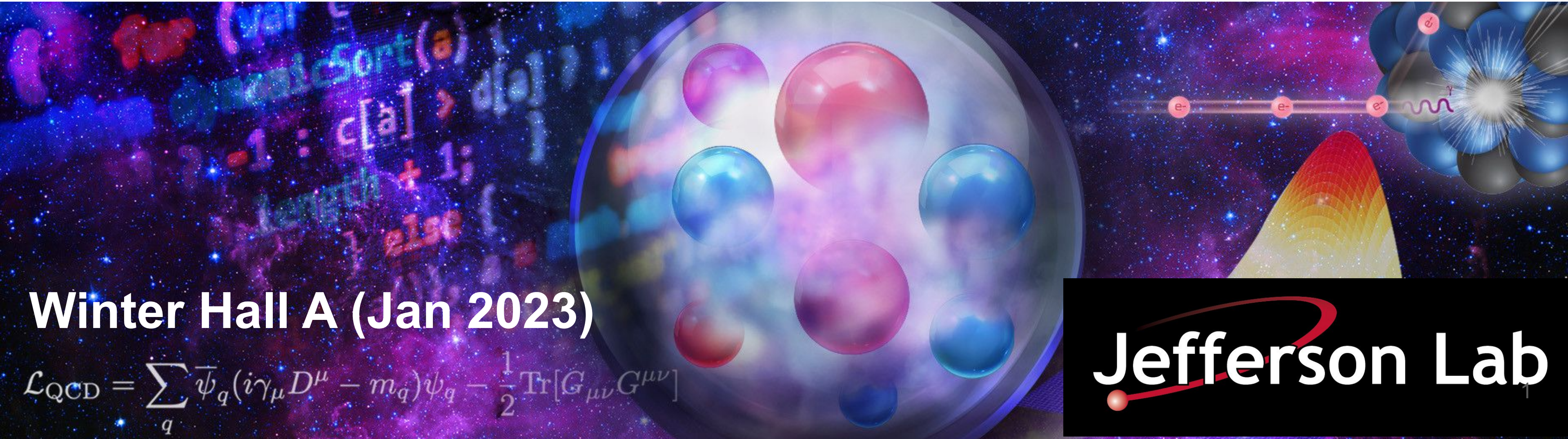
Impact of extracting strange quark distribution of proton from PVDIS experiment

Nobuo Sato



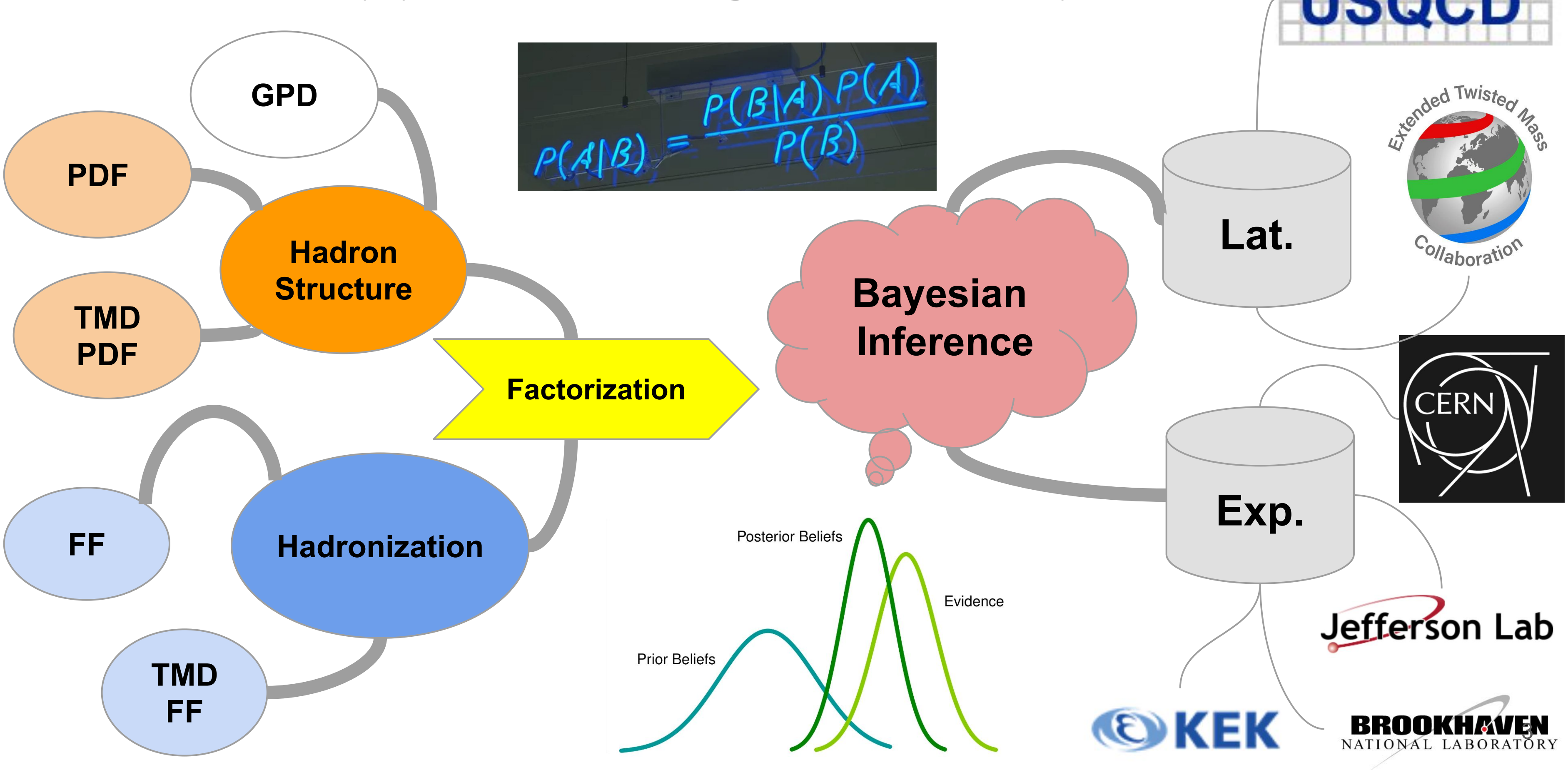
Winter Hall A (Jan 2023)

Jefferson Lab

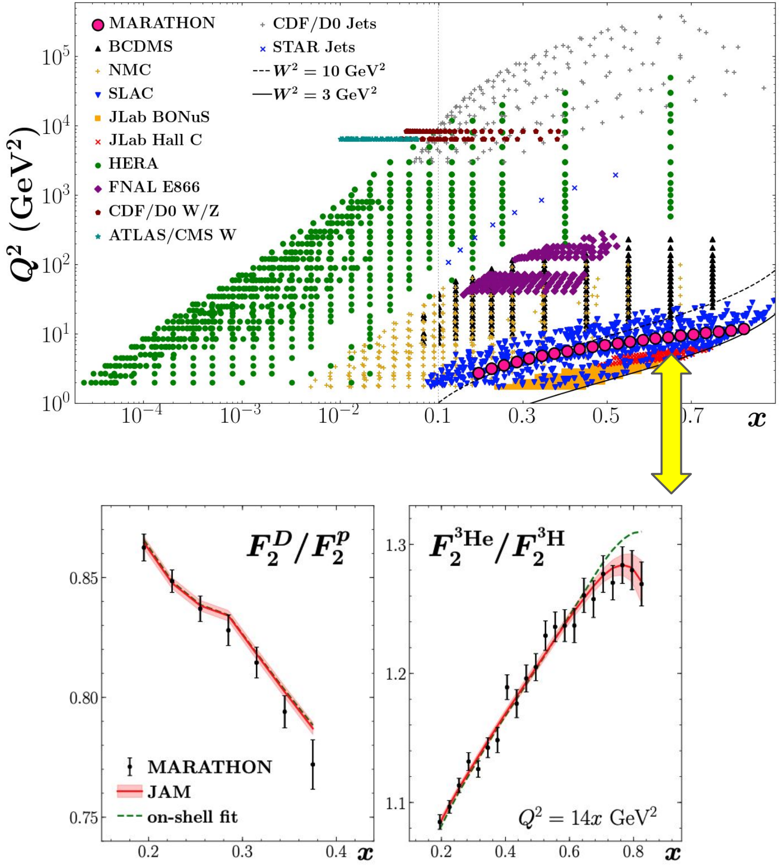
Outline

1. Recent highlights
2. Status of strange pdf
3. Parity violating DIS
4. PVDIS @ SoLID -22
5. Sin2W
6. QED radiative effects
7. Integrating thy/exp/cs

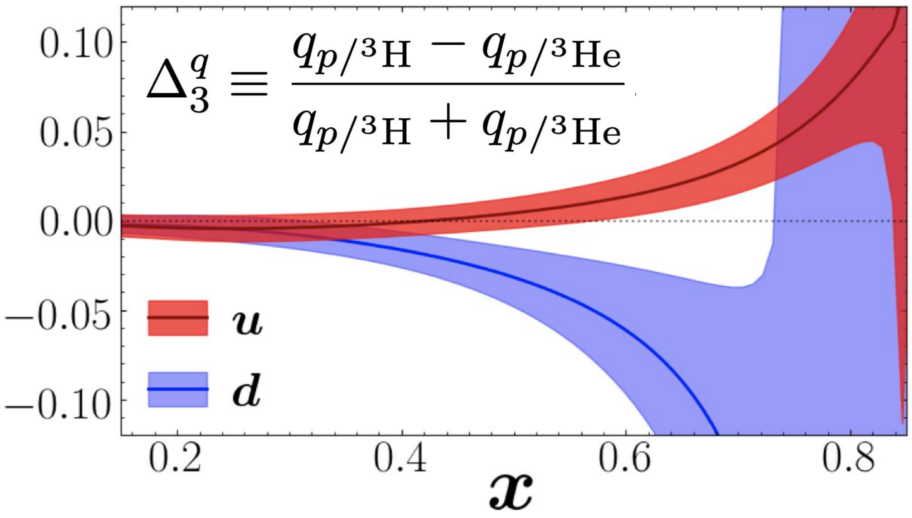
A holistic approach for global analysis



Isovector EMC effects from MARATHON data



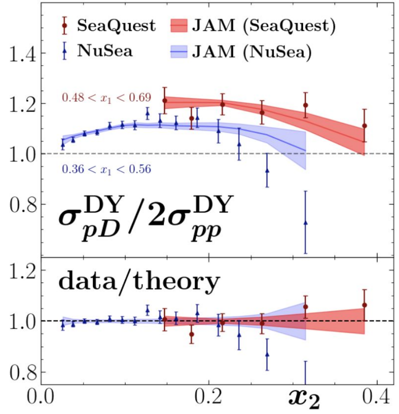
Cocuzza, et al (PRL)

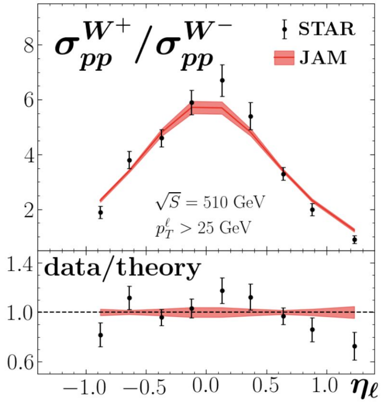


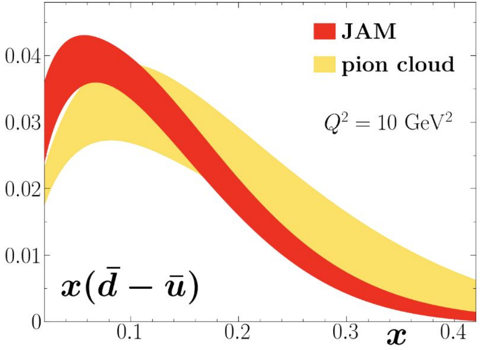
- Global analysis including latest collider *W*/*Z* data and MARATHON *d*/*p*, helium, tritium DIS data
- *Evidence of different medium modifications for u and d quarks*
- *Naive modeling of nuclear PDFs, e.g. u/p/A = d/n/A (violates isospin for non-isoscalar A) is wrong*

Antimatter asymmetry

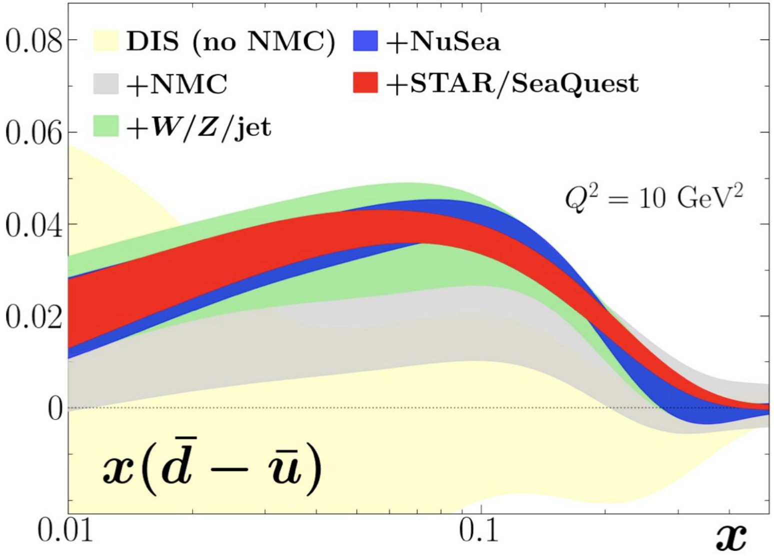
Cocuzza, Melnitchouk, Metz, Sato (PRD)







