# EDMs - A Global Analysis

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# 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
- Degrees of freedom: leptons, non-relativistic nucleons $N$ and pions $\vec{\pi}$
- Possible Lagrangians: **weak-scale** and **hadronic-scale**
- **short-range nucleon** EDM parameter $d_p^{sr} \approx - d_n^{sr}$
- effective **pion-nucleon interaction** $g_\pi^{(0)}, g_\pi^{(1)}$
- $e$ **- N interactions** $C_S^{(0)}, C_P^{(0)}, C_T^{(0)}$
- 7D parameter space: $d_e, C_S^{(0)}, C_P^{(0)}, C_T^{(0)}, g_\pi^{(0)}, g_\pi^{(1)}, d_n^{sr}$

# 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 $g_\pi^{(0)}, g_\pi^{(1)}, d_n^{sr}$)

# SFitter

- Easy to **add new measurements** from different experiments
- Adaptable parameters and predictions
- **statistical/systematic/theory** uncertainties
- Likelihood construction: profiling/marginalization
- Markov chains to construct exclusive likelihoods

# EDMs from Lagrangian

- **Linear** relation of data and parameters: $d_i = \sum \alpha_{i,c_j} c_j$
- Experimental uncertainties approximated as **uncorrelated Gaussians**
- Example: $d_e - C_S$ implementation

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

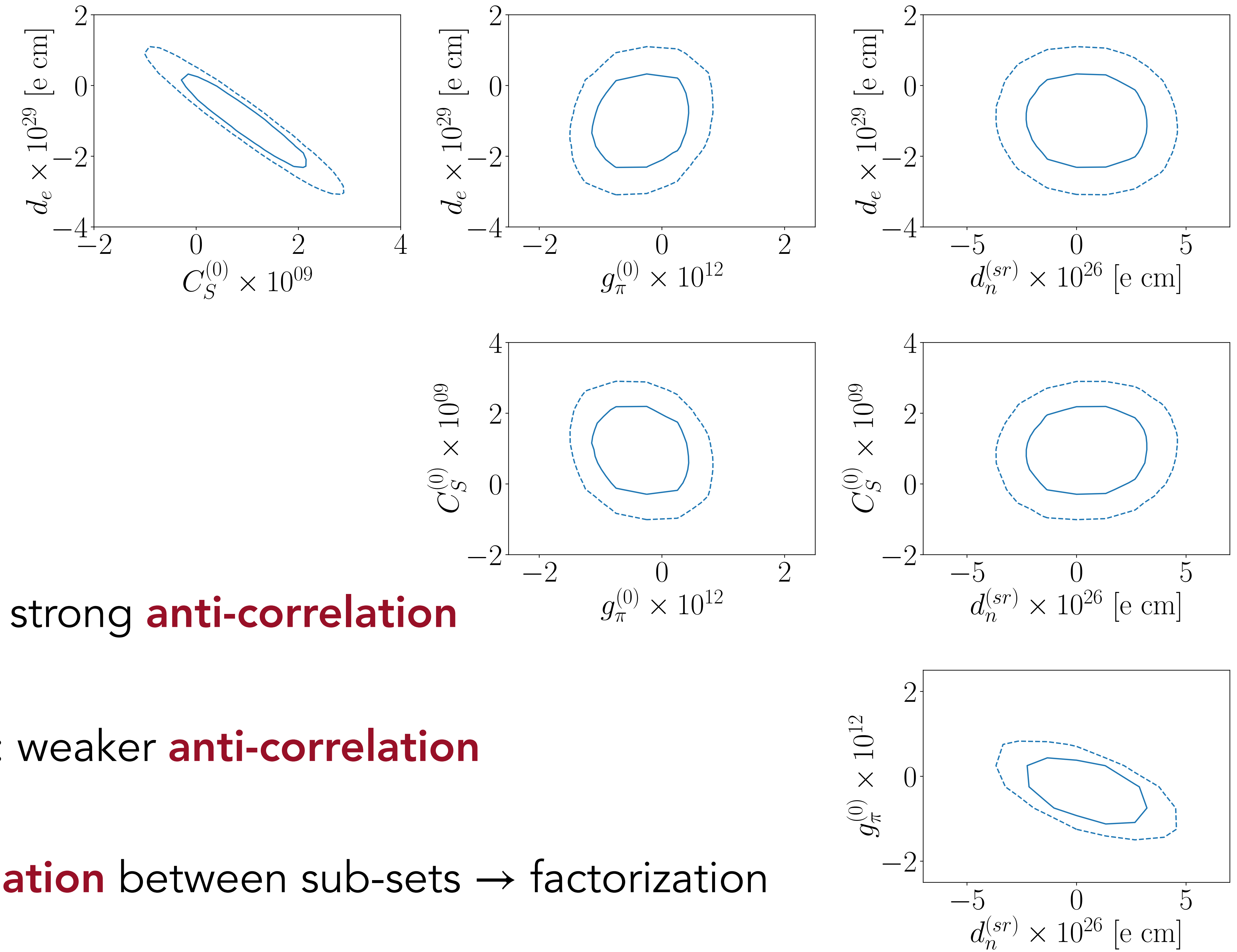
$$= \begin{pmatrix} 1. & 9.17 \cdot 10^{-21} \\ 1. & 1.51 \cdot 10^{-20} \end{pmatrix} \begin{pmatrix} d_e \\ C_S^{(0)} \end{pmatrix}$$

