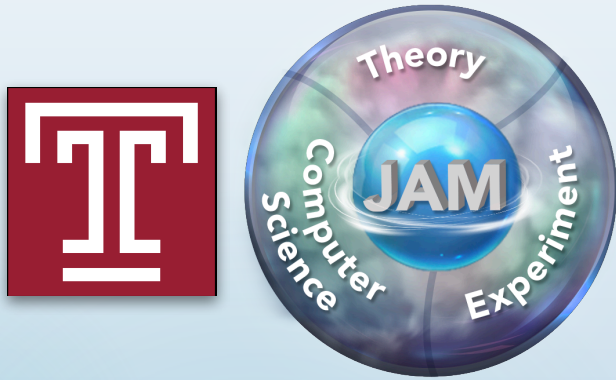


Recent Updates from the JAM Collaboration on Helicity PDFs

Christopher Cocuzza



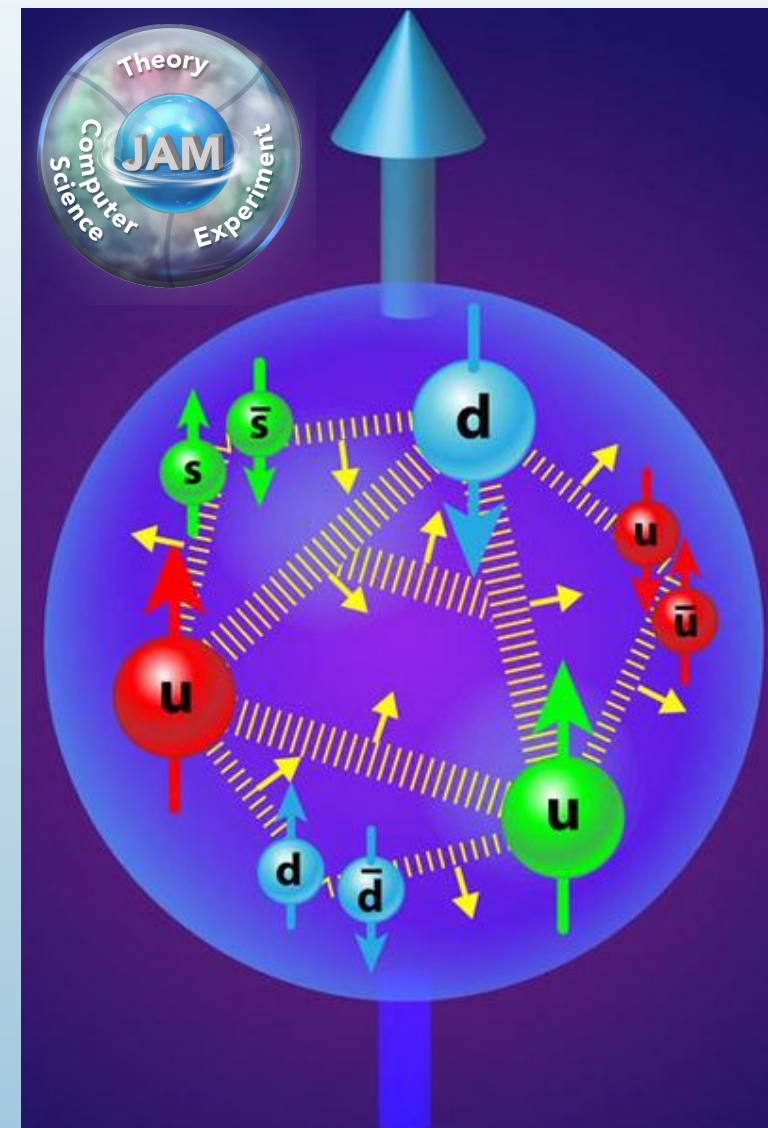
September 26, 2023



JAM Collaboration

3-dimensional structure of nucleons:

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

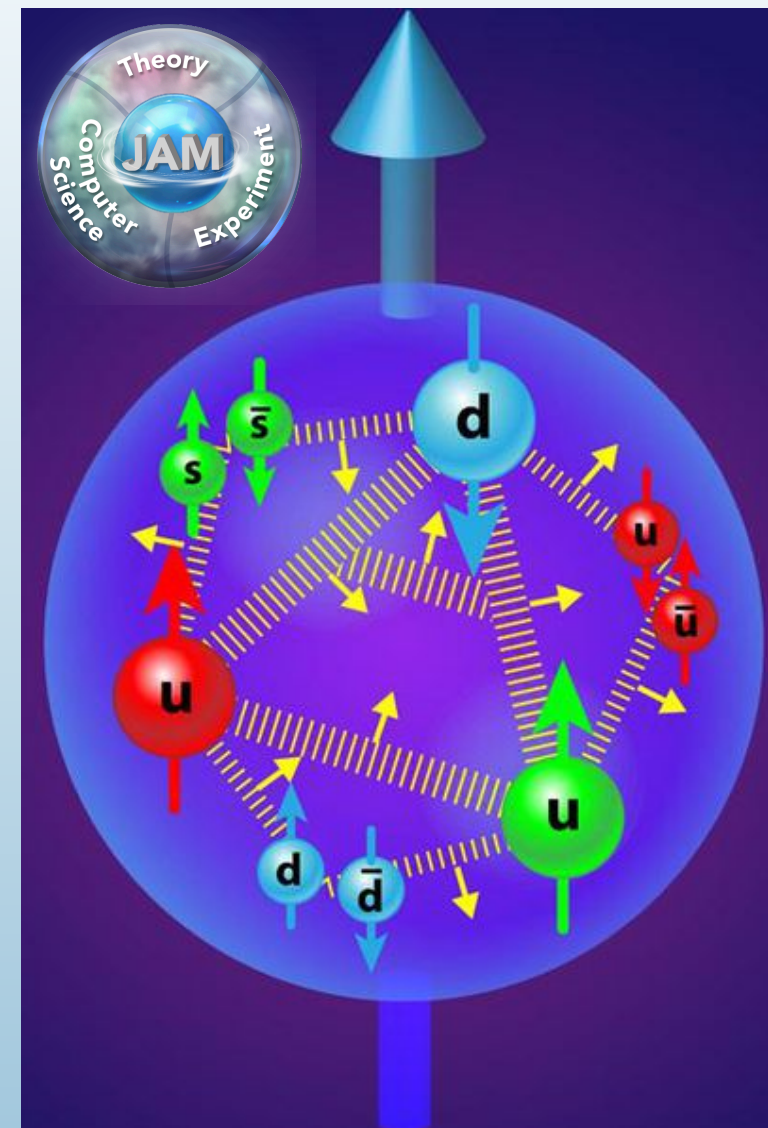


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3-dimensional structure of nucleons:

- 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





Hadron
Structure



Global
QCD
Analysis



Hadron
Structure

Global
QCD
Analysis



Hadron
Structure

Global
QCD
Analysis





Hadron
Structure

Global
QCD
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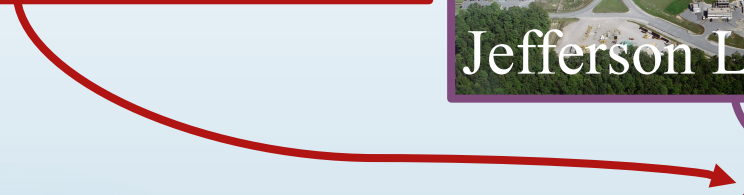
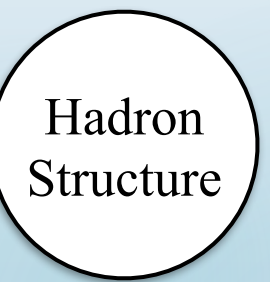




Hadron
Structure

Global
QCD
Analysis







Hadron Structure

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

Param. + Evolve + Factorization

$$\sigma = \sum_{i,j} H_{ij} \otimes f_i \otimes f_j$$

Global QCD Analysis



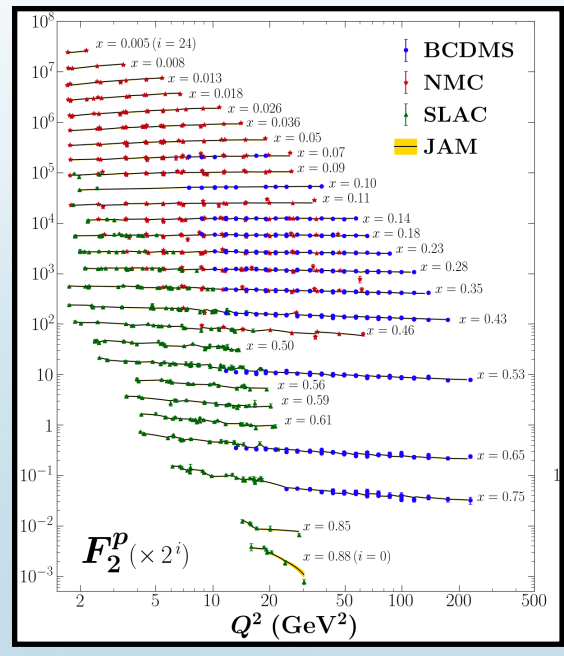


$$\chi^2(\mathbf{a}) = \sum_{i,e} \left(\frac{d_{i,e} - \sum_k r_e^k \beta_{i,e}^k - T_{i,e}(\mathbf{a})/N_e}{\alpha_{i,e}} \right)^2 + \sum_k (r_e^k)^2 + \left(\frac{1 - N_e}{\delta N_e} \right)^2$$

χ^2 Minimization

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

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



Hadron Structure

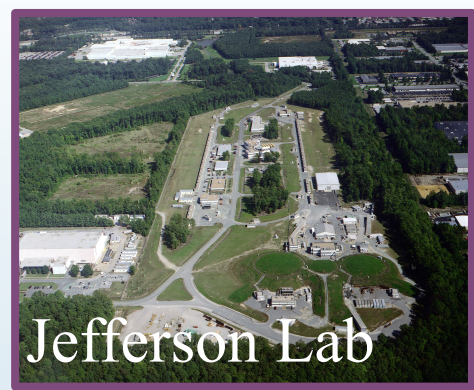
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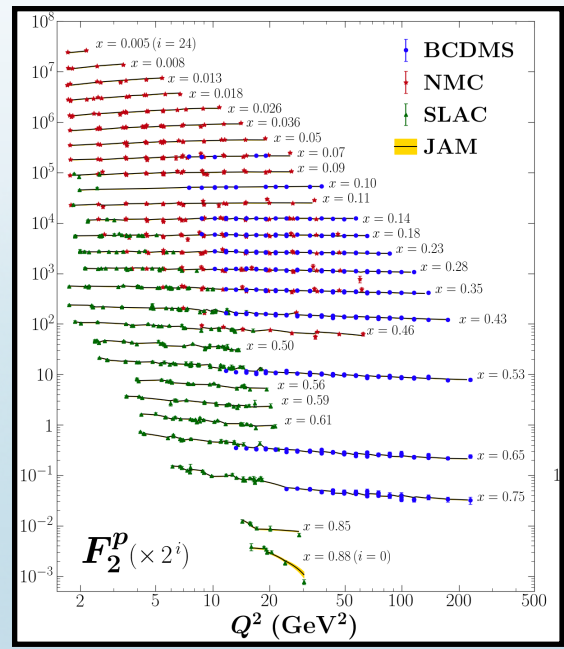


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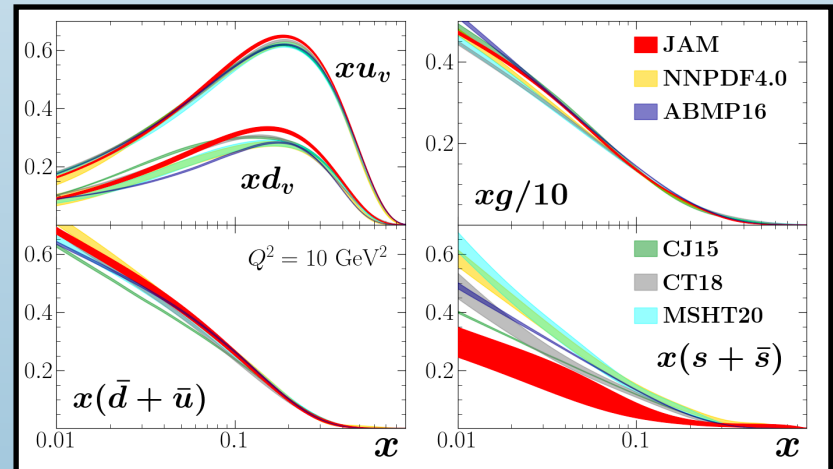
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Global QCD Analysis



Data Resampling

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

Current State of Helicity PDFs

Proton spin puzzle:

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

$$\Delta\Sigma = \int_0^1 dx \sum_q \Delta q^+$$

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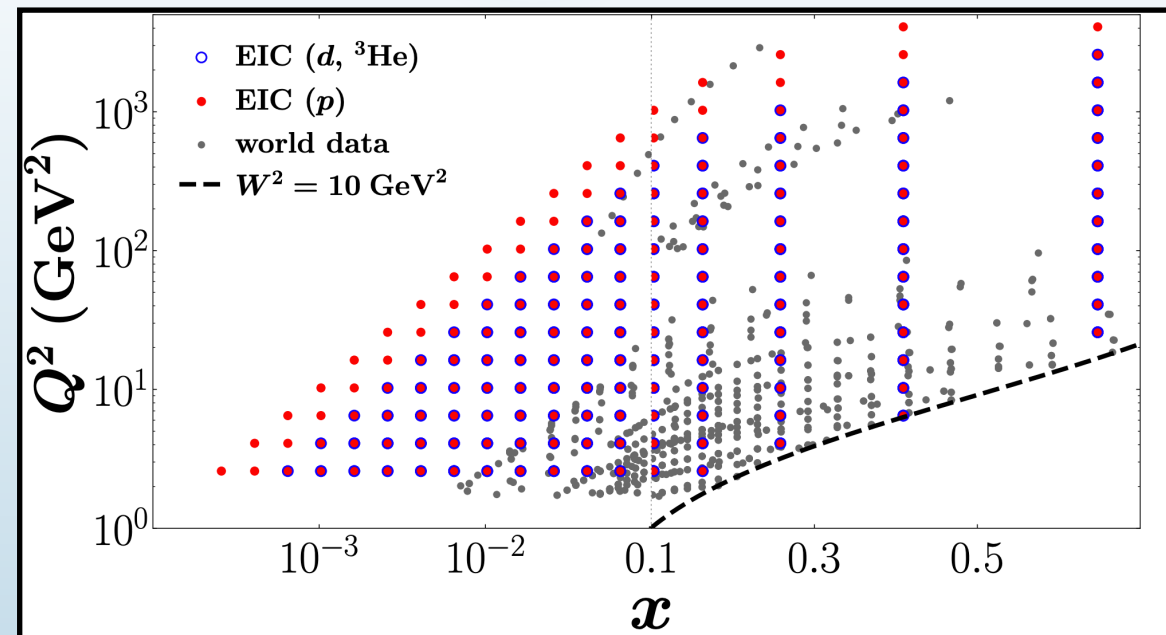
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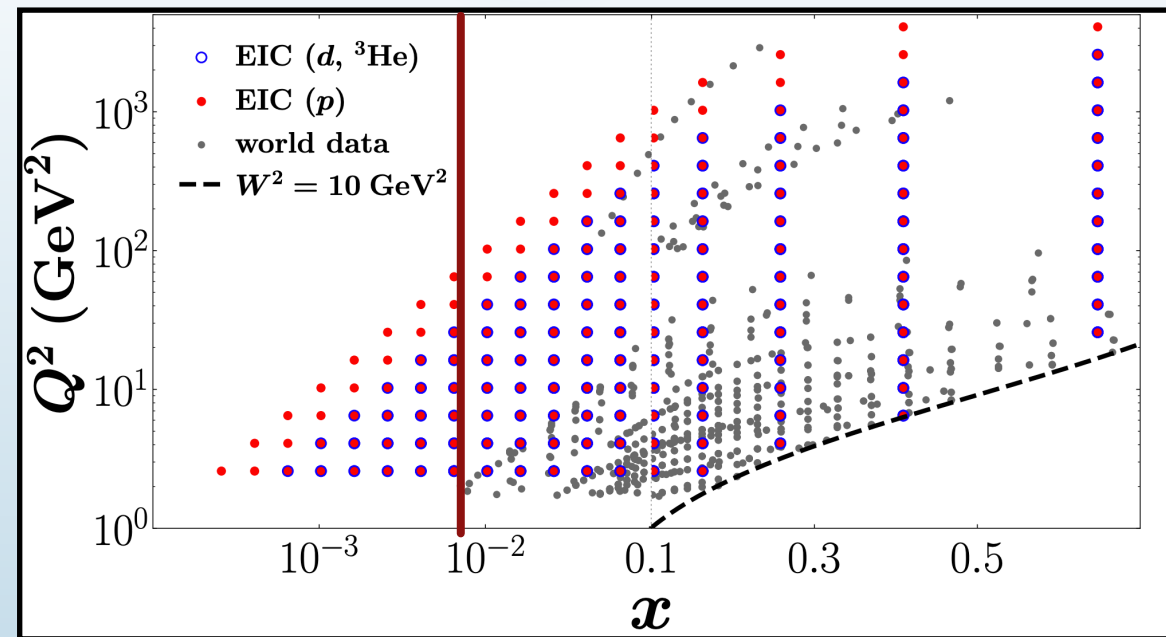
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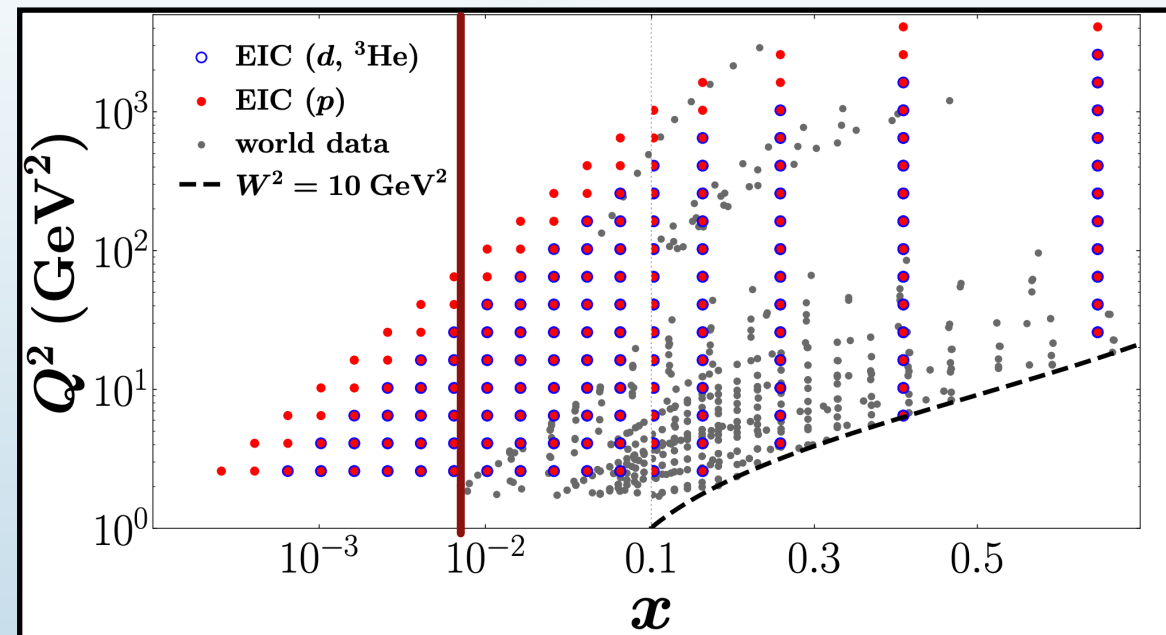
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Still a lot to learn about
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(antiquarks and gluon)

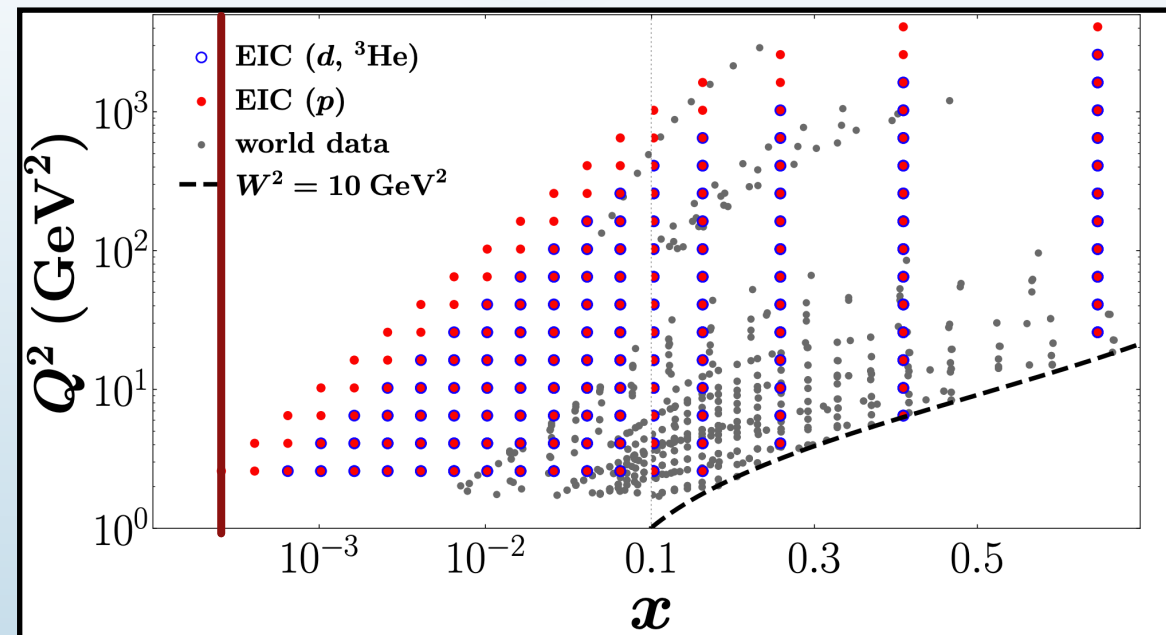
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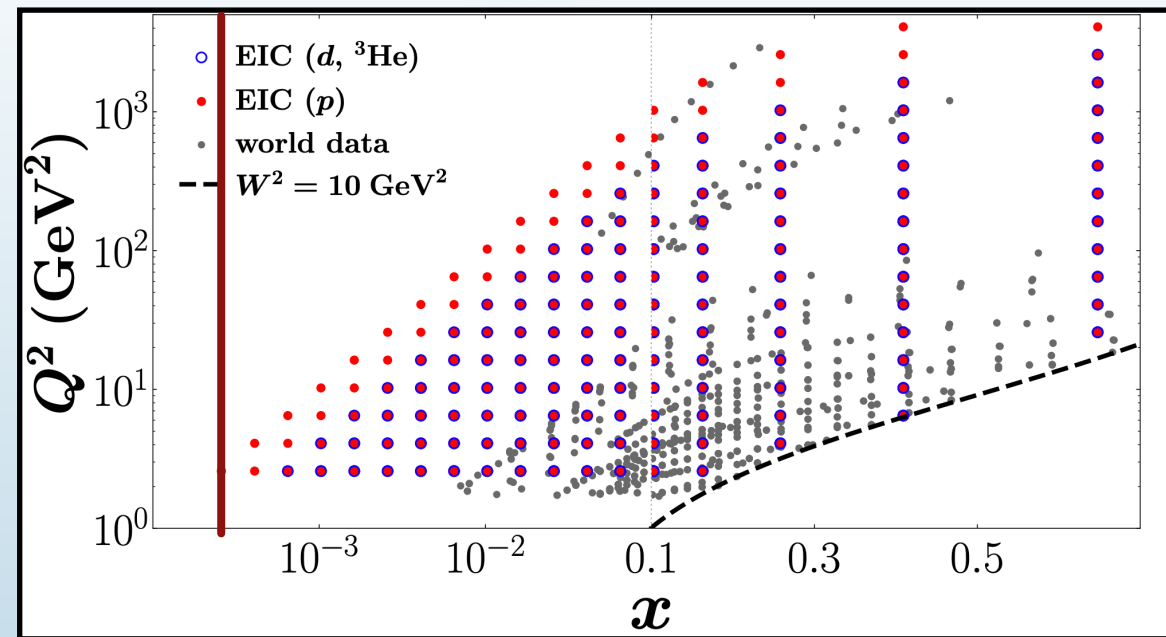
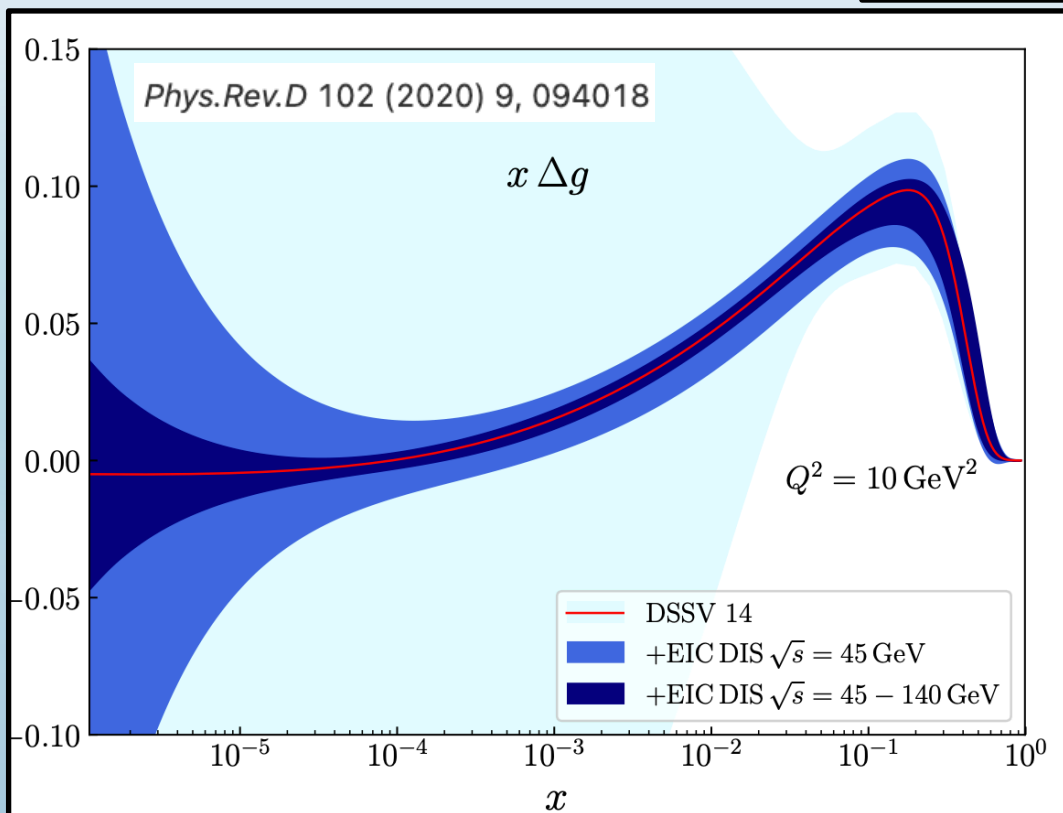
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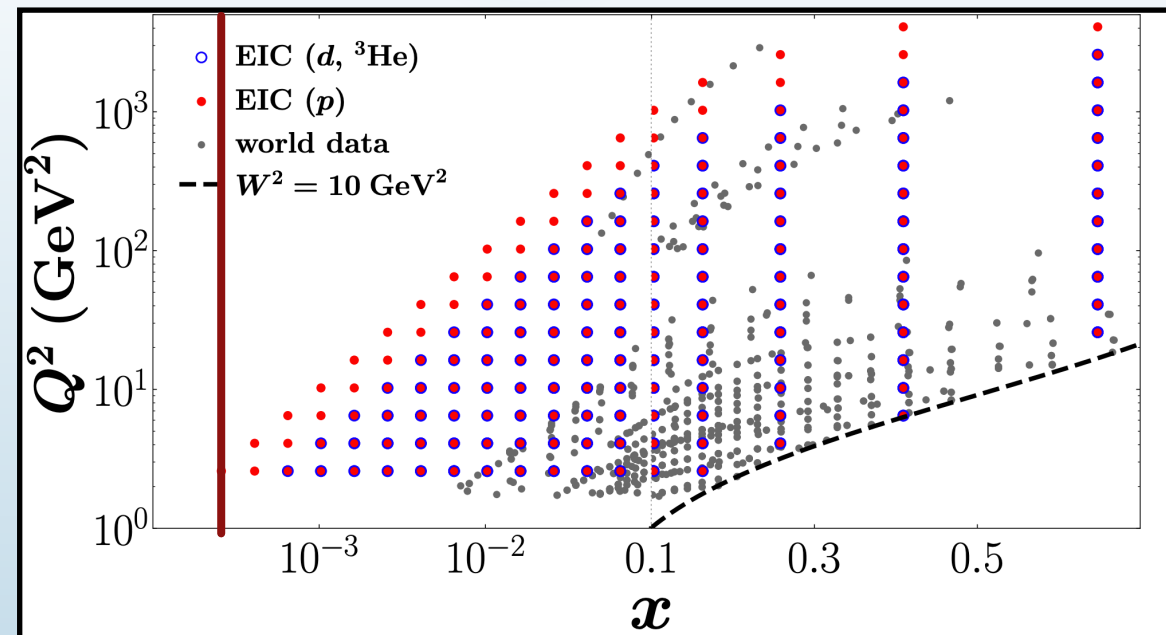
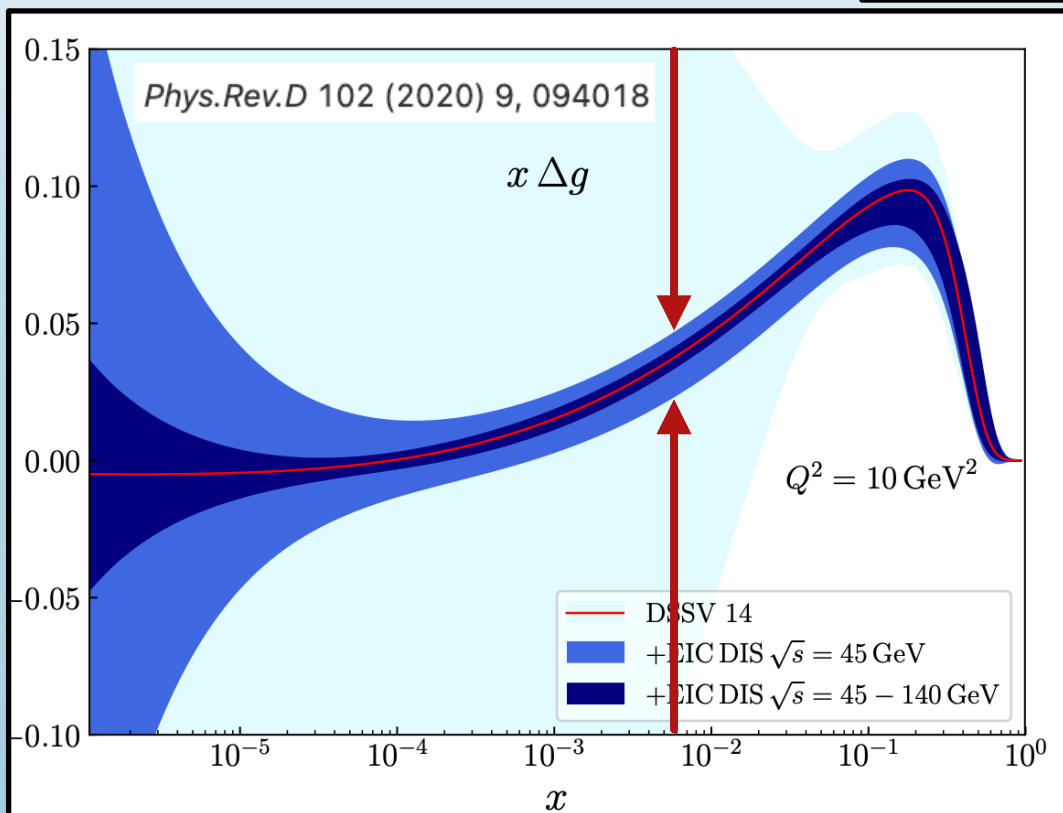
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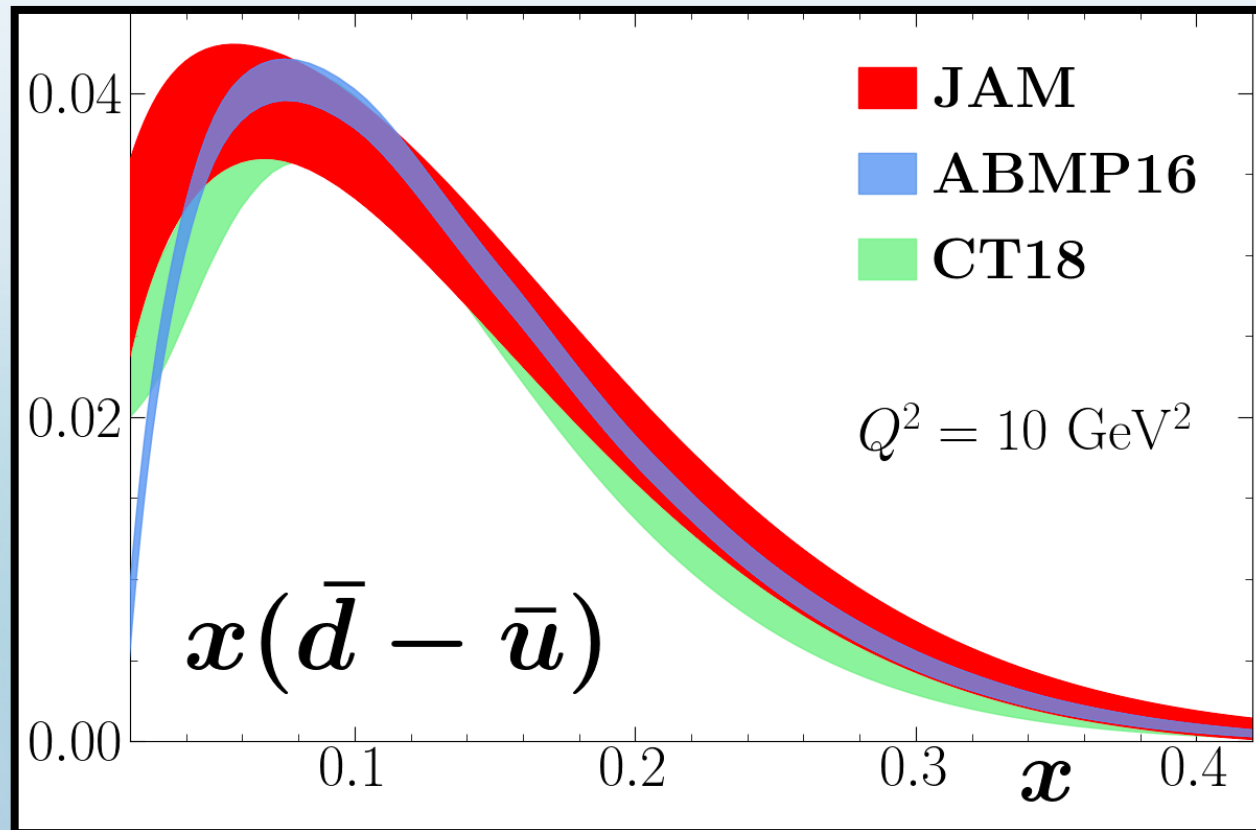
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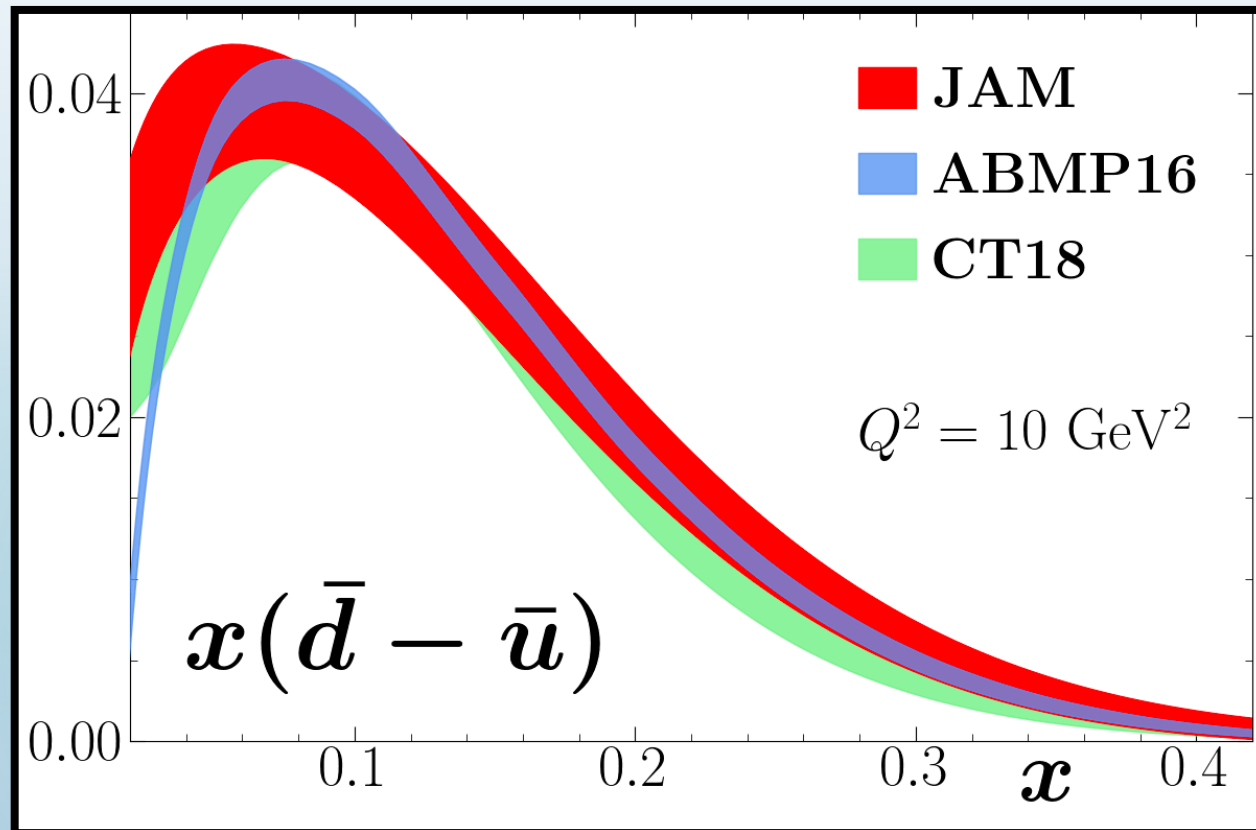


