Constraints on new physics with (anti)neutrino-nucleon scattering data

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NuFACT
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based on

- 2402.14115, 2403.04687, with K. Borah, M. Betancourt, T. Junk and O. Tomalak

Outline

- Introduction
- Theory framework
- Fit procedure and inputs
- Results
- Discussion

Introduction

- Precise knowledge of neutrino-nucleon scattering amplitudes at GeV energies is required for current and future neutrino oscillation experiments

- Beyond their role in neutrino-nucleus cross sections, these amplitudes can be used directly for fundamental physics

- Nucleon-level amplitudes are free from nuclear modeling uncertainties. Standard Model contributions are constrained from electron-proton scattering, muonic atom spectroscopy and muon capture, lattice QCD

Introduction

- consider the application of (anti)neutrino-nucleon scattering data as a probe of new physics in neutrino interactions

- especially constraining in the class of models where new physics is suppressed by m_ℓ/M ($m_\ell =$ lepton mass, $M =$ nucleon mass), so electron-based measurements such as beta decay offer weak constraints.

- accelerator neutrino beams contain largely muon flavor and the lepton mass enhancement is naturally present. Similar to using muonic atoms for proton charge radius (spectroscopy), and nucleon axial radius (weak capture)

Theory framework

- Restrict attention to left-handed neutrinos (could generalize)

In Standard Model, at $m_\ell = 0$, four amplitudes (f_1, f_2, f_A, f_{A3})

$$\bar{\nu}_\ell \gamma^\mu (1-\gamma_5) \ell^+ \times \bar{n} \left[\gamma_\mu \left(\bar{f}_1 + \bar{f}_2 + \bar{f}_A \gamma_5 \right) - \left(\bar{f}_2 + 2 \bar{f}_{A3} \gamma_5 \right) \frac{K_\mu}{M} \right] p$$

At $m_\ell \neq 0$, four more amplitudes (f_3, f_P, f_T, f_R)

$$\frac{m_\ell}{M} \left[\frac{\bar{f}_T}{4} \bar{\nu}_\ell \sigma^{\mu\nu} (1+\gamma_5) \ell^+ \bar{n} \sigma_{\mu\nu} p - \bar{\nu}_\ell (1+\gamma_5) \ell^+ \bar{n} \left(\bar{f}_3 + \bar{f}_P \gamma_5 - \frac{\bar{f}_R}{4} \frac{\gamma^\mu P_\mu}{M} \gamma_5 \right) p \right]$$

Theory framework

- The number of amplitudes is fixed by helicity counting. Our labeling reduces to Llewellyn Smith notation for 6 current-current interactions

ν scattering		*beta decay*
$f_1 \leftrightarrow F_1^V$		C_V
$f_2 \leftrightarrow F_2^V$		
$f_3 \leftrightarrow F_3^V$	second-class vector	C_S
$f_A \leftrightarrow F_A$		C_A
$f_P \leftrightarrow F_P$		
$f_{A3} \leftrightarrow F_3^A$	second-class axial	

- Two additional amplitudes are not given by current-current

f_T	C_T
f_R	

Theory framework

- Compute differential cross section in terms of these amplitudes

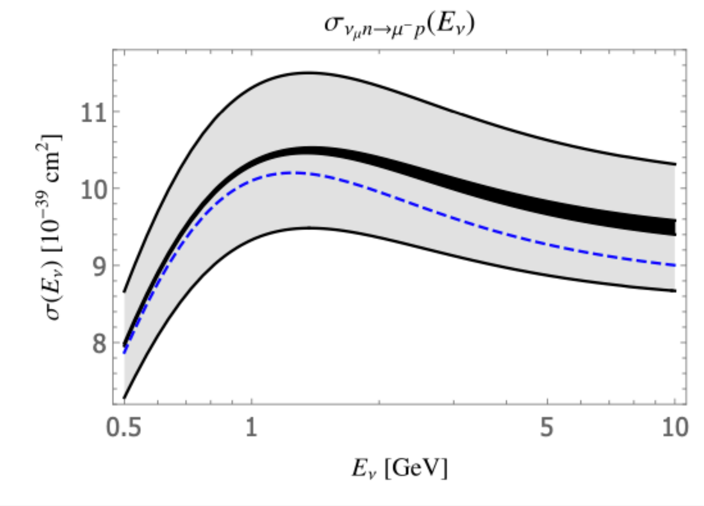
$$\frac{d\sigma}{dQ^2}\left(E_\nu, Q^2\right) = \frac{G_F^2 |V_{ud}|^2}{2\pi}\frac{M^2}{E_\nu^2}\left[\left(\tau + r_\ell^2\right) A\left(\nu, Q^2\right) + \frac{\nu}{M^2} B\left(\nu, Q^2\right) + \frac{\nu^2}{M^4}\frac{C\left(\nu, Q^2\right)}{1+\tau}\right]$$

