Physics drivers for a multi-TeV e^+e^- collider

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Workshop

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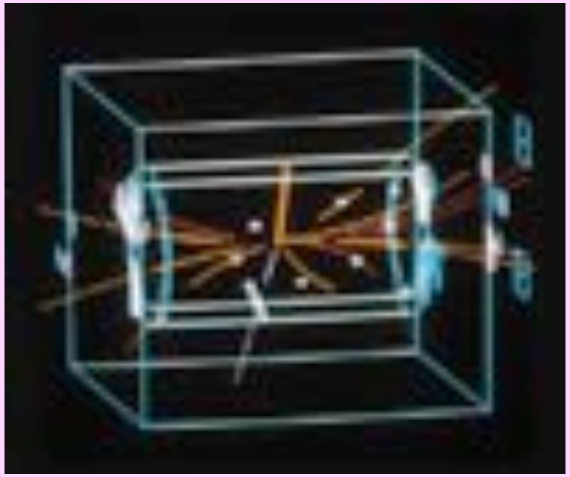
The LHC will define the future of high-energy physics by exploring the “TeV region”

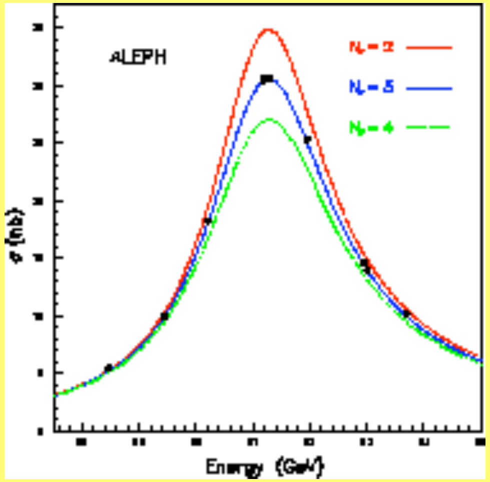
CLIC will study this region from a different point of view

The case of W and Z physics

Discovery of W and Z at SPS



Precision tests of their properties at LEP



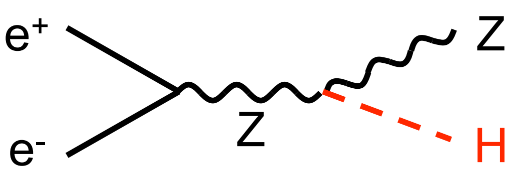
The difficulty is that we don’t know what is the physics at the “TeV region”

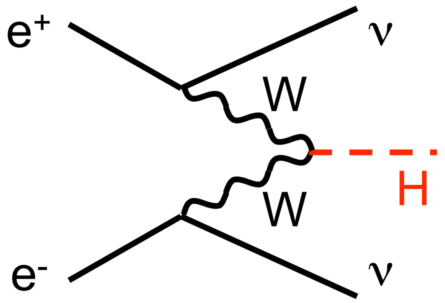
Most likely, CLIC will give important additional information to the LHC results

- Detailed investigation of Higgs physics
- Precision measurements of new physics (rich with info)
- Deeper probe of new EW particles

Higgs Physics

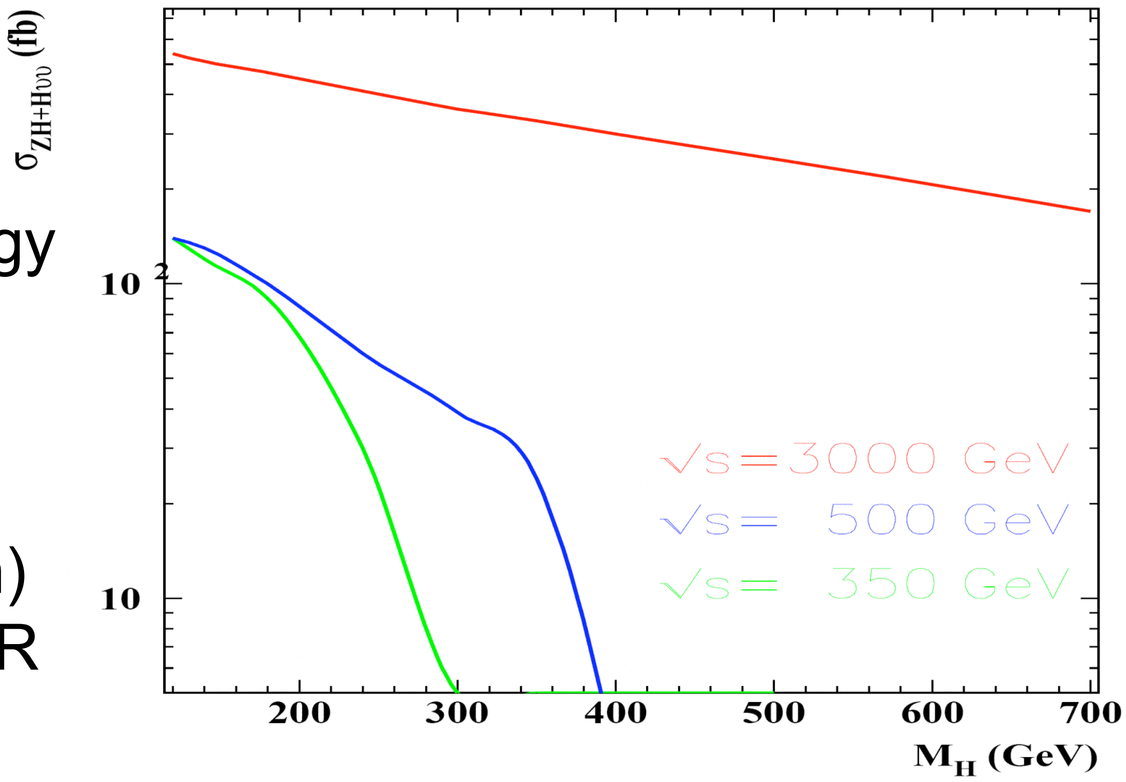
Dominant production





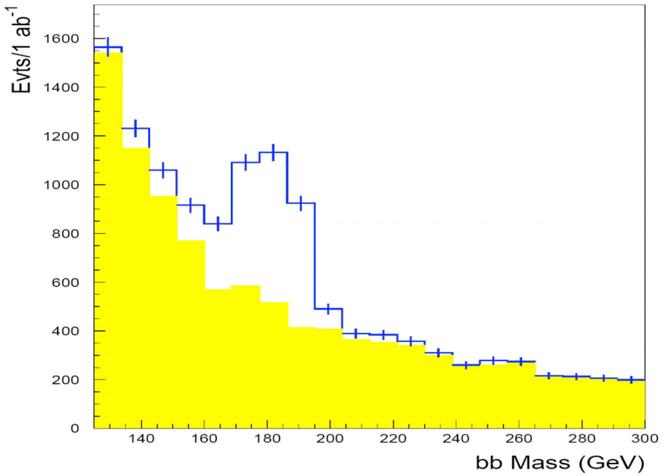
Log growth with *s*

Advantage at high energy



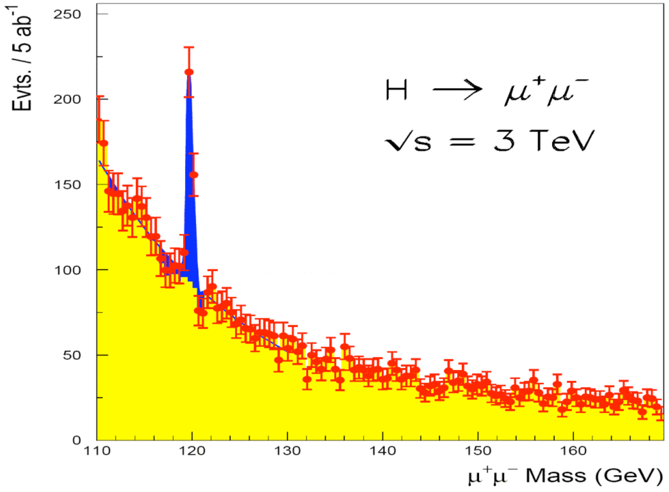
$e^+e^- \rightarrow e^+e^- H$ (from Z strahlung and Z fusion) allows to tag difficult BR

