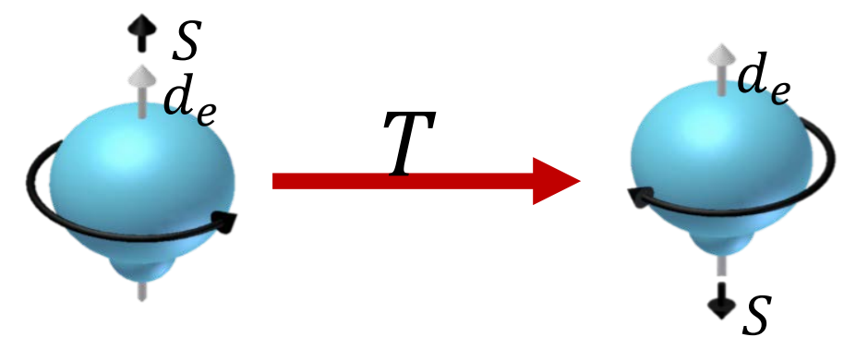
Order-of-magnitude improvement in the limit on the electron electric dipole moment

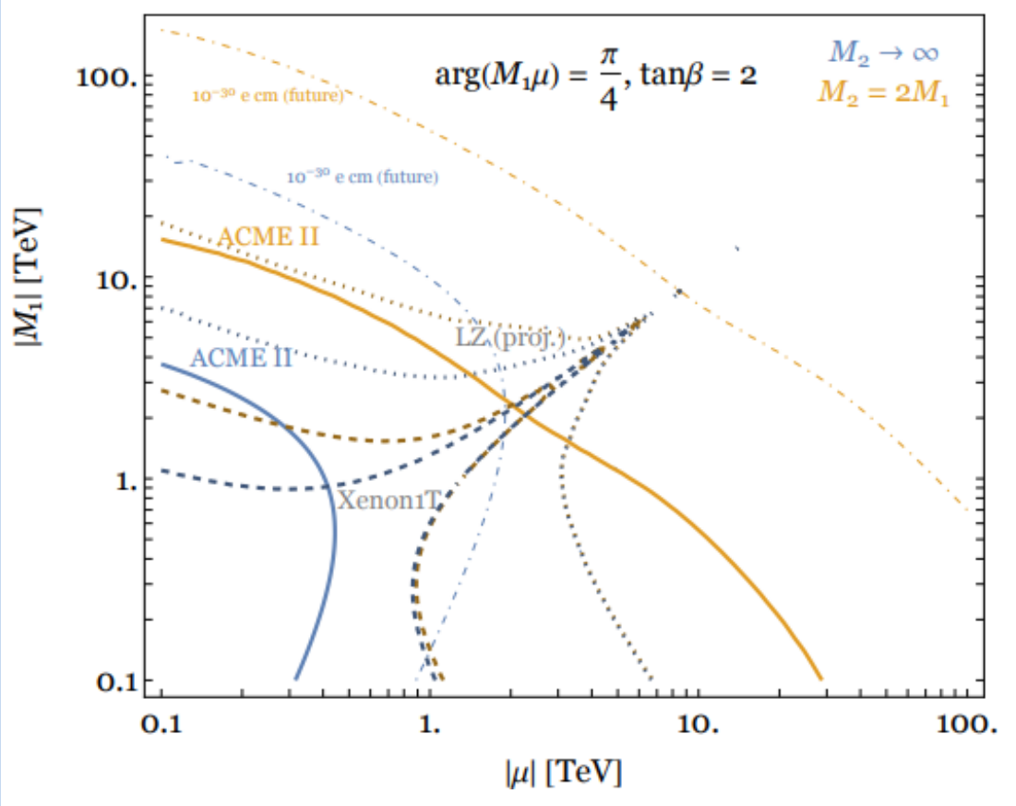
ACME Collaboration: Vitaly Andreev,[1] Daniel G. Ang,[1] David DeMille[2] (PI), John M. Doyle[1] (PI), Gerald Gabrielse[1] (PI), Jonathan Haefner,[1] Nicholas R. Hutzler,[3] Zack D. Lasner,[2] Cole Meisenhelder,[1] Brendon R. O' Leary,[2] Cristian D. Panda,[1] Adam D. West,[2] Elizabeth P. West,[1] Xing Wu[2]
Affiliation: [1]Harvard University, [2]Yale University, [3]California Institute of Technology

