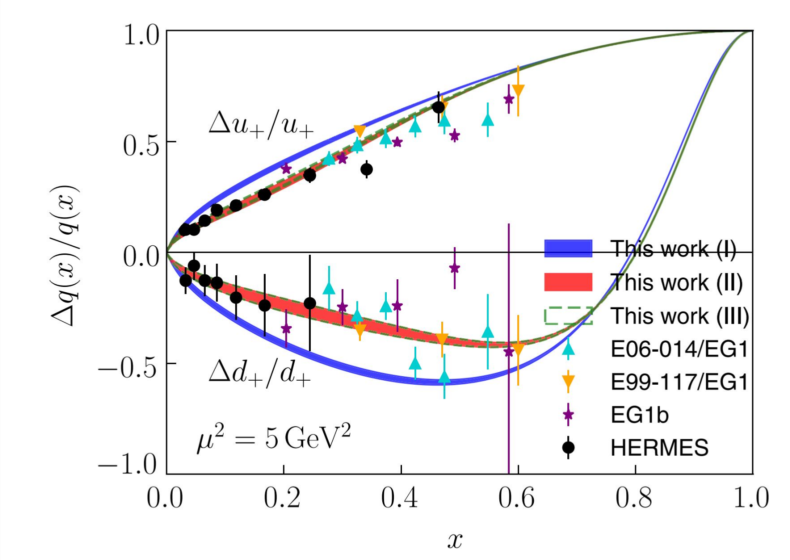
What is Gained By Studying Everything?

- ❖ Check theoretical predictions for A1n at large x_B
- ❖ Using proton and deuteron/He3 data can help constrain Δq/q

LFHQCD



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



T. Liu et al., PRL 124, 8 082003 (2020)

Constructing the Physics Asymmetry

- “Raw Asymmetry”
  - Asymmetry between +/- helicity states normalized by Faraday cup charge
- Dilution Factor
  - Fraction of total events coming from polarized proton/deuteron
- Polarization Term
  - Product of beam and target polarizations

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

How do we get these pieces?

- "Raw Asymmetry"
  - Main observable from data
- Polarization Term
  - Can use dilution factor with theoretical asymmetry to precisely extract from data
- Dilution Factor
  - Can obtain using auxiliary target data but precise data means tricky systematics
  - **What about by modeling targets using fits to world structure function data?**

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

Modeling RG-C Targets

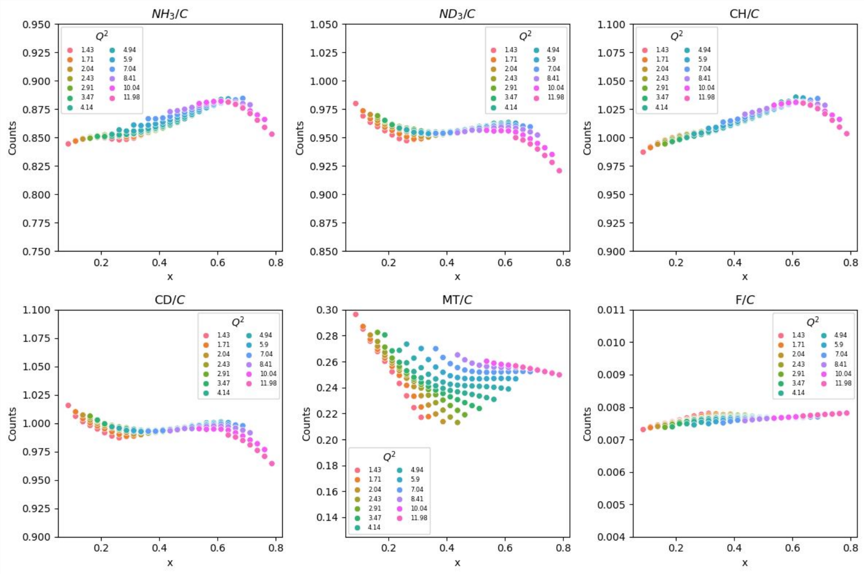
- Determine the number of “counts” for a given target
- Get F1, F2 fits with nuclear corrections (EMC effect, Fermi motion, etc)
- Obtain CS’s then build targets using

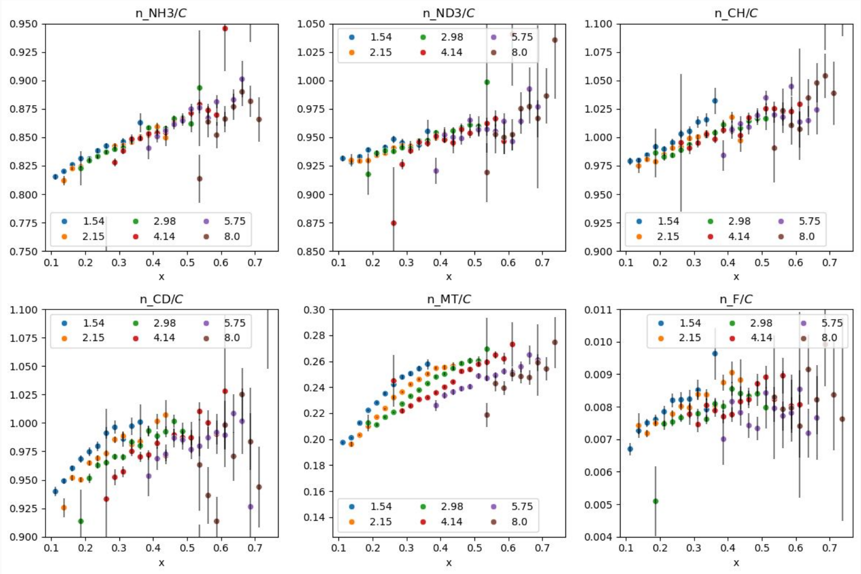
$$\Delta\sigma^N(x,Q^2) = \sigma_{Mott}\left[\frac{1}{\nu}F_2^N + \frac{2}{M}\tan^2(\theta/2)F_1^N\right]$$

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

Modeling Counts for RG-C Targets

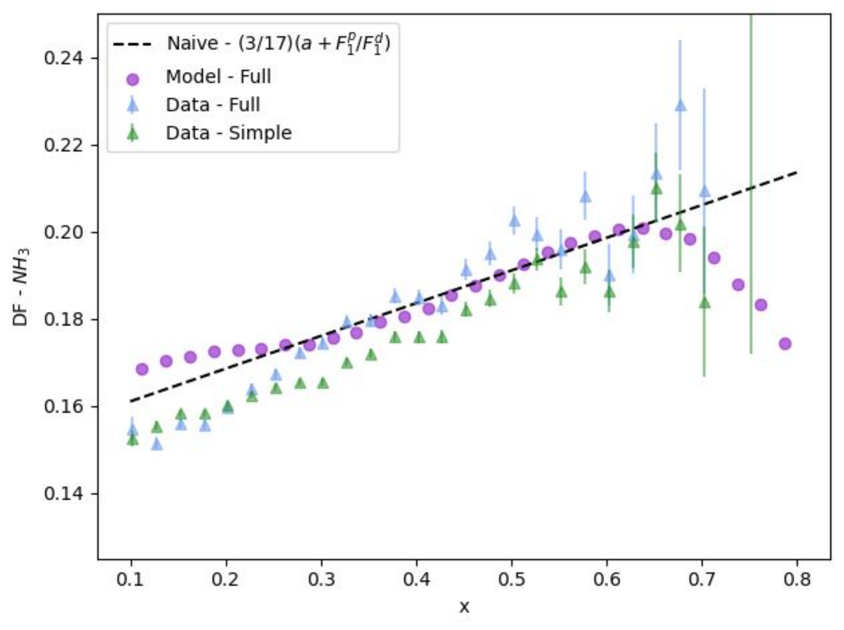
- ❖ Build targets and compare counts between model and data
- ❖ Reasonably close in most cases
  - ➢ Differences from imperfect fits, nuclear corrections, & radiative effects





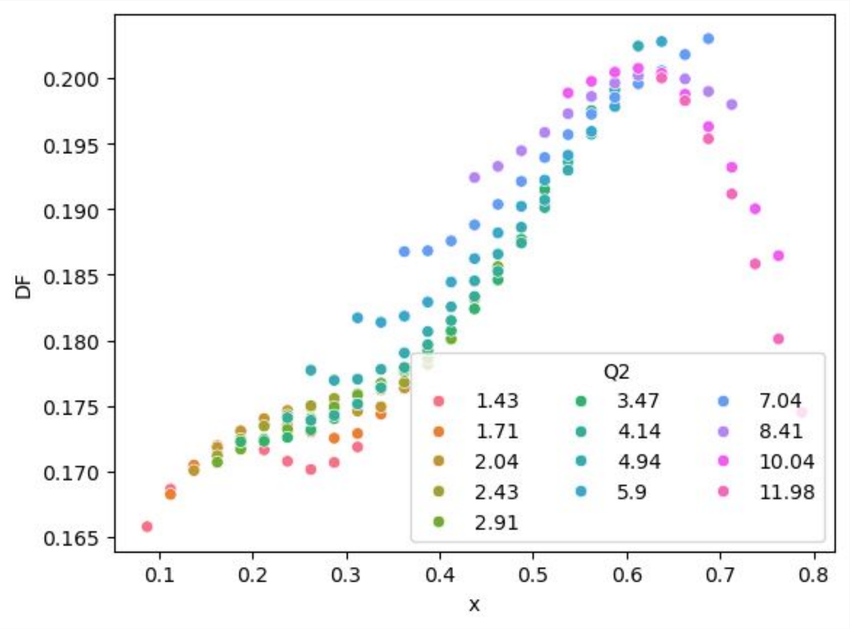
Dilution Factor Model for Proton

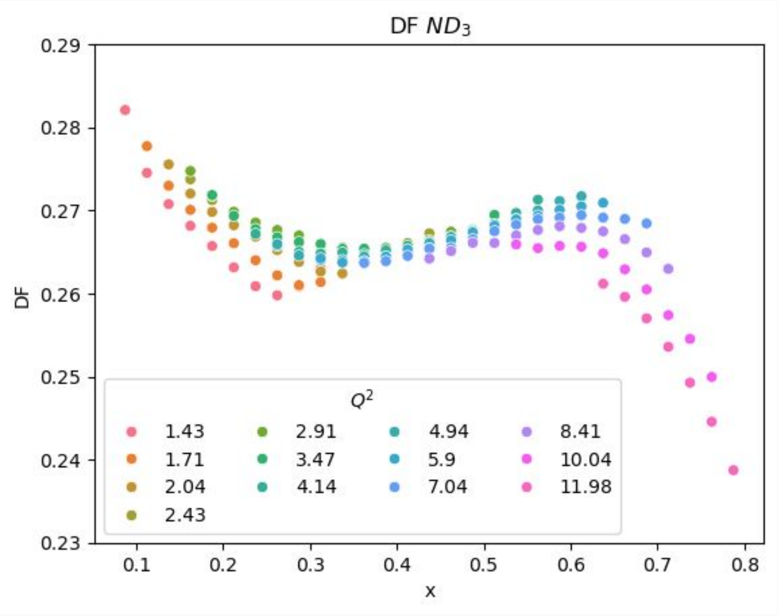
- Naive Model DF~(3/17)(a + F1p/F1d)
- Using fits to world inclusive data (F1F221 Christy-Bosted)
- Shifts between model and data at small *x* (fit issues & radiative effects)



Dilution Factor Model for Proton & Deuteron

- ❖ Overall trends match expectation
- ❖ Some regions with *questionable x* & Q^2 dependences





Obtaining Polarization Term

- Product of beam and target polarization $\boldsymbol{P_b P_t}$
- Obtain from NMR & Møller Polarimeter
  - Large differences from various sources
- Obtain from scattering
  - Elastics - High accuracy, limited statistics
  - DIS - High stats, normalization systematic

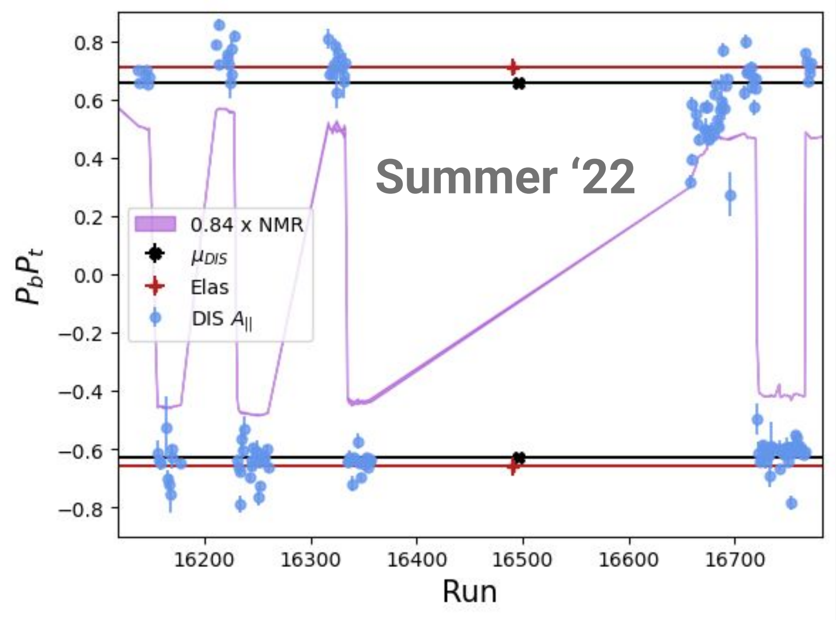
$$A_{||} = \frac{1}{P_b P_t f_{NH_3}} \frac{n^+ - n^-}{n^+ + n^-}$$