Introduction to Sea Asymmetry



Unpolarized

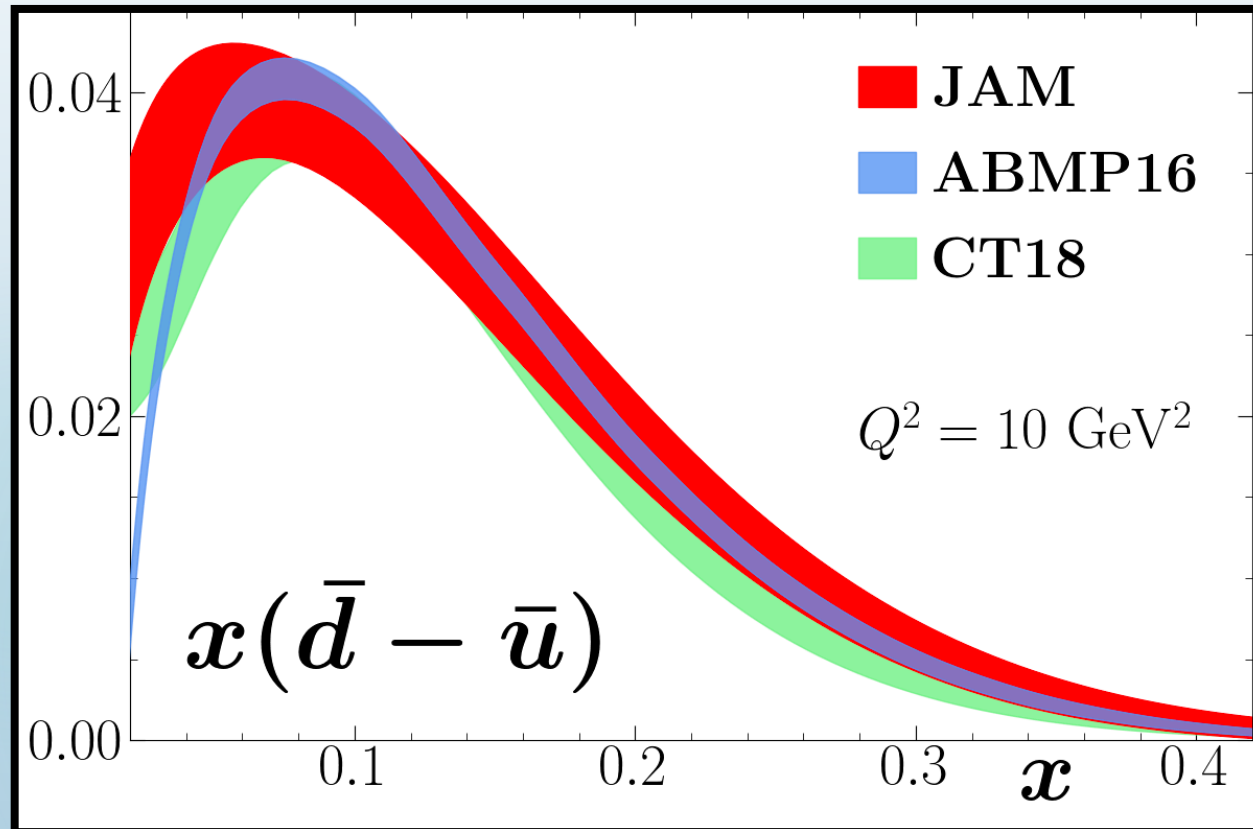
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Unpolarized

Cannot be explained from gluons
splitting into quark-antiquark pairs

Introduction to Sea Asymmetry

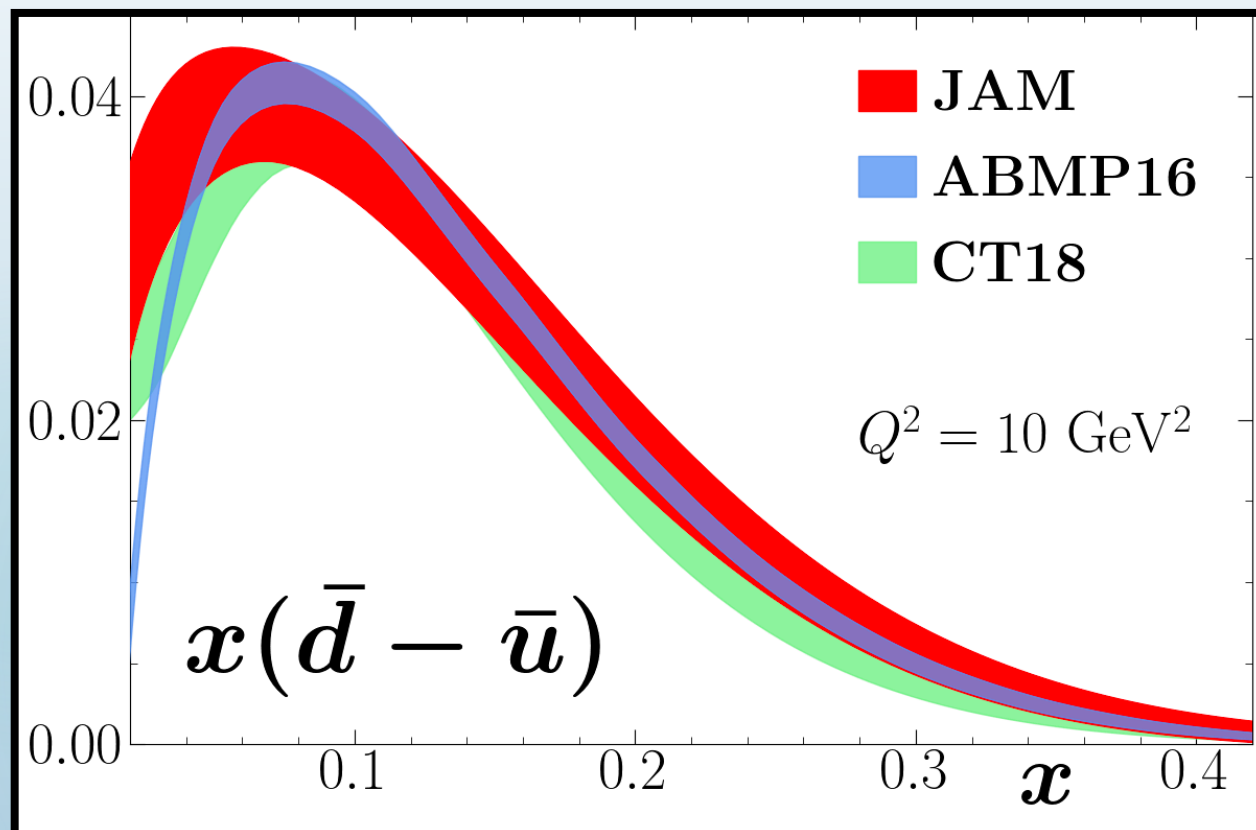


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Meson Cloud Models
Chiral Soliton Models
Statistical Models

Introduction to Sea Asymmetry



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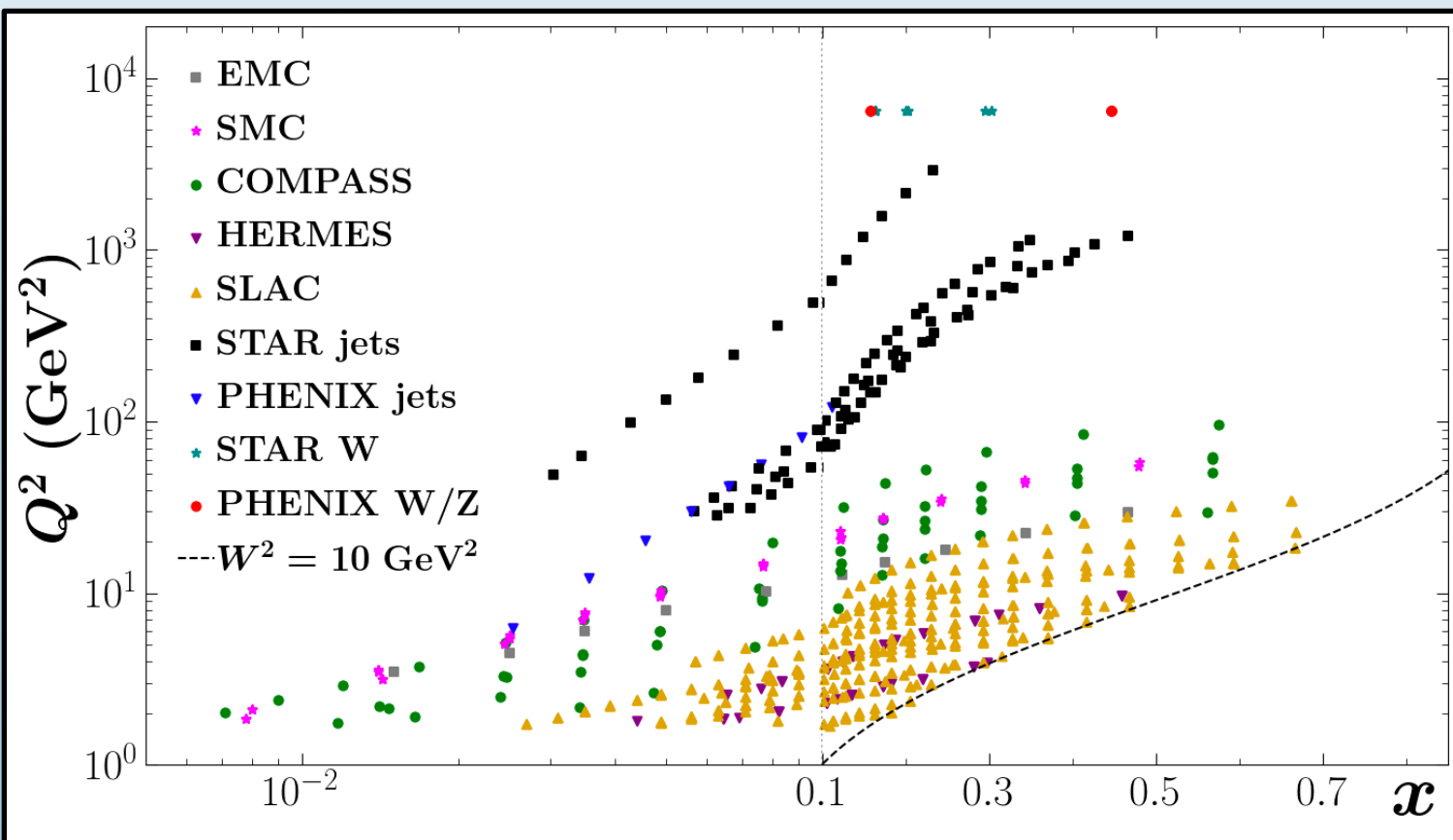
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Meson Cloud Models
Chiral Soliton Models
Statistical Models

Still questions for helicity
asymmetry

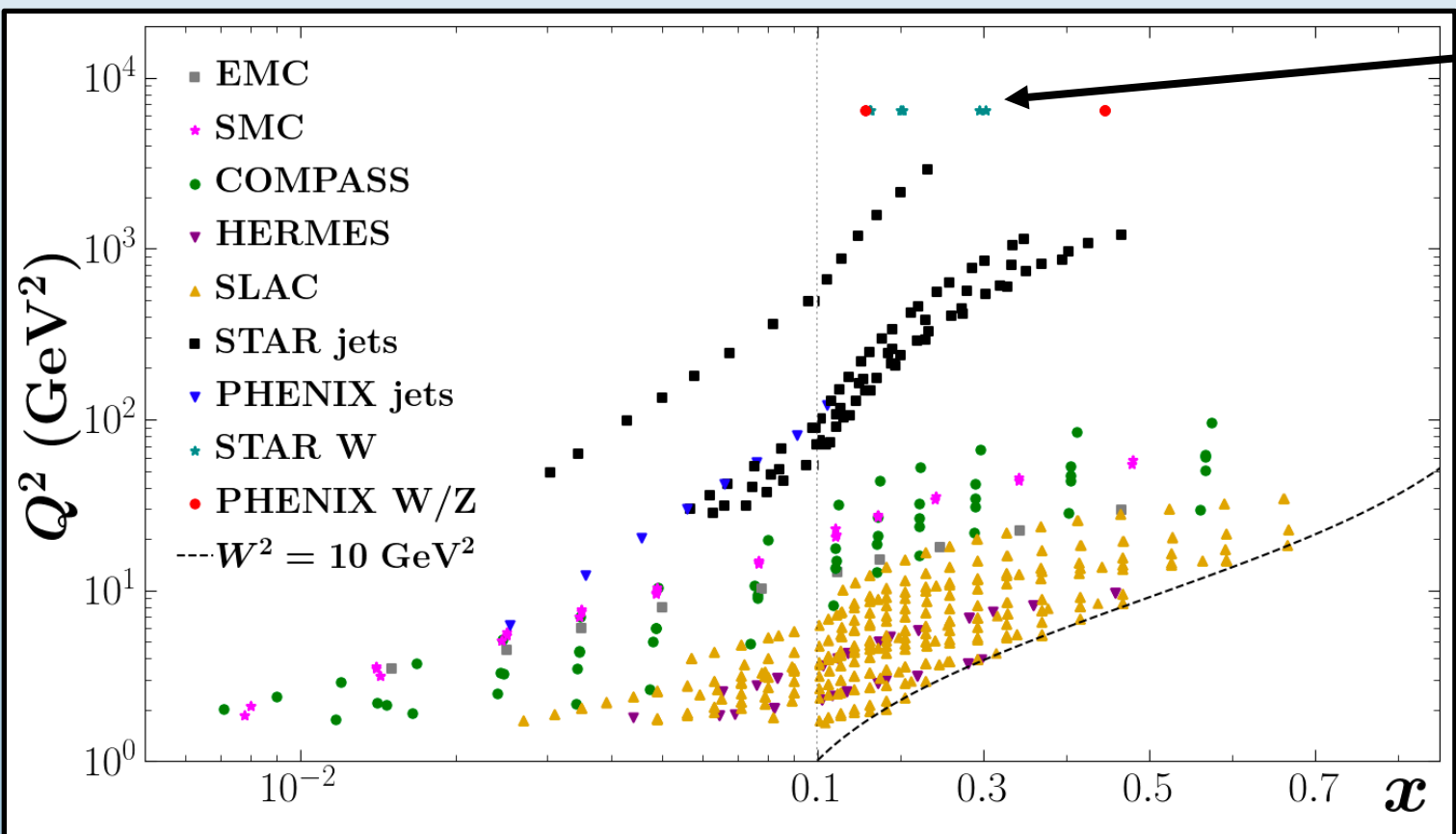
Kinematic Coverage (Helicity)

Deep Inelastic Scattering	COMPASS, EMC, HERMES, SLAC, SMC	365 points
Semi-Inclusive DIS	COMPASS, HERMES, SMC	231 points
W/Z Boson Production	STAR, PHENIX	18 points
Jets	STAR, PHENIX	61 points



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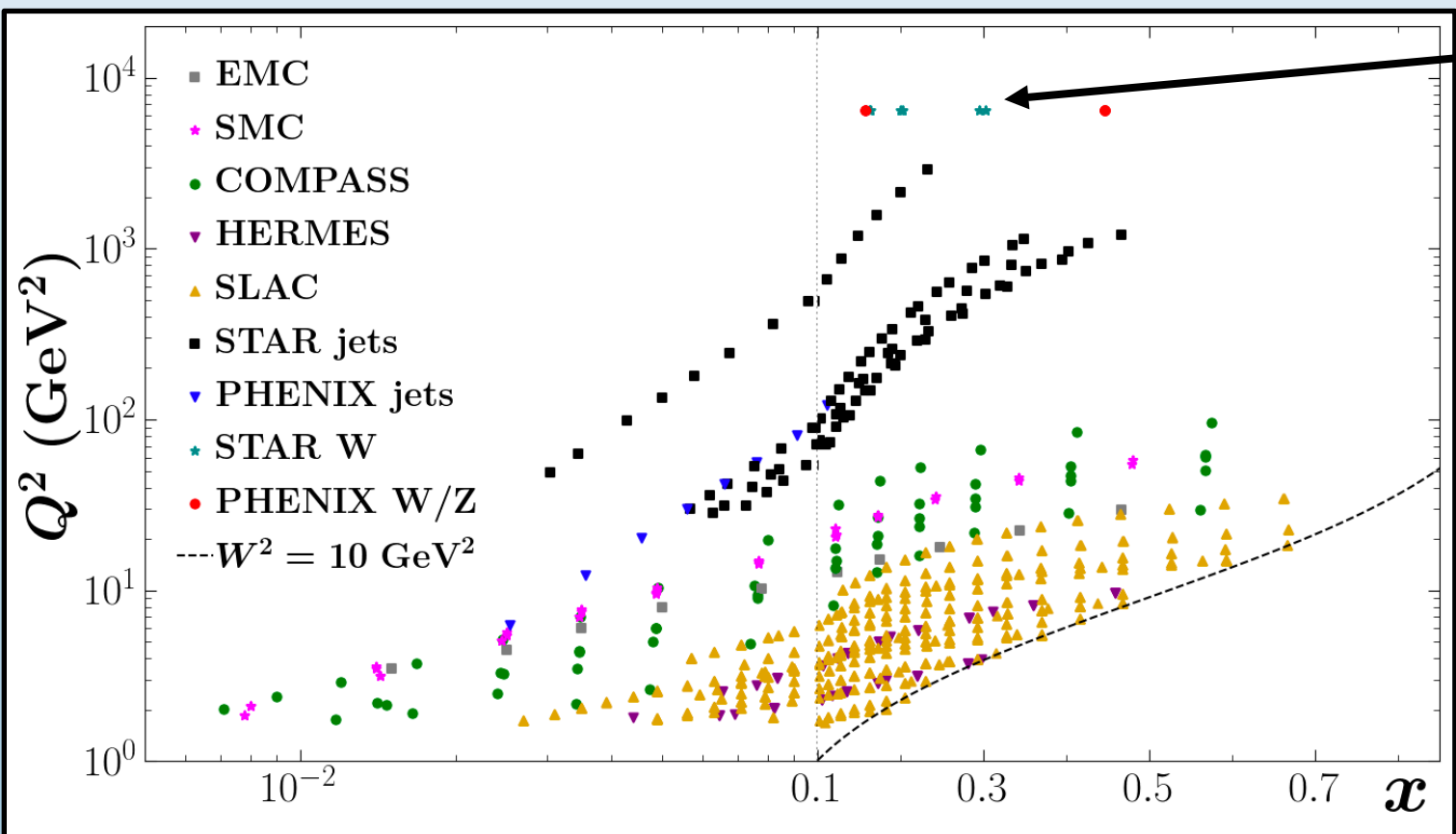
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STAR + PHENIX
W/Z Production

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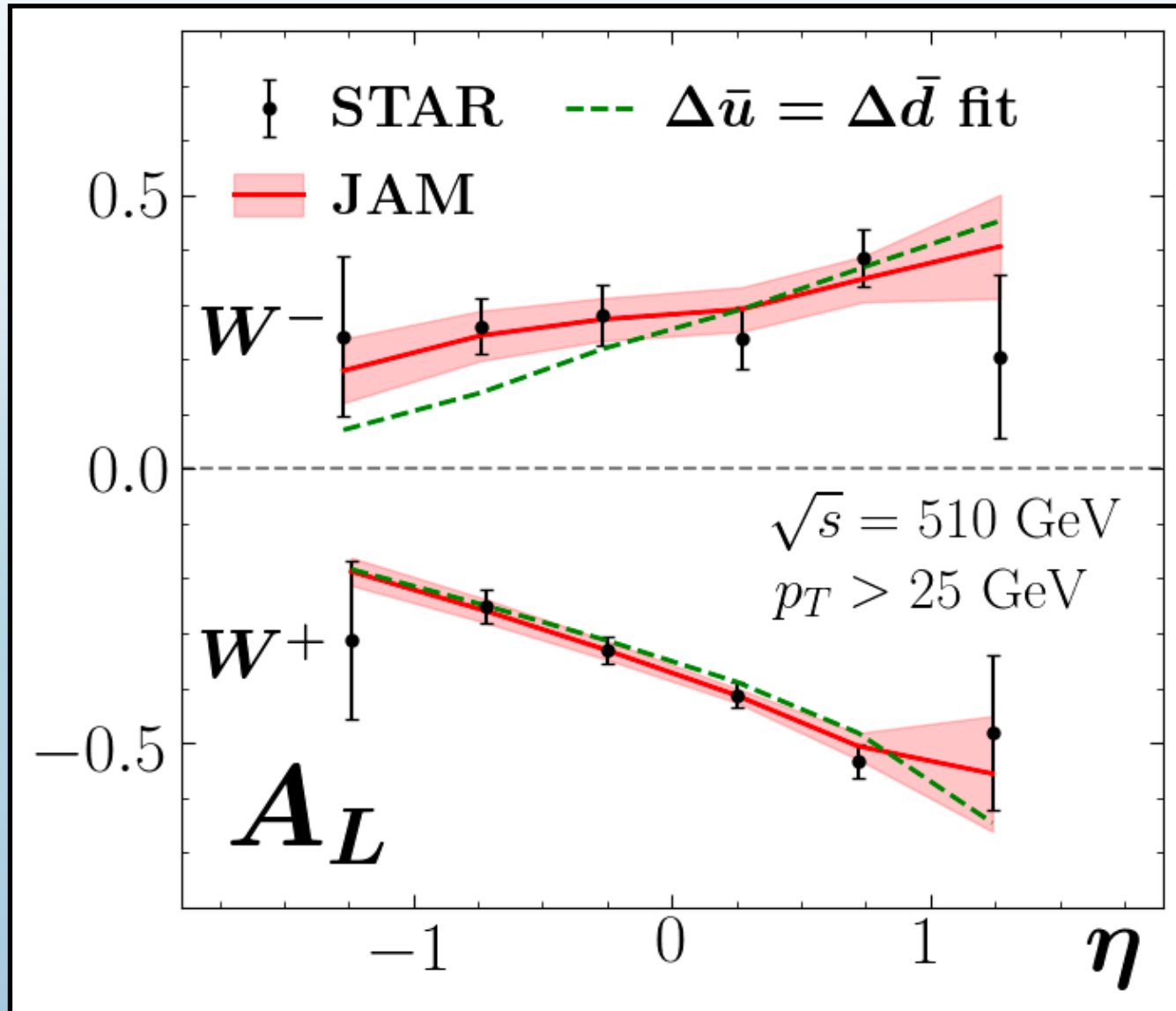
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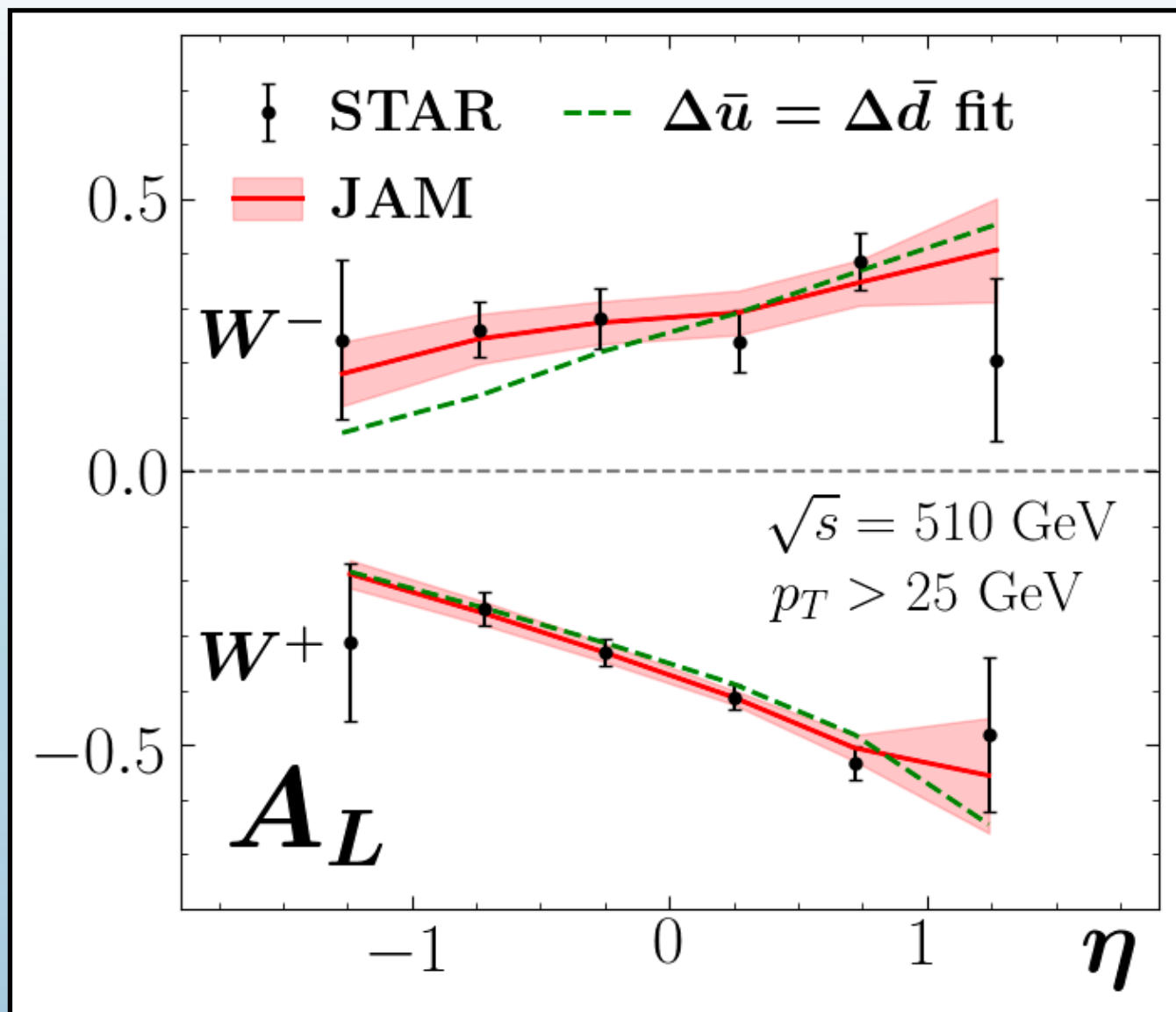
**STAR + PHENIX
W/Z Production**

process	N_{dat}	χ^2/N_{dat}
polarized		
inclusive DIS	365	0.95
SIDIS (π^+, π^-)	64	1.05
SIDIS (K^+, K^-)	57	0.42
SIDIS (h^+, h^-)	110	0.95
inclusive jets	83	0.84
STAR W^\pm	12	0.65
PHENIX W^\pm/Z	6	0.50
total	697	0.89
unpolarized		
inclusive DIS	3908	1.17
SIDIS (π^+, π^-)	498	0.94
SIDIS (K^+, K^-)	494	1.31
SIDIS (h^+, h^-)	498	0.71
inclusive jets	198	1.28
Drell-Yan	205	1.21
W/Z production	153	1.01
total	5954	1.12
SIA (π^\pm)	231	0.91
SIA (K^\pm)	213	0.70
SIA (h^\pm)	120	1.07
total	7215	1.08

