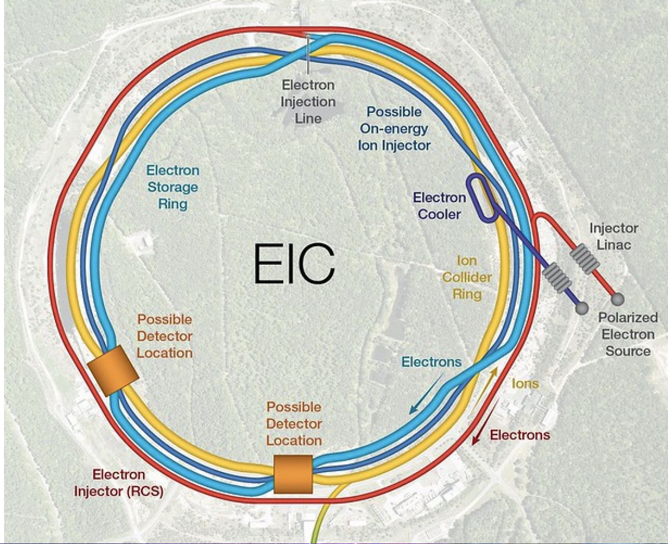
Global analysis and hadron structure

Nobuo Sato



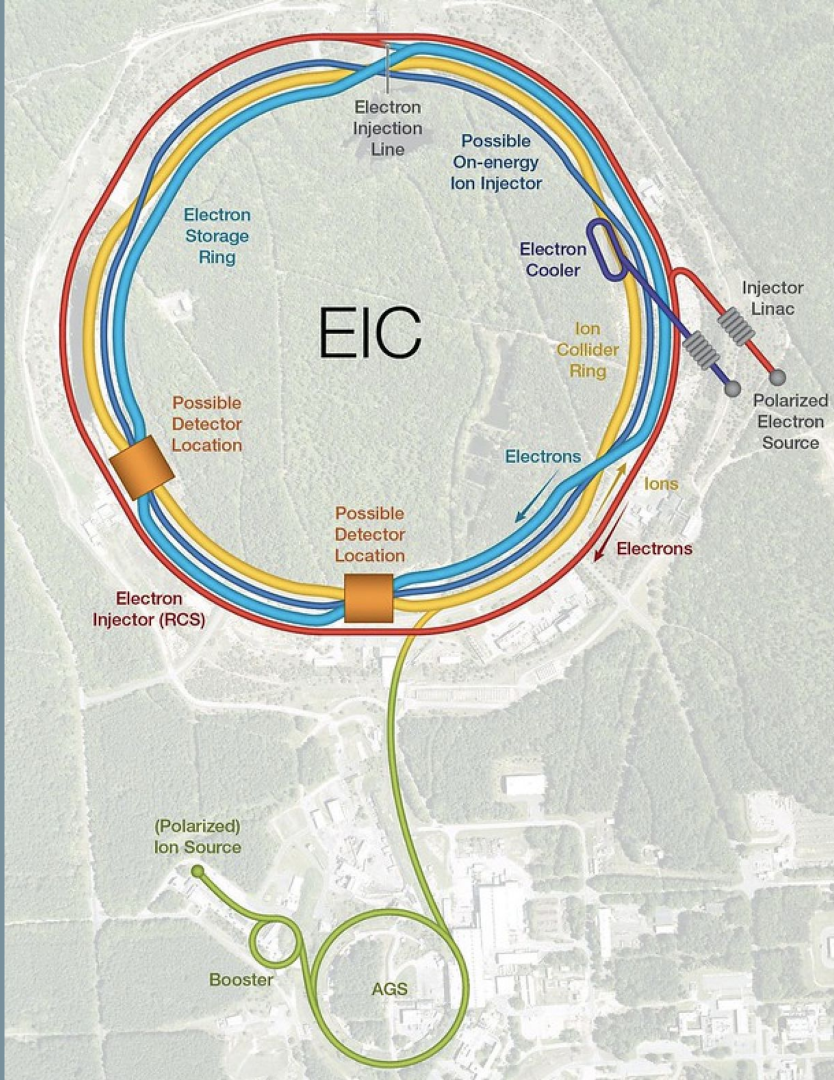
Sep. 20, 2022

Workshop: Theory for EIC in the next decade

Jefferson Lab

Outline

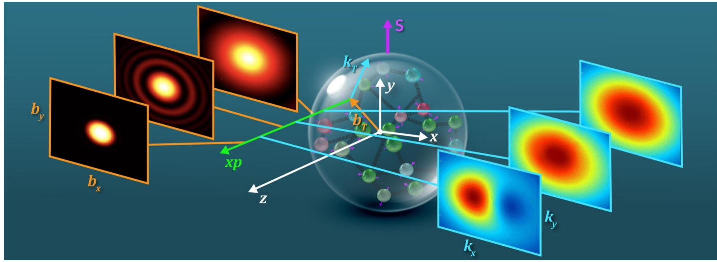
1. Motivations & challenges
2. Lessons from the YR
3. Post YR studies
4. Synergies with LQCD
5. Integrated THY/EXP analysis
6. Summary



Motivations

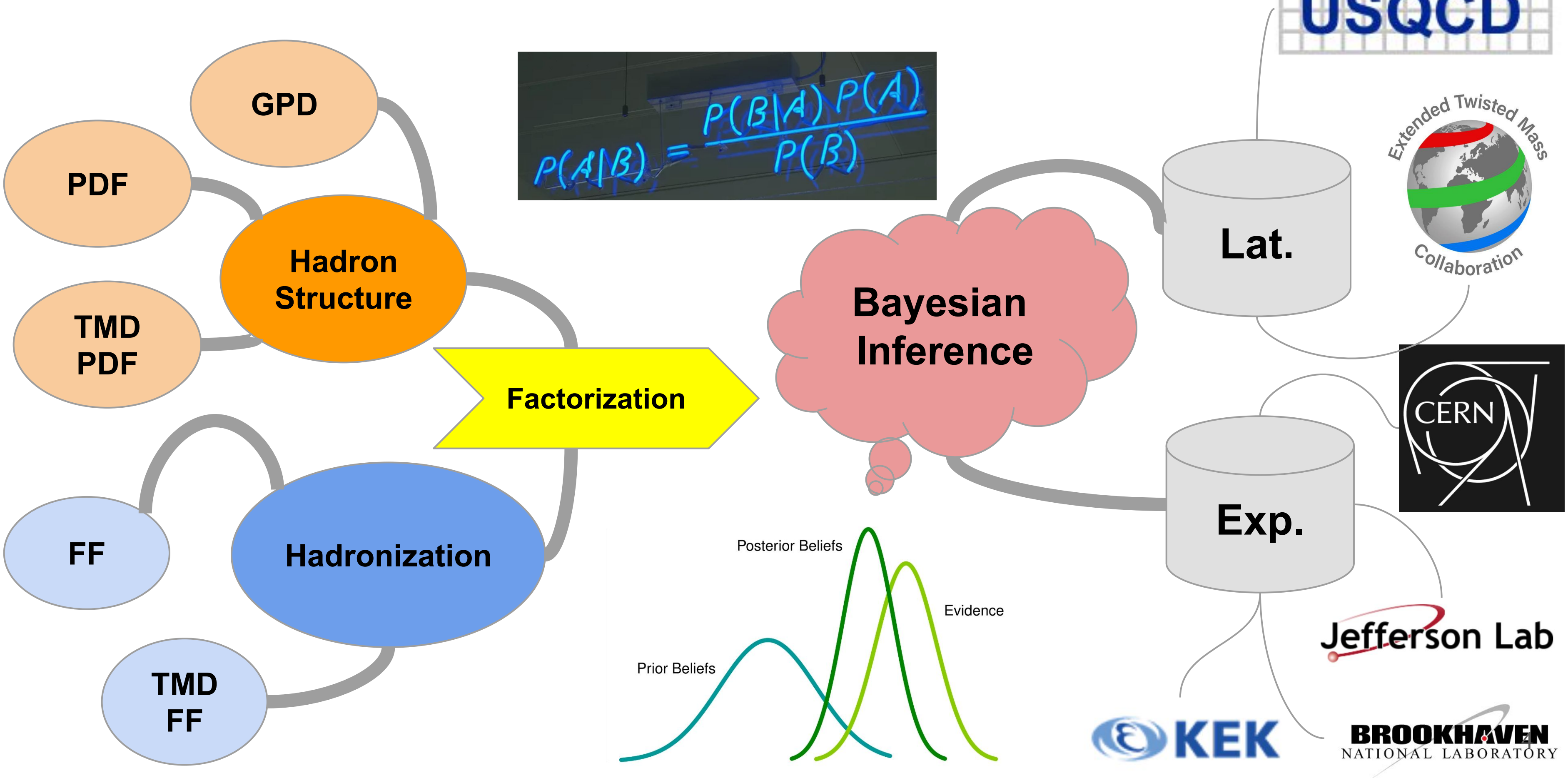
- **Synthesis of 3D tomography/nuclear imaging**: quantum correlation functions (QCFs)
  - hadron structure (PDFs, TMDs, GPDs, HT, ...)
  - hadronization (FFs, TMDFFs)