Testing that Higgs couplings are proportional to mass



$\delta g_{Hbb} / g_{Hbb}$ [%]

120	140	160	180	200	220	m_H [GeV]
1.2	1.3	3.2				LC 350 GeV (500 fb^{-1})
			6	9	14	LC 800 GeV (1 ab^{-1})
			1.6	2.5	3.4	CLIC 3 TeV (3 ab^{-1})

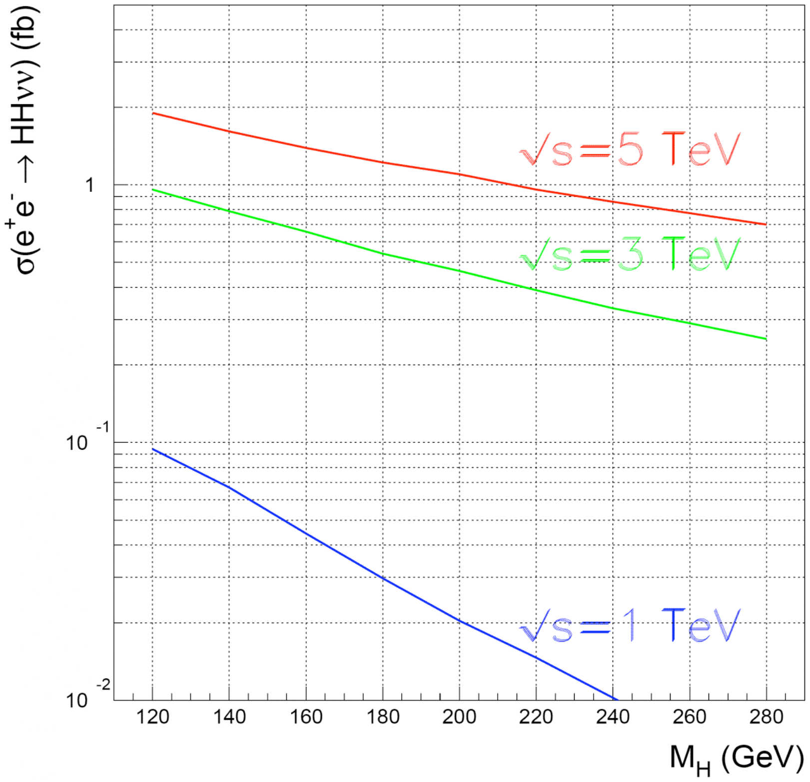


$\delta g_{H\mu\mu} / g_{H\mu\mu}$ [%]

120	140	150	m_H [GeV]
15			LC 800 GeV (1 ab^{-1})
4.2	6.5	11.	CLIC 3 TeV (3 ab^{-1})
13	20	36	SLHC (6000 fb^{-1})

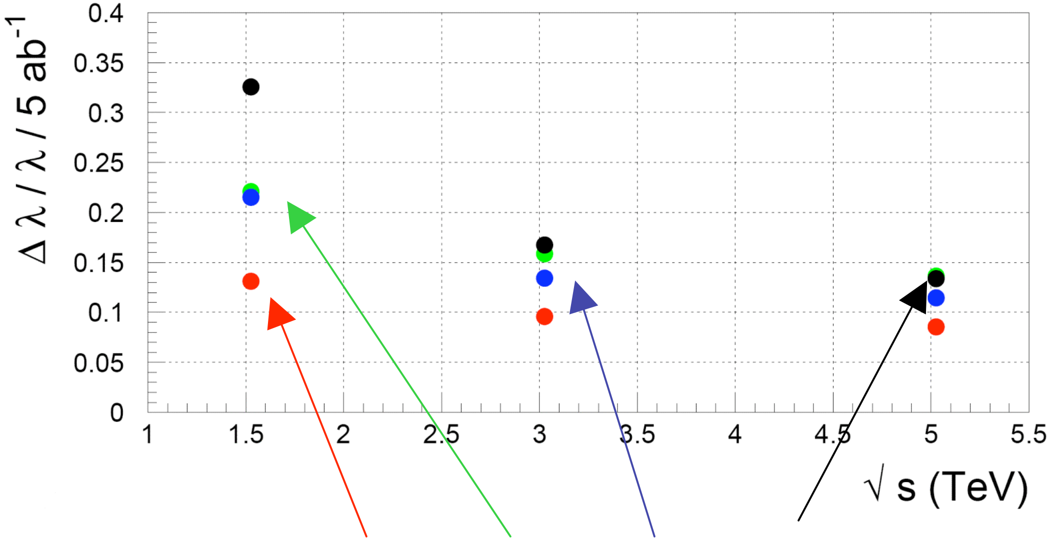
Reconstructing Higgs potential

Triple Higgs coupling using $e^+e^- \rightarrow HH\nu\bar{\nu}$



$\delta g_{HHH} / g_{HHH}$ = 10-15 %

m_H = 120-240 GeV



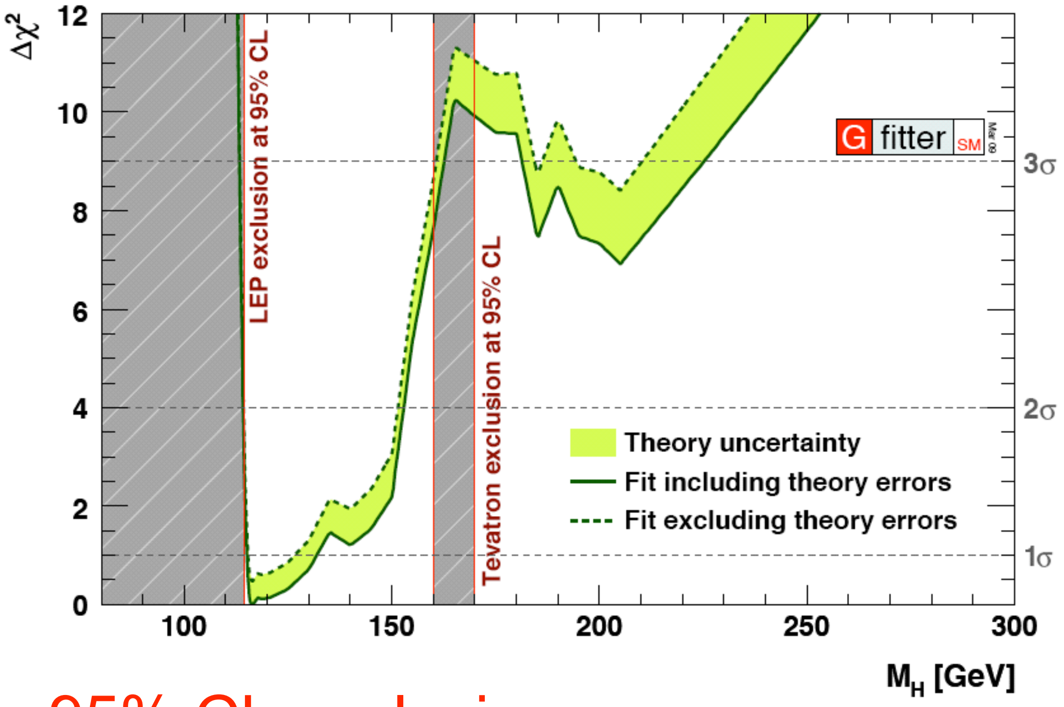
m_H = 120 140 180 240 GeV

SLHC (6000 fb^{-1}) $\delta g_{HHH} / g_{HHH}$ = 19 % (m_H = 170 GeV)

25 % (m_H = 200 GeV)

Why are these measurements useful?

