Global analysis: The true constraining power of different EDM measurements

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Electric dipole moments (EDMs)

- EDMs measured **below electroweak scale**
- Degrees of freedom: Leptons, non-relativistic nucleons N and pions $\vec{\pi}$
- Consider hadronic Lagrangian

$$\mathscr{L}_{had} \supset \boxed{\mathscr{L}_{N,\mathrm{sr}} + \mathscr{L}_{eN} + \mathscr{L}_{\pi N}} \boxed{- \frac{i}{2} F^{\mu\nu} \sum_{\ell} d_{\ell} \left(\bar{\ell} \sigma_{\mu\nu} \gamma_5 \ell \right)}$$

- Describes **nucleon interactions** and **EDM contributions**

Closer look at the hadronic Lagrangian

- **Short-range nucleon** interaction:
  $$\mathscr{L}_{N,\mathrm{sr}} = -\,2\bar{N}\left[d_p^{\mathrm{sr}}\frac{1+\tau_3}{2} + d_n^{\mathrm{sr}}\frac{1-\tau_3}{2}\right] S_\mu N v_\nu F^{\mu\nu}$$

- S_μ and v_μ: Spin and velocity 4-vectors of the nucleon

- d_N^{sr} : **Short-range nucleon EDMs** from isovector and isoscalar contributions

Closer look at the hadronic Lagrangian

- **Effective interactions** with the nucleon:

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

- **Pion-nucleon** interactions:

$$\mathscr{L}_{\pi N} \supset \bar{N}\left[g_\pi^{(0)}\vec{\tau}\cdot\vec{\pi} + g_\pi^{(1)}\pi^0 + g_\pi^{(2)}\left(3\tau_3\pi^0 - \vec{\tau}\cdot\vec{\pi}\right)\right]N$$
$$+C_1\left(\bar{N}N\right)\partial_\mu\left(\bar{N}S^\mu\bar{N}\right) + C_2\left(\bar{N}\vec{\tau}N\right)\cdot\partial_\mu\left(\bar{N}S^\mu\bar{N}\vec{\tau}\right) + \cdots$$

- Neglect interactions with multiple pions

- $g_\pi^{(2)}$ suppressed by one order compared to $g_\pi^{(0,1)}$

Impact of EDMs on BSM physics

- EDMs themselves violate time (T) and parity (P)
- Apply CPT-theorem to SM results in CP violation
- EDMs sensitive to this CP violation
- **Strongest evidence** for BSM physics to explain baryon asymmetry
  - Evidence based on neutron and strong CP problem together with Sakharov condition and CMB

SFitter Framework

- Easy to add new measurements from different experiments
- **Adaptable parameter** and prediction set
- Strong and comprehensive uncertainty treatment
- **Fully correlated systematic uncertainties** between measurements
- Use profiling and marginalization constructing likelihoods

What is new compared to other EDM analyses?

- Having a closer look on correlations
- Investigating flat directions and their origin
- Using a professional fitting tool to get trustworthy results
- Taking theory uncertainties into account (work in progress)

Today's Agenda

1. Set-up of the global analysis - parameters and measurements
2. Results of a global analysis including paramagnetic, diamagnetic and nucleon measurements (Preliminary)
3. Dividing the dataset (Preliminary)

Part 1

Introduction to the global fit - Parameter- and datasets

Restriction and assumptions on parameters

- From the hadronic scale Lagrangian:

$$\{d_e, C_S^{(0,1)}, C_T^{(0,1)}, C_P^{(0,1)}, g_\pi^{(0)}, g_\pi^{(1)}, d_{n,p}^{sr}\}$$

- Relating them to weak-scale leads to **further reductions**
- Use hadronic matrix elements to constrain $C_{(S,P,T)}^{(0,1)}$
- $C_{(S,T,P)}$ linear combination of $C_{(S,P,T)}^{(0)}$ and $C_{(S,P,T)}^{(1)}$
- Remove 3 dof, remain with $C_{(S,P,T)}$

Parameter set used in the global analysis

- Short-range nucleon EDMs dominated by **isovector contribution**
- Use assumption $d_p^{sr} \approx -d_n^{sr}$
- Left with **seven parameter** in the global analysis
- $\{d_e, C_S, C_T, C_P, g_\pi^{(0)}, g_\pi^{(1)}, d_n^{sr}\}$

Measurements included in the global fit

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

- ThO, HfF^+, YbF (constraints d_e, C_S)

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

Nuclear [2001.11966]

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

Challenges with the data set

- Combining measurements from different groups, experiments and systems
- Challenging to get uniting information
- Different coefficients follow different conventions and units

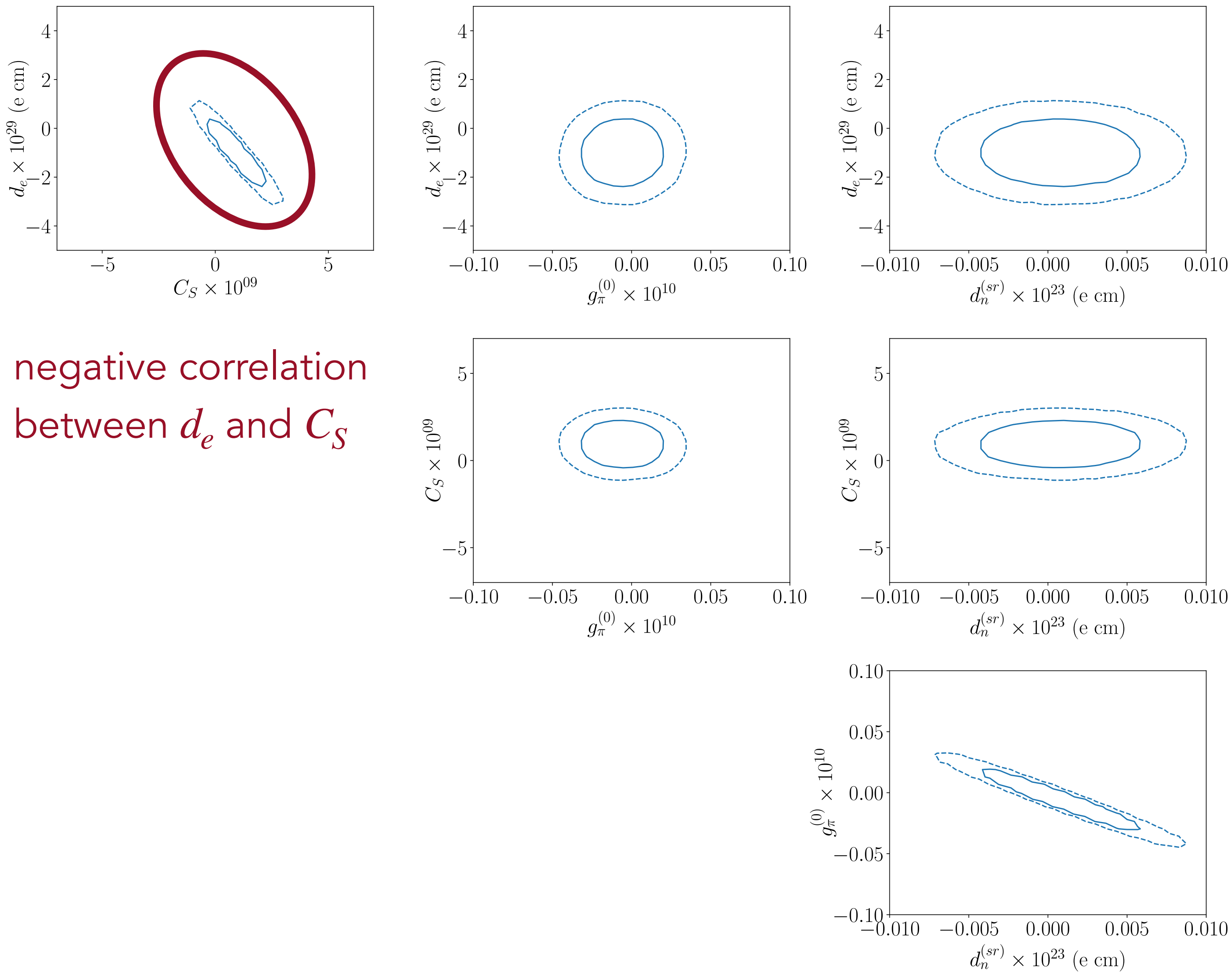
➡ Need to **convert measurements** and parameter into e cm

Part 2

Results of a global analysis including paramagnetic, diamagnetic and nucleon measurements

