Recent Updates from the JAM Collaboration on Helicity PDFs

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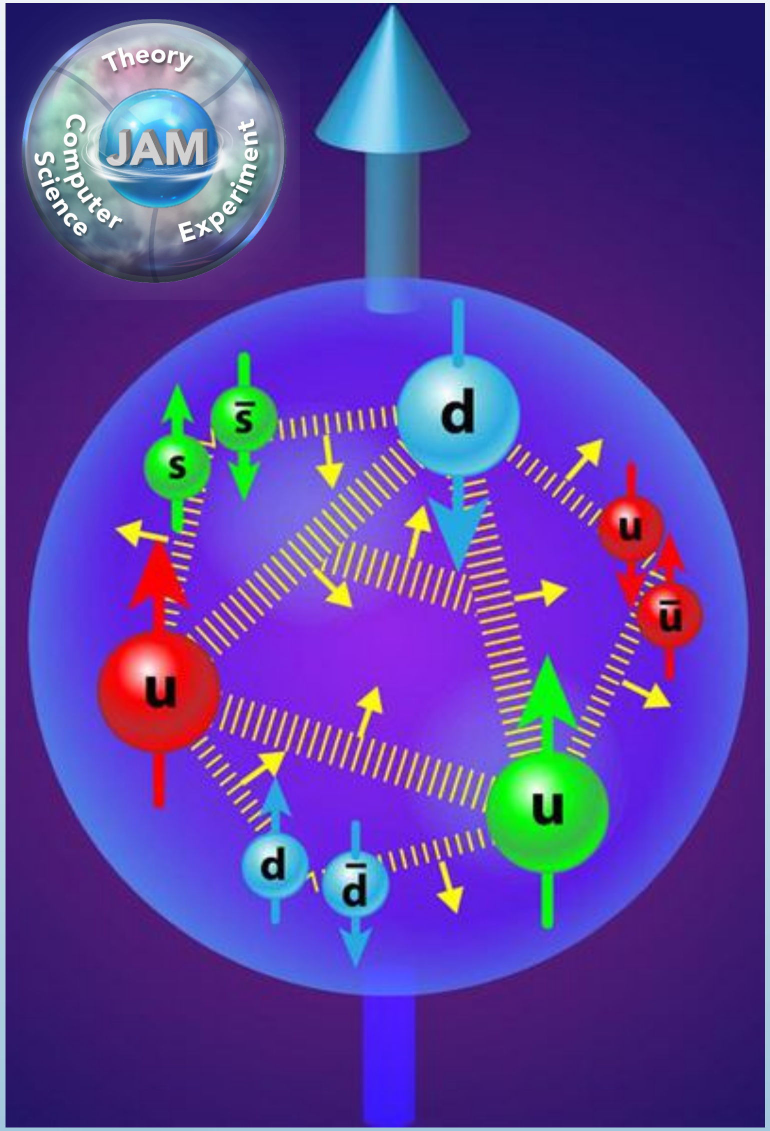
September 26, 2023

JAM Collaboration

3-dimensional structure of nucleons:

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

- Collinear factorization in perturbative QCD
- Simultaneous determinations of PDFs, FFs, etc.
- Monte Carlo methods for Bayesian inference



Introduction

Hadron Structure

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

Param. + Evolve + Factorization

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

USQCD

Extended Twisted Mass Collaboration

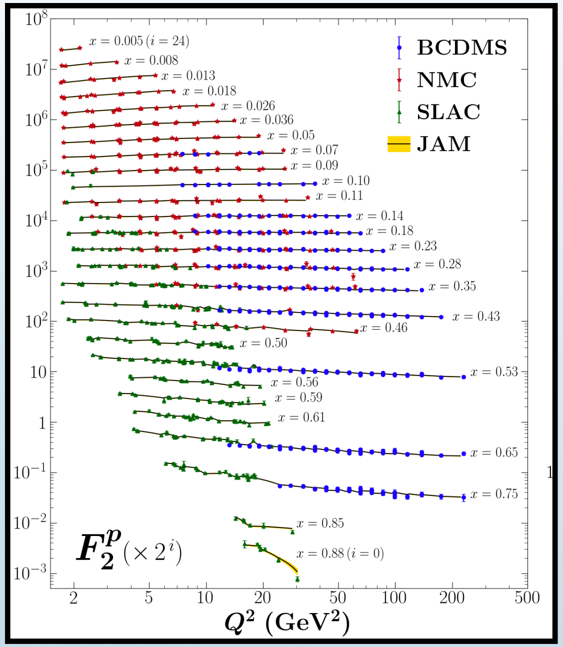
Global QCD Analysis

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

χ^2 Minimization

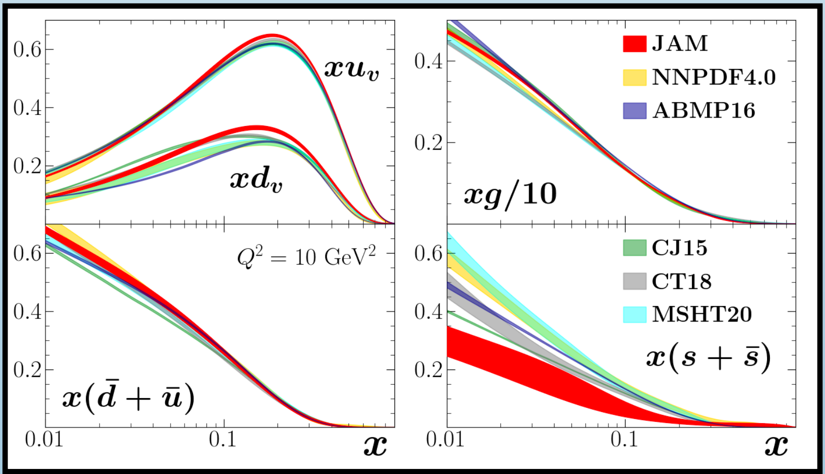
$$\mathcal{L}(\boldsymbol{a}, \text{data}) = \exp\left(-\frac{1}{2} \chi^2(\boldsymbol{a}, \text{data}) \right)$$

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



Data Resampling

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



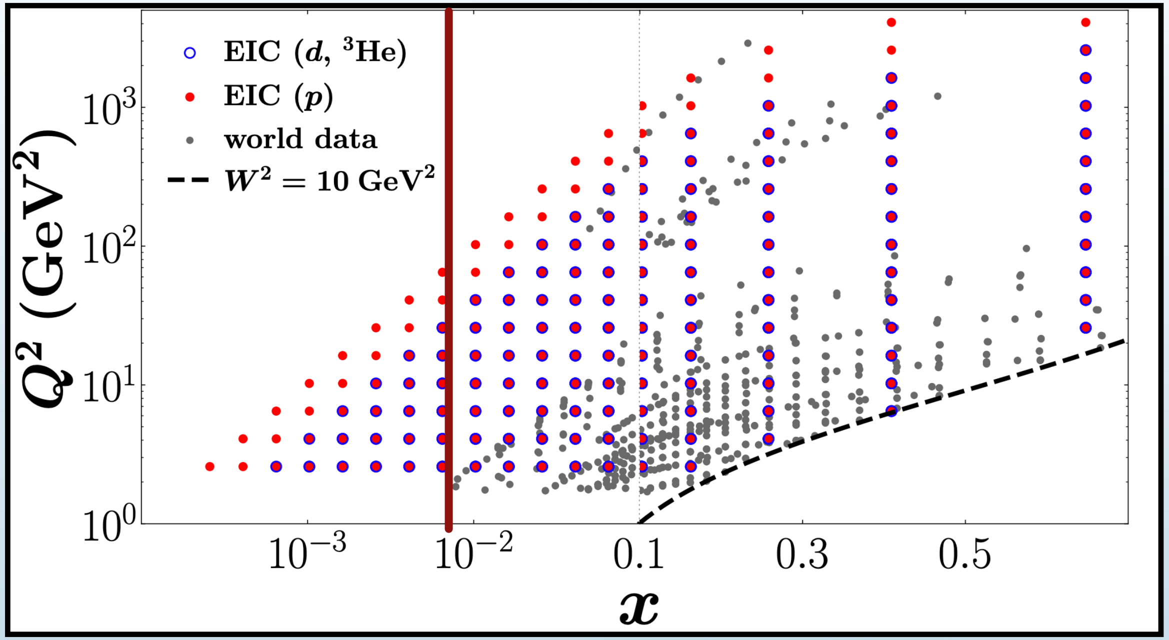
Current State of Helicity PDFs

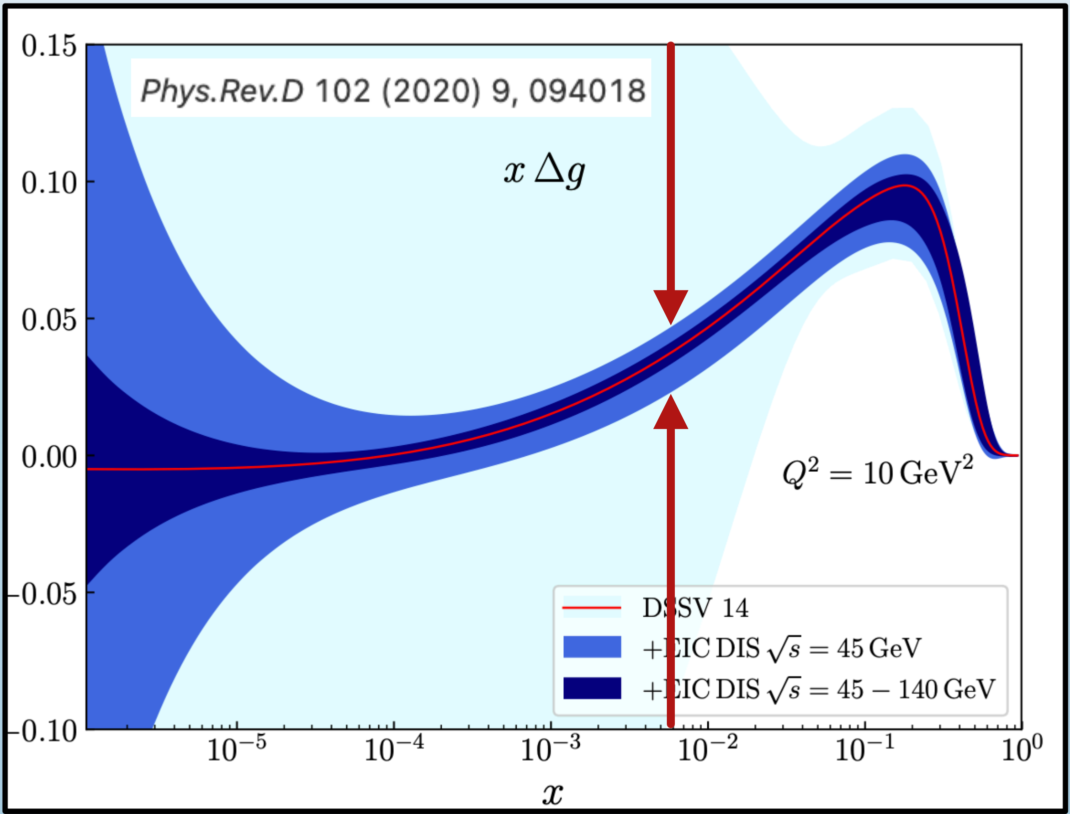
Proton spin puzzle:

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

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

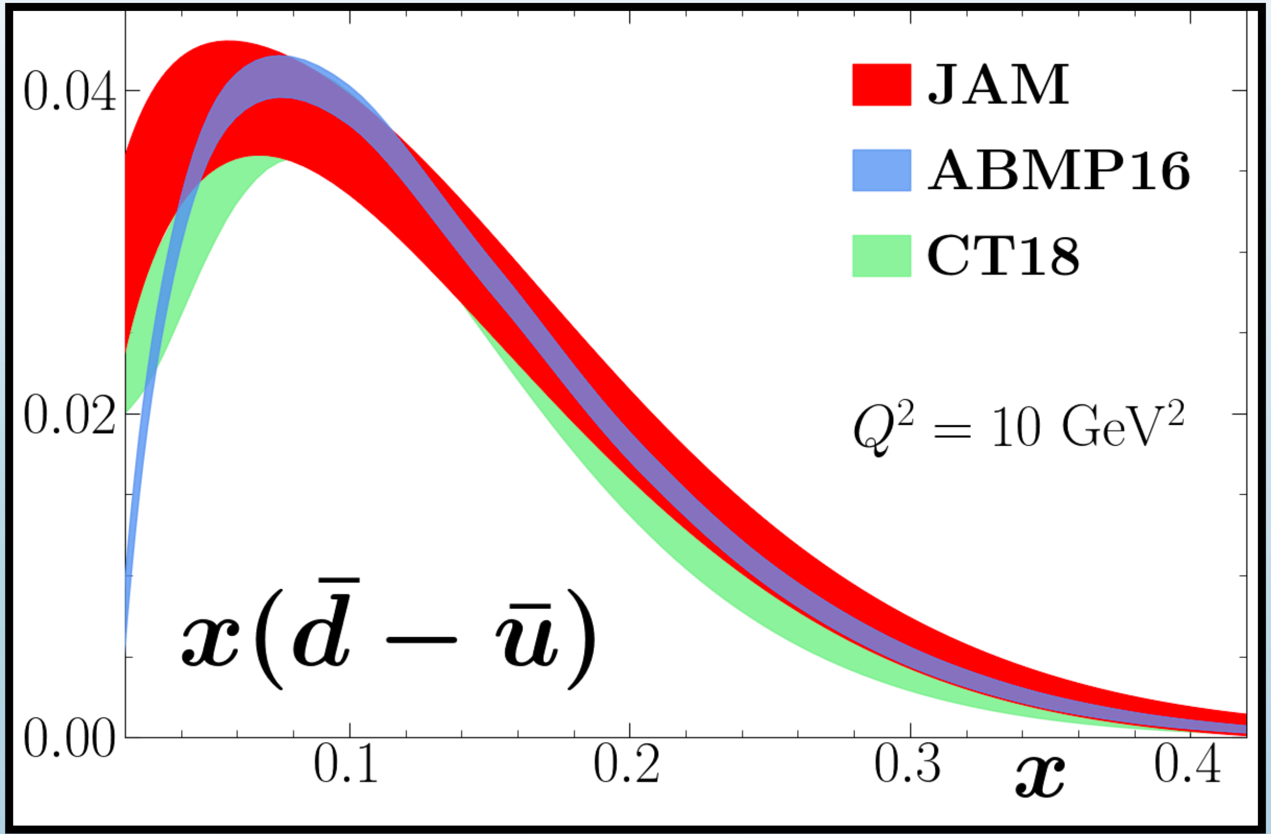
$$\Delta G = \int_0^1 dx \Delta g$$





Still a lot to learn about helicity PDFs!
(antiquarks and gluon)

