Prospects for Evolution of the Linear Collider Physics Program from 240 GeV to 3 TeV

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Brau et al., "The Physics Case for an e+e- Linear Collider", arXiv:1210.0202
Linssen et al., Lebrun et al., CLIC CDR, arXiv:1202.5940, 1209.2543
Baer et al., Physics at the ILC, ILC Detailed Baseline Report (2012)

Physics Goals of Linear Collider

The main goals of the LC physics programme are:

- precise measurements of the properties of the Higgs sector;
- precise measurements of the interactions of top quarks, gauge bosons, and new particles;
- searches for physics beyond the Standard Model (SM), where, in particular, the discovery reach of the LC can significantly exceed that of the LHC for the pair-production of colour-neutral states; and
- sensitivity to new physics through tree-level or quantum effects in high-precision observables.

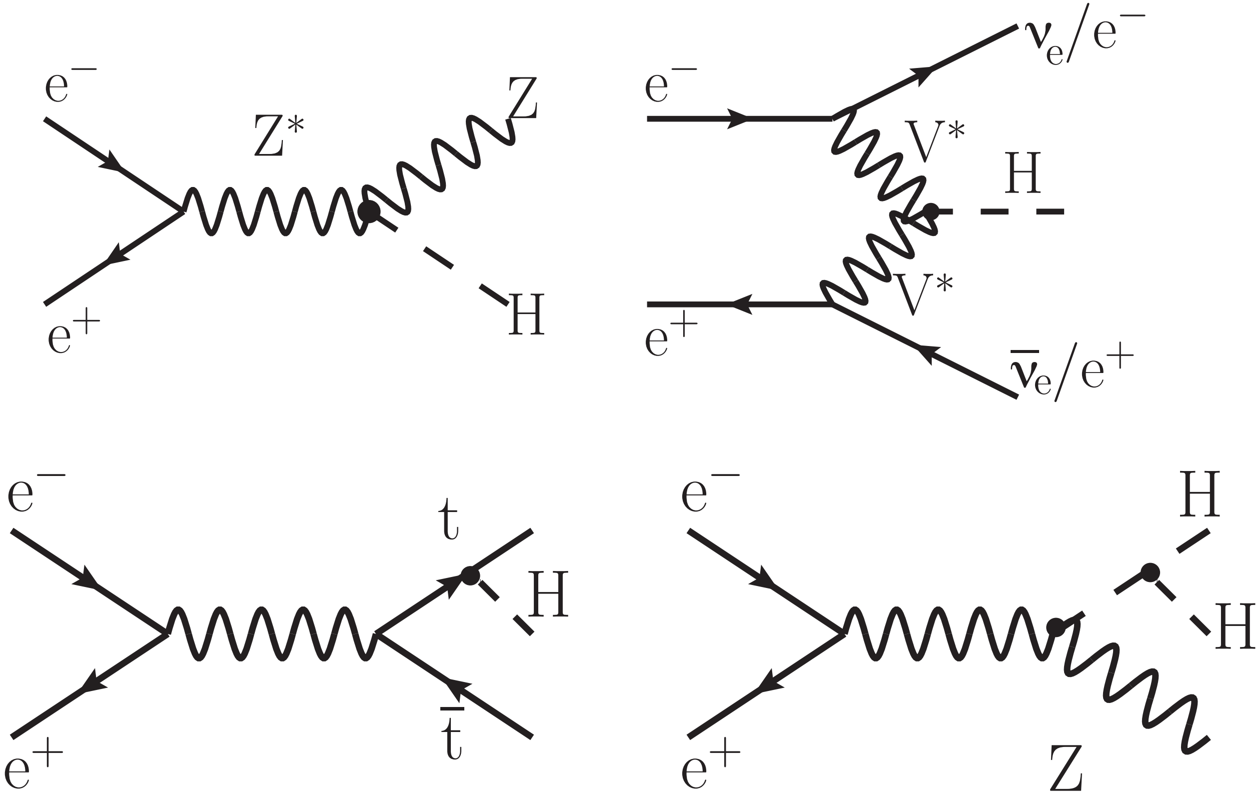
Brau et al., ‘12

Goals of the Higgs Boson Study

- What are the couplings of this particle to other known elementary particles? Is its coupling to each particle proportional to that particle's mass, as required in the SM by the Higgs mechanism?
- What are the mass, width, spin and CP properties of this particle?
- What is the value of the particle's self-coupling? Is this consistent with the expectation from the symmetry-breaking potential?
- Is this particle a single, fundamental scalar as in the SM, or is it part of a larger structure? Is it part of a model with additional scalar doublets? Or, could it be a composite state, bound by new interactions?
- Does this particle couple to new particles with no other couplings to the SM? Is the particle mixed with new scalars of exotic origin, for example, the radion of extra-dimensional models?

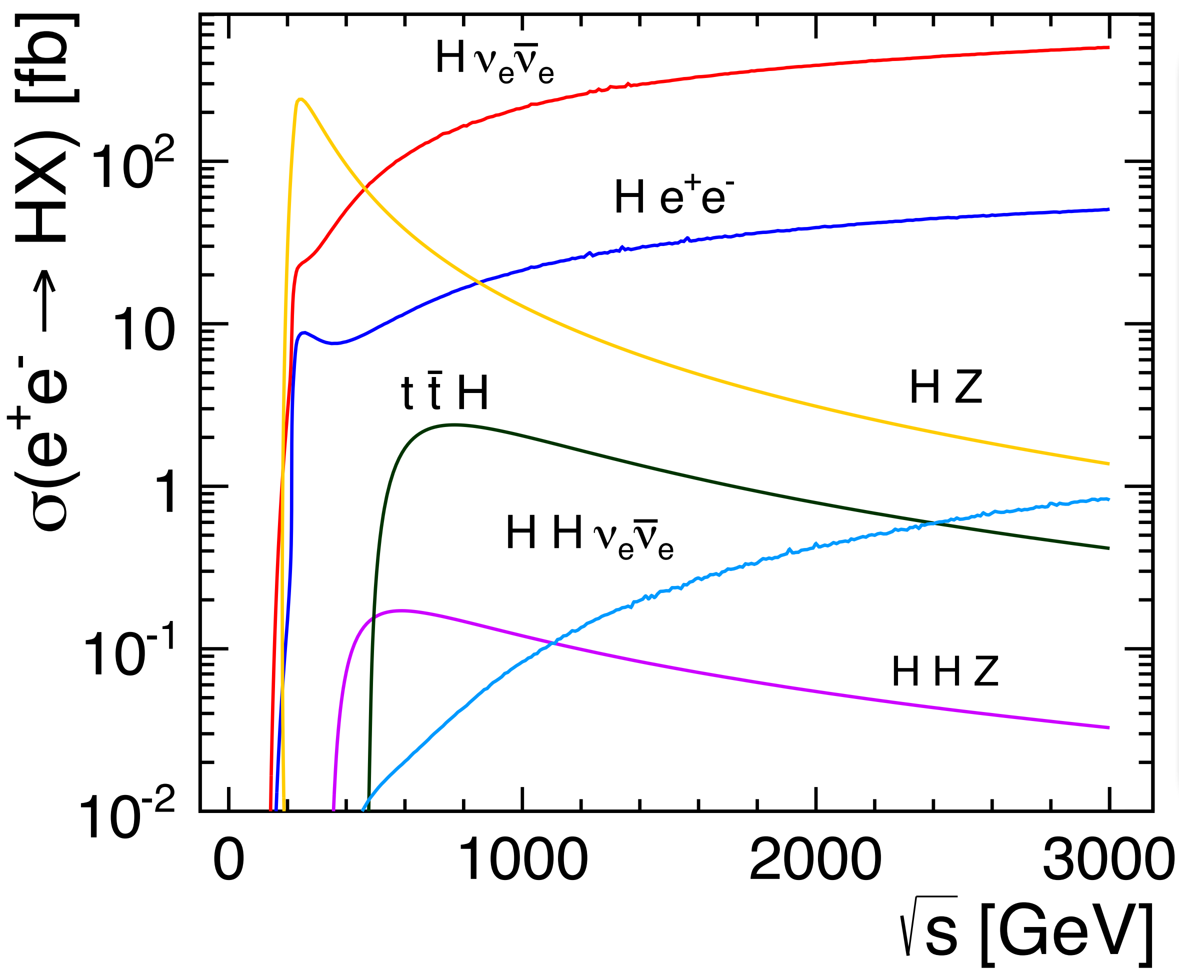
Brau et al., '12

Some Higgs Boson Production Modes at LC



Linssen et al., 1202.5940

Higgs boson Production Cross-Sections



Several thresholds:

