Higgs beyond the LHC (Experiments)

- **Outline**
  - The situation today and until 2022 — See Fabio's talk
  - Measurements and Precision needed after the LHC — See Chris' talk
  - Measurements at Low-Energy Higgs Factories
  - Measurements at High-Energy Higgs Factories
  - Conclusion

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] ATLAS, "Observation of a New Particle in the Search for the SM Higgs Boson with the ATLAS Detector at the LHC", ibid 1-29

[3] F. Cerutti, "Higgs at the LHC", talk given at this meeting on behalf of ATLAS and CMS

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

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

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

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

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

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

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

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

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

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

[14] B. Autin, A. Blondel and J. Ellis, "Prospective Study of Muon Storage Rings at CERN", CERN-99-02 (1999)

[15] D.M. Kaplan, "From Neutrino Factory to Muon Collider", arXiv:1102.1591 (2011)

[16] V. Barger et al., "Physics at Higgs Factories", Snowmass-2001-E110 (2001)

[17] T. Han and Z. Liu, "Direct Measurement of the Higgs Width at a Muon Collider", arXiv:1210.7803 (2012)

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

[19] M.E. Peskin, "Comparison of LHC and ILC capabilities for Higgs boson coupling measurements",arXiv:1207.2516 (2012)

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

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

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

[23] B. Grzadkowski, J. Gunion and J. Pliszka, "Determining the CP nature of a Higgs boson", hep-ph/0003091 (2000)

[24] S.A. Bogacz et al., "SAPPHIRE: A small gg Higgs factory", arXiv:1208.2827 (2012)

[25] D. Asner et al., "Higgs Physics at a gg collider based on CLIC", arXiv:hep-ex/0111056 (2001)

[26] T. Takahashi, "Higgs pair production at a photon collider", talk given at the LCWS12 (Oct. 2012)

[27] M. Velasco, "Physics of $\gamma\gamma$ to Higgs", talk given at this meeting.

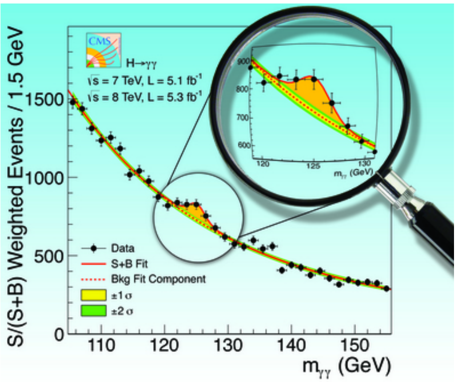
[28] T. Han and B. Mellado, "Higgs Boson Searches and the $Hb\bar{b}$ Coupling at the LHeC", arXiv:0909.2460 (2009)

[29] The LHeC Study Group, "On the Relation of the LHeC and the LHC", ESPP Contribution #175

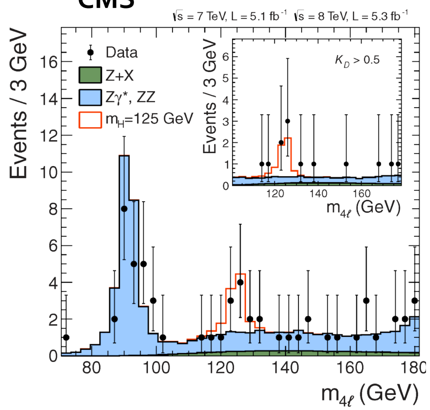
The situation today (1)

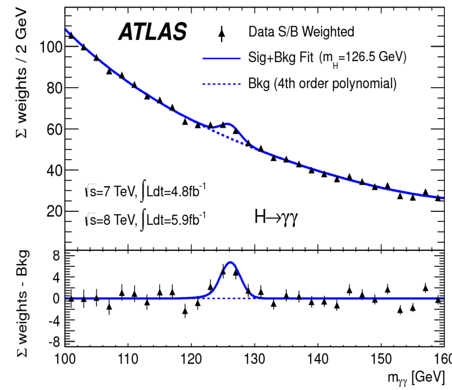
- **A new state was discovered by CMS and ATLAS, with mH = 125.5±0.5 GeV**

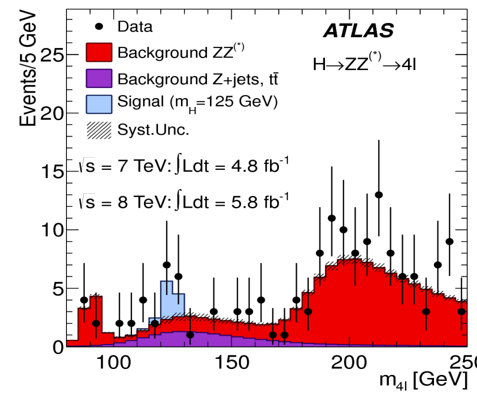
CMS



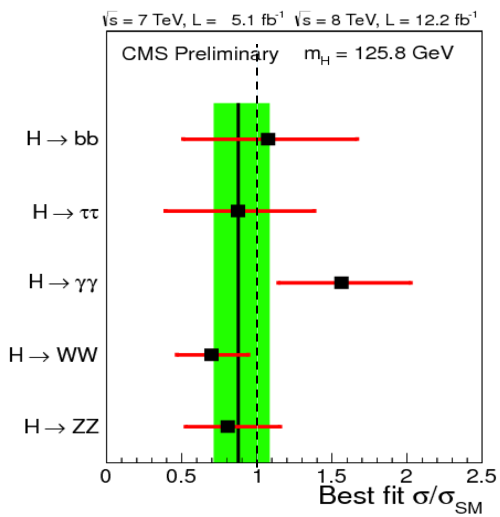
CMS

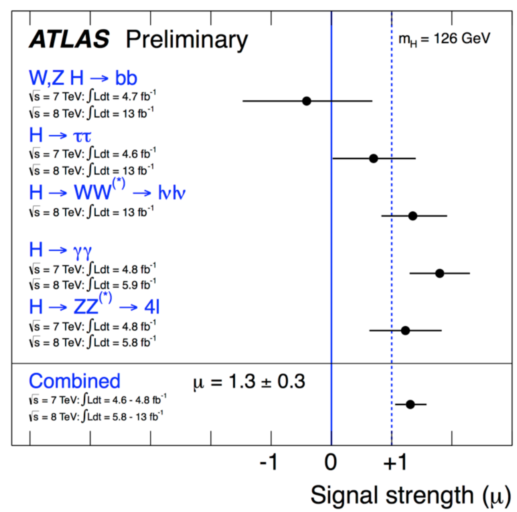






- **Decays to ZZ, γγ, WW, ττ and bb; Properties very much like those of a SM Higgs boson;**

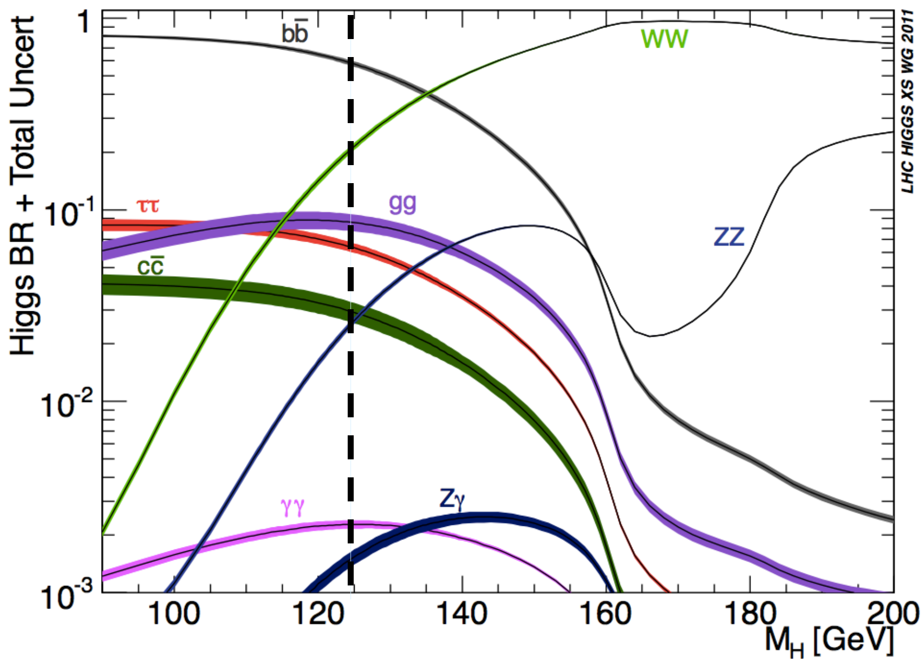




[1,2,3]

The situation today (2)

- **We are here (or thereabout):**



m_H = 125 GeV

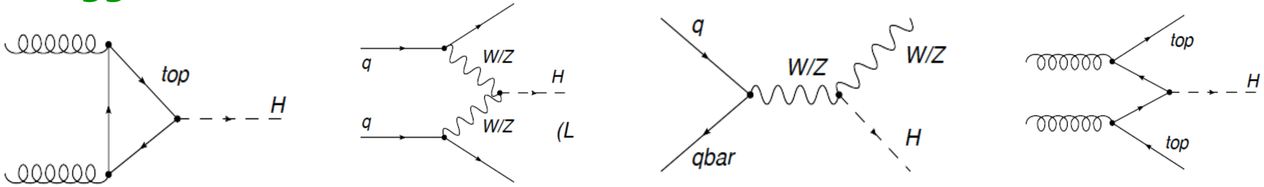
Decay	BR [%]	Unc. [%]
bb	57.9	3.
$\tau\tau$	6.4	6.
cc	2.8	12.
$\mu\mu$	0.022	6.
WW	21.6	4.
gg	8.2	10.
ZZ	2.6	4.
$\gamma\gamma$	0.27	5.
$Z\gamma$	0.16	9.
Γ_H [MeV]	4.0	4.

- **Note : The LHC is a Higgs Factory !**
  - **Total cross section at 8 TeV : 22 pb**
    - 1M Higgs already produced – more than most other Higgs factory projects.
    - 15 Higgs bosons / minute – and more to come.

[4,5]

The situation in 2022

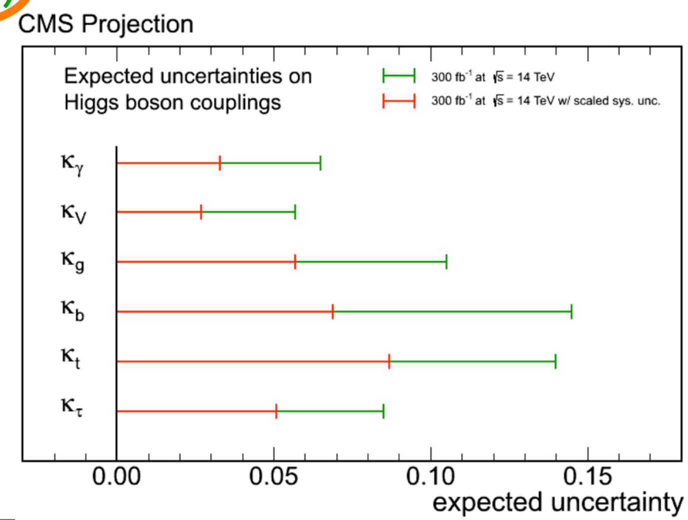
- **The approved LHC programme will be completed** [6,7]
  - With 300 fb^{-1} @ 13 TeV, CMS and ATLAS will measure five production modes
    - $gg \to H$ VBF   WH, ZH   ttH



    - … and six decay modes : $\gamma\gamma$, ZZ, WW, $\tau\tau$, bb, $\mu\mu$
  - CMS projections with 300 fb^{-1}
    - Measure $\sigma(XX)*BR(YY) = \Gamma(XX) * \Gamma(YY) / \Gamma_{tot}(H)$
      - Assume no exotic decays
      - Assume reduce set of couplings
    - Infer the following coupling accuracy
      - 10-15% on fermionic couplings
      - 5-6% on bosonic couplings
      - 5-10% on couplings through loops

