PSEUDO-GOLDSTINI IN GAUGE MEDIATION

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Based on:

Phys. Rev. Lett. **107** (2011) 061601
with Riccardo Argurio and Zohar Komargodski

arXiv: 1112.5058
with Riccardo Argurio, Karen De Causmaecker, Gabriele Ferretti, Kentarou Mawatari, Yoshitaro Takaesu

Plan of the talk

- Introduction
  - Supersymmetry breaking and its mediation
  - Goldstino and its interactions
- Multiple hidden sectors and Pseudo-Goldstino
- Pseudo-Goldstino in Gauge Mediation
  - Pseudo-Goldstino mass
  - Simplified model for Pseudo-Goldstino phenomenology
  - Collider Signatures
- Conclusions and open problems

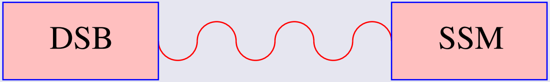
SUPERSYMMETRY AND THE STANDARD MODEL

- SSM candidate for BSM physics (Hierarchy problem, GUT unification, . . .)
- No LHC data up to now, but we are optimistic
- Light colored superpartners strongly disfavoured
- Conventional models of gauge mediation ($\gamma + \not{E}_T$) strongly contrained
- ? Heavy Higgs ?
- New scenarios should be invoked . . .

SUSY BREAKING AND THE SSM

- Supersymmetry must be broken softly around the weak scale !!!
- Soft susy breaking $\equiv$ No quadratic divergencies
- Soft terms include masses for unobserved sparticles (λ, ϕ)

STANDARD PARADIGM: MEDIATION OF SUSY BREAKING



- Hidden sector with spontaneous (dynamical) susy breaking (scale $\Lambda_{susy} \equiv \sqrt{F}$)
- Visible sector SSM with gauge group G_{SM}
- Interactions lead to soft terms in the SSM, e.g. mass m_{soft} to sparticles

GAUGE VS GRAVITY MEDIATION

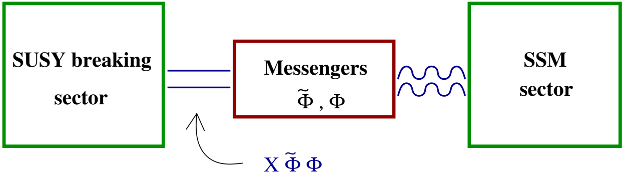
GRAVITY MEDIATION

- Soft terms as Planck suppressed operators
- $m_{soft} \sim \frac{\Lambda_{susy}^2}{M_{Pl}}$
- $\Lambda_{susy} \sim 10^{10-11} GeV$
- Harder to make predictions, FCNC issues

GAUGE MEDIATION

- Typically messengers field charged under G_{SM} and with mass M
- Soft terms via loops of SM gauge fields and messenger fields
- $\Rightarrow m_{soft} \sim \frac{g^2}{16\pi^2} \frac{\Lambda_{susy}^2}{M}$
- (Generically M is a supersymmetric scale s.t.: $\Lambda_{weak} \ll M \ll M_{Pl}$)
- Typically $10^4 GeV < \Lambda_{susy} < 10^9 GeV$
- Calculable model, Flavour blind, μ/B_μ problem, ...

MINIMAL GAUGE MEDIATION



- Supersymmetry breaking parametrized as $< X >= M + \theta^2 F_x$
- Introduce Messengers Φ and $\tilde{\Phi}$ in 5 and $\bar{5}$ of $SU(5)_{MSSM}$ with

$$\Delta\mathcal{L}_{\text{mess}} = \int d^2\theta \, X \, \Phi\tilde{\Phi} \qquad < X >= M + \theta^2 F_x$$

- Susy breaking transmitted through loops of gauge and messengers fields
- Loops generate soft susy breaking terms in the visible sector

$$m_\lambda \sim m_{scalars} \sim \frac{g^2}{16\pi^2}\frac{F_x}{M}$$

- Balanced sparticle spectrum
- MGM is a “toy” model for gauge mediation

Dynamical supersymmetry breaking

- How to generate naturally hierarchy between Λ_{susy} and M_{Pl} ?
- $\Rightarrow$ New gauge group G_h in hidden sector drive susy breaking with strong dynamics effects (typically non perturbative ones)
- Lead to hierarchy between Λ_{susy} and Λ_{UV}

$$\Lambda_{susy} \simeq \Lambda_{UV}\, e^{-\frac{8\pi^2}{b_0 g_h^2(\Lambda_{UV})}}$$

- $\Rightarrow$ Hidden sectors with DSB are intrinsecally strongly coupled !