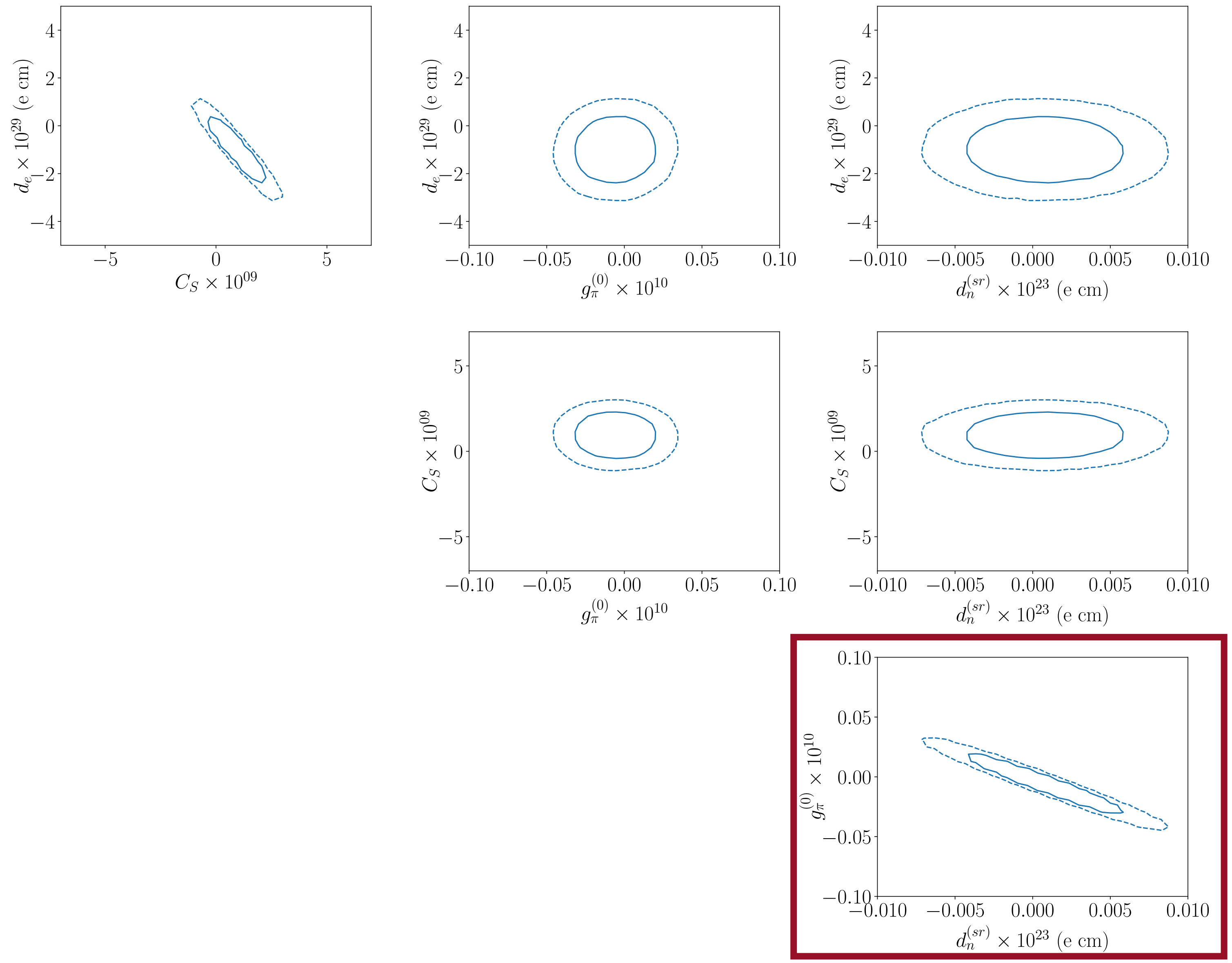
(Preliminary results)

Results of a 4D analysis - Part I



- Parameters $\{d_e, C_S, g_\pi^{(0)}, d_n^{sr}\}$
- Dominant measurements:
  ThO and HfF^+ (d_e and C_S), Hg and neutron ($g_\pi^{(0)}$ and d_n^{sr})

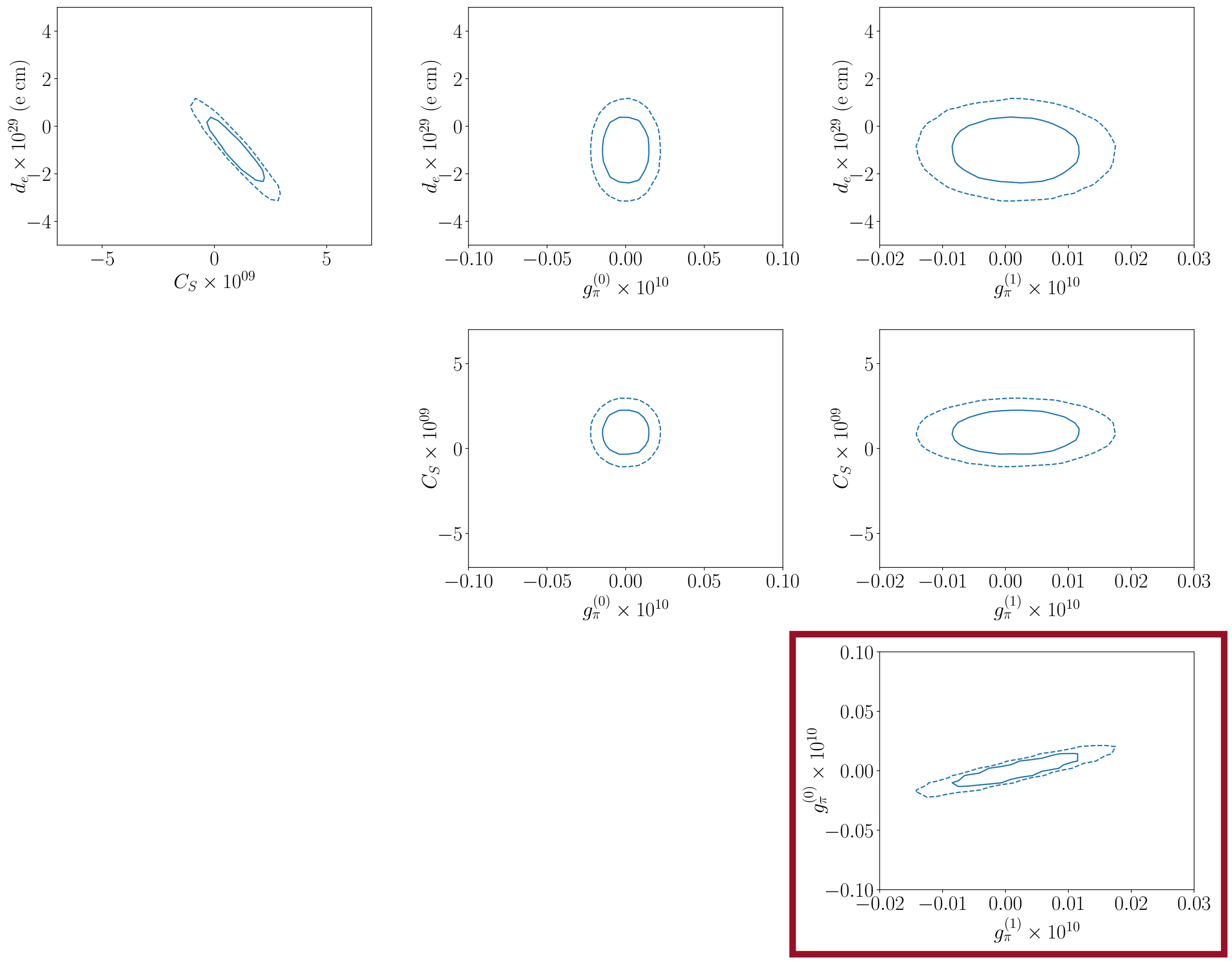
Results of a 4D analysis - Part I



- Parameters $\{d_e, C_S, g_\pi^{(0)}, d_n^{sr}\}$

- Dominant measurements:
  ThO and HfF$^+$ (d_e and C_S), Hg and neutron ($g_\pi^{(0)}$ and d_n^{sr})

