



Beyond the Standard Model Physics at the Linear Collider

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Why a Linear Collider?

- ▶ **Unique environment:** **point-like** initial states, e^+e^- and e^-e^- beam options
tunable \sqrt{s} , **polarization of both beams** P_{e^-} , P_{e^+} , absence of “huge” QCD bckgs
- ▶ **No trigger** required; **no special selection** needed in **classifying events**
- ▶ **Unbiased and comprehensive direct searches** for **New Physics**
- ▶ **Calculability** and **theoretical precision** \Rightarrow **ideal tool** to **identify indirect NP effects**
Theoretical studies “free” from large QCD systematical uncertainties \rightsquigarrow **reach ‰ level**

A Linear Collider: exploring New Physics models

- ▶ **Refine LHC discoveries: probe specific new phenomena**
(already identified) in **clean environment** and with **high precision**
- ▶ **New direct discoveries: LC's reach potentially complementary** to the LHC
Search potential for **colourless states (including Higgs)** and **discovery potential**
largely **surpass the LHC**
- ▶ **Discovery through precision: measure "SM" observables to the highest precision**
High sensitivity and resolution power to NP effects (tiny deviations from SM)

▶ **Beyond the Standard Model**

Beyond the SM: searches for New Physics

★ Conduct model-independent searches

- ▶ Search for **anomalous event rates** in different channels;
- ▶ **Interpret** the results in terms of general **effective operators**
(non-renormalisable, $1/\Lambda_{\text{NP}}$ -suppressed)
- ▶ Certain amount of **theoretical assumptions still required** (spin, mass, couplings)

★ Consider specific New Physics models

- ▶ **Extensions of the SM gauge group** (additional gauge bosons)
- ▶ **Additional particles** (extended Higgs sectors, exotic fermions)
- ▶ **Modified interactions** (composite Higgs, new contact-interactions)
- ▶ **Larger frameworks** (supersymmetry, extra dimensions, ...)

★ To address the SM observational problems and its theoretical puzzles

- ▶ Baryon asymmetry of the Universe; dark matter candidate; ν -phenomena
- ▶ EW symmetry breaking, hierarchy problem, flavour and CP, unification...

New Physics Models: additional gauge bosons

★ **Extended Gauge sectors** \rightsquigarrow organising principle, unification, flavour, DM, ...

▶ **Extra U(1)s, Left-Right models, GUTs - SO(10), E₆, extra dims, Little Higgs, ...**

leading to additional **new, neutral gauge boson Z'**

▶ **LHC searches:** $M_{Z'} \gtrsim 2 - 3 \text{ TeV}$ (precludes on-shell production at LC)

▶ **LC:** sensitive to $M_{Z'} \gg \sqrt{s}$ via **indirect effects** in **precision measurements**

small deviations in $e^+e^- \rightarrow f\bar{f}$ observables, as $\sigma_{\text{tot}}^{f\bar{f}}$, A_{FB}^f and A_{LR}^f

Polarisation: strongly **reduce systematics** in $Z' f\bar{f}$ couplings ($M_{Z'}$ unknown)

▶ An example: **minimal LR model** $SU(2)_R \times U(1)_{B-L} \rightarrow U(1)_Y$

▶ LC	500 GeV	$\mathcal{L} \sim 100 \text{ fb}^{-1}$	$M_{Z'} \sim 9 \text{ TeV}$
	500 GeV	$\mathcal{L} \sim 1 \text{ ab}^{-1}$	$M_{Z'} \sim 16 \text{ TeV}$
▶ CLIC	3 TeV	$\mathcal{L} \sim 1 \text{ ab}^{-1}$	$M_{Z'} \gtrsim 30 \text{ TeV}$

Discovery reach for models of Z' at Linear Collider

- ▶ **LC** operating at $\sqrt{s} = 500 \text{ GeV}$ and **1 TeV** for $\mathcal{L} = 500 \text{ fb}^{-1}$ and 1 ab^{-1}

Polarisation (P_{e^-}, P_{e^+}): unpolarised (0,0); polarised (80%,0), (80%,60%)

- ▶ **Minimal Left-Right symmetric (LRS)**

$$SU(2)_L \times SU(2)_R \times U(1)_{B-L} \rightarrow SU(2)_L \times U(1)_Y$$

- ▶ **“Alternative” Left-Right symmetric (ALR)**

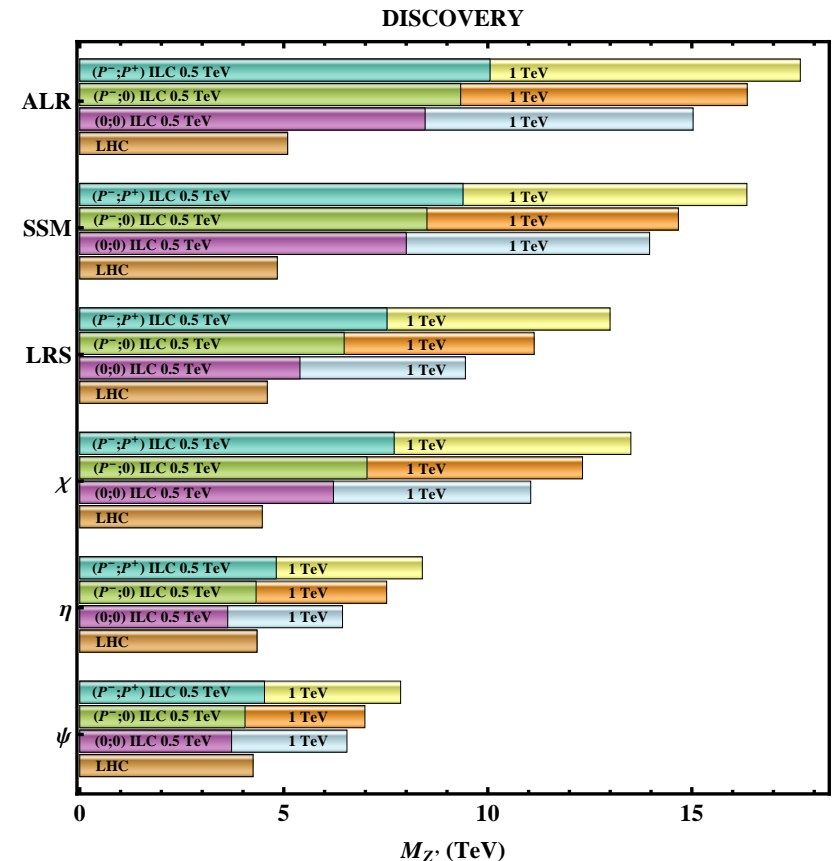
E_6 embedding of LRS

- ▶ **Sequential Standard Model (SSM)**

all Z' couplings same as for the SM Z

- ▶ **E_6 -GUT based: $Z' = Z_\chi \cos \beta + Z_\psi \sin \beta$**

$$\chi (\beta = 0); \eta (\beta = \pi/2); \psi (\beta = \pi - \arctan \sqrt{5/3})$$



[Osland et al, 0912.2806]

- ▶ **Distinguish models** (95% C.L.) for unpolarised (polarised) beams:

$$\sqrt{s} = 500 \text{ GeV} \rightsquigarrow M_{Z'} \lesssim 3.1 \text{ TeV (4 TeV)} ; \sqrt{s} = 1 \text{ TeV} \rightsquigarrow M_{Z'} \lesssim 5.3 \text{ TeV (7 TeV)}$$

New Physics Models: Compositeness

★ Higgs not a fundamental particle, but **composite state of fermions**

▶ EWSB and mass generation \leftrightarrow condensation of multiple fields

▶ Similar phenomenology: **Higgs couplings** (and **observables**) corrected by $\xi = \frac{v^2}{\Lambda_{\text{comp}}^2} \ll 1$

▶ **Precision measurements** of production cross sections $\sigma(VV \rightarrow VV, HH)$ and

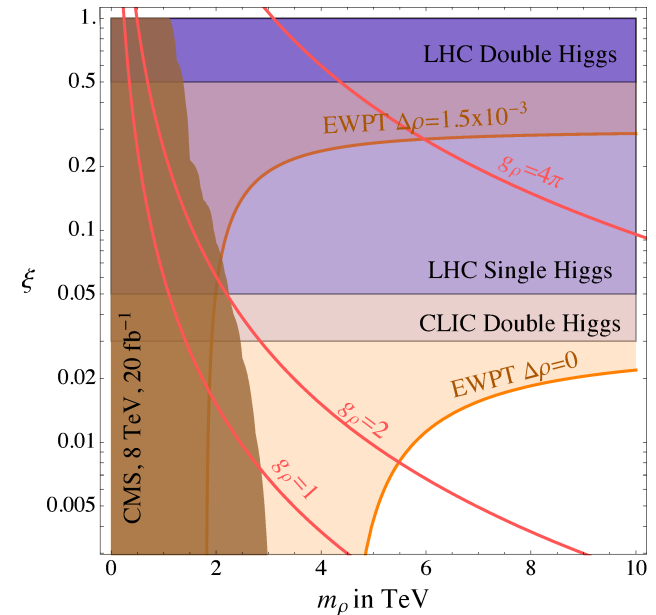
$\sigma(e^+e^- \rightarrow HZ, HH)$ sensitive to Λ_{comp}

▶ LHC	14 TeV	$\mathcal{L} \sim 100 \text{ fb}^{-1}$	$\Lambda_{\text{comp}} \sim 7 \text{ TeV}$
▶ LC	500 GeV	$\mathcal{L} \sim 1 \text{ ab}^{-1}$	$\Lambda_{\text{comp}} \sim 45 \text{ TeV}$
▶ CLIC	3 TeV	$\mathcal{L} \sim 1 \text{ ab}^{-1}$	$\Lambda_{\text{comp}} \sim 60 \text{ TeV}$

▶ **New couplings** from “strong” EWSB:

study **angular distributions** (e.g. final state W)

polarise e^\pm beams!



