What can we learn from PVDIS

Nobuo Sato

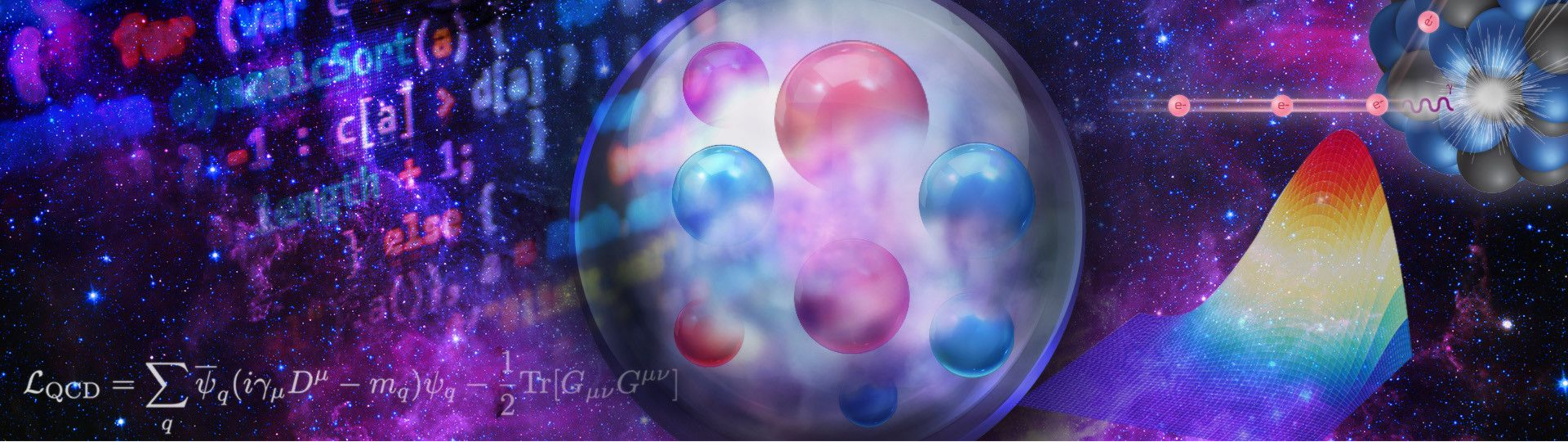
In collaboration with:
T. Liu, J. Qiu & W. Melnitchouk

HEP workshop series '22: Science at Mid x: Anti-Shadowing and the Role of the Sea

Jul 22 2022

Jefferson Lab

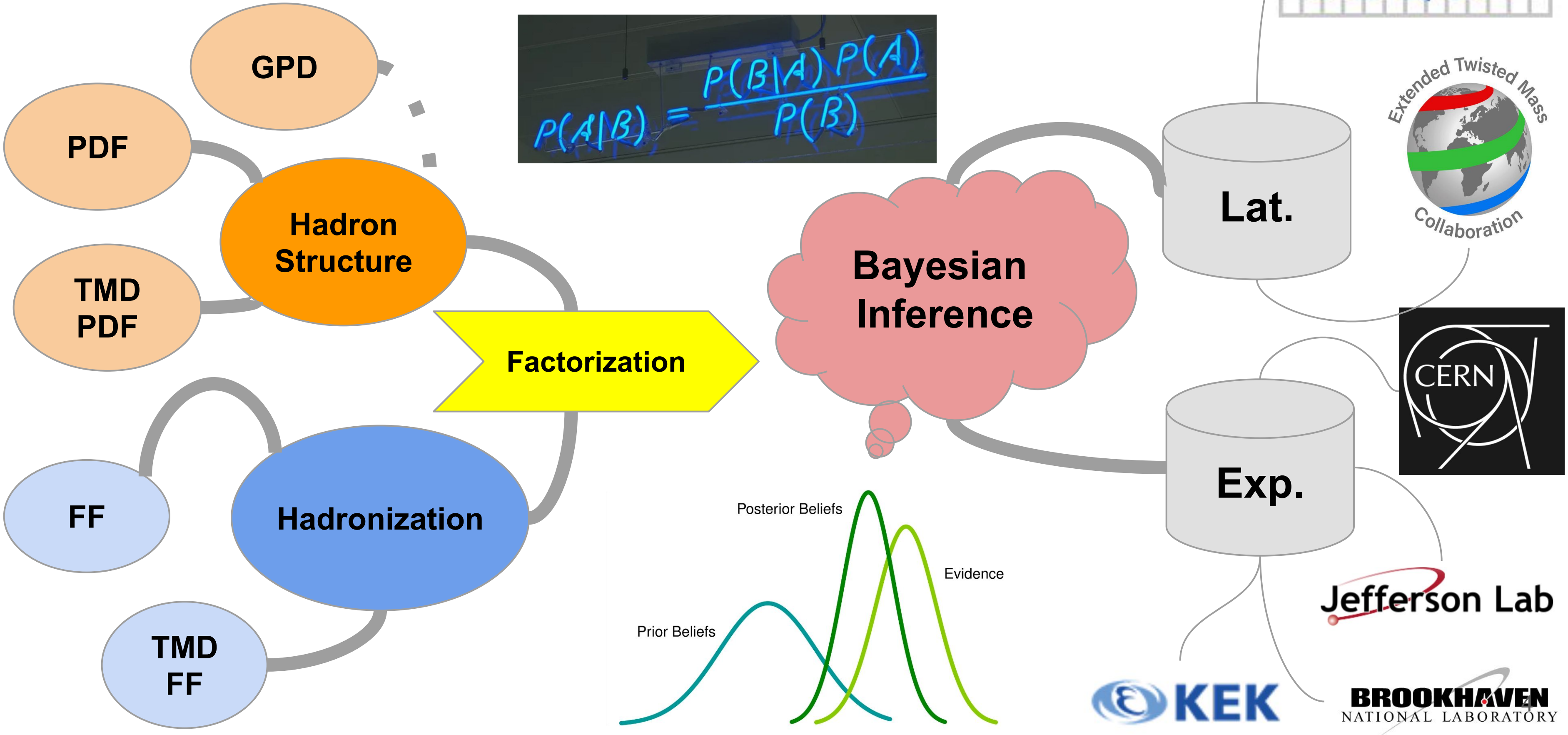
Motivation



JEFFERSON LAB ANGULAR MOMENTUM COLLABORATION

The Jefferson Lab Angular Momentum (JAM) Collaboration is an enterprise involving theorists, experimentalists, and computer scientists from the Jefferson Lab community using QCD to study the internal quark and gluon structure of hadrons and nuclei. Experimental data from high-energy scattering processes are analyzed using modern Monte Carlo techniques and state-of-the-art uncertainty quantification to simultaneously extract various quantum correlation functions, such as parton distribution functions (PDFs), fragmentation functions (FFs), transverse momemtum dependent (TMD) distributions, and generalized parton distributions (GPDs). Inclusion of lattice QCD data and machine learning algorithms are being explored to potentially expand the reach and efficacy of JAM analyses and our understanding of hadron structure in QCD.

The JAM global analysis paradigm



f_1, d_1

Strange quark suppression from a simultaneous Monte Carlo analysis of parton distributions and fragmentation functions

JAM Collaboration • N. Sato (Old Dominion U. and Jefferson Lab) et al. (May 9, 2019)

Published in: *Phys.Rev.D* 101 (2020) 7, 074020 • e-Print: 1905.03788 [hep-ph]

f_1, d_1

Simultaneous Monte Carlo analysis of parton densities and fragmentation functions

Jefferson Lab Angular Momentum (JAM) Collaboration • Eric Moffat (Old Dominion U.) et al. (Jan 12, 2021)

Published in: *Phys.Rev.D* 104 (2021) 1, 016015 • e-Print: 2101.04664 [hep-ph]

$f_1, \Delta f_1$

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

Jefferson Lab Angular Momentum (JAM) Collaboration • Y. Zhou (South China Normal U. and Cape Town U., D
Math. 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]

