Impact of parity-violating DIS on the weak mixing angle and nucleon strangeness

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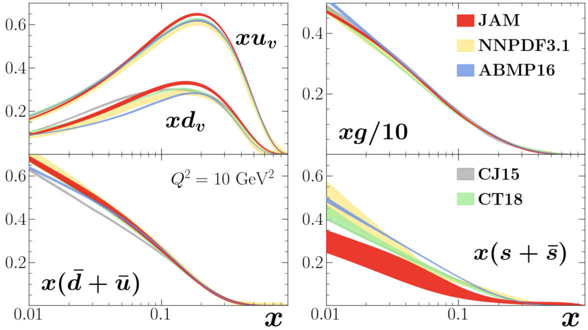
JAM Collaboration

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.

TL;DR: Group studying nucleon/hadron structure through the determination of relevant QCFs

Current Status – strange PDFs



C. Cocuzza, W. Melnitchouk, A. Metz, N. Sato
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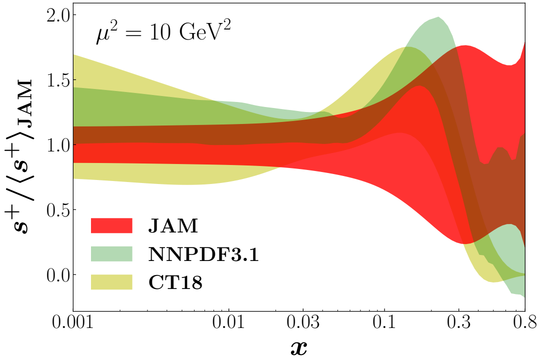
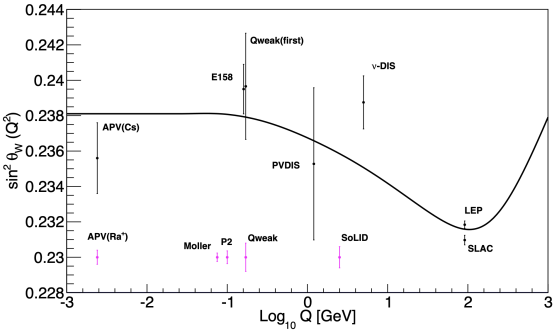
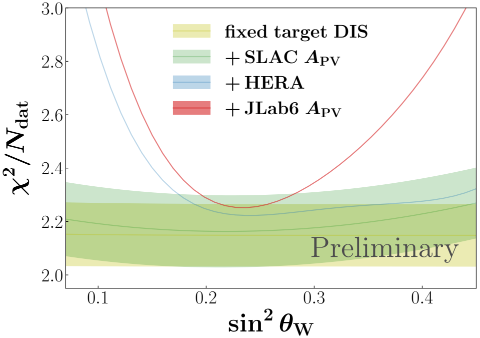


Current Status – $\sin^2\theta_W$

Fundamental Standard Model parameter

$$\begin{pmatrix}\gamma \\ Z^0\end{pmatrix} = \begin{pmatrix}\cos\theta_W & \sin\theta_W \\ -\sin\theta_W & \cos\theta_W\end{pmatrix}\begin{pmatrix}B^0 \\ W^0\end{pmatrix}, \quad \cos\theta_W = \frac{m_W}{m_Z}$$





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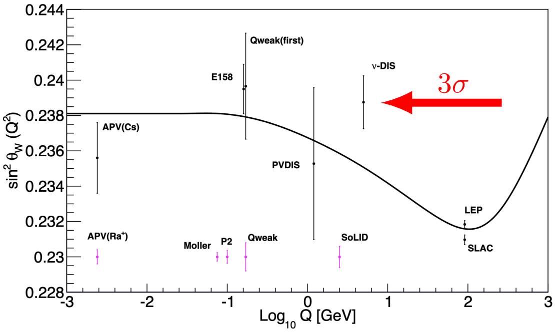
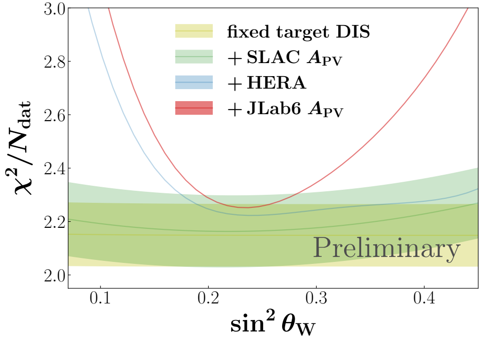
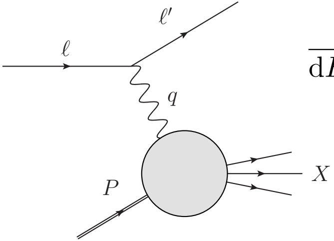


