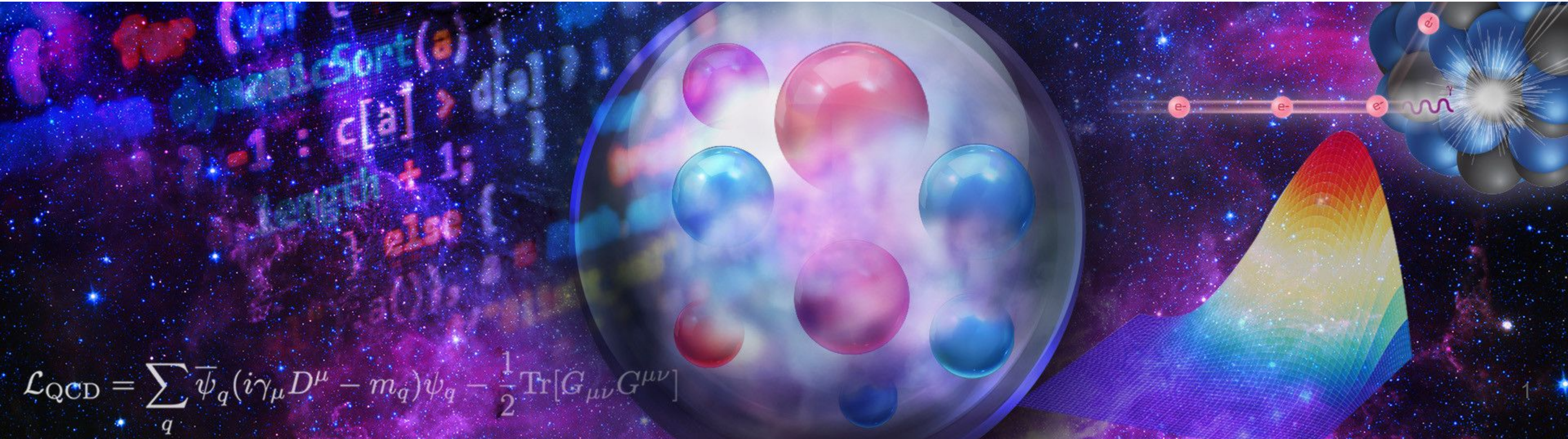
Updates from JAM and beyond

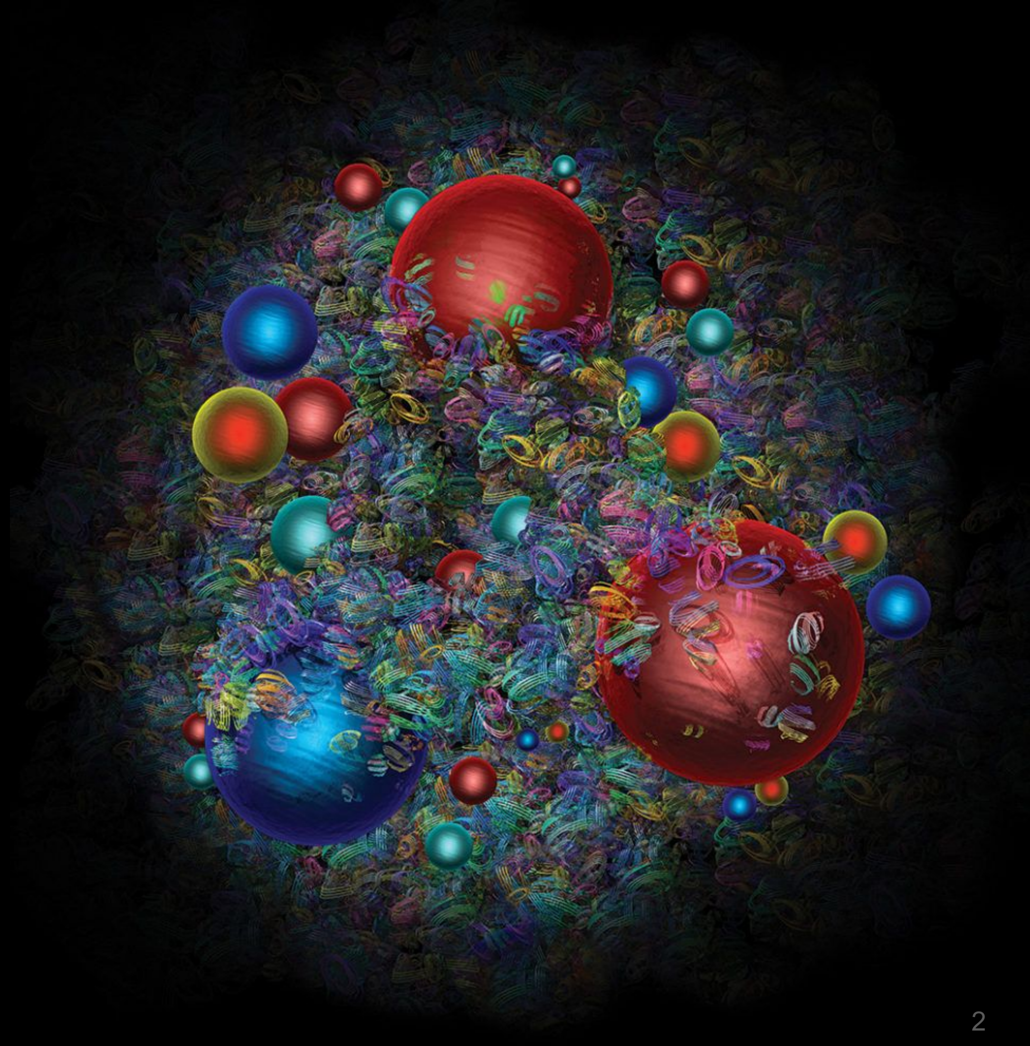
Nobuo Sato

Sep. 21, 2023



Outline

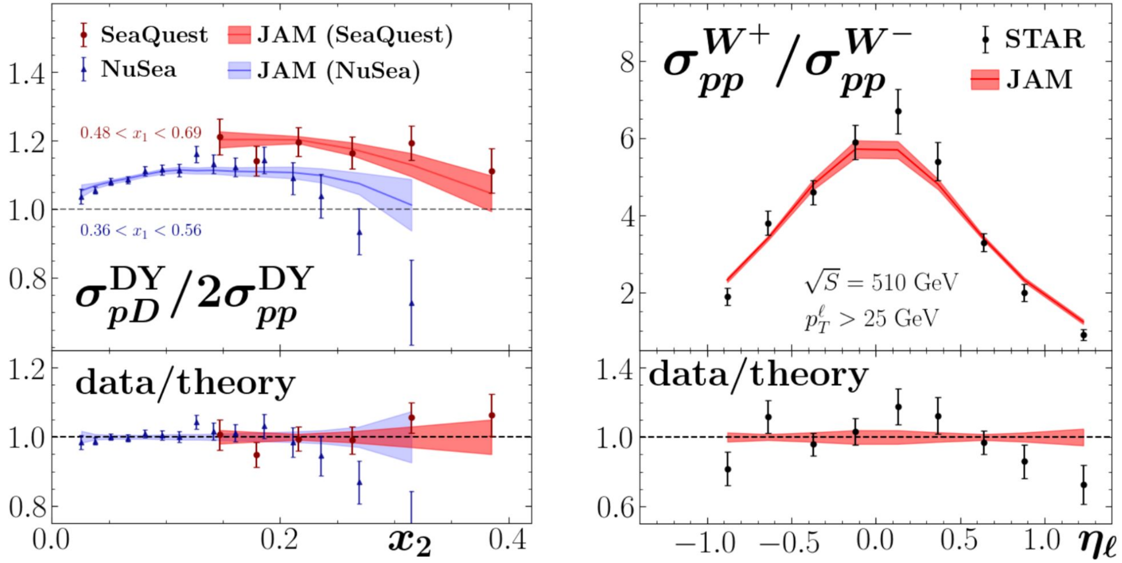
1. Quick updates on PDFs
2. Updates gluon hPDF
3. QuantOm
4. Summary

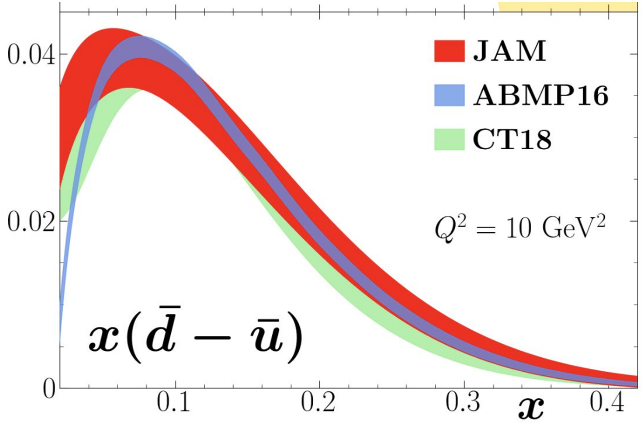


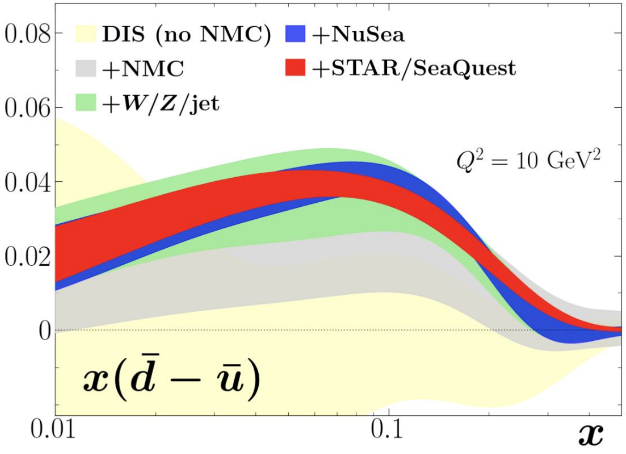
Bayesian Monte Carlo extraction of the sea asymmetry with SeaQuest and STAR data

Jefferson Lab Angular Momentum (JAM) Collaboration • C. Cocuzza (Temple U.) et al. (Sep 1, 2021)

Published in: *Phys.Rev.D* 104 (2021) 7, 074031 • e-Print: 2109.00677 [hep-ph]



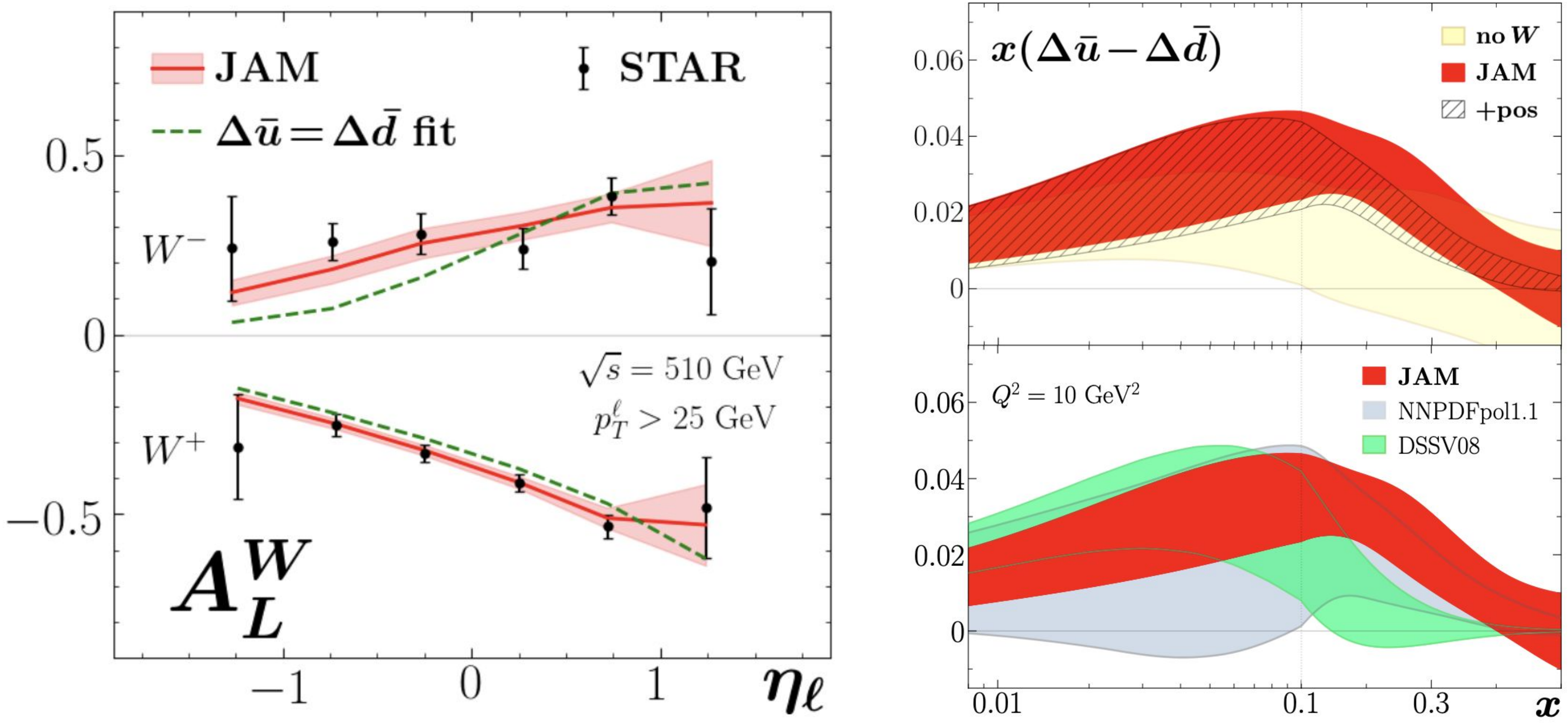




Polarized antimatter in the proton from a global QCD analysis

Jefferson Lab Angular Momentum (JAM) Collaboration • C. Cocuzza (Temple U.) et al. (Feb 7, 2022)

Published in: *Phys.Rev.D* 106 (2022) 3, L031502 • e-Print: 2202.03372 [hep-ph]