Introduction to Sea Asymmetry



Unpolarized

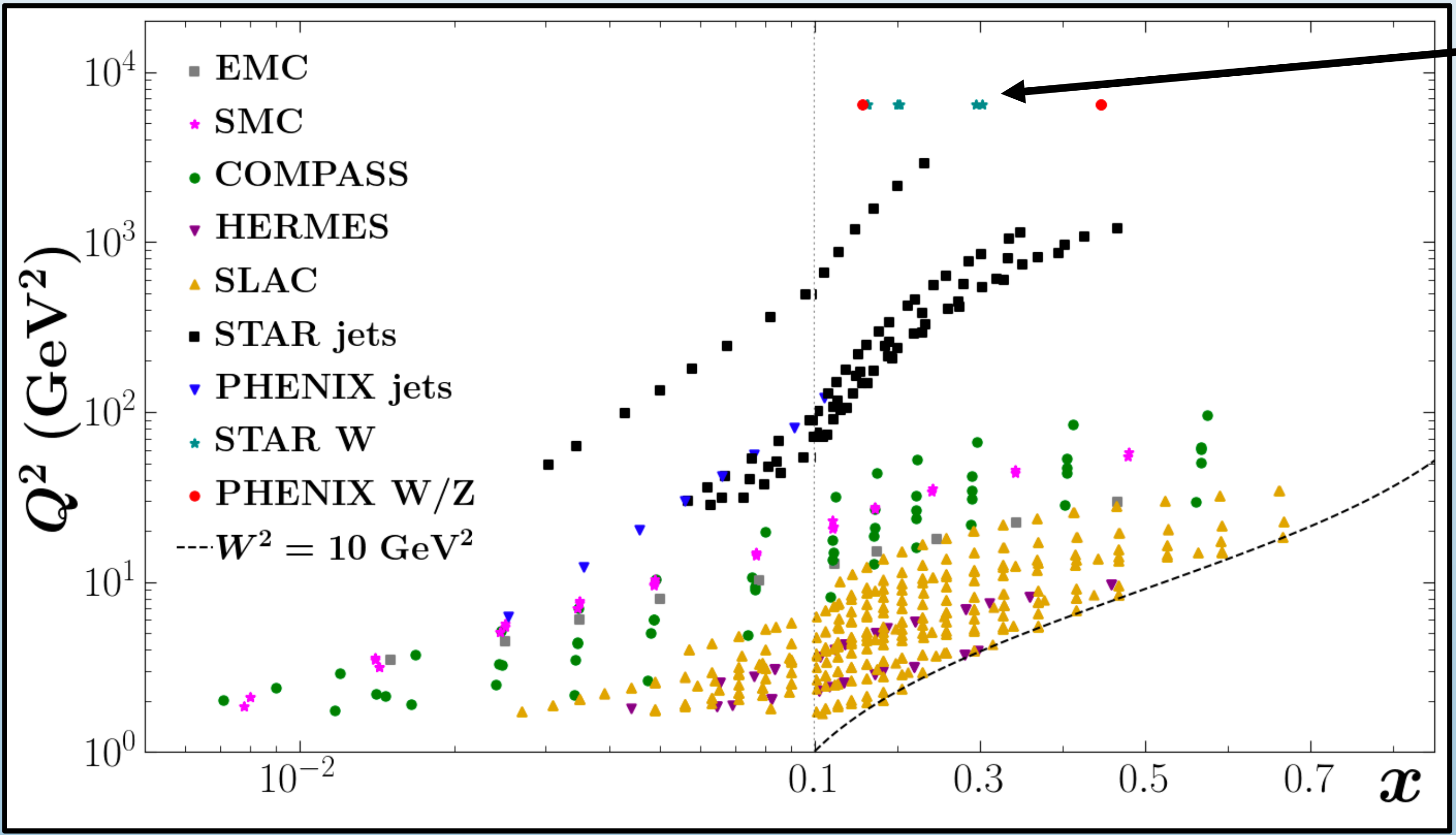
Cannot be explained from gluons splitting into quark-antiquark pairs

Meson Cloud Models
Chiral Soliton Models
Statistical Models

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

Kinematic Coverage (Helicity)

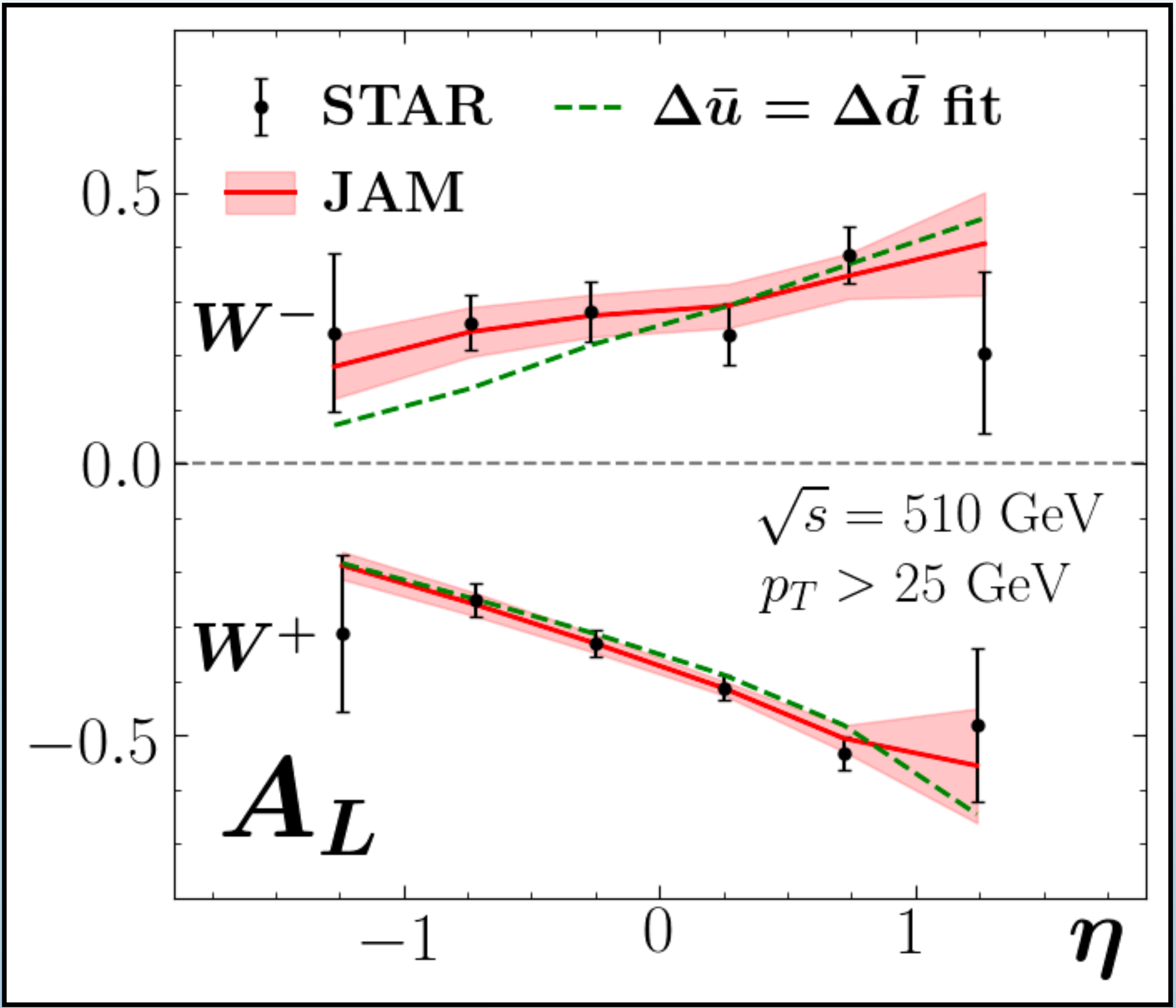
Deep Inelastic Scattering	COMPASS, EMC, HERMES, SLAC, SMC	365 points
Semi-Inclusive DIS	COMPASS, HERMES, SMC	231 points
W/Z Boson Production	STAR, PHENIX	18 points
Jets	STAR, PHENIX	61 points



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 $(\pi^\pm)$	231	0.91
SIA $(K^\pm)$	213	0.70
SIA $(h^\pm)$	120	1.07
total	**7215**	**1.08**

