Prospects for Precision Higgs Physics at Linear Colliders

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on behalf of the Linear Collider Physics & Detector Studies

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Excellence Cluster Universe

Outline - Higgs Program at Linear Colliders

- Introduction

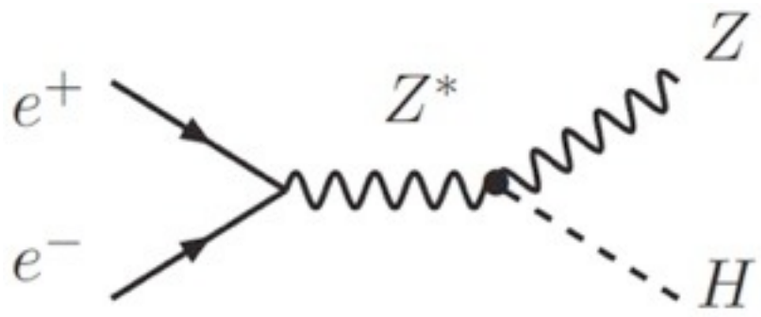
- The Higgs Program at Linear Colliders:
  - Model-independent absolute measurement of coupling to Z
  - Precise measurements of couplings to gauge bosons and fermions
  - Direct study of the Higgs potential by measuring trilinear self-coupling
  - Precise measurement of mass, width, spin, CP properties

- Conclusions

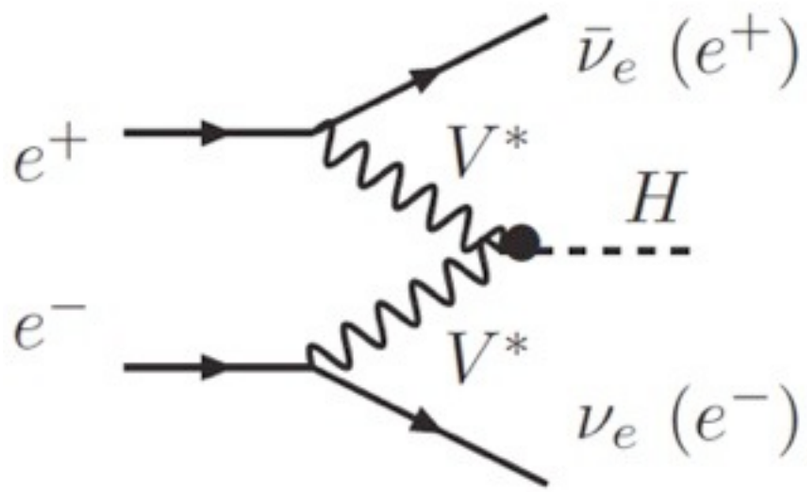
Based on a set of reports prepared by the Linear Collider Community:
ILC RDR, ILD & SiD LOIs, CLIC CDR, soon to come: ILC TDR / DBDs,
LC Input to European Strategy Process, CLIC CDR vol. 3

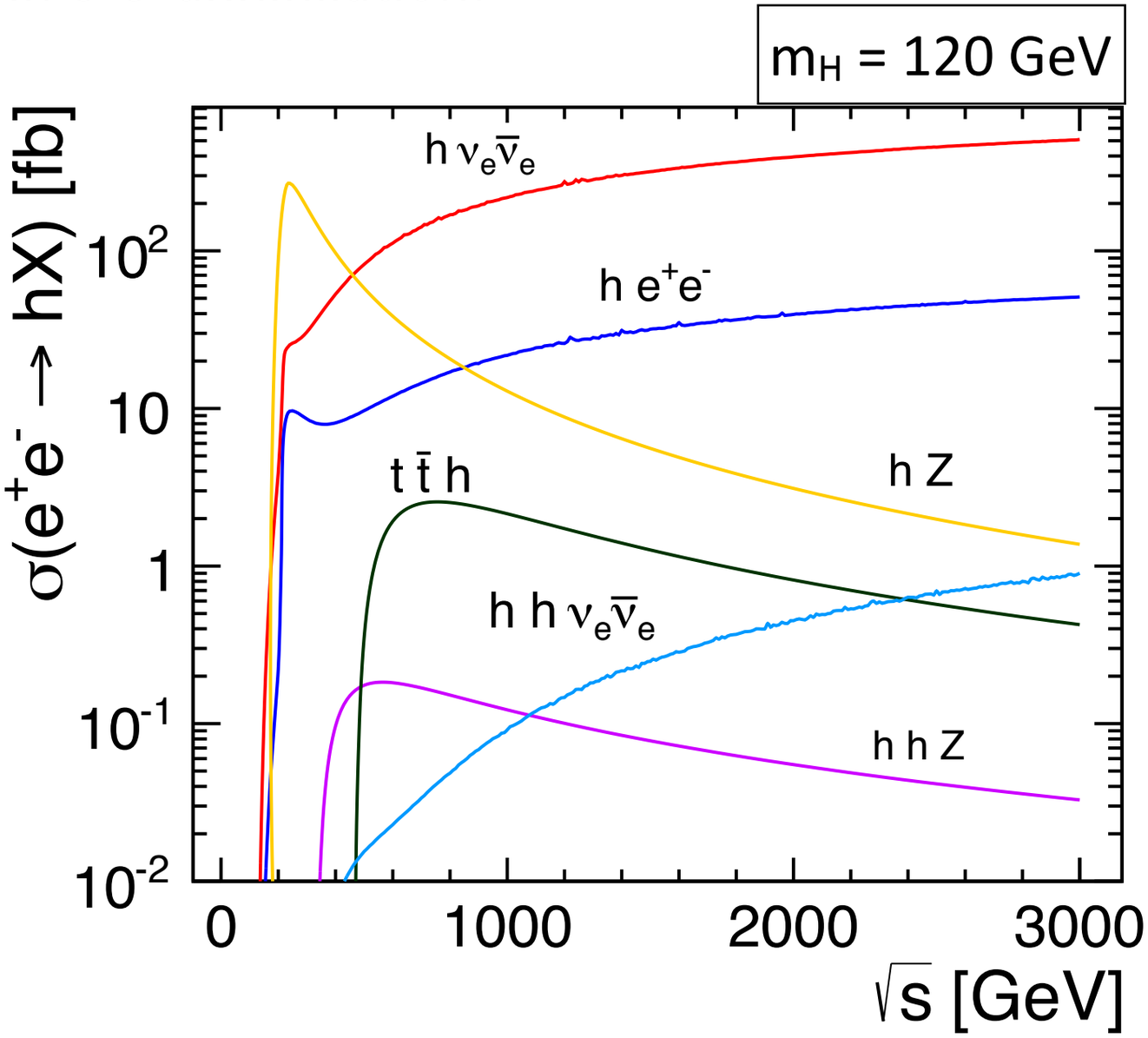
Overview - Higgs Production in e^+e^- Collisions

- The leading Higgs production modes in e^+e^- annihilation:



Higgs-Strahlung (s-channel process):
Dominates from threshold
up to ~ 400 GeV

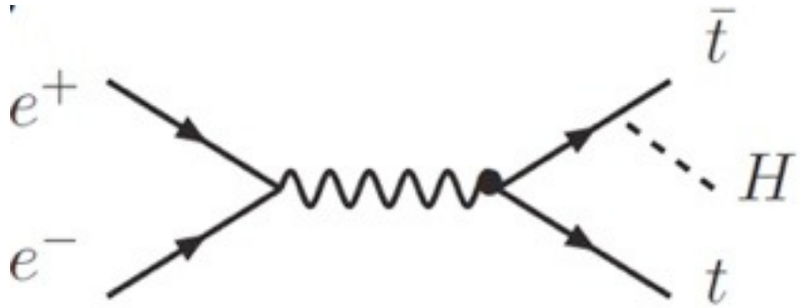




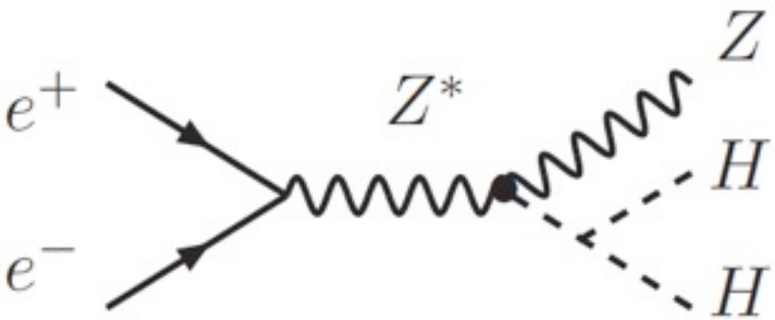
Vector boson fusion (t-channel process):
Dominates above ~ 500 GeV

