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, $1/\Lambda_{\rm NP}$-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), E_6, extra dims, Little Higgs, ...**

  leading to additional new, neutral gauge boson Z'

- **LHC searches: $M_{Z'} \gtrsim$ 2 - 3 TeV** (precludes on-shell production at LC)
- **LC: sensitive to $M_{Z'} \gg \sqrt{s}$** via **indirect effects** in **precision measurements**

  small deviations in $e^+e^- \to f\bar{f}$ 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** $SU(2)_R \times U(1)_{B-L} \to U(1)_Y$

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

Discovery reach for models of Z' at Linear Collider

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

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

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

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

- **"Alternative" Left-Right symmetric (ALR)**

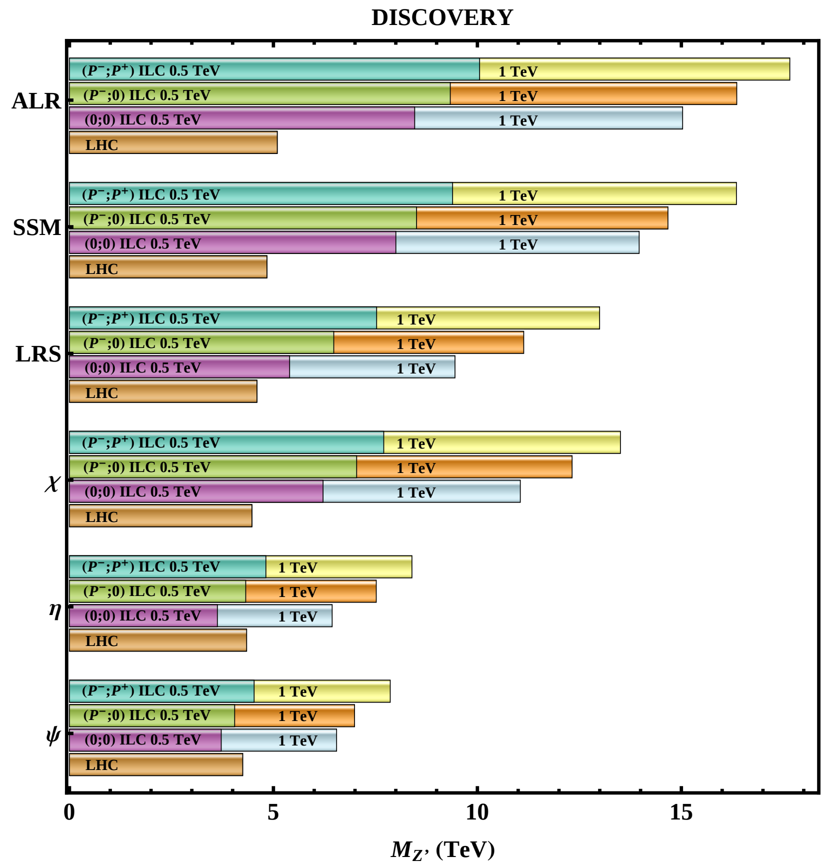
  E_6 embedding of LRS

- **Sequential Standard Model (SSM)**

  all Z' couplings same as for the SM Z

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

  χ $(\beta = 0)$; η $(\beta = \pi/2)$; ψ $(\beta = \pi - \arctan\sqrt{5/3})$



[Osland et al, 0912.2806]

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

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

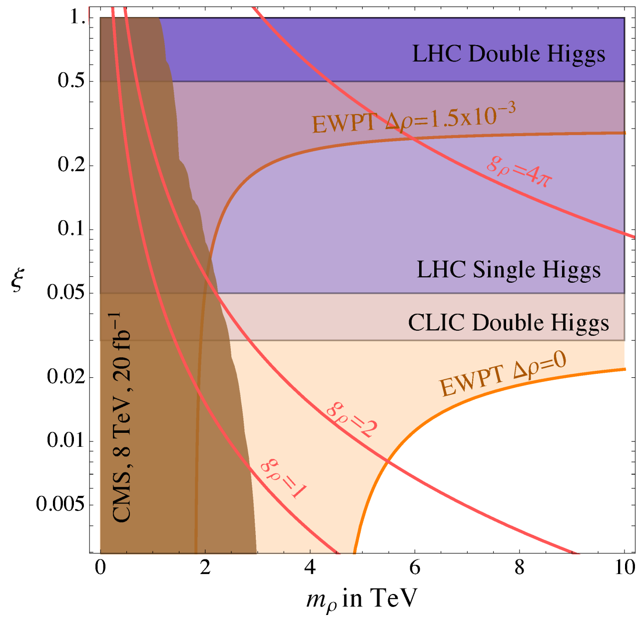
New Physics Models: Compositeness

★ **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** $\xi = \frac{v^2}{\Lambda^2_{\text{comp}}} \ll 1$
- **Precision measurements** of **production cross sections** $\sigma(VV \to VV, HH)$ and

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

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



[Contino et al, 1309.7038]

- **New couplings** from **"strong" EWSB:**

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

  polarise $e^{\pm}$ **beams!**

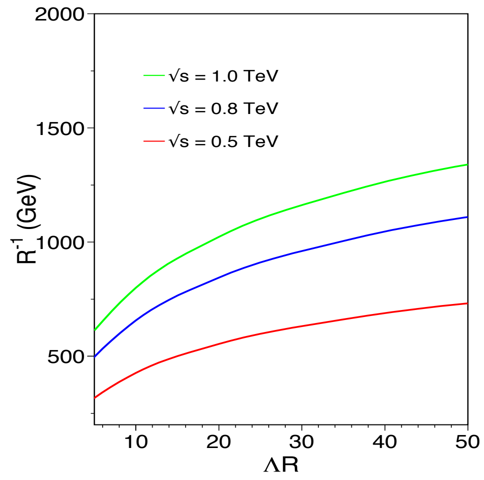
New Physics Models: Extra dimensions

★ **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 + $E^T{}_{\text{miss}}$): $\mathbf{1/R} \gtrsim$ **1.5 TeV**
  - **LC: resonances** (and contact interactions) in $e^+e^- \to f\bar{f}$



[Riemann, 0508136]