126 GeV Hνν, He^+e^-

217 GeV HZ

252 GeV HHνν

343 GeV HHZ

472 GeV Htt

Optimization determines optimal signal to bkgd

Lebrun et al., arXiv:1209.2543

Higgs boson production event rates

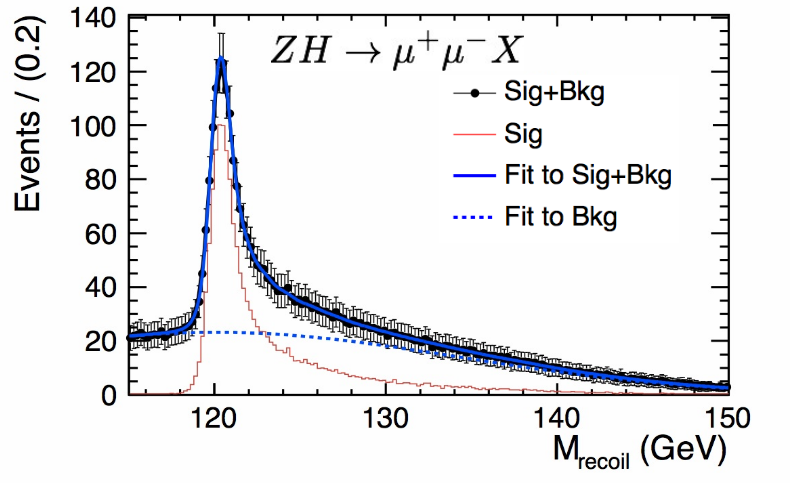
Brau et al., '12

	250 GeV	350 GeV	500 GeV	1 TeV	1.5 TeV	3 TeV
$\sigma(e^+e^- \to ZH)$	240 fb	129 fb	57 fb	13 fb	6 fb	1 fb
$\sigma(e^+e^- \to H\nu_e\bar{\nu}_e)$	8 fb	30 fb	75 fb	210 fb	309 fb	484 fb
Int. $\mathcal{L}$	250 fb^{-1}	350 fb^{-1}	500 fb^{-1}	1000 fb^{-1}	1500 fb^{-1}	2000 fb^{-1}
# ZH events	60,000	45,500	28,500	13,000	7,500	2,000
# $H\nu_e\bar{\nu}_e$ events	2,000	10,500	37,500	210,000	460,000	970,000

Table 1: The leading-order Higgs unpolarised cross sections for the Higgs-strahlung and WW-fusion processes at various centre-of-mass energies for $m_H = 125$ GeV. Also listed is the expected number of events accounting for the anticipated luminosities obtainable within 5 years of initial operation at each energy.

Precision scales at best with 1/Sqrt[Events]. Need "tens of thousands" of events to have chance for < 1% measurements. This is achieved with the contemplated luminosities.

Recoil Mass Measurement



Brau et al., '12

Figure 2: The recoil mass distribution for $e^+e^- \to ZH \to \mu^+\mu^-H$ events with $m_H = 120\,\text{GeV}$ in the ILD detector concept at the ILC [6]. The numbers of events correspond to $250\,\text{fb}^{-1}$ at $\sqrt{s} = 250\,\text{GeV}$, and the error bars show the expected statistical uncertainties on the individual points.

$\sqrt{s}$	250 GeV	350 GeV
Int. $\mathcal{L}$	$250\,\text{fb}^{-1}$	$350\,\text{fb}^{-1}$
$\Delta(\sigma)/\sigma$	3 %	4 %
$\Delta(g_{HZZ})/g_{HZZ}$	1.5 %	2 %

Table 2: Precision measurements of the Higgs coupling to the Z at $\sqrt{s} = 250\,\text{GeV}$and $\sqrt{s} = 350\,\text{GeV}$ based on full simulation studies with $m_H = 120\,\text{GeV}$. Results from [6] and follow-up studies.

[6] Abe et al. [ILD Concept Group], Letter of Intent, 1006.3396.

Higgs Measurements at Various Energies

	250/350 GeV	500 GeV†	3 TeV
$\sigma \times Br(\mathrm{H} \to \mathrm{bb})$	1.0/1.0 %	0.6 %	0.2 %
$\sigma \times Br(\mathrm{H} \to \mathrm{cc})$	7/6 %	4 %	3 %
$\sigma \times Br(\mathrm{H} \to \tau\tau)$	$6^*/6$ %	5 %	?
$\sigma \times Br(\mathrm{H} \to \mathrm{WW})$	8/6 %	3 %	?
$\sigma \times Br(\mathrm{H} \to \mu\mu)$	−/−	?	15 %
$\sigma \times Br(\mathrm{H} \to \mathrm{gg})$	9/7 %	5 %	?

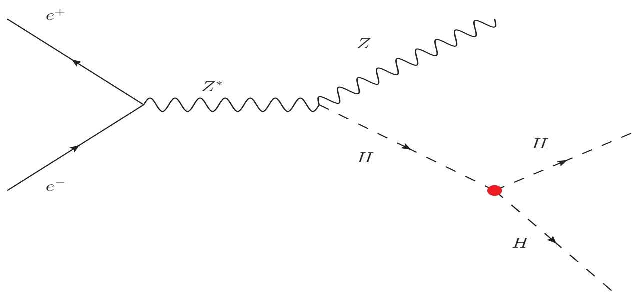
	250/350 GeV	500 GeV†	3 TeV
g_{Hbb}	1.6/1.4 %	?	2 %
g_{Hcc}	4/3 %	2 %	2 %
$g_{\mathrm{H}\tau\tau}$	$3^*/3$ %	2.5 %	?
g_{HWW}	4/3 %	1.4 %	< 2 %
$g_{\mathrm{H}\mu\mu}$	−/−	−	7.5 %
$\frac{g_{\mathrm{HWW}}}{g_{\mathrm{HZZ}}}$	?/?	?	$< 1\,\%^*$
g_{Htt}	−/−	15 %	?

Table 3: The precision on the Higgs branching ratios and couplings obtainable from studies of the Higgs-strahlung process at a LC operating at either $\sqrt{s} = 250\,\mathrm{GeV}$, $\sqrt{s} = 350\,\mathrm{GeV}$ and $\sqrt{s} = 500\,\mathrm{GeV}$. The dagger on the 500 GeV columns indicates that the quoted numbers are based on projections to be updated in [7]. The uncertainties on the couplings include the uncertainties on g_{HZZ} obtained from the absolute measurement of the ZH cross section. Also shown are the precisions achievable from the WW fusion process at a LC operating at 3 TeV. The numbers marked with asterisk are estimates, all other numbers come from full simulation studies with $m_{\mathrm{H}} = 120\,\mathrm{GeV}$. The question marks indicate that the results of ongoing studies are not yet available. In all cases the luminosities assumed are those given in Table 1.