      Model dependent
    - Similar performance for ATLAS

Unknown, not measureable at LHC



Measurements needed after the LHC

- We are entering the precision measurement era
  - Need to characterize the new state
    - Measurement of Higgs branching ratios and related couplings
    - Measurement of the Higgs coupling to the top quark
    - Higgs quantum numbers determination
    - Higgs mass precision measurement
    - Higgs boson self couplings
    - Total Higgs decay width
  - Need to determine the (tree-level) structure of the theory
    - Invisible Higgs decays, Exotic Higgs decays
    - Parameterization of deviations from SM through higher-order operators
  - Need to evaluate (new physics) loop-induced effects
    - Interpretation of the $H \rightarrow \gamma\gamma$ and $H \rightarrow gg$ branching fractions
    - Precision electroweak measurements
    - Precision mass measurements (W, Z, top, …)

(In purple : known to be difficult at the LHC)

(In green : some precision reached with LHC)

Precision needed after the LHC

- **New physics affects the Higgs couplings**
  - SUSY $\frac{g_{hbb}}{g_{h_{SM}bb}} = \frac{g_{h\tau\tau}}{g_{h_{SM}\tau\tau}} \simeq 1 + 1.7\% \left(\frac{1\ \text{TeV}}{m_A}\right)^2$, for tanβ = 5
  - Composite Higgs $\frac{g_{hff}}{g_{h_{SM}ff}} \simeq \frac{g_{hVV}}{g_{h_{SM}VV}} \simeq 1 - 3\% \left(\frac{1\ \text{TeV}}{f}\right)^2$
  - Top partners $\frac{g_{hgg}}{g_{h_{SM}gg}} \simeq 1 + 2.9\% \left(\frac{1\ \text{TeV}}{m_T}\right)^2, \quad \frac{g_{h\gamma\gamma}}{g_{h_{SM}\gamma\gamma}} \simeq 1 - 0.8\% \left(\frac{1\ \text{TeV}}{m_T}\right)^2$
  - Other models may give up to 5% deviations with respect to the Standard Model

- **Strongly influences the strategy for Higgs factory projects**
  - Need a per-cent to sub-per-cent accuracy on couplings
    - If new physics is at or beyond the TeV scale
  - LHC discoveries at 13 TeV may lead to an even broader horizon
    - Will strongly influence the strategy for future collider projects as well
      - ➨ Future projects need to have a physics programme beyond that of LHC

[8,9]

Low-Energy Precision Higgs Factory Concepts

- $\sqrt{s} \leq 350$ GeV : Feasible by 2025 – 2035 ?
  - Goal : Precision measurements of the new state

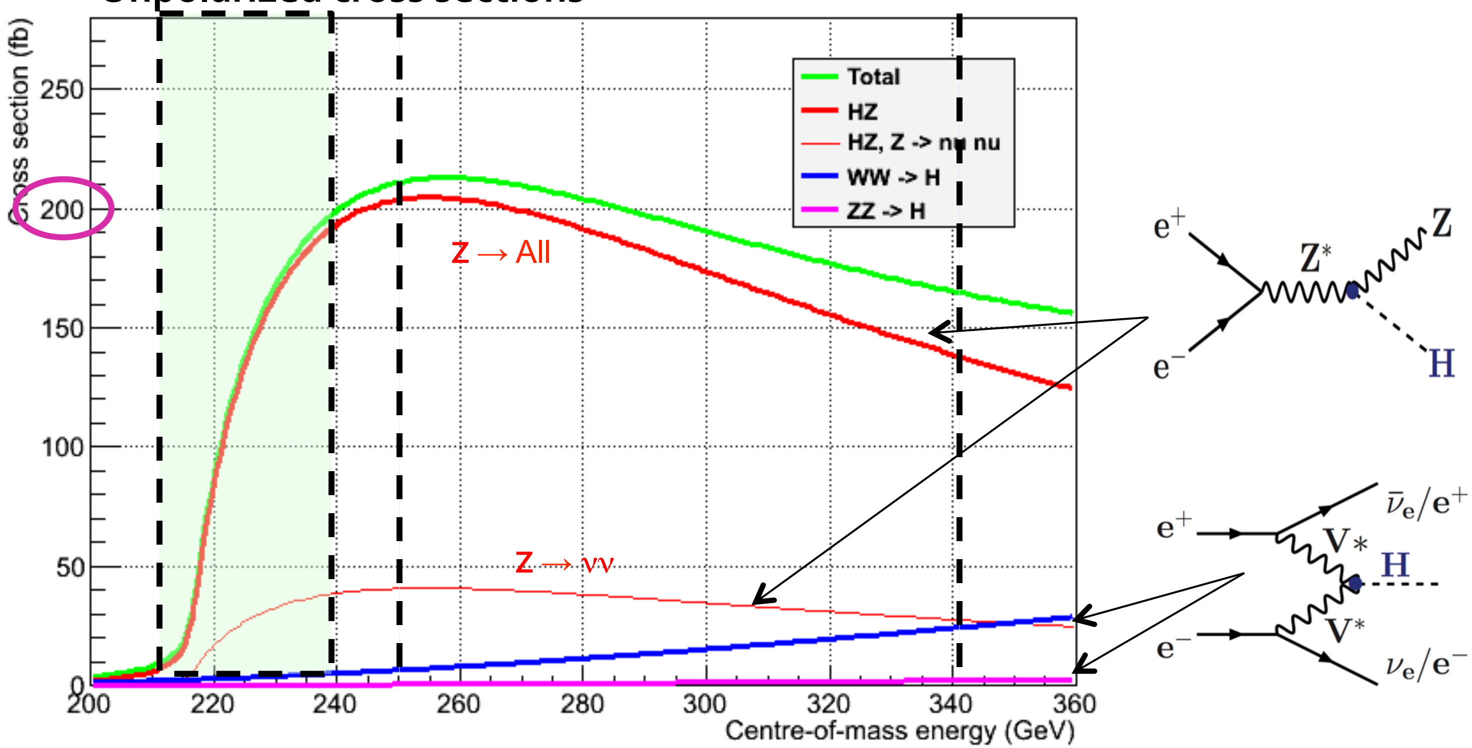
Factory	Example	√s	Benefits from	Extendable	Personal work
e^+e^- (Linear)	ILC	Phase 1 Up to 350 GeV	20 years of R&D	500 Gev (1 TeV?) GigaZ	1991-1995
e^+e^- (Circular)	LEP3	Up to 240 GeV LHC tunnel	ILC, LHeC, LHC b Factories	HL/HE-LHC, 33 TeV TeraZ	1987-2000
	TLEP	Up to 350 GeV New 80km tunnel	ILC, LHeC b Factories	VHE-LHC, 100 TeV TeraZ	2012
$\mu^+\mu^-$ (Circular)	LEMC	125 GeV Up to 350 GeV	MICE R&D ν Factory	5-15 TeV	1997-2002
γγ	CLICHE PLC SAPPHIRE	~125 GeV Up to 300 GeV	ILC, CLIC, LHeC	–	–

Higgs studies in e⁺e⁻ collisions

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

Unpolarized cross sections

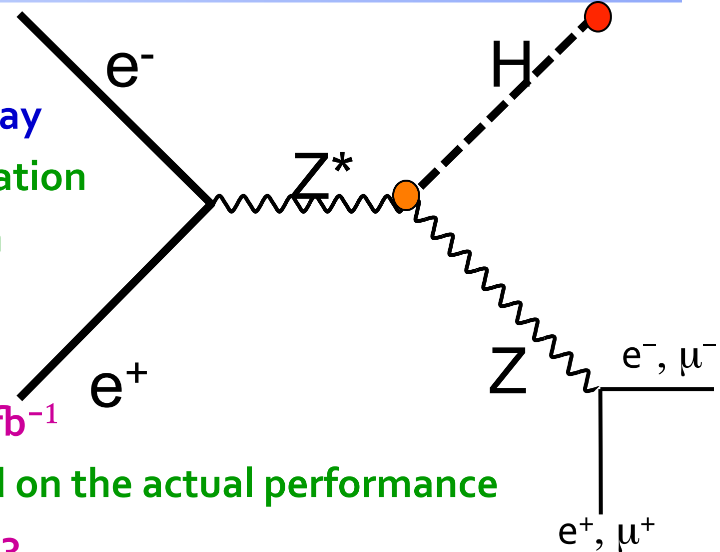
Need 100's fb^{-1}



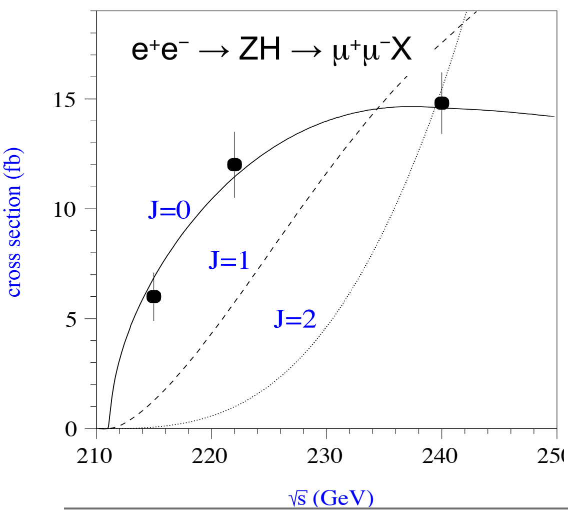
[4]

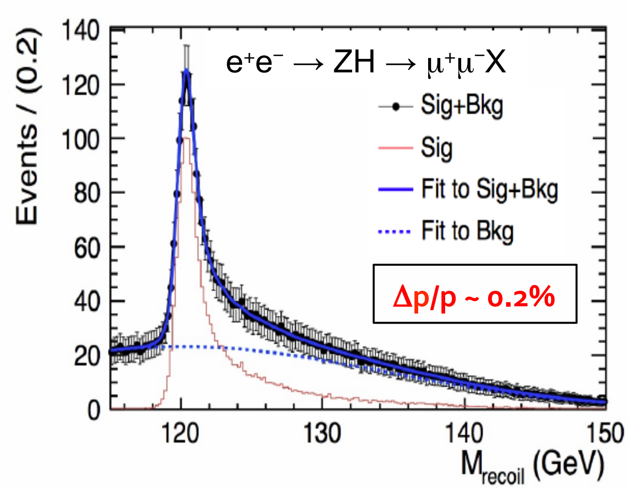
e^+e^- : Higgs measurements at $\sqrt{s}$ ~ 240 GeV (1)

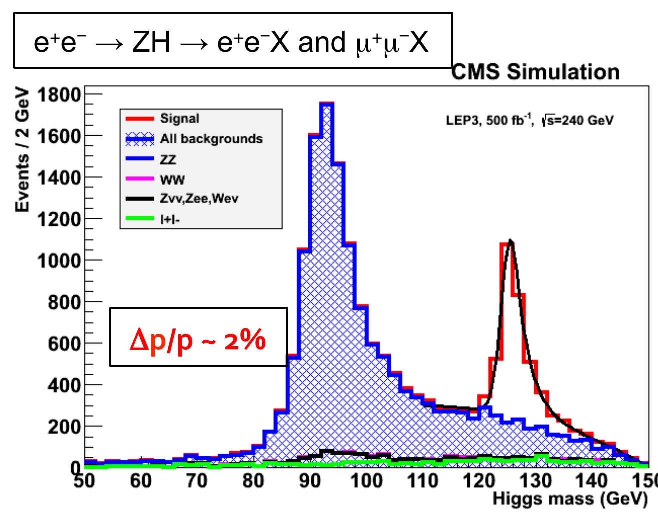
- With $e^+e^- \rightarrow ZH \rightarrow e^+e^-X$ and $\mu^+\mu^-X$ events
  - Measure HZ cross section in a model independent way
    - Find m_H peak from the leptons and E,p conservation
    - Determine spin with three-point threshold scan
      - 10 fb^{-1} / point suffice
    - Determine σ_{HZ} 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]

