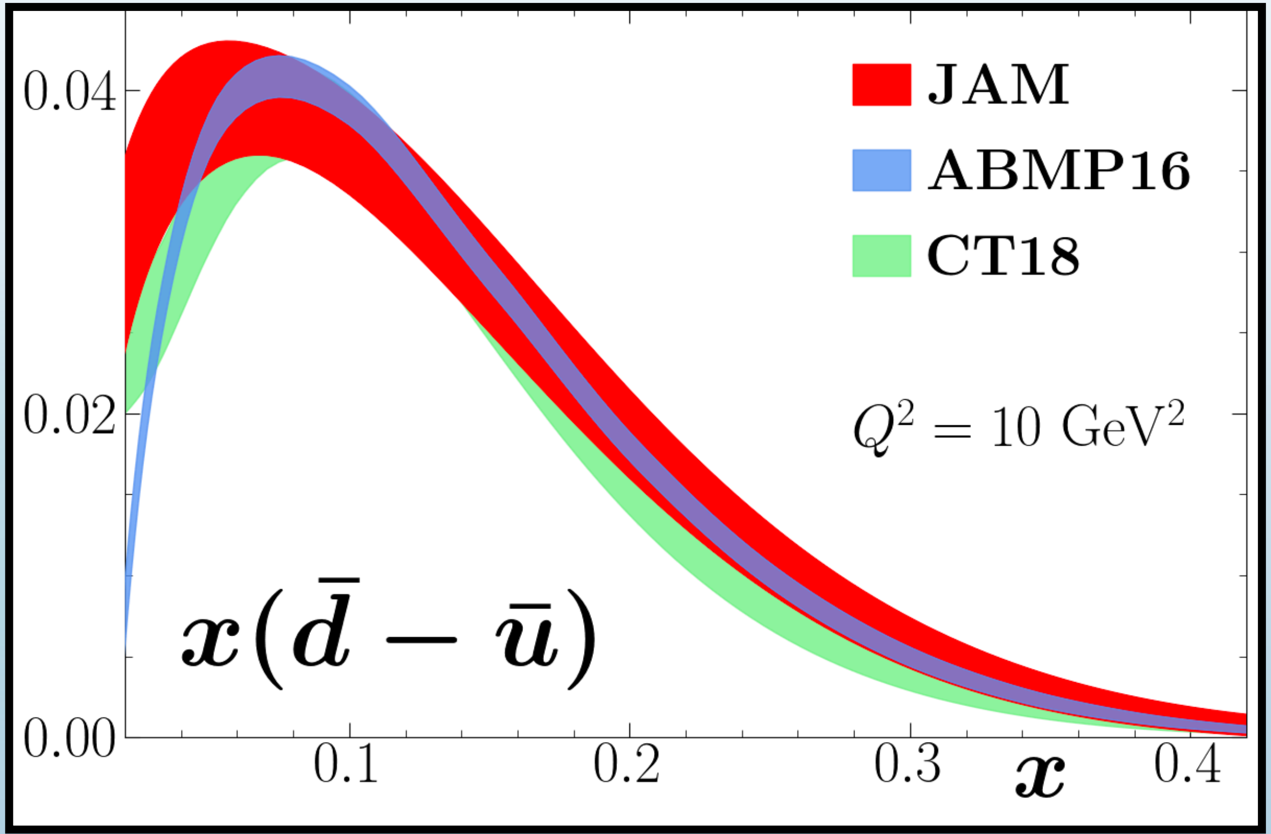
First Extraction of Polarized Sea Asymmetry from Weak Boson Production in Proton-Proton Collisions

Chris Cocuzza (Temple University)
Wally Melnitchouk (Jefferson Lab)
Andreas Metz (Temple University)
Nobuo Sato (Jefferson Lab)

October 22, 2021

SPIN2021
Matsue, Japan

Introduction to Sea Asymmetry



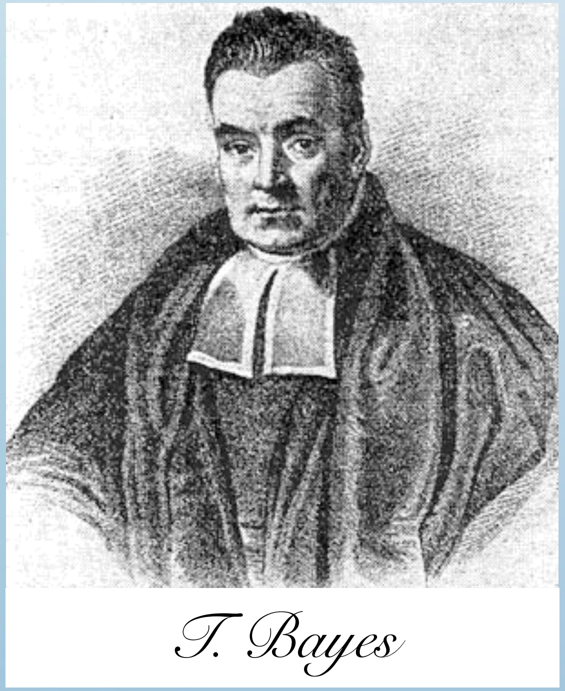
Unpolarized

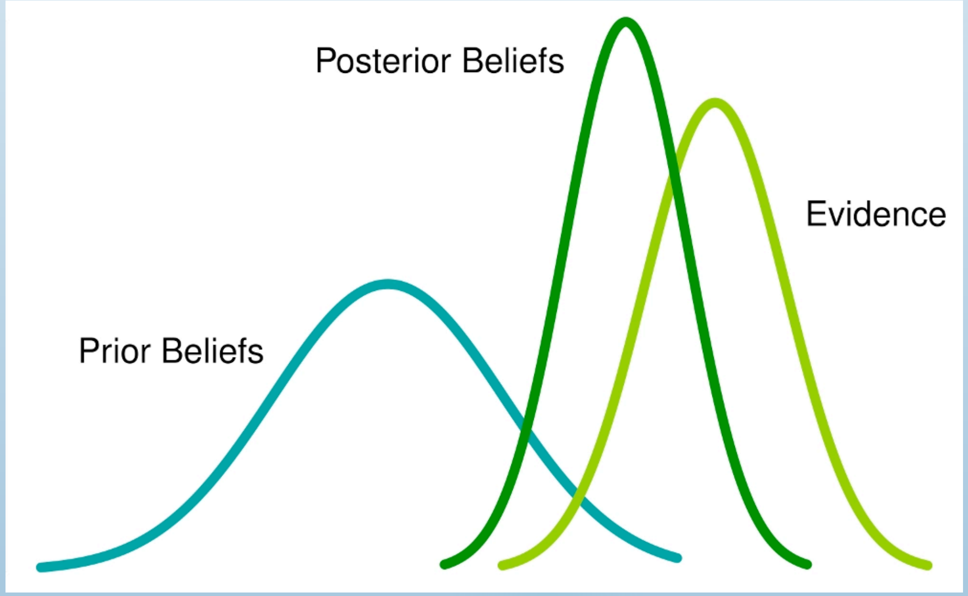
Cannot be explained from gluons splitting into quark-antiquark pairs

Meson Cloud Models
Chiral Soliton Models
Statistical Models

Still questions at high $x > 0.2$ and for helicity asymmetry

1. JAM Methodology
2. Data and Fitting
3. Helicity PDFs
4. Conclusions and Outlook





JAM Collaboration

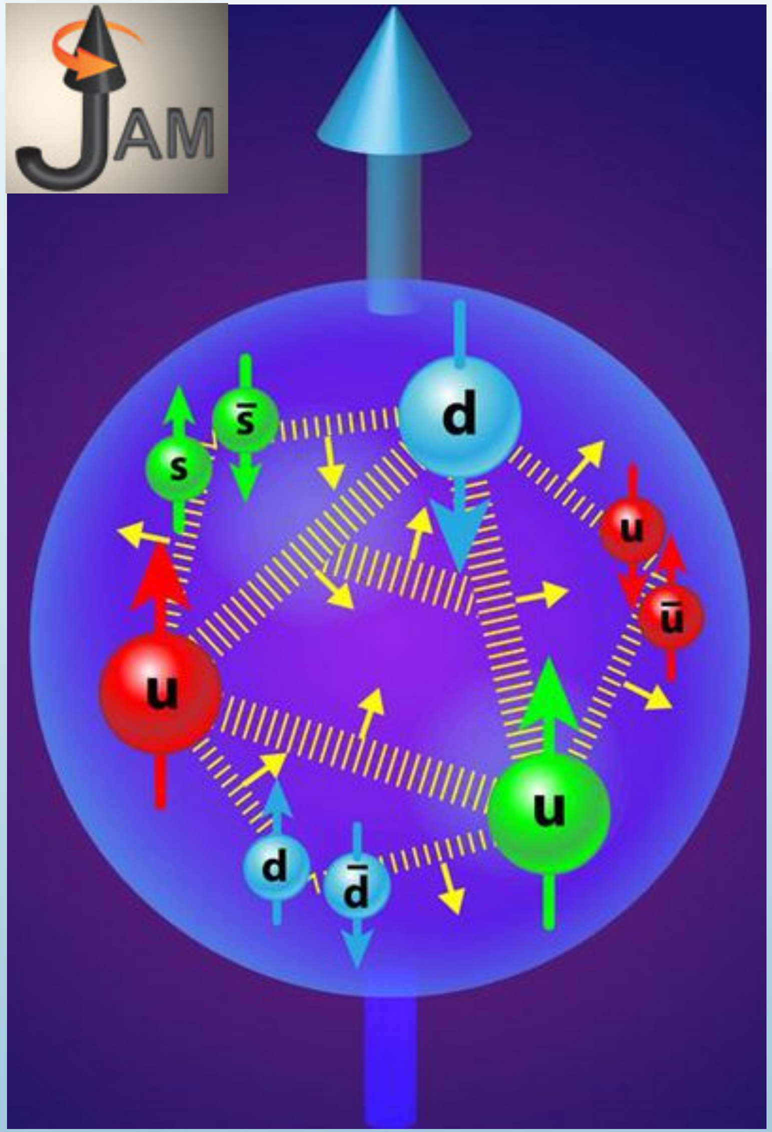
3-dimensional structure of nucleons:

- Parton distribution functions (PDFs)
- Fragmentation functions (FFs)
- Transverse momentum dependent (TMD) distributions
- Generalized parton distributions (GPDs)

