New Physics on the Horizon with CLIC

F. Teubert *(CERN PH Department)*

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Introduction

We know from previous experiments (LEP/SLC, TEVATRON, HERA, etc…) what is the order of magnitude of the energy scale to be investigated: ~1 TeV. (*never ever trust theoreticians*!)

LHC is going to open the way at this energy scale, and after few years will give clear indications of what it is there:

1, Is there a scalar particle like the **SM Higgs**?
2. Are there new particles not predicted by the SM (like **sparticles**)?
3. Do these new particles modify low energy **flavour** changing processes?...

However, once we know the answer to these questions, new questions appear which LHC has a limited potential to answer, if any:

1. Is this scalar particle the responsible for **SSB**? Does it behave as the **SM predicts**?
2. Are these new particles compatible with any of the theories proposed **beyond** the SM?
3. Are **flavour** changing processes compatible with any of these theories?...

We know we need a ***Linear Collider*** *to try to answer (some of) these questions, and progress in a significant way. What we* ***don't know*** *is what is* ***the energy we need*** *of this collider.*

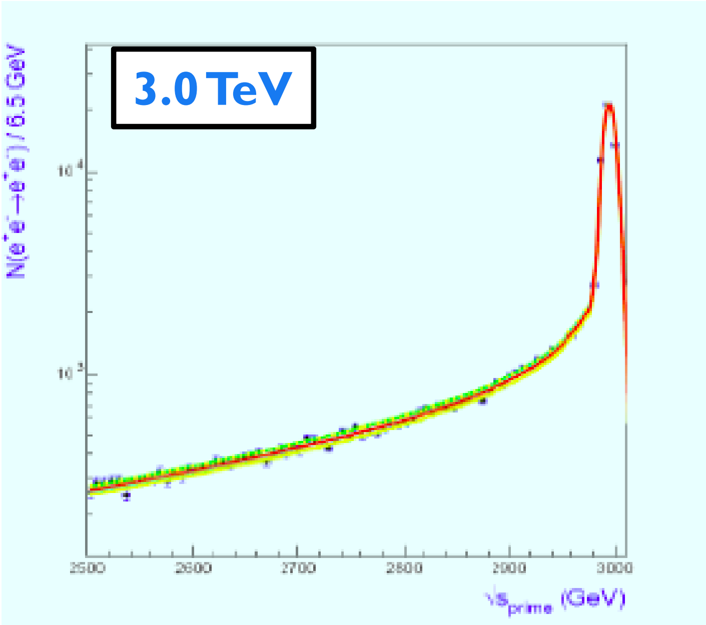
Introduction

The safest option is to plan for the highest possible energy: **CLIC**.

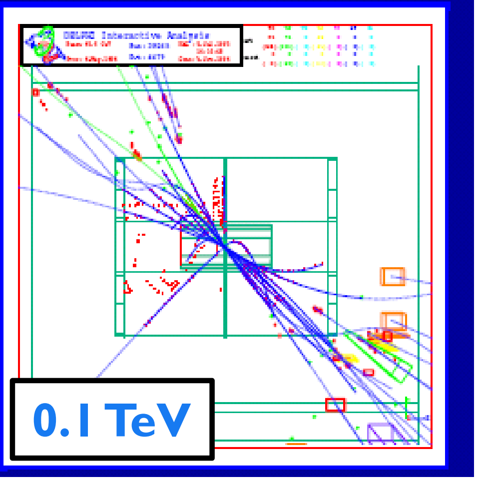
However, this is not the easiest option in terms of machine&detector(s) design and physics analysis.

Not all events are produced at the relevant energy:
  significant beamstrahlung →needs to be measured.

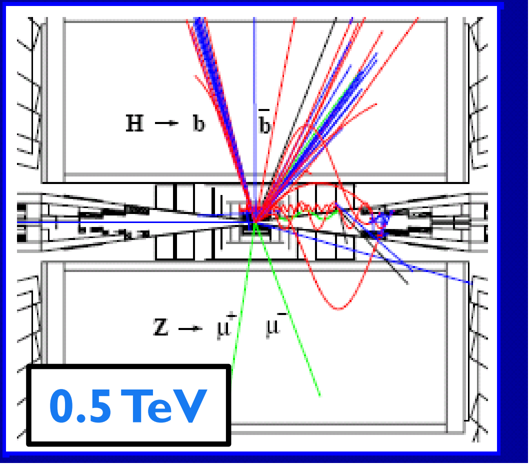
Particle multiplicity at low angles is significantly increased → requires special design at low radius.



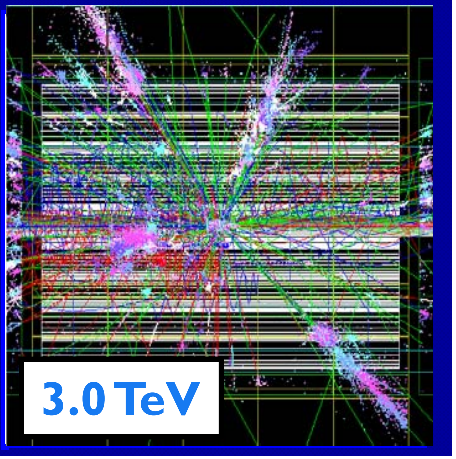
$e^+e^- \longrightarrow Z^0 \longrightarrow bb$



$e^+e^- \longrightarrow Z^0H^0 \longrightarrow \mu^+\mu^-bb$



$e^+e^- \longrightarrow H^+H^- \longrightarrow t\bar{b}\bar{t}b$

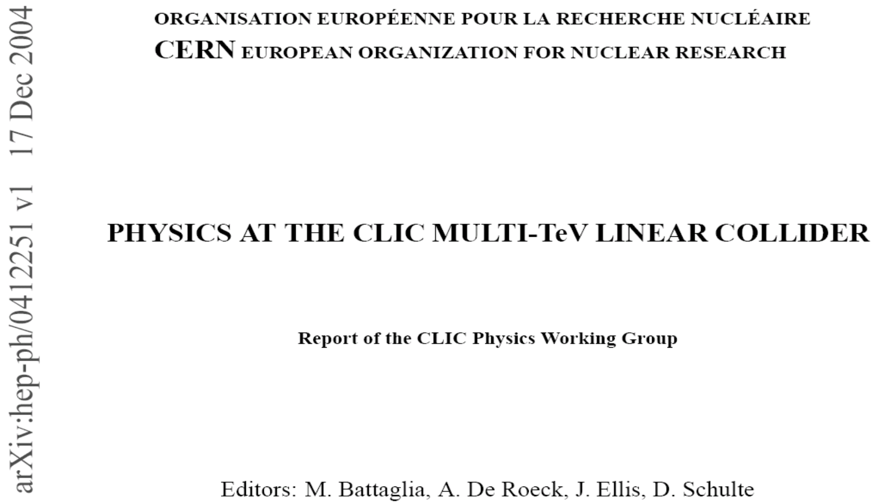


Introduction

Progress in defining the physics potential, the machine parameters and the detector optimization for the ILC & CLIC programs is expected in the coming years, from the effective collaboration and strong synergies within the world-wide efforts on detector R&D, physics and software.

Even if the LHC results asks for several TeVs of energy, CLIC could run over a wide range of energies (eg. 0.5-3 TeV), hence ILC detector concepts are good starting points for the high energy detector(s).

Hence, we assume here a ILC-like detector performance to explore what could be the physics potential of CLIC to answer the questions left after the LHC. Most of the information taken from:



