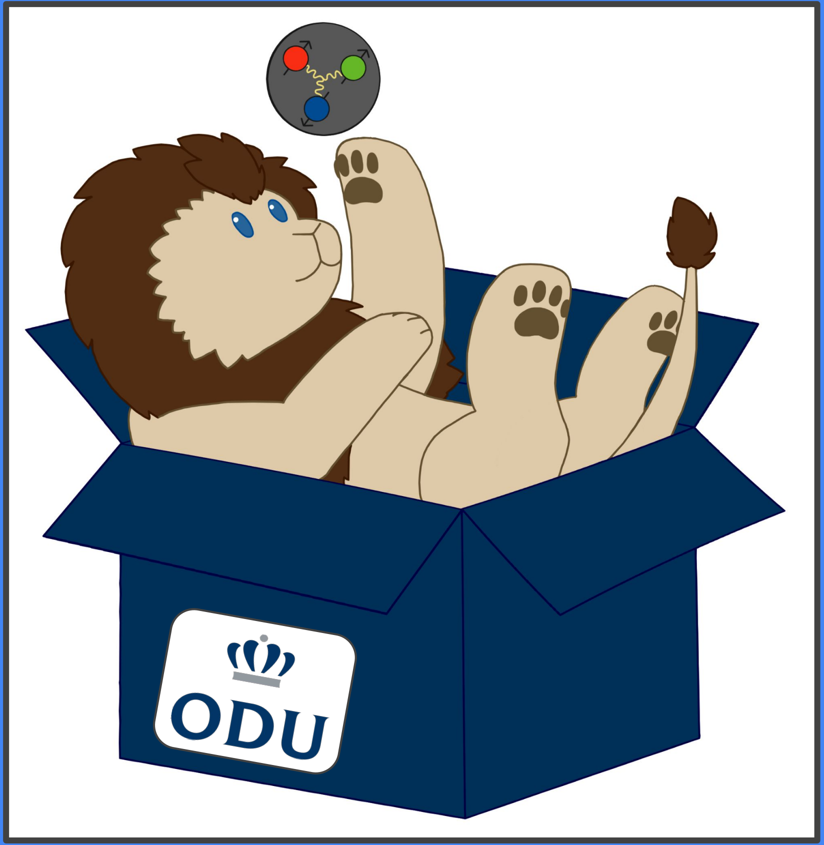
Probing Nucleon Spin Structure From Fixed-Target to the EIC

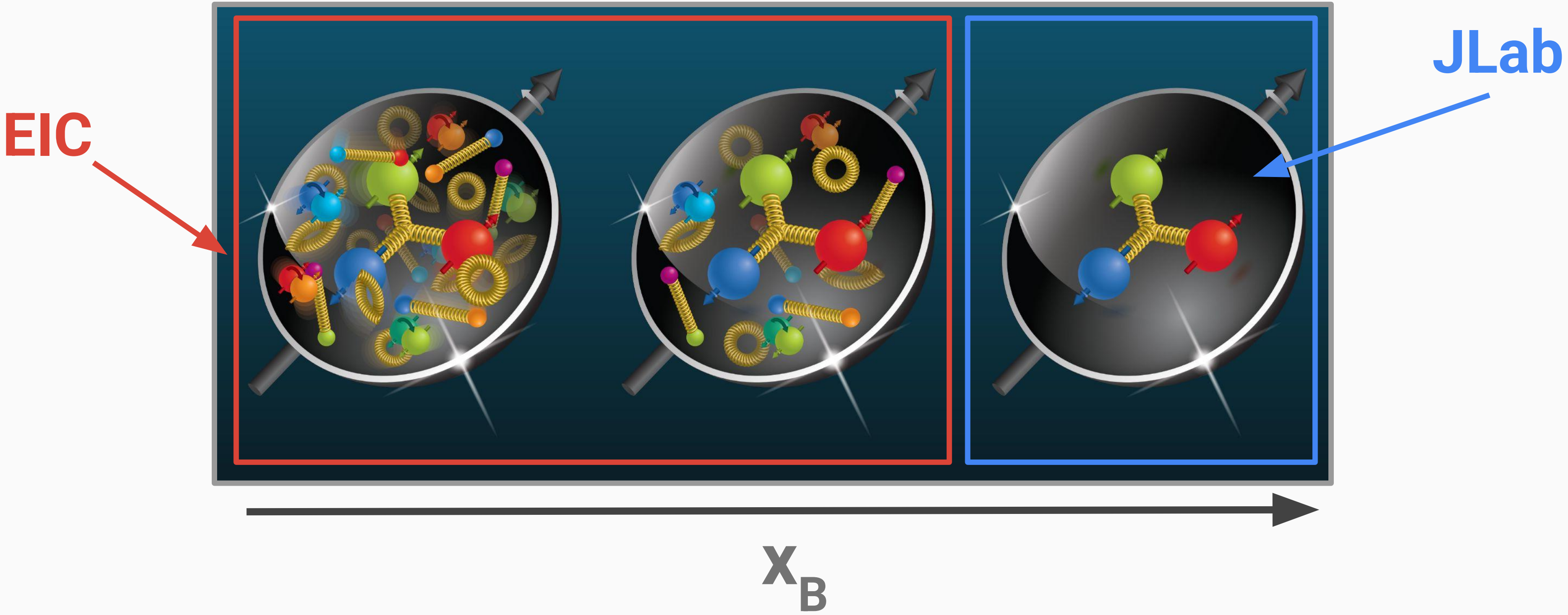
Darren W. Upton (he/they)

05 June 2026



Nucleons - Veritable Soup of Particles

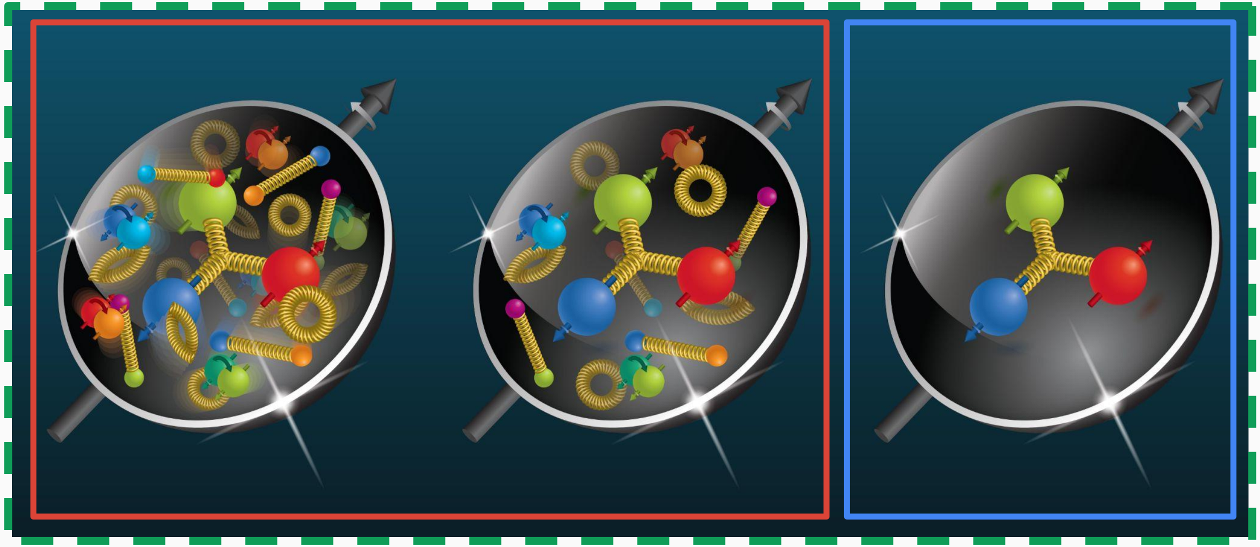
- ❖ Experiments aim to probe distributions of charge, mass, **spin**, etc
- ❖ “Energy” scales highlight valence (3-quark) or quark-gluon sea



Sum Rules

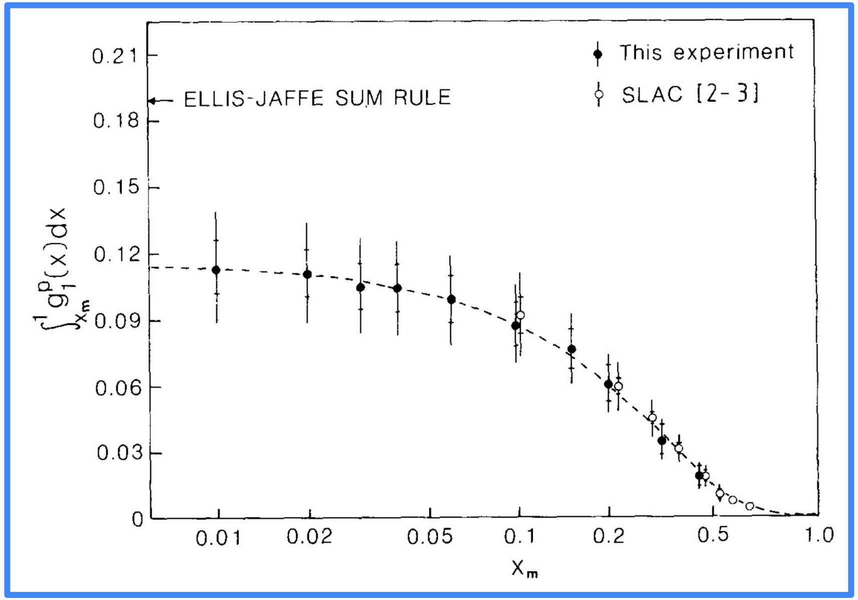
- Connect structure functions to general hadronic properties
- Requires integration over full x-range (combine multiple experiments)