STAR Quality of Fit



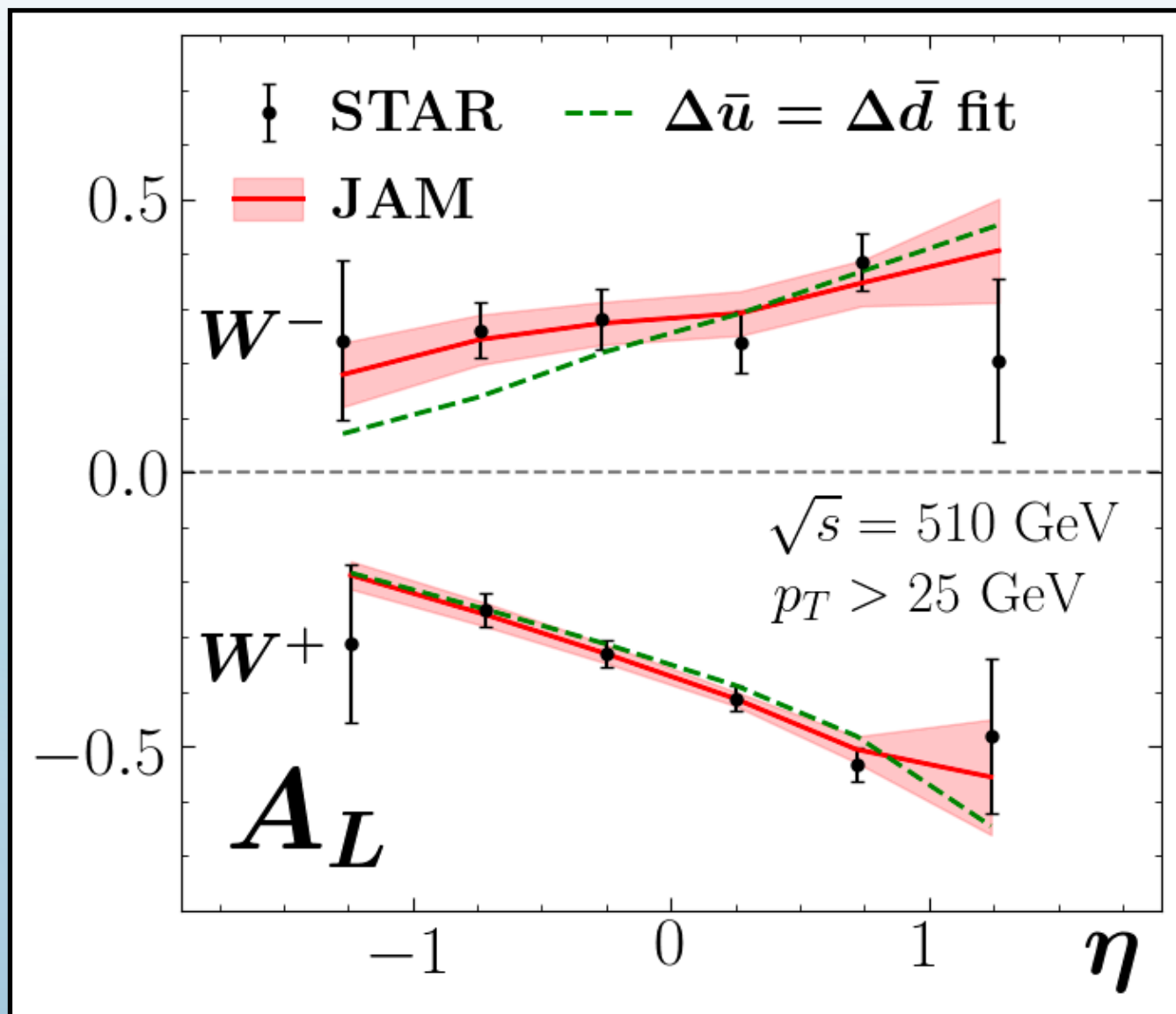
STAR Quality of Fit



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

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

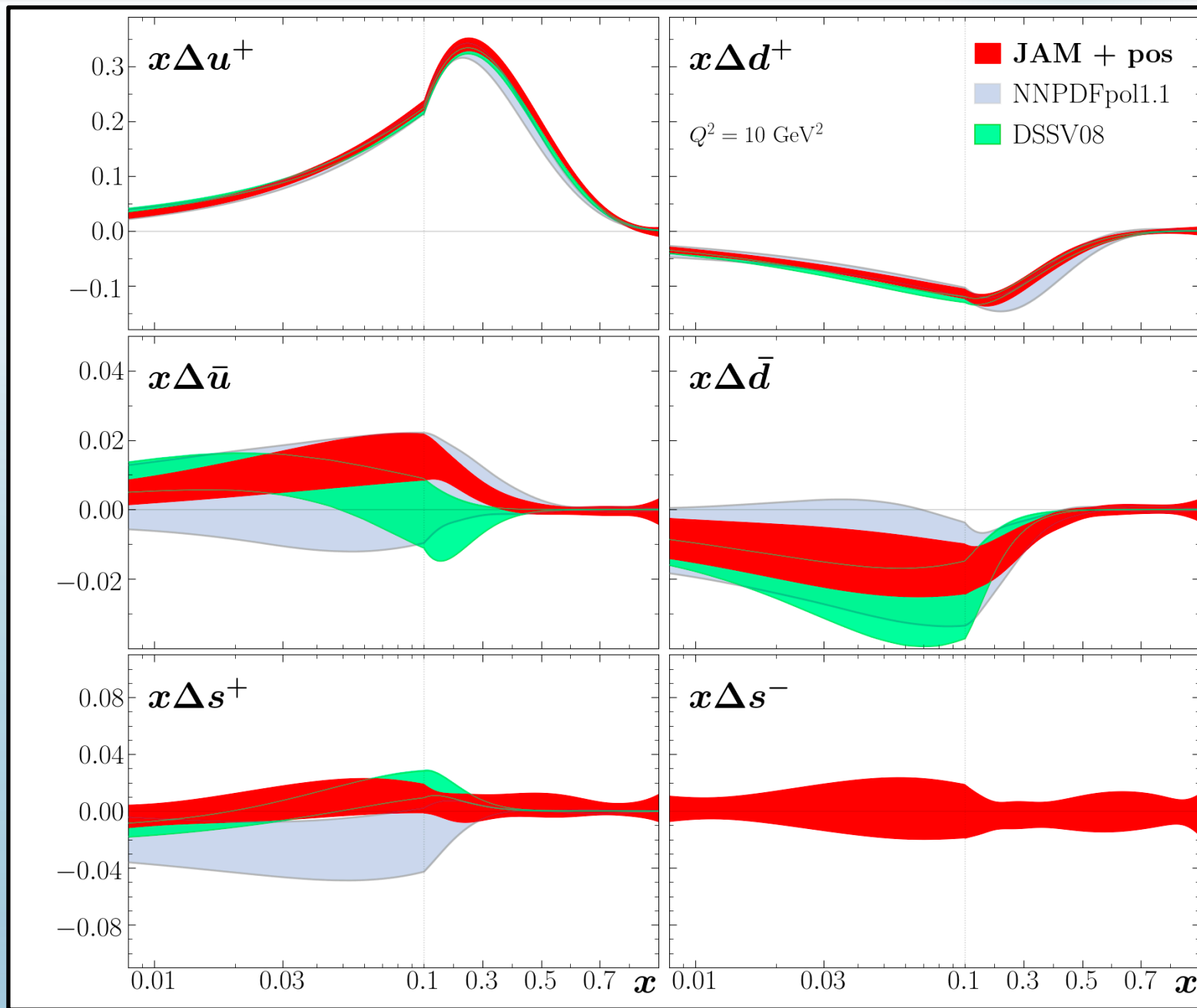
STAR Quality of Fit



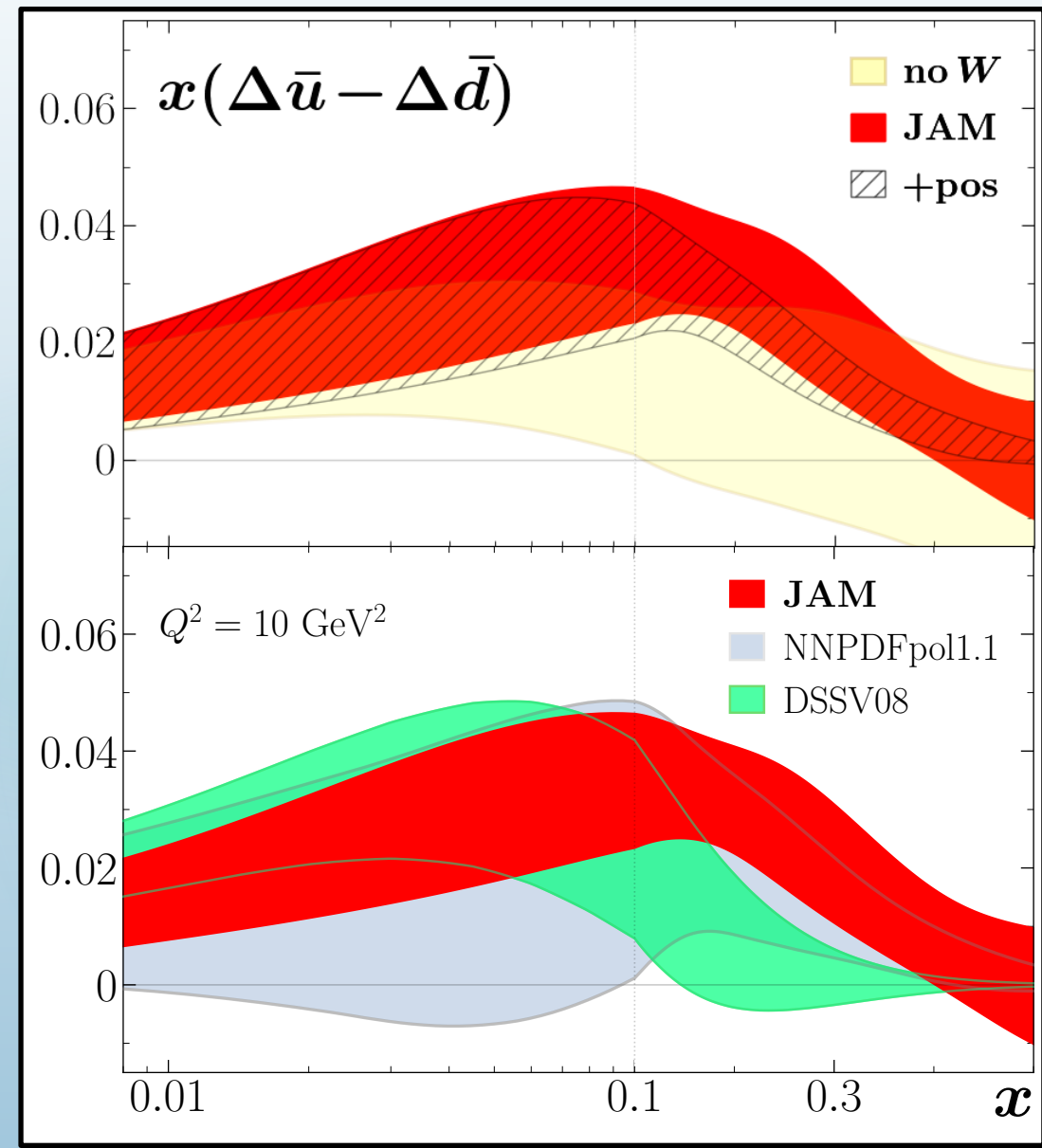
process	N_{dat}	JAM	χ^2/N_{dat}	
			+Pos.	$\Delta\bar{u} = \Delta\bar{d}$
STAR W^\pm	12	0.45	0.61	1.53
PHENIX W^\pm/Z	6	0.47	0.46	0.48
pol. DIS	365	0.93	0.93	0.93
pol. jet	61	1.00	1.03	1.00
total	444	0.92	0.94	0.95

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

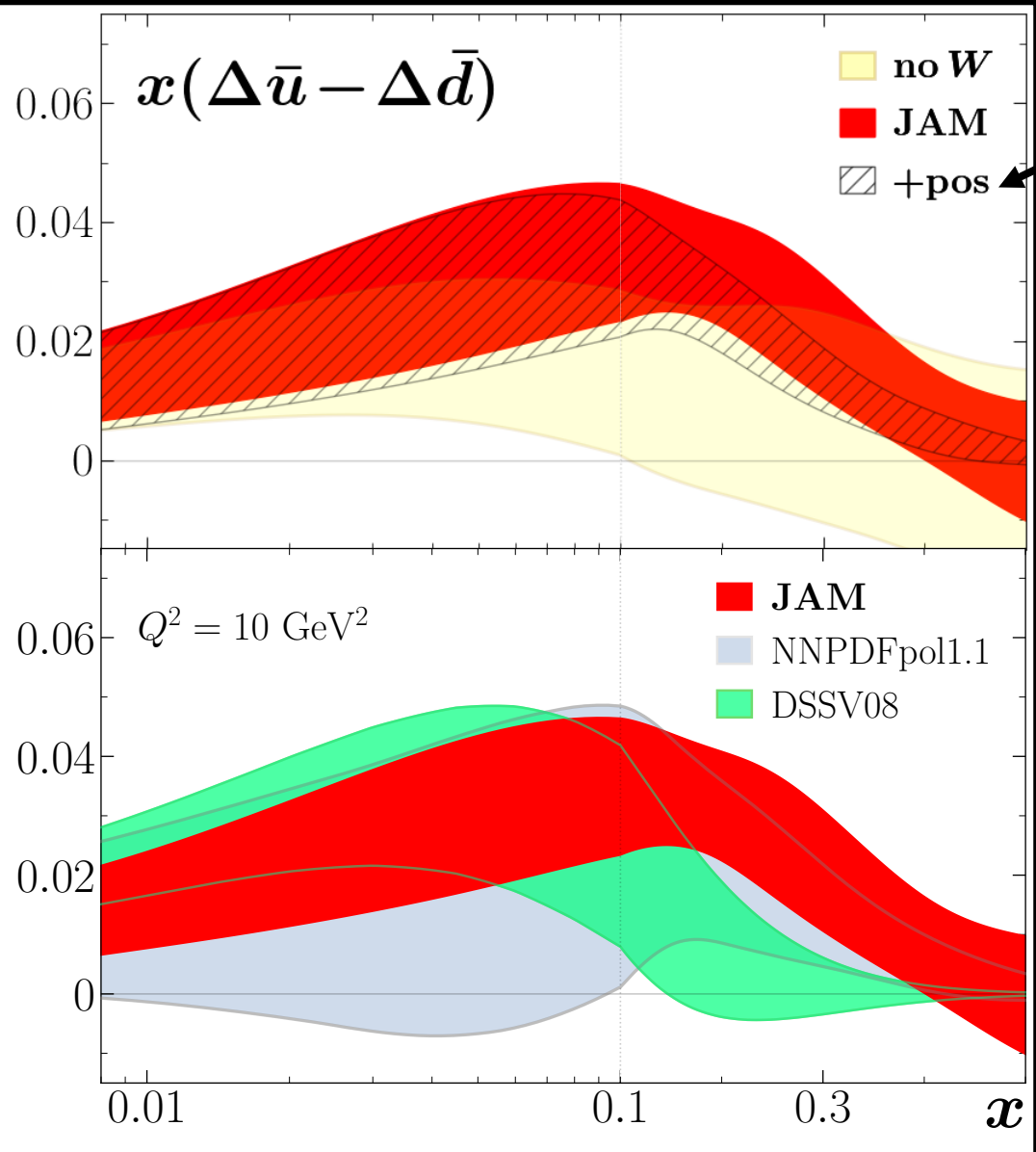
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Resulting Asymmetry

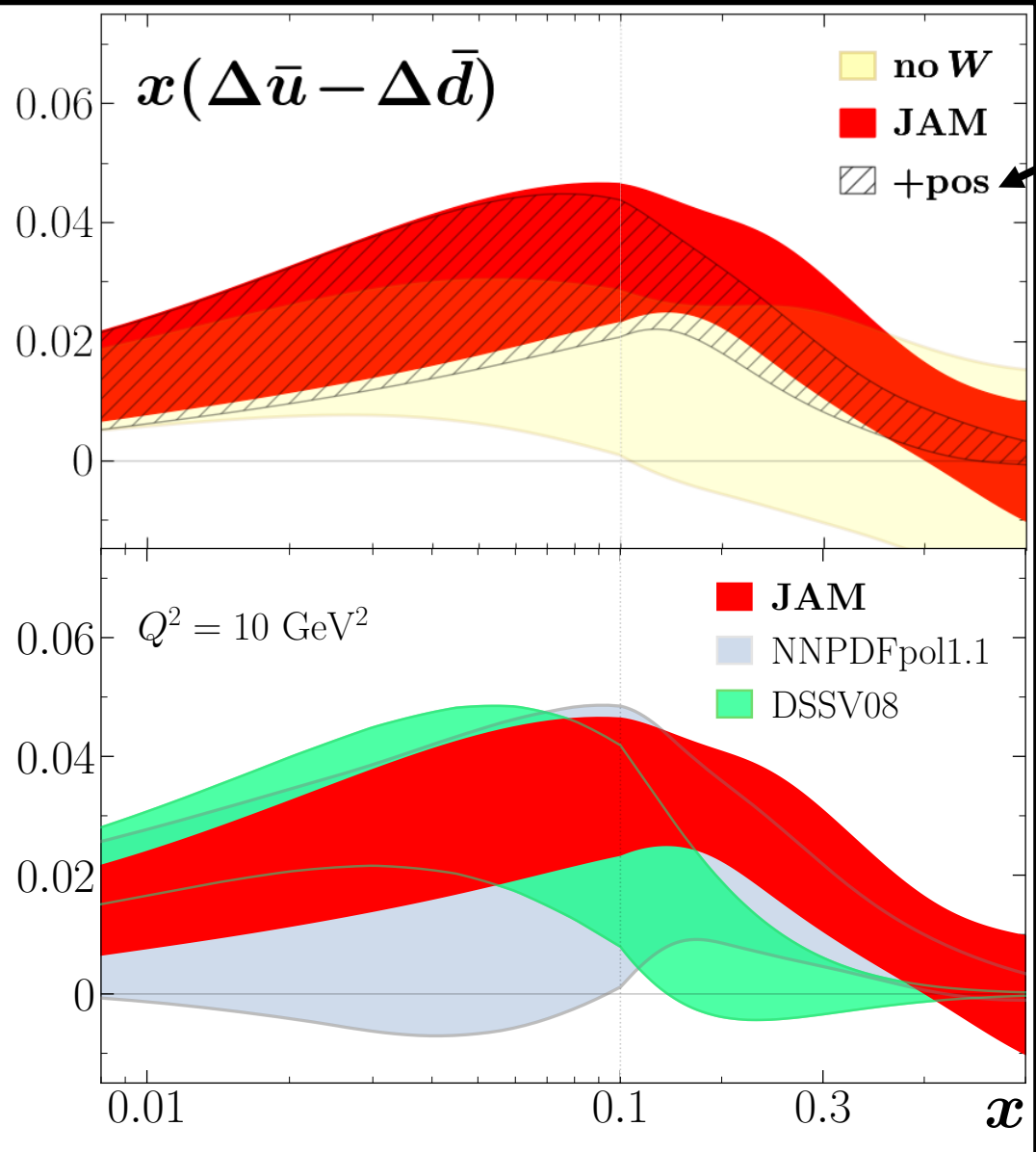


Resulting Asymmetry



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

Resulting Asymmetry

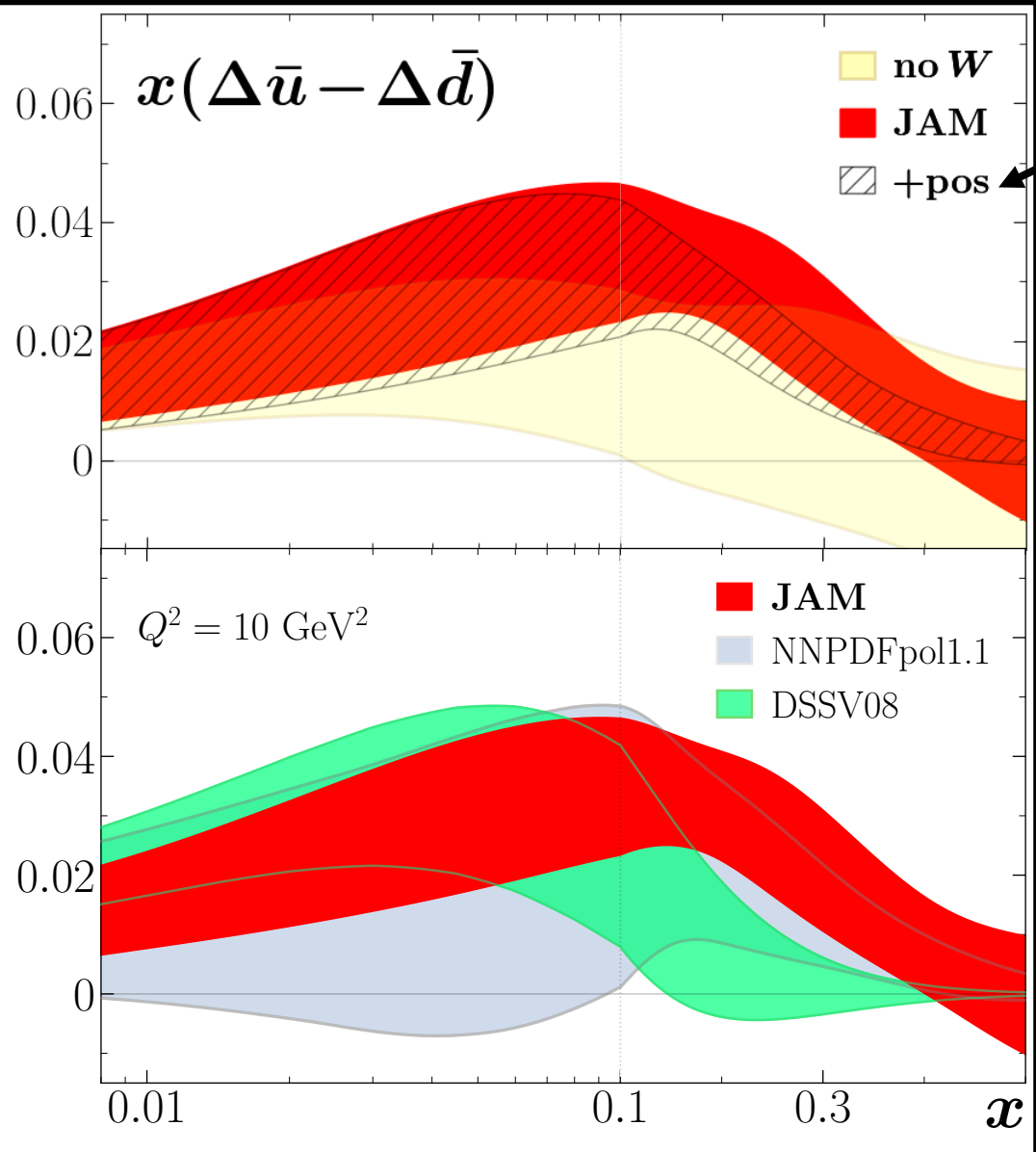


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Can $\overline{\text{MS}}$ parton distributions be negative?
 Alessandro Candido, Stefano Forte and Felix Hekhorn

Positivity and renormalization of parton densities
 John Collins, Ted C. Rogers, Nobuo Sato

Resulting Asymmetry



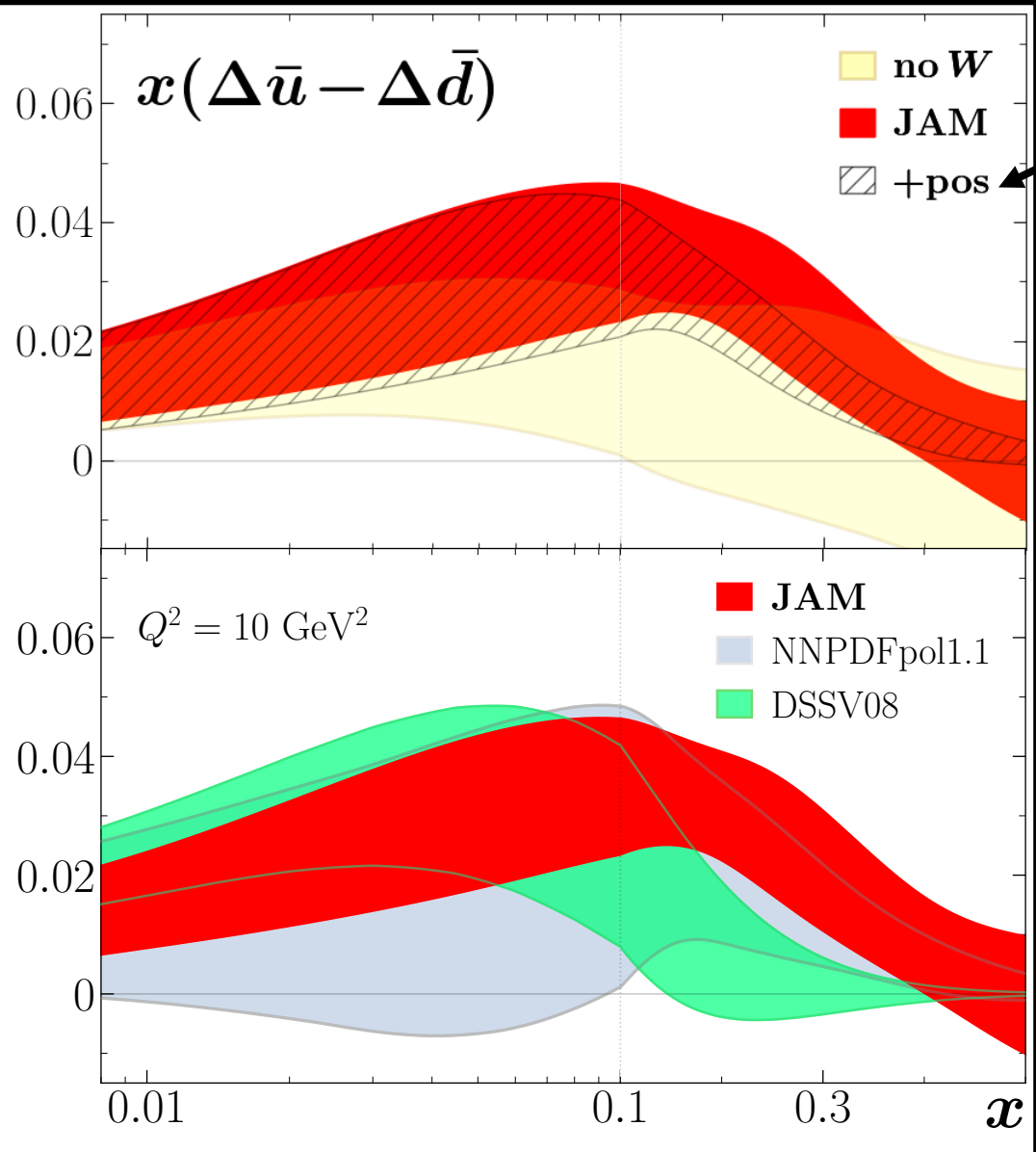
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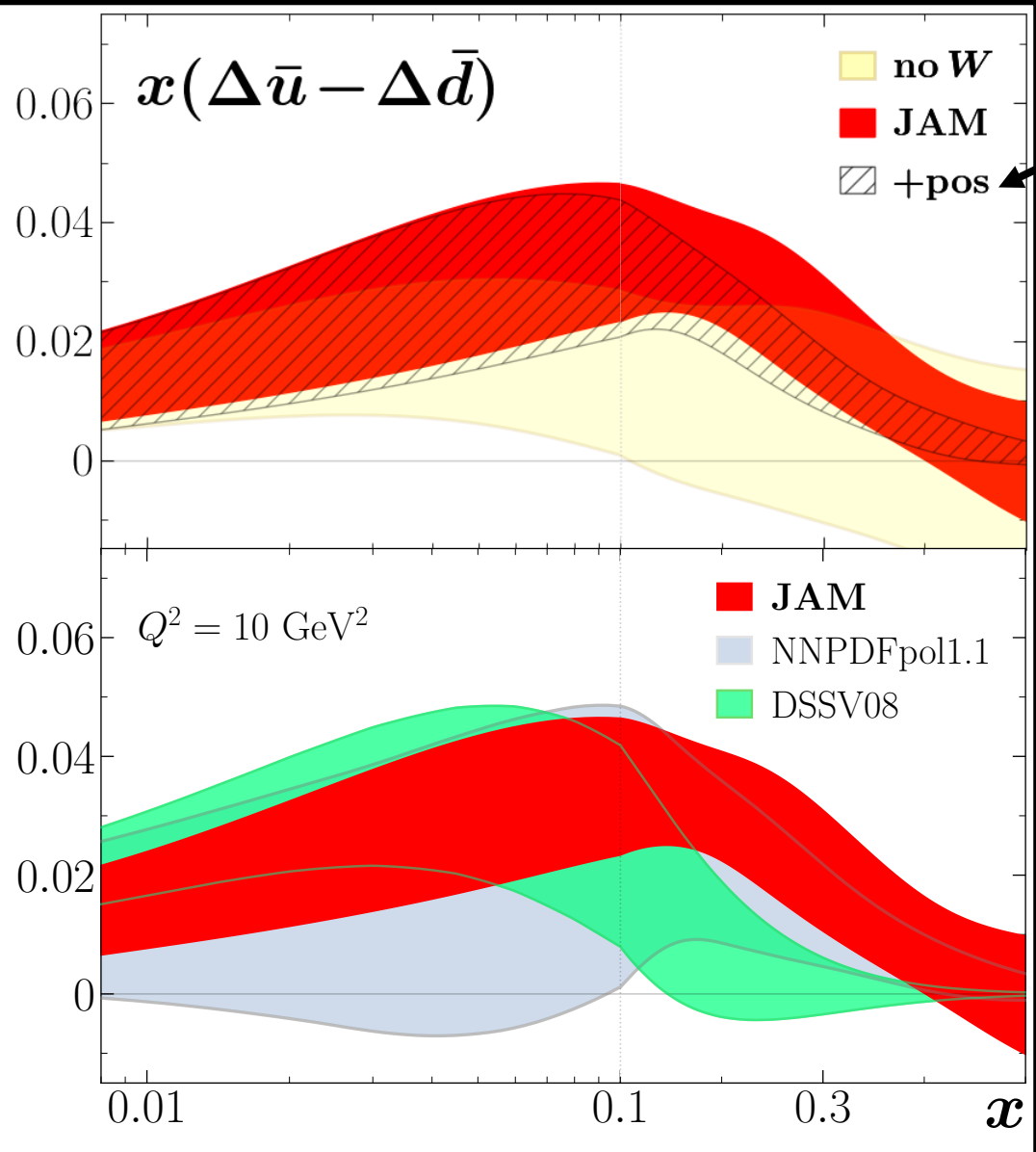
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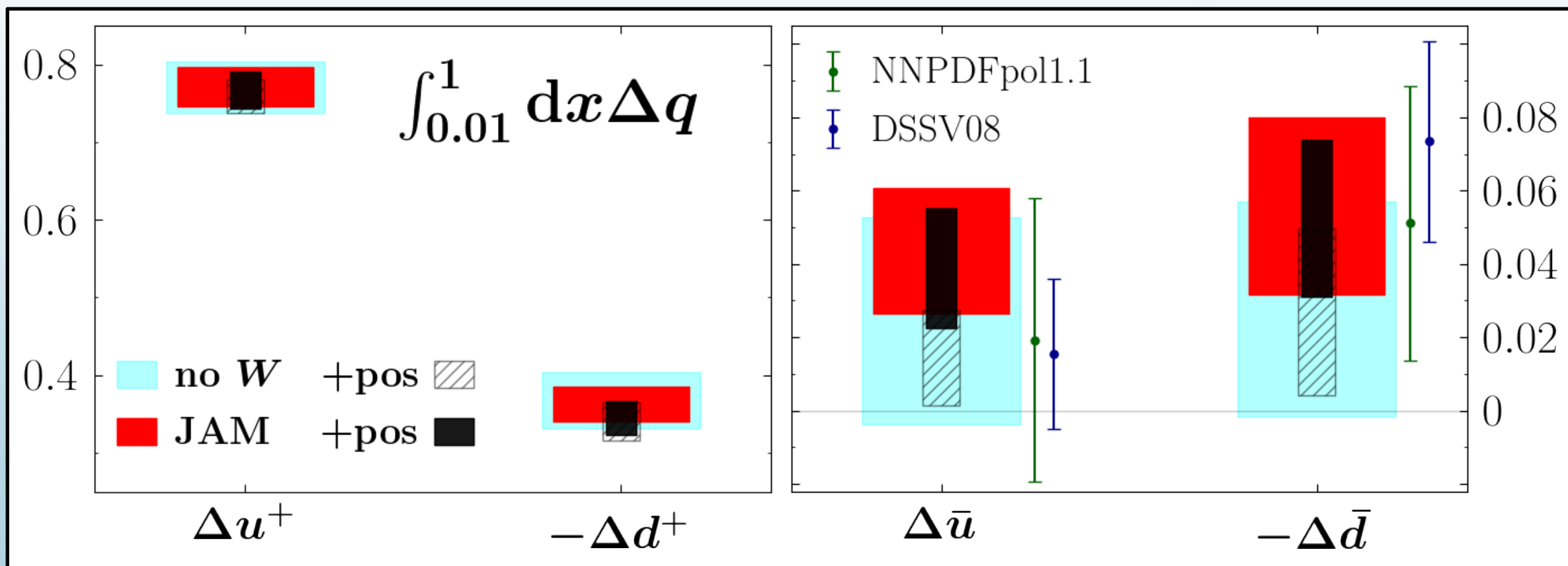
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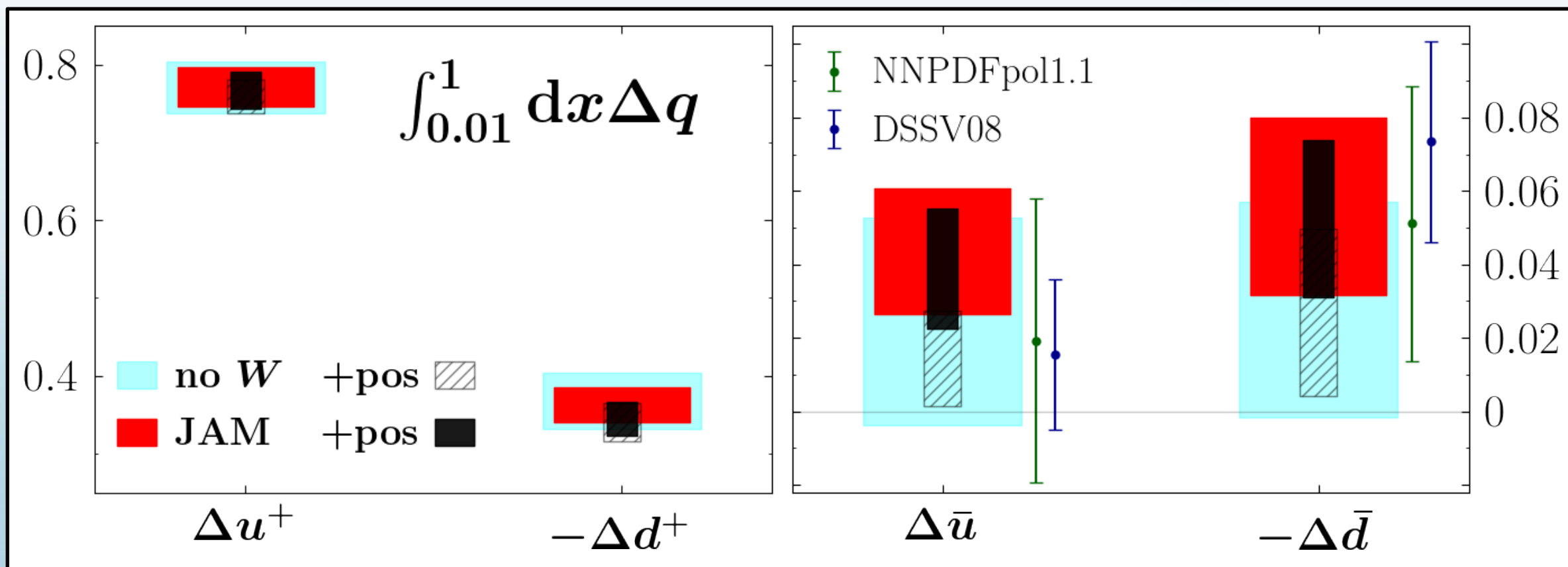
NNPDF shows hint of positive asymmetry at intermediate x