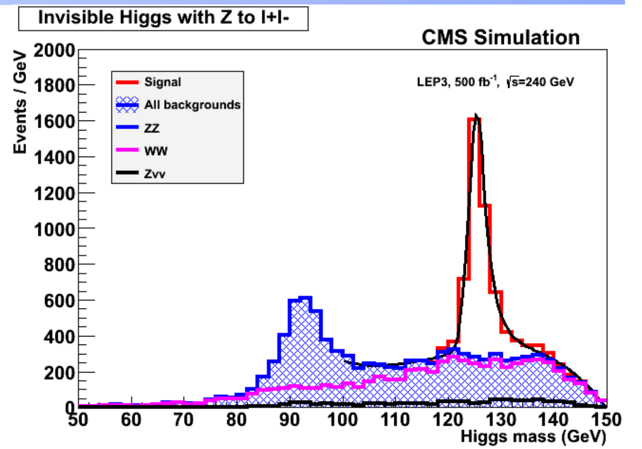






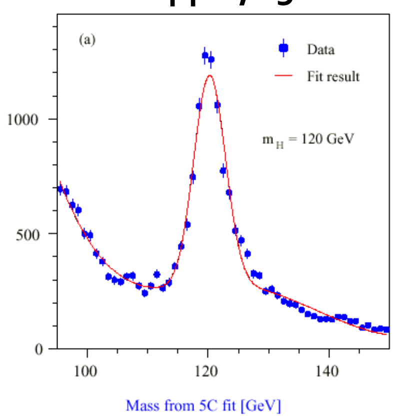
e^+e^- : Higgs measurements at $\sqrt{s}$ ~ 240 GeV (2)

- **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.

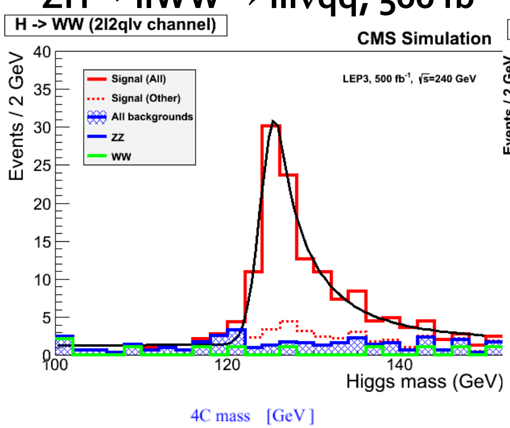


- **Measure other σ_{HZ}×BR(H→ ff,VV)**
  - With exclusive selections of Z and H decays
    - Precision of 1.5% to 8% with 250 fb^{-1} for the copious decays (bb, WW, gg, ττ, cc)
    - Need more luminosity for rare decays (γγ, Zγ, μμ)
      - ➨ Particle flow, b and c tagging, lepton and photon capabilities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

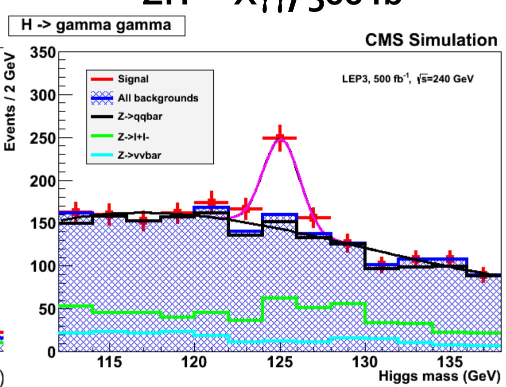
ZH→ qqbb, 250 fb^{-1}



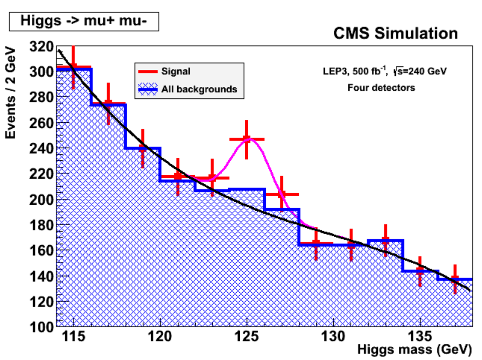
ZH→ llWW→ lllνqq, 500 fb^{-1}



ZH→ Xγγ, 500 fb^{-1}

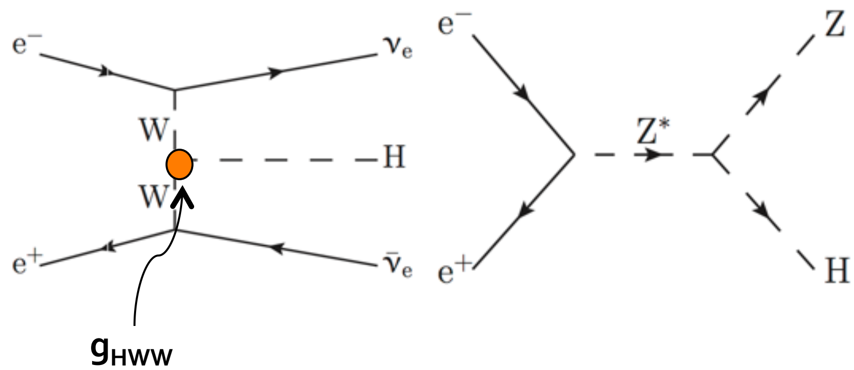


ZH→ Xμμ, 2 ab^{-1}

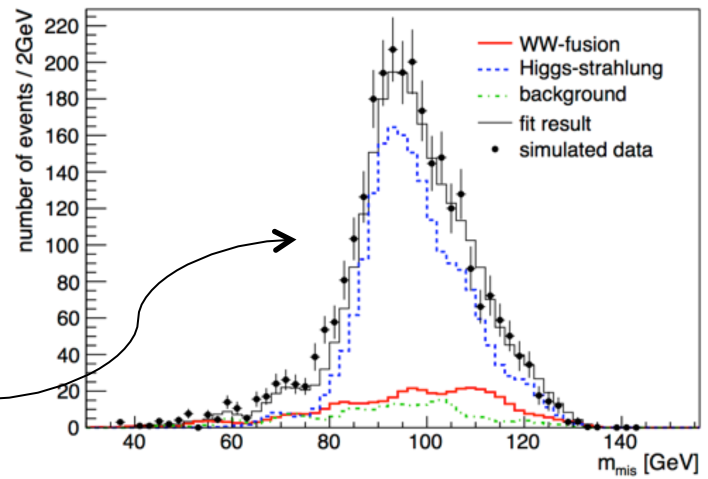


e^+e^- : Higgs measurements at $\sqrt{s}$ ~ 240 GeV (3)

- **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($H\to WW$)



  - 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}



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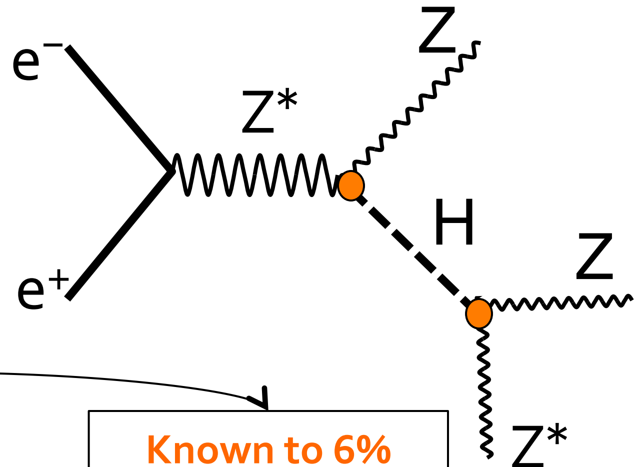
e^+e^- : Higgs measurements at $\sqrt{s}$ ~ 240 GeV (4)

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



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

e^+e^- : Linear vs Circular at $\sqrt{s}$ ~ 240 GeV ? (1)

- A few performance benchmarks (seen from an experimentalist)

	ILC	LEP3	TLEP
Lumi / IP / 5 yrs	250 fb^{-1}	500 fb^{-1}	2.5 ab^{-1}
# IP	1	2 - 4	2 - 4
Lumi / 5 years	0.25 ab^{-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
Cost/Higgs	100 k$	5 k$	3.5 k$

- Measurement precision goes like 1 / $\sqrt{L}$
- Beam polarization increases the signal cross section by ~40% for the linear option
  - A precision of 2.5% at ILC corresponds to ~1.2% at LEP3 and ~0.4% at TLEP
- Beamstrahlung effects ($L_{0.01}$, pileup, detector background) negligible for circular option
- Disclaimer : Cost estimates can easily be wrong by a factor π
  - But numbers are encouraging enough to justify further study of the circular option

e^+e^- : Linear vs Circular at $\sqrt{s}$ ~ 240 GeV ? (2)

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

	ILC	LEP3 (4)	TLEP (4)
σ_{HZ}	2.5%	1.3%	0.4%
BR($H\to bb$)	2.7%	1.4%	0.5%
BR($H\to cc$)	7.3%	4% (*)	1.4%
BR($H\to gg$)	8.9%	4.5% (*)	1.5%
BR($H\to WW^*$)	8.6%	3.0%	1.0%
BR($H\to \tau\tau$)	7.0%	3.0%	0.9%
BR($H\to ZZ^*$)	21%	7.1%	3.1%
BR($H\to \gamma\gamma$)	30%	6.8%	3.0%
BR($H\to \mu\mu$)	–	28%	13%
$\sigma_{WW\to H}$	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

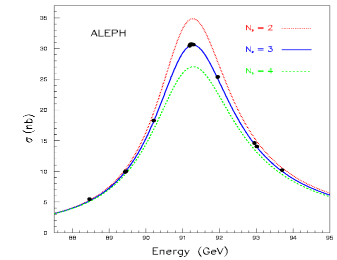
- Precision on couplings ~ half the precision on the corresponding BR or σ
- LEP3 numbers obtained from a CMS simulation x 4, except (*) extrapolated from ILC
- TLEP numbers extrapolated from ILC / LEP3 simulations

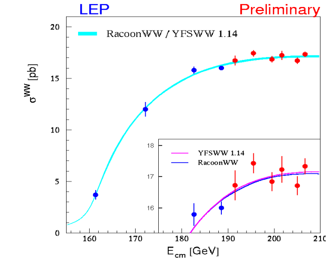
[9,10,11]

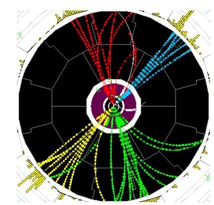
e^+e^- : Linear vs Circular at $\sqrt{s} \leq 250$ GeV ? (1)

- **Other precision measurements**

	LEP	ILC	LEP3	TLEP
$\sqrt{s} \sim m_Z$	MegaZ	GigaZ	~TeraZ	TeraZ
Lumi ($cm^{-2}s^{-1}$) #Z / IP / year Polarization vs LEP1/SLC	Few 10^{31} 2×10^7 no 1	Few 10^{33} Few 10^9 easy ~5-10	Few 10^{35} Few 10^{11} maybe ~100	10^{36} 10^{12} maybe ~150
$\sqrt{s} \sim 2m_W$				
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	10^{35} 1 ab^{-1} 0.4 MeV
$\sqrt{s} \sim$ 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







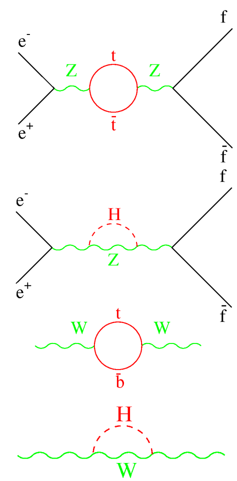
- Error on m_W limited by beam energy precision (obtained from ZZ and Z(γ) events)
- Resonant depolarization method unique for circular colliders for $\sqrt{s} \sim m_Z$
  - Beam energy known to better than 0.1 MeV, important for Γ_Z and m_Z
- No beamstrahlung is an advantage for all these measurements – natural at circular colliders
- Beam polarization enables the A_{LR} measurement – natural at linear colliders