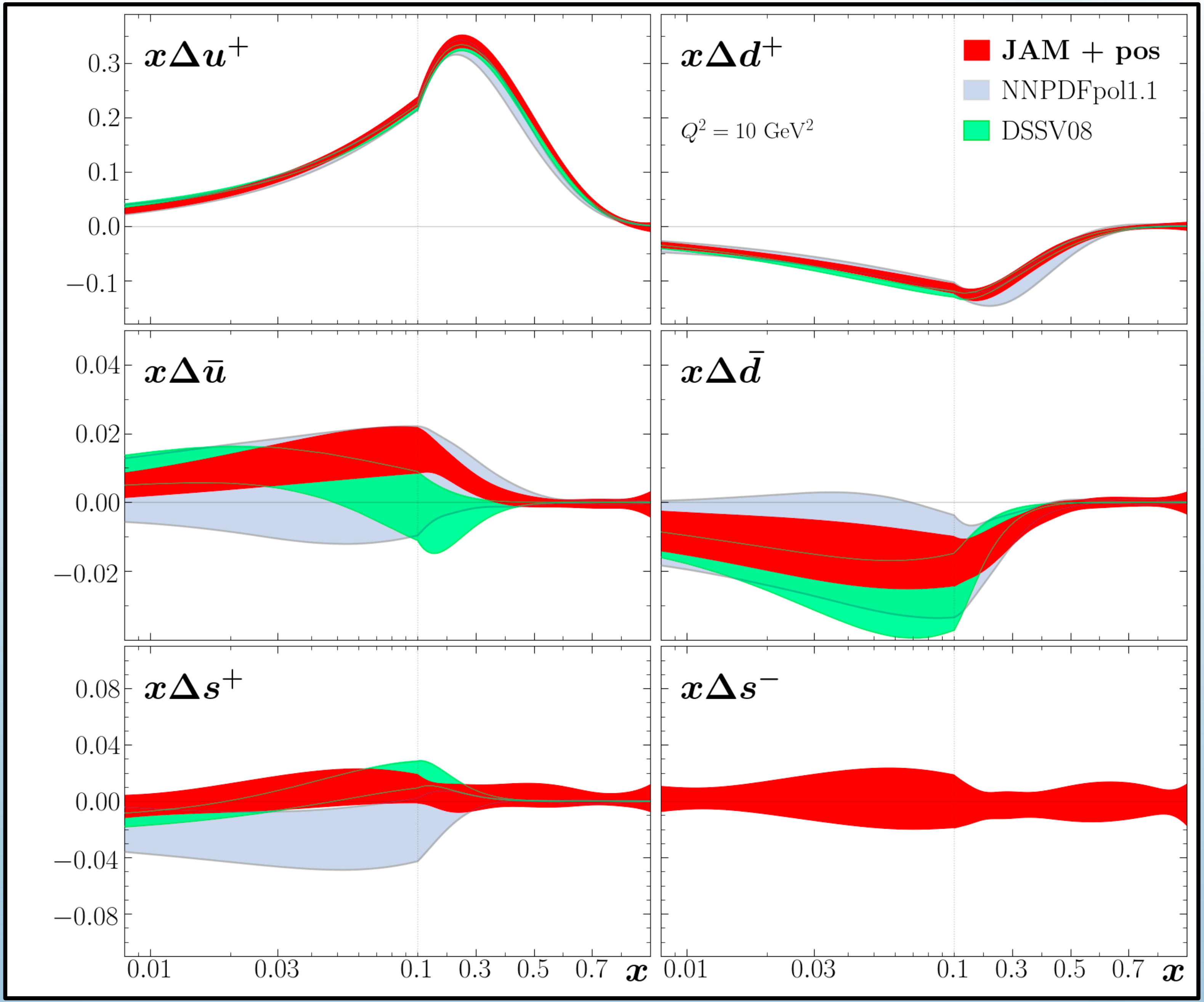
STAR Quality of Fit



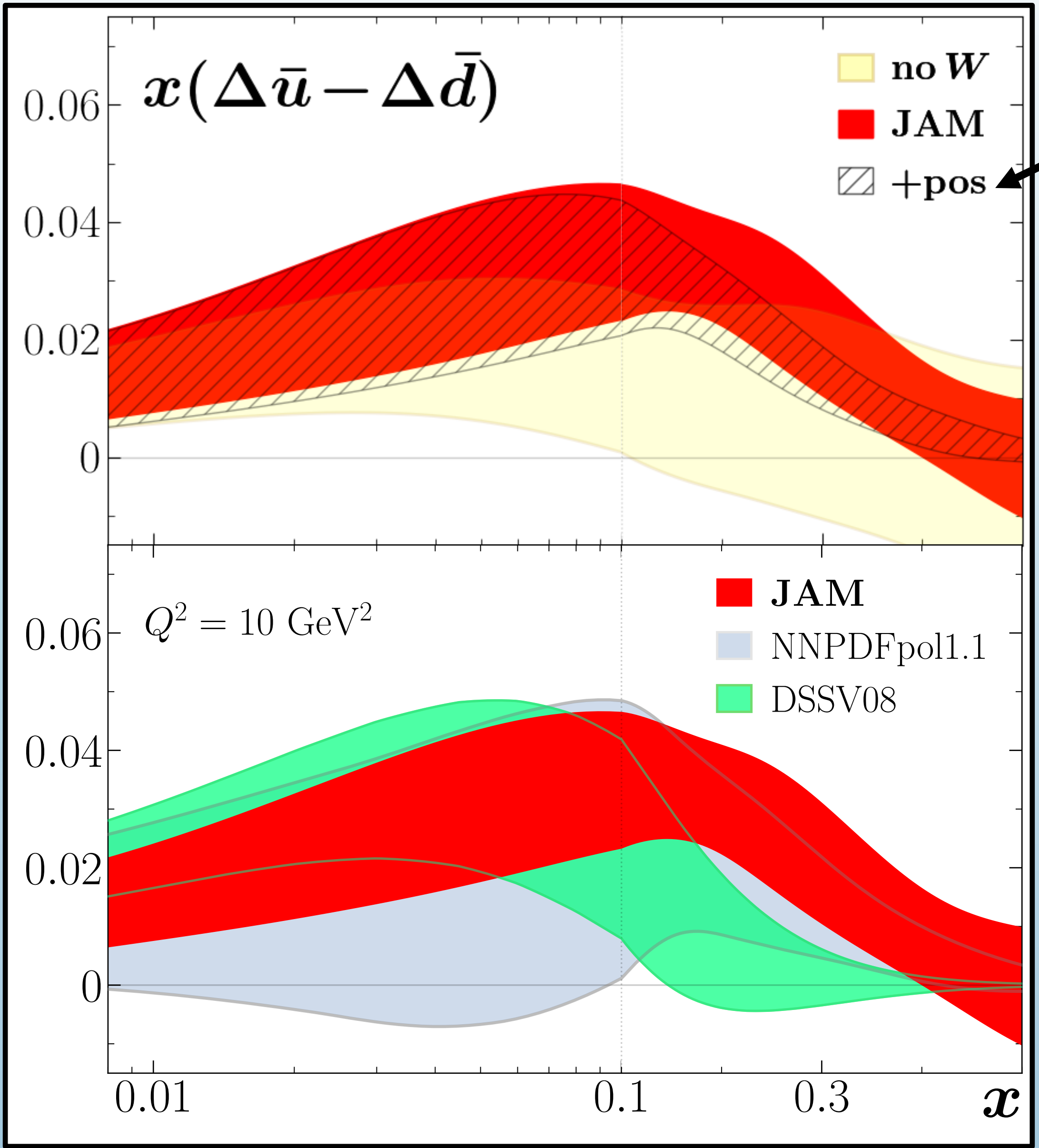
process	N_{dat}	χ^2/N_{dat} JAM	+Pos.	$\Delta\bar{u} = \Delta\bar{d}$
STAR $W^\pm$	12	0.45	0.61	1.53
PHENIX $W^\pm/Z$	6	0.47	0.46	0.48
pol. DIS	365	0.93	0.93	0.93
pol. jet	61	1.00	1.03	1.00
total	**444**	**0.92**	**0.94**	**0.95**

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

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


$x\Delta u^+$
$x\Delta d^+$
JAM + pos
NNPDFpol1.1
DSSV08
$Q^2 = 10$ GeV^2
$x\Delta \bar{u}$
$x\Delta \bar{d}$
$x\Delta s^+$
$x\Delta s^-$
0.3
0.2
0.1
0.0
−0.1
0.04
0.02
0.00
−0.02
0.08
0.04
0.00
−0.04
−0.08
0.01
0.03
0.1
0.3
0.5
0.7
x

Resulting Asymmetry



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

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

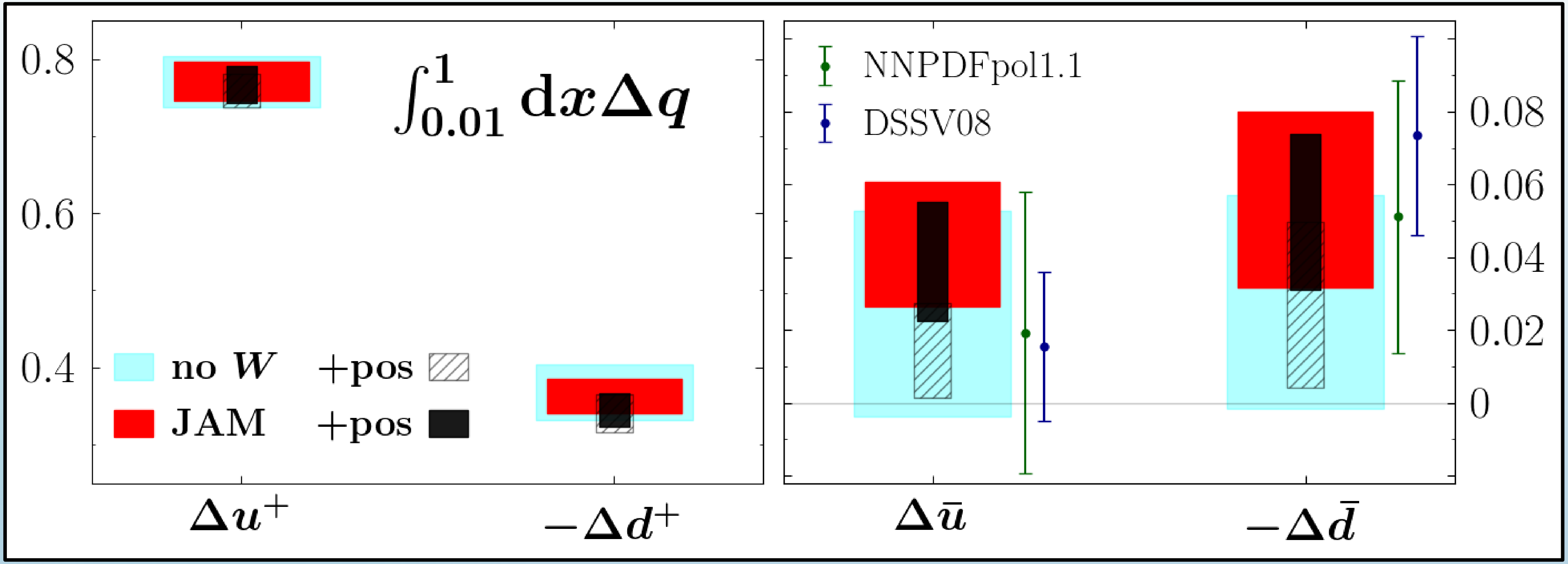
Positivity and renormalization of parton densities
John Collins, Ted C. Rogers, Nobuo Sato

DSSV08 shows positive asymmetry at low $x < 0.1$

NNPDF shows hint of positive asymmetry at intermediate x

Our result is strongly positive in both regions of x

Proton Spin Contributions



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

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

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

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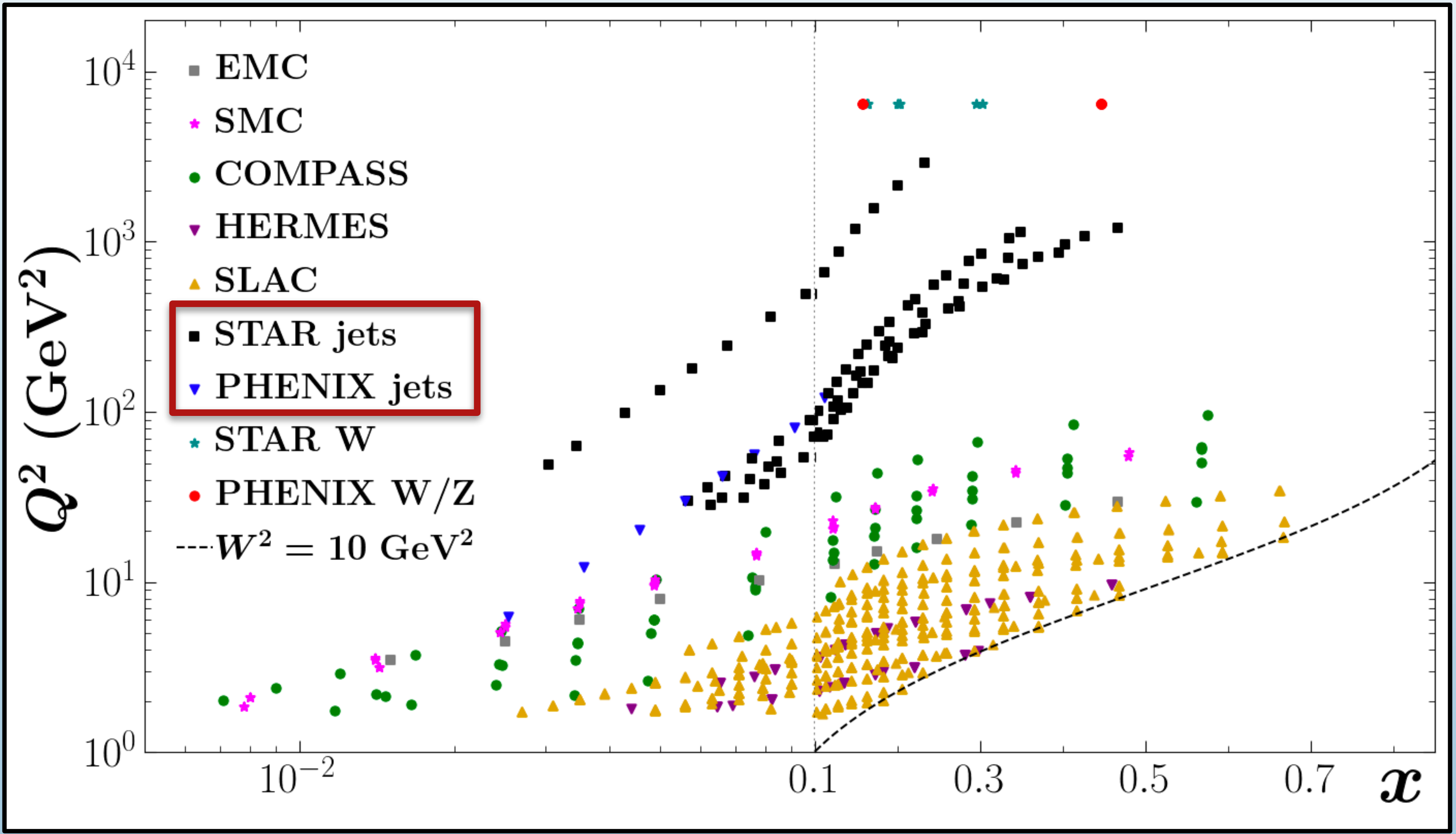
Jets provide most direct constraints on gluon distribution

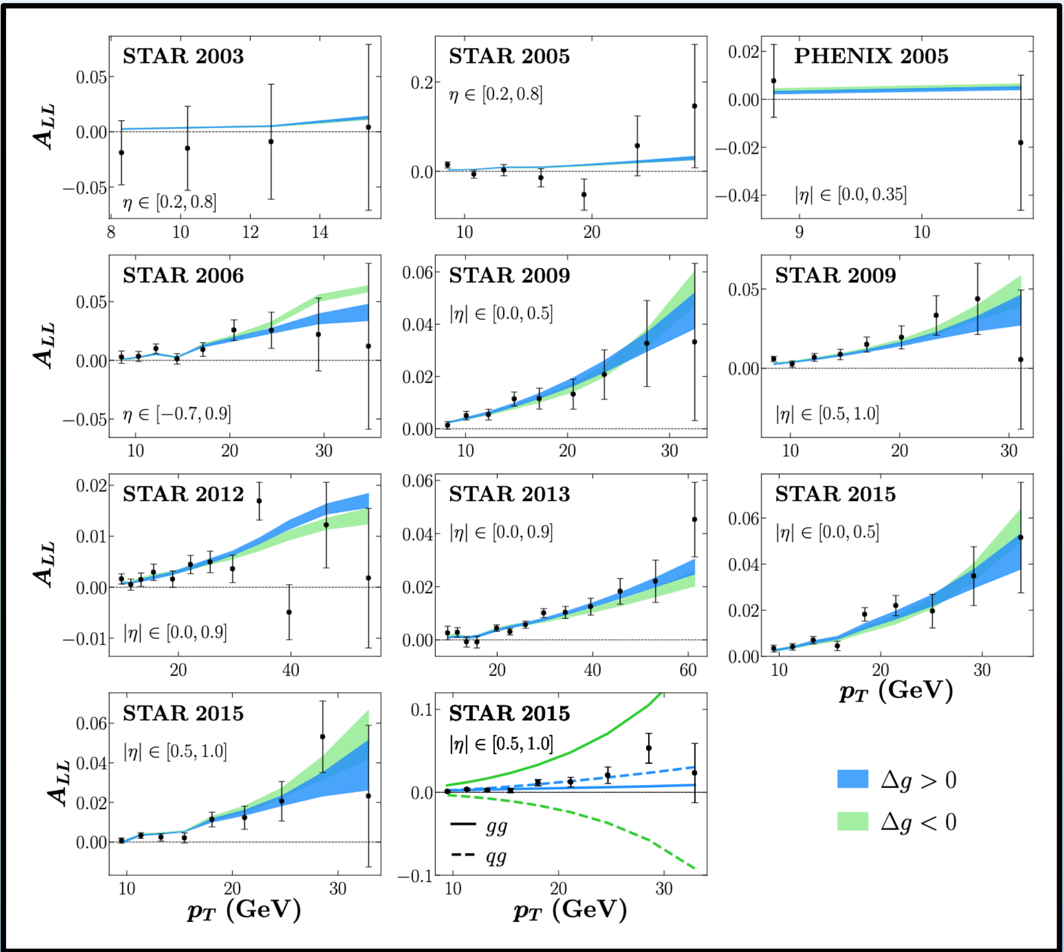


Gluon Helicity

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 [hep-ph]



