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

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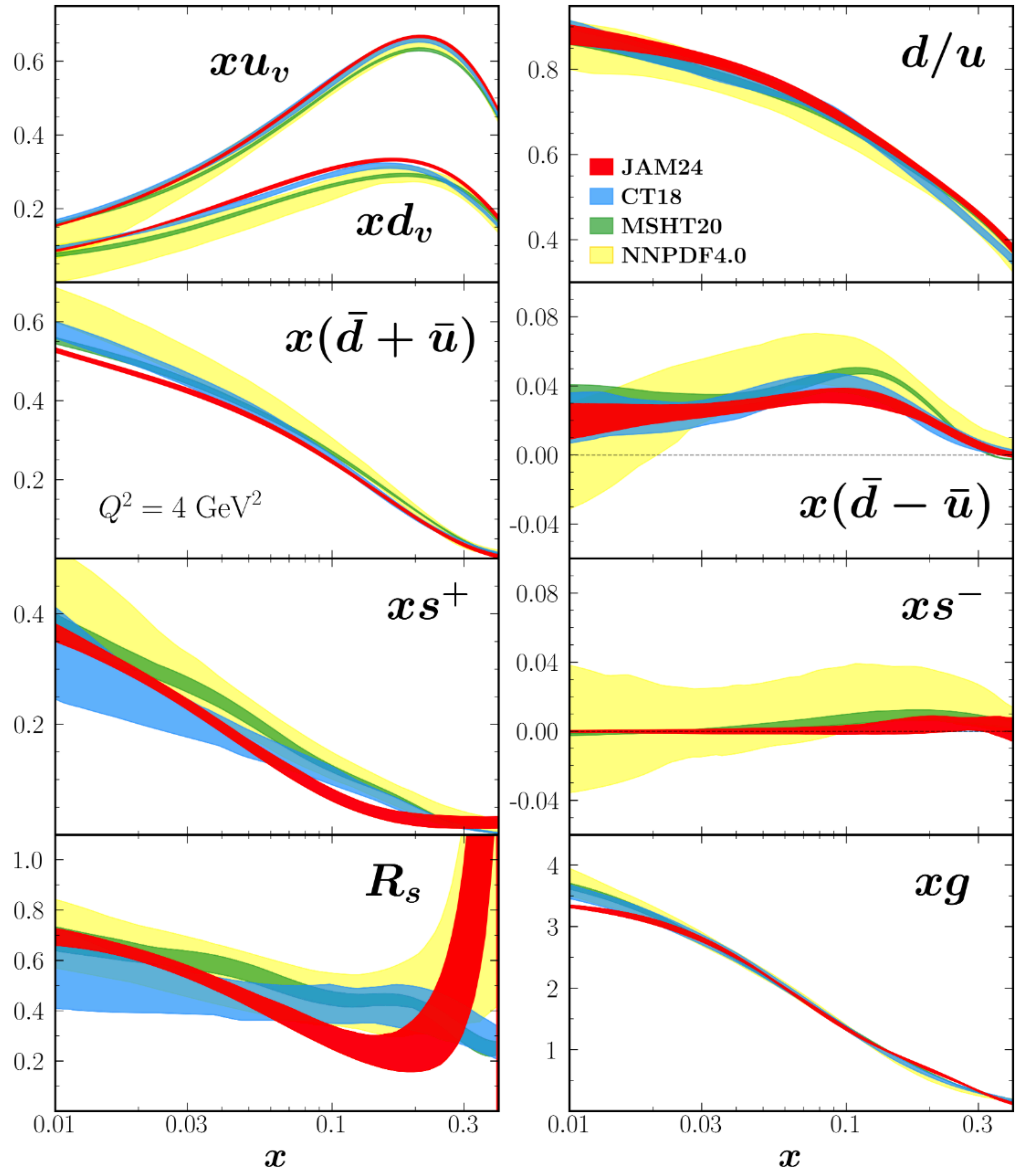
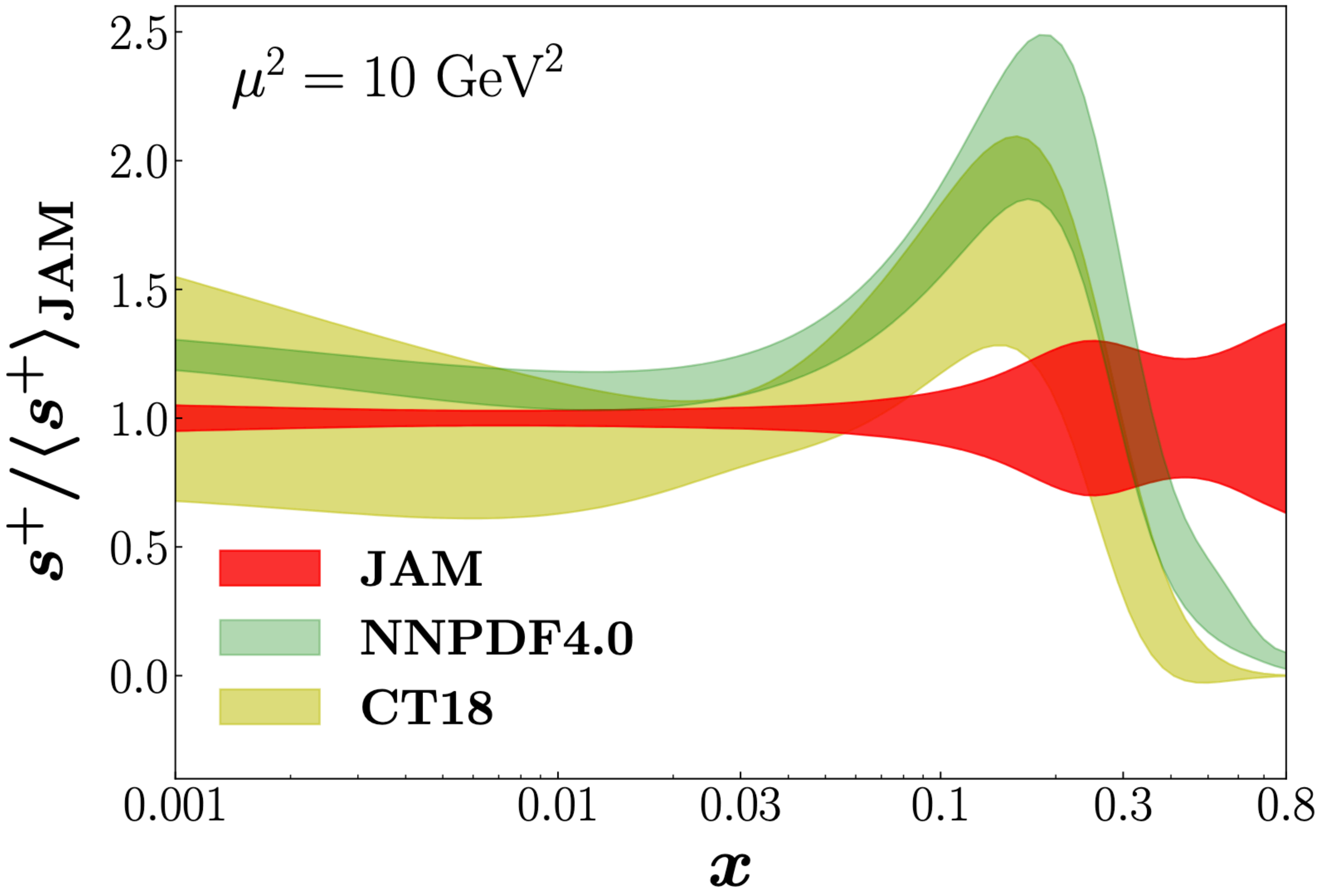
05/23/25

How strange is the proton?