- **Large Extra Dimensions (LED)** [$k \geq$2, $\gtrsim$ TeV^{-1}, 4D SM]
  - **LHC** (jet + $E^T{}_{\text{miss}}$): $\boldsymbol{M_D} \gtrsim$ **3 - 5 TeV** (k=2 ... 6)
  - **LC: graviton contact interaction** effects in $e^+e^- \to G_{KK} \to f\bar{f}$

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

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

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

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

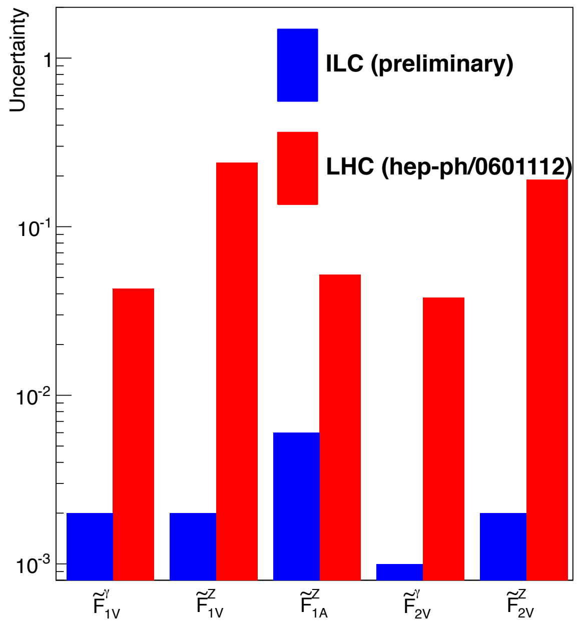
- Anomalous magnetic moment ⇒ **top compositness**

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

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

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

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



- Top asymmetries A^t_{FB} and A^t_{LR} (← polarised beams)

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

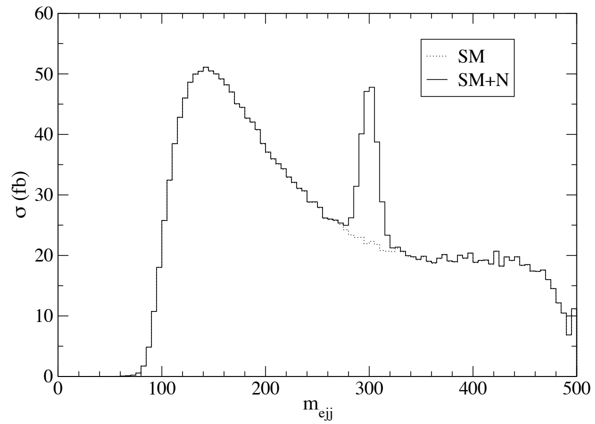
- **LC** at $\sqrt{s} = 500$ **GeV** and $(P_{e^-}, P_{e^+}) = (80\%, 0) \Rightarrow$ **statistical precision** $\sim 1\%$

  $\Delta A^t_{\text{LR}}/A^t_{\text{LR}} = 1.24\%$; $\Delta A^{t_R}_{\text{FB}}/A^{t_R}_{\text{FB}} = 1.2\%$; $\Delta A^{t_L}_{\text{FB}}/A^{t_L}_{\text{FB}} = 1.4\%$ [Doublet et al, 1202.6659]

New Physics Models: exotic fermions

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

- **Models of Majorana neutrinos: type I and III seesaws**

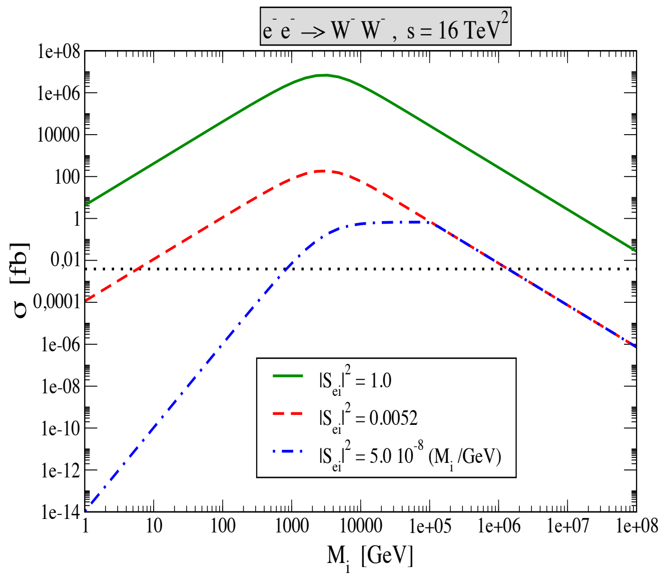


- **Heavy** ν_R searched for in $e^+e^- \to \nu_R\nu \to \ell W\nu \to \ell jj\nu$

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

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

  $\Rightarrow V_{e\nu_R} \lesssim \mathcal{O}(10^{-3})$ [del Aguila et al, 0502189]



- **Inverse $0\nu2\beta$ decay** $(e^-e^- \to W^-W^-)$: **Majorana** ν_R
- **LC:** $\sqrt{s}$ = **4 TeV** $\Rightarrow$ **up to** 10^4 **events expected**

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

[Rodejohann, 1005.2854] $\sqrt{s} \gg$ 1 TeV ($0\nu2\beta$ decay bounds)

- **Doubly charged leptons** $\Sigma^{\pm\pm}$: $e^+e^- \to \gamma, Z \to \Sigma^{++}\Sigma^{--}$
- **LC:** $\sqrt{s}$ = **1.5 TeV**, $\mathcal{L}$ = **100** fb^{-1} $\Rightarrow \mathcal{O}(10^4)$ $\Sigma^{\pm\pm}$ **pairs**

  400 GeV $\lesssim M_{\Sigma^{\pm\pm}} \lesssim$ 700 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 $M_{\tilde{\psi}}$, $\Gamma_{\tilde{\psi}}$, $\sigma^{\text{prod}}_{\tilde{\psi}}$, $\theta^{\tilde{\psi}}_{ij}$, ... and prove their are **spartners!**

  Reconstruct $\mathcal{L}^{\text{eff}}_{\text{SUSY}}$, **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**

  $\Rightarrow$ **discovery reach** close to $\sqrt{s}/2$ for $e^+e^- \to \tilde{\psi}_A\tilde{\psi}_A$, or **higher** for $e^+e^- \to \tilde{\psi}_A\tilde{\psi}_B$

- 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)

  $\Rightarrow$ **precision measurents** - **‰** in **masses and couplings**

  $\Rightarrow$ determination of **properties** of new states - spin, CP, Majorana nature...