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

Positivity constraints rule out negative solution

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

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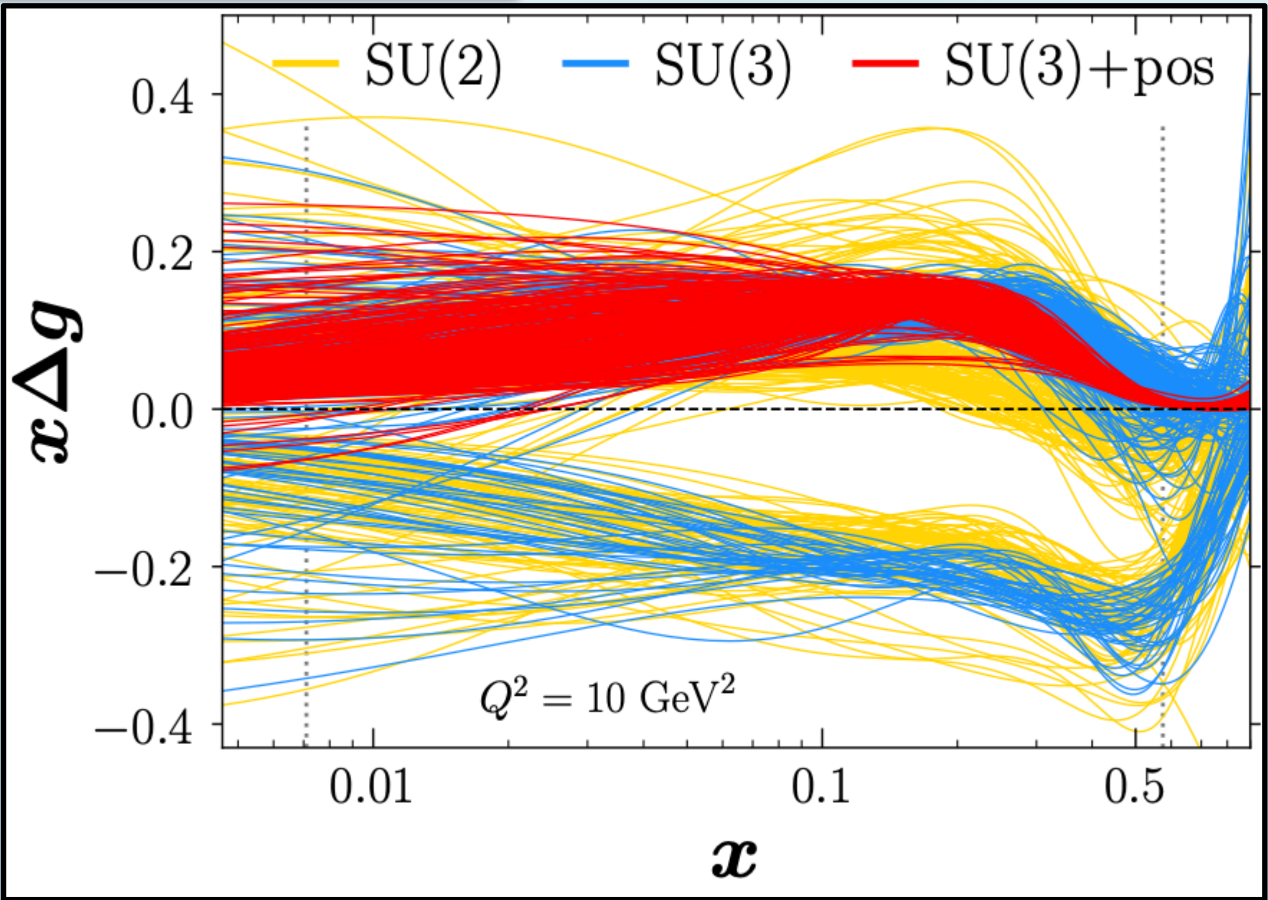
$$|\Delta f(x, Q^2)| < f(x, Q^2)$$



Gluon Helicity

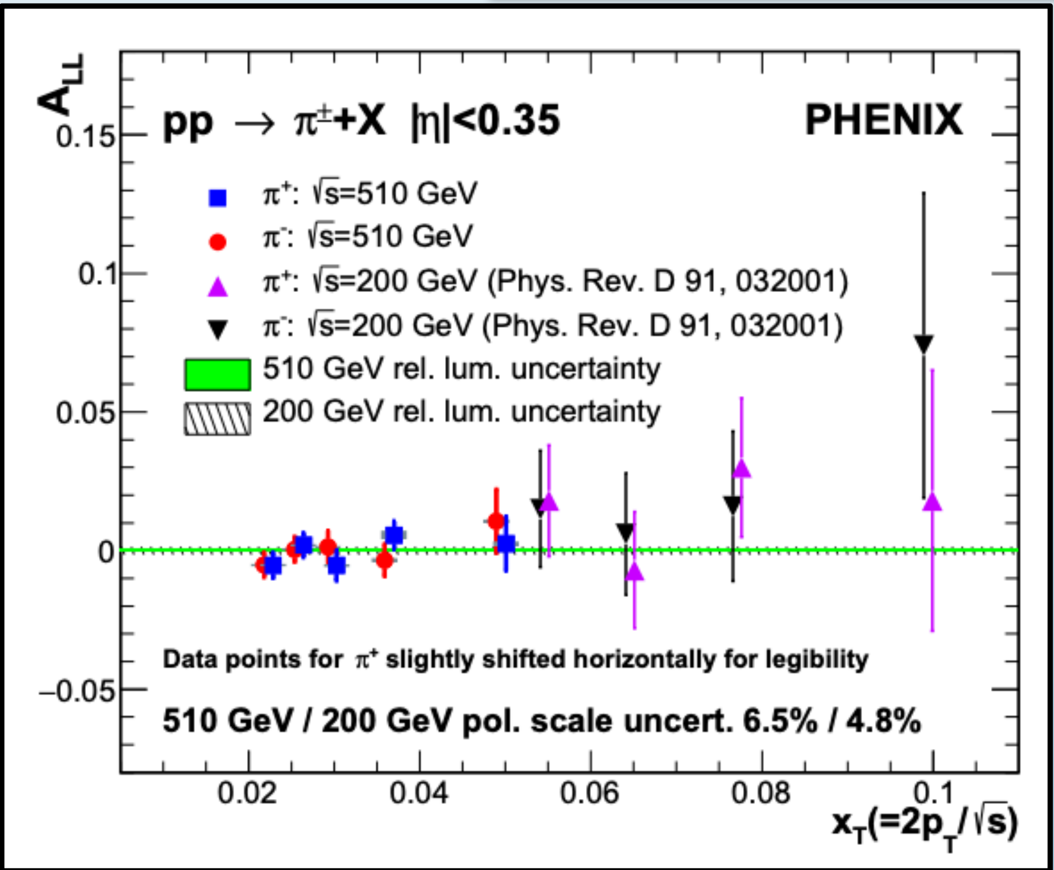
Measurement of charged pion double spin asymmetries at midrapidity in longitudinally polarized $p + p$ collisions at $\sqrt{s}$ = 510 GeV
PHENIX Collaboration • U.A. Acharya (Georgia State U.) et al. (Apr 6, 2020)
Published in: *Phys.Rev.D* 102 (2020) 3, 032001 • e-Print: 2004.02681 [hep-ex]

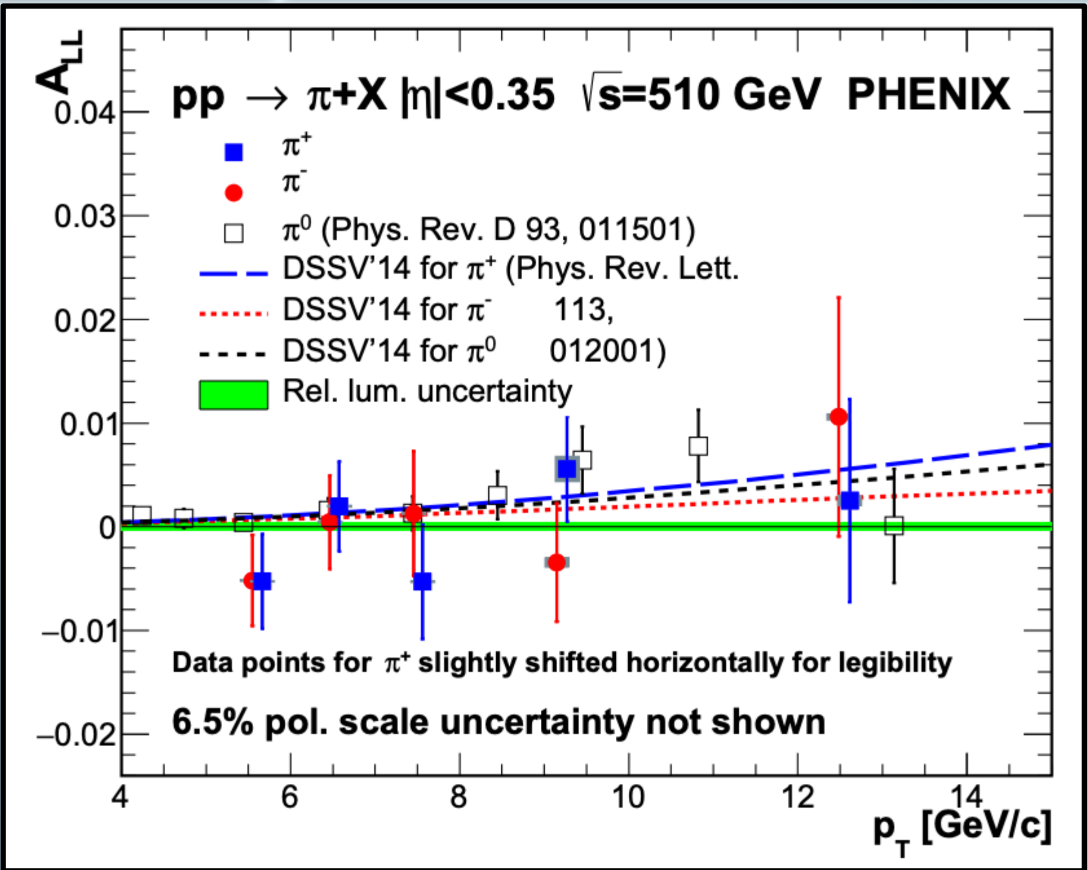
Charged-pion cross sections and double-helicity asymmetries in polarized p+p collisions at $\sqrt{s}$=200 GeV
PHENIX Collaboration • A. Adare (Colorado U.) et al. (Sep 5, 2014)
Published in: *Phys.Rev.D* 91 (2015) 3, 032001 • e-Print: 1409.1907 [hep-ex]