Brau et al., ‘12

Higgs Self-Coupling

See also, Lastovicka's talk at this meeting



M_H=120 GeV
E_{cm}=500 GeV
L_I=2 ab^{-1}

TABLE IV: Cut statistics of $e^+ + e^- \to ZHH \to (l\bar{l})(b\bar{b})(b\bar{b})$

Process	ZHH	$t\bar{t}$	ZZZ	WWZ	ZZ	ZH
generated	1M	4.5M	500K	750K	1.25M	250K
theoretical	304	1062000	1600	72300	1030000	140000
pre-selection	15.4	9023	125	1943	3560	1618
$mva\_tt > 0.98$ $mva\_wwz > 1.0$ $mva\_zz > 0.97$ $mva\_zh > 0.97$ $mva\_zzz > 0$	11.7	312	12.9	12.7	16.5	5.6
$70GeV < M_Z < 110GeV$	9.7	106	11.7	7.5	16.5	0.56
$Y_{cut} > 0.015$	9.1	91.3	10.6	6.9	6.6	0
$2b(H_1)(N_{off} > 0)$	6.3	28	5.5	1.8	0	0
$2b(H_2)(N_{off} > 1)$	3.5	0.71	2.3	0	0	0
$mva\_zzz > 0.86$	3.0	0	0.82	0	0	0

Events after all cuts

Tian et al., '10

Tests of the SM Higgs Boson

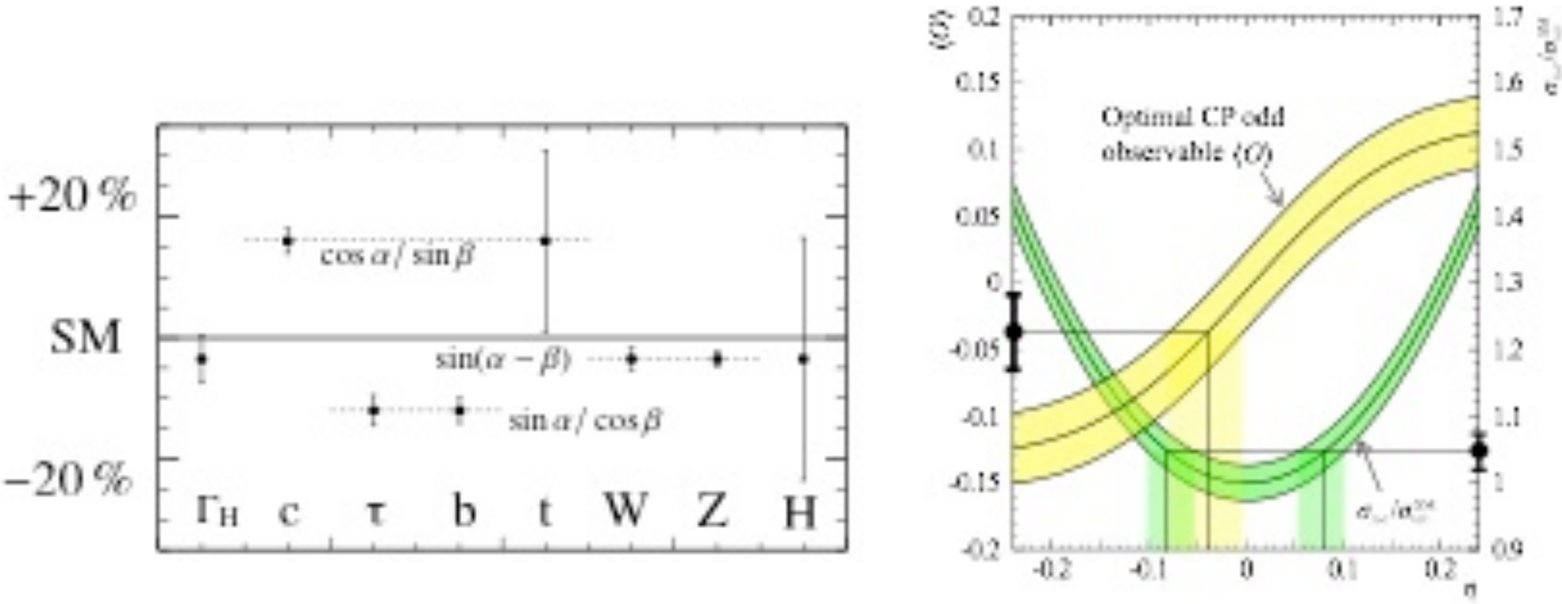
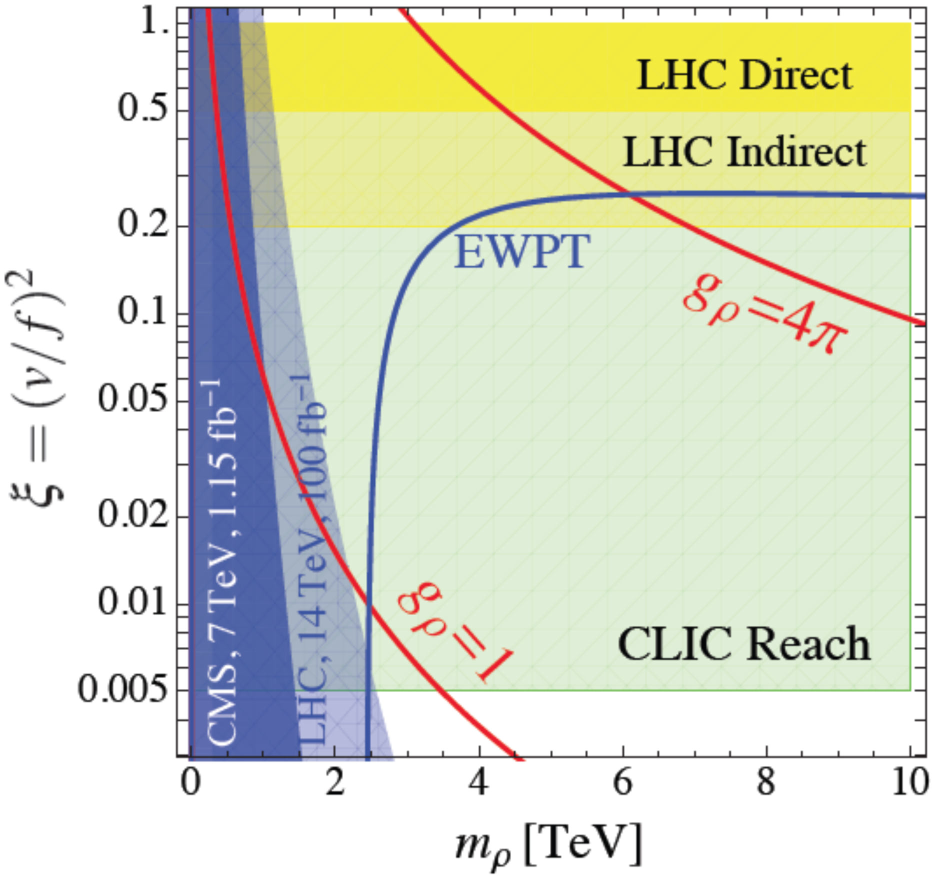


Figure 4: Left: Typical deviations of the Higgs couplings to different particles from the SM predictions in a Two-Higgs-Doublet model. The LC precisions for the various couplings are the same as in Figure 3. Right: Determination of the admixture η of a CP-odd state in $e^+e^- \rightarrow ZH$ at $\sqrt{s} = 350$ GeV with 500 fb^{-1}, using the measurement of the cross section together with an ‘optimally chosen’ CP-odd observable.