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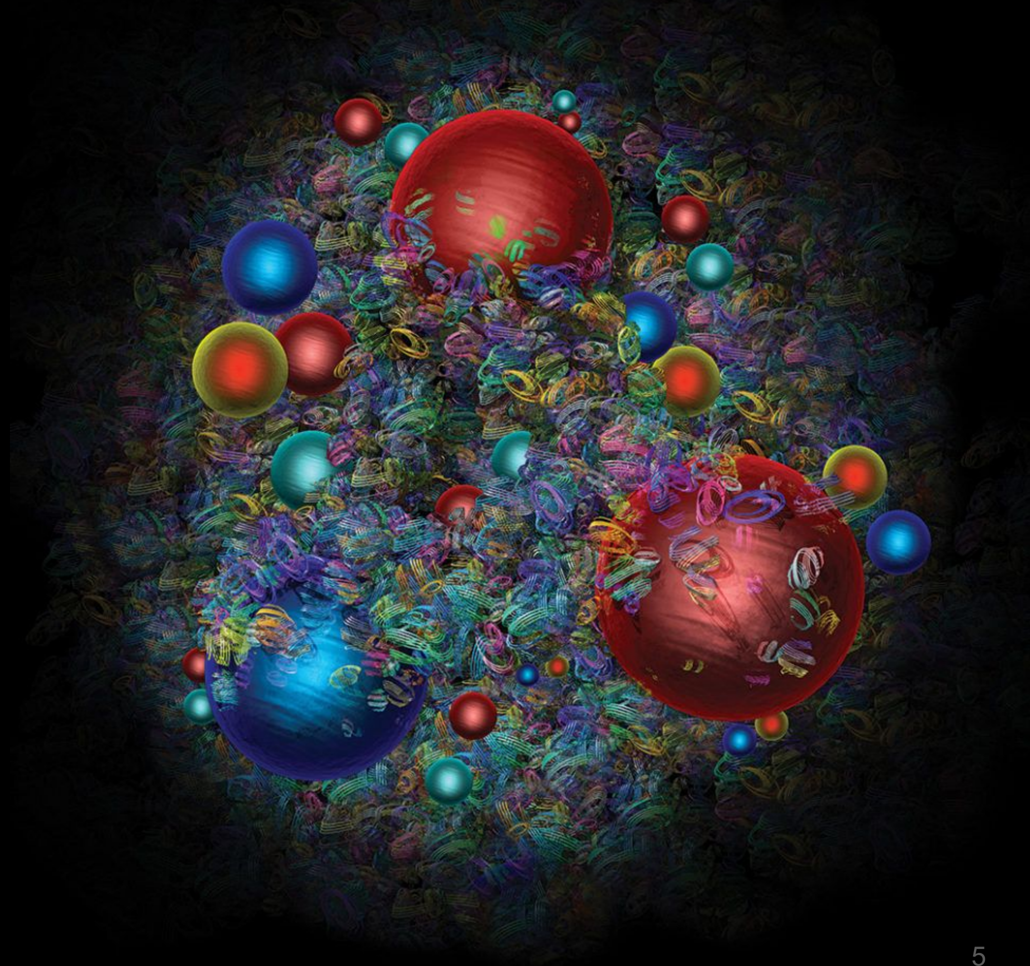
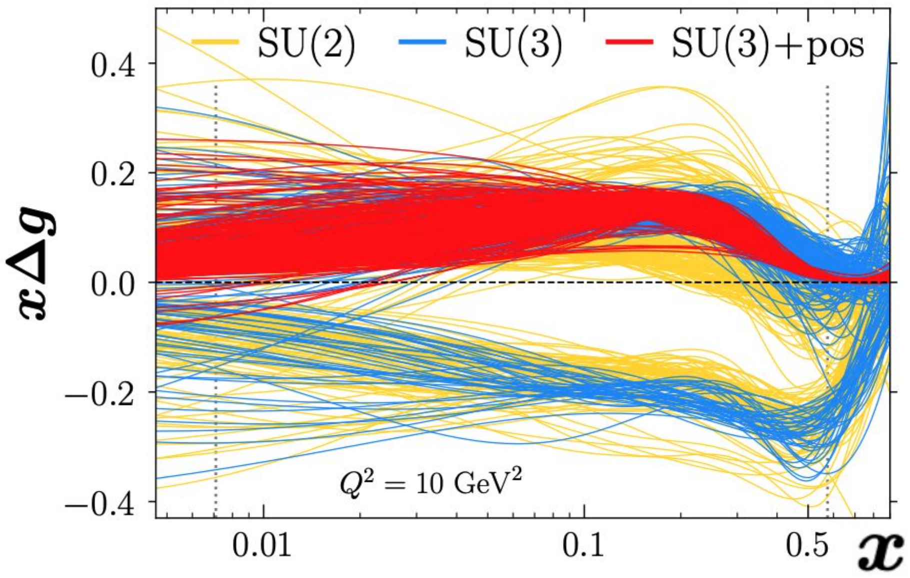


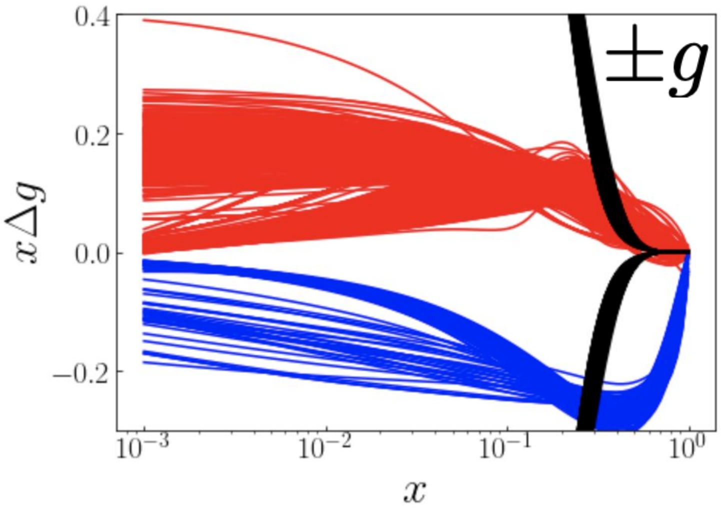
How well do we know the gluon polarization in the proton?

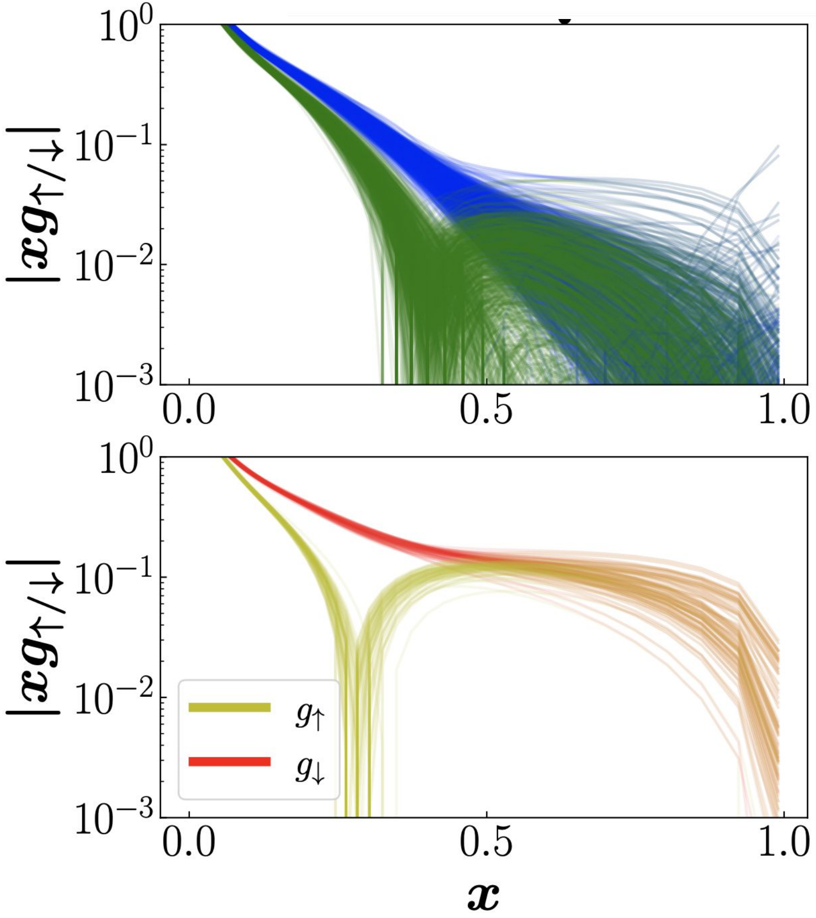
Y. Zhou, N. Sato, and W. Melnitchouk (Jefferson Lab Angular Momentum (JAM) Collaboration)
Phys. Rev. D **105**, 074022 – Published 25 April 2022



Updates on gluon helicity

What do we mean by positivity?





$$g_{\uparrow/\downarrow} = \frac{1}{2}(g \pm \Delta g)$$

Positivity condition ⇨ $g_{\uparrow/\downarrow} > 0$

Are the negative solutions non-sense?

$g_{\uparrow/\downarrow} \overset{?}{>} 0$

Positivity and renormalization of parton densities

John Collins, Ted C. Rogers, and Nobuo Sato
Phys. Rev. D **105**, 076010 – Published 14 April 2022

→ pdfs can be **negative**

- For BSM searches at LHC, negative pdfs leads to negative cross sections in some observables at extreme regions of phase
  - need positive pdfs
- For MCEGs, one needs to initiate the markov chain by sampling parton momentum fractions
  - need positive pdfs
- Exploration of origin of proton spin
  - do need positive pdfs?

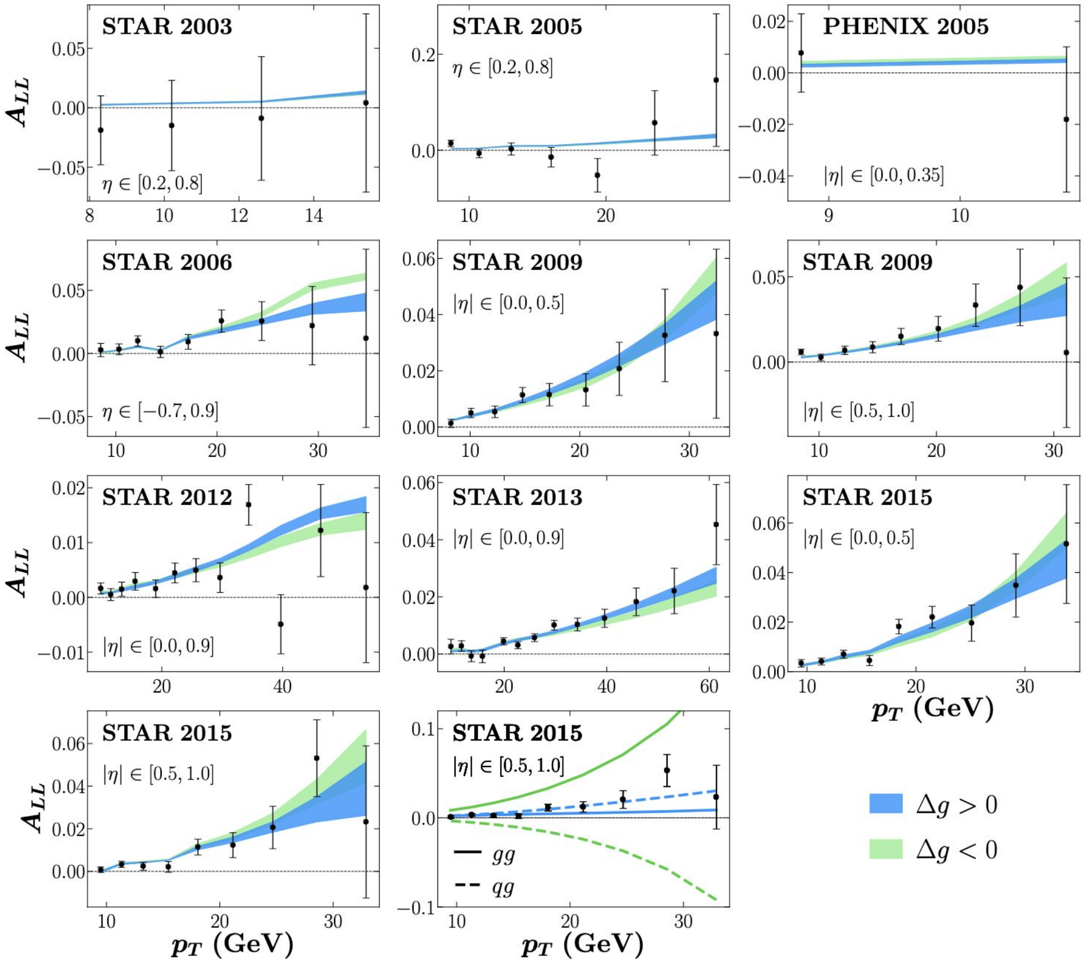
- Negative cross sections are non-sense
  - true for helicity dependent cross sections

$$A_{LL} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$

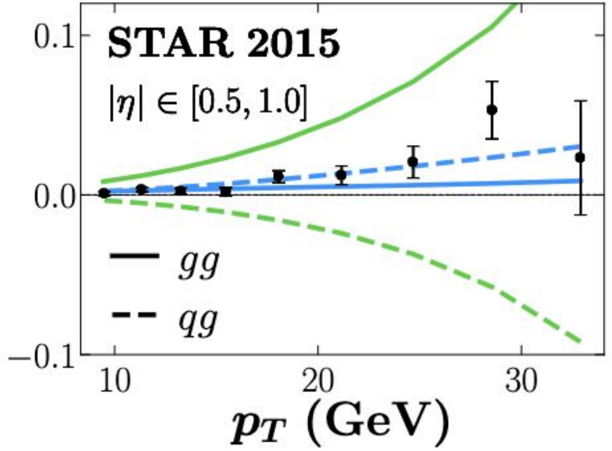
→ $\sigma_\pm > 0$ → $|A_{LL}| < 1$

- Does negative gluon hpdf violate this?

what does the data tell us?



$$|A_{LL}| < 1$$



- Negative qg subchannel is admissible by data
- The gg channel can be large and positive at the expense of negative qg

