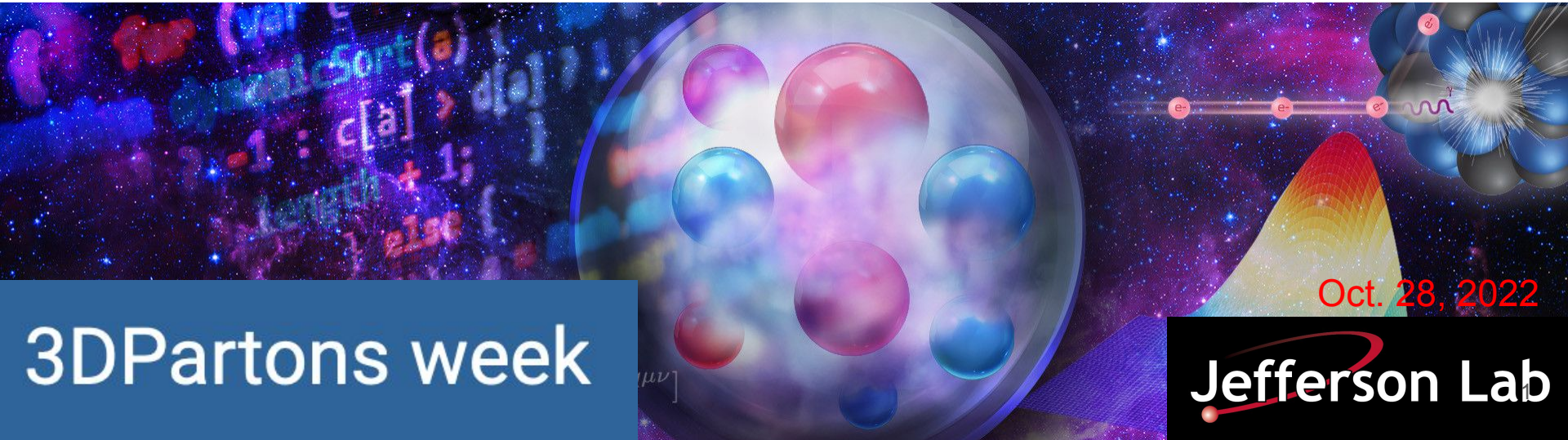
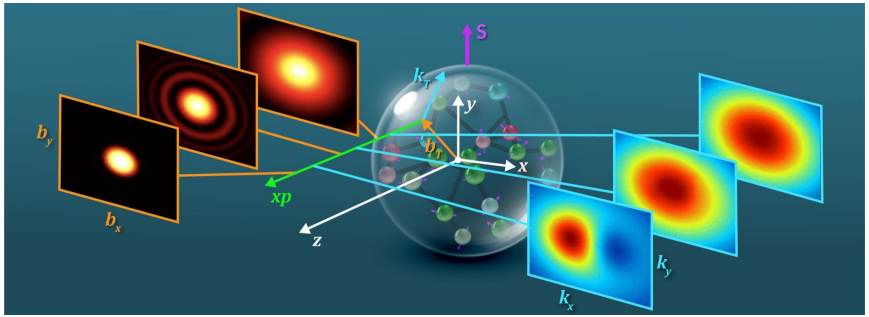
Updates from JAM collaboration

Nobuo Sato



Motivations

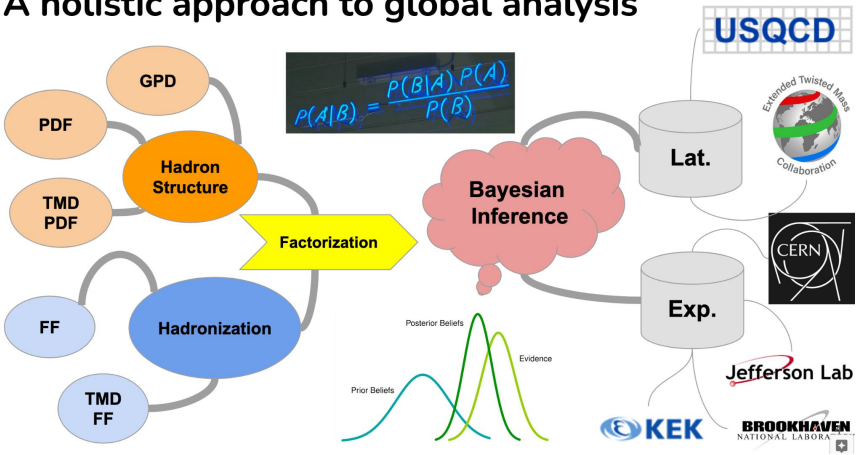


- **WHAT?: Synthesis of 3D tomography/nuclear imaging** - quantum correlation functions (QCFs)
  - hadron structure (PDFs, TMDs, GPDs, ...)
  - hadronization (FFs, TMDFFs)

- **HOW?: Data (EXP), Factorization (THY/LQCD), Inference (CS)**
  - test of universality & theory predictive power
  - significant computing and data analysis
  - systematic improvements (resummation, evolution, HO calculations)
  - synergy with lattice QCD (Bayesian priors)

- **WHY?: Opportunities**
  - origin of proton spin
  - quark and gluon tomography
  - structure of proton sea (strangeness, antimatter asymmetry)
  - origin of nuclear EMC effect
  - small-*x* phenomena
  - precision EW physics (Weinberg angle)
  - …

