Physics at TLEP (and LEP3)

- **Outline**
  - Introduction : The SMS sent by LHC
  - What precision for future measurements ?
  - Possible paths towards the future
  - Measurements at TLEP/LEP3 and comparative study
    - Higgs Factory mode (and top threshold)
    - TeraZ and MegaW modes
  - Upgradeability at higher energies
  - Other issues : detectors, cost, timescale, …
  - Possible work packages
  - Conclusions

Bibliography

[1] CMS, "Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC", Phys.Lett. B716 (2012) 30-61

[2] CMS, "On the mass and spin-parity of the Higgs boson candidate via its decays to Z boson pairs", arXiv:1212:6639 (2012)

[3] CMS, "Properties of the Higgs-like boson in the decay $H\rightarrow Z*Z* \rightarrow 4l$ in pp collisions at $\sqrt{s}=7$ and 8 TeV" , CMS-PAS HIG-13-002 (2013)

[4] K. Monig, "ATLAS and CMS Physics Prospects at the HL-LHC", talk given at the CLIC Workshop (Jan. 2013)

[5] A. Blondel, Experimental Summary talk of the Rencontres de Moriond (Mar. 2012)

[6] LHCb, "First evidence for the decay $B_s^o \rightarrow \mu^+\mu^-$", Phys.Rev.Lett. 110 (2013) 021801

[7] P. Janot and G. Ganis, "The HZHA Generator" in Physics at LEP2, CERN Report 96/01 (Vol.2) 309

[8] S. Dittmaier et al., "Handbook of LHC Higgs cross sections: inclusive observables", CERN-2011-002 (Vol.1) 76

[9] R.S. Gupta, H. Rzehak, J.D. Wells, "How well do we need to measure Higgs boson couplings?", arXiv:1206.3560 (2012)

[10] H. Baer et al., "Physics at the International Linear Collider", in preparation, see http://lcsim.org/papers/DBDPhysics.pdf

[11] CMS, "CMS at the High-Energy Frontier", ESPP Contribution #177

[12] ATLAS, "Physics at a High-Luminosity LHC with ATLAS", ATL-PHYS-PUB-2012-004 (2012), ESPP Contribution #174

[13] M. Zanetti, talk given at the 2nd LEP3 day (Oct. 2012)

[14] H. Stoeck et al., "ILD Letter of Intent", arXiv:1006.3396 (2010)

[15] P. Azzi et al., "Prospective studies for LEP3 with the CMS detector", arXiv 1208.1662 (2012)

[16] J.E. Brau et al., "The physics case for an e^+e^- linear collider", ESPP Contribution #69

[17] C.F. Duerig, "Determination of the Higgs Decay Width at the ILC", talk given at the LCWS12 (Oct. 2012)

[18] P. Janot, "Higgs beyond the LHC", talk given at the HF2012 ICFA Workshop (Nov. 2012)

[19] M. Peskin, "Ultimate Higgs Measurements at ILC, LEP3 and TLEP", talk given at the 3rd TLEP3 day (Jan. 2013)

[20] A. Blondel et al., Report of the ICFA Beam Dynamics Workshop,"*Accelerators =for a Higgs Factory: Linear vs. Circular*", HF2012 (2013)

[21] Electroweak fits run by M. Gruenewald (private communication, Nov. 2012)

[22] P. Janot, "Physics Landscape and TLEP/LEP3 motivation", talk given at the 1st TLEP3 day (Jun. 2012)

[23] A. Blondel, "Possibilities and conditions for very high precision electroweak measurements", talk given at the 3rd TLEP3 day (Jan. 2013)

[24] M.L. Mangano et al., "Higgs cross sections in pp collisions at very high energy", ESPP Contribution #176

[25] T. Price, "Measurement of the top Yukawa coupling at the ILC", talk given at the LCWS12 (Oct. 2012)

[26] J. Tian, "Higgs self-coupling study at ILC", talk given at the LCWS12 (Oct. 2012)

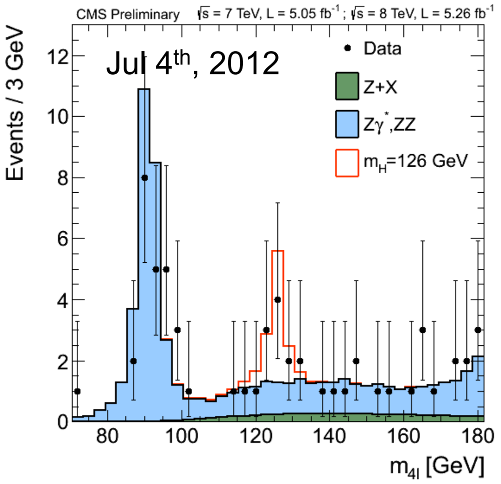
[27] T. Laštovička and J. Strube , "Higgs self-coupling study at CLIC", talk given at the LCWS12 (Oct. 2012)

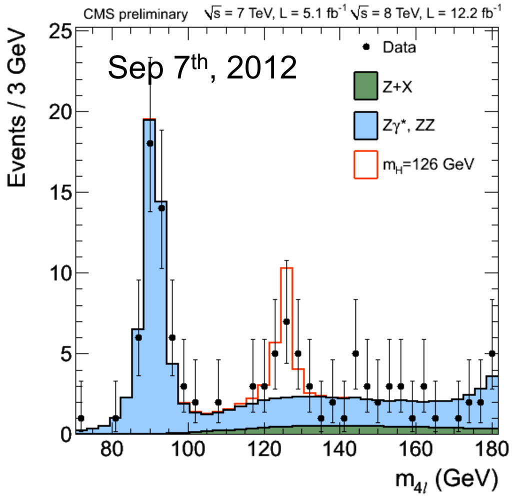
[28] E. Meschi, "Detectors for SHE-LHC and TLEP", talk given at the 3rd TLEP3 day (Jan. 2013)

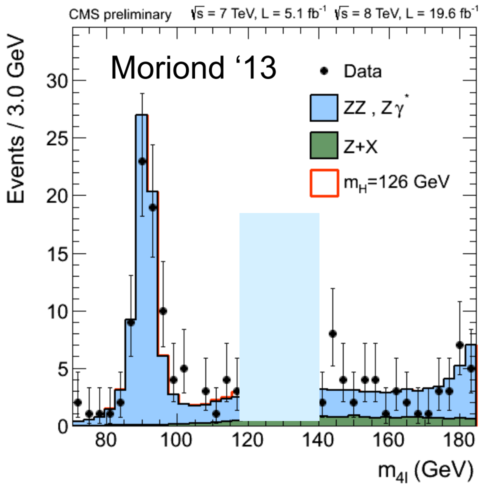
Introduction : The SMS sent by LHC (1)

- **A new boson with mass ~ 126 GeV, and with SMS properties**
  - Example : H(126) → ZZ → 4 leptons in CMS

[1,2,3]







4σ exp., 3.2σ obs.

$\mu = 0.72^{+0.45}_{-0.33}$

5σ exp., 4.5σ obs.

$\mu = 0.80^{+0.35}_{-0.28}$

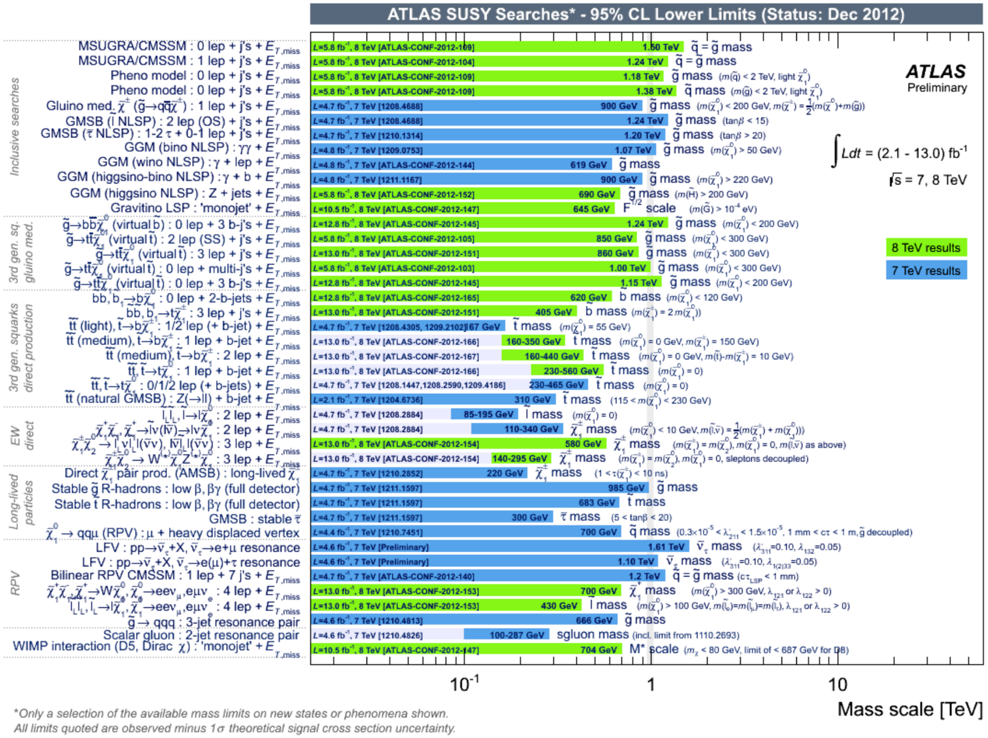
7σ exp., [redacted] σ obs.

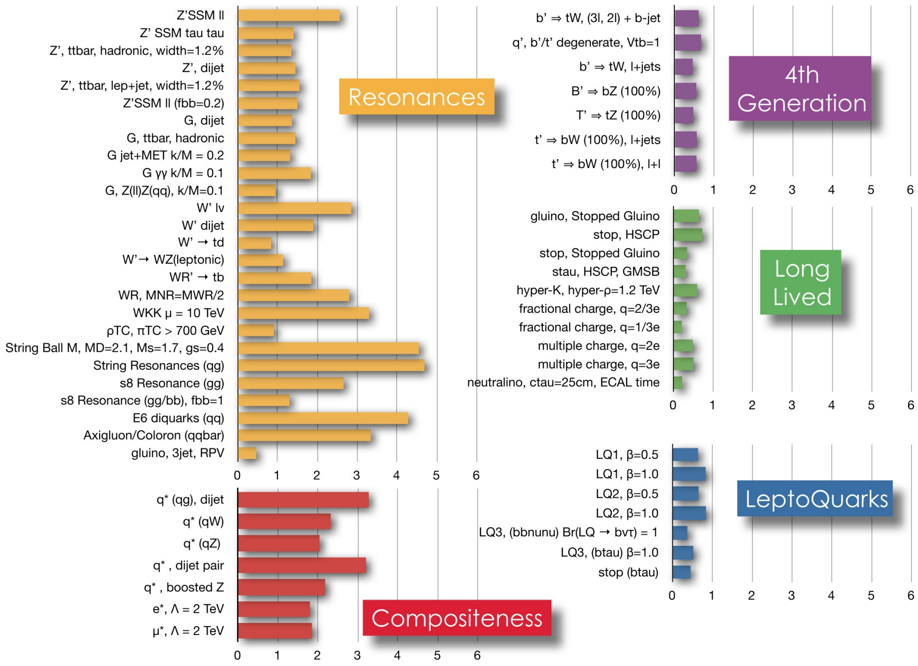
$\mu =$ [redacted] $^{+0.28}_{-0.23}$

- H(126) couples to the Z boson (important for e^+e^- colliders)
- All couplings compatible with those of the Standard Model Scalar
- Scalar hypothesis favoured over pseudo-scalar or spin-2 particle
- m_H known to ~ 400 MeV
- A factor 100 luminosity will bring the statistical uncertainty on μ to a couple %.

Introduction : The SMS sent by LHC (2)

- **No sign of new physics below a scale of several 100's GeV** [4]
  - Supersymmetry (ATLAS) Exotics (CMS)



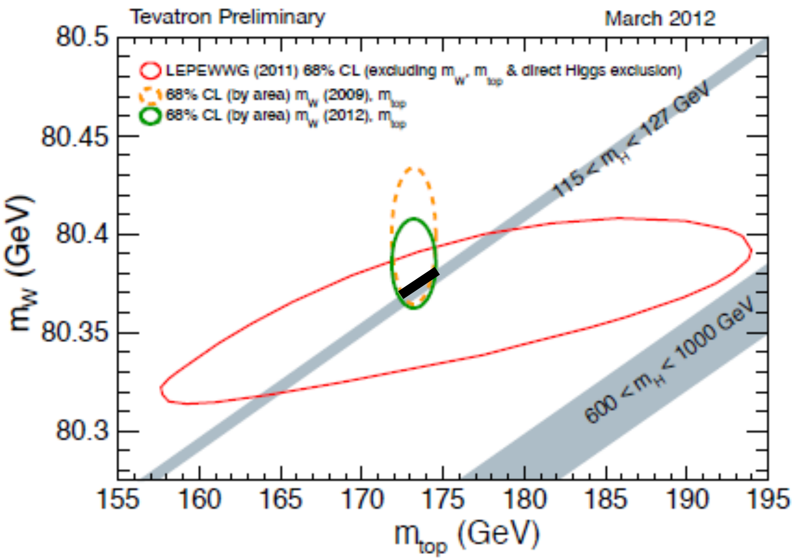


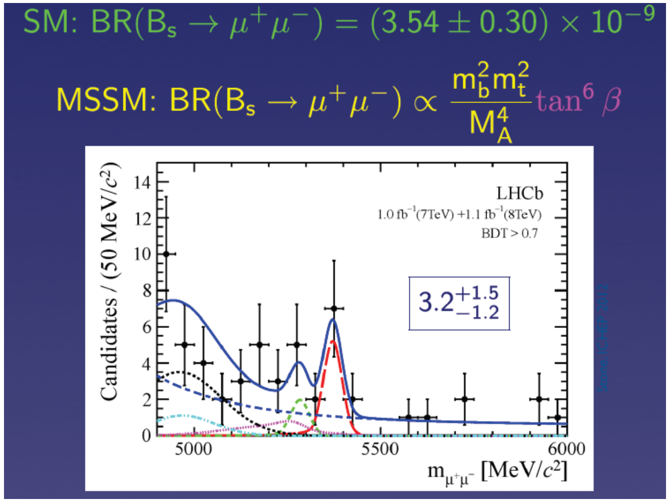
  - Data at higher $\sqrt{s}$ will extend the mass reach to ~500 GeV for SUSY
    - Will know more after the next LHC run at 14 TeV (2015-2017)

Introduction : The SMS sent by LHC (3)

[5,6]

- **If no new physics is found, what next ?**
  - Once m_H is known, the standard model has nowhere to go !





