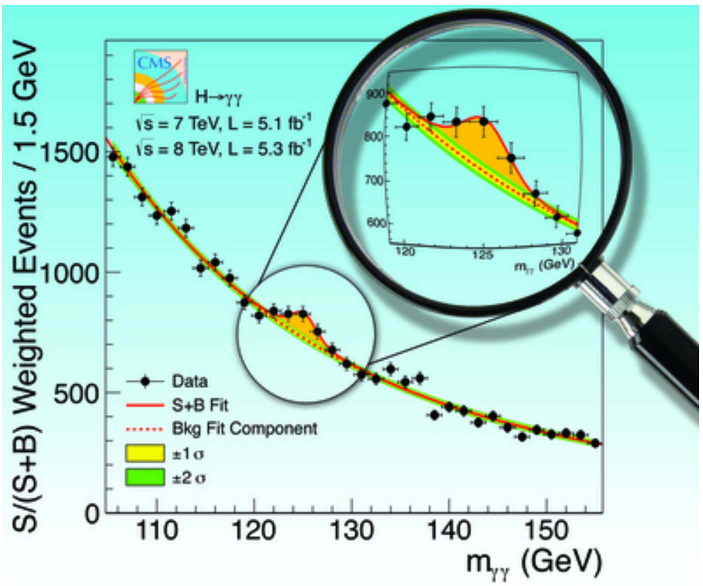
A circular e^+e^- collider to study H(125)?

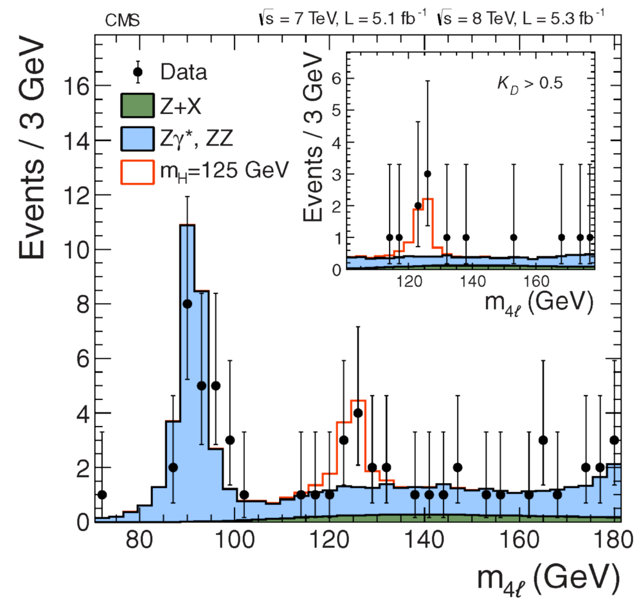
Outline

- Introduction : Strategic Questions
- Circular e^+e^- colliders : LEP3, TLEP
  - What is LEP3 ? What is TLEP ?
  - Why LEP3 ? Why TLEP ?
  - What Physics programme ?
- A CMS primer
  - The CMS performance in a nutshell
    - ➨ With comparison to LC detector proposals
- LEP3 and TLEP as a Higgs Factory with the CMS detector
- Conclusions

Introduction : Strategic Questions (1)