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

# Strongest measurements

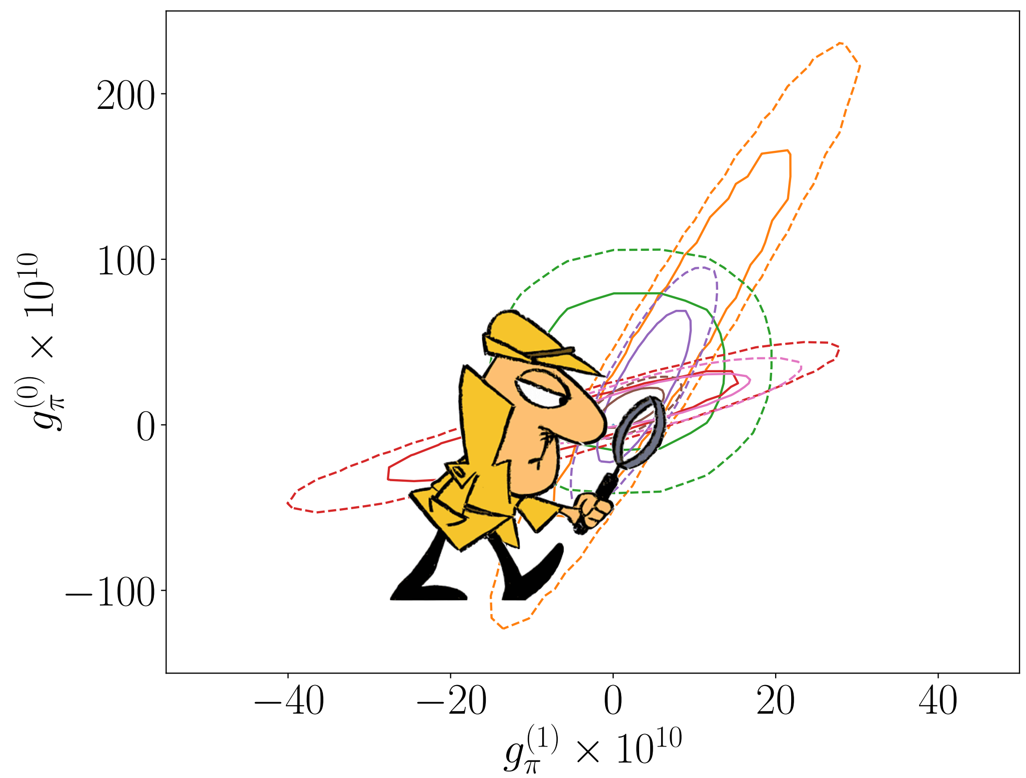
- Strongest measurements: $HfF^+$, ThO, n, Hg
- **4D sub-space** to understand correlations
- Well-constrained (hopefully) parameters: $d_e, C_S^{(0)}, g_\pi^{(0)}, d_n^{sr}$
- $d_e - C_S^{(0)}$ constrained by ThO and $HfF^+$
- $g_\pi^{(0)} - d_n^{sr}$ constrained by Hg and n

