A circular e^+e^- collider to study H(125)?

- **Outline**
  - Introduction : A new era has just started
  - Strategic questions
  - Why is precision needed ?
  - The Boson and the LHC
  - The party line : International Linear e^+e^- Collider (ILC)
  - An advantageous alternative : Circular e^+e^- Colliders (LEP3, TLEP)
    - What ? Where ? Why ? How ? When ? How Much ?
  - The LEP3 and TLEP Physics programme
    - TeraZ, MegaW, Higgs Factory, Top Factory
  - LEP3 and TLEP as a Higgs Factory with the CMS detector
  - 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] 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] P. Janot and G. Ganis, "The HZHA Generator" in Physics at LEP2, CERN Report 96/01 (Vol.2) 309

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

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

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

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

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

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

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

[11] R.W. Assmann, 'LEP Operation and Performance with Electron-Positron Collisions at 209 GeV', Chamonix 2001.

[12] A. Blondel, F. Zimmermann, 'A High Luminosity e^+e^- Collider in the LHC tunnel to study the Higgs Boson,arXiv:1112.2518 (2011)

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

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

[15] A. Butterworth, talk given at the 2nd LEP3 day (Oct. 2012)

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

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

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

[19] J. Osbore and C. Waiijer, "Pre-Feasability Assessment for an 80 km Tunnel Project at CERN", ESPP Contribution #165

[20] A. Blondel et al., "High luminosity e^+e^- circular colliders for precise Higgs and other measurements", ESPP Contribution #173

[21] J. Wenniger, talk given at the 2nd LEP3 day (Oct. 2012)

[22] U. Wienands, talk given at the 2nd LEP3 day (Oct. 2012)

[23] A. Blondel, "A scheme to measure the polarization at the Z pole at LEP" Phys.Lett. B202 (1988) 145, Erratum-ibid. 208 (1988) 531

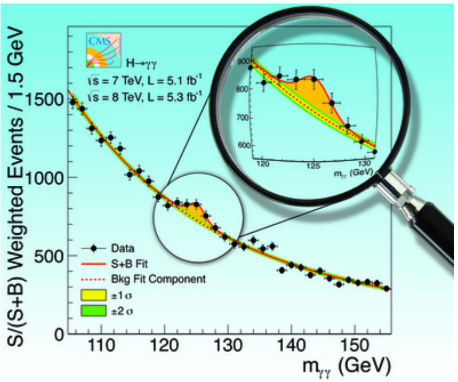
[24] M. Klute et al., "Measuring Higgs Couplings from LHC Data", arXiv:1205.2699 (2012)

[25] W. Lohmann et al., LCWS/ILC2007

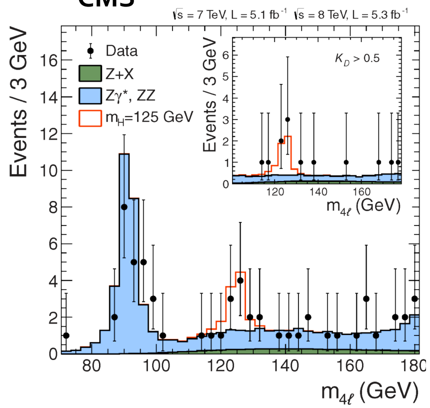
Introduction (1)

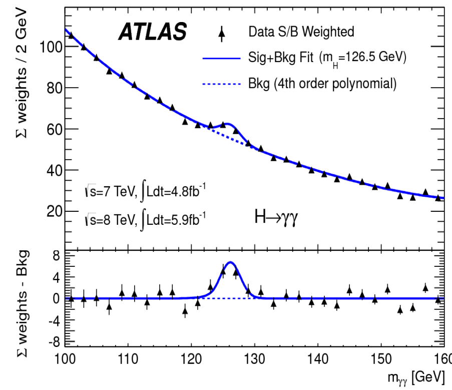
- Reminder : A new state was discovered by CMS and ATLAS

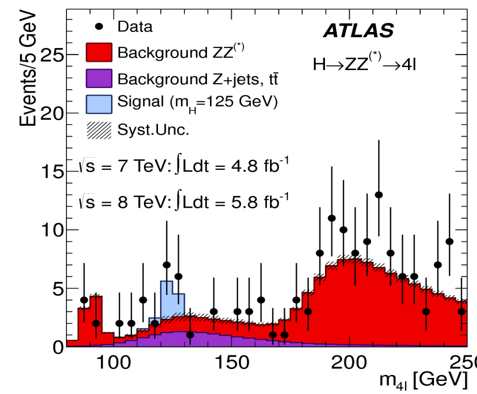
CMS



CMS

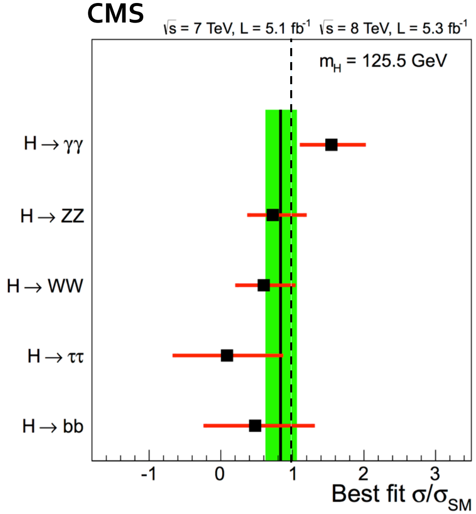


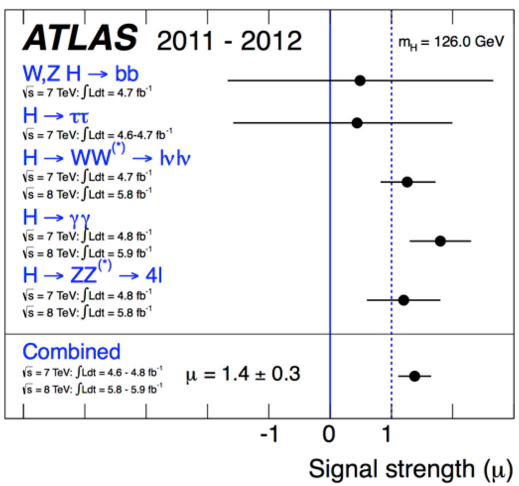




- Decaying in ZZ and γγ, with Higgs-like properties, and $m_H \sim 125.5 \pm 0.5$ GeV/c²

CMS





[1,2]

Introduction (2)

- This discovery strongly influences the strategy for future collider projects
  - We are now 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, …)
  - LHC discoveries at 13 TeV (2015-2022) will lead to an even broader horizon
    - Will strongly influence the strategy for future collider projects as well

Strategic Questions

- **Question #1**
  - What is the precision needed for all these measurements about H(125) ?

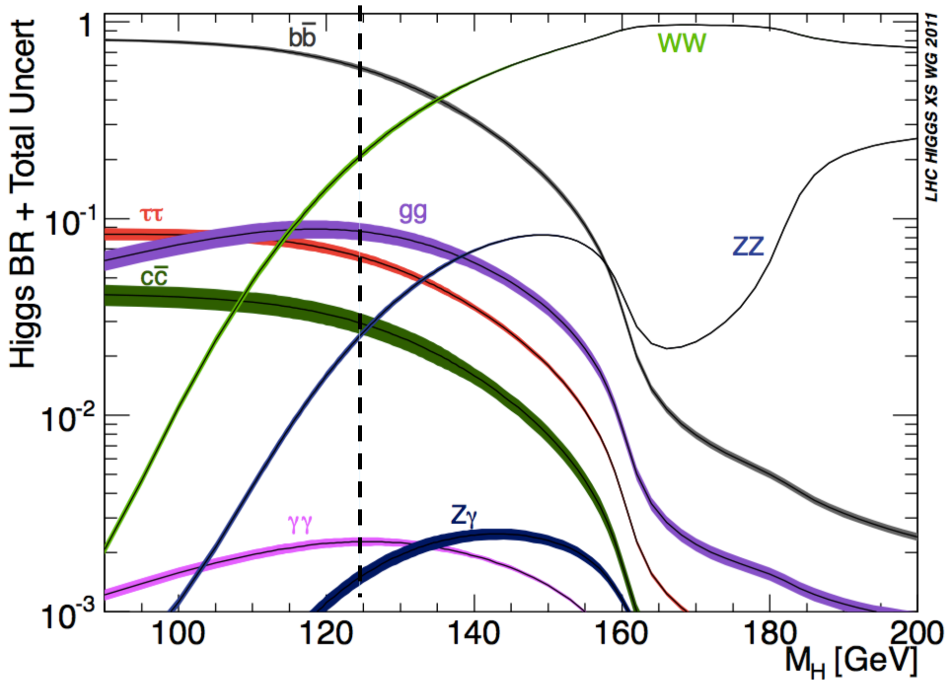
- **Question #2**
  - Can the LHC measure H(125) with enough precision and answer enough questions?
    - Or do we need a complementary machine ?

- **Question #3**
  - If one needs a complementary machine, what is it ?
    - $\mu^+\mu^-$ collider ? Yet too hypothetical, too far in future – not addressed today
    - $\gamma\gamma$ collider ? Too limited a physics programme – not addressed today
    - e^+e^- collider ? Well established linear collider projects exist (ILC, CLIC)
    - If e^+e^-, linear or circular ?

- **Question #4**
  - What can a circular e^+e^- collider do for us ?

Question #1 : Precision Needed (1)

- **Couplings**
  - **Many channels are open – most couplings can be measured from decays**
    - **Large theoretical uncertainties (2 - 6%, mostly QCD) – needs improvements**



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.
ΓH [MeV]	4.0	4.

[3,4]

- **Are the effects of new physics measurable ?**

Question # 1 : Precision Needed (2)

- Couplings (cont'd)
  - Typical tree-level coupling modifications from SUSY
    - Pseudo-scalar A very hard to find at the LHC for moderate tanβ and m_A > 200 GeV

$$\frac{g_{hVV}}{g_{h_{SM}VV}} \simeq 1 - 0.3\% \left(\frac{200\ \mathrm{GeV}}{m_A}\right)^4 \quad \frac{g_{htt}}{g_{h_{SM}tt}} = \frac{g_{hcc}}{g_{h_{SM}cc}} \simeq 1 - 1.7\% \left(\frac{200\ \mathrm{GeV}}{m_A}\right)^2 \quad \frac{g_{hbb}}{g_{h_{SM}bb}} = \frac{g_{h\tau\tau}}{g_{h_{SM}\tau\tau}} \simeq 1 + 40\% \left(\frac{200\ \mathrm{GeV}}{m_A}\right)^2$$

$$\frac{g_{hbb}}{g_{h_{SM}bb}} = \frac{g_{h\tau\tau}}{g_{h_{SM}\tau\tau}} \simeq 1 + 1.7\% \left(\frac{1\ \mathrm{TeV}}{m_A}\right)^2$$

➨ Large effect on Hbb and Hττ coupling

To be measured a priori as precisely as possible

Essentially decoupled from Electroweak Precision Measurements

  - Typical coupling modifications from composite Higgs models
    - All couplings reduce together according to the compositeness scale f

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

To be measured a priori as precisely as possible

Eventually visible in Electroweak (High) Precision Measurements

[5,6]

Question #1 : Precision Needed (3)

- **Couplings (cont'd)**
  - Typical loop-induced effects from top partners (e.g., stops)
    - Light top partners are needed to solve hierarchy problem

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

To be measured a priori as precisely as possible

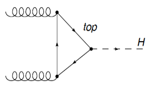
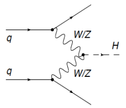
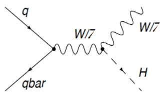
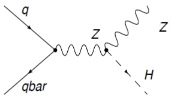
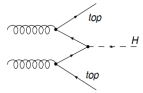
  - Per-cent-level measurements sensitive to new physics at the TeV scale
    - Multi-TeV new physics needs sub-percent precision
    - Some models / parameters give effects of the order of 5%
    - Underlying new physics affect differently each of the couplings
      - ➡ Precise measurement of all couplings gives a clue of the nature of new Physics
      - ➡ Very precise electroweak measurements would complete the understanding

- **Mass**
  - dBR_{Hff}/dm_H ~ −2% / GeV ; dBR_{HVV}/dm_H ~ +6% ; and $d\sigma_{HZ}/dm_H$ ~ −3% @ 125 GeV.
    - A mass measurement to 50 MeV is enough for all practical purposes

[3,6]

Question # 2 : The boson @ LHC (1)

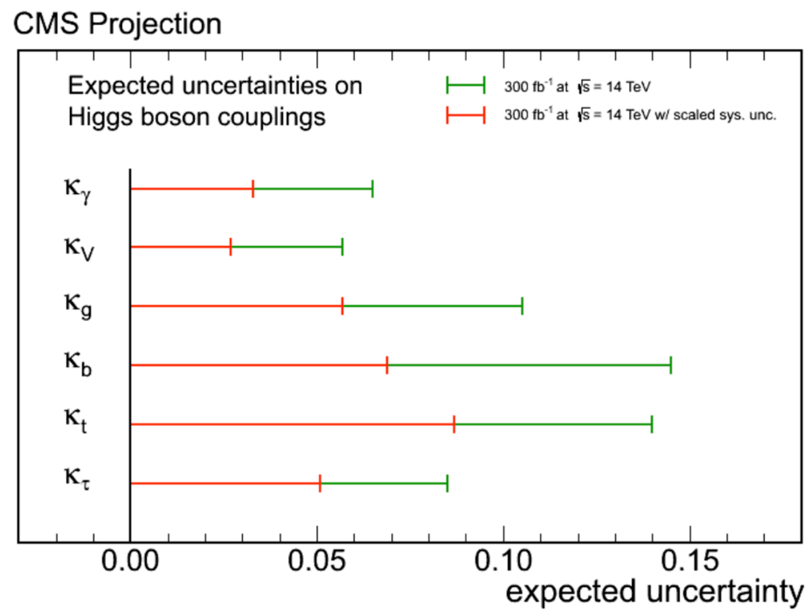
- **The LHC is a Higgs Factory**
  - Total cross section at 8 TeV : 22 pb
    - 1M Higgs already produced
    - 15 Higgs bosons / minute
  - Five different production modes
    - Many couplings testable
  - Do we really need another machine?

Process	Diagram	Cross section [fb]	Unc. [%]
gluon-gluon fusion		19520	15
vector boson fusion		1578	3
WH		697	4
ZH		394	5
ttH		130	15

- **Fundamental measurements:**
  - σ *BR for all channels XX → H → YY
    - Production : gg → H, VBF, WH, ZH, ttH - Only the first two seen so far
    - Decay : $\gamma\gamma$, ZZ, WW, $\tau\tau$, bb, $\mu\mu$ - Only the first three seen so far
  - $\sigma(XX)*BR(YY) = \Gamma(XX) * \Gamma(YY) / \Gamma_{tot}(H)$
    - Cannot extract couplings without assumptions on the total width
      - ➨ Either measure ratios of couplings, or make assumptions.

Question # 2 : The boson @ LHC (2)

- CMS projections assuming no exotic decays and reduced set of couplings [7]
  - Also assumed stable trigger/detector/analysis performance
    - Irrespective of pileup conditions
  - Approved program (300 fb^{-1} @ 13 TeV)
    - 10-15% on fermionic couplings
    - 5-6% on bosonic couplings
    - 5-10% on couplings through loops
  - HL-LHC (3000 fb^{-1} @ 13 TeV)
    - Constant systematic uncertainties
      - Moderate improvement (30%)
      - 5-10% precision on couplings
    - Scaling systematic uncertainties
      - Factor 2-3 improvement
      - 2-4% precision on couplings
    - Might not be sensitive to new physics
      - At scales beyond ~500 GeV

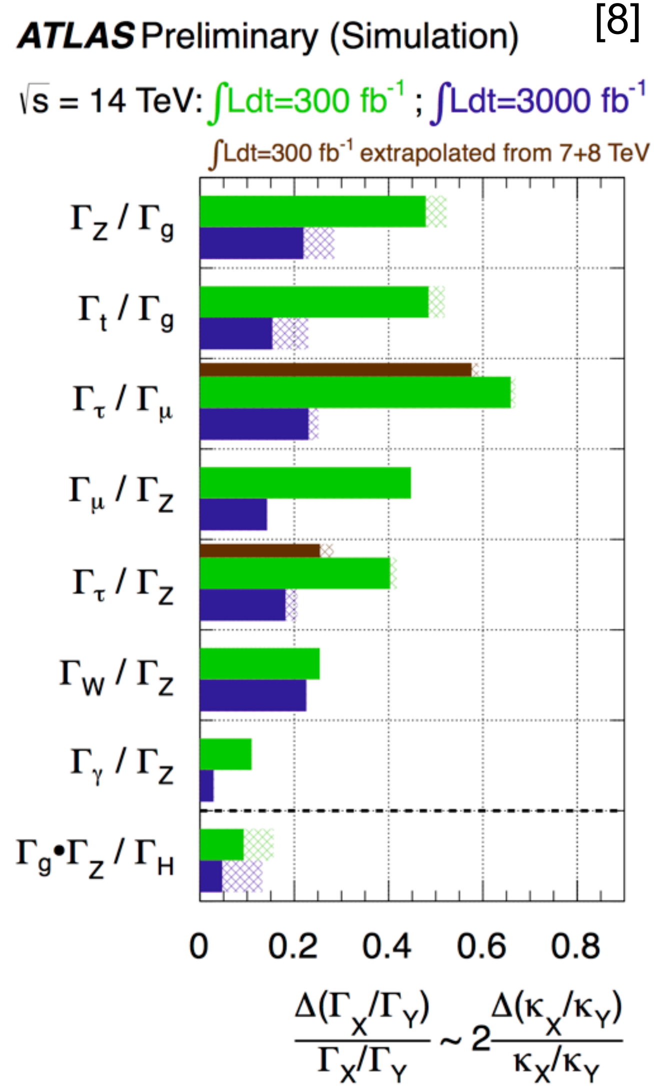


Coupling	Uncertainty (%)			
	300 fb^{-1}		3000 fb^{-1}	
	Scenario 1	Scenario 2	Scenario 1	Scenario 2
κ_γ	6.5	5.1	5.4	1.5
κ_V	5.7	2.7	4.5	1.0
κ_g	11	5.7	7.5	2.7
κ_b	15	6.9	11	2.7
κ_t	14	8.7	8.0	3.9
κ_τ	8.5	5.1	5.4	2.0

Question # 2 : The boson @ LHC (3)

- **ATLAS projections for partial width ratios**
  - Insensitive to most systematic uncertainties
    - While keeping some sensitivity to new physics
  - Approved program (300 fb^{-1} @ 13 TeV)
    - 20-30% on most coupling ratios
    - 10% on g_{HWW}/g_{HZZ}
    - 5% on $g_{H\gamma\gamma}/g_{HZZ}$
  - HL-LHC (3000 fb^{-1} @ 13 TeV)
    - Improvement by a factor 2-3 for most ratios
      - ➨ Except g_{HWW}/g_{HZZ}
    - Might not be sensitive to new physics
      - ➨ At scales beyond ~500 GeV

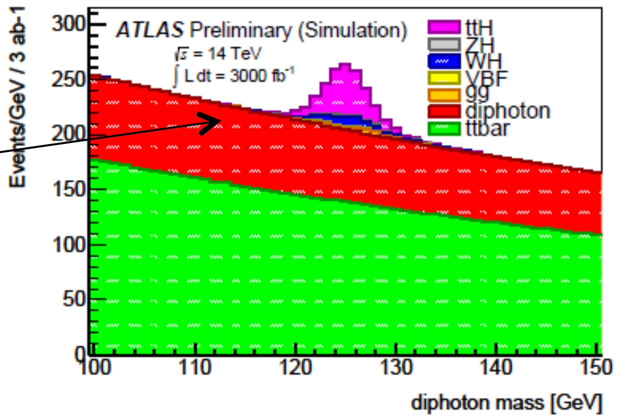
[8]



Note : any precise measurement of one of the couplings would lead mechanically to the determination of the others

Question # 2 : The boson @ LHC (4)

- **Difficult couplings : Htt and HHH**
  - Preliminary analysis from ATLAS for ttH
    - In the ttγγ final state
      - Selection with one lepton
  - Measure signal strength with 20% precision
    - Potential for Htt coupling : ~ 10%
      - With the 3000 fb^{-1} of HL-LHC
  - First look at the double Higgs production from ATLAS
    - In the bbγγ and the bbWW final states : will be tough !
      - Potential for the HHH coupling : ~ 30% (CMS + ATLAS, HL-LHC)
  - Larger potential of HE-LHC
    - Cross sections for ttH and HH increase by large factors (7-10) at 33-40 TeV
      - Substantial increase of the scale for new physics searches, too



(a)

	σ(14 TeV)	R(33)	R(40)	R(60)	R(80)	R(100)
ttH	0.62 pb	7.3	11	24	41	61
HH	33.8 fb	6.1	8.8	18	29	42

- Is HL-LHC the LHC upgrade we want ?