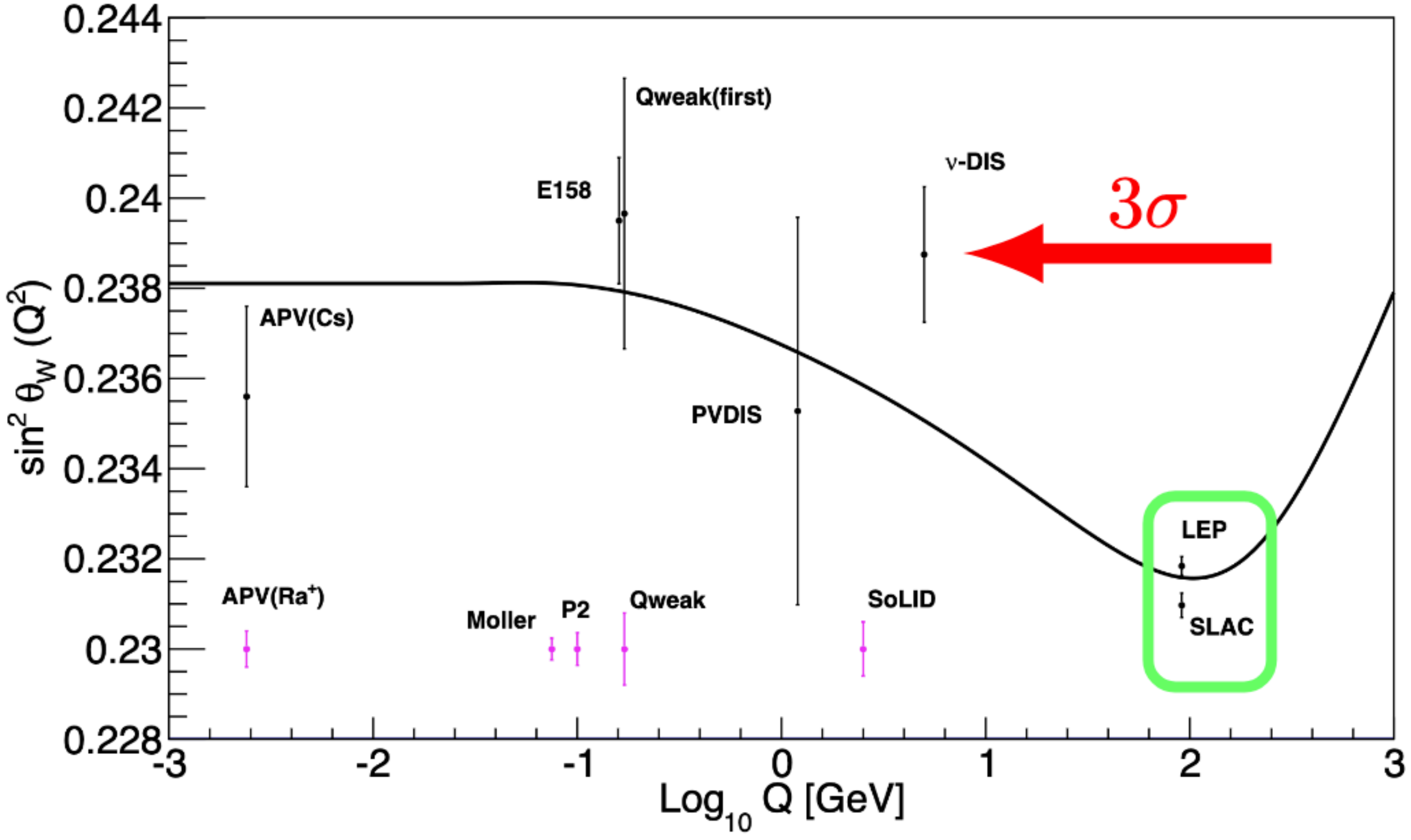
Anderson, Sato, Melnitchouk, arXiv:2501.00665v2 [hep-ph] (2025)