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

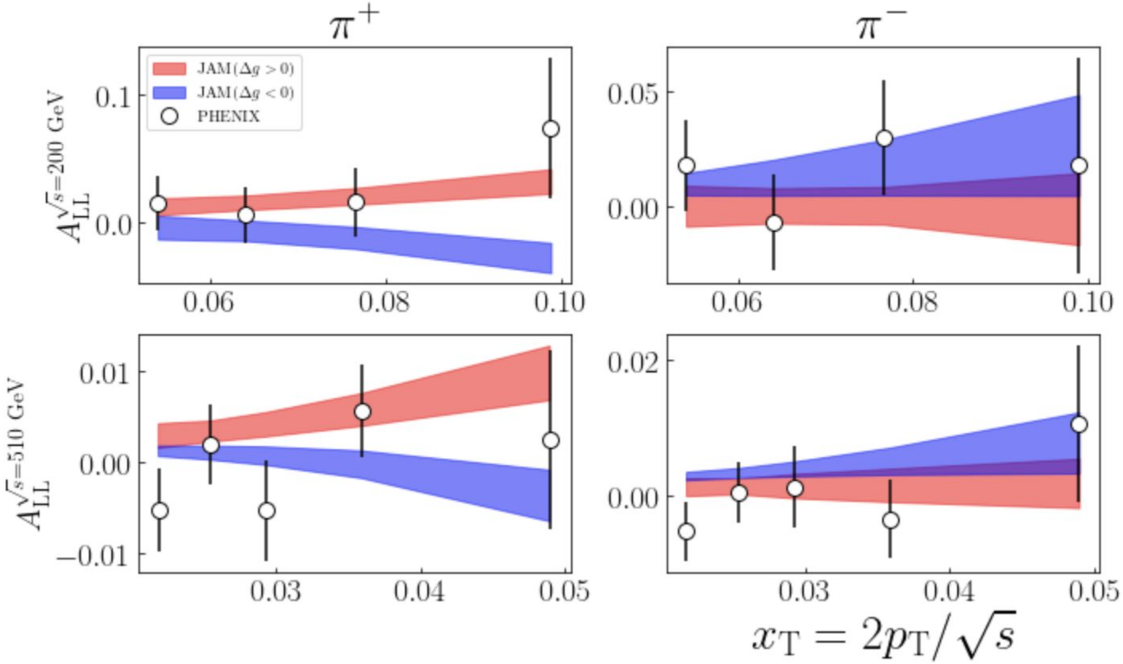
PHENIX Collaboration • U.A. Acharya (Georgia State U.) et al. (Apr 6, 2020)

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]

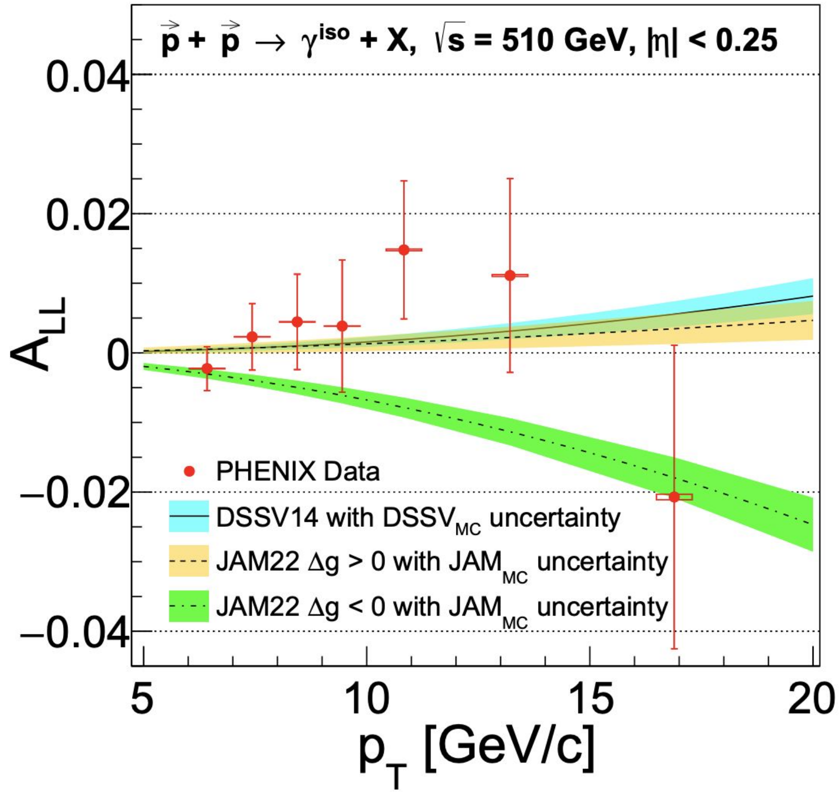


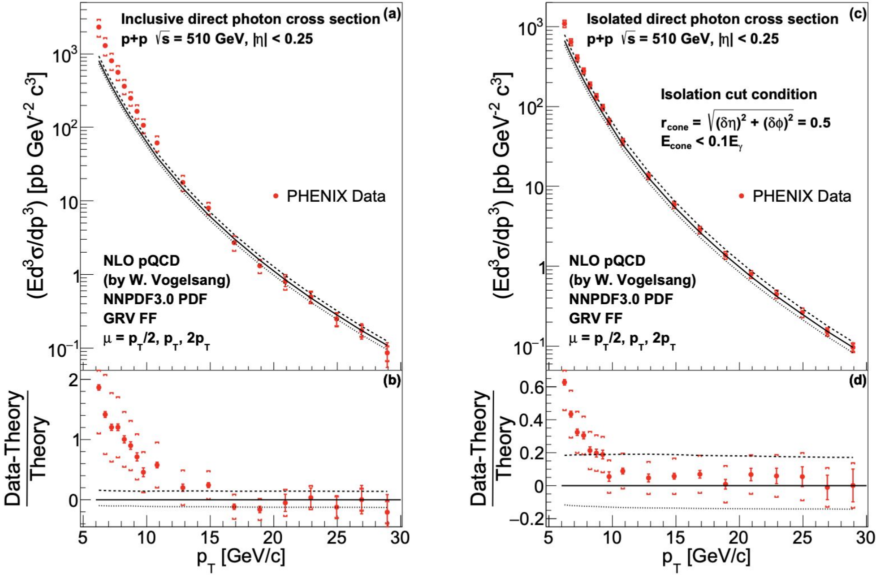
The PHENIX experiment at the Relativistic Heavy Ion Collider has measured the longitudinal double spin asymmetries, A_{LL}, for charged pions at midrapidity ($|\eta| < 0.35$) in longitudinally polarized p+p collisions at $\sqrt{s}$ = 510 GeV. These measurements are sensitive to the gluon spin contribution to the total spin of the proton in the parton momentum fraction x range between 0.04 and 0.09. One can infer the sign of the gluon polarization from the ordering of pion asymmetries with charge alone. The asymmetries are found to be consistent with global quantum-chromodynamics fits of deep-inelastic scattering and data at $\sqrt{s}$ = 200 GeV, which show a nonzero positive contribution of gluon spin to the proton spin.

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]



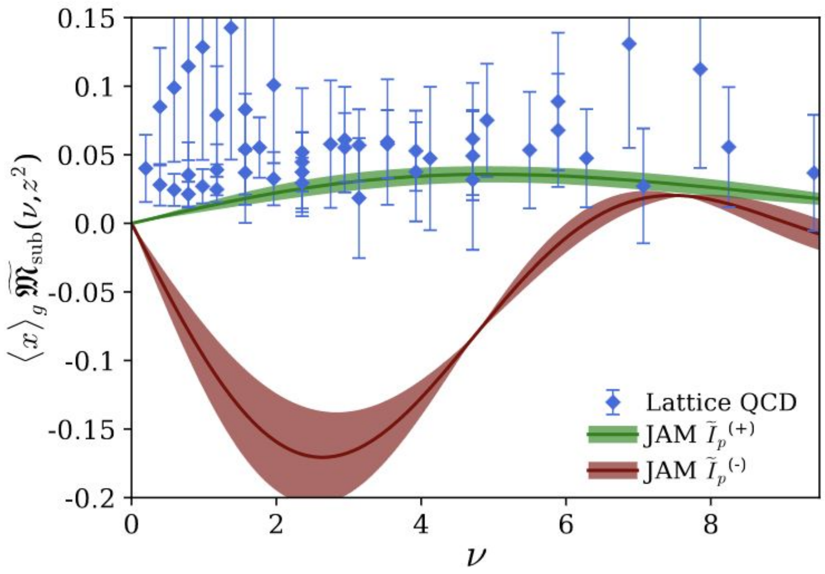


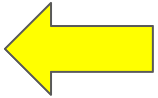
The two dashed curves in Fig. 2 come from the global analysis of the JAM Collaboration [15, 16]. They found there are two distinct sets of solutions for the polarized gluon PDF, Δg, which differ in sign. Even though the solutions with $\Delta g < 0$ violate the positivity assumption, $|\Delta g| < g$, all previous data cannot exclude those solutions due to the mixed contributions from quark-gluon and gluon-gluon interactions. However, the direct-photon A_{LL} comes mainly from the quark-gluon interactions and has $\chi^2 = 4.7$ and 12.6 for 7 data points for the $\Delta g > 0$ and $\Delta g < 0$ solutions, respectively, with the difference of 7.9 between χ^2 values implying that the negative solution is disfavored at more than 2.8σ level.

Toward the determination of the gluon helicity distribution in the nucleon from lattice quantum chromodynamics

HadStruc Collaboration • Colin Egerer (Jefferson Lab) et al. (Jul 18, 2022)

Published in: *Phys.Rev.D* 106 (2022) 9, 094511 • e-Print: 2207.08733 [hep-lat]





Negative delta g seems to be largely disfavored by LQCD

Constraints from LQCD

Constraints from LQCD

$$\widetilde{M}^{\mu\nu;\alpha\beta}(p,z) = \langle p|F^{\mu\nu}(0)W(0;z)\widetilde{F}^{\alpha\beta}(z)|p\rangle$$

For space-like z

$$\widetilde{M}_{00}(p,z) = p_0 p_3 \left[\widetilde{M}^{ti;it}(p,z) + \widetilde{M}^{ij;ji}(p,z)\right]$$

$$= \underbrace{\widetilde{\mathcal{M}}(\nu,z^2)}_{\text{LP matching}} + \underbrace{\frac{m^2 z^2}{\nu}\mathcal{M}_{pp}(\nu,z^2)}_{\text{Beyond LP}} .$$

$$\nu = p \cdot z$$

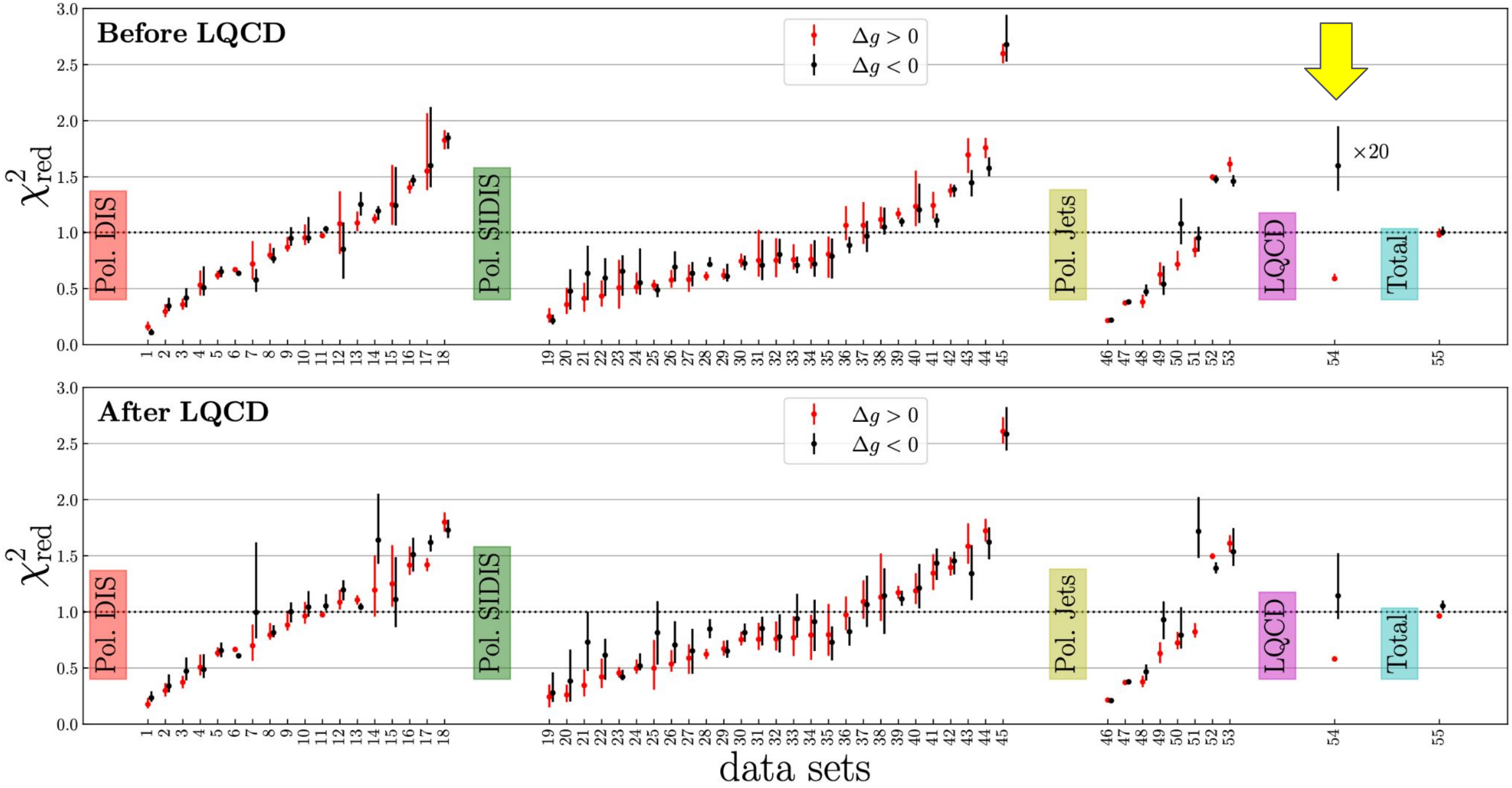
Constraints from LQCD

$$\widetilde{M}_{00}(p,z) \Rightarrow \widetilde{\mathfrak{M}}(\nu,z^2) = \frac{\widetilde{M}_{00}(p,z)/p_0p_3Z_L(z_3/a)}{M_{00}(p=0,z)/m^2}$$

