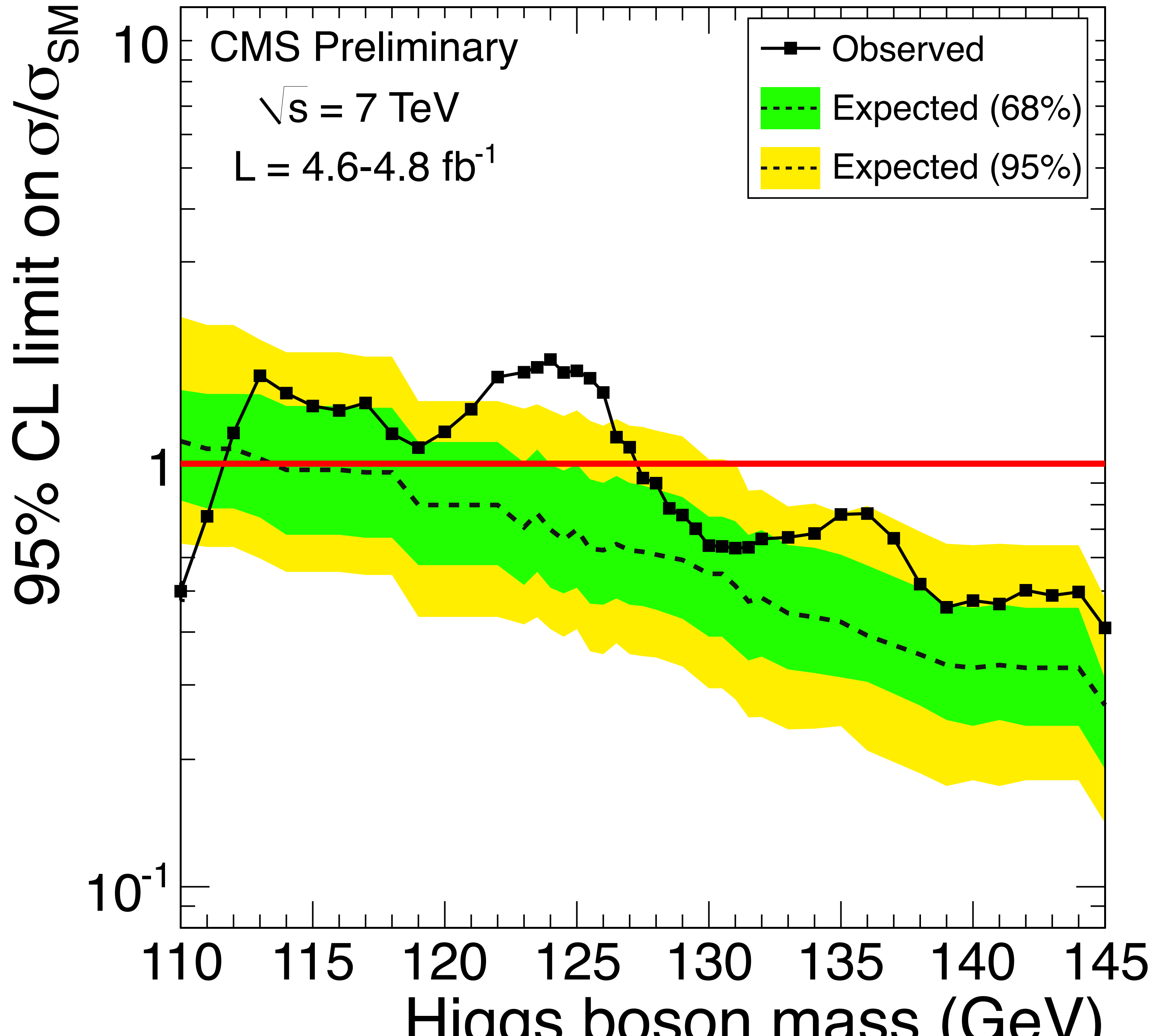
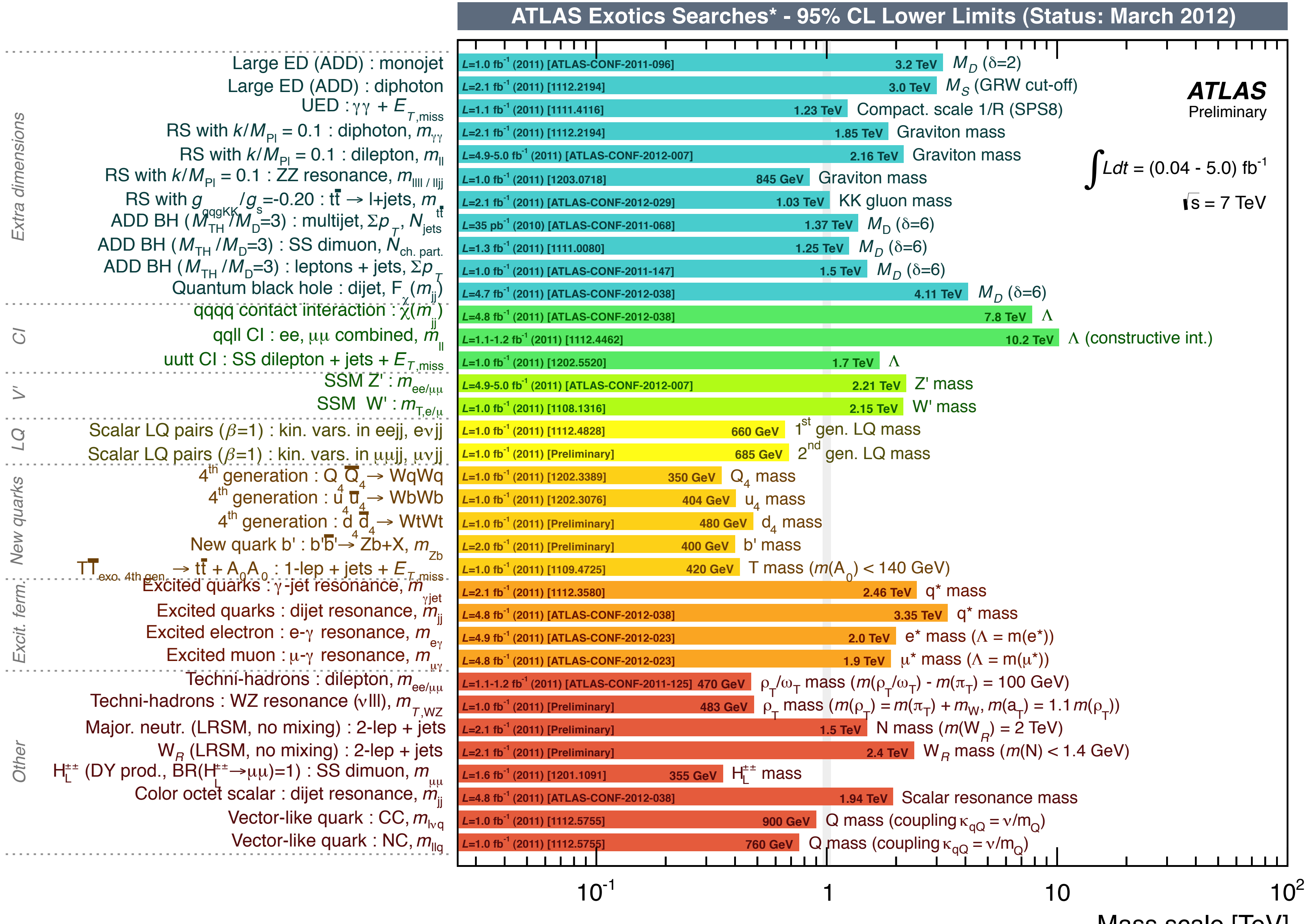
The Physics Potential of an e+e- Collider in Light of LHC Data

