Simultaneous Extraction of Spin-Averaged and Helicity PDFs

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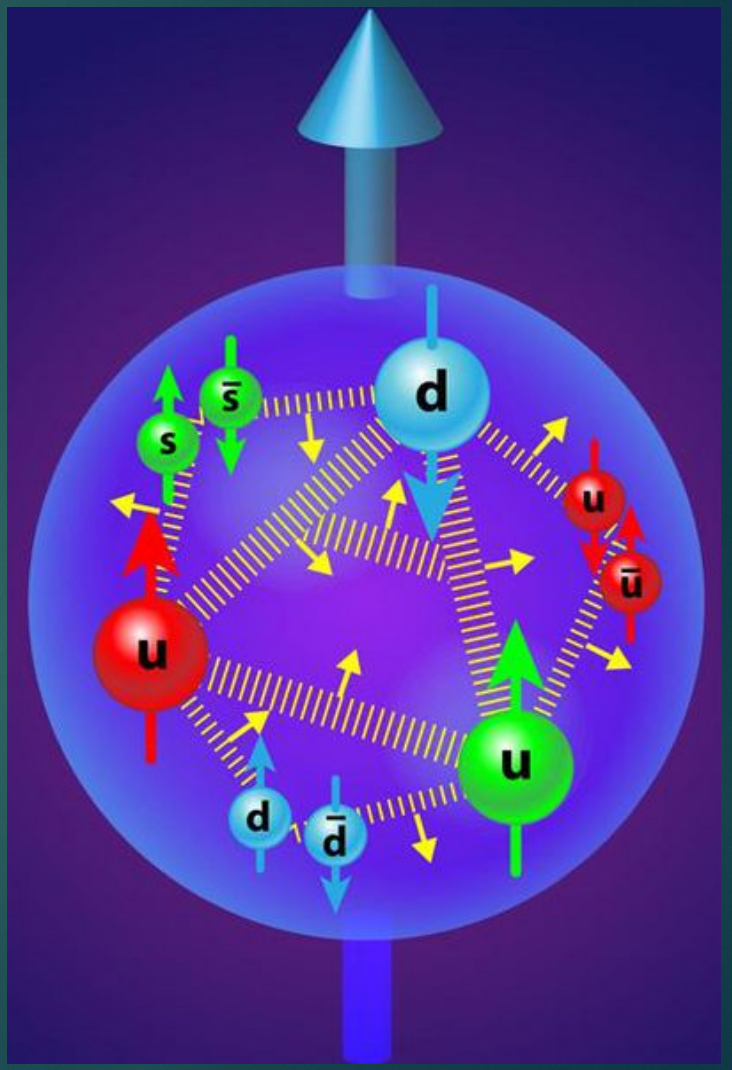
JAM Collaboration

- Understand the 3-dimensional structure of nucleons through global QCD analysis of parton distribution functions (PDFs), fragmentation functions (FFs) and transverse momentum dependent (TMD) distributions.
- Use collinear factorization in perturbative QCD to perform simultaneous determinations of PDFs, FFs, etc.
- Utilize Monte Carlo methods for Bayesian inference to achieve robust uncertainty quantification



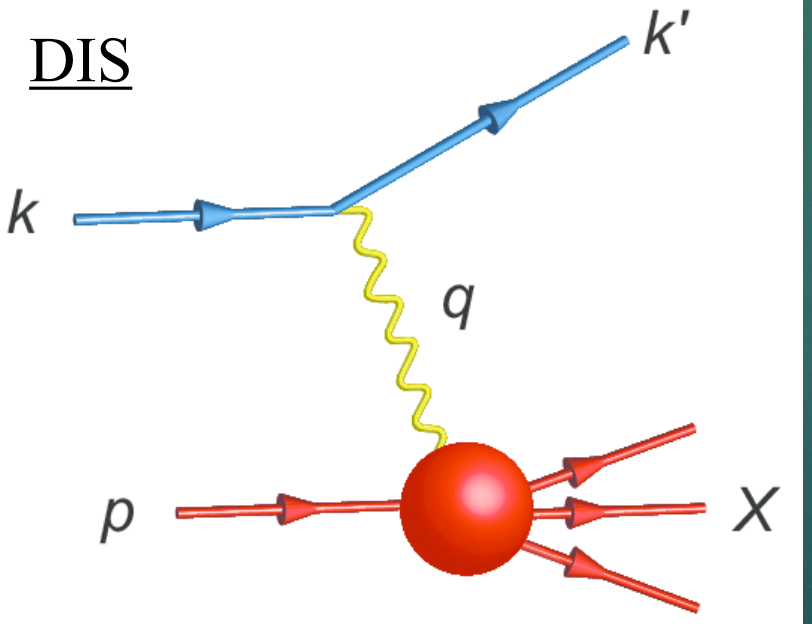
Spin-Averaged PDF + Nuclear Effects Analysis

Spin-Averaged PDF + Nuclear Analysis

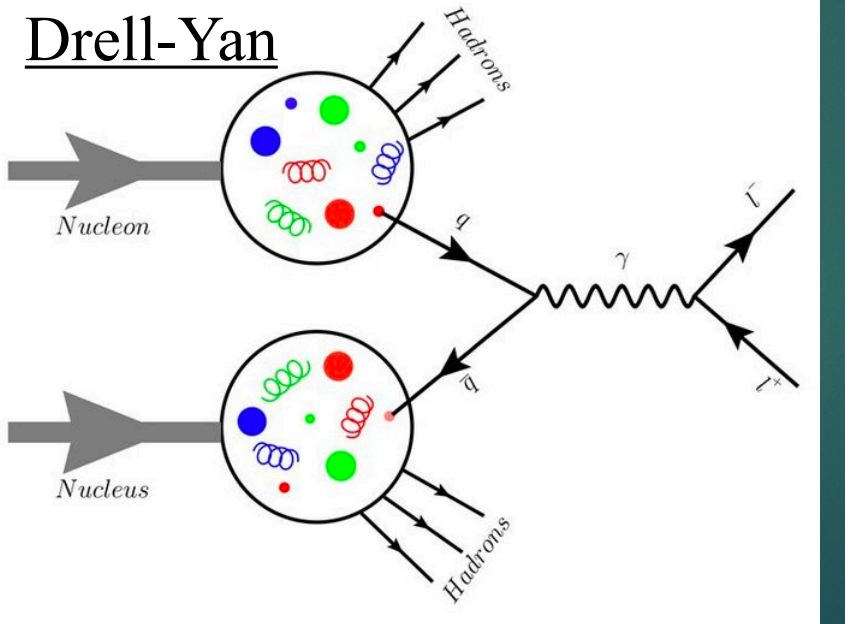
Simultaneous extraction of PDFs, higher twist effects (x^2M^2/Q^2), and nuclear effects.

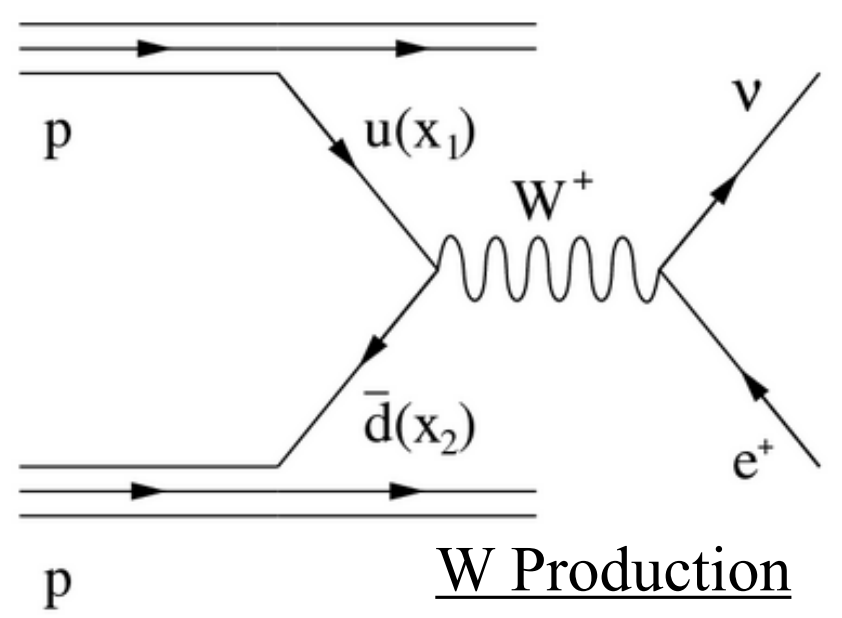
Update JAM analysis with latest W/Z production data (including LHC)

DIS



Drell-Yan

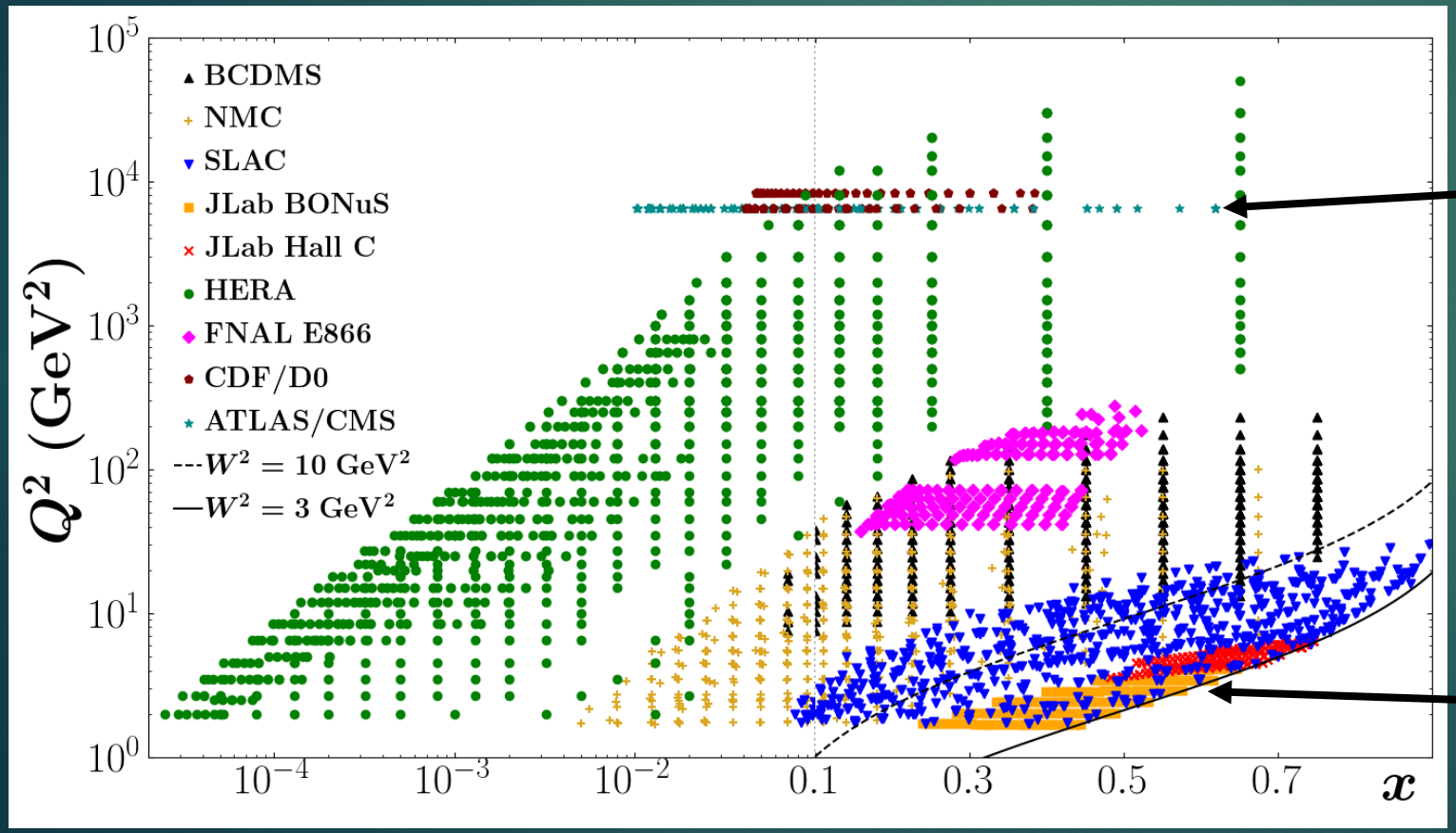




W Production

Data

- **Deep Inelastic Scattering**: BCDMS, NMC, SLAC, HERA, Jefferson Lab (3,863 points)
- **Drell-Yan**: Fermilab E866 (250 points)
- **W/Z Boson Production**: Tevatron CDF/D0, LHC ATLAS/CMS (239 points)