SM: $\mathrm{BR}(B_s \to \mu^+\mu^-) = (3.54 \pm 0.30) \times 10^{-9}$

MSSM: $\mathrm{BR}(B_s \to \mu^+\mu^-) \propto \frac{m_b^2 m_t^2}{M_A^4} \tan^6\beta$

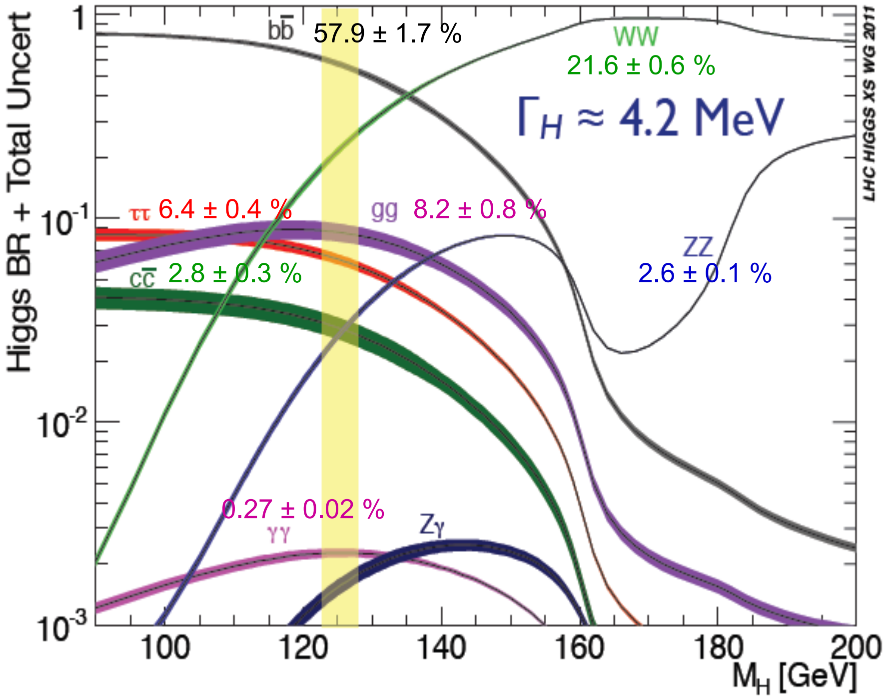
- Very strong incentive to revisit and improve all precision measurements
  - Z pole, WW threshold
  - Higgs couplings
  - Top quark properties
  - Rare decays ($B_s \to \mu\mu$, etc.)
- … and find indirect effects of new physics at larger scales

What is the precision needed ? (1)

❑ Example : Precision for Higgs measurements

[7,8]

- Does H(126)
  - Couple to fermions ?
  - Account for fermion masses ?
  - Fully account for EWSB ?
  - Has SM coupling to gauge bosons ?
  - Decay to new, visible, particles ?
  - Decay to invisible particles ?
  - Have the "proper" mass and width ?
  - Show any sign of new physics ?



- What is the precision needed to answer all these questions in a useful manner ?
  - Simple answer : measure as precisely as possible
    - ➨ Not very informative

What is the precision needed ? (2)

- **Example : Precision for Higgs couplings**
  - Maximal deviations with respect to SM couplings, as a function of new physics scale
    - SUSY $\frac{g_{hbb}}{g_{h_{\rm SM}bb}} = \frac{g_{h\tau\tau}}{g_{h_{\rm SM}\tau\tau}} \simeq 1 + 1.7\% \left(\frac{1\ {\rm TeV}}{m_A}\right)^2$, for tanβ = 5
    - Composite Higgs $\frac{g_{hff}}{g_{h_{\rm SM}ff}} \simeq \frac{g_{hVV}}{g_{h_{\rm SM}VV}} \simeq 1 - 3\% \left(\frac{1\ {\rm TeV}}{f}\right)^2$
    - Top partners $\frac{g_{hgg}}{g_{h_{\rm SM}gg}} \simeq 1 + 2.9\% \left(\frac{1\ {\rm TeV}}{m_T}\right)^2, \quad \frac{g_{h\gamma\gamma}}{g_{h_{\rm SM}\gamma\gamma}} \simeq 1 - 0.8\% \left(\frac{1\ {\rm TeV}}{m_T}\right)^2$
    - Other models may give up to 5% deviations with respect to the Standard Model
  - Maximal deviations for the new physics scale still allowed by LHC results

	ΔhVV	$\Delta h\bar{t}t$	$\Delta h\bar{b}b$
Mixed-in Singlet	6%	6%	6%
Composite Higgs	8%	tens of %	tens of %
Minimal Supersymmetry	$< 1\%$	3%	$10\%^{a}$, $100\%^{b}$

- **Strongly influences the strategy for Higgs factory projects**
  - Need at least a per-cent accuracy on couplings for a 5σ "observation"
    - And sub-percent precision if new physics is at or beyond the TeV scale [9,10]

Paths towards the future : (HL-)LHC (1)

- Executive summary (See Leandro's presentation this morning)

Approved LHC, 300 fb^{-1} at 14 TeV :

- Higgs mass at 100 MeV
- Disentangle Spin 0 vs Spin 2 and main CP component in $\gamma\gamma$/ZZ*
- Coupling precision / Experiment

Z, W,	5-6%
b, τ	10-15%
t, μ	3-2 σ effect
$\gamma\gamma$, gg	5-11%

HL-LHC, 3000 fb^{-1} at 14 TeV:

- Higgs mass at 50 MeV
- More precise studies of Higgs CP sector
- Coupling precision / Experiment

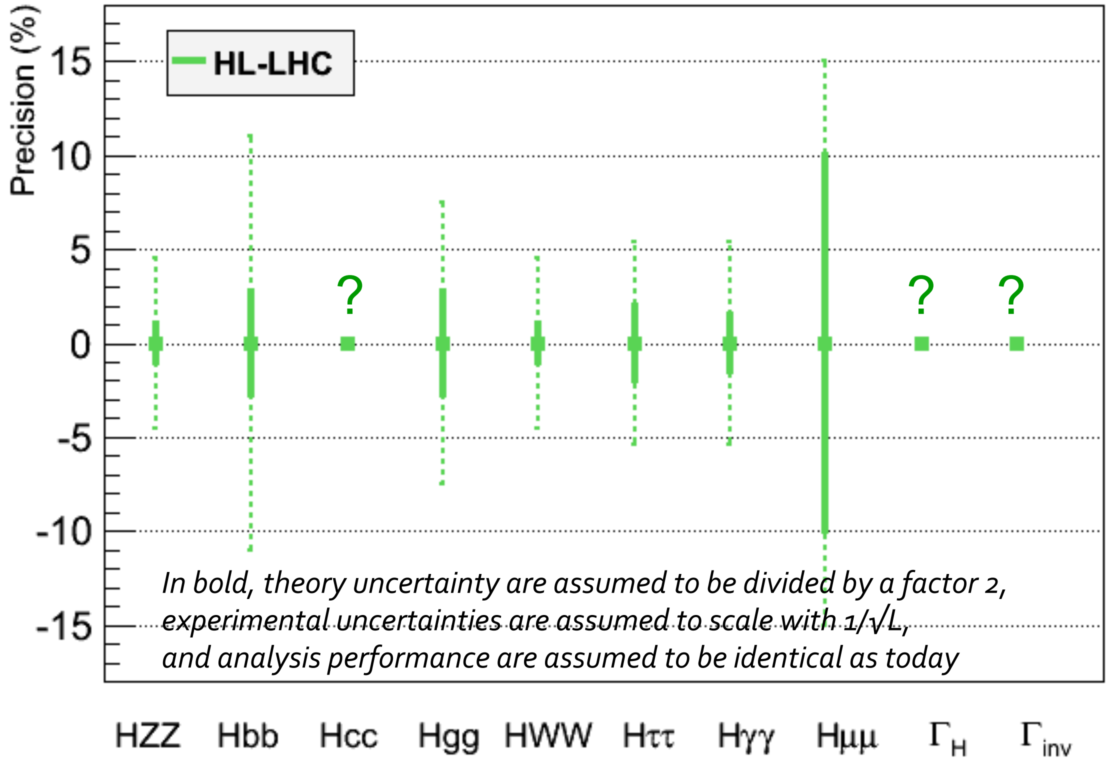
Z, W,	1-5%
b, τ, t, μ	3-10%
$\gamma\gamma$ and gg	2-7%
HH	>3 σ (2 Expts)

Assuming sizeable reduction of theory errors

[11,12]

Paths towards the future : HL-LHC (2)

- Graphic representation of HL-LHC projected performance



In bold, theory uncertainty are assumed to be divided by a factor 2, experimental uncertainties are assumed to scale with 1/√L, and analysis performance are assumed to be identical as today

Assumptions :

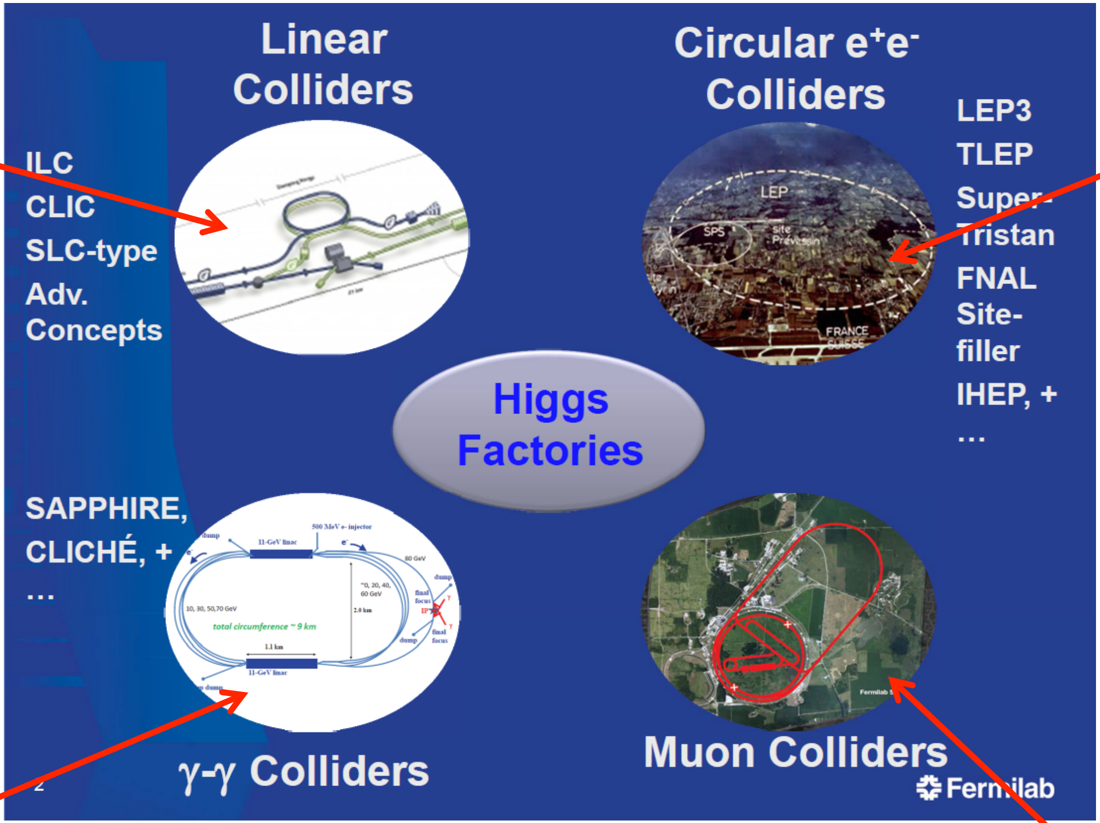
1. No new decay
2. Γ_H from SM (or BR(cc) from SM)

- Much better than originally expected before LHC started
  - Will need vigorous upgrade of CMS and ATLAS detectors
    - Per-cent to sub-percent precision will require new collider(s)

[11]

Paths towards the future : Precision Higgs Factories

- **Several options for Higgs factories are being studied**



Linear Colliders

ILC
CLIC
SLC-type
Adv. Concepts

Circular e^+e^- Colliders

LEP3
TLEP
Super-Tristan
FNAL Site-filler
IHEP, +
…

Higgs Factories

SAPPHIRE,
CLICHÉ, +
…

γ-γ Colliders

Muon Colliders

Studied for decades

This talk

See presentation of Marco Zanetti

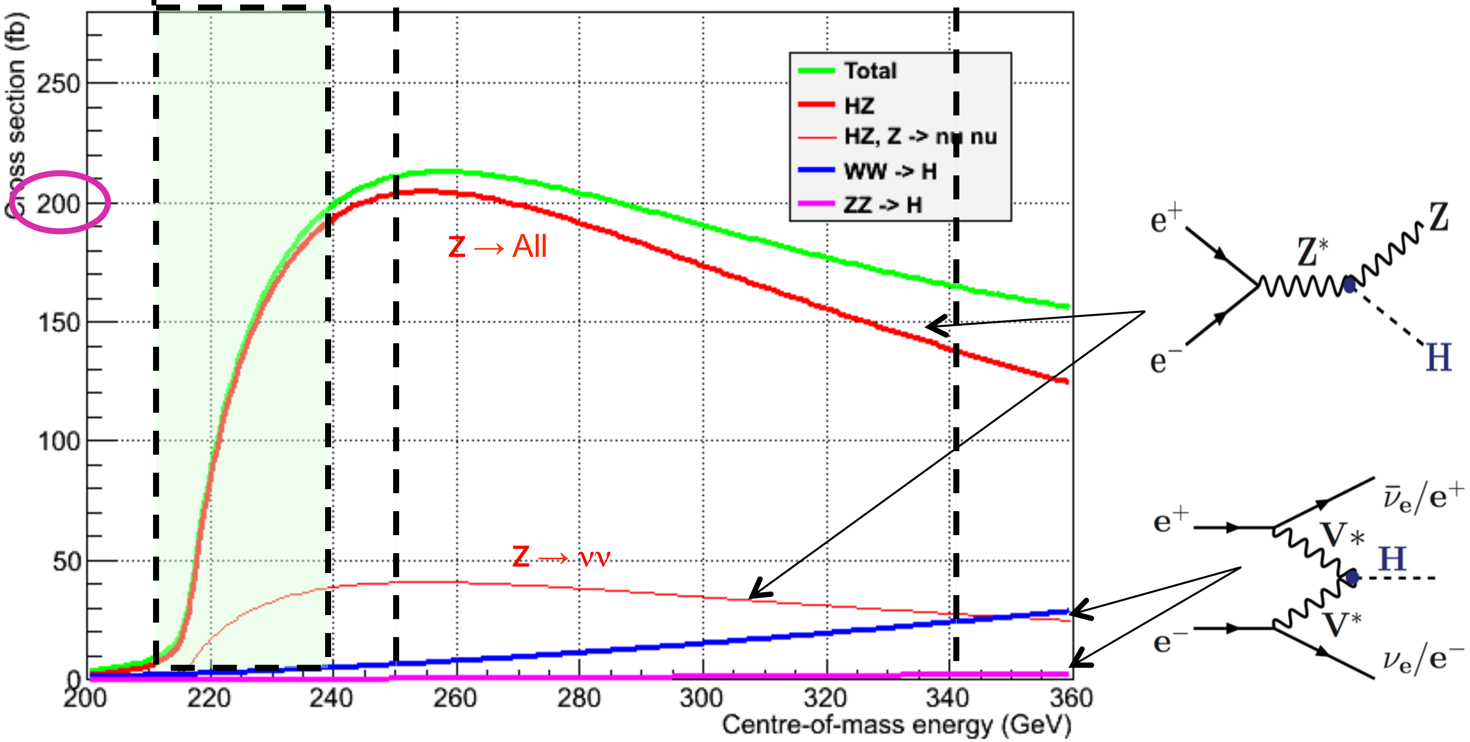
Not encouraged by European Strategy

e^+e^- colliders have largest potential as Precision Higgs Factories

Precision Higgs Factories in e^+e^- collisions (1)

- **Physics case not driven by the fact that the collider is linear or circular**
  - Scan of the HZ threshold : $\sqrt{s}$ = 210-240 GeV — Spin
  - Maximum of the HZ cross section : $\sqrt{s}$ = 240-250 GeV — Mass, BRs, Width, Decays
  - Just below the tt threshold : $\sqrt{s}$ ~ 340-350 GeV — Width, CP