Higgs mass



95% CL exclusion

LEP: $M_H < 114.4$ GeV

Tevatron: 160 GeV $< M_H <$ 170 GeV

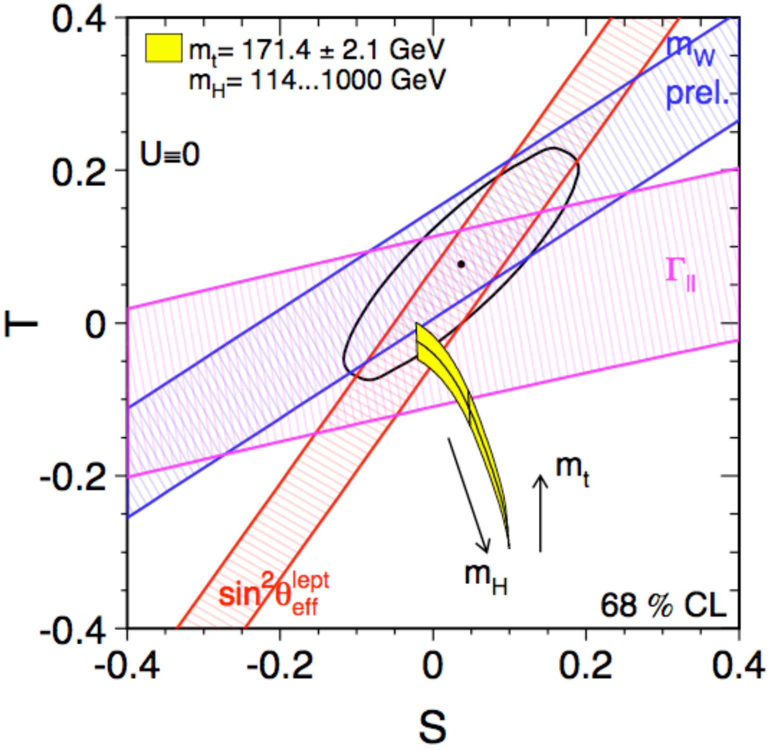
EW: $M_H < 153$ GeV (95% CL)

Even mild modifications of the Higgs sector can relax the bound from EW data

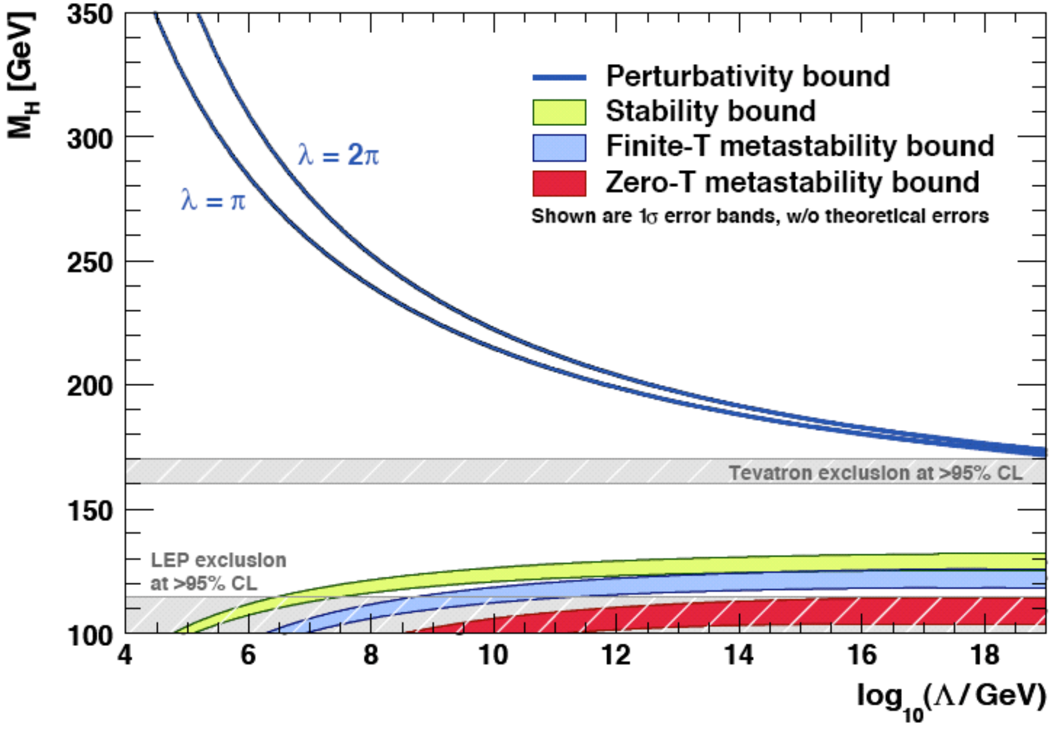
Requires new physics with ΔT=0.2–0.3 and ΔS small

$$S \rightarrow H^{+} W_{\mu\nu} H\, B^{\mu\nu}$$

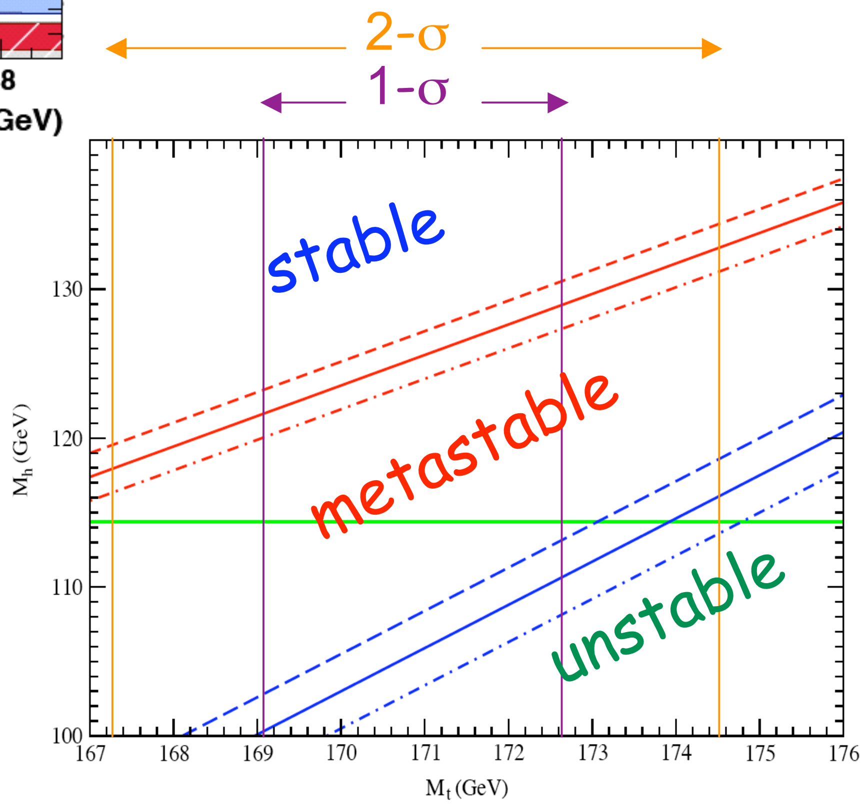
$$T \rightarrow H^{+} D_{\mu} H\, H^{+} D^{\mu} H$$



It can be obtained with a second Higgs doublet with no vev and no coupling to fermions or with a colour-octet Higgs doublet



Measurement of M_H provides information on the fate of the SM



In the metastable region:

- Limits on T_{RH} from the absence of thermal fluctuations
- Limits on H_I from the absence of quantum fluctuations during inflation

Higgs couplings

Is the Higgs elementary or composite?