arXiv:hep-ph/0412251 v1 17 Dec 2004

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

PHYSICS AT THE CLIC MULTI-TeV LINEAR COLLIDER

Report of the CLIC Physics Working Group

Editors: M. Battaglia, A. De Roeck, J. Ellis, D. Schulte

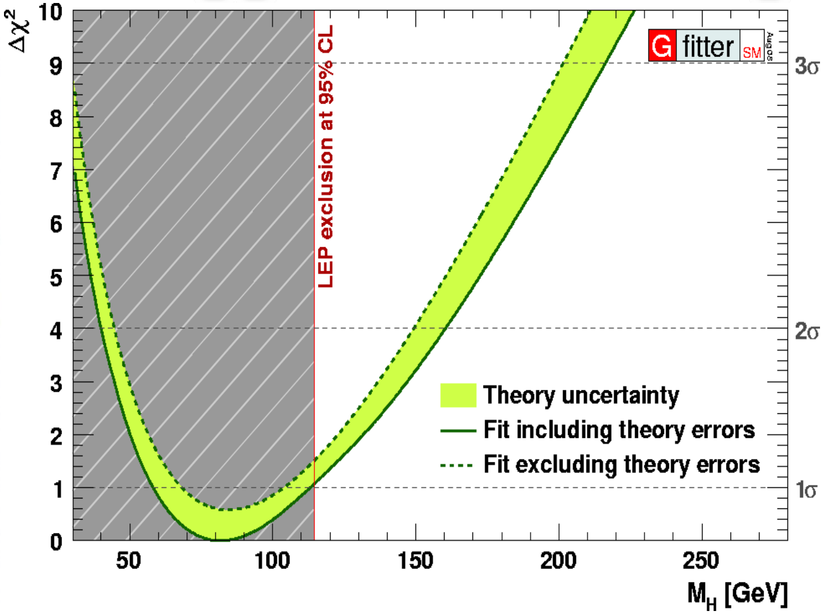
Introduction: CLIC parameters

Center-of-mass energy	CLIC 500 GeV		CLIC 3 TeV	
Beam parameters	**Conservative**	**Nominal**	**Conservative**	**Nominal**
Accelerating structure	502		G	
Total (Peak 1%) luminosity	$0.9(0.6) \cdot 10^{34}$	$2.3(1.4) \cdot 10^{34}$	$1.5(0.73) \cdot 10^{34}$	$5.9(2.0) \cdot 10^{34}$
Repetition rate (Hz)	50			
Loaded accel. gradient MV/m	80		100	
Main linac RF frequency GHz	12			
Bunch charge10^9	6.8		3.72	
Bunch separation (ns)	0.5			
Beam pulse duration (ns)	177		156	
Beam power/beam (MWatts)	4.9		14	
Hor./vert. norm. emitt ($10^{-6}/10^{-9}$)	3/40	2.4/25	2.4/20	0.66/20
Hor/Vert FF focusing (mm)	10/0.4	8 / 0.1	8 / 0.3	4 / 0.07
Hor./vert. IP beam size (nm)	248 / 5.7	202 / 2.3	83 / 2.0	40 / 1.0
Hadronic events/crossing at IP	0.07	0.19	0.57	2.7
Coherent pairs at IP	10	100	$5\ 10^7$	$3.8\ 10^8$
BDS length (km)	1.87		2.75	
Total site length km	13.0		48.3	
Wall plug to beam transfert eff	7.5%		6.8%	
Total power consumption MW	129.4		415	

Assume at least ~0.5 ab^{-1}/year (~0.2 ab^{-1}/year) for 3 TeV (0.5 TeV) options.

Higgs Physics

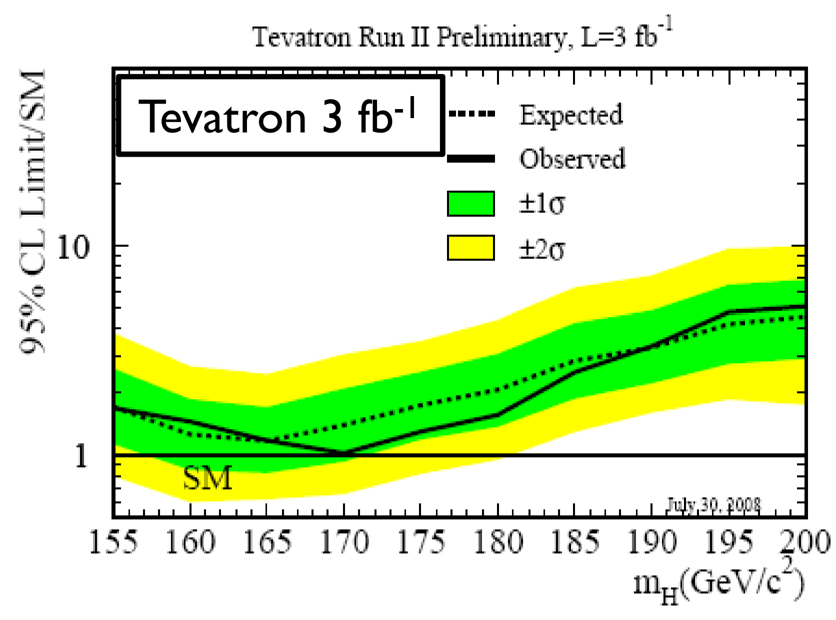
Higgs: Still waiting for the Nobel Prize

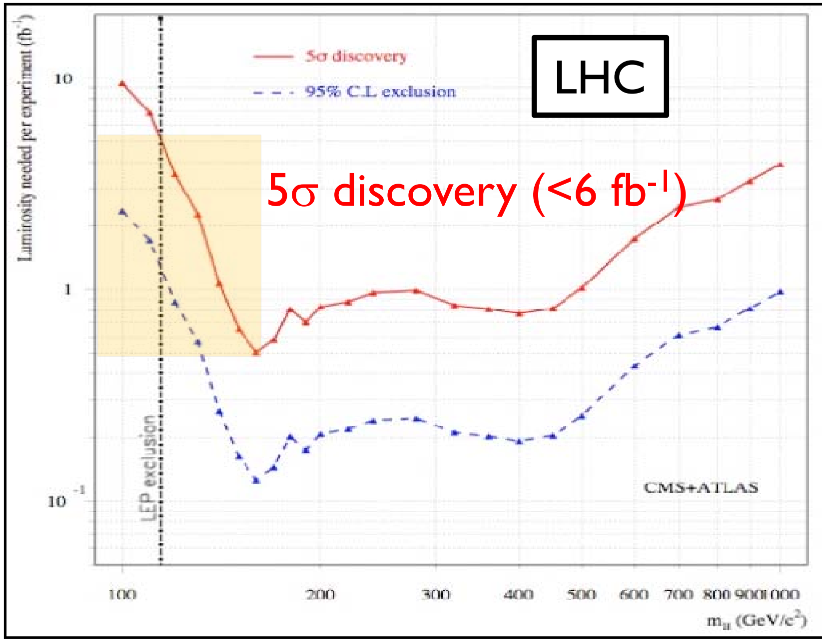


Not likely that the SM Higgs has a mass larger than 200 GeV/c^2.

TEVATRON has started to exclude the region around 170 GeV/c^2.

In the coming years, TEVATRON and/or LHC will show evidence for a relatively light SM Higgs, if it exist.


Tevatron 3 fb^{-1}


LHC

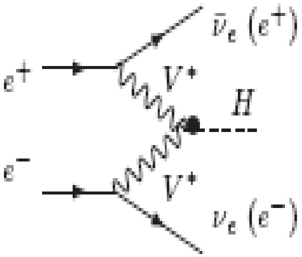
5σ discovery (<6 fb^{-1})

If there is a light SM-like Higgs…

The cross-section at ~3TeV is enormous

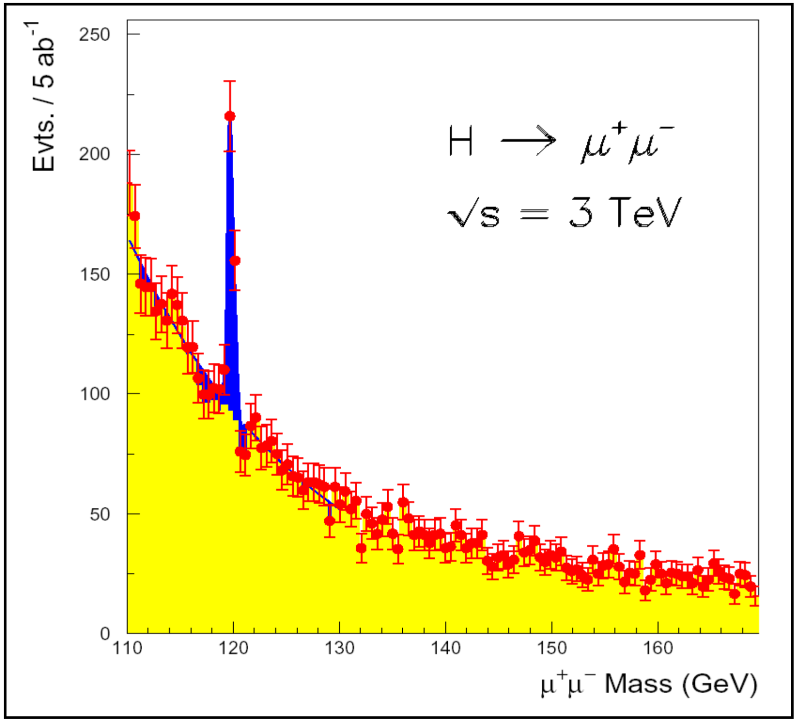
→ access to very rare decays (BR~10^{-4}).

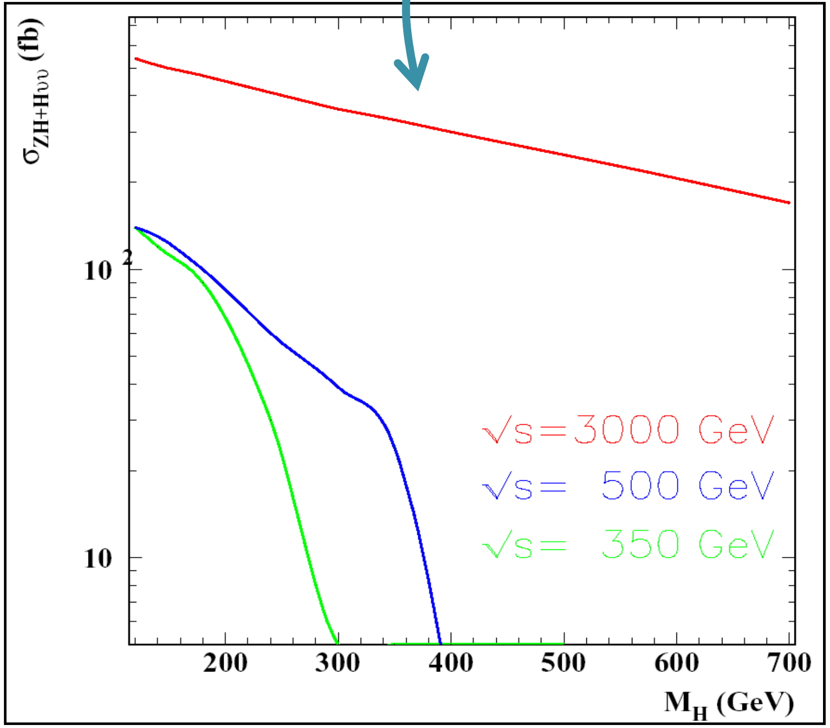
$\sigma \propto 1/s$



$\sigma \propto \log(s)$

Measure Higgs couplings to leptons, for instance with 0.5 ab^{-1}, we expect ~70 H→$\mu^+\mu^-$ decays for M_h=120 GeV/c^2, and measure the couplings with ~4% precision.