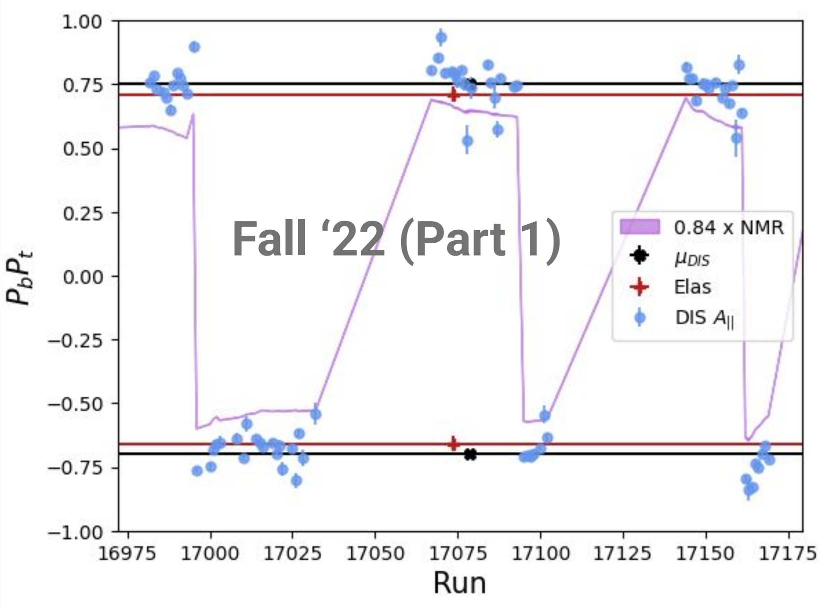
$$A_{||} = \frac{2\tau r_G \left[\frac{M}{E} + r_G(\tau \frac{M}{E} + (1+\tau)\tan^2(\frac{\theta}{2}))\right]}{1 + r_G^2 \tau/\epsilon}$$

$$P_b P_t = \frac{A_{||,raw}}{D_F A_{||,phys}}$$

Obtaining P_bP_t from DIS for NH_3

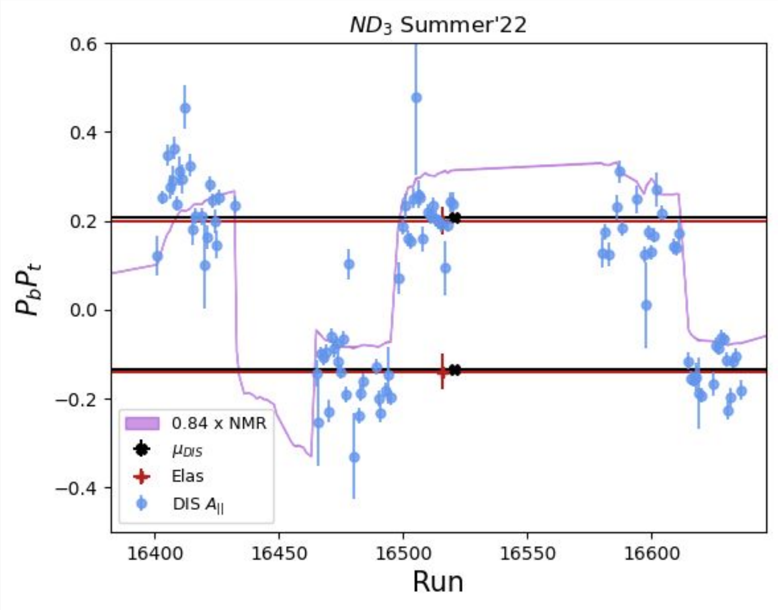
- Using model Dilution Factor & fiducial cuts comparable to elastics
- Maybe a small-ish normalization disagreement with elastics
- Big disagreement with NMR (offset comes from ice build up)

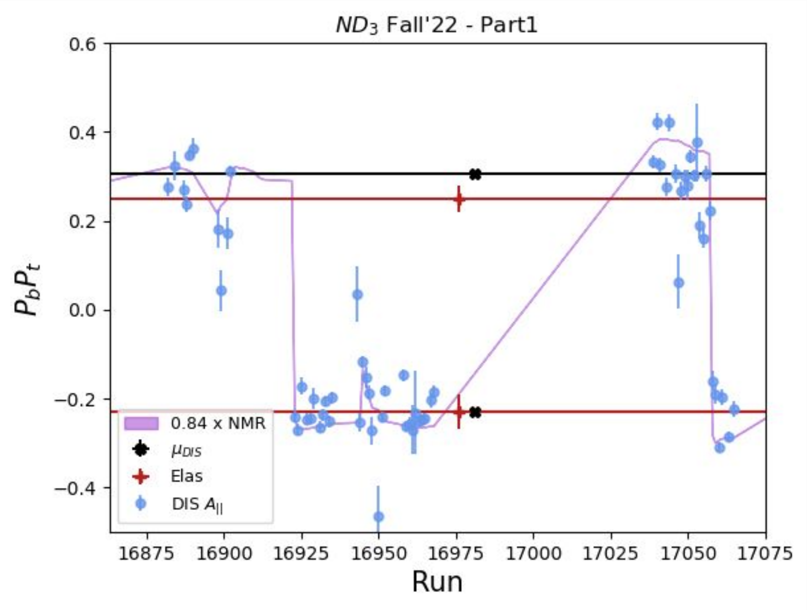




Obtaining $P_b P_t$ from DIS for ND_3

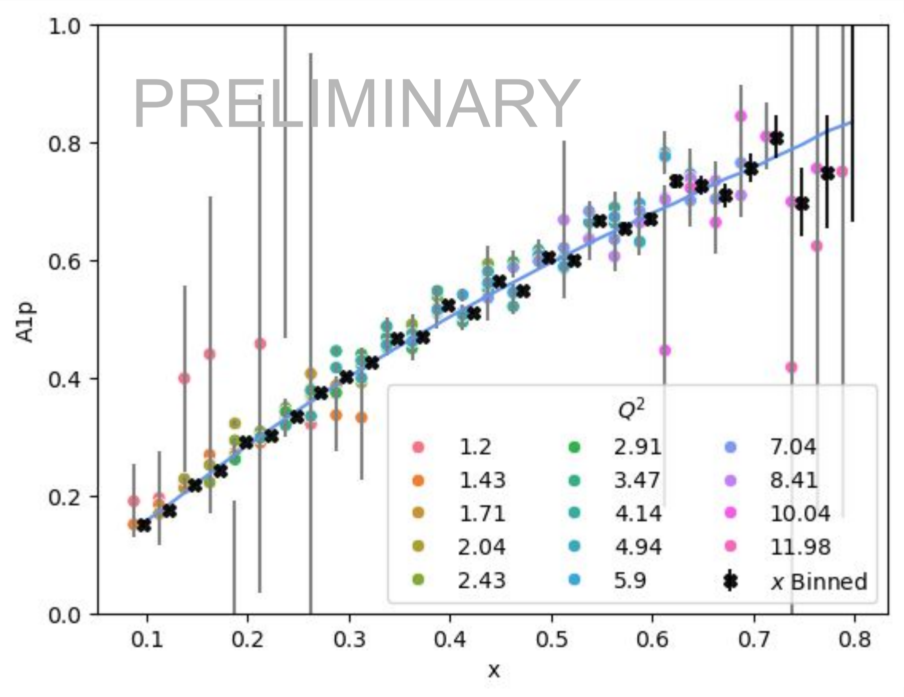
- ❖ Using model for Dilution Factor (accurate on average)
- ❖ Good agreement with elastics (within error bars)
- ❖ More consistent with NMR

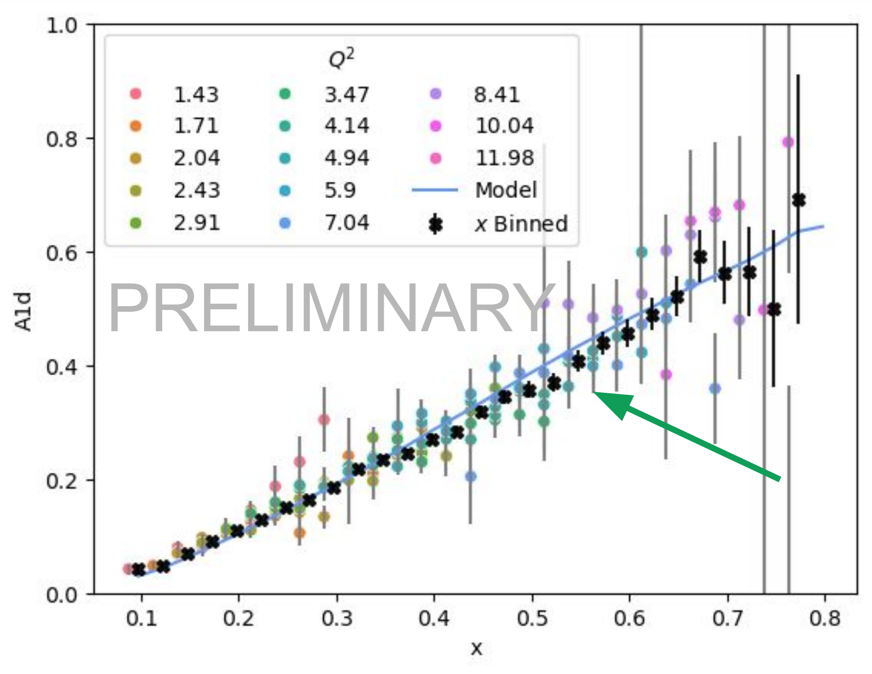




Preliminary $A_1(x,Q^2)$

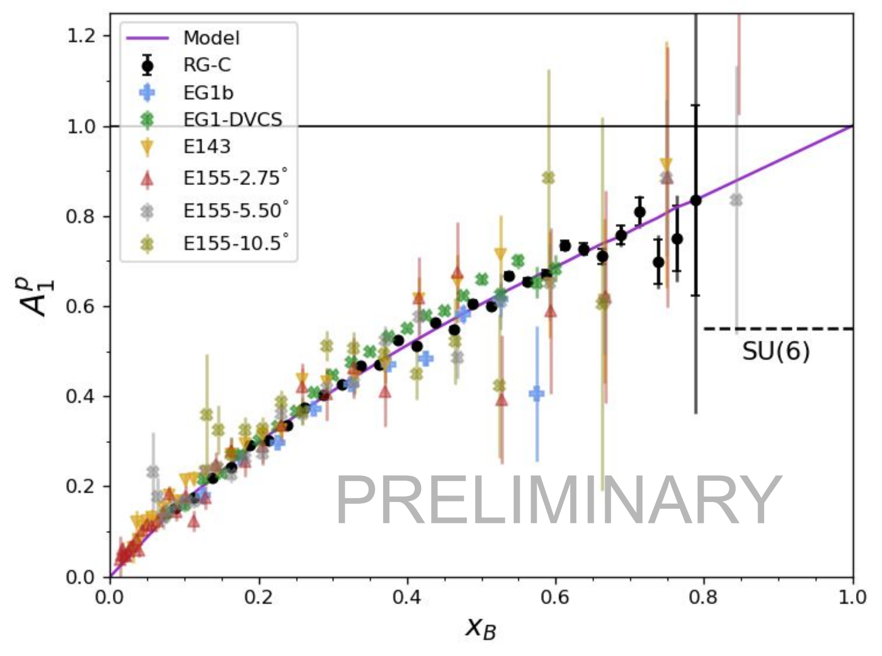
- ❖ Using **all** data, dilution factor models, & run-based $P_b P_t$
- ❖ A1p trend looks good, while A1d might still need more work

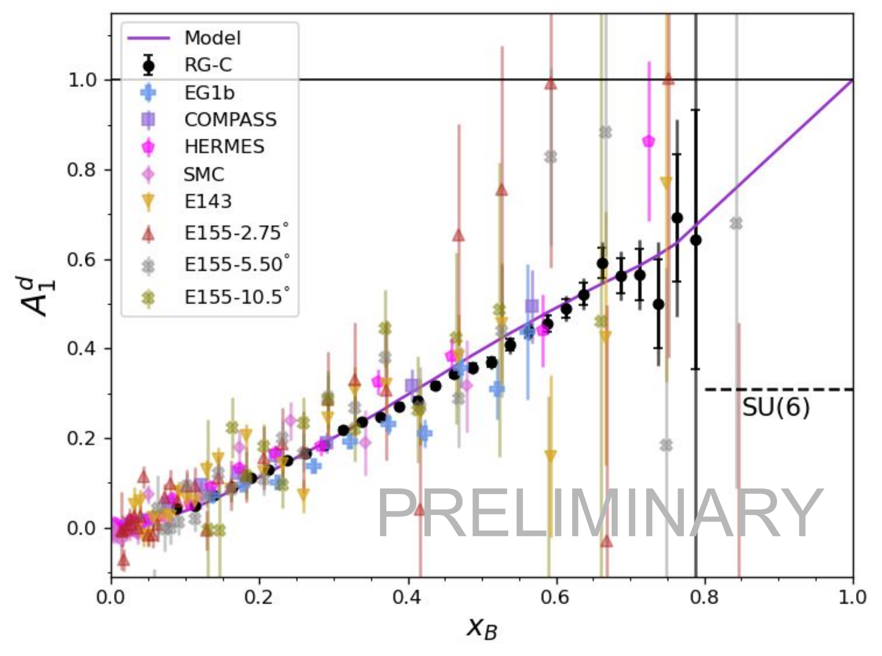




Preliminary $A_1(x)$

- Much better stats than almost any existing data
  - Inner error bars show RGCa + RGCb estimate
- Conclusive evidence than A1d violates SU(6) prediction

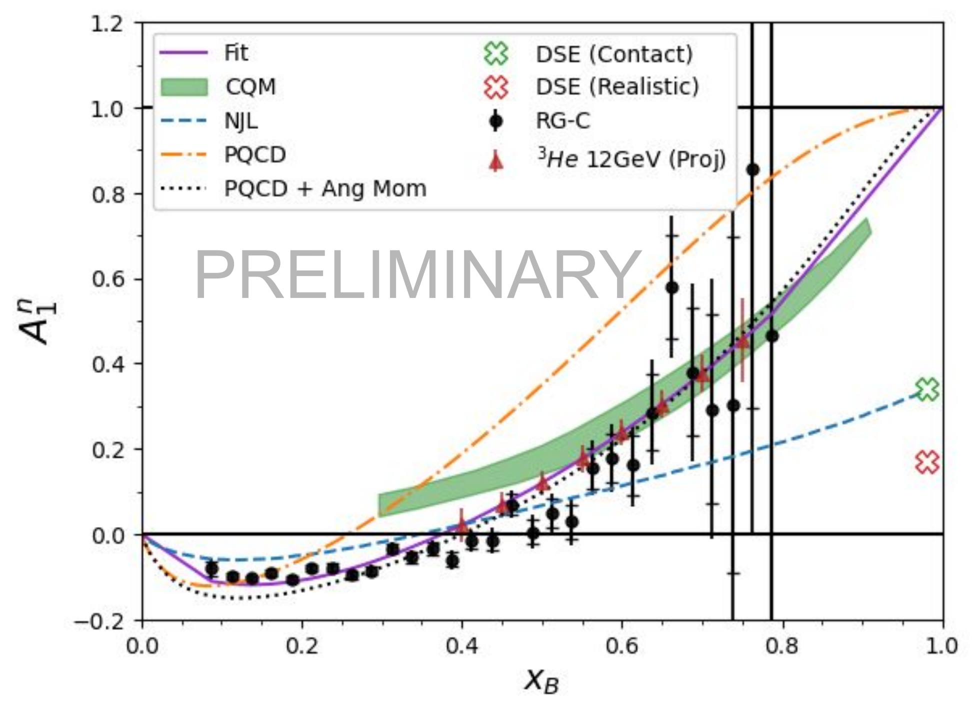




Future of A1n

- Extract A1n(x) from A1d(x) & A1p(x)
- RG-C will be a cross-check for Hall C's A1n from ^{3}He