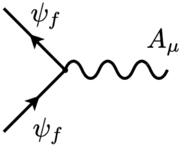


Parity-Violating Deep-Inelastic Scattering



$$\frac{\mathrm{d}\sigma}{\mathrm{d}E'\,\mathrm{d}\Omega} = \frac{1}{2(s-M^2)}\frac{E'}{2(2\pi)^3}\sum_X \int \mathrm{d}\Phi_X (2\pi)^4 \delta^{(4)}(P+q-P_X)$$

$$\times\, |\mathcal{M}_\gamma + \mathcal{M}_Z|^2$$

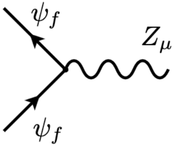


$$-\,i\,\eta_e\, eQ_f\gamma_\mu$$

$$Q^2 = -q^2 = -(\ell - \ell')^2$$

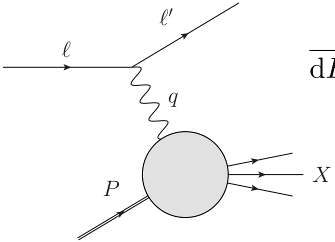
$$x_{\mathrm{B}} = \frac{Q^2}{2P\cdot q}$$

$$y = \frac{P\cdot q}{P\cdot \ell}$$



$$-\,i\,\eta\,\eta_Z\,\frac{g}{\cos\theta_W}\gamma_\mu\left(g_V^f - g_A^f\gamma_5\right)$$

Parity-Violating Deep-Inelastic Scattering



$$\frac{d\sigma}{dE'\,d\Omega} = \frac{1}{2(s-M^2)}\frac{E'}{2(2\pi)^3}\sum_X \int d\Phi_X (2\pi)^4 \delta^{(4)}(P+q-P_X)$$
$$\times\, |\mathcal{M}_\gamma + \mathcal{M}_Z|^2$$

$$\boxed{\frac{d\sigma_{\lambda_\ell}}{dx_B\,dy} = \frac{Q^2}{x}\frac{\pi}{E'}\frac{d\sigma}{dE'\,d\Omega} = \frac{2\pi\alpha^2 y}{Q^4}\sum_i \eta_i C_i L^{\gamma}_{\mu\nu} W^{\mu\nu}_{i,U}}$$

$$Q^2 = -q^2 = -(\ell-\ell')^2$$
$$x_B = \frac{Q^2}{2P\cdot q}$$
$$y = \frac{P\cdot q}{P\cdot \ell}$$

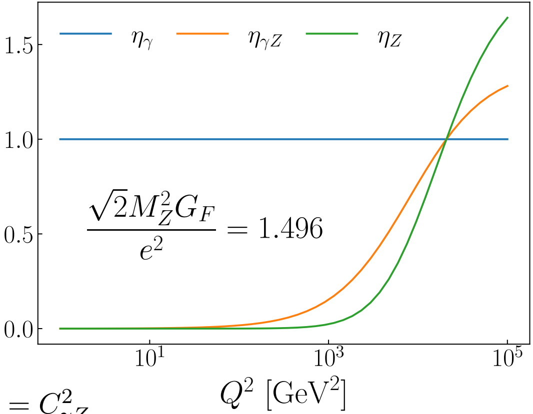
Pieces of the cross section

Kinematic/coupling factors:

$\rightarrow \ \eta_\gamma = 1$

$\rightarrow \ \eta_{\gamma Z} = \dfrac{\sqrt{2} M_Z^2 G_F}{e^2} \dfrac{Q^2}{Q^2 + M_Z^2}$

$\rightarrow \ \eta_Z = \eta_{\gamma Z}^2$



Charge factors:

$\rightarrow \ C_\gamma = 1, \ C_{\gamma Z} = -(g_V^e + Q_l \lambda_l g_A^e), \ C_Z = C_{\gamma Z}^2$

$\rightarrow \ g_A^e = -1/2, \quad g_V^e = -1/2 + 2 \sin^2 \theta_{\mathrm{W}}$

Pieces of the cross section

Leptonic tensor:

$$\to \; L^{\gamma}_{\mu\nu} = 2\big(\ell_\mu \ell'_\nu + \ell'_\mu \ell_\nu - g_{\mu\nu} \ell \cdot l' - i\lambda_\ell \epsilon_{\mu\nu\alpha\beta} \ell^\alpha \ell'^\beta\big)$$

Hadronic tensor:

$$\to \; W^{\mu\nu}_{i,U} = -\widetilde{g}^{\mu\nu} F^i_1(x_{\mathrm{B}}, Q^2) + \frac{\widetilde{P}^\mu \widetilde{P}^\nu}{P \cdot q} F^i_2(x_{\mathrm{B}}, Q^2) + i\epsilon^{\mu\nu\alpha\beta} \frac{P_\alpha q_\beta}{2P \cdot q} F^i_3(x_{\mathrm{B}}, Q^2)$$

$$\frac{\mathrm{d}\sigma_{\lambda_\ell}}{\mathrm{d}x_{\mathrm{B}}\, \mathrm{d}y} = \frac{4\pi\alpha^2}{xyQ^2} \sum_i \eta_i C_i \left[x_{\mathrm{B}} y^2 F^i_1 + \left(1 - y - \frac{x^2_{\mathrm{B}} y^2 M^2}{Q^2}\right) F^i_2 - \lambda_\ell x_{\mathrm{B}} \left(y - \frac{y^2}{2}\right) F^i_3 \right]$$

Parity-Violating Asymmetry

$$\boxed{A_{\mathrm{PV}} = \frac{\mathrm{d}\sigma_+ - \mathrm{d}\sigma_-}{\mathrm{d}\sigma_+ + \mathrm{d}\sigma_-} \approx \frac{G_F Q^2}{4\sqrt{2}\pi\alpha} \frac{2g_A^e F_1^{\gamma Z} Y_1 + g_V^e F_3^{\gamma Z} Y_3}{F_1^\gamma}}$$

$$Y_1 = \left(\frac{1 + R^{\gamma Z}}{1 + R^\gamma}\right) \frac{1 + (1-y)^2 - \frac{y^2}{2}\left[1 + r^2 - \frac{2r^2}{1+R^{\gamma Z}}\right]}{1 + (1-y)^2 - \frac{y^2}{2}\left[1 + r^2 - \frac{2r^2}{1+R^{\gamma}}\right]}, \quad r^2 = 1 + 4M^2 x_{\mathrm{B}}^2/Q^2$$

$$Y_3 = \left(\frac{1 + R^{\gamma Z}}{1 + R^\gamma}\right) \frac{1 - (1-y)^2}{1 + (1-y)^2 - \frac{y^2}{2}\left[1 + r^2 - \frac{2r^2}{1+R^{\gamma}}\right]}, \quad R^i = \frac{F_2^i}{2x_{\mathrm{B}} F_1^i} r^2 - 1$$

Parity-Violating Asymmetry

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$$Y_1 = \left(\frac{1+R^{\gamma Z}}{1+R^\gamma}\right) \frac{1+(1-y)^2 - \frac{y^2}{2}\left[1+r^2-\frac{2r^2}{1+R^{\gamma Z}}\right]}{1+(1-y)^2 - \frac{y^2}{2}\left[1+r^2-\frac{2r^2}{1+R^{\gamma}}\right]}, \qquad r^2 = 1 + \cancel{4M^2 x_{\mathrm{B}}^2/Q^2}$$

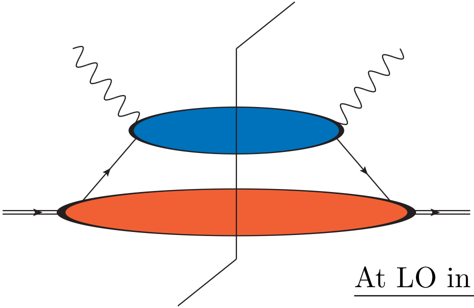
$$Y_3 = \left(\frac{1+R^{\gamma Z}}{1+R^\gamma}\right) \frac{1-(1-y)^2}{1+(1-y)^2 - \frac{y^2}{2}\left[1+r^2-\frac{2r^2}{1+R^{\gamma}}\right]}, \qquad R^i = \frac{F_2^i}{2x_{\mathrm{B}} F_1^i} r^2 - 1 = 0$$