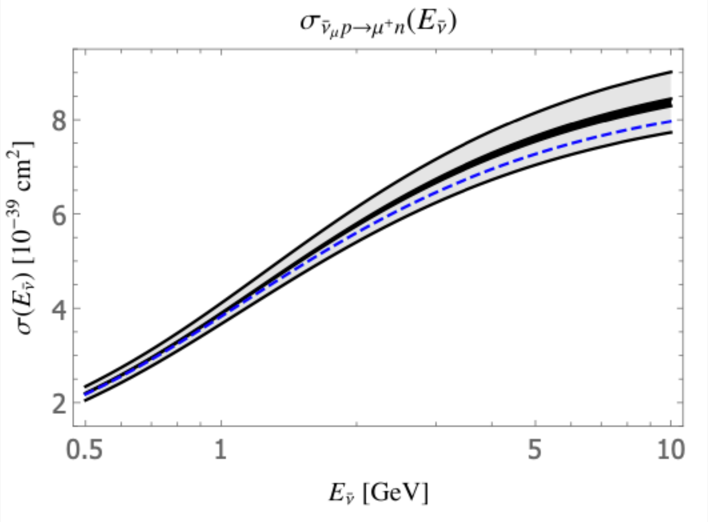
$$\begin{aligned} A = {} & \tau|\bar{g}_M|^2 - |\bar{g}_E|^2 + (1+\tau)|\bar{f}_A|^2 - r_\ell^2\left(|\bar{g}_M|^2 + |\bar{f}_A + 2\bar{f}_P|^2 - 4(1+\tau)\left(|\bar{f}_P|^2 + |\bar{f}_3|^2\right)\right) \\ & - 4\tau(1+\tau)|\bar{f}_{A3}|^2 + \frac{r_\ell^2}{4}\left(\nu^2 + 1 + \tau - \left(1+\tau+r_\ell^2\right)^2\right)|\bar{f}_R|^2 - r_\ell^2\left(1+2r_\ell^2\right)|\bar{f}_T|^2 \\ & - 2r_\ell^2 \mathfrak{Re}\left[\left(\bar{g}_E + 2\bar{g}_M - 2(1+\tau)\bar{f}_{A3}\right)\bar{f}_T^\star\right] + r_\ell^2\left(1+\tau+r_\ell^2\right)\mathfrak{Re}\left[\bar{f}_A\bar{f}_R^\star\right] + 2r_\ell^4\mathfrak{Re}\left[\bar{f}_P\bar{f}_R^\star\right] \end{aligned}$$

$$B = \mathfrak{Re}\left[4\tau\bar{f}_A^*\bar{g}_M - 4r_\ell^2\left(\bar{f}_A - 2\tau\bar{f}_P\right)^*\bar{f}_{A3} - 4r_\ell^2\bar{g}_E\bar{f}_3^\star - 2r_\ell^2\left(3\bar{f}_A - 2\tau\left(\bar{f}_P + \bar{f}_3\right)\right)\bar{f}_T^\star - r_\ell^4\left(\bar{f}_T + 2\bar{f}_{A3}\right)\bar{f}_R^\star\right]$$

$$C = \tau|\bar{g}_M|^2 + |\bar{g}_E|^2 + (1+\tau)|\bar{f}_A|^2 + 4\tau(1+\tau)|\bar{f}_{A3}|^2 + 2r_\ell^2(1+\tau)|\bar{f}_T|^2 - r_\ell^2(1+\tau)\mathfrak{Re}\left[\bar{f}_A\bar{f}_R^\star\right]$$

standard inputs and errors for Standard Model f_1, f_2, f_A, f_P





Theory framework

Small Standard Model contributions to f_3, f_{A3}, f_T, f_R.
Consider BSM constraints

- Lepton mass necessarily appears when f_3, f_T, f_R arise in the SM (including radiative corrections)

$$\bar{\nu}_\ell \gamma^\mu (1-\gamma_5)\ell^+ \times \bar{n} \left[\gamma_\mu \left(\bar{f}_1 + \bar{f}_2 + \bar{f}_A \gamma_5\right) - \left(\bar{f}_2 + 2\bar{f}_{A3}\gamma_5\right) \frac{K_\mu}{M} \right] p$$

$$\frac{m_\ell}{M} \left[\frac{\bar{f}_T}{4} \bar{\nu}_\ell \sigma^{\mu\nu}(1+\gamma_5)\ell^+ \, \bar{n}\sigma_{\mu\nu} p - \bar{\nu}_\ell (1+\gamma_5)\ell^+ \, \bar{n} \left(\bar{f}_3 + \bar{f}_P \gamma_5 - \frac{\bar{f}_R}{4} \frac{\gamma^\mu P_\mu}{M} \gamma_5 \right) p \right]$$

- This lepton mass dependence generalizes to any model obeying minimal lepton flavor violation

$$\bar{e}_R \sigma^{\mu\nu} \lambda_e \Delta L_L \bar{Q}_L \sigma_{\mu\nu} \lambda_D d_R$$

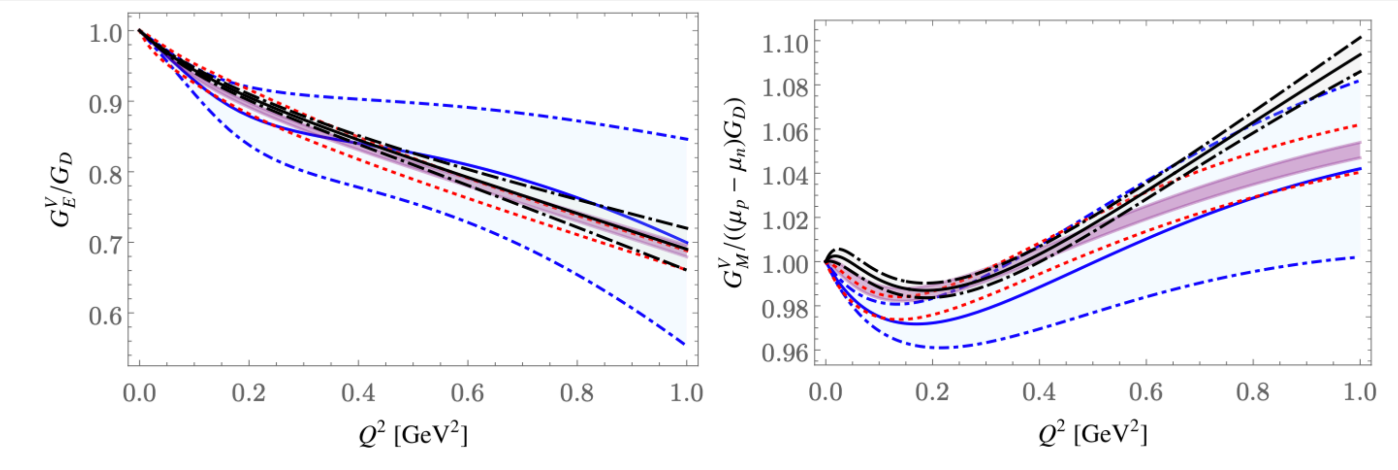
$$(\lambda_e)_{ij} = m_\ell^{(i)} \delta_{ij} \qquad\qquad \Delta_{ij} \propto \delta_{ij} + \mathcal{O}[(\Delta m)^2]$$

