# Simultaneous Extraction of Spin-Averaged and Helicity Light Quark Sea Asymmetries

Christopher Cocuzza (Temple University)

Jake Ethier (Nikhef)
Wally Melnitchouk (Jefferson Lab)
Andreas Metz (Temple University)
Nobuo Sato (Jefferson Lab)

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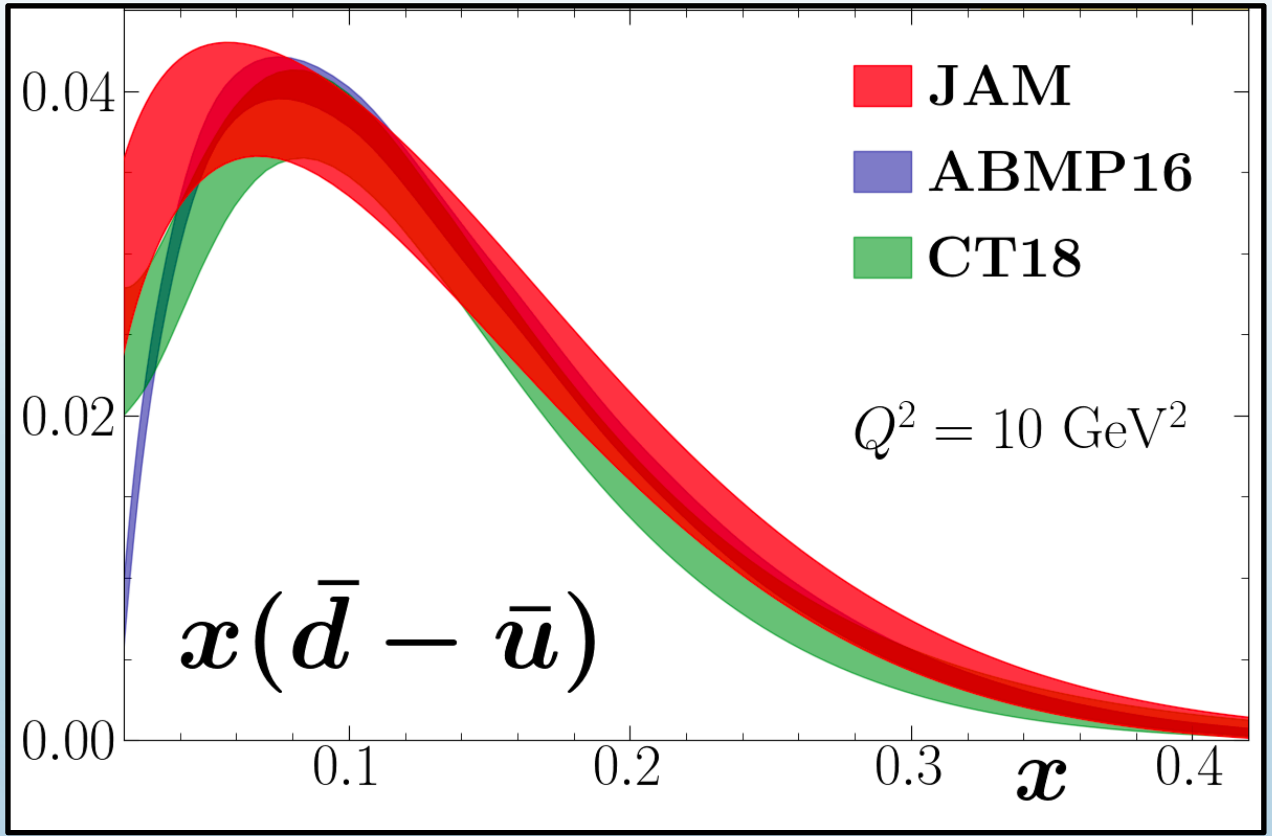
Jefferson Lab Angular Momentum Collaboration

HADRON 2021

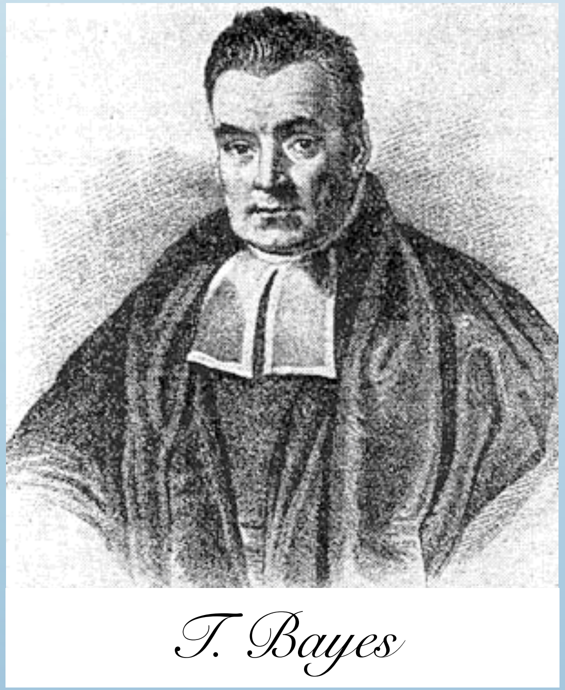
# Introduction

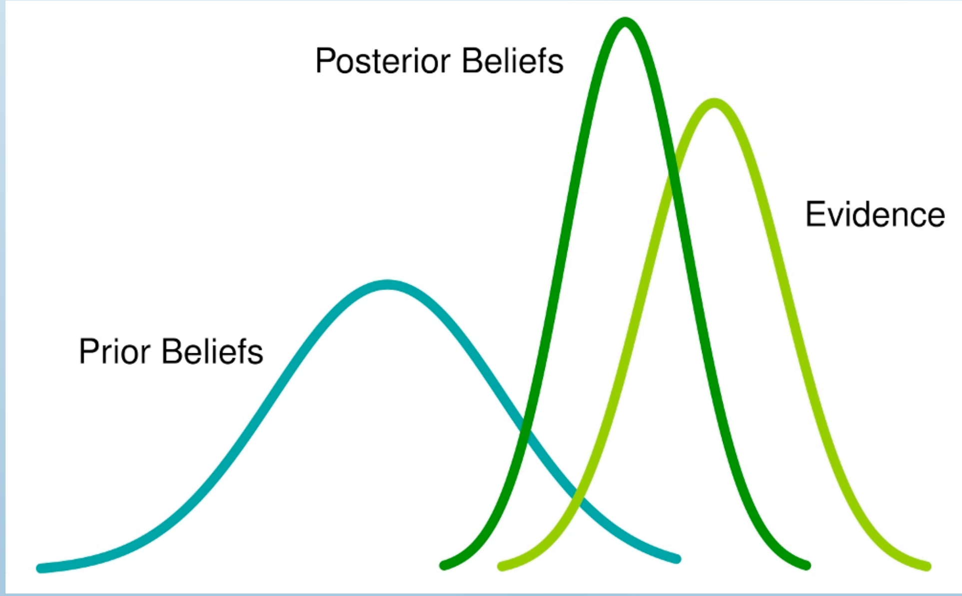



Cannot be explained from gluons splitting into quark-antiquark pairs

Meson Cloud Models
Chiral Soliton Models
Statistical Models

# Part 1:
# JAM Methodology



# JAM Collaboration

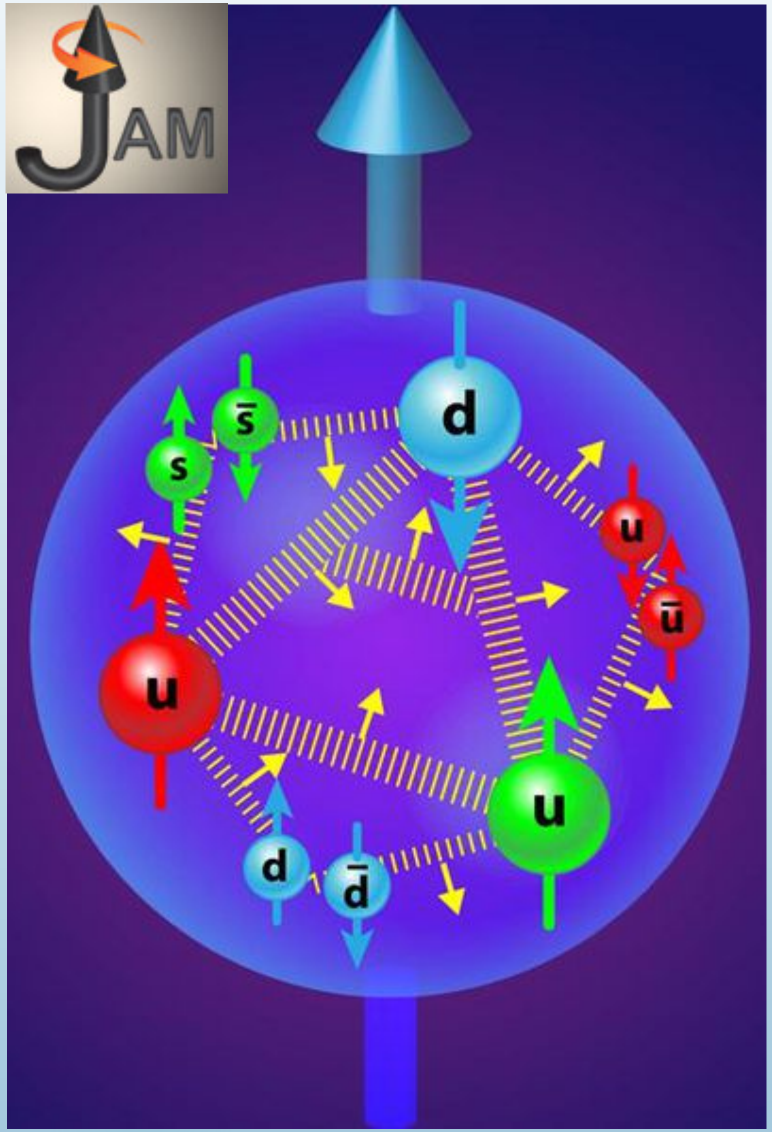
3-dimensional structure of nucleons:

- Parton distribution functions (PDFs)
- Fragmentation functions (FFs)
- Transverse momentum dependent (TMD) distributions + more!

Collinear factorization in perturbative QCD

Simultaneous determinations of PDFs, FFs, etc.

Monte Carlo methods for Bayesian inference



# Parameters to Observables

Parameterize PDFs at input scale $Q_0^2 = m_c^2$

$$f_i(x) = Nx^{\alpha}(1-x)^{\beta}(1+\gamma\sqrt{x}+\eta x)$$

Evolve PDFs using DGLAP

$$\frac{\mathrm{d}}{\mathrm{d}\ \ln(\mu^2)} f_i(x,\mu) = \sum_j \int_x^1 \frac{dz}{z} P_{ij}(z,\mu) f_j(\frac{x}{z},\mu)$$

Calculate Observables

$$d\sigma_{\mathrm{DY}} = \sum_{i,j} H_{ij}^{\mathrm{DY}} \otimes f_i \otimes f_j$$

# The $\chi^2$ function

Now that the observables have been calculated…

Data

Theory

Normalization

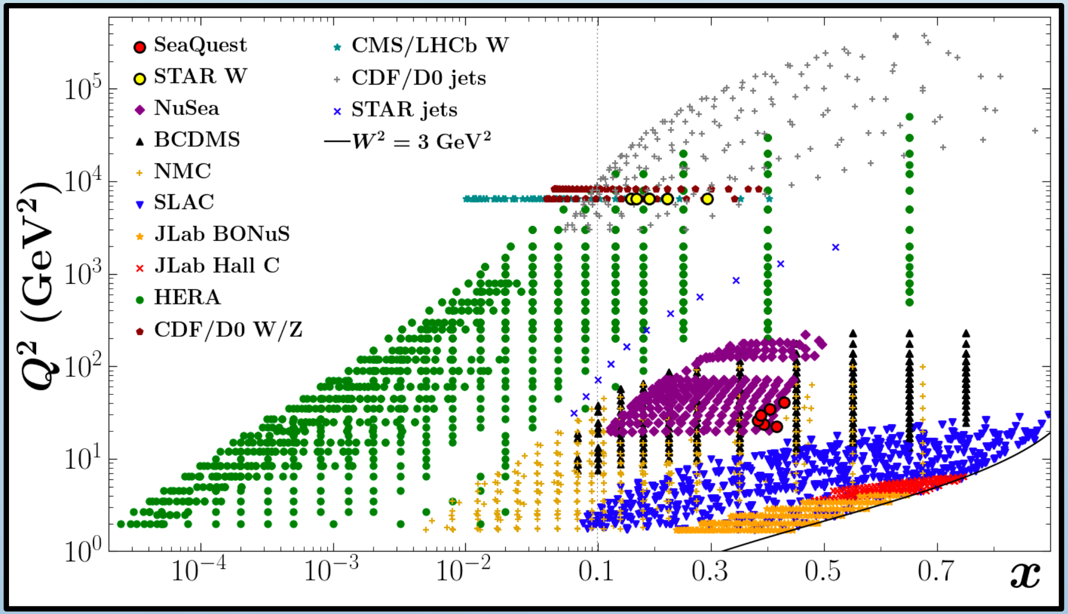
$$\chi^2(\boldsymbol{a}) = \sum_{i,e}\left(\frac{d_{i,e} - \sum_k r_e^k \beta_{i,e}^k - T_{i,e}(\boldsymbol{a})/N_e}{\alpha_{i,e}}\right)^2 + \sum_k \left(r_e^k\right)^2 + \left(\frac{1-N_e}{\delta N_e}\right)^2$$

