Higgs Boson Precision Studies at a Linear Electron Positron Collider

Fermilab
03/05/2001

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Workshop on the future
of Higgs Physics

LINE DRIVE A [illegible] of Linear Collider Double Headers

- **Introduction**
- **The TESLA Collider**
- **Experimentation for Higgs Physics**
- **The Profile of the Higgs Boson**
- **Interpretation 1: Global Fits**
- **Interpretation 2: SUSY**
- **Conclusion**

Introduction

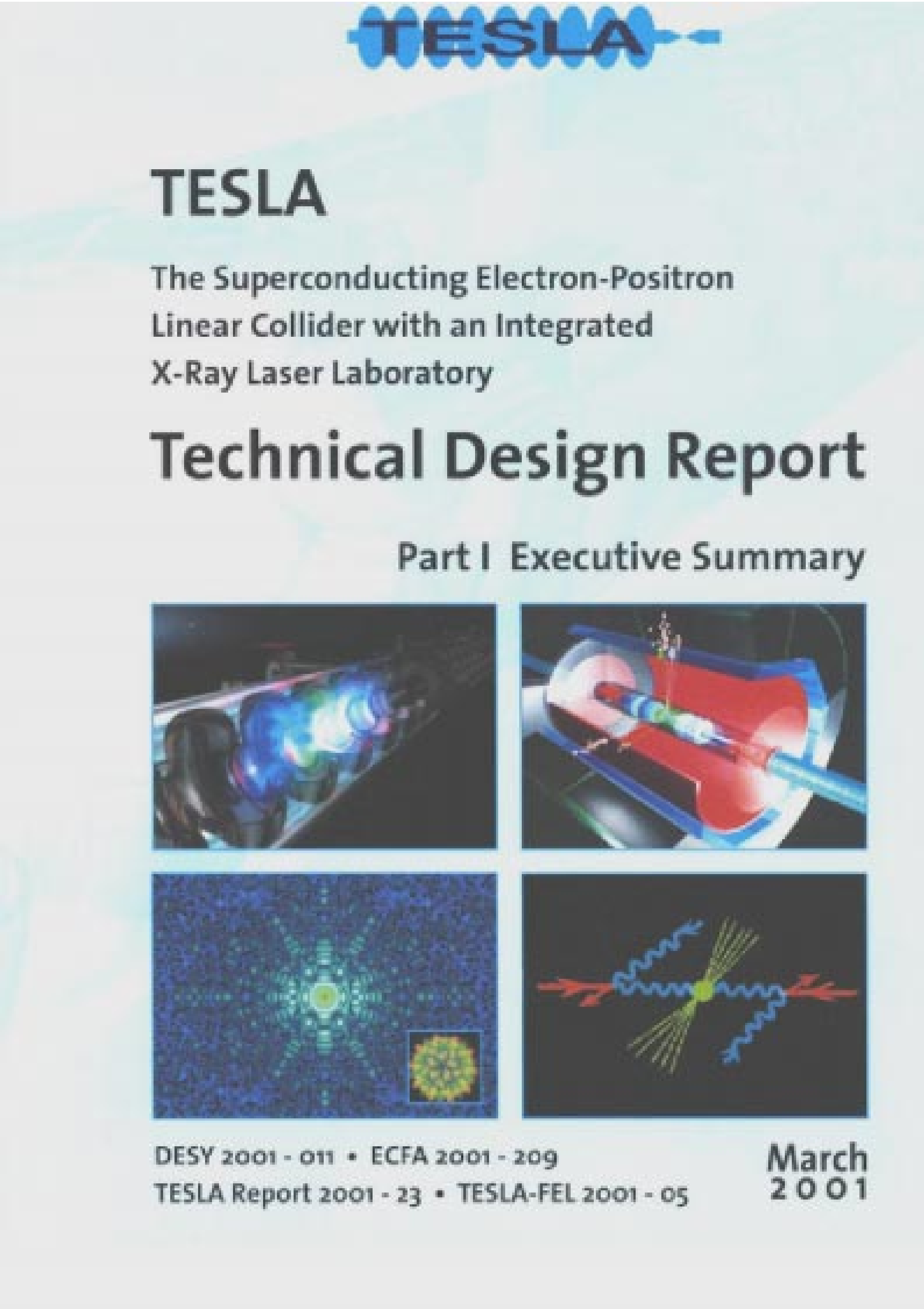
Precise determination of the properties of the Higgs boson (once it has been discovered at Tevatron or LHC) is the key to understand electro–weak symmetry breaking and the origin of mass.

Higgs Bosons have a very rich phenomenology. We need a Higgs factory to address all essential elements of the Higgs mechanism. Such a Higgs factory should offer:

- **Large production rate**
- **Various production modes**
- **Observability of all decay modes**
- **Well defined initial state**
- **Low Backgrounds**
- **Excellent experimental accuracy**

⇒ An Electron–Positron Linear Collider !

The TESLA Collider



TESLA

The Superconducting Electron-Positron
Linear Collider with an Integrated
X-Ray Laser Laboratory

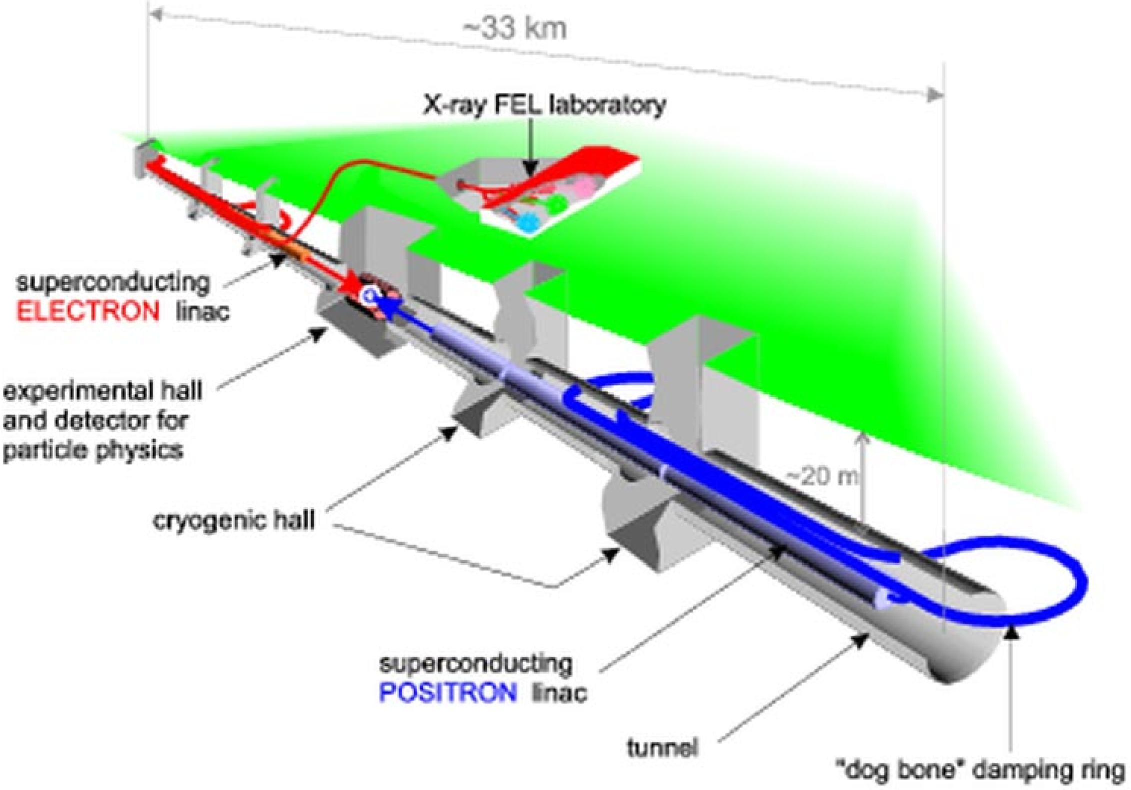
Technical Design Report

Part I Executive Summary

DESY 2001 - 011 • ECFA 2001 - 209
TESLA Report 2001 - 23 • TESLA-FEL 2001 - 05

March
2001

The TESLA Machine



Crucial Parameters:

Technology	**superconducting linear accelerator (1.3 GHz)**
max. Energy	**500 GeV (Phase 1) ... 800++ GeV (Phase 2)**
Luminosity	**3.4$\times 10^{34}$ ... 5 $\times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$**
Polarization	**Electrons 80%, Positrons 40–60%**
Bunchsize@IP	**5 / 553 nm ... 2 / 391 nm ($\longrightarrow$ Beamstrahlung)**
Options	$\gamma\gamma, e\gamma, e^-e^-$
	Giga Z

