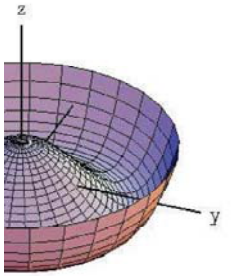
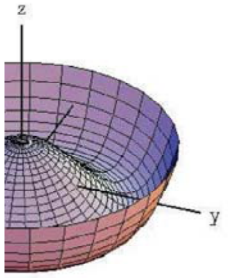


Electro-weak symmetry breaking at machines after the LHC

K. Desch • Universität Bonn • 13/02/2008
Higgs-Maxwell-Workshop • Royal Society of Edinburgh

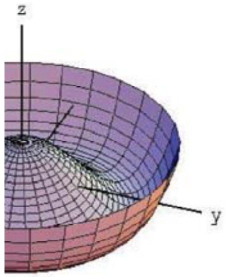
1. EWSB after LHC: What will be left to do?
2. Higgs physics at the ILC
3. Non-Higgs physics at the ILC
4. Beyond the ILC?
5. Summary and Conclusions



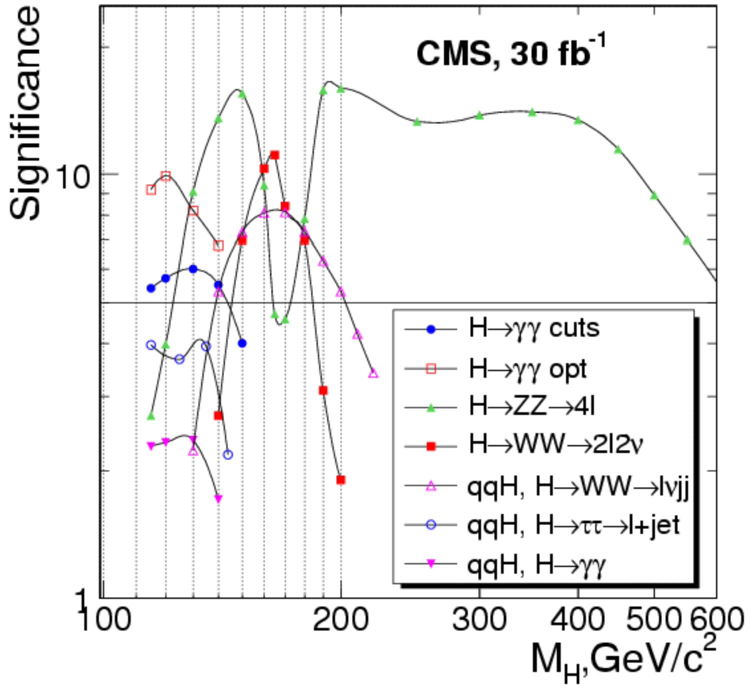
EWSB: Decision point for particle physics

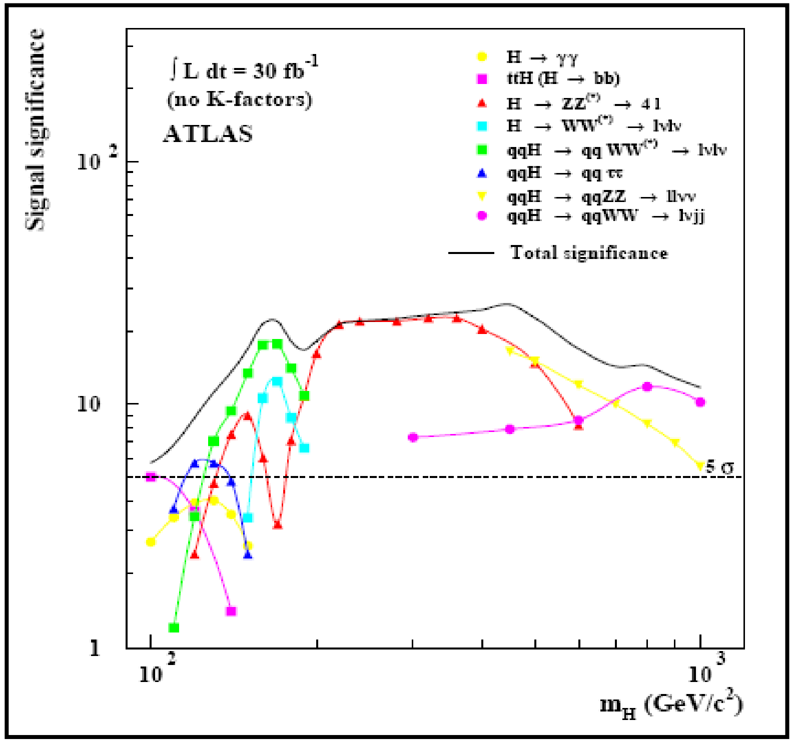
“As yet, none of these theoretical proposals about electroweak-symmetry breaking are entirely satisfying. Hopefully, by the end of this decade, experimental findings at the Tevatron and the LHC will set us on the right track. But the diversity and scope of ideas on electroweak-symmetry breaking suggests that the solution to this riddle will determine the future direction of particle physics.”

Ed Witten



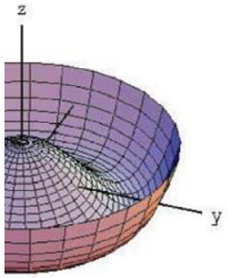
Higgs discovery at the LHC





SM Higgs discovery assured for ~10 fb^{-1} over full mass range if nothing goes wrong

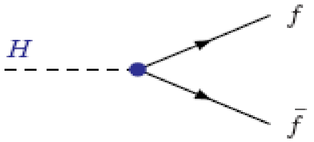
- rather easy (and fast) for $m_H > 140$ GeV
- more involved for light Higgs $m_H < 140$ GeV



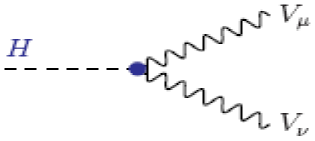
After Discovery:
Characterizing the “Higgs” particle

Mass   Quantum Numbers: Charge   Spin   CP

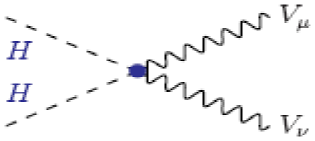
+ Total Width + Coupling strengths:



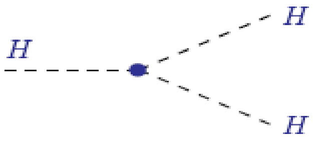
$$g_{Hff} = m_f/v = (\sqrt{2}G_\mu)^{1/2}\, m_f \qquad \times\ (i)$$



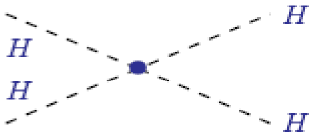
$$g_{HVV} = 2M_V^2/v = 2(\sqrt{2}G_\mu)^{1/2}\, M_V^2 \qquad \times\ (-ig_{\mu\nu})$$



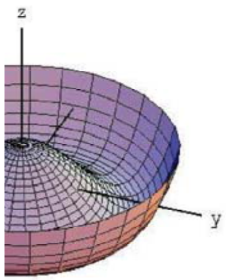
$$g_{HHVV} = 2M_V^2/v^2 = 2\sqrt{2}G_\mu\, M_V^2 \qquad \times\ (-ig_{\mu\nu})$$



$$g_{HHH} = 3M_H^2/v = 3(\sqrt{2}G_\mu)^{1/2}\, M_H^2 \qquad \times\ (+i)$$



$$g_{HHHH} = 3M_H^2/v^2 = 3\sqrt{2}G_\mu\, M_H^2 \qquad \times\ (+i)$$



Measurements at LHC

Mass

<140 GeV: from H→$\gamma\gamma$
>140 GeV: from H→4l

$\Delta m/m \sim 10^{-3}$

Total width:

not possible for m<200 GeV
($\Gamma_{Higgs} \ll \Gamma_{Detector}$)

$\Delta\Gamma/\Gamma \sim 20\%$ (250 GeV)
$\Delta\Gamma/\Gamma \sim 5\%$ (400 GeV)

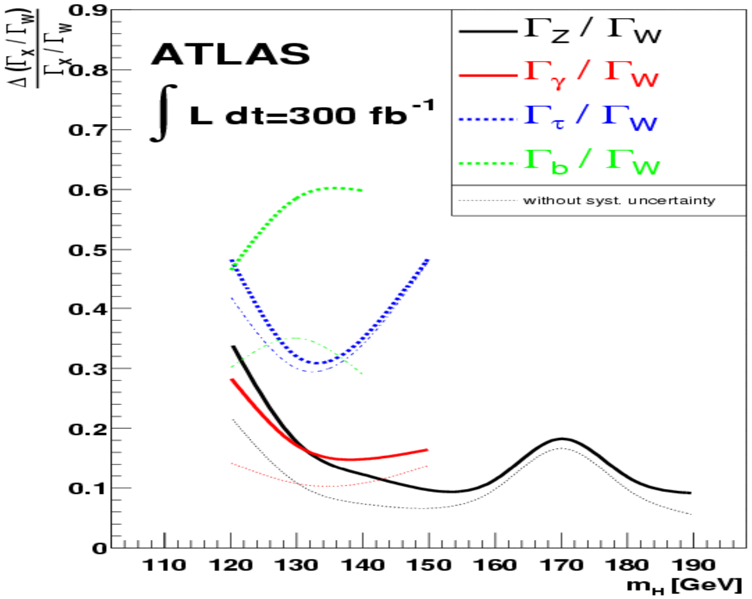
from lineshape in H→ZZ→4l

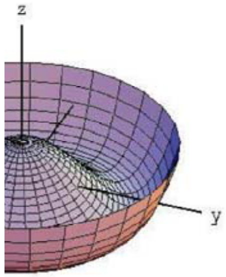
Couplings:

Production rates always contain products of couplings

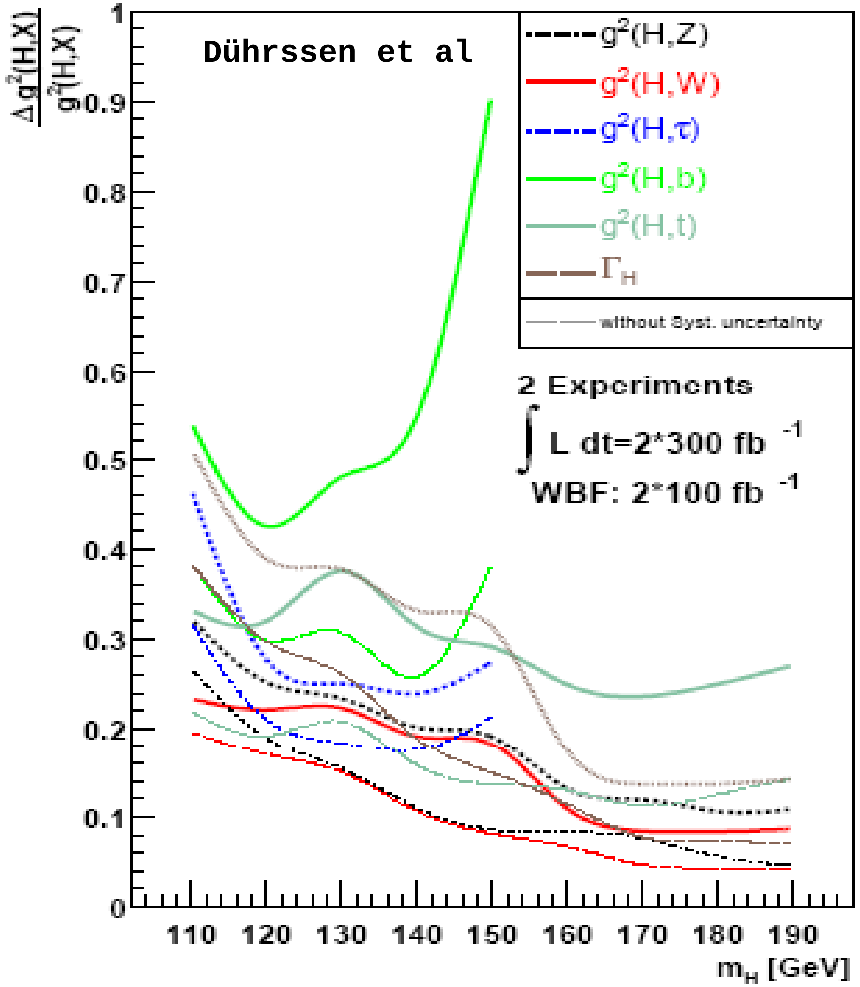
rations of rates ~
rations of partial widths

global Fit with 13 final states





Measurements at LHC

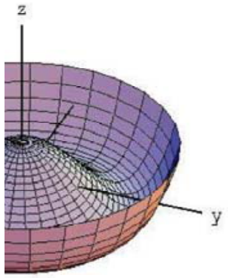


extraction of absolute couplings only with model assumptions:

- $g_V \leq g_V^{SM}$

precision on $\Delta g^2/g^2$ ~ 20-50% on Z,W,τ,b,t

large contribution of systematic error (QCD+PDF-uncertainty in production)



So what will be left to do?