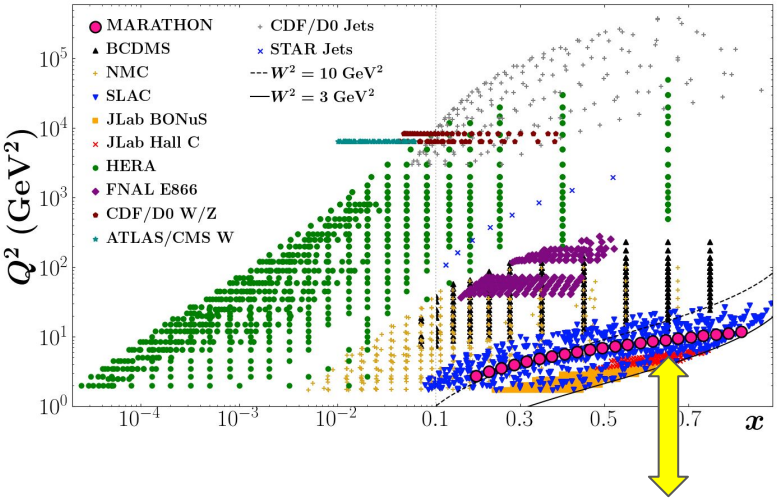
A holistic approach to global analysis

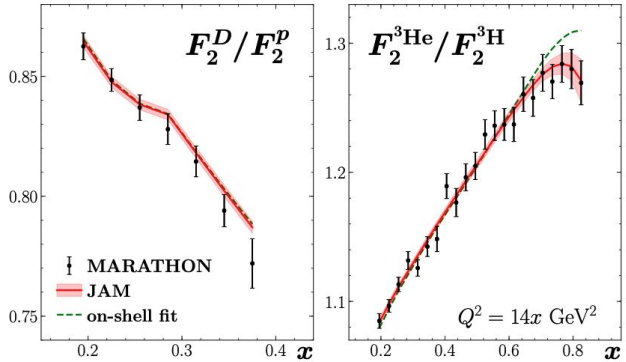


Outline

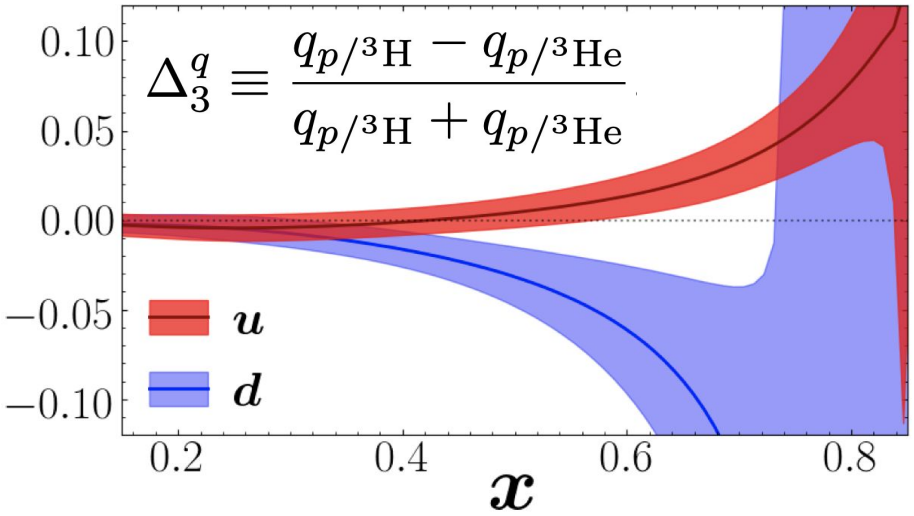
1. Recent JAM results
2. A word on QED effects in eP
3. Opportunities at JLab 20+
4. Integrated THY/EXP analysis

Isovector EMC effects from MARATHON data



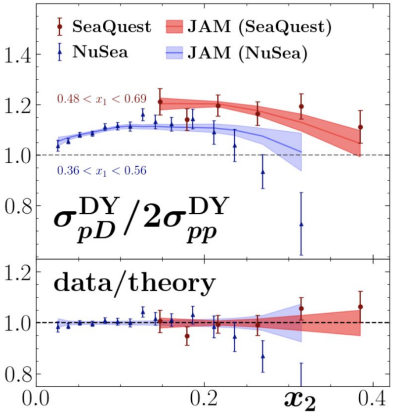


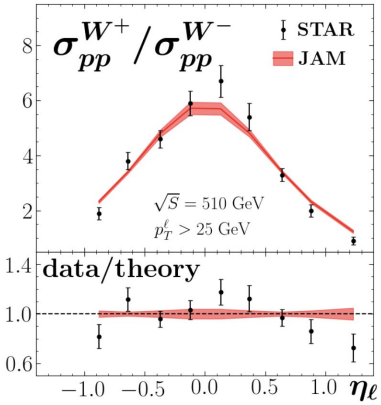
Cocuzza, Melnitchouk, Metz, Sato (PRL)

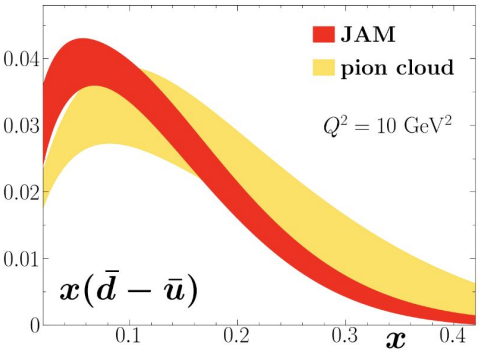


- Global analysis including latest collider *W*/*Z* data and MARATHON *d*/*p*, helium, tritium DIS data
- *Evidence of different medium modifications for u and d quarks*
- *Naive modeling of nuclear PDFs, e.g. u/p/A = d/n/A (violates isospin for non-isoscalar A) is wrong*

Antimatter asymmetry

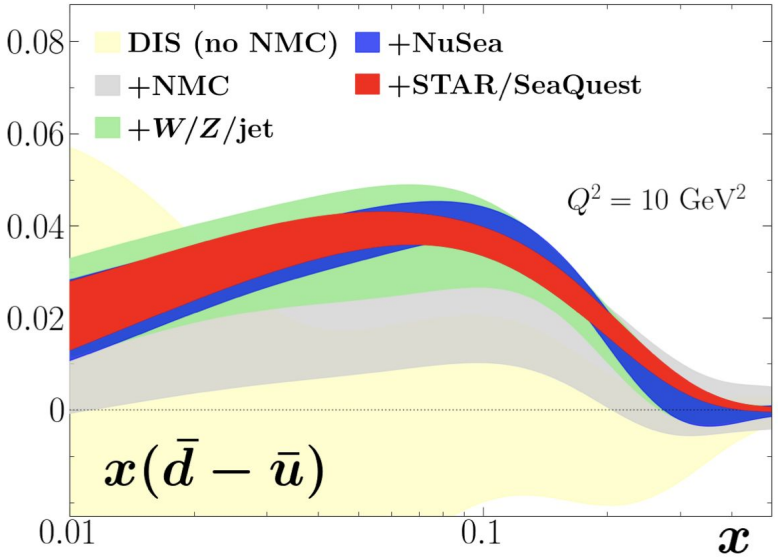






$$(\bar{d} - \bar{u})(x) = \left[\left(f_{n\pi^+} + f_{\Delta^0\pi^+} - f_{\Delta^{++}\pi^-}\right) \otimes \bar{q}_v^{\pi}\right](x),$$

Cocuzza, Melnitchouk, Metz, Sato (PRD)

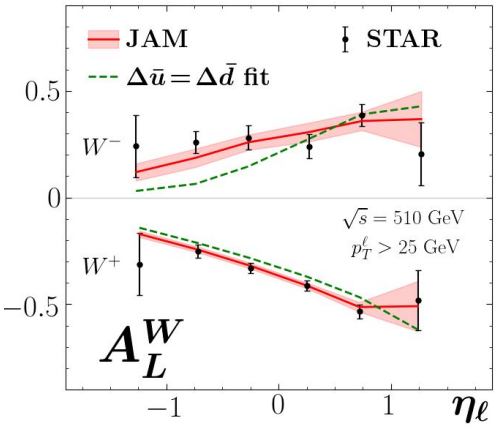


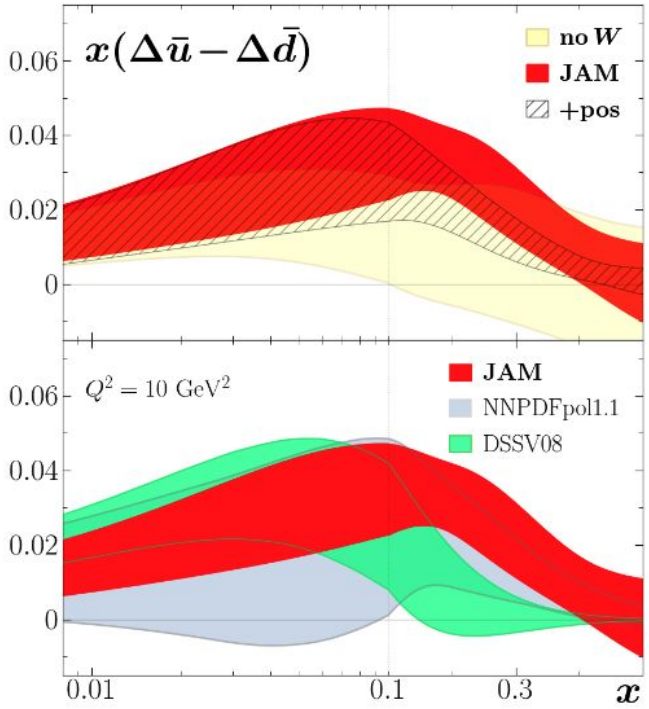
- First global analysis to include latest SeaQuest and STAR data
- Most precise phenomenological extraction of *dbar-ubar* asymmetry to date
- Quantitative test of the pion-cloud model