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 χ^2 function

Now that the observables have been calculated…

Data

Theory

Normalization

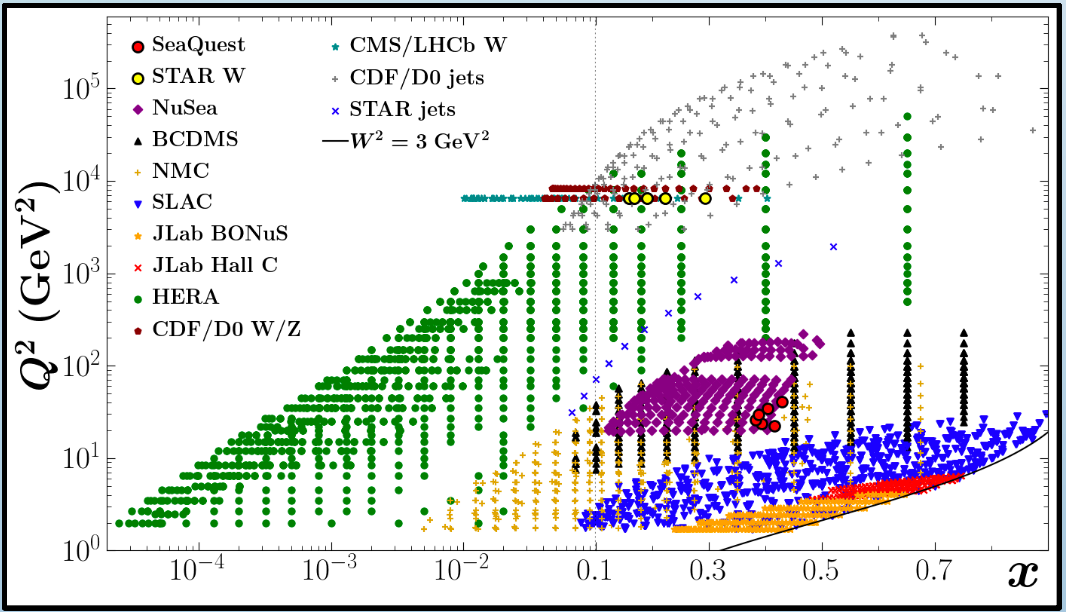
$$\chi^2(\boldsymbol{a}) = \sum_{i,e}\left(\frac{d_{i,e} - \sum_k r_e^k \beta_{i,e}^k - T_{i,e}(\boldsymbol{a})/N_e}{\alpha_{i,e}}\right)^2 + \sum_k \left(r_e^k\right)^2 + \left(\frac{1-N_e}{\delta N_e}\right)^2$$

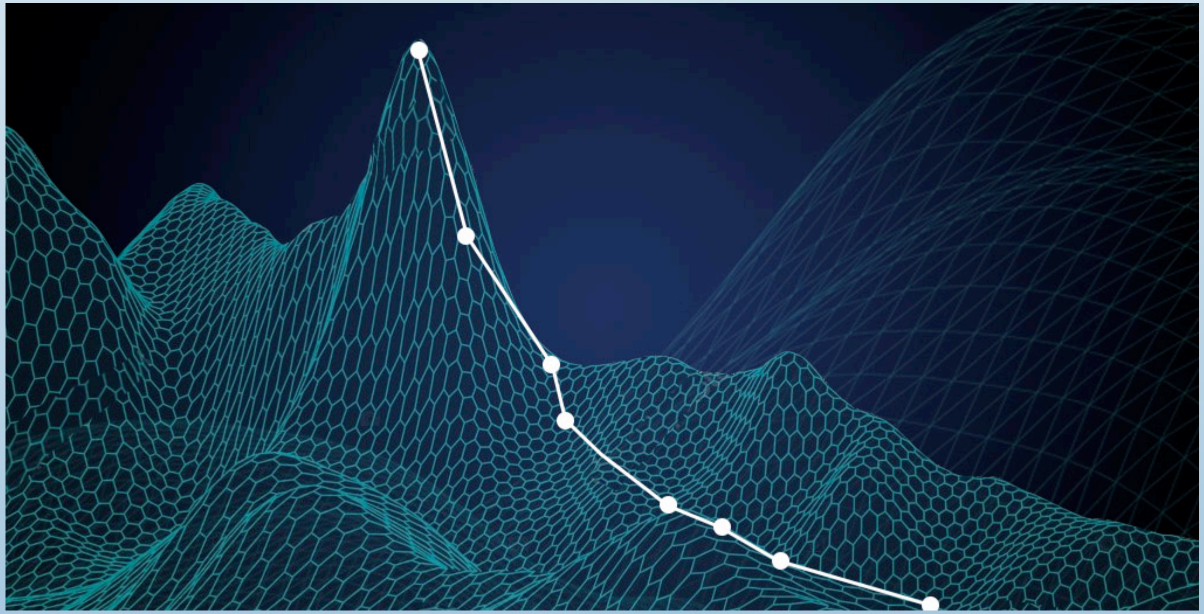
Uncorrelated Uncertainties

Correlated Uncertainties

Normalization Uncertainty

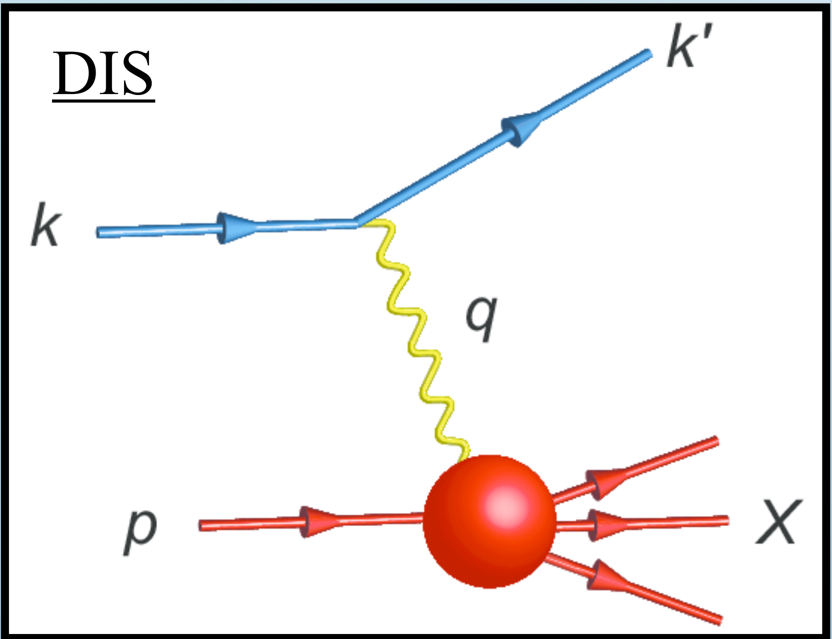
1. JAM Methodology
2. **Data and Fitting**
3. Helicity PDFs
4. Conclusions and Outlook