[Contino et al, 1309.7038]

New Physics Models: Extra dimensions

★ **Extra spatial (compact) dimensions** \rightsquigarrow hierarchy problem, DM, geometrical flavour, ...

▶ Phenomenological models \leftrightarrow **TeV-scale extra dimensions**

▶ Appearance of **Kaluza-Klein resonances** for particles **propagating beyond 4D**

\Rightarrow **towers of KK excitations** - same spin, increasing mass - for **SM and gravitons**

▶ **Universal Extra Dimensions (UED)** [compactified in T^k torus]

▶ **LHC** (diphoton + E^T_{miss}): $1/R \gtrsim 1.5 \text{ TeV}$

▶ **LC: resonances** (and contact interactions) in $e^+e^- \rightarrow f\bar{f}$

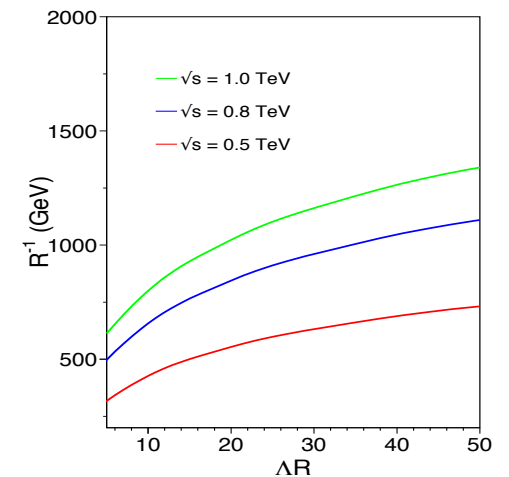
▶ **Large Extra Dimensions (LED)** [$k \geq 2, \gtrsim \text{TeV}^{-1}, 4\text{D SM}$]

▶ **LHC** (jet + E^T_{miss}): $M_D \gtrsim 3 - 5 \text{ TeV}$ ($k=2 \dots 6$)

▶ **LC: graviton contact interaction** effects in $e^+e^- \rightarrow G_{KK} \rightarrow f\bar{f}$

Discovery $\Rightarrow M_D \sim 5 - 5.5 \text{ TeV}$ for $\sqrt{s} = 500 \text{ GeV}$; $M_D \sim 20 - 30 \text{ TeV}$ at CLIC3

Identification of **spin=2 graviton** (@ $\sqrt{s} = 500 \text{ GeV}$) up to **3 TeV**



[Riemann, 0508136]

New Physics Models: impact for top physics

- ★ Unique window to NP at the TeV scale from **top-quark dynamics** (large m_t , Y^t)
 - ▶ **LC**: precise, model-independent measurements of **top couplings to gauge bosons**

$$\sqrt{s} = 500 \text{ GeV}, \mathcal{L} \sim 500 \text{ fb}^{-1}, (P_{e^-}, P_{e^+}) = (80\%, 30\%) \quad [\text{Amjad et al, 1307.8102}]$$

- ▶ Anomalous magnetic moment \Rightarrow **top compositeness**

$$[(g - 2)_t \text{ at } 0.1\% \text{ accuracy}] \rightsquigarrow \Lambda_{\text{comp}}^t \sim 100 \text{ TeV}$$

- ▶ Measurements of $t\bar{t}Z$ & $t\bar{t}W$: probe **top flavour models**

- ▶ Sensitive **probe of $t\bar{t}Z$ and $t\bar{t}\gamma$ vertices** (below 1%)

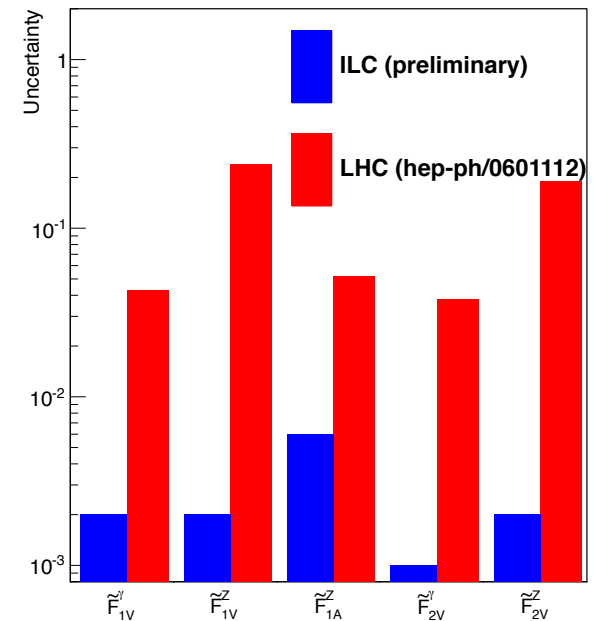
$$\text{from } e^+e^- \rightarrow t\bar{t} \rightarrow \ell^\pm + \text{jets}$$

- ▶ Top asymmetries A_{FB}^t and A_{LR}^t (\leftarrow polarised beams)

high sensitivity to Z' models and **Extra Dimensions** ($\mathcal{O}(\%) \rightsquigarrow M_{KK} \sim 10 - 20 \text{ TeV}$)

- ▶ LC at $\sqrt{s} = 500 \text{ GeV}$ and $(P_{e^-}, P_{e^+}) = (80\%, 0) \Rightarrow$ **statistical precision $\sim 1\%$**

$$\Delta A_{\text{LR}}^t / A_{\text{LR}}^t = 1.24\% ; \Delta A_{\text{FB}}^{tR} / A_{\text{FB}}^{tR} = 1.2\% ; \Delta A_{\text{FB}}^{tL} / A_{\text{FB}}^{tL} = 1.4\% \quad [\text{Doublet et al, 1202.6659}]$$



New Physics Models: exotic fermions

★ Sterile fermions ν_R , triplet fermions $\Sigma \rightsquigarrow$ massive neutrinos, DM candidates

► Models of Majorana neutrinos: type I and III seesaws

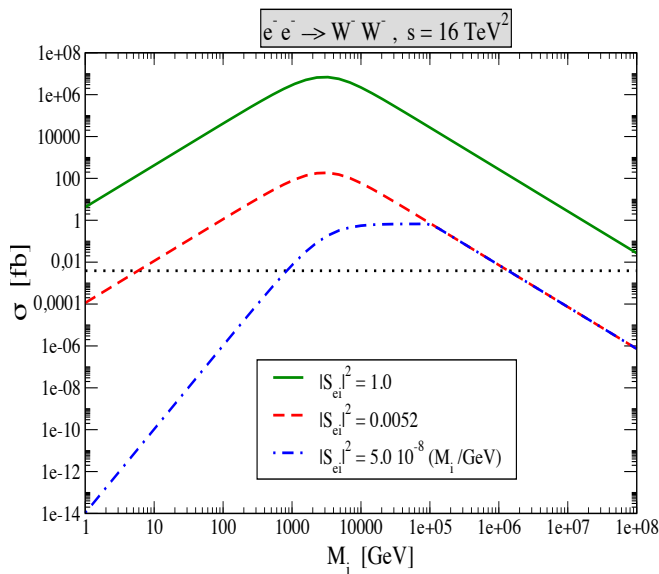
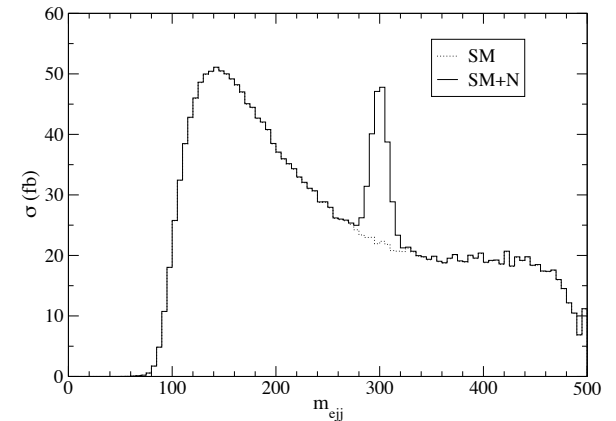
► Heavy ν_R searched for in $e^+e^- \rightarrow \nu_R \nu \rightarrow \ell W \nu \rightarrow \ell j j \nu$

$$\sqrt{s} = 500 \text{ GeV}, \mathcal{L} \sim 500 \text{ fb}^{-1}, (P_{e^-}, P_{e^+}) = (80\%, 60\%)$$

► LC: non-observation $200 \text{ GeV} \lesssim M_{\nu_R} \lesssim 400 \text{ GeV}$

$$\Rightarrow V_{e\nu_R} \lesssim \mathcal{O}(10^{-3})$$

[del Aguila et al, 0502189]



► Inverse $0\nu 2\beta$ decay ($e^-e^- \rightarrow W^-W^-$): Majorana ν_R

► LC: $\sqrt{s} = 4 \text{ TeV} \Rightarrow$ up to 10^4 events expected

Explore regime $1 \text{ TeV} \lesssim M_{\nu_R} \lesssim 10^3 \text{ TeV}$

[Rodejohann, 1005.2854]

$\sqrt{s} \gg 1 \text{ TeV}$ ($0\nu 2\beta$ decay bounds)

► Doubly charged leptons $\Sigma^{\pm\pm}$: $e^+e^- \rightarrow \gamma, Z \rightarrow \Sigma^{++}\Sigma^{--}$

► LC: $\sqrt{s} = 1.5 \text{ TeV}, \mathcal{L} = 100 \text{ fb}^{-1} \Rightarrow \mathcal{O}(10^4)$ $\Sigma^{\pm\pm}$ pairs

$$400 \text{ GeV} \lesssim M_{\Sigma^{\pm\pm}} \lesssim 700 \text{ GeV}$$

[Yue et al, '12]

▶ **Supersymmetric extensions of the SM**

New Physics Models: Supersymmetry

★ **Supersymmetry:** (still) **well motivated BSM** \rightsquigarrow hierarchy problem, unification, DM ...

