Complementarity of Precision Measurements and Current and Future Colliders

Based on `[arXiv:1810.07736]`

with Cari Cesarotti, Yuichiro Nakai, Aditya Parikh, and Matthew Reece

and ongoing work as part of Snowmass 2020

with Sam Homiller and Matthew Reece

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University of Toronto T-HEP Seminar, October 5, 2020

Outline

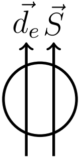
- Why study electron electric dipole moment (eEDM) and lepton flavor violating processes (LFV)?

- Current bounds = (often) beyond current collider scale
    - dimensional analysis
    - specific models (eEDM): QULE and SUSY

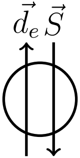
- The case for a high energy muon collider (LFV): high energy reach and clean environment help elucidate the underlying mechanism generating the precision observables.

Why precision observables?

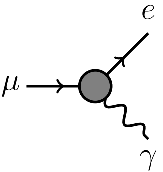
- electron electric dipole moment (eEDM): CP violating. Connected to the origin of matter-antimatter asymmetry of our universe

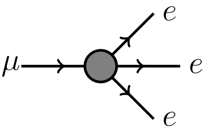


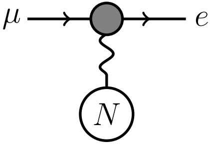
$$\vec{d}_e = d_e \frac{\vec{S}}{S} \xrightarrow{\text{time reversal}} \vec{d}_e = -d_e \frac{\vec{S}}{S}$$



- lepton flavor violating processes (LFV): what generated the flavor structure of the Standard Model? Why is there a large hierarchy of masses?







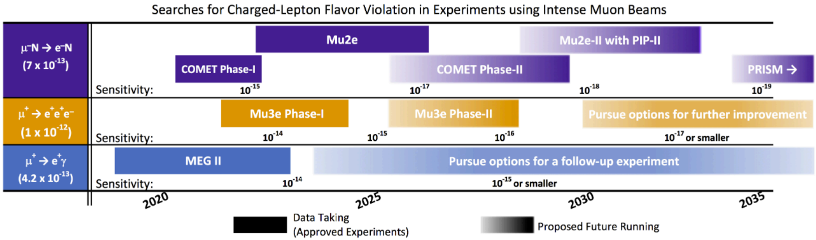
Precisions are connected to high energy

eEDM	$l_i \to l_j + \gamma$	$l_j \to l_i l_i l_i$
$ih^\dagger \ell \bar\sigma^{\mu\nu} \bar e B_{\mu\nu}$	$h^\dagger \ell_i \bar\sigma^{\mu\nu} \bar e_j B_{\mu\nu}$	$\left(l_j \Gamma_1 \bar l_i\right) \left(\bar l_i \, \Gamma_2 l_i\right)$
$ih^\dagger \ell \sigma^i \bar\sigma^{\mu\nu} \bar e W^i_{\mu\nu}$	$h^\dagger \ell_i \sigma^i \bar\sigma^{\mu\nu} \bar e_j W^i_{\mu\nu}$	

The operators all scale as $\sim \frac{1}{\Lambda^2}$ $(\sim \frac{v}{\Lambda^2})$ when generated by new physics as mass scale Λ.

And they are Standard Model background free!*

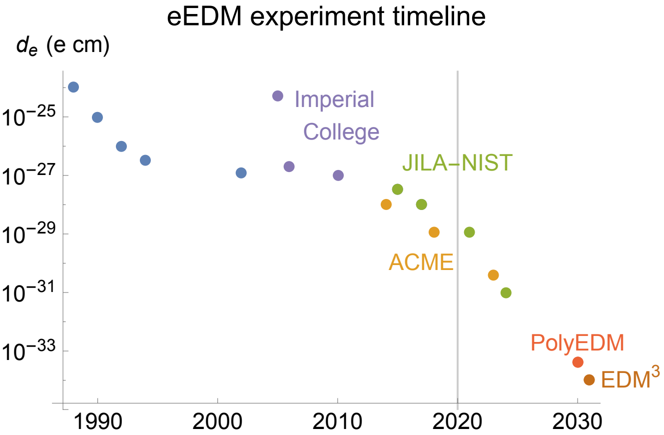
Precision Measurements are Advancing Steadily



[1812.06540 for 2020 Update of the European Strategy for Particle Physics]

1 order of magnitude in sensitivity = 1/4 order of magnitude in Λ.

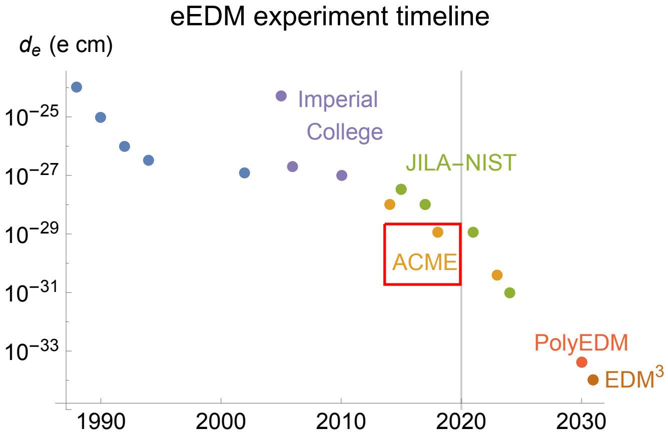
Precision Measurements are Advancing Steadily



[2019 DAMOP]

1 order of magnitude in sensitivity = 1/2 order of magnitude in Λ.

Precision Measurements are Advancing Steadily

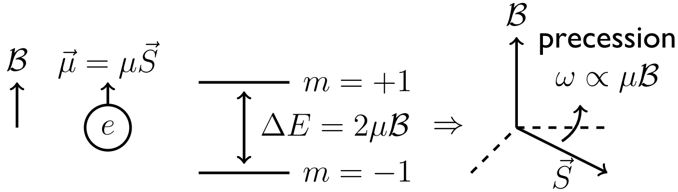


[2019 DAMOP]

1 order of magnitude in sensitivity = 1/2 order of magnitude in Λ.