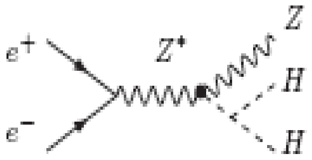


If there is a light SM-like Higgs…

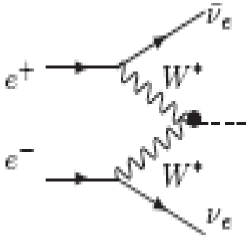
The double Higgs cross-section at ~3TeV is big

→ access to HHH self coupling, hence Higgs potential!

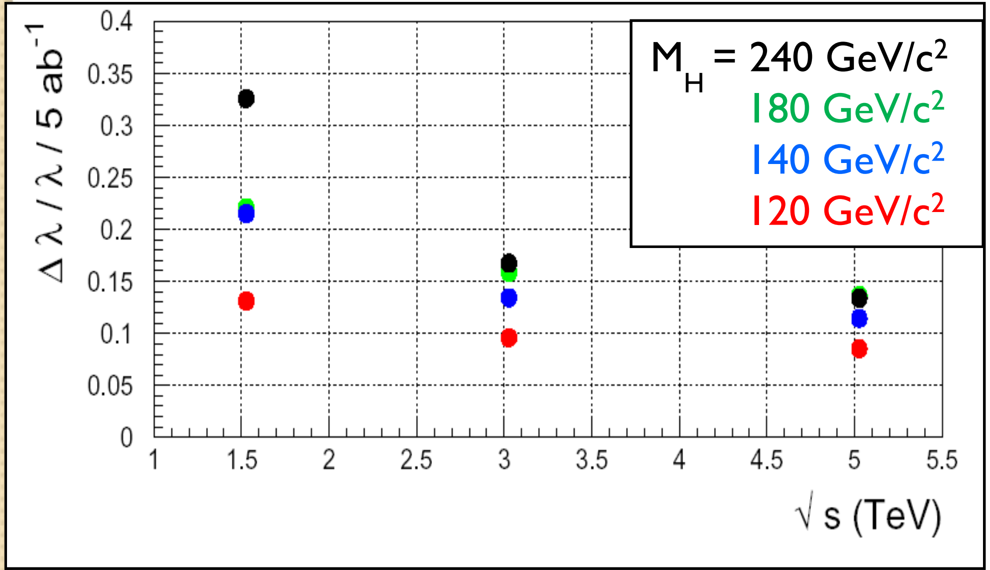
For instance with 5 ab^{-1}, we expect to measure the triple HHH coupling with ~10% precision for M_h=120 GeV/c^2.

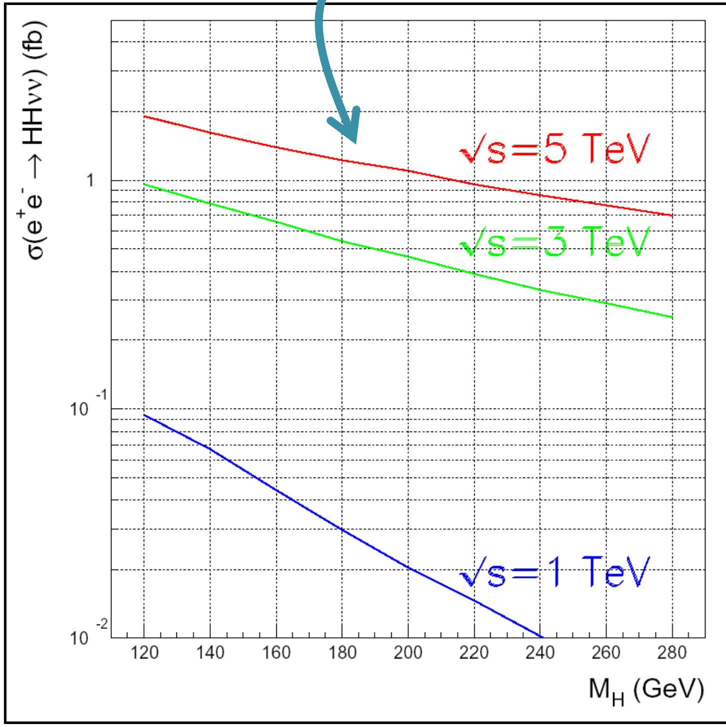


$\sigma \propto 1/s$
~0.2 fb @ 0.5 TeV



$\sigma \propto \log(s)$
~1 fb @ 3 TeV



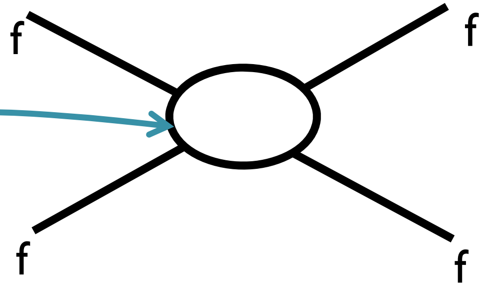


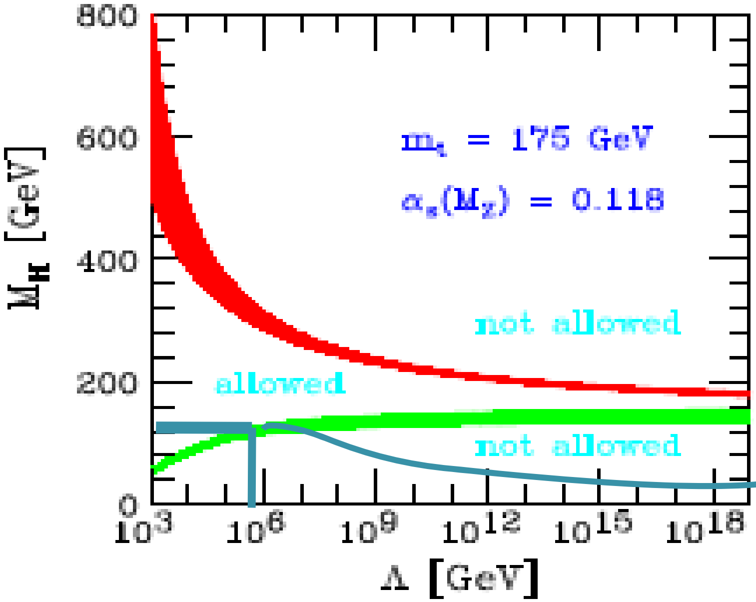
If there is a light SM-like Higgs…

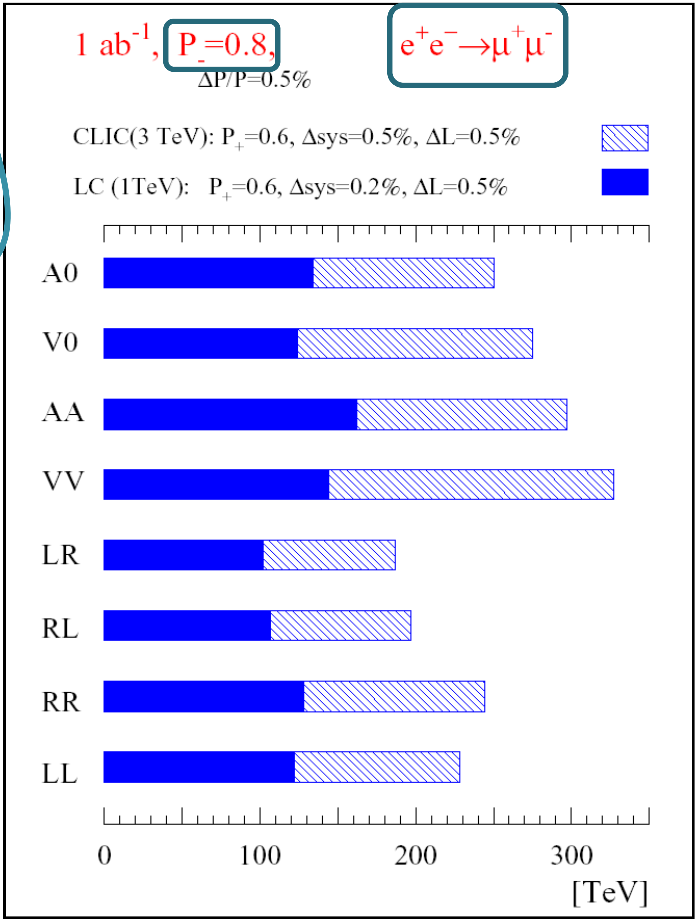
If M_h<~120 GeV/c^2 then $\Lambda < \sim 1000$ TeV in order to stabilize the Higgs potential.

A LC with $\sqrt{s}\sim 10^3$ TeV is not on the agenda, but we can access indirectly this energy region.