The TESLA Machine

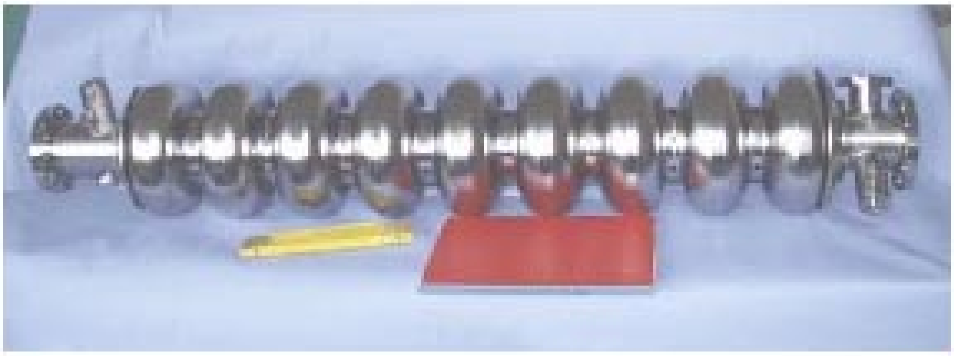
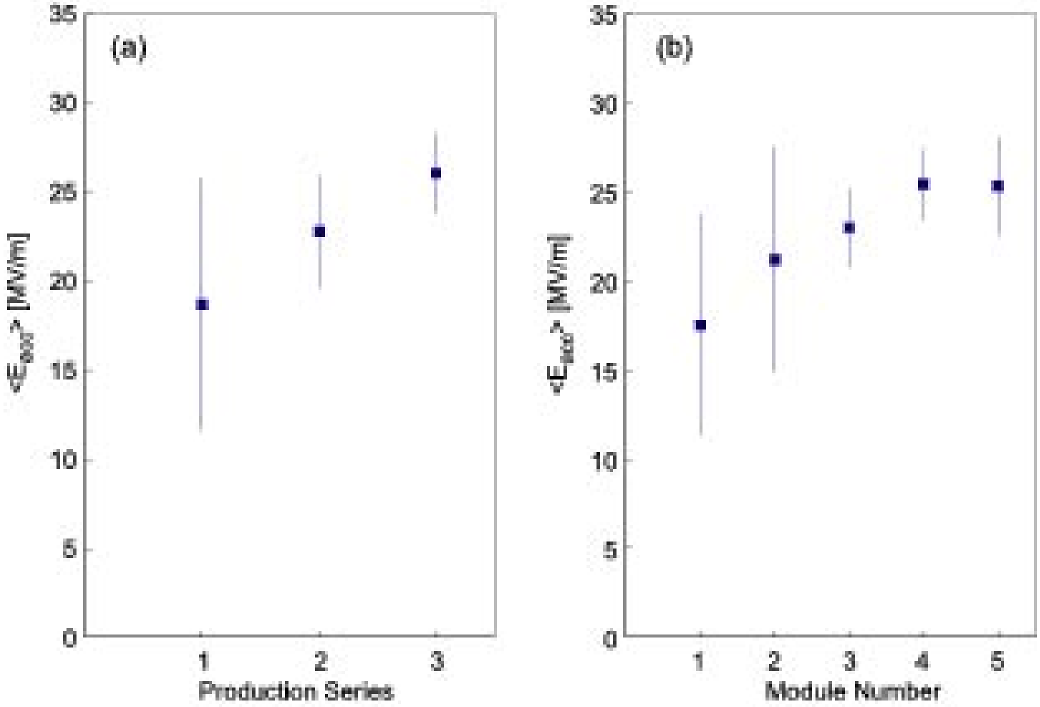


Figure 3.2.1: *The 9-cell niobium cavity for TESLA.*



- **Gradient needed for 500 GeV (23.4 MV/m) routinely achieved in 9-cell cavities**
- **Gradient needed for 800 GeV (37.5 MV/m) achieved in single-cell structures**

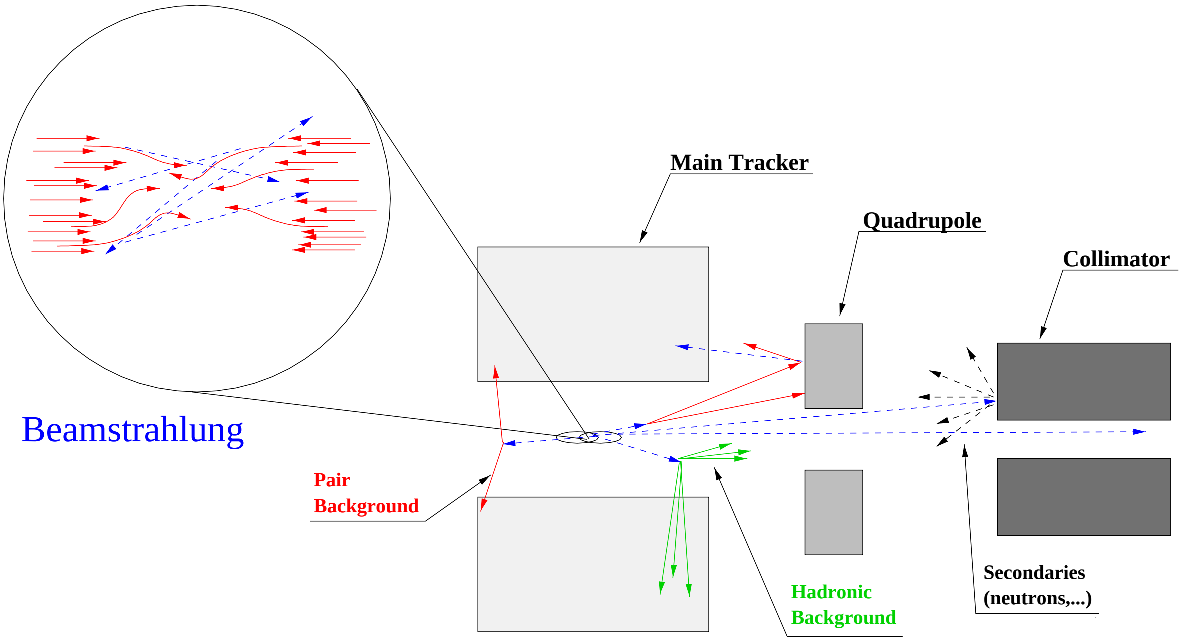
Beamstrahlung

Beams are extremely collimated with large bunch charge

$\longrightarrow$ electrons of one bunch radiate against the coherent field of the other bunch

$$dE \sim \frac{N^2}{\sigma_x^2 \sigma_z}$$

$\longrightarrow$ average energy loss 1.5% for electrons/positrons at 500 GeV



photons are very collimated around beampipe, but

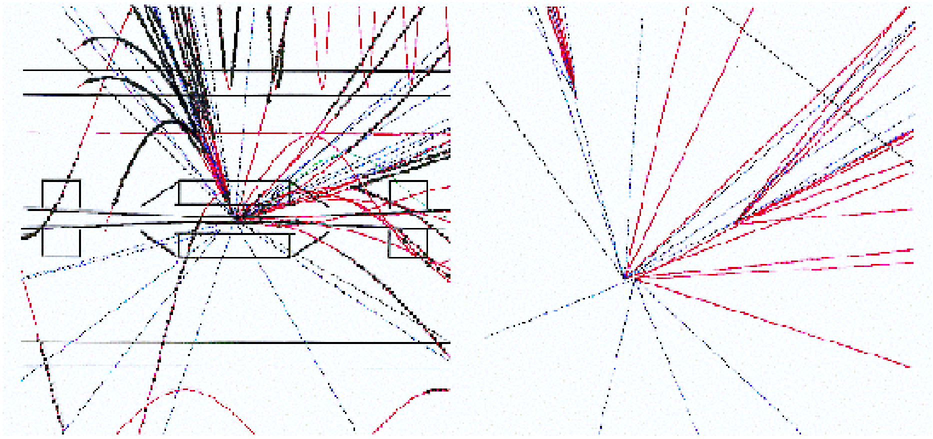
- **$\approx 0.6 \times 10^5 e^+e^-$-pairs per bunch crossing**
- **$\approx$ 1 hadronic event ($\gamma\gamma \longrightarrow$ hadrons) per 10 bunches**
- **secondaries (neutrons, ...)**

Beamstrahlung II

Consequences:

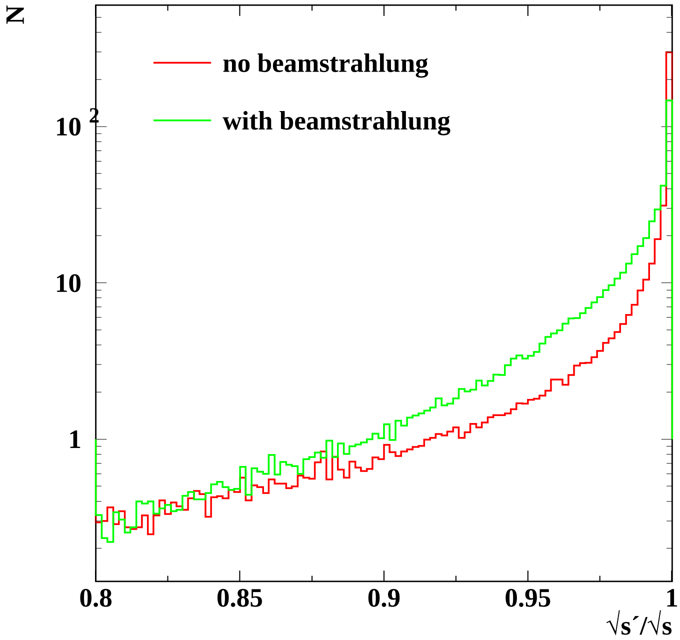
1. **Shield Detector against low-angle e^+e^-–pairs and secondaries $\Rightarrow$ Mask**

2. **Hadronic $\gamma\gamma$–events might overlay real physics events: recognize them!**



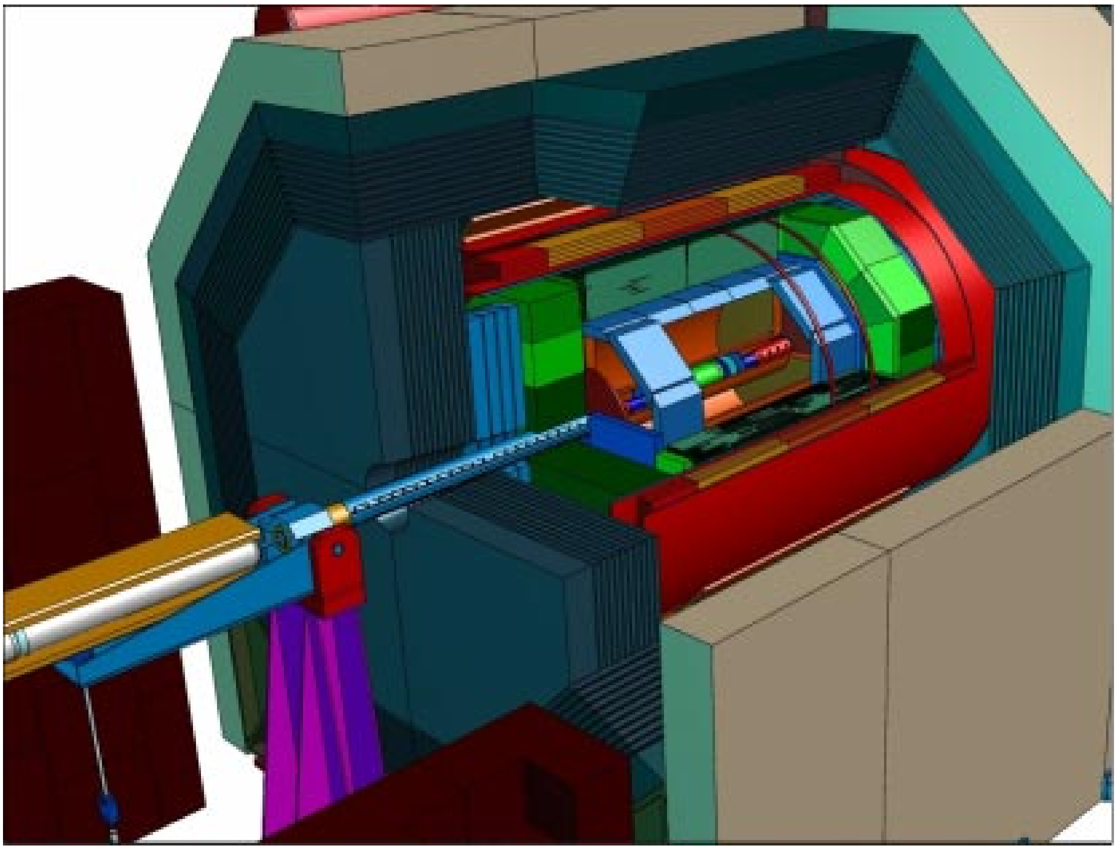
Battaglia
Schulte
(2000)