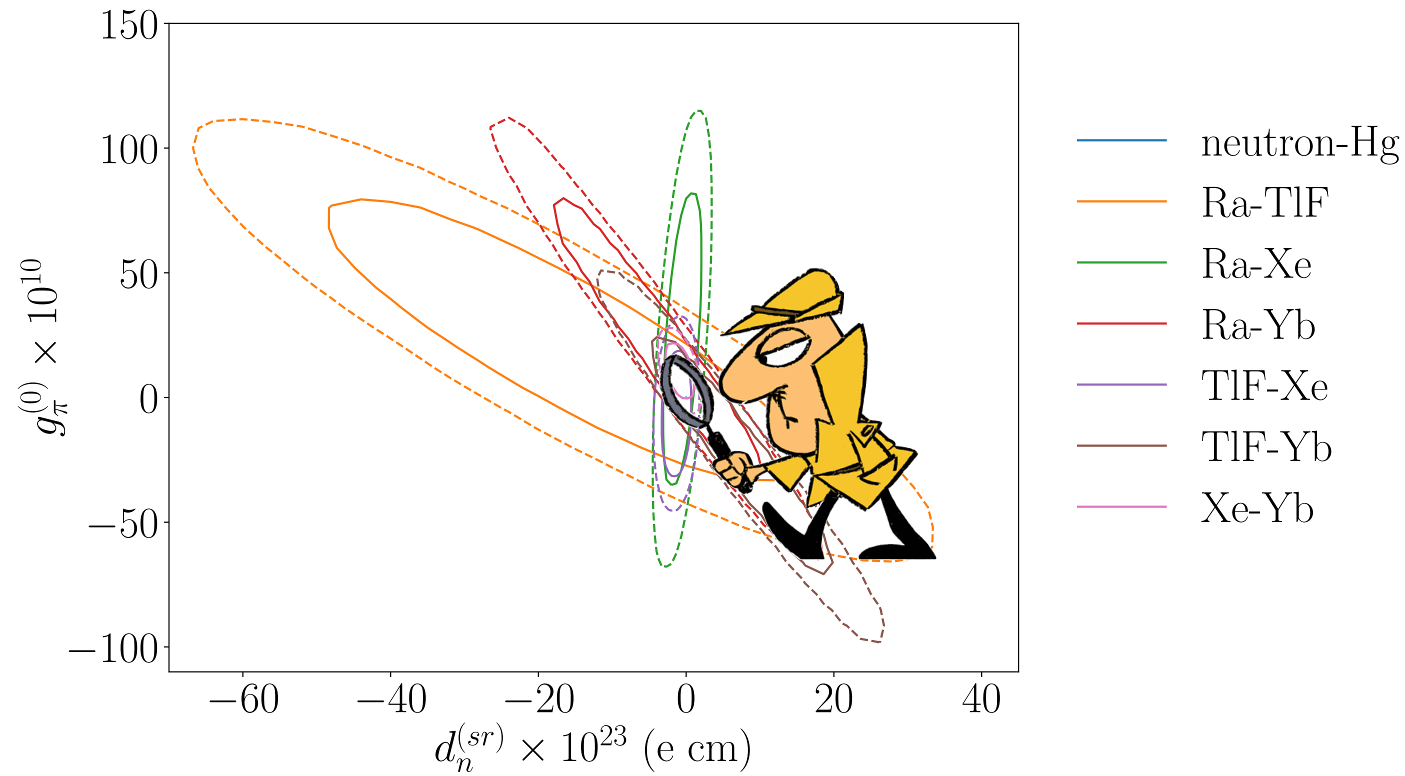
# Well-constrained 4D-space




- $d_e - C_S^{(0)}$: strong **anti-correlation**
- $g_\pi^{(0)} - d_n^{sr}$: weaker **anti-correlation**
- **no correlation** between sub-sets → factorization