Parity-Violating Asymmetry

$$\boxed{A_{\mathrm{PV}} = \frac{\mathrm{d}\sigma_+ - \mathrm{d}\sigma_-}{\mathrm{d}\sigma_+ + \mathrm{d}\sigma_-} \approx \frac{G_F Q^2}{4\sqrt{2}\pi\alpha} \frac{2 g_A^e F_1^{\gamma Z} Y_1 + g_V^e F_3^{\gamma Z} Y_3}{F_1^\gamma}}$$

$$Y_1 = 1, \quad Y_3 = \frac{1-(1-y)^2}{1+(1-y)^2}$$

Collinear factorization and the parton model



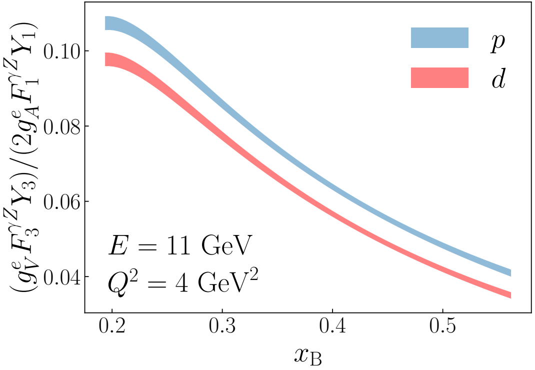
$$W^{\mu\nu}_{i,U} = \sum_i \int_{\xi_{\min}}^1 \frac{\mathrm{d}\xi}{\xi} \color{blue}{\widehat{W}^{\mu\nu}_{i,U}(\hat{x}, Q^2)} \color{red}{f_{i/P}(\xi, \mu^2)}$$

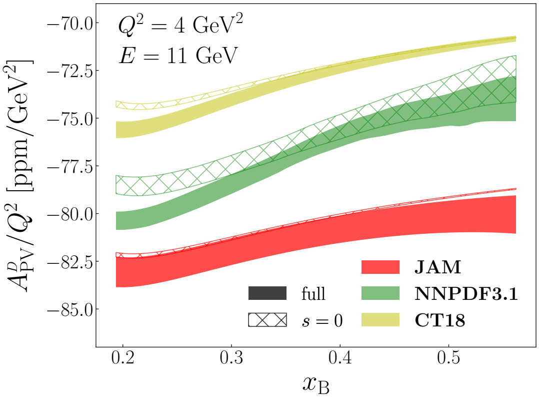
At LO in α_S :

$$\to F_1^{\{\gamma,\gamma Z\}}(x_\mathrm{B}, Q^2) = \sum_q \left\{ \frac{e_q^2}{2}, e_q g_V^q \right\} \left[q(x_\mathrm{B}, Q^2) + \overline{q}(x_\mathrm{B}, Q^2) \right]$$

$$\to F_3^{\gamma Z}(x_\mathrm{B}, Q^2) = \sum_q 2 e_q g_A^q \left[q(x_\mathrm{B}, Q^2) - \overline{q}(x_\mathrm{B}, Q^2) \right]$$

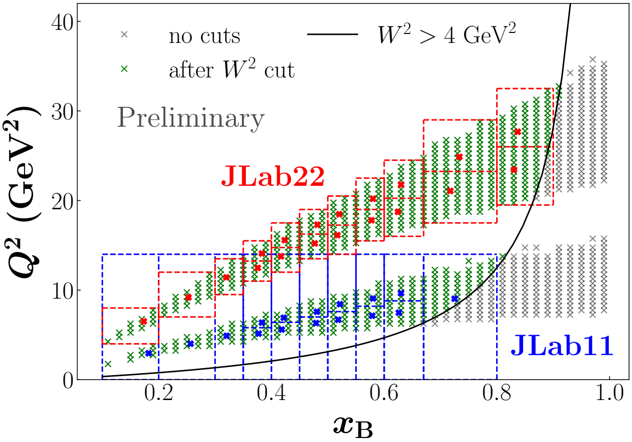
A_{PV} on a deuterium target





$$A_{\mathrm{PV}}^D \approx -\frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\left[\left(\frac{9}{5} - 4\sin^2\theta_{\mathrm{W}}\right) + \frac{2}{25}\frac{s^+}{u^+ + d^+}\right]$$

