Latest Results on Unpolarized and Helicity PDFs

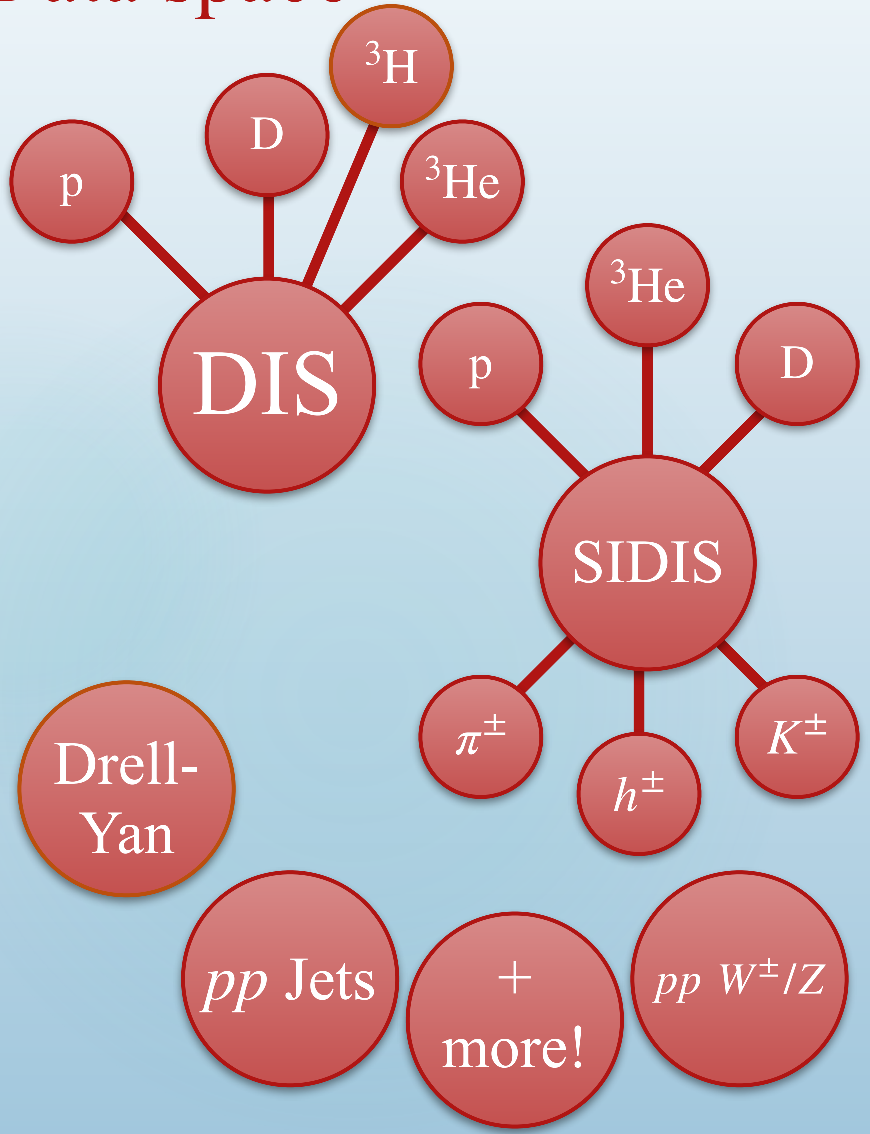
Chris Cocuzza (Temple U.)

August 30, 2022

Current State of Unpolarized Global Analyses

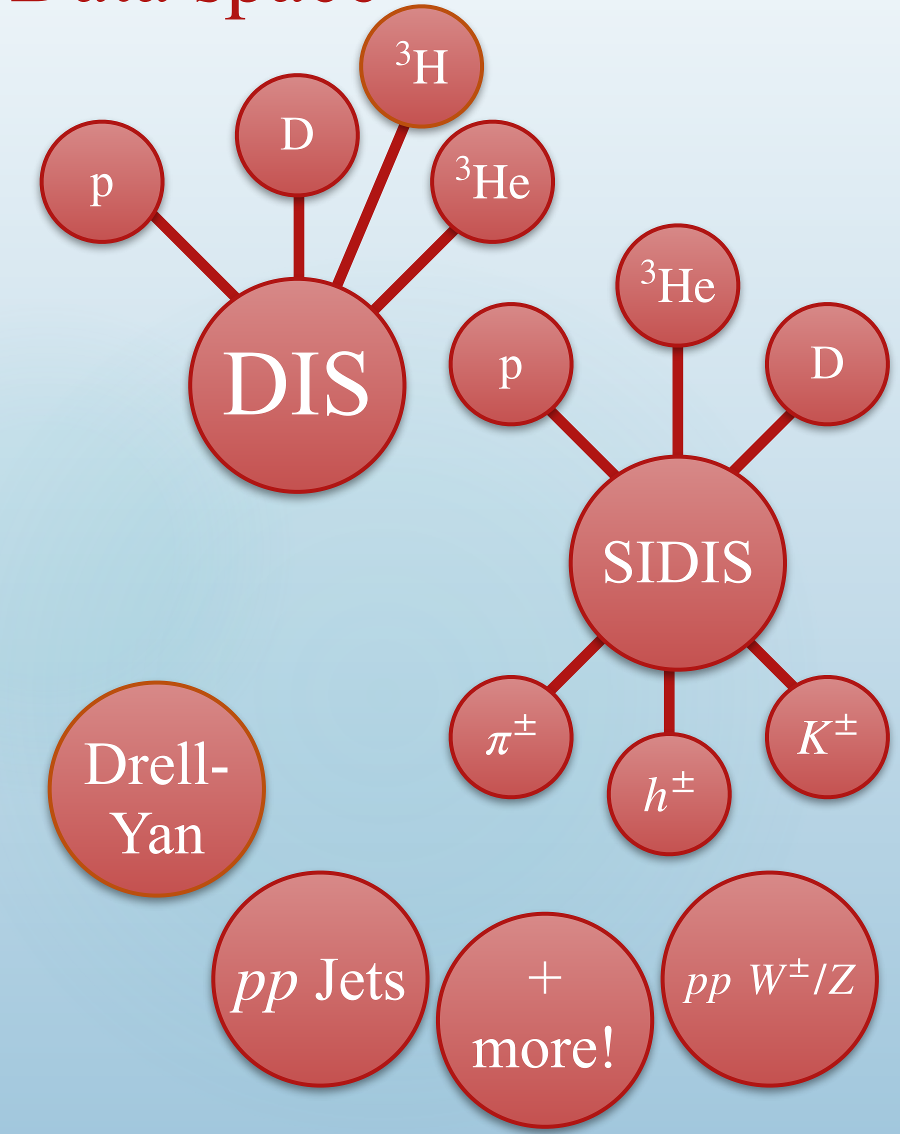
Current State of Unpolarized Global Analyses

Data space

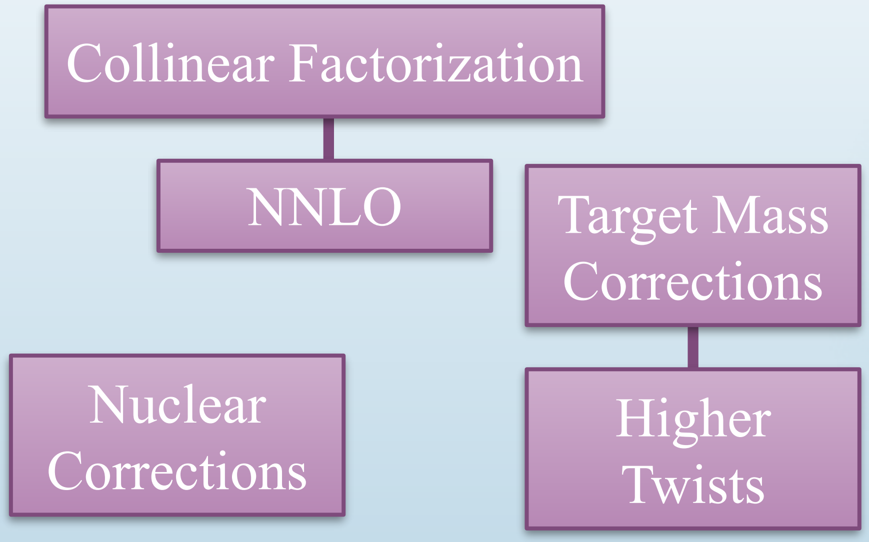


Current State of Unpolarized Global Analyses

Data space

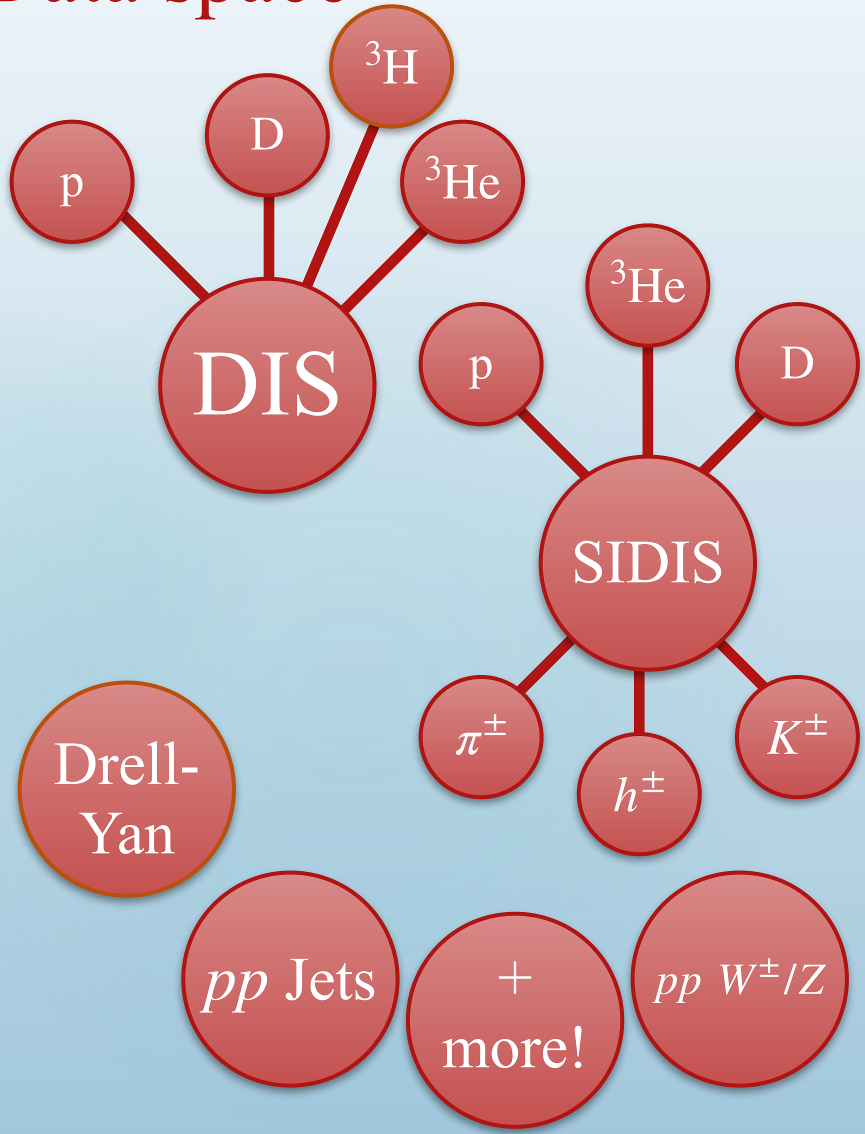


Theory



Current State of Unpolarized Global Analyses

Data space



Theory

- Collinear Factorization
- NNLO
- Target Mass Corrections
- Higher Twists
- Nuclear Corrections

Methodology

- Traditional Parameterization
- Neural Nets
- MC Approach
- Maximum Likelihood +Hessian/Lagrange

Current State of Unpolarized Global Analyses

Data space

DIS: p, D, ^{3}H, ^{3}He

SIDIS: p, ^{3}He, D, $\pi^\pm$, $h^\pm$, $K^\pm$

Drell-Yan

pp Jets

+ more!

pp $W^\pm/Z$

Theory

Collinear Factorization

NNLO

Target Mass Corrections

Higher Twists

Nuclear Corrections

Methodology

Traditional Parameterization

Neural Nets

MC Approach

Maximum Likelihood +Hessian/Lagrange

Simultaneous Paradigm

Helicity PDFs

$h^\pm$

Unpol. PDFs

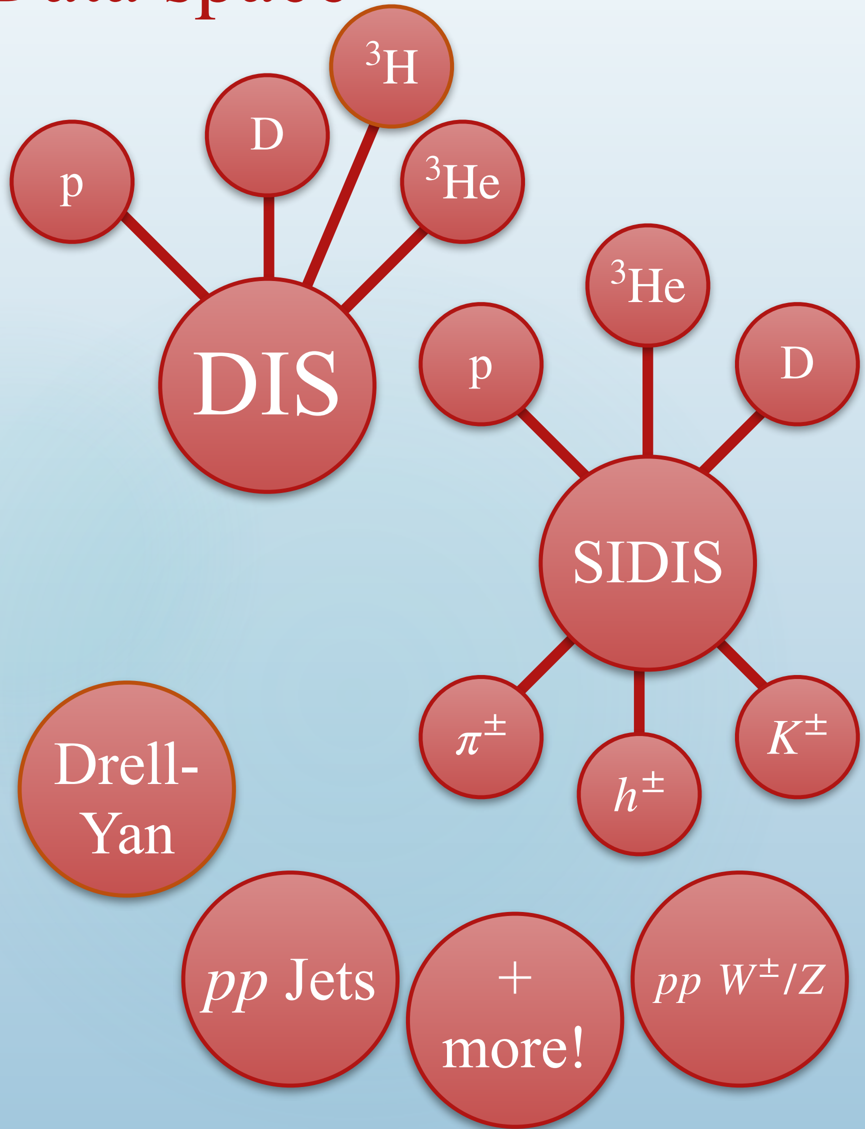
Frag. Functions

$\pi^\pm$

$K^\pm$

Current State of Unpolarized Global Analyses

Data space



Theory

- Collinear Factorization
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Methodology

- Traditional Parameterization ⋯ Neural Nets
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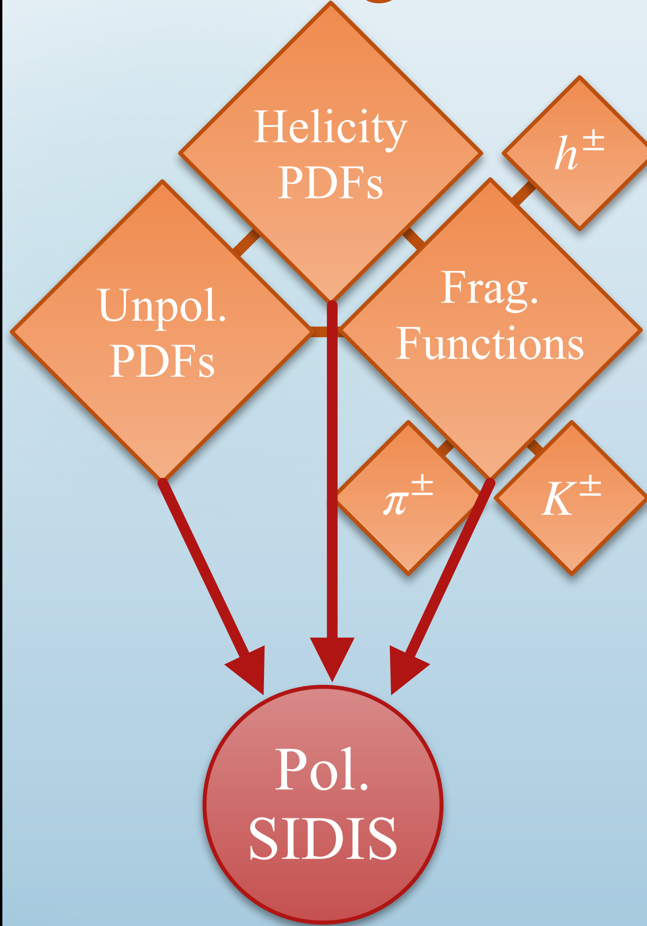
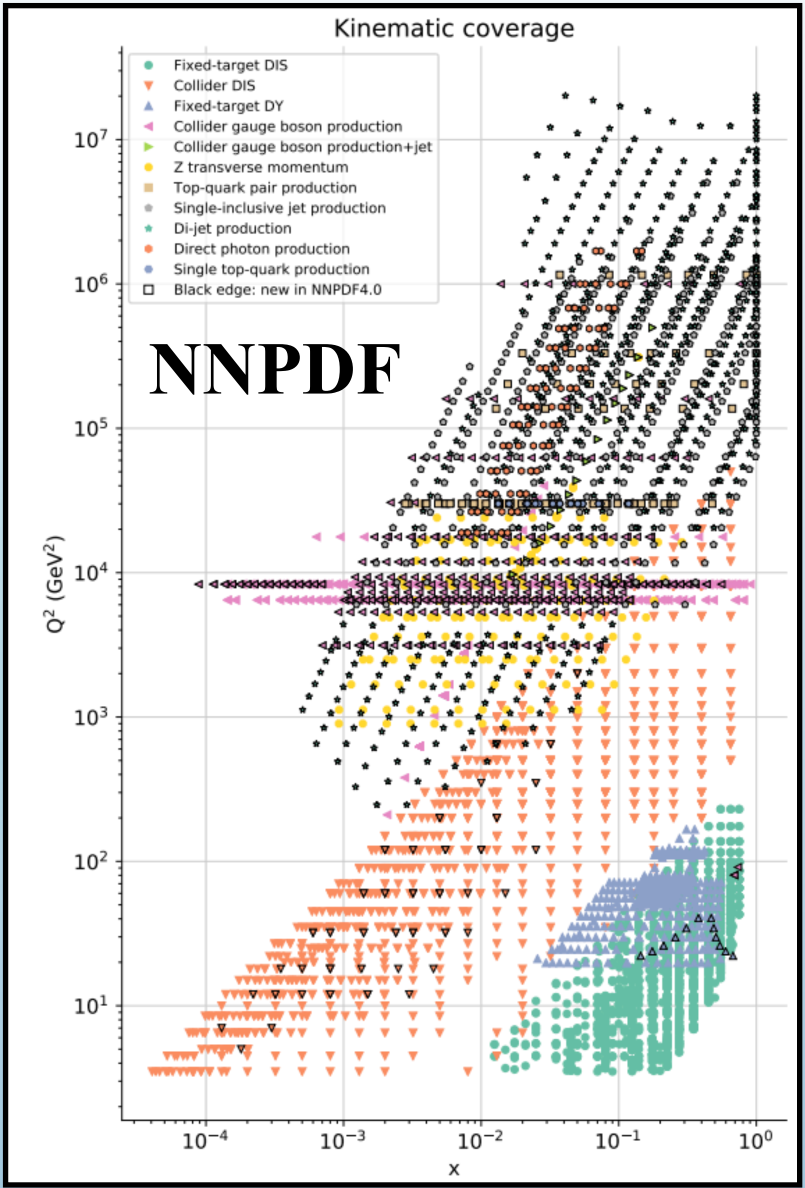
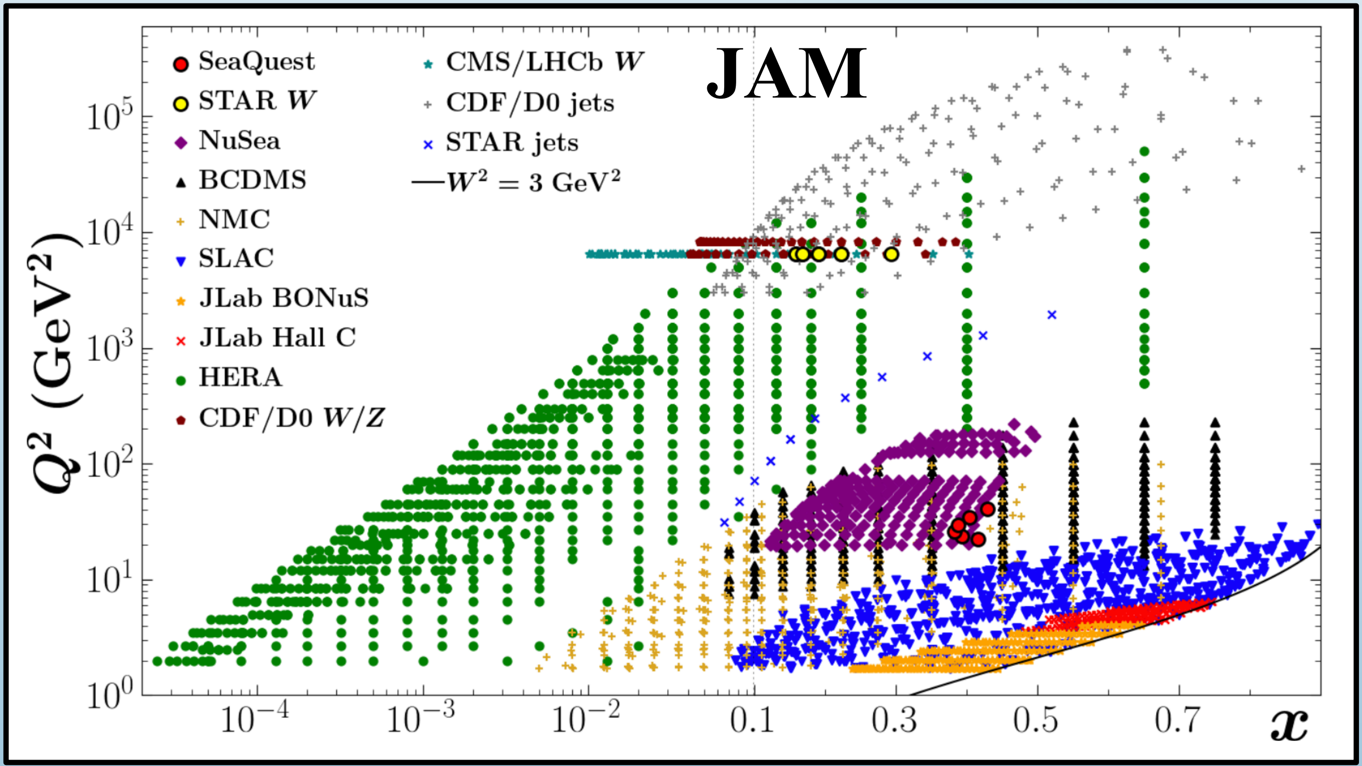
Simultaneous Paradigm

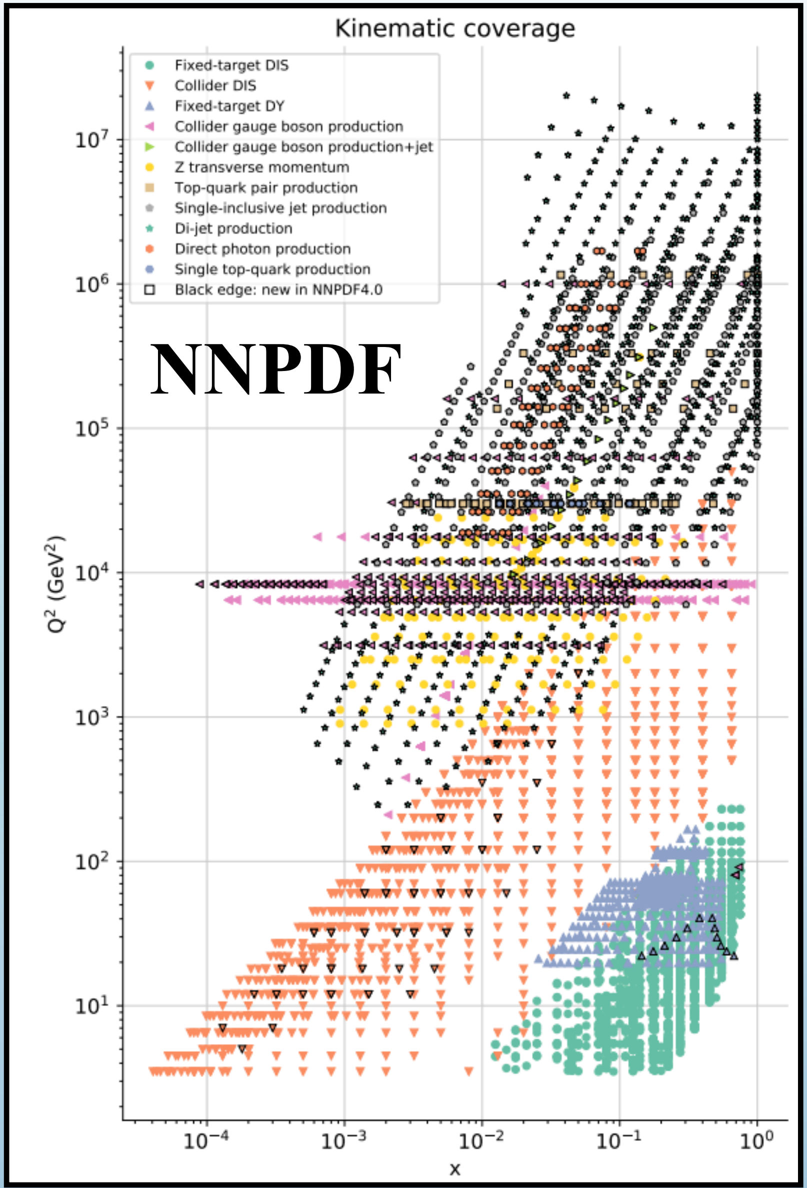


Current State of Unpolarized Global Analyses

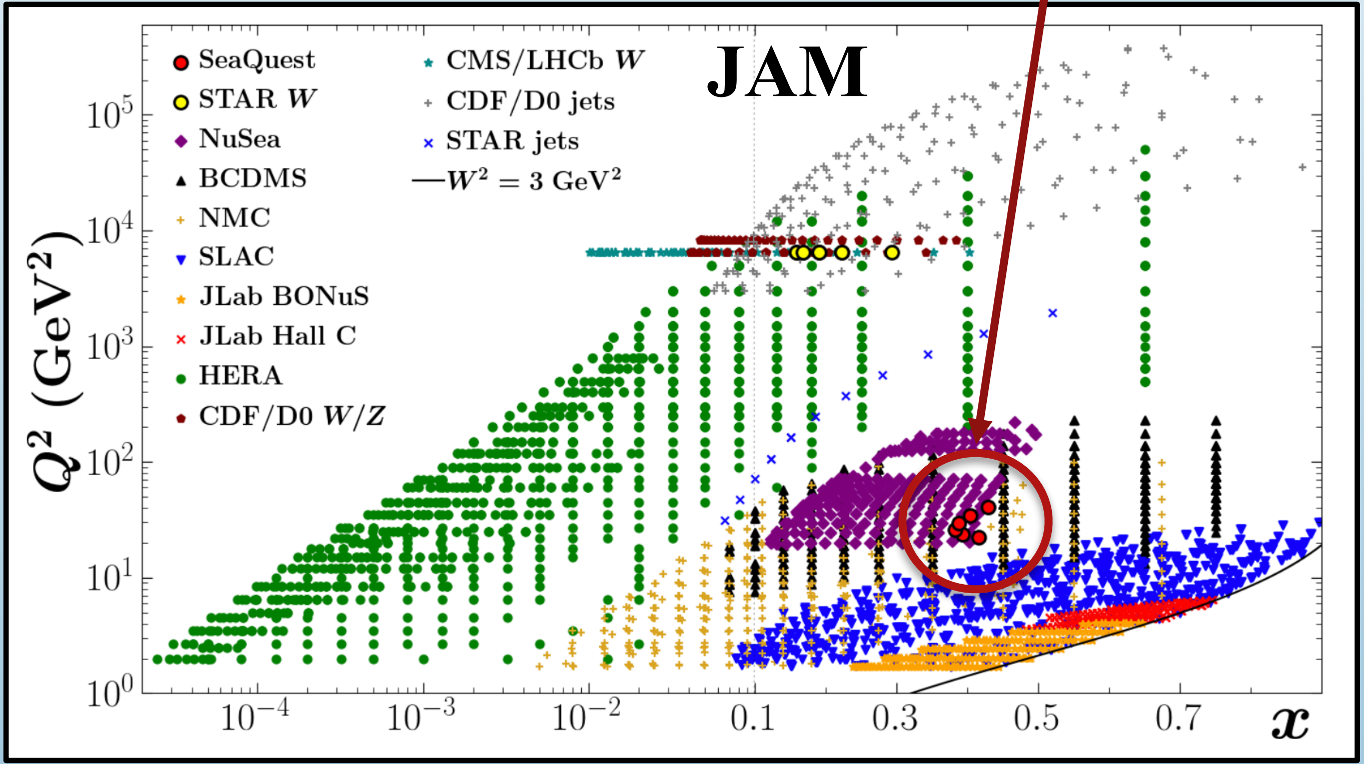




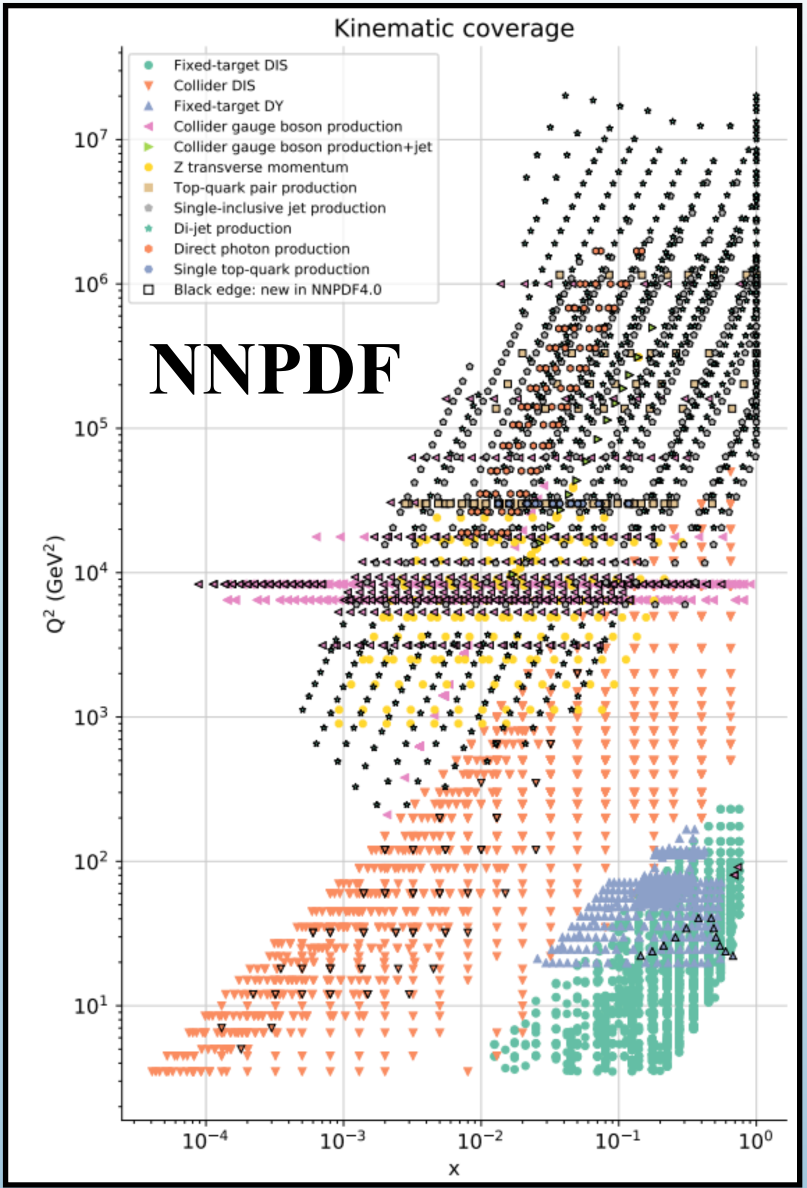
Current State of Unpolarized Global Analyses



New SeaQuest data

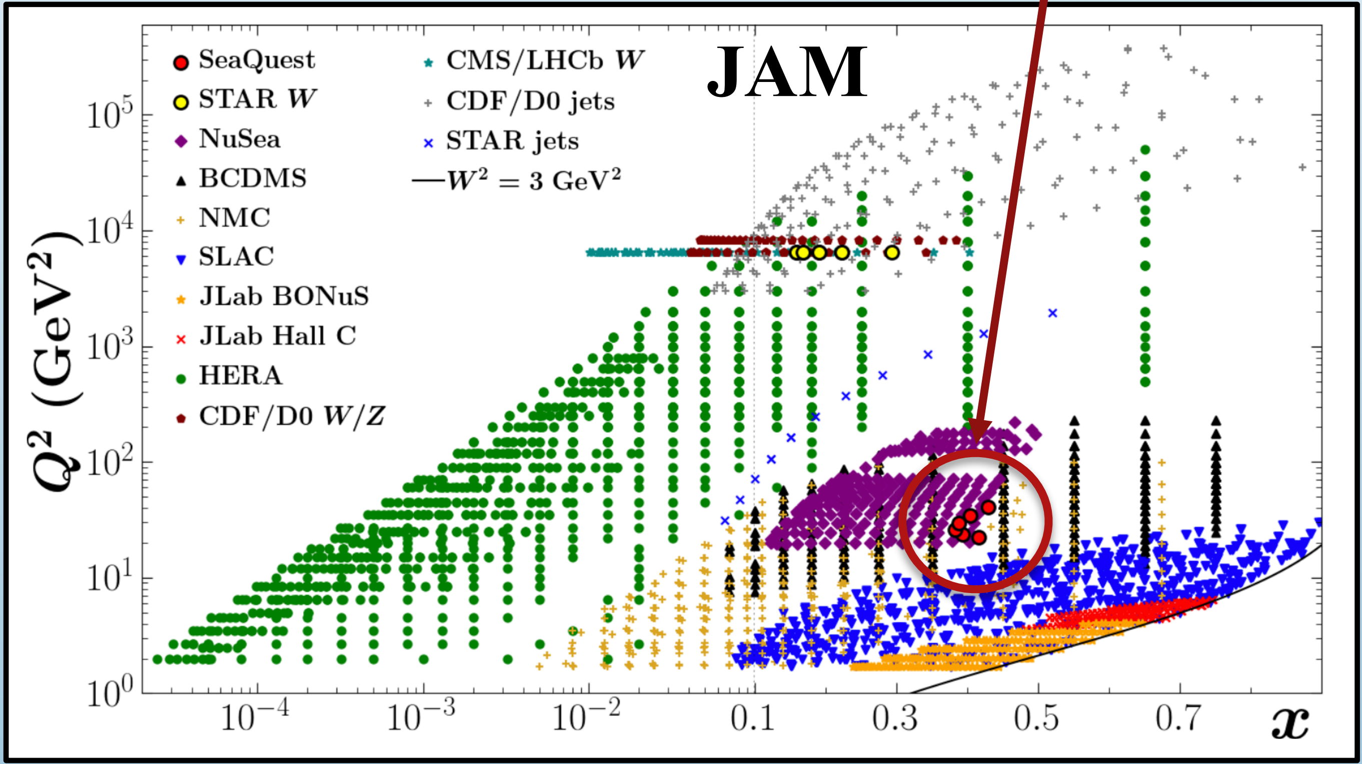


Current State of Unpolarized Global Analyses



New data from the LHC

New SeaQuest data



1. SeaQuest in Global Analyses

2. LHC and NNPDF4.0

3. Helicity Sea Asymmetry

4. Gluon Helicity

Article

The asymmetry of antimatter in the proton

https://doi.org/10.1038/s41586-021-03282-z

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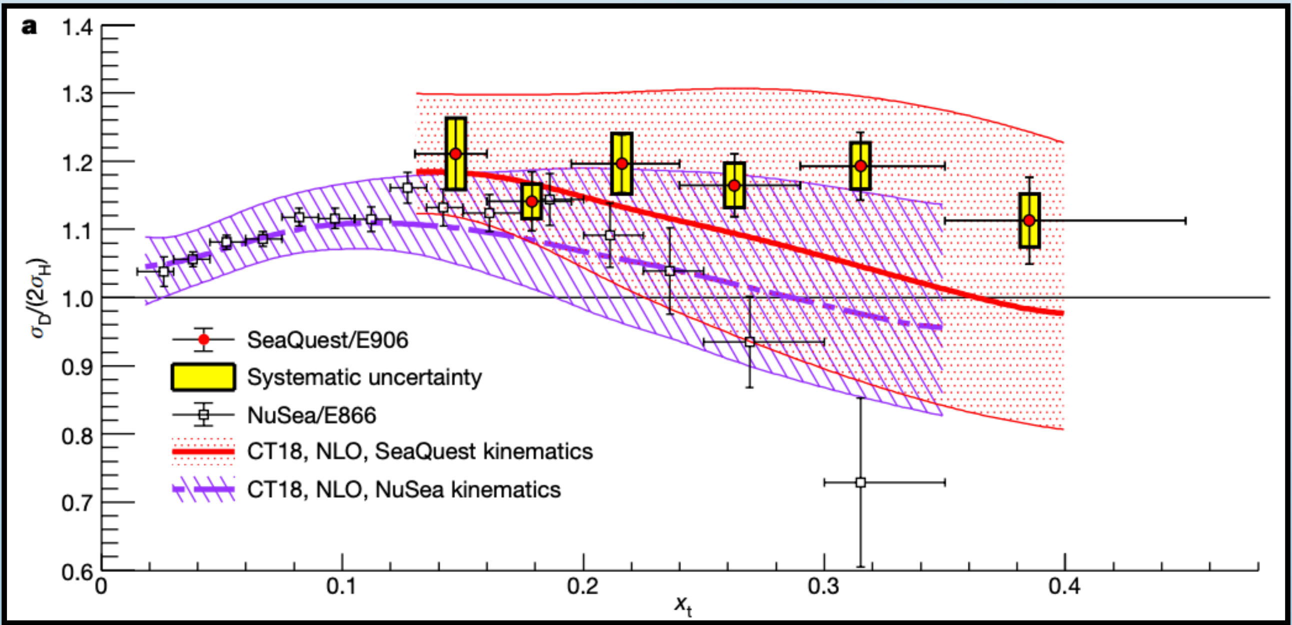
Check for updates

J. Dove[1], B. Kerns[1], R. E. McClellan[1,18], S. Miyasaka[2], D. H. Morton[3], K. Nagai[2,4], S. Prasad[1], F. Sanftl[2], M. B. C. Scott[3], A. S. Tadepalli[5,18], C. A. Aidala[3,6], J. Arrington[7,19], C. Ayuso[3,20], C. L. Barker[8], C. N. Brown[9], W. C. Chang[4], A. Chen[1,3,4], D. C. Christian[10], B. P. Dannowitz[1], M. Daugherity[8], M. Diefenthaler[1,18], L. El Fassi[5,11], D. F. Geesaman[7,21], R. Gilman[5], Y. Goto[12], L. Guo[6,22], R. Guo[13], T. J. Hague[8], R. J. Holt[7,23], D. Isenhower[8], E. R. Kinney[14], N. Kitts[8], A. Klein[6], D. W. Kleinjan[6], Y. Kudo[15], C. Leung[1], P.-J. Lin[14], K. Liu[6], M. X. Liu[6], W. Lorenzon[3], N. C. R. Makins[1], M. Mesquita de Medeiros[7], P. L. McGaughey[6], Y. Miyachi[15], I. Mooney[3,24], K. Nakahara[16,25], K. Nakano[2,12], S. Nara[15], J.-C. Peng[1], A. J. Puckett[6,26], B. J. Ramson[3,27], P. E. Reimer[7]✉, J. G. Rubin[3,7], S. Sawada[17], T. Sawada[3,28], T.-A. Shibata[2,29], D. Su[4], M. Teo[1,30], B. G. Tice[7], R. S. Towell[8], S. Uemura[6,31], S. Watson[8], S. G. Wang[4,13,32], A. B. Wickes[6], J. Wu[10], Z. Xi[8] & Z. Ye[7]



Spin-Averaged Sea Asymmetry (2021-2022)

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

Christopher Cocuzza, Wally Melnitchouk, Andreas Metz, Nobuo Sato

https://arxiv.org/abs/2109.00677
C. Cocuzza *et al*., Phys. Rev. D **104**, no. 7, 074031 (2021).

NNLO constraints on proton PDFs from the SeaQuest and STAR experiments and other developments in the CTEQ-TEA global analysis

Marco Guzzi, T. J. Hobbs, Tie-Jiun Hou, Xiaoxian Jing, Keping Xie, Aurore Courtoy, Sayipjamal Dulat, Jun Gao, Joey Huston, Pavel M. Nadolsky, Carl Schmidt, Ibrahim Sitiwaldi, Mengshi Yan, C.-P. Yuan

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CJ15 global PDF analysis with new electroweak data from the STAR and SeaQuest experiments

Sanghwa Park, Alberto Accardi, Xiaoxian Jing, J.F. Owens

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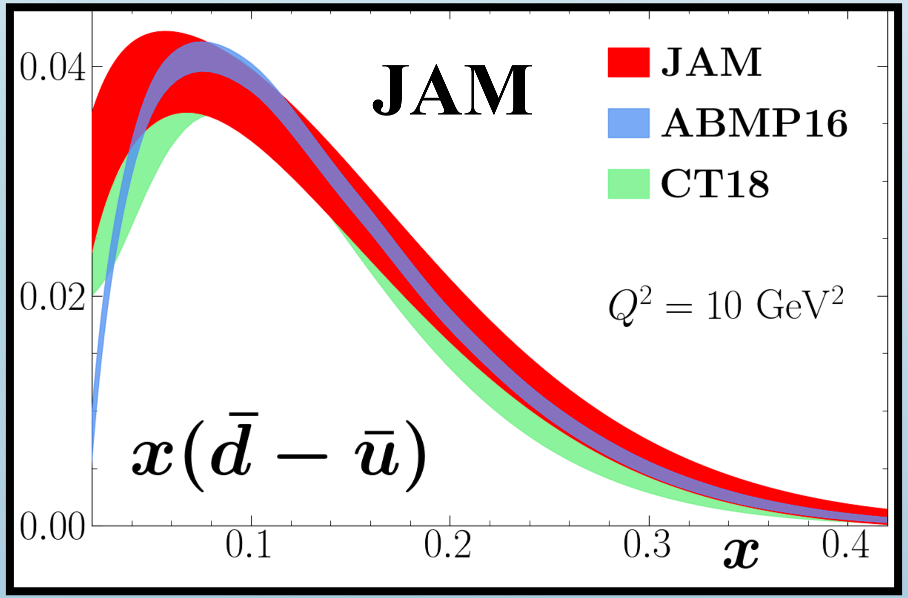

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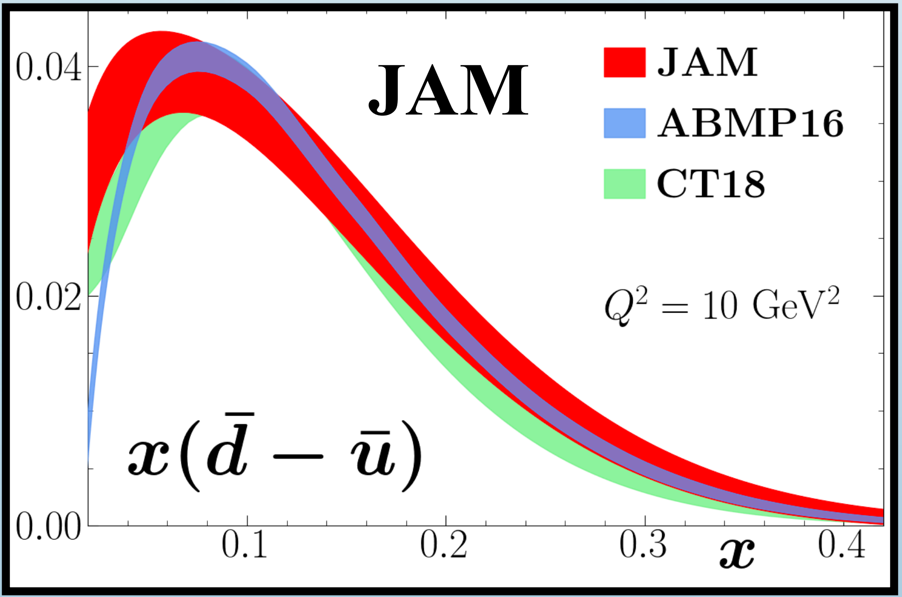
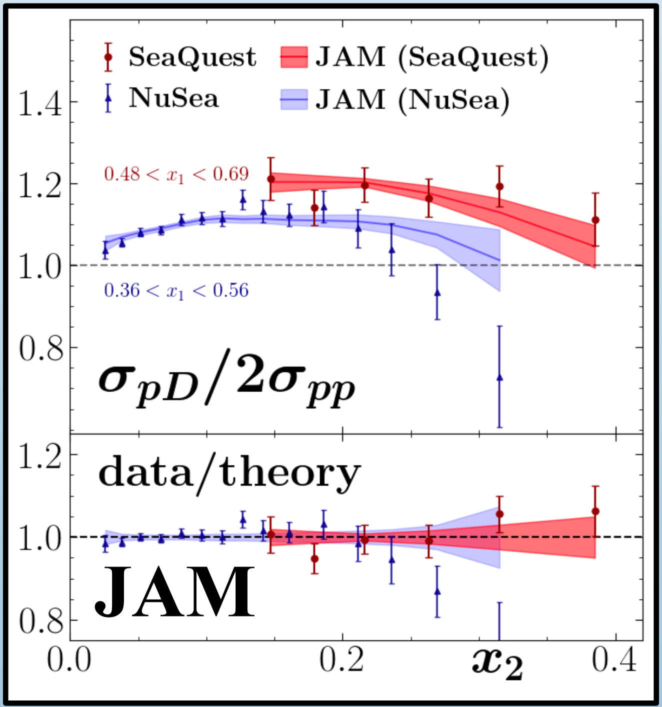
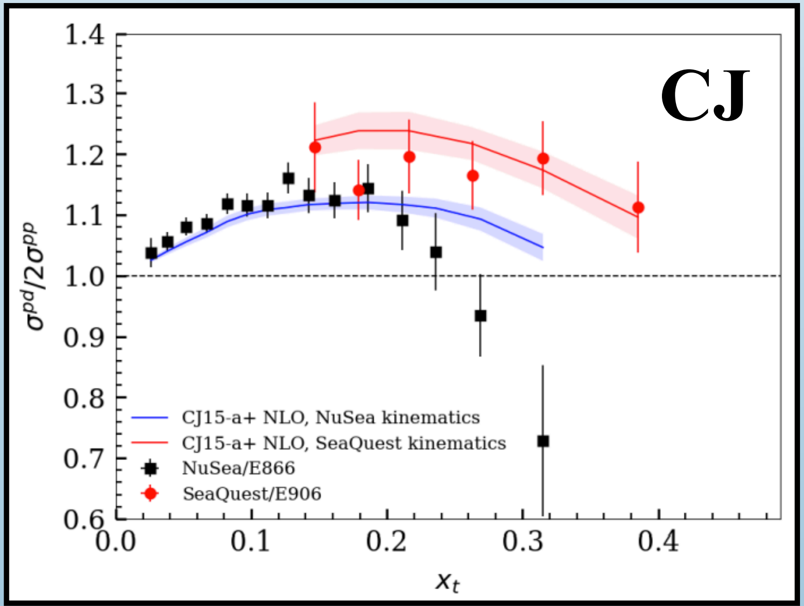
$$\frac{\sigma_{pD}}{2\sigma_{pp}}\Big|_{x_1 \gg x_2} \approx \frac{1}{2}\left[1+\frac{\bar{d}(x_2)}{\bar{u}(x_2)}\right]$$







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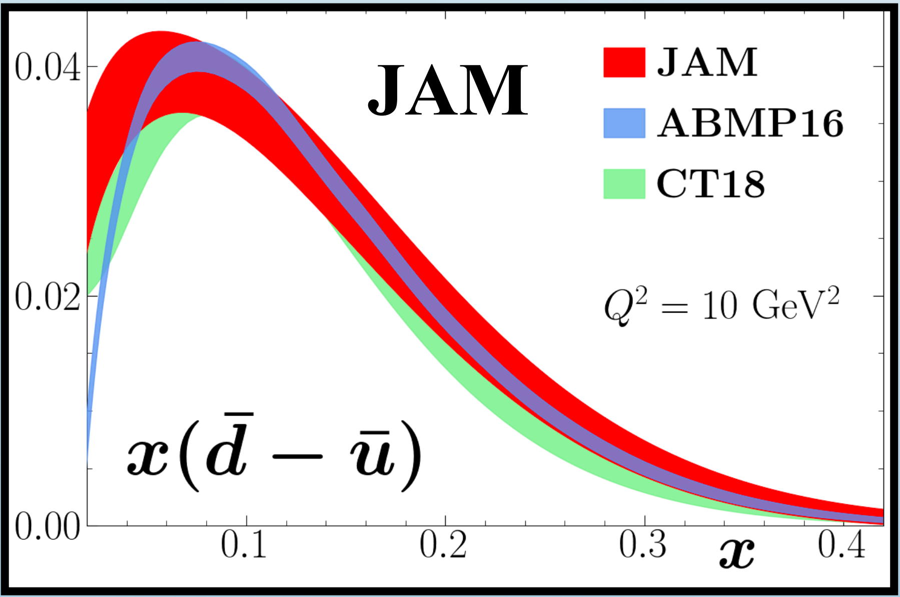
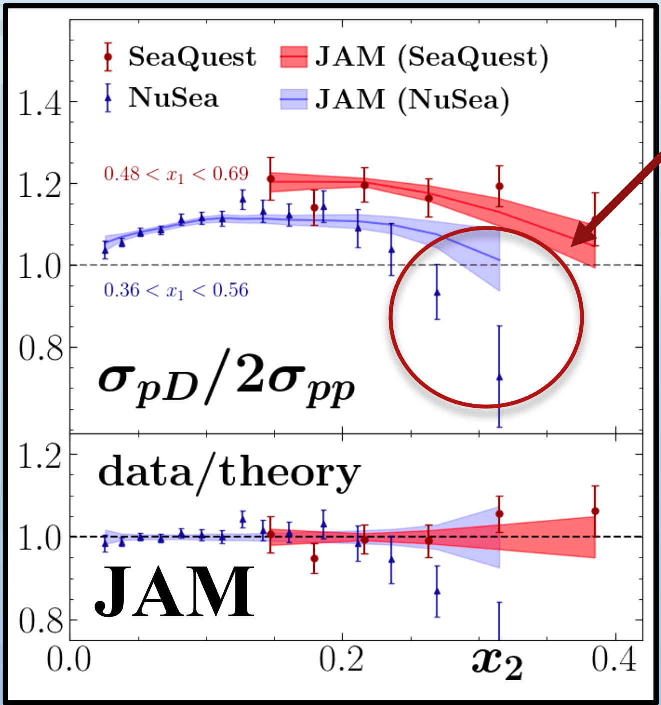
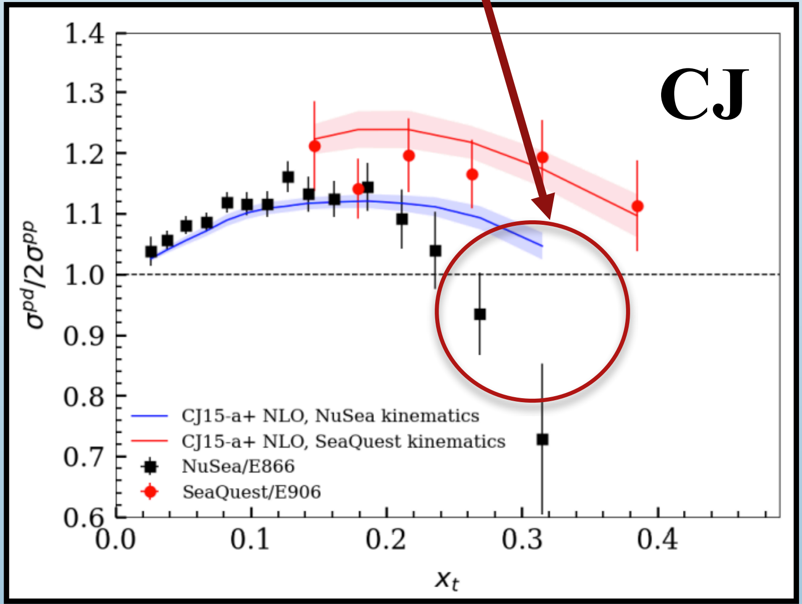
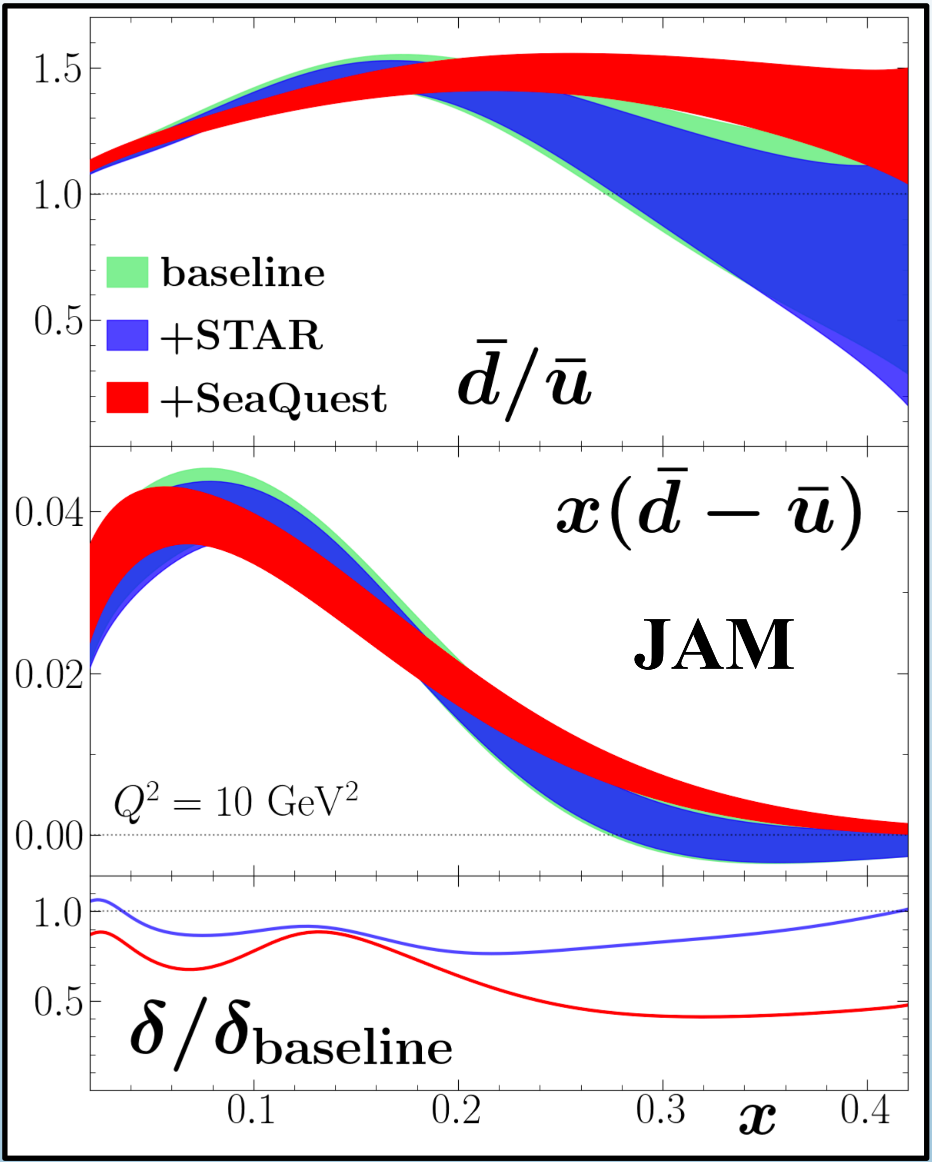


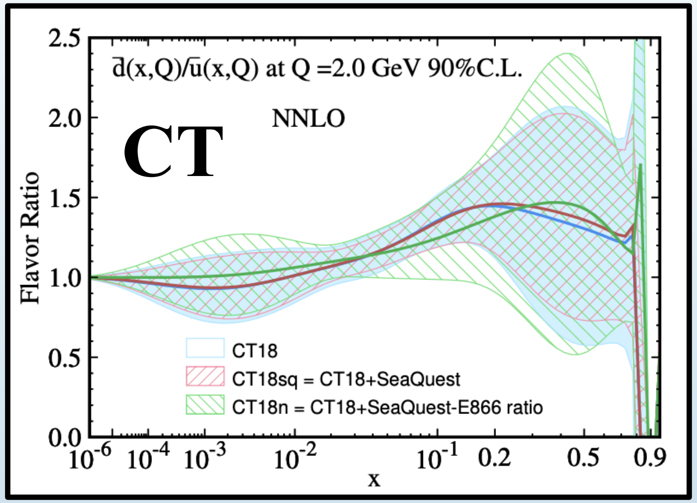


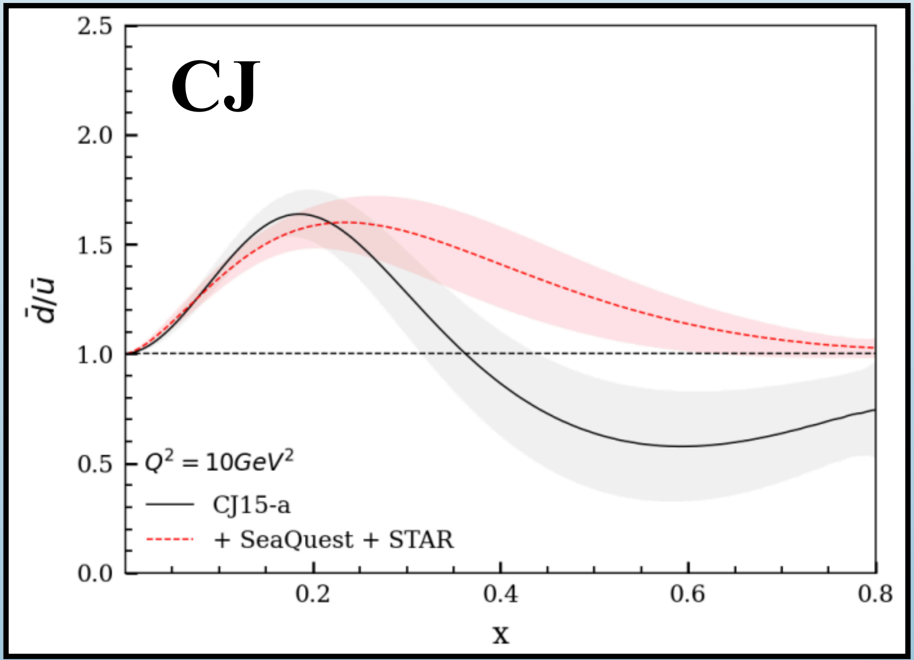
Well-known tension between NuSea and SeaQuest



Spin-Averaged Sea Asymmetry (2021-2022)







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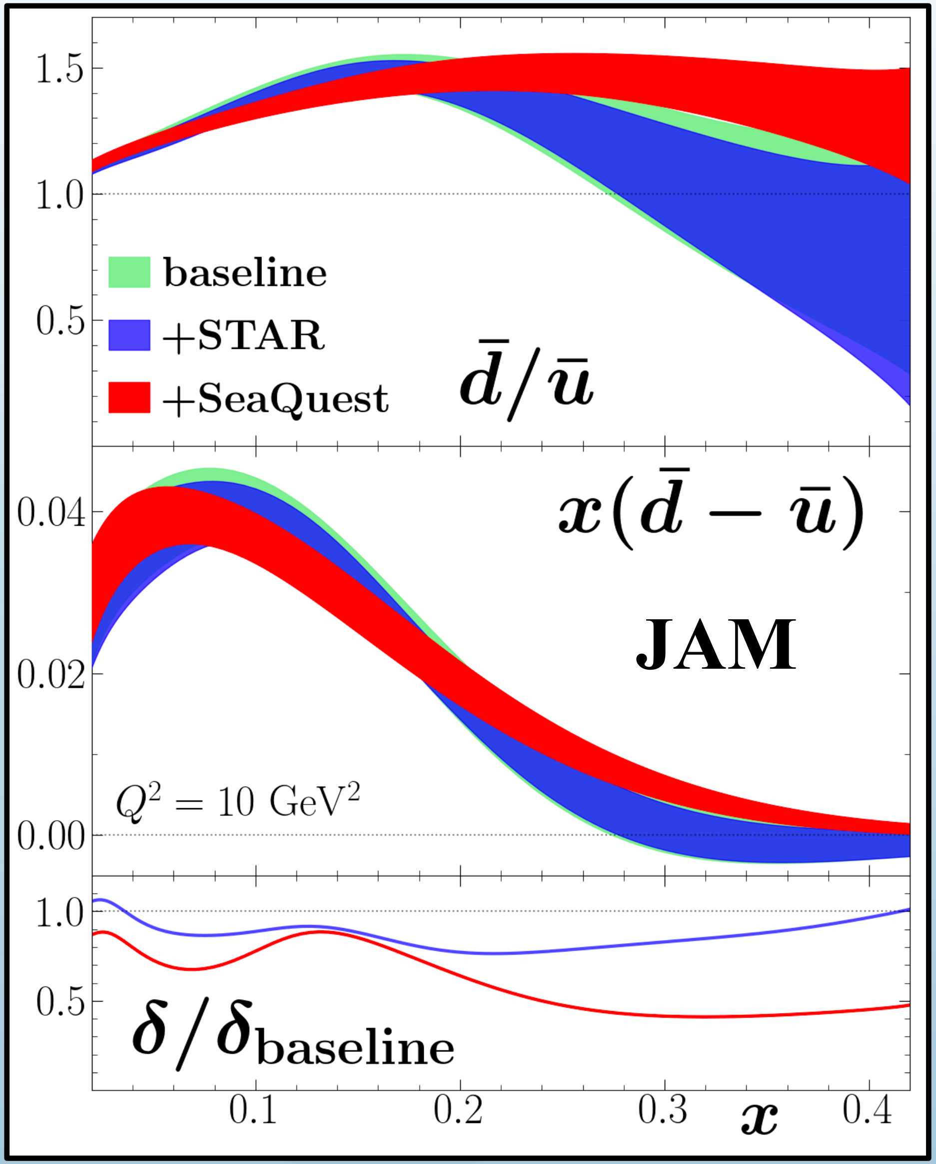
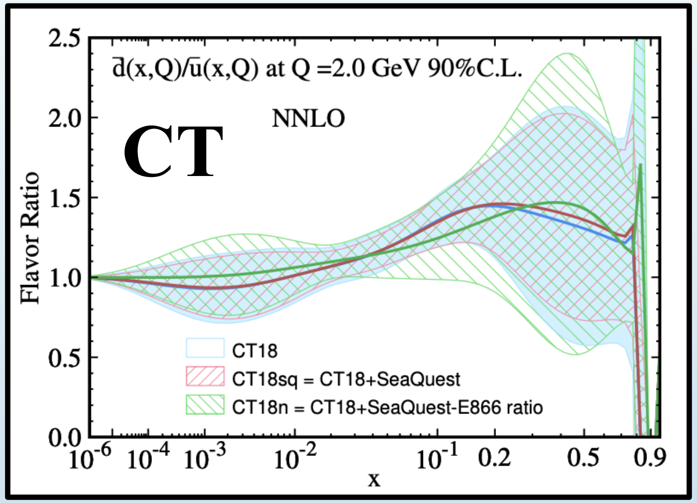
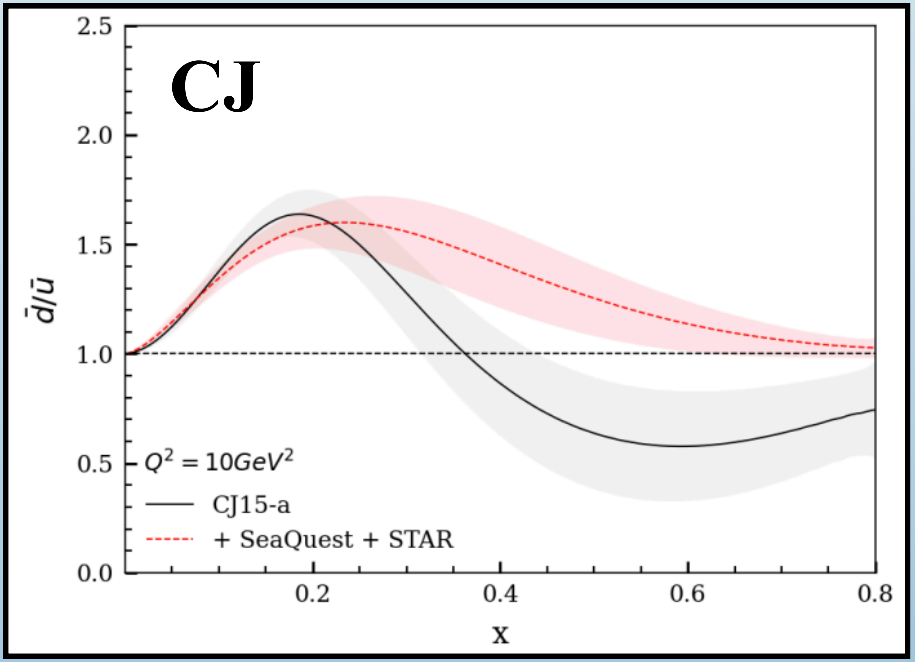




