Theory Uncertainties in a Global EDM Analysis

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IMPRS for Precision Tests of Fundamental Symmetries
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SFitter Framework

- **Adaptable** predictions and parameters
- Markov chain to construct exclusive likelihood
- Use profiling or marginalization for likelihoods
- **Correlated systematic uncertainties** between measurements

Uncertainties in SFitter

- Include **systematic**, **statistic** and **theoretical** uncertainties
- Different distributions: Gaussian, Poisson, flat
- Theory uncertainties: Flat distribution
    - SMEFT analysis: Affect all parameters, symmetric
    - EDM analysis: **Different** for every parameter, **asymmetric**

Electric dipole moments

- Missing explanation of baryon asymmetry in SM
- Need Sakharov conditions: C- and CP-violation
- CP-violation in QCD too small
- EDMs violate time (T) and parity (P)
- EDMs **sensitive to CP-violation**
- **Strongest evidence** for BSM physics to explain baryon asymmetry

Electric Dipole Moments

- EDMs measured below electroweak scale

- **Hadronic-scale** Lagrangian:

$$\mathcal{L}_{\text{had}} \supset \mathcal{L}_{N,\text{sr}} + \mathcal{L}_{\pi N} + \mathcal{L}_{eN} - \frac{i}{2} F^{\mu\nu} d_e \, \bar{e}\sigma_{\mu\nu}\gamma_5$$

$$\mathcal{L}_{N,\text{sr}} = -2\bar{N}\left[d_p^{\text{sr}} \frac{1+\tau_3}{2} + d_n^{\text{sr}} \frac{1-\tau_3}{2}\right] S_\mu N v_\nu F^{\mu\nu}$$

$$\mathcal{L}_{\pi N} = \bar{N}\left[g_\pi^{(0)} \vec{\tau}\cdot\vec{\pi} + g_\pi^{(1)} \pi^0\right] N$$

$$\mathcal{L}_{eN} = -\frac{G_F}{\sqrt{2}} \, (\bar{e} i\gamma_5 e) \, \bar{N}\left(C_S^{(0)} + C_S^{(1)}\tau_3\right) N + \frac{8G_F}{\sqrt{2}} \, v_\nu \, (\bar{e}\sigma^{\mu\nu} e) \, \bar{N}\left(C_T^{(0)} + C_T^{(1)}\tau_3\right) S_\mu N$$
$$- \frac{G_F}{\sqrt{2}} \, (\bar{e} e) \, \frac{\partial^\mu}{m_N} \left[\bar{N}\left(C_P^{(0)} + C_P^{(1)}\tau_3\right) S_\mu N\right]$$

Measurements

Paramagnetic molecules [2212.11841, Nature 562 7727, Nature 473 493]

- ThO, HfF^+, YbF (constraints d_e, $C_S^{(0)}$)

Paramagnetic atoms [PhysRevLett.88.071805, PhysRevLett.63.965]

- ^{205}Tl, ^{133}Cs

Diamagnetic atoms [1601.04339, 1902.02864, 2207.08140, 1606.04931, PhysRevA.44.2783]

- ^{199}Hg, ^{129}Xe, ^{171}Yb, ^{225}Ra, TlF (constraints $C_P^{(0)}, C_T^{(0)}, g_\pi^{(0)}, g_\pi^{(1)}, d_n^{sr}$)

Nucleons [2001.11966]

- neutron (constraints $g_\pi^{(0)}, g_\pi^{(1)}, d_n^{sr}$)