Unpolarized cross sections



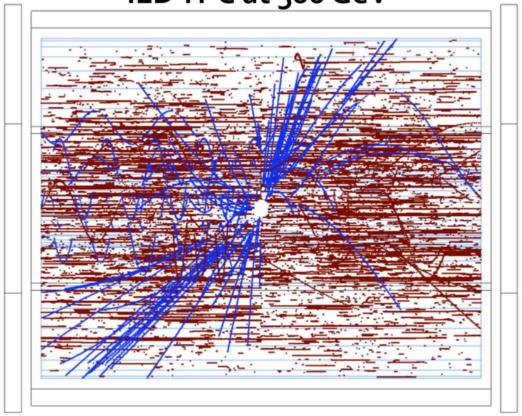
Need 100's fb^{-1}

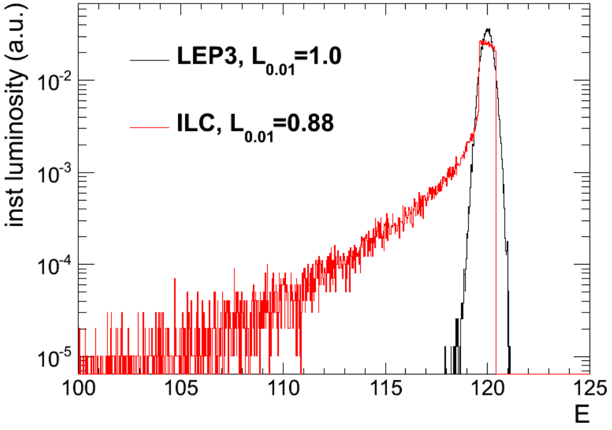
[7]

Precision Higgs Factories in e^+e^- collisions (2)

- **A few specificities :**
  - e^- (e^+) beam polarization is easy at the source (possible) for a linear collider.
    - Not critical for Higgs studies.
  - No beam disruption from Beamstrahlung for a circular collider (σ_y ~ 300 nm vs. 5 nm @ ILC)
    - No EM backgrounds in the detector (photons, e+e- pairs);
    - No beam energy smearing – energy spectrum perfectly known (lumi measurement)
    - Negligible pile-up from $\gamma\gamma$ interactions

ILD TPC at 500 GeV





➨ No drastic requirements for the detector and the background simulation

  - Possibility of operating several IP's simultaneously in circular collider
    - vs. only one IP in linear collider

[13,14]

Precision Higgs Factories in e^+e^- collisions (3)

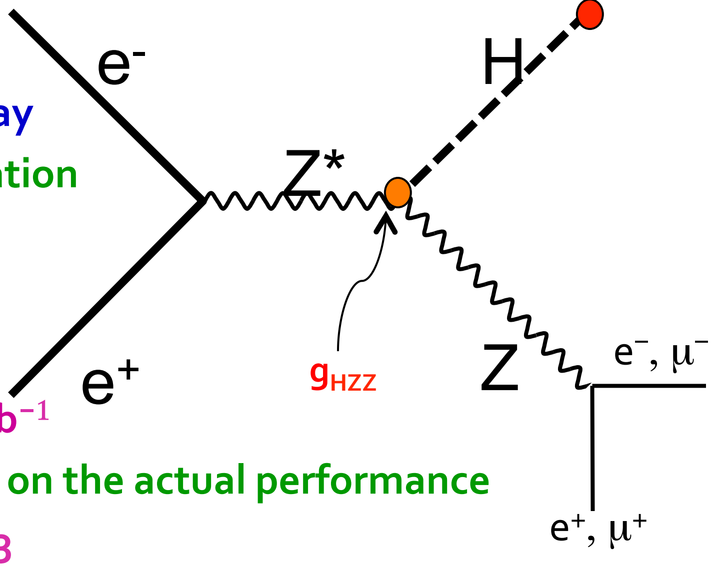
- Number of Higgs bosons produced at $\sqrt{s}$ = 240-250 GeV

	ILC-250	LEP3-240	TLEP-240
Lumi / IP / 5 years	250 fb^{-1}	500 fb^{-1}	2.5 ab^{-1}
# IP	1	2 - 4	2 - 4
Lumi / 5 years	250 fb^{-1}	1 - 2 ab^{-1}	5 - 10 ab^{-1}
Beam Polarization	80%, 30%	–	–
$L_{0.01}$ (beamstrahlung)	86%	100%	100%
Number of Higgs	70,000	400,000	2,000,000
Upgradeable to	ILC 1TeV CLIC 3 TeV	HE-LHC 33 TeV	SHE-LHC 100 TeV

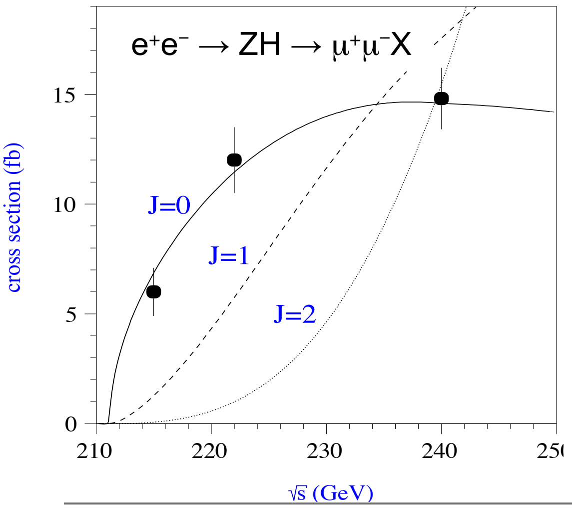
- LEP3 : 4-8 times more luminosity and 3-6 times more Higgs bosons than ILC
- TLEP : 20-40 times more luminosity and 15-30 times more Higgs bosons than ILC
  - In a given amount of time, Higgs coupling precisions scale like
    - 2% for ILC : 1% for LEP3 : 0.3% for TLEP
    - One year of TLEP = five years of LEP3 = 15-30 years of ILC (at 240 GeV)

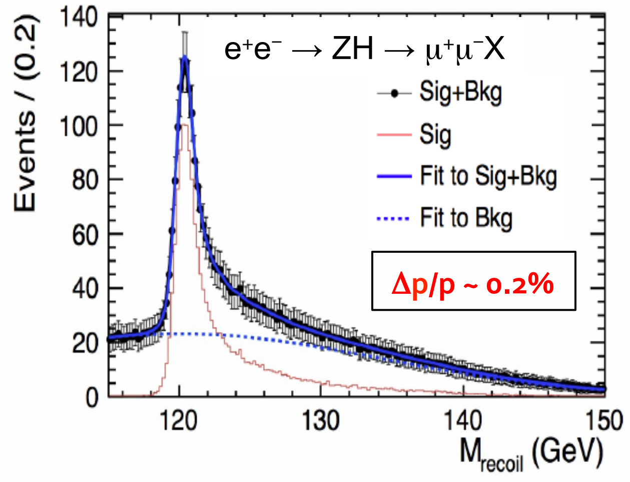
Higgs measurements at $\sqrt{s}$ ~ 240 GeV (1)

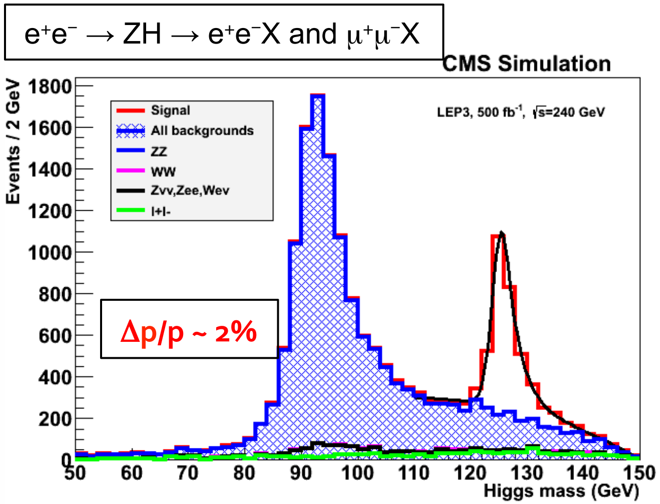
- **With $e^+e^- \to ZH \to e^+e^-X$ and $\mu^+\mu^-X$ events**
  - Measure HZ cross section in a model independent way
    - Find m_H peak from the leptons and E,p conservation
    - Determine spin with three-point threshold scan
      - ➨ 10 fb^{-1} / point suffice
    - Determine σ_{HZ} and g_{HZZ} coupling at 240 GeV
      - ➨ 3% (1.5%) precision on σ_{HZ} (g_{HZZ})with 250 fb^{-1}
    - Good tracker needed, but details mildly depend on the actual performance
      - ➨ Plots below with ILD@ILC and CMS@LEP3



[9,10,11]



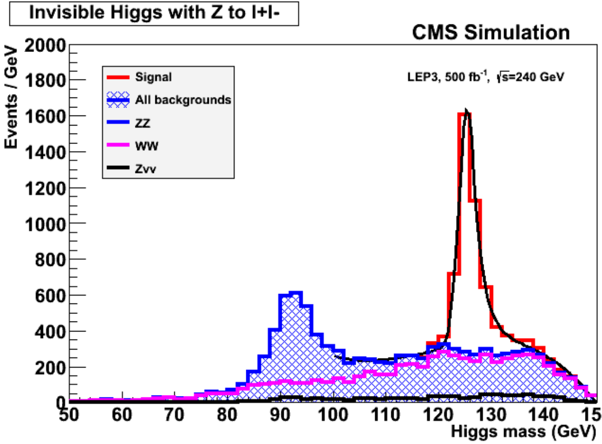




[15,16]

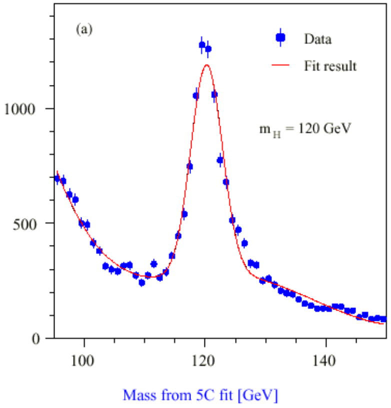
Higgs measurements at $\sqrt{s}$ ~ 240 GeV (2)

- With ZH → e^+e^-X and $\mu^+\mu^-X$ events (cont'd)
  - Measure invisible decay branching ratio (X = nothing)
    - Precision on BR_{INV} ~ 1% with 250 fb^{-1}
    - Or exclude BR_{INV} > ~2% at 95% C.L.

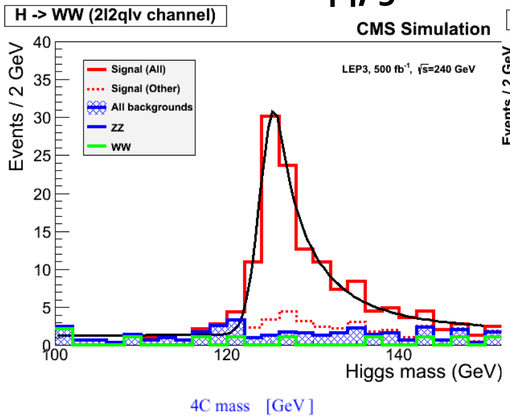


- Measure other σ_{HZ}×BR(H→ ff,VV)
  - With exclusive selections of Z and H decays
    - Precision of 1.5% to 8% with 250 fb^{-1} for the copious decays (bb, WW, gg, ττ, cc)
    - Need more luminosity for rare decays (γγ, Zγ, μμ)
      - ➨ Particle flow, b and c tagging, lepton and photon capabilities needed

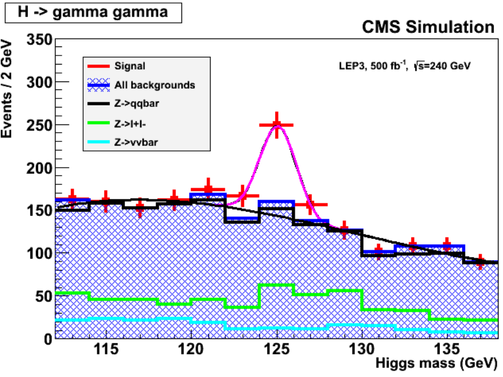
ZH→ qqbb, 250 fb^{-1}



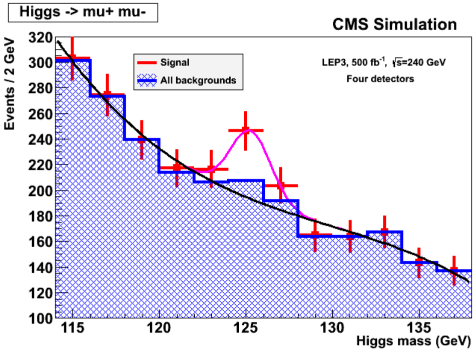
ZH→ llWW→ lllνqq, 500 fb^{-1}



ZH→ Xγγ, 500 fb^{-1}



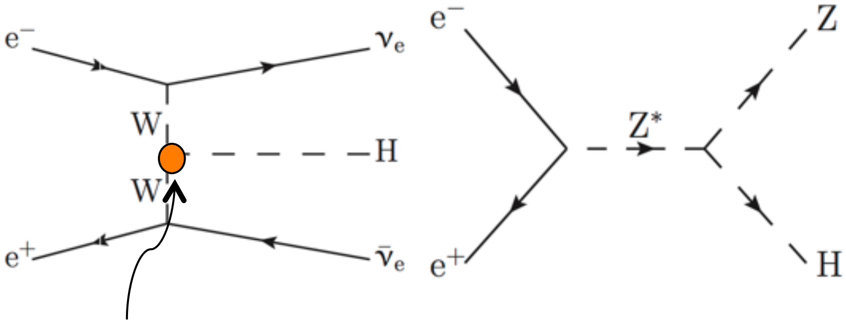
ZH→ Xμμ, 2 ab^{-1}



[10,15,16]

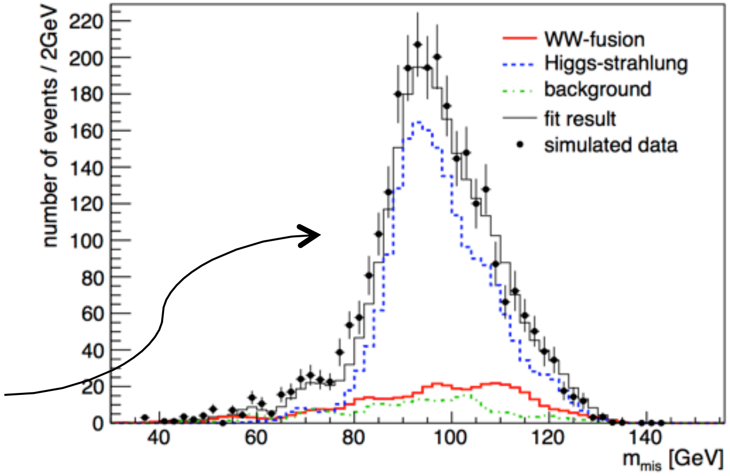
Higgs measurements at $\sqrt{s}$ ~ 240 GeV (3)