[7,8,9]

Question #3 : Another machine ?

- So … do we need another, complementary, machine ?
  - Mass and Spin will be determined at LHC with adequate accuracy quite soon
  - But accuracy on couplings is limited to ~5%
    - Far from the sub-per-cent level required, substantially model dependent

- It seems we would need it … But what would be this other machine ?
  - Must measure couplings to the per cent, in a model-independent way
    - $\mu^+\mu^-$ collider ?
      - ➨ The longest-term project (if at all feasible)

        Very good prospects for total Higgs width direct measurement to a few %

        Ideal for additional, heavier, Higgs bosons (if any)
    - $\gamma\gamma$ collider ?
      - ➨ Probably the worst physics prospects

        Large $\gamma\gamma$ backgrounds into fermion and boson pairs; Untagged Higgs.
    - e^+e^- collider ?
      - ➨ Physics prospects are good and solid projects exist → Today's focus.

        Linear Colliders studied / conceived / designed for two decades

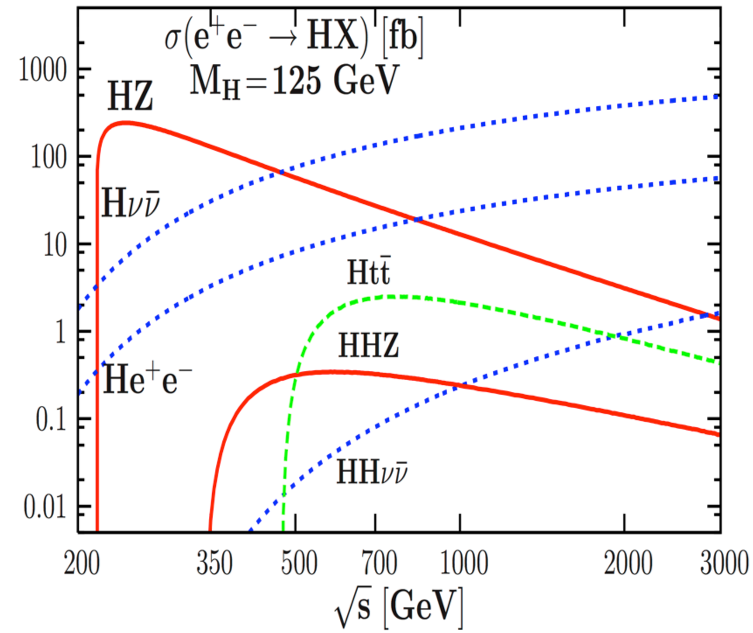
Question #3 : A linear e^+e^- collider ? (1)

- Higgs Physics at a linear e^+e^- collider
  - At the HZ threshold ($\sqrt{s}$ = 250 GeV, 5 years)
    - Tagged Higgs, largest cross section
    - Individual branching ratios to a few %
    - Invisible and exotic decays
    - Possibly total Higgs decay width

250 fb^{-1}

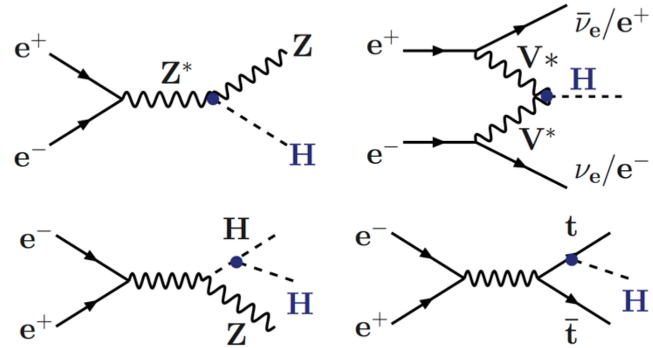
  - At the top threshold ($\sqrt{s}$ = 350 GeV, 5 years)
    - Measure top quark mass with high precision
      - ➨ (Input to EWRC)

350 fb^{-1}



  - At $\sqrt{s}$ = 500 GeV, > 10 years running (ILC)
    - Measure Htt coupling to 15% with e^+e^- ➔ ttH
    - Measure HHH coupling to 50% with e^+e^- ➔ ZHH

1 ab^{-1}



  - At $\sqrt{s}$ = 1-3 TeV (CLIC, ~ 5 years)
    - Measure HHH coupling to 40% with e^+e^- ➔ HHνν (fast simulation)

2 ab^{-1}

[6,10]

Question #3 : A linear e^+e^- collider ? (2)

- New Physics programme at a linear e^+e^- collider ?
  - Could be fantastic … yet no clue of the scale of new Physics from the LHC
    - Might emerge from 2012 data, or from the 13 TeV run from 2015 onwards
    - Yet no argument to go for 500 GeV, 1TeV, or 3 TeV

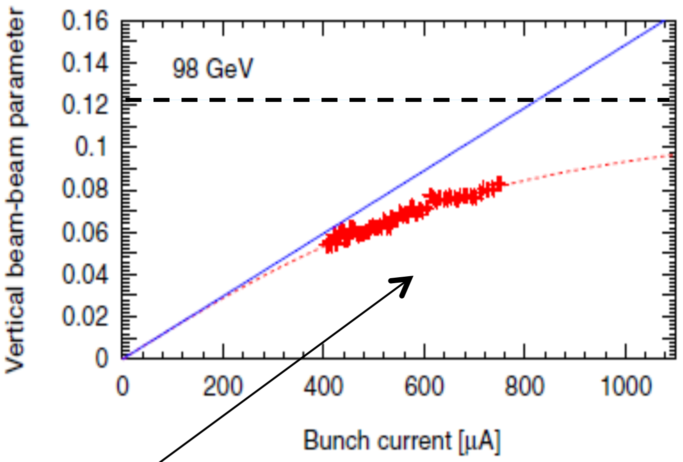
- The sole “guaranteed” physics consists of Higgs precision measurements
  - The really unique physics programme shows up at the ZH threshold
    - Might argue that higher energies give access to the ttH and HHH couplings
      - ➨ But they can be measured with similar/better precision at the HL/HE-LHC
  - Top physics at the threshold is a nice addition
    - To measure the top mass precisely (input to EWRC)
    - To put precise constraints on α_s
    - To look for rare top decays (new physics)
  - Ultra-precise electroweak measurements at the Z pole and the WW threshold
    - A must for the understanding of the EWSB mechanism and hints a new physics

Question #3 : A linear e^+e^- collider ? (3)

- The physics case not driven by the fact that the collider is linear
  - Advantages for Linear Colliders
    - Studied for 30 years – and an example even exist (SLC)
      - ➠ SLC took 10 years to reach 30% of its design luminosity
    - Polarization of e^- beam is easy – electrons polarized at the source.
      - ➠ Nice to have, but not really critical for Higgs study
  - Issues for Linear Colliders
    - Known to be very expensive
      - ➠ To be revised at the end of 2012; current estimate ~10 G$.
    - Luminosity is difficult to get
      - ➠ nm beam size; each collision needs a new beam;
    - Power hungry
      - ➠ up to 300 MW, even at low energy
    - Beam disruption by beamstrahlung effect
      - ➠ Backgrounds (photons, e^+e^- pairs); Beam energy smearing;
    - Only one interaction point

Question #4 : A circular e^+e^- collider ?

- **Closest example : LEP2**
  - Was in the LHC tunnel
  - Reached a centre-of-mass energy of 209 GeV
    - Need only 15 GeV more per beam
  - Peak luminosity was 10^{32} cm^{-2}s^{-1}
    - β^*_y = 5 cm ; σ_y = 3.5 μm
    - Integrated luminosity : 1 fb^{-1}/detector
      - Needs a factor 100 more
      - Note : LEP2 was not at the beam-beam limit



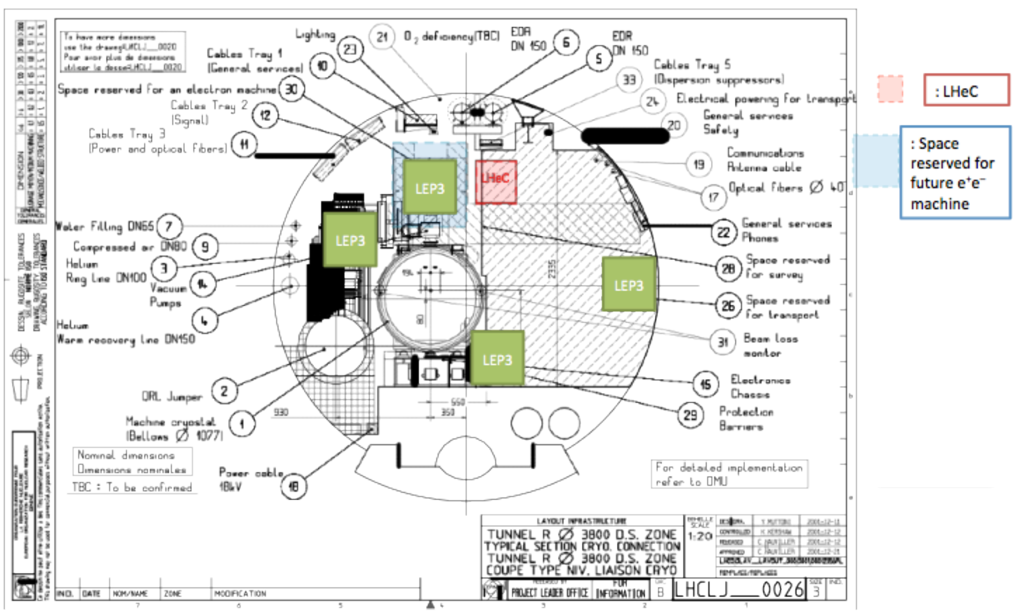
  - RF Frequency was 352 MHz
    - σ_z = 1.6 cm
  - Luminosity lifetime was ~ 3 hours
    - Dominated by Bhabha scattering, $e^+e^- \rightarrow e^+e^-$
  - Beam power was 20 MW
  - Four interaction points, four detectors

- **How can we extrapolate to get the missing GeV and fb^{-1} ?**
  - LEP3 would be the answer

[11,12]

The LEP3 option : Where ?

- **Obviously in the LHC tunnel, too**
  - LEP2 parameters were not that far from what we want
  - The cost would be minimized, by re-using
    - The tunnel — **Save 1 G$**
    - The cooling infrastructure — **Save 1 G$**
    - Two multi-purpose detectors (CMS/ATLAS) — **Save 1 G$**
  - Also saves significant amount of time for construction
  - Integration in the tunnel : less difficult than LHeC (no concurrent operation needed)



[13]

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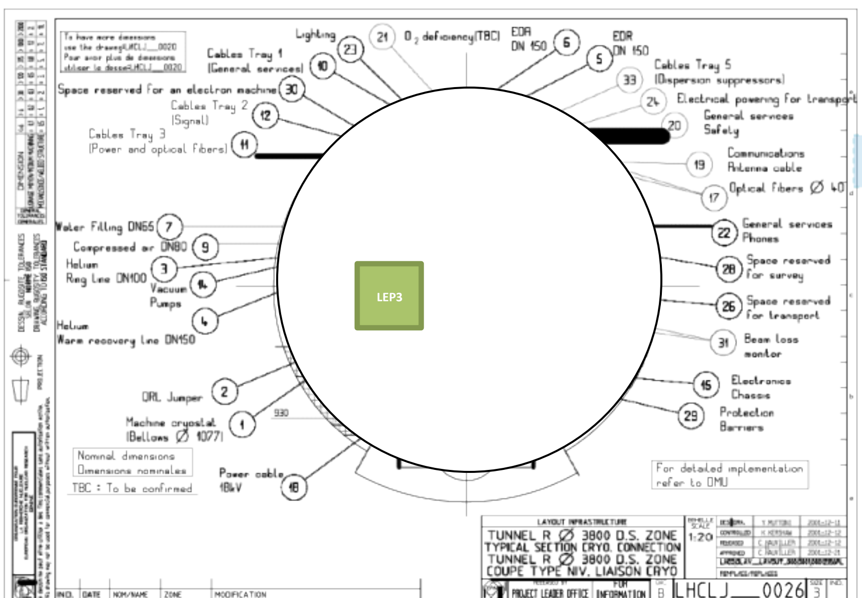


Can also be made much simpler !

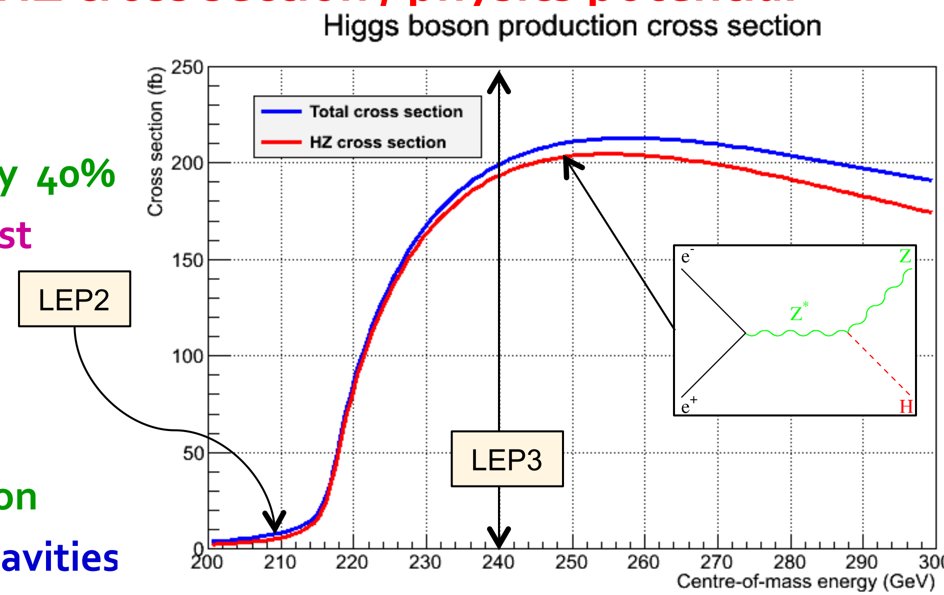
After the 13 TeV programme
(with or without HL-LHC run, choice depends on physics in 2022)

Before the 33 TeV programme
(Should HE-LHC be chosen as our LHC upgrade, cannot start before 2035 to have magnets ready)

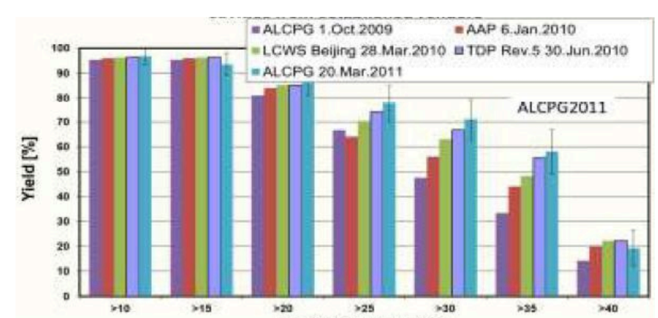
[13]

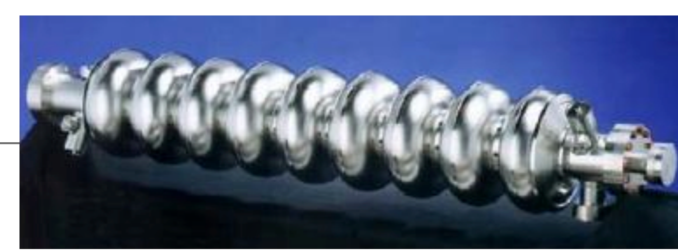
The LEP3 option : Energy ?