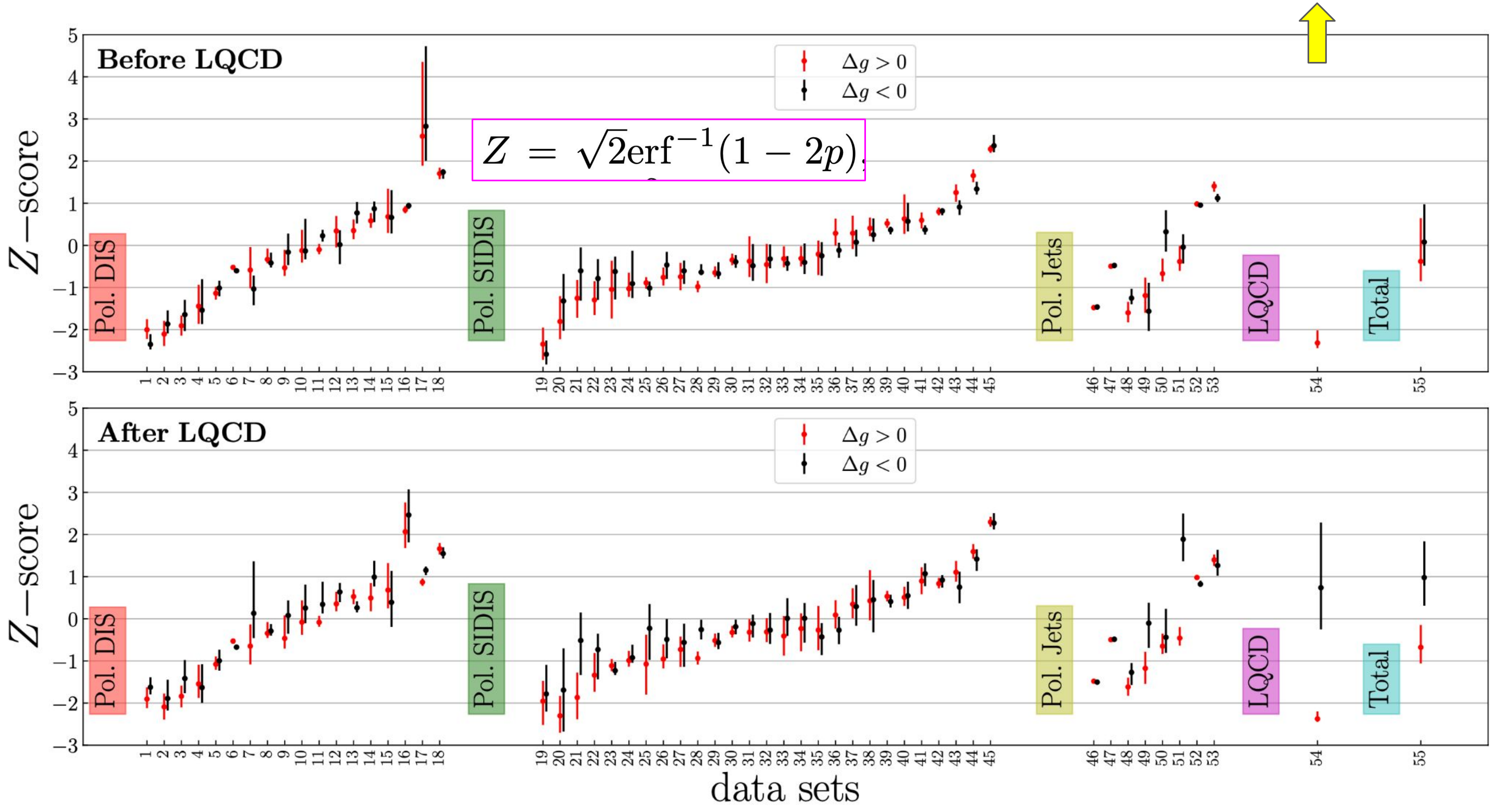
$$\begin{aligned}\widetilde{\mathfrak{M}}(\nu,z^2)\langle x_g\rangle_{\mu^2} = {} & \boxed{\widetilde{\mathcal{I}}_p(\nu,\mu^2)} - \frac{\alpha_s N_c}{2\pi}\int_0^1 \mathrm{d}u\,\widetilde{\mathcal{I}}_p(u\nu,\mu^2)\Bigg\{\ln\left(z^2\mu^2\frac{e^{2\gamma_E}}{4}\right) \\ & \left(\left[\frac{2u^2}{\bar{u}}+4u\bar{u}\right]_+ - \left(\frac{1}{2}+\frac{4}{3}\frac{\langle x_S\rangle_{\mu^2}}{\langle x_g\rangle_{\mu^2}}\right)\delta(\bar{u})\right) \\ & + 4\left[\frac{u+\ln(1-u)}{\bar{u}}\right]_+ - \left(\frac{1}{\bar{u}}-\bar{u}\right)_+ - \frac{1}{2}\delta(\bar{u}) + 2\bar{u}u\Bigg\} \\ & - \frac{\alpha_s C_F}{2\pi}\int_0^1 \mathrm{d}u\,\widetilde{\mathcal{I}}_S(u\nu,\mu^2)\left\{\ln\left(z^2\mu^2\frac{e^{2\gamma_E}}{4}\right)\widetilde{\mathcal{B}}_{gq}(u) + 2\bar{u}u\right\} + \mathcal{O}(\Lambda^2_{\mathrm{QCD}}z^2)\,,\end{aligned}$$

$$\boxed{\widetilde{\mathcal{I}}_p(\nu) = \frac{i}{2}\int_{-1}^{1} \mathrm{d}x\, e^{-ix\nu}\, x\,\Delta g(x)\,.}$$

Balitsky, Morris, Radyushkin ‘22

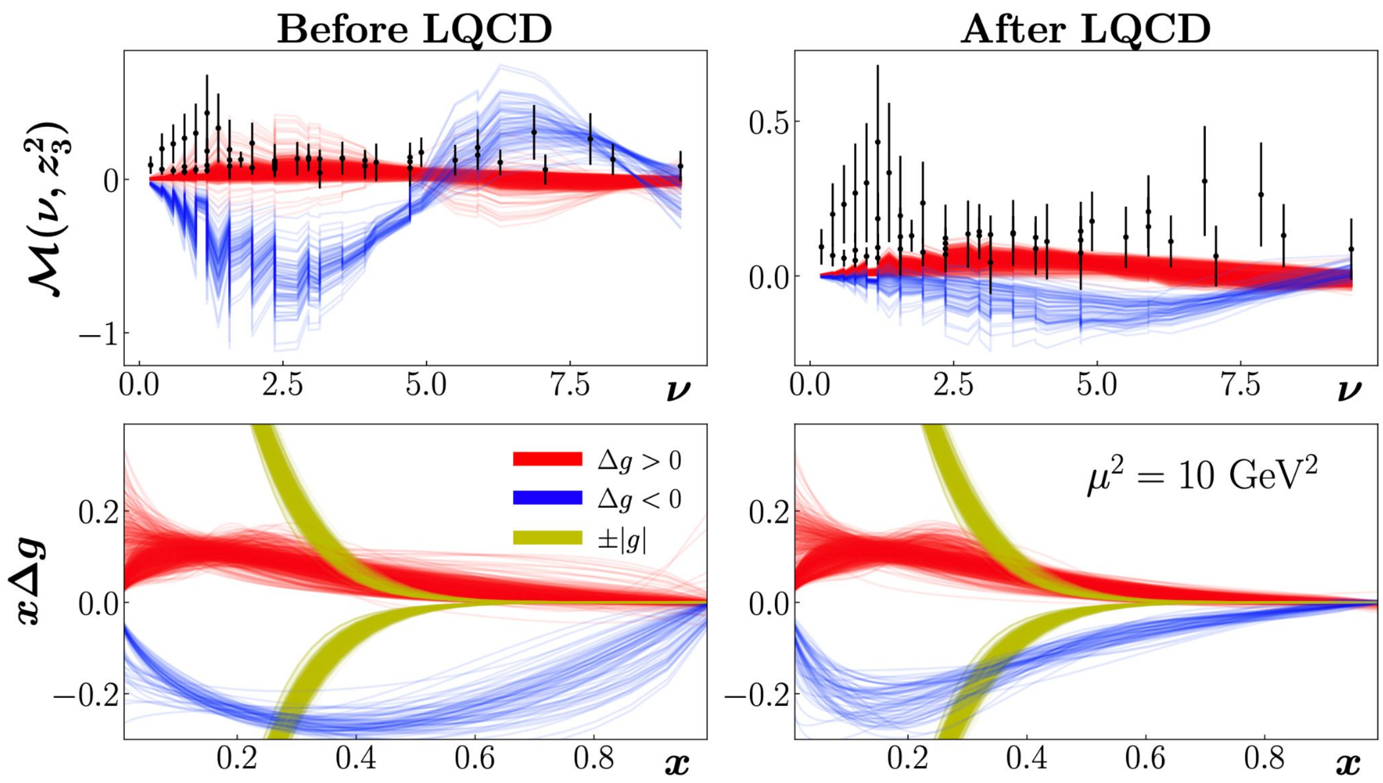


Before LQCD
$\Delta g > 0$
$\Delta g < 0$
$\times 20$
Pol. DIS
Pol. SIDIS
Pol. Jets
LQCD
Total
$\chi^2_{\rm red}$
After LQCD
data sets



Before LQCD
After LQCD
$\Delta g > 0$
$\Delta g < 0$
$Z = \sqrt{2}\mathrm{erf}^{-1}(1 - 2p),$
Z−score
Pol. DIS
Pol. SIDIS
Pol. Jets
LQCD
Total
data sets

Karpie et al, JAM+HadStruc (in preparation)



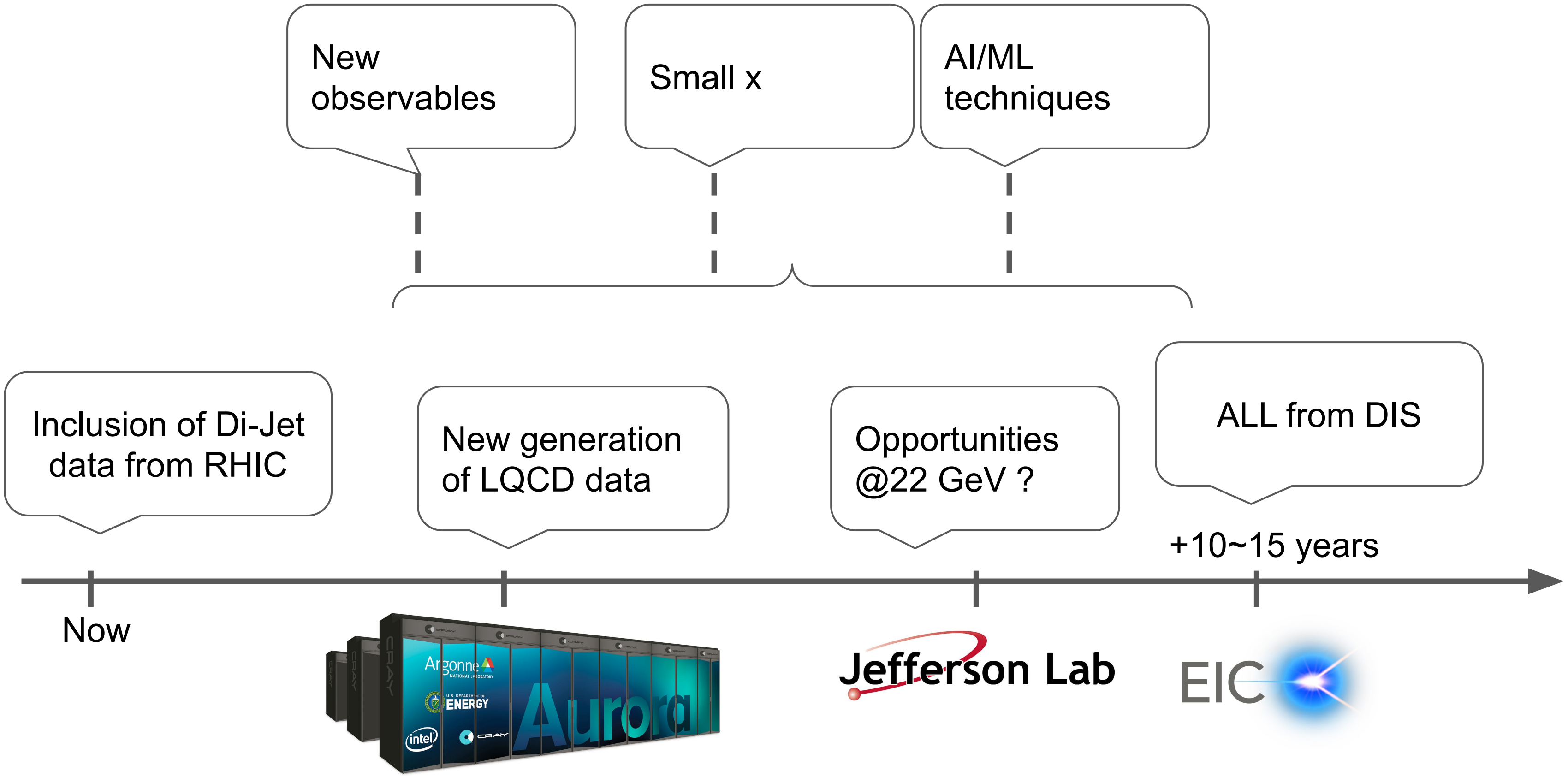
> The error bars only includ diagonal parts of cov matrix

> Offdiagonal entries weakens the constraints

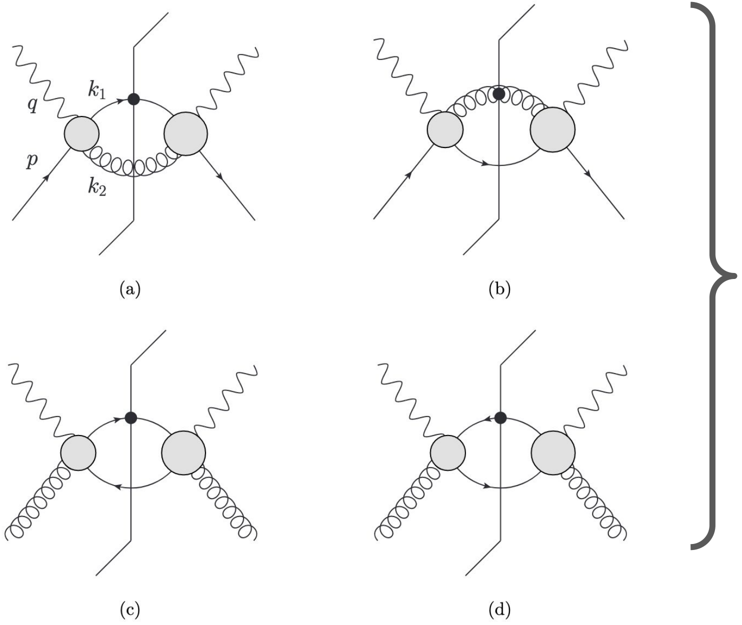
> LQCD data does not remove entirely the negative solutions

> LQCD prefers to less violation of positivity

So, whats next?