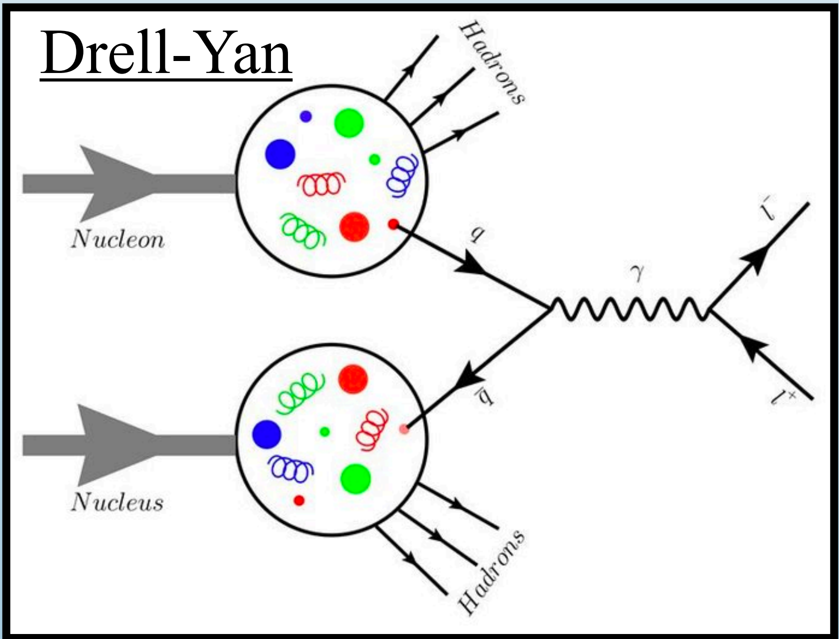


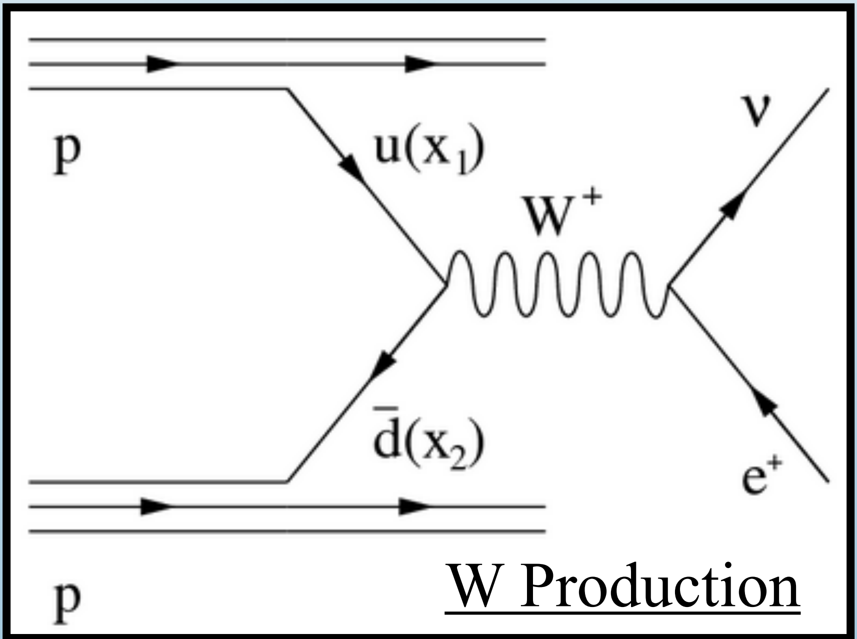


A Global Analysis

Simultaneous extraction of
spin-averaged and helicity PDFs

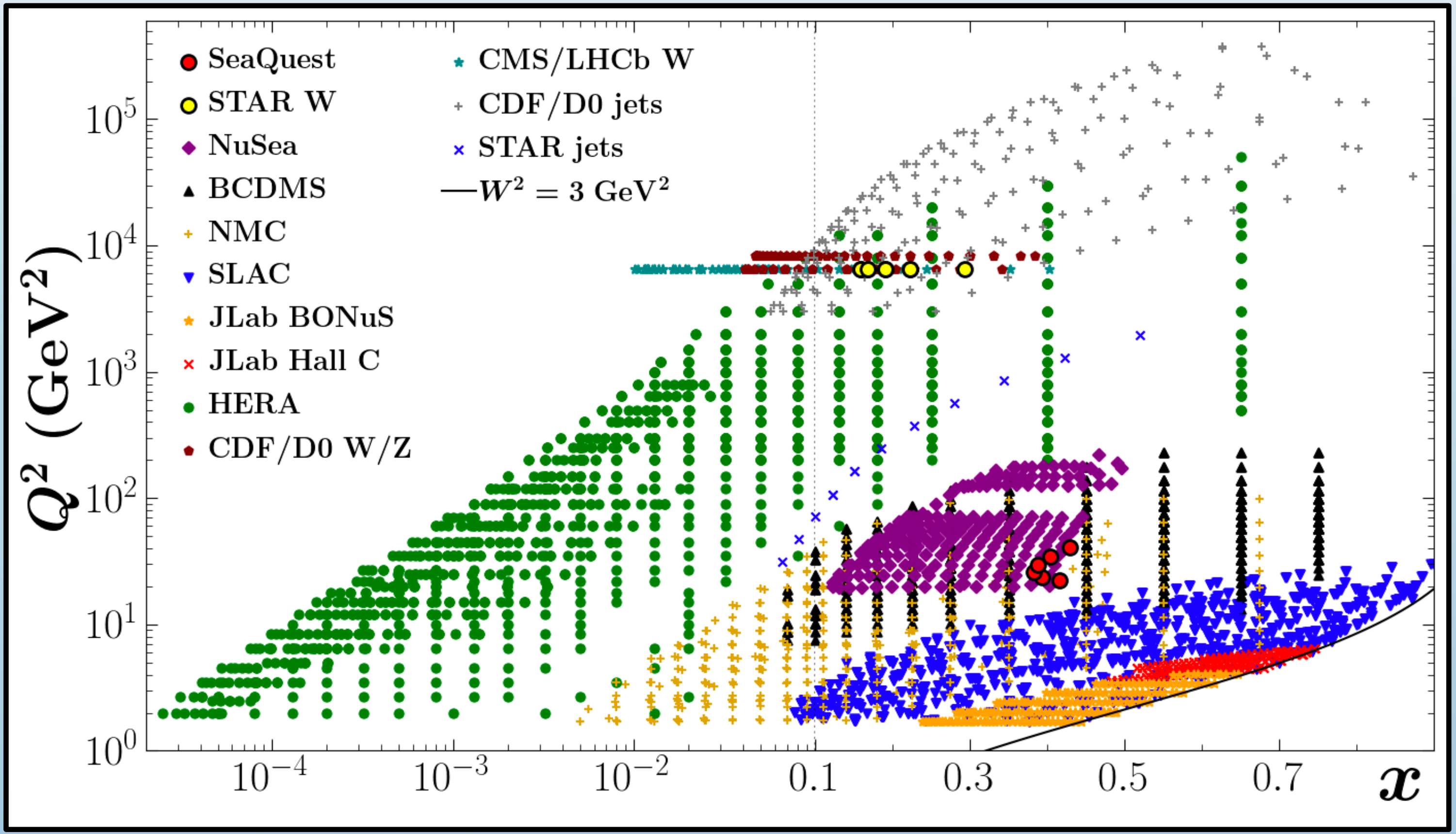






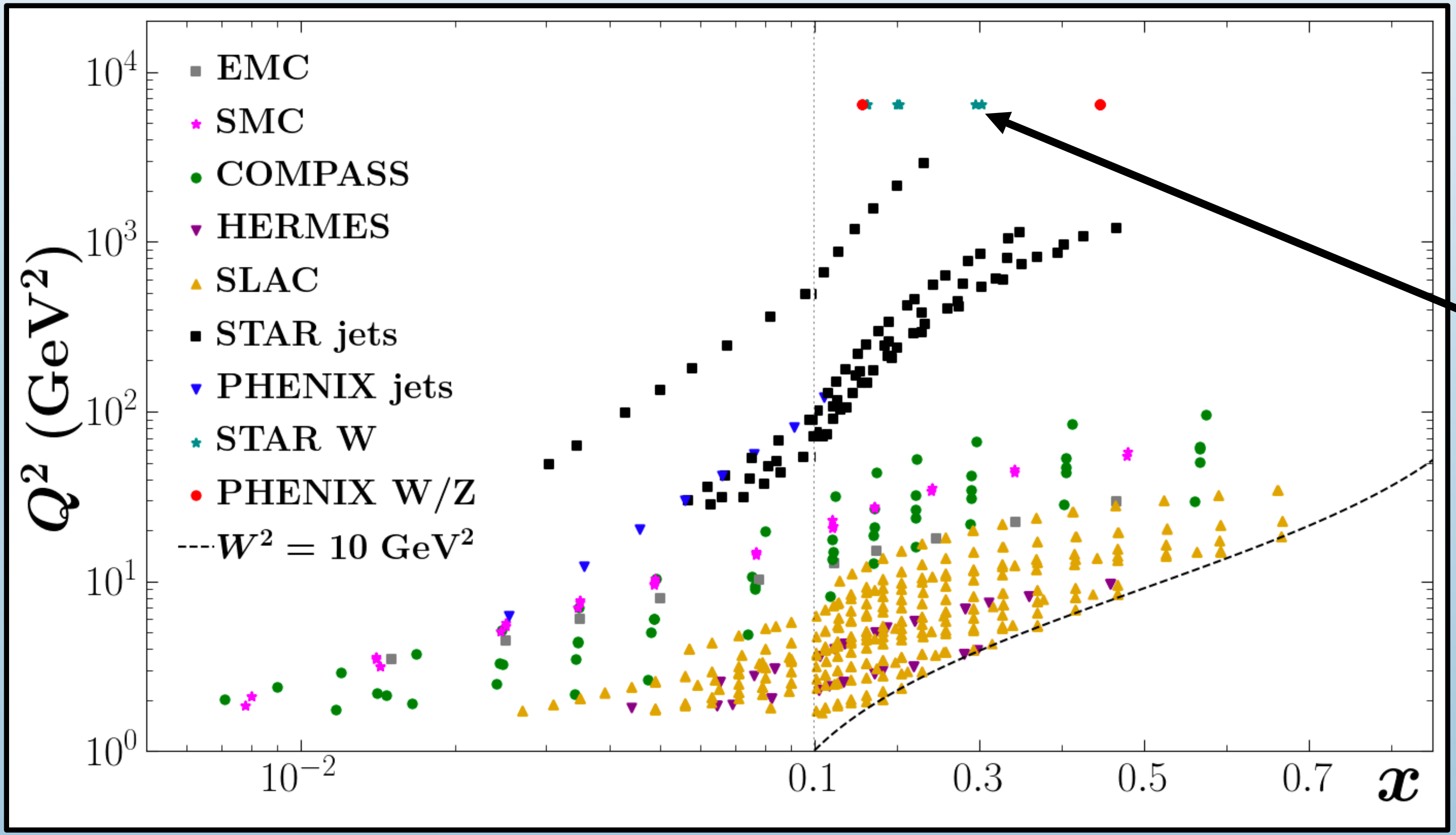
Kinematic Coverage (Spin-Averaged)

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



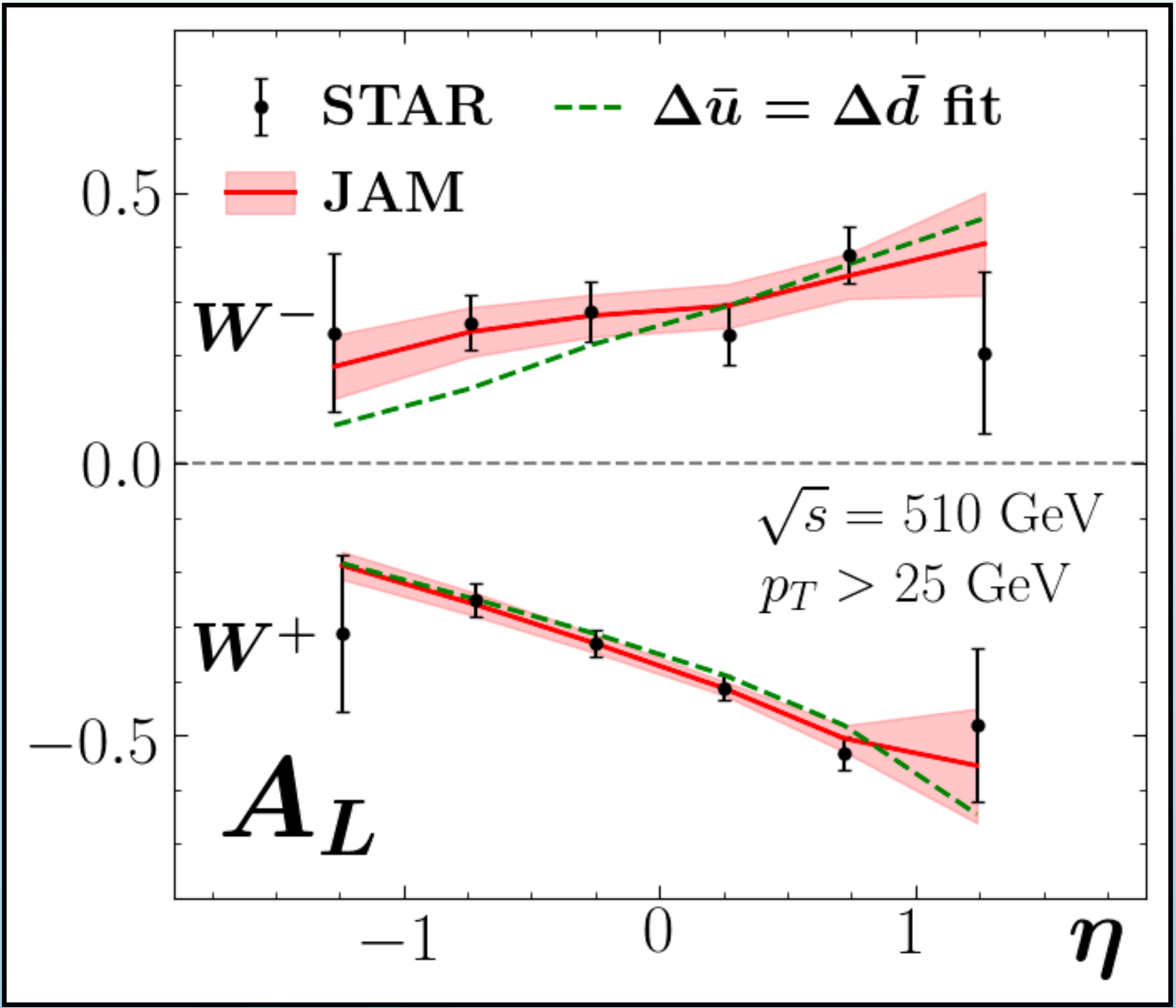
Kinematic Coverage (Helicity)