Polarized antimatter asymmetry

Cocuzza, Melnitchouk, Metz, Sato (PRD)

process	$N_{\rm dat}$	$\chi^2/N_{\rm dat}$
polarized		
inclusive DIS	365	0.93
inclusive jets	83	0.81
SIDIS (π^+,π^-)	64	0.93
SIDIS (K^+,K^-)	57	0.36
STAR $W^\pm$	12	0.53
PHENIX $W^\pm/Z$	6	0.63
total	**587**	**0.85**
unpolarized		
inclusive DIS	3908	1.11
inclusive jets	198	1.11
Drell-Yan	205	1.19
W/Z production	153	0.99
total	**4464**	**1.11**
SIA $(\pi^\pm)$	231	0.85
SIA $(K^\pm)$	213	0.49
total	**5495**	**1.05**





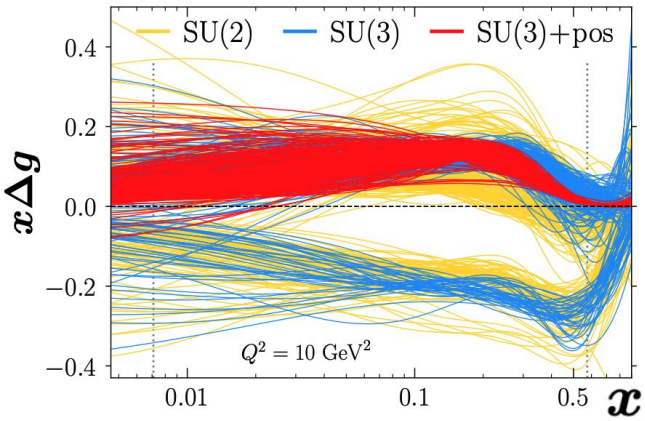
- First simultaneous extraction of unpolarized and helicity PDFs and FFs in global analysis with inclusion of RHIC spin *W*+/- data
- Most precise phenomenological extraction of polarized *dbar-ubar* asymmetry to date

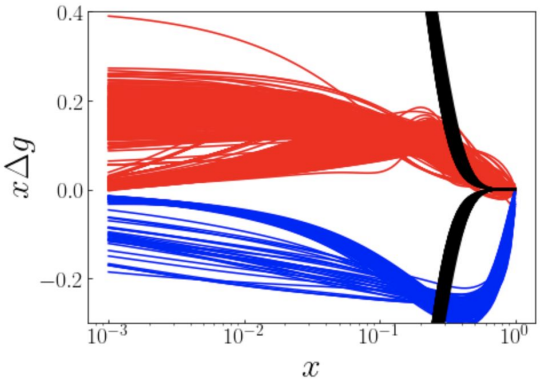
News on Gluon helicity

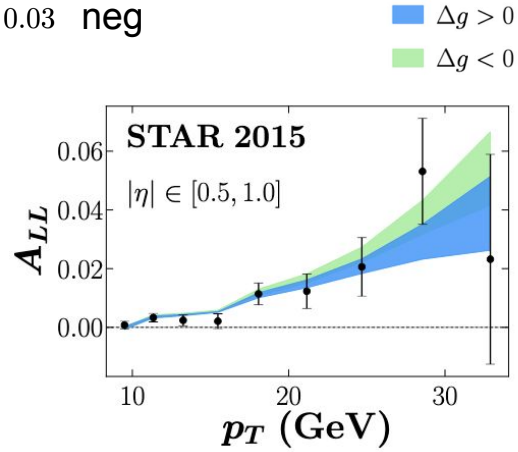
Negative gluon polarization?

$$\int_{0.05}^{1} dx \Delta g(x) = \begin{matrix} 0.23 \pm 0.03 & \text{pos} \\ -0.62 \pm 0.03 & \text{neg} \end{matrix}$$

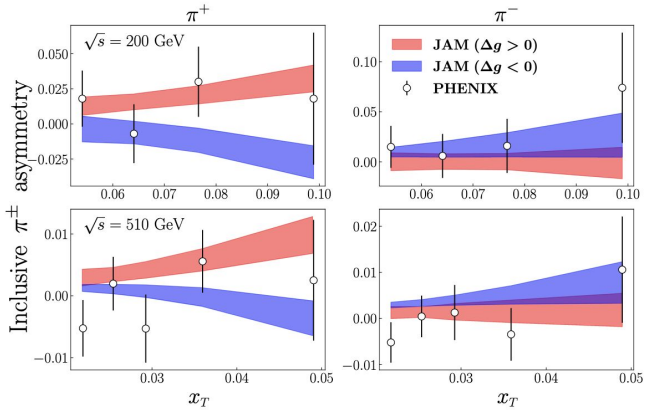
Zhou, Melnitchouk, Sato (PRD)



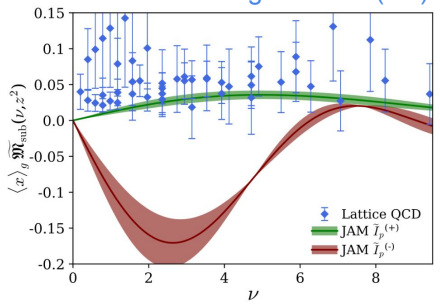




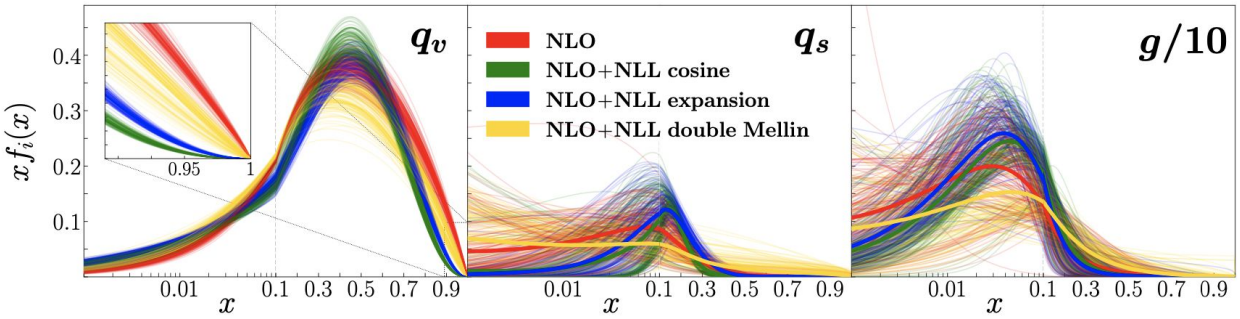
- Inclusion of RHIC polarized jet data allows both positive and negative gluon helicity solutions (in absence of positivity constraints on unpolarized gluon PDF)
- PHENIX has attempted to have empirical confirmation of gluon helicity sign (PRD102.032001, PRD91.032001)