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

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

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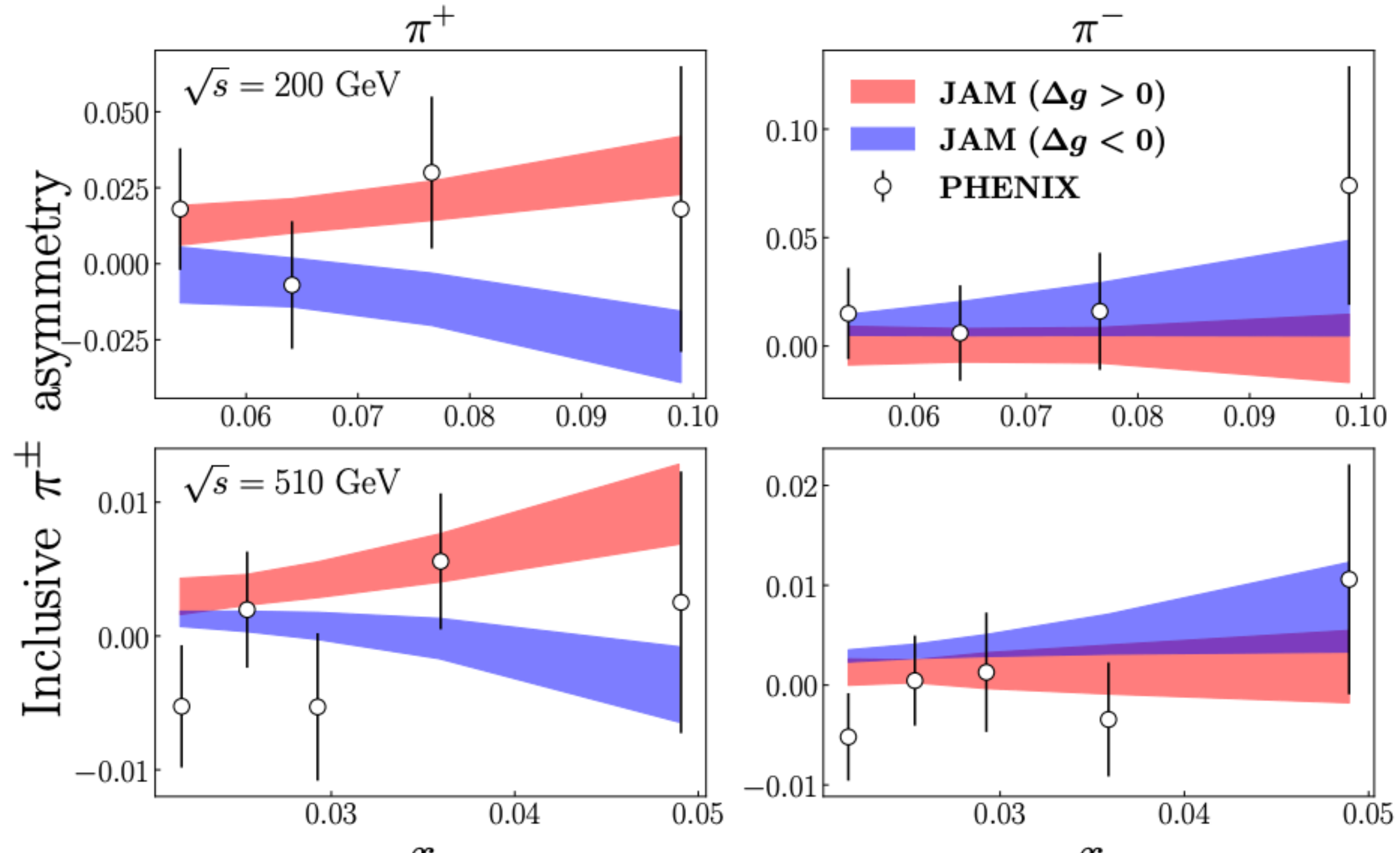
JAM Prediction



Phys.Rev.D 107 (2023) 3, 034033

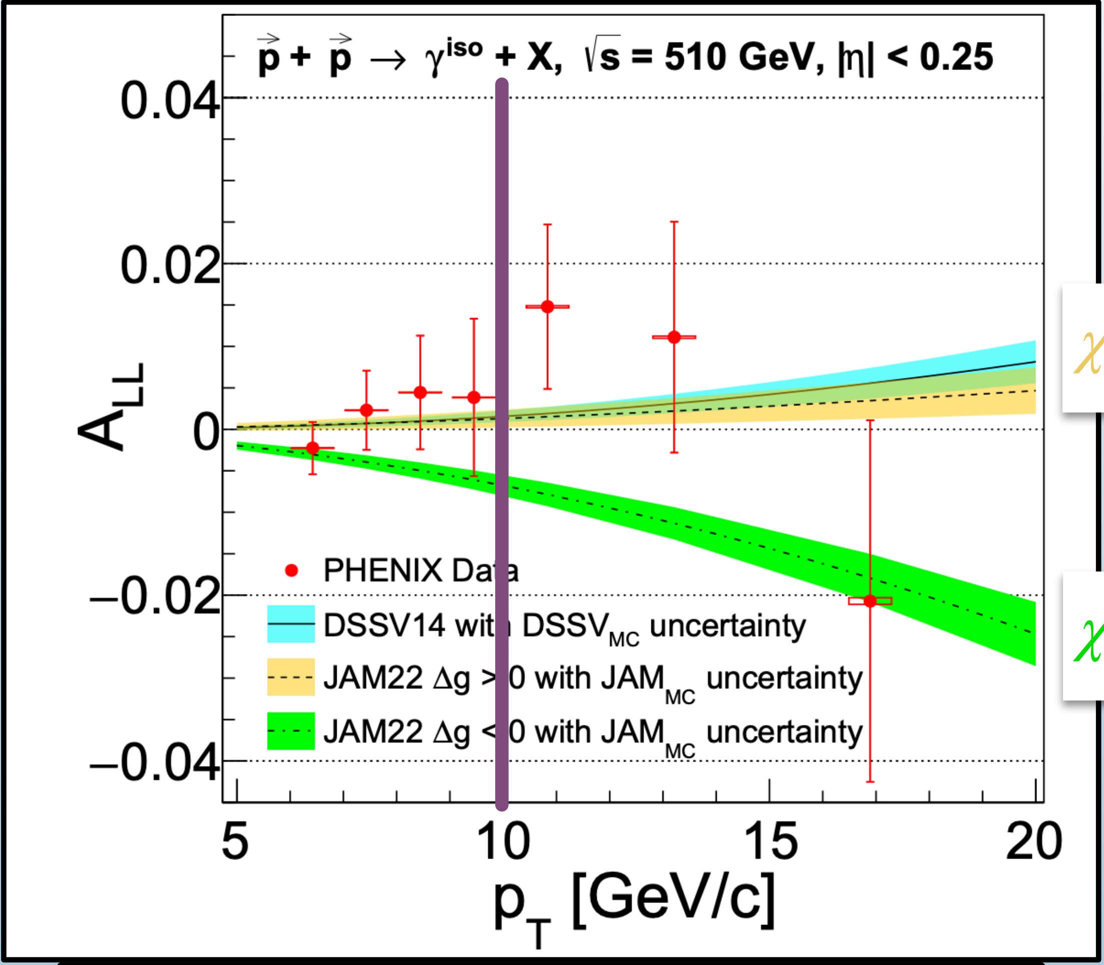
It is inconclusive whether data can distinguish between two solutions

Gluon Helicity

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 [hep-ex]



$\chi^2 = 4.7$

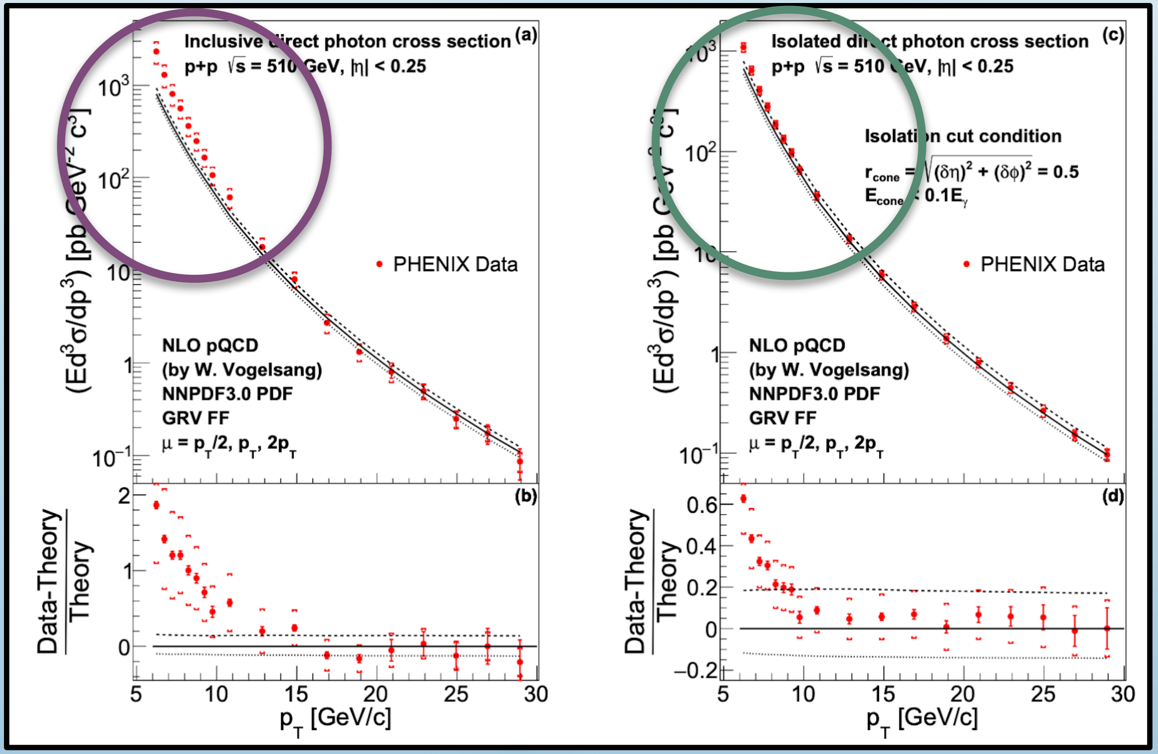
2.8σ

$\chi^2 = 12.6$

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

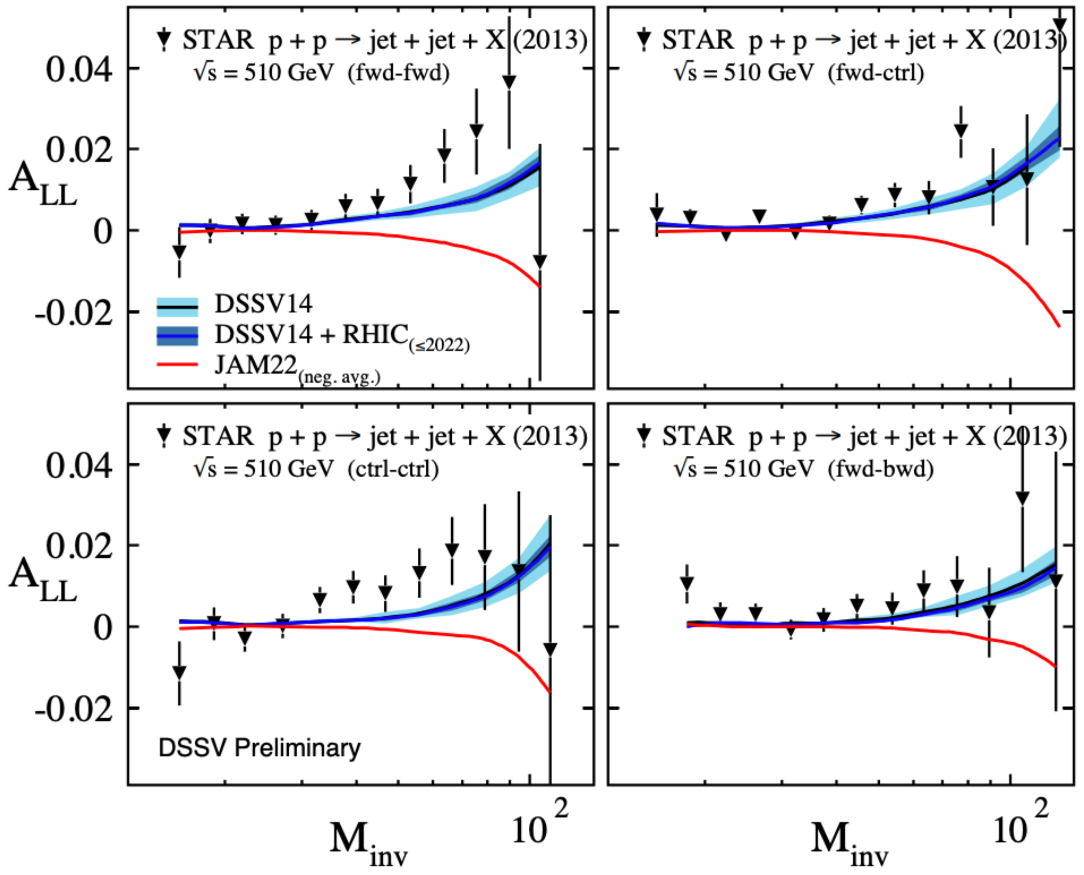


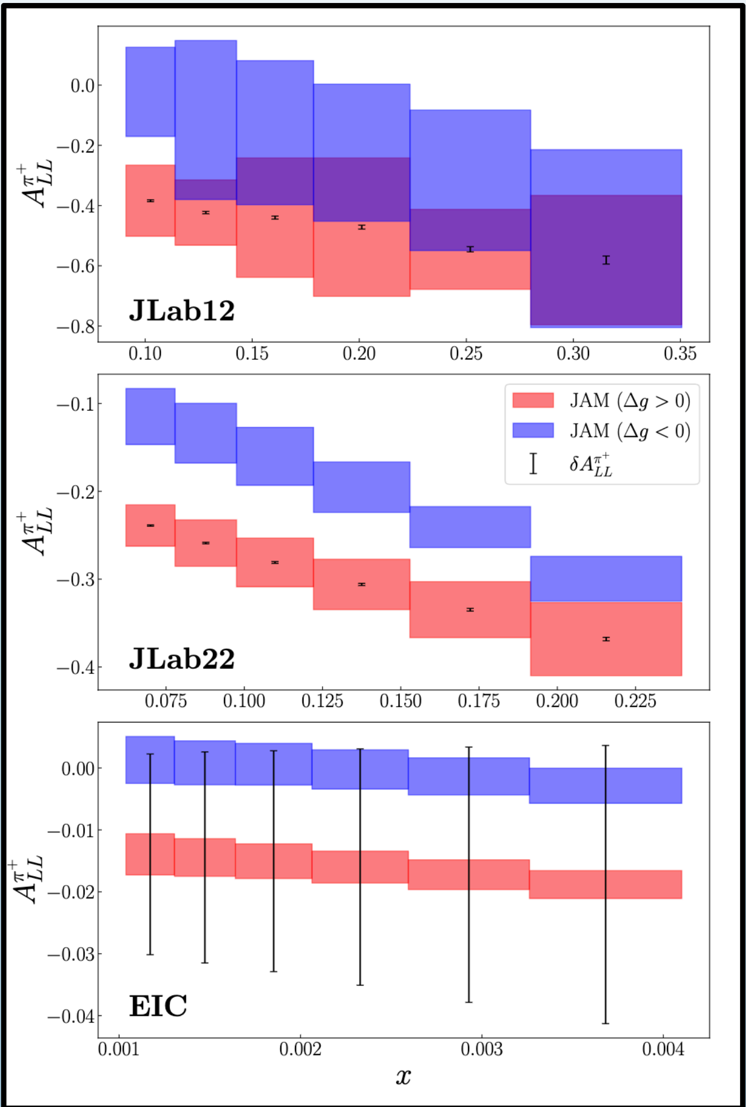
Figure 8: STAR double-helicity asymmetries A_{LL} for dijet production vs dijet invariant mass M_{inv} in polarized pp collisions at $\sqrt{s}$=510 GeV at midrapidity from 2013 data set [21]. DSSV14 evaluation [17] is plotted as the black curve with the 1σ uncertainty band marked in light blue. The blue 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 [hep-ph]

