Bayesian Monte Carlo Extraction of Sea Asymmetry with SeaQuest and STAR Data

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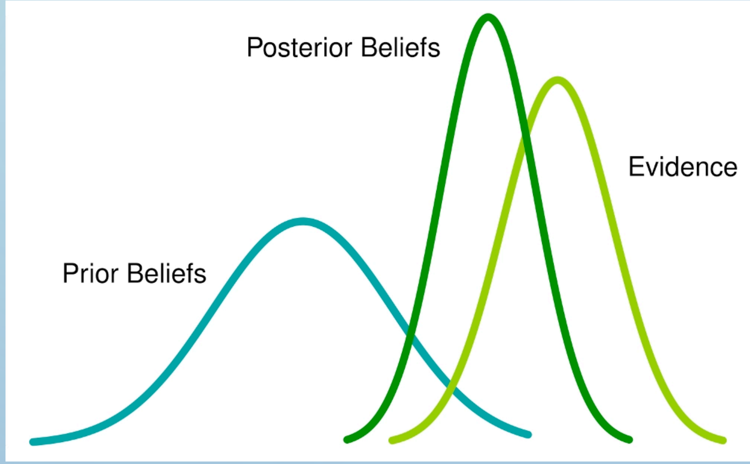
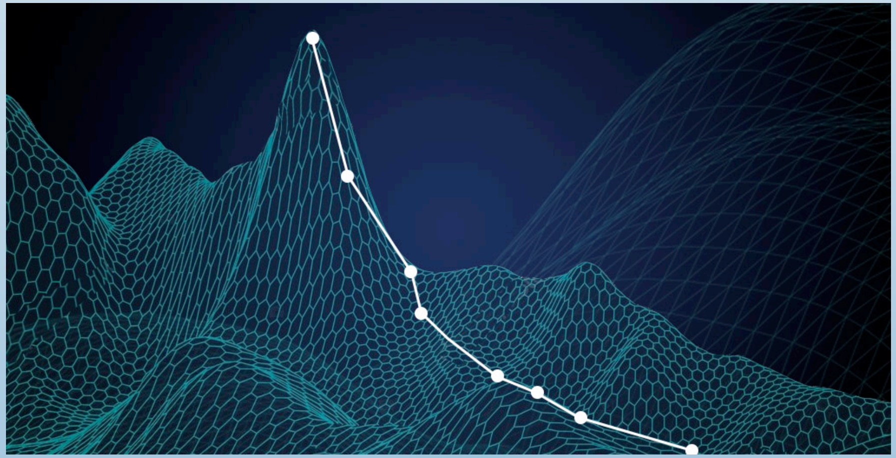
1. Introduction
2. Data and Fitting
3. Extracted Sea Asymmetry
4. Conclusions and Outlook





JAM Collaboration

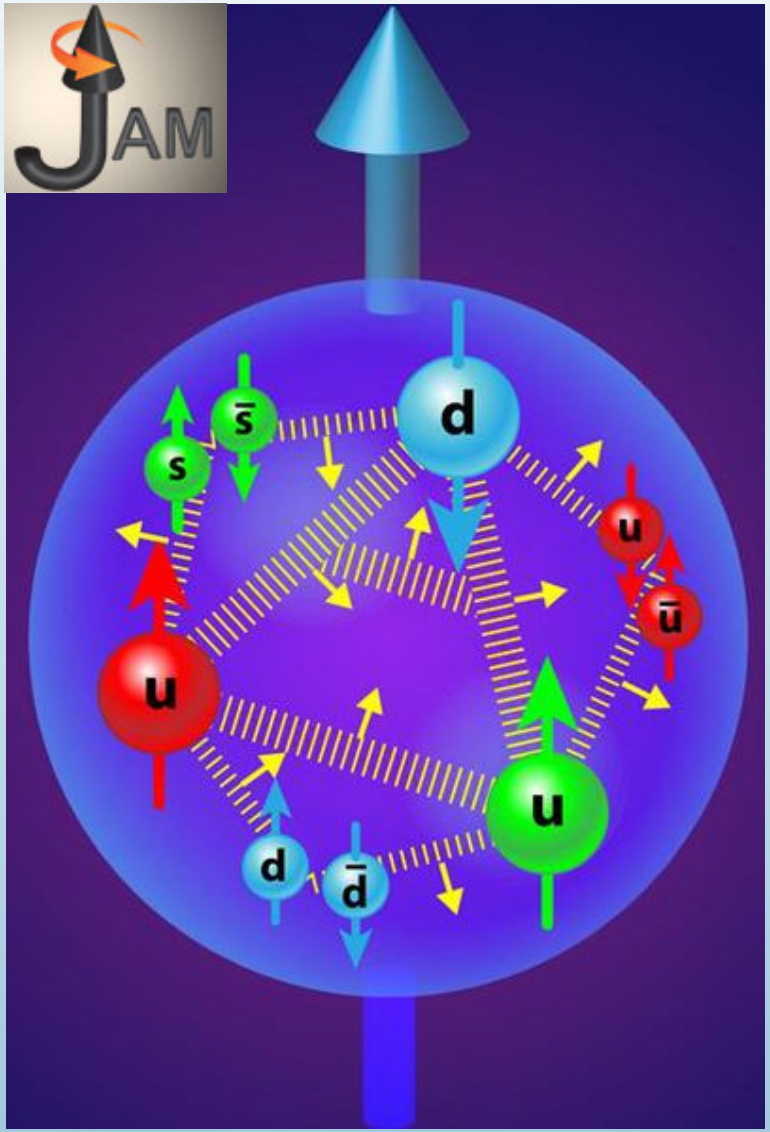
3-dimensional structure of nucleons:

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

Collinear factorization in perturbative QCD

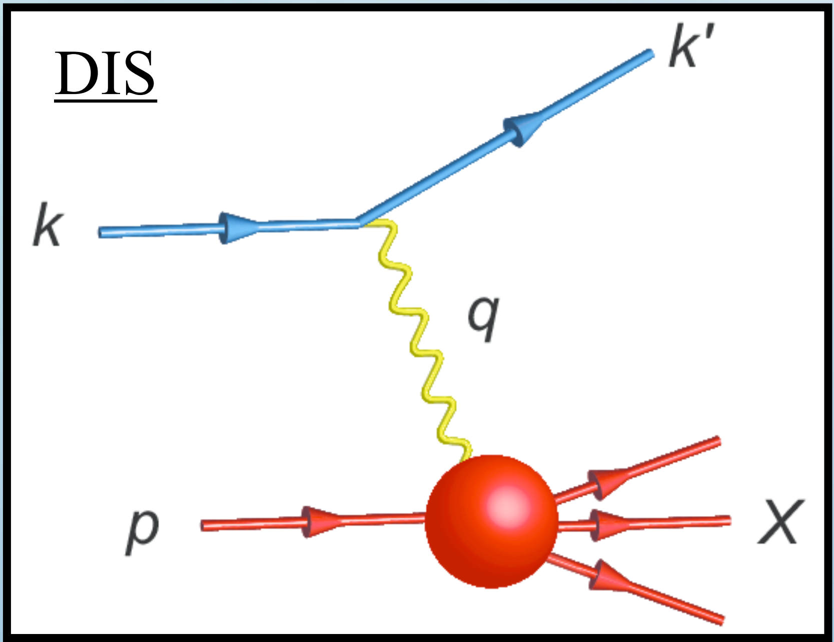
Simultaneous determinations of PDFs, FFs, etc.

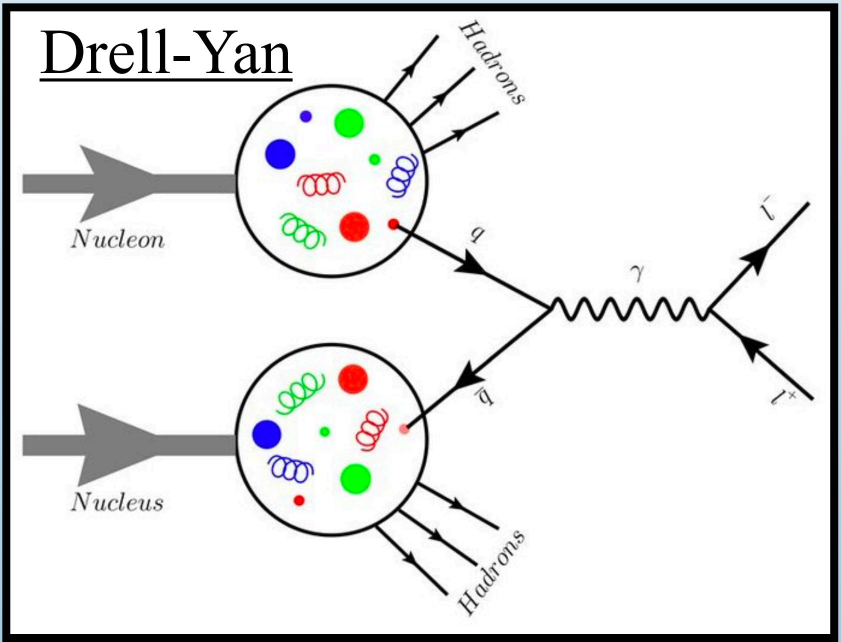
Monte Carlo methods for Bayesian inference