- **Higgs width from the $H\nu\nu$ final state**
  - From $\sigma_{WW\to H}$ and BR($H\to WW$)
    - $\sigma_{WW\to H} \sim g^2_{HWW}$
    - BR($H\to WW$) = $\Gamma_{H\to WW} / \Gamma_H \sim g^2_{HWW} / \Gamma_H$
      - ➨ $\Gamma_H \sim \sigma_{WW\to H}$ / BR($H\to WW$)



g_{HWW}

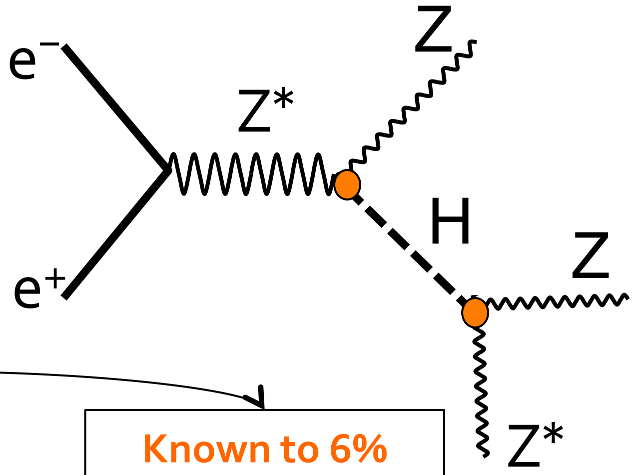
  - Contribution to $H\nu\nu$ from HZ ~ 40 pb
    - Known from ZH → e^+e^-X and $\mu^+\mu^-X$
  - Contribution from WW fusion ~ 6 pb
    - To be measured
  - Select $\nu\nu bb$ events from ZH and WW fusion
    - Needs adequate b tagging and particle flow
  - Fit the missing mass distribution for $N_{WW\to H\to bb}$
    - σ_{HZ} x BR($H\to bb$) known to ~1.5% or better
    - $\sigma_{WW\to H} = N_{WW\to H\to bb}$ / BR($H\to bb$)
      - ➨ Precision on $\sigma_{WW\to H}$ ~ 14% with 250 fb^{-1}
      - ➨ $\Gamma_H \sim \sigma_{WW\to H}$ / BR($H\to WW$), measured up to 15% precision with 250 fb^{-1}



[17]

Higgs measurements at $\sqrt{s}$ ~ 240 GeV (4)

- Higgs width from the ZZZ final state
  - Number of ZZZ events ~ $\sigma_{HZ} \times BR(H\rightarrow ZZ)$
    - $\sigma_{HZ} \sim g^2_{HZZ}$
    - $BR(H\rightarrow ZZ) = \Gamma_{H\rightarrow ZZ}/\Gamma_H \sim g^2_{HZZ} / \Gamma_H$
      - ➨ Number of ZZZ events ~ g^4_{HZZ} / Γ_H



Known to 6%
from l⁺l⁻X events
with 250 fb-1

  - Select $l^+l^- \, l'^+l'^-$ X events (~ background and H →WW free)
    - Number of events in 250 fb^{-1} @ 240 GeV :
      - ➨ 250 $fb^{-1} \times 200$ fb × $BR(H\rightarrow ZZ) \times BR(Z\rightarrow ll)^2 \times 3$

        → About 40 events, of which ~25 selected

  - Hence measure the total width Γ_H with a precision of 21%
    - Reduced to 12% in combination with WW fusion measurement
      - ➨ Could be further reduced with other Z decays

        (Need full simulation and WW/ZZ simultaneous fit)

  - Note : Precision of a few % can be reached on Γ_H if one assumes no exotic Higgs decays

Linear vs Circular at √s ~ 240 GeV

- Precision on H(125) branching fractions, width, mass, … after 5 years

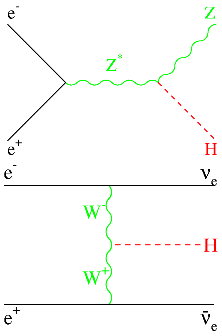
	ILC	LEP3 (4)	TLEP (4)
σ_{HZ}	2.5%	1.3%	0.4%
$\sigma_{HZ} \times BR(H \rightarrow bb)$	1.0%	0.5%	0.1%
$\sigma_{HZ} \times BR(H \rightarrow cc)$	6.9%	4% (*)	1.3%
$\sigma_{HZ} \times BR(H \rightarrow gg)$	8.5%	4.5% (*)	1.4%
$\sigma_{HZ} \times BR(H \rightarrow WW^*)$	8.0%	3.0%	0.9%
$\sigma_{HZ} \times BR(H \rightarrow \tau\tau)$	5.0%	3.0%	0.9%
$\sigma_{HZ} \times BR(H \rightarrow ZZ^*)$	28%	7.1%	3.1%
$\sigma_{HZ} \times BR(H \rightarrow \gamma\gamma)$	27%	6.8%	3.0%
$\sigma_{HZ} \times BR(H \rightarrow \mu\mu)$	–	28%	13%
$\sigma_{WW \rightarrow H}$	12%	5% (*)	2.2%
Γ_H, Γ_{INV}	10% , < 1.5%	4% , < 0.7%	1.8% , < 0.3%
m_H	40 MeV	26 MeV	8 MeV

- LEP3 numbers obtained from a CMS simulation x 4, except (*) extrapolated from ILC
  - Need a refined vertex detector for gg and cc BR accurate measurements
- TLEP numbers extrapolated from LEP3 column

[10,15,16]

Measurements at $\sqrt{s}$ ~ 350 GeV (ILC/TLEP)

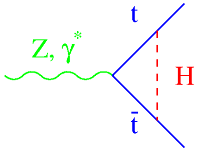
- Luminosity similar for ILC and TLEP
  - At each IP : 350 fb^{-1} over 5 years
    - With possibly 4 detectors at TLEP
  - More study of the Hνν final state with H→bb
    - Contribution from HZ : ~ 25 fb
    - Contribution from WW→H : ~ 25 fb



	ILC (250+350)	TLEP (240+350)
$\sigma_{WW\to H}$	12% → 4%	2.2% → 1.5%
Γ_H	10% → 5.5%	1.8% → 1.3%

➨ Small improvement for other σ×BR's

- Measure CP mixture to ~5%
- Scan of the tt threshold
  - From the cross section

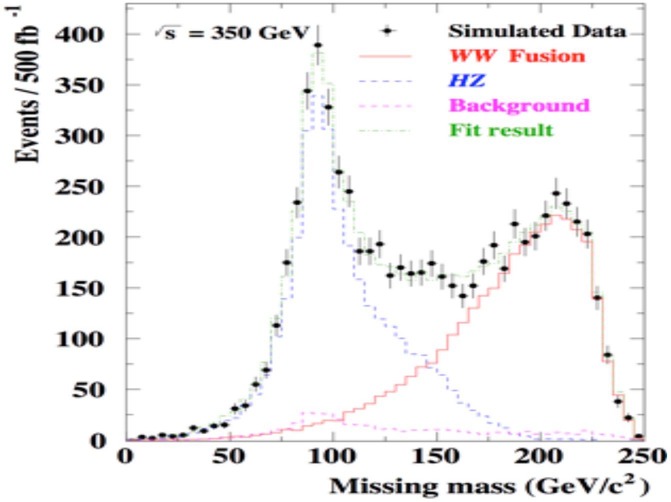


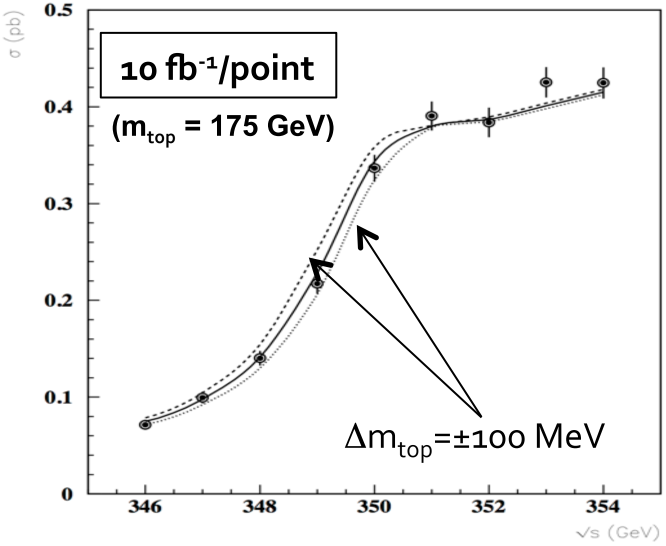
➨ Top mass and width to 50 MeV or better

➨ Probe the ttH coupling to 30%

No beamstrahlung is a advantage

➨ Study rare top decays



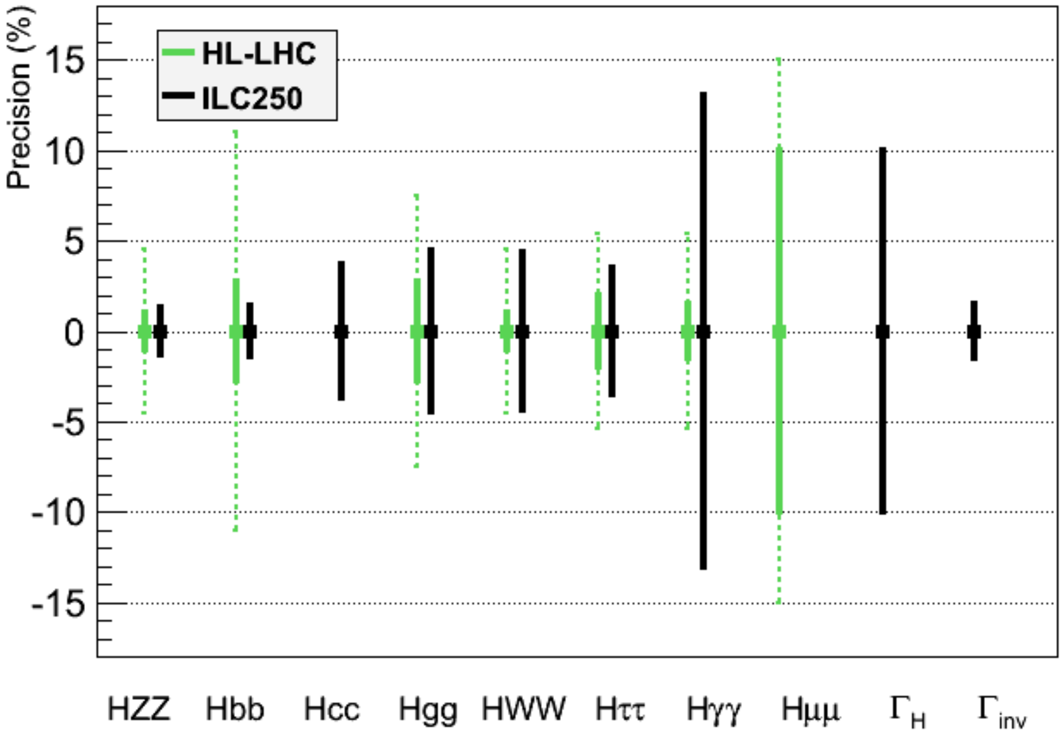


[10,17]

Higgs couplings for Precision Higgs Factories (1)

- **Same assumptions as for HL-LHC for a sound comparison**
  - No exotic decay, Standard Model decay width

$$\boxed{\sigma_{HZ} \propto g^2_{HZZ}, \text{ and } \sigma_{HZ} \times \mathrm{BR}(H \to XX) \propto g^2_{HZZ} g^2_{HXX} / \Gamma_H}$$



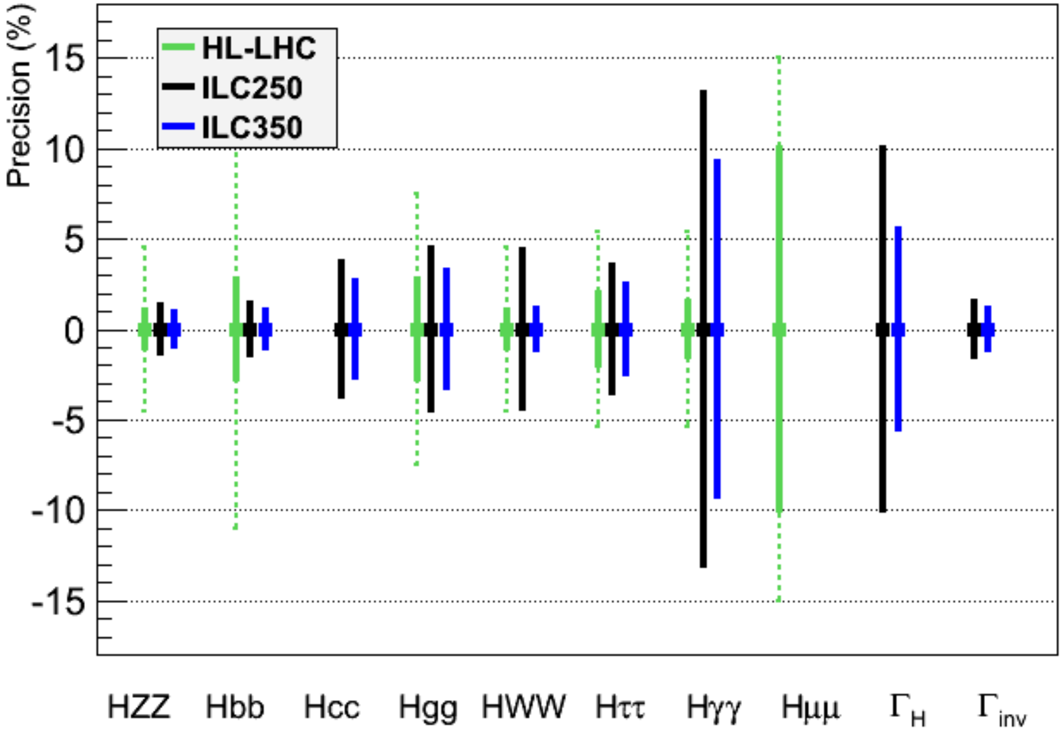
➨ ILC250 would be a good complement to LHC (Γ_H, Γ_{inv}, g_{Hcc}, g_{Hbb})

[11,16]

Higgs couplings for Precision Higgs Factories (2)

- **Same assumptions as for HL-LHC for a sound comparison**
  - No exotic decay, Standard Model decay width

$$\sigma_{HZ} \propto g^2_{HZZ}, \text{ and } \sigma_{HZ} \times \mathrm{BR}(H \to XX) \propto g^2_{HZZ} g^2_{HXX} / \Gamma_H$$

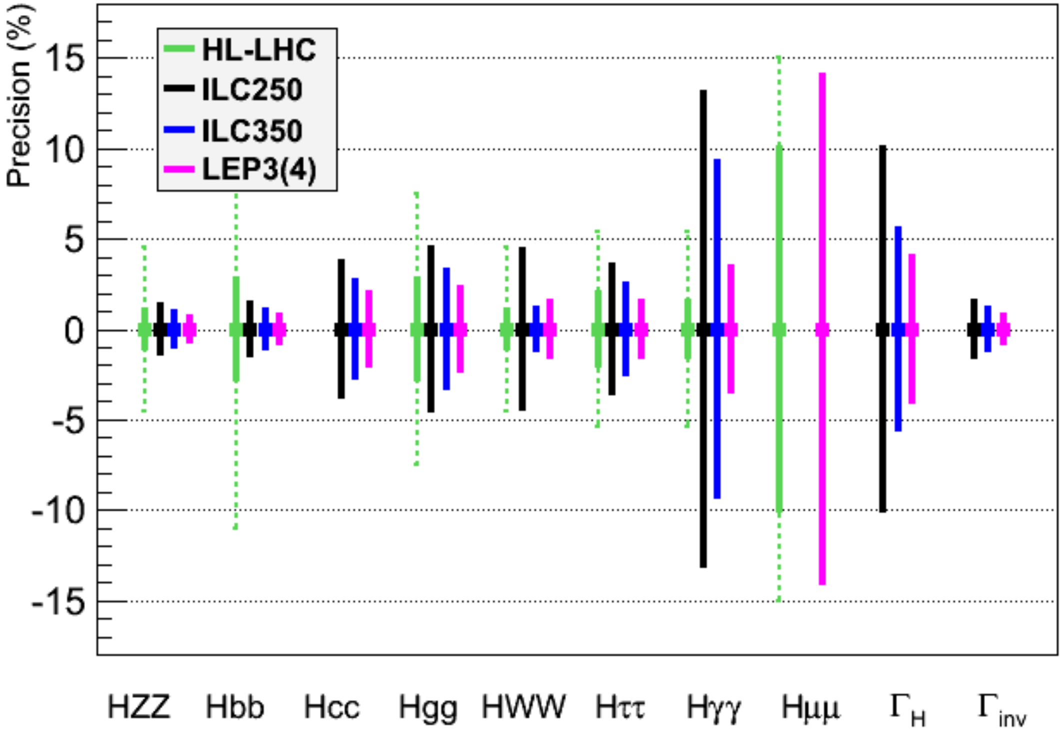


➨ ILC250/350 would be a good complement to LHC (Γ_H, Γ_{inv}, g_{Hcc}, g_{Hbb}) [11,16]