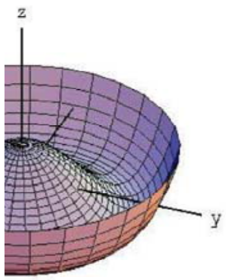
- (likely still have to) measure J^{CP} quantum numbers
- measure the Higgs gauge couplings without model assumptions
- measure Higgs Yukawa couplings without model assumptions
- measure the Higgs self coupling

- check consistency of Higgs properties with SM precision observables

in order to

- fully establish the Higgs mechanism
- look for deviations from SM Higgs realisation

needs a precision instrument



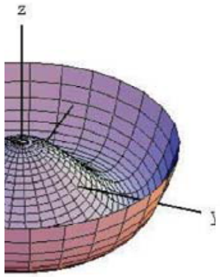
Electron Positron Collisions

Electron positron collisions at high energy provide a powerful tool to explore TeV-scale physics complementary to the LHC

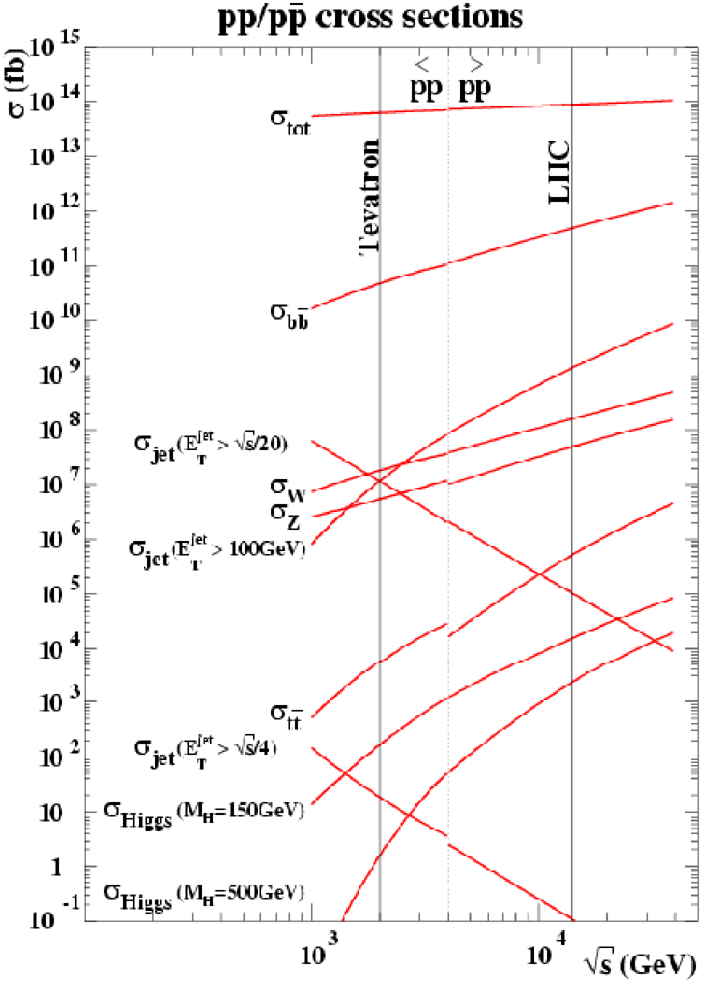
Due to their point-like structure and absence of strong interactions there are clear advantages of e^+e^- collisions:

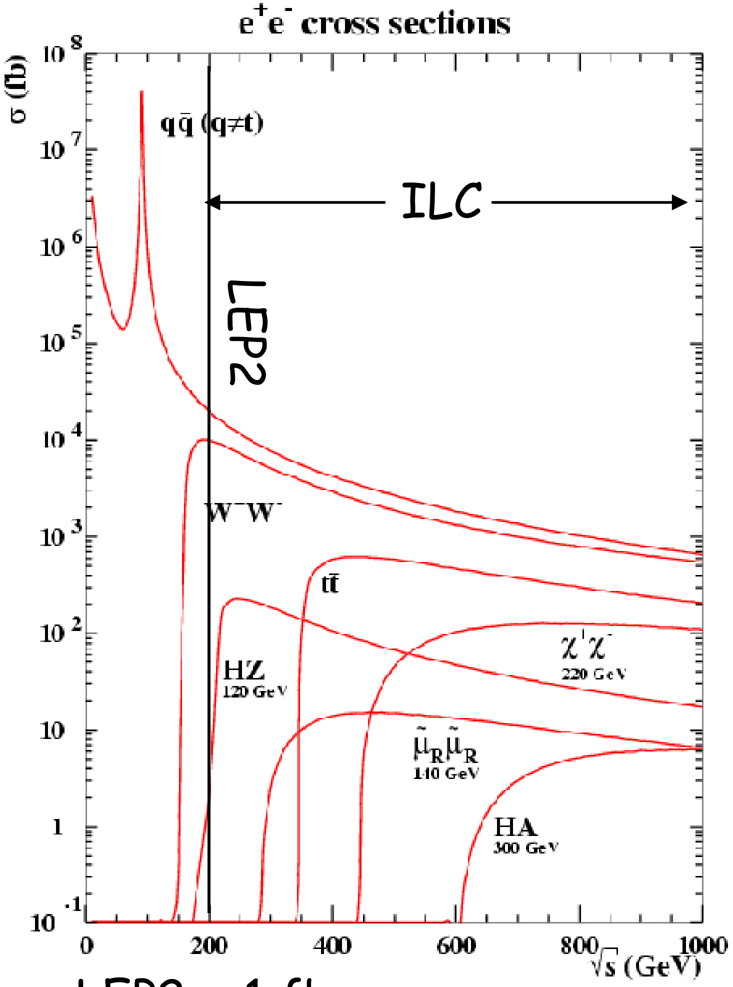
- known and tunable centre-of-mass energy
- clean, fully reconstructable events
- polarized beams
- moderate backgrounds
  → no trigger

→broad consensus for a Linear Collider with up to at least ~500 GeV



Higgs production and backgrounds

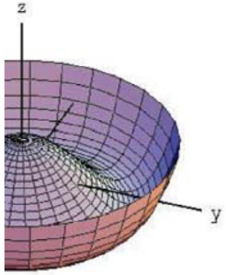




for m_H=120 GeV

Tevatron: ~700fb
LHC : ~30000fb
S/B ~ 10^{-12}

LEP2: ~1 fb
ILC: ~200 fb
S/B ~ 10^{-2}



The International Linear Collider

Huge world-wide effort to be ready for construction by ~2012
(Global Design Effort GDE)
Result of an intense R&D process since 1992

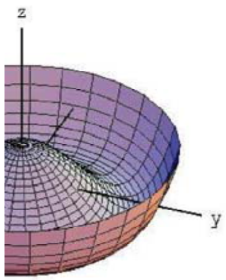
Parameters

The baseline:
e^+e^- LC operating from M_Z to 500 GeV, tunable energy
e^- /e^+ polarization
at least 500 fb^{-1} in the first 4 years

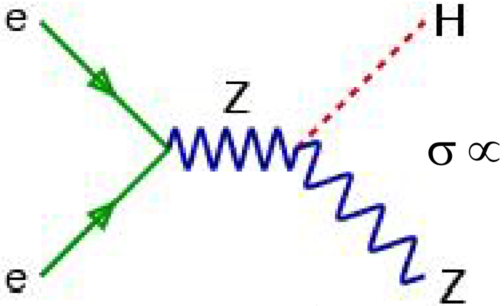
Upgrade: to ~ 1 TeV 500 fb^{-1} /year

Options :
- GigaZ (high luminosity running at M_Z)
- $\gamma\gamma$, $e\gamma$, e^-e^- collisions