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

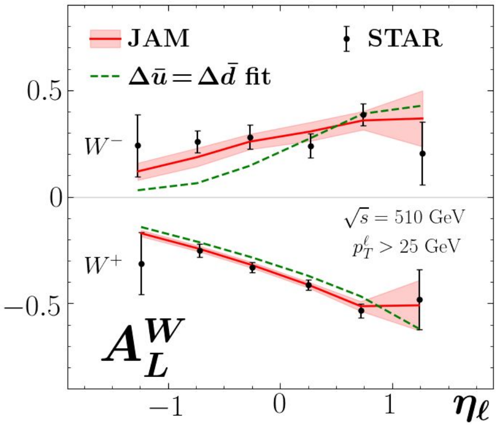


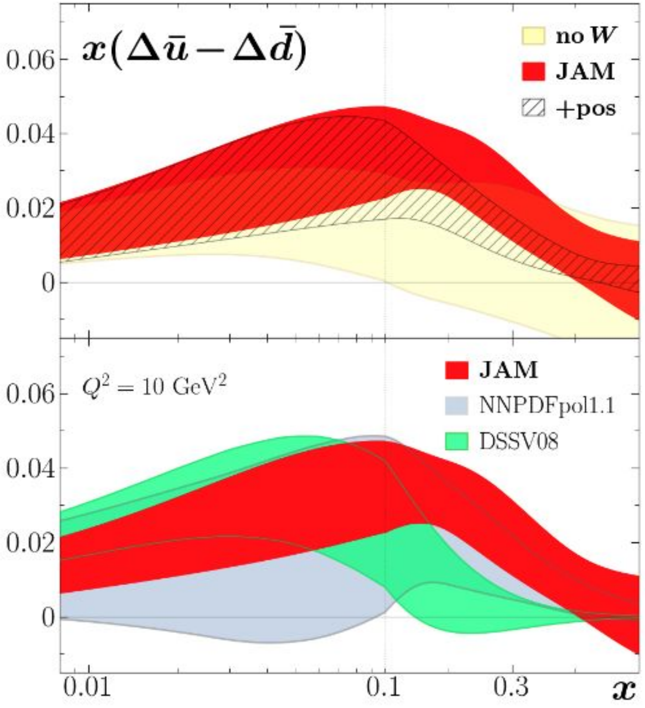
- First global analysis to include latest SeaQuest and STAR data
- Most precise phenomenological extraction of *dbar-ubar* asymmetry to date
- Quantitative test of the pion-cloud model

Polarized antimatter asymmetry

Cocuzza, Melnitchouk, Metz, Sato (PRD)

Process	N_{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**





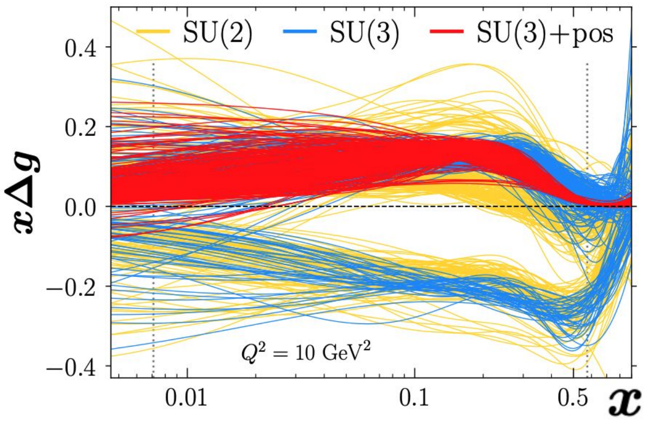
- First simultaneous extraction of unpolarized and helicity PDFs and FFs in global analysis with inclusion of RHIC spin *W*+/- data
- Most precise phenomenological extraction of polarized *dbar-ubar* asymmetry to date

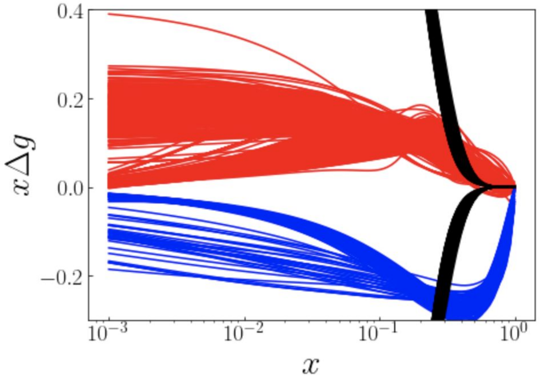
News on Gluon helicity

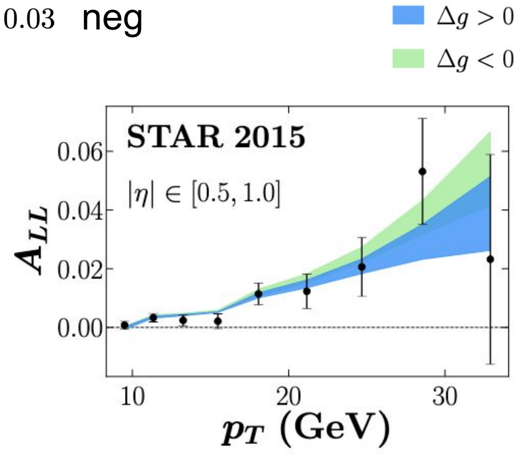
Negative gluon polarization?

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

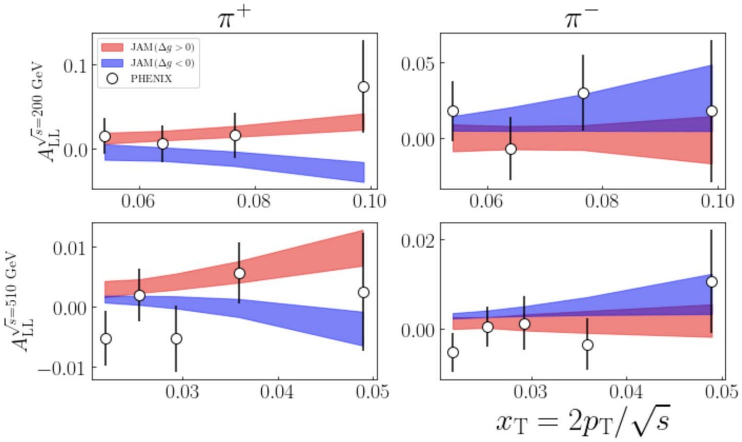
Zhou, Melnitchouk, Sato (PRD)



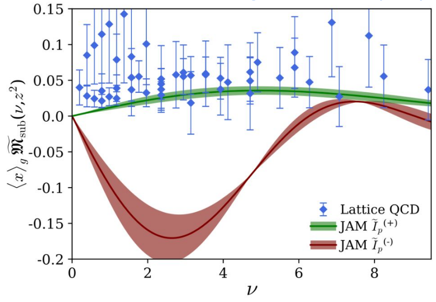




- Inclusion of RHIC polarized jet data allows both positive and negative gluon helicity solutions (in absence of positivity constraints on unpolarized gluon PDF)
- PHENIX has attempted to have empirical confirmation of gluon helicity sign (PRD102.032001, PRD91.032001)



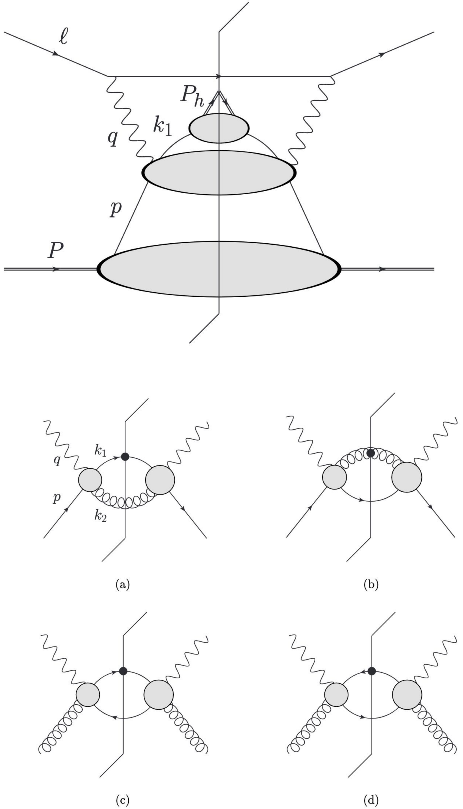
Egerer et al ('22)

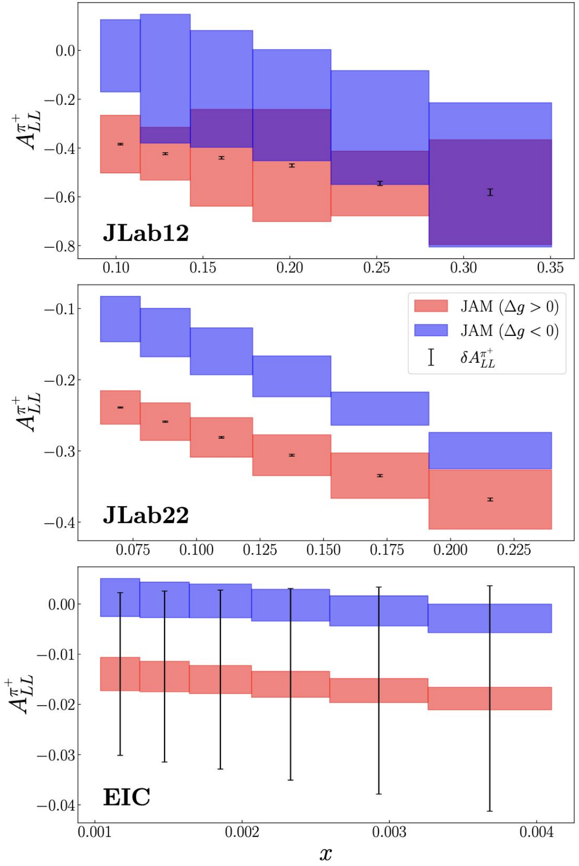


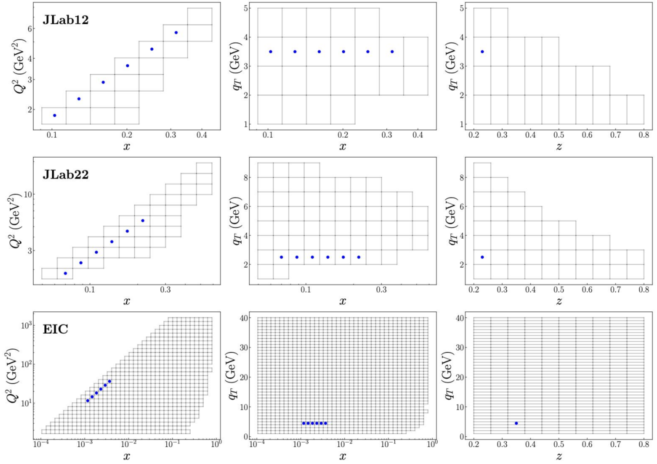
Accessing gluon polarization with high-P_T hadrons in SIDIS

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





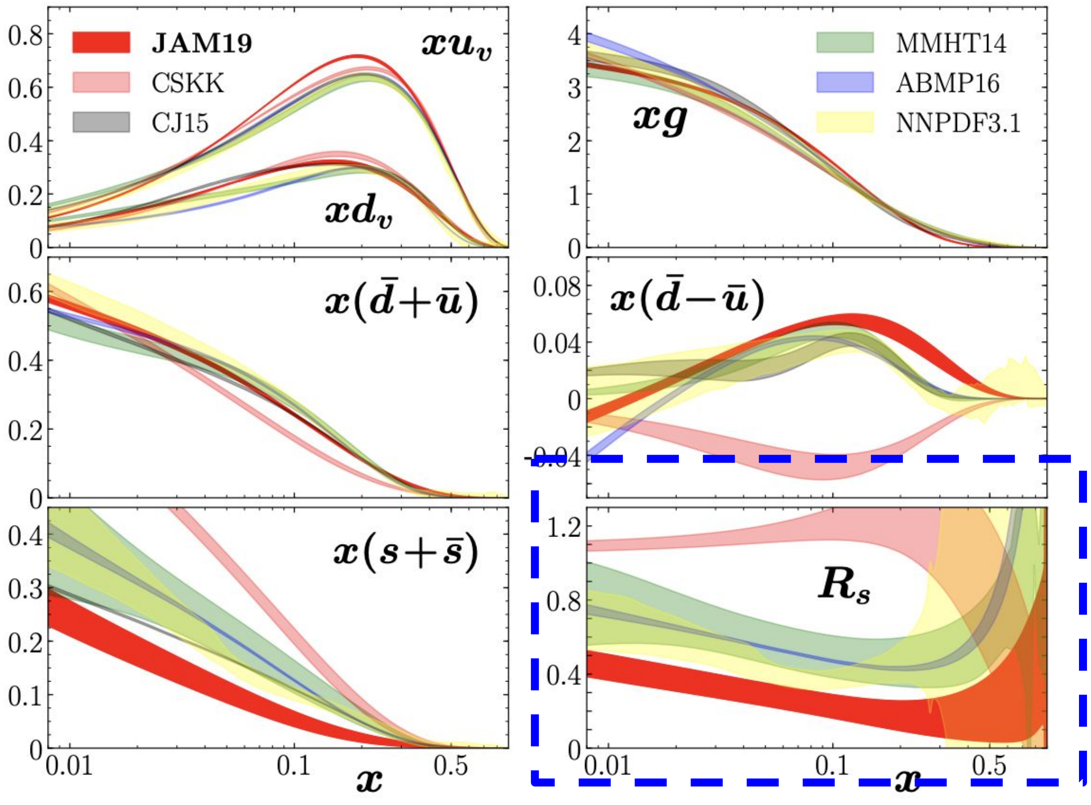


Bottom line: sign of gluon polarization might be resolved empirically at JLab 22

Outline

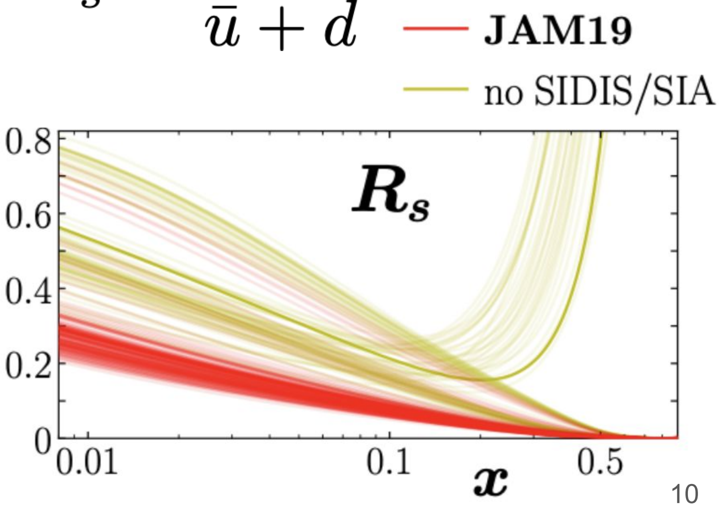
1. Recent highlights
2. Status of strange pdf
3. Parity violating DIS
4. PVDIS @ SoLID -22
5. Sin2W
6. QED radiative effects
7. Integrating thy/exp/cs