Motivation & Theory

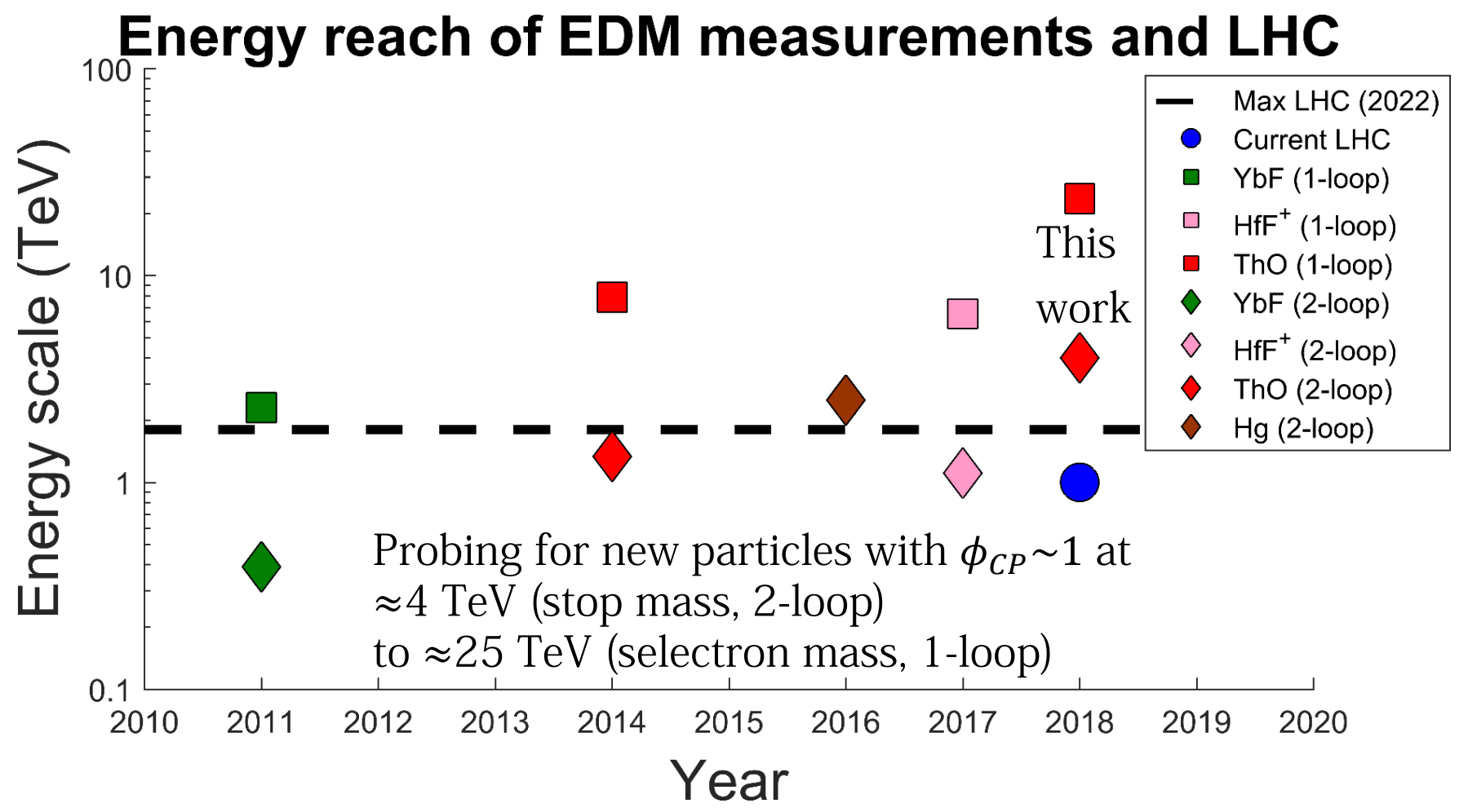
$$H_d = -\vec{d}_e \cdot \vec{\mathcal{E}}$$



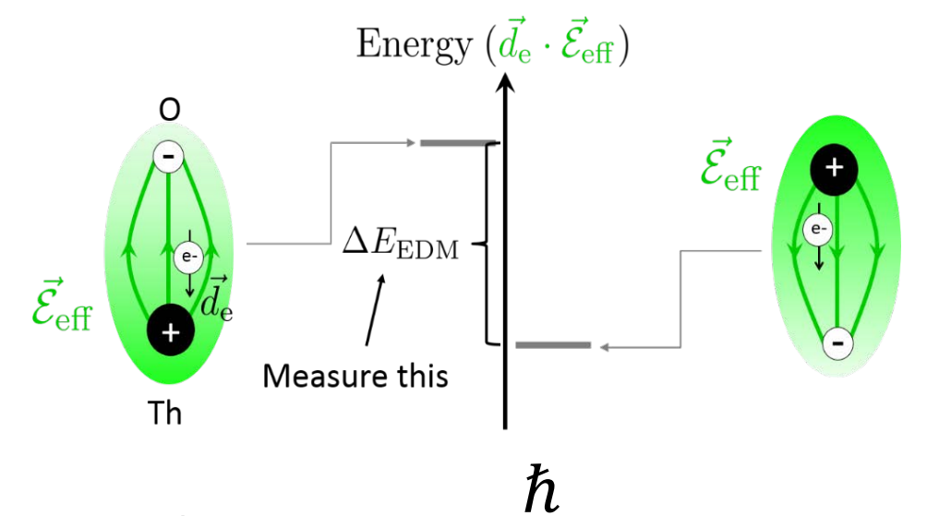
Permanent EDMs violate T-symmetry. Many theories beyond the Standard Model predict T violation and EDMs at current experimental precision.



SUSY particle bounds from this result.
Fig. from Matt Reece (unpublished).
ACME III proj. ($\sim 10^{-30}$ e ·cm) dashed.



Key EDM results since 2010. Two-loop sensitivity from Nakai & Reece (2017). One-loop sensitivity from Feng (2013). LHC scale gives stop mass sensitivity.



$$\delta d_e = \frac{\hbar}{2C\tau\mathcal{E}_{\rm eff}\sqrt{\dot{n}T}}$$

Effective electric field $\mathcal{E}_{\rm eff} : \sim 80$ GV/cm
Precession time $\tau : \sim 1$ ms
Measurement contrast $\mathcal{C} : \sim 0.95$
(Detected) molecule flux $\dot{n}$:
ACME I: $\sim 3 \times 10^4\ s^{-1}$
ACME II: $\sim 1 \times 10^7\ s^{-1}$
ACME I result $d_e = (-2.2 \pm 4.8) \times 10^{-29}\,\mathrm{e\cdot cm}$
$\Rightarrow |d_e| < 9.3 \times 10^{-29}\,\mathrm{e\cdot cm}$
ACME II result $d_e = (4.3 \pm 4.0) \times 10^{-29}\,\mathrm{e\cdot cm}$
$\Rightarrow |d_e| < 1.1 \times 10^{-29}\,\mathrm{e\cdot cm}$