New LHC Data

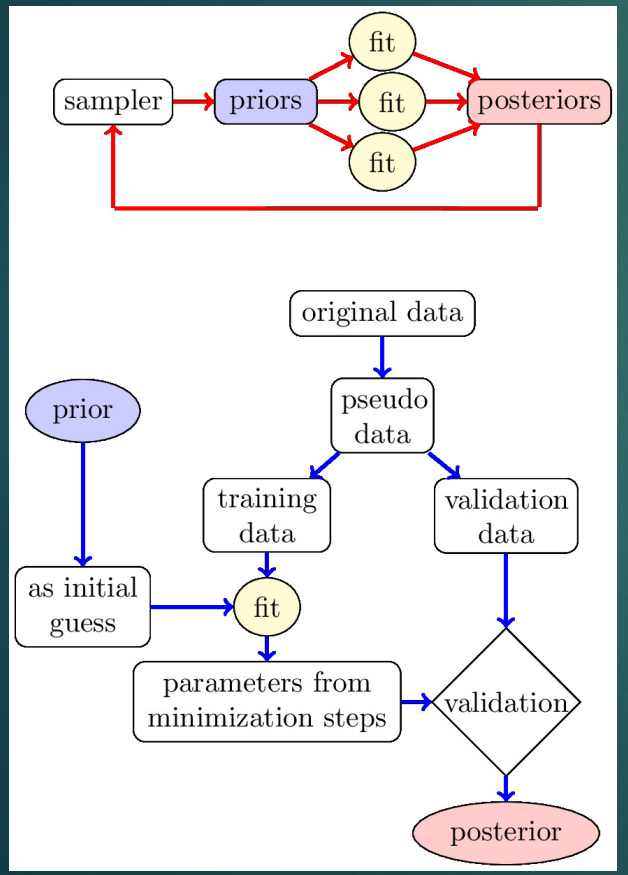
Low W^2 cut allows inclusion of high-x data, particularly from Jefferson Lab

High-x Data (Proton/Deuteron)

JAM Methodology

- Parameterize PDFs at input scale $Q_0^2 = m_c^2$: $f(x) = Nx^{\alpha}(1-x)^{\beta}(1+\gamma\sqrt{x}+\eta x)$
- Evolve PDFs using DGLAP and compute observables
- Determine parameters through Bayesian posterior sampling with likelihood function $e^{-\frac{\chi^2}{2}}$

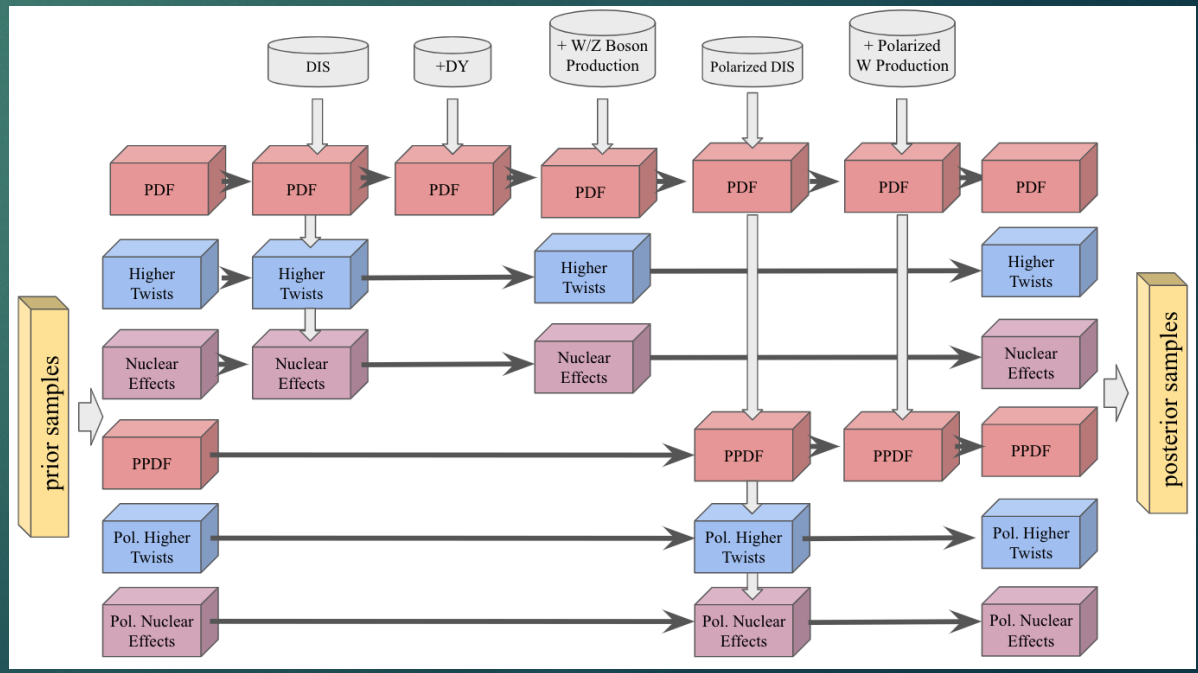
Data Resampling:



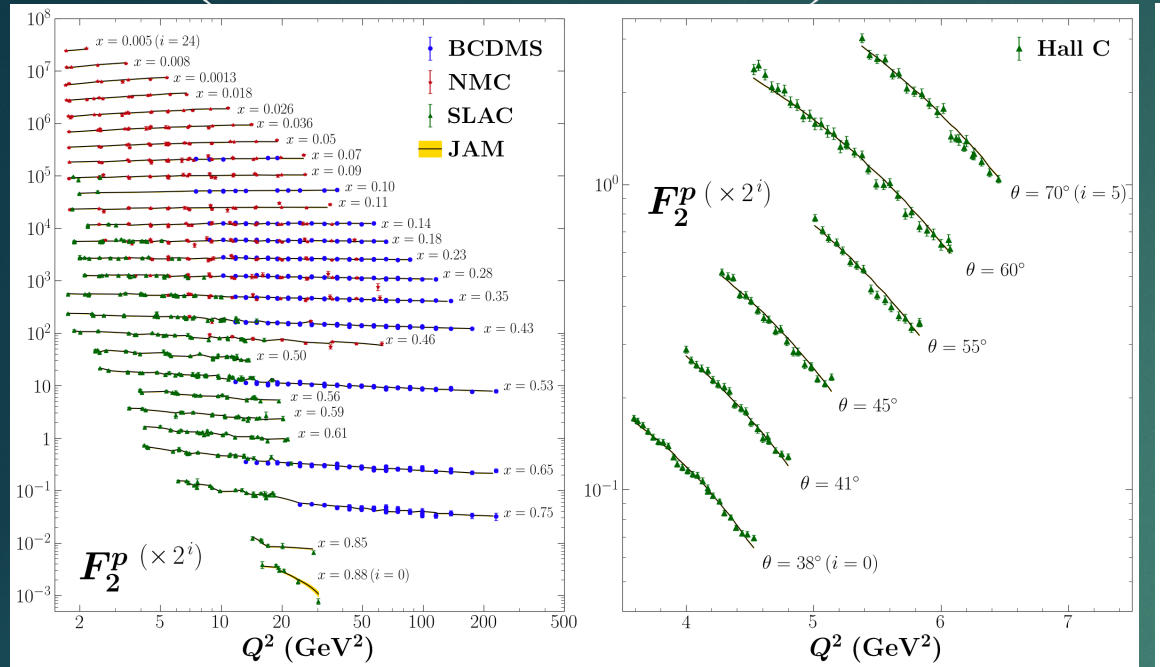
$$\tilde{\sigma} = \sigma + R\alpha$$

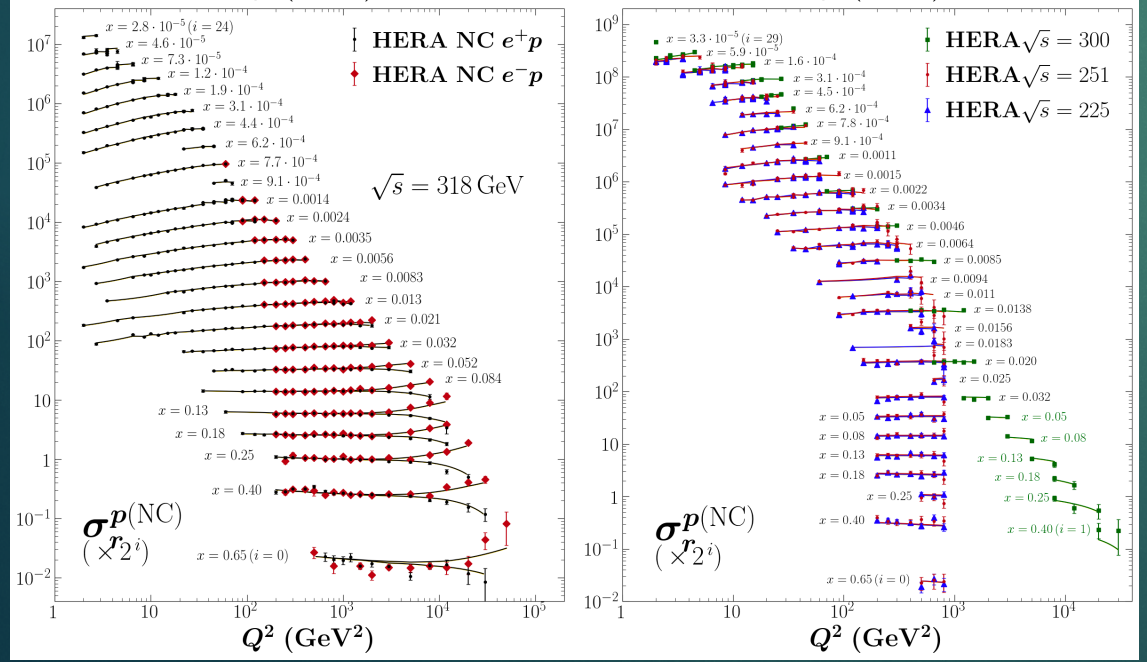
$\tilde{\sigma}$: Pseudo-Data
σ: Original Data
R: Random Gaussian number $N(0,1)$
α: Quadrature sum of uncertainties