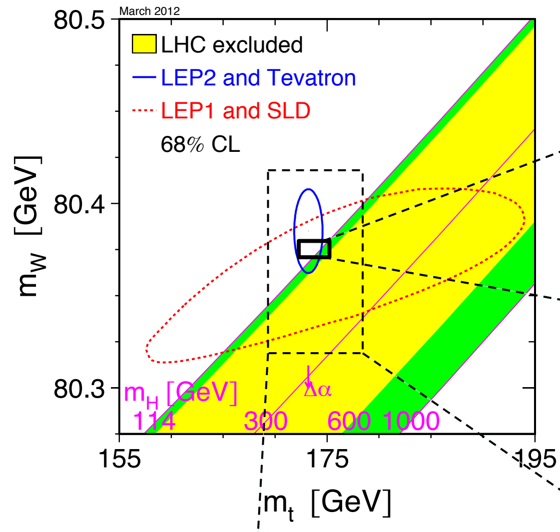
[9,10]

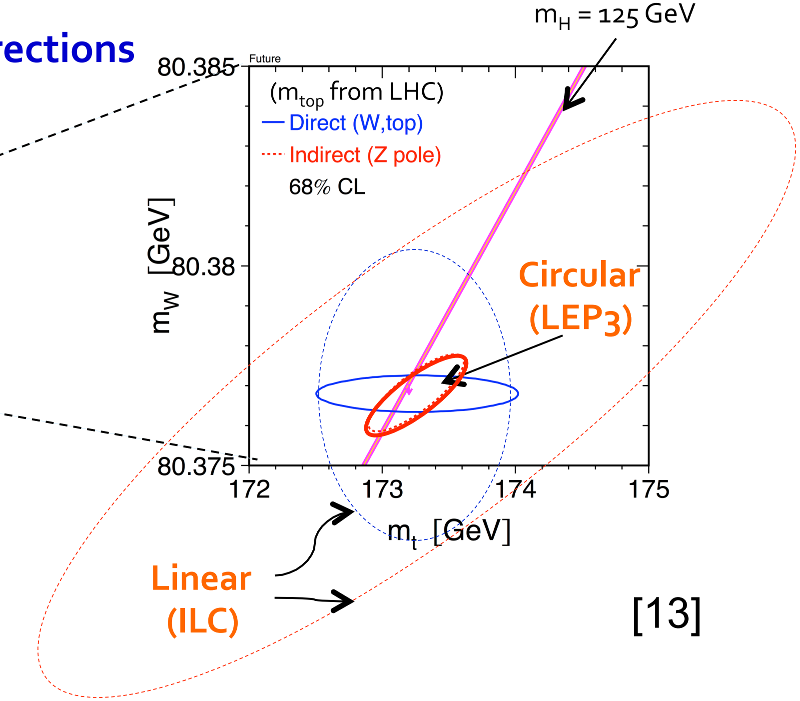
e^+e^- : Linear vs Circular at $\sqrt{s} \leq 250$ GeV ? (2)

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

$$m_W = m_Z \cos\theta_W$$

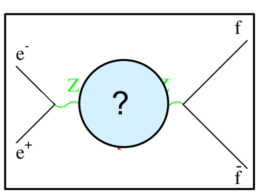


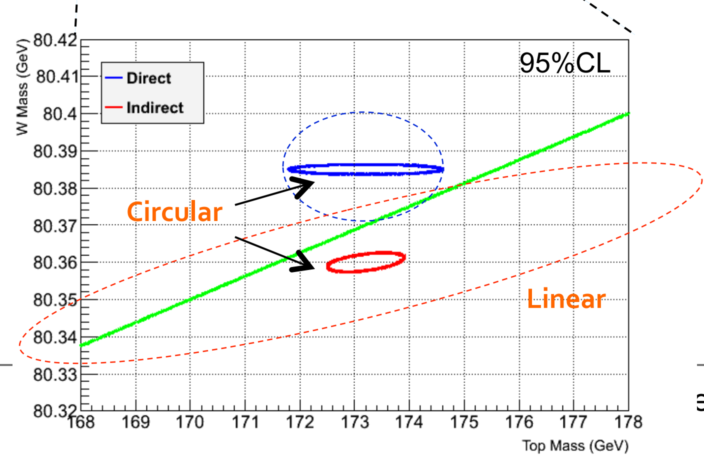




[13]

  - **Case 2 : Some new physics in the loops ?**





With TeraZ and m_W to 0.5 MeV:

Predicts m_{top} to 100 MeV (SM)

LEP predicted m_{top} to 10 GeV (03/1993)

Sensitivity of EWRC to any WINP

(WINP = Weakly Interacting New Physics)

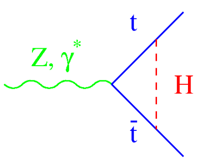
EWRC predicted m_H to 25 GeV w/o WINP

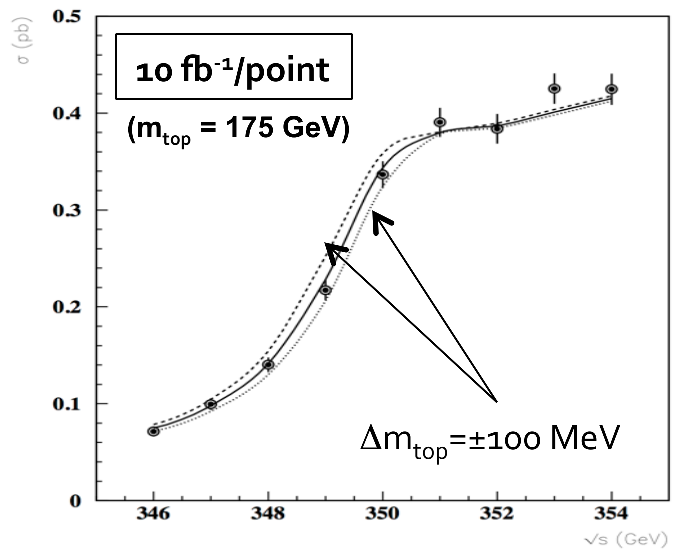
With m_{top} and m_H known : SM closure test

e^+e^- : Measurements at $\sqrt{s}$ ~ 350 GeV (ILC/TLEP)

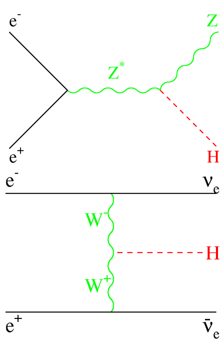
- **Luminosity similar for ILC and TLEP**
  - At each IP : 350 fb^{-1} over 5 years
    - With possibly 4 detectors at TLEP
  - Scan of the tt threshold
    - From the cross section
      - Top mass and width to 50 MeV or better
      - Probe the ttH coupling to 40%

        No beamstrahlung is a advantage
      - Study rare top decays

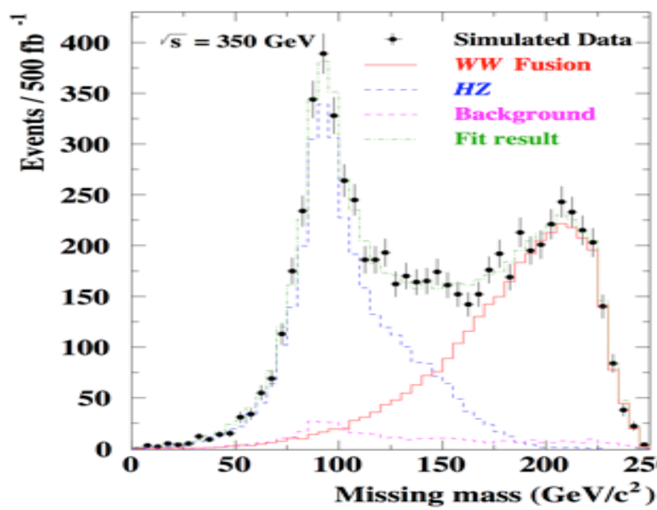




  - More study of the Hνν final state with H→bb
    - Contribution from HZ : ~ 25 fb
    - Contribution from WW→H : ~ 25 fb



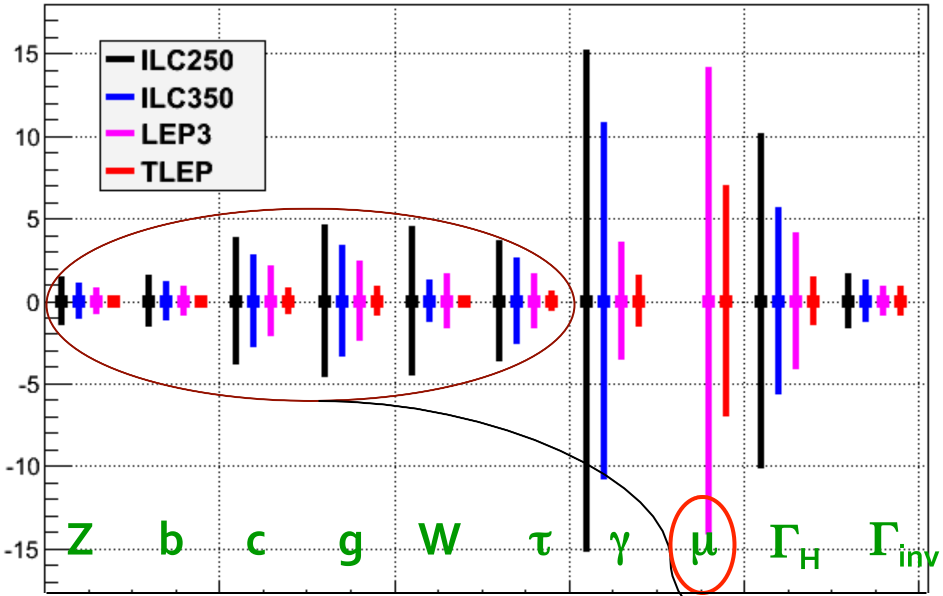
	ILC (250+350)	TLEP (240+350)
$\sigma_{WW\to H}$	11% → 4%	1.5% → 1.1%
Γ_H	10% → 5.5%	1.8% → 1.3%



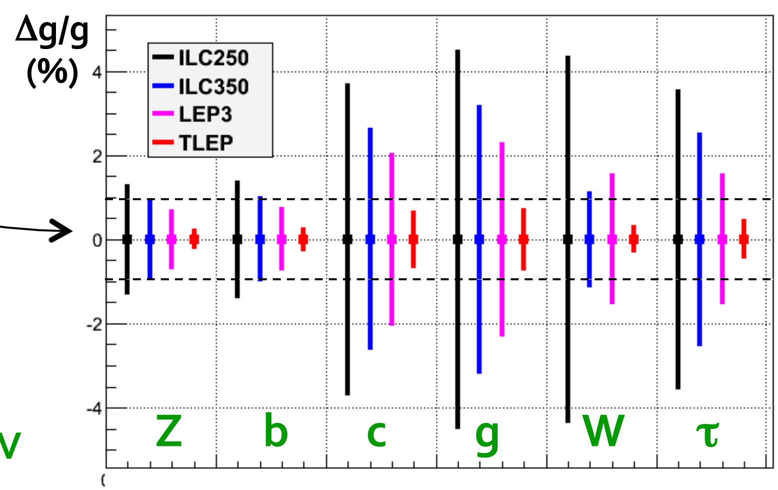
      - Smaller improvement for other BR and σ
  - Measure CP mixture to ~5% from HZ yield and angular distributions