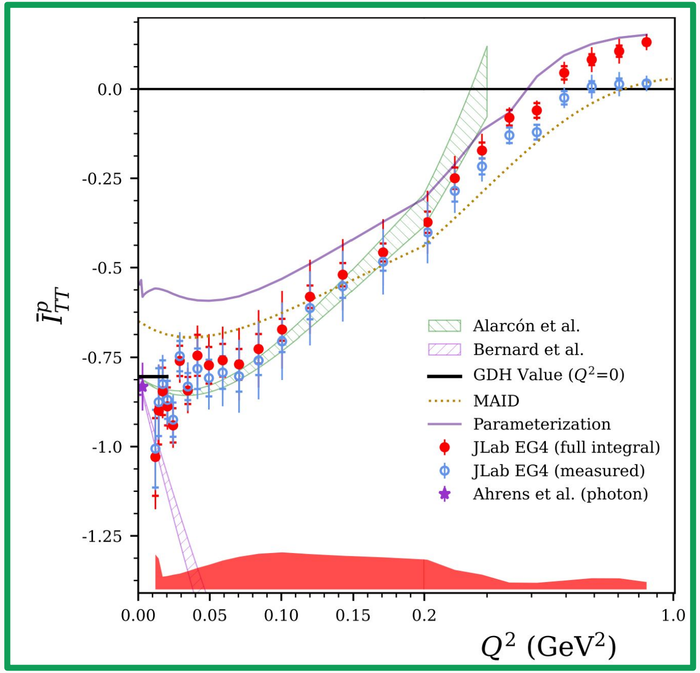
$$\int dx$$



Experimental Tests of Sum Rules

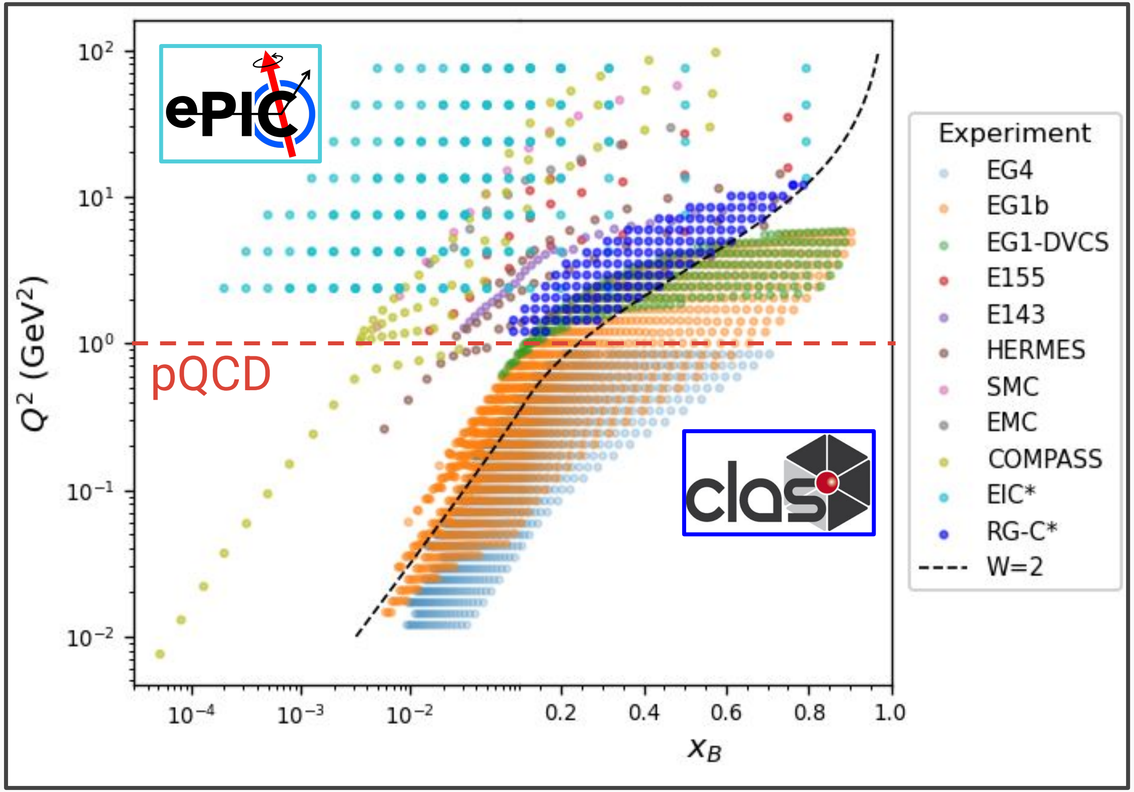
- EMC test of Ellis-Jaffe “sum rule” -> quarks carry little of proton’s spin
- Gerasimov-Drell-Hearn (GDH) compares low-Q^2 to Q^2=0





Why do we need the EIC?

❖ Need *really* low-*x* data at Q^2>1 GeV^2 for pQCD analysis & **sum rule tests**



Bjorken Sum Rule at EIC

High precision measurements of α_s at the future EIC

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High precision measurements of α_s at the future EIC

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Bjorken Sum Rule

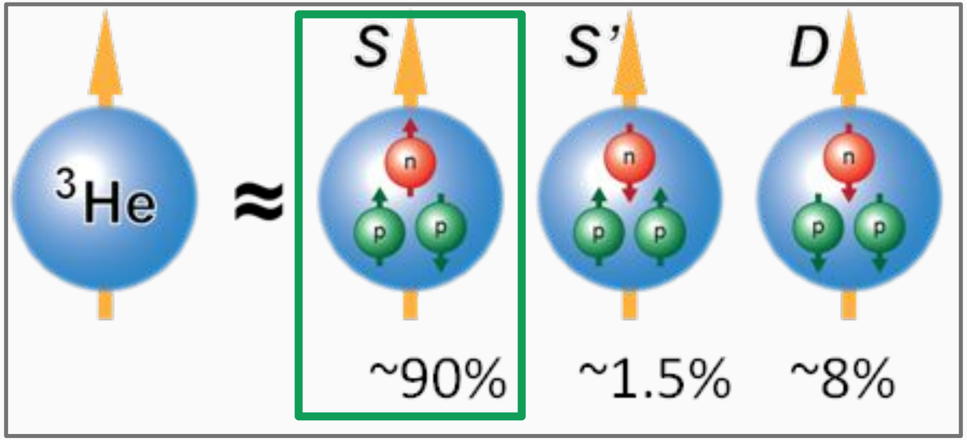
- Isospin symmetry with $Q^2 \to \infty$ convergence
- Integrate g_1 over x to form Γ_1
- $\Gamma_1(Q^2)$ related α_s via axial coupling x pQCD series

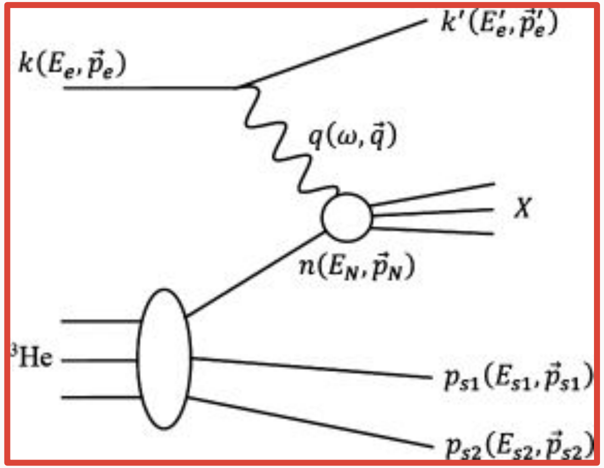
$$\overline{\Gamma}_1(Q^2) = \int_0^{1^-} g_1(x, Q^2)dx$$

$$\Gamma_1^{\mathrm{p-n}}(Q^2) = \sum_{\tau>0} \frac{\mu_{2\tau}^{\mathrm{p-n}}(\alpha_s)}{Q^{2\tau-2}} = \frac{g_A}{6}\left[1 - \frac{\alpha_s(Q^2)}{\pi} - 3.58\left(\frac{\alpha_s(Q^2)}{\pi}\right)^2 - 20.21\left(\frac{\alpha_s(Q^2)}{\pi}\right)^3 - 175.7\left(\frac{\alpha_s(Q^2)}{\pi}\right)^4 - (\sim 893.38)\left(\frac{\alpha_s(Q^2)}{\pi}\right)^5 + \mathcal{O}\left((\alpha_s)^6\right)\right] + \sum_{\tau>1} \frac{\mu_{2\tau}^{\mathrm{p-n}}(\alpha_s)}{Q^{2\tau-2}},$$

Polarized DIS on the "Neutron"

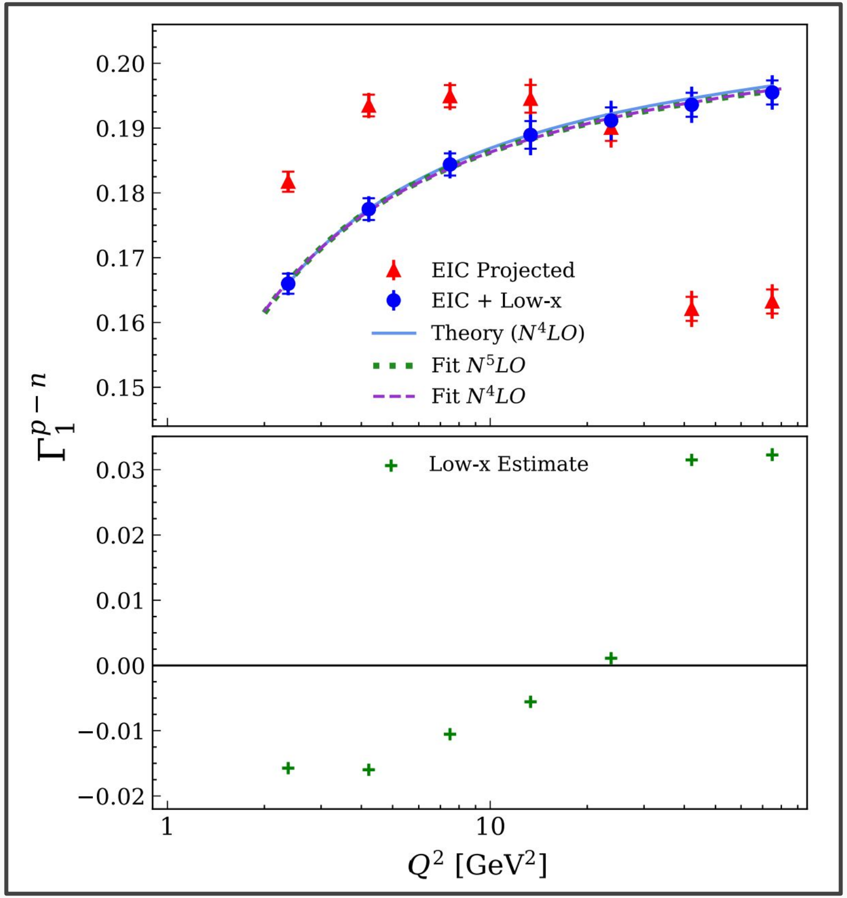
- Proton is "easy" but free neutron polarized target is a fairy tale
  - Current experiments use polarized deuteron (my thesis) or ^{3}He targets
- Proton spins "cancel" in S-state of ^{3}He-> effective polarized neutron
  - Minimize nuclear systematics with double-tagged DIS at EIC





Projections for Bjorken Sum Rule at EIC

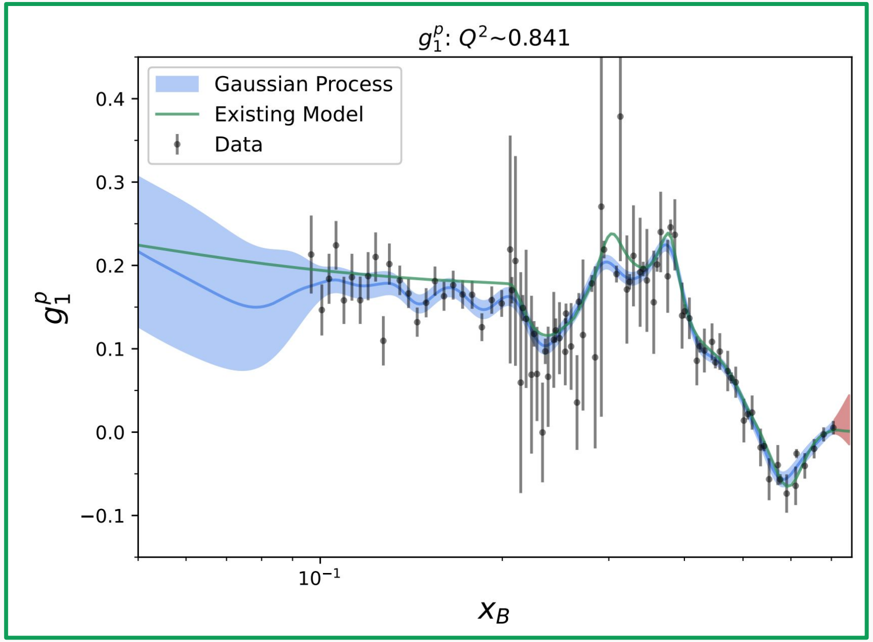
- Integrate"data" to obtain Γ_1
- Estimation for missing low-x comes from Regge theory
- Fit projections to determine α_s
  - Story for another day