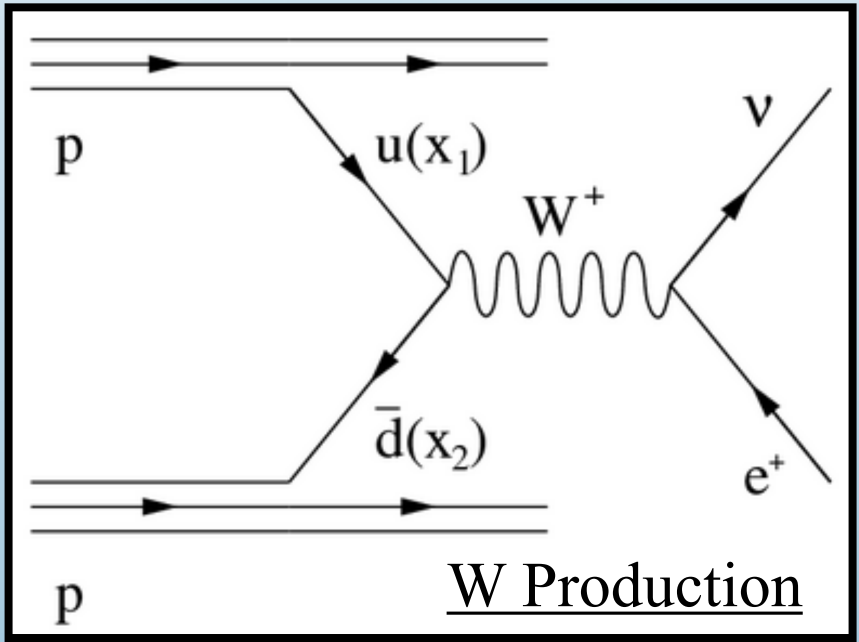


A Global Analysis

Spin-averaged PDFs are extracted using many different processes







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

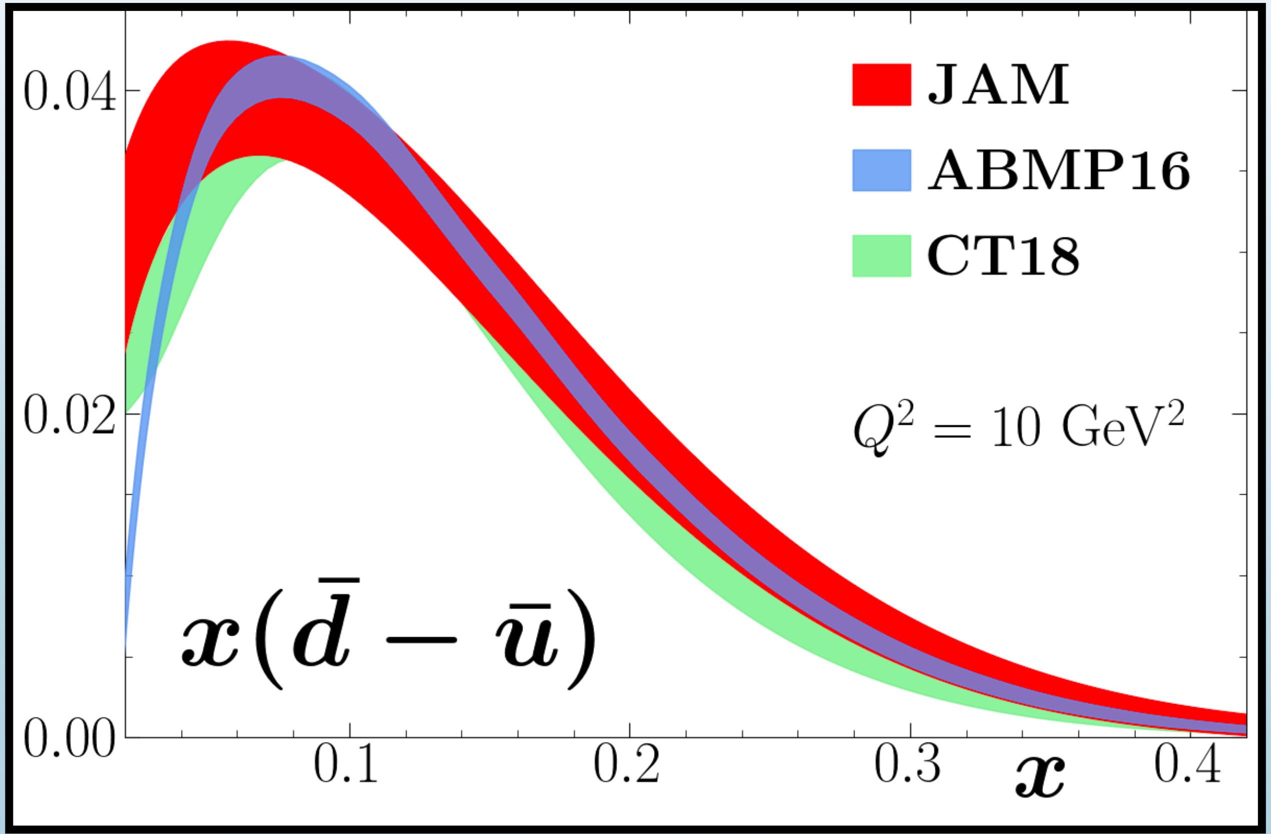
$$\chi^2(\boldsymbol{a}) = \sum_{i,e}\left(\frac{d_{i,e} - \sum_k r_e^k \beta_{i,e}^k - T_{i,e}(\boldsymbol{a})/N_e}{\alpha_{i,e}}\right)^2 + \sum_k \left(r_e^k\right)^2 + \left(\frac{1-N_e}{\delta N_e}\right)^2$$

Uncorrelated Uncertainties

Correlated Uncertainties

Normalization Uncertainty

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

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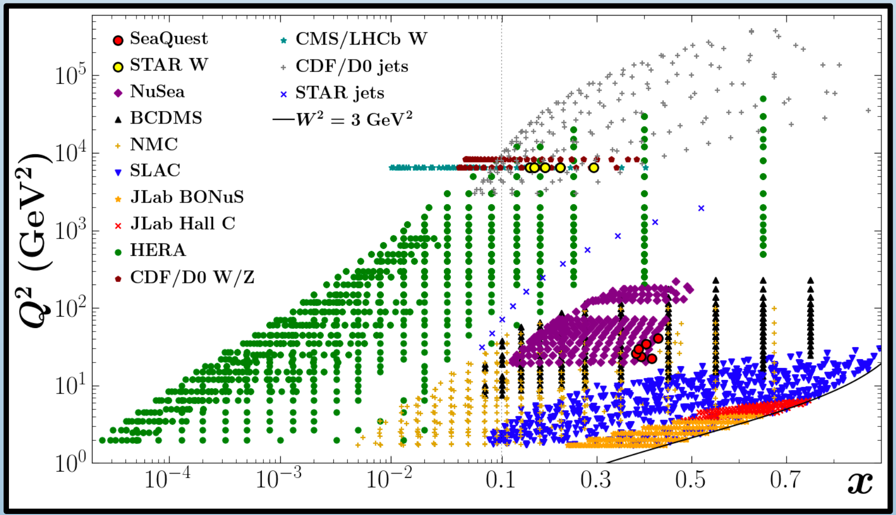
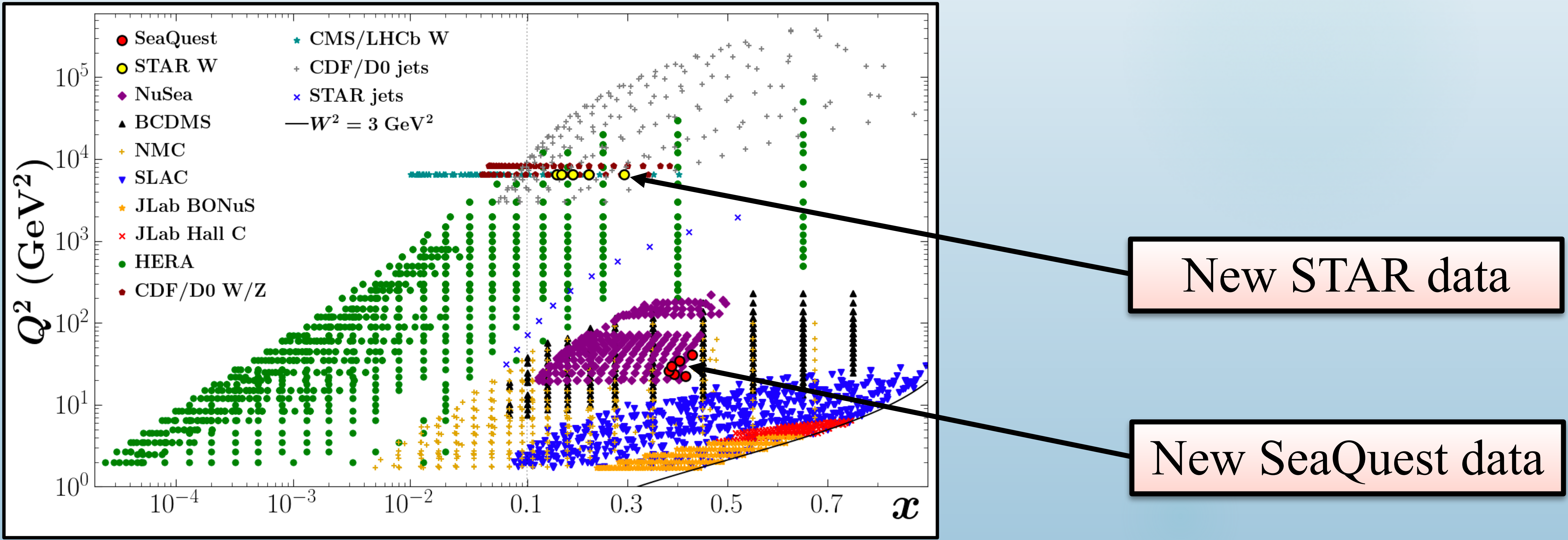
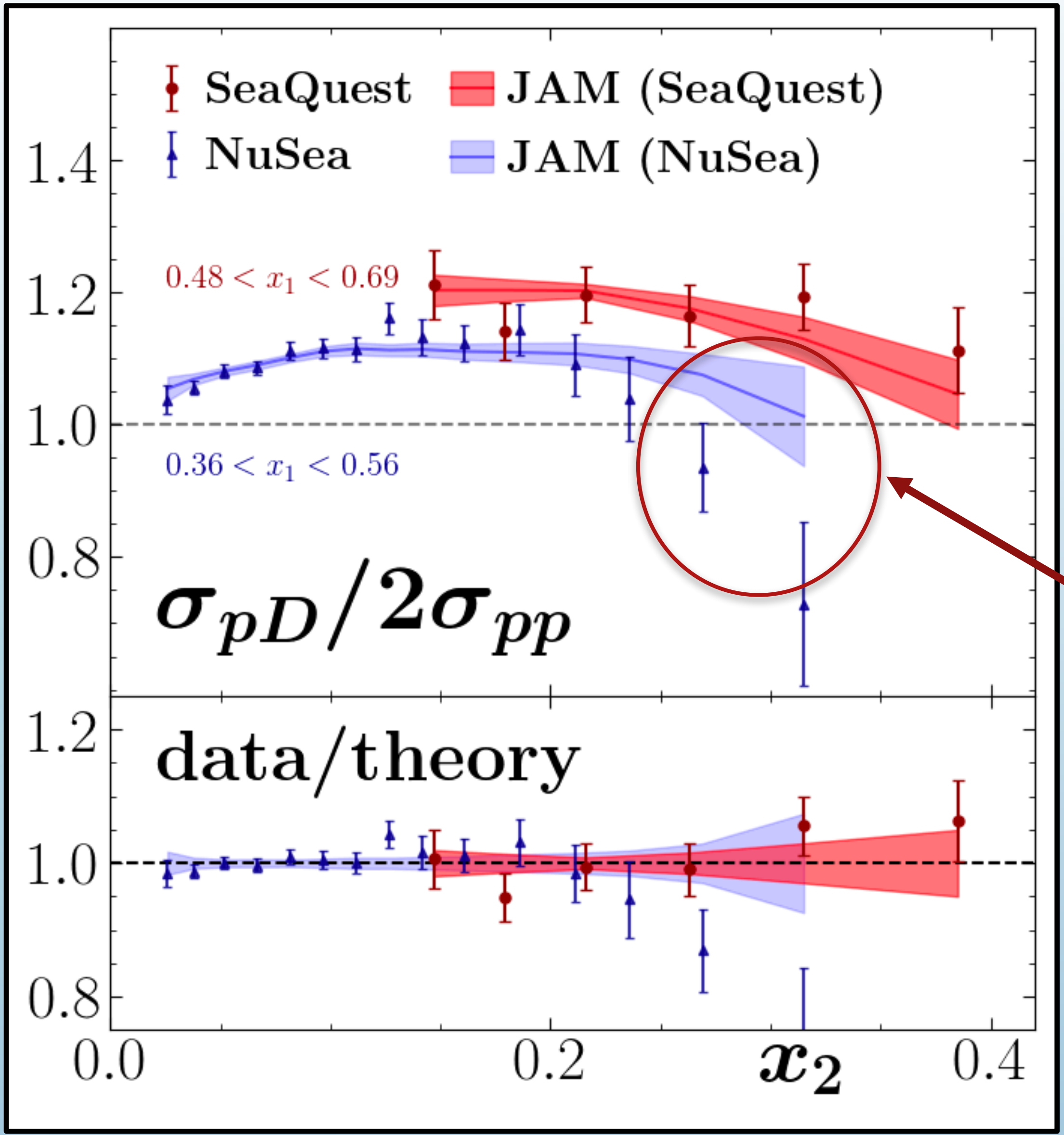