?? Can we provide a formalism to include all these scenarios ??

General Gauge Mediation P. Meade, N. Seiberg and D. Shih: arXiv:0801.3278

- Parametrize susy breaking sector in a model independent way
- Gauge mediation definition

$$\lim g_v \to 0 \qquad \text{No susy breaking in visible sector}$$

- Complete Lagrangian, perturbative in g_v

$$\mathcal{L} = \mathcal{L}_{MSSM} + 2g_v \int d^4\theta V_{MSSM} \mathcal{J}^{SUSYBR}$$

where

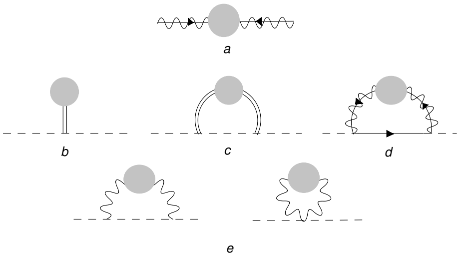
$$2g_v \int d^4\theta V_{MSSM} \mathcal{J}^{SUSYBR} = g_v(J^{SB} D - \lambda j^{SB} - \bar{\lambda}\bar{j}^{SB} - j^{SB}_\mu A^\mu)$$

- $\mathcal{J}^{SUSYBR}$ susycurrent of the susy breaking sector with respect to G_{SM}
- Supersymmetry breaking encoded in two point functions of current

$$\begin{aligned}
\langle J^{SB}(p) J^{SB}(-p)\rangle &= C_0^{SB}(p^2/M^2) , \\
\langle j^{SB}_\alpha(p) \bar{j}^{SB}_{\dot\alpha}(-p)\rangle &= -p_\mu \sigma^\mu_{\alpha\dot\alpha} C^{SB}_{1/2}(p^2/M^2) , \\
\langle j^{SB}_\alpha(p) j^{SB}_\beta(-p)\rangle &= \epsilon_{\alpha\beta} M B^{SB}_{1/2}(p^2/M^2) , \\
\langle j^{SB}_\mu(p) j^{SB}_\nu(-p)\rangle &= (p_\mu p_\nu - p^2 \eta_{\mu\nu}) C^{SB}_1(p^2/M^2) ,
\end{aligned}$$

- M set the susy breaking scale

Soft masses in GGM



- Soft masses

$$m_\lambda = g_v^2 \, M \, B_{1/2}^{SB}(0)$$

$$m_{sf}^2 = -g_v^4 \int \frac{d^4p}{(2\pi)^4 p^2} \left(C_0^{SB}(p^2/M^2) - 4C_{1/2}^{SB}(p^2/M^2) + 3C_1^{SB}(p^2/M^2) \right)$$

- Susy limit

$$B_{1/2}^{SB}(0) = 0, \qquad C_0^{SB} - 4C_{1/2}^{SB} + 3C_1^{SB} = 0$$

- Sum rules for sfermion masses

GOLDSTINO

- What do we know about hidden sector?
- Spontaneous susy breaking $\Rightarrow$ Massless fermion Goldstino
- Eaten via superHiggs mechanism: $m_{3/2} \sim \frac{F}{M_{Pl}}$

GAUGE MEDIATION

$m_{3/2} \ll m_{soft}$

GRAVITY MEDIATION

$m_{3/2} \simeq m_{soft}$

- Typically in gauge mediation $m_{3/2} \sim eV$ (e.g. $\Lambda_{susy} \sim 10^4 - 10^5 GeV$)
- Very light gravitino is like Goldstino in high energy processes
- Interactions with SSM are fixed by supersymmetry

GOLDSTINO COUPLINGS

- Goldstino can be described as constrained superfield Komargodski, Seiberg '10

$$X_{NL}^2 = 0 \qquad \Rightarrow \qquad X_{NL} = \frac{G^2}{2F} + \sqrt{2}\theta G + \theta^2 F$$