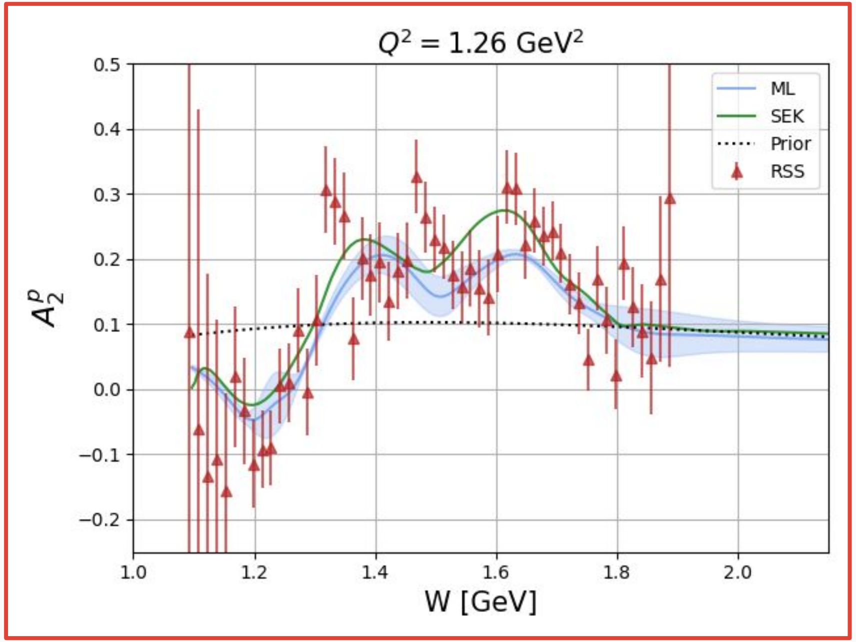


What Else Can Help?

Updating World Fits using ML

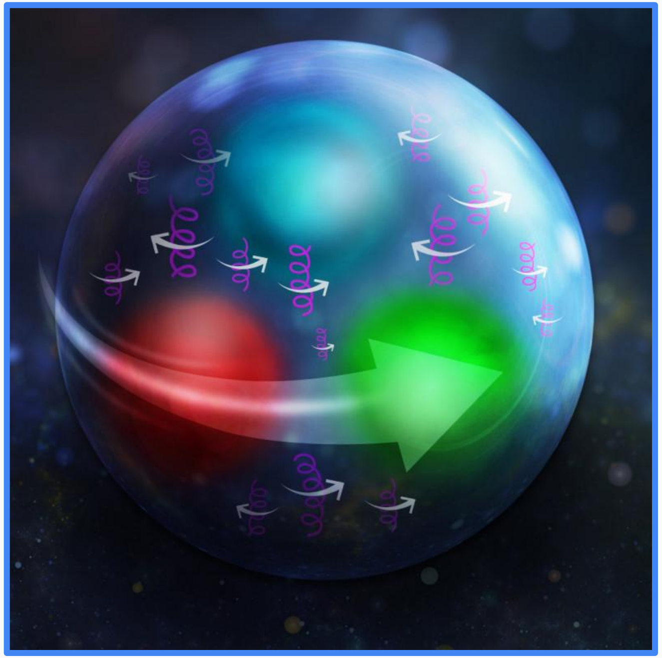
- Supplement measured part with updated models
- Gaussian Processes (GPs) & NNs provide flexible models with UQ





Closing Thoughts

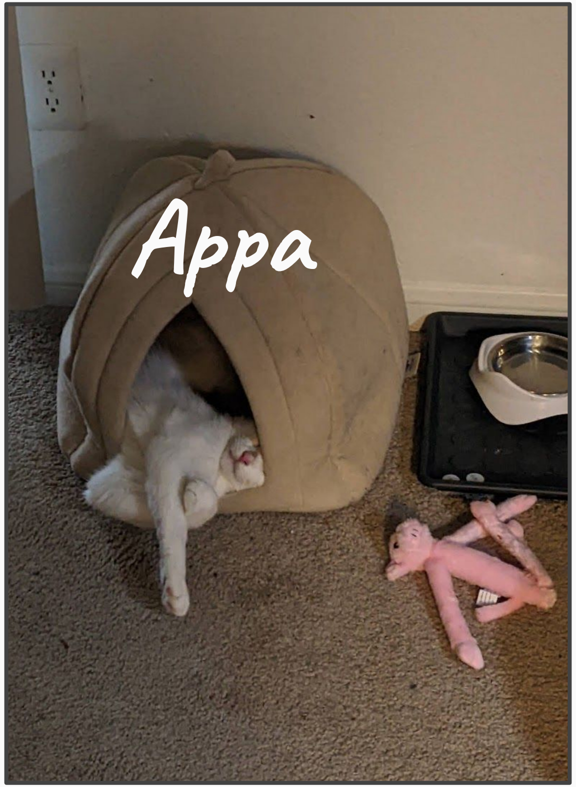
- Experiments test powerful predictions of Sum rules
- EIC offers unique opportunities for spin physics via tagged DIS
- Excellent complementarity between EIC & JLab

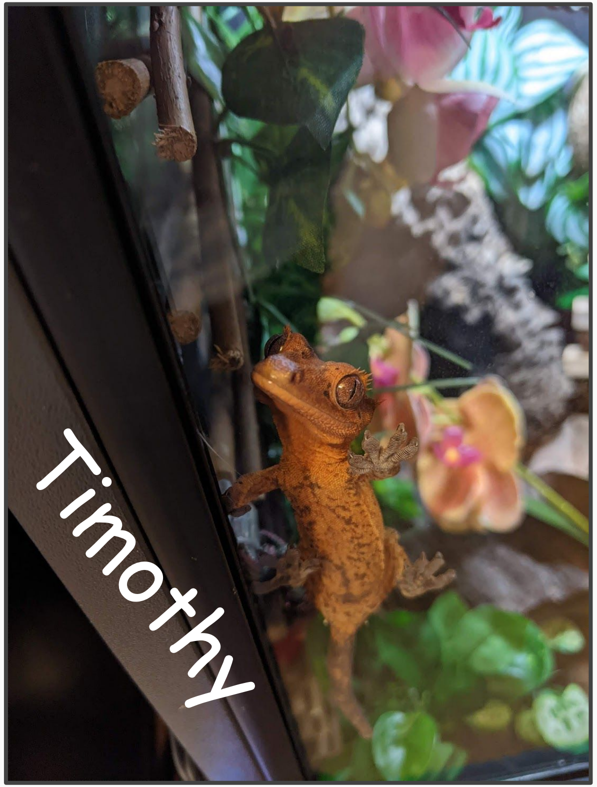


Acknowledgments

- UVA & ODU Nuclear Groups' DOE Grants
- Jefferson Science Associates (JSA) Graduate Fellowship
- ODU Graduate Summer Research Award

Questions/Comments

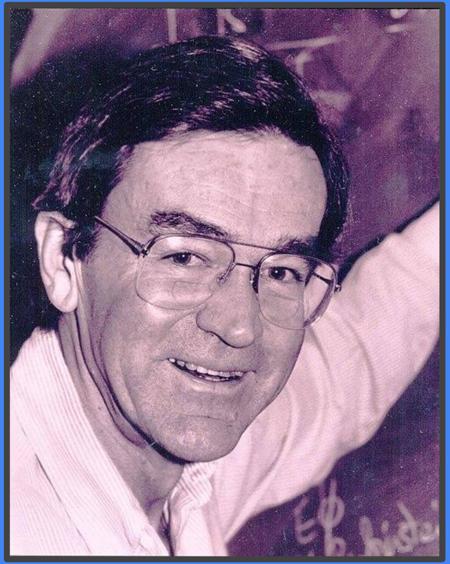




Backup Slides

“Polarisation data has often been the graveyard of fashionable theories. If theorists had their way they might well ban such measurements altogether out of self-protection.”

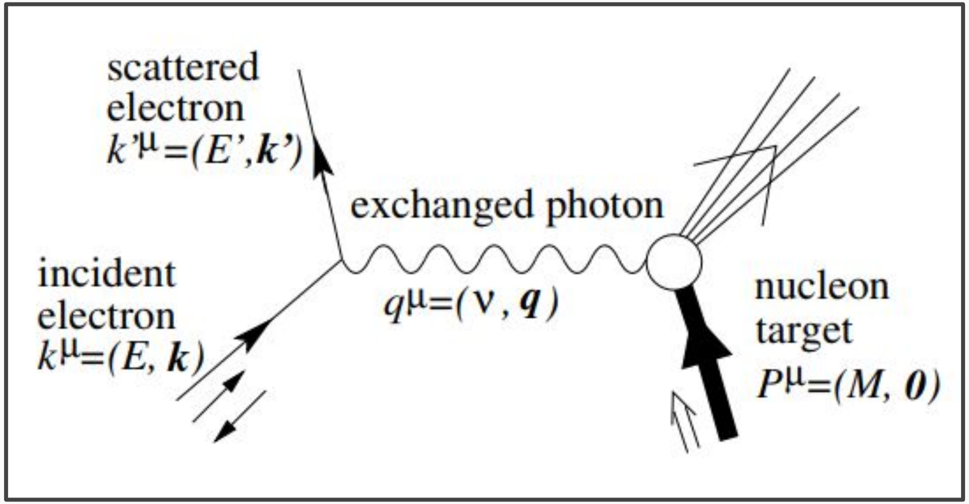
- J. D. Bjorken (1987)



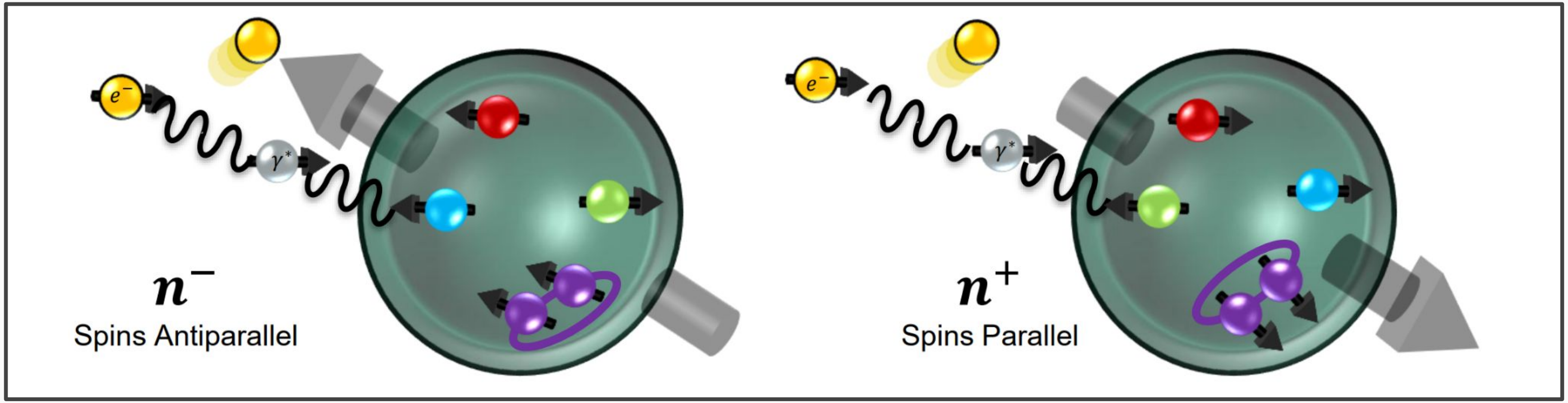
Spin-Polarized Inclusive Lepton Scattering