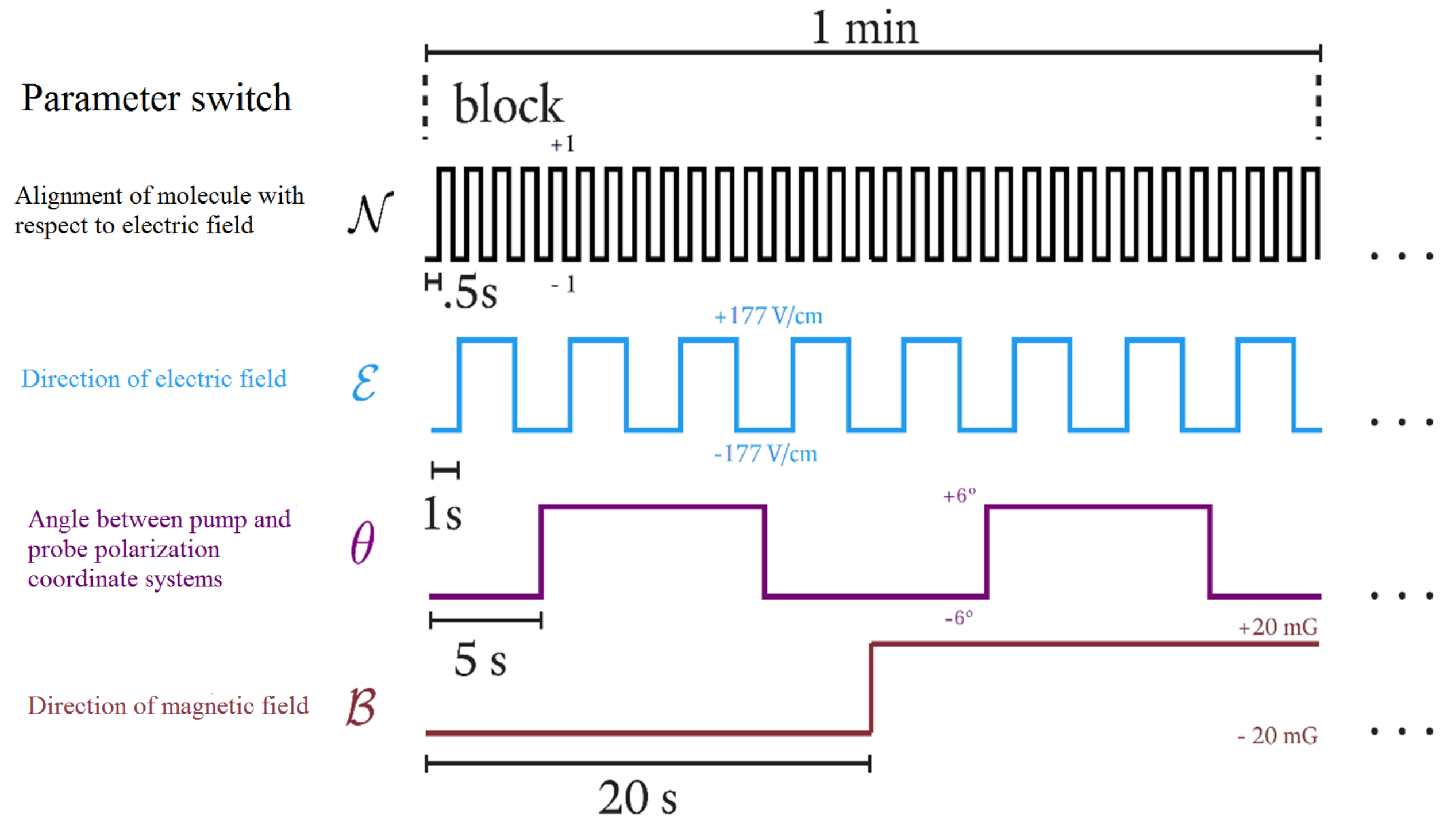
Data Acquisition Structure

The spin precession is performed under a variety of configurations of binary experimental switches, such as the electric and magnetic field directions, under which various terms in the Hamiltonian are odd or even.

This enables us to study the components of the frequency that reverse under experimental switches by taking the difference of frequency measurements made with opposite values of the relevant switches. Throught his we are also able to diagnose and suppress systematic effects.

By performing the experiment with different values of $\tilde{N}$, $\tilde{E}$, and $\tilde{B}$ we can extract the EDM channel $\omega^{\tilde{N}\tilde{E}}$, the component of the precession frequency which is odd under reversal of $\tilde{N}$ and $\tilde{E}$.

This measurement scheme results in robust suppression of systematic effects: any imperfections in the system would have to be correlated with both $\tilde{N}$ and $\tilde{E}$ to become a source of systematic error.