Kinematic Coverage (Spin-Averaged)

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



SeaQuest and NuSea Quality of Fit

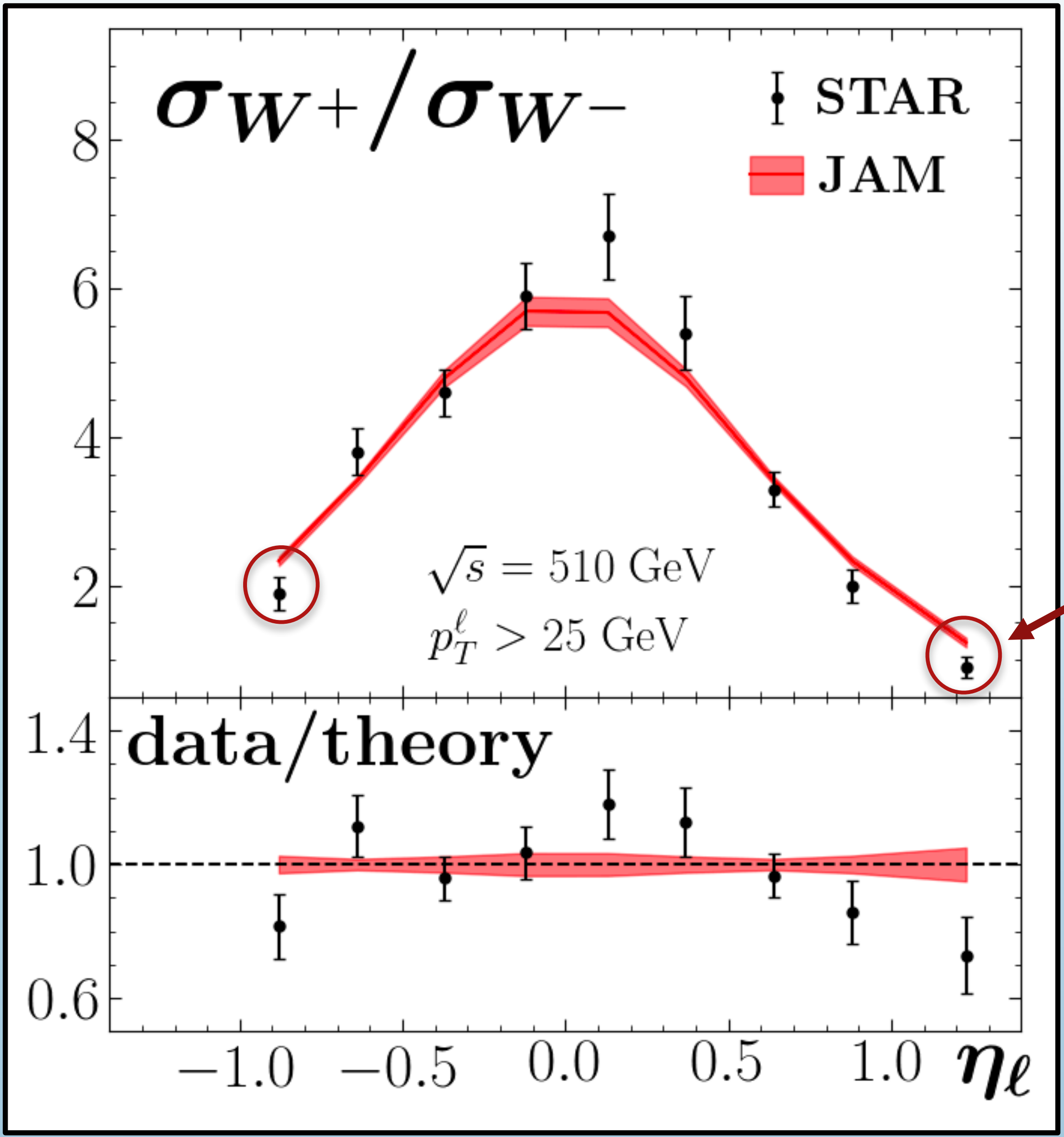


process		$N_{\rm dat}$	$\chi^2/N_{\rm dat}$
Drell-Yan			
NuSea	pp	184	1.21
NuSea	$pD/2pp$	15	1.30
SeaQuest	$pD/2pp$	6	0.82

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

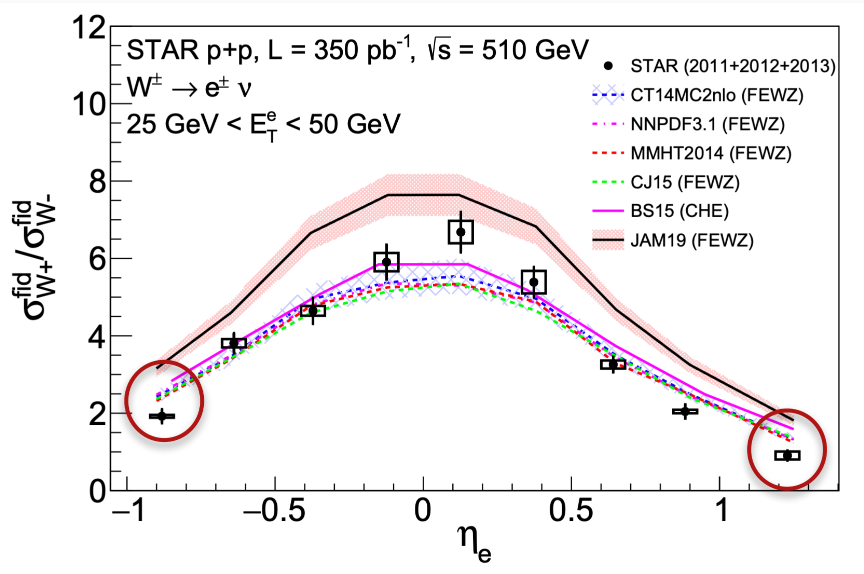
Well-known tension between NuSea and SeaQuest

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)