- Reproduces Volkov-Akulov lagrangian
- The couplings to the SSM reads

$$\mathcal{L} \supset \int d^2\theta \frac{m_\lambda}{2f} X_{NL} \mathcal{W}^2 = \frac{1}{2} m_\lambda \lambda^2 + \frac{i m_\lambda}{\sqrt{2} f}\left(G\lambda D - \frac{i}{2}\lambda\sigma^\mu\bar{\sigma}^\nu G F_{\mu\nu}\right) + \dots$$

$$\mathcal{L} \supset \int d^4\theta \frac{m_\phi^2}{f^2} X_{NL}^\dagger X_{NL} Q^\dagger Q = m_\phi^2 q^\dagger q + \frac{m_\phi^2}{f}\left(G\psi q^\dagger + \bar{G}\bar{\psi} q\right) + \dots$$

- Encodes both soft terms and Goldstino couplings

Multiple susy breaking sectors

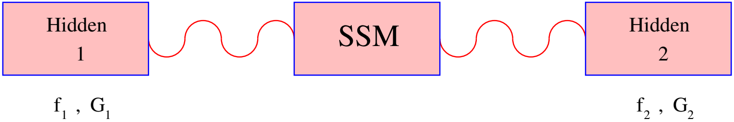
?? What happens if there is more than one susy breaking sector ??

- Suppose to have two susy breaking sectors completely decoupled except for their interaction with the SSM
- What are the pheno consequences?

Every sector has its own Goldstino, but ...

- True Goldstino is massless in the rigid limit and is eaten by the gravitino in supergravity
- Others are extra fermionic particles (Pseudo-Goldstini) Benakli, Moura '07

Two susy breaking sectors



$$G = \frac{1}{f}(f_1 G_1 + f_2 G_2) \qquad \text{True-Goldstino} \qquad m_G = m_{3/2}$$

$$G' = \frac{1}{f}(-f_2 G_1 + f_1 G_2) \qquad \text{Pseudo-Goldstino} \qquad m_{G'} = ???$$

where $f = \sqrt{f_1^2 + f_2^2}$

Observe: soft terms are induced by both sectors, e.g. $m_\lambda = m_\lambda^{(1)} + m_\lambda^{(2)}$

PSEUDO-GOLDSTINO MASS

GRAVITY MEDIATION

CHEUNG, NOMURA, THALER '10

- $m_{G'} = 2m_{3/2} \quad \sim \quad m_{soft}$

??? GAUGE MEDIATION ???

R.ARGURIO, Z.KOMARGODSKI, A.M. '11

- Contribution from gravity are negligible ($m_{3/2} \ll m_{soft}$)
- PseudoGoldstino can get mass from radiative corrections
- Radiative corrections will be the dominant contribution
- Can we give a universal estimate ?

COMPUTATION OF $m_{G'}$

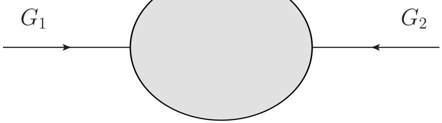
- Lagrangian mass term $-\frac{1}{2}G_i\mathcal{M}^{ij}G_j$
- Mass matrix for the Goldstini (one zero eigenvalue)

$$\mathcal{L} \supset \begin{pmatrix} G_1 & G_2 \end{pmatrix} \begin{pmatrix} -(f_2/f_1)\mathcal{M}_{12} & \mathcal{M}_{12} \\ \mathcal{M}_{12} & -(f_1/f_2)\mathcal{M}_{12} \end{pmatrix} \begin{pmatrix} G_1 \\ G_2 \end{pmatrix}$$

- Pseudo Goldstino mass determined by $\mathcal{M}_{12}$

$$m_{G'} = (\frac{f_1}{f_2} + \frac{f_2}{f_1})\mathcal{M}_{12}$$

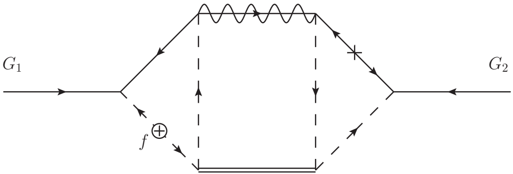
- We have to compute



TOY MODEL: TWO MINIMAL GAUGE MEDIATION

$$W = \int d^2\theta \sum_{i=1}^{2} (\lambda_i X_i + M_i)\Phi_i \tilde{\Phi}_i \quad , \qquad X_i \sim \theta G_i + \theta^2 f_i$$