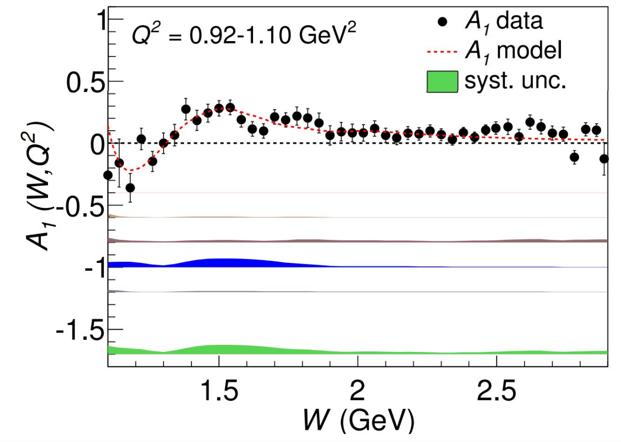
$$A_1^n = \frac{A_1^d F_1^d - A_1^p F_1^p}{F_1^n}$$



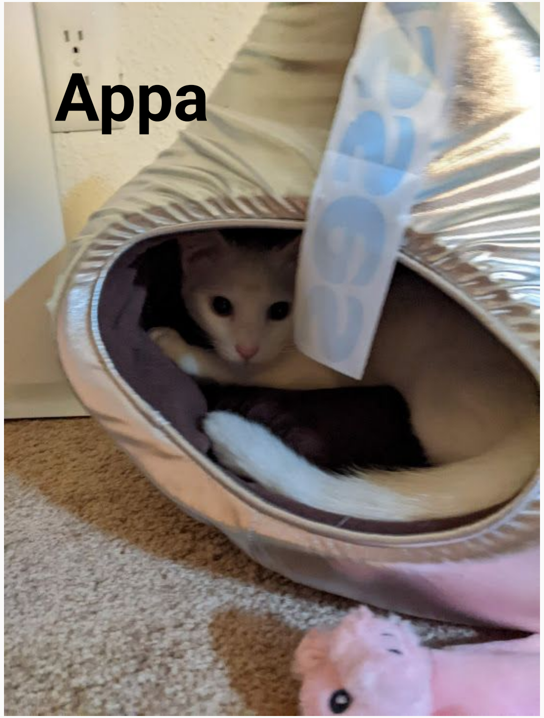
Future Work for Inclusive Analysis

- More detailed inclusive DIS analysis
  - Finely Tuned Models
  - Radiative Corrections
  - Accurate Nuclear Event Generator
- Study resonance region (W<2)
  - Compare against JLab 6 GeV data
- Extract tensor observables
  - UNH group has joined our analysis
- Preparing for RGCb (Part II)

A1d - EG1b

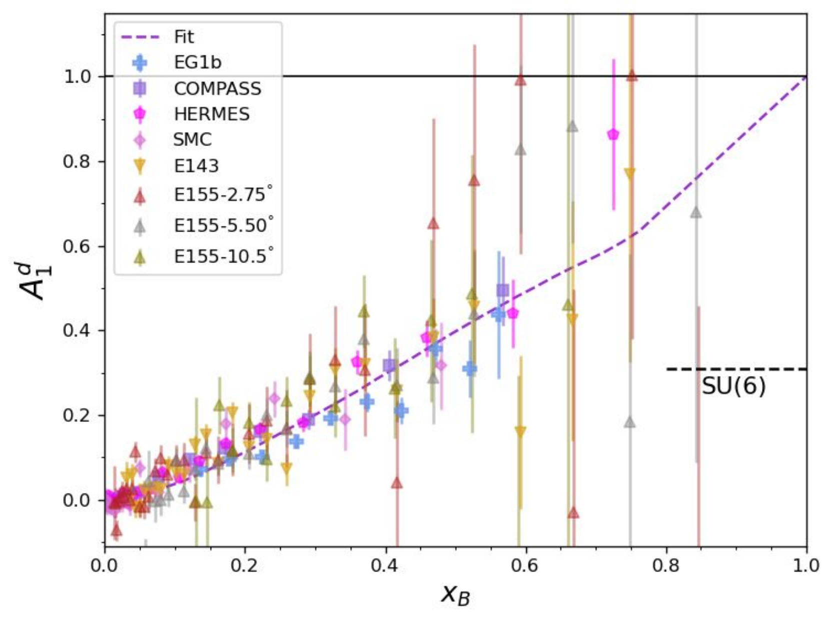


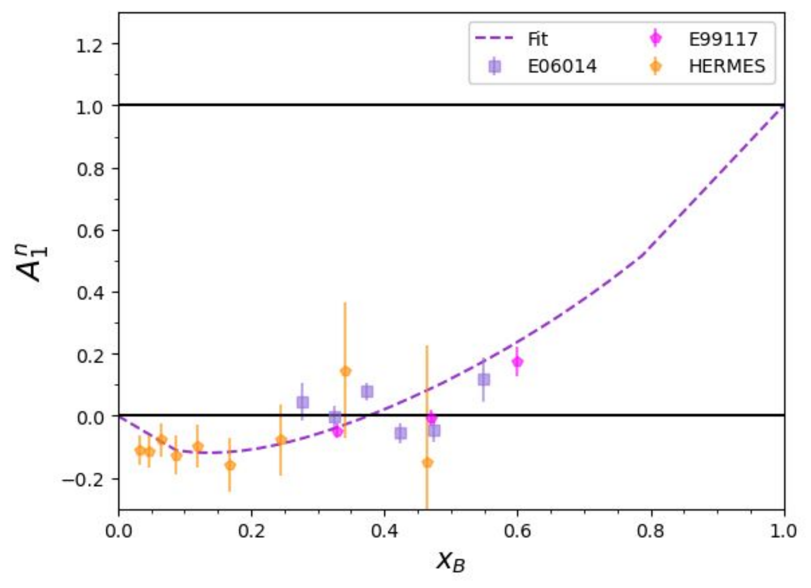
Questions/Comments



What is Known about the Deuteron & Neutron?

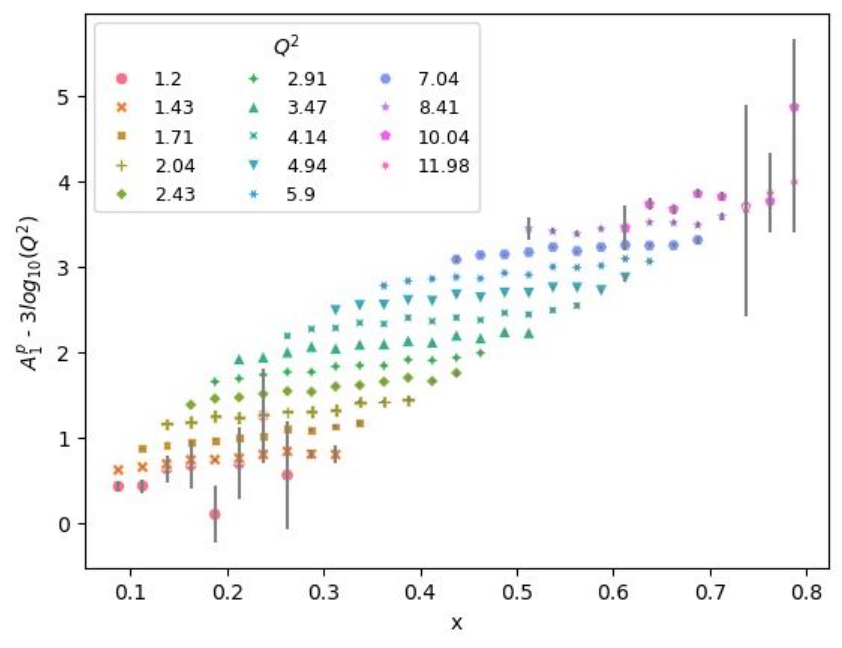
- ❖ The proton is close to being nailed down
- ❖ Decades of experiments using deuteron and He3 provide some insight at low and mid x_B

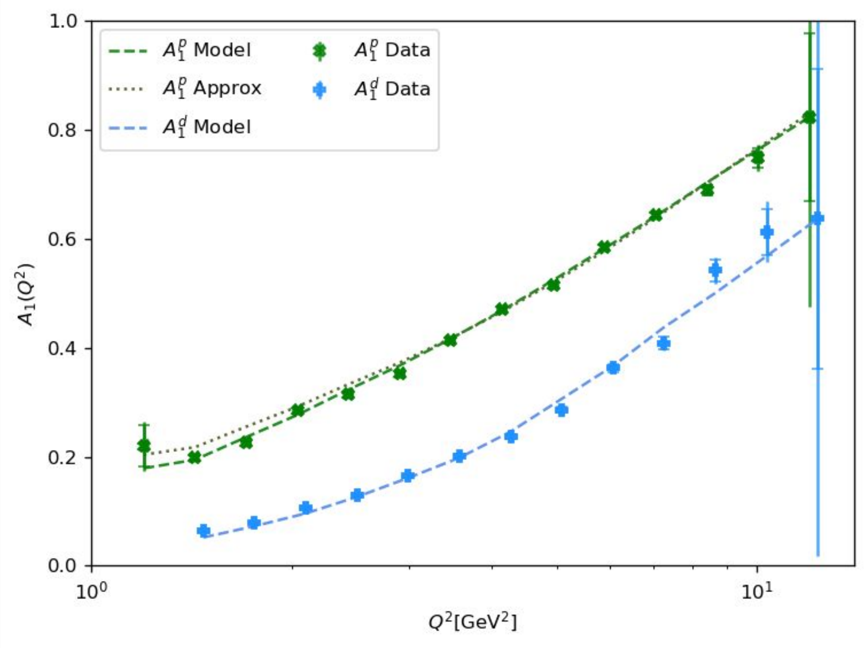




Preliminary A_1(Q2)

- Great precision for Q2-evolution studies
- Big systematics from DF model





Modeling RG-C Targets

- ❖ Determine the number of “counts” for a given target
- ❖ Following stand-alone Dilution Factor Paper
  - ➢ Get fits for F1, F2 to obtain CS
  - ➢ Combine to build target

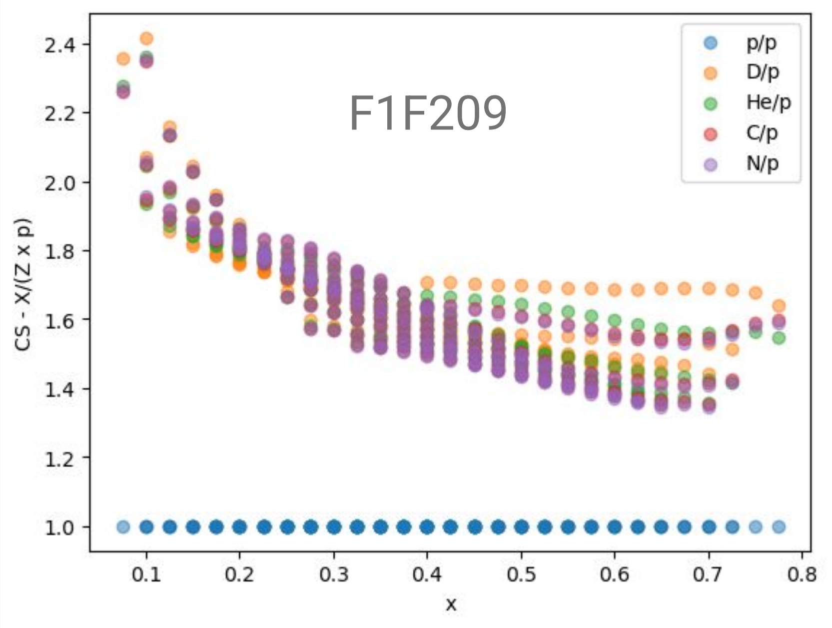
$$\frac{d^2\sigma}{dx dQ^2} = \left(\frac{4\pi\alpha^2}{Q^4}\right)\left[y^2 F_1(x,Q^2) + \left(\frac{1-y}{x} - \frac{My}{2E}\right)F_2(x,Q^2)\right]$$

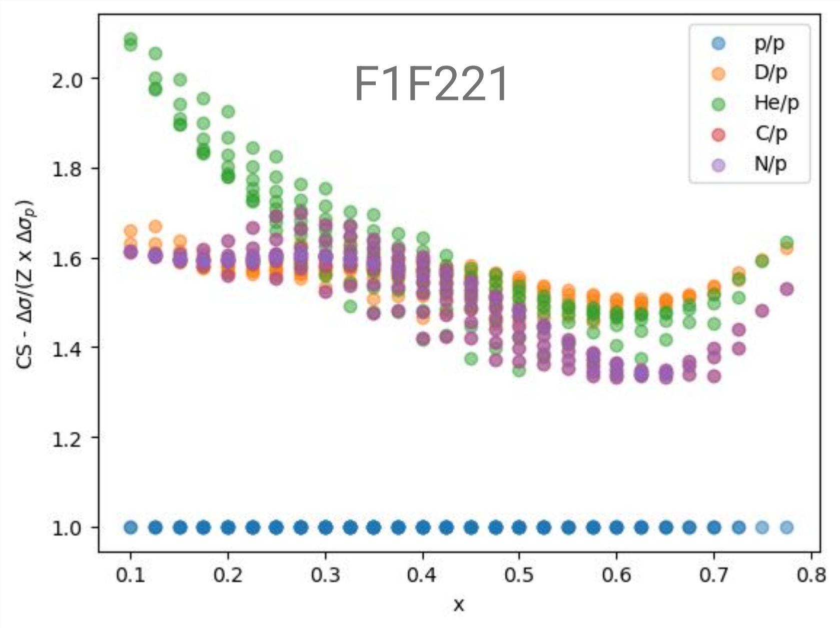
$$\Delta\sigma_Z^A(x,Q^2) = EMC(x,A) \times [(Z \times \Delta\sigma_D(x,Q^2)) + ((A-2Z) \times \Delta\sigma_n(x,Q^2))]$$

$$N_A = X_A f_c \left[l_F \rho_F \Delta\sigma_F + (L - l_A)\rho_{He}\Delta\sigma_{He} + l_A \rho_A \left(\frac{7}{6}\Delta\sigma_C + 3\Delta\sigma_H\right)\right]$$