- **Some illustrative examples**

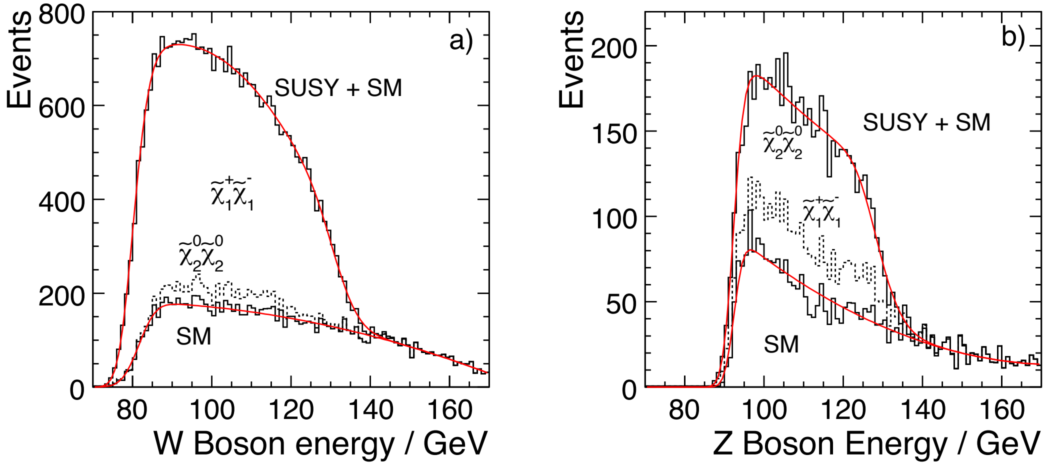
  Chargino and **neutralino** **masses and properties;**

  Slepton masses and charged lepton flavour violation;

  Higgs $\rightsquigarrow$ 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]

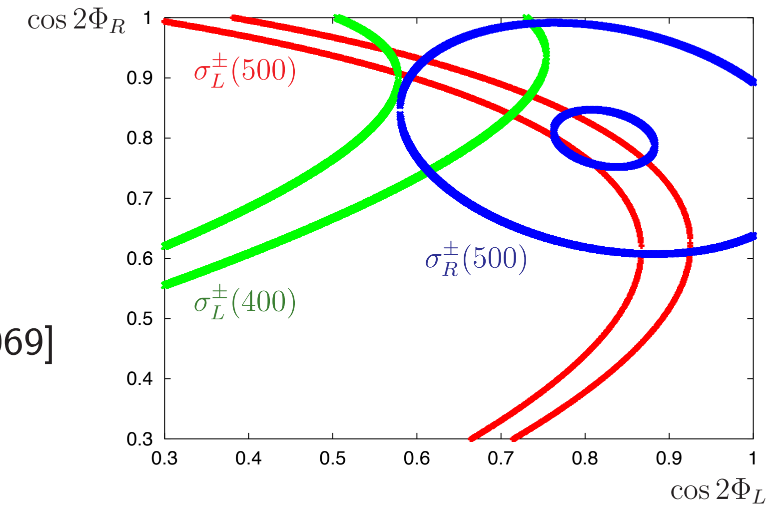
- **EW-ino pair production:** $\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_2^0\tilde{\chi}_2^0$, $\tilde{\chi}_2^0\tilde{\chi}_1^0$

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

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

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

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

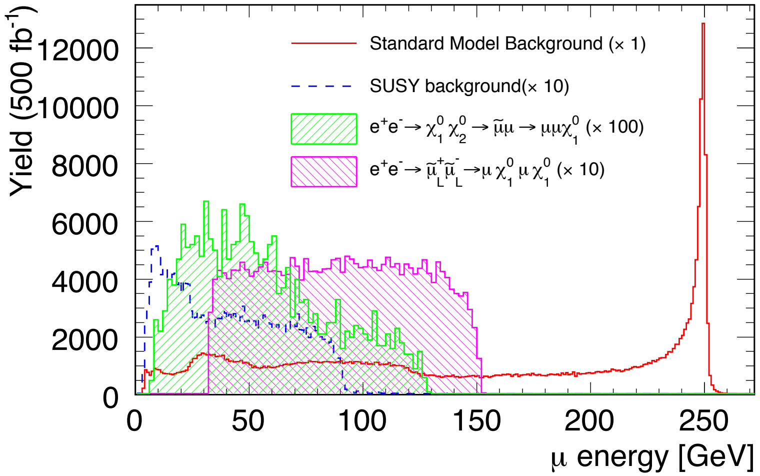
- **Majorana** χ^0 : (polarised) $e^-e^- \to \tilde{e}_L\tilde{e}_L, \tilde{e}_R\tilde{e}_R \to e^-\tilde{\chi}_1^0 e^-\tilde{\chi}_1^0 f\bar{f}$

[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 ⇝ $M_{\tilde{\mu}_L}$ and $M_{\tilde{\chi}^0_1}$
- LC: $\sqrt{s} = 500$ GeV, $\mathcal{L} = 500$ fb^{-1}, P=(80%,60%)

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

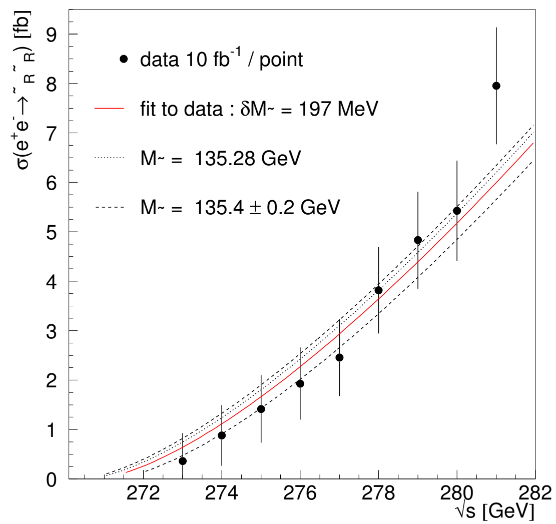
[Berggren et al, 0902.2434]