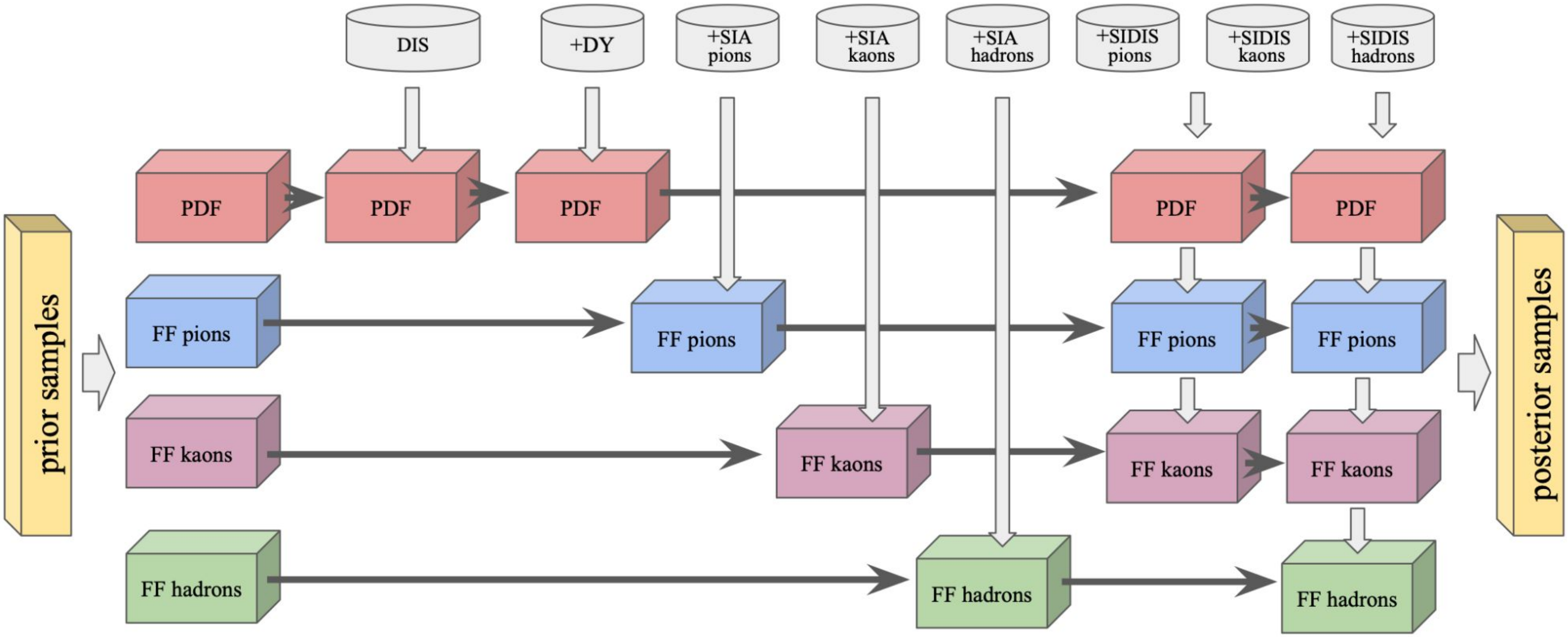
$f_1, \Delta f_1$
d_1

Polarized Antimatter in the Proton from Global QCD Analysis

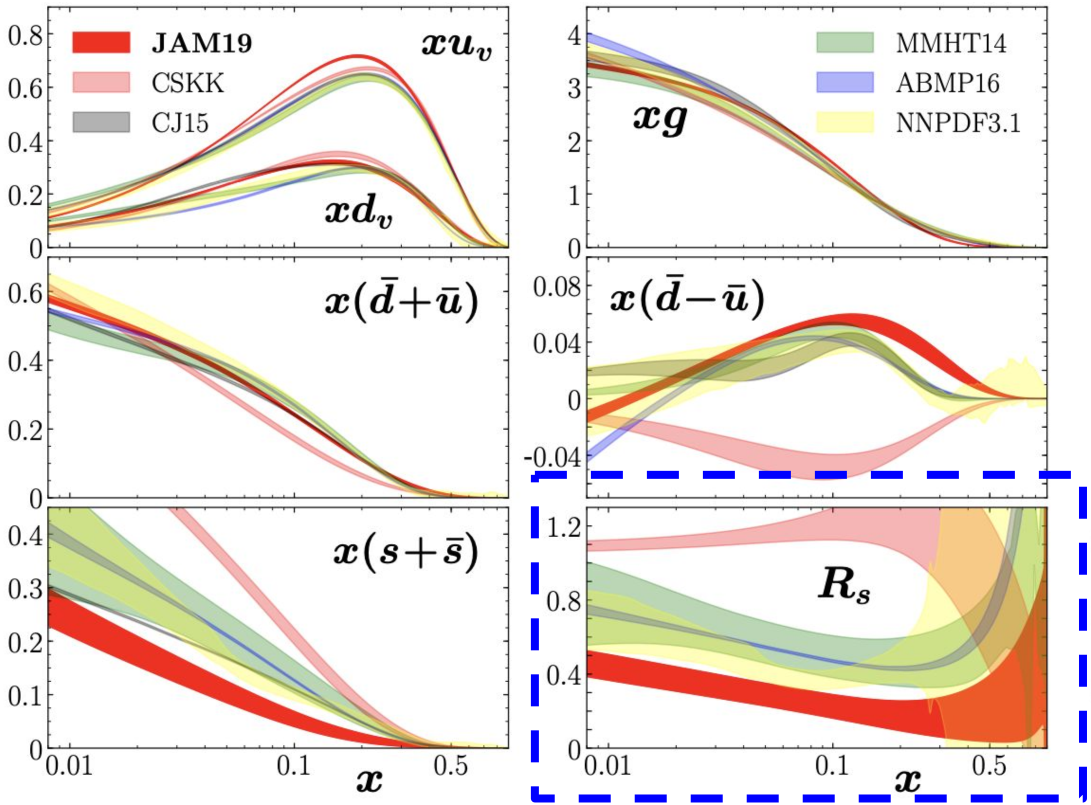
Jefferson Lab Angular Momentum (JAM) Collaboration • C. Cocuzza (Temple U.) et al. (Feb 7, 2022)

e-Print: 2202.03372 [hep-ph]

Multi-step strategy

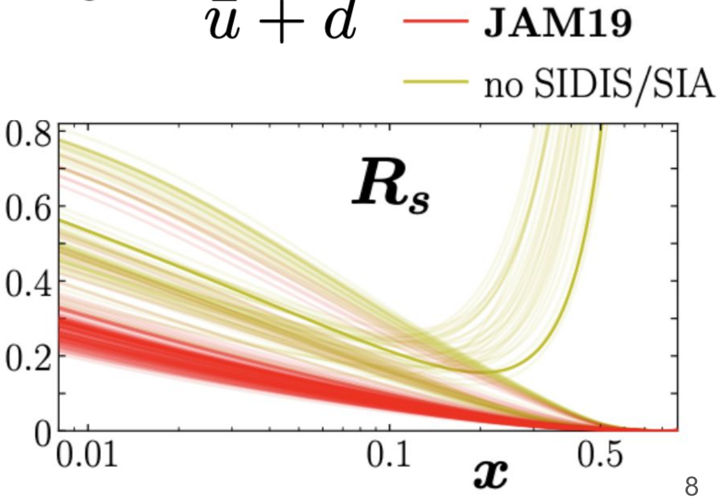


Strange suppression

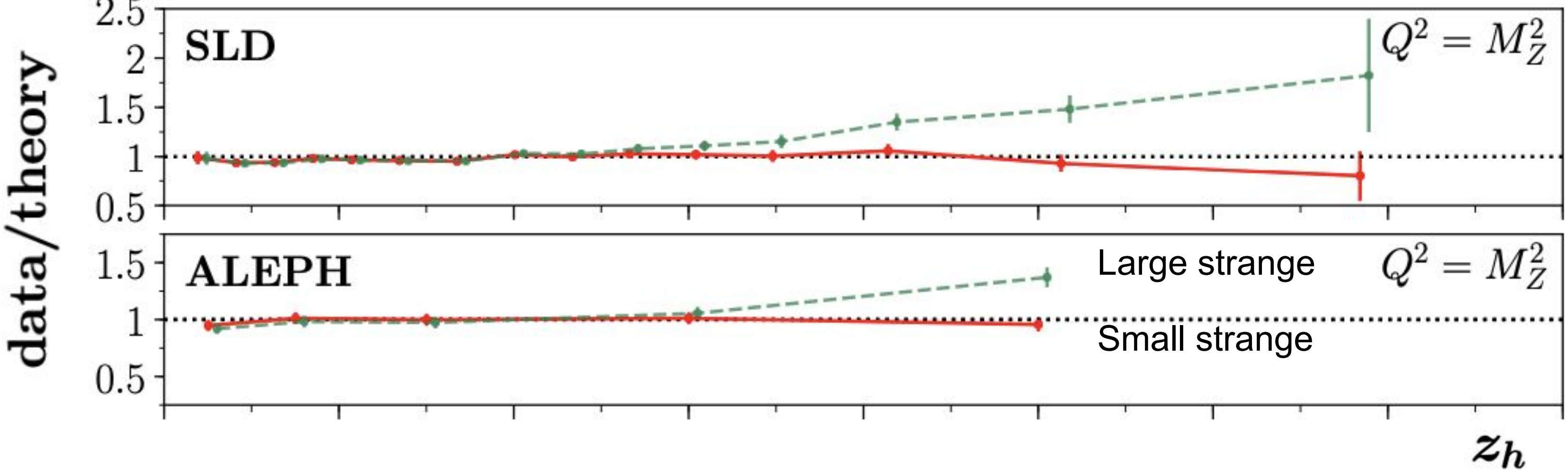


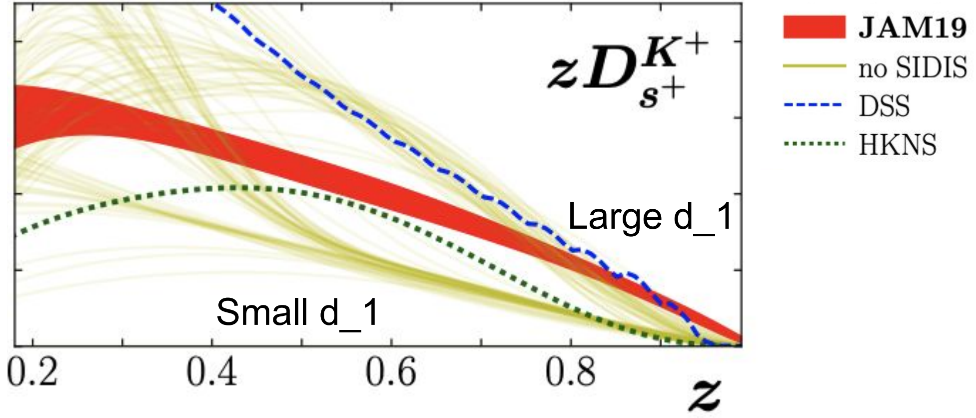
- Strange PDF is one of the least constrained f_1 pdfs
- Different analyses have inferred different sizes of the strangeness

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

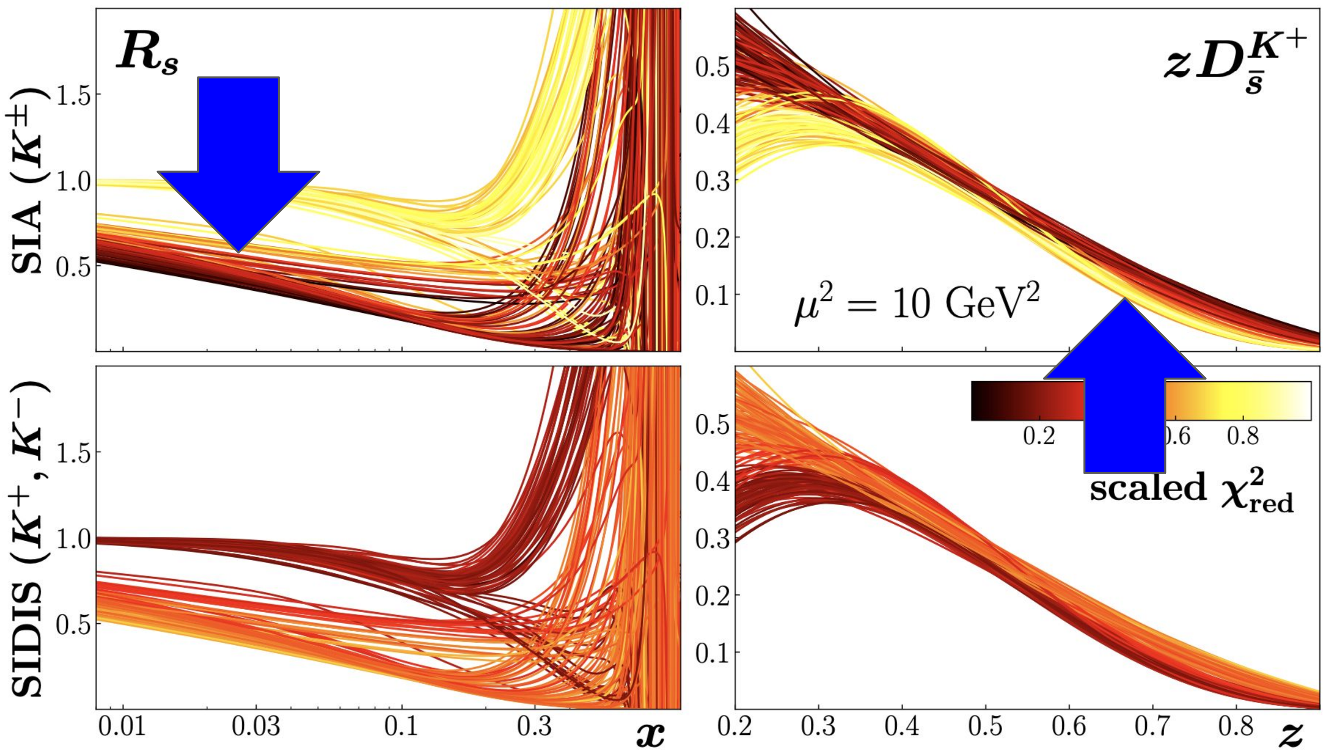


$$e^+e^- \to K^\pm + X$$





- 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

APV

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)