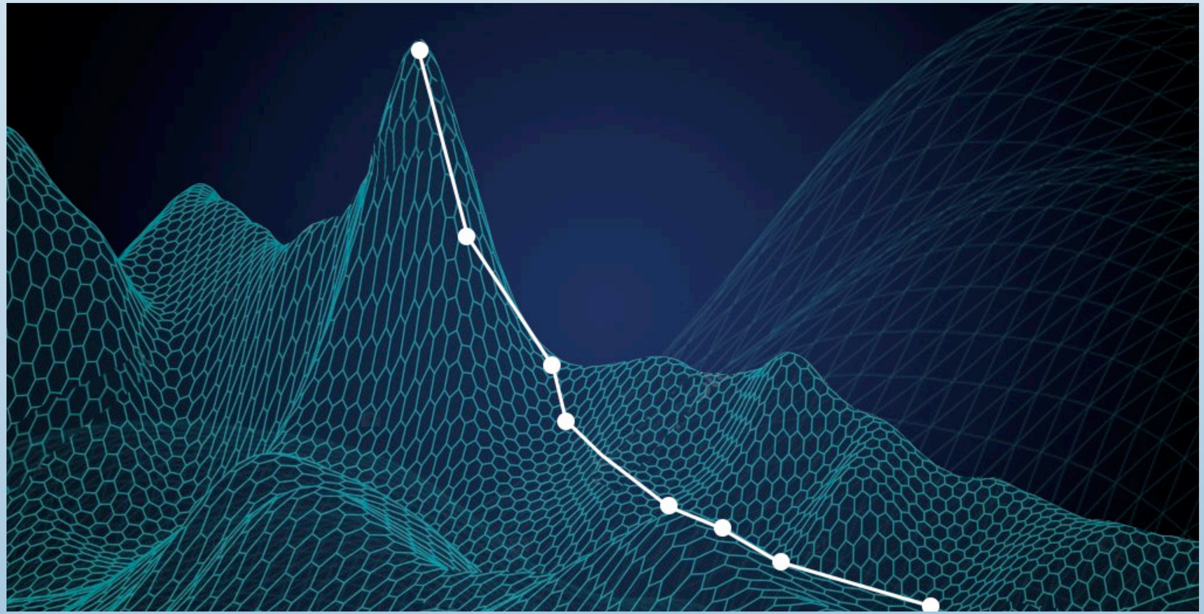
Uncorrelated Uncertainties

Correlated Uncertainties

Normalization Uncertainty

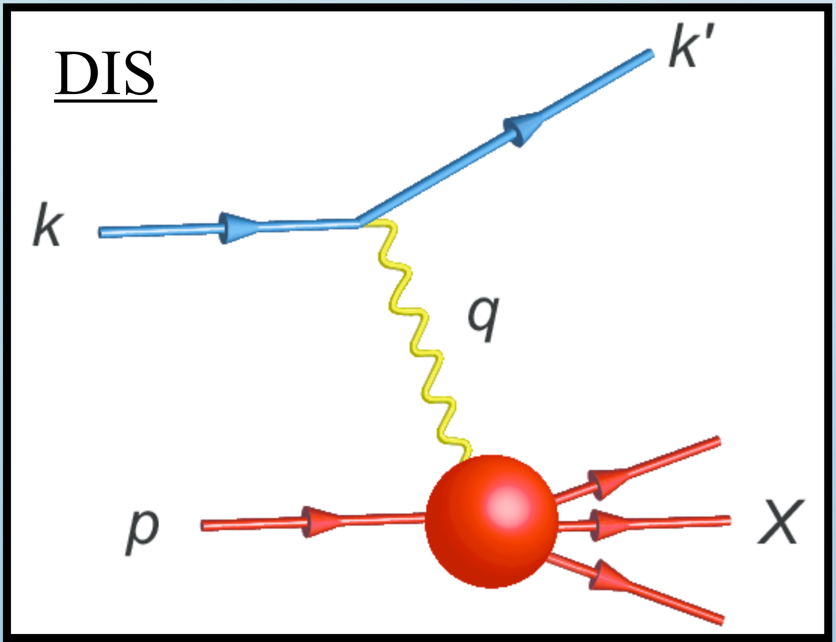
# Part 2: Data and Fitting

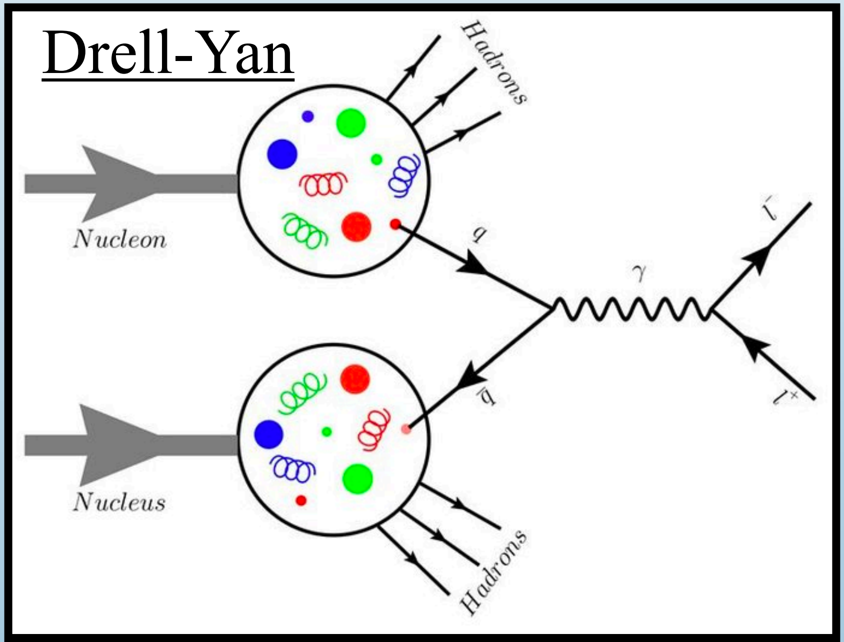


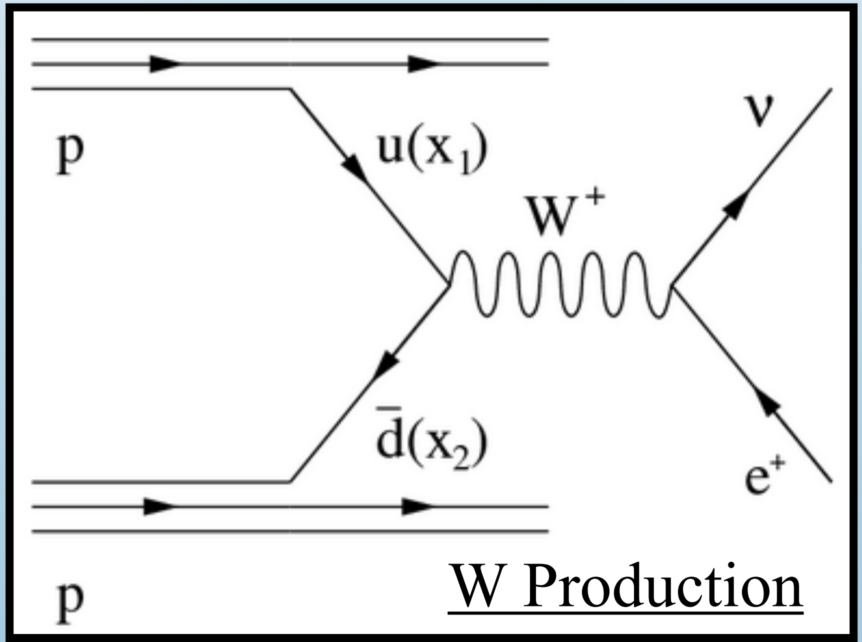



# A Global Analysis

*Simultaneous* extraction of
spin-averaged and helicity PDFs

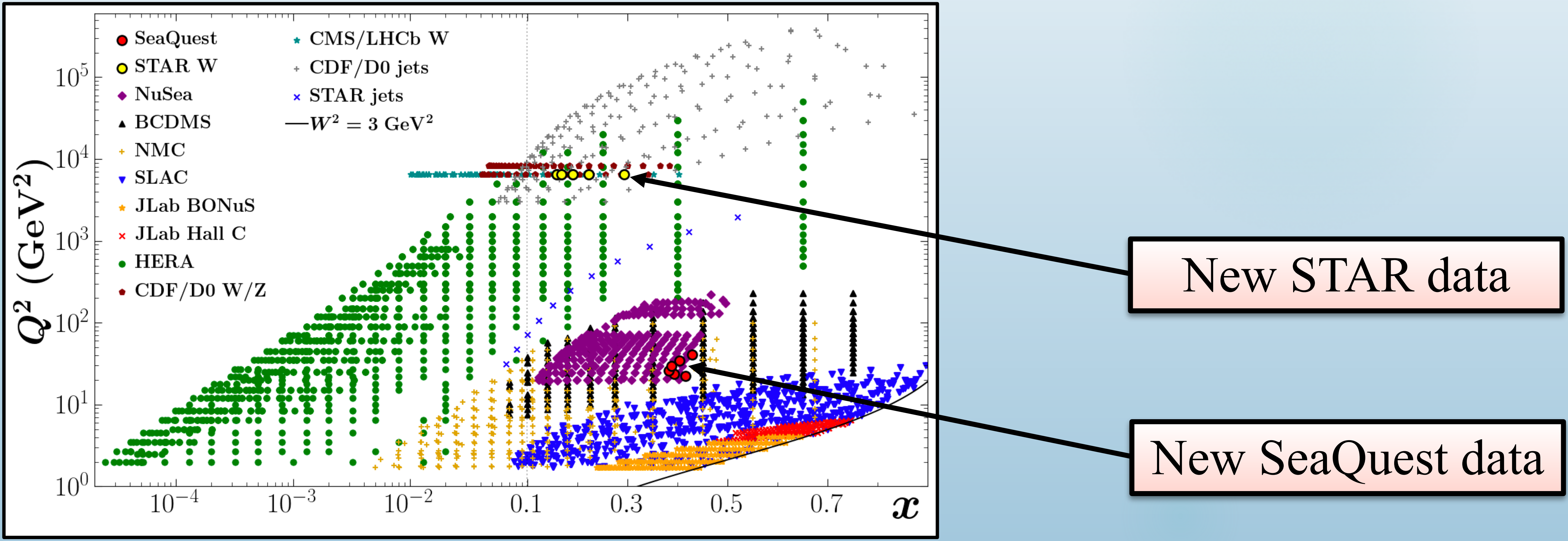


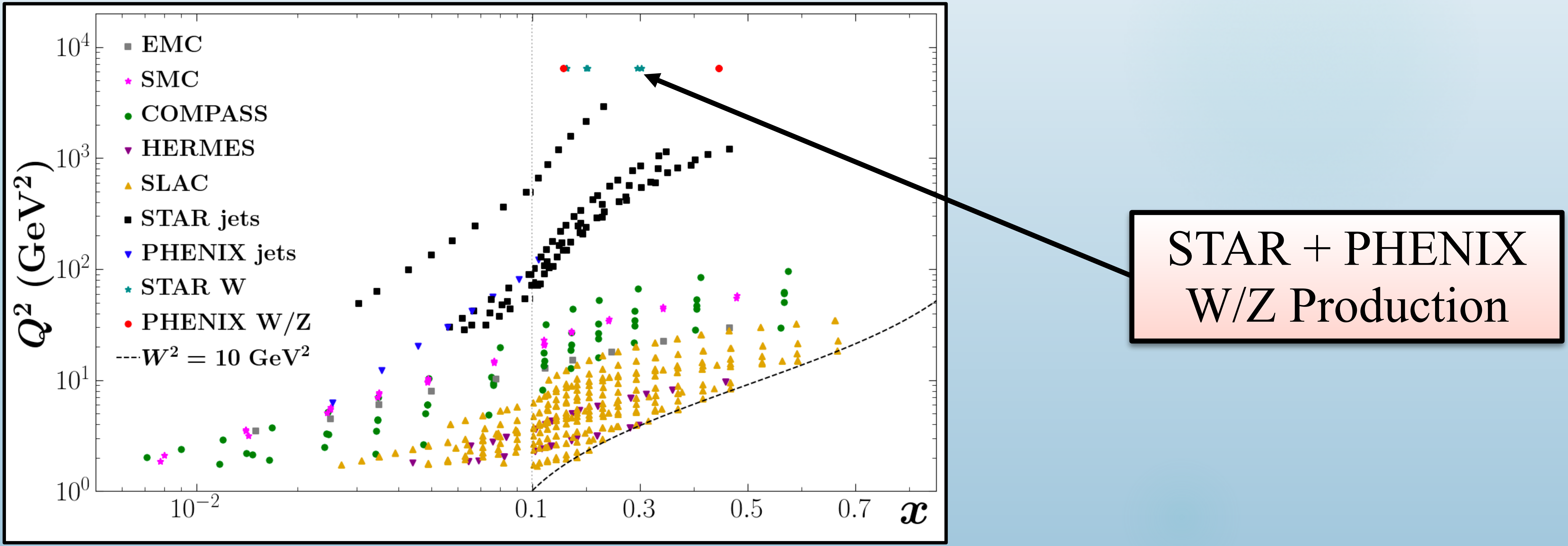
# Kinematic Coverage (Spin-Averaged)

| | | | |
|---|---|---|---|
| **Deep Inelastic Scattering** | BCDMS, NMC, SLAC, HERA, Jefferson Lab | 3863 | points |
| **Drell-Yan** | Fermilab E866, E906 | 205 | points |
| **W/Z Boson Production** | CDF/D0, STAR, LHCb, CMS | 153 | points |
| **Jets** | CDF/D0, STAR | 200 | points |