- Determining smuon mass from threshold scans:

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

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

[Berggren, in 1306.6352]

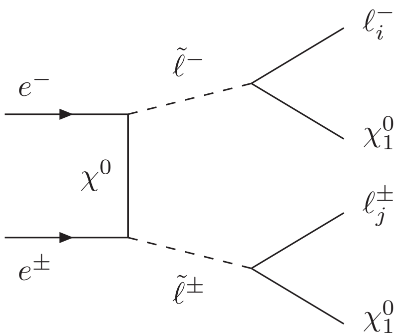


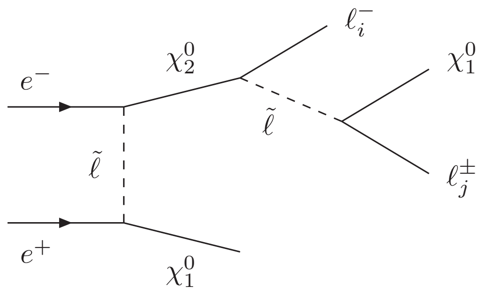
- If flavour violated in the charged (s)lepton sector ⇒ LC ideal to study cLFV!

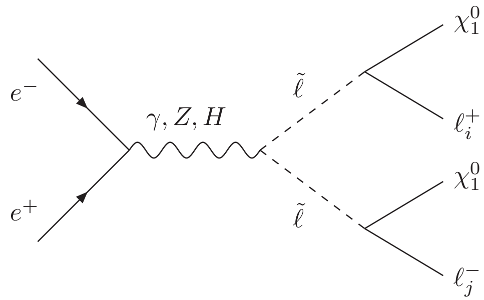
SUSY seesaw at a LC: charged lepton flavour violation

- **Consider** $e^{\pm} e^{-} \to e^{\pm}\mu^{-} + E^{T}_{\text{miss}} \rightsquigarrow \begin{cases} e^{\pm}\mu^{-} + 2\,\chi^0_1 & \text{(signal)} \\ e^{\pm}\mu^{-} + 2\,\chi^0_1 + (2,4)\,\nu & \text{(SUSY backg)} \\ e^{\pm}\mu^{-} + (2,4)\,\nu & \text{(SM}_{m_\nu}\text{ backg)} \end{cases}$

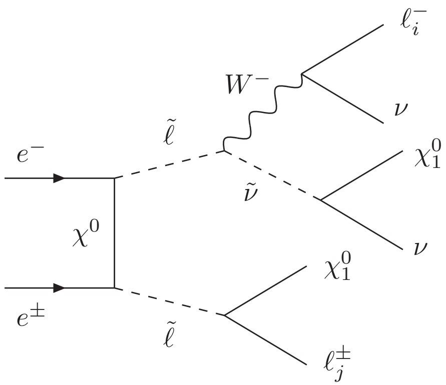
- **Signal events: dominated by LFV SUSY neutral currents**

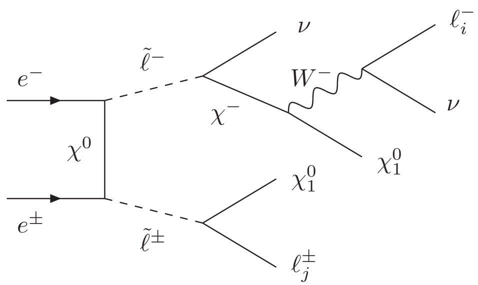


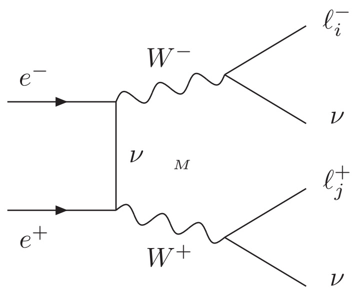


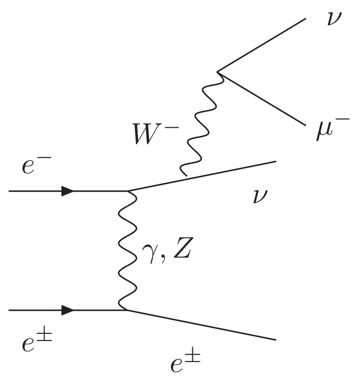


- **SUSY & SM$_{m_\nu}$ backg: cLFV from charged currents** - low-energy **leptonic mixing**





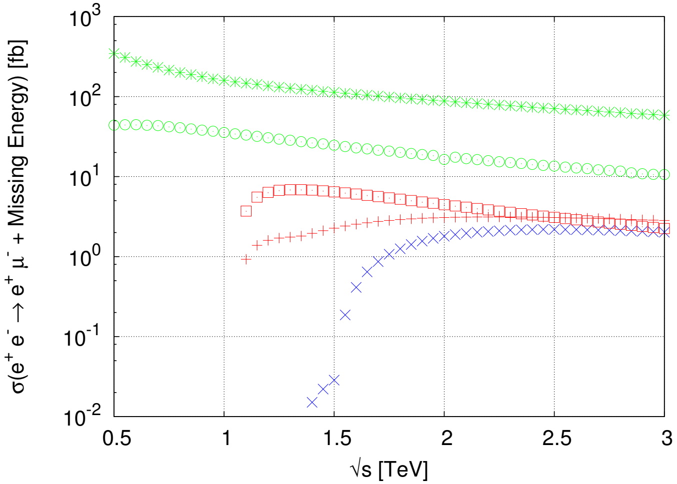




[Abada, Figueiredo, Romao and AMT, 1206.2306]