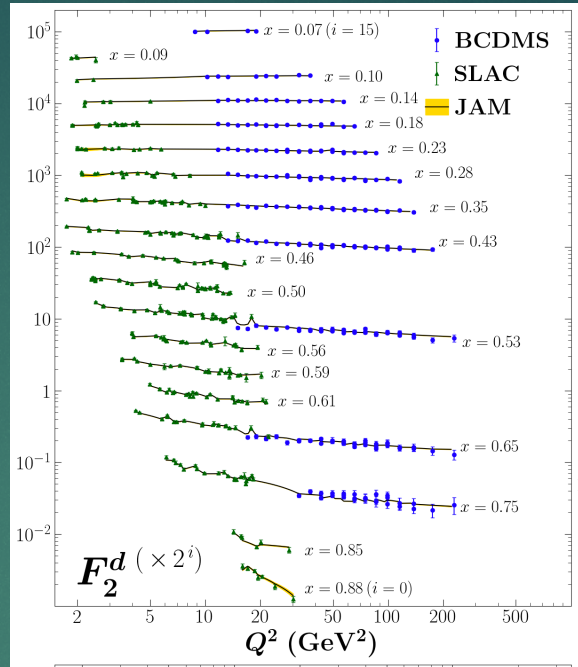
Multi-Step Strategy:

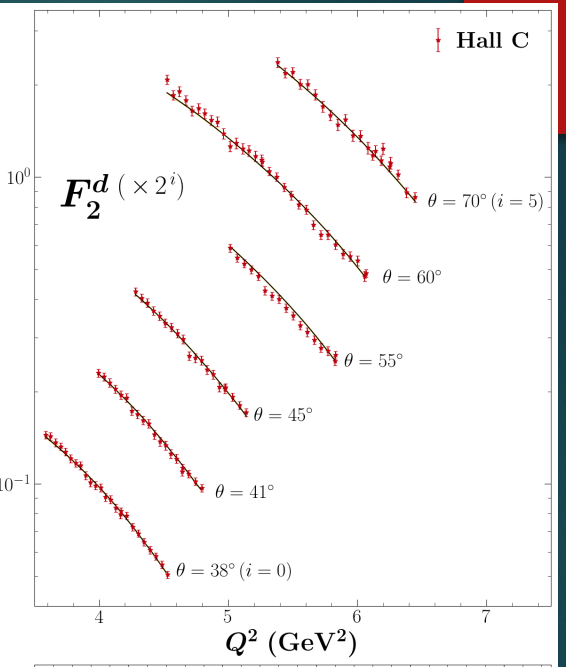


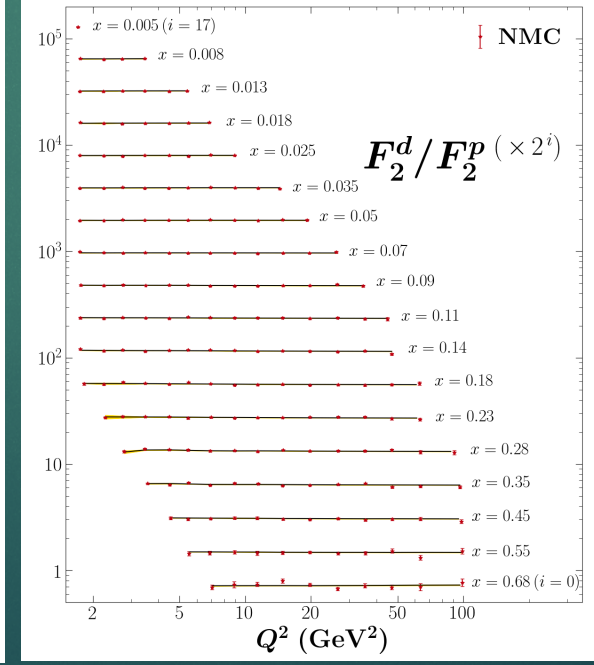
DIS (Neutral Current)

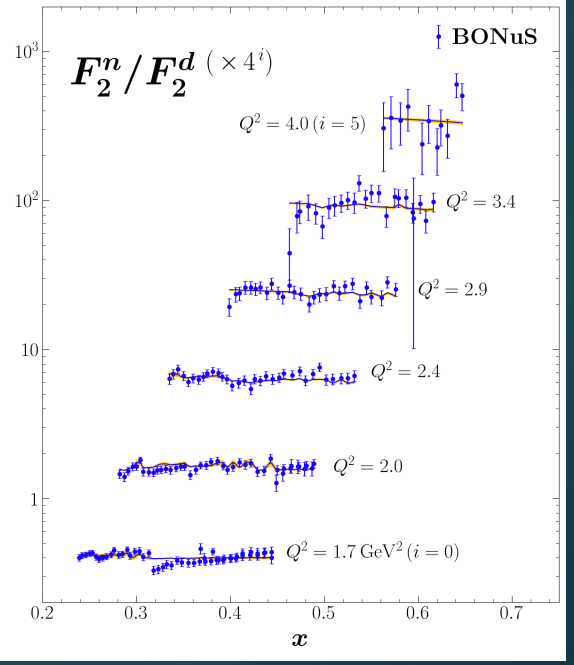




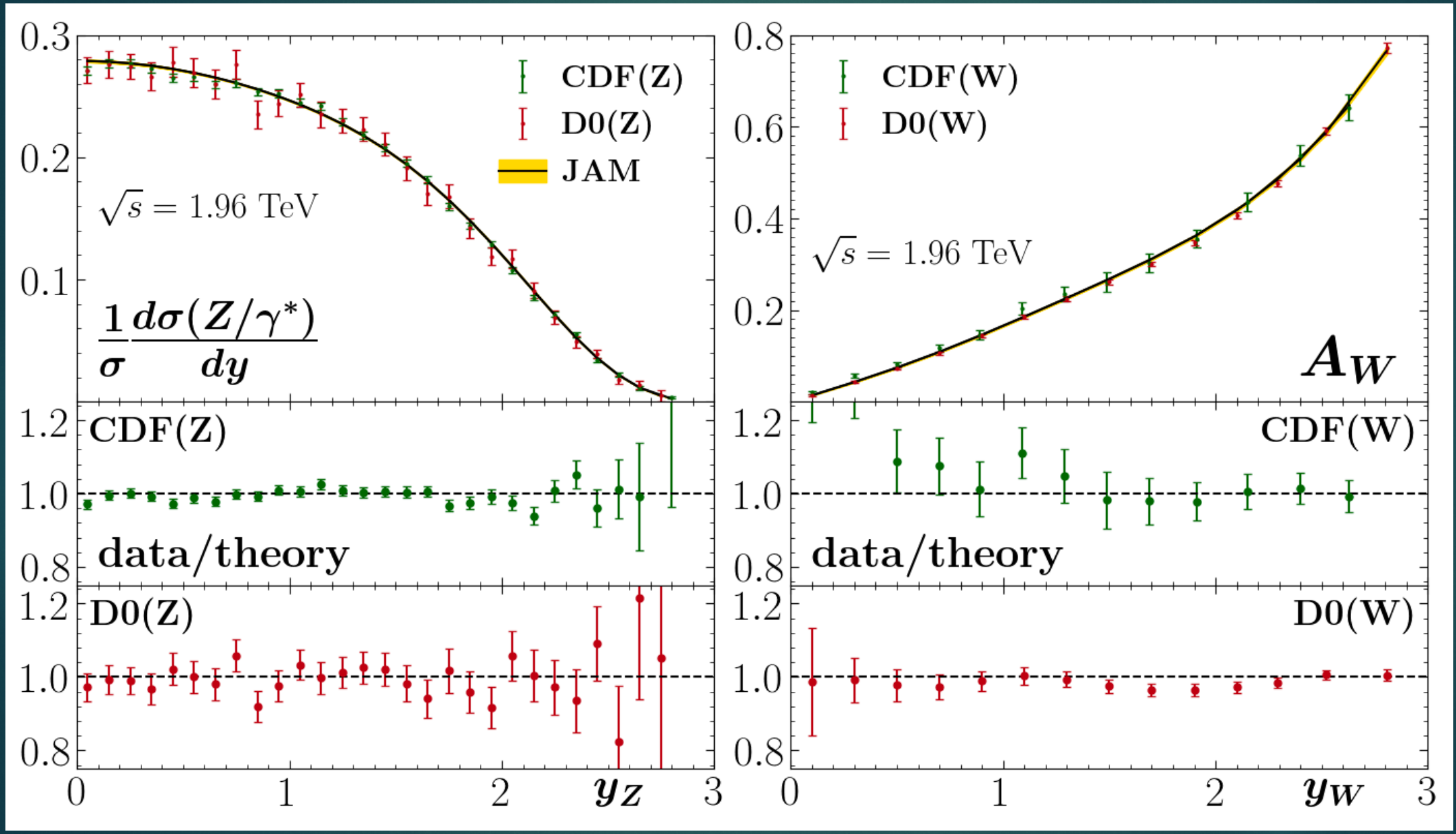




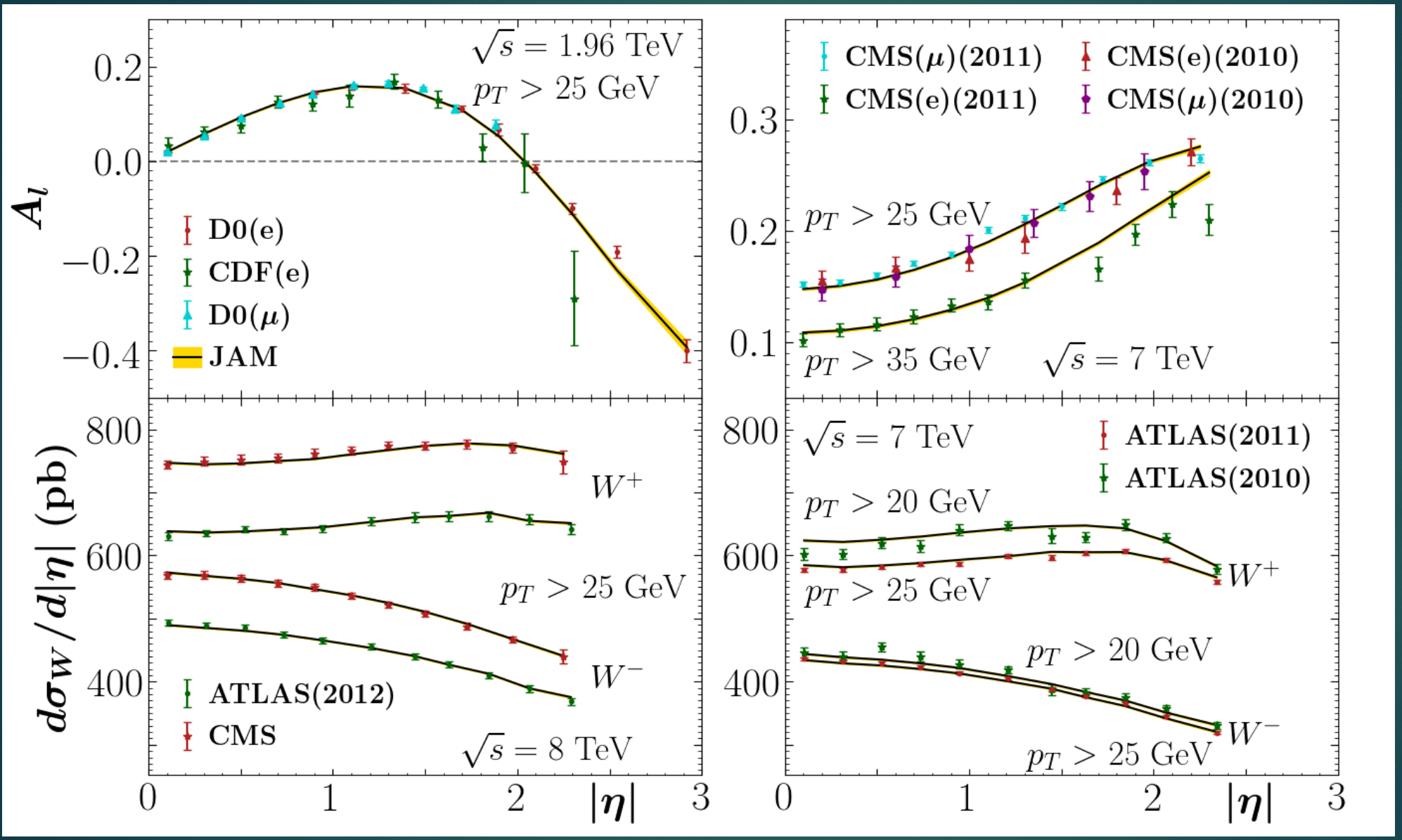




W/Z Boson Production



Lepton Production (including LHC)