Model CS Ratios

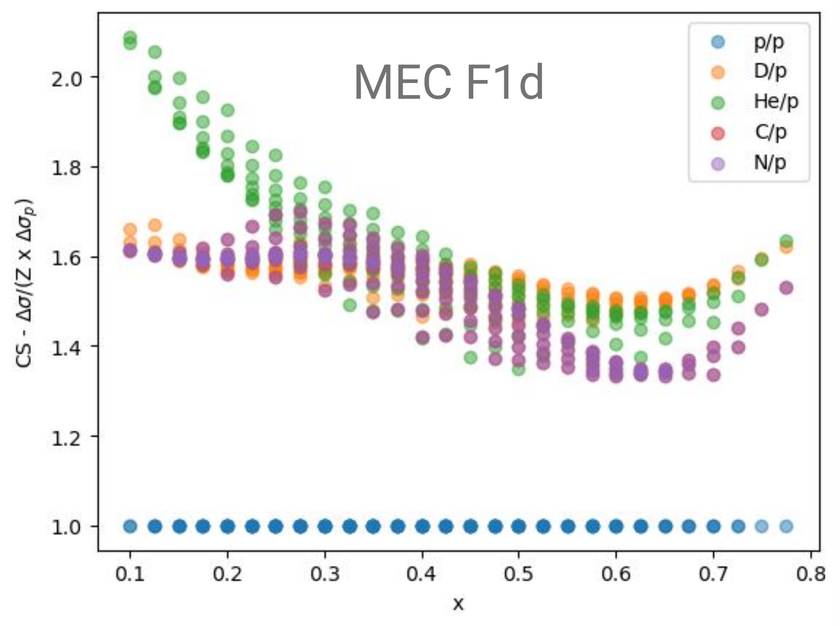
- ❖ Smoother behavior for F1F221 vs F1F209
- ❖ Some trends seem off

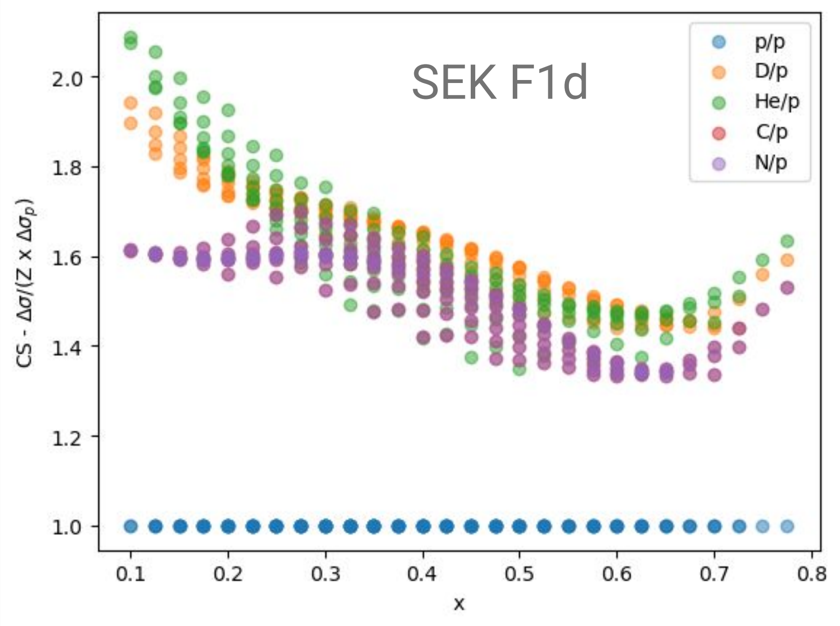




F1F221 CS Ratios

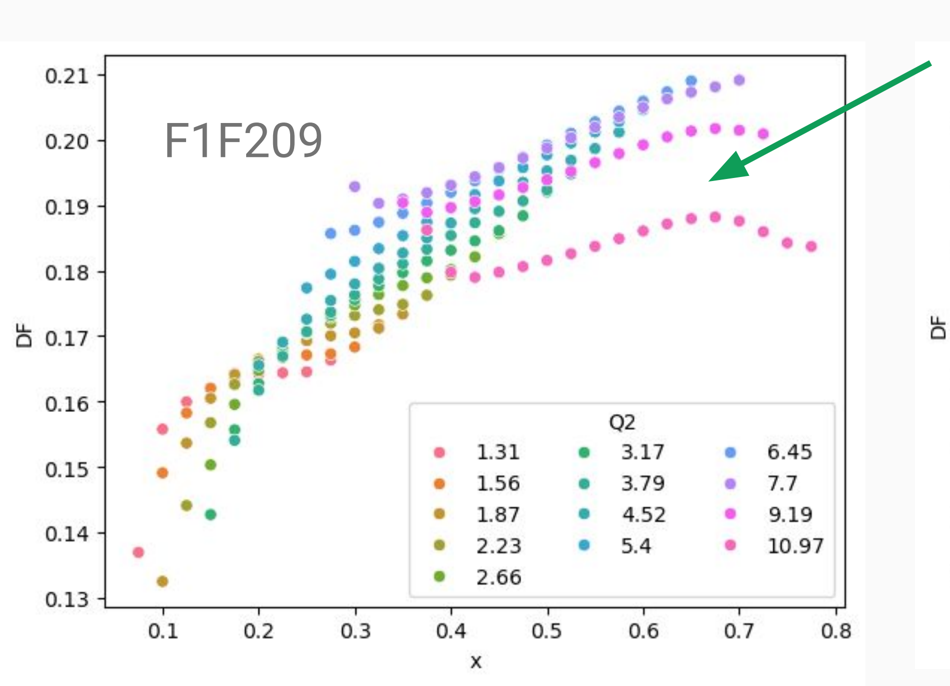
- Inconsistent results for nuclei & MEC deu seems off
  - Carbon & nitrogen have same ratio to proton
- Maybe issues with Fermi smearing scheme or EMC factor in F1F221

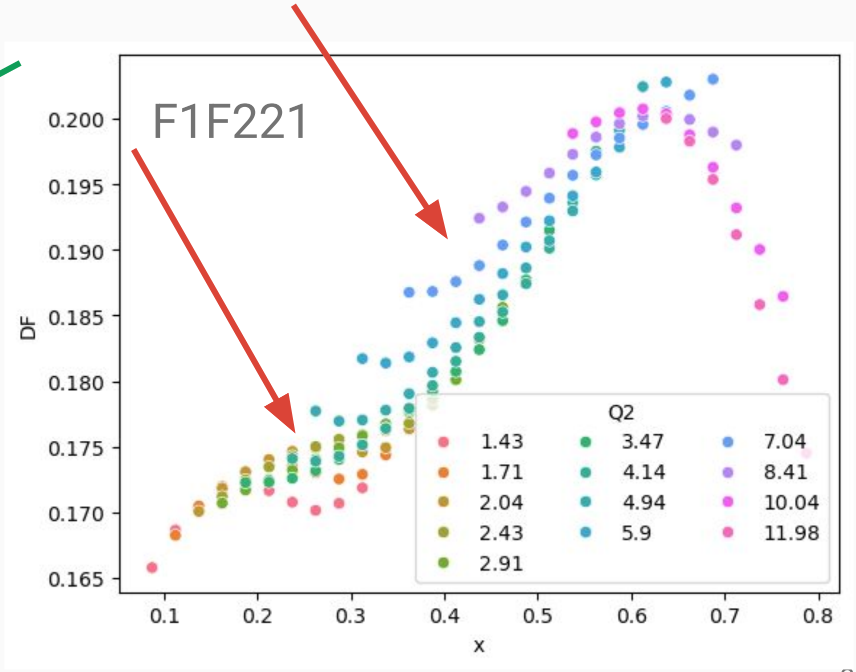




Dilution Factor Model for NH_3

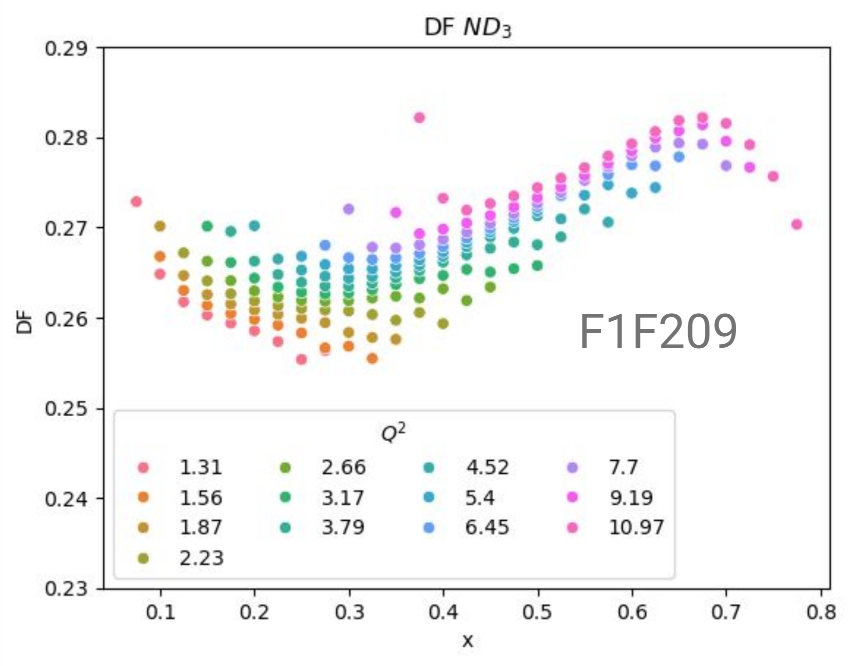
- **Smoother behavior** for F1F221 than F1F209
- **Inflection points** in new DF (nuclear corrections not right?)

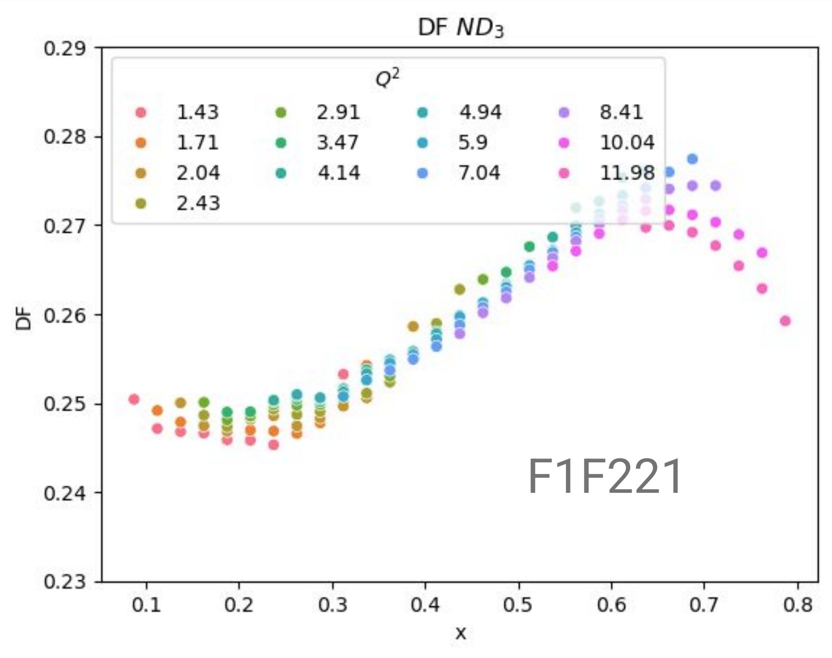




Dilution Factor Model for ND_3

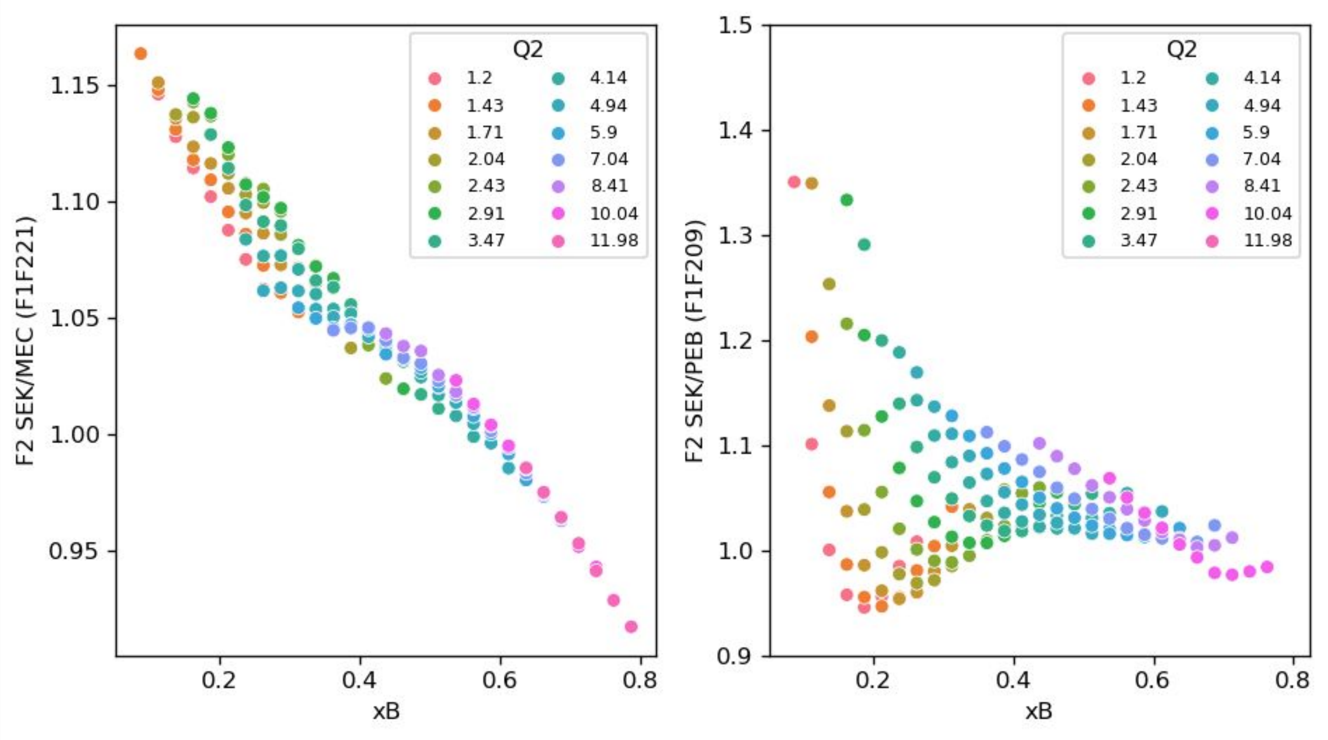
- Far less Q2 dependence but more extreme trends