3. **Beam particles lose energy before interaction (similar to ISR)**



Mönig
Ohl
(1999)

A Detector for TESLA



Looks like ℵ @ TESLA but it is not:

- **take advantage of new technologies and LC goodies (e.g. beampipe radius 1 cm)**
- **design driven by Higgs physics in many aspects:**
  - **Vertex-Detector**
  - **Central Tracking**
  - **Calorimetry**

A Detector for TESLA

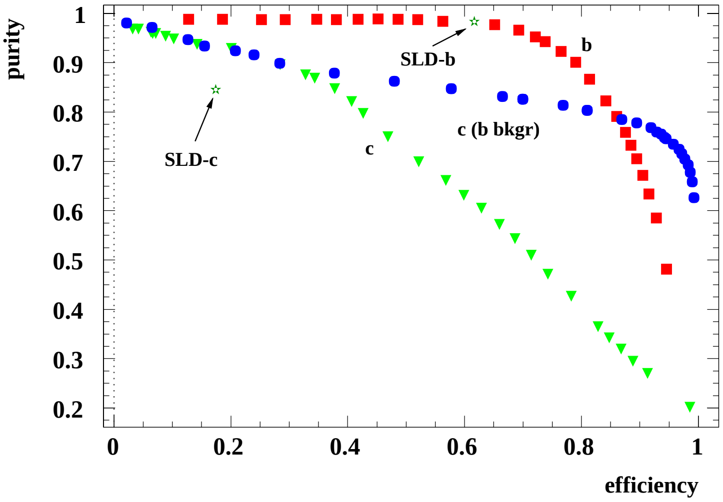
Flavour Tag

⟶ Vertexing

for Higgs

Branching

Ratios (b/c)



Momentum

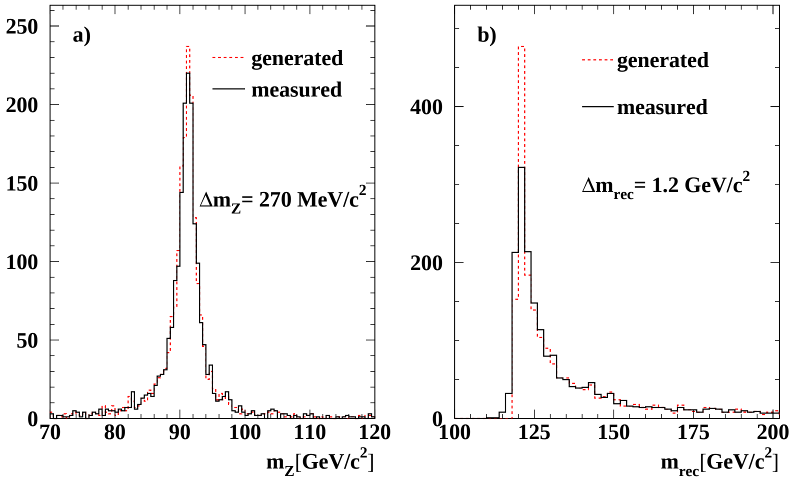
Resolution

⟶ Large TPC

for optimal

recoil mass

resolution



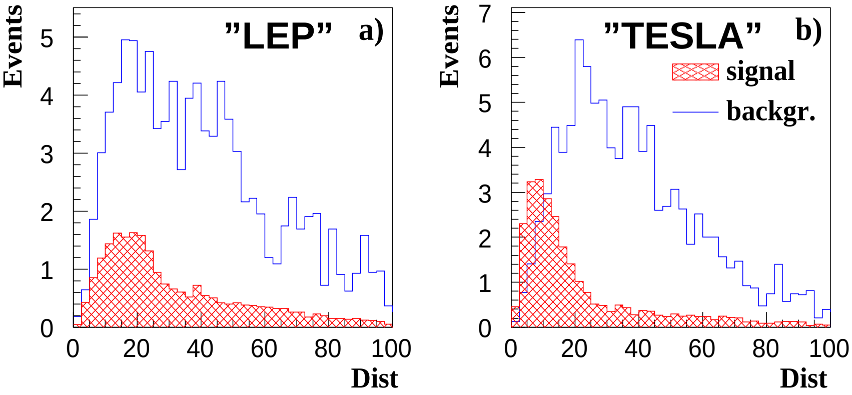
Energy Flow

⟶ SiW Calo

for reconstruction

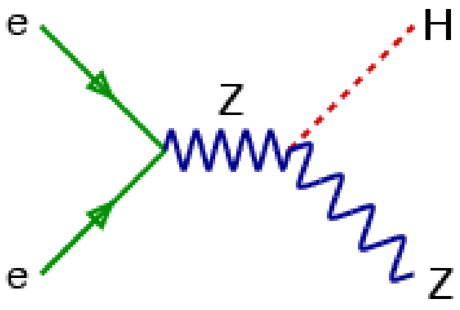
of multijet events

(e.g. ZHH⟶ 6jets)

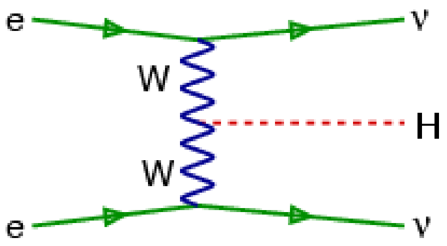


The Profile of the Higgs Boson

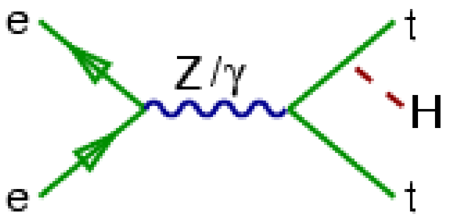
Production Processes



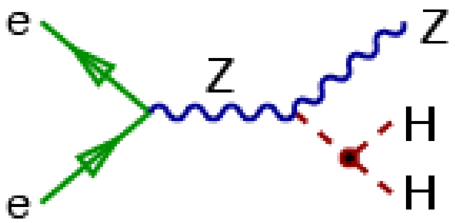
	500 fb^{-1}	500 fb^{-1}	1000 fb^{-1}
	350 GeV	500 GeV	800 GeV
m_H = 120	74000	35000	27000
m_H = 160	52000	29000	24000
m_H = 250	5500	16500	19000



	500 fb^{-1}	500 fb^{-1}	1000 fb^{-1}
	350 GeV	500 GeV	800 GeV
m_H = 120	15500	37500	158000
m_H = 160	7500	25000	126000
m_H = 250	6500	8000	71000



	500 fb^{-1}	500 fb^{-1}	1000 fb^{-1}
	350 GeV	500 GeV	800 GeV
m_H = 120	–	90	2600
m_H = 160	–	–	1500
m_H = 250	–	–	390

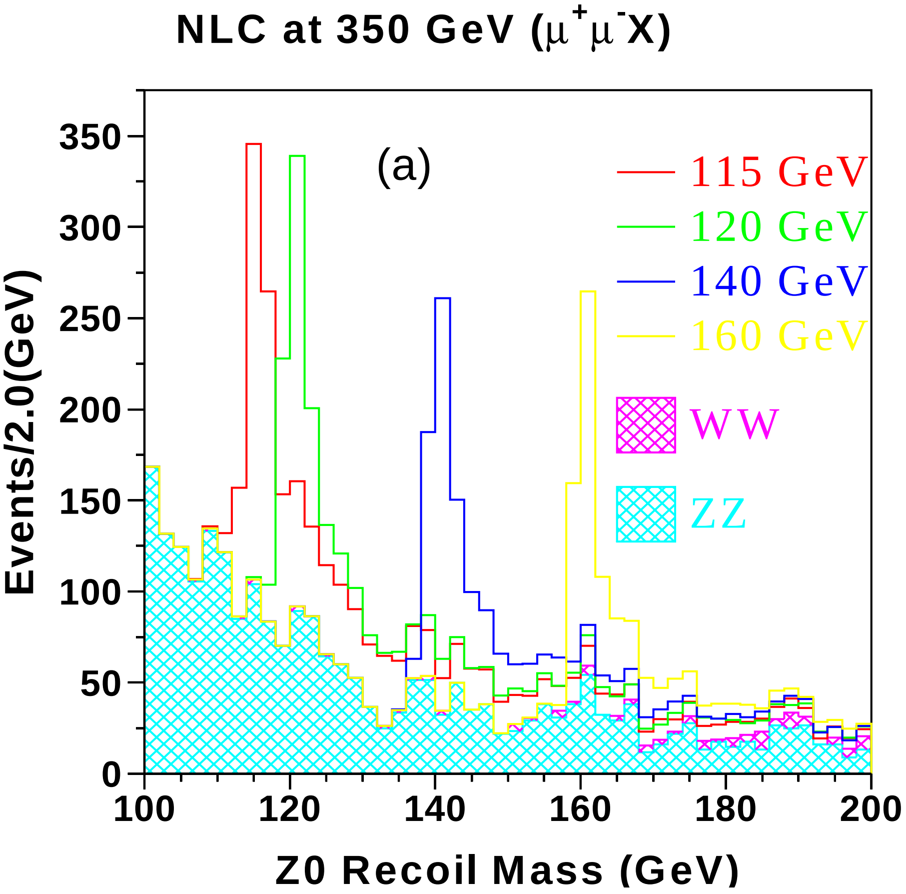


	500 fb^{-1}	500 fb^{-1}	1000 fb^{-1}
	350 GeV	500 GeV	800 GeV
m_H = 120	–	80	160
m_H = 160	–	20	120
m_H = 250	–	–	30