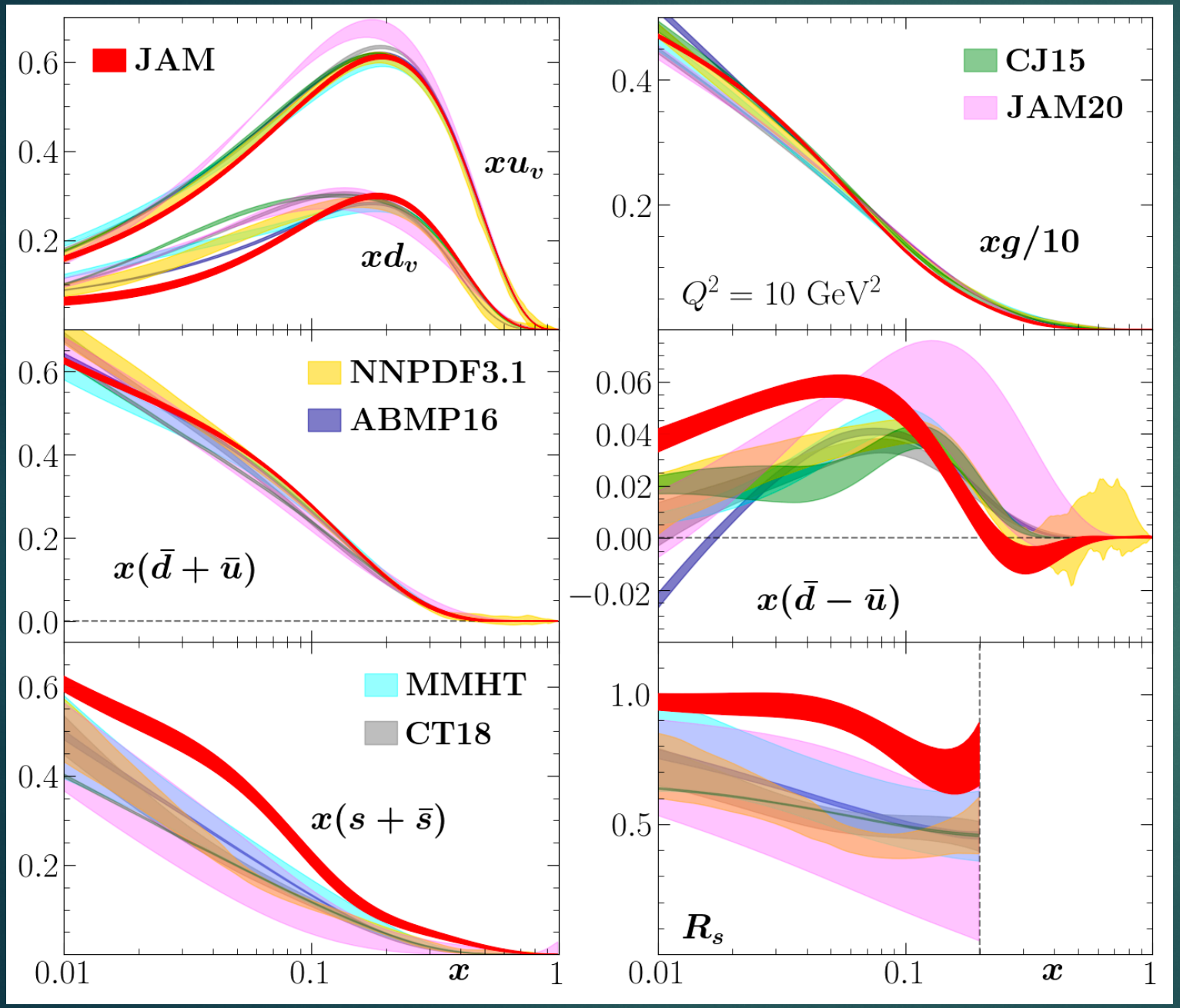
Top left: $p\bar{p}$ data from Tevatron

Everything else: pp data from LHC

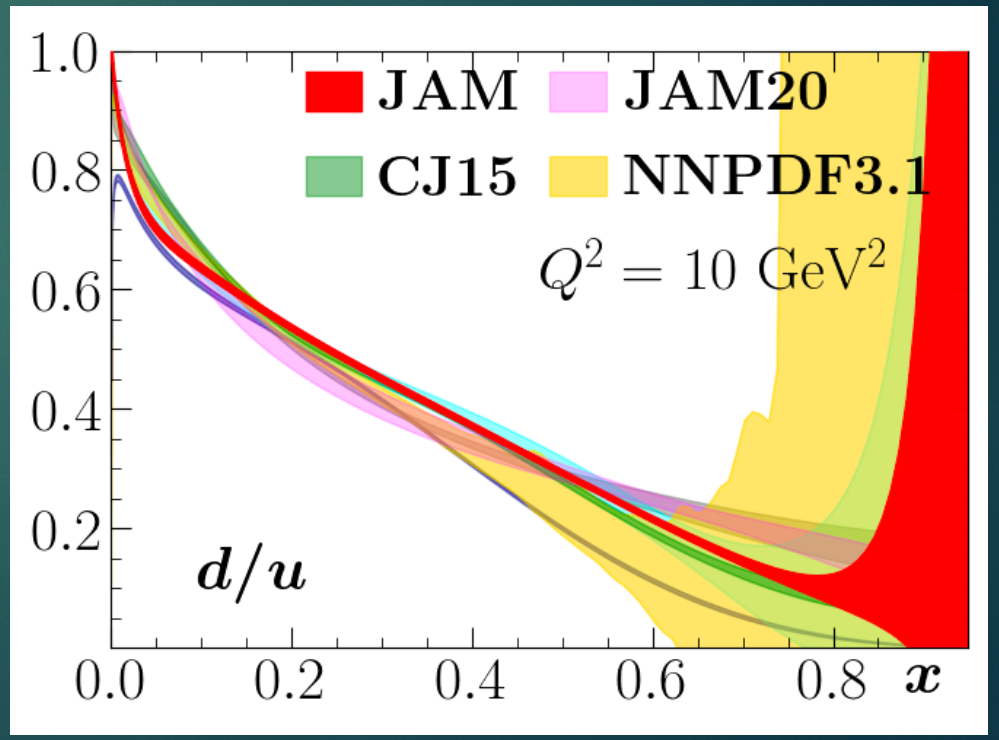
LHC:
$\chi^2/\text{dof} = 1.35$

All data:
$\chi^2/\text{dof} = 1.11$

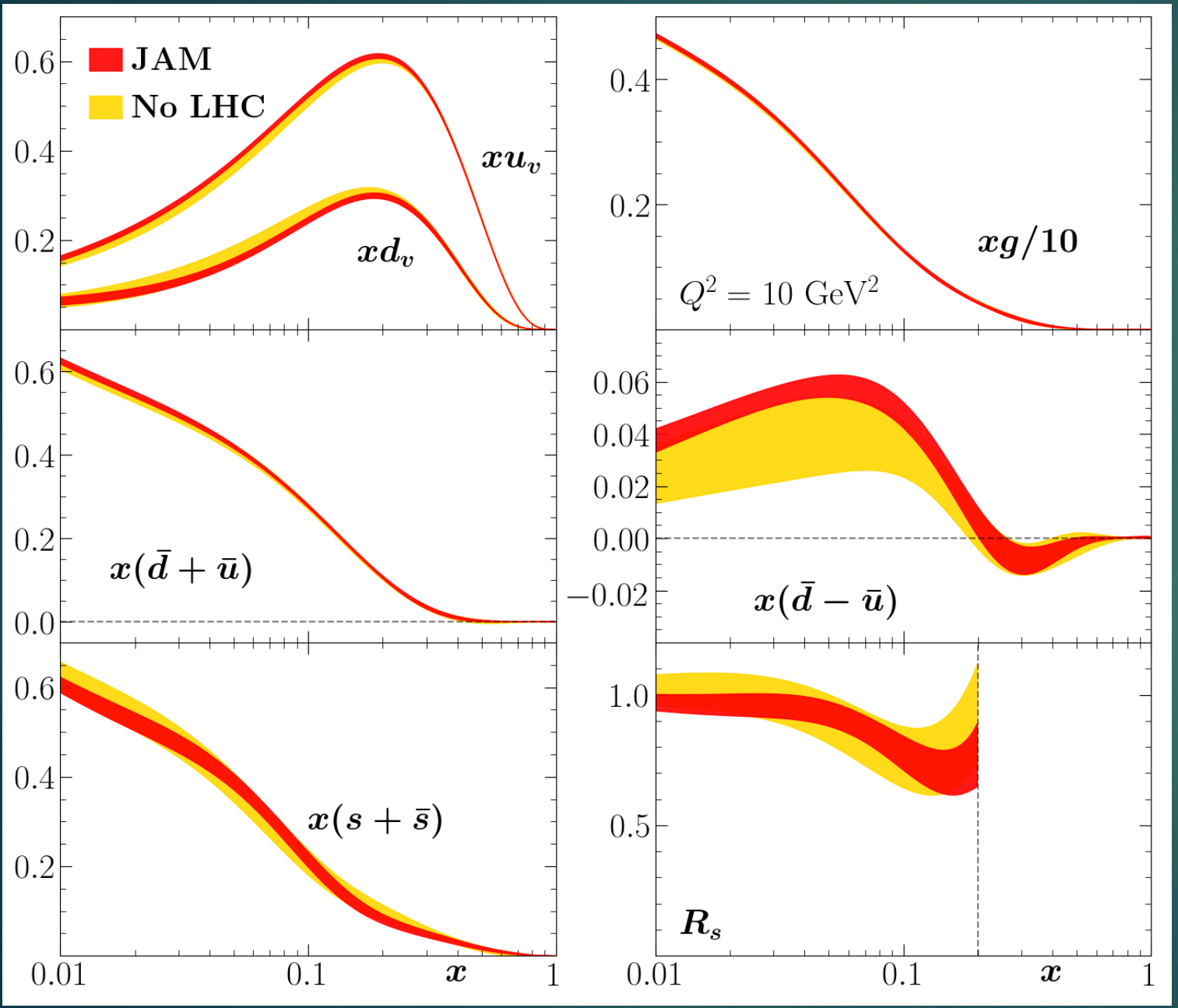
Parton Distribution Functions



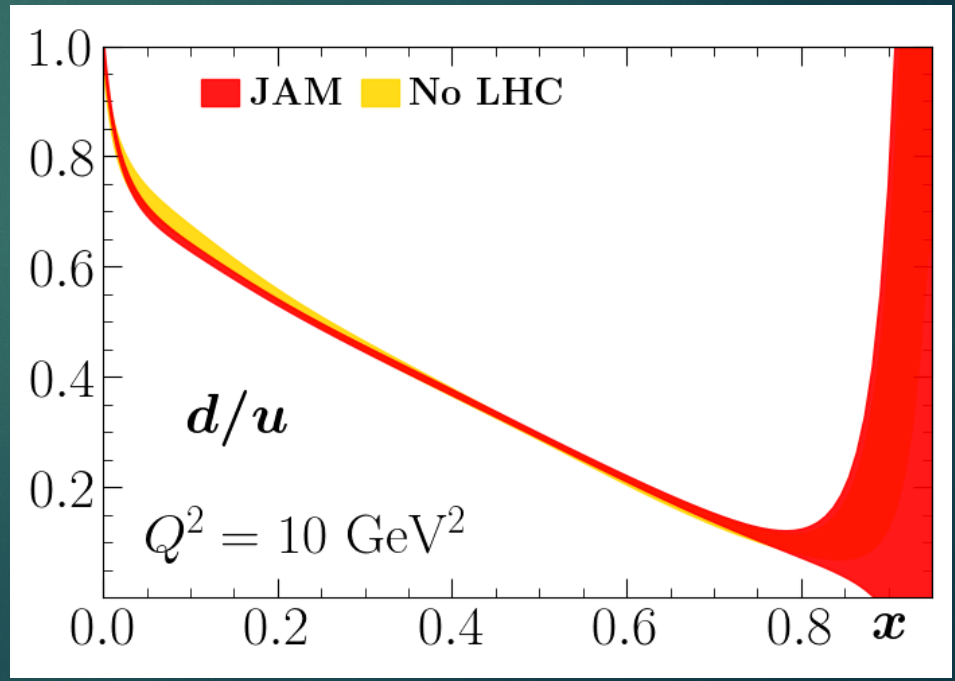
- Large $\bar{d} - \bar{u}$ at low x due to LHC data
- d/u well constrained, except at very high x
- Suppressed d_v, enhanced s^+



Impact of LHC Data



- Constrains u, d quarks at $x < 0.2$
- Constrains and enhances $\bar{d} - \bar{u}$ at $x < 0.2$
- Constrains d/u at $x < 0.3$



Nuclear Effects

Nuclear physics combined with perturbative QCD provides further insights into dynamics within nuclei (i.e. d/u ratio)

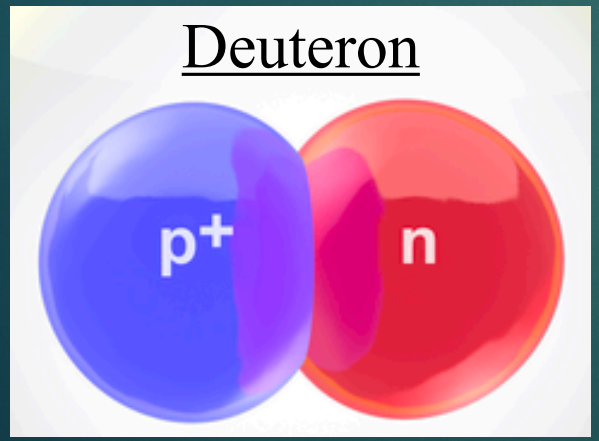
Off-shell Effects:

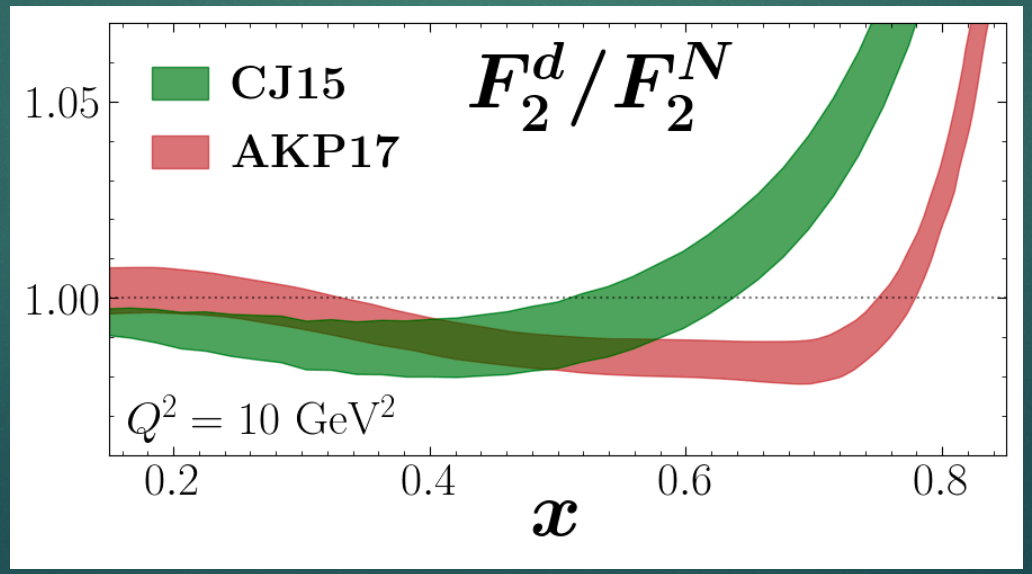
$$F_2^A(x,Q^2) = \sum_N \int \frac{d^4p}{(2\pi)^4} \mathcal{F}_0^N(\varepsilon, \boldsymbol{p}) \left(1 + \frac{\gamma p_z}{M}\right) C_{22}\, \widetilde{F}_2^N\left(\frac{x}{y}, Q^2, p^2\right)$$

$$\widetilde{F}_i^N(x,Q^2,p^2) = F_i^N(x,Q^2)\left(1 + v(p^2)\,\delta f_i^N(x,Q^2) + \mathcal{O}(v^2)\right)$$

$$v(p^2) = (p^2 - M^2)/M^2$$

Deuteron