Choice of options depends on LHC+ILC results

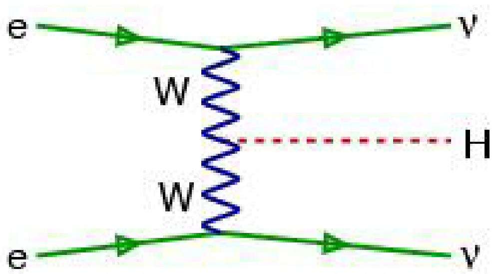


Higgs production at the ILC



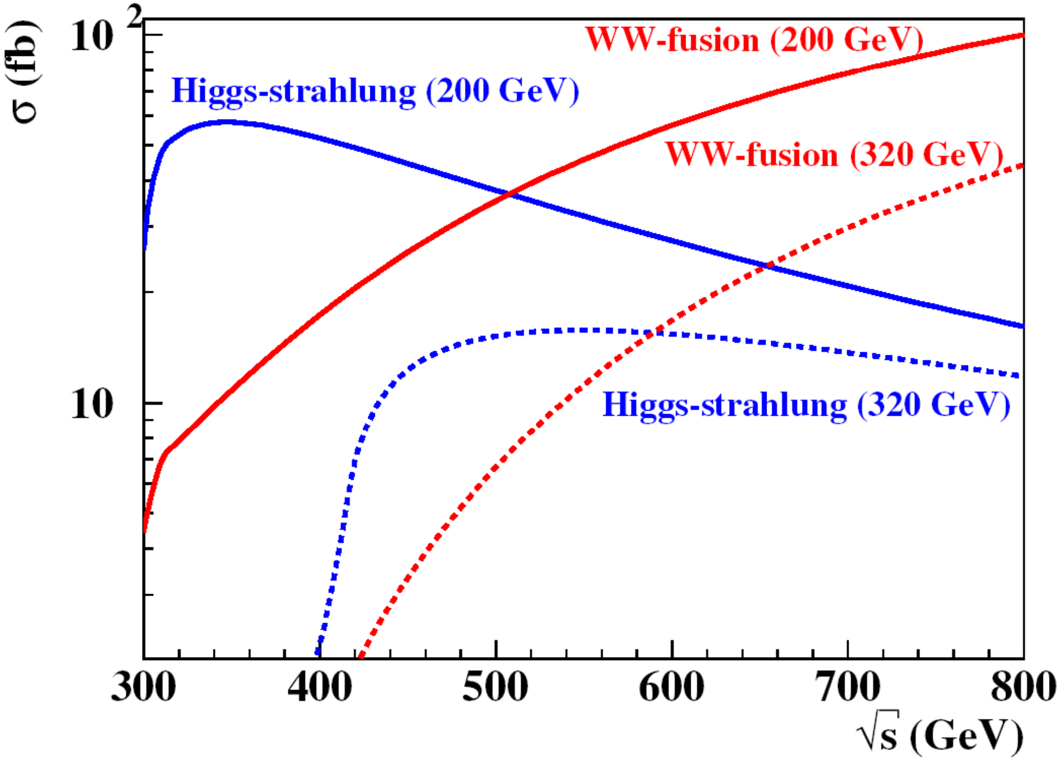
$\sigma \propto\sim 1/s$

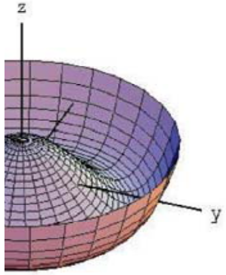
Higgsstrahlung



$\sigma \propto\sim \ln s$

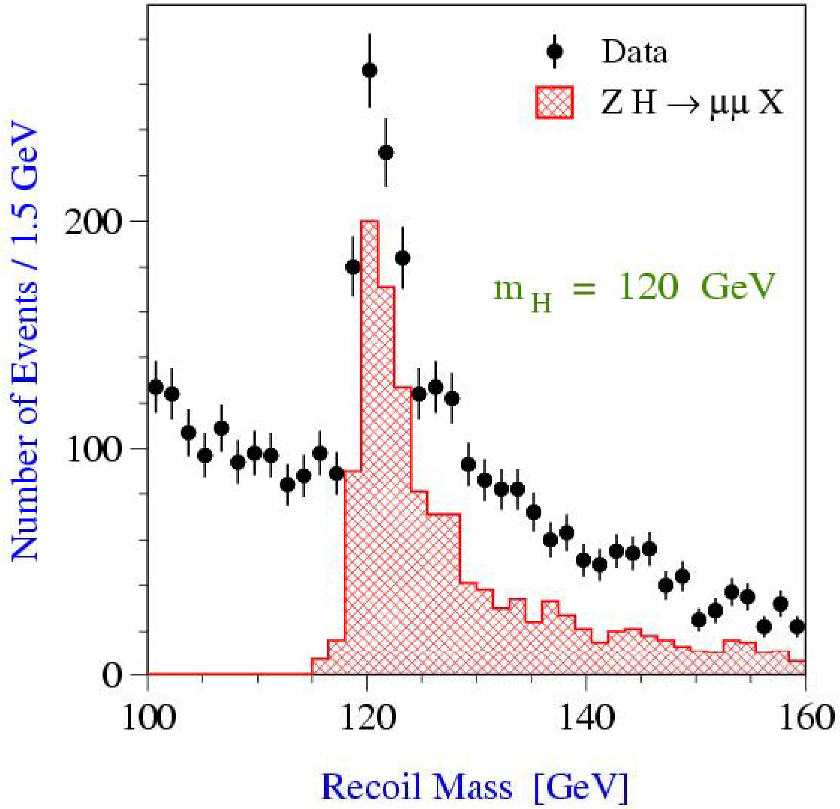
WW-Fusion

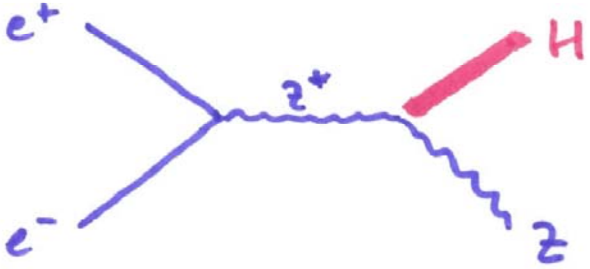




Seeing it without looking at it

anchor of Higgs physics at ILC:
decay-mode independent observation

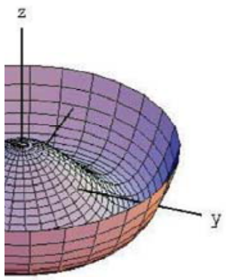




$$m_H^2 = (p_{\ell\ell} - p_{\text{initial}})^2$$

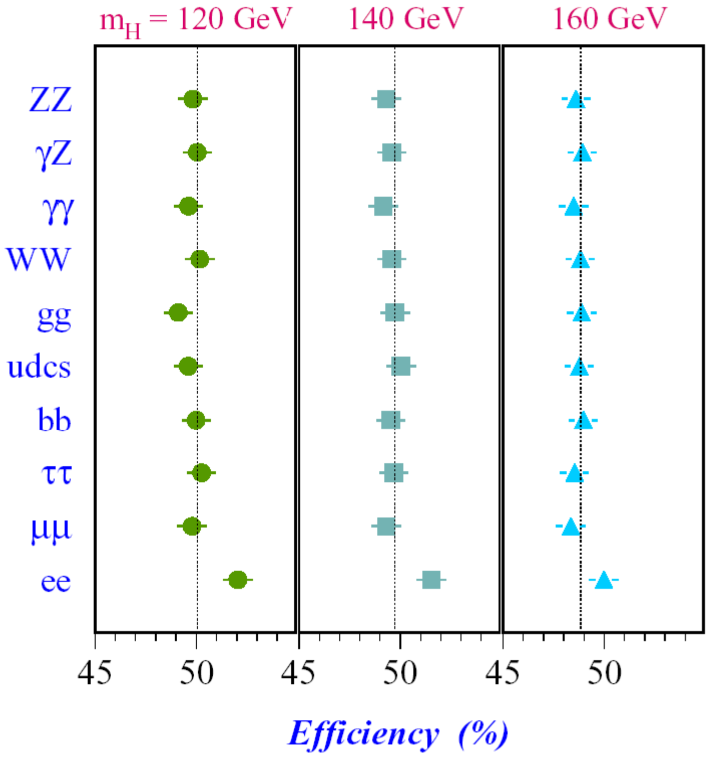
recoil mass

$\Delta\sigma/\sigma$ ~ 2%
$\Delta m/m$ ~ 50 MeV
HZ coupling ~ 1%



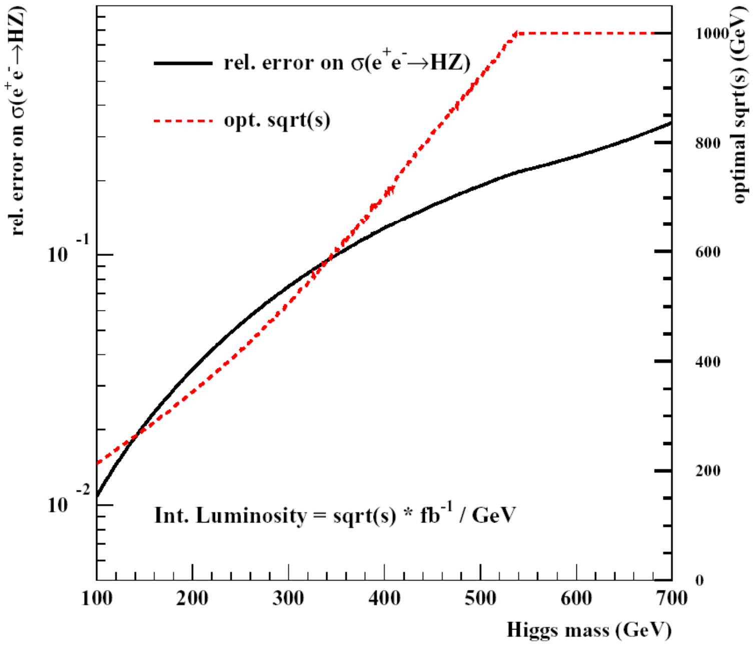
Seeing it without looking at it

efficiency is ~independent of decay mode:

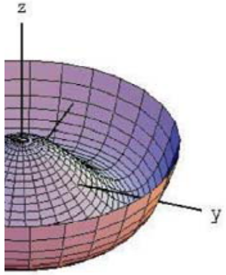


small differences can be corrected with MC

works over the whole range of possible Higgs masses:

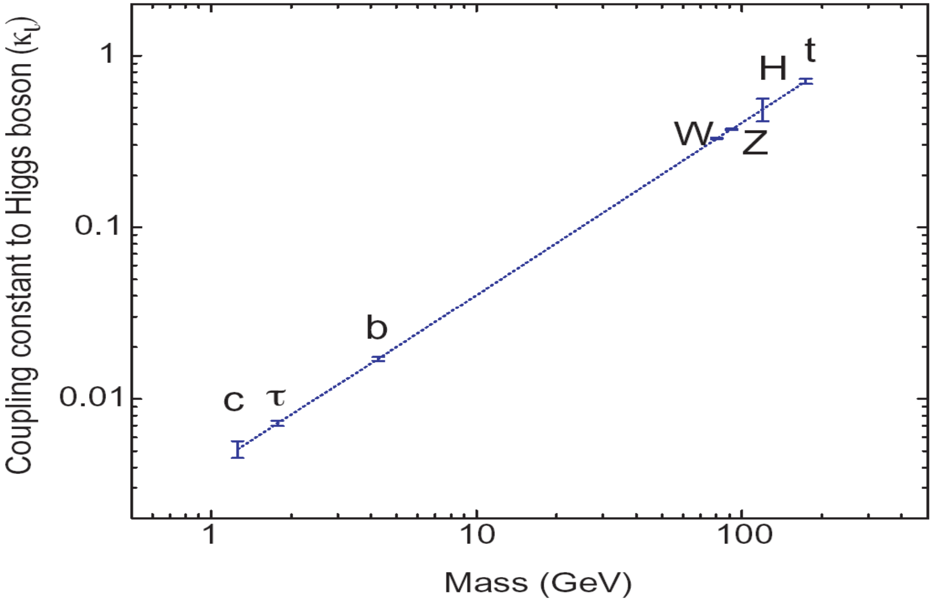


precision on σ(HZ):
1-3% for m_H<200 GeV
3-20% for m_H<500 GeV



Higgs branching ratios

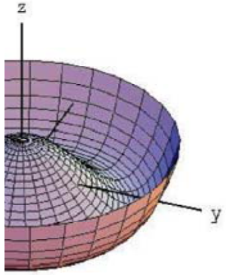
best option to test Yukawa mechanism
$\Gamma(H\to ff) \sim m_f$?



precision: ~%

At the ILC we can measure absolute branching ratios because decay-independent measurement of g_{HZ}:

$$\mathrm{BR}(\mathrm{H}\to\mathrm{X}) = \frac{\left[\sigma(\mathrm{HZ})\cdot\mathrm{BR}(\mathrm{H}\to\mathrm{X})\right]^{\mathrm{meas}}}{\sigma(\mathrm{HZ})^{\mathrm{meas}}}$$



Higgs branching ratios

Most challenging: disentangle
hadronic Higgs decays
H→bb H→cc H→gg

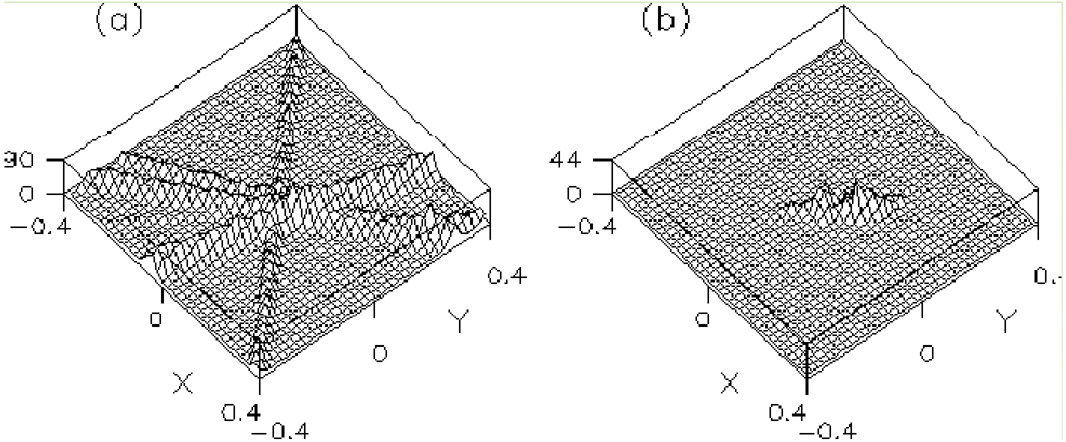
H→bb	68.2%
H→cc	3.0 %
H→gg	6.7 %

for
m_H=120 GeV

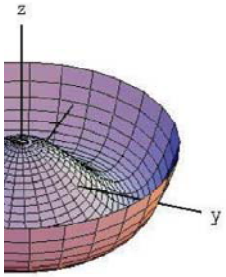
Need very good vertex detector and sophisticated flavour tagging:
Vertex reconstruction using ZVTOP algorithm (SLD)

Tracks interpreted
as 3D probability tubes

Vertices = overlapping
tubes



After vertex reconstruction, use ANN's with vertex+track information
to obtain b- and c-likeness for each jet