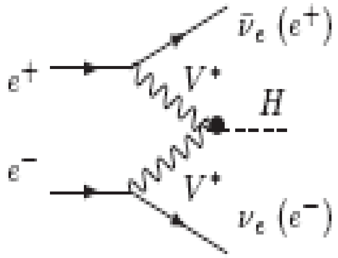
The larger the energy of the LC, the closer we are to this limit through indirect sensitivity to contact Interactions







If there is NP the Higgs may not be light…



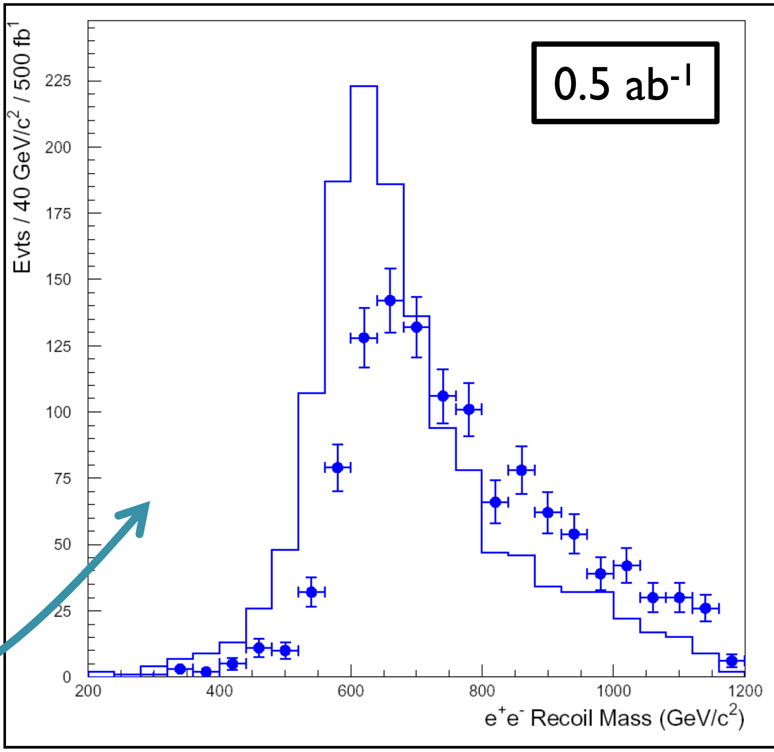
$\boxed{\sigma \propto \log(s)}$

The presence of New Physics may partially cancel the virtual effects of a heavy Higgs and still be in agreement with precision measurements.

Indeed LHC should have discovered a heavy Higgs, and roughly measure its properties. However a precise determination of its mass, width and couplings will require a LC.

The fusion process $ZZ \to e^+e^-H$ can be used as the Higgs-strahlung process at low energies to determine its mass *independent of the decay mode* using the recoil mass.

However the electrons are at very low angles, where backgrounds are worse. Nevertheless, it seems possible to extract a clear signal up to $M_H < 900$ GeV/c^2.



If there is NP the Higgs may not be alone…

The presence of New Physics may introduce new Higgses. For instance we can look for charged Higgses:

$$e^+ e^- \rightarrow H^+ H^- \rightarrow tb\ tb$$

With 3 ab^{-1} and 3 TeV we could reach up to $M_{H\pm}<1.2$ TeV!

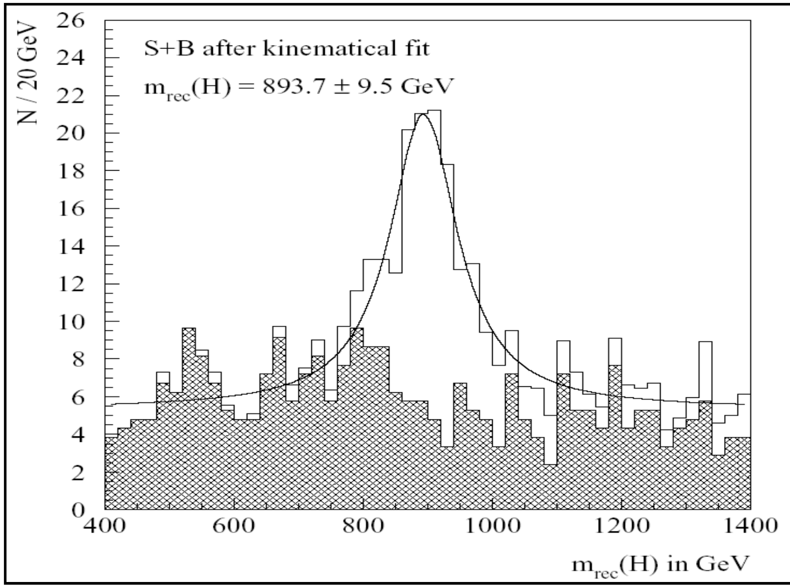
Or we can look for neutral Higgses:

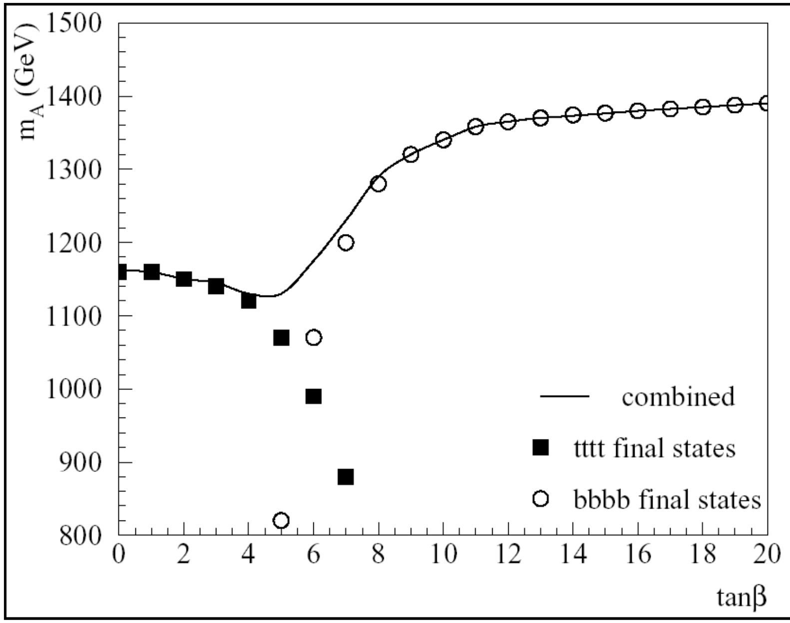
$e^+ e^- \rightarrow H^0 A^0 \rightarrow tt\ tt$ *(low* $\tan\beta$*)*

$e^+ e^- \rightarrow H^0 A^0 \rightarrow bb\ bb$ *(large* $\tan\beta$*)*

With 3 ab^{-1} and 3 TeV we could reach up to $M_A<1.1$ TeV for any value of $\tan\beta$.

Again a LC will provide precision versus what LHC can do…Jet reconstruction is crucial here!





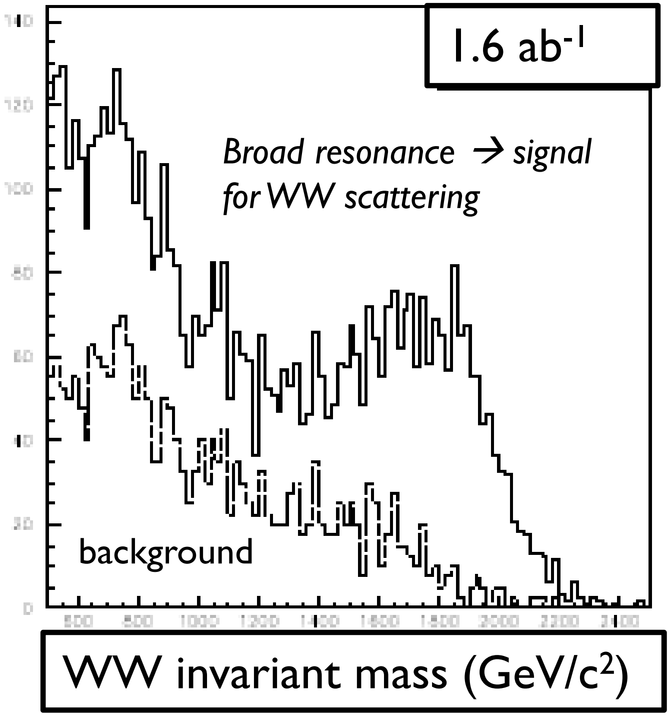
If there is NP the Higgs may not be there…

The presence of New Physics may have as a consequence that there is no Higgs at all (understood as a fundamental particle). LHC should tell us if such is the case, and maybe find a hint for strong WW scattering.

A linear collider at high energy will probably be the best option to study WW scattering with good enough precision, and understand scenarios with composite Higgs, quarks or leptons.

$$e^+e^- \to \nu\bar{\nu}W_L^+W_L^-$$

A LC allows the use of the 4-jet final state, however the higher the energy the closer the jets are.



CLIC & Higgs physics summary

If there is only a light SM-like Higgs, it will be found at hadron colliders, and most of their properties (spin, couplings,…) can be determined with very good precision at a low energy linear collider. However, to complete the measurements of its properties (eg, lepton couplings) and more important, to measure with precision the Higgs potential (hence non-trivial test of the SSB mechanism), a multi-TeV linear collider is crucial.