Overview - Higgs Production in e^+e^- Collisions

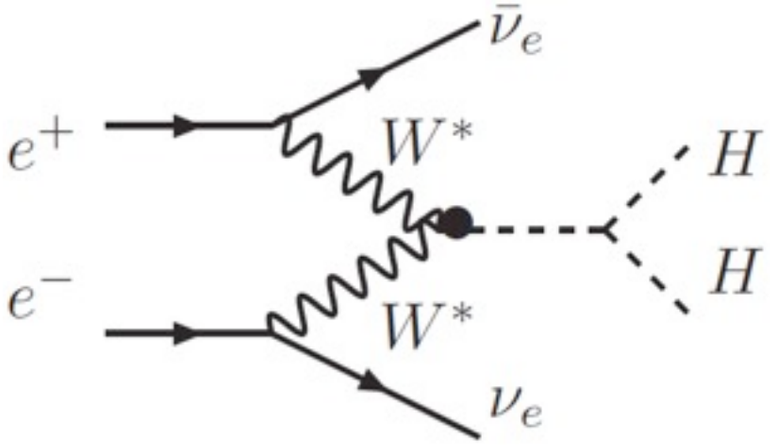
- Sub-leading processes - top Yukawa coupling, self-coupling

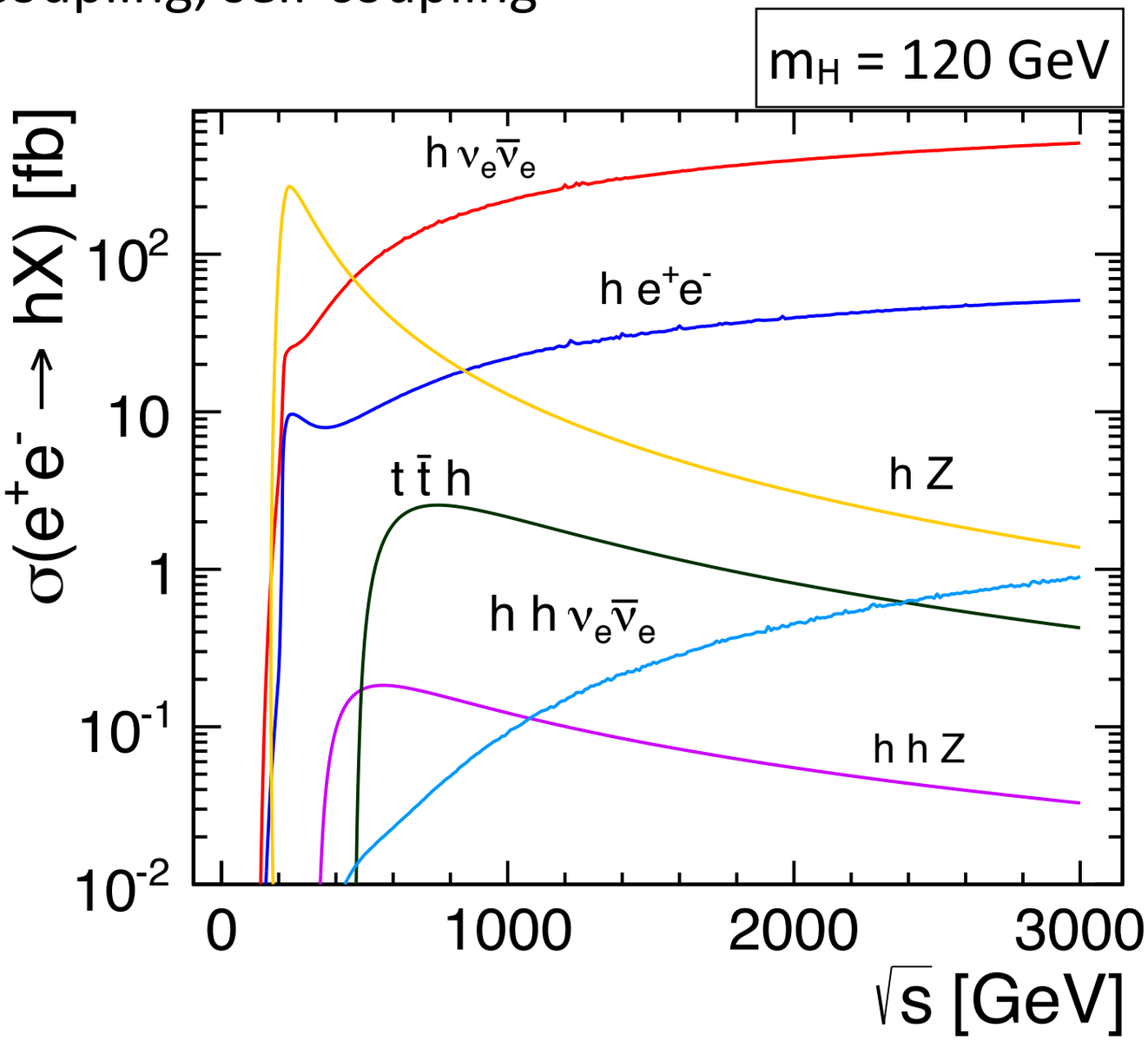


Higgs Strahlung off top quarks (s-channel)



Double Higgs production in Higgs-Strahlung(s-channel)





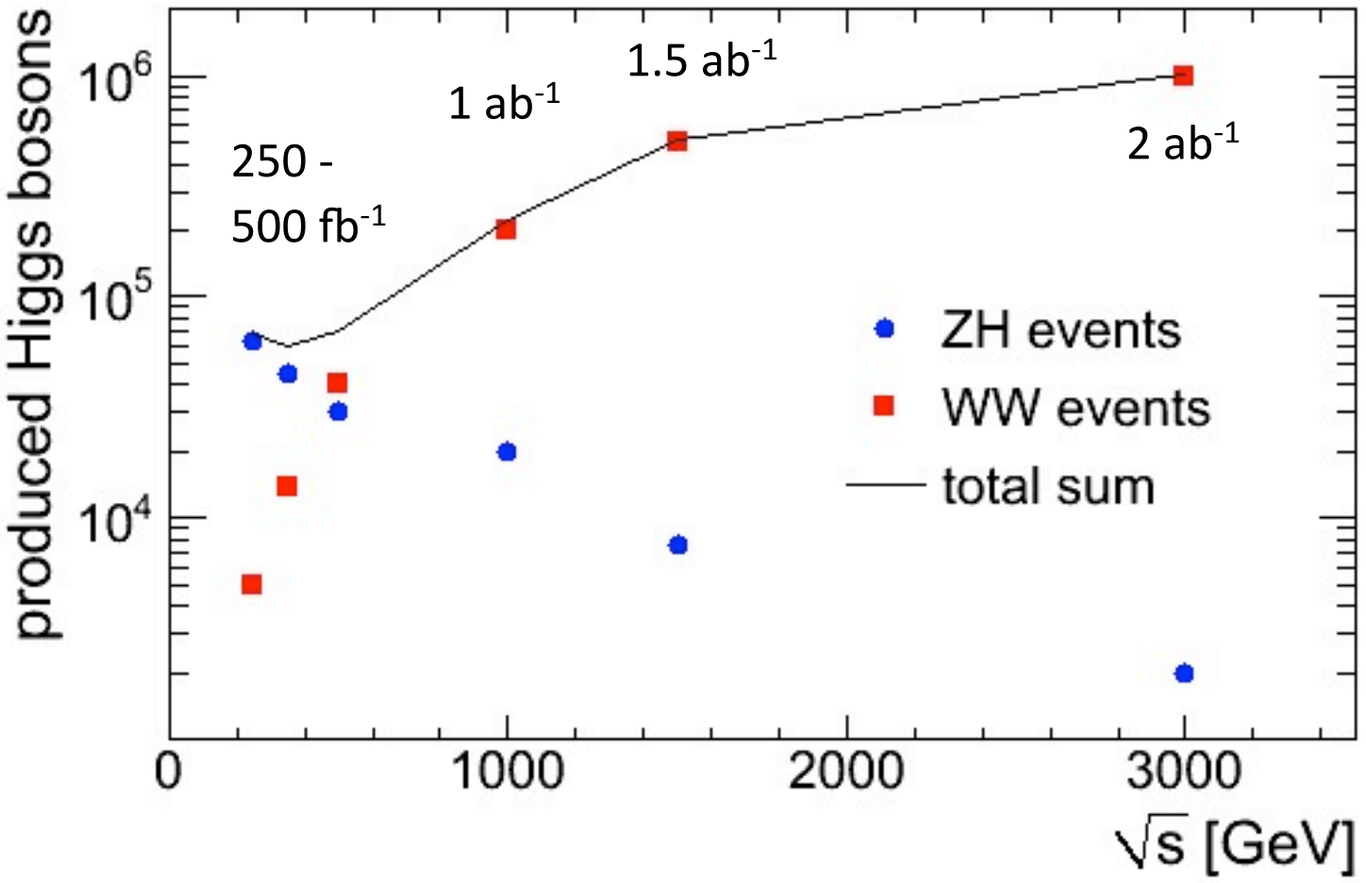
Double Higgs production in vector boson fusion (t-channel)