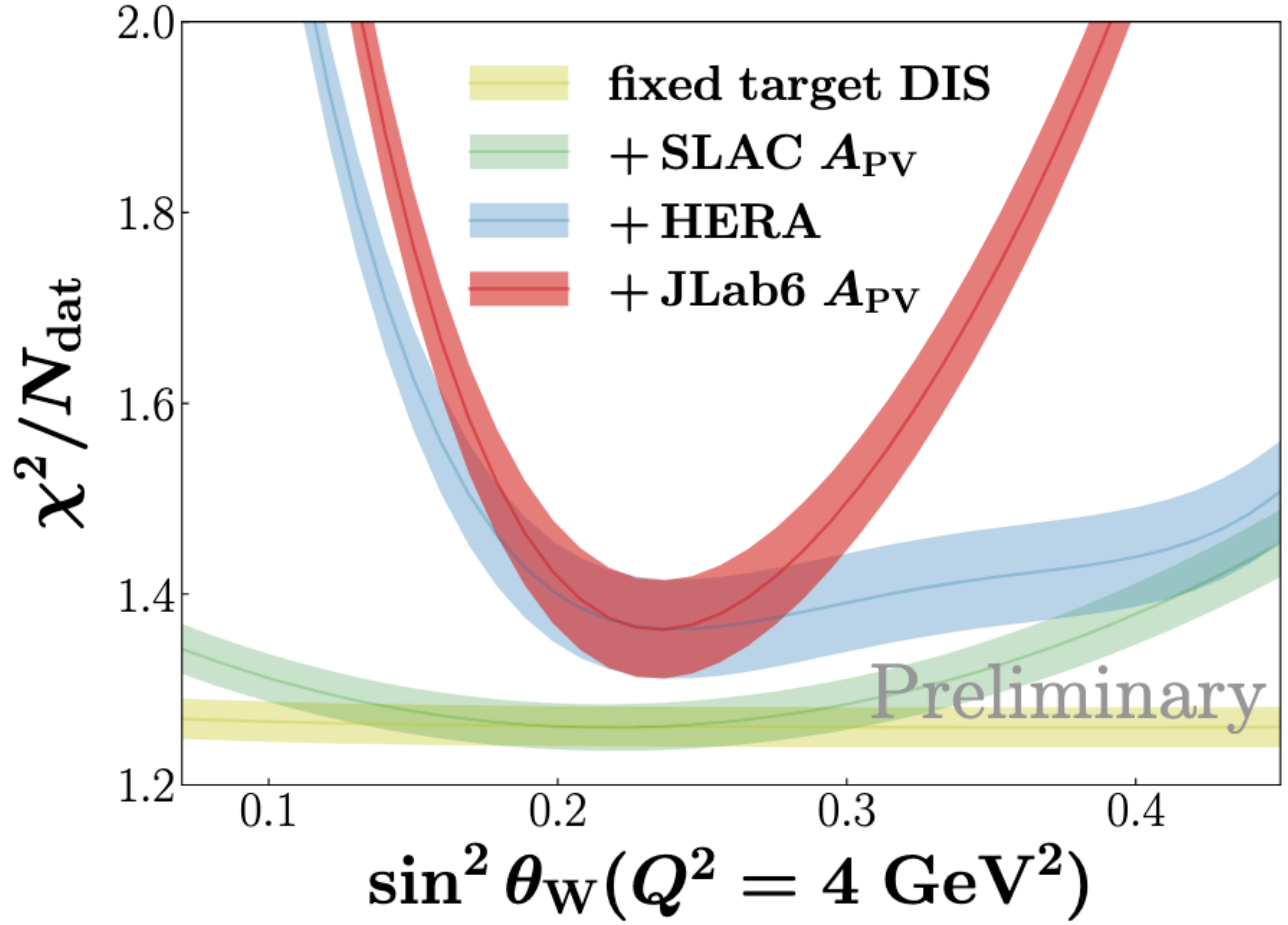


→ size of the strange PDFs? — s^+

→ strange sea asymmetry? — s^-

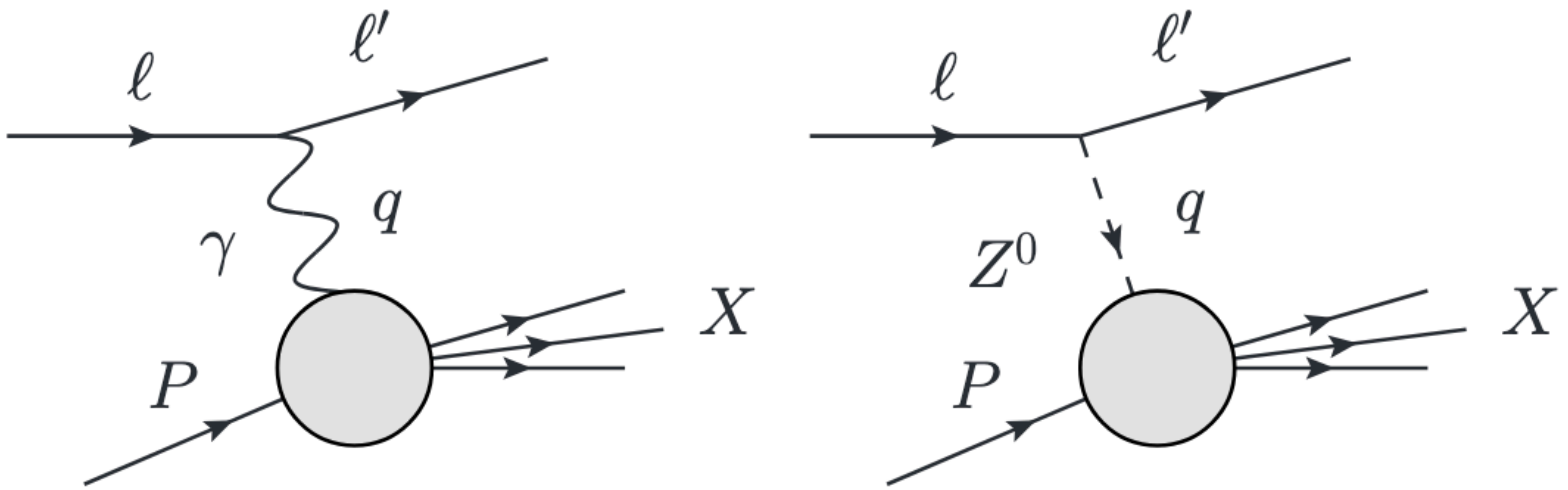
Motivations from BSM physics



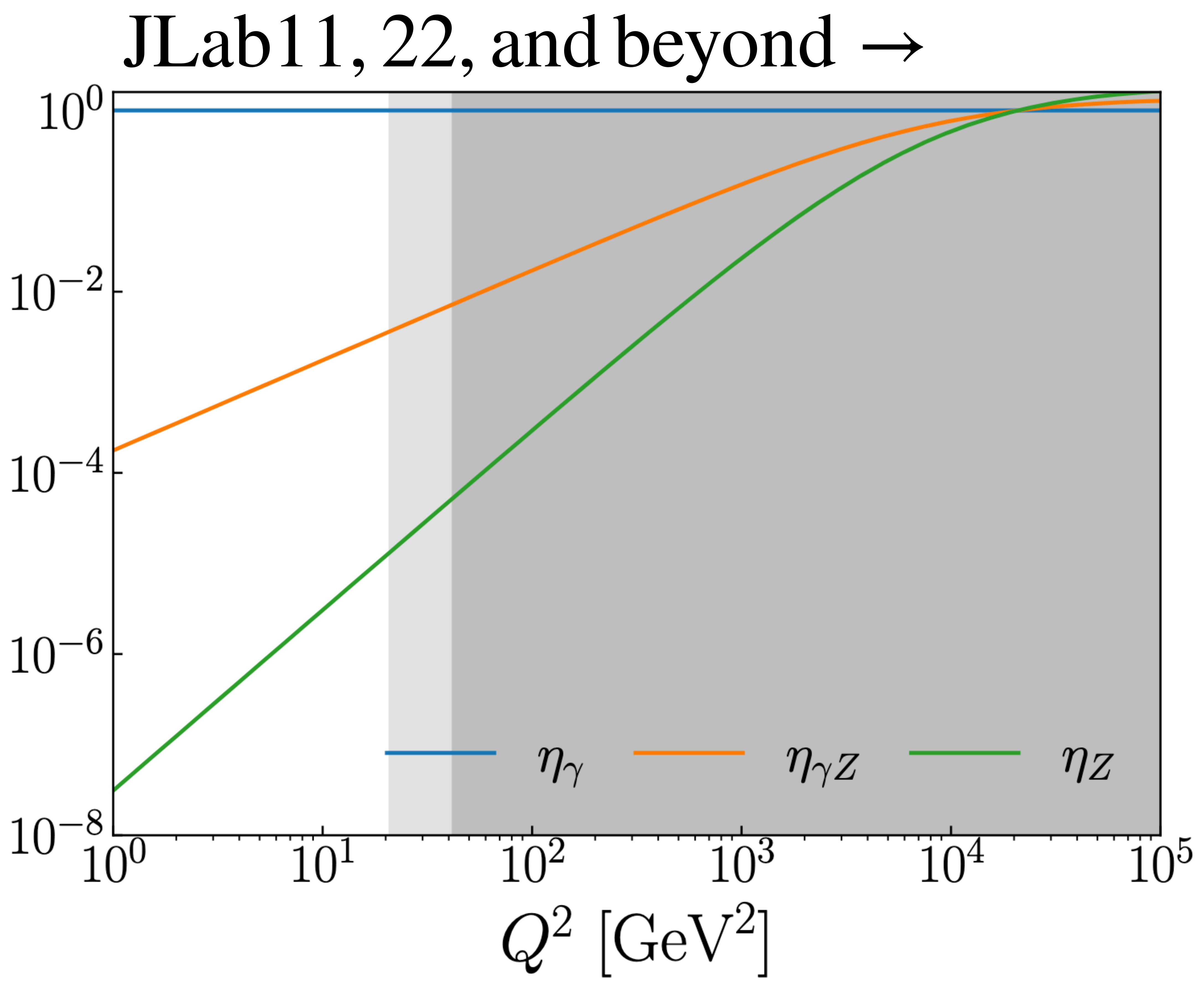


Theoretical Overview and Motivations

Parity-violation in DIS



$$\frac{\mathrm{d}\sigma_{\lambda_\ell}}{\mathrm{d}x\,\mathrm{d}y} = \frac{2\pi\alpha^2 y}{Q^2} \sum_{j\in\{\gamma,\gamma Z,Z\}} \eta_j C_j\, L^{\gamma}_{\mu\nu} W^{\mu\nu}_{j,U}$$



Parity-violating asymmetry

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

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

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

$$Y_3 = \left(\frac{1 + R^{\gamma Z}}{1 + R^\gamma}\right) \frac{1 - (1-y)^2}{1 + (1-y)^2 - \frac{y^2}{2}\left[1 + r^2 - \frac{2r^2}{1 + R^{\gamma}}\right]}, \quad R^i = \frac{F_2^i}{2xF_1^i} r^2 - 1$$

Parity-violating asymmetry

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

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

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

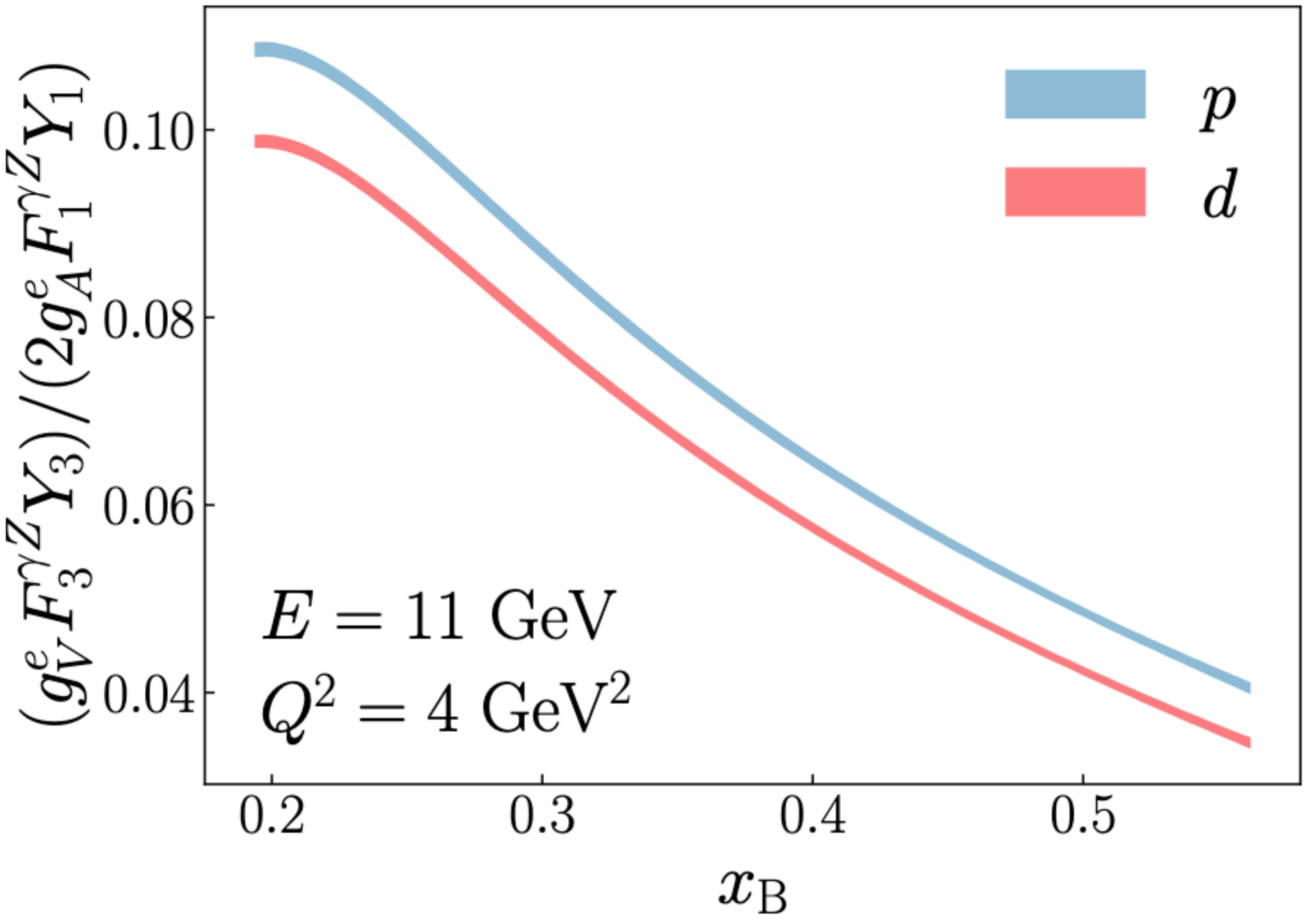
$$Y_3 = \left(\frac{1+R^{\gamma Z}}{1+R^\gamma}\right)\frac{1-(1-y)^2}{1+(1-y)^2 - \frac{y^2}{2}\left[1+r^2-\frac{2r^2}{1+R^{\gamma}}\right]}, \quad R^i = \frac{F_2^i}{2xF_1^i} r^2 - 1 \approx 0$$

Parity-violating asymmetry

$$A_{\rm PV} \approx \frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\left[2g_A^e \frac{F_1^{\gamma Z}}{F_1^\gamma} Y_1 + g_V^e \frac{F_3^{\gamma Z}}{F_1^\gamma} Y_3\right]$$