Cirigliano et al., hep-ph/0507001

Fit procedure/ inputs

- Vector form factors

Borah et al. 2003.13640 (now available in GENIE!)



$$G_E^N(Q^2) = \sum_{k=0}^{k_{\max}} a_k z(Q^2)^k\,, \quad G_M^N(Q^2) = G_M(0)\sum_{k=0}^{k_{\max}} b_k z(Q^2)^k\,, \quad z(Q^2) = \frac{\sqrt{t_{\rm cut}+Q^2}-\sqrt{t_{\rm cut}-t_0}}{\sqrt{t_{\rm cut}+Q^2}+\sqrt{t_{\rm cut}-t_0}}\,.$$

$$[a_1^V, a_2^V, a_3^V, a_4^V] = [-1.576(15), 0.177(77), 2.05(24), 0.88(57)]$$

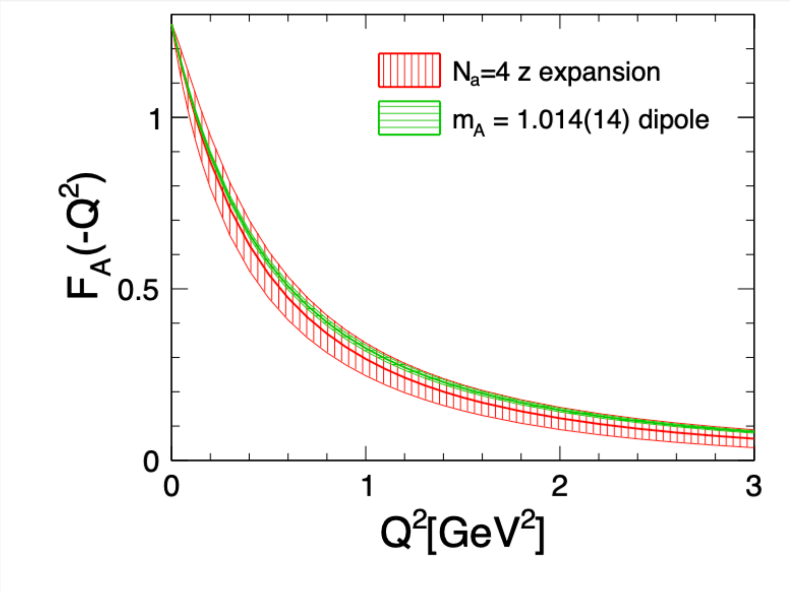
$$[b_1^V, b_2^V, b_3^V, b_4^V] = [-1.456(13), 0.186(67), 1.63(23), -0.73(46)]$$

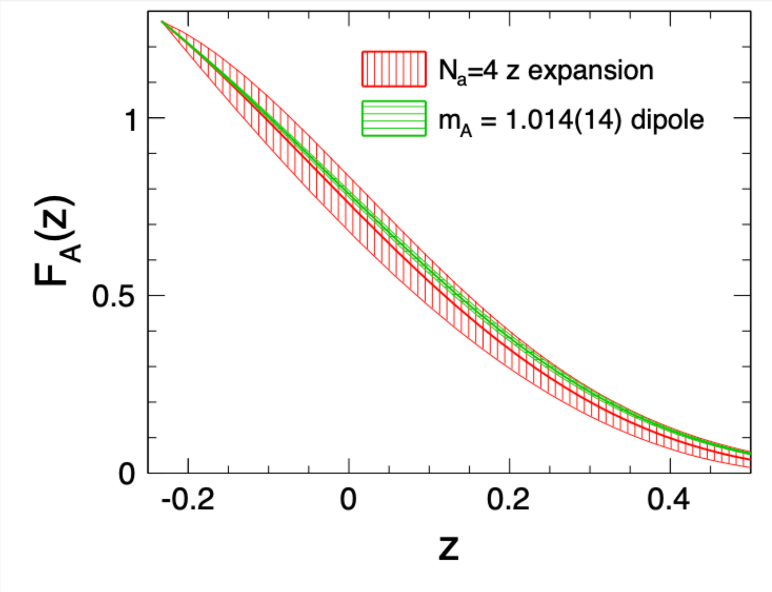
constrained using

- electron scattering, A1, PRAD
- low energy constraints on charge, magnetic moment, charge radius
- complete treatment of radiative corrections

Fit procedure/ inputs

- Axial form factors *Meyer et al. 1603.03048*





$$[a_1, a_2, a_3, a_4] = [2.30(13), -0.6(1.0), -3.8(2.5), 2.3(2.7)]$$

$$C_{ij} = \begin{pmatrix} 1 & 0.350 & -0.678 & 0.611 \\ 0.350 & 1 & -0.898 & 0.367 \\ -0.678 & -0.898 & 1 & -0.685 \\ 0.611 & 0.367 & -0.685 & 1 \end{pmatrix}$$

