Dirac gauginos and their scalar partners

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based on: S.Y. Choi, M. Drees, JK, J.M. Kim, E. Popenda, P.M. Zerwas, Phys.Lett.B 672 (2009)
S.Y. Choi, D. Choudhury, A. Freitas, JK, J.M. Kim, P.M. Zerwas, JHEP 1008 (2010) 025

Outline

- Motivation
- A hybrid N=1/N=2 SUSY model
  - gaugino sector
  - gauge scalar sector
- Phenomenology at colliders
  - sgluon production at the LHC
  - Dirac vs Majorana gauginos
  - EW scalar bosons at ILC/CLIC and their decays
- Summary

Motivation

Supersymmetry – the most elegant and respected proposition for the beyond SM physics

In the simplest realisation each SM particle is paired with a sparticle that differs in spin by ½:

- quarks – squarks
- gauge bosons – gauginos
- leptons – sleptons
- Higgses – higgsinos

If SUSY particles produced at the LHC, it will be crucial to verify that they are superpartners:

measure their spins, couplings, quantum numbers

If gauginos are seen – Majorana as in MSSM, or Dirac ?

Need a model to differentiate

In fact, successes of supersymmetry do not rely on its minimal realisation

Actually Dirac gauginos might be welcome. Going from Majorana to Dirac renders the theory (partially) R-symmetric with interesting features:

- ❖ forbid some couplings and suppress flavor-changing amplitudes with gauginos running in the loops.

  Antoniadis, Benakli, Delgado, Quiros 0610265
  Kribs, Poppitz, Weiner 0712.2039
  Blechman, Ng 0803.3811

- ❖ s-wave $\tilde{\chi}^0_{D1}$ annihilation with meaningful implications for DM

  Belanger et al., 0905.1043
  Chun, Park, Scopel, 0911.5273
  Chun, 1009.0983

- ❖ bring in scalar partners – sgluons and EW gauge scalars

  Plehn, Tait 0810.3919
  Kane, Petrov, Shao, Wang 0805.1397

- ❖ offer an attractive formulation with distinct phenomenology at colliders

A hybrid N=1/N=2 SUSY model

In the MSSM gluinos are Majorana particles with two degrees of freedom to match gluons in a vector super-multiplet.

$$W_\alpha^a = \tilde{g}_\alpha^a + D^a\theta_\alpha + (\sigma^{\mu\nu})_\alpha{}^\beta\theta_\beta G_{\mu\nu}^a + \ldots \qquad \text{R=1}$$

$$\tilde{g}_M = \tilde{g}_L + \tilde{g}_R = \tilde{g}_M^c \quad \Leftrightarrow \quad \tilde{g}_R = (\tilde{g}_L)^c$$

To provide two additional degrees, the N=1 gauge vector super-multiplet can be paired with an additional N=1 gauge chiral super-multiplet

$$\hat{\Sigma}^a = \sigma^a + \sqrt{2}\theta\,\tilde{g}'^a + \theta\theta\,F^a \qquad \text{R=0}$$

$$\tilde{g}_D = \tilde{g}'_L + \tilde{g}_R \neq \tilde{g}_D^c$$

to a vector hyper-multiplet of N=2 supersymmetry

Fayet 1976
Del Aguila et al., 1985
Alvarez-Gaume, Hassan hep-ph/9701069
Fox, Nelson, Weiner hep-ph/0206102
.....

Schematically, the N=2 gauge hyper-multiplet can be decomposed into the usual N=1 vector and chiral supermultiplets:

superfields	$SU(3)_C, SU(2)_I, U(1)_Y$	Spin 1	Spin 1/2	Spin 0	
$\hat{G}_C$ / color	$8,1,0$	g^a	$\tilde{g}^a$		vector
$\hat{G}_I$ / isospin	$1,3,0$	W^i	$\tilde{W}^i$		vector
$\hat{G}_Y$ / hypercharge	$1,1,0$	B	$\tilde{B}$		vector
$\hat{\Sigma}_C$ / color	$8,1,0$		$\tilde{g}'^a$	σ_C^a	chiral
$\hat{\Sigma}_I$ / isospin	$1,3,0$		$\tilde{W}'^i$	σ_I^i	chiral
$\hat{\Sigma}_Y$ / hypercharge	$1,1,0$		$\tilde{B}'$	σ_Y^0	chiral

gauge scalars are R-parity even

N=2 mirror (s)fermions are assumed to be heavy to avoid chirality problems → a hybrid N=1/N=2 SUSY model

QCD sector: gluinos

- old and new gluinos are coupled minimally to the gluon field

$$\mathcal{L}^{g\tilde{g}\tilde{g}}_{\rm QCD} = g_s \mathrm{Tr}\left(\overline{\tilde{g}}\gamma^\mu[g_\mu,\tilde{g}] + \overline{\tilde{g}'}\gamma^\mu[g_\mu,\tilde{g}']\right) \qquad g_\mu = \frac{1}{\sqrt{2}} g^a_\mu \lambda^a$$