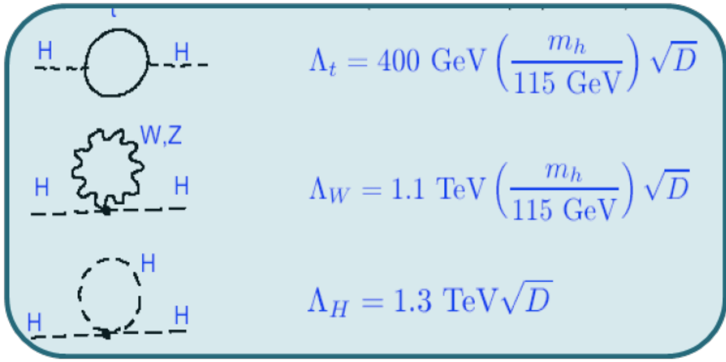
If, as we all hope, there is NP at the TeV scale, the Higgs may be heavy, new Higgses may appear in pairs (requiring $\sqrt{s}>2M_H$) or may even be no Higgs at all. In all cases the argument for a multi-TeV linear collider gets stronger.

Supersymmetry

Reasons why many like Supersymmetry

Without any doubt the most popular framework our friends from the theory departments like to work with is **SUPERSYMMETRY**. This is not only because it makes calculations a bit more bearable, but also:

I. Intrinsic beauty
II. Naturalness or Hierarchy problem
III. Unification of the gauge couplings at 10^{16}GeV
IV. Predicts a light Higgs (Mh < 150 GeV/c^2)
V. Provides a candidate for CDM (if R-parity is assumed)
VI. May be an essential building block of string theories???



$$\Lambda_t = 400\ \mathrm{GeV}\left(\frac{m_h}{115\ \mathrm{GeV}}\right)\sqrt{D}$$

$$\Lambda_W = 1.1\ \mathrm{TeV}\left(\frac{m_h}{115\ \mathrm{GeV}}\right)\sqrt{D}$$

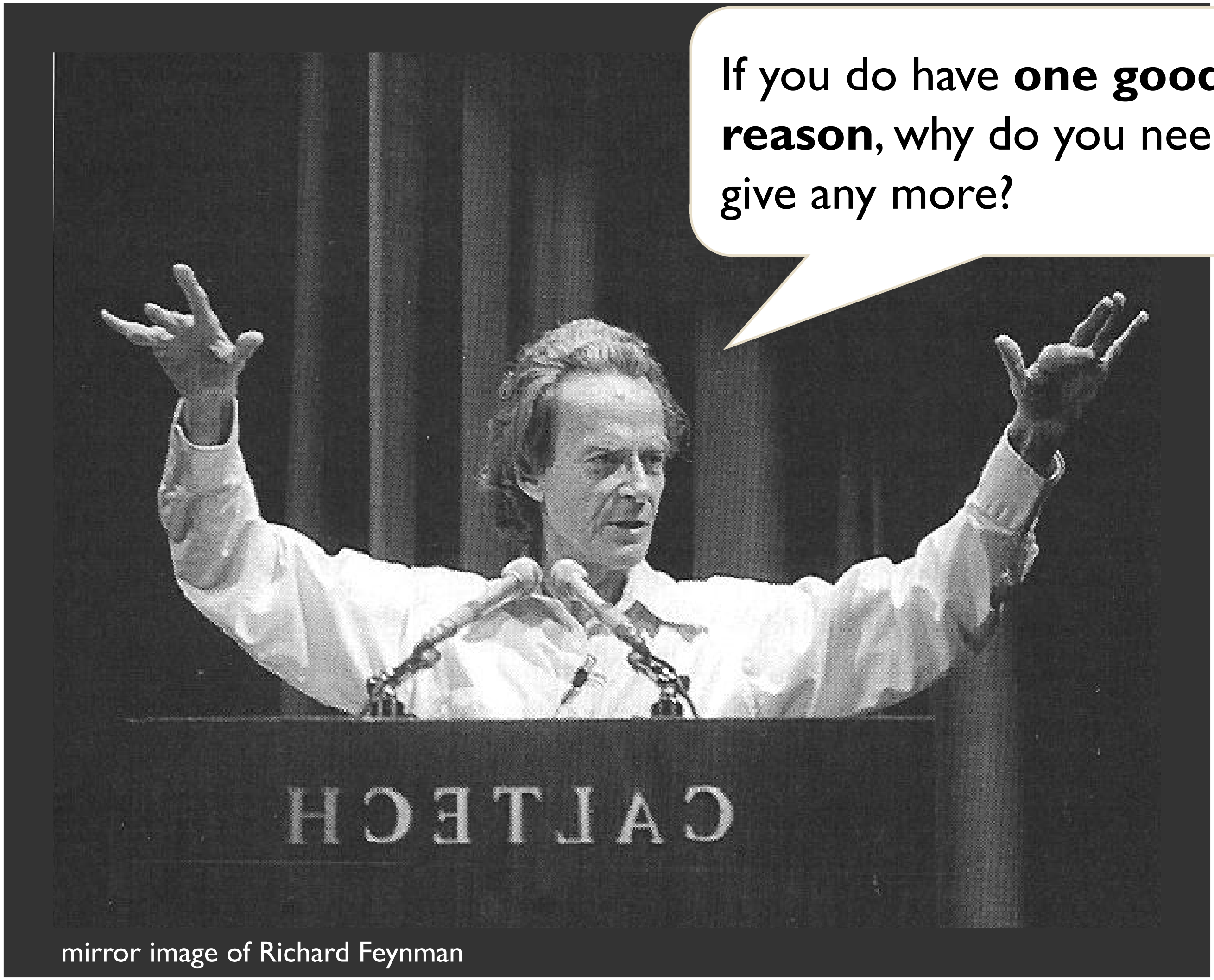
$$\Lambda_H = 1.3\ \mathrm{TeV}\sqrt{D}$$

However, while the Naturalness argument pushes for a light scale for NP, (Λ_{NP} < 1 TeV), the fact that no convincing sign of NP has been seen so far in precision measurements of the EW and Flavour sectors push for larger scales (Λ_{NP} > several TeVs).

Unless, NP is weakly coupled and modifies low energy observables only via loops and they are decoupled to new flavour-violating operators.

The era of speculation on the Weak scale should come to an end with the LHC data!!!

Reasons why many like Supersymmetry



If you do have **one good reason**, why do you need to give any more?

mirror image of Richard Feynman

Sparticles may not be very light

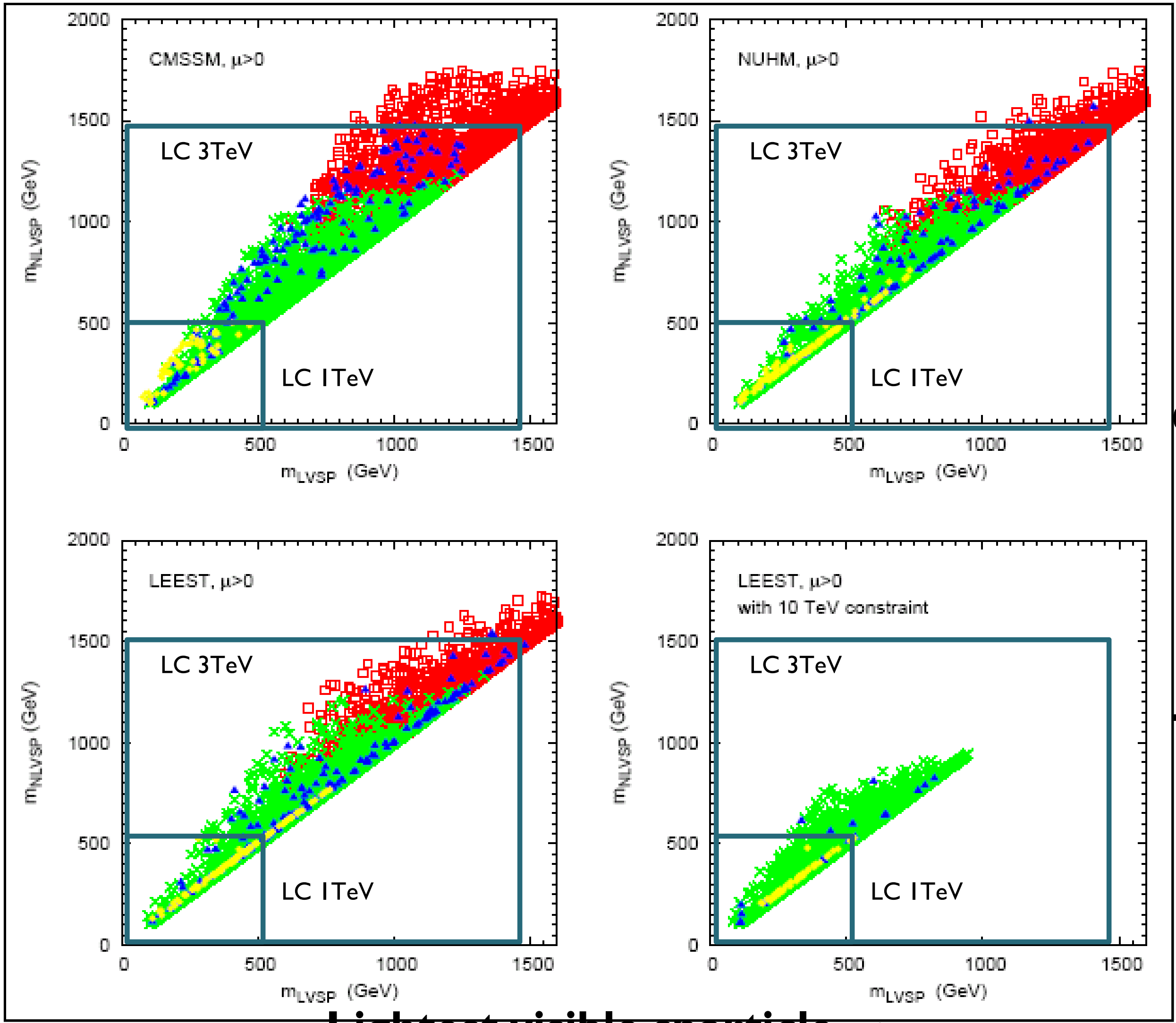
LHC “almost” guaranteed to find SUSY if it has any relevance to the Naturalness problem