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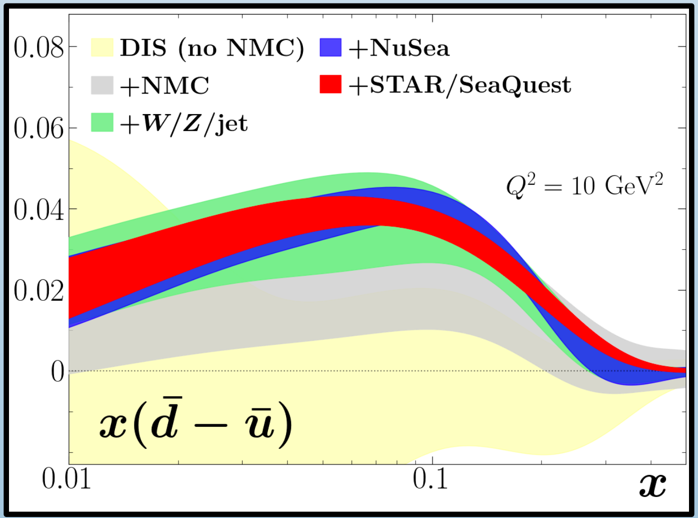
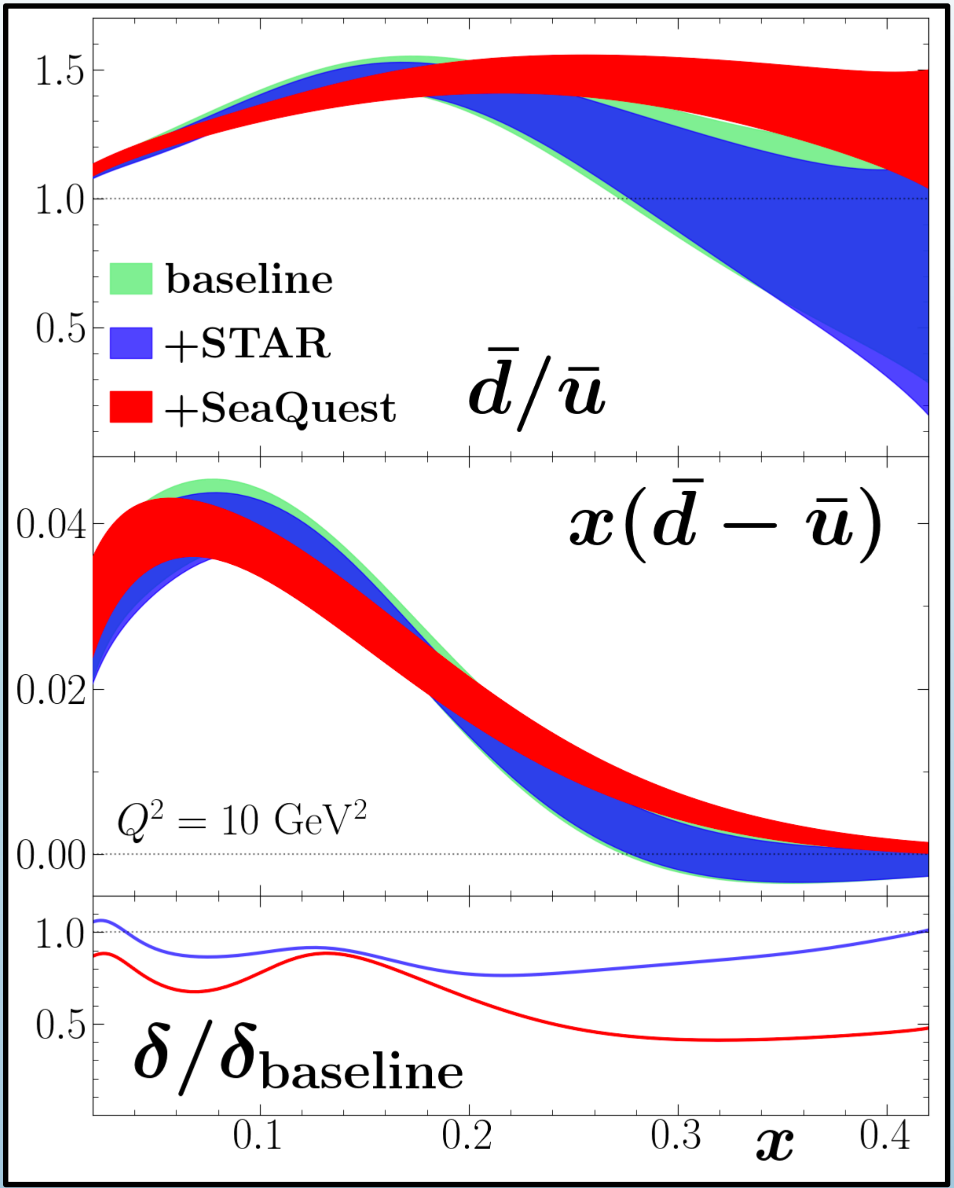