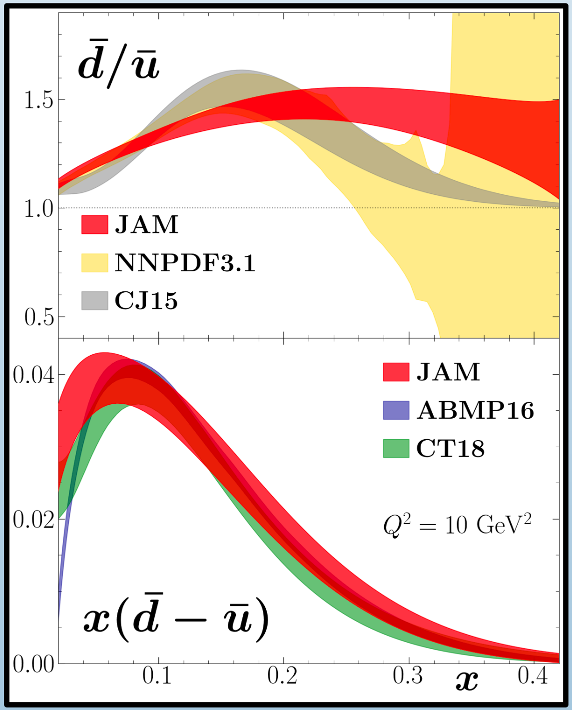


# Kinematic Coverage (Helicity)

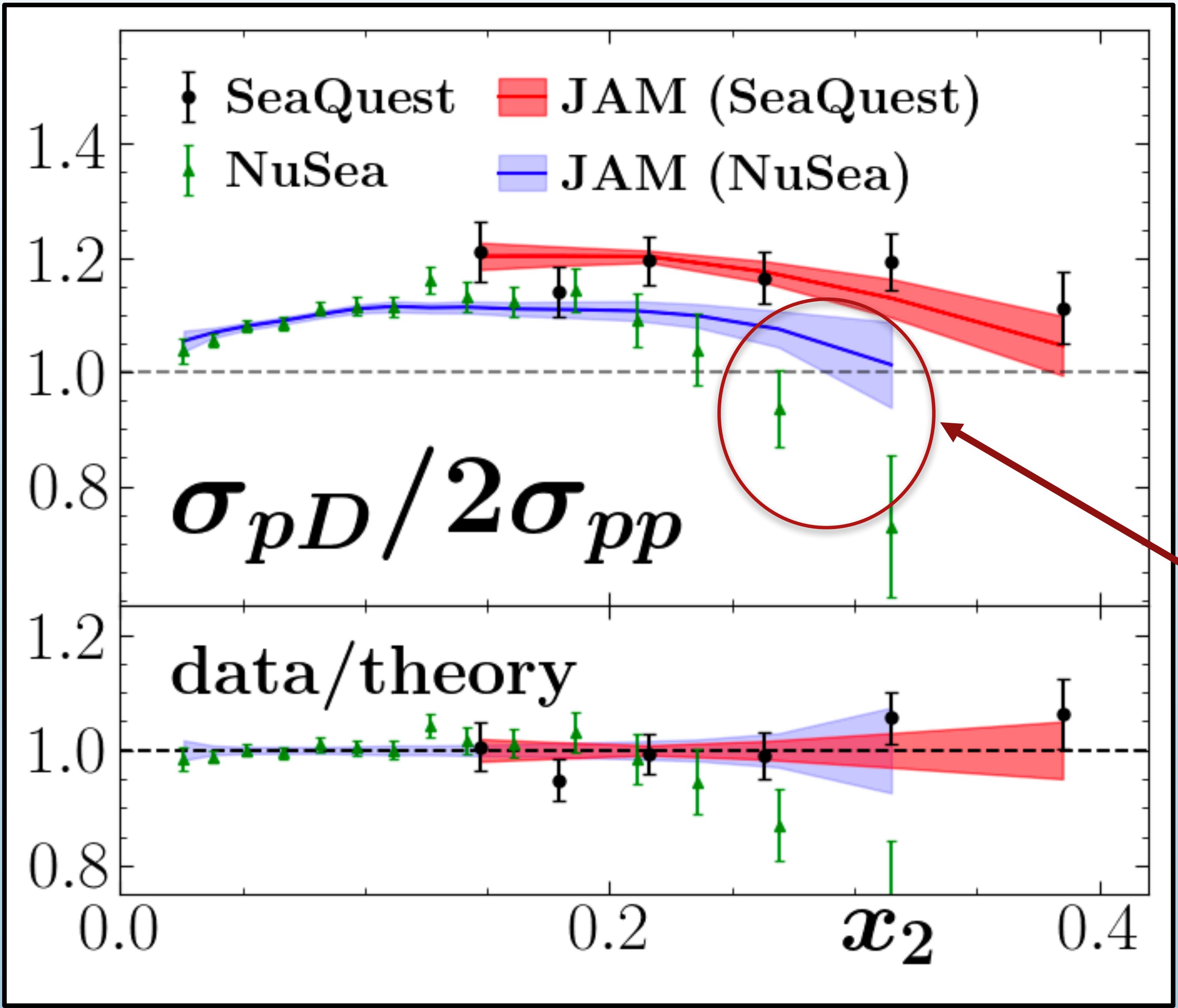
| | | |
|---|---|---|
| **Deep Inelastic Scattering** | COMPASS, EMC, HERMES, SLAC, SMC | 365 points |
| **W/Z Boson Production** | STAR, PHENIX | 18 points |
| **Jets** | STAR, PHENIX | 61 points |



# Part 3:
# Spin-Averaged PDFs



# SeaQuest and NuSea Quality of Fit

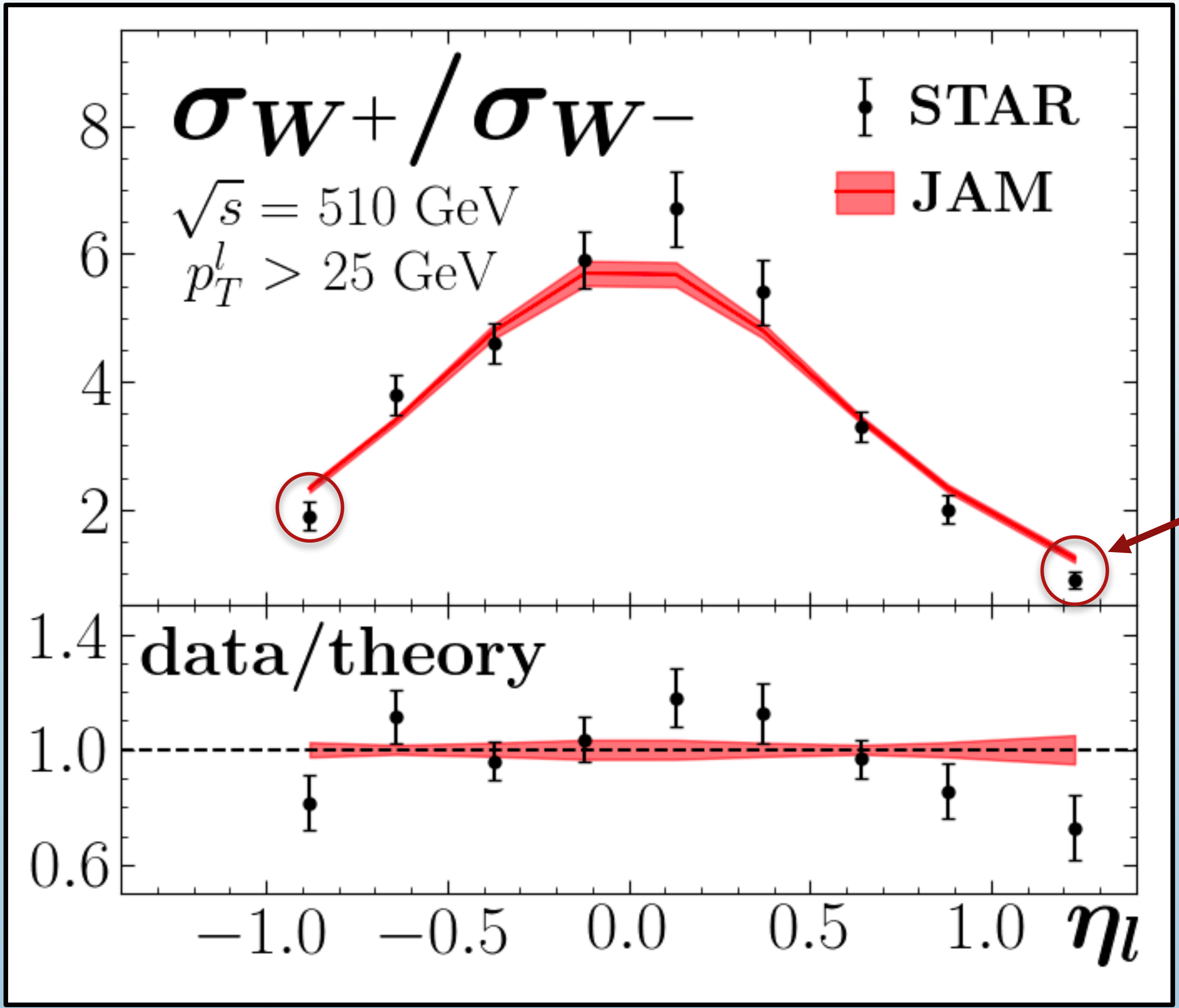



| process | | $N_{\mathrm{dat}}$ | $\chi^2/N_{\mathrm{dat}}$ |
|---|---|---|---|
| Drell-Yan | | | |
| NuSea | $pp$ | 184 | 1.21 |
| NuSea | $pD/2pp$ | 15 | 1.30 |
| SeaQuest | $pD/2pp$ | 6 | 0.82 |

$$\left.\frac{\sigma_{pD}}{2\sigma_{pp}}\right|_{x_1 \gg x_2} \approx \frac{1}{2}\left[1 + \frac{\bar{d}(x_2)}{\bar{u}(x_2)}\right]$$

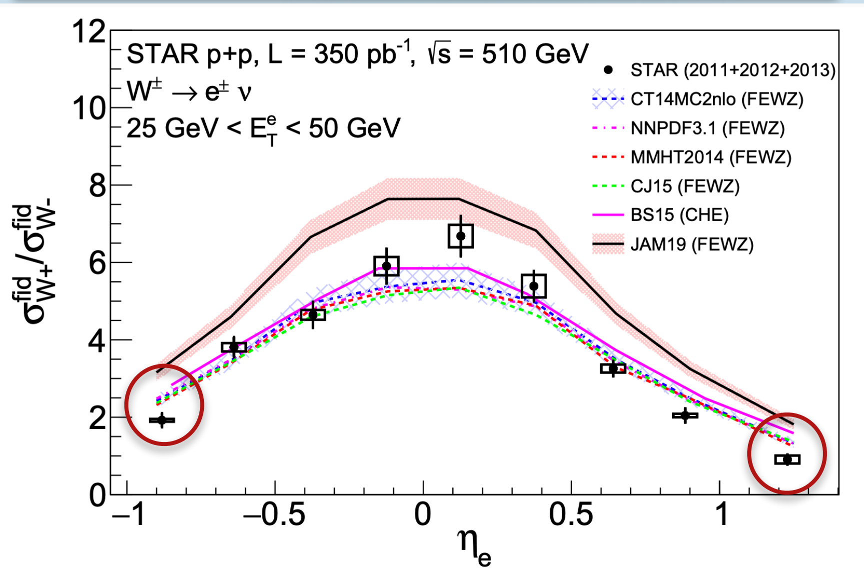
Well-known tension between NuSea and SeaQuest

# STAR Quality of Fit



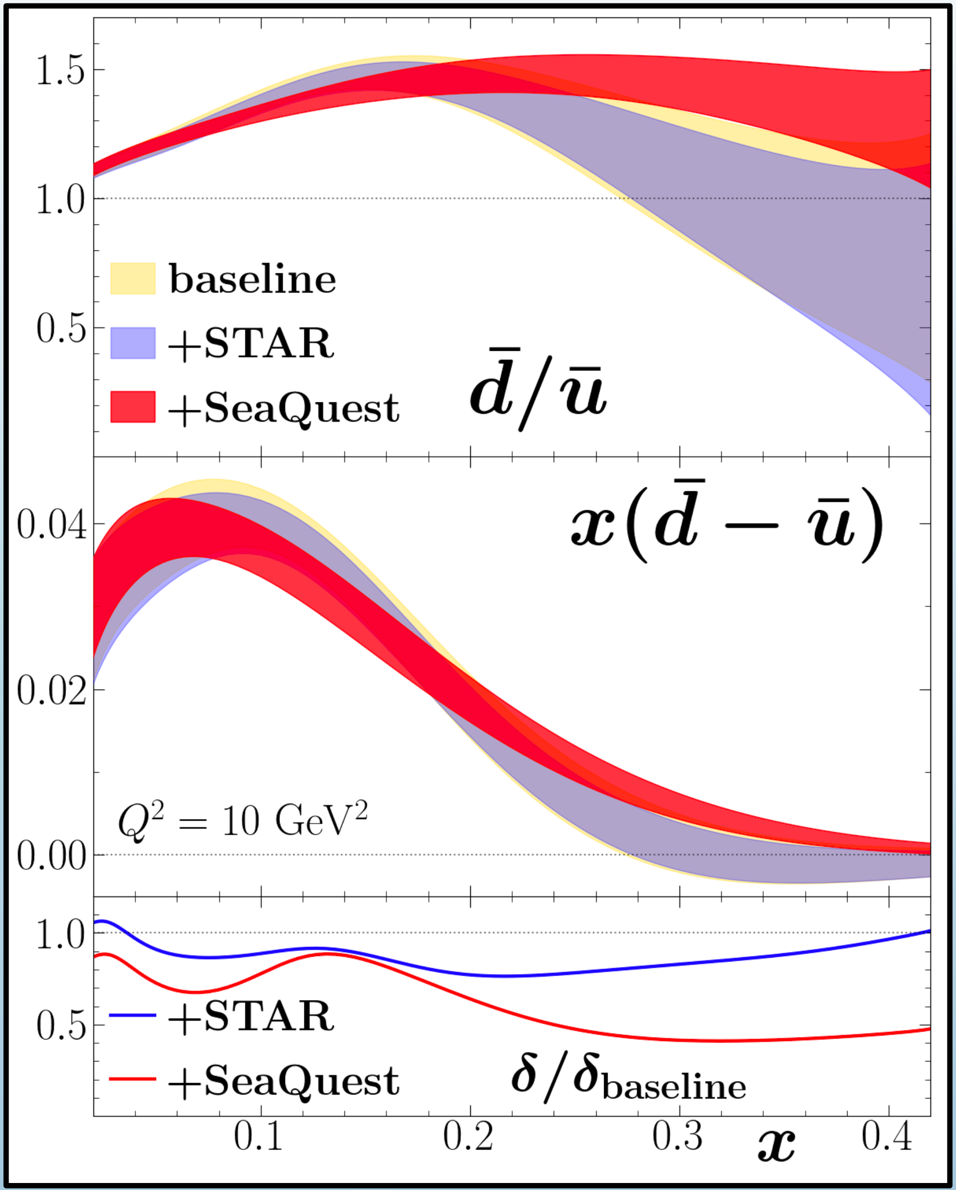

| process | $N_{dat}$ | $\chi^2/N_{dat}$ |
|---|---|---|
| $W$-lepton | | |
| STAR $W^+/W^-$ | 9 | 2.02 |