Observation

Gold plated channel:

$e^+e^- \rightarrow ZH$ **with** $Z \rightarrow e^+e^-, \mu^+\mu^-$



Use recoil mass against $\ell^+\ell^-$ pair:

$\Rightarrow$ **independent of Higgs decay**

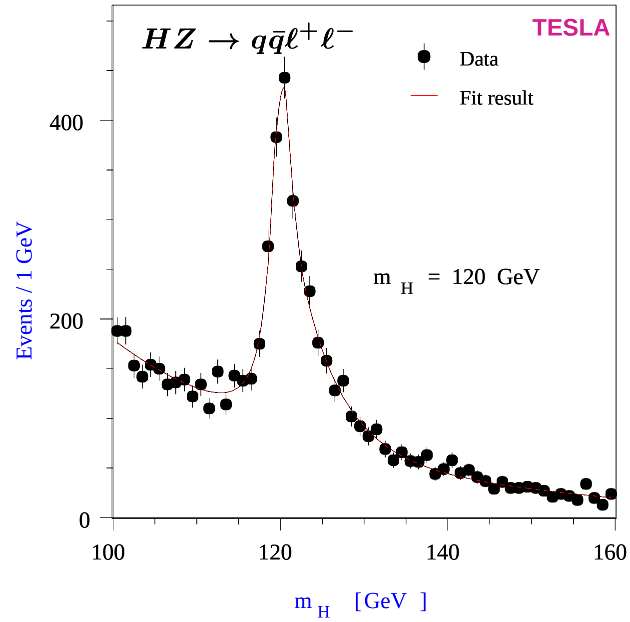
$\Rightarrow$ **direct probe of Higgs coupliung to the Z**

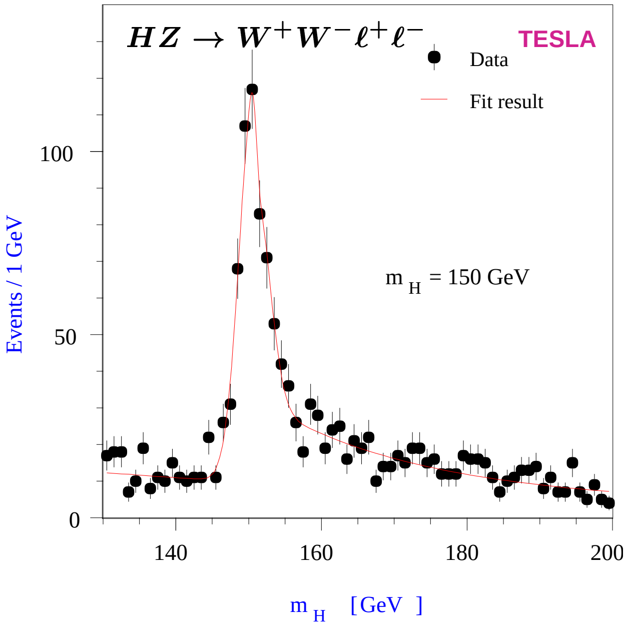
$$\Delta\sigma_{HZ}/\sigma_{HZ} \approx 2\%$$

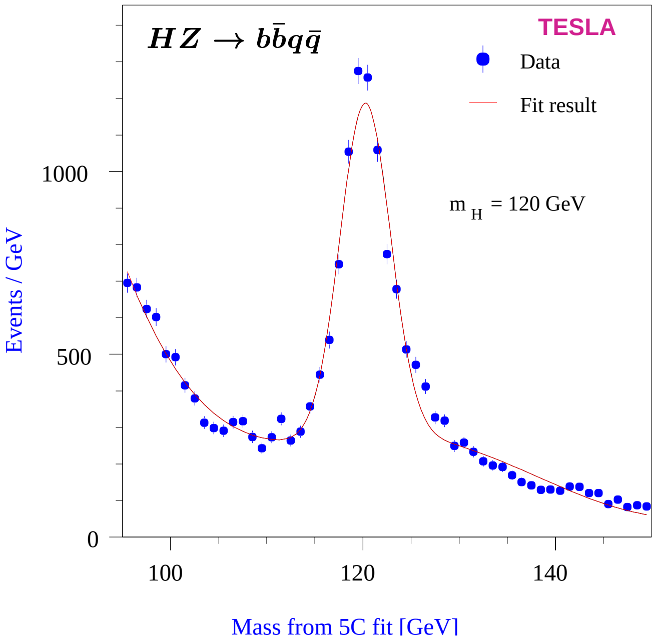
(350 GeV/ 500 fb^{-1})

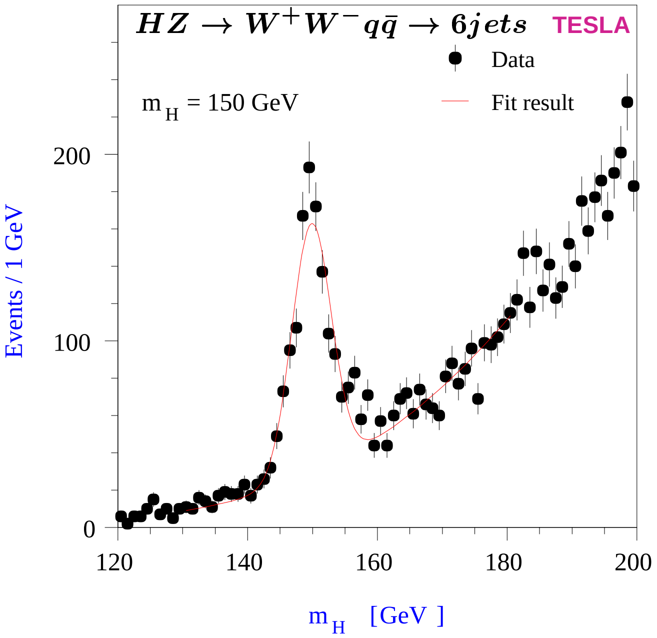
Mass Measurement

Look at exclusive final states:







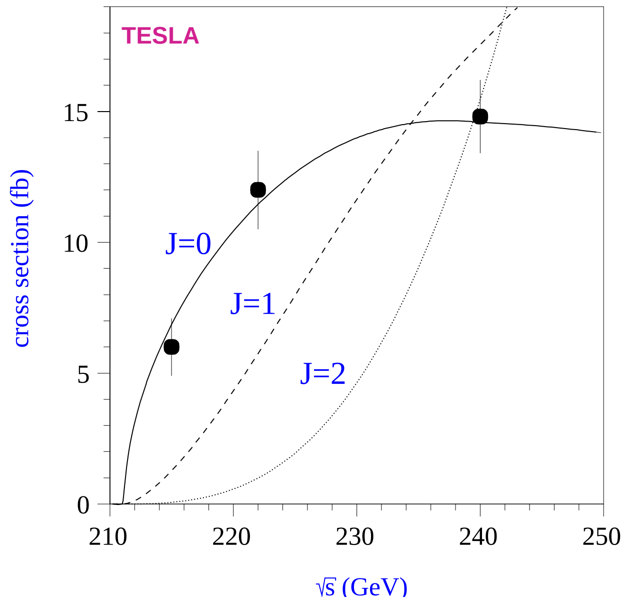


$$\boxed{\Delta m/m \approx 3-5\times 10^{-4}}$$

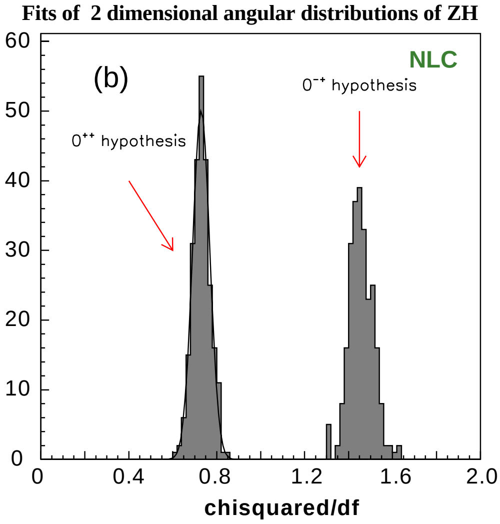
(350 GeV/ 500 fb^{-1}, weakly dependent on m_H)

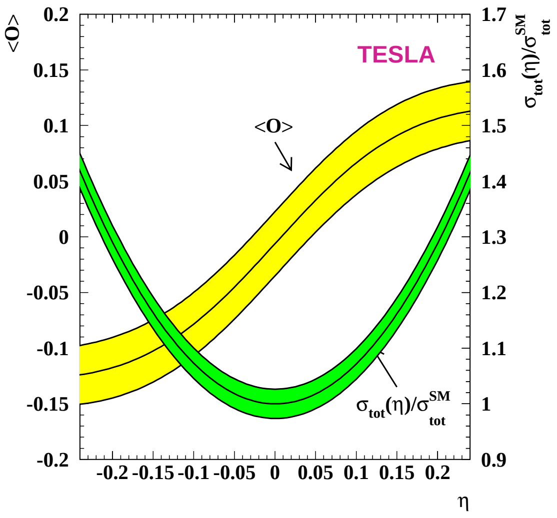
Spin and CP Quantum Numbers

- **Observation of $H \to \gamma\gamma$ or $\gamma\gamma \to H \Rightarrow$ Spin $\neq 1$**
- **β dependence of HZ cross section at threshold**



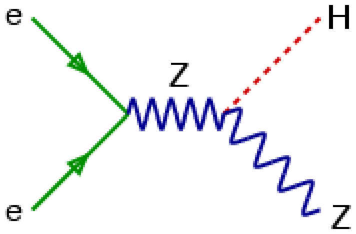
- **Angular distributions of the fermions in $ZH \to f\bar{f}H$**

