CP Violation in Pseudo-Dirac Fermion Oscillations
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Seyda Ipek
University of Washington
ipek@uw.edu

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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.
Problem: EDMs are induced at one-loop level

⇒ No EDM yet means very small CP violating terms

SUSY CP Problem + One solution
**Problem:** EDMs are induced at one-loop level

\[ e_L e_R \bar{e}_L \bar{e}_R \gamma \Rightarrow \text{No EDM yet means very small CP violating terms} \]

**Solution:** R-symmetric SUSY

- sfermions, gauginos: \( U(1)_R \) charge +1
  - Left-right sfermion mixing is forbidden
  - Majorana masses are forbidden for gauginos

Kribs, Poppitz, Weiner, PRD 78 2007
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
- $\lambda$ 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:
  \[-\mathcal{L}_{\text{mass}} = m_D \lambda \mathcal{O} + m_D^* \lambda^\dagger \mathcal{O}^\dagger\]
Pseudo-Dirac Fermions

- $U(1)_R$ is always broken by supergravity!
- Approximate $U(1)_R \rightarrow$ Majorana masses for $\lambda$ and $\mathcal{O}$:
  \[-\delta \mathcal{L}_{\text{mass}} = \frac{1}{2} (m_\lambda \lambda \lambda + m_\mathcal{O} \mathcal{O} \mathcal{O}) + \text{h.c.}\]
  
  $\Psi \rightarrow$ pseudo-Dirac fermion
- Mass Hamiltonian:
  \[\mathcal{H}_{\text{mass}} = \begin{pmatrix} m_D & \frac{1}{2}(m_\lambda^* + m_\mathcal{O}) \\ \frac{1}{2}(m_\lambda + m_\mathcal{O}^*) & m_D \end{pmatrix}\]

  with eigenvalues $M_{1,2} = m_D \pm \frac{1}{2} |m_\lambda + m_\mathcal{O}^*|$
Mass eigenstates $\neq$ interaction eigenstates!  
$\implies$ Oscillations!

Pseudo-Dirac fermion has 4 states: 
$$(R^+, \uparrow), (R^+, \downarrow), (R^-, \uparrow), (R^-, \downarrow)$$

Oscillations mix only $2 \times 2$ 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:

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

where $q$=quark doublet, $\ell$=lepton doublet, $d^c$=anti-quark singlet

If $\Delta m \sim \Gamma$ $\Rightarrow$ observe oscillations before decay.
CP violation in Pseudo-Dirac Fermion Oscillations

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

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- $H_{mass} + \text{interactions} \Rightarrow \text{effective Hamiltonian:}$

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

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

- If $\Delta m \sim \Gamma \Rightarrow \text{observe oscillations before decay.}$
How do we get CP violation from oscillations?

- CP violation needs a relative phase between $M$ and $\Gamma$.

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

\[
\begin{align*}
\ell^+ & \quad |R^+\rangle & \quad |R^-\rangle \\
\ell^- & \quad |R^-\rangle & \quad |R^+\rangle \\
\end{align*}
\]
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

\[
\begin{array}{c}
\ell^+ \\
\vdots \\
|R^-\rangle \\
+ \\
|R^+\rangle \\
\vdots \\
\ell^+ \\
\end{array}
\]

- If there is CP violation:

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

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

$N^{++}$: number of events with two $\ell^+$s
Summary

- Pseudo-Dirac fermions are a feature of SUSY models with approximate $U(1)_R$ 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 → CP violation in oscillations.
- Can have $O(1)$ CP violating effect if oscillation and decay rates are comparable.
- Can give same sign dilepton asymmetry.
THANK YOU!