Higgs couplings for Precision Higgs Factories (3)

- **Same assumptions as for HL-LHC for a sound comparison**
  - No exotic decay, Standard Model decay width

$$\sigma_{HZ} \propto g^2_{HZZ}, \text{ and } \sigma_{HZ} \times \mathrm{BR}(H \to XX) \propto g^2_{HZZ} g^2_{HXX} / \Gamma_H$$



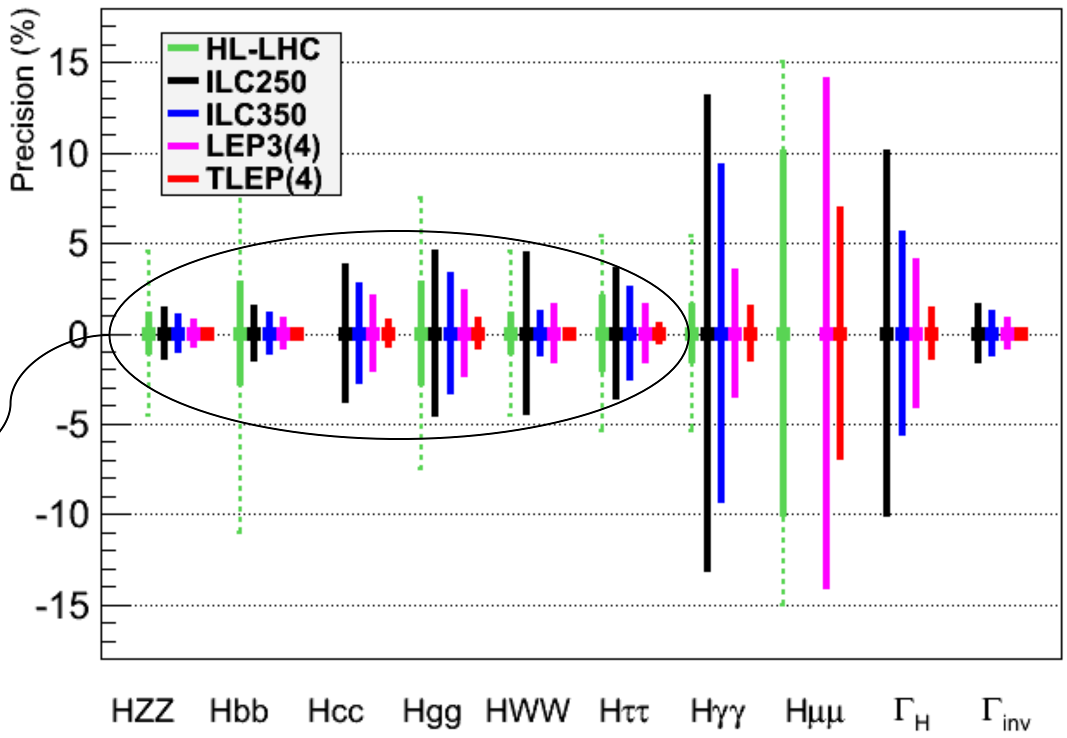
➨ LEP3 would be an advantageous back-up : larger lumi, several IP, smaller cost

[11,16,17]

Higgs couplings for Precision Higgs Factories (4)

- **Same assumptions as for HL-LHC for a sound comparison**
  - No exotic decay, Standard Model decay width

$$\sigma_{HZ} \propto g^2_{HZZ}, \text{ and } \ \sigma_{HZ} \times \mathrm{BR}(H \to XX) \propto g^2_{HZZ}\, g^2_{HXX} / \Gamma_H$$



See zoom
Next page

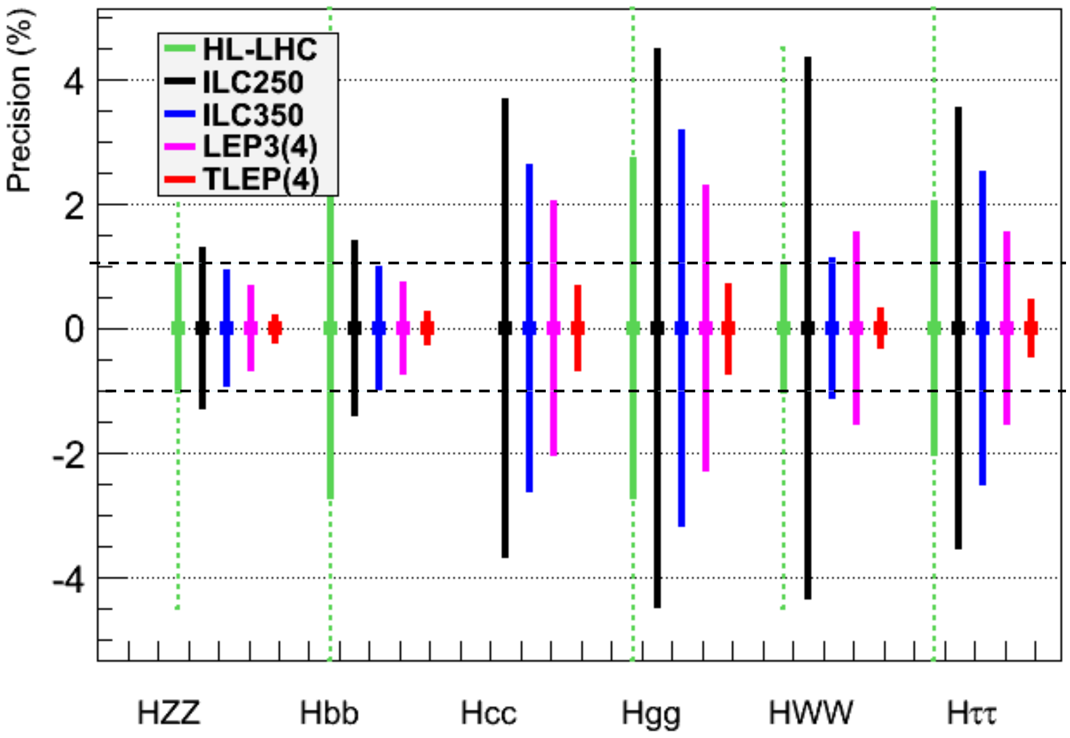
➨ TLEP would be a superior option (see zoom next page)

[11,16,17]

Higgs couplings for Precision Higgs Factories (5)

- **Same assumptions as for HL-LHC for a sound comparison**
  - No exotic decay, Standard Model decay width

$$\sigma_{HZ} \propto g^2_{HZZ}, \text{ and } \sigma_{HZ} \times \mathrm{BR}(H \to XX) \propto g^2_{HZZ} g^2_{HXX} / \Gamma_H$$



±1%

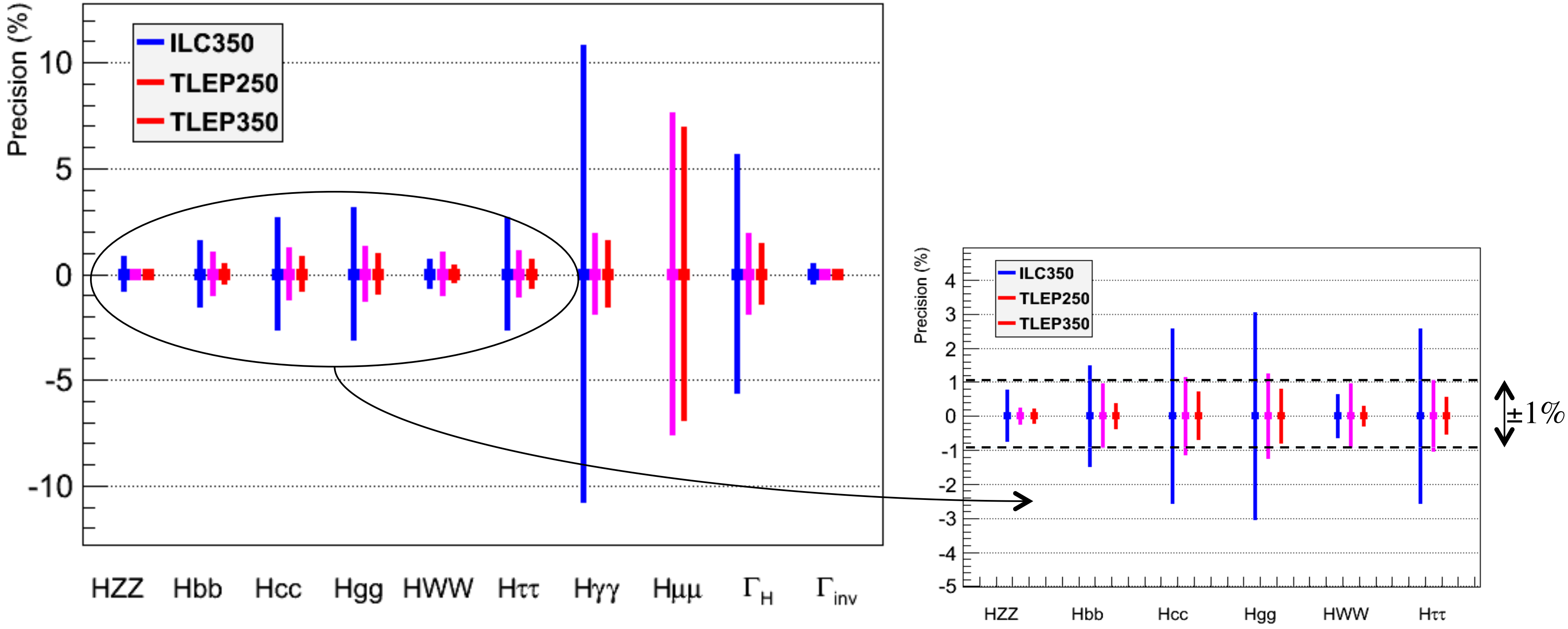
➨ TLEP : sub-percent precision, needed for NP sensitivity beyond 1 TeV

[11,16,17,18]

Higgs couplings for Precision Higgs Factories (6)

- **Same conclusion when Γ_H is a free parameter in the fit**
  - Plot shown only for ILC350 and TLEP, with an accurate width measurement

$$\sigma_{HZ} \propto g^2_{HZZ}, \text{ and } \sigma_{HZ} \times \mathrm{BR}(H \to XX) \propto g^2_{HZZ} g^2_{HXX} / \Gamma_H$$



➨ TLEP : sub-percent precision, adequate for NP sensitivity beyond 1 TeV

[19]

Higgs couplings for Precision Higgs Factories (7)