constrained using

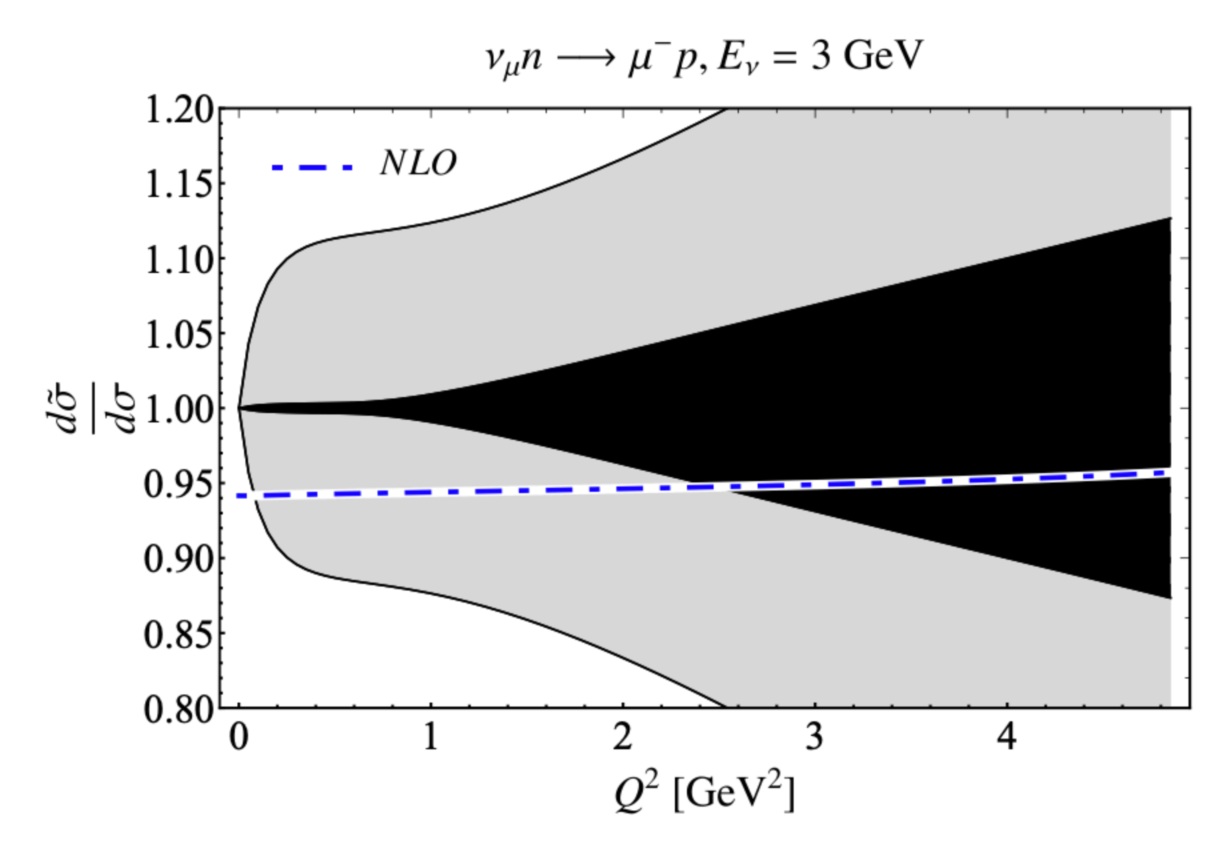
- ANL, BNL, FNAL deuterium bubble chamber data
- vector form factor inputs

Fit procedure/ inputs

- Radiative corrections

Tomalak et al. 2105.07939

Tomalak et al. 2204.11379



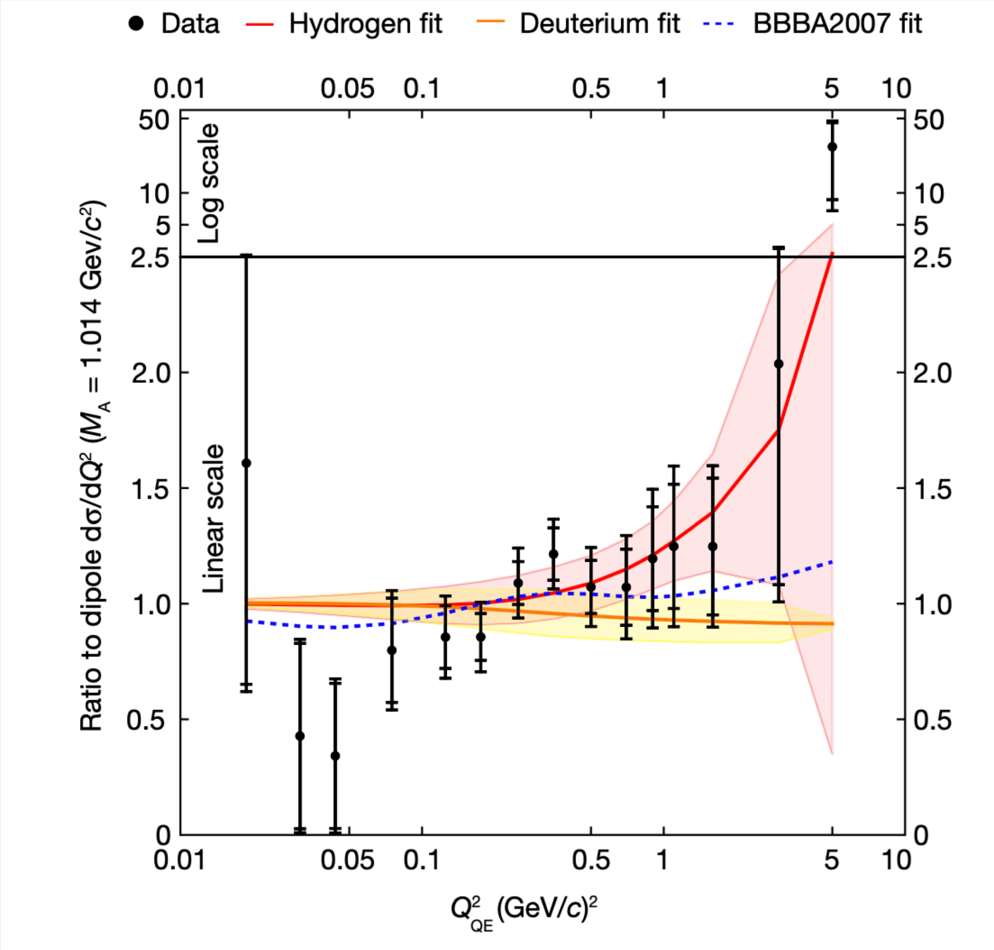
- Significant corrections, especially to exclusive observables, and to electron versus muon ratios