JAM19

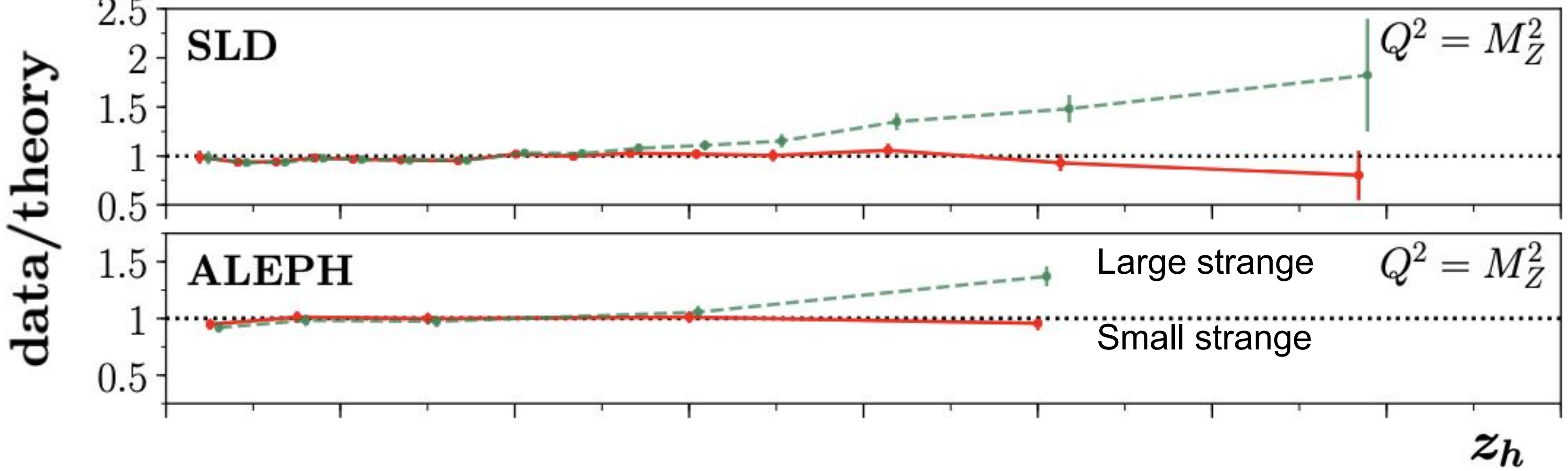


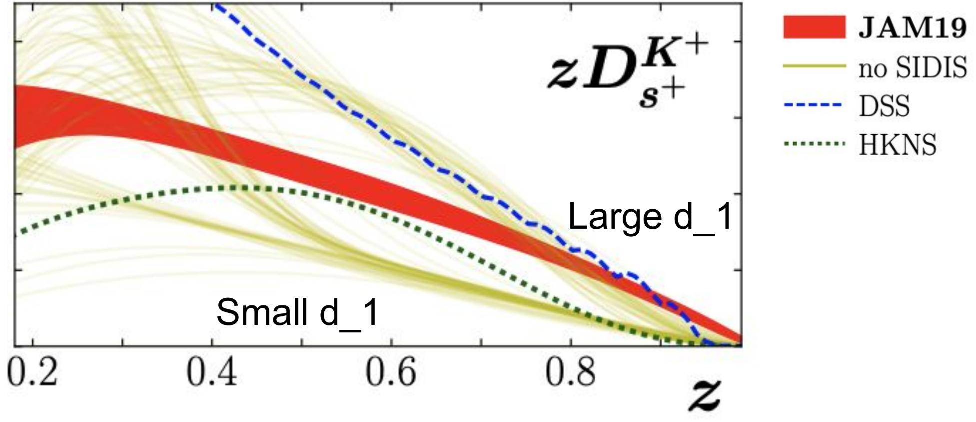
- Strange PDF is one of the least constrained f_1 pdfs
- Different analyses have inferred different sizes of the strangeness

$$R_s = \frac{s+\bar{s}}{\bar{u}+\bar{d}}$$

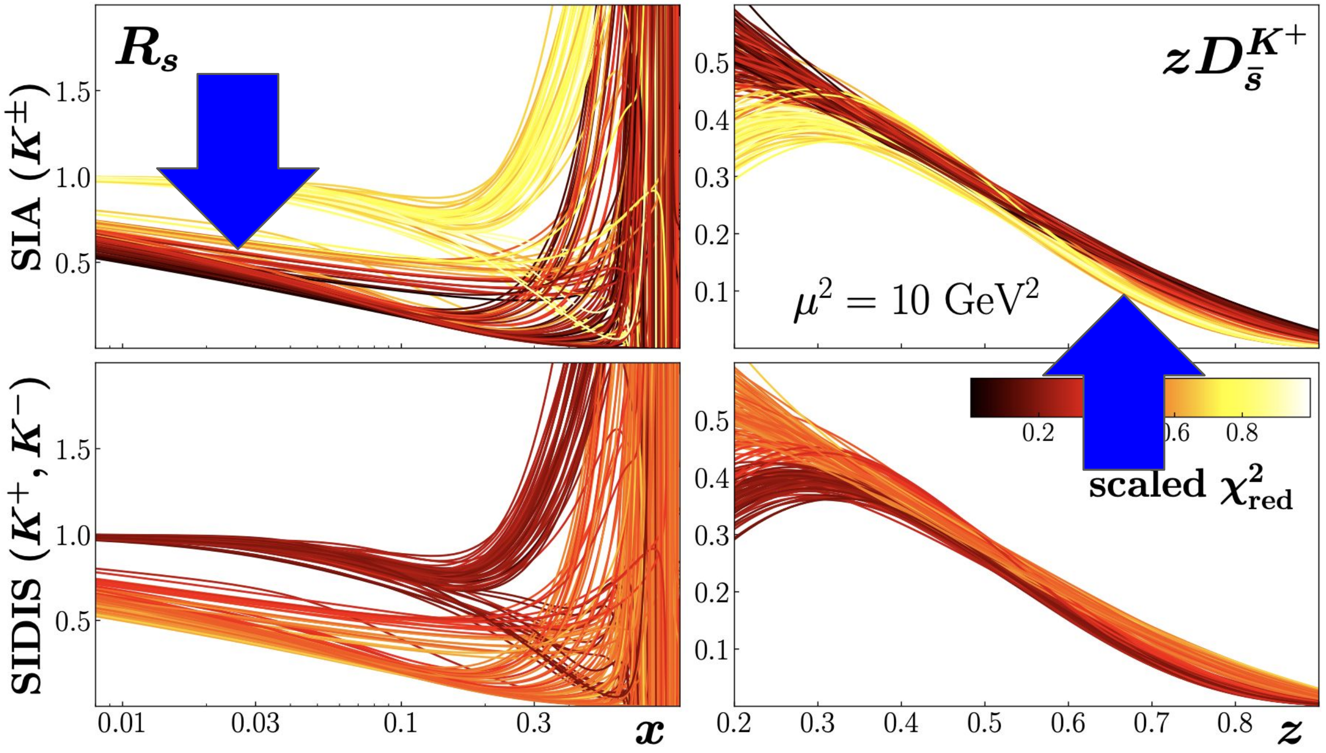


$e^+e^- \to K^\pm + X$





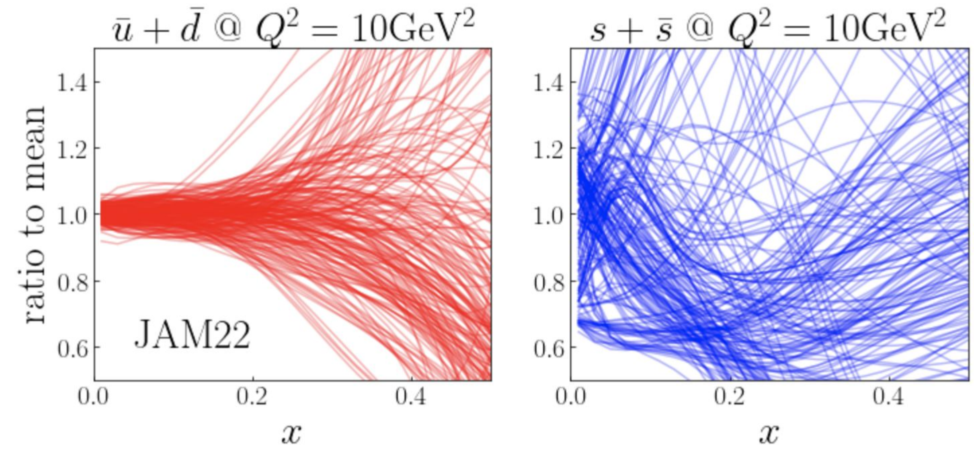
- LEP kaon data disfavors small s --> K fragmentation
- SIDIS data compensates large strange FF by suppressing strange PDF



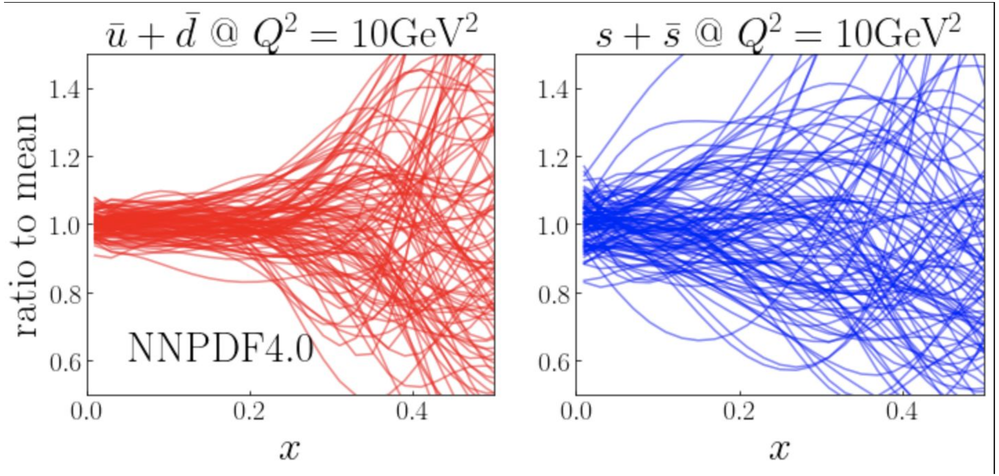
Bottom line:

Simultaneous analysis suggests a strong strange suppression, and differs from other global analyses using LHC data