Brau et al., ‘12



LHC: WW scattering and strong double Higgs production

LHC: single Higgs processes

CLIC: double Higgs production via vector boson fusion

LHC: direct search WZ =>3 leptons

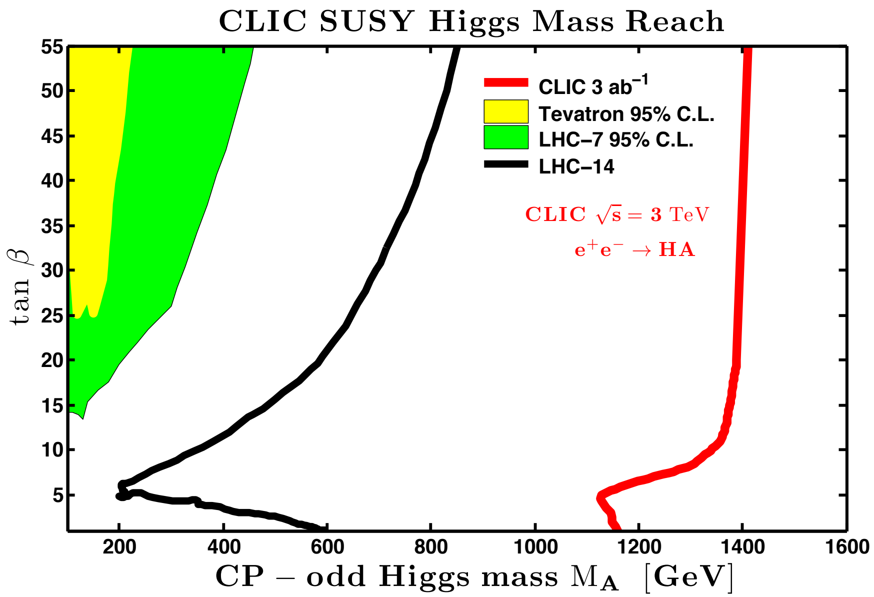
$$\mathscr{L} = \frac{1}{2}\left(\partial_\mu h\right)^2 - V(h) + \left(m_W^2 W_\mu^+ W^{\mu -} + \frac{m_Z^2}{2} Z_\mu Z^\mu\right)\left[1 + 2a\frac{h}{v} + b\frac{h^2}{v^2} + \dots\right] + \dots$$

$$V(h) = \frac{1}{2} m_h^2 h^2 + d_3 \left(\frac{m_h^2}{2v}\right) h^3 + d_4 \left(\frac{m_h^2}{8v^2}\right) h^4 + \dots$$

$$a = \sqrt{1-\xi}\,, \qquad b = 1 - 2\xi\,, \qquad d_3 = \sqrt{1-\xi}\,, \qquad \delta_b \equiv 1 - \frac{b}{a^2}\,, \qquad \delta_{d_3} \equiv 1 - \frac{d_3}{a}$$

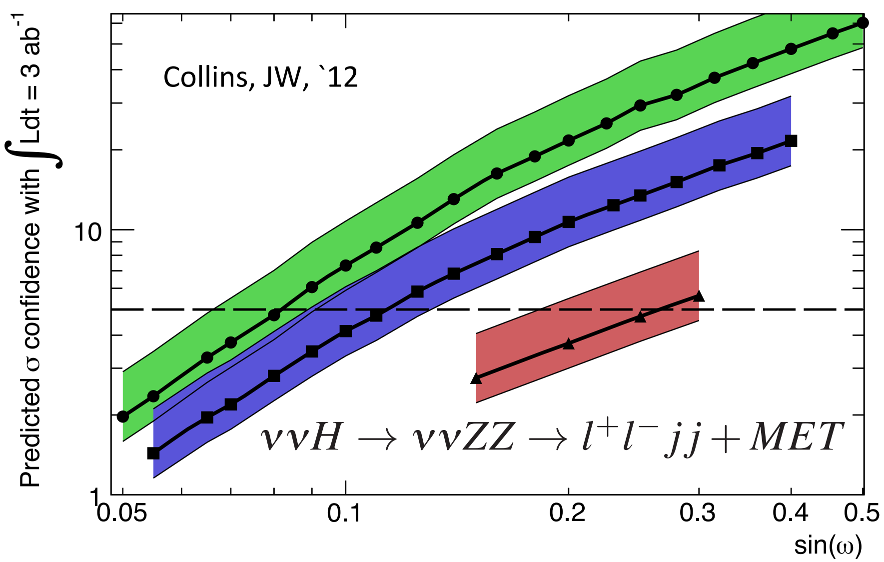
Contino et al. (from Linssen et al.), ‘12

Heavy Higgs Bosons



Linssen et al., 2012

Searches for the heavier scalar Higgs boson reach nearly $E_{cm}/2$.



Green/Purple/Red = 1 / 1.5 / 2 TeV

Singlet Higgs mixing with SM Higgs:

$$\Phi_{SM} = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v + \phi_{SM}(x) \end{pmatrix}, \; \Phi_H = \frac{1}{\sqrt{2}}(\xi + \phi_H(x))$$

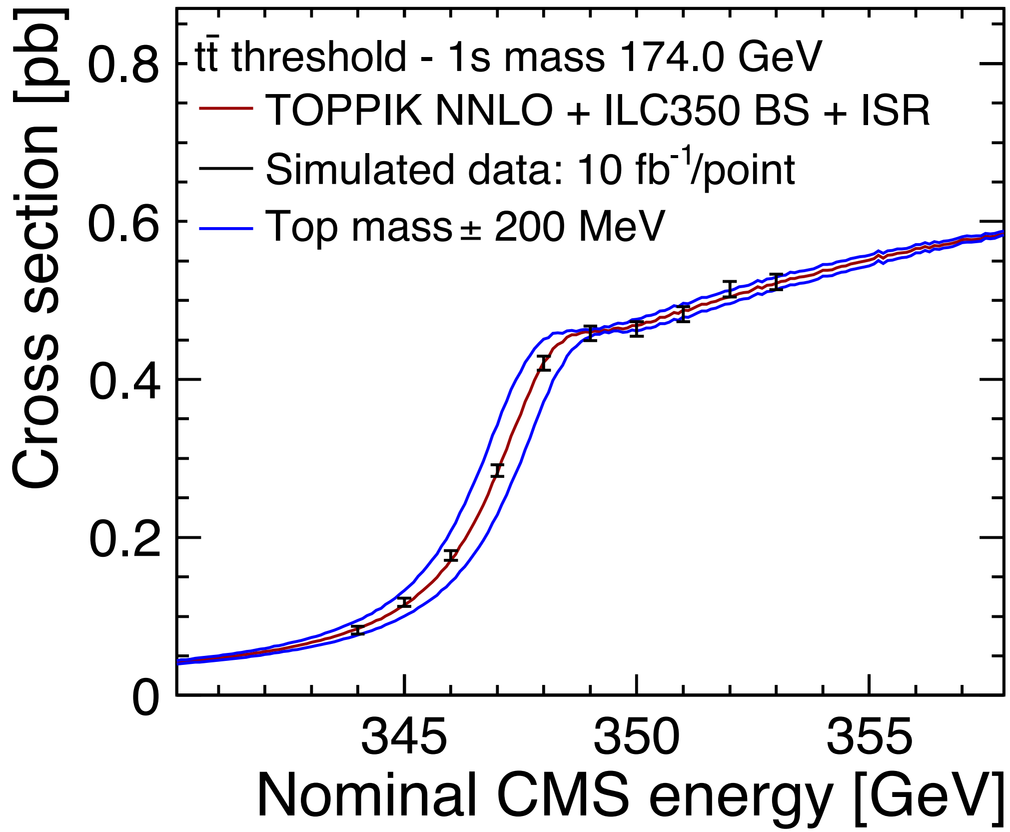
$$\mathscr{L}_{\text{Higgs}} = |D_\mu \Phi_{SM}|^2 + |D_\mu \Phi_H|^2 + m^2_{\Phi_{SM}}|\Phi_{SM}|^2 + m^2_{\Phi_H}|\Phi_H|^2 - \lambda|\Phi_{SM}|^4 - \rho|\Phi_H|^4 - \eta|\Phi_{SM}|^2|\Phi_H|^2$$

$$\phi_{SM} = \cos\omega\, h + \sin\omega\, H$$
$$\phi_H = -\sin\omega\, h + \cos\omega\, H$$

$$\tan 2\omega = \frac{\eta v \xi}{\rho\xi^2 - \lambda v^2}$$

$$M^2_{h,H} = (\lambda v^2 + \rho\xi^2) \mp \sqrt{(\lambda v^2 - \rho\xi^2)^2 + \eta^2 v^2 \xi^2}.$$