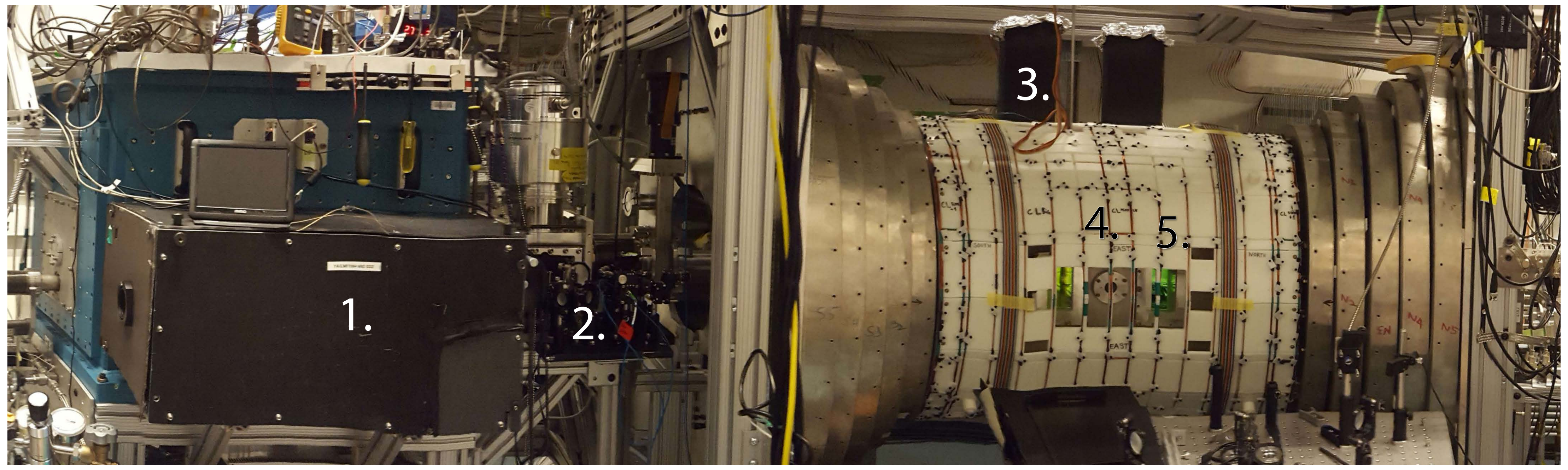
Degeneracy of States: 4

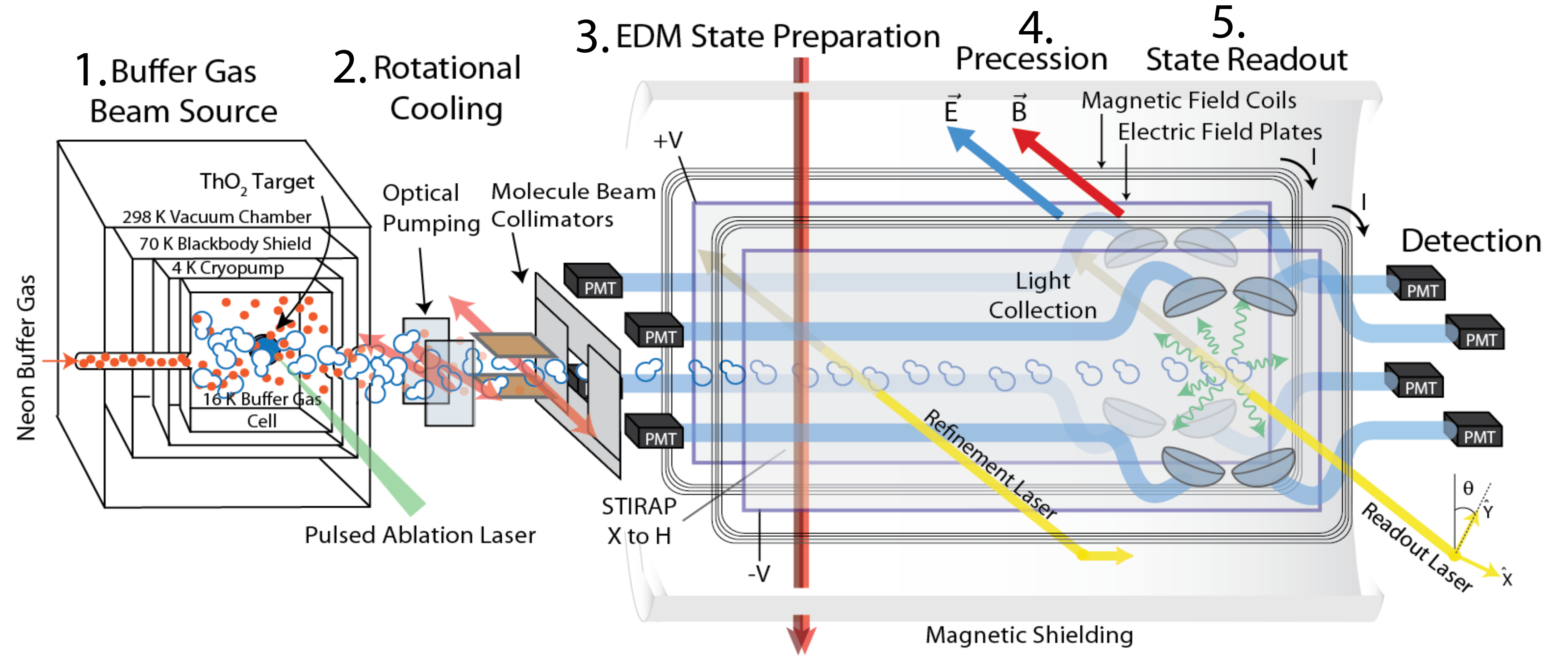
$$\omega(\tilde{N},\tilde{E},\tilde{B}) = \tilde{N}\omega^{\tilde{N}} + \tilde{E}\omega^{\tilde{E}} + \tilde{B}\omega^{\tilde{B}} + \boxed{\tilde{N}\tilde{E}\omega^{\tilde{N}\tilde{E}}} + \tilde{N}\tilde{B}\omega^{\tilde{N}\tilde{B}} + \tilde{E}\tilde{B}\omega^{\tilde{E}\tilde{B}} + \tilde{N}\tilde{E}\tilde{B}\omega^{\tilde{N}\tilde{E}\tilde{B}}$$