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

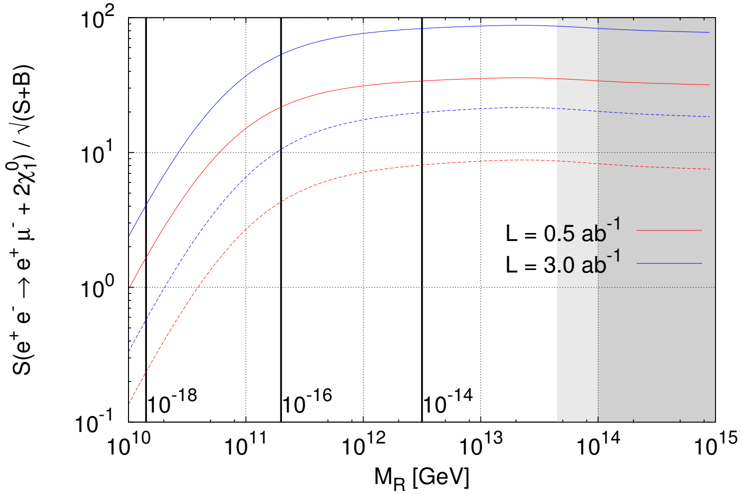
$*$, $+$, $\times$ $\to$ unpolarised

$\circ$, $\square$ $\to e^+_L e^-_L$

m_i	GeV
χ^0_1	400
χ^0_2, $\chi^\pm_1$	760
$\tilde{\nu}_L$	656
$\tilde{\ell}_R$	410
$\tilde{\ell}_L$	663

- **Dominant** SM$_{m_\nu}$ backg (disentangled from SUSY events - cuts, etc);

  Polarisation: **enhance signal;** reduce (remove) SM$_{m_\nu}$ (**SUSY**) backg



- **Significance** for SUSY [–] and SUSY+SM$_{m_\nu}$ [$\cdots$] backg

  $\Rightarrow$ typically $\mathcal{S} \gtrsim \mathbf{10}$ (unpolarised)

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

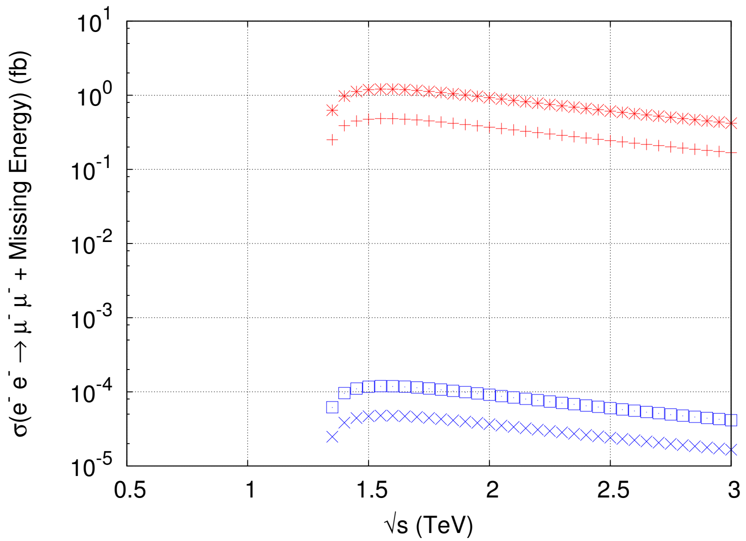
  $\mathcal{O}(10^3)$ **events** for $\mathcal{L} = 0.5$ **ab**$^{-1}$

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

SUSY seesaw at a LC: the "golden channel" for cLFV

▶ **Consider** $e^- e^- \to \mu^- \mu^- + E^T_{\text{miss}} \leadsto \begin{cases} \mu^- \mu^- + 2\,\chi^0_1 & \text{(signal)} \\ \mu^- \mu^- + 2\,\chi^0_1 + (2,4)\,\nu & \text{(SUSY backg)} \end{cases}$

SM_{m_ν} backg negligible ...



■ cLFV signal

■ SUSY backg

$+$, $\times$ $\to$ unpolarised

$*$, $\square$ $\to$ $e^-_L e^-_L$

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

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

▶ **Ideal cLFV discovery channel** $\Rightarrow$ $e^- e^- \to \mu^- \mu^- + E^T_{\text{miss}}$ [provided $\sqrt{s}$ large ...]

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

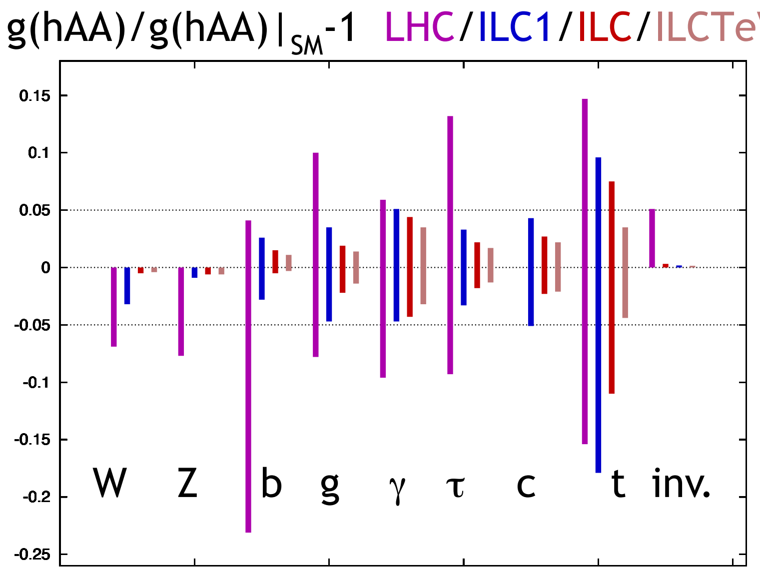
▶ **RR-polarised e^- can test seesaw hypothesis: $\tilde{\ell}$ cLFV predominantly LL phenomenon**

- **Enlarged Higgs sectors**

New Physics Models: modified Higgs sectors

★ **Modified Higgs sectors** ⇝ EWSB, hierarchy problem, DM candidates, massive νs...