▶ **Extra Higgs doublet** and **superpartners** ($\Delta_{\text{spin}}=1/2$; same couplings and quantum #s)

▶ **BSM** with **multiple new scalars and fermions** (Higgs, EW states, etc)

complete and calculable framework \Rightarrow illustrate **LC power for direct spectroscopy!**

▶ “**Establishing SUSY**”: measure $M_{\tilde{\psi}}$, $\Gamma_{\tilde{\psi}}$, $\sigma_{\tilde{\psi}}^{\text{prod}}$, $\theta_{ij}^{\tilde{\psi}}$, ... and prove their are **spartners!**

Reconstruct $\mathcal{L}_{\text{SUSY}}^{\text{eff}}$, connect with **high-scale model...**

▶ **LHC:** good prospects for discovery of “**pair-produced**” coloured states $\sim 2 - 3$ TeV

Recent bounds & Higgs discovery \Rightarrow **change of paradigm** in “**natural**” SUSY models

EW states (non-coloured) harder: $\tilde{\chi}^{\pm}$, $\tilde{\chi}^0$, $\tilde{\ell}$, $\tilde{\nu}$ mostly **from \tilde{q} , \tilde{g} cascade decays**

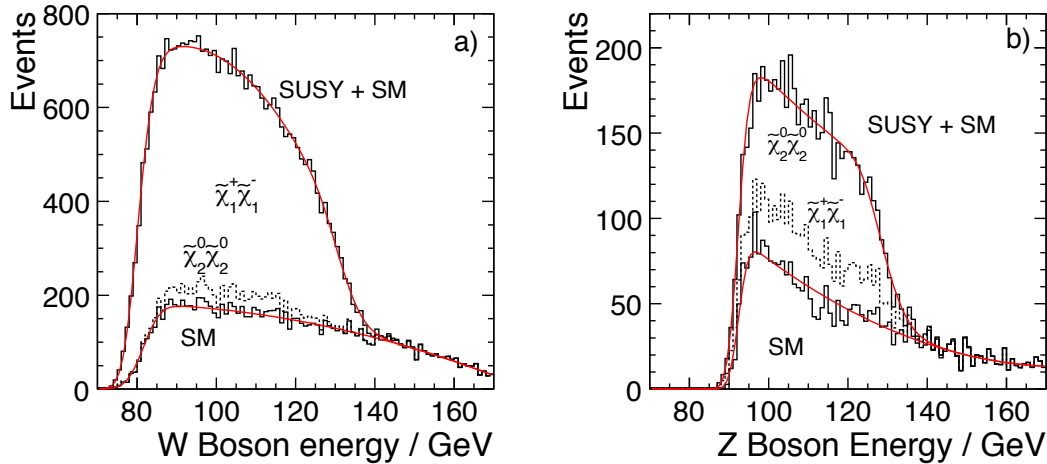
▶ **Most model-independent bounds** on **EW SUSY particles** set by **LEP!**

Supersymmetry at a Linear Collider

- ▶ For sufficiently high \sqrt{s} , **direct production of EW states**, with manageable bckgs
 - ⇒ **discovery reach** close to $\sqrt{s}/2$ for $e^+e^- \rightarrow \tilde{\psi}_A\tilde{\psi}_A$, or **higher** for $e^+e^- \rightarrow \tilde{\psi}_A\tilde{\psi}_B$
- ▶ **Linear Collider** will provide **independent checks** of any **LHC findings**
- ▶ **Unique LC features** (low QCD backg, tunable \sqrt{s} , high \mathcal{L} , polarisation, e^-e^- option)
 - ⇒ **precision measurements** - ‰ in **masses and couplings**
 - ⇒ determination of **properties** of new states - spin, CP, Majorana nature...
- ▶ **Some illustrative examples**
 - Chargino** and **neutralino** masses and properties;
 - Slepton masses** and **charged lepton flavour violation**;
 - Higgs** \leftrightarrow special case of **extended Higgs sectors**

Assuming Rp conserving models, viable DM not imposed as constraint

SUSY at a Linear Collider: EW-inos



[Suehara and List, 0906.5508]

► **EW-ino pair production:** $\tilde{\chi}_1^+ \tilde{\chi}_1^-$, $\tilde{\chi}_2^0 \tilde{\chi}_2^0$, $\tilde{\chi}_2^0 \tilde{\chi}_1^0$

$$\tilde{\chi}_1^- \rightarrow W \tilde{\chi}_1^0, \tilde{\chi}_2^0 \rightarrow Z \tilde{\chi}_1^0$$

► **LC:** $\sqrt{s} = 500$ GeV, $\mathcal{L} = 500$ fb⁻¹, $P=(80\%,30\%)$

$$\Delta^{\text{stat}} \sigma^{\text{prod}} / \sigma^{\text{prod}}(\chi_1^\pm, \chi_2^0) = (0.84, 2.75)\%$$

$$\Delta^{\text{stat}} M(\chi_1^\pm, \chi_2^0, \chi_1^0) = (2.9, 1.7, 1.0) \text{ GeV}$$

► **Chargino (wino-higgsino) mixing:**

► **LC:** $\sqrt{s} = 400/500$ GeV, $\mathcal{L} = 100$ fb⁻¹, $P=(80\%,60\%)$

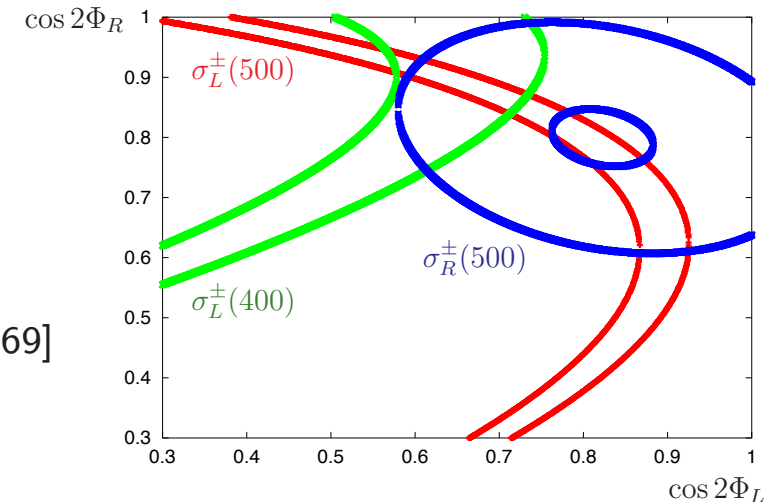
$$\cos 2\phi_L = [0.62, 0.72]; \cos 2\phi_R = [0.87, 0.91]$$

[Desch et al, 0312069]

► **Establish nature (bino - wino - higgsino)**

and determine **fundamental parameters** (e.g. μ)

► **Majorana χ^0 :** (polarised) $e^- e^- \rightarrow \tilde{e}_L \tilde{e}_L, \tilde{e}_R \tilde{e}_R \rightarrow e^- \tilde{\chi}_1^0 e^- \tilde{\chi}_1^0 f \bar{f}$

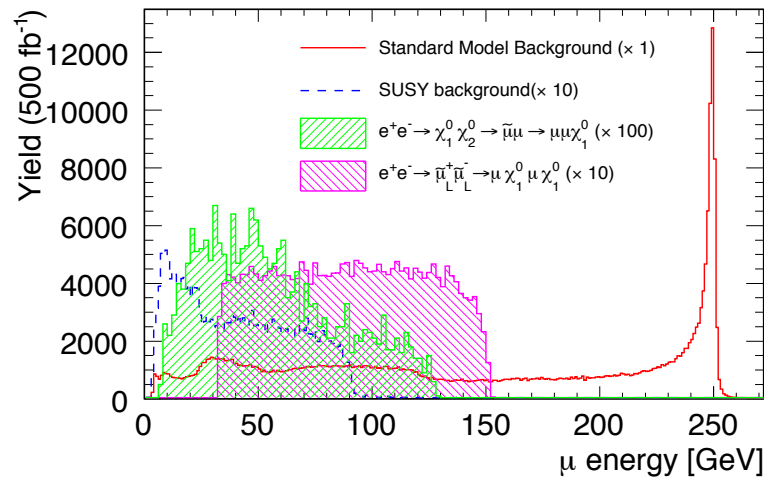


[Aguilar-Saavedra and AMT, 0307001]

SUSY at a Linear Collider: sleptons

- **Sleptons** abundantly pair produced at a **Linear Collider** (depending on \sqrt{s})

clean signatures, possible threshold scans, polarisation and optimal μ, e detection



- **Lepton energy spectrum: edges** $\rightsquigarrow M_{\tilde{\mu}_L}$ and $M_{\tilde{\chi}_1^0}$

- **LC: $\sqrt{s} = 500$ GeV, $\mathcal{L} = 500$ fb⁻¹, $P=(80\%,60\%)$**

$$M_{\tilde{\mu}_L} = 189.9 \text{ GeV} \pm 100 \text{ MeV} ; \Delta(M_{\tilde{\chi}_1^0}) = 920 \text{ MeV}$$

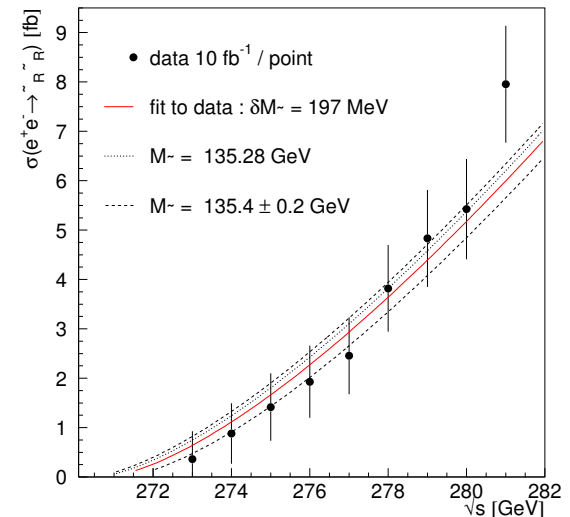
[Berggren et al, 0902.2434]