# Hadronic sector



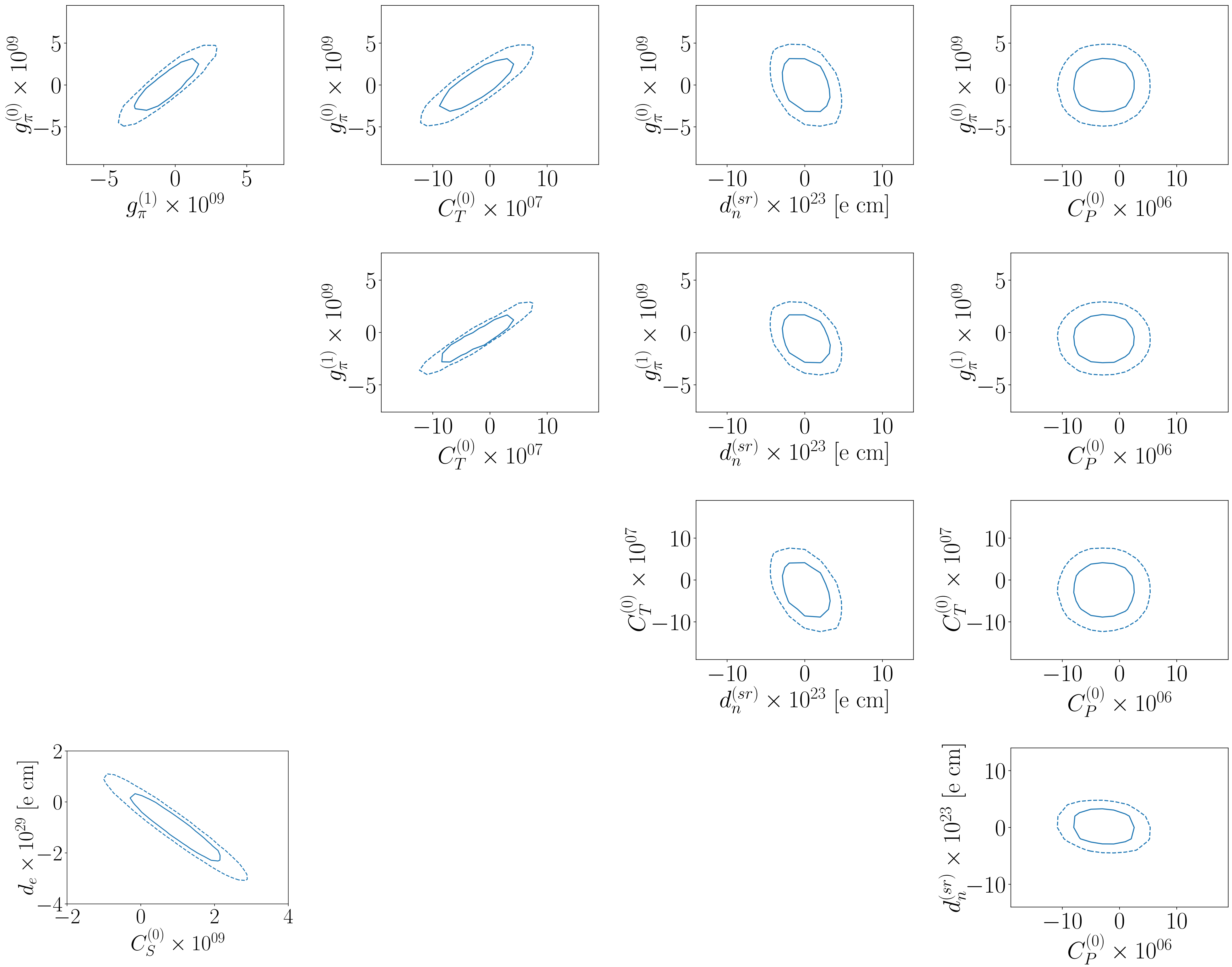




- Expand hadronic analysis to $g_\pi^{(0)}, g_\pi^{(1)}, d_n^{sr}$
- Hg, neutron measurements: **strongest constraints**
- Rich **correlations** for $g_\pi^{(0)}, g_\pi^{(1)}$, aligned **correlations** for $g_\pi^{(0)}, d_n^{sr}$

