Higgs Factory

Higgs Factory Workshop
Fermilab, 14-16 2012

Physics session

Warnings:

1. Physics was not the primary goal of the workshop.

2. report precisions based on claimed performances

3. more extensive discussion on Higgs physics would be needed!

Welcome, Introduction and Physics

Convener: Alain Blondel (University of Geneva)

09:00 **Welcome** *05'*
Speaker: Pier Oddone (Fermilab)

09:05 **Strategy for Higgs Study** *20'*
Speaker: Young-Kee Kim (FNAL)
Material: Slides

09:30 **Higgs at the LHC** *30'*
Speaker: Fabio Cerutti (LBNL - Berkeley)
Material: Slides

10:10 **Higgs beyond the LHC - theories** *30'*
Speaker: Chris Quigg (Fermilab)
Material: Slides

10:55 **Coffee Break** *20'*

11:15 **Higgs beyond the LHC - experiments** *30'*
Speaker: Patrick JANOT (CERN Geneva, Switzerland)
Material: Slides

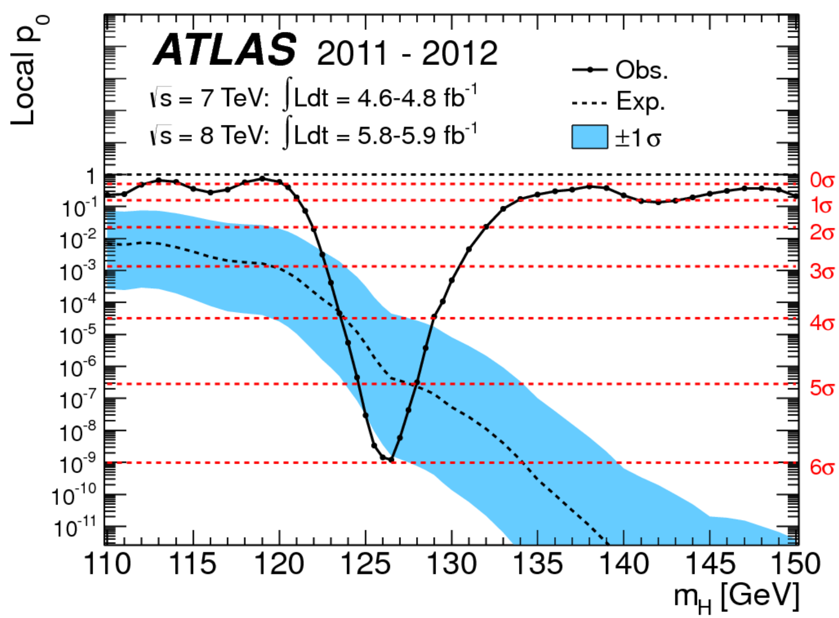
12:00 **Accelerators for a Higgs Factory** *20'*
Speaker: Stuart Henderson (Fermilab)
Material: Slides

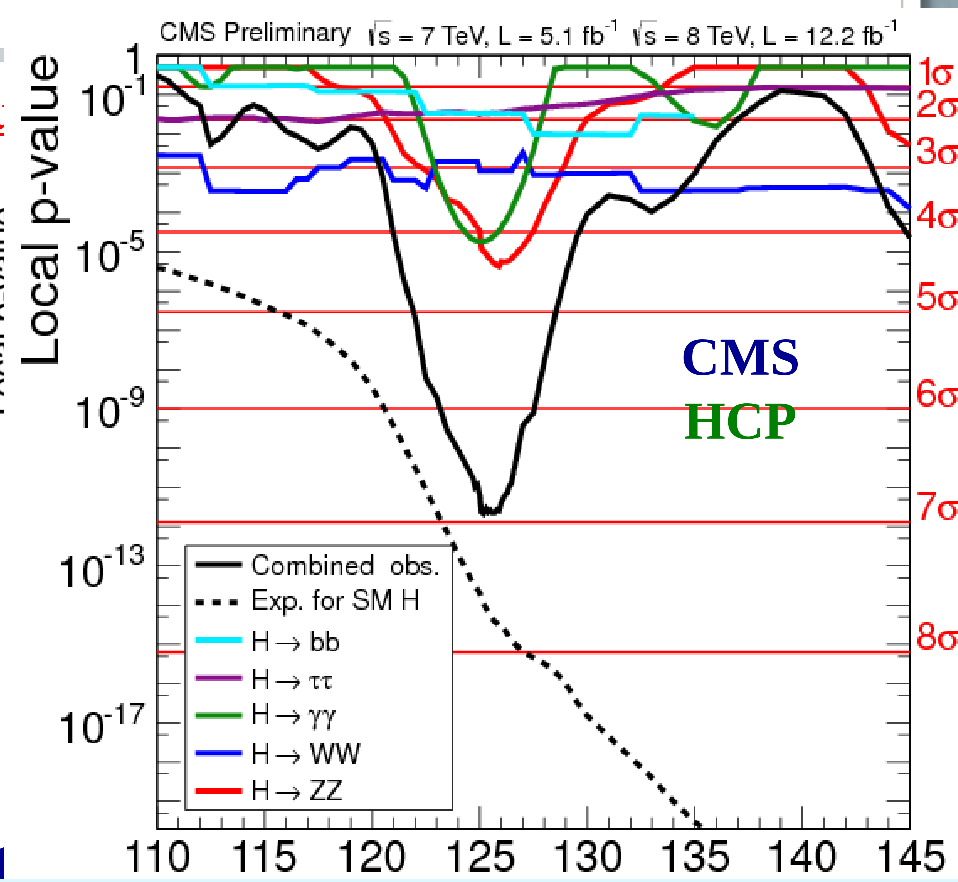
11:00 **Physics of μμ --> Higgs** *15'*
Speaker: Tao Han (University of Wisconsin)

13:45 **Physics of gamma+gamma --> Higgs** *15'*
Speaker: Mayda Velasco (Northwestern University)

The Higgs Boson Discovery

4th Ju





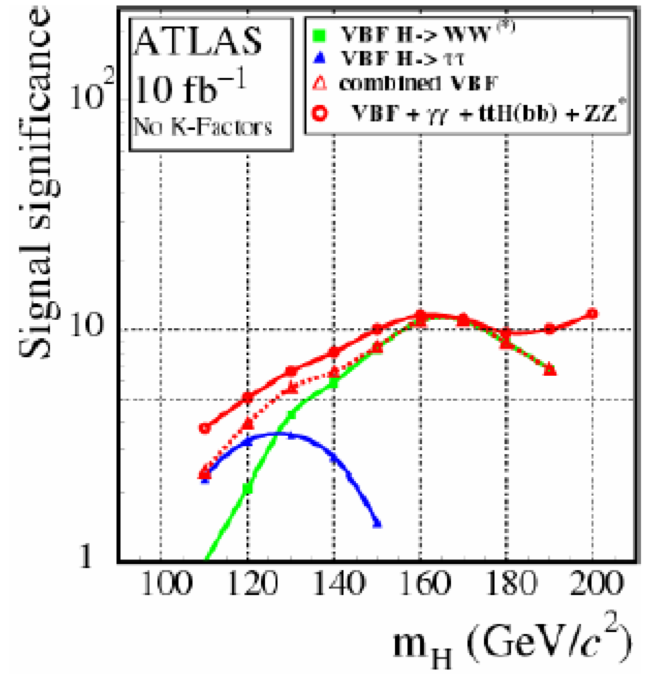
Discovered Higgs-like Boson: Cl

– observed: 6.9; expected: 7.8

Is this the SM one ? From searches to measurements

LHC has done better than projected:

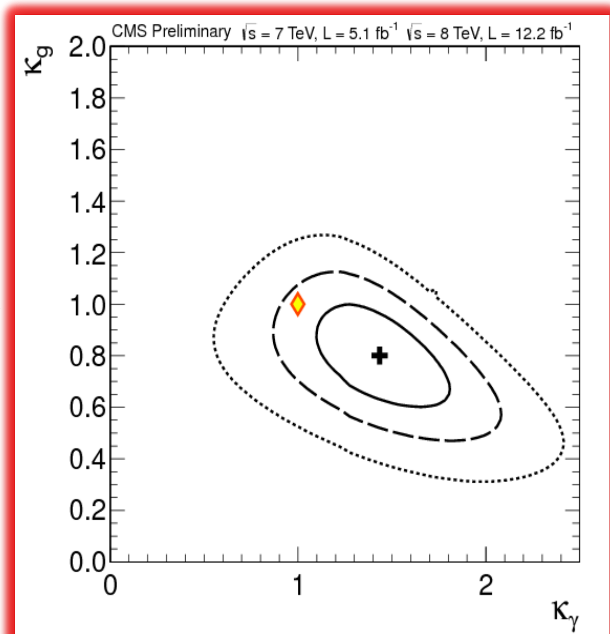
here is a plot from ATLAS in 2005,
expected ~4σ with 10fb-1 at 14TeV →



HCP 2012 (Kyoto):
-- mass (125.9±0.4 GeV/c²) *(my average)*
-- spin parity (0+ preferred at 2.45σ -- CMS)

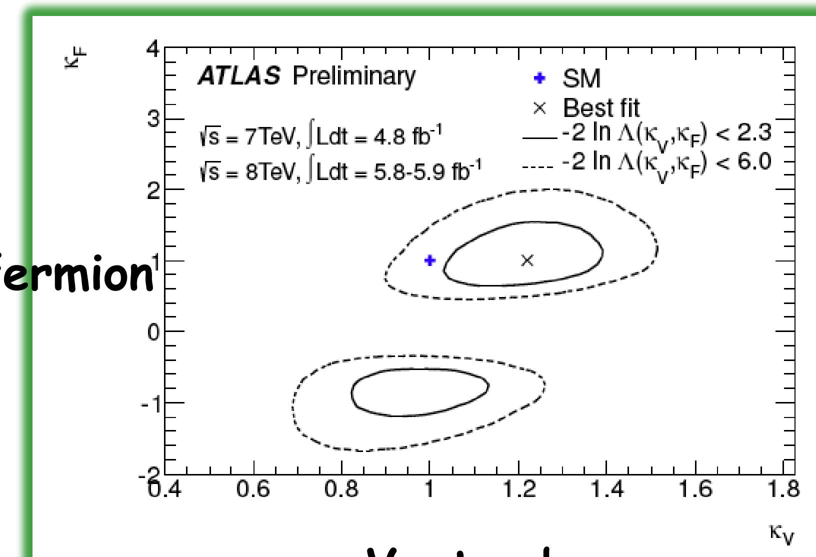
already measuring couplings at ±20% level …
(with a number of assuptions)

$$\frac{g_{H\text{-gluon}}}{g^{SM}_{H\text{-gluon}}} = \kappa_g$$

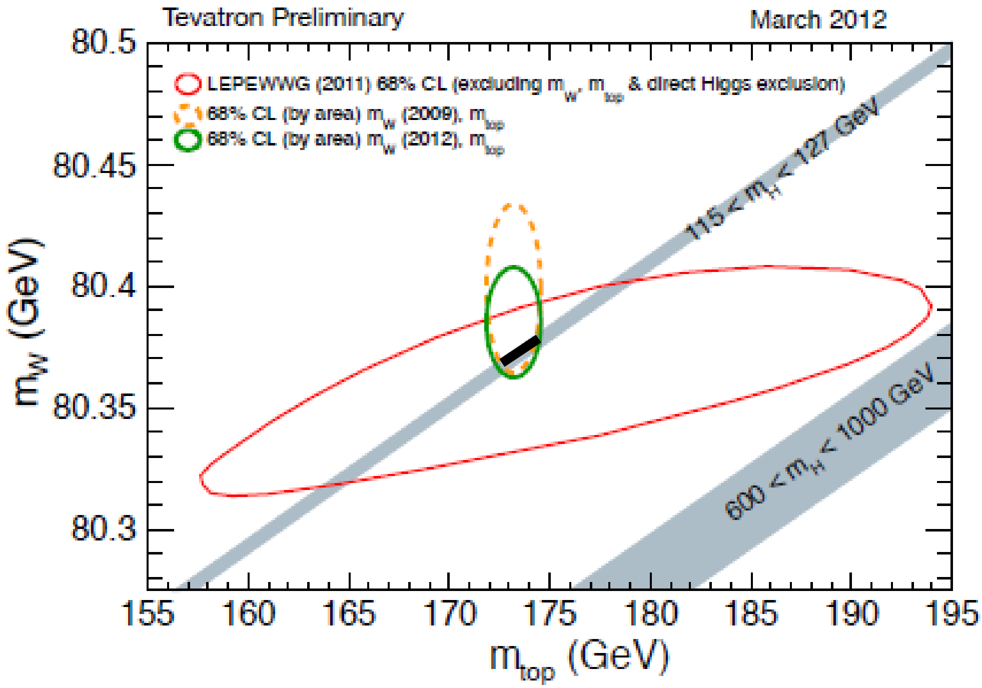


Photon

fermion

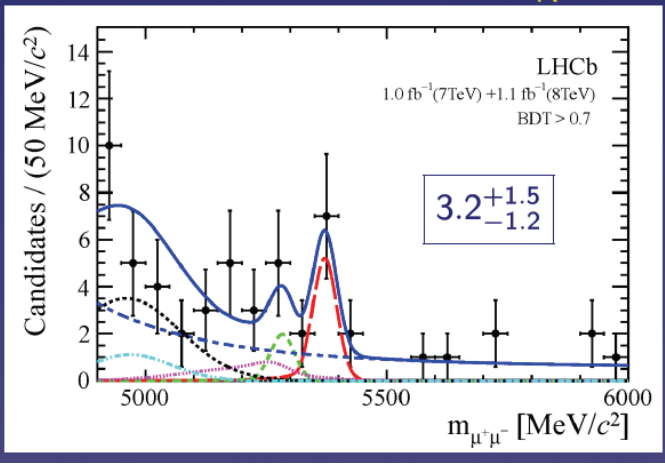


Vector boson



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

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



When m_H is known the EW precision measurements have no more freedom!