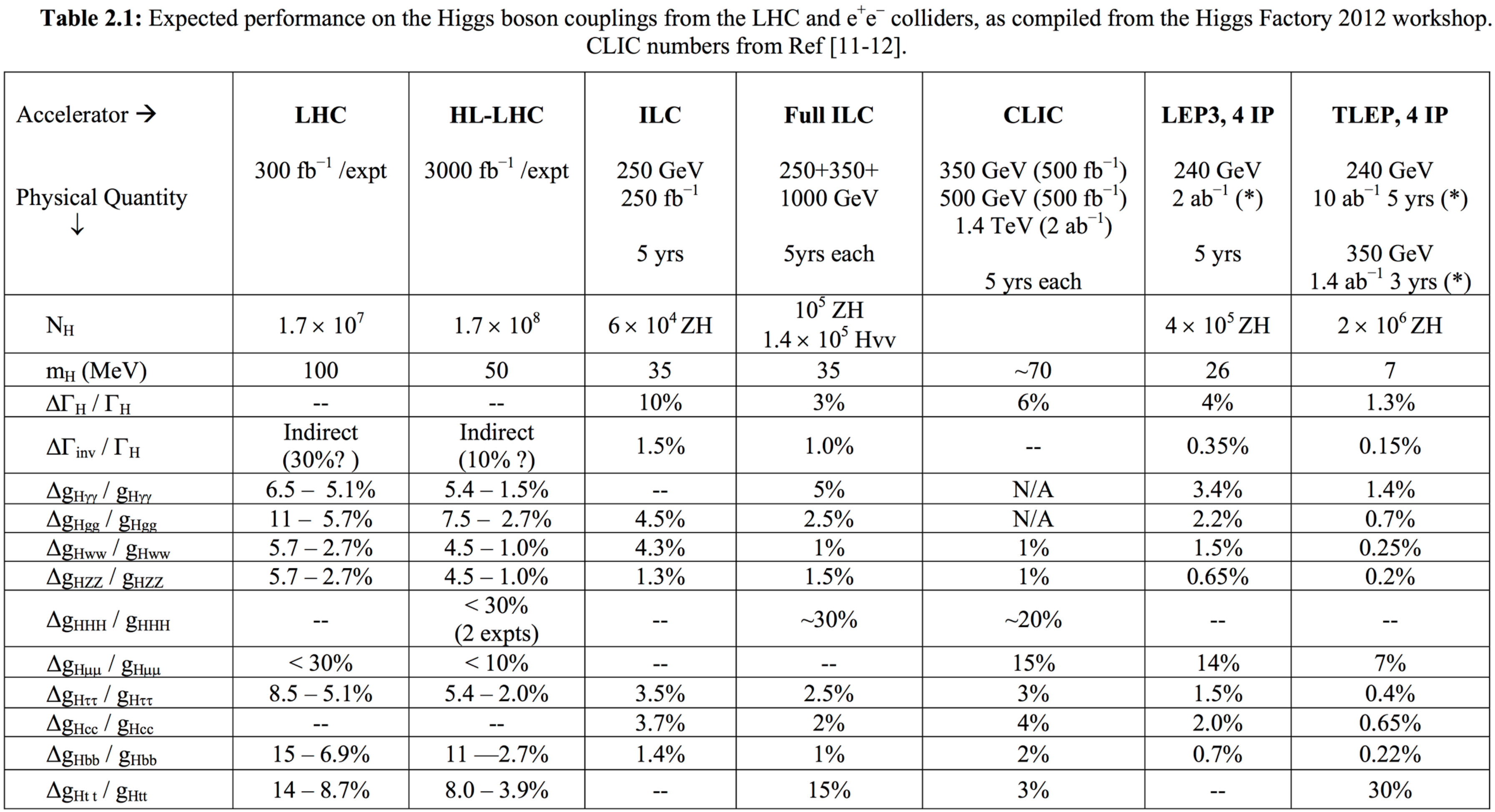


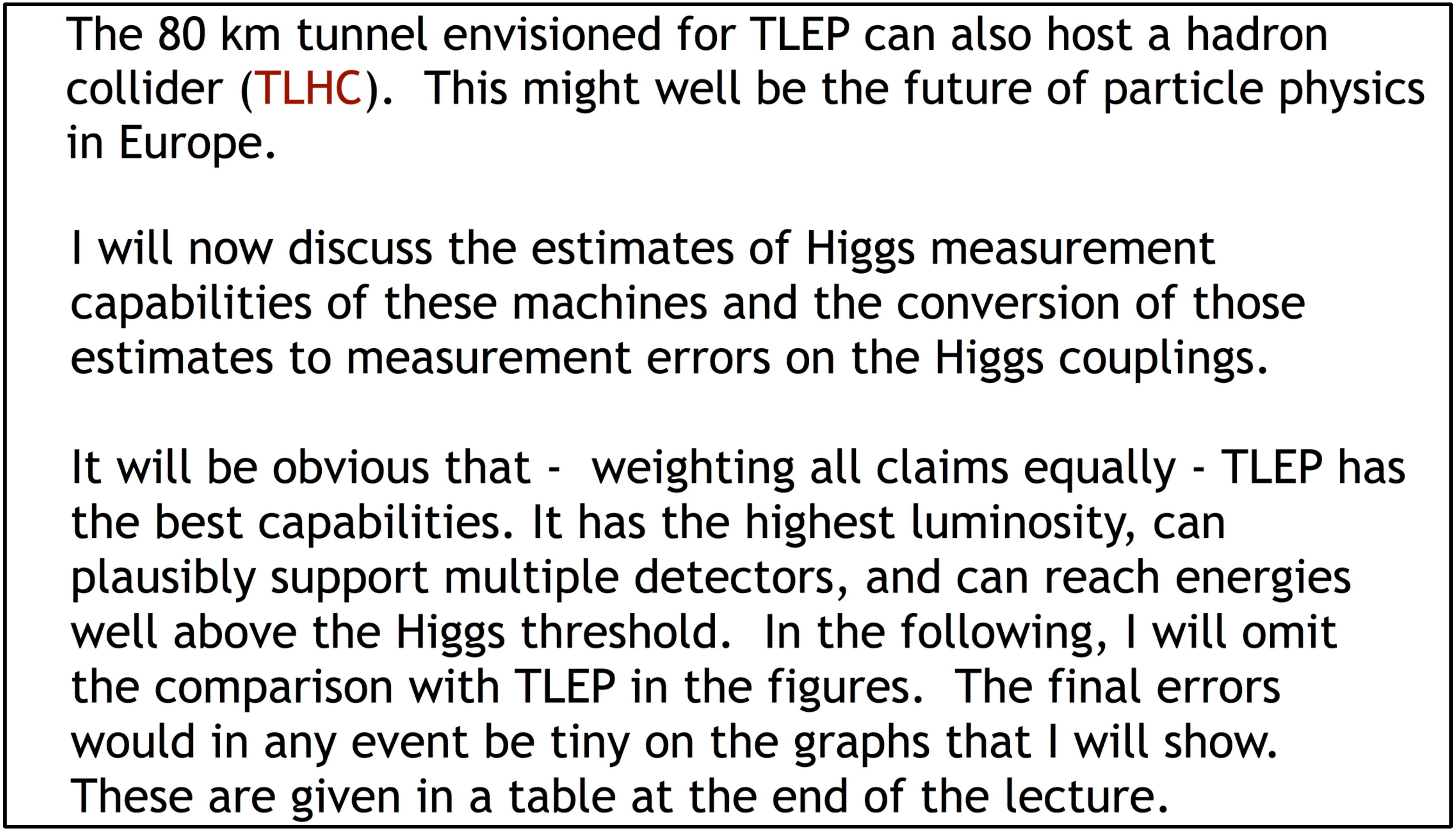
Table 2.1: Expected performance on the Higgs boson couplings from the LHC and e^+e^- colliders, as compiled from the Higgs Factory 2012 workshop. CLIC numbers from Ref [11-12].

Accelerator → Physical Quantity ↓	**LHC** 300 fb^{-1} /expt	**HL-LHC** 3000 fb^{-1} /expt	**ILC** 250 GeV 250 fb^{-1} 5 yrs	**Full ILC** 250+350+ 1000 GeV 5yrs each	**CLIC** 350 GeV (500 fb^{-1}) 500 GeV (500 fb^{-1}) 1.4 TeV (2 ab^{-1}) 5 yrs each	**LEP3, 4 IP** 240 GeV 2 ab^{-1} (*) 5 yrs	**TLEP, 4 IP** 240 GeV 10 ab^{-1} 5 yrs (*) 350 GeV 1.4 ab^{-1} 3 yrs (*)
N_H	1.7×10^7	1.7×10^8	6×10^4 ZH	10^5 ZH 1.4×10^5 Hvv		4×10^5 ZH	2×10^6 ZH
m_H (MeV)	100	50	35	35	~70	26	7
$\Delta\Gamma_H / \Gamma_H$	--	--	10%	3%	6%	4%	1.3%
$\Delta\Gamma_{inv} / \Gamma_H$	Indirect (30%?)	Indirect (10% ?)	1.5%	1.0%	--	0.35%	0.15%
$\Delta g_{H\gamma\gamma} / g_{H\gamma\gamma}$	6.5 – 5.1%	5.4 – 1.5%	--	5%	N/A	3.4%	1.4%
$\Delta g_{Hgg} / g_{Hgg}$	11 – 5.7%	7.5 – 2.7%	4.5%	2.5%	N/A	2.2%	0.7%
$\Delta g_{Hww} / g_{Hww}$	5.7 – 2.7%	4.5 – 1.0%	4.3%	1%	1%	1.5%	0.25%
$\Delta g_{HZZ} / g_{HZZ}$	5.7 – 2.7%	4.5 – 1.0%	1.3%	1.5%	1%	0.65%	0.2%
$\Delta g_{HHH} / g_{HHH}$	--	< 30% (2 expts)	--	~30%	~20%	--	--
$\Delta g_{H\mu\mu} / g_{H\mu\mu}$	< 30%	< 10%	--	--	15%	14%	7%
$\Delta g_{H\tau\tau} / g_{H\tau\tau}$	8.5 – 5.1%	5.4 – 2.0%	3.5%	2.5%	3%	1.5%	0.4%
$\Delta g_{Hcc} / g_{Hcc}$	--	--	3.7%	2%	4%	2.0%	0.65%
$\Delta g_{Hbb} / g_{Hbb}$	15 – 6.9%	11 —2.7%	1.4%	1%	2%	0.7%	0.22%
$\Delta g_{Htt} / g_{Htt}$	14 – 8.7%	8.0 – 3.9%	--	15%	3%	--	30%

[20]

Higgs couplings for Precision Higgs Factories (8)

- **A slide from M. Peskin at the 3rd TLEP/LEP3 Worskshop (10-Jan-2013)**



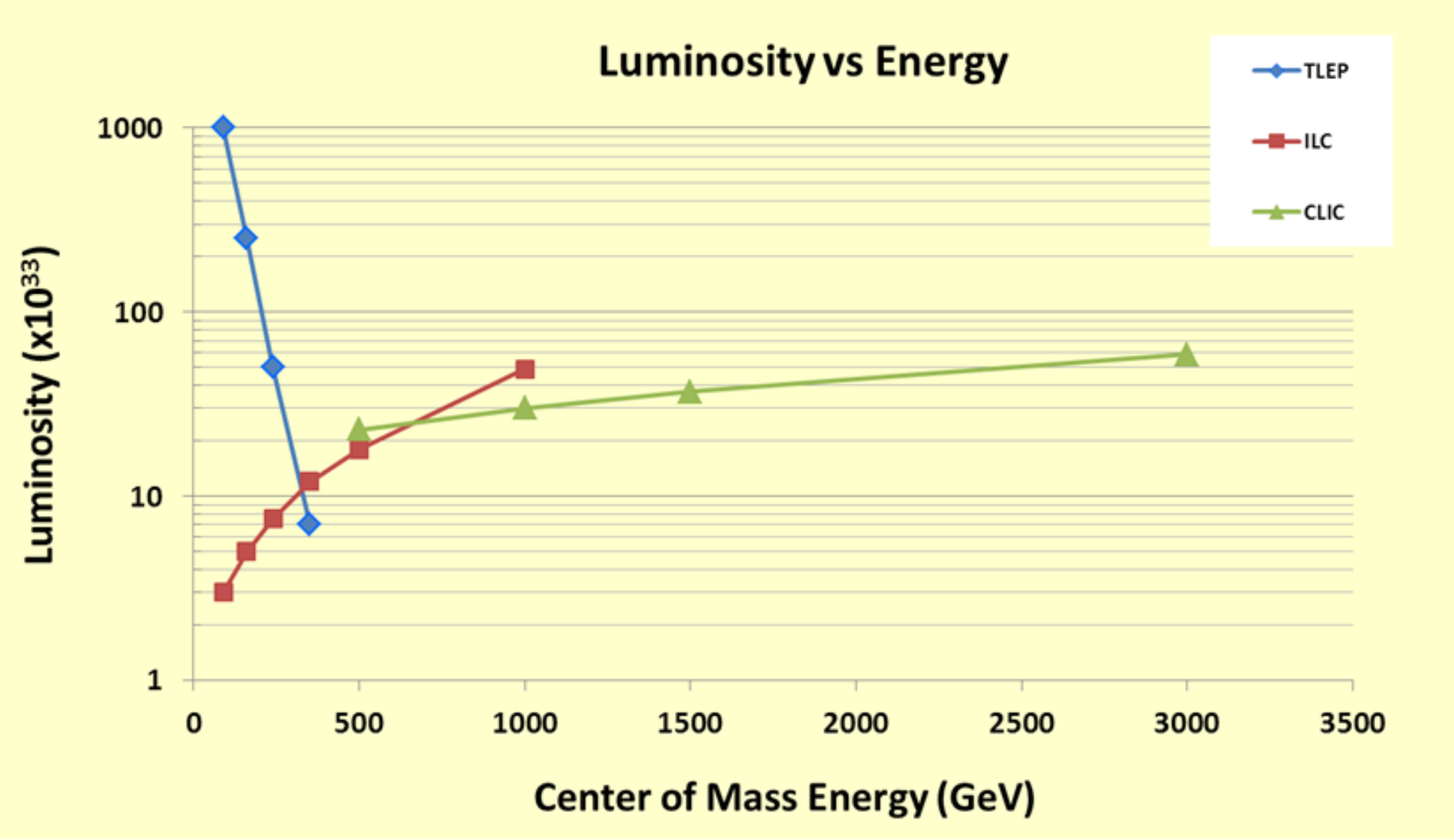
The 80 km tunnel envisioned for TLEP can also host a hadron collider (TLHC). This might well be the future of particle physics in Europe.

I will now discuss the estimates of Higgs measurement capabilities of these machines and the conversion of those estimates to measurement errors on the Higgs couplings.

It will be obvious that - weighting all claims equally - TLEP has the best capabilities. It has the highest luminosity, can plausibly support multiple detectors, and can reach energies well above the Higgs threshold. In the following, I will omit the comparison with TLEP in the figures. The final errors would in any event be tiny on the graphs that I will show. These are given in a table at the end of the lecture.

Measurements at smaller √s (1)

- Larger luminosity at smaller √s for circular colliders
  - Use the RF power to accelerate more bunches : L ~ $1/E^4$
    - Crossing point with ILC at √s ~ 350 GeV

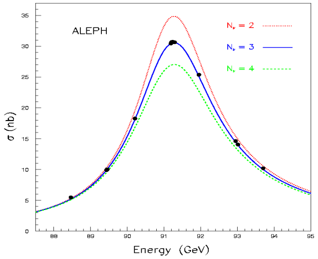


Measurements at smaller √s (2)

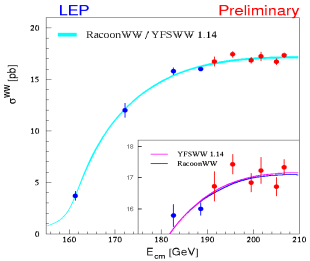
- **Revisit and improve the LEP precision measurements**
  - Can do the entire LEP1 physics programme
    - In 5 minutes (TLEP) ; in 1h (LEP3); or in a week (ILC)
  - Huge potential in a year of TLEP (LEP3) at √s = m_Z or $2m_W$:

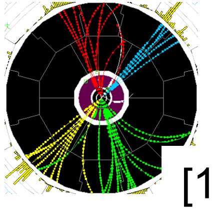
	LEP	ILC	LEP3	TLEP
√s ~ m_Z	MegaZ	GigaZ	~TeraZ	TeraZ
Lumi ($cm^{-2}s^{-1}$) #Z / IP / year Polarization vs LEP1	Few 10^{31} 2×10^7 no 1	Few 10^{33} Few 10^9 easy ~5-10	Few 10^{35} Few 10^{11} maybe ~50	10^{36} 10^{12} maybe ~100
√s ~ $2m_W$				
Lumi ($cm^{-2}s^{-1}$) Lumi / IP / year Error on m_W	Few 10^{31} 10 pb^{-1} 220 MeV	Few 10^{33} 50 fb^{-1} 7 MeV	5×10^{34} 500 fb^{-1} 0.7 MeV	2.5×10^{35} 2.5 ab^{-1} 0.4 MeV
√s ~ 200-250 GeV				
Lumi ($cm^{-2}s^{-1}$) Lumi / IP / 5 years Error on m_W	10^{32} 500 pb^{-1} 33 MeV	5×10^{33} 250 fb^{-1} 3 MeV	10^{34} 500 fb^{-1} 1 MeV	5×10^{34} 2.5 ab^{-1} 0.4 MeV

Asymmetries, Lineshape



WW threshold



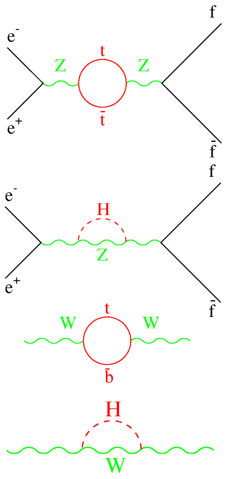


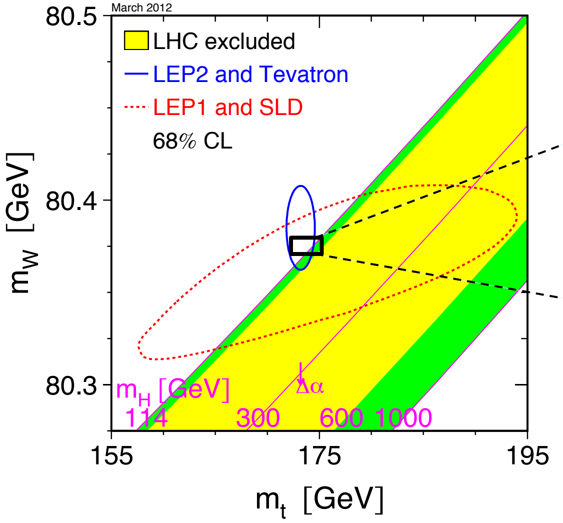
[15,16]

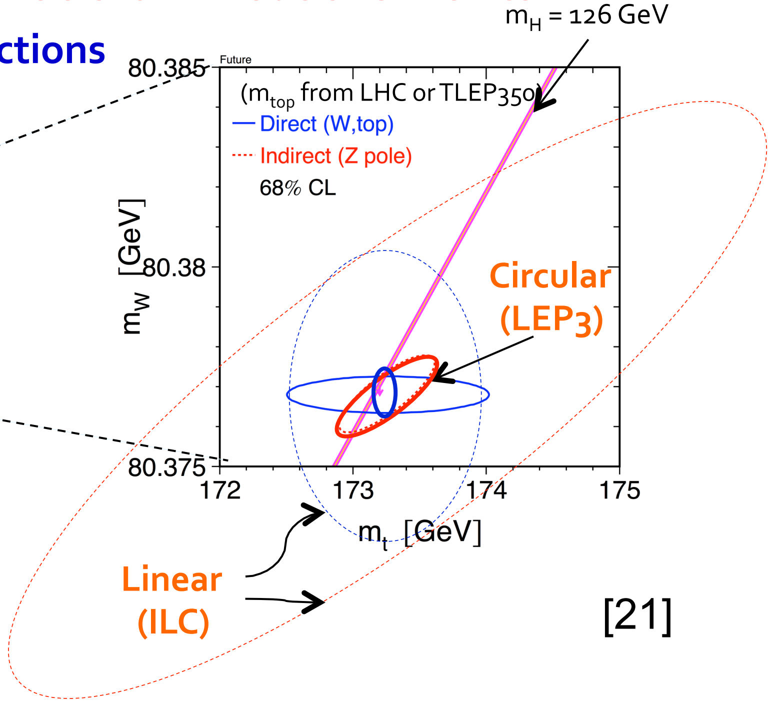
Measurements at smaller √s (3)