- **We have it !**



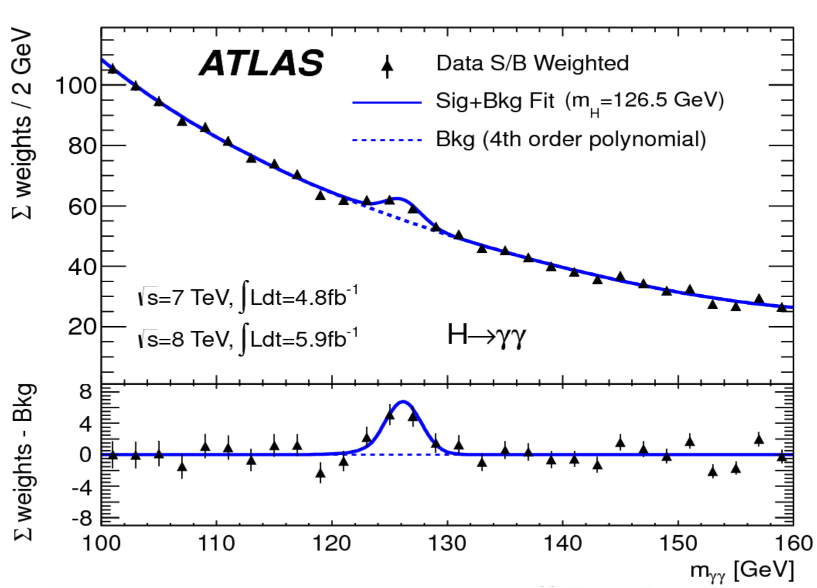


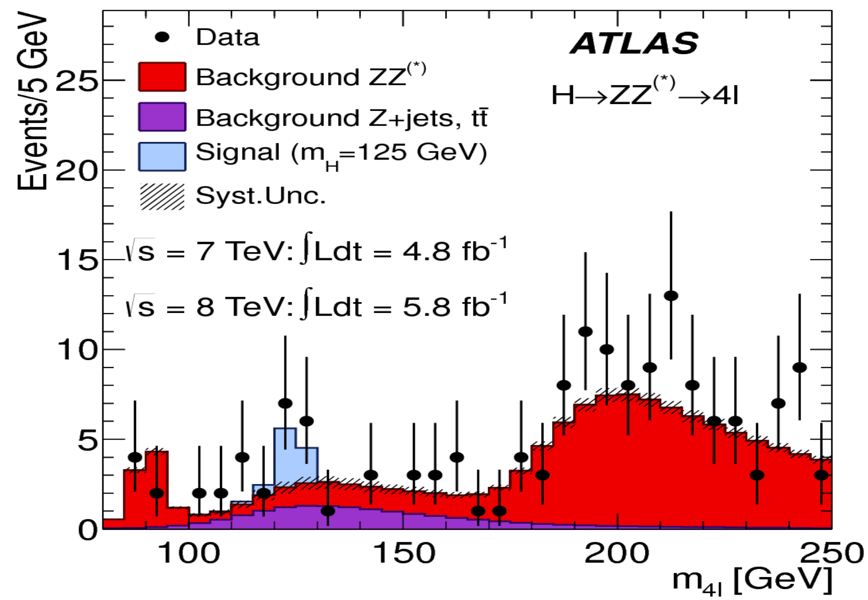
- **New state, with Higgs-like properties, and m_H = 125.3 ± 0.6 GeV/c²**
  - **We are now entering the precision measurement era**
    - **Need to characterize the new state**
    - **Need to characterize the (tree-level) structure of the theory**
    - **Need to evaluate (new physics) loop-induced effects**

      S, T, U ($\varepsilon_1,\varepsilon_2,\varepsilon_3$) parameterization ?

Introduction : Strategic Questions (1)

- **We have it !**





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      S, T, U (ε_1,ε_2,ε_3) parameterization ?

Introduction : Strategic Questions (2)

Shopping list

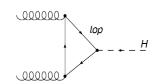
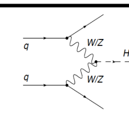
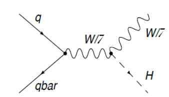
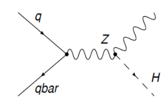
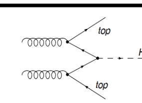
- Higgs branching ratios (and related couplings) measured with % precision or better
- Measurement of the Higgs coupling to the top quark
- Higgs quantum numbers determination
- Higgs mass precision measurement
- Higgs boson self coupling (triple and quartic)
- Total Higgs decay width
- Invisible Higgs decays, Exotic Higgs decays
- Precision electroweak measurements (tests of EW symmetry breaking)
- Precision mass measurements (W, Z, top, …) and relation with Higgs couplings
- Parameterization of new physics

- You name it …

  - Some of these items known to be difficult at the LHC
    - ➨ Especially towards the end of the list

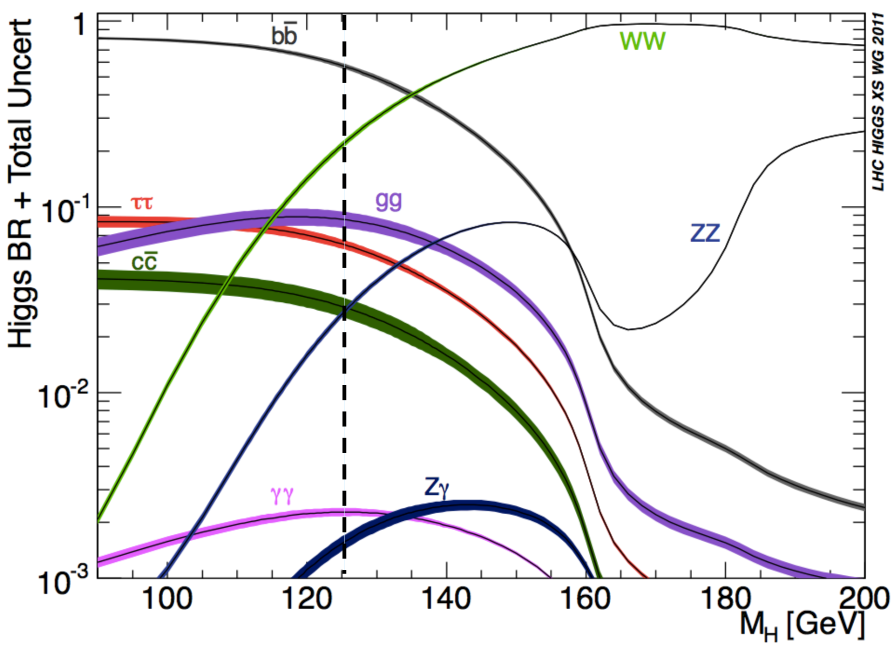
Introduction : Strategic Questions (3)

- **Strategic Question #1**
  - Can the LHC measure H(125) with enough precision, and answer enough questions ?
    - Or do we need a complementary machine ?
  - The LHC is a Higgs Factory !
    - Total cross section : 22 pb
      - ➨ 1M Higgs already produced
      - ➨ 15 Higgs bosons / minute
    - Five different production modes
      - ➨ Many couplings testable

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

  - Do we really need another machine?