JAM22



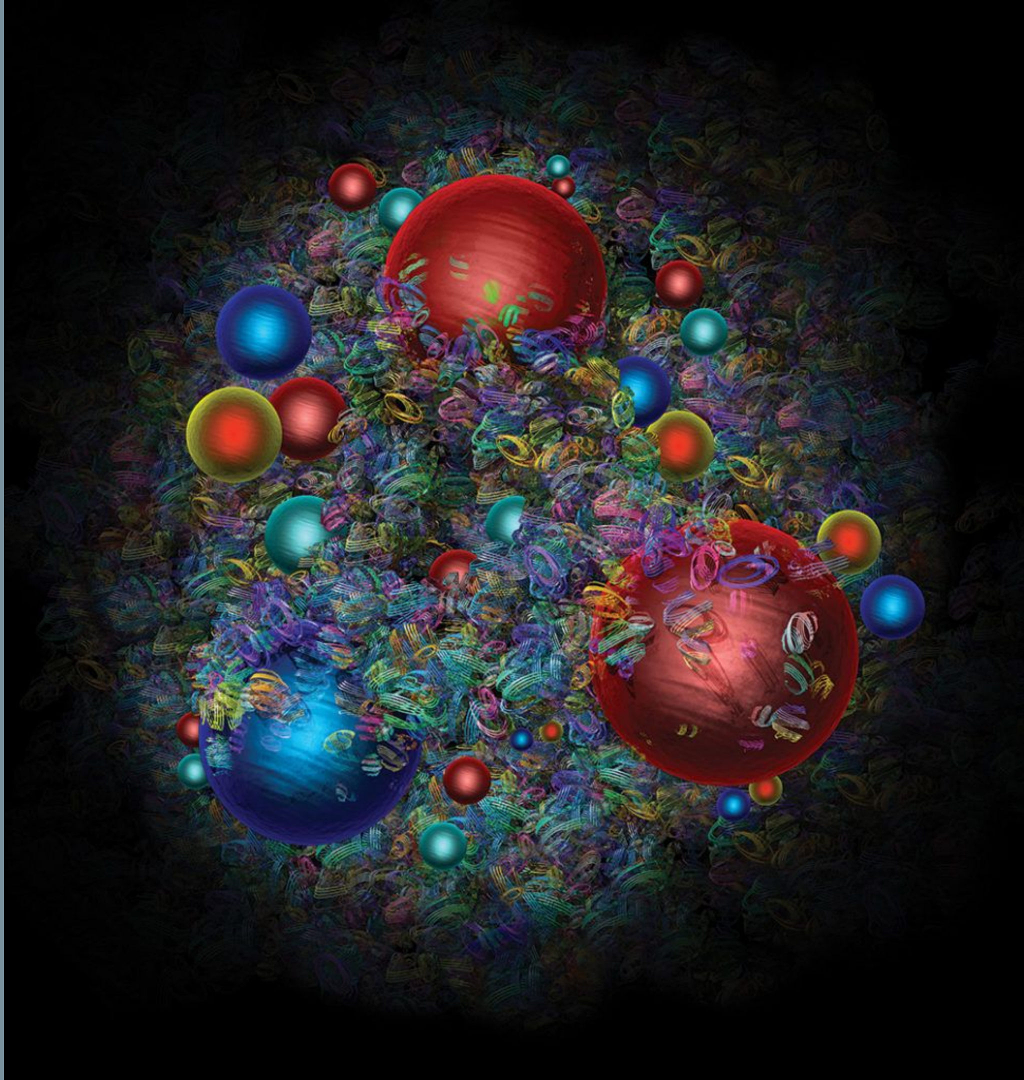
Process	N_{dat}	χ^2/N_{dat}
Polarized		
Inclusive DIS	365	0.95
SIDIS (π^+, π^-)	64	1.05
SIDIS (K^+, K^-)	57	0.42
SIDIS (h^+, h^-)	110	0.95
Inclusive jets	83	0.84
STAR $W^\pm$	12	0.65
PHENIX $W^\pm/Z$	6	0.50
Total	**697**	**0.89**
Unpolarized		
Inclusive DIS	3908	1.17
SIDIS (π^+, π^-)	498	0.94
SIDIS (K^+, 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**



*Strangeness pdf is mostly **fiction**!*

Outline

1. Recent highlights
2. Status of strange pdf
3. Parity violating DIS
4. PVDIS @ SoLID -22
5. Sin2W
6. QED radiative effects
7. Integrating thy/exp/cs



PHYSICAL REVIEW D VOLUME 18, NUMBER 9 1 NOVEMBER 1978

Model-independent remarks on electron-quark parity-violating neutral-current couplings

J. D. Bjorken
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305
(Received 10 July 1978)

$$\frac{A^{eD}(Q^2,\nu,y)_{AV}}{Q^2} \propto \frac{l_{\mu\nu}\int \langle D|[j^\mu(x)J^\nu(0)+J^\mu(x)j^\nu(0)]|D\rangle e^{iq\cdot x}d^4x}{l_{\mu\nu}\int\langle D|j^\mu(x)j^\nu(0)|D\rangle e^{iq\cdot x}d^4x};$$

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

$$\epsilon_{VA}(e,u)=\tfrac{1}{2}(1-4\sin^2\theta_W),$$
$$\epsilon_{VA}(e,d)=-\tfrac{1}{2}(1-4\sin^2\theta_W),$$
$$\epsilon_{AV}(e,u)=\tfrac{1}{2}(1-\tfrac{8}{3}\sin^2\theta_W),$$
$$\epsilon_{AV}(e,d)=-\tfrac{1}{2}(1-\tfrac{4}{3}\sin^2\theta_W).$$

If δ is small then Apv on deuteron is highly sensitive to $\sin^2\theta_W$.

1978 –> 2014

From currents to partons

Measurement of Parity-Violating Asymmetry in Electron-Deuteron Inelastic Scattering

D. Wang, R. Subedi,* G. D. Cates, M. M. Dalton, X. Deng, D. Jones, N. Liyanage, V. Nelyubin,
K. D. Paschke, S. Riordan, K. Saenboonruang,† R. Silwal, W. A. Tobias, and X. Zheng
University of Virginia, Charlottesville, Virginia 22904, USA . . . . .

Measurement of Parity-Violating Asymmetry in Electron-Deuteron Inelastic Scattering

D. Wang, R. Subedi,* G. D. Cates, M. M. Dalton, X. Deng, D. Jones, N. Liyanage, V. Nelyubin,
K. D. Paschke, S. Riordan, K. Saenboonruang,† R. Silwal, W. A. Tobias, and X. Zheng
University of Virginia, Charlottesville, Virginia 22904, USA . . . . .

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

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

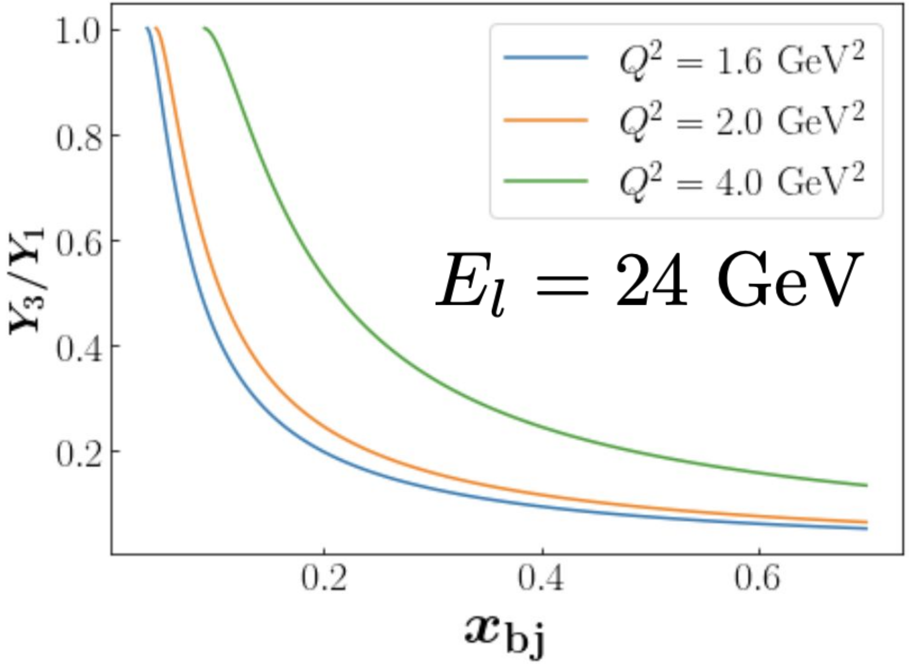
$$a_3(x) = g_V^e \frac{F_3^{\gamma Z}}{F_1^{\gamma}},$$

$$Y_1 = \left[\frac{1+R^{\gamma Z}}{1+R^{\gamma}}\right]\frac{1+(1-y)^2 - \frac{y^2}{2}\left[1+r^2-\frac{2r^2}{1+R^{\gamma Z}}\right]}{1+(1-y)^2-\frac{y^2}{2}\left[1+r^2-\frac{2r^2}{1+R^{\gamma}}\right]}$$

$$Y_3 = \left[\frac{r^2}{1+R^{\gamma}}\right]\frac{1-(1-y)^2}{1+(1-y)^2-\frac{y^2}{2}\left[1+r^2-\frac{2r^2}{1+R^{\gamma}}\right]}.$$

y dependence at JLab 20+ GeV

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



$$Y_1 = \left[\frac{1+R^{\gamma Z}}{1+R^{\gamma}}\right]\frac{1+(1-y)^2-\frac{y^2}{2}\left[1+r^2-\frac{2r^2}{1+R^{\gamma Z}}\right]}{1+(1-y)^2-\frac{y^2}{2}\left[1+r^2-\frac{2r^2}{1+R^{\gamma}}\right]}$$

$$Y_3 = \left[\frac{r^2}{1+R^{\gamma}}\right]\frac{1-(1-y)^2}{1+(1-y)^2-\frac{y^2}{2}\left[1+r^2-\frac{2r^2}{1+R^{\gamma}}\right]}.$$

$$r^2 = 1+\frac{Q^2}{\nu^2}$$

Parton level view...

$$a_1(x) \;=\; 2g_A^e \frac{F_1^{\gamma Z}}{F_1^{\gamma}} \qquad\qquad a_3(x) \;=\; g_V^e \frac{F_3^{\gamma Z}}{F_1^{\gamma}}$$

At LO in QCD we have

$$\begin{aligned}
F_1^{\gamma}(x,Q^2) &= \frac{1}{2}\sum Q_{q_i}^2 \left[q_i(x,Q^2)+\bar{q}_i(x,Q^2)\right] \\
F_1^{\gamma Z}(x,Q^2) &= \sum Q_{q_i} g_V^i \left[q(x,Q^2)+\bar{q}_i(x,Q^2)\right] \\
F_3^{\gamma Z}(x,Q^2) &= 2\sum Q_{q_i} g_A^i \left[q_i(x,Q^2)-\bar{q}_i(x,Q^2)\right]
\end{aligned}$$

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

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

$$a_1 = \frac{2\left(c^+ + u^+\right)\left(8s_w^2 - 3\right) + \left(d^+ + s^+\right)\left(4s_w^2 - 3\right)}{4c^+ + d^+ + s^+ + 4u^+}$$

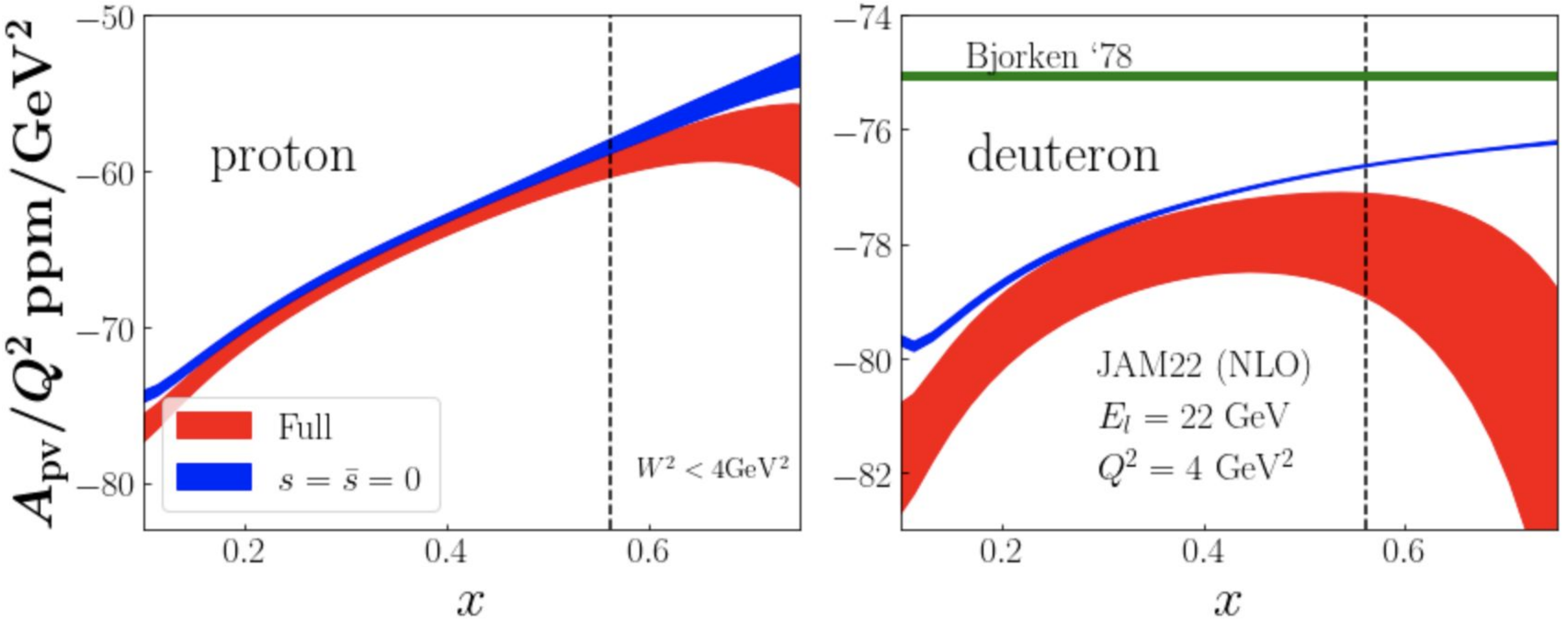
$$a_3 = \frac{3\left(4s_w^2 - 1\right)\left(2c^- + d^- + s^- + 2u^-\right)}{4c^+ + d^+ + s^+ + 4u^+}$$