Our result is strongly positive in both regions of x

Proton Spin Contributions

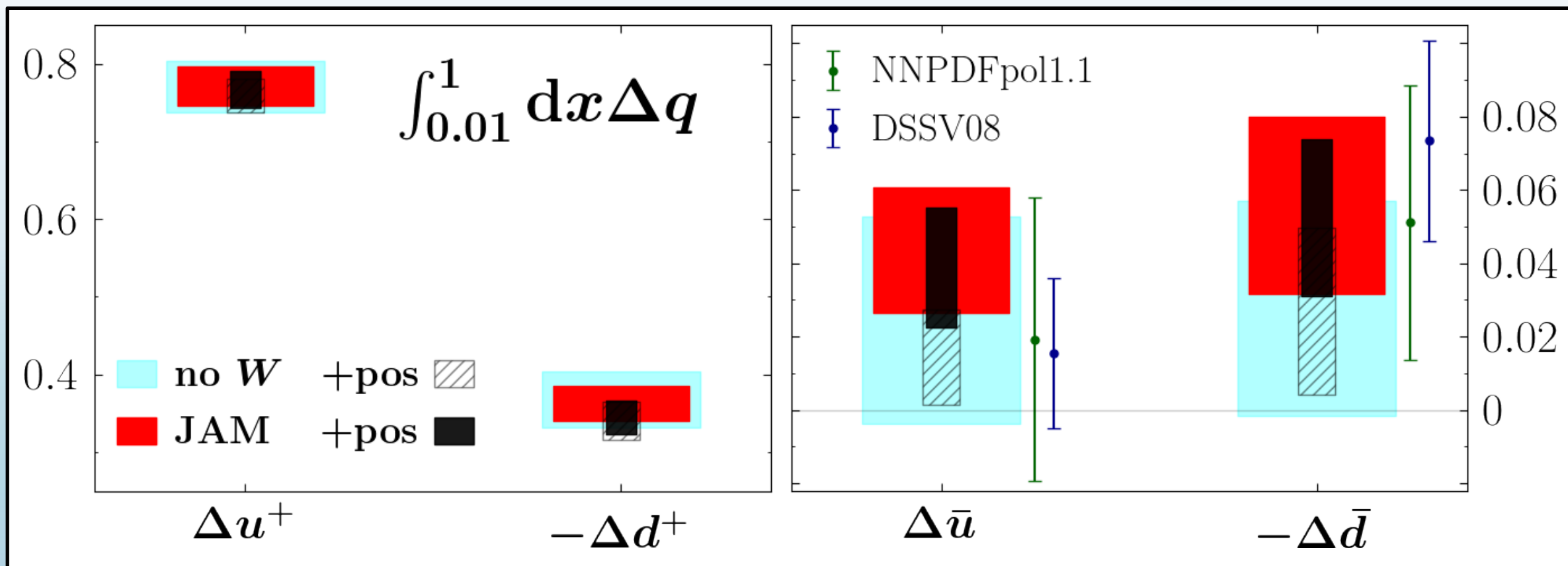


Proton Spin Contributions



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

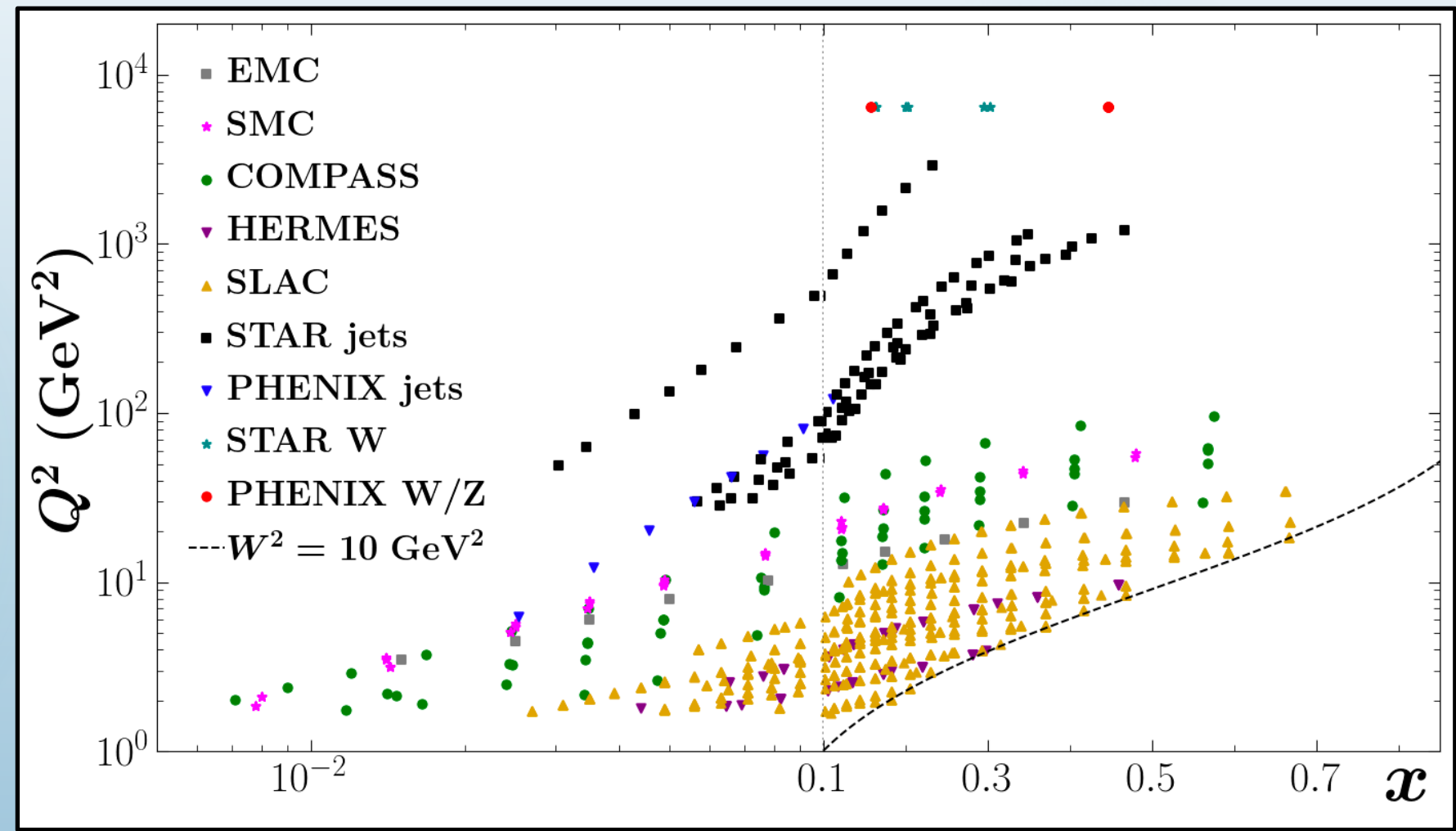
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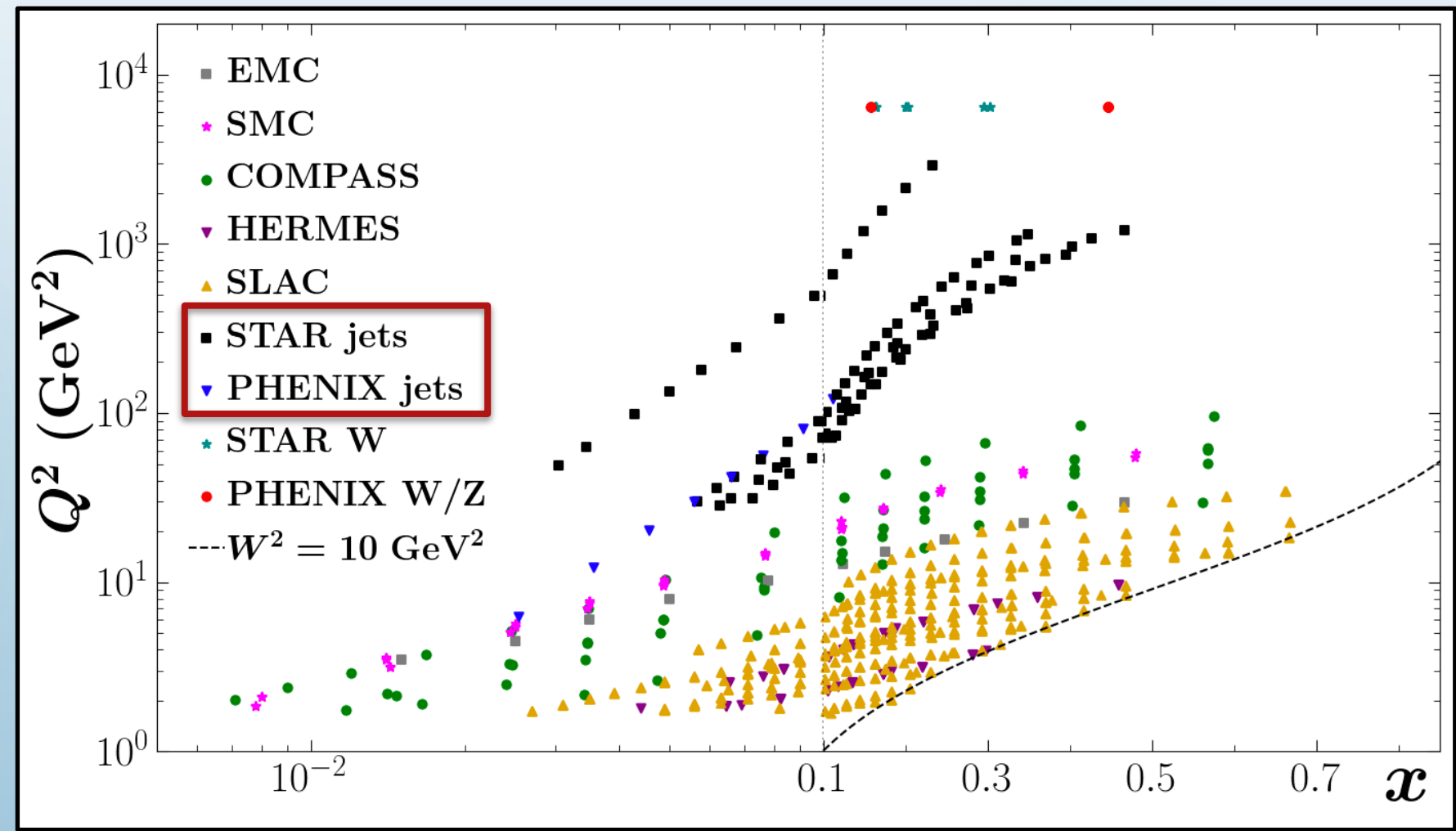
Flavor	JAM moment (truncated)	Lattice Moment (full)	Difference
Δu^+	0.779(34)	0.864(16)	10%
Δd^+	-0.370(40)	-0.426(16)	13%

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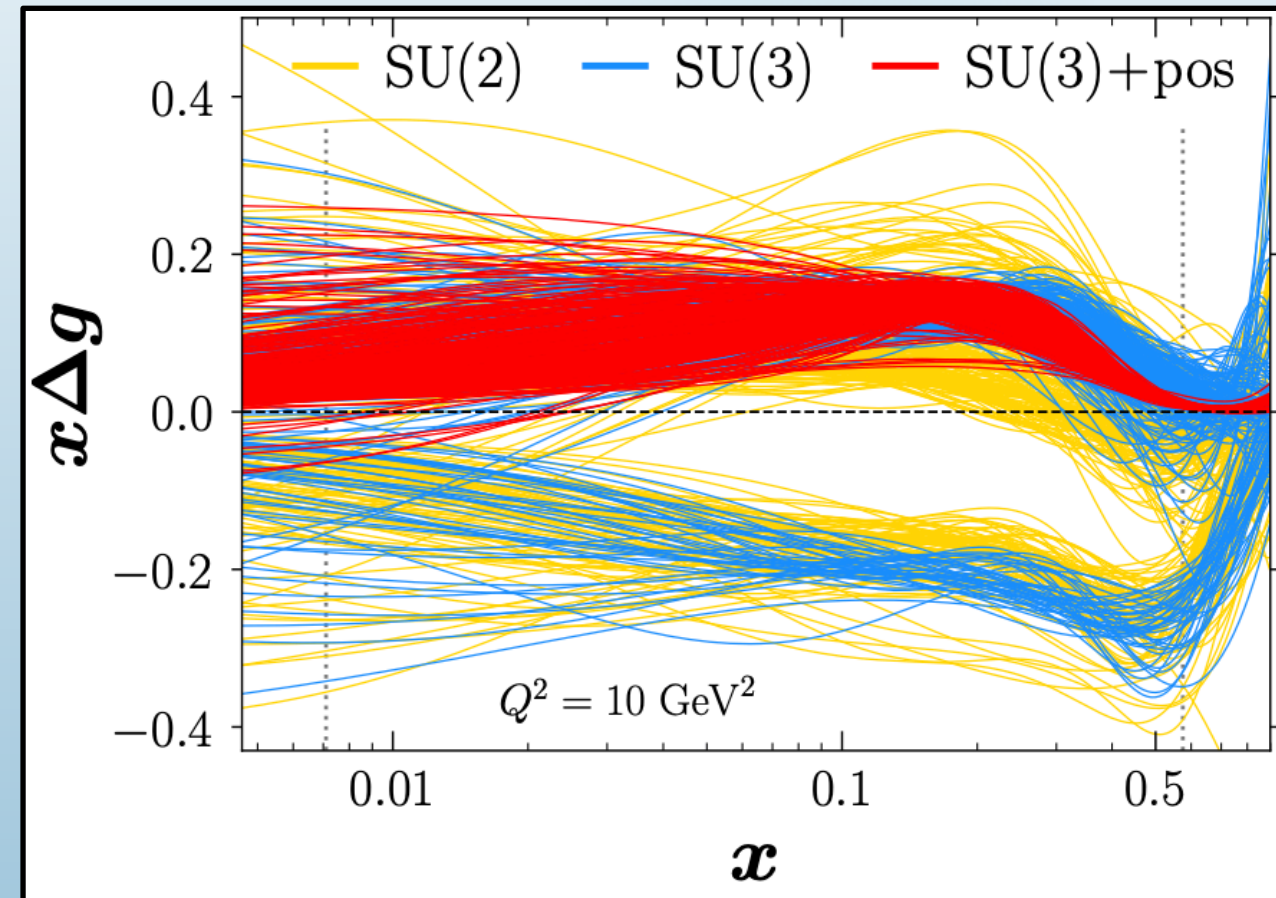
Jets provide most direct constraints on gluon distribution



How well do we know the gluon polarization in the proton? #1

Jefferson Lab Angular Momentum (JAM) Collaboration • Y. Zhou (South China Normal U. and UCLA and William-Mary Coll. and Jefferson Lab) et al. (Jan 6, 2022)

Published in: *Phys.Rev.D* 105 (2022) 7, 074022 • e-Print: [2201.02075](https://arxiv.org/abs/2201.02075) [hep-ph]

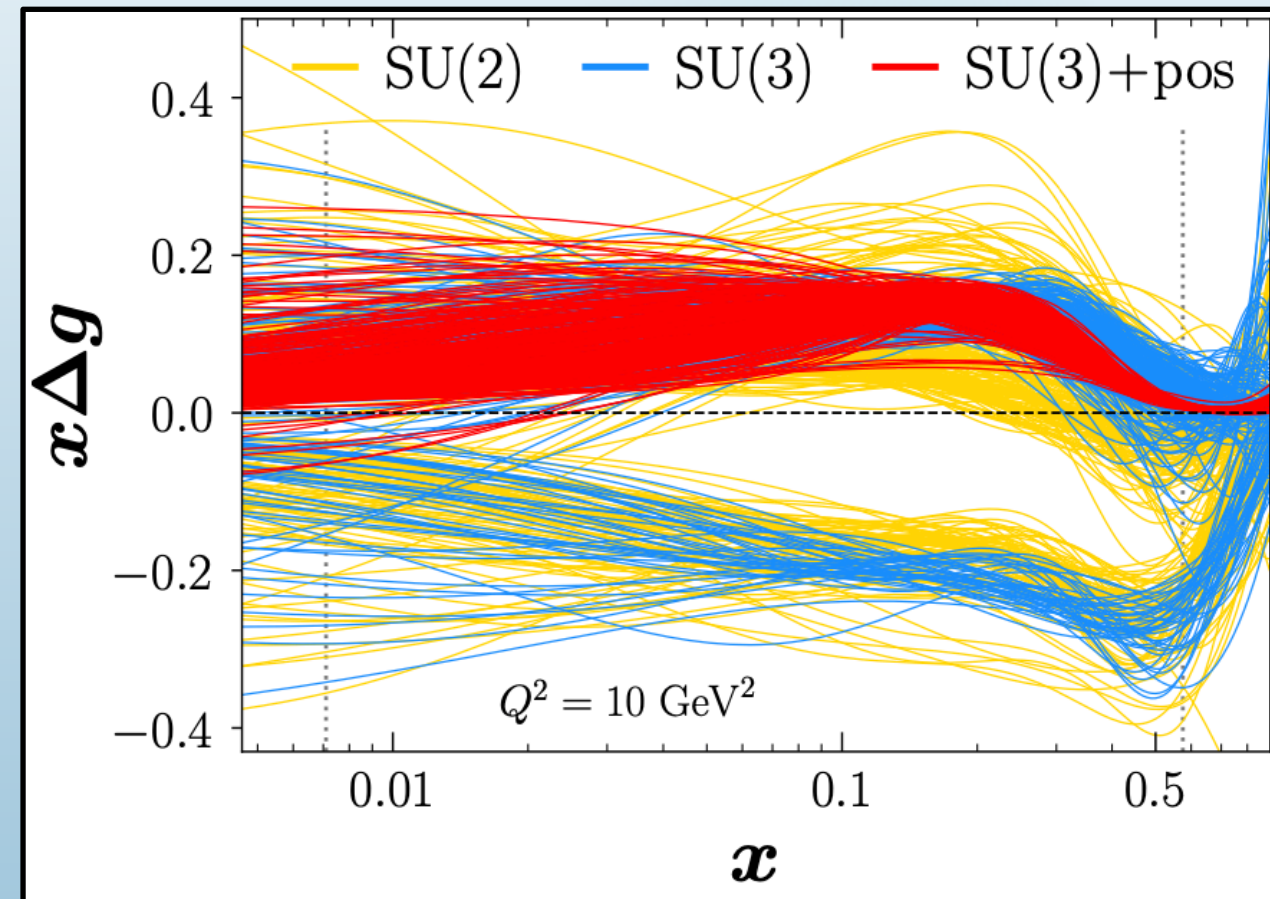


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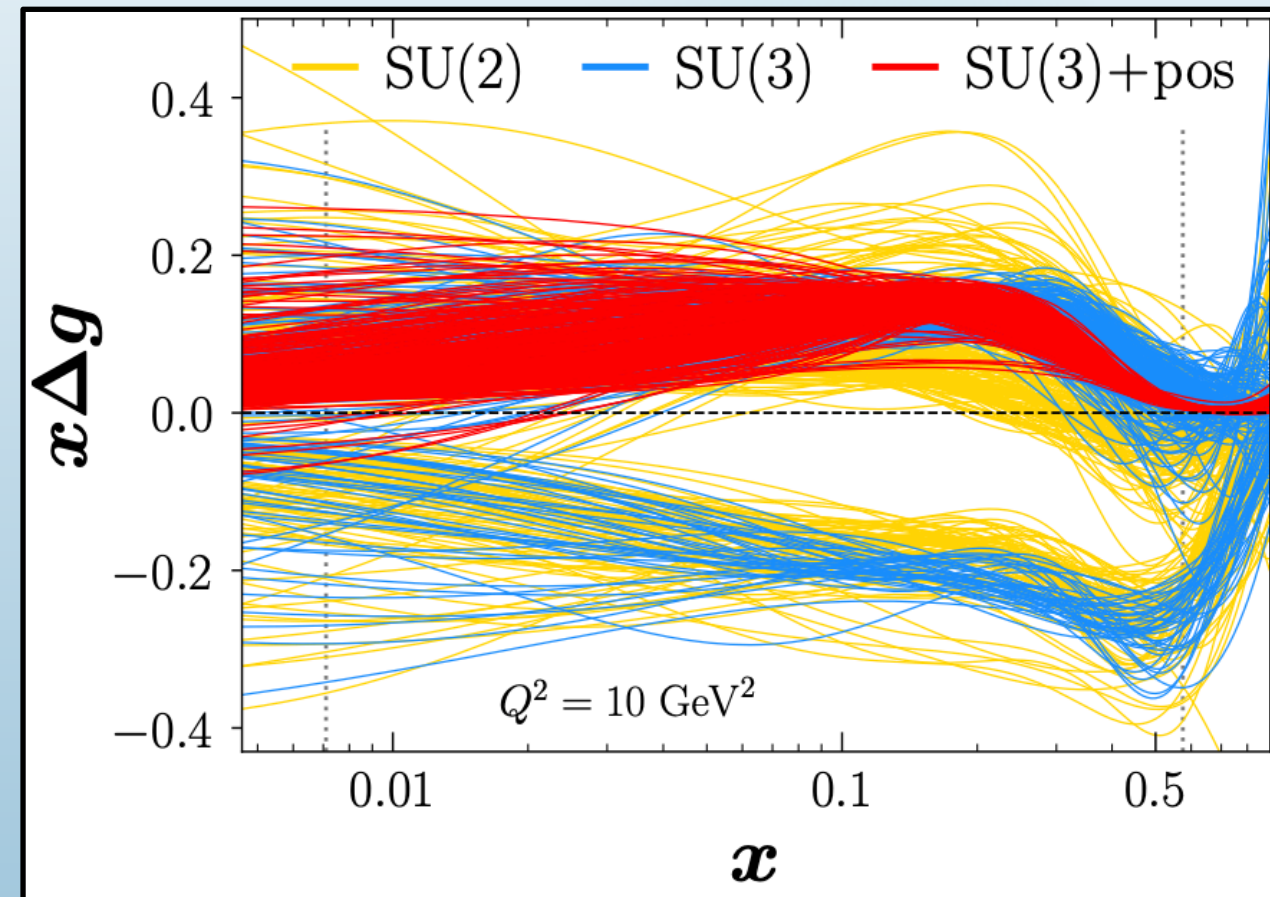
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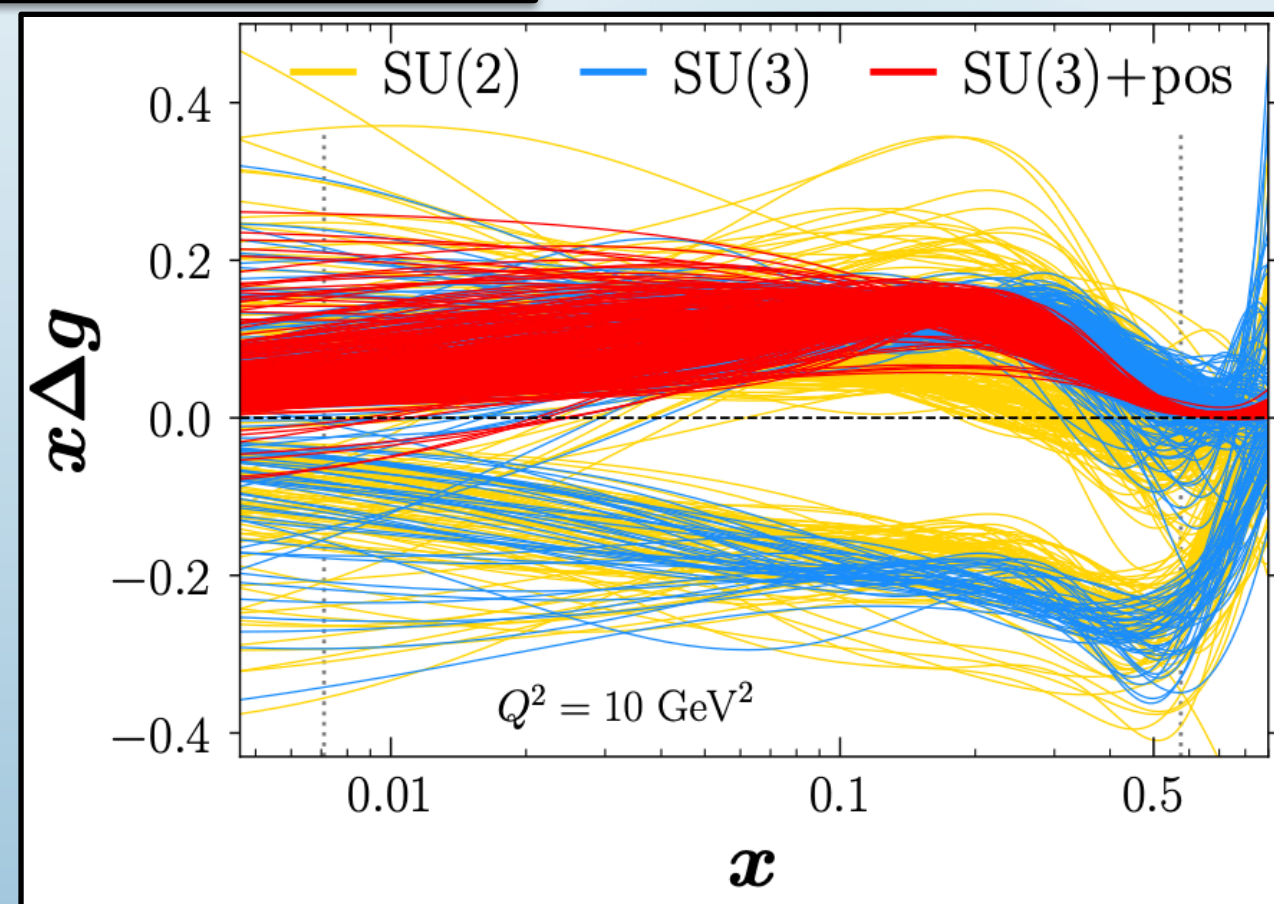
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Positivity constraints rule out negative solution

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

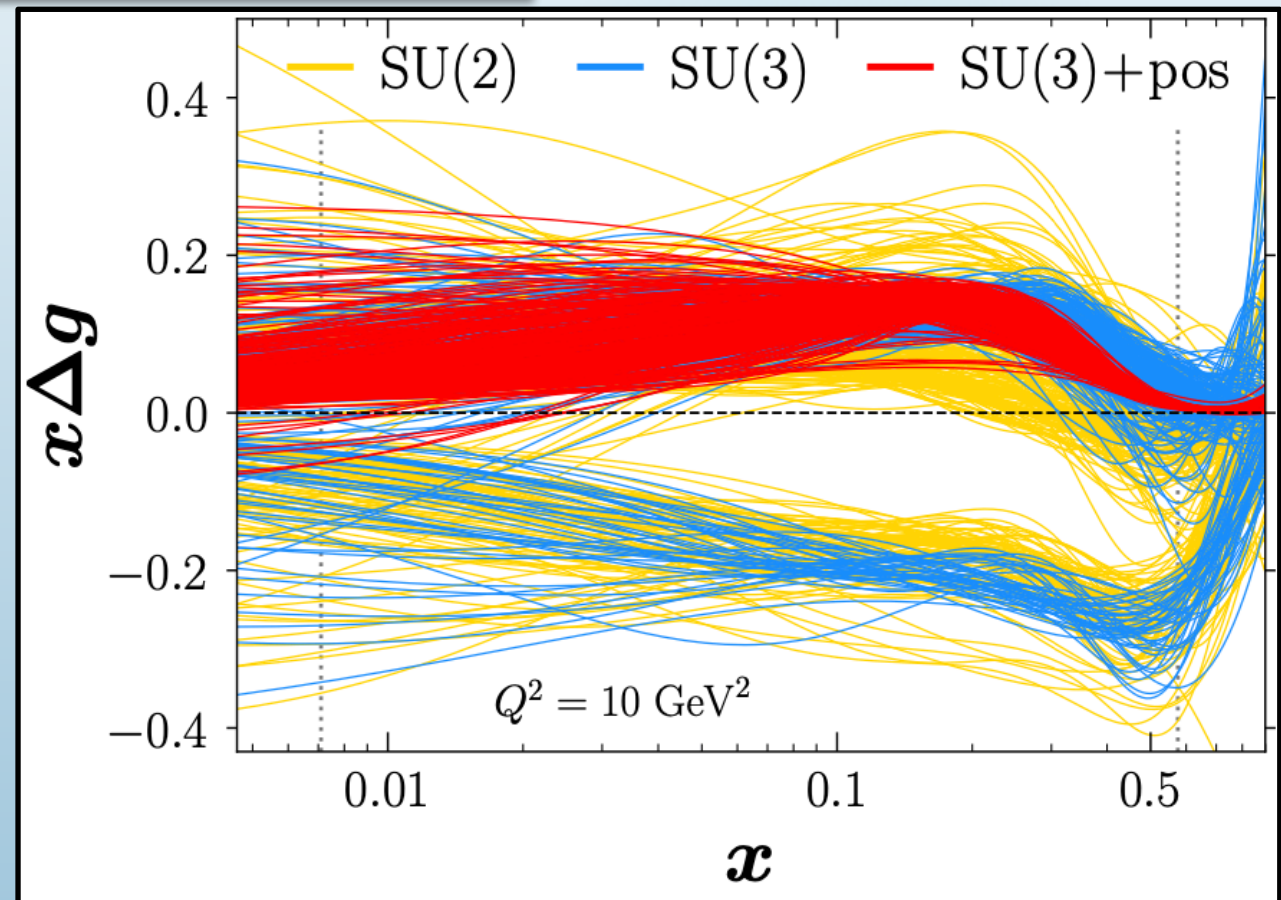
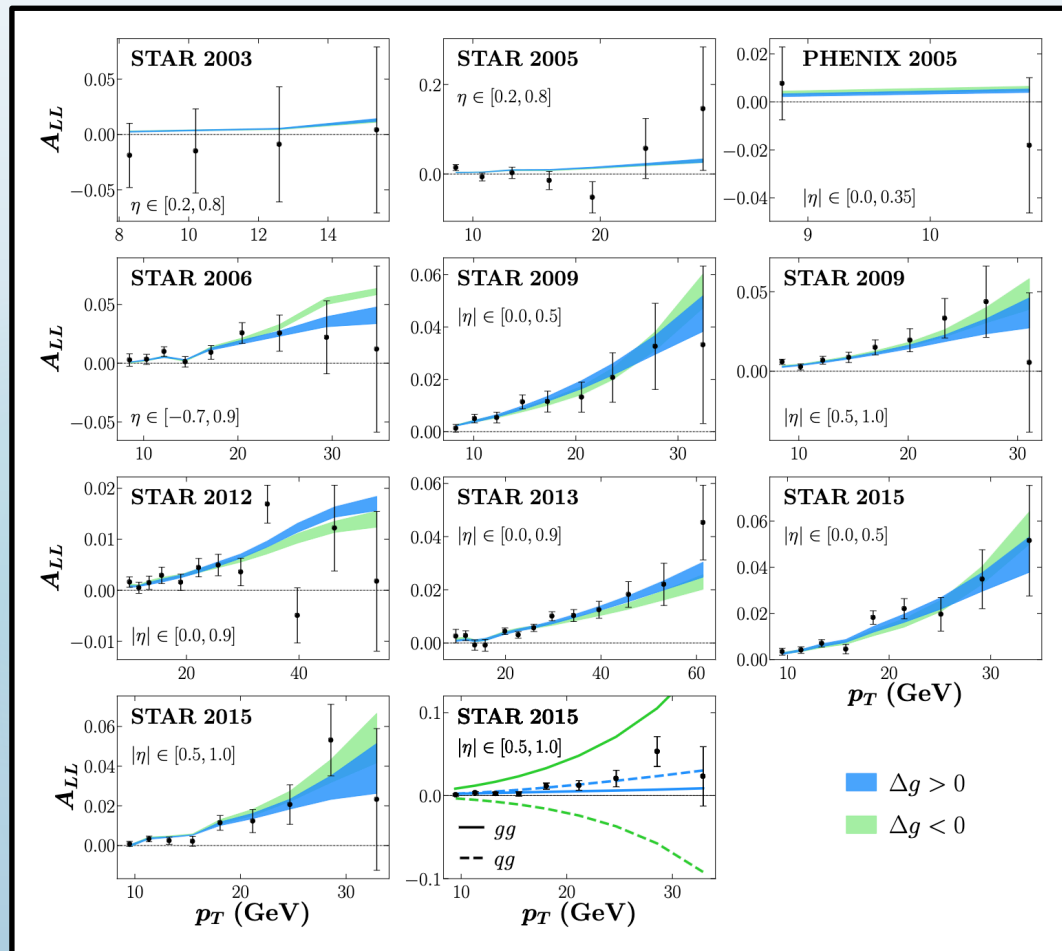


How well do we know the gluon polarization in the proton? #1
 Jefferson Lab Angular Momentum (JAM) Collaboration • Y. Zhou (South China Normal U. and UCLA and William-Mary Coll. and Jefferson Lab) et al. (Jan 6, 2022)
 Published in: *Phys.Rev.D* 105 (2022) 7, 074022 • e-Print: [2201.02075](https://arxiv.org/abs/2201.02075) [hep-ph]

Can $\overline{\text{MS}}$ parton distributions be negative?
 Alessandro Candido, Stefano Forte and Felix Hekhorn
 Positivity and renormalization of parton densities
 John Collins, Ted C. Rogers, Nobuo Sato

Positivity constraints rule out negative solution

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



$$A_{LL}^{\text{jet}} \sim (\Delta g)^2 + \Delta q \Delta g + \dots$$

Measurement of charged pion double spin asymmetries at midrapidity in longitudinally polarized $p + p$ collisions at $\sqrt{s} = 510$ GeV

PHENIX Collaboration • U.A. Acharya (Georgia State U.) et al. (Apr 6, 2020)

Published in: *Phys.Rev.D* 102 (2020) 3, 032001 • e-Print: [2004.02681](https://arxiv.org/abs/2004.02681) [hep-ex]

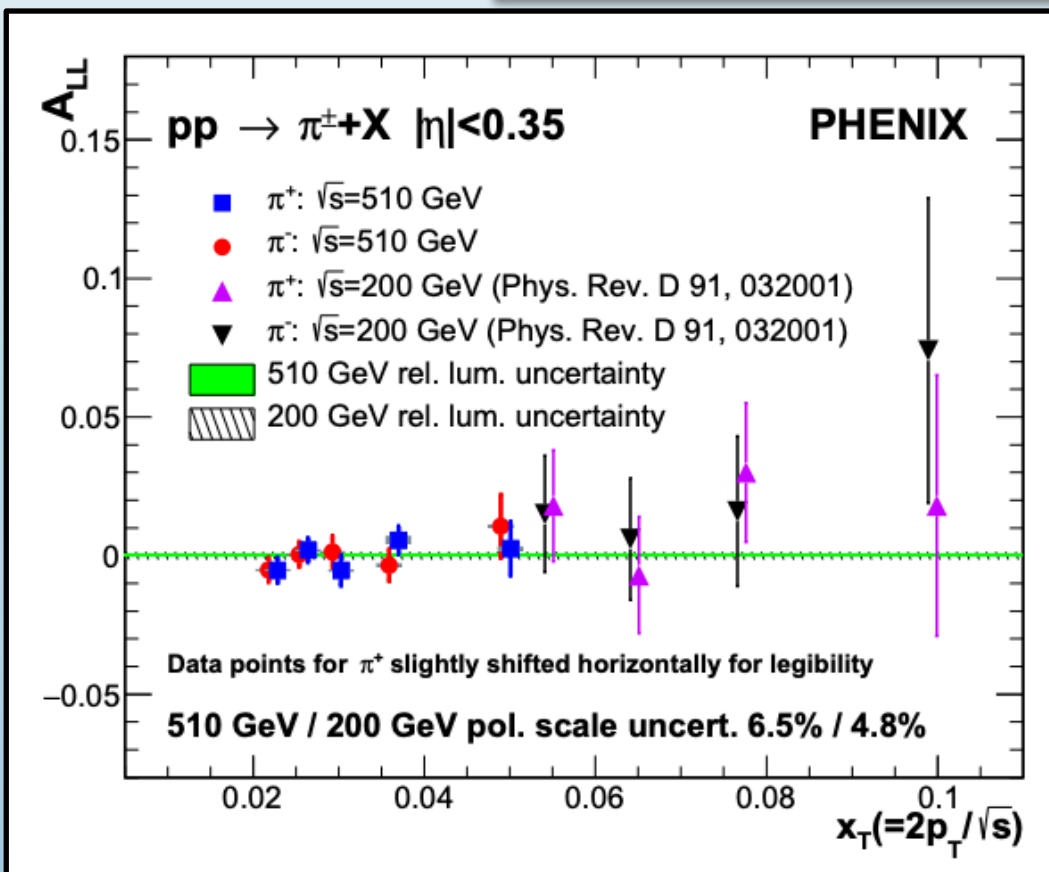
Charged-pion cross sections and double-helicity asymmetries in polarized $p+p$ collisions at $\sqrt{s}=200$ GeV