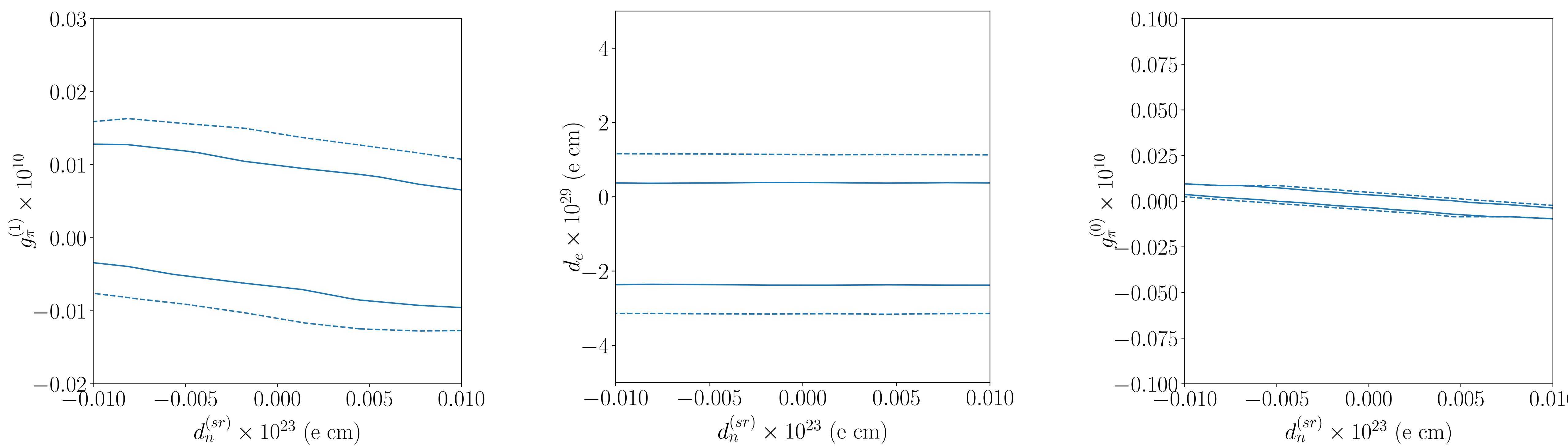
Results of a 4D analysis - Part II



- Parameters $\{d_e, C_S, g_\pi^{(0)}, g_\pi^{(1)}\}$

- Dominant measurements:
  ThO and HfF^+ (d_e and C_S), Hg and neutron ($g_\pi^{(0)}$ and $g_\pi^{(1)}$)

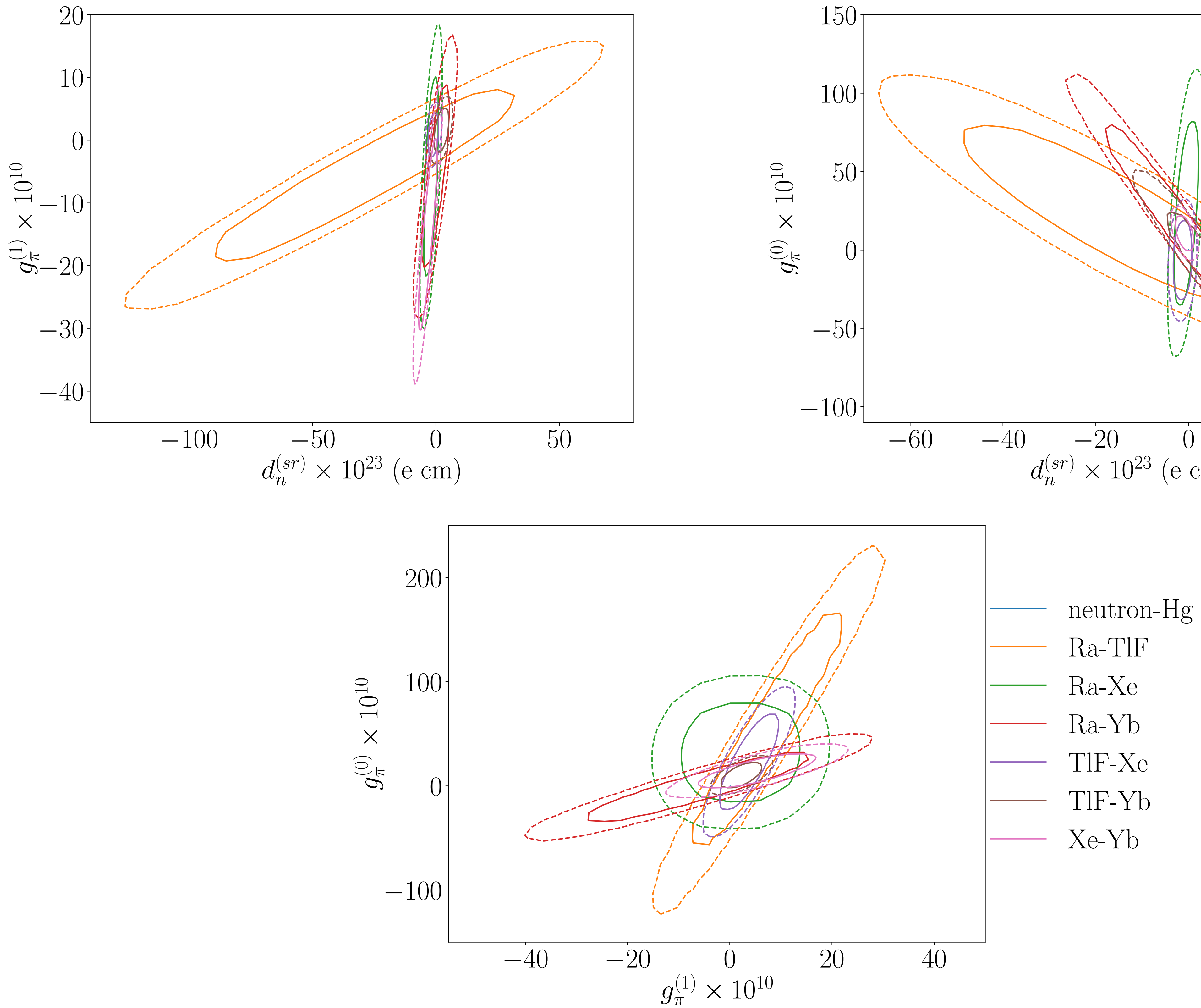
Adding a fifth parameter



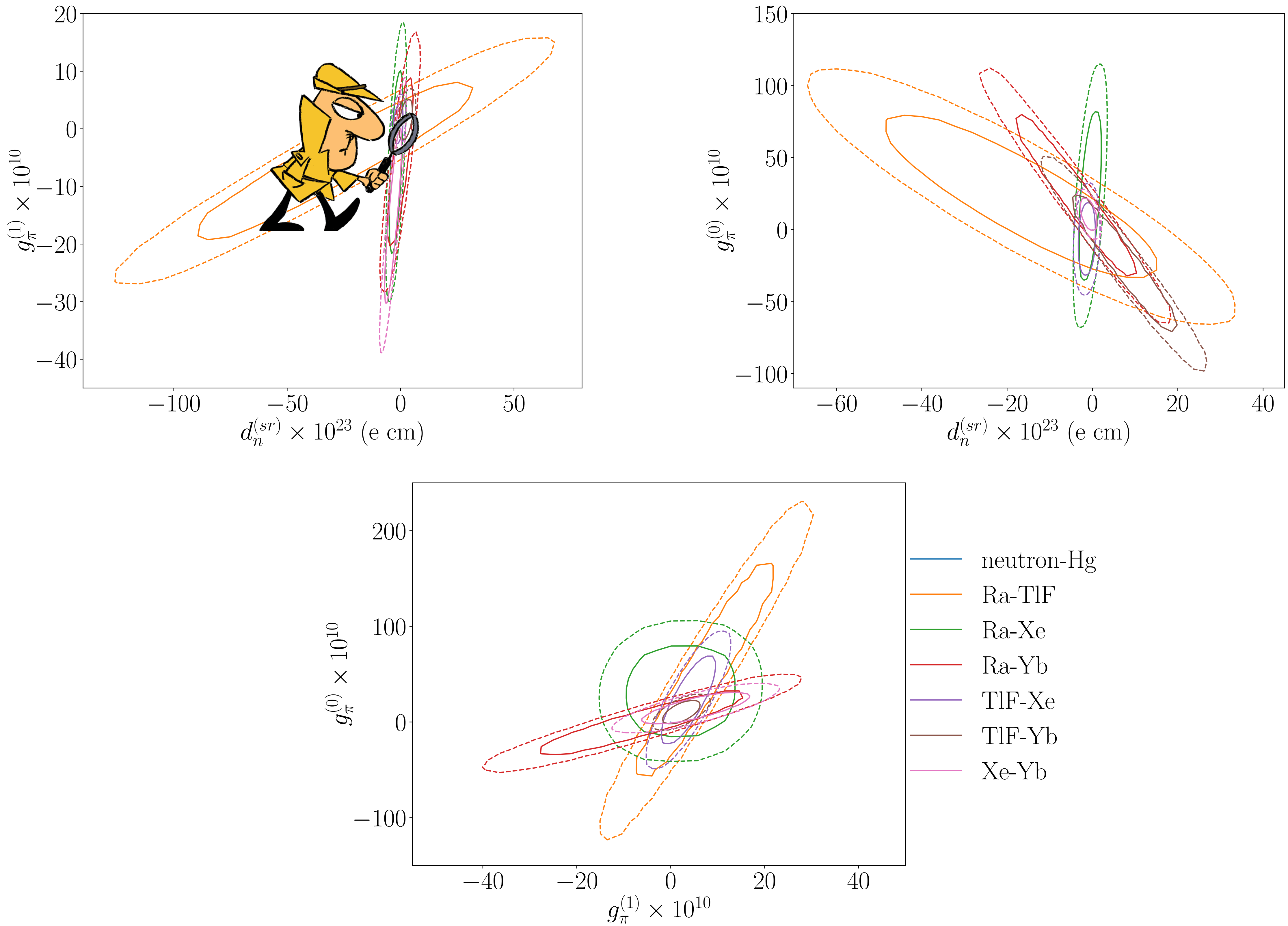
- Combining both 4D measurements, same parameter range
- Leading to **flat directions** in one parameter