- ▶ 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 $\delta g_{hxx} = \frac{g_{hxx}}{g_{hxx}^{\text{SM}}}$



[Peskin, 1207.2516]

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

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

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

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

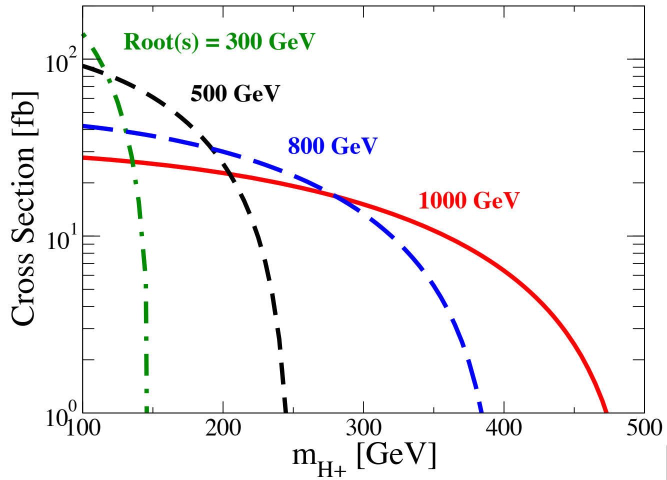
- ▶ Composite: $\delta g_{hVV} \approx 1 - 3\% \, (1 \text{ TeV}/f)^2$

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

- ▶ **Disentangling NP contributions ⇒ precision measurements $\mathcal{O}(\%)$ of Higgs couplings!**
- ▶ **Linear Collider:** optimal environment ⇝ $\sqrt{s} = 500$ **GeV** ⇒ $\delta g_{hxx} \lesssim 5\%$

New Physics Models: extended Higgs sectors

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



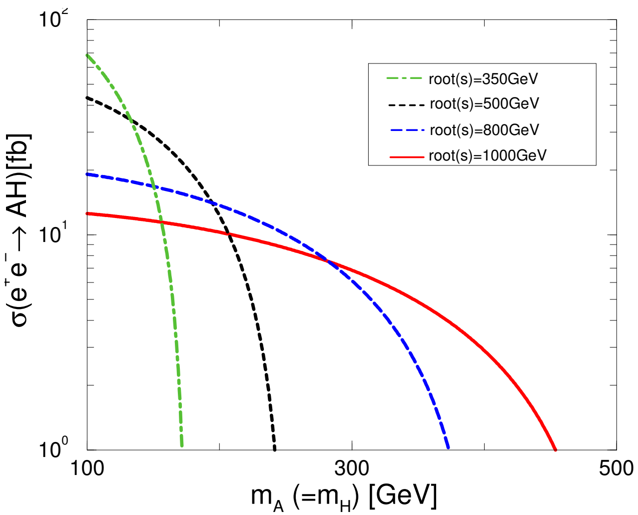
▶ Charged Higgs: **production** only depends on $M_{H^\pm}$

final states depend on **spectrum...**

▶ LC: $e^+e^- \to H^+H^- \to t\bar{b}\,\bar{t}b|_{\text{MSSM}}$

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

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



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

▶ **Decays (fermions)** ⇒ determine g_{Hff} and g_{Aff}

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

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

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

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

$\Delta\Gamma_{A,H}^{\text{MSSM}} \sim \mathcal{O}$ (20 - 40%); $\Delta M_H^{\text{MSSM}} \sim \mathcal{O}$ (1 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 $\sim$ **98 GeV**; $H_2 \sim$ **125 GeV, SM-like, enhanced** $\gamma\gamma$ rates; viable DM

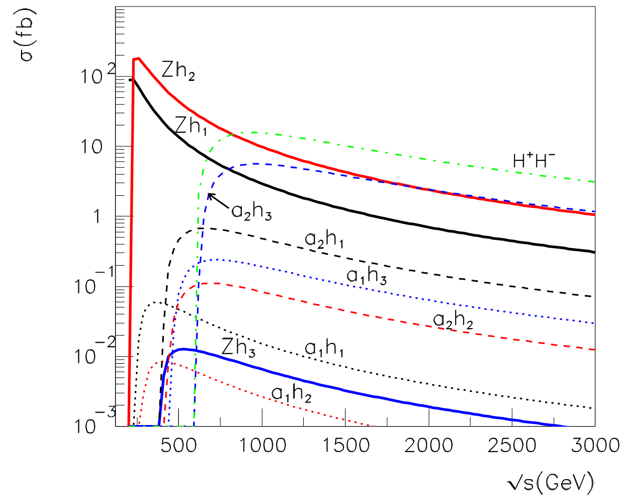
- **LC: Large rates** for ZH, HH, HA **production**

  $\sqrt{s} \sim 1$ **TeV**, $\mathcal{L} = 1$ **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



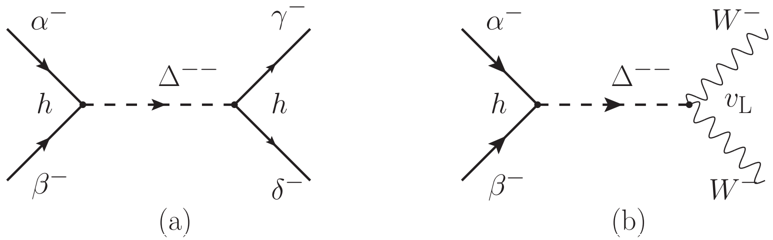
[Belanger et al, 1209.1976]

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**, ...

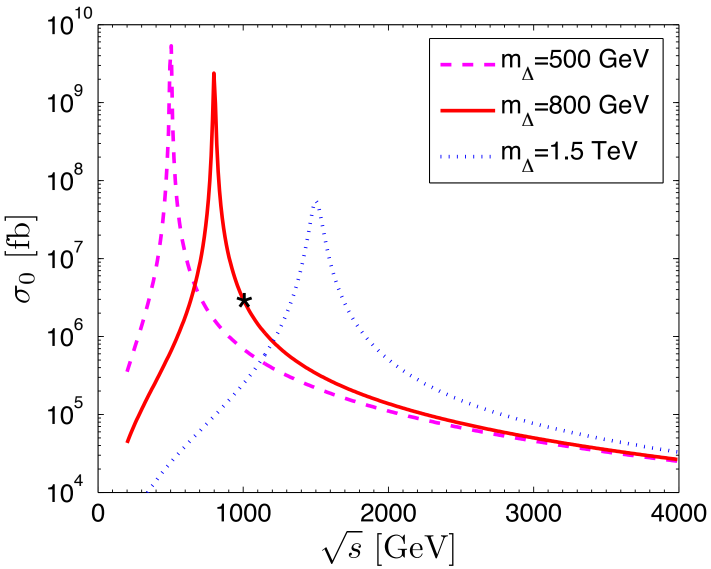
$$\Delta = \begin{pmatrix} \Delta^+/\sqrt{2} & \Delta^{++} \\ \Delta^{++} & -\Delta^+/\sqrt{2} \end{pmatrix}$$