Difficult to describe at extreme rapidity




J. Adam *et al*. [STAR], Phys. Rev. D. **103**, 012001 (2021)

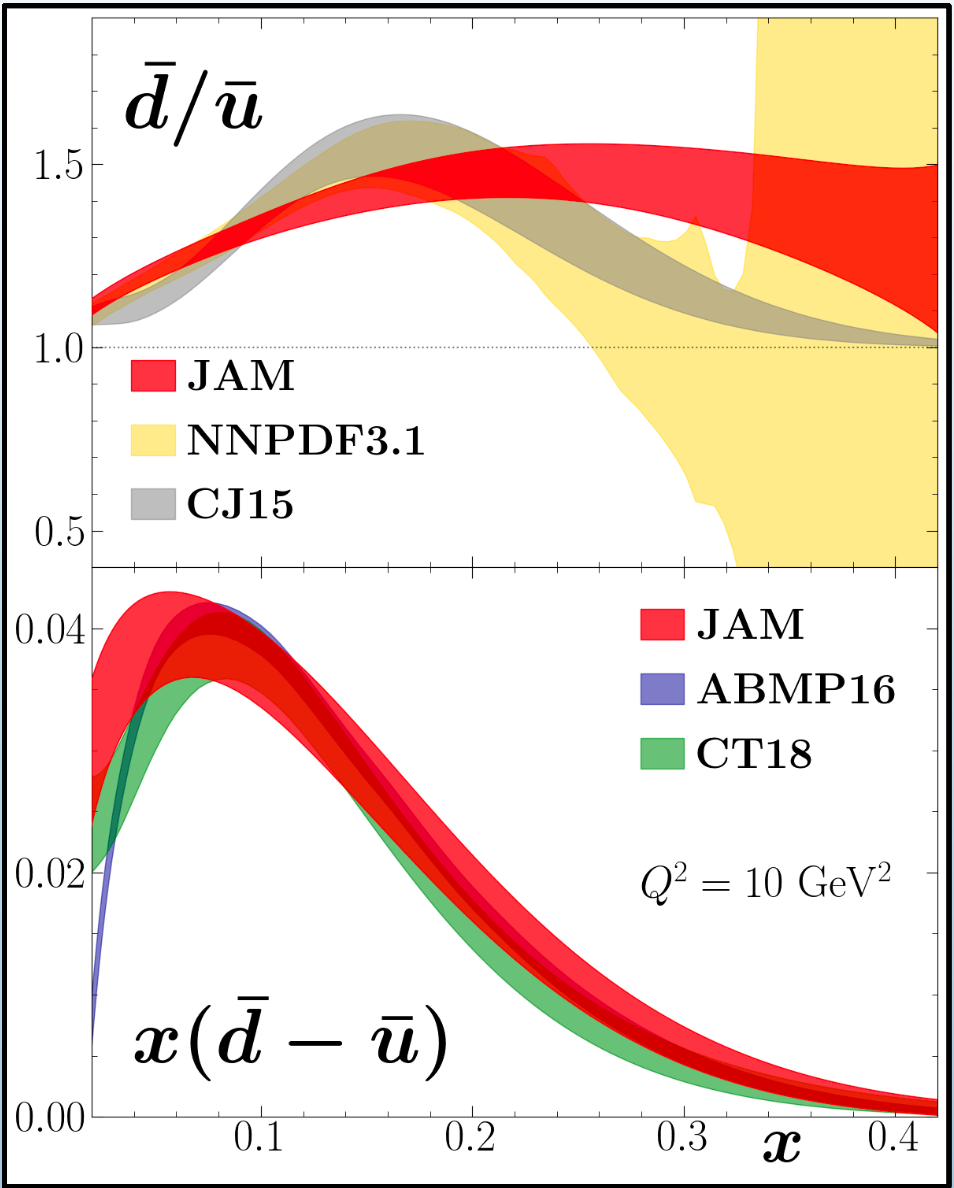
# Impact from STAR and SeaQuest



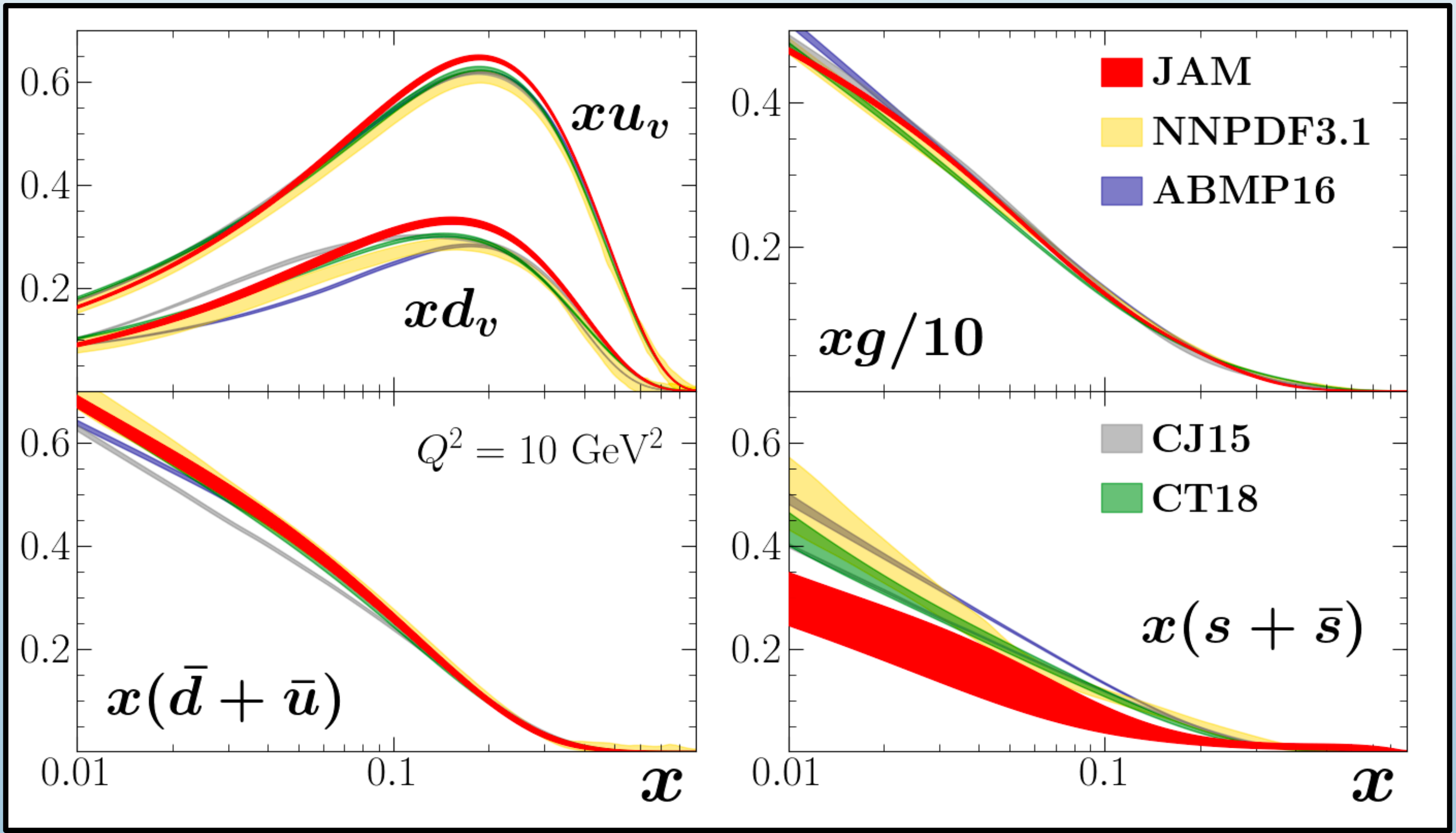

**STAR:** Moderate reduction of uncertainties

**SeaQuest**: Large reduction of uncertainties, especially at $x > 0.2$.
$\bar{d}/\bar{u} > 1$ up to $x \approx 0.4$, in agreement with models

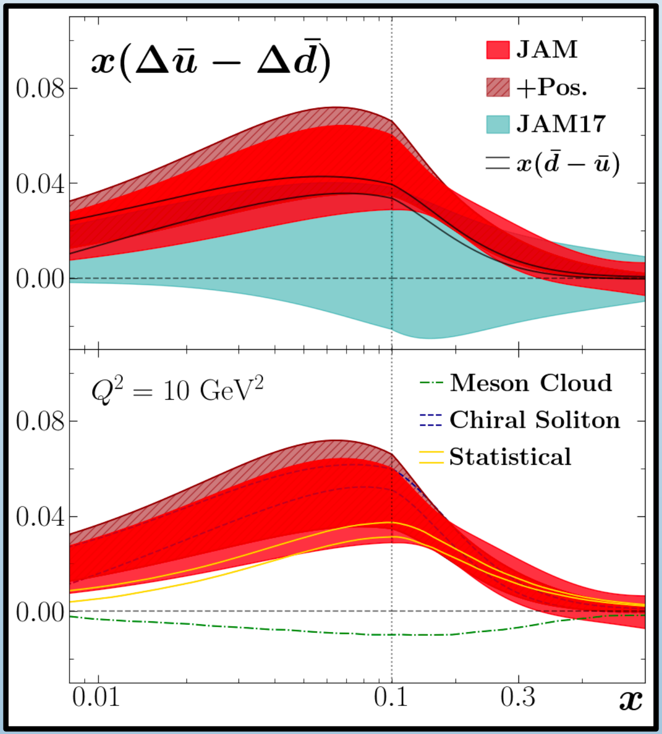
# Resulting PDFs



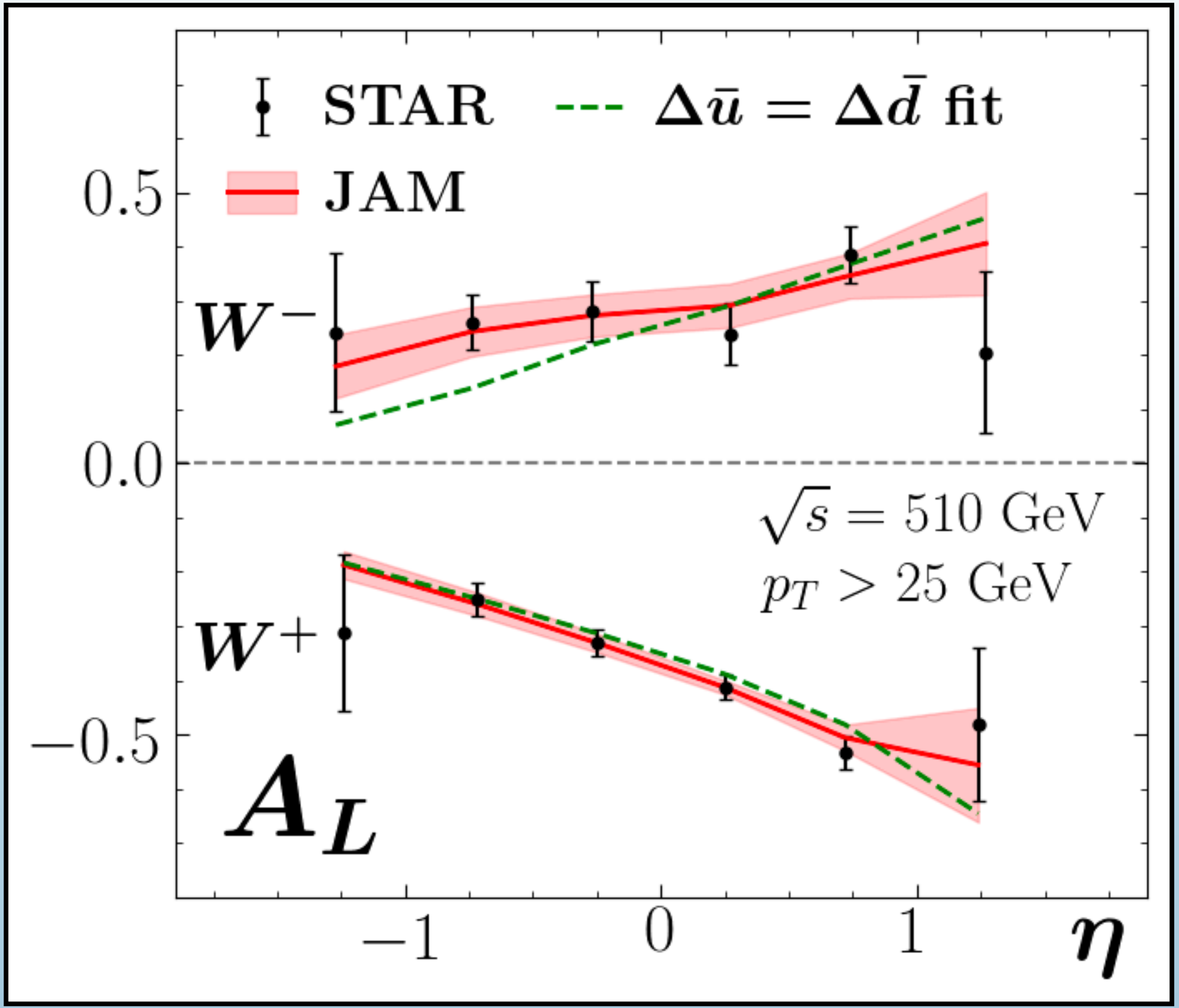

Results for asymmetry largely agree with ABMP16, CT18;
disagree with NNPDF3.1, CJ15 at high $x$.