$$\tilde{N},\tilde{E},\tilde{B} \in \{+1,-1\}$$

EDM frequency

ACME II Apparatus





Contributions to the Systematic Uncertainty

Parameter	Uncertainty	
Non-reversing Electric Field, $\mathcal{E}^{nr}$	0.38 σ_{stat}	These parameters showed shifts in the EDM channel
$\tilde{N}\tilde{E}$ and $\tilde{N}\tilde{E}\tilde{B}$ correlated contrast variations, $\lvert\mathcal{C}\rvert^{\tilde{N}\tilde{\mathcal{E}}}$, $\lvert\mathcal{C}\rvert^{\tilde{N}\tilde{\mathcal{E}}\tilde{\mathcal{B}}}$	0.34 σ_{stat}	
Magnetic field gradients, $\frac{\partial\mathcal{B}_z}{\partial z}$, $\frac{\partial\mathcal{B}_z}{\partial y}$	0.16 σ_{stat}	
STIRAP $\tilde{N}\tilde{E}$ correlated phase $\omega_{ST}^{\tilde{N}\tilde{E}}$	0.003 σ_{stat}	
$\tilde{E}$ correlated phases, $\phi^{\tilde{E}}$	0.003 σ_{stat}	
Other magnetic field gradients	0.36 σ_{stat}	These parameters showed no shift but a limit was included in the error bar
$\tilde{N}\tilde{E}$ correlated refinement laser power, $\mathcal{P}_{ref}^{\tilde{N}\tilde{E}}$	0.29 σ_{stat}	
Non-reversing magnetic field, $\mathcal{B}_z^{nr}$	0.28 σ_{stat}	
Transverse magnetic fields, $\mathcal{B}_x^{nr}$, $\mathcal{B}_y^{nr}$	0.25 σ_{stat}	
Refinement/readout laser detunings	0.20 σ_{stat}	
$\tilde{N}$ correlated detunings	0.13 σ_{stat}	
Total	0.83 σ_{stat}	

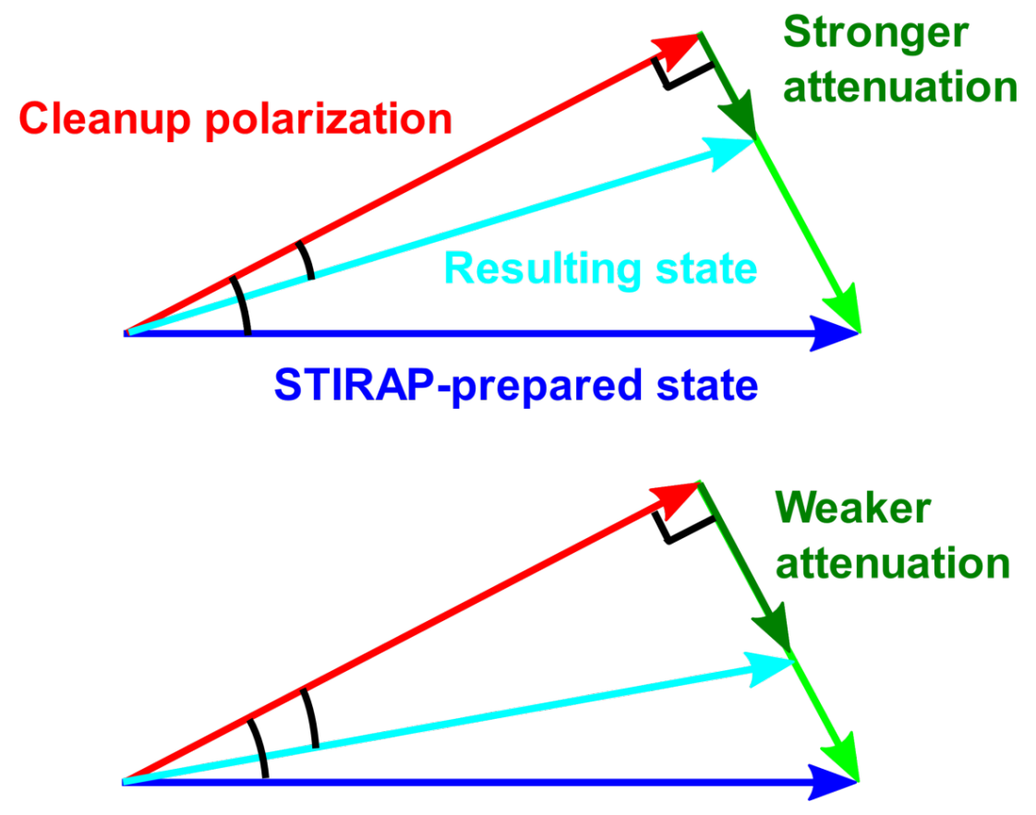
We varied 40 different experiment parameters in the search for systematic errors. These include magnetic fields, electric fields, laser powers, laser detunings, laser pointing, laser polarization, molecular beam clipping, experiment timing, and analysis.
Where possible, we intentionally exaggerate the parameter and assume ω depends linearly on the parameter P. The systematic error under optimal conditions ($P = \bar{P}$) is given as

