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

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September 5, 2021

Jefferson Lab Angular Momentum Collaboration

22nd edition
PANIC Lisbon Portugal
Particles and Nuclei International Conference

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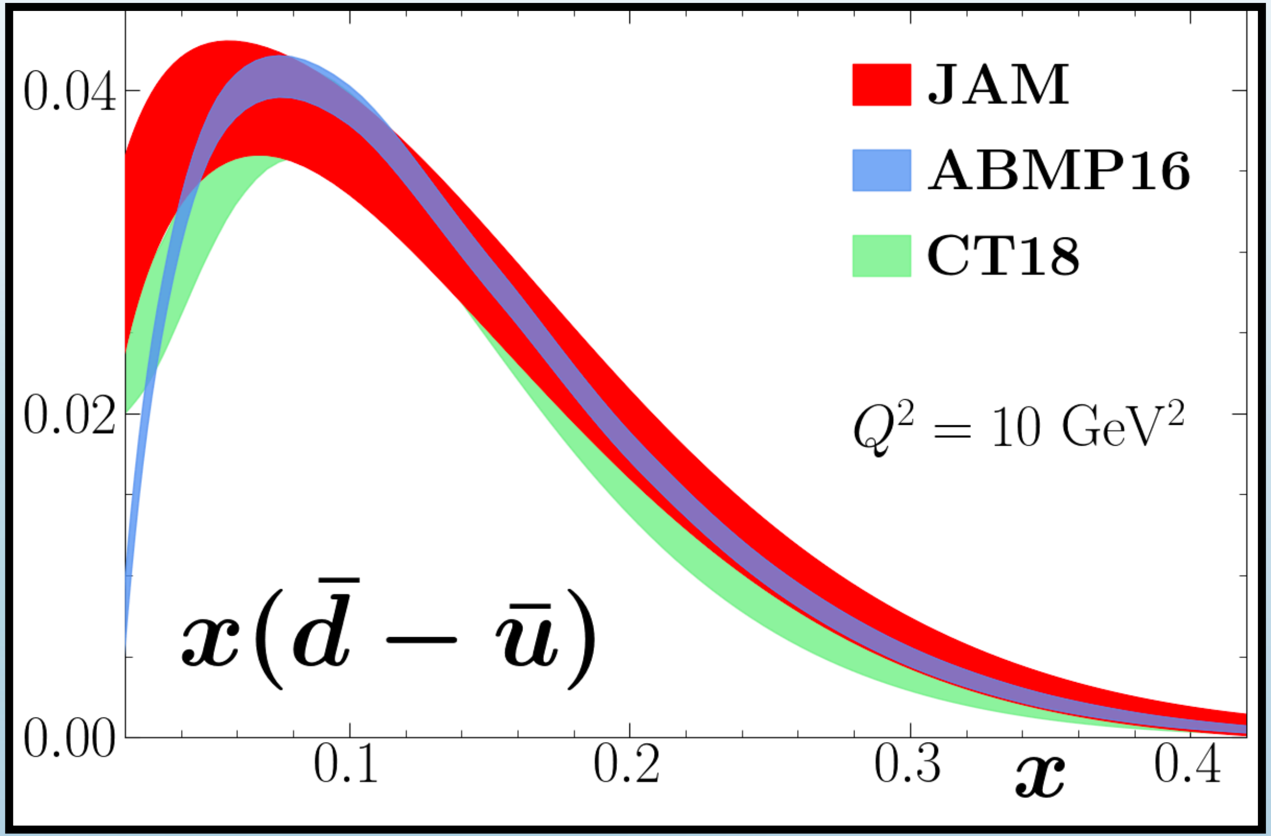
Nobuo Sato (Jefferson Lab)

Introduction to Sea Asymmetry

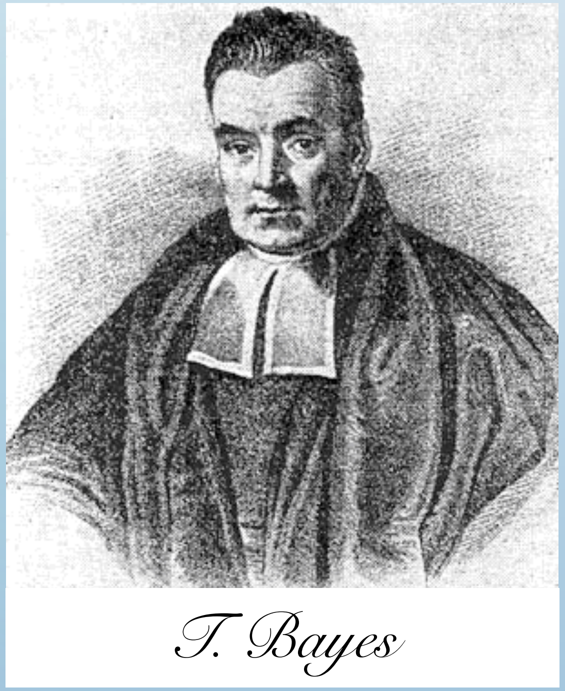


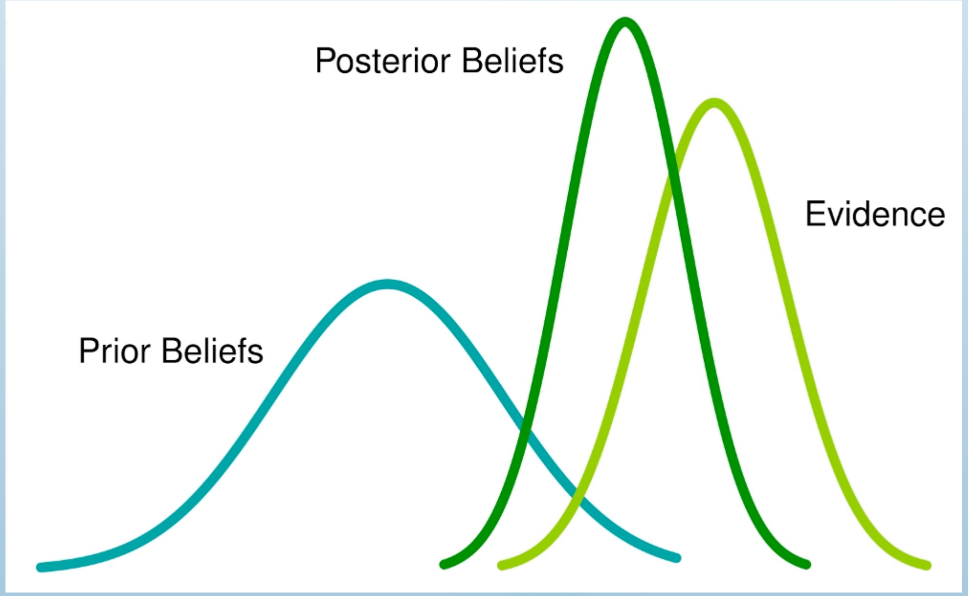
Cannot be explained from gluons splitting into quark-antiquark pairs

Meson Cloud Models
Chiral Soliton Models
Statistical Models

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

Part 1: JAM Methodology





JAM Collaboration

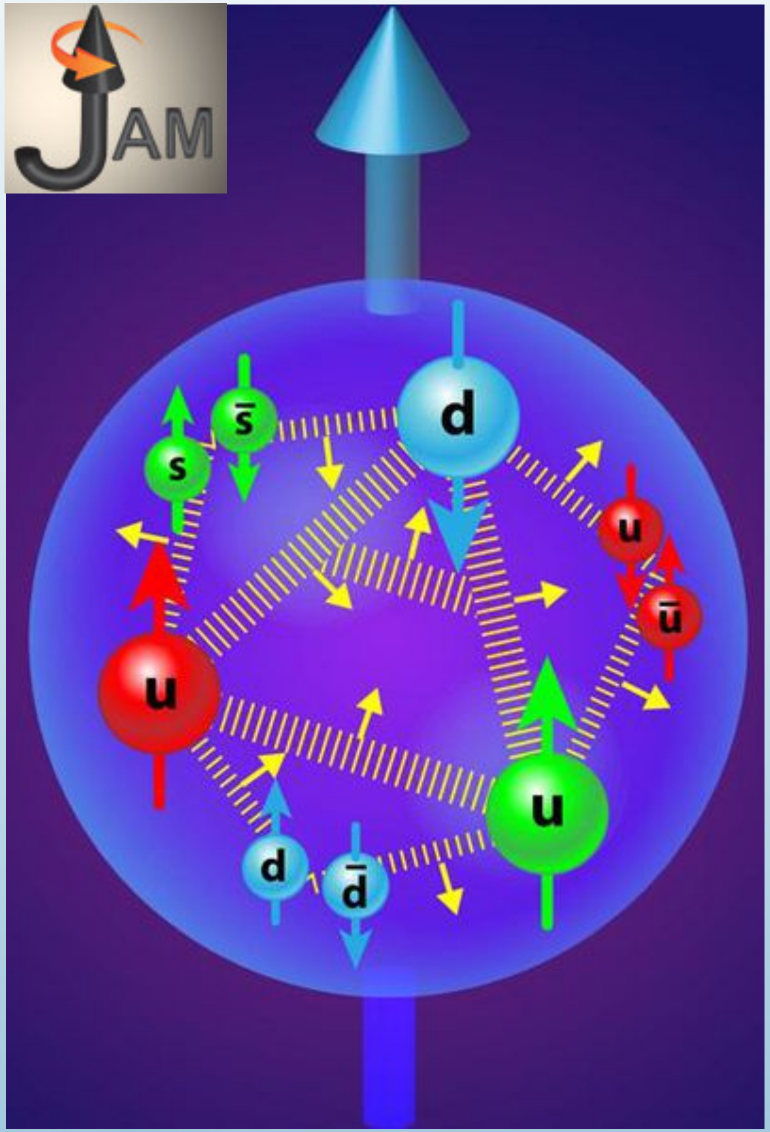
3-dimensional structure of nucleons:

- 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 $Q_0^2 = m_c^2$

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

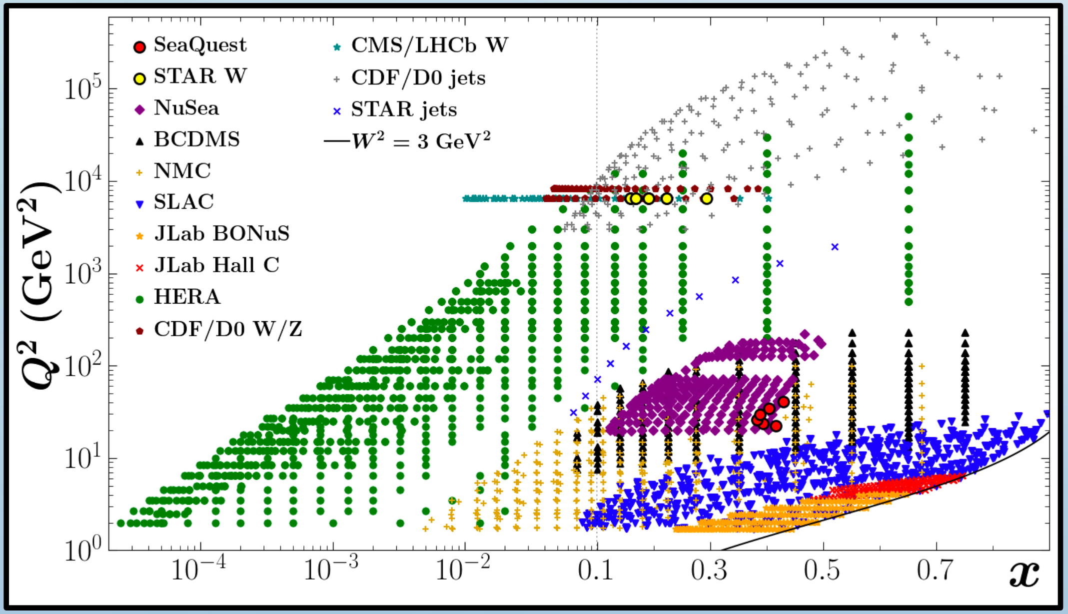
Evolve PDFs using DGLAP

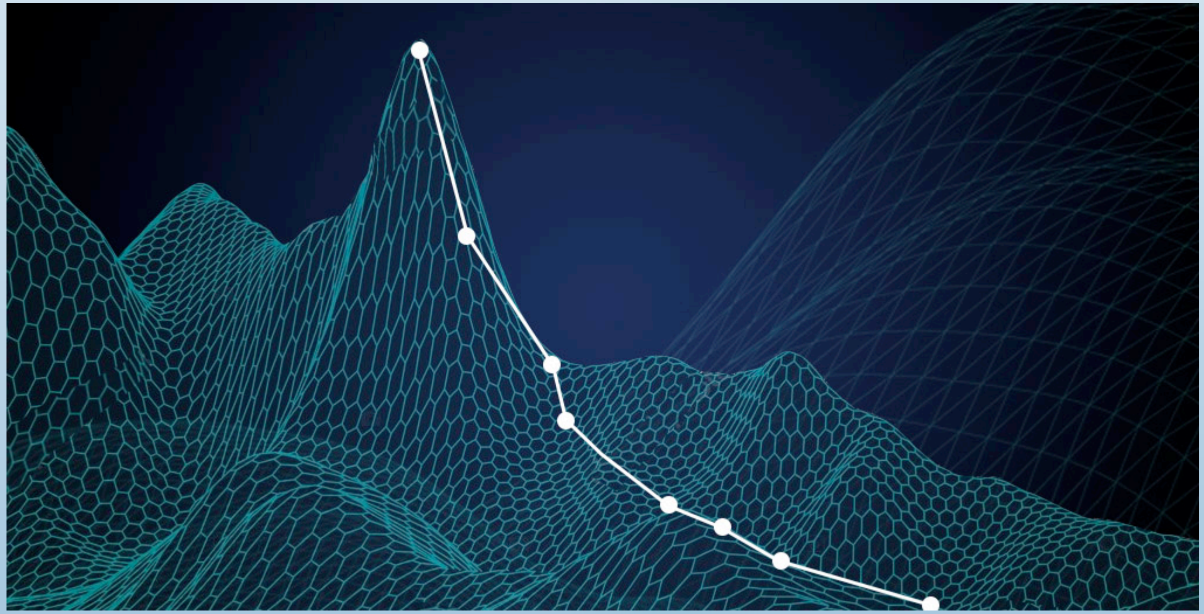
$$\frac{\mathrm{d}}{\mathrm{d}\ \ln(\mu^2)} f_i(x,\mu) = \sum_j \int_x^1 \frac{dz}{z} P_{ij}(z,\mu) f_j(\frac{x}{z},\mu)$$