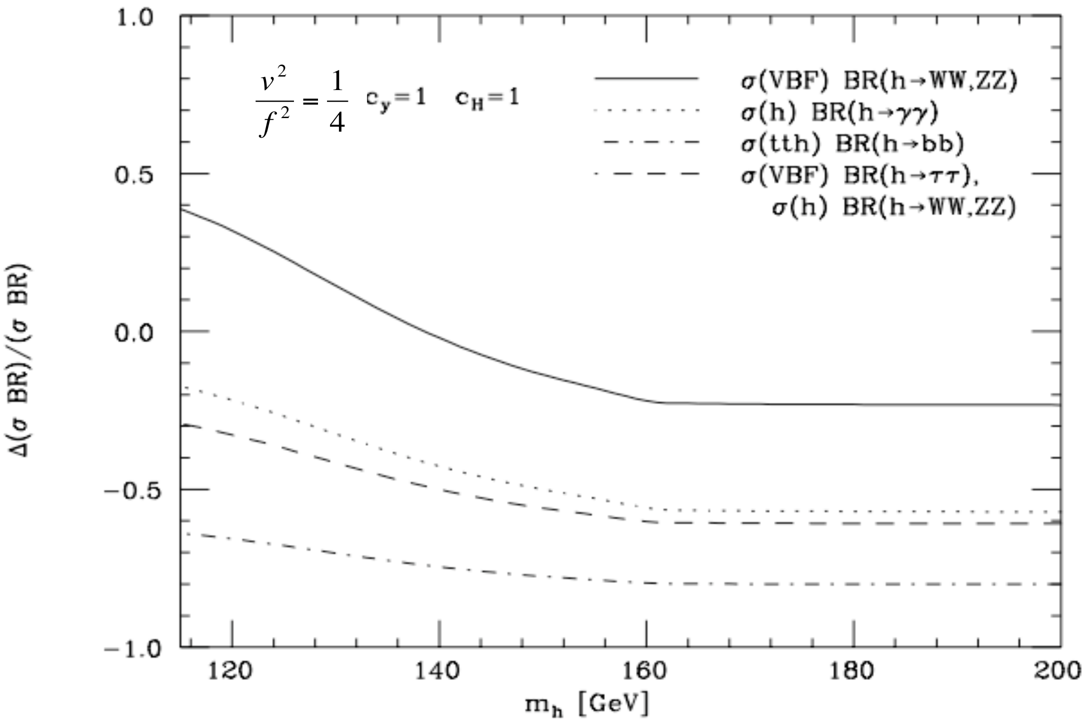
Determine the nature of the force that breaks EW

Elementary
- SM (with $130 < m_H < 160$ GeV)
- SUSY (H,Q,L are all chiral superfields)

Composite: Higgs is a light remnant of a strong force
- pseudoGoldstone
- Little Higgs
- Gauge-Higgs unification
- Holographic Higgs
- ….

The couplings of a composite Higgs are modified by terms of order v^2/f^2, where $4\pi f$ is the compositeness scale Λ

The effects in $\sigma_h\, BR_h$ are of the order of $\left(\frac{10\ \mathrm{TeV}}{\Lambda}\right)^2 \times 10\%$



Deviations from SM Higgs couplings can test v^2 / f^2 up to

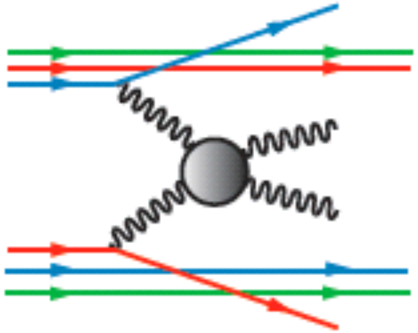
LHC 20–40 %

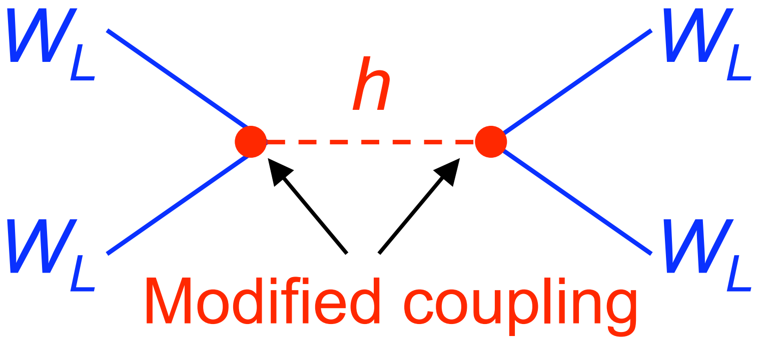
SLHC 10 %

CLIC 1 % $\Rightarrow 4\pi f = 30$ TeV

Genuine signal of Higgs compositeness at high energies

In spite of light Higgs, longitudinal gauge-boson scattering amplitude violates unitarity at high energies





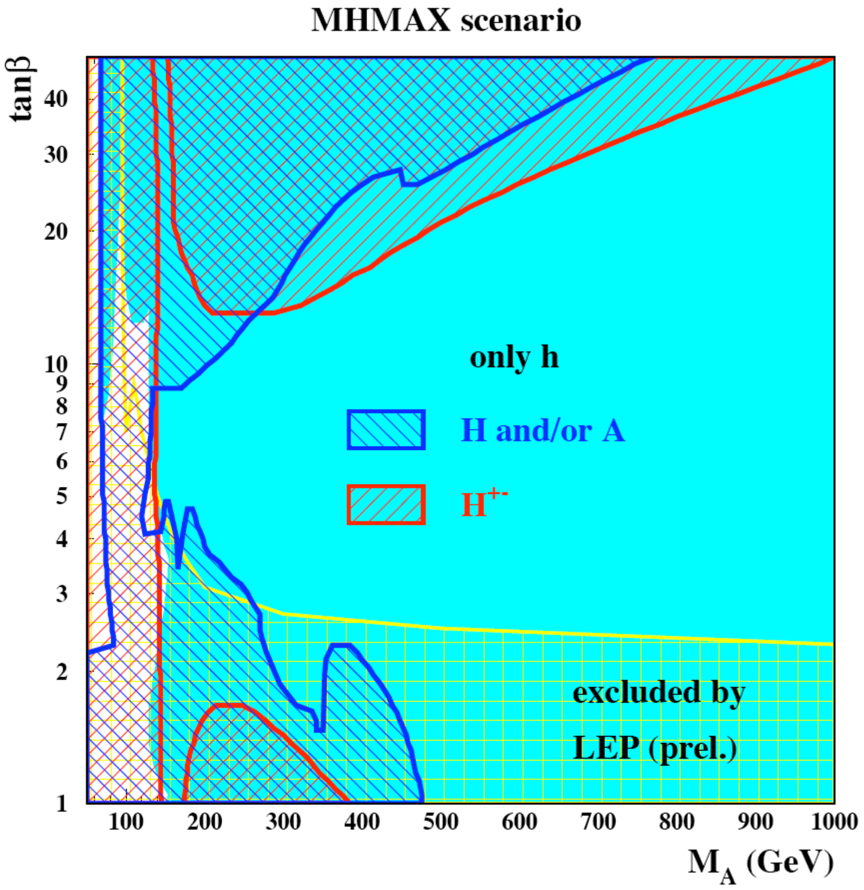
$$\sigma\left(pp \to V_L V_L' X\right) = \frac{v^4}{f^4}\,\sigma\left(pp \to V_L V_L' X\right)_{\not H}$$