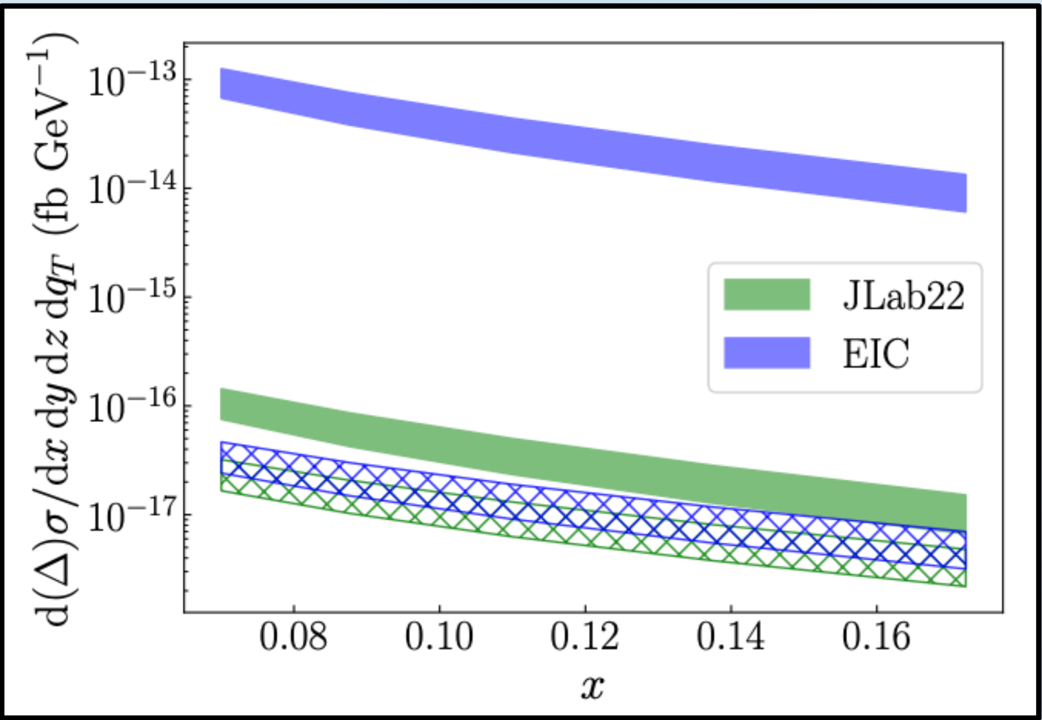
$$\vec{l} + \vec{N} \rightarrow l' + h + X$$



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

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



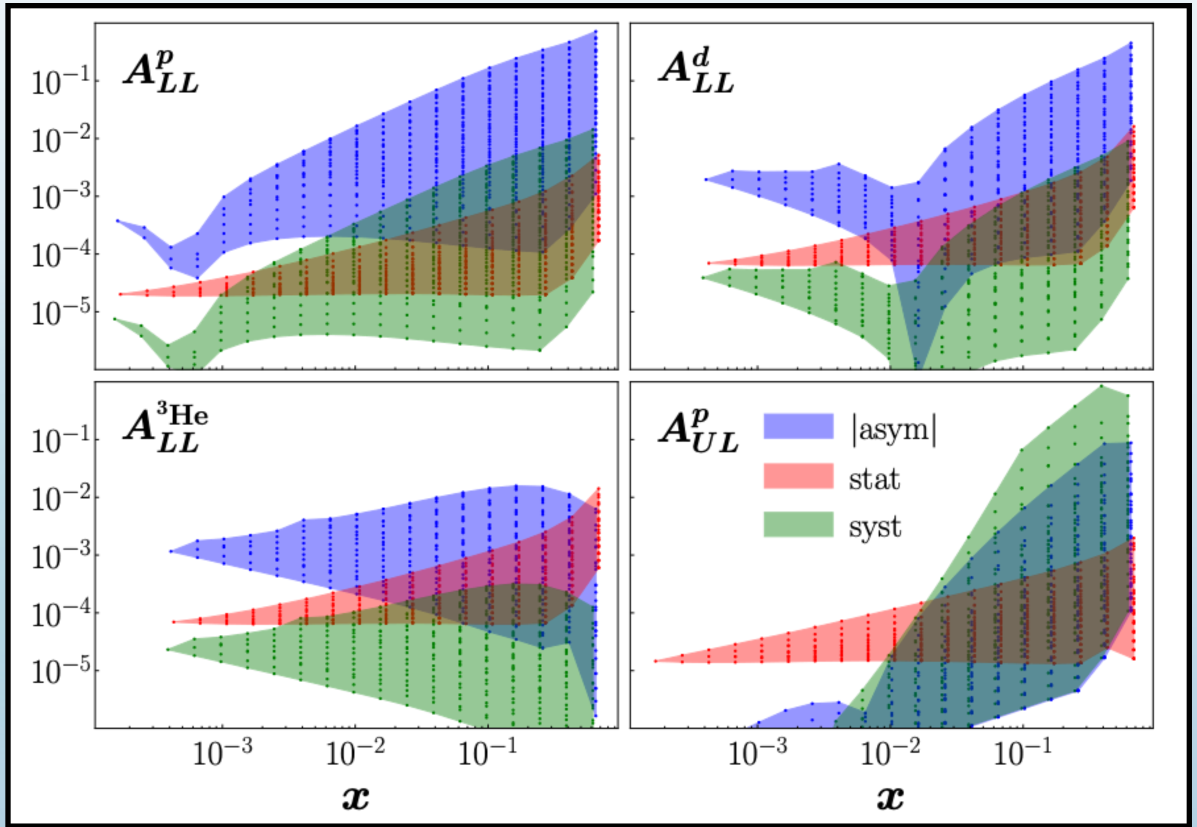
Future Experiments

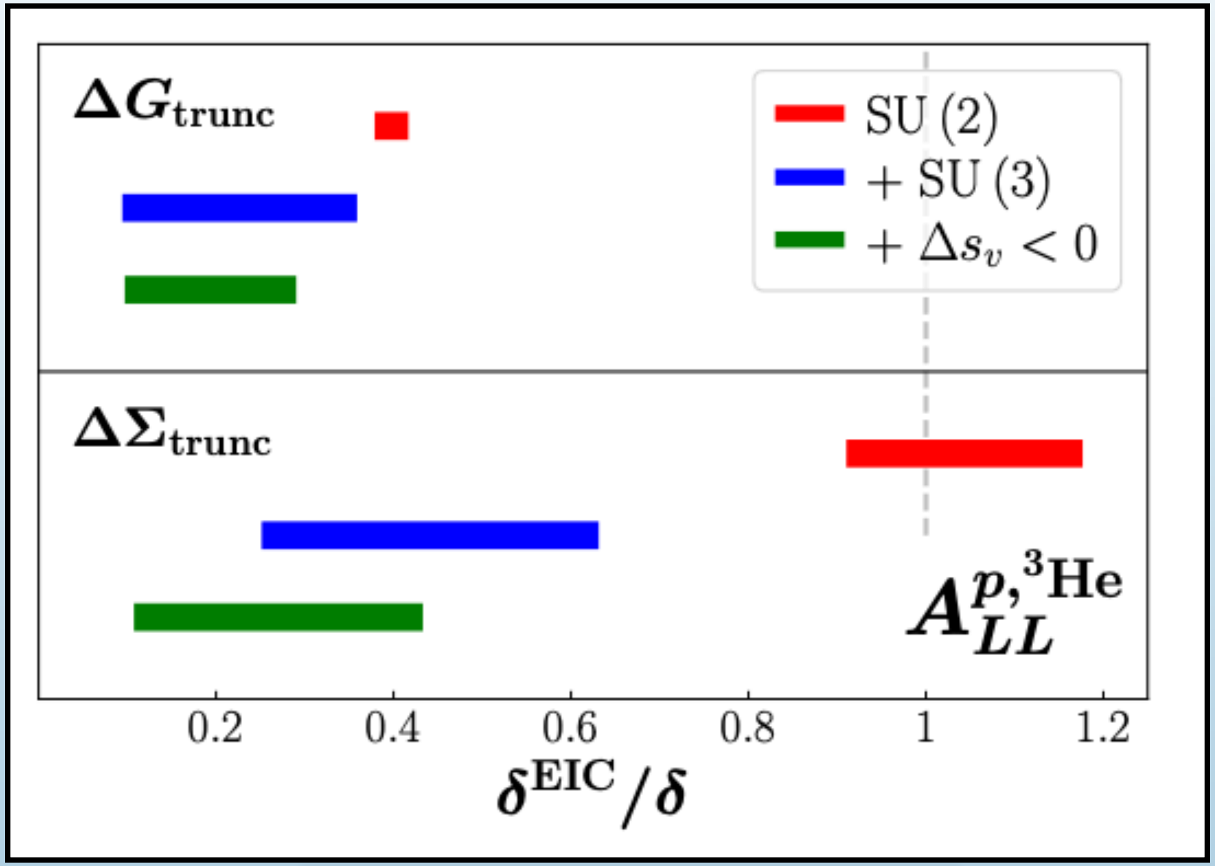
Revisiting quark and gluon polarization in the proton at the EIC

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 [hep-ph]

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

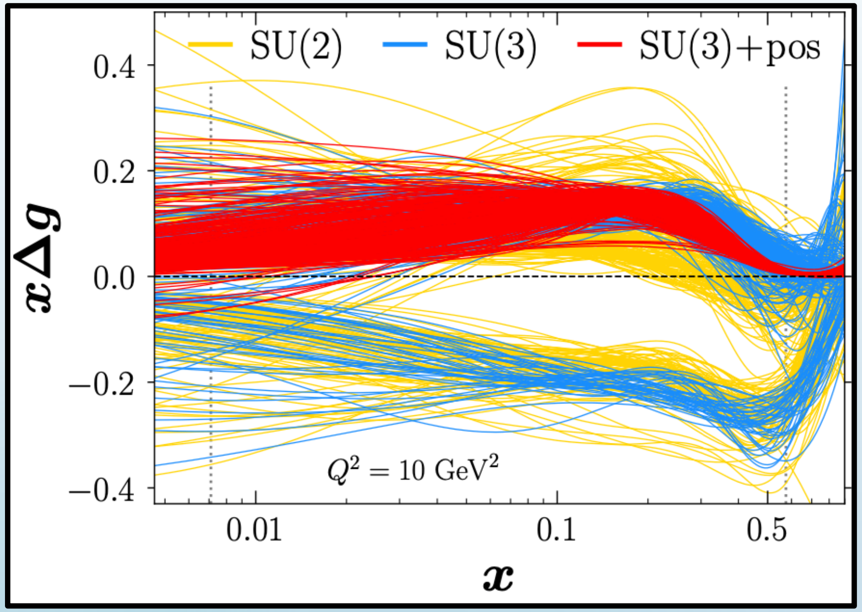




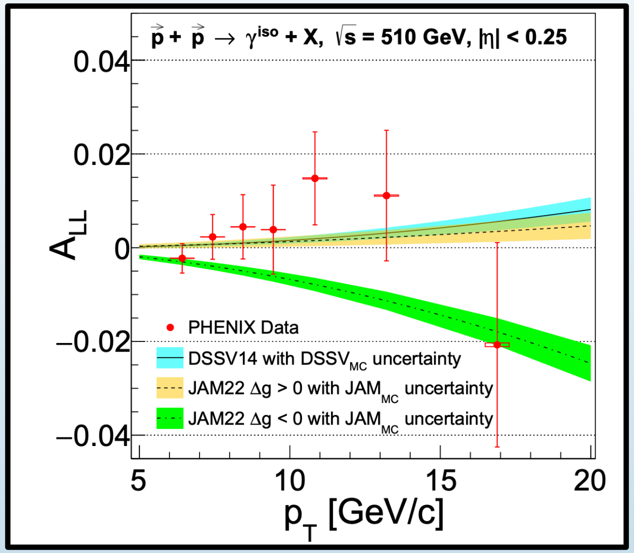
$$\Delta G_{\mathrm{trunc}} = \int_{10^{-4}}^{1} \mathrm{d}x \Delta g(x)$$