- quarks and squarks interact only with old gluinos

$$\mathcal{L}^{q\tilde{q}\tilde{g}}_{\rm QCD} = -g_s\left[\overline{q_L}\tilde{g}\,\tilde{q}_L - \overline{q_R}\tilde{g}\,\tilde{q}_R + \mathrm{h.c.}\right]$$

- gluino mass: Majorana mass terms are not R-symmetric,
  but Dirac type are allowed

  In the $\tilde{g}', \tilde{g}$ basis, the mass matrix gives rise to two Majorana mass eigenstates

$$\mathcal{M}_g = \begin{pmatrix} M_3' & M_3^D \\ M_3^D & M_3 \end{pmatrix}$$

Limiting cases:

- for , standard MSSM gluino is recovered
- for $M_3 = M_3' = 0$, Dirac gluino $\tilde{g}_D = \tilde{g}_R + \tilde{g}'_L$ with mass $|M_3^D|$

EW gauginos:

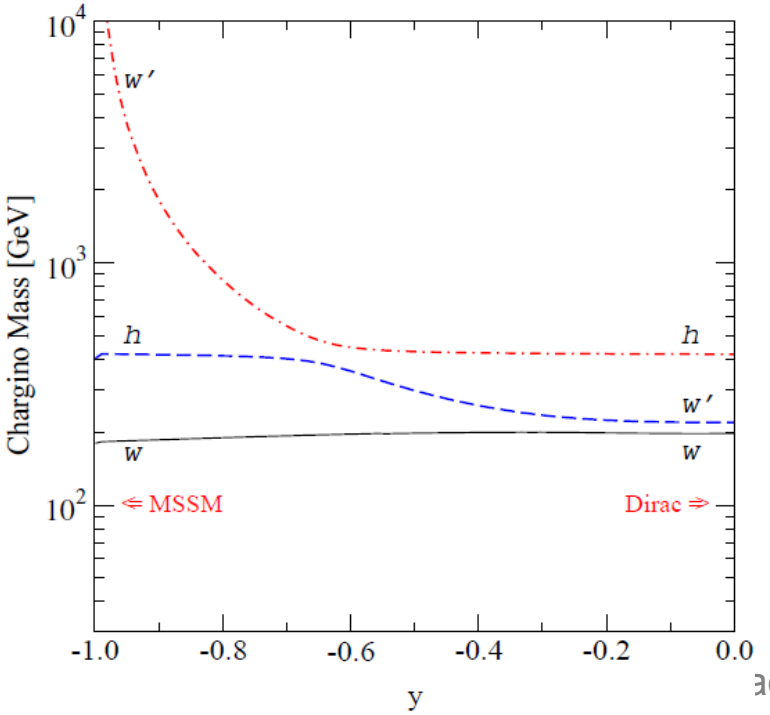
Dirac-type mass $\mathcal{A}_D = \int d^4x\, d^2\theta\, M^D\, \theta^\alpha\, \mathrm{tr}\, \hat{G}_\alpha \hat{\Sigma}$

charginos $\{\tilde{W}'^-_L, \tilde{W}^-_L, \tilde{H}^-_{dL}\}$

$$\begin{pmatrix} M_2' & M_2^D - g v_I & -\lambda_I v_u \\ M_2^D + g v_I & M_2 & \frac{1}{\sqrt{2}} g v_d \\ \lambda_I v_d & \frac{1}{\sqrt{2}} g v_u & \mu_c \end{pmatrix}$$

neutralinos $\{\tilde{B}', \tilde{B}, \tilde{W}'^0, \tilde{W}^0, \tilde{H}^0_u, \tilde{H}^0_d\}$

$$\begin{pmatrix} M_1' & M_1^D & 0 & 0 & -\frac{1}{\sqrt{2}}\lambda_Y v_d & -\frac{1}{\sqrt{2}}\lambda_Y v_u \\ M_1^D & M_1 & 0 & 0 & \frac{1}{2} g' v_u & -\frac{1}{2} g' v_d \\ 0 & 0 & M_2' & M_2^D & -\frac{1}{\sqrt{2}}\lambda_I v_d & -\frac{1}{\sqrt{2}}\lambda_I v_u \\ 0 & 0 & M_2^D & M_2 & -\frac{1}{2} g v_u & \frac{1}{2} g v_d \\ -\frac{1}{\sqrt{2}}\lambda_Y v_d & \frac{1}{2} g' v_u & -\frac{1}{\sqrt{2}}\lambda_I v_d & -\frac{1}{2} g v_u & 0 & -\mu_n \\ -\frac{1}{\sqrt{2}}\lambda_Y v_u & -\frac{1}{2} g' v_d & -\frac{1}{\sqrt{2}}\lambda_I v_u & \frac{1}{2} g v_d & -\mu_n & 0 \end{pmatrix}$$