Calculate Observables

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

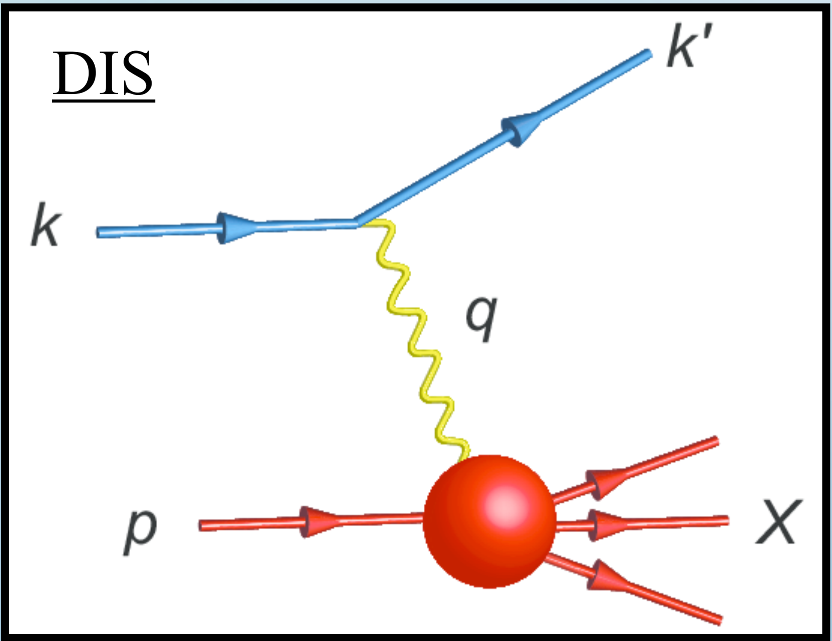
Part 2: Data and Fitting

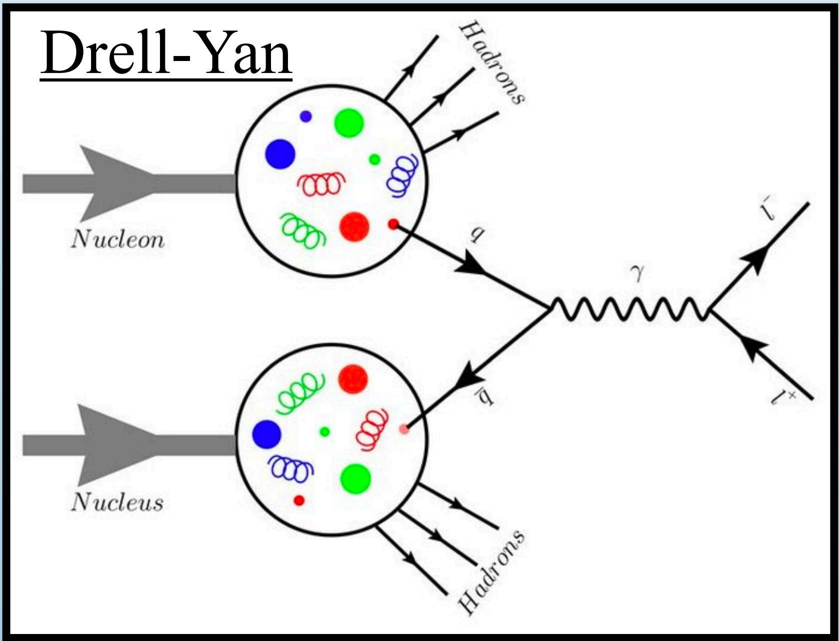


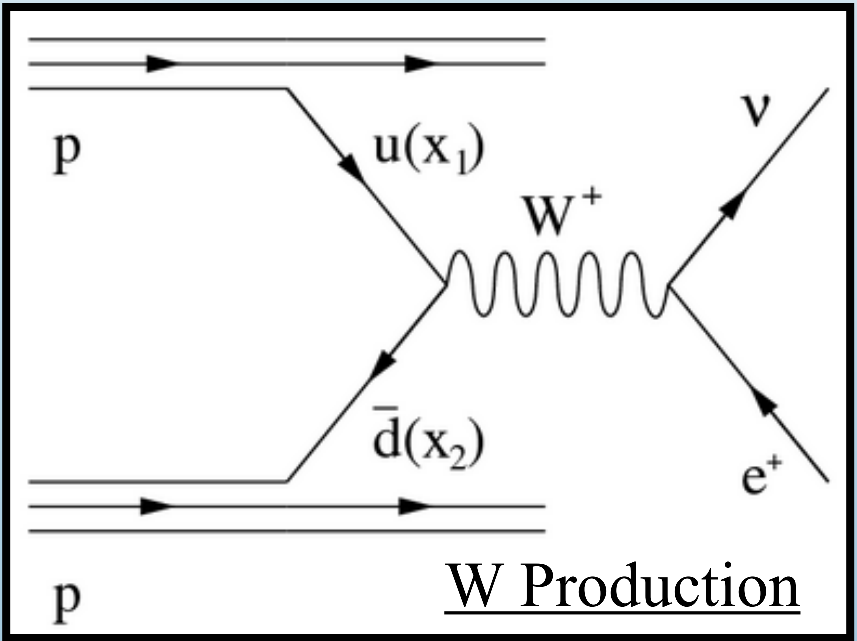


A Global Analysis

Simultaneous extraction of
spin-averaged and helicity PDFs

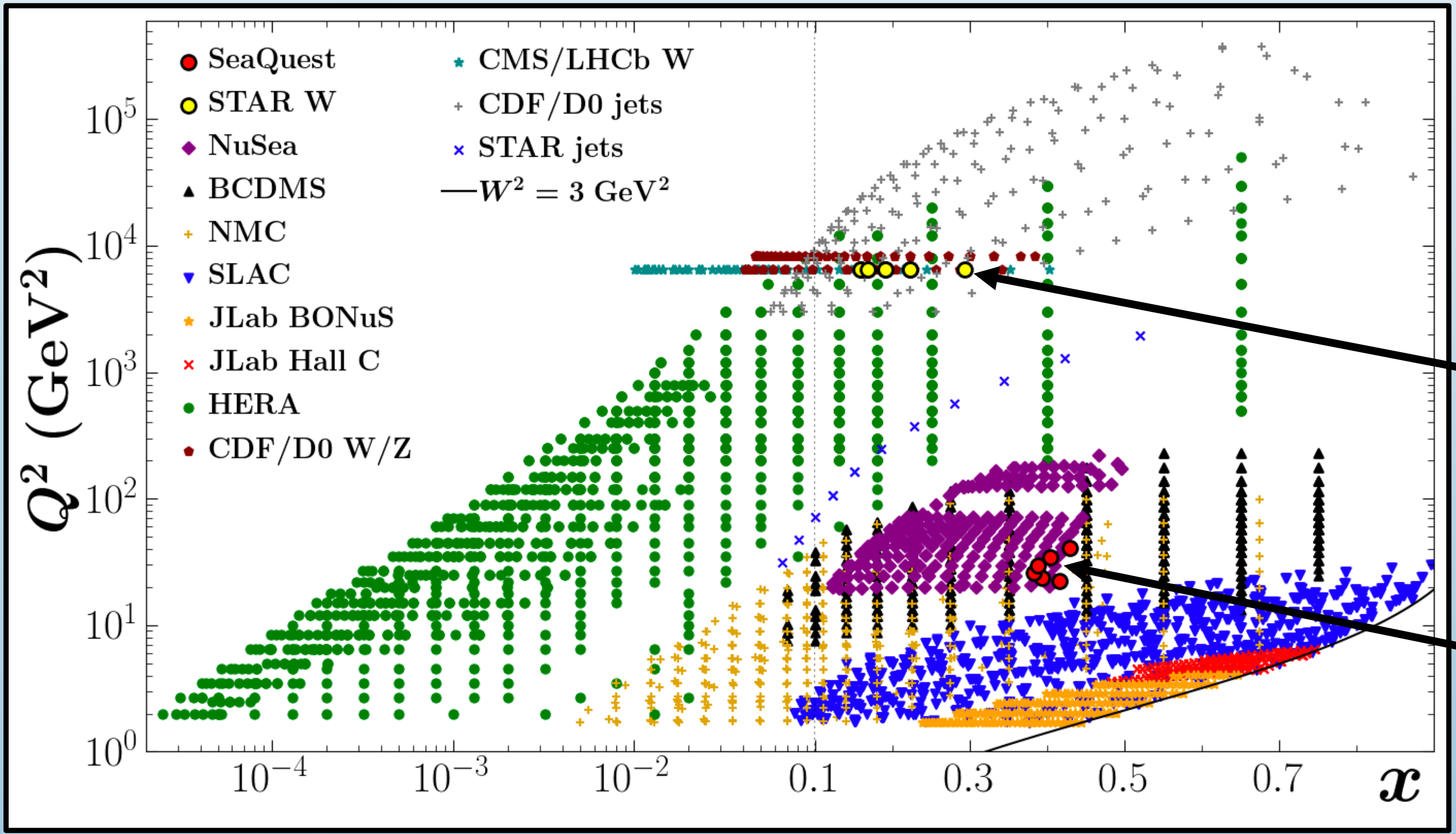






Kinematic Coverage (Spin-Averaged)

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

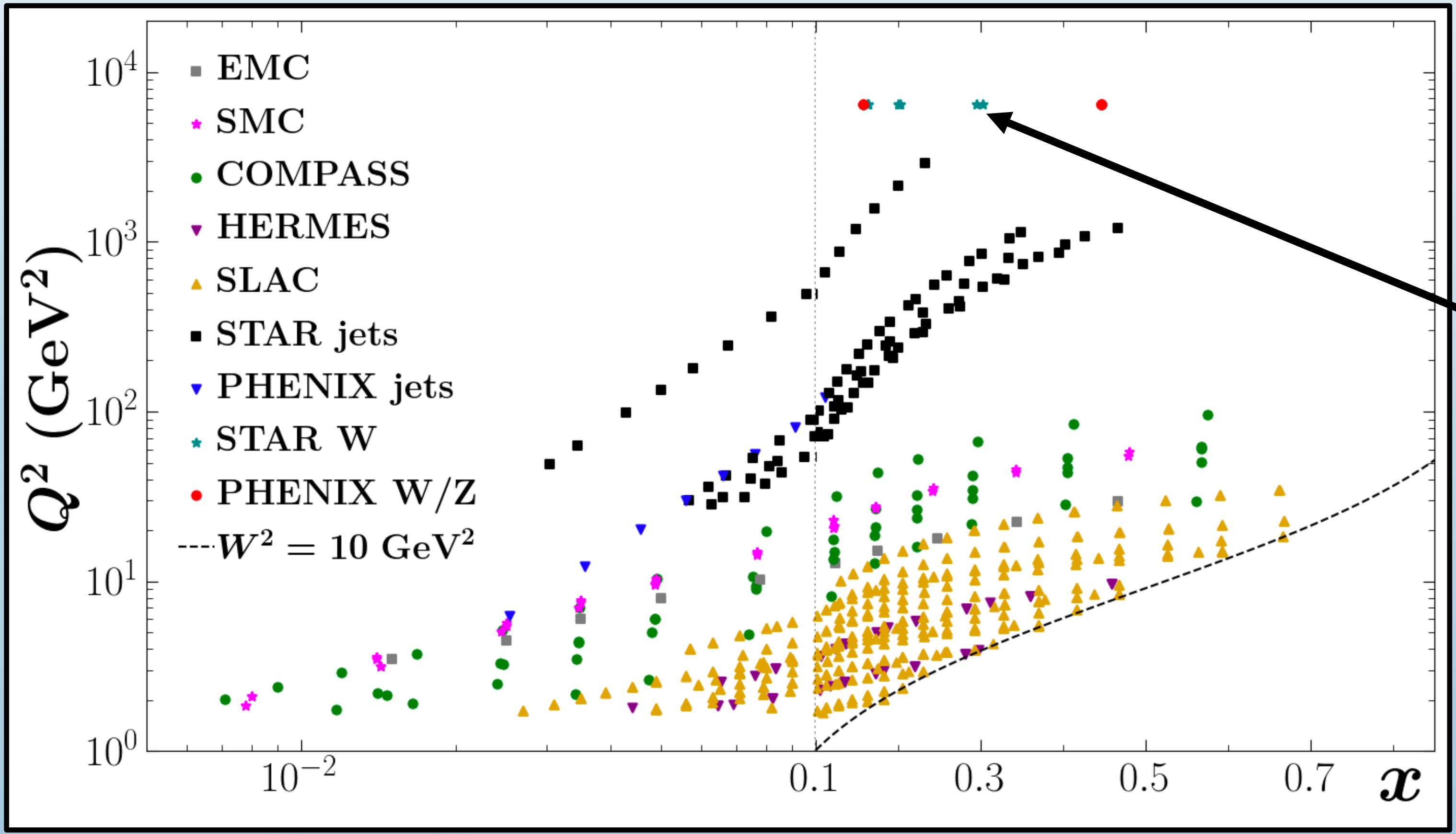


New STAR data

New SeaQuest data

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

Part 3: Spin-Averaged PDFs

High Energy Physics – Phenomenology

[Submitted on 2 Sep 2021]