- **Test of universality & theory predictive power**
  - systematic improvements (resummation, evolution, HO calculations)
  - synergy with lattice calculations (Bayesian priors)
  - identification of regions of phase space where existing theory framework is applicable (phenomenology)



- **Opportunities**
  - origin of proton spin
  - quark and gluon tomography
  - structure of proton sea (strangeness / antimatter asymmetry)
  - origin of nuclear EMC effect
  - precision EW physics (Weinberg angle)
  - …

A holistic approach to global analysis



Challenges: *data and theory*

- **Inverse/deconvolution problem**
  - factorization theorems do not allow solutions of QCFs in closed form
  - QCFs cannot be measured, only inferred from data
  - need to use parametric models for QCFs, and tune to match data
  - *ad hoc* priors are often needed (positivity, vanishing of PDFs, …)

- **Incomplete experimental information**
  - need for complementarity between experimental programs (JLab, EIC, RHIC, ...)
  - integration of lattice QCD calculations –> theory priors
  - precision of data (statistical & systematic)

- **Limitations of theory framework**
  - limited efforts in understanding QED effects in *ep* (DIS, SIDIS, …)
  - issues with multi-scale observables (TMDs in SIDIS)
  - …

Challenges: *methodology*

- **Underdeveloped Bayesian inference for QCFs**
  - field is moving towards MC approach (away from Maximum likelihood-based analyses) – *good!*
  - current MC approaches are based on data resampling instead of full MCMC
  - *ad hoc* choices for priors (positivity, specific parametrizations, ...)
  - *ad hoc* choices for likelihood (mostly Gaussian)

- **Numerical tools for 3D tomography**
  - numerical libraries for phenomenology still missing – codes not centralized
    — need to incentivise the community to build such libraries
  - visualization tools for 3D imaging

- **Theory input for experiments**
  - event generators for 3D tomography (needed for simulations) still in their infancy
  - issues with unfolding for detector effects (ill-defined problem)
    — how to remove detector effects, as well as QED effects?

Challenges: *impact studies*

- **Importance**
  - all physics analyses should undergo a series of feasibility studies
  - physics analysis should have significant involvement of both theorists and experimentalists
  - forecasting impact of future measurements is, by its nature, an evolving and improvable task
  - primarily a data analysis task, and suitable for partnerships with off-domain scientists (CS, applied math, statistics, …)

- **Issues**
  - there is no dedicated/established collaborative WG between experimentalists and theorists to continuously improve forecasting of future analyses — lack of incentives (especially for theorists) to work with pseudo data.
  - Yellow Report exercise was a good starting point, but many things remain to be done
  - typical time frame for such an exercise is very short ("we did what we could do")
  - no uniform agreement to consolidate impact studies with standardized metrics (e.g., exclusion plots in BSM physics, …)

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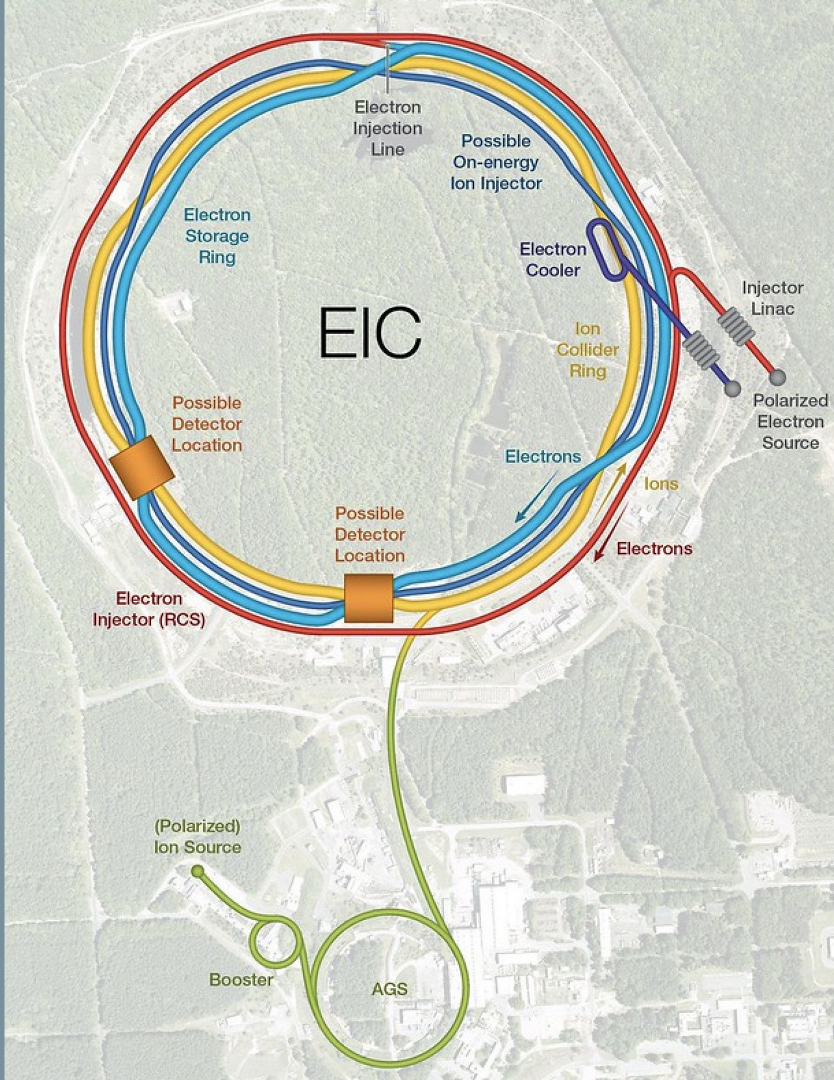
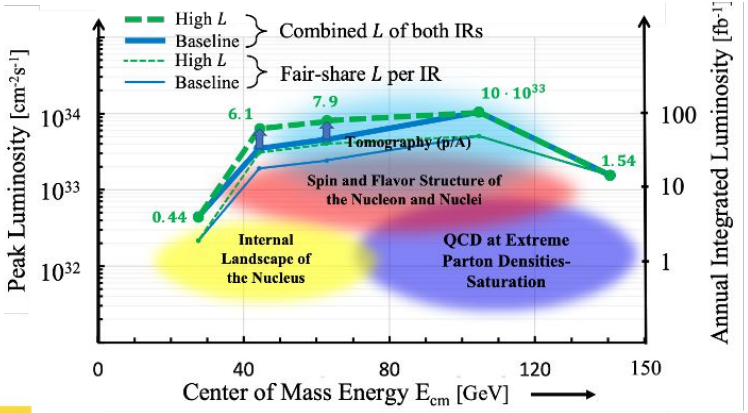


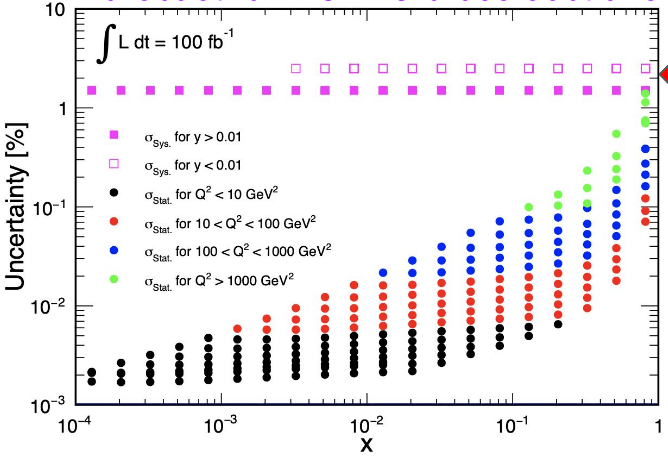
Yellow Report (2020-2021)