Pol. High pT SIDIS

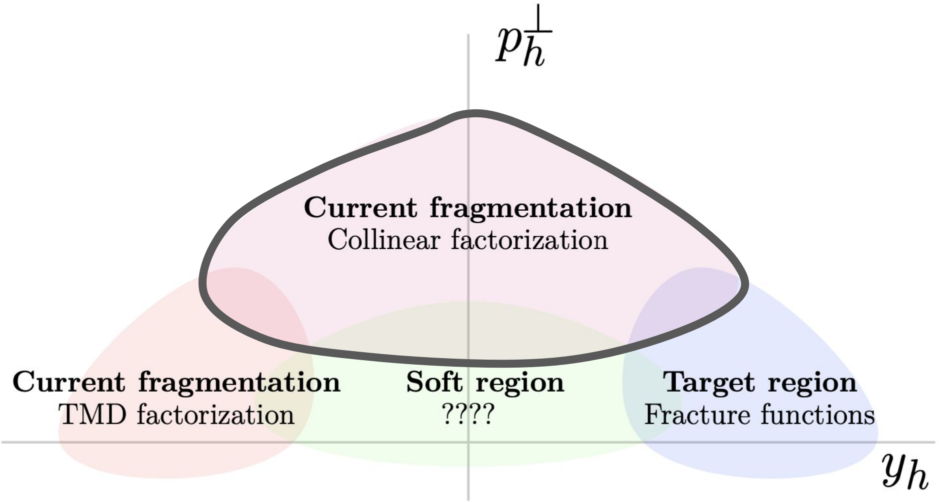


Gluon initiated subprocess appears at the same order as quarks in pQCD

Accessing gluon polarization with high-P_T hadrons in SIDIS

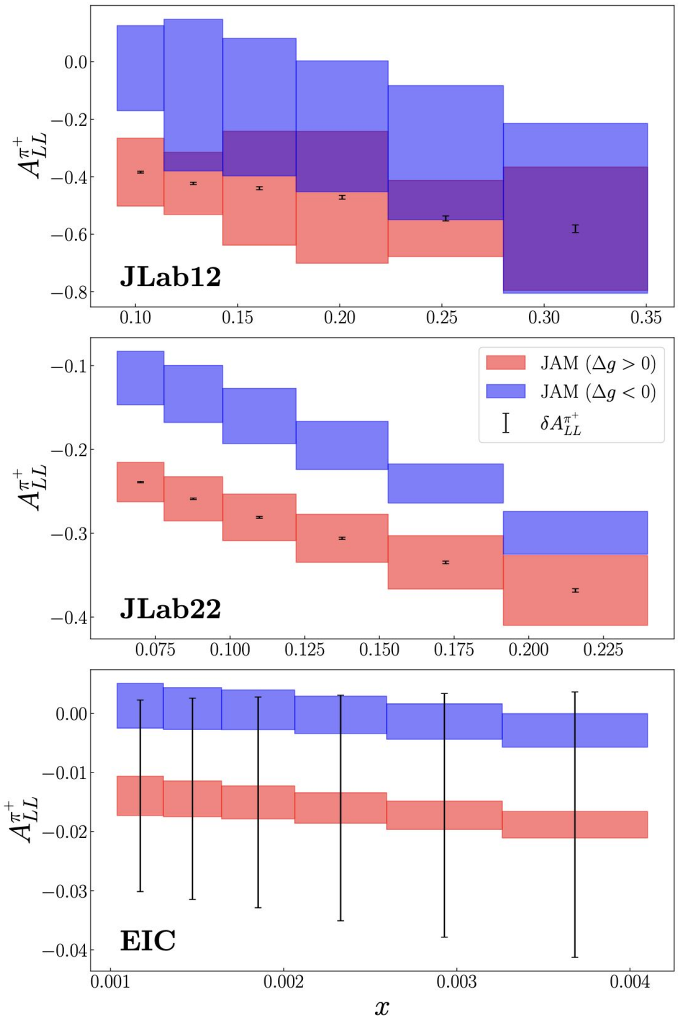
R.M. Whitehill (Wichita State U.), Yiyu Zhou (South China Normal U. and UCLA), N. Sato (Jefferson Lab), W. Melnitchouk (Jefferson Lab and Adelaide U., Sch. Chem. Phys.)

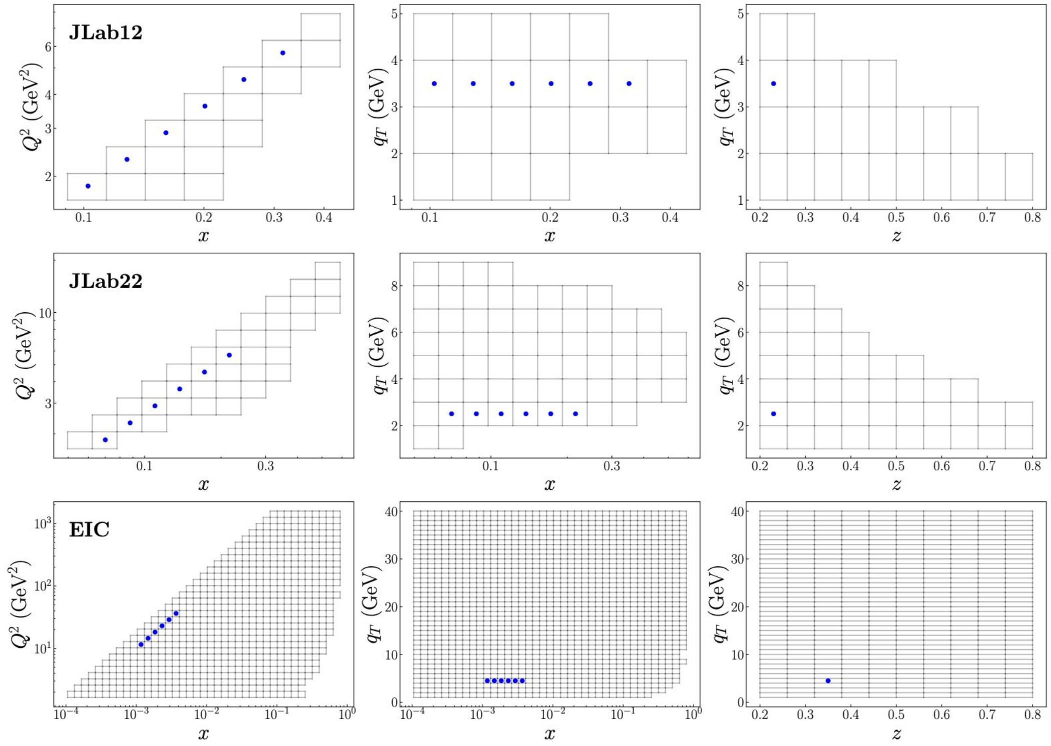
Oct 21, 2022



$$4P_h^0 E' \frac{d\sigma_h}{d^3\boldsymbol{\ell}' d^3\boldsymbol{P}_h} = \sum_{ij} \int_x^1 \frac{d\xi}{\xi} \int_z^1 \frac{d\zeta}{\zeta^2} \left(4k_1^0 E' \frac{d\hat{\sigma}_{ij}}{d^3\boldsymbol{\ell}' d^3\boldsymbol{k}_1} \right) f_{i/N}(\xi)\, D_{h/j}(\zeta),$$

$$4P_h^0 E' \frac{d\Delta\sigma_h}{d^3\boldsymbol{\ell}' d^3\boldsymbol{P}_h} = \sum_{ij} \int_x^1 \frac{d\xi}{\xi} \int_z^1 \frac{d\zeta}{\zeta^2} \left(4k_1^0 E' \frac{d\Delta\hat{\sigma}_{ij}}{d^3\boldsymbol{\ell}' d^3\boldsymbol{k}_1} \right) \Delta f_{i/N}(\xi)\, D_{h/j}(\zeta),$$

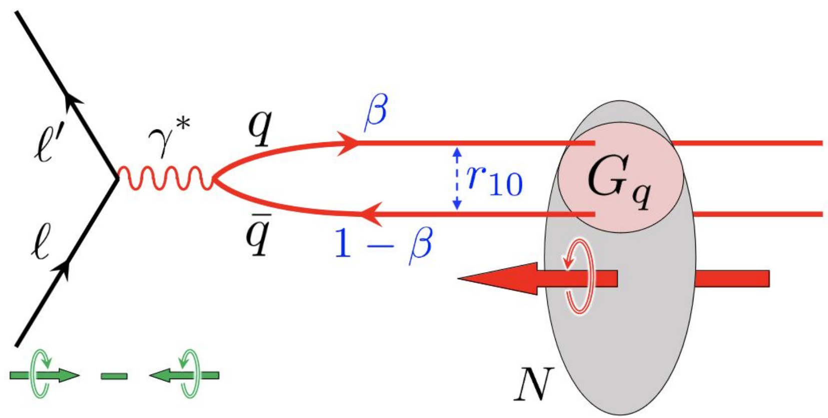




Bottom line: sign of gluon polarization might be resolved empirically with pol SIDIS

Global analysis of polarized DIS & SIDIS data with improved small-x helicity evolution

Daniel Adamiak (Ohio State U. and Jefferson Lab), Nicholas Baldonado, Yuri V. Kovchegov (Ohio State U.), W. Melnitchouk (Jefferson Lab), Daniel Pitonyak (Lebanon Valley Coll.) Show All(9)



$$Q_q^{(0)}(s_{10},\eta) = a_q\,\eta + b_q\,s_{10} + c_q\,,$$
$$\widetilde{G}^{(0)}(s_{10},\eta) = \widetilde{a}\,\eta + \widetilde{b}\,s_{10} + \widetilde{c}\,,$$
$$G_2^{(0)}(s_{10},\eta) = a_2\,\eta + b_2\,s_{10} + c_2\,.$$

Input to evolution

$$\begin{aligned} Q_q(x_{10}^2, zs) = Q_q^{(0)}(x_{10}^2, zs) &+ \frac{N_c}{2\pi}\int_{1/x_{10}^2 s}^{z}\frac{dz'}{z'}\int_{1/z's}^{x_{10}^2}\frac{dx_{21}^2}{x_{21}^2}\,\alpha_s\!\left(\frac{1}{x_{21}^2}\right)\Big[2\,\widetilde{G}(x_{21}^2, z's) + 2\,\widetilde{\Gamma}(x_{10}^2, x_{21}^2, z's) \\ &+ Q_q(x_{21}^2, z's) - \overline{\Gamma}_q(x_{10}^2, x_{21}^2, z's) + 2\,\Gamma_2(x_{10}^2, x_{21}^2, z's) + 2\,G_2(x_{21}^2, z's)\Big] \\ &+ \frac{N_c}{4\pi}\int_{\Lambda^2/s}^{z}\frac{dz'}{z'}\int_{1/z's}^{\min[x_{10}^2 z/z', 1/\Lambda^2]}\frac{dx_{21}^2}{x_{21}^2}\,\alpha_s\!\left(\frac{1}{x_{21}^2}\right)\Big[Q_q(x_{21}^2, z's) + 2\,G_2(x_{21}^2, z's)\Big]\,, \end{aligned} \tag{9a}$$

$$\begin{aligned} \overline{\Gamma}_q(x_{10}^2, x_{21}^2, z's) = Q_q^{(0)}(x_{10}^2, z's) &+ \frac{N_c}{2\pi}\int_{1/x_{10}^2 s}^{z'}\frac{dz''}{z''}\int_{1/z''s}^{\min[x_{10}^2, x_{21}^2 z'/z'']}\frac{dx_{32}^2}{x_{32}^2}\,\alpha_s\!\left(\frac{1}{x_{32}^2}\right)\Big[2\,\widetilde{G}(x_{32}^2, z''s) \\ &+ 2\,\widetilde{\Gamma}(x_{10}^2, x_{32}^2, z''s) + Q_q(x_{32}^2, z''s) - \overline{\Gamma}_q(x_{10}^2, x_{32}^2, z''s) + 2\,\Gamma_2(x_{10}^2, x_{32}^2, z''s) + 2\,G_2(x_{32}^2, z''s)\Big] \\ &+ \frac{N_c}{4\pi}\int_{\Lambda^2/s}^{z'}\frac{dz''}{z''}\int_{1/z''s}^{\min[x_{21}^2 z'/z'', 1/\Lambda^2]}\frac{dx_{32}^2}{x_{32}^2}\,\alpha_s\!\left(\frac{1}{x_{32}^2}\right)\Big[Q_q(x_{32}^2, z''s) + 2\,G_2(x_{32}^2, z''s)\Big]\,, \end{aligned} \tag{9b}$$

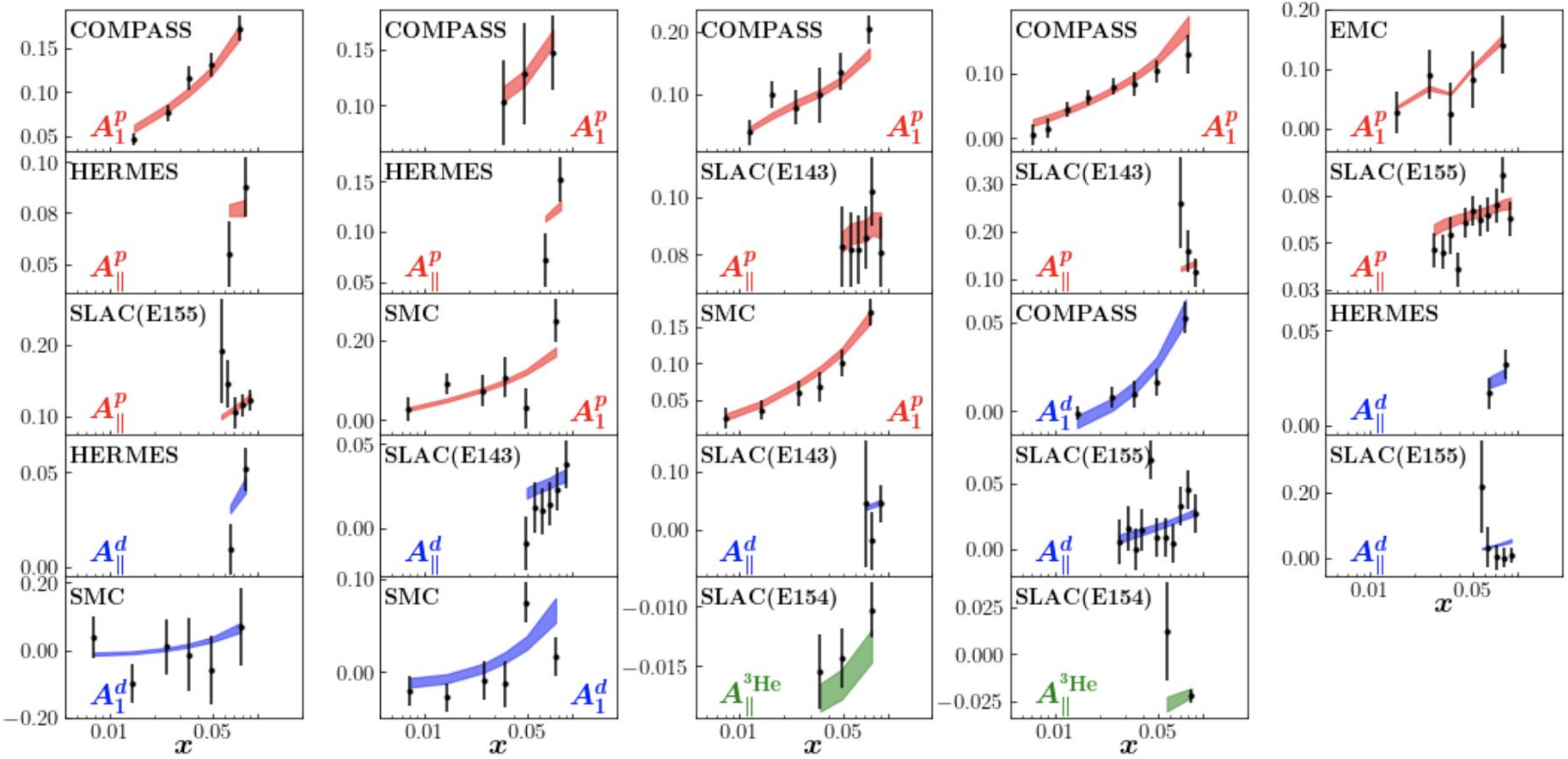
$$\begin{aligned} \widetilde{G}(x_{10}^2, zs) = \widetilde{G}^{(0)}(x_{10}^2, zs) &+ \frac{N_c}{2\pi}\int_{1/x_{10}^2 s}^{z}\frac{dz'}{z'}\int_{1/z's}^{x_{10}^2}\frac{dx_{21}^2}{x_{21}^2}\,\alpha_s\!\left(\frac{1}{x_{21}^2}\right)\Big[3\,\widetilde{G}(x_{21}^2, z's) + \widetilde{\Gamma}(x_{10}^2, x_{21}^2, z's) \\ &+ 2\,G_2(x_{21}^2, z's) + \left(2 - \frac{N_f}{2N_c}\right)\Gamma_2(x_{10}^2, x_{21}^2, z's) - \frac{1}{4N_c}\sum_q \overline{\Gamma}_q(x_{10}^2, x_{21}^2, z's)\Big] \\ &- \frac{1}{8\pi}\int_{\Lambda^2/s}^{z}\frac{dz'}{z'}\int_{\max[x_{10}^2, 1/z's]}^{\min[x_{10}^2 z/z', 1/\Lambda^2]}\frac{dx_{21}^2}{x_{21}^2}\,\alpha_s\!\left(\frac{1}{x_{21}^2}\right)\left[\sum_q Q_q(x_{21}^2, z's) + 2\,N_f\,G_2(x_{21}^2, z's)\right], \end{aligned} \tag{9c}$$