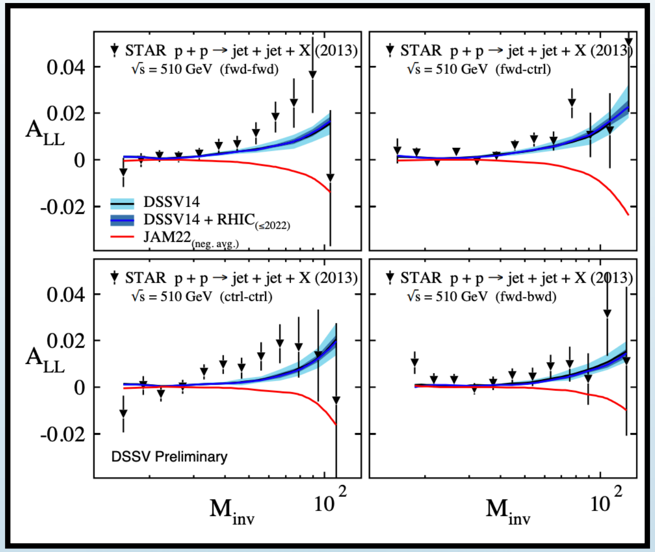
Conclusions and Outlook

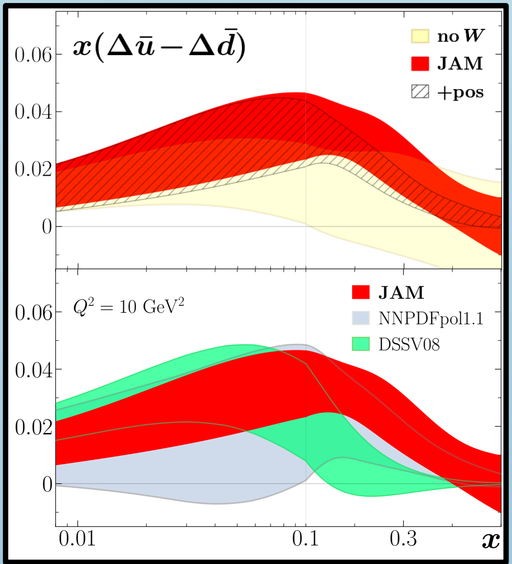
Current JAM analyses have two gluon solutions



New data from RHIC may help distinguish them

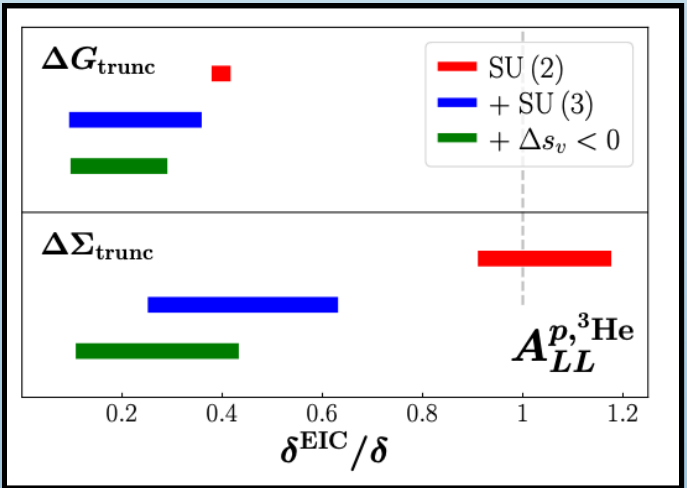


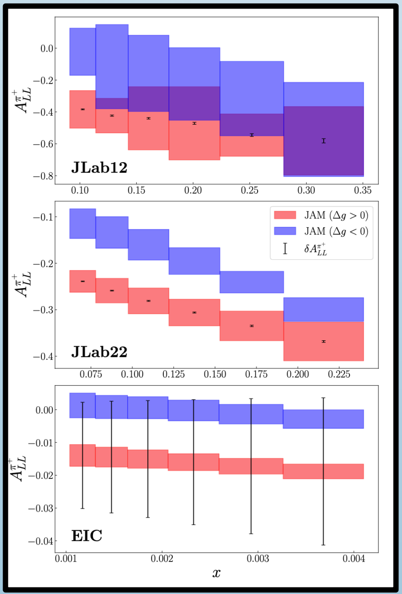




Nonzero sea asymmetry

Future data from the EIC and JLab should provide new information





Extra Slides

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

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

Evolve PDFs using DGLAP

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

Calculate Observables

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

Mellin Space Techniques

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

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…

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

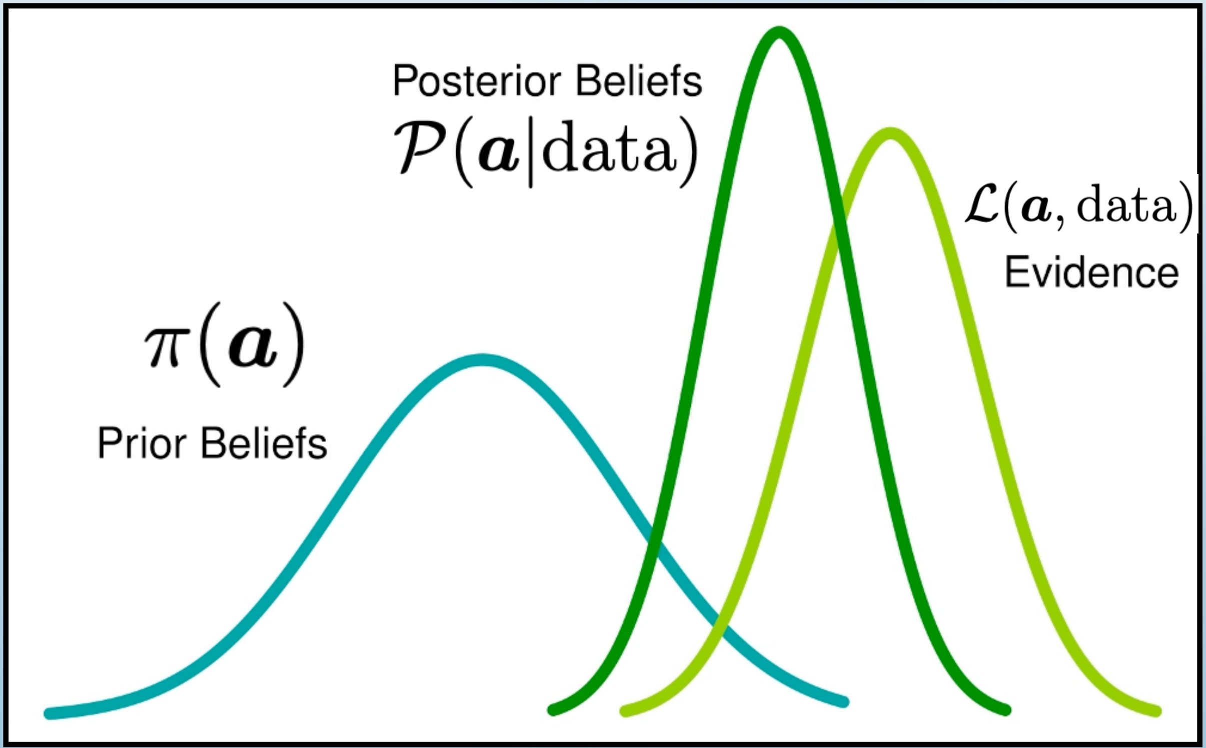
Now that we have calculated $\chi^2(\boldsymbol{a}, \text{data})$…

Likelihood Function

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

Bayes' Theorem

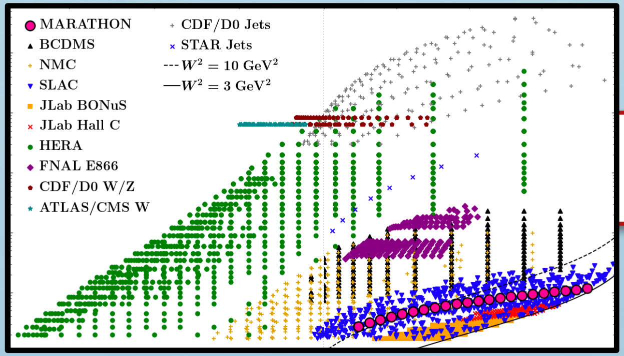
$$\mathcal{P}(\boldsymbol{a}|\text{data}) \sim \mathcal{L}(\boldsymbol{a}, \text{data})\, \pi(\boldsymbol{a})$$



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

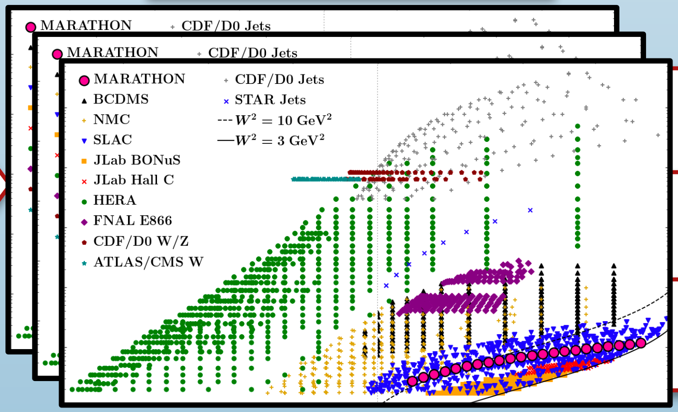
Data ↑ σ

Original Data



DR

Replica Data

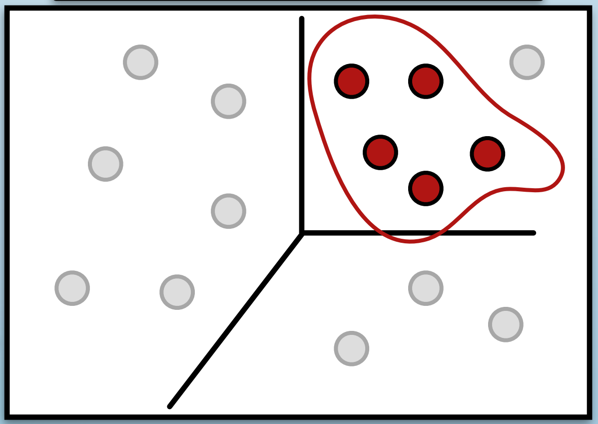


Maximum Likelihood

Maximum Likelihood

Maximum Likelihood

Parameter Space



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

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

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

Exact, but

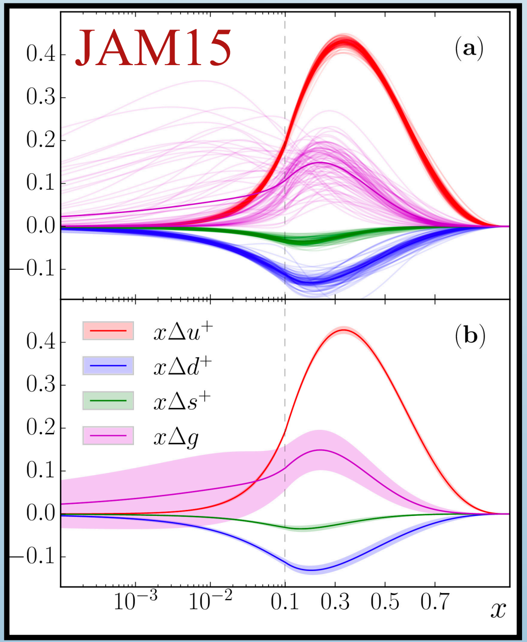
$n = \mathcal{O}(100)$!