N=2 relation for couplings

$\lambda_I = g/\sqrt{2}$ and $\lambda_Y = -g'/\sqrt{2}$

$M_1^{(D)} \approx M_2^{(D)}/2$

$M_2' = my/(1+y)\,,$

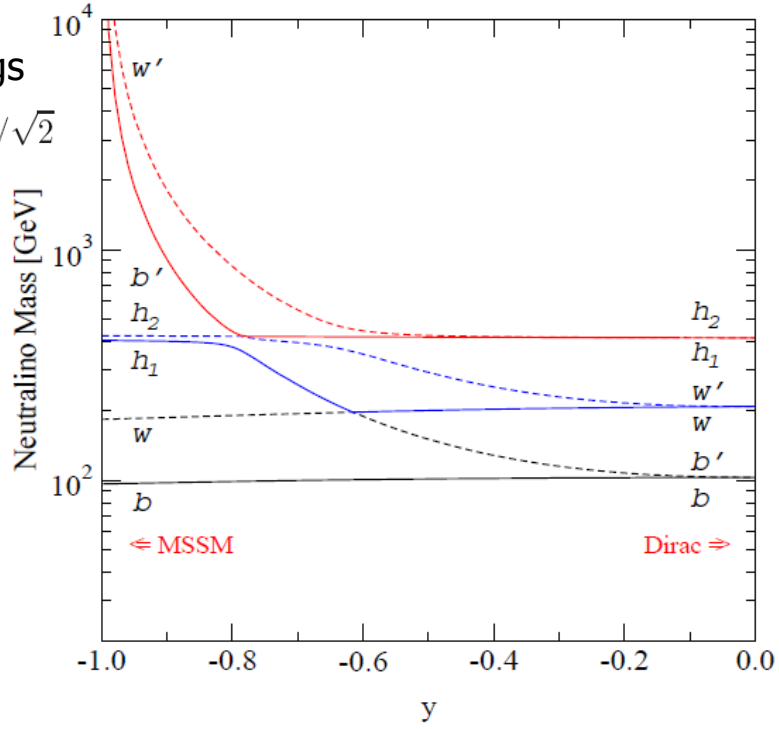
$M_2 = -my\,,$

$M_2^D = m\,,$

$\mu = 2m\,,$

$m = 200$ GeV

$\tan\beta = 5$



ac gauginos and their scal

Colored scalars: sgluons

Tree-level couplings

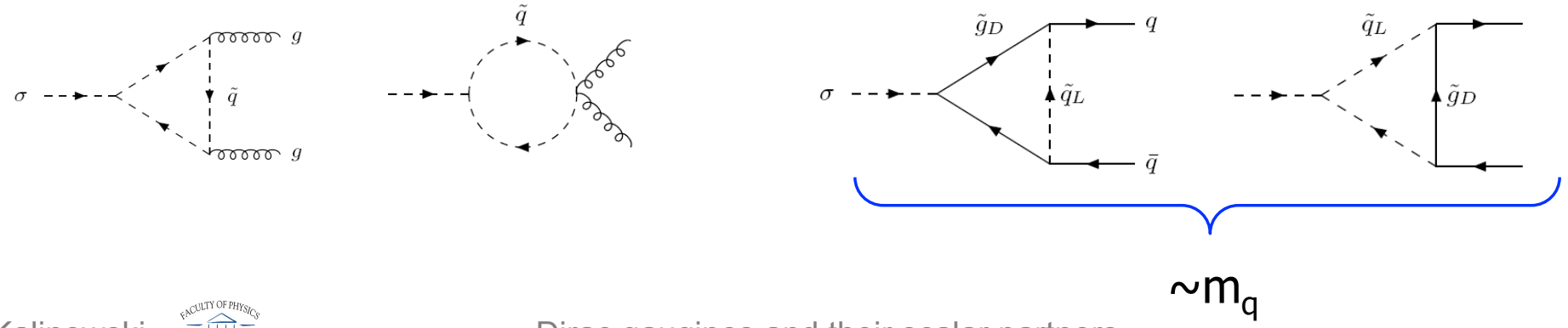
- $\sigma\sigma^* g$ and $\sigma\sigma^* gg$ couplings as required by gauge invariance
- to gluinos $-\sqrt{2}\, i\, g_s\, f^{abc}\, \overline{\tilde{g}_L'^a}\, \tilde{g}_R^b\, \sigma_C^c + \text{h.c.}$
- Dirac gluino mass => trilinear scalar couplings to squarks

$$-\sqrt{2}\, g_s\, M_C^D\, (\sigma_C^a + \sigma_C^{a*}) \left(\tilde{q}_L^* \frac{\lambda^a}{2} \tilde{q}_L - \tilde{q}_R^* \frac{\lambda^a}{2} \tilde{q}_R \right)$$