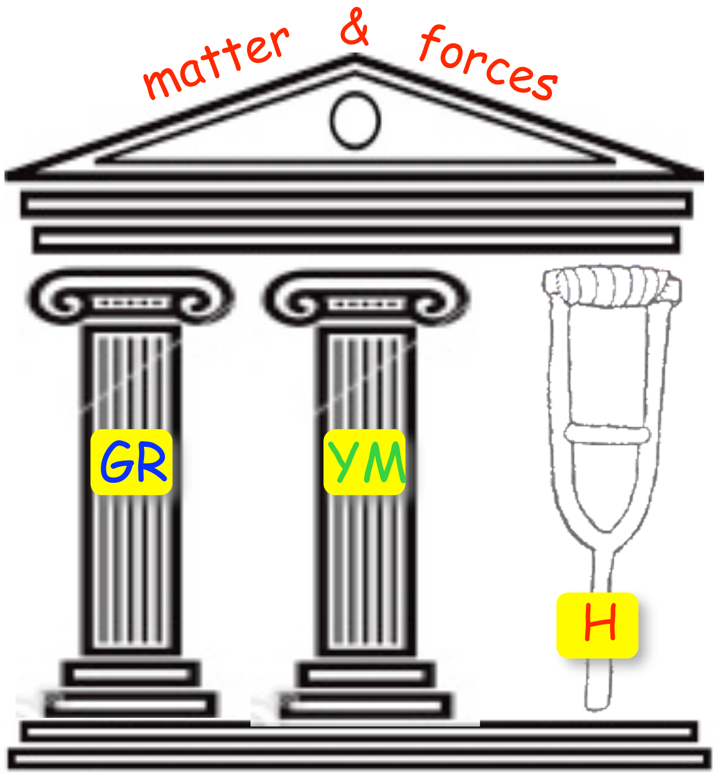
$V_L V_L$ scattering is an important channel, even for light Higgs

Only preliminary studies for CLIC

The structure of the Higgs sector

There are many unsatisfactory features in the Higgs sector





The LHC may be blind to non-minimal Higgs structures

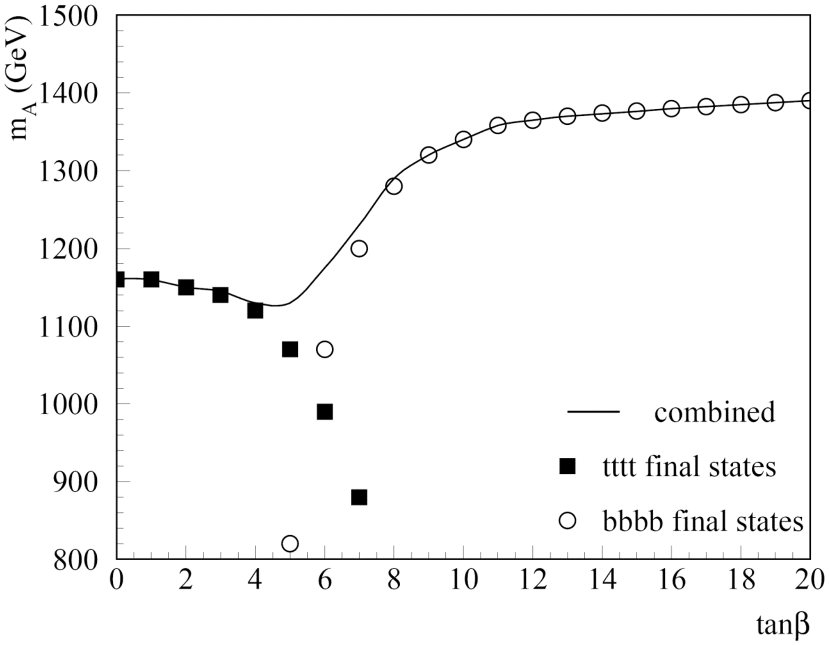
SUSY Heavy Higgs bosons can be identified at CLIC

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

CLIC $\sqrt{s}$=3 TeV, L=3 ab^{-1} reaches m_{H^+}=1.2 TeV for BR($H^+ \rightarrow t\bar{b}$)=1

Accuracy of 0.5-1.0% in mass for 600< m_{H^+}<900 GeV and 5-7% in $\sigma \times$BR

$e^+e^- \rightarrow H^0 A^0$



The great excitement about the LHC is about physics in the “TeV region” beyond the Higgs

Prototype: supersymmetry

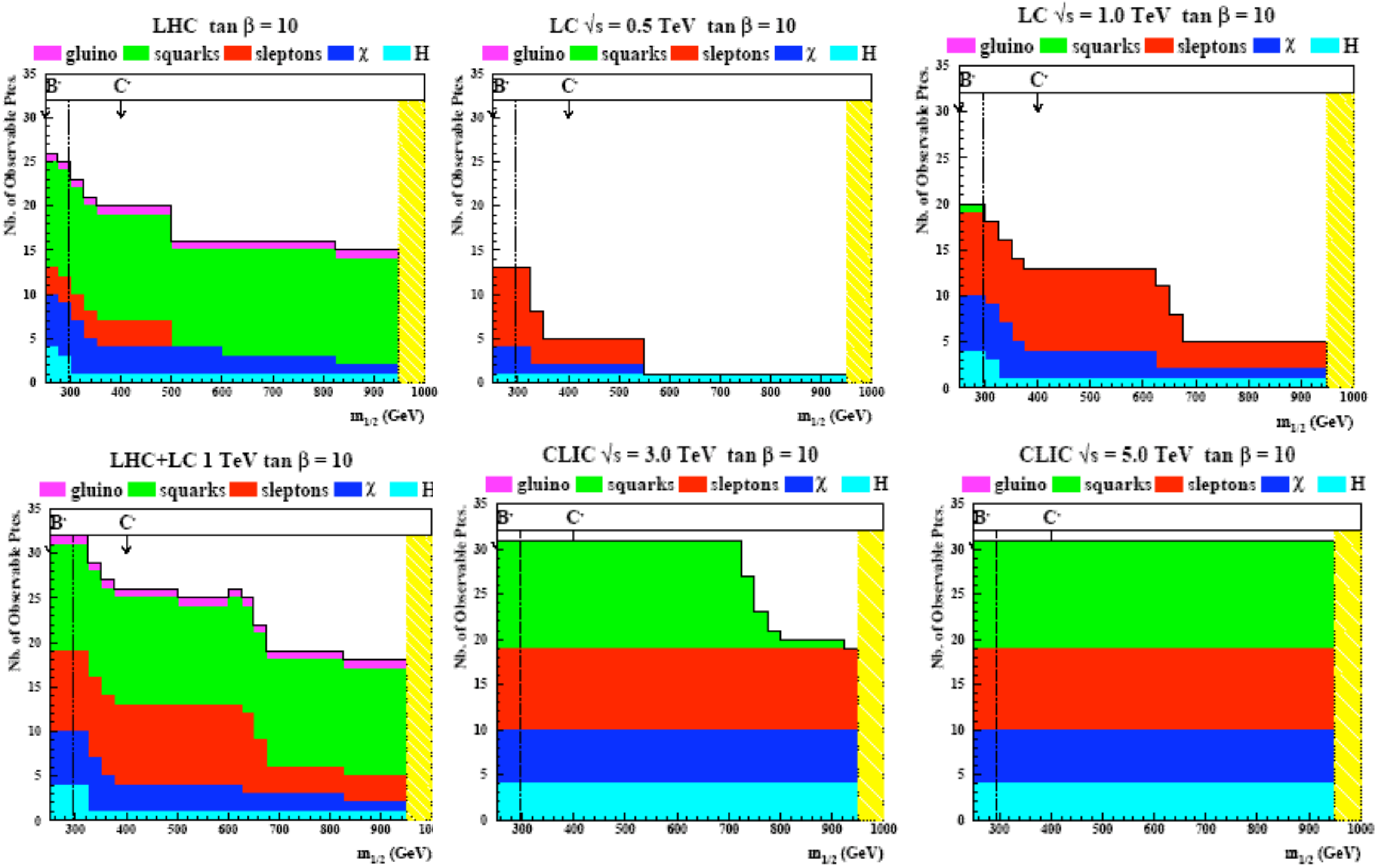
If the LHC discovers supersymmetry, we are facing many urgent issues:

1. Reconstruct the entire spectrum
   (and confirm supersymmetry)

LHC: squarks up to 2.5 TeV; sleptons up to 300-400 GeV

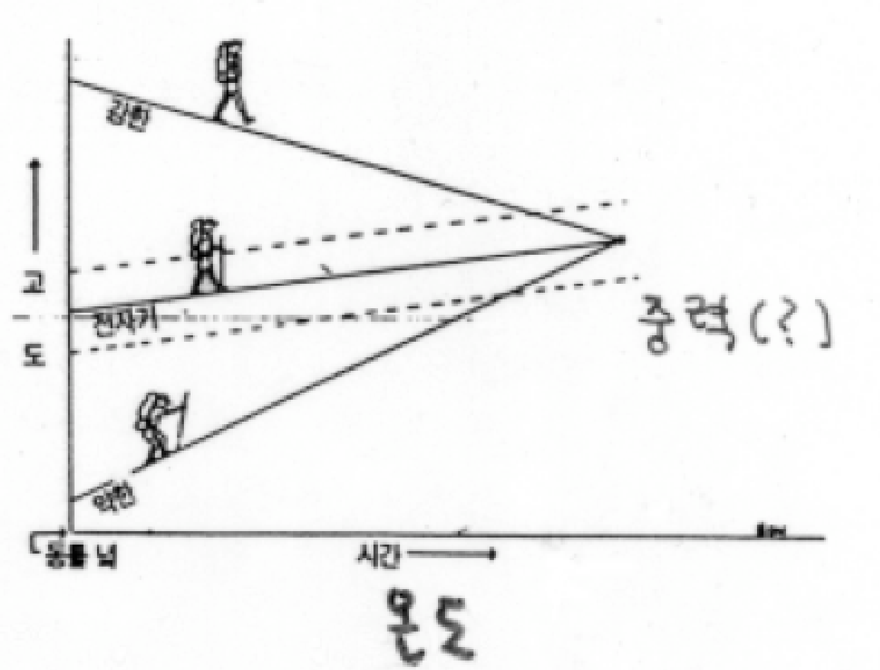
CLIC: squarks up to 1.5 TeV; sleptons up to 1.5 TeV

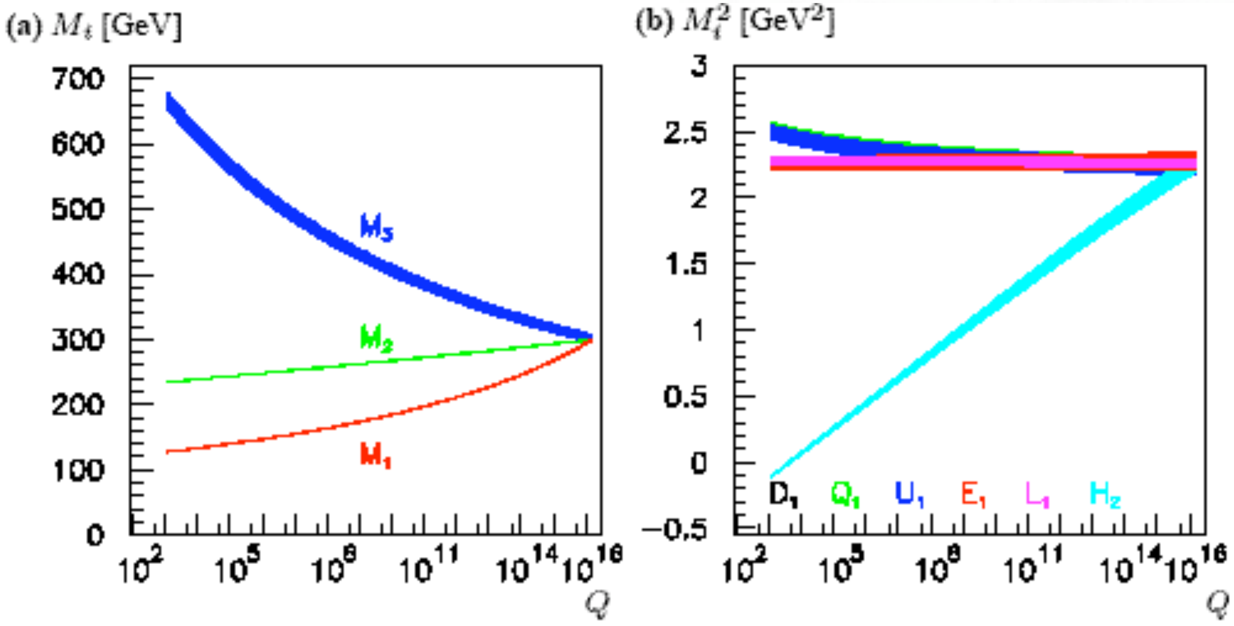
Completing the susy spectrum



2. Precise parameter determination

Susy terms provide a window to very short distances (log dependence on cut-off) see example of α_s

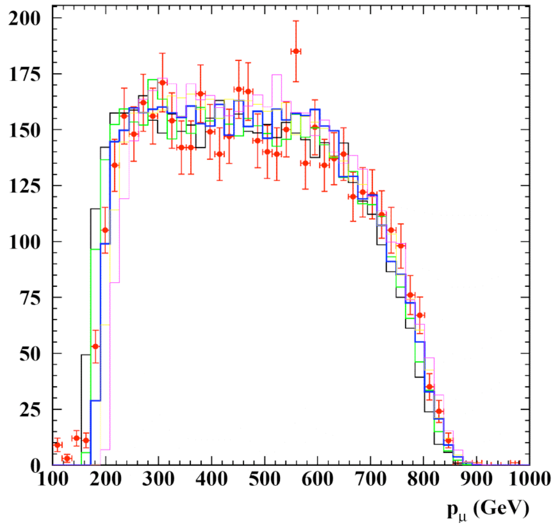


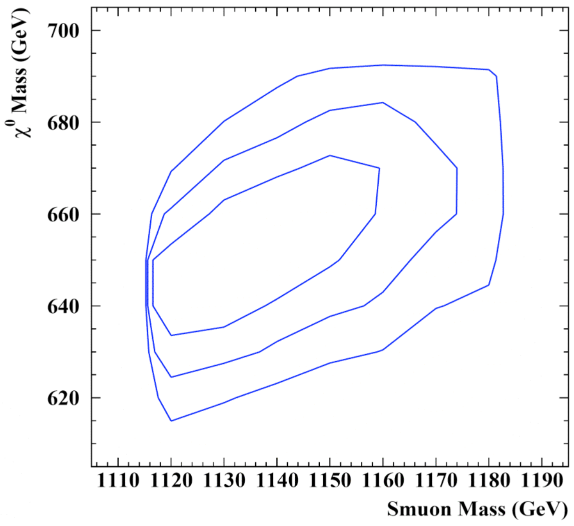


Mass determinations: $e^+e^- \to \tilde{\mu}_L^+\tilde{\mu}_L^- \to \mu^+\chi_1^0\mu^-\chi_1^0$

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

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





Two-parameter fit

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

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

- Energy scan of cross section close to threshold

$\delta\tilde{m}_\mu = 15$ GeV

LHC mass determinations improve if info from CLIC is included in decay chains

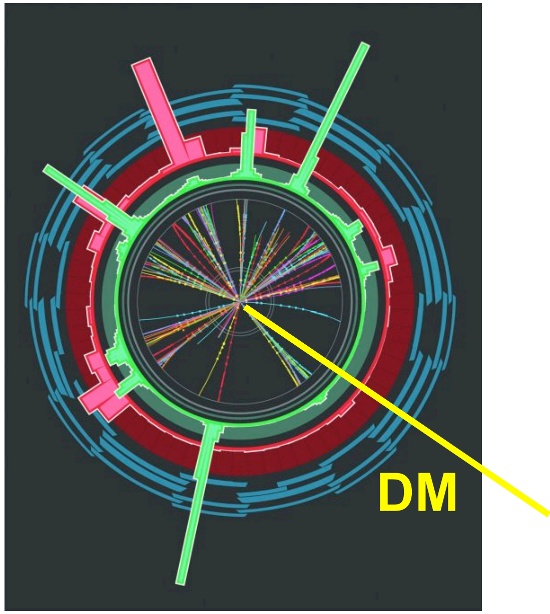
3. Identification of susy relations

Supersymmetry implies relations between couplings (cross sections and decay rates)