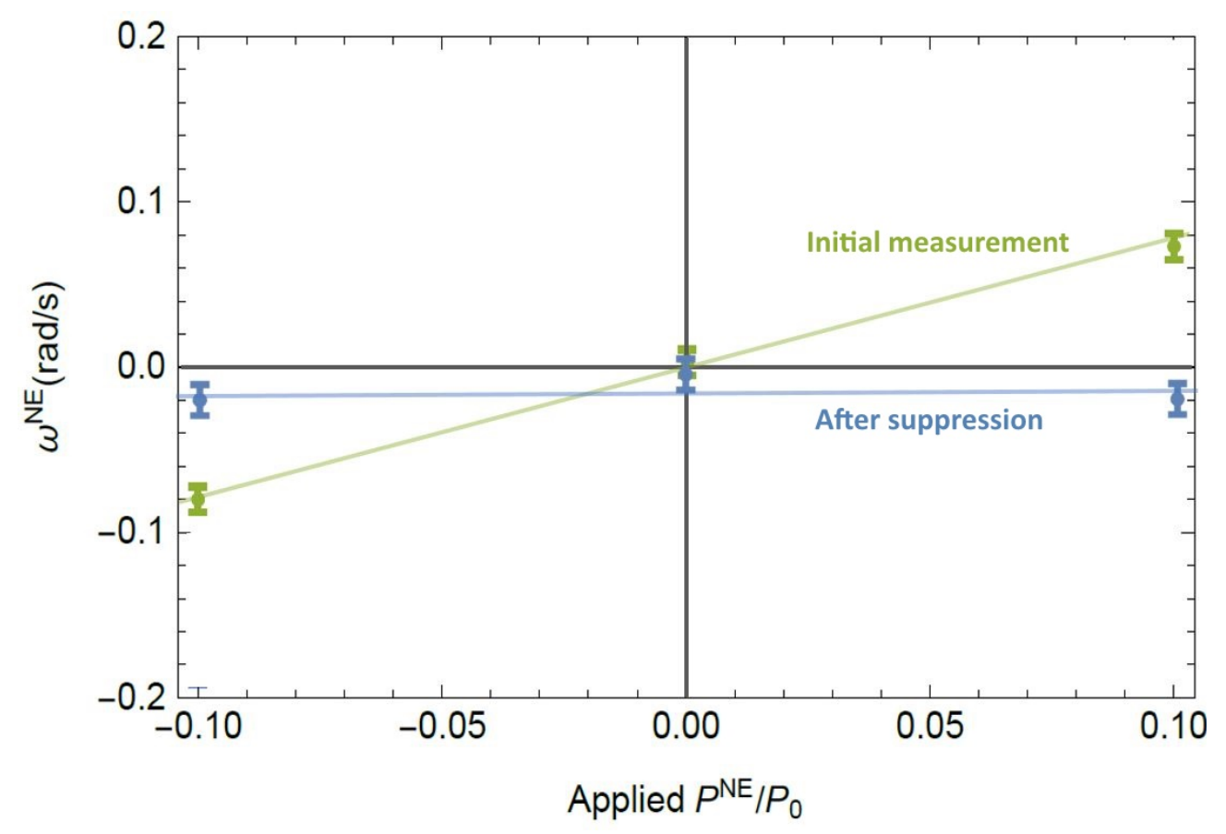
$$\omega_P^{\tilde{N}\tilde{E}} = (\partial\omega^{\tilde{N}\tilde{E}}/\partial P)\bar{P}.$$

The final contribution to the systematic uncertainty is computed from linear error propagation of the two variables $\bar{P}$ and $\partial\omega^{\tilde{N}\tilde{E}}/\partial P$.

Example Systematic 1: Correlation Between Prepared Phase and Laser Power

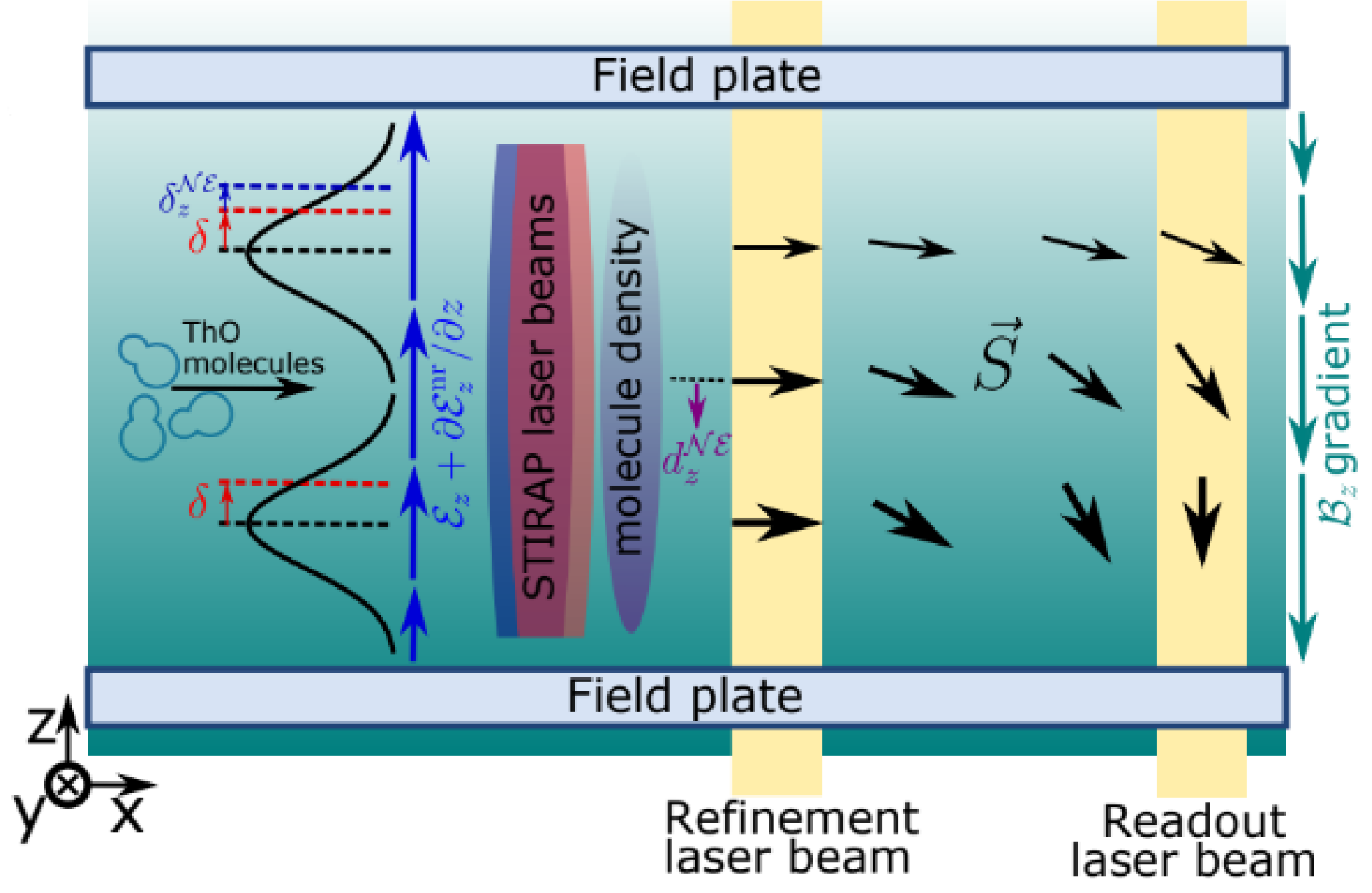
We discovered a nonzero dependence of $\omega^{\tilde{N}\tilde{E}}$ vs the refinement laser power: $P^{app} = P^{nr}(1 + \tilde{N}\tilde{E}\frac{P^{\tilde{N}\tilde{E}}}{P^{nr}})$. The slope depended on the global polarization angle of the lasers. This dependence arose from a misalignment in the angle between the initial spin state (prepared by STIRAP) and the refinement laser polarization. The refinement laser was not perfectly attenuating the component of the spin perpendicular to its polarization, resulting in a shift in $\omega^{\tilde{N}\tilde{E}}$ when $P^{\tilde{N}\tilde{E}}$ is applied.
We are able to suppress this effect by both increasing the refinement laser power and tuning the global polarization angle.