ACME II experiment: overview

- Recall Larmor precession of electron spin:



ACME II experiment: overview

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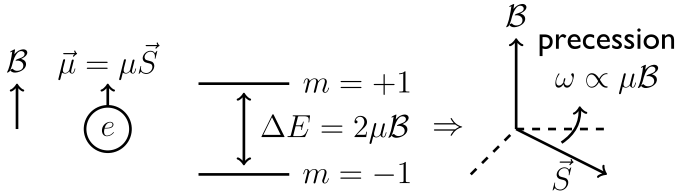


$\mathcal{B}$

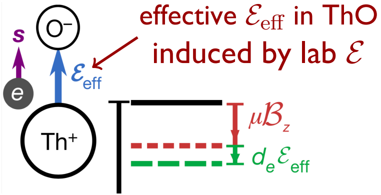
$\vec{\mu} = \mu \vec{S}$

$\Delta E = 2\mu\mathcal{B} \Rightarrow$

precession

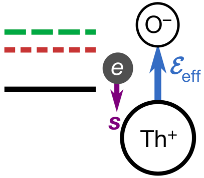
$\omega \propto \mu\mathcal{B}$

- electric dipole moment creates entirely analogous precession
- Under an external $\mathcal{B}_z$ and $\mathcal{E}$:



effective $\mathcal{E}_{\text{eff}}$ in ThO induced by lab $\mathcal{E}$

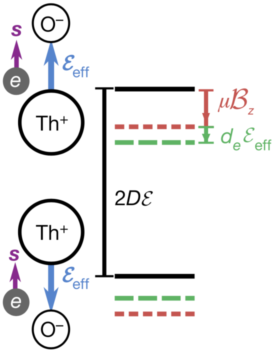
Spin up state



Spin down state

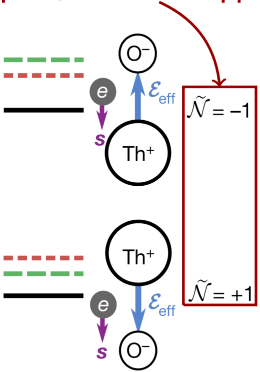
ACME II experiment: overview

EDM of ThO molecule can be flipped w.r.t to the lab $\mathcal{E}$, which changes the sign of $\mathcal{E}_{\rm eff}$ relative to electron spin:

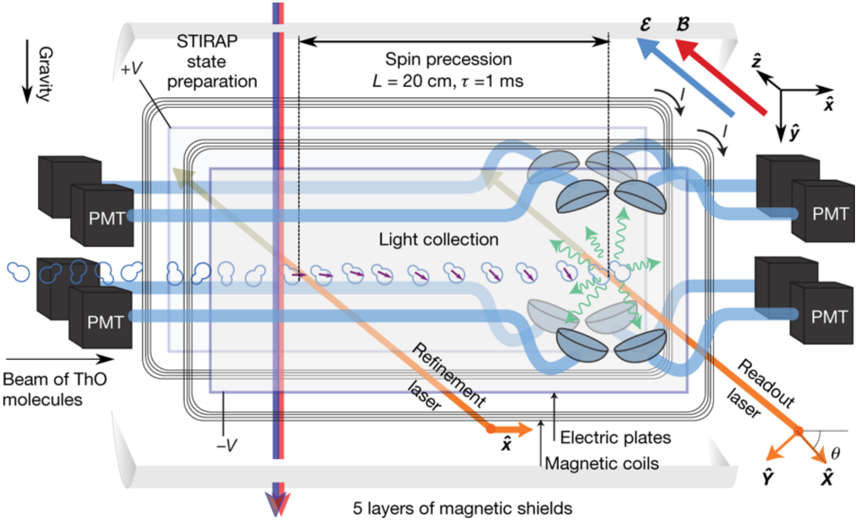


$\tilde{\mathcal{N}} = -1 \rightarrow +1$

flips $\mathcal{E}_{\rm eff}$ without flipping $\mathcal{E}$



ACME II experiment: setup



Current bounds = collider scale and beyond

dimensional analysis

ACME II = Collider Scale or Beyond

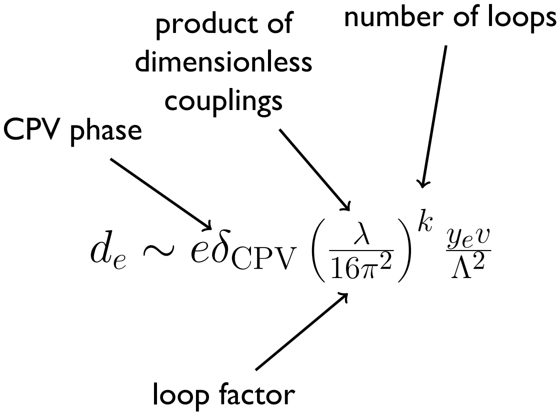
A conservative analysis

Claim: $|d_e| < 1.1 \times 10^{-29}\ e\ \mathrm{cm}$ is probing $\mathrm{TeV} \sim 1000\ \mathrm{TeV}$

$$\boxed{d_e \sim e\delta_{\mathrm{CPV}} \left(\frac{\lambda}{16\pi^2}\right)^k \frac{y_e v}{\Lambda^2}}$$

ACME II = Collider Scale or Beyond

A conservative analysis



product of dimensionless couplings

number of loops

CPV phase

$$d_e \sim e\delta_{\rm CPV}\left(\frac{\lambda}{16\pi^2}\right)^k\frac{y_e v}{\Lambda^2}$$

loop factor

ACME II = Collider Scale or Beyond

A conservative analysis

diagram contain coupling $\propto y_e$ (conservative)

$$d_e \sim e\delta_{\mathrm{CPV}} \left(\frac{\lambda}{16\pi^2}\right)^k \frac{y_e v}{\Lambda^2}$$