- **Strategic Question #1 (cont'd)**
  - **Many decay channels are open, with sizeable branching fractions**



m_H = 125 GeV

Decay	BR [%]	Unc. [%]
bb	57.7	3.3
$\tau\tau$	6.32	5.7
cc	2.91	12.2
$\mu\mu$	0.022	6.0
WW	21.5	4.3
gg	8.57	10.2
ZZ	2.64	4.3
$\gamma\gamma$	0.23	5.0
$Z\gamma$	0.15	9.0
Γ_H [MeV]	4.07	4.0

- **125 GeV/c² is a very good place to be**
  - ➨ **Product of all (SM) branching fractions is maximal**

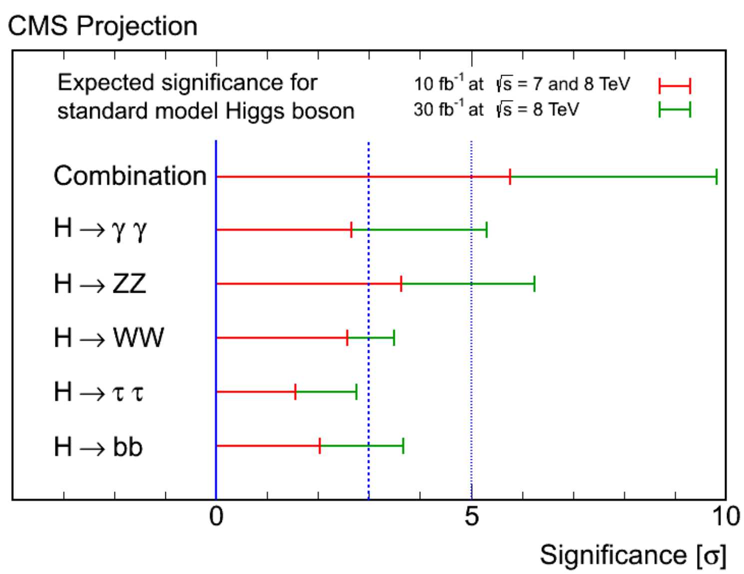
Introduction : Strategic Question (5)

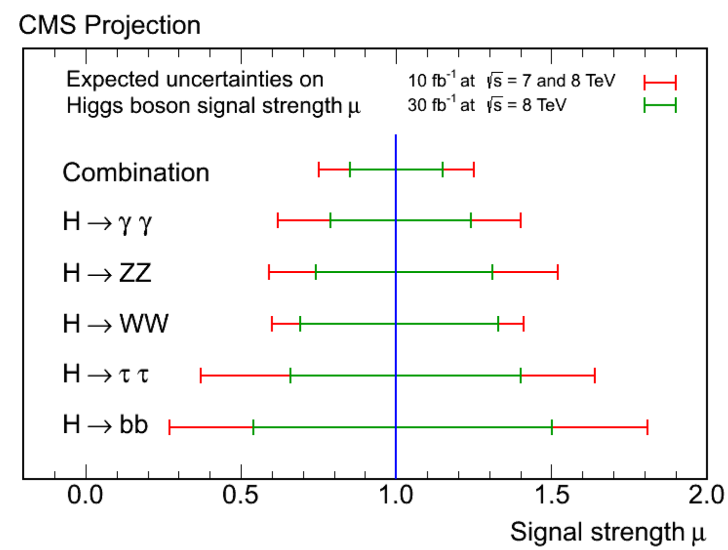
- **Strategic Question #1 (cont'd)**
  - But signal are buried under enormous background
    - Only a small fraction of the Higgs bosons are useful
      - ➨ Limited statistical power, large systematic uncertainties

Channel	Mass range [GeV]	Lumi'11 [1/fb]	Lumi'12 [1/fb]	Topologies	gF	VBF	WH &ZH	ttH
H → γγ	110-150	5.1	5.3	incl. + VBF	☺	☺	-	-
H → ττ	110-145	4.9	5.0	0/1 jet + VBF + WH + ZH	☺	☺	☺	-
H → bb	110-135	5.0	5.0	WH + ZH + ttH	-	-	☺	☺
H → ZZ → 4l	110-600	5.1	5.3	inclusive	☺	-	-	-
H → WW → 2l2v	110-600	4.9	5.3	0/1 jet + VBF + WH + ZH	☺	☺	☺	-
H → ZZ → 2l2v	200-600	5.0	5.0	0/1 jet + VBF	☺	☺	-	-
H → ZZ → 2l2q	130-600	4.9	-	0/1/2 b-tags	☺	-	-	-
H → WW → lvqq	240-600	4.9	5.1	inclusive	☺	-	-	-

Introduction : Strategic Question (6)

- **Strategic Question #1 (cont'd)**
  - **Decay modes : Projecting CMS results for 2012**
    - **Expect > 3σ in many channels, but moderate accuracy on signal strength**