➡ Problem: Only **four dominant measurements**

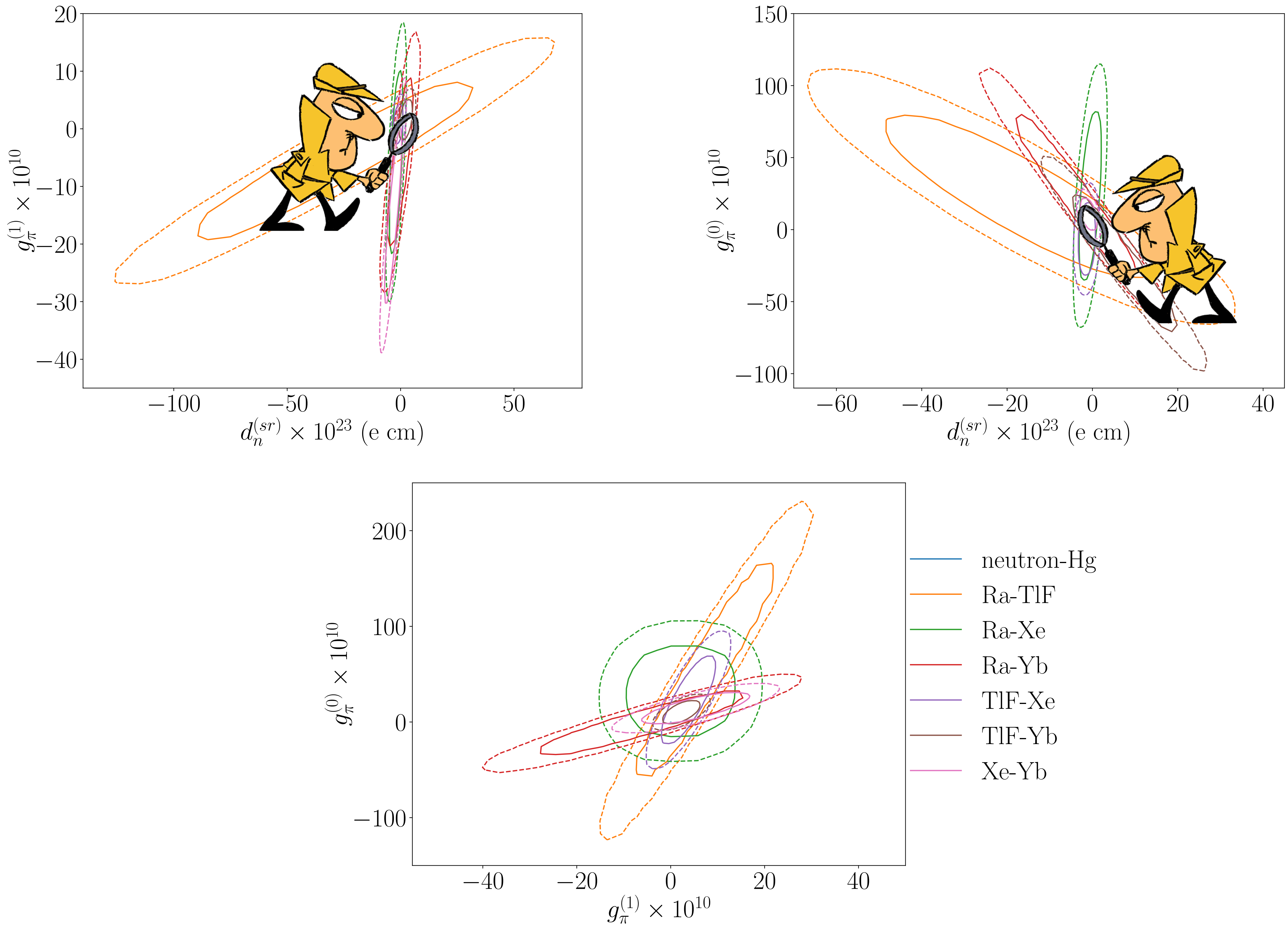
Problem with measurements



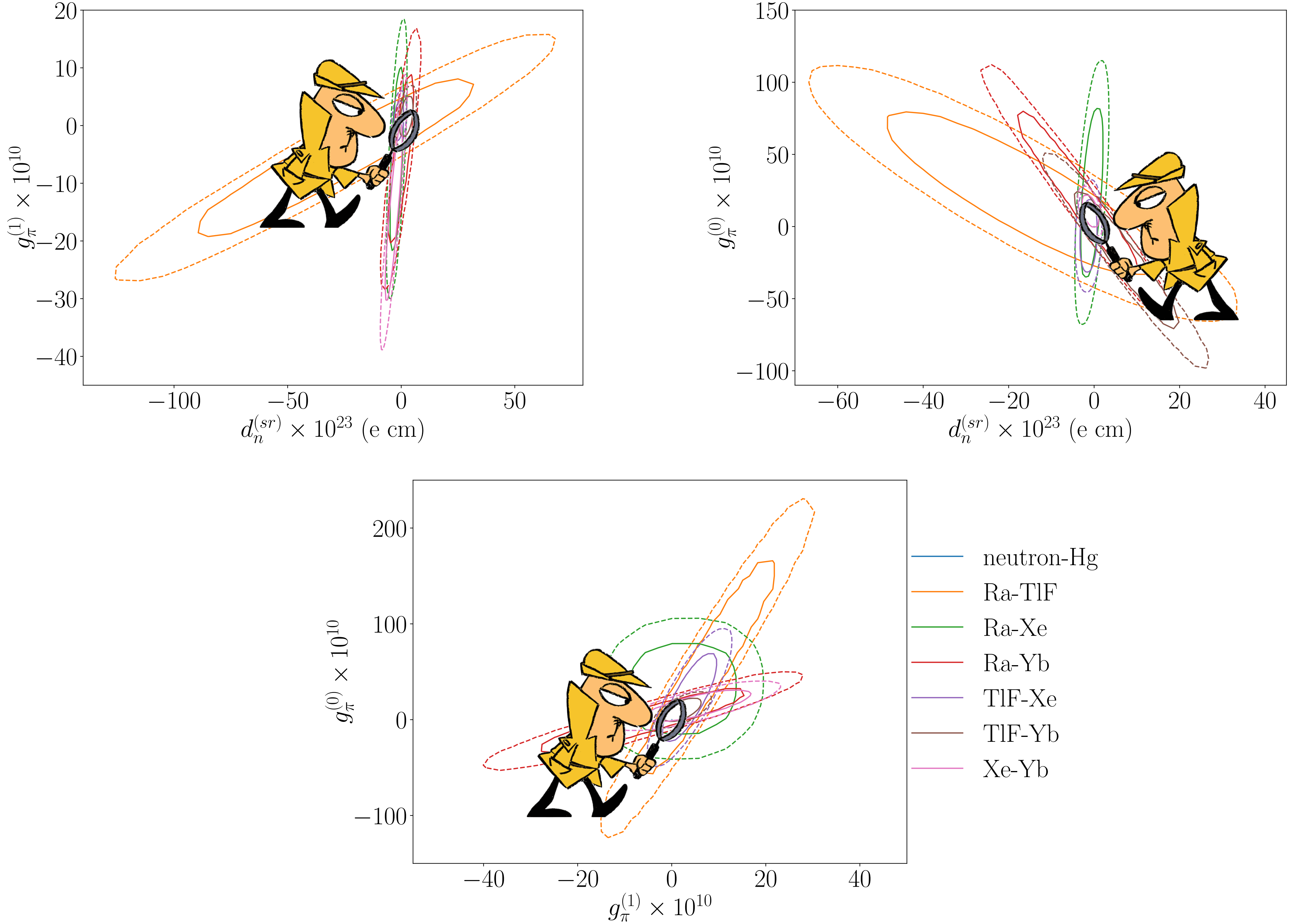
Problem with measurements



Problem with measurements



Problem with measurements

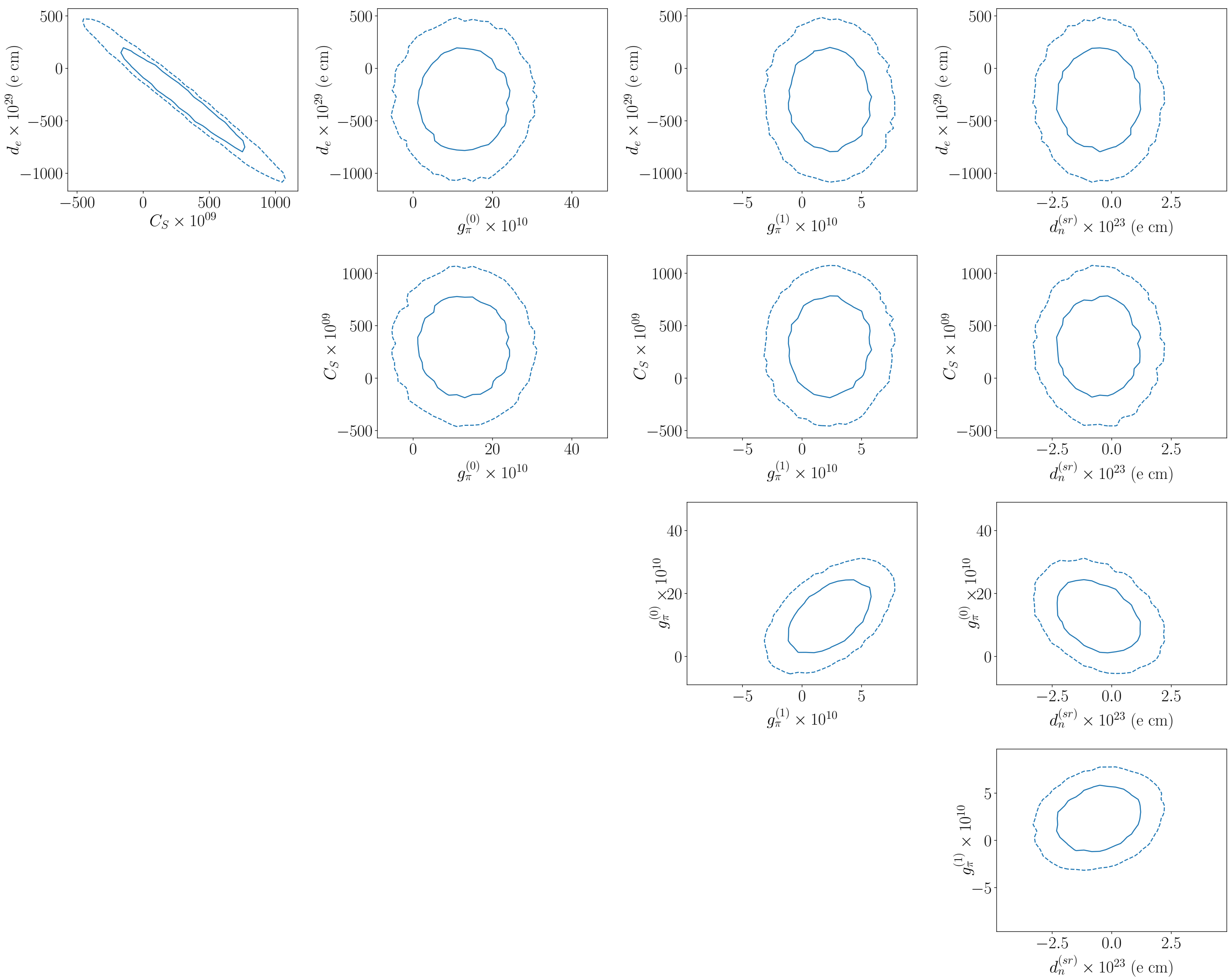