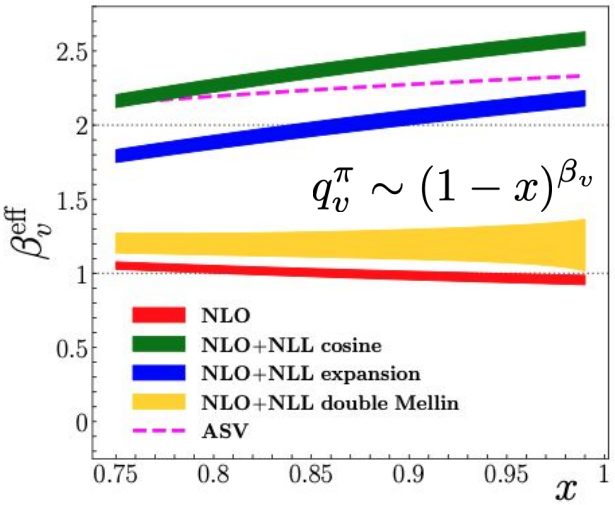
Egerer et al ('22)



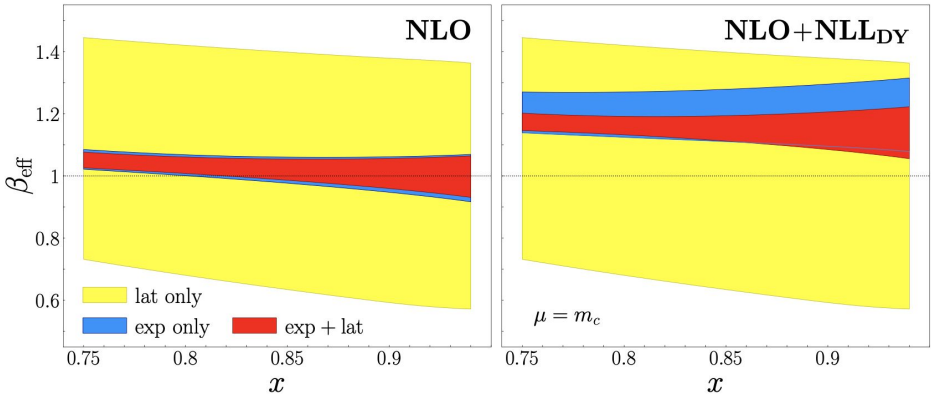
Pion structure



Barry, Ji, Melnitchouk, Sato (PRL)



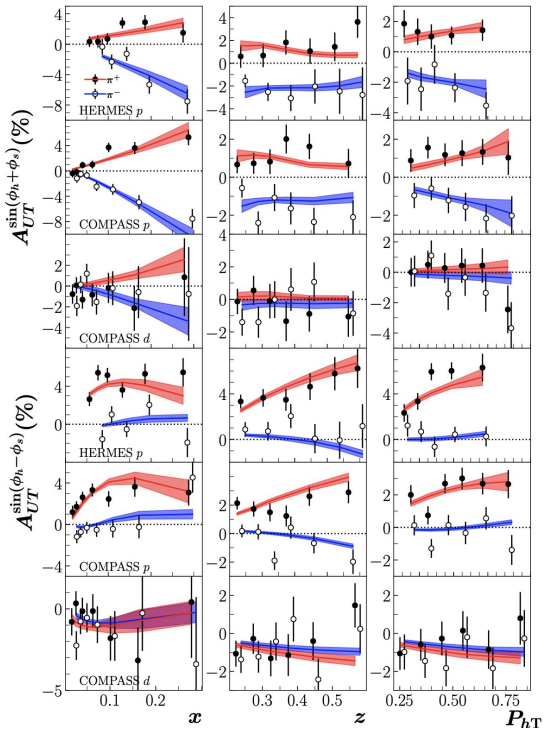
Barry, et al (PRD) - JAM & HadStruct

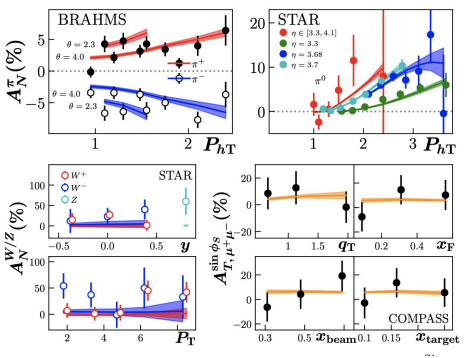


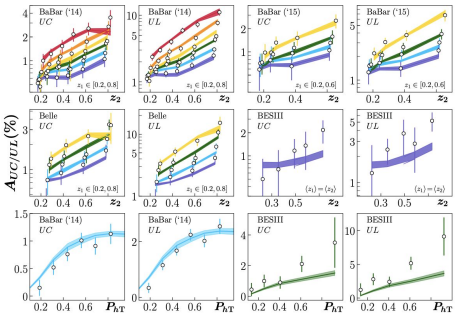
- Improved pQCD framework indicates large *x* pion pdf is closer to 1 despite QCD model calculations
- Results are also stable after the inclusion LQCD Ioffe time distributions

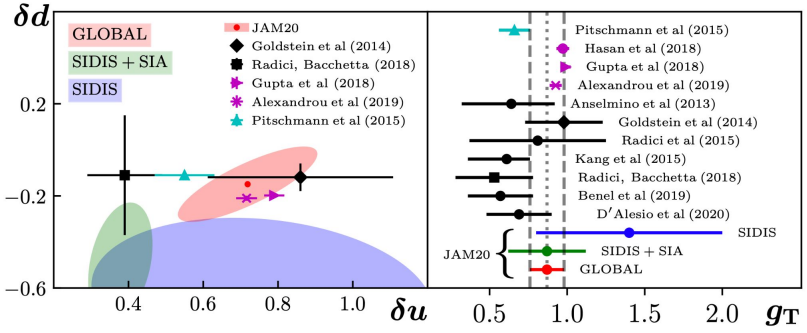
Global analysis of SSAs (TMD+CT3 framework)

Cammarota, et al (PRD)