Low-energy e⁺e⁻ Higgs Factories : Summary

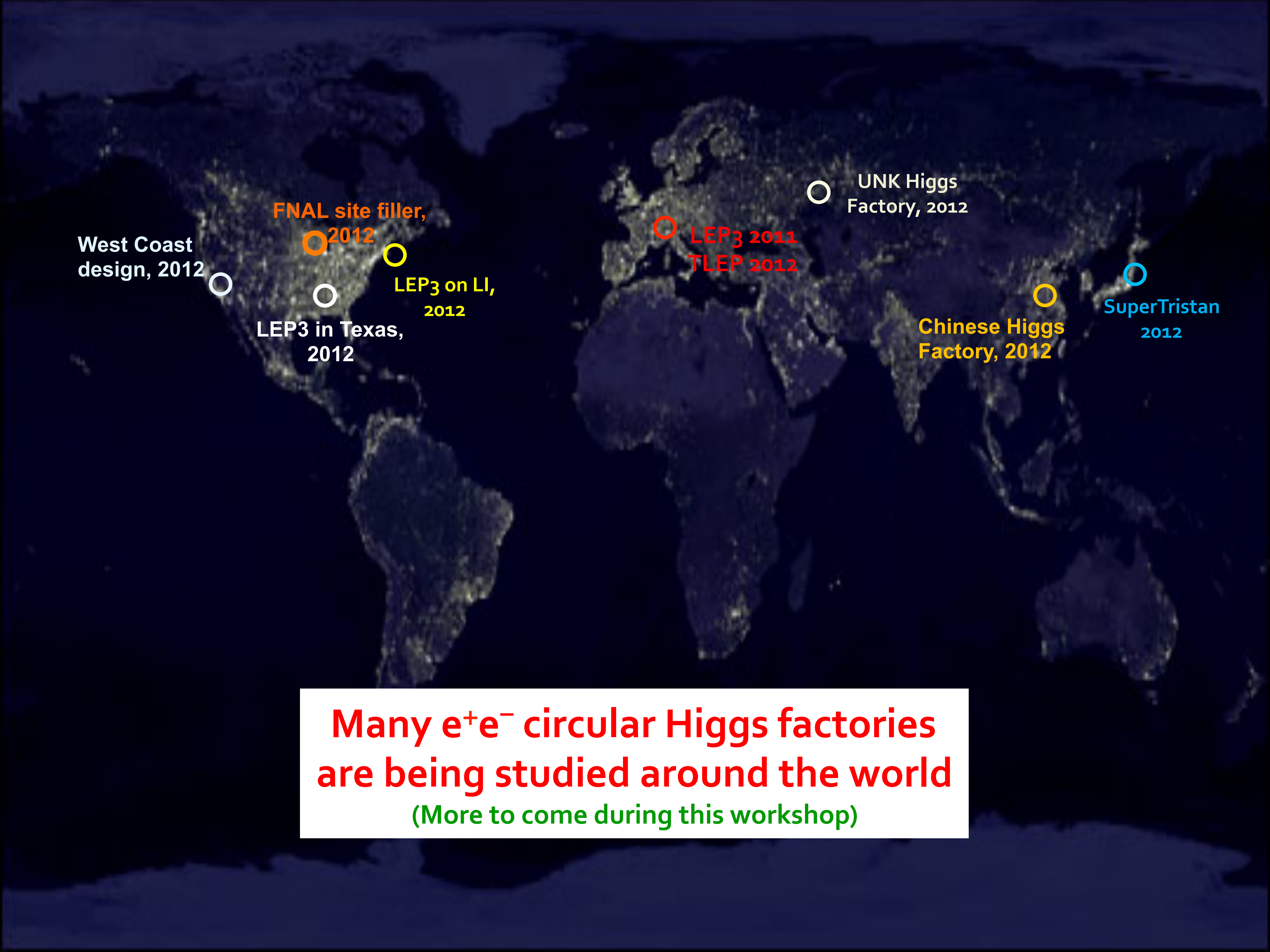
- **Precision on couplings and width (if advertised luminosities are achieved)**



Remember LHC, 300 fb^{-1} : [3]
10-15% on fermionic couplings
5-6% on bosonic couplings
5-10% on couplings through loops
and possibly 2-10% on all couplings with 3 ab^{-1}



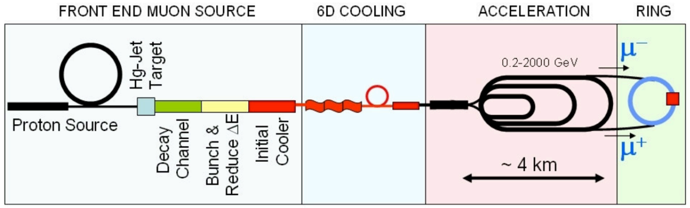
- ILC250/350 would be a good complement to LHC
- LEP3 could be an advantageous backup
  - Larger lumi, Several IP's, TeraZ, Cost
- TLEP would be a superior option
  - Precision adequate for testing NP beyond TeV
    - In Higgs decays and in EWRC



Many e^+e^- circular Higgs factories are being studied around the world

(More to come during this workshop)

$\mu^+\mu^-$ Collider vs e^+e^- Collider ? (1)



- **Much work needed to realize a $\mu^+\mu^-$ collider**
  - Linear e^+e^- : R&D is essentially over
  - Circular e^+e^- : everything is "off-the-shelf"
  - A $\mu^+\mu^-$ collider needs all what it takes for a ν Factory, plus
    - Superb 6D muon cooling feasibility needs to be demonstrated (MICE and beyond)
    - The $\mu\mu$H coupling needs to be ascertained (e.g., with HL-LHC, LEP3, TLEP)
    - Ways to fight huge detector background from muon decays must be studied
      - ➨ Might take a decade or two … but once it is done …
- **Muons are leptons (~ like electrons) and heavy (~ like protons)**
  - A $\mu^+\mu^-$ collider can a priori do all what an e^+e^- collider can do
  - A $\mu^+\mu^-$ collider ring can be as small as a proton collider (negligible synchrotron radiation)
    - With LHC dipole magnets of 9 T, allowing for 2000 turns / muon

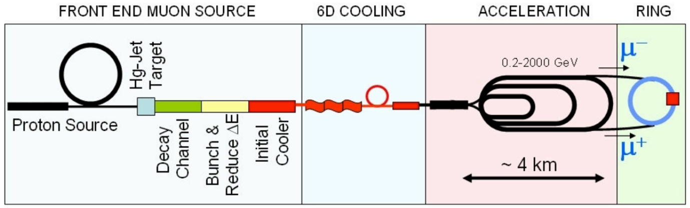
	Z Factory	Higgs Factory	Top Factory
$\sqrt{s}$ (GeV)	91.2	240	350
Circumference (m)	160	410	600

A new ring for each new energy !

[14,15]

- Luminosity limited by the beam energy spread requirement
  - ➨ A few 10^{33} cm^{-2}s^{-1} for $\delta E/E$ = 1% with a 4 MW source (decreases with $\delta E/E$)

$\mu^+\mu^-$ Collider vs e^+e^- Collider ? (1)



- **Much work needed to realize a $\mu^+\mu^-$ collider**
  - Linear e^+e^- : R&D is essentially over
  - Circular e^+e^- : everything is "off-the-shelf"
  - A $\mu^+\mu^-$ collider needs all what it takes for a ν Factory, plus
    - Superb 6D muon cooling feasibility needs to be demonstrated (MICE)
    - The μμH coupling needs to be ascertained (e.g., with HL-LHC, LEP3, TLEP)
    - Ways to fight huge detector background from muon decays must be studied
      - ➨ Might take a decade or two … but once it is done …
- **Muons are leptons (~ like electrons) and heavy (~ like [illegible]rotons)**
  - A $\mu^+\mu^-$ collider can a priori do all what an e^+e^- collider [illegible]
  - A $\mu^+\mu^-$ collider ring can be as small as a proton co[illegible] synchrotron radiation)
    - With LHC dipole magnets of 9 T, allo[illegible]s / muon

	Z Factory	[illegible]y	Top Factory
√s (GeV)	[illegible]	240	350
Circumference (m)	[illegible]	410	600

A new ring for each new energy !

[14,15]

  - Luminosit[illegible] beam energy spread requirement
    - ➨ [illegible] $^{-1}$ for δE/E = 1% with a 4 MW source (decreases with δE/E)

Cannot improve (yet) over the e^+e^- options

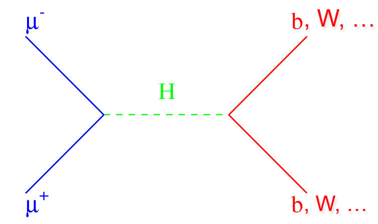
Increase the source power ?

$\mu^+\mu^-$ Collider vs e^+e^- Collider ? (2)

[16,17]

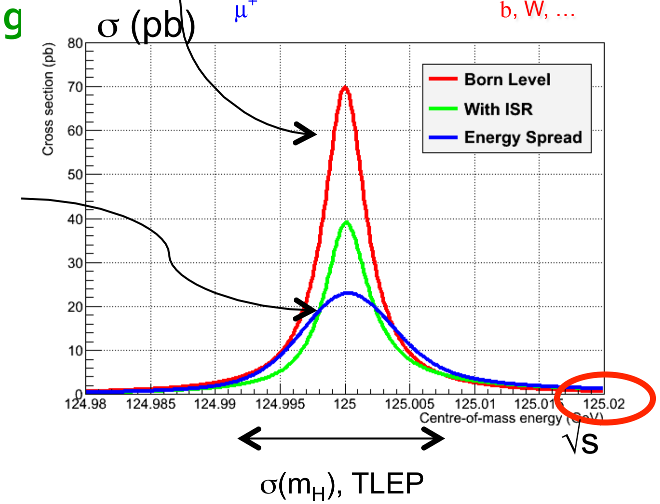
- **A $\mu^+\mu^-$ collider can do things that an e^+e^- collider cannot do**
  - Direct coupling to H expected to be larger by a factor m_μ/m_e

$$\sigma(\mu^+\mu^- \to H) \approx 40000 \times \sigma(e^+e^- \to H)$$ [σ_{peak} = 70 pb at tree level]



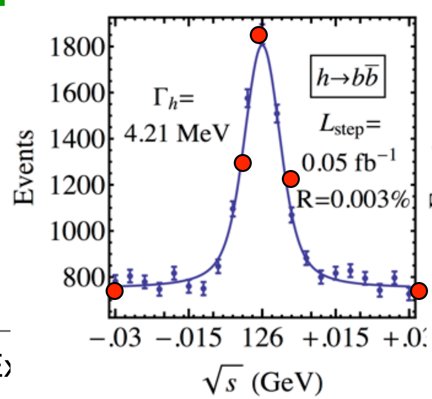
  - Beam energy spread $\delta E/E$ may be reduced to 3×10^{-5}
    - 6D Cooling, no beamstrahlung, ~no bremsstrahlung
    - For $\delta E/E$ = 0.003% (δE ~ 3.6 MeV, Γ_H ~ 4 MeV)
      - ➨ Corresponding luminosity ~ 10^{31} cm^{-2}s^{-1}

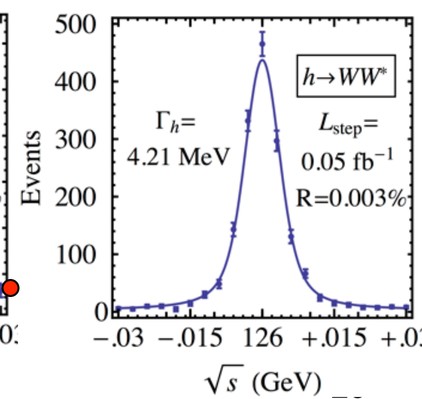
Expect 2300 Higgs events in 100 pb^{-1}/ year