James Wells
CERN & University of Michigan

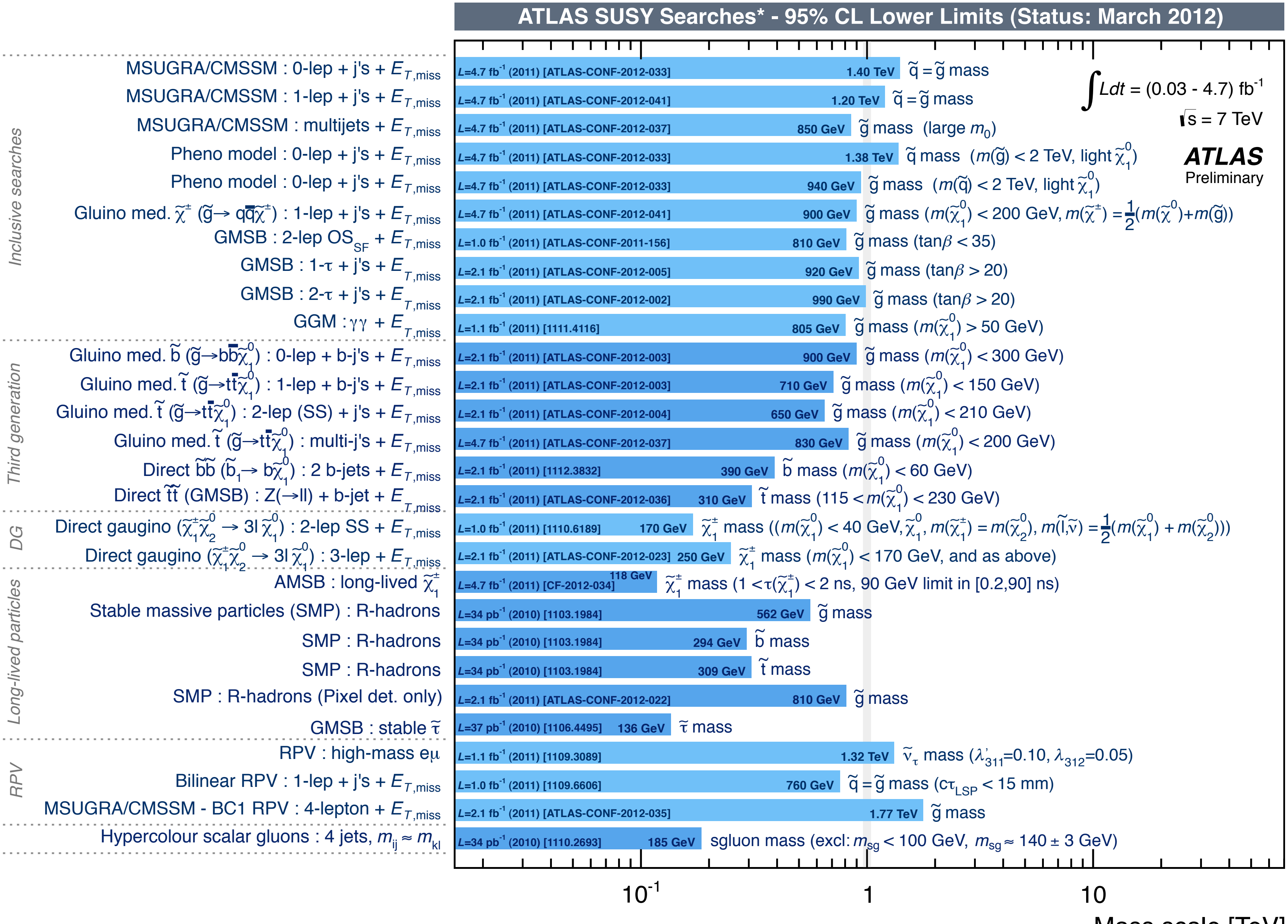
June 2012



CMS Preliminary
$\sqrt{s}$ = 7 TeV
L = 4.6-4.8 fb^{-1}
Observed
Expected (68%)
Expected (95%)
95% CL limit on σ/σ_{SM}
Higgs boson mass (GeV)
10
1
10^{-1}
110
115
120
125
130
135
140
145



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



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

DRAFT: The Physics Case for an e^+e^- Linear Collider

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Report Commissioned for the European Strategy Process, 2012

	250 GeV	350 GeV	500 GeV	1 TeV	1.5 TeV	3 TeV
$\sigma(e^+e^- \to ZH)$	250 fb	130 fb	60 fb	20 fb	5 fb	1 fb
$\sigma(e^+e^- \to H\nu_e\bar{\nu}_e)$	20 fb	40 fb	80 fb	220 fb	320 fb	510 fb
Int. $\mathcal{L}$	250 fb^{-1}	350 fb^{-1}	500 fb^{-1}	1000 fb^{-1}	1500 fb^{-1}	2000 fb^{-1}
# ZH events	62,500	45,500	30,000	20,000	7,500	2,000
# $H\nu_e\bar{\nu}_e$ events	5,000	14,000	40,000	200,000	500,000	1,000,000

Table 1: The Higgs cross sections for the Higgsstrahlung and WW-fusion processes at various centre-of-mass energies and a comparison of the expected number of events accounting for the anticipated luminosities at these energies.

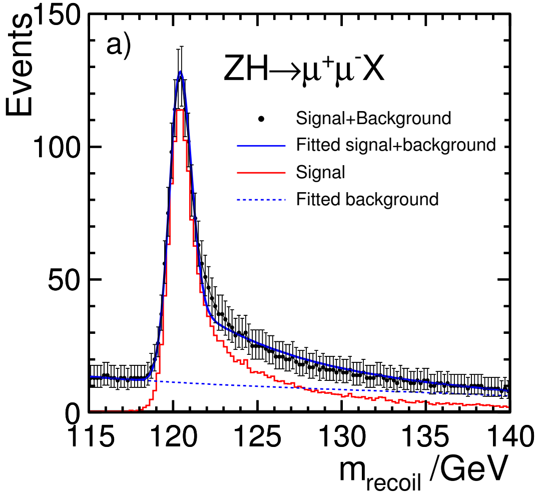


Figure 1: The recoil mass distribution in simulated $e^+e^- \to ZH \to \mu^+\mu^- H$ events in the ILD detector concept at the ILC [10]

$\sqrt{s}$	250 GeV	350 GeV
Int. $\mathcal{L}$	250 fb^{-1}	350 fb^{-1}
$\Delta(\sigma)/\sigma$	3 %	4 %
$\Delta(g_{\mathrm{HZZ}})/g_{\mathrm{HZZ}}$	1.5 %	1.8 %

Table 2: Precisions measurements of the Higgs coupling to the Z at $\sqrt{s} = 250$ GeVand $\sqrt{s} = 350$ GeV.

	250 GeV	350 GeV	3 TeV
$B(\mathrm{H} \to \mathrm{bb})$	2.7 %	2.3 %	2 %
$B(\mathrm{H} \to \mathrm{cc})$	8 %	6 %	3 %
$B(\mathrm{H} \to \mathrm{gg})$	9 %	7 %	?
$B(\mathrm{H} \to \tau\tau)$	6 %*	6 %	?
$B(\mathrm{H} \to \mu^+\mu^-)$	–	–	15 %
$B(\mathrm{H} \to \mathrm{WW}^*)$	< 13 %	< 13 %*	?
g_{Hbb}	1.6 %	1.4 %	< 2 %
g_{Hcc}	4 %	3 %	2 %
$g_{\mathrm{H}\tau\tau}$	3 %	3 %	?
g_{HWW}	< 6 %	< 6 %	< 2 %
g_{HZZ}	1.5 %	1.8 %	?
$g_{\mathrm{HWW}}/g_{\mathrm{HZZ}}$	?	?	< 1 %*

Table 3: The precision on the Higgs branching ratios and couplings obtainable from studies of the Higgsstrahlung process at a LC operating at either $\sqrt{s} = 250$ GeV or $\sqrt{s} = 350$ GeV for respective integrated luminosities of 250 fb^{-1} and 350 fb^{-1}. The uncertainties on the couplings include the uncertainties on g_{HZZ}. Also shown are the precisions achievable at a LC operating at 3 TeV. The numbers marked with asterisk are estimates, all other numbers come from full simulation studies. The question marks indicate that the results of ongoing studies are not yet available.

	500 GeV	1.4 TeV	3.0 TeV
$\sigma(e^+e^- \to ZHH)$	0.2 fb	–	–
$\sigma(e^+e^- \to \nu_e\bar{\nu}_e HH)$	–	0.2 fb	0.9 fb
$\Delta\lambda/\lambda$	$< 50\,\%$	$< 20\,\%$	$< 25\,\%$

Table 4: Current estimates of precision on the Higgs self-coupling achievable at a high energy LC.