Part 3

Dividing the dataset

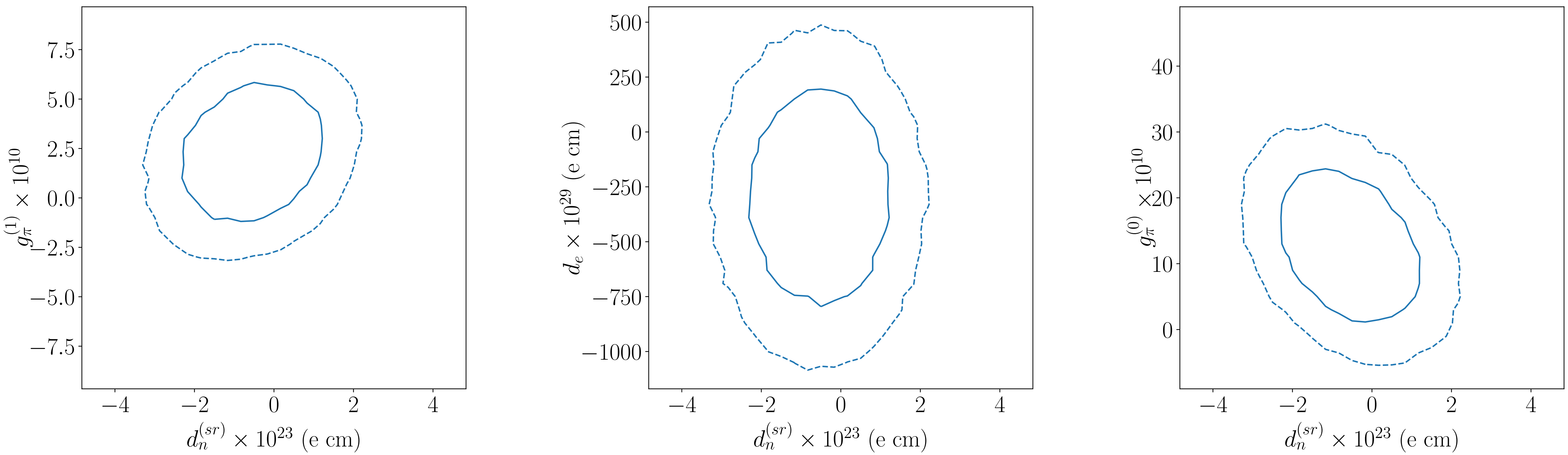
(Preliminary results)

Using bad measurements - 5D global analysis



- **Removing** ThO, HfF^+, Hg and neutron measurements
  - Constraining all parameters, but with broader ranges