➡ Although R-parity even, single sgluon cannot be produced in pp collisions at tree-level

Loop induced couplings

- to a gluon or quark pair through diagrams with squarks



EW scalars

two Higgs doublets + iso-triplet σ_I^i and hypercharge singlet σ_Y^0

$$H_u^0 = \frac{1}{\sqrt{2}}\left[s_\beta(v+h) + c_\beta H + i(c_\beta A - s_\beta a)\right], \qquad H_u^+ = c_\beta H^+ - s_\beta a^+$$

$$H_d^0 = \frac{1}{\sqrt{2}}\left[c_\beta(v+h) - s_\beta H + i(s_\beta A + c_\beta a)\right], \qquad H_d^- = s_\beta H^- + c_\beta a^-$$

$$\sigma_Y^0 = \frac{1}{\sqrt{2}}(v_Y + s_Y + i a_Y),$$

$$\sigma_I^3 = \frac{1}{\sqrt{2}}(v_I + s_I + i a_I), \quad \sigma_I^1 = \frac{1}{\sqrt{2}}(\sigma_2^+ + \sigma_1^-), \quad \sigma_I^2 = \frac{i}{\sqrt{2}}(\sigma_2^+ - \sigma_1^-)$$

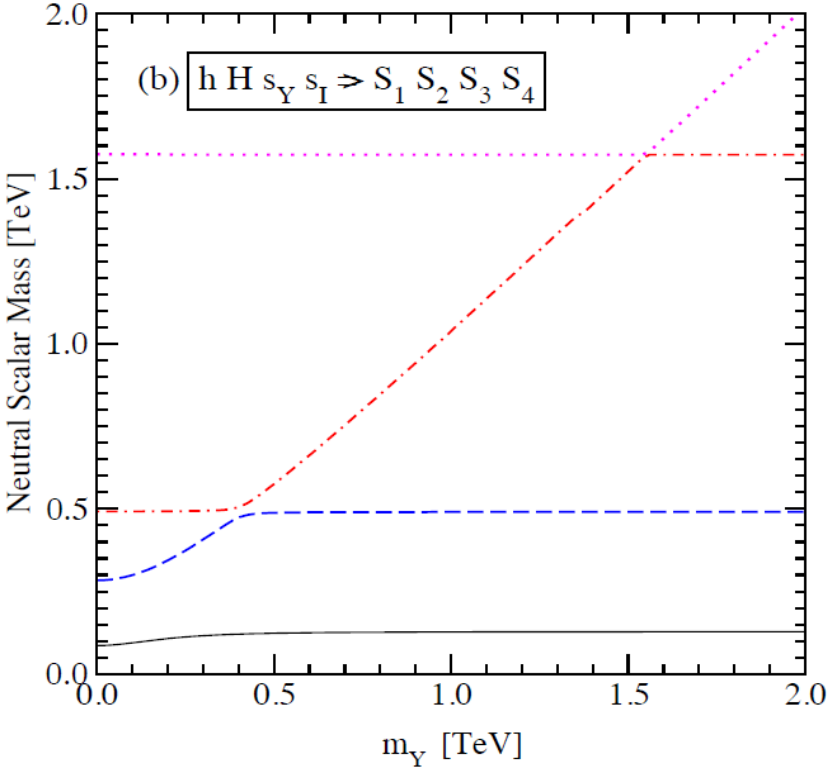
Gauge boson masses $\quad m_Z^2 = \frac{1}{4}(g'^2 + g^2)v^2, \qquad m_W^2 = \frac{1}{4}g^2 v^2 + g^2 v_I^2$

$\Delta\rho = \rho - 1 = 4v_I^2/v^2$ ➡ $v_I \leq 3\,\text{GeV}$

pseudoscalars A, a_Y, a_I

neutral scalars h, H, s_Y, s_I

charged scalars $H^\pm, s_1^\pm, s_2^\pm$



Phenomenology at colliders

- Sgluon production at the LHC
- Dirac vs Majorana gauginos
- EW scalar boson production and decays

Only few examples will be shown: more in
arXiv:1005.0818 [hep-ph]