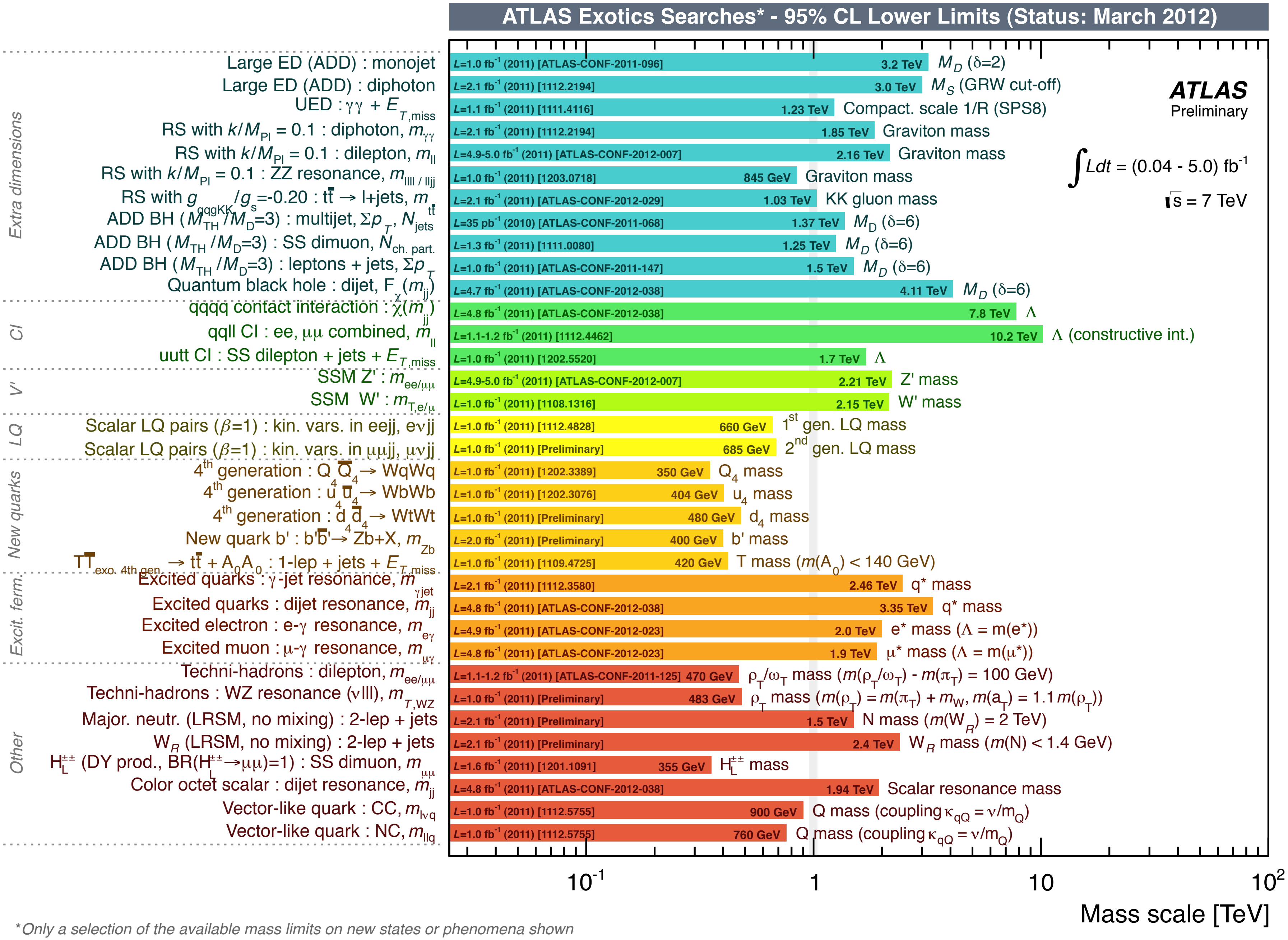
Top Physics

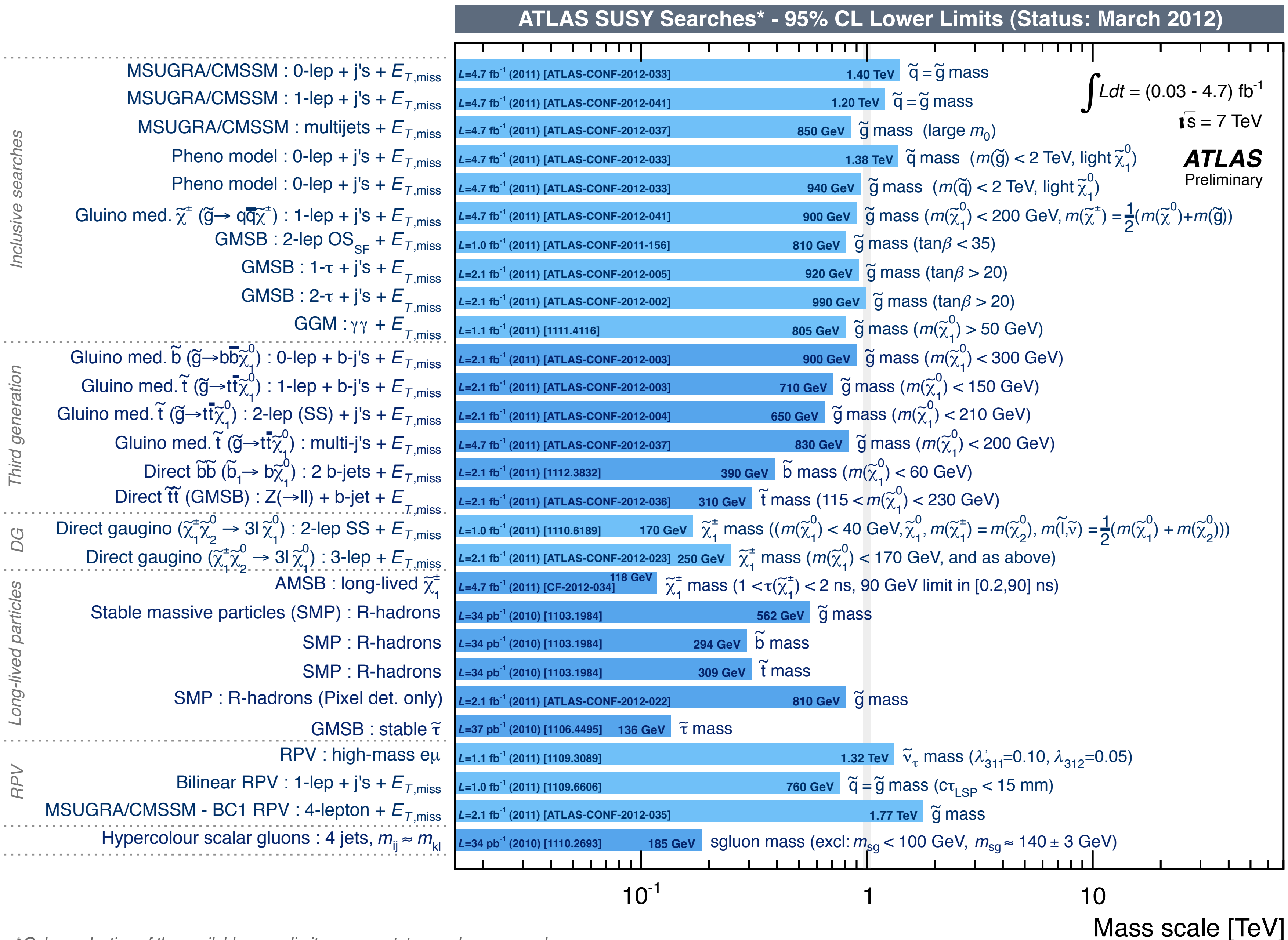


Preliminary:
Baer et al., Physics at ILC, DBD Report.