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

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

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

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

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

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

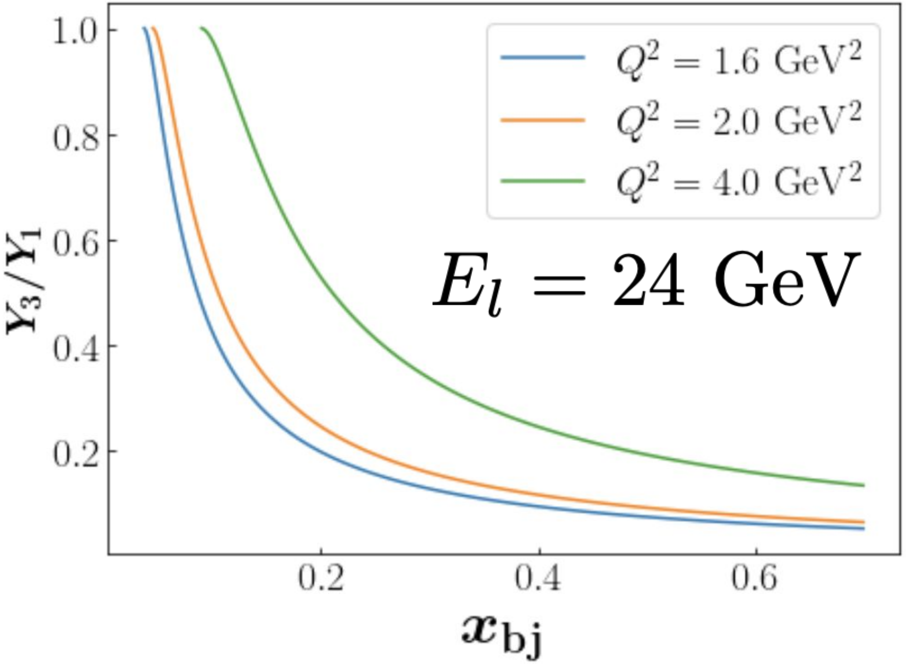
$$Y_1 = \left[\frac{1+R^{\gamma Z}}{1+R^{\gamma}}\right] \frac{1+(1-y)^2 - \frac{y^2}{2}\left[1+r^2-\frac{2r^2}{1+R^{\gamma Z}}\right]}{1+(1-y)^2 - \frac{y^2}{2}\left[1+r^2-\frac{2r^2}{1+R^{\gamma}}\right]}$$

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

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

y dependence at JLab 20+ GeV

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



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

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

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

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

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

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

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

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

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

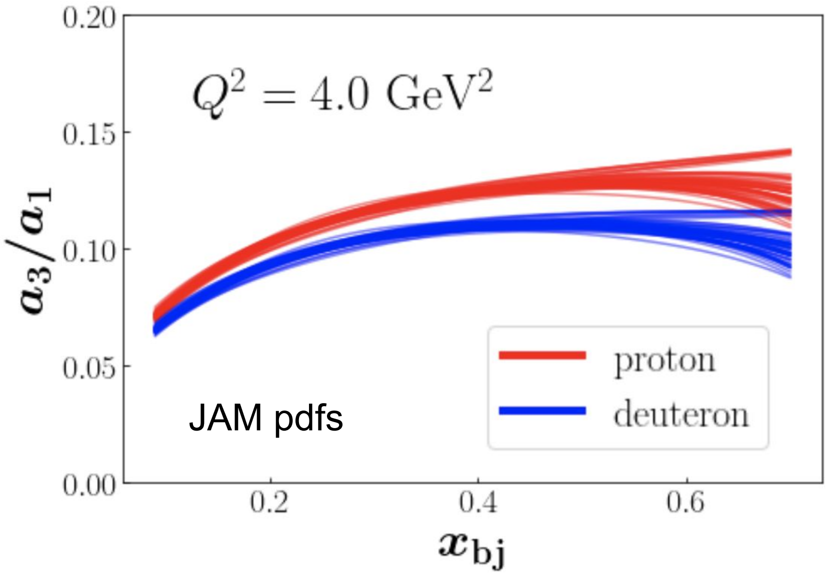
If we ignore s and c and use deuteron target

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

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

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

$E_l = 24\ \mathrm{GeV}$




```
a1
```

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

```
a3
```

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

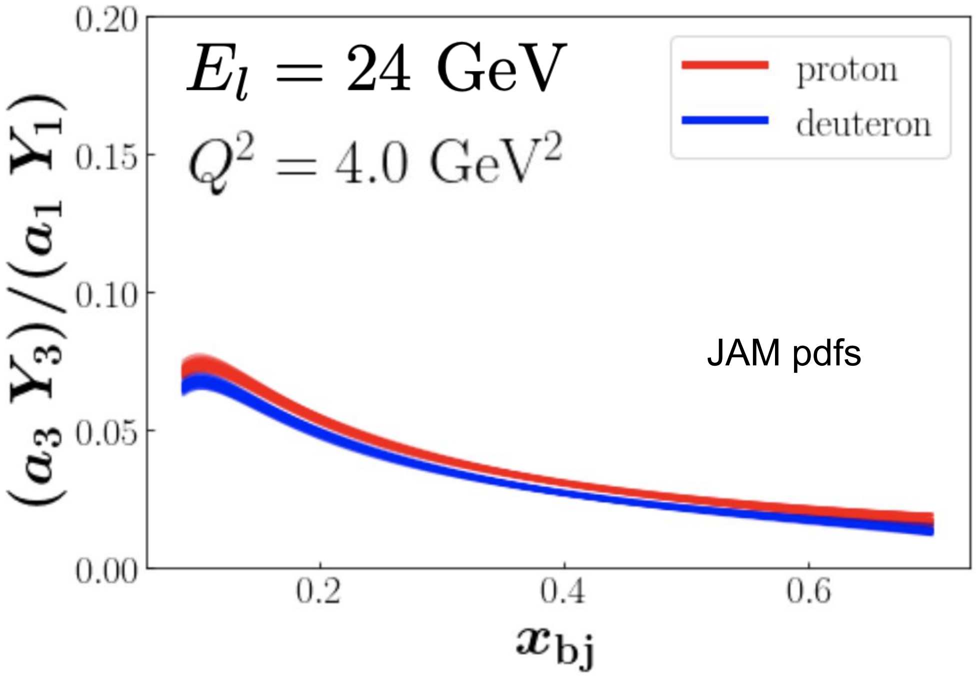
```
expr=a3/a1
expr=expr.subs(s2w,236/sy.S(1000))
expr=expr.subs(cp,0).subs(sp,0).subs(cm,0).subs(sm,0)
expr=expr.subs(dm,dp).subs(um,up).subs(up,2*dp)
sy.Eq(sy.S('a_3/a_1'),expr.simplify())
```