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



STAR + PHENIX W/Z Production

STAR Quality of Fit

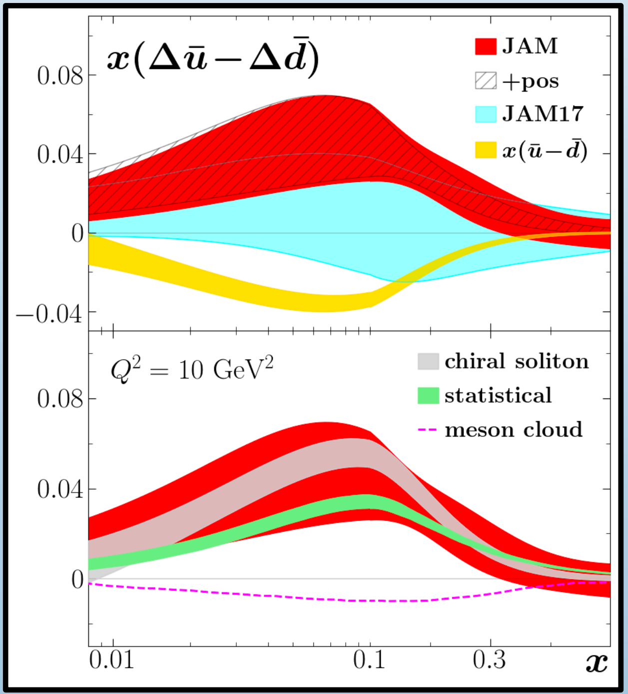


process	N_{dat}	χ^2/N_{dat} JAM	+Pos.	$\Delta\bar{u} = \Delta\bar{d}$
STAR $W^\pm$	12	0.45	0.61	1.53
PHENIX $W^\pm/Z$	6	0.47	0.46	0.48
pol. DIS	365	0.93	0.93	0.93
pol. jet	61	1.00	1.03	1.00
total	**444**	**0.92**	**0.94**	**0.95**

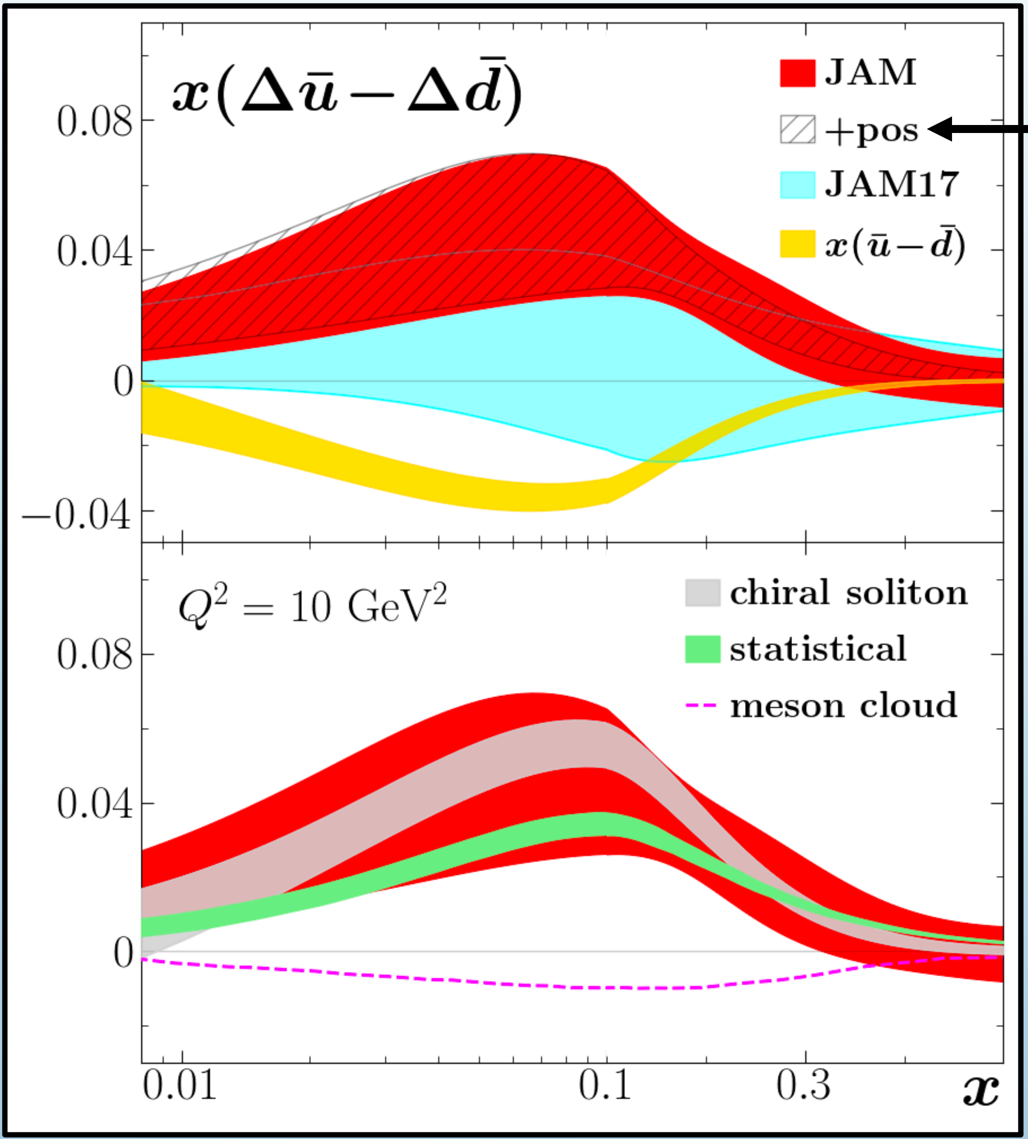
$$A_L^{W^+}(y_W) \propto \frac{\Delta\bar{d}(x_1)u(x_2) - \Delta u(x_1)\bar{d}(x_2)}{\bar{d}(x_1)u(x_2) + u(x_1)\bar{d}(x_2)}$$

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

1. JAM Methodology
2. Data and Fitting
3. **Helicity PDFs**
4. Conclusions and Outlook



Resulting Asymmetry



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

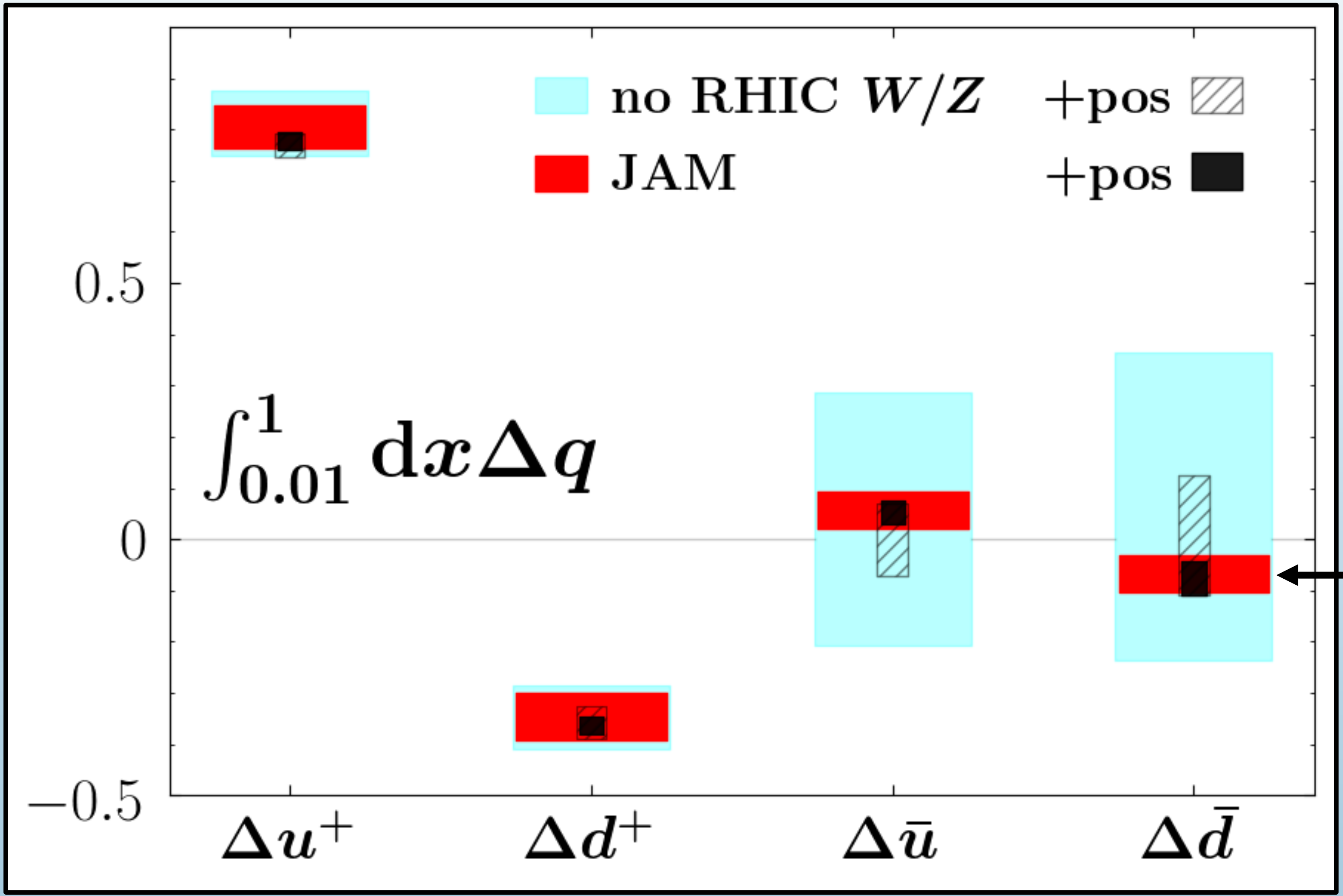
JAM17: inclusive + semi-inclusive DIS data