- Leading contribution at 3 loops



- Two different effective vertices
  - $G\lambda D$
  - $F^\dagger G \partial \bar{\lambda} D$
- Only first vertex is captured in the low energy lagrangian

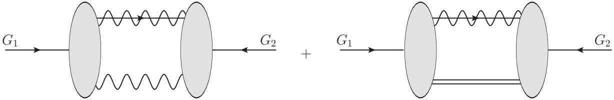
?? Can we provide a model independent answer in gauge mediation ??

Pseudo-Goldstino mass

- Lagrangian for the two susy breaking sector case

$$\mathcal{L}(G_1, G_2, B_{1/2}^{(1,2)}, C_i^{(1,2)}) = \mathcal{L}_{GGM}^{(1)} + \mathcal{L}_{GGM}^{(2)} + \mathcal{L}_{Gold}^{(1)} + \mathcal{L}_{Gold}^{(2)} + \dots$$

- $\mathcal{L}_{Gold}$: interactions of the Goldstini with SM fields
- We have the vertices to compute $\mathcal{M}_{12} \Rightarrow m_{G'}$
- Leading contribution at order g^4



⇒ Pseudo-Goldstino mass

$$m_{G'} = \frac{g^4}{2}\left(\frac{1}{f_1^2} + \frac{1}{f_2^2}\right) \int \frac{d^4p}{(2\pi)^4} B_{1/2}^{(1)} \left(C_0^{(2)} - 4C_{1/2}^{(2)} + 3C_1^{(2)}\right) + 1 \leftrightarrow 2$$

- We can check that True Goldstino remains massless
- We can check the expression in toy model (two copies of MGM)

Pseudo-Goldstino mass: comments

- Estimate $m_{G'}$, assuming same susy scale M in the two sectors

$$m_{G'} \simeq \frac{g^4}{(16\pi^2)^3}\left(\frac{f_1}{f_2}+\frac{f_2}{f_1}\right)\left(\frac{f_1}{M}+\frac{f_2}{M}\right)$$

- For $f_1 \sim f_2 \sim f$ and typical gauge mediation scenario

$$m_{G'} \simeq \frac{g^4}{(16\pi^2)^3}\frac{f}{M} \simeq \frac{g^2}{(16\pi^2)^2} m_{soft} \simeq 1GeV$$

- $m_{G'}$ is enhanced if susy breaking scales are different

$$f_1 \gg f_2 \qquad \Rightarrow \qquad m_{G'} \simeq \frac{g^2}{(16\pi^2)^2} m_{soft}\left(\frac{f_1}{f_2}\right) \simeq 100GeV$$

- But we cannot unbalance too much the two sector scales

!!! Typical mass scale of Pseudo Goldstino in gauge mediation is GeV !!!

Pseudo-Goldstino in gauge med: summary

- More hidden sectors with susy breaking
- $\Rightarrow$ New fermionic light particle: Pseudo-Goldstino
- Probe of the hidden sector

- We extracted its SSM couplings in Gauge mediation
- We computed its mass
- Pseudo Goldstino mass

$$m_{G'} \simeq 1GeV - 100GeV$$

- Our computation dominates over gravity as long as $\sqrt{f} \leq 10^9 GeV$

Phenomenology of G' in colliders

- Typically Pseudo Goldstino G' is the NLSP
- LSP is the gravitino
- G' decays to G Cheng Huang Low Menon '10
- e.g. for $f_1 \gg f_2$

$$\Gamma_{G' \to G} \sim \frac{m_{G'}^9}{f_{eff}^4} \left(\frac{f_2}{f_1} \right)^2$$

- Lifetime of G': from few seconds to cosmologically time scale

$\Rightarrow$ We consider G' stable for collider physics

- Build Simplified model for SSM, Goldstino and Pseudo-Goldstino
- Phenomenology mainly characterized by LSP, NLSP and LOSP