Top Yukawa coupling: LHC+ILC synergy

LHC: measures

$\sigma_{tth} \times BR(H \rightarrow bb)$

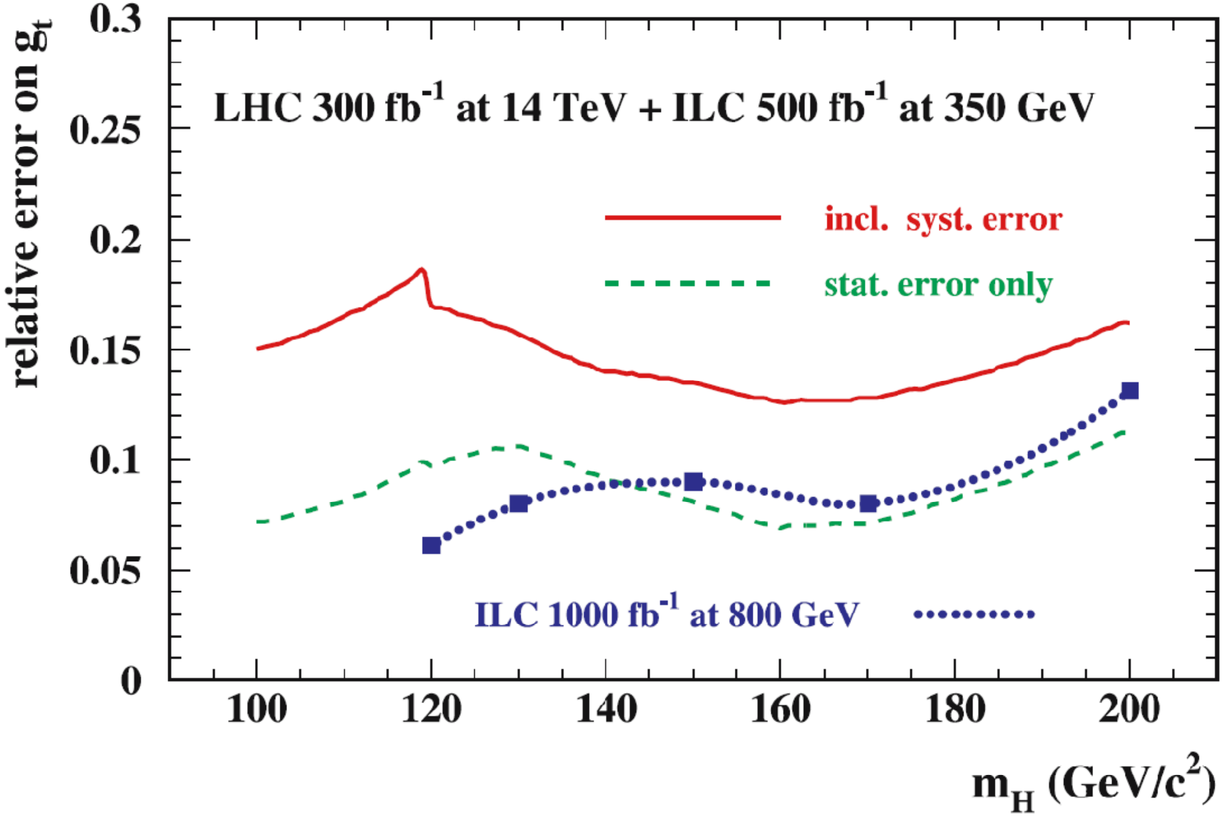
$\sigma_{tth} \times BR(H \rightarrow WW)$

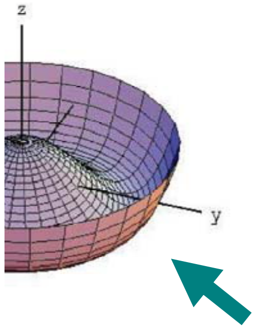
$\rightarrow g_t^2 \times BR(H \rightarrow xx)$

ILC: measures BRs

$BR(H \rightarrow bb)$

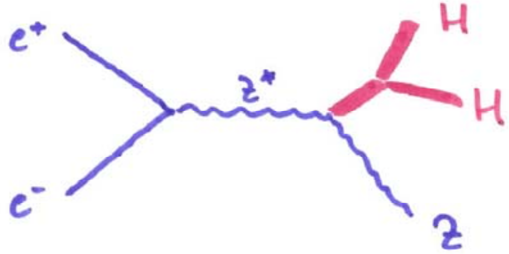
$BR(H \rightarrow WW)$





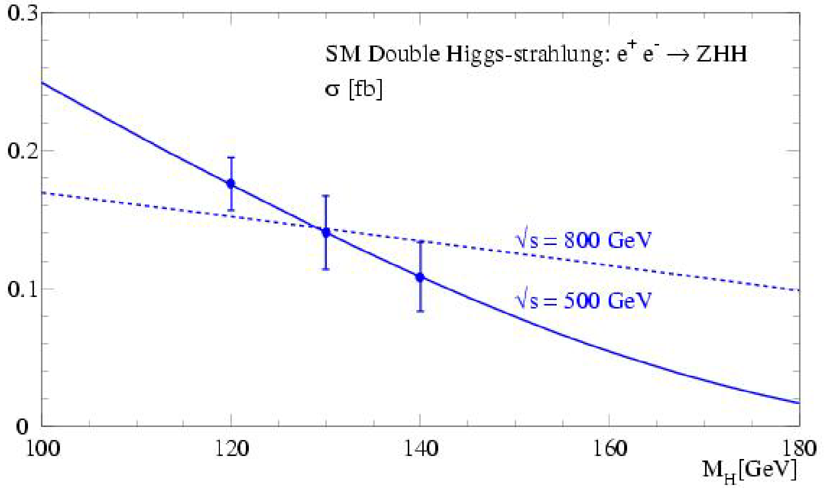
Higgs self coupling

closely linked to shape to Higgs potential
→ most important test of spontaneous
symmetry breaking

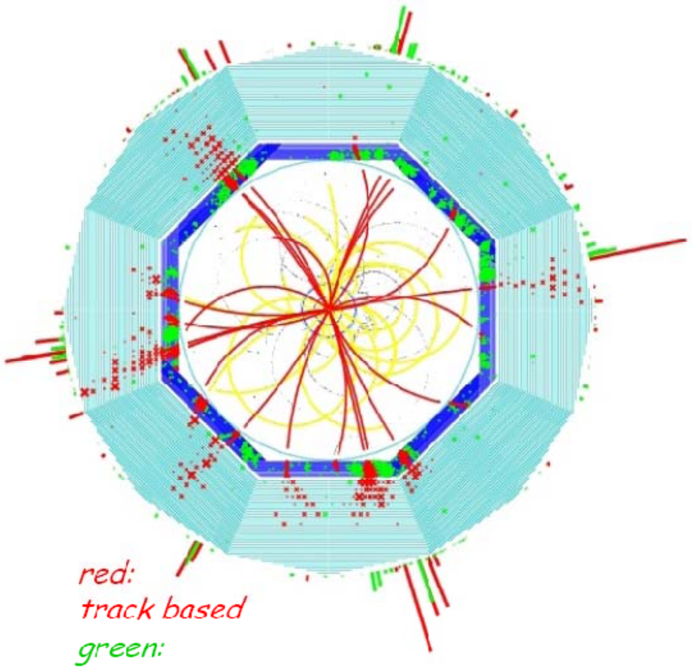


measurement at LHC seems impossible

ILC: double Higgs-Strahlung:

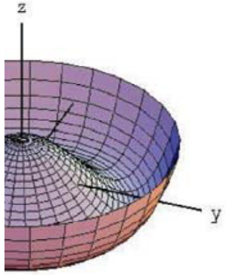


$\Delta\lambda/\lambda$ = 20% @ 500 GeV
12% @ 1 TeV (?)



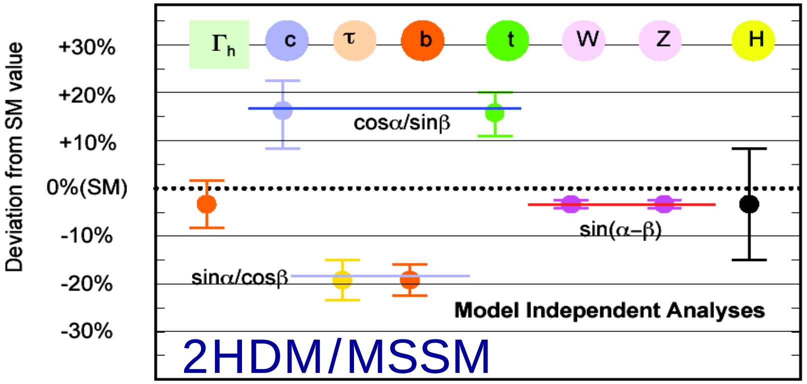
red:
track based
green:
calorimeter based

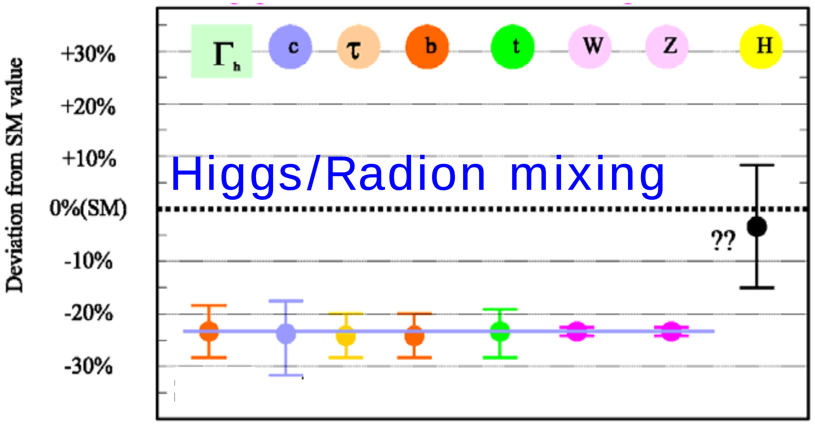
ZHH → qqbbbb



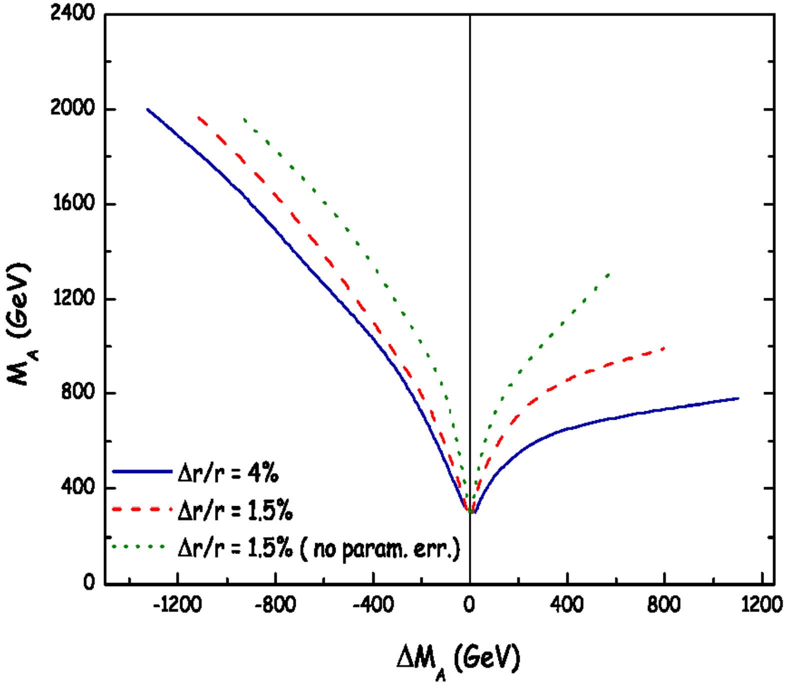
Why is precision so important?

distinguish models



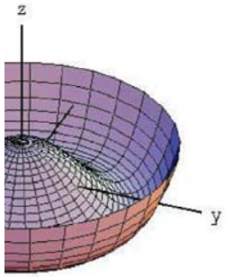


indirect mass determination of heavy Higgses, if there (MSSM):



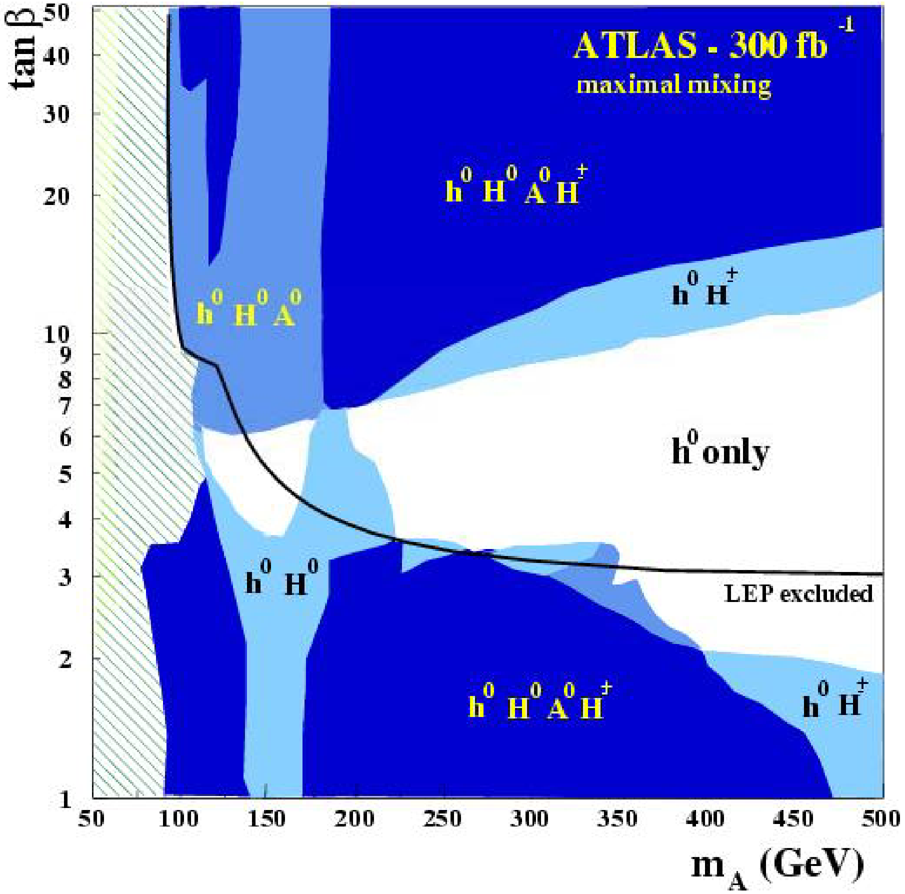
Δm_A = 30% for m_A = 800 GeV

also in parameter regions where LHC is blind



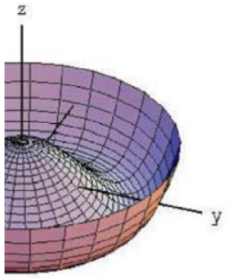
SUSY Higgs Bosons

To prove the structure of the Higgs sector, the heavier Higgs bosons have to be observed either directly or through loop-effects.