The $t\bar{t}$ production cross-section scan near the threshold, leading to 30 MeV determination of the top mass. The study is based on full simulation of the ILD detector and includes initial state radiation, beamstrahlung and other machine-induced effects

Where is New Physics?





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

New Physics (NP) Targets

At present no compelling higher energy (> higgs,top scale) target for direct NP.

NP considerations then argue for "highest energy achievable" with appropriately scaled luminosity.

No "Physics Case" can be made directly from NP considerations. However, the "Physics Potential" can be detailed.

Study "best" NP scenarios of today and ask if LC at some energy and luminosity can provide substantial, important and qualitative gains over previous experiments (LHC, etc.).

Studies have shown very strong "Physics Potential" for LC, with that potential increasing with collision energy.

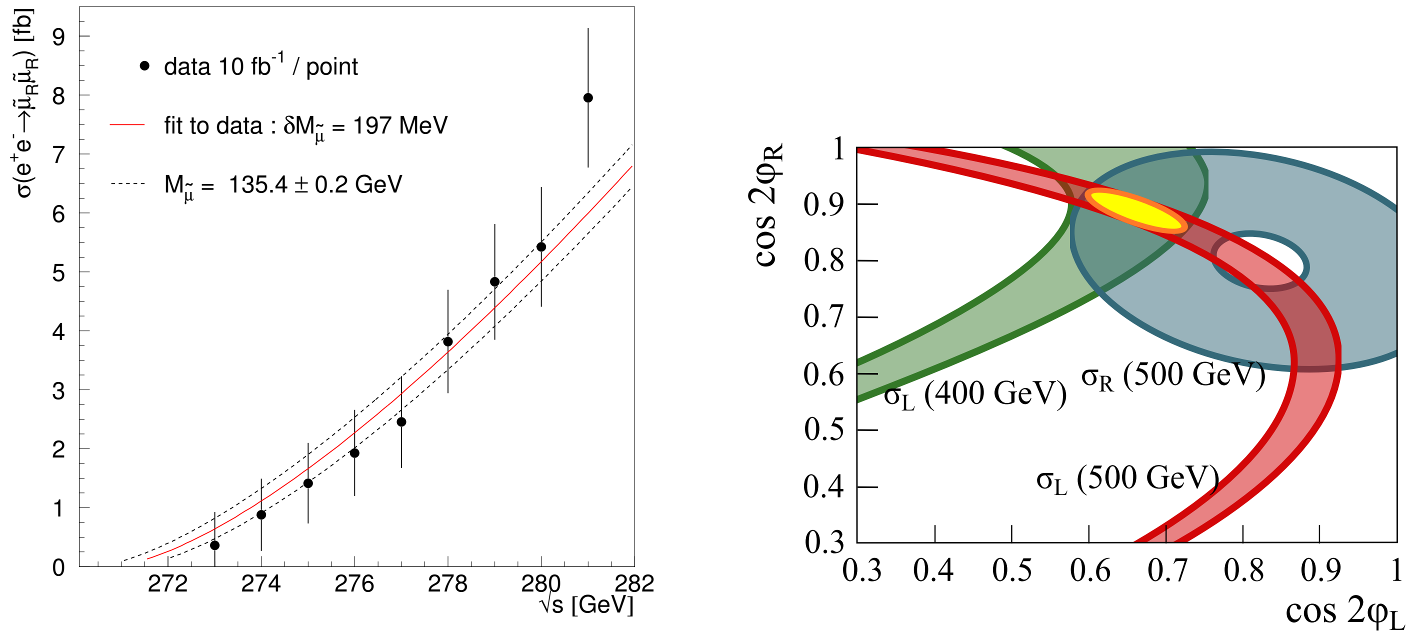
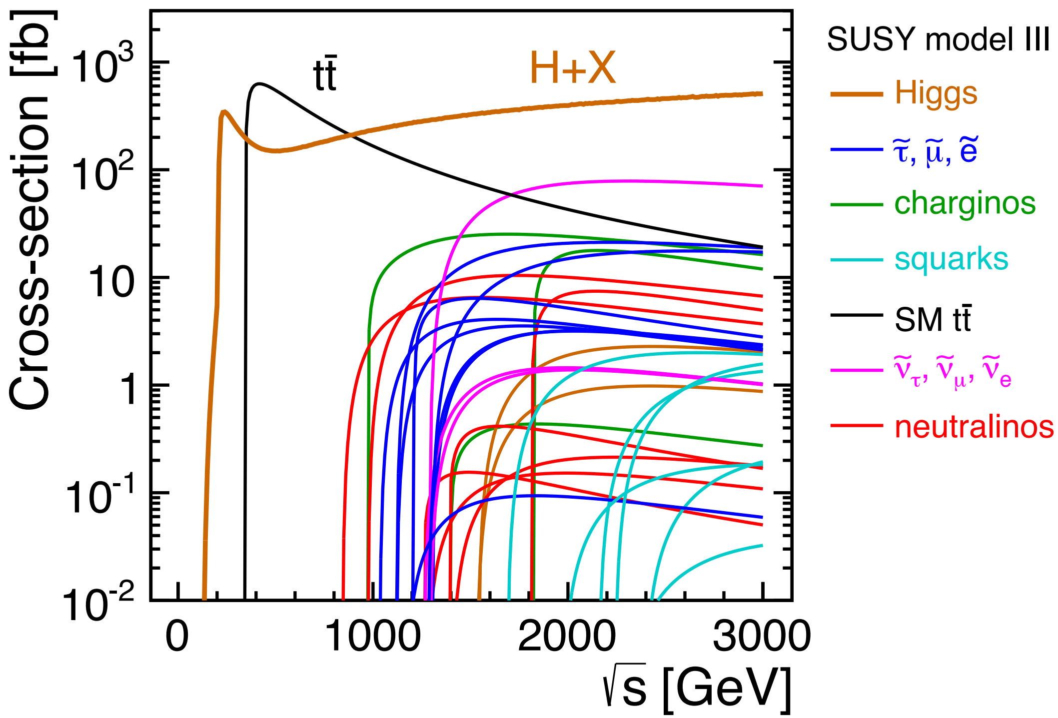


Figure 5: Left: Cross section at threshold for the production of the superpartners of the right-handed muons at the LC, $e^+e^- \to \tilde{\mu}_R\tilde{\mu}_R$, from which the spin of the produced particles can be determined and their mass can be precisely measured (limited by statistics; the plot shows a 'difficult' scenario with backgrounds from other light SUSY particles). Right: Determination of the chargino mixing angles $\cos 2\phi_{L,R}$ from LC measurements with polarised beams and at different centre-of-mass energies.