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

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

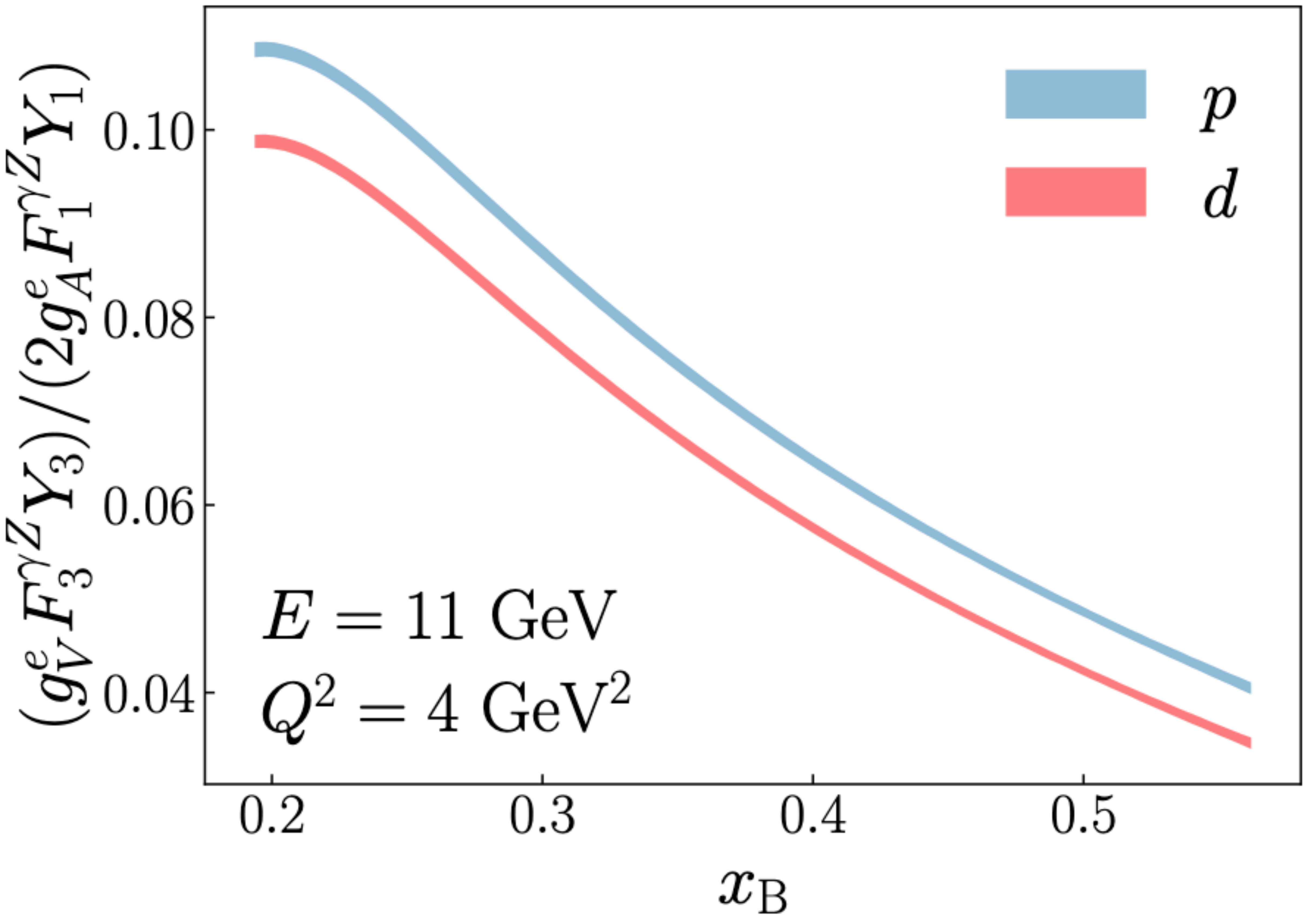


Parity-violating asymmetry

$$A_{\rm PV} \approx -\frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\frac{\sum_q 2e_q g_V^q q^+}{\sum_q e_q^2 q^+}$$

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

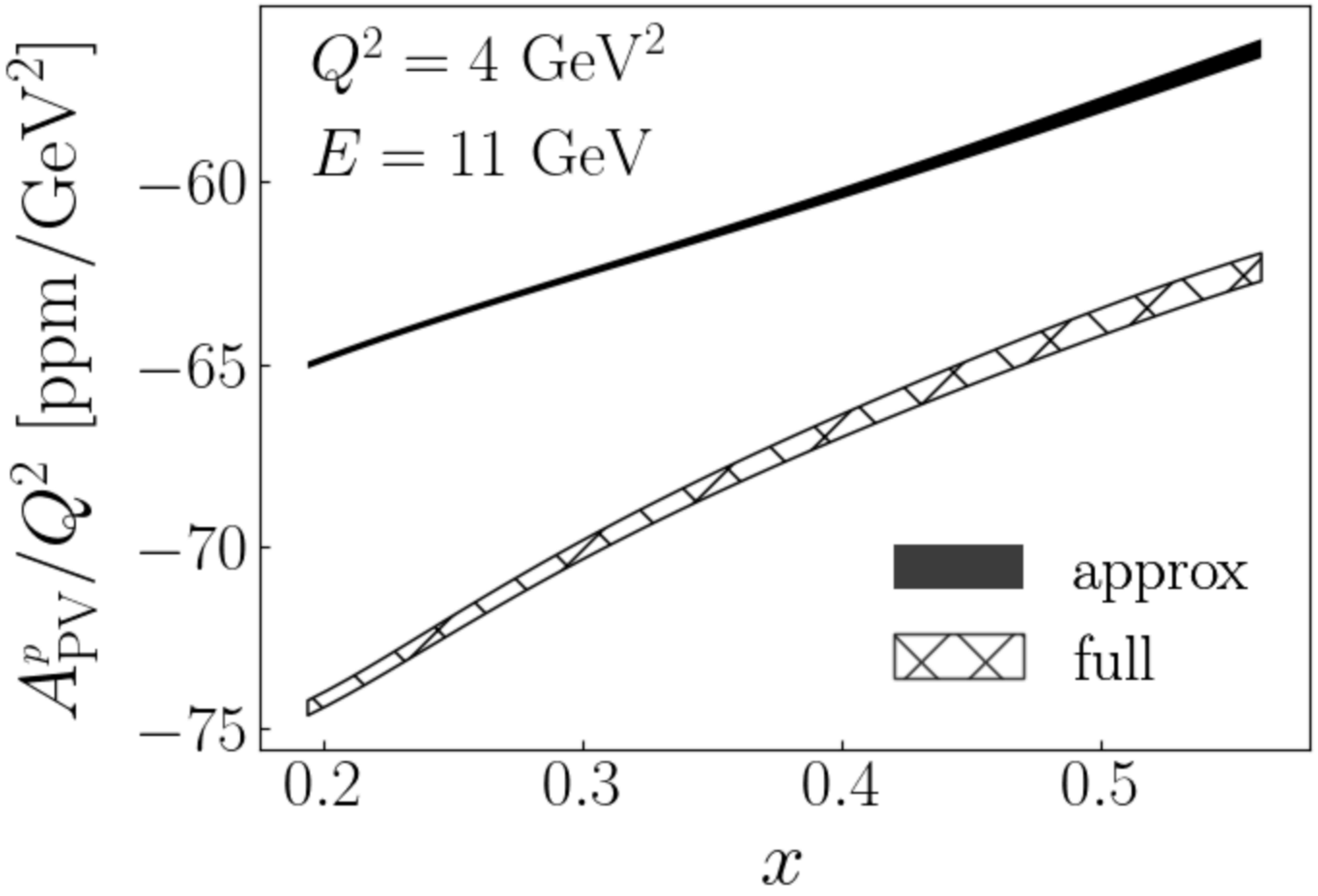
$$Y_1 \approx 1, \quad Y_3 \approx \frac{1-(1-y)^2}{1+(1-y)^2}$$