- **Would open a whole new book in EWSB precision measurements**
  - Case 1 : Only SM physics in EW Radiative Corrections

$$m_W = m_Z \cos\theta_W$$



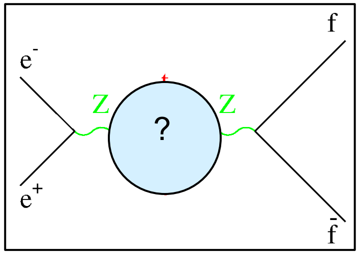




[21]

- With TeraZ and m_W to 0.3 MeV at TLEP :
  - ➨ Predicts m_{top} to 100 MeV (SM) - was 10 GeV at LEP.
- With m_{top} and m_H measured at TLEP240/350:
  - ➨ SM accurate closure test

- Case 2 : Some weakly interacting new physics in the loops ?
  - Will cause inconsistency between the various observables



Measurements at smaller $\sqrt{s}$ (4)

- Experimental challenges are numerous : TLEP(Z) [22,23]
  - At TLEP(Z), the hadronic Z event rate will be 30 kHz
    - Same rate of bunch crossings as at LHC (40 MHz)
    - CMS current high-level trigger rate is about 1 kHz
      - (But hadronic Z events typically 20 times smaller than typical LHC event)
    - Need to design a detector and a DAQ system able to cope with these rates
      - A clever mixture of LHC detector (rate) and ILC detector (precision)
        - Need to study what is the precision needed for each sub-detectors
        - Is a CMS-like detector sufficient ? (~OK for Higgs studies)
  - Small angle Bhabha event rate (lumi measurement) will be even larger
    - Essential to measure cross sections, hence the Z lineshape (m_Z, Γ_Z)
      - Negligible beamstrahlung is a great advantage
        - No background in the luminometers
        - Energy spectrum perfectly known (hence Bhabha cross section)
      - Will need theoretical developments to understand σ_{e+e-} to better than 5×10^{-5}
  - Limiting uncertainties on $\alpha_{QED}(m_Z)$ and $\alpha_s(m_Z)$ must be overcome
    - Possible with the billions of $e^+e^- \rightarrow e^+e^-\gamma$, $\mu^+\mu^-\gamma$ and $q\bar{q}g$ events ?
      - Will affect all Z peak asymmetries, and m_Z vs m_W interpretation

Measurements at smaller √s (5)

- ❑ Experimental challenges are numerous : TLEP(Z)
  - ◆ Z lineshape needs a precise beam energy measurement
    - Resonant depolarization unique @ circular machines
      - ➨ Intrinsic precision ~ 100 keV (LEP1) / measurement

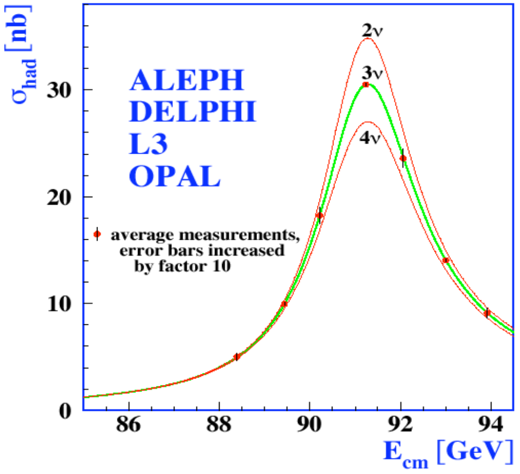
        Decreases like 1 / √#(Measurements)
    - Requires beam transverse polarization
      - ➨ In one non-colliding bunch, during operations

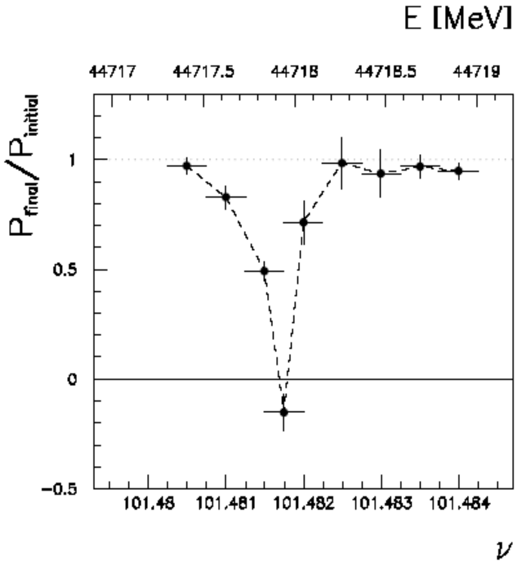
        Continuous energy measurement

        No extrapolation needed (tides, trains, rain…)
    - Will require installation of polarization wigglers
      - ➨ Natural polarization time ~ 150 h at TLEP …
  - ◆ Polarized asymmetry (A_{LR}) requires longitudinal polarization
    - Hence spin rotators and polarimeters at each IP
      - ➨ Then need to keep polarization in collisions

        That's the main unknown

        Dedicated operations with lower luminosity ?
    - Dedicated study is needed here

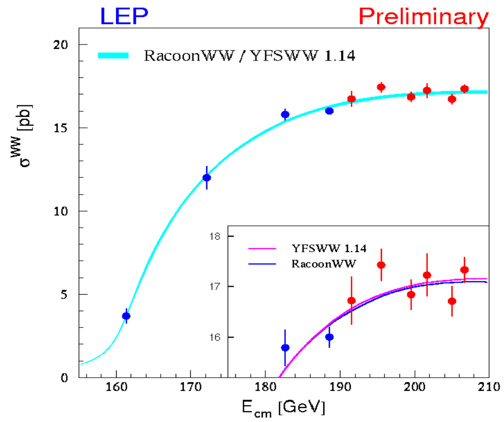


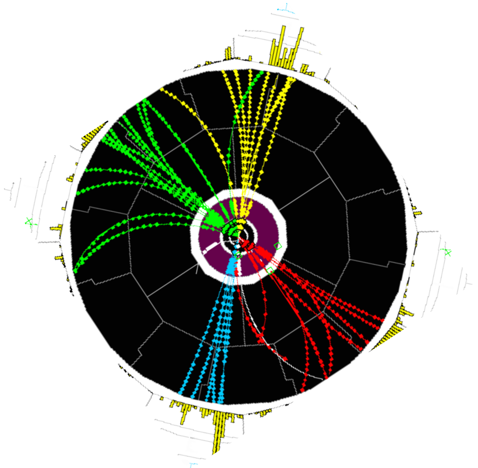


[22,23]

Measurements at smaller $\sqrt{s}$ (6)

- Experimental challenges are numerous : m_W at TLEP(W) and TLEP(H) [22]
  - With 2.5 ab^{-1} at TLEP(W) and 10^7 WW events/expt at threshold : $\sigma(m_W)$ ~ 0.4 MeV
  - With 2.5 ab^{-1} at TLEP(H), 4×10^7 W pairs/expt : $\sigma(m_W)$ ~ 0.2 MeV





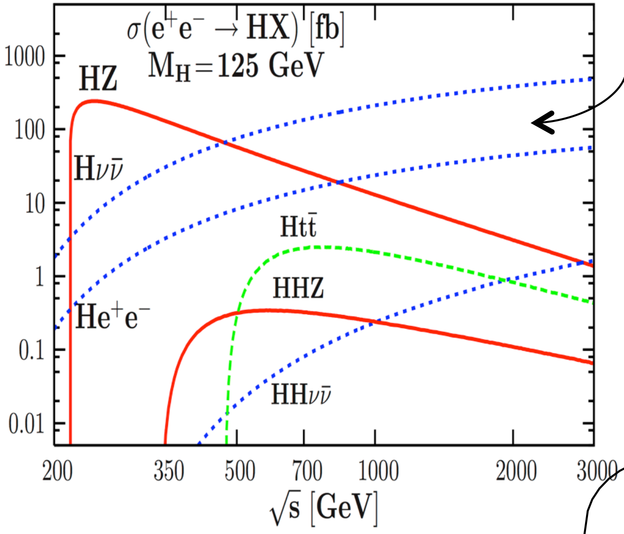
  - Need to know beam energy to few 0.1 MeV, but no beam polarization at these energies
    - Use the precision Z mass measurement from the Z pole
      - With 5×10^7 Z(γ) events ($Z \rightarrow e^+e^-, \mu^+\mu^-$) / expt at TLEP(W)
      - With 2×10^6 Z pairs and 5×10^6 Z(γ) events ($Z \rightarrow e^+e^-, \mu^+\mu^-$) / expt at TLEP(H)

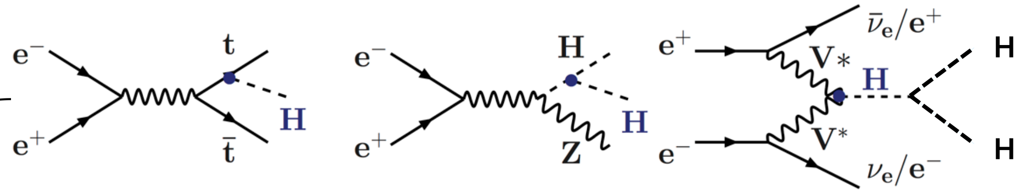
        Can reach combined statistical precision on E_{beam} of 0.2 MeV and 0.4 MeV
    - Need to understand all systematic effects that would affect the measurement
      - Both theoretical and experimental

Upgradeability at larger √s (1)

- **All existing proposals have access to larger √s** [24]
  - To discover New Physics in a direct manner
  - To measure more difficult Higgs couplings : g_{Htt} and g_{HHH}
    - ILC350 can be upgraded to ILC500/ILC1TeV, or even to CLIC (3 TeV)
    - LEP3 can be upgraded to (or preceded by) HE-LHC (33 TeV)
    - TLEP can be upgraded to SHE-LHC (100 TeV)

Cross sections in e^+e^- collisions



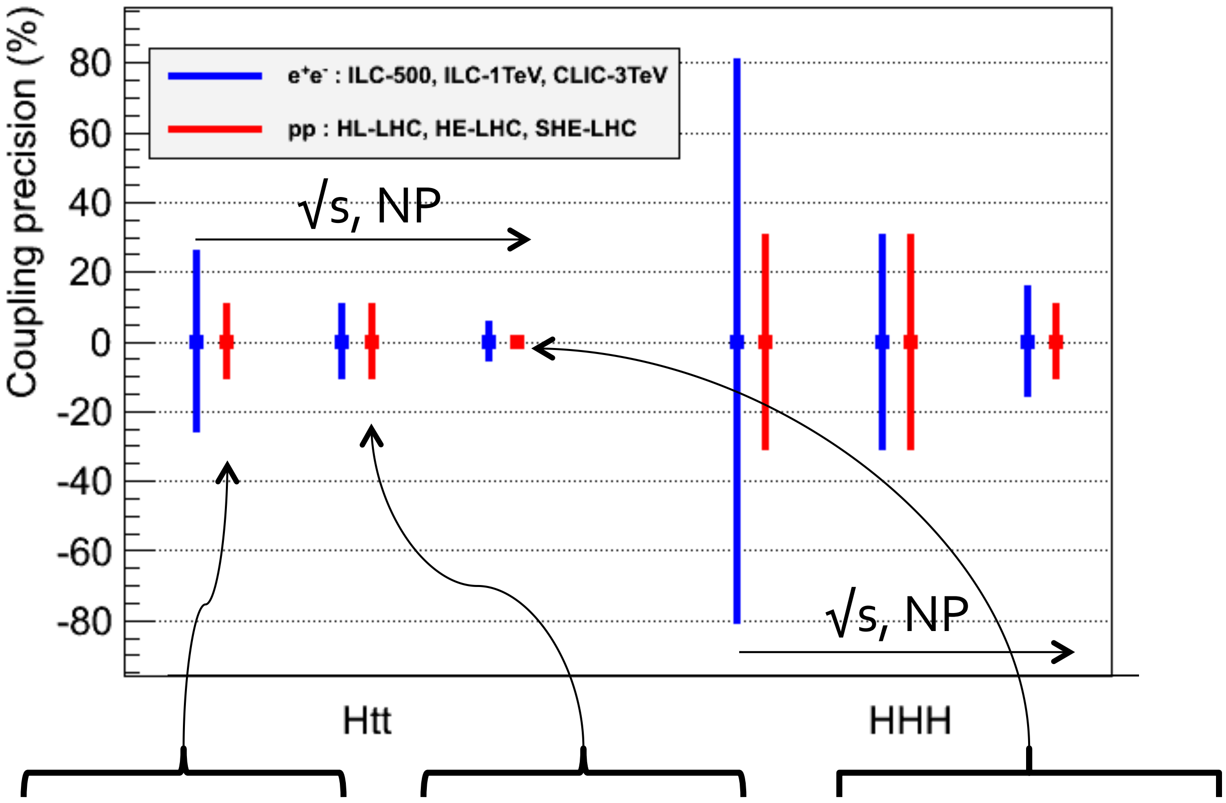


Cross sections in pp collisions

	σ(14 TeV)	R(33)	R(40)	R(60)	R(80)	R(100)
ggH	50.4 pb	3.5	4.6	7.8	11.2	14.7
VBF	4.40 pb	3.8	5.2	9.3	13.6	18.6
WH	1.63 pb	2.9	3.6	5.7	7.7	9.7
ZH	0.90 pb	3.3	4.2	6.8	9.6	12.5
ttH	0.62 pb	7.3	11	24	41	61
HH	33.8 fb	6.1	8.8	18	29	42

Upgradeability at larger √s (2)

- **Summary for Htt and HHH couplings** [11,12,25,26,27]
  - Other Higgs couplings benefit marginally from high energy