Theory uncertainties

- **Linear** relation of data and parameters: $d_i = \sum \alpha_{i,c_j}\, c_j$

System i	α_{i,d_e}	$\alpha_{i,C_S^{(0)}}$ [e cm]	$\alpha_{i,C_P^{(0)}}$ [e cm]	$\alpha_{i,C_T^{(0)}}$ [e cm]	$\alpha_{i,g_\pi^{(0)}}$ [e cm]	$\alpha_{i,g_\pi^{(1)}}$ [e cm]	$\alpha_{i,d_n^{\mathrm{sr}}}$	$\alpha_{i,d_p^{\mathrm{sr}}}$
n	–	–	–	–	$1.38^{\pm 0.02} \cdot 10^{-14}$	$2.73^{\pm 0.02} \cdot 10^{-16}$	1	−1
^{205}Tl	$-558^{\pm 28}$ [74]	$-6.77^{\pm 0.34} \cdot 10^{-18}$	$1.5^{+2}_{-0.7} \cdot 10^{-19}$	$8.8^{\pm 0.9} \cdot 10^{-21}$	n/a	n/a	n/a	n/a
^{133}Cs	$123^{\pm 4}$	$7.80^{+0.2}_{-0.8} \cdot 10^{-19}$	$-1.4^{+0.8}_{-2} \cdot 10^{-20}$	$1.7^{\pm 0.2} \cdot 10^{-20}$	–	–	–	–
^{199}Hg	$-0.012^{+0.0094}_{-0.002}$ [75, 76]	$-1.26^{+0.7}_{-1.2} \cdot 10^{-21}$	$6.6^{+1.2}_{-0.3} \cdot 10^{-23}$	$-6.4^{+3}_{-4} \cdot 10^{-21}$	$-1.18^{+0.19}_{-2.62} \cdot 10^{-17}$	$1.6^{+0}_{-6.5} \cdot 10^{-17}$	$-1.56^{\pm 0.39} \cdot 10^{-4}$	$-1.56^{\pm 0.39} \cdot 10^{-5}$
^{129}Xe	$-8^{+0}_{-8} \cdot 10^{-4}$ [76, 77]	$-2.1^{+1.2}_{-2.5} \cdot 10^{-22}$	$1.7^{+0.5}_{-0.4} \cdot 10^{-23}$	$1.24^{+0.78}_{-0.61} \cdot 10^{-21}$	$-0.4^{+1.2}_{-23} \cdot 10^{-19}$	$-2.2^{+1.1}_{-17} \cdot 10^{-19}$	$1.7^{+0.7}_{-0} \cdot 10^{-5}$	$3.51^{\pm 0.88} \cdot 10^{-6}$
^{171}Yb	$(-0.012^{+0.01145}_{-0.002})$ [78]	$-9.1^{+5}_{-11} \cdot 10^{-22}$	$4.5^{+1.8}_{-1.1} \cdot 10^{-23}$	$-4.4^{+2.2}_{-2.9} \cdot 10^{-21}$	$-9.5^{\pm 2.4} \cdot 10^{-18}$	$1.3^{\pm 0.33} \cdot 10^{-17}$	$-1.13^{\pm 0.28} \cdot 10^{-4}$	$-1.13^{\pm 0.28} \cdot 10^{-5}$
^{225}Ra	$-0.054^{\pm 0.002}$ [76]	$8.6^{+9.5}_{-4.5} \cdot 10^{-21}$	$-7.0^{+1.7}_{-2.6} \cdot 10^{-22}$	$-4.5^{+2.0}_{-2.5} \cdot 10^{-20}$	$1.7^{+5.2}_{-0.8} \cdot 10^{-15}$	$-6.9^{+3.1}_{-21} \cdot 10^{-15}$	$-5.36^{\pm 1.34} \cdot 10^{-4}$	$-1.11^{\pm 0.28} \cdot 10^{-4}$
TlF	$81^{\pm 20}$ [50, 70]	$5.6^{+4.9}_{-2.5} \cdot 10^{-18}$	$2.4^{+1.0}_{-1.9} \cdot 10^{-19}$	$4.8^{+1.2}_{-1.1} \cdot 10^{-16}$	$1.9^{+0.1}_{-1.4} \cdot 10^{-14}$	$-1.6^{\pm 0.4} \cdot 10^{-13}$	$-9.47^{\pm 2.37} \cdot 10^{-2}$	$-4.59^{\pm 1.15} \cdot 10^{-1}$
HfF^+	1	$9.17^{\pm 0.06} \cdot 10^{-21}$	–	–	–	–	–	–
ThO	1	$1.51^{+0}_{-0.2} \cdot 10^{-20}$	–	–	–	–	–	–
YbF	1	$8.99^{\pm 0.70} \cdot 10^{-21}$	–	–	–	–	–	–
	$\eta^{(m)}_{i,d_e} \left[\frac{\mathrm{mrad}}{\mathrm{s}\ e\ \mathrm{cm}}\right]$	$k^{(m)}_{i,C_S} \left[\frac{\mathrm{mrad}}{\mathrm{s}}\right]$	α_{i,C_P}	α_{i,C_T}	$\alpha_{i,g_\pi^{(0)}}$	$\alpha_{i,g_\pi^{(1)}}$	$\alpha_{i,d_n^{\mathrm{sr}}}$	$\alpha_{i,d_p^{\mathrm{sr}}}$
HfF^+	$3.49^{\pm 0.14} \cdot 10^{28}$ [75, 79–82]	$3.2^{+0.1}_{-0.2} \cdot 10^{8}$ [75, 79, 80]	–	–	–	–	–	–
ThO	$-1.21^{+0.05}_{-0.39} \cdot 10^{29}$ [75, 83–85]†	$-1.82^{+0.42}_{-0.27} \cdot 10^{9}$ [75, 83, 85–87]†	–	–	–	–	–	–
YbF	$-1.96^{\pm 0.15} \cdot 10^{28}$ [75, 86–89]	$-1.76^{\pm 0.2} \cdot 10^{8}$ [75, 86–88]	–	–	–	–	–	–