Linear Colliders - Full Exploration of the Higgs Sector

- Two accelerator concepts: ILC and CLIC
  - ILC: Proven superconducting RF structures, 500 GeV with upgrade to 1 TeV
    Physics currently studied in the range from 250 GeV to 1 TeV
  - CLIC: Two-beam acceleration concept, still in development, energy stages from 500 GeV to 3 TeV, Physics currently studied in the range from 350 GeV to 3 TeV

- High number of Higgs bosons at all energies:
  Exploit precise reconstruction at lower energies, high statistics and access to sub-leading channels at higher energies

For a mass of 126 GeV, a wide range of decays and couplings are accessible at a LC



Detectors for Precision Physics

- Two detector concepts:
  ILD and **SiD** (CLIC variants adapted for higher energy and higher backgrounds)

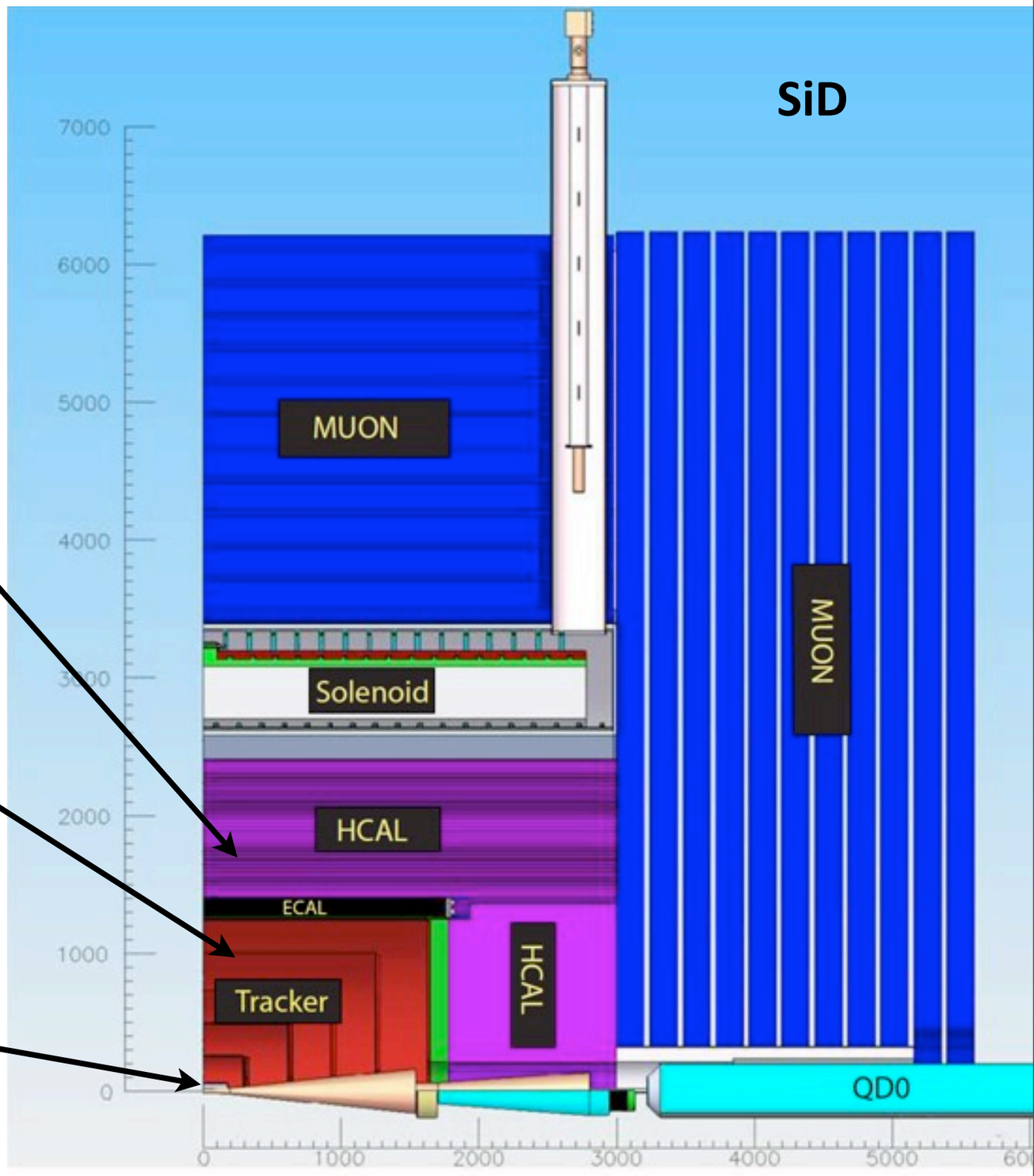
highly granular calorimeters:
particle flow event reconstruction:
3 - 4% jet energy resolution

high resolution trackers: excellent momentum measurement of charged particles

$$\sigma_{1/p_T} \approx 2 \times 10^{-5} \mathrm{GeV}^{-1}$$

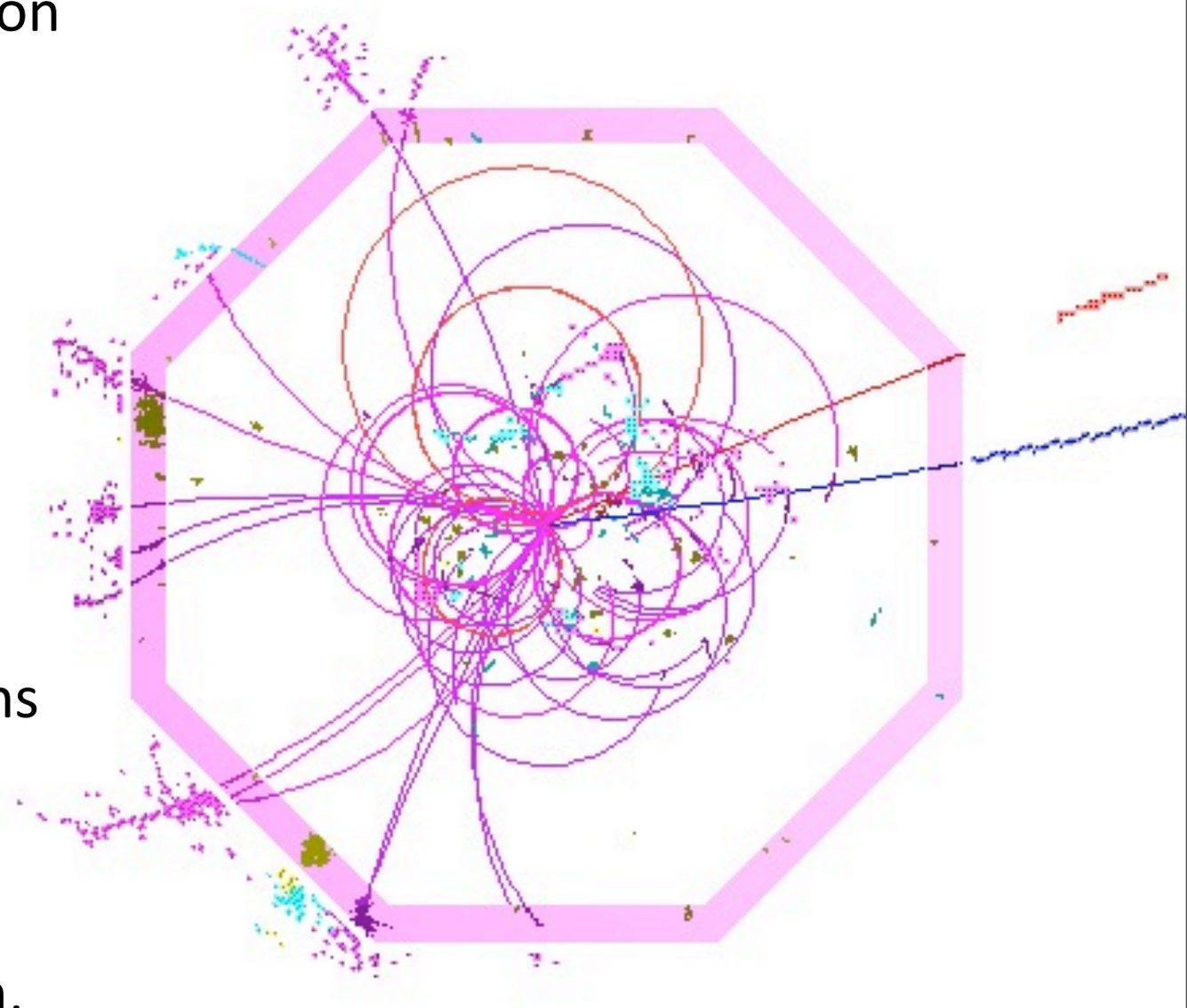
precision vertexing:
key for flavor tagging

$$\sigma_{r\phi} = 5\mu\mathrm{m} \oplus \frac{10}{p(\mathrm{GeV})\sin^{3/2}\theta}\mu\mathrm{m}$$



Full Simulation Studies

- Extensive simulation and reconstruction frameworks have been set up
  - Key aspects validated with test beam data
- All studies: m_H = 120 GeV
- Most results shown here:
  Obtained with full detector simulations including physics and beam related backgrounds
- Full particle flow event reconstruction, neural-net based flavor tagging, ...