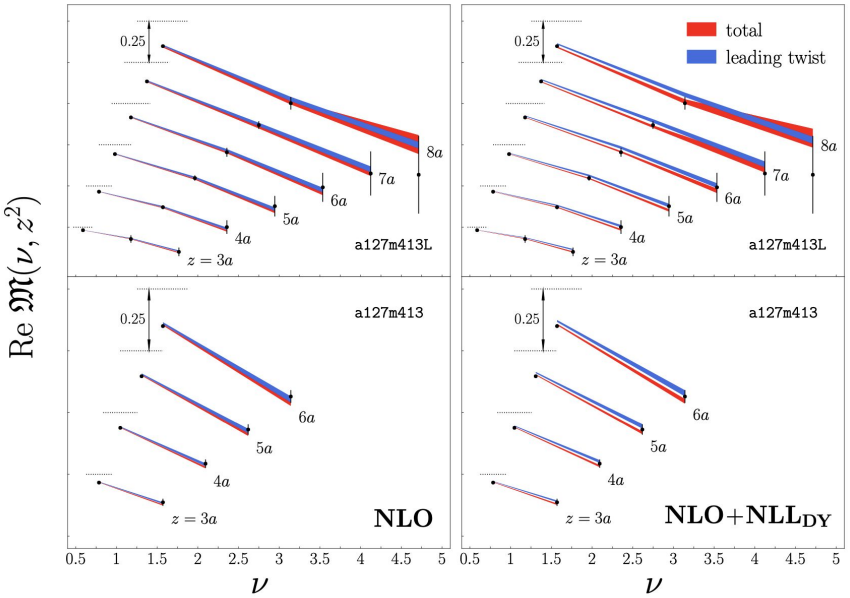


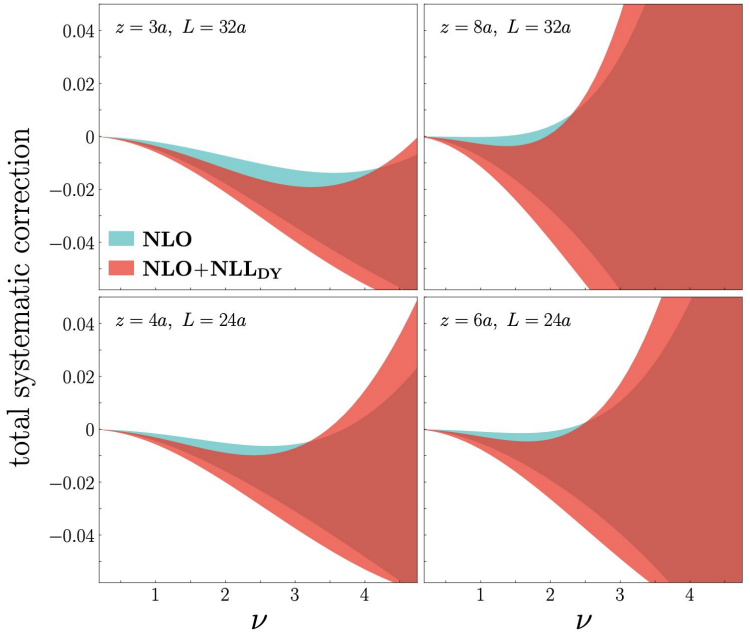


- Exploratory study for a global analysis of all single-spin asymmetries from *ep*, *e+e-* add *pp* reactions using the parton model TMD with collinear twist-3 framework.
- Extracted flavor-dependent transversity in good agreement with LQCD for the first time.

Synergies with LQCD - *pion structure*

Barry et al. (‘22)
JAM+HadStruct

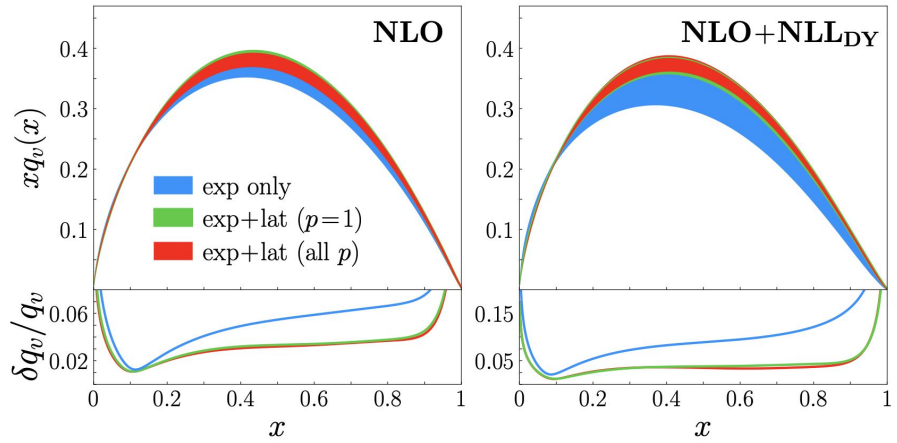


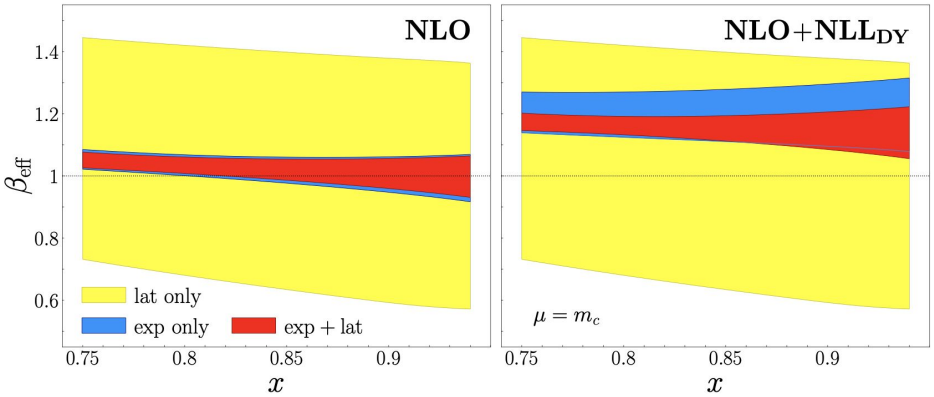


$$\mathrm{Re}\,\mathfrak{M}(\nu, z^2) = \int_0^1 \mathrm{d}x\; q_v(x, \mu_{\mathrm{lat}})\, \mathcal{C}^{\text{Rp-ITD}}\left(x\nu, z^2, \mu_{\mathrm{lat}}\right) + \boxed{z^2 B_1(\nu) + \frac{a}{|z|} P_1(\nu) + e^{-m_\pi (L-z)} F_1(\nu)}\,.$$

Experimental data can provide insights into LQCD systematics

Synergies with LQCD - *pion structure*



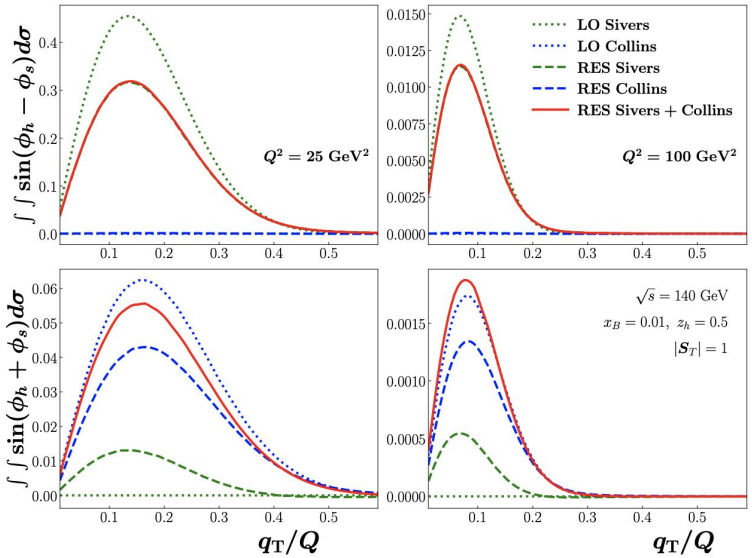


- LQCD can aid hadron structure studies in cases where constraints from experiments are limited - *“lattice priors”*
- Theory Center has expertise from JAM & HadStruc and has started collaborative research work