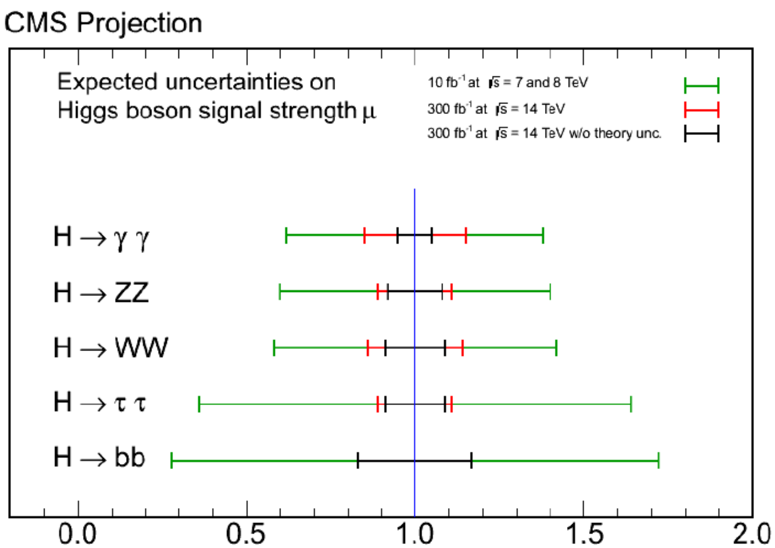


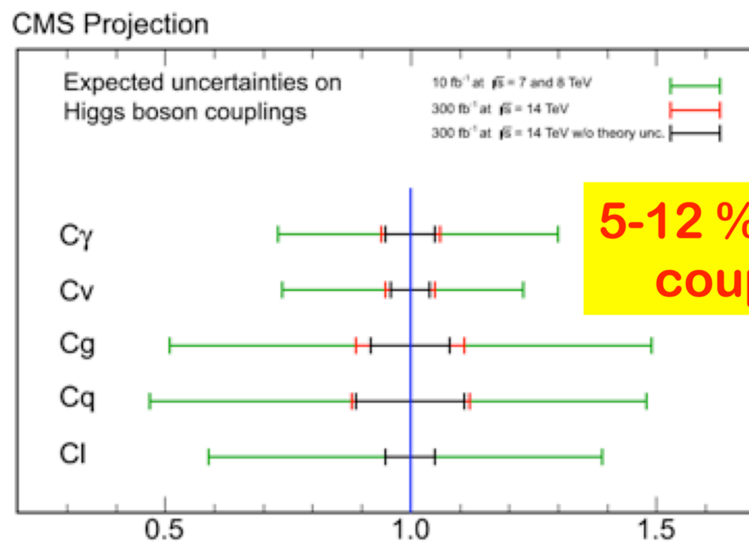


➨ **... or challenge the standard model if a decay is not seen**

Introduction : Strategic Questions (7)

- **Strategic Question #1 (cont'd)**
  - **Projecting results with 300 fb^{-1} at 13 TeV**





5-12 % unc. on couplings

(See Giovanni's presentation yesterday)

- **Uncertainty ~5% seems feasible for γγ and ZZ**
  - **Improvement by 20% from 0.3 to 3 ab^{-1} (constant systematic uncertainties)**
  - **Many assumptions and caveats in the projections**

For example, assumes that CMS performance stays the same (not proven)

Introduction : Strategic Questions (8)

- **Strategic Question #2**
  - If one needs a complementary machine, what is this machine ?
    - e^+e^- collider ?
    - Linear or circular ?
    - Muon collider ?
    - $\gamma\gamma$ collider ?
  - A $\gamma\gamma$ collider has probably the worst physics prospects
    - Large $\gamma\gamma$ backgrounds into fermion and boson pairs
    - Untagged Higgs
  - A $\mu^+\mu^-$ collider is probably the longest term project (if at all feasible)
    - Very good prospects for total Higgs width direct measurement
      - ➨ Through a s-channel scan of the Higgs resonance (a la LEP1)
  - Today's discussion focuses on e^+e^- colliders
    - With a particular emphasis on the new, circular, machine project
      - ➨ And comparison with its linear counterpart

Introduction : Strategic Questions (9)

- **Strategic Question #2 (cont'd)**
  - Physics prospect at linear e^+e^- colliders are good (and studied for decades)
    - Latest reference :

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

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

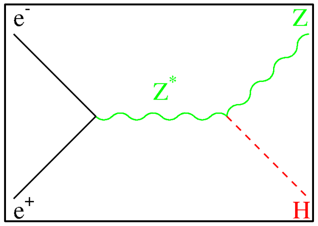
James E. Brau[a], Rohini M. Godbole[b], Francois R. Le Diberder[c], M.A. Thomson[d], Harry Weerts[e], Georg Weiglein[f], James D. Wells[g], Hitoshi Yamamoto[h]

A Report Commissioned by the Linear Collider Community[†]

  - At a given √s and L, the physics case is not driven by the fact that the collider is linear
    - Advantage : e^- polarization is easy at the source
      - Not critical for Higgs study, though
    - Difficulties :
      - Linear Collider known to be very expensive (15 G$, 8G€)
      - Luminosity is difficult to get (nm beam size, etc., remember SLC …)
      - Power hungry (up to 300 MW, even at low energy)
      - Backgrounds and energy smearing from beam disruption (beamstrahlung)
      - One interaction point

Introduction : Strategic Questions (10)