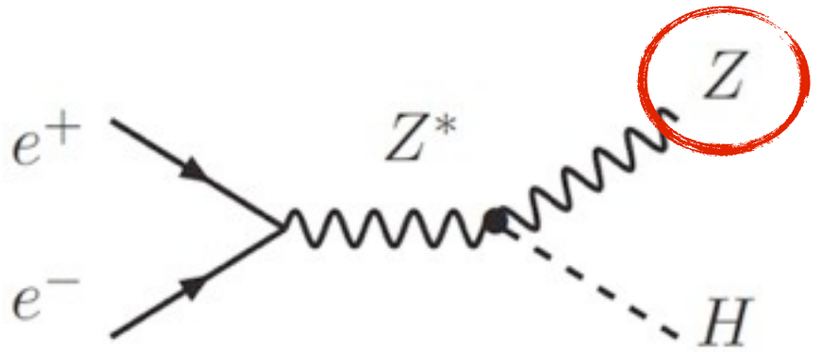


$$e^+e^- \to ZH \to \mu^+\mu^- b\bar{b}$$

350 GeV, CLIC_ILD

Model-Independent Measurements: Coupling to Z

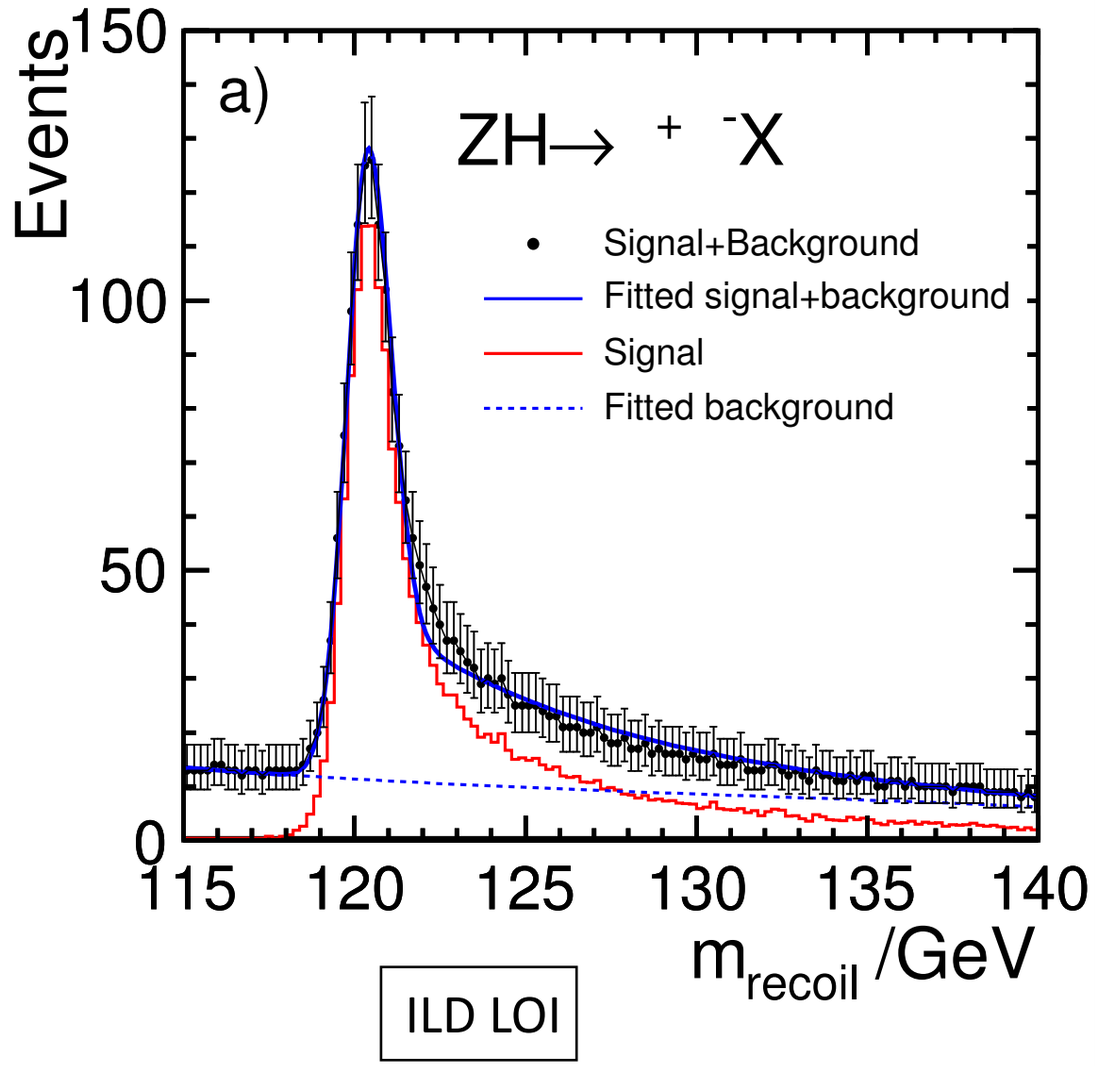
- Uniquely possible at lepton colliders: Model-independent measurement of the Higgs coupling to the Z and of the mass



only measure the Z recoiling against the Higgs boson: totally independent of Higgs decay

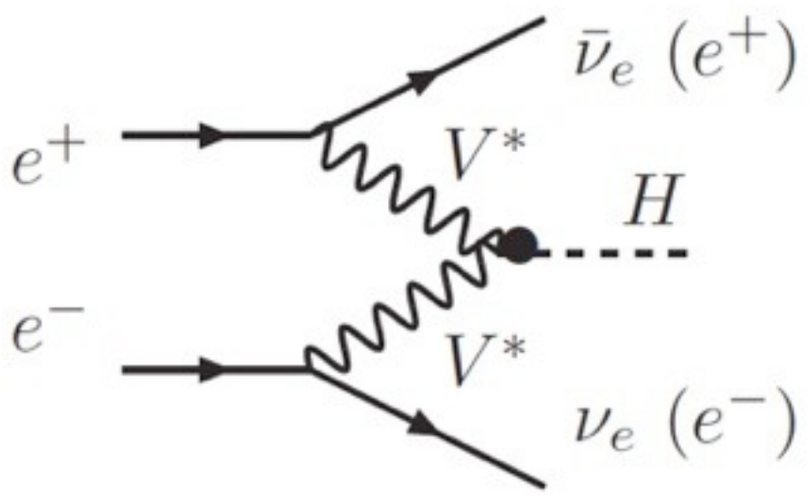
Highest measurement precision: Z decaying into leptons: Exploit excellent momentum resolution, in particular for muons

Highest precision close to threshold
At 250 GeV with 250 fb^{-1}: 2.5% on cross section, 1.3% on coupling



Coupling to the W

- Directly accessible in WW fusion:



Measurement of the production cross section in one visible decay also measured model-independently in the ZH - process allows to extract the coupling
1.4% at 500 GeV (500 fb^{-1}), comparable at higher energy

- In addition: The ZZ fusion process has a cross section on the level of 10% of the WW fusion: At high luminosities (and high cross sections) in the TeV and multi-TeV regime, the ratio of Higgs to W and Higgs to Z coupling can be extracted at the sub-percent level: A sensitive test of the predictions of the Higgs mechanism!