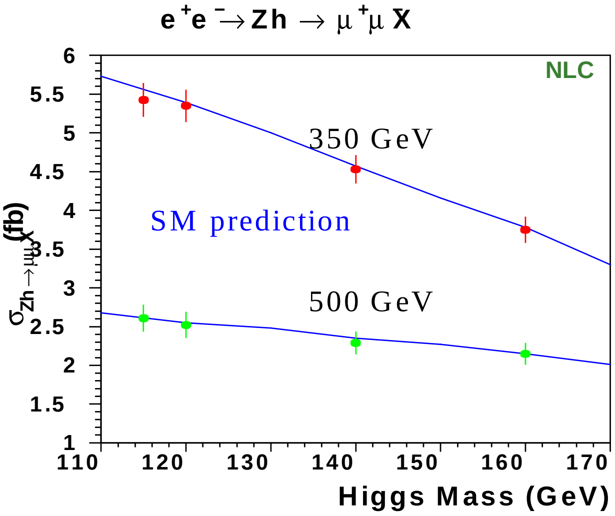




Higgs Couping to Gauge Bosons

- unambigous g_{HZZ} coupling from $e^+e^- \to HZ$ using recoil mass method

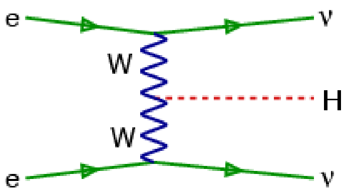


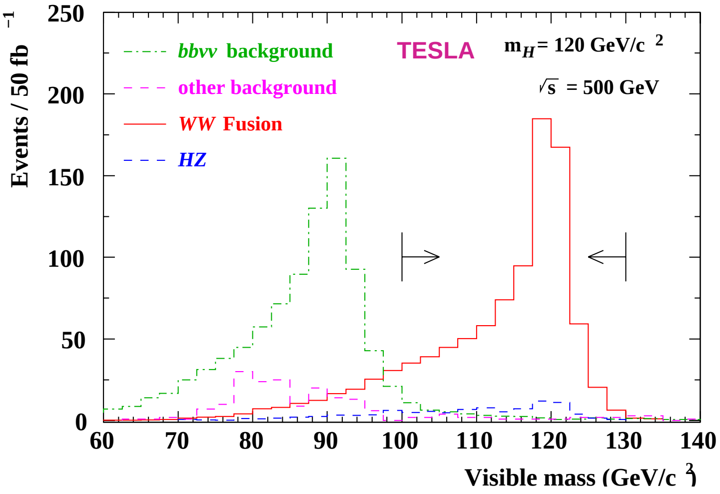


- g_{HWW} in two ways:

1. WW–fusion cross section $e^+e^- \to H\nu_e n\bar{u}_e$
2. Branching ratio BR($H \to W^+W^-$)

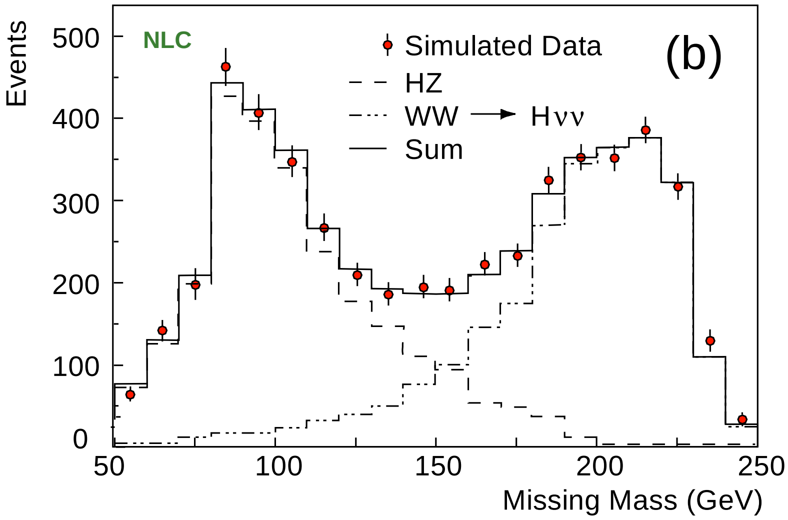
WW–Fusion:





Higgs Couping to Gauge Bosons

disentangle Higgsstrahlung and WW–Fusion through different spectra in missing mass:



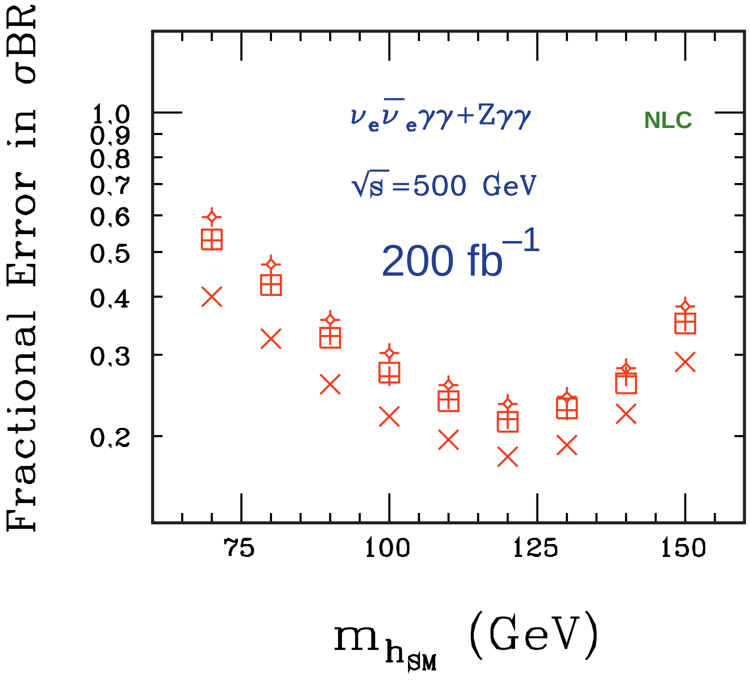
Accuracies:

Measurement	120 GeV	140 GeV	160 GeV
$\sigma(e^+e^- \to HZ)$ (1)	2.5%	2.7%	3.0%
$\sigma(e^-e^- \to H\nu_e\bar{\nu}_e)$ (2)	2.8%	3.7%	13.0%
BR($H \to WW^{(*)}$) (1)	5.1%	2.5%	2.1%
BR($H \to ZZ^{(*)}$) (1)			16.9%

500 fb^{-1}, (1): 350 GeV, (2): 500 GeV

Higgs "Coupling" to Photons

- **Branching ratio into photons:**



tiny SM-BR

need to combine

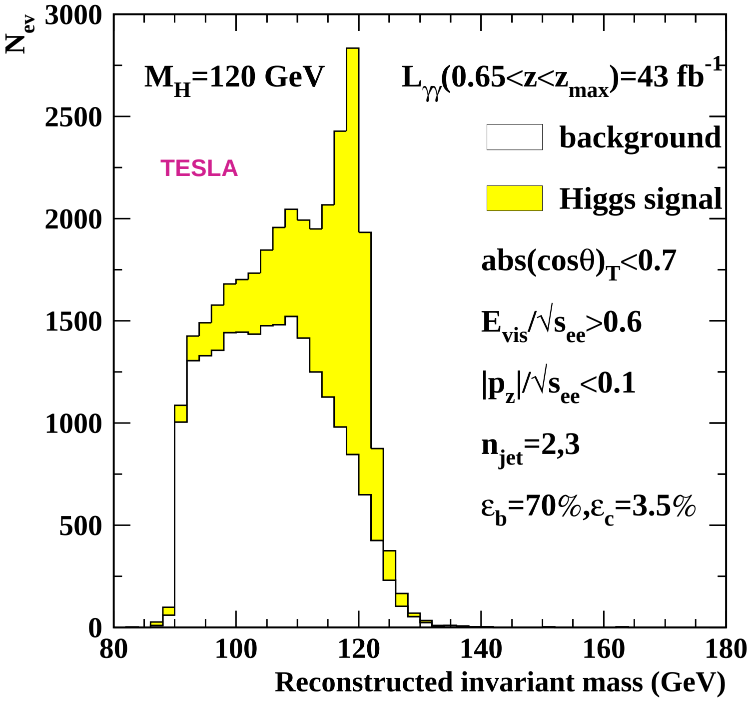
Higgstrahlung and

WW–Fusion

$\Delta BR/BR \sim$ 20%

can be reached

- **Higgs production at the $\gamma\gamma$ collider: $\gamma\gamma \to H$**



large cross section

but also large backgrounds

QCD background under control

needs very good c/b supression

$$\boxed{\Delta\Gamma_{\gamma\gamma}/\Gamma_{\gamma\gamma} = 2-3\%}$$

The Total Higgs Decay Width

For $m_H < 2m_Z$ the total width Γ_H is too small (in the SM) to be measured directly $\Rightarrow$ Semi–direct method:

$$BR(H \to X) = \frac{\Gamma_{\text{partial}}(H \to X)}{\Gamma_{\text{tot}}}$$

$$\Rightarrow \Gamma_{\text{tot}} = \frac{\Gamma_{\text{partial}}(\text{from production})}{BR(H \to X)}$$

Possibilities:

(1) $X = \gamma\gamma$: Good accuracy from $\gamma\gamma \to H$ but poor $BR(H \to \gamma\gamma)$ measurement.

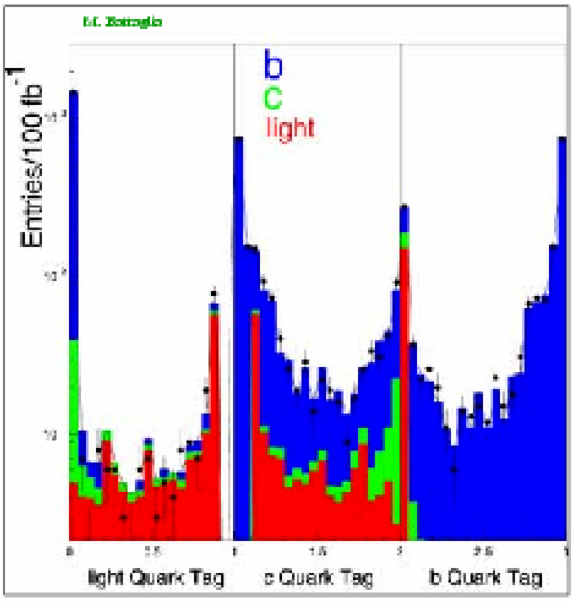
(2) $X = WW$: Good measurement for both production ($WW \to H$) and $BR(H \to WW)$.