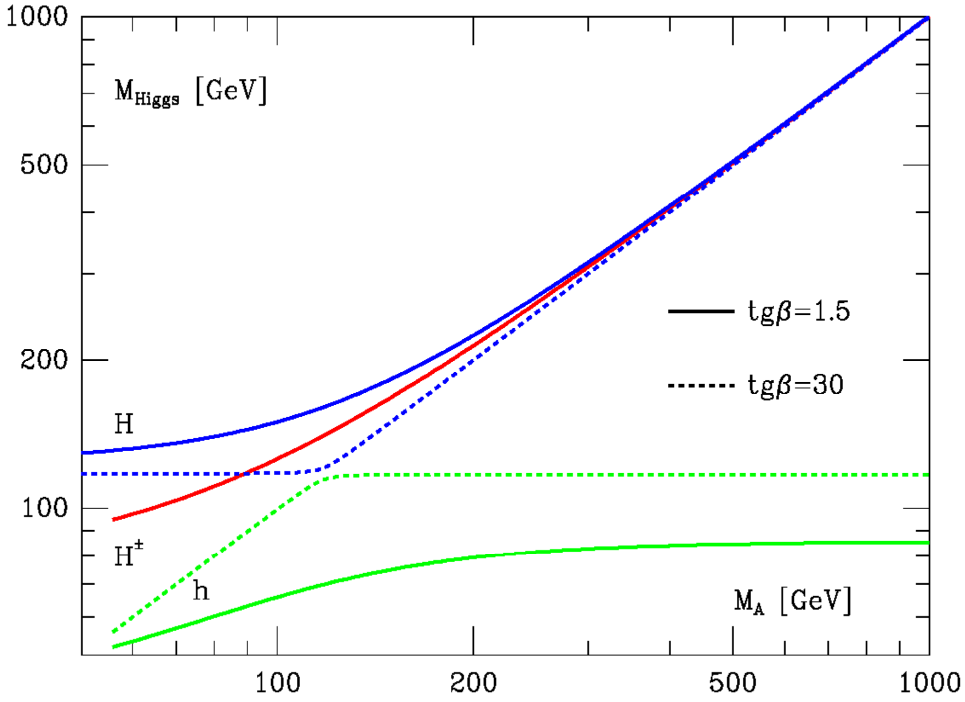


Direct observation difficult in part of parameter space at LHC in spite of rather low-mass A^0

(only bb,ττ decays!)



SUSY Higgs Bosons

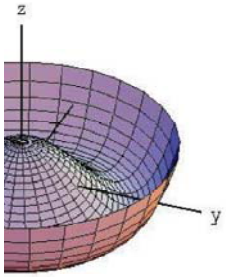


Production processes:

$$\left.\begin{array}{l} e^+e^- \to h\,Z \\ e^+e^- \to HA \end{array}\right\} \propto\sim \sin^2(\beta-\alpha)$$

$$\left.\begin{array}{l} e^+e^- \to HZ \\ e^+e^- \to h\,A \end{array}\right\} \propto\sim \cos^2(\beta-\alpha)$$

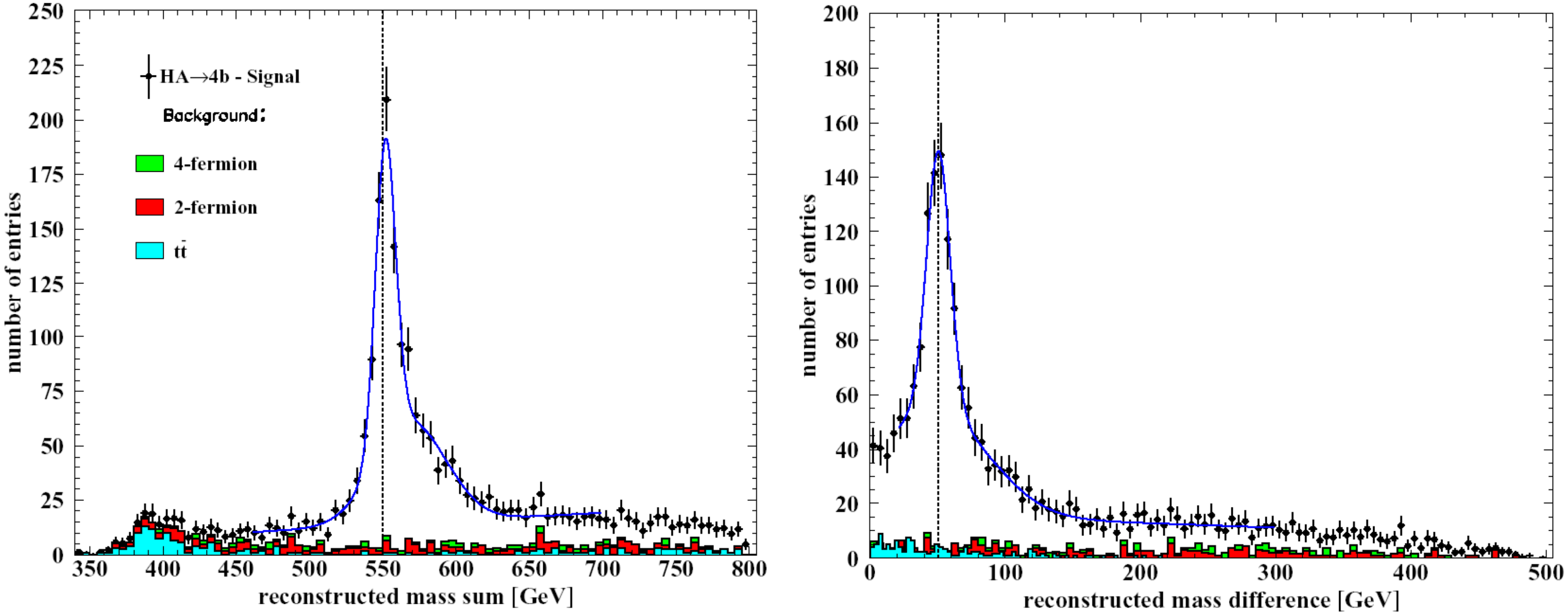
Most challenging: ‘decoupling limit’
$\sin^2(\beta-\alpha) \to 1$, m_A large
h becomes SM like
H/A/$H^\pm$ heavy and mass degenerate



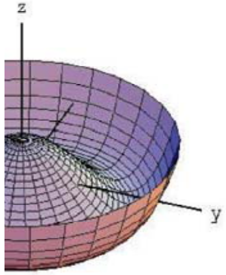
SUSY Higgs Bosons at ILC

Very clear signal in HA → bbbb
100 – 1000 MeV mass precision due to kinematic fit
drawback: pair production → mass reach ~ √s / 2

Example for m_H=250 GeV / m_A=300 GeV at $\sqrt{s}$ = 800 GeV:



also HA→ $bb\tau\tau$ and H^+H^- studied
generic limitation: pair production: $m_{H/A/H^\pm} < \sqrt{s} / 2$



Invisible Higgs Decays at ILC

Many SM extensions predict invisible Higgs decays, e.g.:

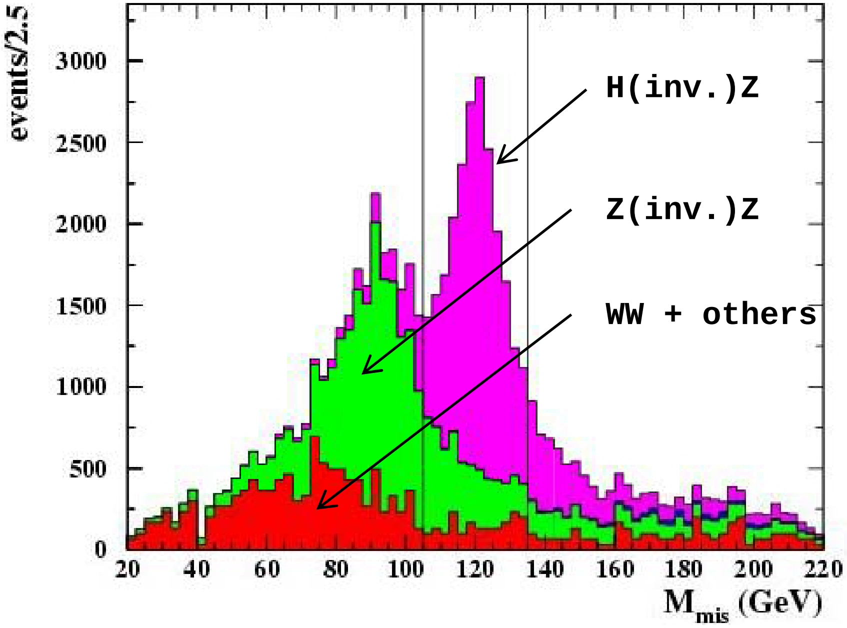
- MSSM $H \to \chi^0_1 \chi^0_1$
- Extra Dimensions
- Model with new singlets (NMSSM,Majoron Models)
- Stealthy Higgs

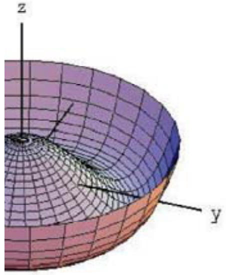
Estimate sensitivity from 1 = BR(vis) + BR(invis)

or explicit reconstruction of $Z \to qq, ll$ + missing energy final states

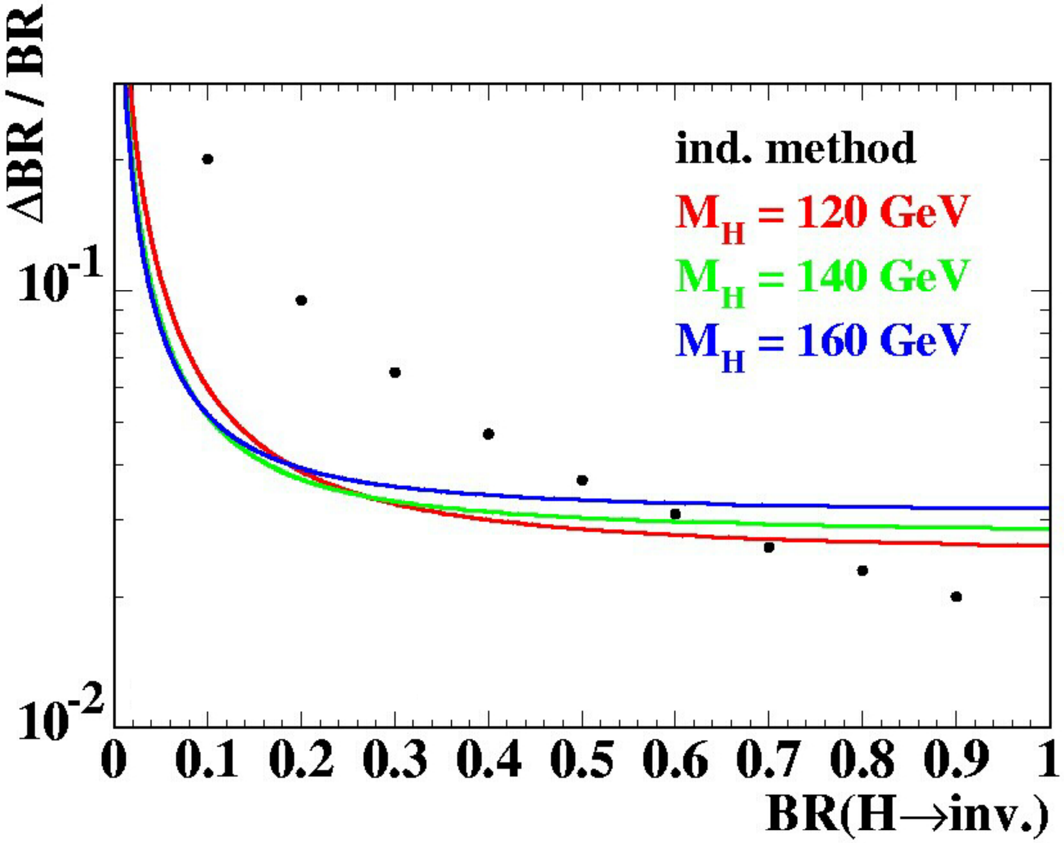
Example:

$$\sqrt{s} = 350\, GeV, L = 500\ fb^{-1}$$
$$m_H = 120, 140, 160\ GeV$$





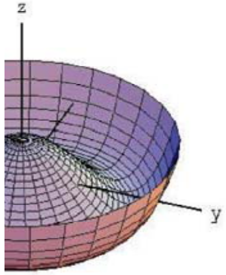
Invisible Higgs Decays at ILC



Result for 500 fb^{-1}@350 GeV (m_H=120 GeV):