Agreement with Statistical and Chiral Soliton models

Cannot generate large asymmetry directly from meson cloud

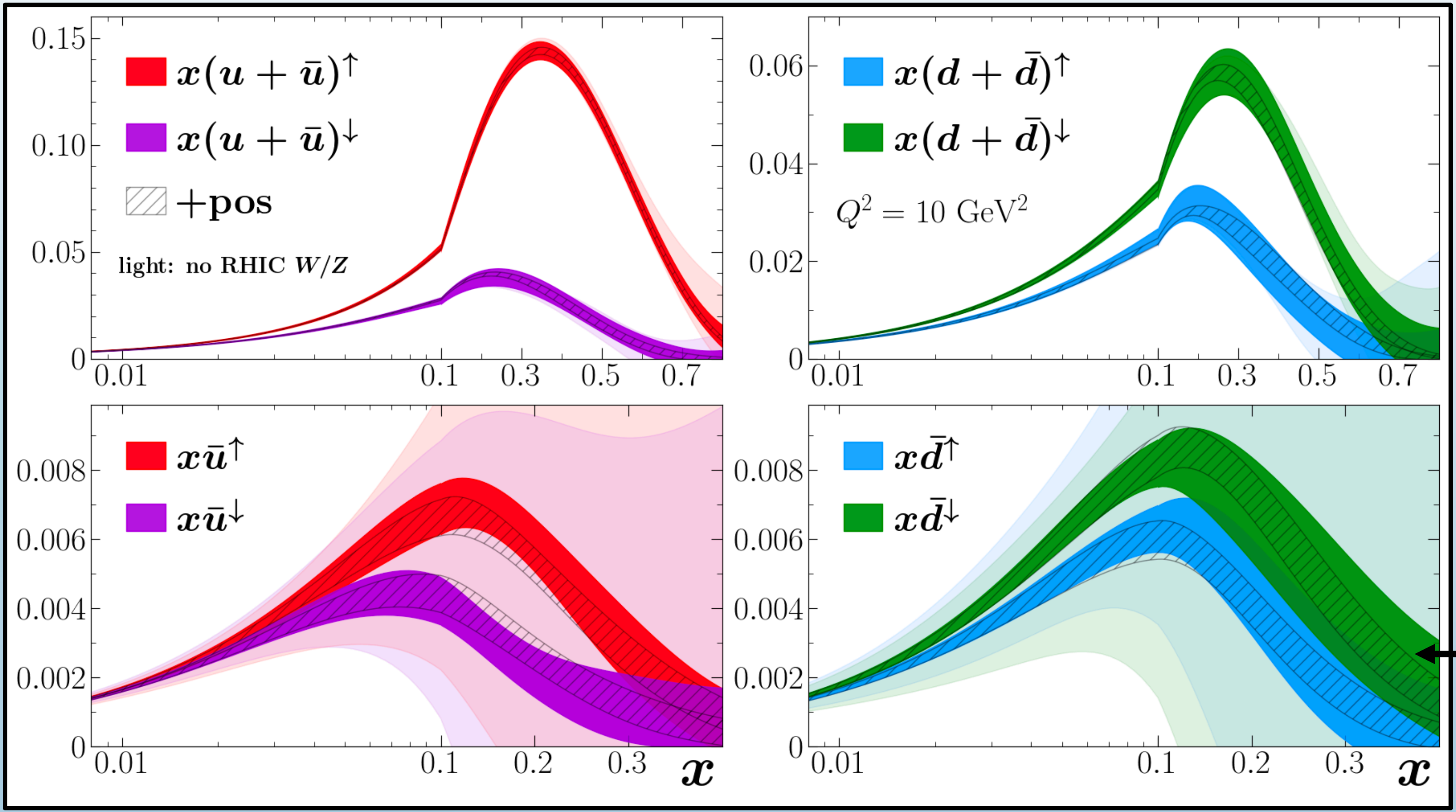
Statistical Model: C. Bourrely and J. Soffer, Nucl. Phys. **A941**, 307-334 (2015)
Meson Cloud Model: F. G. Cao and A. I. Signal, Phys. Rev. D. **68**, 074002 (2003)
Chiral Soliton Model: M. Wakamatsu and T. Watabe, Phys. Rev. D. **874**, 38-84 (2013)

Proton Spin Contributions



Inclusion of RHIC W/Z data shows that $\Delta\bar{u}$ ($\Delta\bar{d}$) contribution is small and positive (negative)