EW precision measurements, rare decays ($B_S \to \mu\mu$, etc…)

-- 4th generation

-- SUSY

-- Higgs triplets

-- etc. etc.

Strong incentive to revisit and improve Z pole measurements and m_W…

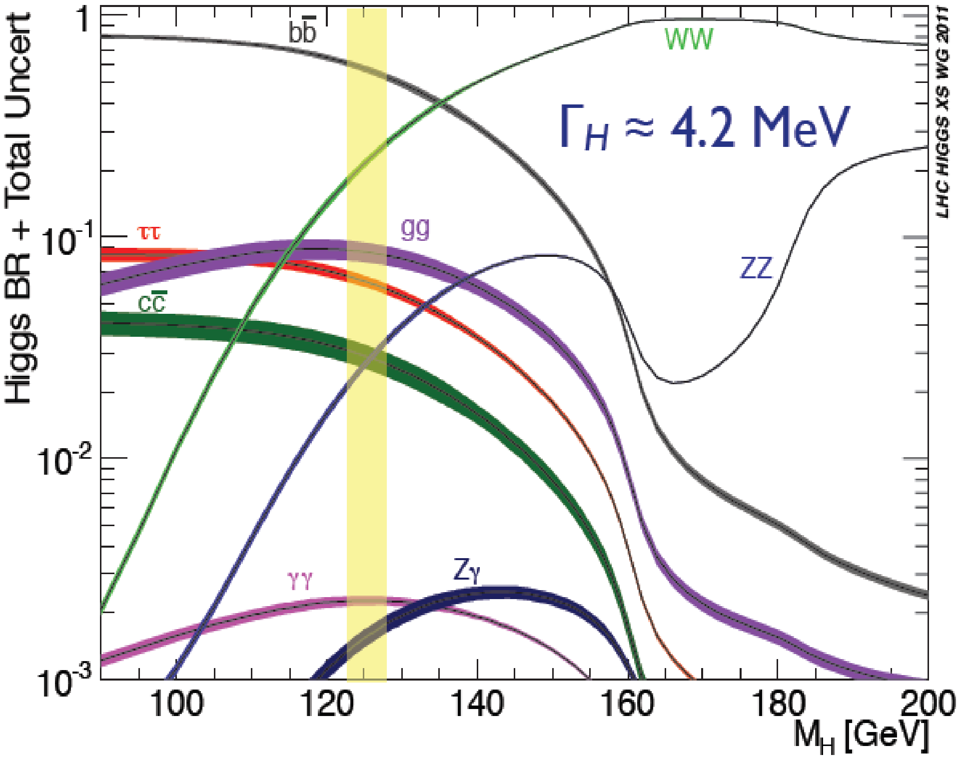
The questions (Young-Kee-Kim):

Is this the Standard Model Higgs?
A Higgs beyond the SM?

Measure the properties of this new particle with high precision

your Banker's question:
What precision is needed to answer the question?

Once the Higgs boson mass is known, the Standard Model is entirely defined.
-- with the notable exception of neutrino masses, nature & mixings
******the only new physics there is******
but expect these to be ~ decoupled from Higgs observables (really?)



Does H(125.9)
Fully accounts for EWSB (*W, Z couplings*)?
Couples to fermions?
Accounts for fermion masses?
Fermion couplings ∝ masses?
Are there others?
Quantum numbers? CP eigenstate?
SM branching fractions to gauge bosons?
Decays to new or invisible particles?
All production modes as expected?
Implications of *MH ≈ 126 GeV?*
Any sign of new strong dynamics?

your Banker's question:
What precision is needed to answer the question?

The theorists (Chris Quigg) answer:

Some guidance from other theorists

R.S. Gupta, H. Rzehak, J.D. Wells, "How well do we need to measure Higgs boson couplings?", arXiv:1206.3560 (2012)
H. Baer et al., "Physics at the International Linear Collider", in preparation, http://lcsim.org/papers/DBDPhysics.pdf

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

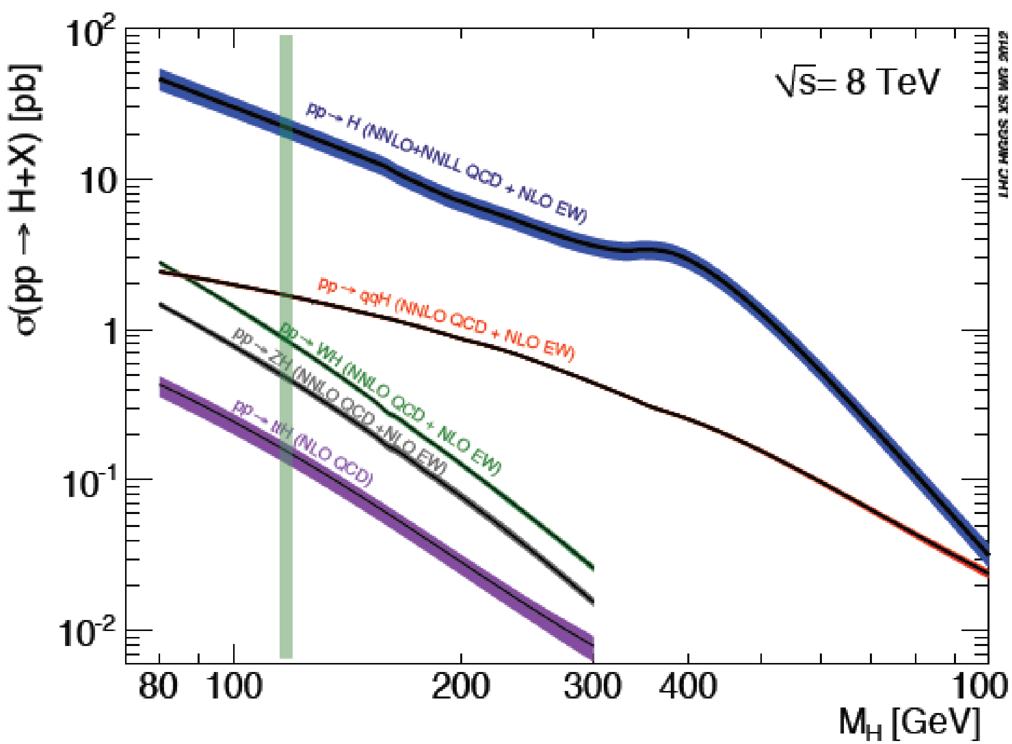
Composite Higgs $\frac{g_{hff}}{g_{h_{SM}ff}} \simeq \frac{g_{hVV}}{g_{h_{SM}VV}} \simeq 1 - 3\% \left(\frac{1 \text{ TeV}}{f}\right)^2$

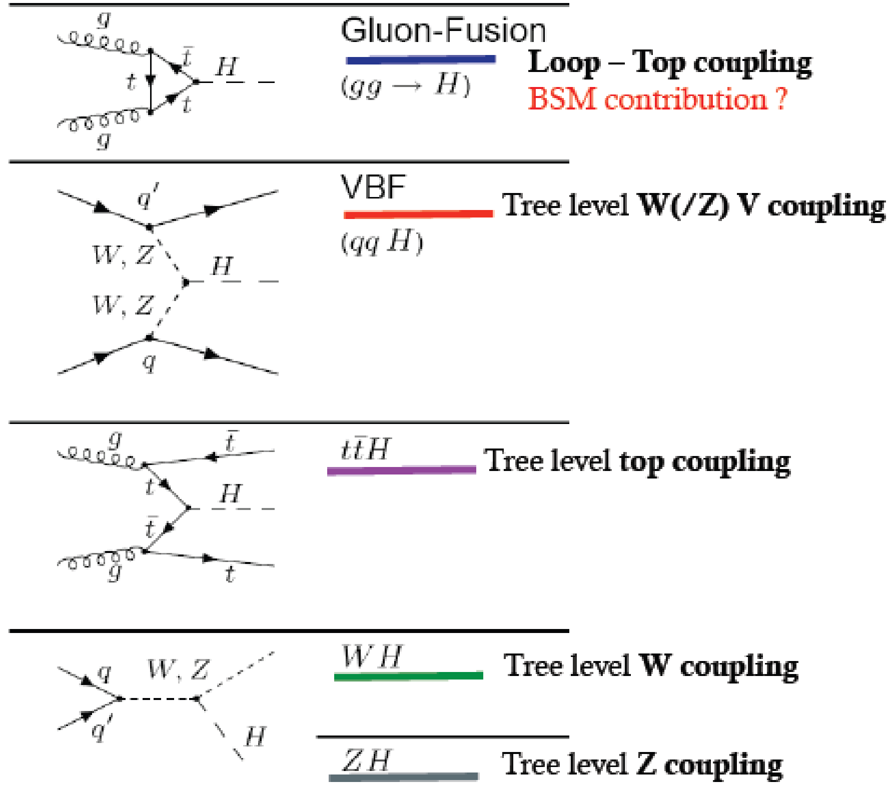
Top partners $\frac{g_{hgg}}{g_{h_{SM}gg}} \simeq 1 + 2.9\% \left(\frac{1 \text{ TeV}}{m_T}\right)^2, \quad \frac{g_{h\gamma\gamma}}{g_{h_{SM}\gamma\gamma}} \simeq 1 - 0.8\% \left(\frac{1 \text{ TeV}}{m_T}\right)^2$

Other models may give up to 5% deviations with respect to the Standard Model

Sensitivity to "TeV" new physics needs per-cent to sub-per-cent accuracy on couplings for 5 sigma discovery

LHC discoveries/(or not) at 13 TeV will be crucial to understand the strategy for future collider projects





The LHC is a Higgs Factory !

1M Higgs already produced – more than most other Higgs factory projects.
15 Higgs bosons / minute – and more to come (gain factor 3 going to 13 TeV)

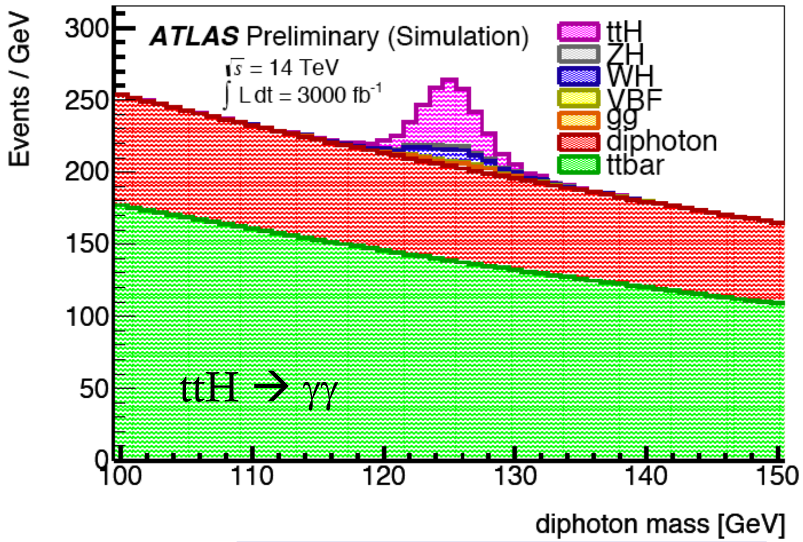
Difficulties: several production mechanisms to disentangle and significant systematics in the production cross-sections σ_{prod}
Challenge will be to constrain systematics by measuring related processes.

$$\sigma_{i\to f}^{\ observed} \propto \sigma_{prod} \frac{(g_{Hi})^2 (g_{Hf})^2}{\Gamma_H}$$

extract couplings to initial and final state
if i=f as in ZH with H→ ZZ → absolute normalization

Couplings at HL-LHC: ATLAS

- MC Samples at 14 TeV from Fast-Sim.
  - Truth with smearing: best estimate of physics objects dependency on pile-up
  - Validated with full-sim. up to μ~70



- Analyses included in ATLAS study:
  - H→ γγ 0-jet and VBF
  - H → ττ VBF lep-lep and lep-had
  - H → ZZ → 4ℓ
  - H→ WW → ℓνℓν 0-jet and VBF
  - WH/ZH → γγ
  - **ttH → γγ (ttH → μμ) Direct top Y coupling**
  - **H → μμ Second generation fermion coupling**
  - **HH→ bb γγ Higgs Self-Couplings**