$$\frac{a_3}{a_1} = \frac{35}{271}$$

```
35/271
```

0.12915129151291513

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

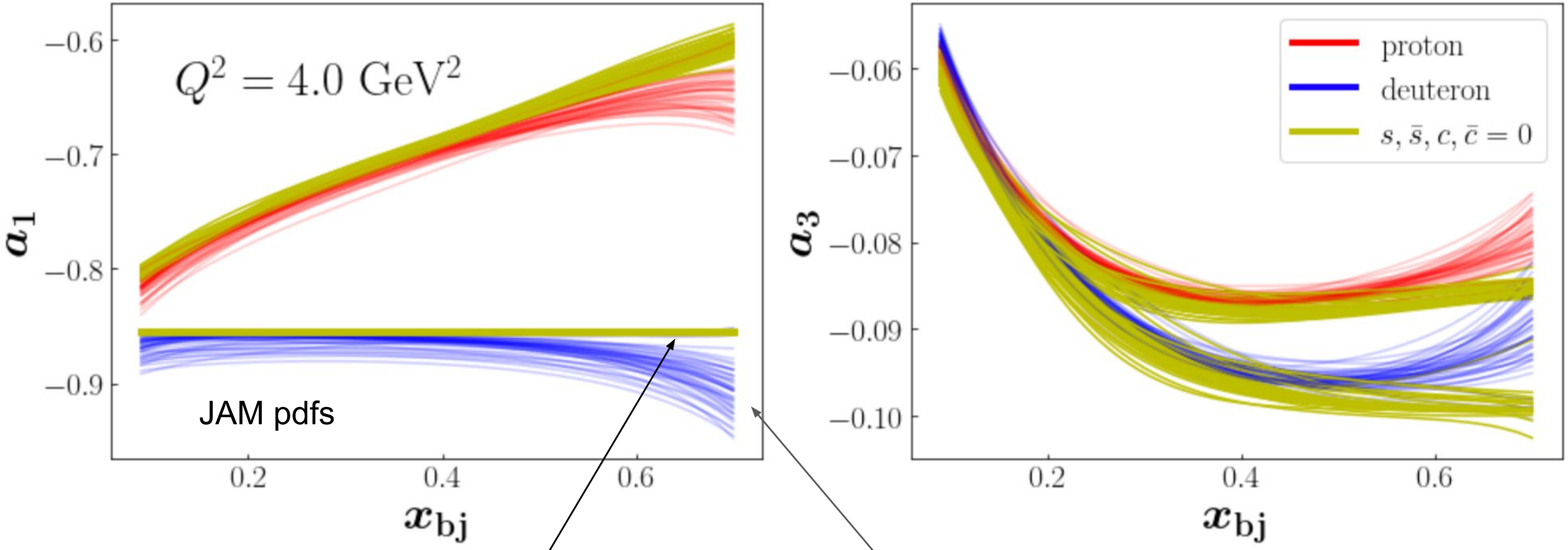


$$a_1(x) = 2g_A^e \frac{F_1^{\gamma Z}}{F_1^{\gamma}}$$

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

At this kinematics, F3 is very suppressed, so most of the action is from F1

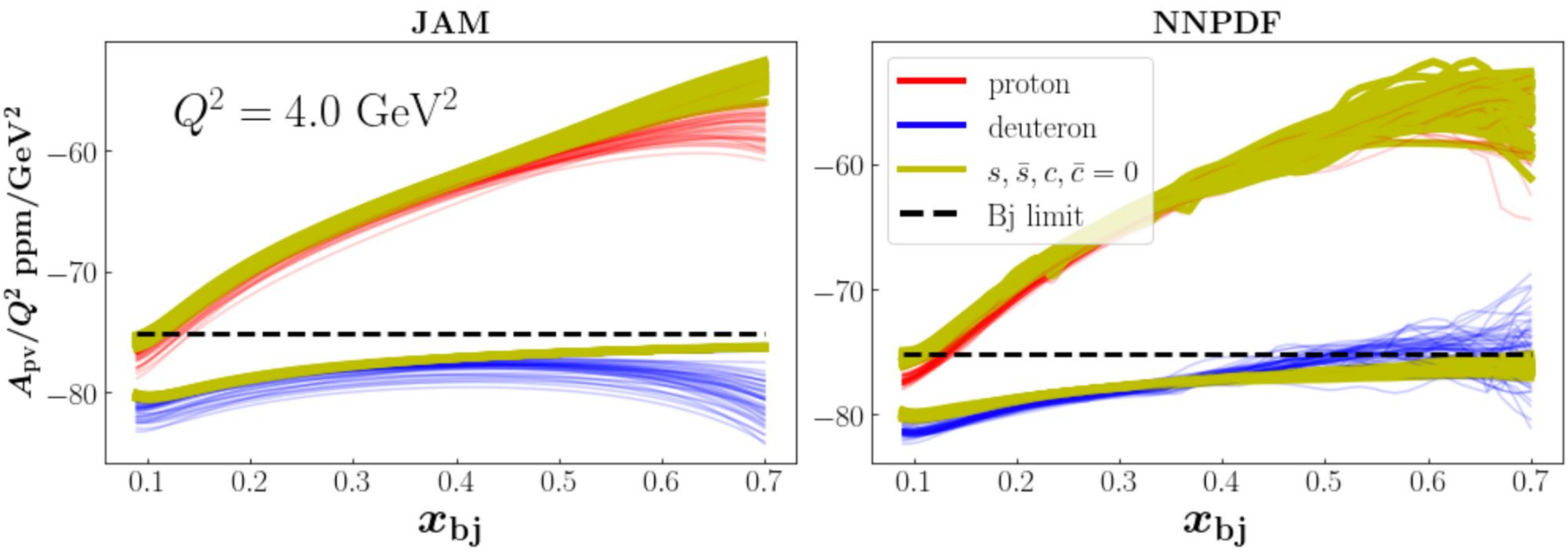
$$s,\ sb,\ c,\ cb = 0$$



If s,c=0 and u=d

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

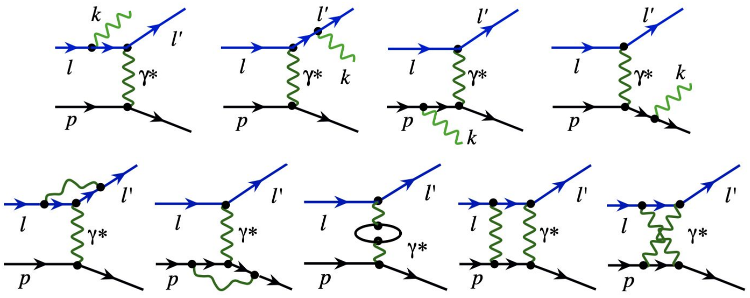
But not all replicas go to the Bj limit
-> so s, sb are not zero



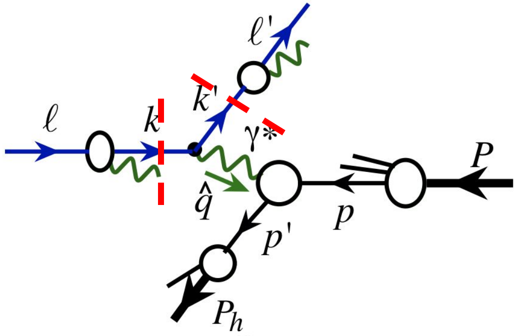
- Do we really know strangeness at large x?
- Apv has the potential to pin down strange quark PDF

A word on QED effects...

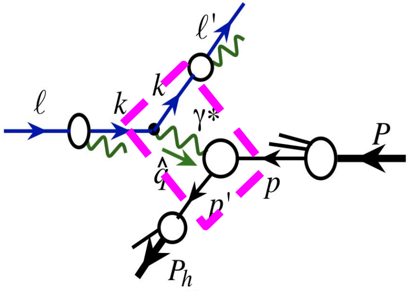
Liu, Melnitchouk, Qiu, Sato (‘20, `21)



QED
resummation



Hybrid QED+QCD factorization



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

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

Collinear LDFs and LFFs

Collinear PDFs

Short distance hard part

Collinear LDFs and LFFs

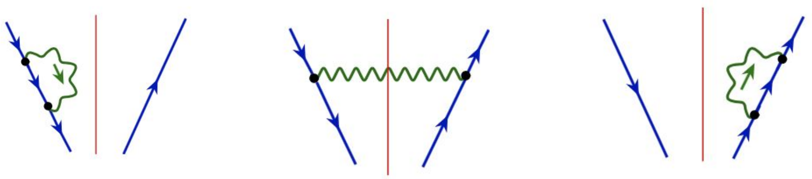
$$f_{i/e}(\xi) = \int \frac{dz^-}{4\pi} \, e^{i\xi\ell^+ z^-} \langle e | \, \overline{\psi}_i(0) \gamma^+ \Phi_{[0,z^-]} \, \psi_i(z^-) | e \rangle$$

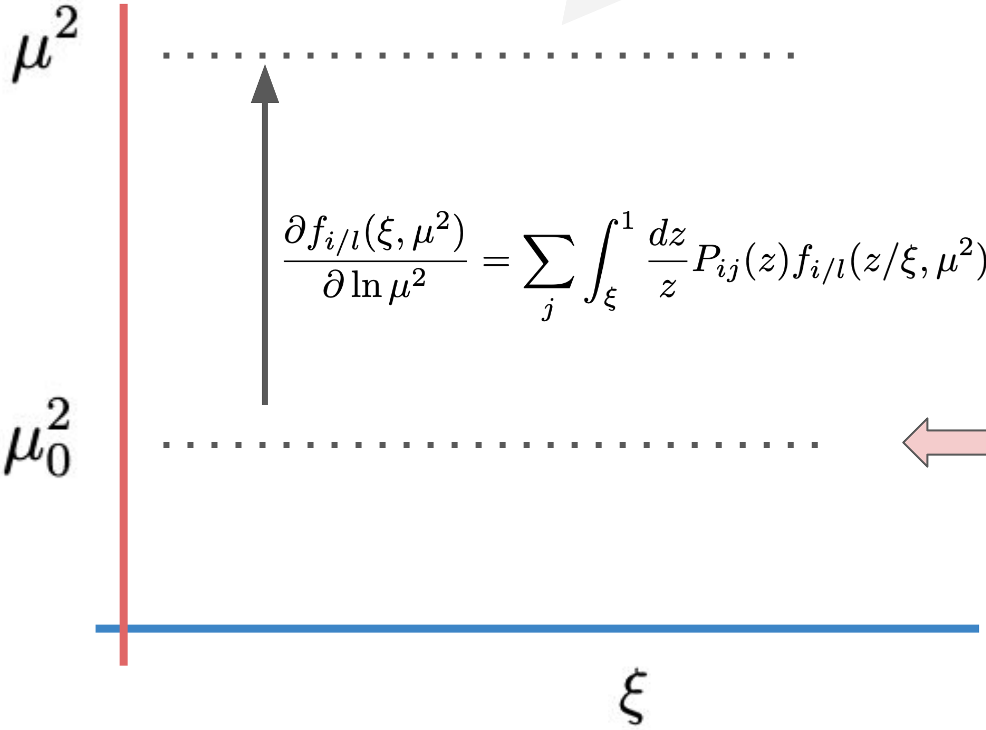
$$D_{e/j}(\zeta) = \frac{\zeta}{2} \sum_X \int \frac{dz^-}{4\pi} e^{i\ell'^+ z^- / \zeta} \, \mathrm{Tr}\left[\gamma^+ \langle 0 | \, \overline{\psi}_j(0) \Phi_{[0,\infty]} \, | e, X \rangle \langle e, X | \psi_j(z^-) \Phi_{[z^-,\infty]} | 0 \rangle \right]$$