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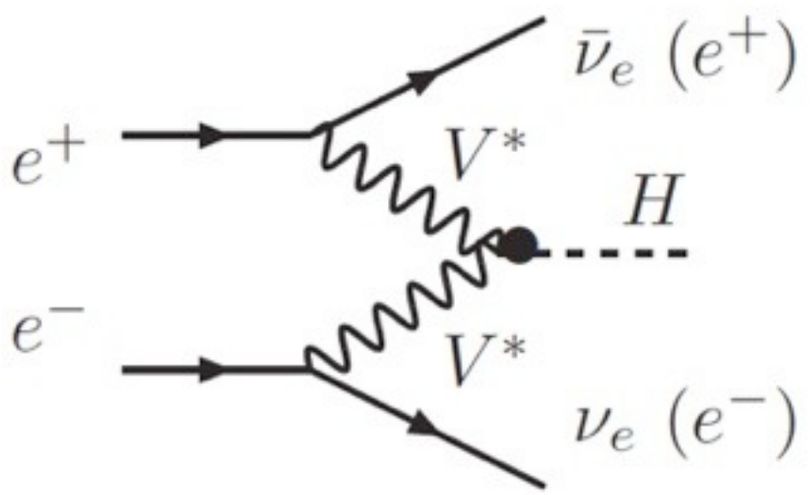

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  Total width accessible by combining coupling to W and H ->WW* partial width:
  $\Delta\Gamma H / \Gamma H$ at the 5% level

Coupling to Fermions

- Flavor tagging, τ ID key to identify different Higgs decays:

ILC RDR, ILD& SiD LoI, CLIC CDR

- H -> bb
- H -> cc
- H -> gg
- H-> ττ

Measurement of branching fractions in Higgs-Strahlung or WW fusion, depending on energy

Extraction of coupling using measured coupling to Z or W

Precision of couplings:

1.4% for b quarks

3% for c quarks

3% for τ

BR to gluons 7%

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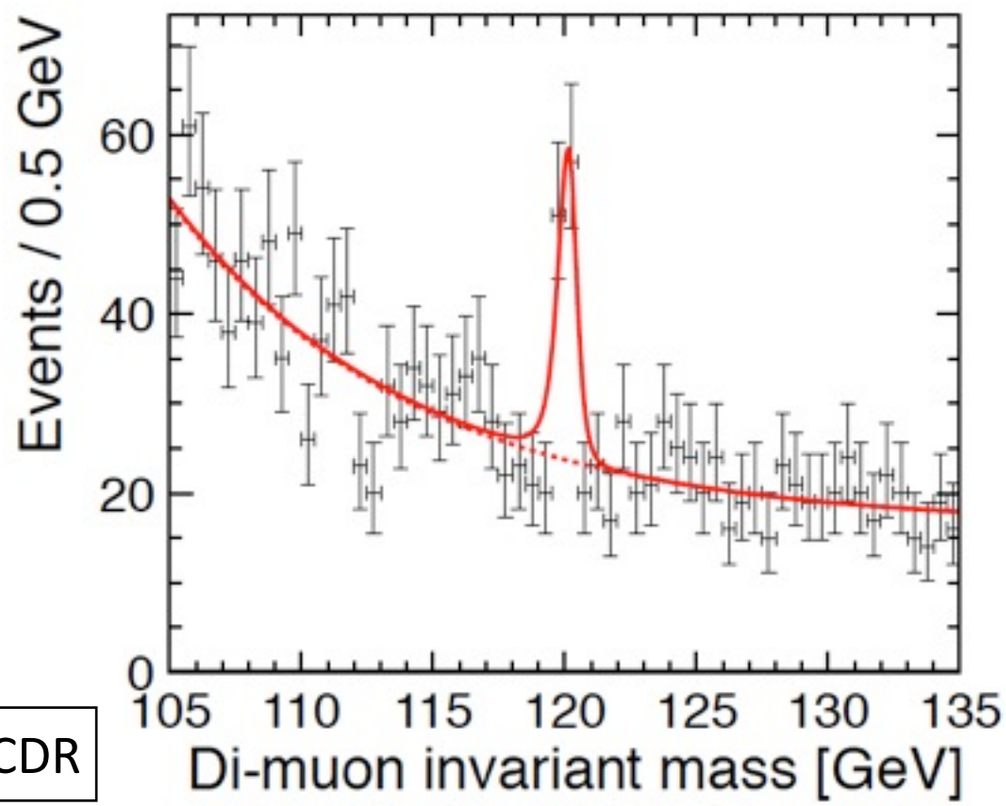
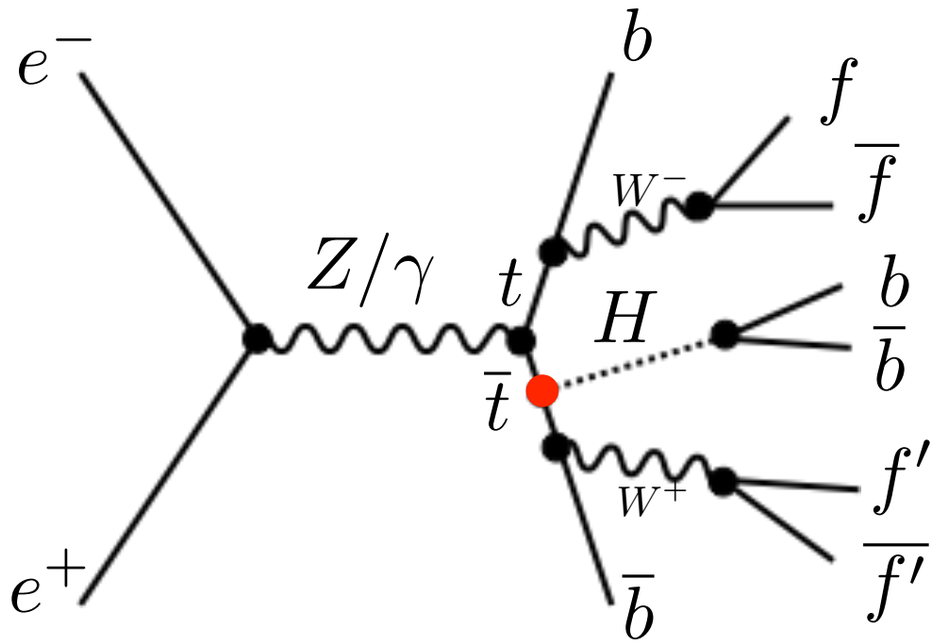
- A particularly tough one: coupling to muons - BR 0.03% for a 120 GeV Higgs
  - Requires high cross sections and high integrated luminosity
  - At 3 TeV with 2 ab^{-1}: Branching ratio measurable to 15% (coupling 8%)



CLIC CDR

Top Yukawa Coupling

- A challenging process:



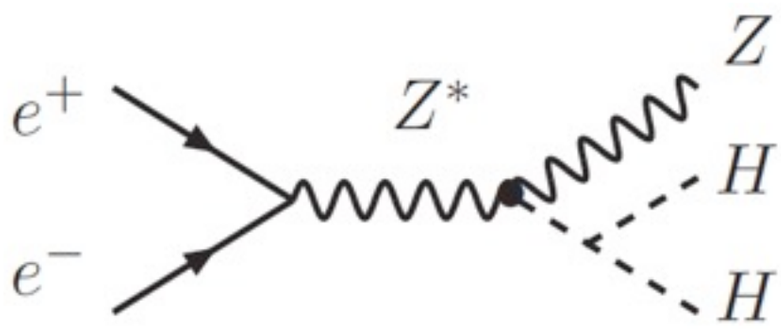
For dominant Higgs decay into b-quarks:
Two Ws, four b quarks, up to 8 jets in the final state

- Threshold slightly below 500 GeV, cross section maximum around 800 GeV of approximately 2.5 fb
  - Low cross section at 500 GeV, receives a boost from top bound-state effects

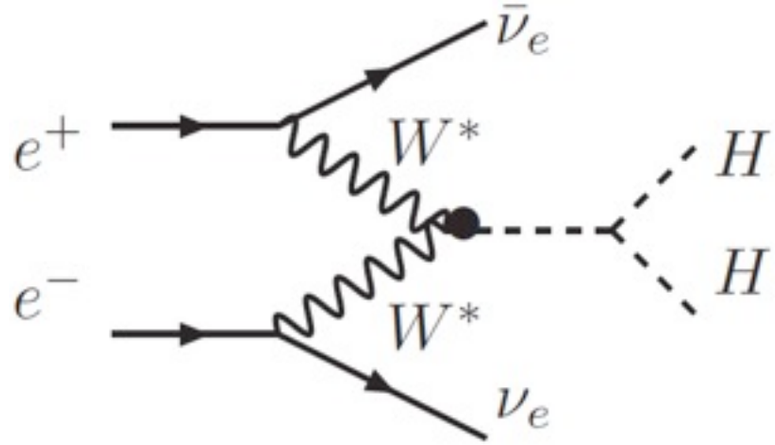
- Full simulation studies currently in progress for 500 GeV and 1 TeV preliminary results indicate 10% or better on coupling is achievable