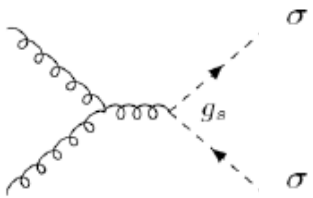
Sgluon production at the LHC

Choi, Drees, Freitas, Zerwas 0808.2410

Choi, Drees, JK, Kim, Popenda, Zerwas 0812.3586

Sgluons can be produced

- in pairs

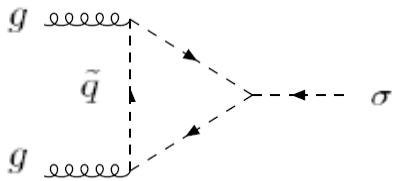


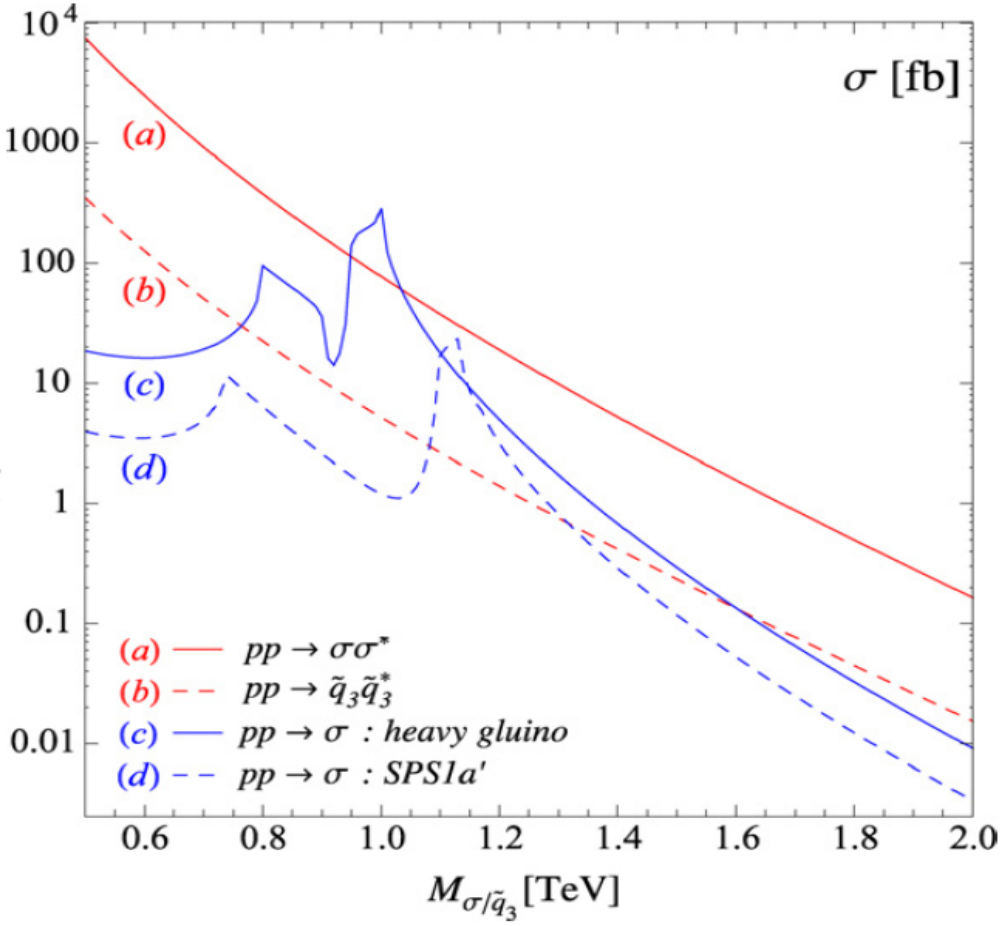
with spectacular decays

$$\sigma \to \tilde{g}\tilde{g} \to qq\tilde{q}\tilde{q} \to qqqq + \tilde{\chi}\tilde{\chi}$$

$$\sigma \to \tilde{q}\tilde{q} \to qq + \tilde{\chi}\tilde{\chi}\,,$$

- singly





in principle reconstructible in loop-induced decay modes

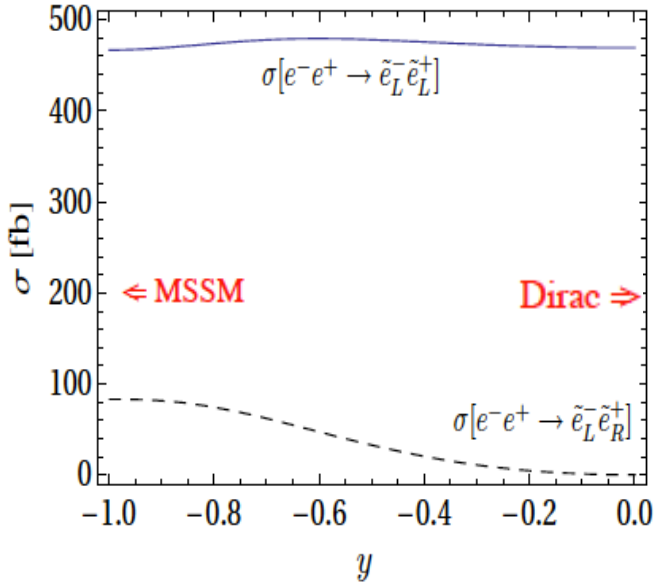
$$\sigma \to t\bar{t} \to b\bar{b}W^+W^-$$