(3) $X = WW$ in decay and $X = ZZ$ in production ($e^+e^- \to HZ$) and assume $g_{HZZ} = g_{HWW} \cos\theta_W$.

Option	120 GeV	140 GeV	160 GeV
(1)	23%		
(2)	6.1%	4.5%	13.4%
(3)	5.6%	3.7%	3.6%

500 fb^{-1} at 500 GeV

Higgs Coupling to Fermions



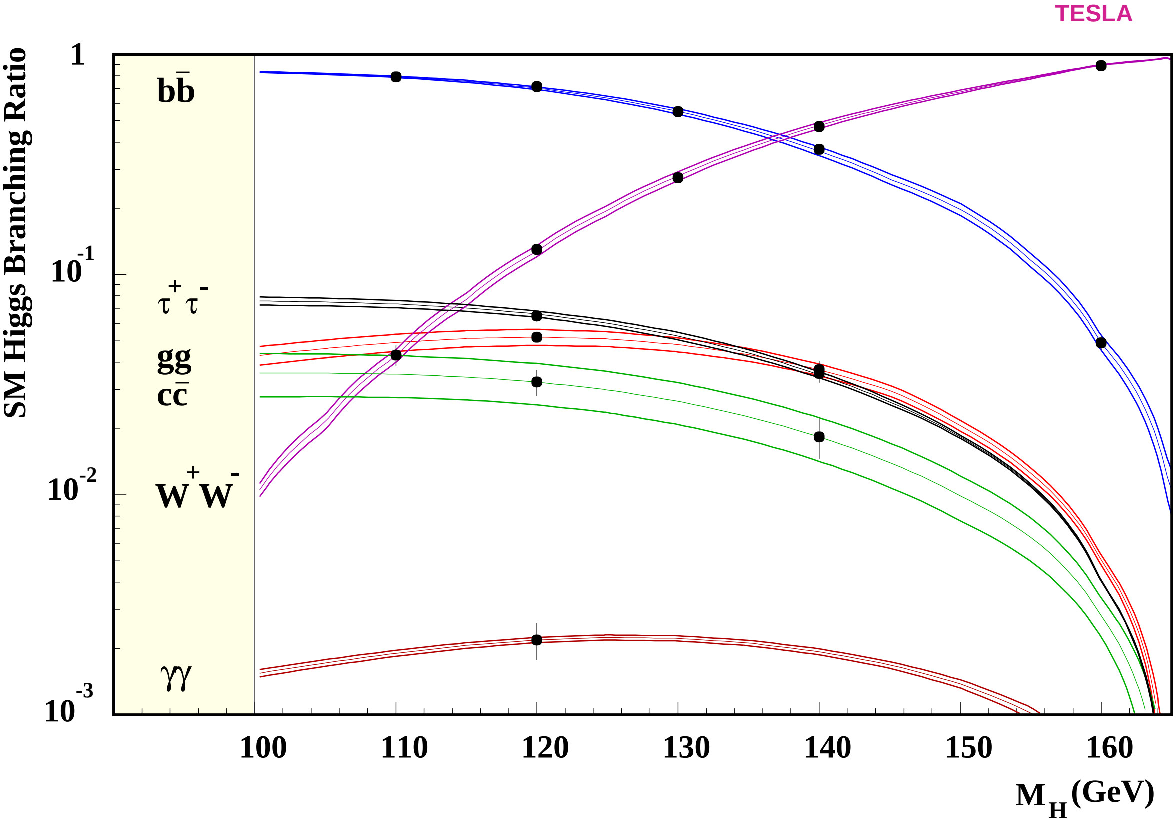
main task:

disentagle b-,c- and g+uds jets

use simultaneous binned

likelihood fit to the shapes

of three tagging variables



Higgs Coupling to Fermions

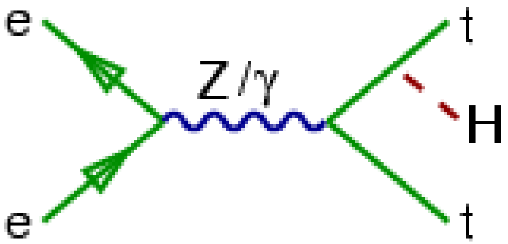
Accuracy on Higgs Branching Ratios (TESLA)

decay mode	m_H = 120 GeV	m_H = 140 GeV
$H \to b\bar{b}$	2.4%	2.6%
$H \to c\bar{c}$	8.3%	19.0%
$H \to gg$	5.5%	14.0%
$H \to \tau^+\tau^-$	5.0%	8.0%
$H \to W^+W^-$	5.1%	2.5%
$H \to \gamma\gamma$	$\sim$ 20%	

for 500 fb^{-1} at $\sqrt{s} = 350$ GeV

NLC study (J. Brau et al.) at $\sqrt{s} = 500$ GeV yields almost consistent numbers (some details to be understood)

Higgs Coupling to top-Quark



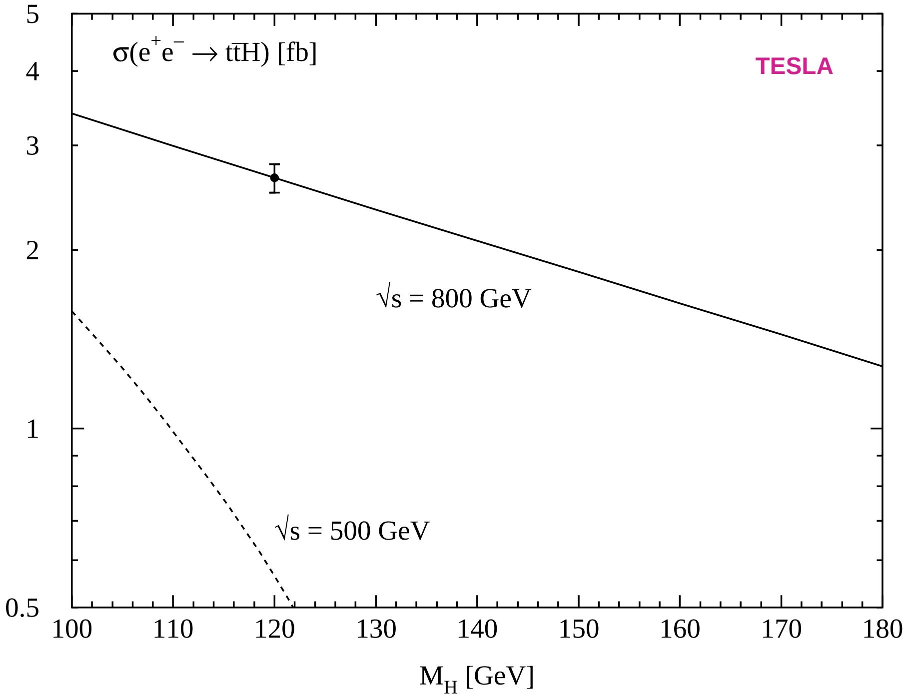
Signature (for m_H <160 GeV): $t\bar{t}H \rightarrow WWbbbb$

(8 fermions!)

Analysis done for hadronic and semileptonic WW finals states using an ANN

Low cross section and many massive particles

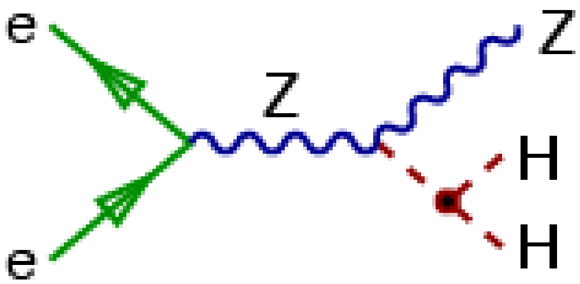
$\longrightarrow$ need high luminosity and high energy



$$\boxed{\Delta\sigma_{ttH}/\sigma_{ttH} \sim 11\%}$$

for $M_H = 120$ GeV, $\sqrt{s} =$ 800 GeV, 1000 fb^{-1}

The Higgs Potential



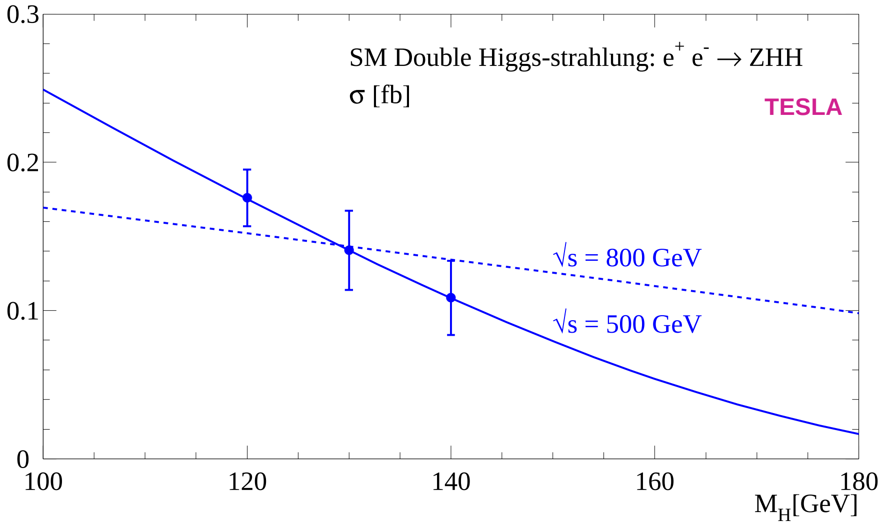
measurement of Higgs self coupling:

$e^+e^- \rightarrow q\bar{q}b\bar{b}b\bar{b}$ **and**

$e^+e^- \rightarrow \ell^+\ell^-b\bar{b}b\bar{b}$

needs very efficient b-tagging and

jet reconstruction (energy flow measurement)



$$\boxed{\Delta\lambda_{HHH}/\lambda_{HHH} \approx 20\%}$$

for $m_H = 120$ **GeV,** $\sqrt{s} = 500$ **GeV, 1000 fb**$^{-1}$

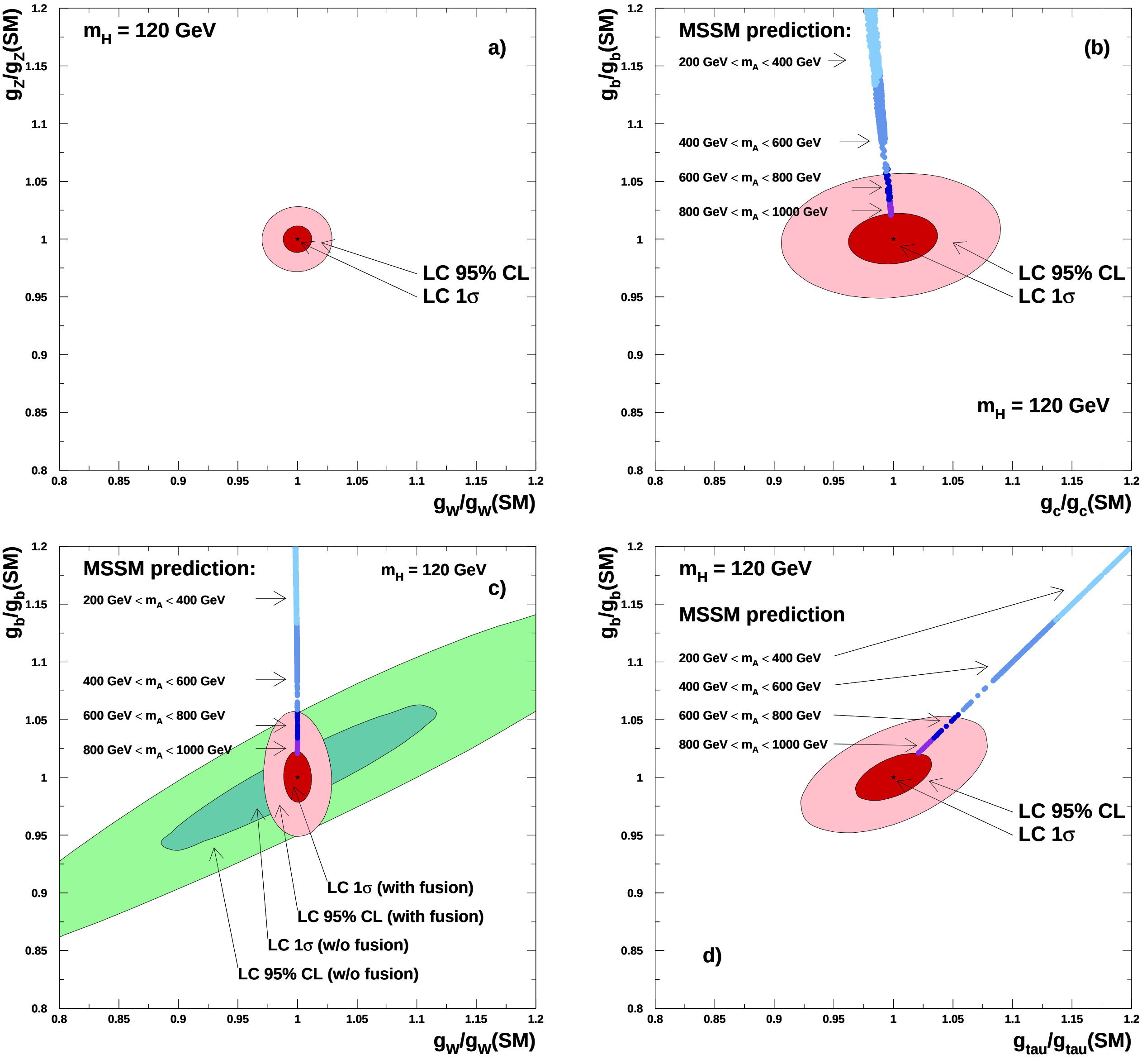
Interpretation 1: A Global Fit

How to make most efficient use of the whole set of measurements? ⇒ a global fit (HFITTER).

Include experimental correlation between the different measurements. Theoretical uncertainties could be (but are not so far) included into the fit.

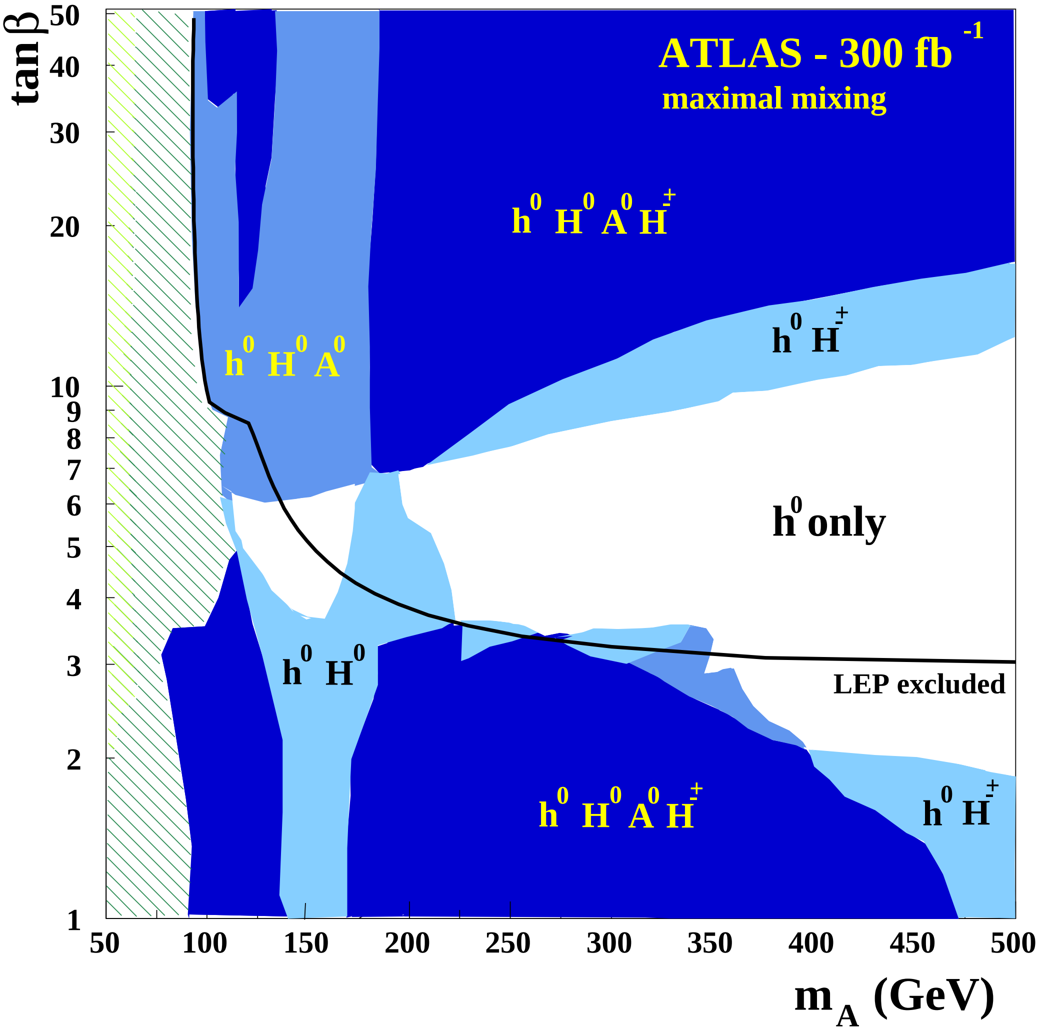
m_H	120 GeV	140 GeV
g_{HZZ}	1 %	1 %
g_{HWW}	1 %	2 %
g_{Hbb}	2 %	2 %
g_{Hcc}	3 %	10 %
g_{Htt}	3 %	6 %
$g_{H\tau\tau}$	3 %	5 %
$\frac{g_{HWW}}{g_{HZZ}}$	2 %	2 %
$\frac{g_{Hcc}}{g_{Hbb}}$	4 %	10 %
$\frac{g_{H\tau\tau}}{g_{Hbb}}$	3 %	4 %
$\frac{g_{H\tau\tau}}{g_{HWW}}$	3 %	4 %
$\frac{g_{Htt}}{g_{HWW}}$	3 %	4 %

Interpretation 1: Global Fit



Interpretation 2: Supersymmetry

Situation with LHC only:



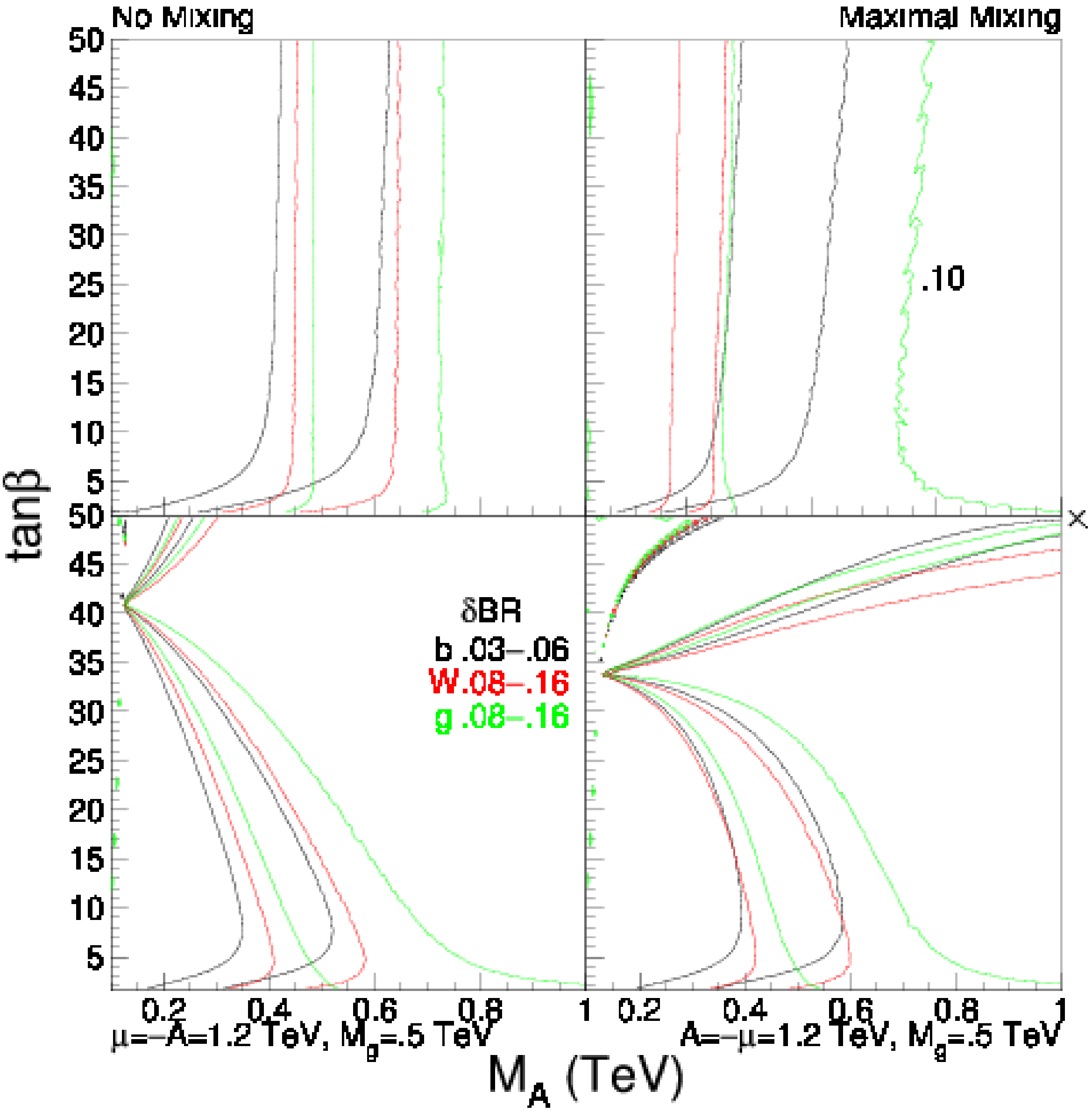
Region with only one 'SM-like' Higgs visible