- **Determining smuon mass from threshold scans:**

for $\mathcal{L} = 10$ fb⁻¹ / point and $P=(80\%,30\%)$

$$\Delta(M_{\tilde{\mu}_L}) = 197 \text{ MeV}$$

[Berggren, in 1306.6352]

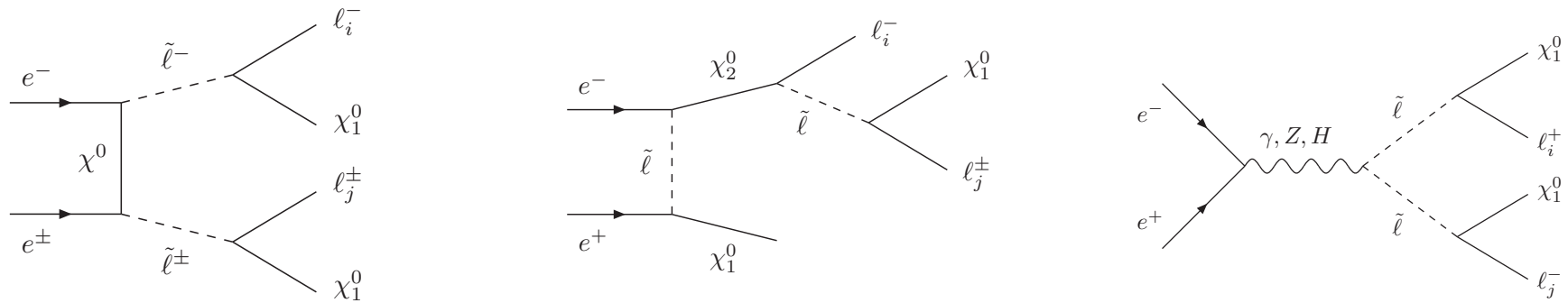


- If flavour violated in the **charged (s)lepton sector** \Rightarrow **LC ideal to study cLFV!**

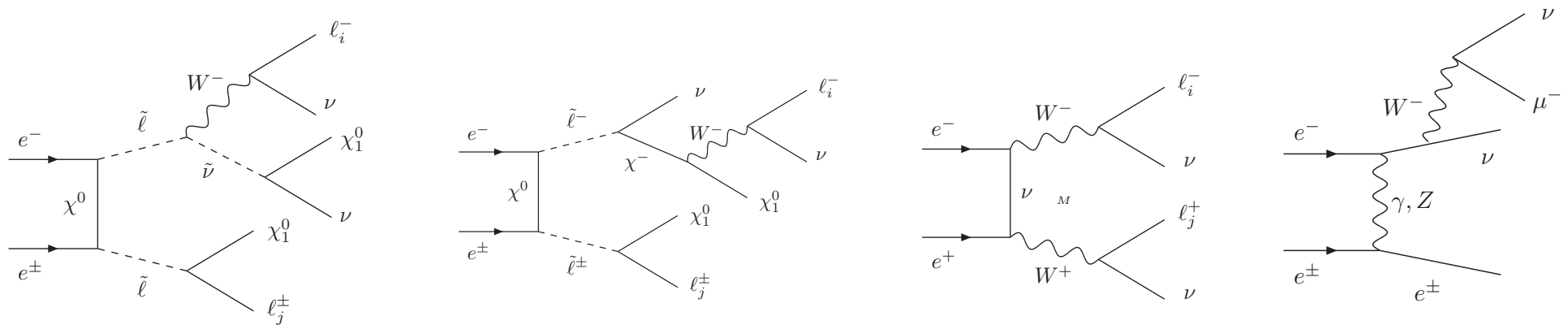
SUSY seesaw at a LC: charged lepton flavour violation

- Consider $e^\pm e^- \rightarrow e^\pm \mu^- + E_{\text{miss}}^T \iff$
- | | |
|---------------------------------------|---|
| $e^\pm \mu^- + 2\chi_1^0$ | (signal) |
| $e^\pm \mu^- + 2\chi_1^0 + (2, 4)\nu$ | (SUSY backg) |
| $e^\pm \mu^- + (2, 4)\nu$ | (SM _{mν} backg) |

- **Signal** events: dominated by **LFV SUSY neutral currents**

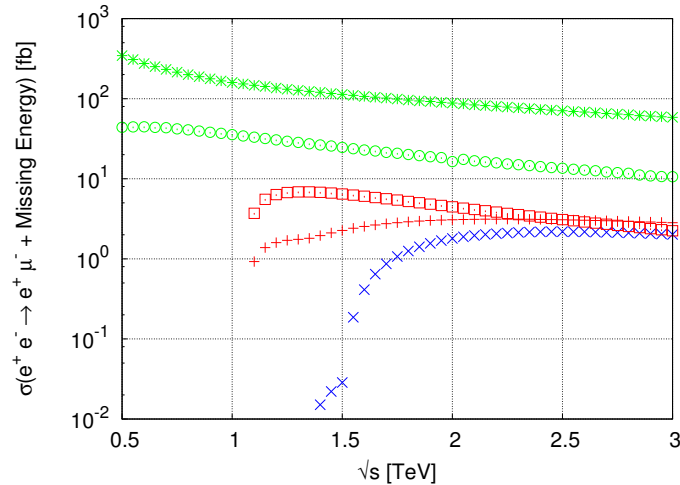


- **SUSY & SM_{m ν} backg: cLFV from charged currents - low-energy leptonic mixing**



SUSY seesaw at a LC: cLFV in e^+e^- beam option

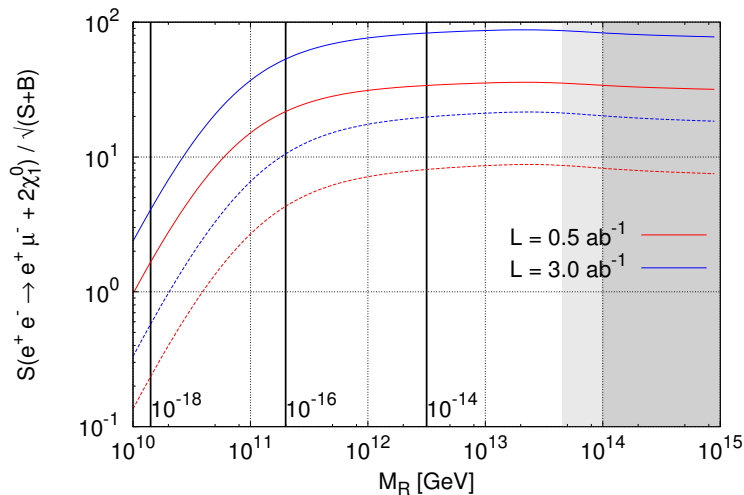
- Consider **illustrative example**: unpolarised and (ideal) **fully polarised LL** beams



- SM backg
- cLFV signal
- SUSY backg
- *, +, × → unpolarised
- , □ → $e_L^+ e_L^-$

m_i	GeV
χ_1^0	400
χ_2^0, χ_1^\pm	760
$\tilde{\nu}_L$	656
$\tilde{\ell}_R$	410
$\tilde{\ell}_L$	663

- **Dominant SM_{m_ν} backg** (disentangled from SUSY events - cuts, etc);
Polarisation: enhance signal; reduce (remove) SM_{m_ν} (SUSY) backg



- **Significance** for SUSY [-] and SUSY+ SM_{m_ν} [...] backg
⇒ typically $\mathcal{S} \gtrsim 10$ (unpolarised)

- For $\sqrt{s} = 2$ TeV and seesaw scale $M_R \sim 10^{12}$ GeV:

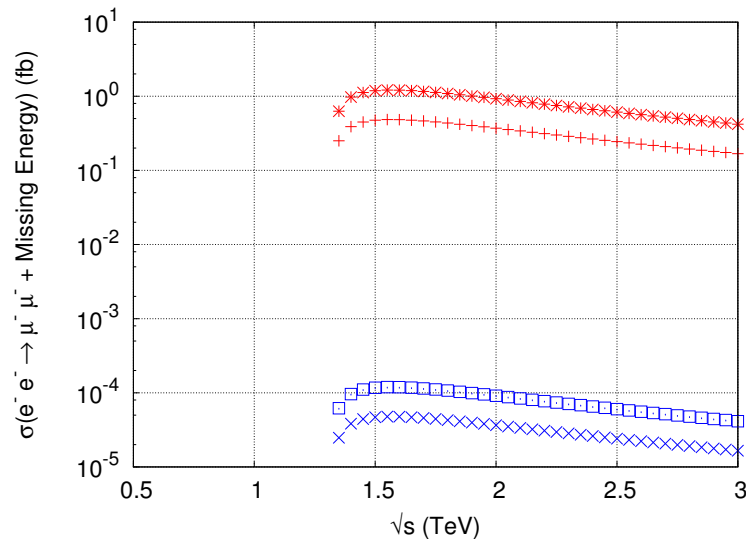
$\mathcal{O}(10^3)$ events for $\mathcal{L} = 0.5 \text{ ab}^{-1}$

$\mathcal{O}(10^4)$ events for $\mathcal{L} = 3 \text{ ab}^{-1}$

SUSY seesaw at a LC: the “golden channel” for cLFV

► Consider $e^- e^- \rightarrow \mu^- \mu^- + E_{\text{miss}}^T \leftrightarrow \begin{cases} \mu^- \mu^- + 2\chi_1^0 & \text{(signal)} \\ \mu^- \mu^- + 2\chi_1^0 + (2, 4)\nu & \text{(SUSY backg)} \end{cases}$

SM_{m ν} backg negligible ...