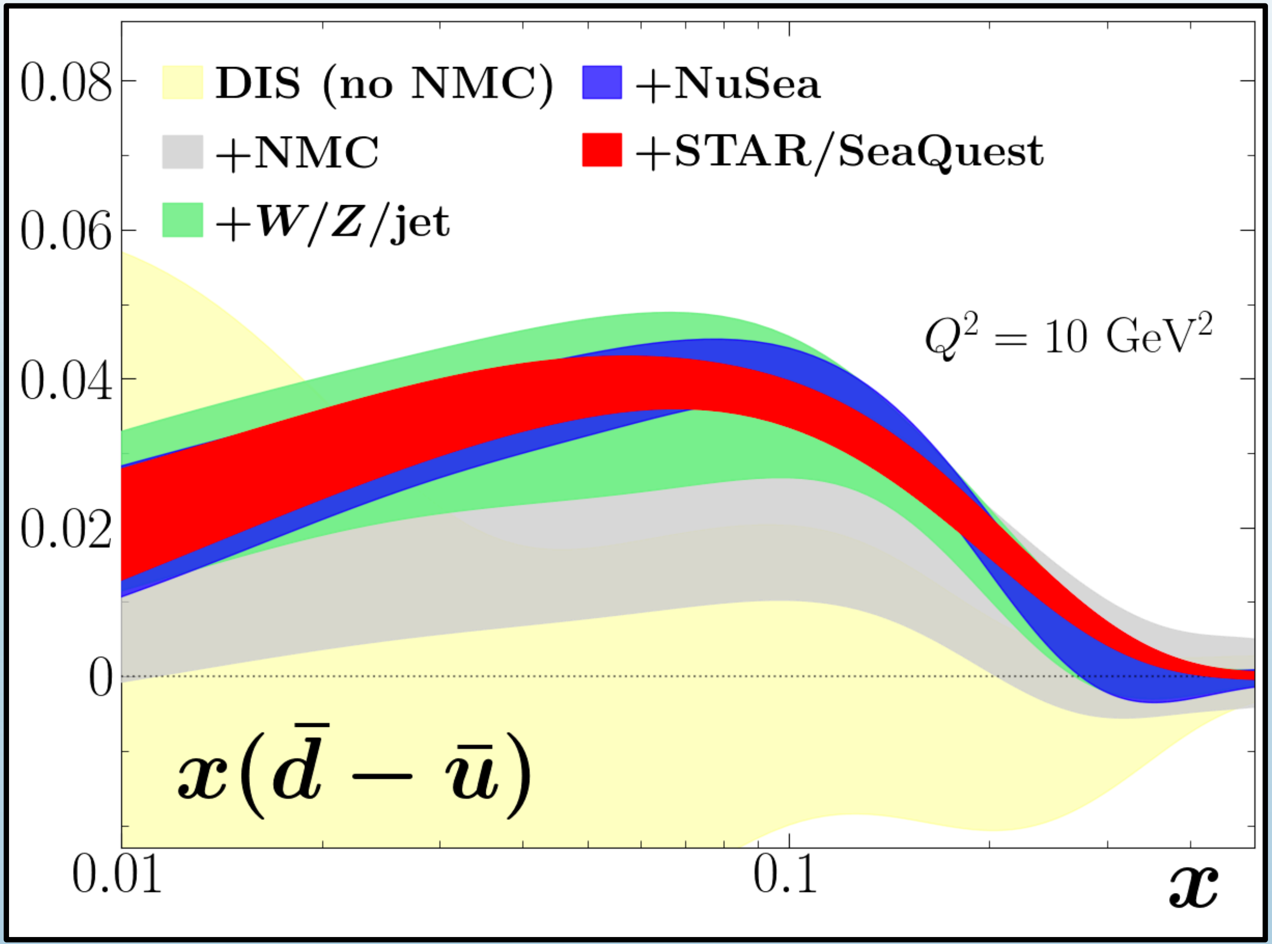
Impact from STAR and SeaQuest

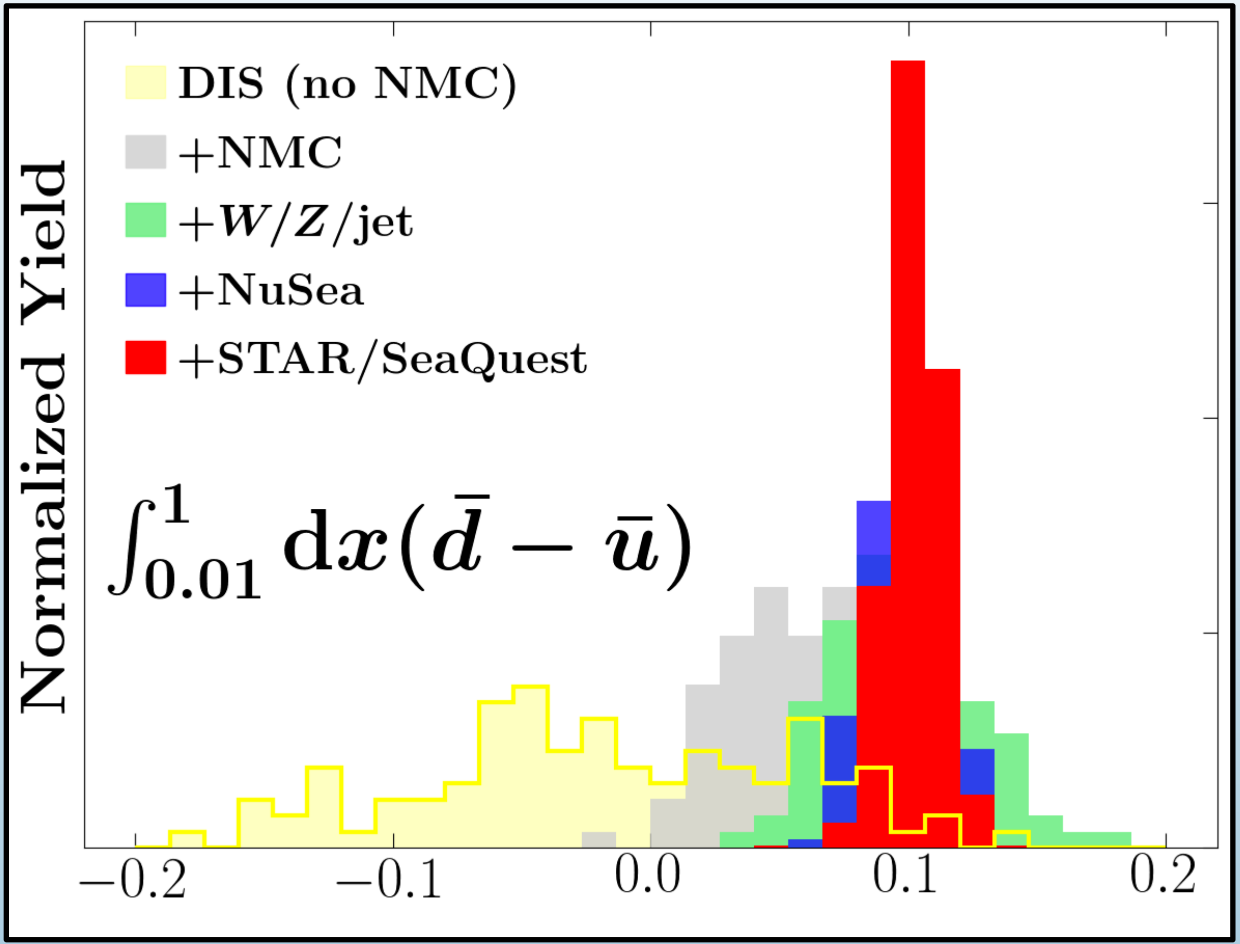


STAR: Moderate reduction of uncertainties

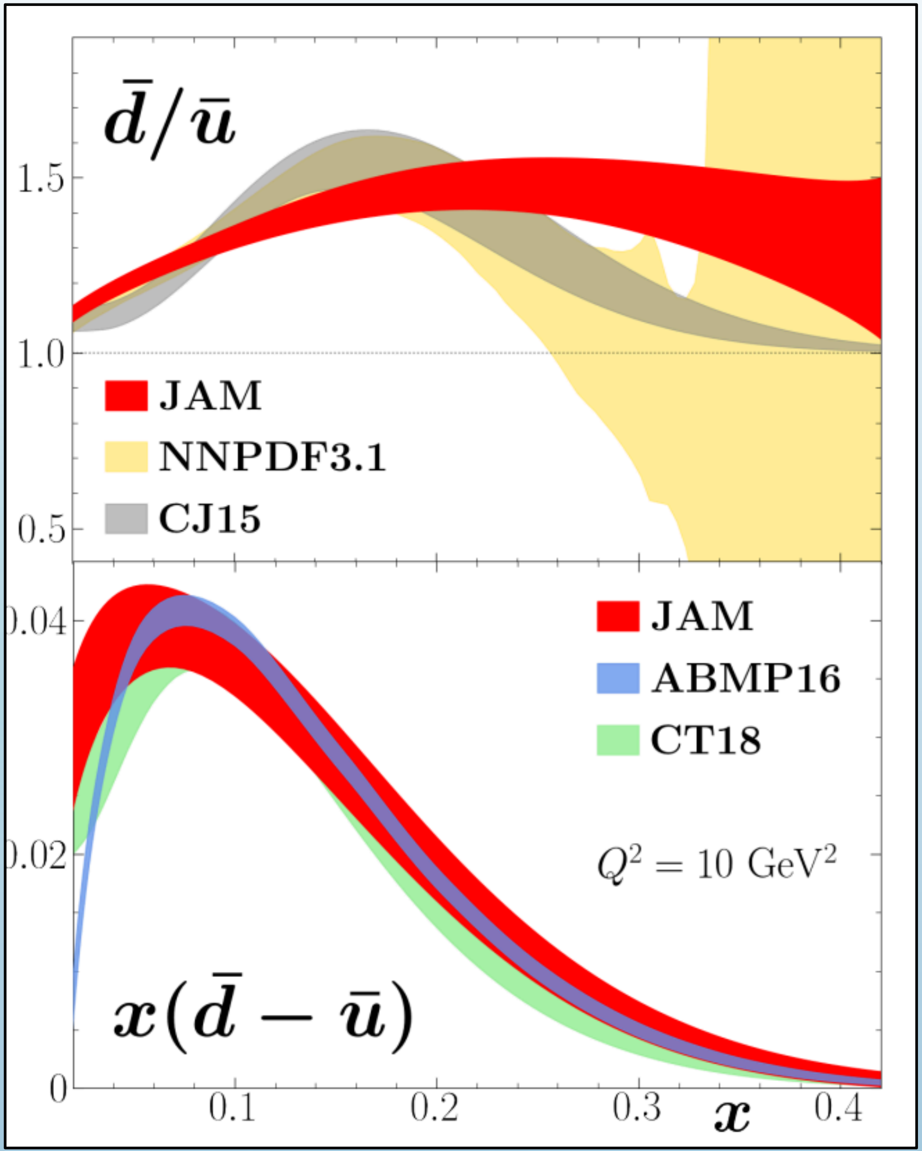
SeaQuest: Large reduction of uncertainties, especially at $x > 0.2$. $\bar{d}/\bar{u} > 1$ up to $x \approx 0.4$, in agreement with models

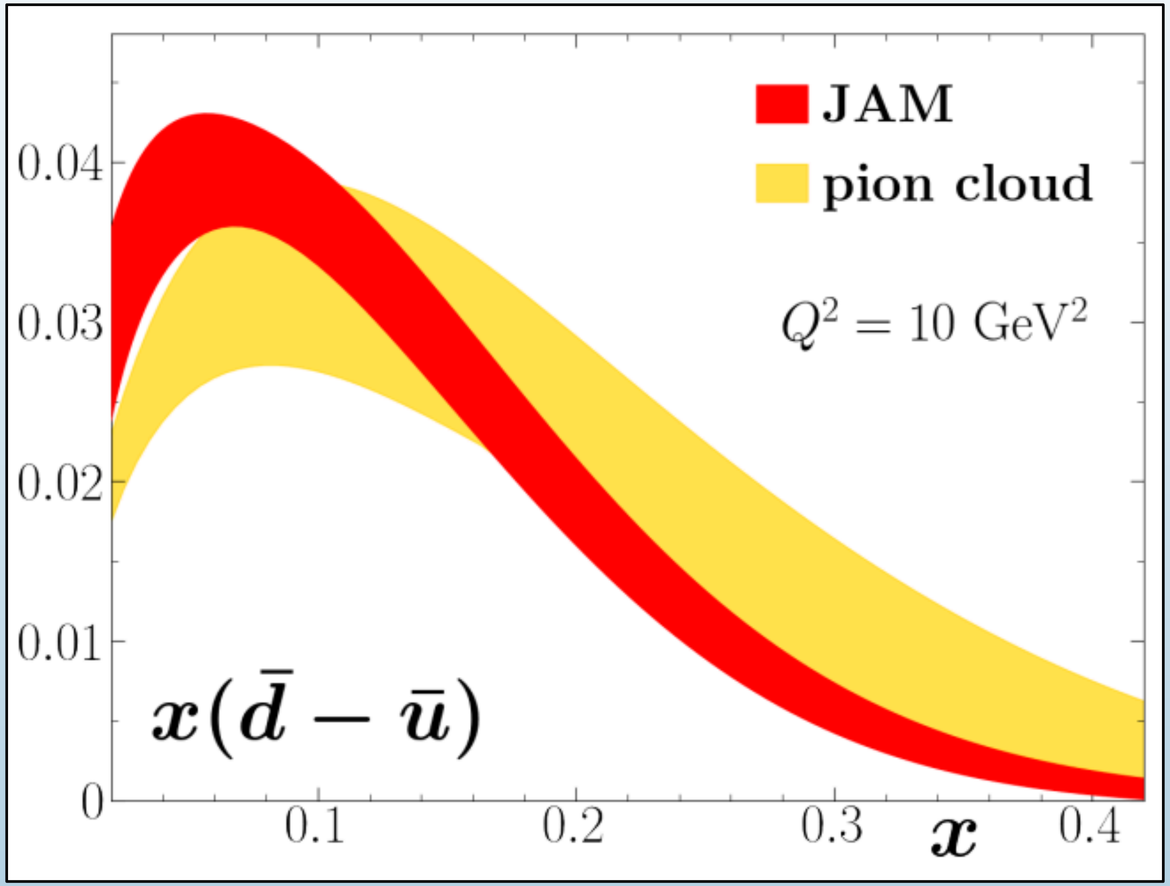
Sources of Asymmetry



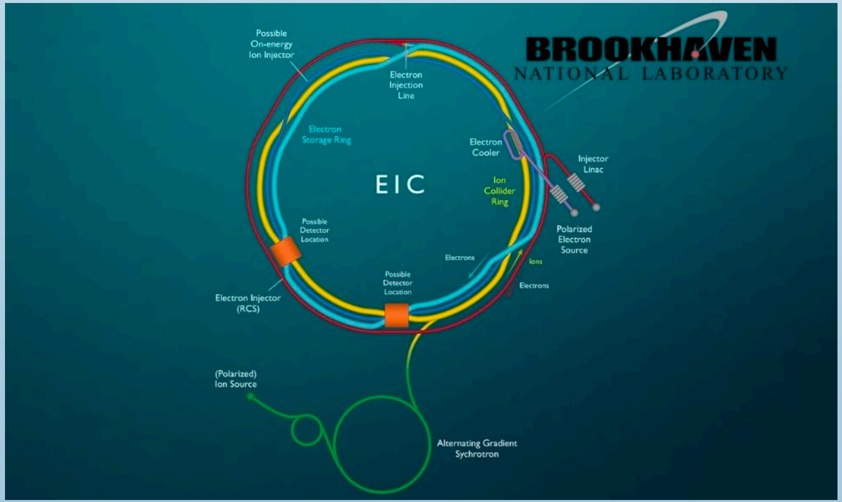


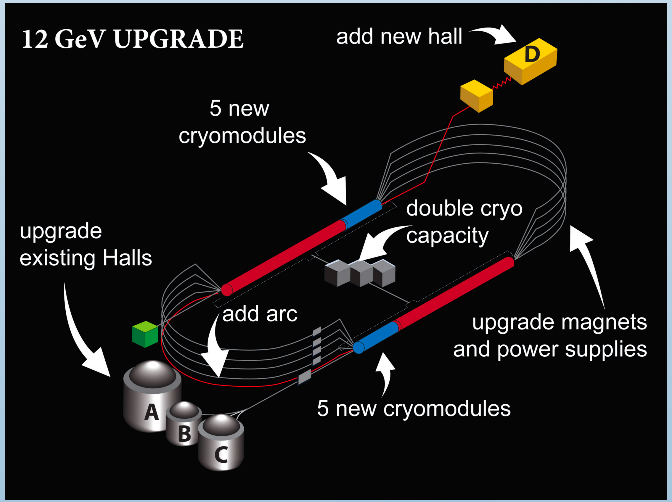
Comparison to other fits and pion cloud model