# Part 4: Helicity PDFs



# STAR Quality of Fit

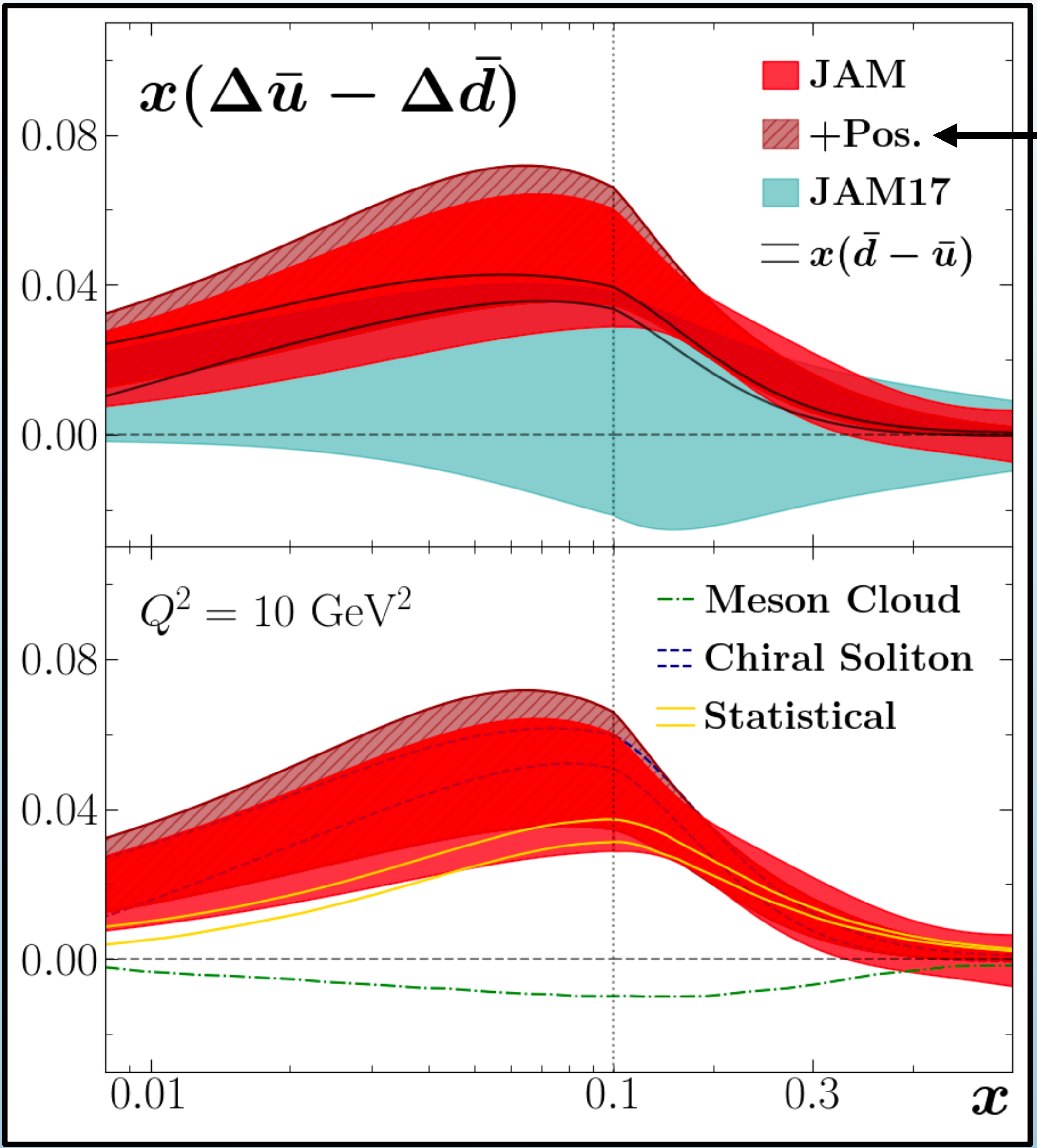



| process | $N_{\rm dat}$ | $\chi^2/N_{\rm dat}$ JAM | +Pos. | $\Delta\bar{u} = \Delta\bar{d}$ |
|---|---|---|---|---|
| STAR $W^\pm$ | 12 | 0.45 | 0.61 | 1.53 |
| PHENIX $W^\pm/Z$ | 6 | 0.47 | 0.46 | 0.48 |
| pol. DIS | 365 | 0.93 | 0.93 | 0.93 |
| pol. jet | 61 | 1.00 | 1.03 | 1.00 |
| **total** | **444** | **0.92** | **0.94** | **0.95** |

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

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

# Resulting Asymmetry




Positivity Constraints:
$|\Delta f(x, Q^2)| < f(x, Q^2)$

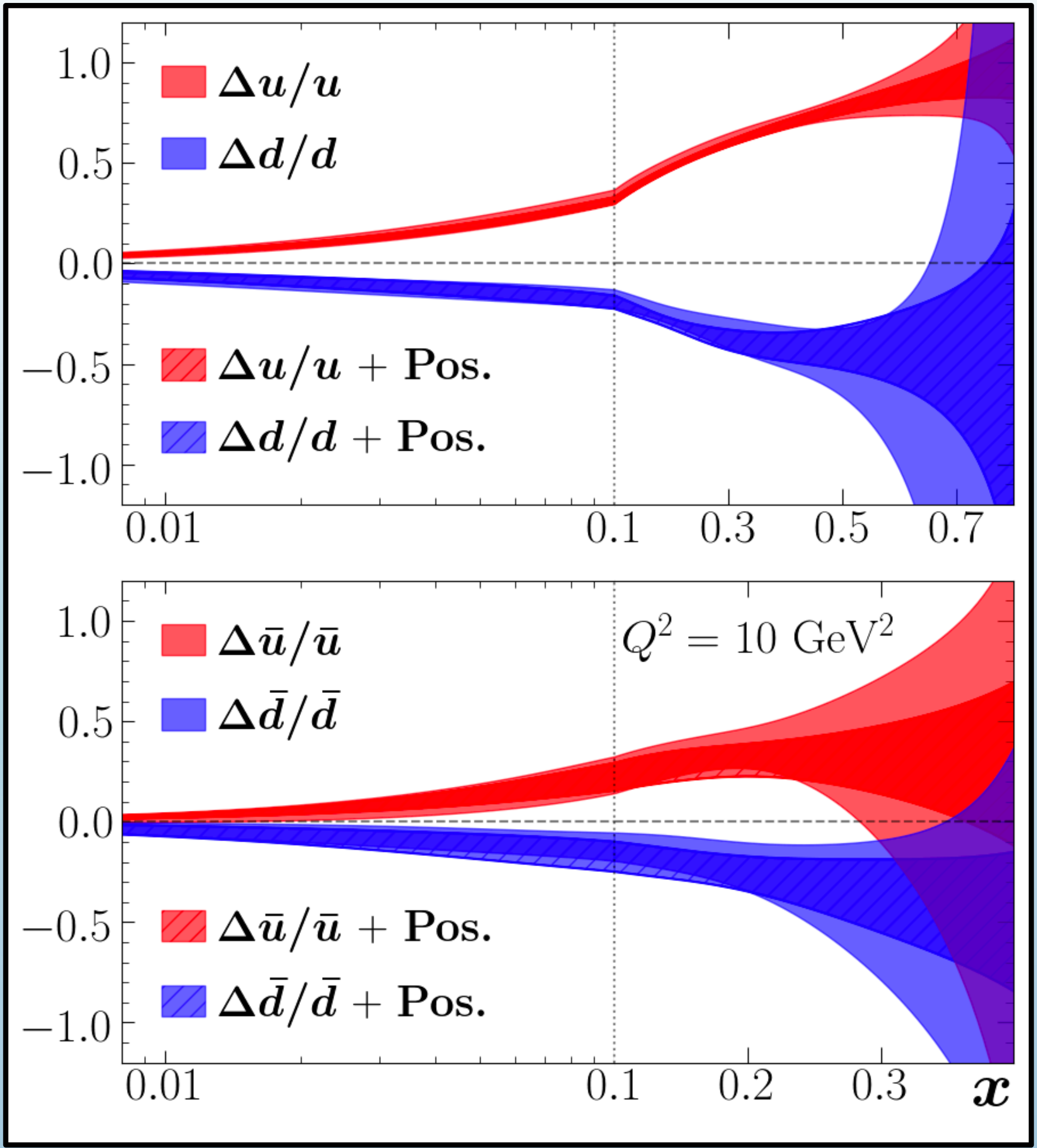
**JAM17**: inclusive + semi-inclusive DIS data

Agreement with Statistical and Chiral Soliton models

Meson Cloud contribution is not sufficient for asymmetry


Statistical Model: C. Bourrely and J. Soffer, Nucl. Phys. **A941**, 307-334 (2015)
Meson Cloud Model: F. G. Cao and A. I. Signal, Phys. Rev. D. **68**, 074002 (2003)
Chiral Soliton Model: M. Wakamatsu and T. Watabe, Phys. Rev. D. **874**, 38-84 (2013)

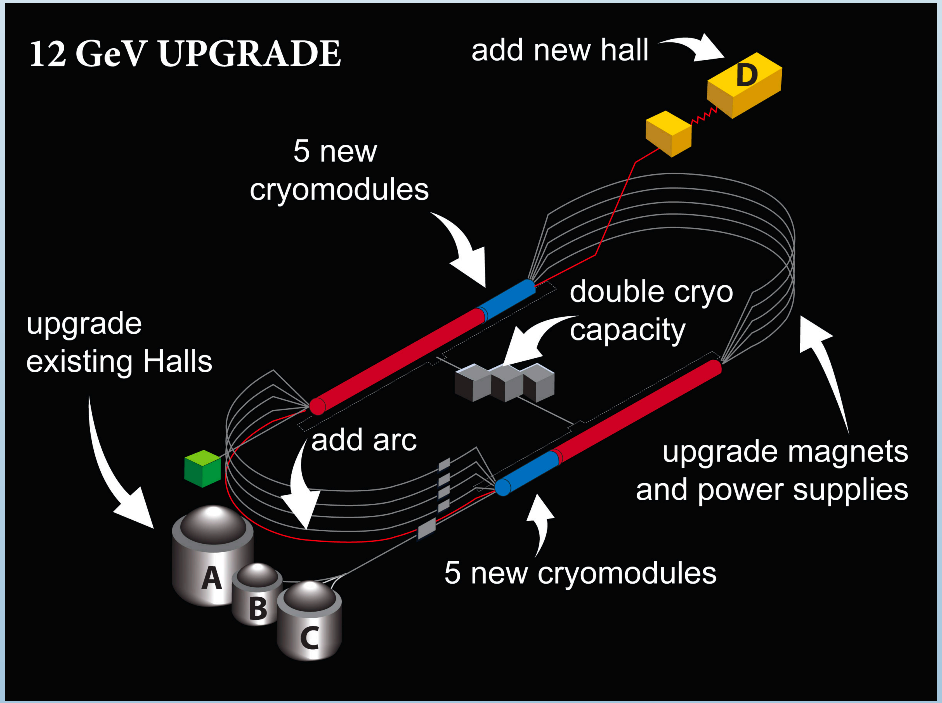
# Quark and Antiquark Polarizations




First self-consistent extraction using *simultaneous* fit

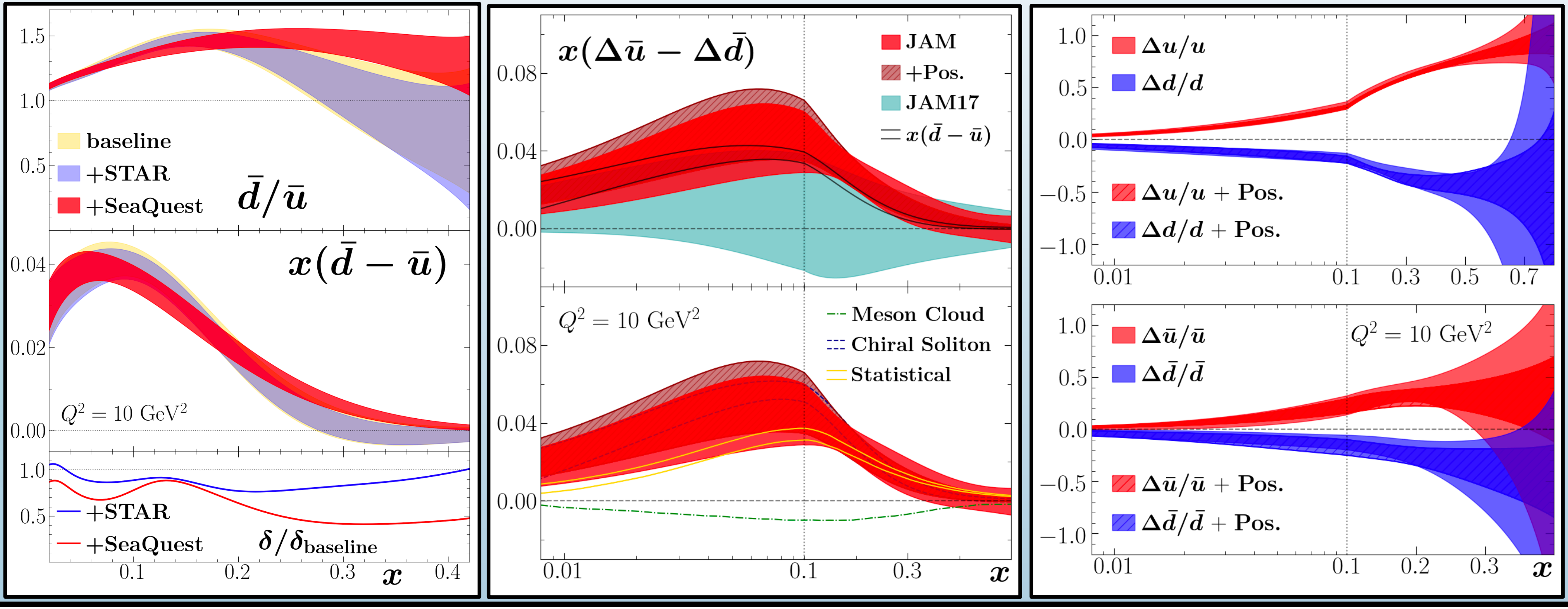
Antiquark ratios have same signs as quark ratios