- Lots of people joined - some left, some stayed
- Despite COVID, the community managed to push it over the finish line
- Many things were left out… “but we did what we could do”



Yellow Report: *inclusive reactions*

Forecast for NC DIS cross sections

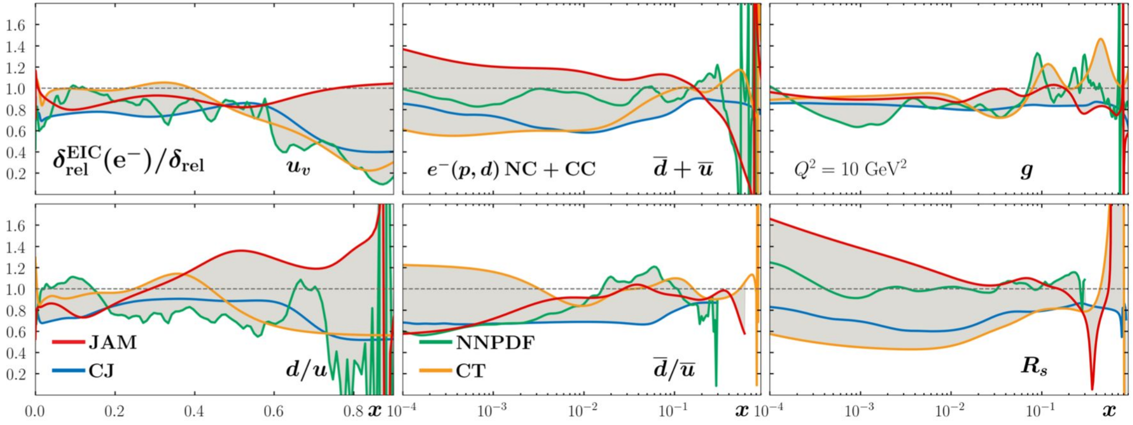


Systematic effects:

- 1% QED corrections
- 1 - 2% detector effects
- 2.5 - 4.5% normalization uncertainties

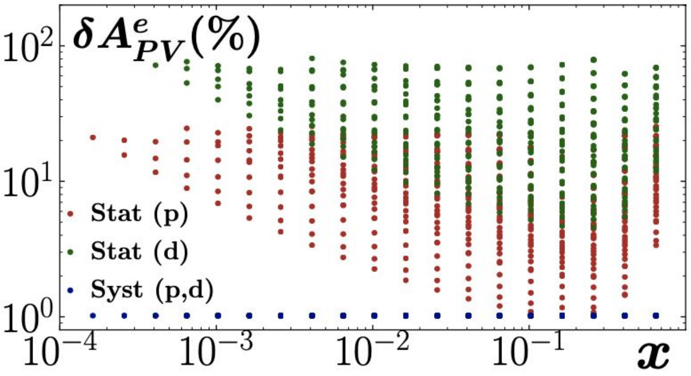
- Spread of relative PDF errors indicates a reshuffling of the flavor structure in the presence of EIC "optimistic" data

Impact of NC DIS on PDFs @ 50% sys "optimistic"

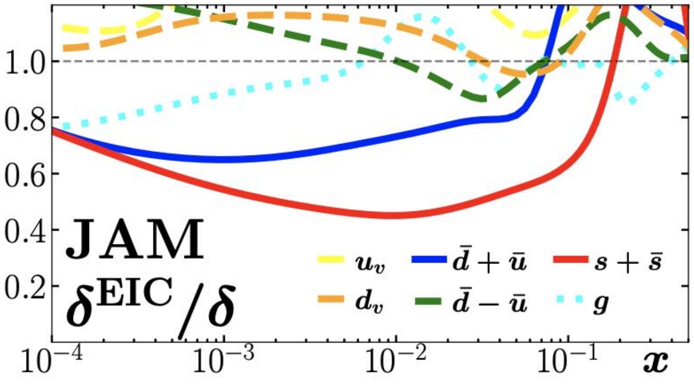


Yellow Report: *Apv electron*

Forecast for Apv uncertainties



Impact of Apv on PDFs



$$A_{PV} = -\frac{G_F Q^2}{4\sqrt{2}\pi\alpha(Q^2)}\left[a_1(x,Q^2)Y_1(x,y,Q^2) + a_3(x,Q^2)Y_3(x,y,Q^2)\right]$$

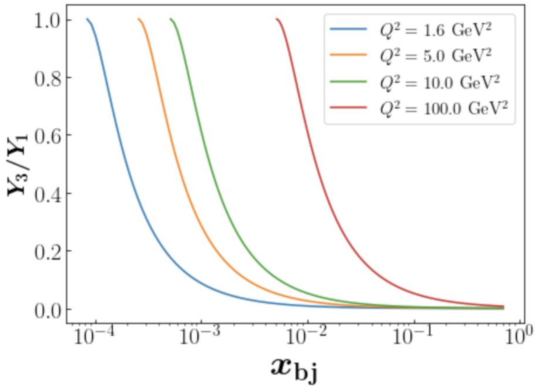
$$a_1(x) = 2g_A^e \frac{F_1^{\gamma Z}}{F_1^{\gamma}}$$

$$a_3(x) = g_V^e \frac{F_3^{\gamma Z}}{F_1^{\gamma}}\ ,$$

$$F_1^{\gamma}(x,Q^2) = \frac{1}{2}\sum Q_{q_i}^2\left[q_i(x,Q^2) + \bar{q}_i(x,Q^2)\right]$$

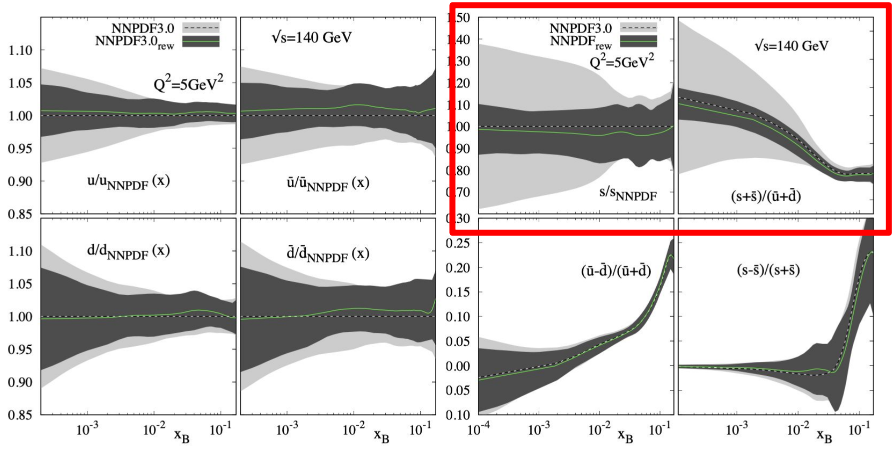
$$F_1^{\gamma Z}(x,Q^2) = \sum Q_{q_i} g_V^i\left[q(x,Q^2) + \bar{q}_i(x,Q^2)\right]$$

$$F_3^{\gamma Z}(x,Q^2) = 2\sum Q_{q_i} g_A^i\left[q_i(x,Q^2) - \bar{q}_i(x,Q^2)\right]$$