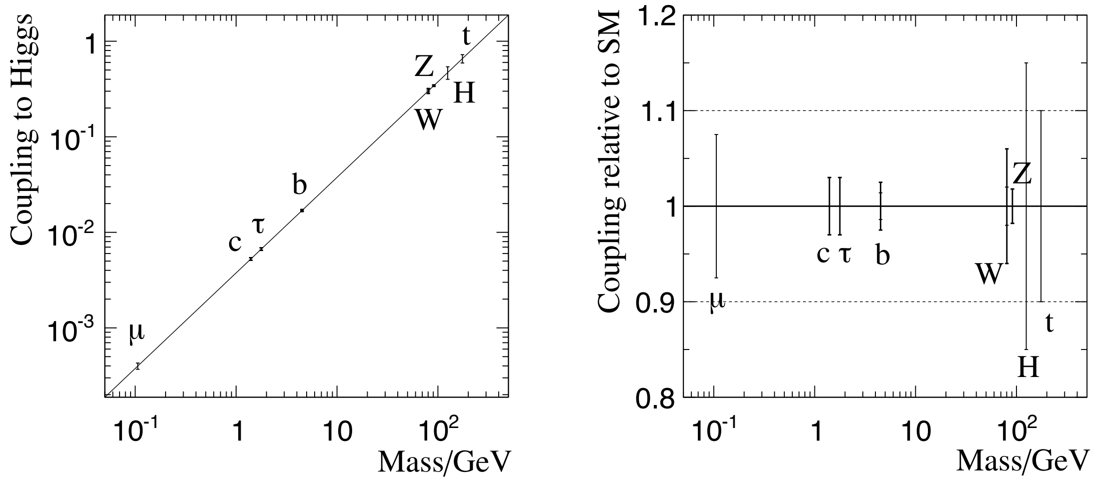


Figure 2: The LC precision on the relation between the Higgs couplings to the masses of the particles.

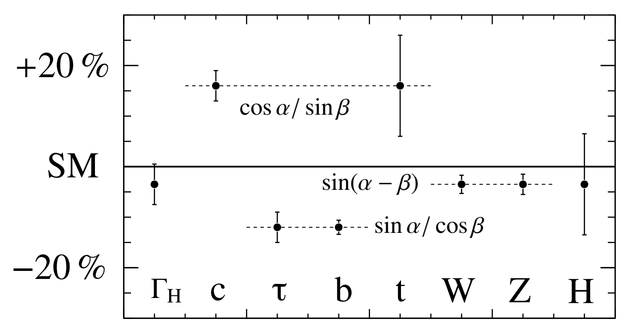


Figure 3: Typical deviations of the Higgs couplings to different particles from the SM predictions in a Two-Higgs-Doublet model. The LC precisions for the various couplings are indicated.

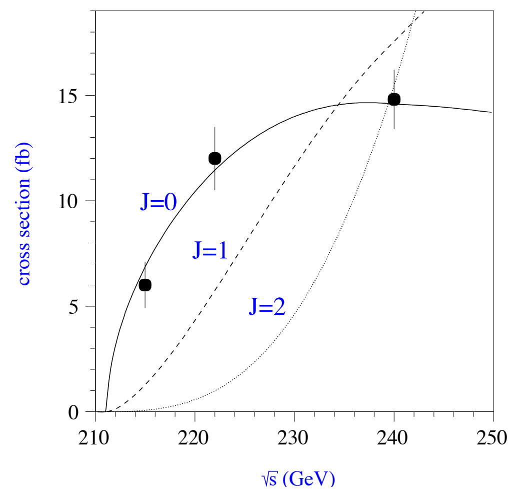


Figure 4: The $e^+e^- \rightarrow ZH$ cross section energy dependence near threshold for different spin states.

CLIC Conceptual Design Report

PHYSICS AND DETECTORS AT CLIC

CLIC CONCEPTUAL DESIGN REPORT

FINAL RELEASE FOR PUBLICATION

20/12/2011

CDR has been released as of last December:
https://edms.cern.ch/document/1177771

1. Physics Potential
2. Experimental Conditions and Detector Requirements
3. Detector Concepts
4. Vertex Detectors
5. Tracking System
6. Calorimetry
7. Detector Magnet System
8. Muon System
9. Very Forward Calorimeters
10. Readout Electronics and Data Acquisition System
11. Interaction Region and Detector Integration
12. Physics Performance
13. Future Plans and R&D Prospects

Focus of this short talk is on the Physics Potential

Organization

Introductory Comments

Topic sub-editors:

Higgs Physics: Abdelhak Djouadi (Orsay), Markus Schumacher (Freiburg)

Supersymmetry: Sabine Kraml (Grenoble), Werner Porod (Würzburg)

Alternative Scenarios: Roberto Contino (Rome), Christophe Grojean (CERN)

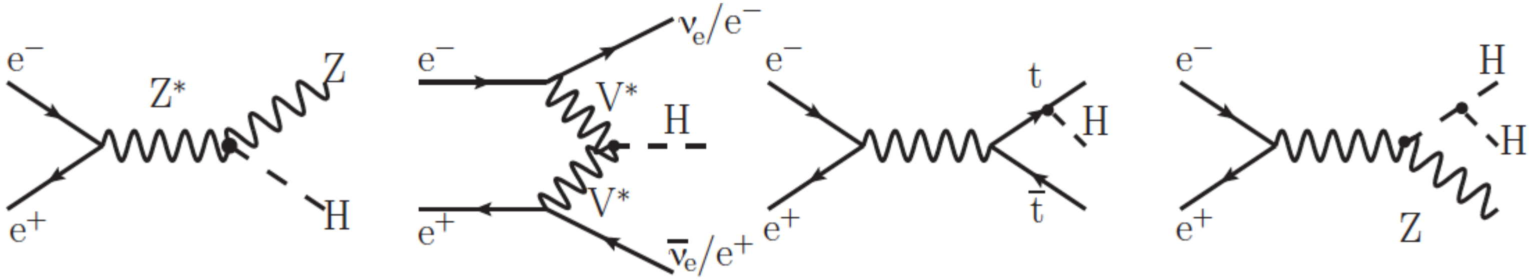
Precision: Andre Hoang (Vienna), Klaus Moenig (DESY)

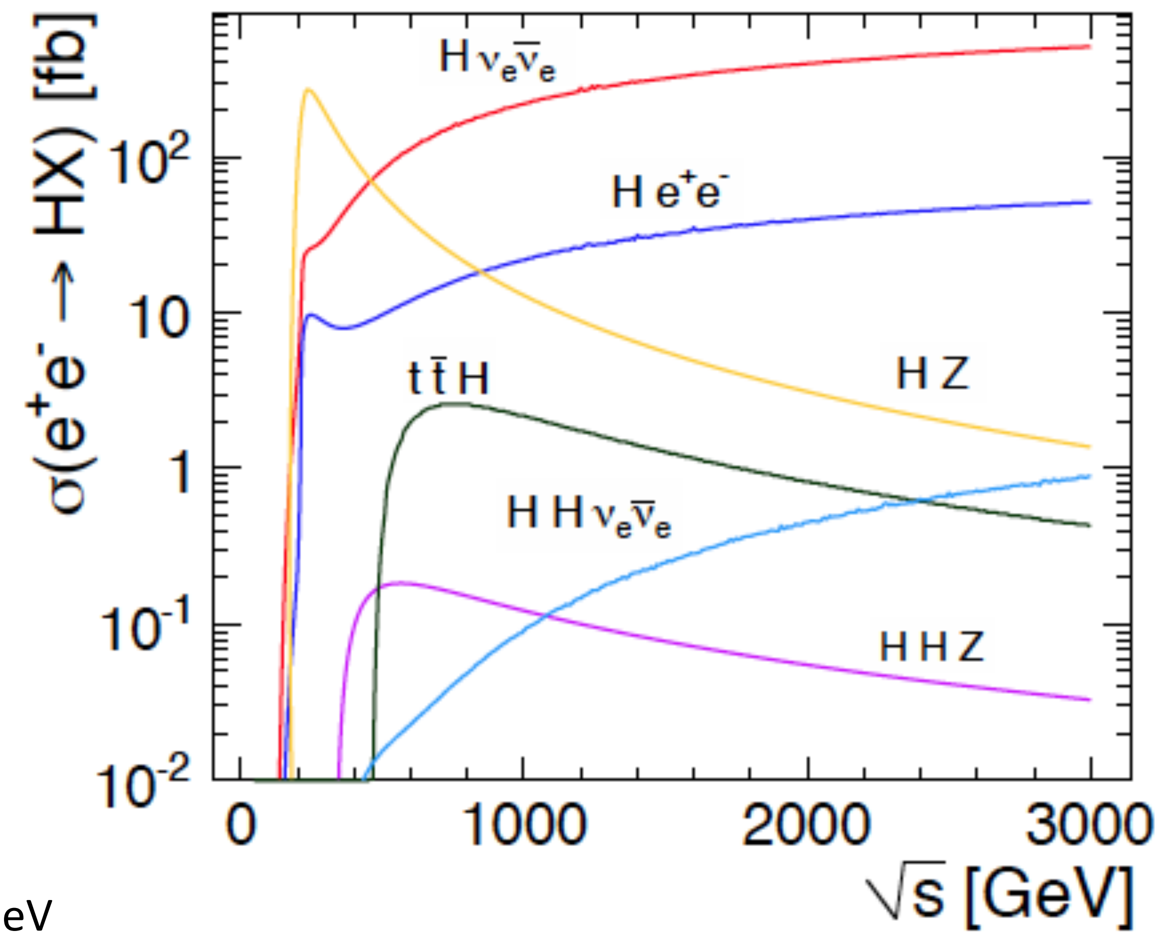
Polarisation: Gudi Moortgat-Pick (DESY), JW (CERN/Michigan)