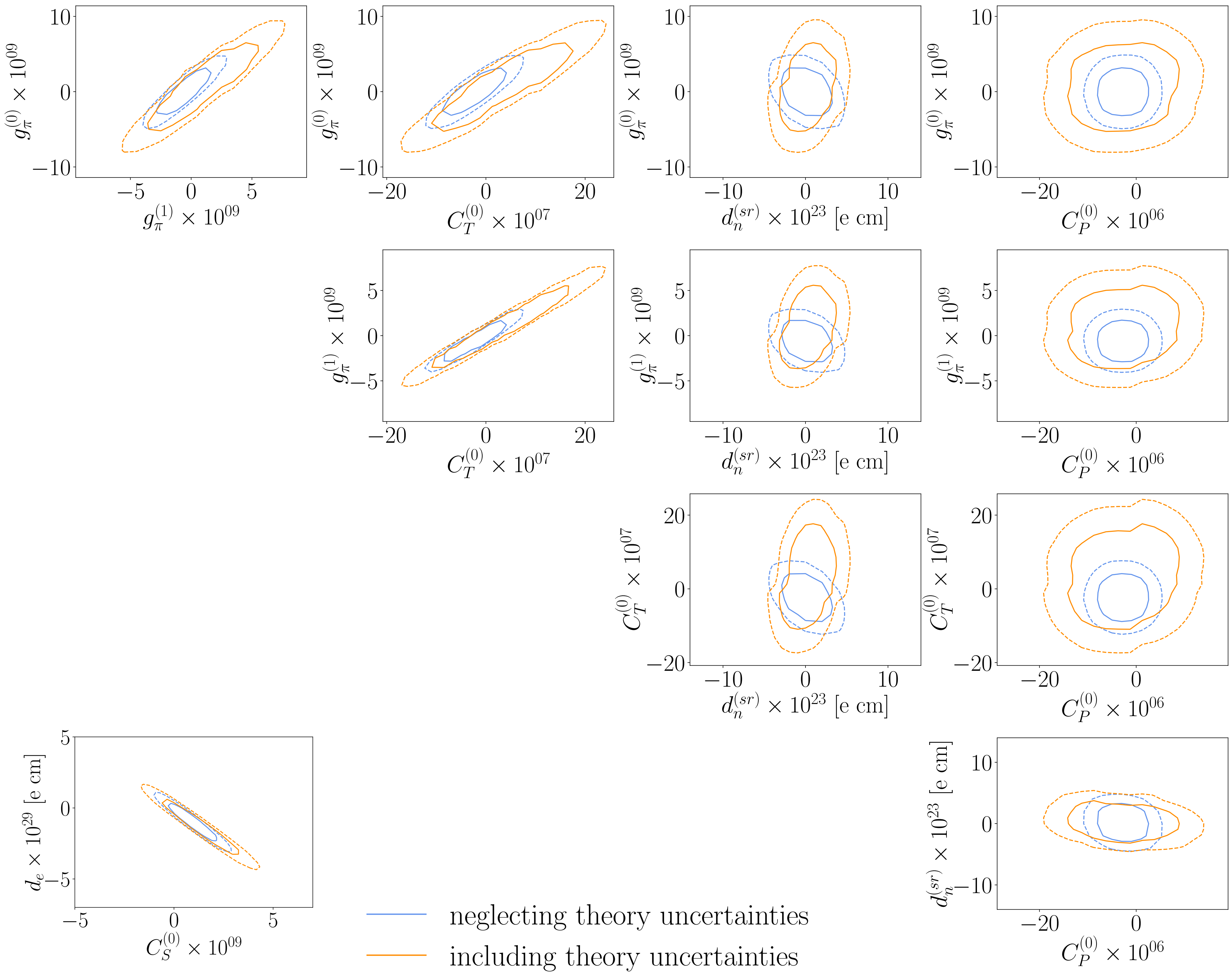
# Global analysis

- 2D-subspace $d_e - C_s^{(0)}$ from ThO and $HfF^+$ **factorized**
- 5D parameter-set: $C_P^{(0)}, C_T^{(0)}, g_\pi^{(0)}, g_\pi^{(1)}, d_n^{sr}$
- Ignoring $10^{-3}$-correlations from Hg and n
- **Not enough strong measurements** means profile likelihood dominated by typical measurements
- n and Hg without impact and numerically hard → remove from dataset