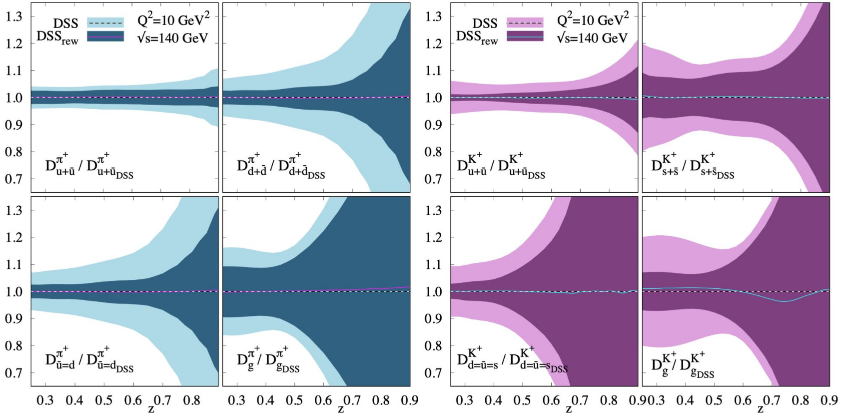
Yellow Report: *SIDIS (pT integrated)*

Impact of upol. SIDIS pions & kaons on PDFs



- Significant impact on the strange PDF given the projected precision of SIDIS Kaon multiplicities

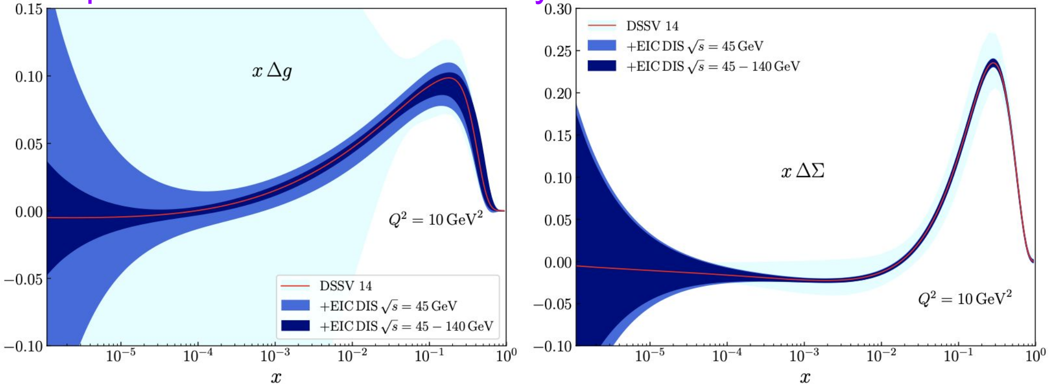
Impact of upol. SIDIS pions & kaons on FFs



- Analysis is based on PDF reweighting and more comprehensive analysis with full simultaneous global analysis should be in the to do list.

Yellow Report: *helicity pdfs*

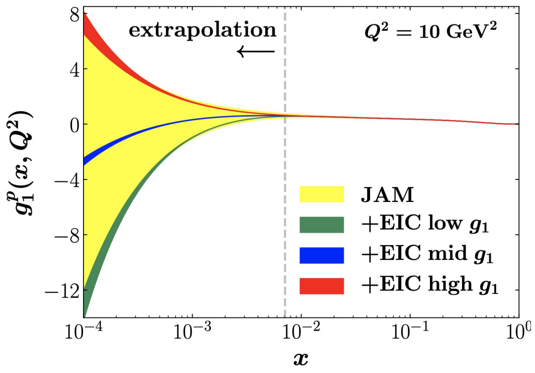
Impact of DIS DSAs on helicity PDFs

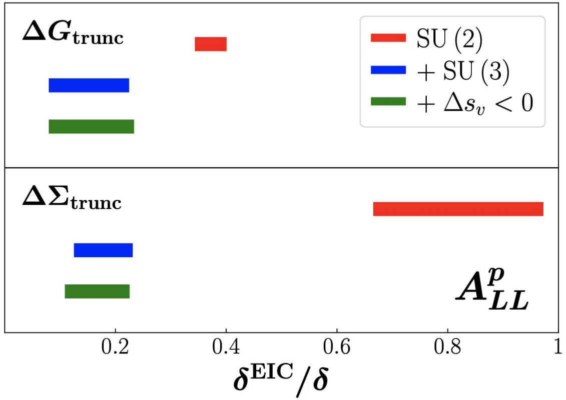


- DIS DSAs can constrain gluon helicity thanks for the large Q2 lever arm
- Constraints on the singlet and gluon will bring new insights on proton spin puzzle

UQ of the role of extrapolation region

- For impact studies, is also important to explore various systematic effects, eg extrapolation uncertainties, assumptions





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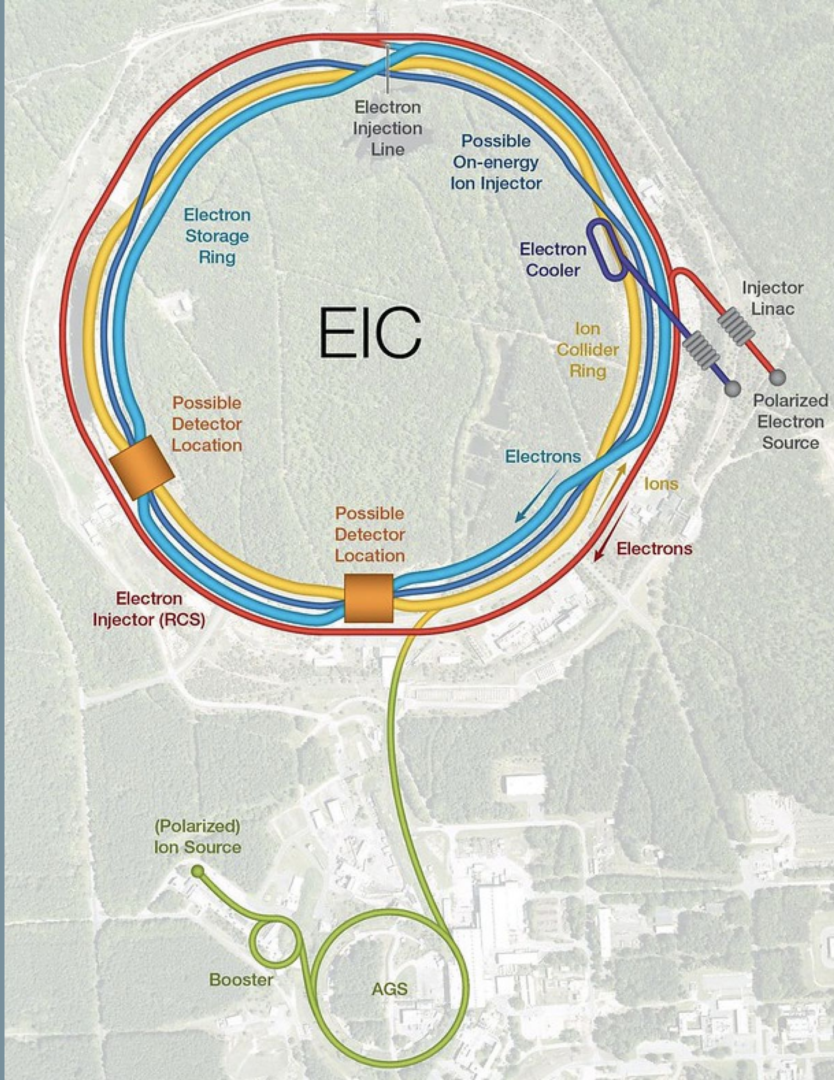
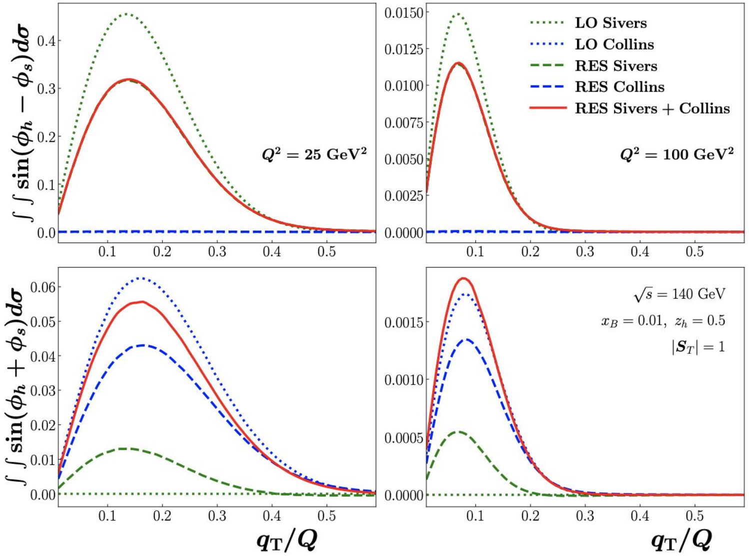