- **Strategic Question #2 (cont'd)**
  - Higgs Physics at an e^+e^- machine
    - At the ZH threshold ($\sqrt{s}$ = 240 GeV)
      - Tagged Higgs
      - Individual branching ratios to the %
      - Invisible and exotic decays
      - Possibly total Higgs decay width



    - At the top threshold ($\sqrt{s}$ = 350 GeV)
      - Measure top quark mass with high precision (input to EWRC)
    - At $\sqrt{s}$ = 500 GeV
      - Measure Htt coupling at 15% with $e^+e^- \rightarrow$ ttH

        Measurable with similar precision at HE/HL-LHC through ttH production
    - At $\sqrt{s}$ = 1 TeV or more
      - Measure HHH coupling to 20% with $e^+e^- \rightarrow$ ZHH

        Measurable at HE/HL-LHC with similar precision with gg $\rightarrow$ HH production
  - The really unique physics seems to be the Higgs factory at the ZH threshold
    - (Plus top physics at the tt threshold would be nice)
      - And maybe at $\sqrt{s} = m_Z, m_W$ for EW precision measurements ?

Introduction : Strategic Questions (10)

- **Strategic Question #2 (cont'd)**
  - Higgs Physics at an e^+e^- machine
    - At the ZH threshold ($\sqrt{s}$ = 240 GeV)
      - Tagged Higgs
      - Individual branching ratios to the %
      - Invisible and exotic decays
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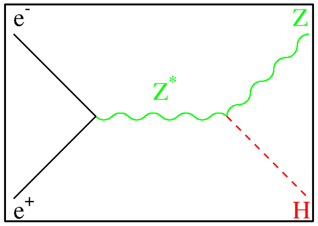
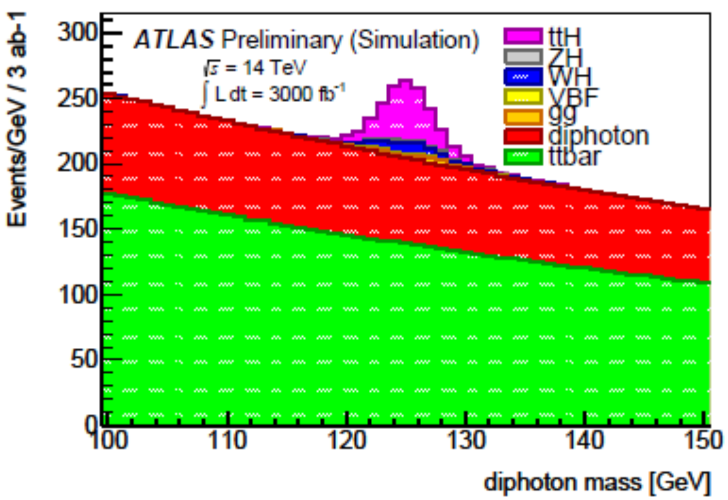
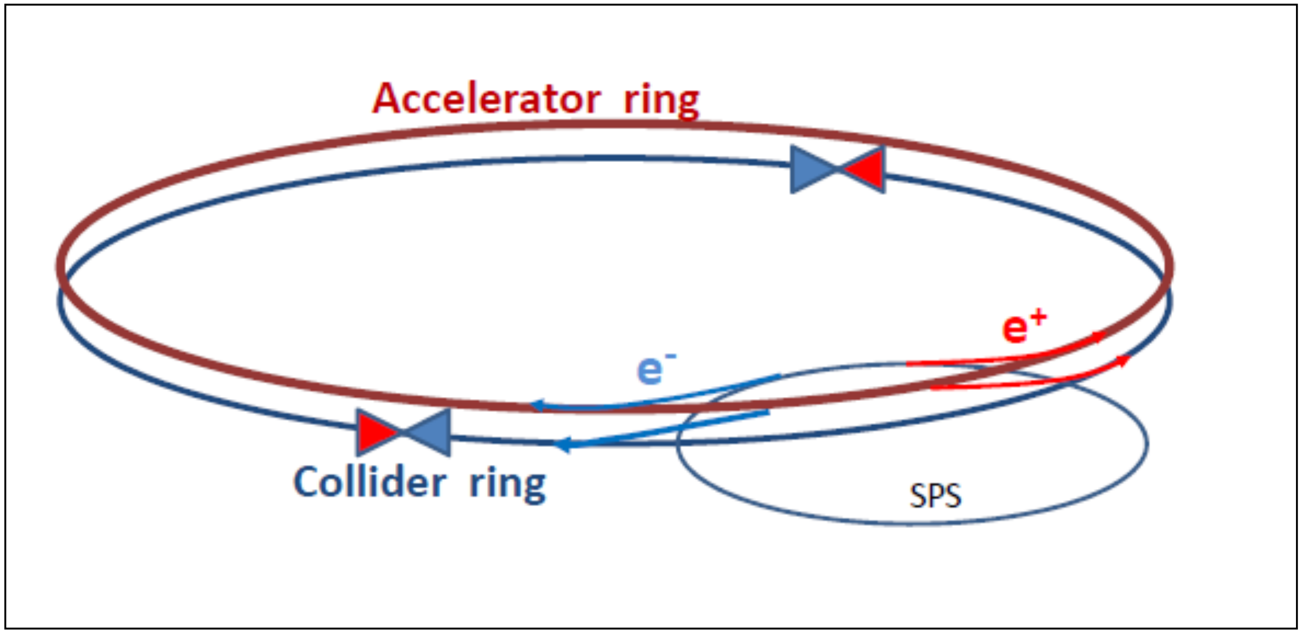




ATLAS @ HL-LHC w/ ttH

Introduction : Strategic Questions (11)

- **Strategic Question #3**
  - What can a circular e+e- collider do for us ?
  - Is it the complementary machine that we need ?