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

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

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



- **LC: study** $e^-e^- \to \Delta^{--} \to \ell_i^-\ell_j^-$

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

  $$\sigma^{\text{prod}}(e^-e^- \to \ell_i^-\ell_j^-) \sim \sigma_0 |Y^{ee}Y^{ij}|^2$$

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

[Rodejohann and Zhang, 1011.3606]

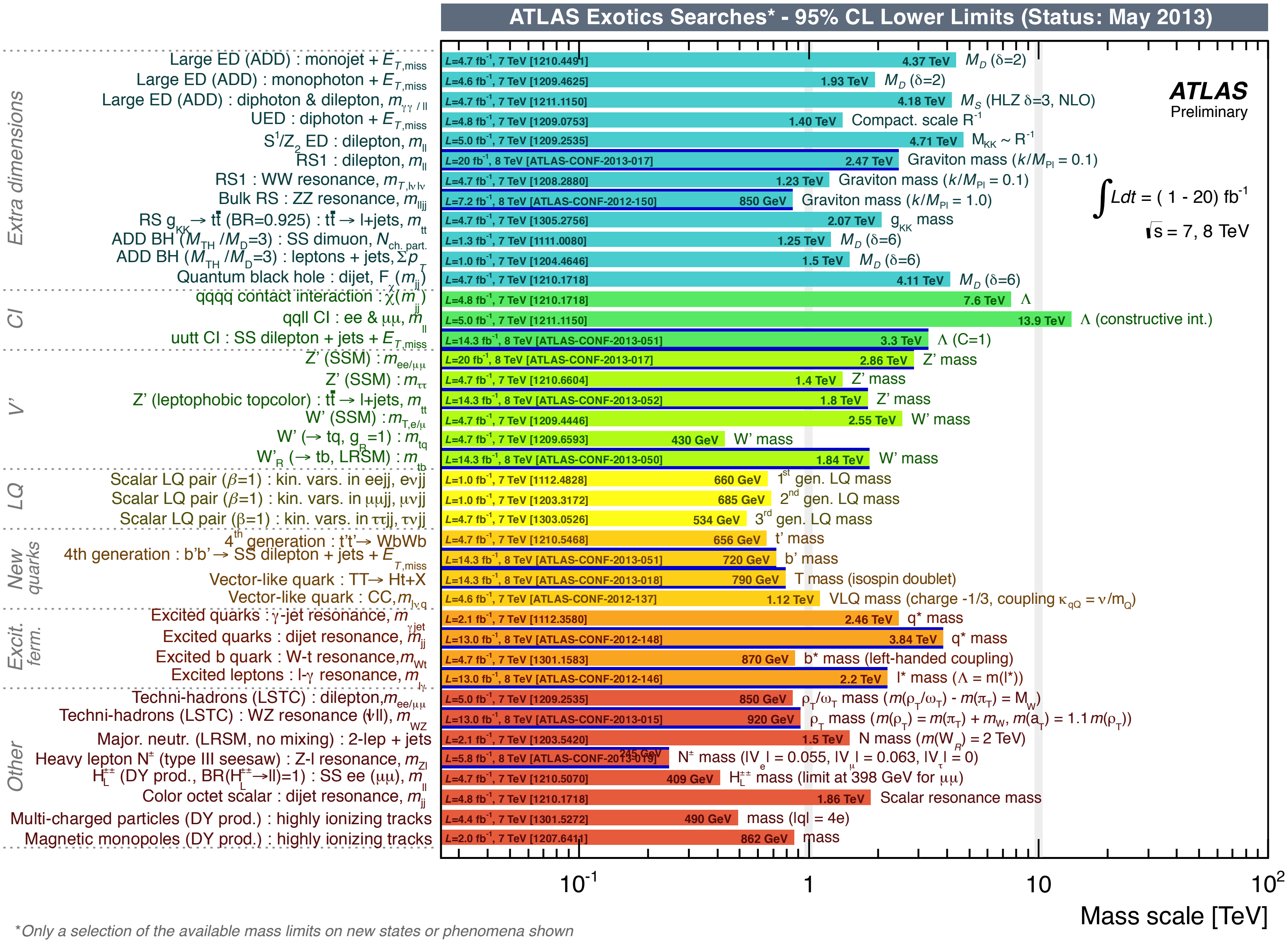
▶ Concluding remarks

BSM at a Linear Collider: (th) outlook

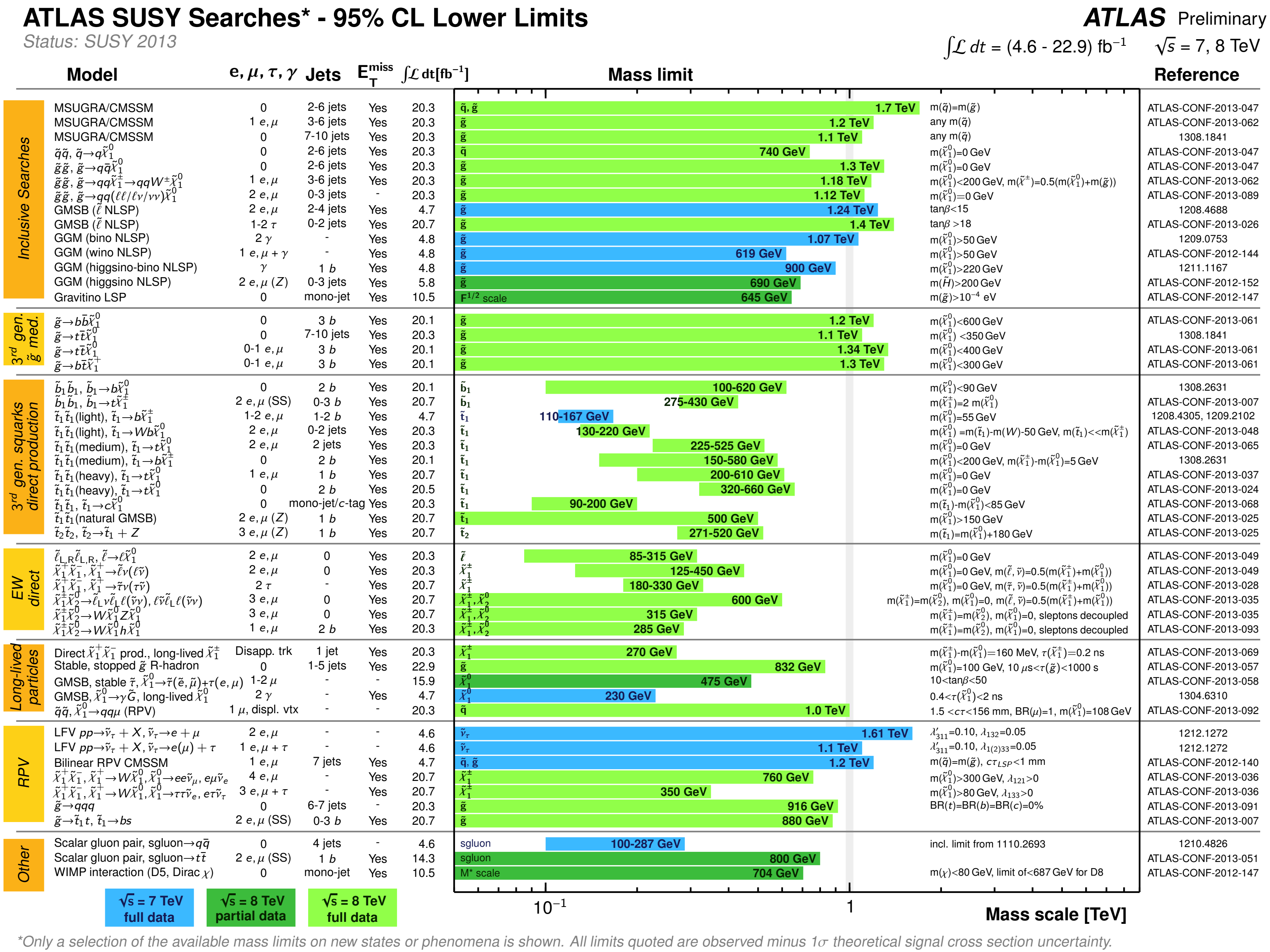
- Early LHC runs $\rightsquigarrow$ no sign of New Physics at the TeV scale
- Collected data has led re-evaluation of many New Physics scenarios;
  but LHC info is likely incomplete!
- Linear Collider has a very rich physics programme
- Discovery reach of a Linear Collider can exceed that of the LHC
- 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

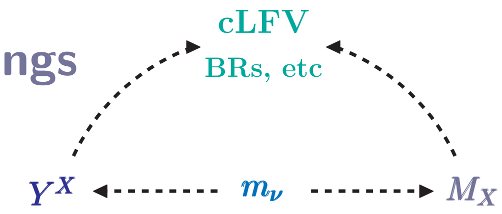


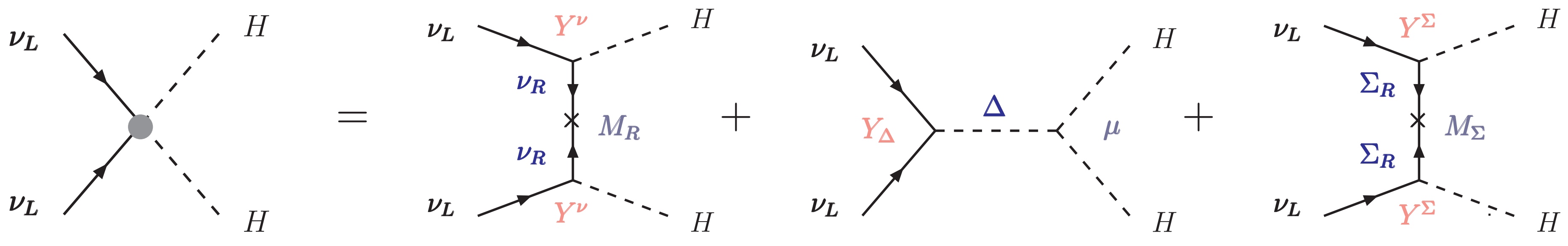
LHC bounds on BSM: SUSY



cLFV and the seesaw mechanism

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





$\frac{1}{\Lambda} L\,L\,H\,H$ — **“Seesaw mechanism”**

ν_R (fermion singlet) — **Type I**

Δ (scalar triplet) — **Type II**

Σ_R (fermion triplet) — **Type III**