- **is it supersymmetric ?**
- **can one determine SUSY parameters ? ($\Rightarrow m_A$?)**

Distinguish SM from MSSM

In the MSSM the Decay Branching Ratios differ from the SM values. Even without seeing the heavy Higgs Bosons SM and MSSM can be distiguished.

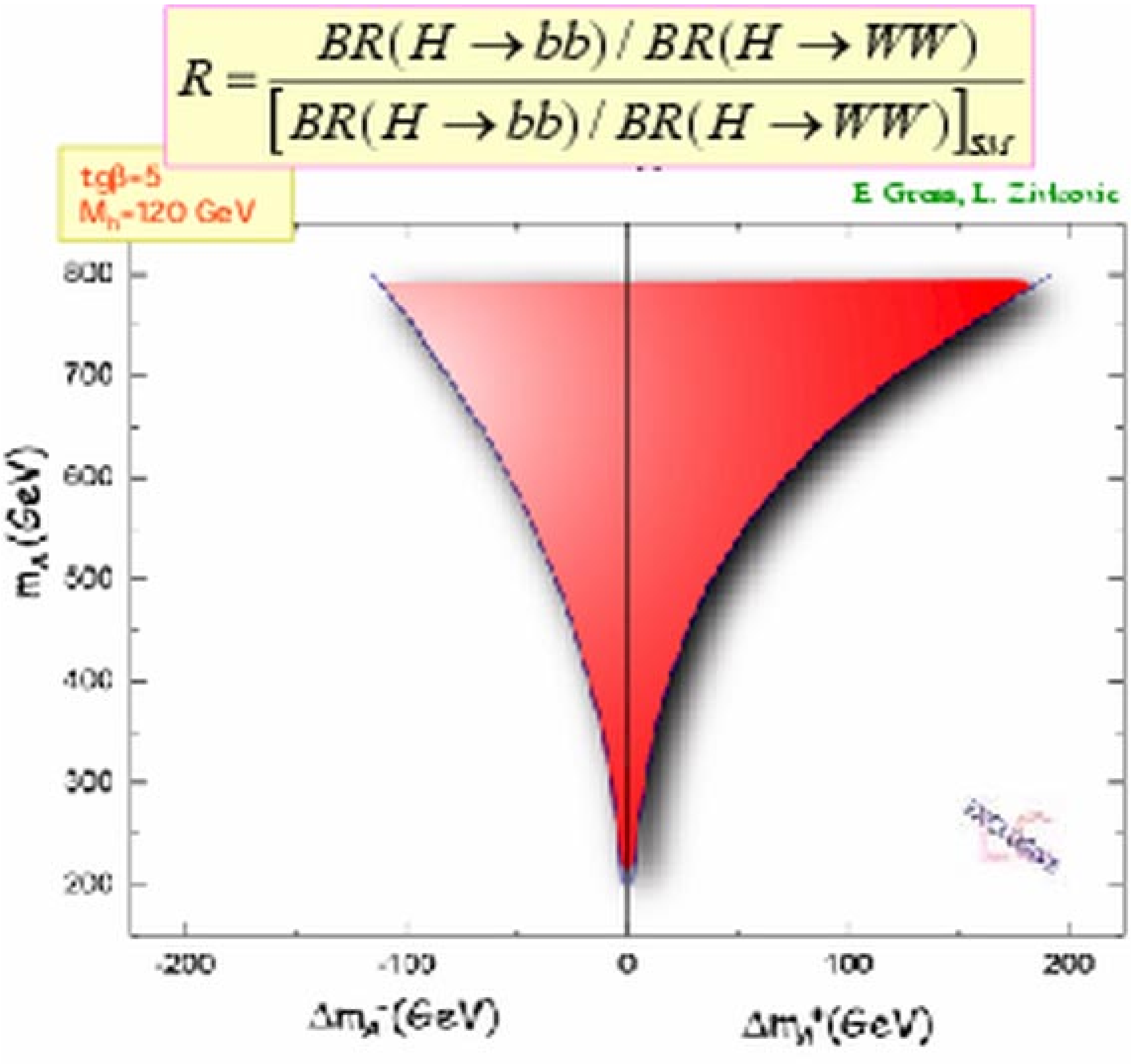
Carena, Logan et al.



...but the reach in m_A depends on the SUSY parameters.

Distinguish SM from MSSM

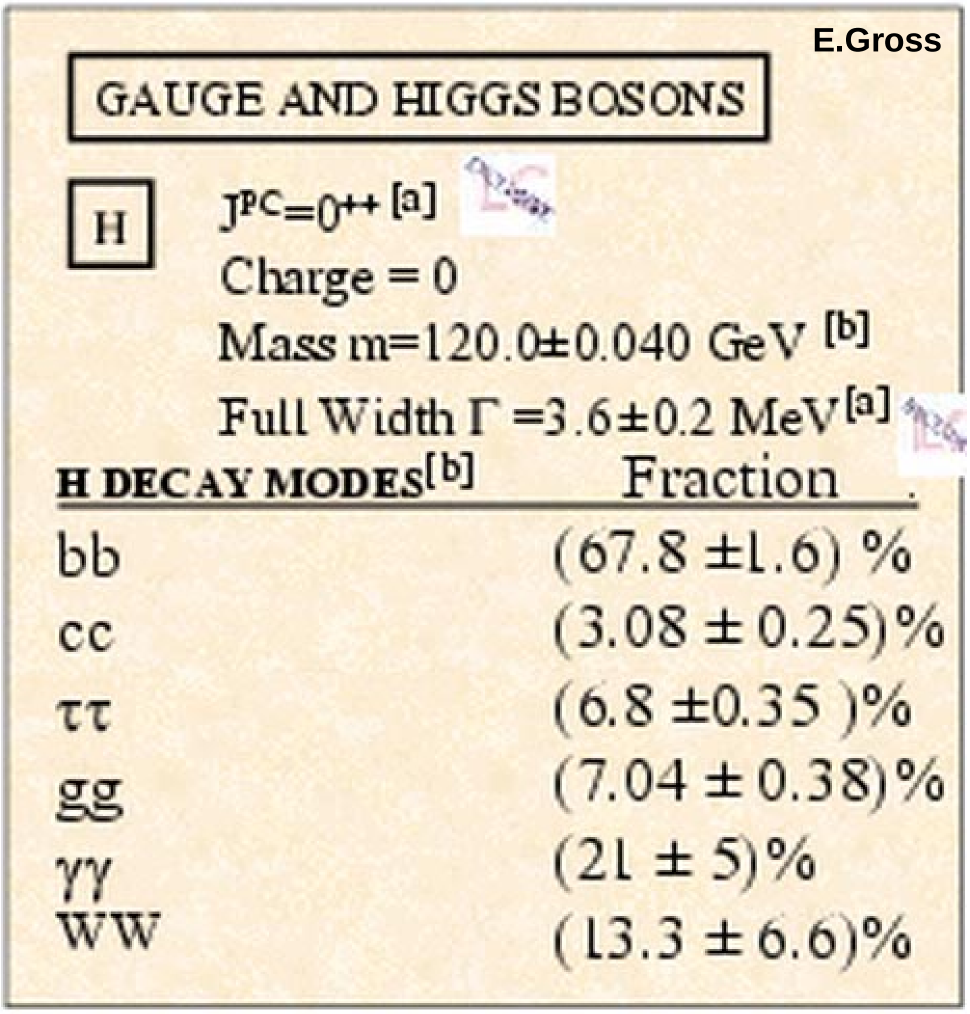
and even m_A can be indirectly estimated:



$$R = \frac{BR(H \to bb) / BR(H \to WW)}{\left[BR(H \to bb) / BR(H \to WW)\right]_{SM}}$$

Conclusion

The experimental status in 2012 (PDG) might look like that:



E.Gross

GAUGE AND HIGGS BOSONS

H

$J^{PC}=0^{++}$ [a]

Charge = 0

Mass m=120.0±0.040 GeV [b]

Full Width Γ =3.6±0.2 MeV [a]

H DECAY MODES[b]	Fraction
bb	(67.8 ±1.6) %
cc	(3.08 ± 0.25)%
$\tau\tau$	(6.8 ±0.35)%
gg	(7.04 ± 0.38)%
$\gamma\gamma$	(21 ± 5)%
WW	(13.3 ± 6.6)%

Let’s do these measurements!

- **We know how to do them (machine, detector, analysis)**
- **We know many ways how to interpret them (theory)**
- **We do not know a more promising way to obtain this important insight into microscopic physics.**