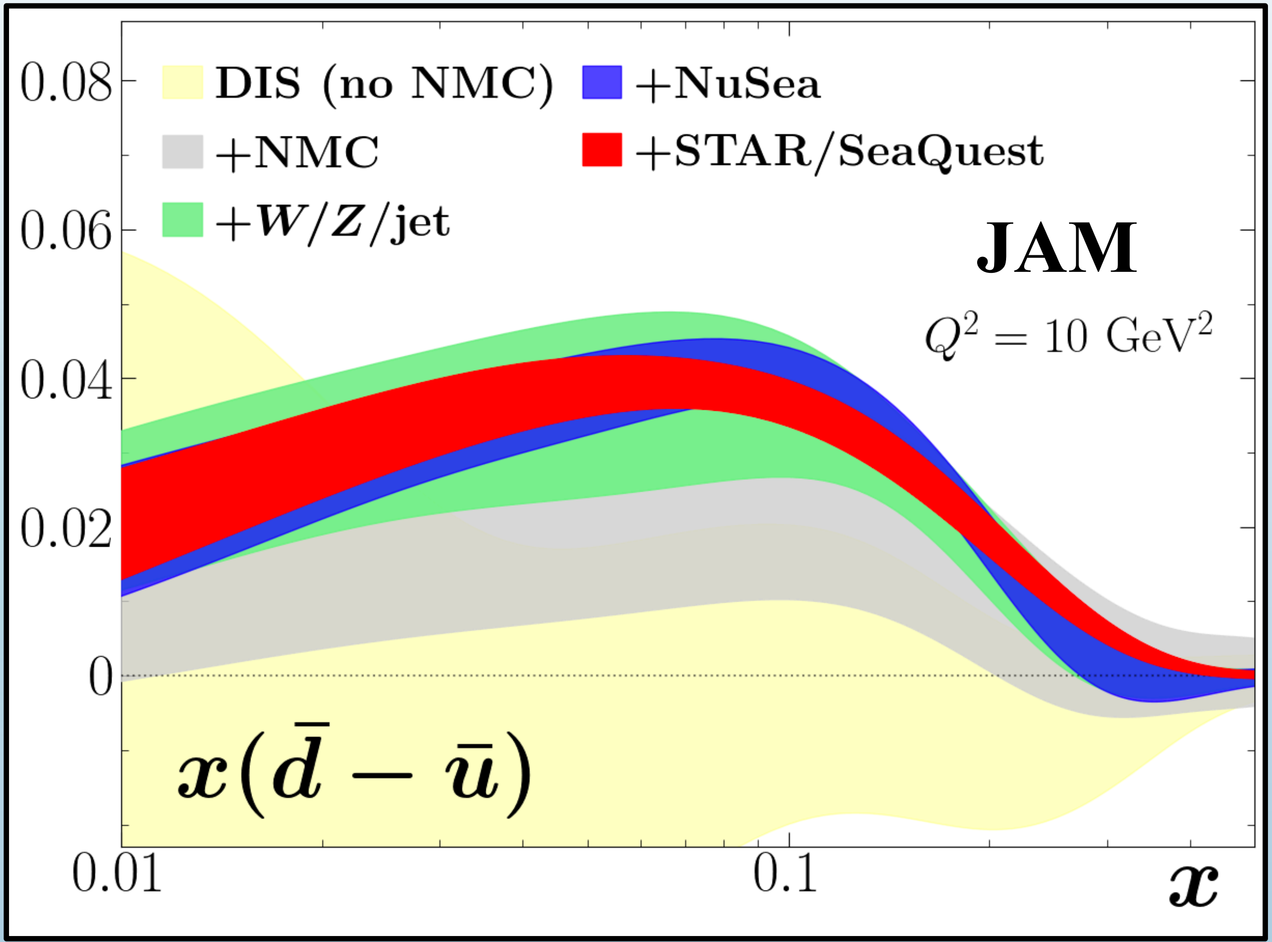


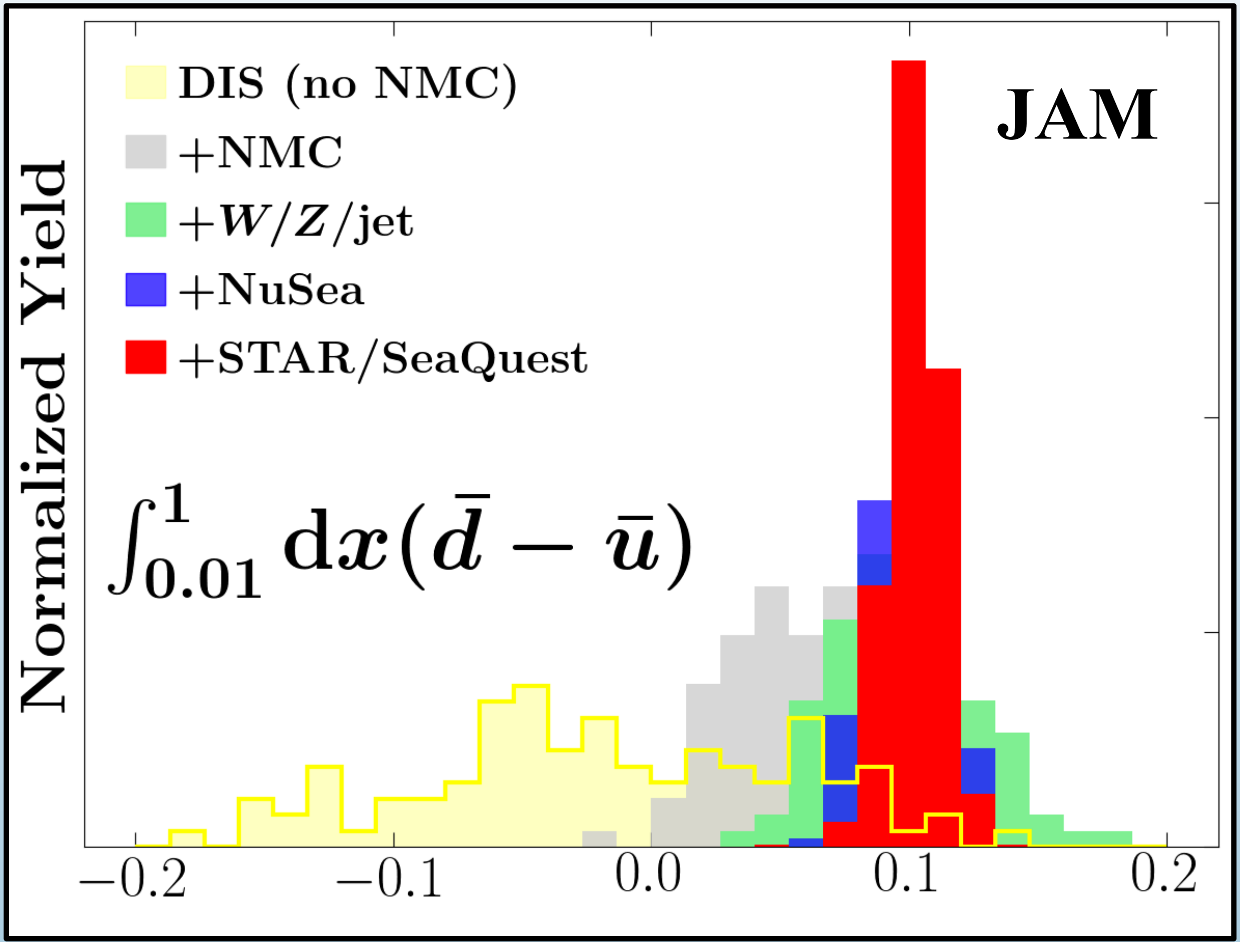
JAM and CJ find increase in central value at $x > 0.2$

JAM finds significant reduction in uncertainties

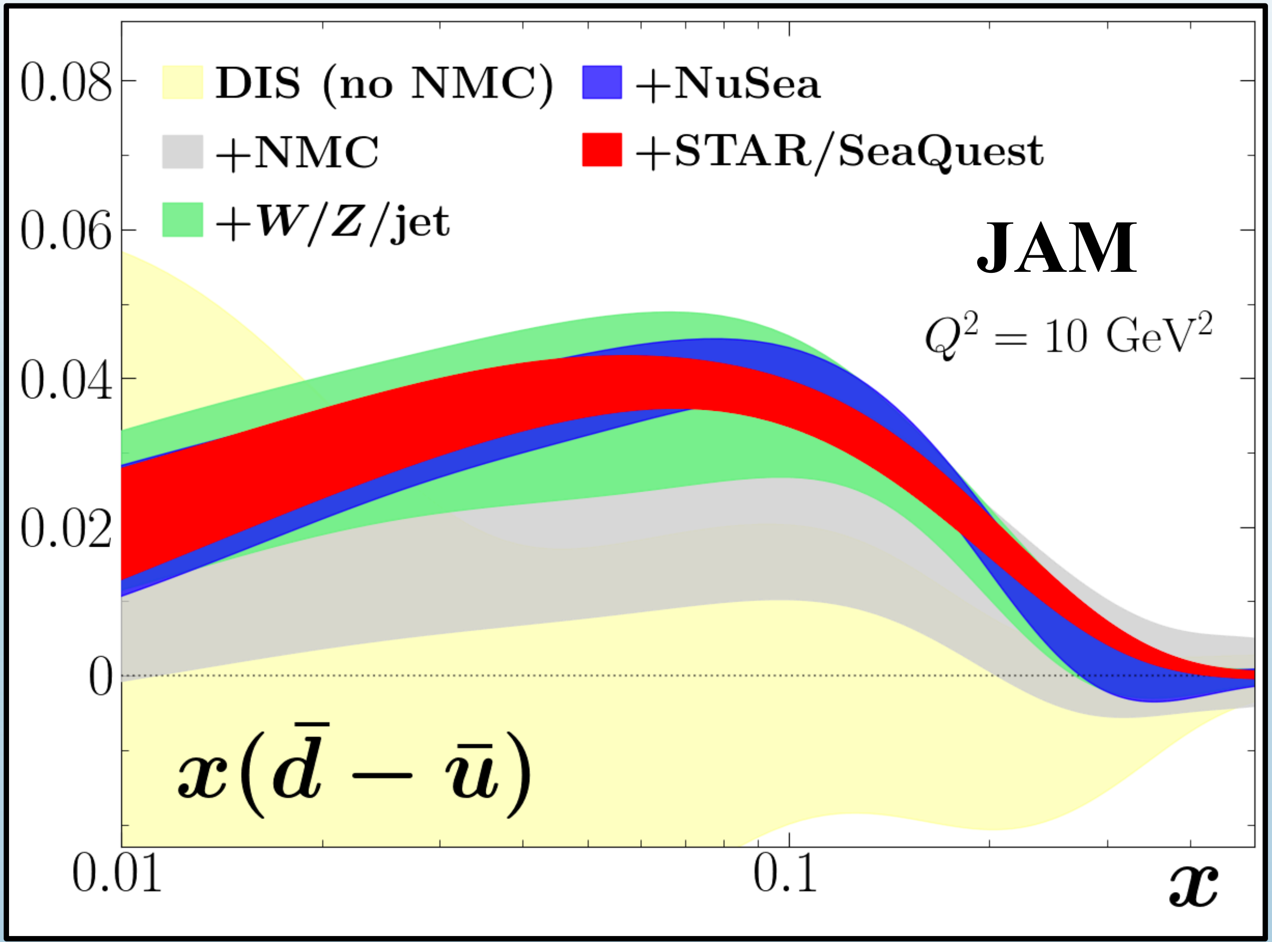
CT finds small reduction in uncertainties

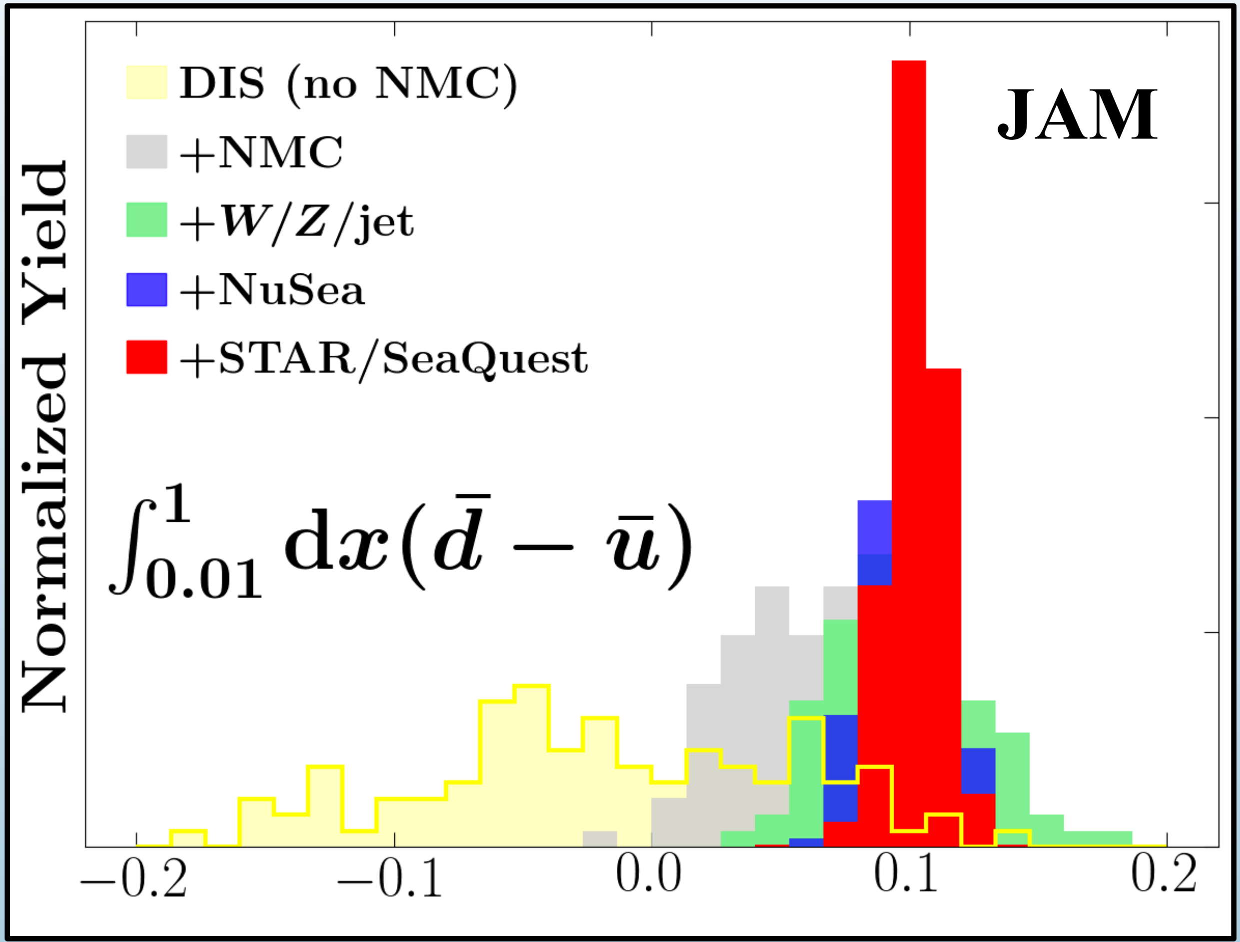
Spin-Averaged Sea Asymmetry (2021-2022)





Spin-Averaged Sea Asymmetry (2021-2022)





→ Jae Nam, "Recent STAR Results on the Unpolarized Light Quark Flavor Structure at RHIC", PDF: Tuesday 4:00 PM

→ Eric Moffat, "Fragmentation Functions using JAM methodology", PDF: Saturday 3:30 PM

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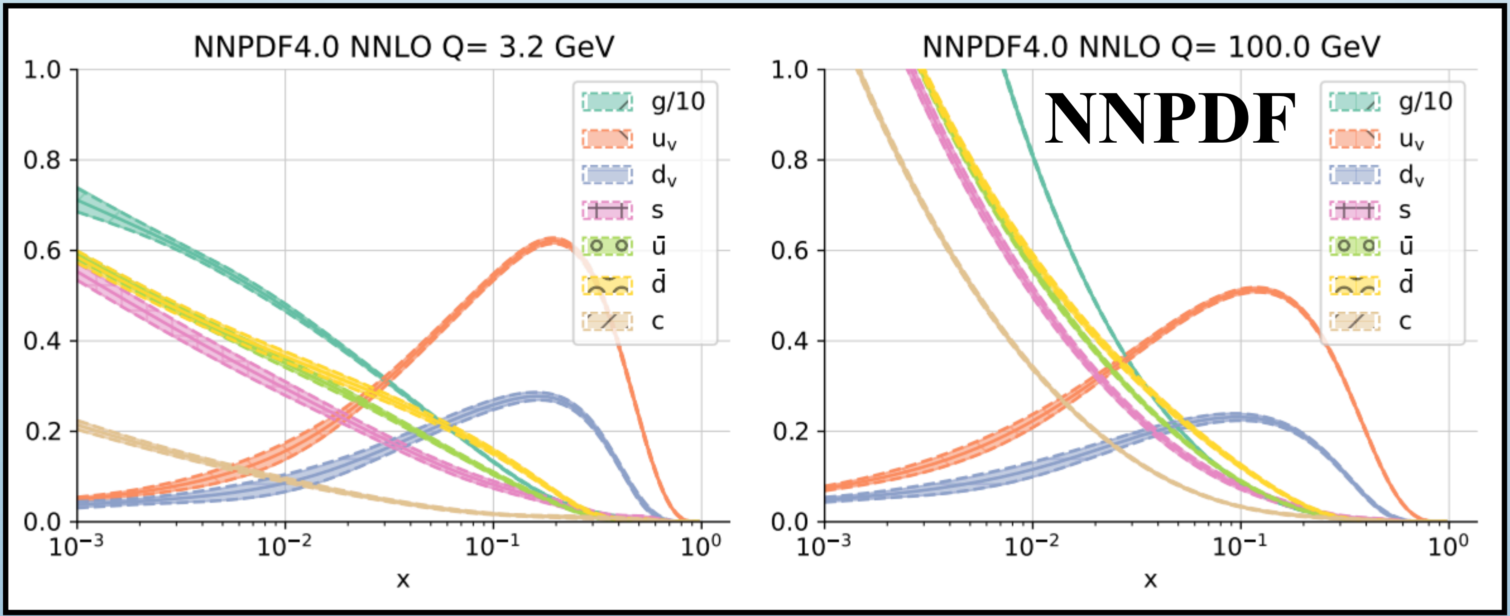
2. LHC and NNPDF4.0

3. Helicity Sea Asymmetry

4. Gluon Helicity

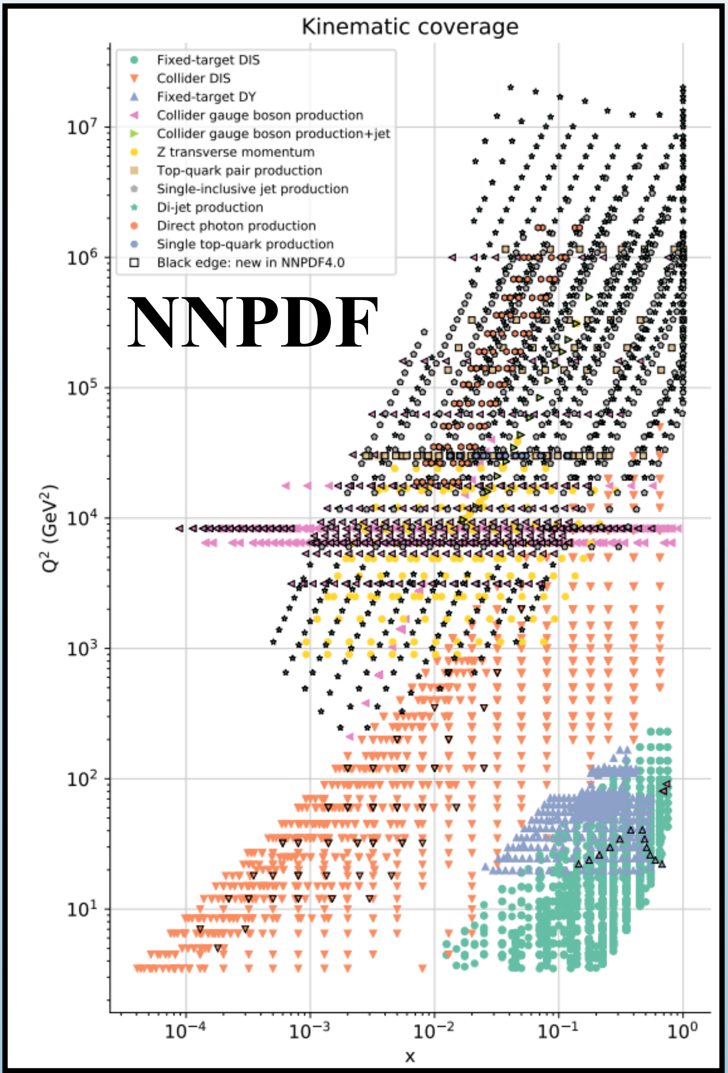


Latest LHC Results (2022)

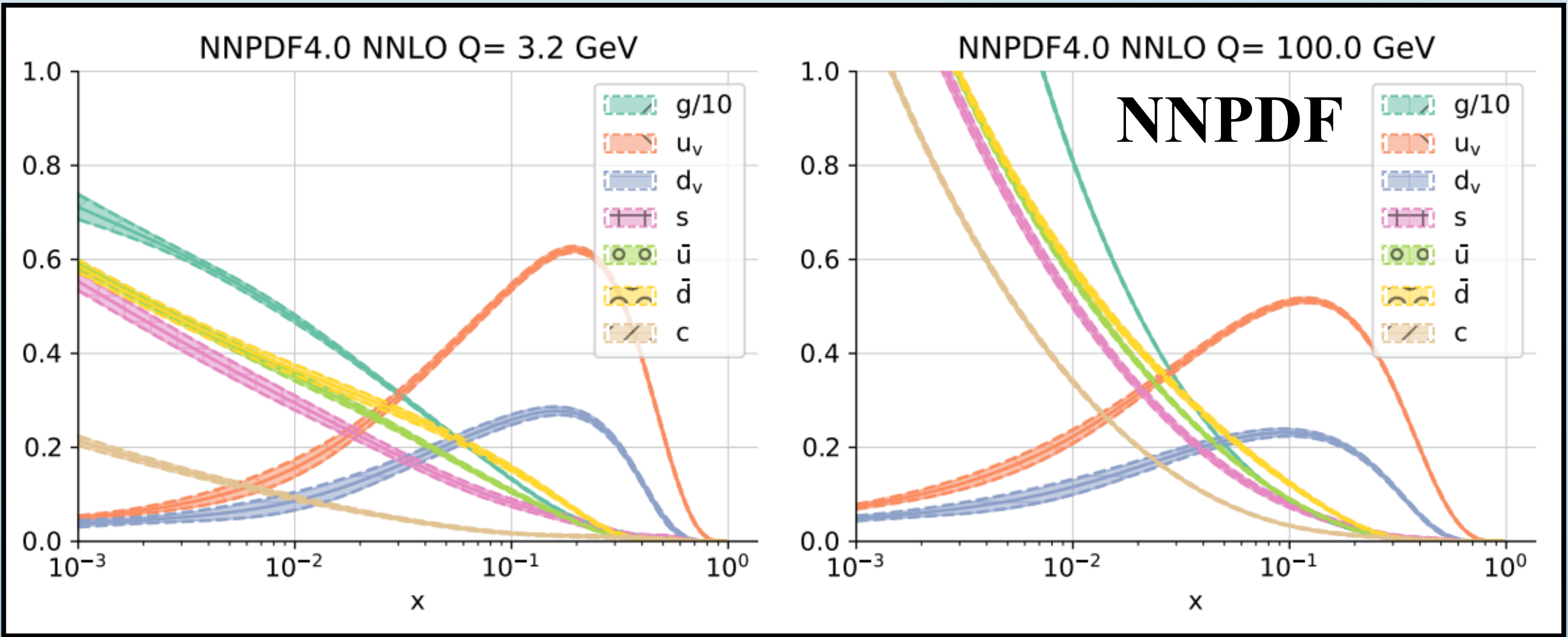
The Path to Proton Structure at One-Percent Accuracy

Richard D. Ball, Stefano Carrazza, Juan Cruz-Martinez, Luigi Del Debbio, Stefano Forte, Tommaso Giani, Shayan Iranipour, Zahari Kassabov, Jose I. Latorre, Emanuele R. Nocera, Rosalyn L. Pearson, Juan Rojo, Roy Stegeman, Christopher Schwan, Maria Ubiali, Cameron Voisey, Michael Wilson

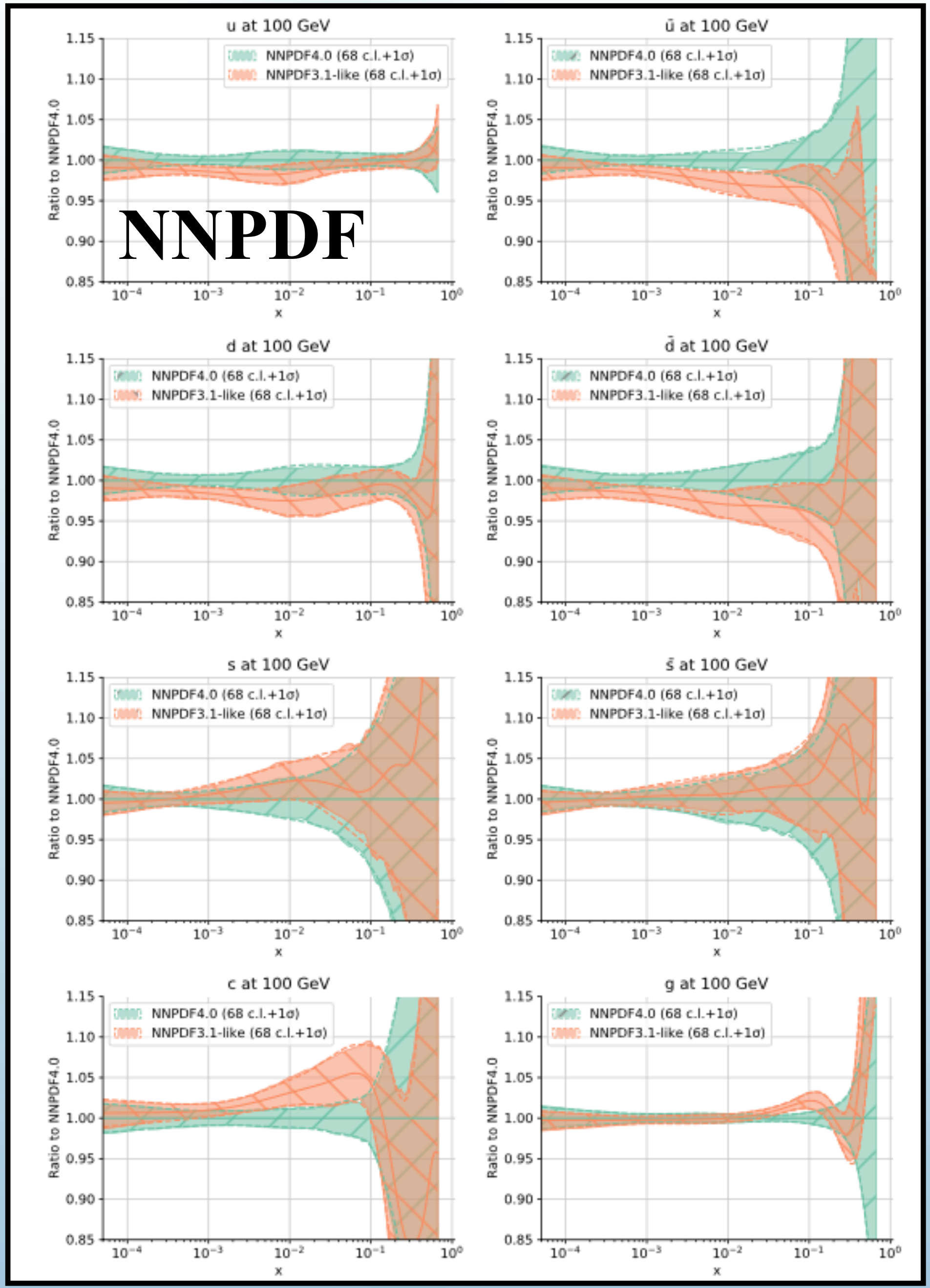
https://arxiv.org/abs/2109.02653
R. D. Ball *et al.*, Eur. Phys. J. C. **82**, no. 5, 428 (2022).



- di-jet production
- direct photon production
- gauge boson production + jets
- top-quark pair production

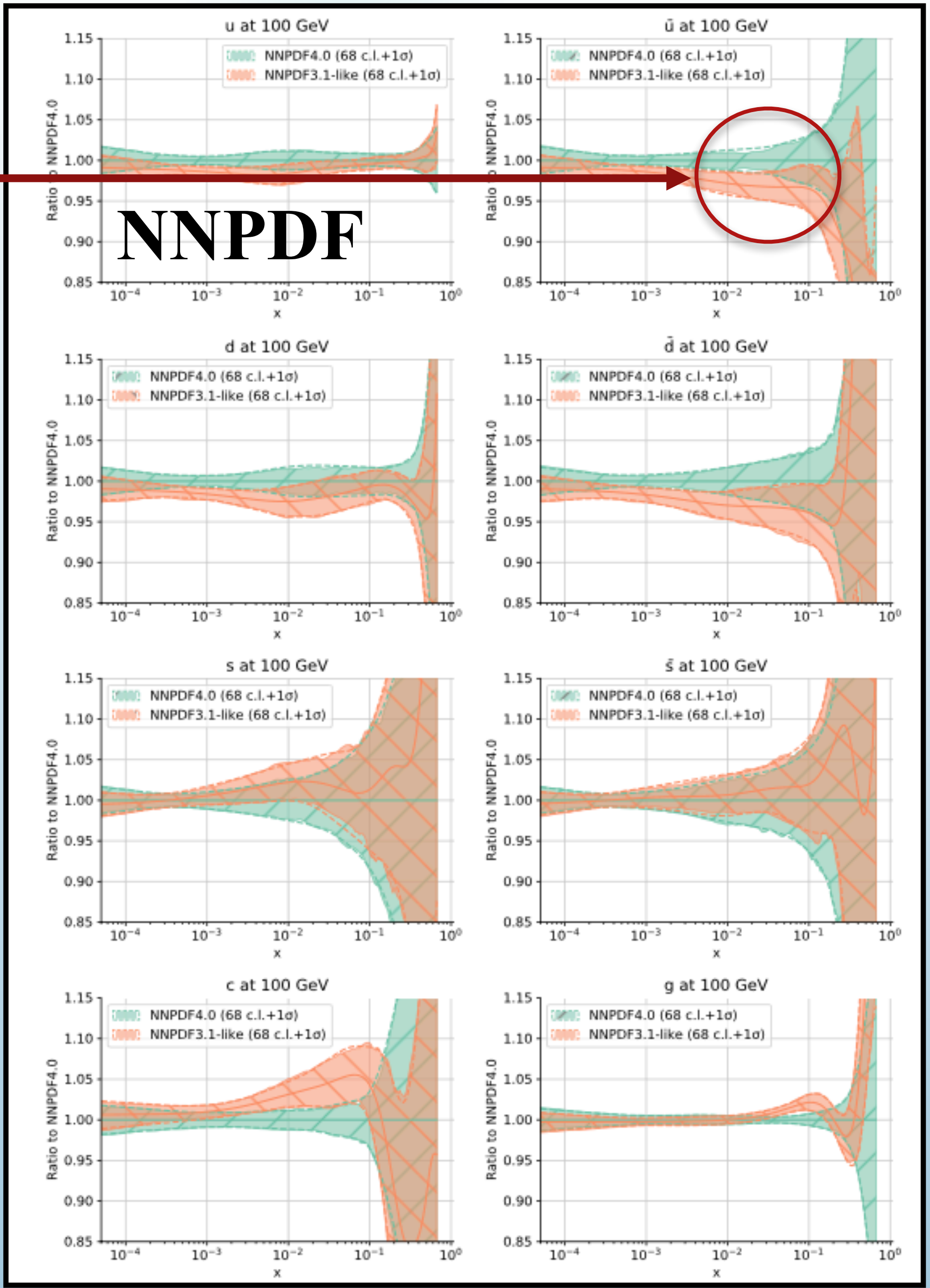


LHC Results (2021-2022)



LHC Results (2021-2022)

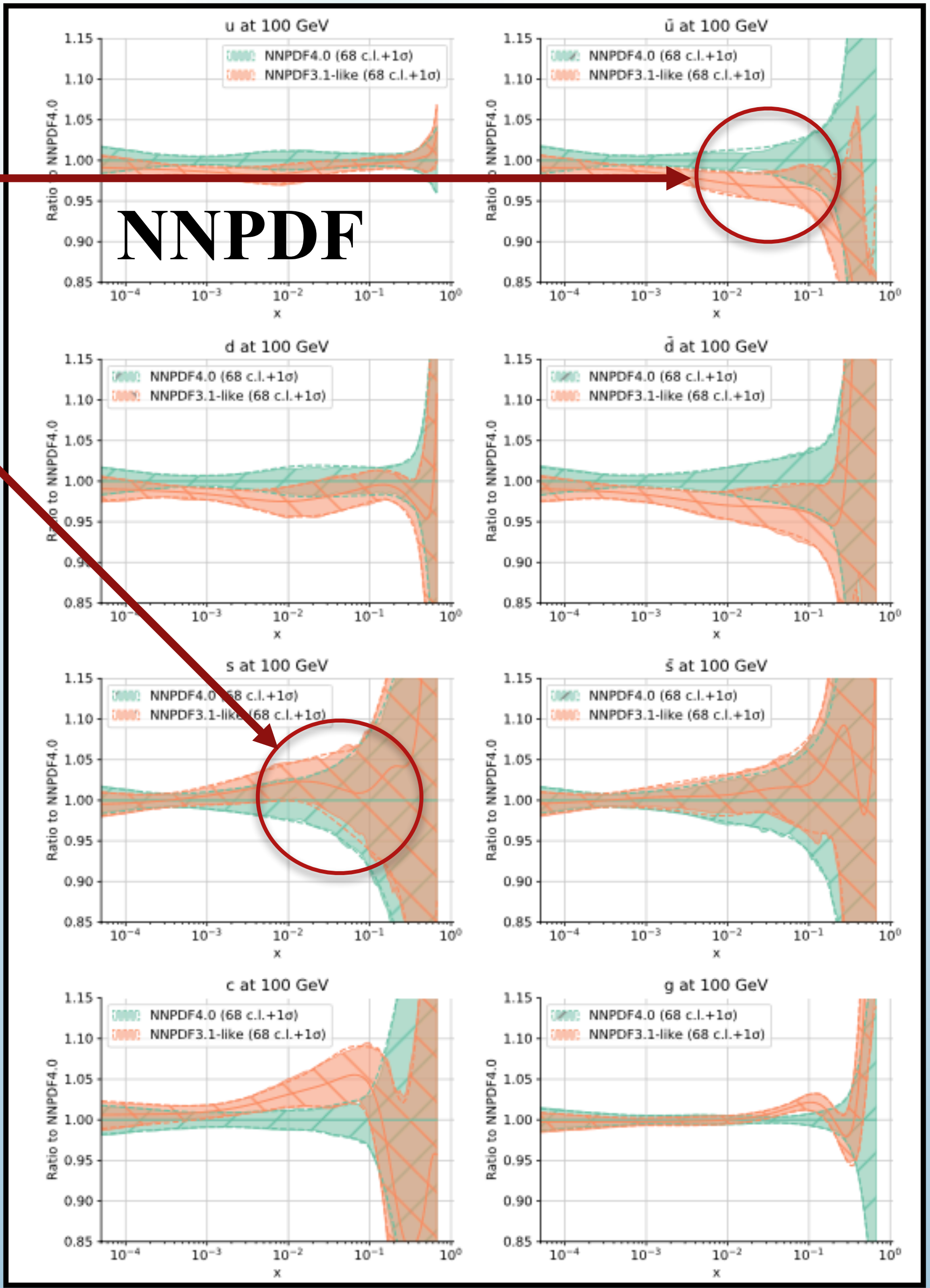
3% suppression
$0.01 < x < 0.1$



LHC Results (2021-2022)

3% suppression
$0.01 < x < 0.1$

Slight suppression

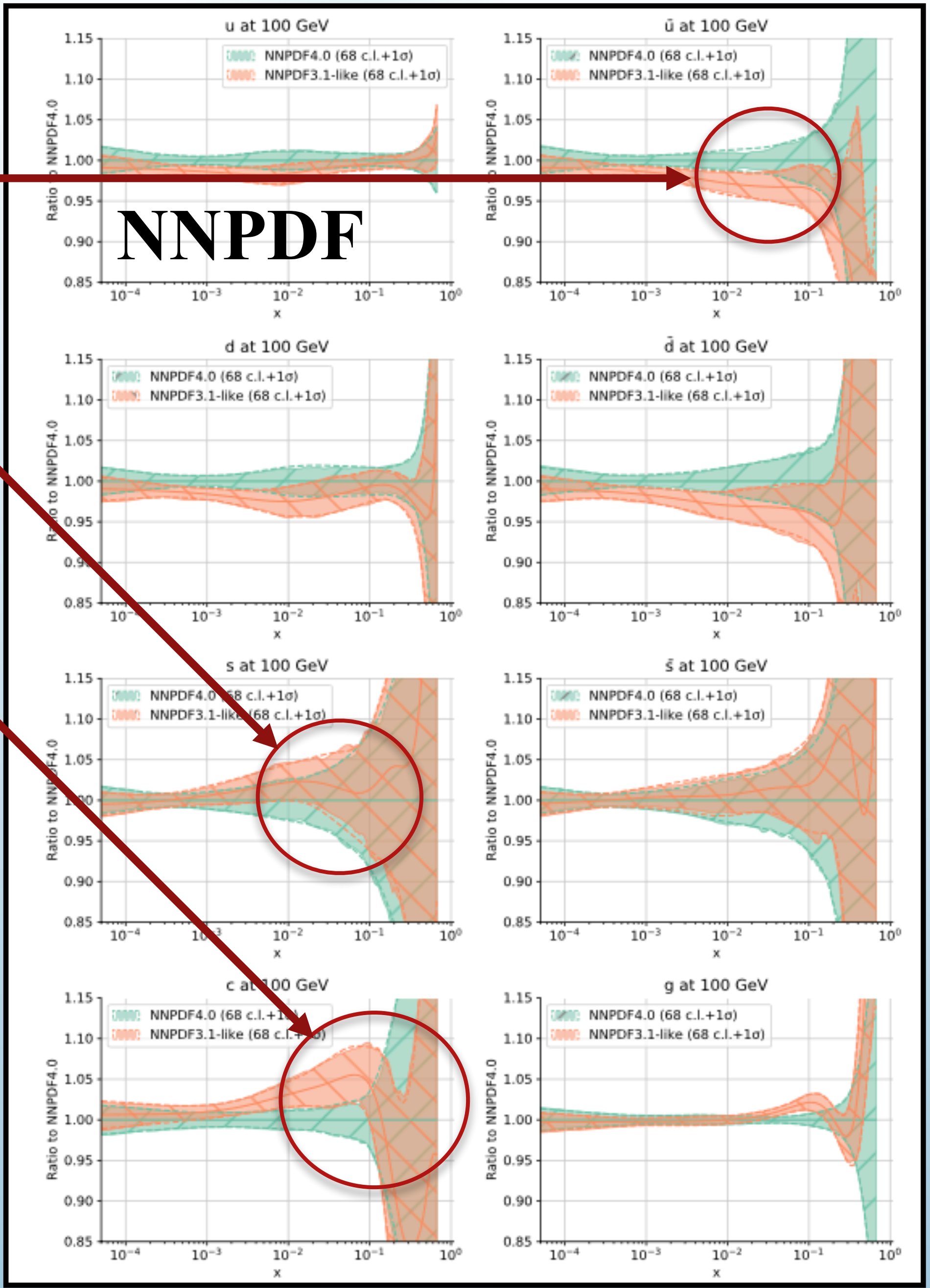


LHC Results (2021-2022)

3% suppression
$0.01 < x < 0.1$

Slight suppression

5% suppression
$0.01 < x < 0.1$
10% enhancement
$x > 0.1$



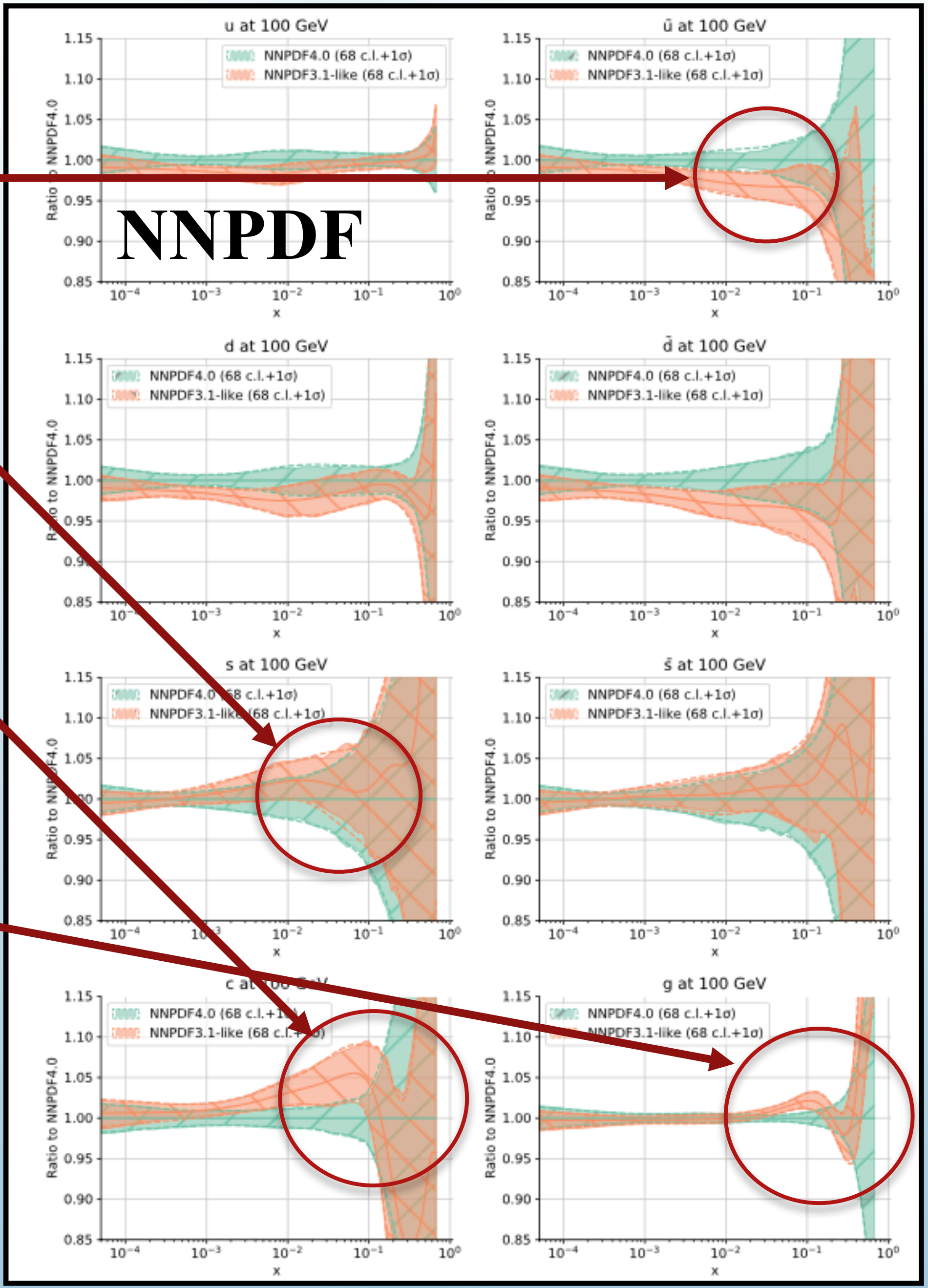
LHC Results (2021-2022)

3% suppression
$0.01 < x < 0.1$

Slight suppression

5% suppression
$0.01 < x < 0.1$
10% enhancement
$x > 0.1$

3% suppression
$x \approx 0.1$
3% enhancement
$x \approx 0.3$



LHC Results (2021-2022)

LHC inclusive gauge boson + jet production

3% suppression
$0.01 < x < 0.1$

Slight suppression

5% suppression
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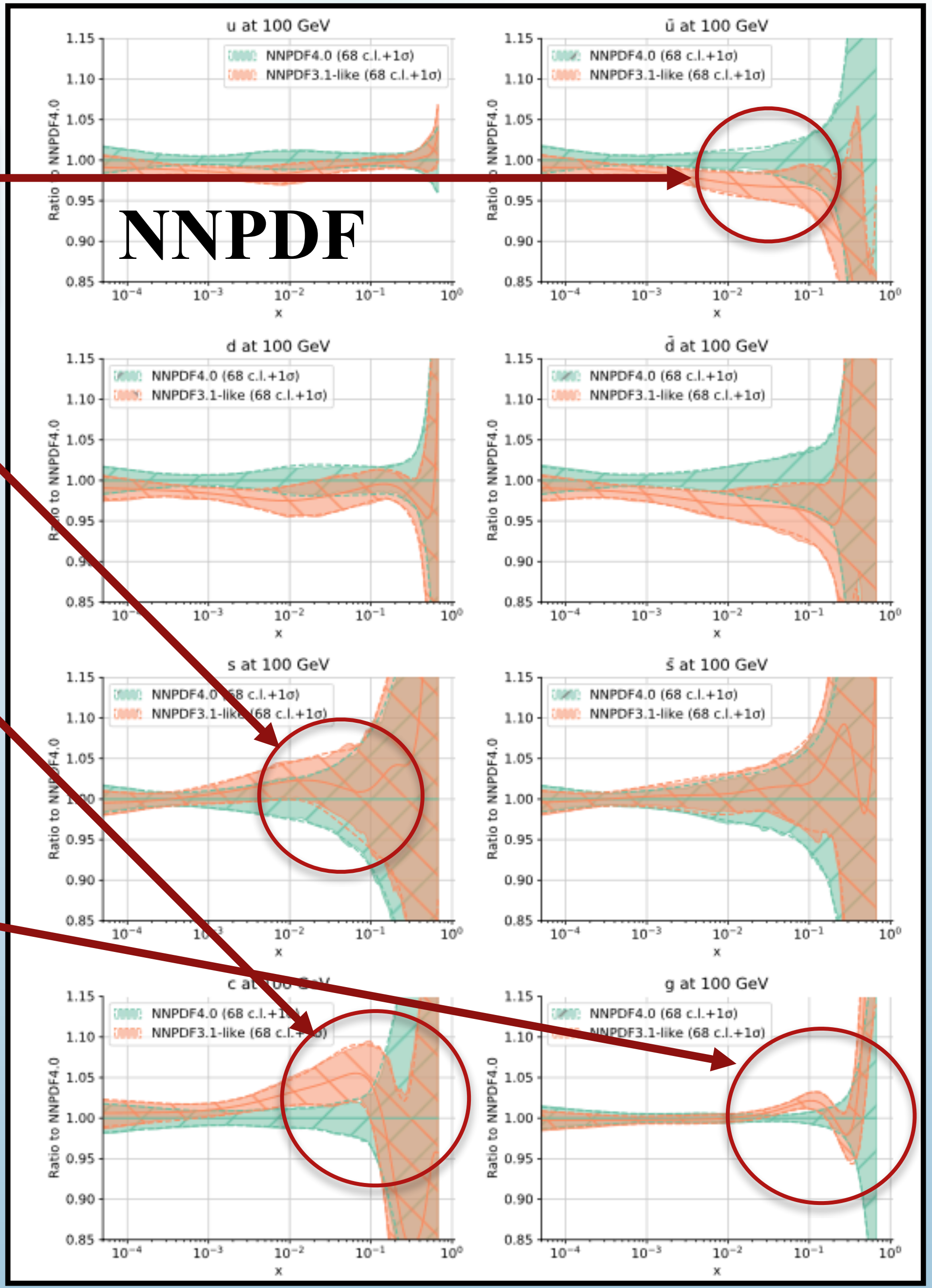
10% enhancement
$x > 0.1$

3% suppression
$x \approx 0.1$
3% enhancement
$x \approx 0.3$



LHC Results (2021-2022)

LHC inclusive gauge boson + jet production

LHC inclusive single jet and dijet

3% suppression
$0.01 < x < 0.1$

Slight suppression

5% suppression
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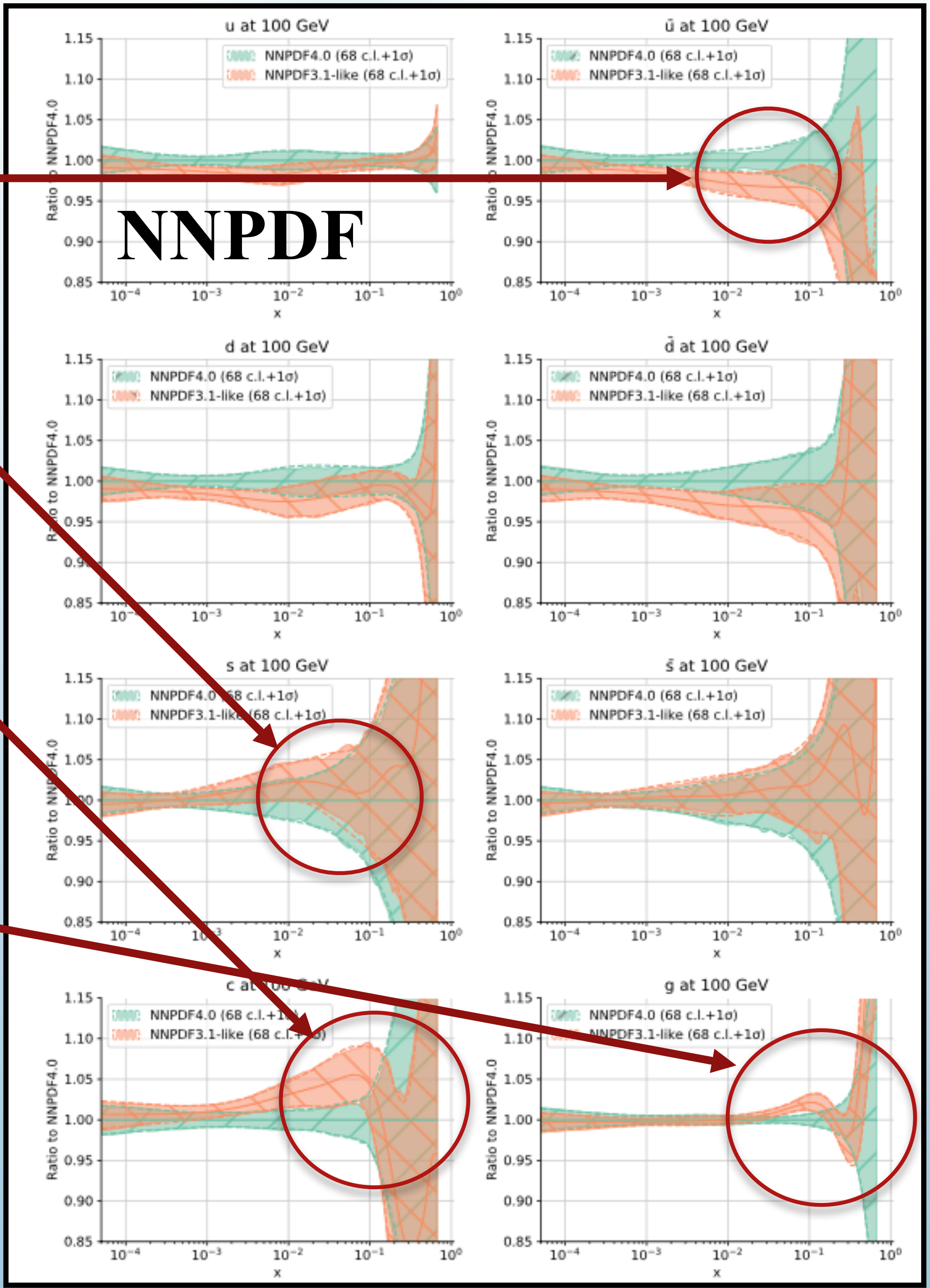

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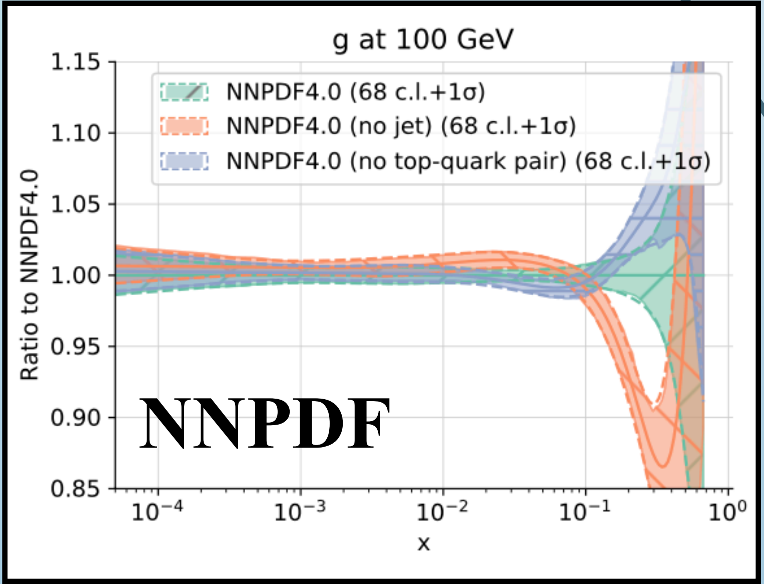
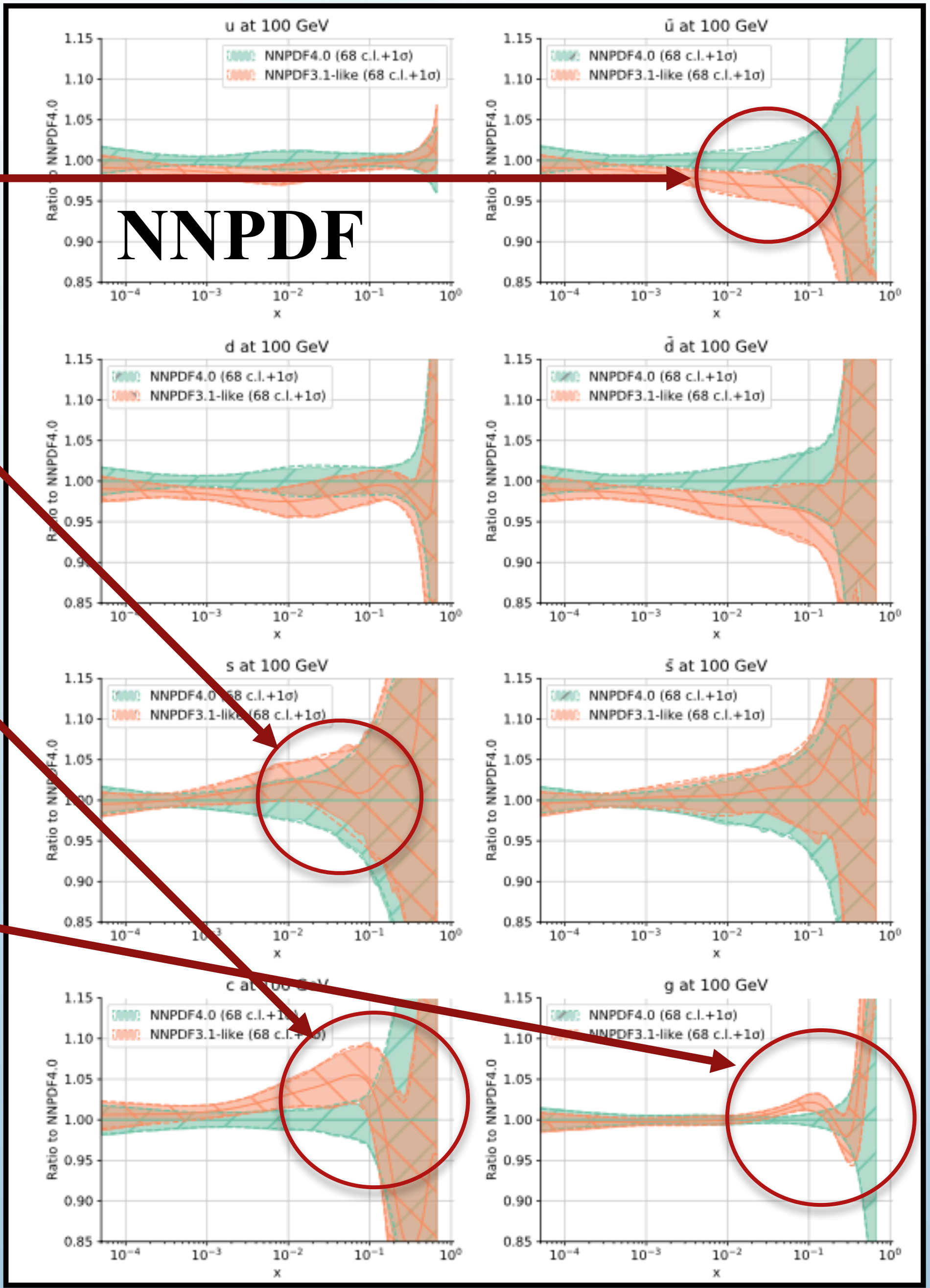




LHC Results (2021-2022)

New CTEQ global analysis of quantum chromodynamics with high-precision data from the LHC

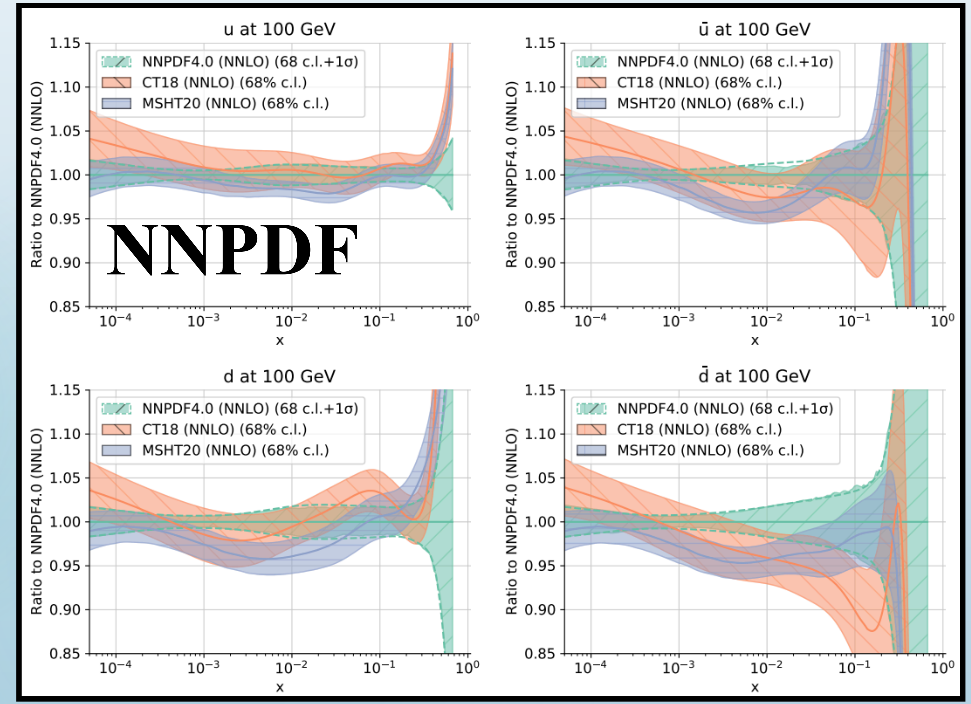
Tie-Jiun Hou, Jun Gao, T. J. Hobbs, Keping Xie, Sayipjamal Dulat, Marco Guzzi, Joey Huston, Pavel Nadolsky, Jon Pumplin, Carl Schmidt, Ibrahim Sitiwaldi, Daniel Stump, C.-P. Yuan

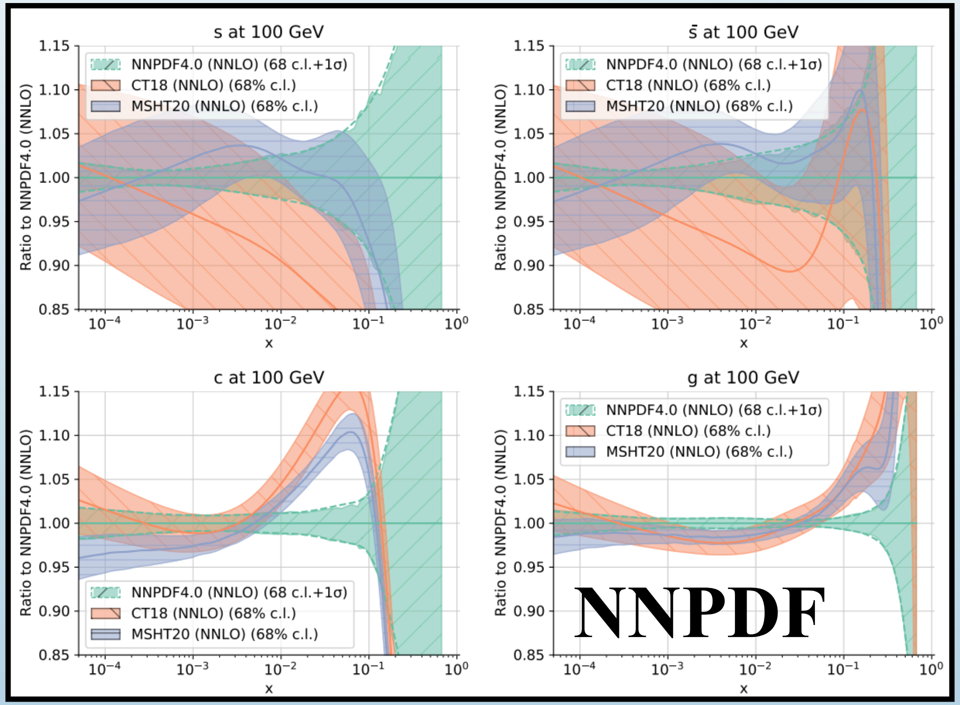
https://arxiv.org/abs/1912.10053
T.J. Hou *et al*., Phys. Rev. D **103**, no. 1, 014013 (2021).

Parton distributions from LHC, HERA, Tevatron and fixed target data: MSHT20 PDFs

S. Bailey, T. Cridge, L. A. Harland-Lang, A. D. Martin, R.S. Thorne

https://arxiv.org/abs/2012.04684
S. Bailey *et al*., Eur. Phys. J. C. **81**, no. 4, 341 (2021).