- **Energy chosen to maximize the HZ cross section / physics potential** [14,15]
  - Maximum is at 260 GeV : 212 fb
  - Only 6% smaller at 240 GeV : 200 fb
    - But reduces SR energy losses by 40%
      - ➨ Also reduces operation cost
    - Best for Physics ~ 237±11 [28]



- **Getting the energy at small cost**
  - SR energy losses : 6-7 GeV / turn
    - LC : 120 GeV lost at each collision
  - Would need only 300-350 ILC-type cavities
    - Gradient : 20 MV/m, Frequency 1.3 GHz
  - Present parameters foresee 580 ILC-type cavities
    - To increase the momentum acceptance
      - ➨ Needed for beamstrahlung, see later
    - Total length : 818 meters (LEP2 : 864 m)
  - RF power during operation : 50 MW/beam
  - Issue : Power handling of the RF couplers
    - Needs R&D – or use SPL cavities (700 MHz)

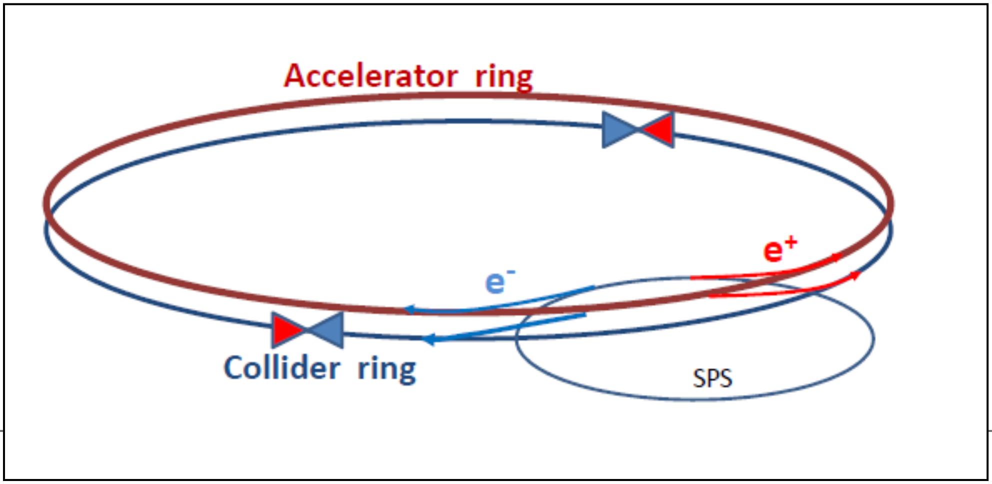




The LEP3 option : Luminosity ?

- **Getting a factor 100 in luminosity wrt LEP2 ?**
  - Needs more focusing : Reduce β^*_y from 5 cm to 1 mm and β^*_x from 1.5 cm to 2 mm
    - The LHeC optics can be applied and does the job !
      - Beam sizes at IP : σ_x = 71 μm ; σ_y = 0.32 μm, still quite relaxed.
  - Needs in turn shorter bunches
    - ILC cavities : The RF frequency increases from 352 MHz to 1.3 GHz
      - Reduces bunch length from 1.6 cm to 0.23 cm
  - Expected luminosity : 1.07×10^{34} cm^{-2} s^{-1} at 240 GeV (i.e., 100 fb^{-1} / year / IP)
    - Bhabha scattering burns the beams : lifetime ~ o(15) minutes
      - Requires continuous top-up injection (with a B-factory-like design)

(Requires 6 GV more RF as well, for the accelerator ring)

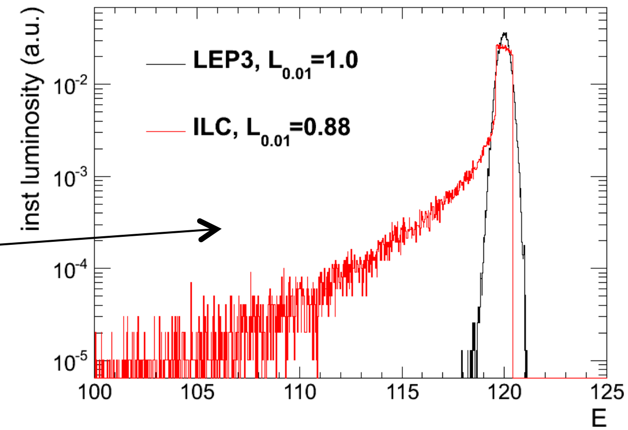


[12]

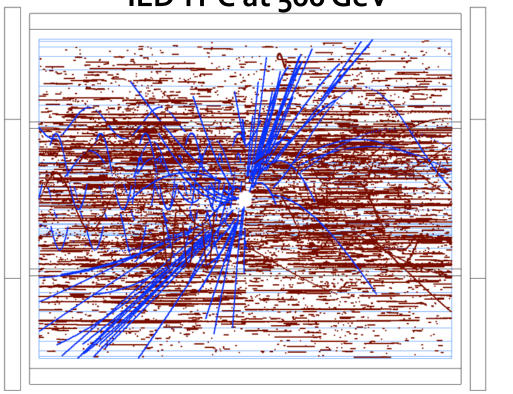
The LEP3 option : Beamstrahlung ? (1)

[16,17]

- **Luminosity at LEP3 obtained with 45 kHz repetition rate**
  - Hence the relaxed beam parameters : vertical beam size = 320 nm
    - To be compared with ILC : 5 nm ; or CLIC : 1 nm
  - A lot of good consequences
    - Reliable operation of the machine
    - Negligible beamstrahlung effects for physics
      - ~100% of the collisions within 1% of the nominal beam energy (cf. 88% for ILC)
      - Beam energy spread ~0.1% (cf. ~2% for ISR)
        Beam energy spectrum perfectly known
    - Negligible PU rate from γγ interactions
      - PU probability ~0.3%
        cf. 4 events / pulse in CLIC
        cf. 2-3 events / bunch in ILC
    - Negligible backgrounds from beam disruption
      - No specific requests for the detector
        Tracker, forward detectors, …
      - No specific requests for background simulation

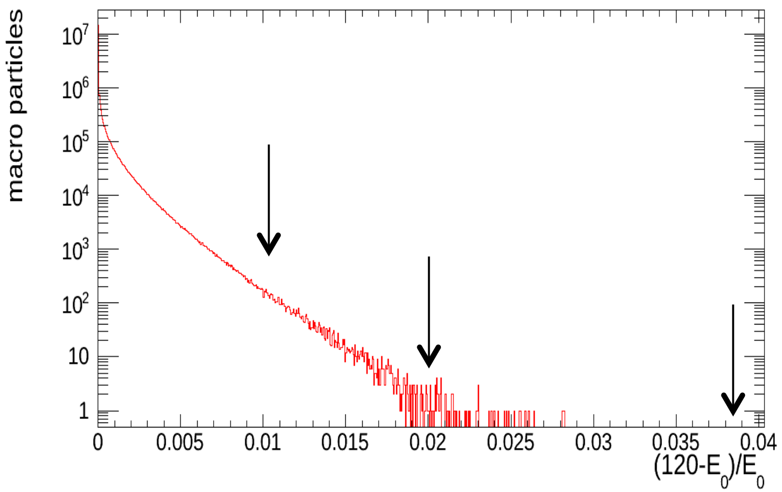


ILD TPC at 500 GeV



The LEP3 option : Beamstrahlung ? (2)

- Luminosity at LEP3 obtained with 45 kHz repetition rate (cont'd) [16]
  - Small beamstrahlung losses are cumulative
    - For each collision
      - 0.01% of the electrons have ΔE/E>1%
      - 10^{-6} of the electrons have ΔE/E>2%
      - 10^{-10} of the electrons have ΔE/E>4%



  - Hence, beam lifetime decreasing exponentially with energy acceptance
    - Unacceptable losses with a 1% energy acceptance
      - Beam lost in less than 1 second
    - Large losses with a 2% energy acceptance
      - About 1% of the beam lost every second, beam lost within in a minute
    - Negligible losses with a 4% energy acceptance
      - Requires more RF voltage to keep these energy tails in

        (hence the 580 cavities for a very comfortable margin)
      - Needs to study compatibility with the low-β optics

The LEP3 option : Other goodies

- Collider rings have historically delivered
  - According to design, and often exceeding it
    - See most recent examples : LEP1, LEP2, PEP2, KEKB
  - Design LEP3 parameters give 1.1 x 10^{34} $cm^{-2}s^{-1}$ at 240 GeV
    - It is a factor 2 larger than the ILC at the same energy
      - Not counting the beamstrahlung effects in ILC
    - The current parameters can be (and will be) optimized
      - No showstopper has yet been identified

Parameter	Design LEP1 / LEP2	Achieved LEP1 / LEP2
Bunch current	0.75 mA	1.00 mA
Total beam current	6.0 mA	8.4 / 6.2 mA
Vertical beam-beam parameter	0.03	0.045 / 0.083
Emittance ratio	4.0 %	0.4 %
Maximum luminosity	16 / 27 10^{30} $cm^{-2}s^{-1}$	34 / 100 10^{30} $cm^{-2}s^{-1}$
IP beta function β_x	1.75 m	1.25 m
IP beta function β_y	7.0 cm	4.0 cm
Max. beam energy	95 GeV	104.5 GeV
Av. RF gradient	6.0 MV/m	7.2 MV/m

- Number of detectors
  - LEP3 can accommodate four interaction points (as was LEP2)
    - Four detectors = four times the integrated luminosity
      - All Higgs branching fraction measurements will be statistically limited
      - Systematic cross checks
    - Four collaborations = four times the number of people involved
      - Important sociological argument
    - Can accommodate two linear-collider-type detectors in addition to CMS & ATLAS
      - 20 years of detector R&D and collaboration building can be capitalized

The LEP3 option : Cost

- Could build LEP3 for a canonical 1 billion $
  - Obtained from the known price of RF cavities, klystrons, and magnets
    - The rest of the infrastructure and two detectors exist already
  - A factor ~10 smaller than a linear collider, roughly
  - Price of the Higgs boson ?
    - Expect 100,000 Higgs bosons / detector over a period of 5 years at LEP3
      - Basic investment in the two-detector configuration : ~ 5 k$ / Higgs boson
      - Basic investment in the four-detector configuration : ~ 5 k$ / Higgs boson

        Two add'l detectors cost ~ 1 B$, but twice more Higgs bosons to analyse
    - Expect 50,000 Higgs bosons over a period of 5 years at ILC250
      - Basic investment in the ILC configuration : ~200 k$ / Higgs boson

        Each Higgs boson is 40 times more expensive than at LEP3

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        ach Higgs boson is 40 times more expensive than at LEP3

Disclaimer : numbers in this slide can be off by a factor 2

But encouraging enough to justify a design study

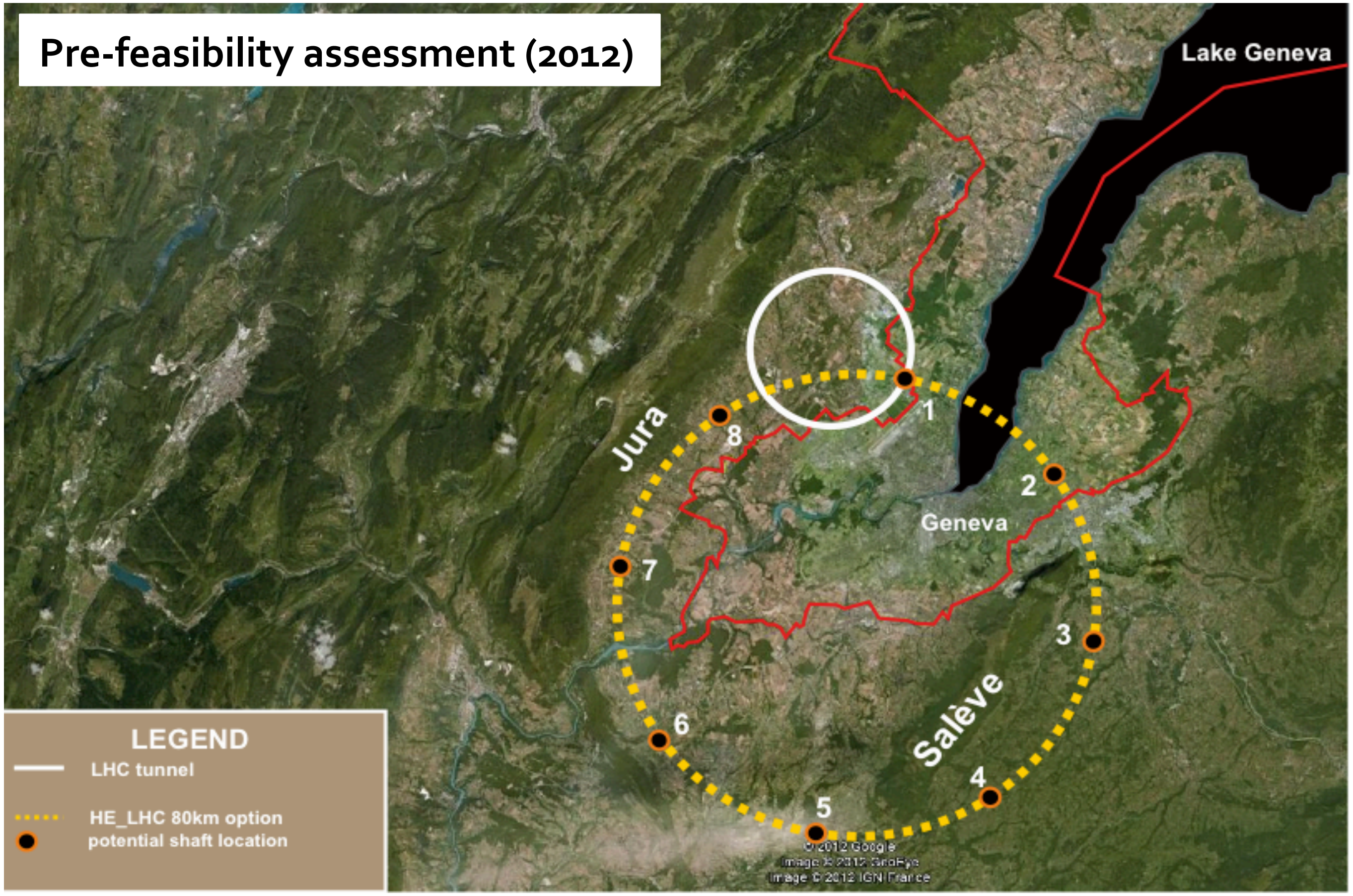
The LEP3 option : When ?

- Possible timescale for LEP3 [13,15,18]
  - Conceptual design report at the end of 2014
    - Need to study a few issues, of which :
      - Power dissipation in RF Couplers
      - Protection against synchrotron radiation
      - Integration of the accelerator ring with detectors
  - If the case is still present, decision to go ahead taken during LS2 (2017)
    - Depends on LHC physics outcomes (50-100 fb^{-1} at 13 TeV)
    - Technical design report in 2019-2020
  - If the case is still present, installation can start at LS3 (2022)
    - Depends on LHC physics outcomes (300 fb^{-1} at 13 TeV)
    - LEP took 18 months to install
  - Physics could start around 2024, for 10 years
    - Fits well with the possibility of HE-LHC
      - High-field magnets could be ready by 2032-2035
    - Cohabitation with HL-LHC is suboptimal, more difficult, but feasible
      - Would mean alternate periods for HL-LHC and LEP3

Could also do without HL-LHC : Depends on LHC physics outcomes

A long-term vision for CERN : TLEP (1)

- A 80-km tunnel around Geneva avoiding Jura, Saleve, and Vuache [19]
  - Could host a 350 GeV e^+e^- collider (called TLEP) as a first step
    - Feasible by 2025 - 2030 ? Needs a long-term decision for CERN.



A long-term vision for CERN : TLEP (2)

- **Three main physics arguments**
  - Reaches $\sqrt{s}$ = 350 GeV (top threshold) with L = 6.10^{33} cm^{-2}s^{-1}, same RF as LEP3
    - Top mass, α_s, rare top decays, WW → H, …
  - With the available beam power, can accommodate more bunches at $\sqrt{s}$ = 240 GeV
    - Reaches 5.10^{34} cm^{-2}s^{-1} at the ZH threshold (conservative)
      - ➨ With 2 or 4 detectors, up to 40 x more Higgs bosons than the ILC at 240 GeV
  - Is extendable
    - As a second step, tunnel can accommodate a VHE-LHC
      - ➨ $\sqrt{s}$ = (80km/27km) × (20T/8T) × 14 TeV = 100 TeV

- **Cost ? (from extrapolations)**

LEP tunnel: 0.7 G$
9km LHeC: 0.25 G$

< 2 x LEP3
~RF, magnets

  - Tunnel and Collider would be the largest contributors : say 2.5 - 3.5G$ + 2 G$
  - Detectors would be next : say 1 or 2G$ for two or four detectors
  - Still less expensive than a linear collider : 5 to 7 G$
    - Individual Higgs cost over a five-year period : ~ 2.5 to 3.5 k$ / Higgs boson
      - ➨ Each Higgs boson is, again, 50-80 times less expensive than at a linear collider
  - If you had 10 billion $, where would you put them ? ILC ? TLEP + VHE-LHC ?
    - Probably imprudent to decide now