perturbatively calculable if we neglect hadronic components

RGE

Resummation of collinear logs





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

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

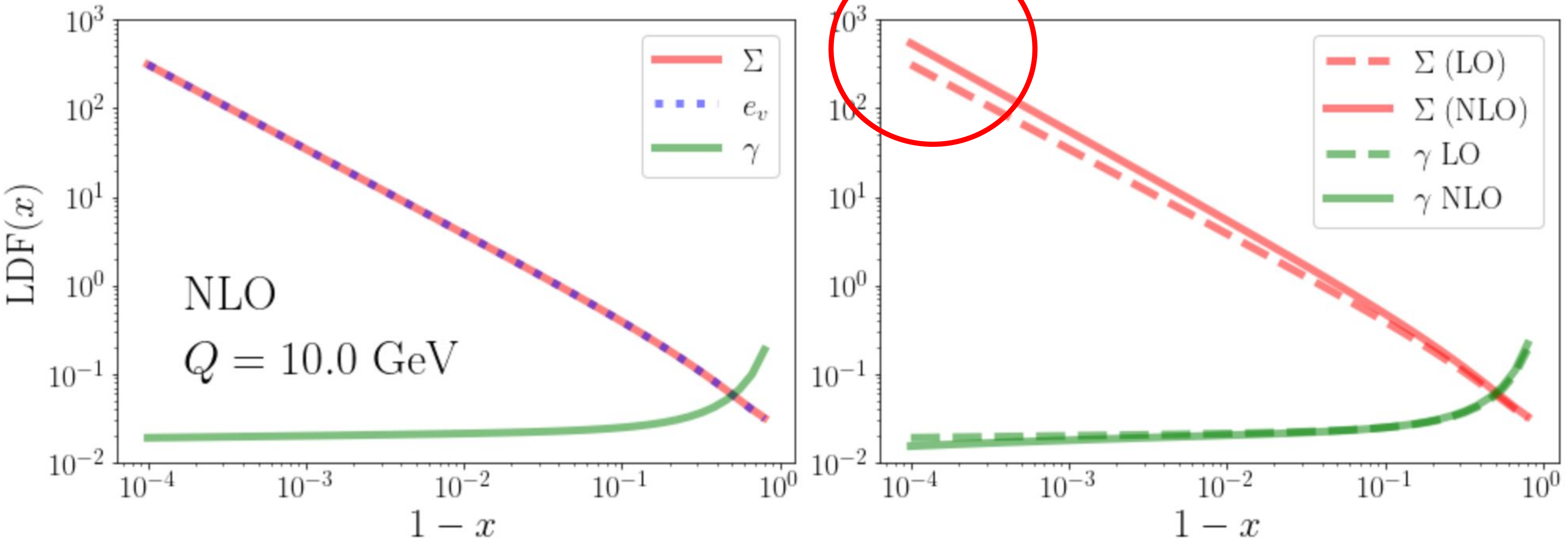
$$f^{(1)}_{e/e}(\xi,\mu_0^2) = \frac{\alpha}{2\pi}\left[\frac{1+\xi^2}{1-\xi}\ln\frac{\mu_0^2}{(1-\xi)^2 m_e^2}\right]_+$$

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

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

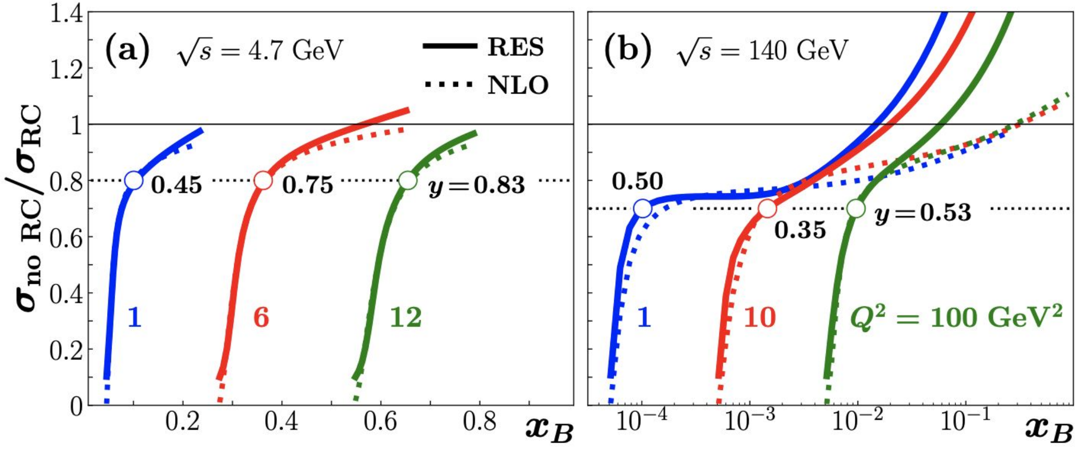
Evolution effects

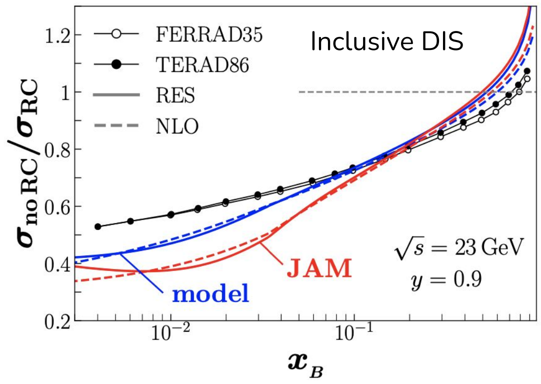
LDFs peaks at the endpoint



Some examples from inclusive DIS

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

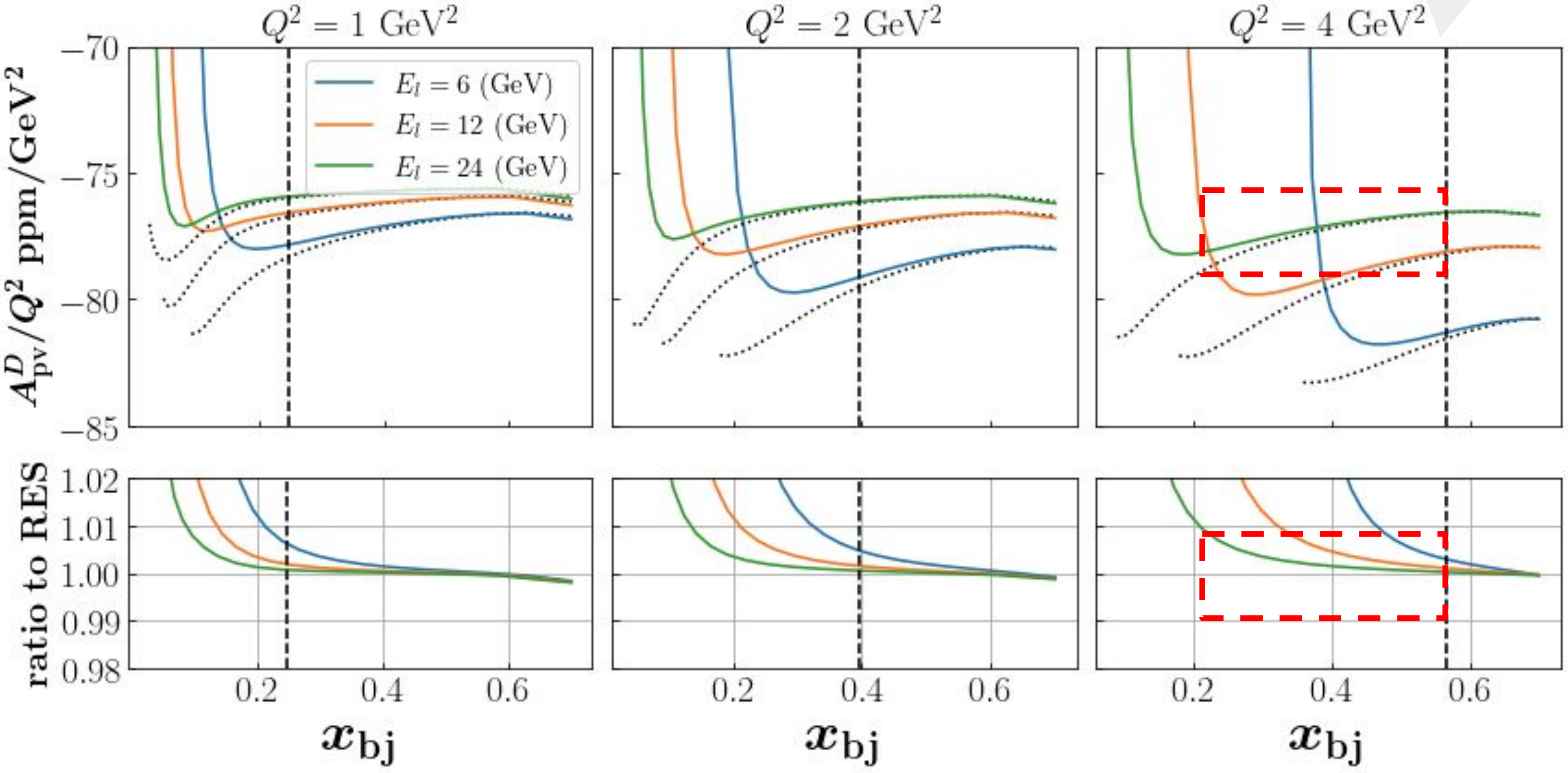




- QED "corrections" depend on the input hadronic tensor
- Not possible to construct model-independent QED RC corrections
- Need to include QED in global analysis