Very Robust channel
Good S/B
Statistically limited

Couplings fit at HL-LHC

CMS

Coupling	Uncertainty (%)			
	300 fb^{-1}		3000 fb^{-1}	
	Scenario 1	Scenario 2	Scenario 1	Scenario 2
κ_γ	6.5	5.1	5.4	1.5
κ_V	5.7	2.7	4.5	1.0
κ_g	11	5.7	7.5	2.7
κ_b	15	6.9	11	2.7
κ_t	14	8.7	8.0	3.9
κ_τ	8.5	5.1	5.4	2.0

CMS Projection

Assumption NO invisible/undetectable contribution to Γ_H:

- Scenario 1: system./Theory err. unchanged w.r.t. current analysis
- Scenario 2: systematics scaled by 1/sqrt(L), theory errors scaled by ½

✓ γγ loop at 2-5% level

✓ down-type fermion couplings at 2-10% level

✓ direct top coupling at 4-8% level

✓ gg loop at 3-8% level

Conclusions

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

- Higgs mass at 100 MeV
- Disentangle Spin 0 vs Spin 2 and main CP component in ZZ*
- Coupling rel. precision/Exper.
  - Z, W, b, τ 10-15%
  - t, μ 3-2 σ observation
  - γγ and gg 5-11%

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

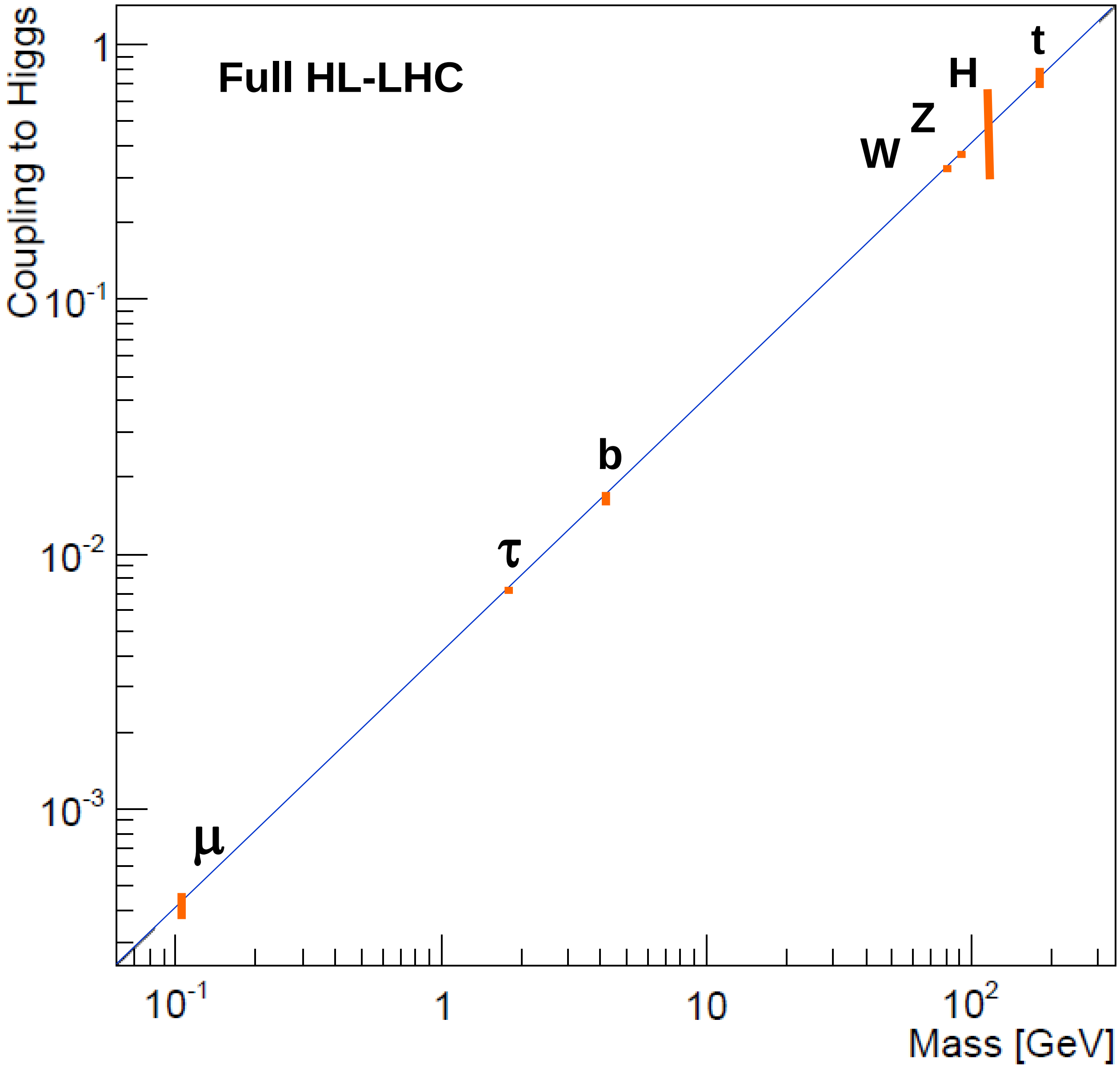
- Higgs mass at 50 MeV
- More precise studies of Higgs CP sector
- Couplings rel. precision/Exper.
  - Z, W, b, τ, t, μ 2-10%
  - γγ and gg 2-5%
  - H→HH >3 σ observation (2 Exper.)

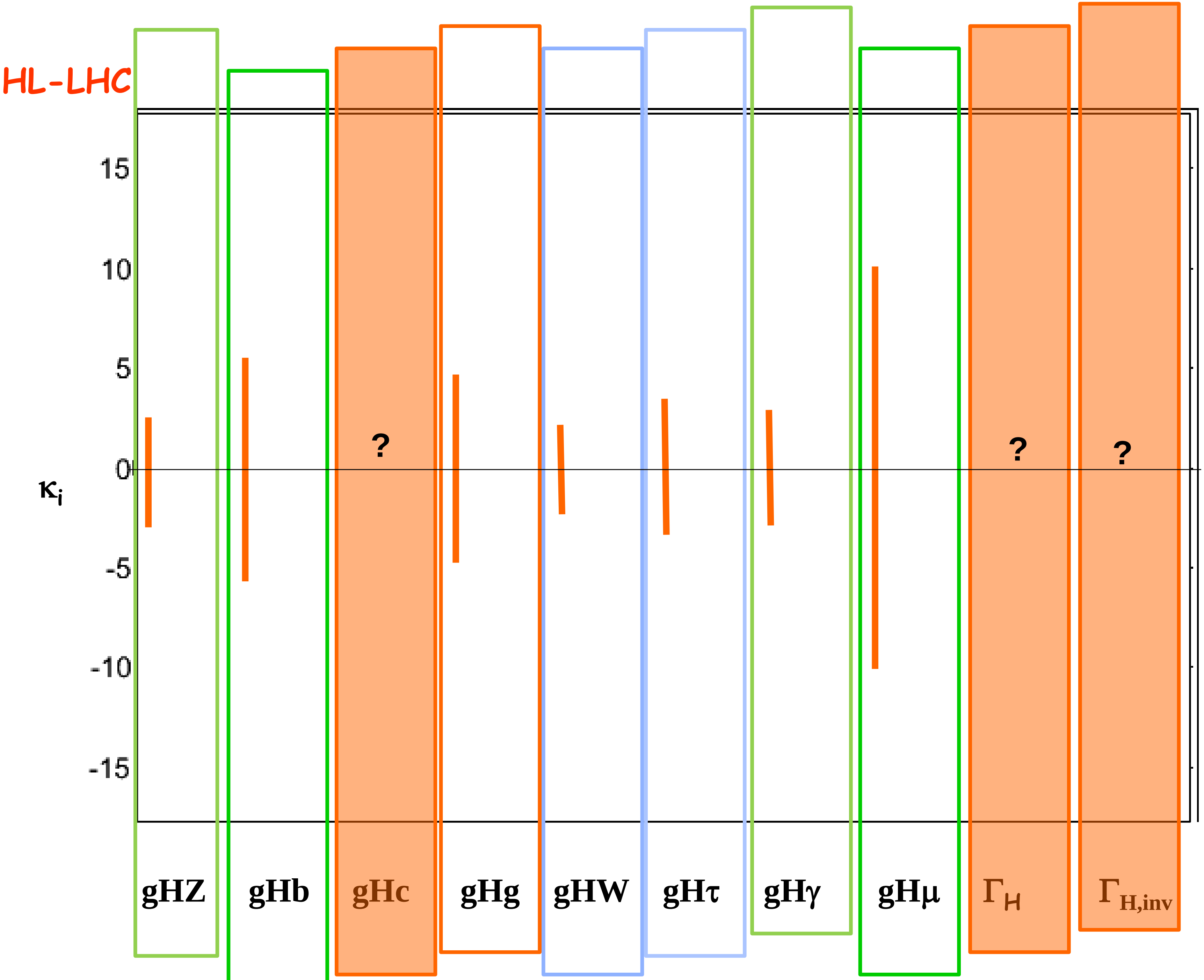
Assuming sizeable reduction of theory errors

LHC experiments entered the Higgs properties measurement era: this is just the beginning !
LHC Upgrade crucial step towards precision tests of the nature of the newly-discovered boson

$g_{H\gamma} \rightarrow 3\%$

$g_{H\gamma} \rightarrow 3\%$



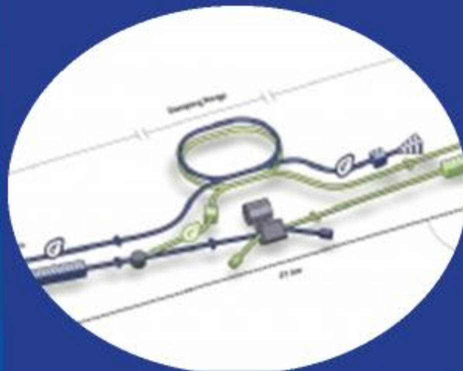

HL-LHC
15
10
5
0
-5
-10
-15
κi
?
?
?
gHZ
gHb
gHc
gHg
gHW
gHτ
gHγ
gHμ
ΓH
ΓH,inv

Higgs Factories Dreams

S. Henderson

Linear Colliders

ILC
CLIC
SLC-type
Adv. Concepts

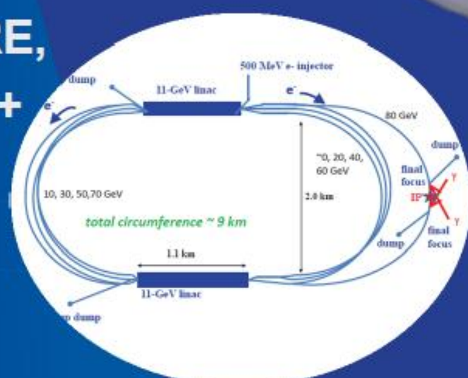


Circular e^+e^- Colliders

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

Higgs Factories

SAPPHIRE,
CLICHÉ, +
…



γ-γ Colliders

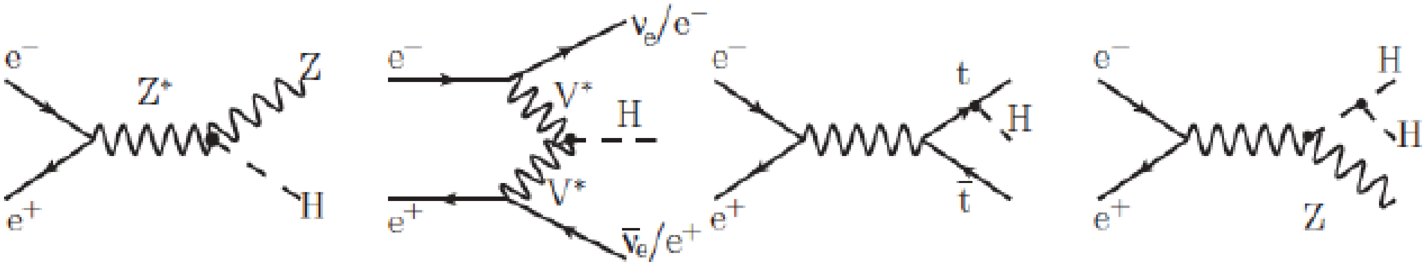
Muon Colliders

2

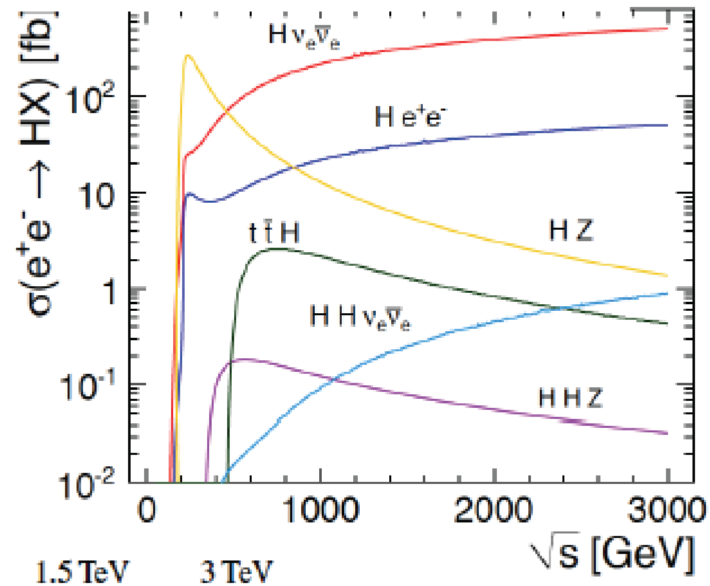
Fermilab

Wyatt, Cracow

Higgs in e^+e^-



Many studies performed using full Geant-based MC



Integrated luminosity and numbers of events expected for initial 5 years running at each value of E_{cm}