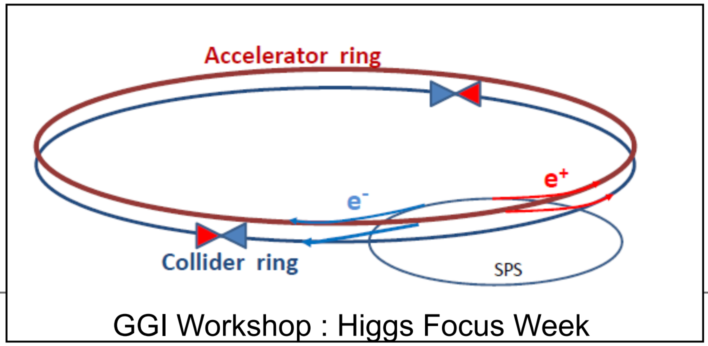
- That's the topic of the next 40 slides
  - ➨ Two options studied : LEP3 (27km), TLEP (80km)

Introduction : Strategic Questions (12)

- **Strategic Question #3 (cont'd)**
  - For the 27km option, let's try to extrapolate from LEP2
    - Reached 209 GeV – we were almost there
    - Luminosity lifetime ~ 3 hours
    - Beam power was 20 MW
    - Instantaneous luminosity was 10^{32} cm^{-2}s^{-1}
    - β^* was 5 cm
    - LEP2 was not at the beam-beam limit
    - RF Frequency was 352 MHz
  - Would need a factor 100 more instantaneous luminosity for a Higgs factory
    - More focussing : β^* = 1mm
      - ➨ LHeC optics design can be used and does the job
    - Shorter bunches
      - ➨ ILC cavities (RF frequency 1.3 GHz) can be used
    - Hence go at the beam-beam limit
      - ➨ And increase the luminosity to 10^{34} cm^{-2}s^{-1}
      - ➨ Similar beam power for the same energy (20MW)

A LEP3 Primer : What is LEP3 ?

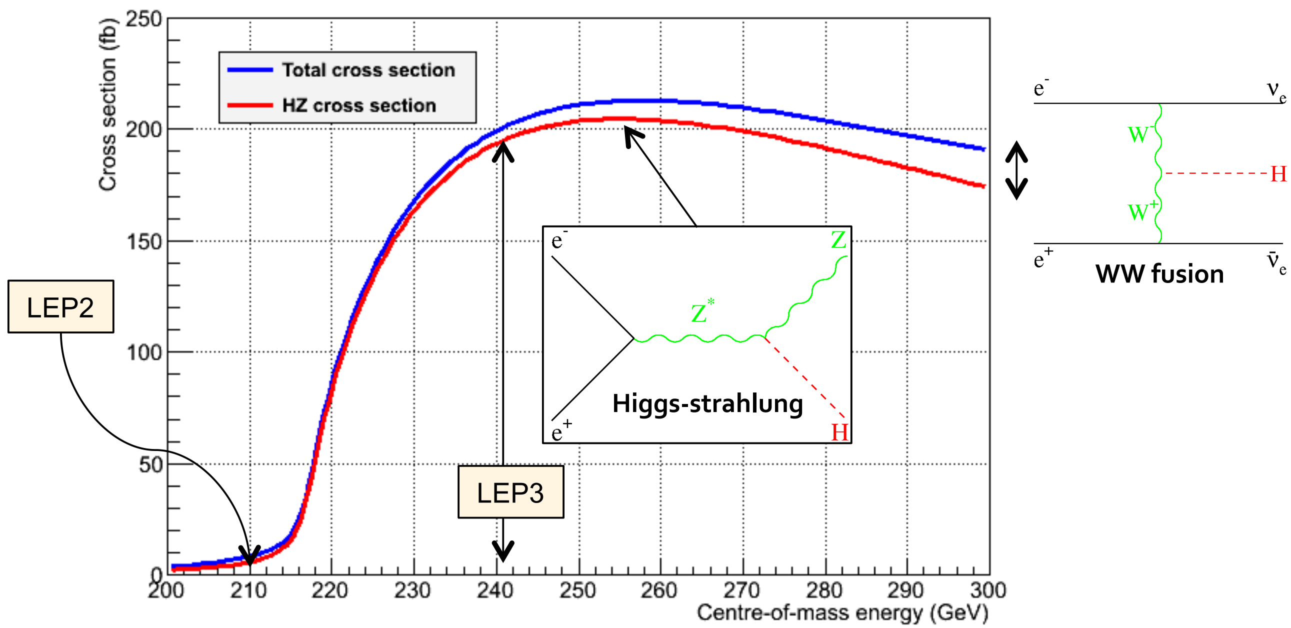
- LEP3 is a proposal for studying the feasibility of a 27 km e^+e^- ring
  - In the LHC tunnel
    - With or without cohabitation with LHC
      - A project with a new, 80 km, tunnel is also studied (TLEP)
  - With a collision energy of up to 240 GeV
    - Collisions at the Z pole and at the WW threshold as well
      - No collisions at the t-tbar threshold with this proposal
  - With an instantaneous luminosity larger than 10^{34} $s^{-1}cm^{-2}$ at the top energy
    - And even larger at smaller energies
    - Delivered to up to four interaction points
      - In particular to ATLAS and CMS
  - With a beam lifetime of o(10 minutes), dominated by Bhabha scattering
    - Requires continuous top-up injection (with a B-factory-like design)