Simulating pseudo-data



$$\langle A_{\rm PV} \rangle_{\rm bin} = \sum_{i \in {\rm replicas}} A_{{\rm PV},i}/N_{\rm replicas}$$

Error budget:

$\rightarrow \delta^{\rm stat} A_{\rm PV} = \left(P\sqrt{\mathcal{L}\sigma_{\rm bin}}\right)^{-1}$

$\rightarrow \delta^{\rm thy} A_{\rm PV} = \left|A_{\rm PV}^{\rm (RC)} - A_{\rm PV}\right|$

$\rightarrow \delta^{\rm syst} A_{\rm PV}/A_{\rm PV} = 0.5\%$

Note:

$\rightarrow P = 85\%$

$\rightarrow {\rm d}\mathcal{L}/{\rm d}t = 4.85 \times 10^{38}\ {\rm cm}^{-2}\ {\rm s}^{-1}$

$\rightarrow$ run time: 50 days/target

Radiative corrections

$$\frac{\mathrm{d}\sigma_{(U/L)U}}{\mathrm{d}x_{\mathrm{B}}\,\mathrm{d}y} = \int_{\zeta_{\min}}^{1} \frac{\mathrm{d}\zeta}{\zeta^2} \underbrace{D_{e/e}(\zeta,\mu^2)}_{\text{LFF}} \int_{\xi_{\min}}^{1} \mathrm{d}\xi \, \underbrace{f_{e/e}(\xi,\mu^2)}_{\text{LDF}} \left[\frac{Q^2}{x_{\mathrm{B}}} \frac{\hat{x}_{\mathrm{B}}}{\hat{Q}^2}\right] \frac{\mathrm{d}\hat{\sigma}_{(U/L)U}}{\mathrm{d}\hat{x}_{\mathrm{B}}\,\mathrm{d}\hat{y}}$$

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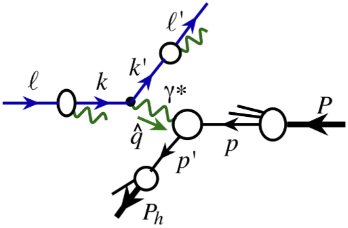
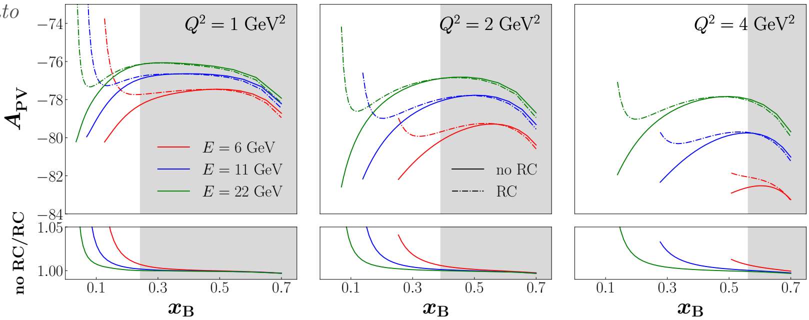
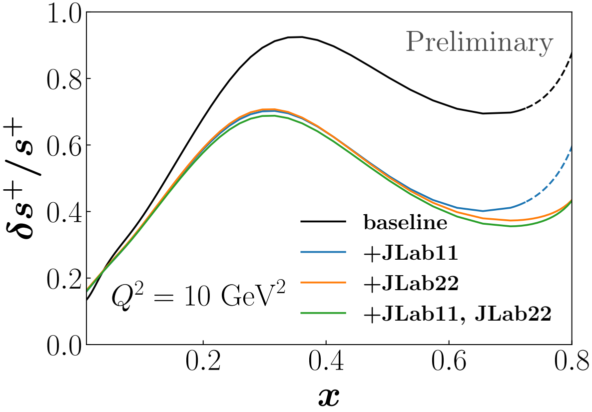
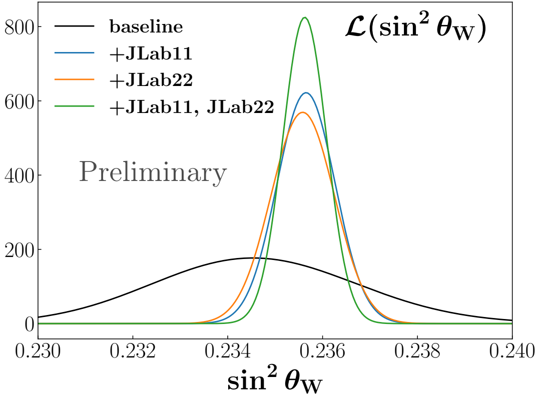