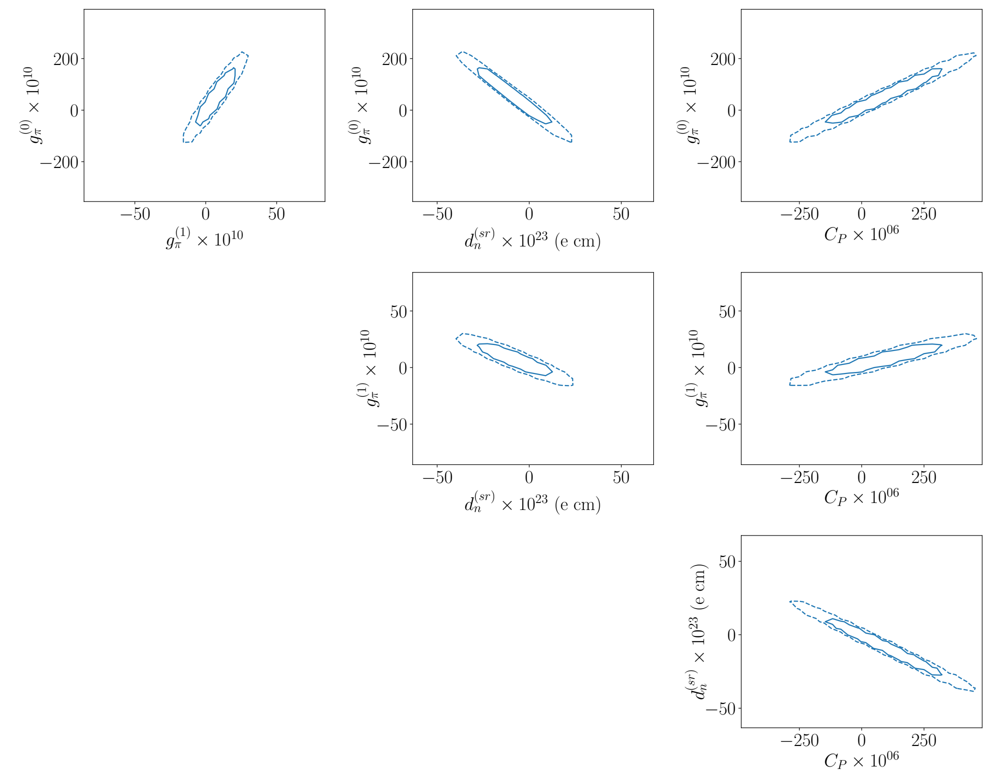
Using bad measurements - 5D global analysis



- $\{d_e, C_S, g_\pi^{(0)}, g_\pi^{(1)}, d_n^{sr}\}$
- **Range differs** from previous analysis (previous: $\mathcal{O}(0.01)$)

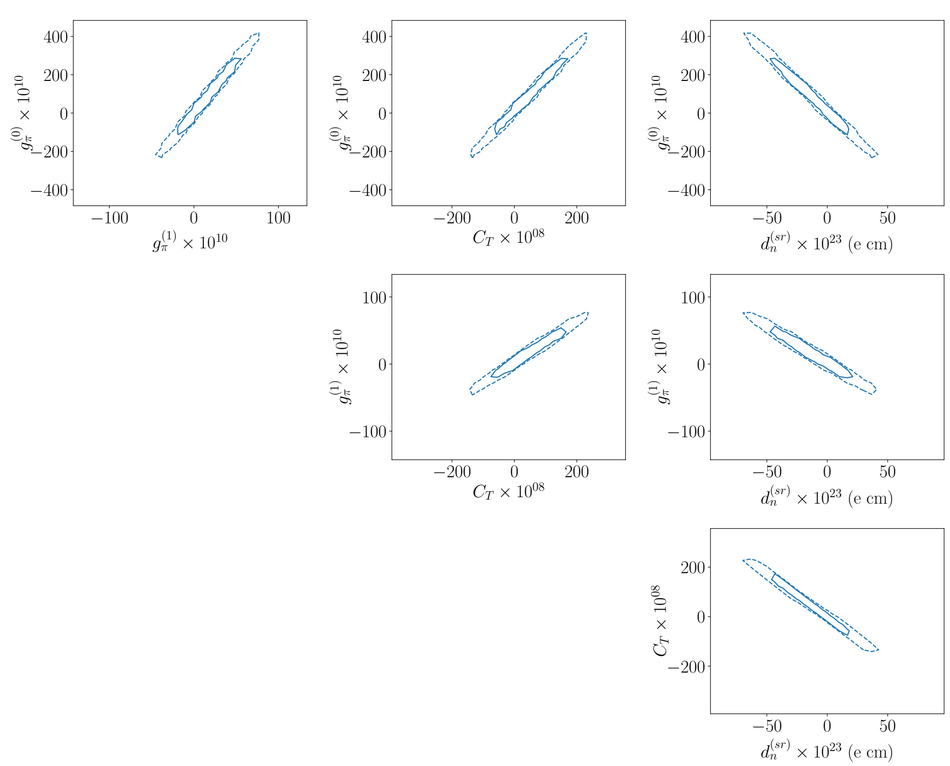
Using bad measurements - 6D global analysis

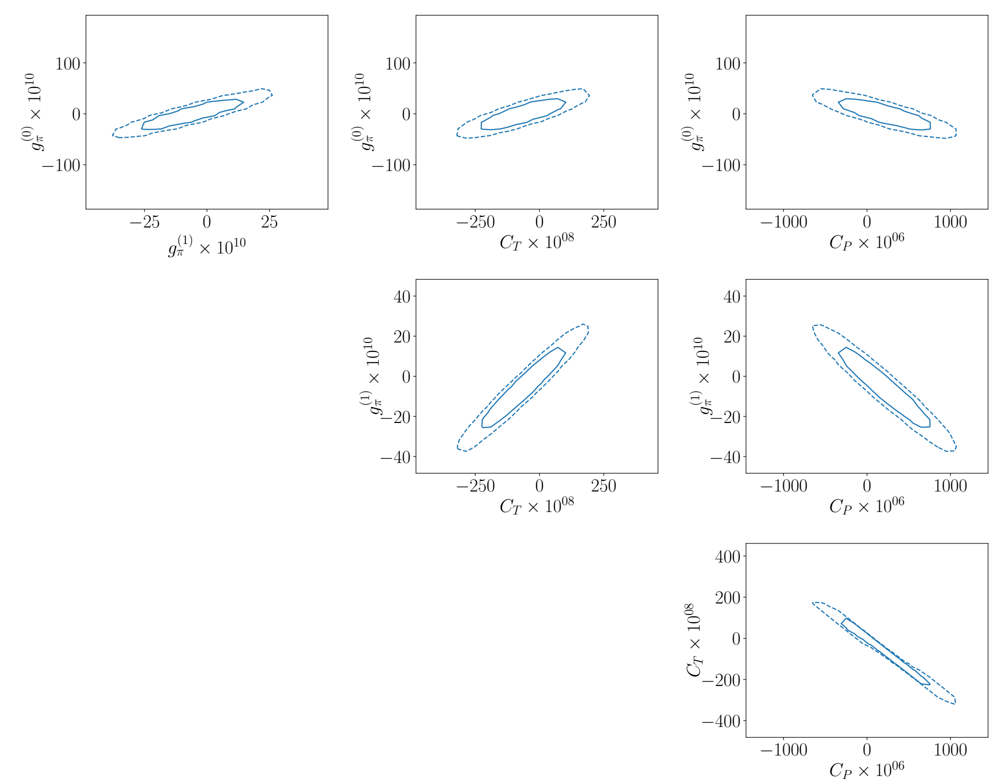
- Leptonic part remains the same



- Combinations:
  $C_P - C_T$: Anti-correlated
  $d_n^{sr} - C_P$: Anti-correlated
  $d_n^{sr} - C_T$: Anti-correlated

- Bad constraints in 7D global analysis





Conclusion and Outlook

- Some problems in a global EDM analysis
- Good constraints and results for up to four parameter
- Higher dimensions: need to **divide data set**
  - Constraints differ by several orders of magnitude

➡ **Still a lot to do** for theory and experiment!