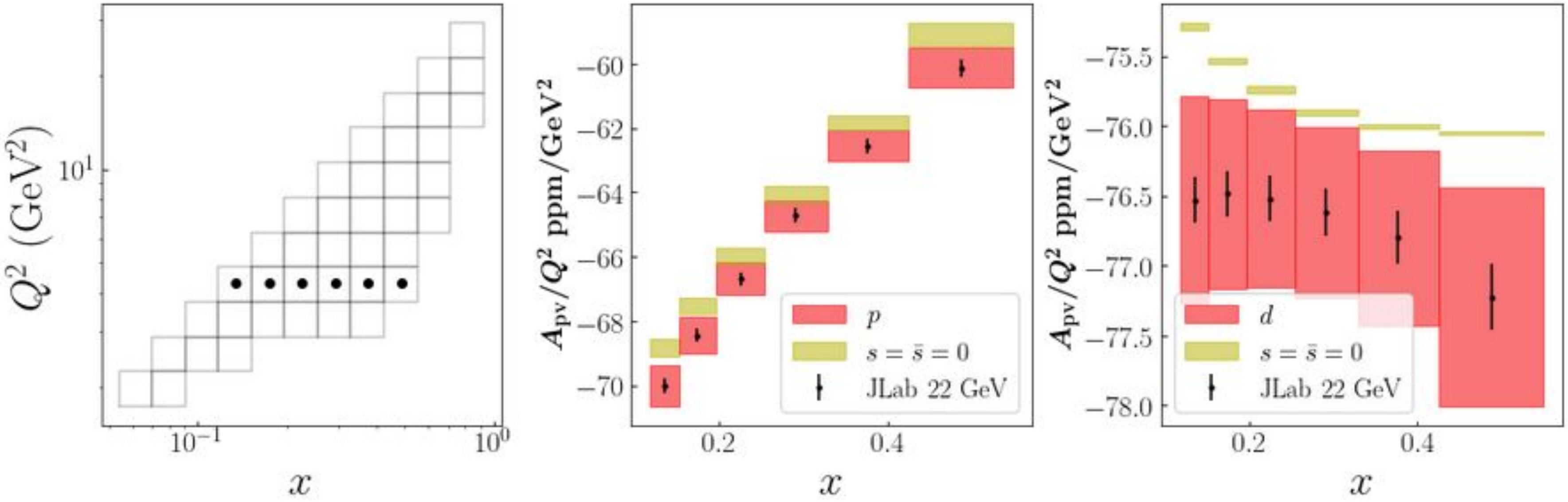
Apv with QED effects

W2 > 4 GeV2



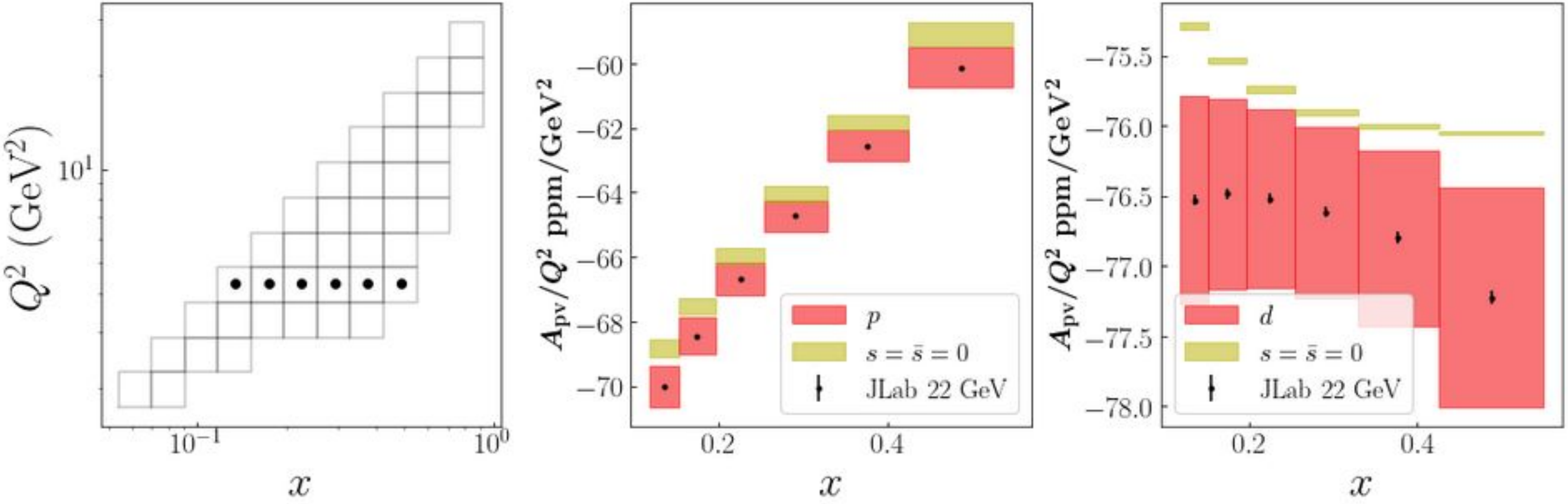
Quick simulation @ JLab 22 GeV

L=700 fb^-1 -> 40 uA, 30cm, 30 days and acceptance 8.4×10^-4 (From M. Dalton)



Quick simulation @ JLab 22 GeV

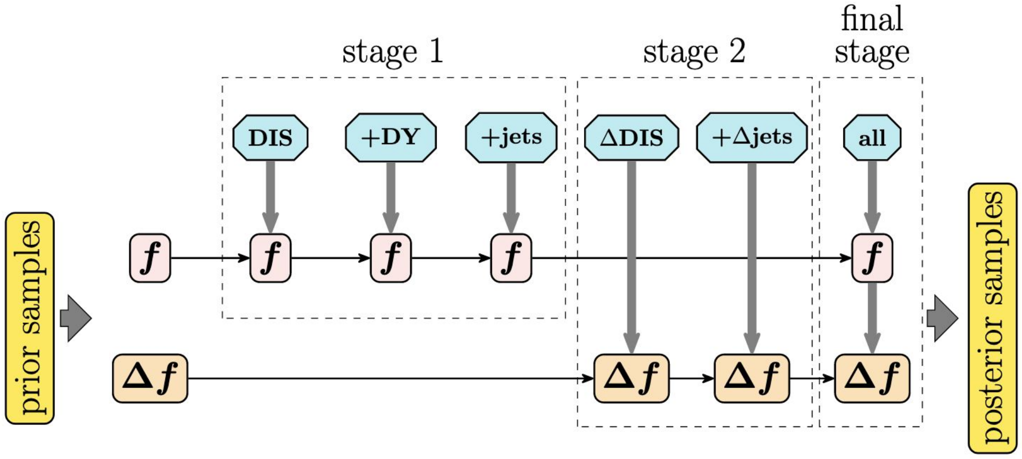
L=15000 fb^-1 -> 40 uA, 30cm, 30 days and acceptance 0.018 (From M. Dalton)

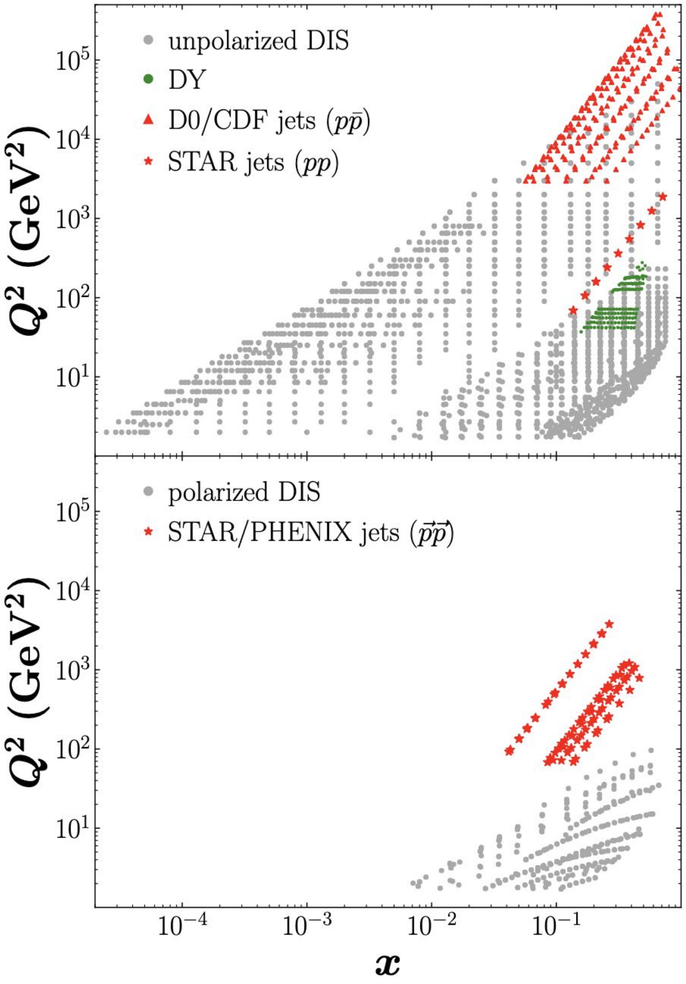


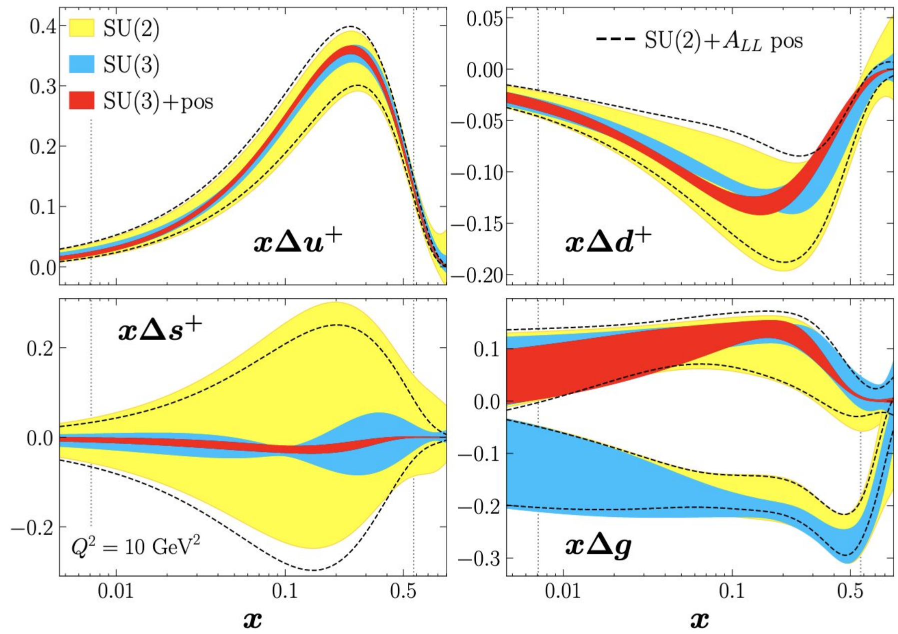
Another opportunity -> gluon polarization from SIDIS

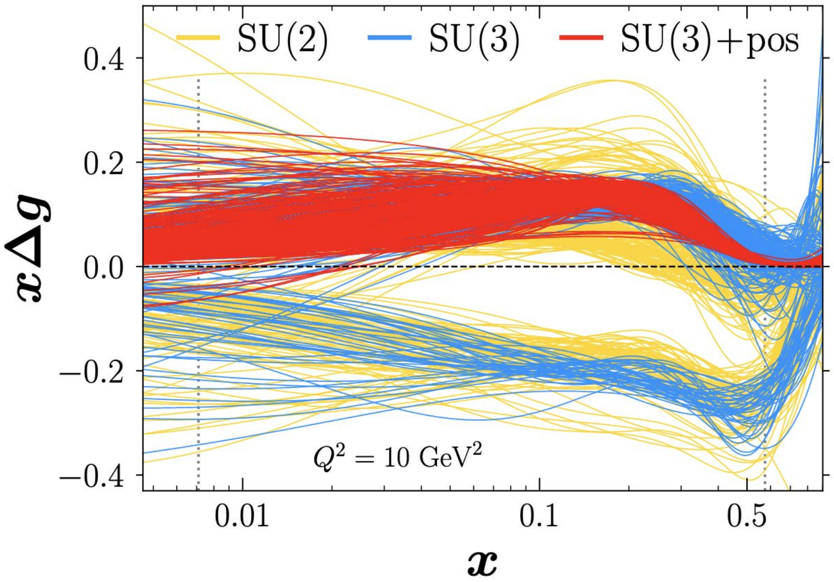
How well do we know the gluon polarization in the proton?