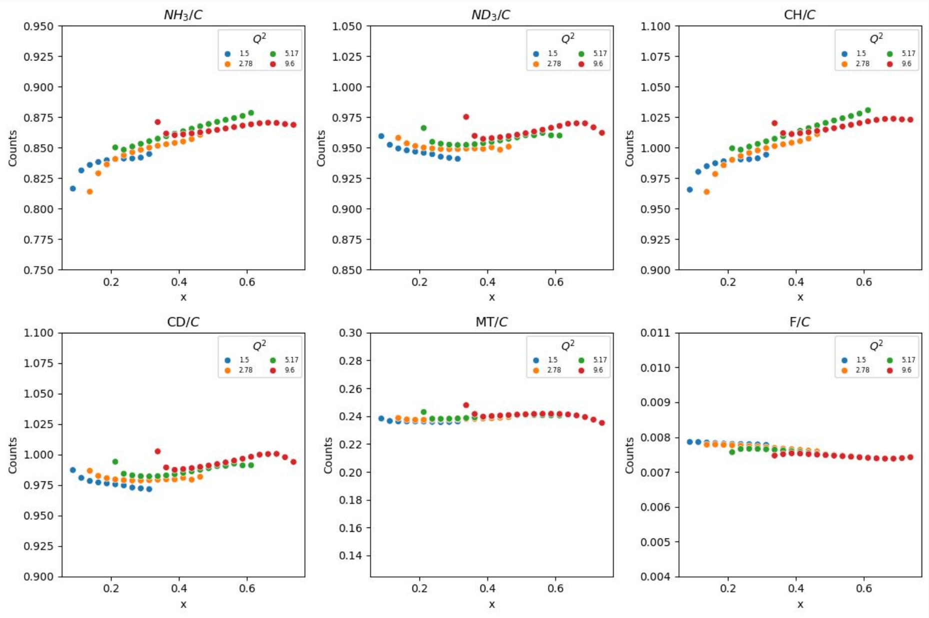
F2d Ratios

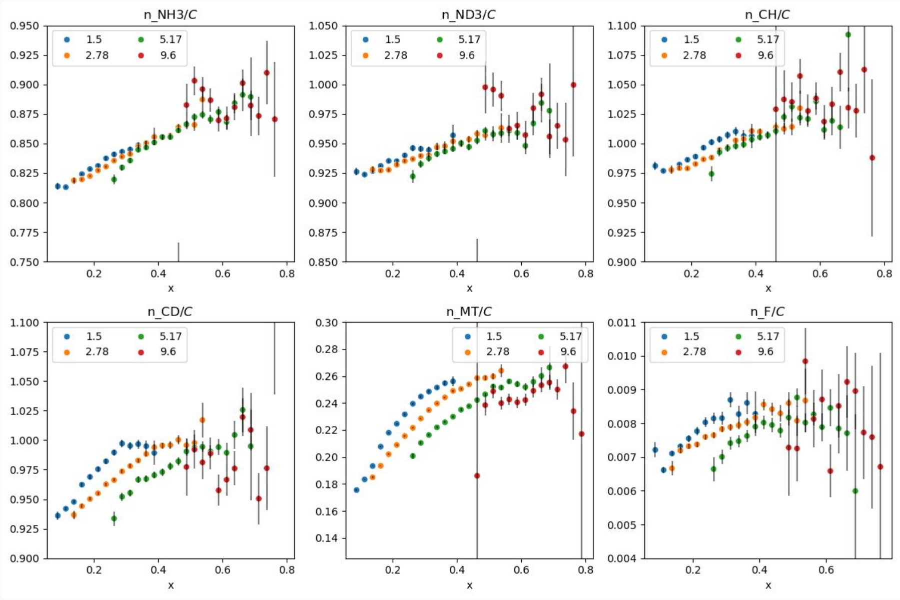
- Older fit has some fluctuations but new fit has clear trend



Model vs Data Counts

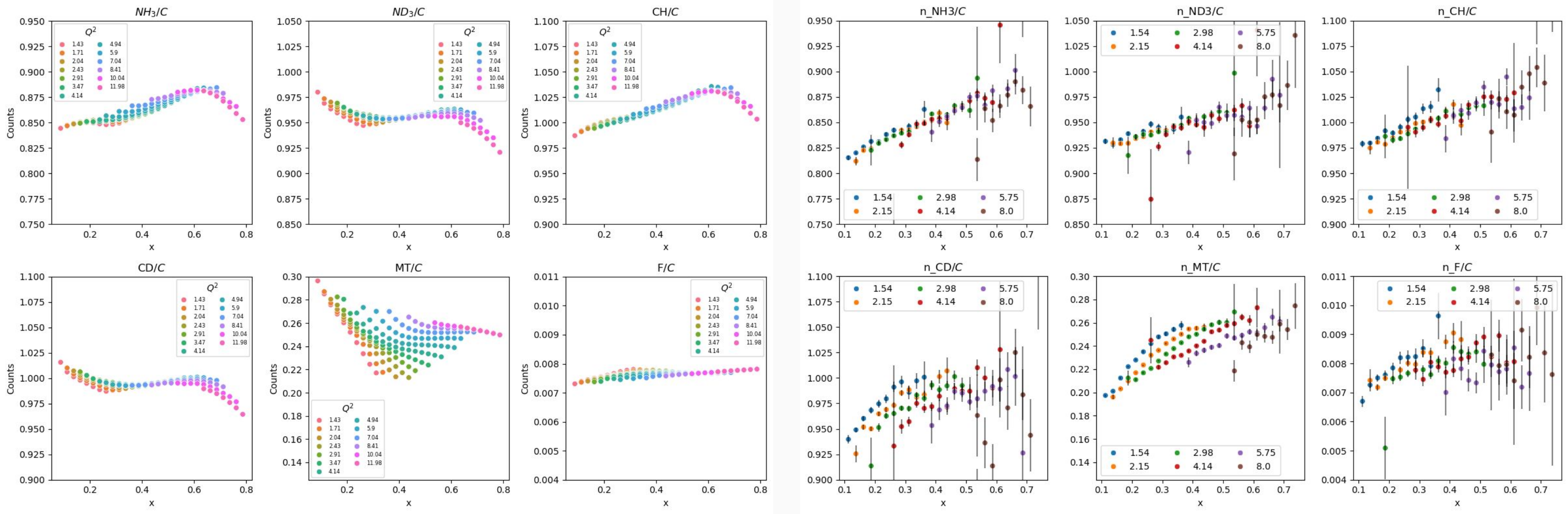
❖ F1F209 Model & Spring ‘23 Data



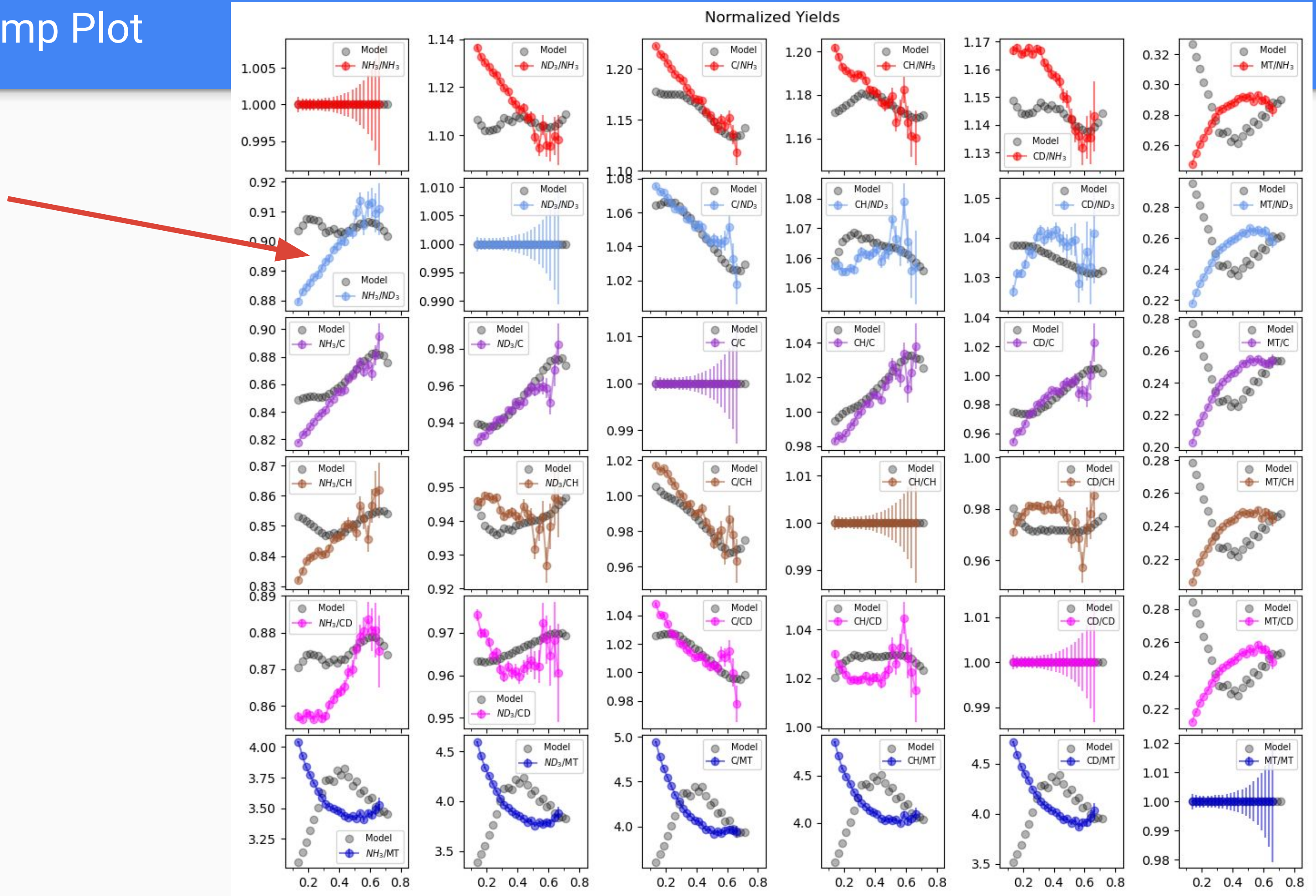


Model vs Data Counts

❖ F1F221 Model & Spring ‘23 Data (more Q2 bins)

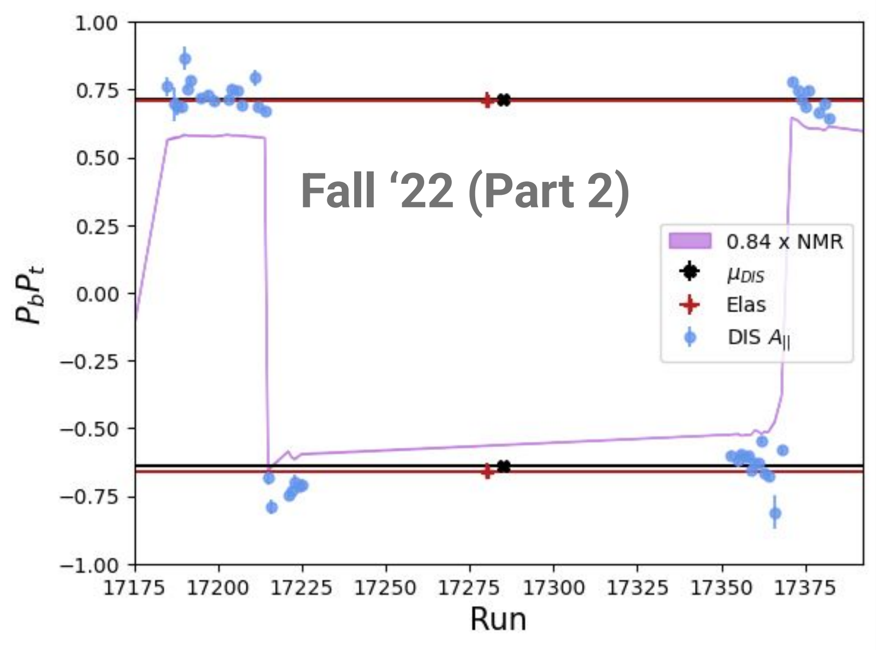


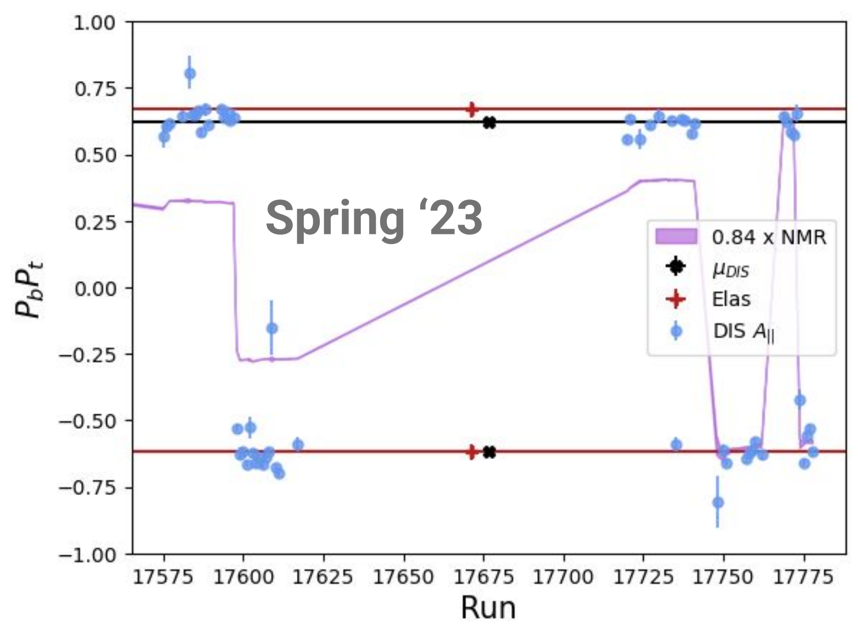
Postage Stamp Plot



Obtaining P_bP_t from DIS for NH_3

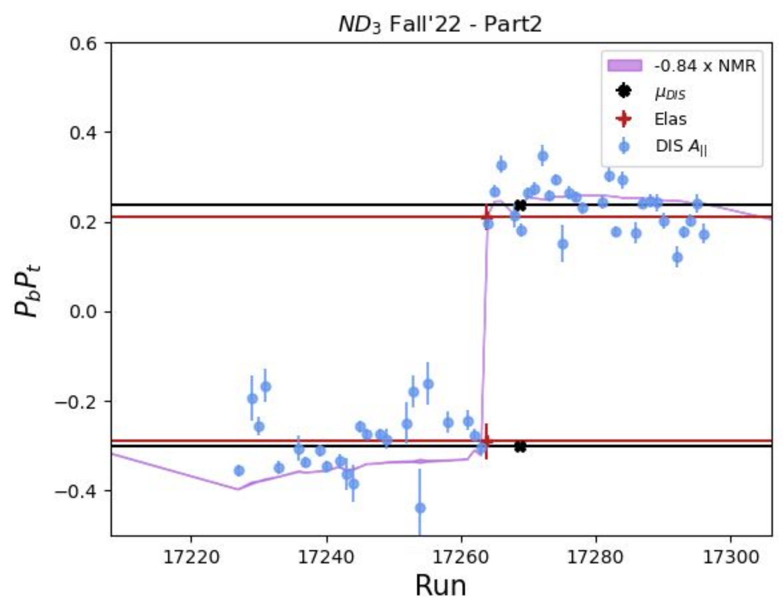
- ❖ Part 2 -> After the solenoid flip
- ❖ Good agreement with elastics
- ❖ Inconsistent disagreement with NMR