  - Polarization, beam energy and energy spectrum
    - Can be measured with an exquisite precision
      - ➨ From the electrons of the muon decays
  - Then measure the lineshape of the Higgs at $\sqrt{s}$ ~ m_H
    - Five-point scan, 50 + 100 + 200 + 100 + 50 pb^{-1}
      - ➨ Precision from H→bb and WW :

m_H	σ_{Peak}	Γ_H
0.1 MeV	0.6 pb	0.2 MeV
10^{-6}	2.5%	5%





$\mu^+\mu^-$ Collider vs e^+e^- Collider ? (3)

- **Comparison with e^+e^-** [16,23]
  - Precision on m_H is 100 times better
    - No real impact on underlying physics …
  - Precision on Γ_H (5%) is similar to ILC (6%) and LEP3 (4%), worse than TLEP (2%)
    - Can improve by increasing the power of the proton source (L goes like Power²)
  - σ_{Peak} is a whole new measurement : what does it bring ?
    - Maximally sensitive to Γ_H when $\delta E = \Gamma_H\sqrt{\pi}/2$
      - Effectively reduces error on Γ_H to 3%
      - And measure BR($H\to\mu\mu$) or $\Gamma(H\to\mu\mu)$ to 3%

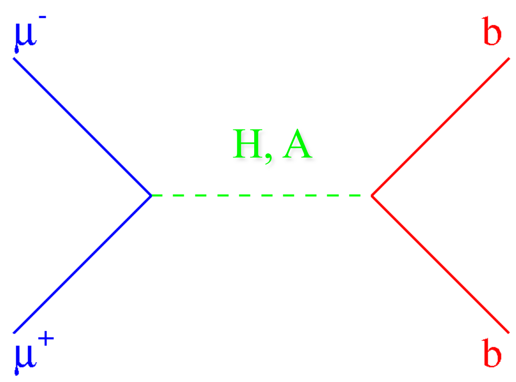
        $g_{H\mu\mu}$ to 1.5% (cf 14% @ LEP3 and 6.5% at TLEP)
  - Other couplings better determined in e^+e^- collisions
  - Need significantly higher luminosity for $\mu^+\mu^-$ colliders to become unique Higgs factories

$$\sigma_{peak} \propto BR_{\mu\mu}BR_{bb}\left(1+\frac{8}{\pi}\frac{\delta E^2}{\Gamma_H^2}\right)^{-\frac{1}{2}}$$

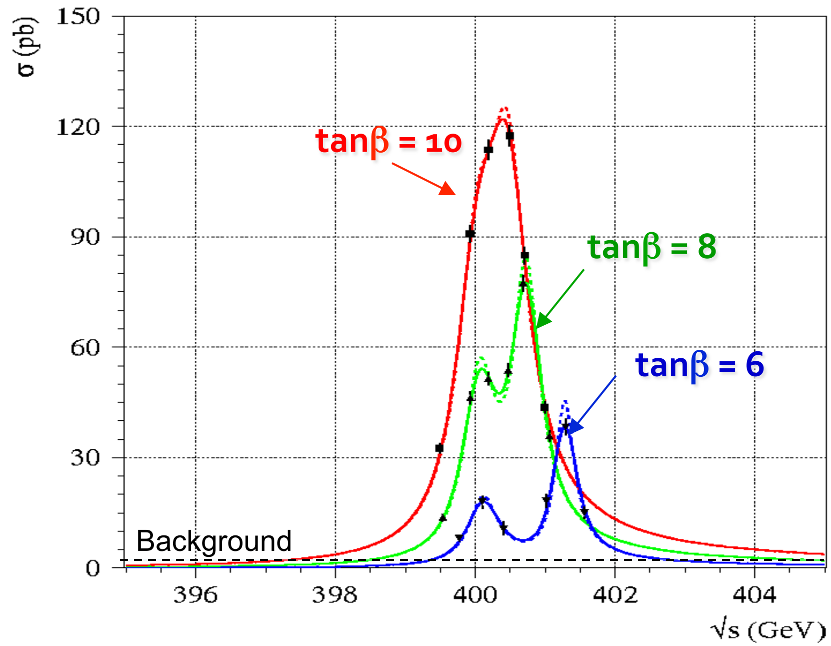
  - Note : CP Studies
    - Can see $\mu^+\mu^-\to A$ at least as well as $\mu^+\mu^-\to H$
      - Unlike e^+e^- colliders for which AZZ couplings is absent at tree level
    - Disentangling a A/H mixture is challenging
      - Need higher L, high muon beam polarization, and specific P_-/P_+ orientations

$\mu^+\mu^-$ Collider vs e^+e^- Collider ? (4)

- **Probably better suited for the study of a richer Higgs sector ?** [14]
  - Ex: m_A = 400 GeV/c², m_h = 125 GeV/c², m_{SUSY} = 1 TeV/c²
    (~very difficult to see at LHC, need 1 TeV e^+e^-)
    - H,A widths ~ 500 MeV → $\delta E/E$ can be increased to 0.1% → L = 5×10^{32} $cm^{-2}s^{-1}$
  - Larger potential for CP and CP violation studies

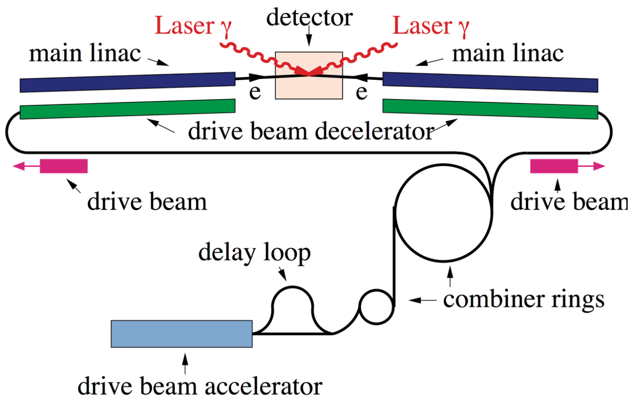


Error bars = 1 week of running

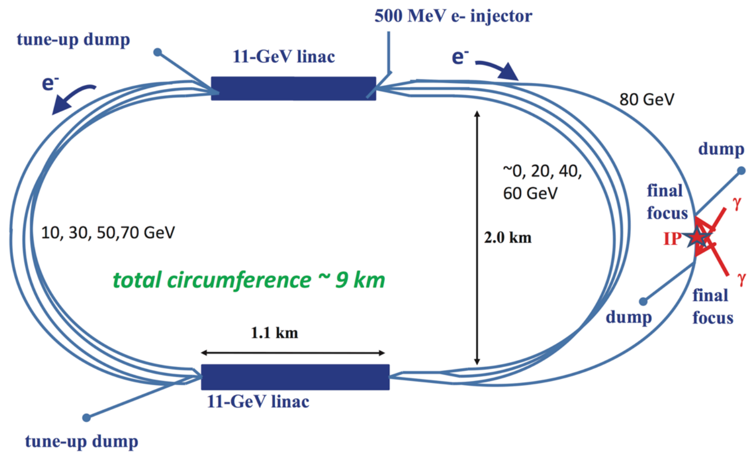


Higgs Physics at a γγ Collider (1)

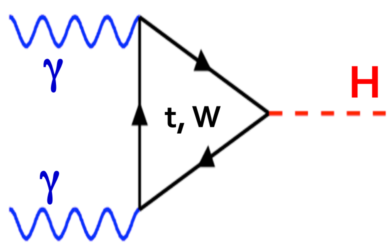
- **Need two polarized 80 GeV e⁻ beams and two polarized LASERs** [24,25]
  - Can be a natural extension of a linear collider (here : CLICHE)

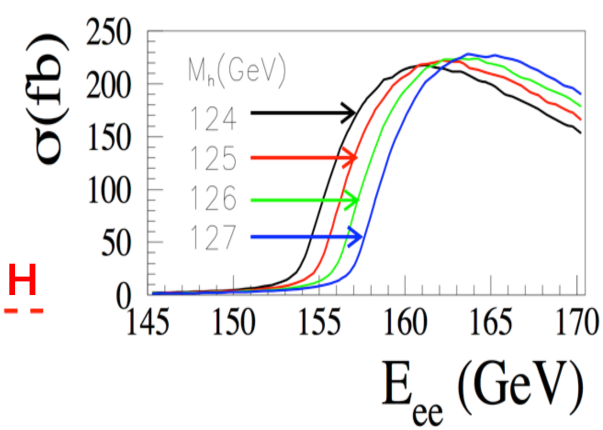


  - … or use two recirculating LINACs (here : SAPPHIRE)



  - Typical performance benchmarks with $P_e = 0.8$
    - γγ → H cross section ~ 200 fb
      - ➨ 3 times smaller if $P_e = 0.0$
    - ~20,000 Higgs bosons / year
      - ➨ Same as LEP3 (but one IP)
    - Fully polarized photons
      - ➨ Flexible polarizations



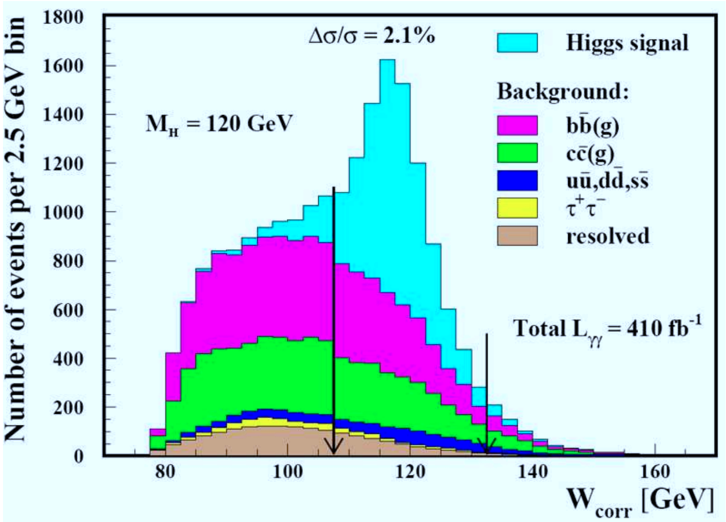


Higgs Physics at a $\gamma\gamma$ Collider (2)

- **Precision after 5 years : First estimates**

$\sigma_{\gamma\gamma\to H}$ × BR(H→bb)	1%
$\sigma_{\gamma\gamma\to H}$ × BR(H→WW*)	3%
$\sigma_{\gamma\gamma\to H}$ × BR(H→ZZ*)	5%
$\sigma_{\gamma\gamma\to H}$ × BR(H→$\gamma\gamma$)	10%
$\sigma_{\gamma\gamma\to H}$ × BR(H→Zγ)	16%
Γ_H	11%
m_H	50 MeV

Example : $\gamma\gamma$→H→bb



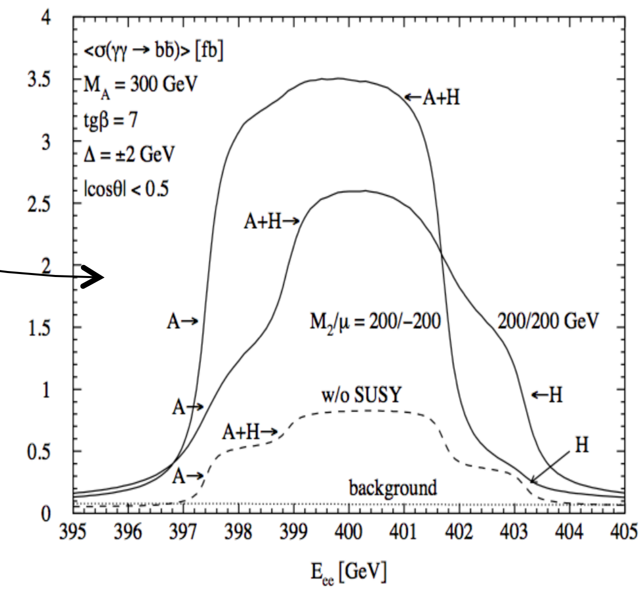
- Need inputs from e⁺e⁻ collider, e.g., BR(H→bb), to get $\sigma_{\gamma\gamma\to H}$
  - Unique measurement of $g_{H\gamma\gamma}$ to 1%, sensitive to NP through loops
    - Cf 3.5% @ LEP3 and 1.5% @ TLEP
  - Other figures similar to / worse than LEP3 precision. No cc, gg measurement.