# Global analysis

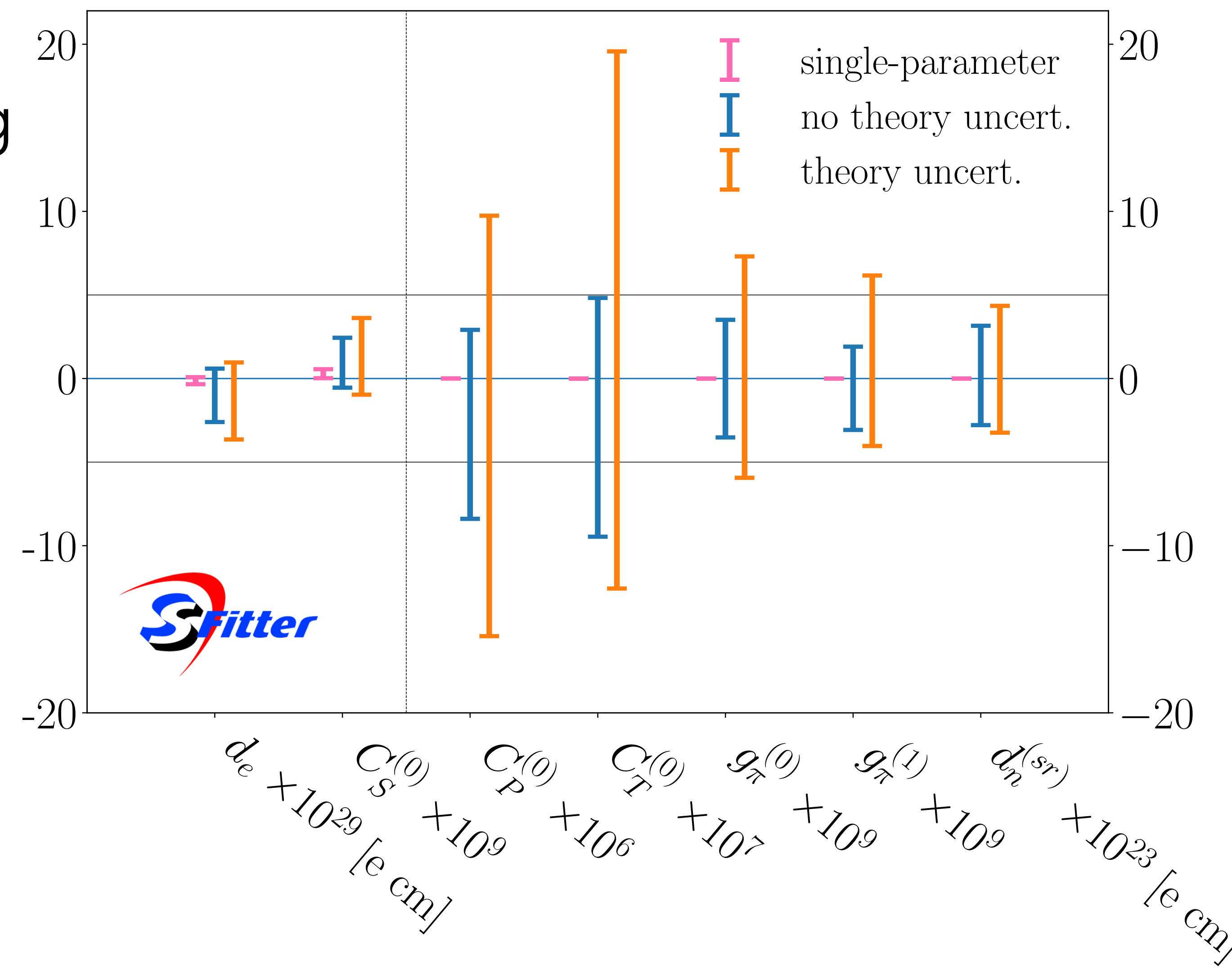


# Theory uncertainties in correlations



# Conclusion and Outlook

- 11 measurement for 7 parameters $d_e, C_S^{(0)}, C_P^{(0)}, C_T^{(0)}, g_\pi^{(0)}, g_\pi^{(1)}, d_n^{sr}$
- Four strongest measurements constraining $d_e, C_S^{(0)}, g_\pi^{(0)}, d_n^{sr}$
- Strong limits on $d_e - C_S^{(0)}$ factorizing
- Hadronic sector **highly correlated**
- Theory uncertainties
  (1) $d_e - C_S^{(0)}$: **mild impact**
  (2) hadronic: **weaker constraints**