Machine Parameter Summary

- Parameters not yet optimized

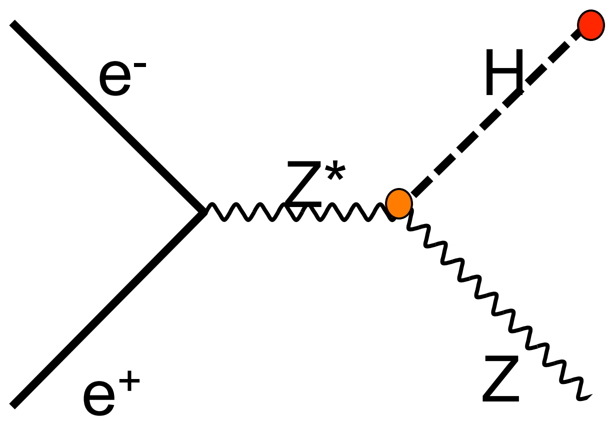
Parameter	LEP2	LEP3	TLEP-Z	TLEP-H	TLEP-t
beam energy E_b [GeV]	104.5	120	45.5	120	175
circumference [km]	26.7	26.7	80	80	80
beam current [mA]	4	7.2	1180	24.3	5.4
# bunches/beam	4	4	2625	80	12
$\#e^-$/beam [10^{12}]	2.3	4.0	2000	40.5	9.0
horizontal emittance [nm]	48	25	30.8	9.4	20
vertical emittance [nm]	0.25	0.10	0.15	0.05	0.1
bending radius [km]	3.1	2.6	9.0	9.0	9.0
partition number J_ε	1.1	1.5	1.0	1.0	1.0
momentum compaction α_c [10^{-5}]	18.5	8.1	9.0	1.0	1.0
SR power/beam [MW]	11	50	50	50	50
β^*_x [m]	1.5	0.2	0.2	0.2	0.2
β^*_y [cm]	5	0.1	0.1	0.1	0.1
σ^*_x [μm]	270	71	78	43	63
σ^*_y [μm]	3.5	0.32	0.39	0.22	0.32
hourglass F_{hg}	0.98	0.67	0.71	0.75	0.65
E^{SR}_{loss}/turn [GeV]	3.41	6.99	0.04	2.1	9.3
V_{RF},tot [GV]	3.64	12.0	2.0	6.0	12.0
$\delta_{max,RF}$ [%]	0.77	4.2	4.0	9.4	4.9
ξ_x/IP	0.025	0.09	0.12	0.10	0.05
ξ_y/IP	0.065	0.08	0.12	0.10	0.05
f_s [kHz]	1.6	3.91	1.29	0.44	0.43
E_{acc} [MV/m]	7.5	20	20	20	20
eff. RF length [m]	485	600	100	300	600
f_{RF} [MHz]	352	1300	700	700	700
δ^{SR}_{rms} [%]	0.22	0.23	0.06	0.15	0.22
$\sigma^{SR}_{z,rms}$ [cm]	1.61	0.23	0.19	0.17	0.25
L/IP[10^{32}cm^{-2}s^{-1}]	1.25	107	10335	490	65
number of IPs	4	2	2	2	2
beam lifetime [min]	360	16	74	32	54
Υ_{BS} [10^{-4}]	0.2	10	4	15	15
n_γ/collision	0.08	0.60	0.41	0.50	0.51
ΔE^{BS}/col. [MeV]	0.1	33	3.6	42	61
ΔE^{BS}_{rms}/col. [MeV]	0.3	48	6.2	65	95

[20]

The LEP3 Physics Programme (1)

- LEP3 as a Higgs Factory, $\sqrt{s}$ = 240 GeV : Five years
  - With an instantaneous luminosity of 10^{34} $cm^{-2}s^{-1}$
    - 500 fb^{-1} / experiment, i.e., 100,000 Higgs events in each detector

Signal	BR (%)	Events
$H \to b\bar{b}$	57.9	57,870
$H \to W^+W^-$	21.6	21,630
$H \to gg$	8.19	8,200
$H \to \tau^+\tau^-$	6.40	6,400
$H \to c\bar{c}$	2.83	2,820
$H \to ZZ$	2.62	2,620
$H \to \gamma\gamma$	0.27	266
$H \to Z\gamma$	0.16	160
$H \to \mu^+\mu^-$	0.02	22



- With $Z \to e^+e^-$ or $\mu^+\mu^-$, measure σ_{HZ}

  Count events independently of the Higgs boson decay
- Then measure $\sigma_{HZ} \times BR(H \to XX)$

  With exclusive final state selection, including invisible and exotic decays
- Obtain model independent measurements of HXX couplings

  See CMS study for the achievable precision

The LEP3 Physics Programme (1)

- **LEP3 as a Higgs factory, $\sqrt{s}$ = 240 GeV : Five years (cont'd)**
  - Backgrounds are manageable, rates are small – as at LEP2, very basic trigger suffice

Background	σ (pb)	Events	Rate (Hz)
$e^+e^- \to Z^*/\gamma^* \to q\bar{q}$	50	25,000,000	0.50
$e^+e^- \to Z^*/\gamma^* \to \ell^+\ell^-$	12.5	6,250,000	0.12
$e^+e^- \to W^+W^-$	16	8,000,000	0.16
$e^+e^- \to ZZ$	1.3	650,000	0.01
$e^+e^- \to We\nu$	1.35	700,000	0.01
$e^+e^- \to Ze^+e^-$	3.8	1,900,000	0.04
$e^+e^- \to Z\nu\bar{\nu}$	0.032	16,000	–
$e^+e^- \to e^+e^-$ (Bhabha)	5,000	$2.5\,10^9$	50
$\gamma\gamma \to \ell^+\ell^-, q\bar{q}$	15,000	$7.5\,10^9$	150

    - Large Bhabha scattering cross section (above 5° off the beam axis)
      - ➨ Allow the integrated luminosity to be measured to better than 0.1%

        No systematic from beam energy spectrum (no beamstrahlung)

  - Can also measure other Higgs properties (no difference wrt linear collider)
    - Mass
    - Spin from HZ threshold scan
    - CP from angular distributions

The LEP3 Physics Programme (2)

- LEP3 as a Higgs factory, $\sqrt{s}$ = 240 GeV : Five years (cont'd)
  - Direct measurement of the W mass with $e^+e^- \rightarrow W^+W^- \rightarrow$ qqqq, lνqq
    - With ~8 million WW events in 500 fb^{-1}, and extrapolating from LEP2 figures
      - ➨ Statistical uncertainty on m_W ~ 1 MeV/c^2 / experiment
  - Requires a precise beam energy measurement, from the knowledge of m_Z
    - With ~650,000 ZZ events (of which 400,000 without $Z \rightarrow \nu\nu$)
      - ➨ Statistical uncertainty on E_{beam} ~ 5 MeV / experiment
    - With 1 million Z(γ) events (with $Z \rightarrow e^+e^-, \mu^+\mu^-$) [radiative returns]
      - ➨ Statistical uncertainty on E_{beam} ~ 3 MeV / experiment

        May be improved with the use of $Z \rightarrow$ hadrons ?
  - Combined expected accuracy on m_W
    - With 4 experiments
      - ➨ Can reach a combined precision on m_W of ~1 MeV/c^2

        Today, LEP + Tevatron reached a precision of 15 MeV/c^2

        Will be difficult to improve at the LHC beyond 10 MeV/c^2

The LEP3 Physics Programme (3)

- LEP3 as a TeraZ factory, $\sqrt{s} \sim m_Z$: One year
  - With the available RF power, can keep 50 times more current at $\sqrt{s} \sim mZ$
    - Distributed in 200 x 200 bunches
      - Identical bunches as at 240 GeV : same beamstrahlung, same pileup, …
    - But instantaneous luminosity of 5×10^{35} $cm^{-2}s^{-1}$
      - 250 times larger than the linear collider GigaZ option
      - Integrated luminosity three orders of magnitude larger

        5 ab^{-1} / experiment, and four detectors

        Total of o(10^{12} Z) : LEP3 is a TeraZ factory

        Can repeat the LEP1 programme every 10 minutes

        Continuous detector calibration cancel all experimental uncertainties
  - Interesting observation : Event rate
    - Z decays + Bhabha events (1^{o}) + γγ collisions add up to a rate of 25 kHz
      - CMS high-level trigger currently collects events at a rate of 1kHz

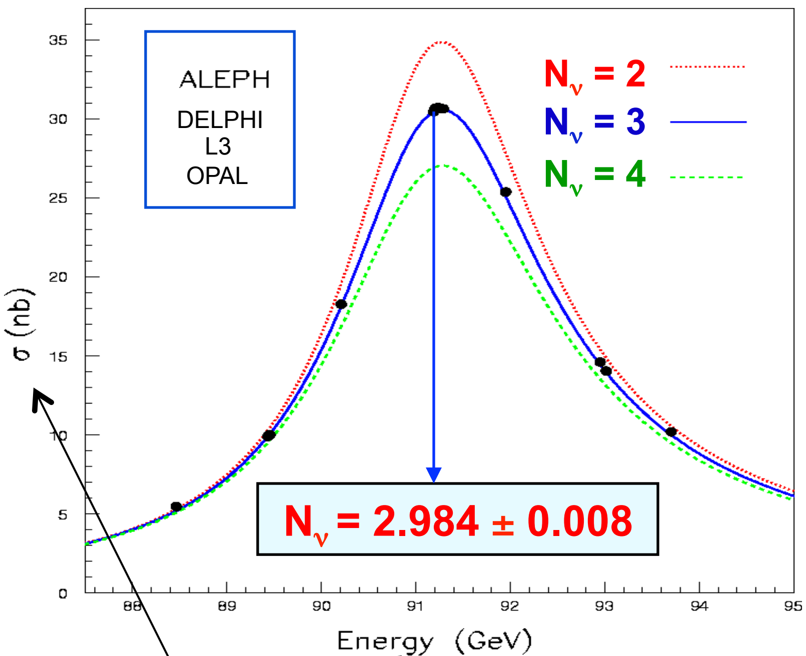
        A factor 25 to find ?
      - Luckily, CMS events at LHC are big and slow to process

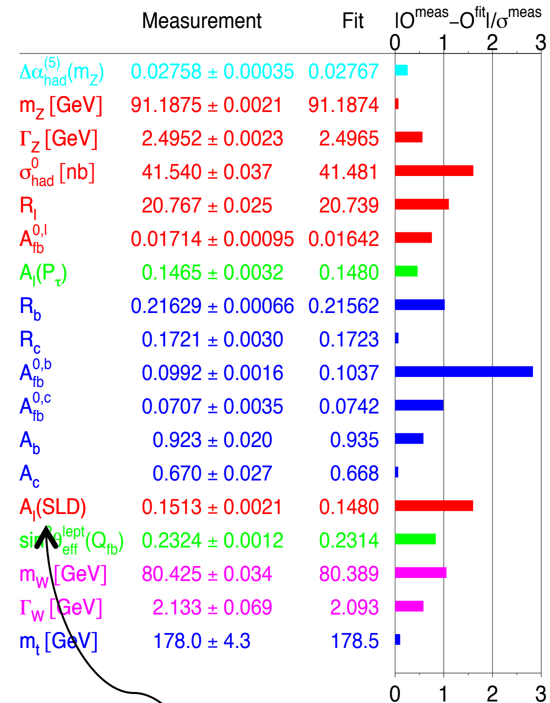
        Especially with 30-40 PU events

        Typically 20 times bigger/slower than a LEP3 Z hadronic decay

The LEP3 Physics Programme (4)

- LEP3 as a TeraZ factory, $\sqrt{s} \sim m_Z$: One year (cont'd)
  - Repeat all LEP1 / SLD measurements with 25 to 100 times better precision





- L : Requires Luminosity measurement (dedicated luminometers)
- E : Requires beam Energy measurement (resonant depolarization)
- P : Could require beam Polarization (towards A_{LR} measurement)

The LEP3 Physics Programme (5)

- Digression : Luminosity measurement
  - Dedicated luminometers from 1 to 5 degrees of the beam axis
    - Placed in front of the focusing quadrupoles
      - No specific study done for LEP3 yet

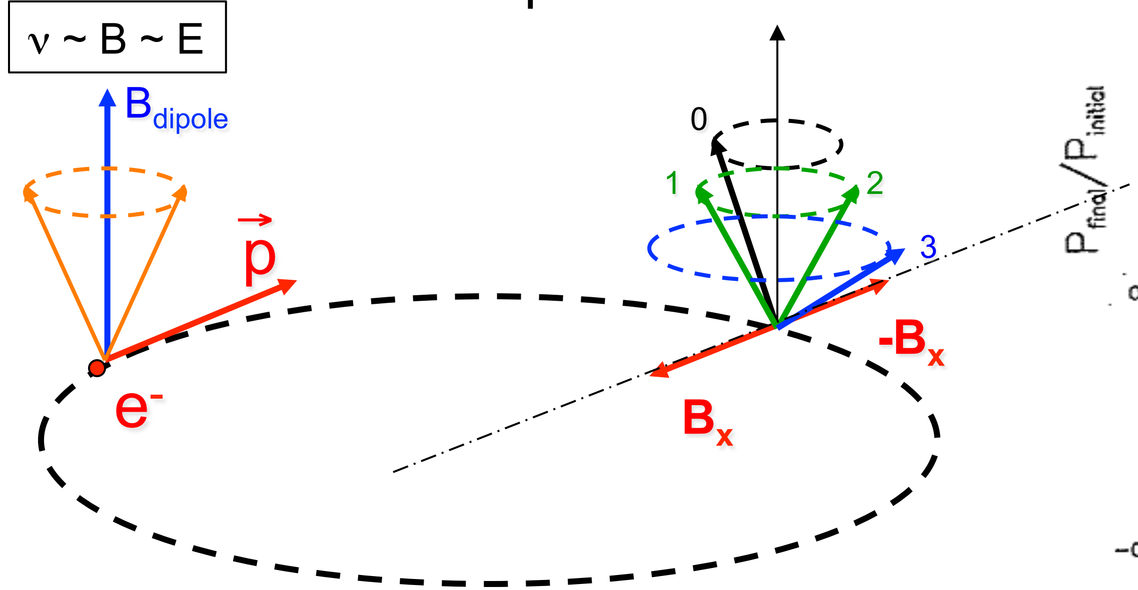
        Negligible beamstrahlung is a great advantage
      - Need theoretical developments to understand σ_{e+e-} to better than 5 x 10^{-5}

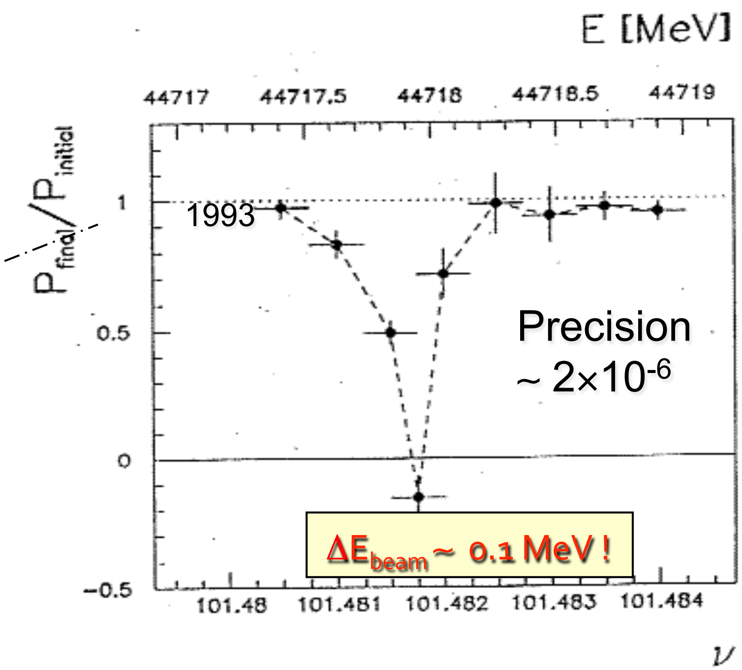
- Digression : Polarization and polarization measurement
  - LEP1 : reached 60% polarization with a single beam at 45 GeV [21]
    - Polarization was lost in collision because of design flaws
      - Should be possible to maintain it with some care in the design
    - Spin-rotator for LEP3 may re-use HERA, SuperB or LHeC experience [22]
  - Polarization in situ measurement, together with A_{LR}
    - Scheme with alternate polarized and unpolarized bunches exists [23]
  - Not critical for the LEP3 programme at the Z pole
    - Can be arranged as a separate programme for the A_{LR} measurement

The LEP3 Physics Programme (6)

- **Digression : Beam energy measurement**
  - Ultra-precise resonant depolarization method, unique to a ring
    - Precision limited to 2 MeV at LEP1 by the extrapolation to collision conditions
      - At LEP3, can use one of the 200 bunches to make this measurement

        No extrapolation needed !





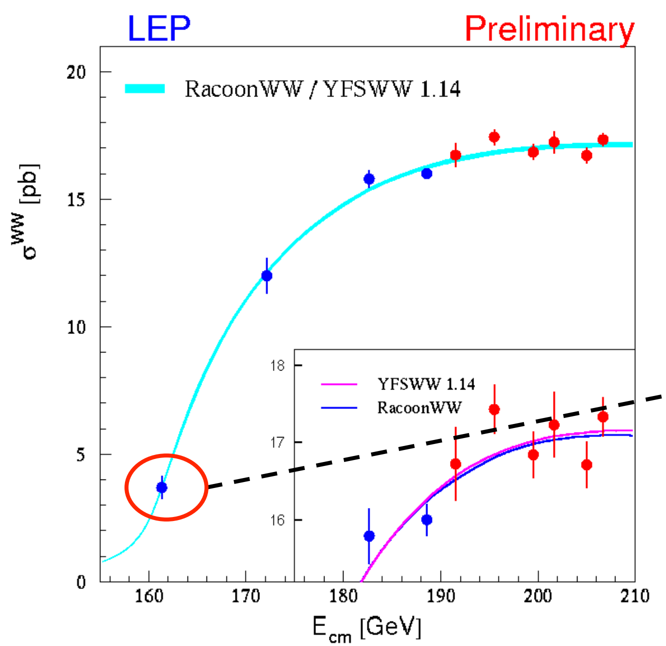
- Ultimate precision better than 0.1 MeV

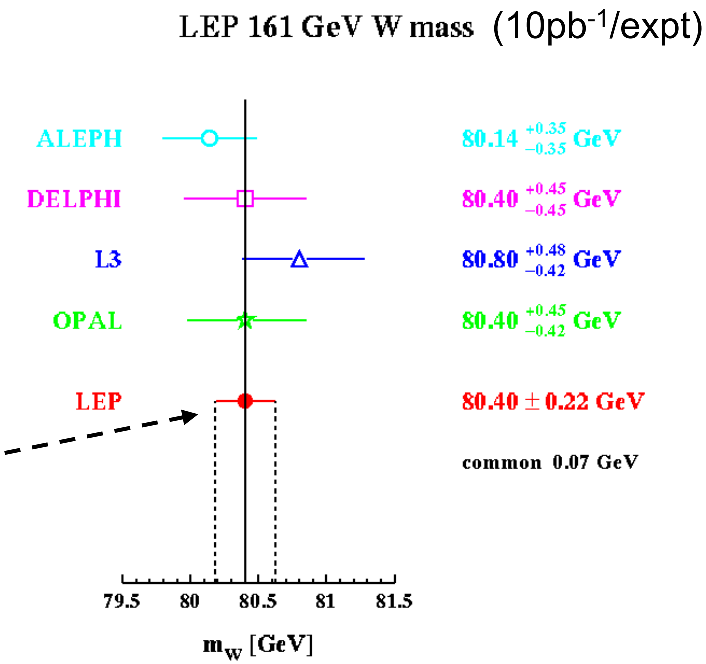
  Measure Γ_Z to better than 0.1 MeV

  (limited to 2 MeV @ LEP1: tides; TGV, rain; + extrapolation)