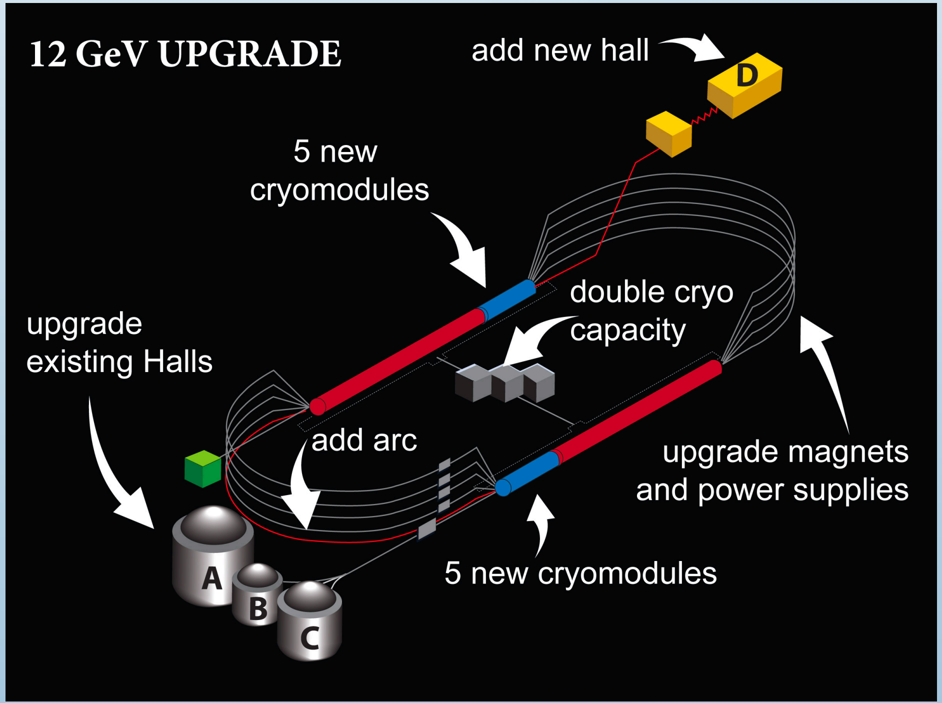
Spin Up/Down PDFs



$$q^{\uparrow\downarrow} = \frac{1}{2}(q \pm \Delta q)$$

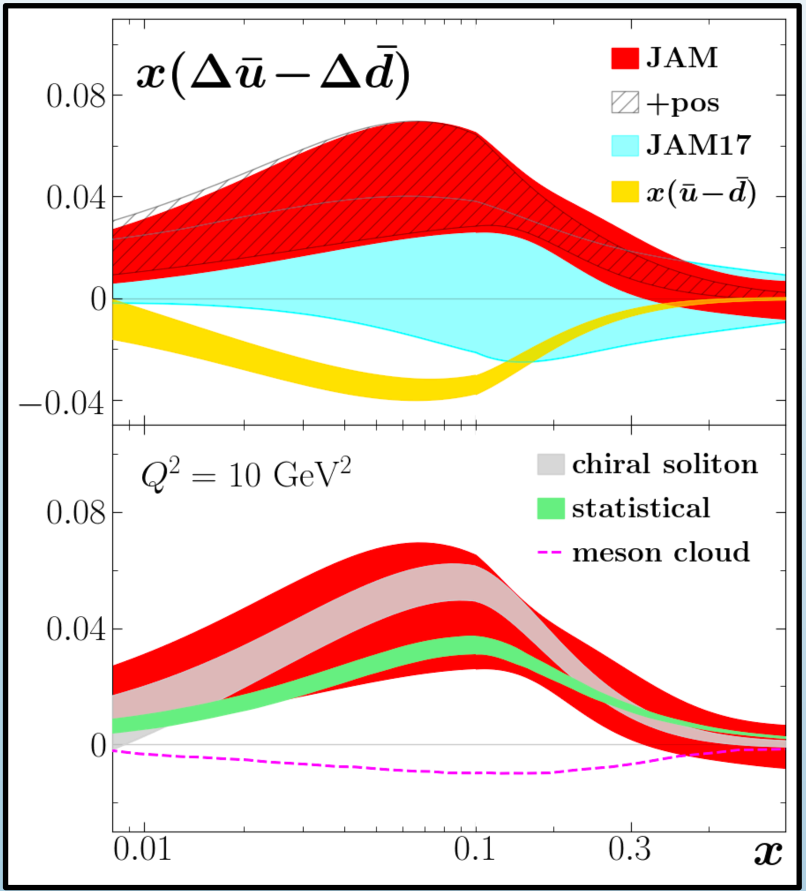
Large impact from RHIC

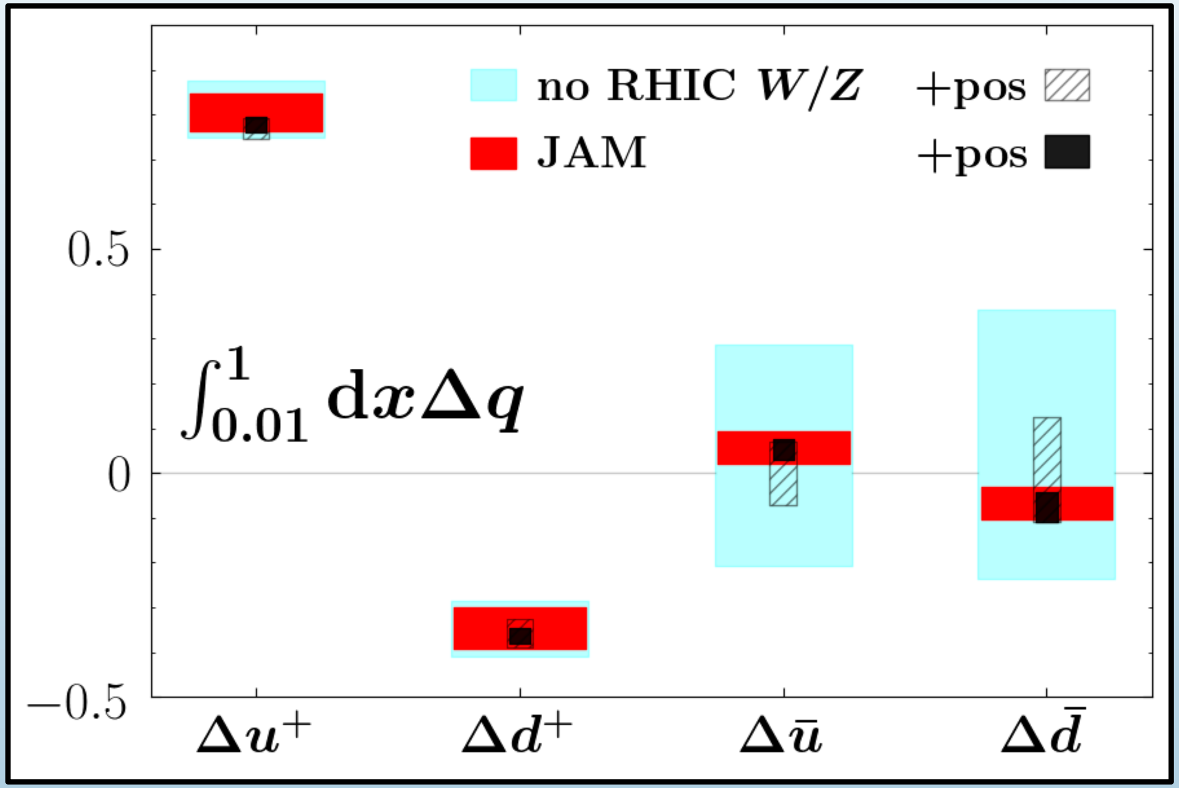
1. JAM Methodology
2. Data and Fitting
3. Helicity PDFs
4. Conclusions and Outlook



Results Summary

First global QCD analysis of latest STAR *W* data





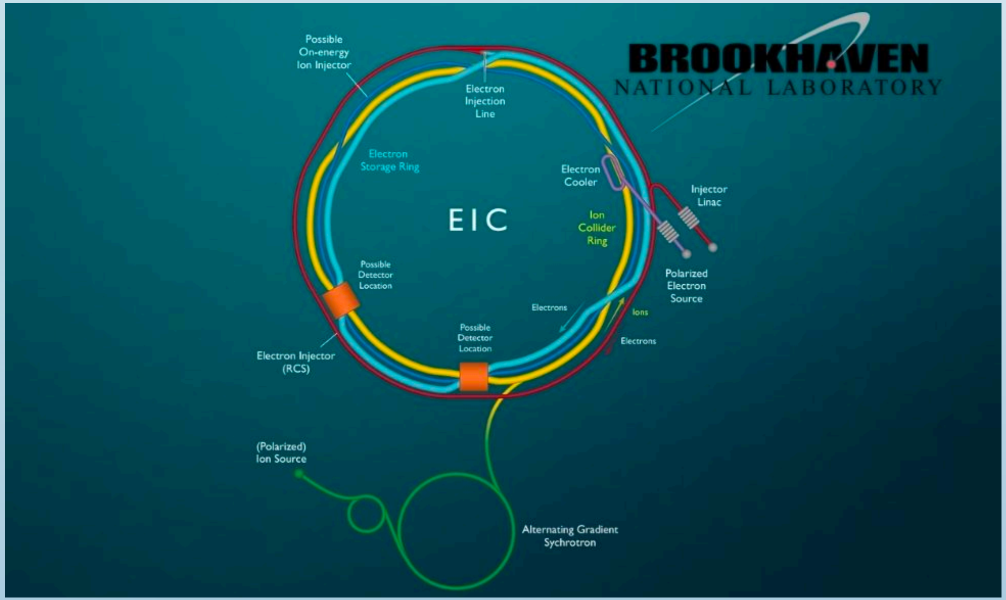
Simultaneous global QCD analysis of spin-averaged and helicity PDFs

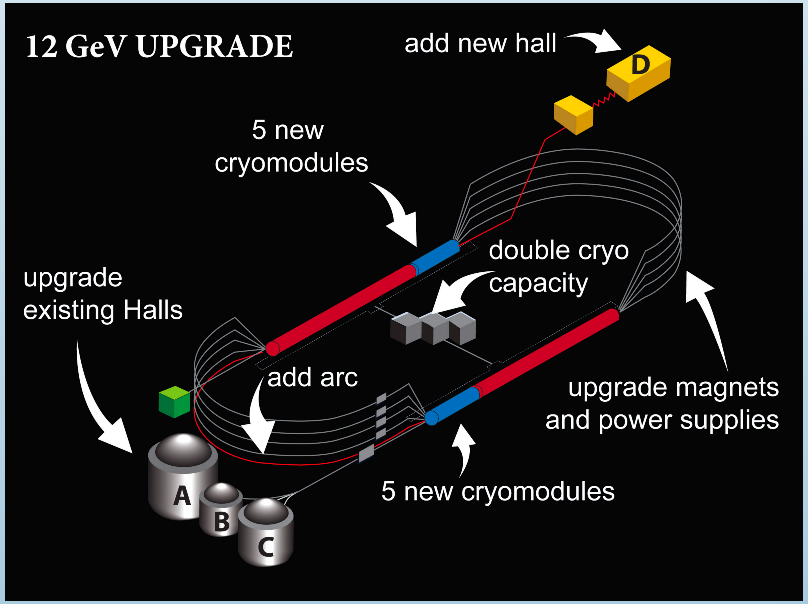
Outlook

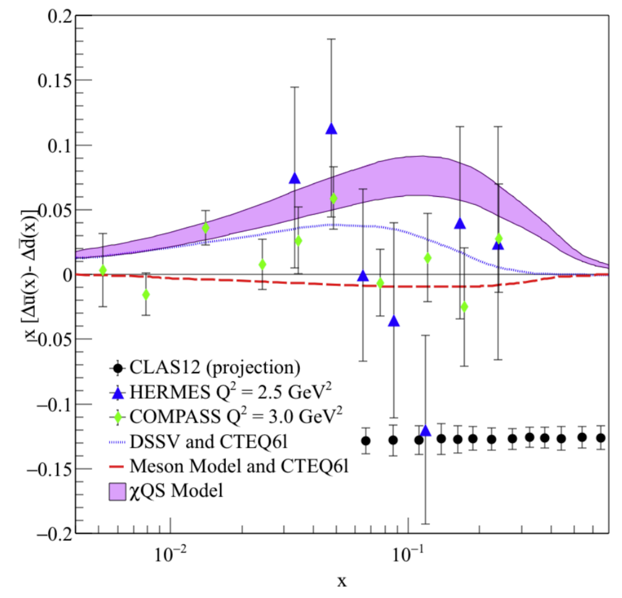
Combine analysis with semi-inclusive DIS data from HERMES, COMPASS.

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

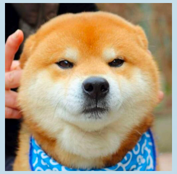
Andreas Metz

Wally Melnitchouk

Nobuo Sato

JAM Jefferson Lab Angular Momentum Collaboration

Thank you to Jacob Ethier, Yiyu Zhou, and Patrick Barry for helpful discussions

Extra Slides

Bayes' Theorem

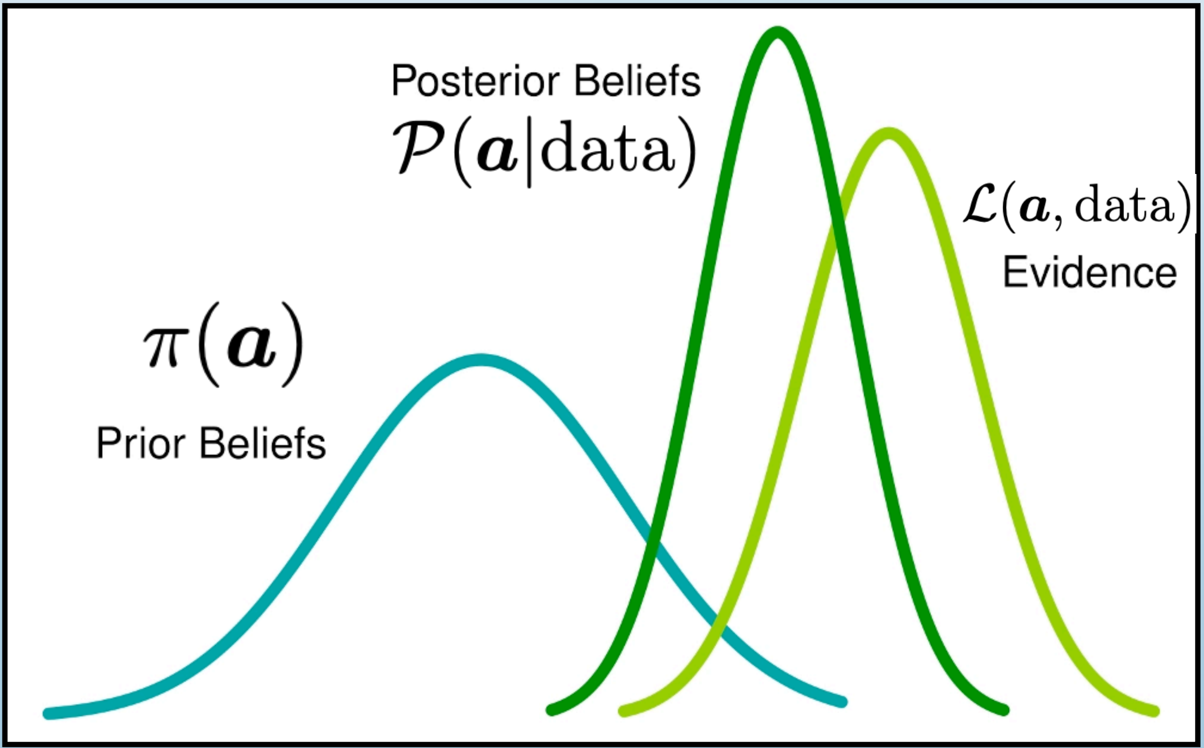
Now that we have calculated $\chi^2(\boldsymbol{a}, \text{data})$…