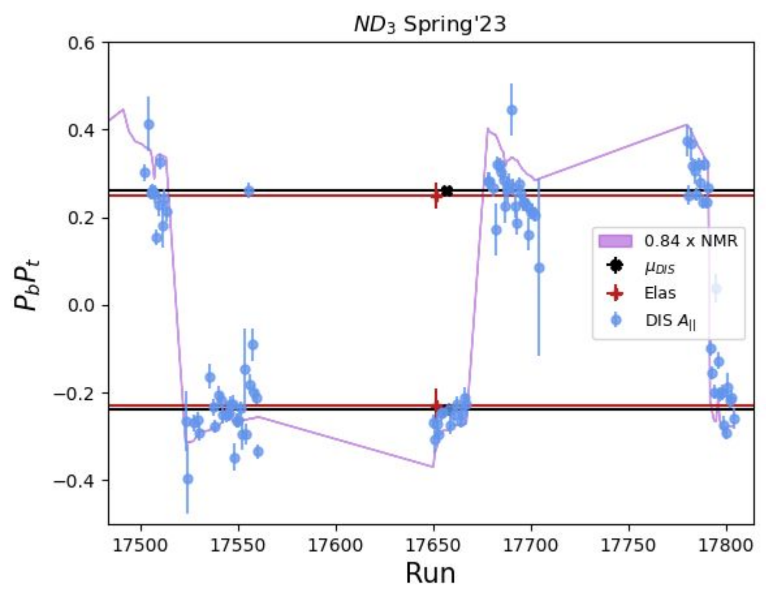




Obtaining P_bP_t from DIS for ND_3

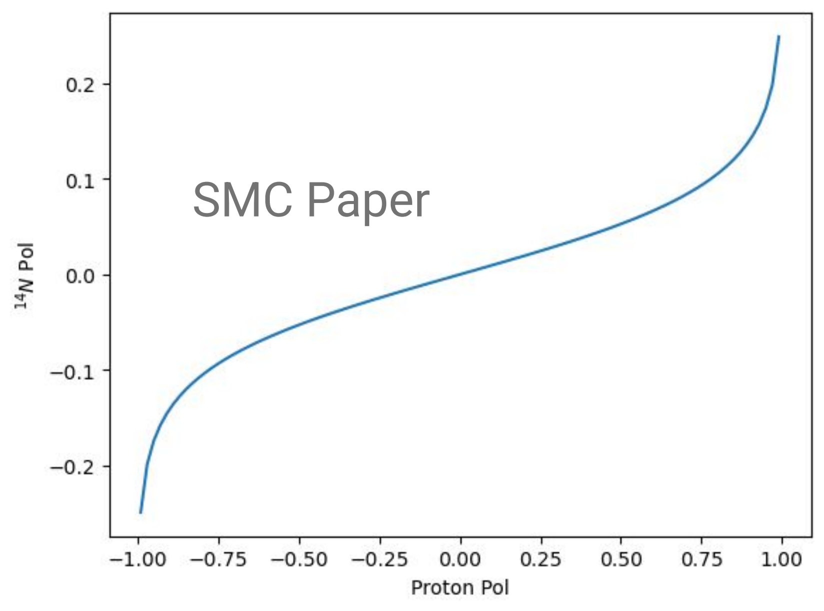
- Part 2 -> After the solenoid flip
- Good agreement with elastics (within error bars)
- Sometimes disagreement with NMR but inconsistent





Future Work - Nitrogen Correction

- $P_b P_t$ with ^{14}N polarization corrections (SMC paper)
- Sebastian says small (SMC correction is at most a few percent)

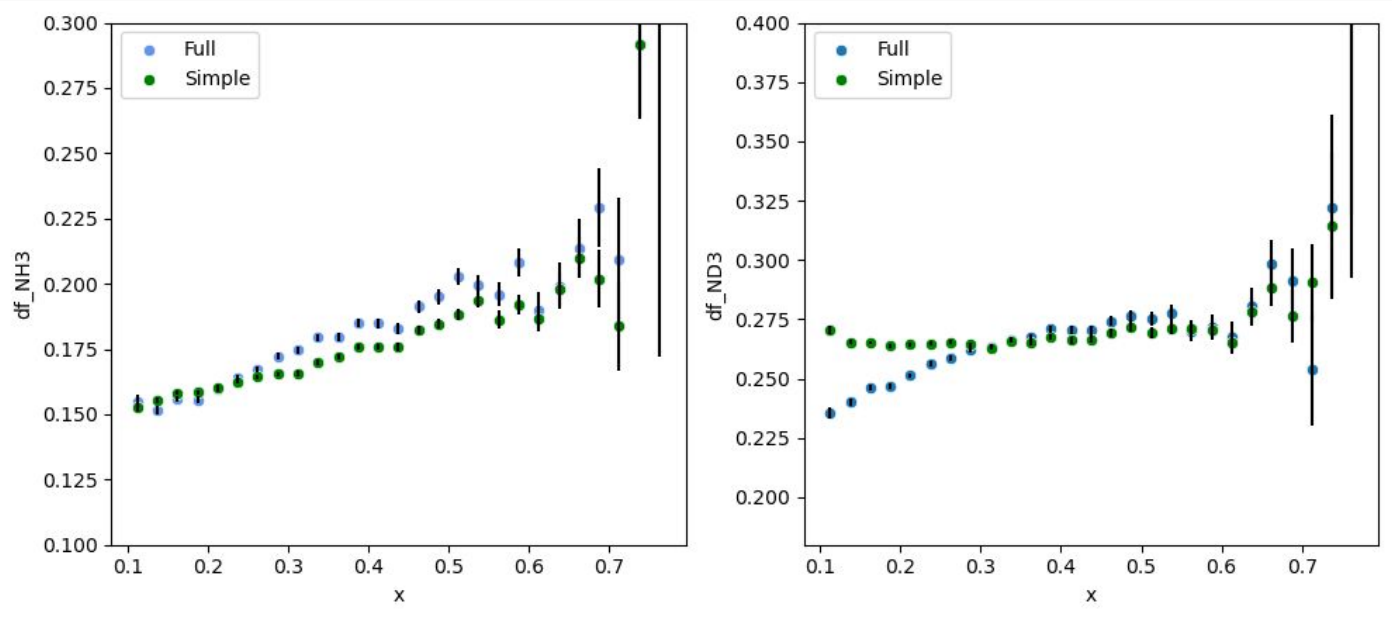


$$P_{\mathrm{N}} = \frac{4\tanh\left(\frac{\omega_{\mathrm{N}}}{\omega_{\mathrm{p}}}\operatorname{arctanh}(P_{\mathrm{p}})\right)}{3+\tanh^2\left(\frac{\omega_{\mathrm{N}}}{\omega_{\mathrm{p}}}\operatorname{arctanh}(P_{\mathrm{p}})\right)} .$$

$$A_{\mathrm{m}} = \frac{N^+ - N^-}{N^+ + N^-} = f P_{\mathrm{b}} P_{\mathrm{p}} \left(A_{\mathrm{p}} + \frac{n_{\mathrm{N}} P_{\mathrm{N}}}{n_{\mathrm{p}} P_{\mathrm{p}}} \frac{\sigma_{\mathrm{N}} A_{\mathrm{N}}}{\sigma_{\mathrm{p}}} \right)$$

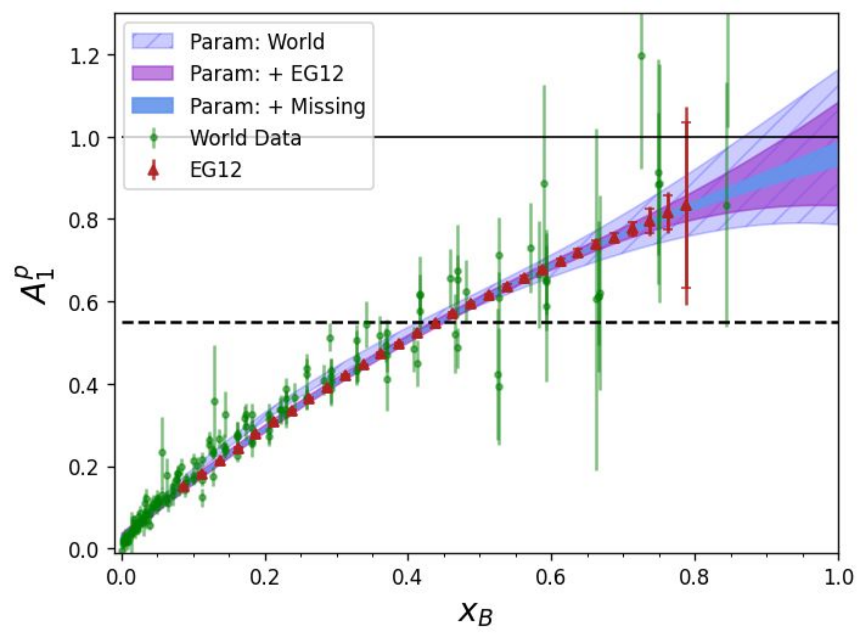
Data-Driven DF for Spring

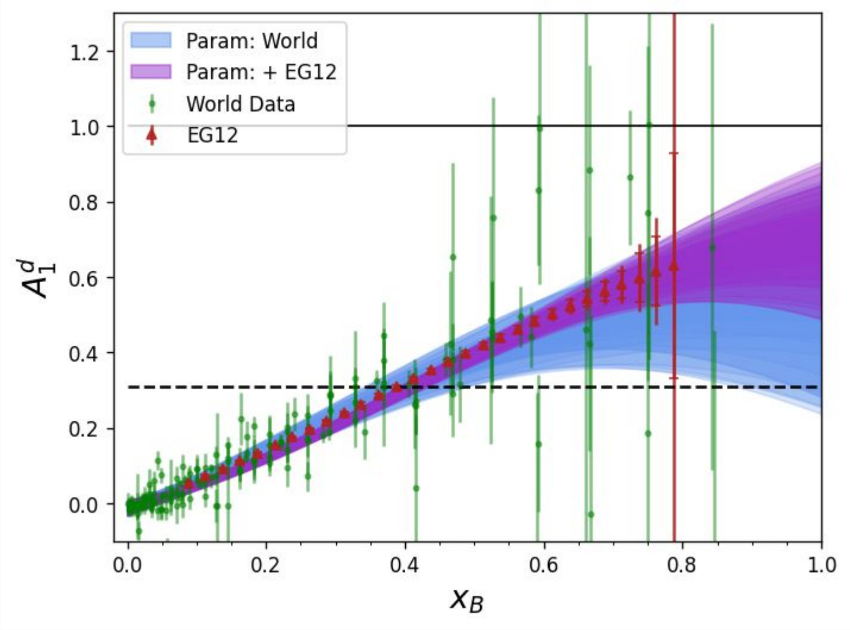
- Using contraction corrections, cut on y<.65 & integrated over Q^2
- Very tight cut to really minimize Rad Effects



Extrapolation of $A_1(x=1)$ using Gaussian Process

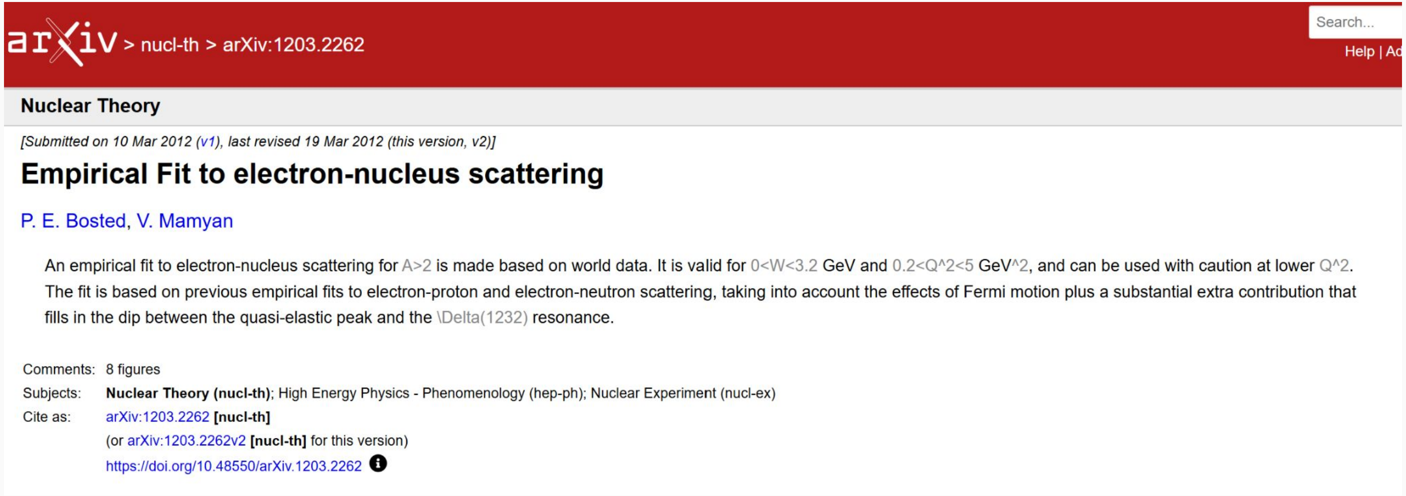
- (Update with current results but story should be similar)
- Update priors to naïve $A_1 \sim x^{0.72}$ & A1d~?