	250 GeV	350 GeV	500 GeV	1 TeV	1.5 TeV	3 TeV
$\sigma(e^+e^- \to ZH)$	240 fb	129 fb	57 fb	13 fb	6 fb	1 fb
$\sigma(e^+e^- \to H\nu_e\bar{\nu}_e)$	8 fb	30 fb	75 fb	210 fb	309 fb	484 fb
Int. $\mathcal{L}$	250 fb^{-1}	350 fb^{-1}	500 fb^{-1}	1000 fb^{-1}	1500 fb^{-1}	2000 fb^{-1}
# ZH events	60,000	45,500	28,500	13,000	7,500	2,000
# $H\nu_e\bar{\nu}_e$ events	2,000	10,500	37,500	210,000	460,000	970,000

Latest reference:

ILC ESD-2012/4, CLIC-Note-949 (July 30, 2012)

The Physics Case for an e^+e^- Linear Collider

James E. Brau[a], Rohini M. Godbole[b], Francois R. Le Diberder[c], M.A. Thomson[d],
Harry Weerts[e], Georg Weiglein[f], James D. Wells[g], Hitoshi Yamamoto[h]

A Report Commissioned by the Linear Collider Community[†]

The Higgs at a Linear e+e- Collider has been studied for many years
Community is large and well organized

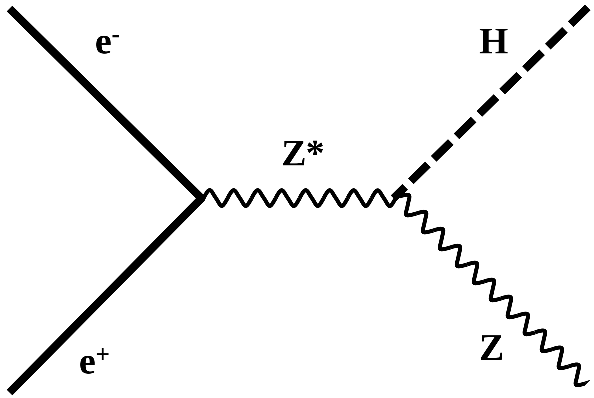
At a given Ecm and Luminosity, the physics has marginally
to do with the fact that the collider is *linear*

--specifics: -+- e- polarization is easy at the source for ILC
(not critical for Higgs)
-- Beam energy calibration at Z peak (perhaps WW) for rings
-- EM backgrounds from beam disruption in Linear
-- one IP in linear vs several Ips in circular.

Higgs production mechanism

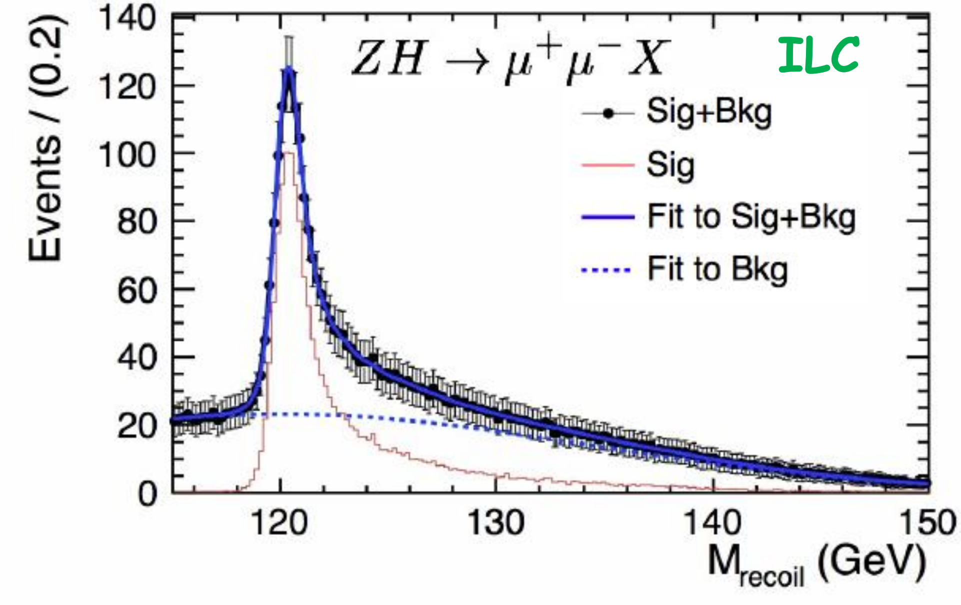
In e^+e^- the Higgs is produced by "higgstrahlung" close to threshold

Production xsection has maximum near threshold ~200 fb
$10^{34}/cm^2/s$ ➔ 20'000 HZ events per year.



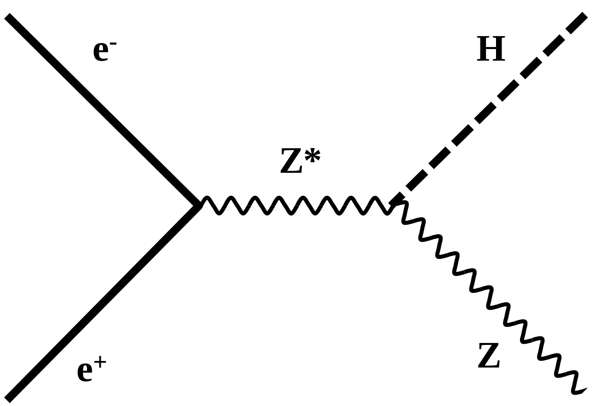
H – tagging by missing mass to Z decay

For a Higgs of 125GeV, a centre of mass energy of ~240GeV is best
➔ kinematical constraint near threshold for high precision in mass, width, selection purity

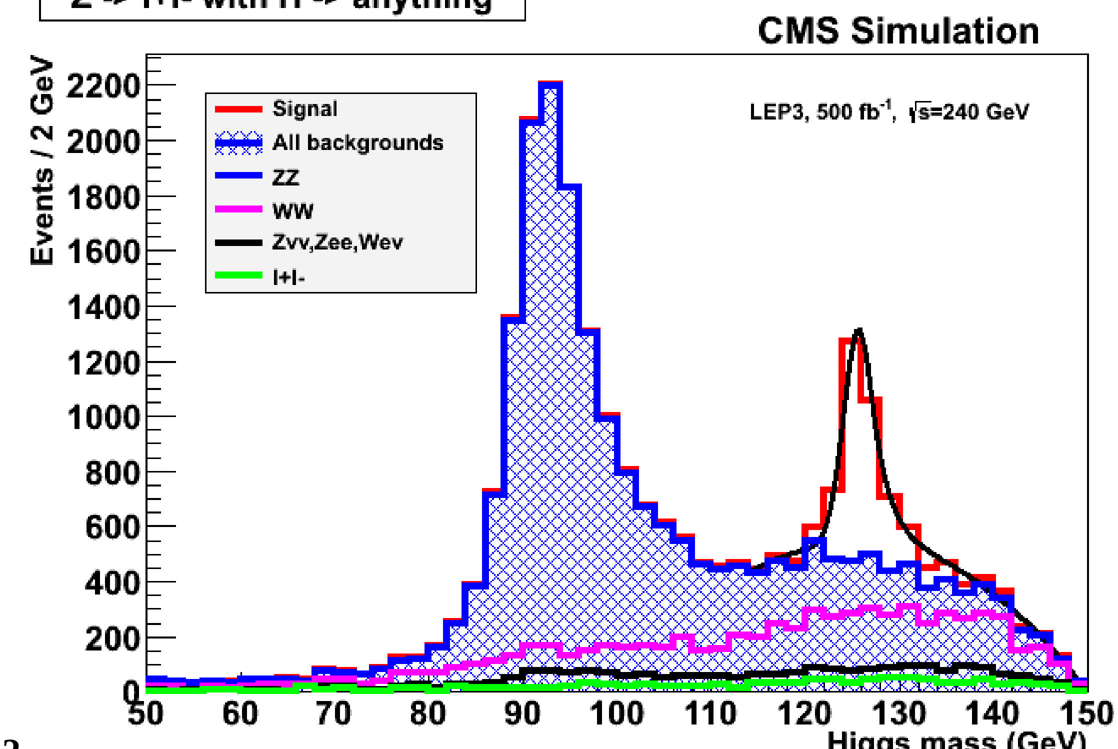


Z – tagging
by missing mass

total rate $\propto g_{HZZ}^2$
ZZZ final state $\propto g_{HZZ}^4 / \Gamma_H$
➔ measure total width Γ_H
empty recoil = invisible width
'funny recoil' = exotic Higgs decay
easy control below theshold



Z -> l+l- with H -> anything



LC-REP-2012-071, ILC ESD-2012/4, CLIC-Note-949 (July 30, 2012)

The Physics Case for an e^+e^- Linear Collider

James E. Brau[a], Rohini M. Godbole[b], Francois R. Le Diberder[c], M.A. Thomson[d], Harry Weerts[e], Georg Weiglein[f], James D. Wells[g], Hitoshi Yamamoto[h]

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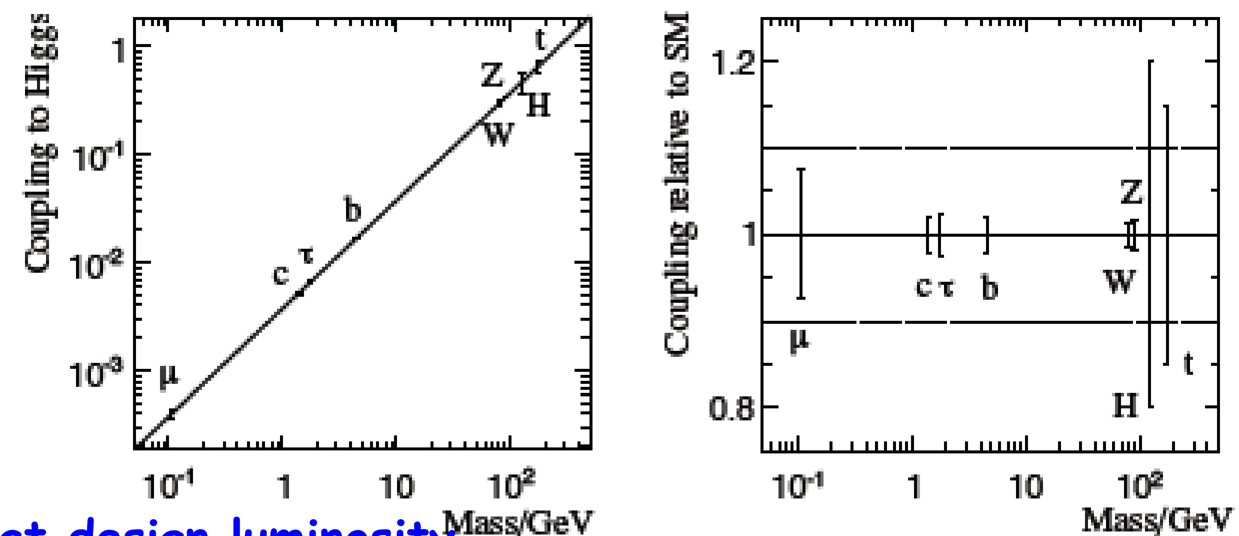
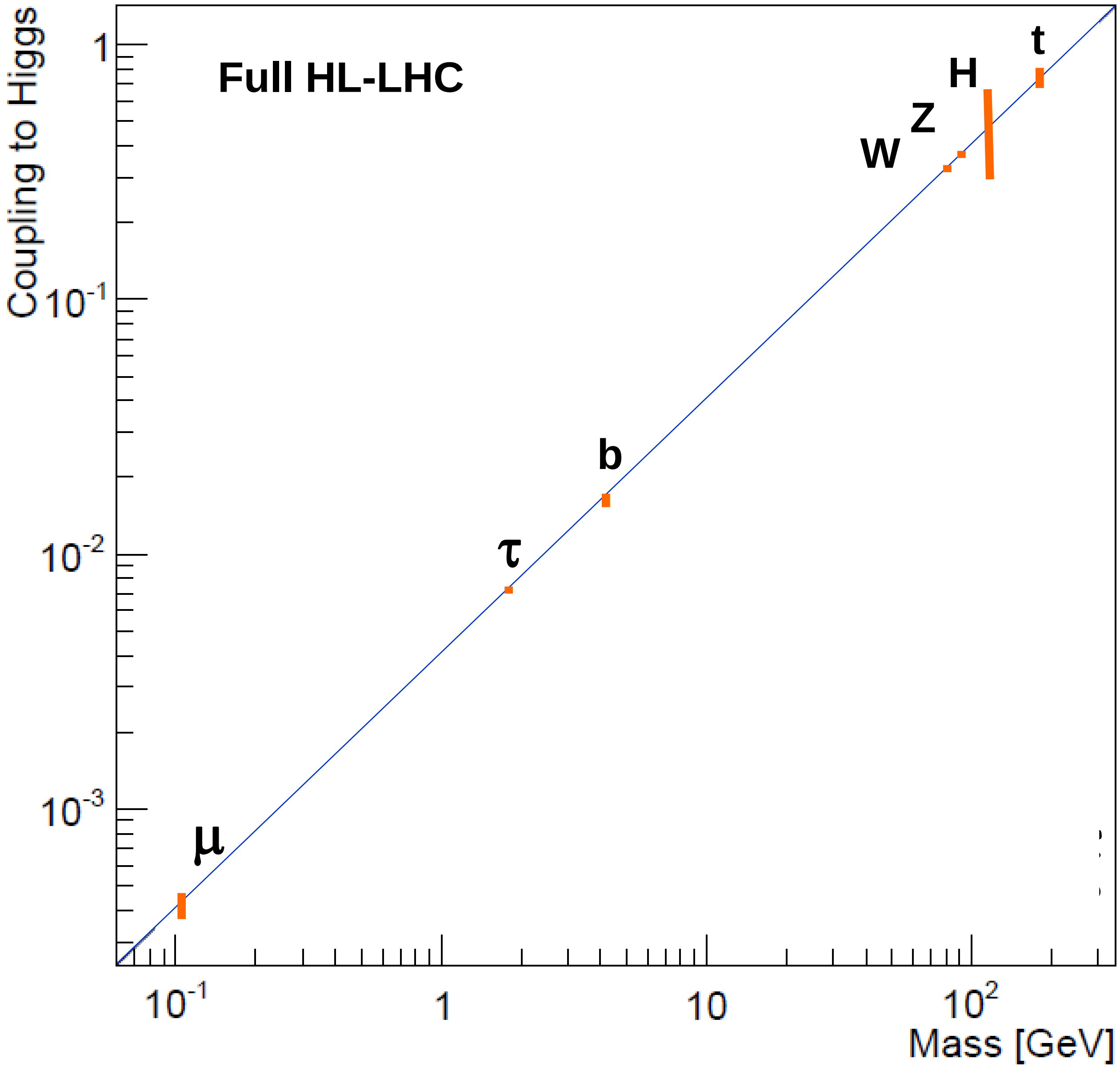