- Subleading in the current analysis

Fit procedure/ inputs

- Use MINERvA antineutrino-proton data

Nature 614 (2023) 48



- separated H from C scattering using kinematics

- 15 bins, errors, correlations

Fit procedure/ inputs

- Use standard inputs for dominant f_1, f_2, f_A, f_P

- Use dipole ansatz for BSM contributions to f_3, f_T, f_S, f_R

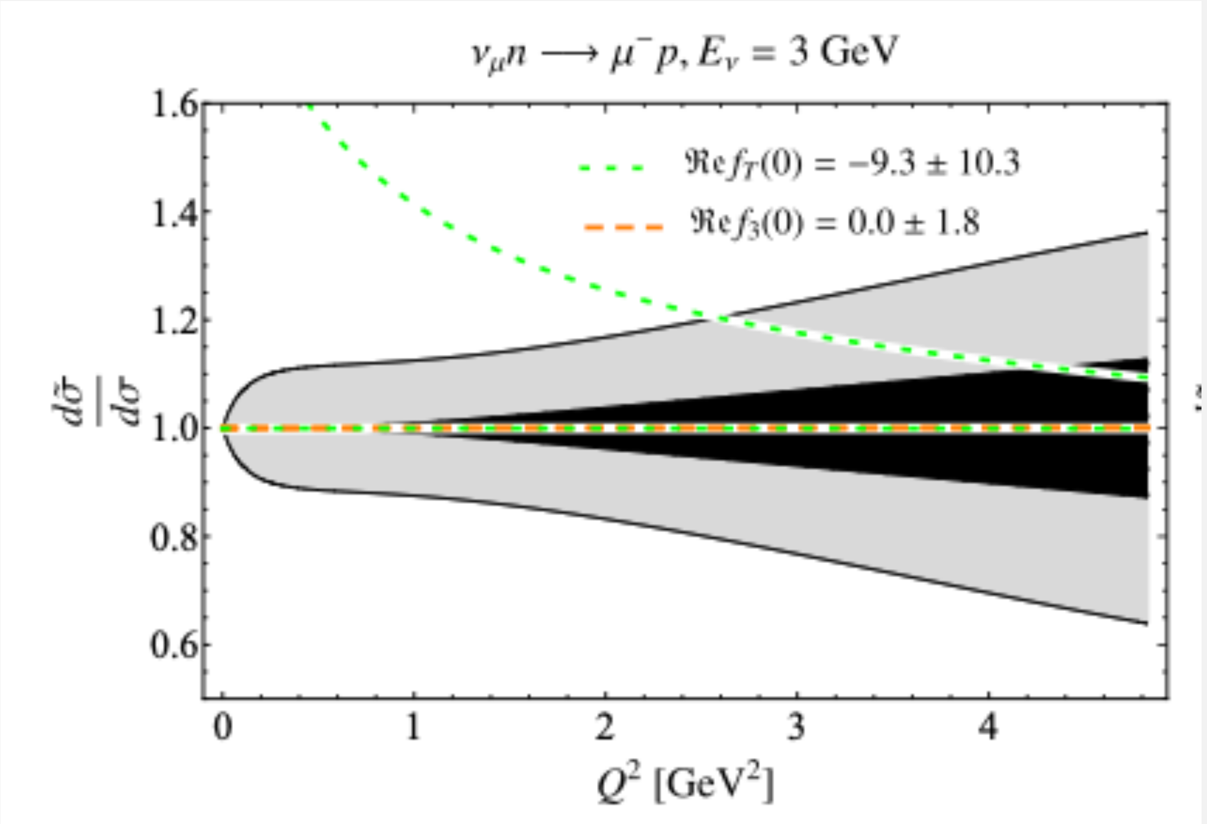
$$\bar{f}^j_i\left(\nu, Q^2\right) = \frac{\mathrm{Re}\bar{f}^j_i(0) + i\mathrm{Im}\bar{f}^j_i(0)}{\left(1 + \frac{Q^2}{\Lambda^2}\right)^2}$$

- Perform fit using errors and correlations of SM inputs, quote results for length of 1σ confidence interval

Results

- Real parts

	$\Re\mathfrak{e}\bar{f}_3$	$\Re\mathfrak{e}\bar{f}_T$	$\Re\mathfrak{e}\bar{f}_{A3}$	$\Re\mathfrak{e}\bar{f}_R$
$\bar{\nu}p$ scattering	$88.4^{+33.5}_{-58.0}$	$-0.5^{+5.0}_{-4.8}$	$-1.0^{+0.4}_{-0.3}$ & $1.0^{+0.3}_{-0.4}$	$-80.1^{+40.6}_{-26.0}$
beta decay	0.0 ± 1.8 [72]	-9.3 ± 10.3 [73]	0.0 ± 0.075 [66]	