The LEP3 Physics Programme (7)

- **LEP3 as a MegaW factory, $\sqrt{s} \sim 2m_W$: One year**
  - Reminder : What was achieved at LEP2





$m_W = (80.40 \pm 0.22)$ GeV/c²

  - With 10^{35} cm^{-2}s^{-1}, i.e., 1 ab^{-1} in a year (10^5 times larger data sample)
    - Δm_W reduced to 0.7 MeV per experiment (stat. only)
      - ➨ Grand combination with 240 GeV leads to a precision of 300 keV on m_W

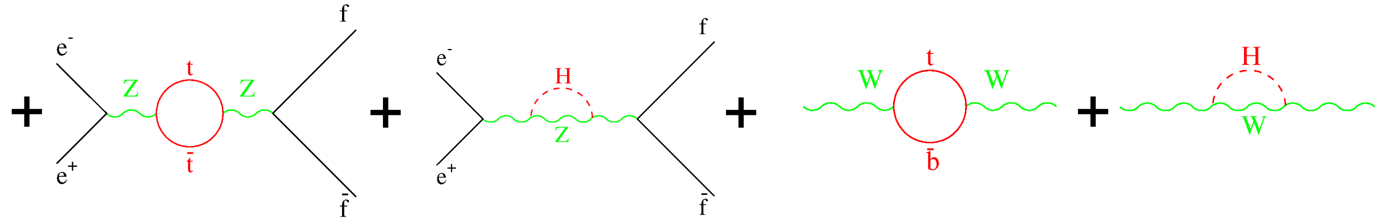
        Resonant depolarization might not be operational at $E_{beam} \sim 80$ GeV

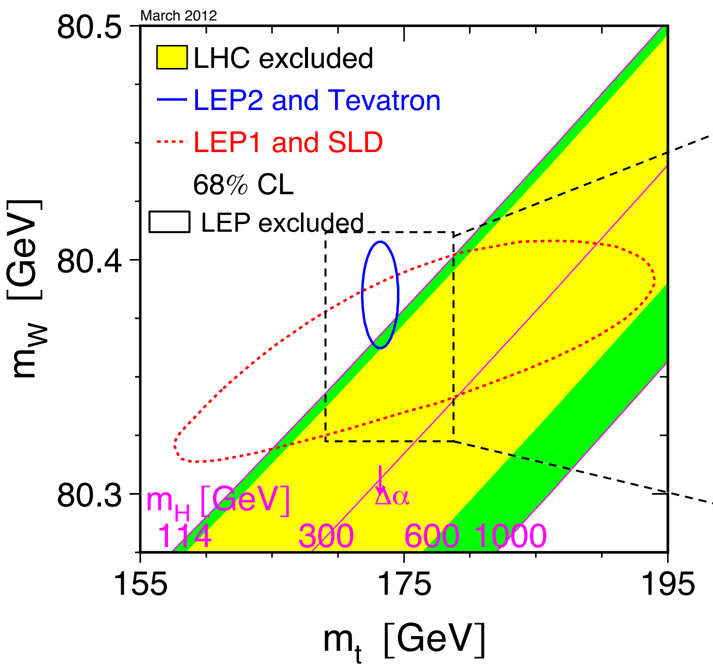
        Alternatively, use 2×10^7 Z(γ) events for a similar precision on $\langle E_{beam} \rangle$

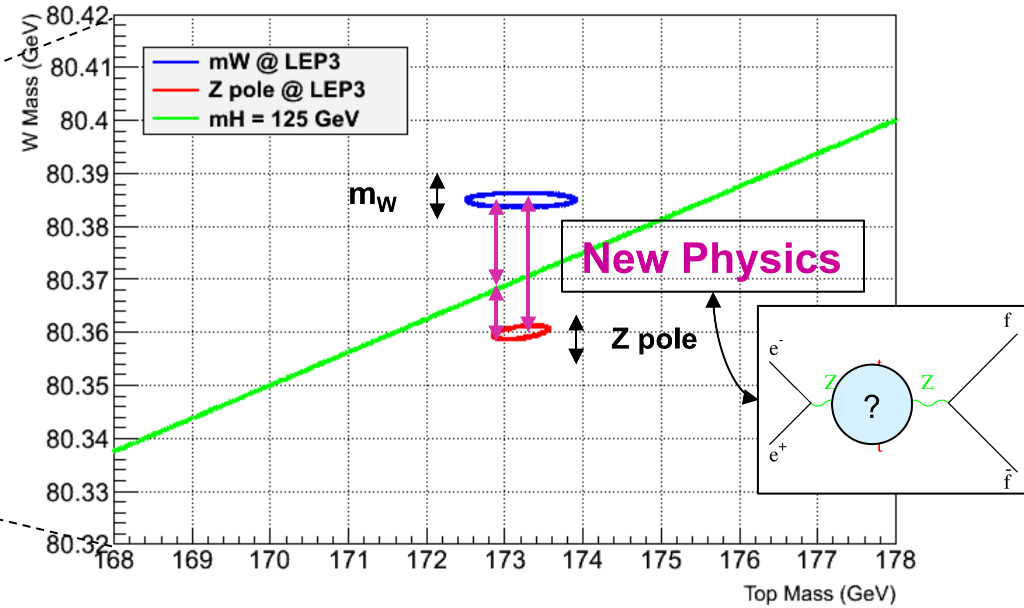
The LEP3 Physics Programme (8)

- Opens a whole new book in EWSB precision measurements:

$$m_W = m_Z \cos\theta_W$$







- March 2012 (Moriond)

After LHC + LEP3 (conservative)

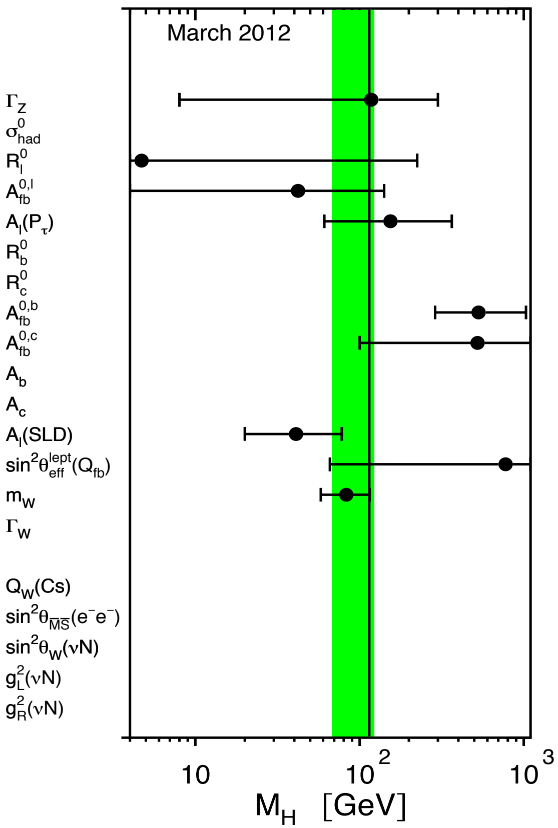
1 MeV for m_W, factor 25 at the Z pole (+500 MeV for m_{top})

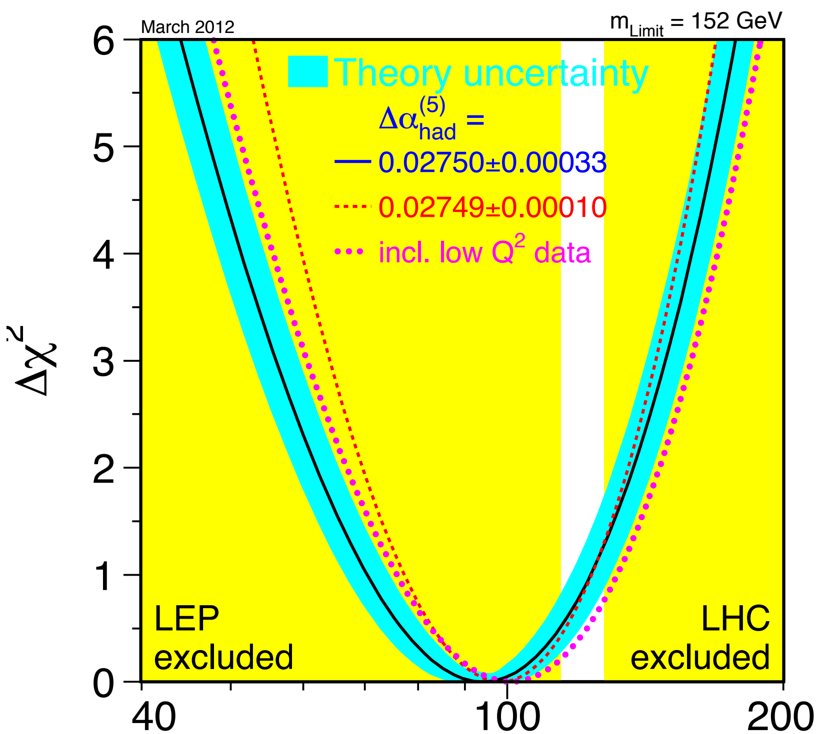
The LEP3 Physics Programme (9)

- **Will pave the way towards future facilities at the energy frontier**
  - **All electroweak measurements become sensitive to weakly interacting new physics**
    - **Each observable depends on S,T,U in a different way**
      - **For example :**

$$m_H = 94^{+29}_{-24}\ \mathrm{GeV}/c^2$$

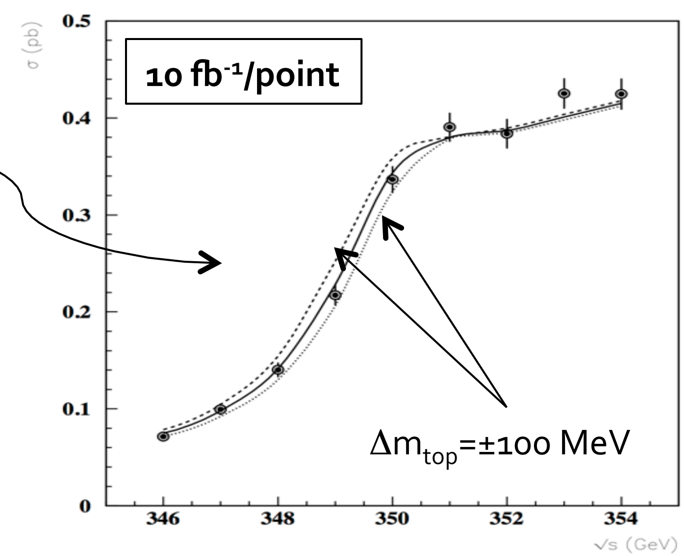
$$m_H \leq 152\ \mathrm{GeV}/c^2 \text{ at } 95\%\ \mathrm{C.L.}$$

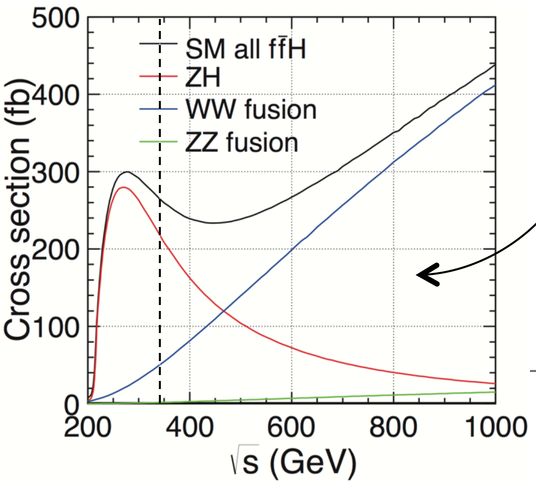




The TLEP Physics Programme

- Same as LEP3, with less synchrotron radiation, plus…
  - Five to ten times more luminosity at $\sqrt{s}$ = 240 GeV
    - Can do in a couple years what a linear collider would do in 40 years.
  - Two to five times more luminosity at $\sqrt{s} = m_Z$ or $2m_W$
    - Ultimate precision for all electroweak observables
  - Top physics at $\sqrt{s}$ = 350 GeV
    - Measure the top mass to 50 MeV
    - And more Higgs measurements
      - More statistics for HZ
      - WW fusion opens up for g_{HWW}

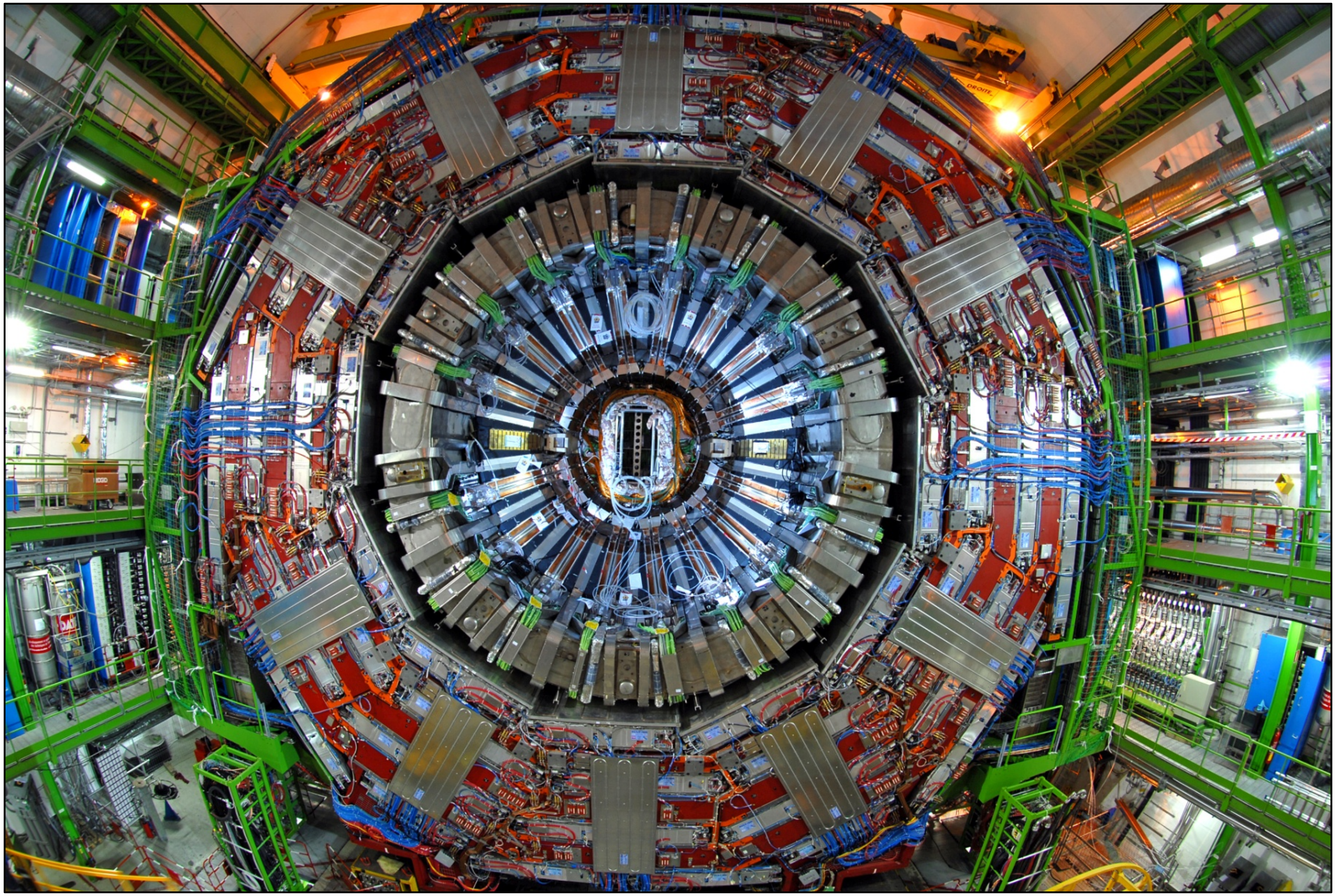




[6]

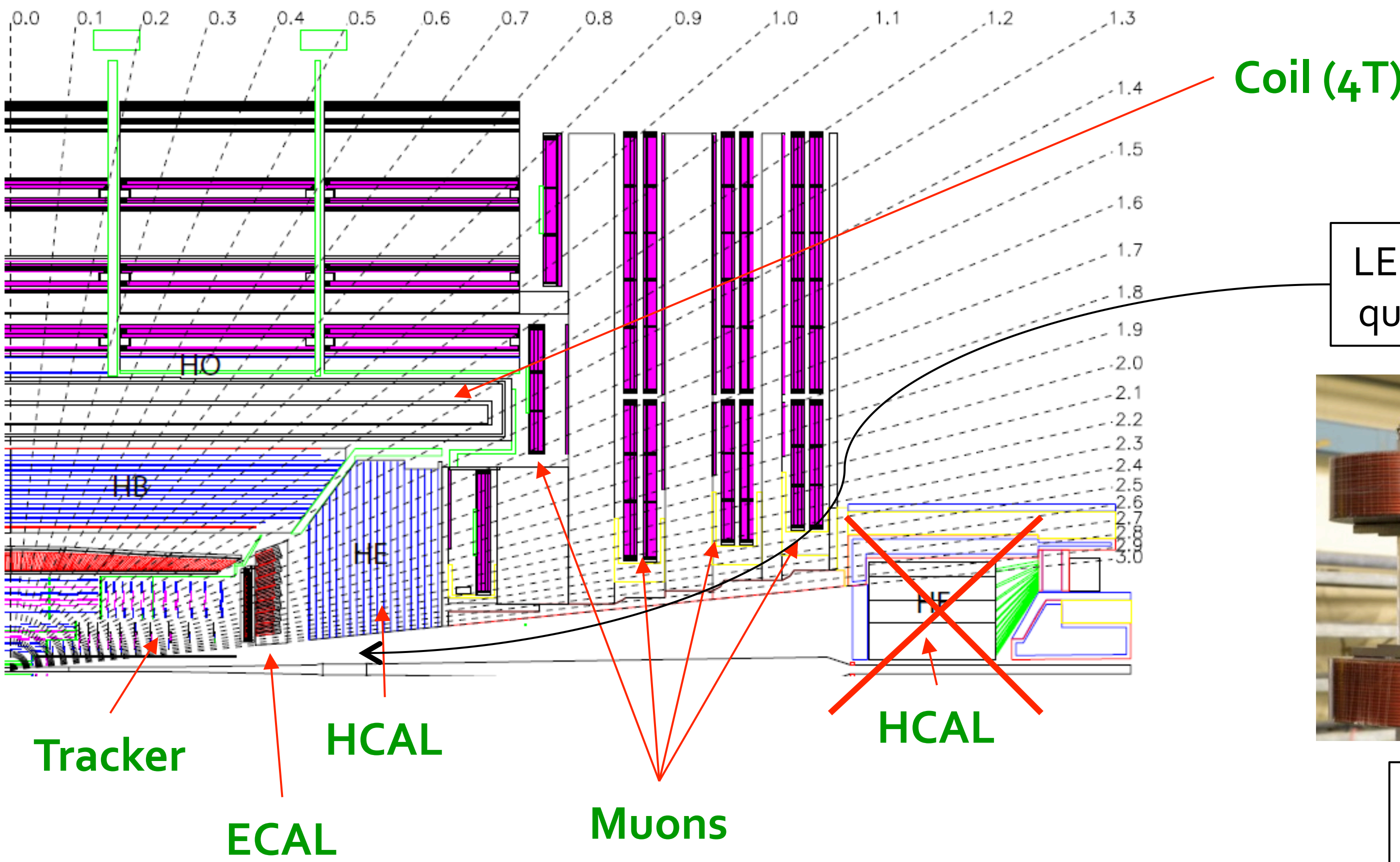
Precision Measurements with CMS ? (1)