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$$\vec{p} + \vec{p} \rightarrow \pi^\pm + X$$

Charge ordering:
If $\Delta g > 0 : A_{LL}^{\pi^+} > A_{LL}^{\pi^0} > A_{LL}^{\pi^-}$



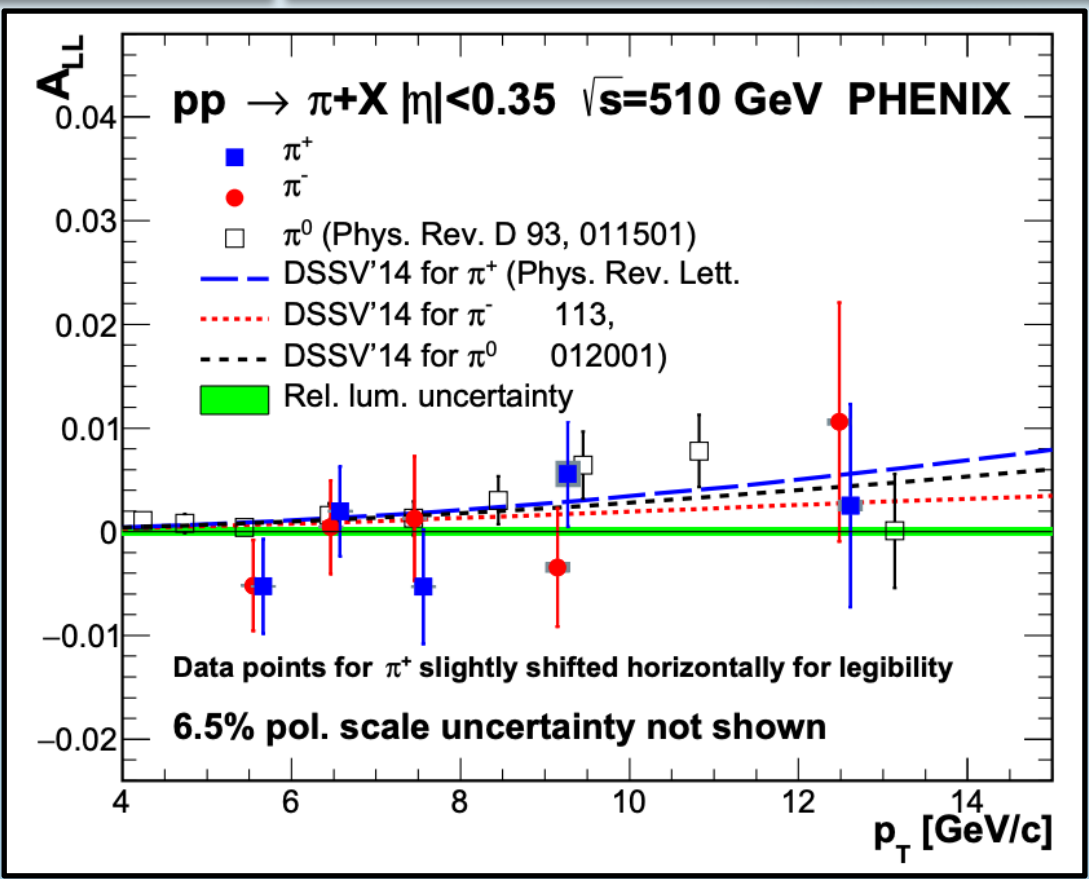
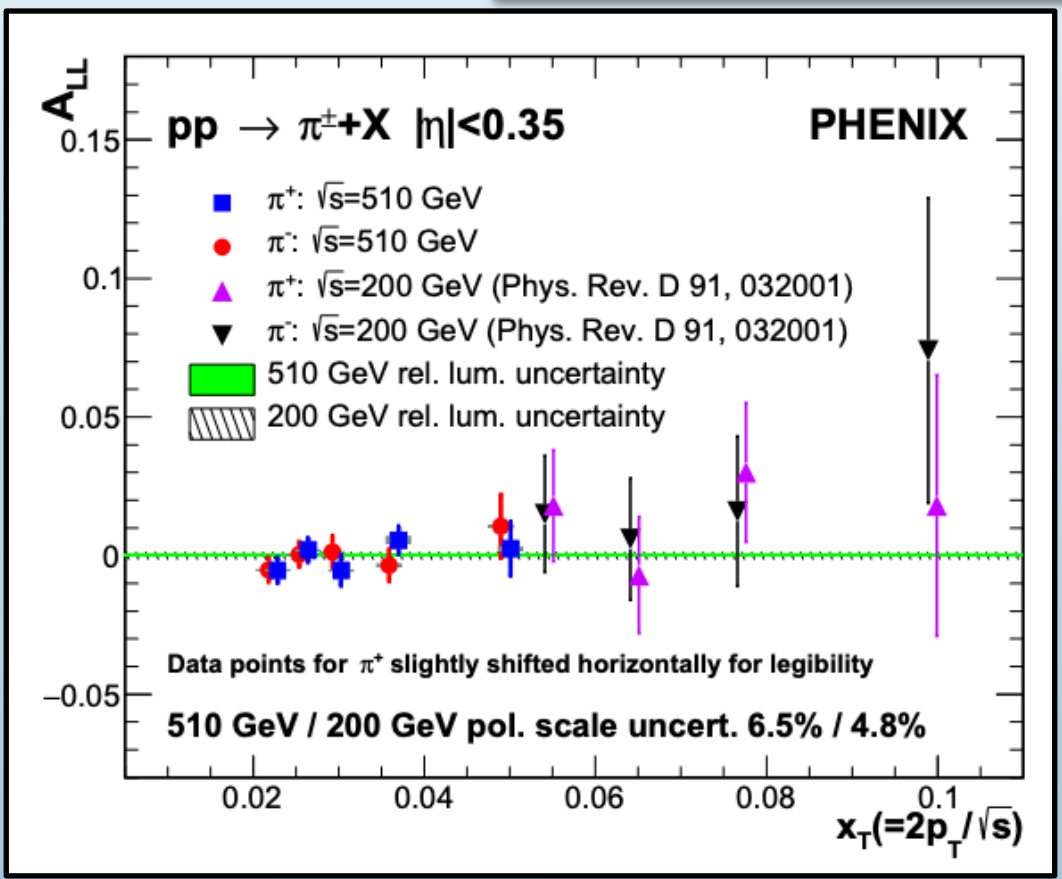
Measurement of charged pion double spin asymmetries at midrapidity in longitudinally polarized $p + p$ collisions at $\sqrt{s} = 510$ GeV
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Charge ordering:
 If $\Delta g > 0 : A_{LL}^{\pi^+} > A_{LL}^{\pi^0} > A_{LL}^{\pi^-}$

Consistent with DSSV14 analysis (which included 210 GeV data) with $\Delta g > 0$



Phys.Rev.Lett. 113 (2014) 1, 012001

Measurement of charged pion double spin asymmetries at midrapidity in longitudinally polarized $p + p$ collisions at $\sqrt{s} = 510$ GeV

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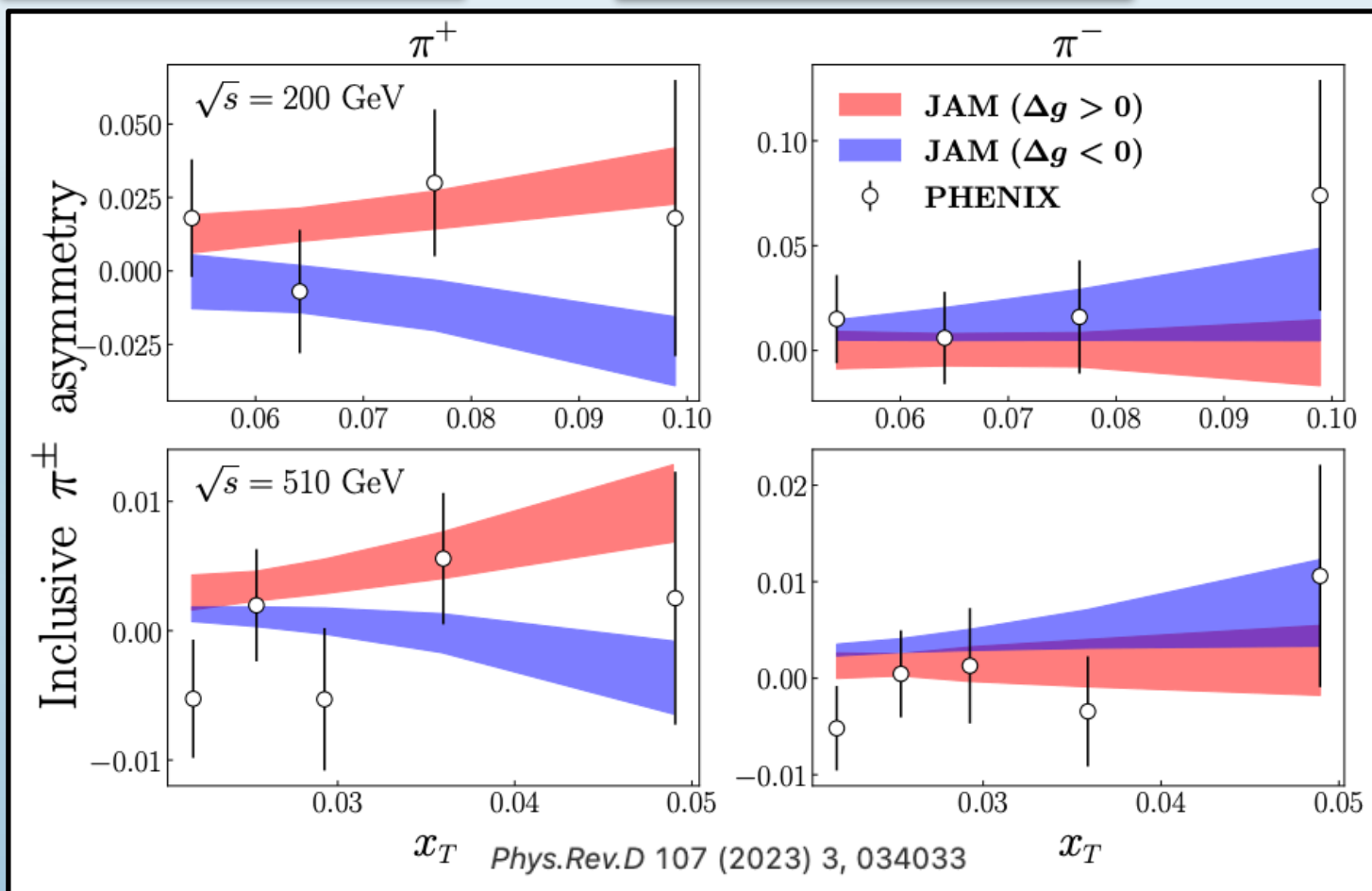
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JAM Prediction



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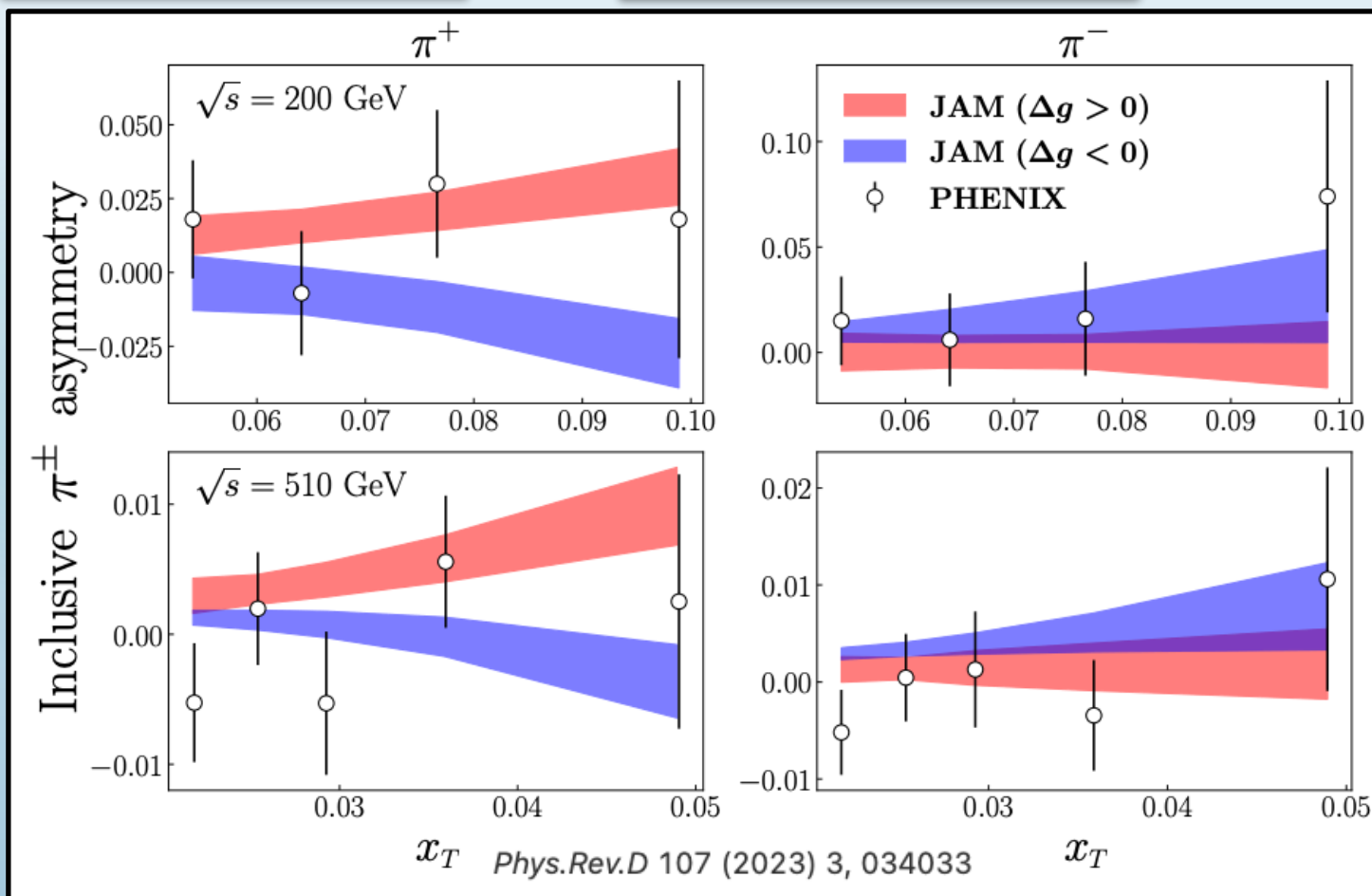
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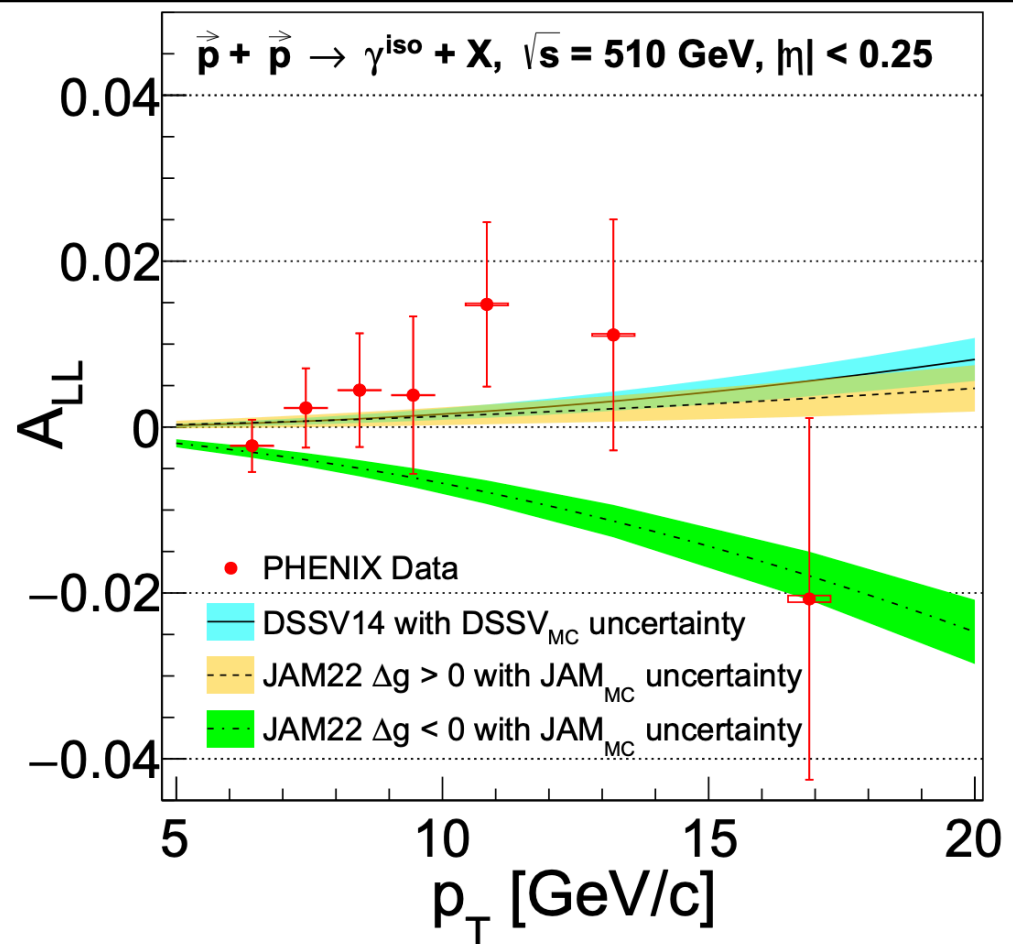


It is inconclusive whether data can distinguish between two solutions

Measurement of Direct-Photon Cross Section and Double-Helicity Asymmetry at $\sqrt{s} = 510$ GeV in $\vec{p} + \vec{p}$ Collisions

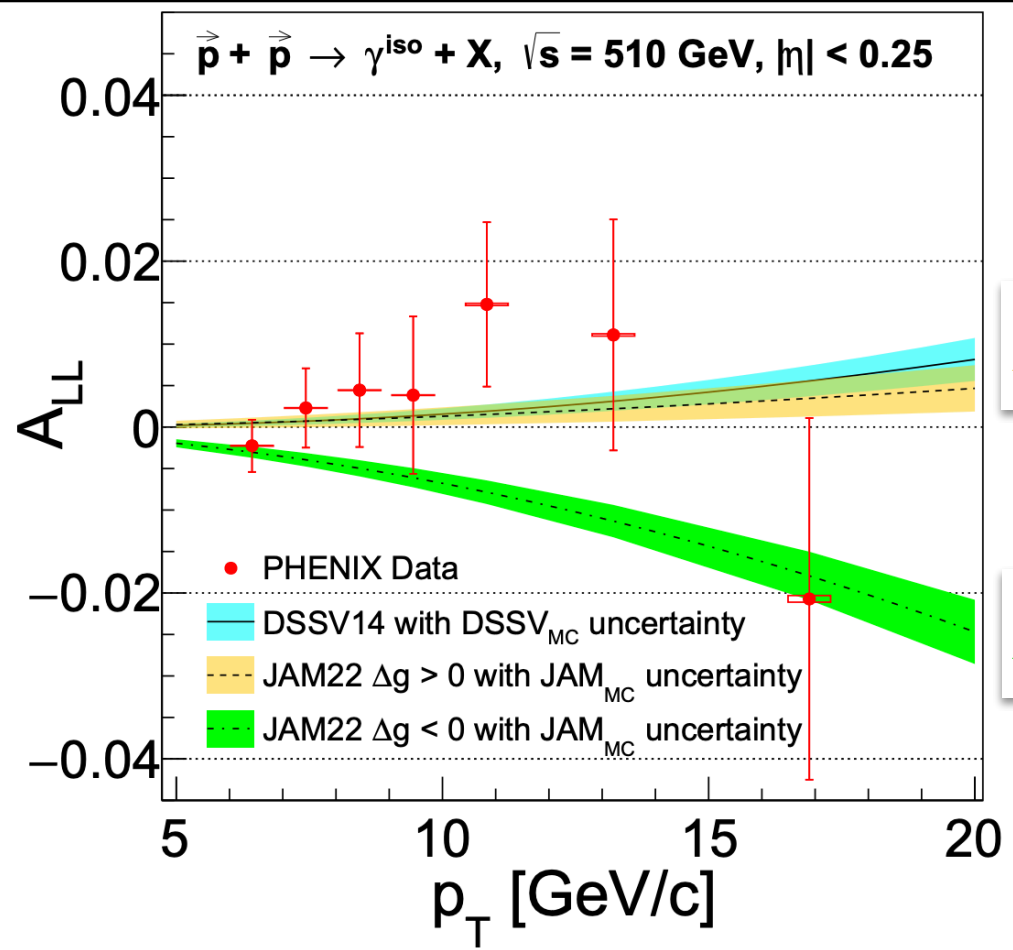
PHENIX Collaboration • U. Acharya (Georgia State U., Atlanta) et al. (Feb 16, 2022)

e-Print: [2202.08158](https://arxiv.org/abs/2202.08158) [hep-ex]



Direct sensitivity to the sign of Δg !

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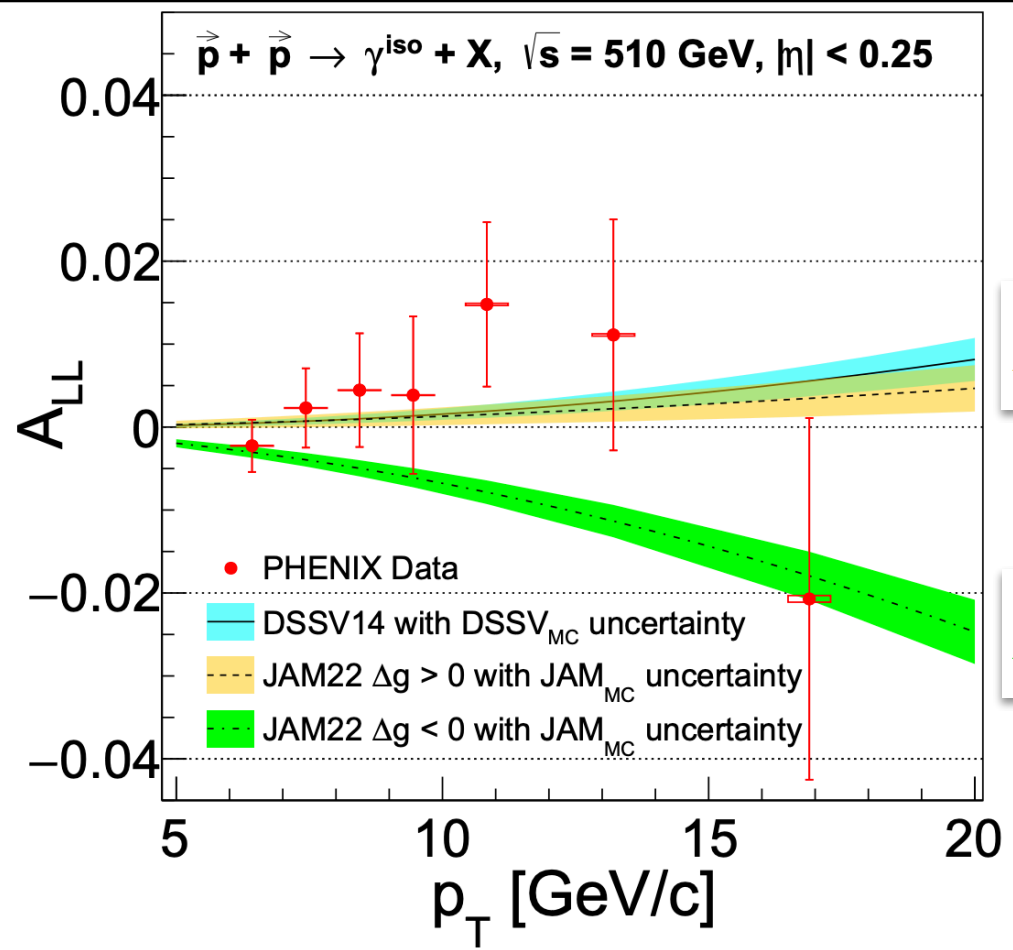


$\chi^2 = 4.7$

$\chi^2 = 12.6$

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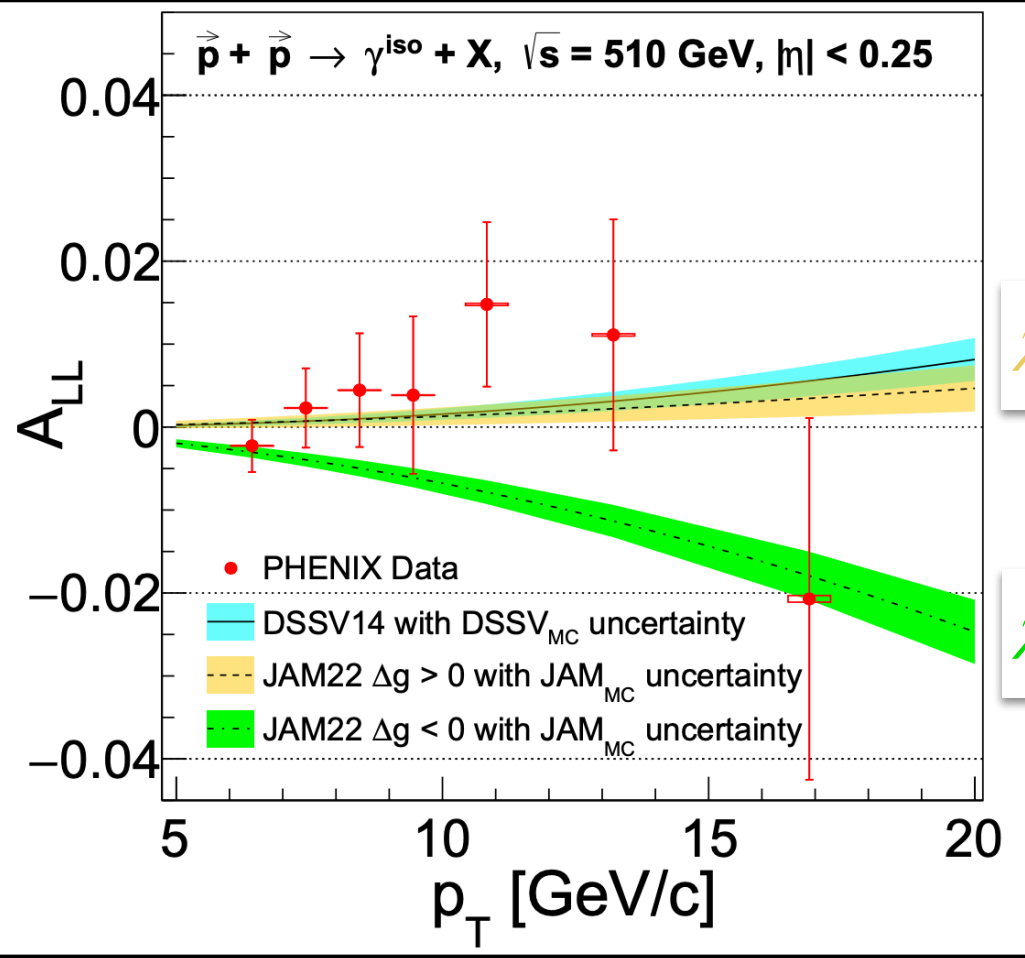
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2.8σ

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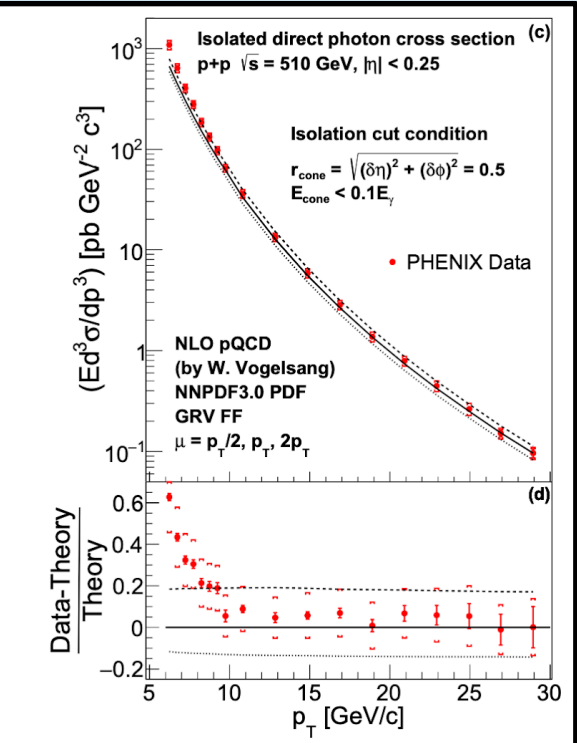
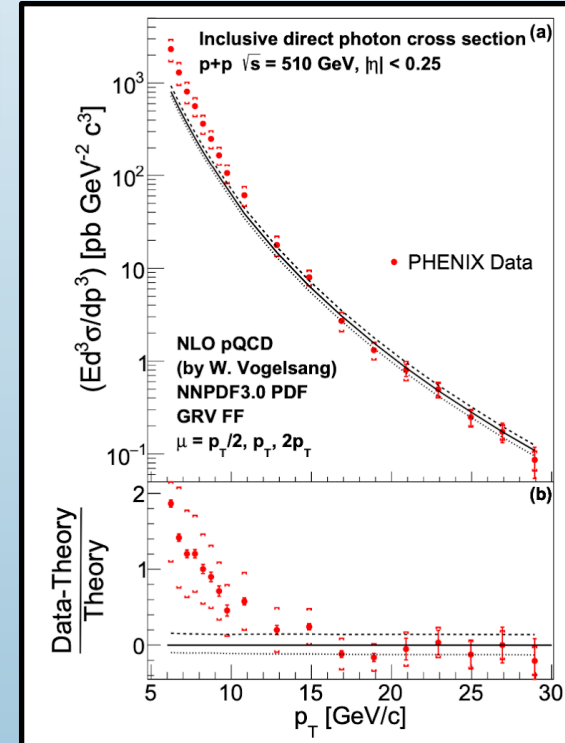


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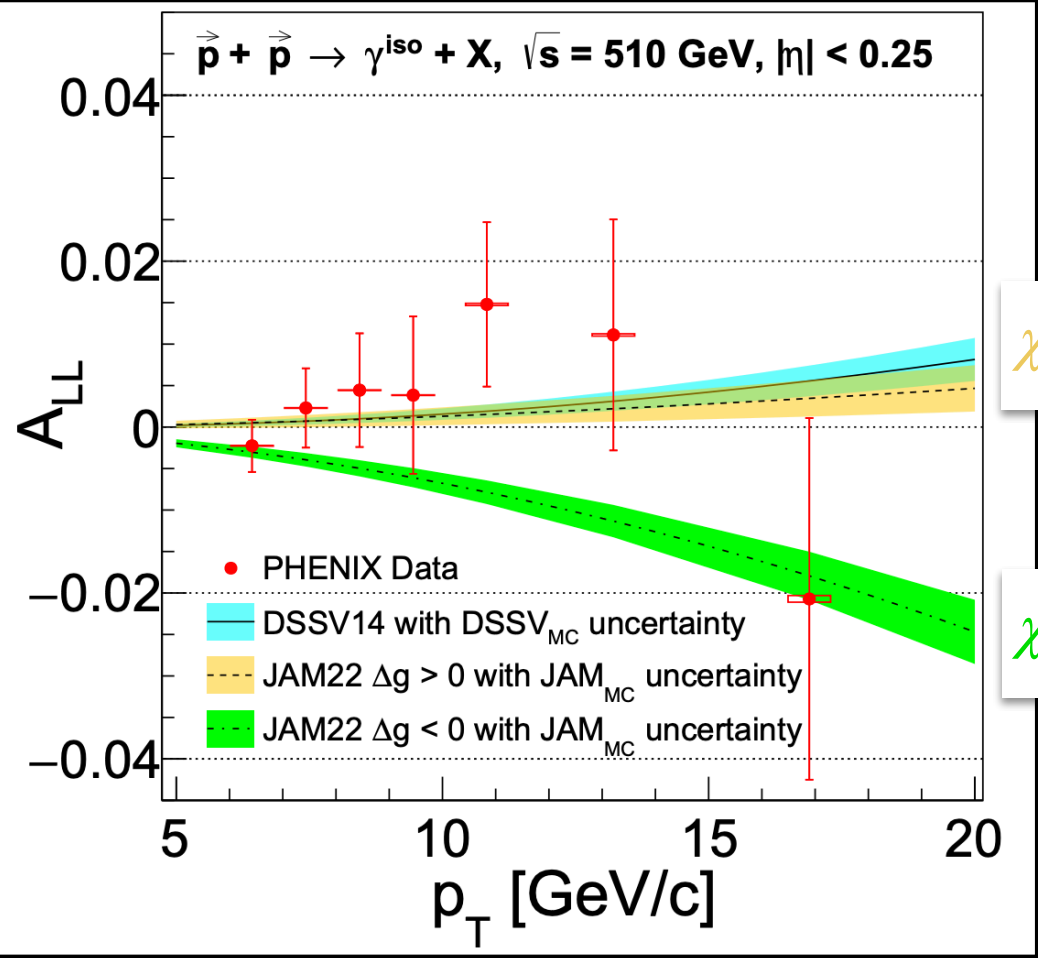
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 e-Print: 2202.08158 [hep-ex]