Mass relations allows the identification of the mechanism of susy breaking

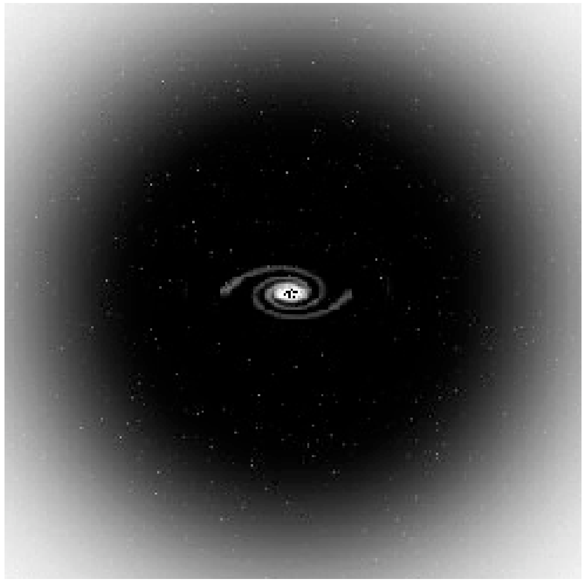
4. Reconstruction of the DM relic abundance

Discovery of DM at the LHC is of primary importance



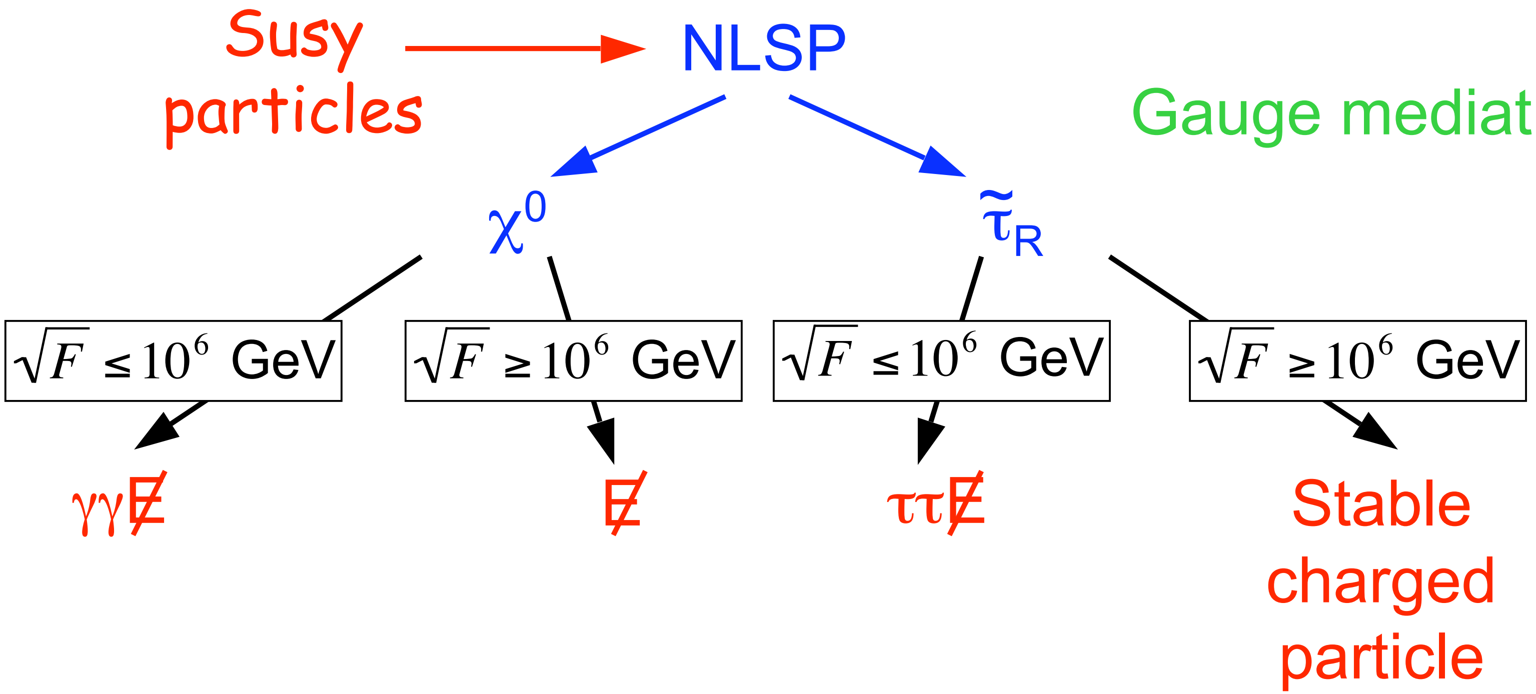
Missing energy is a trademark of DM, but is it sufficient to claim its discovery?

Direct and indirect detection



Very different detector requirements

Neutralino LSP ⇒ Missing energy + hard particles



Susy particles → NLSP

χ^0

$\tilde{\tau}_R$

$\sqrt{F} \leq 10^6$ GeV → $\gamma\gamma\not{E}$

$\sqrt{F} \geq 10^6$ GeV → $\not{E}$

$\sqrt{F} \leq 10^6$ GeV → $\tau\tau\not{E}$

$\sqrt{F} \geq 10^6$ GeV → Stable charged particle

Gauge mediation

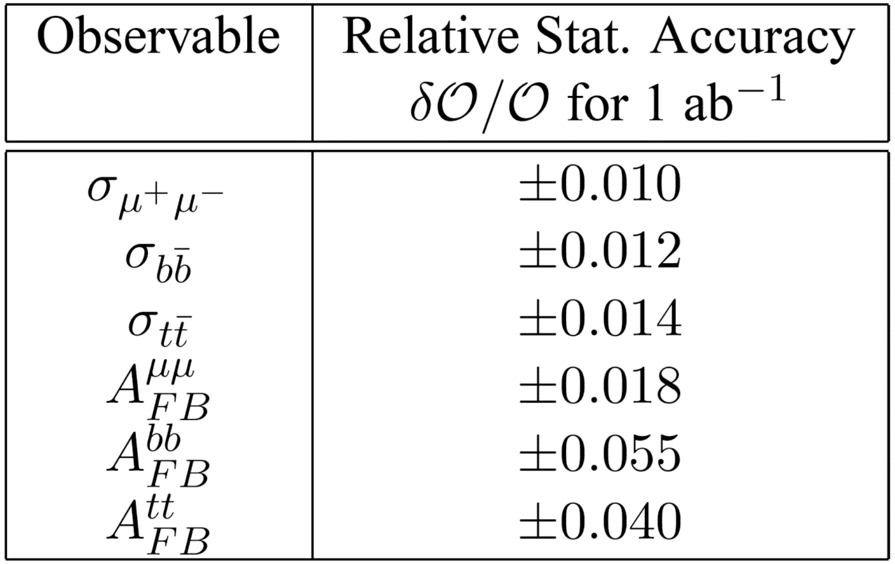
W-ino LSP ⇒ $m_{\chi^\pm} - m_{\chi^0} \approx \dfrac{\alpha M_W}{2(1+\cos\theta_W)} \approx 165$ MeV