Higgs Self-Coupling

- Higgs self-coupling is accessible via two processes in e^+e^- annihilation:



cross section 0.2 fb @ 500 GeV



cross section 0.2 fb @ 1.4 TeV, 0.9 fb @ 3 TeV

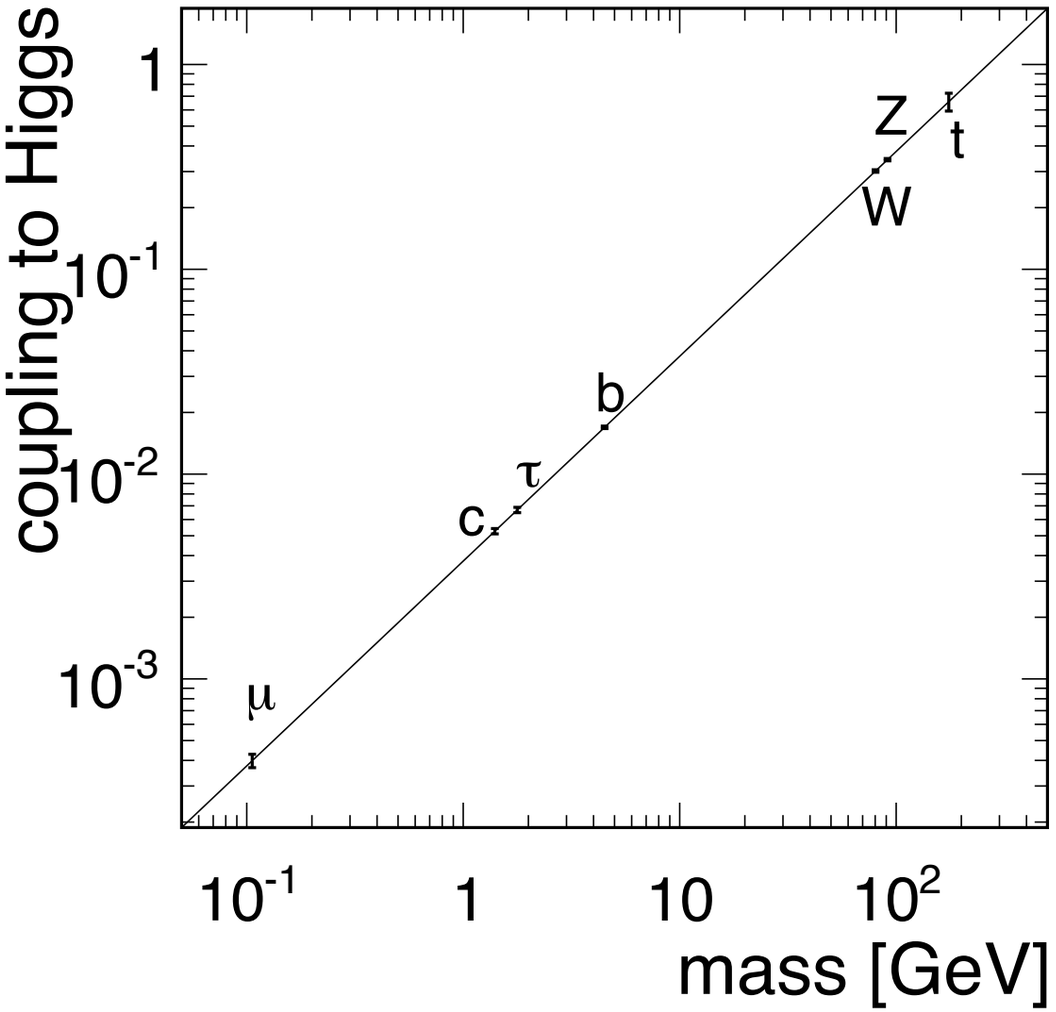
➪ challenging analysis: Multi-jet final states, flavor tagging key for background control

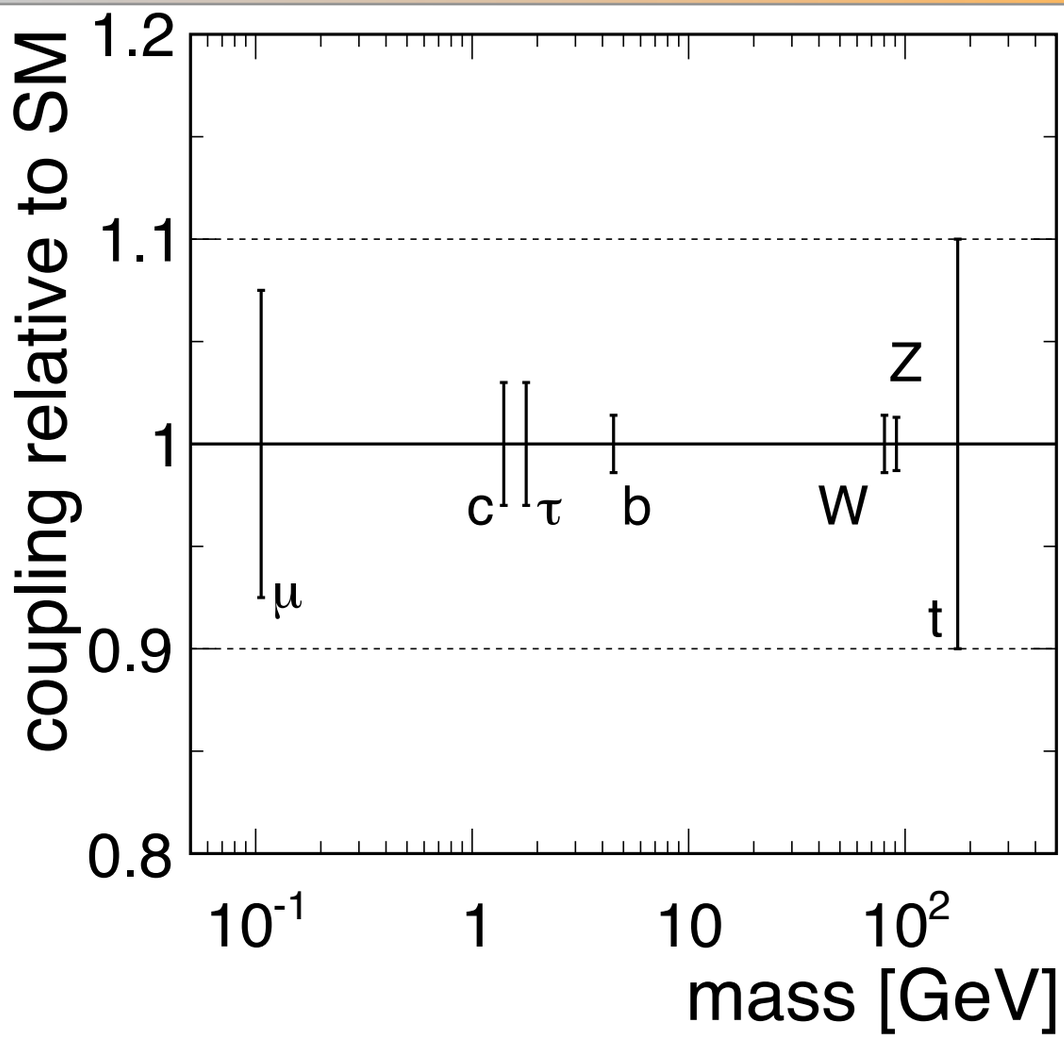
➪ requires high integrated luminosities

- Coupling obtained from cross section measurement, using the relation between σ and λ provided by theory

Full simulation studies are ongoing

Higgs Couplings - Summary

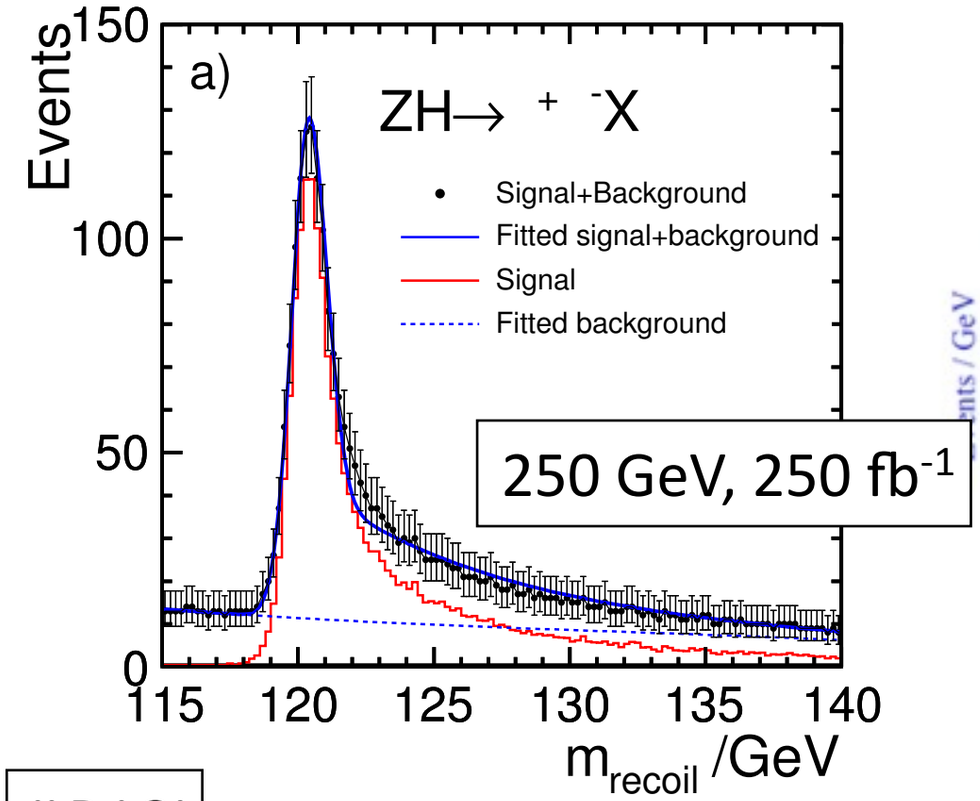




- A Linear Collider running at several energies will provide precise measurements of relevant Higgs couplings: Possibility to confirm the Higgs mechanism of the SM
- Precision matters: Detect deviations, for example due to extended Higgs sectors (SUSY, composite, ..):Expected on the 10% - 15% level in fermions,on the few % level in gauge bosons in typical Two-Higgs-Doublet models