Physics case built on bring together many different elements into this one document:
- Past CLIC study results
- Current benchmark studies
- Latest theory views consistent with all measured data
- Theory analyses suggesting viable search strategies and results

Chapter 1 Editors: Gian Giudice, James Wells (CERN-PH-TH)

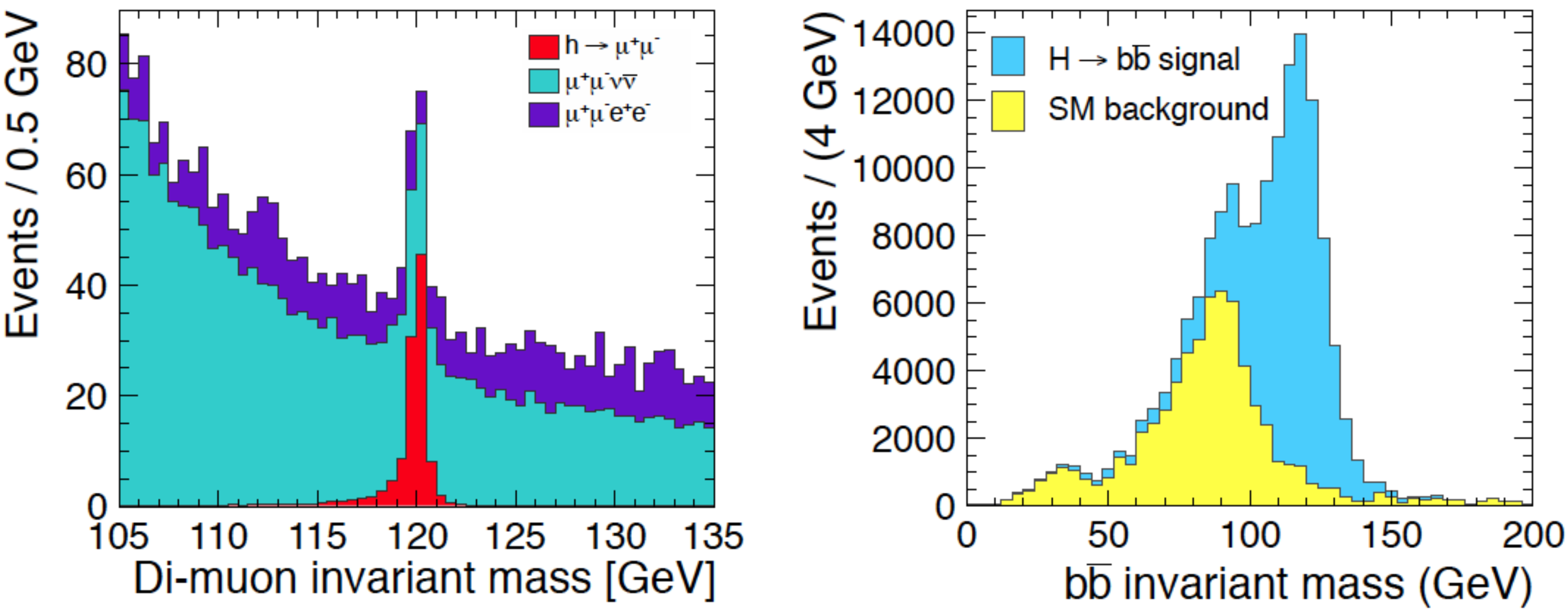
Higgs Physics





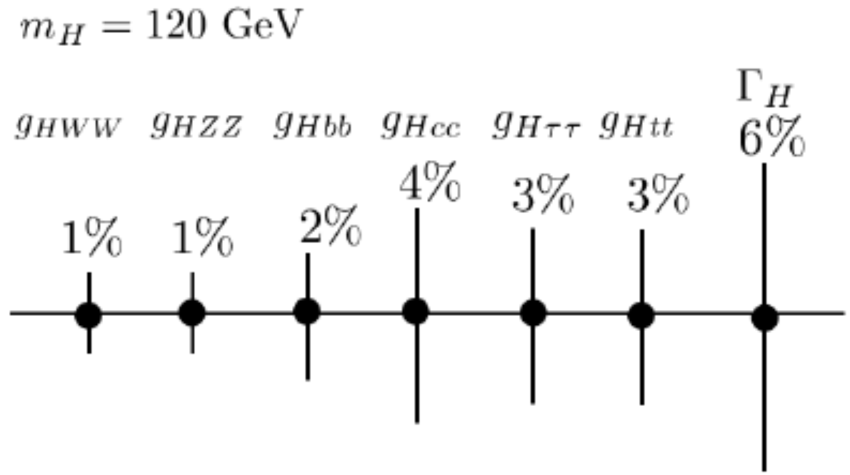
M_{higgs} = 120 GeV

Δ(σ x Br(μ+μ−)) = 15% stat. unc.   Δ(σ x Br(bb)) = 0.2% stat. unc.



(a) $e^+e^- \to H\nu\bar{\nu}, H \to \mu^+\mu^-$ (b) $e^+e^- \to H\nu\bar{\nu}, H \to b\bar{b}$

Fig. 1.3: Reconstructed sample for two Higgs channels with $M_H = 120$ GeV at CLIC with $\sqrt{s} = 3$ TeV with 2 ab^{-1}. The histograms are stacked distributions of signal and background reconstructed using the CLIC_SiD detector (see Chapter 12).



	Coupling determination(%)	Sensitivity to SM deviation (%)
Hbb	2	4
Hcc	3	6
$H\mu\mu$	15	15

Fig. 1.2: Relative error in the Higgs boson coupling determination to different particle species. The top diagram is for a Higgs mass of 120 GeV at $\sqrt{s} = 500$ GeV and with 500 fb^{-1} of integrated luminosity, except $g_{Ht\bar{t}}$, which is obtained at $\sqrt{s} = 800$ GeV with 1 ab^{-1}. The bottom table gives coupling constant determination and sensitivity to deviations from the SM obtained at CLIC 3 TeV with 2 ab^{-1} for 120 GeV Higgs boson mass (see text for further explanation).

Extremely good resolution on the heavy Higgs masses and widths.

m_A = 743.7 +- 1.7 GeV

m_{H+} = 746.9 +- 2.1 GeV

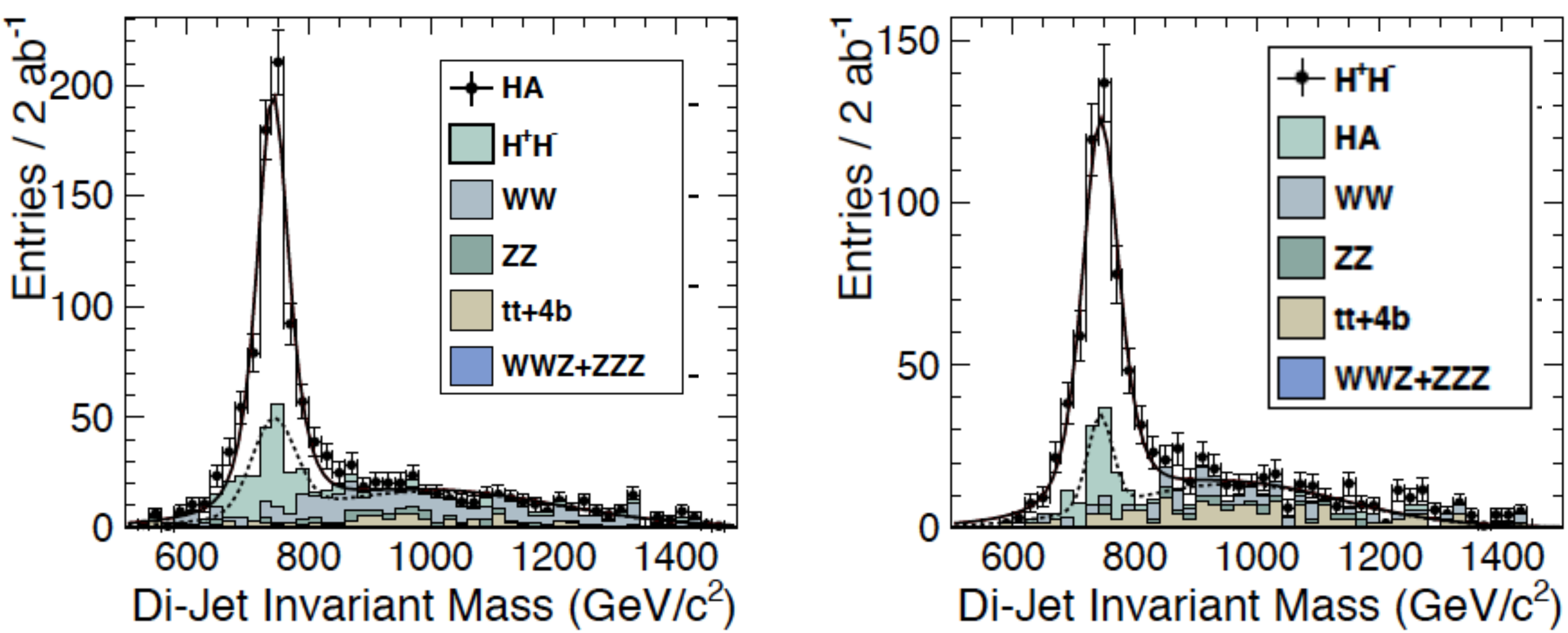


Fig. 1.5: Higgs mass peak reconstruction in the processes $e^+e^- \to HA$ (left), and in $e^+e^- \to H^+H^-$ (right), at a CLIC detector using *model II*, see Chapter 12. The corresponding background channels are shown as well. The finite Higgs widths are taken into account.