■ cLFV signal

■ SUSY backg

+ , × → unpolarised

* , □ → $e_L^- e_L^-$

► Reduced backgs: subdominant SUSY $\mathcal{O}(10^{-4})$

► **500 - 3000 events** for $\mathcal{L} = 0.5 - 3 \text{ ab}^{-1}$

► **Ideal cLFV discovery channel** $\Rightarrow e^- e^- \rightarrow \mu^- \mu^- + E_{\text{miss}}^T$ [provided \sqrt{s} large ...]

► Confirm t-channel exchange of **Majorana particle**

► **RR-polarised e^-** can test seesaw hypothesis: $\tilde{\ell}$ cLFV predominantly **LL phenomenon**

▶ **Enlarged Higgs sectors**

New Physics Models: modified Higgs sectors

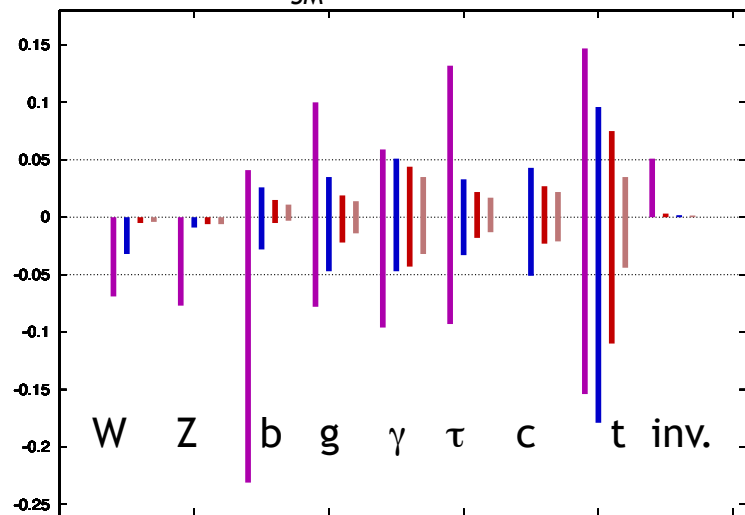
★ **Modified Higgs sectors** \rightsquigarrow EWSB, hierarchy problem, DM candidates, massive ν s...

▶ Scalar singlets; Multi-doublet models (2HDM, SUSY, ...); Higgs triplets, ...

▶ **Enlarged spectrum:** neutral H_i^0, A_i^0 , charged H^\pm , doubly charged $\Delta^{\pm\pm}$

▶ **Modified couplings:** mixing with extra “Higgs” or NP in loops $\delta g_{hxx} = \frac{g_{hxx}}{g_{hxx}^{\text{SM}}}$

$g(hAA)/g(hAA)|_{\text{SM}} - 1$ LHC/ILC1/ILC/ILCTeV



[Peskin, 1207.2516]

▶ 2HDM: $\delta g_{hVV} \approx 1 - 0.3\% (200 \text{ GeV}/M_A)^2$

$$\delta g_{htt} \approx 1 - 1.7\% (200 \text{ GeV}/M_A)^2 \dots$$

▶ Little Higgs (scalar T): $\delta g_{hgg} \approx 1 + 1.4\% (1 \text{ TeV}/M_T)^2$

$$\delta g_{h\gamma\gamma} \approx 1 - 0.4\% (1 \text{ TeV}/M_T)^2$$

▶ Composite: $\delta g_{hVV} \approx 1 - 3\% (1 \text{ TeV}/f)^2$

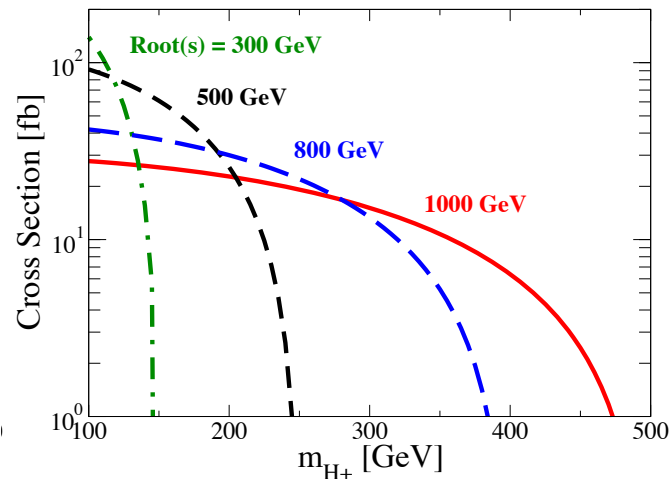
$$\delta g_{hff} \approx 1 - (3 - 9)\% (1 \text{ TeV}/f)^2$$

▶ **Disentangling NP contributions** \Rightarrow precision measurements $\mathcal{O}(\%)$ of Higgs couplings!

▶ **Linear Collider:** optimal environment $\rightsquigarrow \sqrt{s} = 500 \text{ GeV} \Rightarrow \delta g_{hxx} \lesssim 5\%$

New Physics Models: extended Higgs sectors

★ Multi-doublet models: additional scalars, pseudoscalars and charged states

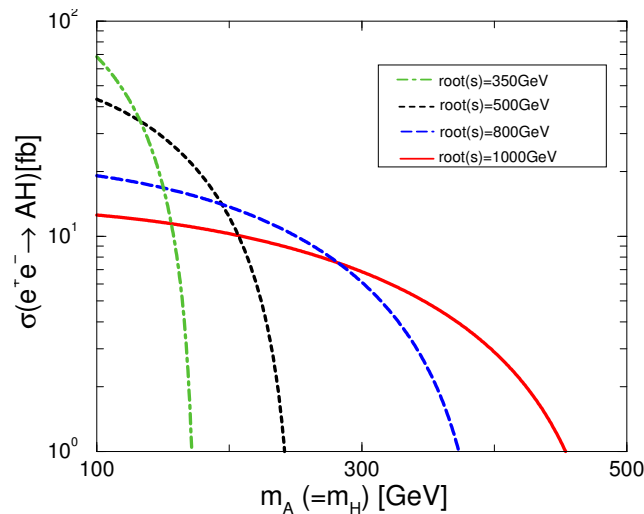


- ▶ **Charged Higgs:** production only depends on M_{H^\pm}
final states depend on spectrum...

- ▶ **LC:** $e^+e^- \rightarrow H^+H^- \rightarrow t\bar{t}t\bar{t}|_{\text{MSSM}}$

$$\sqrt{s} = 800 \text{ GeV}, \mathcal{L} = 1 \text{ ab}^{-1} \quad \Delta M_{H^\pm}^{\text{MSSM}} \sim \mathcal{O}(1.5\%)$$

[Gunion et al, '88; Djouadi et al, '93]



- ▶ **Pseudoscalar:** $\sigma(AH)$ depends **only** on $M_A \approx M_H$

- ▶ **Decays (fermions)** \Rightarrow determine g_{Hff} and g_{Aff}

Type II 2HDM (SUSY) $\rightsquigarrow \{4b, 2b2\tau\}$

Type I 2HDM $\rightsquigarrow \{4b, 2b2\tau, 2b2j\} \dots$

Type X 2HDM (lepton) $\rightsquigarrow \{4\tau\}$

- ▶ **LC:** $\Delta\sigma(e^+e^- \rightarrow AH \rightarrow 4b)_{\text{MSSM}} \sim \mathcal{O}(2-7\%)$

$$\Delta\Gamma_{A,H}^{\text{MSSM}} \sim \mathcal{O}(20 - 40\%); \quad \Delta M_H^{\text{MSSM}} \sim \mathcal{O}(1 \text{ GeV})$$

New Physics Models: extended Higgs sectors

★ Next-to Minimal Supersymmetric Standard Model

- ▶ Singlet superfield \Rightarrow extra neutral scalar H , pseudoscalar A and neutralino $\tilde{\chi}^0$
- ▶ Different phenomenology: possibility of light H_1 and A_1 (singlet-like) and singlino-like LSP (\rightsquigarrow dark matter); new states hard to produce and detect...

▶ Study case:

Scenario	m_{h_1}	m_{h_2}	m_{h_3}	m_{a_1}	m_{a_2}	m_{H^\pm}	$m_{\tilde{\chi}_1^0}$	Ωh^2	LSP singlino	LSP Higgsino	$R_{gg}^{h_2}(\gamma\gamma)$
I	99	124	311	140	302	295	76	0.099	18%	75%	1.62

$H_1 \Rightarrow$ LEP $b\bar{b}$ excess ~ 98 GeV; $H_2 \sim 125$ GeV, SM-like, enhanced $\gamma\gamma$ rates; viable DM

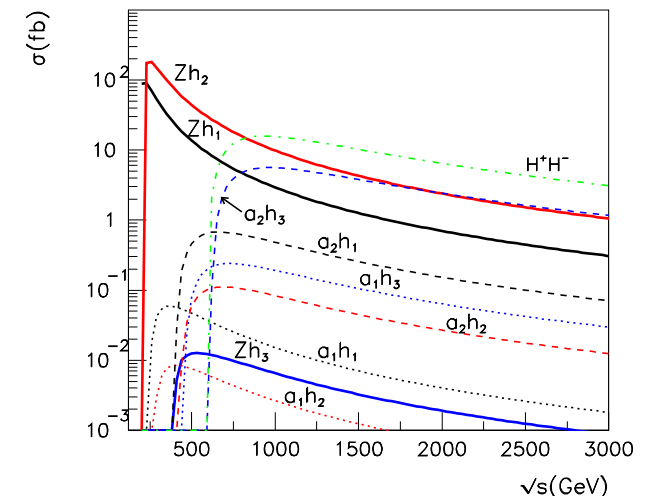
- ▶ LC: Large rates for ZH , HH , HA production

$$\sqrt{s} \sim 1 \text{ TeV}, \mathcal{L} = 1 \text{ ab}^{-1}$$

Final states $(t\bar{t})(t\bar{t})$, $(t\bar{t})(\tilde{\chi}_1^0\tilde{\chi}_1^0)$, ... easily identifiable

- ▶ LC: crucial to disentangle MSSM \leftrightarrow NMSSM

Higgs and neutralino sectors

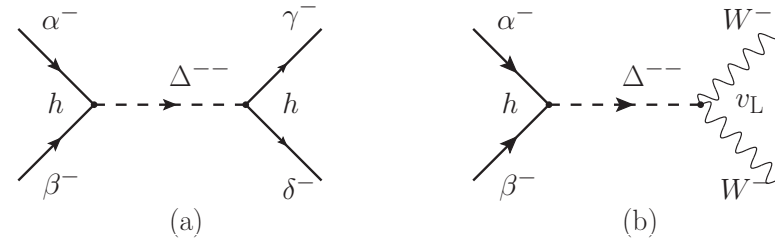


New Physics Models: exotic Higgs

★ **Higgs Triplets and doubly charged scalars** \rightsquigarrow massive neutrinos (type II seesaw)

► Phenomenological implications: **EW precision** (ρ), ν -phenomena, **cLFV**, ...