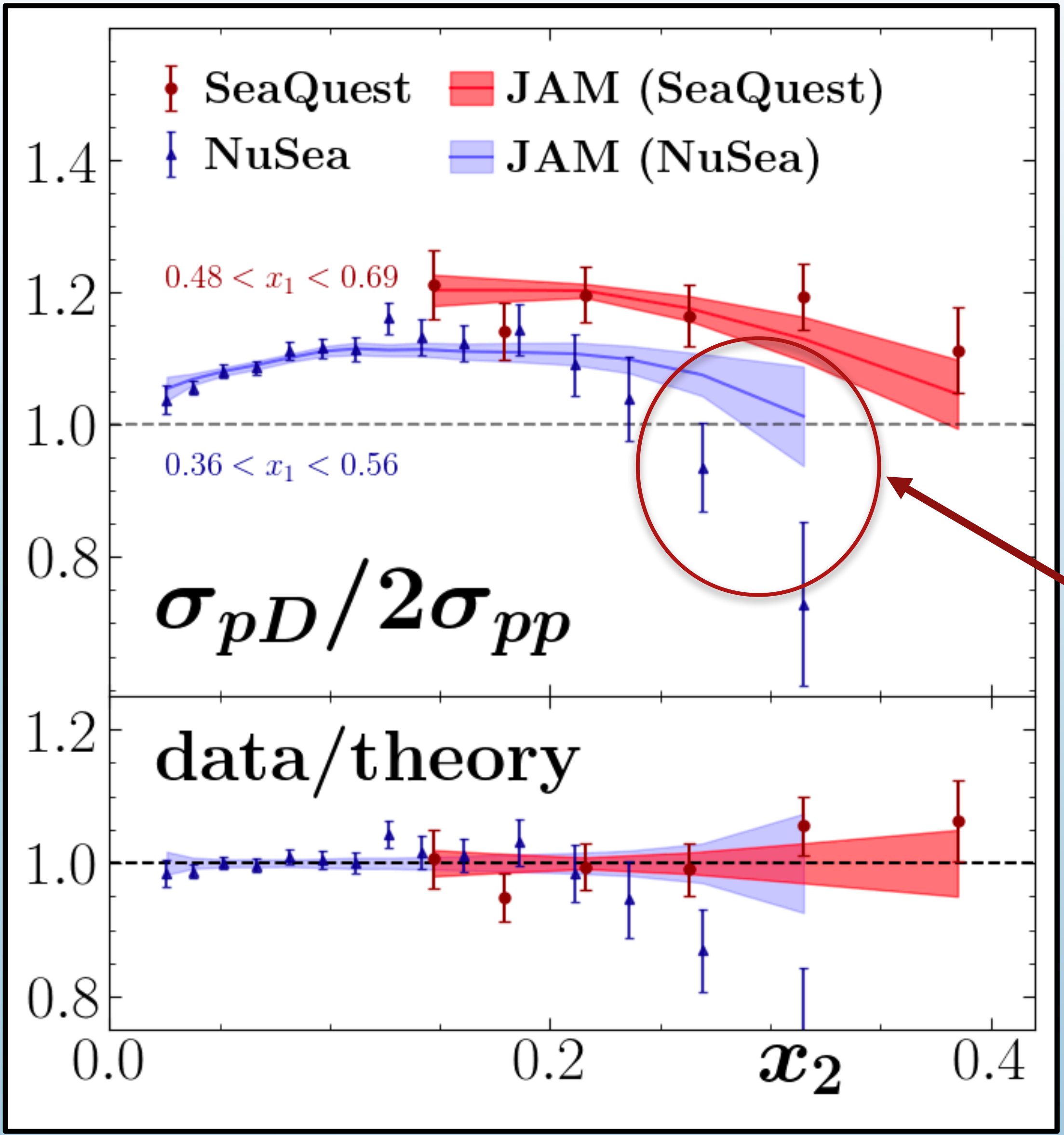
Bayesian Monte Carlo extraction of sea asymmetry with SeaQuest and STAR data

Christopher Cocuzza, Wally Melnitchouk, Andreas Metz, Nobuo Sato

We perform a global QCD analysis of unpolarized parton distributions within a Bayesian Monte Carlo framework, including the new W-lepton production data from the STAR Collaboration at RHIC and Drell-Yan di-muon data from the SeaQuest experiment at Fermilab. We assess the impact of these two new measurements on the light antiquark sea in the proton, and the $\bar{d}-\bar{u}$ asymmetry in particular. The SeaQuest data are found to significantly reduce the uncertainty on the $\bar{d}/\bar{u}$ ratio at large parton momentum fractions x, strongly favoring an enhanced $\bar{d}$ sea up to $x \approx 0.4$, in general agreement with nonperturbative calculations based on chiral symmetry breaking in QCD.

https://arxiv.org/abs/2109.00677

SeaQuest and NuSea Quality of Fit

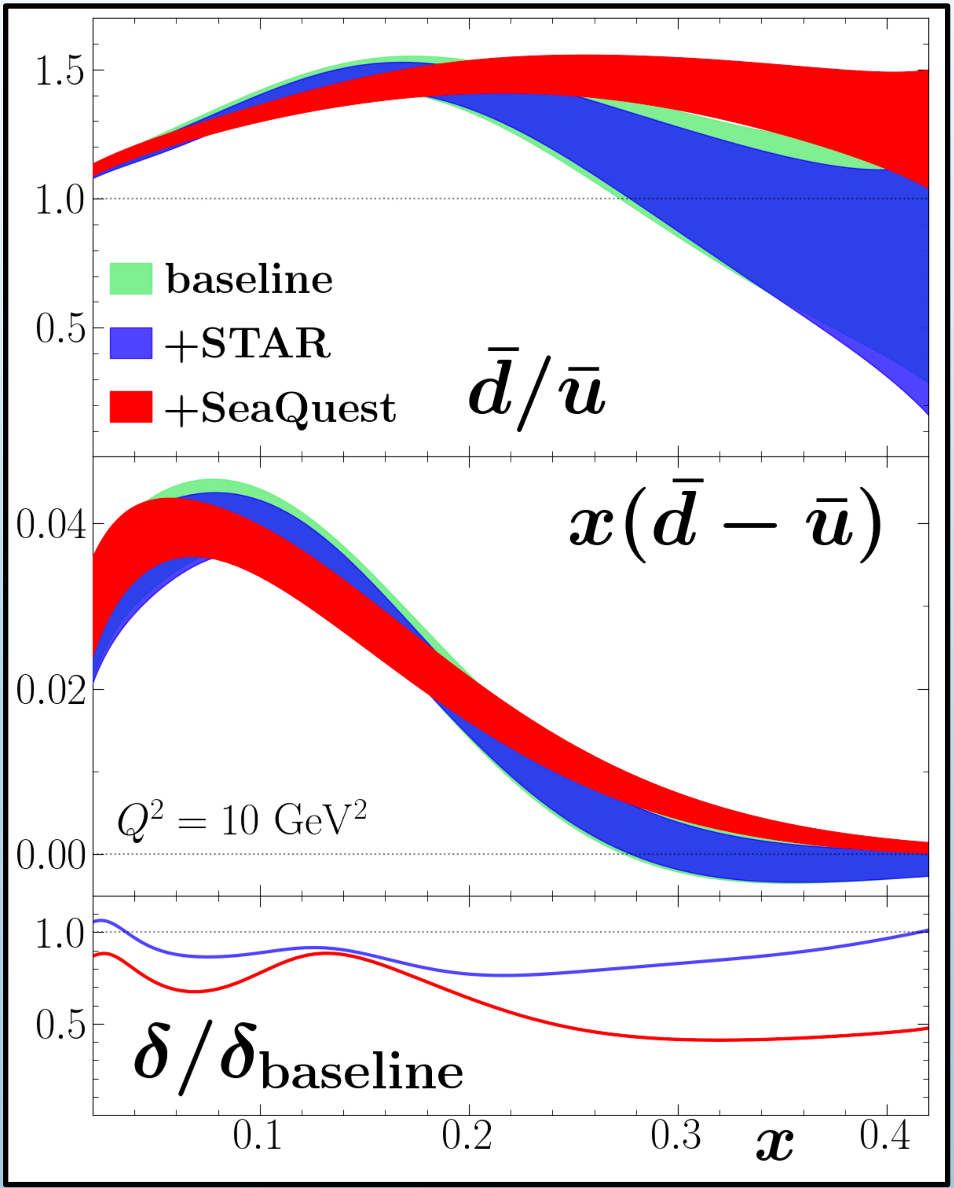


process		$N_{\rm dat}$	$\chi^2/N_{\rm dat}$
Drell-Yan			
NuSea	pp	184	1.21
NuSea	$pD/2pp$	15	1.30
SeaQuest	$pD/2pp$	6	0.82