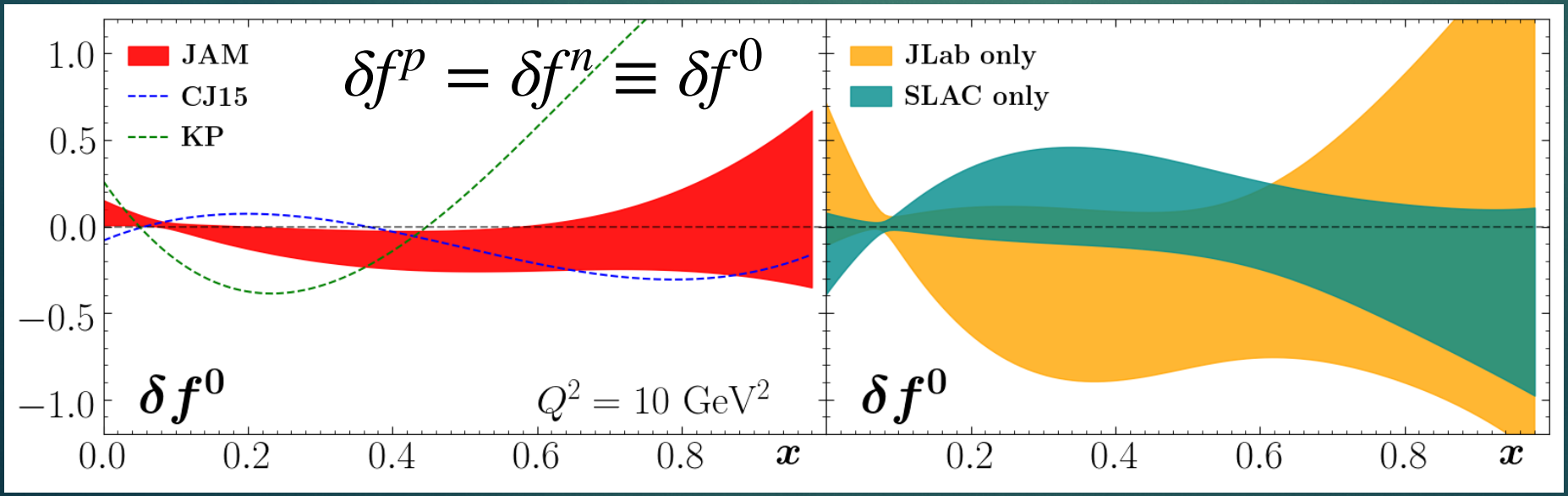


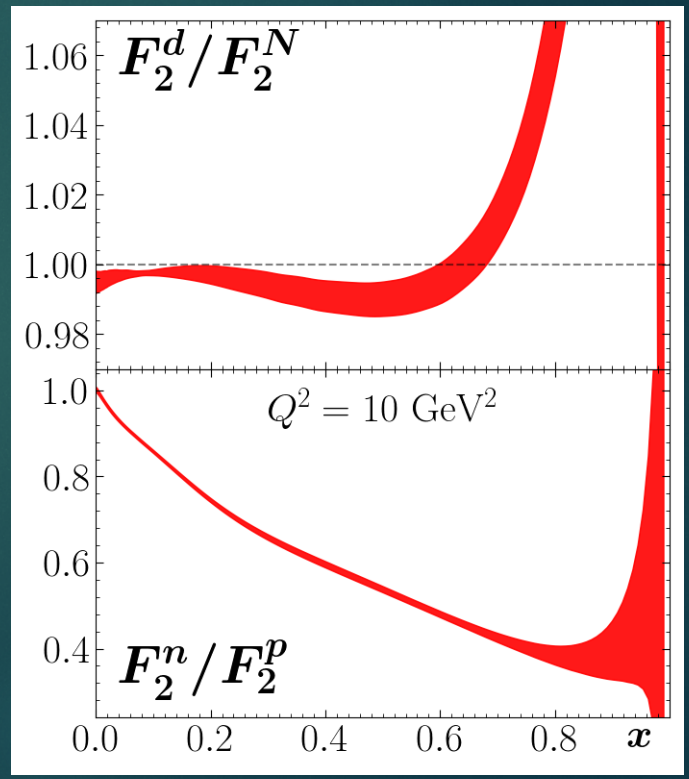
F_2^n/F_2^p ratio

d/u ratio

Off-shell Corrections

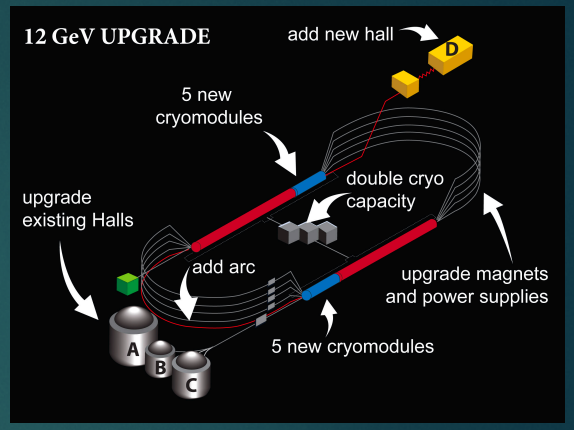
- Consistent with zero, due to tension between Jefferson Lab and SLAC data
- Different than CJ15 and KP results
- Result is consistent regardless of
  - parameterization choice
  - choice of target mass correction (GP, AOT)
  - choice of deuteron wave function (Paris, AV18, CD-Bonn, WJC-1, WJC-2)

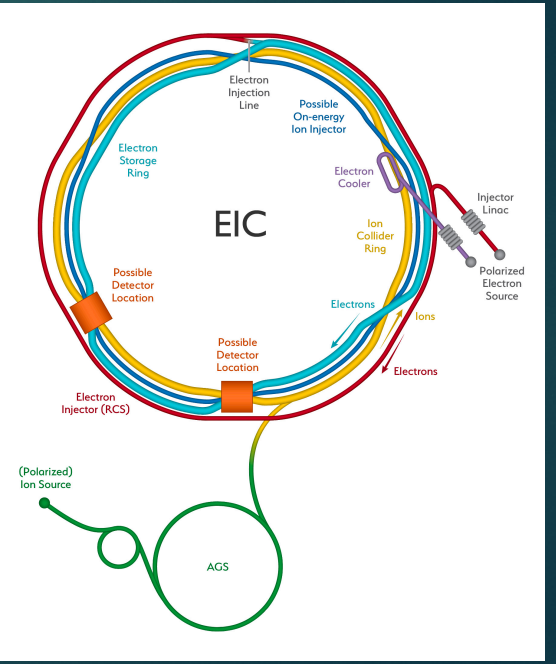




Conclusions and Outlook

- New LHC data provides new constraints at $x < 0.2$ on the valence quarks, sea asymmetry, and d/u ratio.
- Sea asymmetry at low x is found to be larger than previous extractions.
- d_v at low x is found to be smaller, while s^+ is found to be larger.
- Off-shell corrections are found to be consistent with zero due to tension in datasets. Result is consistent regardless of parameterization or model choice.
- New data from Jefferson Lab needed for off-shell corrections (Marathon with tritium and helium targets, BONuS with "neutron" target, and more JLab 12 GeV experiments)
- EIC will provide further constraints on PDFs. Parity-violating DIS could provide information on strange distribution.