- Study nucleons using “clean” electromagnetic probe
- Polarized leptons scatter off polarized **target**

- Kinematic Variables
  - ***Q^2***: Four-momentum transfer squared (resolution scale)
  - ***x***: Momentum fraction carried by struck parton
  - ***W***: Invariant mass of system



Double-Spin Asymmetries in Lepton Scattering

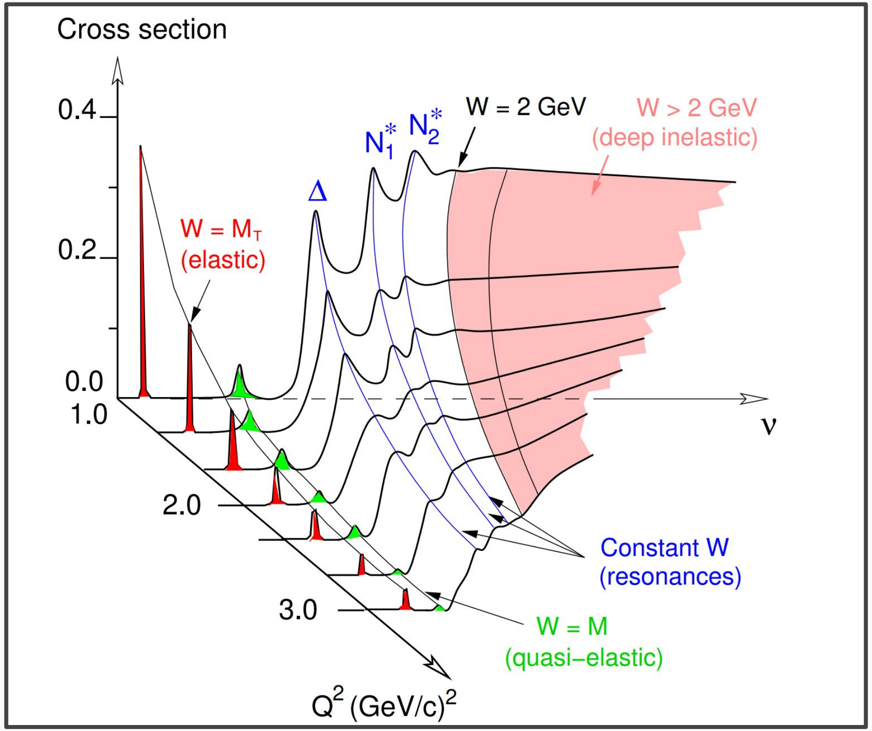


$$A_{||}(x,Q^2) = \frac{n^- - n^+}{n^- + n^+} = D\left(A_1(x,Q^2) + \eta A_2(x,Q^2)\right)$$

$$A_1(x,Q^2) \propto \frac{g_1(x,Q^2)}{F_1(x,Q^2)}$$

Kinematic Regions

- JLab experiments cover **resonances** & **deep inelastic** regions
- Monte Carlo simulation requires model coverage over all kinematics

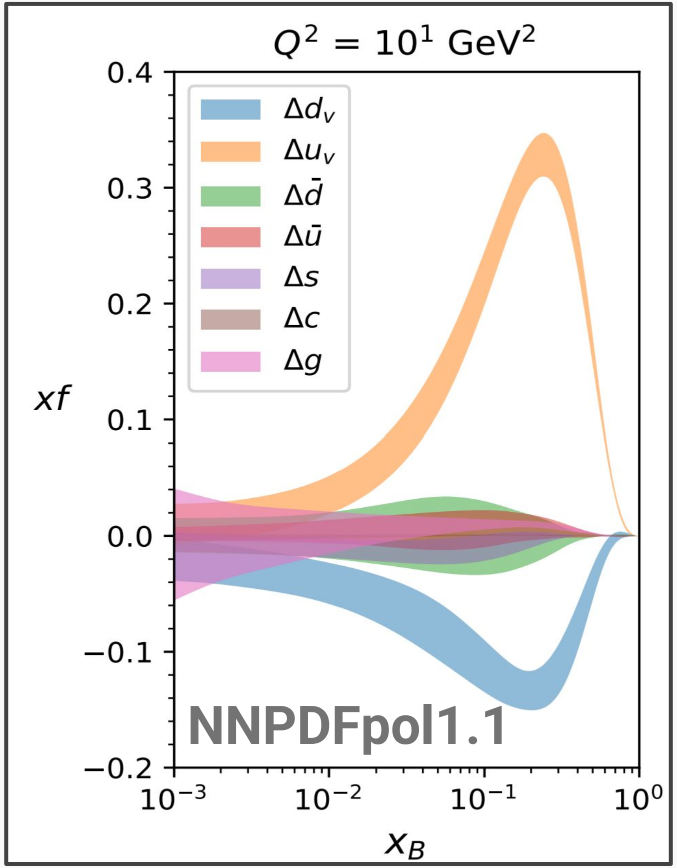


Longitudinal Spin Structure

- g_1 is sum over helicity PDFs Δf which is diff of spin aligned & anti-aligned PDFs
- Helicity/Polarized PDFs encode the product of probability and polarization

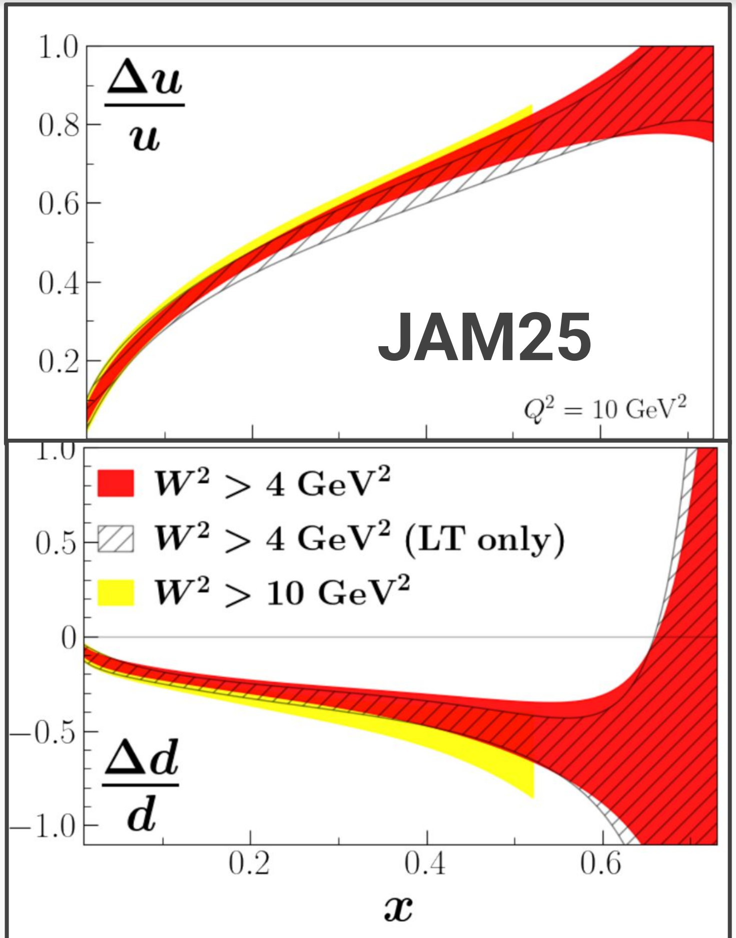
$$\Delta f_i = f_i^{\uparrow} - f_i^{\downarrow}$$

$$g_1(x) = \frac{1}{2}\sum_i e_i^2 \Delta f_i(x)$$



Quark Polarization at Large x

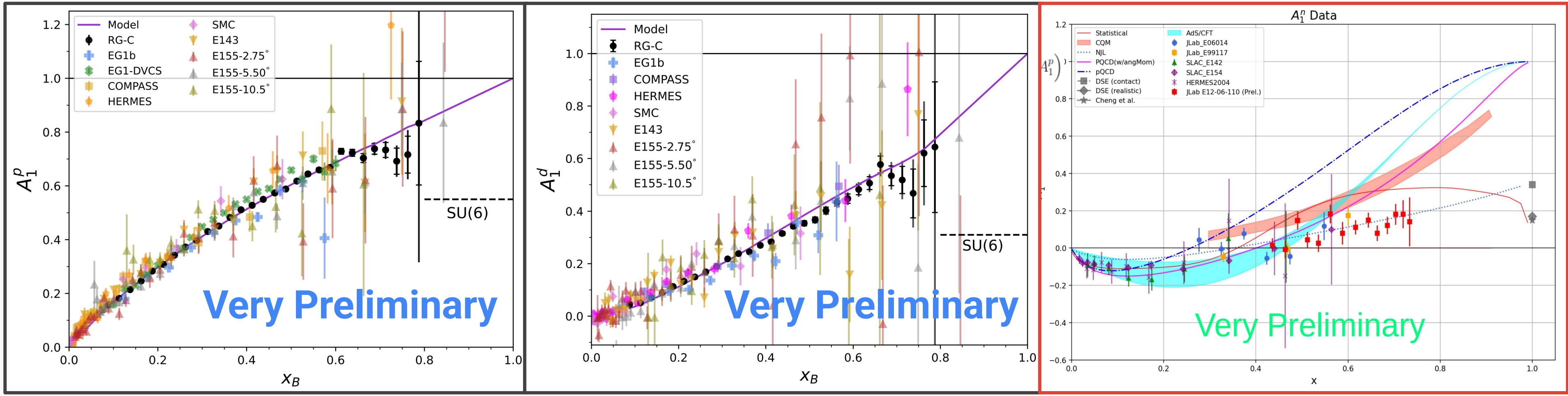
- Global QCD unpol & pol PDF fits
- New JLab data for p, d, & ^{3}He will constrain large-x



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

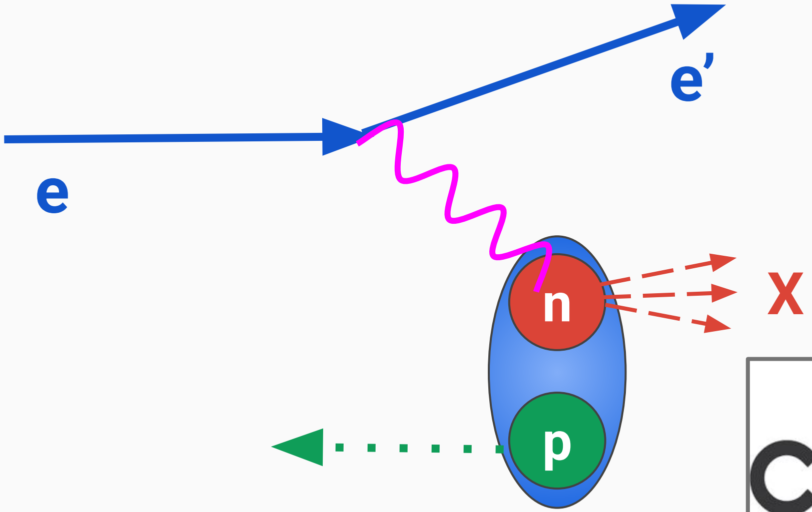
JLab 12-GeV Data

- Precision mapping of $0.1 \lesssim x \lesssim 0.8$
- Figures highlight impact at **large *x*** for preliminary results from 12-GeV JLab using **CLAS12** (pro & deu) & Hall C (^{3}He)