$$\begin{aligned} \widetilde{\Gamma}(x_{10}^2, x_{21}^2, z's) = \widetilde{G}^{(0)}(x_{10}^2, z's) &+ \frac{N_c}{2\pi}\int_{1/x_{10}^2 s}^{z'}\frac{dz''}{z''}\int_{1/z''s}^{\min[x_{10}^2, x_{21}^2 z'/z'']}\frac{dx_{32}^2}{x_{32}^2}\,\alpha_s\!\left(\frac{1}{x_{32}^2}\right)\Big[3\,\widetilde{G}(x_{32}^2, z''s) \\ &+ \widetilde{\Gamma}(x_{10}^2, x_{32}^2, z''s) + 2\,G_2(x_{32}^2, z''s) + \left(2 - \frac{N_f}{2N_c}\right)\Gamma_2(x_{10}^2, x_{32}^2, z''s) - \frac{1}{4N_c}\sum_q \overline{\Gamma}_q(x_{10}^2, x_{32}^2, z''s)\Big] \\ &- \frac{1}{8\pi}\int_{\Lambda^2/s}^{z' x_{21}^2/x_{10}^2}\frac{dz''}{z''}\int_{\max[x_{10}^2, 1/z''s]}^{\min[x_{21}^2 z'/z'', 1/\Lambda^2]}\frac{dx_{32}^2}{x_{32}^2}\,\alpha_s\!\left(\frac{1}{x_{32}^2}\right)\left[\sum_q Q_q(x_{32}^2, z''s) + 2\,N_f\,G_2(x_{32}^2, z''s)\right], \end{aligned} \tag{9d}$$

$$G_2(x_{10}^2, zs) = G_2^{(0)}(x_{10}^2, zs) + \frac{N_c}{\pi}\int_{\Lambda^2/s}^{z}\frac{dz'}{z'}\int_{\max\left[x_{10}^2, \frac{1}{z's}\right]}^{\min\left[\frac{z}{z'}x_{10}^2, \frac{1}{\Lambda^2}\right]}\frac{dx_{21}^2}{x_{21}^2}\,\alpha_s\!\left(\frac{1}{x_{21}^2}\right)\left[\widetilde{G}(x_{21}^2, z's) + 2\,G_2(x_{21}^2, z's)\right], \tag{9e}$$

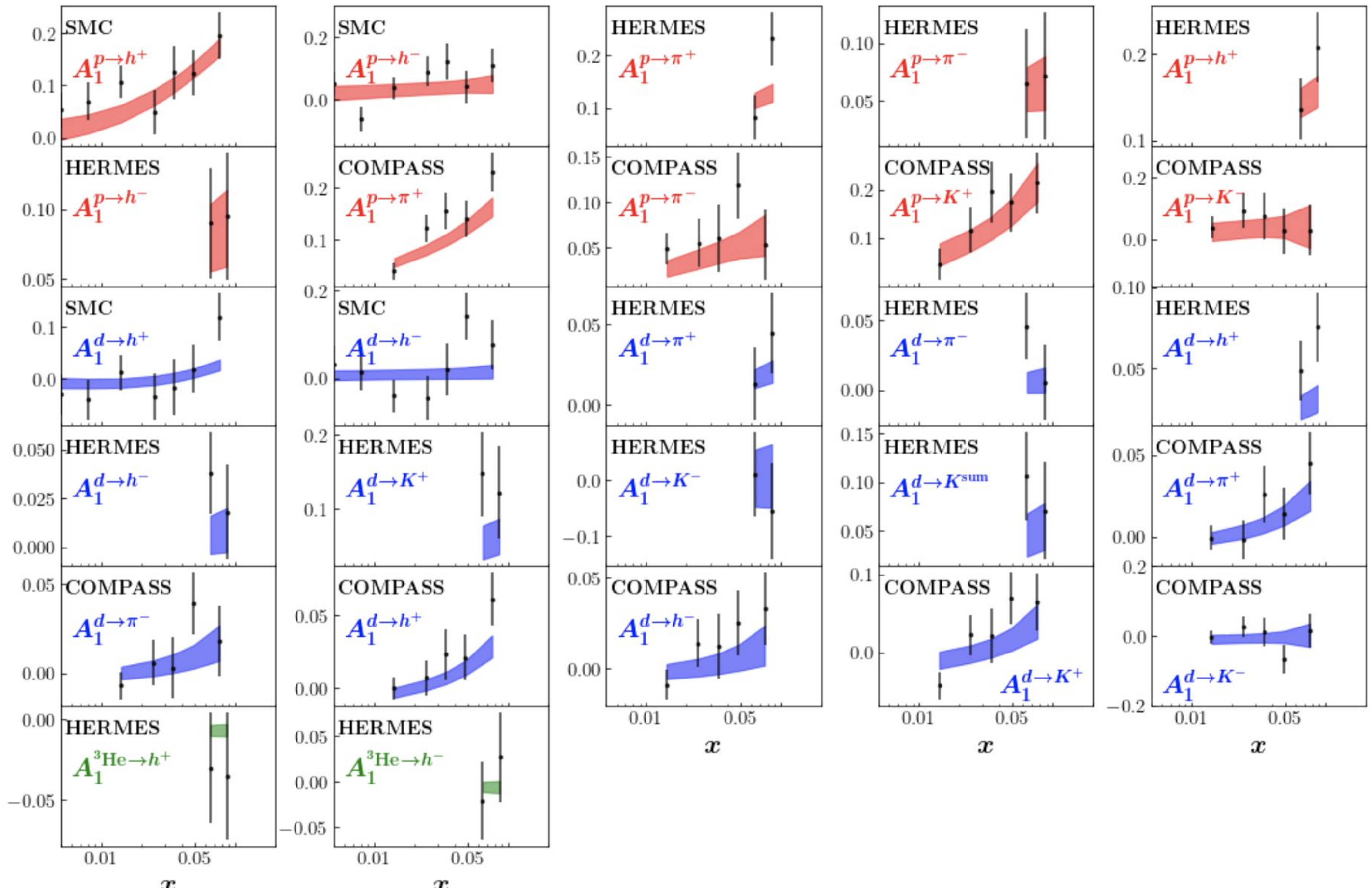
$$\Gamma_2(x_{10}^2, x_{21}^2, z's) = G_2^{(0)}(x_{10}^2, z's) + \frac{N_c}{\pi}\int_{\Lambda^2/s}^{z'\frac{x_{21}^2}{x_{10}^2}}\frac{dz''}{z''}\int_{\max\left[x_{10}^2, \frac{1}{z''s}\right]}^{\min\left[\frac{z'}{z''}x_{21}^2, \frac{1}{\Lambda^2}\right]}\frac{dx_{32}^2}{x_{32}^2}\,\alpha_s\!\left(\frac{1}{x_{32}^2}\right)\left[\widetilde{G}(x_{32}^2, z''s) + 2\,G_2(x_{32}^2, z''s)\right]. \tag{9f}$$

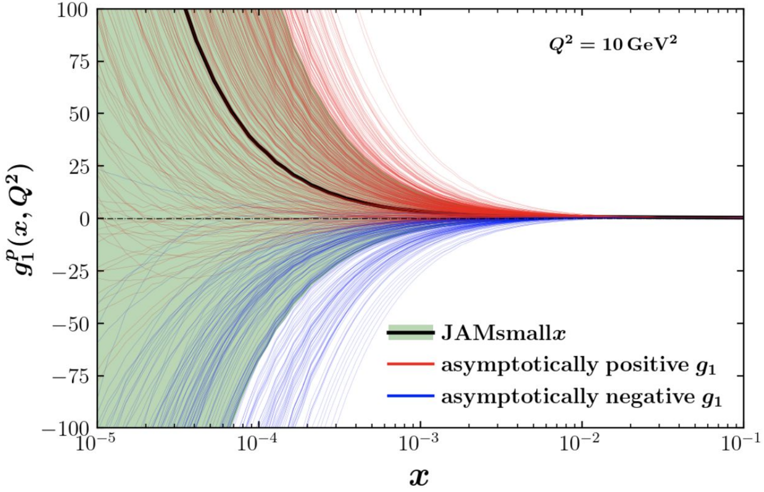
DSAs in DIS

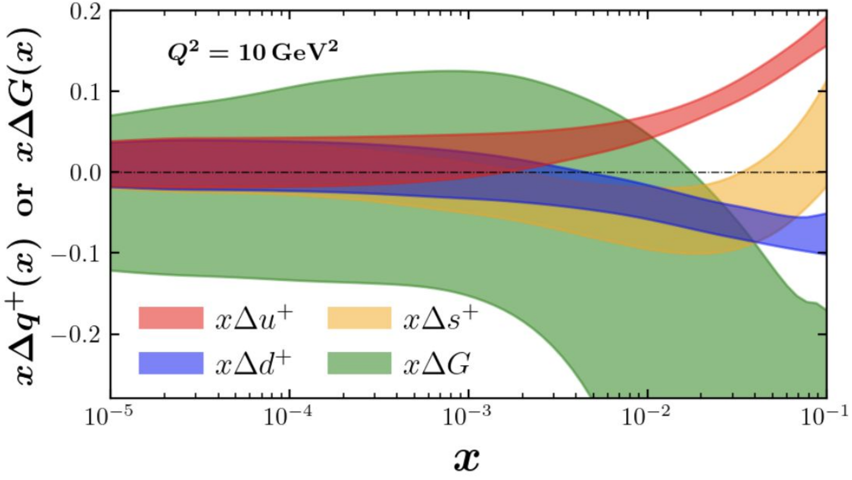


COMPASS
HERMES
SLAC(E155)
SMC
SLAC(E143)
SLAC(E154)
EMC
A_1^p
$A_\parallel^p$
A_1^d
$A_\parallel^d$
$A_\parallel^{^3He}$
x
0.01
0.05

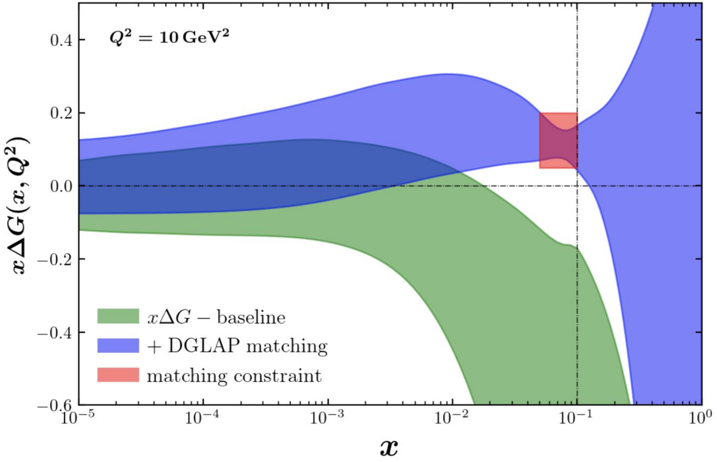
DSAs in SIDIS







Forcing to match with DGLAP based results



- A general trend for negative gluon polarization at large x
- Inclusion of “delta g data point”, can change the trend without altering the agreement with data
- More work is needed to match with high x frameworks

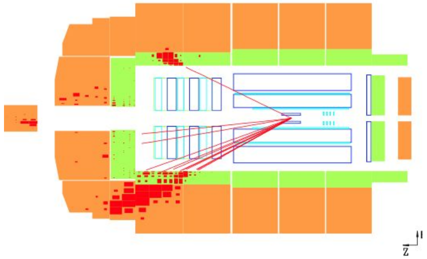
Outline

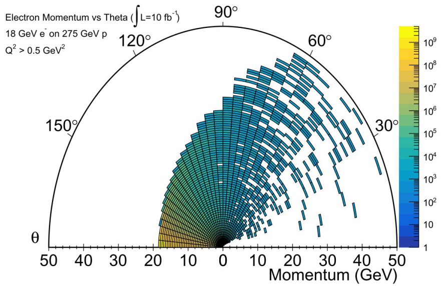
1. Quick updates on PDFs
2. Updates gluon hPDF
3. QuantOm
4. Summary

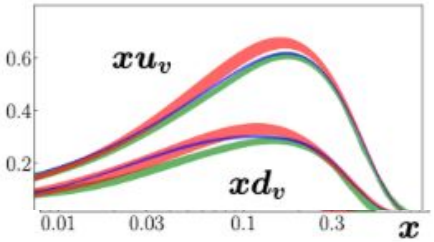
Existing paradigm -> histogram approach

Inverse problem　　Inverse problem

Detector level events → Detector level histograms → Unfolded histograms → Deconvolution "femtography"