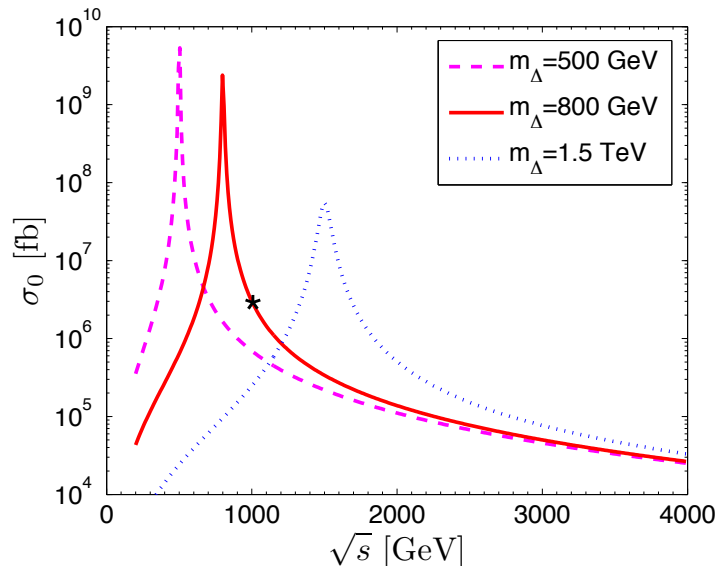
$$\Delta = \begin{pmatrix} \Delta^+/\sqrt{2} & \Delta^{++} \\ \Delta^{++} & -\Delta^+/\sqrt{2} \end{pmatrix}$$



► **LC**: substantial **EW Higgs pair production**; possible $e^-e^- \xrightarrow{\Delta^{--}} W^-W^-$

Study $e^+e^- \rightarrow \Delta^{--}\Delta^{++} \rightarrow l^+l^+jjjj\nu\nu\nu\nu$ (bckgd sufficiently reduced) [Aoki et al, 1110.4625]

$M_{\Delta^{--}} = 200 \text{ GeV}$, $\sigma^{\text{prod}}(\Delta^{--}\Delta^{++}) \sim 100 \text{ fb} \Rightarrow \sigma \sim 10 \text{ fb}$ for same-sign dilepton



► **LC**: study $e^-e^- \rightarrow \Delta^{--} \rightarrow l_i^- l_j^-$

\Rightarrow sensitive to ν mass scale and **Majorana phases**

$$\sigma^{\text{prod}}(e^-e^- \rightarrow l_i^- l_j^-) \sim \sigma_0 |Y^{ee} Y^{ij}|^2$$

► **Discovery**: shed light on mechanism of ν -mass generation, and ν -parameters

[Rodejohann and Zhang, 1011.3606]

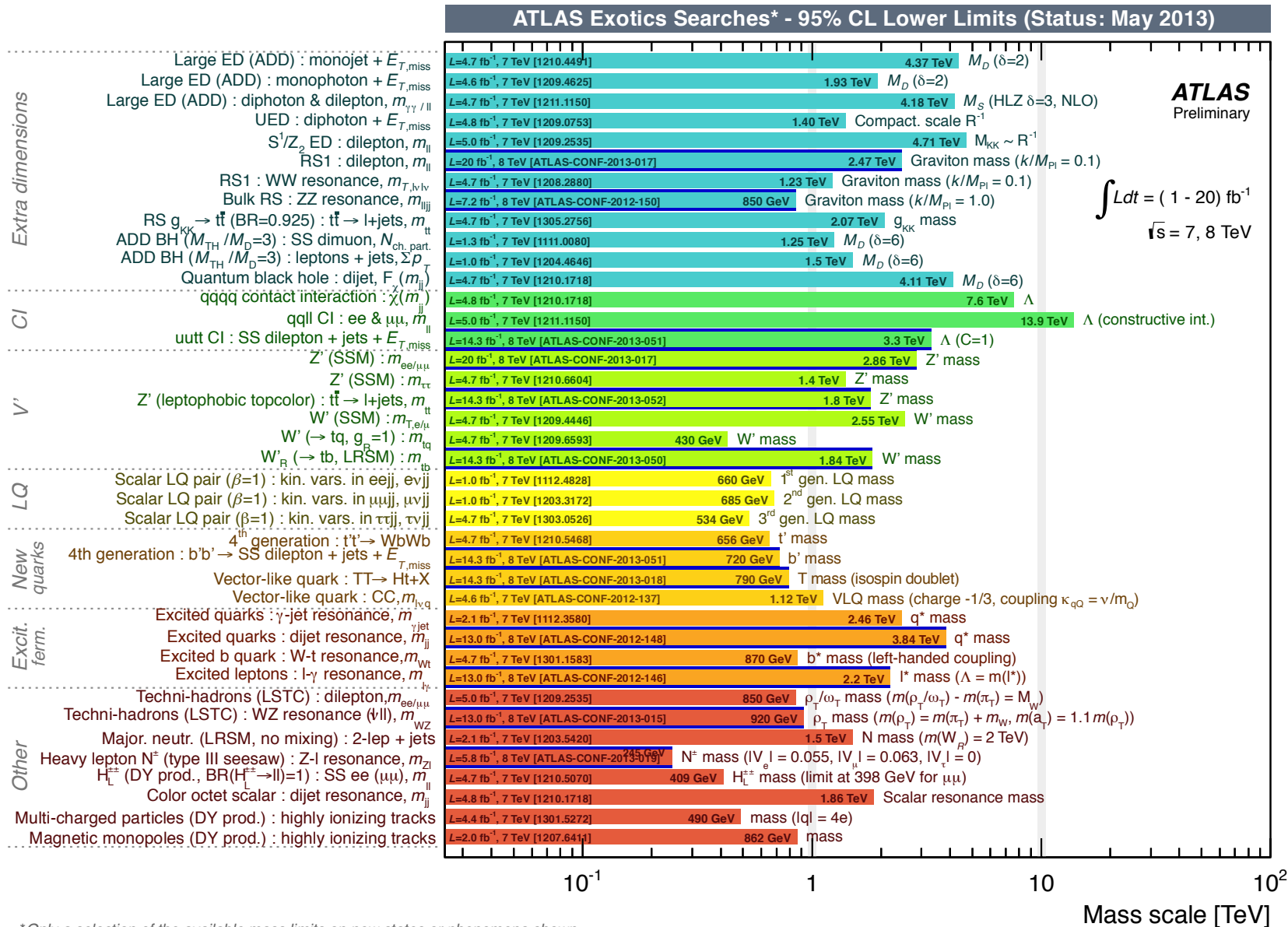
▶ **Concluding remarks**

BSM at a Linear Collider: (th) outlook

- ▶ Early LHC runs \rightsquigarrow no sign of New Physics at the TeV scale
- ▶ Collected data has led re-evaluation of many New Physics scenarios;
but LHC info is likely incomplete!
- ▶ Linear Collider has a very rich physics programme
- ▶ Discovery reach of a Linear Collider can exceed that of the LHC
- ▶ Unique Linear Collider features \Rightarrow instrumental precision machine (SM, Higgs, etc...)
- ▶ Crucial in sensitivity to New Physics effects from different BSM models
(tree level or higher-order) in numerous observables

▶ **Additional slides**

LHC bounds on BSM: Exotics



*Only a selection of the available mass limits on new states or phenomena shown

LHC bounds on BSM: SUSY

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: SUSY 2013

ATLAS Preliminary

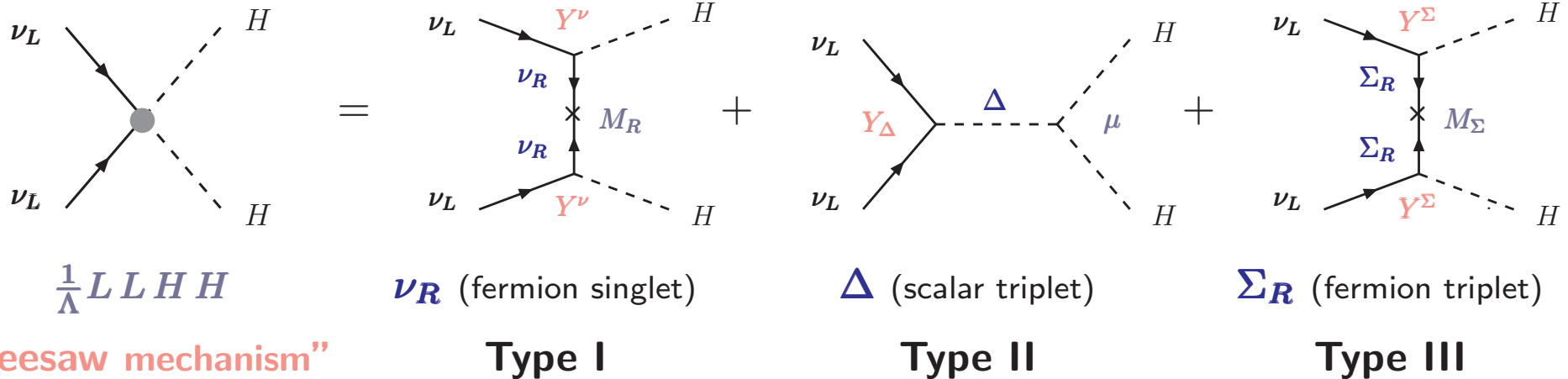
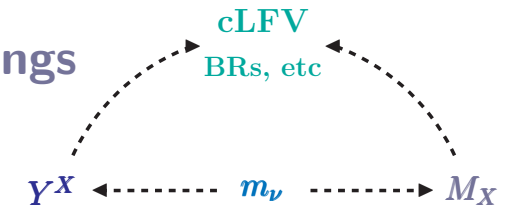
$$\int \mathcal{L} dt = (4.6 - 22.9) \text{ fb}^{-1} \quad \sqrt{s} = 7, 8 \text{ TeV}$$