Seesaw	$\tilde{\mathcal{C}}_5$	New Physics scales	$\tilde{\mathcal{C}}_6$	cLFV obs
Fermionic singlet (type I)	$Y_N^T \frac{1}{M_N} Y_N$	$Y_N \sim \mathcal{O}(1) \Rightarrow M_N \approx 10^{15}$ 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)	$4 Y_\Delta \frac{\mu_\Delta}{M_\Delta^2}$	$Y_\Delta \sim \mathcal{O}(1) \Rightarrow M_\Delta \approx$ **TeV** **($\mu_\Delta \ll 1$!)**	$\frac{1}{M_\Delta^2} Y_{\Delta\alpha\beta} Y^\dagger_{\Delta\gamma\delta}$	**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 $(M_{\text{GUT}} \to M_R)$

  induces flavour-violating terms in slepton soft-breaking masses

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

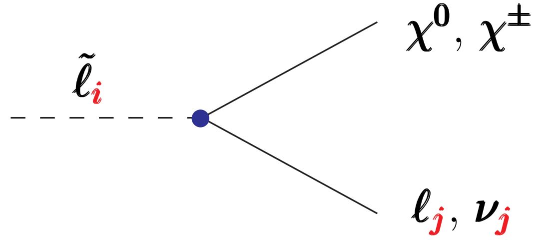
[Borzumati, Masiero; Hisano; ...]

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

- **Misalignement** of **flavour** and **physical** eigenstates: $R^{\tilde{\ell}\,\dagger}\,M^2_{\tilde{\ell}}\,R^{\tilde{\ell}} = \text{diag}(m^2_{\tilde{\ell}_i})$ $\quad R^{\tilde{\ell}} \neq 1!$

$$\{\tilde{e}_L,\, \tilde{\mu}_L,\, \tilde{\tau}_L,\, \tilde{e}_R,\, \tilde{\mu}_R,\, \tilde{\tau}_R\} \quad \not\leftrightarrow \quad \{\tilde{\ell}_1,\, \dots,\, \tilde{\ell}_6\}$$

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



$\bullet \propto R^{\tilde{\ell}}_{ij}$

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

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