CP Violation in Pseudo-Dirac Fermion Oscillations

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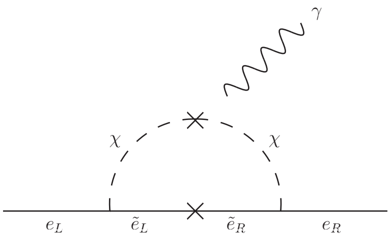
work with David McKeen, and Ann Nelson

We need more CP violation

- **CP violation in the SM**
  Only source: The CP violating phase in the quark mixing matrix (CKM matrix).
- **Do we need more CP violation?**
  Yes. SM CP violation is too small to explain the asymmetry of 10^{-8} between quarks and anti-quarks in the early universe (*baryogenesis*)
- **New physics?**
  Definitely. But CP violation is constrained by (lack of) electric dipole moments.

SUSY CP Problem + One solution

- **Problem**: EDMs are induced at one-loop level



$\Rightarrow$ No EDM yet means very small CP violating terms

SUSY CP Problem + One solution

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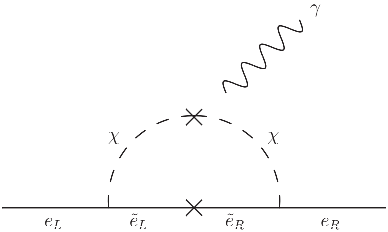

⇒ No EDM yet means very small CP violating terms

- **Solution:** R-symmetric SUSY

Hall, Randall, Nuc.Phys.B-352.2 1991
Kribs, Poppitz, Weiner, PRD 78 2007

sfermions, gauginos: $U(1)_{\mathrm{R}}$ charge $+1$

⇒ – Left-right sfermion mixing is forbidden

– Majorana masses are forbidden for gauginos

Dirac Fermions in R-symmetric SUSY

- Dirac masses for gauginos $\rightarrow$ new chiral adjoints
  e.g. $\lambda \equiv (8,1,0)_{+1}$: gluino
  $\mathcal{O} \equiv (8,1,0)_{-1}$: Dirac partner of gluino
- λ and $\mathcal{O}$ are (Weyl) components of a Dirac gluino:

$$\Psi_D = \begin{pmatrix} \lambda \\ i\sigma_2\mathcal{O}^* \end{pmatrix}$$

with conserved R-charge, and Dirac mass:

$$-\mathcal{L}_{\mathrm{mass}} = m_D \lambda \mathcal{O} + m_D^* \lambda^\dagger \mathcal{O}^\dagger$$

Pseudo-Dirac Fermions

- $U(1)_{\mathrm{R}}$ is always broken by supergravity!
- Approximate $U(1)_{\mathrm{R}} \rightarrow$ Majorana masses for λ and $\mathcal{O}$:

$$-\delta\mathcal{L}_{\mathrm{mass}} = \frac{1}{2}\left(m_{\lambda}\lambda\lambda + m_{\mathcal{O}}\mathcal{O}\mathcal{O}\right) + \mathrm{h.c.}$$

$\Psi \rightarrow$ pseudo-Dirac fermion

- Mass Hamiltonian:

$$\mathcal{H}_{mass} = \begin{pmatrix} m_D & \frac{1}{2}(m_{\lambda}^{*} + m_{\mathcal{O}}) \\ \frac{1}{2}(m_{\lambda} + m_{\mathcal{O}}^{*}) & m_D \end{pmatrix}$$

with eigenvalues $M_{1,2} = m_D \pm \frac{1}{2}\left|m_{\lambda} + m_{\mathcal{O}}^{*}\right|$

Pseudo-Dirac Fermion Oscillations

Thomas, Sarid, PRL 85 (2000)
Grossman, Shakya, Tsai, PRD 88 (2013)

- Mass eigenstates $\neq$ interaction eigenstates!
  $\Longrightarrow$ Oscillations!
- Pseudo-Dirac fermion has 4 states:
  $(R^+, \uparrow), (R^+, \downarrow), (R^-, \uparrow), (R^-, \downarrow)$
- Oscillations mix only 2×2 blocks:
  - $(R^+, \uparrow)$ can oscillate into $(R^-, \uparrow)$
  - $(R^+, \downarrow)$ can oscillate into $(R^-, \downarrow)$