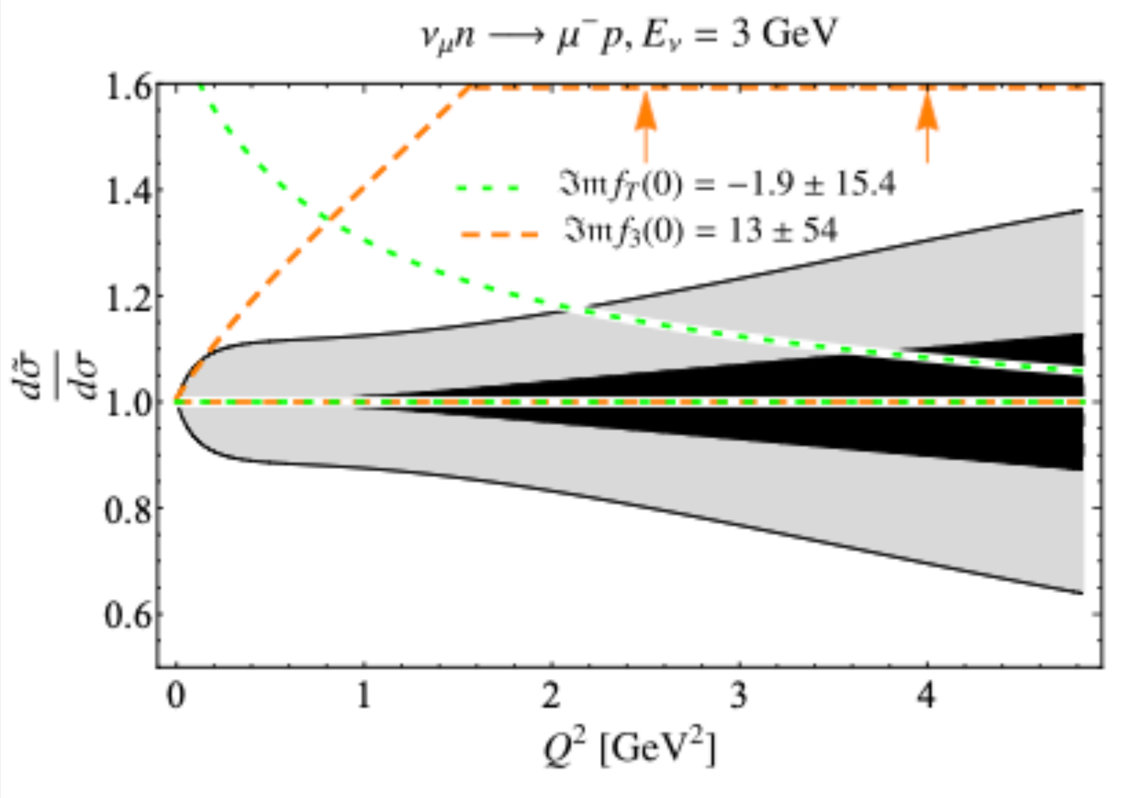
- neutrino scattering improves constraints on Re(fT), versus beta decay

[66] M. Day and K. S. McFarland, Phys. Rev. D **86**, 053003 (2012), arXiv:1206.6745 [hep-ph].
[72] J. C. Hardy and I. S. Towner, Phys. Rev. C **102**, 045501 (2020)
[73] M. González-Alonso, O. Naviliat-Cuncic, and N. Severijns, Prog. Part. Nucl. Phys. **104**, 165 (2019), arXiv:1803.08732 [hep-ph].

Results

- Imaginary parts

	$\mathfrak{Im}\bar{f}_3$	$\mathfrak{Im}\bar{f}_T$	$\lvert\mathfrak{Im}\bar{f}_{A3}\rvert$	$\lvert\mathfrak{Im}\bar{f}_R\rvert$
$\bar{\nu}p$ scattering	$-82.1^{+34.6}_{-23.8}$ & $82.1^{+23.8}_{-34.6}$	0.0 ± 4.9	$1.00^{+0.29}_{-0.43}$	$69.9^{+20.9}_{-30.9}$
beta decay	13.0 ± 54.0 [73]	-1.9 ± 15.4 [73]		



- neutrino scattering improves constraints on Im(fT), and provides comparable constraint on Im(f3) versus beta decay

[73] M. González-Alonso, O. Naviliat-Cuncic, and N. Severijns, Prog. Part. Nucl. Phys. **104**, 165 (2019), arXiv:1803.08732 [hep-ph].

Results

- Translate to Lee-Yang coefficients

$$\mathrm{Re}C_T = -1^{+14}_{-13} \times 10^{-4}$$

$$|\mathrm{Im}C_T| \leq 1.3 \times 10^{-3}$$

$$|\mathrm{Im}C_S| = 45^{+13}_{-19} \times 10^{-3}$$

- Improvement by factor of 2.1, 3.1, 1.2 compared to beta decay

Discussion/future

Other data sets

- have used MINERvA data which includes a complete error matrix

- lower neutrino energy of BNL deuterium data more sensitive to scalar interaction

- DUNE/LBNF may provide high statistics data for antineutrino-hydrogen

Alvarez-Ruso et al. 2203.11298

- Neutrino-nucleus interactions can be considered

Kopp, Rocco, Tabrizi 2401.07902

Discussion/future

Lattice QCD inputs

- MINERvA data dominates error budget
- for consistent separation of SM / BSM, could use lattice inputs for vector, axial form factors
- interesting tension between lattice QCD and deuterium FA extraction

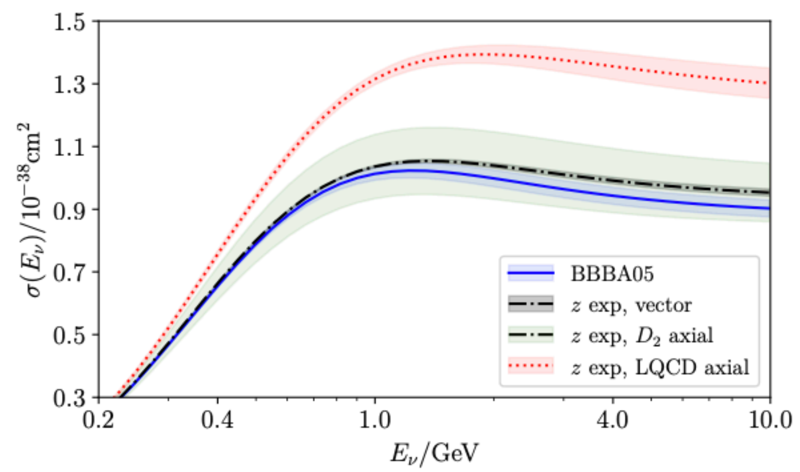


Figure 2: Neutrino cross sections on a free neutron, with their uncertainty bands, for various choices of parameterization explained in the bullet list provided in the Section 2.