SIMPLIFIED MODEL FOR G AND G' AND LOSP NEUTRALINO χ

$$\begin{aligned}\mathcal{L}_{simp} &= \mathcal{L}_{MSSM} + \mathcal{L}_{kin}(G) + \mathcal{L}_{kin}(G') + a_\gamma \frac{m_\chi}{F} G\chi F_{\mu\nu} + \\ &+ a_\gamma K_\gamma \frac{m_\chi}{F} G'\chi F_{\mu\nu} + m_{G'} G'G' + \dots\end{aligned}$$

where $a_\gamma = N_{11}^* \cos\theta_W + N_{12}^* \sin\theta_W$
and $m_\chi = m_\chi^{(1)} + m_\chi^{(2)}$

- $\dots$ coupling to scalars and to Z boson
- $m_{G'}$ generated at loop level, we estimated $m_{G'} \sim 100 GeV$
- K_γ parameter

$$K_\gamma \simeq -\frac{m_\chi^{(1)}}{m_\chi}\frac{f_2}{f_1} + \frac{m_\chi^{(2)}}{m_\chi}\frac{f_1}{f_2}$$

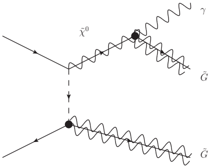
- we can take $0 < K_\gamma < 10^3$
- $\Rightarrow$ K_γ determines the branching ratio of the Neutralino decay

χ DECAY IN STANDARD SINGLE SECTOR CASE

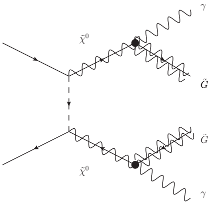
- SUSY decay chain will terminate in production of χ
- χ can decay only to $G + \gamma$ or (suppressed) $G + Z$

$$\Gamma(\chi \to \gamma G) \simeq \frac{a_\gamma^2}{16\pi} \frac{m_\chi^5}{F^2}$$

- If χ prompt decay the signal can be



$\gamma + \not{E}_T(GG)$



$\gamma + \gamma + \not{E}_T(GG)$

- First process gives a lower bound on $m_{3/2} = \frac{F}{\sqrt{3}M_{Planck}}$
- Second process cross section is independent of $m_{3/2}$

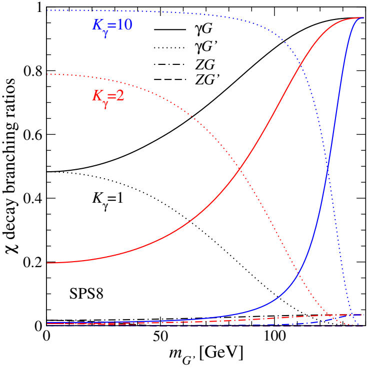
χ DECAY IN THE TWO SECTOR CASE

- Here χ can decay both to G and to G'
- Branching ratios determine the signatures we can expect

- Solid lines: decay to true Goldstino and γ
- Dotted lines: decay to Pseudo-goldstino and γ
- Decay to Z boson negligible

$$\Gamma(\chi \to \gamma G) \simeq \frac{a_\gamma^2}{16\pi}\frac{m_\chi^5}{F^2}$$

$$\Gamma(\chi \to \gamma G') \simeq \frac{K_\gamma^2 a_\gamma^2}{16\pi}\frac{m_\chi^5}{F^2}\left(1-\frac{m_{G'}^2}{m_\chi^2}\right)^3$$



Warm up: Two γ signal at e^+e^- collider

$$e^+e^- \to \chi_0\chi_0 \to (G' \text{ or } G)\gamma\ (G' \text{ or } G)\gamma$$

- Total cross section is $O(100)$ fb for $\sqrt{s} = 500$ GeV and $m_\chi = 140$ GeV
- σ not enhanced by G' couplings
- $\sigma \sim$ (Pair production of two χ) $\times$ (Branching ratios)^2
- E.g.: production of two G'