If we ignore s and c and use deuteron target

$$a_1 = 4s_w^2 - \frac{9}{5}$$

$$a_3 = \frac{3\left(d^- + 2u^-\right)\left(4s_w^2 - 1\right)}{5u^+}$$

Apv with full QCD theory @ NLO



Bottom line: Apvd uncertainties correlates significantly from strangeness

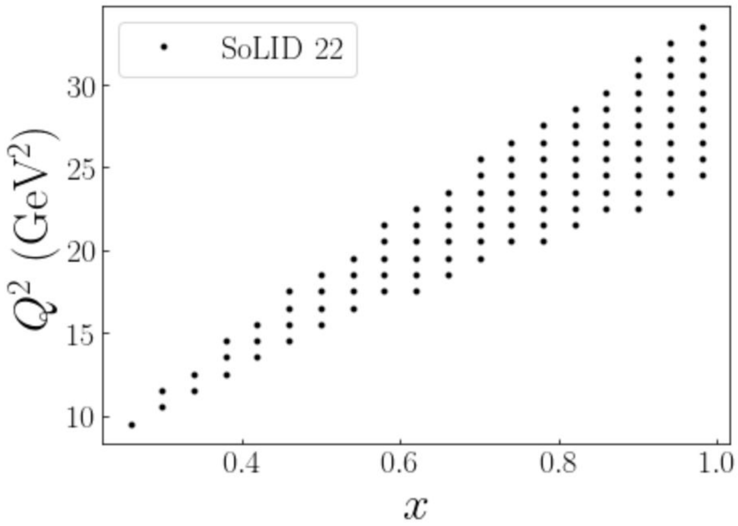
Outline

1. Recent highlights
2. Status of strange pdf
3. Parity violating DIS
4. PVDIS @ SoLID -22
5. Sin2W
6. QED radiative effects
7. Integrating thy/exp/cs

Simulation at SoLID 22

	Q2min	Q2max	xmin	xmax	acceptance	xmid	Q2mid	W2	rs
1	9.0	10.0	0.24	0.28	0.150635	0.26	9.5	27.9183055384...	6.42432...
2	10.0	11.0	0.28	0.32	0.208101	0.300000...	10.5	25.3798439999...	6.42432...
3	11.0	12.0	0.28	0.32	0.137562	0.300000...	11.5	27.7131773333...	6.42432...
4	11.0	12.0	0.32	0.36	0.226112	0.339999...	11.5	23.2033734117...	6.42432...
5	12.0	13.0	0.32	0.36	0.267877	0.339999...	12.5	25.1445498823...	6.42432...
6	12.0	13.0	0.36	0.4	0.227464	0.38	12.5	21.2745808421...	6.42432...
7	13.0	14.0	0.36	0.4	0.355759	0.38	13.5	22.9061597894...	6.42432...
8	14.0	15.0	0.36	0.4	0.185517	0.38	14.5	24.5377387368...	6.42432...
9	13.0	14.0	0.4	0.44	0.220877	0.420000...	13.5	19.5227011428...	6.42432...
10	14.0	15.0	0.4	0.44	0.377228	0.420000...	14.5	20.9036535238...	6.42432...
11	15.0	16.0	0.4	0.44	0.305199	0.420000...	15.5	22.2846059047...	6.42432...
12	14.0	15.0	0.44	0.48	0.218991	0.459999...	14.5	17.9015831304...	6.42432...

Thanks to: T. Liu & M. Dalton for providing the table

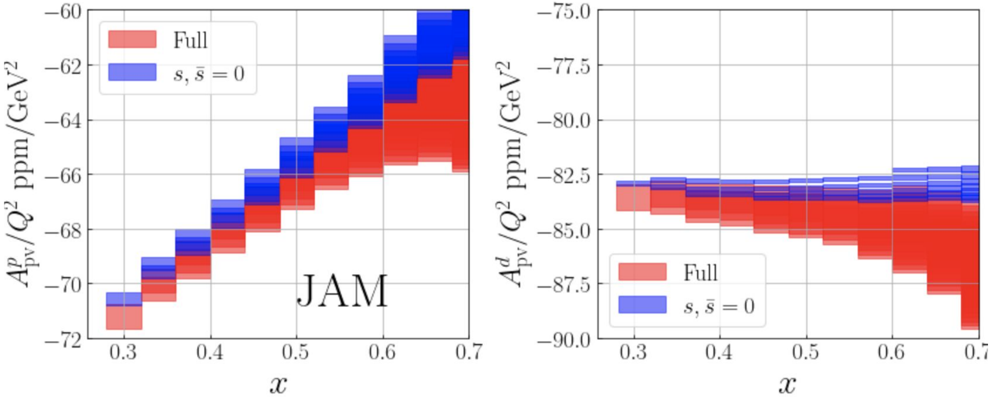


$$N_{\text{bin}} = \mathcal{L} \left. \frac{d\sigma}{dx dQ^2} \right|_{\text{mid}} \times \Delta x \, \Delta Q^2$$

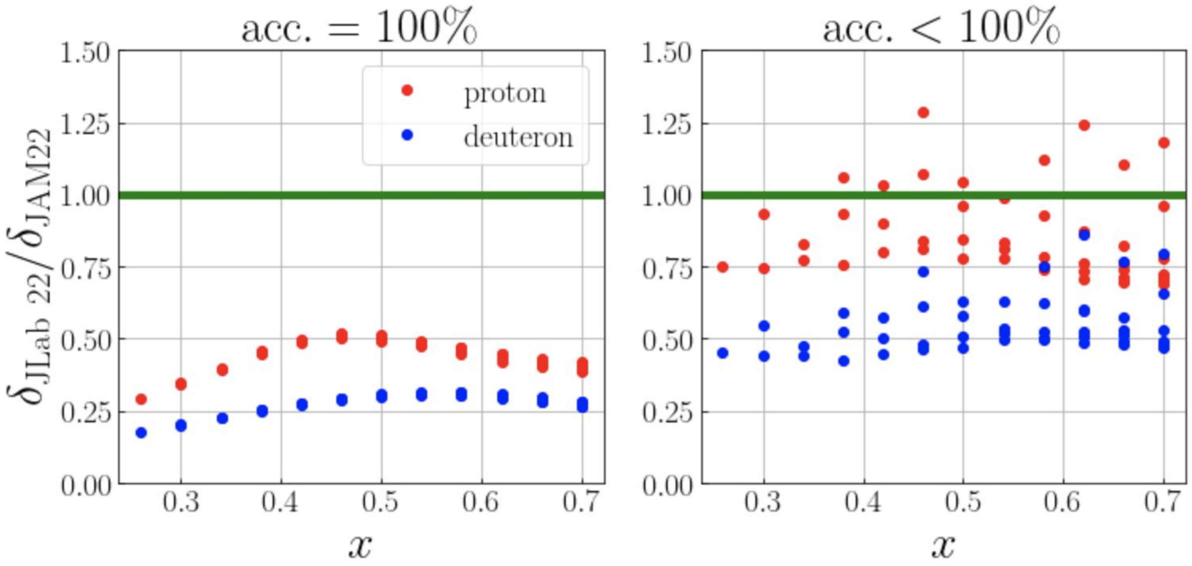
$$\delta A_{\text{pv}} = \frac{1}{\sqrt{N_{\text{bin}}}}$$

$$\mathcal{L} = 5.0 \times 10^{38} \text{cm}^{-2} s^{-1}$$

200 days of data taking

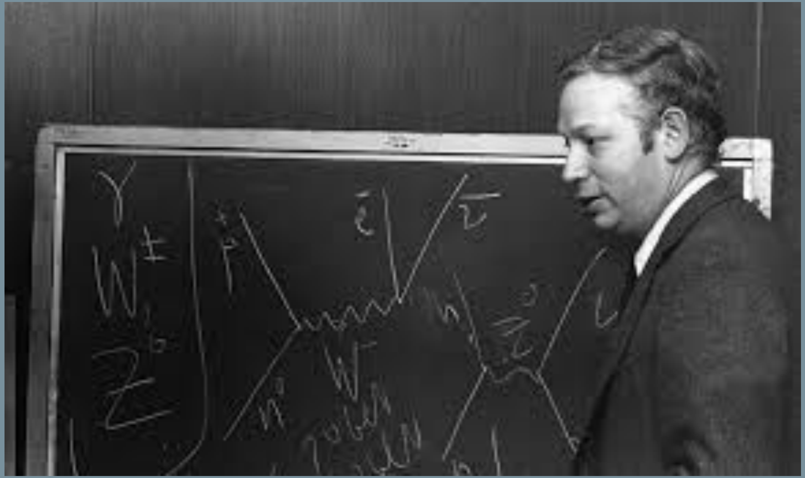


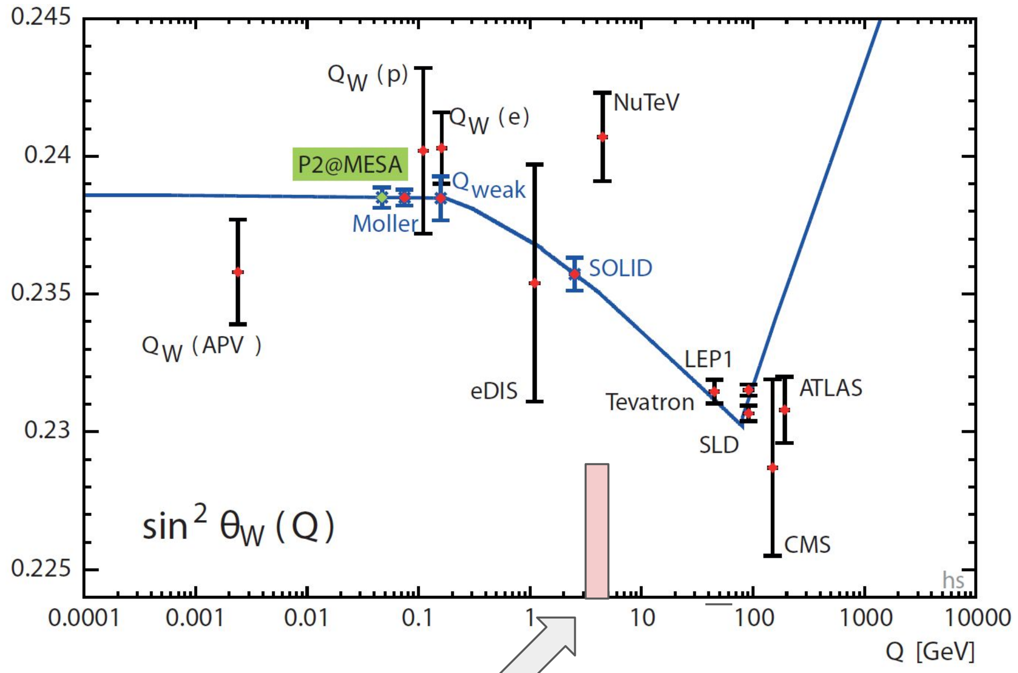
Spread represents PDF uncertainties

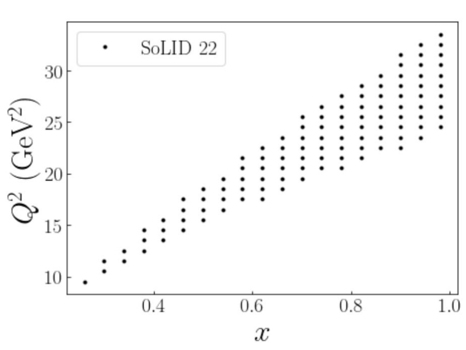


Outline

1. Recent highlights
2. Status of strange pdf
3. Parity violating DIS
4. PVDIS @ SoLID -22
5. Sin2W
6. QED radiative effects
7. Integrating thy/exp/cs







In principle there are two unknowns:

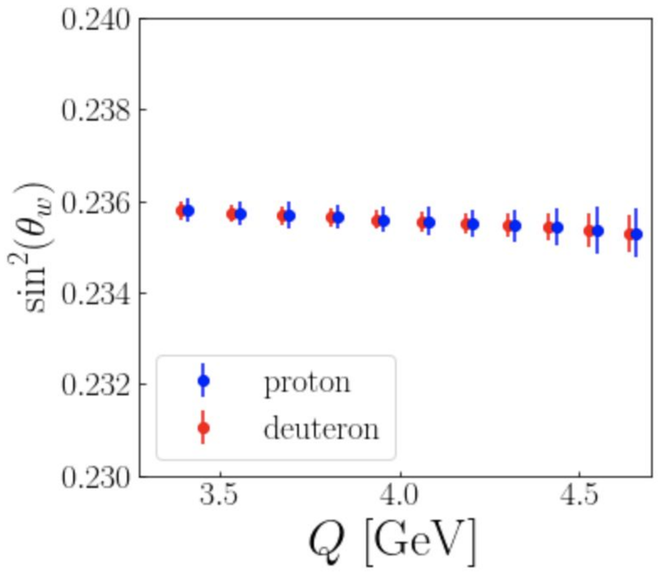
1) The running of sin2w as a function of scale
2) The value of sin2w at a given scale