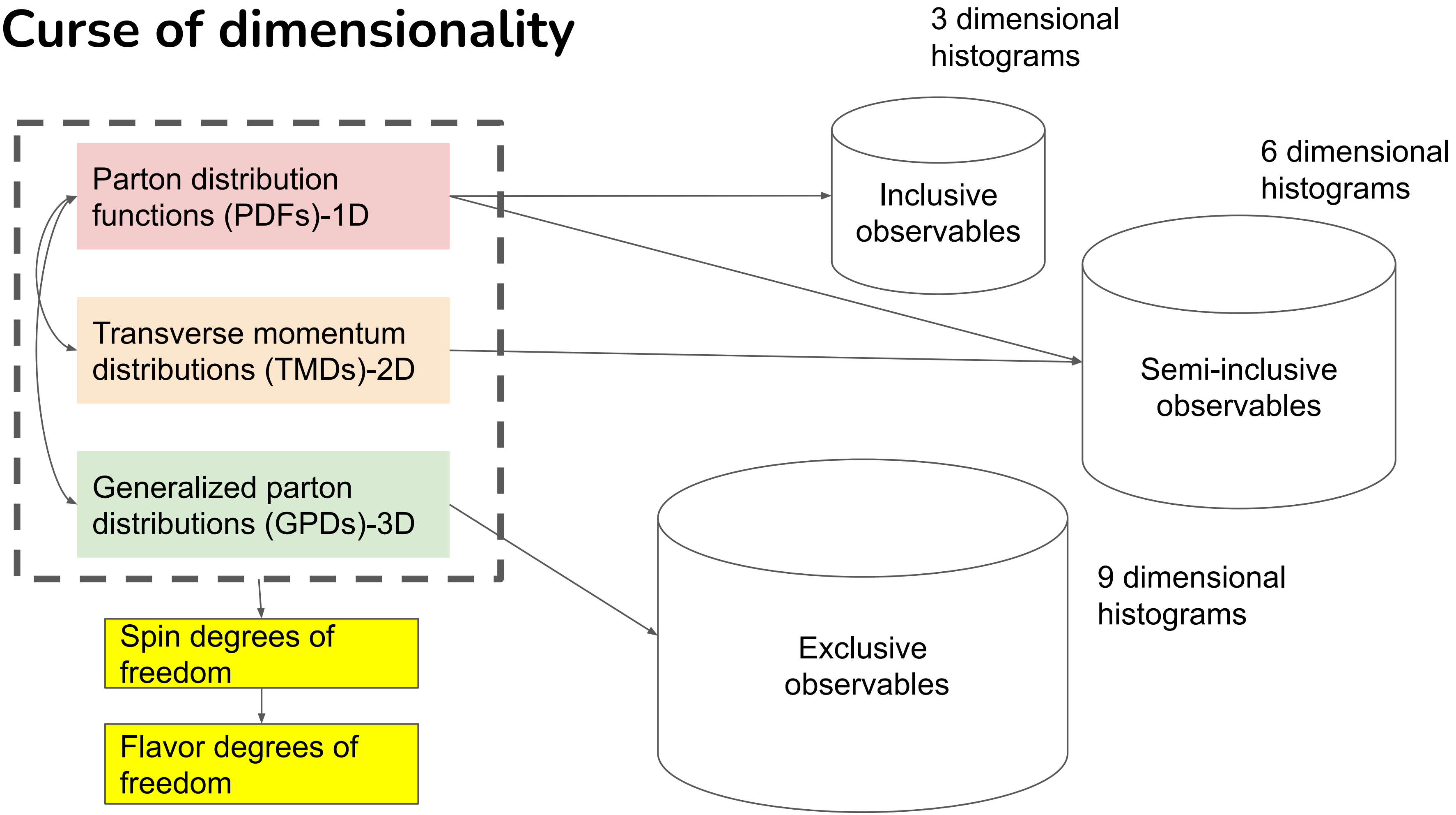






1D QCFs

Curse of dimensionality

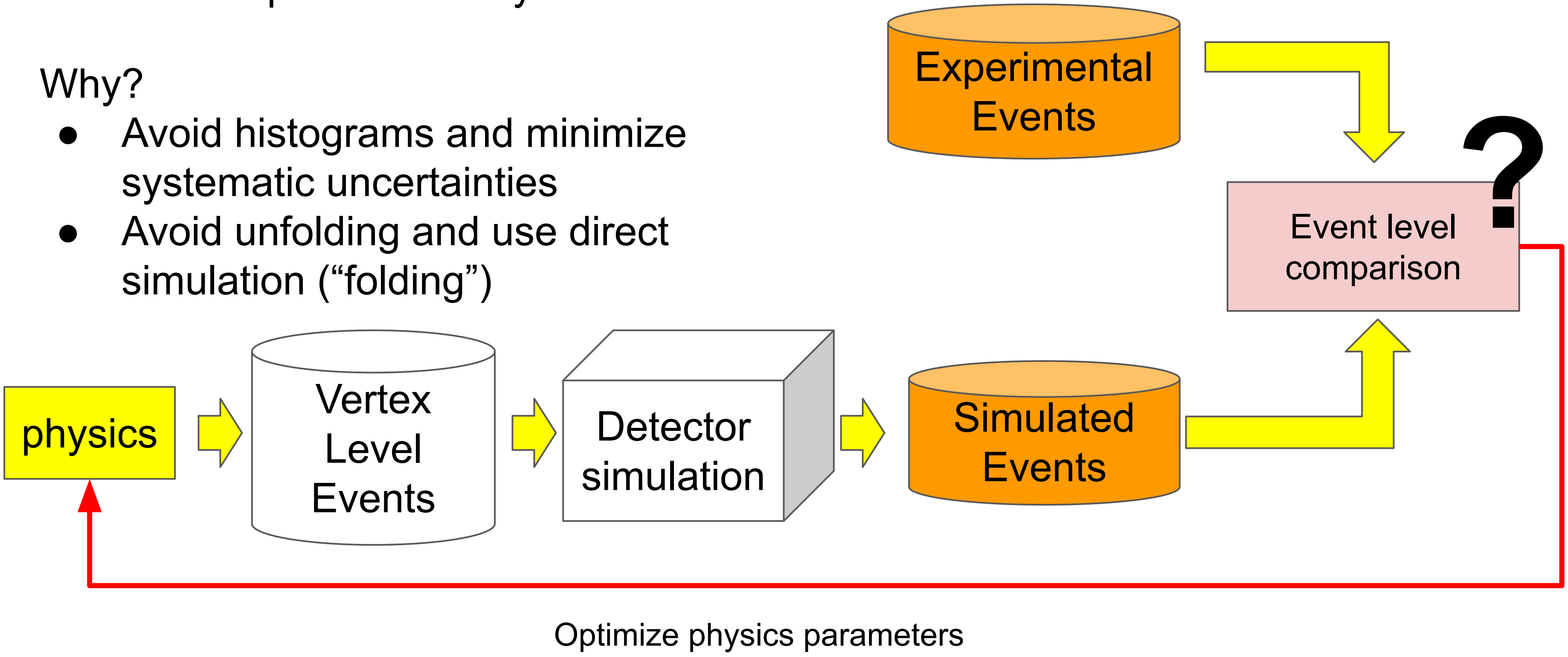


Event-based analysis?

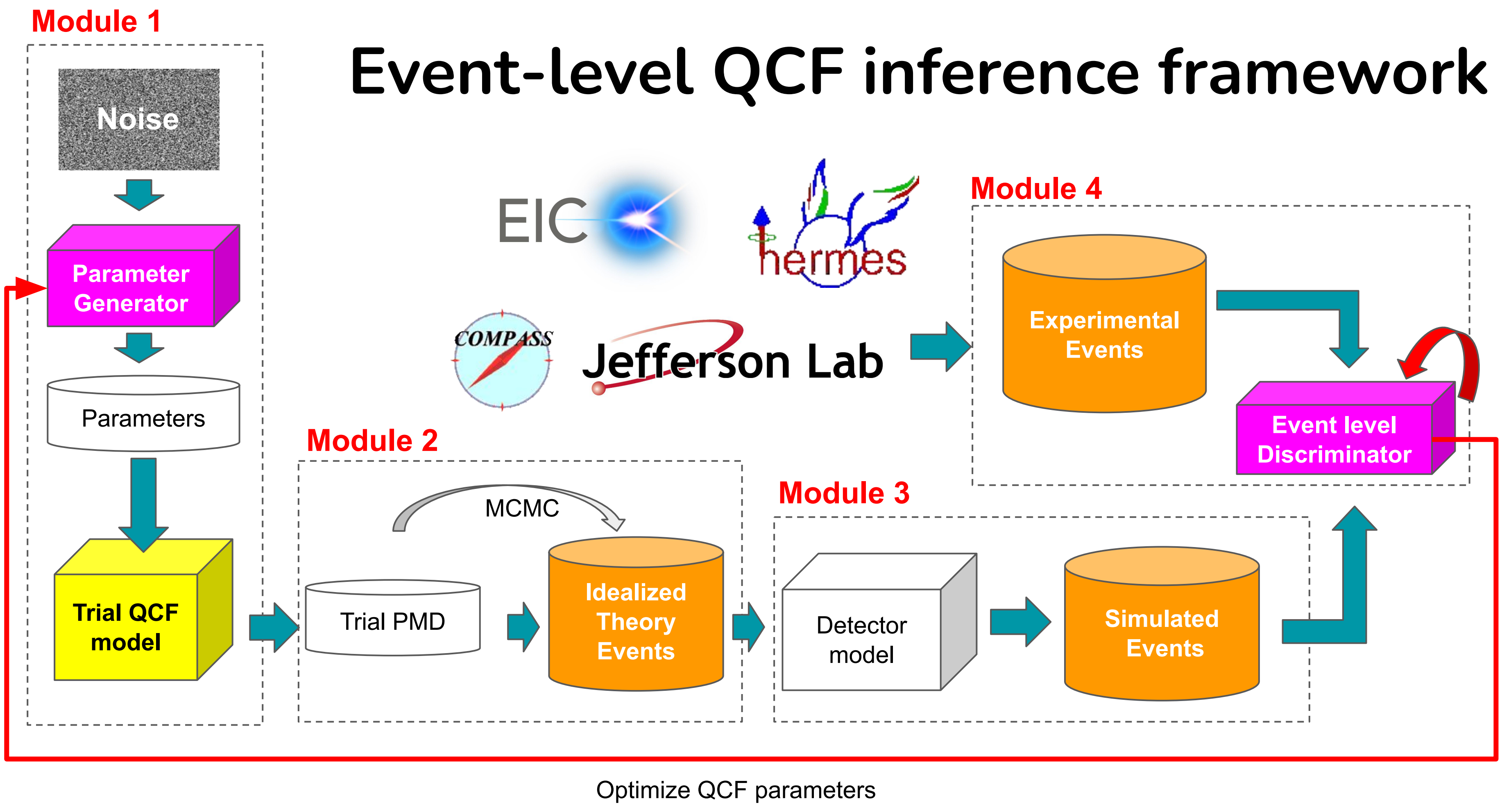
Can we compare real vs synthetic events?

Why?

- Avoid histograms and minimize systematic uncertainties
- Avoid unfolding and use direct simulation (“folding”)



Event-level QCF inference framework

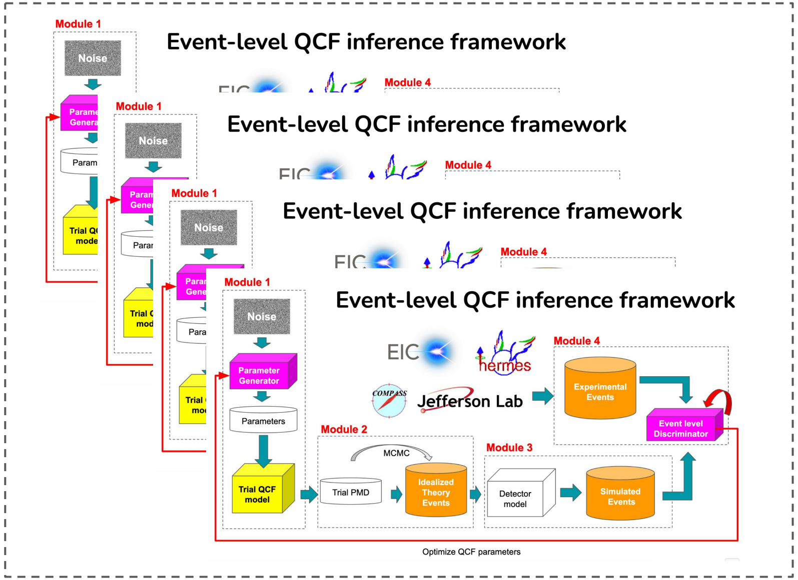


Opportunities

- Unified Theory+Exp analysis framework for hadron structure -> paradigm shift
- Near real time analysis and expedite scientific discovery

Challenges

- Big event level data processing from JLab/EIC requires large scale computing -> exascale computing
- Dedicated distributed ML workflow needs to be developed



QuantOm Collaboration

Argonne NATIONAL LABORATORY

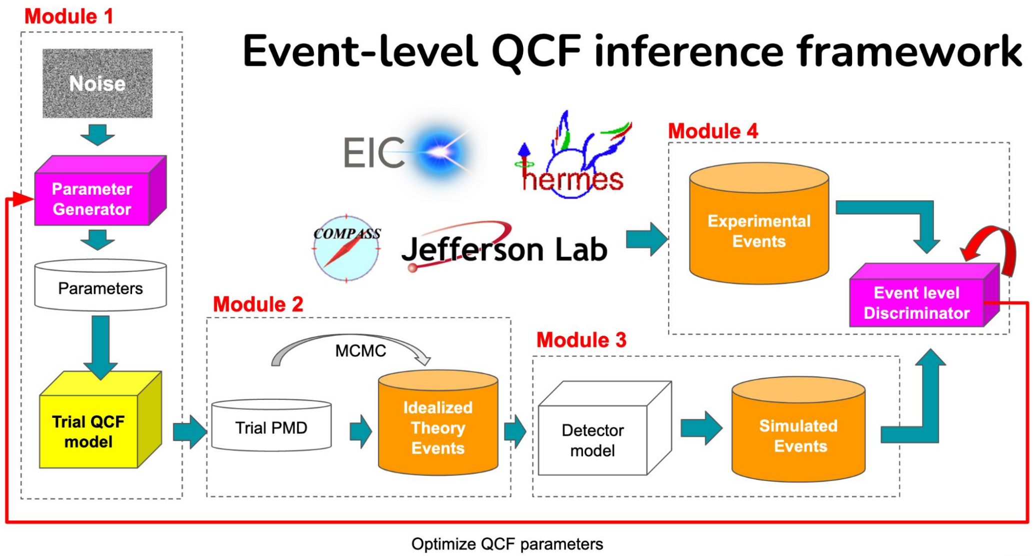
Jefferson Lab

VT

Supported by DOE SciDAC funds

OLD DOMINION UNIVERSITY

One big challenge



- Use of ML requires to implement theory codes using differentiable programming
- It requires to render all the calculations as tensor operations to make use of autodiff
- **Q:** how to start differentiations from phase space samples?