Higgs vev

mass scale of new physics

ACME II = Collider Scale and Beyond

A conservative analysis

Assuming $\lambda = g^2 = (0.65)^2$ and $\delta_{\text{CPV}} = 1$,
$|d_e| < 1.1 \times 10^{-29}\ e\ \text{cm}$ translates to

$$d_e \sim e\delta_{\text{CPV}} \left(\frac{\lambda}{16\pi^2}\right)^k \frac{y_e v}{\Lambda^2}$$

$$\Rightarrow \Lambda > \begin{cases} 1000 \text{ TeV} & \text{(0 loop)} \\ 50 \text{ TeV} & \text{(1 loop)} \\ 3 \text{ TeV} & \text{(2 loop)} \end{cases}$$

Limits competitive to colliders, even at 2-loop (more on this later)

LFV bounds = Collider Scale or Beyond

MEG	SINDRUM
BR$(\mu \to e\gamma) < 4.2 \times 10^{-13}$	BR$(\mu \to 3e) < 1.0 \times 10^{-12}$
$\mathcal{O}_{\mu e\gamma} \sim \left(\frac{\lambda}{16\pi^2}\right)^k \frac{ev}{\Lambda^2}$	$\mathcal{O}_{\mu 3e} \sim \left(\frac{\lambda}{16\pi^2}\right)^k \frac{1}{\Lambda^2}$

$$\Lambda > \begin{cases} 3.8 \times 10^4 \text{ TeV} & \text{(0 loop)} \\ 2000 \text{ TeV} & \text{(1 loop)} \\ 100 \text{ TeV} & \text{(2 loop)} \end{cases} \qquad \begin{cases} 273 \text{ TeV} & \text{(0 loop)} \\ 14.1 \text{ TeV} & \text{(1 loop)} \\ 0.73 \text{ TeV} & \text{(2 loop)} \end{cases}$$

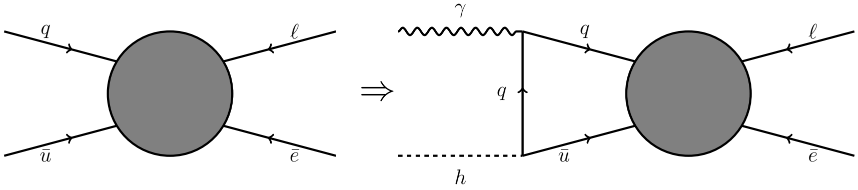
Depending on the flavor structure of the model, constraint will be weaker.

Current bounds = collider scale and beyond

eEDM models: QULE and SUSY

QULE: general

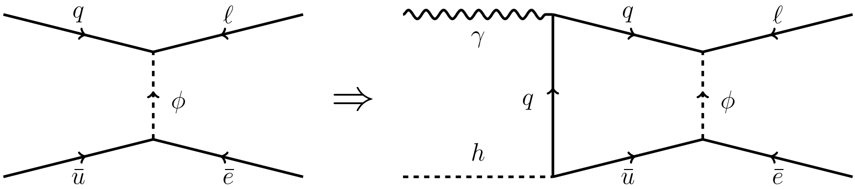
- $\text{QULE} = (\bar{q}\sigma_{\mu\nu}u)(\bar{l}\sigma^{\mu\nu}e)$
- QULE generate eEDM with one additional loop:



k-loop QULE ⇒ (k+1)-loop eEDM

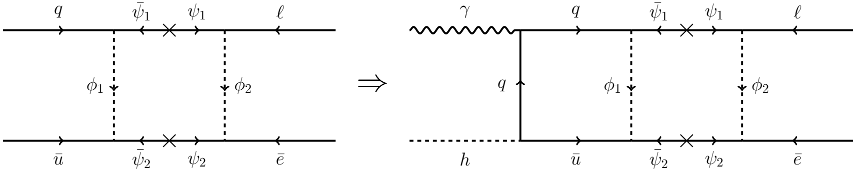
- QULE doesn't require new physics to couple to the Higgs.

QULE at tree-level



- ϕ is leptoquark; either $(3, 2, 7/6)$ or $(3, 1, -1/3)$.
- Nothing is proportional to y_e; need to impose naturalness constraint on overall diagram, which gives $|y_{1t}y_{2t}| < \mathcal{O}(10^{-6})$.
- At max $|y_{1t}y_{2t}|$ allowed by naturalness, $|d_e| < 1.1 \times 10^{-29}\ e\ \mathrm{cm}$ gives $m_\phi > \mathcal{O}(500\ \mathrm{TeV})$ [J. M. Arnold, B. Fornal, and M. B. Wise (2013)]

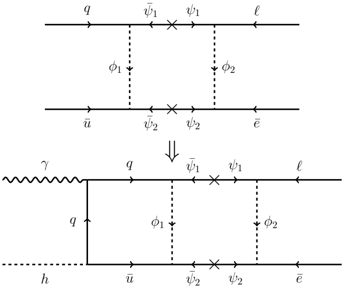
QULE at 1-loop: structure

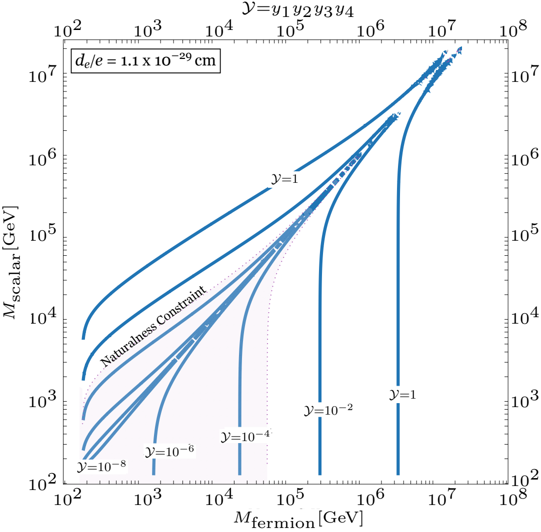


Infinitely many possibilities for the quantum number of $\psi_1, \psi_2, \phi_1, \phi_2$. Some notable scenarios are:

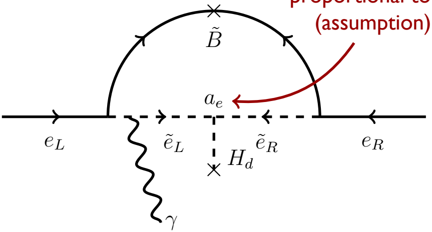
- SUSY: e.g. $\phi_1 = \tilde{u}, \bar{\psi}_1 = \tilde{H}_u, \psi_1 = \tilde{H}_d, \phi_2 = \tilde{e}, \bar{\psi}_2 = \psi_2 = \tilde{B}^0$.
- New physics parities: new particles cascade decay to a neutral, parity-odd particle (can serve as dark matter candidate)
- Leptoquarks: e.g. $\phi_2 = (3, 2)_{7/6}$ that decays to a quark and a lepton

QULE at 1-loop: result

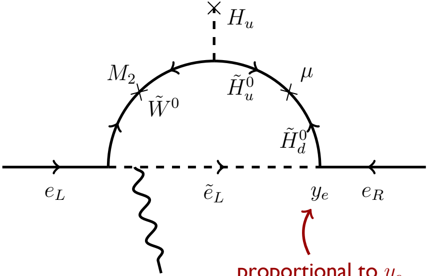




SUSY 1-loop eEDM: structure



proportional to y_e
(assumption)

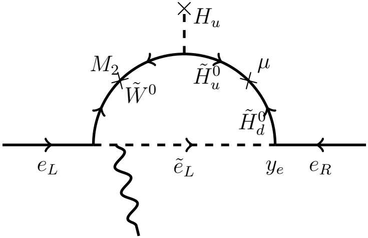


proportional to y_e

(If there are flavor-violating couplings, will generate $\mu \to e\gamma$.)

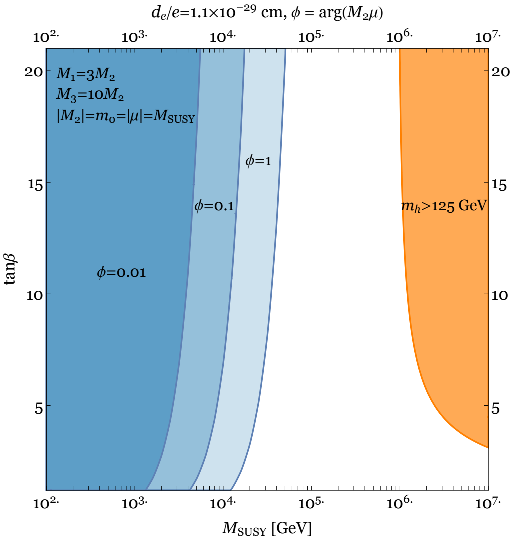
At 1-loop, one of the new particles must have lepton number.

SUSY 1-loop eEDM: results



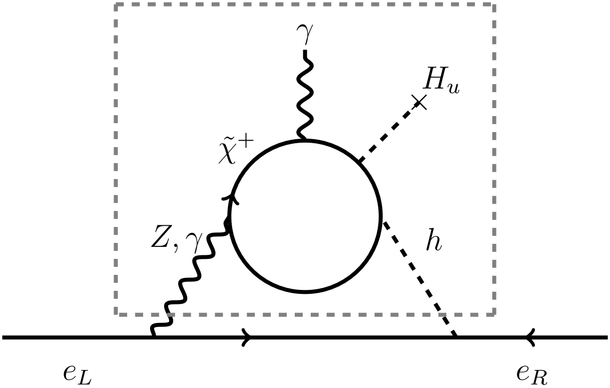
Assumes

$$m_{\text{slepton}} = m_{\text{squark}} = m_0$$



Split SUSY 2-loop eEDM: structure

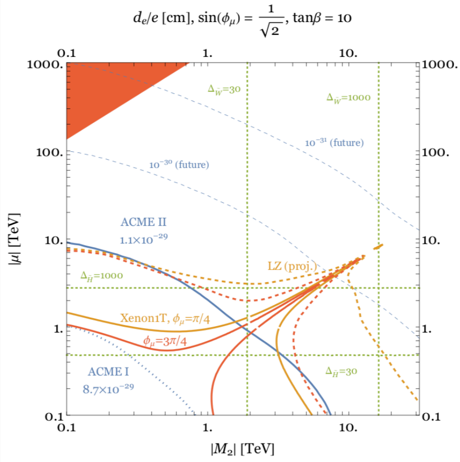
If we decouple squarks, sleptons, and heavy Higgs, dominant eEDM comes from loops of charginos and neutralinos.



Generic new physics with electroweak interaction will generate 2-loop eEDM.