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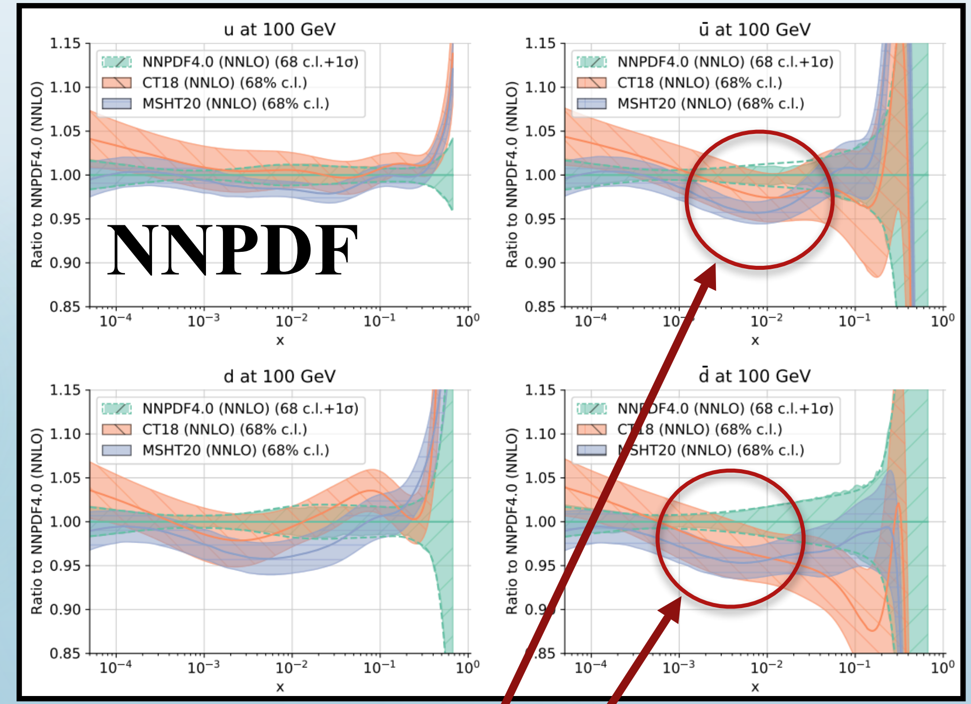

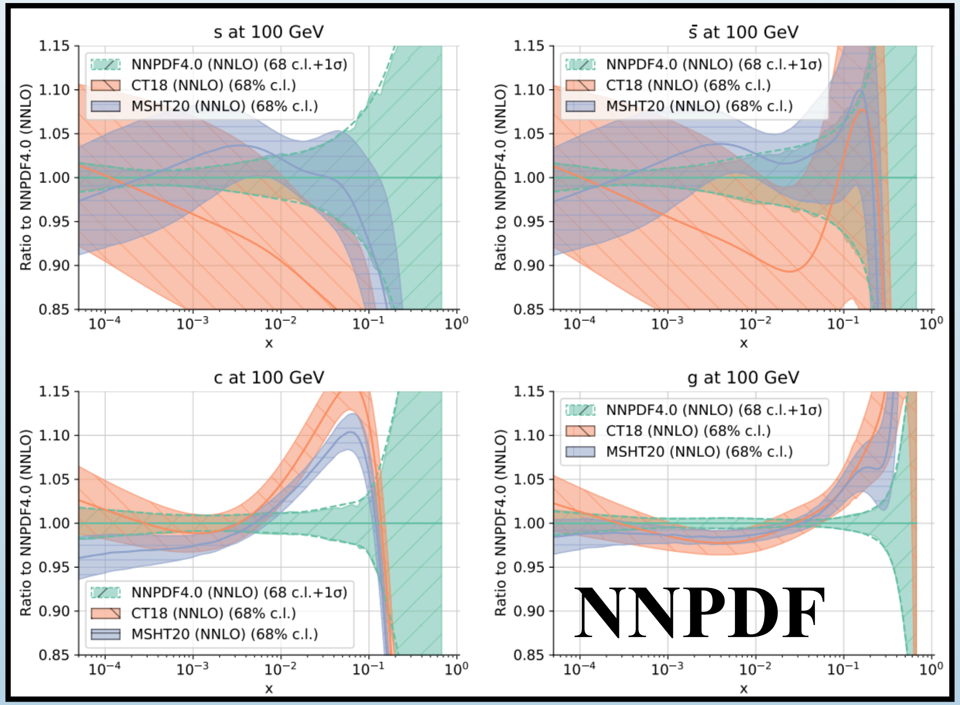

No SeaQuest, LHCb 13 TeV
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LHC Results (2021-2022)

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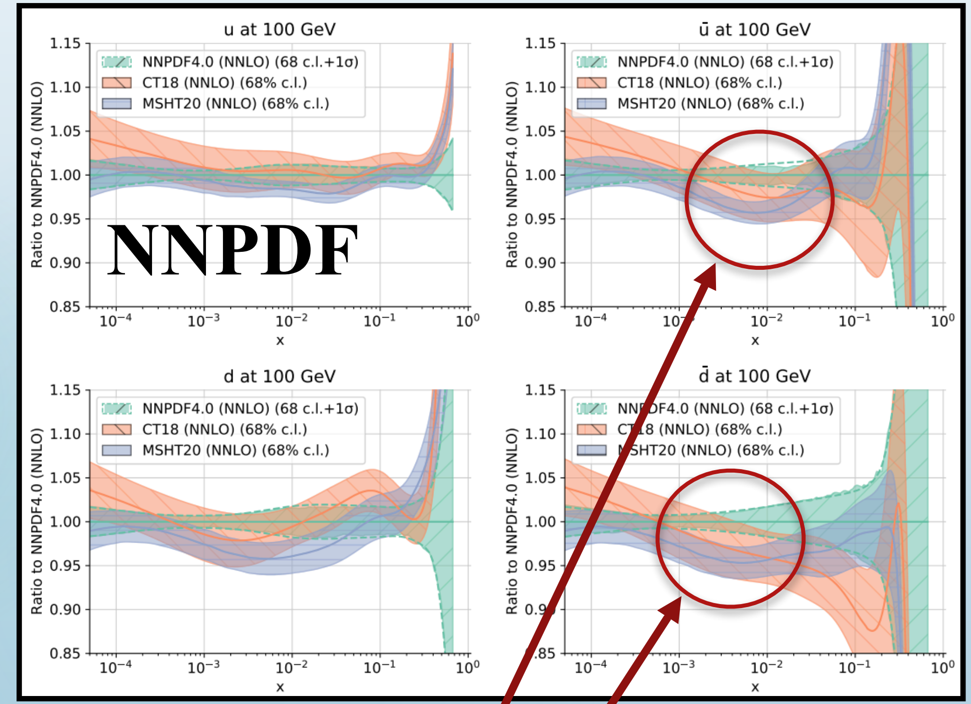

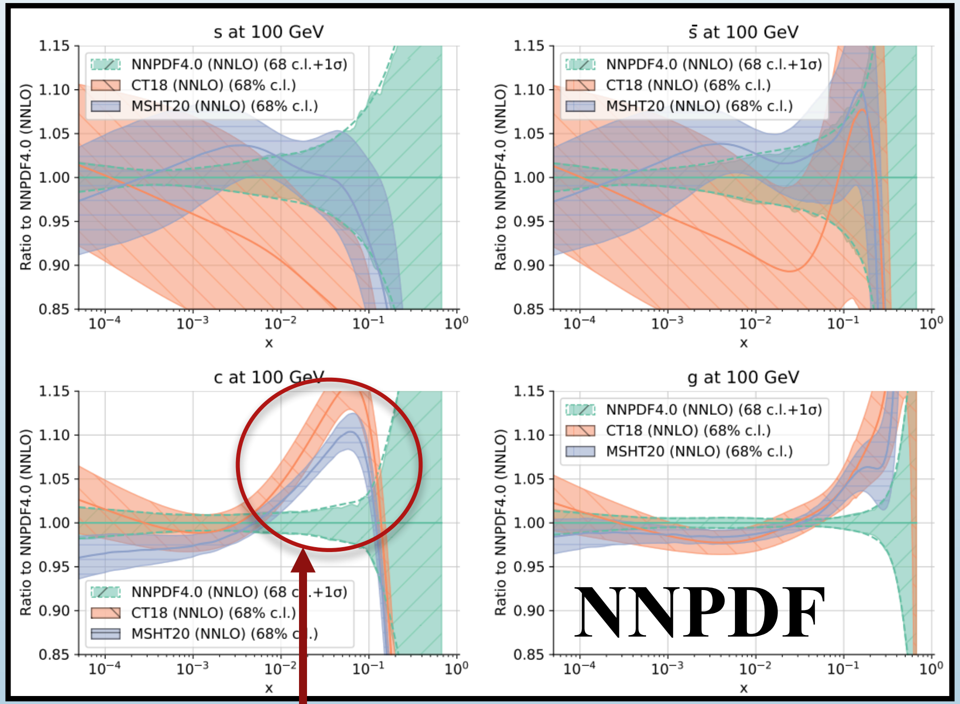

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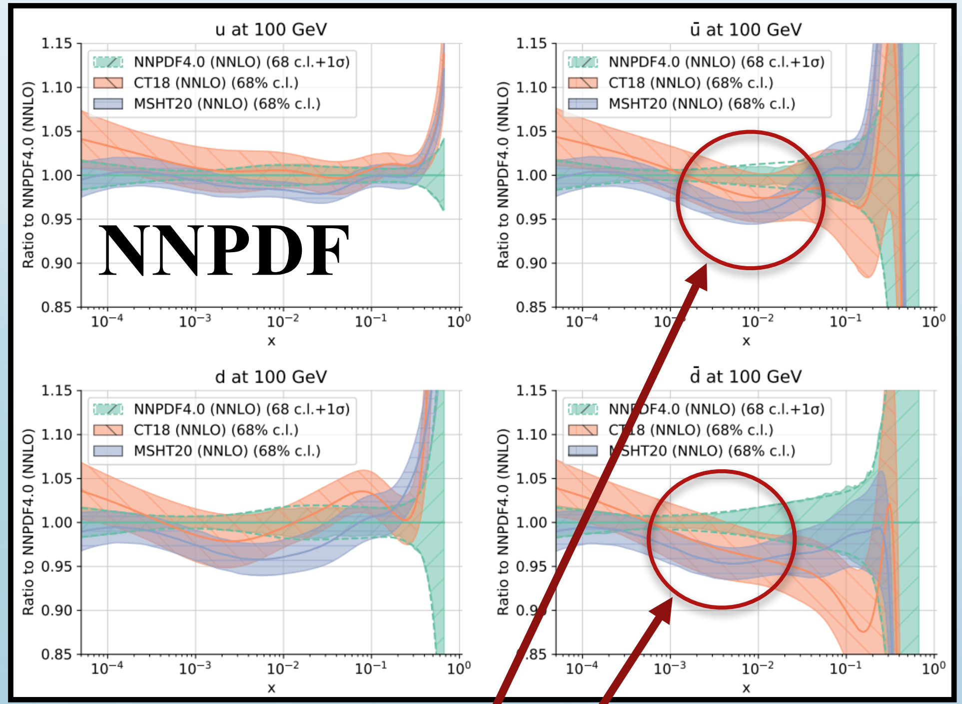

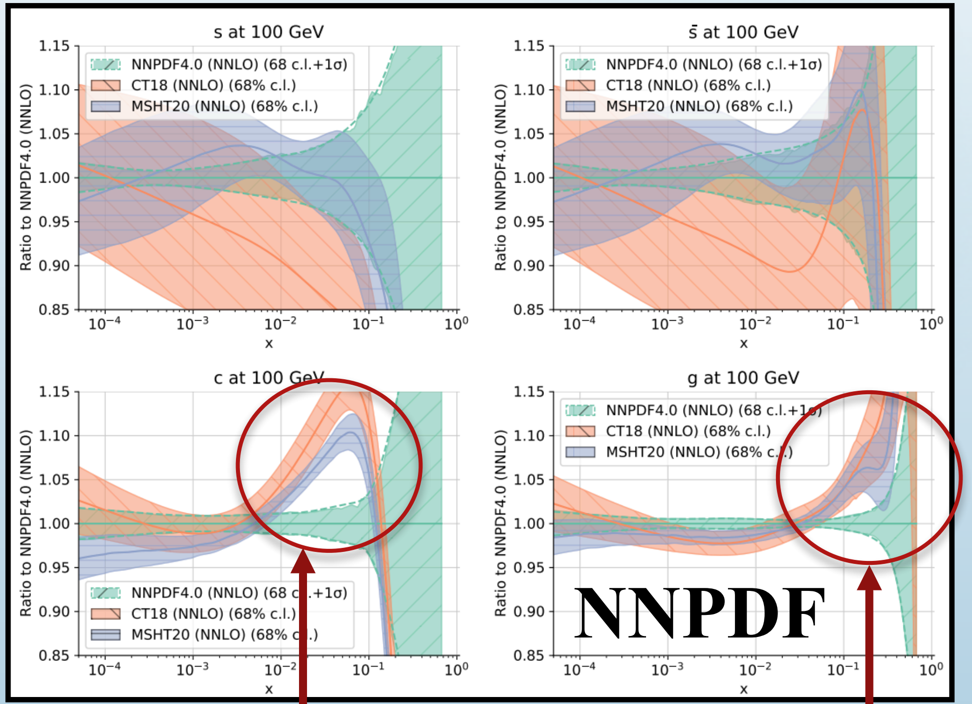

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Current State of Polarized Global Analyses

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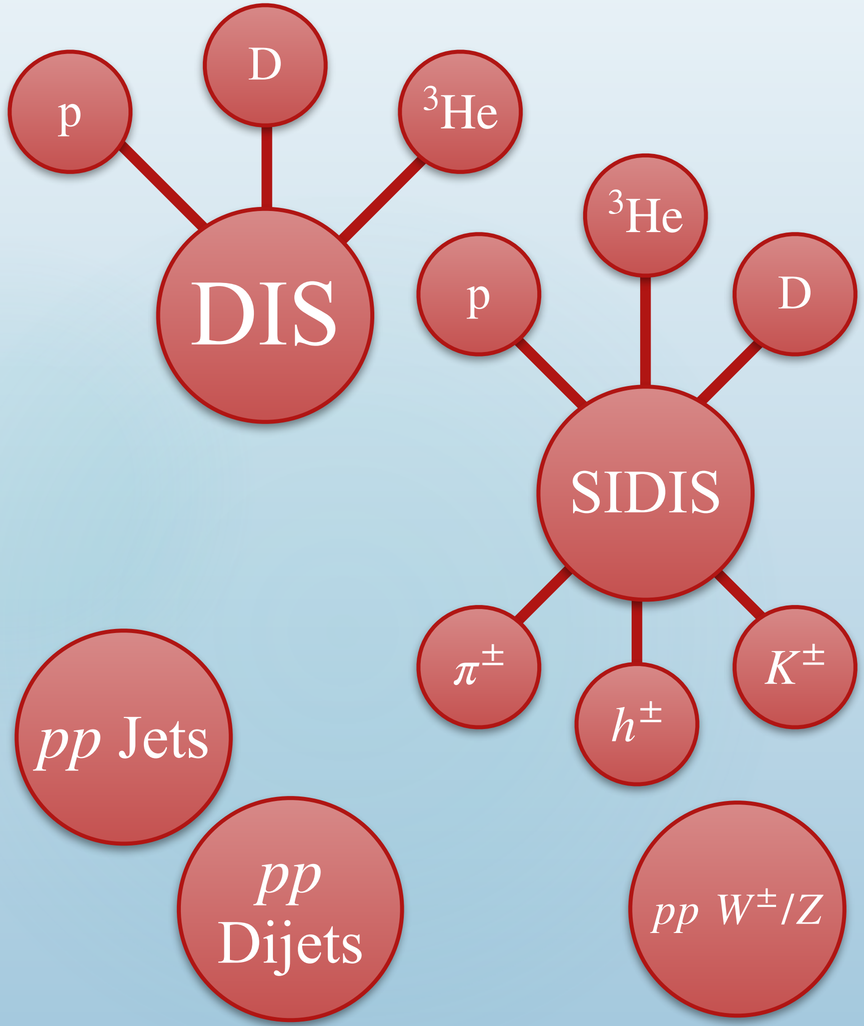
Data space



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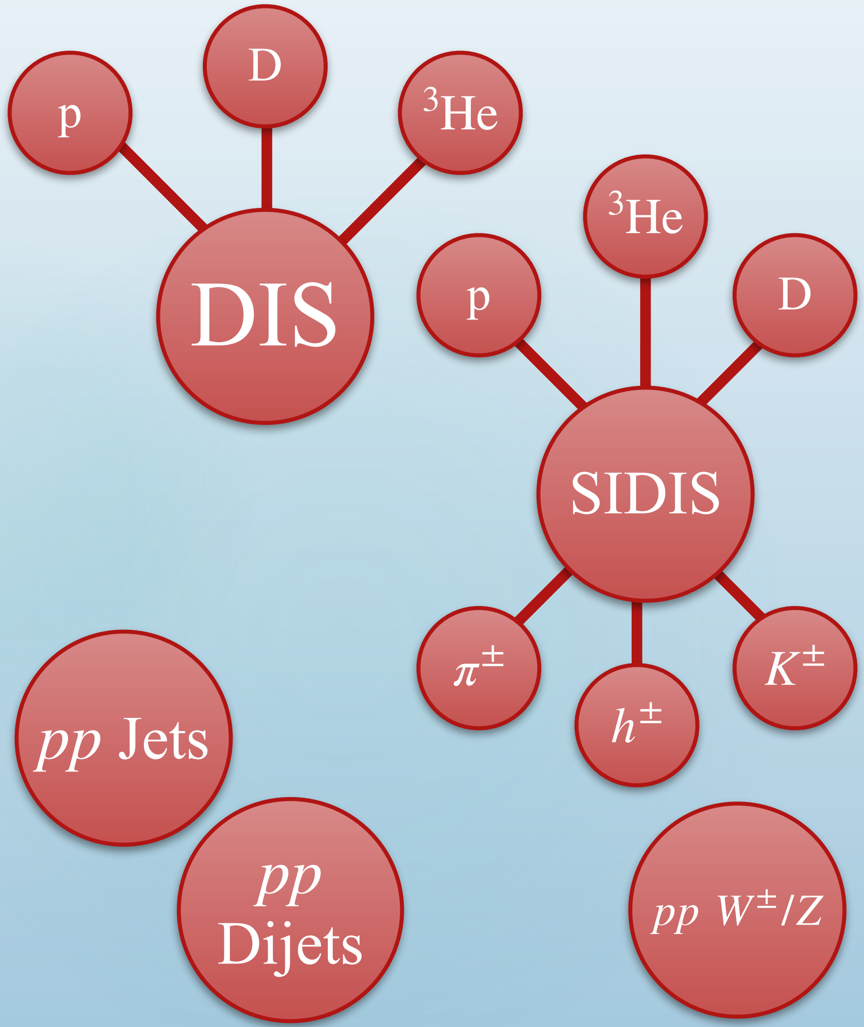
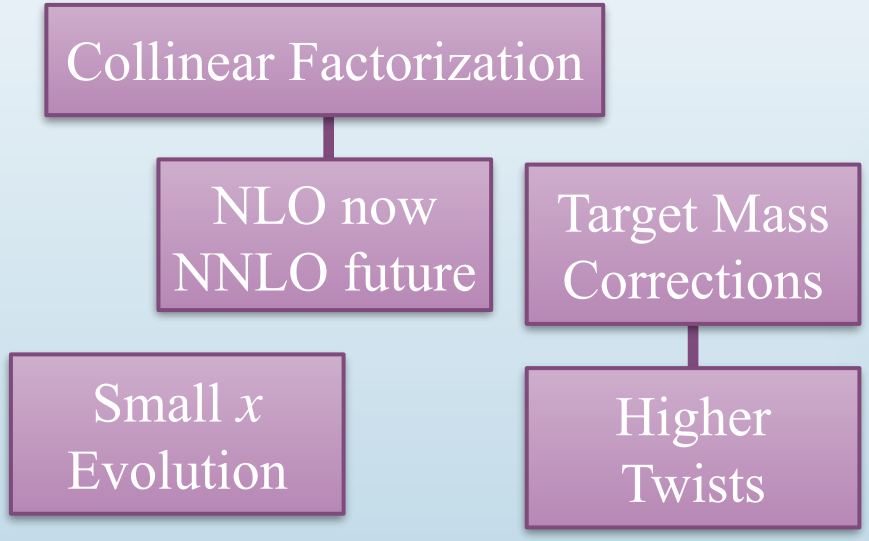


Theory



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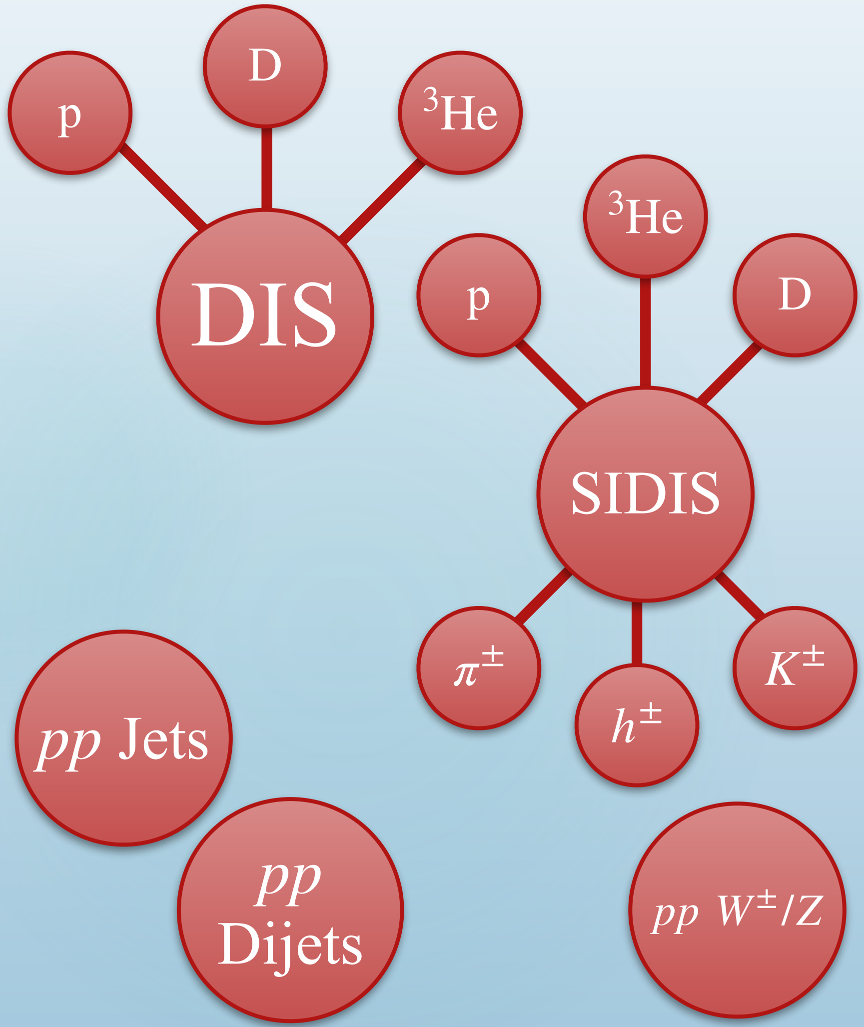

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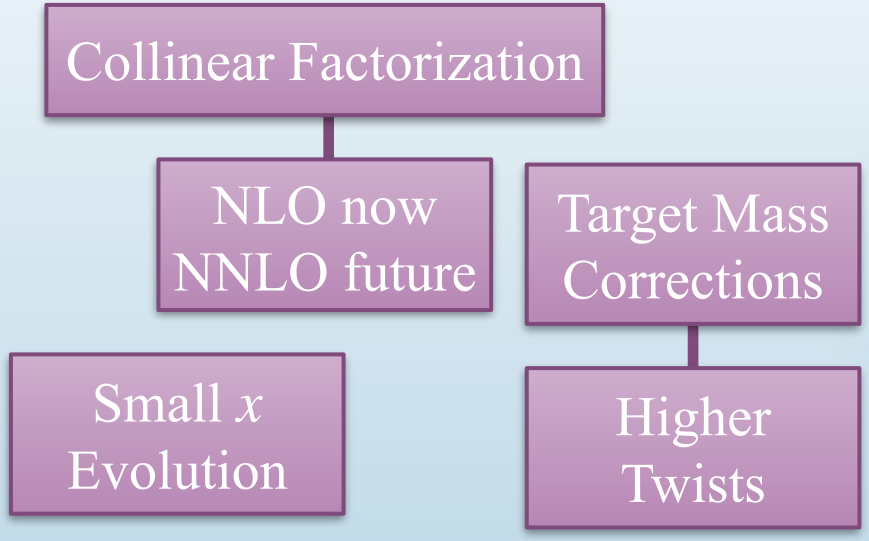
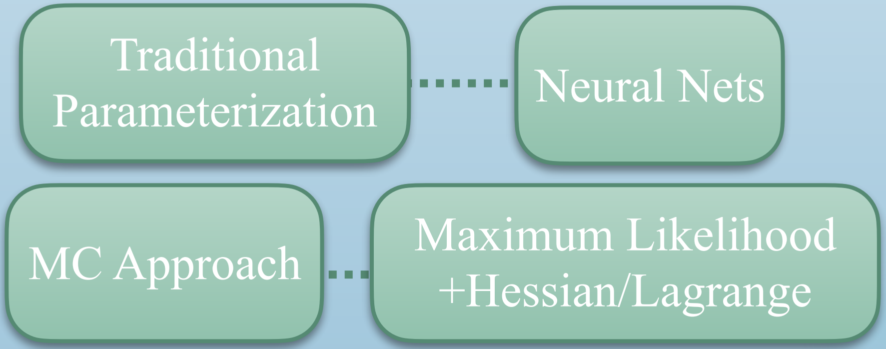


Methodology



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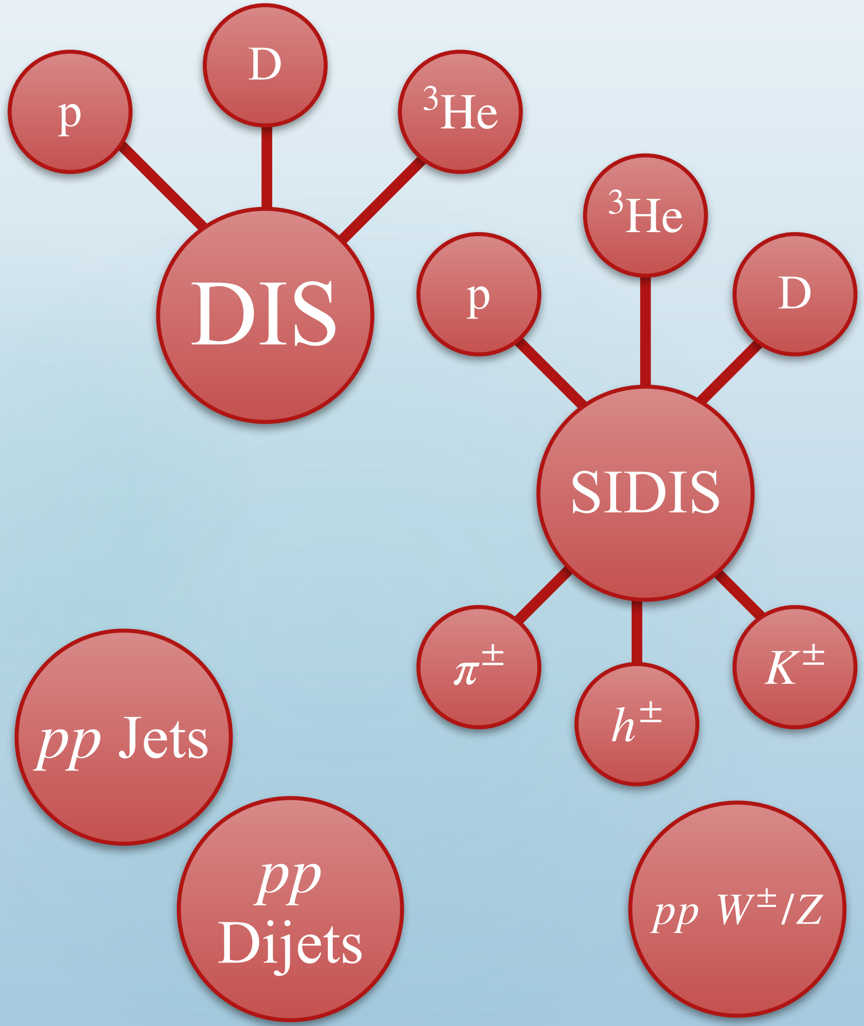


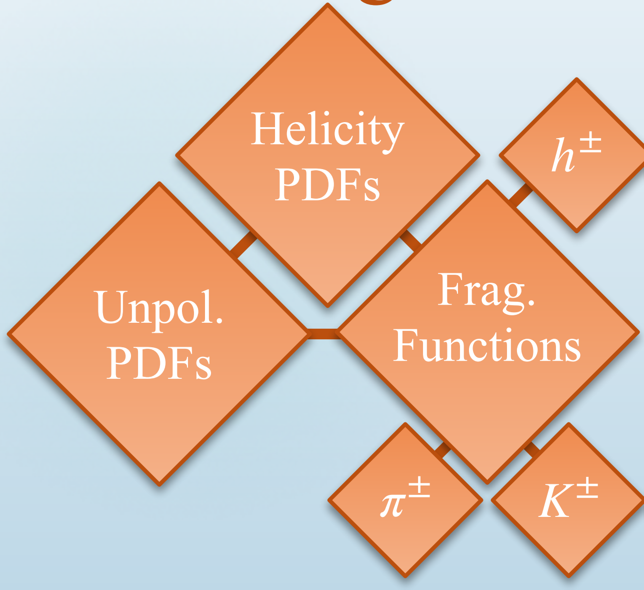
Theory

- Collinear Factorization
- NLO now NNLO future
- Target Mass Corrections
- Small x Evolution
- Higher Twists

Methodology

- Traditional Parameterization
- Neural Nets
- MC Approach
- Maximum Likelihood +Hessian/Lagrange

Simultaneous Paradigm



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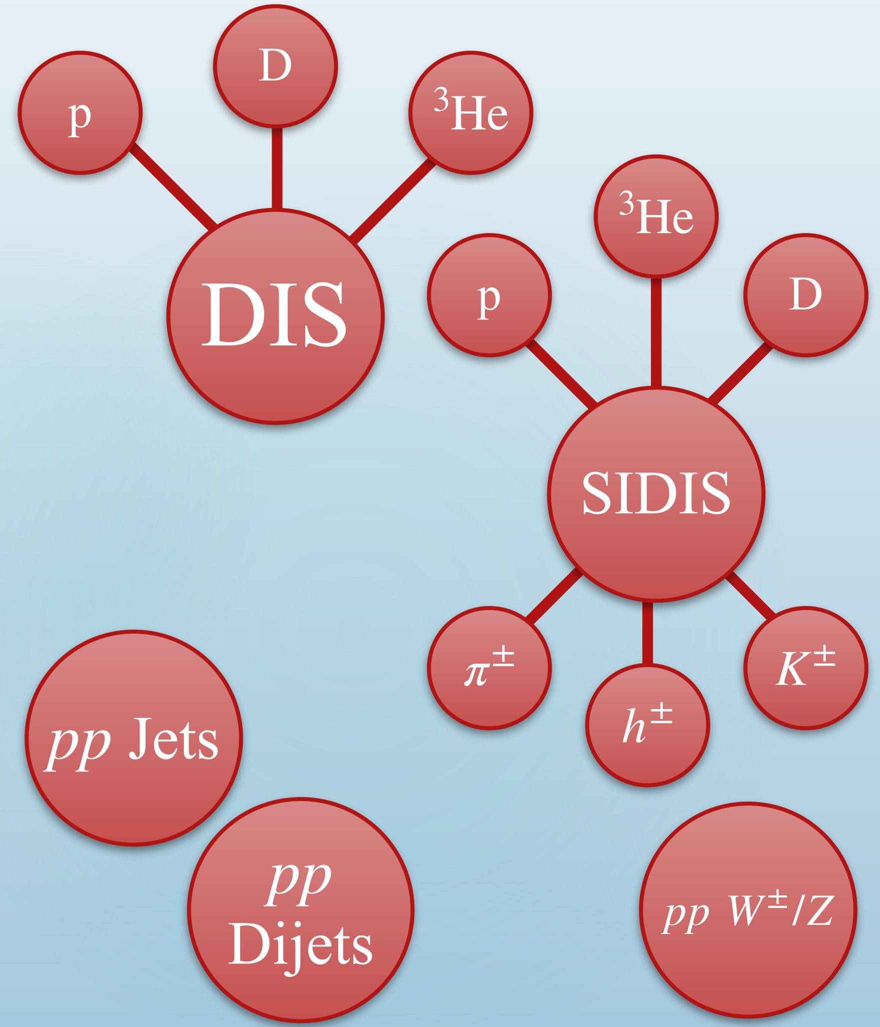

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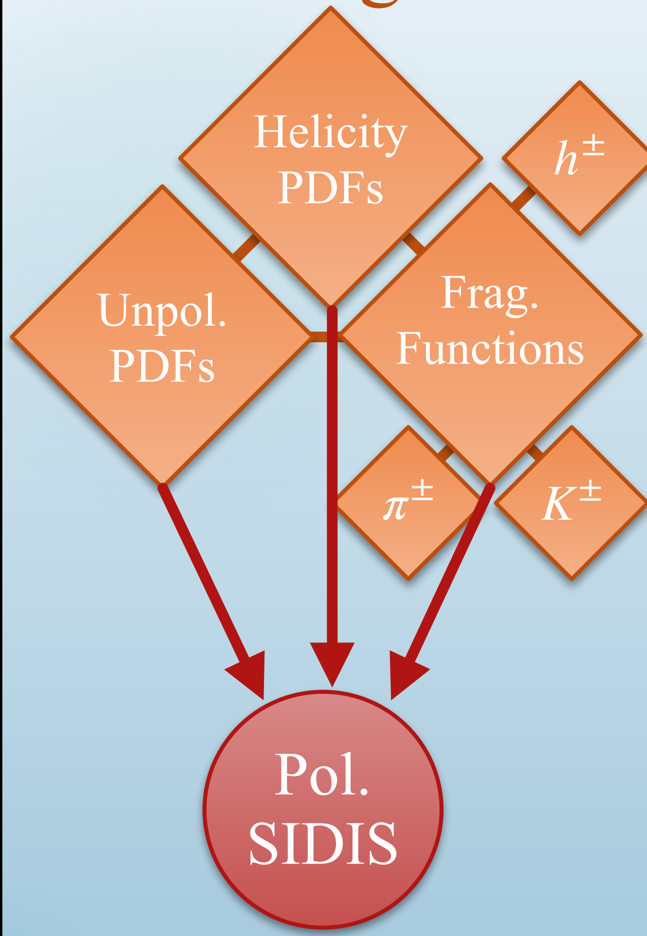

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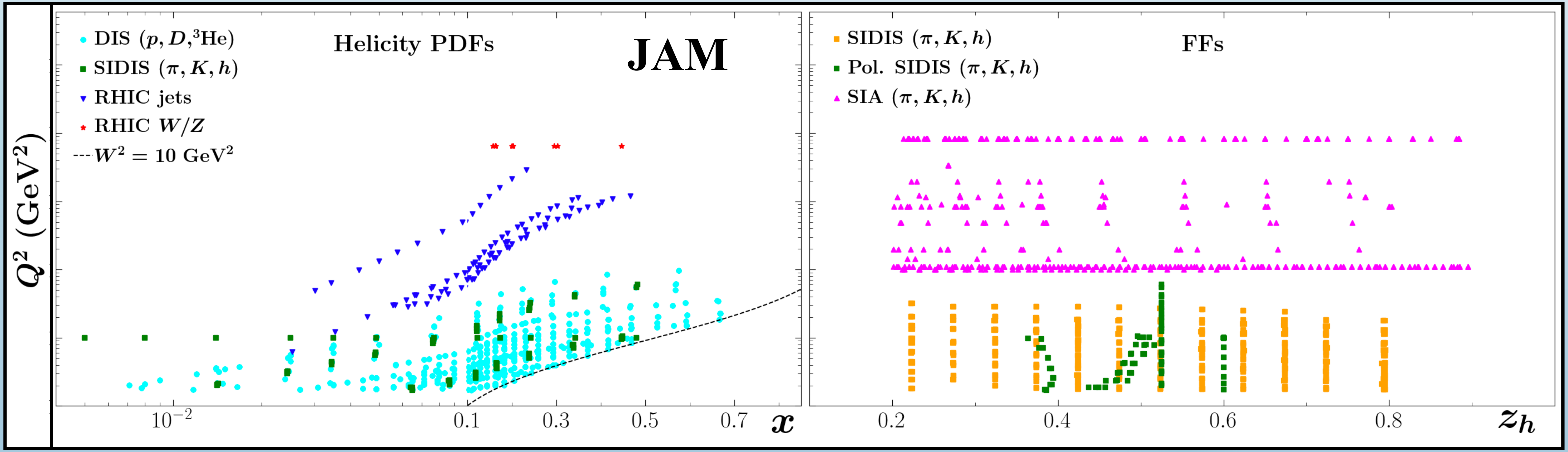

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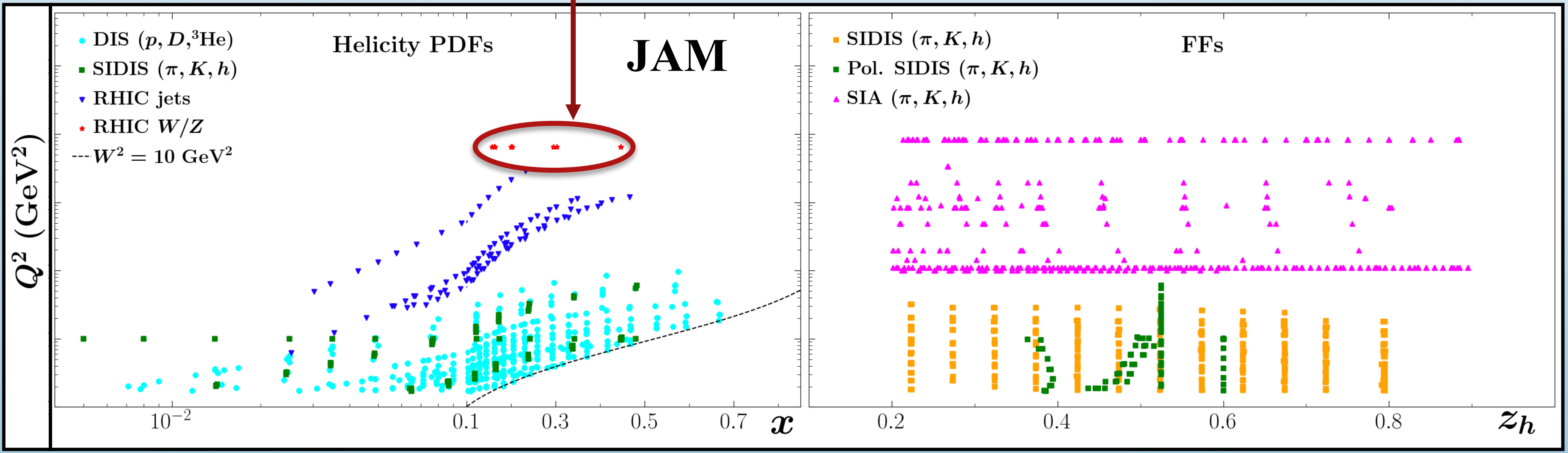
New RHIC W/Z data



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RHIC jet data

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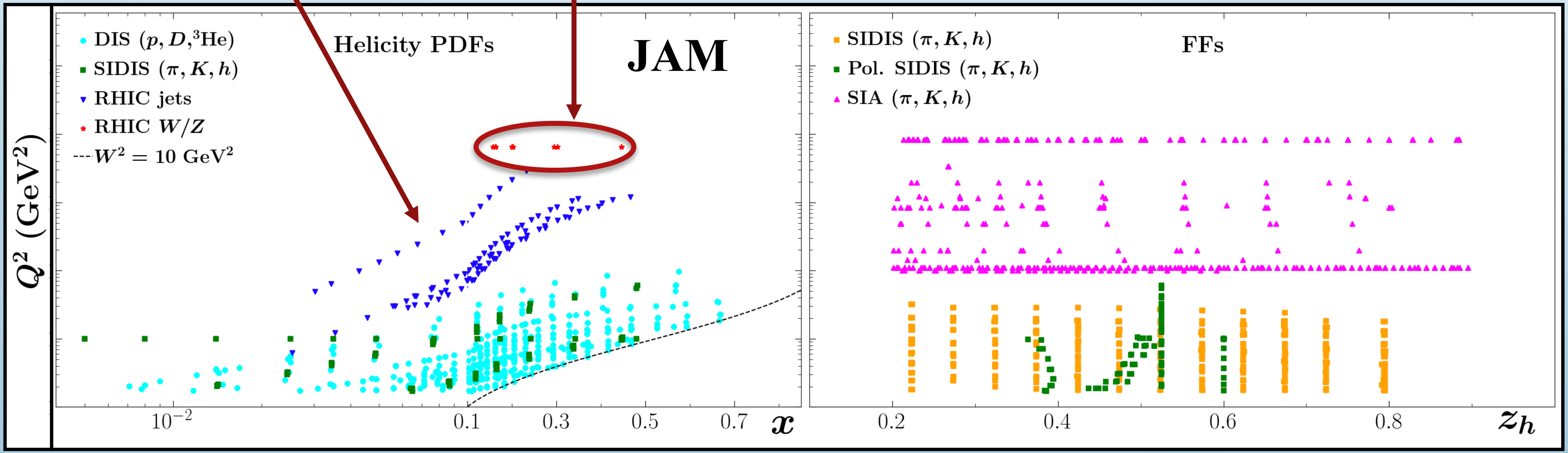

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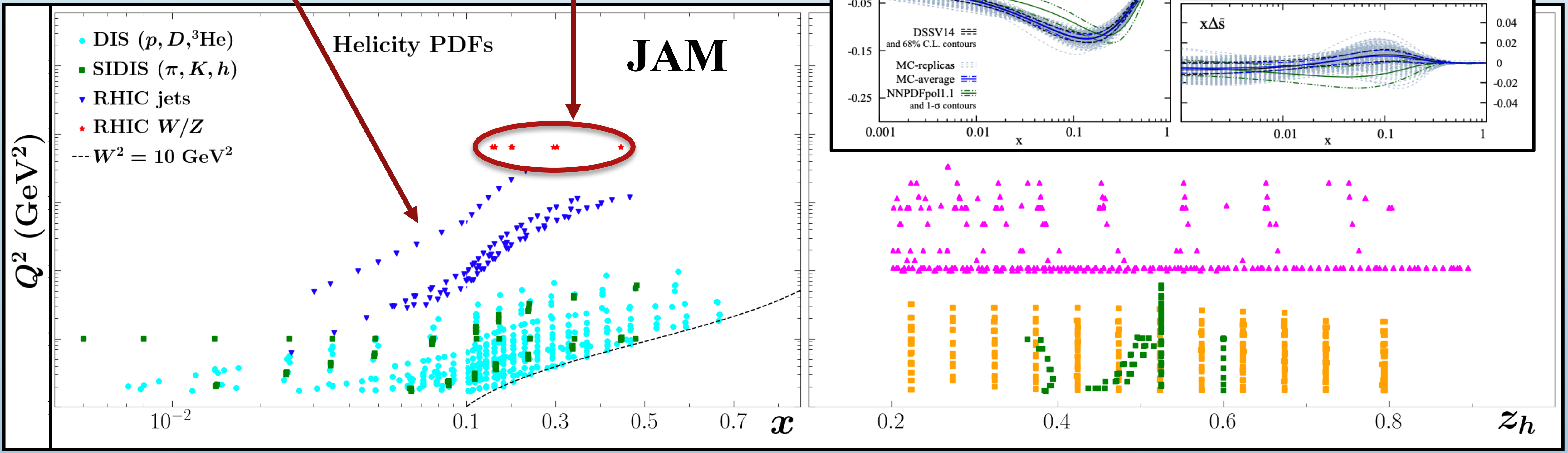

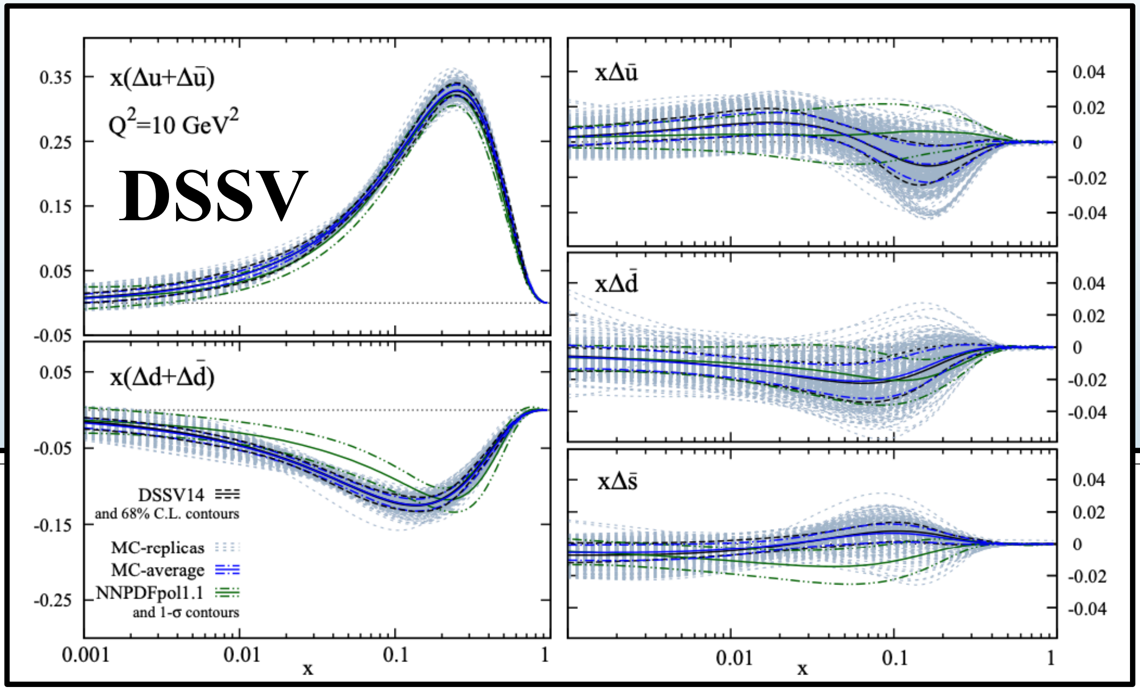

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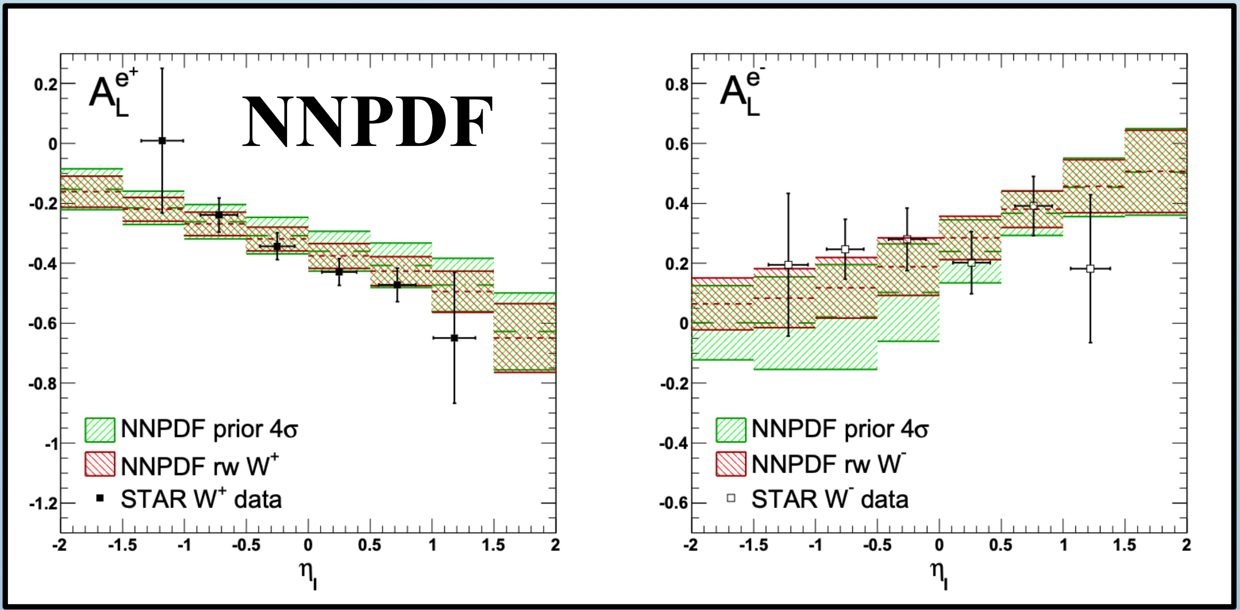

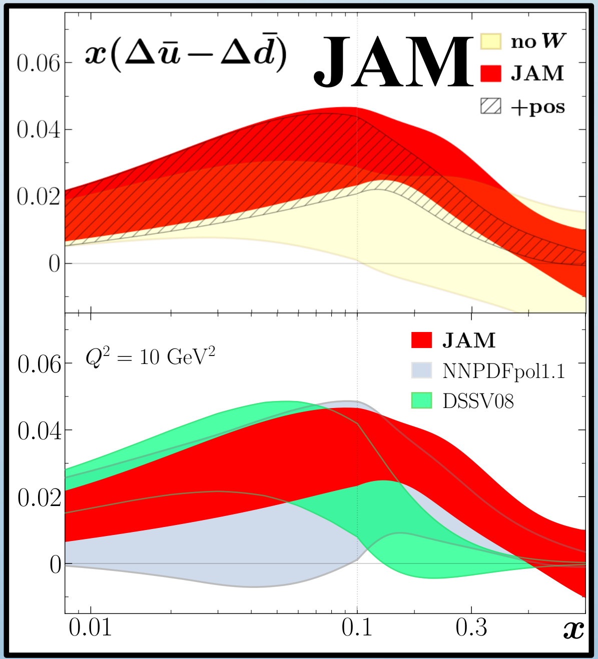

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$$A_L^{W^-}(y_W) \propto \frac{\Delta\bar{u}(x_1)d(x_2) - \Delta d(x_1)\bar{u}(x_2)}{\bar{u}(x_1)d(x_2) + d(x_1)\bar{u}(x_2)}$$

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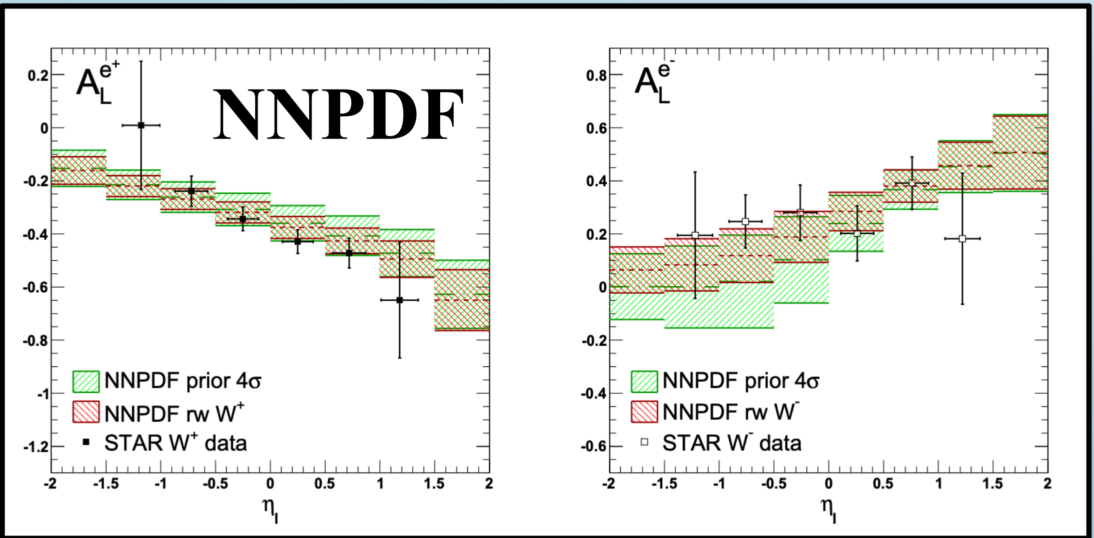

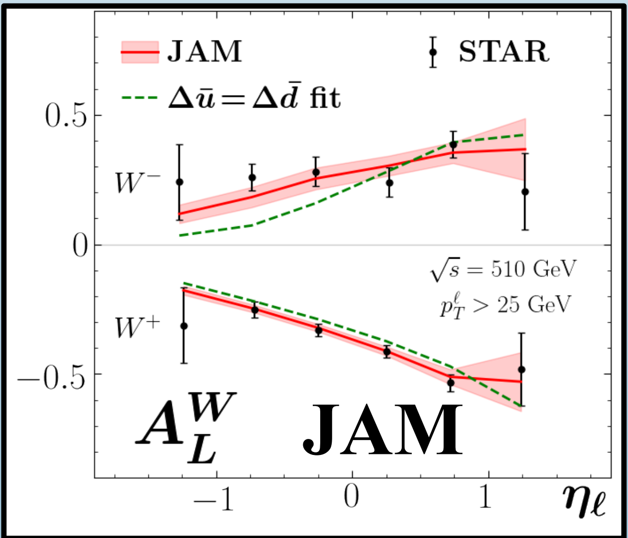

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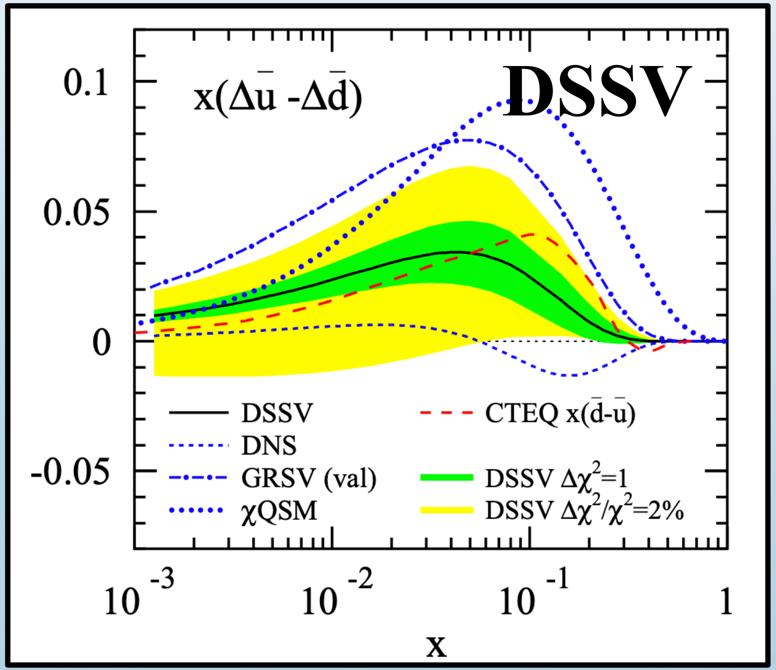

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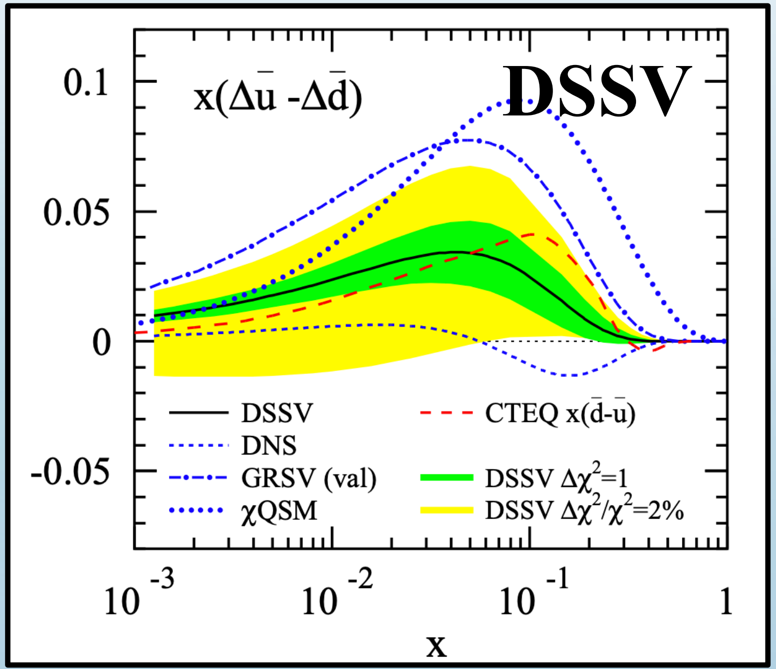

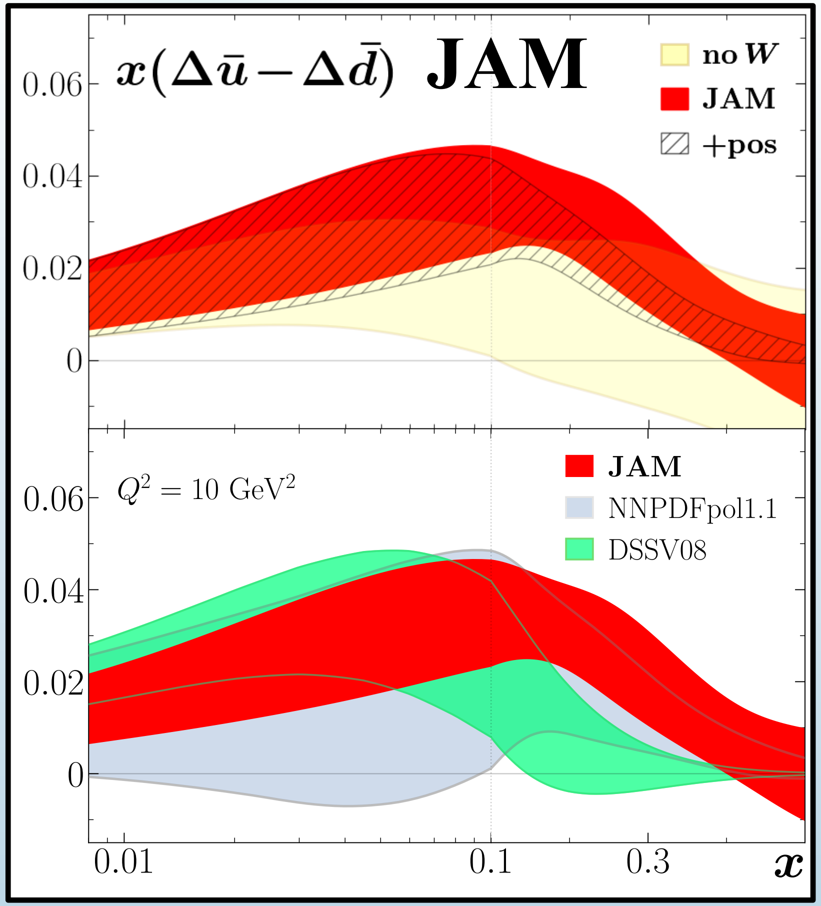

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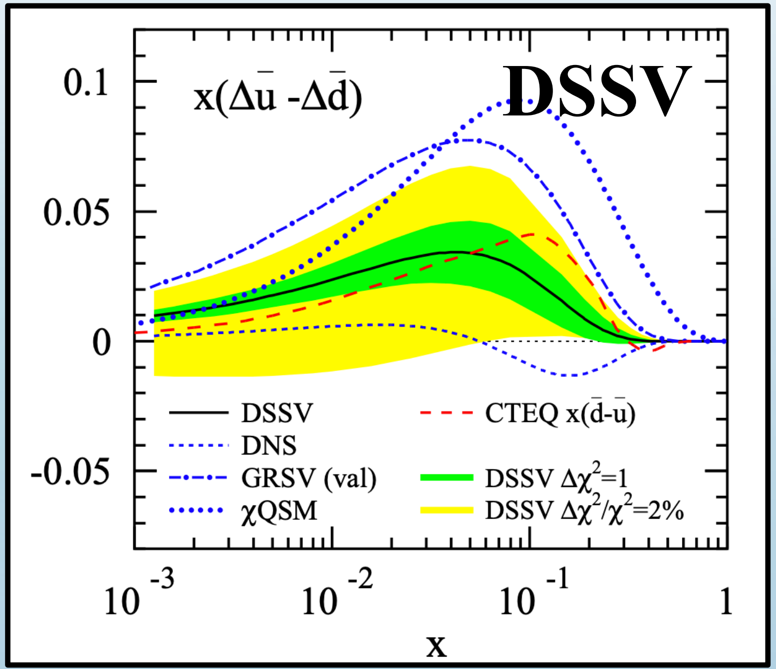

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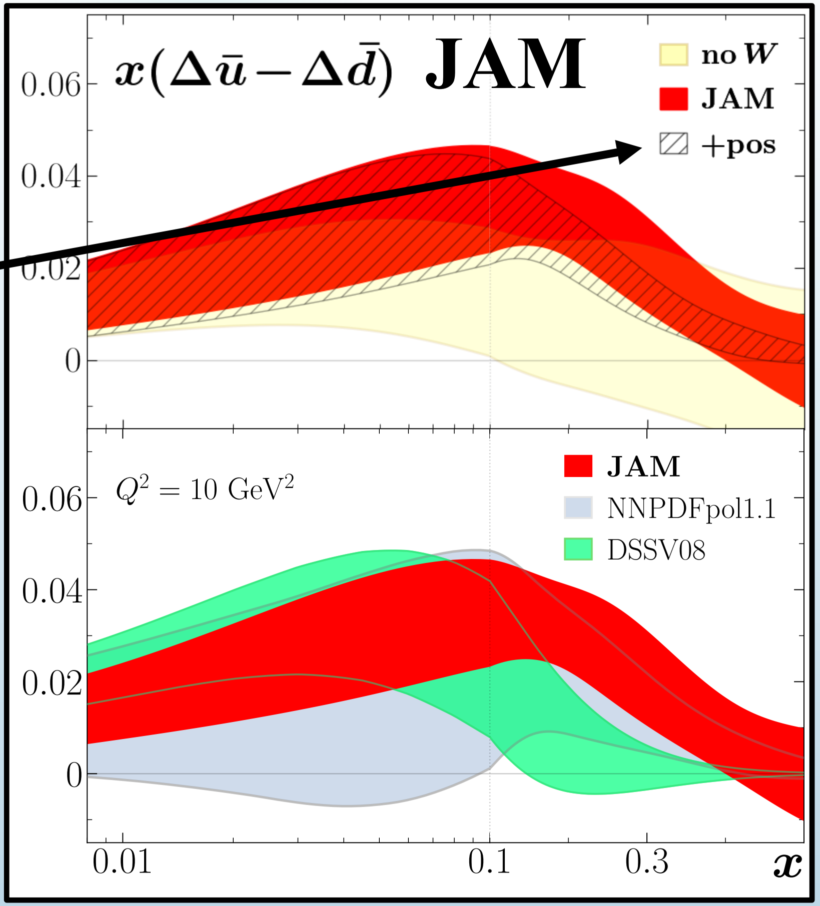

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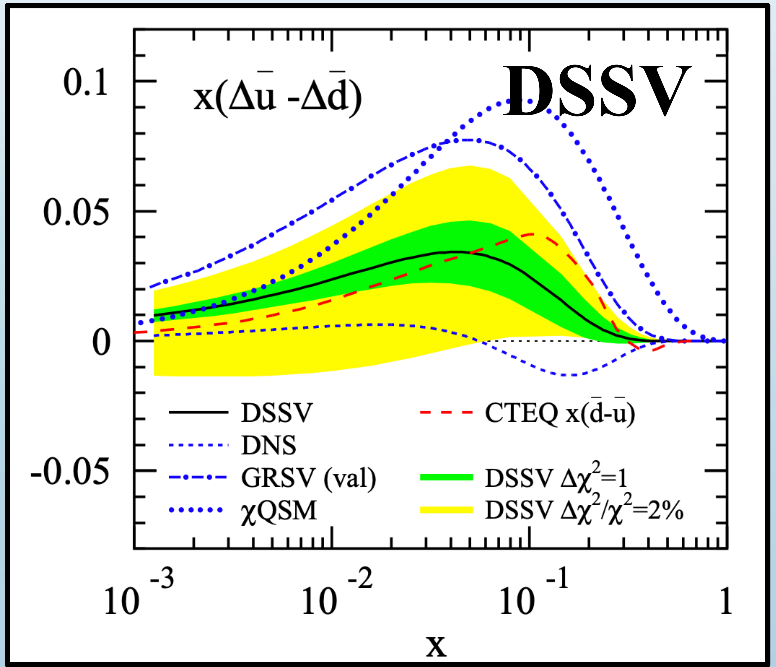