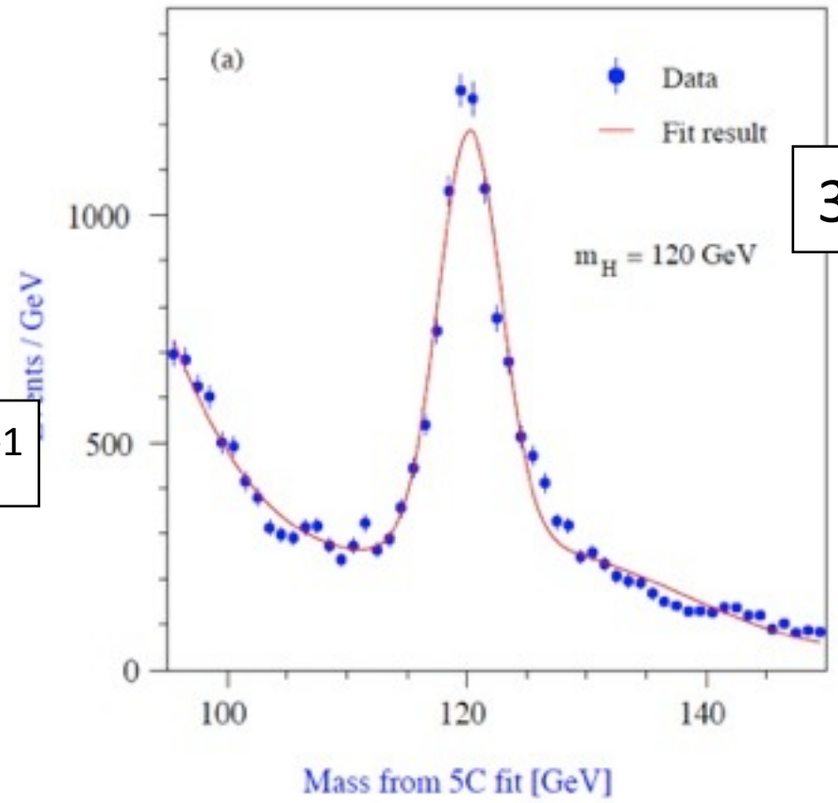
Higgs Properties: Mass, Spin CP Quantum Numbers

- Mass best measured in ZH events:



250 GeV, 250 fb^{-1}

ILD LOI



$ZH \to q\bar{q}b\bar{b}$

350 GeV, 500 fb^{-1}

mass resolution improved by kinematic fitting

ILC RDR

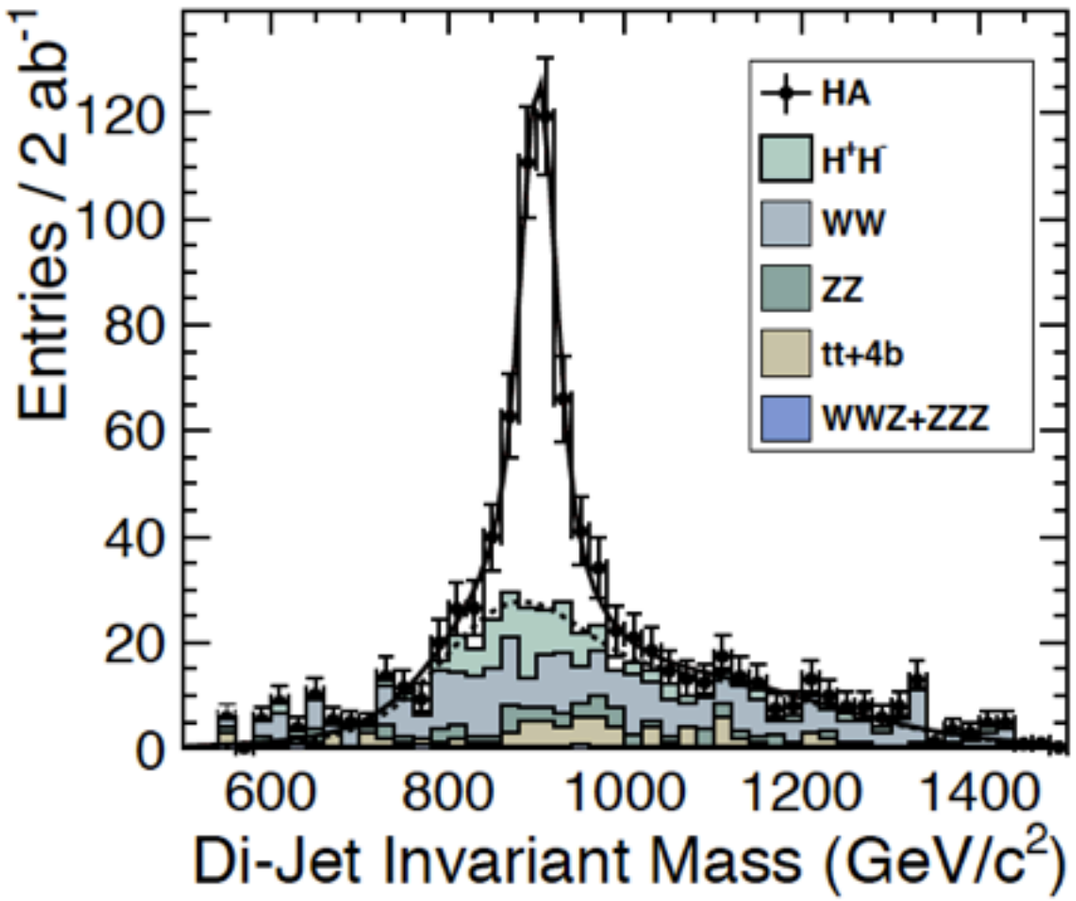
- Close to threshold using the recoil mass, with additional requirements for jet activity to further suppress background, full reconstruction further from threshold

Both approaches: Precision better than 50 MeV

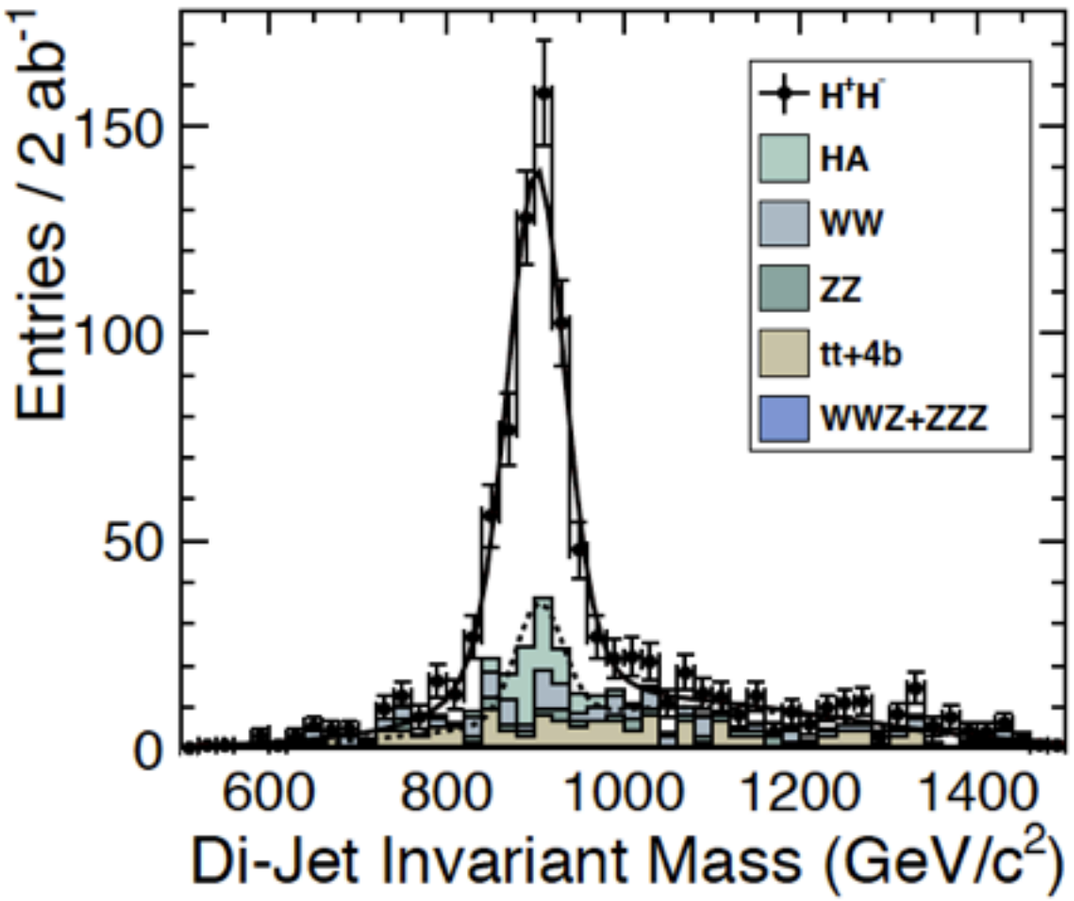
- Spin and CP quantum numbers can be cleanly obtained from threshold behavior and from angular distribution of Z, H, and decay products