# Backup slides

# Single-parameter ranges

| System $i$ | $d_e$ [$e$ cm] | $C_S$ | $C_P$ | $C_T$ |
|---|---|---|---|---|
| Tl | $(7.2 \pm 7.7) \cdot 10^{-28}$ | $(5.9 \pm 6.4) \cdot 10^{-8}$ | $(-2.7 \pm 3.0) \cdot 10^{-6}$ | $(-4.5 \pm 4.9) \cdot 10^{-5}$ |
| Cs | $(-1.4 \pm 5.6) \cdot 10^{-26}$ | $(-2.3 \pm 8.9) \cdot 10^{-6}$ | $(1.3 \pm 5) \cdot 10^{-4}$ | $(-1.1 \pm 4.2) \cdot 10^{-4}$ |
| $^{199}$Hg | $(-1.8 \pm 2.6) \cdot 10^{-28}$ | $(-1.7 \pm 2.5) \cdot 10^{-9}$ | $(3.4 \pm 4.8) \cdot 10^{-8}$ | $(-3.4 \pm 4.9) \cdot 10^{-10}$ |
| $^{129}$Xe | $(2.2 \pm 2.3) \cdot 10^{-25}$ | $(8.3 \pm 8.7) \cdot 10^{-7}$ | $(-1.0 \pm 1.1) \cdot 10^{-5}$ | $(-1.4 \pm 1.5) \cdot 10^{-7}$ |
| $^{171}$Yb | $(5.7 \pm 4.4) \cdot 10^{-25}$ | $(7.5 \pm 5.7) \cdot 10^{-6}$ | $(-1.5 \pm 1.2) \cdot 10^{-4}$ | $(1.6 \pm 1.2) \cdot 10^{-6}$ |
| $^{225}$Ra | $(-7.4 \pm 1.1) \cdot 10^{-23}$ | $(4.7 \pm 7) \cdot 10^{-4}$ | $(-5.7 \pm 8.5) \cdot 10^{-3}$ | $(-8.9 \pm 13) \cdot 10^{-5}$ |
| TlF | $(-2.1 \pm 3.6) \cdot 10^{-25}$ | $(-3.0 \pm 5.1) \cdot 10^{-6}$ | $(-7.1 \pm 12) \cdot 10^{-5}$ | $(-3.6 \pm 6.1) \cdot 10^{-8}$ |
| $HfF^+$ | $(-1.3 \pm 2.1) \cdot 10^{-30}$ | $(-1.4 \pm 2.3) \cdot 10^{-10}$ | | |
| ThO | $(4.3 \pm 4.1) \cdot 10^{-30}$ | $(2.9 \pm 2.7) \cdot 10^{-10}$ | | |
| YbF | $(-2.4 \pm 5.9) \cdot 10^{-28}$ | $(-2.7 \pm 6.6) \cdot 10^{-8}$ | | |
| | $g_\pi^{(0)}$ | $g_\pi^{(1)}$ | $d_n^{\mathrm{sr}}$ | $d_p^{\mathrm{sr}}$ |
| $n$ | $(0 \pm 8.1) \cdot 10^{-13}$ | $(0 \pm 4.1) \cdot 10^{-11}$ | $(0 \pm 1.1) \cdot 10^{-26}$ | $(0 \pm 1.1) \cdot 10^{-26}$ |
| $^{199}$Hg | $(-1.9 \pm 2.7) \cdot 10^{-13}$ | $(1.4 \pm 2.0) \cdot 10^{-13}$ | $(-1.4 \pm 2.0) \cdot 10^{-26}$ | $(-1.4 \pm 2.0) \cdot 10^{-25}$ |