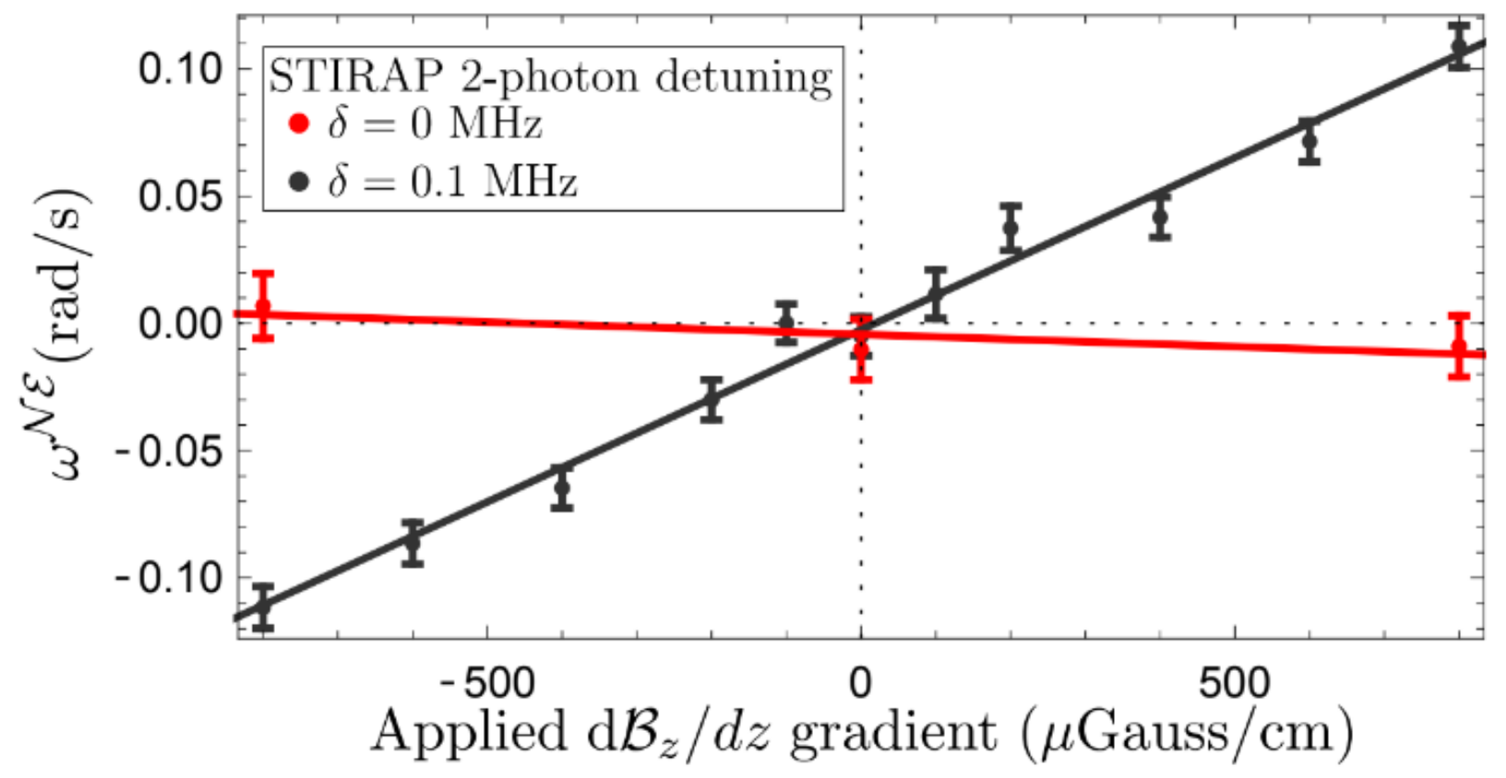




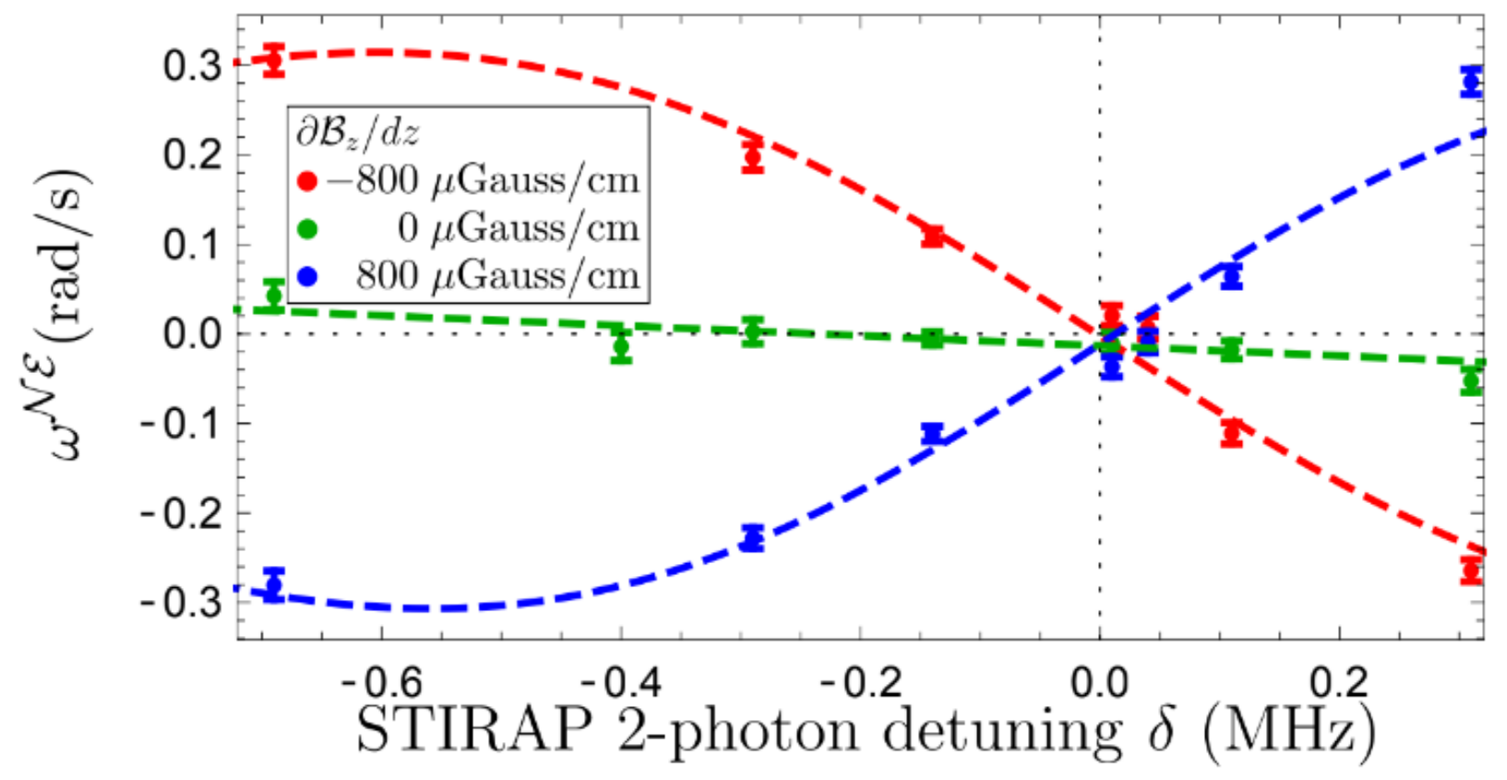
Example Systematic 2: Non-reversing Electric Field Gradients Coupling to Magnetic Field Gradients and Laser Detunings

1) Patch effects and voltage offsets can produce a gradient in the non-reversing electric field, $\frac{\partial\mathcal{E}^{nr}}{\partial z}$.
2) This produces an $\tilde{N}\tilde{E}$ correlated detuning gradient, $\frac{\partial\delta^{\tilde{N}\tilde{E}}}{\partial z}$.
3) Any detuning gradient couples to the efficiency, η, of our state preparation procedure (STIRAP) if we are not on resonance ($\frac{\partial\eta}{\partial\delta} \neq 0$).
4) The combination of $\frac{\partial\delta^{\tilde{N}\tilde{E}}}{\partial z}$ and $\frac{\partial\eta}{\partial\delta}$ produces an $\tilde{N}\tilde{E}$ correlated shift in the beam center of mass along z, $dz^{\tilde{N}\tilde{E}}$.
5) A magnetic field gradient $\frac{\partial\mathcal{B}}{\partial z}$ produces a spatially dependent precession frequency, which couples to the shift in center of mass to produce a shift in the EDM channel, $\omega^{\tilde{N}\tilde{E}} = \frac{\partial\omega}{\partial\mathcal{B}} \times \frac{\partial\mathcal{B}}{\partial z} \times dz^{\tilde{N}\tilde{E}}$.
This systematic produces a shift in $\omega^{\tilde{N}\tilde{E}}$ that is proportional to $\frac{\partial\mathcal{E}^{nr}}{\partial z} \times \delta \times \frac{\partial\mathcal{B}}{\partial z}$.





We are unable to tune $\frac{\partial\mathcal{E}_z}{\partial z}$, but we are able to experimentally control δ and $\frac{\partial\mathcal{B}_z}{\partial z}$.
We exaggerate these parameters in order to both measure their effects on $\omega^{\tilde{N}\tilde{E}}$, and determine the correct values to null their effects.



We were also able to confirm this model by amplifying the effect and observing an $\tilde{N}\tilde{E}$ correlated z-dependence in our fluorescence signal. This was made possible by separating the data from our PMTs based on location.

Outlook

We have measured the electron EDM with a statistical uncertainty given by $\sigma_{stat} = 3.1 \times 10^{-30}\,\mathrm{e\cdot cm}$ and the systematic errors considered together give a smaller contribution. Our result provides a limit on the electron EDM that is an order of magnitude smaller than the best previous measurement, probing physics at energy scales of $\sim 3 - 30$ TeV.

References

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More information: www.electronedm.info