🟥 all samples

🟩 Detectable @ LHC

🟦 Provide Dark Matter

🟨 Dark Matter Detectable Directly

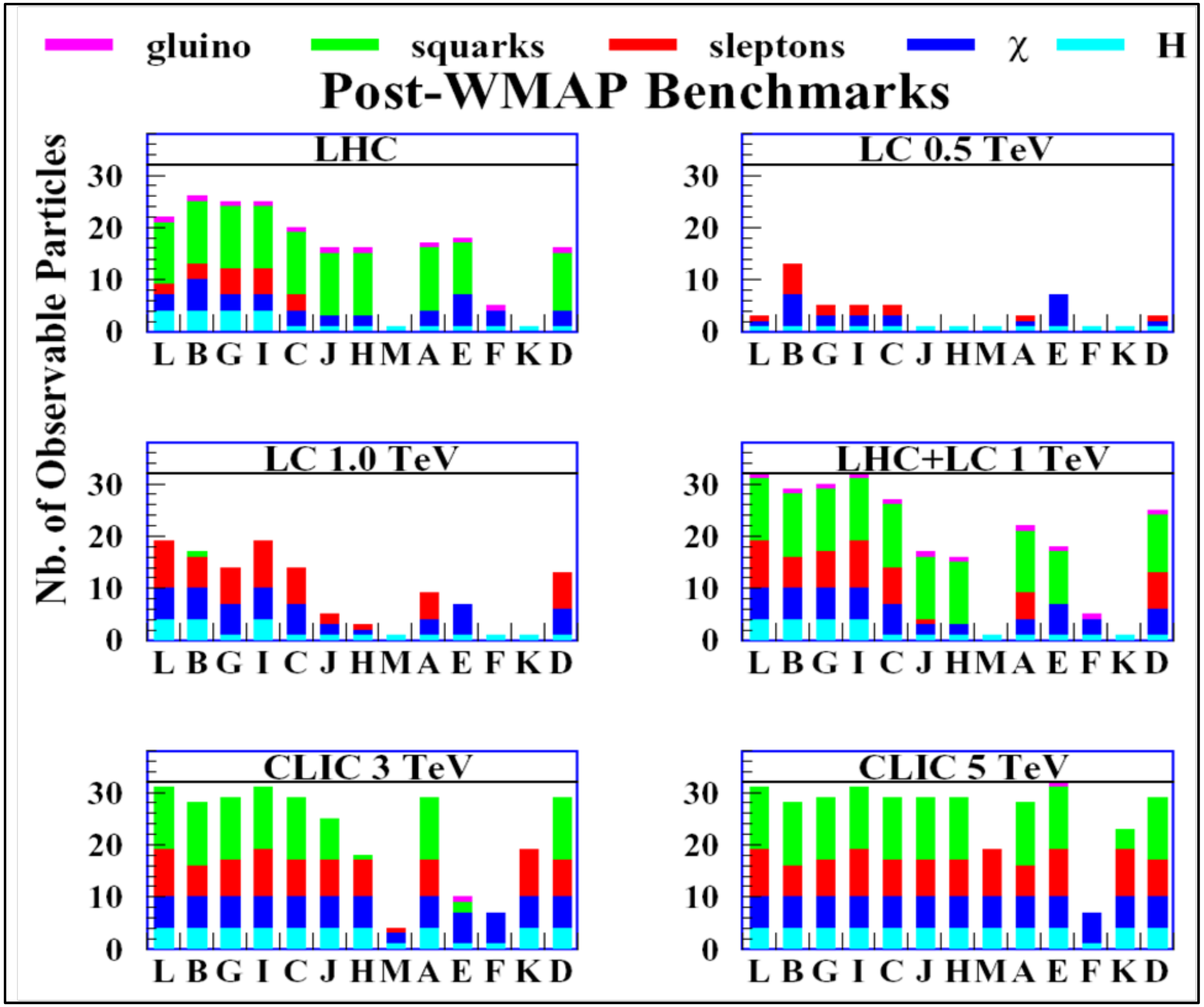


← Second lightest visible sparticle

Lightest visible sparticle →

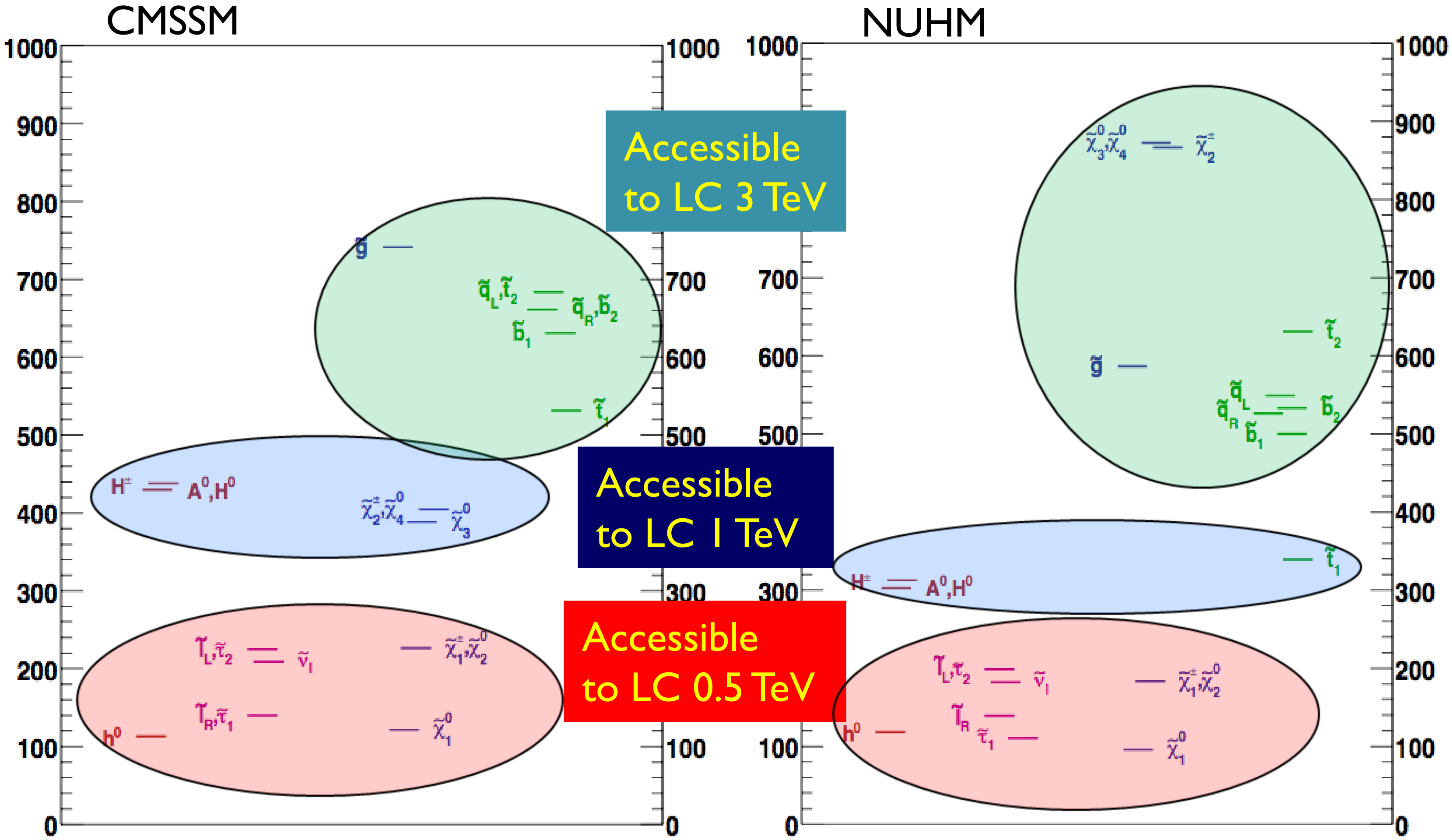
LHC vs LC

LHC is good with sparticles that mainly interact strongly, (gluino, squarks, …), while a LC could complement the spectra with sparticles that mainly interact weakly (sleptons, neutralinos,…)



Supersymmetry: reach of different accelerators

Within a SUSY model (CMSSM, NUHM, etc..) we can use low energy measurements, in particular b→sγ, the limit on M_h and g_μ-2, to evaluate the most probable mass spectra, see for instance *arXiv 0808.4128.*


CMSSM

NUHM

Accessible to LC 3 TeV

Accessible to LC 1 TeV

Accessible to LC 0.5 TeV

Example: looking for heavy neutralinos

$$\tilde{\chi}_j^0 \to \ell^\pm \tilde{\ell}^\mp \to \ell^+ \ell^- \tilde{\chi}_1^0$$