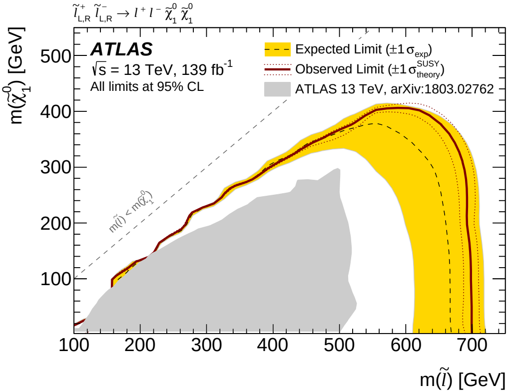
Split SUSY 2-loop eEDM: results

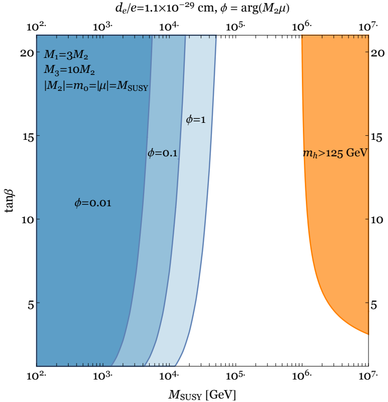
We fix the CPV phase in eEDM: $\phi_\mu \equiv \arg(\mu M_2 b_\mu^*) = \pi/4$, and assume $\arg(M_1) = \arg(M_2)$.



Δ: measure of degree of fine-tuning.

ACME II vs LHC SUSY Search





LHC search in general only depends on particle mass, while eEDM depends on CPV phase.

The case for a high energy muon collider

ongoing work as part of Snowmass 2020

with Sam Homiller and Matthew Reece

High energy reach

A muon collider combines the advantage of an e^+e^- and a pp collider:

- e^+e^-: all of beam energy $\sqrt{s}$ is available for collision.
- pp: loss of energy by synchrotron radiation is small.

Even a 14 TeV muon collider will be an upgrade in the energy reach from the LHC.

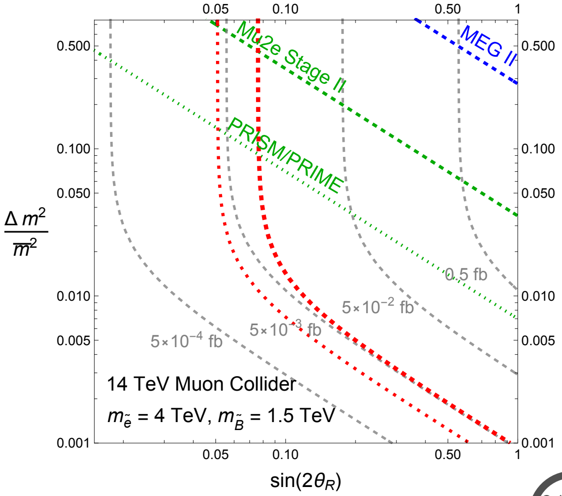
Clean environment helps unravel the physics behind the LFV observables

$\mu^+\mu^- \to \tilde{e}^+_{1,2}\tilde{e}^-_{1,2} \to \mu e \tilde{B}\tilde{B}$ from mass mixing in SUSY sector.

$$\Delta m^2 = m^2_{\tilde{e}_1} - m^2_{\tilde{e}_2}$$

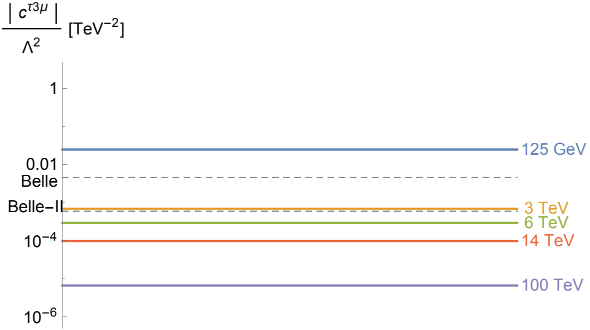
$$\sin(2\theta_R) = \frac{\tilde{m}^2_{e,12}}{m^2_{\tilde{e}_1} - m^2_{\tilde{e}_2}}$$

red curves:
reach at 1 and 5 ab^{-1}



Clean environment produces competitive bounds on effective operators

Constraint on $\frac{c^{\tau 3\mu}}{\Lambda^2}\tau\mu\mu\mu$ from search for $\mu^+\mu^- \to \mu\tau$ and $\tau \to 3\mu$



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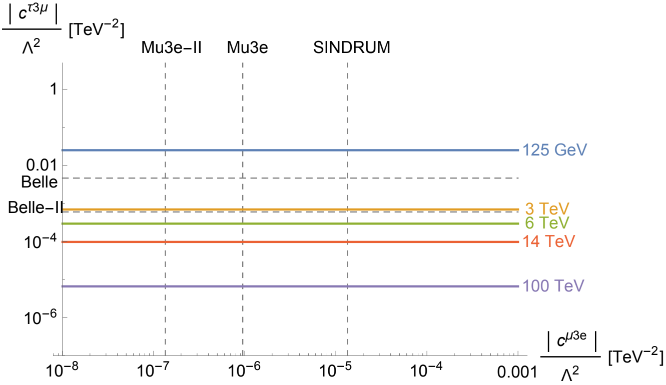
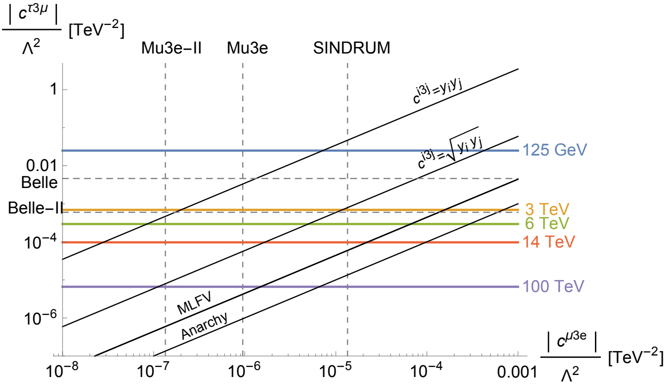


Constraint on $\frac{c^{\mu 3e}}{\Lambda^2}\mu eee$ from search for $\mu \to 3e$

Clean environment produces competitive bounds on effective operators



Given a flavor ansatz, can relate the two constraints.