# Conclusions and Outlook



# Results Summary

**First global QCD analysis of SeaQuest and STAR data**

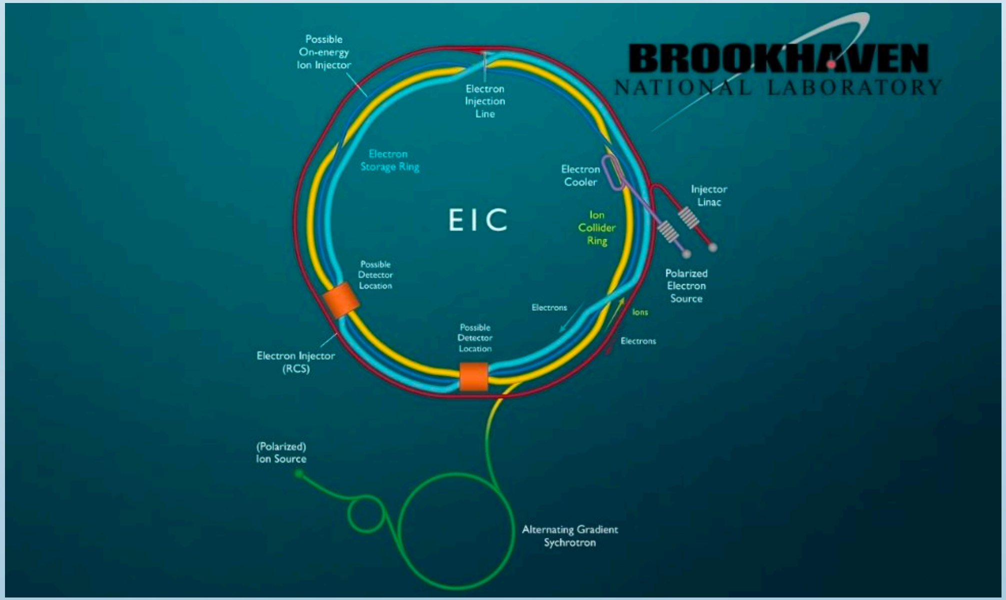


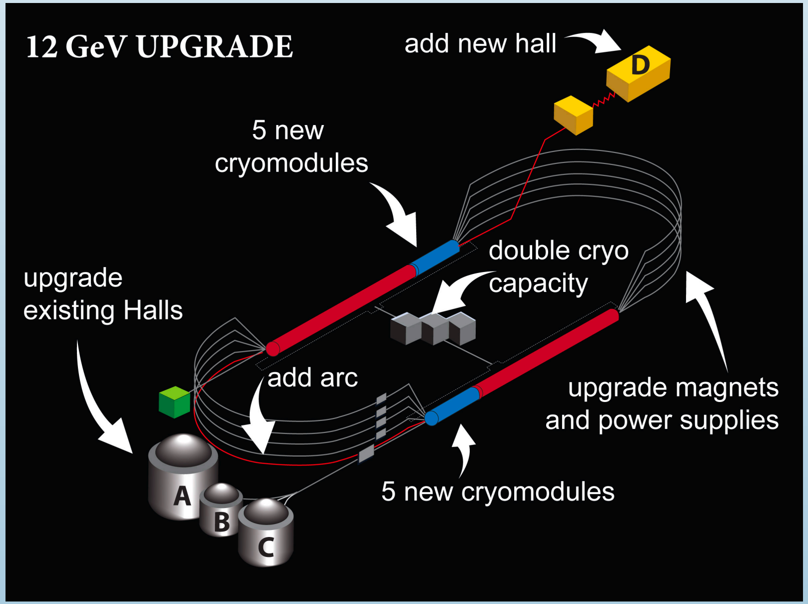

**Simultaneous global QCD analysis of spin-averaged and helicity PDFs**

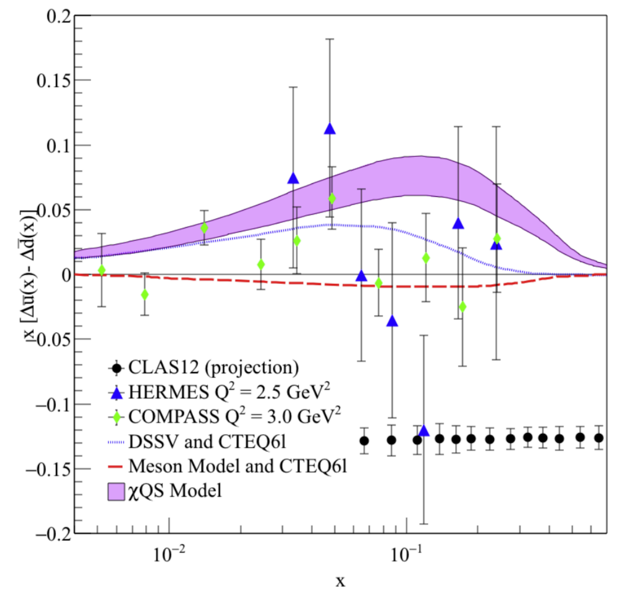
# Outlook

**Jefferson Lab CLAS12**: Semi-inclusive DIS

**EIC**: First polarized electron-ion collider



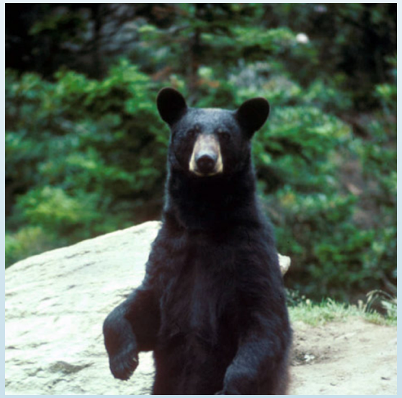

D. F. Geesaman and P. E. Reimer, Rep. Prog. Phys. **82**, 046301 (2019)

# Collaboration

Andreas Metz

Wally Melnitchouk

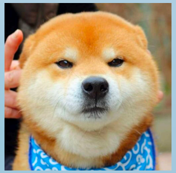
Jacob Ethier

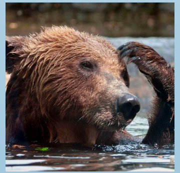


Nobuo Sato

JAM Jefferson Lab Angular Momentum Collaboration

Thank you to Yiyu Zhou and Patrick Barry for helpful discussions





# Extra Slides

# Bayes' Theorem

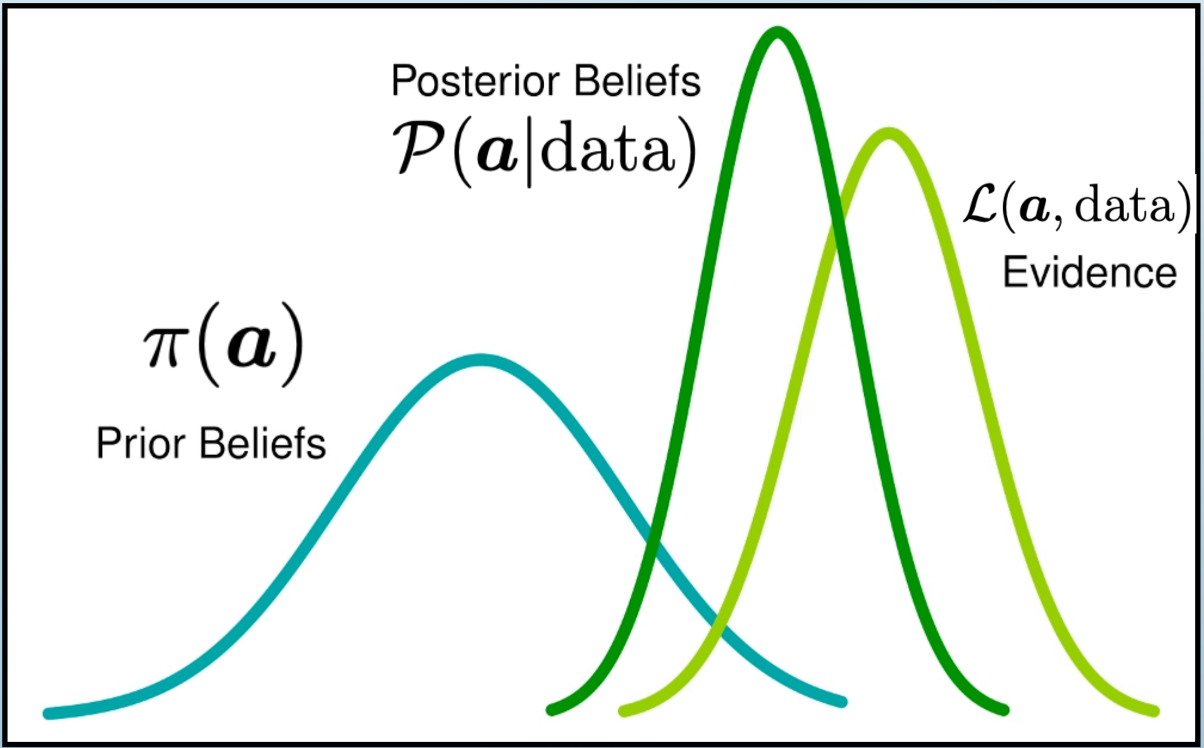
Now that we have calculated $\chi^2(\boldsymbol{a}, \text{data})$…

**Likelihood Function**

$$\mathcal{L}\left(\boldsymbol{a}, \text{data}\right) = \exp\left(-\frac{1}{2}\chi^2\left(\boldsymbol{a}, \text{data}\right)\right)$$

**Bayes' Theorem**

$$\mathcal{P}(\boldsymbol{a}|\text{data}) \sim \mathcal{L}(\boldsymbol{a}, \text{data})\, \pi(\boldsymbol{a})$$

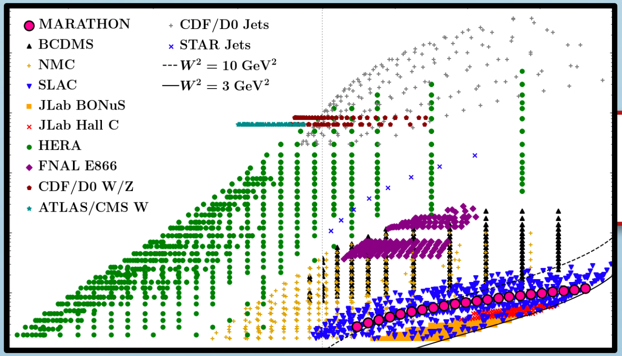


# Data Resampling

Pseudo-Data → $$\tilde{\sigma} = \sigma + N(0,1)\ \alpha$$ ← Uncorrelated Uncertainties