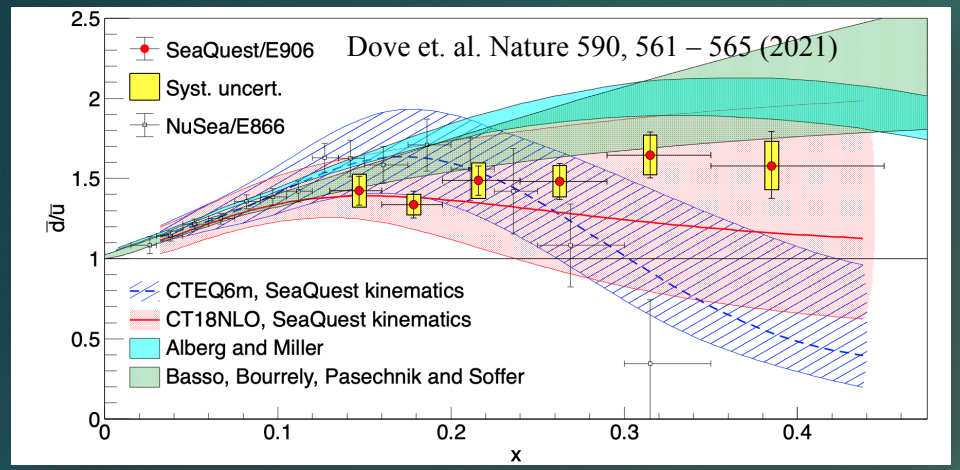




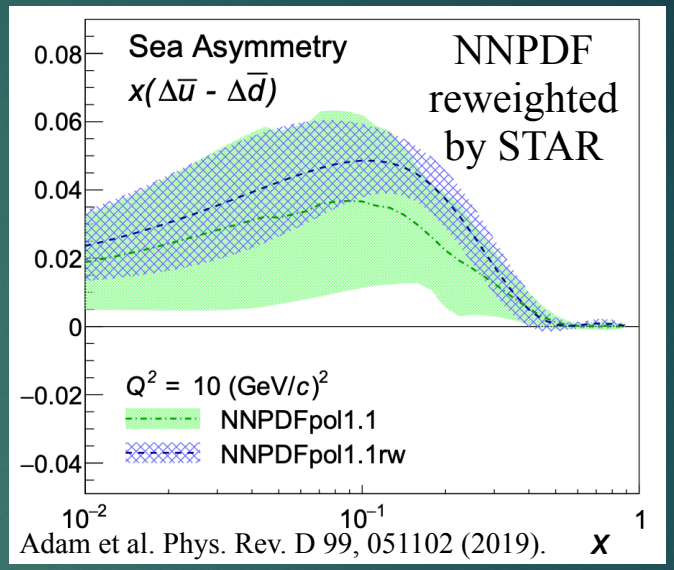
Helicity PDF Analysis

Helicity PDF Analysis

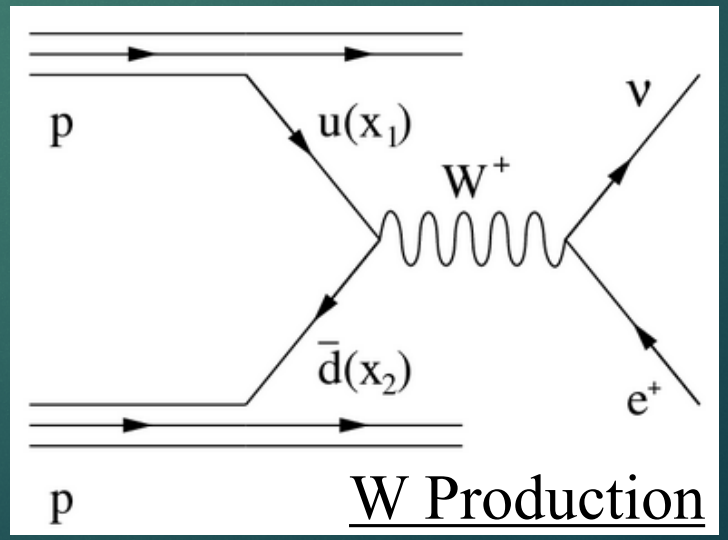
Lots of research into unpolarized sea asymmetry $\bar{d} - \bar{u}$



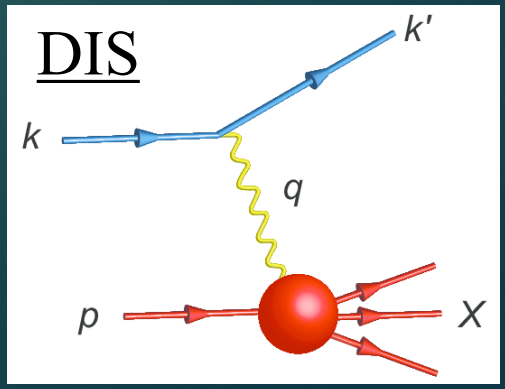
Less is known on polarized sea asymmetry $\Delta\bar{u} - \Delta\bar{d}$



First global QCD analysis of polarized W production data from STAR, with simultaneous extraction of spin-averaged and helicity PDFs

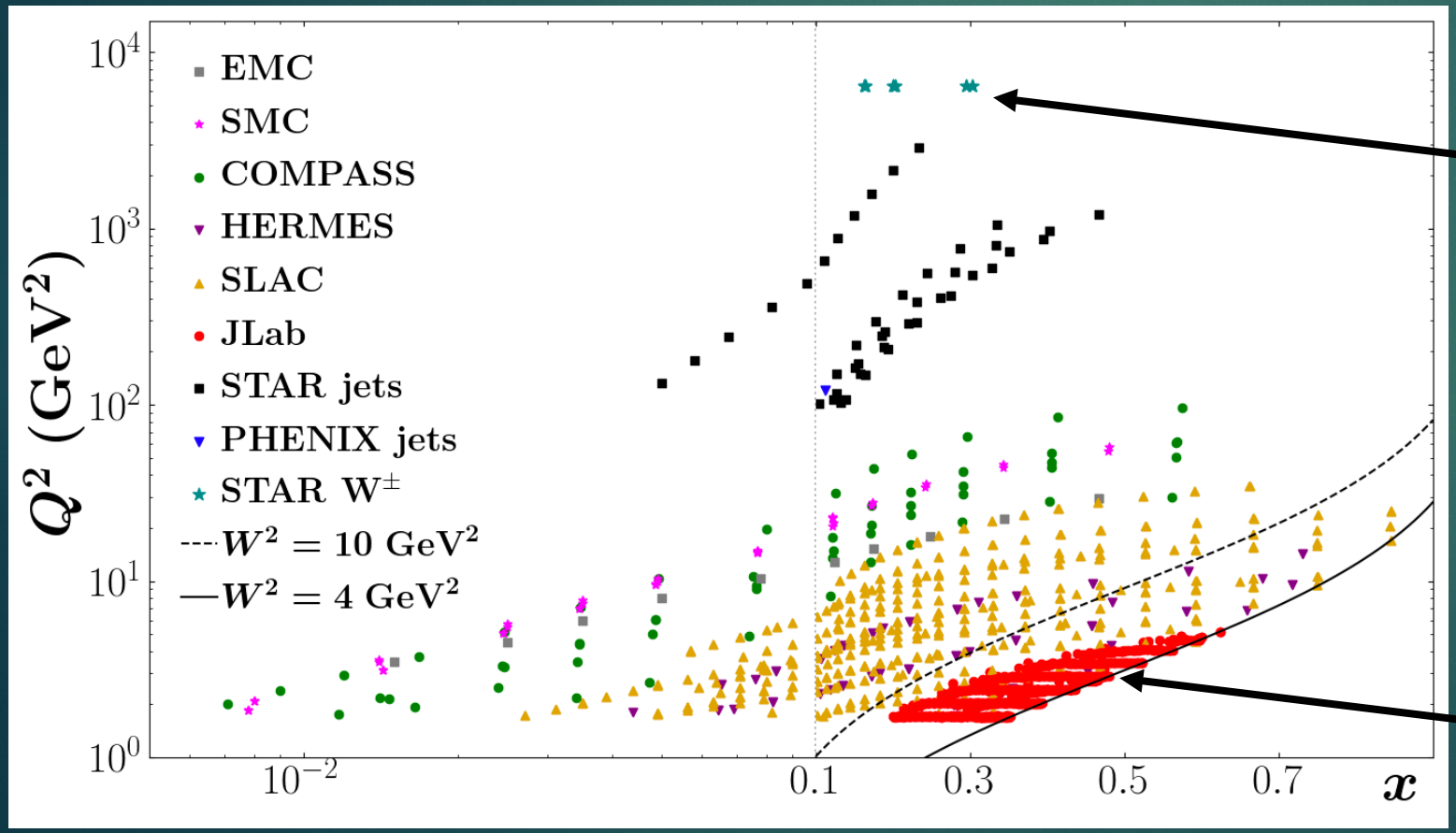


+ Jets



Data

- **Deep Inelastic Scattering**: EMC, SMC, COMPASS, HERMES, SLAC, Jefferson Lab (1,675 points)
- **Jets**: RHIC STAR/PHENIX (45 points)
- **W Production**: RHIC STAR (12 points)