Model	e, μ , τ , γ	Jets	E_T^{miss}	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Mass limit	Reference		
Inclusive Searches	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	\tilde{q}, \tilde{g} 1.7 TeV	$m(\tilde{q})=m(\tilde{g})$	ATLAS-CONF-2013-047
	MSUGRA/CMSSM	1 e, μ	3-6 jets	Yes	20.3	\tilde{g} 1.2 TeV	any $m(\tilde{q})$	ATLAS-CONF-2013-062
	MSUGRA/CMSSM	0	7-10 jets	Yes	20.3	\tilde{g} 1.1 TeV	any $m(\tilde{q})$	1308.1841
	$\tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	\tilde{q} 740 GeV	$m(\tilde{\chi}_1^0)=0 \text{ GeV}$	ATLAS-CONF-2013-047
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	\tilde{g} 1.3 TeV	$m(\tilde{\chi}_1^0)=0 \text{ GeV}$	ATLAS-CONF-2013-047
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qq\tilde{\chi}_1^0 \rightarrow qqW\tilde{\chi}_1^0$	1 e, μ	3-6 jets	Yes	20.3	\tilde{g} 1.18 TeV	$m(\tilde{\chi}_1^0) < 200 \text{ GeV}, m(\tilde{\chi}^\pm)=0.5(m(\tilde{\chi}_1^0)+m(\tilde{g}))$	ATLAS-CONF-2013-062
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qq(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$	2 e, μ	0-3 jets	-	20.3	\tilde{g} 1.12 TeV	$m(\tilde{\chi}_1^0)=0 \text{ GeV}$	ATLAS-CONF-2013-089
	GMSB ($\tilde{\ell}$ NLSP)	2 e, μ	2-4 jets	Yes	4.7	\tilde{g} 1.24 TeV	$\tan\beta < 15$	1208.4688
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ	0-2 jets	Yes	20.7	\tilde{g} 1.4 TeV	$\tan\beta > 18$	ATLAS-CONF-2013-026
	GGM (bino NLSP)	2 γ	-	Yes	4.8	\tilde{g} 1.07 TeV	$m(\tilde{\chi}_1^0) > 50 \text{ GeV}$	1209.0753
	GGM (wino NLSP)	1 e, $\mu + \gamma$	-	Yes	4.8	\tilde{g} 619 GeV	$m(\tilde{\chi}_1^0) > 50 \text{ GeV}$	ATLAS-CONF-2012-144
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	4.8	\tilde{g} 900 GeV	$m(\tilde{\chi}_1^0) > 220 \text{ GeV}$	1211.1167
	GGM (higgsino NLSP)	2 e, μ (Z)	0-3 jets	Yes	5.8	\tilde{g} 690 GeV	$m(H) > 200 \text{ GeV}$	ATLAS-CONF-2012-152
Gravitino LSP	0	mono-jet	Yes	10.5	$F^{1/2}$ scale 645 GeV	$m(\tilde{g}) > 10^{-4} \text{ eV}$	ATLAS-CONF-2012-147	
3 rd gen. \tilde{g}, \tilde{b} med.	$\tilde{g} \rightarrow b\tilde{b}\tilde{\chi}_1^0$	0	3 b	Yes	20.1	\tilde{g} 1.2 TeV	$m(\tilde{\chi}_1^0) < 600 \text{ GeV}$	ATLAS-CONF-2013-061
	$\tilde{g} \rightarrow t\tilde{t}\tilde{\chi}_1^0$	0	7-10 jets	Yes	20.3	\tilde{g} 1.1 TeV	$m(\tilde{\chi}_1^0) < 350 \text{ GeV}$	1308.1841
	$\tilde{g} \rightarrow t\tilde{t}\tilde{\chi}_1^0$	0-1 e, μ	3 b	Yes	20.1	\tilde{g} 1.34 TeV	$m(\tilde{\chi}_1^0) < 400 \text{ GeV}$	ATLAS-CONF-2013-061
	$\tilde{g} \rightarrow b\tilde{t}\tilde{\chi}_1^0$	0-1 e, μ	3 b	Yes	20.1	\tilde{g} 1.3 TeV	$m(\tilde{\chi}_1^0) < 300 \text{ GeV}$	ATLAS-CONF-2013-061
3 rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\tilde{\chi}_1^0$	0	2 b	Yes	20.1	\tilde{b}_1 100-620 GeV	$m(\tilde{\chi}_1^0) < 90 \text{ GeV}$	1308.2631
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow t\tilde{\chi}_1^0$	2 e, μ (SS)	0-3 b	Yes	20.7	\tilde{b}_1 275-430 GeV	$m(\tilde{\chi}_1^0)=2 m(\tilde{\chi}_1^0)$	ATLAS-CONF-2013-007
	$\tilde{t}_1\tilde{t}_1$ (light), $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^\pm$	1-2 e, μ	1-2 b	Yes	4.7	\tilde{t}_1 110-167 GeV	$m(\tilde{\chi}_1^0)=55 \text{ GeV}$	1208.4305, 1209.2102
	$\tilde{t}_1\tilde{t}_1$ (light), $\tilde{t}_1 \rightarrow Wb\tilde{\chi}_1^0$	2 e, μ	0-2 jets	Yes	20.3	\tilde{t}_1 130-220 GeV	$m(\tilde{\chi}_1^0)=m(\tilde{t}_1)-m(W)-50 \text{ GeV}, m(\tilde{t}_1) < m(\tilde{\chi}_1^\pm)$	ATLAS-CONF-2013-048
	$\tilde{t}_1\tilde{t}_1$ (medium), $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$	2 e, μ	2 jets	Yes	20.3	\tilde{t}_1 225-525 GeV	$m(\tilde{\chi}_1^0)=0 \text{ GeV}$	ATLAS-CONF-2013-065
	$\tilde{t}_1\tilde{t}_1$ (medium), $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^\pm$	0	2 b	Yes	20.1	\tilde{t}_1 150-580 GeV	$m(\tilde{\chi}_1^0) < 200 \text{ GeV}, m(\tilde{\chi}_1^\pm)-m(\tilde{\chi}_1^0)=5 \text{ GeV}$	1308.2631
	$\tilde{t}_1\tilde{t}_1$ (heavy), $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$	1 e, μ	1 b	Yes	20.7	\tilde{t}_1 200-610 GeV	$m(\tilde{\chi}_1^0)=0 \text{ GeV}$	ATLAS-CONF-2013-037
	$\tilde{t}_1\tilde{t}_1$ (heavy), $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$	0	2 b	Yes	20.5	\tilde{t}_1 320-660 GeV	$m(\tilde{\chi}_1^0)=0 \text{ GeV}$	ATLAS-CONF-2013-024
	$\tilde{t}_1\tilde{t}_1$ (natural GMSB)	2 e, μ (Z)	1 b	Yes	20.7	\tilde{t}_1 500 GeV	$m(\tilde{t}_1)-m(\tilde{\chi}_1^0) < 85 \text{ GeV}$	ATLAS-CONF-2013-025
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + Z$	3 e, μ (Z)	1 b	Yes	20.7	\tilde{t}_2 271-520 GeV	$m(\tilde{t}_1) > 150 \text{ GeV}$	ATLAS-CONF-2013-025
EW direct	$\tilde{\ell}_L\tilde{\ell}_R, \tilde{\ell}_L, \tilde{\ell}_R \rightarrow \tilde{\chi}_1^0$	2 e, μ	0	Yes	20.3	$\tilde{\ell}$ 85-315 GeV	$m(\tilde{\chi}_1^0)=0 \text{ GeV}$	ATLAS-CONF-2013-049
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\pm, \tilde{\chi}_1^\pm \rightarrow \tilde{\ell}\nu(\tilde{\ell}\bar{\nu})$	2 e, μ	0	Yes	20.3	$\tilde{\chi}_1^\pm$ 125-450 GeV	$m(\tilde{\chi}_1^\pm)=0 \text{ GeV}, m(\tilde{\ell}, \bar{\nu})=0.5(m(\tilde{\chi}_1^\pm)+m(\tilde{\chi}_1^0))$	ATLAS-CONF-2013-049
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\pm, \tilde{\chi}_1^\pm \rightarrow \tilde{\tau}\nu(\tilde{\tau}\bar{\nu})$	2 τ	-	Yes	20.7	$\tilde{\chi}_1^\pm$ 180-330 GeV	$m(\tilde{\chi}_1^\pm)=0 \text{ GeV}, m(\tilde{\tau}, \bar{\nu})=0.5(m(\tilde{\chi}_1^\pm)+m(\tilde{\chi}_1^0))$	ATLAS-CONF-2013-028
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^0 \rightarrow \tilde{\ell}_L\nu\tilde{\ell}_L(\tilde{\nu}\nu), \tilde{\ell}\tilde{\nu}\tilde{\ell}_L(\tilde{\nu}\nu)$	3 e, μ	0	Yes	20.7	$\tilde{\chi}_1^\pm, \tilde{\chi}_1^0$ 315 GeV 600 GeV	$m(\tilde{\chi}_1^\pm)=m(\tilde{\chi}_1^0), m(\tilde{\chi}_1^0)=0, m(\tilde{\ell}, \bar{\nu})=0.5(m(\tilde{\chi}_1^\pm)+m(\tilde{\chi}_1^0))$	ATLAS-CONF-2013-035
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^0 \rightarrow W\tilde{\chi}_1^\pm Z\tilde{\chi}_1^0$	3 e, μ	0	Yes	20.7	$\tilde{\chi}_1^\pm, \tilde{\chi}_1^0$ 315 GeV	$m(\tilde{\chi}_1^\pm)=m(\tilde{\chi}_1^0), m(\tilde{\chi}_1^0)=0$, sleptons decoupled	ATLAS-CONF-2013-035
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^0 \rightarrow W\tilde{\chi}_1^\pm h\tilde{\chi}_1^0$	1 e, μ	2 b	Yes	20.3	$\tilde{\chi}_1^\pm, \tilde{\chi}_1^0$ 285 GeV	$m(\tilde{\chi}_1^\pm)=m(\tilde{\chi}_1^0), m(\tilde{\chi}_1^0)=0$, sleptons decoupled	ATLAS-CONF-2013-093
	Long-lived particles	Direct $\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	Yes	20.3	$\tilde{\chi}_1^\pm$ 270 GeV	$m(\tilde{\chi}_1^\pm)-m(\tilde{\chi}_1^0)=160 \text{ MeV}, \tau(\tilde{\chi}_1^\pm)=0.2 \text{ ns}$
Stable, stopped \tilde{g} R-hadron		0	1-5 jets	Yes	22.9	\tilde{g} 832 GeV	$m(\tilde{\chi}_1^0)=100 \text{ GeV}, 10 \mu\text{s} < \tau(\tilde{g}) < 1000 \text{ s}$	ATLAS-CONF-2013-057
GMSB, stable $\tilde{\tau}, \tilde{\chi}_1^\pm \rightarrow \tilde{\tau}(\tilde{e}, \tilde{\mu}) + \tau(e, \mu)$		1-2 μ	-	-	15.9	$\tilde{\chi}_1^\pm$ 475 GeV	$0.4 < \tau(\tilde{\chi}_1^\pm) < 2 \text{ ns}$	ATLAS-CONF-2013-058
GMSB, $\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$		2 γ	-	Yes	4.7	$\tilde{\chi}_1^0$ 230 GeV	$1.5 < c\tau < 156 \text{ mm}, \text{BR}(\mu)=1, m(\tilde{\chi}_1^0)=108 \text{ GeV}$	1304.6310
$\tilde{q}\tilde{q}, \tilde{\chi}_1^0 \rightarrow qq\mu$ (RPV)		1 μ , disp. vtx	-	-	20.3	\tilde{q} 1.0 TeV		ATLAS-CONF-2013-092
RPV	LFV $pp \rightarrow \tilde{\nu}_e + X, \tilde{\nu}_e \rightarrow e + \mu$	2 e, μ	-	-	4.6	$\tilde{\nu}_e$ 1.61 TeV	$\lambda_{111}^e=0.10, \lambda_{132}^e=0.05$	1212.1272
	LFV $pp \rightarrow \tilde{\nu}_e + X, \tilde{\nu}_e \rightarrow e(\mu) + \tau$	1 e, $\mu + \tau$	-	-	4.6	$\tilde{\nu}_e$ 1.1 TeV	$\lambda_{111}^e=0.10, \lambda_{1(2)33}^e=0.05$	1212.1272
	Bilinear RPV CMSSM	1 e, μ	7 jets	Yes	4.7	\tilde{q}, \tilde{g} 1.2 TeV	$m(\tilde{q})=m(\tilde{g}), c\tau_{\text{LSP}} < 1 \text{ mm}$	ATLAS-CONF-2012-140
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp, \tilde{\chi}_1^\pm \rightarrow W\tilde{\chi}_1^0, \tilde{\chi}_1^\pm \rightarrow ee\nu_\mu, e\mu\nu_e$	4 e, μ	-	Yes	20.7	$\tilde{\chi}_1^\pm$ 760 GeV	$m(\tilde{\chi}_1^0) > 300 \text{ GeV}, \lambda_{121} > 0$	ATLAS-CONF-2013-036
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp, \tilde{\chi}_1^\pm \rightarrow W\tilde{\chi}_1^0, \tilde{\chi}_1^\pm \rightarrow \tau\tau\nu_e, e\tau\nu_e$	3 e, $\mu + \tau$	-	Yes	20.7	$\tilde{\chi}_1^\pm$ 350 GeV	$m(\tilde{\chi}_1^0) > 80 \text{ GeV}, \lambda_{133} > 0$	ATLAS-CONF-2013-036
	$\tilde{g} \rightarrow qq\tilde{q}$	0	6-7 jets	-	20.3	\tilde{g} 916 GeV	$\text{BR}(\tilde{t})=\text{BR}(\tilde{b})=\text{BR}(\tilde{c})=0\%$	ATLAS-CONF-2013-091
$\tilde{g} \rightarrow \tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow b\tilde{s}$	2 e, μ (SS)	0-3 b	Yes	20.7	\tilde{g} 880 GeV		ATLAS-CONF-2013-007	
Other	Scalar gluon pair, sgluon $\rightarrow q\tilde{q}$	0	4 jets	-	4.6	sgluon 100-287 GeV	incl. limit from 1110.2693	1210.4826
	Scalar gluon pair, sgluon $\rightarrow t\tilde{t}$	2 e, μ (SS)	1 b	Yes	14.3	sgluon 800 GeV		ATLAS-CONF-2013-051
	WIMP interaction (D5, Dirac χ)	0	mono-jet	Yes	10.5	M^* scale 704 GeV	$m(\chi) < 80 \text{ GeV}$, limit of $< 687 \text{ GeV}$ for D8	ATLAS-CONF-2012-147