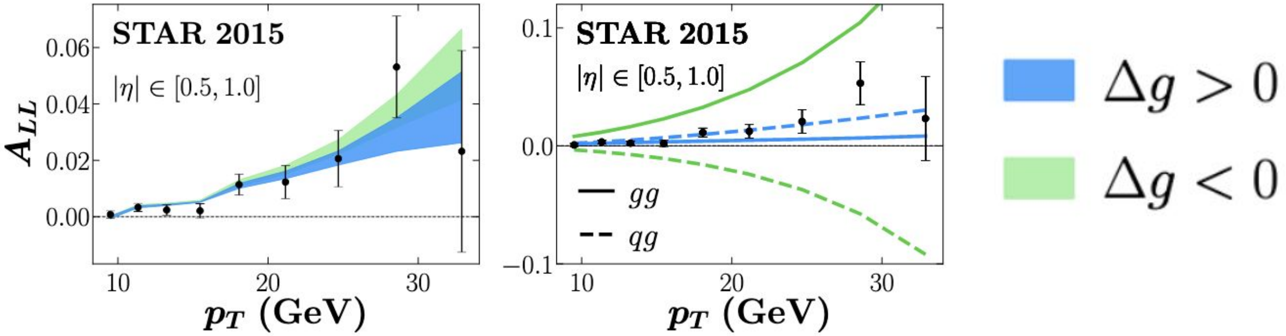
Y. Zhou, N. Sato, and W. Melnitchouk (Jefferson Lab Angular Momentum (JAM) Collaboration)
Phys. Rev. D **105**, 074022 – Published 25 April 2022





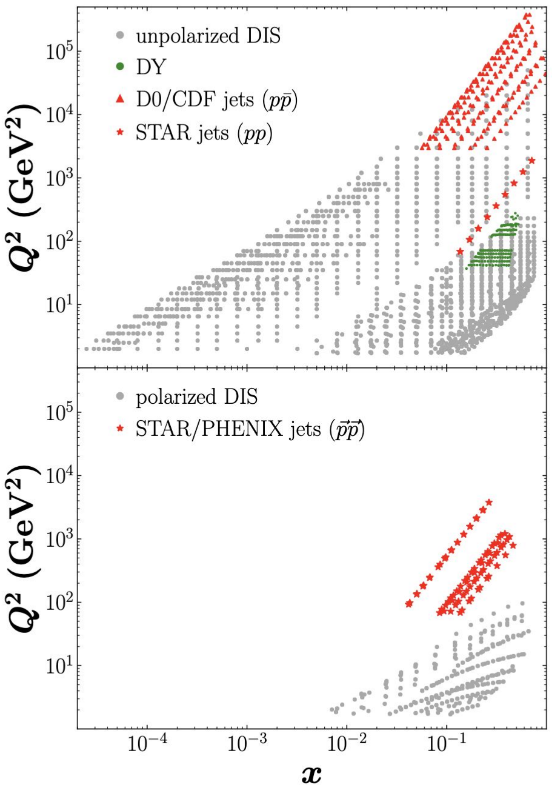


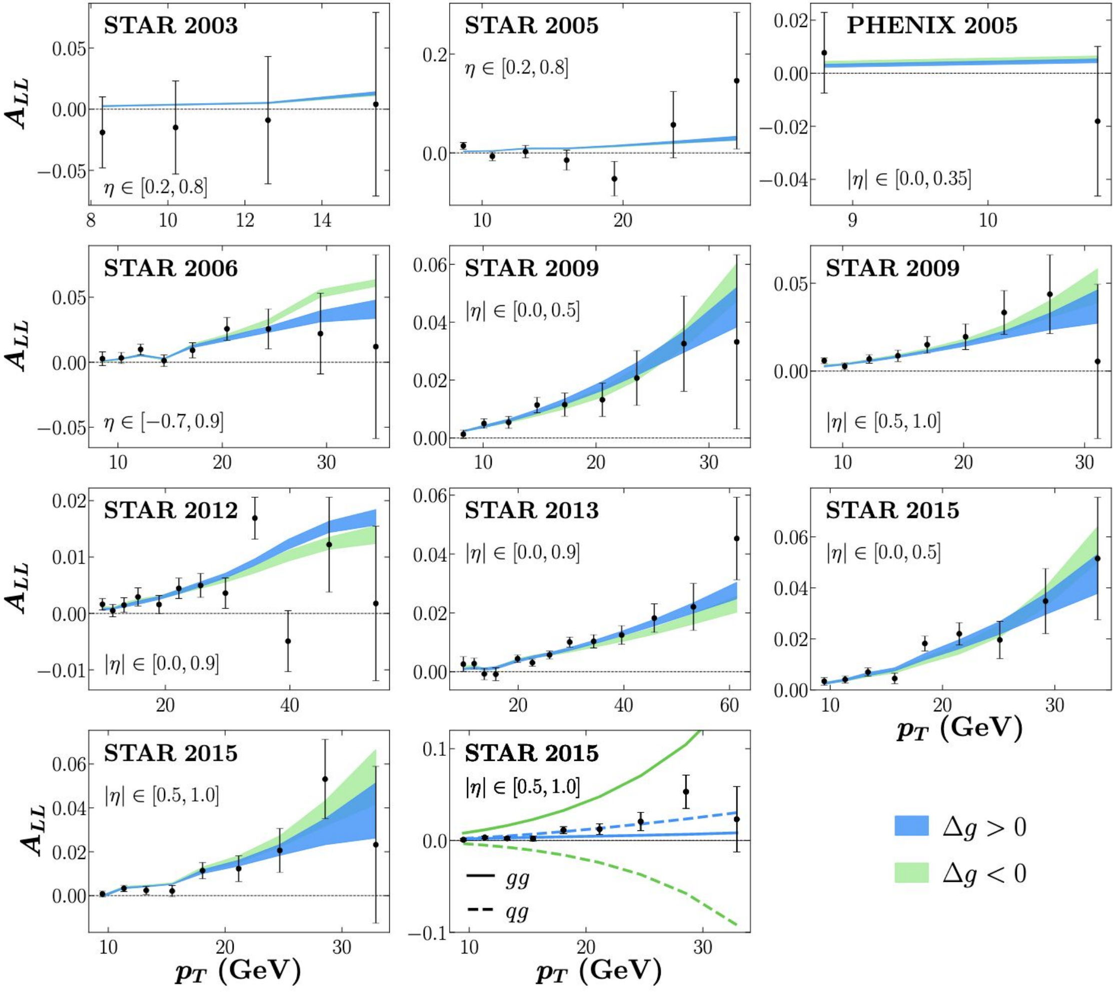




Polarized jet data cannot discriminate between positive & negative solutions

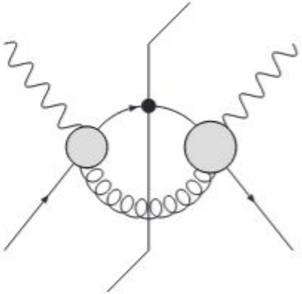
Polarized Jets





Accessing gluon polarization with high-P_T hadrons in SIDIS

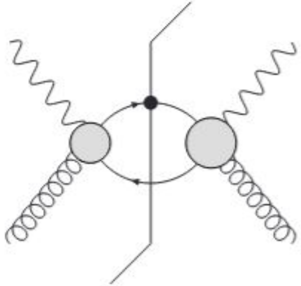
Richard Whitehill,[1] Yiyu Zhou,[2] N. Sato,[3] and W. Melnitchouk[3]



(a)

$$4P_{\rm H}^0 E' \frac{\mathrm{d}(\Delta)\sigma_H}{\mathrm{d}^3\mathbf{l}'\mathrm{d}^3\mathbf{P}_{\rm H}} = \sum_{i,j}\int_x^1 \frac{\mathrm{d}\xi}{\xi}\int_z^1 \frac{\mathrm{d}\zeta}{\zeta^2}\left(4k_1^0 E' \frac{\mathrm{d}\hat{\sigma}_{ij}}{\mathrm{d}^3\mathbf{l}'\mathrm{d}^3\mathbf{k}_1}\right)(\Delta) f_{i/P}(\xi) D_{H/j}(\zeta).$$

At LO, all the flavors contributes including gluons!



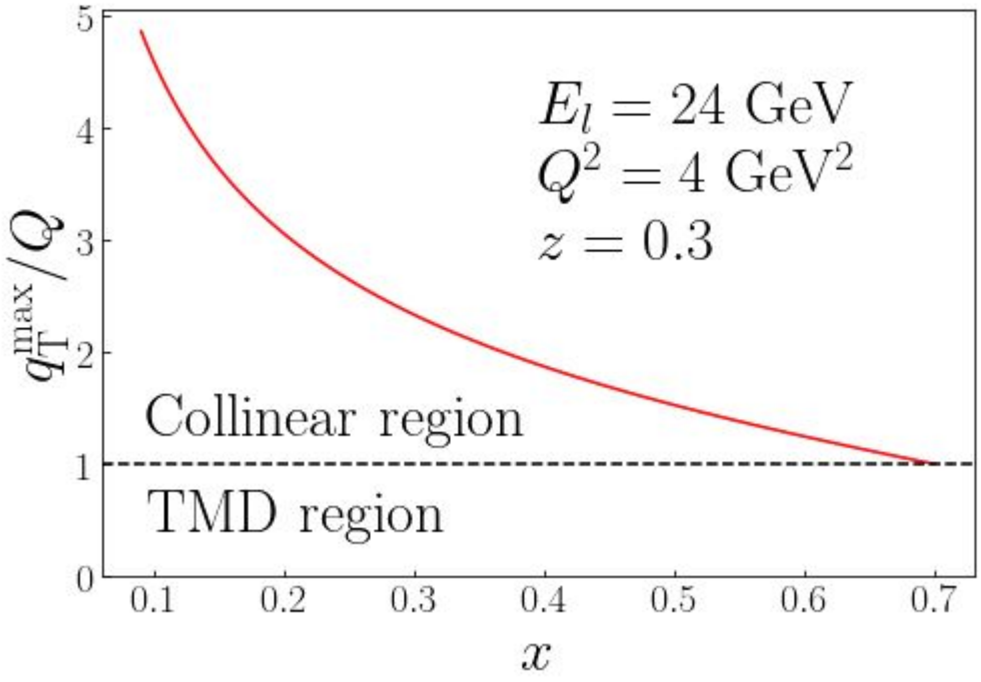
(c)