Nuclear Corrections via F1F209 Model

- Based on ArXiV paper: https://arxiv.org/pdf/1203.2262
  - Q2, W2 limits are smaller than RG-C data (careful with conclusions)
- F1F209.F code from SF Code Base
  - Wrapped into Python using F2Py



arXiv > nucl-th > arXiv:1203.2262

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Nuclear Theory

[Submitted on 10 Mar 2012 (v1), last revised 19 Mar 2012 (this version, v2)]

Empirical Fit to electron-nucleus scattering

P. E. Bosted, V. Mamyan

An empirical fit to electron-nucleus scattering for A>2 is made based on world data. It is valid for 0<W<3.2 GeV and 0.2<Q^2<5 GeV^2, and can be used with caution at lower Q^2. The fit is based on previous empirical fits to electron-proton and electron-neutron scattering, taking into account the effects of Fermi motion plus a substantial extra contribution that fills in the dip between the quasi-elastic peak and the \Delta(1232) resonance.

Comments: 8 figures

Subjects: **Nuclear Theory (nucl-th)**; High Energy Physics - Phenomenology (hep-ph); Nuclear Experiment (nucl-ex)

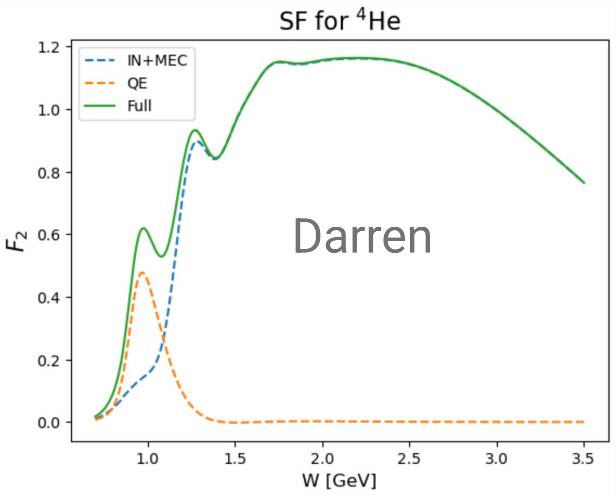
Cite as: arXiv:1203.2262 **[nucl-th]**

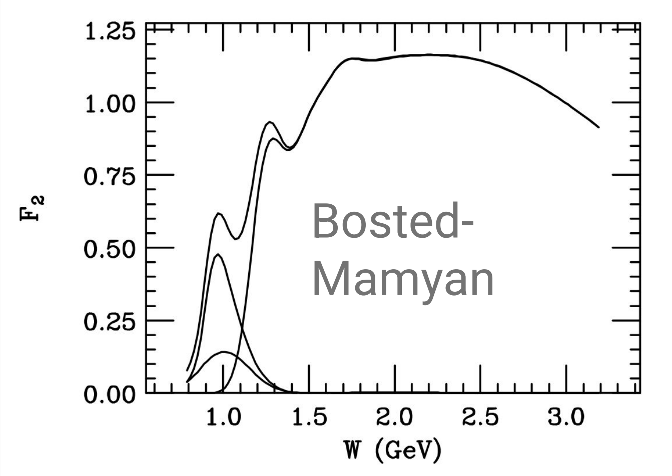
(or arXiv:1203.2262v2 **[nucl-th]** for this version)

https://doi.org/10.48550/arXiv.1203.2262

SF Output Comparison

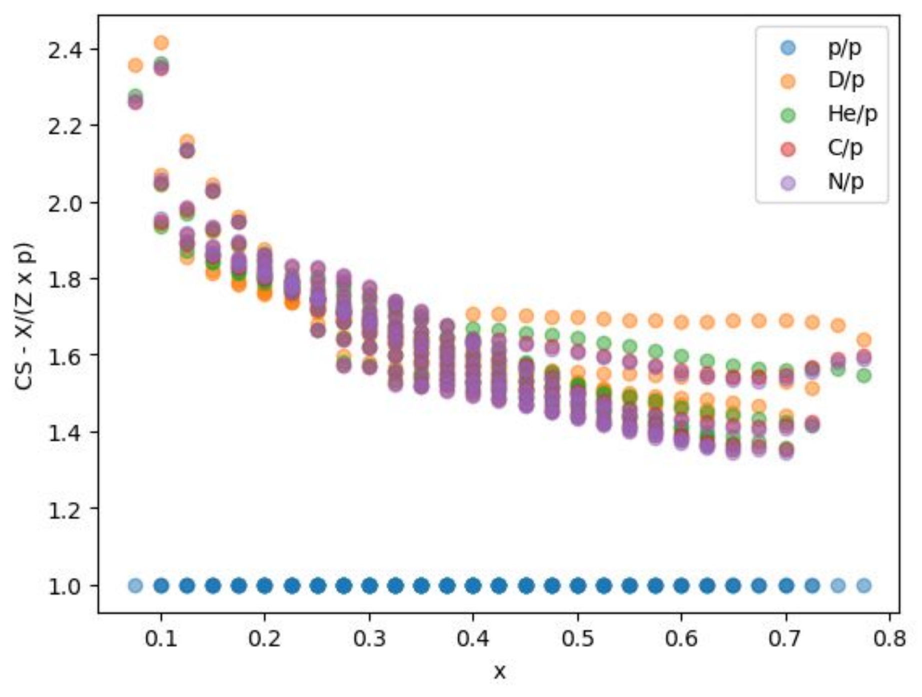
- SF outputs come from several models pieced together
  - Christy-Bosted param of proton/deuteron SF (2007)
  - EMC Correction from S. Rock (1994)
  - Quasi-elastic - A=2 PEB pre-int Paris WF (2006) & A>2 J Amaro et al (2005)
  - MEC - Dip between quasi & Delta (????)
  - Nuclear Fermi smearing - (F1F2 2009)





Cross Section Model

- CS Ratios for nucleus/proton
- Same equation as before but using SFs with Fermi smearing



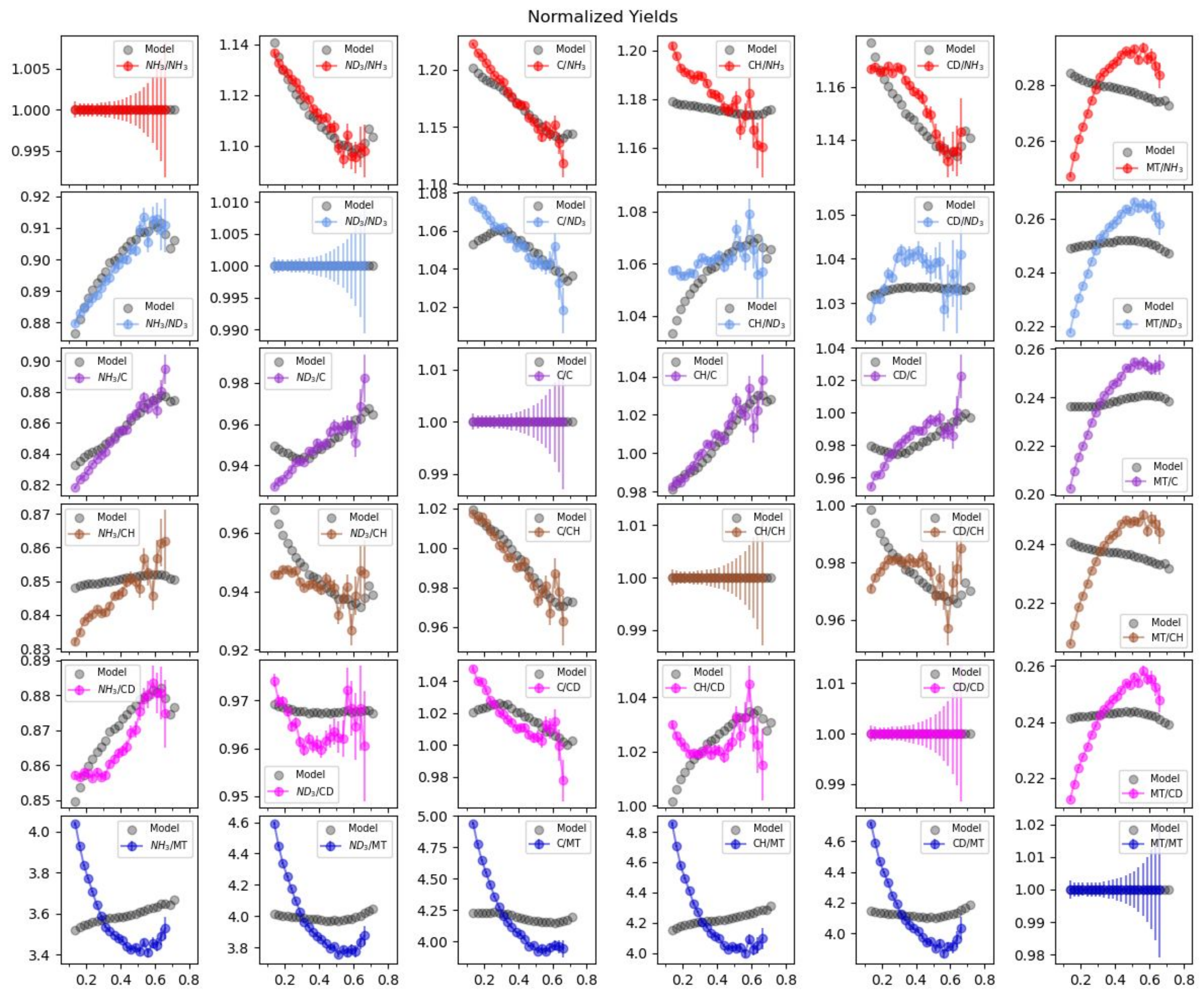

```
CS = ((4*pi*alphaS_sq)/Q2**2) * ((y**2 * F1) + ((1-y) - (x**2*Mp**2*y**2)/(Q2))*(F2/x))
```

NEW Yield Ratios

- Same cuts

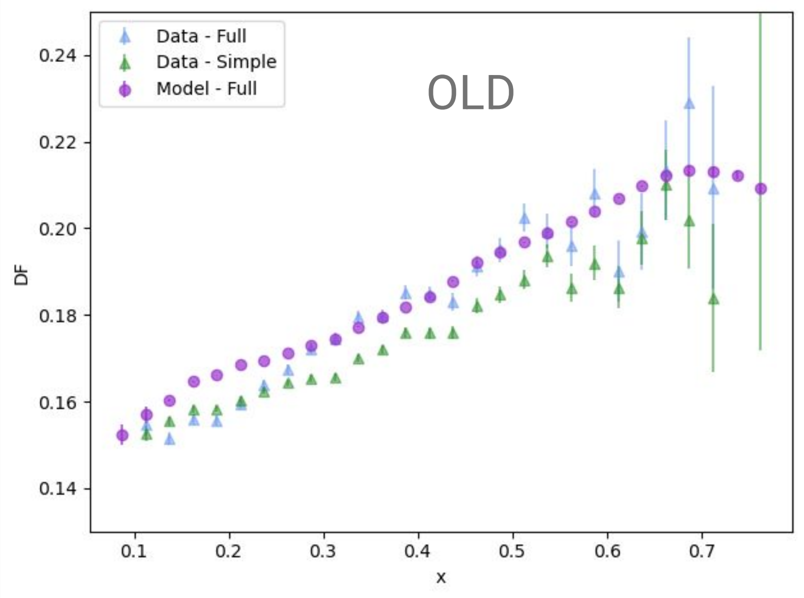
Model

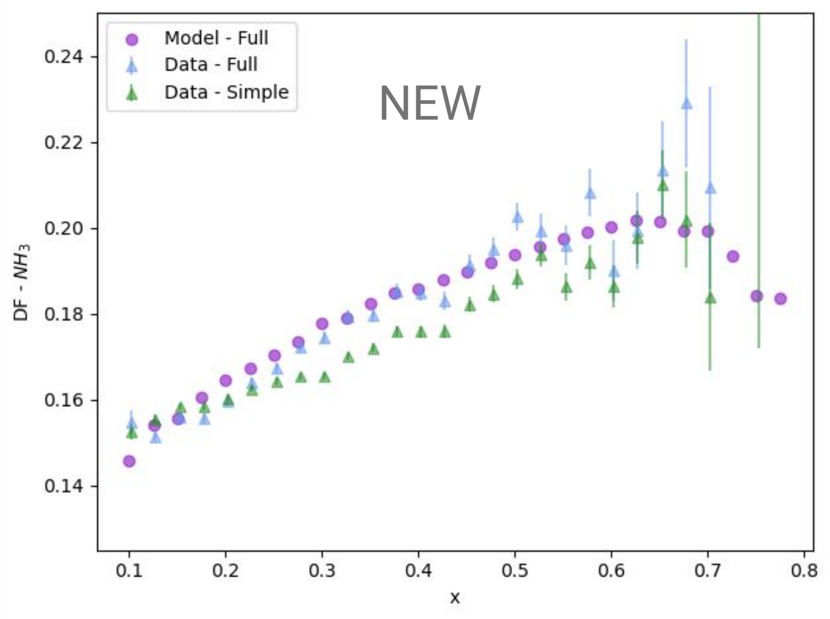
- PF=0.514
- Better agreement in ammonia but worse for CD_2