Outline

1. Recent JAM results
2. A word on QED effects in eP
3. Opportunities at JLab 20+
4. Integrated THY/EXP analysis

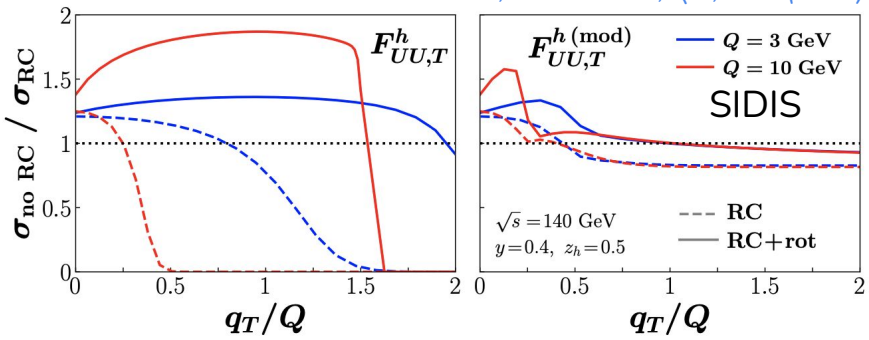
QED effects in eP reactions

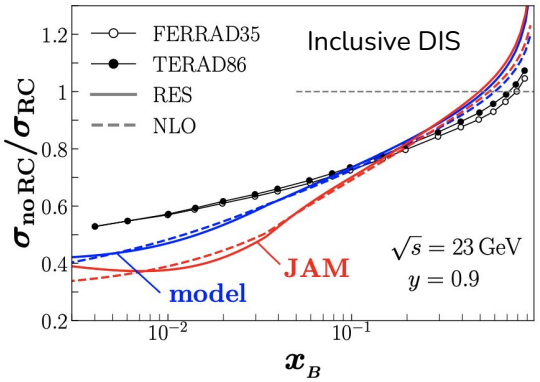


- Hybrid QED+QCD framework to study SSAs in SIDIS within global analysis
- *Crucial to control QED backgrounds in transverse spin asymmetries*

Towards a global analysis includes QED effects

Liu, Melnitchouk, Qiu, Sato (JHEP)





- Non-uniqueness of QED RC corrections
- Need for a combined analysis including QED and QCD effects

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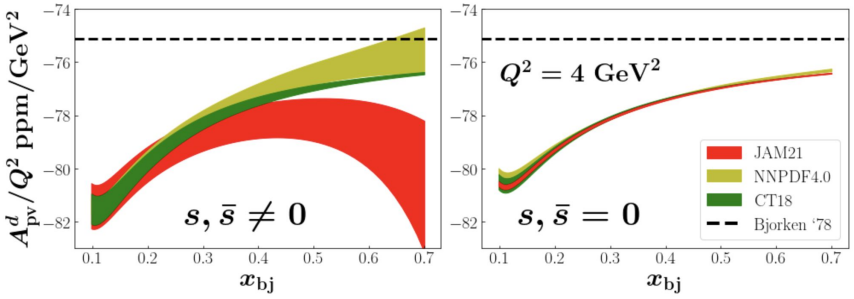
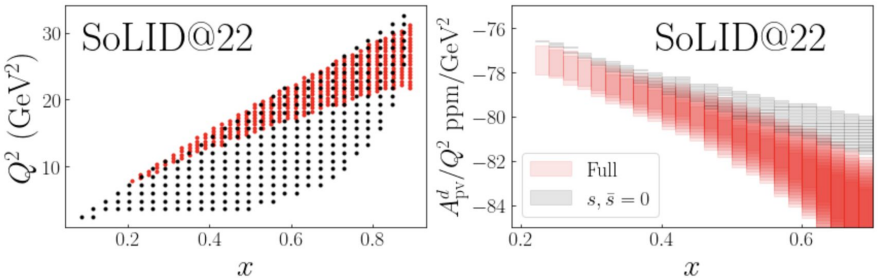
Strangeness & Apv deuteron

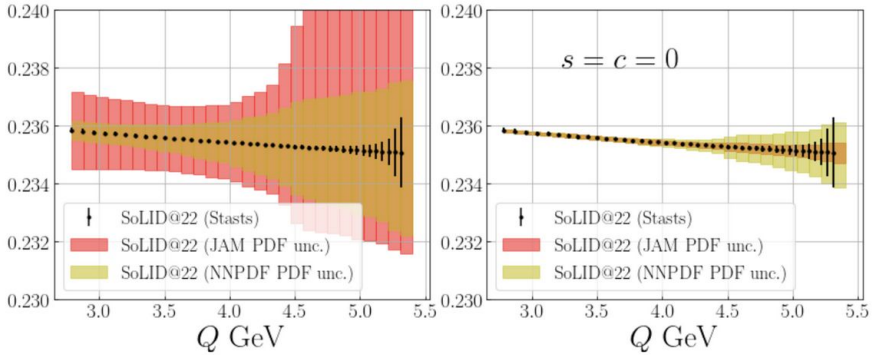
Bjorken `78

$$\frac{A^{eD}}{Q^2}\Big|_{y=0} = -\frac{3G}{10\pi\alpha\sqrt{2}}\left[2\epsilon_{AV}(e,u)\left(1+\tfrac{3}{10}\,\delta\right) - \epsilon_{AV}(e,d)\left(1-\tfrac{6}{5}\,\delta\right)\right].$$

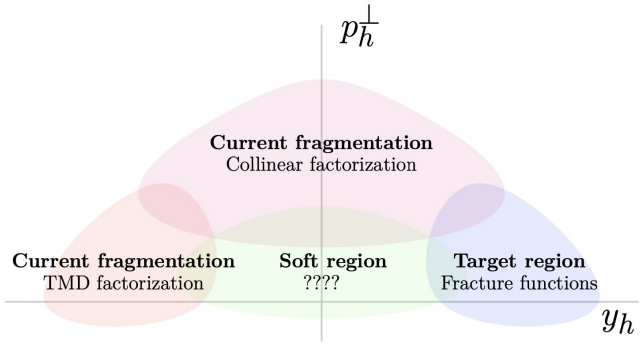


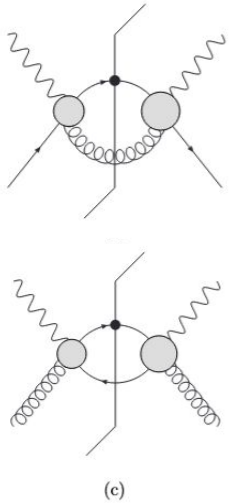


- Apv(deuteron) has the opportunity to access directly Weinberg angle
- However, limited knowledge of strange quark PDF induces larger uncertainties for sin^2θw from Apv D
- **Opportunity:** SIDIS (JLab/EIC), LQCD, … to enhance the discovery potential of the Apv program