Next steps

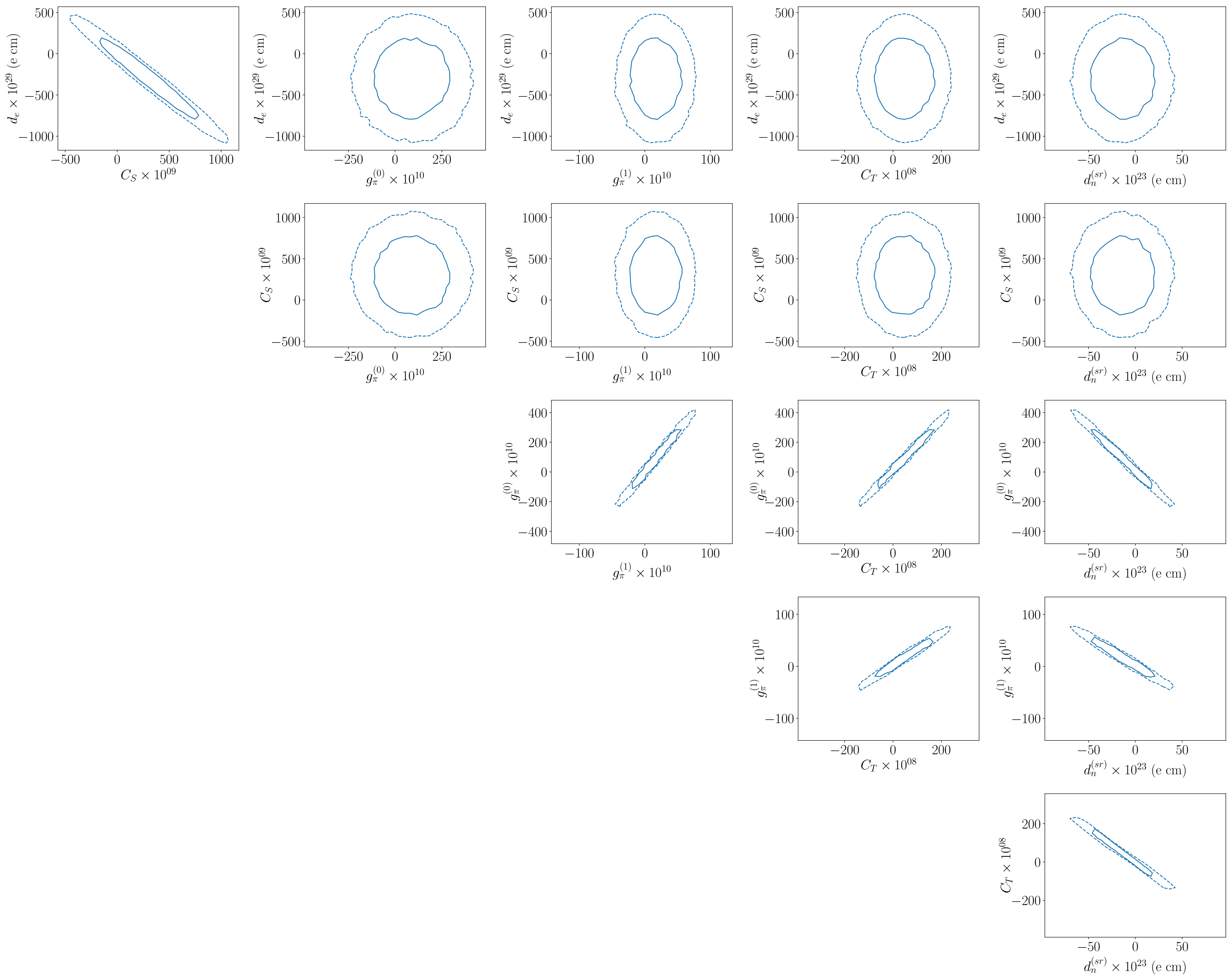
- Including theory uncertainties for measurements
- More tests on a seven dimensional analysis
- Apply the different concepts of profiling and marginalization

➡ A lot to do, stay tuned for future results and publications

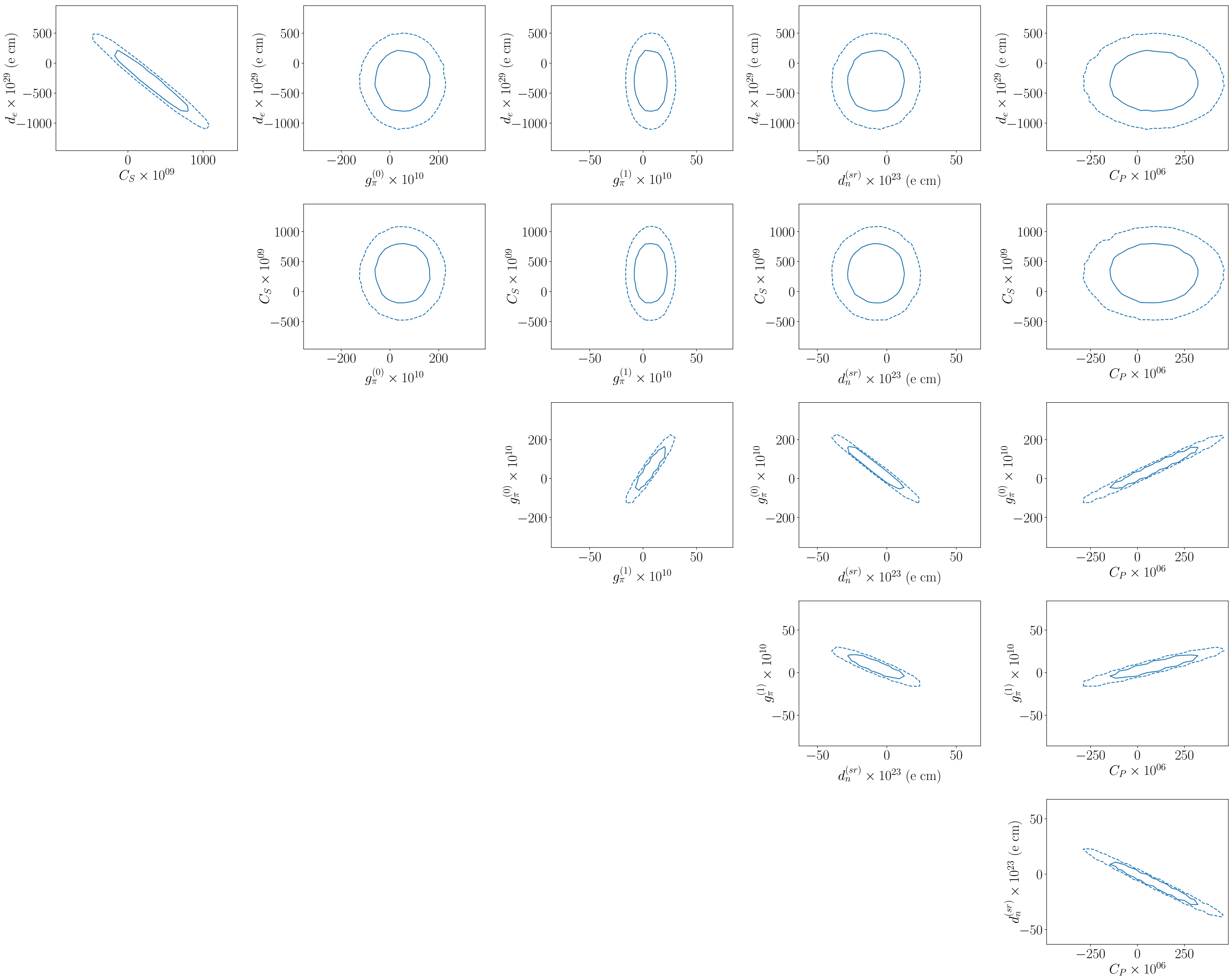
Thanks for listening :)

Backup slides

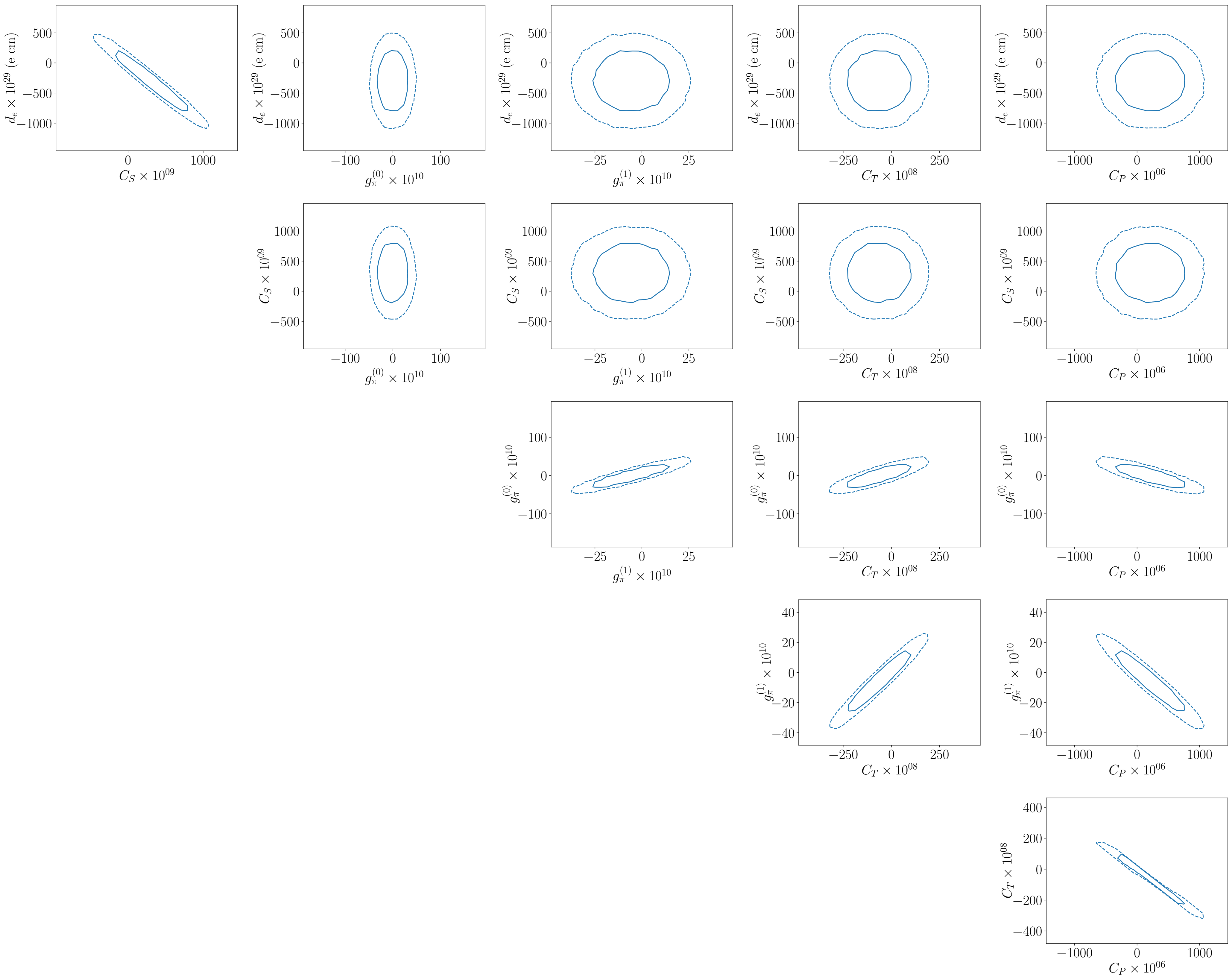
Using bad measurements - 6D global analysis