Comparison for Dilution Factor Models

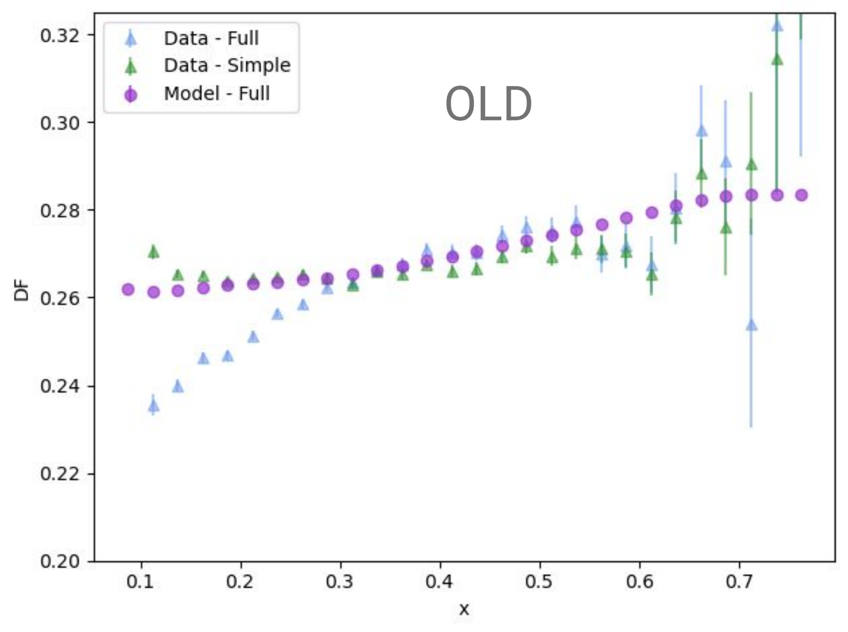
- Using PF=0.514
- Old has inflection at x~0.15 & x~0.3
- New varies more smoothly from low to large x (questionable for x>.7)

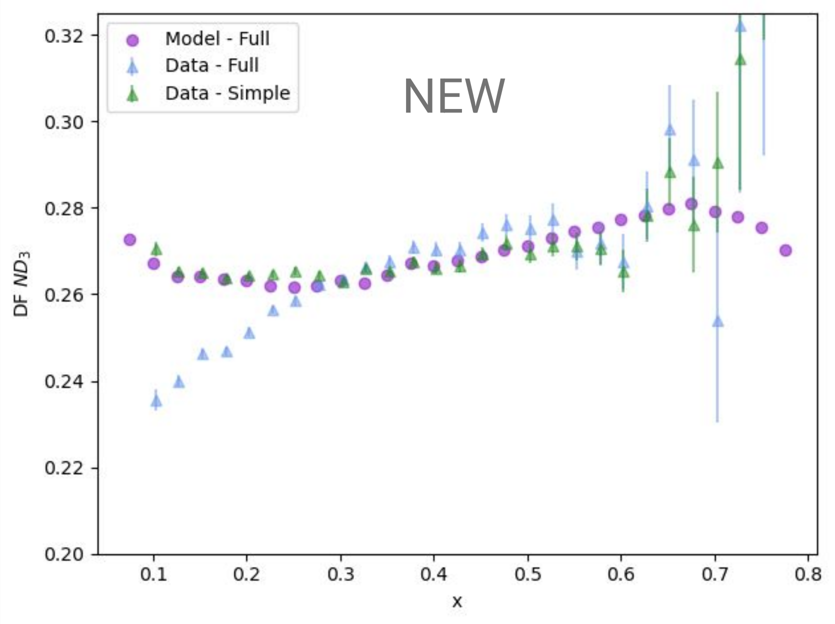




Comparison for Dilution Factor Models for ND_3

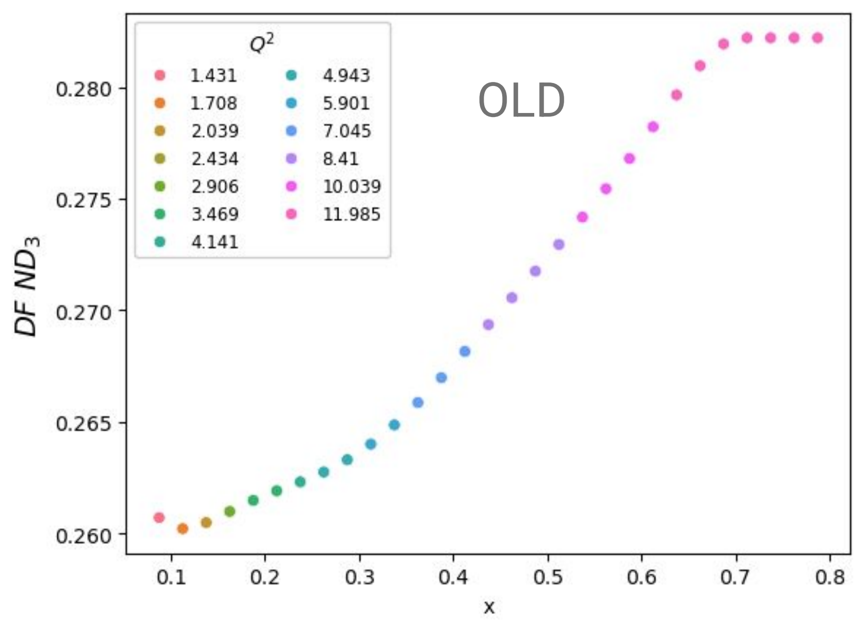
- Same but for ND_3
- Old looks smoother but new tracks better with data

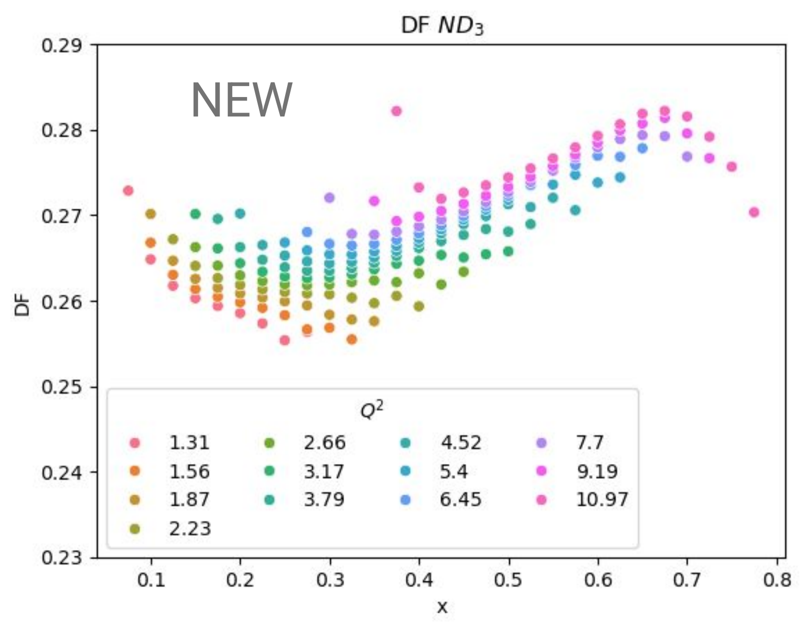




Dilution Factor Model Q2 Dependence for ND_3

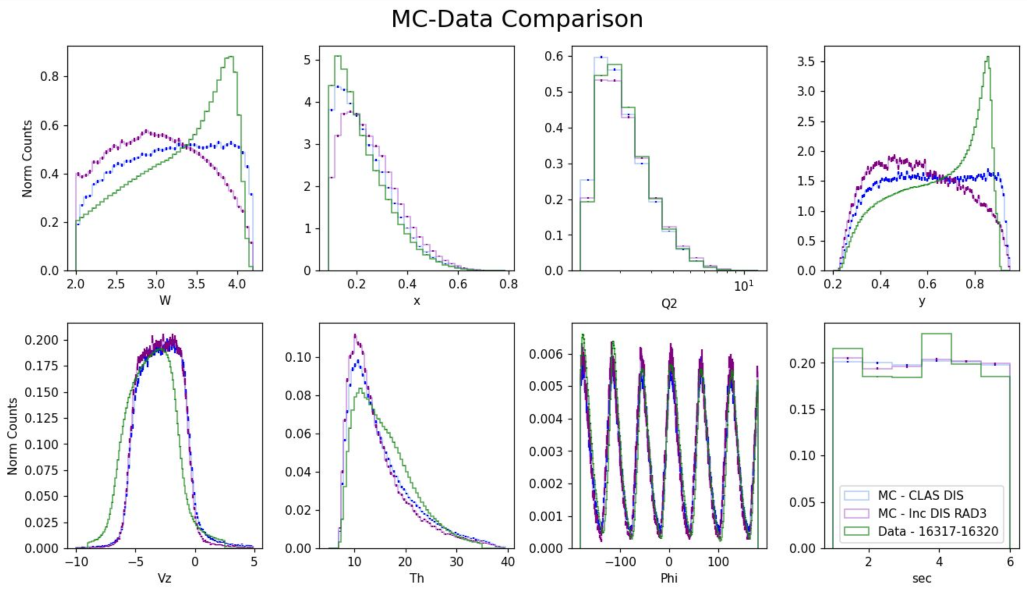
- Old has no dependence without Q2-dep nuclear effects
- New increases with Q2





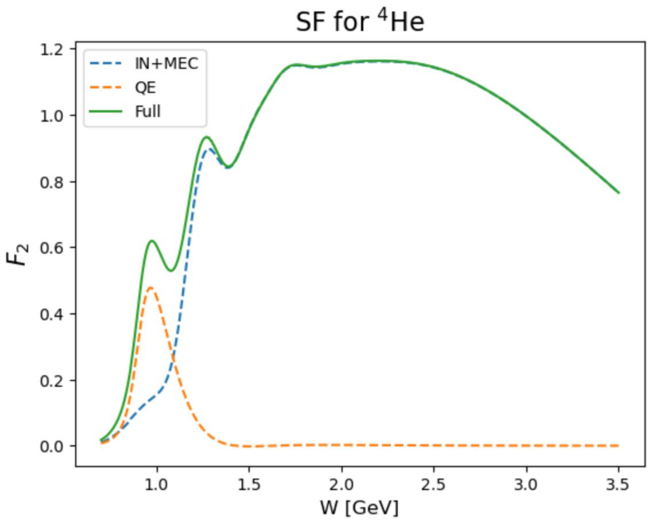
Current State of MC

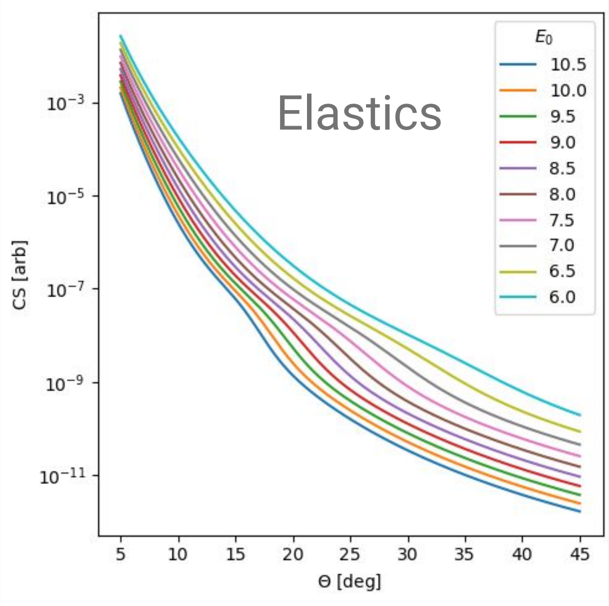
- Problems with current event generators
  - Only for proton and deuteron
  - Minimal evidence of properly included Rad Effects



F1F209 Model

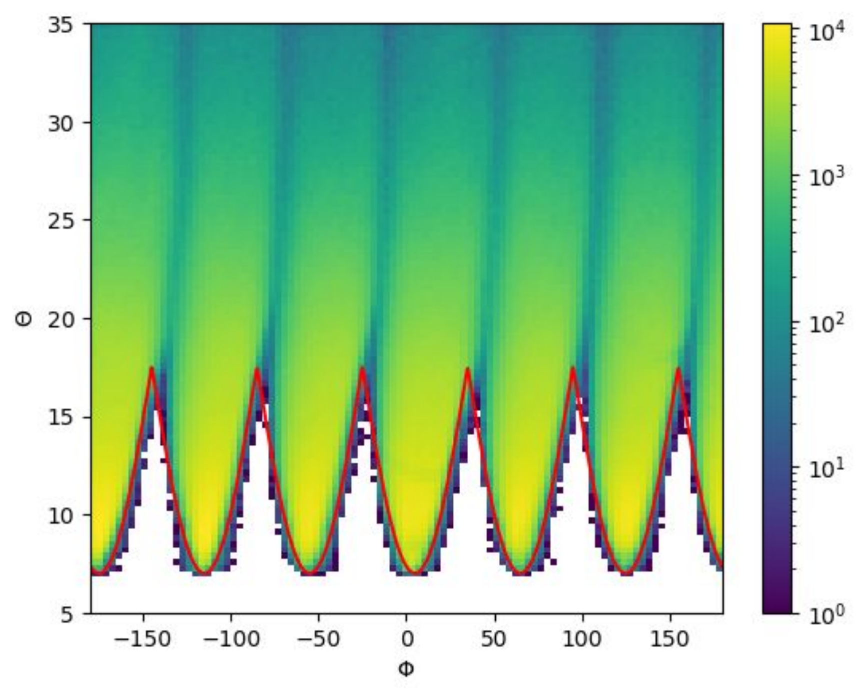
- F1F209 Structure Functions for QE, Resonance, & Inelastic regions
- Elastics using Arrington parameterization
- Weights from differential CS's





CLAS12 Resolution & Acceptance

- Angular & energy resolution
  - σ_θ = 0.058 deg
  - $\sigma_{E'}$ = 0.1 x sqrt(E')
- 1st-order for angular acceptance
  - Keep if $\theta > a - b|\cos(3(\varphi - c))|$



Radiative Effects

- Based on neutrino event gen: https://arxiv.org/pdf/2409.05736
- Pre-Scattering -> λ_1
  - Assume scattering at halfway point
- Post-Scattering -> λ_2
  - Use scattering angle θ
- Internal -> See paper
  - Now neglected for results

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

$$g \equiv bt + \lambda$$

$$\lambda_1 \equiv \frac{\alpha}{\pi}\left[\ln\left(\frac{4|\vec{k}_1|^2}{m_e^2}\right) + 2\ln\left(\frac{|\vec{k}_1|}{|\vec{k}_2|}\right) - 1\right] \simeq \frac{\alpha}{\pi}\left[\ln\left(\frac{4|\vec{k}_1|^2}{m_e^2}\right) - 1\right]$$

$$\lambda_2 \simeq \frac{\alpha}{\pi}\left[\ln\left(\frac{4|\vec{k}_2|^2}{m_e^2}\right) - 1 + 2\ln\left(\frac{1-\cos\theta_2}{2}\right)\right].$$