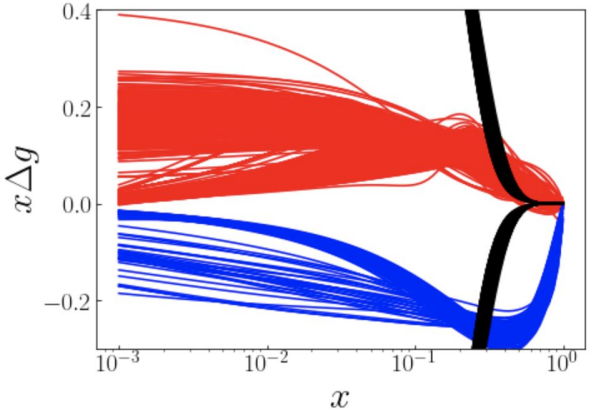


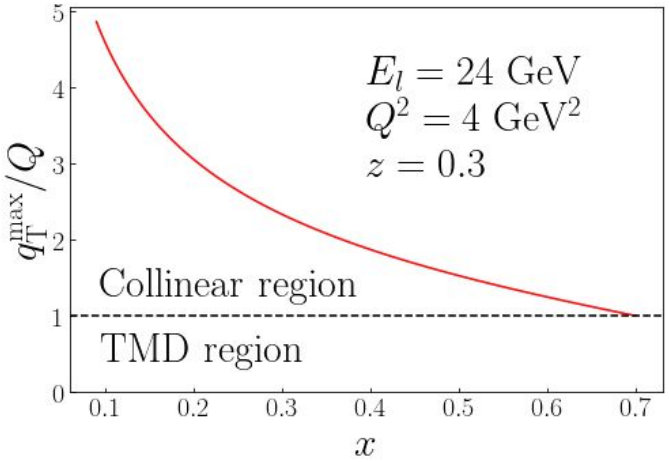
Gluon helicity & High pT SIDIS



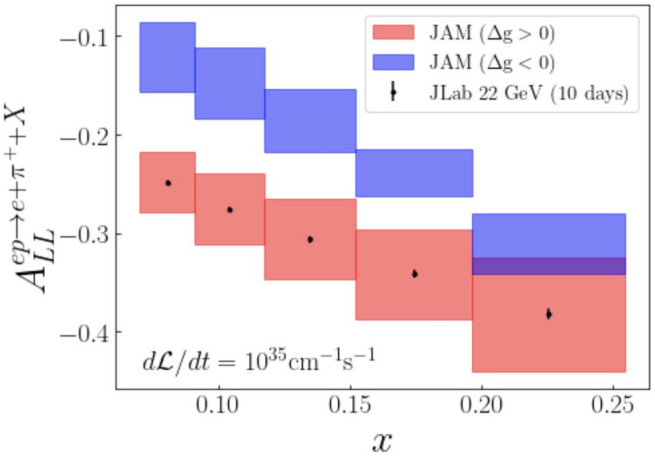


Whitehill, Zhou, Melnitchouk, NS '22





- Hadron production with large transverse momentum has an opportunity to discriminate the sign of gluon polarization
- Future experiments @ JLab 22 and EIC, has phase space to apply collinear factorization



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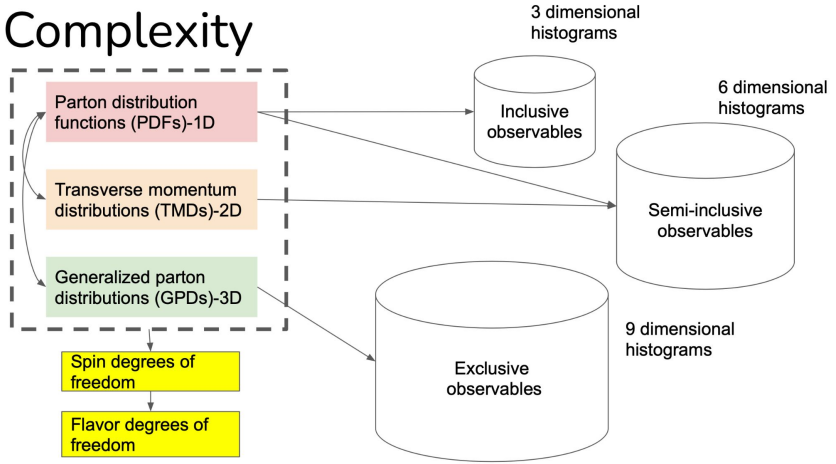
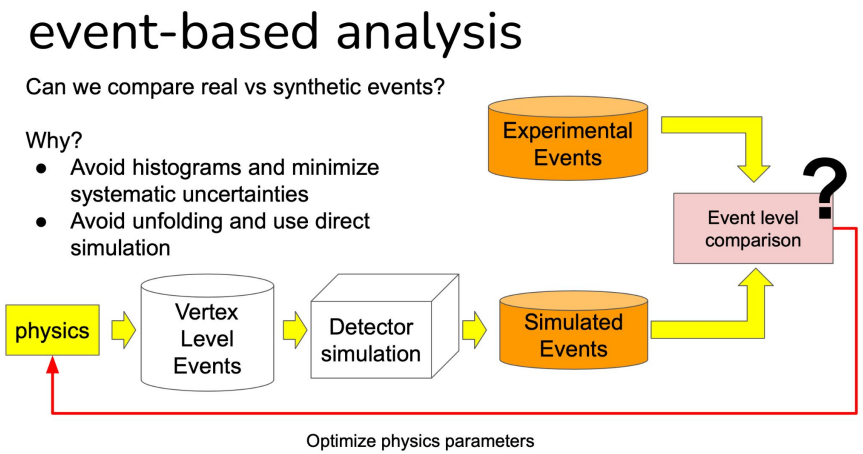
Integrated theory & experimental analysis