Tagged DIS on the "Neutron" via BONuS

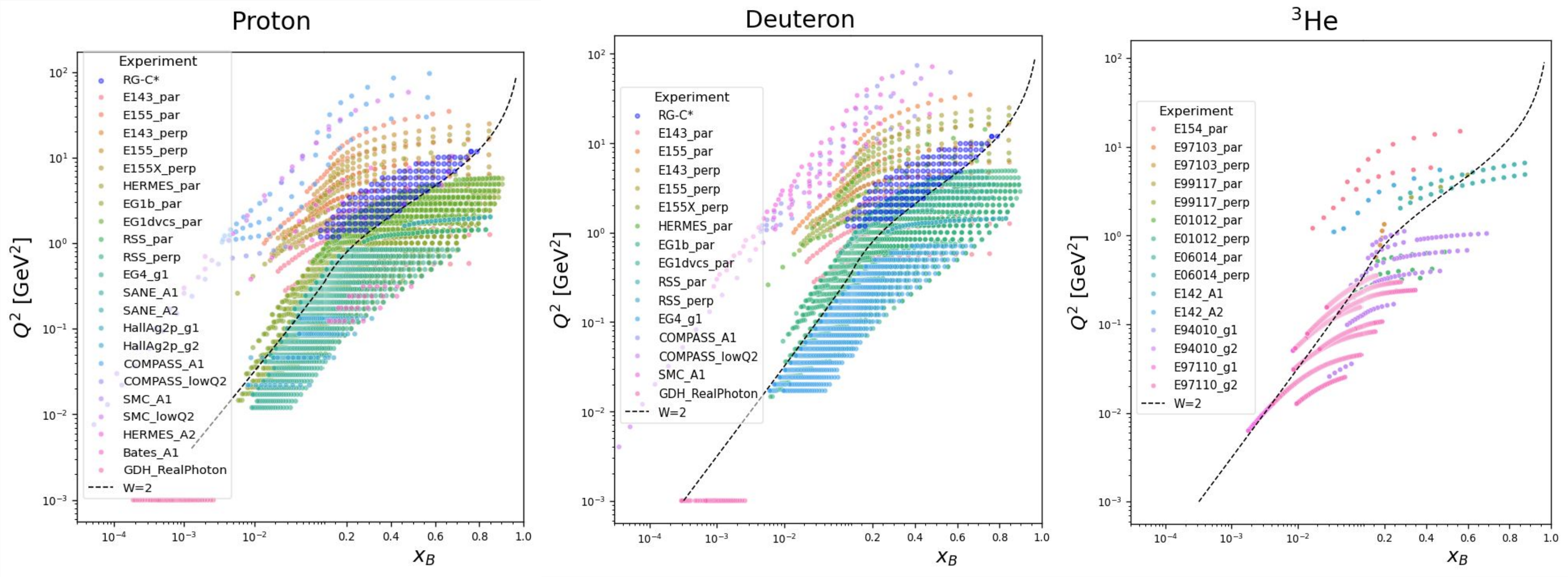
- Barely Offshell Neutron Structure (BONuS)
-



BONuS-12 & Crew

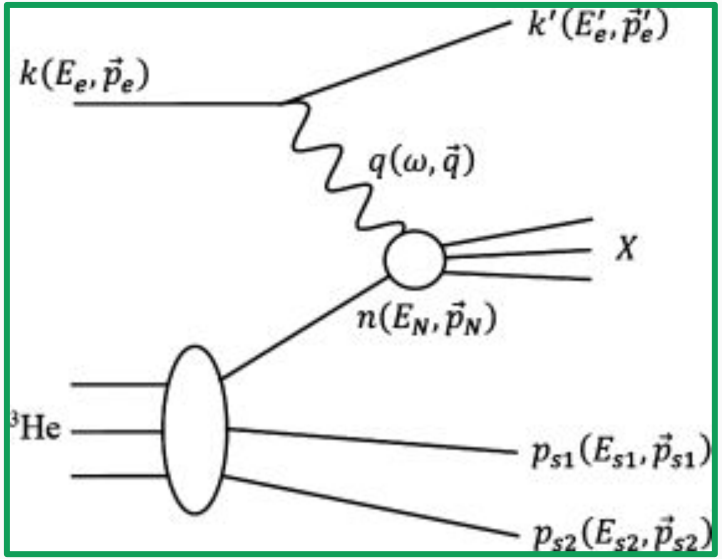
World Data

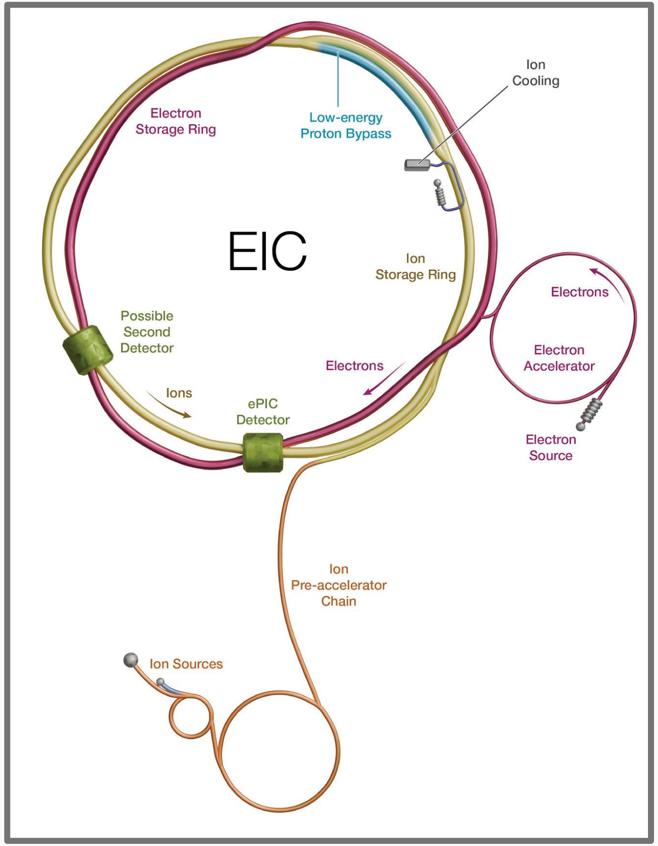
- Wealth of data but sparse & non-uniform precision (>50 sets)
- Combination of data for proton, ^{2}H, & ^{3}He from many experiments



Experiment at the Future EIC

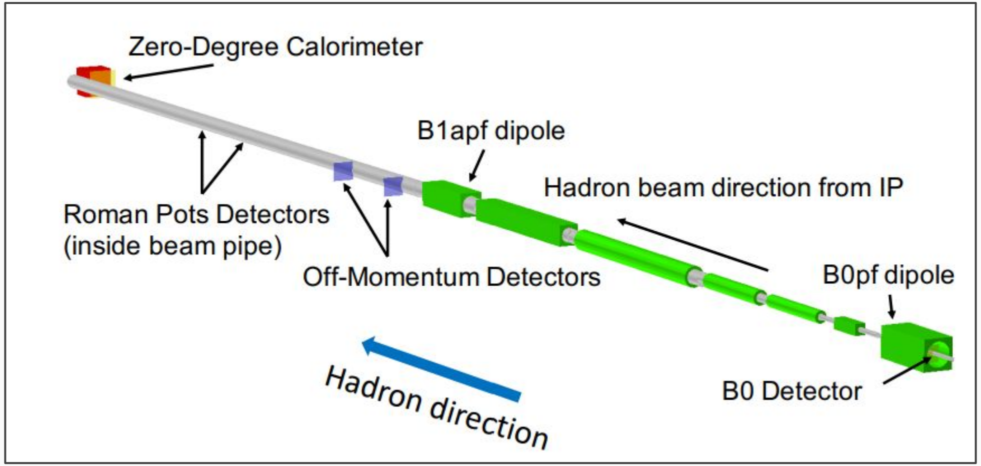
- High polarization for *e-p* and *e-^{3}He*
- Measure protons in ^{3}He break-up using tagged DIS with Far-Forward detectors

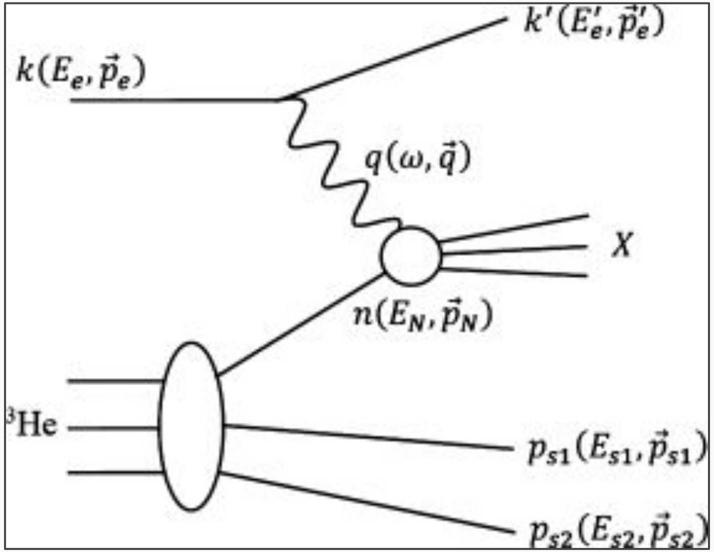




Doubly-Tagged DIS at the EIC

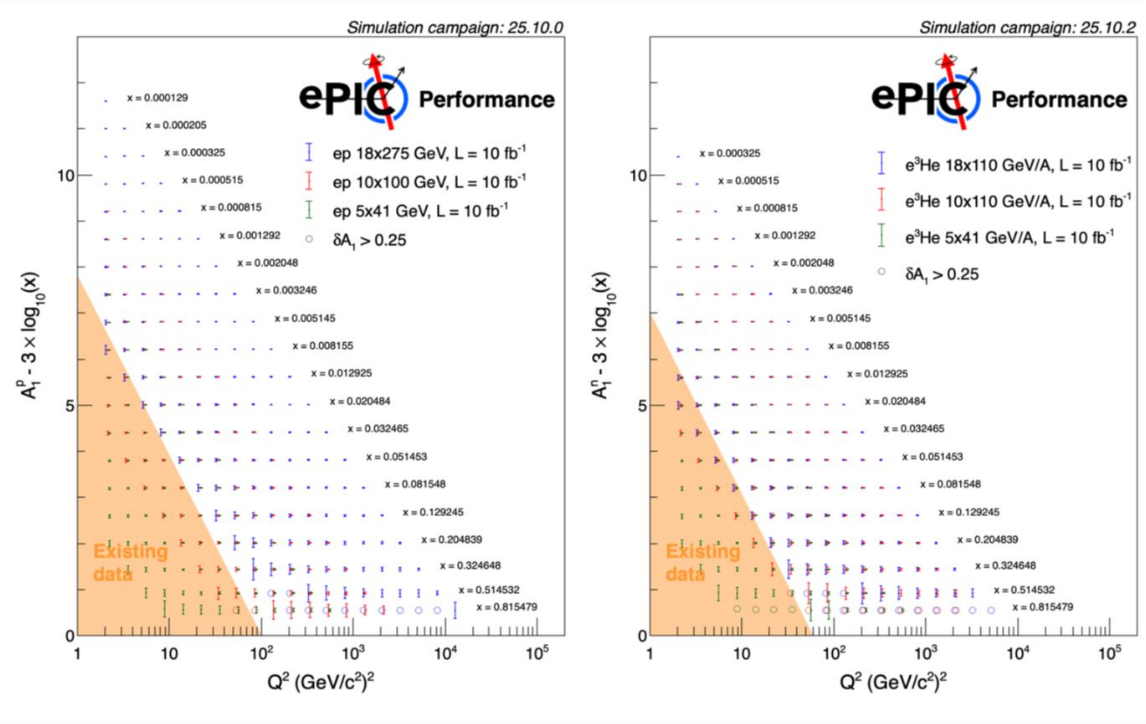
- Measure protons from ^{3}He break-up
- Minimize systematics coming from nuclear corrections to 3He
  - Select scattering from quasi-free neutron
- Accomplished by detector stack in far-forward region