CP violation in Pseudo-Dirac Fermion Oscillations

Ipek, McKeen, Nelson (in preparation)

- R-violating interactions $\rightarrow$ gluino decay:

$$g\lambda q d^c \ell + g' \mathcal{O} q d^c \ell + \mathrm{h.c.}$$

where q=quark doublet, ℓ=lepton doublet, d^c=anti-quark singlet

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- $\mathcal{H}_{mass}$ + interactions $\Rightarrow$ effective Hamiltonian:

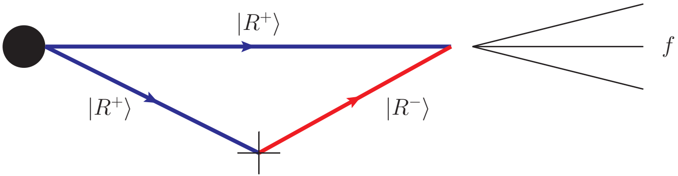
$$\mathcal{H}_{eff} = \mathbf{M} - \frac{i}{2}\mathbf{\Gamma} = \begin{pmatrix} m_D - i\Gamma/2 & m_{12} - i\Gamma_{12}/2 \\ m_{12}^* - i\Gamma_{12}^*/2 & m_D - i\Gamma/2 \end{pmatrix}$$

$m_{12} = \frac{m_\lambda^* + m_\mathcal{O}}{2} = 2\Delta m \rightarrow$ oscillation frequency.

- If $\Delta m \sim \Gamma \Rightarrow$ observe oscillations before decay.

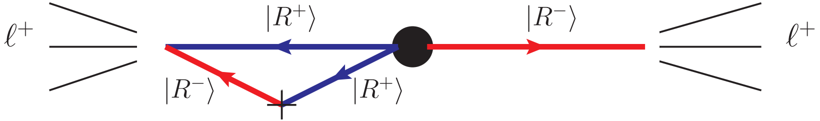
How do we get CP violation from oscillations?

- CP violation needs a relative phase between $\mathbf{M}$ and $\mathbf{\Gamma}$.
- Two ways to get CP violation:
  1. CP violation in mixing
  2. CP violation in interference between decays without mixing and with mixing:



Example: Same Sign Dilepton Asymmetry

- Remember interactions: $g\lambda q d^c \ell + g' \mathcal{O} q d^c \ell + \text{h.c.}$
- Produce equal numbers of R^+ and R^- states,
  Look for final states with same sign dileptons



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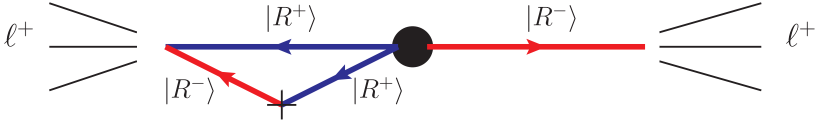

- If there is CP violation:

$$\frac{N^{++}-N^{--}}{N^{++}+N^{--}} = \frac{4\Delta m \Gamma^3 \Im(g^* g')(|g|^2 - |g'|^2)}{4\Gamma^4 |g|^2 |g'|^2 + \Delta m^4 (|g|^2 + |g'|^2)^2 + 2\Gamma^2 \Delta m^2 \left[(|g|^2 + |g'|^2)^2 - 2(\Im(g^* g'))^2\right]}$$

$\Rightarrow$ Asymmetry when $\Im(g^* g') \neq 0$ and $|g| \neq |g'|$

N^{++}: number of events with two ℓ^+s

Summary

- Pseudo-Dirac fermions are a feature of SUSY models with approximate $U(1)_{\mathrm{R}}$ symmetry
- Two oppositely charged states of the pseudo-Dirac fermion can oscillate into each other
- If the Dirac partners can decay into the same final state $\rightarrow$ CP violation in oscillations
- Can have $\mathcal{O}(1)$ CP violating effect if oscillation and decay rates are comparable
- Can give same sign dilepton asymmetry.

THANK YOU!