see also M. Peskin, arXiv:1207.2516v1 (with th. assumptions) no HL-LHC

ILC/CLIC
10 years at design luminosity

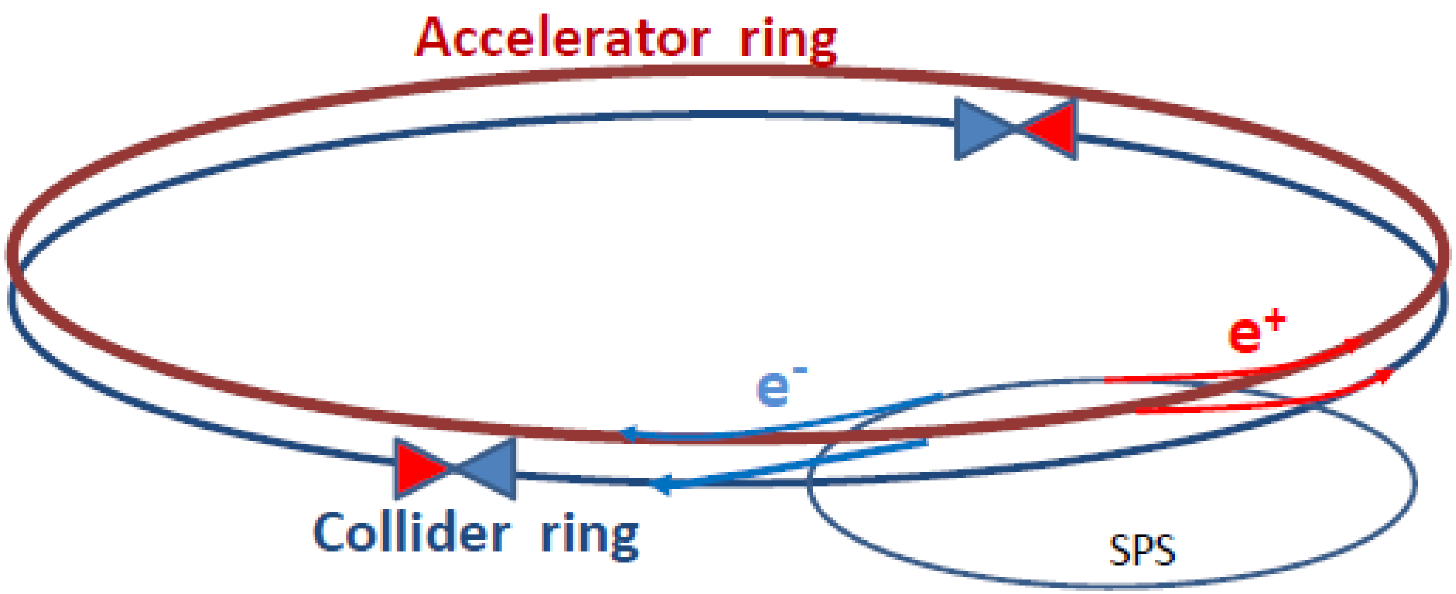
Figure 3: An illustration of the typical precisions to which the relation between the Higgs couplings to the masses of the particles can be tested at a linear collider, assuming operation at one energy point below and one above $\sqrt{s} = 500\,\mathrm{GeV}$ with the integrated luminosities of Table 1. The ultimate sensitivity will depend on the precise integrated luminosity recorded and the centre-of-mass energies at which the LC is operated. The two plots show the absolute and relative precision that can be reached. The values shown assume SM couplings.


Full HL-LHC
Coupling to Higgs
Mass [GeV]
1
10^{-1}
10^{-2}
10^{-3}
10^{-1}
1
10
10^{2}
μ
τ
b
W
Z
H
t

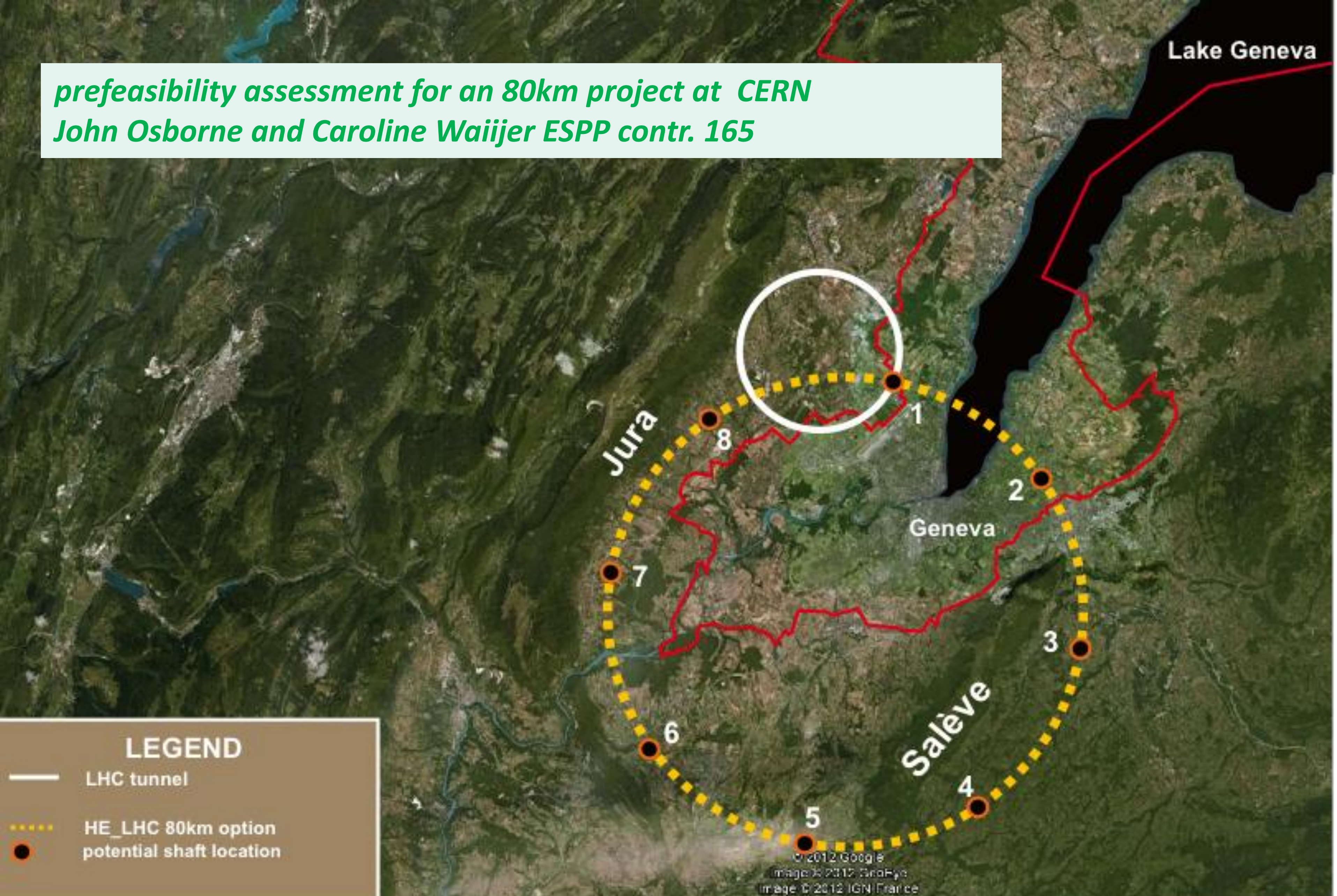
What about a circular machine? LEP2 was not that far after all.
One year of LEP2 → ~200pb^{-1} x 4 exp. need 100fb^{-1}!
How can one increase over LEP 2 (average) luminosity by a factor 500 without exploding the power bill?

Answer is in the B-factory design: a very low vertical emittance ring with higher intrinsic luminosity

electrons and positrons have a much higher chance of interacting
→ much shorter lifetime (few minutes)
→ feed beam continuously with a ancillary accelerator



prefeasibility assessment for an 80km project at CERN
John Osborne and Caroline Waiijer ESPP contr. 165



LEP3, TLEP

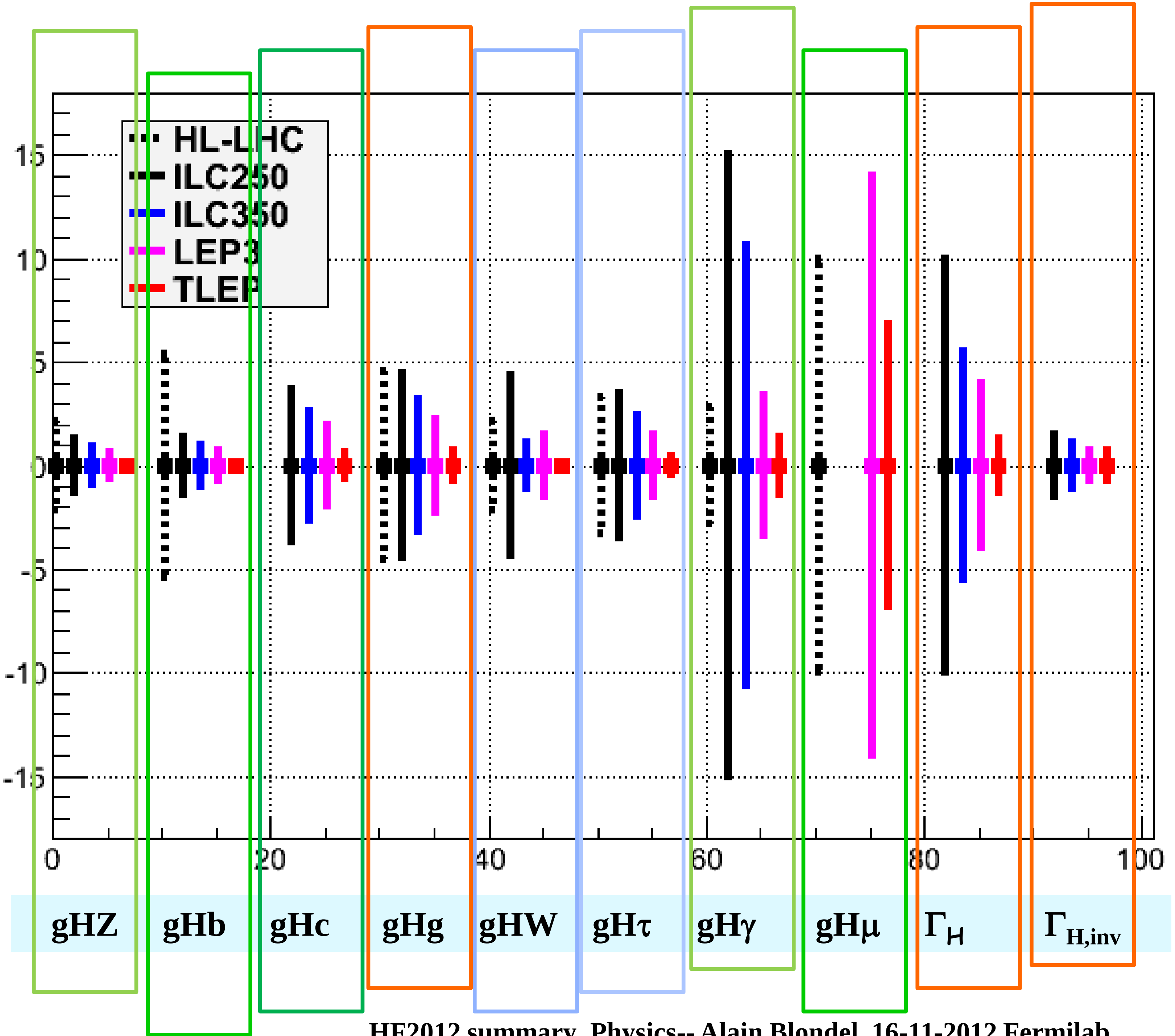
Zimmermann

($e^+e^- \to ZH$, $e^+e^- \to W^+W^-$, $e^+e^- \to Z$, [$e^+e^- \to t\bar{t}$])

key parameters

	LEP3	TLEP
circumference	26.7 km	80 km
max beam energy	120 GeV	175 GeV
max no. of IPs	**2-8 times**	**10-40 times**
luminosity at 350 GeV c.m.	**ILC lumi**	**ILC lumi**
luminosity at 240 GeV c.m.	**at ZH thresh.**	**at ZH thresh.**
luminosity at 160 GeV c.m.	5×10^{34} cm^{-2}s^{-1}	2.5×10^{35} cm^{-2}s^{-1}
luminosity at 90 GeV c.m.	2×10^{35} cm^{-2}s^{-1}	10^{36} cm^{-2}s^{-1}