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

Well-known tension between NuSea and SeaQuest

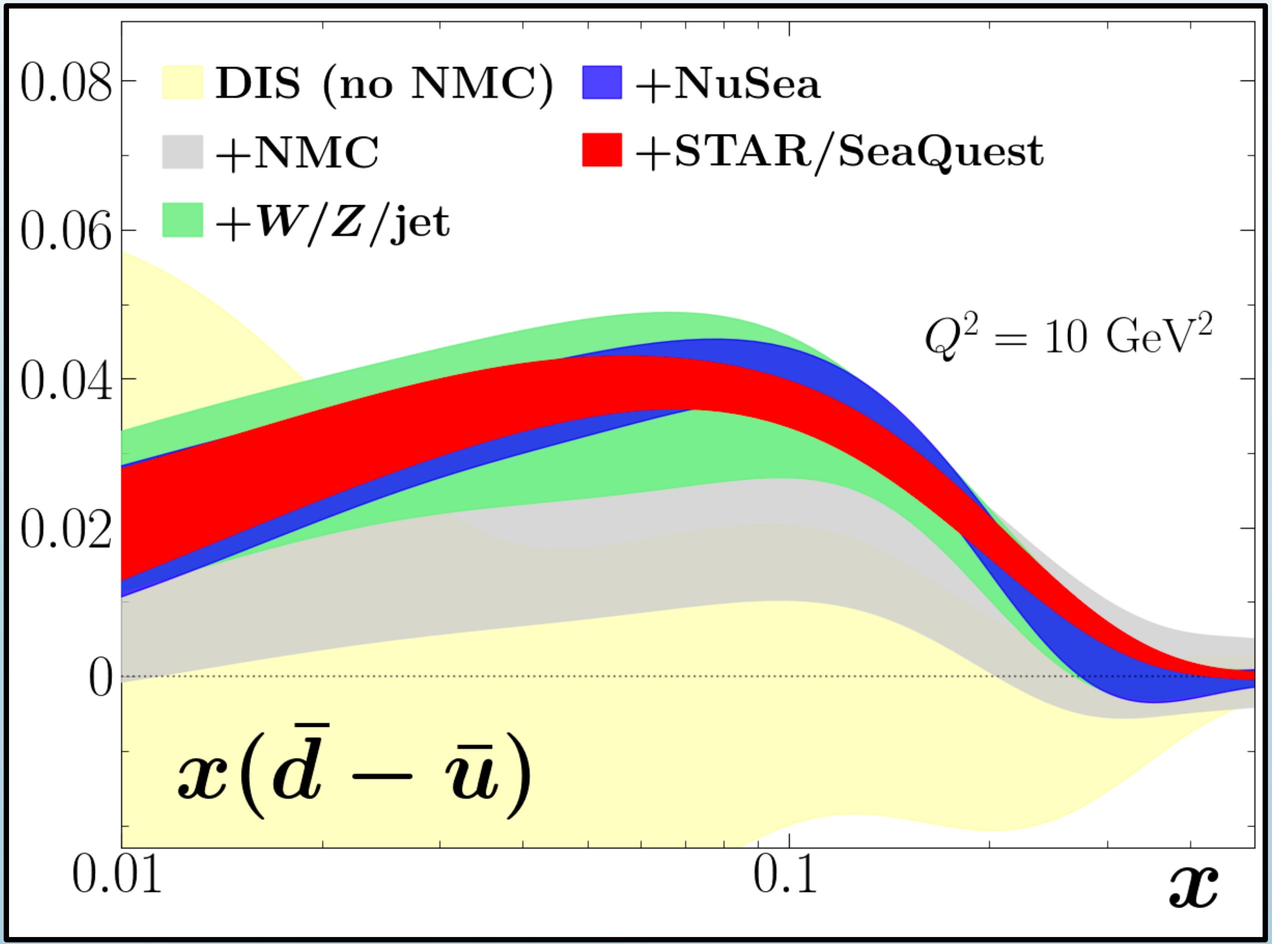
Impact from STAR and SeaQuest

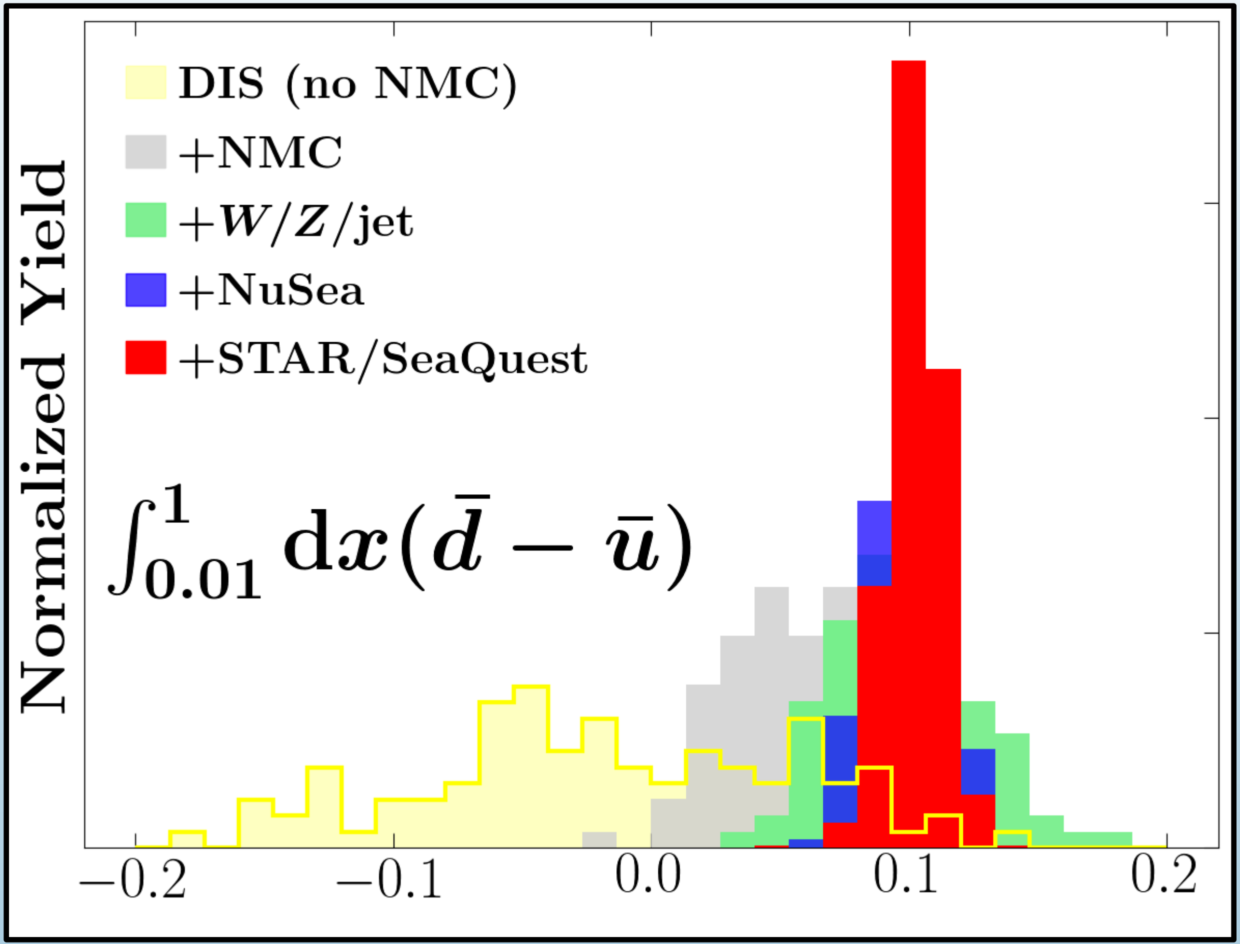


STAR: Moderate reduction of uncertainties

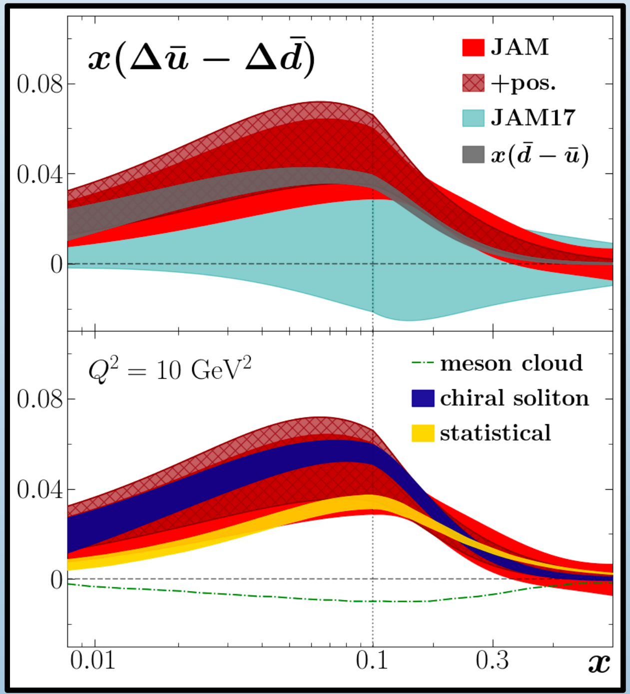
SeaQuest: Large reduction of uncertainties, especially at $x > 0.2$.
$\bar{d}/\bar{u} > 1$ up to $x \approx 0.4$, in agreement with models

Sources of Asymmetry

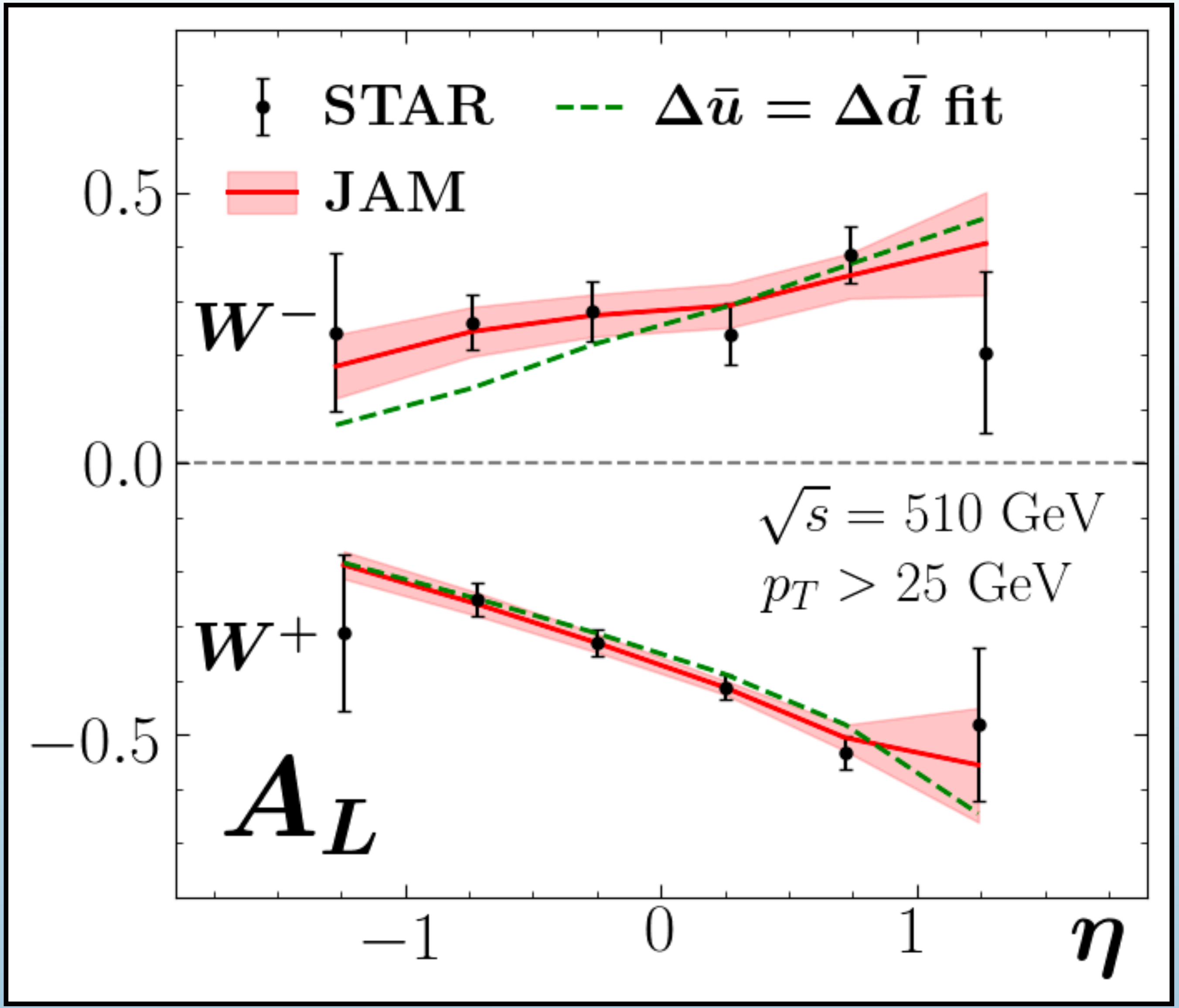




Part 4: Helicity PDFs



STAR Quality of Fit

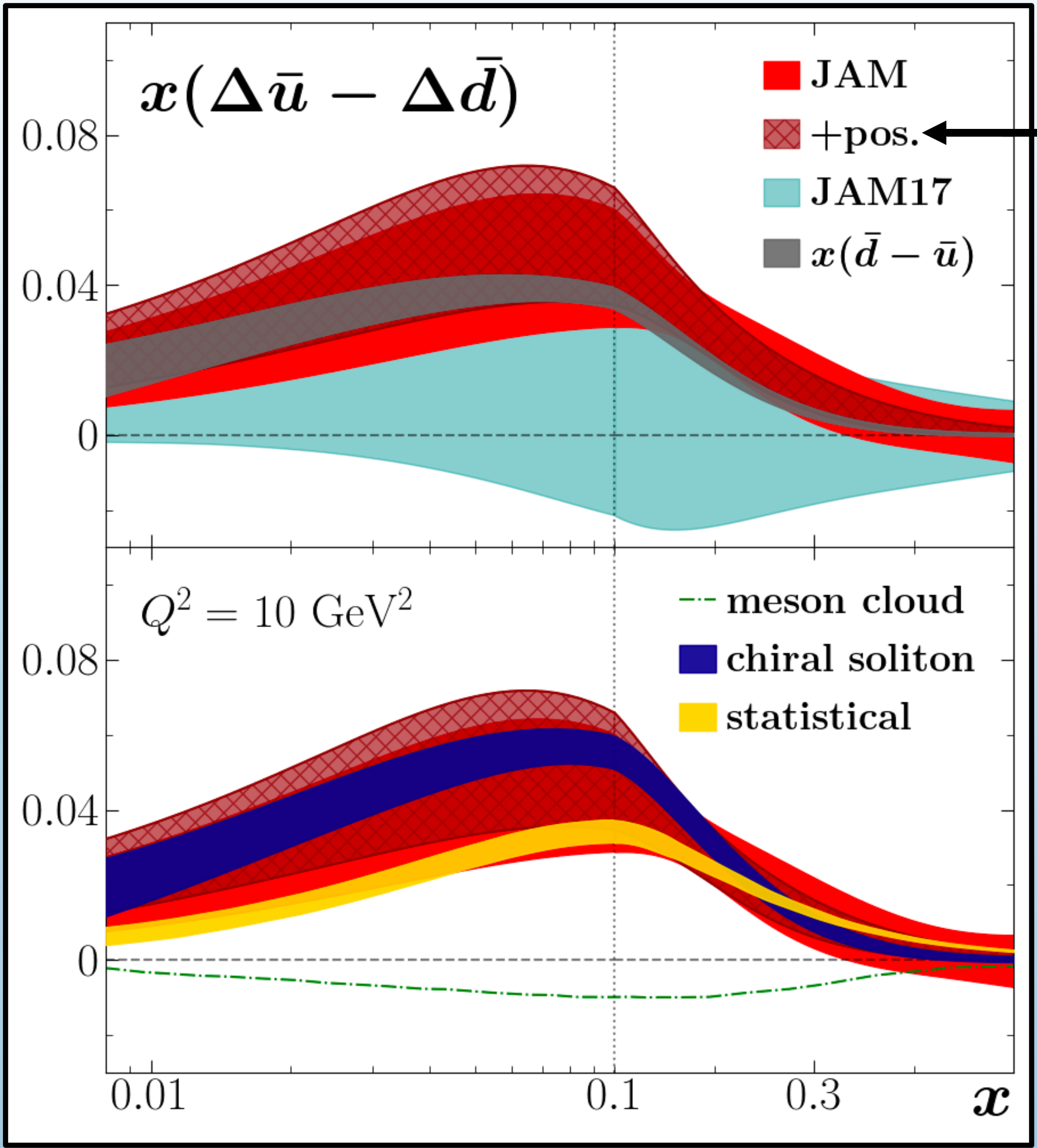


process	$N_{\rm dat}$	$\chi^2/N_{\rm dat}$ JAM	$\chi^2/N_{\rm dat}$ +Pos.	$\chi^2/N_{\rm dat}$ $\Delta\bar{u} = \Delta\bar{d}$
STAR $W^\pm$	12	0.45	0.61	1.53
PHENIX $W^\pm/Z$	6	0.47	0.46	0.48
pol. DIS	365	0.93	0.93	0.93
pol. jet	61	1.00	1.03	1.00
total	**444**	**0.92**	**0.94**	**0.95**

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

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

Resulting Asymmetry



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

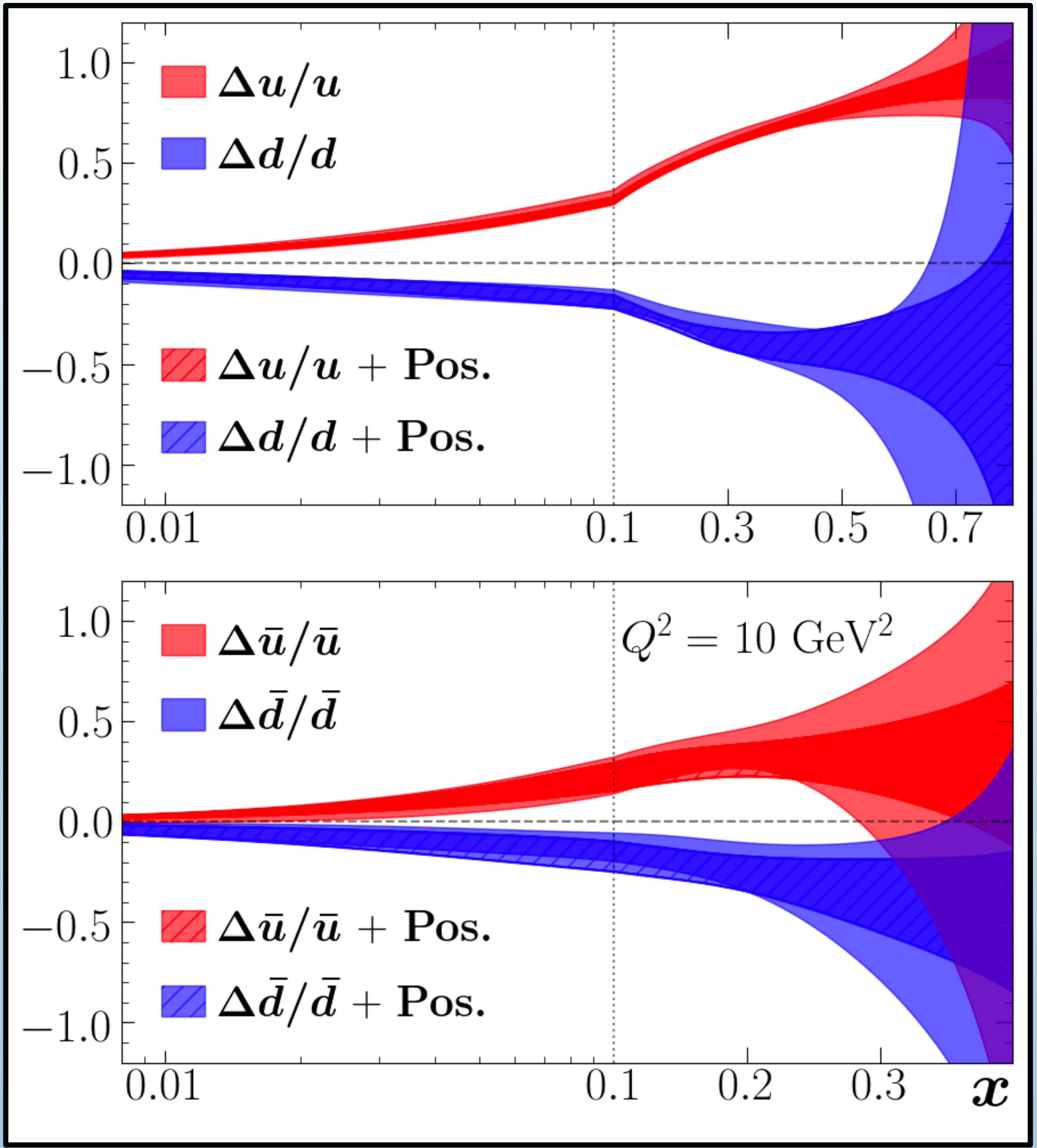
JAM17: inclusive + semi-inclusive DIS data