Point-by-point extraction of sin2w

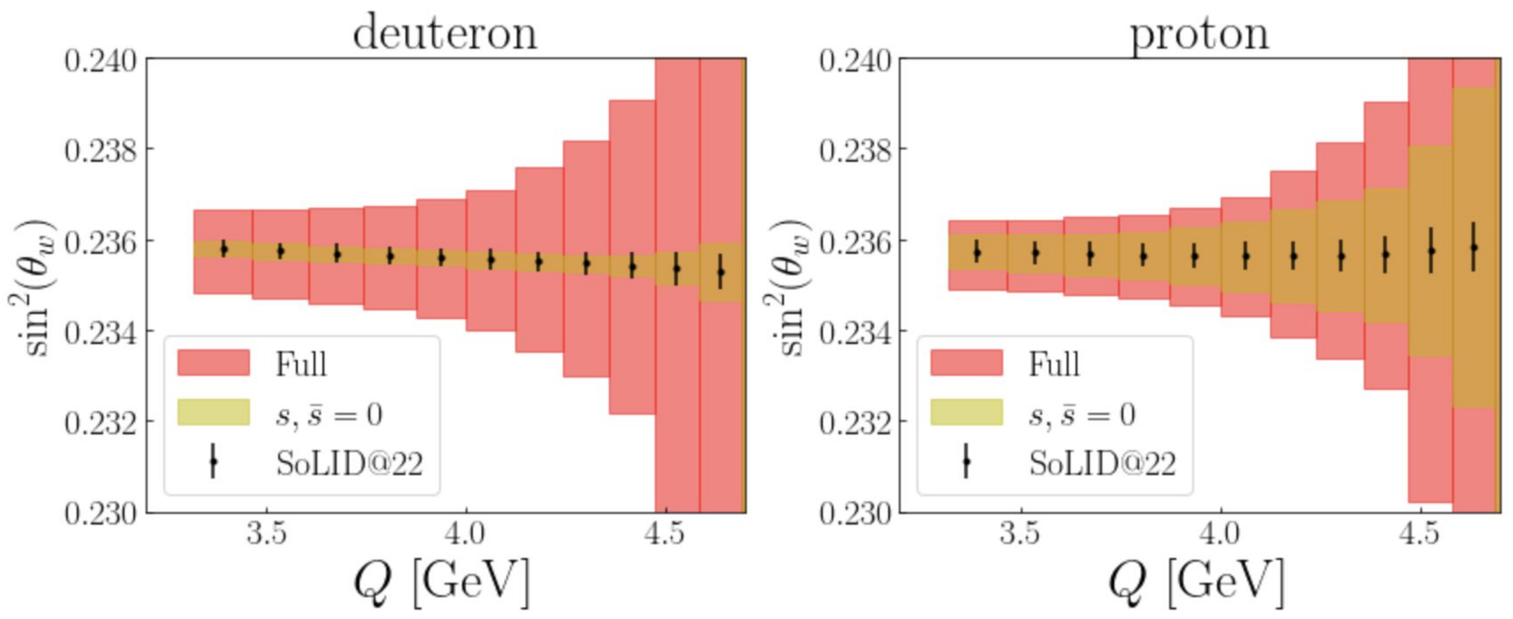
$$\sin^2\theta_W(Q) = \frac{2\sqrt{2}\pi A_{pv} F_1^{gg}\alpha}{F_3^{gZ} G_F Q^2 Y_3} - \frac{F_1^{gZ} Y_1 g_A}{F_3^{gZ} Y_3} + \frac{1}{4}$$

Procedure:

- Measure Apv
- Use existing knowledge of structure functions to solve for sin2w point-by-point in Q
- Combine different x values using linear regression.
- Propagate uncertainties from Apv using gaussian approximation



Taking into account PDF errors

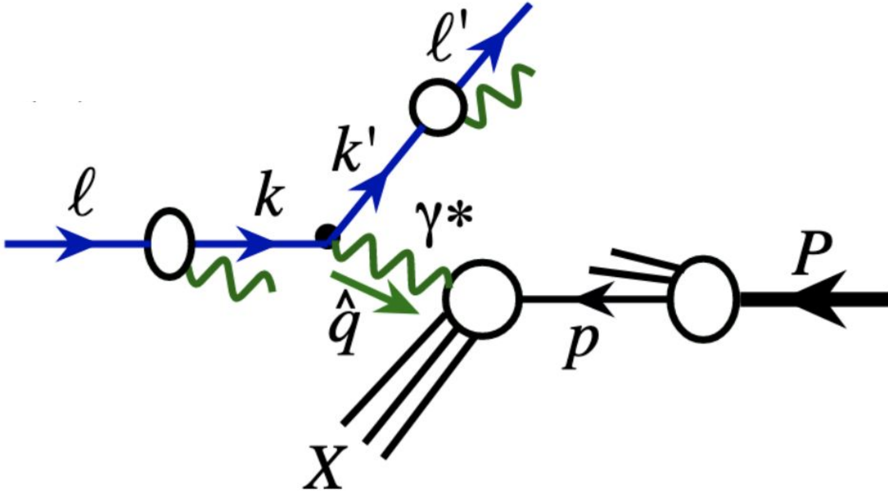


Bottom line: using protons and deuteron, one can solve for the unknowns eg strangeness + sin2w

Simultaneous fit of pdfs and eweak parameters!

Outline

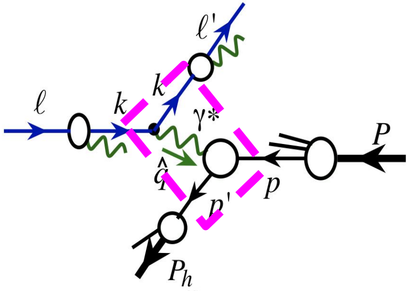
1. Recent highlights
2. Status of strange pdf
3. Parity violating DIS
4. PVDIS @ SoLID -22
5. Sin2W
6. QED radiative effects
7. Integrating thy/exp/cs



Factorized approach to radiative corrections for inelastic lepton-hadron collisions

Tianbo Liu, W. Melnitchouk, Jian-Wei Qiu, and N. Sato
Phys. Rev. D **104**, 094033 – Published 19 November 2021

Hybrid QED+QCD factorization



$$E' \frac{d\sigma_{\text{DIS}}}{d^3\ell'} = \frac{1}{2s} \sum_{ija} \int_{z_L}^{1} \frac{d\zeta}{\zeta^2} \int_{x_L}^{1} \frac{d\xi}{\xi} \underline{D_{e/j}(\zeta)\, f_{i/e}(\xi)}$$

$$\times \int_{x_h}^{1} \frac{dx}{x} f_{a/N}(x)\, \widehat{H}_{ia\to j}(\xi,\zeta,x) + \mathcal{O}\Big(\frac{1}{\ell'^2_T}\Big),$$

Collinear LDFs and LFFs

Collinear PDFs

Short distance hard part

Collinear LDFs and LFFs

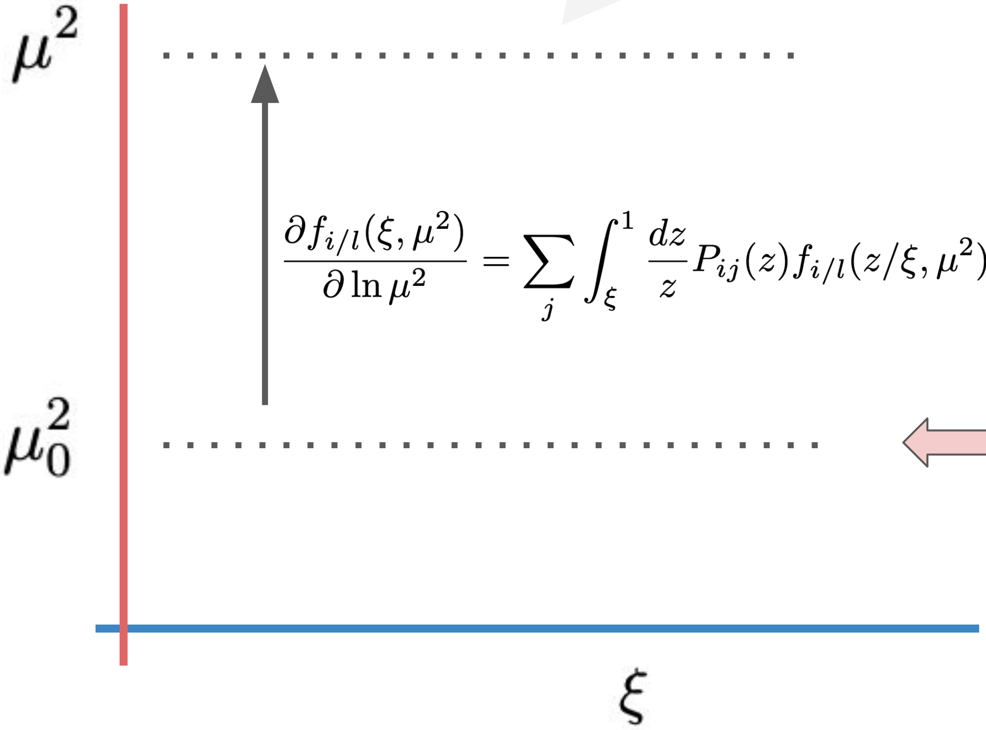
$$f_{i/e}(\xi) = \int \frac{dz^-}{4\pi}\, e^{i\xi\ell^+ z^-} \langle e|\,\overline{\psi}_i(0)\gamma^+\Phi_{[0,z^-]}\,\psi_i(z^-)|e\rangle$$

$$D_{e/j}(\zeta) = \frac{\zeta}{2}\sum_X \int \frac{dz^-}{4\pi} e^{i\ell'^+ z^-/\zeta}\, \mathrm{Tr}\big[\gamma^+\langle 0|\,\overline{\psi}_j(0)\Phi_{[0,\infty]}\,|e,X\rangle\langle e,X|\psi_j(z^-)\Phi_{[z^-,\infty]}|0\rangle\big].$$

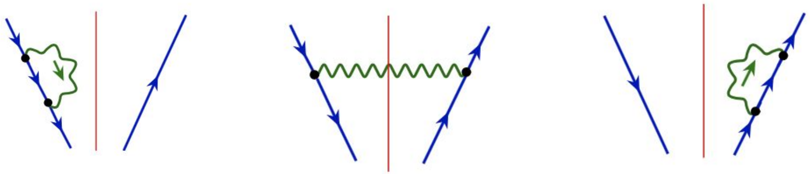
perturbatively calculable if we neglect hadronic components

RGE

Resummation of collinear logs



$$\frac{\partial f_{i/l}(\xi,\mu^2)}{\partial \ln \mu^2} = \sum_j \int_\xi^1 \frac{dz}{z} P_{ij}(z) f_{i/l}(z/\xi,\mu^2)$$



$$f^{(0)}_{e/e}(\xi) = \delta(\xi - 1)$$

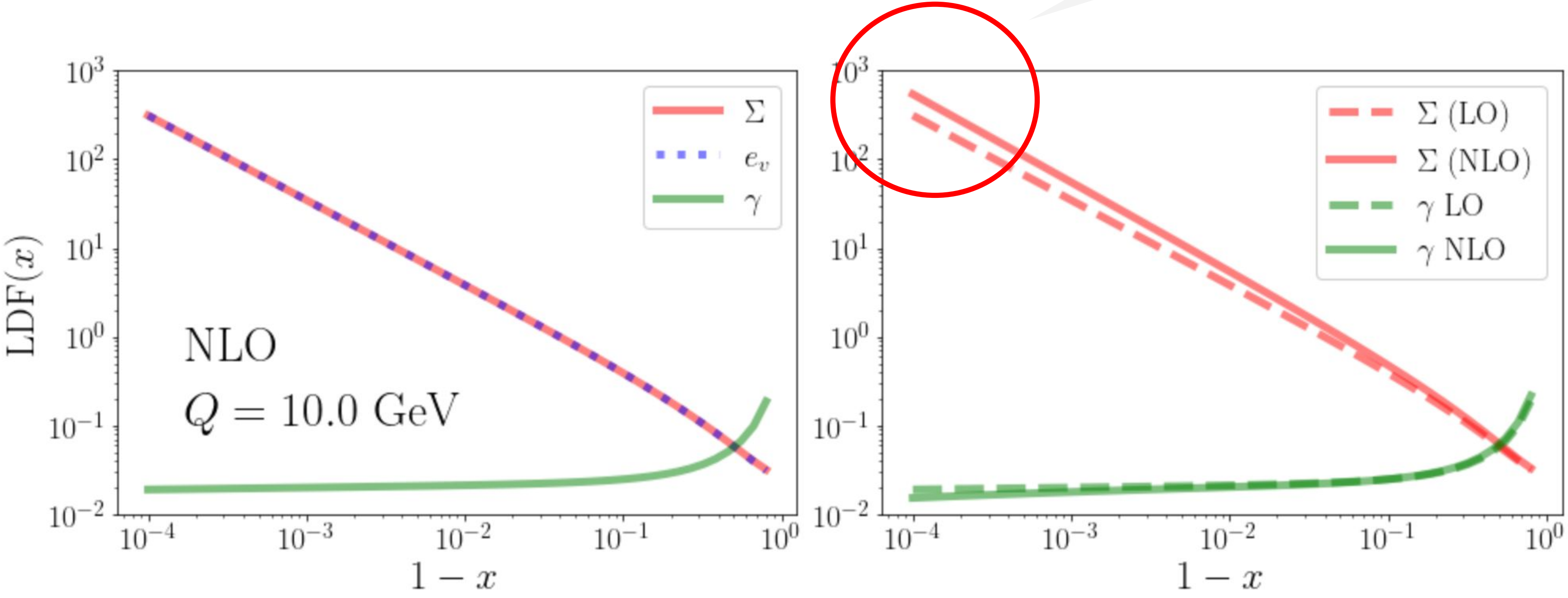
$$f^{(1)}_{e/e}(\xi,\mu_0^2) = \frac{\alpha}{2\pi}\left[\frac{1+\xi^2}{1-\xi}\ln\frac{\mu_0^2}{(1-\xi)^2\, m_e^2}\right]_+$$

$$D^{(0)}_{e/e}(\zeta) = \delta(\zeta - 1)$$

$$D^{(1)}_{e/e}(\zeta,\mu_0) = \frac{\alpha}{2\pi}\left[\frac{1+\zeta^2}{1-\zeta}\ln\frac{\zeta^2\mu_0^2}{(1-\zeta)^2\, m_e^2}\right]_+$$