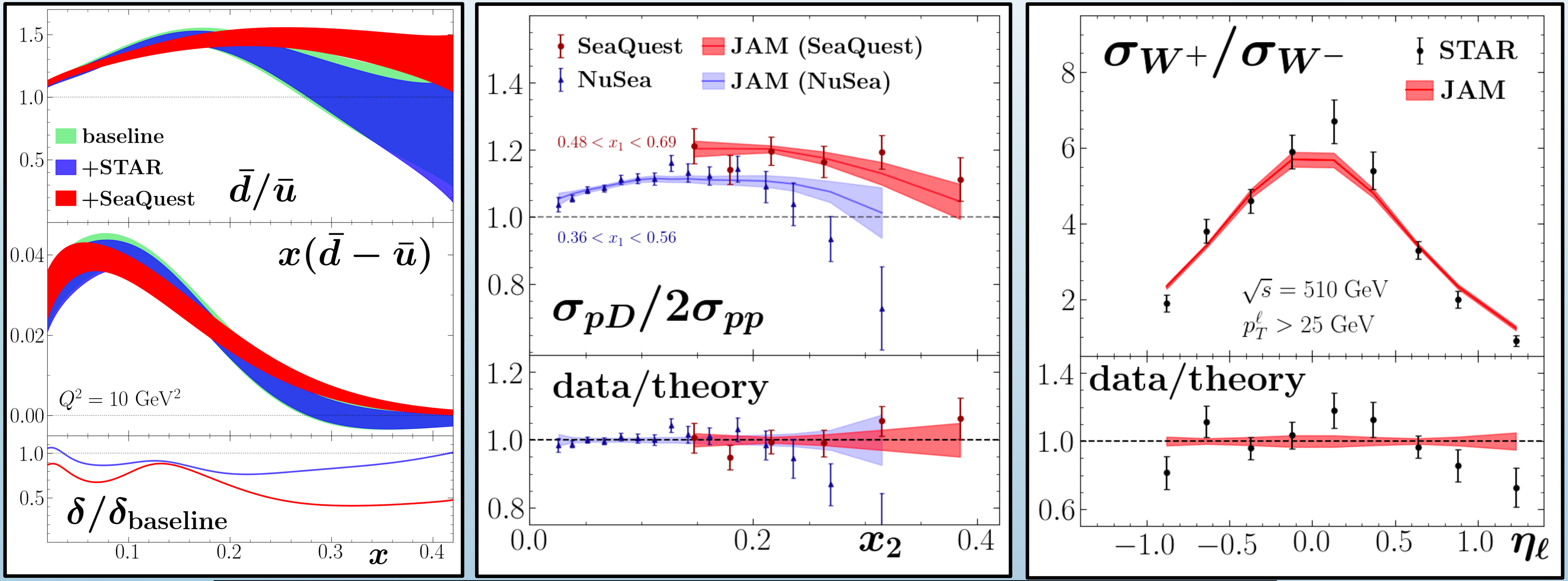
Good agreement with pion cloud model


BROOKHAVEN
NATIONAL LABORATORY
EIC
Possible On-energy Ion Injector
Electron Injection Line
Electron Storage Ring
Electron Cooler
Injector Linac
Ion Collider Ring
Polarized Electron Source
Possible Detector Location
Electrons
Ions
Electrons
Possible Detector Location
Electron Injector (RCS)
(Polarized) Ion Source
Alternating Gradient Sychrotron


12 GeV UPGRADE
add new hall
D
5 new cryomodules
double cryo capacity
upgrade existing Halls
add arc
upgrade magnets and power supplies
5 new cryomodules
A
B
C

Results Summary

First global QCD analysis of SeaQuest and STAR data

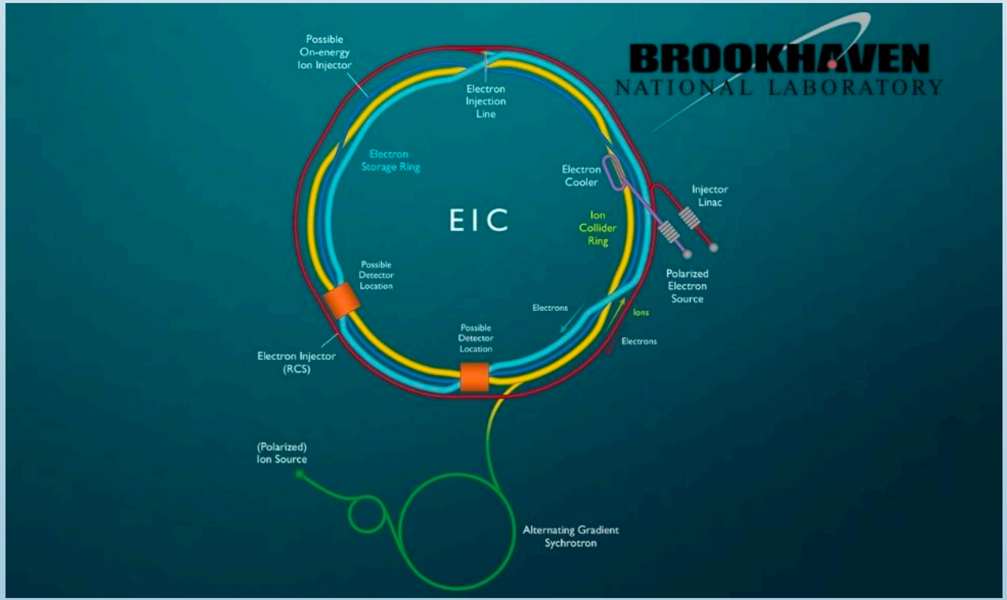


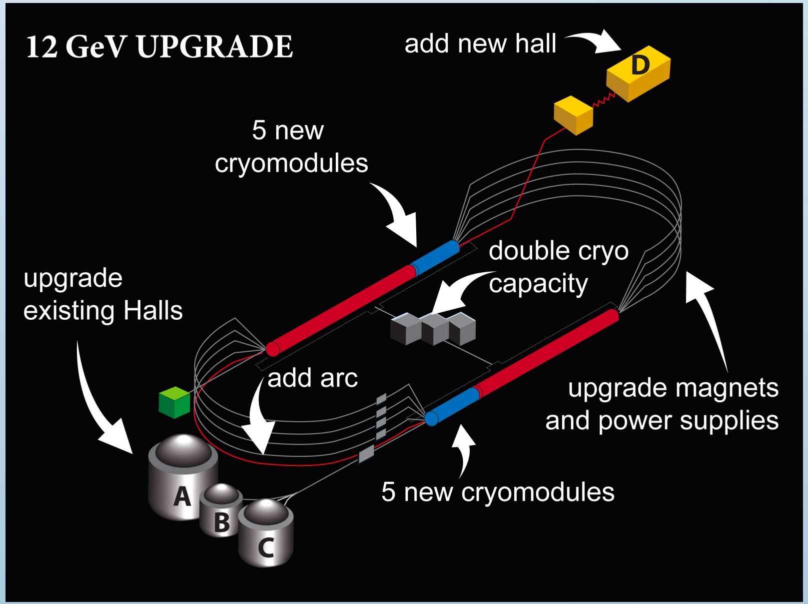
https://arxiv.org/abs/2109.00677

C. Cocuzza *et al.*, Phys. Rev. D. **104**, no. 7, 074031 (2021).

Outlook

Combine analysis with semi-inclusive DIS data from COMPASS.
Jefferson Lab 12 GeV upgrade: Precise high-*x* DIS data
EIC: First polarized electron-ion collider





Collaboration

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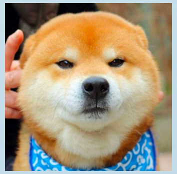
JAM Jefferson Lab Angular Momentum Collaboration

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

Backup

Bayes' Theorem

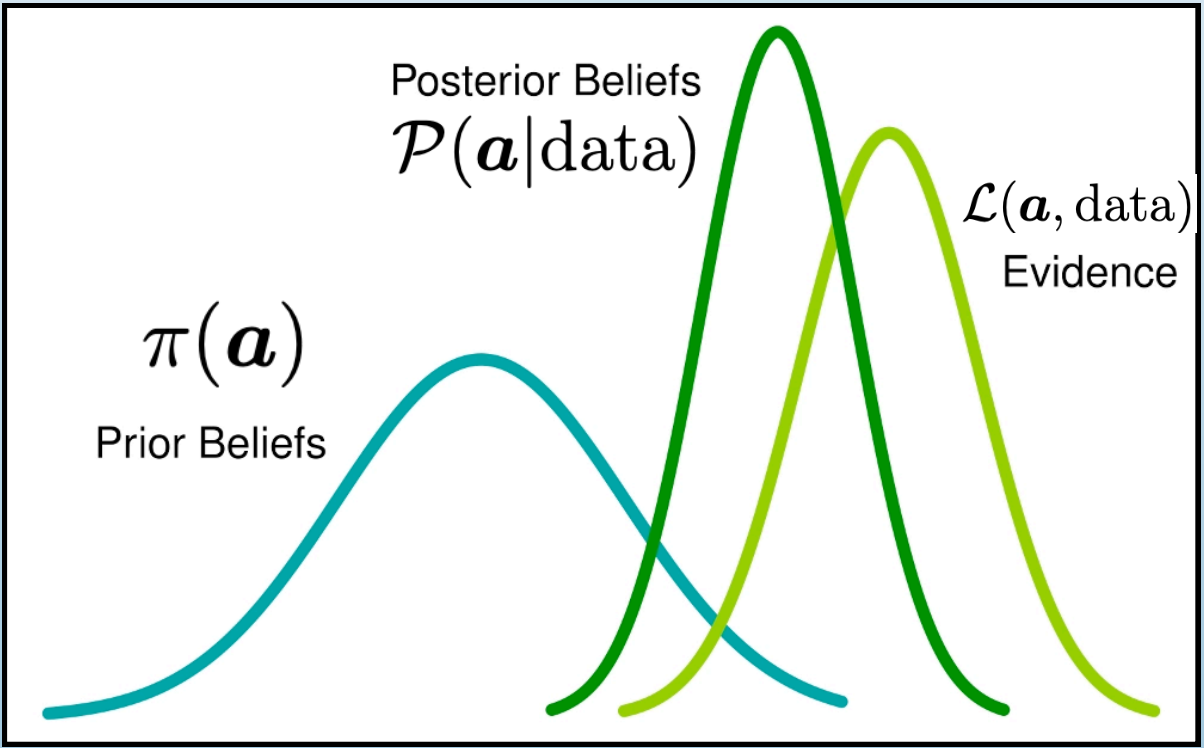
Now that we have calculated $\chi^2(\boldsymbol{a}, \text{data})$…