Agreement with Statistical and Chiral Soliton models

Meson Cloud model is not compatible with extraction

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)

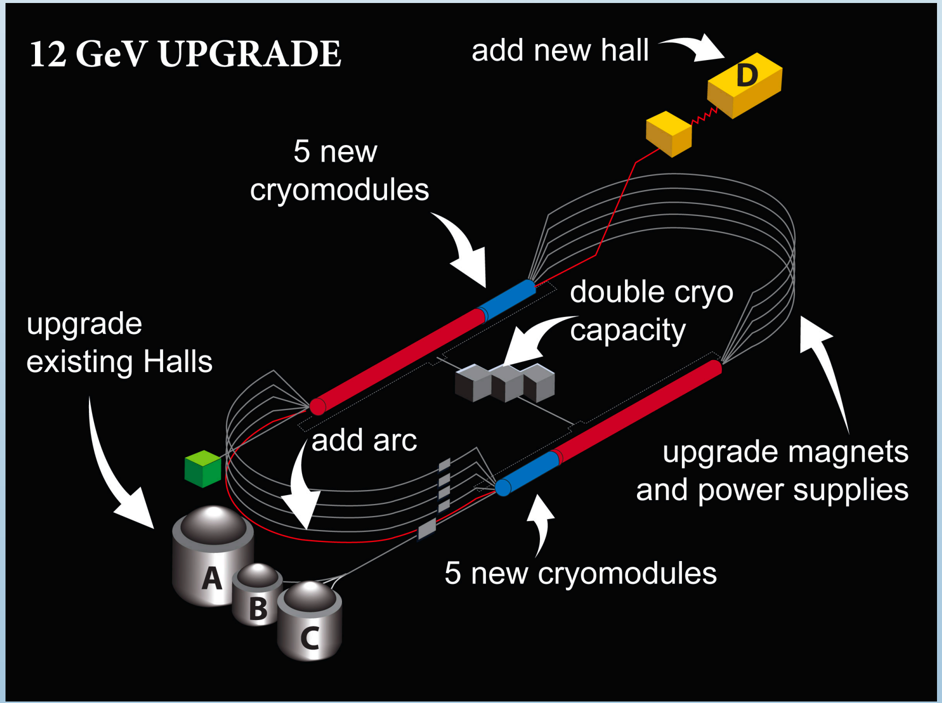
Quark and Antiquark Polarizations



First self-consistent extraction using *simultaneous* fit

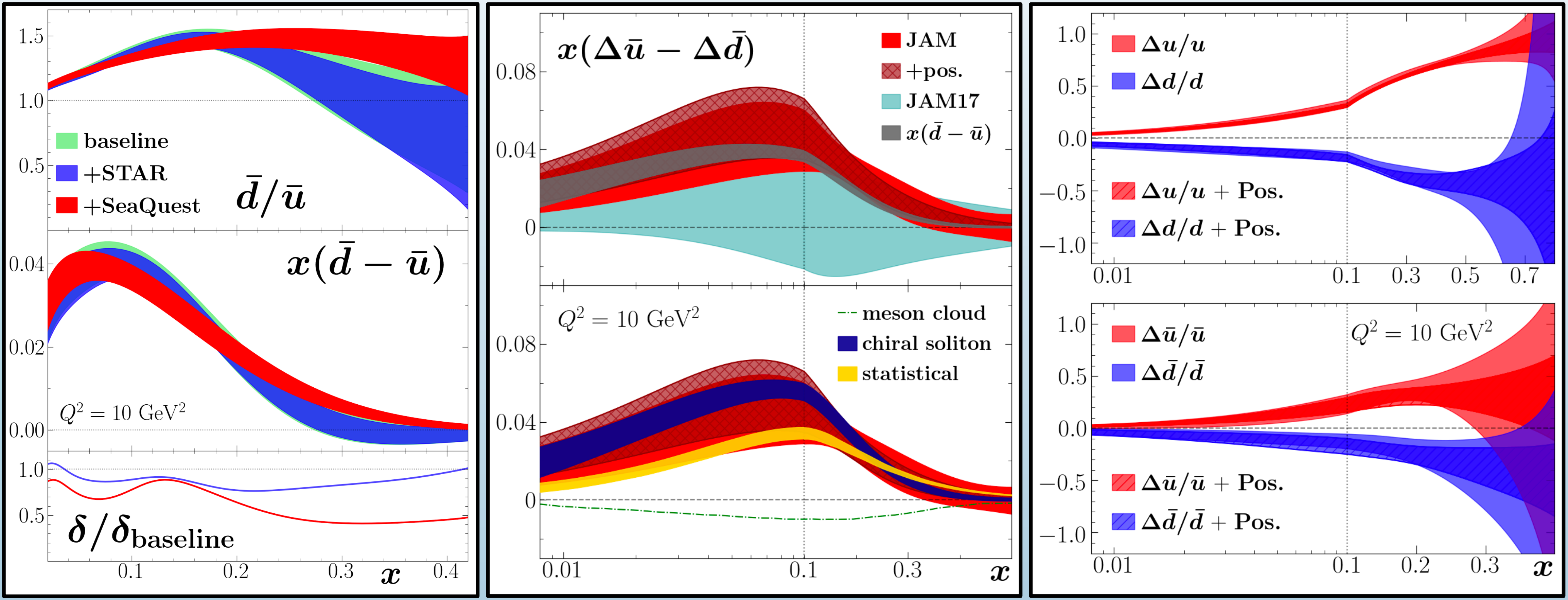
Antiquark ratios have same signs as quark ratios

Conclusions and Outlook



Results Summary

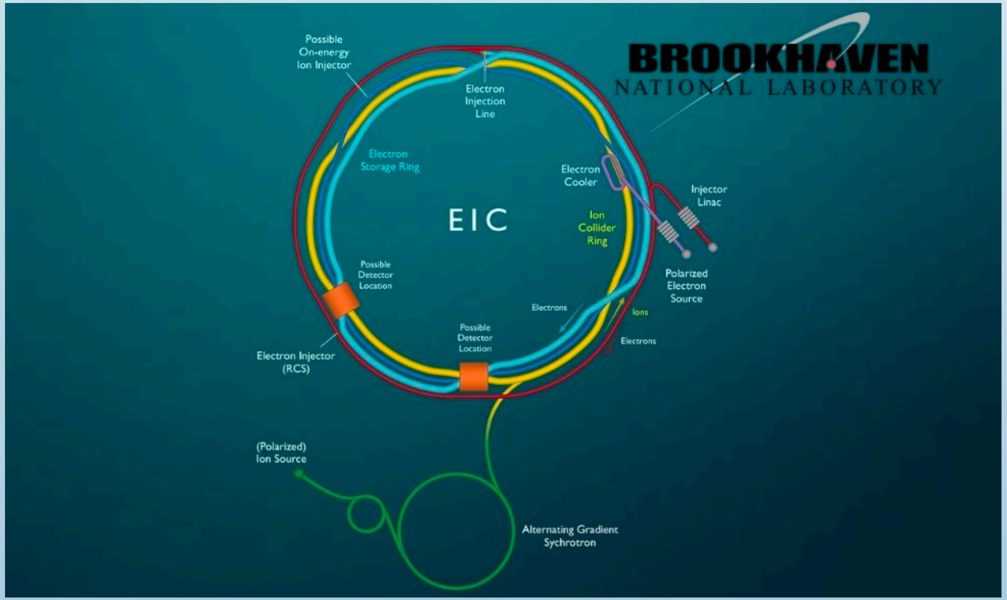
First global QCD analysis of SeaQuest and STAR data

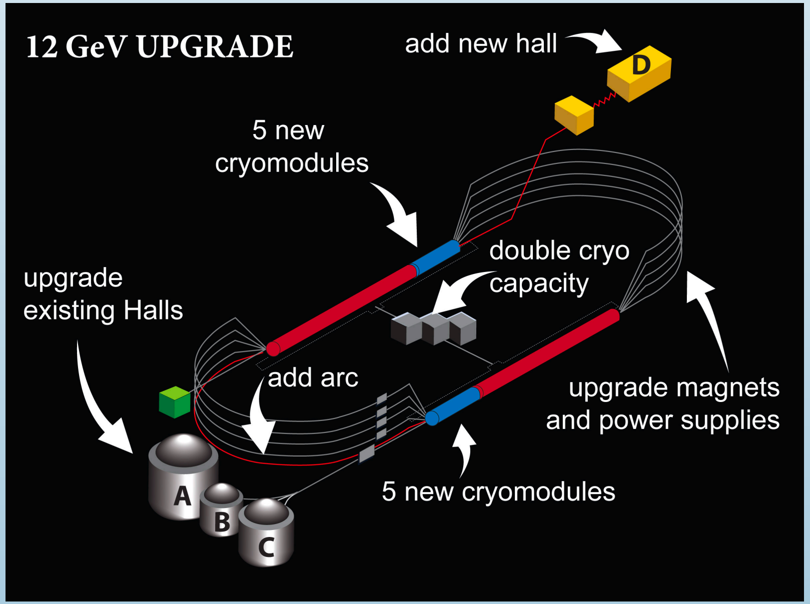


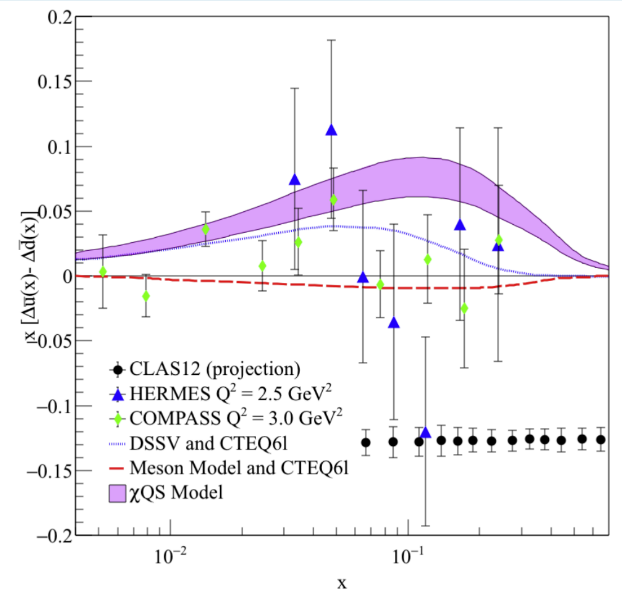
Simultaneous global QCD analysis of spin-averaged and helicity PDFs

Outlook

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

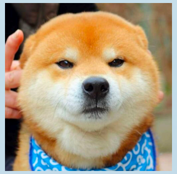
Andreas Metz

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

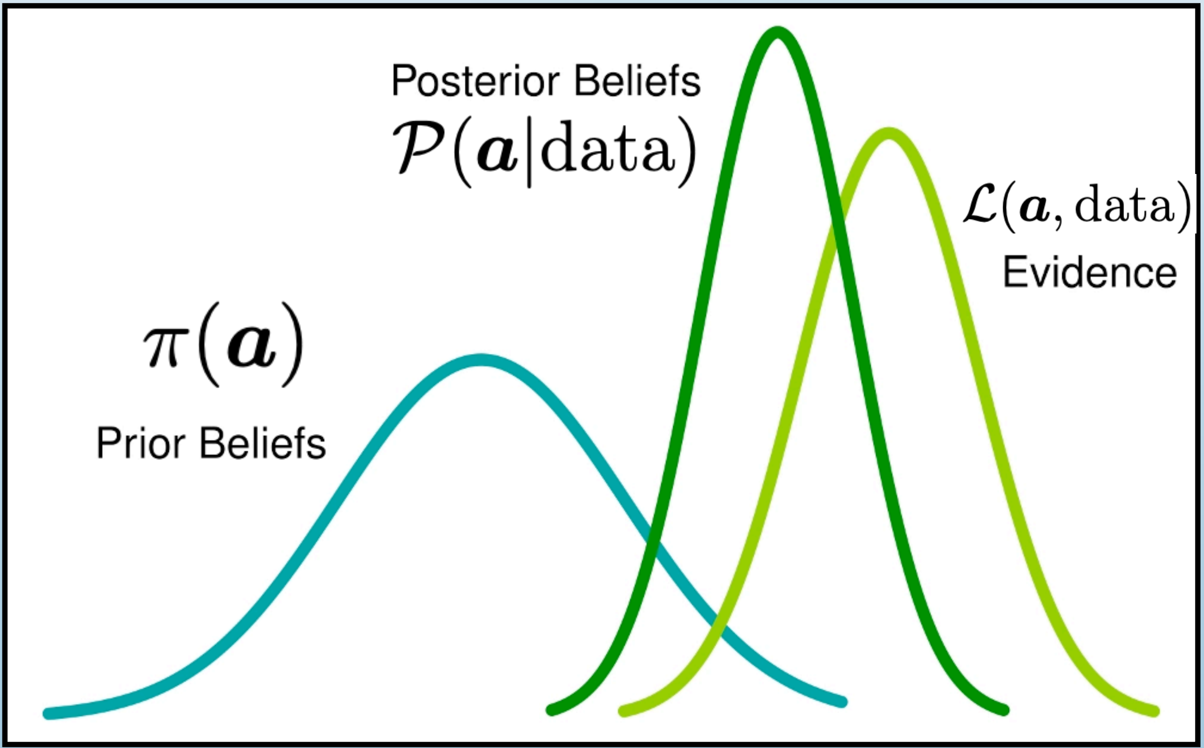
Now that we have calculated $\chi^2(\boldsymbol{a}, \text{data})$…