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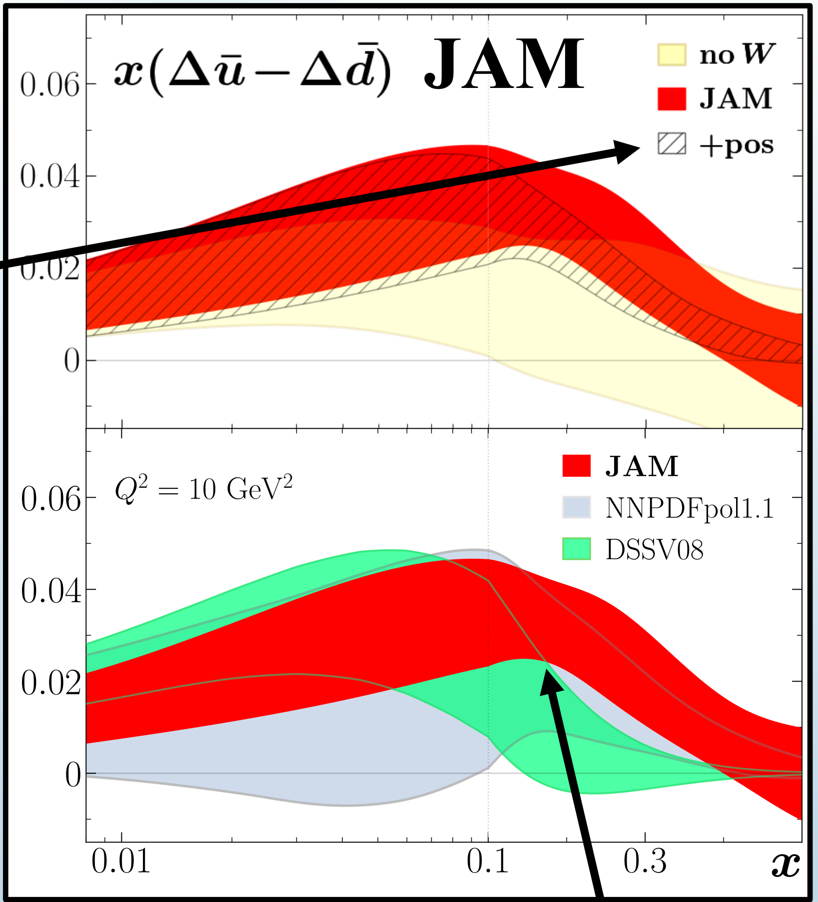
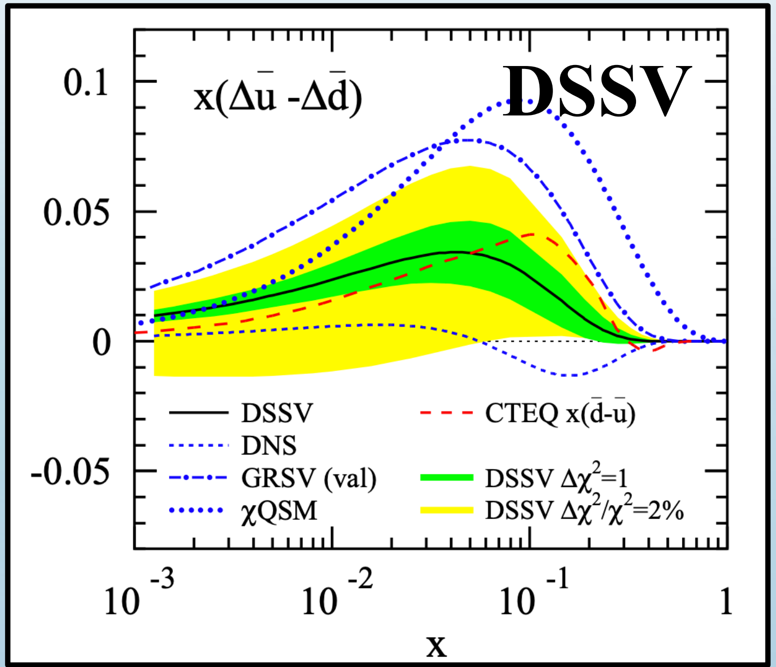


First positive extraction at moderate x

Helicity Sea Asymmetry (2009-2022)



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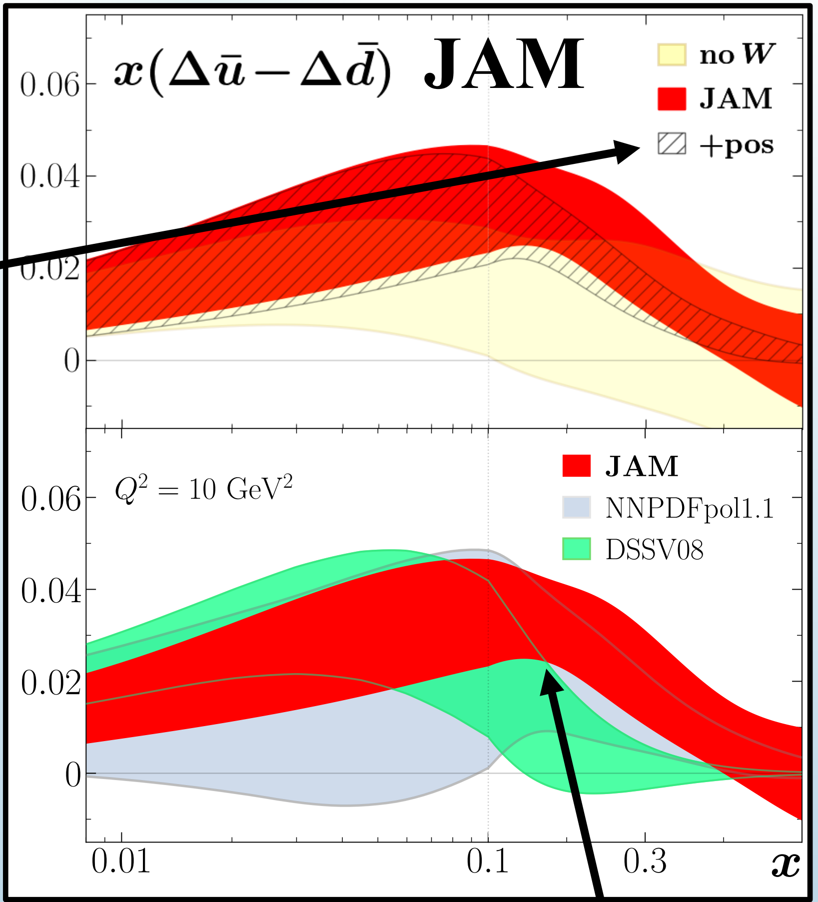

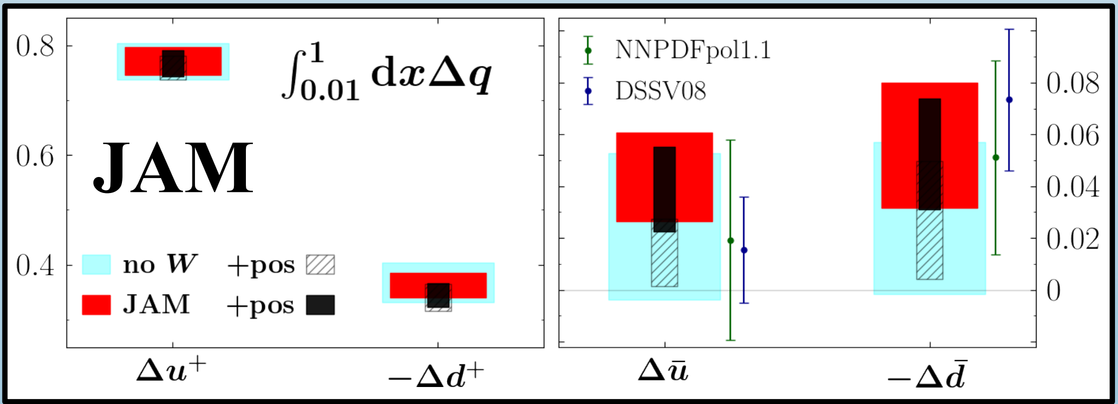

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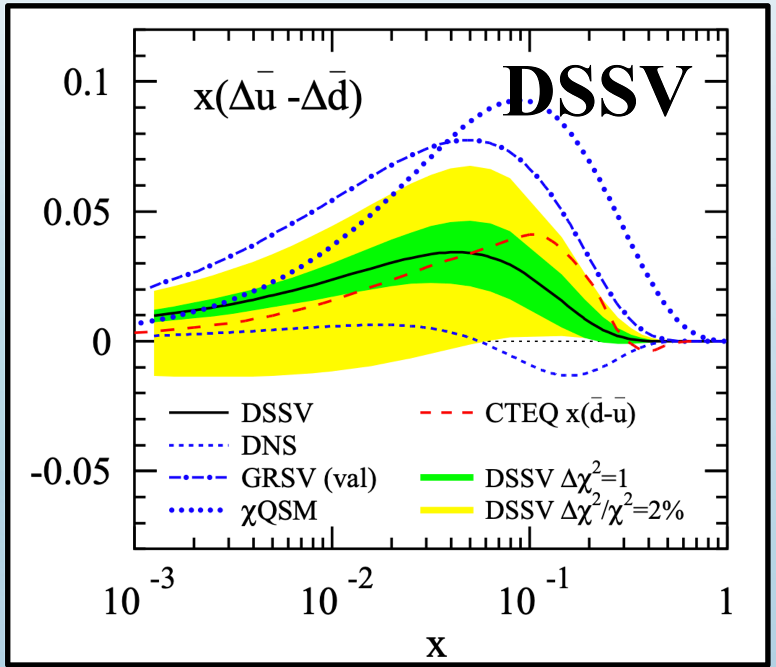

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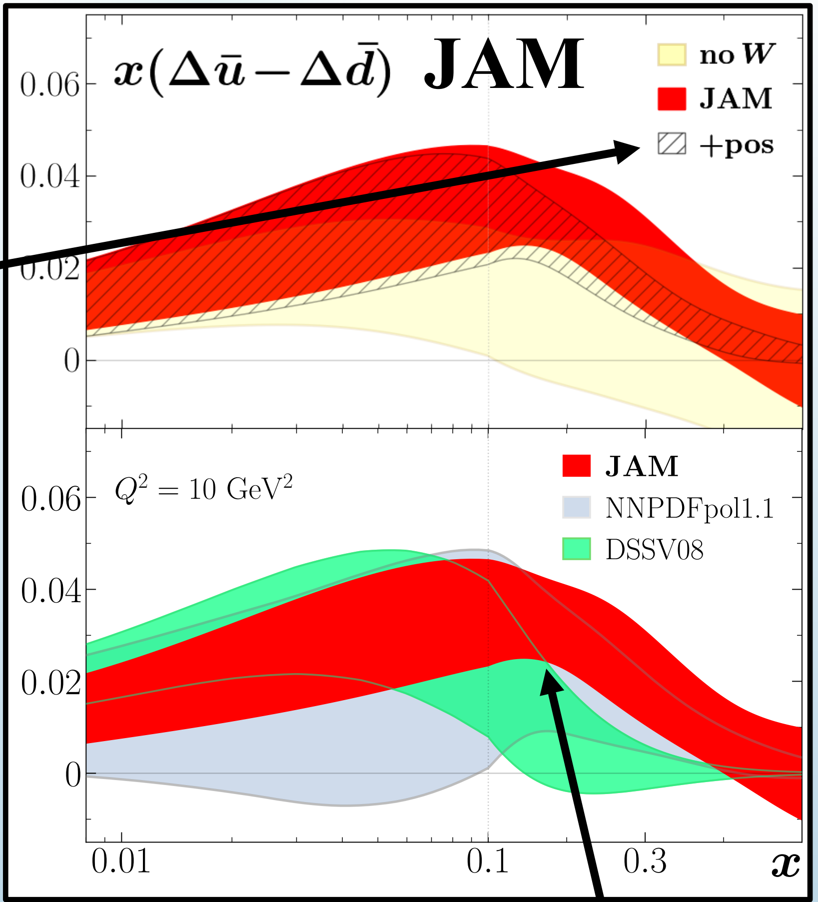

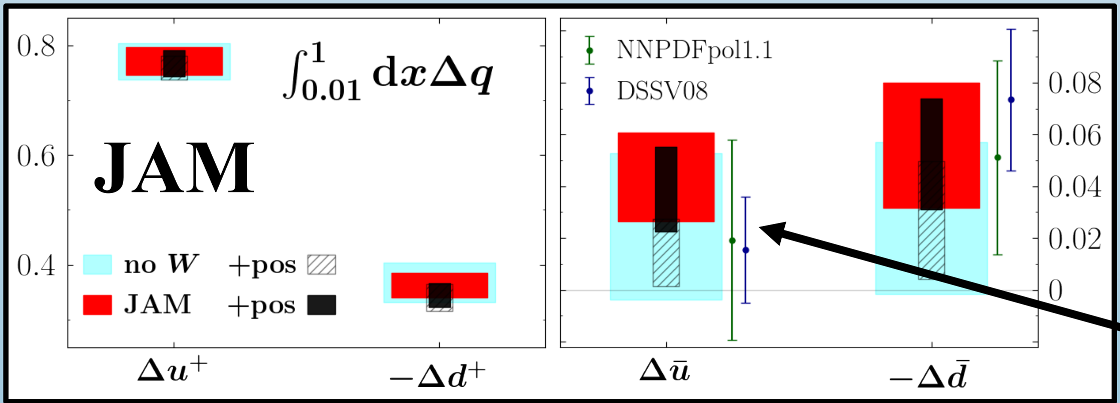

First positive extraction at moderate x

First non-zero extraction of $\Delta\bar{u}$ moment

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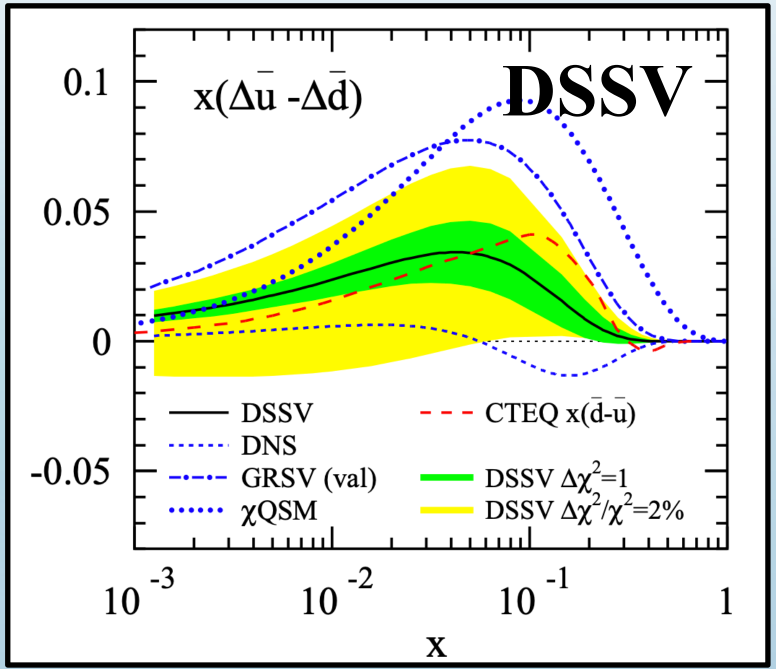
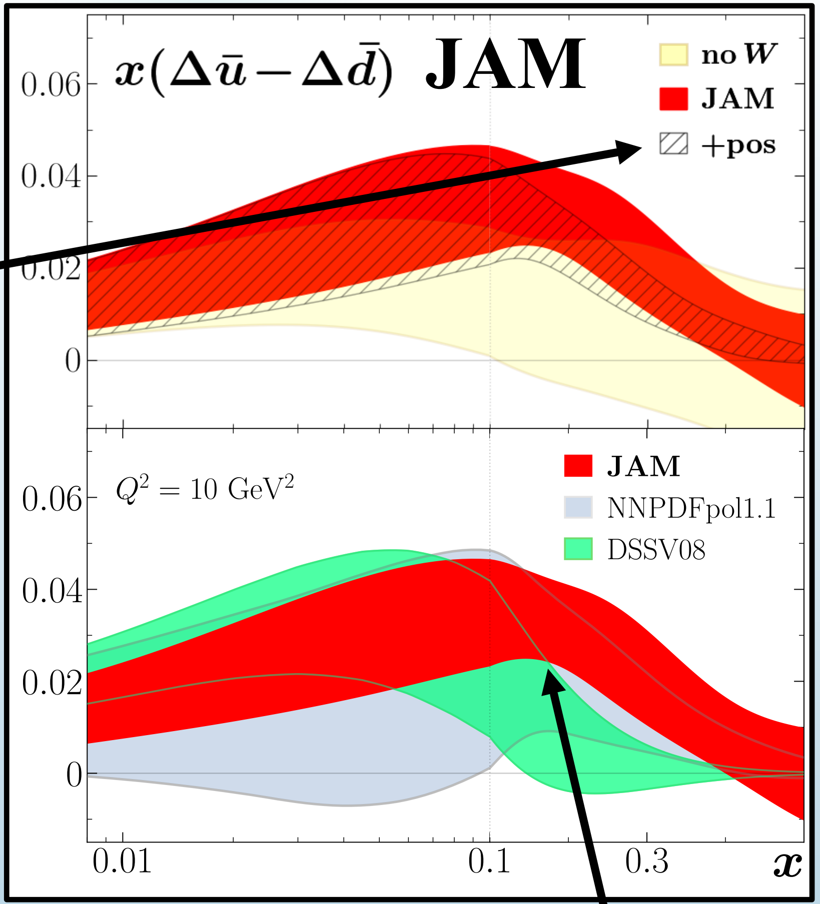
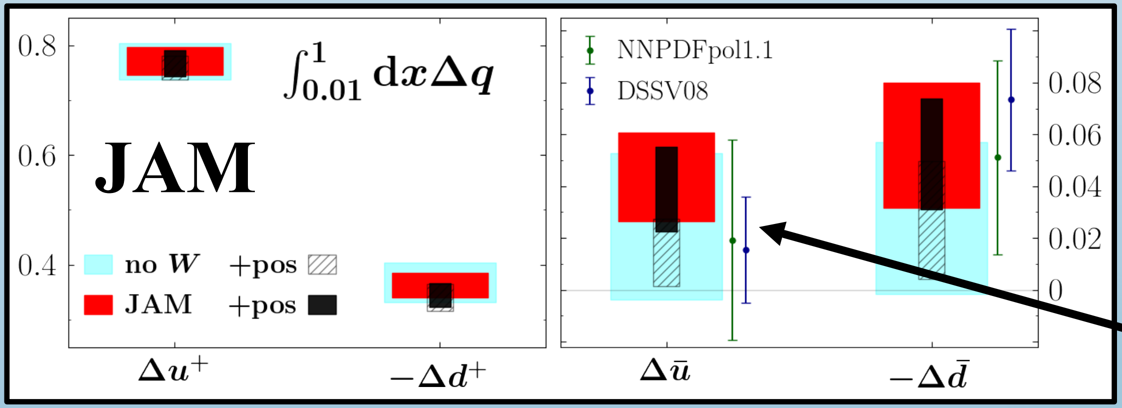


$$|\Delta f(x,Q^2)| < f(x,Q^2)$$

Flavor	JAM moment (truncated)	Lattice Moment (full)	Diff.
Δu^+	0.771(25)	0.864(16)	11%
Δd^+	-0.363(23)	-0.426(16)	15%
$\Delta\bar{u}$	0.044(17)		
$\Delta\bar{d}$	-0.056(24)		

C. Alexandrou *et al.*, Phys. Rev. D **101**, 094513 (2020).





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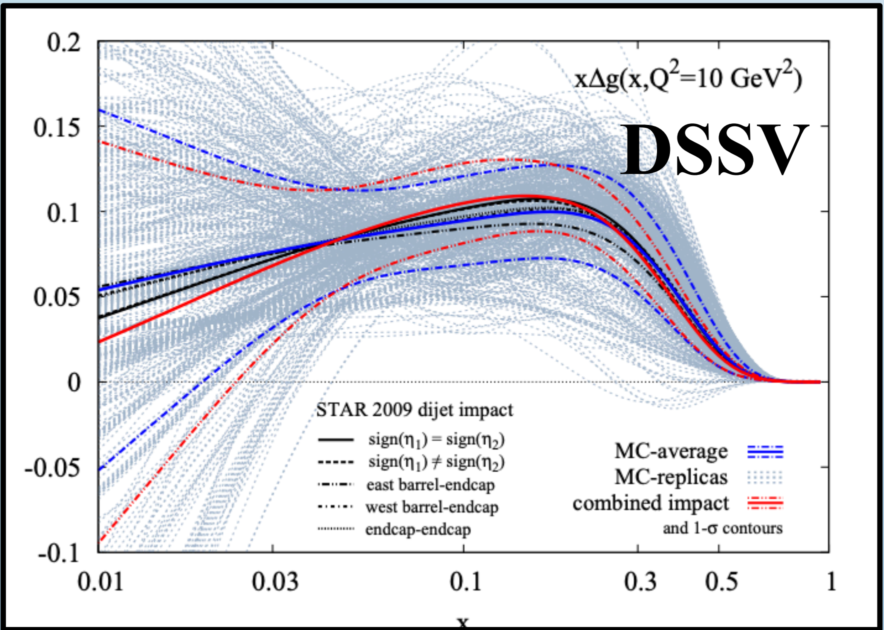

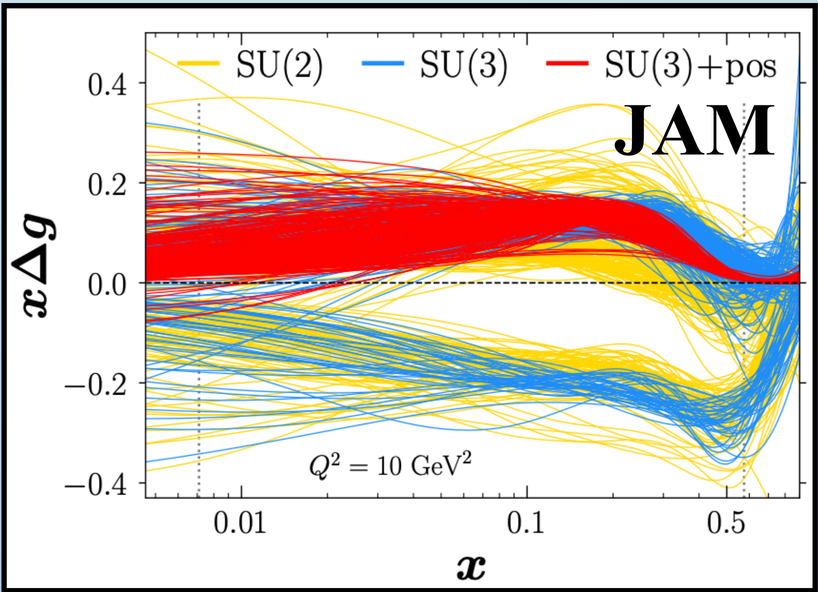

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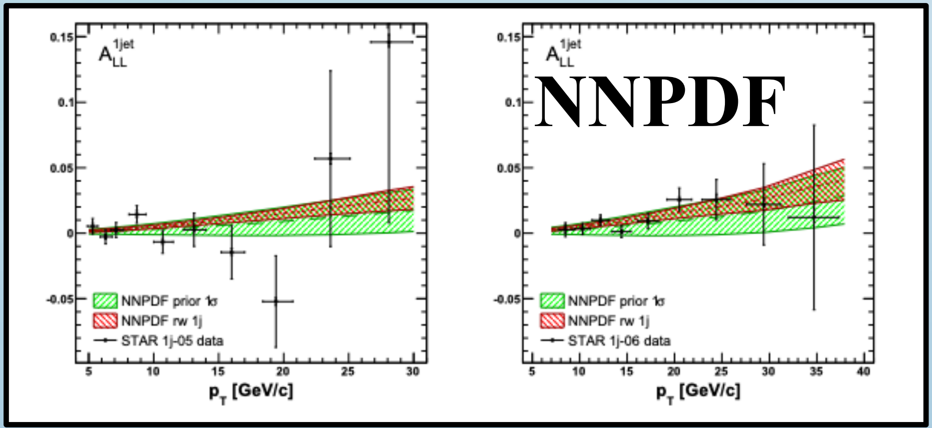

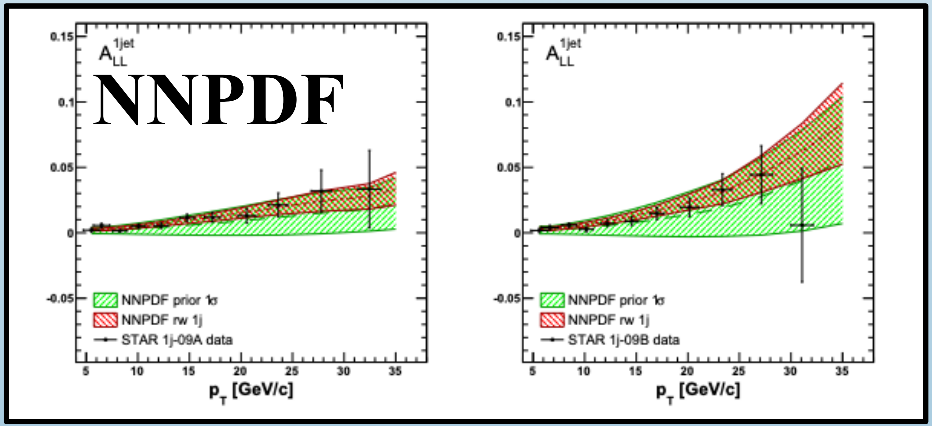

Gluon Polarization (2014-2022)

A first unbiased global determination of polarized PDFs and their uncertainties
Emanuele R.Nocera, Richard D.Ball, Stefano Forte, Giovanni Ridolfi, Juan Rojo (The NNPDF Collaboration)

https://arxiv.org/abs/1406.5539
E. R. Nocera *et al*., Nucl. Phys. B **887**, 276-308 (2014).

Monte Carlo sampling variant of the DSSV14 set of helicity parton densities
Daniel de Florian, Gonzalo Agustin Lucero, Rodolfo Sassot, Marco Stratmann, Werner Vogelsang

https://arxiv.org/abs/1902.10548
D. de Florian *et al*., Phys. Rev. D **100**, no. 11, 114027 (2019).

How well do we know the gluon polarization in the proton?
Y. Zhou, N. Sato, W. Melnitchouk

https://arxiv.org/abs/2201.02075
Y. Zhou *et al*., Phys. Rev. D **105**, no. 7, 074022 (2022).

NNPDFpol (2014): used single-jet data from RHIC (up to 2009 runs)
DSSV (2019): used single and di-jet data from RHIC (up to 2009 runs)
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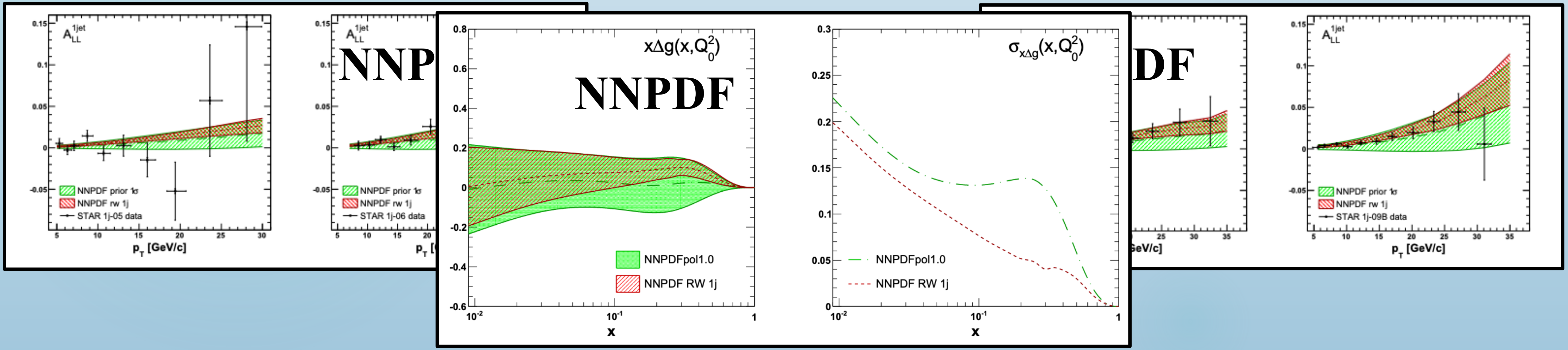

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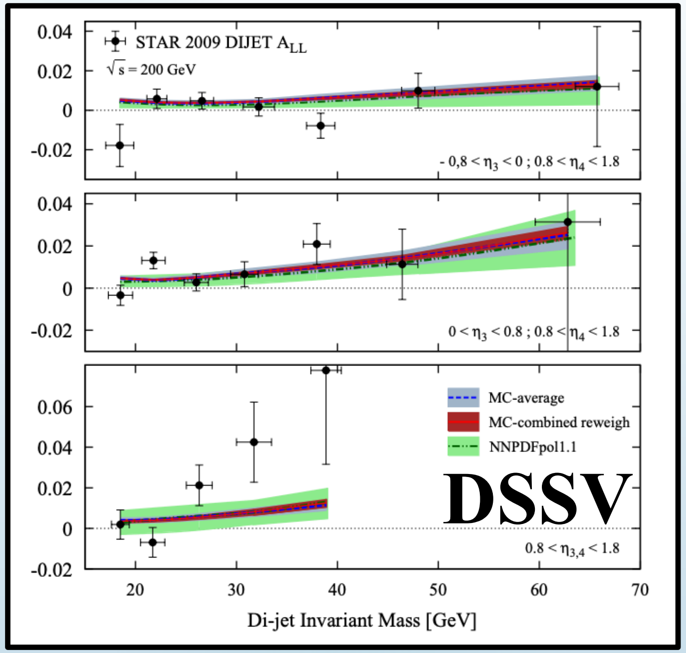

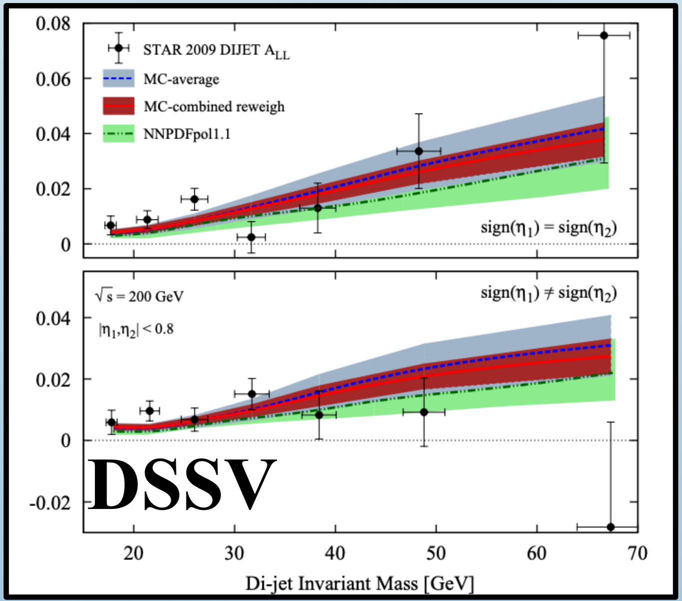

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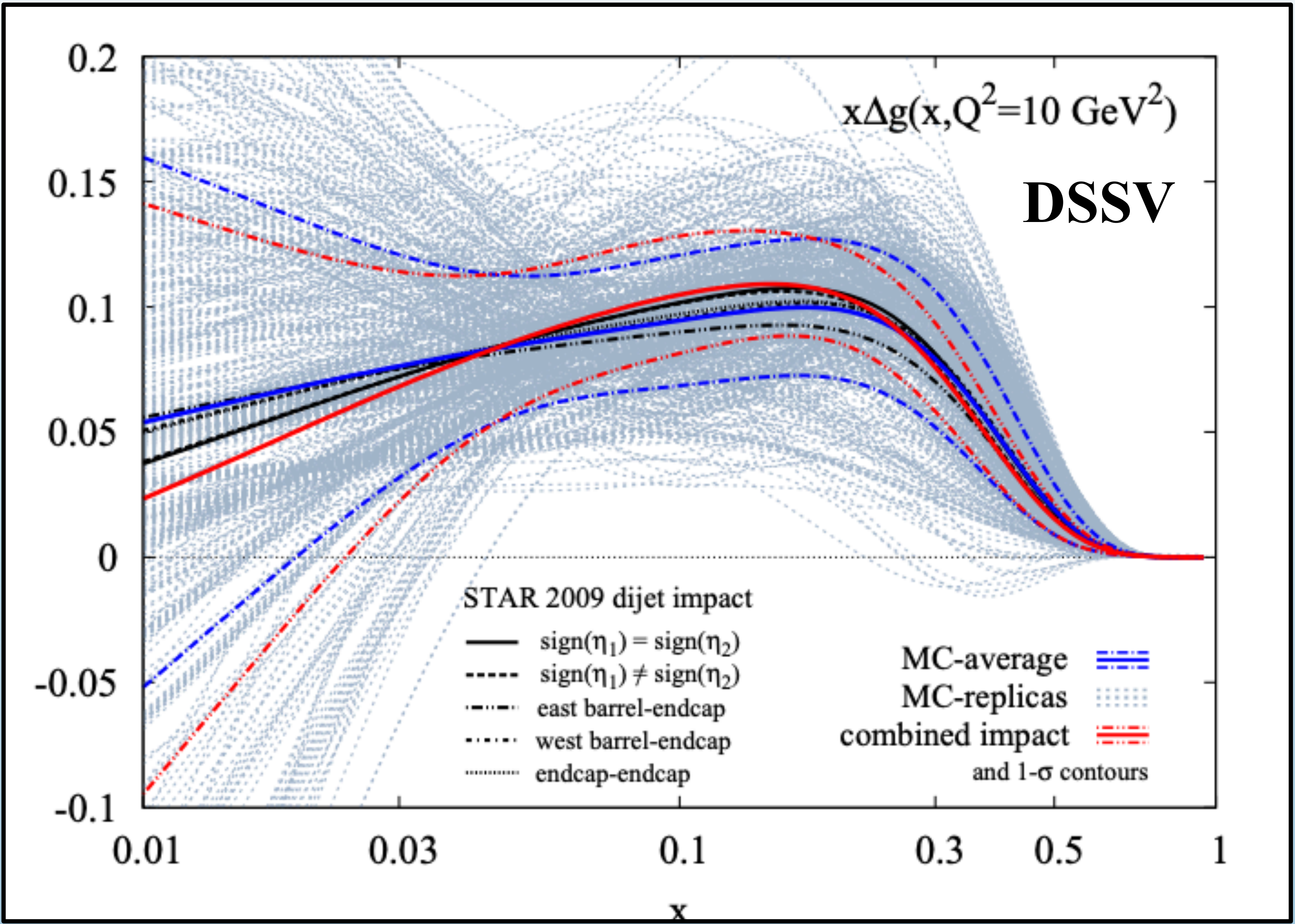

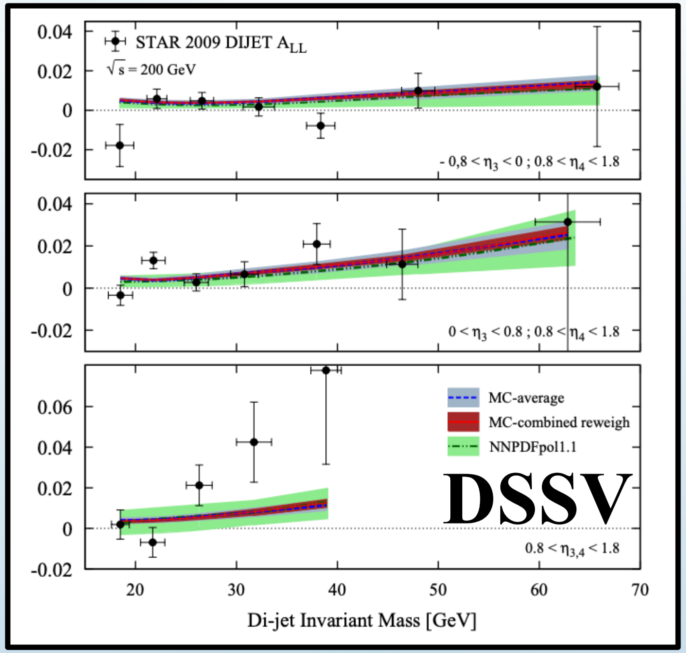

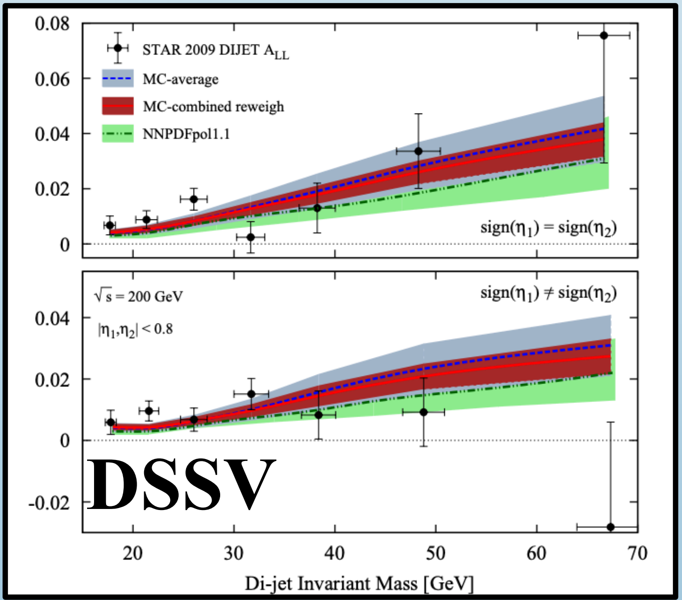

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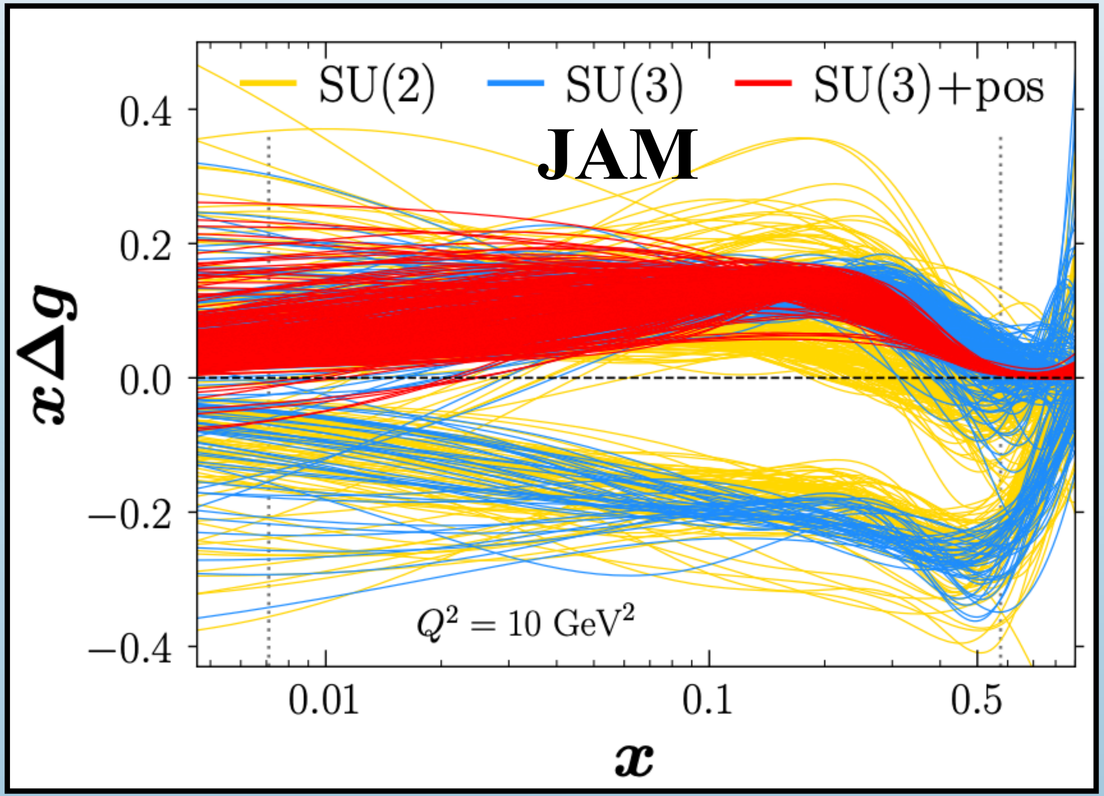

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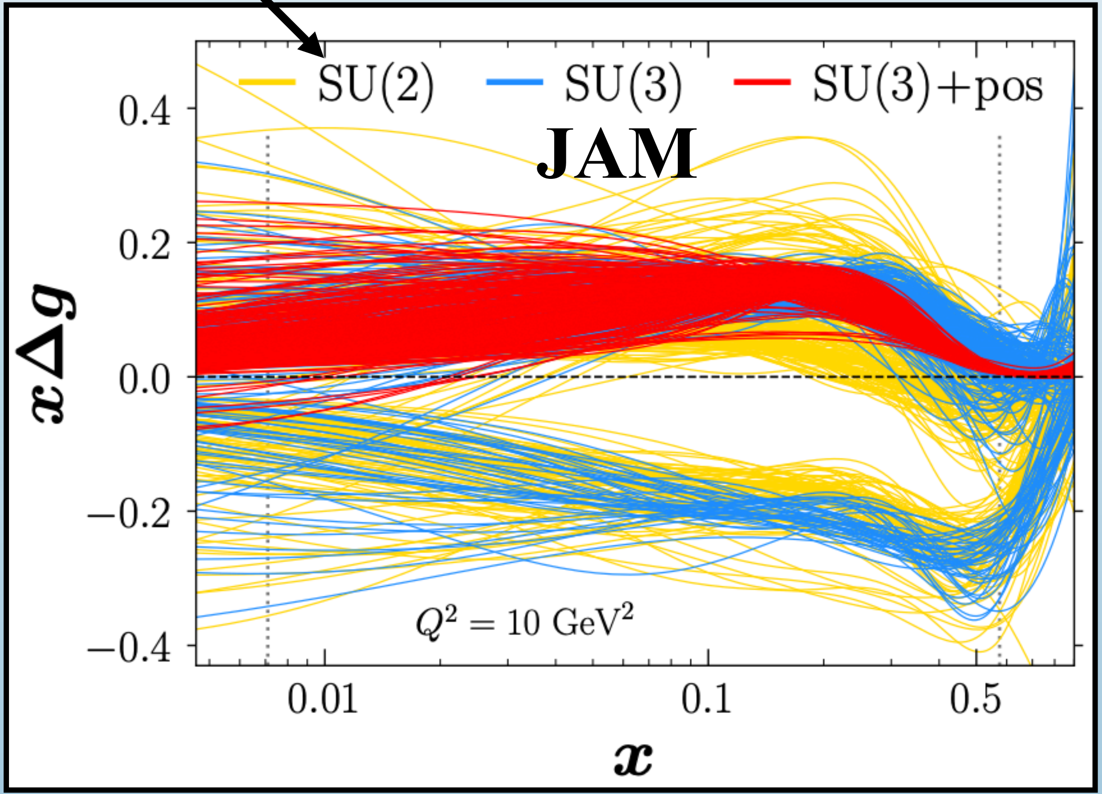
$$\int_0^1 \mathrm{d}x \left[\Delta u^+ - \Delta d^+\right] = g_A$$



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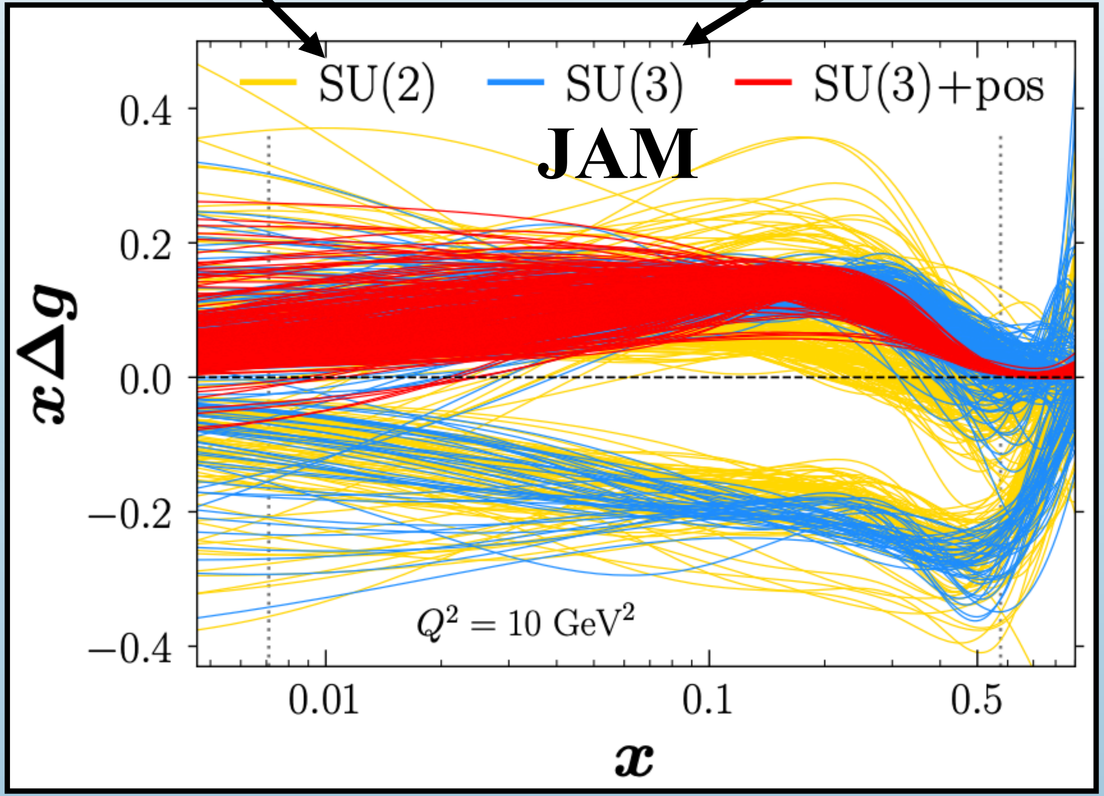

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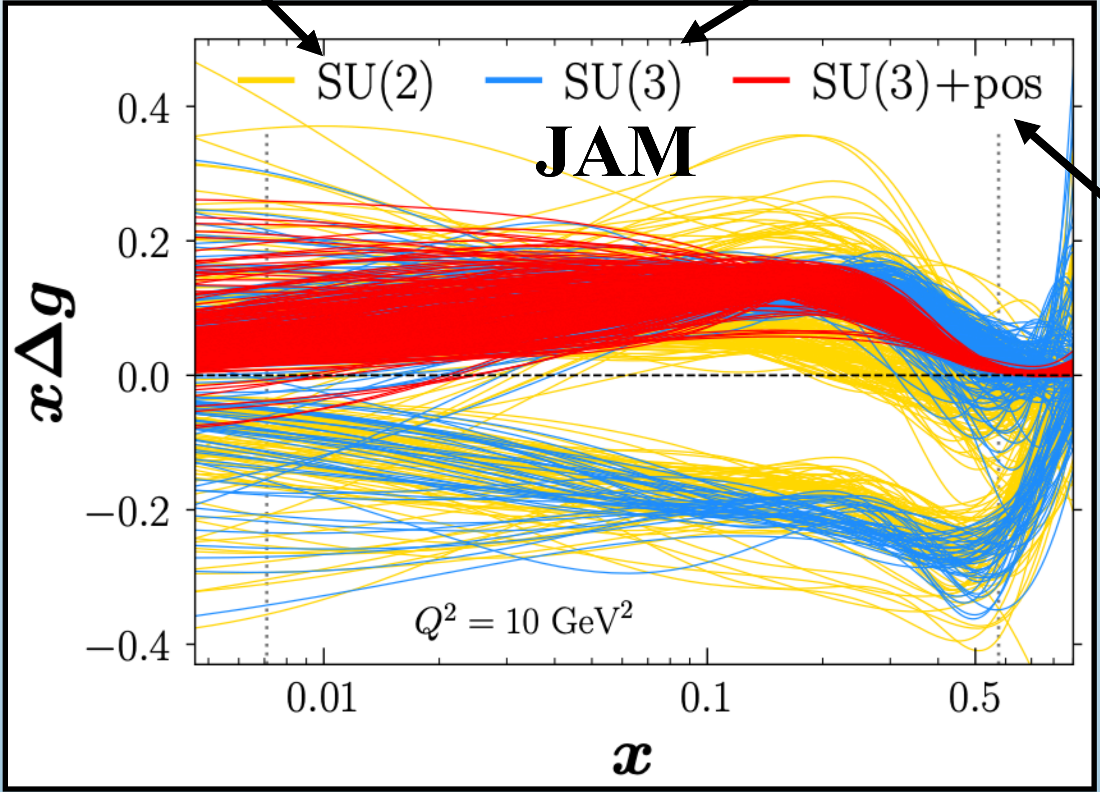

$$|\Delta f(x, Q^2)| < f(x, Q^2)$$

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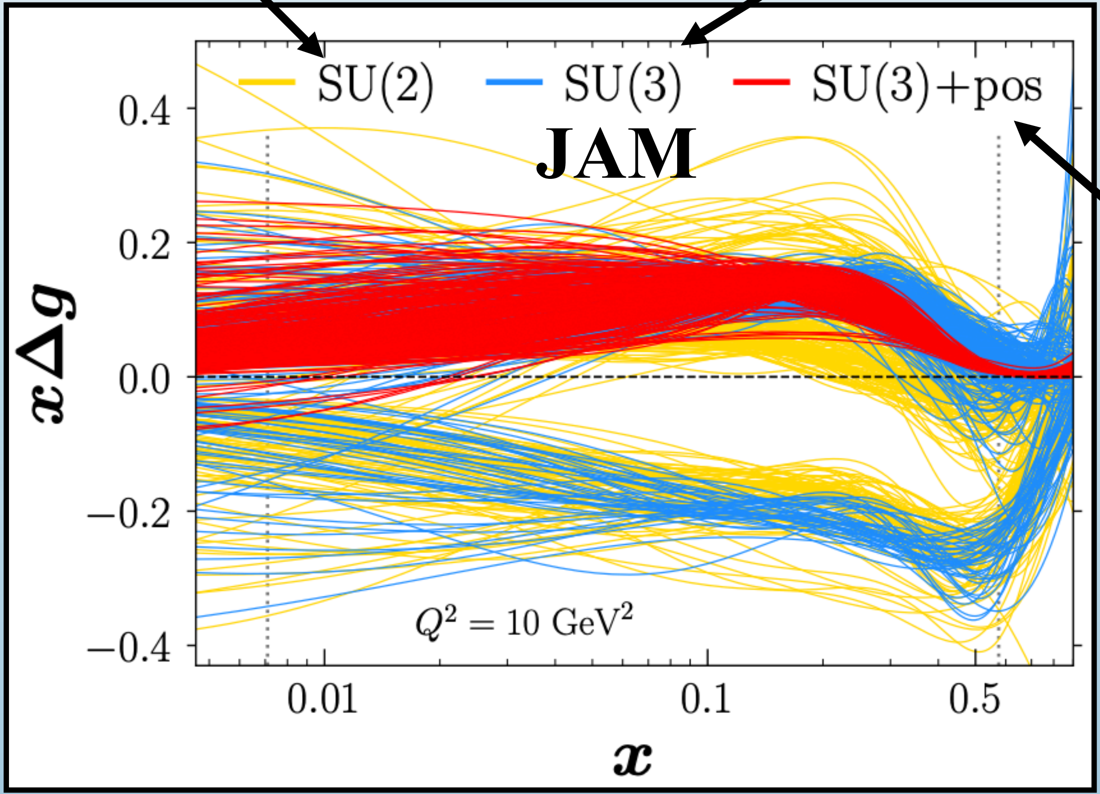

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Can $\overline{\mathrm{MS}}$ parton distributions be negative?

Alessandro Candido, Stefano Forte and Felix Hekhorn

Positivity and renormalization of parton densities

John Collins, Ted C. Rogers, Nobuo Sato

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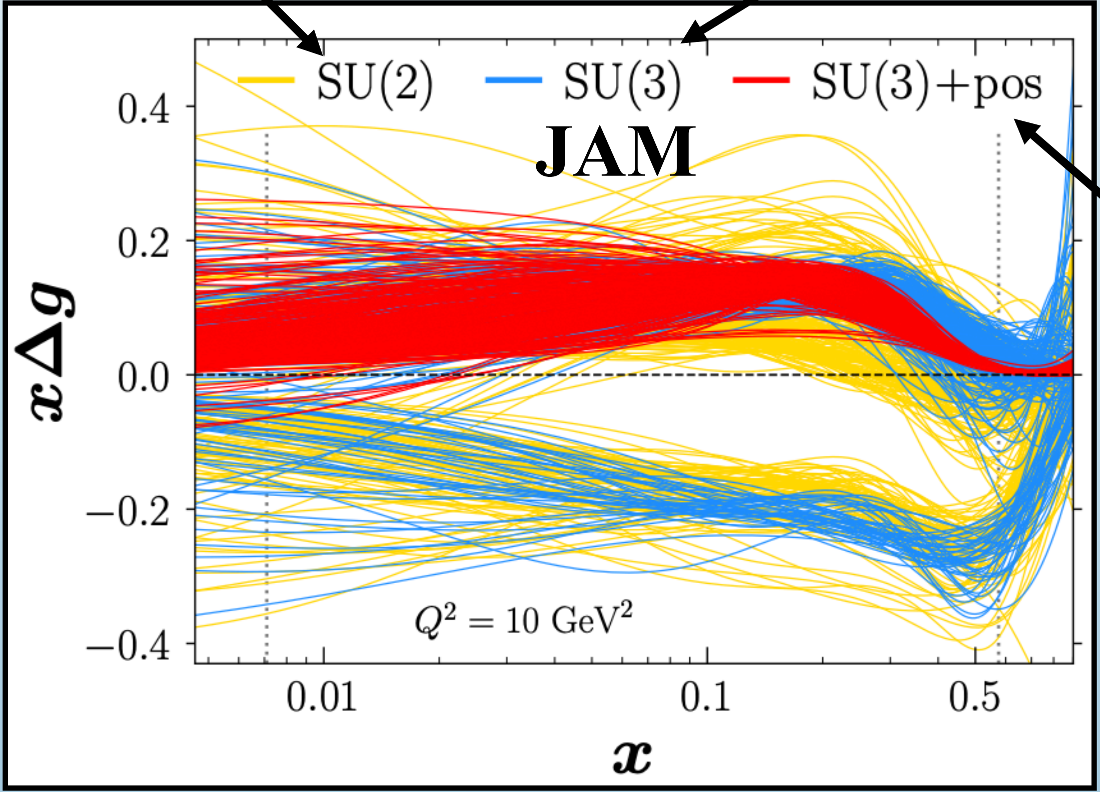

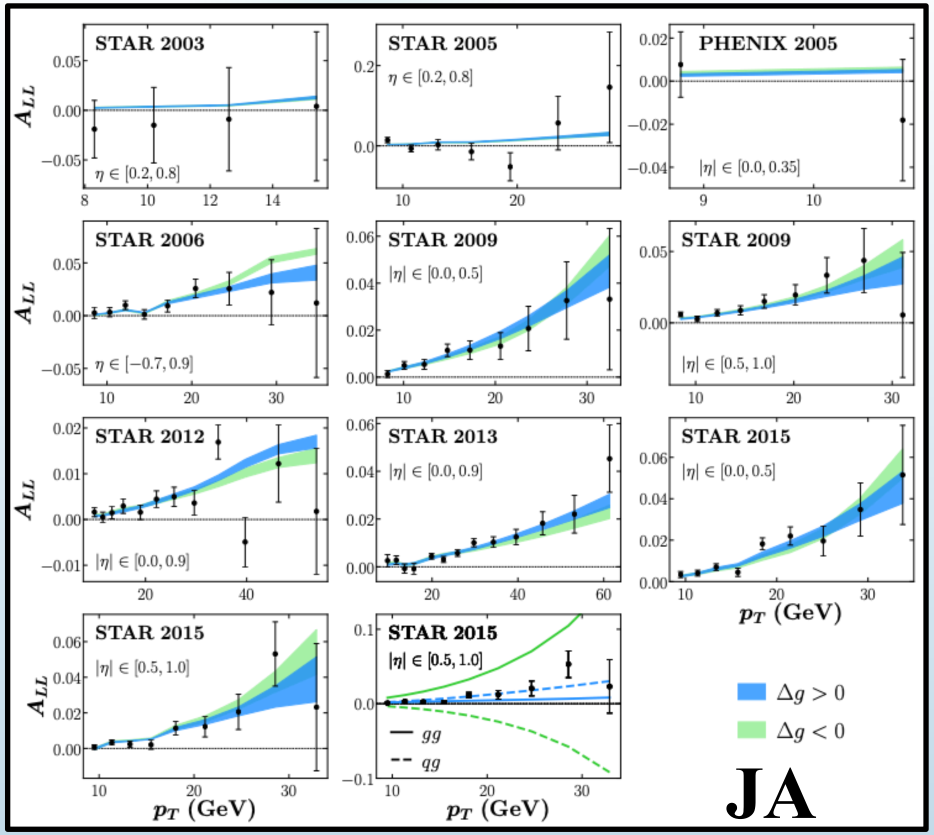

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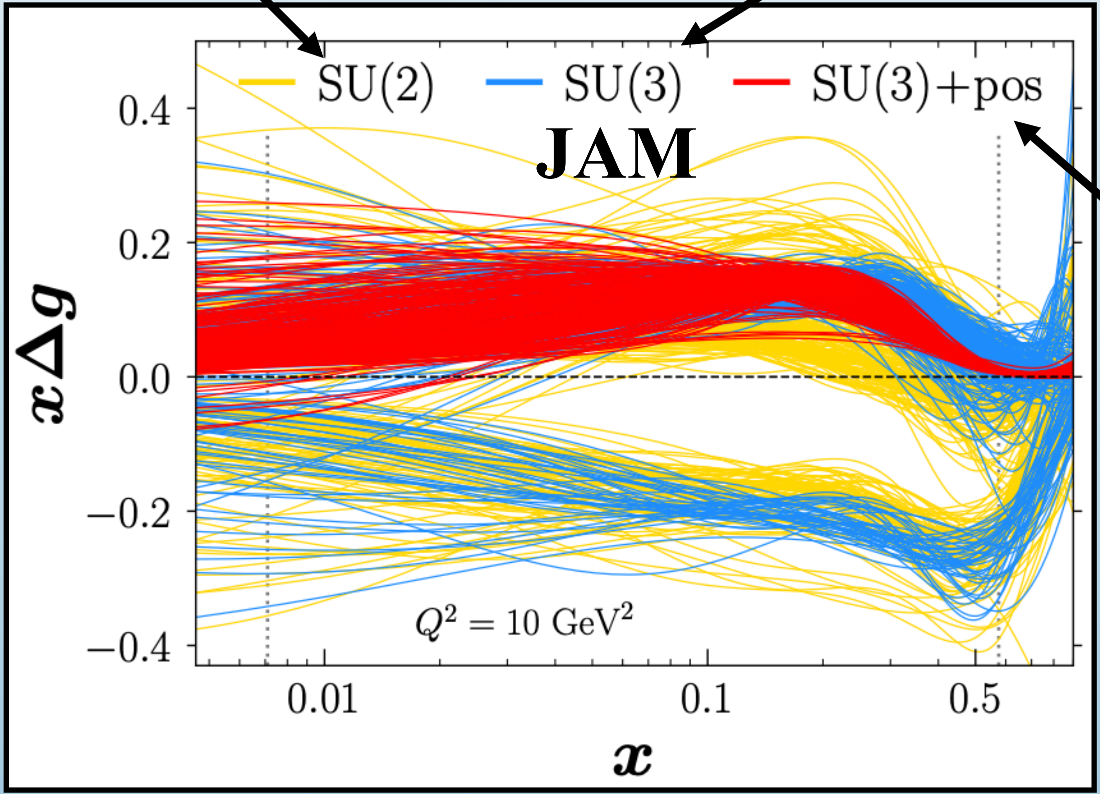

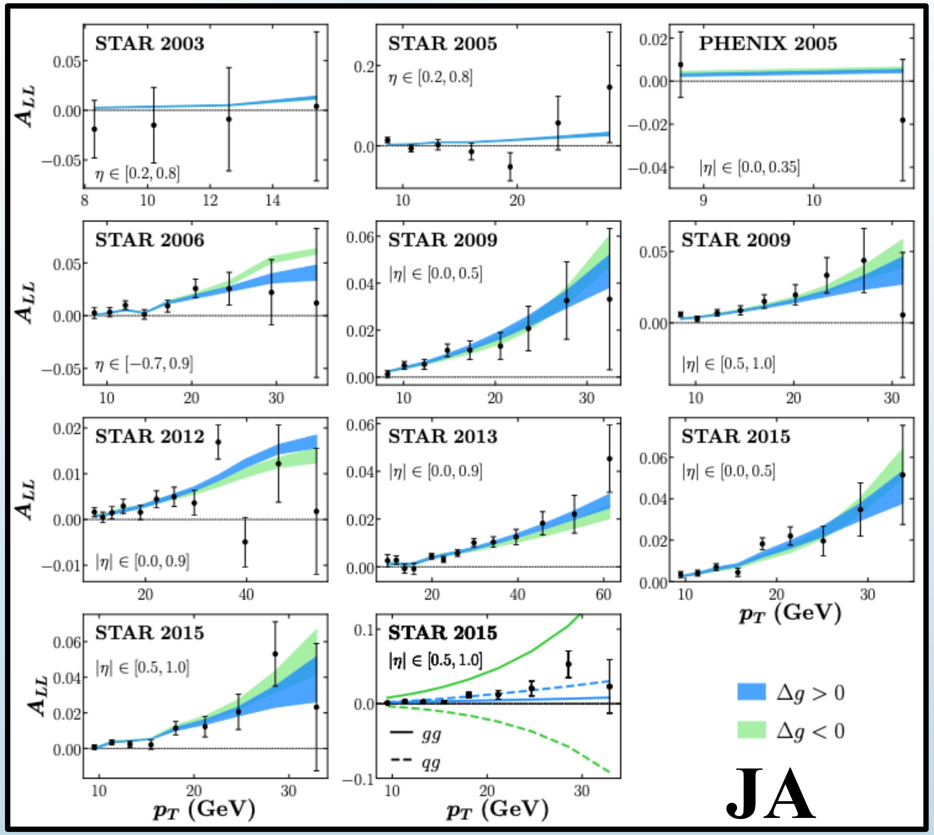

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→ Nobuo Sato, “Progress in the exploration of nucleon’s spin structures”, PDF: Wednesday 2:30 PM

Lattice in Global Analyses (2021-The future!)