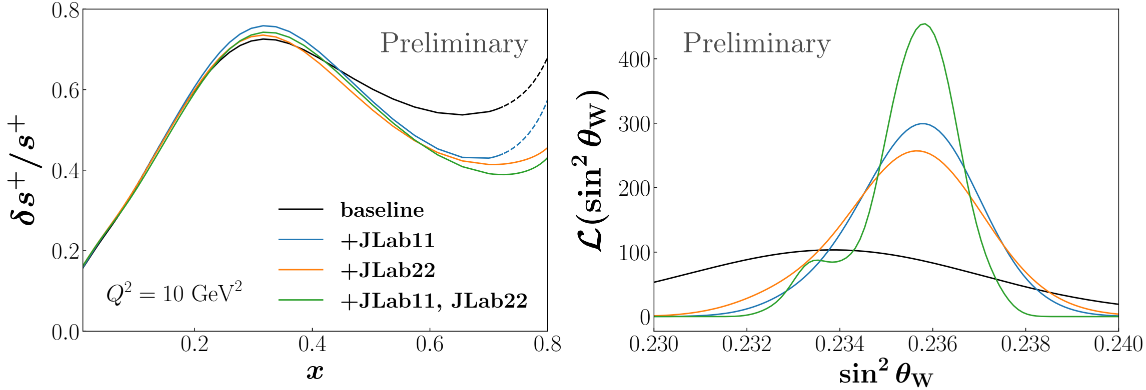


Separate impact on $\sin^2\theta_W$ and s^+





Combined impact on $\sin^2\theta_W$ and s^+



Summary and Outlook

- Strange sea inside the nucleon needs to be constrained to achieve a better understanding of the longitudinal structure of the nucleon
- Tension in understanding of low-Q^2 behavior of $\sin^2\theta_W$ calling into question SM validity
- A_{PV} is a unique and clean observable that can be used to achieve these goals
- Future work:

$\rightarrow$ Quantification of higher twist effects/uncertainties

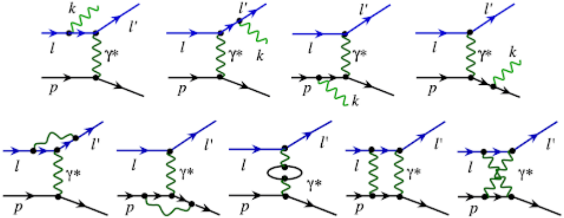
$\rightarrow$ electron/positron PVDIS for constraint of sea quark asymmetries

$\rightarrow$ Polarized A_{PV}?

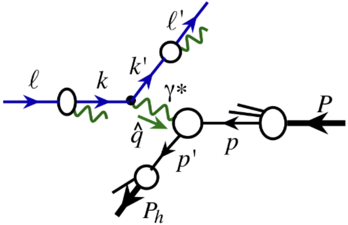
$\rightarrow$ Charge symmetry violation (i.e. how wrong is isospin symmetry?)