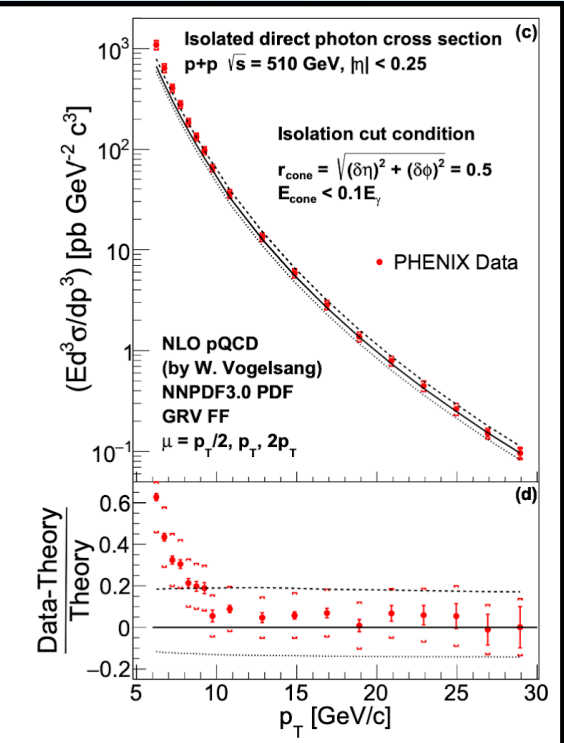
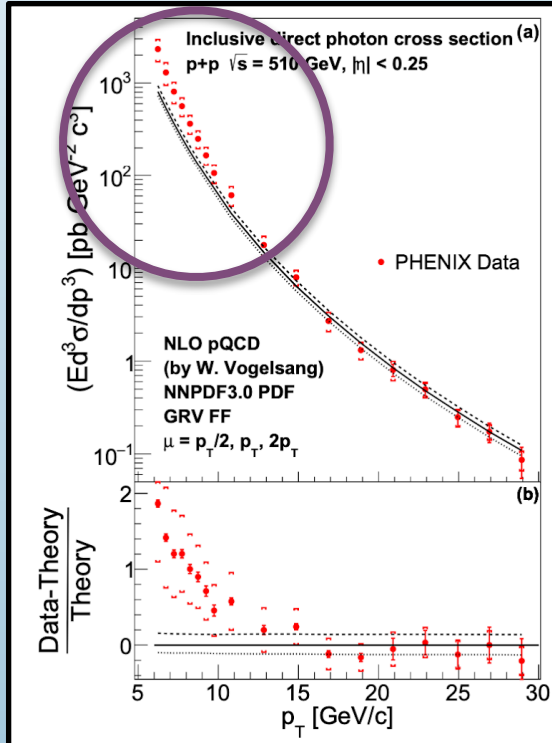
$\chi^2 = 4.7$

2.8σ

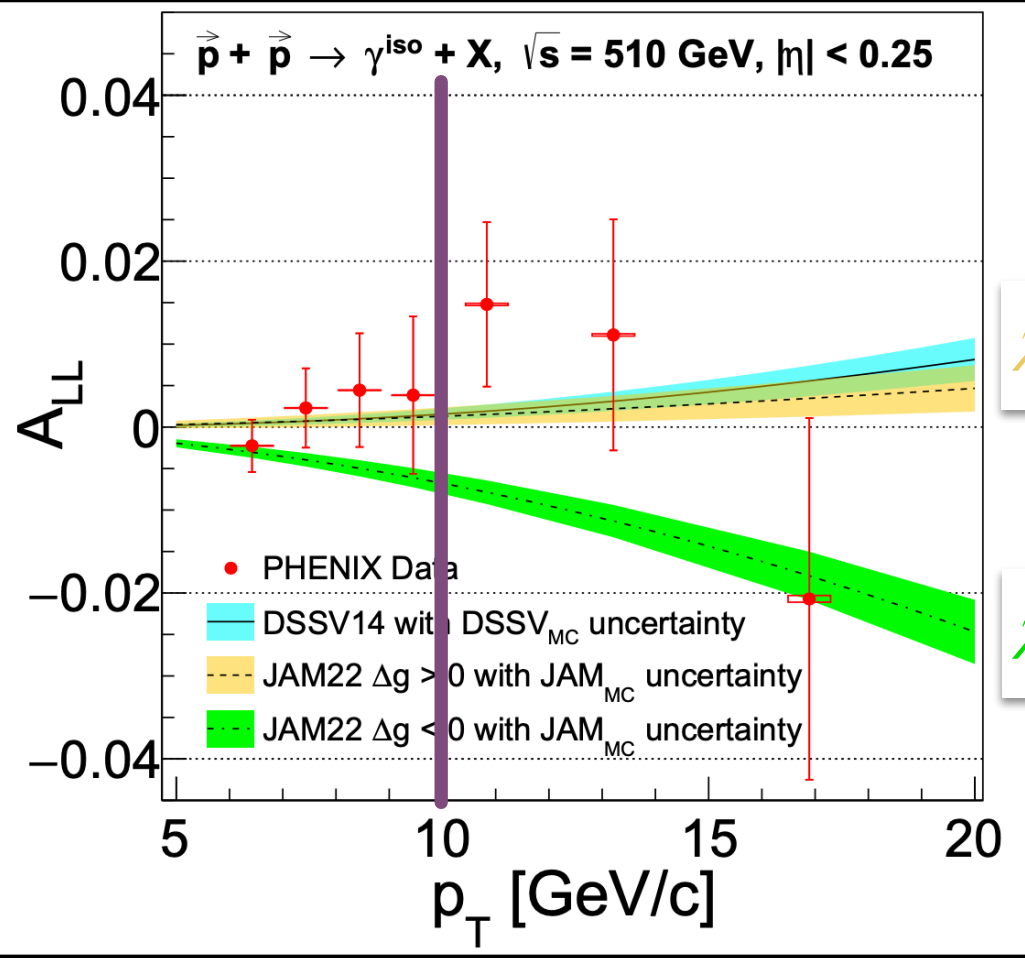
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Direct sensitivity to the sign of Δg !

Potential issues at $P_T < 10$



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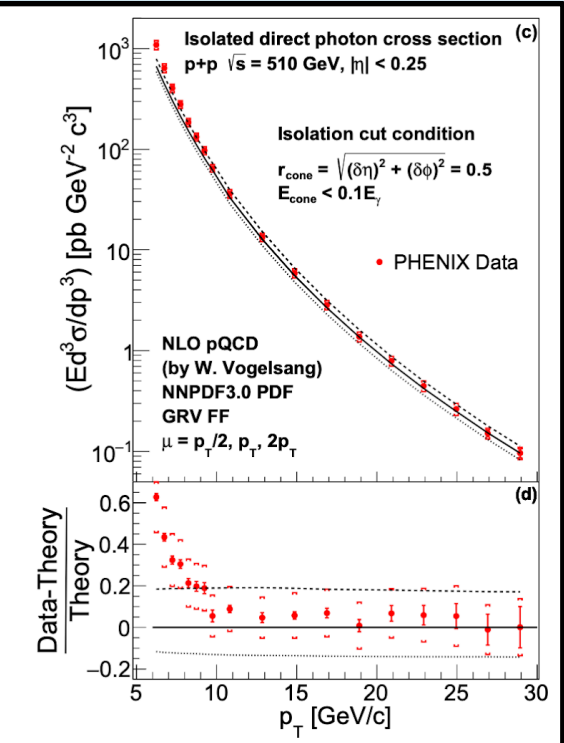
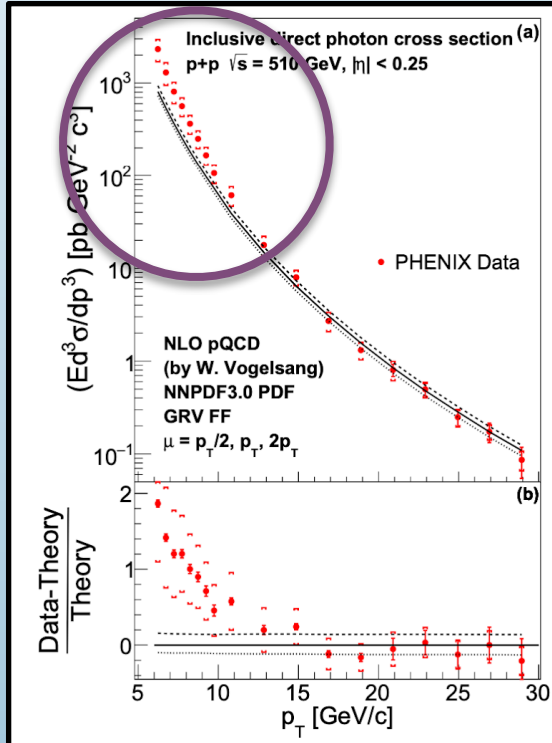


$\chi^2 = 4.7$

2.8σ

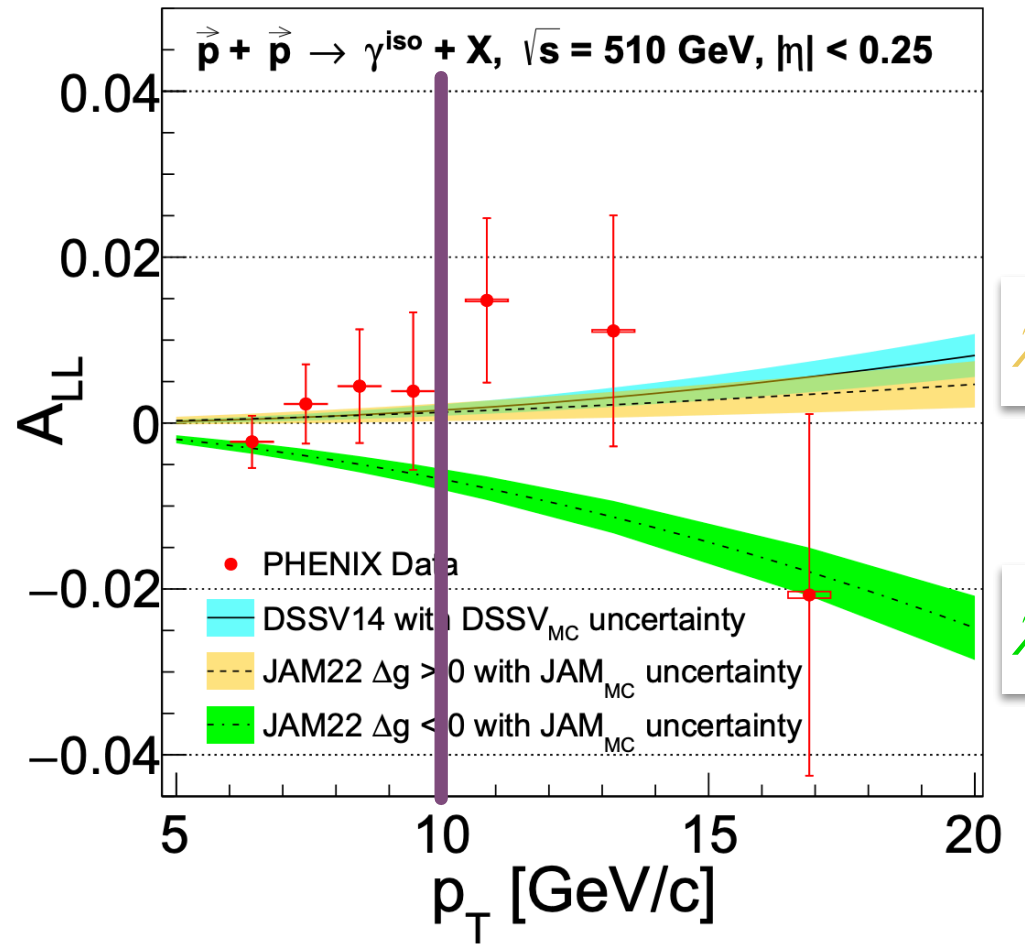
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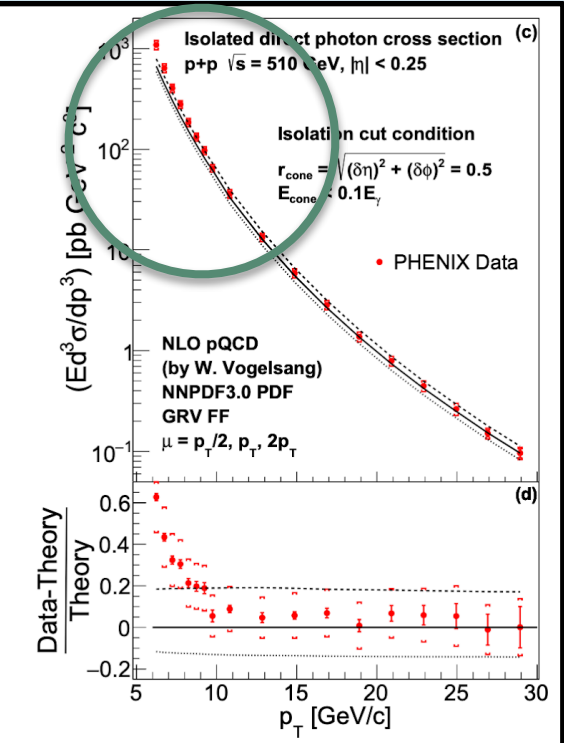
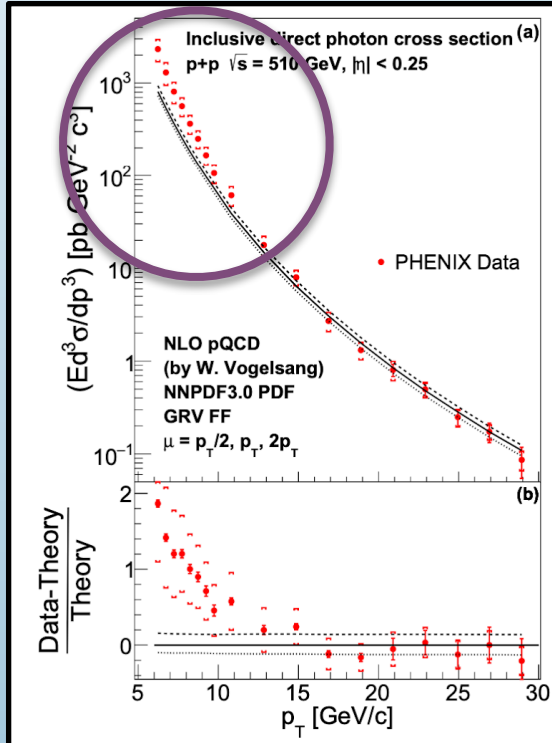
2.8σ

$\chi^2 = 12.6$

Direct sensitivity to the sign of Δg !

May be aided by isolation cut

Potential issues at $P_T < 10$



The RHIC Cold QCD Program

White Paper

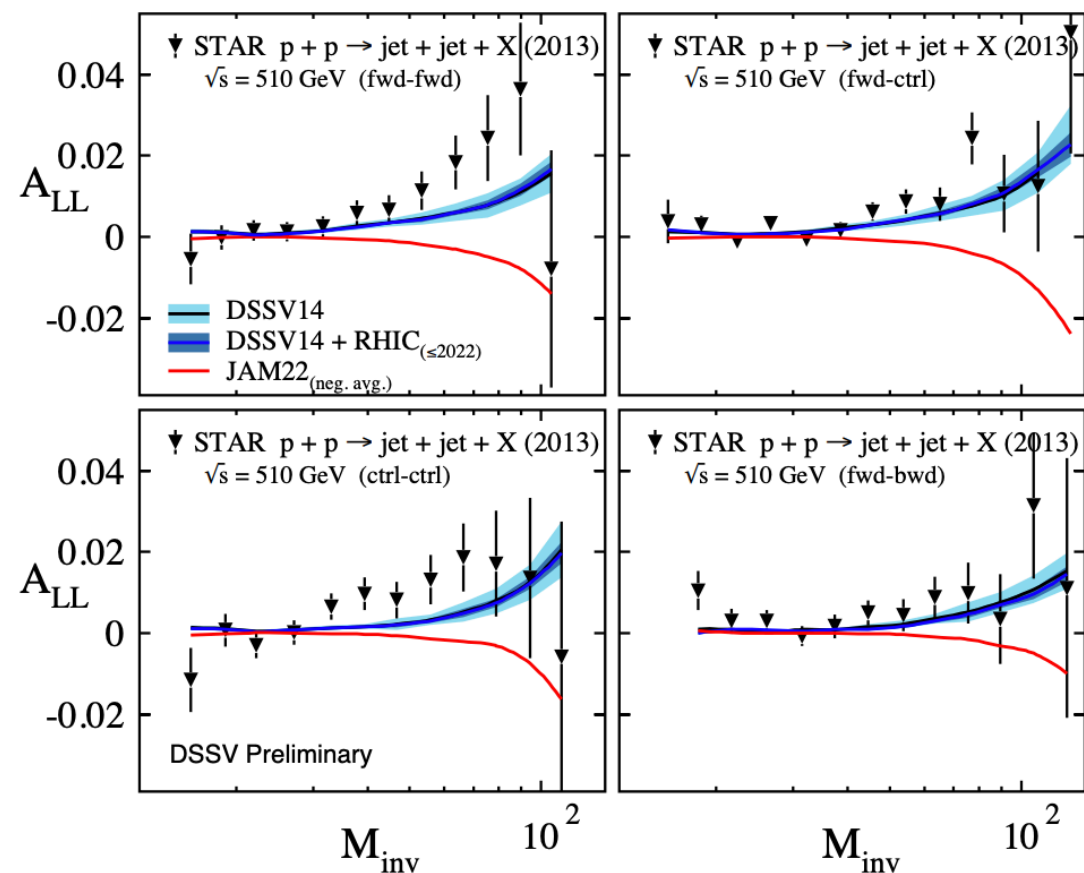
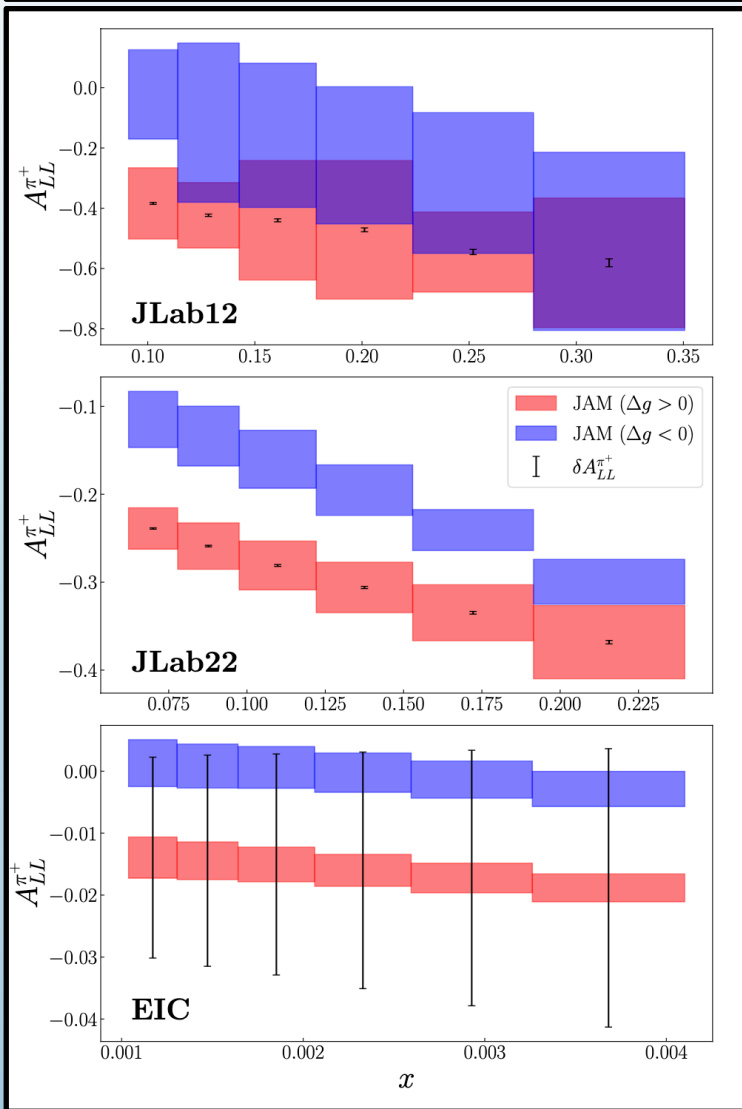


Figure 8: STAR double-helicity asymmetries A_{LL} for dijet production vs dijet invariant mass M_{inv} in polarized pp collisions at $\sqrt{s}=510$ GeV at midrapidity from 2013 data set [21]. DSSV14 evaluation [17] is plotted as the black curve with the 1σ uncertainty band marked in light blue. The blue curve with 1σ uncertainty band in dark blue shows the impact of all the data sets included in the new preliminary DSSV fit [2] as in Fig. 6. The red curves show the JAM $\Delta g < 0$ solution [41] calculated by the DSSV group.

Accessing gluon polarization with high- P_T hadrons in SIDIS
 Jefferson Lab Angular Momentum (JAM) Collaboration • R.M. Whitehill (Wichita State U.) et al. (Oct 21, 2022)
 Published in: *Phys.Rev.D* 107 (2023) 3, 034033 • e-Print: [2210.12295](https://arxiv.org/abs/2210.12295) [hep-ph]

$$\vec{l} + \vec{N} \rightarrow l' + h + X$$

$\mathcal{L} = 86 \text{ fb}^{-1}$ for JLab
 $\mathcal{L} = 10 \text{ fb}^{-1}$ for EIC

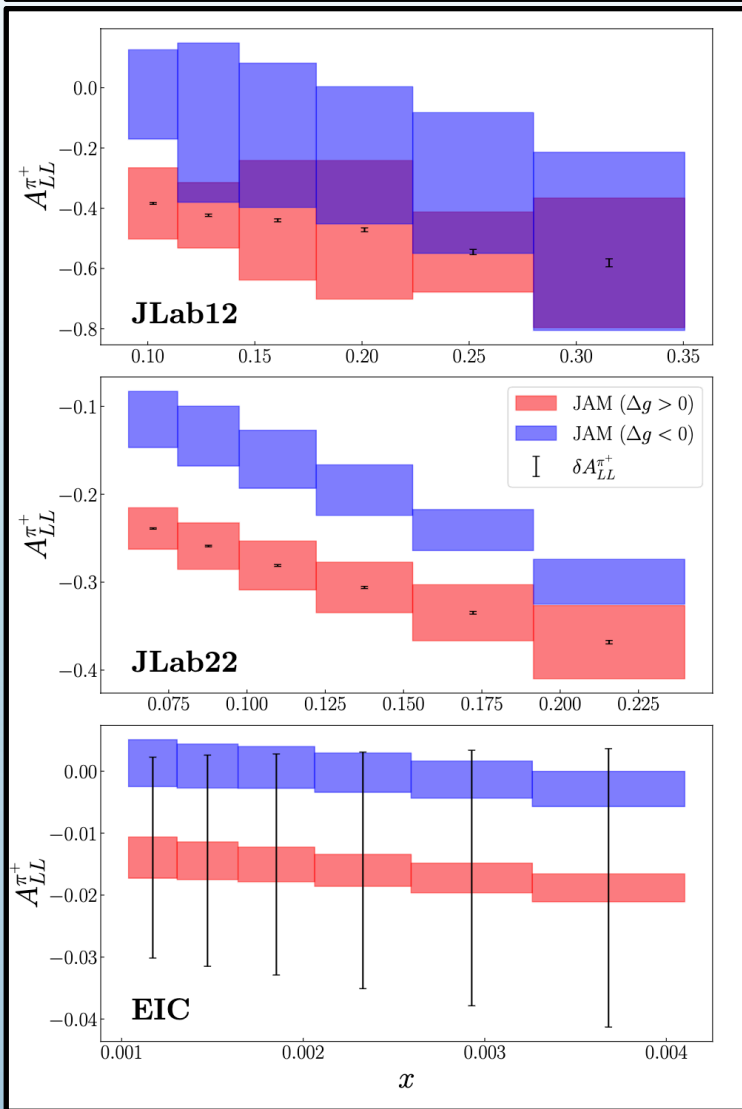


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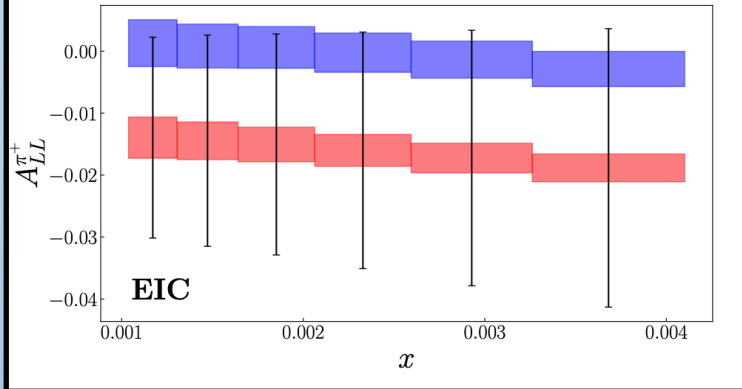
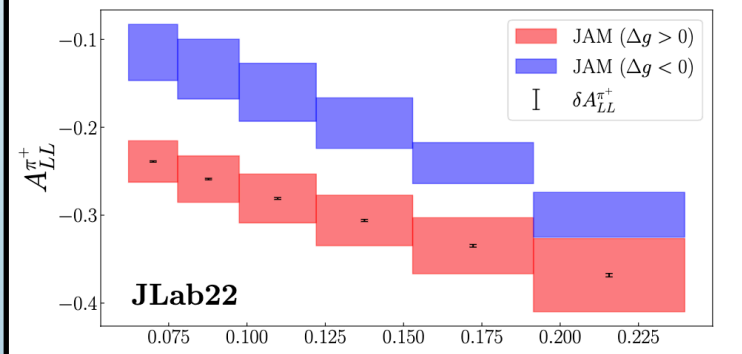
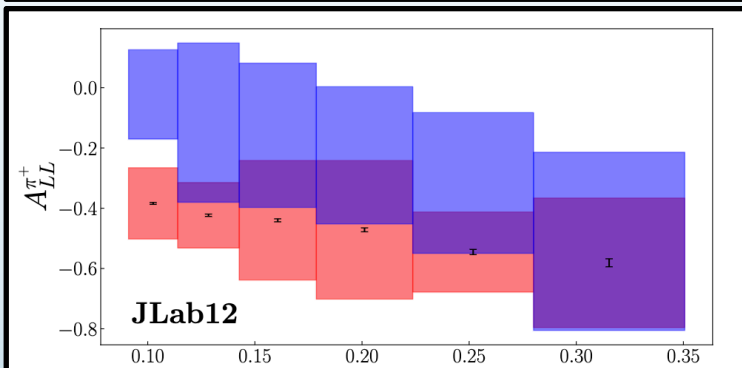
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JLab22 has stronger distinguishing power due to more evolution and access to smaller x



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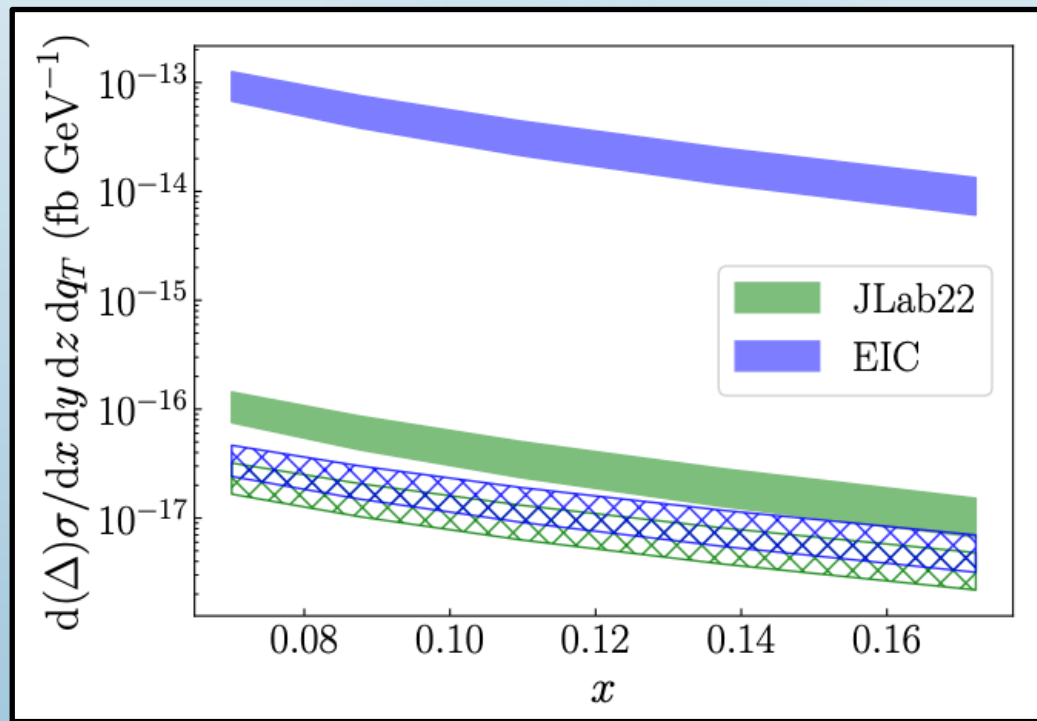
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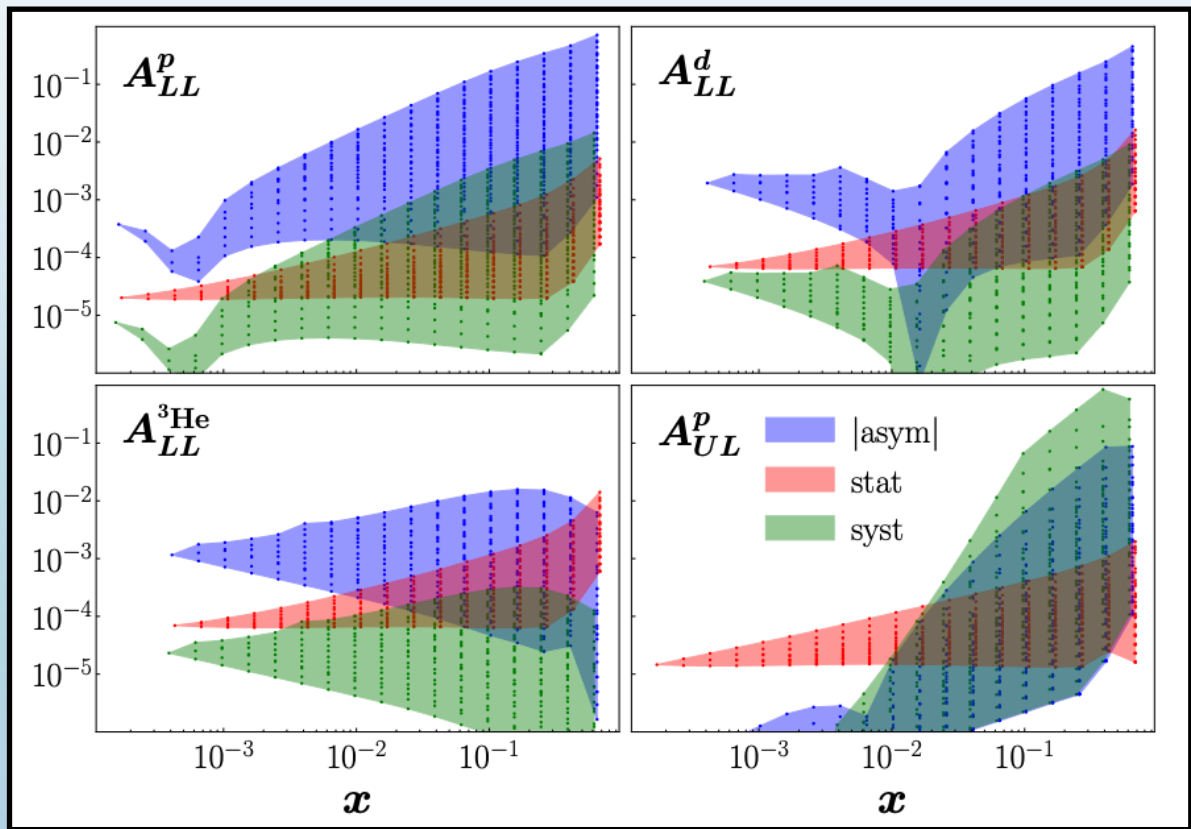
EIC asymmetry is small due to scaling behavior of unpolarized cross section

JLab22 has stronger distinguishing power due to more evolution and access to smaller x



Revisiting quark and gluon polarization in the proton at the EIC
 Jefferson Lab Angular Momentum (JAM) Collaboration • Y. Zhou (William-Mary Coll.) et al. (May 10, 2021)
 Published in: *Phys.Rev.D* 104 (2021) 3, 034028 • e-Print: [2105.04434](https://arxiv.org/abs/2105.04434) [hep-ph]