Confronting lattice parton distributions with global QCD analysis

J. Bringewatt, N. Sato, W. Melnitchouk, Jian-Wei Qiu, F. Steffens, M. Constantinou

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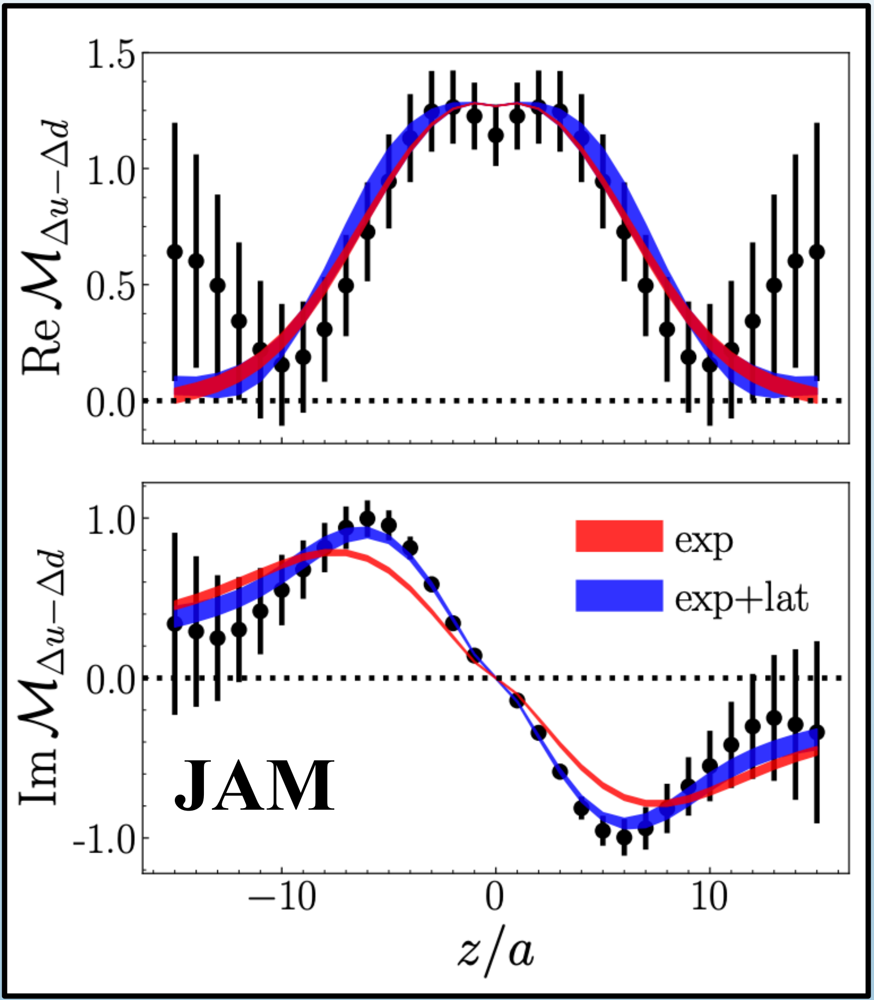

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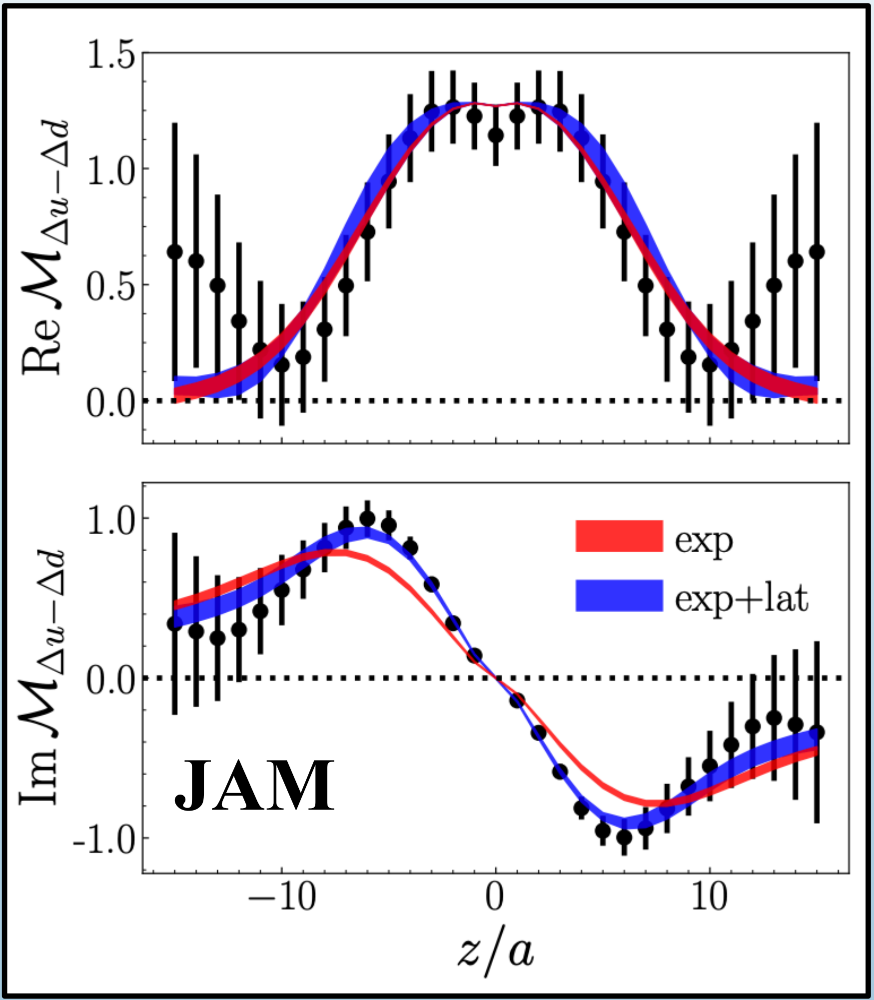

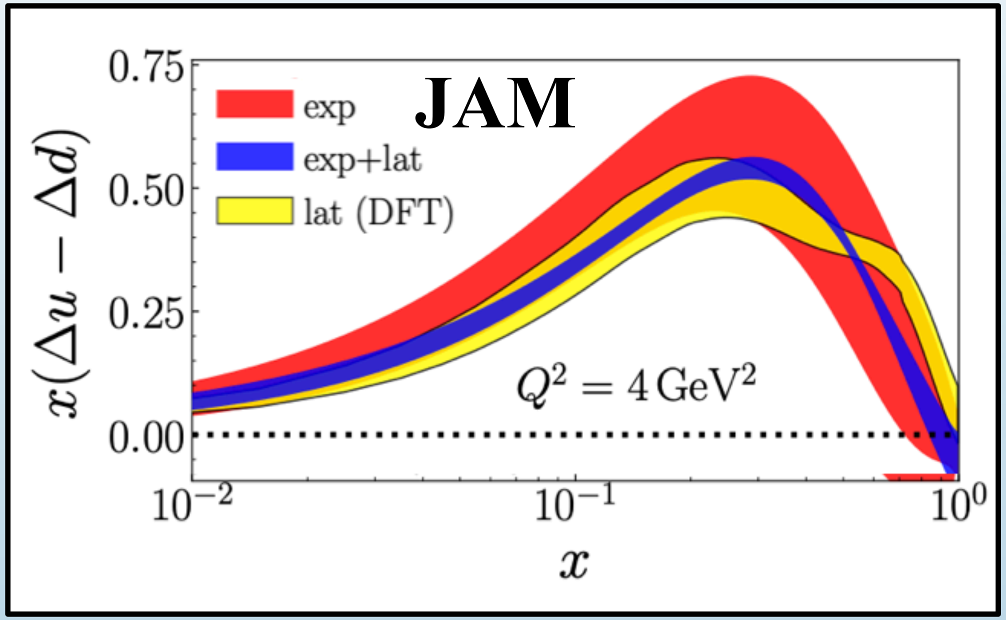

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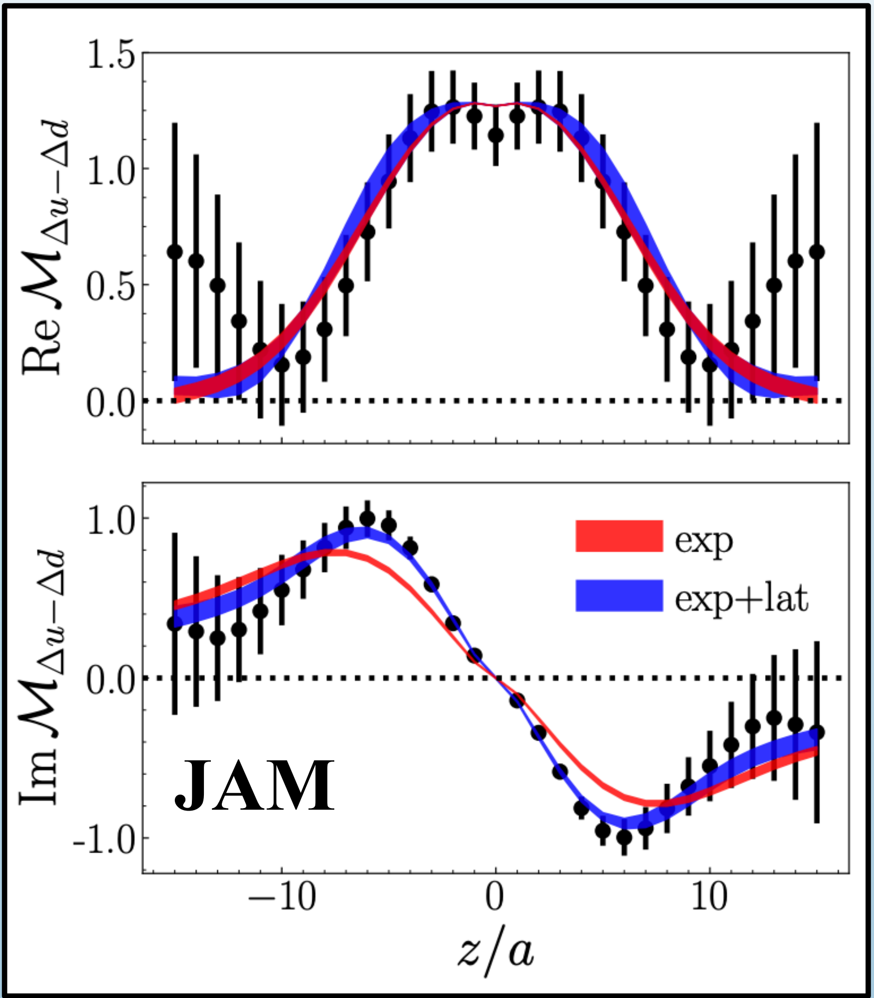
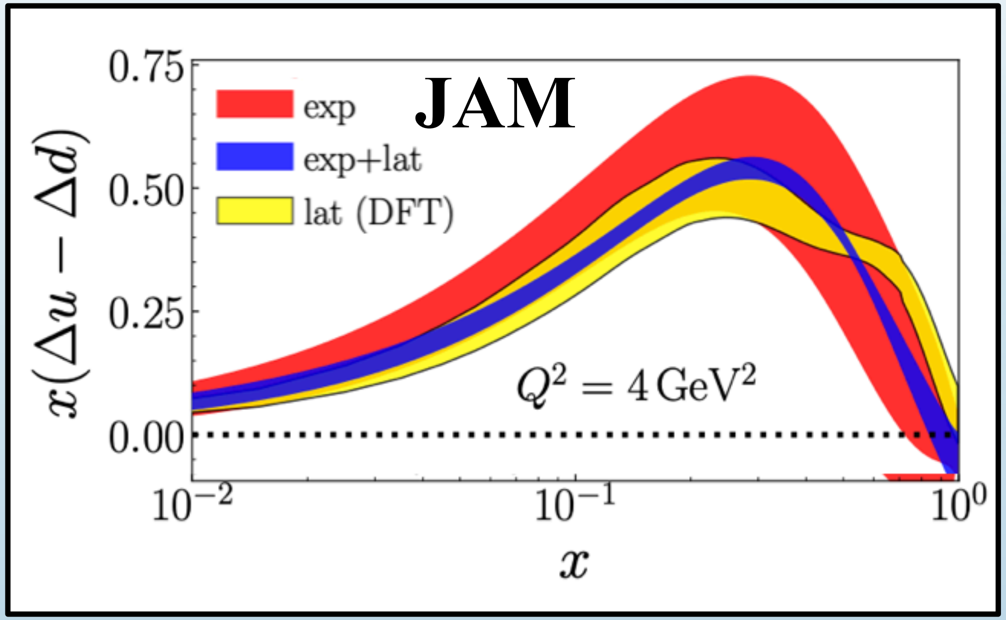
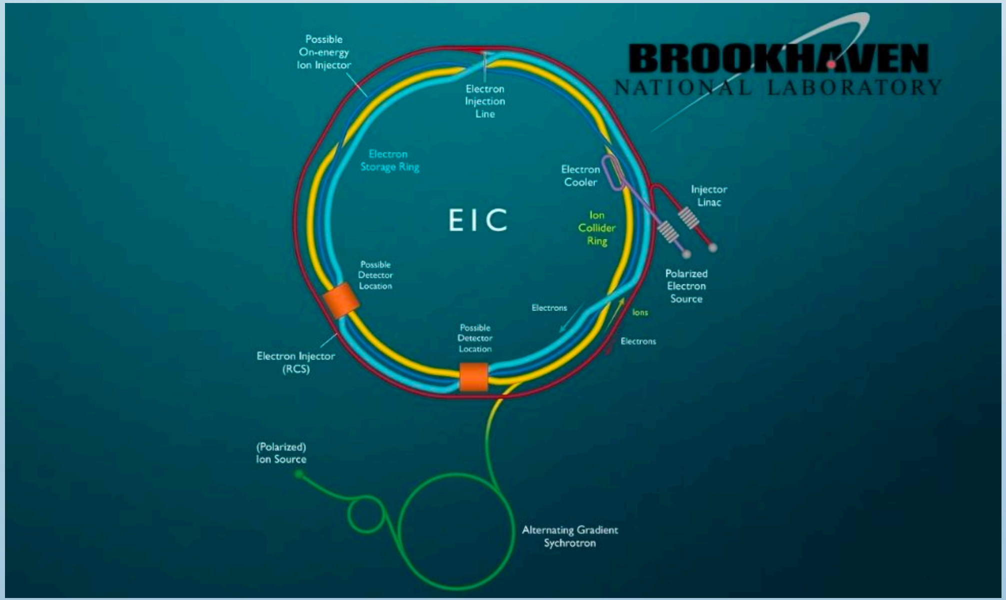
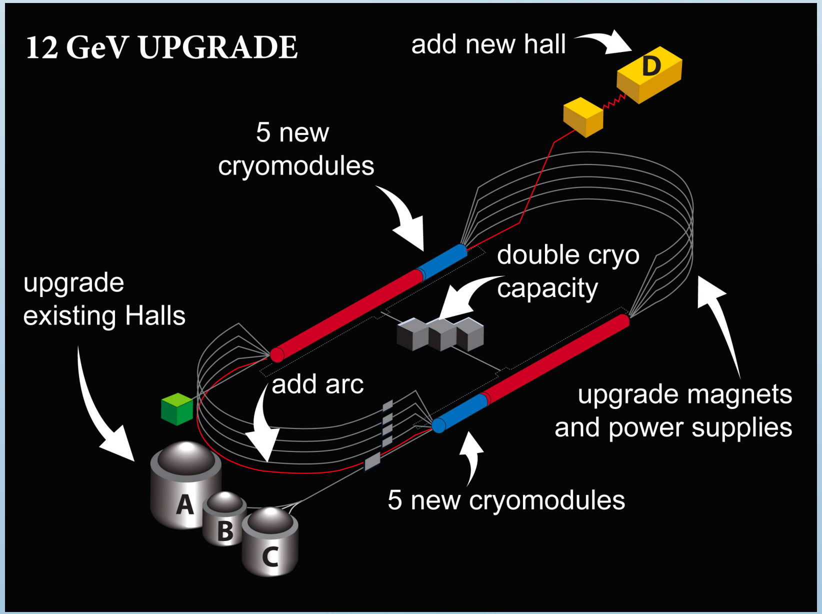




Combining experiment and lattice in a global QCD analysis is feasible!

Summary and Outlook



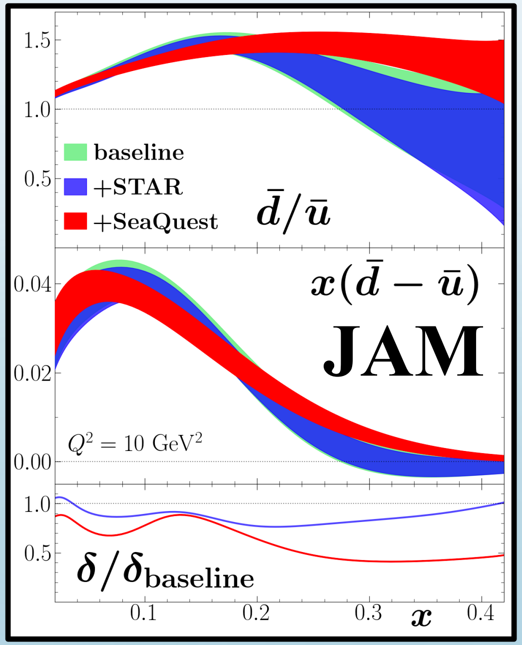


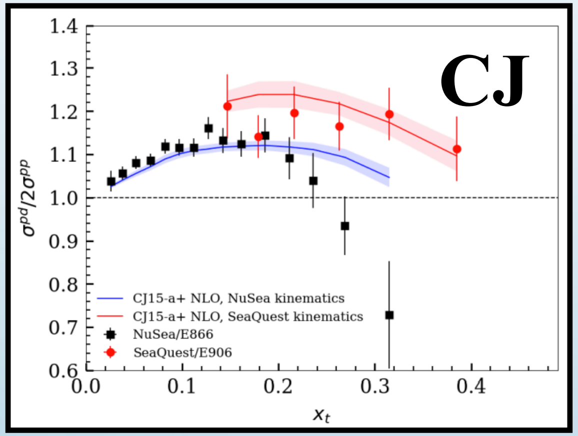
Summary

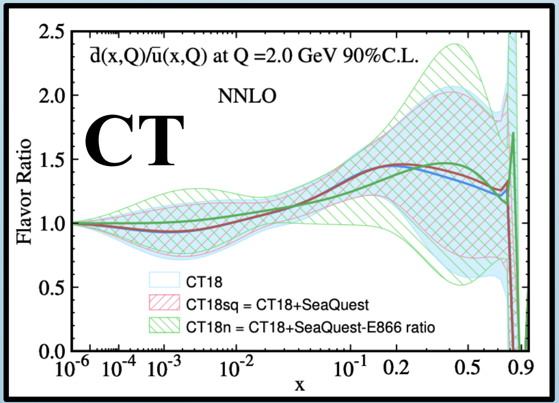
Bayesian Monte Carlo extraction of sea asymmetry with SeaQuest and STAR data

NNLO constraints on proton PDFs from the SeaQuest and STAR experiments and other developments in the CTEQ-TEA global analysis

CJ15 global PDF analysis with new electroweak data from the STAR and SeaQuest experiments







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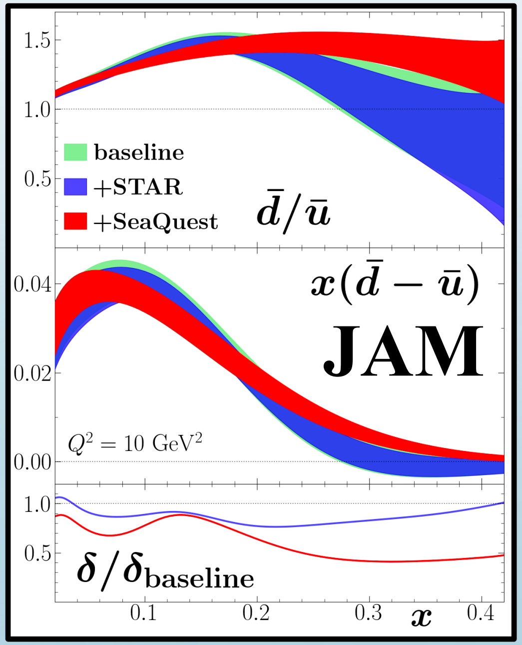
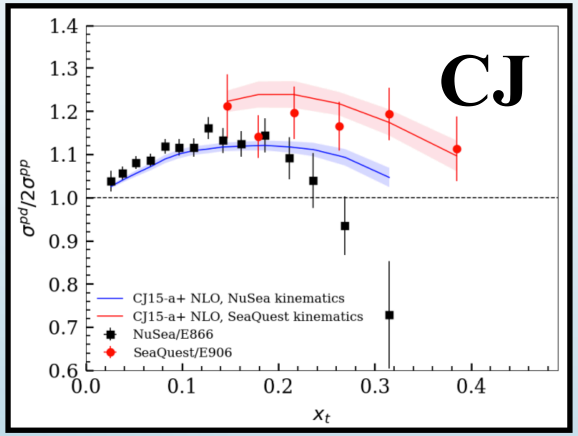
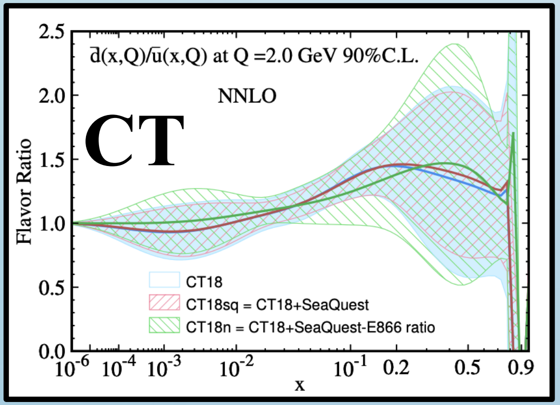


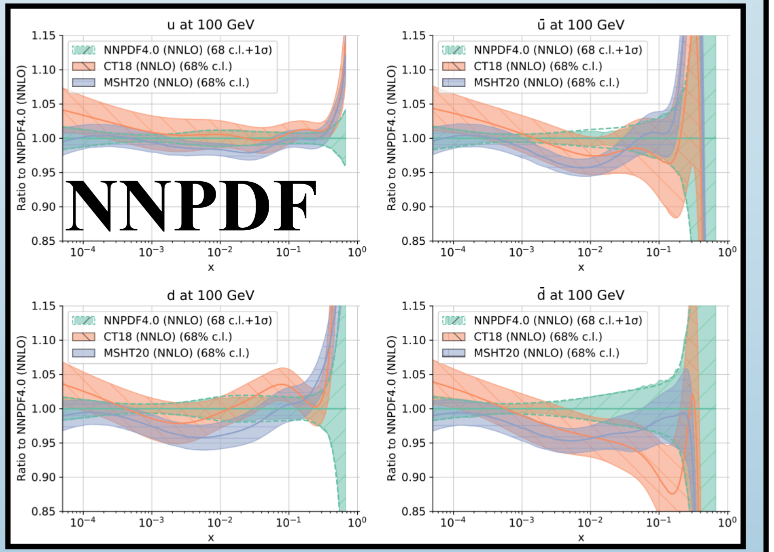


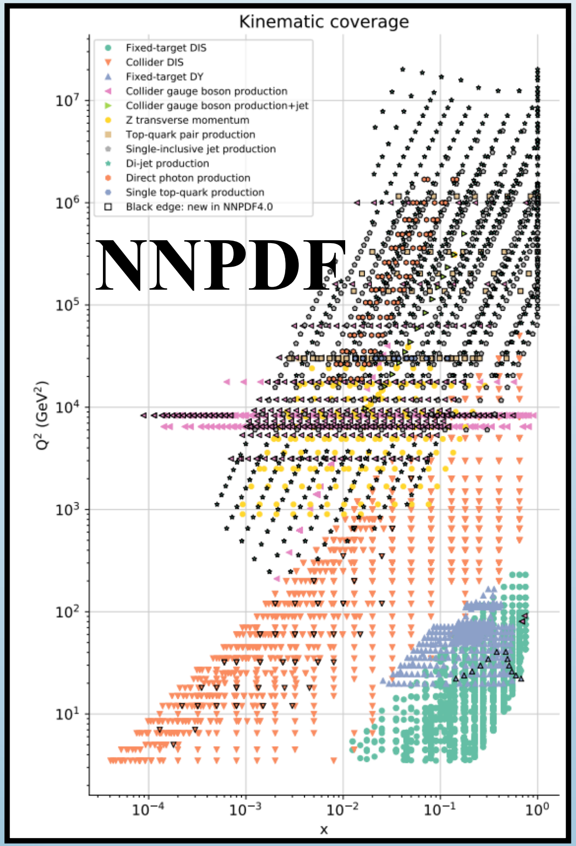


The Path to Proton Structure at One-Percent Accuracy

New CTEQ global analysis of quantum chromodynamics with high-precision data from the LHC

Parton distributions from LHC, HERA, Tevatron and fixed target data: MSHT20 PDFs



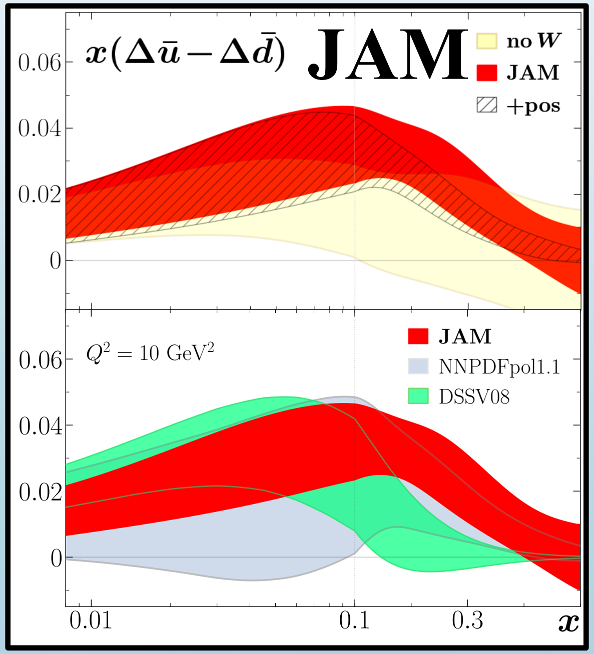


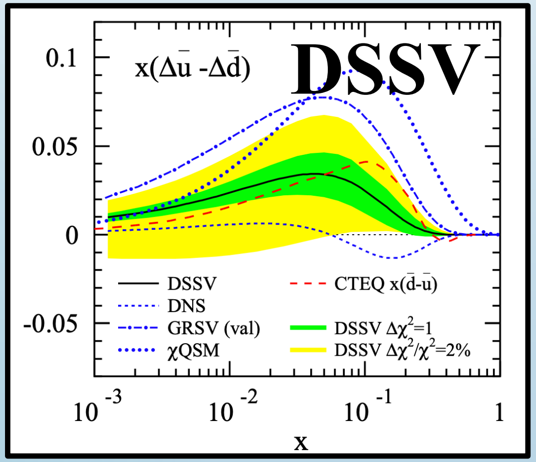
Summary

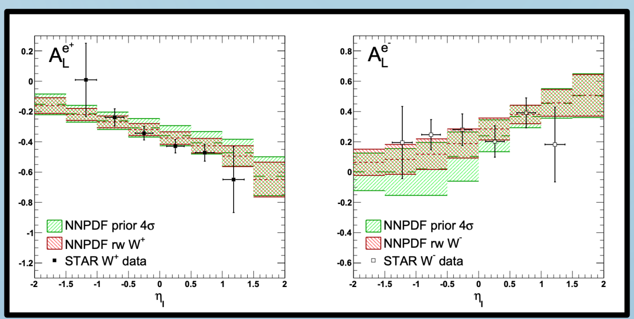
Extraction of Spin–Dependent Parton Densities and Their Uncertainties

A first unbiased global determination of polarized PDFs and their uncertainties

Polarized Antimatter in the Proton from Global QCD Analysis







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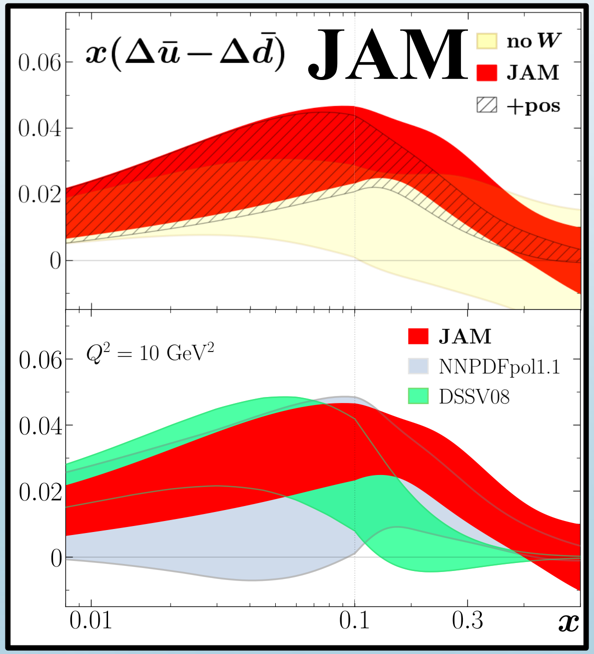

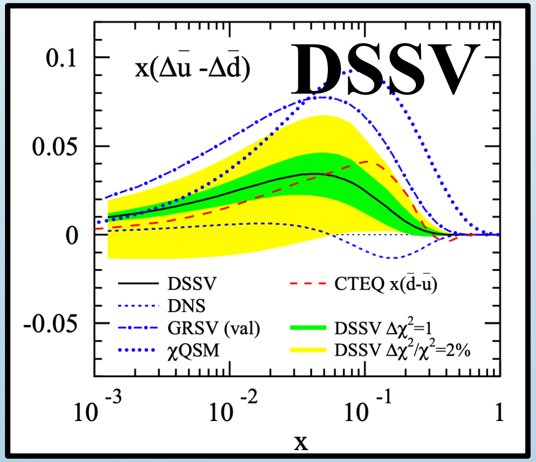

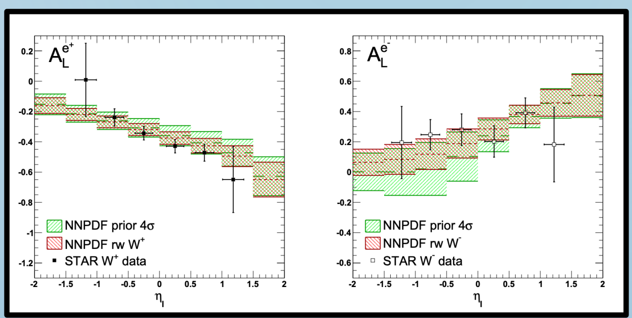

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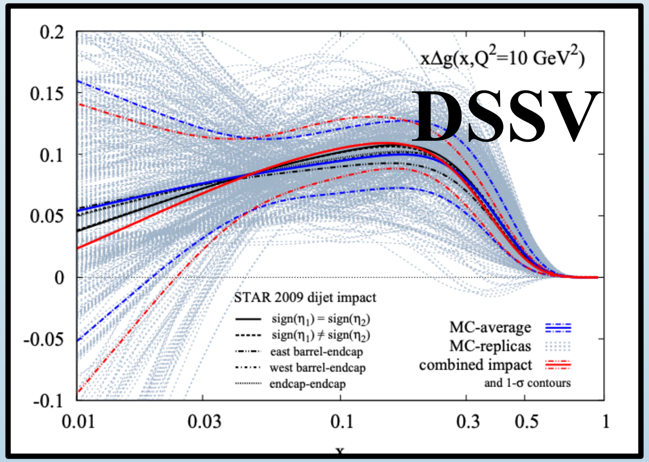
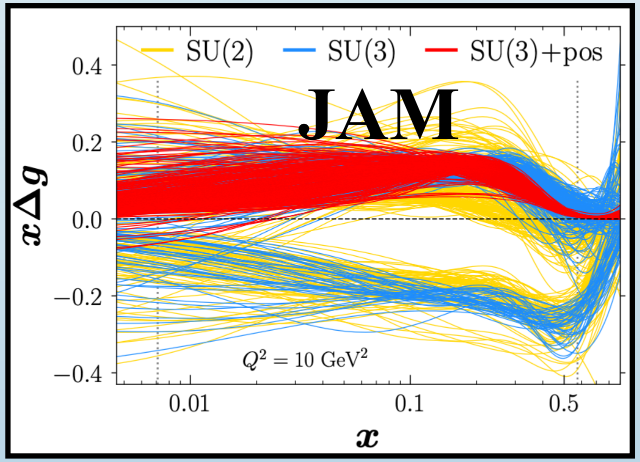
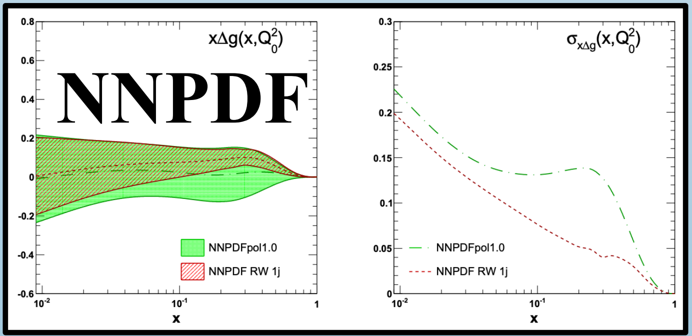




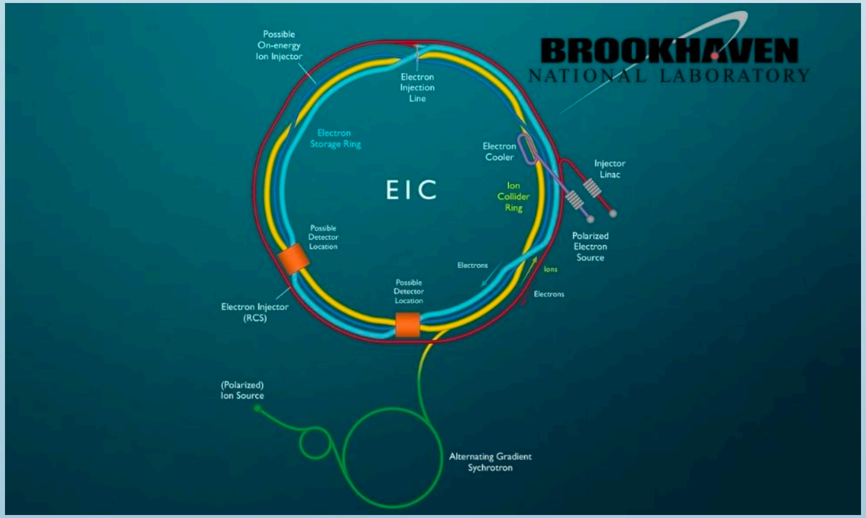


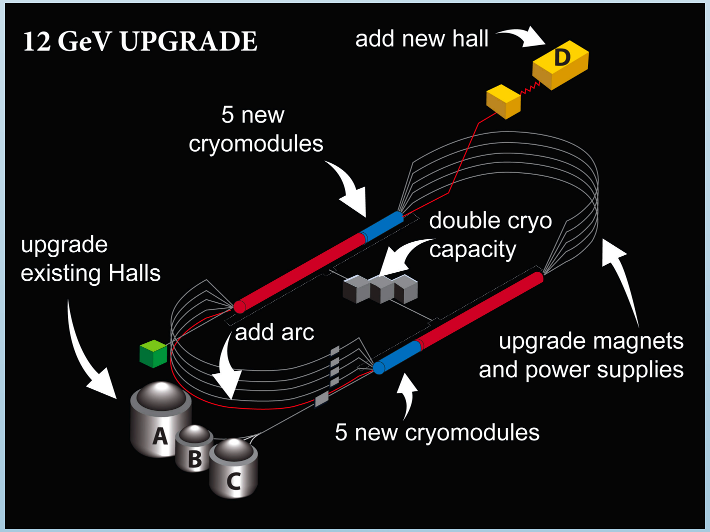
Outlook

Jefferson Lab 12 GeV will provide new information on helicity PDFs and nuclear effects at high *x*

EIC will provide new information on helicity PDFs at low *x*

Continued input from lattice QCD





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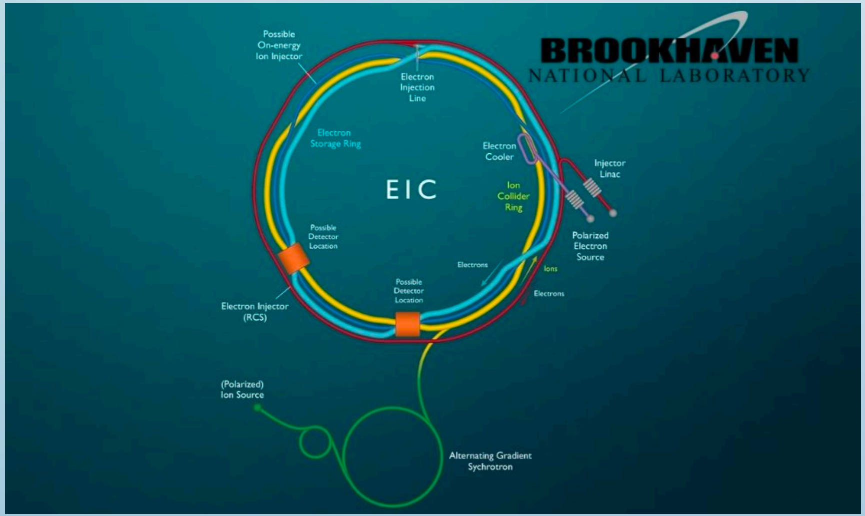
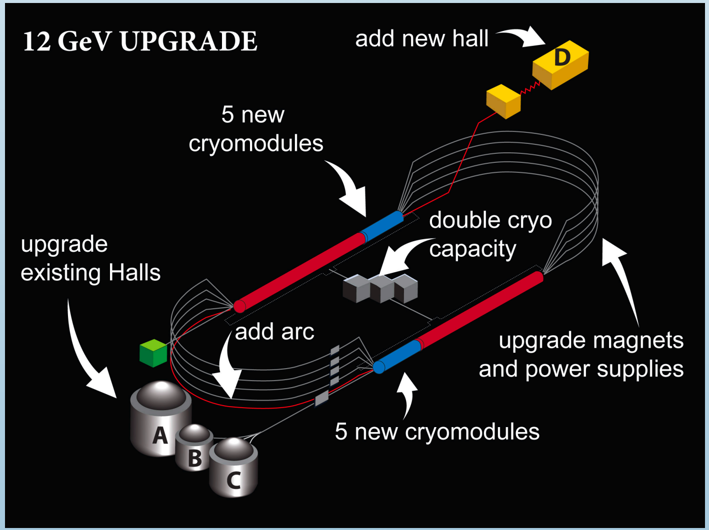




→ Timothy Hobbs, “PDFs from EIC, lattice, and the LHC”, HE: Tuesday 2:00 PM

Collaboration

Andreas Metz

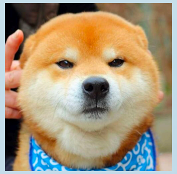
Wally Melnitchouk

Nobuo Sato

JAM Jefferson Lab Angular Momentum Collaboration

www.jlab.org/theory/jam

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

Extra

JAM Collaboration

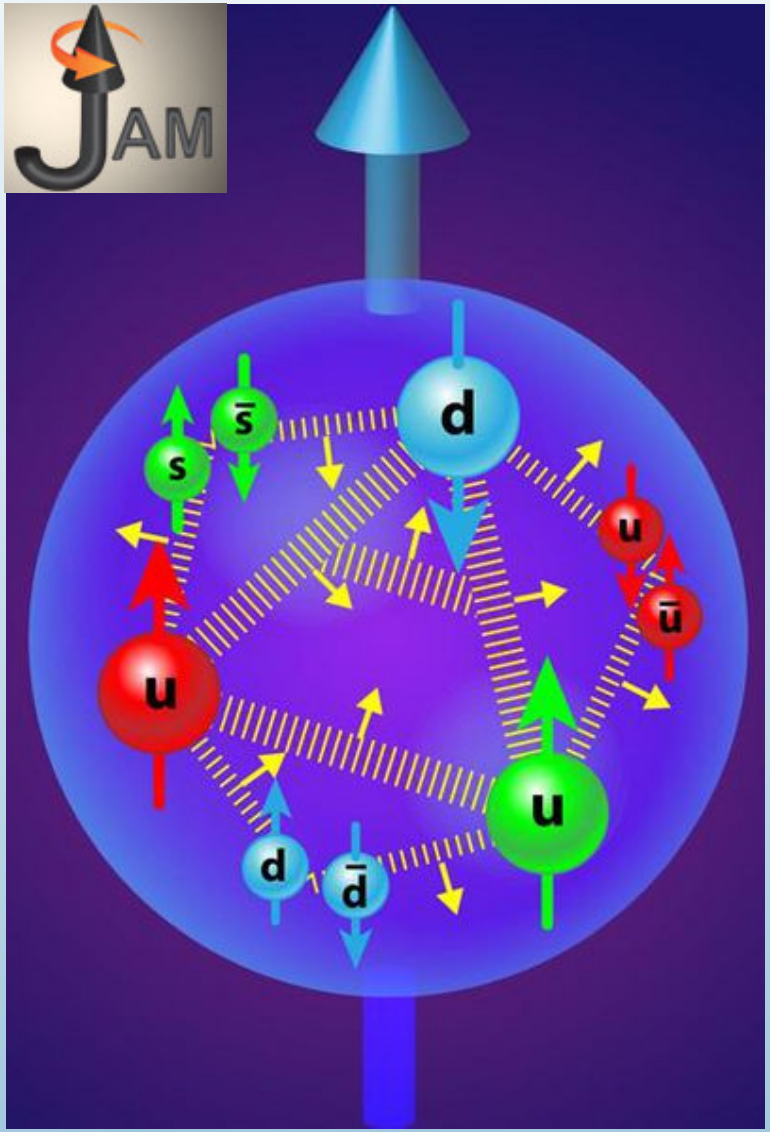
3-dimensional structure of nucleons:

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

Collinear factorization in perturbative QCD

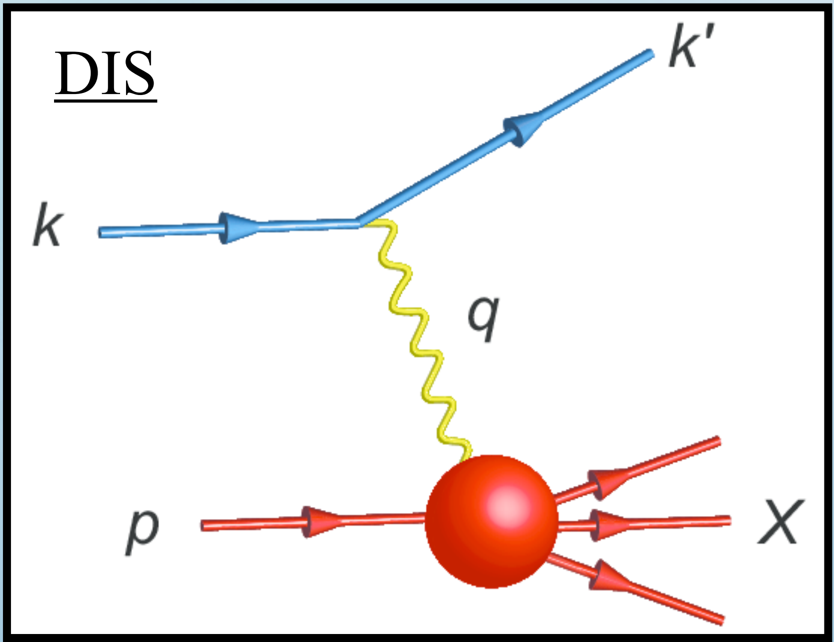
Simultaneous determinations of PDFs, FFs, etc.

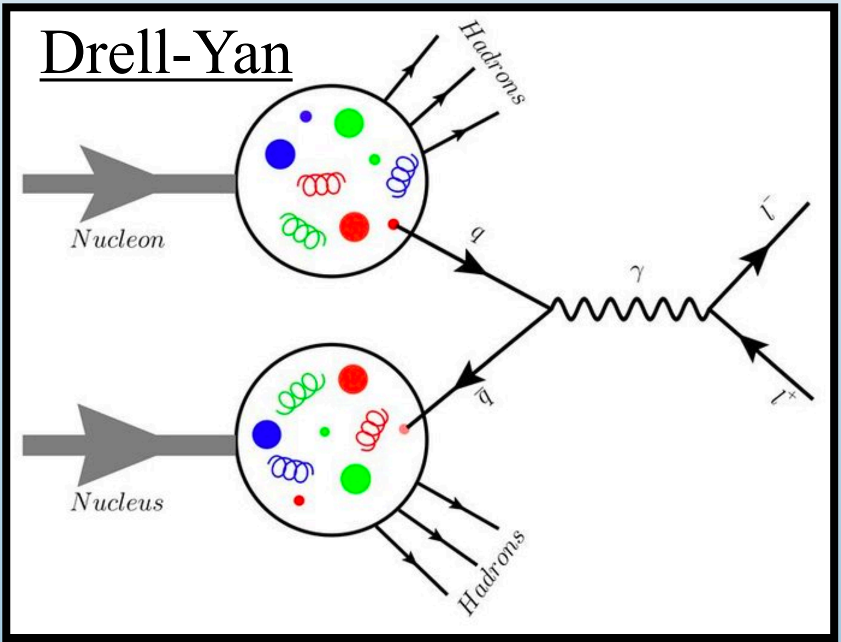
Monte Carlo methods for Bayesian inference

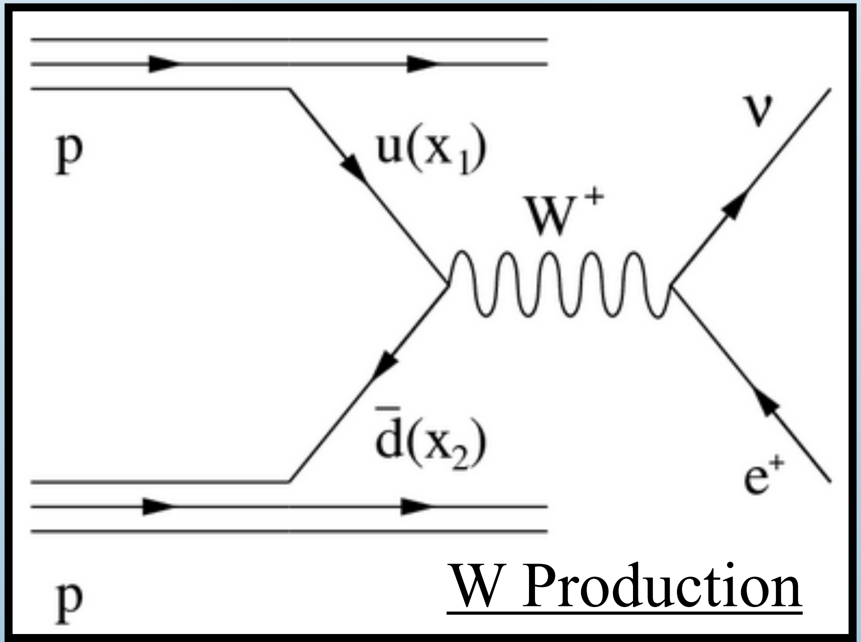


A Global Analysis

Simultaneous extractions of
spin-averaged PDFs, helicity PDFs, and FFs







Database

Spin-Averaged PDFs

DIS	BCDMS, NMC, SLAC, HERA, JLab	3863
Drell-Yan	Fermilab E866, E906	205
W/Z Boson	CDF/D0, STAR, LHCb, CMS	153
Jets	CDF/D0, STAR	198

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Helicity PDFs

Polarized DIS	COMPASS, EMC, HERMES, SLAC, SMC	365
Polarized W/Z Boson	STAR, PHENIX	18
Polarized Jets	STAR, PHENIX	83

Database

Spin-Averaged PDFs

Helicity PDFs

π, K, h FFs + PDFs

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SIDIS	COMPASS, EMC, HERMES, SLAC, SMC	1490
Polarized SIDIS	COMPASS, HERMES, SMC	231
SIA	ARGUS, BABAR, BELLE, TASSO, TPC, TOPAZ, SLD, ALEPH, OPAL, DELPHI	564

Database

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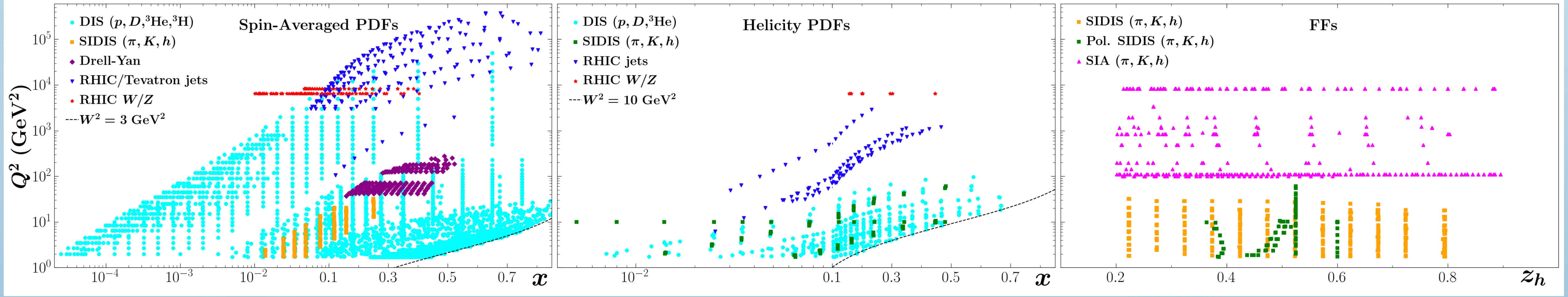
Polarized SIDIS	COMPASS, HERMES, SMC	231
SIA	ARGUS, BABAR, BELLE, TASSO, TPC, TOPAZ, SLD, ALEPH, OPAL, DELPHI	564



Parameters to Observables

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

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

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Evolve PDFs using DGLAP

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

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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…

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

The χ^2 function

Now that the observables have been calculated…

Data

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Uncorrelated Uncertainties

Correlated Uncertainties

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

Bayes' Theorem

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

Likelihood Function

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

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Likelihood Function

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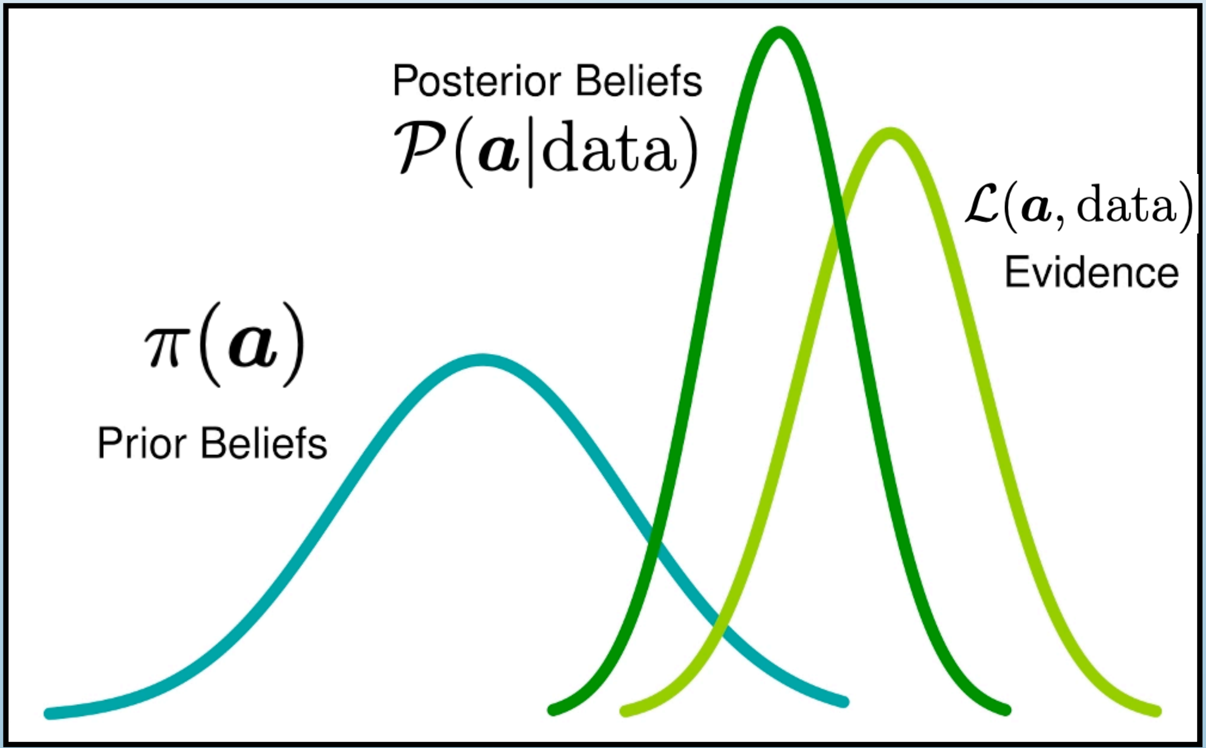
Bayes' Theorem

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



Data Resampling

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

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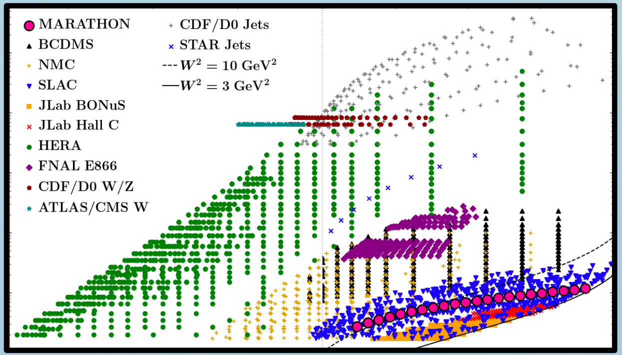
Data

Original Data



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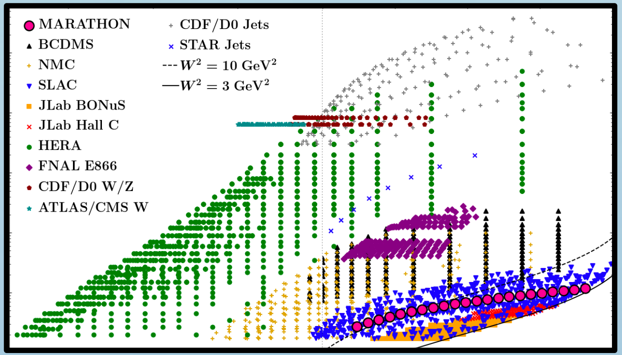

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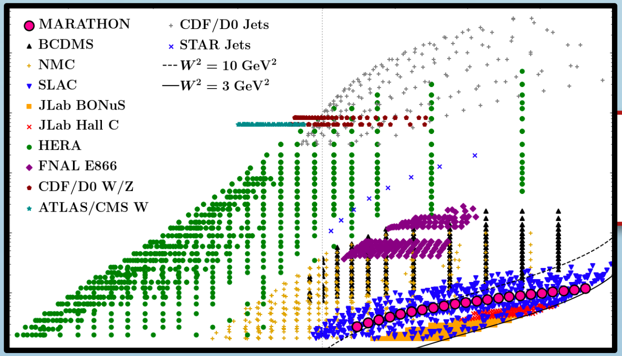
Pseudo-Data

Data

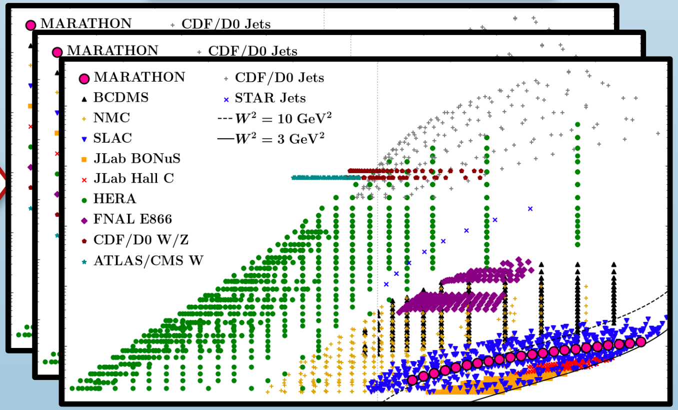
Uncorrelated Uncertainties

Original Data



DR

Replica Data



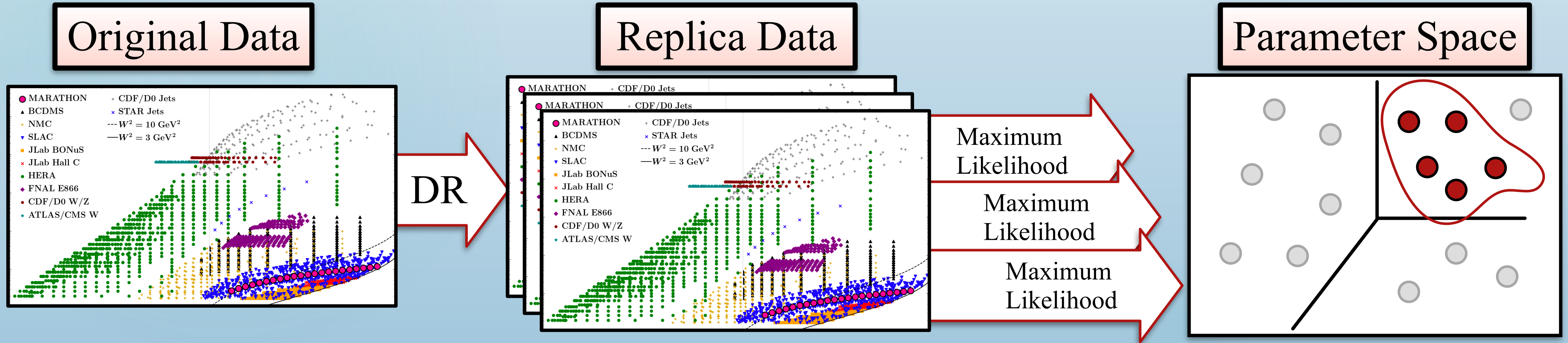
Data Resampling

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

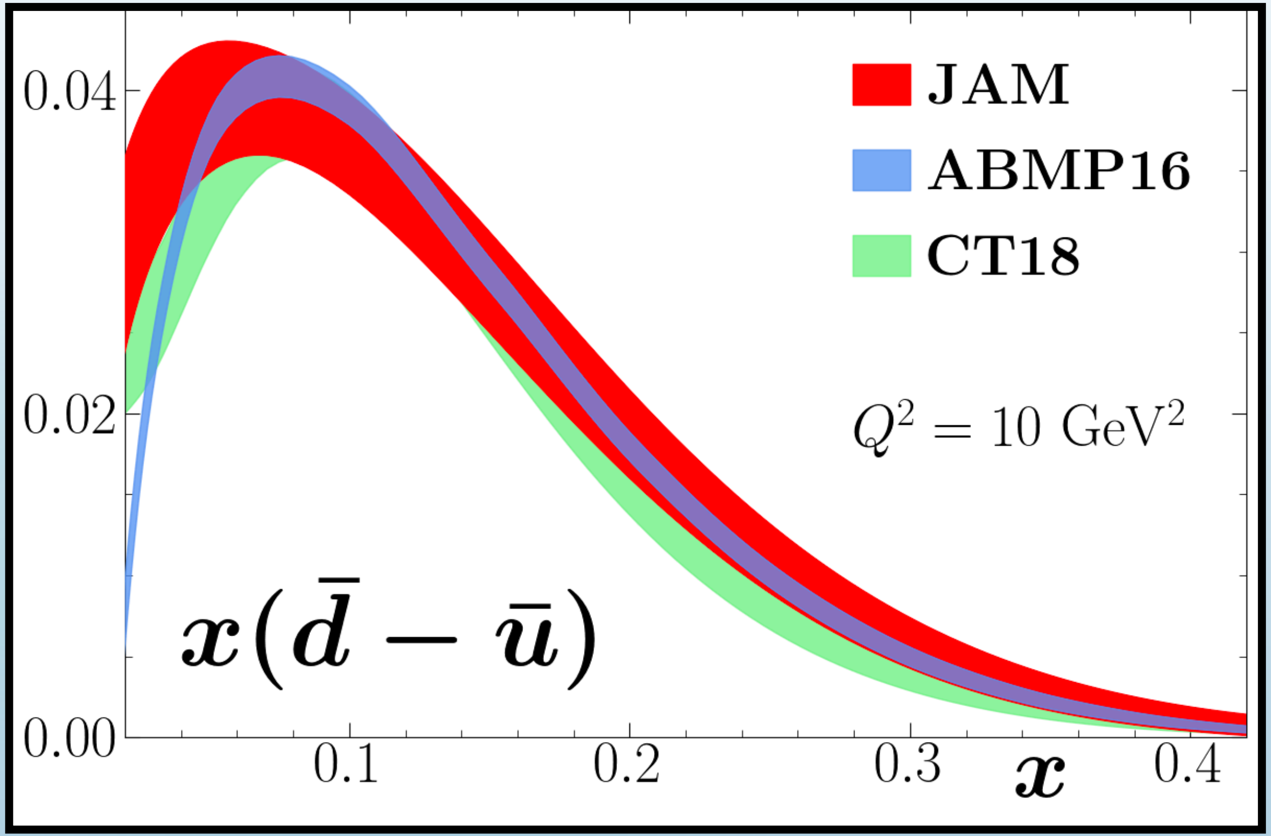
Pseudo-Data → $\tilde{\sigma}$

Data → σ

Uncorrelated Uncertainties → α

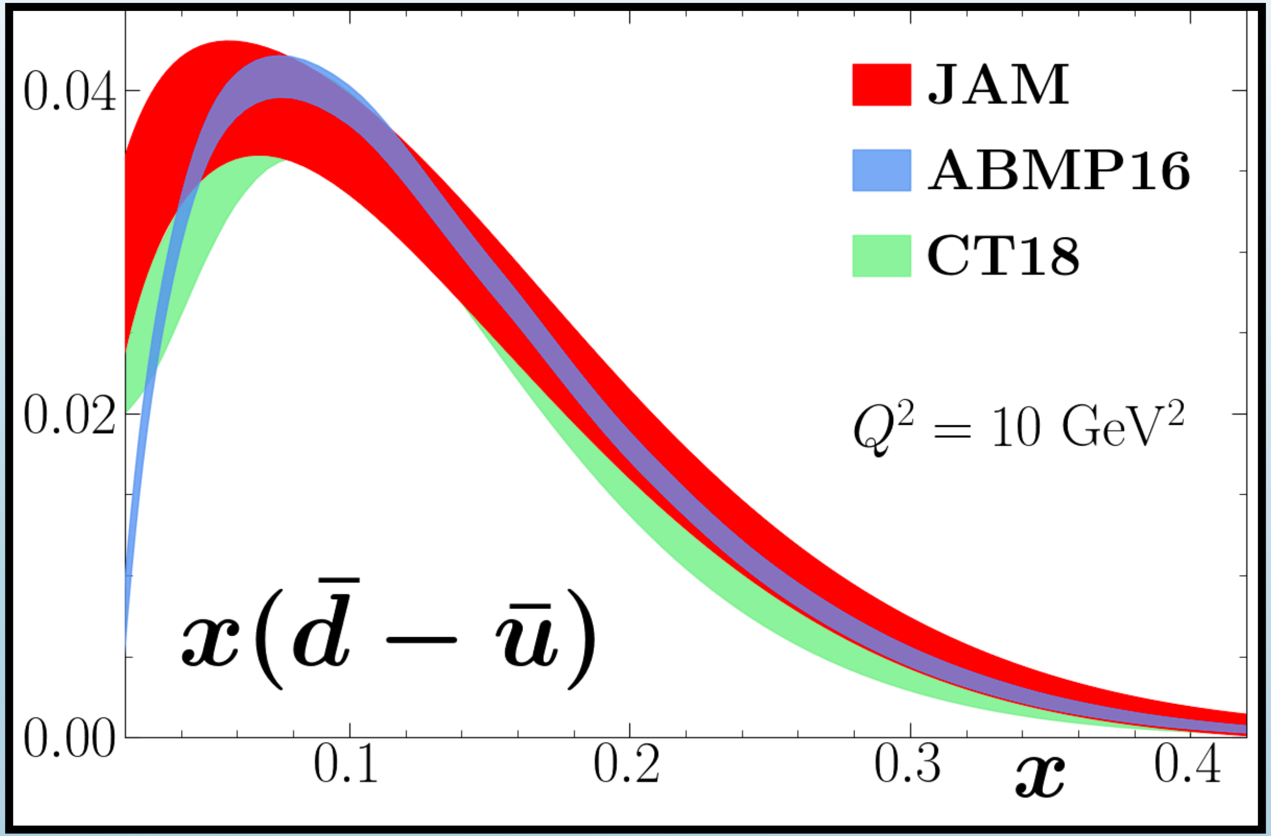


Introduction to Sea Asymmetry



Unpolarized

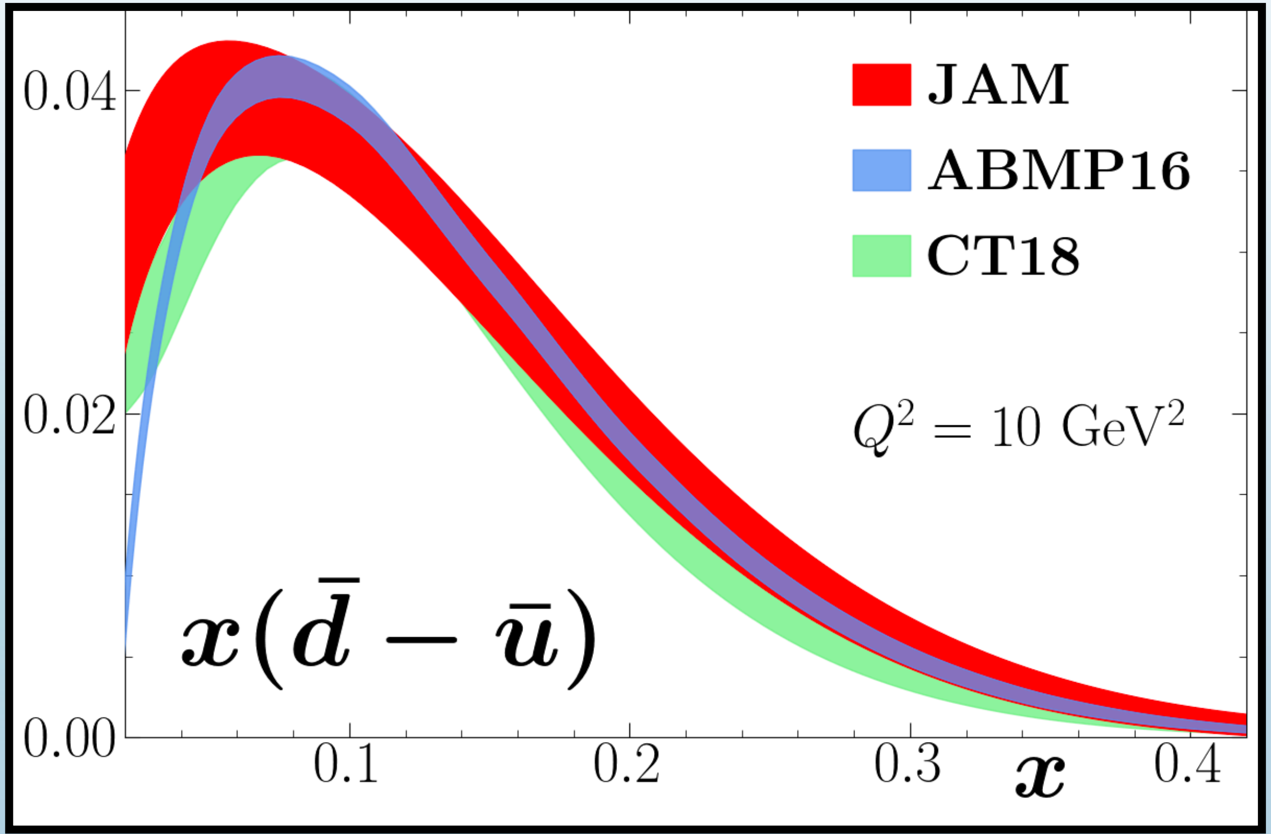
Introduction to Sea Asymmetry



Unpolarized

Cannot be explained from gluons splitting into quark-antiquark pairs

Introduction to Sea Asymmetry



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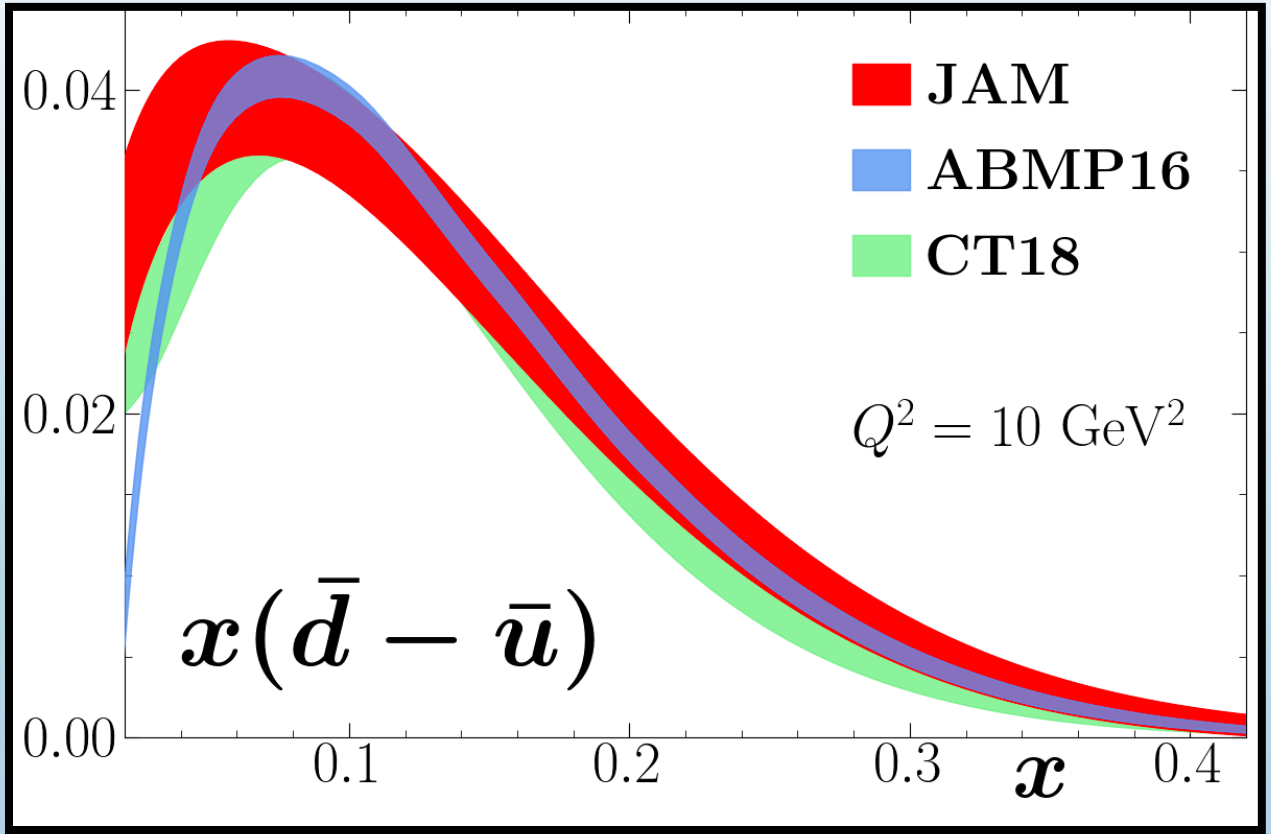
Meson Cloud Models
Chiral Soliton Models
Statistical Models