DIS as example

pdf parameters

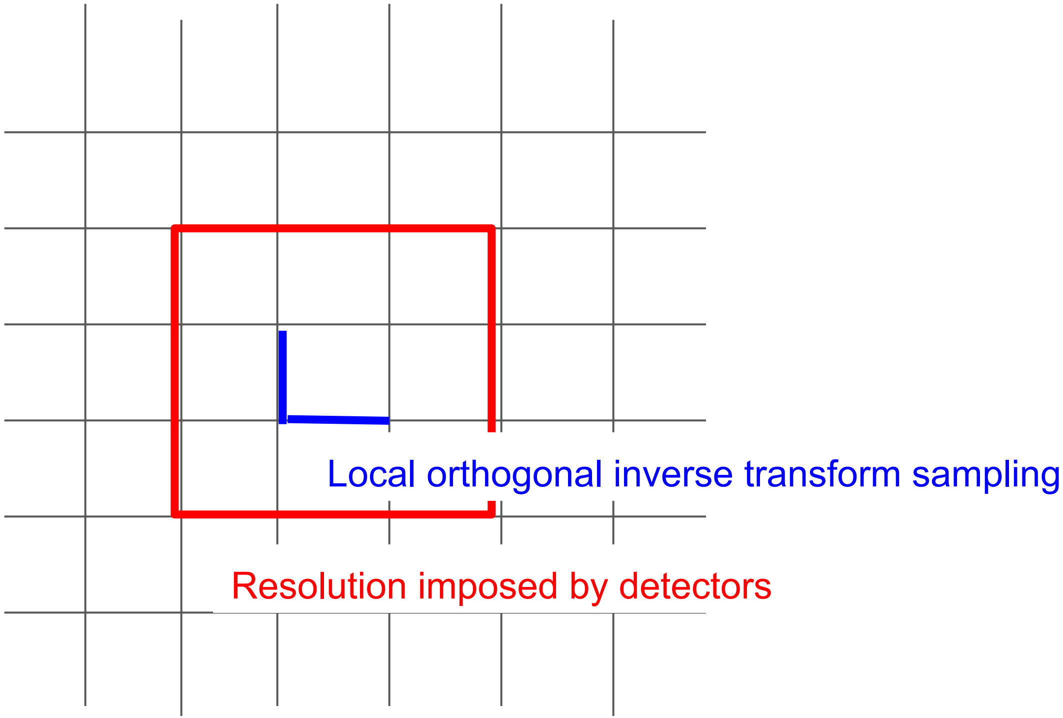
$$\frac{d\sigma}{dx\,dQ^2}(x, Q^2|\theta) \Rightarrow \nabla_\theta \frac{d\sigma}{dx\,dQ^2}(x, Q^2|\theta)$$

Autodiff means compute this exactly

The challenge

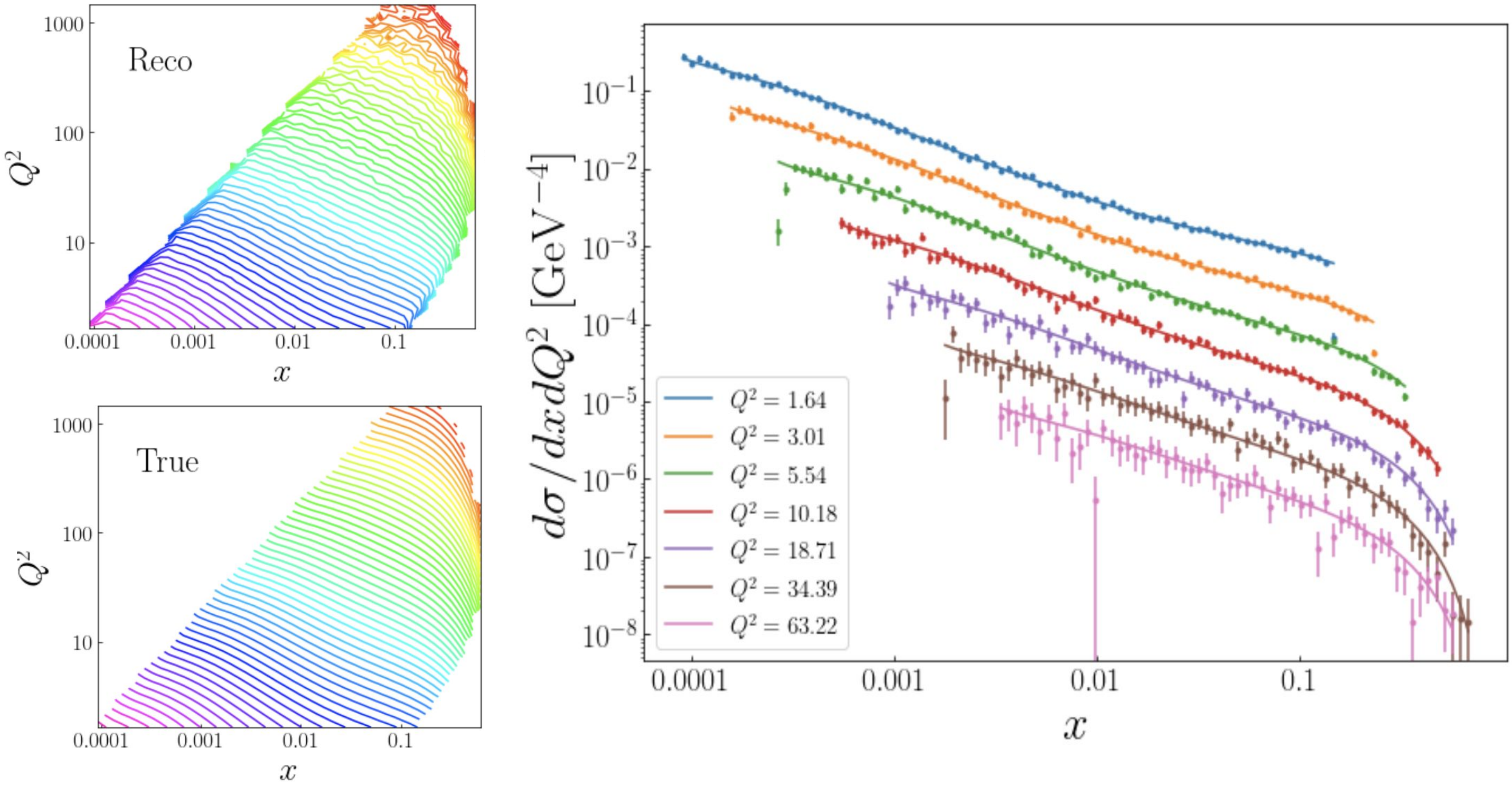
$$(x, Q^2) \sim \frac{d\sigma}{dx\,dQ^2}(x, Q^2|\theta) \overset{?}{\Rightarrow} (\nabla_\theta x, \nabla_\theta Q^2)$$

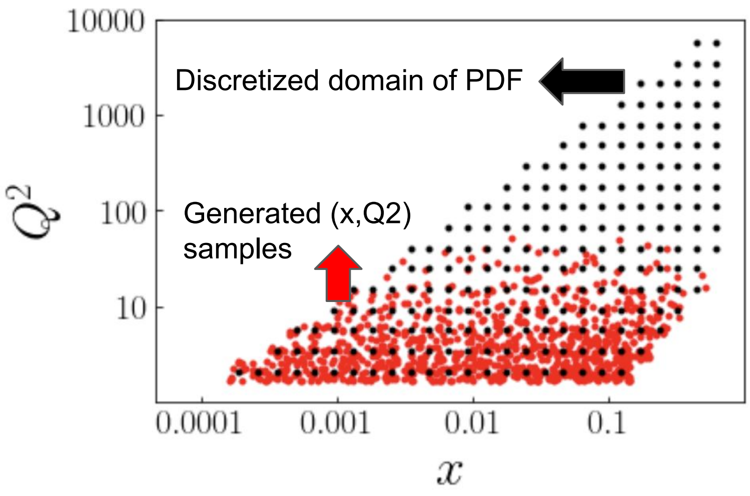
Basic idea -> (LOITS)



Discretize domain of the cross sections

- In real life, experimental detectors has finite resolution
- Within the blue box we can sample each dimension independently, since correlations within the red box are not important
- For problems with low dimensionality, apply local orthogonal inverse CDF sampling (blue box).
- Number of samples on each region are set by the integral of the cross sections over the n-dim bin


Reco
True
Q^2
x
0.0001
0.001
0.01
0.1
10
100
1000
$d\sigma/dxdQ^2$ [GeV^{-4}]
$Q^2 = 1.64$
$Q^2 = 3.01$
$Q^2 = 5.54$
$Q^2 = 10.18$
$Q^2 = 18.71$
$Q^2 = 34.39$
$Q^2 = 63.22$
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}




```
nx=30; nQ2=20
mceg=MCEG(rs=140,tar='p',W2min=10,nx=nx,nQ2=nQ2)
evts=mceg.gen_events(100,verb=False)
test=torch.sum(evts)
test.backward()
print(mceg.idis.pdf.par_u.grad)
print(mceg.idis.pdf.par_d.grad)
```

$\boldsymbol{\theta}$

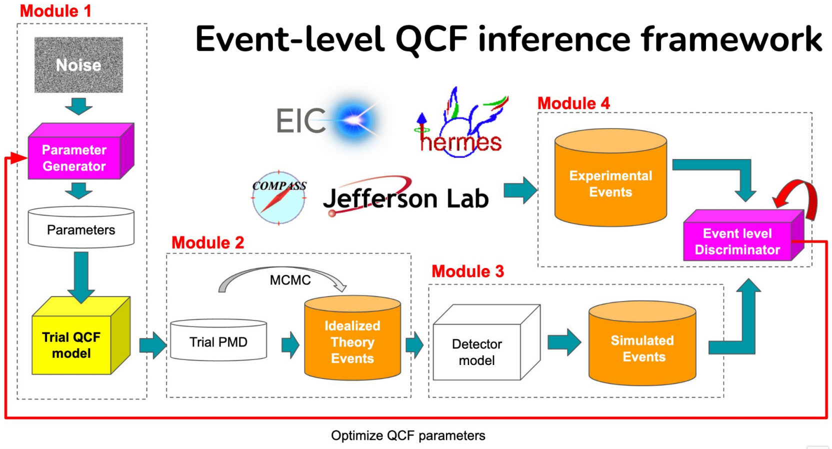
```
100%|██████████| 551/551 [00:00<00:00, 29313.31it/s]
100%|██████████| 551/551 [00:00<00:00, 72697.75it/s]
100%|██████████| 551/551 [00:00<00:00, 6211.91it/s]
100%|██████████| 551/551 [00:00<00:00, 29782.49it/s]
100%|██████████| 551/551 [00:00<00:00, 73949.24it/s]
100%|██████████| 551/551 [00:00<00:00, 6209.34it/s]
<ipython-input-9-e192b5f0ec6e>:155: UserWarning: To copy construct from a
use sourceTensor.clone().detach() or sourceTensor.clone().detach().requir
orch.tensor(sourceTensor).
  n=torch.tensor(self.weights*N,dtype=int)
100%|██████████| 551/551 [00:00<00:00, 10528.08it/s]
tensor([-4.9285e+00,  4.4495e+00,  9.0302e+00,  5.5294e-01, -4.9363e+00,
        -7.3421e+00,  9.5754e-04, -5.7717e-02, -9.8959e-02,  5.9418e-03,
         2.2897e-02,  3.4158e-02,  6.6659e-04,  2.1068e-03,  3.2545e-03,
         9.9635e-05,  2.7180e-04,  4.2440e-04])
tensor([-1.9141e+00,  4.5396e-01,  1.5571e+00, -5.3361e-01, -1.3639e+00,
        -1.7020e+00, -3.8108e-03, -1.1582e-02, -1.7321e-02,  2.9140e-03,
         5.7380e-03,  7.7209e-03,  2.3161e-04,  4.7768e-04,  6.8488e-04,
         2.6972e-05,  5.7034e-05,  8.4781e-05])
```

$$\nabla_{\theta} x(u, \boldsymbol{\theta}) \neq 0$$

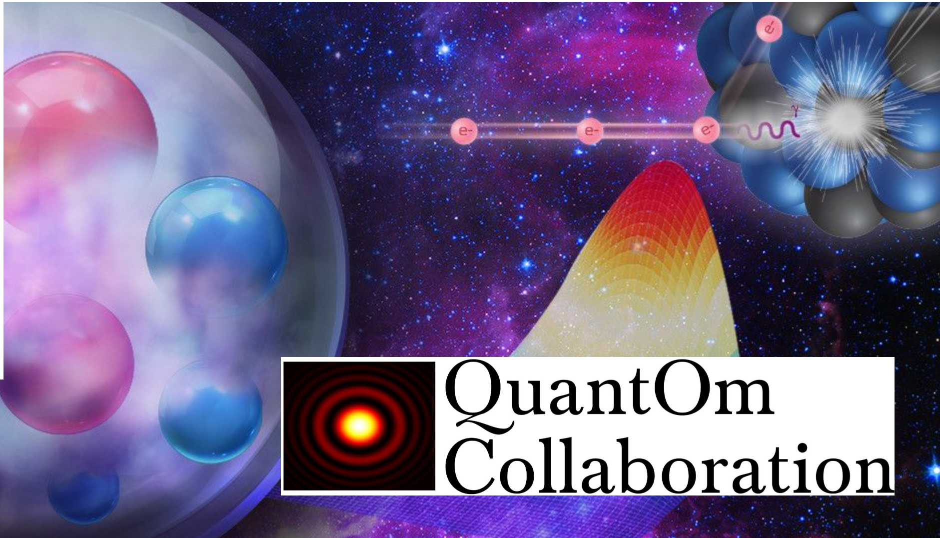
$$\nabla_{\theta} Q^2(u, \boldsymbol{\theta}) \neq 0$$

Success!

Summary



- The story of gluon polarization is still evolving
- New era of global analysis of hadron structure *unified theory & experiment* analysis
- AI/ML provides new tools/tricks to map QCFs from events and boost the discovery potential of current and future experimental facilities
- Parton physics is now @ SciDAC



$$\mathcal{L}_{QCD} = \sum_q \bar{\psi}_q (i\gamma_\mu D^\mu - m_q)\psi_q - \frac{1}{2}\mathrm{Tr}[G_{\mu\nu}G^{\mu\nu}]$$

QuantOm Collaboration