See arXiV:1208.0504

A LEP3 Primer : Why 240 GeV ?

- Because it maximizes the Higgs production cross section



- Maximum is actually at $\sqrt{s}$ = 255 GeV, so why 240 GeV really ?
  - Cross section only 6% smaller
    - σ = 200 fb at 240 GeV -> 20,000 Higgs bosons / year
  - Energy losses (synchrotron radiation in a ring ↗ E^4), hence cost, 40% smaller

A LEP3 Primer : Why a ring ? (1)

- **Argument #1 : Cost of the RF**
  - One-turn losses at 240 GeV amount to 6-7 GeV
    - Compare to 120 GeV losses at a 240 GeV linear collider !
  - Would need only 300-350 ILC-type cavities
    - With a reasonable assumption for the gradient : 20 MV/m
  - Present parameters foresee 580 ILC-type cavities
    - To increase the momentum acceptance (beamstrahlung, see later)
      - ➨ Corresponds to a total length of 818 meters

        To be compared with the 864 m of LEP2
  - Cost of the RF power during operation (50 MW/beam) also reduced
- **Argument #2 : Number of detectors**
  - Present parameters are meant for four interaction points
    - 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 (at least) two linear-collider-type detectors

A LEP3 Primer : Why a ring ? (2)

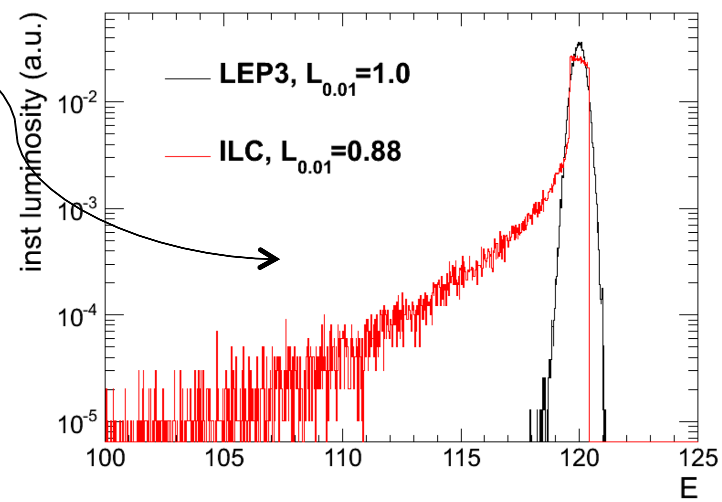
- **Argument #3 : Relaxed beam parameters**
  - Circulating beams with 45 kHz repetition rate (in the 4x4 bunches configuration)
    - To be compared to 5 Hz in ILC and 50 Hz in CLIC
  - Can relax beam dimensions for the same or larger instantaneous luminosity
    - e.g., vertical beam size :
      - CLIC : 1 nm; ILC : 5 nm; LEP3 : 320 nm;
    - Consequence #1 : negligible beamstrahlung effects [for physics]
      - ~100% of the collisions are within 1% of the nominal beam energy

        cf. 88% for ILC
      - Beam energy spread ~0.1%

        cf. ~2% for ISR
    - Consequence #2 : negligible PU rate
      - $\sigma_{\gamma\gamma \to hadrons}$ = 15 nb @ 240 GeV
      - Rate of 150 Hz @ 10^{34} $cm^{-2}s^{-1}$
      - PU probability ~0.3%

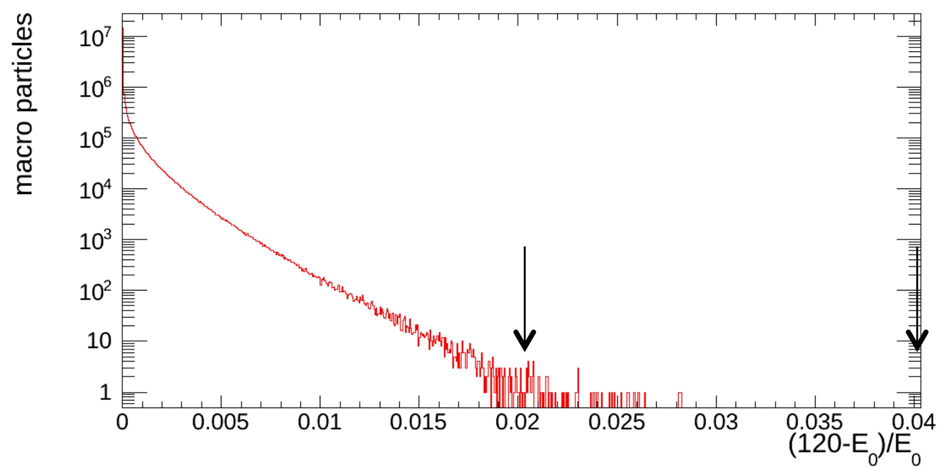
        cf. 4 events / pulse in CLIC

        cf. 2-3 events / bunch in ILC
    - Consequence #3 : negligible backgrounds from beam disruption.