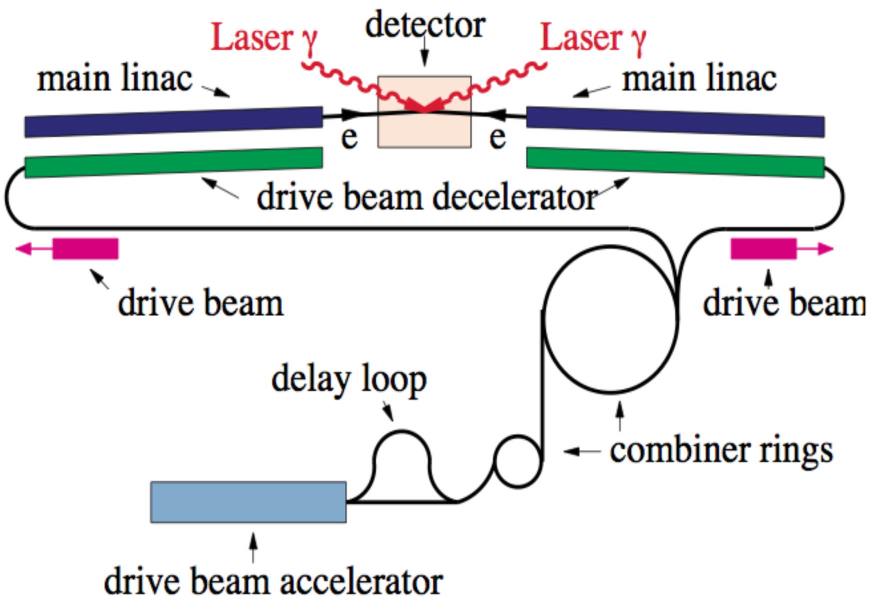
at the *Z* pole repeating LEP physics programme in a few minutes…

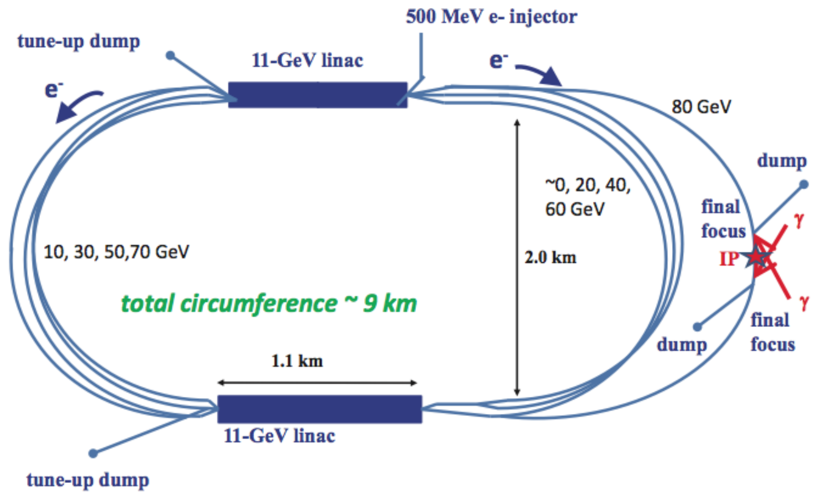

HL-LHC
ILC250
ILC350
LEP3
TLEP
15
10
5
0
-5
-10
-15
0
20
40
60
80
100
gHZ
gHb
gHc
gHg
gHW
gHτ
gHγ
gHμ
Γ_H
Γ_H,inv

Machines considered:

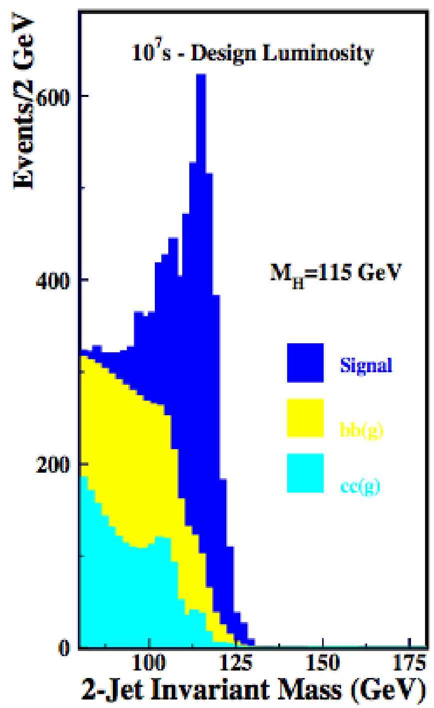
#1 Light Higgs Factory: CLICHE, ILC (TESLA) & SAPPHiRE

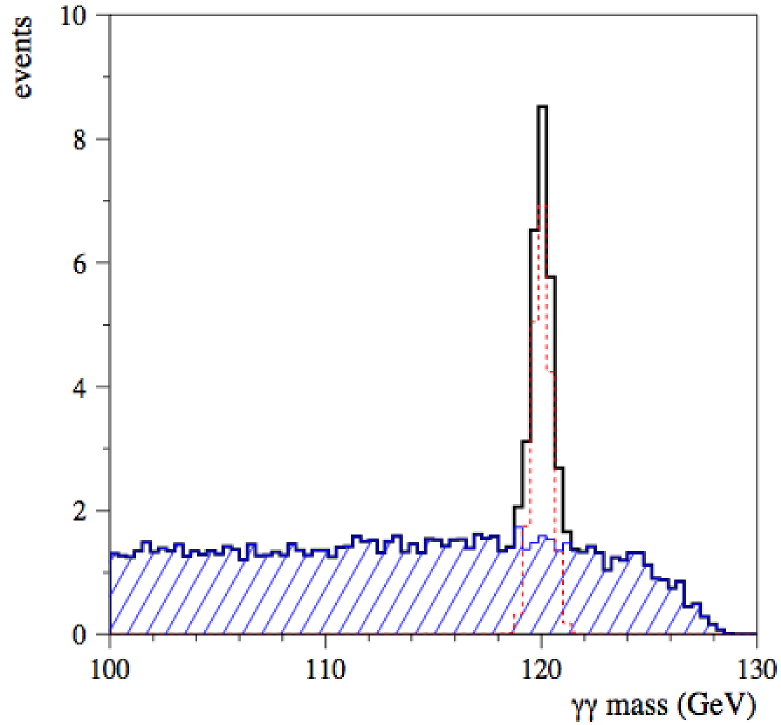
Machine	$E_{e^+e^-}$ (GeV)	$M_{h_{SM}}$ (GeV)	Yield/year	Ref.
CLICHE	150	115	22.5k	hep-ex/0110056
CLICHE	160	120	23.6k	Correct for $\Gamma_{\gamma\gamma}$
TESLA	160	120	21.0k	hep-ex/0101056
SAPPHiRE	160	125	20.0k	1208.2827
e^+e^-	$350_{TESLA}(500_{NLC})$	120	3.5k(20k) Tag(Raw)	hep-ph/0101165





$h^0 \to b\bar{b}$ and $h^0 \to \gamma\gamma$ hep-ex/0110056





2% measurement of $\{\Gamma_{\gamma\gamma} \times Br(h \to b\bar{b})\}$ within a year!

21% measurement of $\{\Gamma_{\gamma\gamma} \times Br(h \to \gamma\gamma)\}$ within a year!

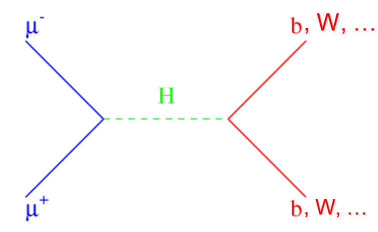
150 MeV mass measurement in 0.5 year! Schmitt, Stenz & Velasco

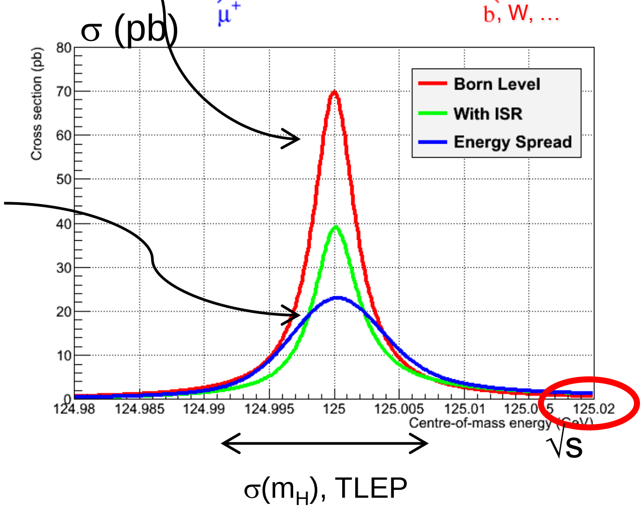
$\mu^+\mu^-$ Collider vs e^+e^- Collider ?

- **A $\mu^+\mu^-$ collider can do things that an e^+e^- collider cannot do** [16,17]
  - Direct coupling to H expected to be larger by a factor m_μ/m_e

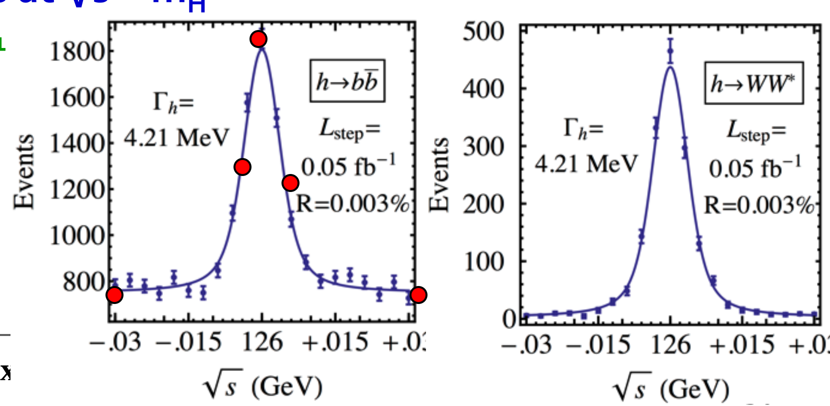
    $\sigma(\mu^+\mu^- \to H) \approx 40000 \times \sigma(e^+e^- \to H)$ σ_{peak} = 70 pb at tree level]
  - Can it be built + beam energy spread $\delta E/E$ be reduced to 3×10^{-5} ?
    - 4D+6D Cooling needed!
    - For $\delta E/E$ = 0.003% (δE ~ 3.6 MeV, Γ_H ~ 4 MeV)
    - no beamstrahlung, reduced bremsstrahlung
      - ➔ Corresponding luminosity ~ 10^{31} cm^{-2}s^{-1}

        Expect 2300 Higgs events in 100 pb^{-1}/ year
  - Using g-2 precession, beam energy and energy spectrum
    - Can be measured with exquisite precision (<100 keV)
      - ➔ From the electrons of muon decays
  - Then measure the detailed lineshape of the Higgs at $\sqrt{s}$ ~ m_H
    - Five-point scan, 50 + 100 + 200 + 100 + 50 pb^{-1}



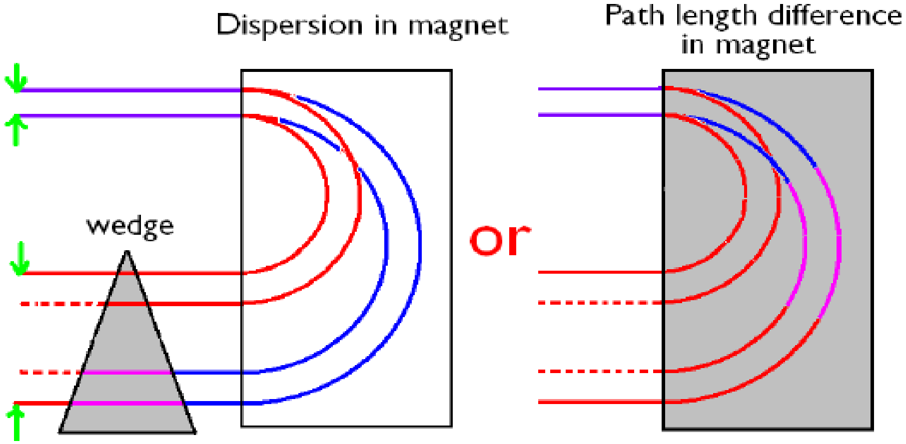


m_H	σ_{Peak}	Γ_H
0.1 MeV	0.6 pb	0.2 MeV
10^{-6}	2.5%	5%



COOLING -- Principle is straightforward...