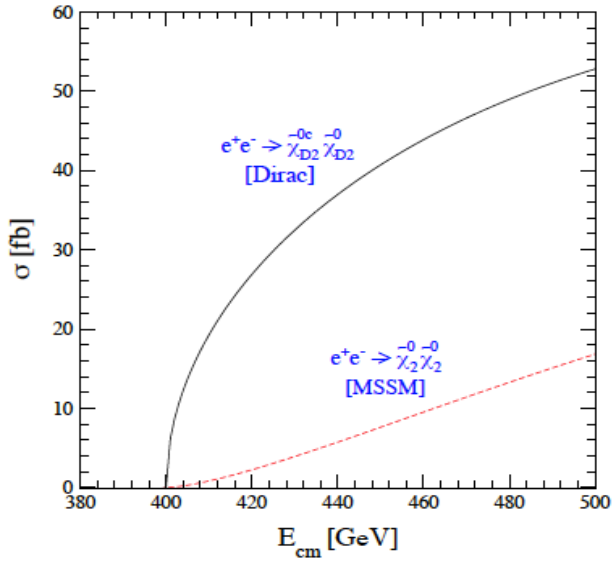
$$\sigma \to gg\,.$$

Dirac vs Majorana gauginos

1. sfermion pair production

the conserved D charge kills the opposite (same) sign and chirality selectron production in e^-e^+ (e^-e^-) collisions





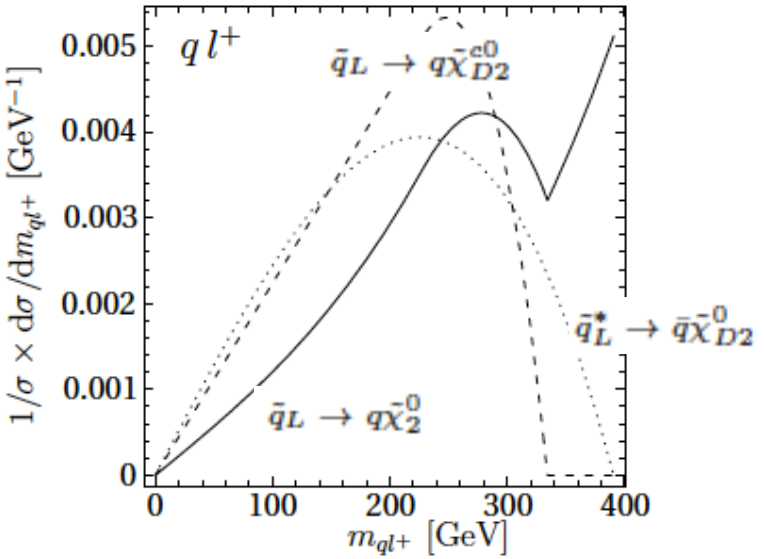
2. onset of diagonal neutralino pair production