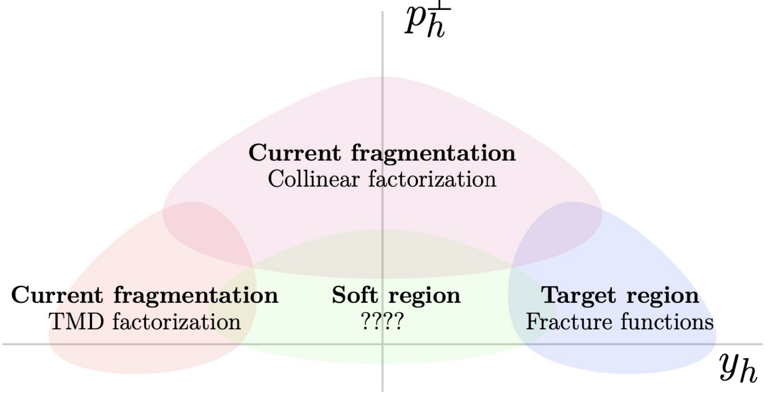
$$\frac{\mathrm{d}\Delta\hat{\sigma}_{\rm q,q}}{\mathrm{d}\hat{x}\,\mathrm{d}y\,\mathrm{d}\hat{z}\,\mathrm{d}P_{\rm T}^2} = -\frac{16\,(2-y)\,(Q^4\,(\hat{x}^2\hat{z}^2+1)-\hat{x}^2\hat{z}^2q_T^4)}{3\hat{x}y\,(\hat{x}-1)\,(Q^2\hat{z}-Q^2-\hat{z}q_T^2)}, \tag{A4}$$

$$\frac{\mathrm{d}\Delta\hat{\sigma}_{\rm q,g}}{\mathrm{d}\hat{x}\,\mathrm{d}y\,\mathrm{d}\hat{z}\,\mathrm{d}P_{\rm T}^2} = \frac{16\hat{x}\,(2-y)\,(Q^4\,(\hat{x}\hat{z}^2-2\hat{x}\hat{z}+2)+2Q^2\hat{z}q_T^2\,(1-\hat{x})-\hat{x}\hat{z}^2q_T^4)}{3y\,(\hat{x}-1)\,(Q^2\hat{x}\hat{z}-Q^2\hat{x}+Q^2-\hat{x}\hat{z}q_T^2)}, \tag{A5}$$

$$\frac{\mathrm{d}\Delta\hat{\sigma}_{\rm g,q}}{\mathrm{d}\hat{x}\,\mathrm{d}y\,\mathrm{d}\hat{z}\,\mathrm{d}P_{\rm T}^2} = \frac{2Q^2\,(y-2)\,(Q^4\,(2\hat{x}^2\hat{z}^2-2\hat{x}^2\hat{z}+2\hat{x}-1)+2Q^2\hat{x}\hat{z}q_T^2\,(1-\hat{x})-2\hat{x}^2\hat{z}^2q_T^4)}{\hat{x}y\,(Q^2\,(\hat{z}-1)-\hat{z}q_T^2)\,(Q^2\hat{x}\hat{z}-Q^2\hat{x}+Q^2-\hat{x}\hat{z}q_T^2)}. \tag{A6}$$

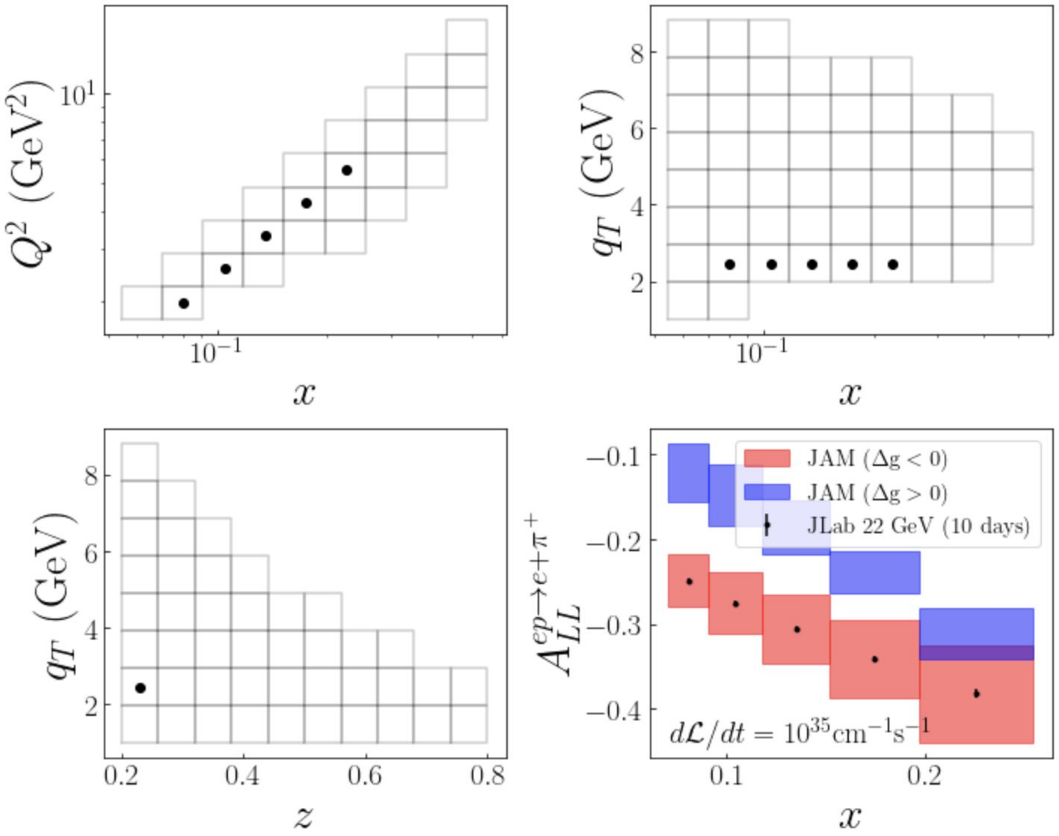
SIDIS phase space





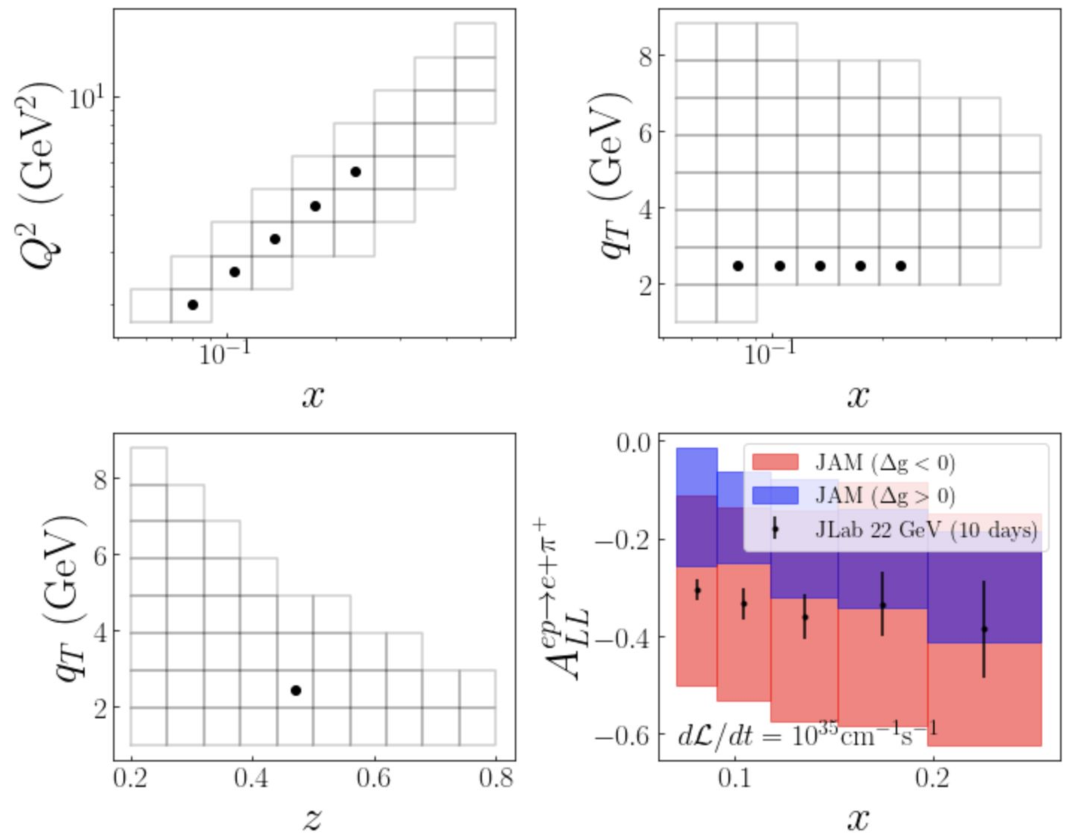
- For 0.1<x<0.3 there, there is phase space with large transverse momentum

Quick simulation @ JLab 22 GeV



L=86 fb^-1

Quick simulation @ JLab 22 GeV



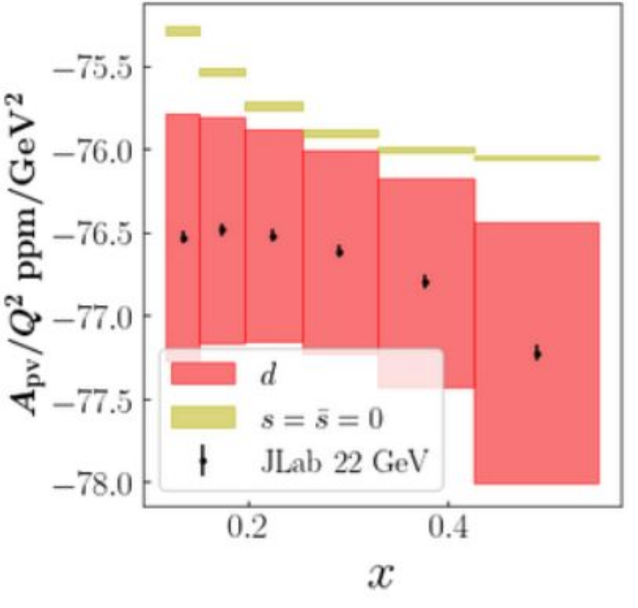
L=86 fb^-1

Summary/Outlook

- Sea quark PDFs at large x are still elusive, especially in strange sector

- Apv offers important constraints especially at JLab 24 GeV, where QED effects are under control

- sin2θw constraints from Apv D require more precise knowledge of strange pdfs –> ==simultaneous extraction paradigm is needed==



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