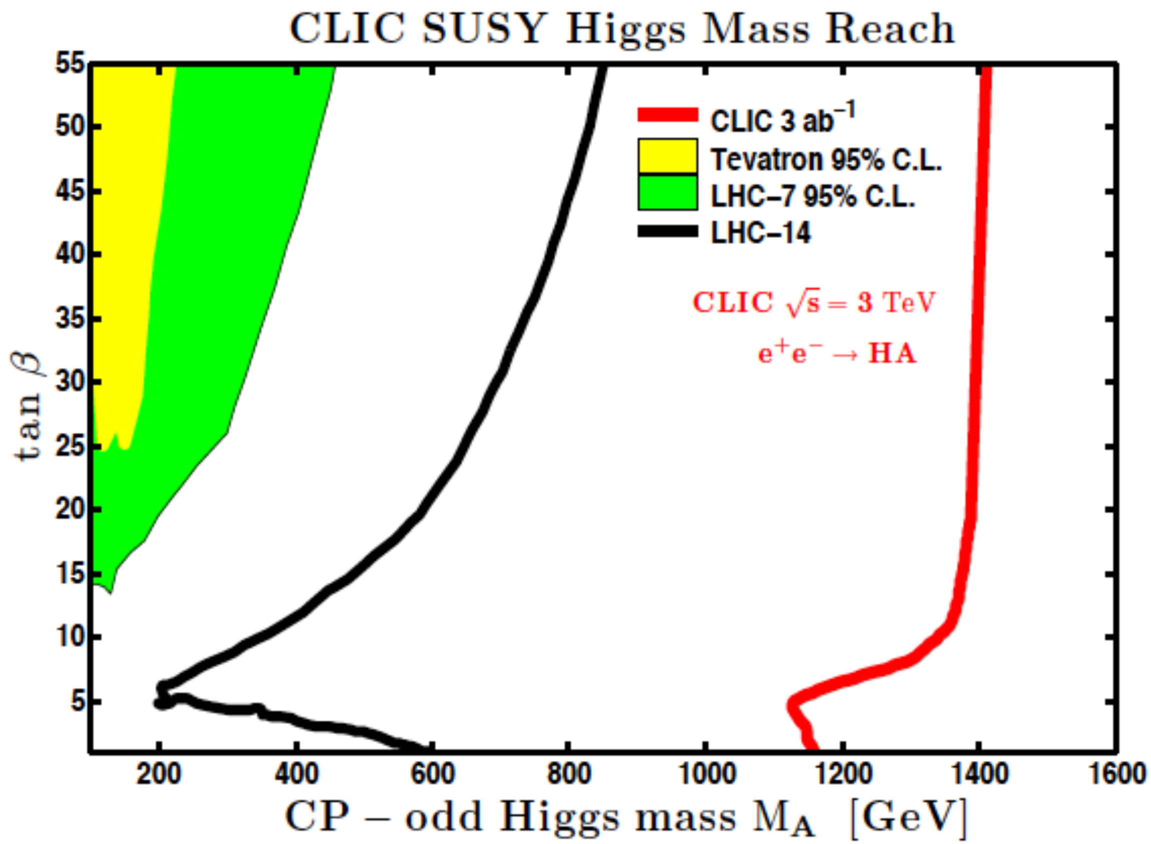


Fig. 1.18: Search reach in the $m_A - \tan\beta$ plane for LHC and CLIC. The left-most coloured regions are current limits from the Tevatron with ~ 7.5 fb^{-1} of data at $\sqrt{s} = 1.96$ TeV and from ~ 1 fb^{-1} of LHC data at $\sqrt{s} = 7$ TeV. The black line is projection of search reach at LHC with $\sqrt{s} = 14$ TeV and 300 fb^{-1} of luminosity [78]. The right-most red line is search reach of CLIC in the HA mode with $\sqrt{s} = 3$ TeV. This search capacity extends well beyond the LHC. A linear collider at $\sqrt{s} = 500$ GeV can find heavy Higgs mass eigenstates if their masses are below kinematic threshold of 250 GeV.

At the LHC the heavy Higgs are not expected to be discovered in this case.

At CLIC 3 TeV, they can be discovered, and can help resolve between models.

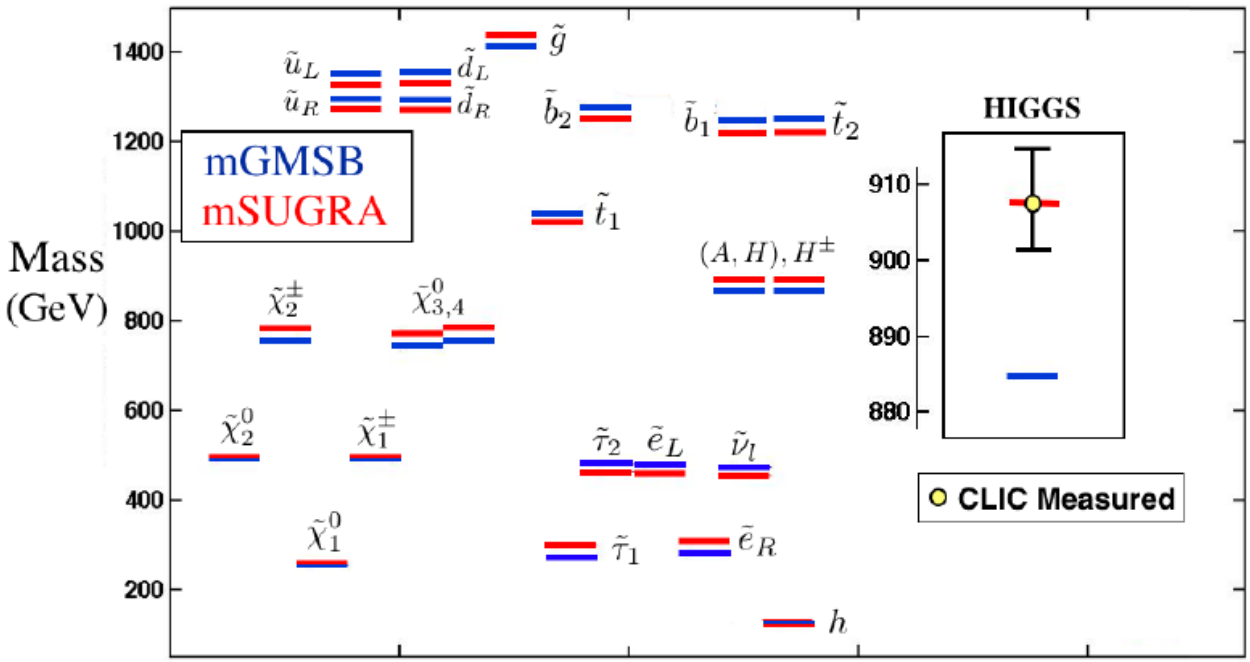


Fig. 1.19: Resolving SUSY breaking models and masses with CLIC: Shown are the nearly degenerate spectra of a mSUGRA model and a mGMSB model. Assuming some of the SUSY particles masses are measured, with a spectrum of the type above predicted by the different models of Supersymmetry breaking, CLIC would be able to discern not only some of the slepton masses and the heavier charginos within the two models, but also the SUSY Higgs masses. For mSUGRA the soft masses are $m_0 =$ 175 GeV, $m_{1/2} = 645$ GeV, $A_0 = 0$, with $\tan\beta = 10$ and $\mu > 0$. For mGMSB the number of messengers are $n_l = n_q = 5$, and $\Lambda_{\rm SUSY} = 4 \cdot 10^4$ GeV, $M_{\rm Mess} = 10^{12}$ GeV, with $\tan\beta = 10$.