- higher reach for heavy states
- implications for DM scenarios

3. squark cascade decays: different chirality structure

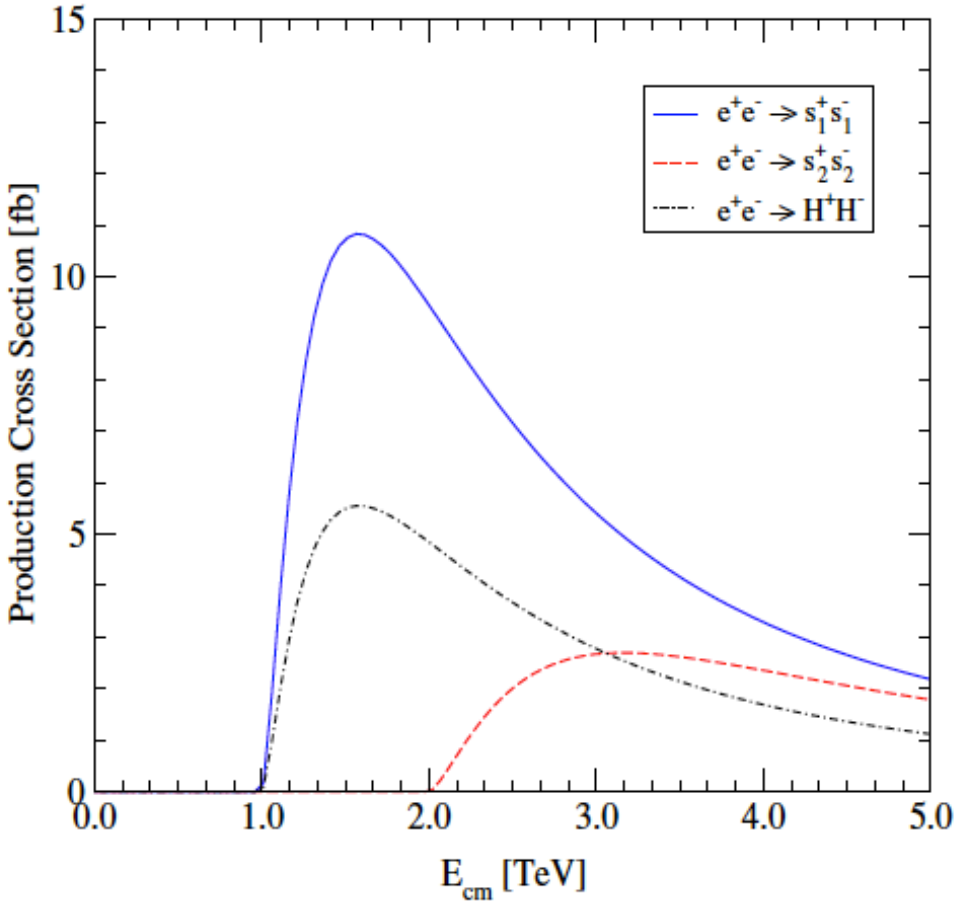
$$\text{MSSM:} \quad \tilde{q}_L \to q\,\tilde{\chi}_2^0 \to q\,l^\pm\,\tilde{l}_L^\mp \to q\,l^\pm\,l^\mp\,\tilde{\chi}_1^0\,,$$
$$\text{Dirac:} \quad \tilde{q}_L \to q\,\tilde{\chi}_{D2}^{c0} \to q\,l^+\,\tilde{l}_L^- \to q\,l^+\,l^-\,\tilde{\chi}_1^0$$

imprint in angular distributions



EW scalar production at ILC/CLIC and their decays

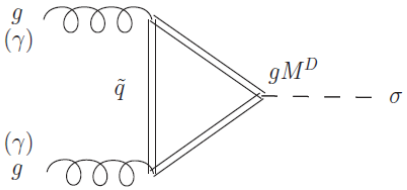
- resonant s-channel production strongly suppressed since coupling ~m_e
- neutral sigma states $\sigma^0_{I,Y}$ cannot be pair-produced in e+e-
- but charged states can be pair-produced via Z and γ exchange



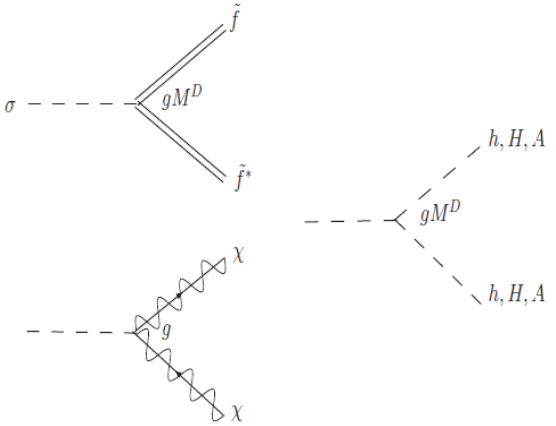
$$M_{s_1^\pm, H^\pm} = 0.5\,\text{TeV}$$