ΔBR/BR(invis) = 10% for BR(invis) = 5%

5σ observation down to BR = 2%

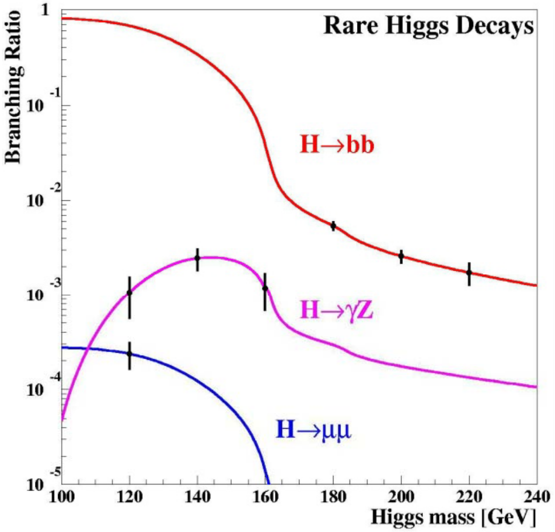


What the ILC cannot do…

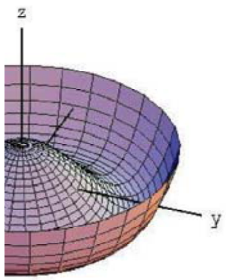
If something which resembles Peter's Higgs is realized in Nature the ILC will see it and measure most parameters

Things which go beyond ILCs capabilities:

- measure the trilinear selfcoupling if m_H >~ 200-250 GeV ??
- measure the quartic selfcoupling (no „known" machine can)
- discover very heavy additional Higgs bosons
  (e.g. SUSY H,A,H+ if m> ~500 GeV)
- observe very rare decays (BR < 10^{-4})



(see later…)

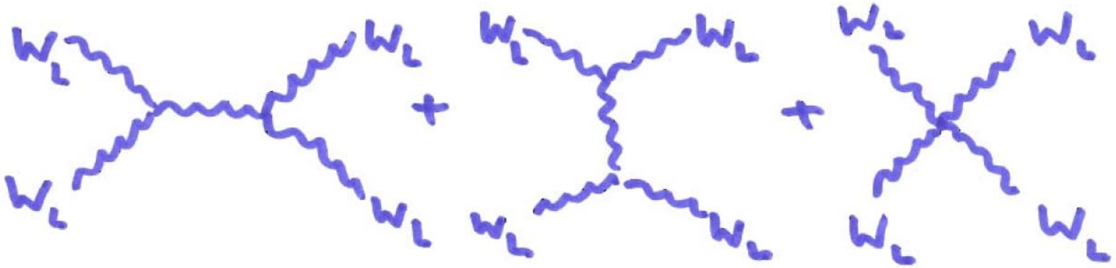


Alternatives

In spite of the excellent agreement of the data with the SM Higgs hypothesis there is no guarantee for its existence!

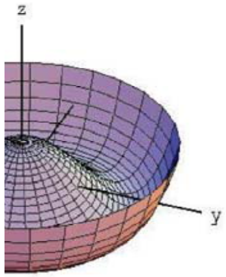
The discovery of the SM Higgs Boson at Tevatron or LHC would be a major breakthrough!!!

→ absence of a <TeV Higgs boson requires new interactions at the TeV scale



diverges for $\sqrt{s} \to \infty$, violates unitarity at $\sqrt{s} \approx 1.2$ TeV

Technicolor, Higgsless Models, …
in general in tension with precision data, but…



If LHC sees no Higgs…

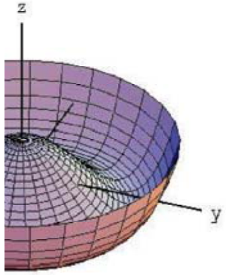
…a linear collider becomes particular important!

- has a Higgs particle been missed at the LHC?
  → model-independent discovery at ILC

- if new particles beyond direct mass reach of ILC become visible at LHC → temptation to produce them in $e^+e^-/\mu^+\mu^-$ (especially Z´ - like states which can be s-channel produced)

if that is not realizable in a timely fashion, or simply „nothing" is seen at LHC, precision measurements of SM processes at ILC can reveal a lot about the new physics

Precise measurements of $e^+e^- \rightarrow 2f, 4f, 6f(!)$



Generic approach towards „Higgsless“ scenarios

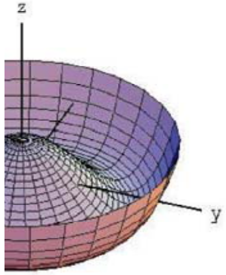
- assume only that $SU(2)_L \times U(1)_Y$ is broken spontaneously down to $U(1)_Q$
- Effective Lagrangian contains 10 dim-4 Operators
- 5 obey $SU(2)_C$, i.e. they protect $\rho \sim 1$.

$$
\begin{aligned}
L_1 &= \frac{\alpha_1}{16\pi^2}\frac{gg'}{2}B_{\mu\nu}\,\mathrm{tr}\Big(\sigma_3 W^{\mu\nu}\Big)\\
L_2 &= \frac{\alpha_2}{16\pi^2}\mathrm{i}g' B_{\mu\nu}\,\mathrm{tr}\Big(\sigma_3 V^\mu V^\nu\Big)\\
L_3 &= \frac{\alpha_3}{16\pi^2}2\mathrm{i}g\,\mathrm{tr}\Big(W_{\mu\nu}V^\mu V^\nu\Big)\\
L_4 &= \frac{\alpha_4}{16\pi^2}\,\mathrm{tr}\Big(V_\mu V_\nu\Big)\,\mathrm{tr}\Big(V^\mu V^\nu\Big)\\
L_5 &= \frac{\alpha_5}{16\pi^2}\,\mathrm{tr}\Big(V_\mu V^\mu\Big)\,\mathrm{tr}\Big(V_\nu V^\nu\Big)\,,
\end{aligned}
$$

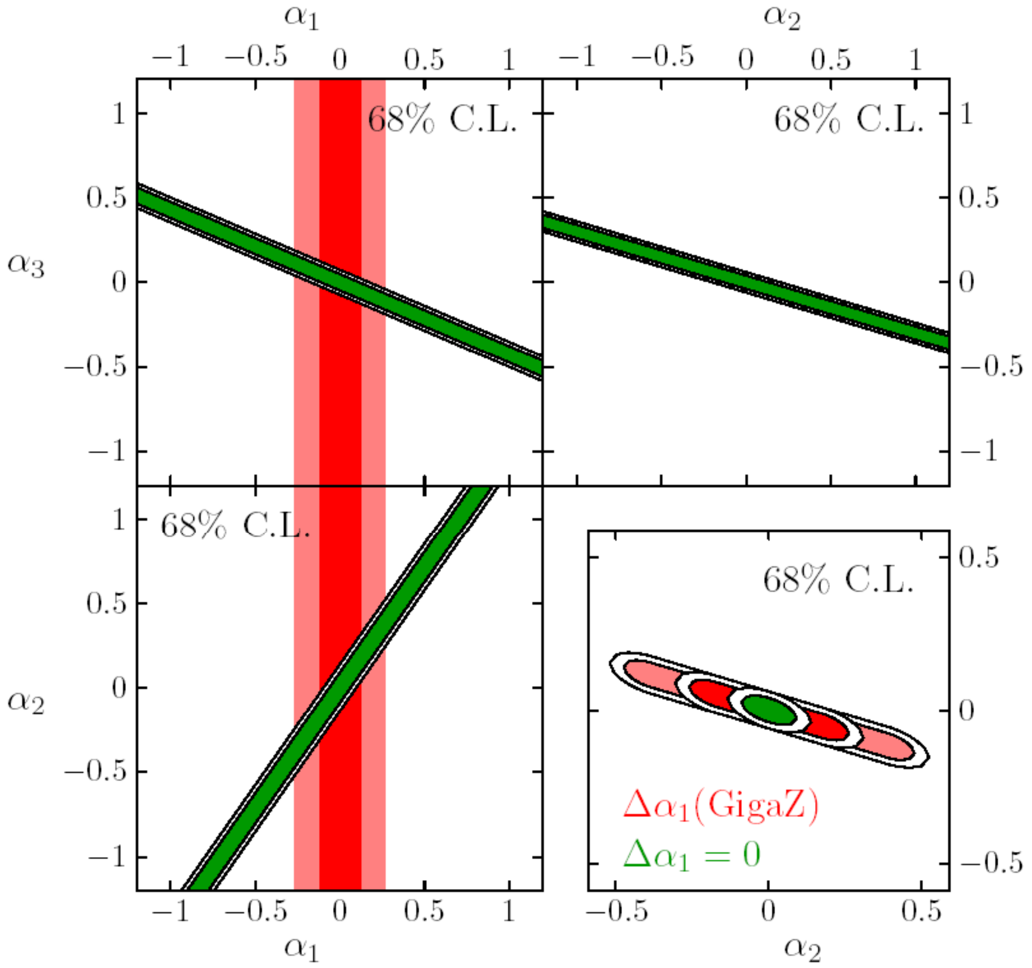
L_1, L_2, L_3 can be probed in W pair production (reinterpretation of anomaluous TGC couplings)

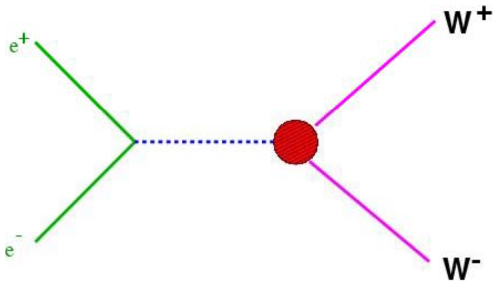
L_4,L_5 probed in VV→VV scattering

couplings α_I relate to scale of new physics $\frac{\alpha_i}{16\pi^2} = \left(\frac{v}{\Lambda_i^*}\right)^2$