Heavy Higgs - SUSY

- At a multi-TeV LC, also heavy Higgses, for example in SUSY (H^0, A^0, $H^{\pm}$), are easily accessible:



(a) $e^+e^- \to b\bar{b}b\bar{b}$



(b) $e^+e^- \to t\bar{b}b\bar{t}$

0.3% precision for TeV-scale masses at a 3 TeV LC

Summary & Outlook

- A e^+e^- Linear Collider provides access to all aspects of Higgs physics in a clean environment at various collider energies

- Unique possibility to measure the ZH coupling in a model-independent way
- Precise determination of the coupling to c, τ, b, W, Z, t, and, at high energy and high luminosity, μ
- Direct study of the Higgs potential by a measurement of the tri-linear self-coupling

- Measurement of the Higgs mass on the 50 MeV level, determination of spin and CP quantum numbers

⇨ Full exploration of the Higgs sector - and the possibility for fascinating discoveries!

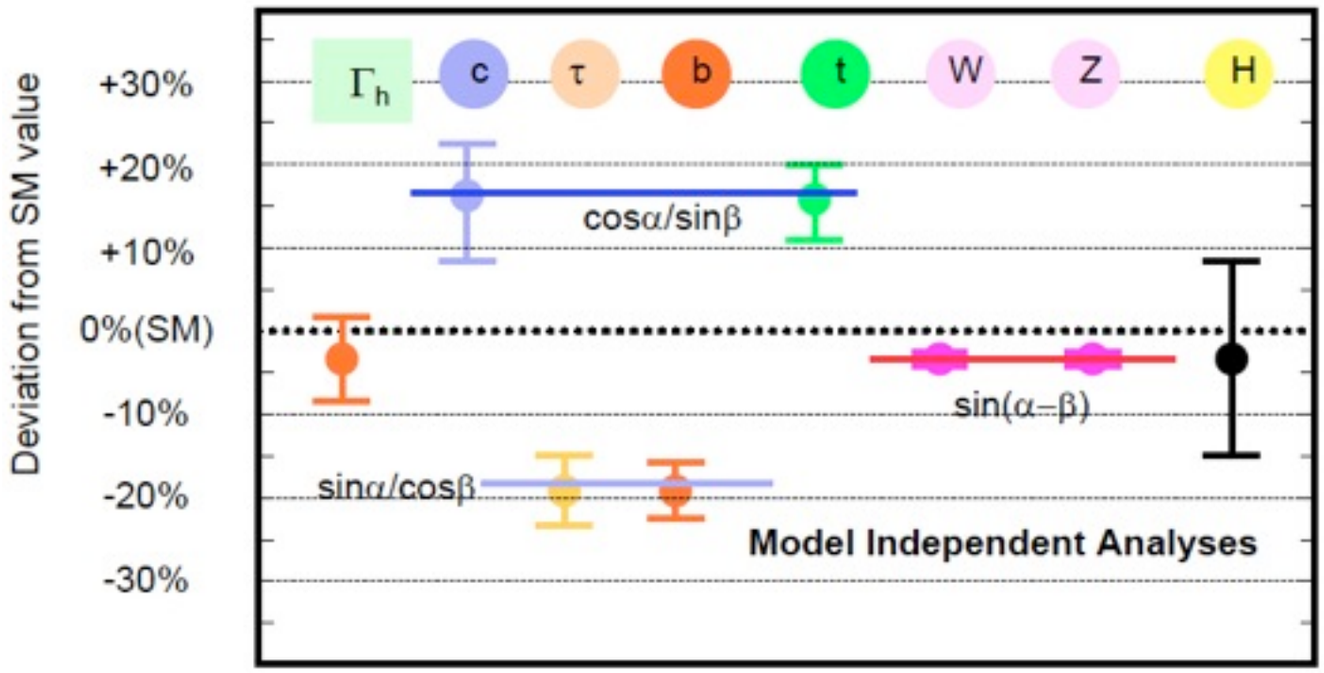
Further Information

- ILC Reference Design Report “Physics at the ILC”, arXiv:0709.1893 [hep-ph]
- ILD Letter of Intent, arXiv:1006.3396 [hep-ex]
- SiD Letter of Intent, arXiv:0911.0006 [physics.ins-det]
- CLIC Conceptual Design Report “Physics and Detectors at CLIC”, arXiv:1202.5940 [physics.ins-det]

Backup

Deviations of Higgs Couplings for BSM Models

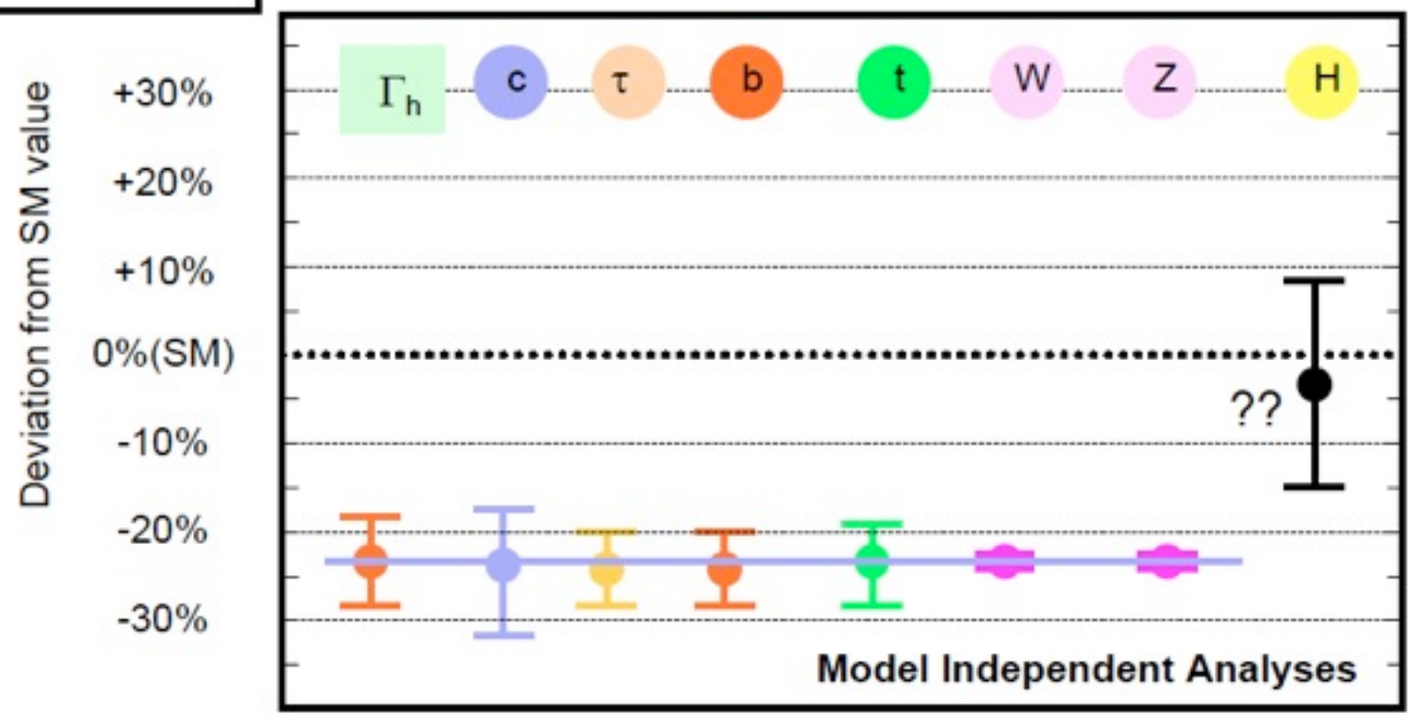
- Expected deviations of couplings for Two-Higgs Double models (SUSY, ...)



note: ignore error bars on couplings

- Extra dimensional models

  Radion-Higgs mixing



see also: talk by X. Prudent in SUSY session on Thursday afternoon