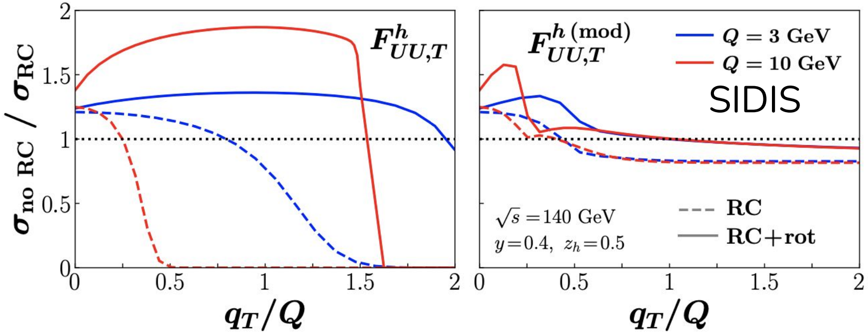
QED effects in eP reactions

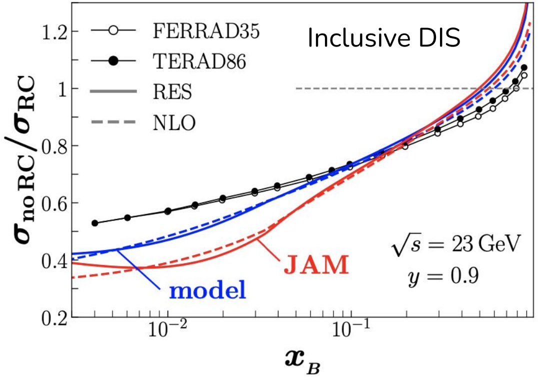


- Hybrid QED+QCD framework to study SSAs in SIDIS
  within global analysis
- *Crucial to control QED backgrounds in transverse spin asymmetries*

Towards a global analysis includes QED effects

Liu, Melnitchouk, Qiu, Sato (JHEP)





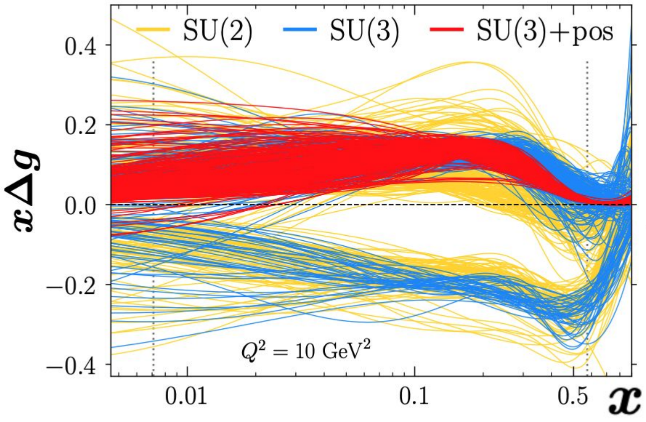
- Non-uniqueness of QED RC corrections
- Need for a combined analysis including QED and QCD effects

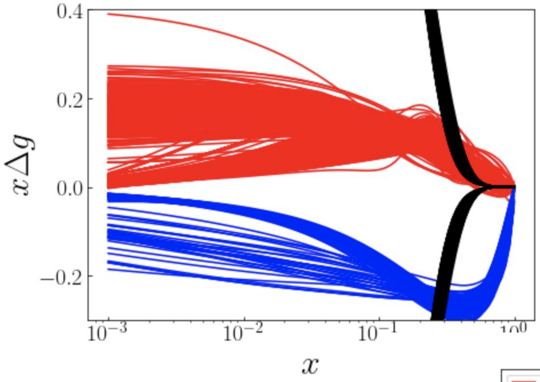
News on Gluon helicity

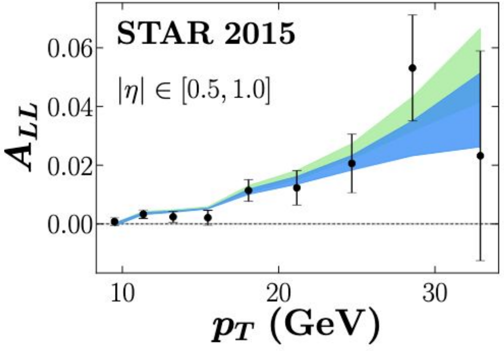
Negative gluon polarization?

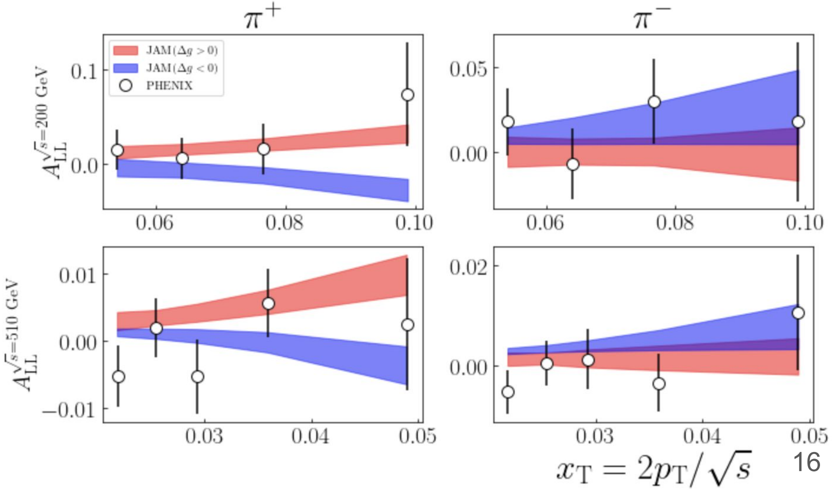
$$\int_{0.05}^{1} dx\,\Delta g(x) = \begin{matrix} 0.23 \pm 0.03 & \text{pos} \\ -0.62 \pm 0.03 & \text{neg} \end{matrix}$$

Zhou, Melnitchouk, Sato (PRD)



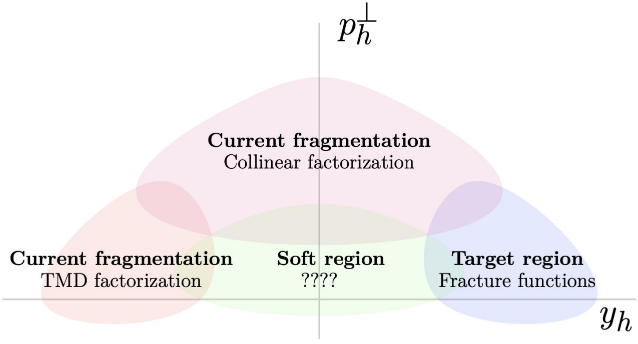


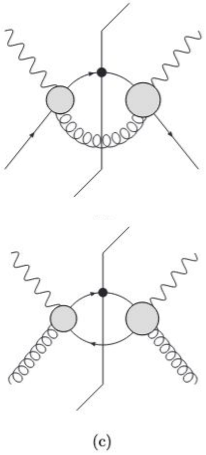


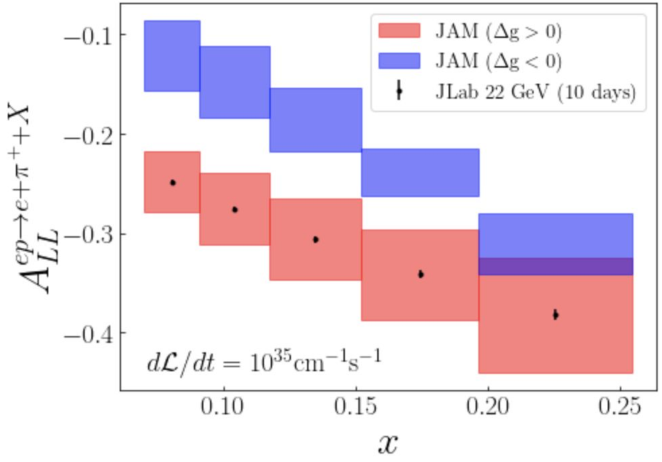


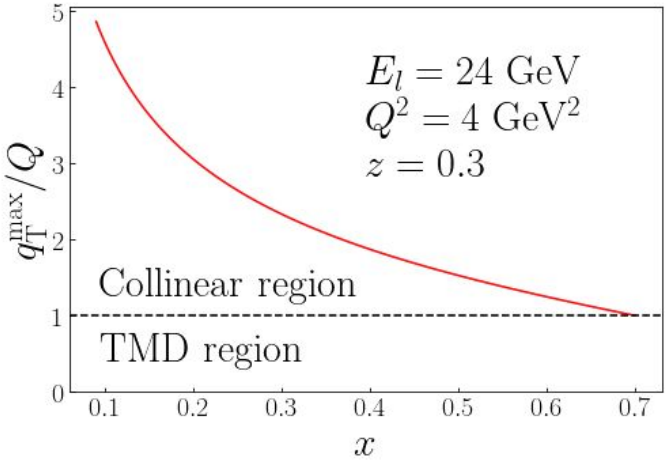
- Inclusion of RHIC polarized jet data allows both positive and negative gluon helicity solutions (in absence of positivity constraints on unpolarized gluon PDF)
- Phenix has attempted to have empirical confirmation of gluon helicity sign (PRD102.032001, PRD91.032001)
- *Gluon helicity currently not as well constrained as was believed (independent of theory bias)*