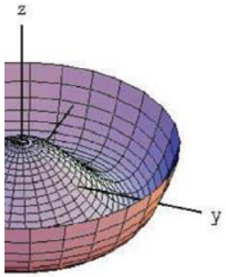


Strong EWSB: Triple Gauge Couplings



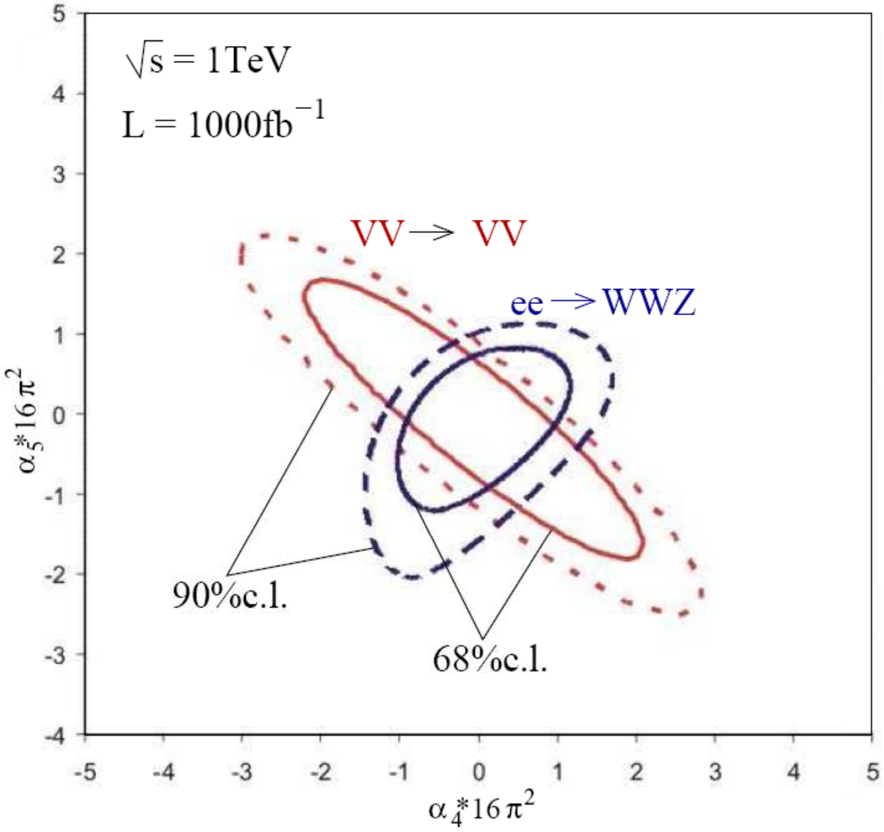


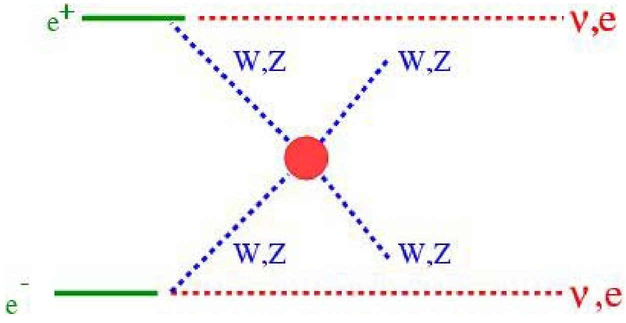
$\alpha_1 = 0$	80%+0%	80%+60%
Λ_2^*	5.4 TeV	8.8 TeV
Λ_3^*	8.2 TeV	10.7 TeV



Strong EWSB: Quartic Gauge Couplings

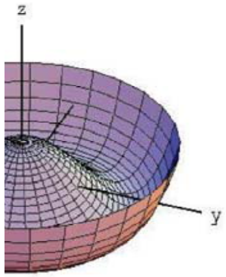
Effective Lagrangian approach to study 4V-interaction





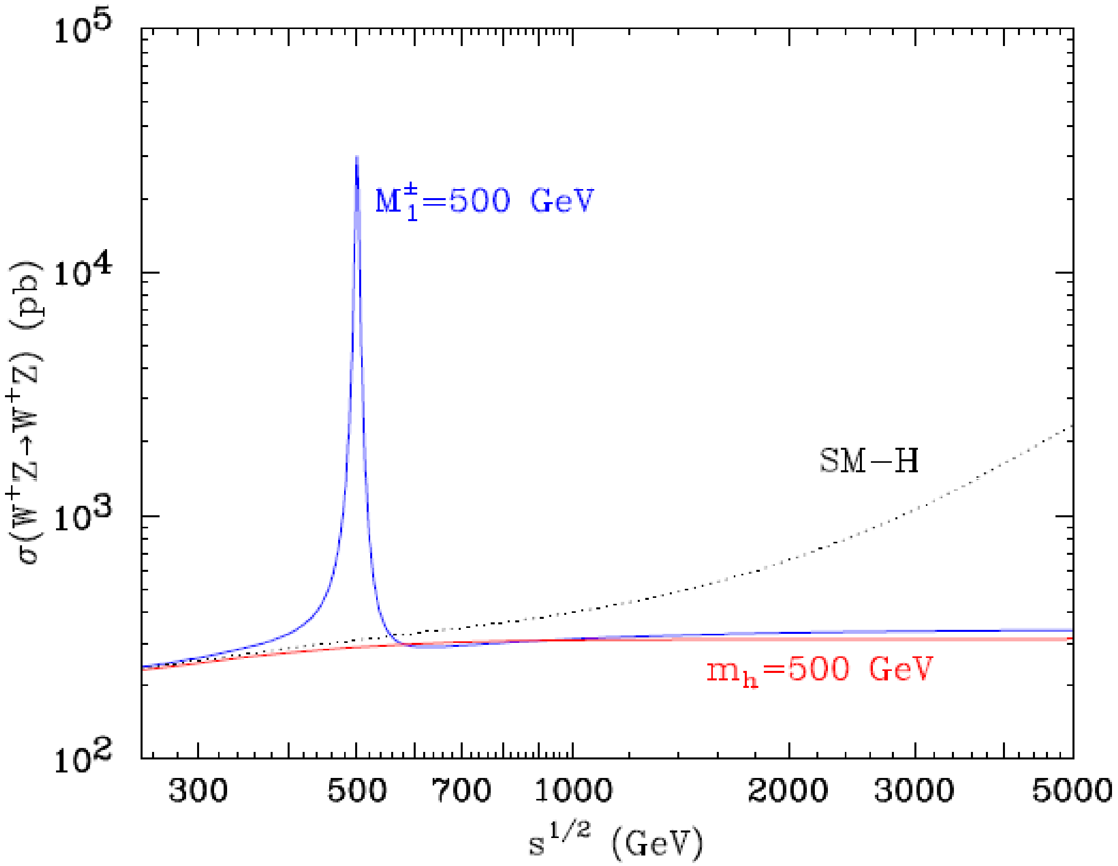
$$\frac{\alpha_i}{16\pi^2} = \left(\frac{v}{\Lambda_i^*}\right)^2$$

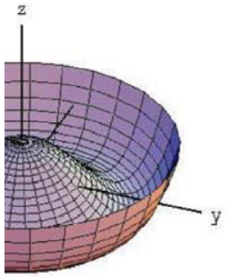
ILC (1TeV) sensitivity translates into Λ ~ 3 TeV reach for α_i ~ o(1)



Higgsless Models

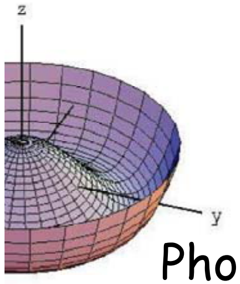
One specific example which would produce deviations in α_4 /α_5 (WZ→WZ)





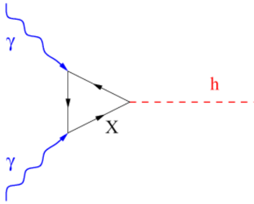
5. EWSB beyond LHC and ILC

- Photon Collider
- CLIC
- Muon Collider



Higgs Physics at a Photon Collider

Photon Collider: unique place to study Higgs $\gamma\gamma$ partial width in s-channel $\gamma\gamma \to H$ production

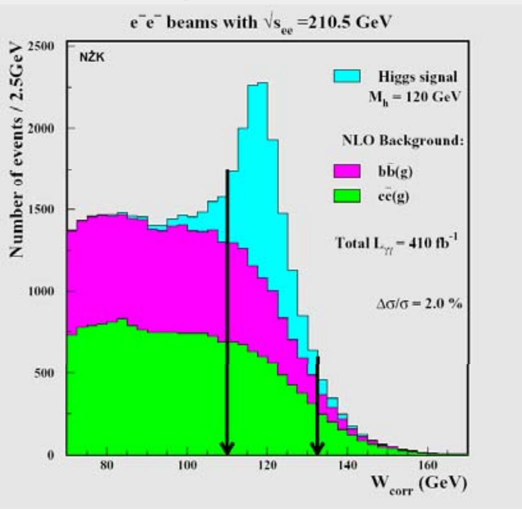


$$\sigma(\gamma\gamma \to \mathrm{H} \to \mathrm{X}) = \frac{4\pi^2}{\mathrm{m_H^3}}\Gamma(\mathrm{H} \to \gamma\gamma)\cdot\mathrm{BR}(\mathrm{H} \to \mathrm{X})(1+\lambda_1\lambda_2)$$

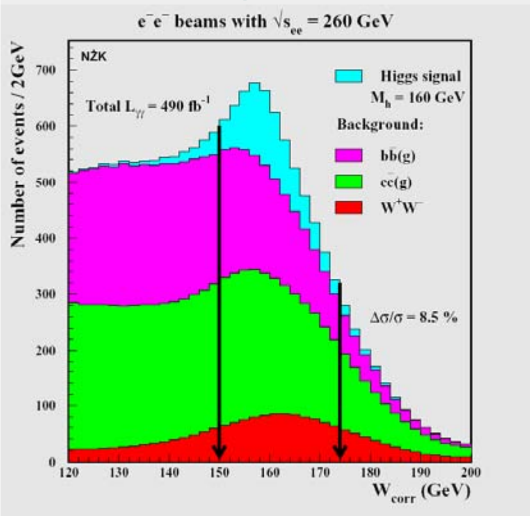
$$(\lambda_i = \text{helicity of photon } i)$$

Sensitive to any massive charged particle in the loop → universal NP probe
Combination with Higgs-BR's from e^+e^- can give total Higgs width (later)
Assume Higgs mass known → tune $\sqrt{s_{\gamma\gamma}}$ to peak position

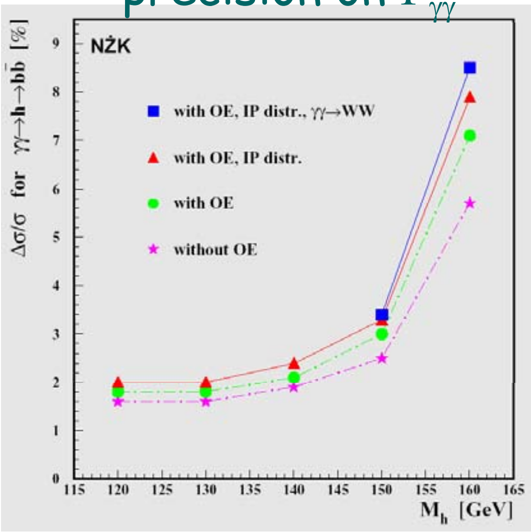
H→bb signal (m_H=120)

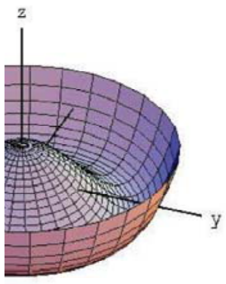


H→WW signal (m_H=160)



precision on $\Gamma_{\gamma\gamma}$





CLIC

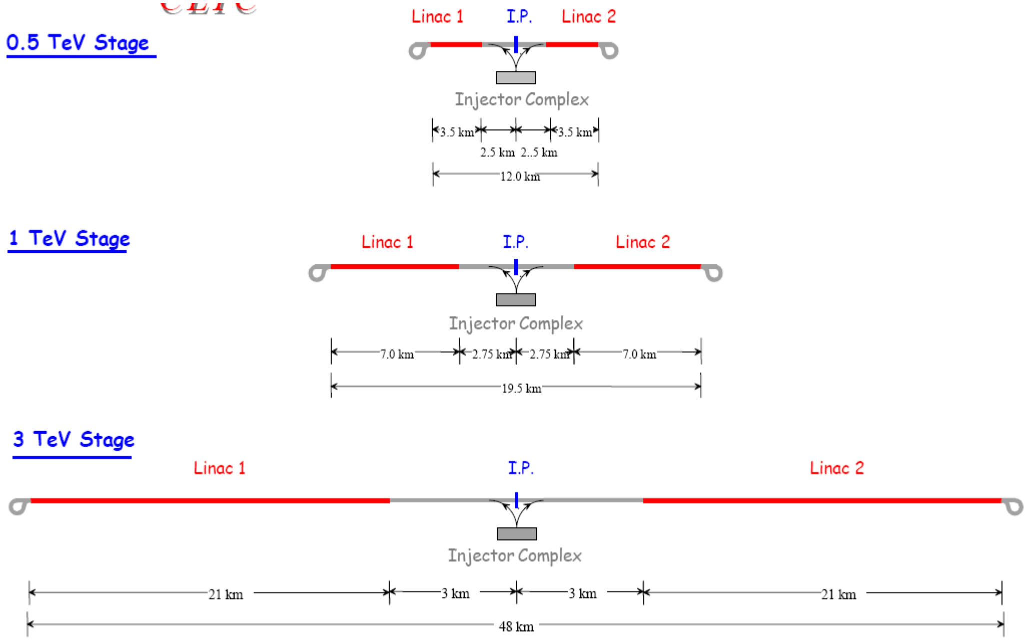
Electron-positron linear collider using
two-beam acceleration scheme, new parameters since Dec06

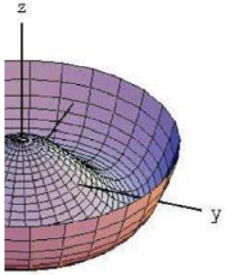
Main Linac RF frequency	**30 GHz ⇒ 12 GHz**
Accelerating field	**150 MV/m ⇒ 100 MV/m**
Overall length @ E_{CMS}= 3 TeV	**33.6 km ⇒ 48.2 km**