Meyer, Walker-Loud, Wilkinson 2201.01839

Discussion/future

Combination with collider bounds

- bounds are tighter than FASERnu for muon-flavor tensor interaction
- assuming only high-scale new physics, Standard Model Effective Theory scalar operators constrained by EDMs

implement MFV including neutrino mass splitting

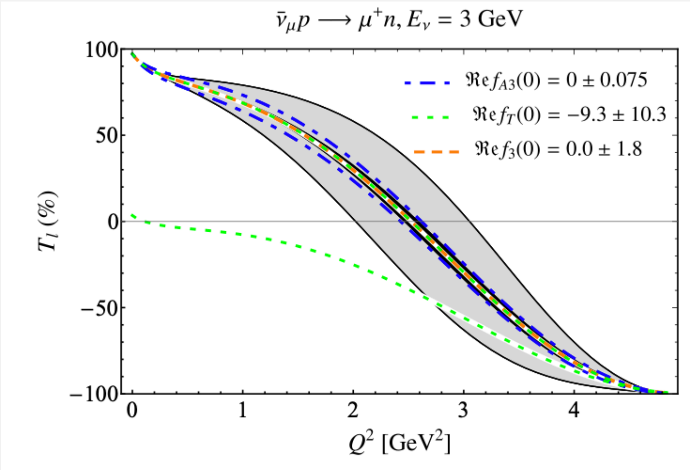
$$\bar{e}_R \sigma^{\mu\nu} \lambda_e \Delta L_L \bar{Q}_L \sigma_{\mu\nu} \lambda_D d_R$$

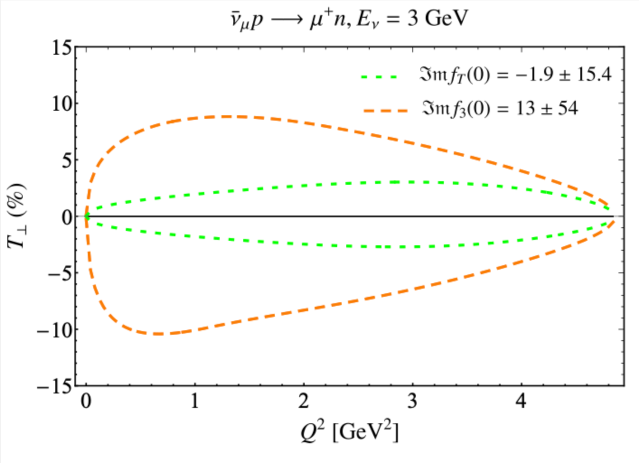
$$(\lambda_e)_{ij} = m_\ell^{(i)} \delta_{ij} \qquad \Delta_{ij} \propto \delta_{ij} + \mathcal{O}[(\Delta m)^2]$$

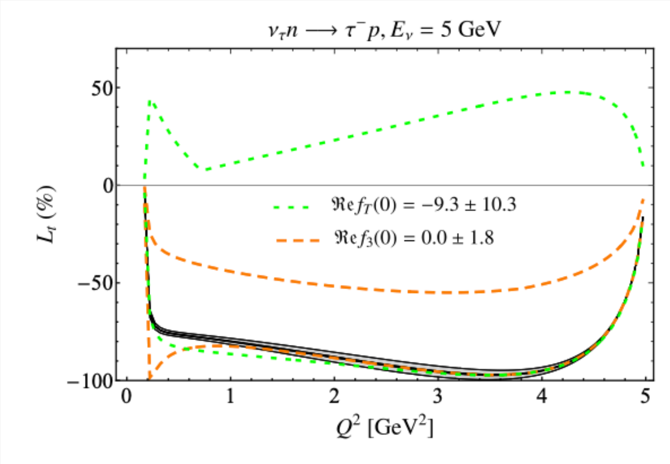
Discussion/future

- ***Polarization observables***
  - conceivable that future experiments may have sensitivity to e.g. final state tau lepton polarization, even polarized-target initial state nucleon

Alvarez-Ruso et al. 2203.11298







Borah et al. 2403.04687

Summary

- neutrino data constrain BSM contributions to charged current interactions
- constraints on amplitudes stronger than precision beta decay for Re(CT), Im(CT), Im(CS)
- interesting studies and combinations to pursue with other datasets