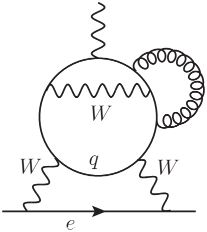
Conclusion

- eEDM and LFV processes are powerful probe of new physics, reaching mass scale of TeV and beyond.
- Sensitivities of these observables are expected to improve by orders of magnitude in the near future.
- A collider is necessary to understand the physics generating the precision observables.
- A muon collider can provide both high energy reach and clean environment that helps elucidate the underlying physics.

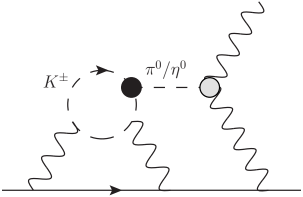
Backup slides

Why eEDM: it is SM background free

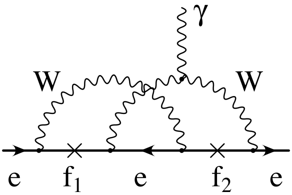
- Quark sector: $|d_e| \sim 10^{-43}\ e\ \mathrm{cm}$, and CPV electron-nucleon interaction faking eEDM: $|d_e| \sim 10^{-38}\ e\ \mathrm{cm}$ [M. Pospelov and A. Ritz (2014)]
- Strong $\bar{\theta}$ angle: $|d_e| \lesssim 10^{-37}\ e\ \mathrm{cm}$ [K. Choi and J.-y. Hong (1991)]
- Lepton sector: expect $d_e \sim 10^{-43}\ e\ \mathrm{cm}$, at most $\sim 10^{-33}\ e\ \mathrm{cm}$ with fine tuning [M. Pospelov et al. (2004)]



[M. Pospelov and A. Ritz (2014)]



[D. Ghosh and R. Sato (2018)]



[M. Pospelov et al. (2004)]

Many new physics models are expected to produce eEDM much larger than these.

Something pretending to be eEDM

- ACME II experiment constrains the linear combination of eEDM and the CP-odd electron-nucleon coupling $-iC_S\bar{e}\gamma^5 e\bar{N}N$:

$$d_{\mathrm{ThO}} \approx d_e + kC_S$$

$$k \approx 1.6 \times 10^{-15}\ \mathrm{GeV}^2\ e\ \mathrm{cm}$$

- Whether the QULE contributes more to C_S or d_e depends on which flavour of quark new physics couples to:

$$\left|\frac{d_{\mathrm{ThO;\ eEDM}}}{d_{\mathrm{ThO;}\ C_S}}\right| \approx \frac{m_q \log(M/m_q)}{\pi^2 \times 1.6 \times 10^{-15}\ \mathrm{GeV}^2\ \mathrm{cm}\ \langle N|\,\bar{q}q\,|N\rangle}$$

$$\approx \begin{cases} 6 \times 10^{-3}, & q = u, \\ 2 \times 10^{2}, & q = c, \\ 2 \times 10^{6}, & q = t, \end{cases} \quad (\text{assuming } M = 10\ \mathrm{TeV})$$

.

C_S constraints

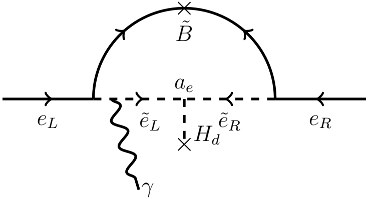
$$C_{qe} \sim \delta_{\text{CPV}} \left(\frac{y^2}{16\pi^2}\right)^k \frac{m_q m_e}{v^2 \Lambda^2}$$

$$\Rightarrow \Lambda > \begin{cases} 300 \text{ GeV} & \text{(0 loop)} \\ 20 \text{ GeV} & \text{(1 loop)} \\ 0.8 \text{ GeV} & \text{(2 loop)} \end{cases} \tag{1}$$

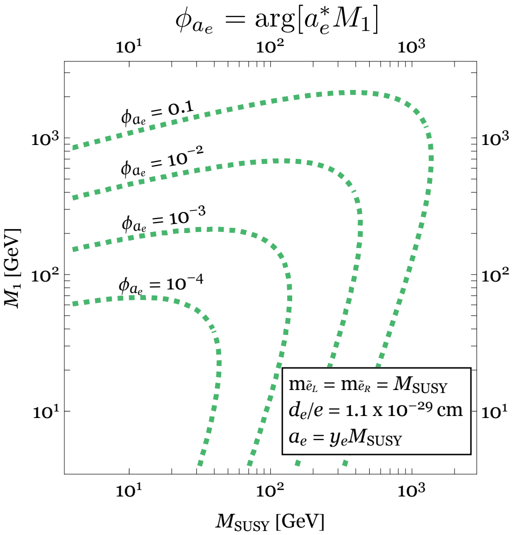
$$C_{qe} \sim \delta_{\text{CPV}} \frac{16\pi^2 m_e}{m_q} \frac{1}{\Lambda^2}$$

$$\Rightarrow \Lambda > \begin{cases} 10^5 \text{ TeV} & \text{(0 loop)} \\ 10^5 \text{ TeV} & \text{(1 loop)} \\ 10^5 \text{ TeV} & \text{(2 loop)} \end{cases} \tag{2}$$

SUSY 1-loop eEDM: results



Contribution from other neutralinos negligible since $M_1 >> v$



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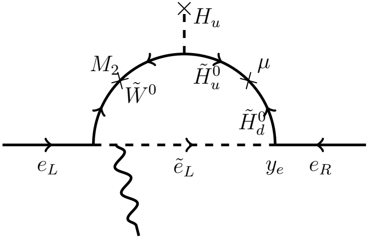