EDMs from Lagrangian

- Experimental uncertainties approximated as **uncorrelated Gaussians**
- Example: $d_e - C_S$ implementation

$$\begin{pmatrix} d_{\mathrm{HfF}^+} \\ d_{\mathrm{ThO}} \end{pmatrix} = \begin{pmatrix} \alpha_{\mathrm{HfF}^+,d_e} & \alpha_{\mathrm{HfF}^+,C_S^{(0)}} \\ \alpha_{\mathrm{ThO},d_e} & \alpha_{\mathrm{ThO},C_S^{(0)}} \end{pmatrix} \begin{pmatrix} d_e \\ C_S^{(0)} \end{pmatrix}$$

$$= \begin{pmatrix} 1. & 9.17 \cdot 10^{-21} \\ 1. & 1.51 \cdot 10^{-20} \end{pmatrix} \begin{pmatrix} d_e \\ C_S^{(0)} \end{pmatrix}$$

$$= \begin{pmatrix} 1. & 0 \\ 0 & 5.93 \cdot 10^{-21} \end{pmatrix} \begin{pmatrix} d_e \\ C_S^{(0)} \end{pmatrix}$$

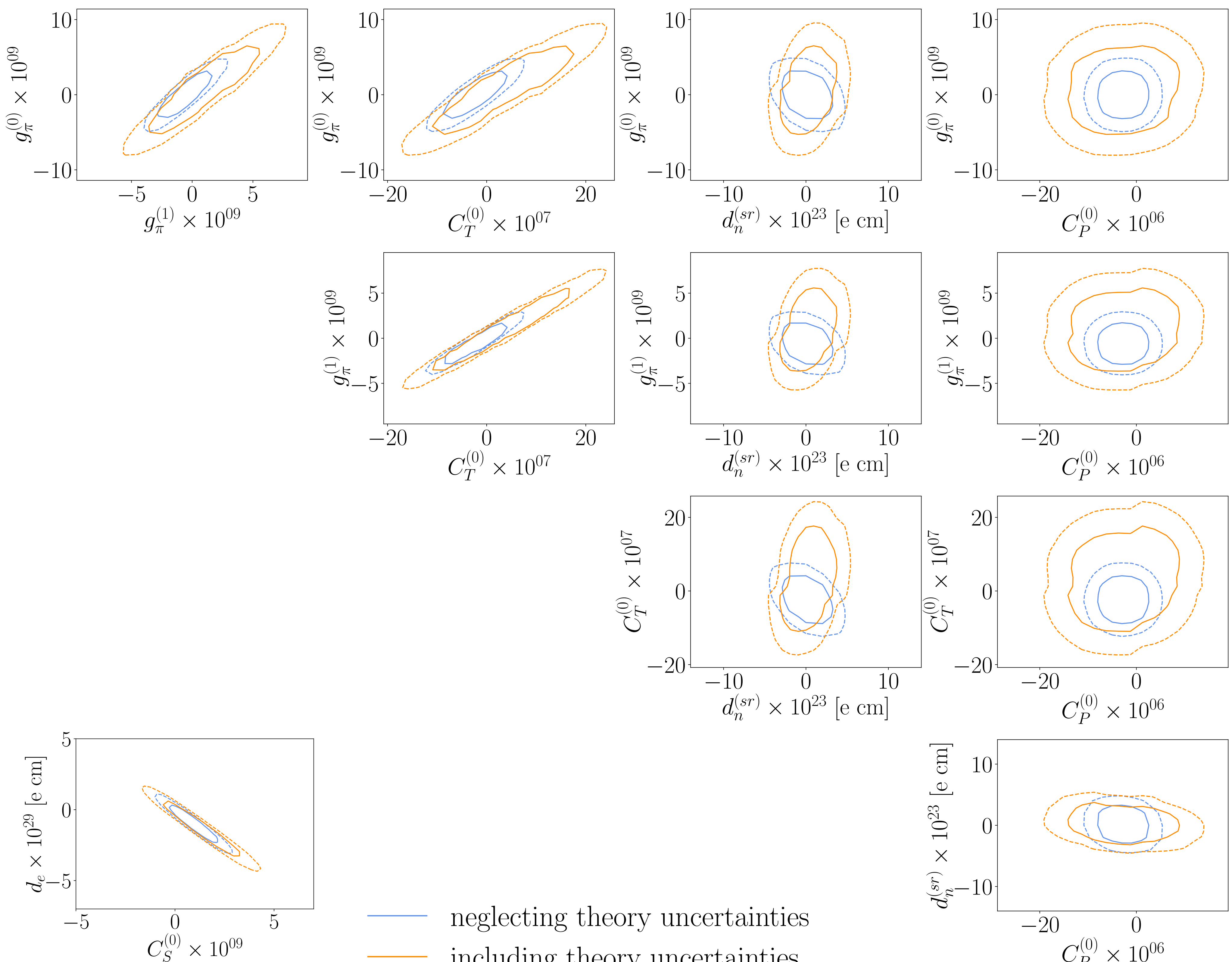
Theory uncertainties

- **Uncorrelated** between measurements and parameters
- Profiling **flat likelihood** from nuisance parameters