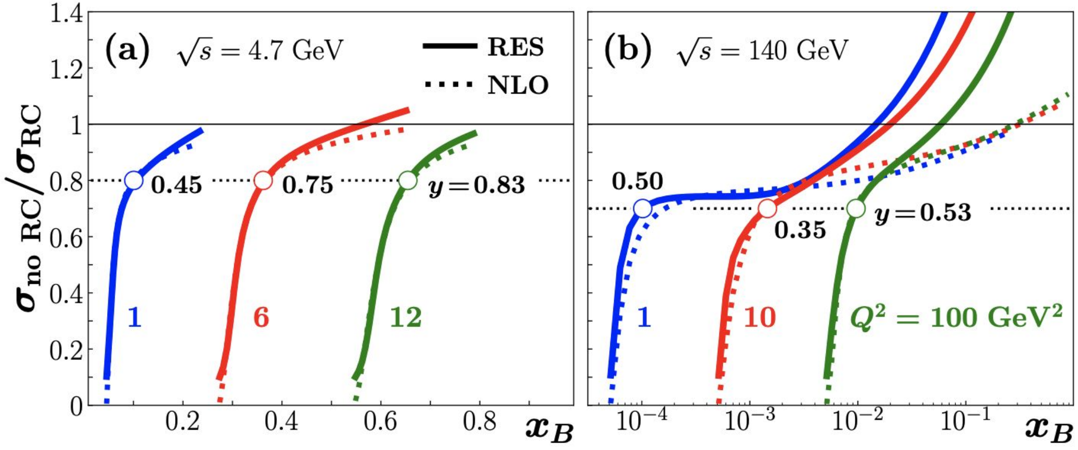
Evolution effects

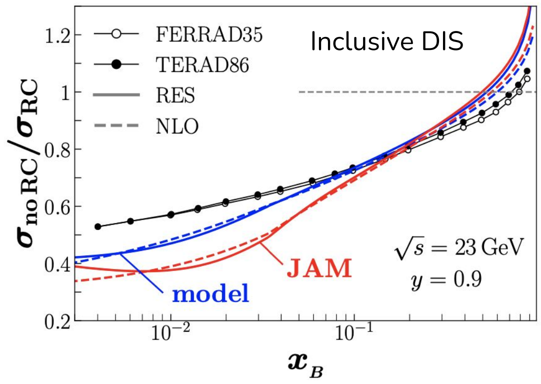
LDFs peaks at the endpoint



Some examples from inclusive DIS

Liu, Melnitchouk, Qiu, Sato ('20, `21)

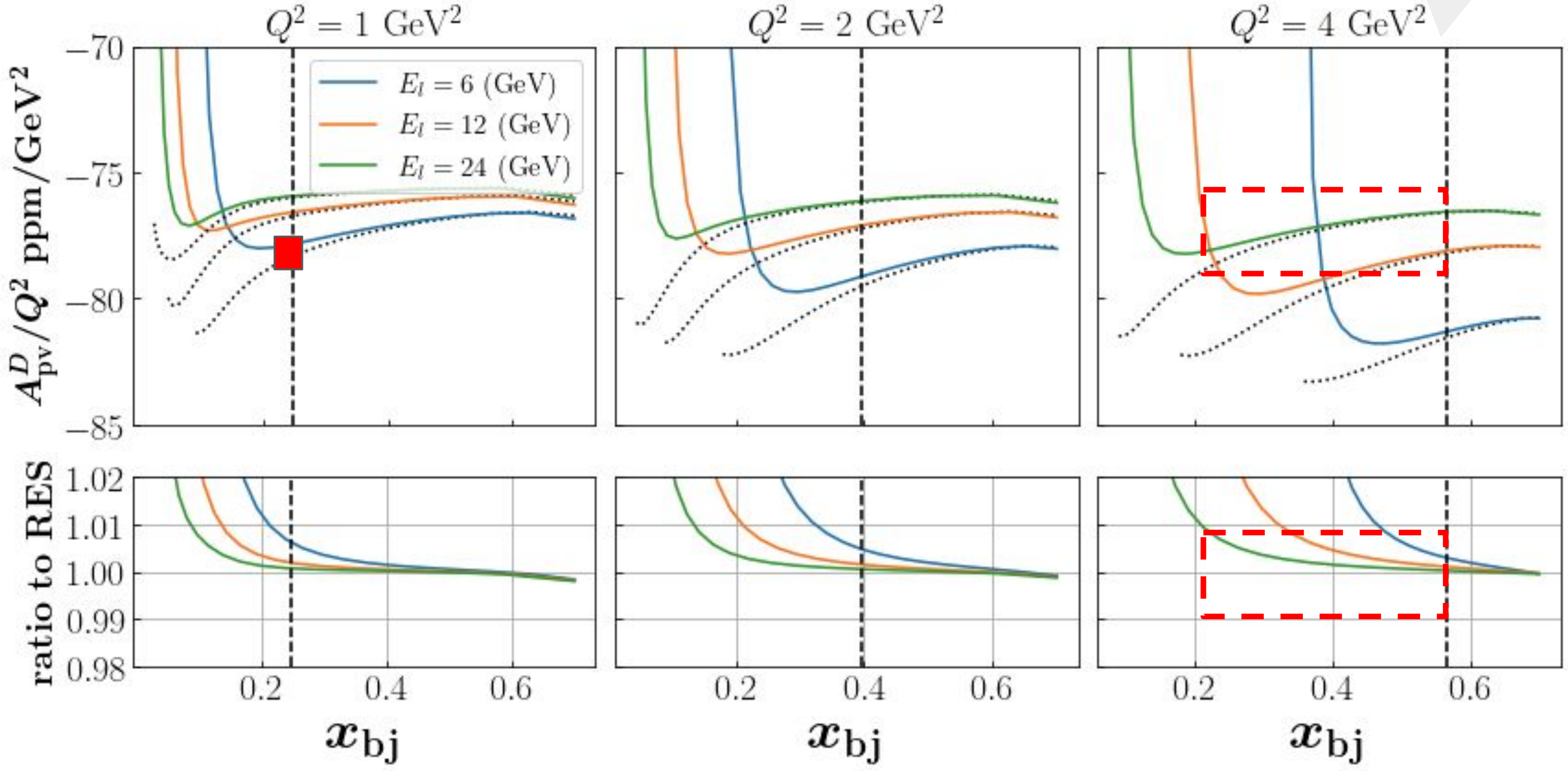




- QED "corrections" depend on the input hadronic tensor
- Not possible to construct model-independent QED RC corrections
- Need to include QED in global analysis

Apv with QED effects

W2 > 4 GeV2



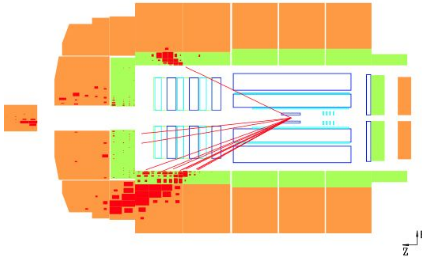
Outline

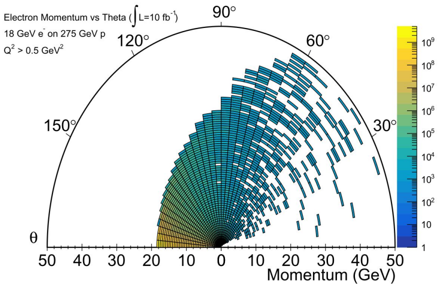
1. Recent highlights
2. Status of strange pdf
3. Parity violating DIS
4. PVDIS @ SoLID -22
5. Sin2W
6. QED radiative effects
7. Integrating thy/exp/cs

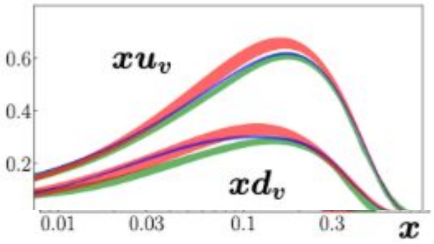
Existing paradigm -> histogram approach

Inverse problem   Inverse problem

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

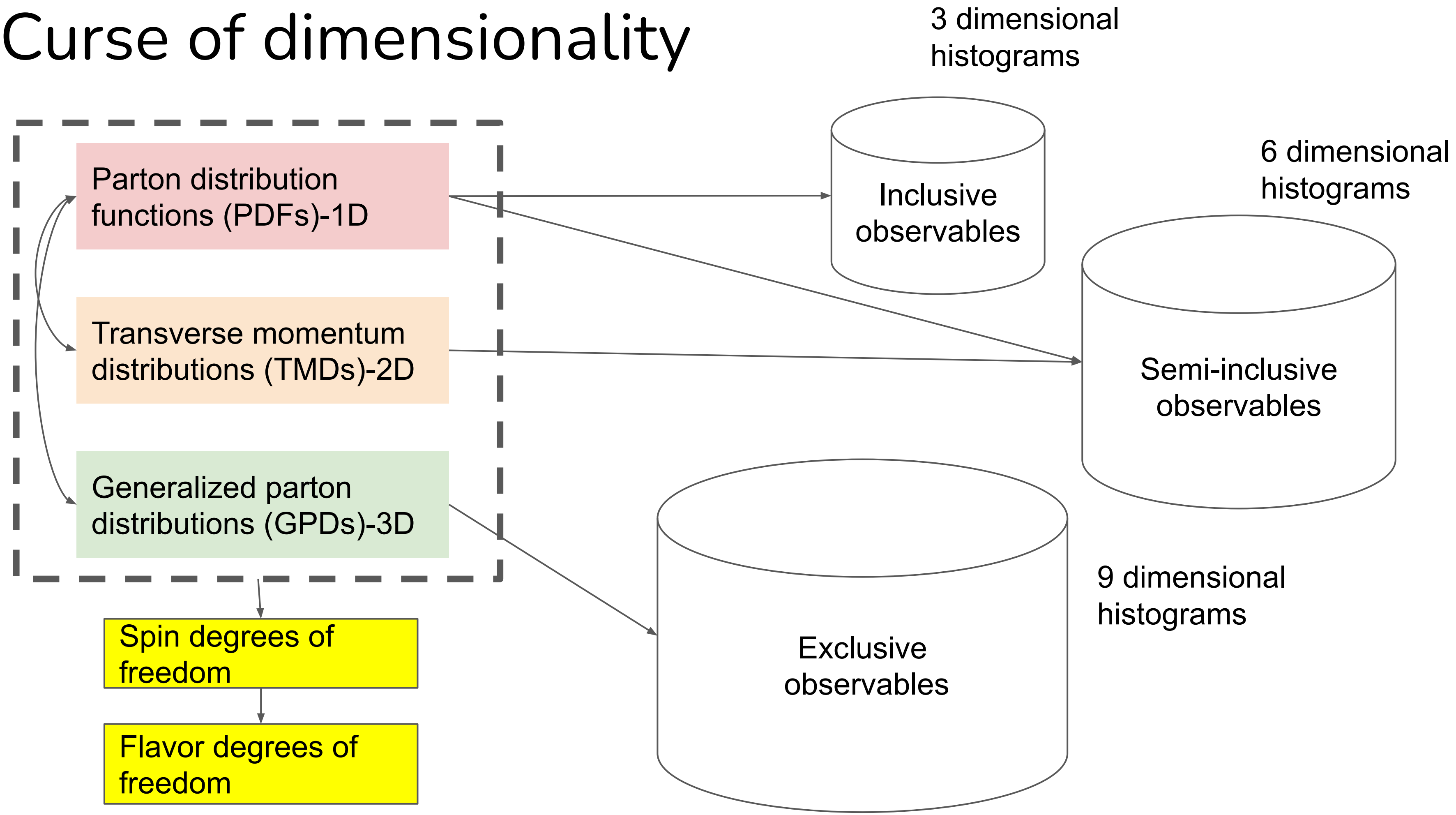






1D QCFs

Curse of dimensionality

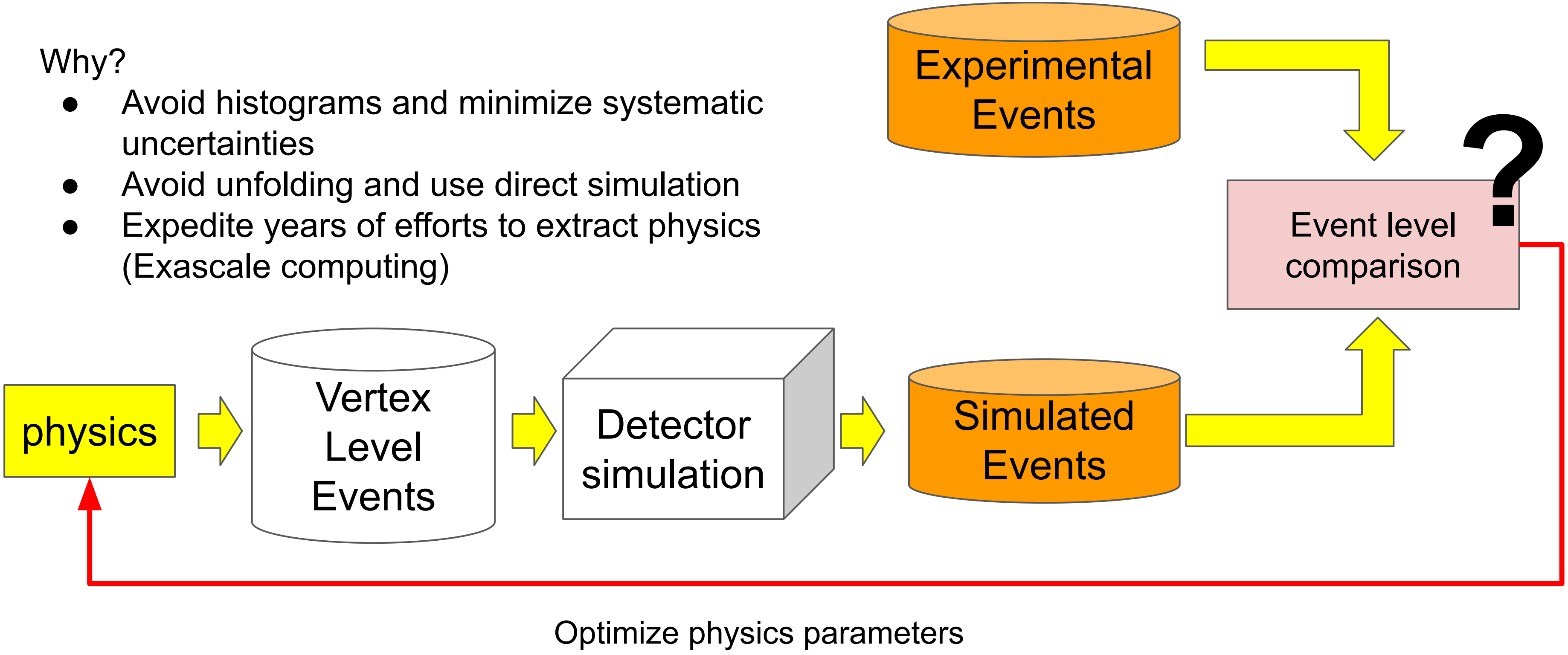


Event-based analysis for global analysis?