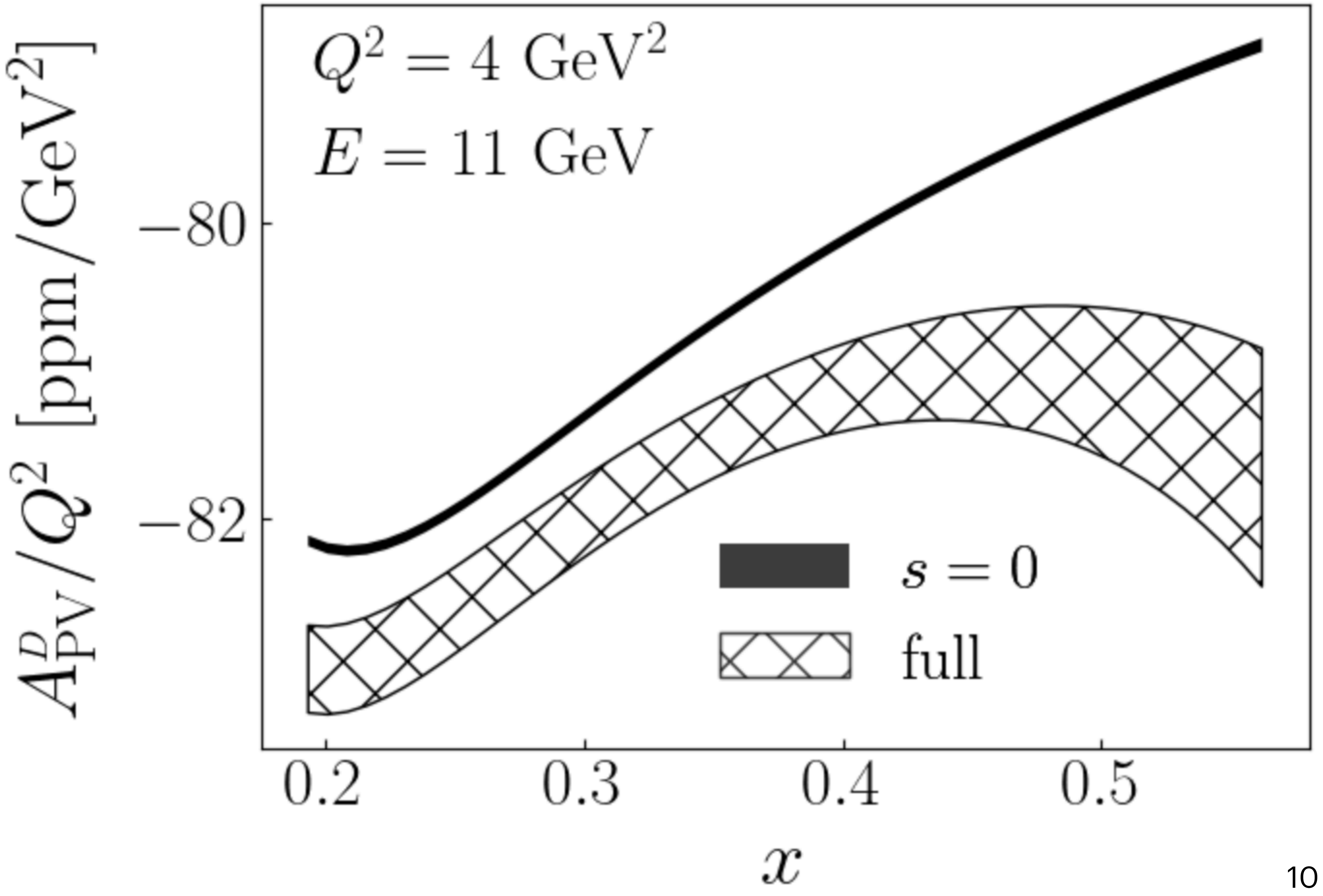


$A_{\rm PV}$: proton and deuterium targets

$$A_{\rm PV}^p \approx -\frac{G_F Q^2}{4\sqrt{2}\pi\alpha}(3g_V^u)\frac{1-\frac{g_V^d}{2g_V^u}d/u}{1+\frac{1}{4}d/u}$$

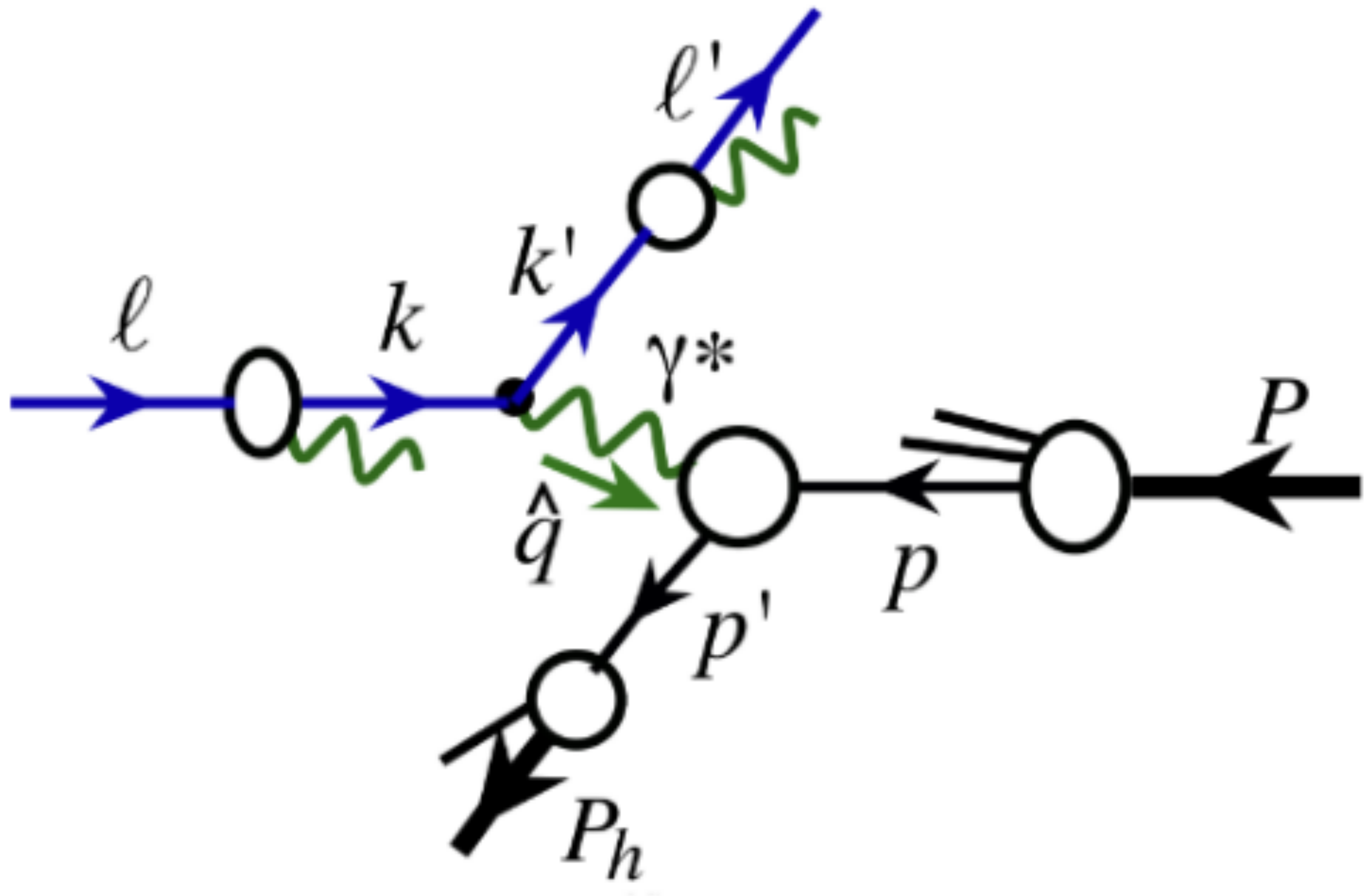
$$A_{\rm PV}^D \approx -\frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\left[\left(\frac{9}{5}-4\sin^2\theta_{\rm W}\right)+\frac{2}{25}\frac{s^+}{u^++d^+}\right]$$