| $^{129}$Xe | $(4.4 \pm 4.6) \cdot 10^{-9}$ | $(8 \pm 8.3) \cdot 10^{-10}$ | $(-1.0 \pm 1.1) \cdot 10^{-23}$ | $(-5.0 \pm 5.2) \cdot 10^{-23}$ |
| $^{171}$Yb | $(7.2 \pm 5.5) \cdot 10^{-10}$ | $(-5.2 \pm 4.0) \cdot 10^{-10}$ | $(6.0 \pm 4.6) \cdot 10^{-23}$ | $(6.0 \pm 4.6) \cdot 10^{-22}$ |
| $^{225}$Ra | $(2.4 \pm 3.5) \cdot 10^{-9}$ | $(-5.8 \pm 8.7) \cdot 10^{-10}$ | $(-7.5 \pm 11) \cdot 10^{-21}$ | $(-3.6 \pm 5.4) \cdot 10^{-20}$ |
| TlF | $(-9.0 \pm 15) \cdot 10^{-10}$ | $(1.1 \pm 1.8) \cdot 10^{-10}$ | $(1.8 \pm 3.1) \cdot 10^{-22}$ | $(3.7 \pm 6.3) \cdot 10^{-23}$ |

# EDMs from Lagrangian

- Relation of data and parameters: $d_i = \sum \alpha_{i,c_j} c_j$
- **Linearization** different from other global analyses
- Experimental uncertainties **uncorrelated Gaussians**

| System $i$ | $\alpha_{i,d_e}$ | $\alpha_{i,C_S^{(0)}}$ [$e$ 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] | $\alpha_{i,d_n^{sr}}$ | $\alpha_{i,d_p^{sr}}$ |
|---|---|---|---|---|---|---|---|---|
| $n$ | – | – | – | – | $1.38^{\pm 0.02} \cdot 10^{-14}$ | $2.73^{\pm 0.02} \cdot 10^{-16}$ | 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 | $8.99^{\pm 0.70} \cdot 10^{-21}$ | – | – | – | – | – | – |
| | $\eta^{(m)}_{i,d_e} \left[\frac{\text{mrad}}{\text{s } e \text{ cm}}\right]$ | $k^{(m)}_{i,C_S} \left[\frac{\text{mrad}}{\text{s}}\right]$ | $\alpha_{i,C_P}$ | $\alpha_{i,C_T}$ | $\alpha_{i,g_\pi^{(0)}}$ | $\alpha_{i,g_\pi^{(1)}}$ | $\alpha_{i,d_n^{sr}}$ | $\alpha_{i,d_p^{sr}}$ |
| $HfF^+$ | $3.49^{\pm 0.14} \cdot 10^{28}$ [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] | – | – | – | – | – | – |