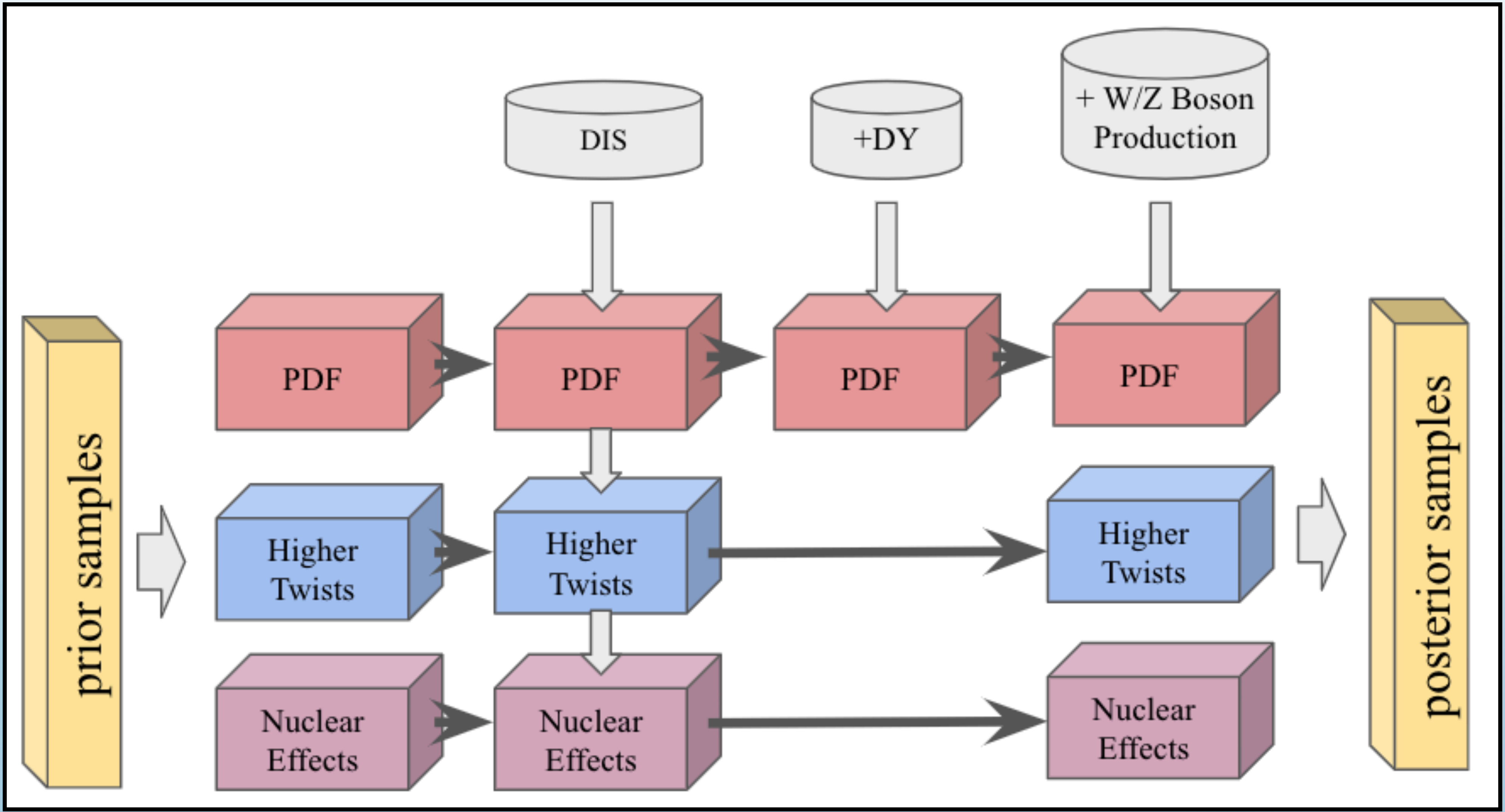
Build an MC ensemble

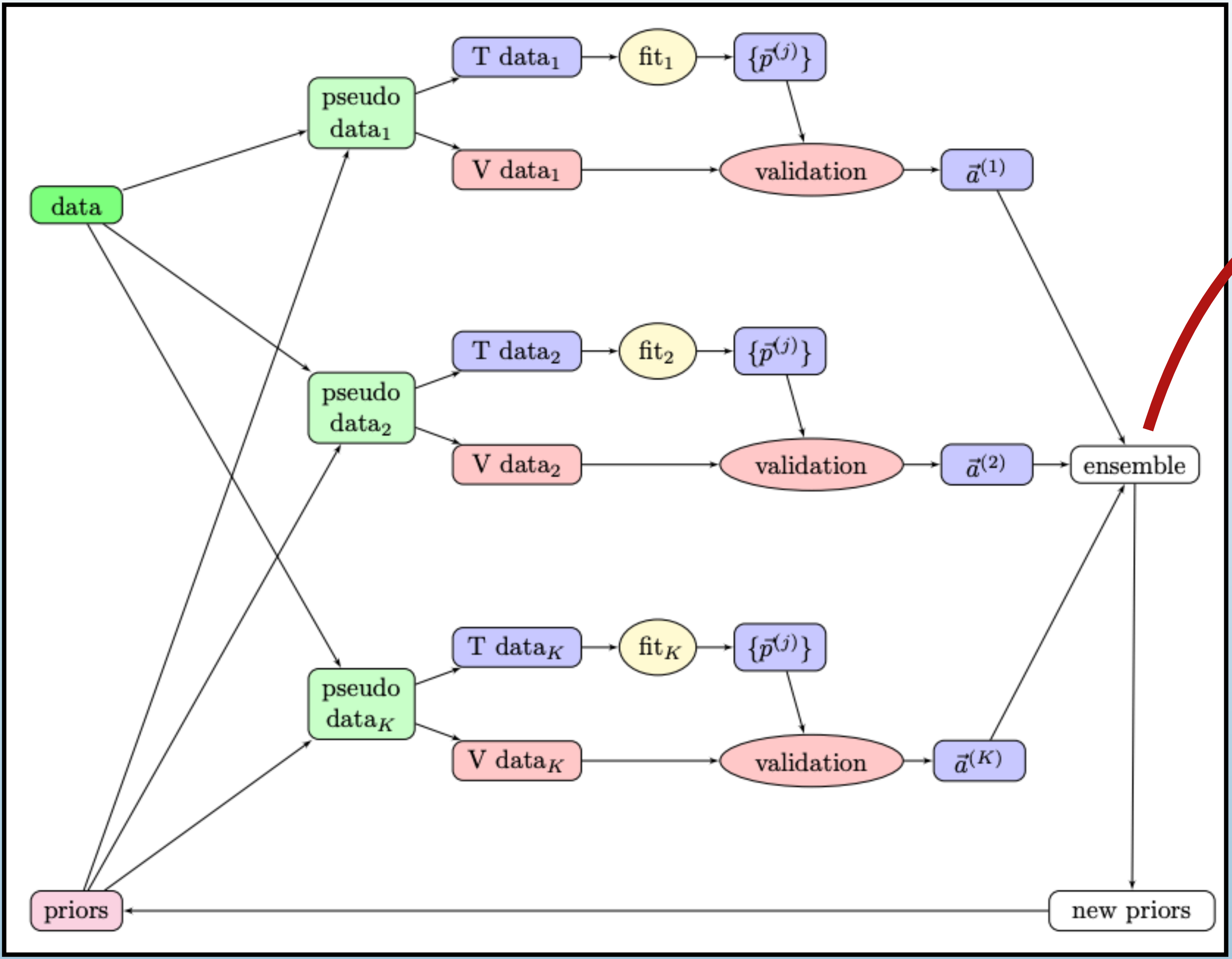
$$E[O] \approx \frac{1}{N}\sum_k O(\boldsymbol{a}_k)$$

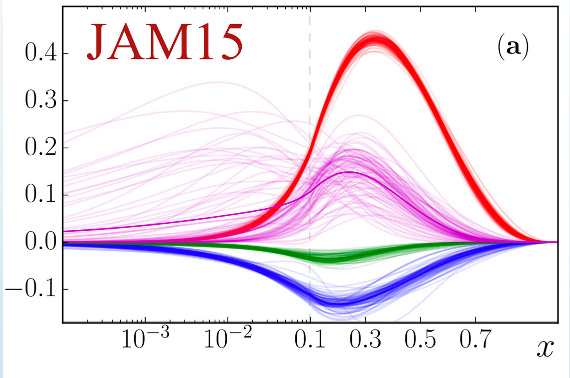
$$V[O] \approx \frac{1}{N}\sum_k \left[O(\boldsymbol{a}_k) - E[O]\right]^2$$

Average over k sets of the parameters (replicas)



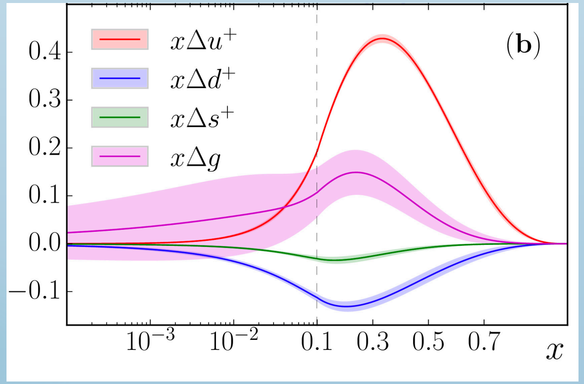

DIS
+DY
+ W/Z Boson Production
prior samples
PDF
PDF
PDF
PDF
Higher Twists
Higher Twists
Higher Twists
Nuclear Effects
Nuclear Effects
Nuclear Effects
posterior samples





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

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



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)

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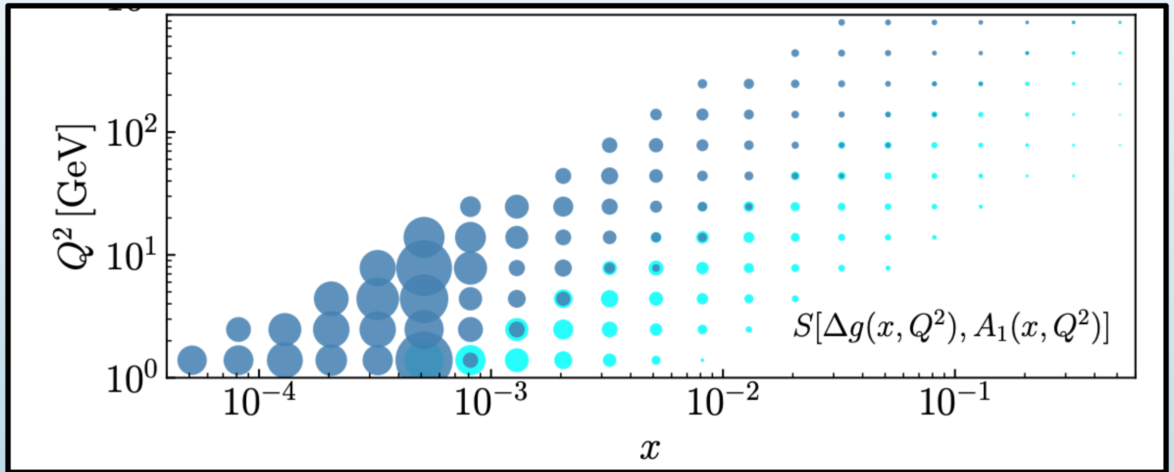
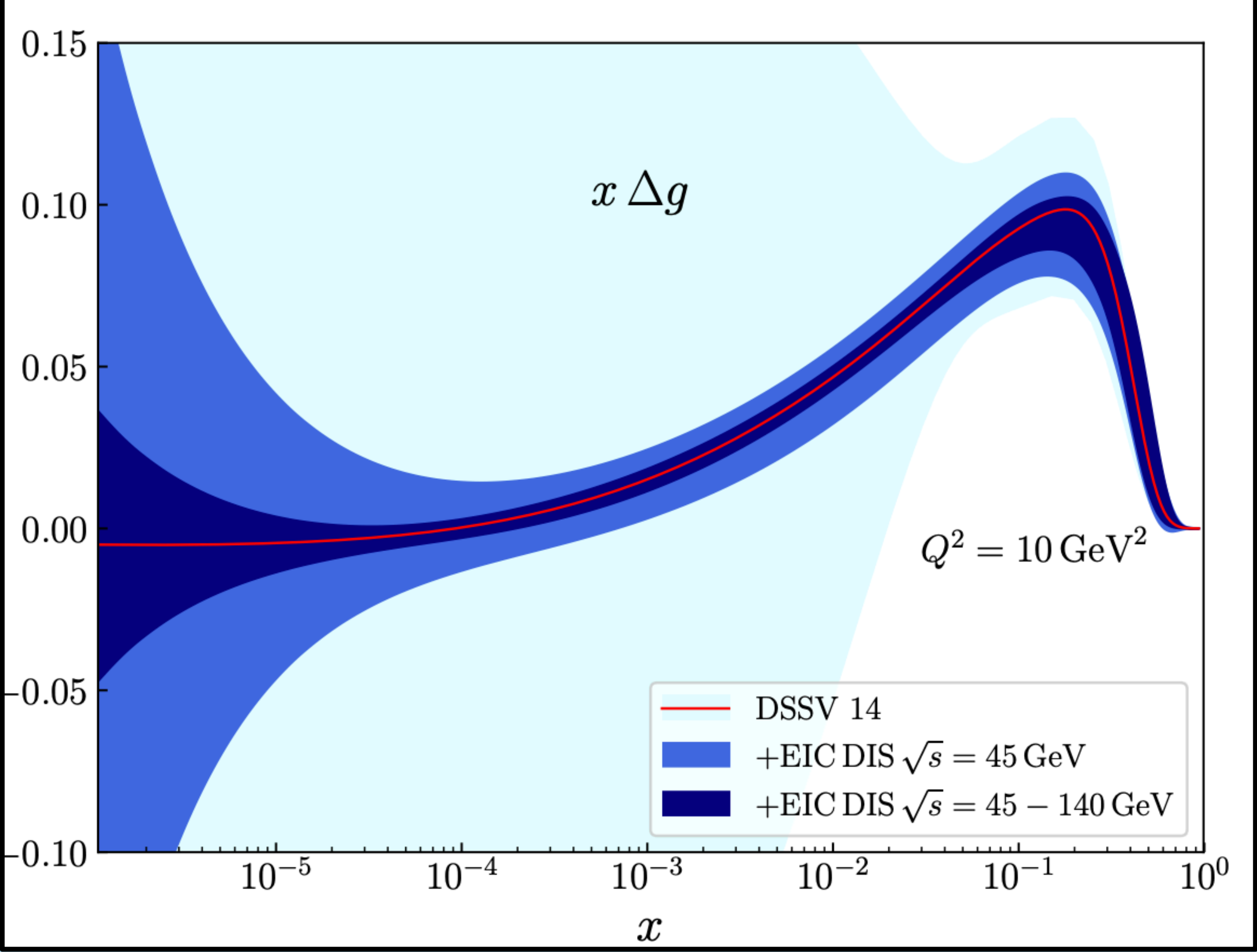
$$\vec{l} + \vec{N} \to l' + X$$



Sensitivity of A_1 to Δg



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

Positivity

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)

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As regards the positivity issue itself, there are several points to make. First, we emphasize that we have not argued that $\overline{\mathrm{MS}}$ pdfs *must* be negative for any particular choice of scales or $\mu_{\overline{\mathrm{MS}}}$. 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