Using bad measurements - 6D global analysis



Using bad measurements - 6D global analysis



Using bad measurements - 7D global analysis

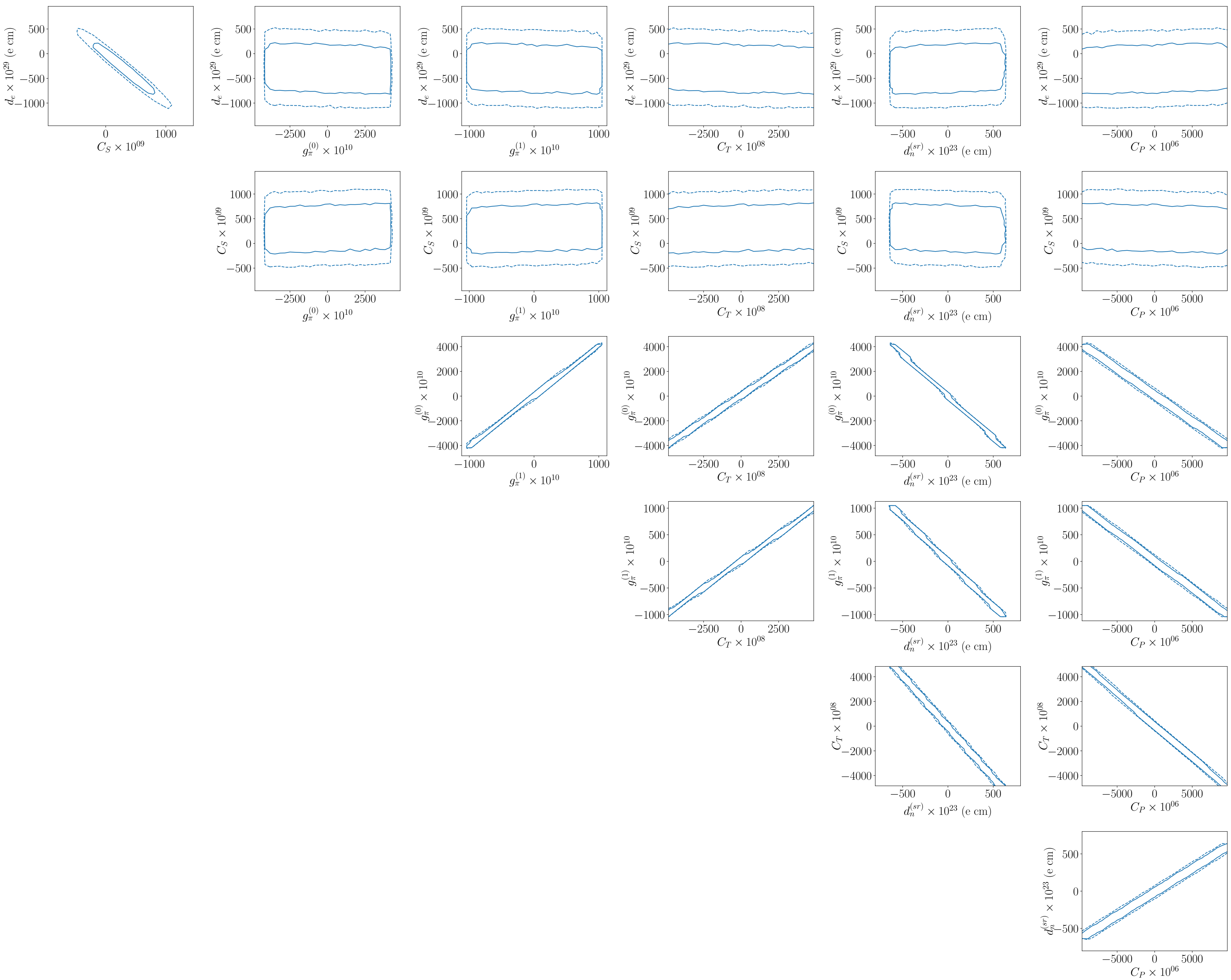


Table with measurements

System i	Measured d_i $[e\,\text{cm}]$	Upper limit on $\lvert d_i \rvert$ $[e\,\text{cm}]$
n	$(0.0 \pm 1.1_{\text{stat}} \pm 0.2_{\text{syst}}) \cdot 10^{-26}$	$2.2 \cdot 10^{-26}$
^{205}Tl	$(-4.0 \pm 4.3) \cdot 10^{-25}$	$1.1 \cdot 10^{-24}$
^{133}Cs	$(-1.8 \pm 6.7_{\text{stat}} \pm 1.8_{\text{syst}}) \cdot 10^{-24}$	$1.4 \cdot 10^{-23}$
HfF^+	$(-1.3 \pm 2.0_{\text{stat}} \pm 0.6_{\text{syst}}) \cdot 10^{-30}$	$4.8 \cdot 10^{-30}$
ThO	$(4.3 \pm 3.1_{\text{stat}} \pm 2.6_{\text{syst}}) \cdot 10^{-30}$	$1.1 \cdot 10^{-29}$
YbF	$(-2.4 \pm 5.7_{\text{stat}} \pm 1.5_{\text{syst}}) \cdot 10^{-28}$	$1.2 \cdot 10^{-27}$
^{199}Hg	$(2.20 \pm 2.75_{\text{stat}} \pm 1.48_{\text{syst}}) \cdot 10^{-30}$	$7.4 \cdot 10^{-30}$
^{129}Xe	$(-1.76 \pm 1.82) \cdot 10^{-28}$	$4.8 \cdot 10^{-28}$
^{171}Yb	$(-6.8 \pm 5.1_{\text{stat}} \pm 1.2_{\text{syst}}) \cdot 10^{-27}$	$1.5 \cdot 10^{-26}$
^{225}Ra	$(4 \pm 6_{\text{stat}} \pm 0.2_{\text{syst}}) \cdot 10^{-24}$	$1.4 \cdot 10^{-23}$
TlF	$(-1.7 \pm 2.9) \cdot 10^{-23}$	$6.5 \cdot 10^{-23}$

2212.11841, Nature 562 7727, Nature 473 493, PhysRevLett.88.071805, PhysRevLett.63.965, 1601.04339, 1902.02864, 2207.08140, 1606.04931, PhysRevA.44.2783, 2001.11966

Which parameter is constrained by which system?

parameter	experimental system
d_e	paramagnetic molecules
C_S	paramagnetic molecules
C_T	diamagnetic systems (Hg, Xe)
C_P	diamagnetic systems (Hg, Xe)
$g_\pi^{(0)}$	neutron, Hg
$g_\pi^{(1)}$	Hg, neutron, other diamagnetic systems
d_n^{sr}	neutron, Hg

Direct comparison of ‘good’ and ‘bad’ data