- The CMS detector exists and runs in pp collisions
  - Data can be used to check the predictions of the simulation

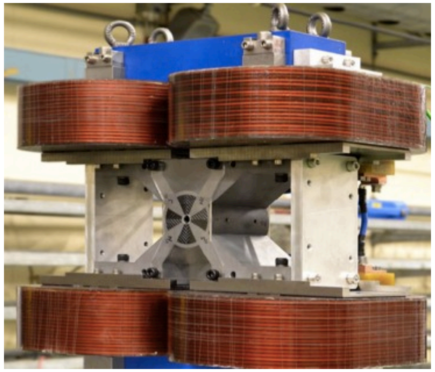


Precision Measurements with CMS ? (2)

- Longitudinal view



LEP3 needs focusing quadrupoles at ±4m

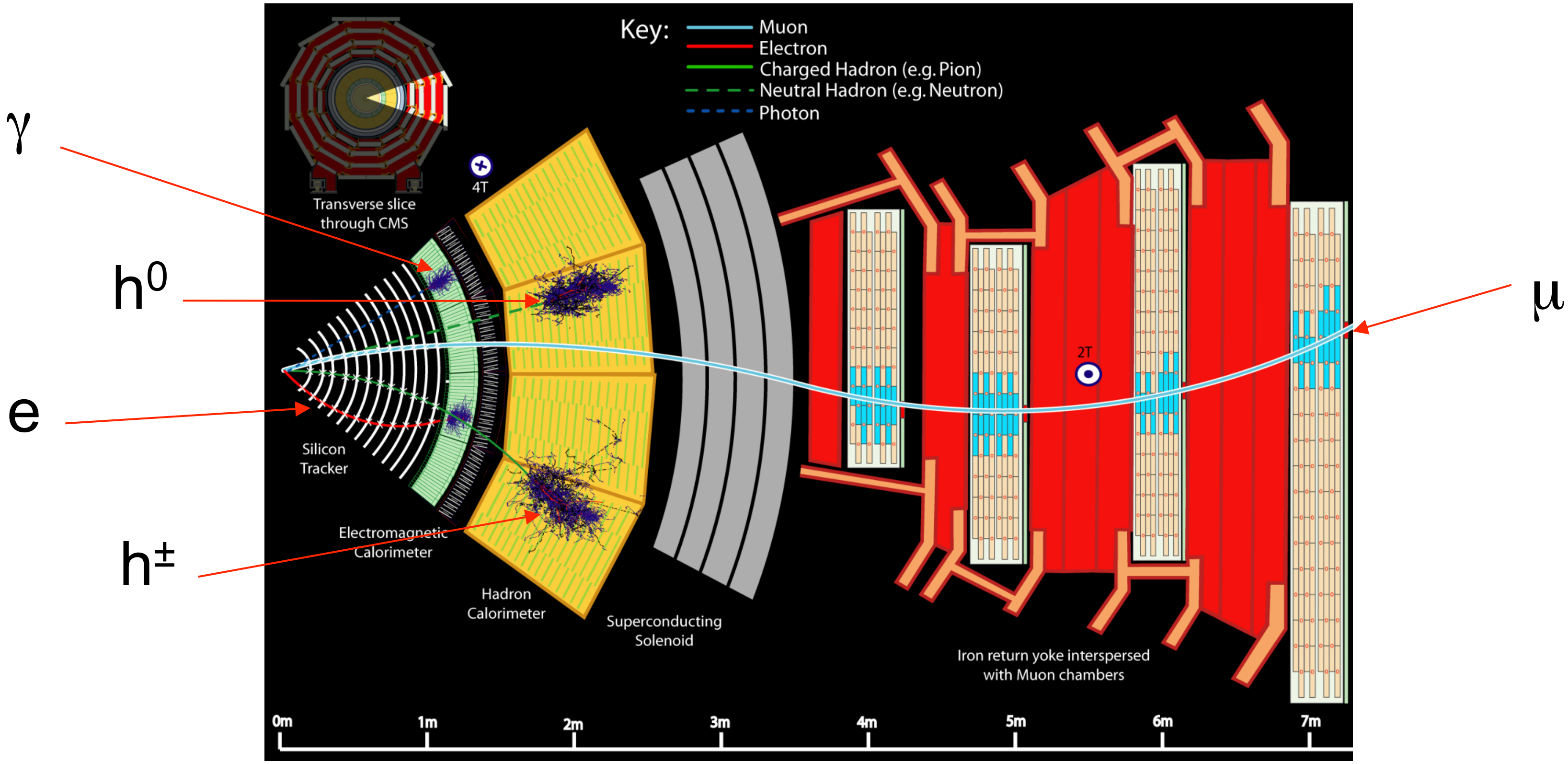


Very small CLIC prototypes exist and would fit !

- Next challenge : Accelerator beam pass-through !
  - Or more creative solution ?

Precision Measurements with CMS ? (3)

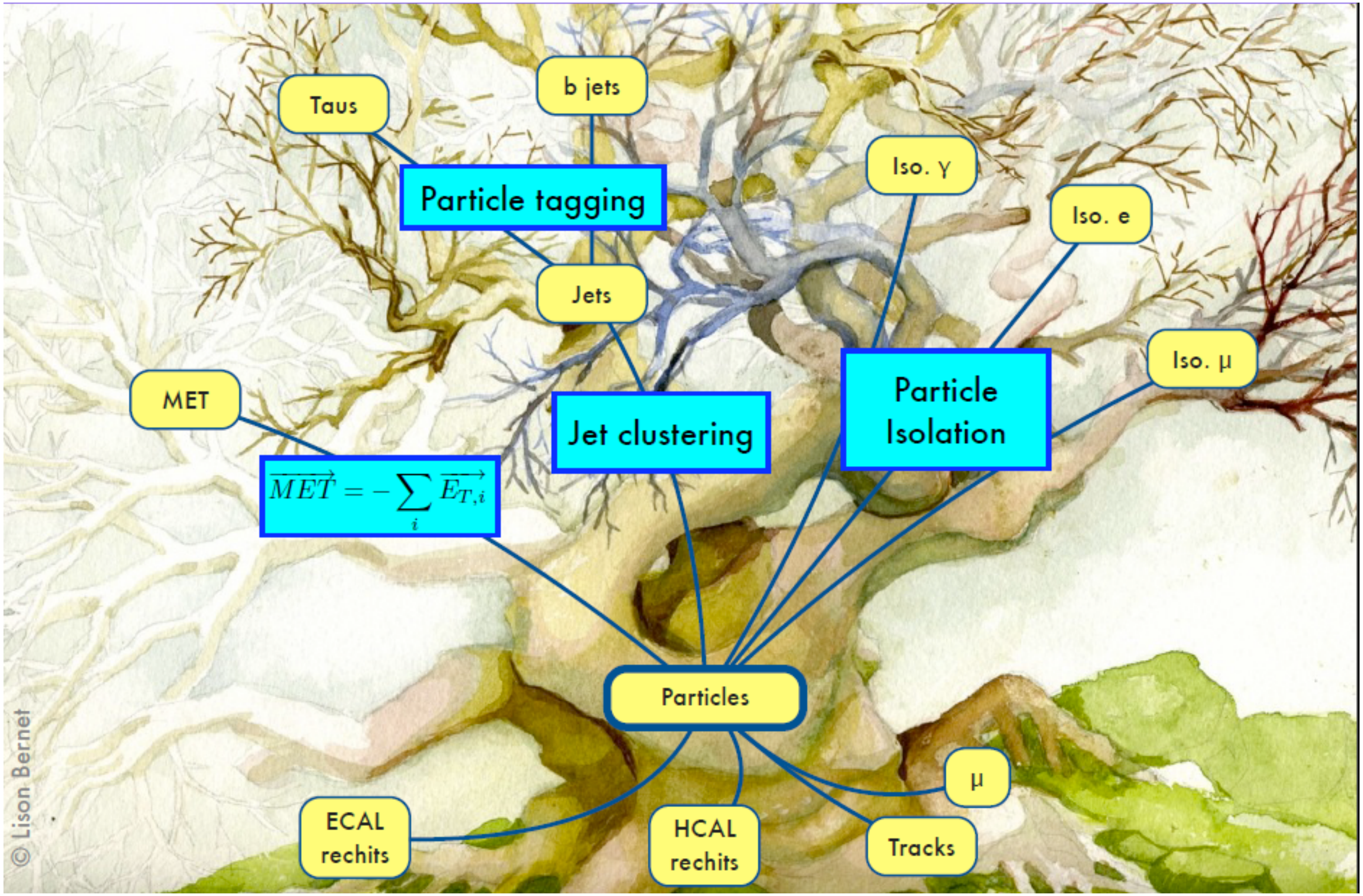
- An octant in the transverse view



- Large magnetic field, efficient tracking / muon Id, fine ECAL granularity, simple design
  - Well suited for particle-flow reconstruction
    - Although not initially designed for that (unlike LC detectors)

Precision Measurements with CMS ? (4)

- **A global event description :**



Precision Measurements with CMS ? (5)

- Comparison with a typical LC detector

Object	CMS	LC
Jets	50%/√E+4%	25-30%/√E
Missing energy	50%√ΣE	25%√ΣE
Muon momentum	2%	0.2%
Electron momentum	2%	0.2%
b tagging	30%	50%

c tagging or gluon tagging not yet attempted in CMS

- CMS typically 2-10 times worse than LC typical detector
  - Not a real surprise : it was not optimized for e^+e^- collisions
    - ➨ Let's see the impact on Higgs precision measurements (CMS vs LC detector)

Higgs Precision Measurements with CMS

- **General comment about the analyses**
  - All "results" given in the next slides are realistic, but also very conservative
    - Full CMS detector simulation is used throughout
      - 500 fb^{-1} were simulated/reconstructed for signal and backgrounds
        - Simulation of the 5 years of LEP3 could be done within a week
      - No optimization of the reconstruction was attempted, e.g.,
        - Tracking could have been made more efficient for the simple LEP3 events
        - b tagging could have included soft-lepton tags
        - Upgraded pixel detector could have been used in the simulation
        - Jet algorithms could have been optimized
      - The exact same analysis tools as for the recent CMS Higgs search were used
    - Very basic selection algorithms were developed
      - Mostly because analysis started in June and had to finish July 31st …
        - No multivariate analysis was attempted
        - No constrained fits were used – only simple jet energy rescaling so far
    - In the grand combination with four detectors, all detectors are assumed to be CMS
      - While at least two would obviously be LC-type detectors
    - Not all Higgs decay channels have yet been addressed

Higgs Precision Measurements with CMS

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      - While at least two would obviously be LC-type detectors
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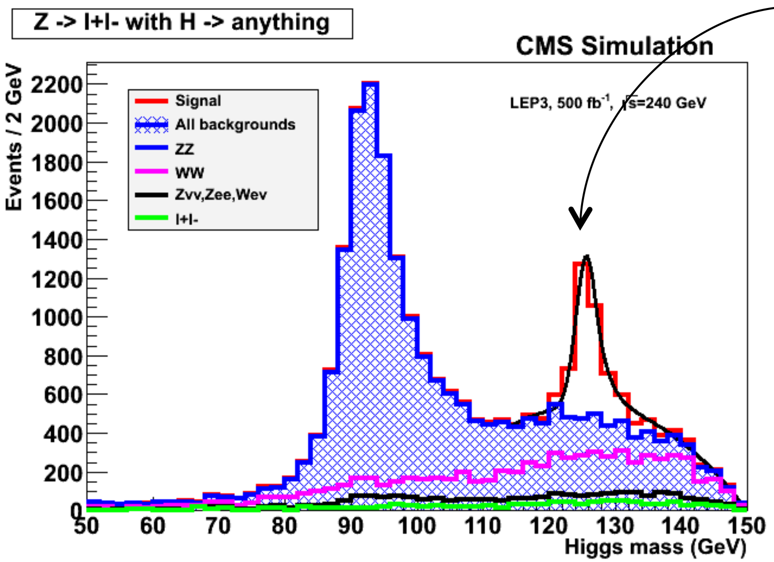
Examples that follow to be taken as illustration only

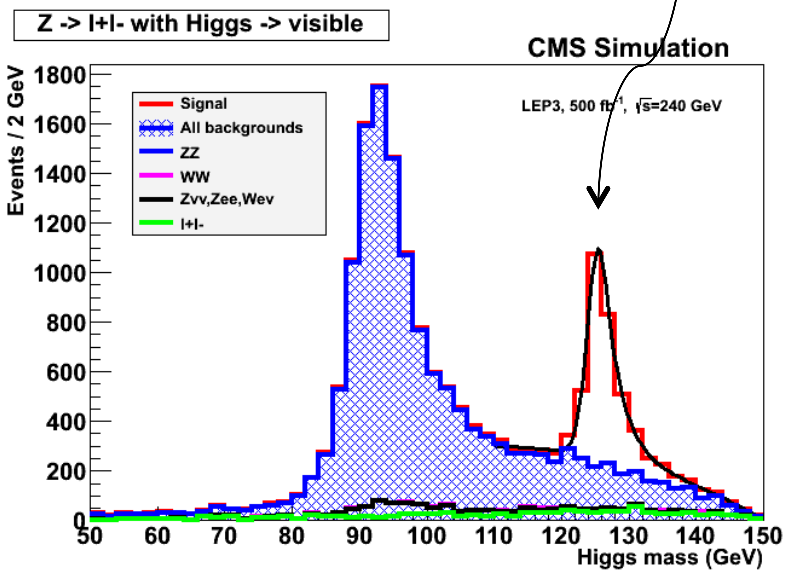
Room for very substantial improvements

See [14] for more details

Measurement of the $e^+e^- \rightarrow ZH$ cross section

- **Model-independent measurement with $Z \rightarrow e^+e^-, \mu^+\mu^-$**
  - Two oppositely-charged same-flavour leptons
  - With possible Bremsstrahlung photons, invariant mass within 5 GeV of the Z mass
  - Reject radiative events (ISR) with p_T , p_Z , acoplanarity cuts (+ photon veto)
    - Display the mass recoiling to the two leptons, and fit (Crystal Ball + pol3)
      - ➨ 3.1% precision on σ_{HZ}
    - If the invisible decay width can be excluded, request the recoil to be visible
      - ➨ 2.6% precision on σ_{HZ}





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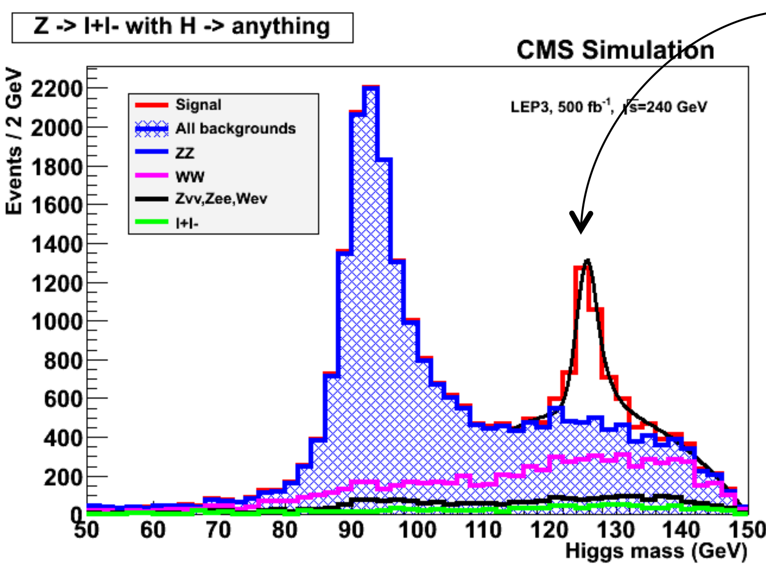
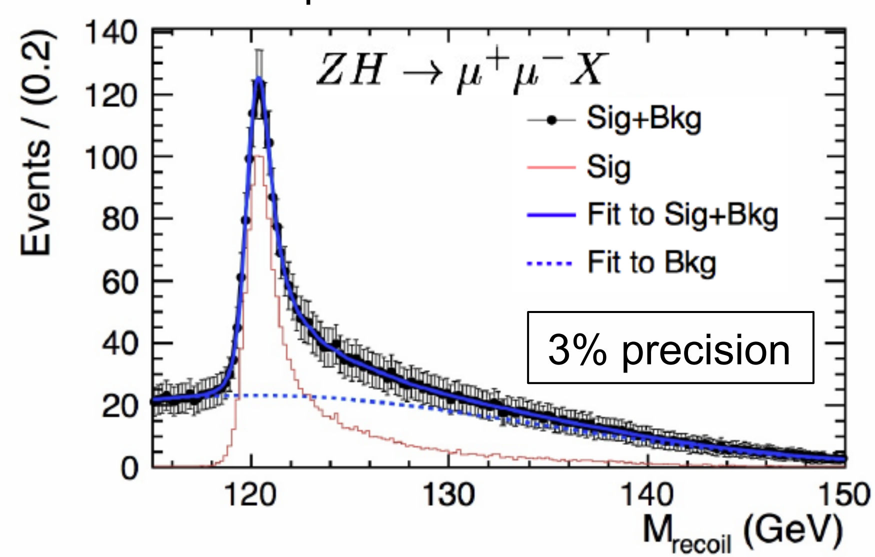
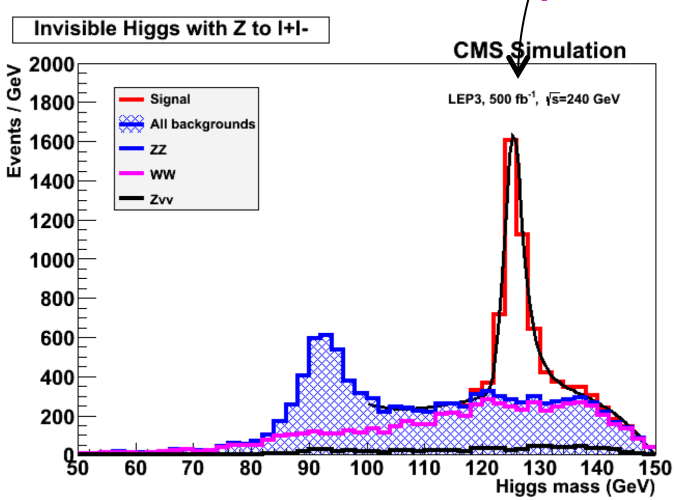