Le Diberder et al., `12

Supersymmetry Example

Neutralinos ($\tilde{\chi}^0_{1,2,3,4}$) :	357, 487, 904, 911
Charginos ($\tilde{\chi}^{\pm}_{1,2}$) :	487, 911
Sleptons ($\tilde{e}_R$, $\tilde{e}_L$, $\tilde{\nu}_e$) :	559, 650, 644
($\tilde{\tau}_1$, $\tilde{\tau}_2$, $\tilde{\nu}_\tau$) :	517, 642, 630
Gluino ($\tilde{g}$) :	1114
Squarks ($\tilde{t}_1$, $\tilde{t}_2$, $\tilde{b}_1$, $\tilde{b}_2$) :	844, 1120, 1078, 1191
($\tilde{d}_R$, $\tilde{u}_R$, $\tilde{d}_L$, $\tilde{u}_L$) :	2167, 2181, 2197, 2196
Higgs Bosons (h^0, A^0, H^0, $H^{\pm}$) :	118, 765, 765, 769



Lebrun et al., ‘12

Stau mass determination

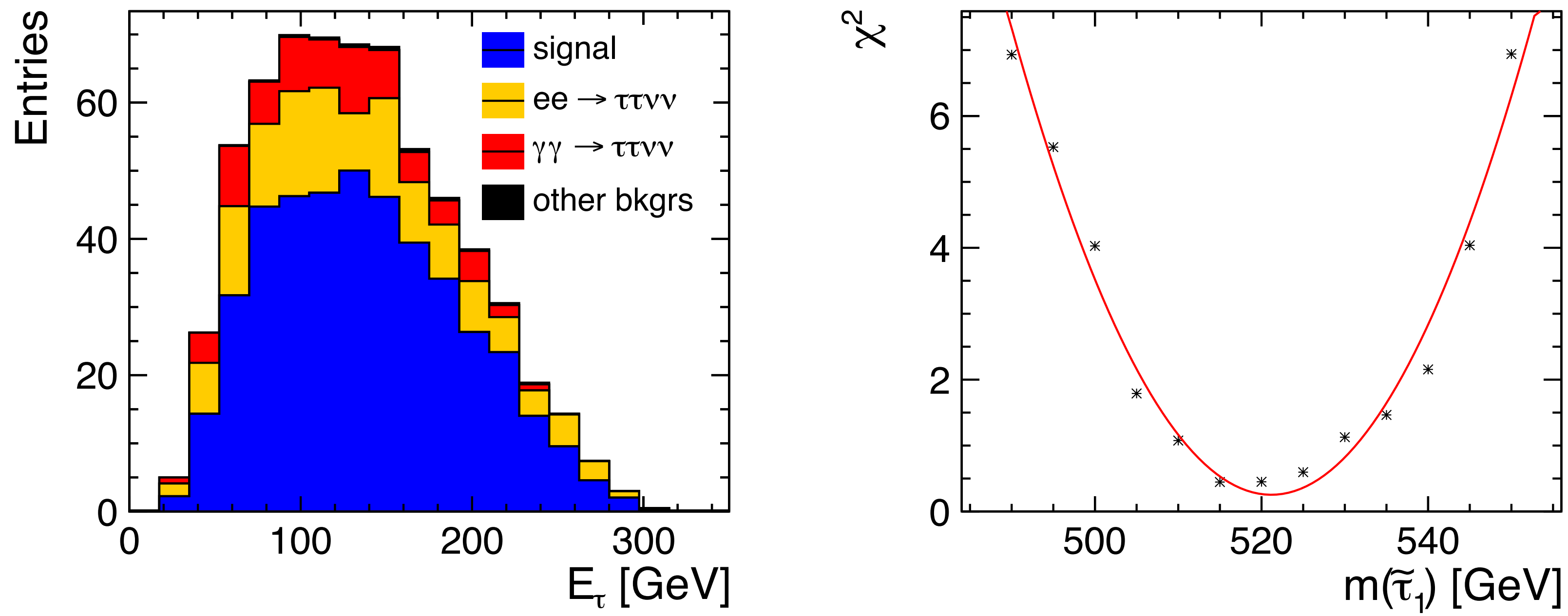


Fig. 6.5: Reconstructed τ energy after event selection with a BDT. Signal and background histograms are stacked (left). χ^2 values for templates with different $\tilde{\tau}$ mass assumptions compared to the reconstructed energy distribution. The measured $\tilde{\tau}$ mass is given by the minimum of the distribution. The generated $\tilde{\tau}$ mass is 517 GeV (right).

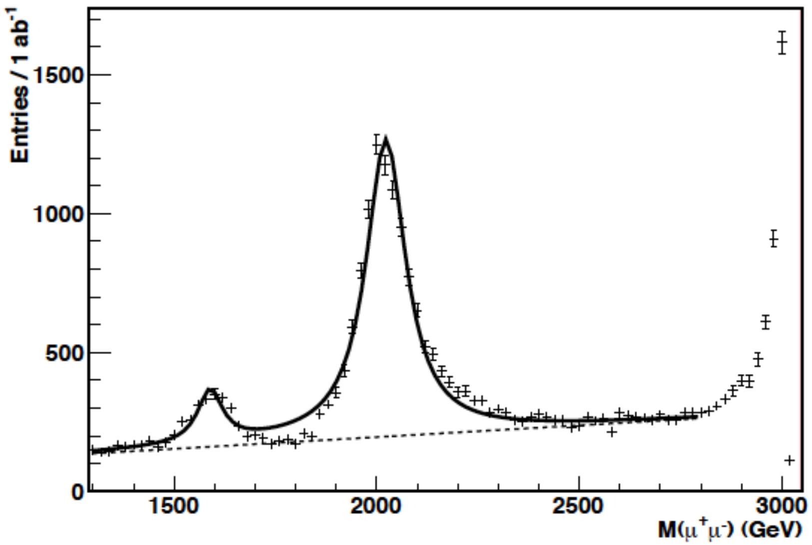
Lebrun et al., `12

Table 6.3: Summary table of the CLIC SUSY benchmark analyses results obtained with full detector simulations with background overlaid. All studies are performed at a centre-of-mass energy of 1.4 TeV and for an integrated luminosity of 1.5 ab^{-1}.

$\sqrt{s}$ (TeV)	Process	Decay mode	SUSY model	Measured quantity	Unit	Generator value	Stat. error
1.4	Sleptons production	$\widetilde{\mu}_R^+\widetilde{\mu}_R^- \to \mu^+\mu^-\widetilde{\chi}_1^0\widetilde{\chi}_1^0$	III	σ	fb	1.11	2.7%
				$\tilde{\ell}$ mass	GeV	560.8	0.1%
				$\widetilde{\chi}_1^0$ mass	GeV	357.8	0.1%
		$\widetilde{e}_R^+\widetilde{e}_R^- \to e^+e^-\widetilde{\chi}_1^0\widetilde{\chi}_1^0$		σ	fb	5.7	1.1%
				$\tilde{\ell}$ mass	GeV	558.1	0.1%
				$\widetilde{\chi}_1^0$ mass	GeV	357.1	0.1%
		$\widetilde{\nu}_e\widetilde{\nu}_e \to \widetilde{\chi}_1^0\widetilde{\chi}_1^0 e^+e^-W^+W^-$		σ	fb	5.6	3.6%
				$\tilde{\ell}$ mass	GeV	644.3	2.5%
				$\widetilde{\chi}_1^\pm$ mass	GeV	487.6	2.7%
1.4	Stau production	$\widetilde{\tau}_1^+\widetilde{\tau}_1^- \to \tau^+\tau^-\widetilde{\chi}_1^0\widetilde{\chi}_1^0$	III	$\widetilde{\tau}_1$ mass	GeV	517	2.0%
				σ	fb	2.4	7.5%
1.4	Chargino production	$\widetilde{\chi}_1^+\widetilde{\chi}_1^- \to \widetilde{\chi}_1^0\widetilde{\chi}_1^0 W^+W^-$	III	$\widetilde{\chi}_1^\pm$ mass	GeV	487	0.2%
				σ	fb	15.3	1.3%
	Neutralino production	$\widetilde{\chi}_2^0\widetilde{\chi}_2^0 \to h/Z^0 h/Z^0 \widetilde{\chi}_1^0\widetilde{\chi}_1^0$		$\widetilde{\chi}_2^0$ mass	GeV	487	0.1%
				σ	fb	5.4	1.2%

Lebrun et al., `12

Z' physics: Extraordinary discovery reach (well beyond LHC), and simultaneous capability to determine couplings and discern models.