Introduction to Sea Asymmetry



Unpolarized

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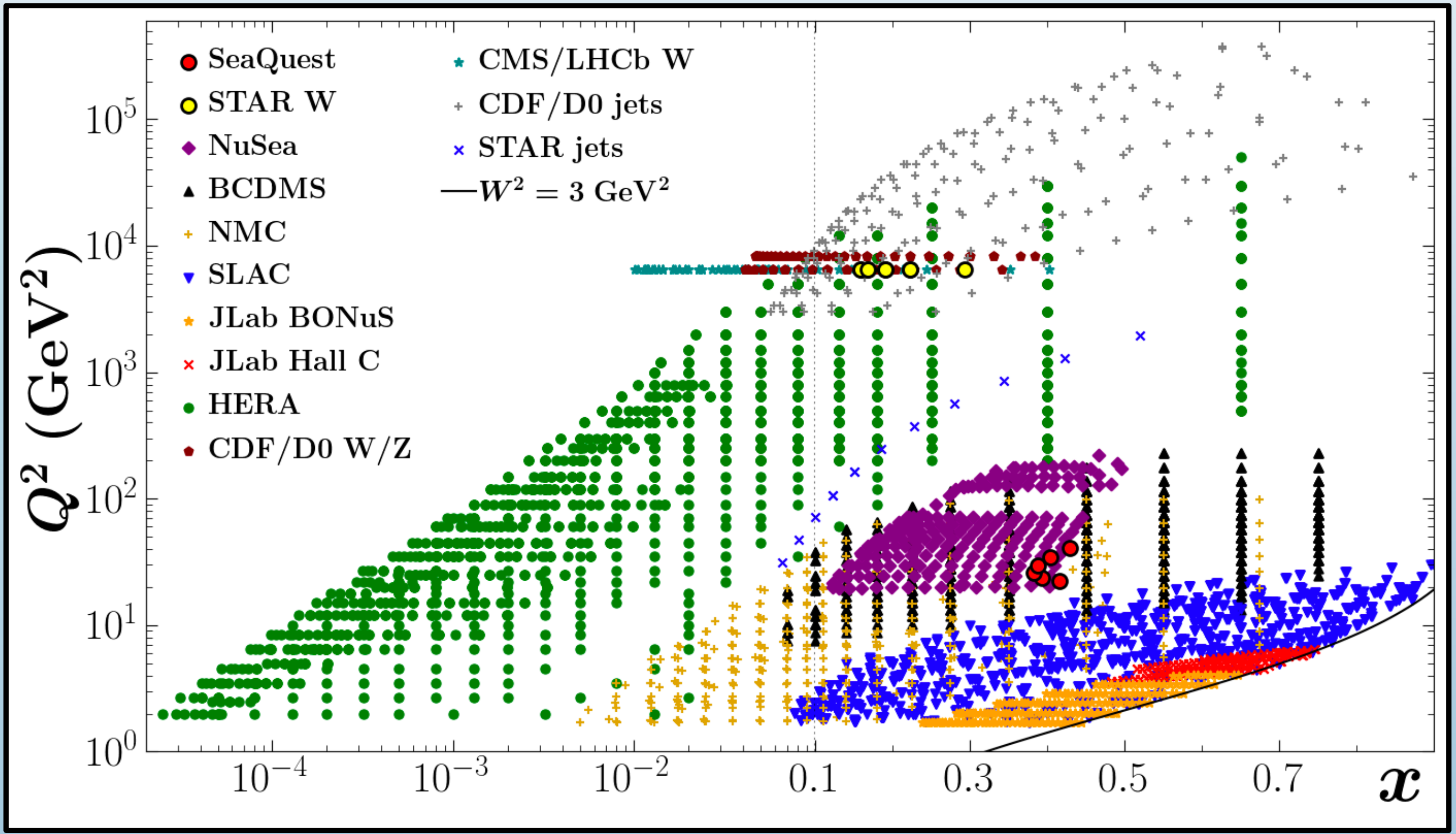
Meson Cloud Models
Chiral Soliton Models
Statistical Models

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

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



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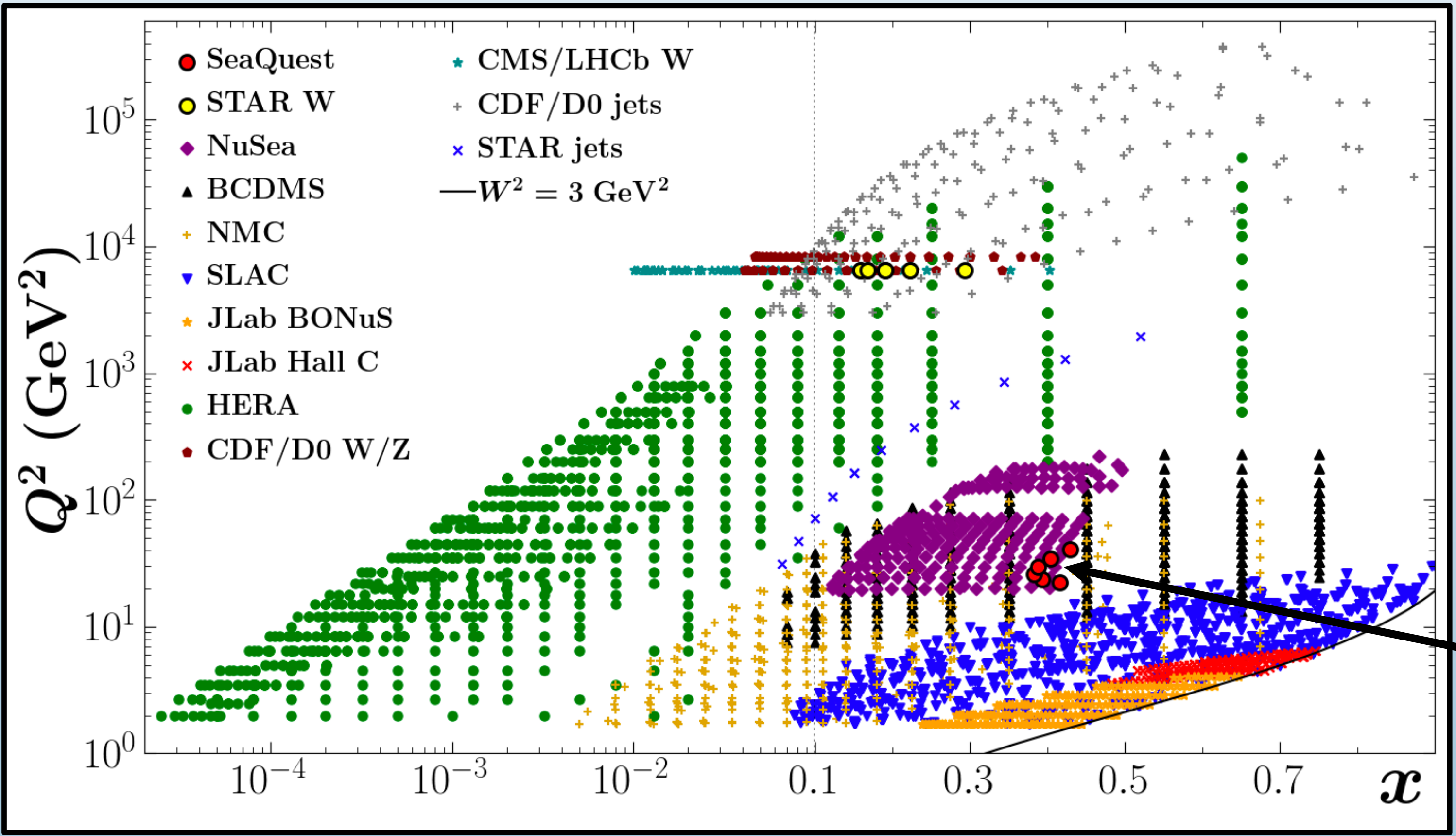

New SeaQuest data

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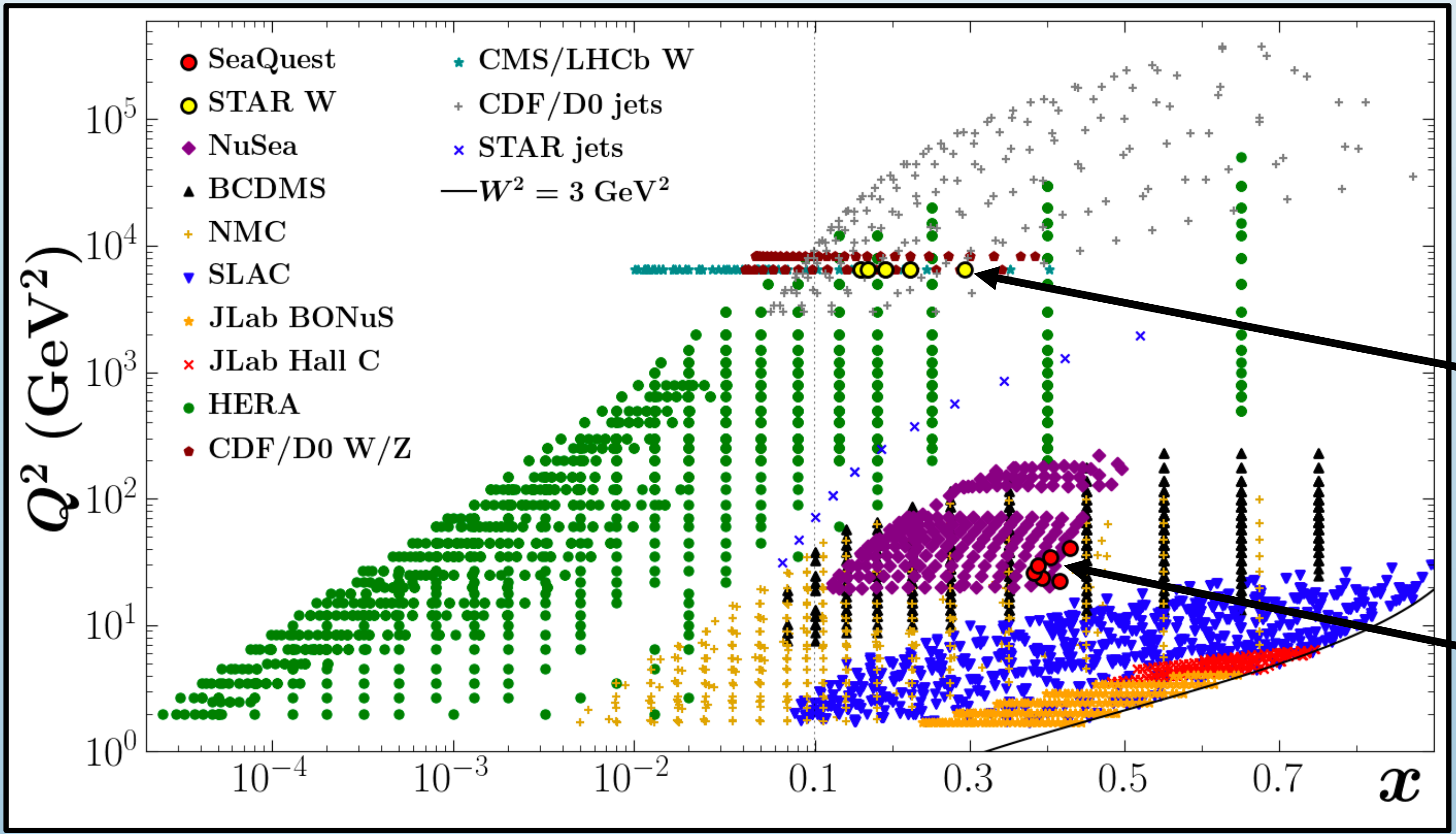
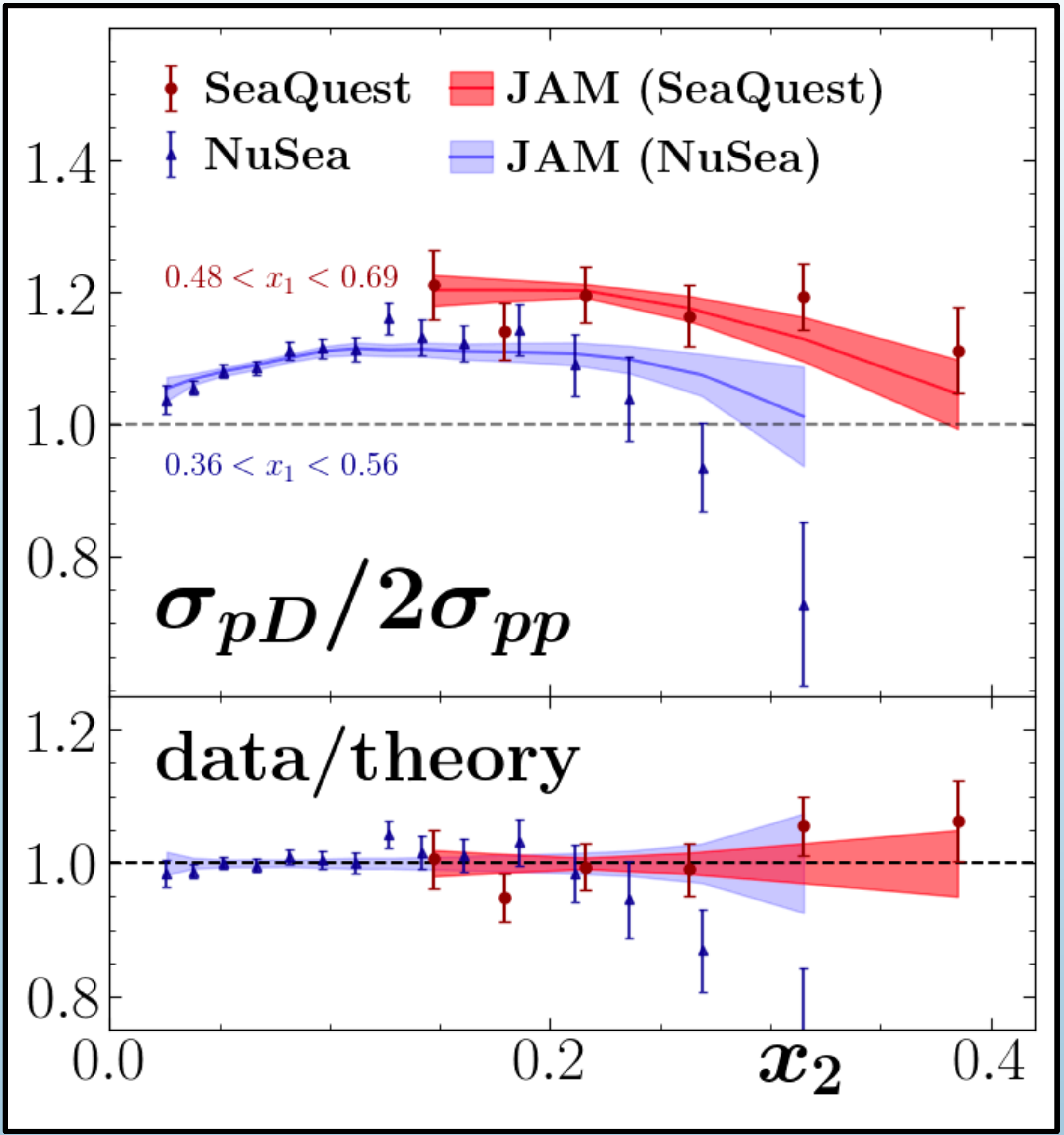


New STAR data

New SeaQuest data

SeaQuest and NuSea Quality of Fit



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

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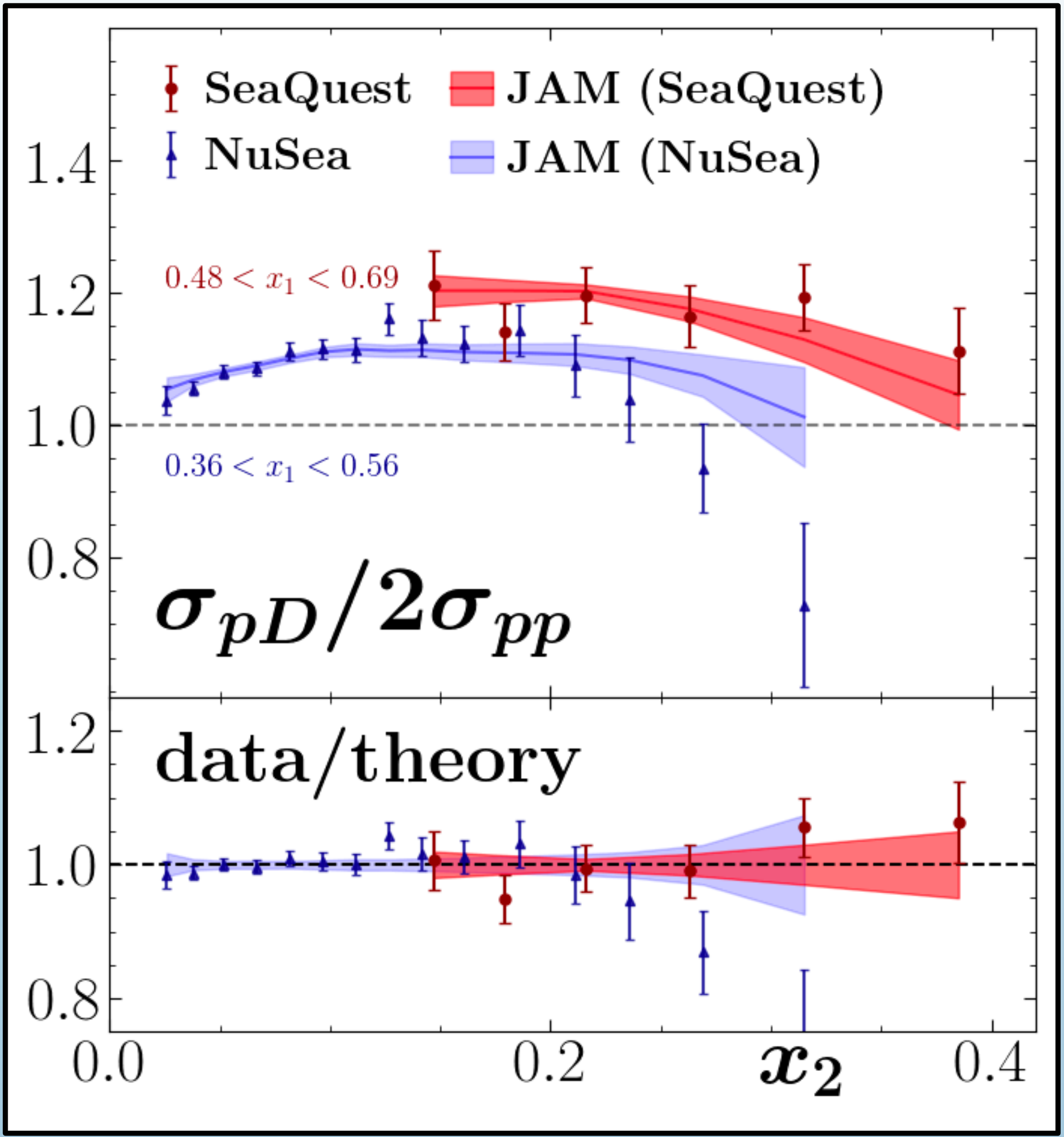

process		$N_{\rm dat}$	$\chi^2/N_{\rm dat}$
Drell-Yan			
NuSea	pp	184	1.21
NuSea	$pD/2pp$	15	1.30
SeaQuest	$pD/2pp$	6	0.82

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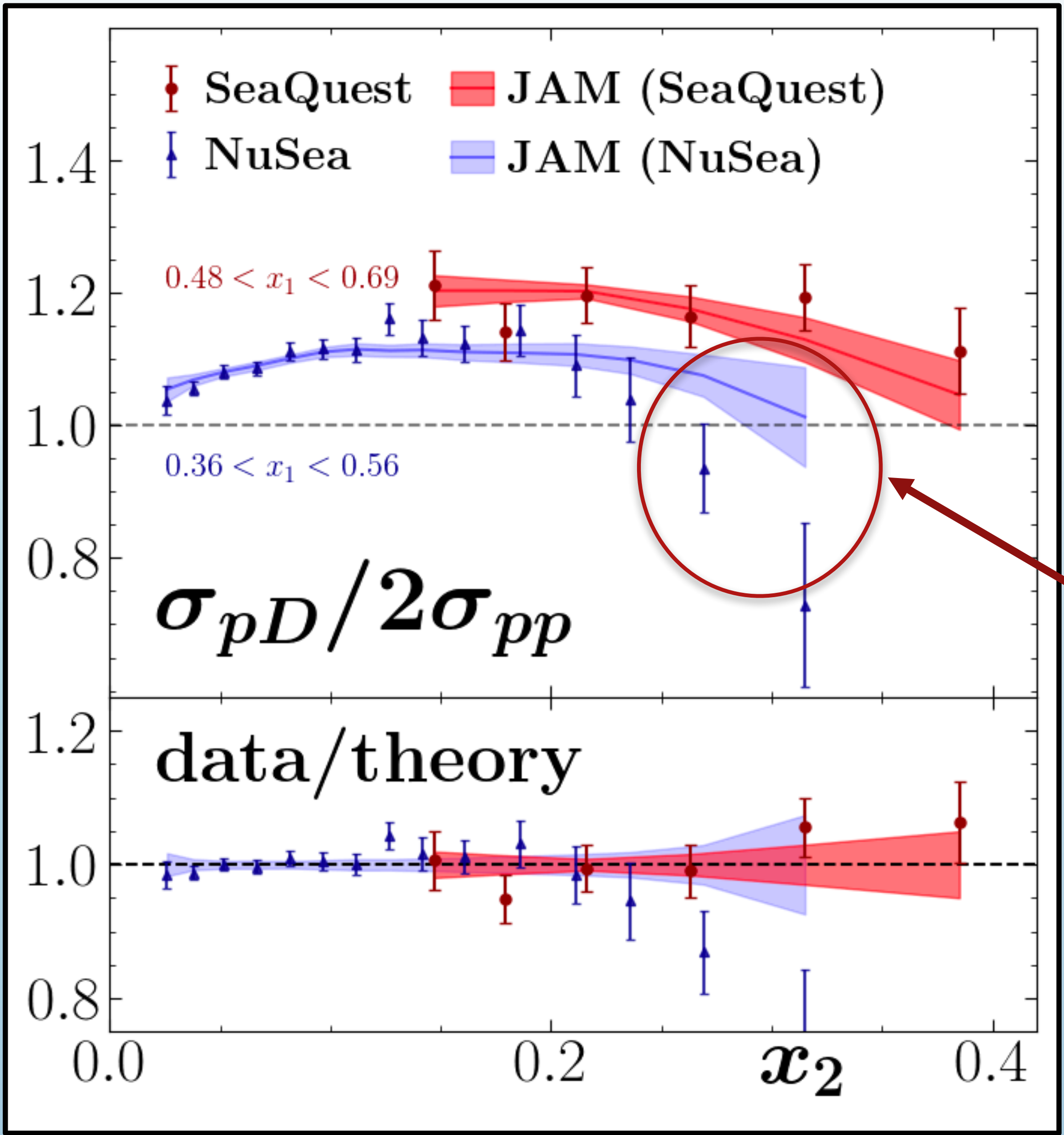

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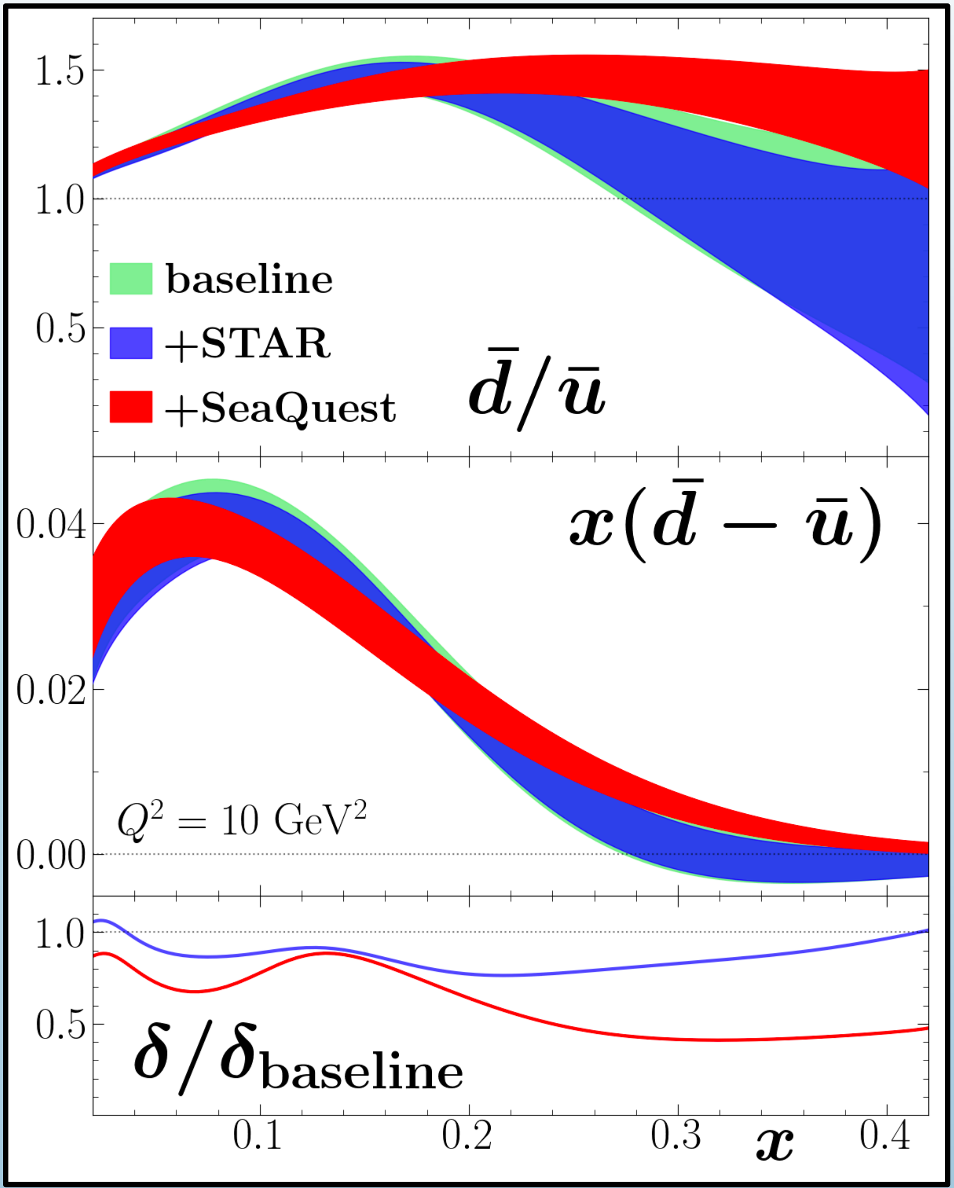
Well-known tension between NuSea and SeaQuest

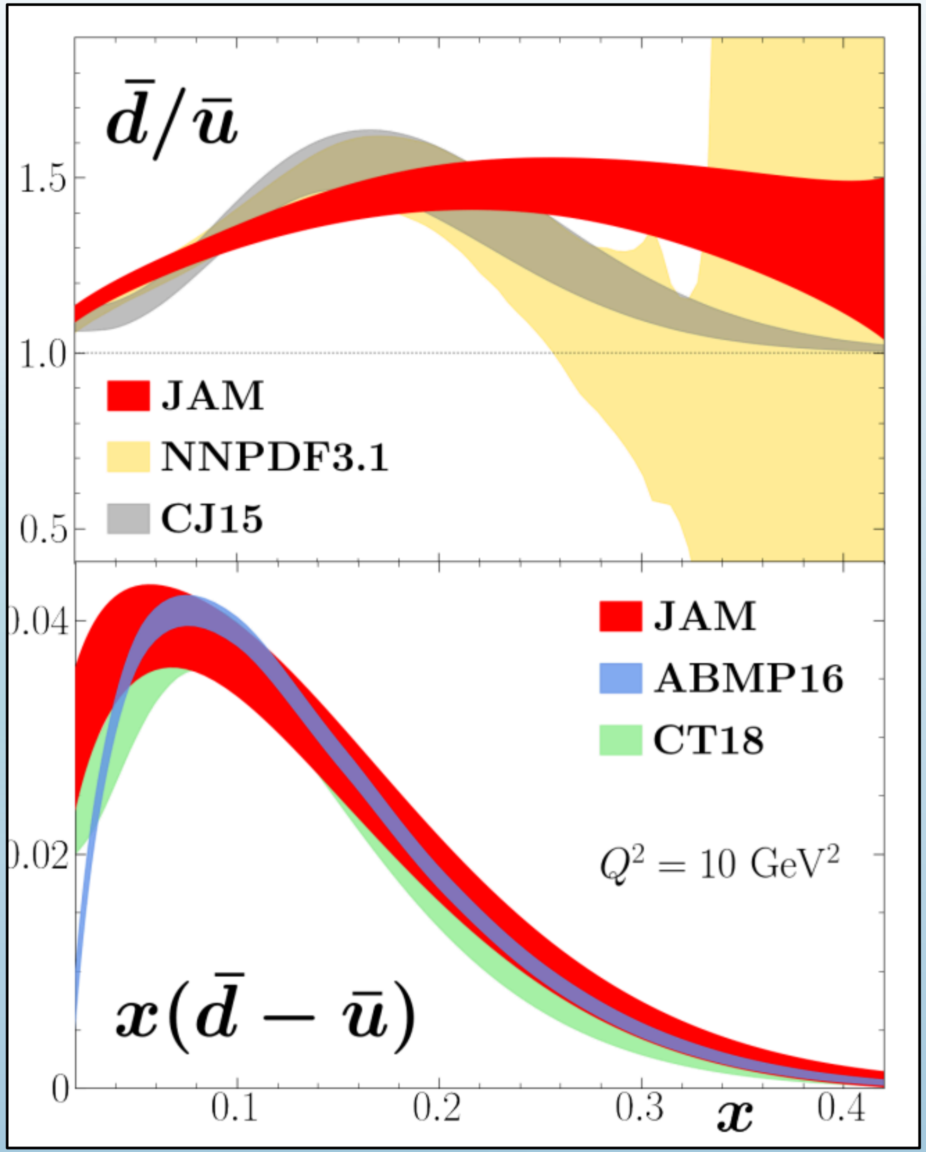
Impact from STAR and SeaQuest



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

Comparison to other fits and pion cloud model



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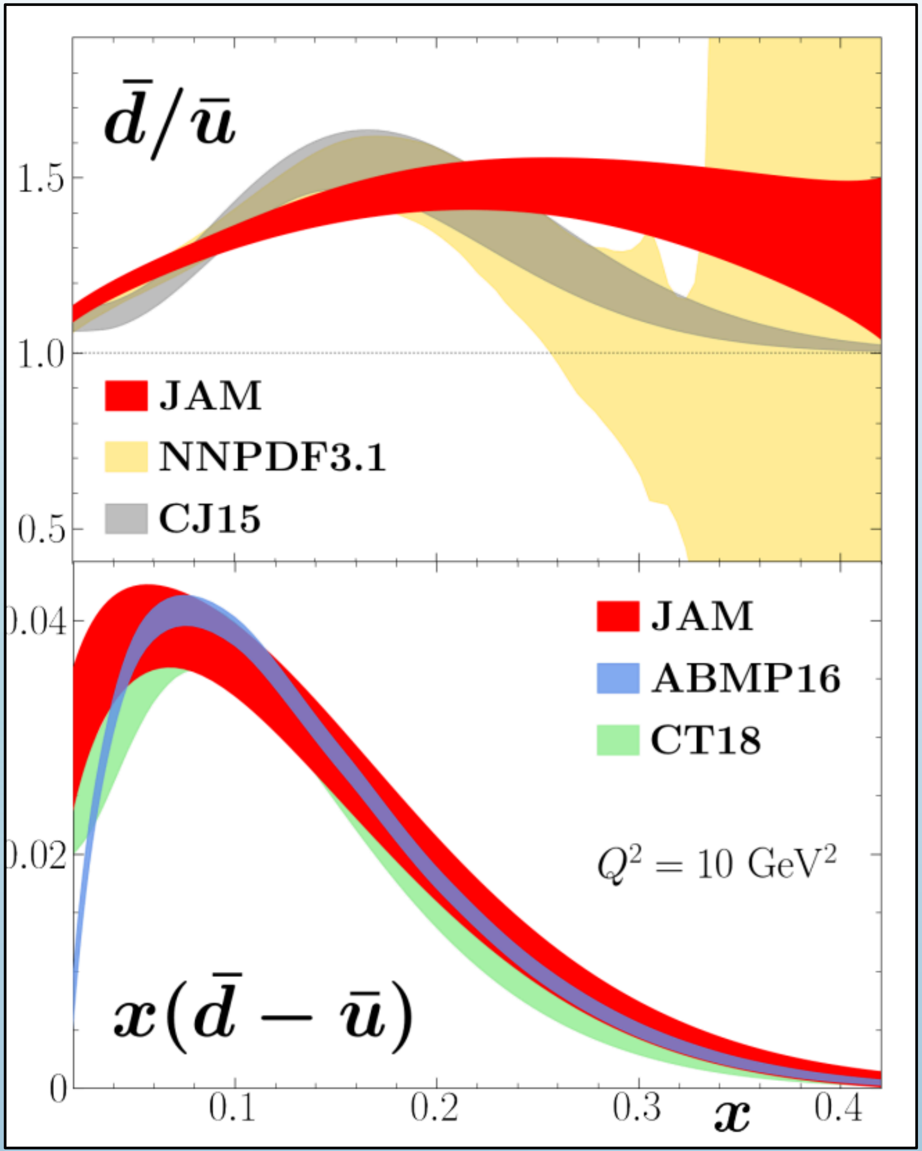
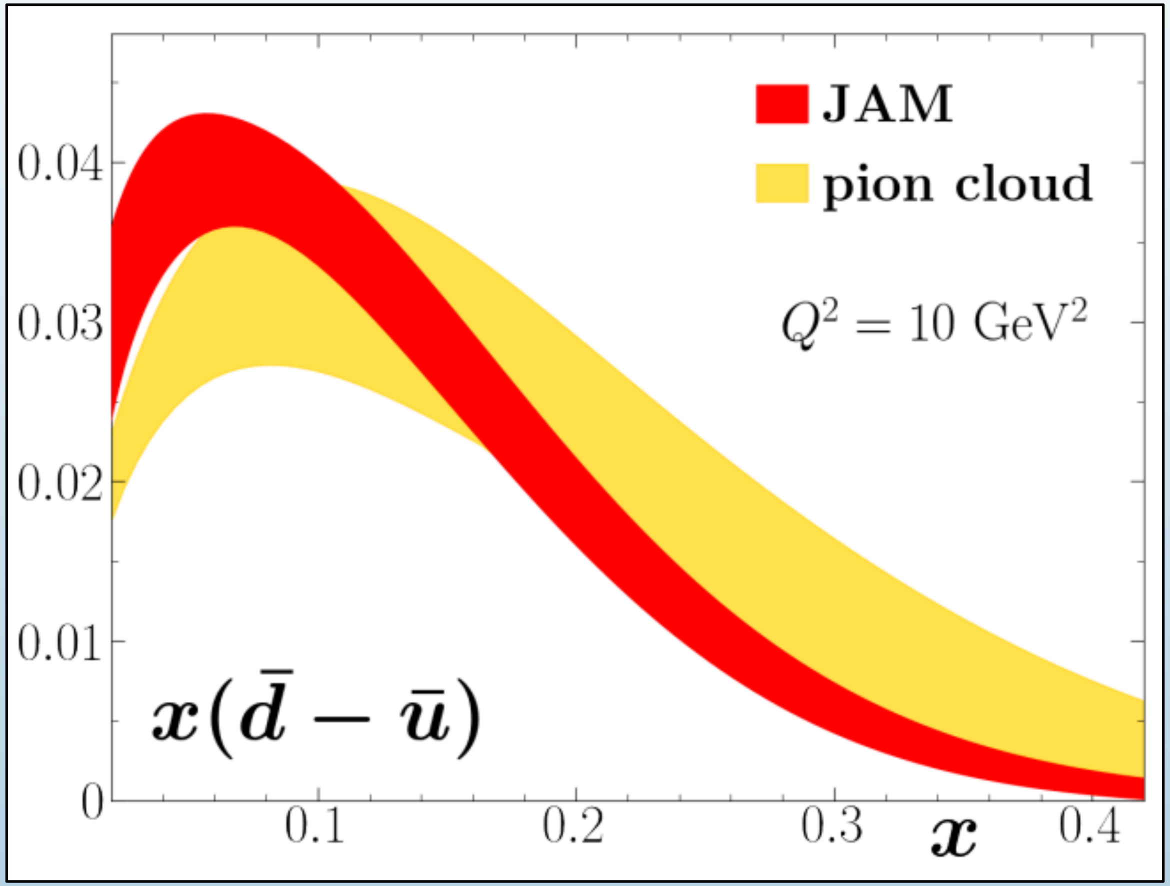
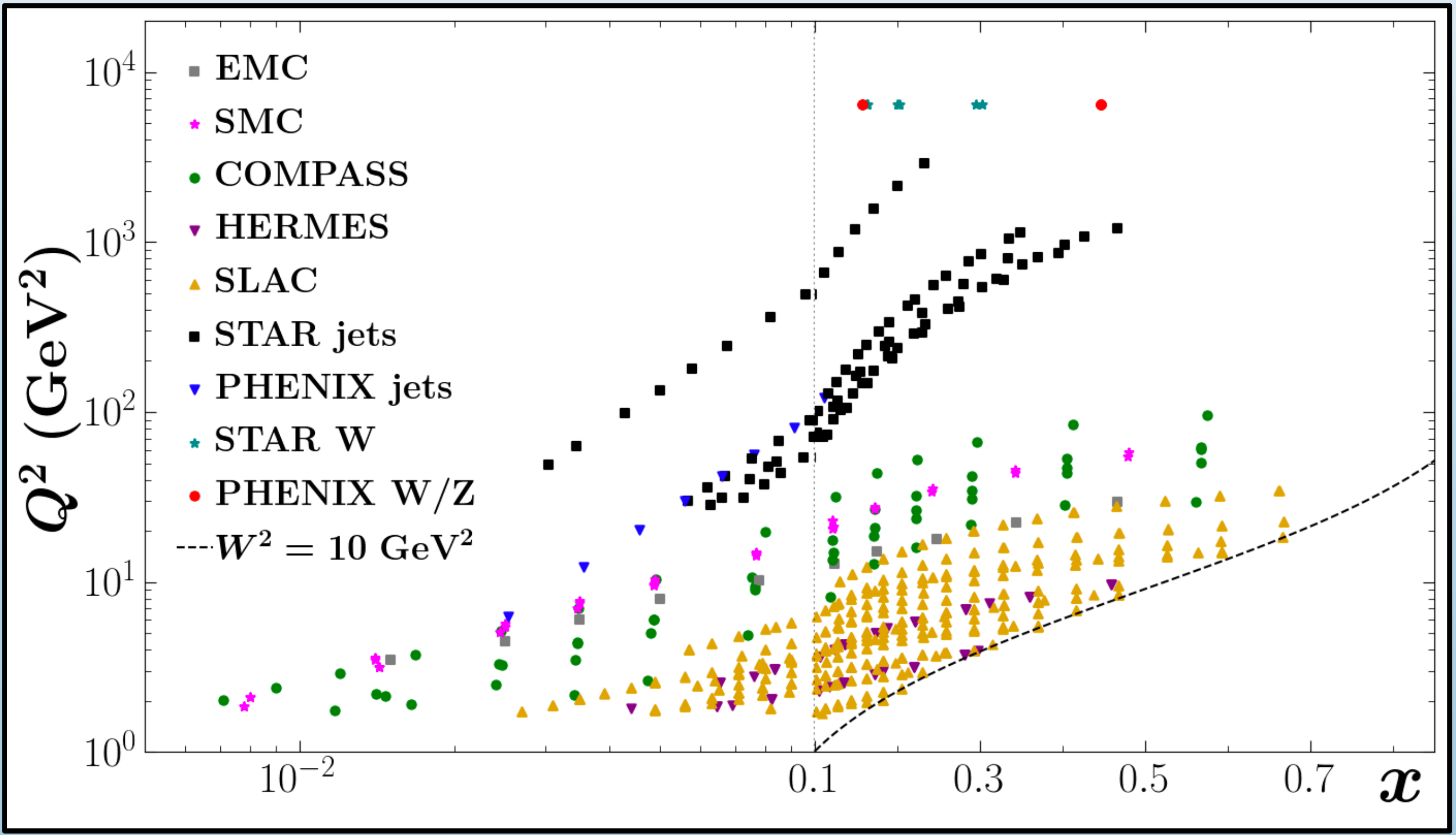




Good agreement with pion cloud model

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



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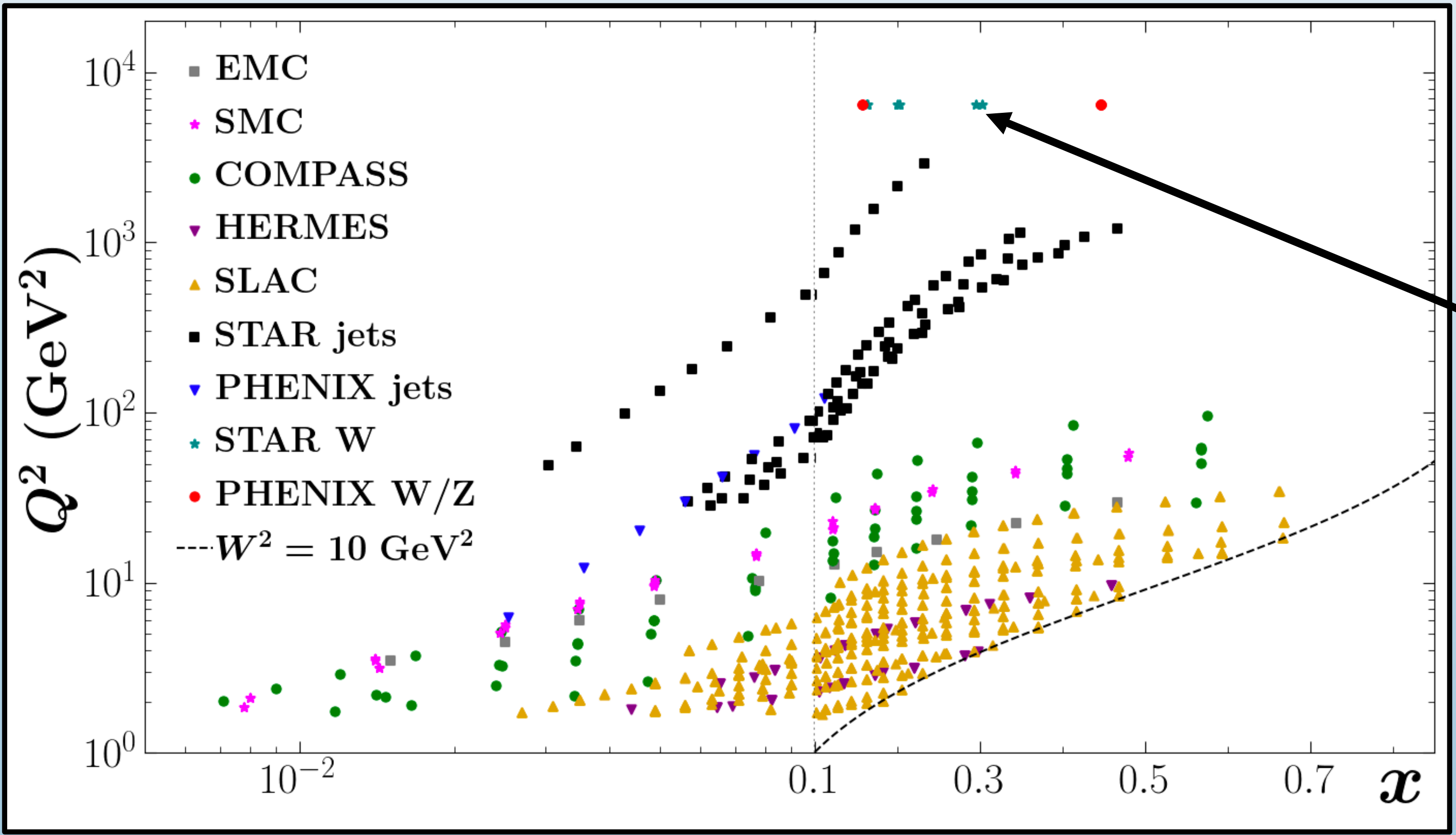

STAR + PHENIX W/Z Production

Small x Global Analysis (2021)

First analysis of world polarized DIS data with small-x helicity evolution

Daniel Adamiak,[1,*] Yuri V. Kovchegov,[1,†] W. Melnitchouk,[2]
Daniel Pitonyak,[3,‡] Nobuo Sato,[2,§] and Matthew D. Sievert[4,¶]

https://arxiv.org/abs/2102.06159

D. Adamiak *et al.*, Phys. Rev. D **104**, no. 3, L031501 (2021).

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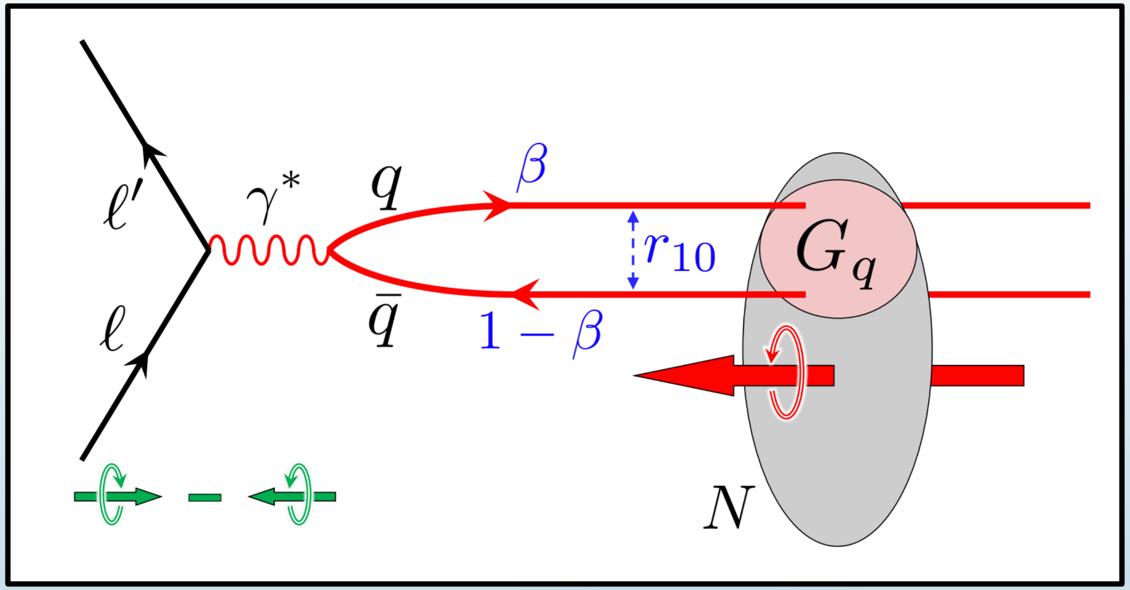

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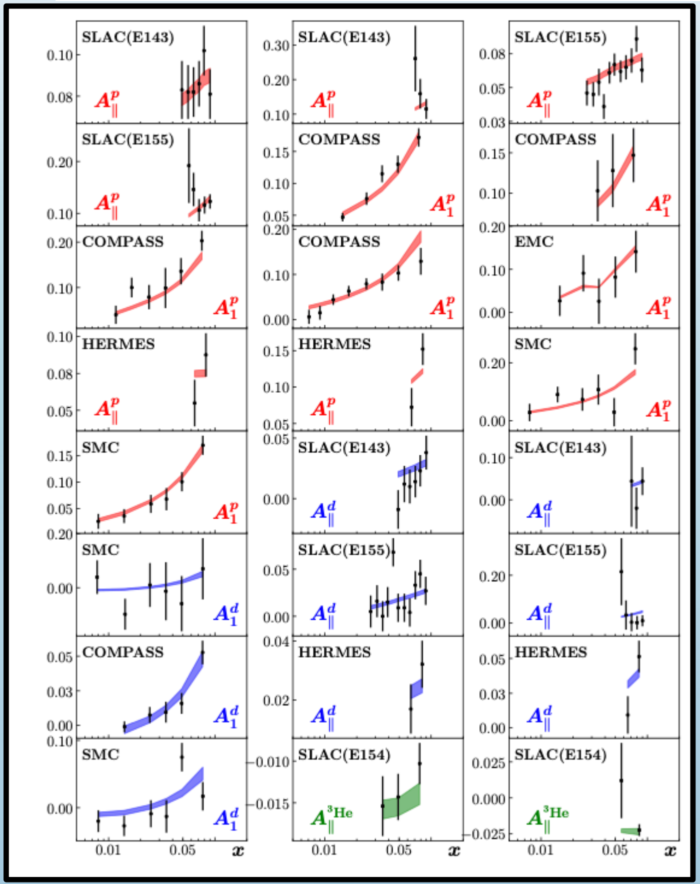
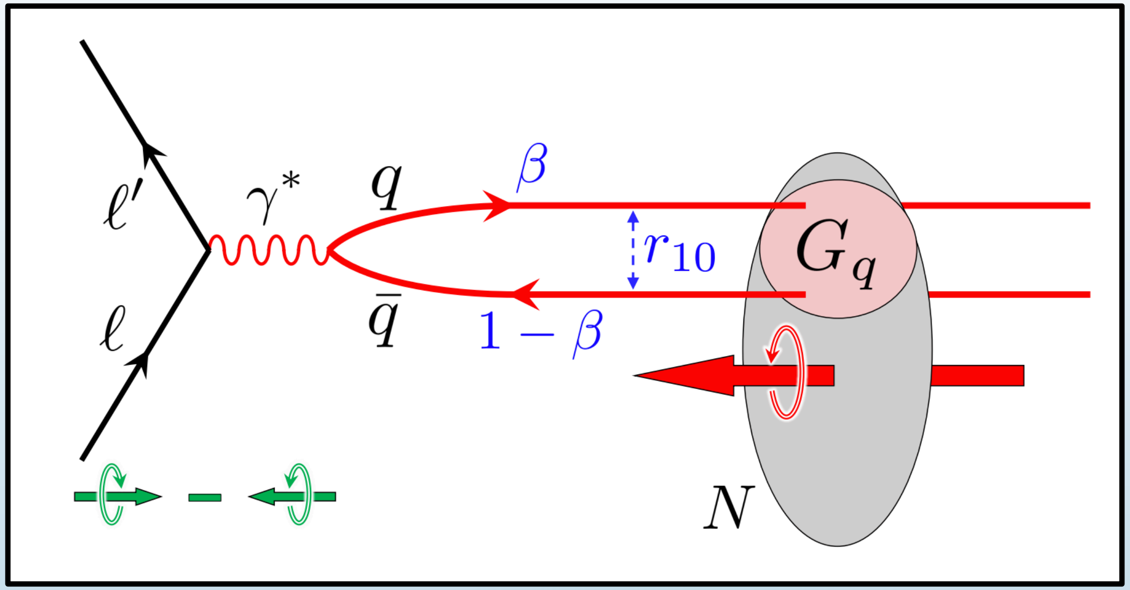


$x < 0.1$



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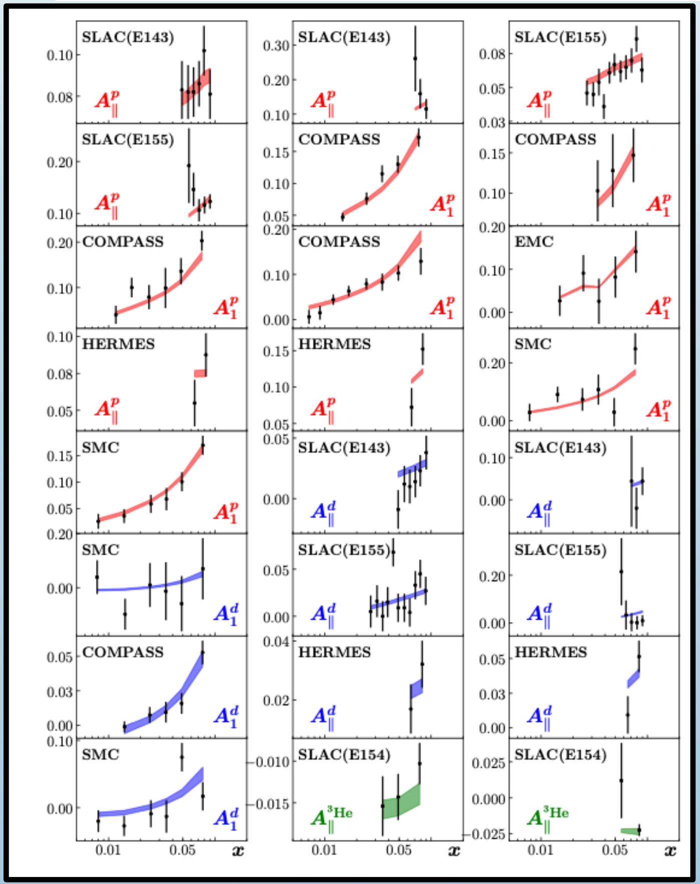

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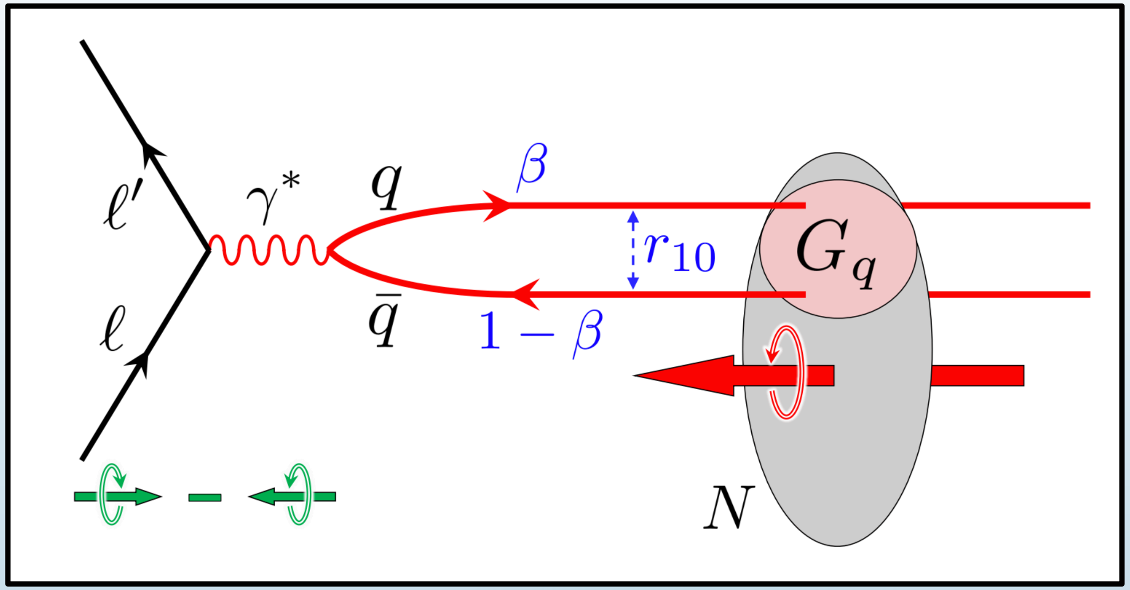

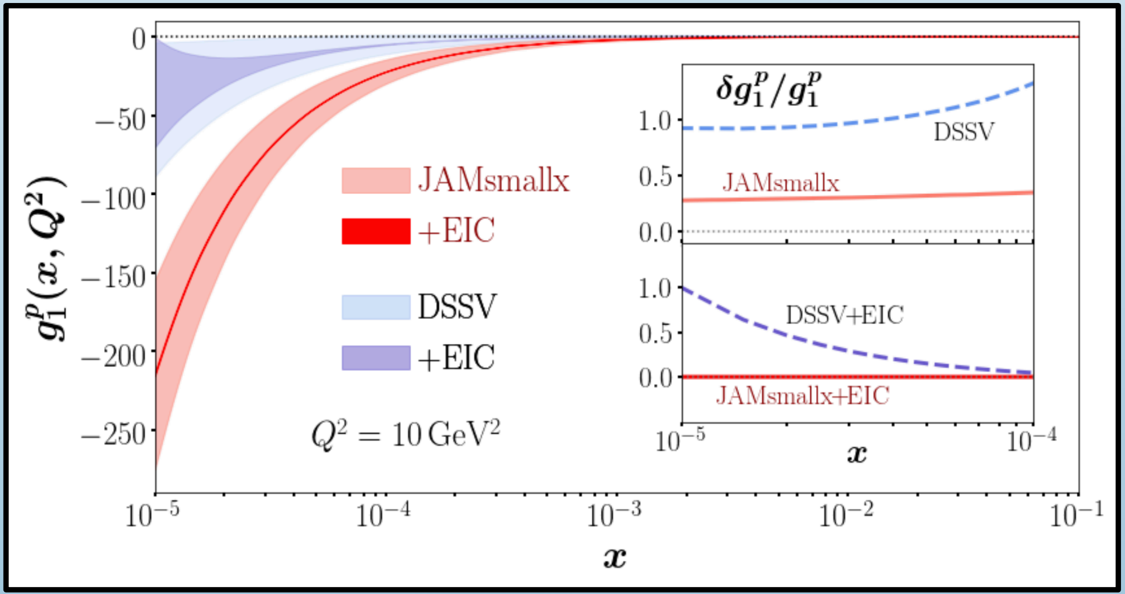

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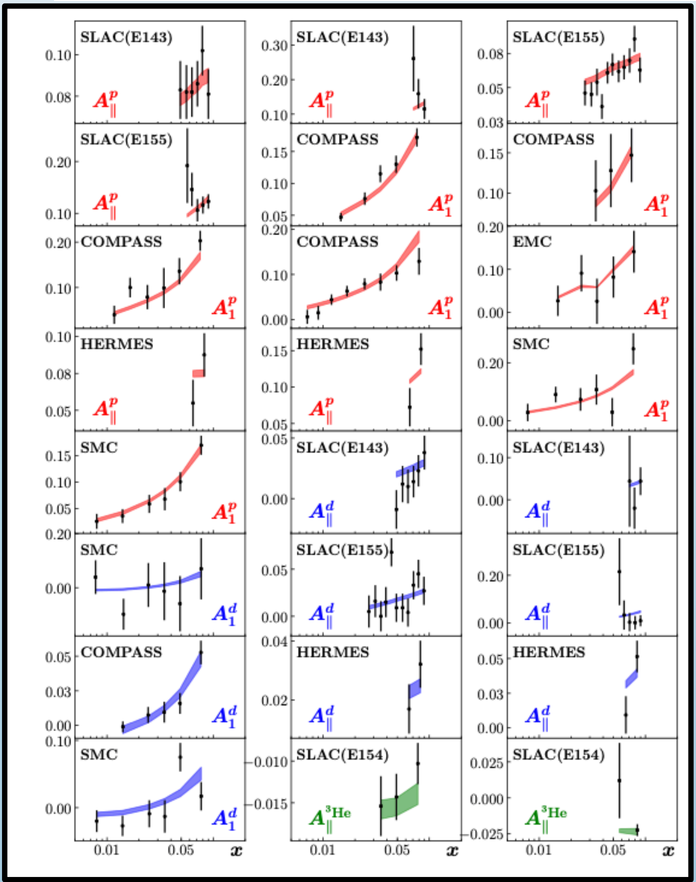

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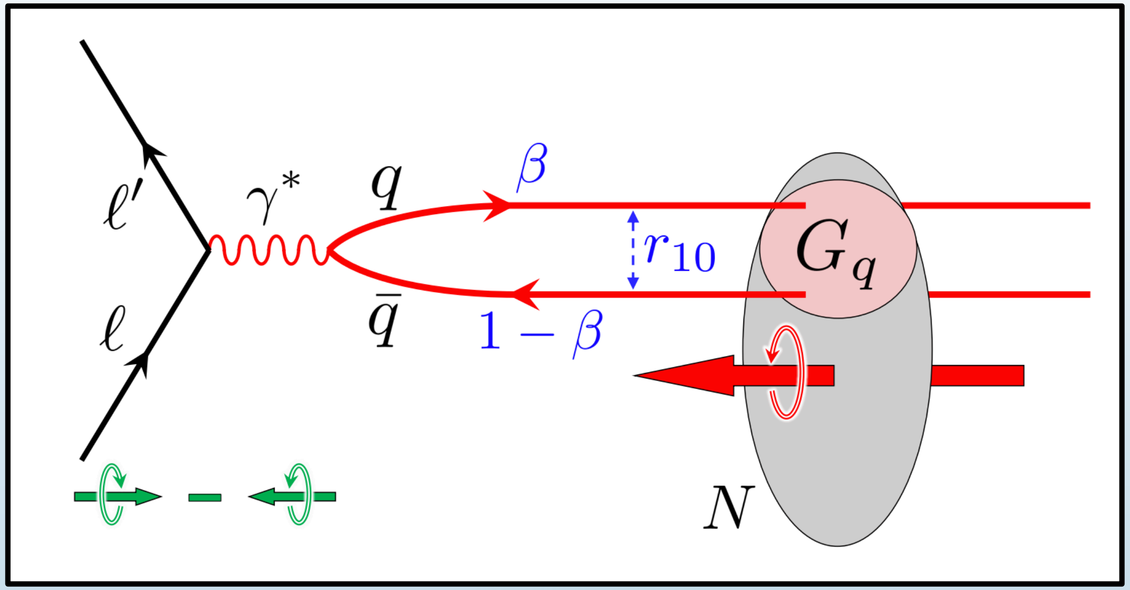
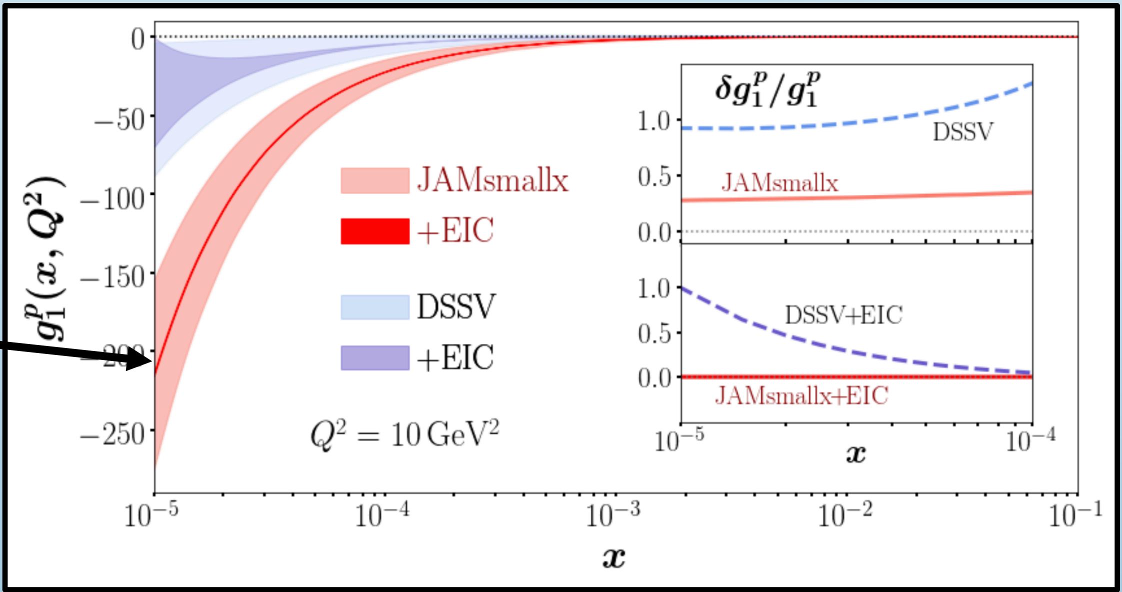


Prediction, not extrapolation!