Thank you

Backup

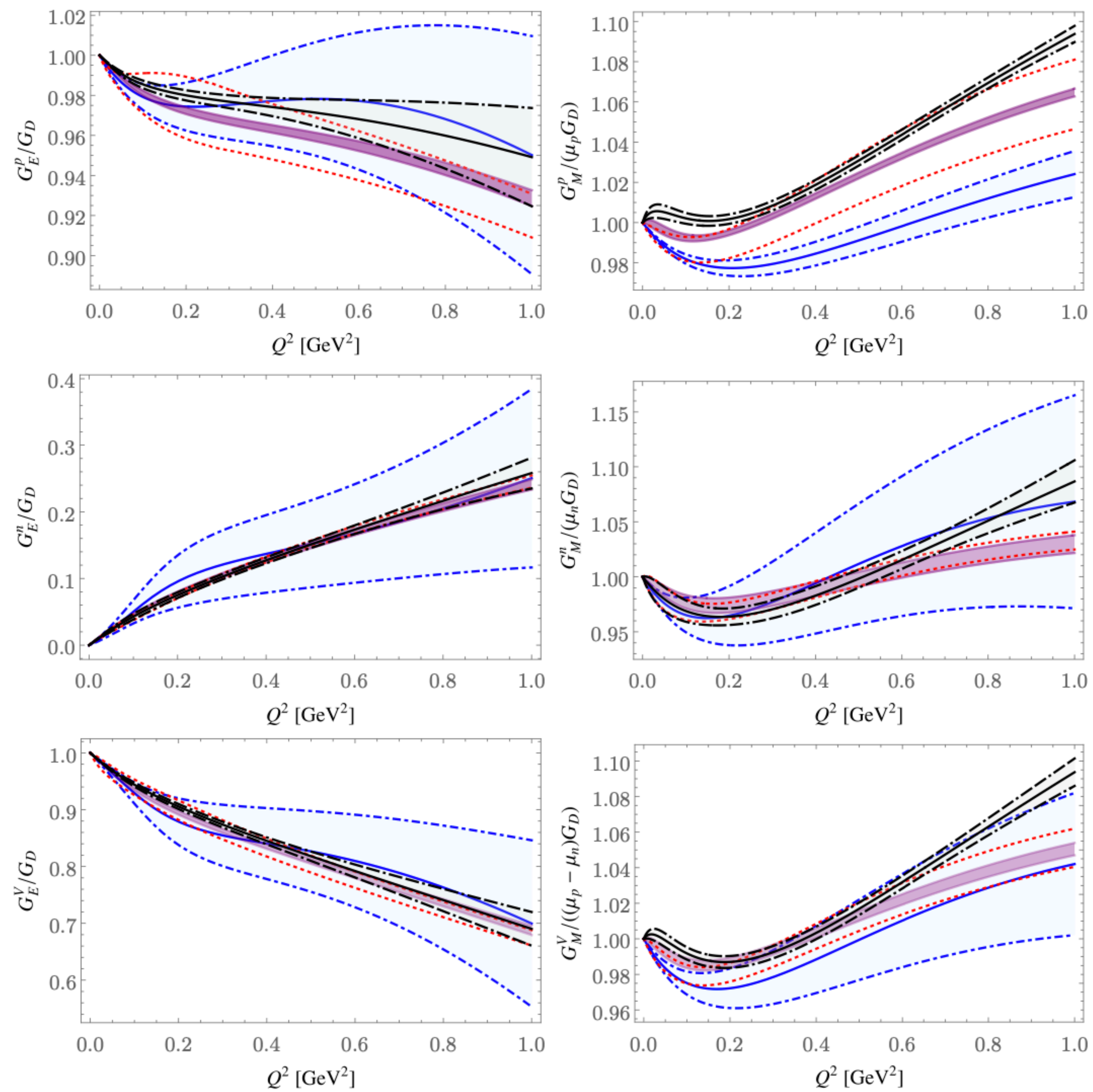


Figure 4: Plots of 1σ bands of G_E^p and G_M^p [top], G_E^n and G_M^n [middle], and G_E^V and G_M^V [bottom] from different fits. The black long dash-dotted curves are the results of the following: the p fit of line 1 in Table 1 [top]; the n fits of lines 2 and 3 in Table 1 [middle]; and the iso ($1\,\mathrm{GeV}^2$) fit of line 4 in Table 1 [bottom]. The purple bands are the results of the iso ($3\,\mathrm{GeV}^2$) fit of line 5 in Table 1. The red dotted curves correspond to the global fit of Ref. [7], and the blue dash-dotted curves are the BBBA2005 result of Ref. [99].

Borah et al. 2003.13640

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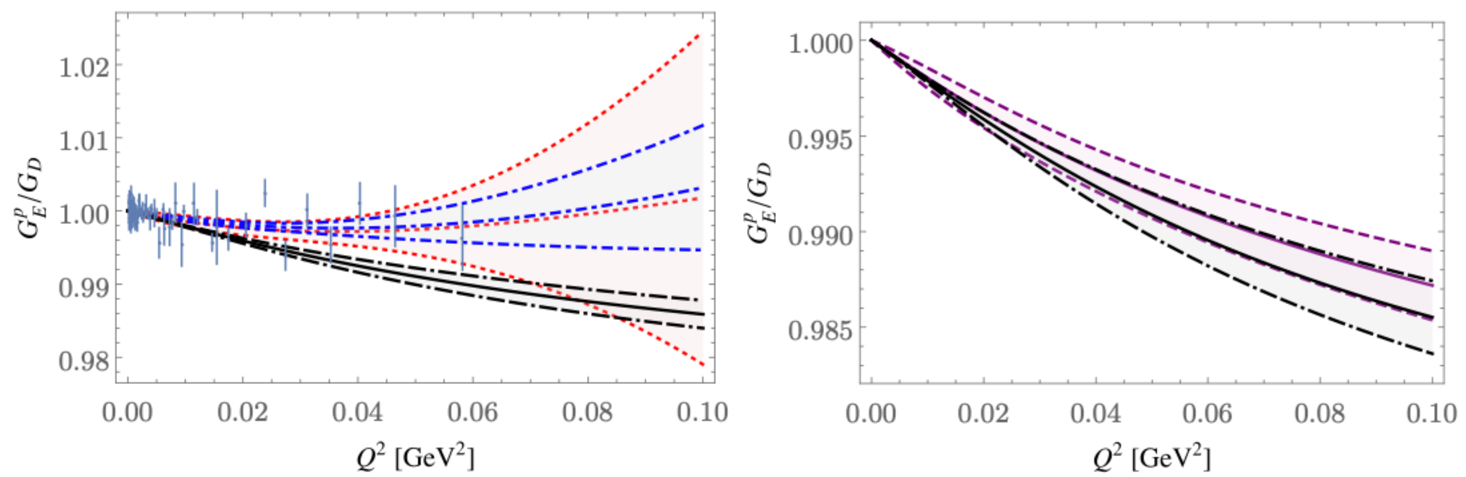

Figure 5: Comparison of G_E^p from fits with and without PRad data. In both plots, the black, long dash-dotted curve is our default (proton) fit. On the left-hand side, blue points are the tabulated PRad form factors with statistical errors; the blue, dash-dotted curve is the PRad extraction; and the red, dotted curve is our extraction from PRad data. On the right-hand side, we compare our default fit to the fit when the μH constraint is replaced by PRad data (purple, dashed curve).

Borah et al. 2003.13640

Backup

Borah et al. 2402.14115