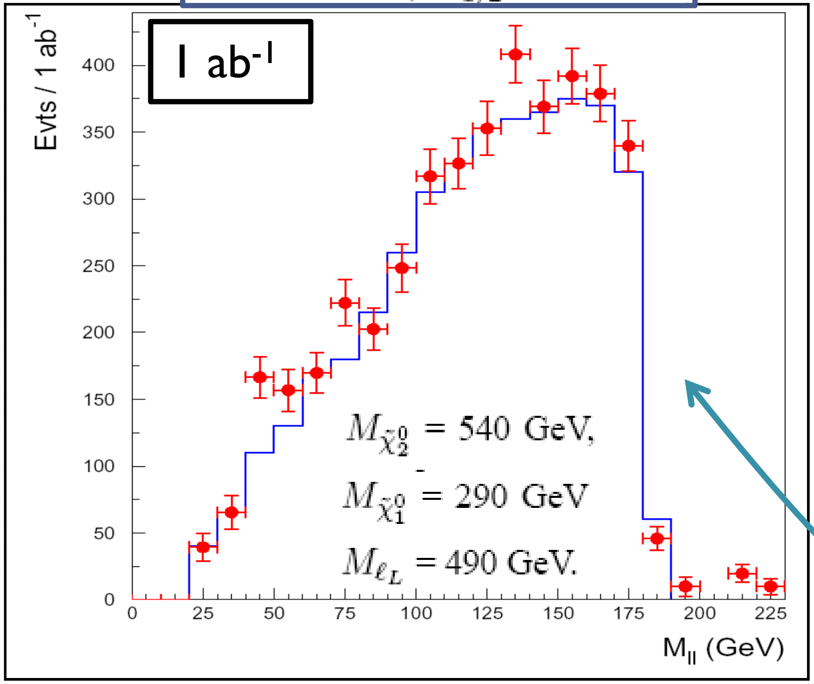
Gives an excess of events in the l^+l^- invariant mass distribution. A simultaneous fit of the *slepton* and $\chi_{1,2}$ mass gives ~2% precision with 1 ab^{-1}. The precision is dominated by the correlation between parameters rather than the effect of beamstrahlung.

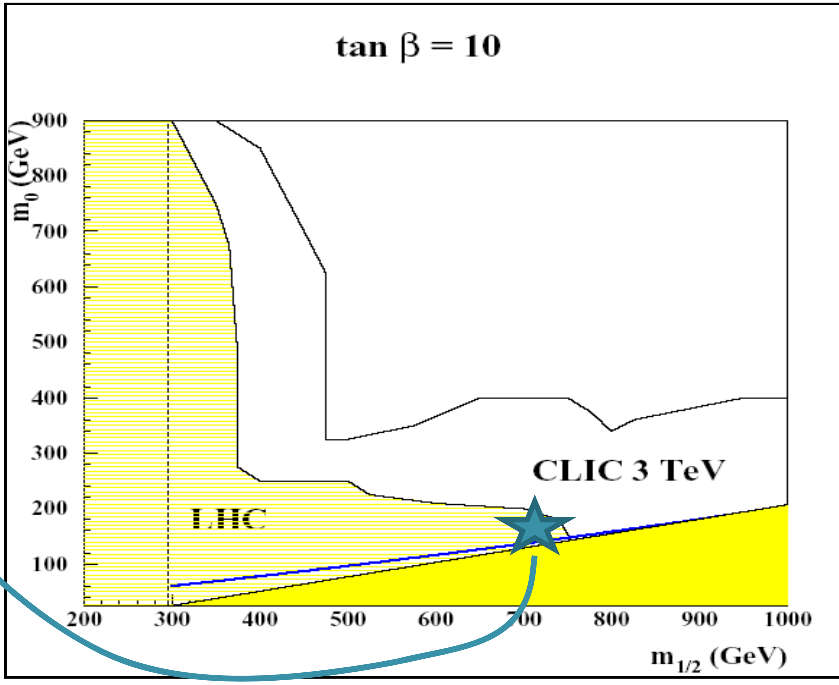
$$\tilde{\chi}_3^0 \to \tilde{\chi}_{1,2}^0 Z^0$$

$$\tilde{\chi}_4^0 \to \tilde{\chi}_{1,2}^0 h^0$$

Also $\chi_{3,4}$ are accesible in a multi-TeV LC.

m_0 = 150 GeV, $m_{1/2}$ = 700 GeV





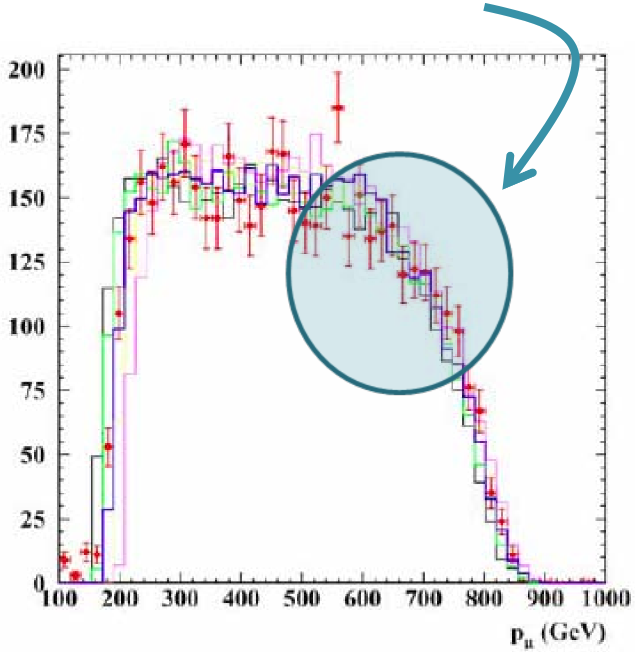
Example: looking for heavy sleptons

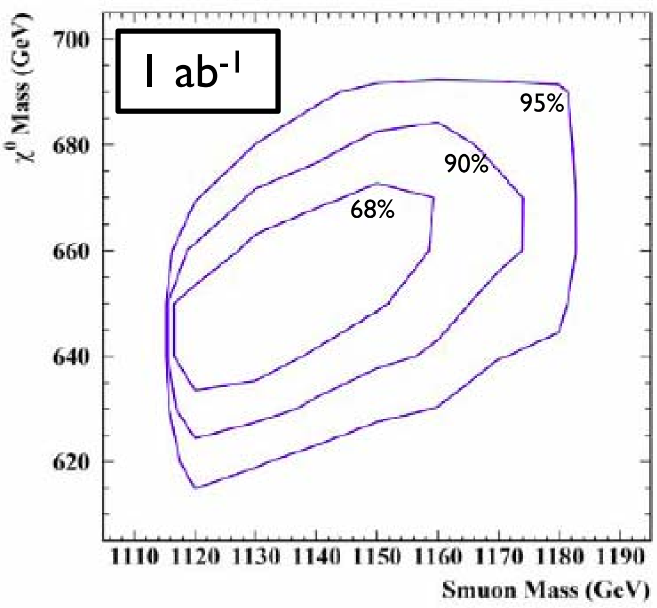
Mass determinations: $e^+e^- \to \tilde{\mu}_L^+\tilde{\mu}_L^- \to \mu^+\chi_1^0\mu^-\chi_1^0$

- If $\sqrt{s} >> 2\tilde{m}_\mu$, μ spectrum end points

$$E_{\min,\max} = \frac{\sqrt{s}}{4}\left(1-\tilde{m}_\chi^2/\tilde{m}_\mu^2\right)\left(1\pm\sqrt{1-4\tilde{m}_\mu^2/s}\right)$$