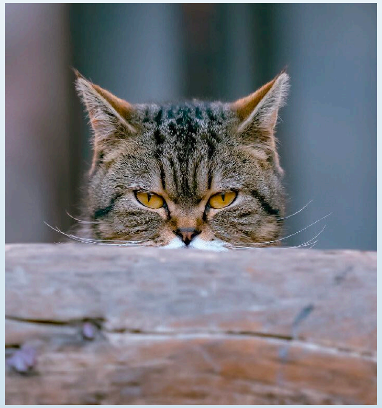


Collaboration

Andreas Metz

Wally Melnitchouk

Hanjie Liu



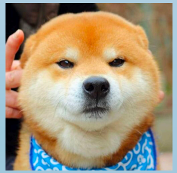
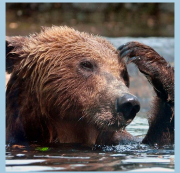
Anthony Thomas

Thia Keppel

Nobuo Sato

Jefferson Lab Angular Momentum Collaboration

Thank you to Yiyu Zhou and Patrick Barry for helpful discussions

Error Quantification

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

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

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

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

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Average over k sets of the parameters (replicas)

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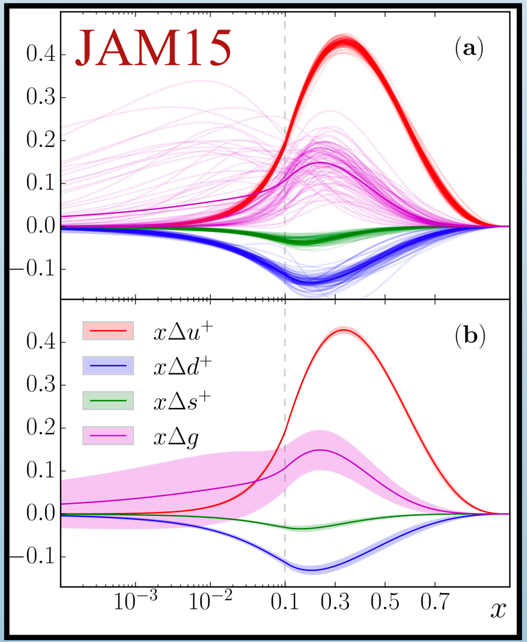
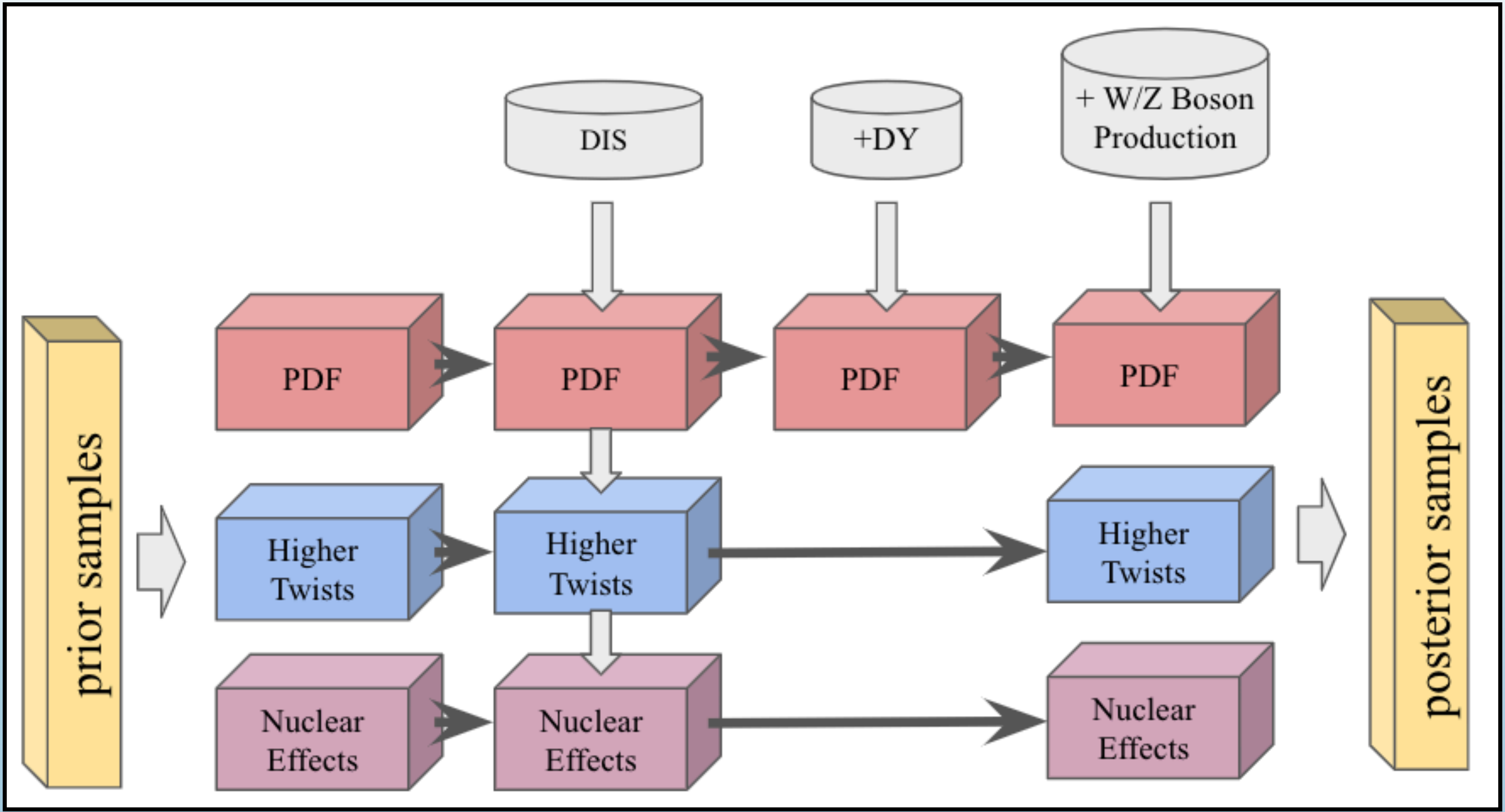
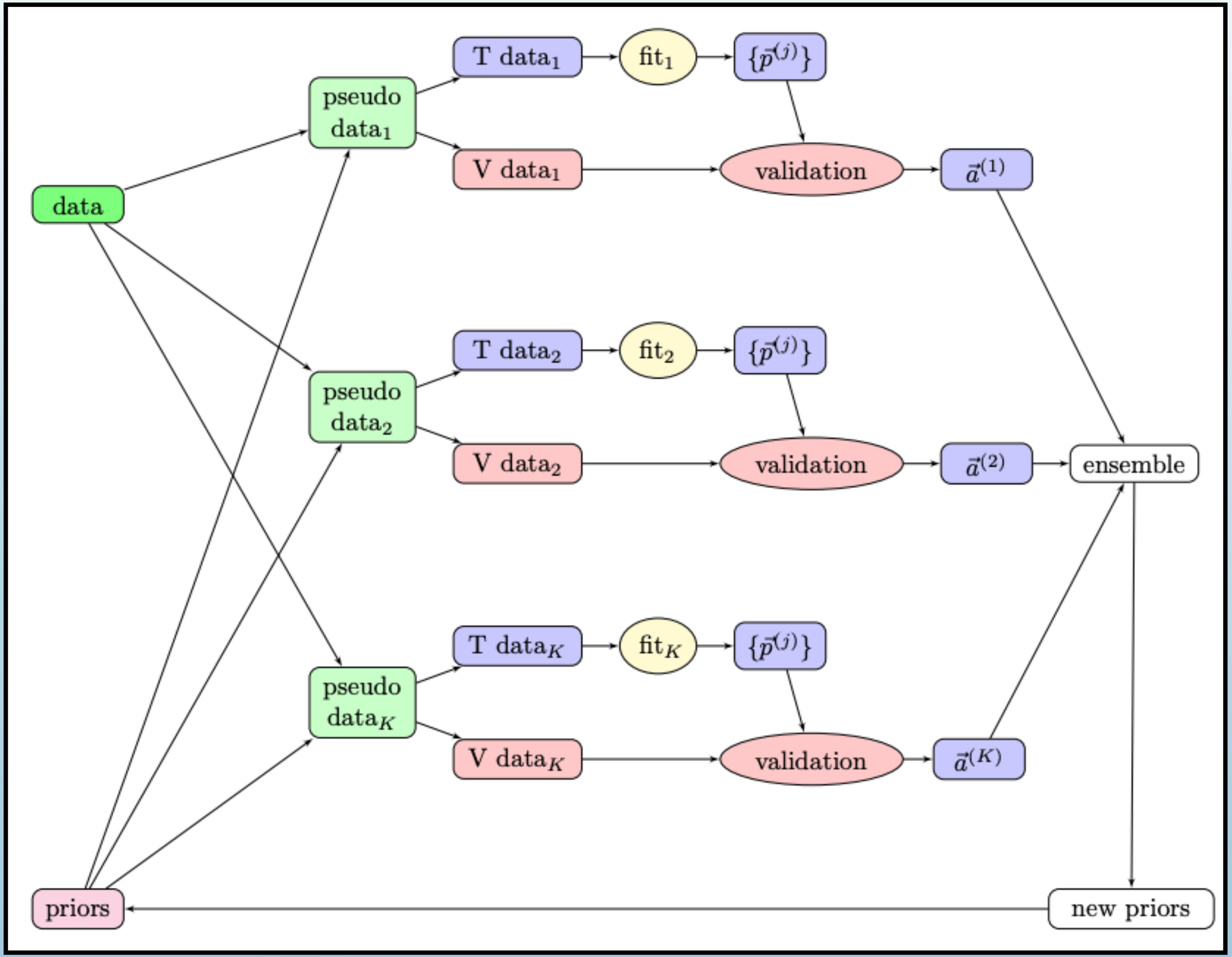


Multi-Step Strategy



Putting it all together…



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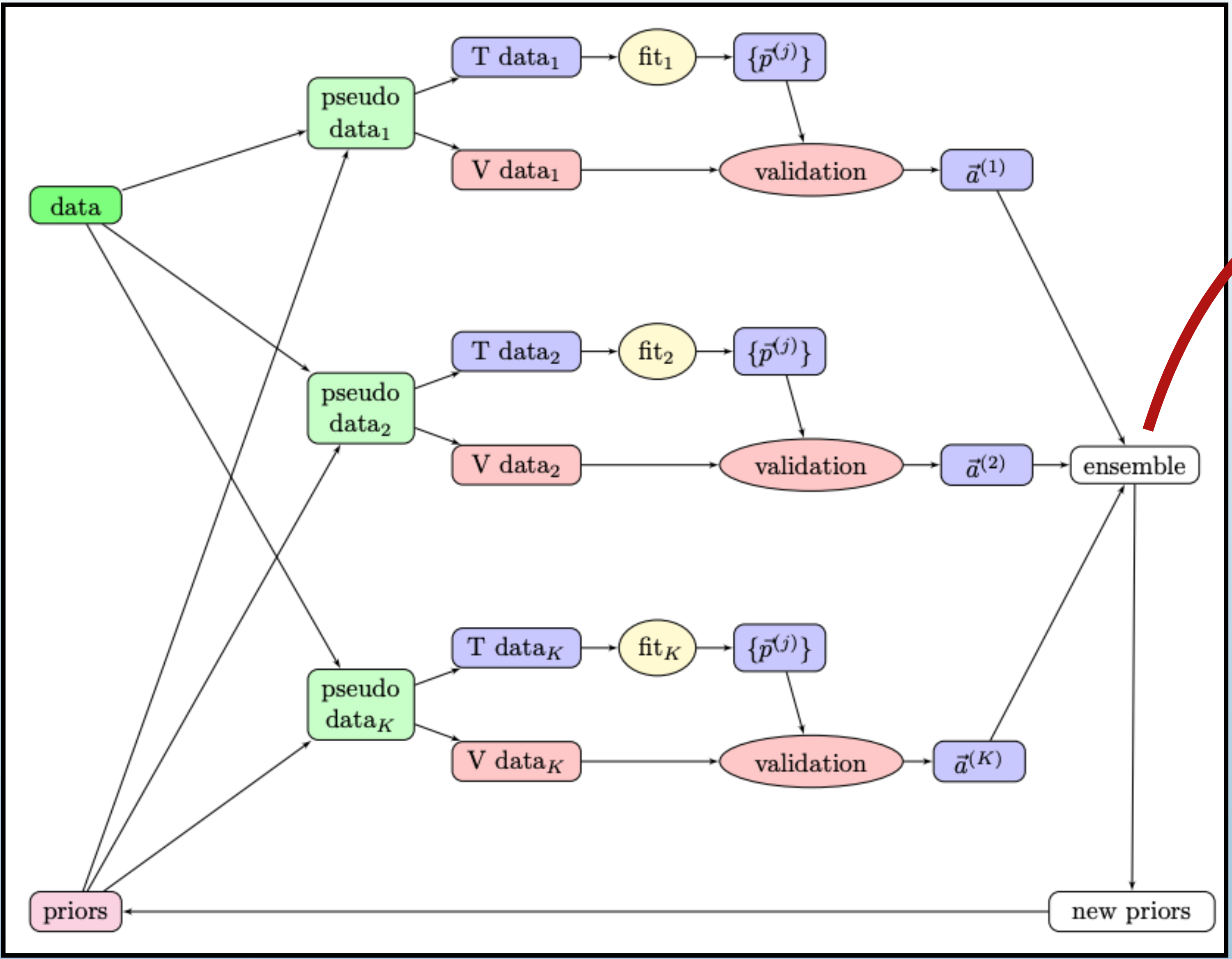

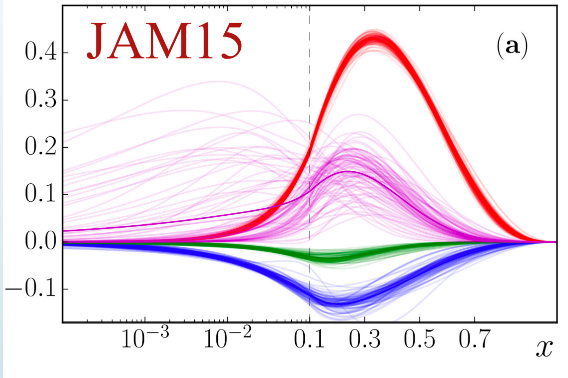

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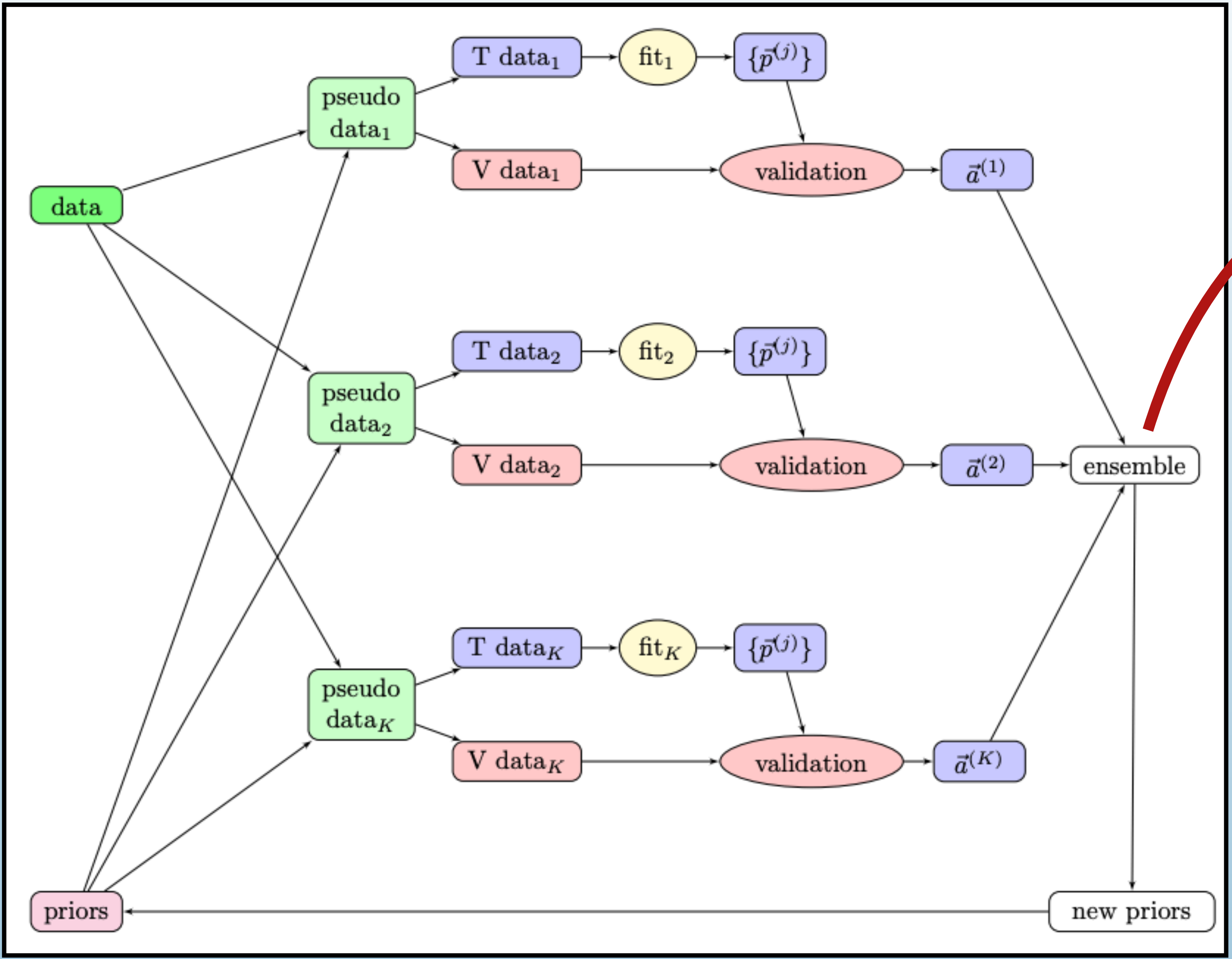

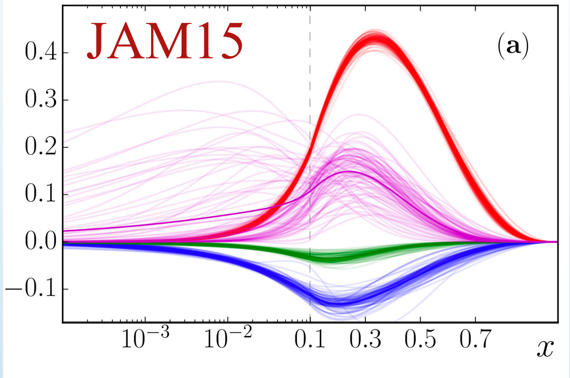

+

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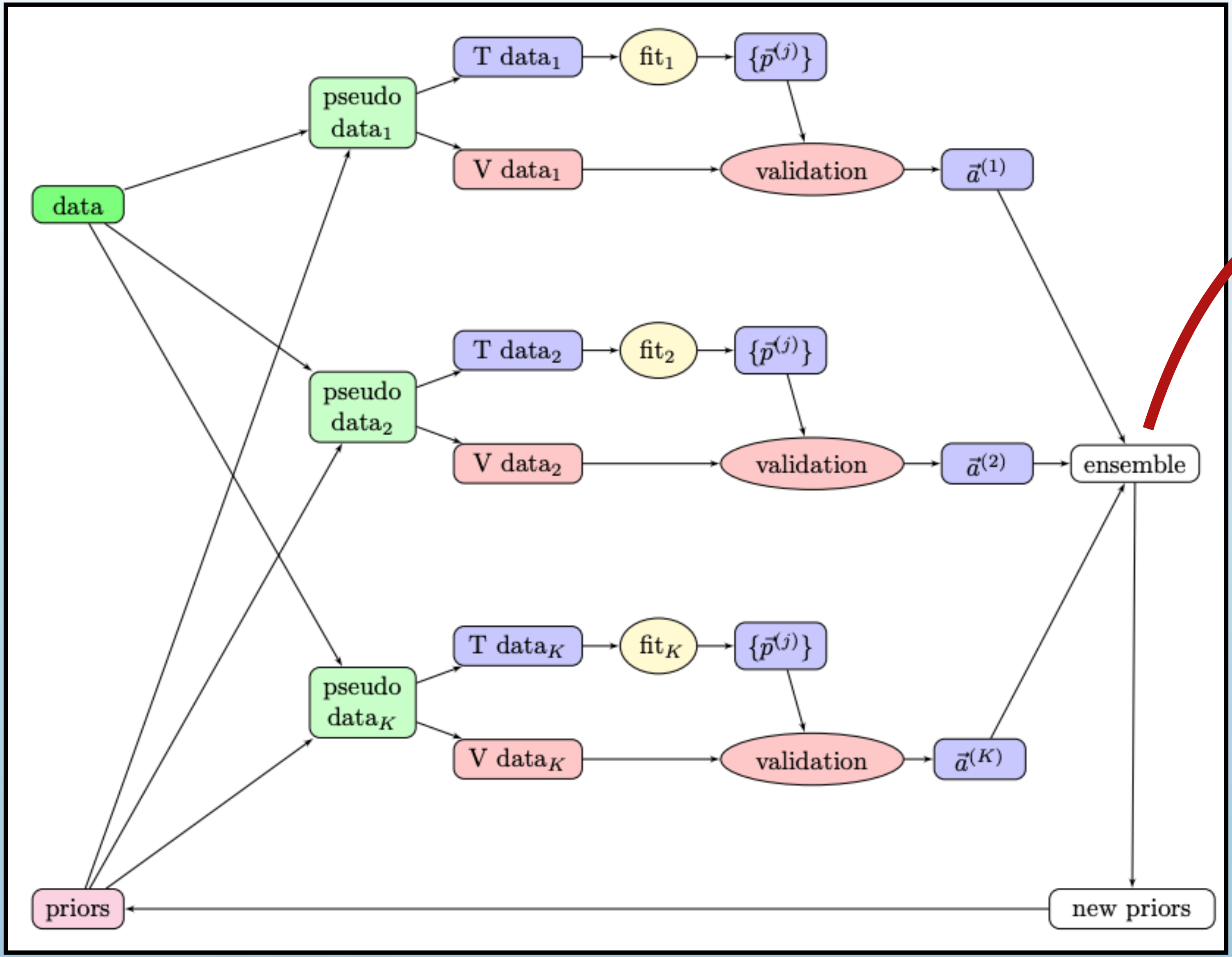

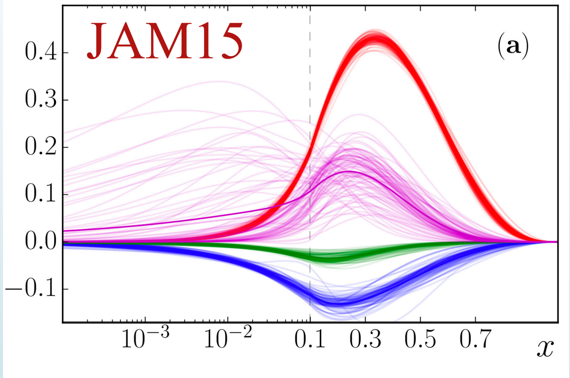

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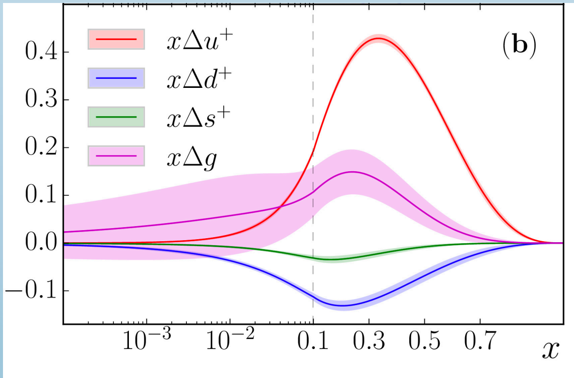
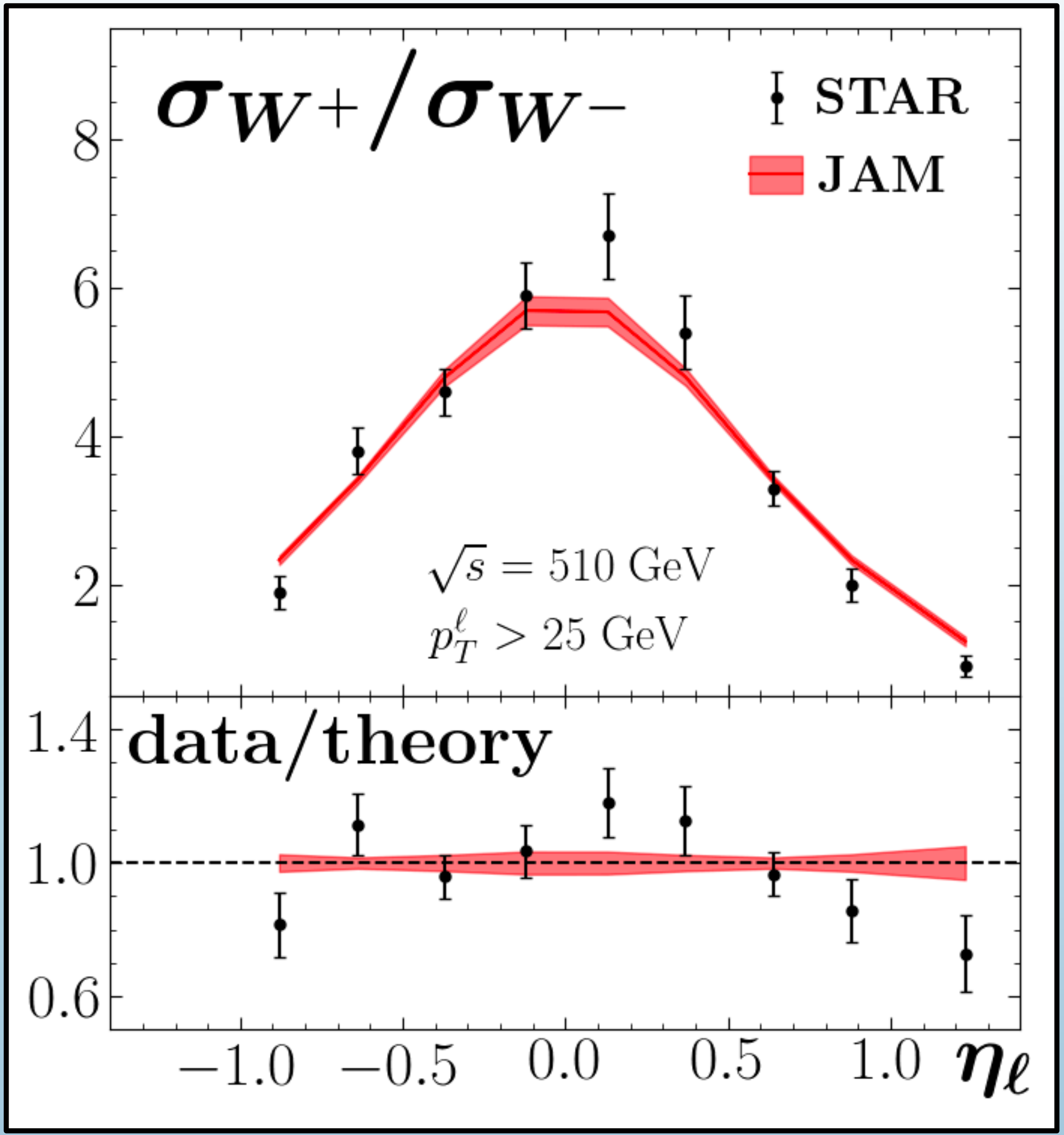


STAR Quality of Fit



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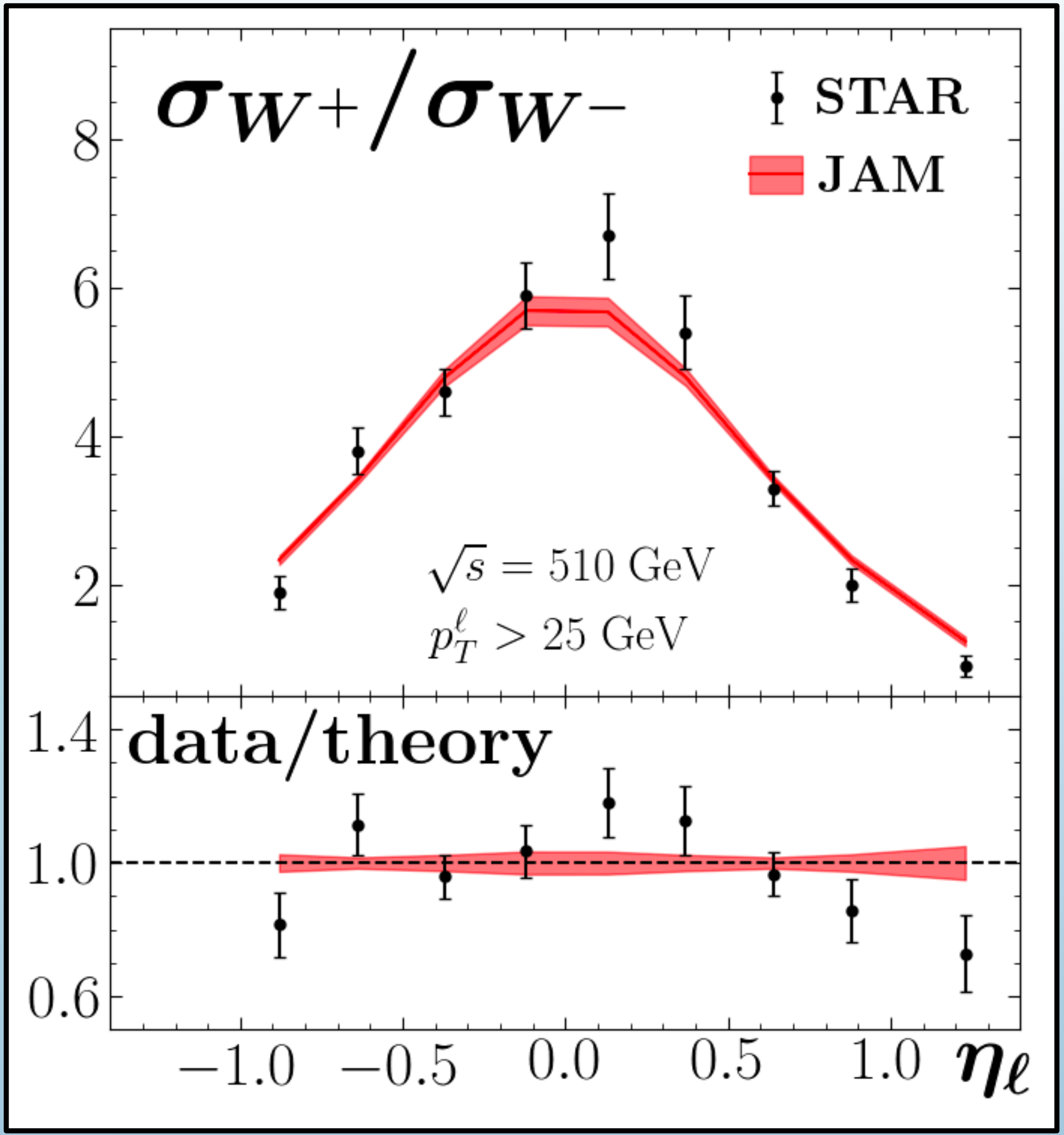

process	$N_{\rm dat}$	$\chi^2/N_{\rm dat}$
W-lepton		
STAR W^+/W^-	9	2.02

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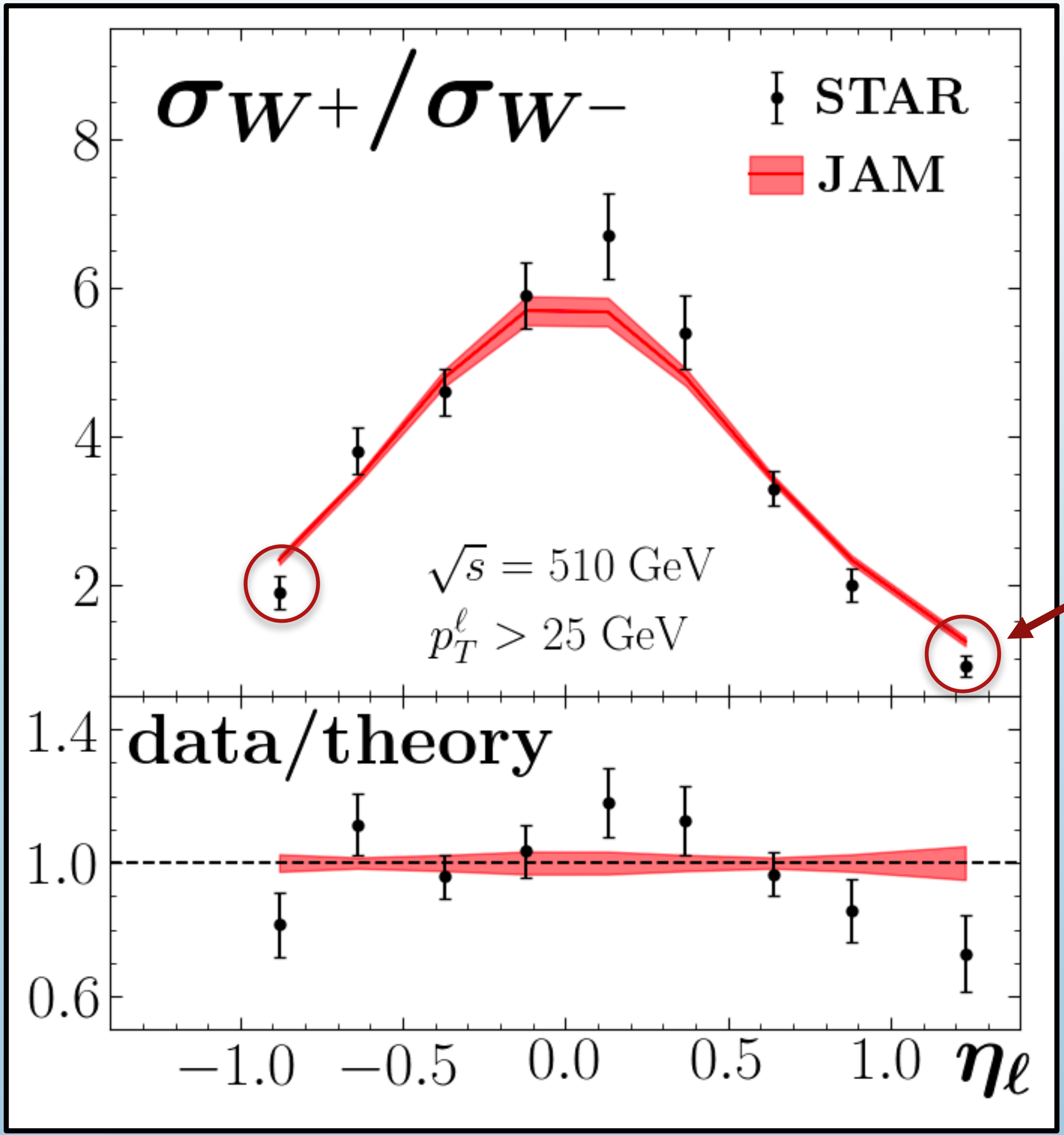

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Difficult to describe at extreme rapidity

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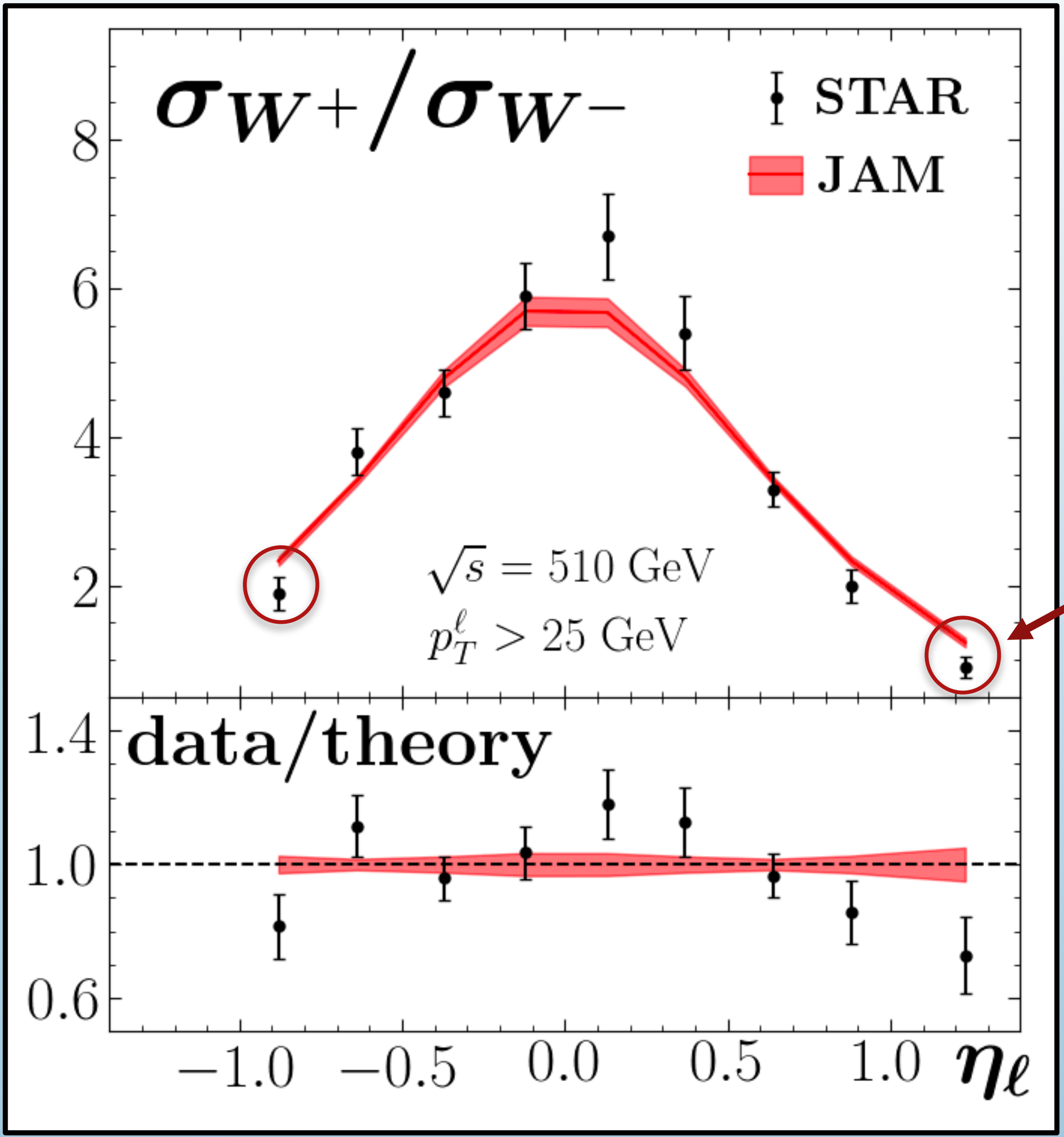

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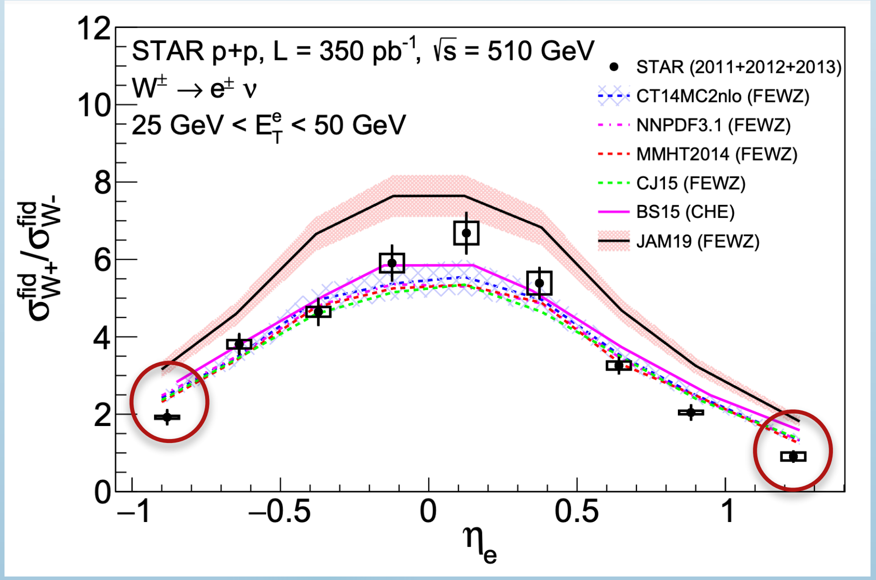
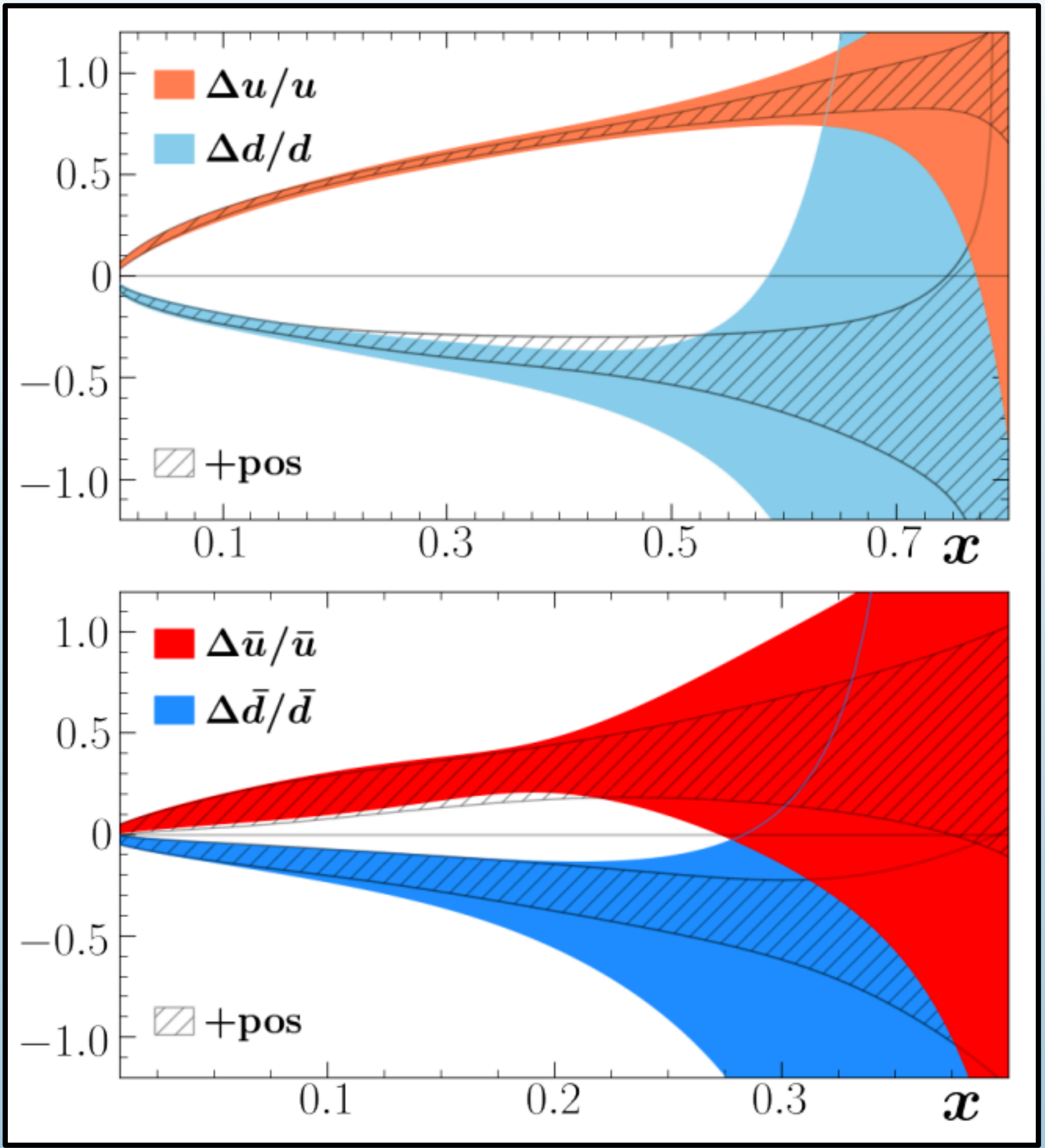


J. Adam *et al.* [STAR], Phys. Rev. D. **103**, 012001 (2021)

Quark and Antiquark Polarizations



EIC Impact on Helicity PDFs (2021)

Revisiting quark and gluon polarization in the proton at the EIC

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https://arxiv.org/abs/2105.04434

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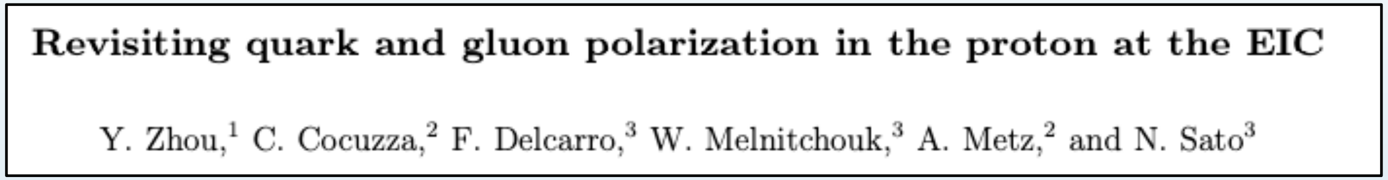

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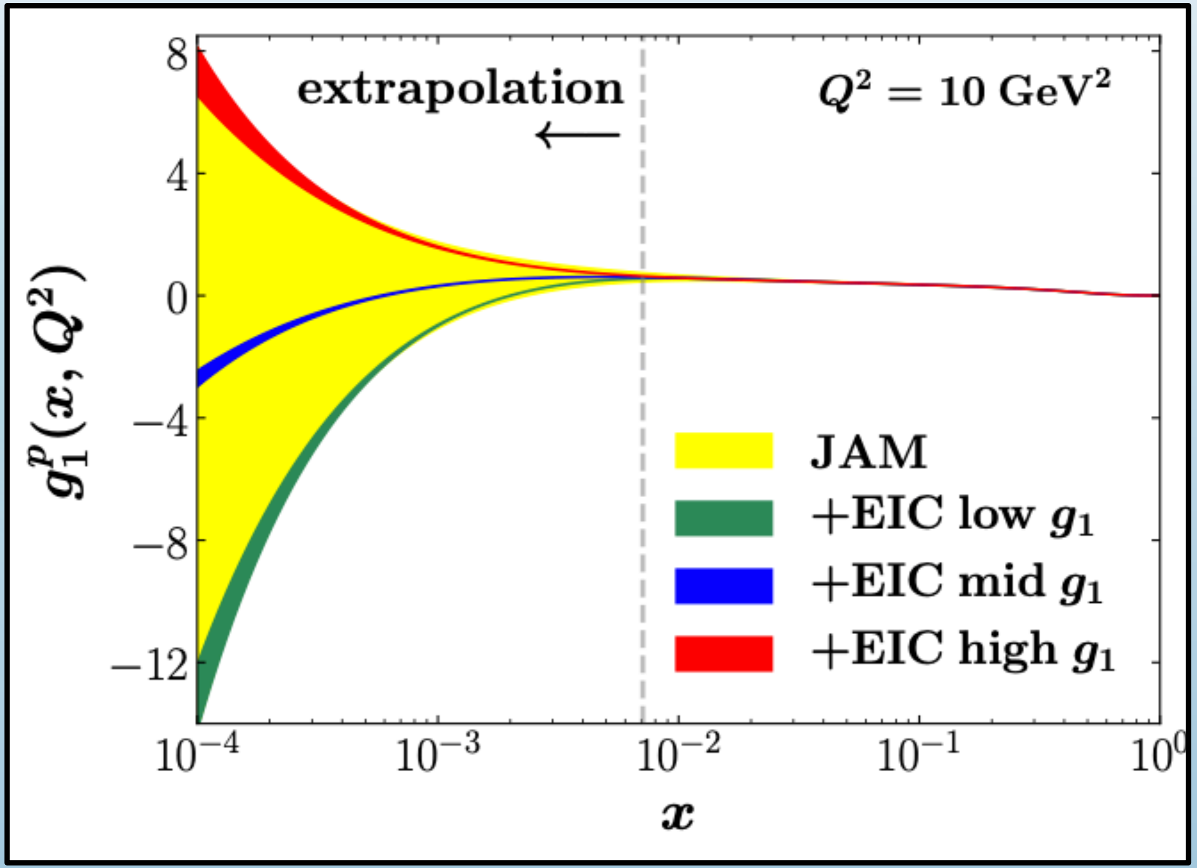

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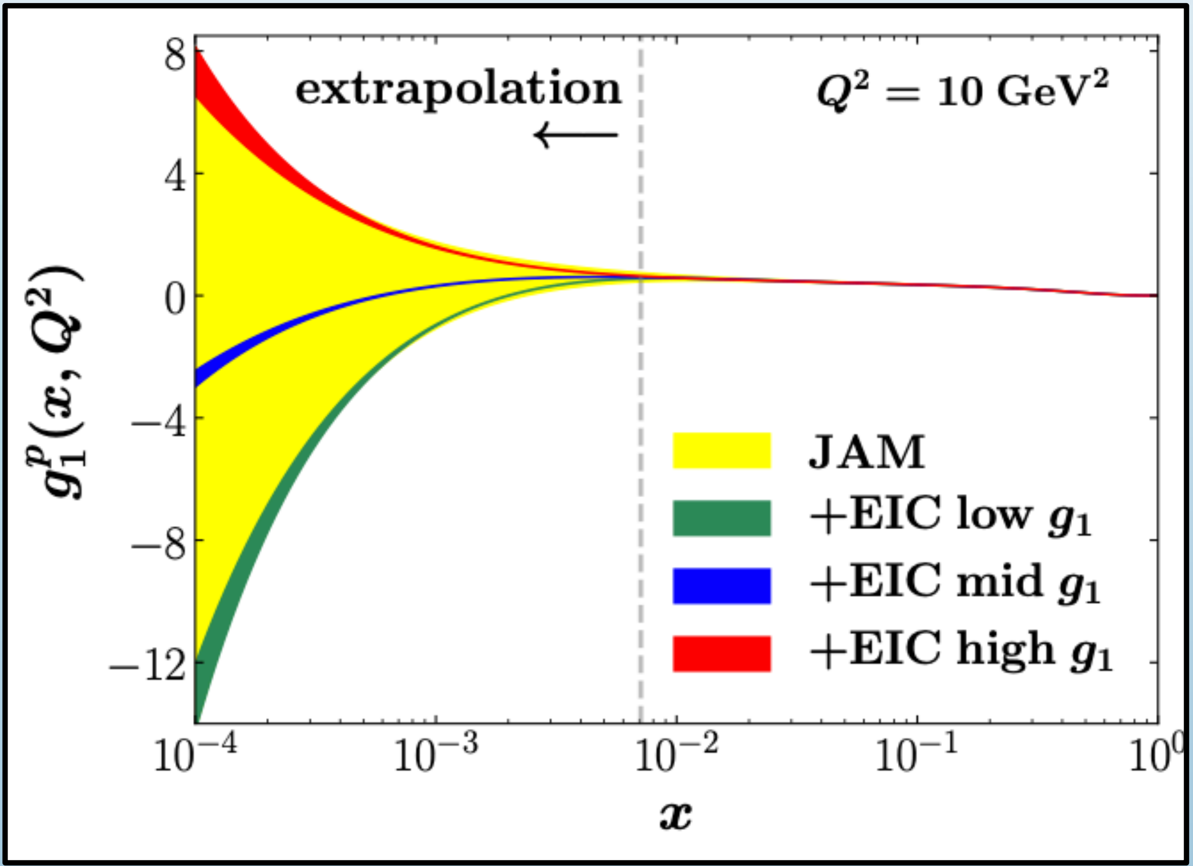

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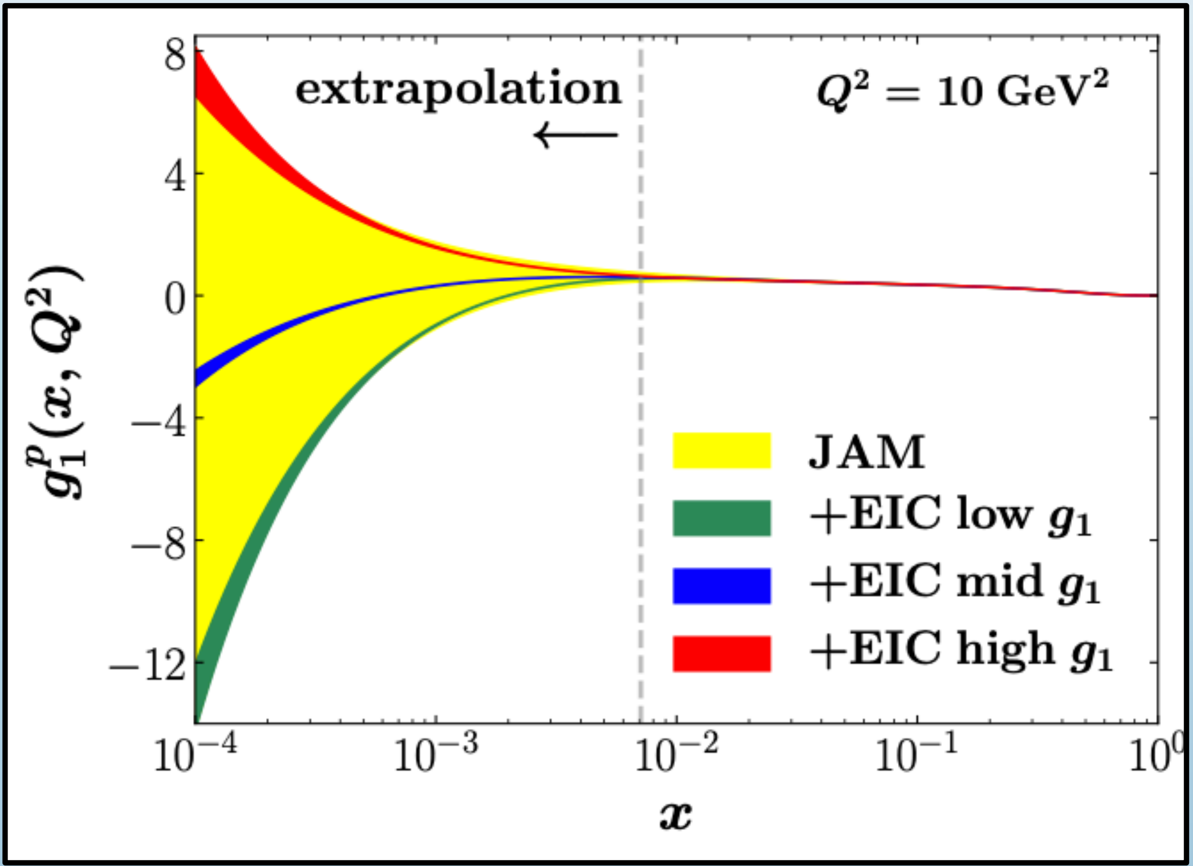

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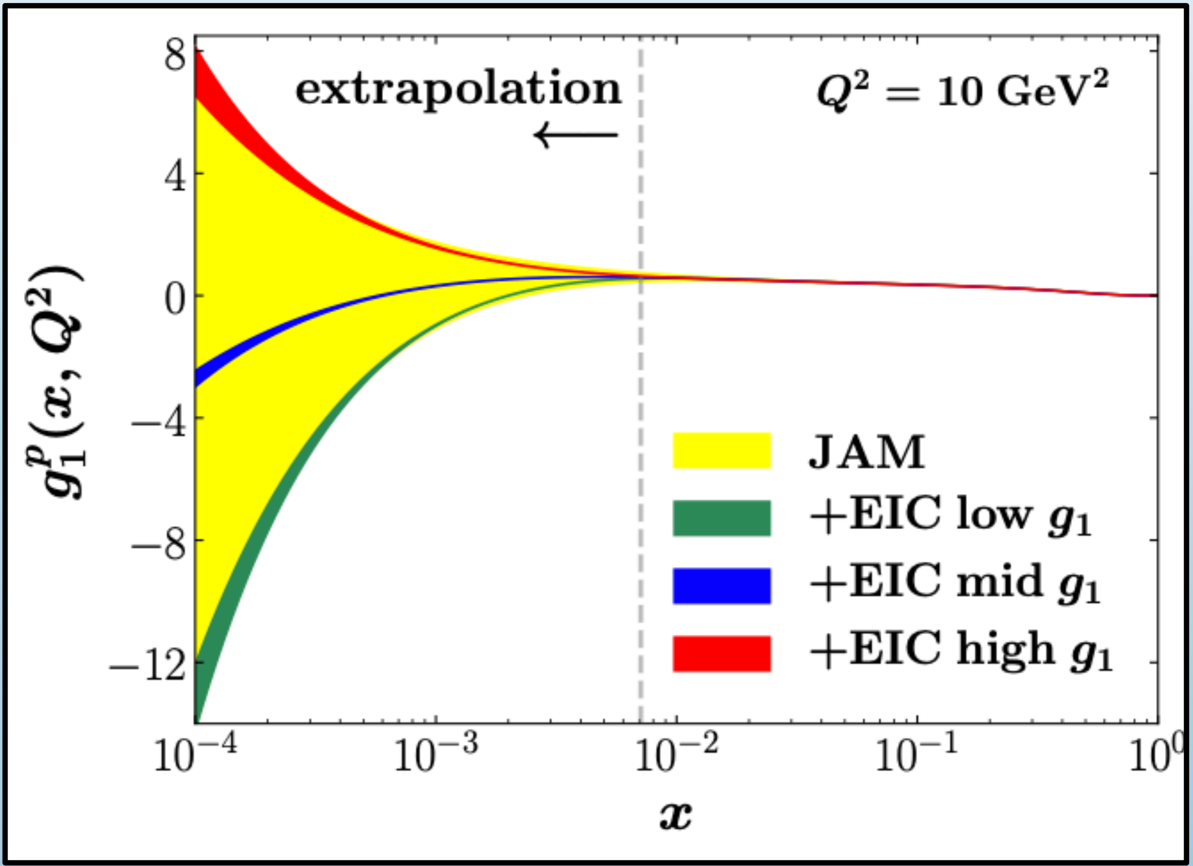

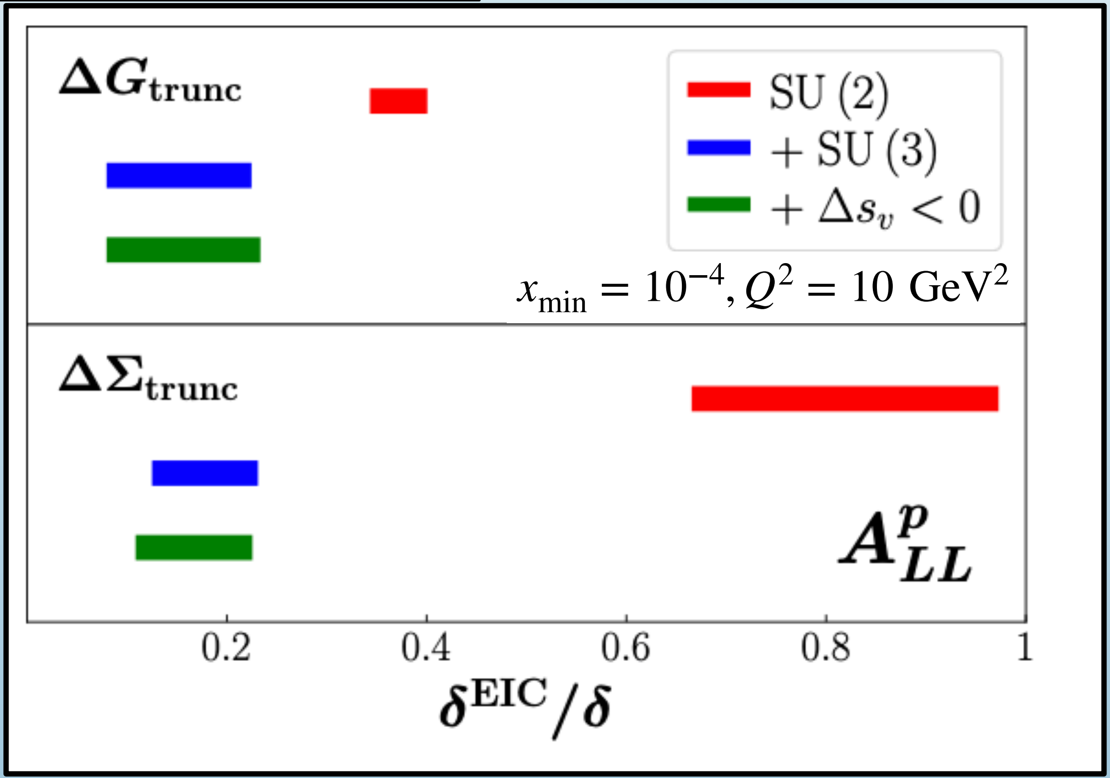

Impact of Parity Violating DIS (2021)

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$$\boxed{A_{UL} = \frac{G_F x Q^2}{2\sqrt{2}\pi\alpha}\left(\frac{g_A^e Y^- g_1^{\gamma Z} + g_V^e Y^+ g_5^{\gamma Z}}{xy^2 F_1 + (1-y)F_2}\right)}$$

Impact of Parity Violating DIS (2021)