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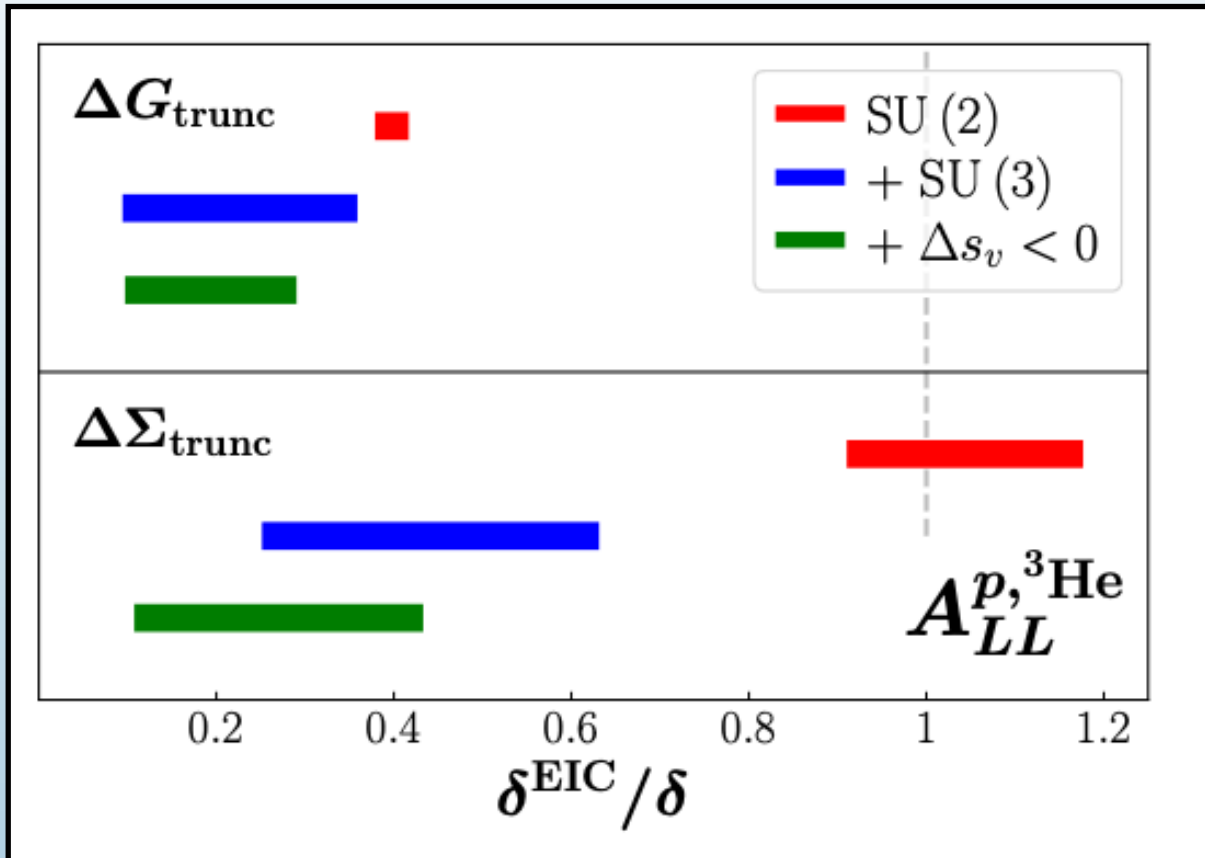
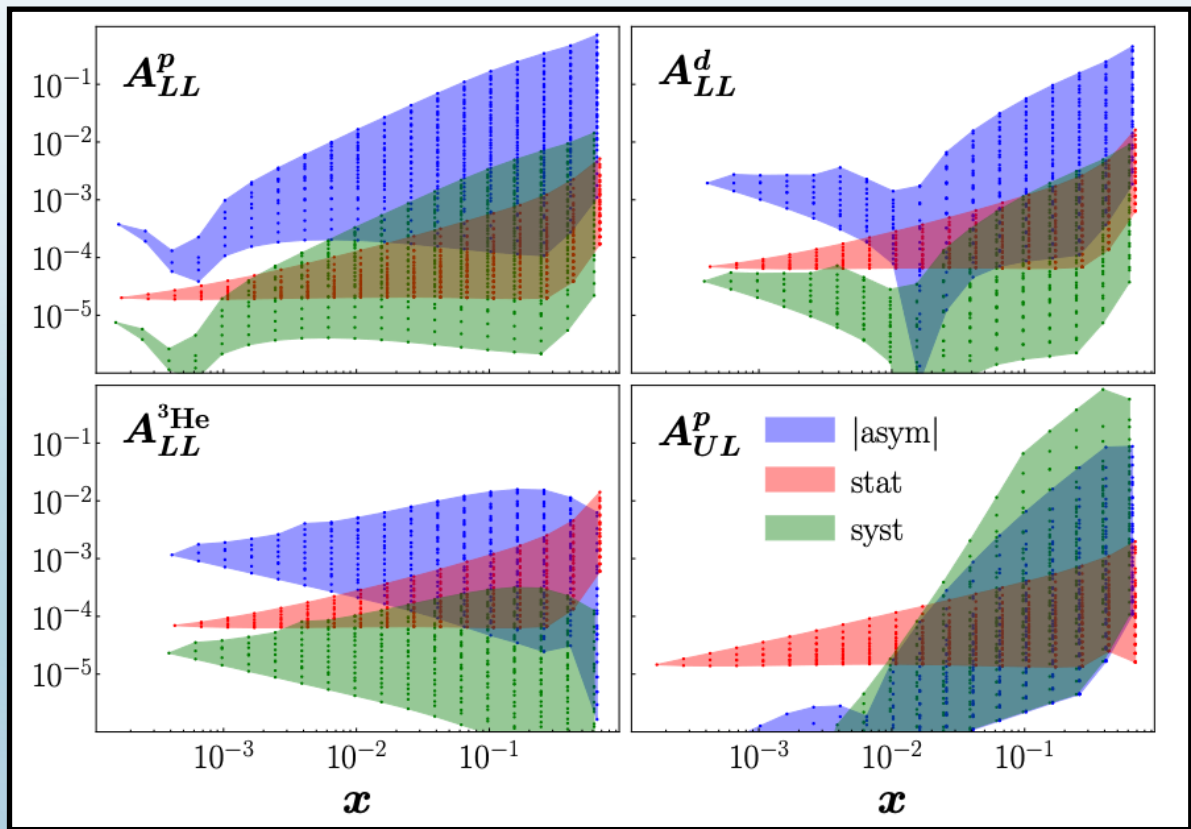


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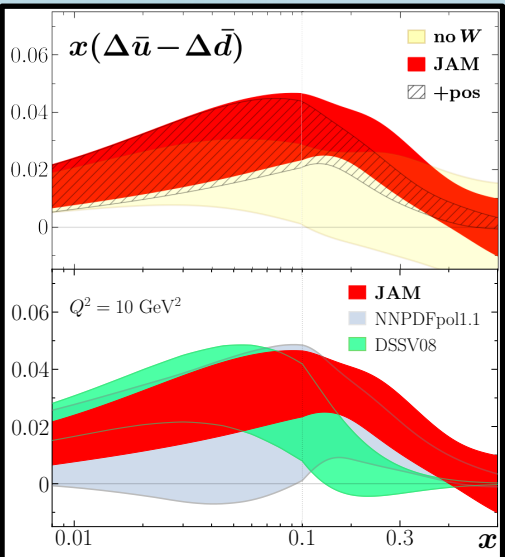
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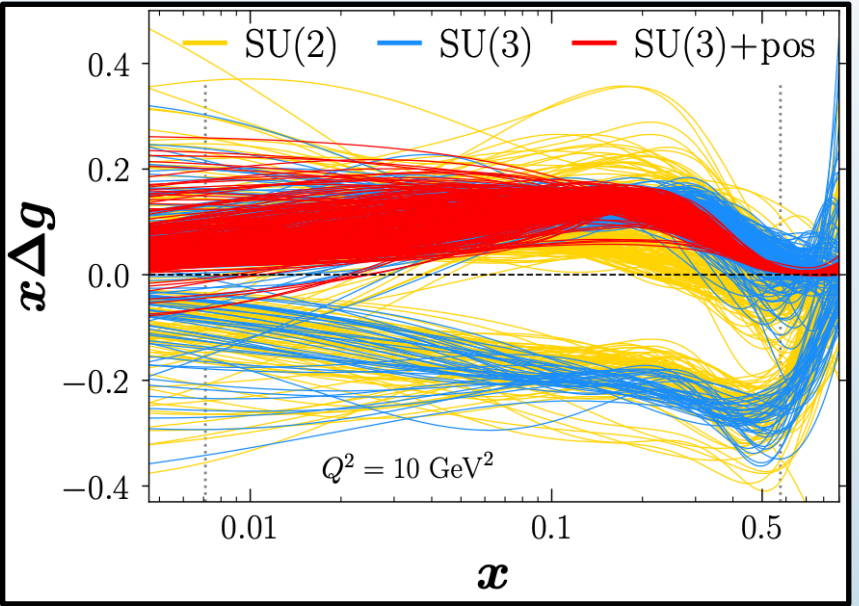


$$\Delta G_{trunc} = \int_{10^{-4}}^1 dx \Delta g(x)$$

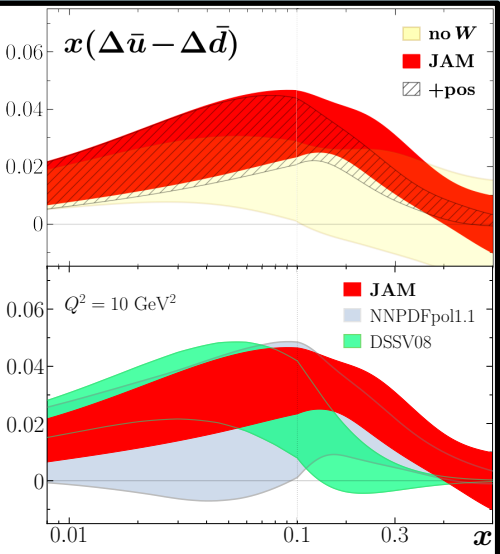
Nonzero sea asymmetry



Current JAM analyses have two gluon solutions

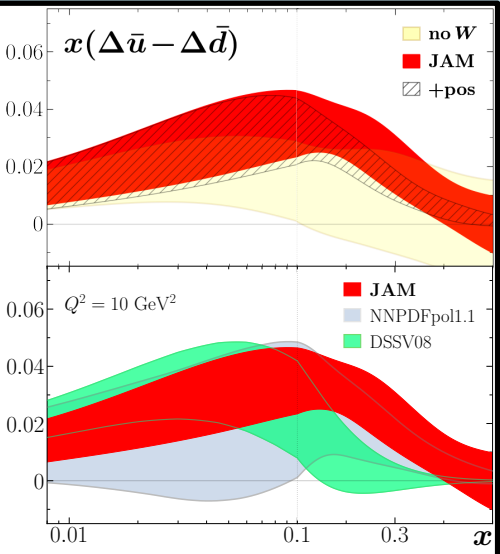
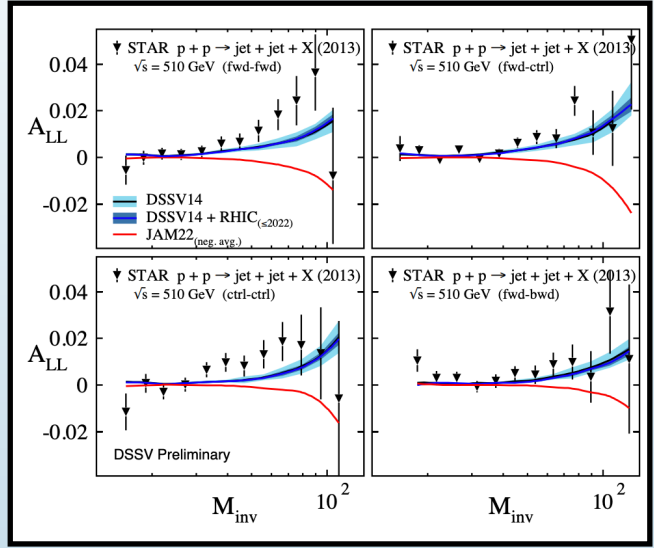
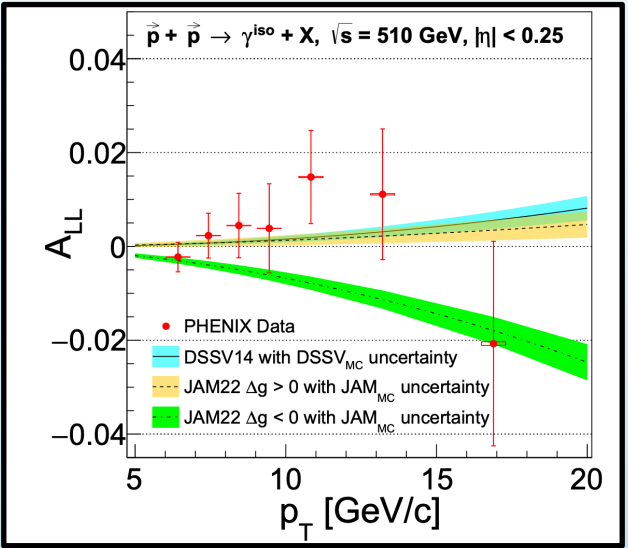
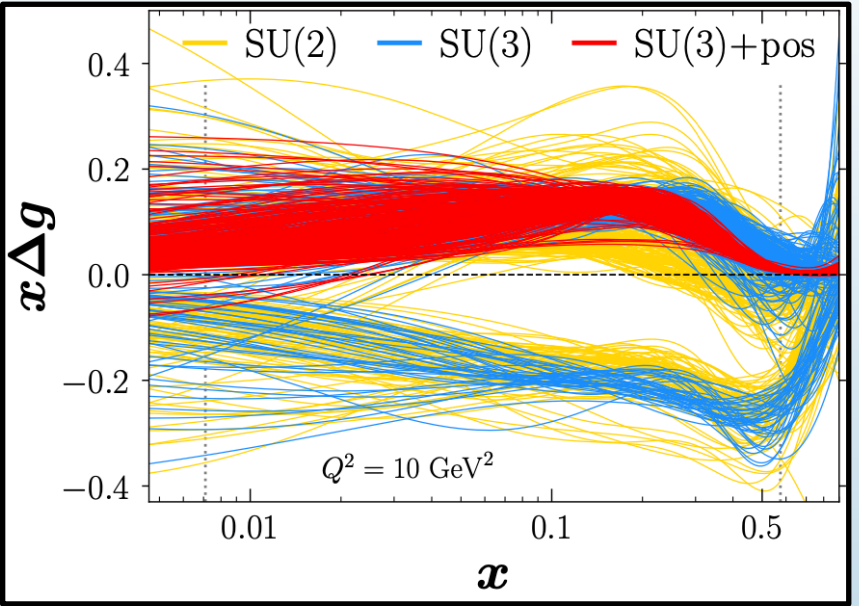


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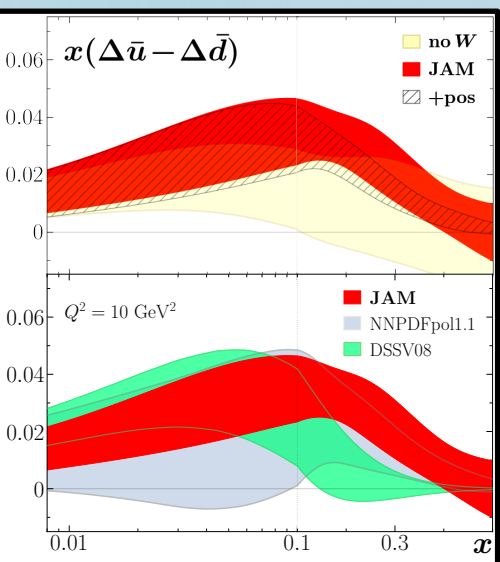
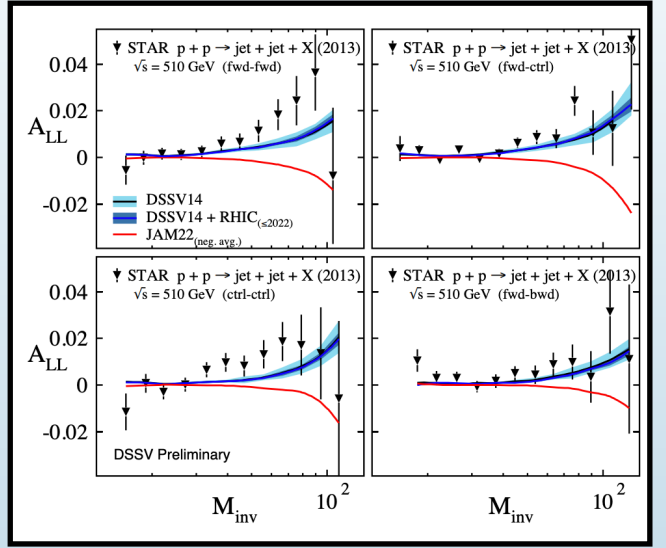
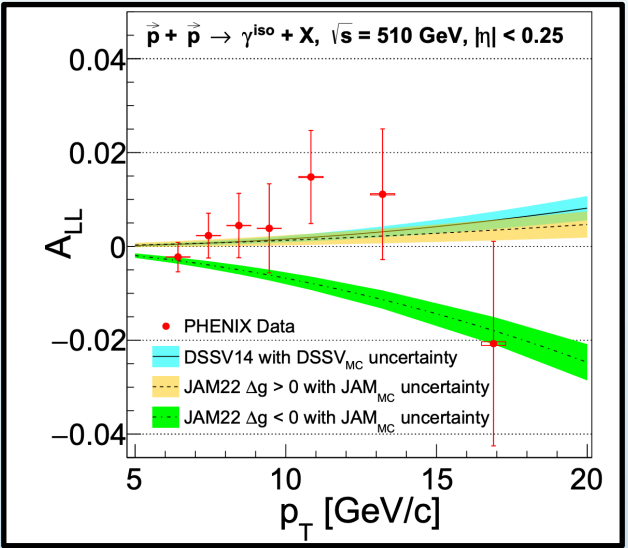
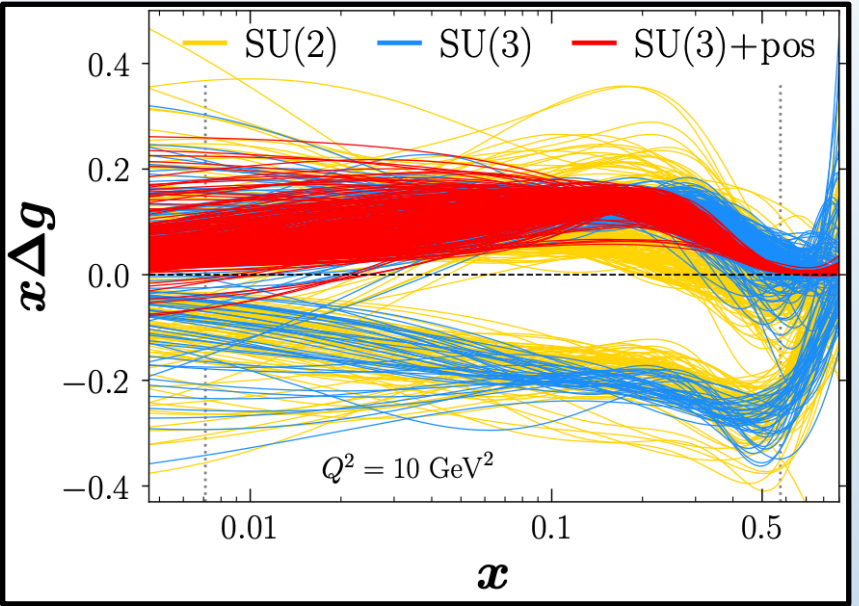
New data from RHIC may help distinguish them



Nonzero sea asymmetry

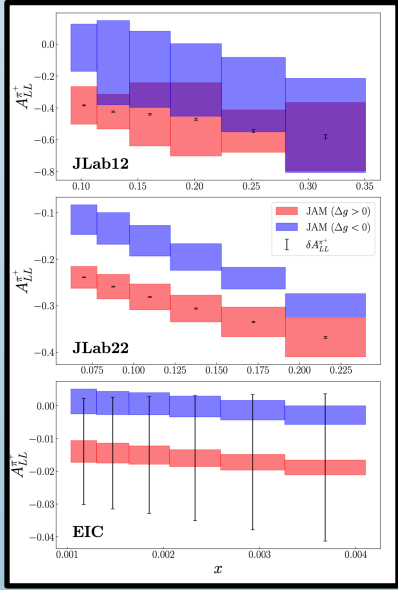
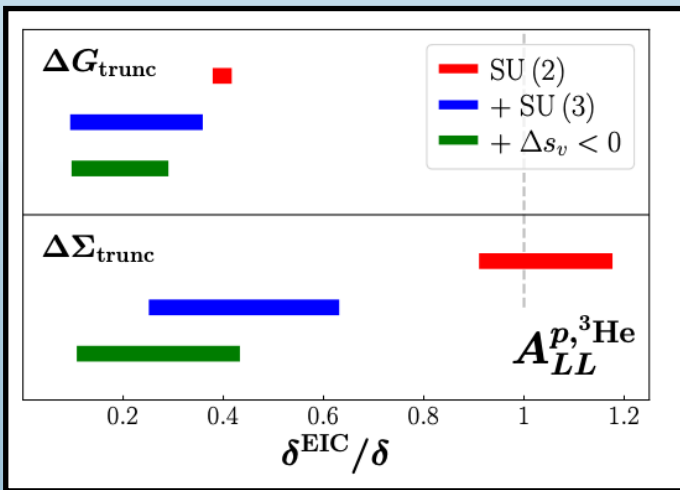
Current JAM analyses have two gluon solutions

New data from RHIC may help distinguish them



Nonzero sea asymmetry

Future data from the EIC and JLab should provide new information



Extra Slides

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

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

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

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Evolve PDFs using DGLAP

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

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

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Calculate Observables

$$d\sigma^{pp} = \sum_{ij} H_{ij}^{pp} \otimes f_i \otimes f_j$$

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Mellin Space Techniques

$$d\sigma^{pp} = \sum_{ijkl} \frac{1}{(2\pi i)^2} \int dN \int dM \tilde{f}_j(N, \mu_0) \tilde{f}_l(M, \mu_0) \\ \otimes \left[x_1^{-N} x_2^{-M} \tilde{\mathcal{H}}_{ik}^{pp}(N, M, \mu) U_{ij}^S(N, \mu, \mu_0) U_{kl}^S(M, \mu, \mu_0) \right]$$

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

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$$d\sigma^{pp} = \sum_{ij} H_{ij}^{pp} \otimes f_i \otimes f_j$$

Mellin Space Techniques

$$d\sigma^{pp} = \sum_{ijkl} \frac{1}{(2\pi i)^2} \int dN \int dM \tilde{f}_j(N, \mu_0) \tilde{f}_l(M, \mu_0) \\ \otimes \left[x_1^{-N} x_2^{-M} \tilde{\mathcal{H}}_{ik}^{pp}(N, M, \mu) U_{ij}^S(N, \mu, \mu_0) U_{kl}^S(M, \mu, \mu_0) \right]$$

$$\sigma = \sum_{ij} H_{ij} \otimes f_i \otimes f_j + \mathcal{O}(1/Q)$$

Experimentally measured
cross-section

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Experimentally measured
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$$\sigma = \sum_{ij} H_{ij} \otimes f_i \otimes f_j + \mathcal{O}(1/Q)$$

“Hard part” (process dependent)
Cross-section at parton level
Calculated in perturbative QCD

Experimentally measured
cross-section

“Soft part” (process independent)
Describes internal structure

$$\sigma = \sum_{ij} H_{ij} \otimes f_i \otimes f_j + \mathcal{O}(1/Q)$$

“Hard part” (process dependent)
Cross-section at parton level
Calculated in perturbative QCD

Now that the observables have been calculated...

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

Now that the observables have been calculated...

Data

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

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Data

Theory

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

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Uncorrelated
Uncertainties

Now that the observables have been calculated...

The diagram illustrates the components of a chi-squared fit. It shows the relationship between Data and Theory, and how they are combined in the chi-squared function. The fit includes uncorrelated uncertainties and correlated uncertainties.

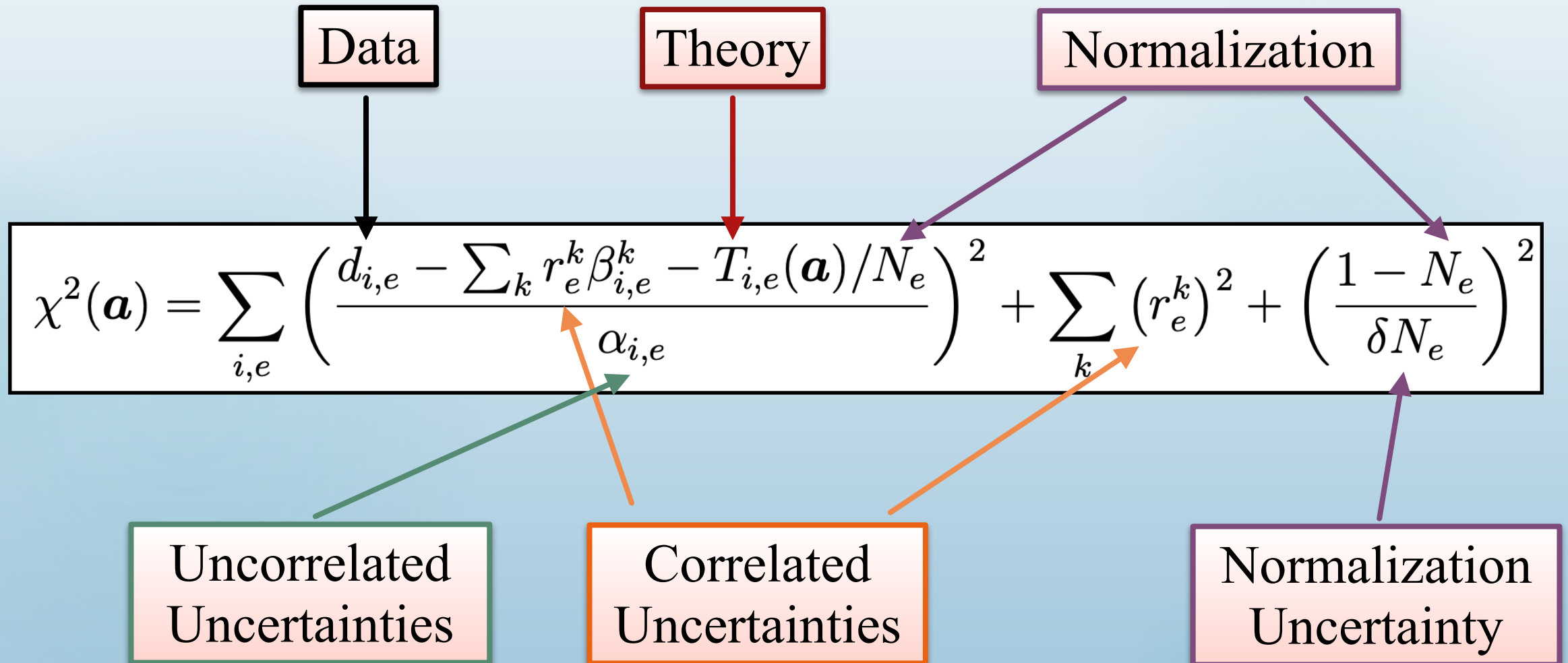
Data and **Theory** are shown in boxes above the equation. Arrows point from these boxes to the corresponding terms in the equation.

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

Uncorrelated Uncertainties (green box) points to $\alpha_{i,e}$.

Correlated Uncertainties (orange box) points to r_e^k .

Now that the observables have been calculated...



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

Likelihood Function

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

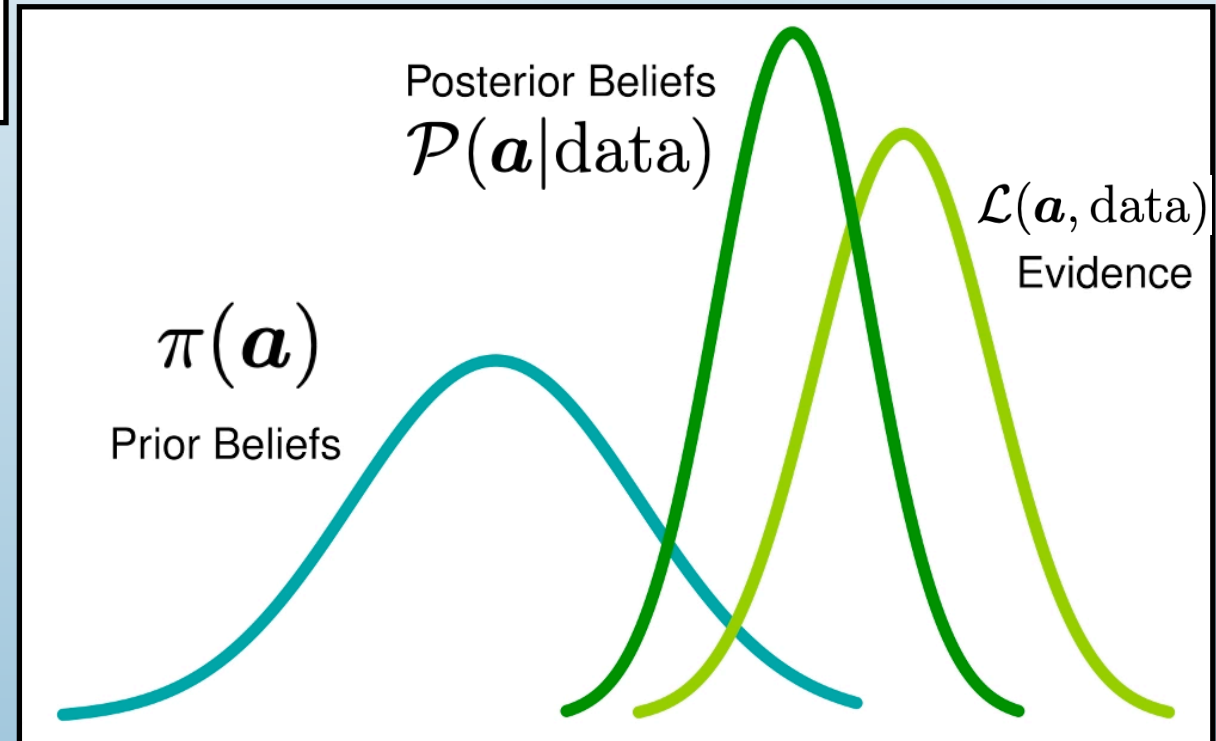
Now that we have calculated $\chi^2(\mathbf{a}, \text{data}) \dots$

Likelihood Function

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

Bayes' Theorem

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

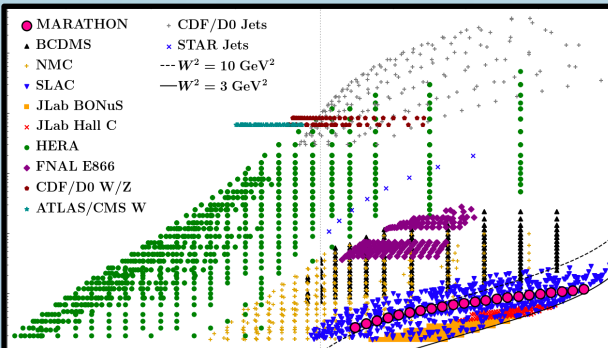


$$\tilde{\sigma} = \sigma + N(0,1) \alpha$$

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Data

Original Data

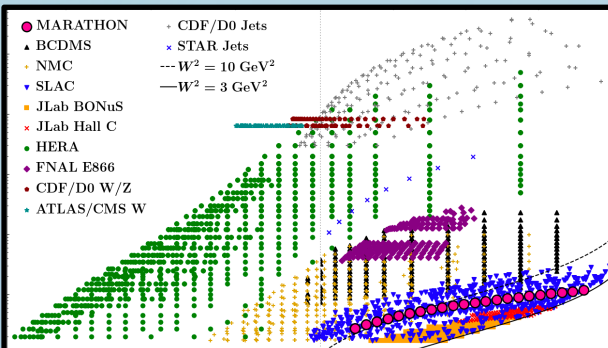


$$\tilde{\sigma} = \sigma + N(0,1) \alpha$$

Uncorrelated
Uncertainties

Data

Original Data



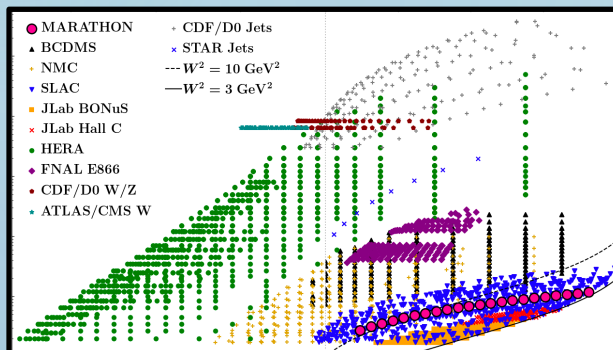
Pseudo-Data

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

Uncorrelated
Uncertainties

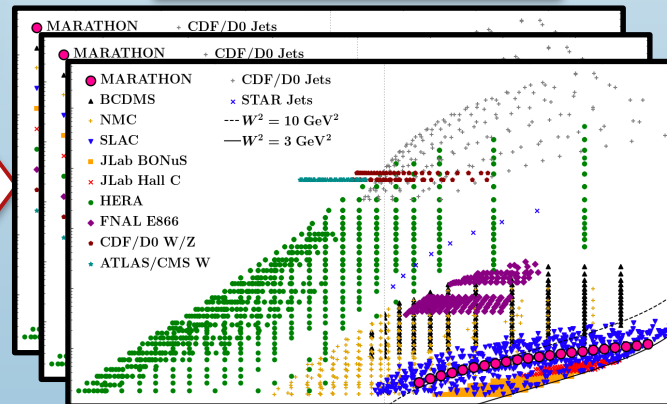
Data

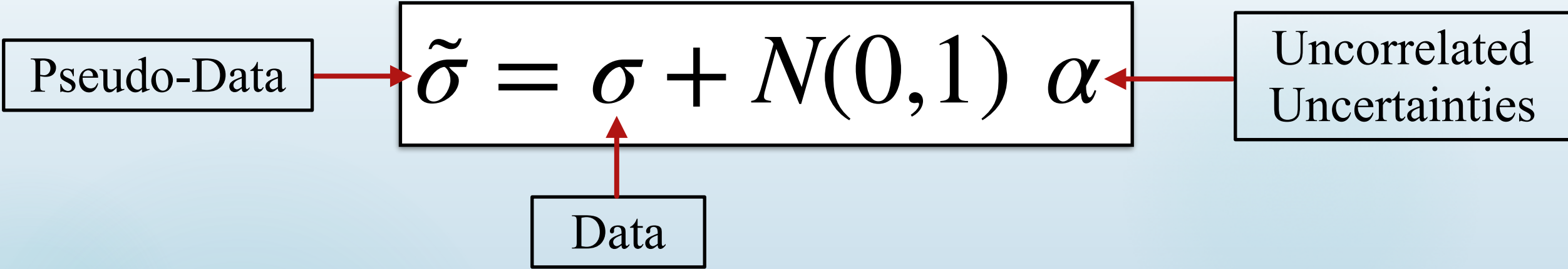
Original Data



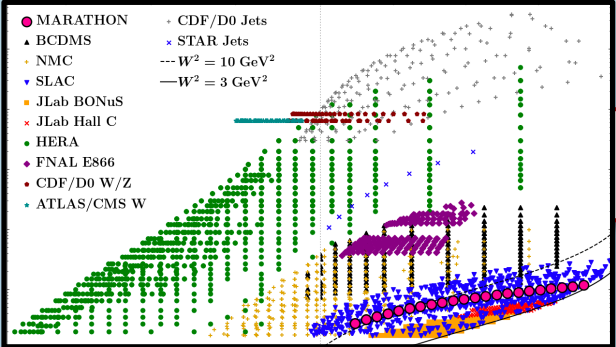
DR

Replica Data



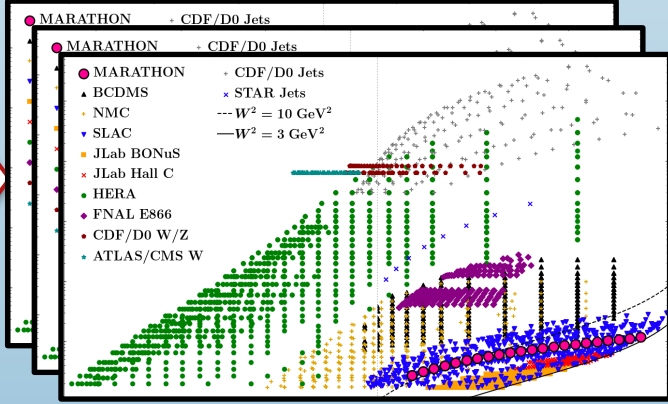


Original Data



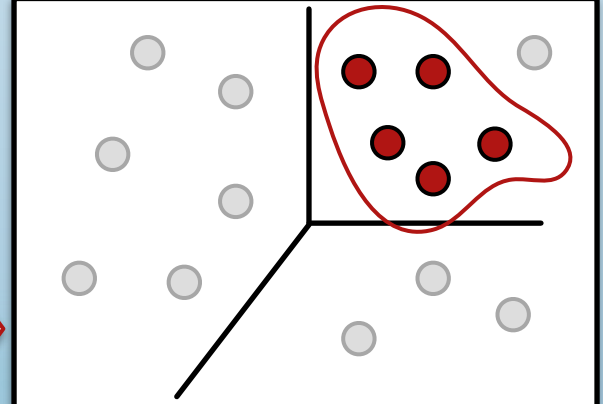
DR \rightarrow

Replica Data



Maximum Likelihood \rightarrow
 Maximum Likelihood \rightarrow
 Maximum Likelihood \rightarrow