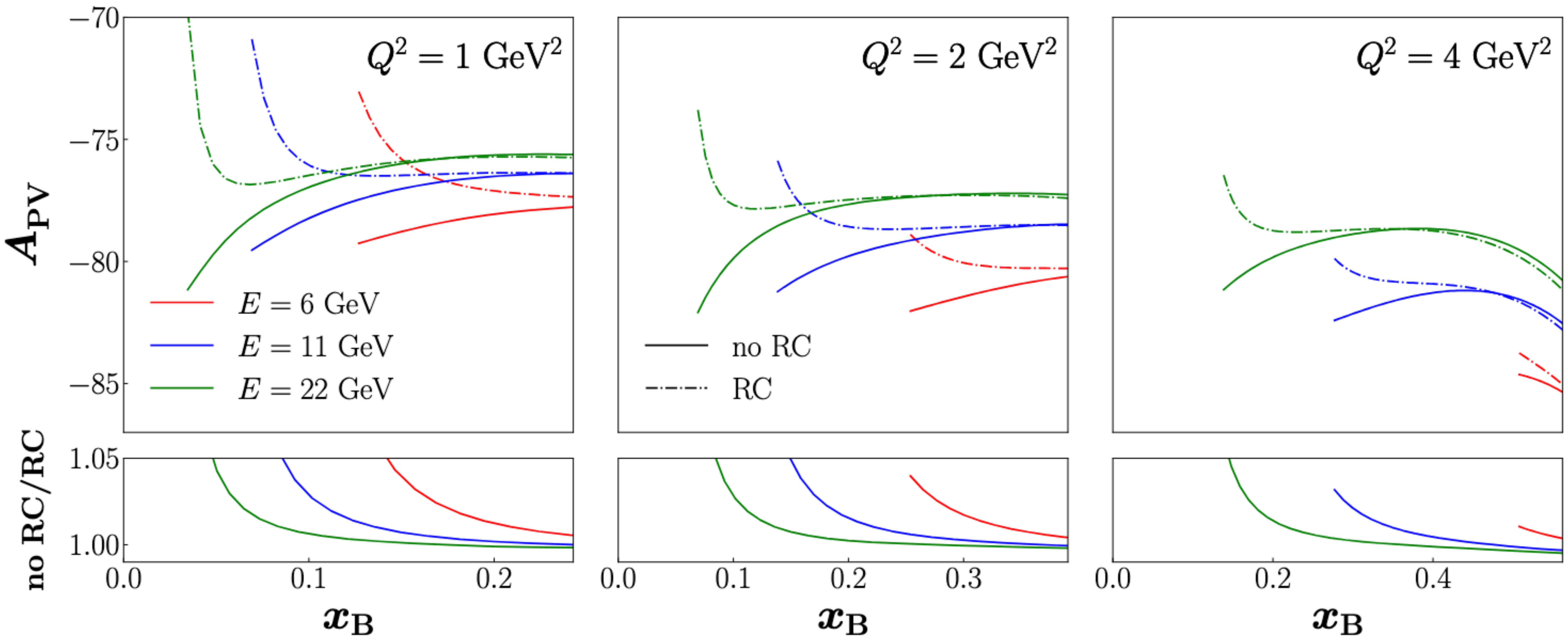


QED radiative corrections

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



T. Liu *et al.*, JHEP 11 (2021)



Higher twist corrections

Multiplicative HT's

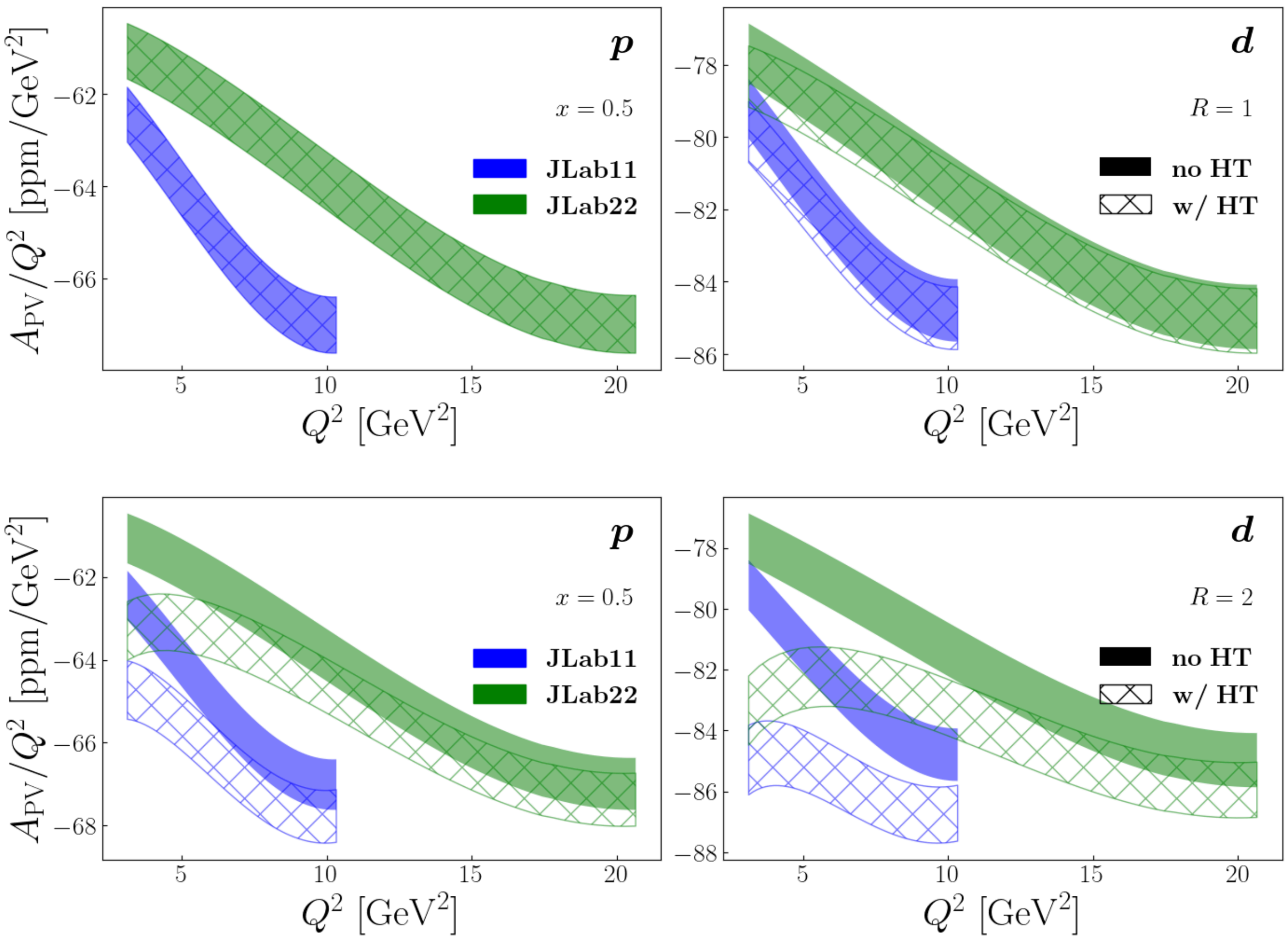
$$F_i^{\gamma} = F_{i,LT}^{\gamma}\left(1 + \frac{H_i^{\gamma}}{Q^2}\right)$$

C. Cocuzza *et al.*, PRL 127, 242001 (2021)

$$F_i^{\gamma Z} = F_{i,LT}^{\gamma Z}\left(1 + \frac{H_i^{\gamma Z}}{Q^2}\right) \quad ???$$

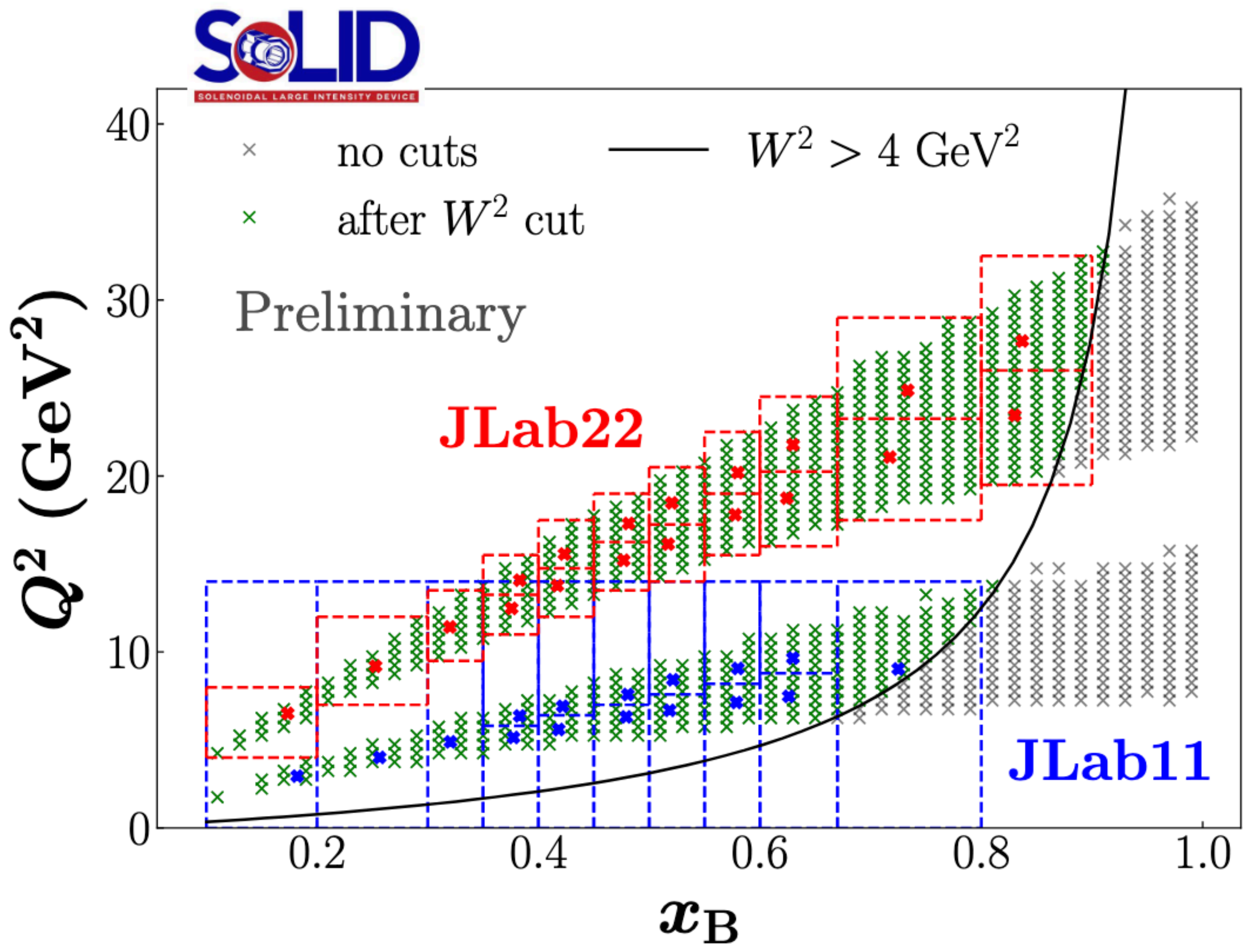
Model:

$$\rightarrow H_i^{\gamma Z} = R\, H_i^{\gamma}$$



Impact Study

Simulating pseudo-data



Scenarios

1. stat. + exp. syst. uncertainties
2. (1) + QED effects
3. (2) + HT effects

Experimental configuration

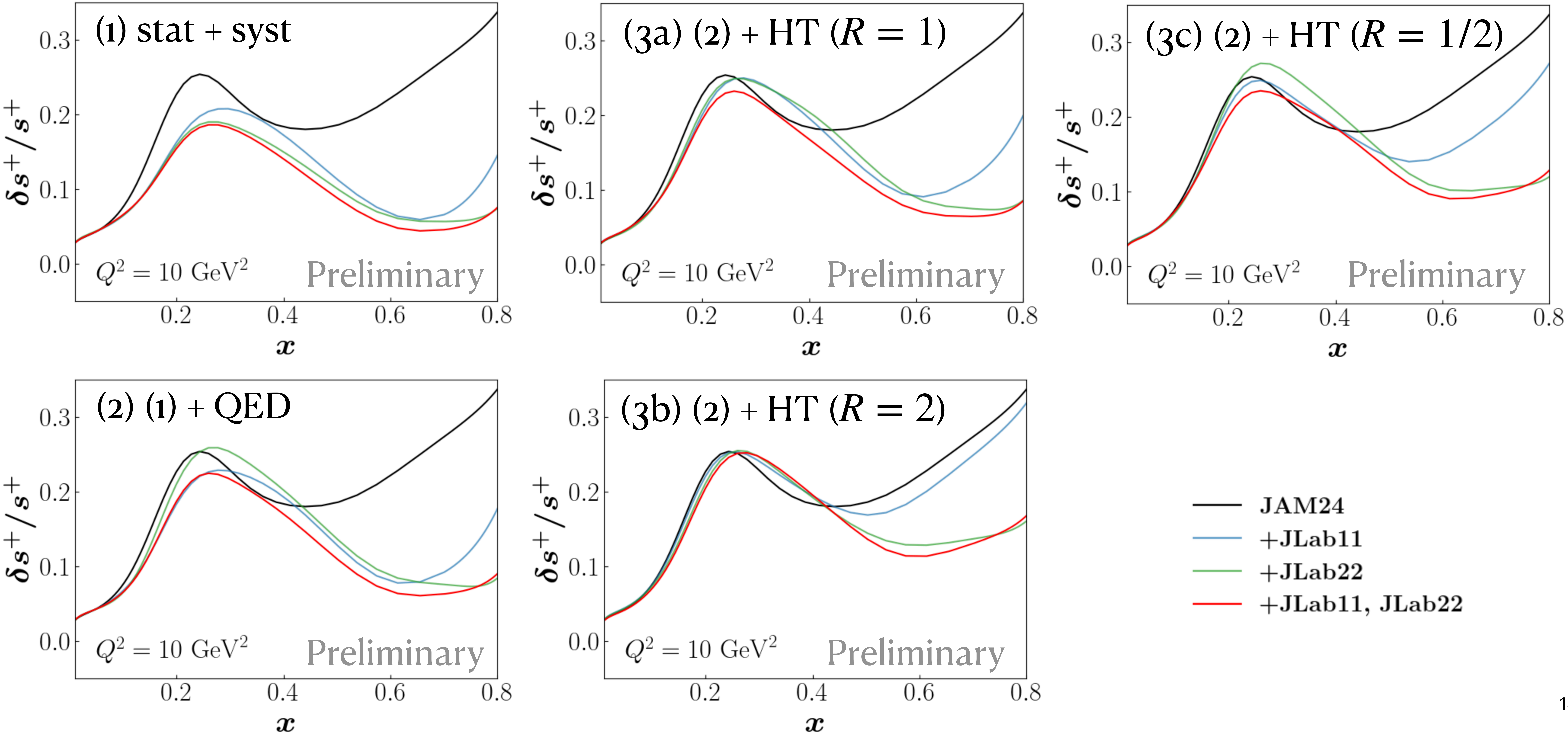
→ $P = 85\,\%$

→ $\mathrm{d}\mathscr{L}/\mathrm{d}t = 4.85 \times 10^{38}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$