  (1) error bars added linearly

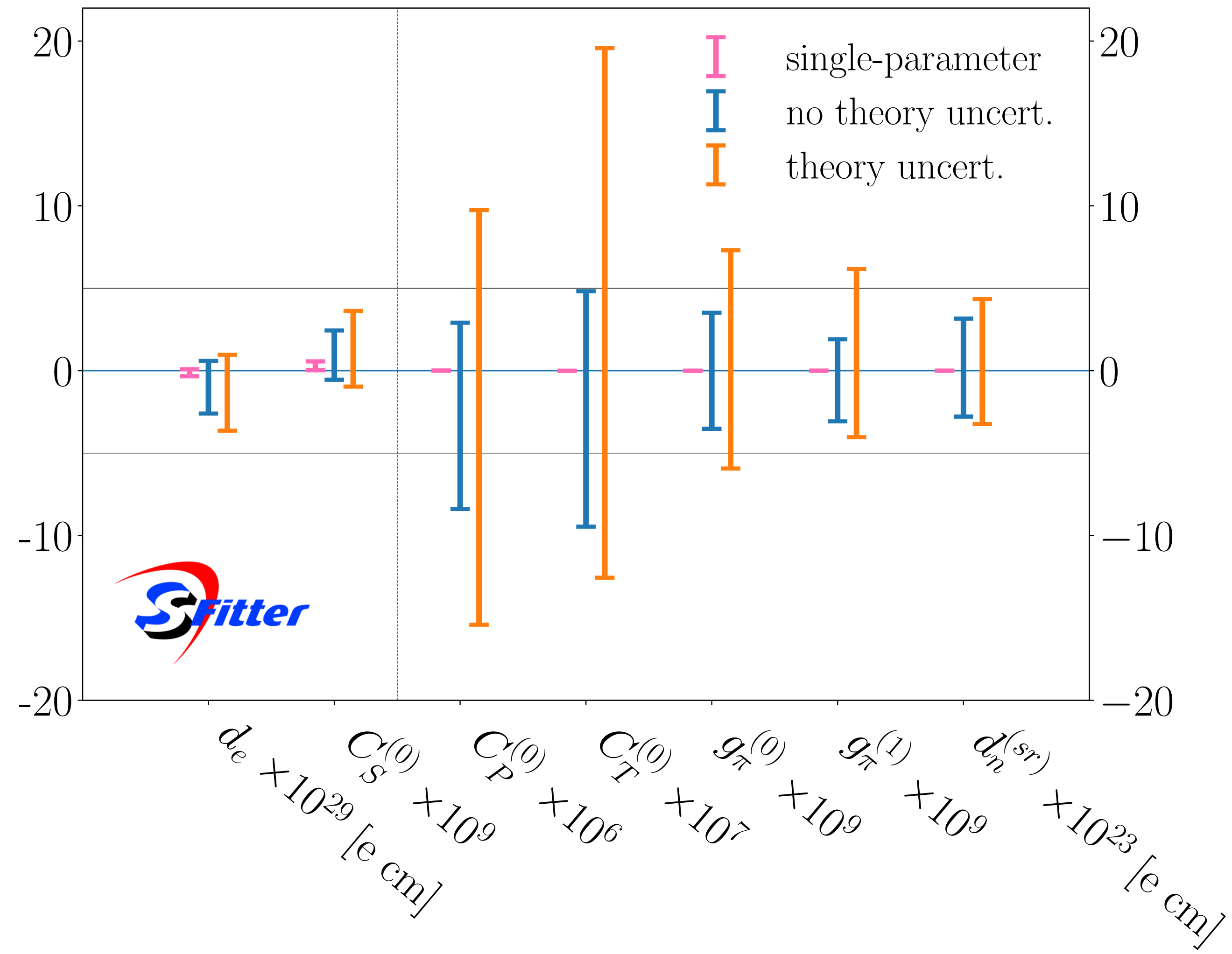
  (2) dependencies consistent with $\alpha = 0$ removed
- Applied to every measurement and model parameter
- Shift central value for symmetry

Global analysis



Conclusion and Outlook

- Theory uncertainties
  (1) semileptonic: **mild impact**
  (2) hadronic: **weaker constraints**



- Small shifts in global analysis

- Next steps:
  Include correlations
  Extend to marginalization