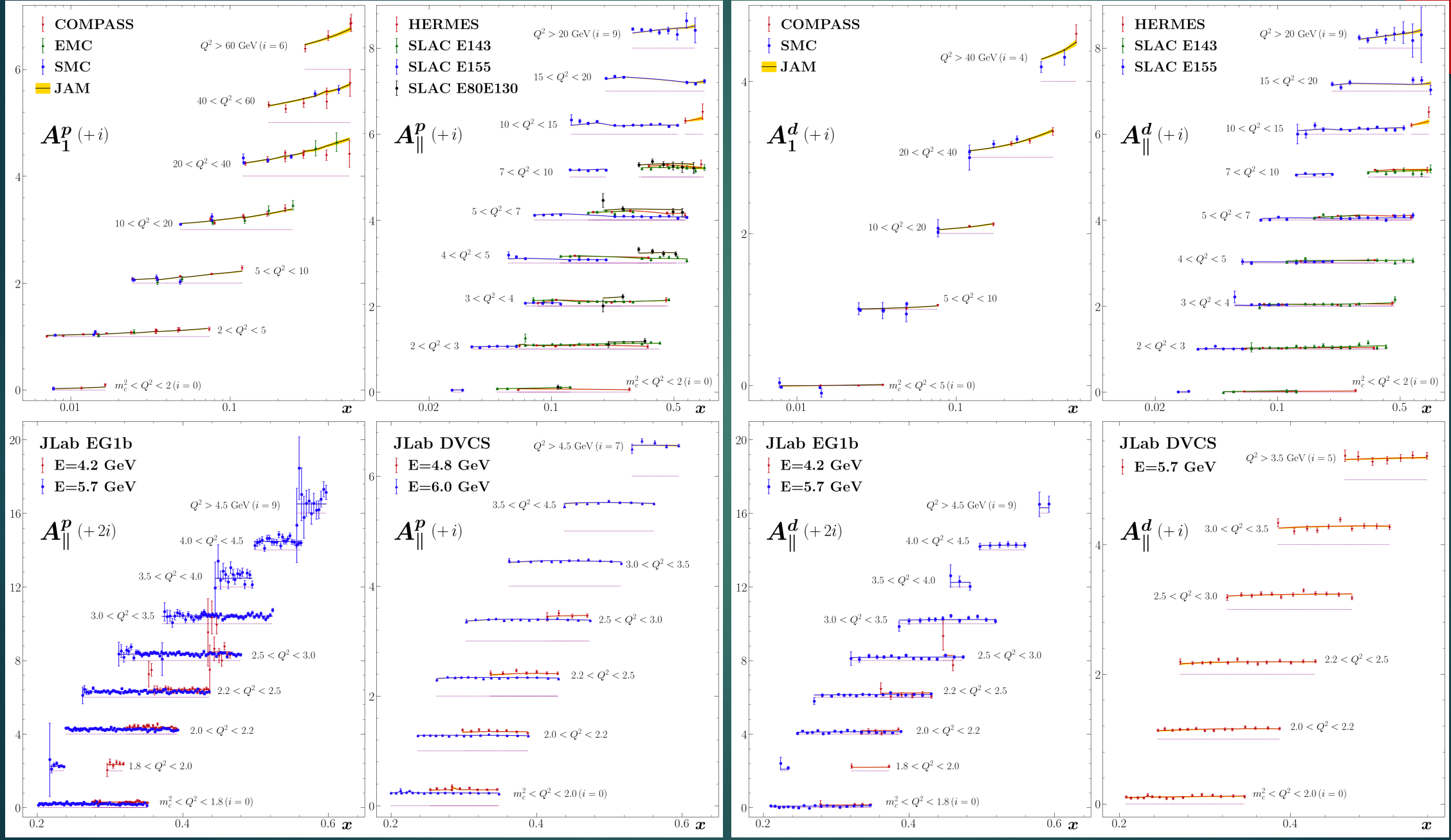


New STAR Data

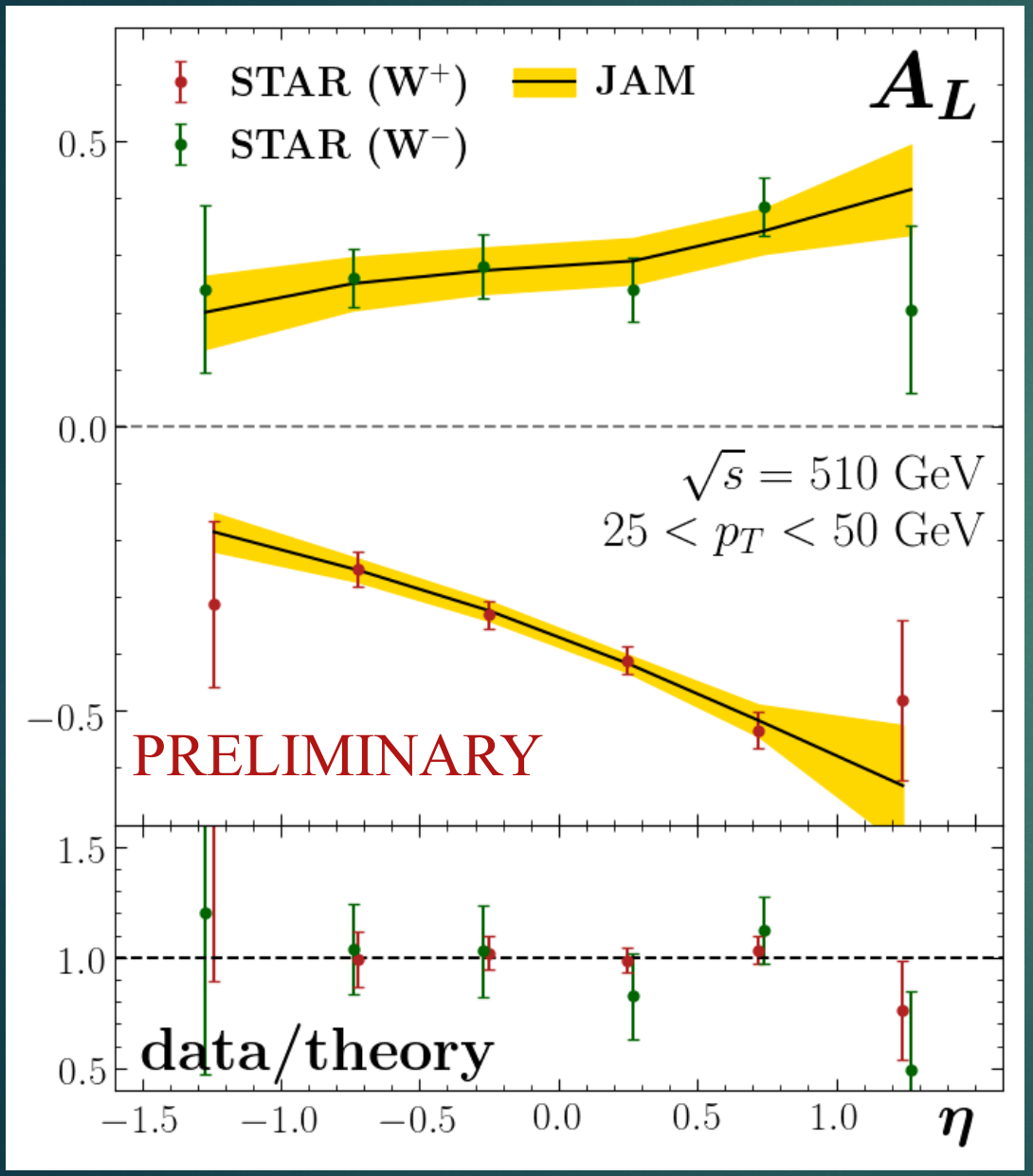
Low W^2 cut allows inclusion of high-x Jefferson Lab data

High-x Data (Proton/Deuteron/Helium)

Polarized DIS



Single-Spin Asymmetry from STAR



$$A_L^{W^+}(y_W) \propto \frac{\Delta\bar{d}(x_1)u(x_2) - \Delta u(x_1)\bar{d}(x_2)}{\bar{d}(x_1)u(x_2) + u(x_1)\bar{d}(x_2)}$$

$$A_L^{W^-}(y_W) \propto \frac{\Delta\bar{u}(x_1)d(x_2) - \Delta d(x_1)\bar{u}(x_2)}{\bar{u}(x_1)d(x_2) + d(x_1)\bar{u}(x_2)}$$

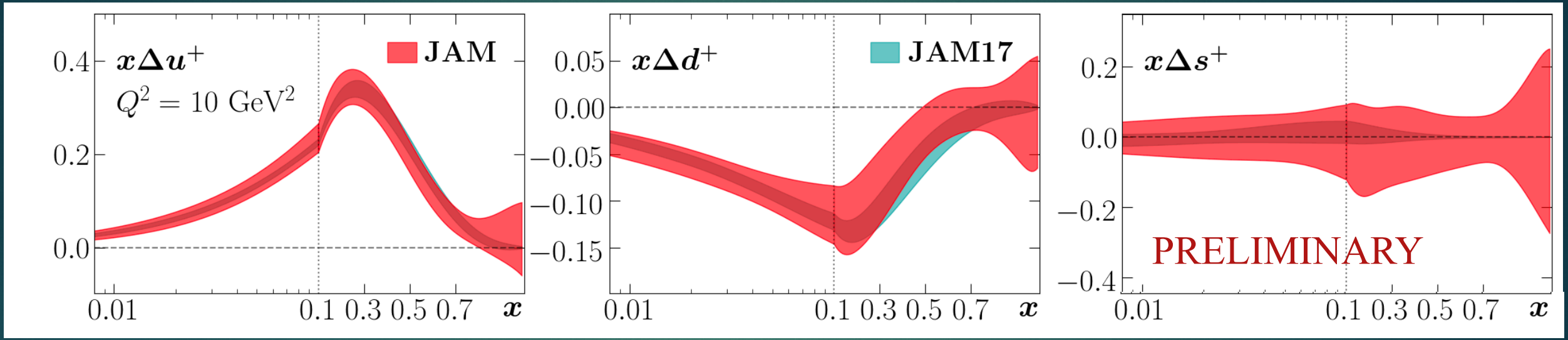
Simultaneous analysis of spin-averaged and helicity PDFs important for this observable!

Data is impossible to fit with $\Delta\bar{u} = \Delta\bar{d}$
Breaking this assumption, we find:

STAR: χ^2/# points = 0.50

Overall: χ^2/# points = 1.11

Helicity PDFs

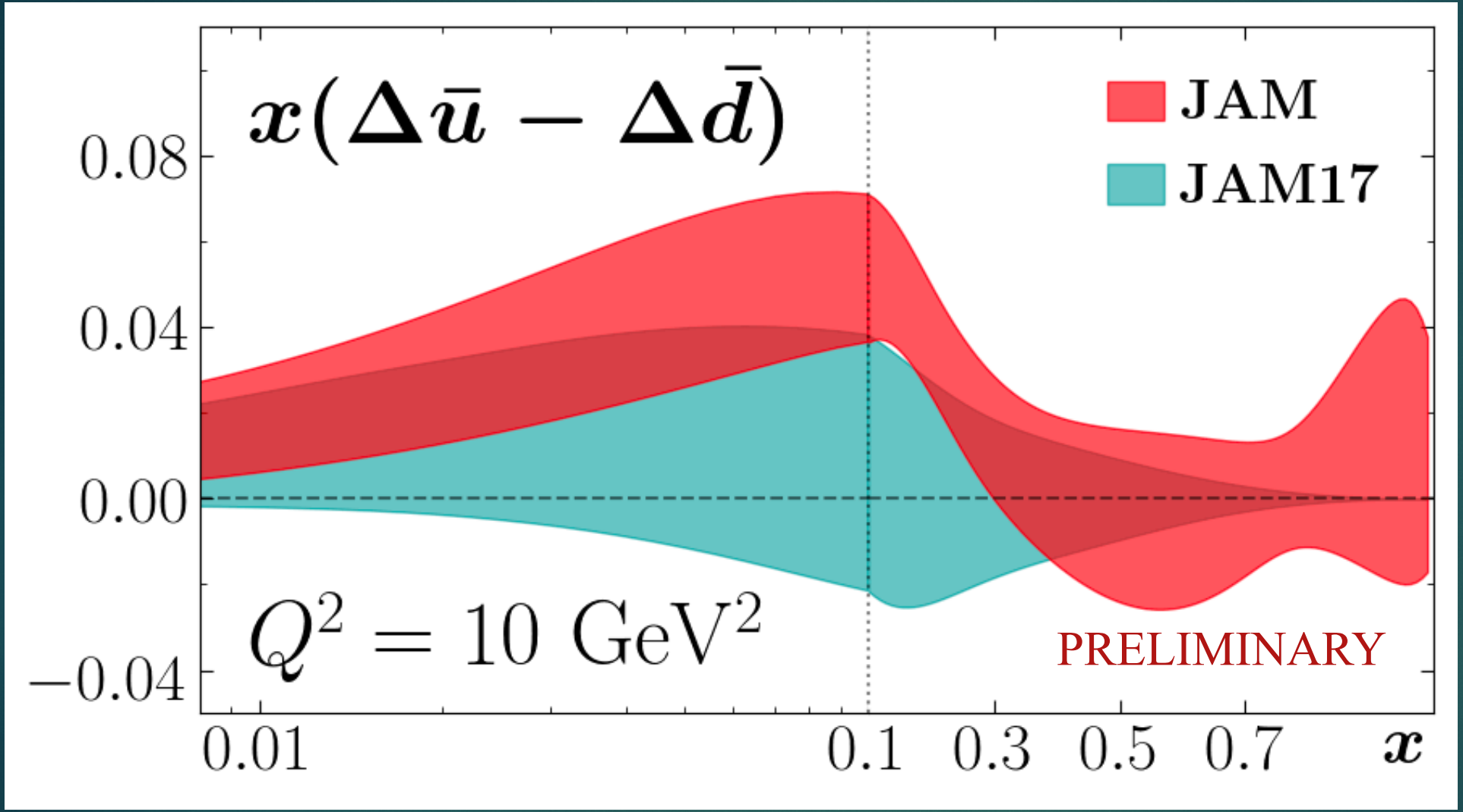


JAM17: Simultaneous analysis of helicity PDFs, pion FFs, and kaon FFs using SIDIS

Values for $g_A = 1.24(4)$ and $a_8 = 0.46(21)$ taken from JAM17 and used to impose SU(2) and SU(3) in this analysis

No positivity constraints in this analysis.

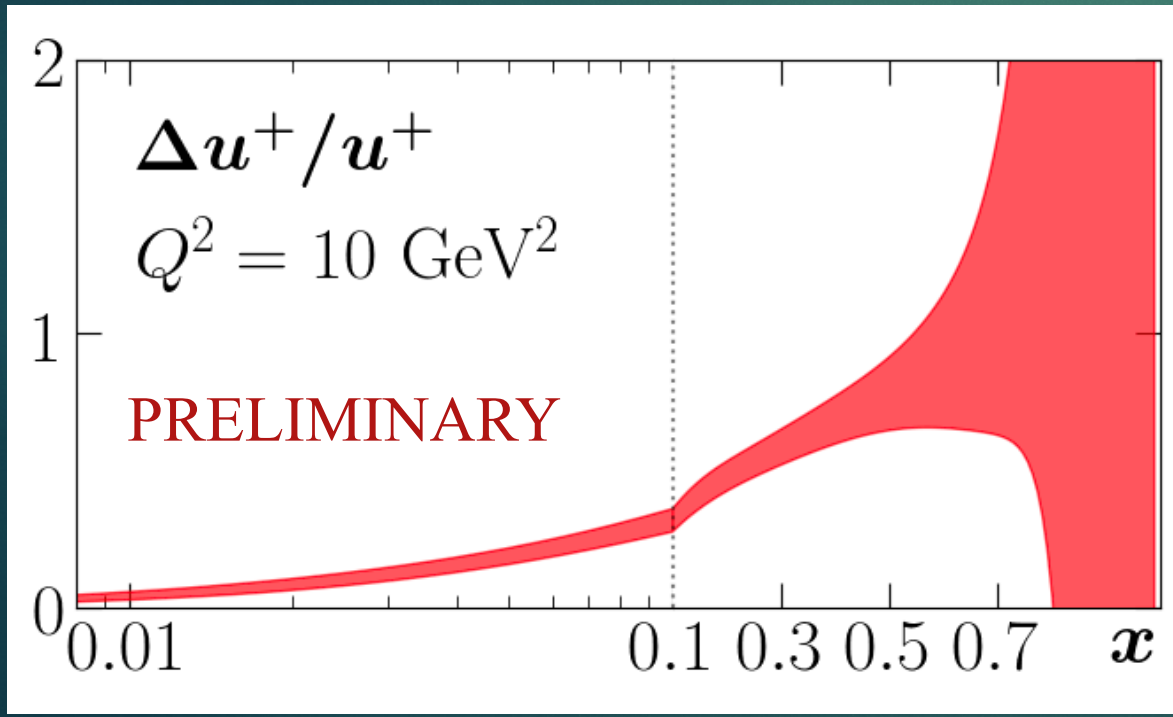
Sea Asymmetry

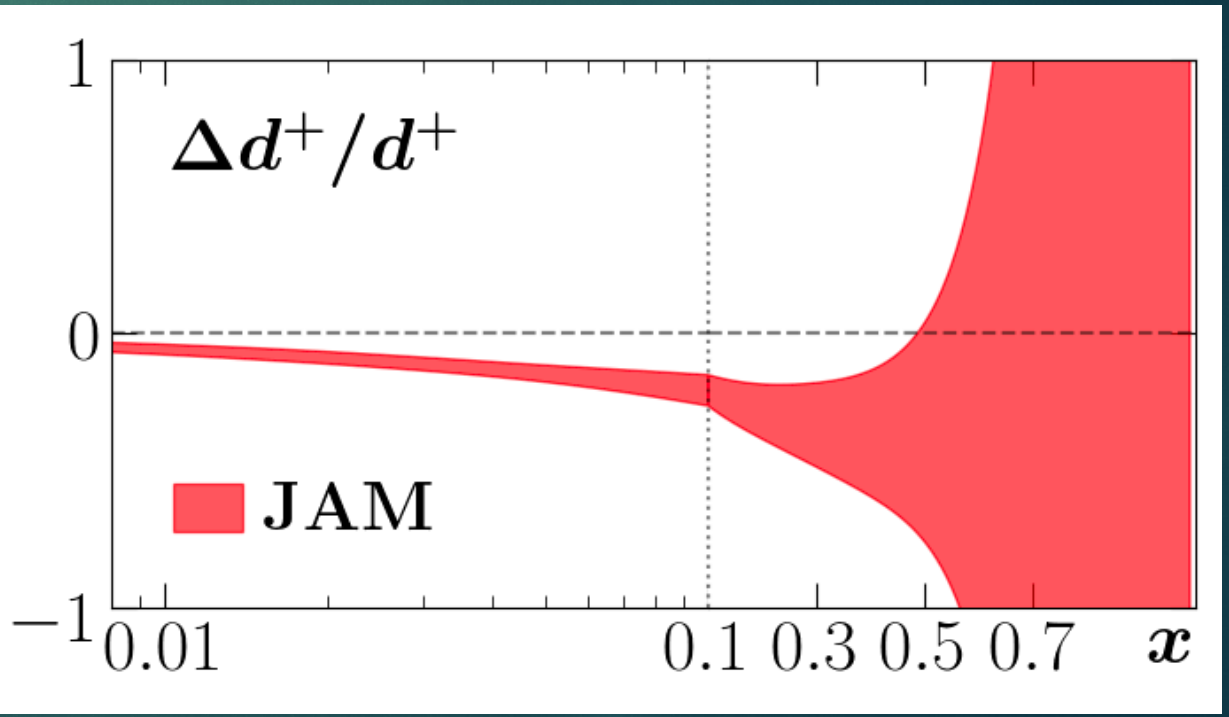


Asymmetry is positive below $x = 0.3$! Opposite of unpolarized PDFs.

Quark Polarizations

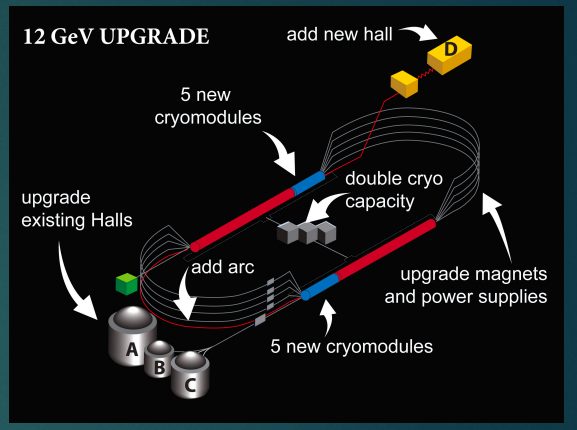
Simultaneous extraction of spin-averaged and helicity PDFs allows for completely consistent extraction of quark polarizations!

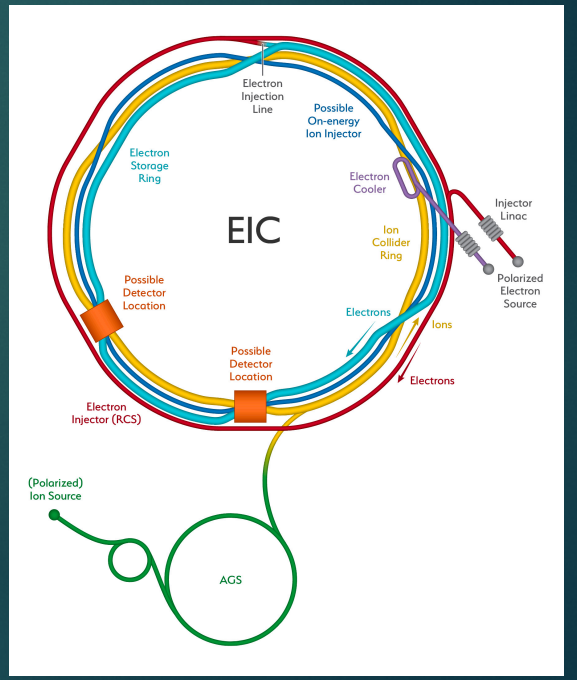




Conclusions and Outlook

- First global QCD analysis of polarized W and polarized jet from RHIC within simultaneous analysis of spin-averaged and helicity PDFs.
- First confirmation of positive sea asymmetry from global QCD analysis
- Future analysis: Simultaneous extraction with pion and kaon fragmentation functions (improve upon JAM17)
- JLab 12 GeV program and EIC extremely important for giving constraints on helicity PDFs, with the EIC being the first polarized electron-hadron collider.





Collaboration

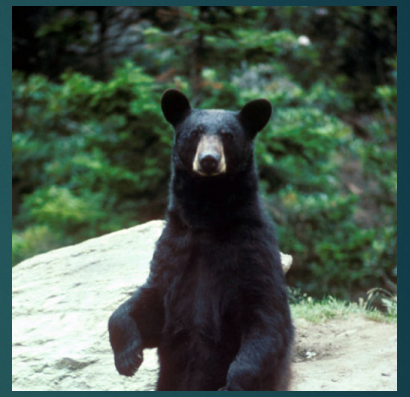
This project was done in collaboration with:

Andreas Metz

Wally Melnitchouk

Nobuo Sato

Jacob Ethier



Jefferson Lab Angular Momentum Collaboration

Thank you to Yiyu Zhou and Patrick Barry for helpful discussions.

Extra: Higher Twist