Here beamstrahlung is a very important issue! uncertainty ~2 larger





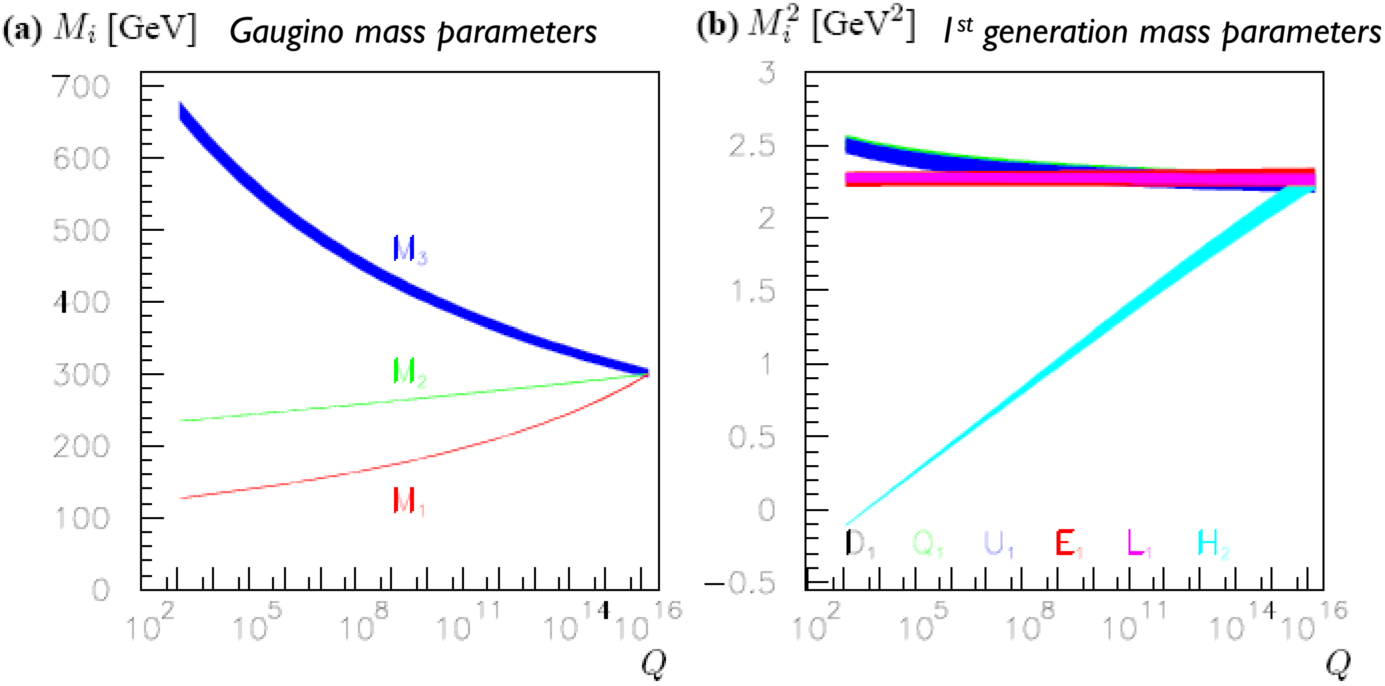
$\tilde{m}_\mu = (1145 \pm 25)\,\text{GeV}$ $\boxed{2\%}$

$\tilde{m}_\chi = (652 \pm 22)\,\text{GeV}$ $\boxed{3\%}$

Precision gives access to the high-scale SUSY parameters.

A multi-TeV LC will provide enough precision in the determination of all masses. It will also provide precise measurements of the mixing parameters, in particular in the *stop* sector (which plays a very important role in the renormalization equations).

Then, we can use these renormalization equations to test if they meet at a single energy scale → hence non-trivial test of the SUSY breaking mechanism.


(a) M_i [GeV] *Gaugino mass parameters*

(b) M_i^2 [GeV^2] *Ist generation mass parameters*

CLIC & Supersymmetry summary

If SUSY is a useful concept to deal with the Naturalness problem, it will be discovered at LHC. Part of the spectrum, however, will require a LC able to produce copiously weakly interacting particles. The minimal energy depends on what is found at LHC.

Most probably we will need CLIC to cover the full SUSY spectrum, but even more important, to measure with precision the masses, mixing angles, couplings and quantum numbers of these new particles. These precise measurements will allow to unravel the SUSY breaking mechanism and learn about the GUT scale.

Other than SUSY

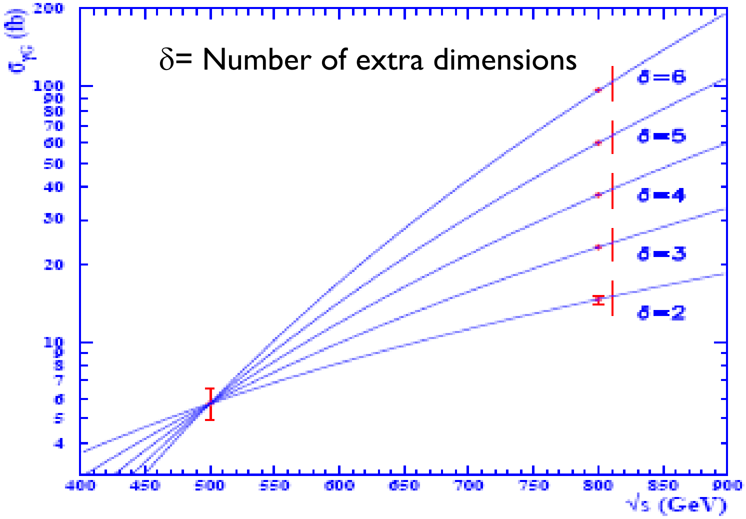
Extra Dimensions

Any alternative to SUSY that has to deal with the Naturalness problem, will have some visible effects at the TeV scale.

One way to deal with the different scales involved, is to think as gravity living in more dimensions that we can feel, hence its weakness is only apparent, and there is only one fundamental energy scale.

$$e^+e^- \to \gamma G_{KK}$$

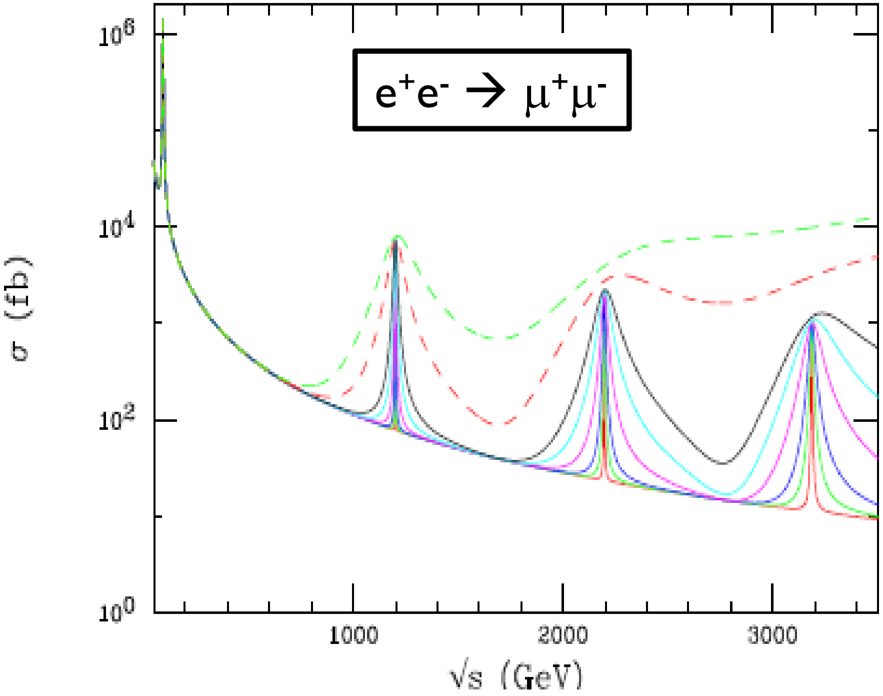
By counting the number of events with missing energy and photons, at different centre-of-mass energies we can measure the number of extra dimensions and the Planck scale.

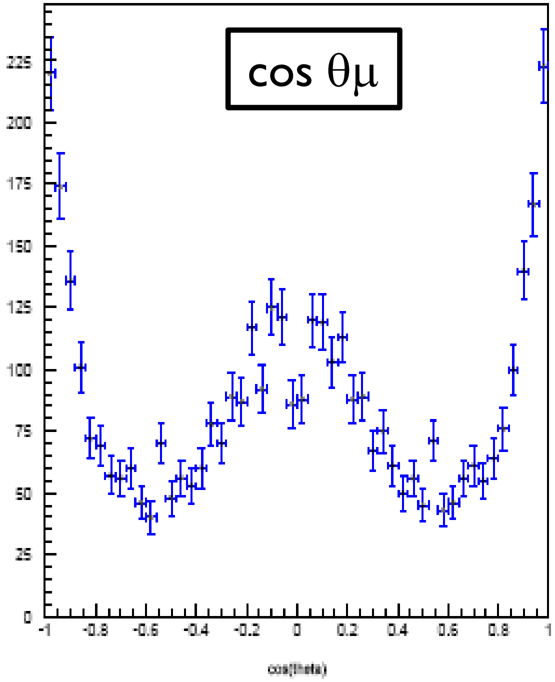


Not possible at LHC, easy at a LC with enough energy!

Extra Dimensions

The presence of KK gravitons would change dramatically the dilepton Drell-Yan process at LHC. LHC may see a signal that disagrees with the SM, but we need to establish the gravitational nature of the observation, i.e. the presence of Spin 2 gravitons!





Conclusions

Process LHC/ILC/SLHC/CLIC 3,5 TeV

Squarks	2.5	0.4	3	1.5	2.5
Sleptons	0.34	0.4		1.5	2.5
New gauge boson Z′	5	8	6	22	28
Excited quark q*	6.5	0.8	7.5	3	5
Excited lepton l*	3.4	0.8		3	5
Two extra space dimensions	9	5–8.5	12	20-35	30–55
Strong $W_L W_L$ scattering	2σ	-	4σ	70σ	90σ
Triple-gauge Coupling(TGC) (95%)	.0014	0.0004	0.0006	0.00013	0.00008

Integrated luminosities used are 100 fb–1 for the LHC, 500 fb–1 for the 800 GeV LC, and 1000 fb–1 for the SLHC and CLIC. Most numbers given are TeV, but for strong WLWL scattering the numbers of standard deviations, and pure numbers for the triple gauge coupling (TGC).

Conclusions

We all hope LHC will soon tell us what is the NP (if any) that deals with the symmetry breaking of the SM.

For all scenarios studied there is a fundamental added value on having a LC at the multi-TeV range. We need not only to discover that the SM is wrong, but we also have to learn what is the right model for NP.

Experimentation at CLIC is probably more challenging (backgrounds, beamstrahlung, etc…) but they don't look like insurmountable problems.

Let's make sure than when the LHC opens the way, we have all the technological choices available so that we can get the best physics output .