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

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



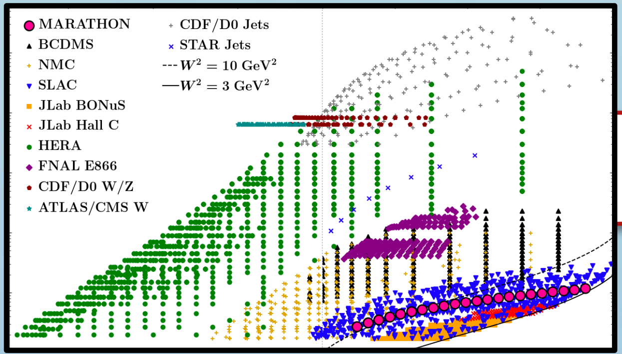
Data Resampling

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

↑

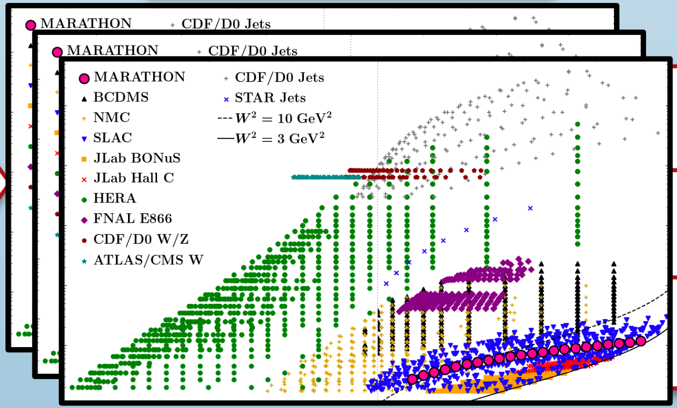
Data

Original Data



DR

Replica Data

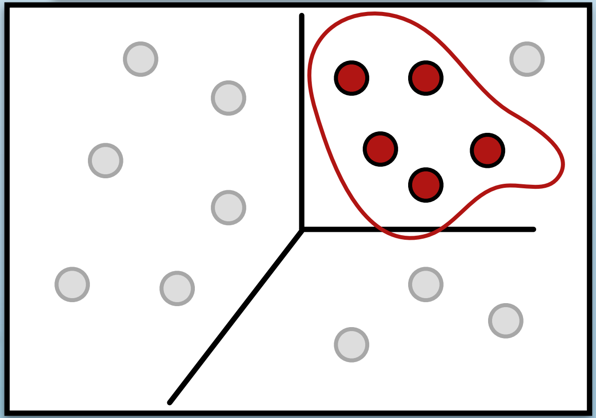


Maximum Likelihood

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))

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

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

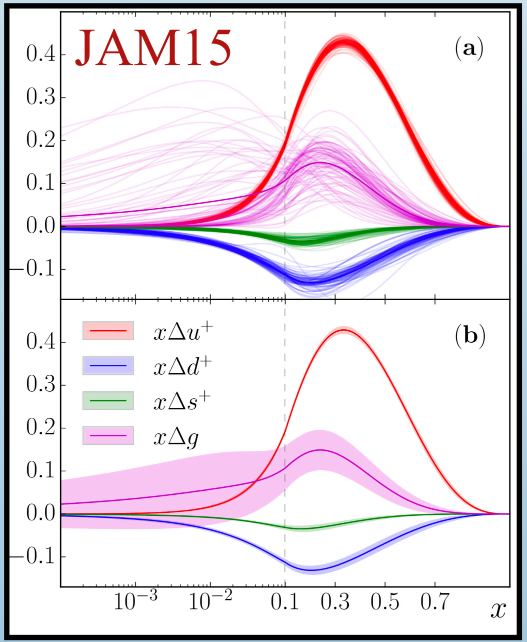
Exact, but $n = \mathcal{O}(100)$!

Build an MC ensemble

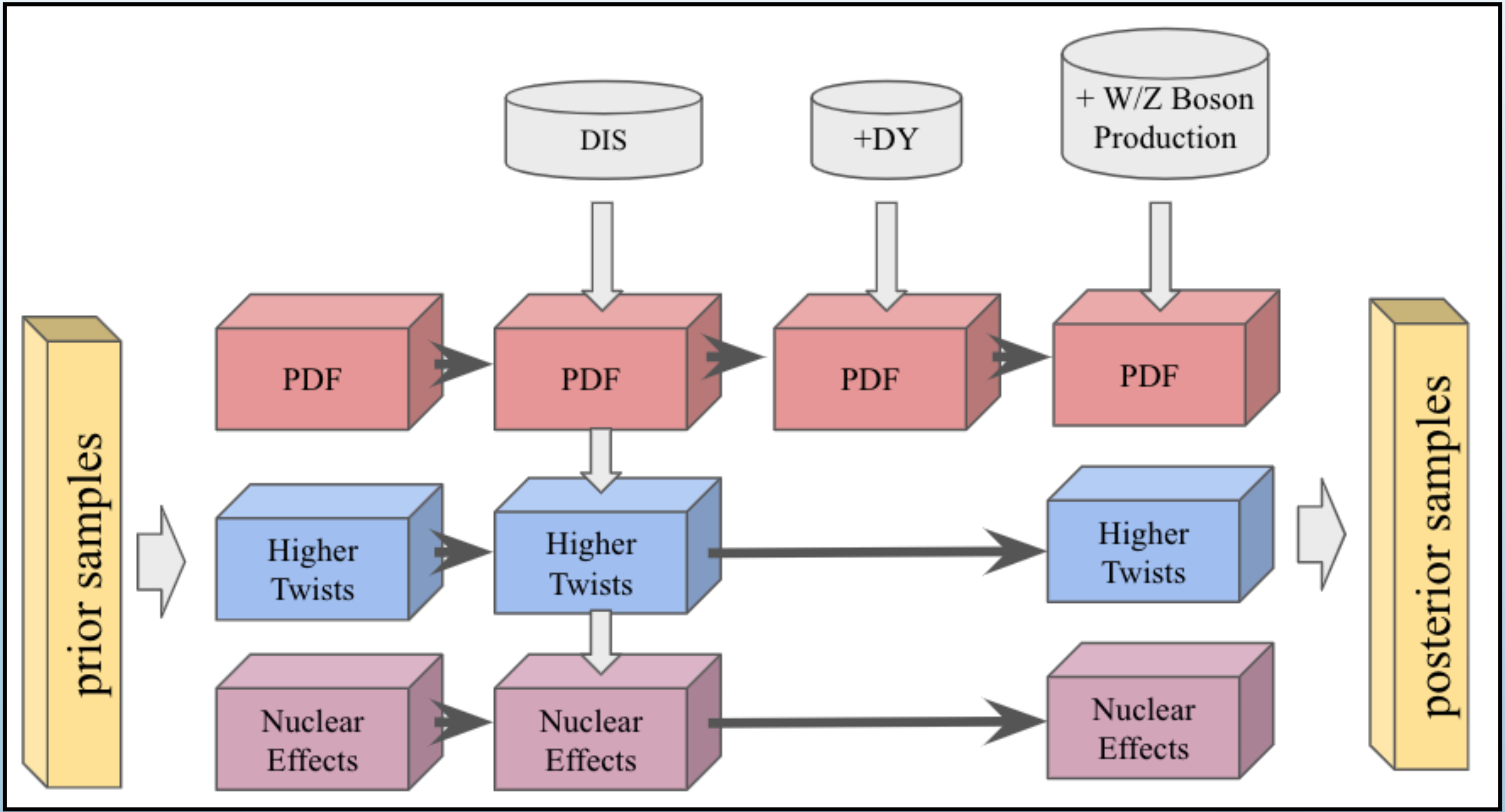
$$E[O] \approx \frac{1}{N} \sum_k O(\boldsymbol{a}_k)$$