Gluon helicity @ JLab++







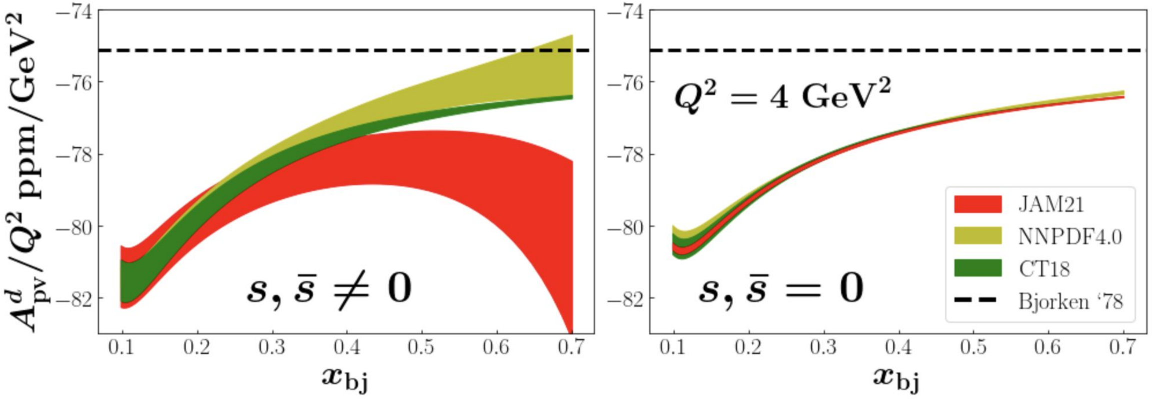


- Hadron production with large transverse momentum has an opportunity to discriminate the sign of gluon polarization
- For JLab 22 as well as EIC there would be plenty of phase space to use collinear factorization
- More dedicated studies are on the way

Strangeness & Apv deuteron @ JLab++

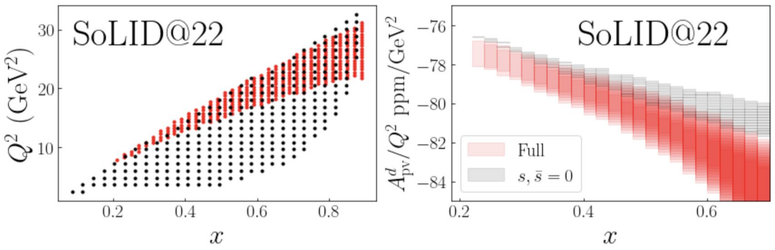
Bjorken `78

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



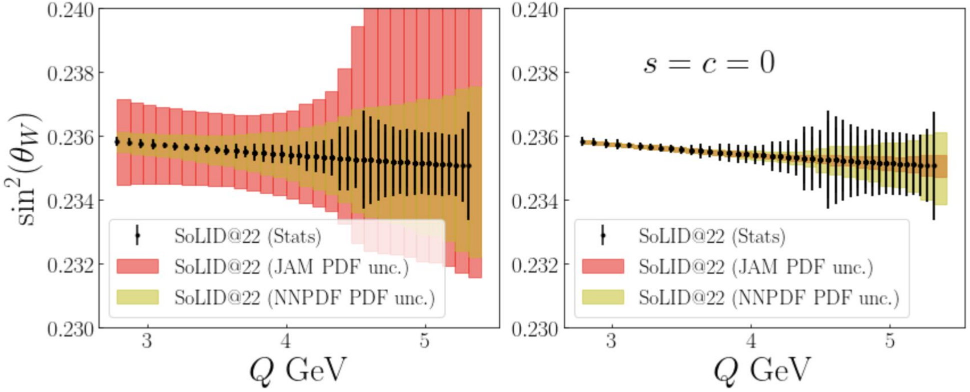
- Apv on deuteron has the opportunity to access directly Weinberg angle
- However, limited knowledge of strange pdf induces larger uncertainties for sin^2w from Apv D
- On the other hand, under the SM hypothesis, Apv D can explore strangeness in the large x region

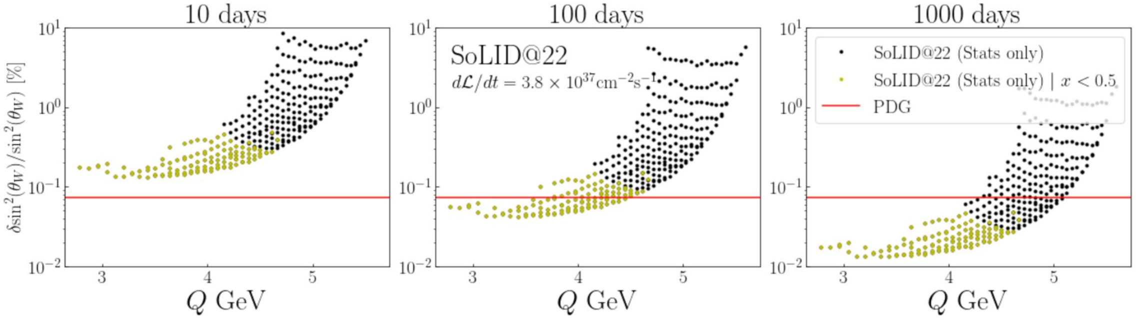
Strangeness & Apv deuteron @ JLab++



- Apv D has a significant constraining power on strange pdf -> tested on two PDFs sets (JAM, NNPDF)

- Luminosity is critical to discover how strange the proton is!





- If strangeness is constrained elsewhere (LQCD, other HEP observables), high lum. Apv D will deliver precision EW measurements