Can we compare real vs synthetic events?

Why?

- Avoid histograms and minimize systematic uncertainties
- Avoid unfolding and use direct simulation
- Expedite years of efforts to extract physics (Exascale computing)



QuantOm Collaboration

Jefferson Lab

Argonne NATIONAL LABORATORY

VT

OLD DOMINION UNIVERSITY

Theory

- Jianwei Qiu (PI)
- NS
- Adam Freez (postdoc)

Experiment

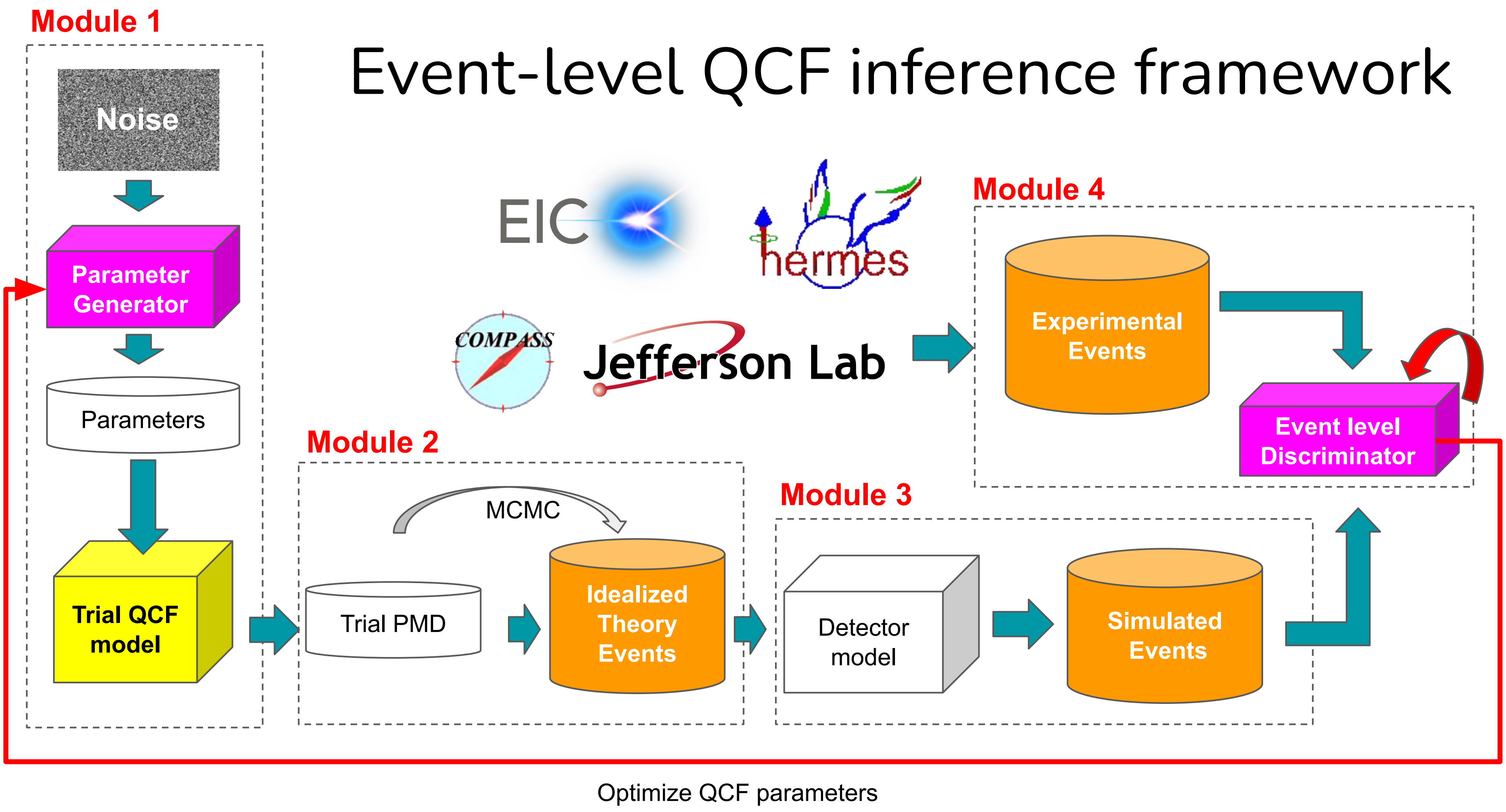
- Markus Diefenthaler
- Daniel Lersch

CS

- Malachi Schram
- Kishan Rajput
- Daniel Lersch
- Yasir Alanazi (postdoc)

Supported by DOE SciDAC

Event-level QCF inference framework

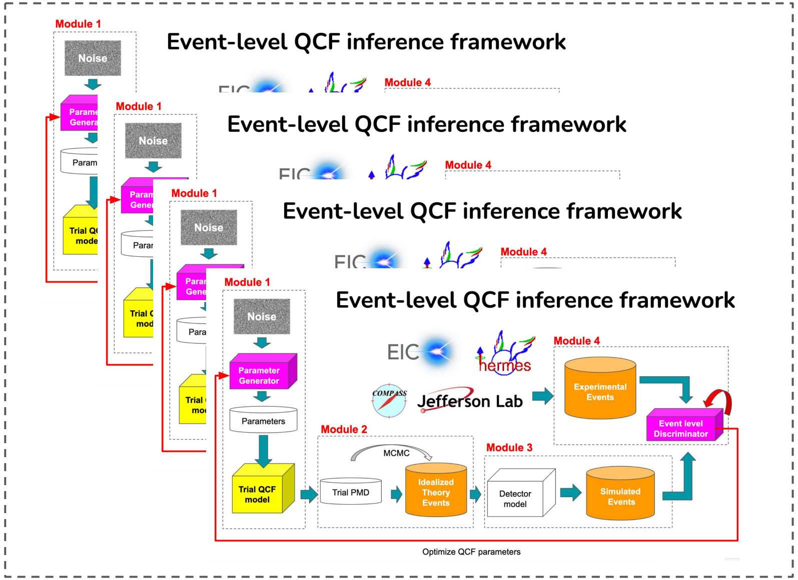


Opportunities

- 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



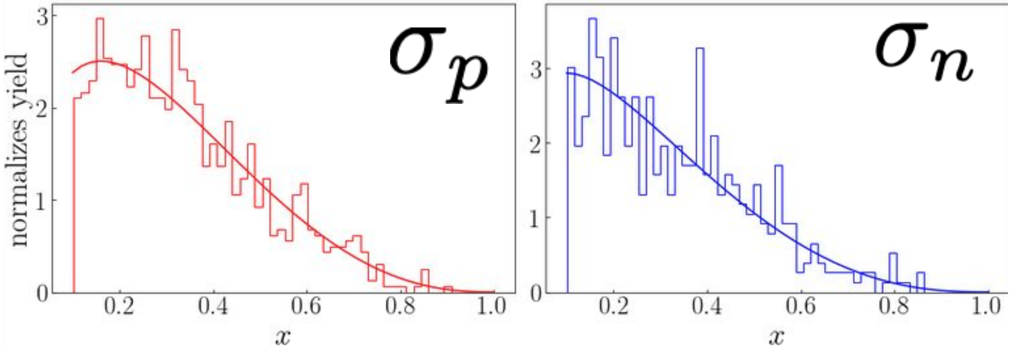
An example with a proxi theory

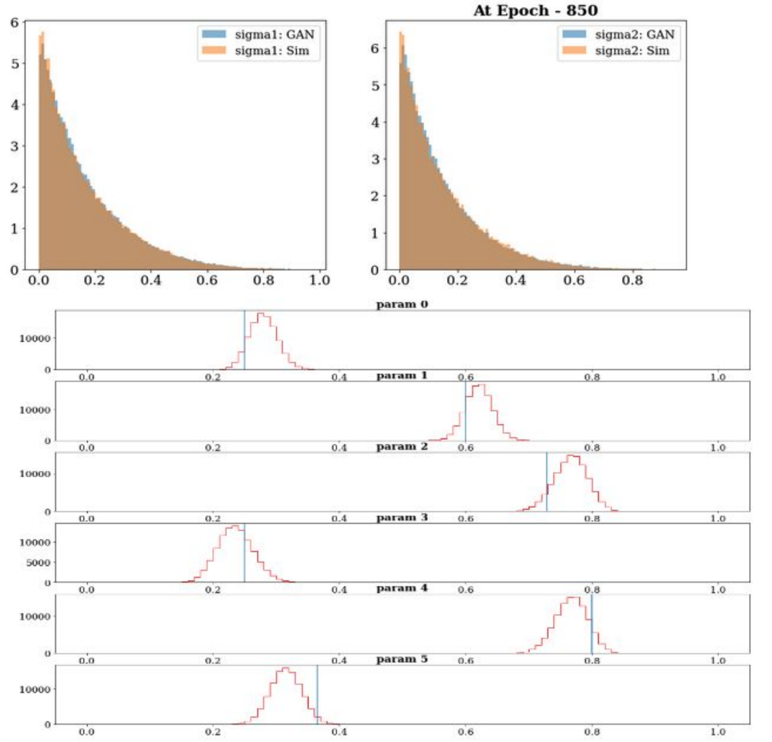
$$u(x) = N_u x^{a_u} (1-x)^{b_u}$$
$$d(x) = N_d x^{a_d} (1-x)^{b_d}$$

6 parameter QCFs model

$$\sigma_p(x) = 4\,u(x) + d(x),$$
$$\sigma_n(x) = 4\,d(x) + u(x).$$

Proxi cross sections



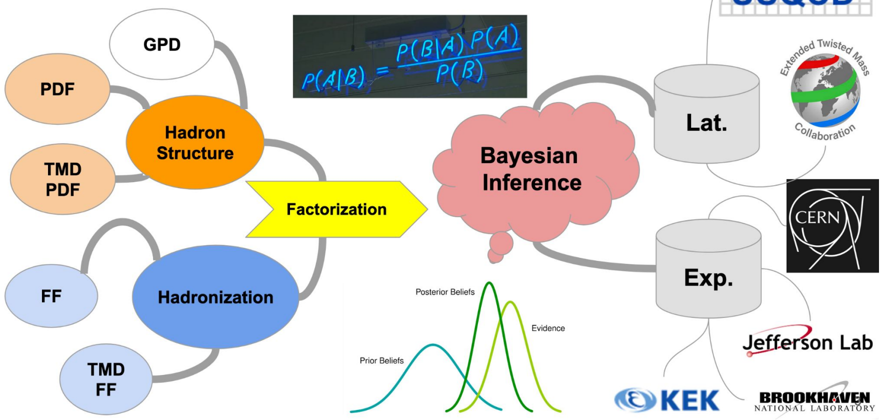


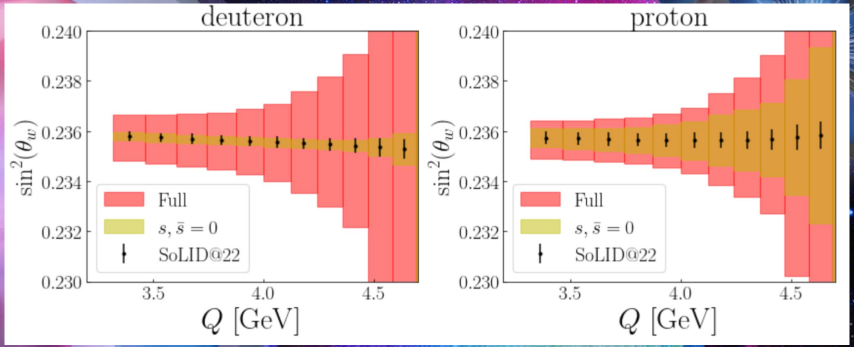
Workflow can produce parameter samples close to the truth

Summary

- Apv program is critical to map finer details of hadron structure -> the strange sector of the nucleon
- Precision electroweak studies requires the use of simultaneous global analysis framework
- We really need JLab 22!

A holistic approach for global analysis





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