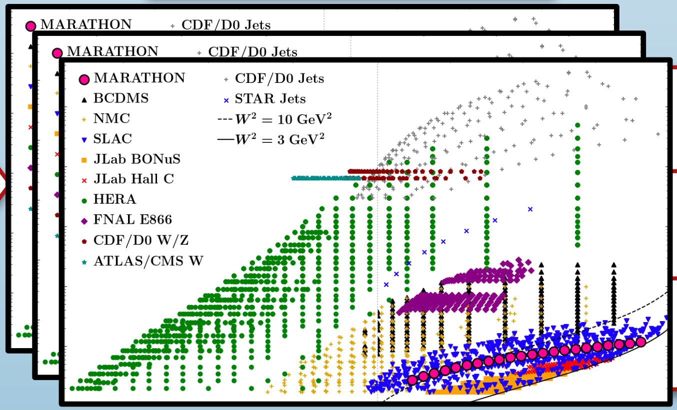
↑ Data

Original Data




DR →

Replica Data

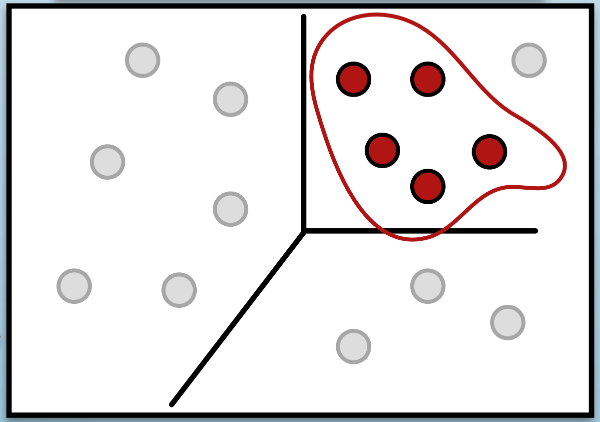



Maximum Likelihood →

Maximum Likelihood →

Maximum Likelihood →

Parameter Space



# Error Quantification

For a quantity $O(\boldsymbol{a})$: (for example, a PDF at a given value of $(x, Q^2)$)

$$E[O] = \int d^n a\ \rho(\boldsymbol{a}\,|\,data)\ O(\boldsymbol{a})$$

$$V[O] = \int d^n a\ \rho(\boldsymbol{a}\,|\,data)\ \left[O(\boldsymbol{a}) - E[O]\right]^2$$

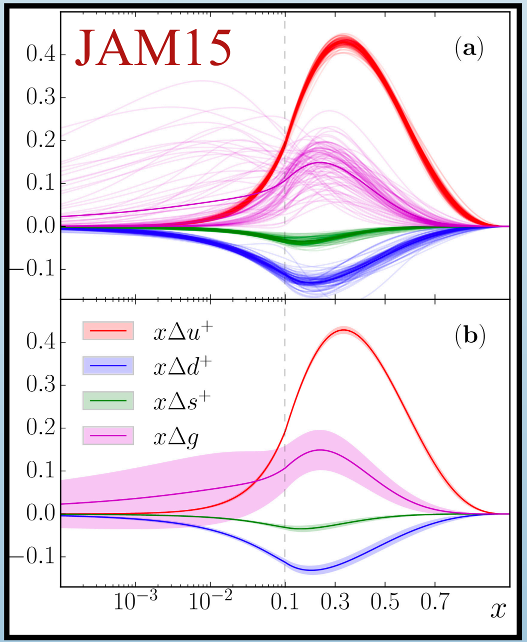
Exact, but
$n = \mathcal{O}(100)$!

Build an MC ensemble

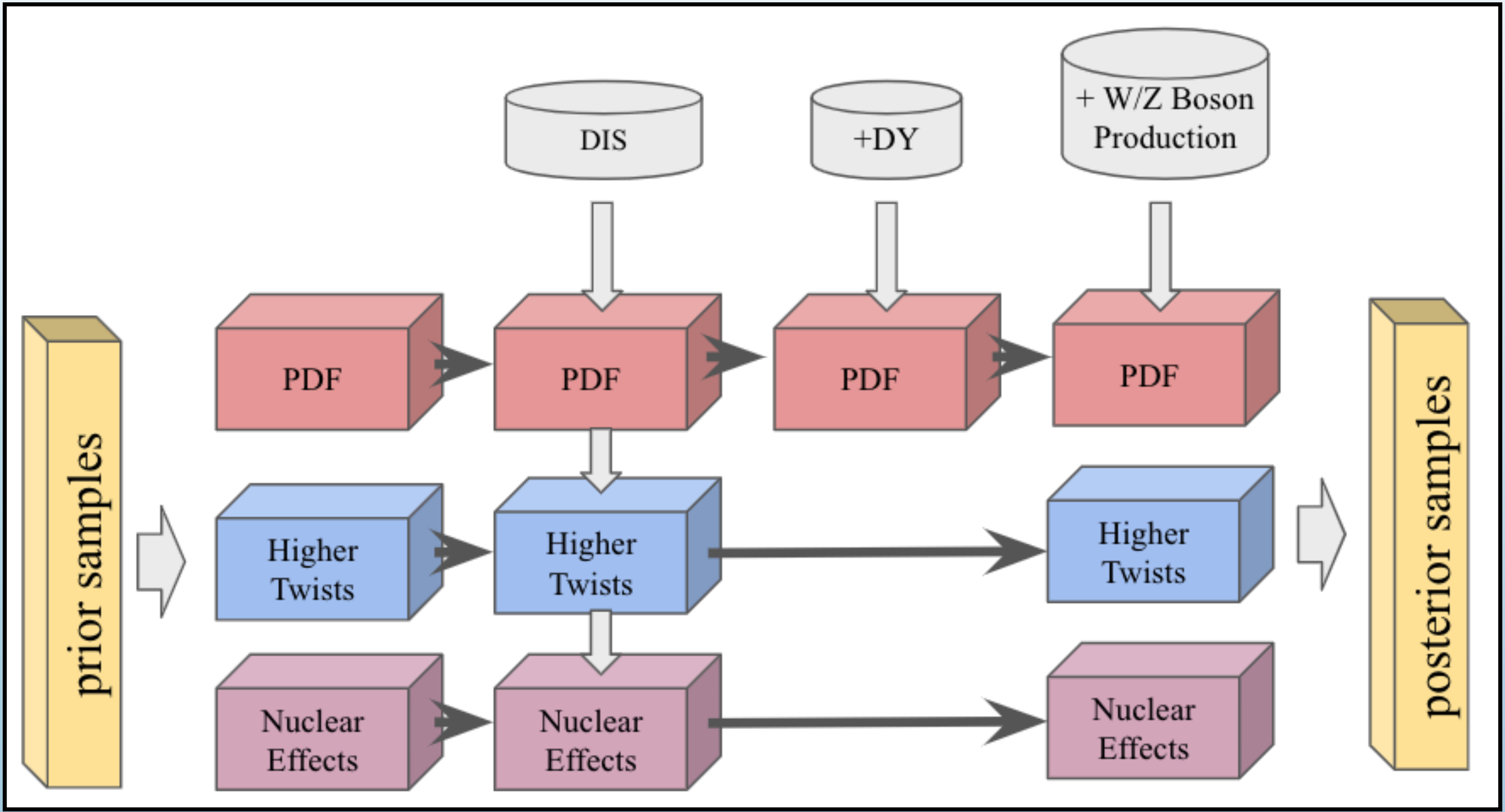
$$E[O] \approx \frac{1}{N}\sum_k O(\boldsymbol{a}_k)$$

$$V[O] \approx \frac{1}{N}\sum_k \left[O(\boldsymbol{a}_k) - E[O]\right]^2$$

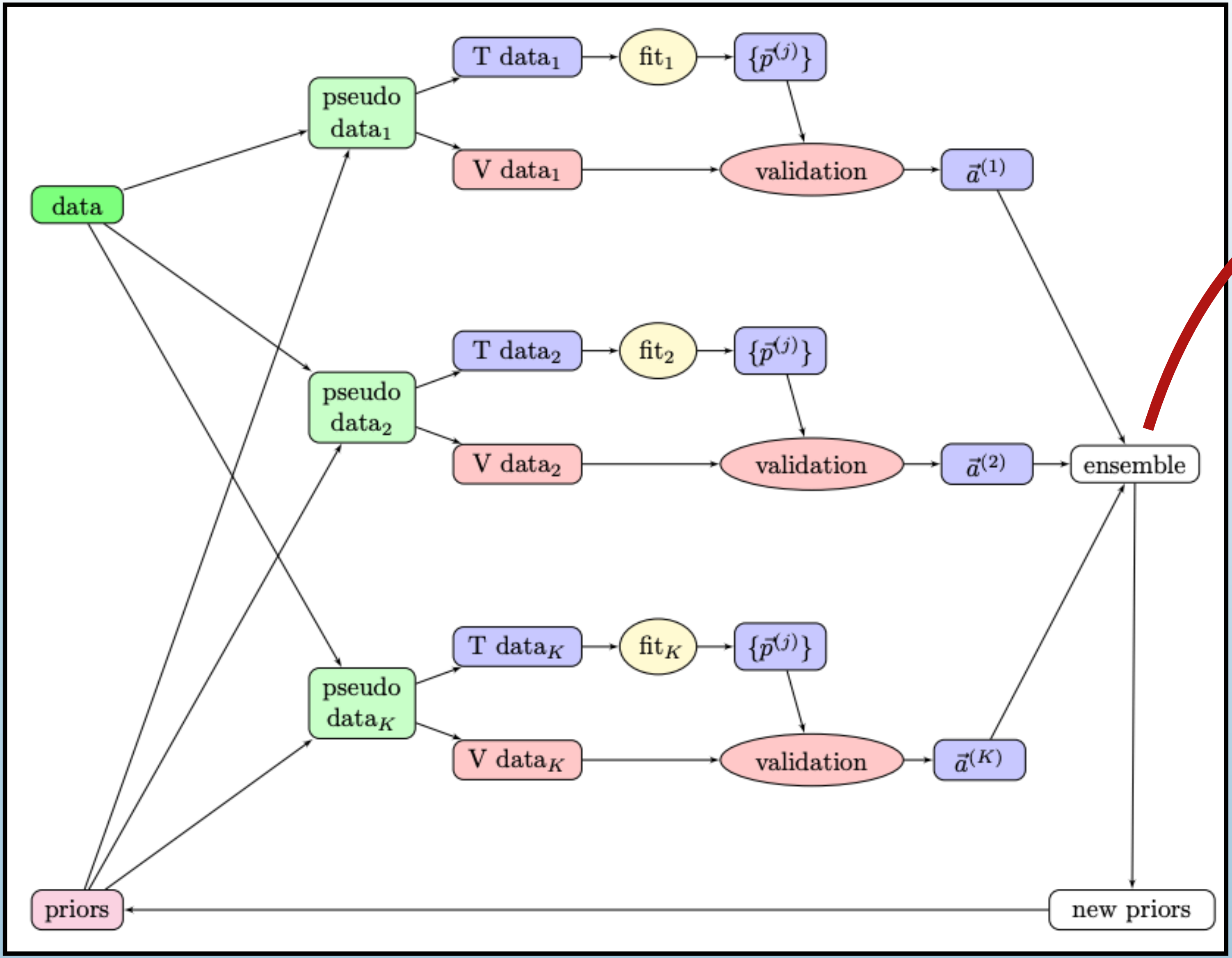
Average over $k$ sets of the parameters (replicas)

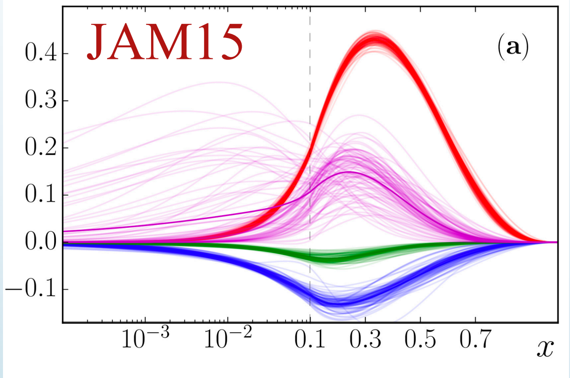


# Multi-Step Strategy



# Putting it all together…

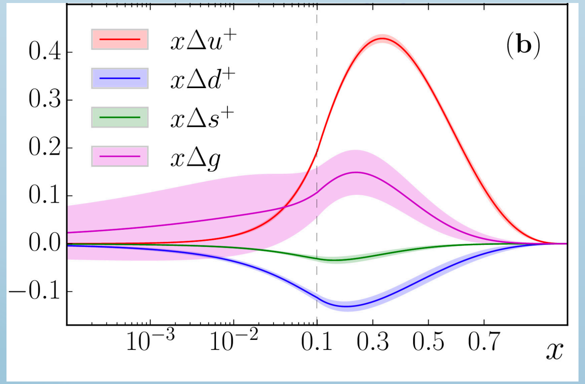


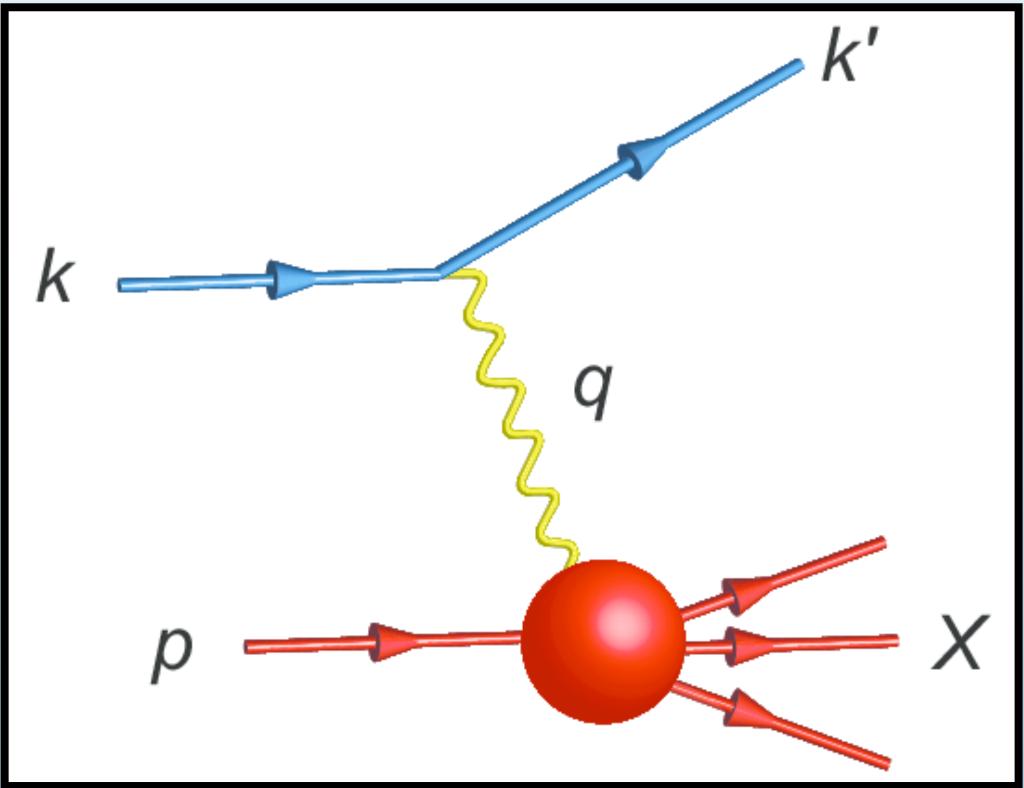

+

$$E[O] \approx \frac{1}{N}\sum_k O(\boldsymbol{a}_k)$$

$$V[O] \approx \frac{1}{N}\sum_k \left[O(\boldsymbol{a}_k) - E[O]\right]^2$$



# Deep Inelastic Scattering




Virtuality:

$$Q^2 = -q^2$$

Bjorken $x$:

$$x = \frac{Q^2}{2p \cdot q}$$

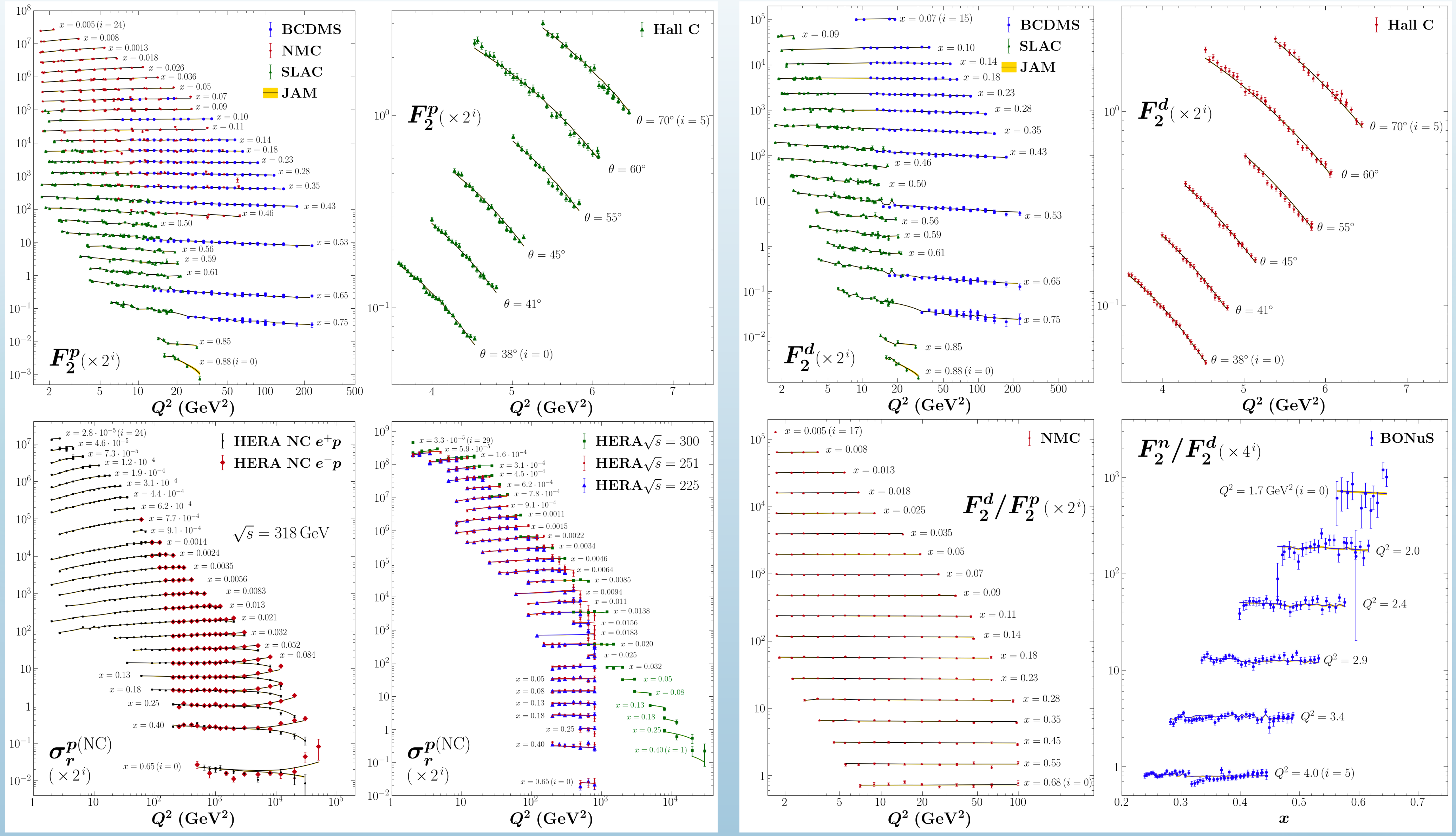
Invariant mass of outgoing particles:

$$W^2 = (p + q)^2$$

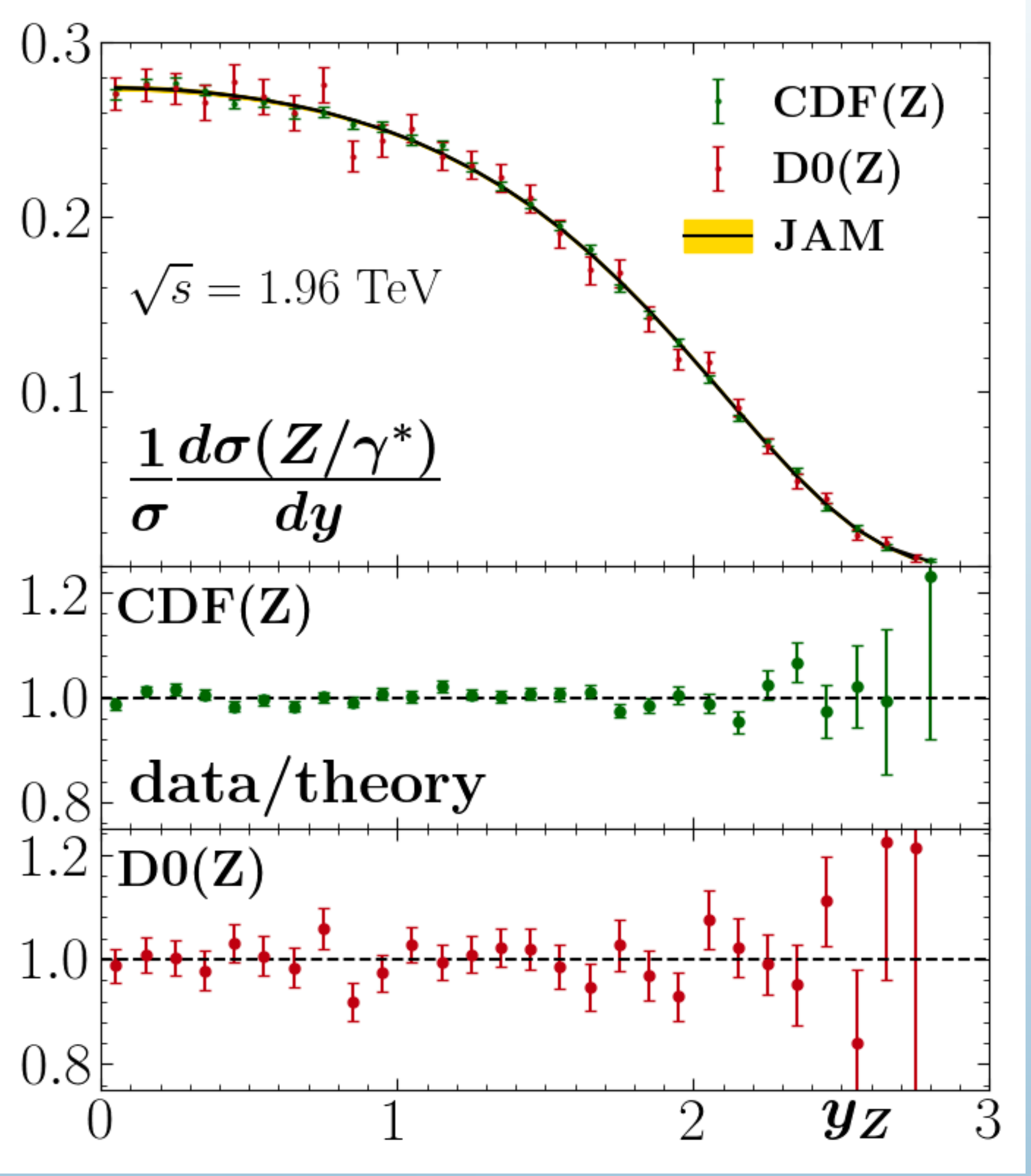
# All $\chi^2/N_{\text{dat}}$ (Spin-Averaged)

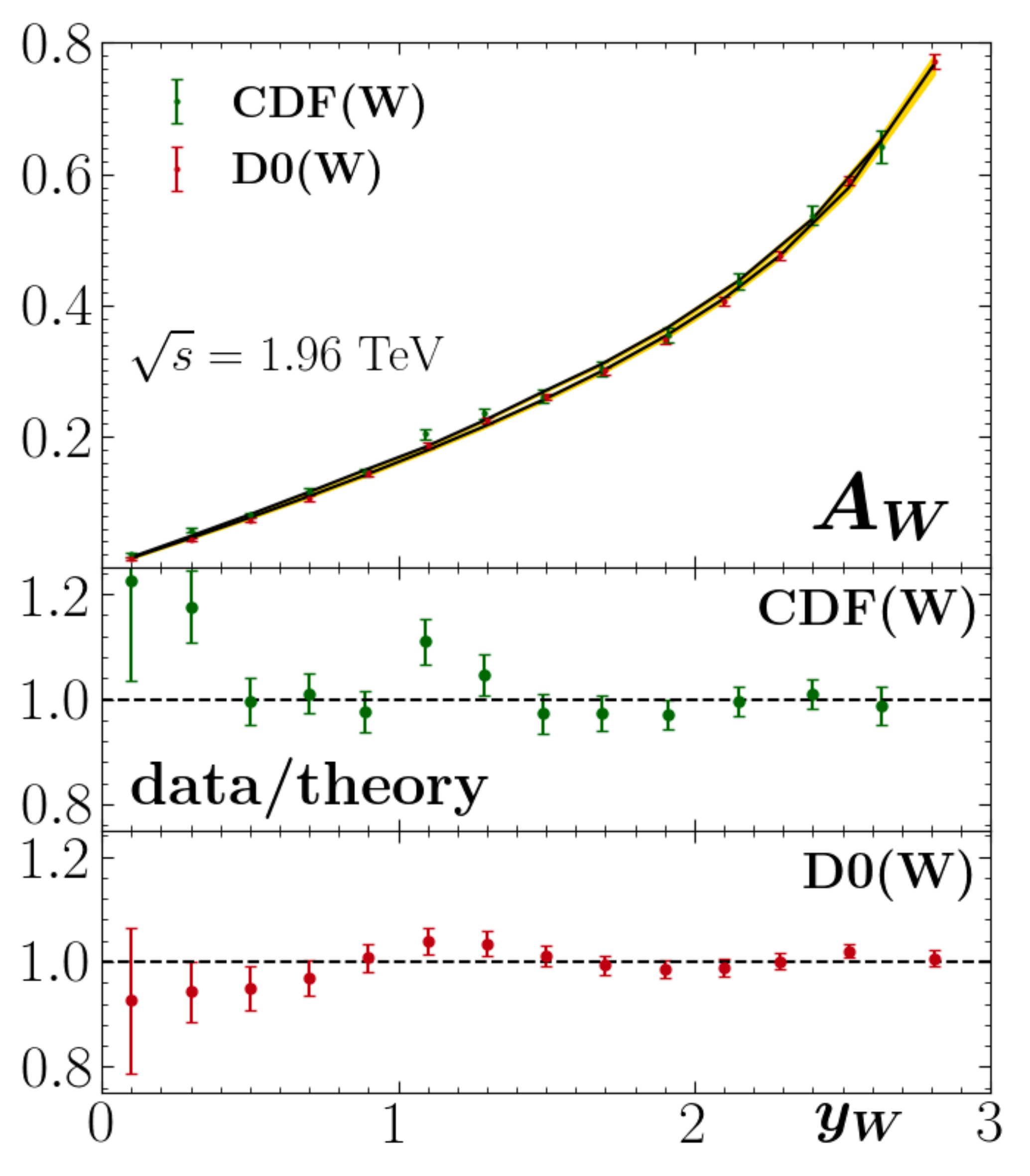
| process | $N_{\text{dat}}$ | $\chi^2/N_{\text{dat}}$ |
|---|---|---|
| DIS | | |
| fixed target | 2678 | 1.05 |
| HERA | 1185 | 1.27 |
| Drell-Yan | | |
| NuSea $pp$ | 184 | 1.21 |
| NuSea $pD/2pp$ | 15 | 1.30 |
| SeaQuest $pD/2pp$ | 6 | 0.82 |
| $W$-lepton | | |
| STAR $W^+/W^-$ | 9 | 2.02 |
| CMS charm asym. | 45 | 0.74 |
| LHCb charm asym. | 16 | 0.44 |
| Tevatron $W$ charge asym. | 27 | 1.18 |
| Tevatron $Z$ rapidity | 56 | 0.97 |
| jet | 200 | 1.11 |
| **total** | **4421** | **1.12** |

# DIS (Neutral Current)



# W/Z Boson Production



# Lepton Production