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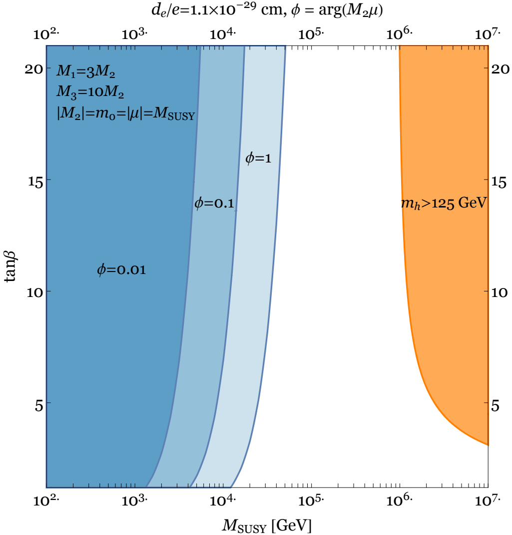

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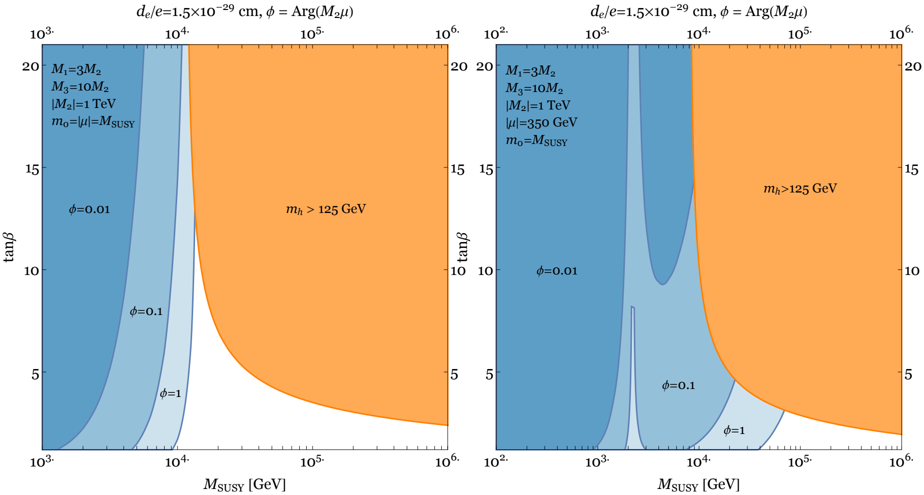
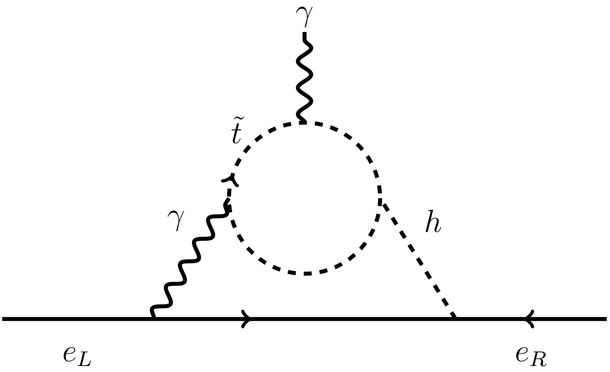


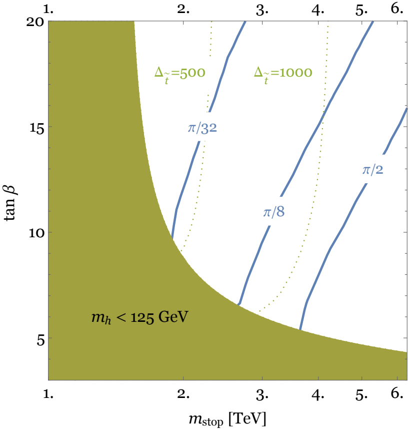
Natural SUSY eEDM: structure

Natural SUSY: only higgsinos, stops, left-handed sbottom and gauginos are light.

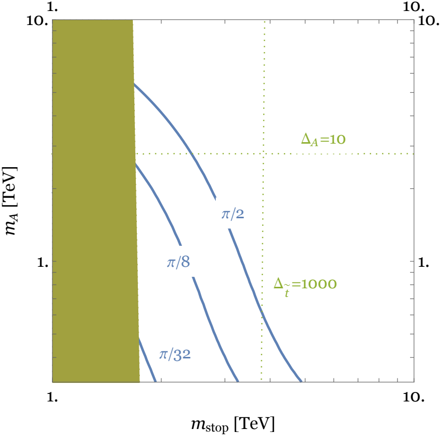


Natural SUSY eEDM: results

Higgs mass is realized by by stop loops with a large A-term.



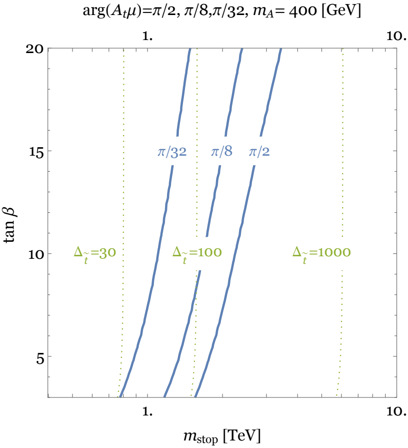
$\arg(A_t\mu)=\pi/2,\ \pi/8, \pi/32, m_A = 400$ [GeV]