Likelihood Function

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

Bayes' Theorem

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



Error Quantification

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

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

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

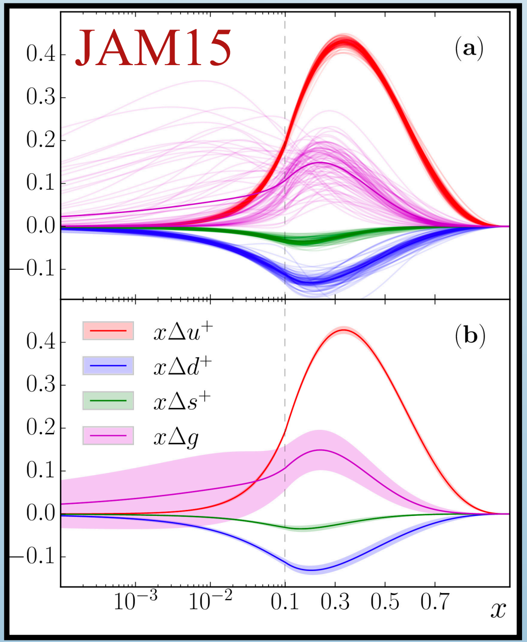
Exact, but $n = \mathcal{O}(100)$!

Build an MC ensemble

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

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

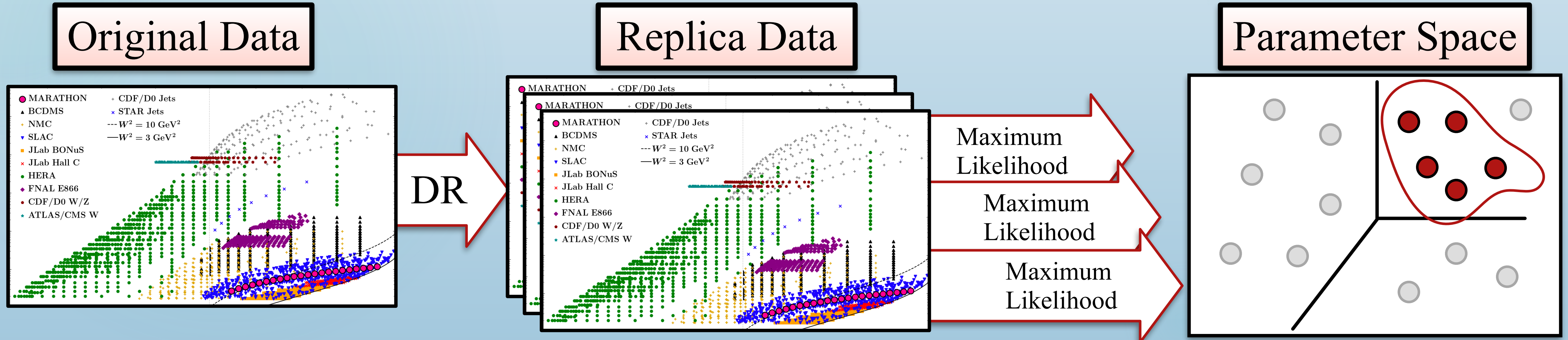
Average over k sets of the parameters (replicas)