Anomaly mediation

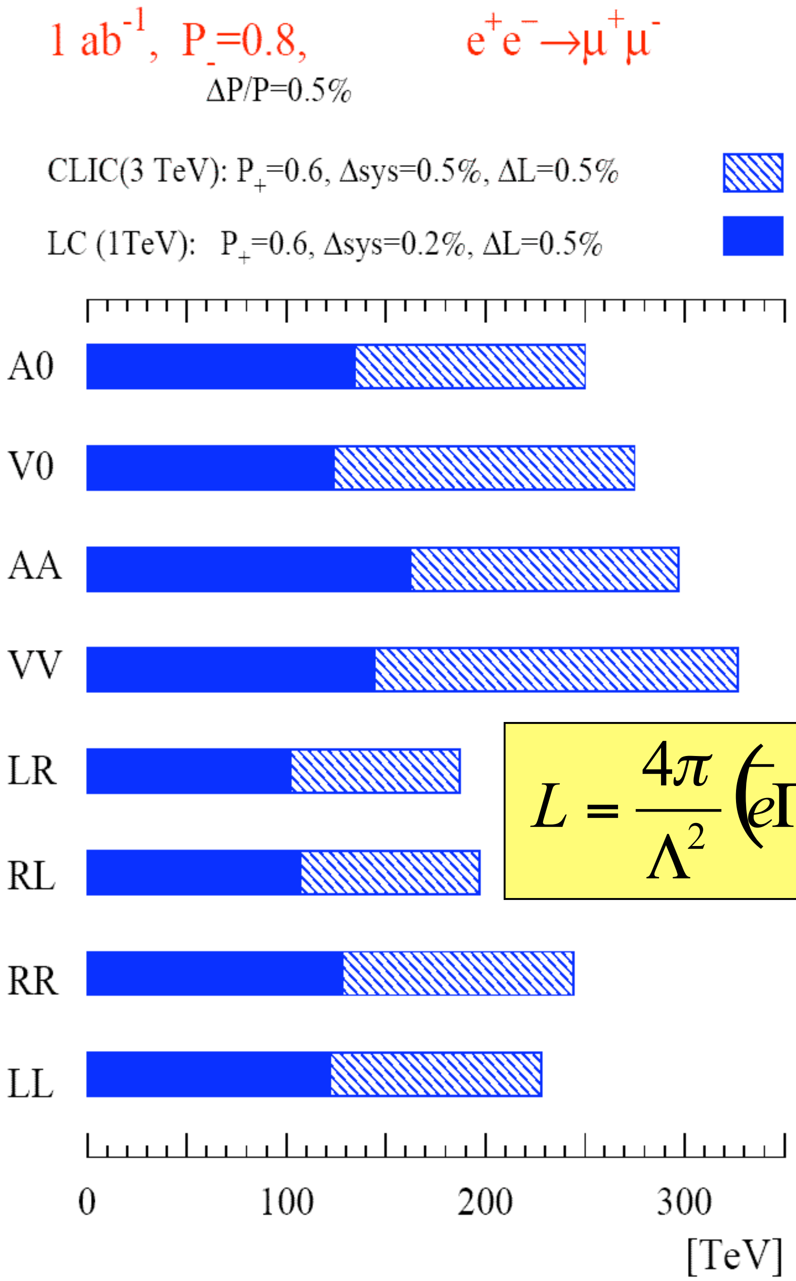
Decay $\tilde{W}^\pm \to \pi^\pm \tilde{W}^0$ (soft pions)

Gravitino LSP ⇒ Long-lived stau

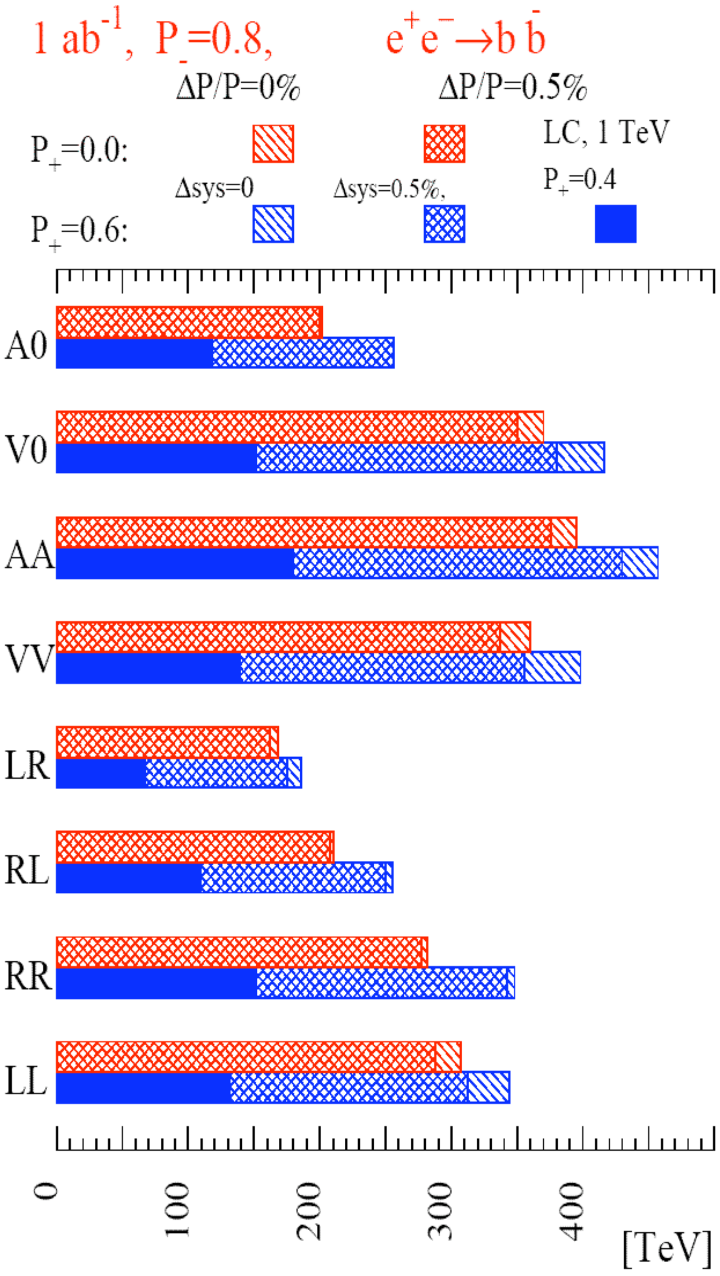
Precision measurements allow indirect probes of new physics



Observable	Relative Stat. Accuracy $\delta\mathcal{O}/\mathcal{O}$ for 1 ab^{-1}
$\sigma_{\mu^+\mu^-}$	±0.010
$\sigma_{b\bar{b}}$	±0.012
$\sigma_{t\bar{t}}$	±0.014
$A_{FB}^{\mu\mu}$	±0.018
A_{FB}^{bb}	±0.055
A_{FB}^{tt}	±0.040



$$L = \frac{4\pi}{\Lambda^2}\left(\bar{e}\Gamma^{\mu} e\right)\left(\bar{f}\Gamma_{\mu} f\right)$$



For √s=5 (10) TeV, L=5 ab^{-1} probe Λ≈400-800 (500-1000) TeV

	LHC 100 fb^{-1}	ILC 800 GeV 500 fb^{-1}	SLHC 1000 fb^{-1}	CLIC 3 TeV 1000 fb^{-1}	CLIC 5 TeV 1000 fb^{-1}
Squarks [TeV]	2.5	0.4	3	1.5	2.5
Sleptons [TeV]	0.34	0.4		1.5	2.5
New gauge boson Z' [TeV]	5	8	6	22	28
Excited quark q* [TeV]	6.5	0.8	7.5	3	5
Excited lepton l* [TeV]	3.4	0.8		3	5
Two extra space dimensions [TeV]	9	5–8.5	12	20-35	30–55
Strong W_LW_L scattering	2σ	-	4σ	70σ	90σ
Triple-gauge Coupling (95%)	.0014	0.0004	0.0006	0.00013	0.00008

Conclusions

- The LHC will determine the future of high-energy physics
- CLIC is one of the best options to complement and extend the LHC research programme
- Detailed investigation of the Higgs sector and discovery of new Higgs bosons
- Precise parameter determination (identification of the theory, tests of unification, reconstruction of DM density)
- Indirect probes up to 200-400 TeV