Longitudinal:

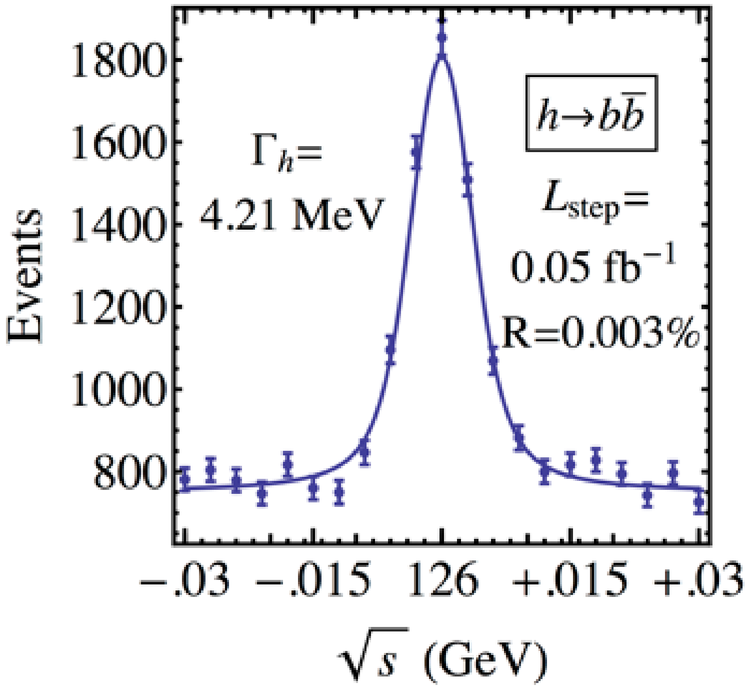


Emittance exchange involves ionization varying in space which cancels the dispersion of energies in the beam.

This can be used to reduce the energy spread and is of particular interest for

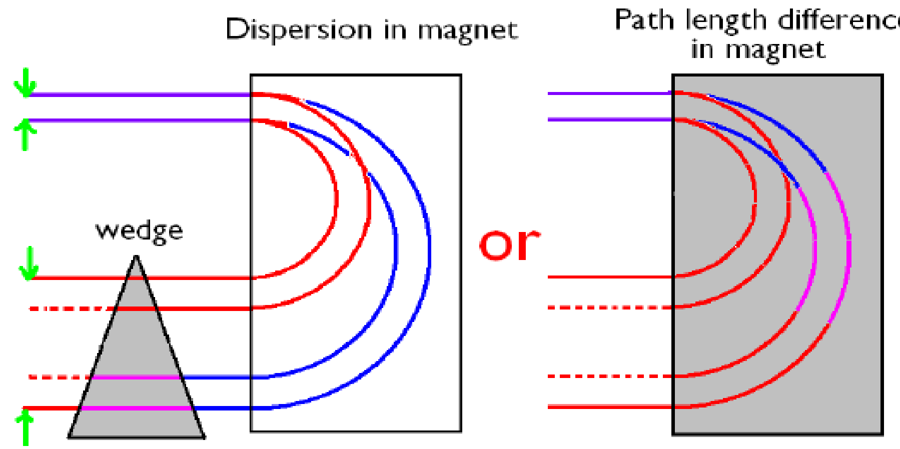
$$\mu^+ \mu^- \rightarrow H\ (125)$$

since the Higgs is very narrow (~4.2 MeV)

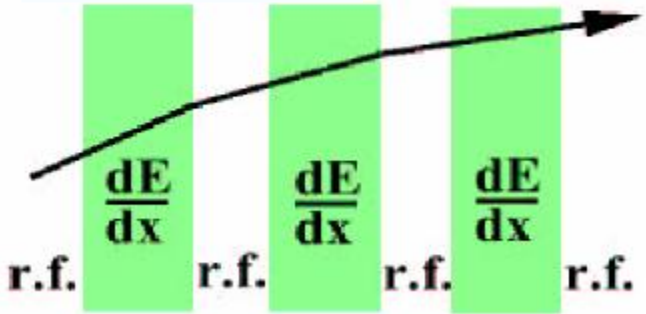


COOLING -- Principle is straightforward...

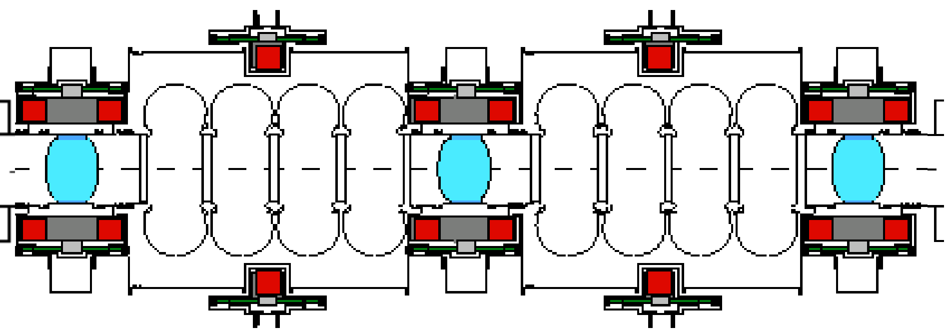
Longitudinal:



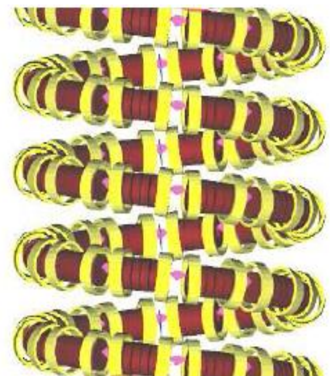
Transverse:



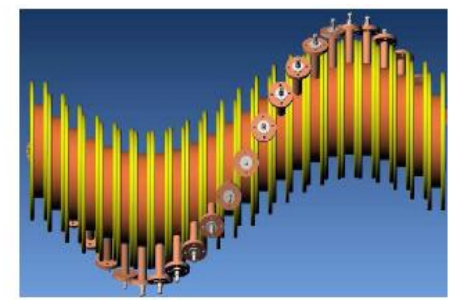
Practical realization is not!



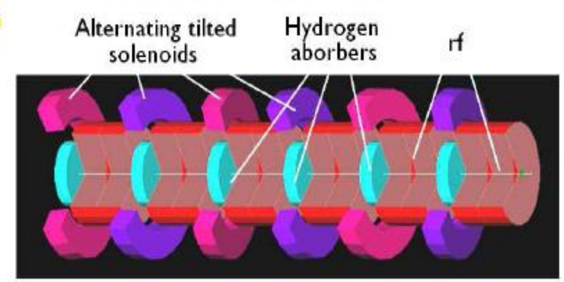
MICE cooling channel (4D cooling)



Guggenheim



Helical Cooling Channel



Snake

6D candidate cooling lattices

CONCLUSIONS

With the discovery of H(126) a new chapter is open in Particle Physics.

It will take a long time and should be planned carefully with an open mind. Chosing now the wrong machine will keep us for picking the right one in due time.

HL-LHC will be already an impressive Higgs Factory and the next step should make large improvement over it.

The circular e+e- Higgs factories open very interesting possibilities:

-- LEP3 as a cheaper back-up to the ILC
 and
-- TLEP as a superior, high precision Higgs factory
   --with long term prospect towards a very high energy hadron collider.
now….

LET'S SEE WHAT THE ACCELERATORS CAN DO!

BACK-UPS

Circular e^+e^- Collider as a Higgs Factory

- **Advantages:**
  - **At 240 GeV, potentially a higher luminosity to cost ratio than a linear one**
  - **Based on mature technology and rich experience**
  - **Some designs can use existing tunnel and site**
  - **More than one IP**
  - **Tunnel of a large ring can be reused as a pp collider in the future**

- **Challenges:**
  - **Beamstrahlung limiting beam life time requires lattice with large momentum acceptance**
  - **RF and vacuum problem from synchrotron radiation**
  - **A lattice with low emittance**
  - **Efficiency of converting wall power to synchrotron radiation power**
  - **Limited energy reach**
  - **No comprehensive study; design study report needed.**

Linear e^+e^- Collider as a Higgs Factory

- **Advantages:**
  - **Extensive design and prototyping work have been done**
  - **Big investment have been made. Key technologies are in hand.**
  - **There exist well-organized international collaborations led respectively by the ILC GDE and CLIC Collaboration (to be combined under the Linear Collider Director appointed by ICFA)**
  - **Important step towards high energy e+e- collisions**
  - **Polarized beams (e- 80%, e+ 30%)**
  - **A front runner (in terms of readiness)**
- **Challenges:**
  - **High cost**
- **Specific issues:**
  - **ILC**
    - **FFS (goal emittance has not yet been achieved at ATF2)**
    - **Polarized Positron source works only for E_{e-} > 350GeV**
    - **Industrialization of SRF**
    - **For Higgs factory: Need 10 Hz for e+ production, or use unpolarized e+ beam as a backup scheme**
  - **CLIC**
    - **Accelerating structure**
    - **Industrialization of major components**
    - **From CDR to TDR**

Conclusions(2)

Alternate Higgs factories considered include

- -- circular e+e- collider
- -- $\gamma\gamma$ collider
- -- $\mu\mu$ collider

In combination with HL-LHC the physics coverage of e+e- machines is quite complete.

A $\gamma\gamma$ collider is a good add-on to linear collider

- --one should discuss carefully what can be done at $\gamma\gamma$ collider that cannot be done between LHC and e+e- collider
- --the claim of uniqueness is 2% resolution on $\Gamma\gamma\gamma$; very interesting

A study dedicated to the understanding of the feasibility of the machine and of the specificity of the measurements would be worthwhile

A muon collider could do everyting an e+e- could do if same luminosity can be reached.

- --If an energy resolution of 0.003% can be achieved (4D and 6D cooling!) s-channel Higgs production allows superb measurements of the H(126) line shape and 'fine structure' exploration
- -- A muon collider is completely unique to study the H/A system of a Higgs doublet model
- -- it remains the best way to reach >3 TeV energy collisions between point like particles.

Conclusions(3)

-- e+e- ring collider offer a potentially better luminosity/cost ratio than the linear one and the possibility to have several IPs.

-- Much progress has been brought about by the experience of LEP2 B factories and Synchrotron light sources.

-- The main point of the HF2012 workshop was to understand whether the performance of circular machines could be as high as advertised

The answer is 'maybe' but there is lots of work to do to establish this.
There are also ideas to push the luminosity further.
This calls for a design study of circular e+e- Higgs Factory

-- If the luminosities advertised can be reached, the resolutions on most Higgs couplings can be improved from a few % to below percent precisions, opening the possibility of discovery of TeV scale new physics.

-- Revisiting Z pole and W threshold is now a must. This can be done at both circular and linear machines with some differences regarding energy calibration and polarization.

Extension possibilities

1. LEP3 (C=27km) is limited to the ZH threshold at 240 GeV
   TLEP (C=80km) can reach 350 GeV.
   all rings can accept up to 4 collision points and run at the Z peak
   80km ring e+e- collider 1st step to O(100 TeV) pp collider
   400-500 GeV is the end limit to circular machines.

2. linear machines can be upgraded to energies up to ~1 or even 3 TeV

3. the time structure is very different between linear (pulsed) and circular (CW) which has impact on the detector design.
   The ILC detectors as presently designed would not work on a ring.

4. A muon collider remains the most promising option for the very high energy exploration with point-like particles.

Conclusions

-- The newly discovered H(126) candidate is a fascinating particle of a new nature (elementary scalar!) that deserves detailed measurements

-- There is much more to understand about Higgs physics measurements and their potential to test physics beyond the SM. This should be discussed in a dedicated and detailed Higgs Physics workshop.

<u>-- LHC is/will be an impressive Higgs factory.</u> This must be taken into account in any future machine discussion!