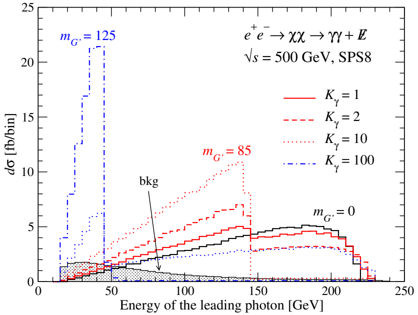
$$\sigma_{G'G'\gamma\gamma} =_{nwa} \sigma_{\chi_0\chi_0}(\frac{\Gamma_{\chi_0\to G'\gamma}}{\Gamma_{\chi_0}})^2$$

- if $K_\gamma \gg 1$ then $\sigma_{G'G'\gamma\gamma} \simeq \sigma_{\chi_0\chi_0}$
- Final products (G or G') depend on branching ratios
- Signal always $2\gamma + \not{E}_T$
- $\not{E}_T$ can be carried by a massless G or a massive G' particle
- $\Rightarrow$ Interesting and structured shapes in $\not{E}_T$ and E of the photons

TWO γ SIGNAL AT e^+e^- COLLIDER

$$e^+e^- \to \chi_0\chi_0 \to (G' \text{ or } G)\gamma\ (G' \text{ or } G)\gamma$$

- Most energetic photon E_γ



- Photon are softer for heavy G' with enhanced K_γ couplings
- Edges of energy distribution determine both χ and G' masses

$$E_\gamma^{\max,\min} = \frac{\sqrt{s}}{4}\left(1 - \frac{m_{G'}^2}{m_\chi^2}\right)\left(1 \pm \sqrt{1 - \frac{4m_\chi^2}{s}}\right)$$

PRODUCTION OF PSEUDO-GOLDSTINI IN *pp* COLLISIONS

- At parton level same process that in e^+e^- collisions
- Consider heavy colored superpartners

- $\gamma\gamma + MET$ signal given by Neutralino pair production

$$pp \to \chi_0\chi_0 \to (G' \text{ or } G)\gamma \ (G' \text{ or } G)\gamma$$

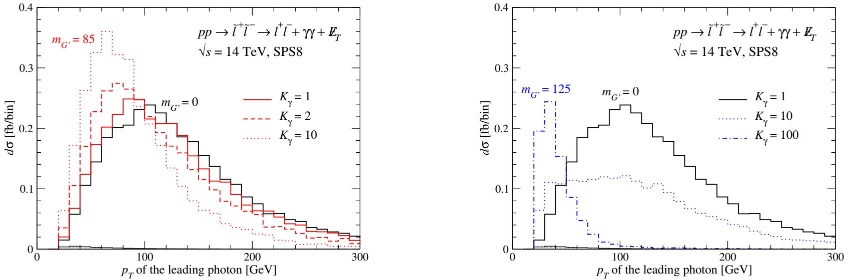
- Cross section is too small compared to the BKG

- Clean signal is with leptons $l^+l^- + \gamma\gamma + MET$
- Sleptons pair production

$$pp \to \tilde{l}^+_{R/L}\tilde{l}^-_{R/L} \to l^+l^- + \gamma\gamma + \not{E}_T \qquad l = e, \mu$$

- Cross section is small ($O(10)$fb at 14TeV) but SM BKG is negligible
- We applied standard cuts on lepton and photon p_T and pseudorapidity

MADGRAPH SIMULATIONS FOR pp COLLISIONS



- Profiles are less clear than in e^+e^- collision, however

GENERICALLY WITH MORE SUSY BREAKING SECTOR:

- More structured γ spectrum with respect to the single sector (only G)
- Photons are softer (for heavy G')
- Harder to detect !!!

Conclusions

- Supersymmetry is a promising and rich framework for BSM physics
- Simple hypothesis can lead to unconventional signatures

- Model with more hidden sectors in gauge mediation are interesting
- $\Rightarrow$ Effectively more light fermionic particles G' in the spectrum
- G' is probe of hidden sectors
- G' mass around GeV generically in gauge mediation
- $\Rightarrow G'$ natural candidate for NLSP in gauge mediated models
- Characteristic collider phenomenology
  - New shape in $\not{E}_T$ because invisible particle $m_{G'} \sim GeV$
  - Softer photons (for χ LOSP)

Open issues

- Other LOSP scenarios (stau, stop, ...)
- Cosmological issues (Dark matter candidate)