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

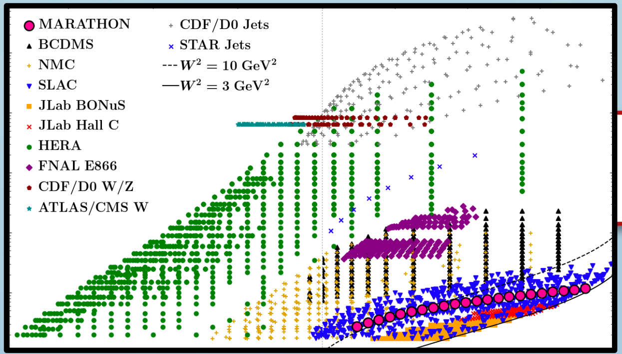
$$\tilde{\sigma} = \sigma + N(0,1)\ \alpha$$

Pseudo-Data → $\tilde{\sigma}$

Data → σ

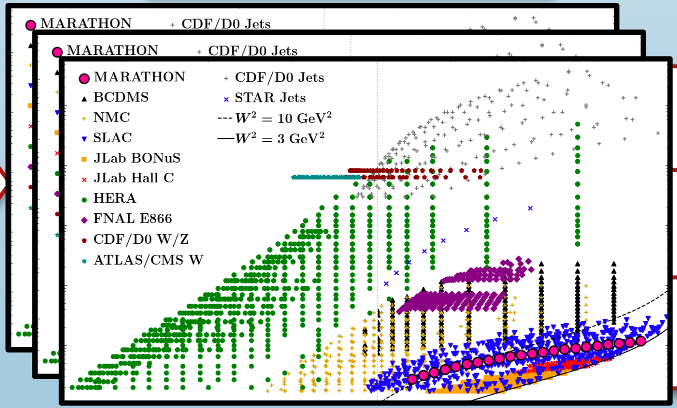
Uncorrelated Uncertainties → α

Original Data



DR

Replica Data

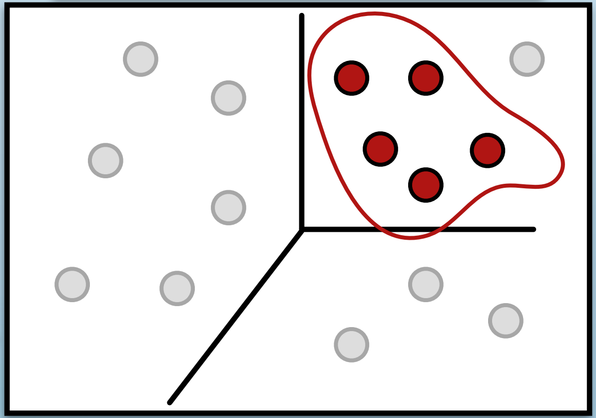


Maximum Likelihood

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))

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

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

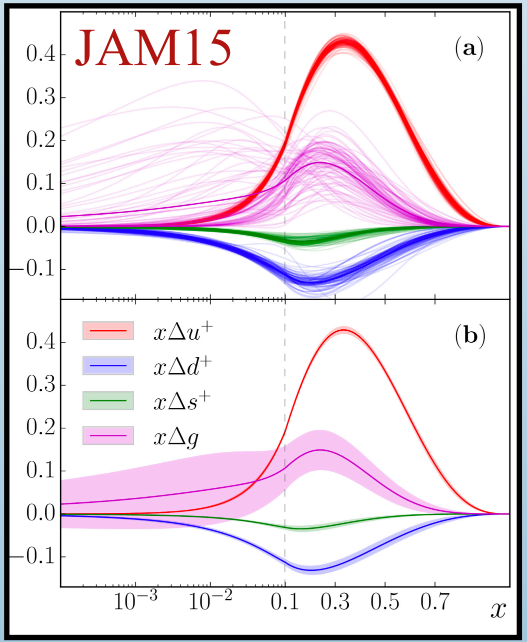
Exact, but $n = \mathcal{O}(100)$!

Build an MC ensemble

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

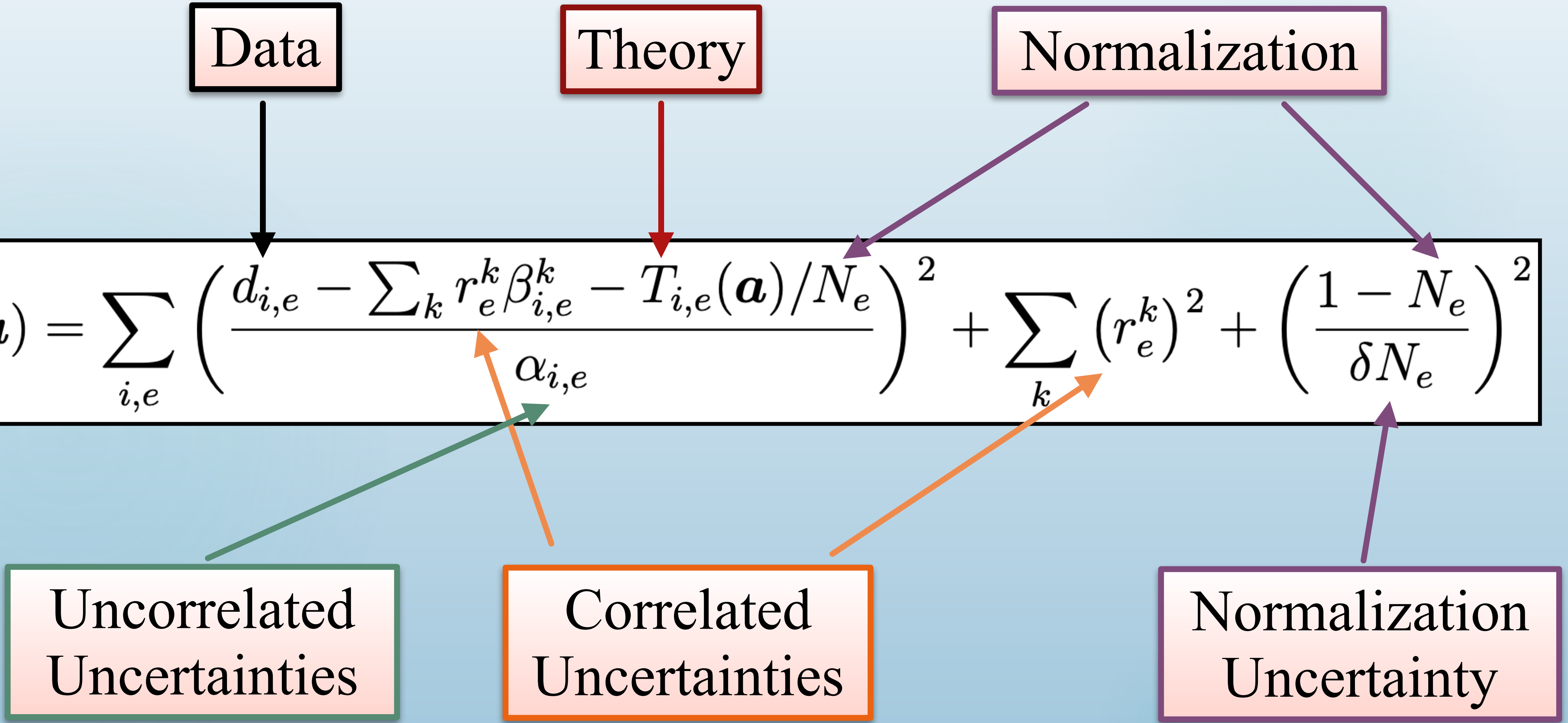
$$V[O] \approx \frac{1}{N} \sum_k \left[O(\boldsymbol{a}_k) - E[O]\right]^2$$

Average over k sets of the parameters (replicas)