Peak luminosity
(at 3 TeV):
$7\ 10^{34}\ cm^{-2}s^{-1}$
$2\ 10^{34}\ cm^{-2}s^{-1}$
(within 1% of E_{max})

staged
construction?

aim at feasibility
proof by 2010



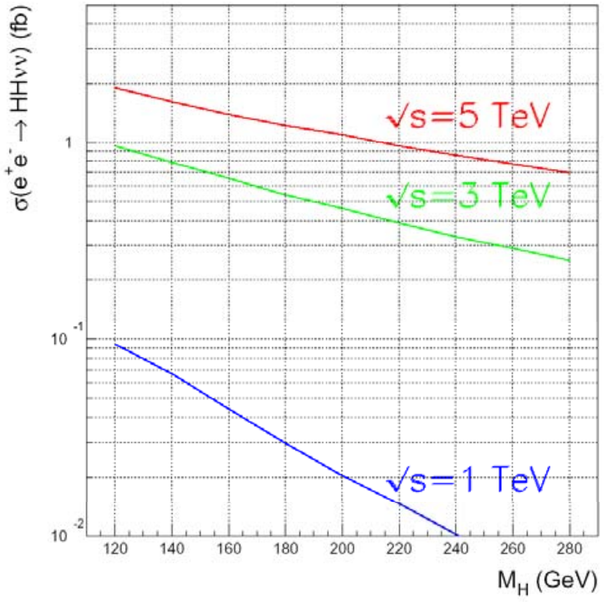


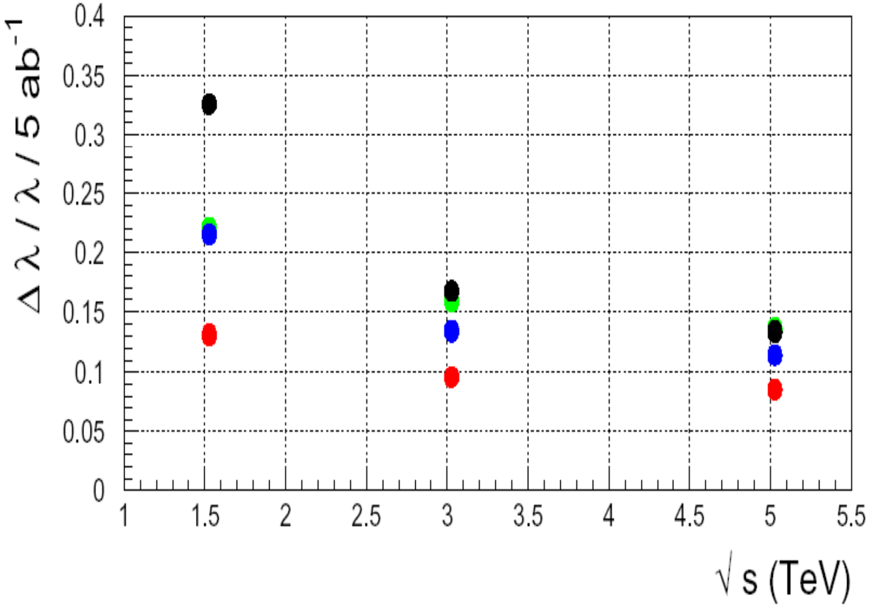
Higgs Physics at CLIC (3 TeV)

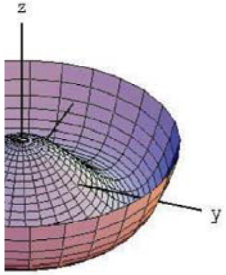
If low-mass Higgs boson is found at LHC, a ~<500 GeV LC will be is definitely necessary for model-independent Higgs profile (Higgs-Strahlung, ~1/s)

Additional possibilities at multi-TeV:

-Take advantage of rising WW-fusion cross section (huge #Higgs)
 → improve precision and mass reach for trilinear coupling meas:

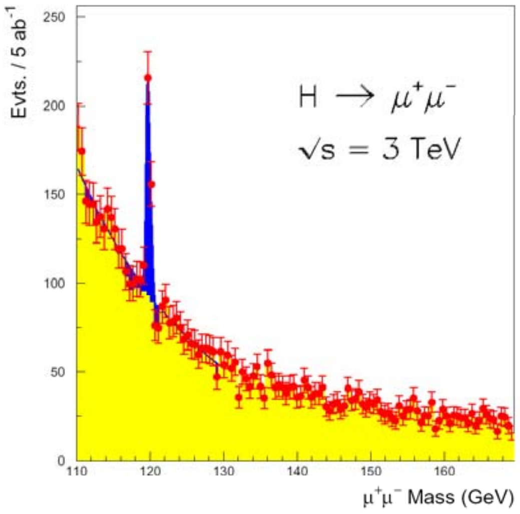




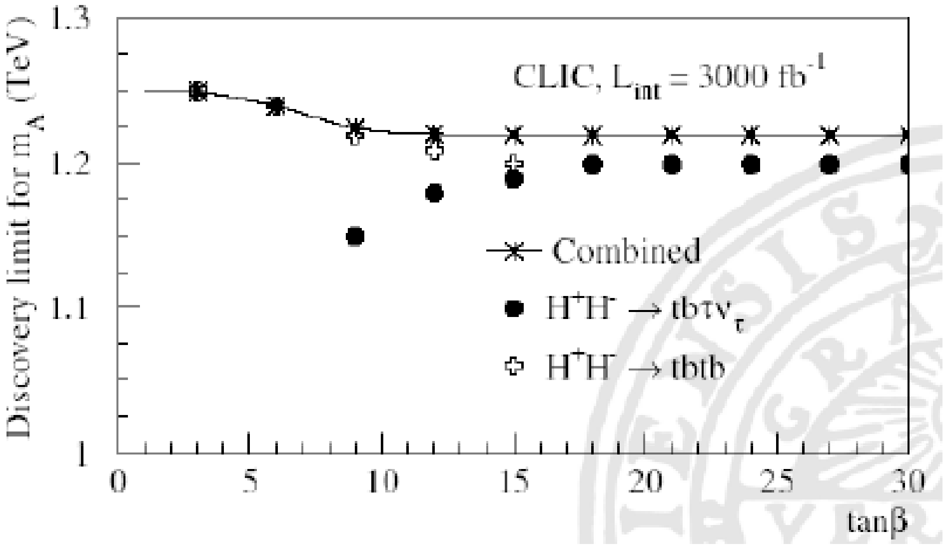


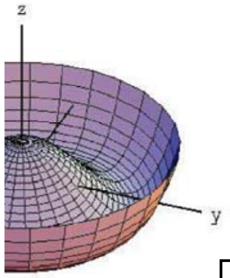
Higgs Physics at CLIC (3 TeV)

Ultra-rare decays:



Higher mass-reach for heavy SUSY Higgs:



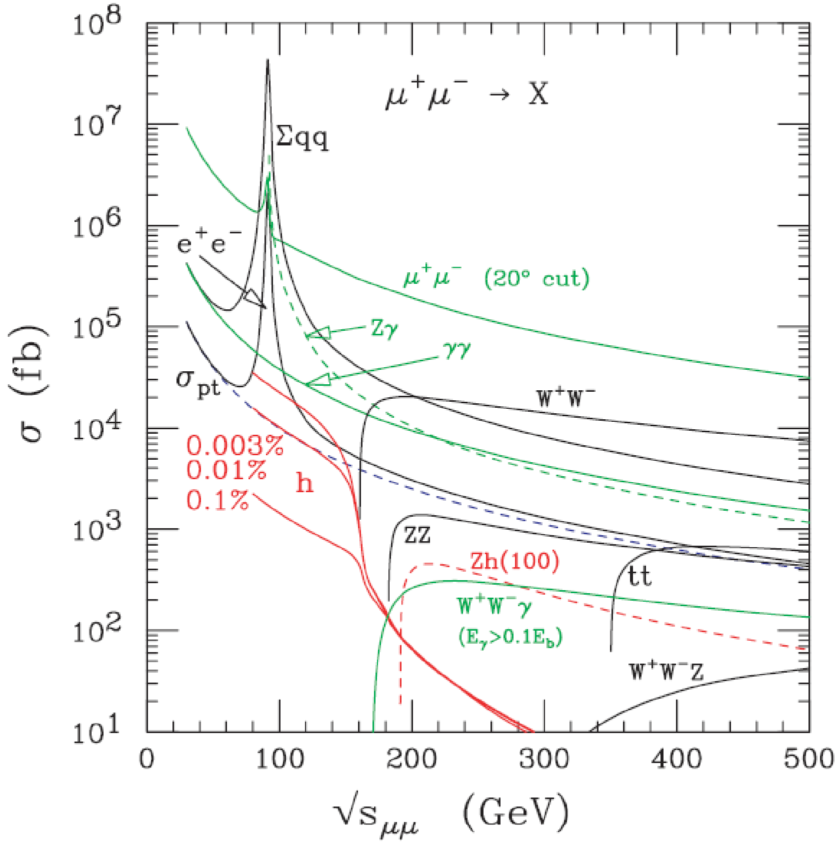


A Muon Collider?

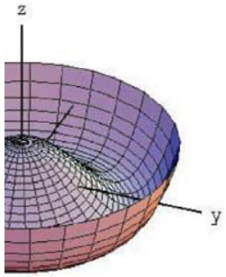
C.Quigg

For many purposes, a lepton is a lepton . . .

SM cross sections



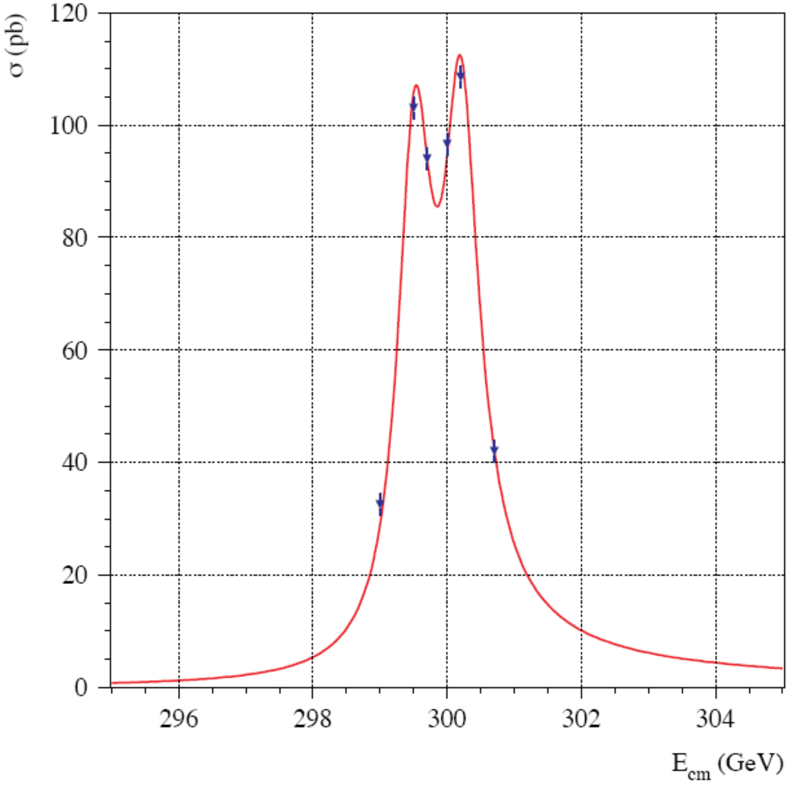
. . . but sometimes, mass matters: $m_\mu^2/m_e^2 = 42\,750$



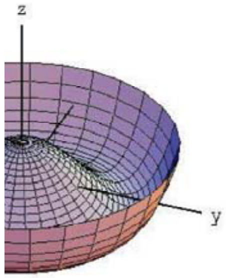
Higgs Physics at a Muon Collider

Example:

Supersymmetric Higgs bosons: $\mu^+\mu^- \to H/A \to bb$



$M_A = 300$ GeV, $\tan\beta = 10$, $\delta E/E = 3 \times 10^{-5}$, 25 pb^{-1}/point Janot



Summary and Conclusions

- LHC will most likely reveal first insight in the cause of EWSB
- The discovery of a Higgs boson as predicted in the SM and consistent with precision data will call for a o(500 GeV) linear collider – the ILC
- In the absence of a Higgs at LHC, precision measurements at the ILC can guide the way togehter with the LHC
- Multi-TeV colliders (CLIC,μC) can complete the picture