A_1 Projections for ePIC

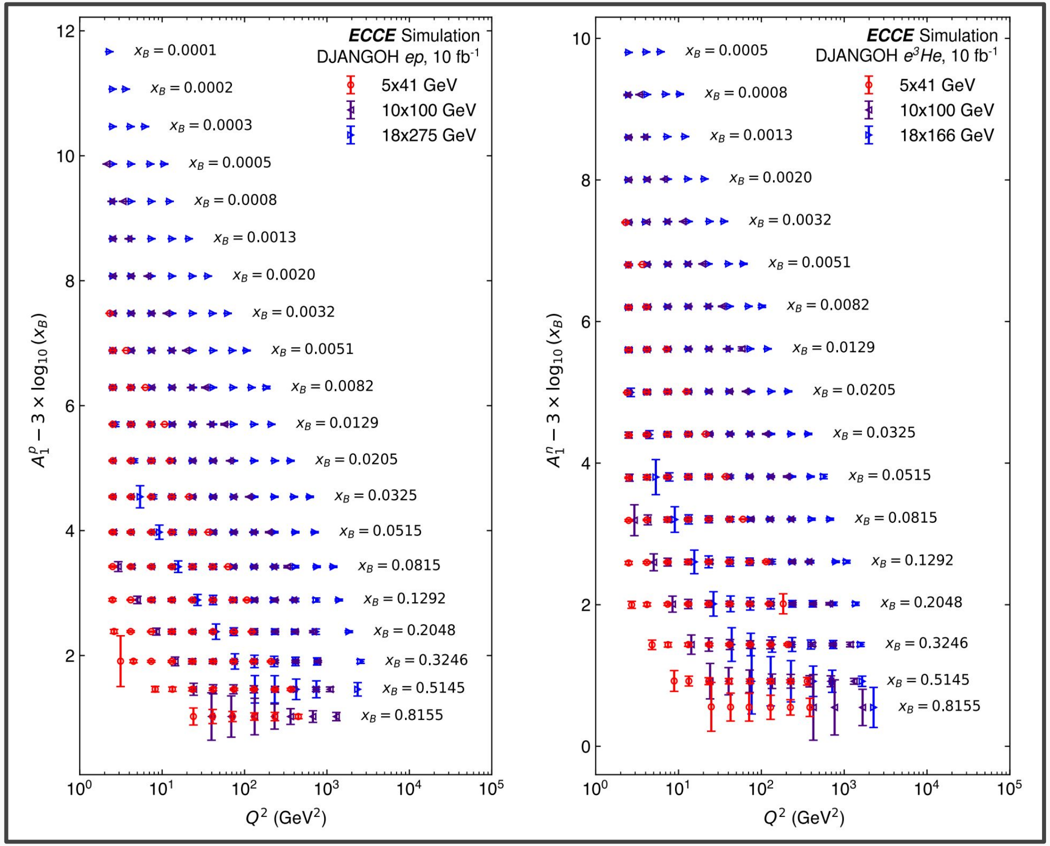
- Simulated for ePIC



Bjorken Sum Rule

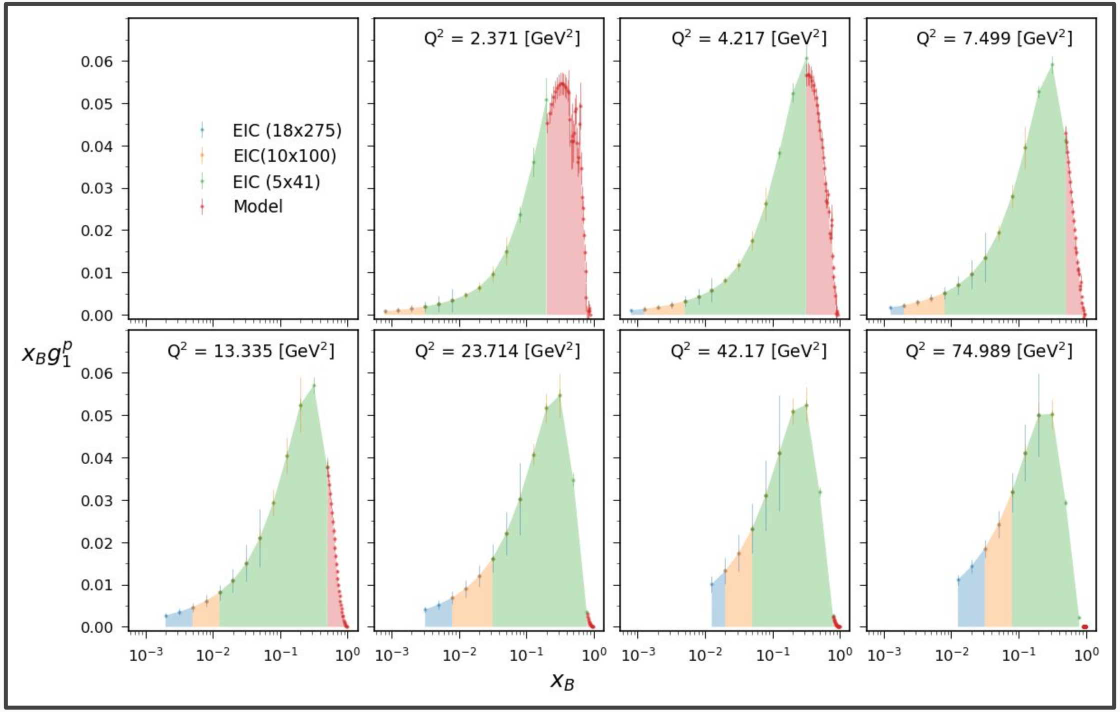
A_1 Projections for EIC

- Simulated for ECCE
- Huge kinematic coverage



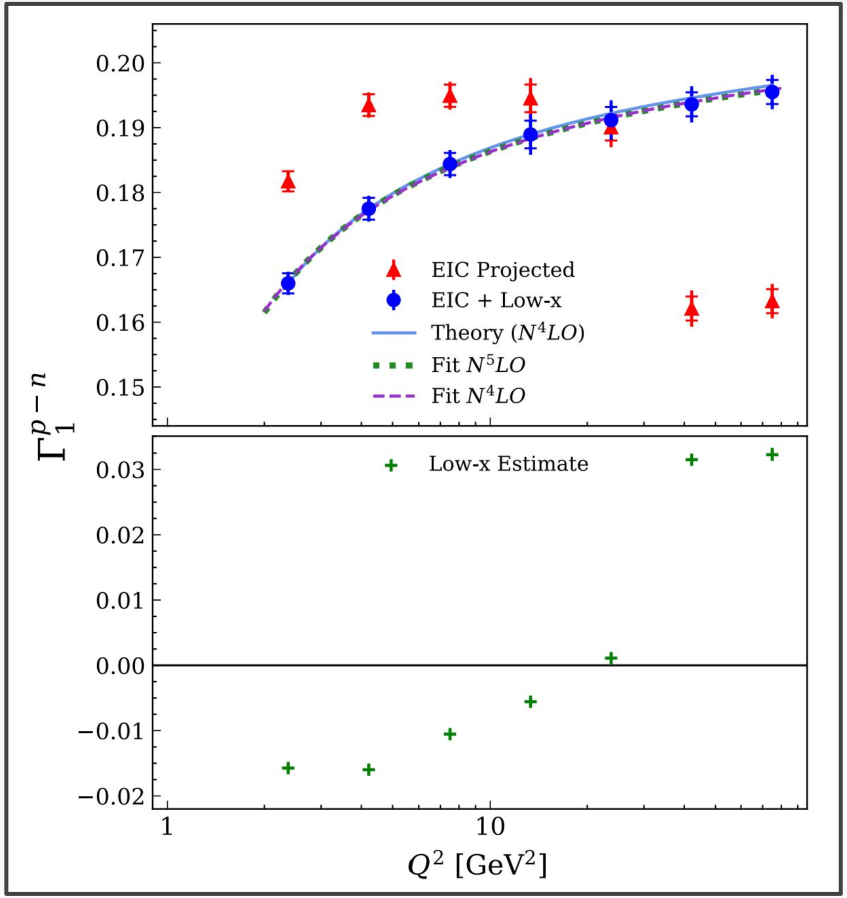
EIC Projections & Model from JLab Data

- Using model to fill-in coverage at large *x*
- Color is associated with region with best precision



Moments & Fitting for α_s

- Integration over *x* provides Γ_1
- Fit projections at N^{X}LO
- Estimation for missing low-*x* comes from Regge theory