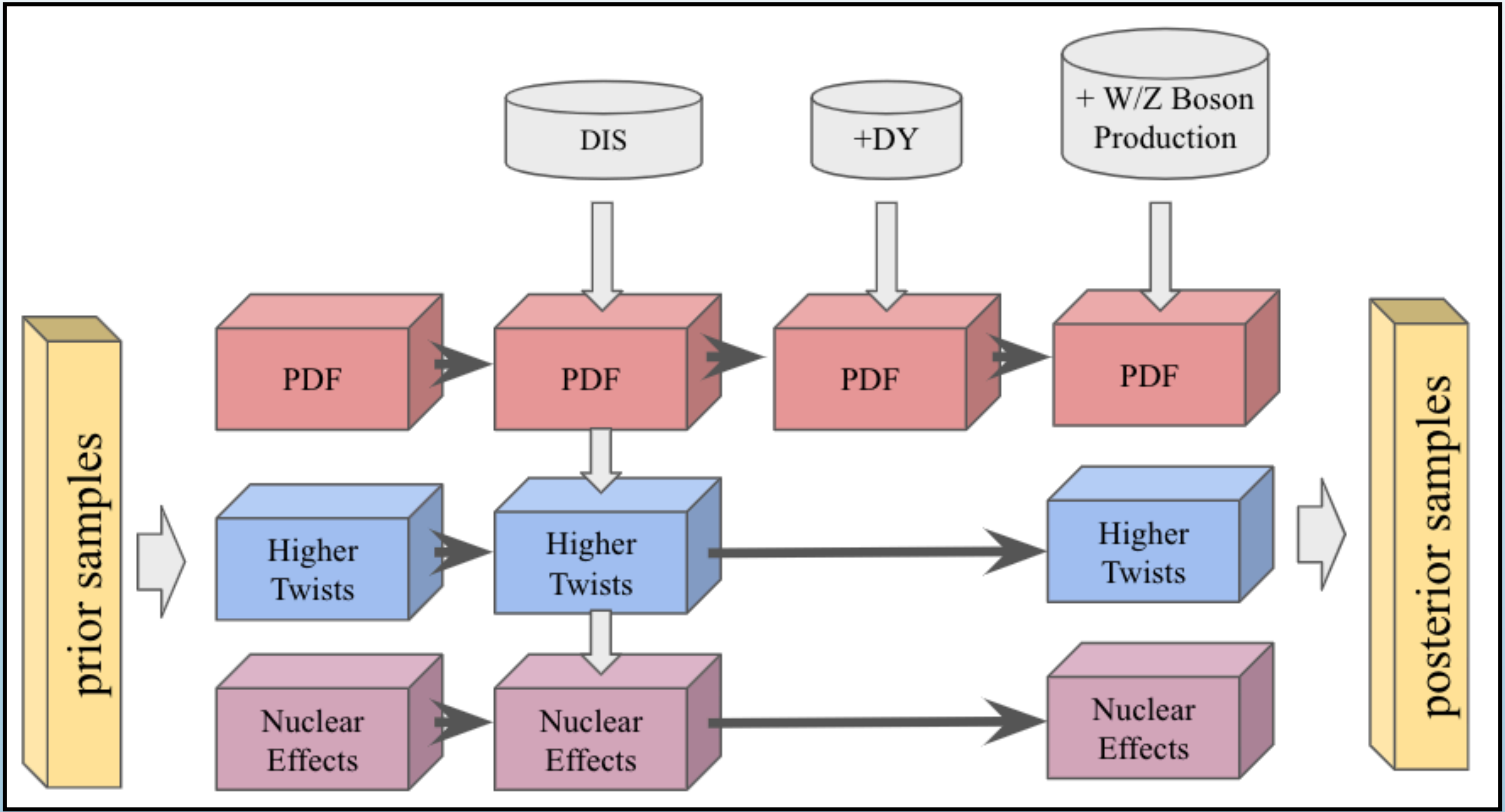
The χ^2 function

Now that the observables have been calculated…

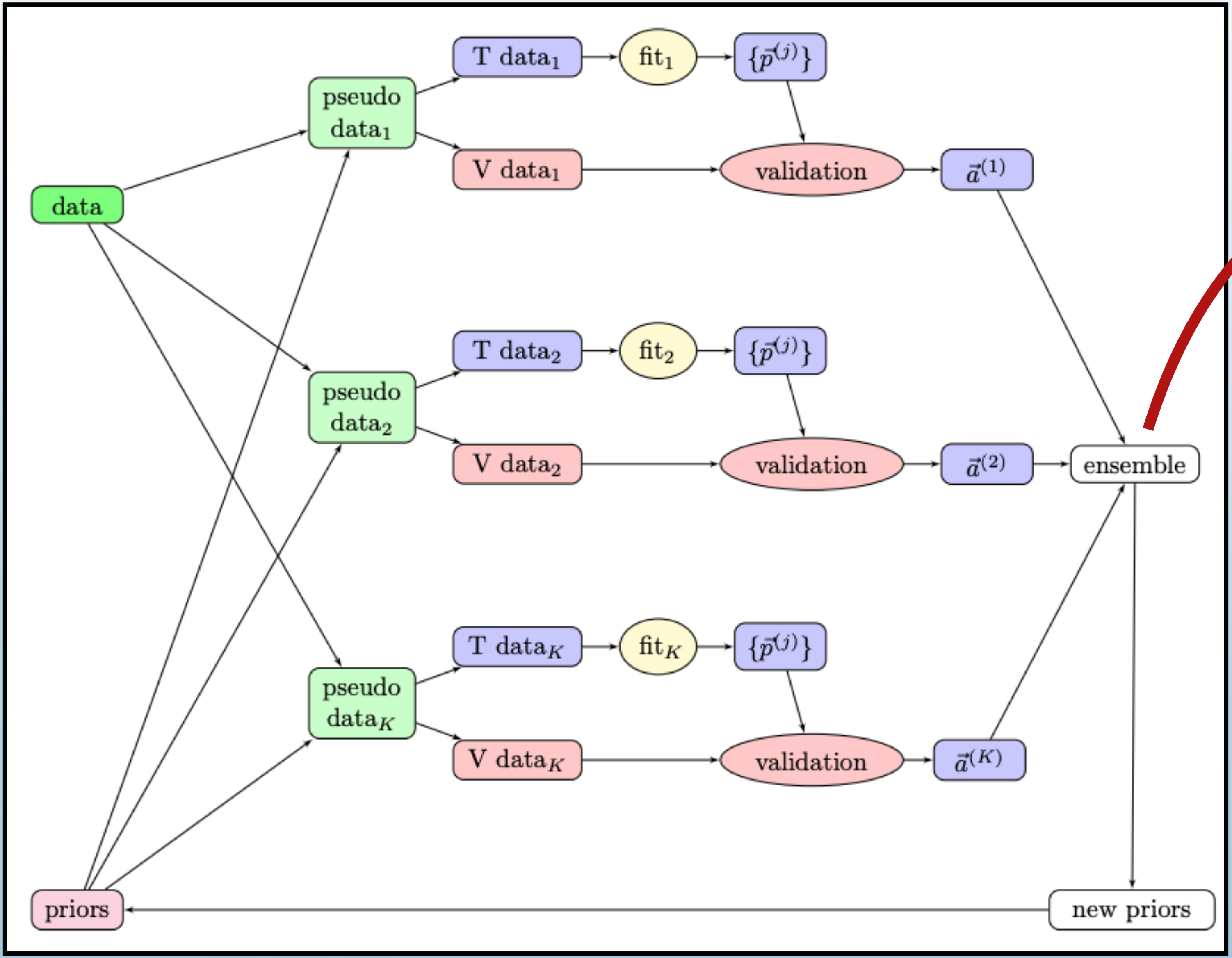


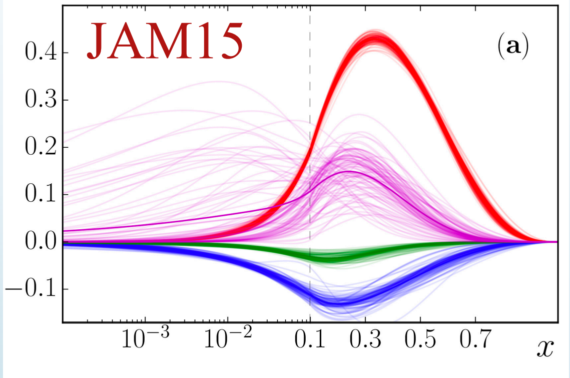
$$\chi^2(\boldsymbol{a}) = \sum_{i,e} \left(\frac{d_{i,e} - \sum_k r_e^k \beta_{i,e}^k - T_{i,e}(\boldsymbol{a})/N_e}{\alpha_{i,e}} \right)^2 + \sum_k \left(r_e^k\right)^2 + \left(\frac{1 - N_e}{\delta N_e}\right)^2$$

Multi-Step Strategy



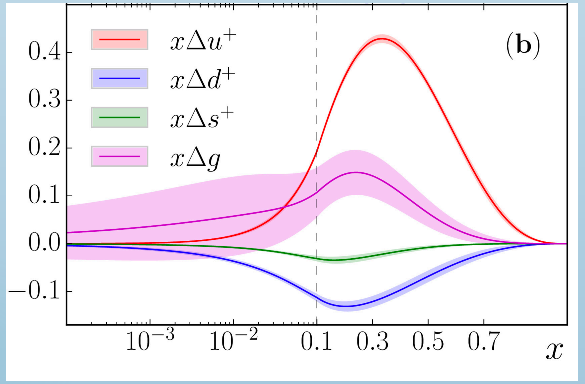
Putting it all together…



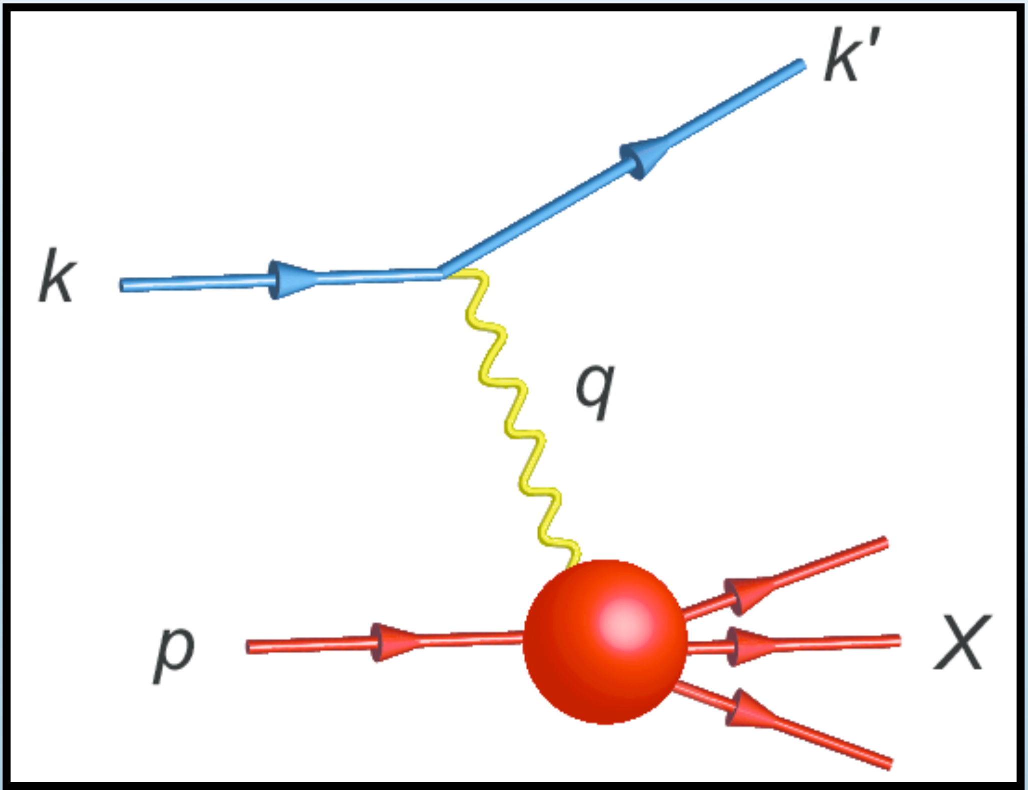


$$E[O] \approx \frac{1}{N}\sum_k O(\boldsymbol{a}_k)$$

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



Deep Inelastic Scattering



Virtuality:

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

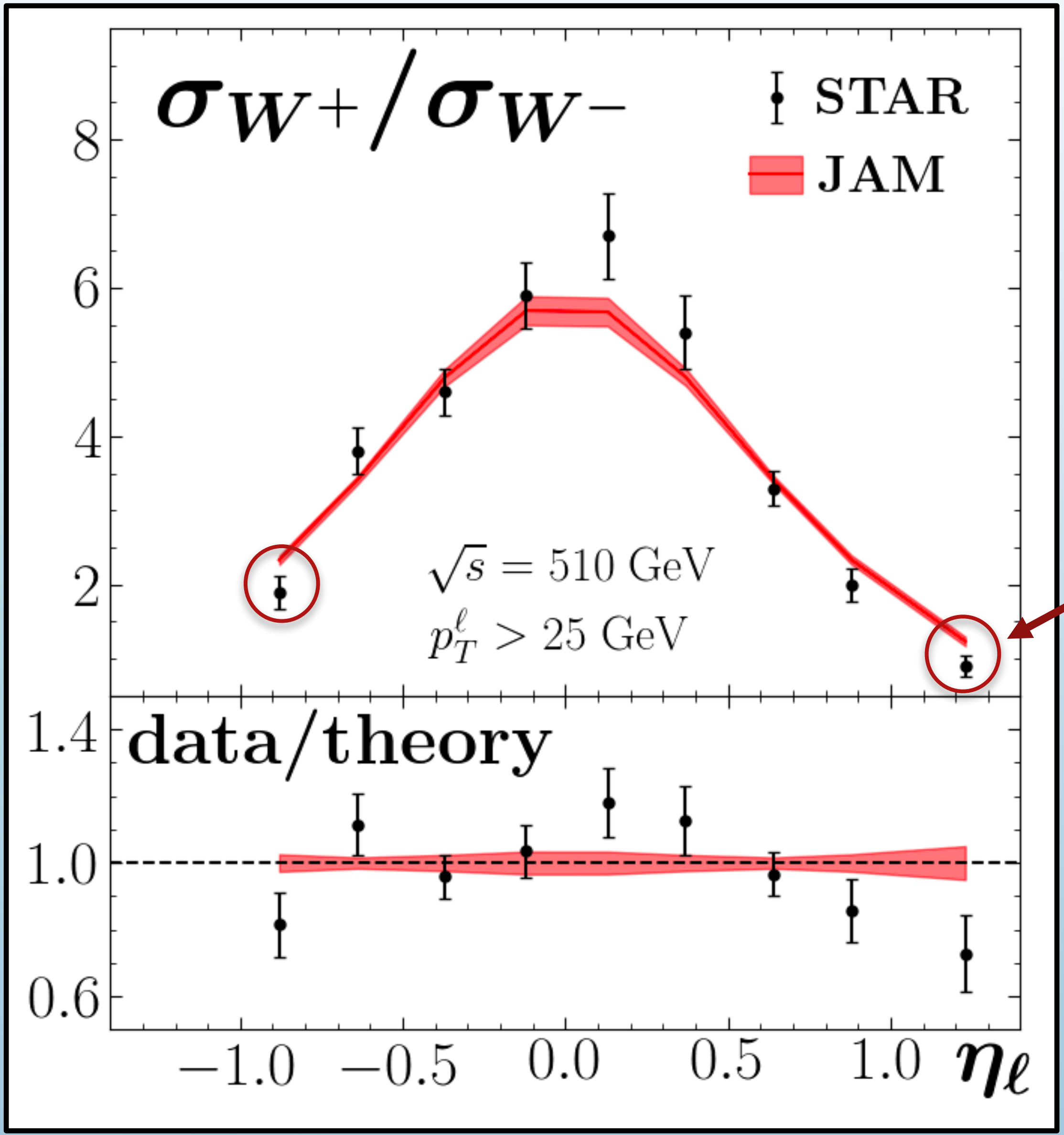
Bjorken x:

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

Invariant mass of outgoing particles:

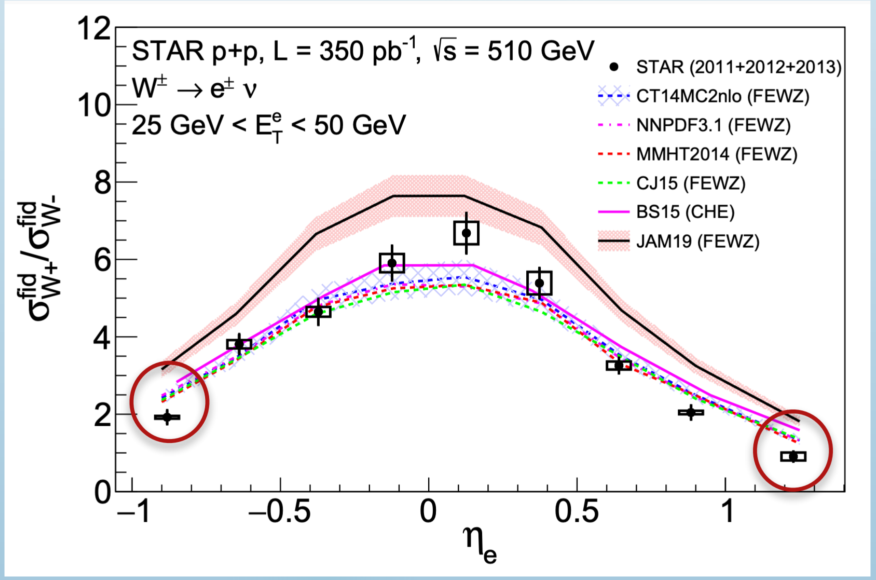
$$W^2 = (p + q)^2$$

STAR Quality of Fit



process	N_{dat}	χ^2/N_{dat}
W-lepton		
STAR W^+/W^-	9	2.02

Difficult to describe at extreme rapidity

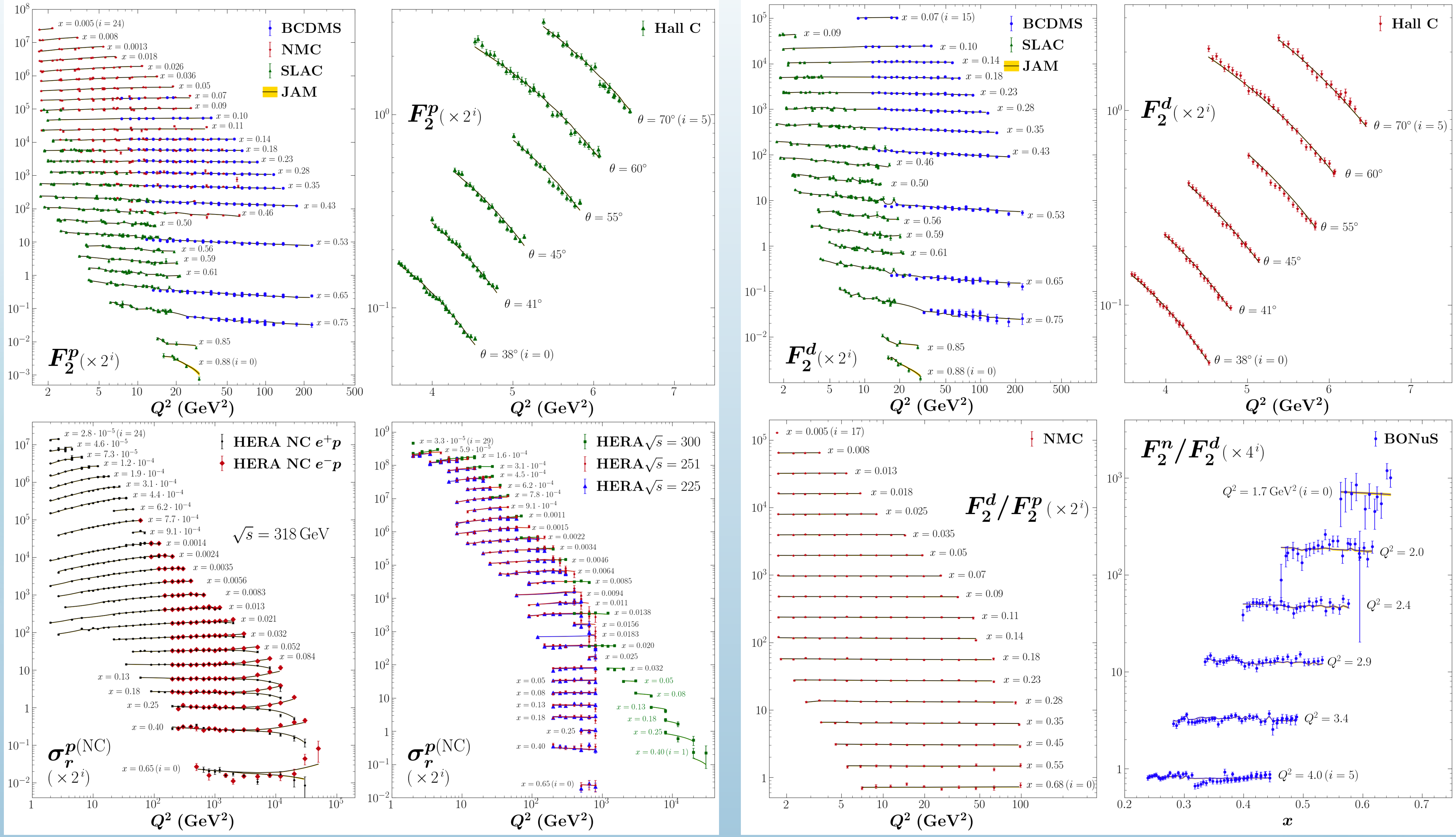


J. Adam *et al*. [STAR], Phys. Rev. D. **103**, 012001 (2021)

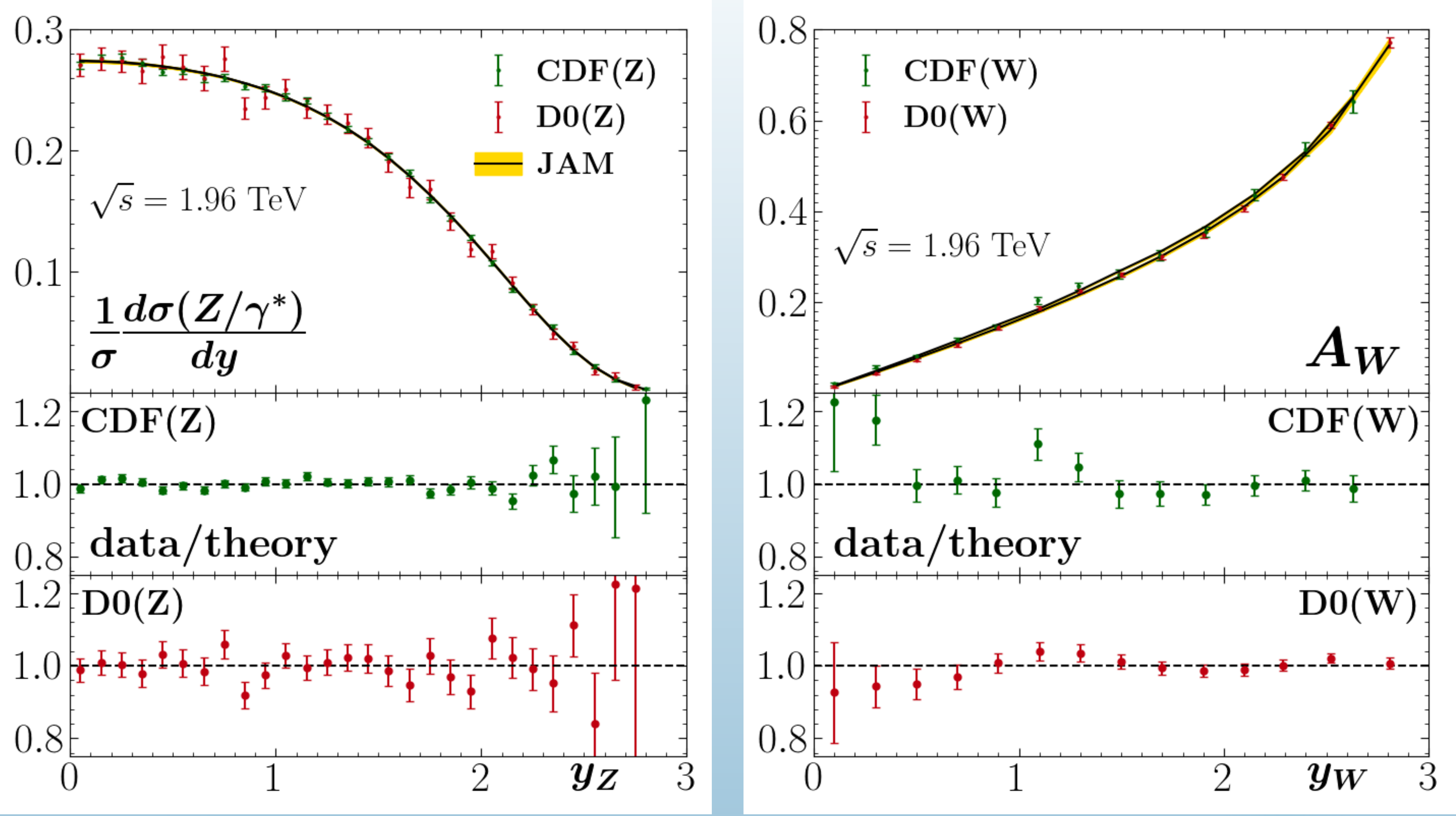
All χ^2/N_{dat} (Spin-Averaged)

process	N_{dat}	χ^2/N_{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**

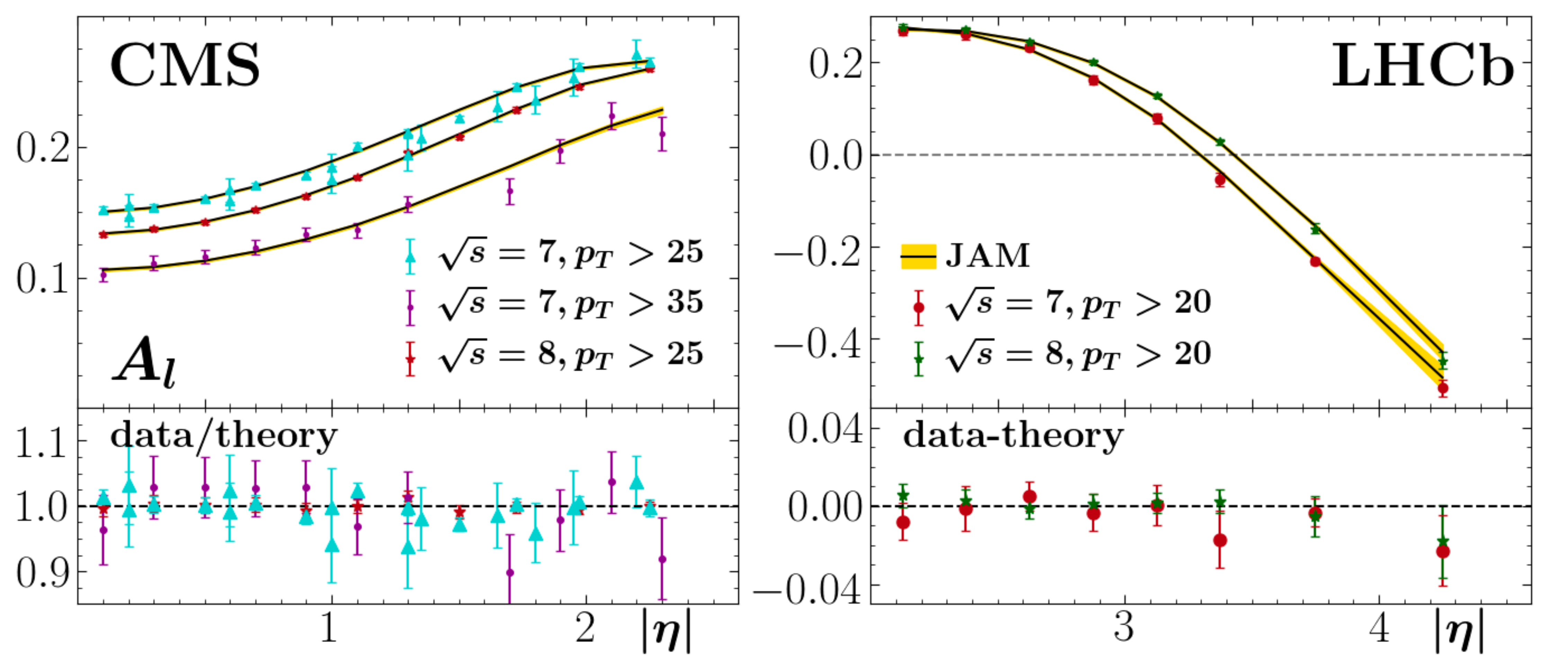
DIS (Neutral Current)



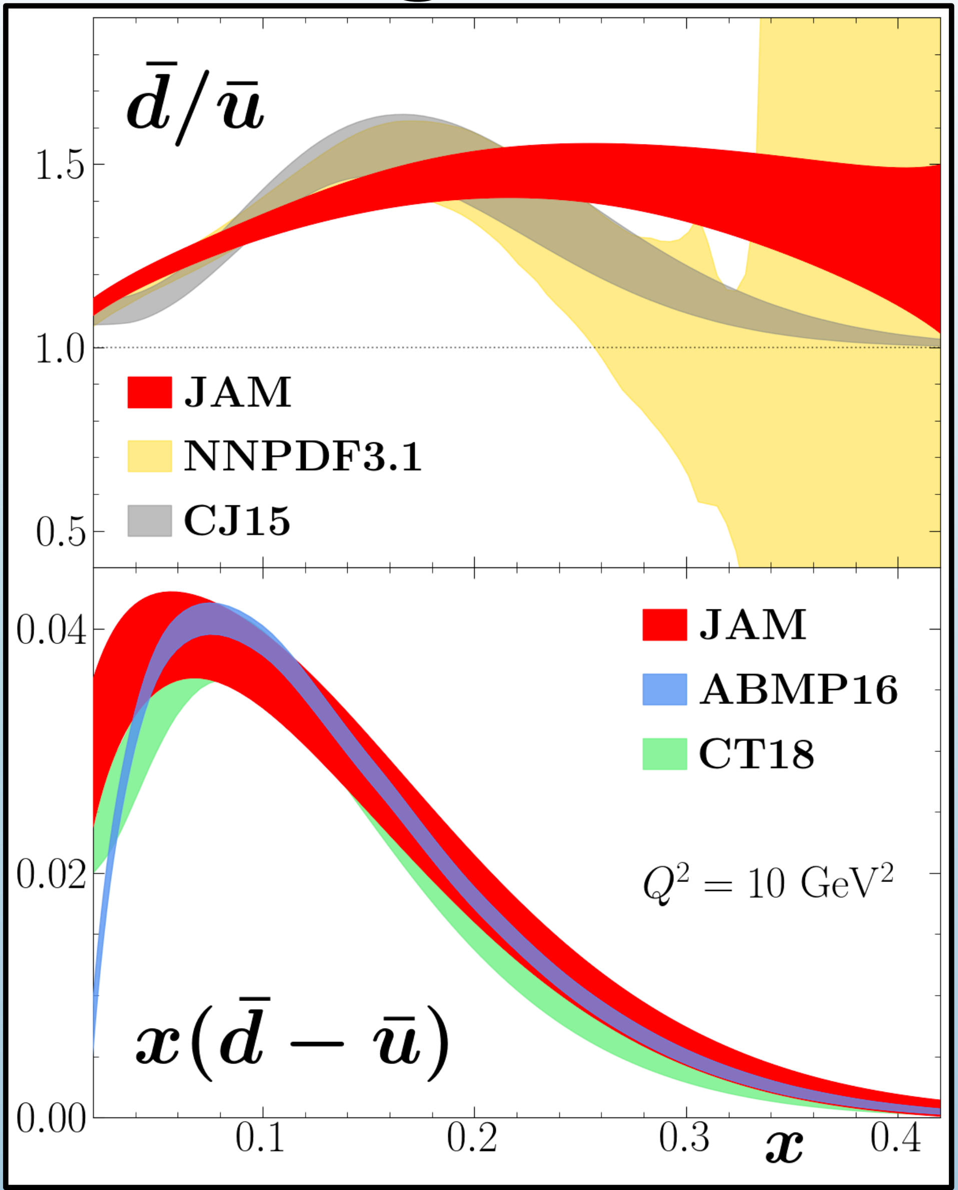
W/Z Boson Production



Lepton Production



Resulting PDFs



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