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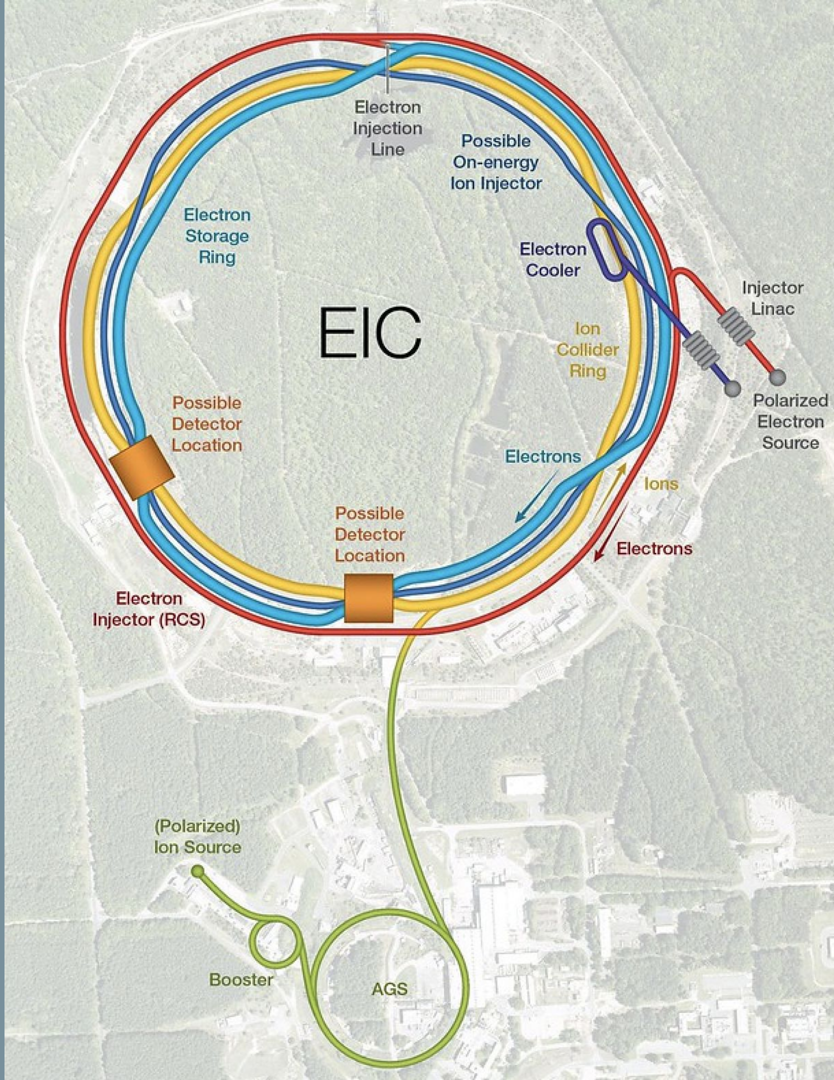
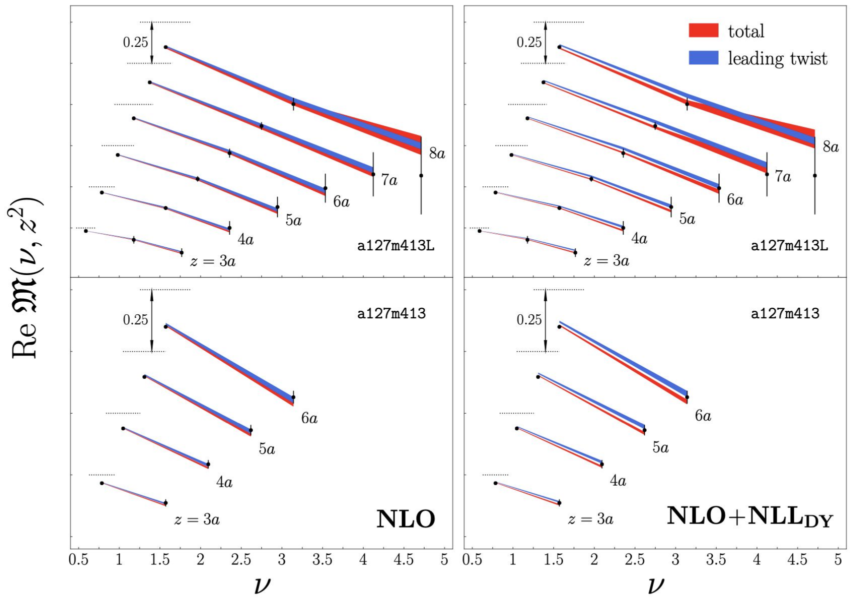
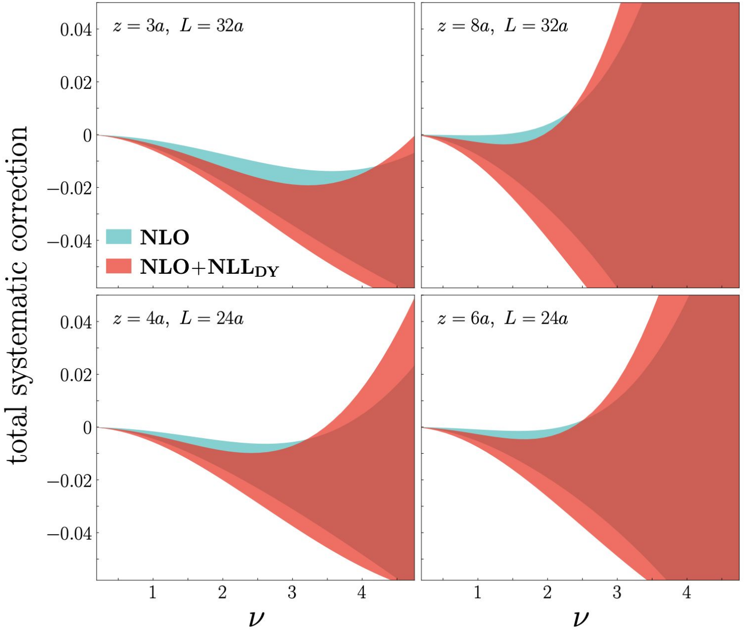


Synergies with LQCD - *pion structure*

Barry et al. ('22)
JAM+HadStruct

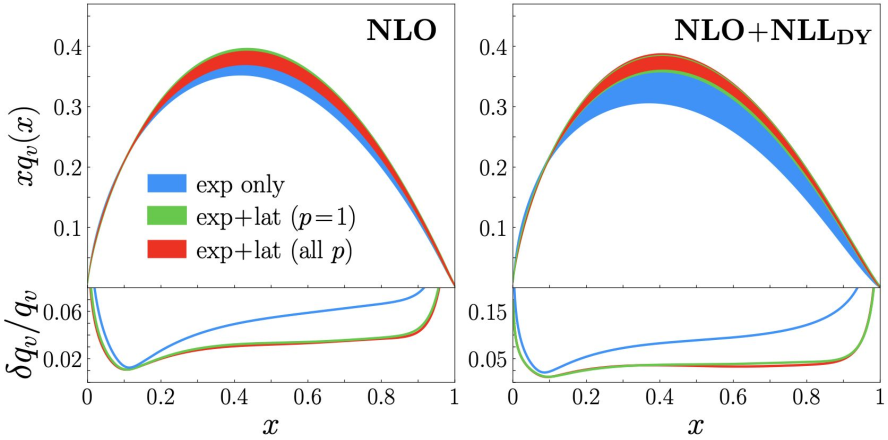


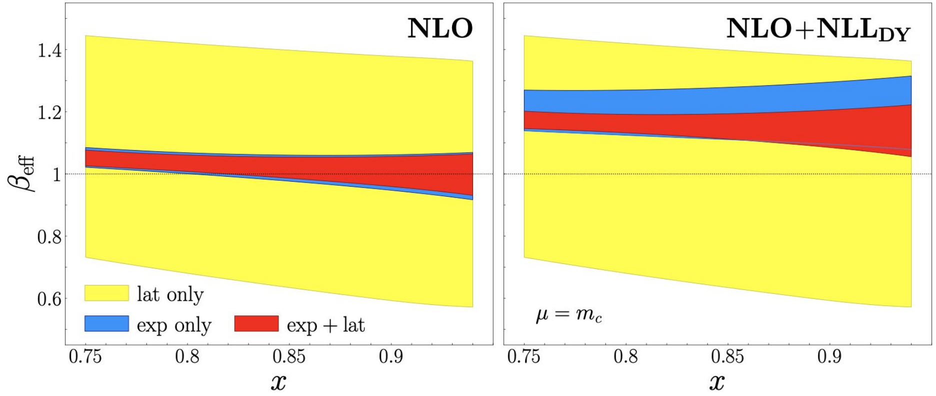


$$\mathrm{Re}\ \mathfrak{M}(\nu, z^2) = \int_0^1 \mathrm{d}x\ q_v(x, \mu_{\mathrm{lat}})\, \mathcal{C}^{\mathrm{Rp\text{-}ITD}}\left(x\nu, z^2, \mu_{\mathrm{lat}}\right)$$
$$+ \boxed{z^2 B_1(\nu) + \frac{a}{|z|} P_1(\nu) + e^{-m_\pi (L-z)} F_1(\nu)}\,.$$