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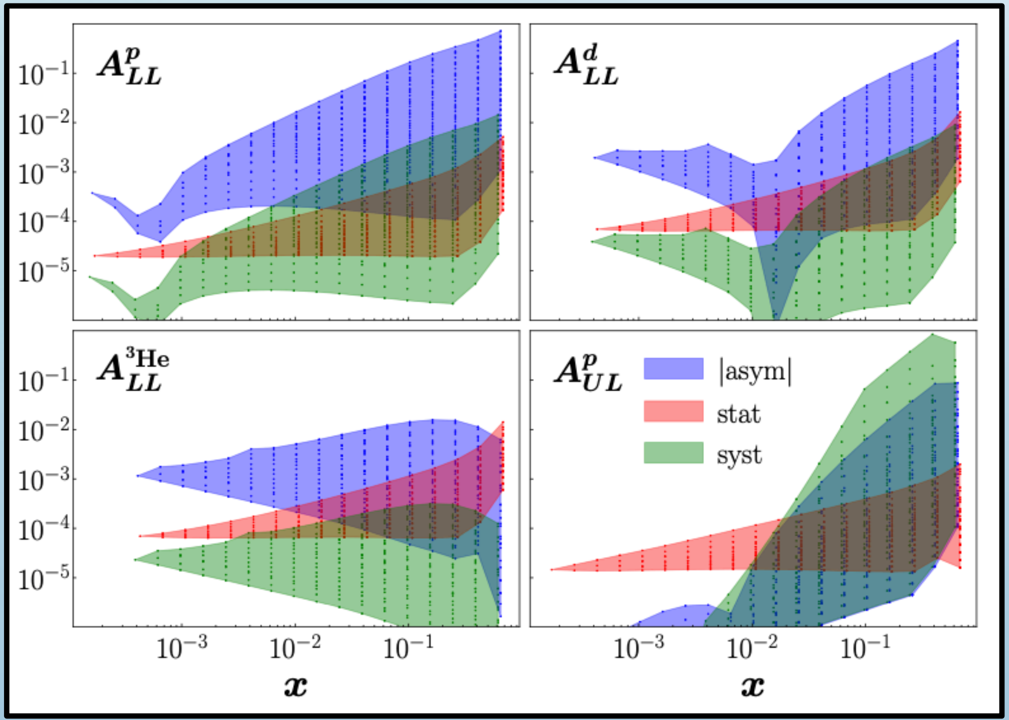

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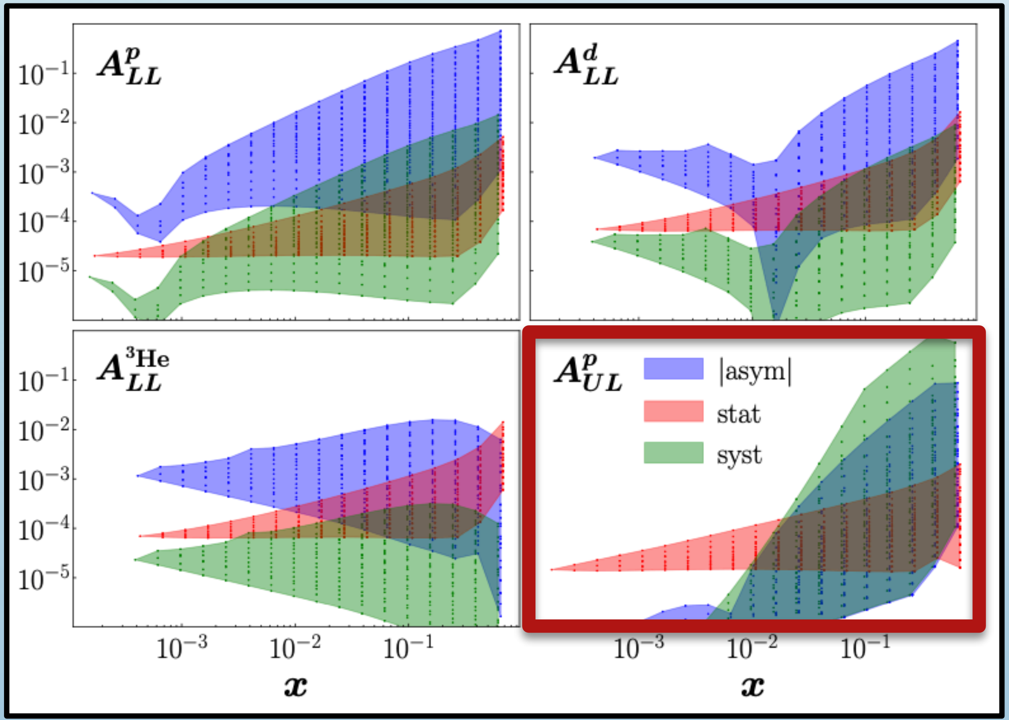

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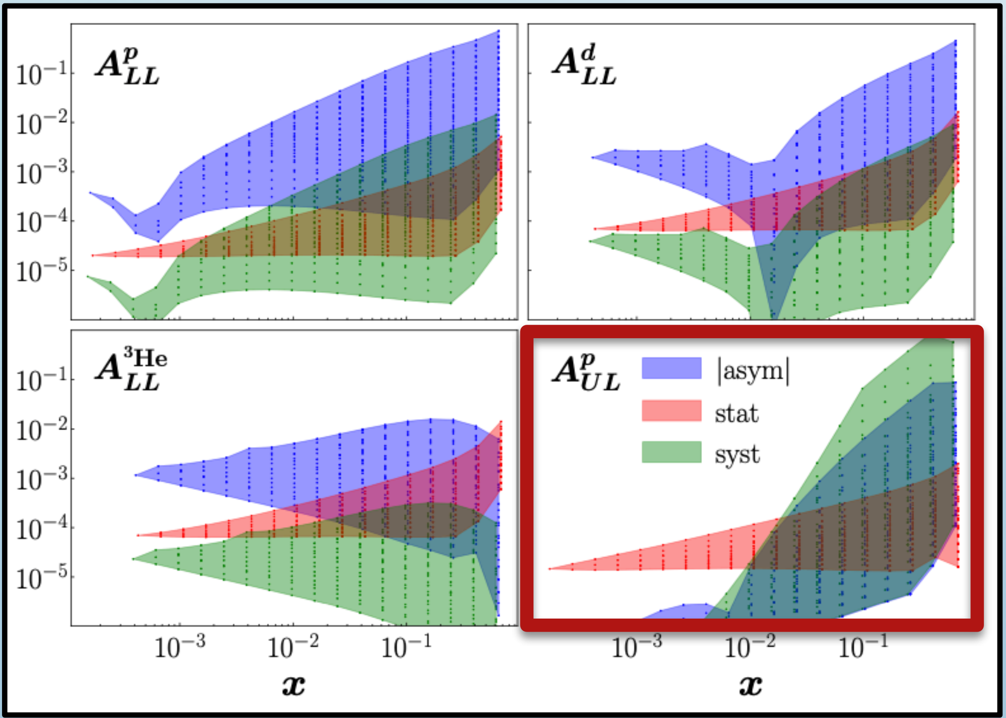

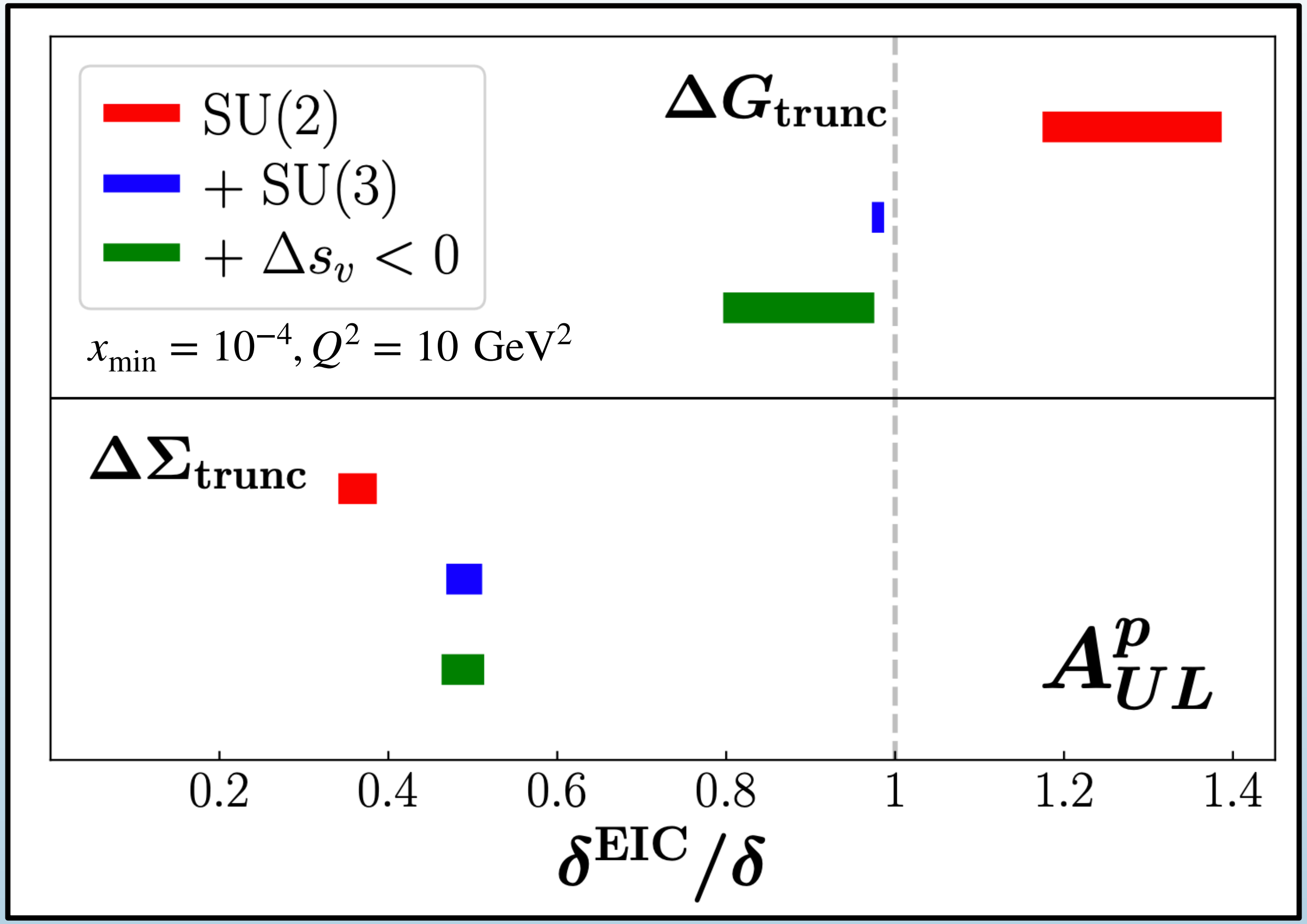

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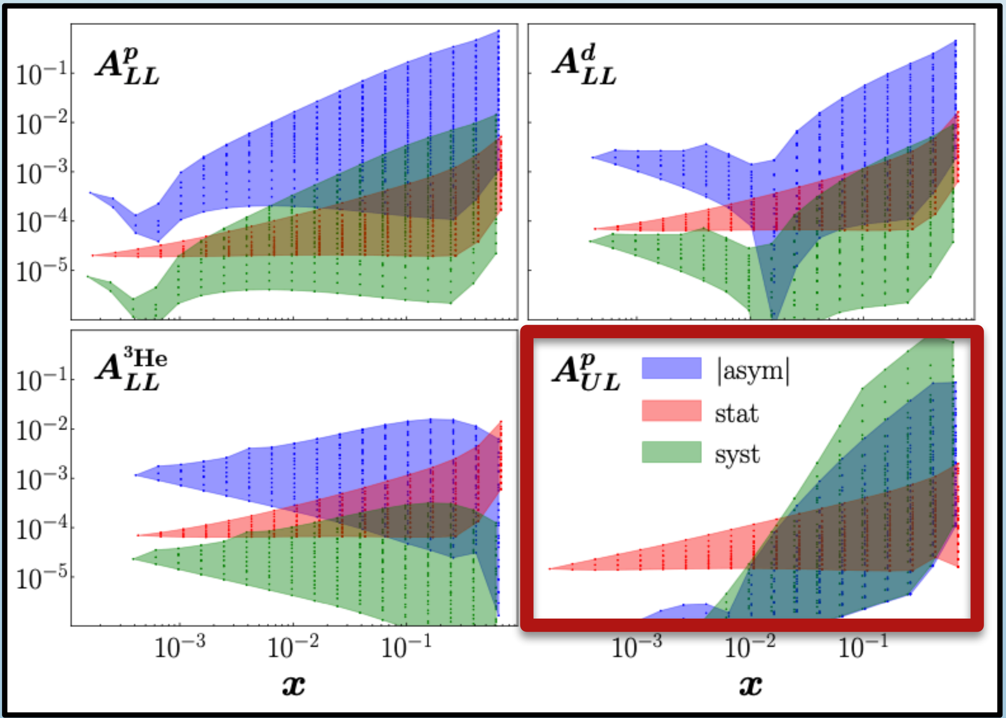

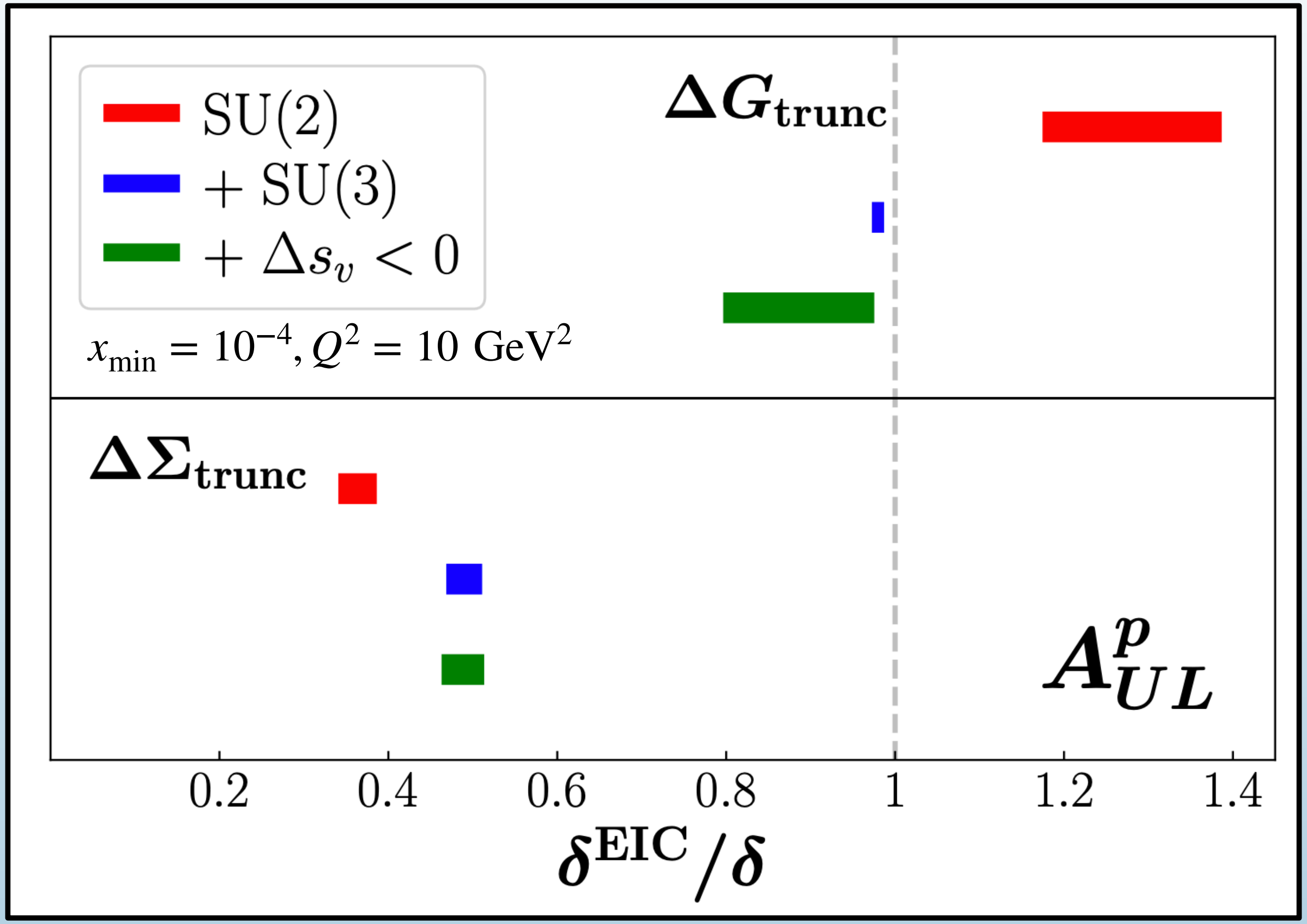

No impact on ΔG, but large impact on $\Delta\Sigma$ thanks to constraints on Δs^+

Impact of EIC at small x (2021)

First analysis of world polarized DIS data with small-x helicity evolution

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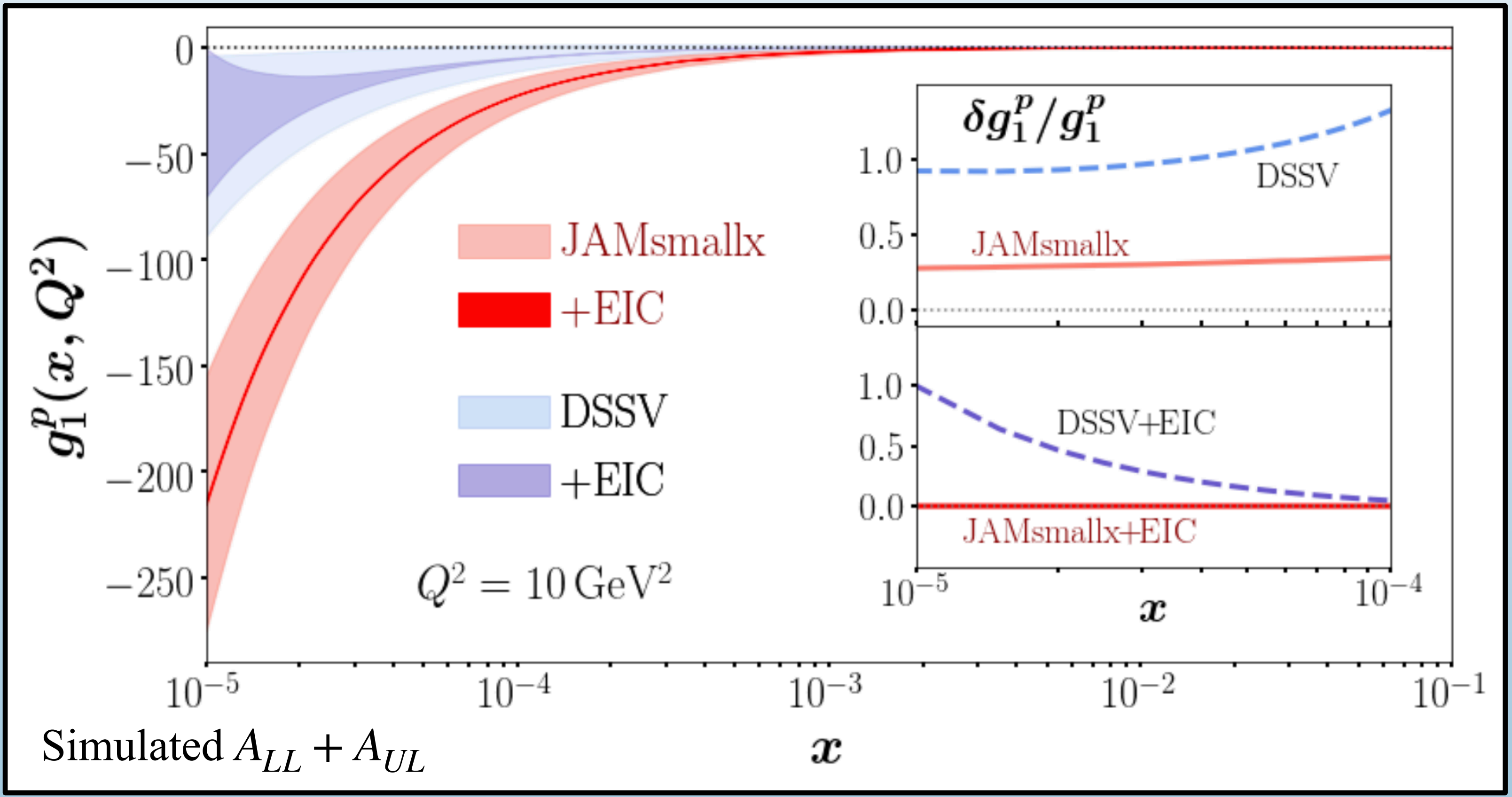

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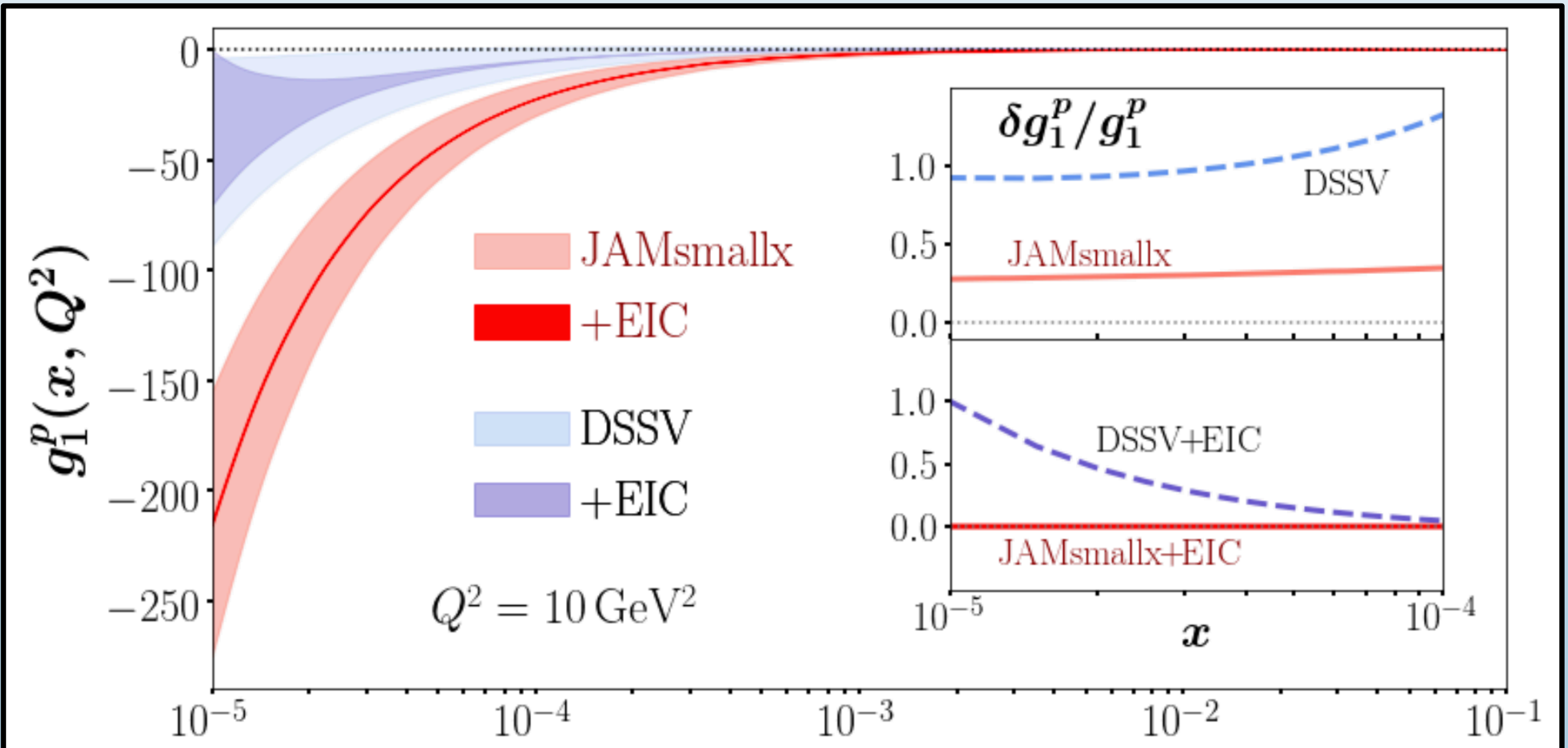
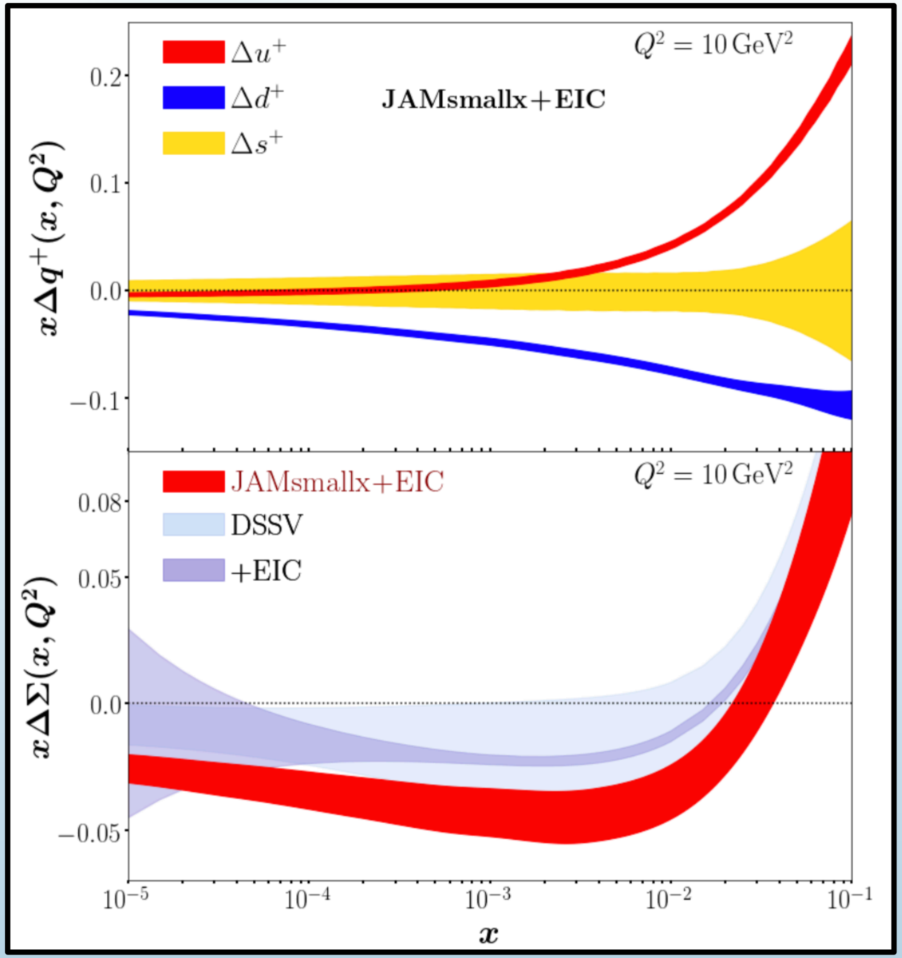


Simulated $A_{LL} + A_{UL}$



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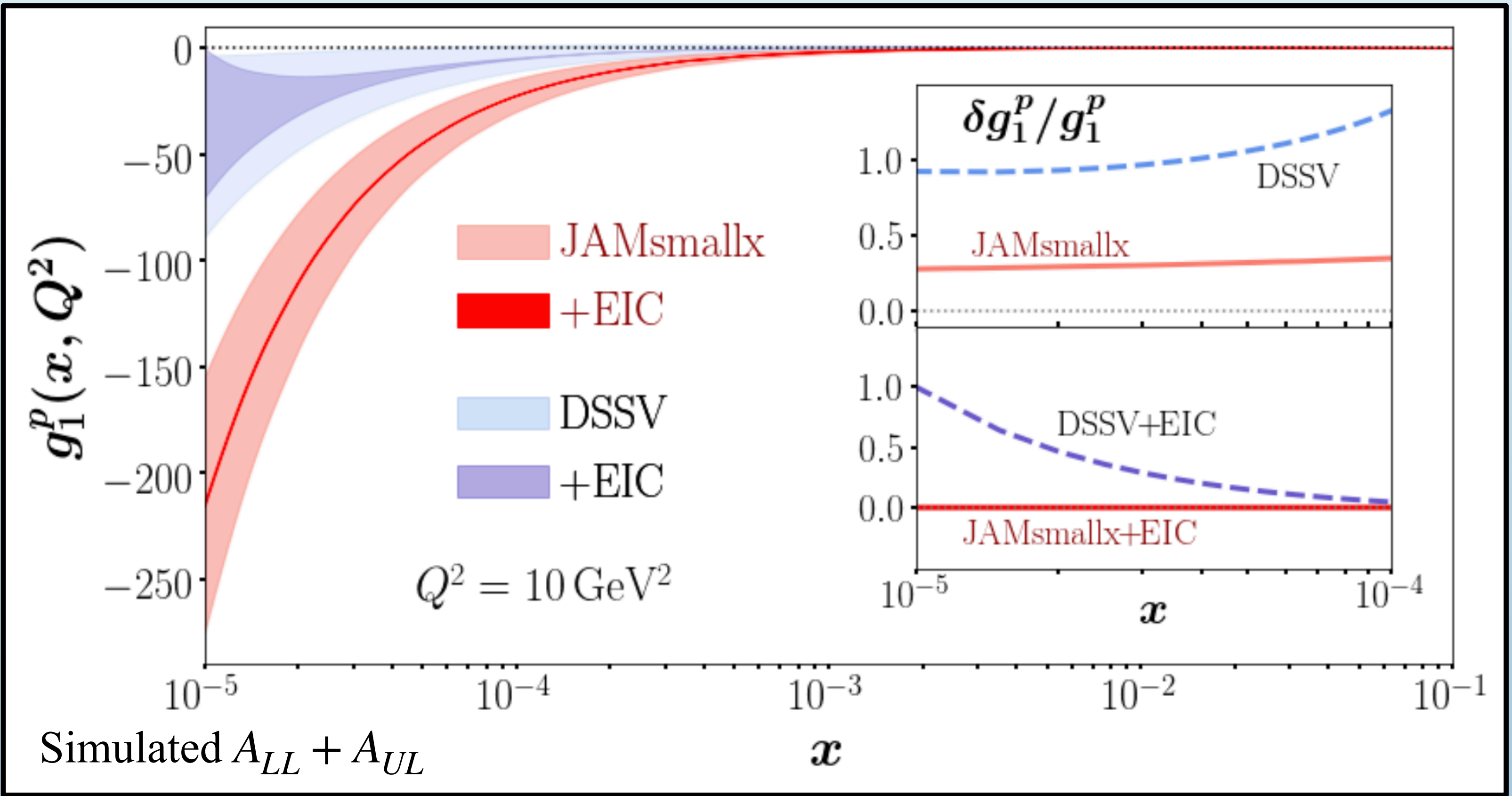

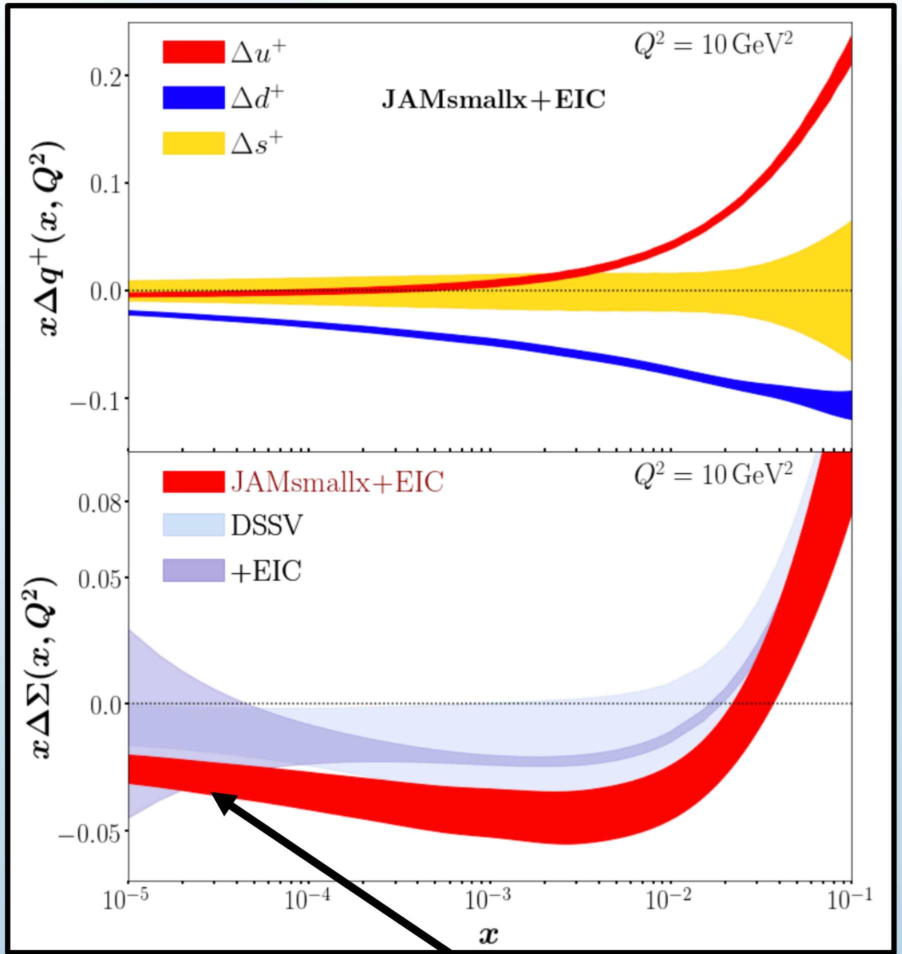

Uncertainties remain consistent even below EIC kinematics

Current State of Helicity PDFs

Proton spin puzzle:

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

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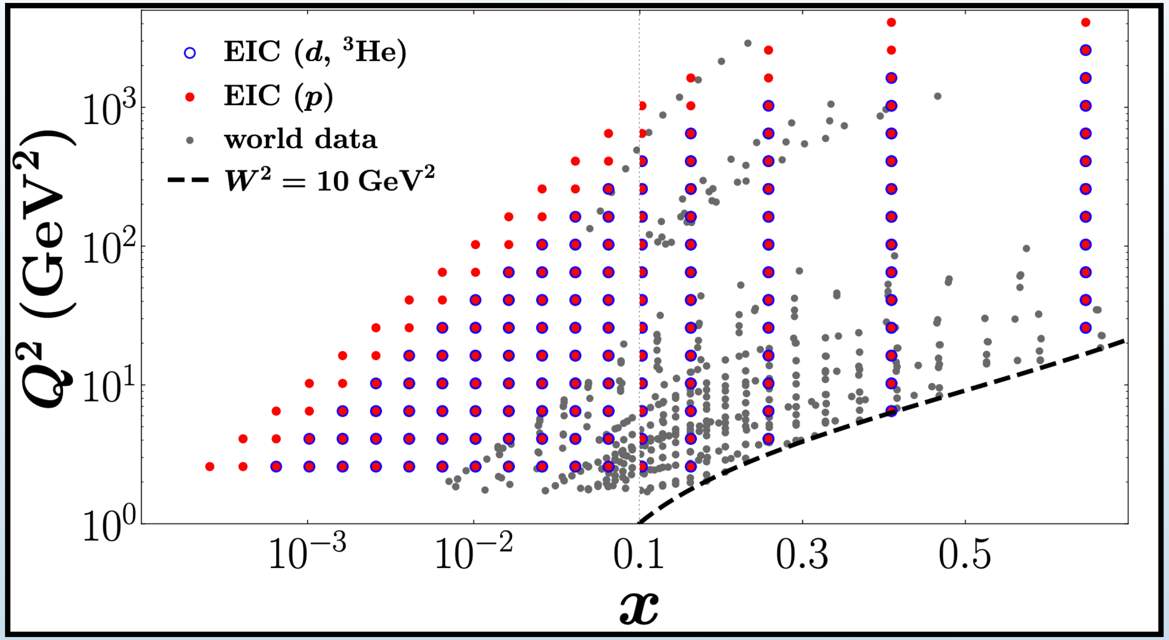

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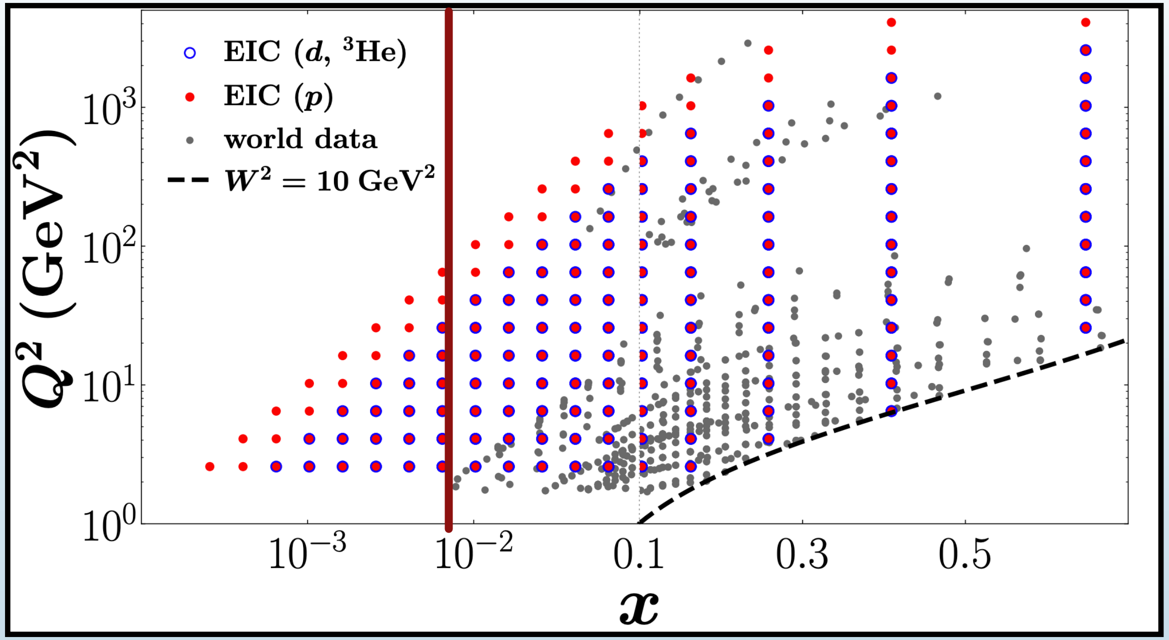

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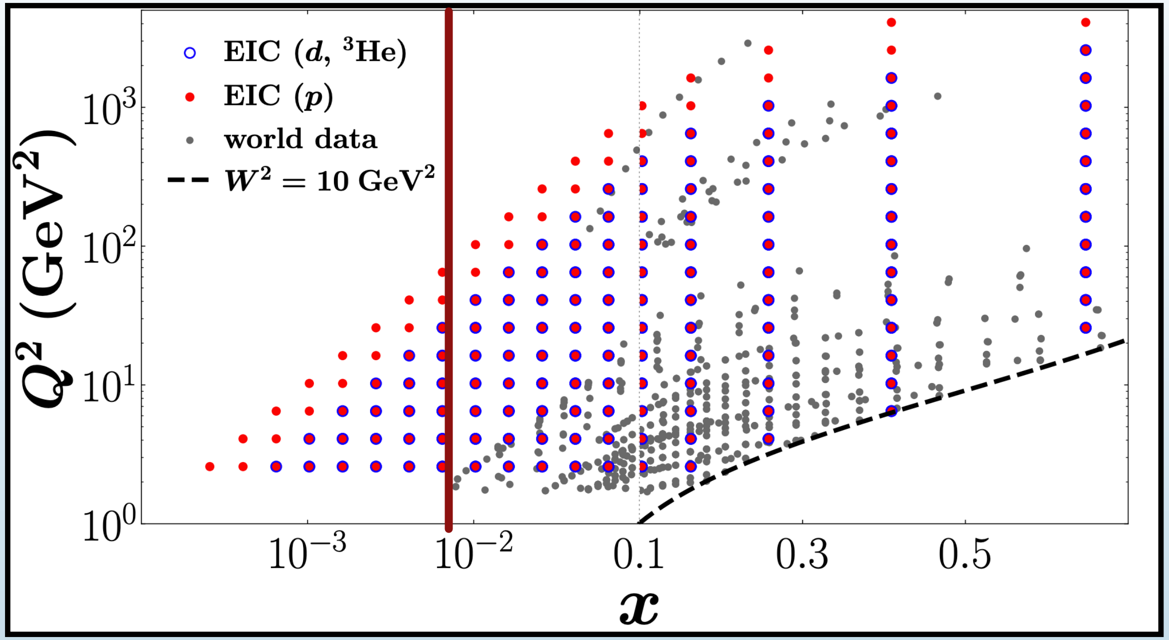

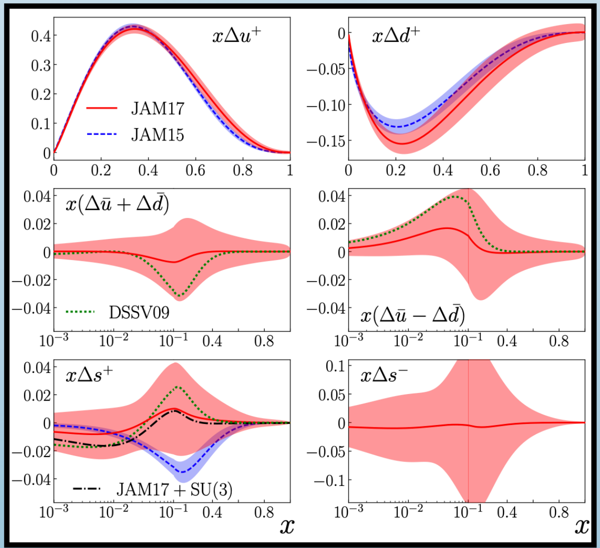

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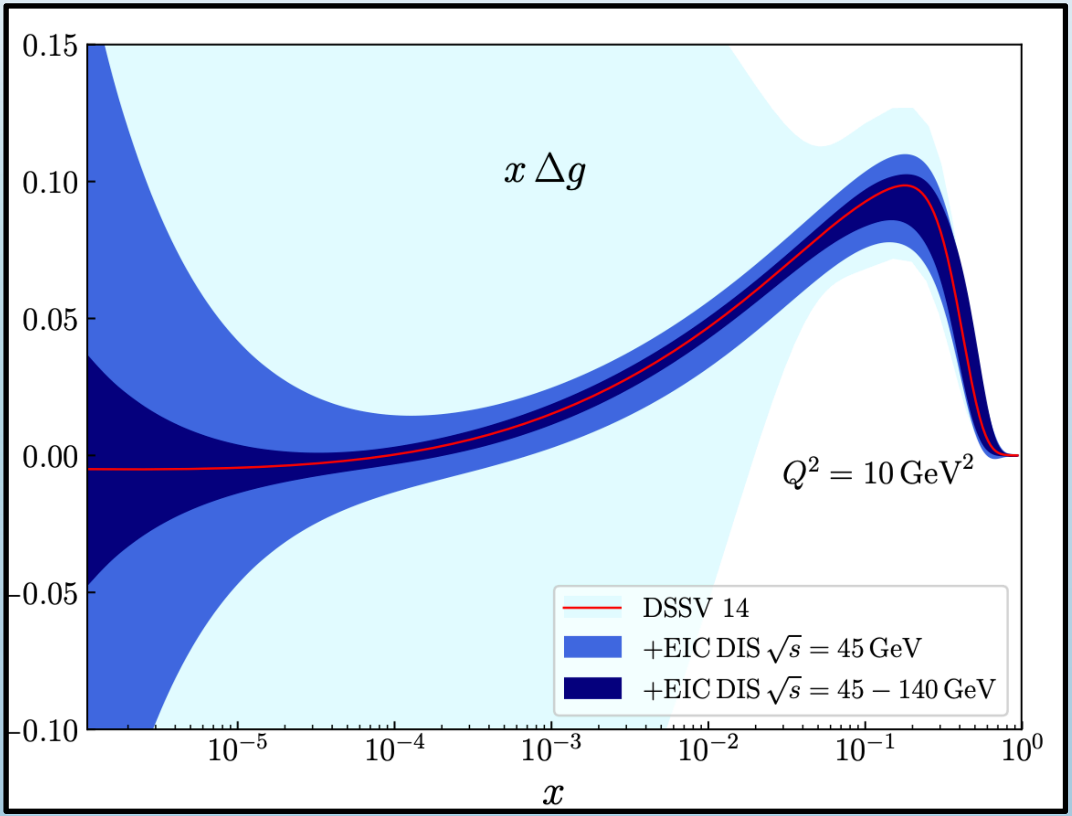

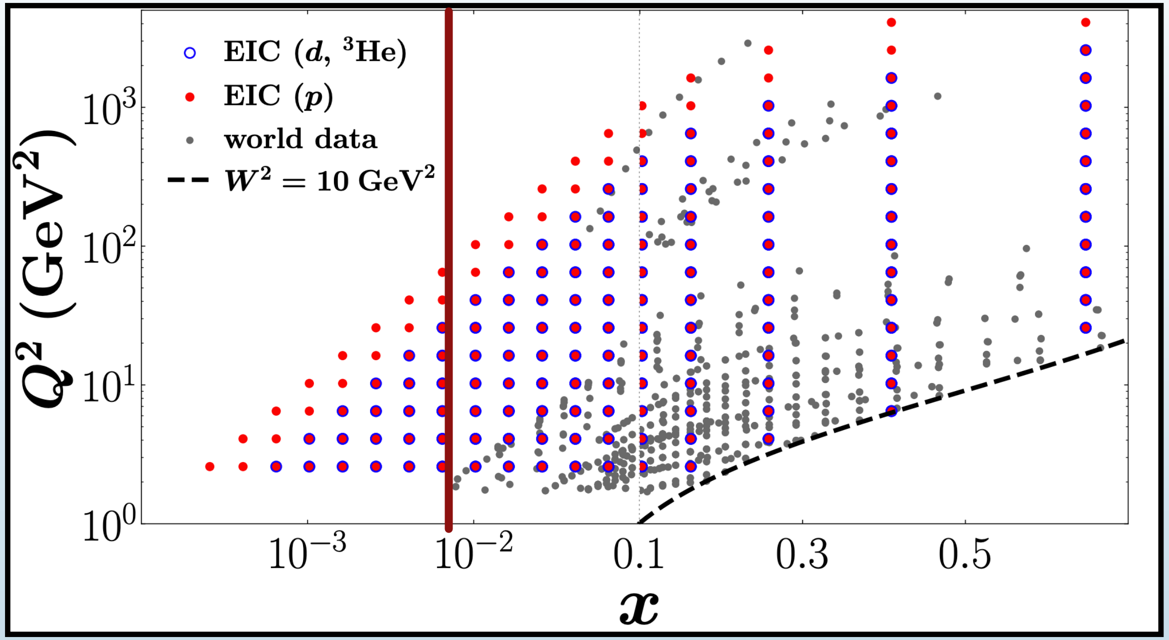

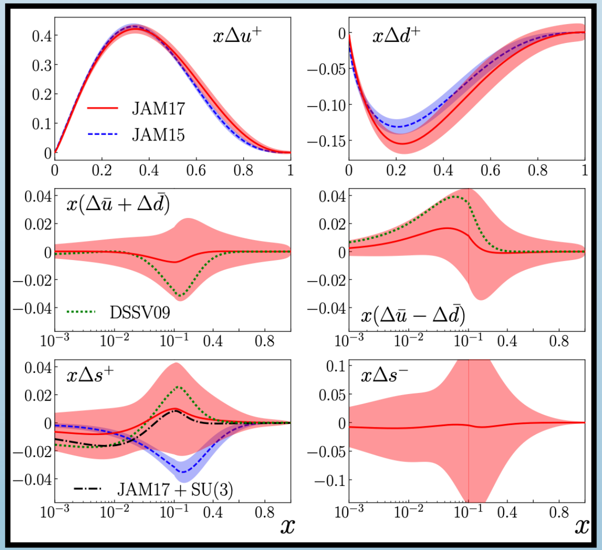

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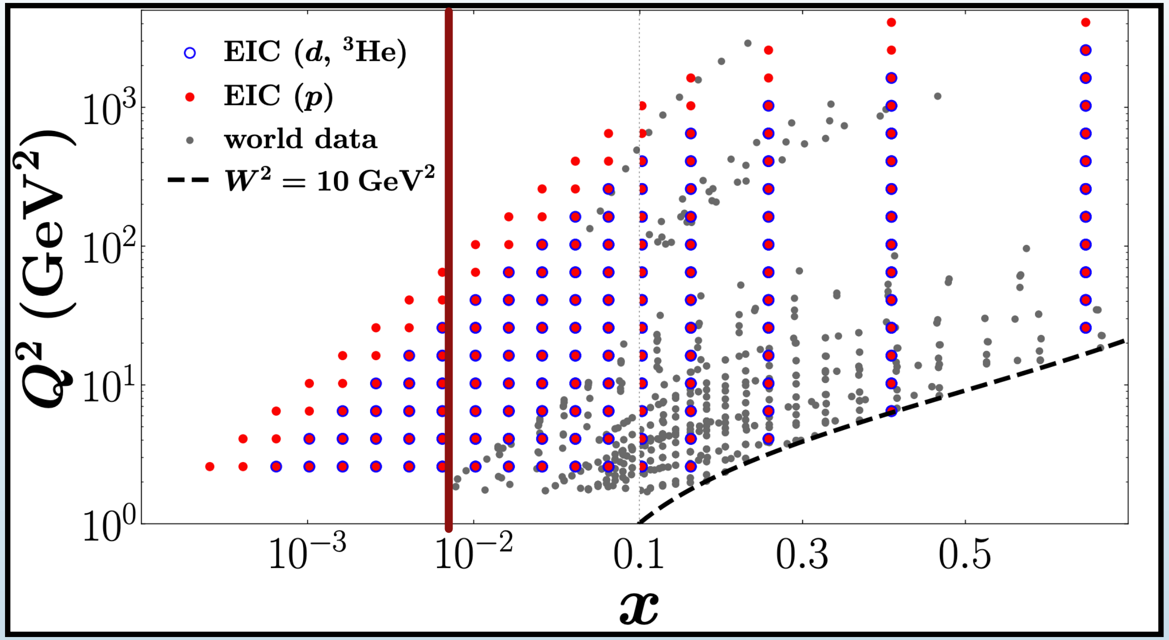
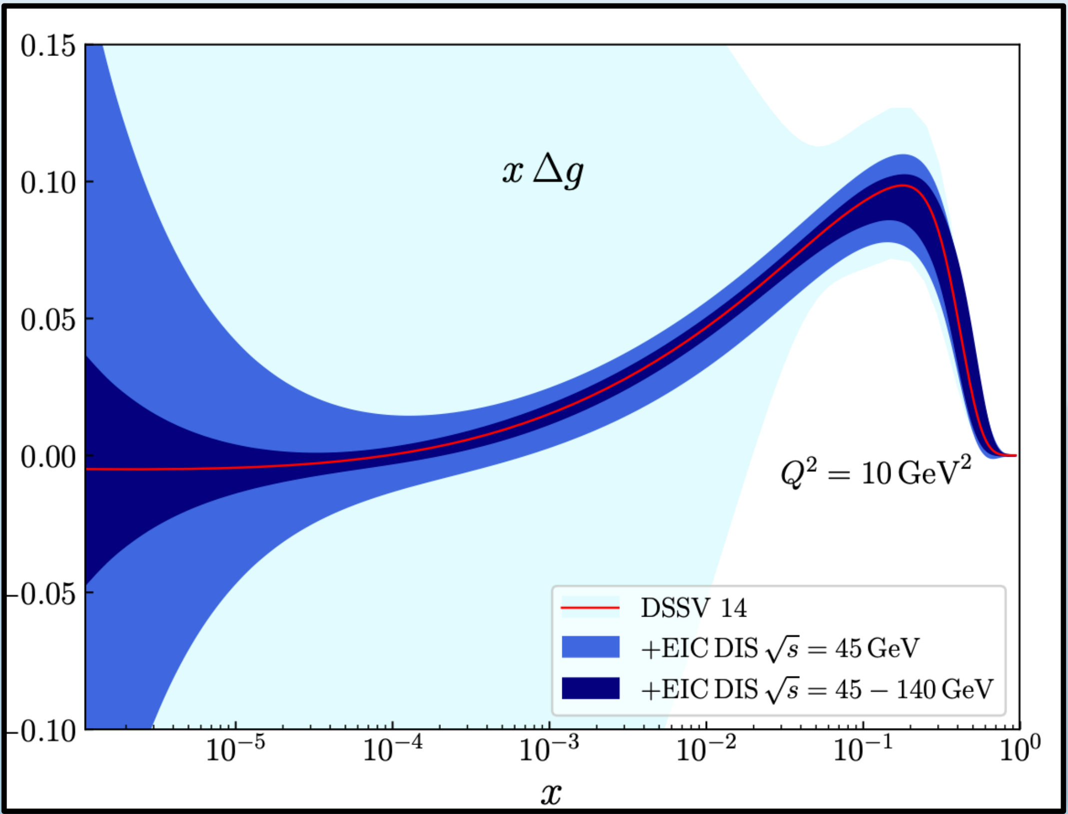
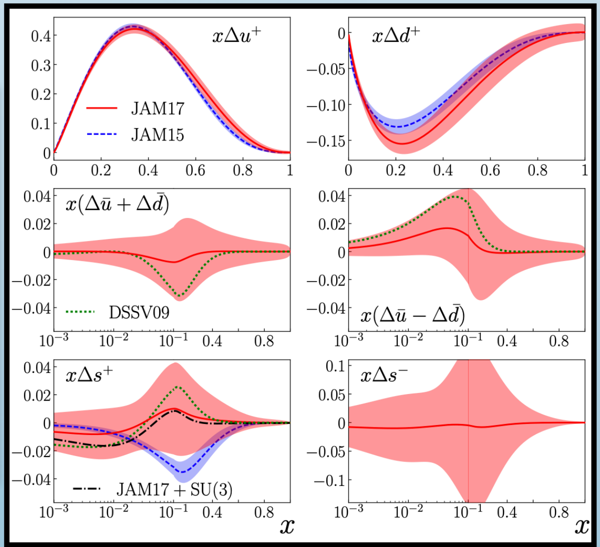




Still a lot to learn about helicity PDFs at low x and the helicity sea quark PDFs!



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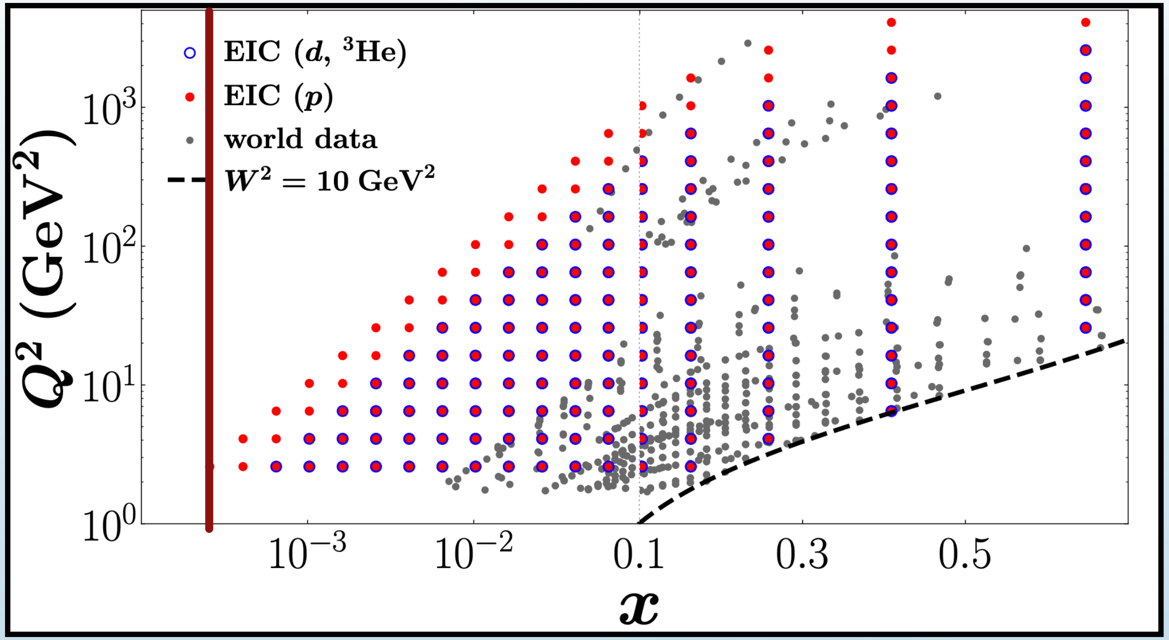

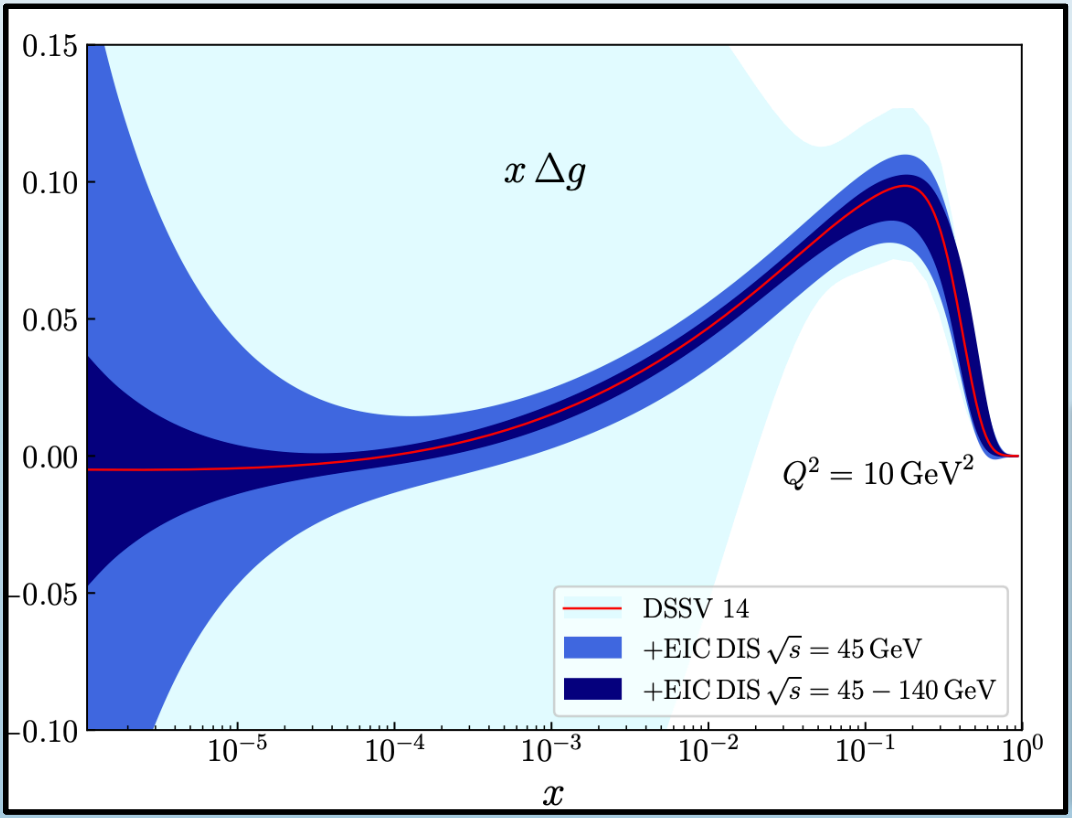

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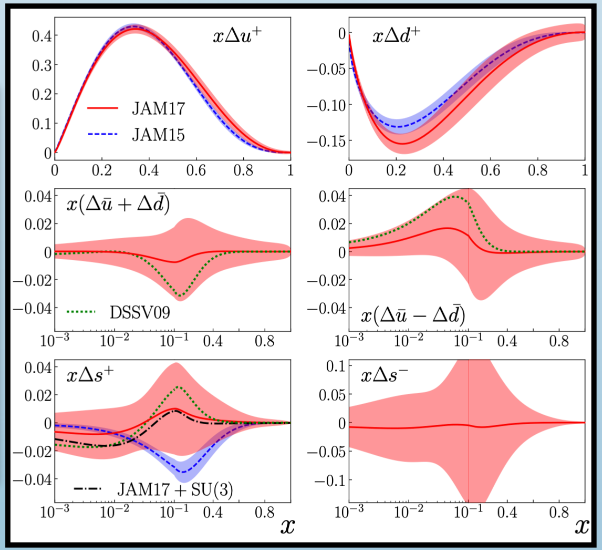

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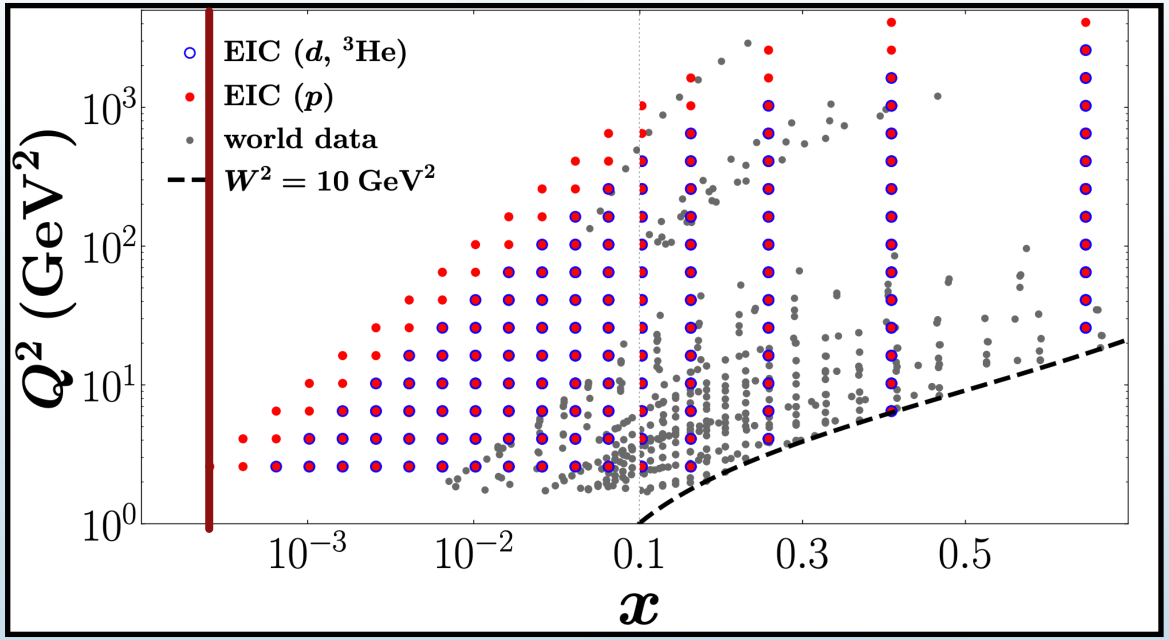

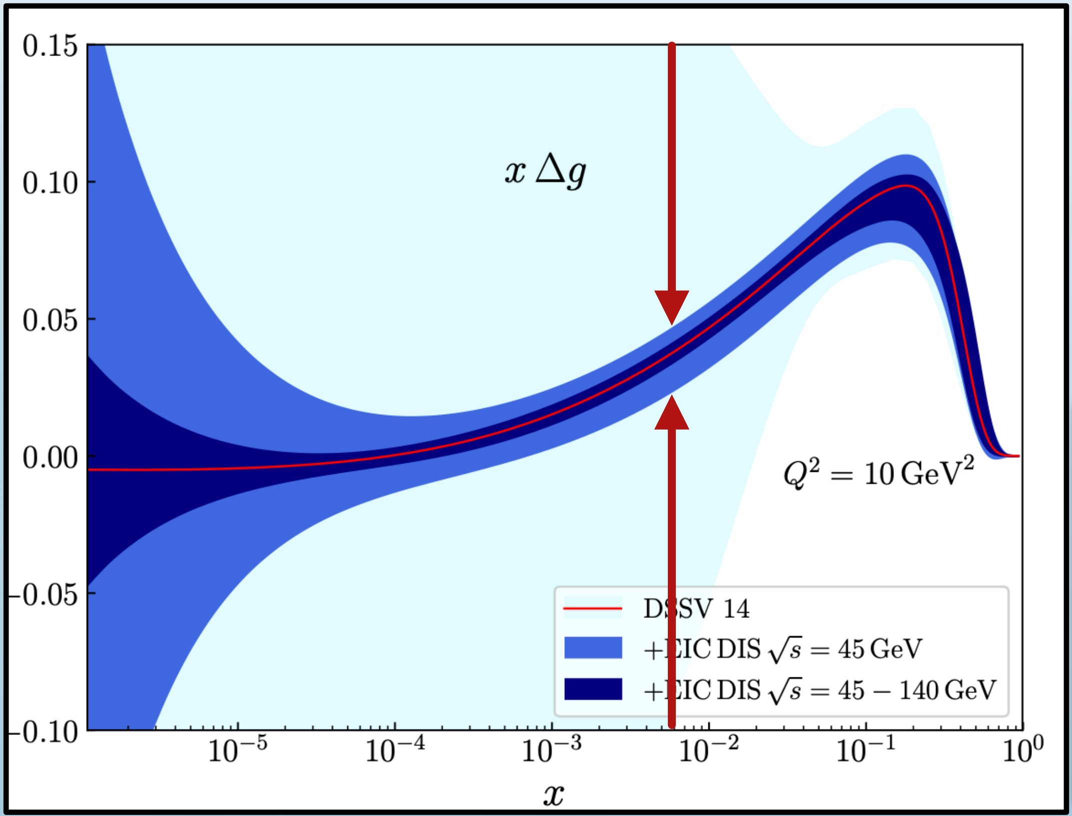

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