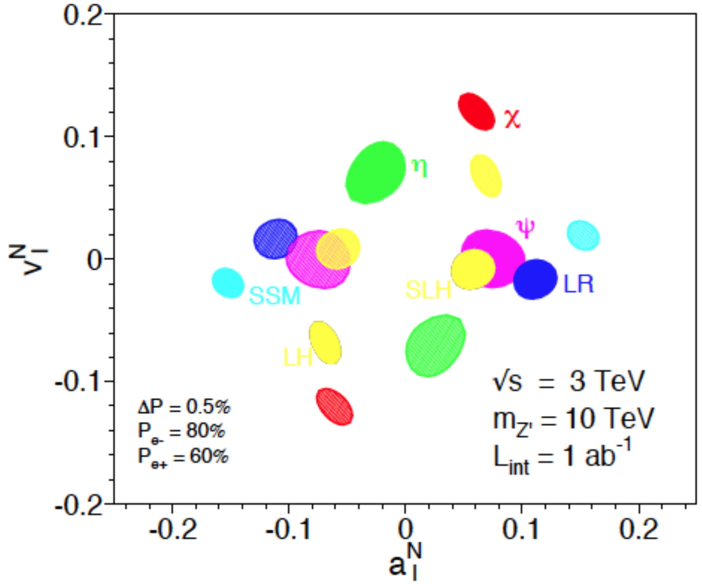


Fig. 1.16: Left: Observation of new gauge boson resonances in the $\mu^+\mu^-$ channel by auto-scan at 3 TeV. The two resonances are the $Z_{1,2}$ predicted by the 4-site Higgsless model of [67]. Right : Expected resolution at CLIC with $\sqrt{s} = 3$ TeV and $\mathscr{L} = 1$ ab^{-1} on the "normalised" leptonic couplings of a 10 TeV Z′ in various models, assuming lepton universality. The couplings can be determined up to a twofold ambiguity. The mass of the Z′ is assumed to be unknown. χ, η and ψ refer to various linear combinations of $U(1)$ subgroups of E_6; the SSM has the same couplings as the SM Z; LR refers to $U(1)$ surviving in Left-Right model; LH is the Littlest Higgs model and SLH, the Simplest Little Higgs model. The two fold ambiguity is due to the inability to distinguish (a, v) from $(-a, -v)$. The degeneracy between the ψ and SLH models might be lifted by including other channels in the analysis ($t\bar{t}$, $b\bar{b}$, ...).

Extreme sensitivity (>> LHC) to higher dimensional operators.

$$\mathcal{L}_{CI} = \sum_{i,j=L,R} \eta_{ij} \frac{g^2}{\Lambda^2} (\bar{e}_i \gamma^\mu e_i)(\bar{f}_j \gamma_\mu f_j)$$

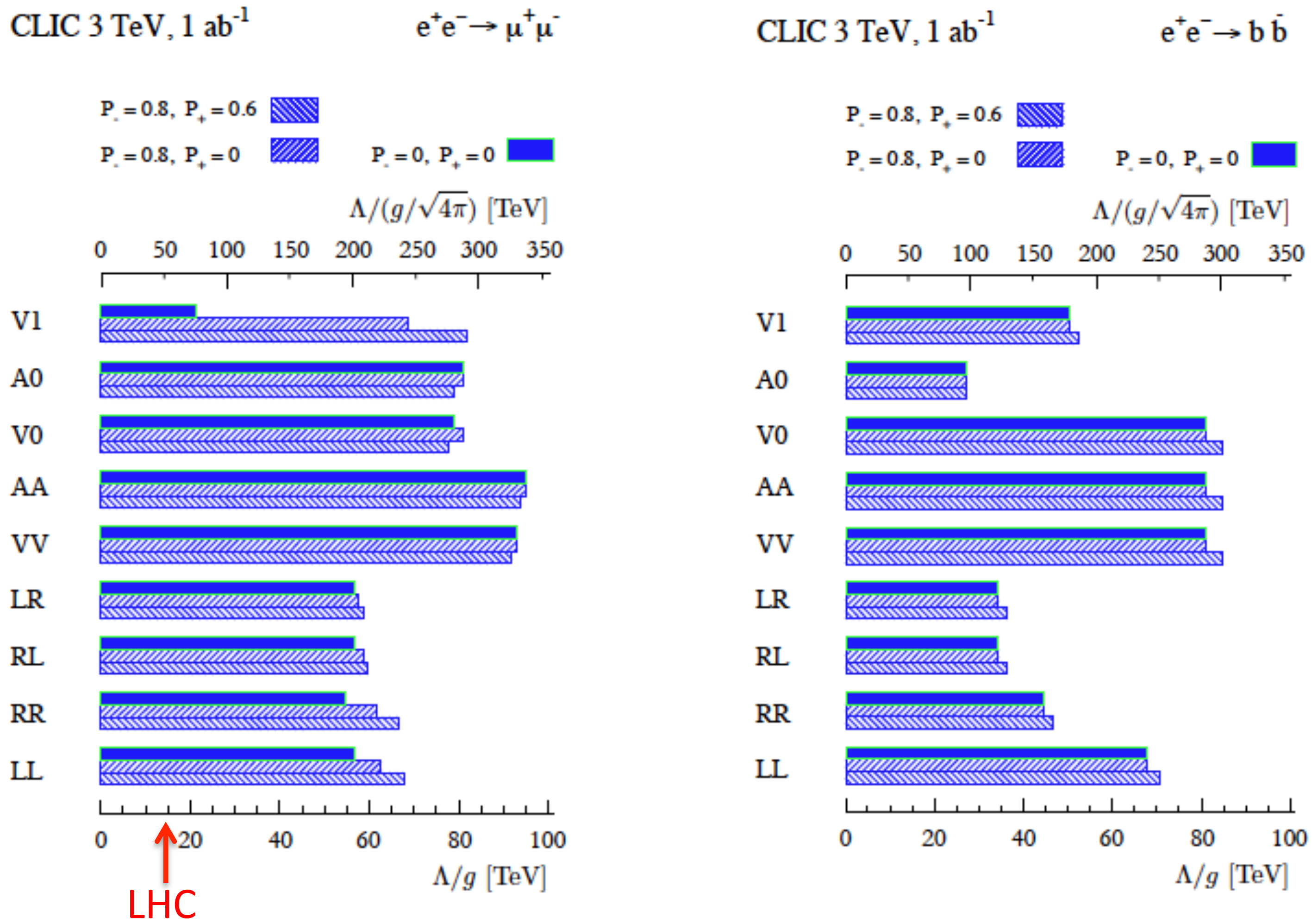


Fig. 1.14: Limits on the scale of contact interactions (Λ/g) that can be set by CLIC in the $\mu^+\mu^-$ (left) and $b\bar{b}$ (right) channels with $\sqrt{s} = 3$ TeV and $\mathcal{L} = 1$ ab^{-1}. A degree of polarisation $P_- = 0, 0.8$ ($P_+ = 0, 0.6$) has been assumed for the electrons (positrons). The various models are defined in Table 6.6 of [20], except the model V1 which is defined as $\{\eta_{LL} = \pm, \eta_{RR} = \mp, \eta_{LR} = 0, \eta_{RL} = 0\}$.

Conclusions

Excellent opportunities to study Higgs, top and New Physics at many energy stages from 240 GeV on upwards.

Clear “physics case” for LC studying to death the Higgs boson and top quark in energy range of 240 GeV to ~600 GeV (from ZH maximum cross-section to Htt maximum cross-section).

Clear “physics potential” for LC exploring NP in the range of LHC discoveries and beyond, for energies of ~1 TeV and beyond.