Supersymmetry

After the LHC, there may be much to discover and measure within SUSY at CLIC.

Electroweak states (e.g., sleptons and charginos) particularly difficult at LHC.

There is even the prospect of no sign of SUSY at LHC but discovery at CLIC.

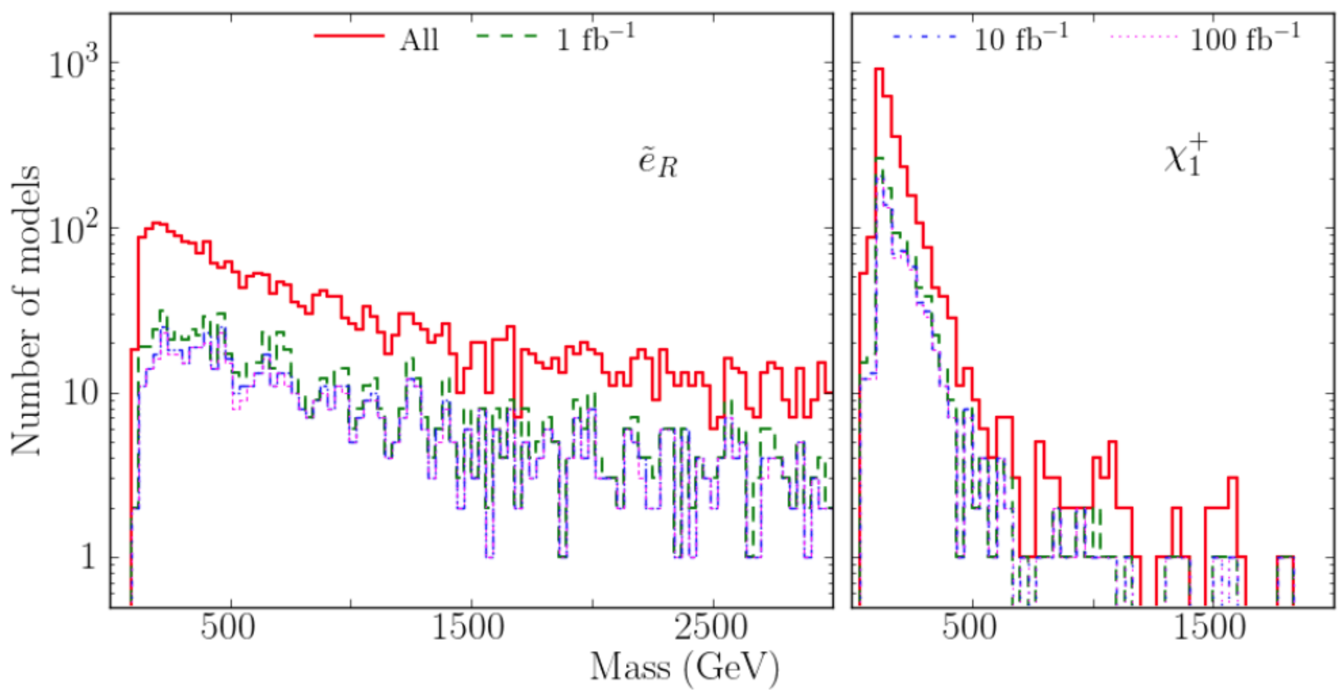


Fig. 1.8: Distribution of $\tilde{\chi}_1^{\pm}$ (right) and $\tilde{e}_R$ (left) masses of pMSSM points that escape 14 TeV LHC searches with 1 fb^{-1}, 10 fb^{-1} and 100 fb^{-1} of integrated luminosity [41]. The top red histograms show the mass distributions in the full model set.

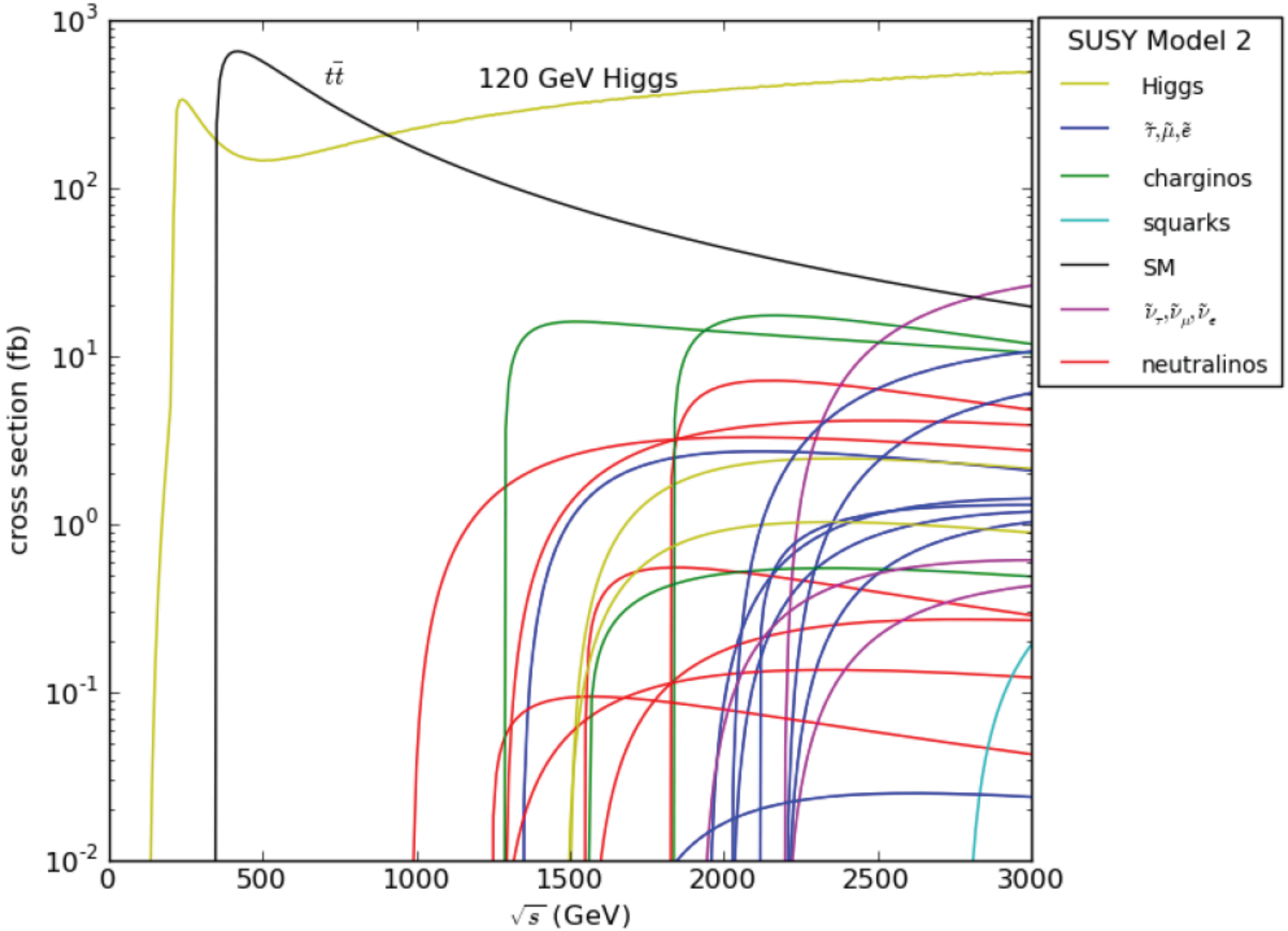


Fig. 1.9: SUSY production cross sections (in fb) of *model II* as a function of $\sqrt{s}$. Every line of a given colour corresponds to the production cross section of one of the particles in the legend, e.g. the three green lines are, per increasing threshold, $e^+e^- \to \tilde{\chi}_1^- \tilde{\chi}_1^+$, $e^+e^- \to \tilde{\chi}_1^\mp \tilde{\chi}_2^\pm$, and $e^+e^- \to \tilde{\chi}_2^- \tilde{\chi}_2^+$ respectively. The first threshold is the $e^+e^- \to ZH$ production.

Table 1.1: Values of the SUSY particle masses of the chosen benchmark point (*model II*) and estimated experimental statistical accuracies at CLIC, as obtained in the analyses presented in Chapter 12, and also in [20] (indicated with *). All values are in GeV. The last column is either out of kinematic reach or not studied.