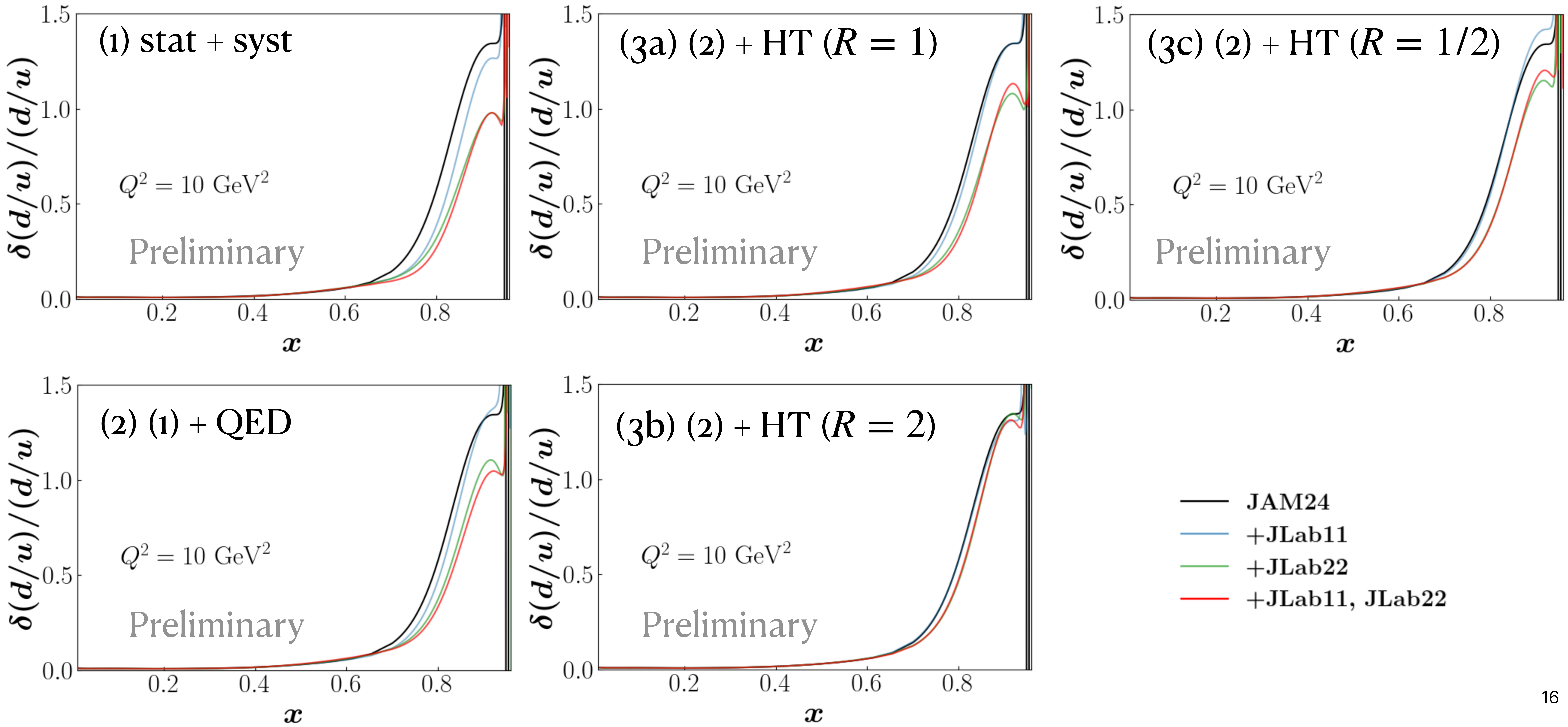
→ run time: 50 days/target

→ $\delta^{\mathrm{syst}} A_{\mathrm{PV}} = 0.5\,\%$

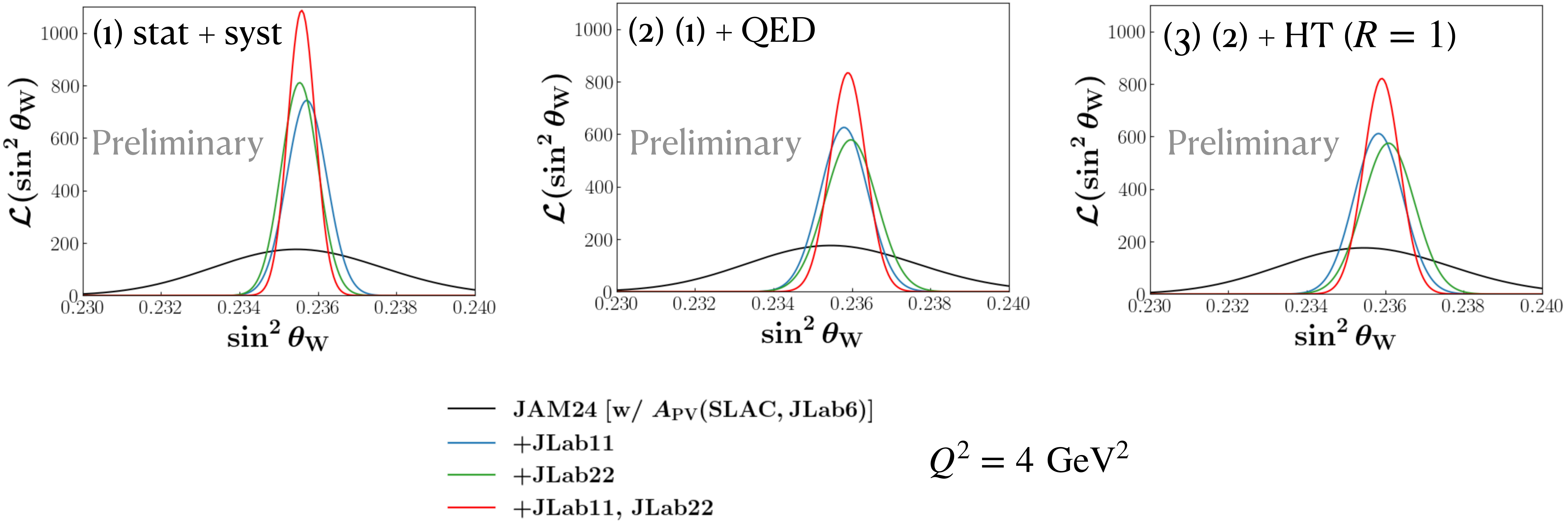
Impact on PDFs — strangeness



Impact on PDFs — d/u

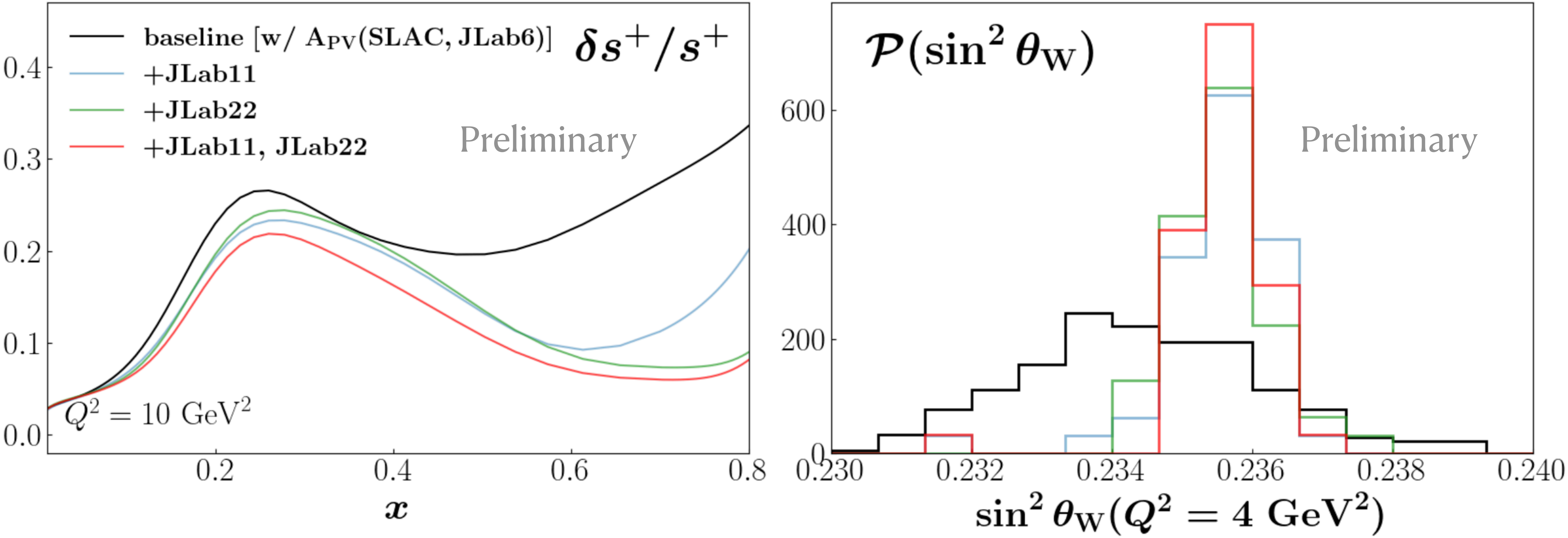


Impact on weak-mixing angle



$Q^2 = 4\ \text{GeV}^2$

Simultaneous impact on PDFs + $\sin^2\theta_W$



Full uncertainties ($R = 1$)

Conclusions/Outlook

A_{PV} is a unique and clean observable that can be used in future global analyses to make progress toward

1) constraint of nucleon strangeness for better understanding of nucleon structure

→ up to ~20% reduction in uncertainties for 11 & 22 GeV

→ QED, HT effects may wash out 11 GeV signal ⇒ 22 GeV data gives cleanest signal

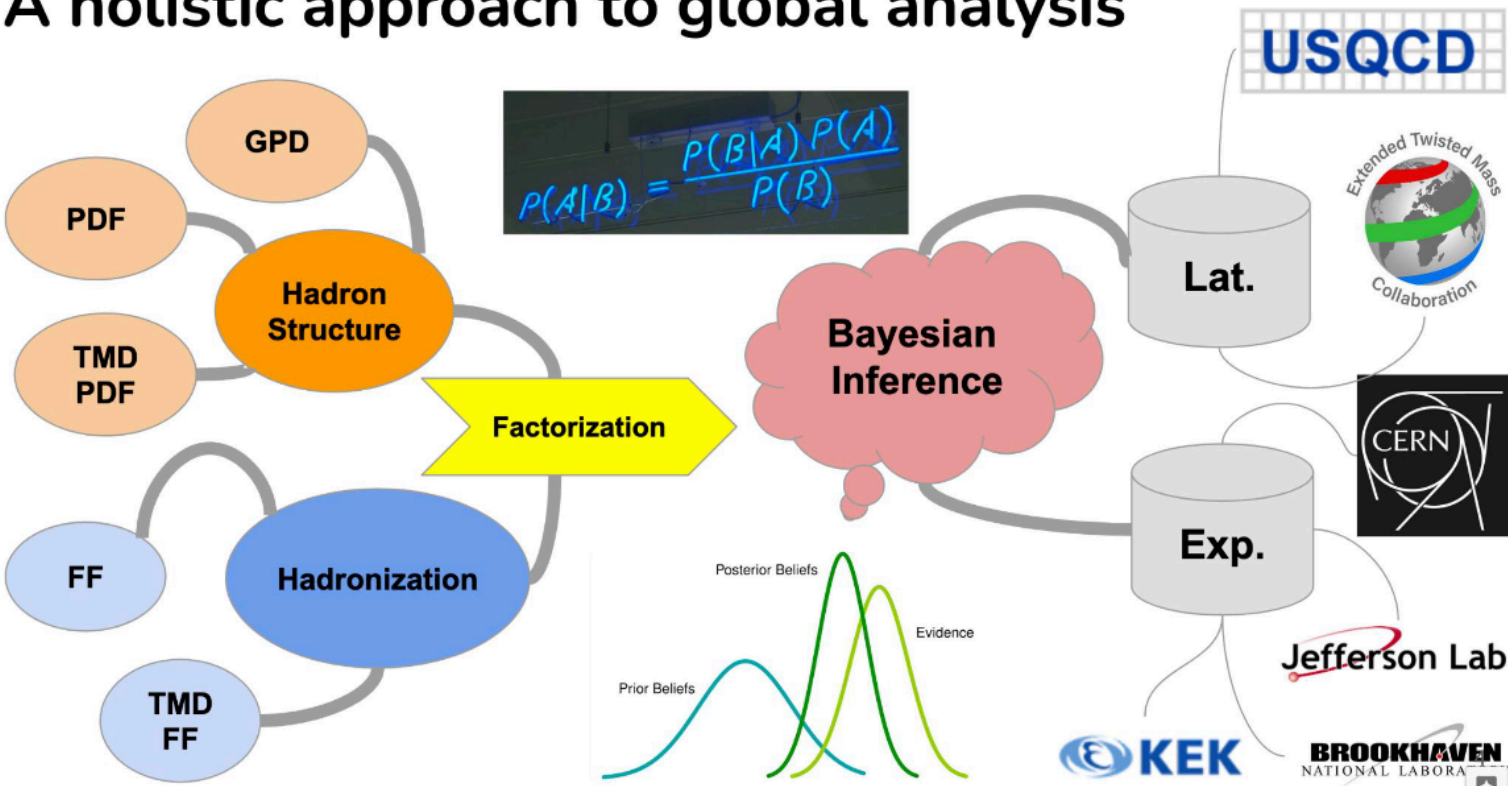
2) tests of BSM physics through the determination of the weak-mixing angle

→ significant constraint at low-Q^2; signal may be more resistant to some systematics

Reinforcements

Global QCD analysis

A holistic approach to global analysis



Global QCD analysis

Factorization: $\mathcal{O} = \mathcal{H} \otimes \text{QCFs}$

Bayes' theorem:

$\rightarrow \mathcal{P}(\vec{a}\,|\,\text{data}) \sim \mathcal{L}(\vec{a}, \text{data})\pi(\vec{a})$

$\rightarrow \mathcal{L}(\vec{a}\,|\,\text{data}) = \exp(-\chi^2(\vec{a}, \text{data})/2)$

Monte Carlo Replicas: $\widetilde{\text{data}} \sim \mathcal{N}(\text{data}, \Sigma)$

$$\chi^2 = \sum_{e,i} \left(\frac{d_{e,i} - \sum_k r_{e,k}\beta^k_{e,i} - T_{e,i}/N_e}{\alpha_{e,i}} \right)^2 + \sum_{e,k} r^2_{e,k} + \sum_e \left(\frac{1 - N_e}{\delta N_e} \right)^2$$

$$\mathrm{E}[\mathcal{O}] = \frac{1}{N_{\text{rep}}} \sum_{i=1}^{N_{\text{rep}}} \mathcal{O}(\vec{a}_i)$$

$$\mathrm{V}[\mathcal{O}] = \frac{1}{N_{\text{rep}}} \sum_{i=1}^{N_{\text{rep}}} \Big(\mathcal{O}(\vec{a}_i) - \mathrm{E}[\mathcal{O}] \Big)^2$$