A_1 Projections for EIC

- Simulated for ECCE
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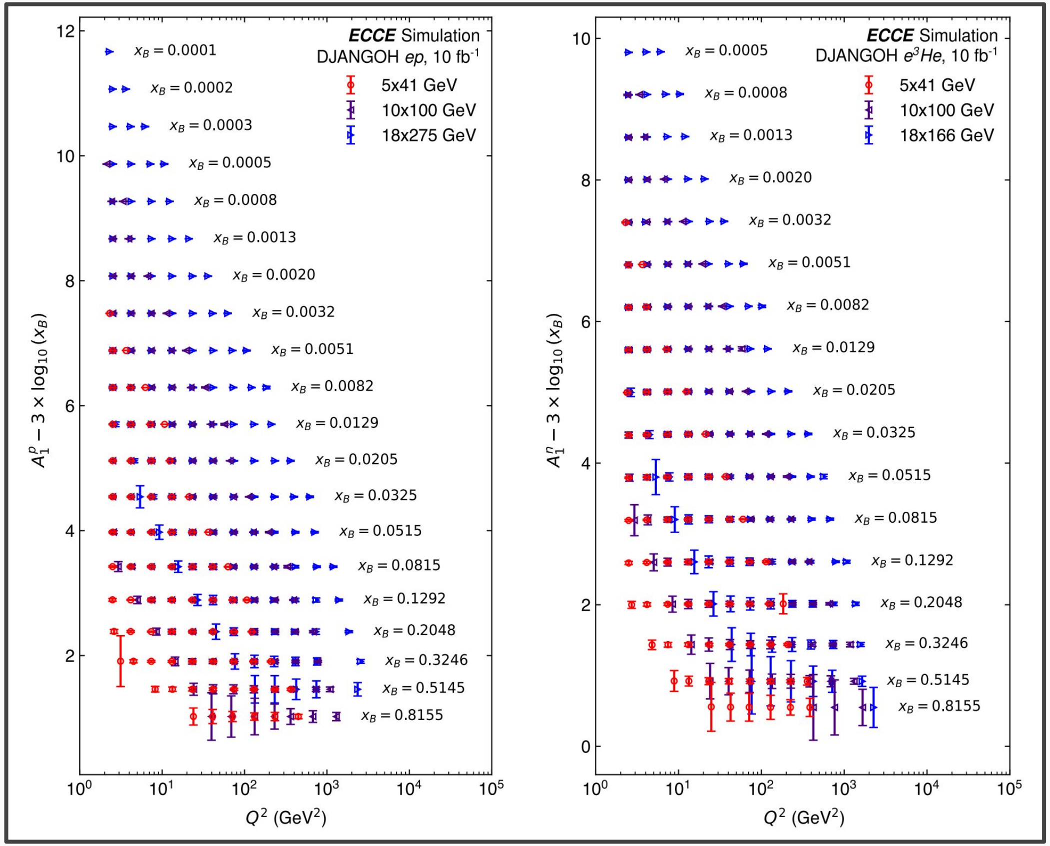
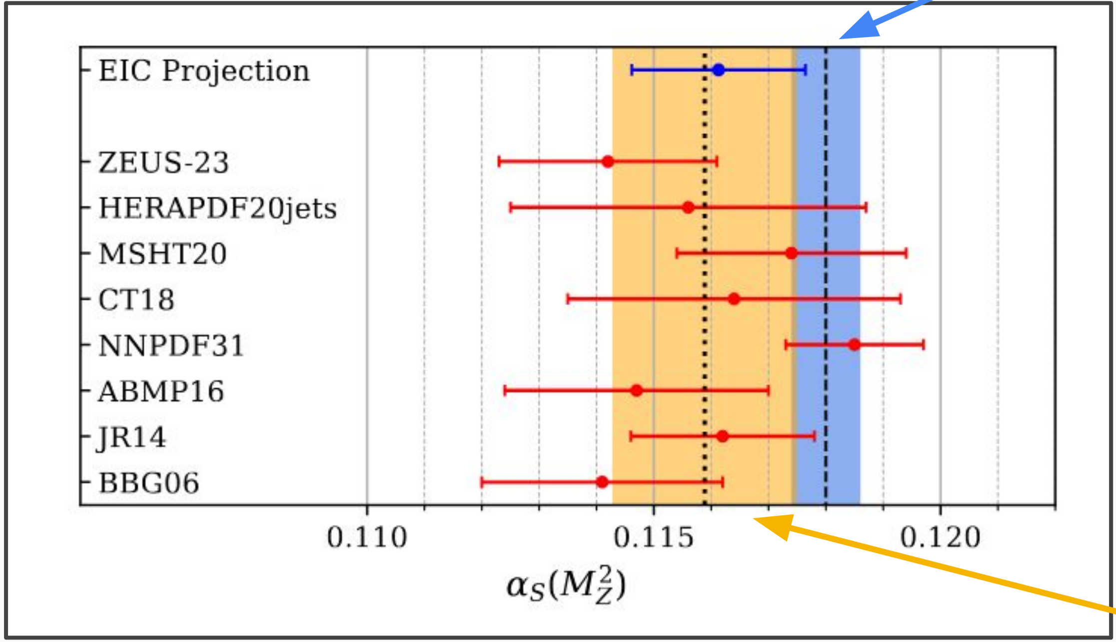


How does this Compare?

❖ EIC precision is competitive against existing *global analyses*

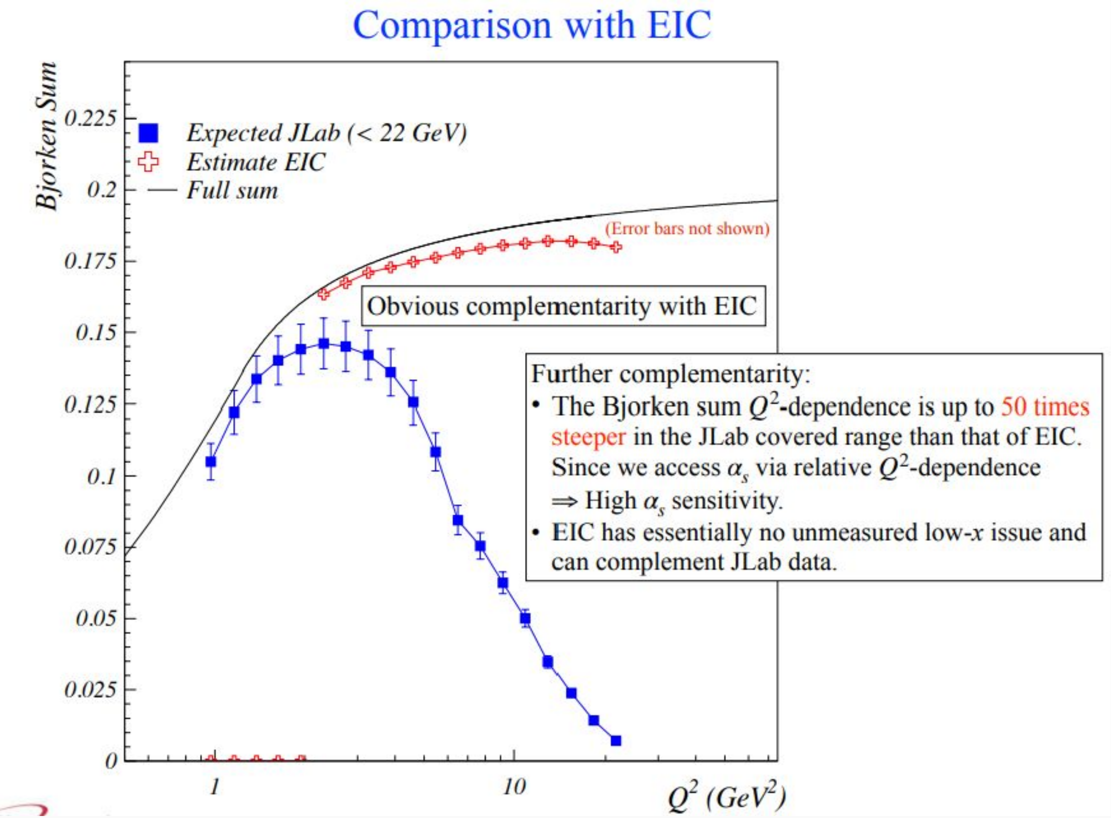
World Mean



DIS PDF Mean

Synergy with JLab Energy Upgrade

❖ Mo

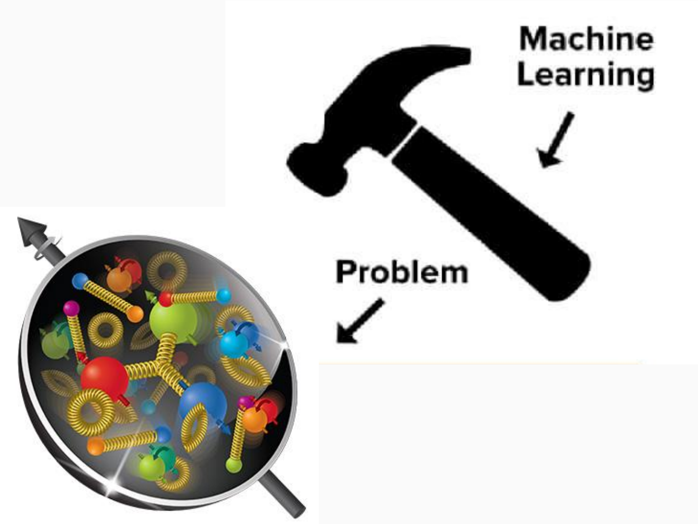


A. Deur, JLab 22 GeV Open Discussion (2023)

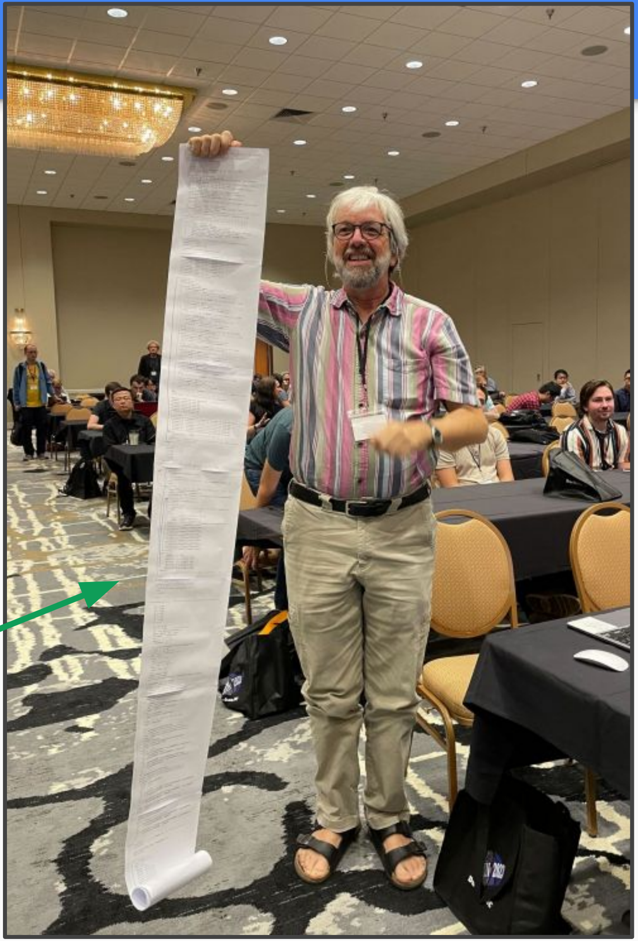
ML Fit Slides

Upgrading Models for Large x

- Need models for my thesis experiment
- Fortran model is difficult to use & update
- New data since previous patchwork fits
- Use ML to model over **entire** kinematics



Existing Model (**SEK**)



My Advisor: **S**ebastian **E**. **K**uhn

Simultaneous Fits of A_1 & A_2 in Global Analysis

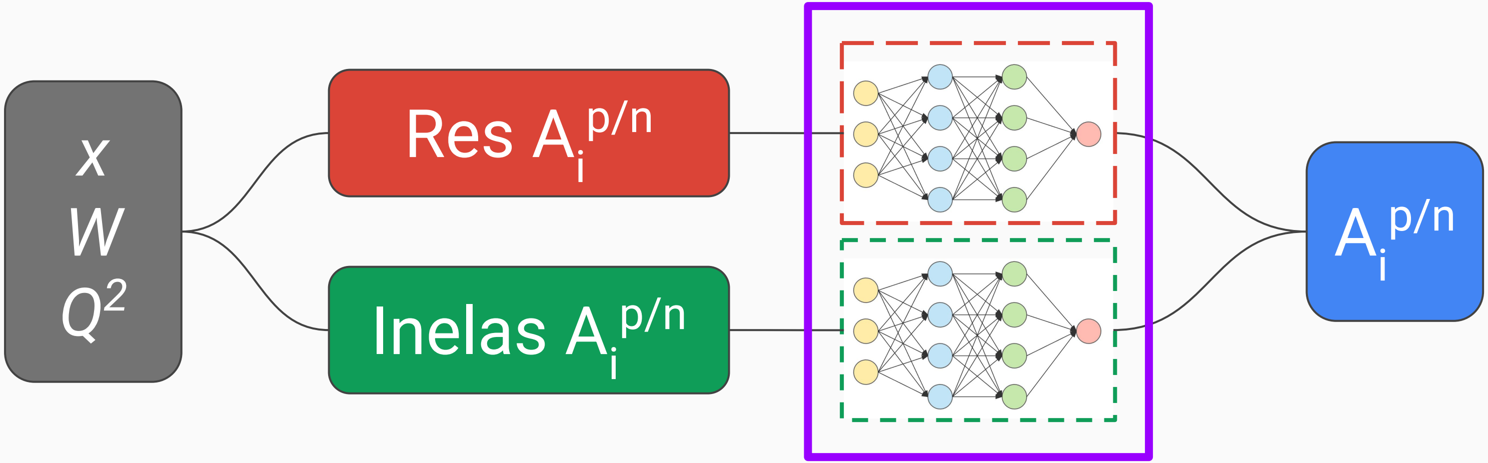
- Experiments measure asymmetries $A_{||}$ & $A_\perp$
  - Decompose into virtual photon asymmetries A_1 & A_2
- SimultFit of proton and neutron A_1 & A_2
  - Leverage kinematic factors, constraints, & sum rules
  - Use nuclear corrections for deuteron and ^{3}He