ILC500, HL-LHC

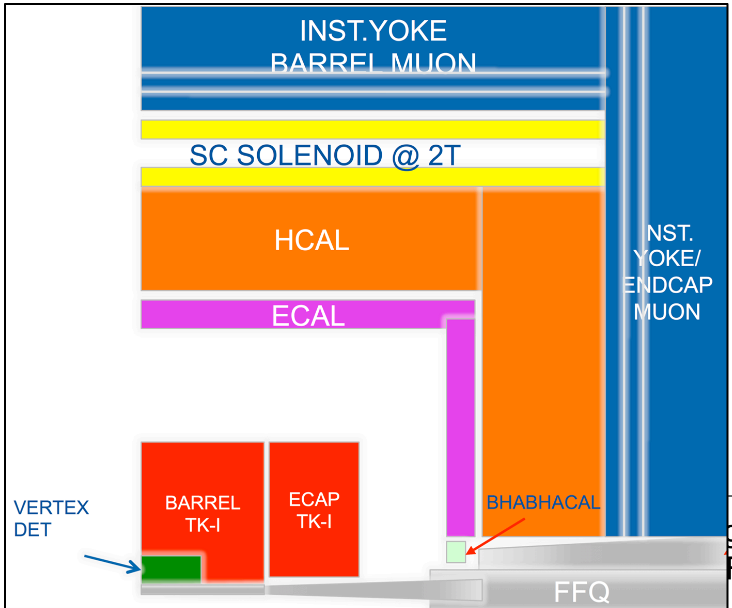
ILC1TeV, HE-LHC

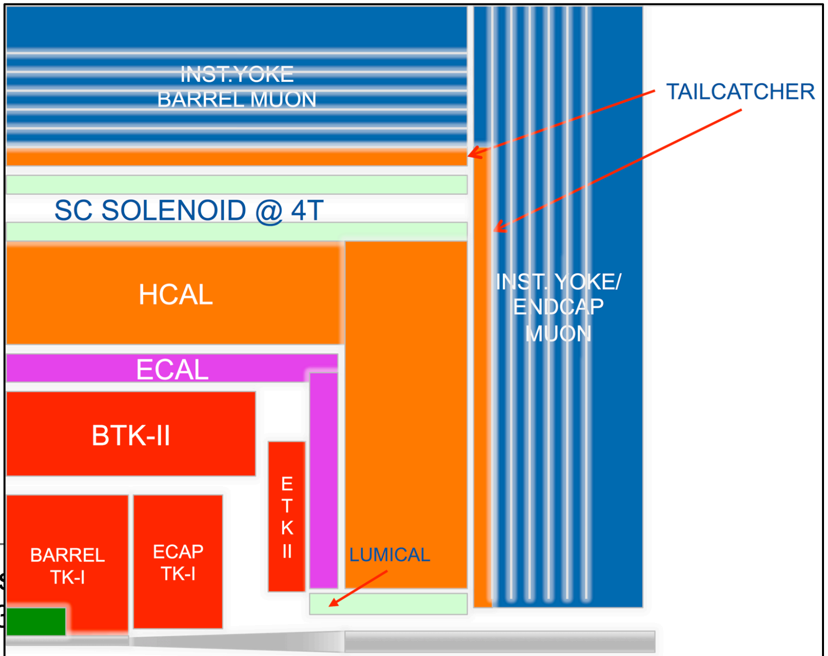
CLIC3TeV, SHE-LHC

- For similar new physics reach, similar ttH/HHH precision with pp and e^+e^- colliders

Detectors for TLEP and LEP3 (1)

- For LEP3, obvious detectors are CMS and ATLAS [28]
  - CMS demonstrated to be adequate with today's design + upgraded pixel detector
    - Phase 2 upgrades : LEP3 could be seen as an alternative to HL-LHC
    - Tunnel By-passes need to be dug out for the accelerating ring
- For TLEP, new detectors are in order (used CMS for Higgs studies in this talk)
  - Holistic view : design caverns and detectors to be re-used in pp collisions (as new)
    - TeraZ sets the scale for DAQ (2600 bunches) + forward EM calorimetry (lumi)
    - TLEP(H) sets the scale for precision (tracker, ECAL, particle flow, b tagging)
    - SHE-LHC sets the scale for magnetic field, calorimeter depths, tracker p_T reach
      - ➨ Could envision a staged approach





Detectors for TLEP and LEP3 (2)

- **Basic requirements (examples)** [28]
  - Vertex detector with impact parameter resolution ~ 5 μm (CMS : 20 μm)
    - For b and c tagging
      - ➨ Very large number of channels (cf ILC)
  - Tracker detector with $\sigma(p_T)/p_T^2 \sim 10^{-5}$ (CMS : 10^{-4})
    - For precise recoil mass determination in $(Z \to l^+l^-) + H$ and in $H \to \mu^+\mu^-$
      - ➨ All silicon, with large number of channels
  - ECAL resolution of the order of 1% at 60 GeV (~same as CMS)
    - For $H \to \gamma\gamma$ (and all decays with electrons : WW, ZZ, $\tau\tau$)
  - ECAL and HCAL with decent transverse and longitudinal segmentation, inside the coil
    - For Particle Flow towards HZ and WW → H discrimination (and precise jets, p_{miss})
      - ➨ Study trade-offs between ILC proposals and CMS crystals
  - Efficient and pure muon Id
    - For $H \to ZZ, W^+W^-, \mu^+\mu^-, \tau^+\tau^-$
  - Extremely fast DAQ
    - Detector with ~10^{10} channels
      - ➨ TLEP-H : low occupancy, zero suppression, read out each BX (100 kHz)

Simple trigger needed for TeraZ (40 MHz -> 100 kHz)

Possible Timescales

- Similar timescales for TLEP and LEP3

- TLEP
  - Design study : 2013-2017
  - Next European Strategy Workshop : 2017-2018
  - Decision to go and start digging : 2018-2019
  - Start installation in parallel with HL-LHC running : 2023 - …
  - Start running at the end of HL-LHC running : 2030 - …

- LEP3
  - Design study : 2013-2017 (spin-off of TLEP design study)
  - Next European Strategy Workshop : 2017-2018
  - Decision to go : 2018-2019
  - Start installation at the end of LHC running : 2022 - …
    - Tunnel probably irradiated at the end of HL-LHC
      - ➨ LEP3 is an alternative of HL-LHC, and could be followed by HE-LHC in 2040
  - Start running when ready : 2027 - …

Cost (can be wrong by a factor 2)

LEP3 : A cost-effective option

- Tunnel : 0 \$ - Cryoplant : 0\$
- Two detectors : 0\$ - Four detectors : 1 G\$
- RF + Magnets + Injector Ring : 1 G\$

Total : 1 – 2 G\$

- 100,000 Higgs boson / detector / 5 years @ 240 GeV : 5 k\$ / Higgs boson

TLEP : A long-term vision

- Tunnel : 3 G\$ - Cryoplant : 1 G\$
- Four detectors : 2 G\$
- RF + Magnet + Injector Ring : 1 G\$

Total : 7 G\$

of which 6 G\$ in common with SHE-LHC

- 500,000 Higgs boson / detector / 5 years @ 240 GeV : < 3.5 k\$ / Higgs boson

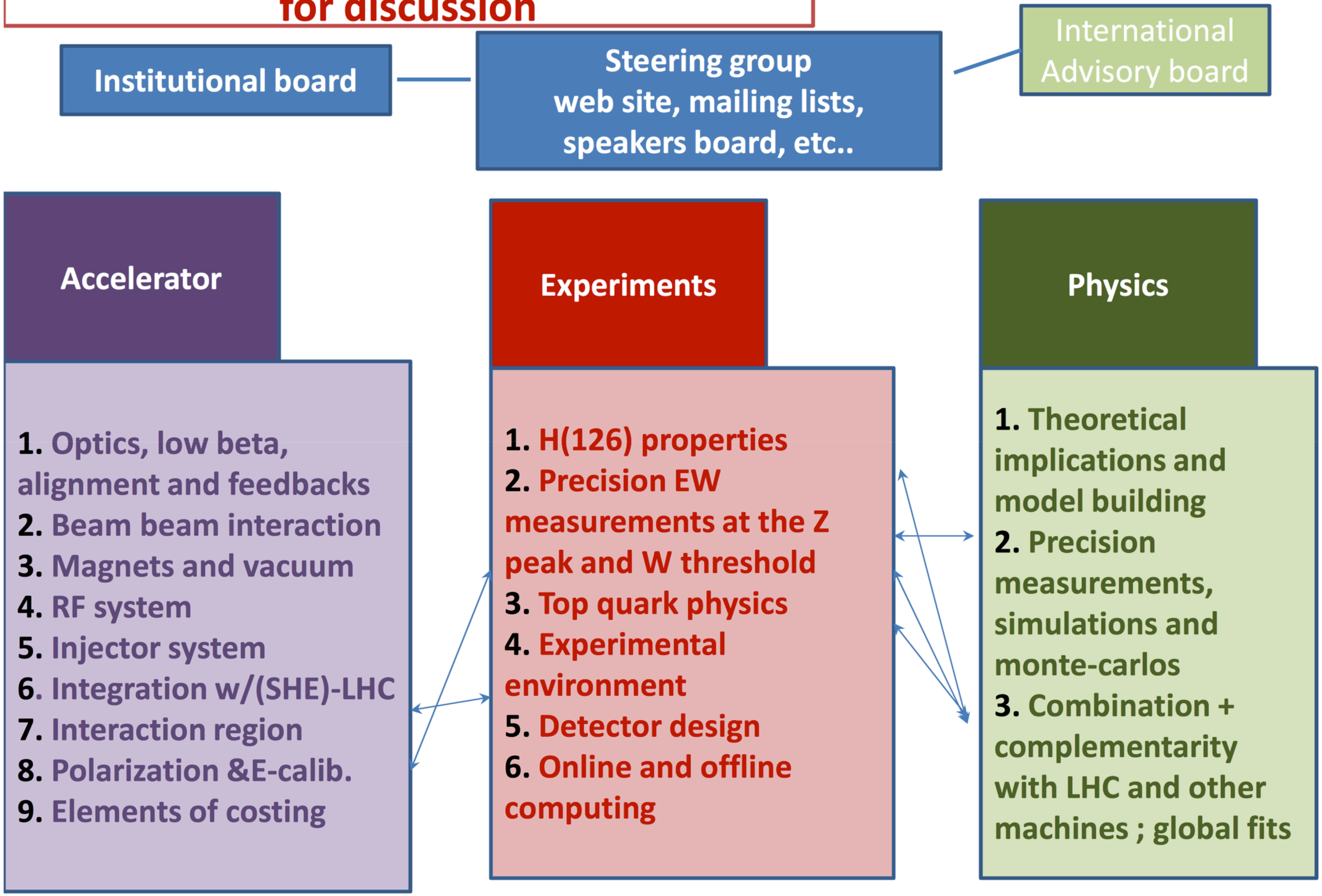
Comparison with ILC

- Total Cost : ~ 10 G\$
- 70,000 Higgs boson / 5 years @ 240 GeV

150 k\$ / Higgs boson

Possible Work Packages

TLEP design study –preliminary structure for discussion



Institutional board

Steering group
web site, mailing lists, speakers board, etc..

International Advisory board

Accelerator

1. Optics, low beta, alignment and feedbacks
2. Beam beam interaction
3. Magnets and vacuum
4. RF system
5. Injector system
6. Integration w/(SHE)-LHC
7. Interaction region
8. Polarization &E-calib.
9. Elements of costing

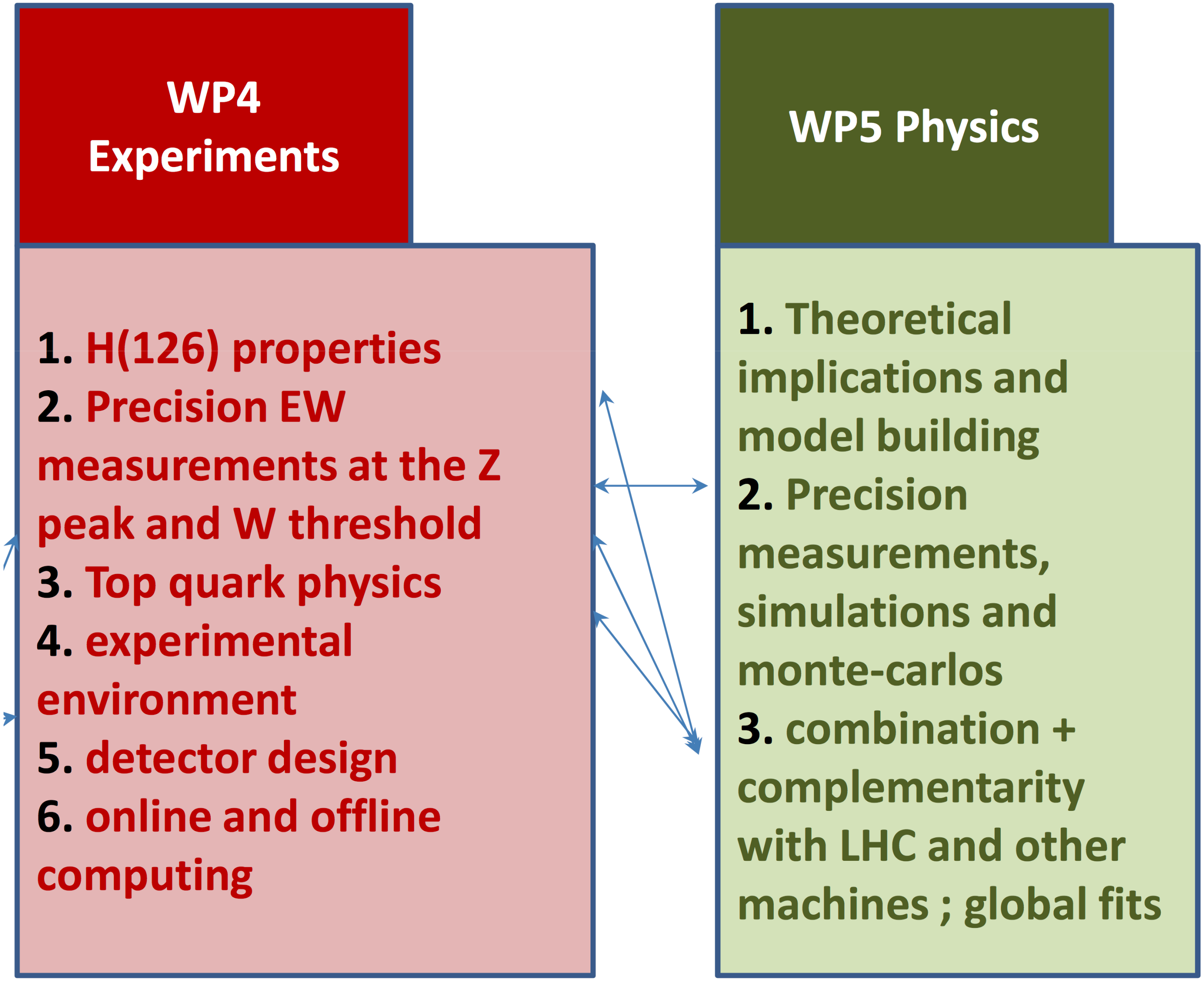
Experiments

1. H(126) properties
2. Precision EW measurements at the Z peak and W threshold
3. Top quark physics
4. Experimental environment
5. Detector design
6. Online and offline computing

Physics

1. Theoretical implications and model building
2. Precision measurements, simulations and monte-carlos
3. Combination + complementarity with LHC and other machines ; global fits

Possible Work Packages



WP4 Experiments

1. H(126) properties
2. Precision EW measurements at the Z peak and W threshold
3. Top quark physics
4. experimental environment
5. detector design
6. online and offline computing

WP5 Physics

1. Theoretical implications and model building
2. Precision measurements, simulations and monte-carlos
3. combination + complementarity with LHC and other machines ; global fits

Conclusions (1)

- A very much SM-like Higgs boson was discovered at the LHC
  - So far with no evidence of BSM Physics or of an extended Higgs sector
    - Up to a scale of several hundred GeV to 1 TeV

- A sub-per-cent precision Higgs factory will be critical
  - For establishing whether the SM-like boson is THE Higgs boson
  - To see whether there is any evidence for small deviations from SM predictions
  - To provide hints for the energy scale of the BSM physics that couples to the Higgs boson
  - To possibly unravel an extended Higgs sector

- Adequately high-statistics Z and W factories will also be important
  - To do the ultimate closure test of the SM from the knowledge of m_{top} and m_H
  - To probe Weakly-Interacting New Physics beyond to TeV scale

Conclusions (2)

- The LHC run at 13 TeV may revolutionize the current physics perspective
  - New discoveries will strongly influence the strategy for future collider projects
    - And so will absence of new discoveries, possibly even more strongly
      - We will know much more in 2015-2017

- Future projects should therefore encompass
  - A high-precision Higgs factory
    - Including high-statistics Z, W, and possibly top, factories
  - A high-energy-frontier facility able to study the new physics discovered at the LHC
    - And to probe much higher scales

- It is probably too early (and maybe imprudent) to decide now
  - The European Strategy Group encourages studies of e^+e^- and pp colliders at CERN
    - The TLEP + SHE-LHC package is a (the?) long term vision for Europe
    - The LEP3 + HE-LHC package would be a cost-effective back-up solution