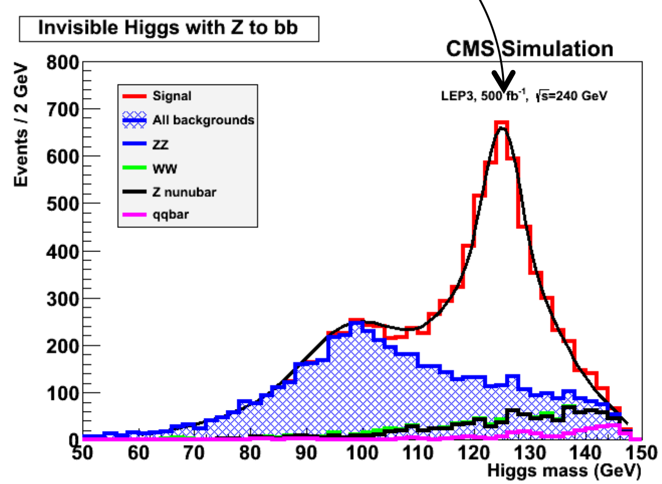
Comparison with ILC studies



Measurement of σ_{HZ} x BR(H→invisible)

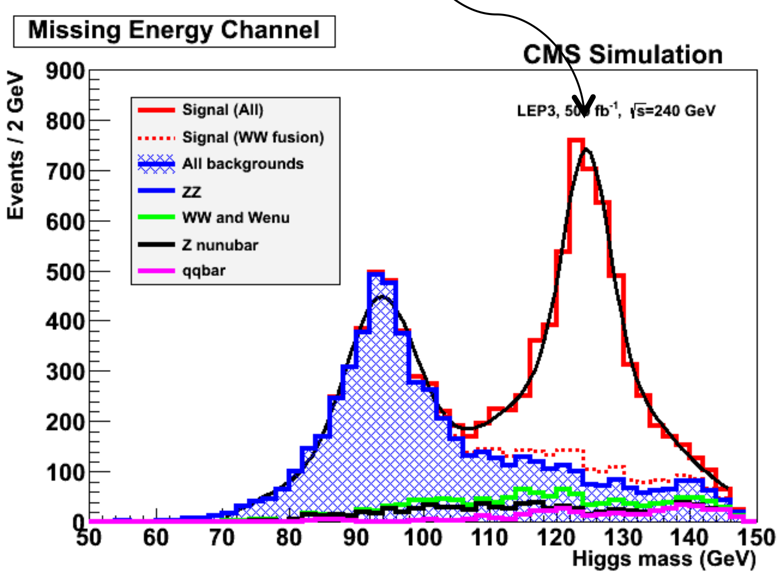
- **Same approach as before**
  - With the requirement that the event consists of only the two leptons (+Brem)
    - Display the mass recoiling against the two leptons (with BR_{invis} = 100%)
  - Complete the analysis with Z -> b bbar
    - Force the events to form two jets, and apply very pure b tagging criterion
    - Invariant mass with 15 GeV of the Z mass
    - Same cuts on p_T, p_Z, acoplanarity, as in the dilepton case
  - With BR_{invis} = 100%, measure σ_{HZ} to 2.2%
    - Can exclude BR_{invis} values all the way down to 1.5% if not signal is observed
      - ➨ In that case, measure σ_{HZ} to 2.7% (with the visible final state)

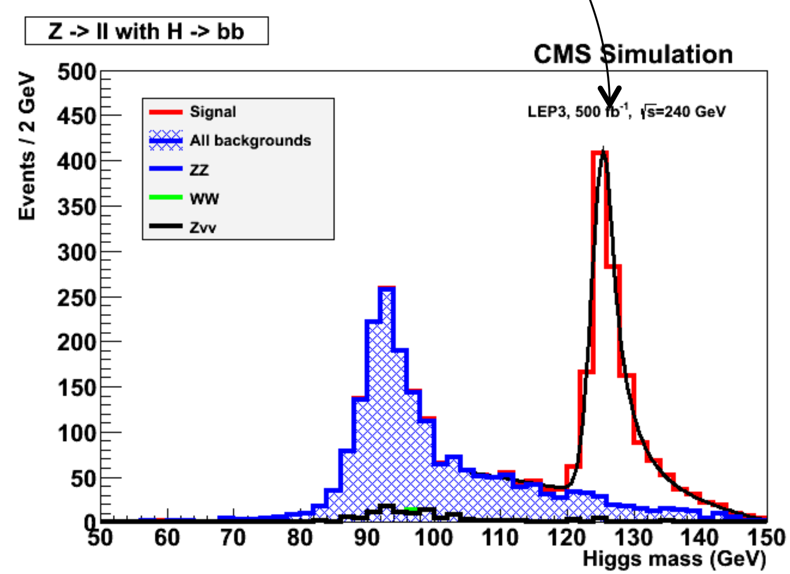




Measurement of σ_{HZ} x BR(H→bb)

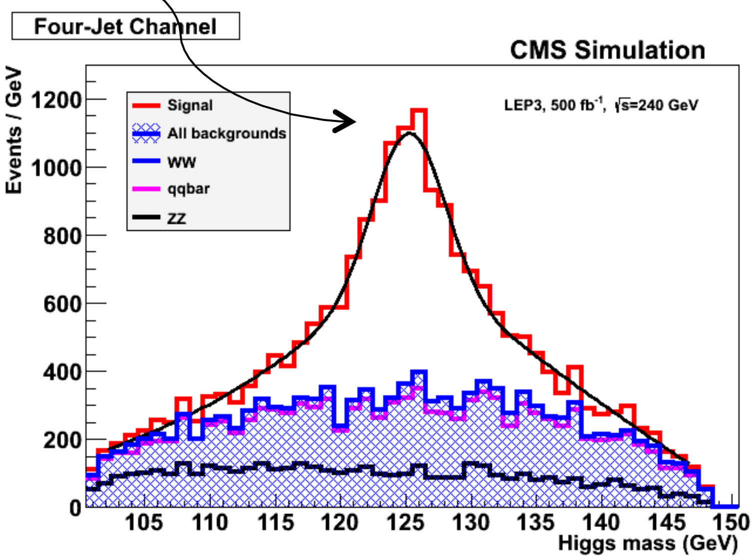
- **Leptonic final state : $Z \to e^+e^-, \mu^+\mu^-$**
  - Exact same selection as for the σ_{HZ} measurement
    - Force the rest of the event to form two jets, and apply a tight b tagging
      - ➨ Precision of 3.1% on σ_{HZ} x BR(H→bb)
- **Missing energy final state : $Z \to \nu\nu$**
  - Exact same selection as for invisible Higgs with $Z \to bb$
    - Substitute missing mass for visible mass, and display the rescaled visible mass
      - ➨ Precision of 1.8% on σ_{HZ} x BR(H→bb)





Measurement of σ_{HZ} x BR(H→bb)

- **The four-jet channel : Z → qq**
  - Force the event to form four jets, all identified as hadronic jets (particle multiplicty)
  - No significant missing energy : visible mass > 180 GeV
  - Four jet energies rescaled to satisfy E,p conservation (directions unchanged)
    - Distance to ZZ and WW hypotheses in excess of 10 GeV
    - One pair compatible with a Z, the other (the Higgs) with mass larger than 100 GeV
    - If several such combinations exist, take that with the largest b tag for the H pair
      - Display $m_H = m_{12} + m_{34} - 91.2$ GeV
  - Background shape taken from simulation
    - Fit to a 3rd order polynomial
  - Signal fit to a double Gaussian
    - Precision of 1.5% on σ_{HZ} x BR(H→bb)

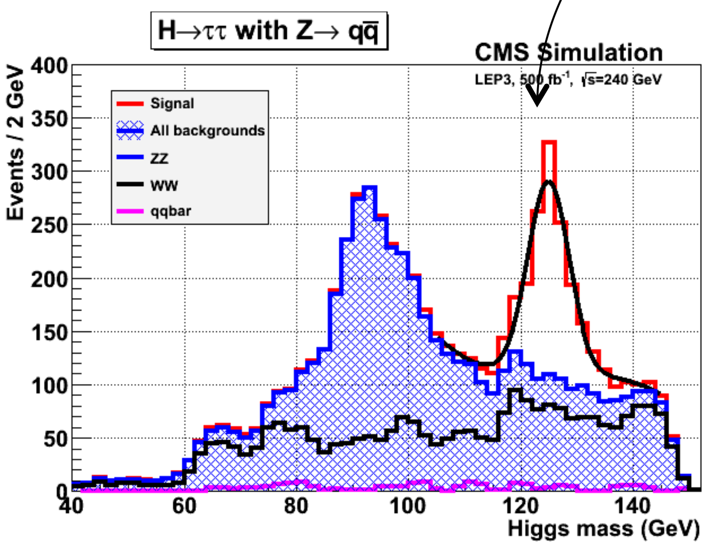


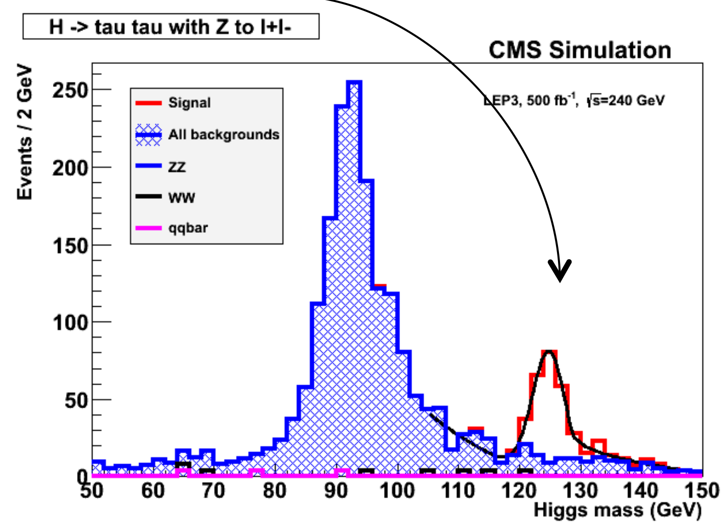
- **Combined precision : 1.0%**
  - Hot news : 5C and 6C improve this by ~20%
    - Not displayed / not used here

Measurement of σ_{HZ} x BR($H \rightarrow \tau^+\tau^-$)

- Analysis similar to the bb decay
  - Substitute tau tagging for b tagging
    - Addressed only the hadronic and leptonic Z decays
      - No mass determination in the missing energy channel

- Combined precision of 4.3% on σ_{HZ} x BR($H \rightarrow \tau\tau$)

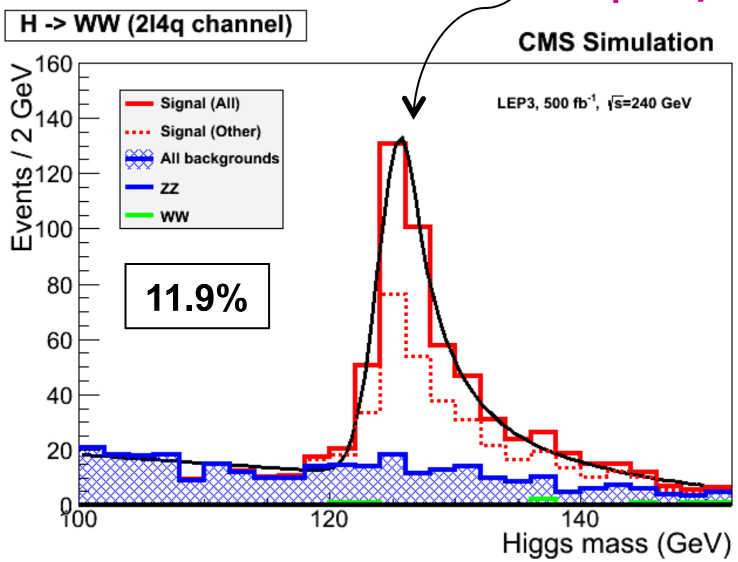


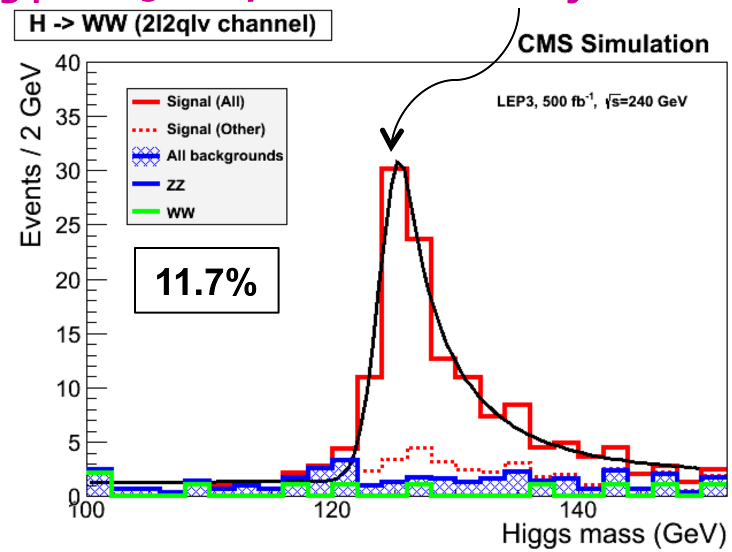


Measurement of σ_{HZ} x BR(H→W^+W^-)

- **Many Z and WW decay channels analysed**
  - Leptonic decays
    - Select the lepton pairs as for the HZ cross section measurement
    - Request the recoiling to consist of
      - Either four hadronic jets (WW → 4q)

        With anti-b-tagging cut (rejects H → bb)
      - Or an additional lepton, missing pT > 15 GeV, and at least one jet (WW→ lνqq)

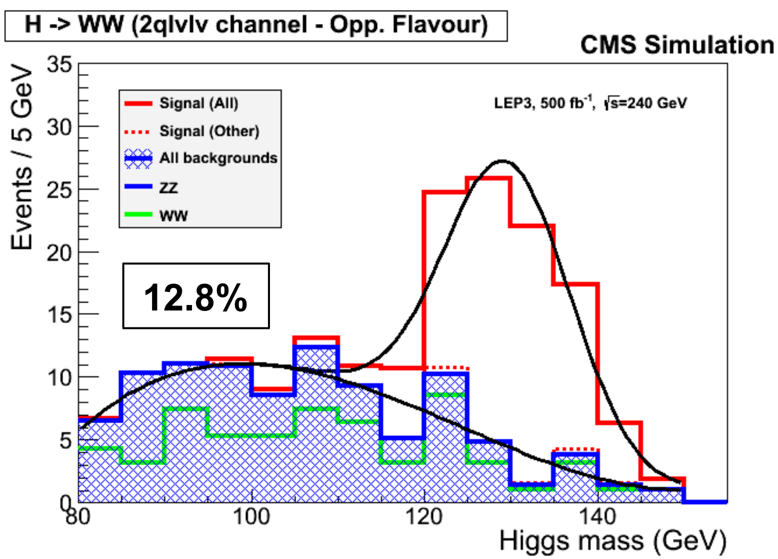


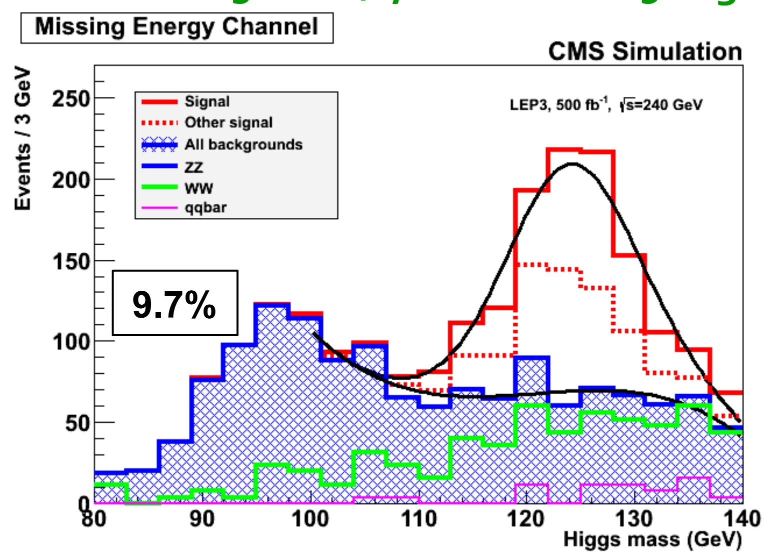


- Background from other Higgs decay channels significant
  - Take if from the SM for the time being. Will do a global fit eventually.