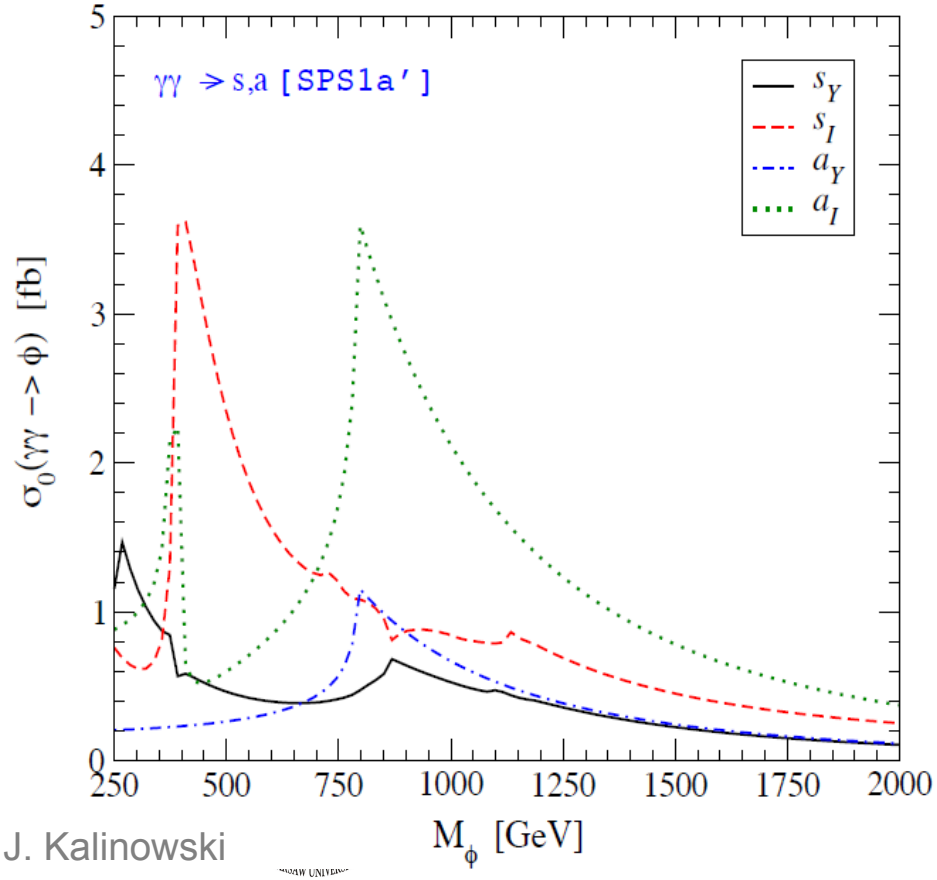
$$M_{s_2^\pm} = 1.0\,\text{TeV}.$$

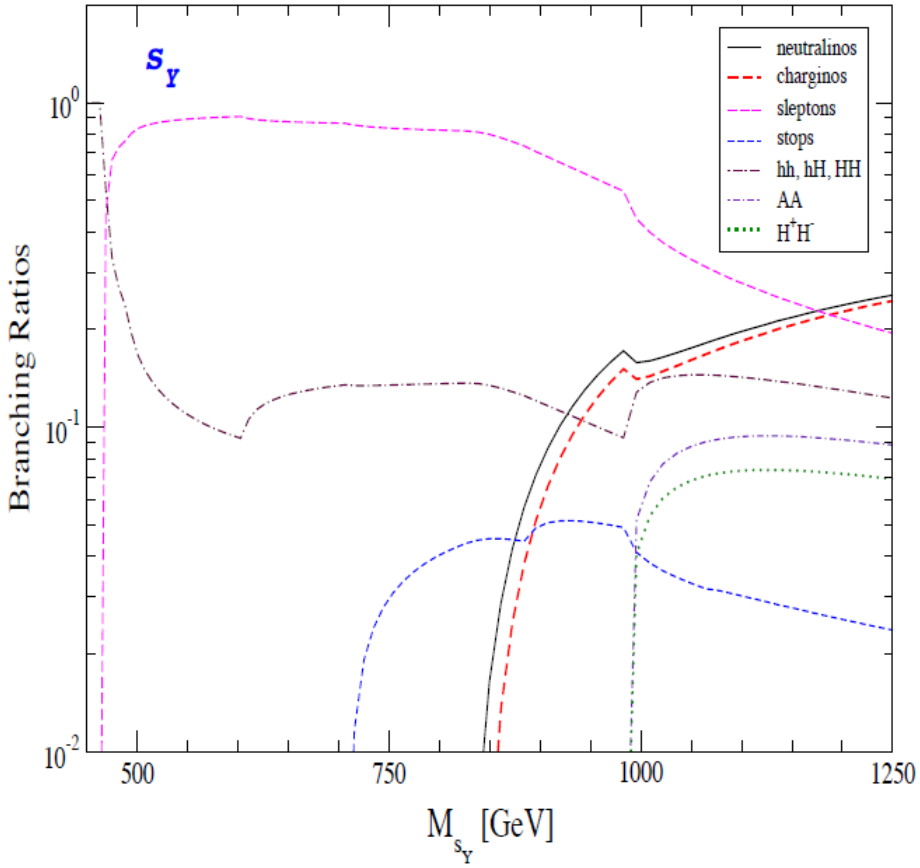
Gamma colliders ideal for searching for heavy scalars/pseudoscalars



decays via







and

Summary

- Alternative N=1/N=2 SUSY hybrid realisation discussed
- Doubling of gauginos gives rise to new states

  16 Majorana gluinos ➔ 8 Dirac gluinos

  6 Majorana neutralinos ➔ 3 Dirac neutralinos

  3 charginos
- Dirac vs Majorana nature tested in several ways, implications for DM
- Adjoint scalars expand significantly the scalar sector

  new SU(2)xU(1) states mix with Higgs fields
- Scale of new degrees is restricted by experiment
- A variety of production channels and decay modes

  sgluons produced singly and in pairs in pp collisions

  charged iso-vector scalars can be pair-produced at e+e-

  $\gamma\gamma$ collisions offer production channels to all scalars and pseudoscalars