Measurements →

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

ML Technique - Physics Informed NNs

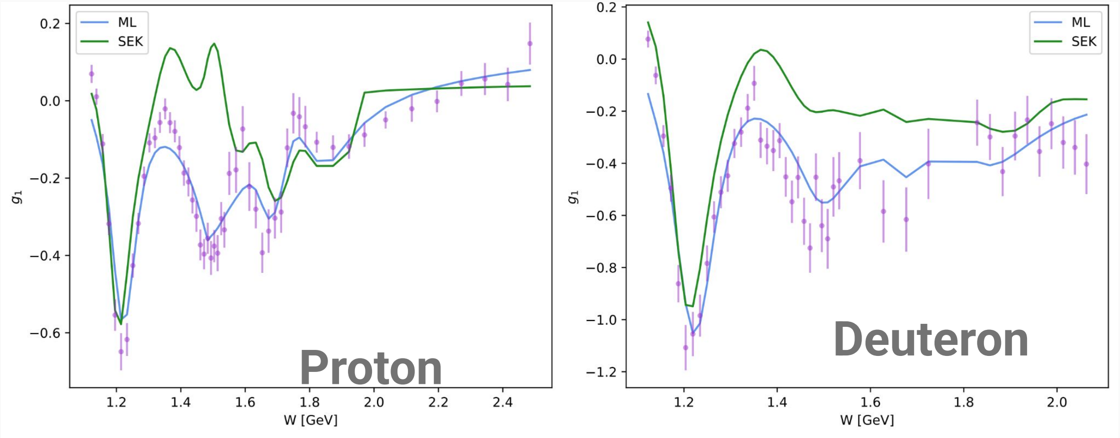
- Architecture - TensorFlow DNN with standard techniques & pieces
  - Physics priors for resonance and inelastic baseline behavior
  - **DNN** learns deviations from priors for each region
- Minimization function (loss) composed of χ^2 & physics penalties
  - Normalization (n_i) - For each experiment set
  - $\mathcal{L} = \chi^2 + \Sigma_i (n_i/\delta_i)^2 + \beta_j P_j$ (β_j scale penalty P_j)



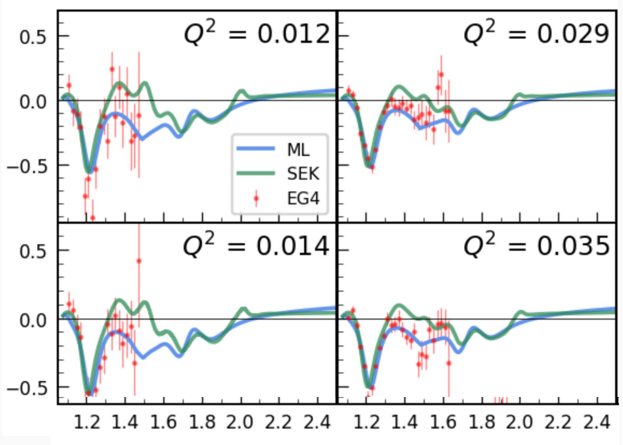
ML Results - Low Q^2

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

Real Photon Data

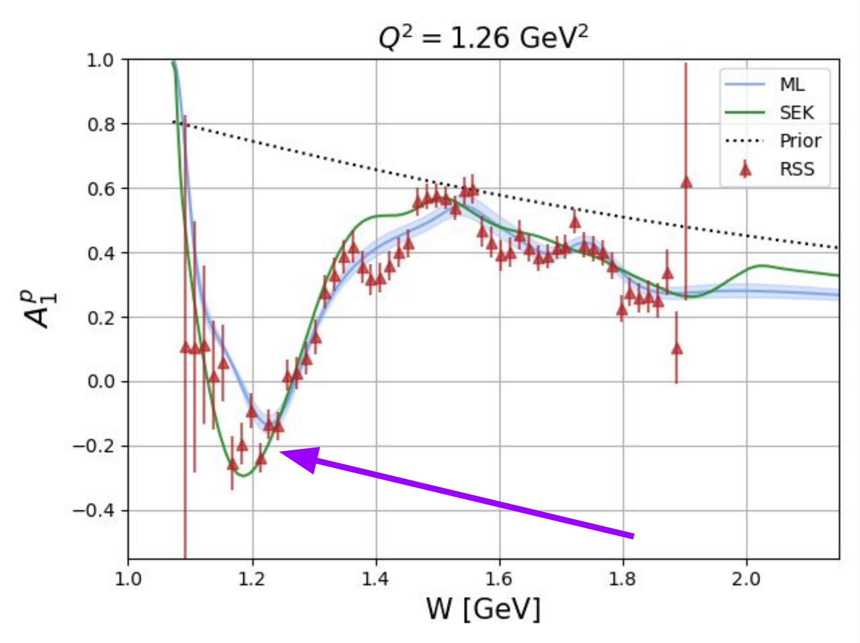


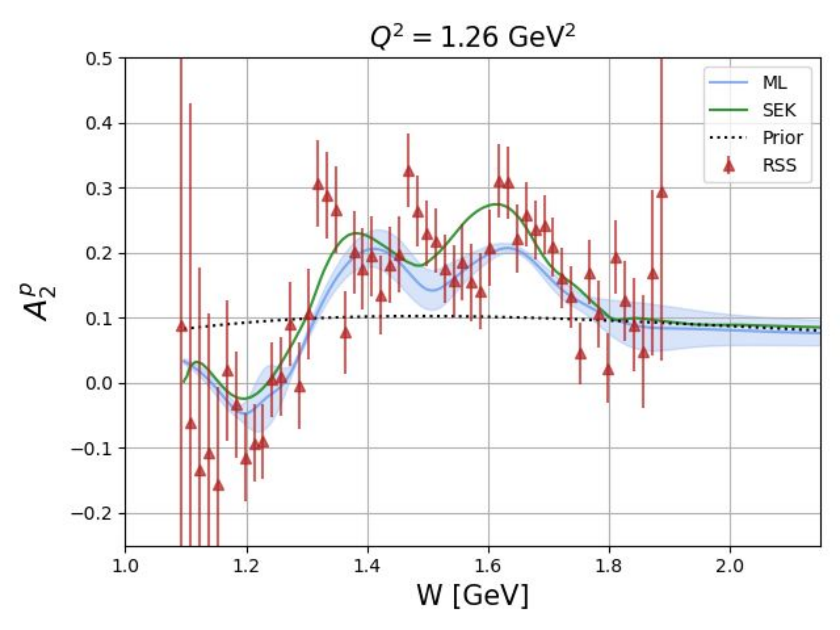
EG4 Proton Data



ML Results - Moderate Q^2

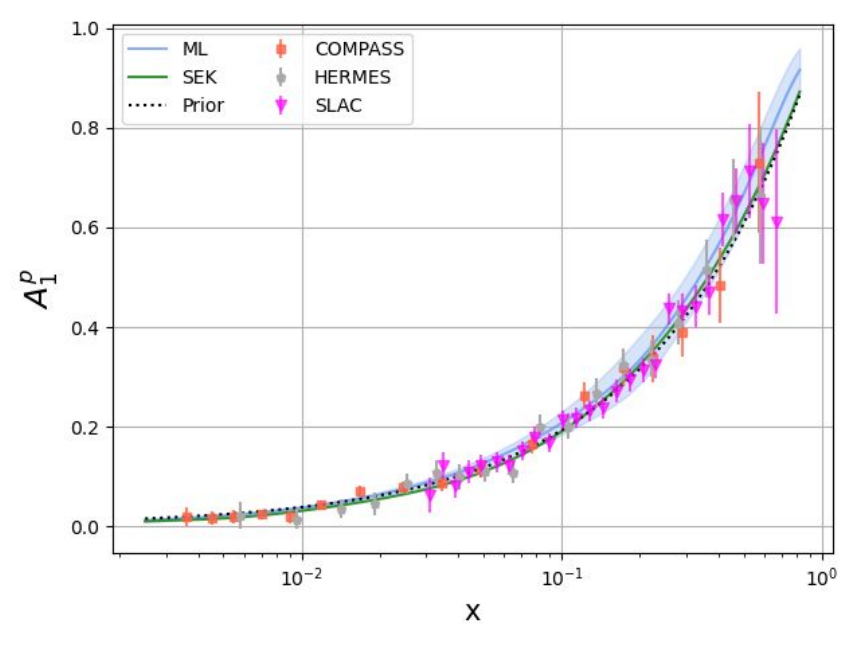
- Determine ML uncertainty from ensemble approach
- **Inelastic priors** poorly describe resonances
- Deviations from **SEK A_1 fit** around **Δ peak (W~1.2 GeV)**

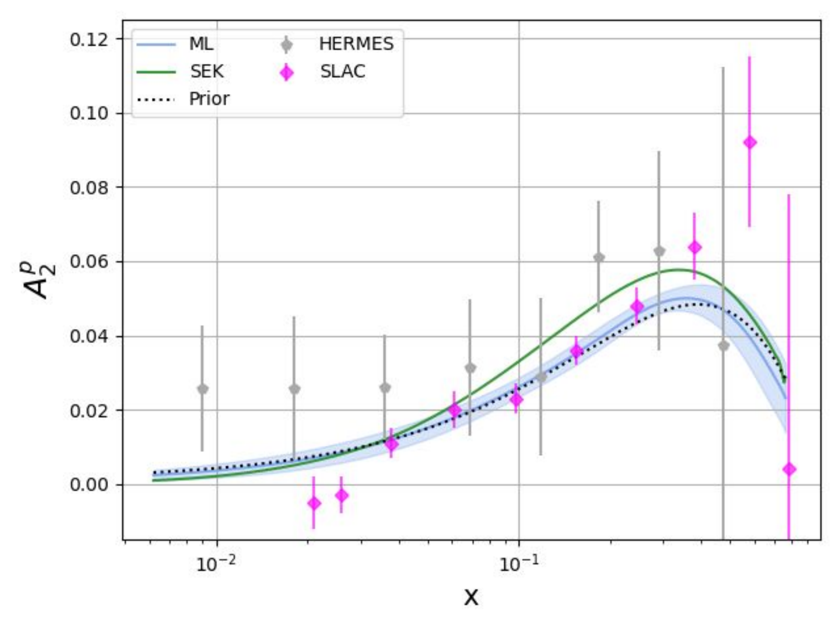




ML Results - Large Q^2

- NN shifts already okay priors (maybe not enough for A_2)
- ML uncertainty for A_1 is larger than data (likely normalization issue)





ML Results - Moments

- Moments are integrals
- Trends for Γ_1 miss theory at large Q^2
- Γ_2 constraint needs more work (should be closer to zero)

$$\overline{\Gamma}_1(Q^2) = \int_0^{1^-} g_1(x, Q^2)\,dx$$