*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

cLFV and the seesaw mechanism

★ **Seesaw mechanism:** explain **small ν masses** with “natural” couplings via **new dynamics** at “heavy” scale



Seesaw	$\tilde{\mathcal{C}}_5$	New Physics scales	$\tilde{\mathcal{C}}_6$	cLFV obs
Fermionic singlet (type I)	$Y_N^T \frac{1}{M_N} Y_N$	$Y_N \sim \mathcal{O}(1) \Rightarrow M_N \approx 10^{15} \text{ GeV}$ $M_N \sim M_{\text{GUT}}???$	$\left(Y_N^\dagger \frac{1}{M_N^\dagger} \frac{1}{M_N} Y_N \right)_{\alpha\beta}$...
Fermionic triplet (type III)	$Y_\Sigma^T \frac{1}{M_\Sigma} Y_\Sigma$	“ ”	$\left(Y_\Sigma^\dagger \frac{1}{M_\Sigma^\dagger} \frac{1}{M_\Sigma} Y_\Sigma \right)_{\alpha\beta}$...
Scalar triplet (type II)	$4Y_\Delta \frac{\mu_\Delta}{M_\Delta^2}$	$Y_\Delta \sim \mathcal{O}(1) \Rightarrow M_\Delta \approx \text{TeV}$ $(\mu_\Delta \ll 1!)$	$\frac{1}{M_\Delta^2} Y_{\Delta\alpha\beta} Y_{\Delta\gamma\delta}^\dagger$	large BRs ! constrain model!

Type-I SUSY seesaw: flavour violating slepton masses

- ▶ **mSUGRA-like SUSY seesaw:** Y^ν unique source of **FV**

- ▶ Even for **universal** soft-breaking terms **RGE running of Y^ν** ($M_{\text{GUT}} \rightarrow M_R$)

induces **flavour-violating** terms in slepton soft-breaking masses

$$(\Delta m_{\tilde{L}}^2)_{ij} = -\frac{1}{8\pi^2} (3m_0^2 + A_0^2) (Y^{\nu\dagger} L Y^\nu)_{ij} \quad L = \log(M_{\text{GUT}}/M_N)$$

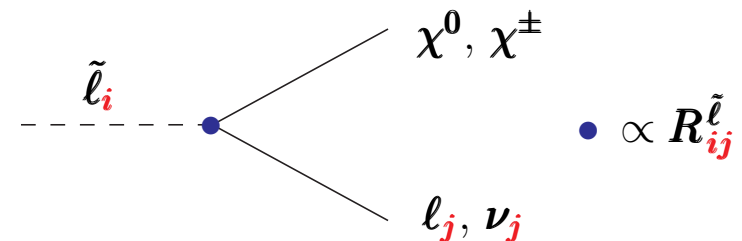
[Borzumati, Masiero; Hisano; ...]

$$(M_{\tilde{\ell}}^2)_{ij} \neq 0!$$

- ▶ **Misalignment of flavour and physical eigenstates:** $R^{\tilde{\ell}\dagger} M_{\tilde{\ell}}^2 R^{\tilde{\ell}} = \text{diag}(m_{\tilde{\ell}_i}^2) \quad R^{\tilde{\ell}} \neq 1!$

$$\{\tilde{e}_L, \tilde{\mu}_L, \tilde{\tau}_L, \tilde{e}_R, \tilde{\mu}_R, \tilde{\tau}_R\} \leftrightarrow \{\tilde{\ell}_1, \dots, \tilde{\ell}_6\}$$

LFV manifest in **neutral** and
charged **lepton-slepton** interactions



- ▶ Expect many interesting **flavour violating** transitions in **charged leptons!**

[“observables” $\propto (Y^\nu)^n$; important degree of correlation ...]