Particle	Mass	Stat. acc.
$\tilde{\chi}_1^0$	340.3	±3.3
$\tilde{\chi}_2^0$	643.1	±9.9
$\tilde{\chi}_3^0$	905.5	±19.0*
$\tilde{\chi}_4^0$	916.7	±20.0*
$\tilde{\chi}_1^\pm$	643.2	±3.7
$\tilde{\chi}_2^\pm$	916.7	±7.0*
$\tilde{e}_R^{\pm}$	1010.8	±2.8
$\tilde{\mu}_R^{\pm}$	1010.8	±5.6
$\tilde{\nu}_1$	1097.2	±3.9

Particle	Mass	Stat. acc.
h	118.5	±0.1*
A	742.0	±1.7
H	742.0	±1.7
$H^\pm$	747.6	±2.1

Quantity	Value	Stat. acc.
$\Gamma(A)$	22.2	±3.8
$\Gamma(H^\pm)$	21.4	±4.9

Particle	Mass
$\tilde{\tau}_1$	670
$\tilde{\tau}_2$	974
$\tilde{t}_1$	1393
$\tilde{t}_2$	1598
$\tilde{b}_1$	1544
$\tilde{b}_2$	1610
$\tilde{u}_R$	1818
$\tilde{u}_L$	1870
$\tilde{g}$	1812

Table 1.2: Fitted parameters in GeV from the chargino/neutralino sector. Each column represents a local minimum in the best fit to the data.

M_1	342.1 ± 3.5	-341.9 ± 3.5	341.8 ± 3.5	-342.3 ± 3.5
M_2	655.3 ± 6.0	655.3 ± 6.1	654.2 ± 6.1	654.2 ± 6.1
μ	924.8 ± 6.2	924.8 ± 6.2	-925.5 ± 6.2	-925.5 ± 6.2

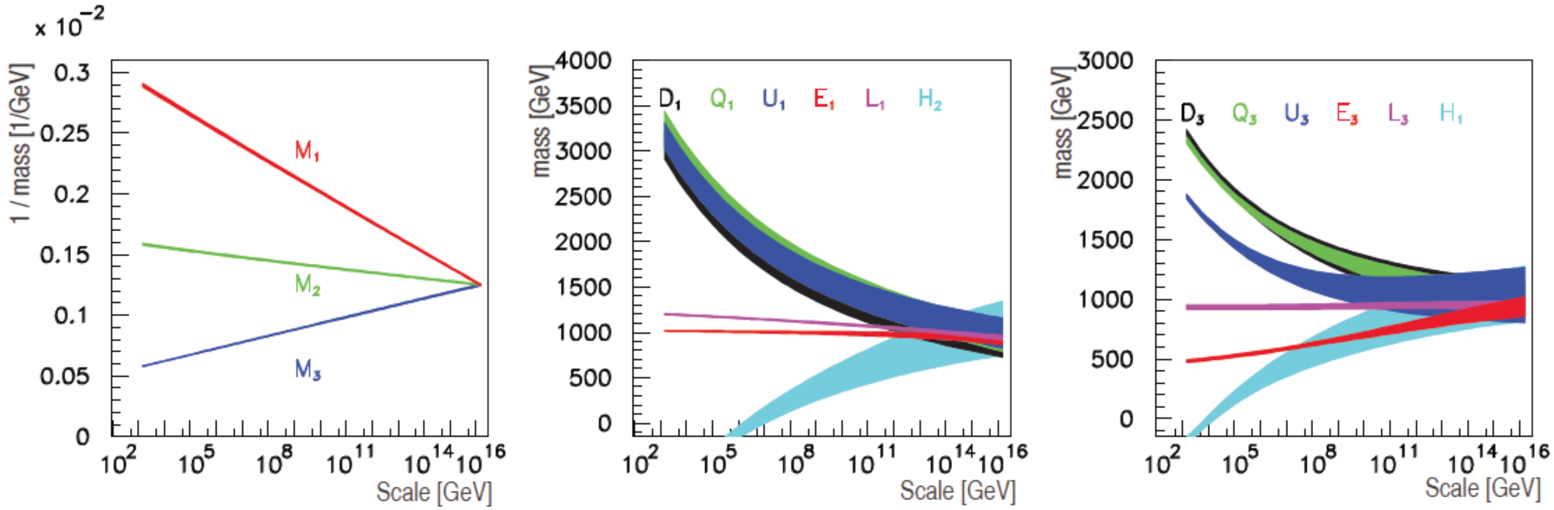
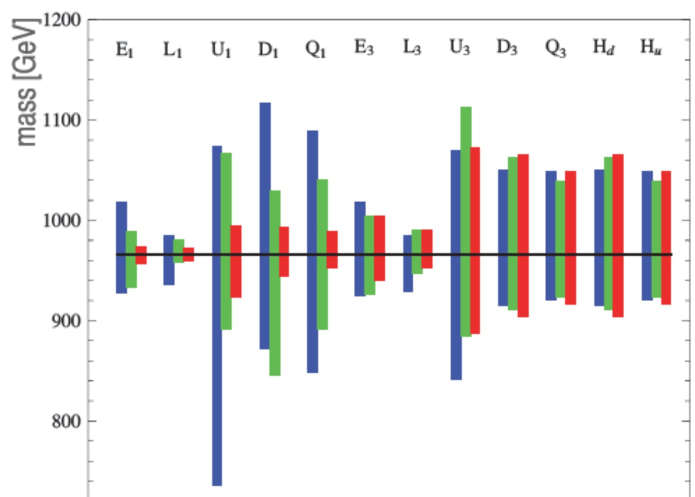


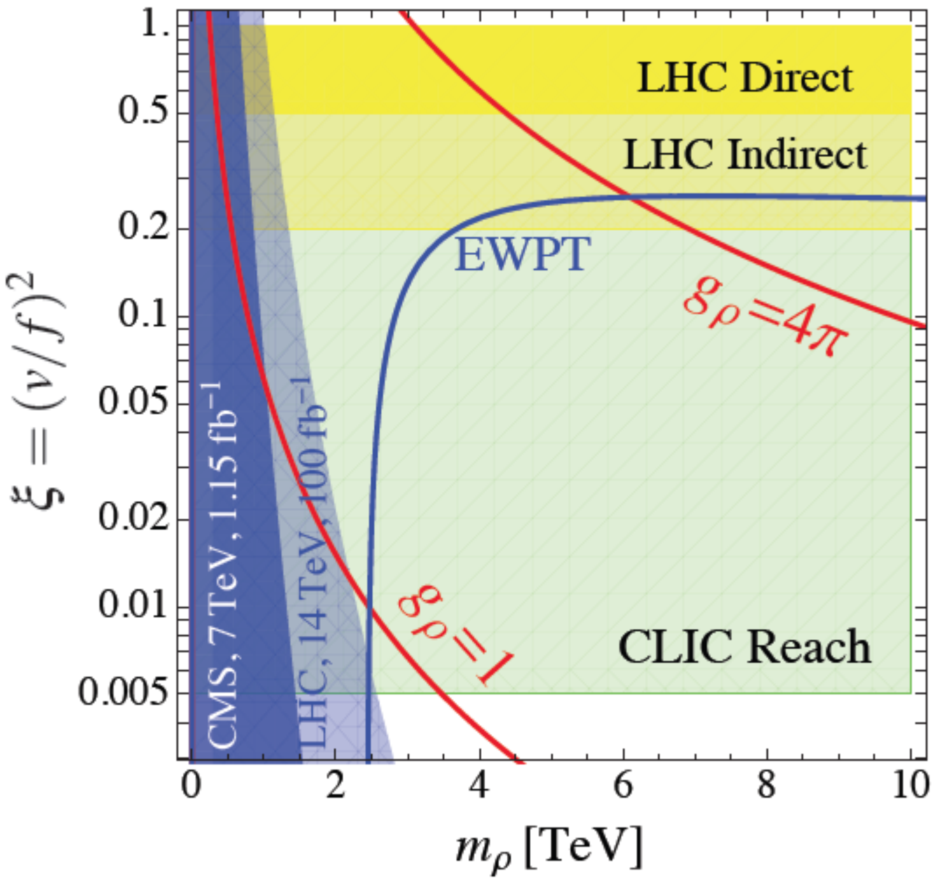
Fig. 1.10: Extrapolation of SUSY-breaking parameters from the electroweak to the GUT scale for *model II*, assuming 3% measurement precision on the physical sfermion masses.



Also, Dark Matter relic abundance can be inferred statistically to $\Omega h^2 = 0.10$ +- 0.02

Fig. 1.11: One sigma range of the determined scalar mass parameters at the GUT scale assuming 5% (blue), 3% (green) and 1% (red) measurement precision on the physical sfermion masses. The black line indicates the nominal value $m_0 = 966$ GeV.