Parameter Space



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

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

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

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

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



Build an MC ensemble

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

Build an MC ensemble

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

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

Average over k sets
of the parameters
(replicas)

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

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

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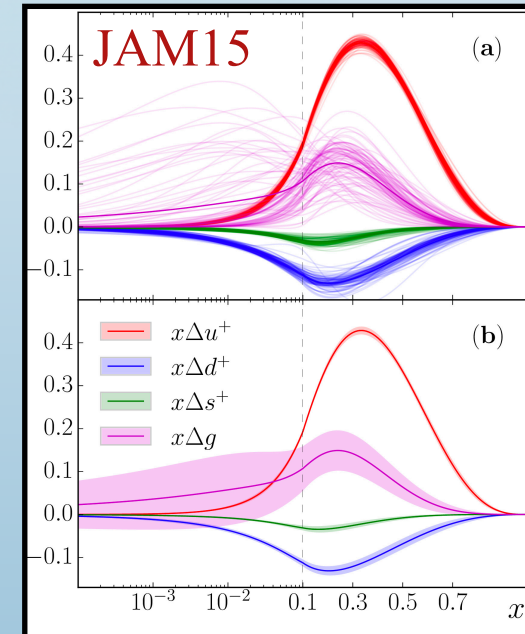
Build an MC ensemble

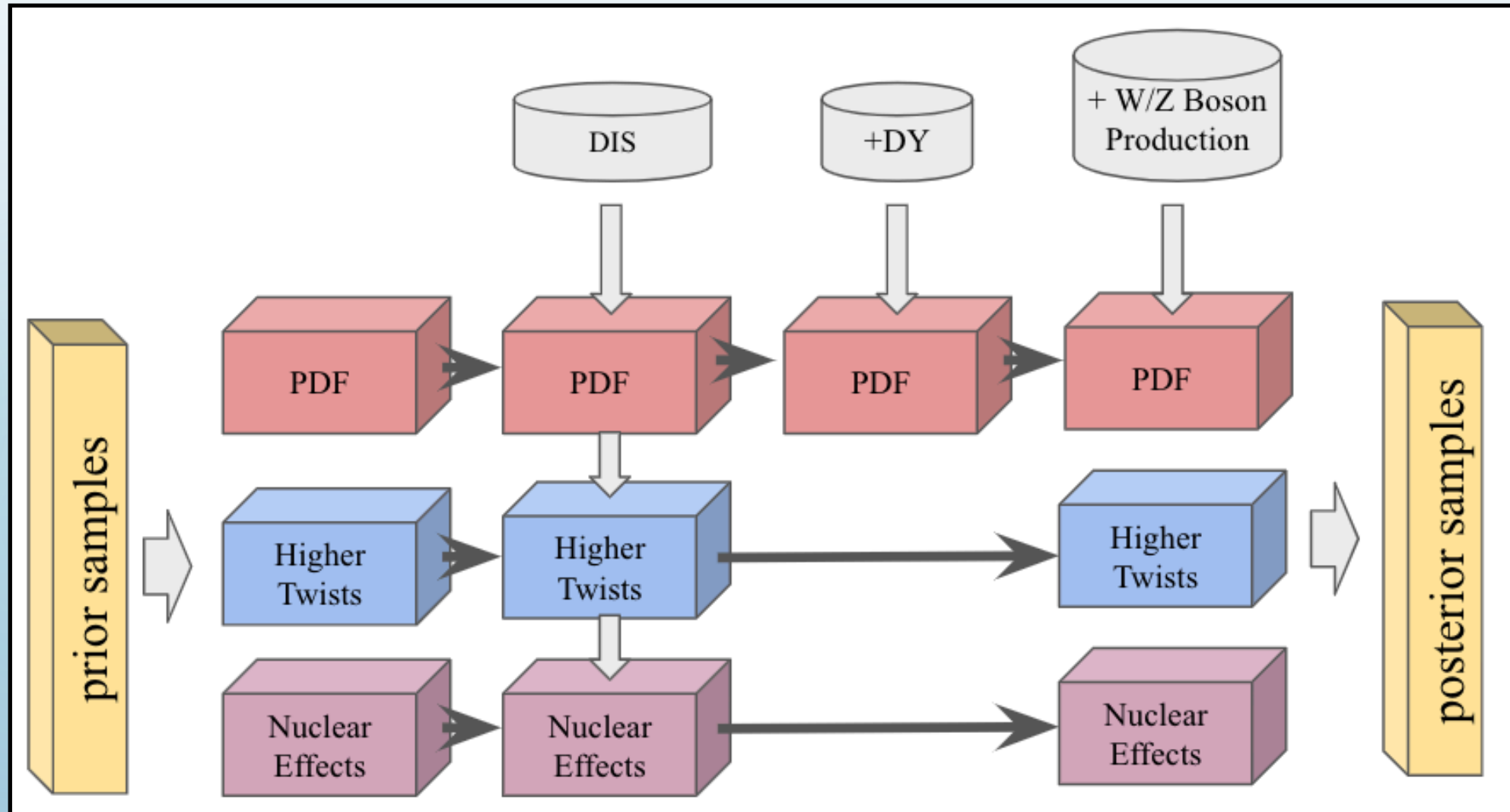
$$E[O] \approx \frac{1}{N} \sum_k O(\mathbf{a}_k)$$

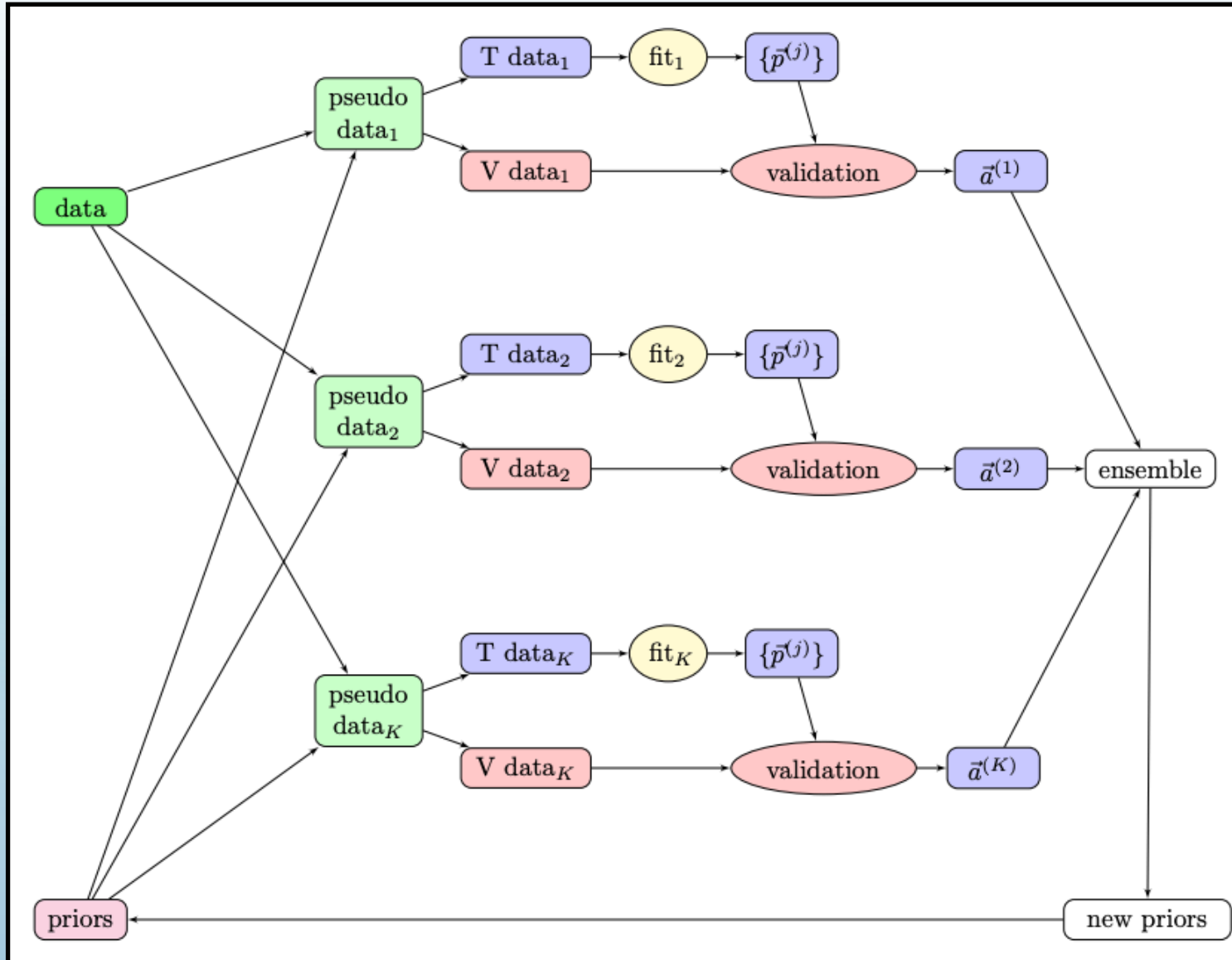
$$V[O] \approx \frac{1}{N} \sum_k [O(\mathbf{a}_k) - E[O]]^2$$

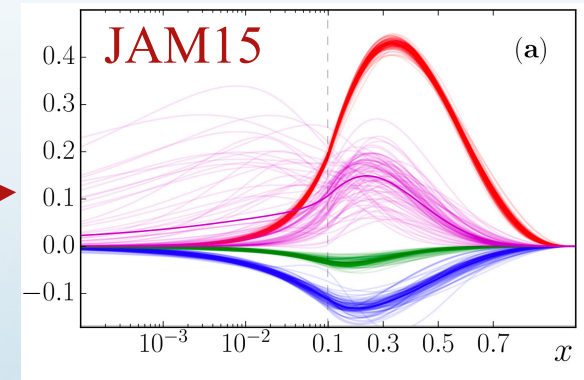
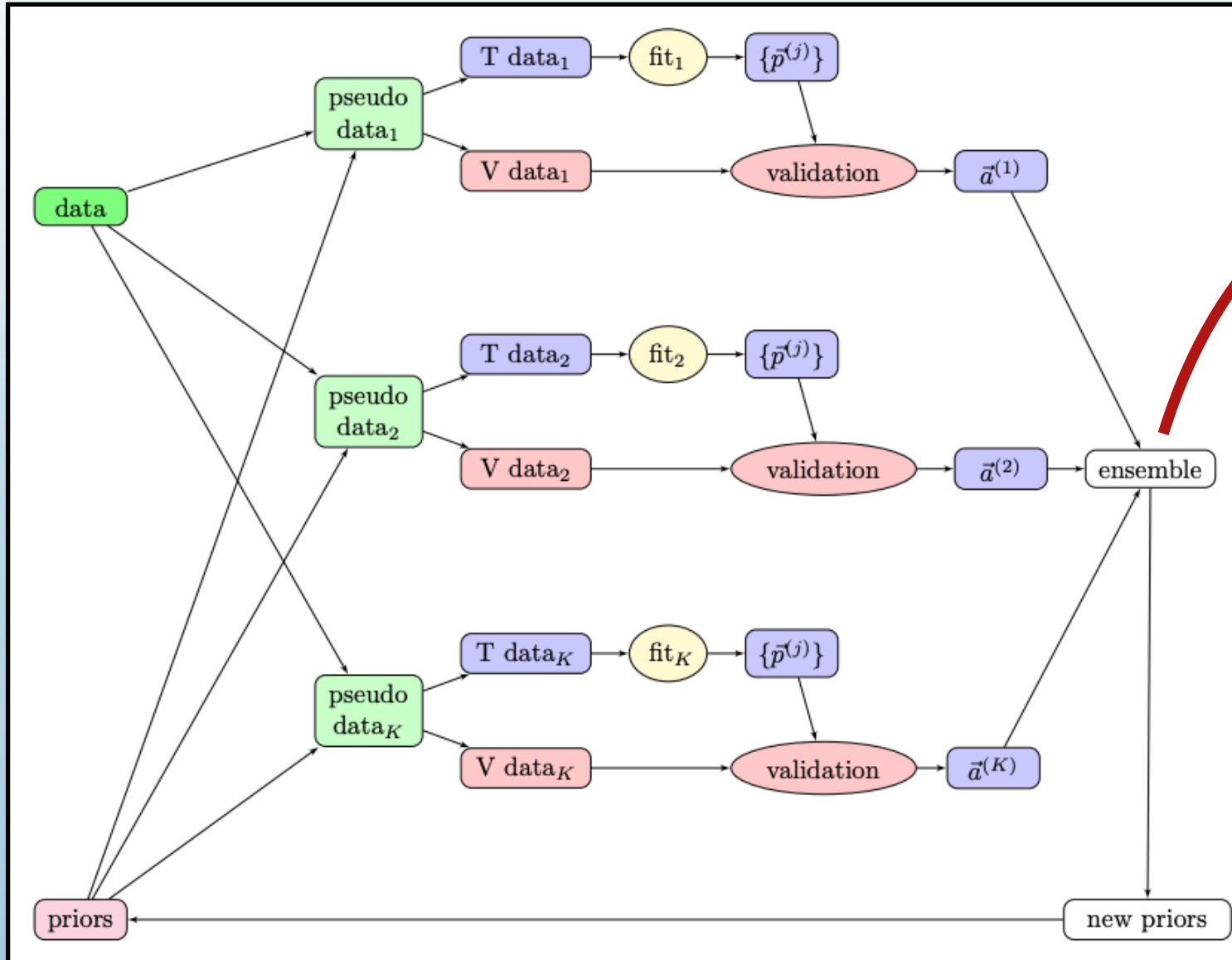
Exact, but
 $n = \mathcal{O}(100)$!

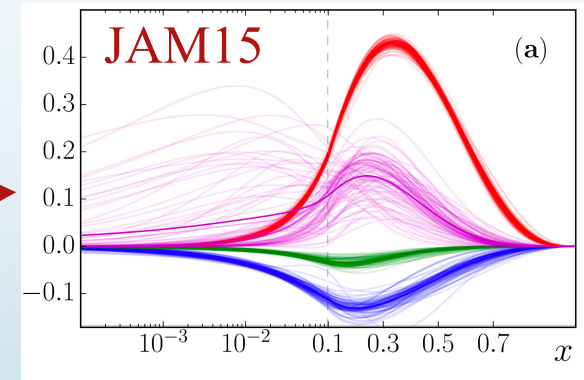
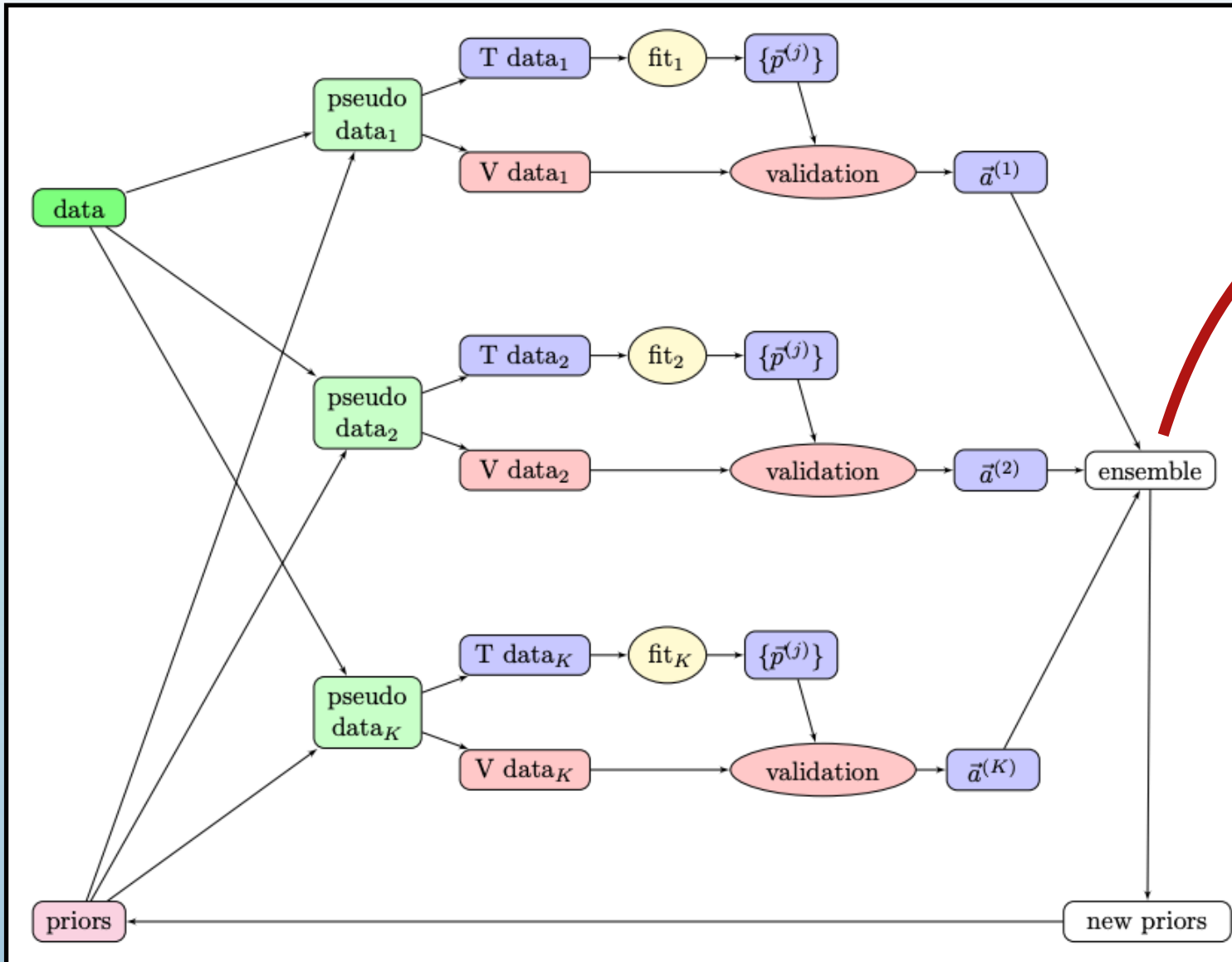
Average over k sets
of the parameters
(replicas)







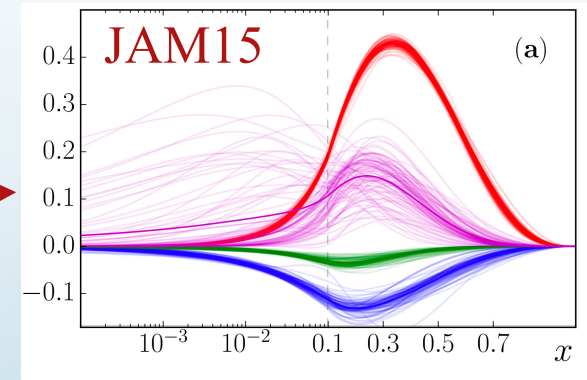
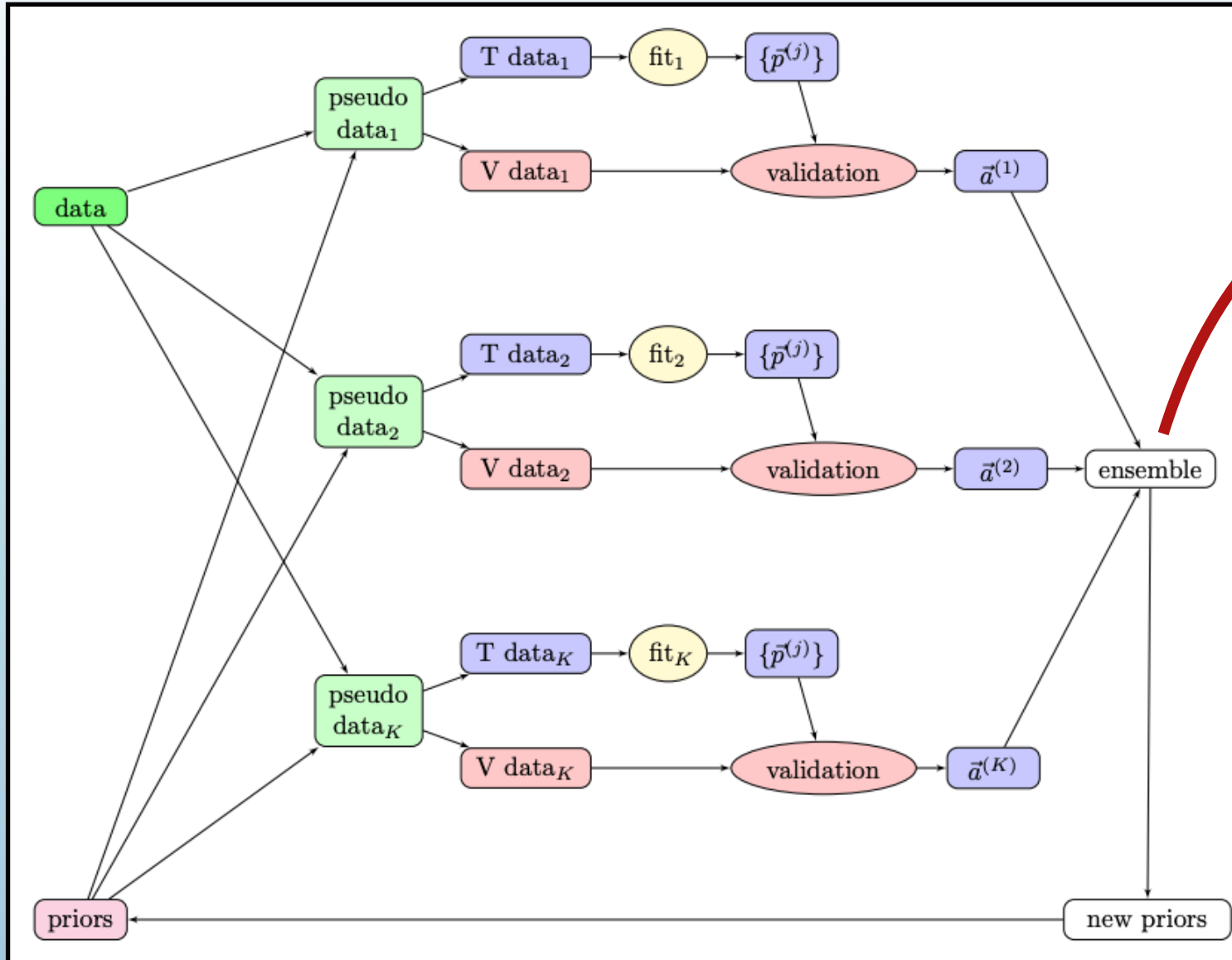




+

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

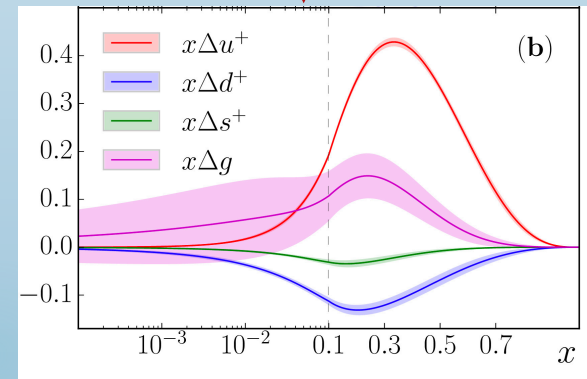
$$V[O] \approx \frac{1}{N} \sum_k [O(\mathbf{a}_k) - E[O]]^2$$



+

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

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

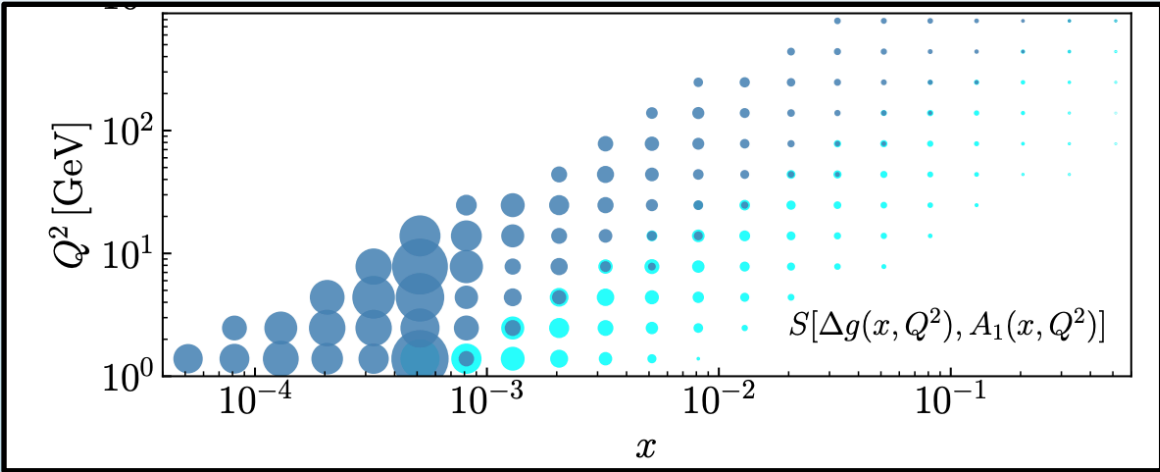


Revisiting helicity parton distributions at a future electron-ion collider #2

Ignacio Borsa (U. Buenos Aires), Gonzalo Lucero (U. Buenos Aires), Rodolfo Sassot (U. Buenos Aires), Elke C. Aschenauer (Brookhaven Natl. Lab.), Ana S. Nunes (Brookhaven Natl. Lab.) (Jul 16, 2020)

Published in: *Phys.Rev.D* 102 (2020) 9, 094018 • e-Print: [2007.08300](https://arxiv.org/abs/2007.08300) [hep-ph]

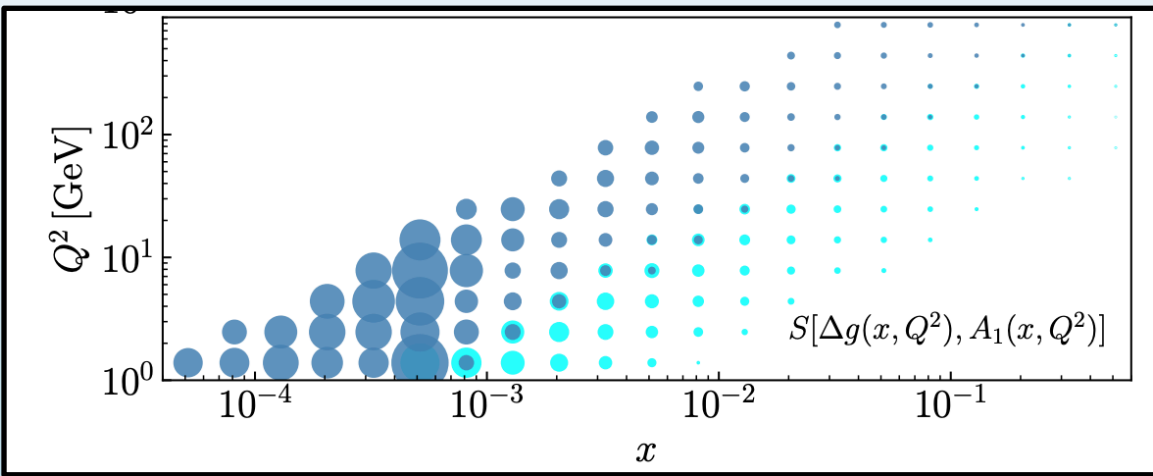
$$\vec{l} + \vec{N} \rightarrow l' + X$$



Sensitivity of A_1 to Δg

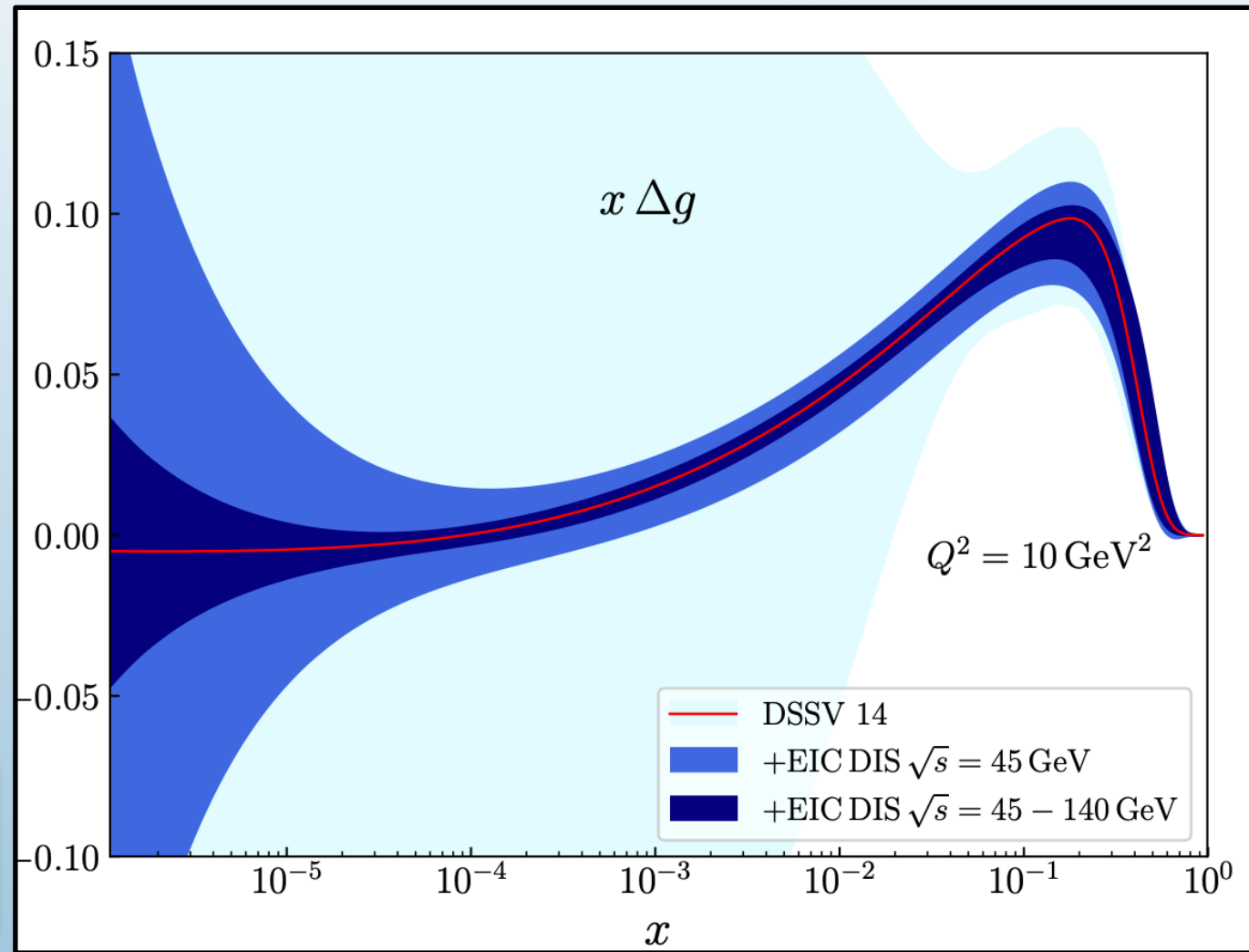
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$$\vec{l} + \vec{N} \rightarrow l' + X$$



Sensitivity of A_1 to Δg

Large impact on Δg predicted, especially below $x \approx 0.01$



- DSSV 14
- █ +EIC DIS $\sqrt{s} = 45$ GeV
- █ +EIC DIS $\sqrt{s} = 45 - 140$ GeV

Positivity and renormalization of parton densities

#1

John Collins (Penn State U.), Ted C. Rogers (Old Dominion U. and Jefferson Lab), Nobuo Sato (Jefferson Lab) (Nov 1, 2021)

Published in: *Phys.Rev.D* 105 (2022) 7, 076010 • e-Print: [2111.01170](https://arxiv.org/abs/2111.01170) [hep-ph]

As regards the positivity issue itself, there are several points to make. First, we emphasize that we have not argued that $\overline{\text{MS}}$ pdfs *must* be negative for any particular choice of scales or $\mu_{\overline{\text{MS}}}$. Rather we proved that nothing in the definition of pdfs or in the factorization theorems themselves excludes negativity as a possibility, especially at low or moderate input scales. But we did show arguments that indicate that certain generic situations do tend to lead to negative pdfs of partons with small pdfs, notably for non-valence quarks. Giving a full theoretical answer to the question of whether a particular pdf turns negative depends on its large distance/low energy non-perturbative properties, as the sensitivity to mass scales in the example of Sec. VIII illustrates. Also, the failure of