Measurement of σ_{HZ} x BR(H→W^+W^-)

- **Many decay channels analysed (cont'd)**
  - Hadronic Z decays, fully leptonic WW decays (WW → lνlν)
    - Two leptons, opposite charge, opposite flavour, mass between 10 and 70 GeV/c^2
      - Same lepton flavours also studied, but statistically less interesting
    - Missing transverse momentum > 25 GeV/c
    - Recoiling system with N_{ch}>10 and compatible with the Z mass (±25 GeV/c^2)
  - Invisible Z decays, fully hadronic WW decays (WW → 4q)
    - Request four jets, no electron, no muon, no tau, anti-b-tagging cut
    - Missing mass > 75 GeV/c^2, missing momentum > 30 GeV/c, direction > 25 degrees





Measurement of σ_{HZ} x BR(H→W^+W^-)

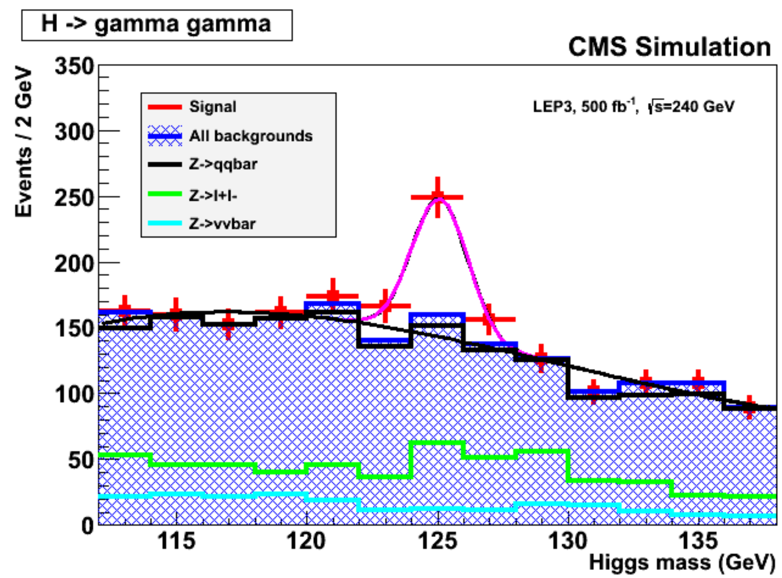
- **Combined precision on σ_{HZ} x BR(H→W^+W^-)**
  - Can potentially improve with a study of the fully hadronic final state (6 jets)
    - Being worked on
  - The four individual channels give a precision of 11.9%, 11.7%, 12.8% and 9.7%
    - Combines to a precision on σ_{HZ} x BR(H→W^+W^-) of 5.6%

- **Toward a measurement of σ_{HZ} x BR(H→cc, gg)**
  - The above assumes the SM (or the measured values) for the other signal channels
    - Small and dominated by bb in llqqlν and in 2qlνlν
    - Larger, 50% bb and 50% gg+cc in ll4q and in 2ν4q
    - The llqq final state (two jets, anti-b-tag) is instead enriched in gg and cc (no WW)
      - Could simultaneously fit gg and cc together with WW

        Take bb and ZZ from the measurements
    - Under study as we speak
      - Would benefit from the upgraded pixel detector
      - Would benefit from dedicated c and gluon tagging algorithms
    - We know that it is possible from ILC studies.

Measurement of σ_{HZ} x BR(H➔γγ)

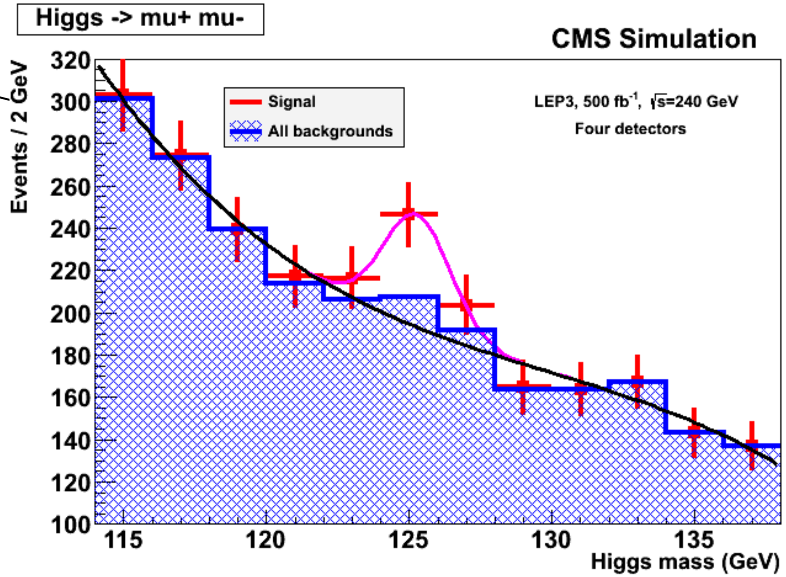
- **Quite rare a decay …**
  - About 250 H -> γγ events expected in 500 fb^{-1}
  - Main background consist of double radiative returns to the Z mass
    - e+e- → ννγγ, eeγγ, μμγγ, ττγγ, and qqγγ (both photons in the detector acceptance)
  - Two photons with energy > 40 GeV, in the tracker acceptance, isolated
    - Take the pair for which the recoiling mass is closest to the Z mass
  - Reject radiative events
    - Higgs momentum direction more than 25 degrees away from the beam axis
    - Rapidity gap smaller than 2.0



- **Selection efficiency ~ 60%**
  - Precision of 14% on σ_{HZ} x BR(H➔γγ)
  - Better diphoton mass resolution at hand
    - (Energy regression used at CMS/LHC)

Measurement of σ_{HZ} x BR($H \rightarrow \mu^+\mu^-$)

- **Even rarer a decay …**
  - About 22 $H \rightarrow \mu^+\mu^-$ events expected in 500 fb^{-1}
    - Definitely need the four detectors here : almost 90 events expected !
  - Two oppositely charged muons (+ potential bremsstrahlung photons)
  - Mass recoiling the muon pair with 15 Gev of the Z mass
  - Reject WW -> $\mu\nu\mu\nu$ by requesting two add'l jets
    - Also rejects Z -> $\nu\nu$ (20% of HZ)
  - Reject double radiative mm events by requesting no purely electromagnetic jets
    - Also rejects Z -> ee (3.4% of HZ)
  - Display the muon pair mass



- **A 4σ excess**
  - Precision of 28% on σ_{HZ} x BR($H \rightarrow \mu\mu$)
    - Essential for a muon collider project
  - Better dimuon mass resolution would help
    - But already OK with CMS x 4

Summary of LEP3/TLEP measurements

- Under the very conservative assumptions already stated :

		LEP3 (2)	LEP3 (4)	
σ_{HZ}		1.9%	1.3%	
$\sigma_{HZ} \times BR(H \to b\bar{b})$		0.8%	0.5%	
$\sigma_{HZ} \times BR(H \to \tau^+\tau^-)$		3.0%	2.2%	
$\sigma_{HZ} \times BR(H \to W^+W^-)$		3.6%	2.5%	
$\sigma_{HZ} \times BR(H \to \gamma\gamma)$		9.5%	6.6%	
$\sigma_{HZ} \times BR(H \to \mu^+\mu^-)$		–	28%	
$\sigma_{HZ} \times BR(H \to \text{invisible})$		1%	0.7%	
g_{HZZ}		0.9%	0.6%	
g_{Hbb}		1.0%	0.7%	
$g_{H\tau\tau}$		2.0%	1.5%	
g_{Hcc}		?	?	
g_{HWW}		2.2%	1.5%	
$g_{H\gamma\gamma}$		4.9%	3.4%	
$g_{H\mu\mu}$		–	14%	
g_{Htt}		–	–	
m_H (MeV/c^2)		37	26	

- Per-cent to sub-per-cent accuracy achieved on Hbb, Hττ, HZZ, and HWW couplings
  - (2) or (4) detectors assumed to be CMS.

Summary of LEP3/TLEP measurements

- Extrapolation for TLEP with 5 x more luminosity and 2 ILC-type detectors

	LEP3 (2)	LEP3 (4)	TLEP (2)
σ_{HZ}	1.9%	1.3%	0.7%
$\sigma_{HZ} \times BR(H \to b\bar{b})$	0.8%	0.5%	0.2%
$\sigma_{HZ} \times BR(H \to \tau^+\tau^-)$	3.0%	2.2%	1.3%
$\sigma_{HZ} \times BR(H \to W^+W^-)$	3.6%	2.5%	1.6%
$\sigma_{HZ} \times BR(H \to \gamma\gamma)$	9.5%	6.6%	4.2%
$\sigma_{HZ} \times BR(H \to \mu^+\mu^-)$	–	28%	17%
$\sigma_{HZ} \times BR(H \to \text{invisible})$	1%	0.7%	0.4%
g_{HZZ}	0.9%	0.6%	0.3%
g_{Hbb}	1.0%	0.7%	0.4%
$g_{H\tau\tau}$	2.0%	1.5%	0.6%
g_{Hcc}	?	?	0.9%
g_{HWW}	2.2%	1.5%	0.9%
$g_{H\gamma\gamma}$	4.9%	3.4%	2.2%
$g_{H\mu\mu}$	–	14%	9%
g_{Htt}	–	–	–
m_H (MeV/c^2)	37	26	11

- HZZ, HWW, Hbb, Hττ, Hcc : few per-mil precision; 4 detectors would improve further.
  - WW → H still to be studied at 350 GeV; Not included here.

Summary of LEP3/TLEP measurements

- Comparison with ILC (Higgs Factory at $\sqrt{s}$ = 250 GeV) [10]

	ILC	LEP3 (2)	LEP3 (4)	TLEP (2)
σ_{HZ}	3%	1.9%	1.3%	0.7%
$\sigma_{HZ} \times BR(H \to b\bar{b})$	1%	0.8%	0.5%	0.2%
$\sigma_{HZ} \times BR(H \to \tau^+\tau^-)$	6%	3.0%	2.2%	1.3%
$\sigma_{HZ} \times BR(H \to W^+W^-)$	8%	3.6%	2.5%	1.6%
$\sigma_{HZ} \times BR(H \to \gamma\gamma)$	?	9.5%	6.6%	4.2%
$\sigma_{HZ} \times BR(H \to \mu^+\mu^-)$	–	–	28%	17%
$\sigma_{HZ} \times BR(H \to \text{invisible})$	?	1%	0.7%	0.4%
g_{HZZ}	1.5%	0.9%	0.6%	0.3%
g_{Hbb}	1.6%	1.0%	0.7%	0.4%
$g_{H\tau\tau}$	3%	2.0%	1.5%	0.6%
g_{Hcc}	4%	?	?	0.9%
g_{HWW}	4%	2.2%	1.5%	0.9%
$g_{H\gamma\gamma}$	?	4.9%	3.4%	2.2%
$g_{H\mu\mu}$	–	–	14%	9%
g_{Htt}	–	–	–	–
m_H (MeV/c^2)	50	37	26	11

- LEP3 : uncertainties typically smaller by a factor 2-3 than the ILC
- TLEP : uncertainties typically smaller by a factor 5 than the ILC

Summary of LEP3/TLEP measurements

Comparison with LHC and HL-LHC

(CMS and SFitter projections) [8,23]

	ILC	LEP3 (2)	LEP3 (4)	TLEP (2)	LHC (300)	HL-LHC
σ_{HZ}	3%	1.9%	1.3%	0.7%	–	–
$\sigma_{HZ} \times BR(H \to b\bar{b})$	1%	0.8%	0.5%	0.2%	–	–
$\sigma_{HZ} \times BR(H \to \tau^+\tau^-)$	6%	3.0%	2.2%	1.3%	–	–
$\sigma_{HZ} \times BR(H \to W^+W^-)$	8%	3.6%	2.5%	1.6%	–	–
$\sigma_{HZ} \times BR(H \to \gamma\gamma)$	?	9.5%	6.6%	4.2%	–	–
$\sigma_{HZ} \times BR(H \to \mu^+\mu^-)$	–	–	28%	17%	–	–
$\sigma_{HZ} \times BR(H \to \mathrm{invisible})$	?	1%	0.7%	0.4%	–	–
g_{HZZ}	1.5%	0.9%	0.6%	0.3%	13%/5.7%	4.5%
g_{Hbb}	1.6%	1.0%	0.7%	0.4%	21%/14.5%	11%
$g_{H\tau\tau}$	3%	2.0%	1.5%	0.6%	13%/8.5%	5.4%
g_{Hcc}	4%	?	?	0.9%	?/?	?
g_{HWW}	4%	2.2%	1.5%	0.9%	11%/5.7%	4.5%
$g_{H\gamma\gamma}$	?	4.9%	3.4%	2.2%	?/6.5%	5.4%
$g_{H\mu\mu}$	–	–	14%	9%	?	?
g_{Htt}	–	–	–	–	14%	8%
m_H (MeV/c^2)	50	37	26	11	100	100

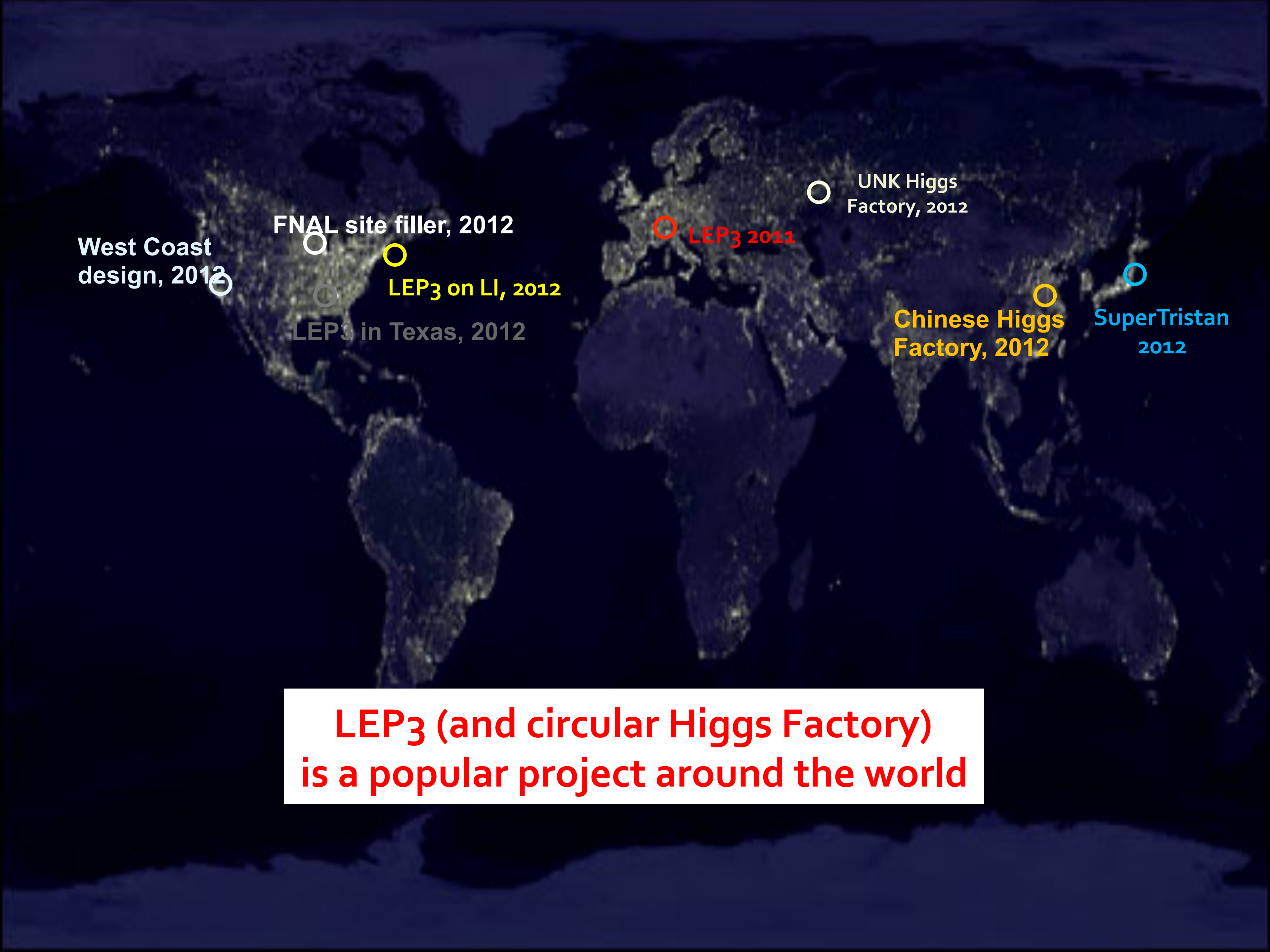
- **LEP3/TLEP exceed substantially LHC sensitivity**
  - ➨ **Even in its highest luminosity version**

Conclusions (1)

- **LEP3 is an exciting project for Physics**
  - Higgs physics better than the full 1 TeV ILC programme
    - When combined with HL-LHC or better, HE-LHC, for ttH and HHH couplings
  - Unique electroweak precision measurements
    - Sensitive to weakly interacting new physics beyond the TeV scale
      - ➨ Together with Higgs coupling measurements

- **LEP3 is a cheap project**
  - It is therefore an interesting opportunity for Europe, for CERN,
    - And even for the LHC and ILC collaborations !
      - ➨ Even if they don't fully realize it as we speak …
  - The money saved can be used for other exciting projects
    - HE-LHC, VHE-LHC, CLIC @ 3 TeV

- **LEP3 is a popular project**
  - A lot of interest around the world



LEP3 (and circular Higgs Factory) is a popular project around the world

Conclusions (2)

- LEP3 might even be feasible, in little time
  - Almost everything is "off the shelf" – lots of synergies with other projects
  - But it is not an "easy" machine
    - Fitting LEP3 in the LHC tunnel together with LHC is not easy, and sub-optimal
      - Need to weigh the relative merits of LEP3 + HE-LHC and of HL-LHC + HE-LHC

        As an option for ATLAS and CMS
      - The choice really depends on the LHC findings in the next 5 years

        LEP3 operation could start around 2024-2025, for 10 years
    - A number of accelerator issues still need to be worked out
      - RF coupler, optics energy acceptance, 2nd ring integration, synchroton radiation, …

- TLEP is a superior machine (energy and luminosity)
  - A tiny bit more expensive – although not as much as ILC
  - With a much longer timescale – requires a long-term vision for CERN
  - "Extendable" towards a VHE-LHC

Conclusions (3)

- **Final concluding statements**

  - If the LHC measurements are not sufficient to show the way towards new physics
    - a lepton collider will be necessary
  - For this purpose, LEP3 and TLEP can provide an economical and robust solution
    - To study the H(125) state with high precision
    - To perform outstanding precision measurements of the Z, W, H (top)
    - With higher statistics than a linear collider
    - At more than one interaction point
  - Within our lifetimes