- Possibility of CP and CP violation studies with different input photon polarizations
  - See Mayda Velasco's presentation on Friday

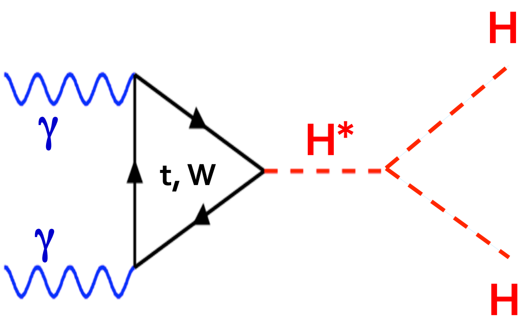
[27]

Higgs Physics at a γγ Collider (3)

- **Possible studies at higher energy**
  - Extended Higgs sector
    - Example : m_A = 300 GeV
      - ➨ 200 GeV electron beams
      - ➨ Lineshape sensitive to γγ polarizations



  - Unique possibility of measuring the HHH coupling ?
    - Through γγ→HH→bbbb with 210 GeV electron beams
      - ➨ After 5 years : 35 signal events vs 15 background
        - $\sigma_{\gamma\gamma\to HH}$ measured to 20%
        - Coupling measured to 10%
      - ➨ Needs full simulation confirmation
        - (7 orders of magnitude background reduction)



[26,27]

Higgs Physics at High Energy : Possible Choices

- **More Higgs Physics can be done at higher energy**
  - In particular measure more couplings : ttH, HHH, …
    - But the choice could also be motivated by the new physics reach

Machine	Example	√s	Benefits from	Lumi / 5 yr	When?	New Physics ?
pp	HL-LHC HE-LHC VHE-LHC	13 TeV 33 TeV 100 TeV	LHC tunnel LHC tunnel TLEP tunnel	3 ab^{-1} 300 fb^{-1} 300 fb^{-1}	2025 2035 2040	– ++ +++
e^+e^- (Linear)	ILC CLIC	0.5 (1?) TeV 1 – 3 TeV	ILC250/350 Ongoing R&D	0.5 (1?) ab^{-1} 2 ab^{-1}	2040 2035	–/+ ++
$\mu^+\mu^-$ (Circular)	HEMC	5 – 15 TeV	LEMC	2 ab^{-1}	?	+++
ep	LHeC	1.4TeV	LHC p beam	10-100 fb^{-1}	2025	–

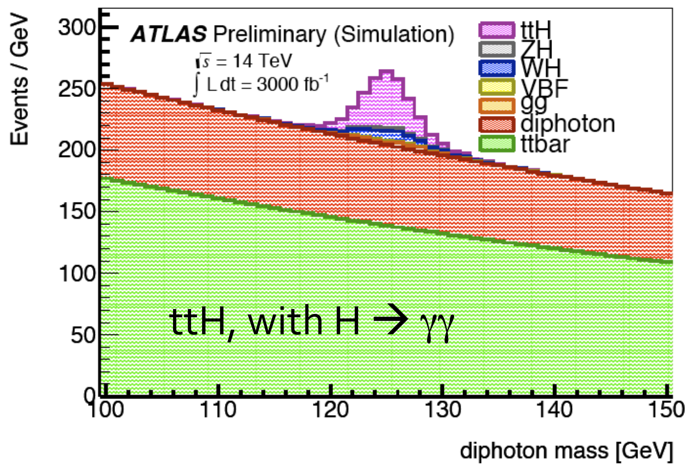
- Let's see if the new physics reach matches the Higgs physics capabilities.

Higgs Physics with HL-LHC

- **From LHC to HLC-LHC** [3]
  - Assuming LHC analyses have the same performance with 200 PU events
    - … and a possible reduction of the theoretical uncertainties (pdfs, etc…)

Coupling	LHC	HL-LHC	ILC350	TLEP
$H\gamma\gamma$	5.1 – 6.5%	1.5 – 5.4%	11%	1.4%
HVV	2.7 – 5.7%	1.0 – 4.5%	0.9%	0.2%
Hgg	5.7 – 11%	2.7 – 7.5%	3.0%	0.7%
Hbb	6.9 – 15%	2.7 – 11%	1.0%	0.2%
$H\tau\tau$	5.1 – 8.5%	2.0 – 5.4%	2.5%	0.4%

- New production modes accessible with more lumi
  - Measure Htt coupling to 10%
  - Measure $H\mu\mu$ coupling to 10%
    - ➨ Cf TLEP : 7%, LEMC : 3%
  - Measure HHH coupling to 30%
- No additional new physics with respect to LHC
  - And very challenging experimental conditions



Higgs Physics with (V)HE-LHC

- **What's new at higher energy ?** [18]
  - The Higgs cross sections increase substantially

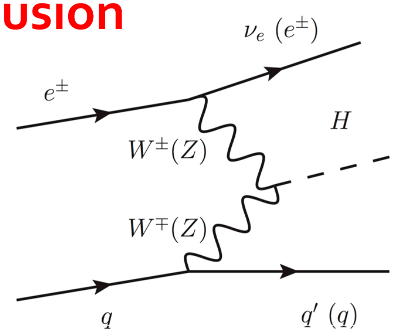
	σ(14 TeV)	R(33)	R(40)	R(60)	R(80)	R(100)
ggH	50.4 pb	3.5	4.6	7.8	11.2	14.7
VBF	4.40 pb	3.8	5.2	9.3	13.6	18.6
WH	1.63 pb	2.9	3.6	5.7	7.7	9.7
ZH	0.90 pb	3.3	4.2	6.8	9.6	12.5
ttH	0.62 pb	7.3	11	24	41	61
HH	33.8 fb	6.1	8.8	18	29	42

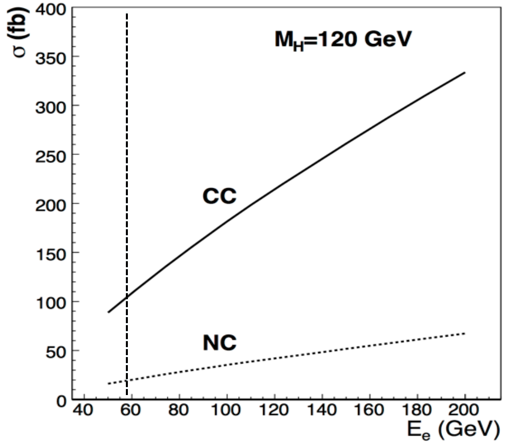
    - HE-LHC would do like 1 ab^{-1} of HL-LHC for HVV, Hbb, Hγγ, Hgg and Hbb
      - ➨ But about the same as HL-LHC on Htt and HHH
    - VHE-LHC would do like 6 ab^{-1} of HL-LHC for HVV, Hbb, Hγγ, Hgg and Hbb
      - ➨ But much better on Htt (2%) and HHH (10%)

  - Possibly a whole lot of new physics becomes accessible
    - The larger the energy, the better

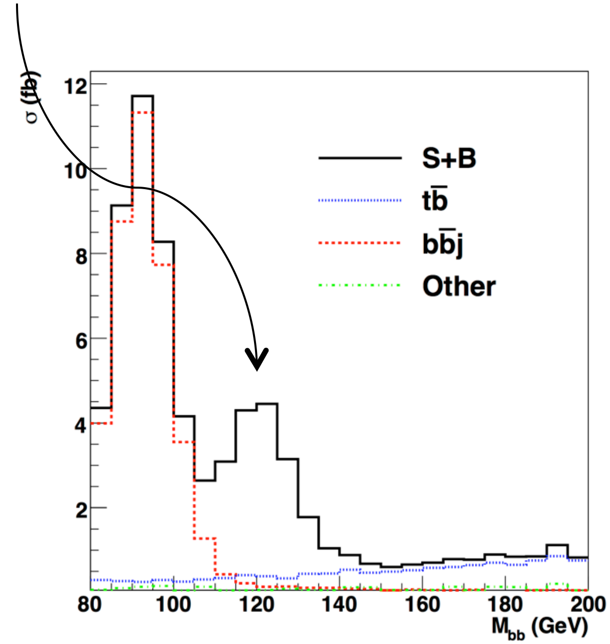
Higgs Physics in ep collisions (LHeC)

- **Production through Vector Boson Fusion**
  - Cross section : 100 fb with E_e = 60 GeV
    - Luminosity : 10 to 100 fb^{-1} / year
      - ➨ 1,000 to 10,000 events / year





  - Measure g^2_{HWW} × BR(H→bb) to 7% in 5 years @ E_e=60 GeV
    - Reduced to 2% with the 100 fb^{-1}/year upgrade

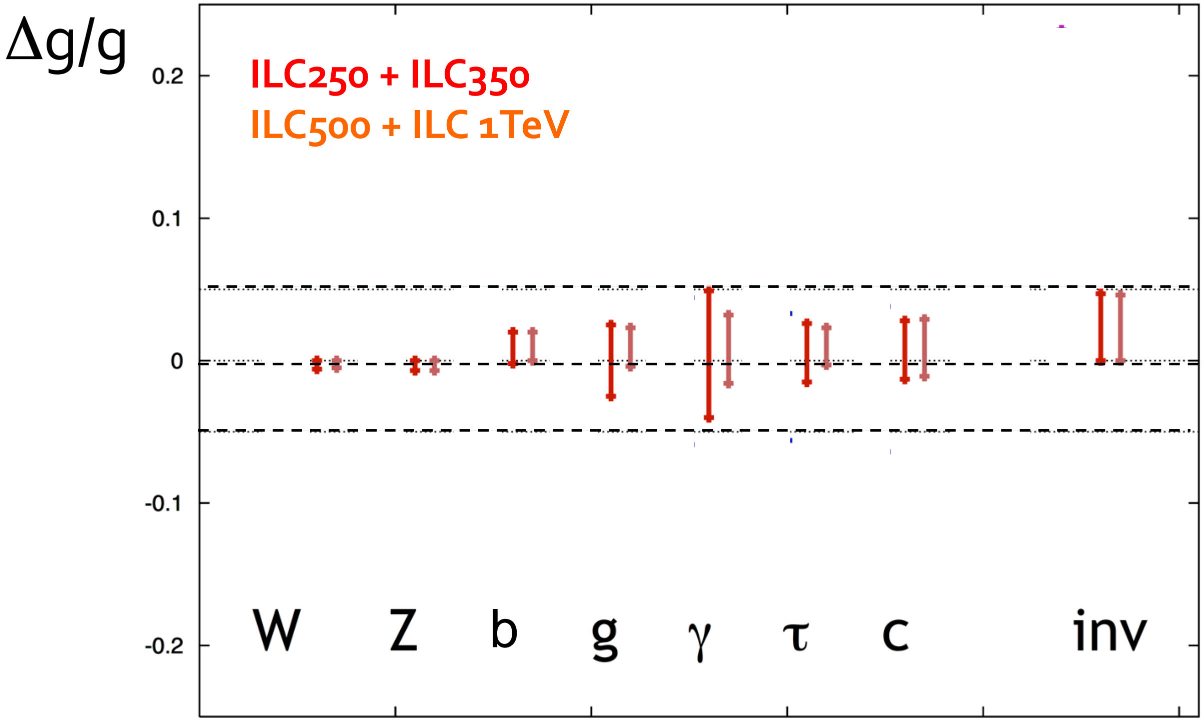


- **Unique LHeC contribution to Higgs physics**
  - Possible drastic reduction of the pdf uncertainties
    - May allow HL-LHC to reach its full potential
      - ➨ (Some of the pdf work to be done @LHC)

- **Not much new physics is to be expected, but …**
  - The e^- beam can be used for a γγ collider
    - See earlier in this talk