Backup Slides

Collinear LDFs and LFFs



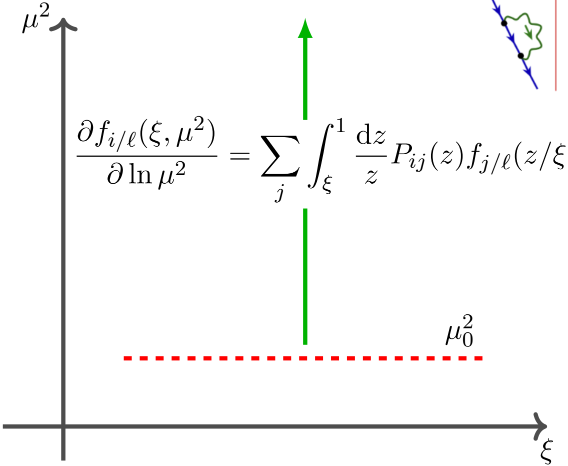
QED
resummation



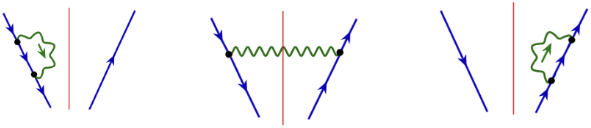
$$f_{i/e}(\xi) = \int \frac{\mathrm{d}z^-}{4\pi} e^{i\xi\ell^+ z^-} \langle e|\overline{\psi}_i(0)\gamma^+ \Phi_{[0,z^-]\psi_i(z^-)}|e\rangle$$

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

LDF and LFF RGE



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



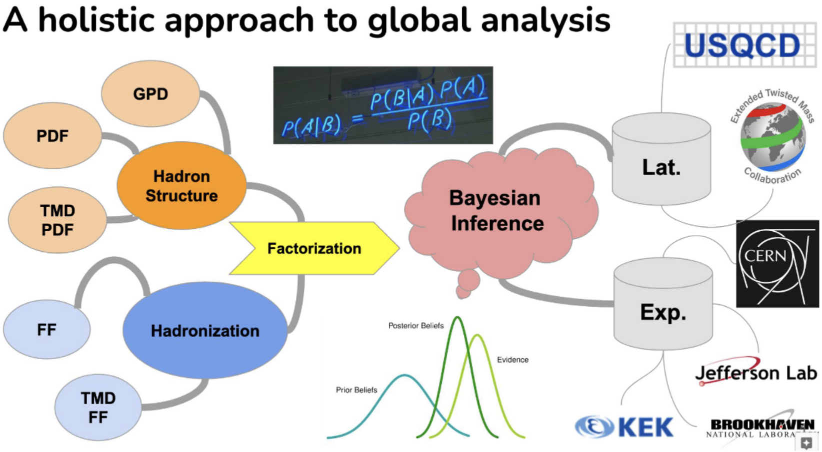
$$f^{(0)}_{e/e}(\xi,\mu_0^2) = \delta(\xi-1)$$

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

$$D^{(0)}_{e/e}(\zeta,\mu_0^2) = \delta(\zeta-1)$$

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

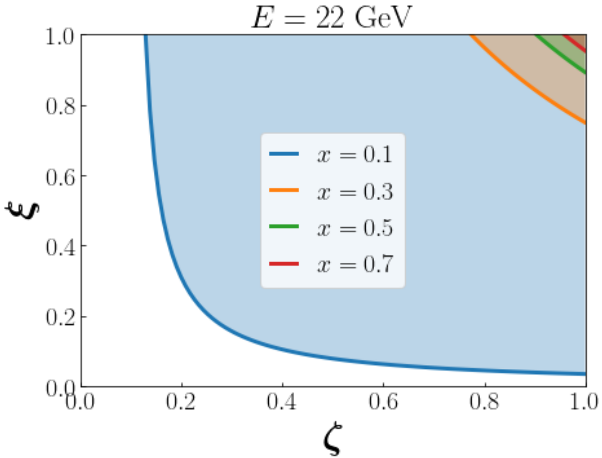
JAM Global Analysis Paradigm



Why $\chi^2_{\text{red}} = 2$?

$$\chi^2(\mathbf{a}, \text{data}) = \sum_{e,i} \left(\frac{d_{e,i} - \sum_k r_{e,k} \beta^k_{e,i} - T_{e,i}(\mathbf{a})/N_e}{\alpha_{e,i}} \right)^2 + \sum_{e,k} r^2_{e,k}$$

Fitting PDFs with hybrid QED+QCD factorization



$$\zeta_{\text{min}} = 1 - (1 - x_{\text{B}})y$$

$$\xi_{\text{min}} = \frac{1 - y}{\zeta - x_{\text{B}}y}$$