-- The linear collider ILC can perform measurements at few% level for the Higgs invisible width, search for exotic decays, and improvement of bb, cc, W, Z couplings wrt LHC by factors 2-5

-- for $\gamma\gamma$, $\tau\tau$, $\mu\mu$, ttH, HHH, HL-LHC will do ~ as well or better

-- There is a strong motivation to investigate if one could do better

-- more precise or/and cheaper

-- Now that the Higgs mass is known, a new round of precision EWRC measurements is strongly motivated. (Predicted m_{top}, m_{Higgs}, now sensitive inclusively to EW-coupled new physics)

Higgs Physics with high-energy e^+e^- colliders

1. Similar precisions to the 250/350 GeV Higgs factory for W,Z,b,g,tau,charm, gamma and total and invisible width

2. ttH coupling possible with similar precision as HL-LHC (8-10%)

3. Higgs self coupling also very difficult… precision 20-30% similar to HL-LHC

I have to conclude that on the basis of the study of H(126) alone is concerned, the high energy e+e- collider is not compelling

Reversely, the Higgs physics can be done with CLIC at high energy

CLIC can work at 250 GeV onwards

- can it be brought down to the Z pole?

Higgs boson production at LHC

8 TeV

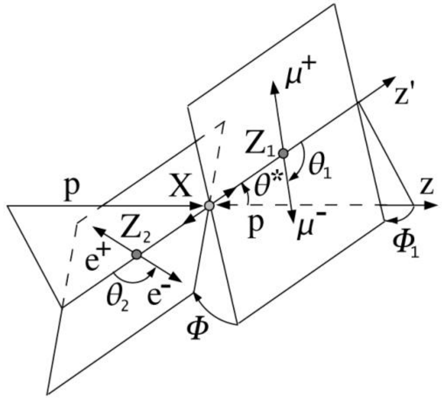
M_H(125 GeV)	σ(fb)	$\delta(th)_{TOT}$	$\delta(th)_{QCD-Scale}$	$\delta(th)_{PDF+\alpha s}$	$\delta\sigma/\delta M$(.5GeV)
ggH	19.5×10^3	**15%**	**8%**	**7%**	0.8%
VBF	1.58×10^3	3%	0.2%	3%	0.4%
WH	697	4%	0.5%	4%	1.3%
ZH	394	5%	1.5%	4%	1.3%
ttH	130	**14%**	**7%**	**8%**	1.9%

Theory systematics more relevant for ggH and ttH - Mass dependency very weak

--Important measurements at any moment depend on what is already known

What are the expected precisions from HL-LHC?

-- mass (125.9±0.4 GeV/c^2) *(my average)*
-- spin parity (0+ preferred at 2.45σ -- CMS) →



Couplings :
-- H-Z and H-W (κ$_V$ to ~20%)
-- H-t,b,c (κ$_f$ to ~20%)
-- H-τ, μ
-- H-invisible (dark matter candidates)
-- H-exotic
-- H-gluon, H-γ (20-30%)
-- H self coupling

-- CP violation
-- detailed line shape (more than one peak etc…)

green = today
black = HL-LHC
red = no claim to be possible

$\kappa_i = g_i^{meas} / g_i^{SM}$

$$(\sigma \cdot \mathrm{BR})(gg \to H \to \gamma\gamma) = \sigma_{SM}(gg \to H) \cdot \mathrm{BR}_{SM}(H \to \gamma\gamma) \cdot \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$$

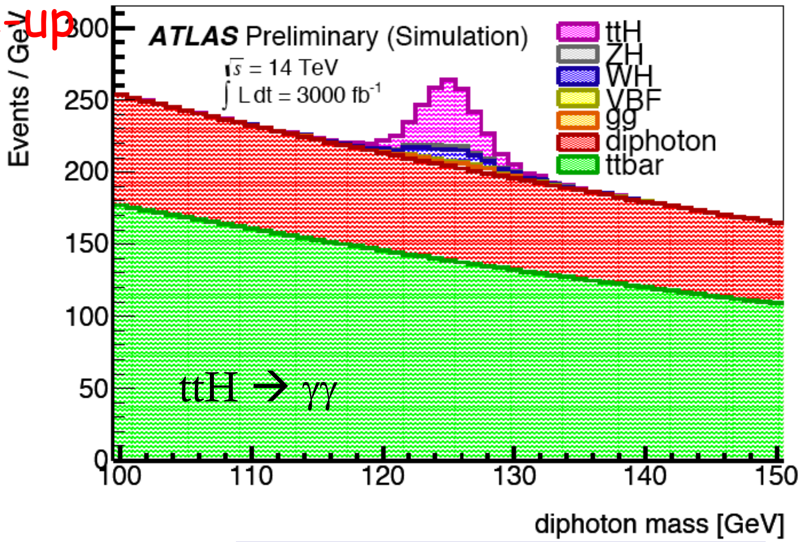
Couplings at HL-LHC: ATLAS

MC Samples at 14 TeV from Fast-Sim.

- Truth with smearing: best estimate of physics objects dependency on pile-up
- Validated with full-sim. up to μ~70

Analyses included in ATLAS study:

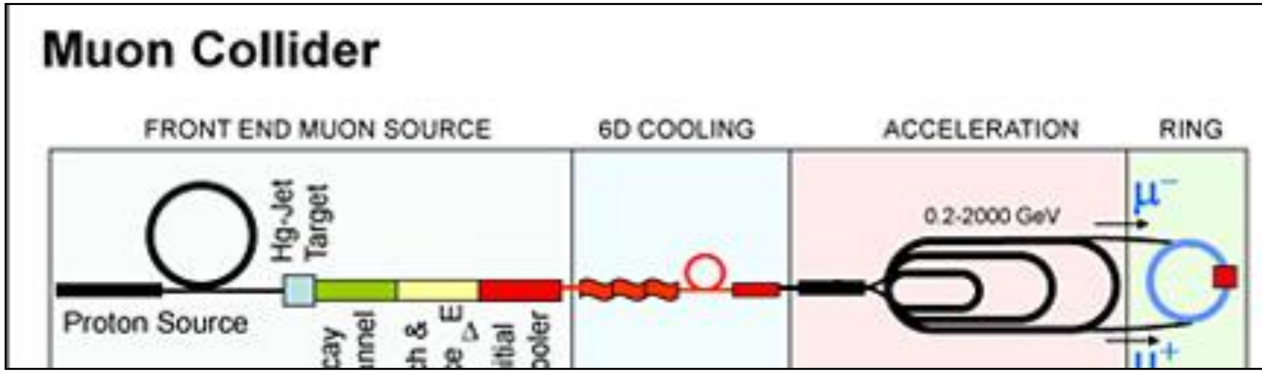
- H→ γγ 0-jet and VBF
- H → ττ VBF lep-lep and lep-had
- H → ZZ → 4ℓ
- H→ WW → ℓνℓν 0-jet and VBF
- WH/ZH → γγ
- **ttH → γγ (ttH → μμ) Direct top Y coupling**
- **H → μμ Second generation fermion coupling**
- **HH→ bb γγ Higgs Self-Couplings**

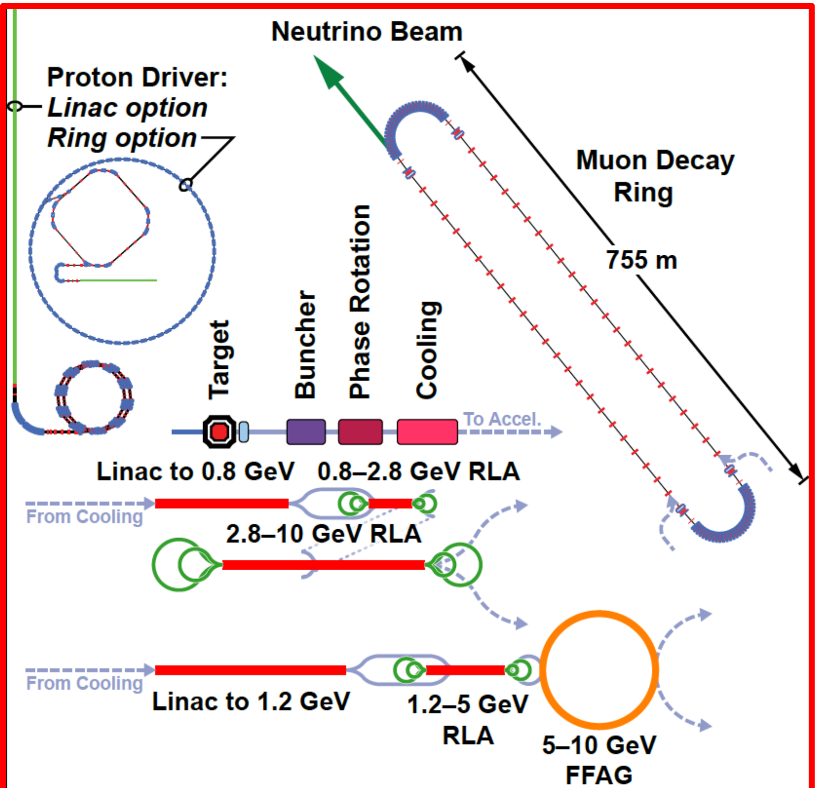


Very Robust channel
Good S/B
Statistically limited

MICE

Neutrino Factory





MICE is one of the critical R&D experiments towards neutrino factories and muon colliders

With the growing importance of neutrino physics + the existence of a light Higgs (125 GeV) physics could be turning this way very fast!

Cooling and more generally the initial chain capture, buncher, phase rotation and cooling rely on complex beam dynamics and technology, such as

High gradient (~>16 MV/m) RF cavities embedded in strong (>2T) solenoidal magnetic field

MANY CHALLENGES!

MUON COOLING → HIGH INTENSITY NEUTRINO FACTORY
HIGH LUMINOSITY MUON COLLIDER

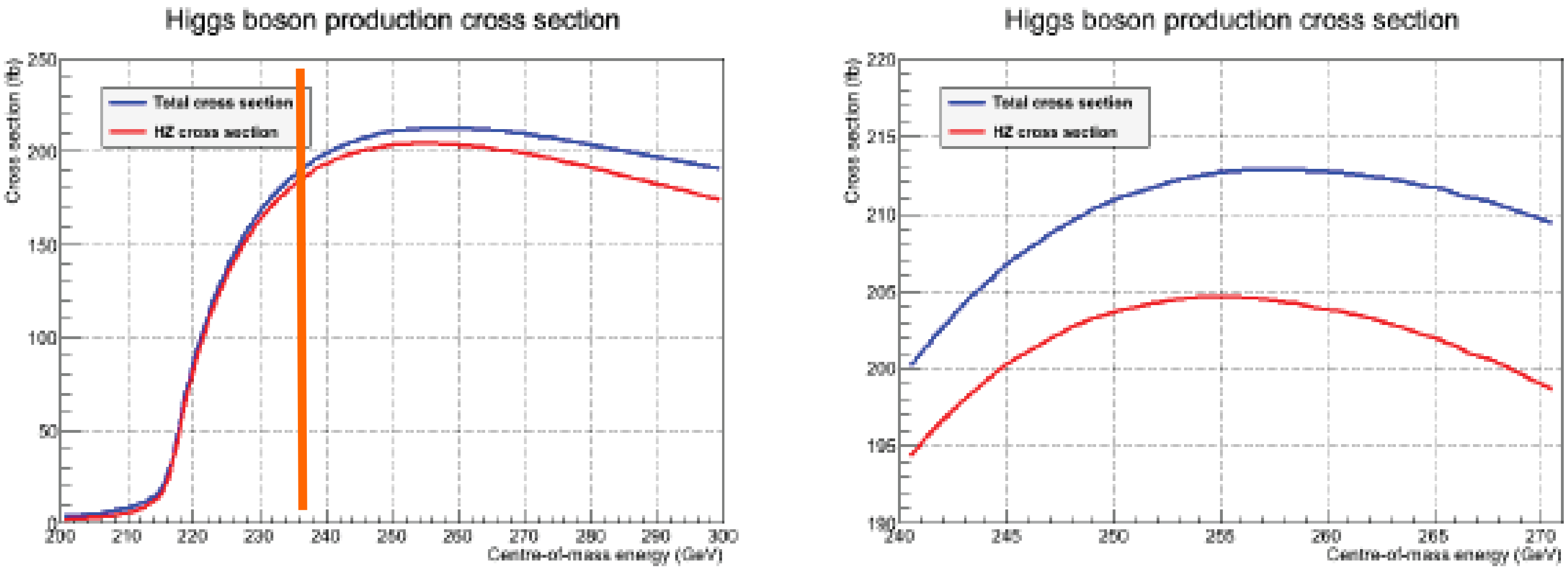


Figure 5: The Higgs boson production cross section as a function of the centre-of-mass energy. The red curve corresponds to the Higgsstrahlung process only, $e^+e^- \rightarrow HZ$, and the blue curve includes the WW and ZZ fusion processes as well, together with their interference with the Higgsstrahlung process. The right graph is a zoom of the left graph around the maximum of the cross section.

Prospective Studies for LEP3
with the CMS Detector

Patrizia Azzi[3], Colin Bernet[1], Cristina Botta[1], Patrick Janot[1],
Markus Klute[2], Piergiulio Lenzi[1], Luca Malgeri[1], and Marco Zanetti[2]

[1] CERN, Geneva
[2] Massachusetts Institute of Technology
[3] INFN, Sezione di Padova

best for tagged ZH physics:
Ecm= m_H+111±10
W. Lohmann et al LCWS/ILC2007

take 240 GeV.