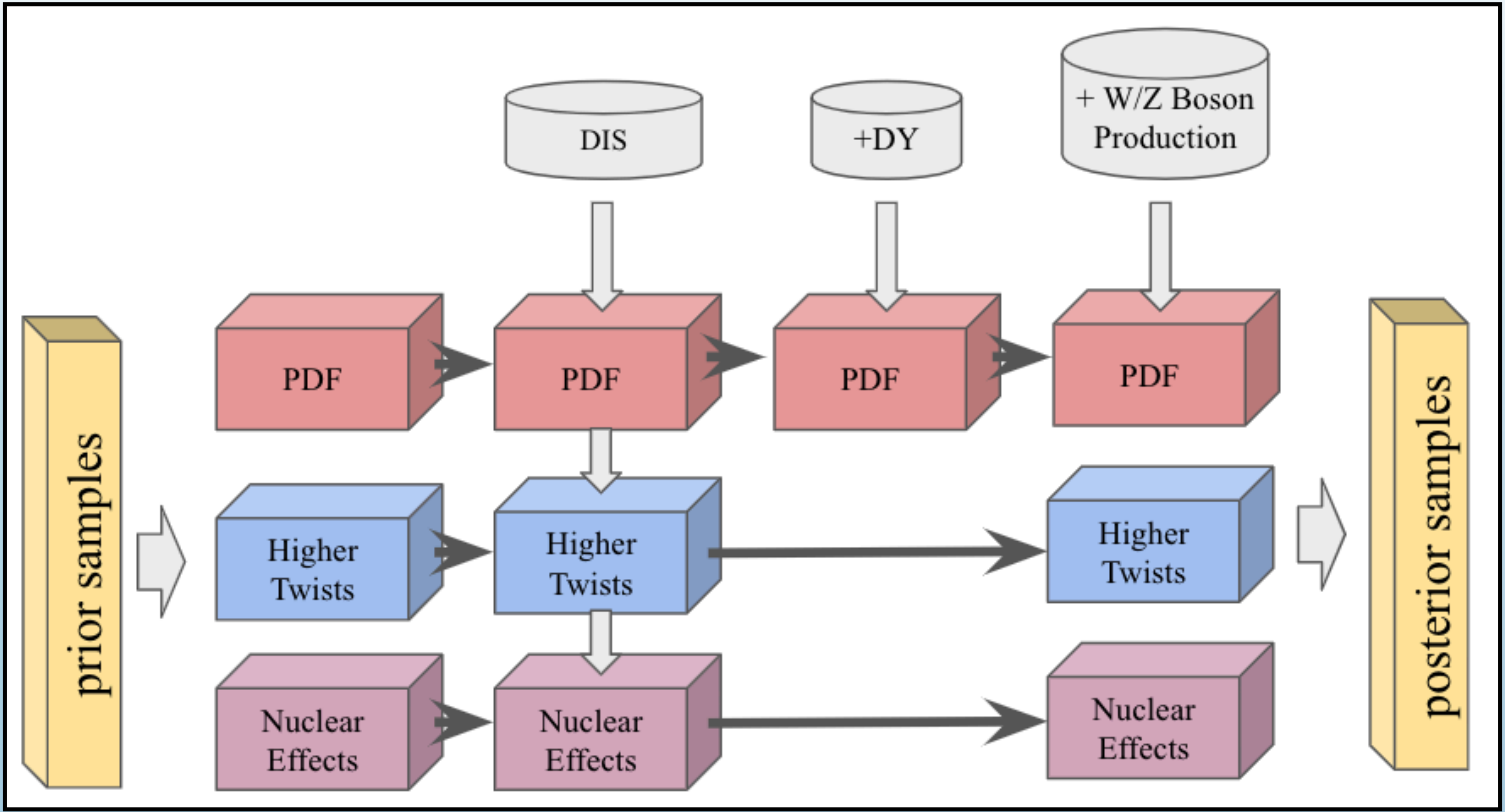
Data Resampling

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

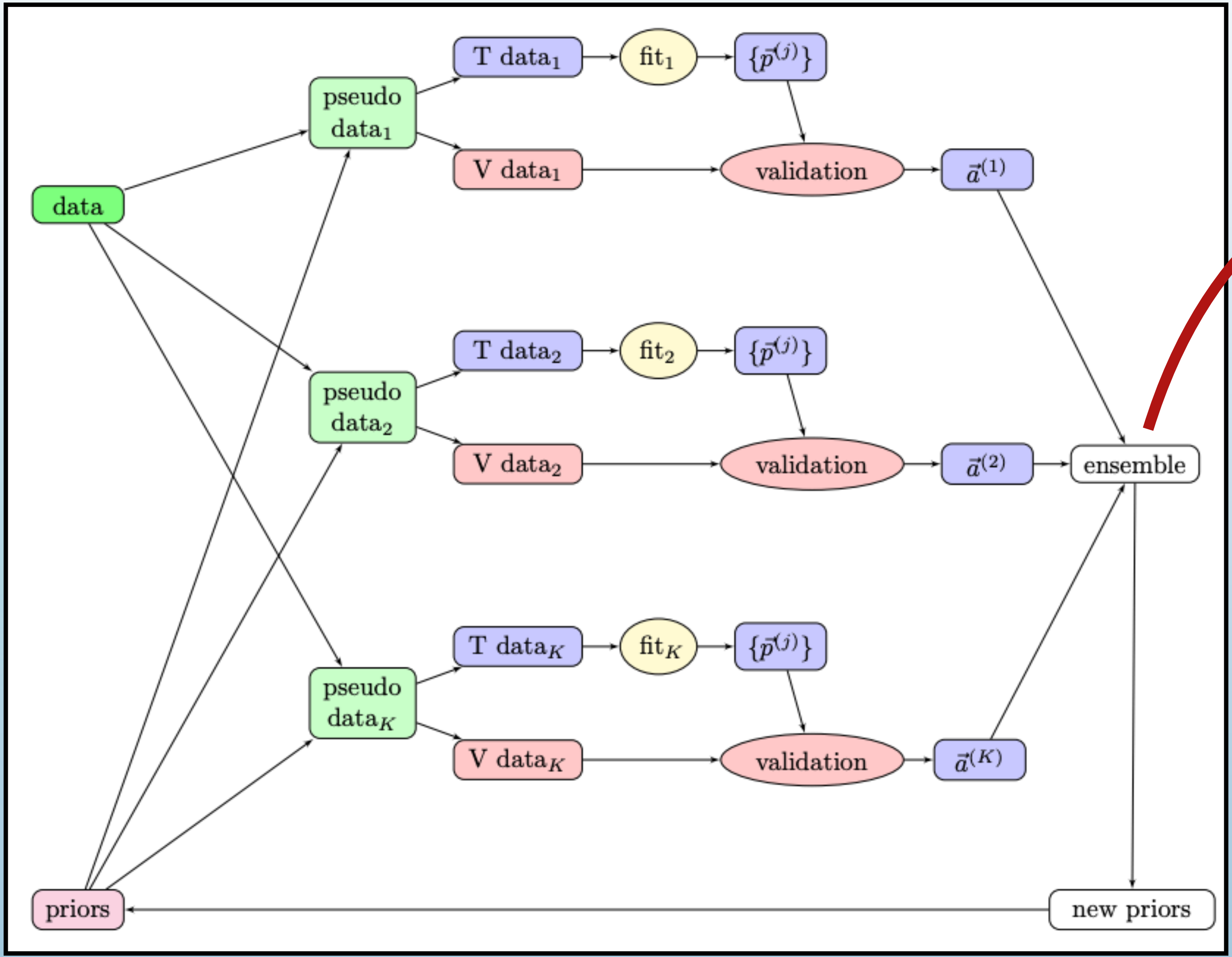
↑ Data

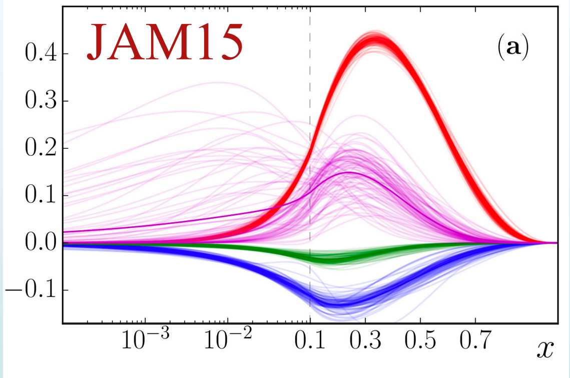


Multi-Step Strategy



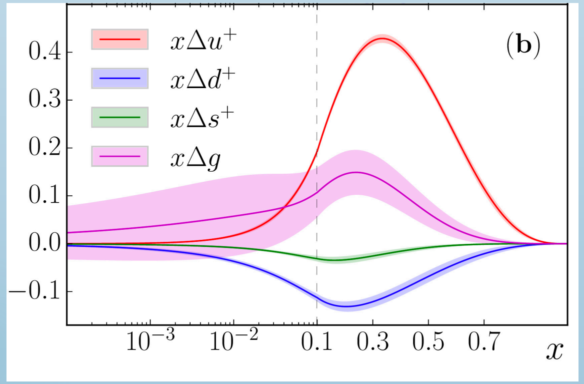
Putting it all together…



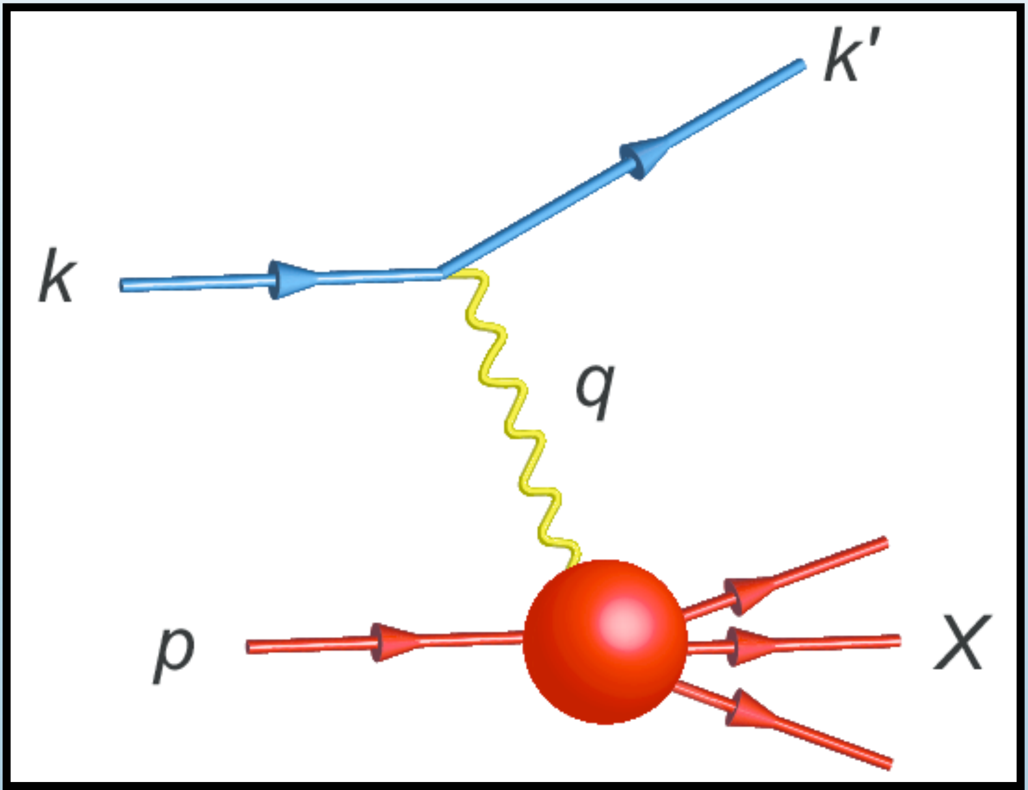


$$E[O] \approx \frac{1}{N}\sum_k O(\boldsymbol{a}_k)$$

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



Deep Inelastic Scattering



Virtuality:

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

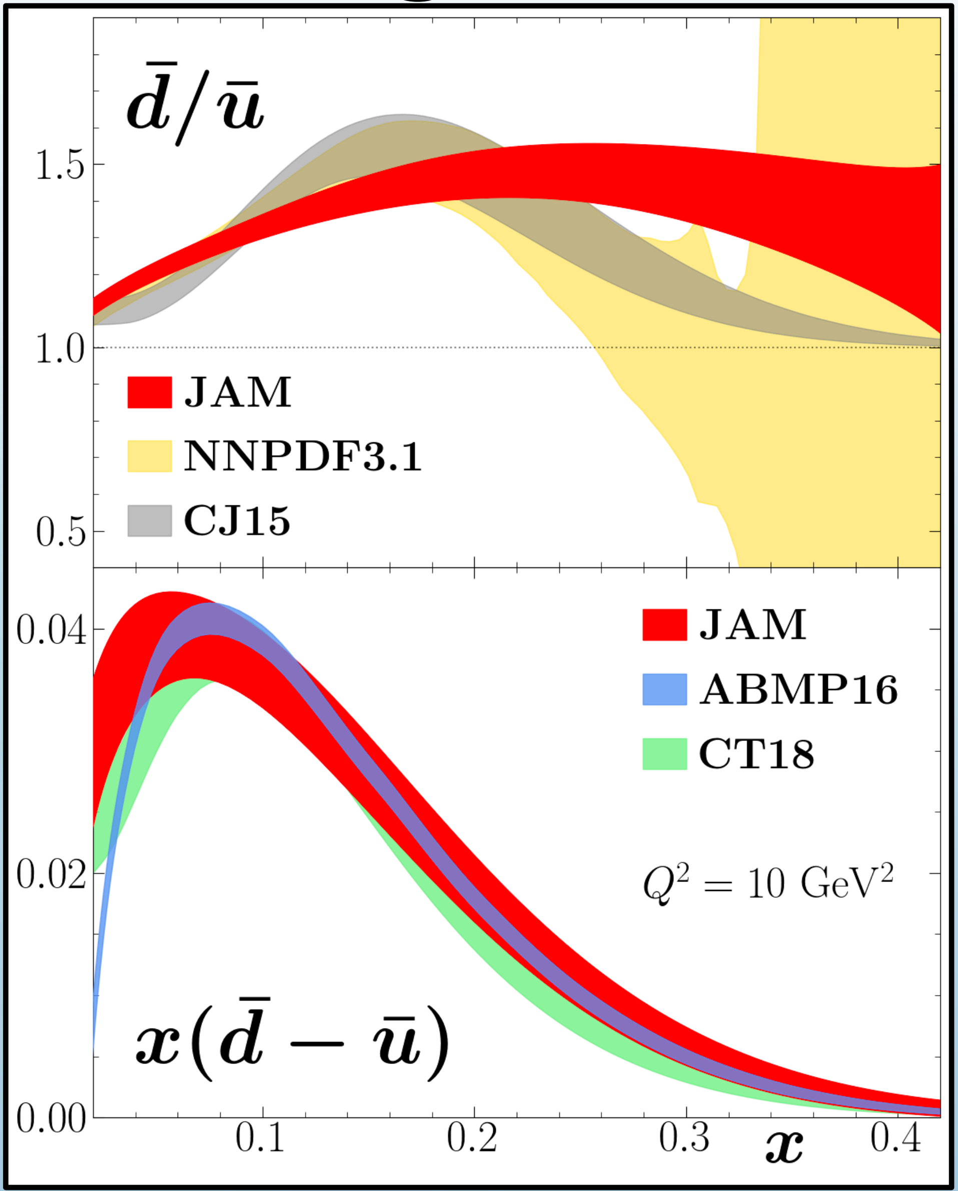
Bjorken x:

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

Invariant mass of outgoing particles:

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

Resulting PDFs



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