QuantOm Collaboration

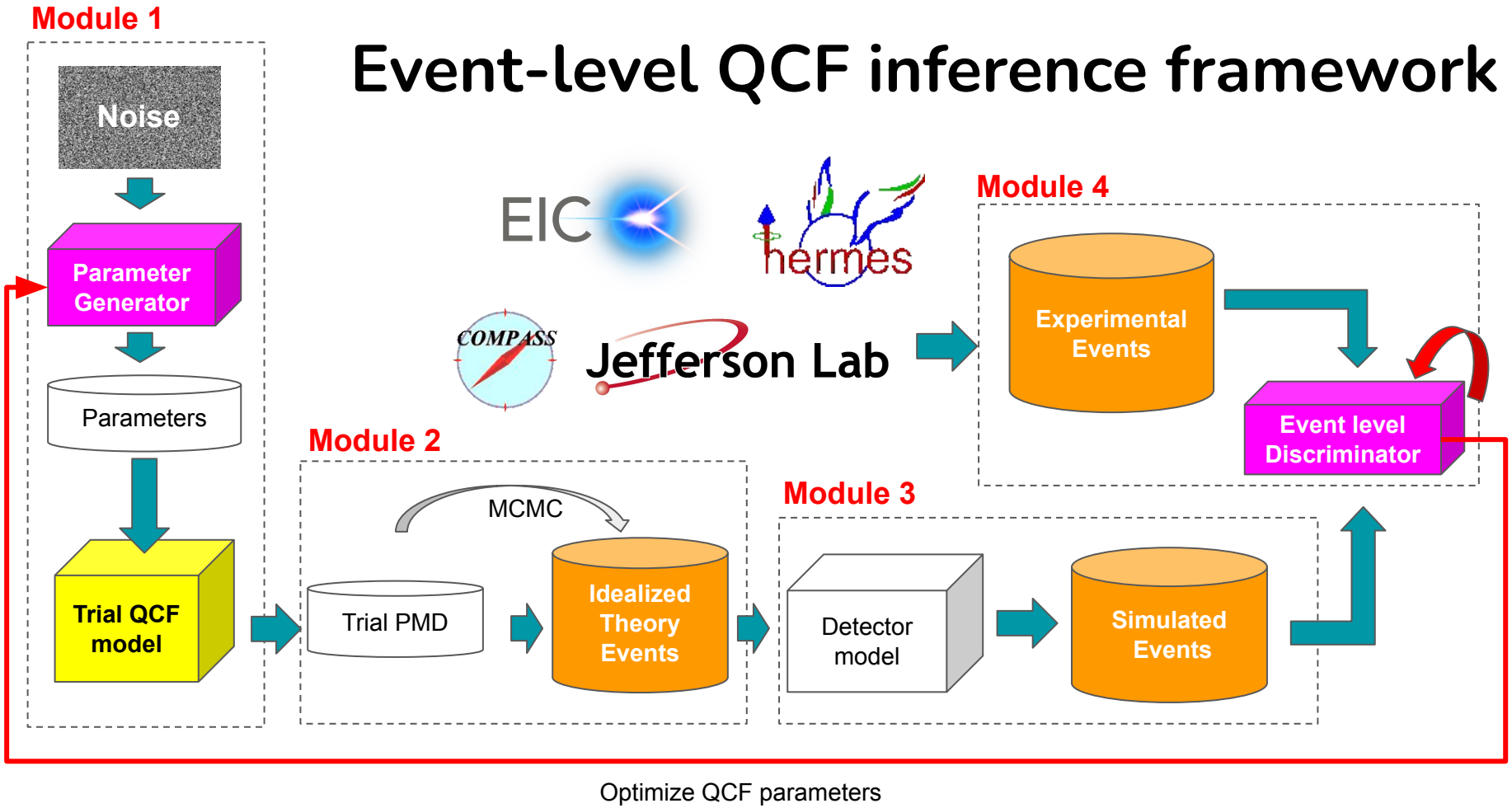
Argonne NATIONAL LABORATORY

Jefferson Lab

VT

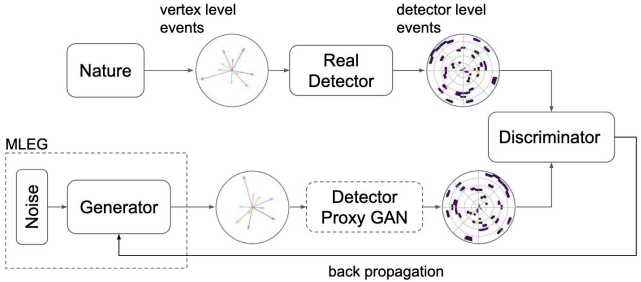
- New collaboration between domain and off-domain scientists towards and end-to-end event-level analysis framework
- Supported by SciDAC

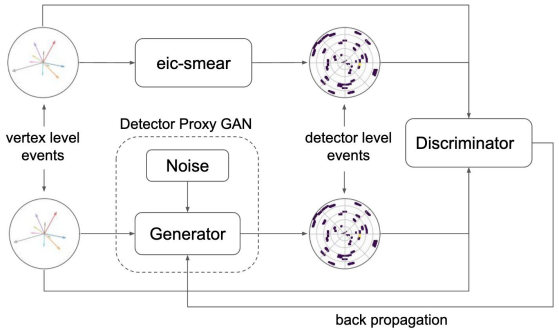
Event-level QCF inference framework

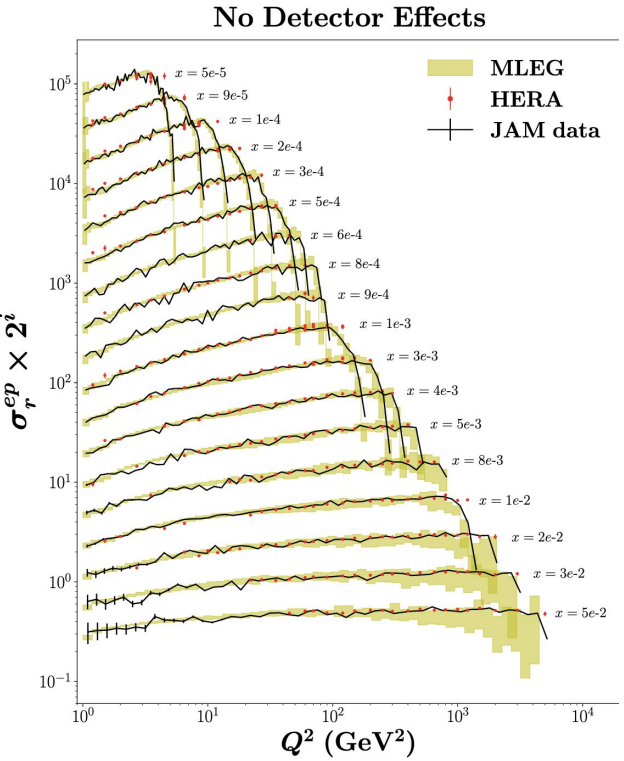


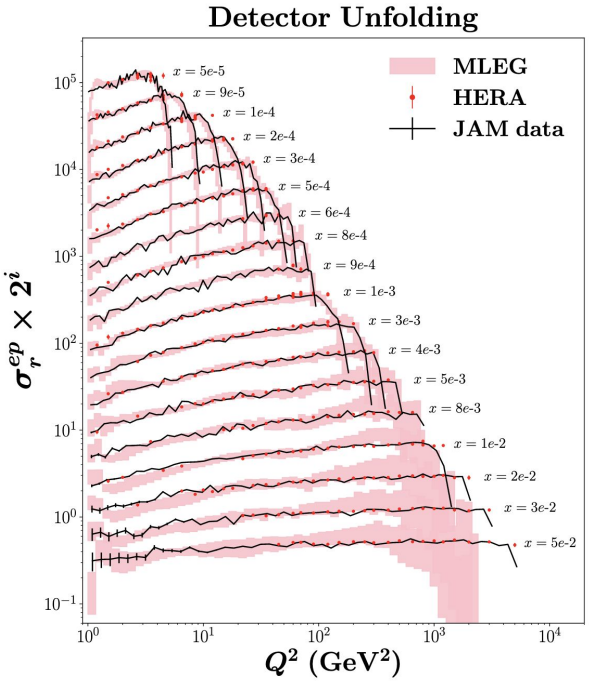
Preliminary work

Alasani, et al. '22









Summary/Outlook

New era of global analysis of hadron structure –> new tools, new tricks (theory + experiment + data analysis)

Simultaneous extraction paradigm is important for proper UQ

JAM collaboration

Staff / Faculty

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