Higgs Strong Interaction



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

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

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

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

Z’ and Contact Interactions

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

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

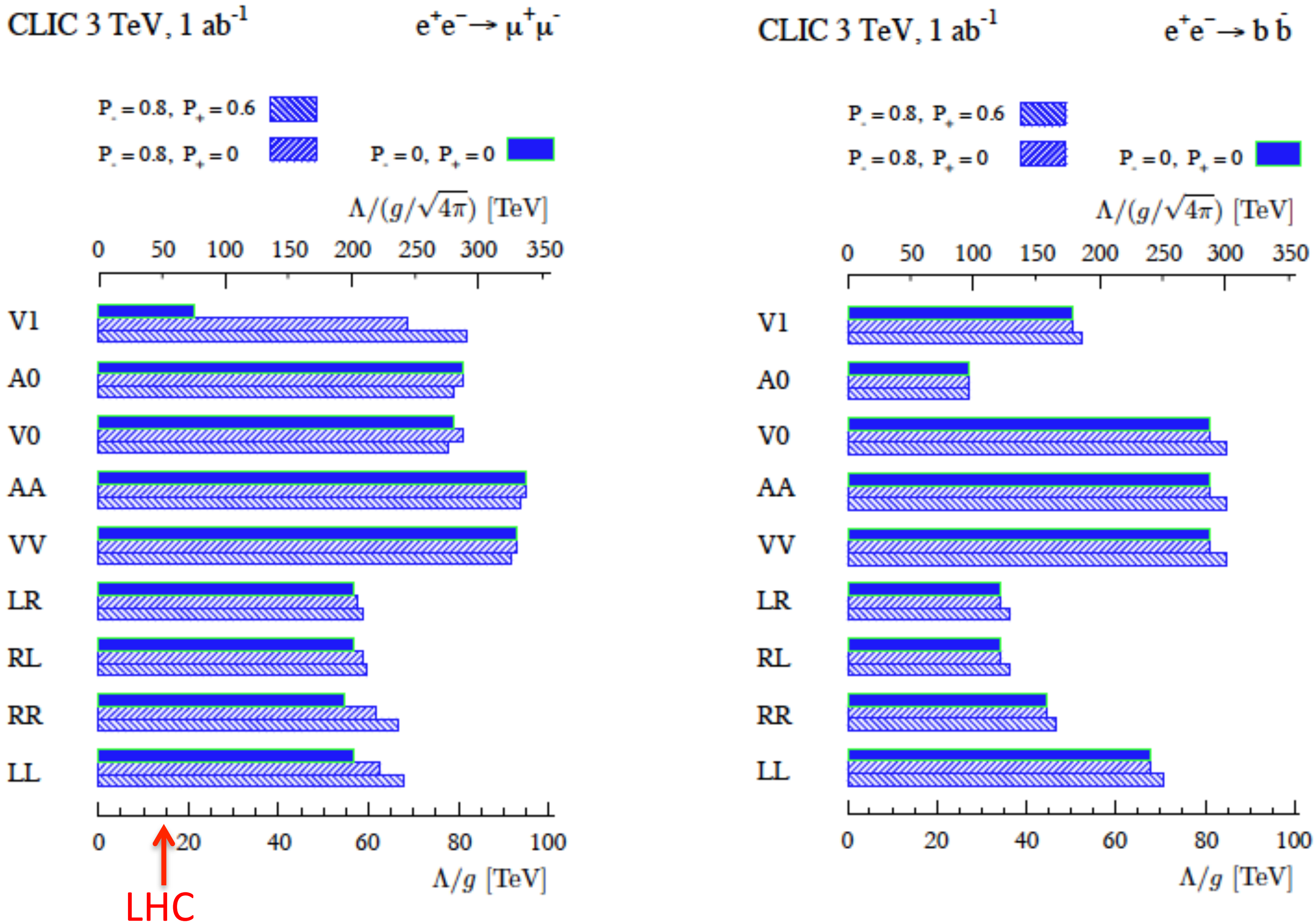


Fig. 1.14: Limits on the scale of contact interactions (Λ/g) that can be set by CLIC in the $\mu^+\mu^-$ (left) and $b\bar{b}$ (right) channels with $\sqrt{s} = 3$ TeV and $\mathcal{L} = 1$ ab^{-1}. A degree of polarisation $P_- = 0, 0.8$ ($P_+ = 0, 0.6$) has been assumed for the electrons (positrons).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

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

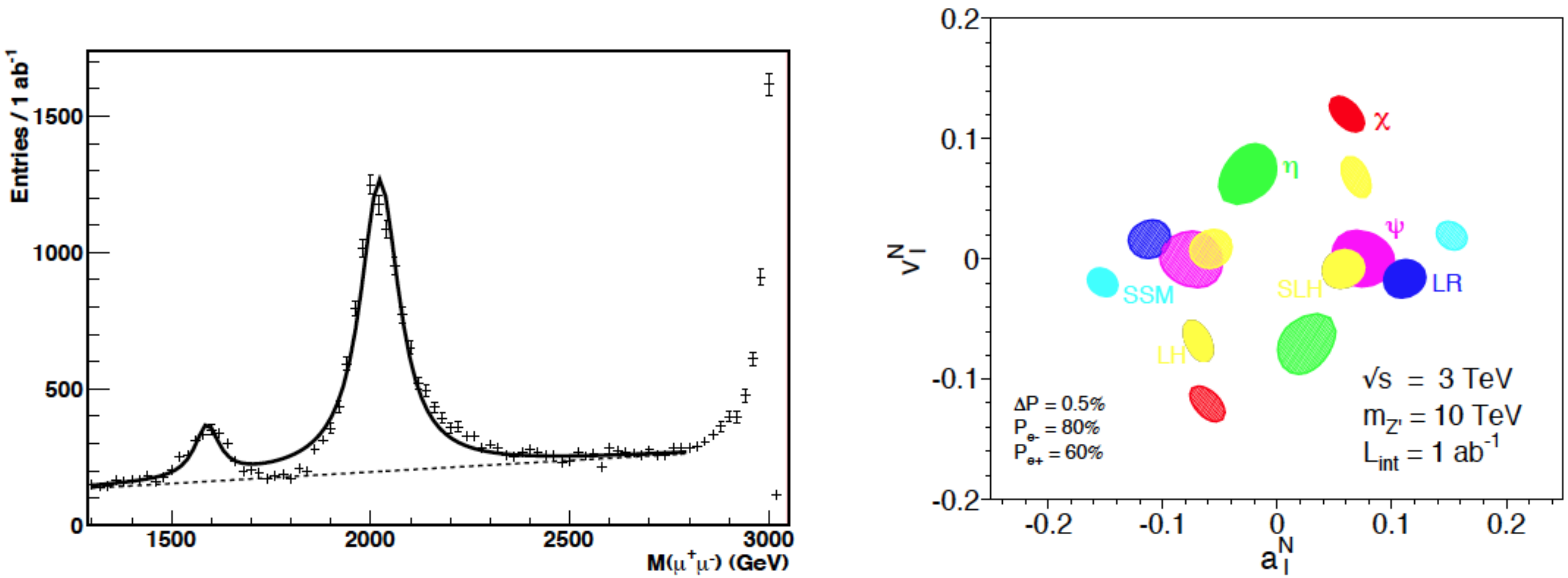


Fig. 1.16: Left: Observation of new gauge boson resonances in the $\mu^+\mu^-$ channel by auto-scan at 3 TeV. The two resonances are the $Z_{1,2}$ predicted by the 4-site Higgsless model of [67]. Right : Expected resolution at CLIC with $\sqrt{s} = 3$ TeV and $\mathscr{L} = 1$ ab^{-1} on the “normalised” 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 ($t\bar{t}$, $b\bar{b}$, ...).

Conclusions

- Precise physics potential conditioned on LHC results
- Excellent capabilities for Higgs precision measurements
- Excellent capabilities for discovering electroweak states
- Excellent reach in composite/higher dimensional operators

Near future: Respond to LHC results. Motivate and define energy staging options.

Table 1.6: Discovery reach of various theory models for different colliders and various levels of integrated luminosity, $\mathscr{L}$ [73]. LHC14 and the luminosity-upgraded SLHC are both at $\sqrt{s}$ =14 TeV. LC800 is an 800 GeV e^+e^- collider and CLIC3 is $\sqrt{s}$ =3 TeV. TGC is short for Triple Gauge Coupling, and "μ contact scale" is short for LL μ contact interaction scale Λ with $g = 1$ (see Section 1.4).

New particle	collider: $\mathscr{L}$:	LHC14 100 fb^{-1}	SLHC 1 ab^{-1}	LC800 500 fb^{-1}	CLIC3 1 ab^{-1}
squarks [TeV]		2.5	3	0.4	1.5
sleptons [TeV]		0.3	-	0.4	1.5
Z' (SM couplings) [TeV]		5	7	8	20
2 extra dims M_D [TeV]		9	12	5-8.5	20-30
TGC (95%) (λ_γ coupling)		0.001	0.0006	0.0004	0.0001
μ contact scale [TeV]		15	-	20	60
Higgs compos. scale [TeV]		5-7	9-12	45	60