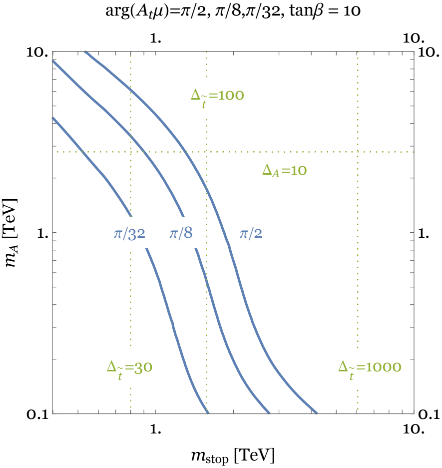


$\arg(A_t\mu)=\pi/2, \pi/8, \pi/32$, $\tan\beta$ = 10

Natural SUSY eEDM: results

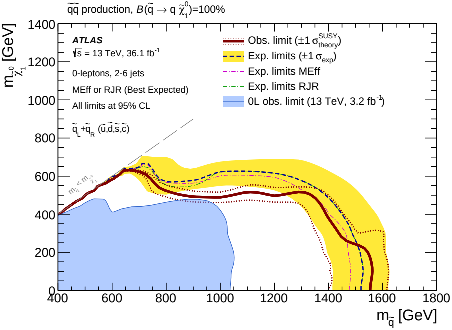
Higgs mass is realized by some other interaction. A-term radiatively generated by gluino with mass = 2 TeV.

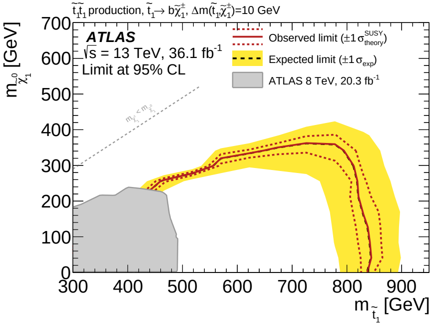




ACME II vs LHC SUSY Search

Squark limits

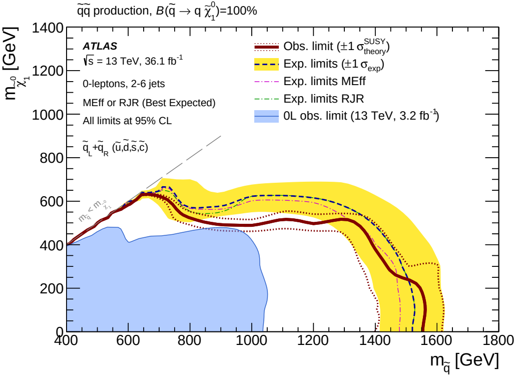


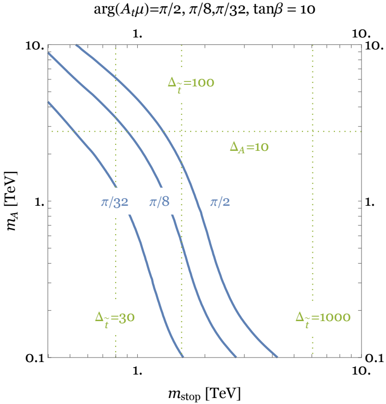


LHC search in general only depends on particle mass, while eEDM depends on CPV phase.

ACME II vs LHC SUSY Search

Squark limits





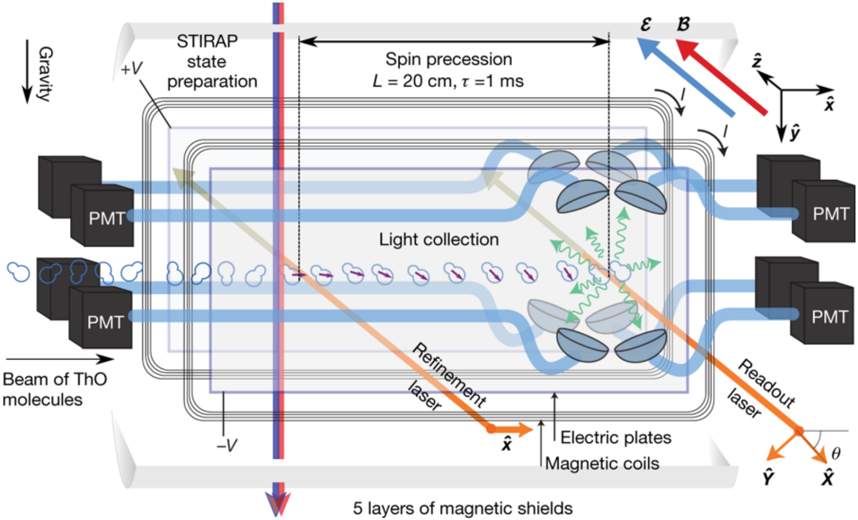
LHC search in general only depends on particle mass, while eEDM depends on CPV phase.

ACME II experiment: but actually how??

Given radius of electron $< 10^{-18}\ \mathrm{m}$, $|d_e| < 1.1 \times 10^{-29}\ e\ \mathrm{cm}$ is equivalent to anisotropy of a strand of hair over the diameter of the Earth.

- ThO molecule: $\sim 100\ \mathrm{GV\ cm^{-1}}$ effective electric field under $\lesssim 100\ \mathrm{V\ cm^{-1}}$ lab field.
- "Binary switches" to reject backgrounds:
  - direction of $\mathcal{E}$, sign of $\tilde{N}$, direction of $\mathcal{B}$... Total of 7 switches in the experiment.
  - d_e is odd under $\mathcal{E}$ direction and $\mathrm{sgn}\tilde{N}$, and even under all other switches; many systematics, e.g. $\mathcal{B}$ from leakage currents, do not share the same parity structure.
- Further investigation of systematics of over 40 experimental parameters.

ACME II experiment: setup



Next generation of ACME?

- Concrete areas of improvement: [ACME collaboration (2018)]
  - order of magnitude increase in detection efficiency by optical cycling
  - order of magnitude increase in number of molecules by electric or magnetic focusing of ThO beam
  - dominant systematic errors in ACME II can be supressed with improved magnetic-field control and reduced polarization gradients in the laser beams.
- Future generations might involve molecules with longer coherence time (maintaining a uniform $\mathcal{E}$ and $\mathcal{B}$ fields would be more challenging)