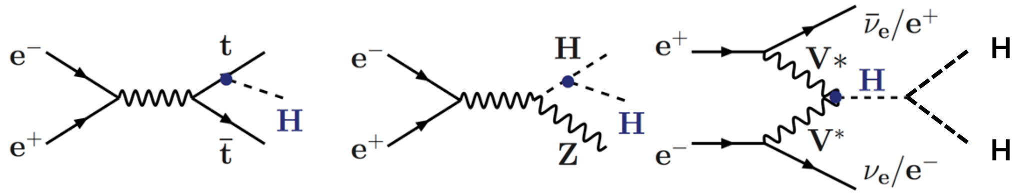
Higgs Physics with high-energy e^+e^- colliders (1)

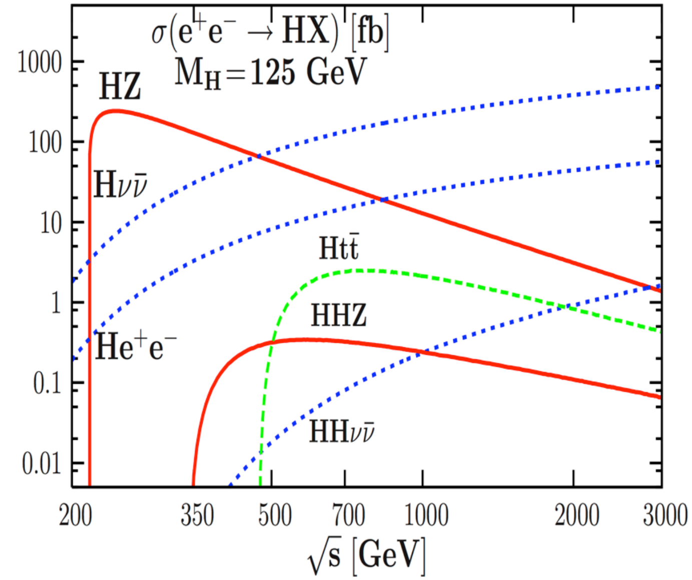
- Improvements of couplings measured at lower energy ? [19]
  - Minute improvements with respect to the 250/350 GeV Higgs factory
    - Most of the precision comes from the HZ production
      - ➨ Cross section largest at 250 GeV, Higgs boson tagged by the Z



Higgs Physics with high-energy e^+e^- colliders (2)

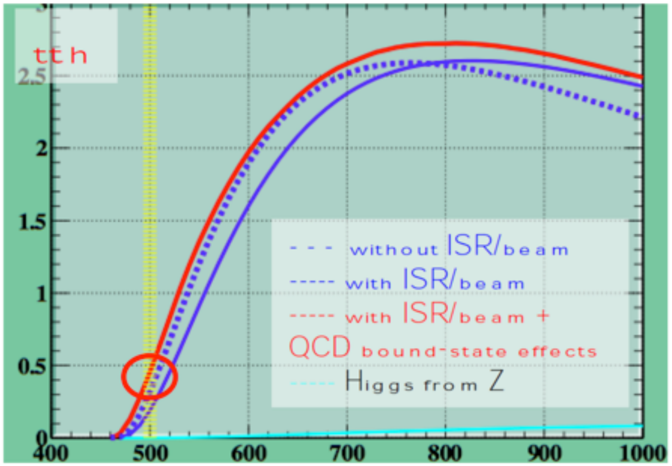
Other couplings : Htt and HHH





- $e^+e^- \rightarrow$ ttH with H→bb @ 500 GeV
  - Cross section quite uncertain (±20%)
    - Large QCD bound state effects
    - Large brems/beam-strahlung effects
  - Use 8 jets and 6 jets + lepton final states
    - With 500 fb^{-1} and 80% beam polarization

$$\frac{\Delta g_{Htt}}{g_{Htt}} = 15\%_{stat} \oplus 20\%_{syst} \approx 25\%$$



- $e^+e^- \rightarrow$ ttH with H→bb @ 1 TeV is easier
  - With 1 ab^{-1} and 100% beam polarization

$$\frac{\Delta g_{Htt}}{g_{Htt}} = 5\%_{stat} \oplus 8\%_{syst} \approx 10\%$$

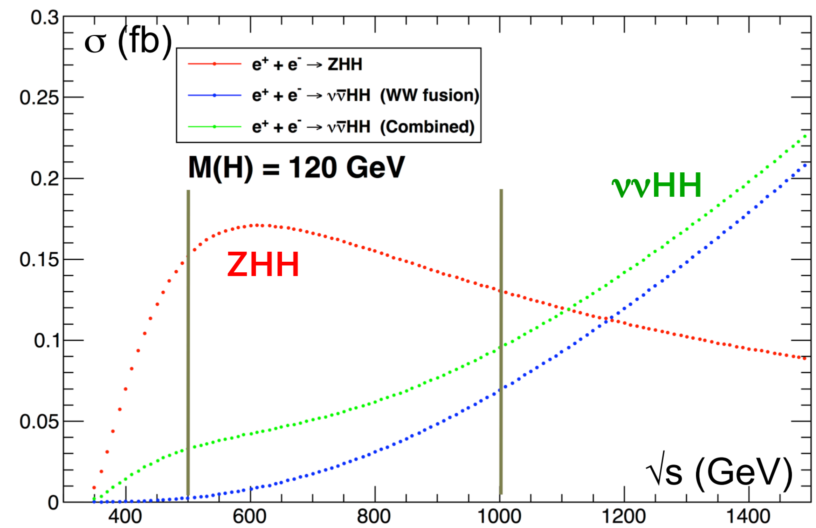
[20]

Higgs Physics with high-energy e^+e^- colliders (3)

- **Other couplings : Htt and HHH (cont'd)**

s/b

- $e^+e^- \to$ ZHH with HH→bbbb
  - 6/18 With 500 fb⁻¹ @ 500 GeV $\frac{\Delta g_{HHH}}{g_{HHH}} \approx 80\%$
- $e^+e^- \to \nu\nu$HH with HH→bbbb (Fast simulation only here)
  - 18/14 With 1 ab⁻¹ @ 1 TeV $\frac{\Delta g_{HHH}}{g_{HHH}} \approx 30\%$
  - 30/300 With 1.5 ab⁻¹ @ 1.4 TeV $\frac{\Delta g_{HHH}}{g_{HHH}} \approx 30\%$
  - 300/2500 With 2 ab⁻¹ @ 3 TeV $\frac{\Delta g_{HHH}}{g_{HHH}} \approx 15\%$



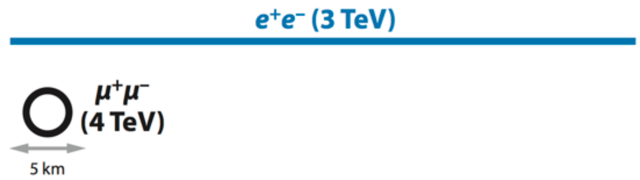
All numbers assume 80% polarization of the electron beam, as it increases the signal cross section by 40 to 70%.

- **New Physics ?**
  - There is minute hope for new physics at 500 GeV, not yet unveiled by the LHC
    - The larger the energy, the better the prospects

[21,22]

Higgs Physics with high-energy $\mu^+\mu^-$ colliders

- **Muon colliders can do the same as e^+e^- colliders**
  - Similar integrated luminosities can be reached (no need to have $\delta E/E < 0.1\%$)
    - Much smaller tunnels are needed

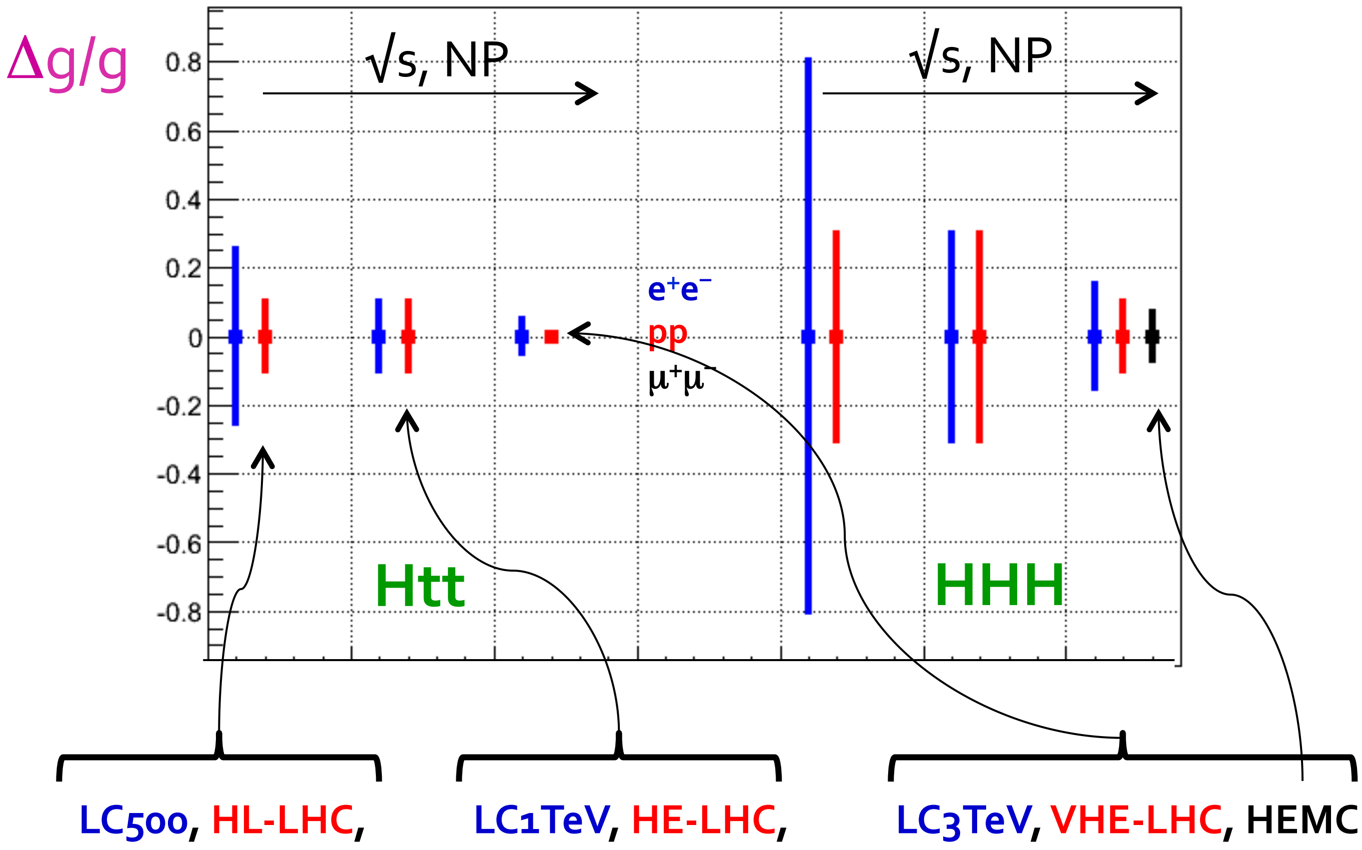


    - Several IPs are possible (ring)
    - Much larger energies accessible (no synchrotron radiation)
      - e.g., 5 TeV in the LHC tunnel, 15 TeV in the TLEP tunnel
    - But challenging issues must be faced
      - Huge muon decay background in the detector (same as at lower energies)
      - Neutrino radiation becomes problematic above 4 TeV

- **IF the challenges can be solved**
  - Possibly measure the HHH coupling to 5% precision at the highest energy (?)
  - With possibly a whole lot of new physics accessible

Higgs measurements at high energy : Summary

- **Summary limited to Htt and HHH couplings**
  - **Other couplings benefit marginally from high energy**



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

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

- 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 possibilities presented here should help provide strategic guidance
    - Meanwhile, studies of all Higgs factory concepts must be encouraged