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

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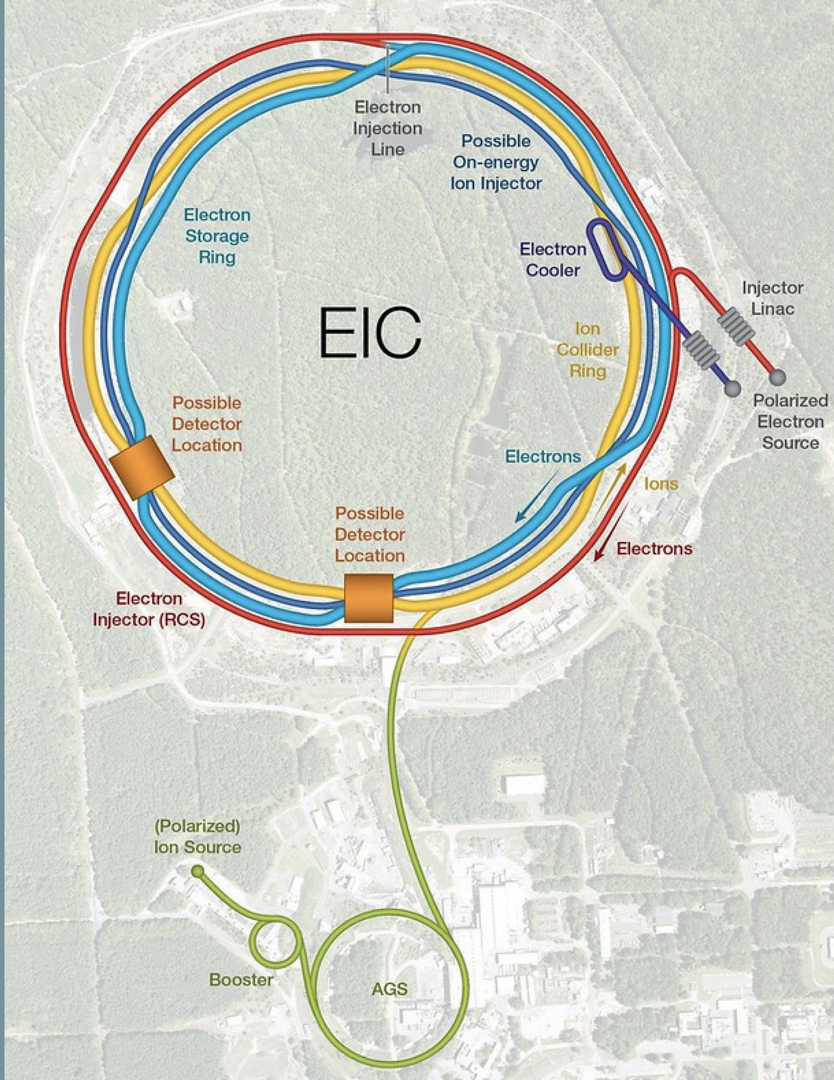
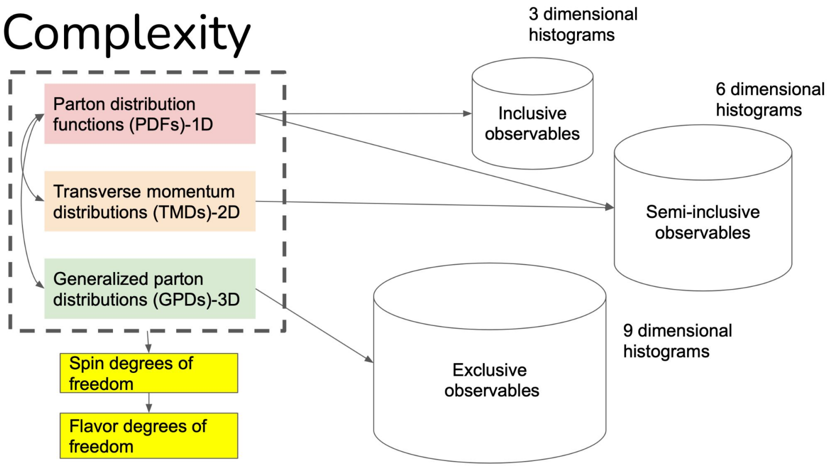


Integrated theory & experimental analysis

Complexity

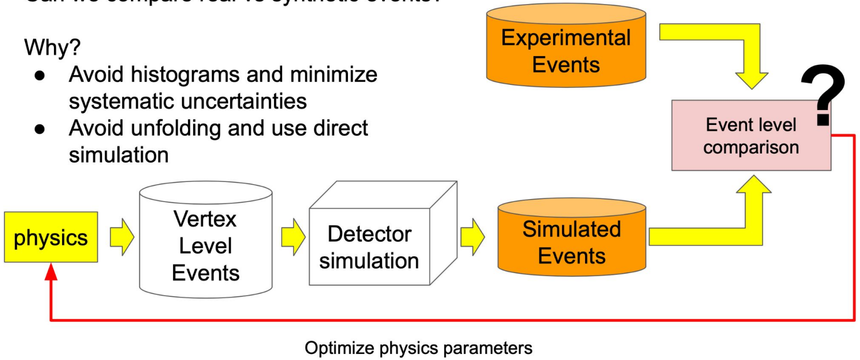


event-based analysis

Can we compare real vs synthetic events?

Why?

- Avoid histograms and minimize systematic uncertainties
- Avoid unfolding and use direct simulation



QuantOm Collaboration

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

- Support by DOE - (NP&ASCAR) under SciDAC funds

Summary

- Global analysis sits at the intersection of theory, experiment and data science -- has the potential discover novel QCD phenomena (eg Cteq).

- Its full realization on existing and future facilities will deliver physics that are important beyond hadronic physics community -- EW physics, nucleon tensor charge,..

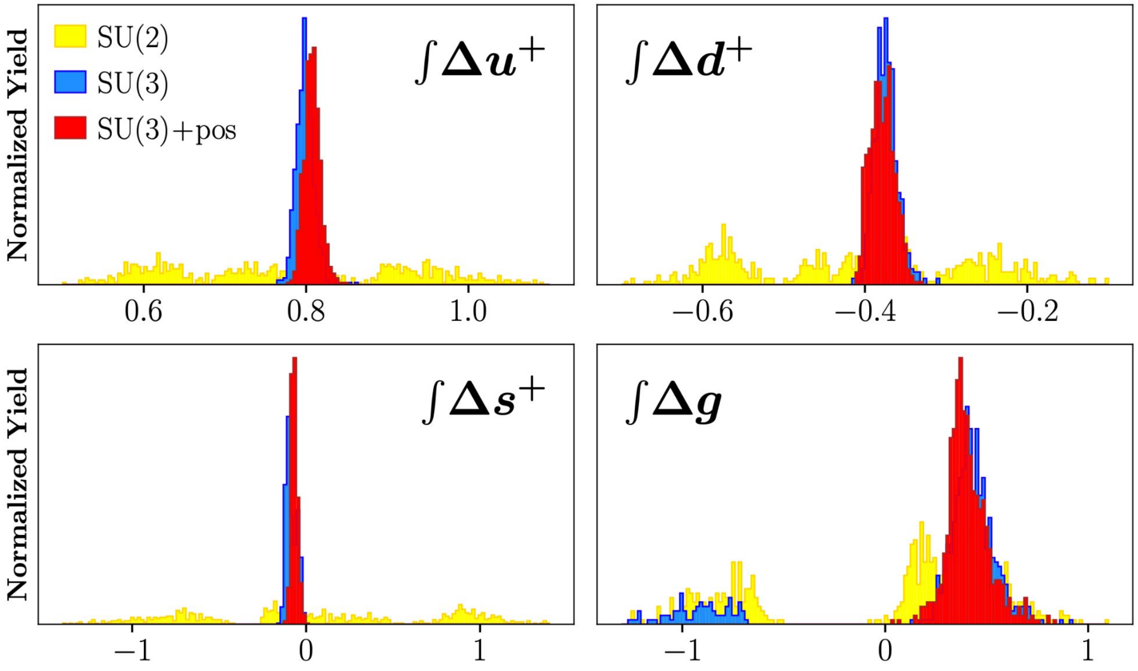
- It is a multi-disciplinary activity (with strong synergies with LQCD) and this subfield has the opportunity to explore collaborations with CS, applied math, statistic, HPC, etc. -- eg opportunities with SciDAC

- Theorists plays an important role from formal developments up to numerical data analysis (currently there is a lack of support in this area). More incentives, proper career development in this area is strongly recommended.

Backup

Zhou, Melnitchouk, Sato `20

$x_{\min} = 0.0071$ to 1



COMPASS

arXiv:1503.08935v1