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

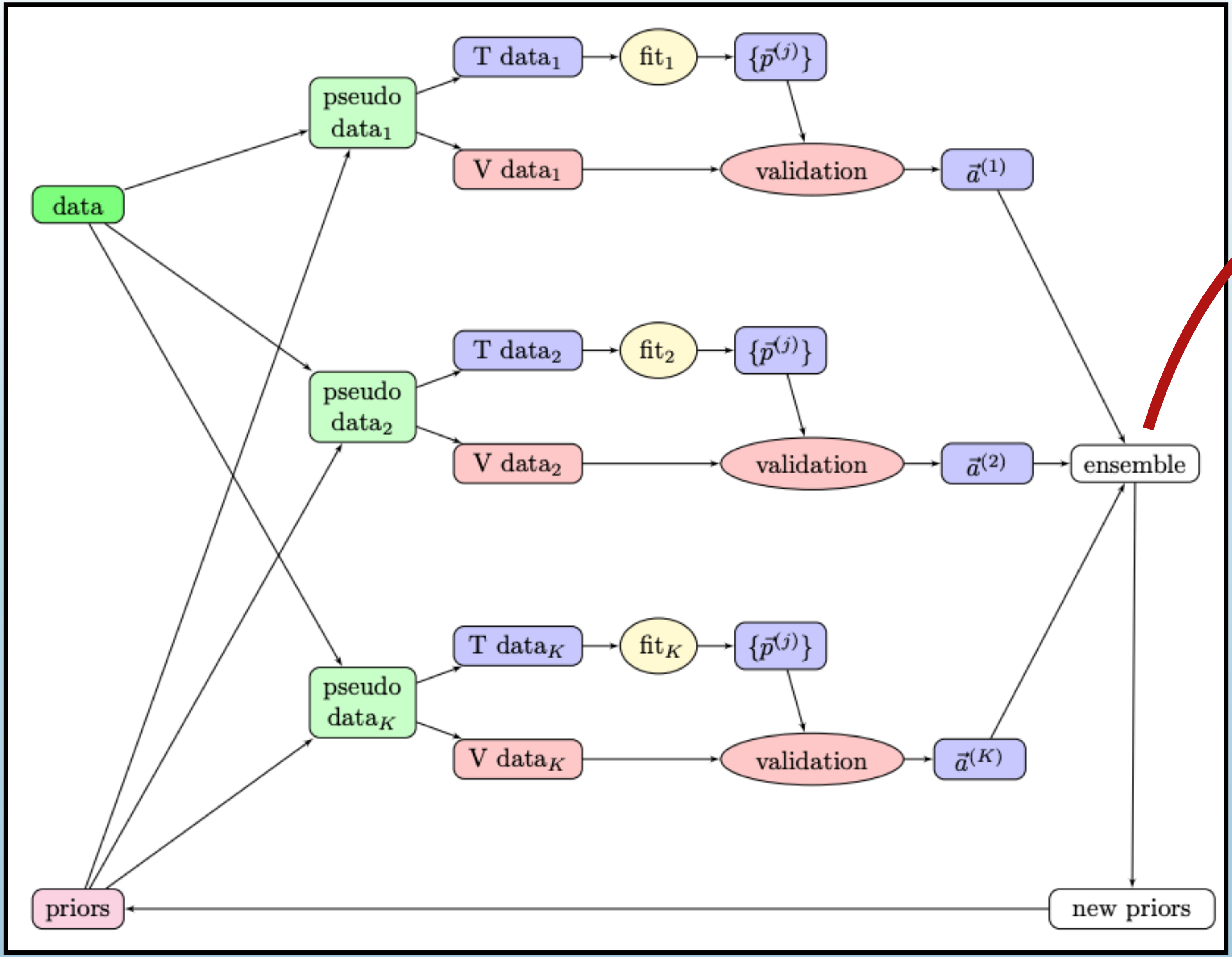
Average over k sets of the parameters (replicas)

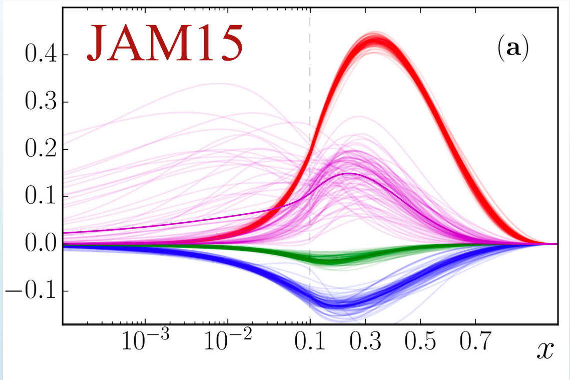


Multi-Step Strategy



Putting it all together…

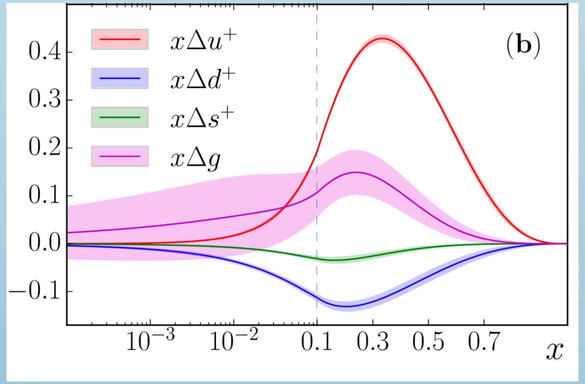




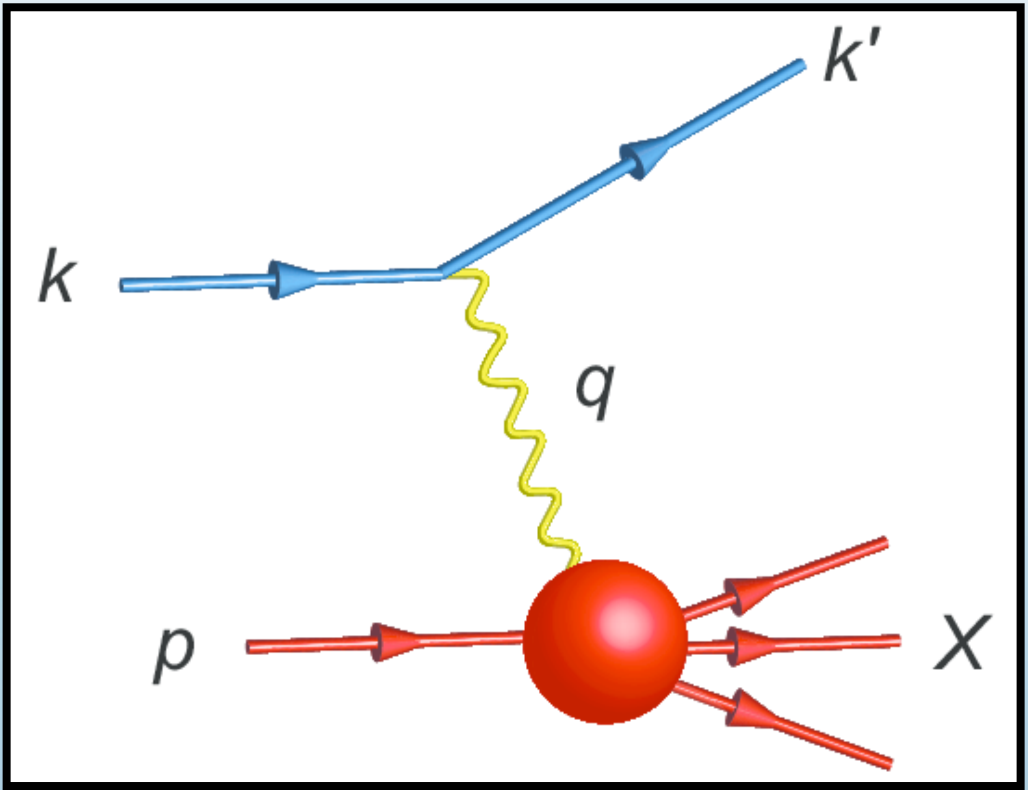
+

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

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



Deep Inelastic Scattering



Virtuality:

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

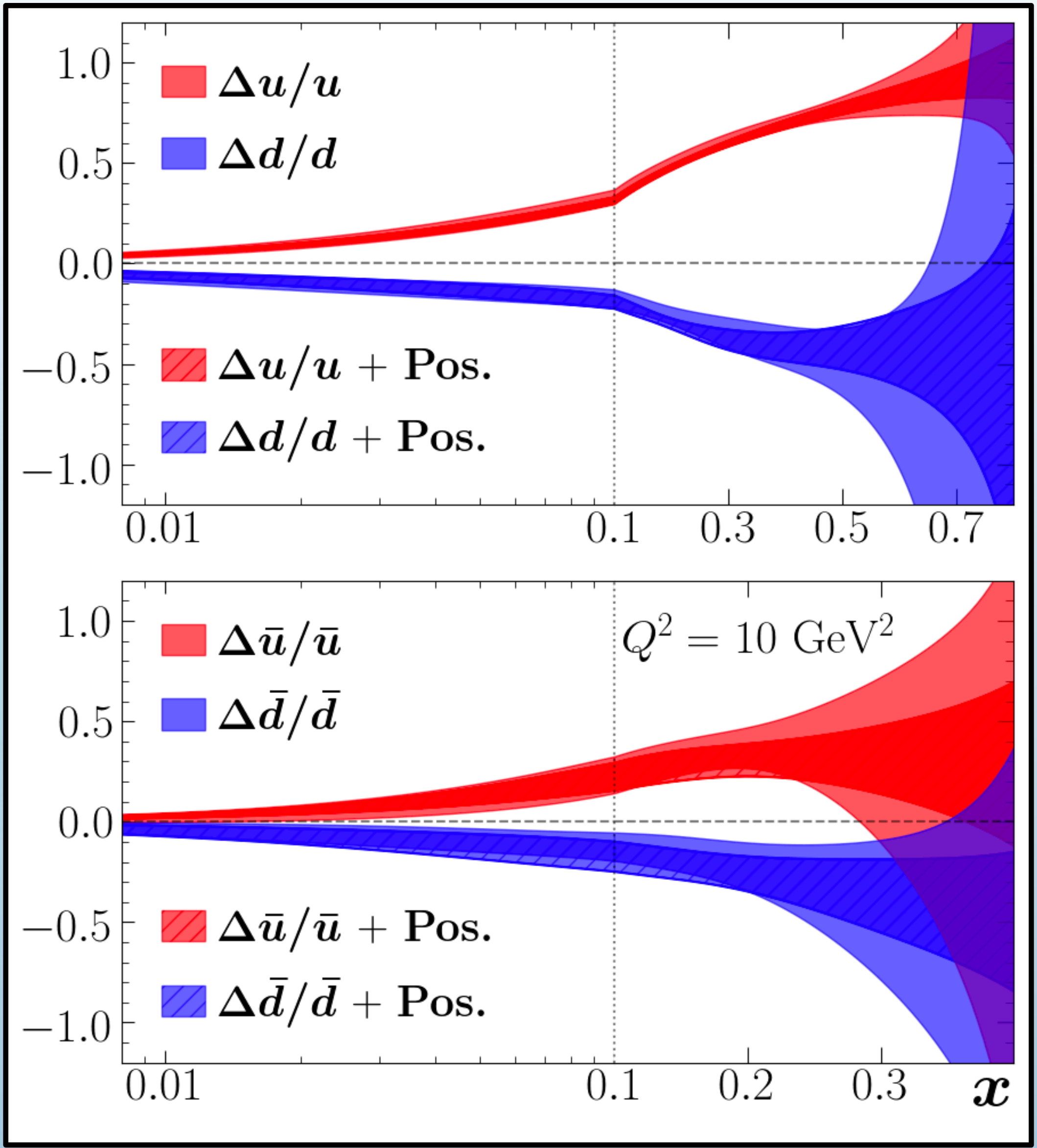
Bjorken x:

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

Invariant mass of outgoing particles:

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

Quark and Antiquark Polarizations



First self-consistent extraction using *simultaneous* fit

Antiquark ratios have same signs as quark ratios