A LEP3 Primer : Why a ring ? (3)

- Digression : Beamstrahlung
  - Beamstrahlung spectrum has tails :



  - With 45 kHz repetition rate, these tails lead to large accumulated beam losses
    - Hence a beam lifetime decreasing exponentially with energy acceptance
      - ➨ Losses will be large with a 2% energy acceptance

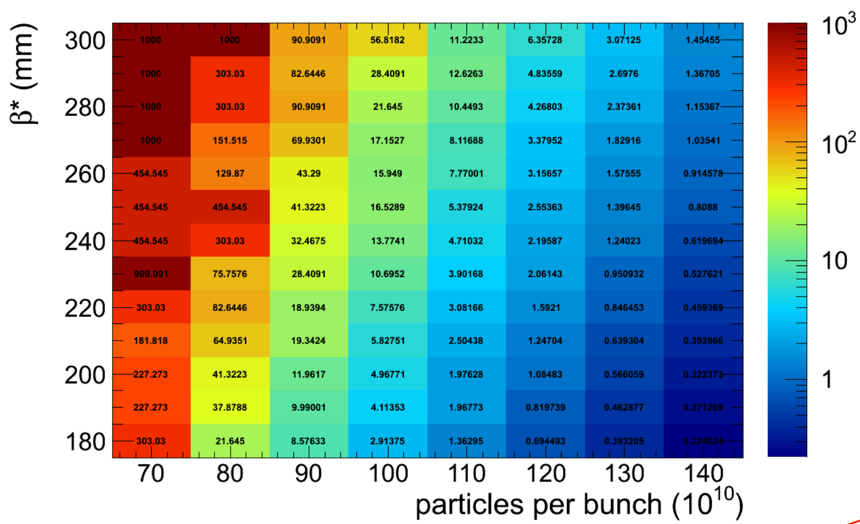
        About 1% of the beam lost every second
      - ➨ May be acceptable with a 4% energy acceptance

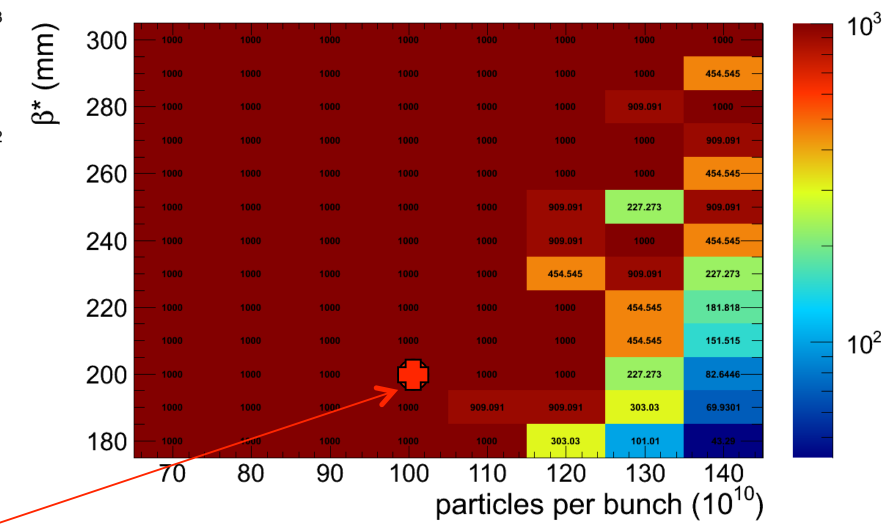
        The latter requires more RF accelerating gradient

        (hence the 580 cavities for a very comfortable margin)

A LEP3 Primer : Why a ring ? (4)

- **Digression : Beamstrahlung (cont'd)**
  - Guinea-pig simulation: lifetime (sec) vs β_x^* (mm) and number of particle per bunch
    - With 2% energy acceptance
    - With 4% energy acceptance





- LEP3 current parameters for a lifetime ~ 16 minutes a L = $10^{34}cm^{-2}s^{-1}$
  - β_x^* = 0.2 m
  - # particles / bunch = 10^{12}

A LEP3 Primer : Why a ring ? (5)

- **Argument #4 : Collider rings have historically delivered**
  - According to design, and often exceeding it
    - See most recent examples : LEP1, LEP2, PEP2, KEKB
  - Current design parameters for LEP3 give 1.1 x 10^{34} $cm^{-2}s^{-1}$ at 240 GeV
    - It is a factor 2 larger than the ILC luminosity 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

        See e.g., https://indico.cern.ch/conferenceDisplay.py?confId=193791
  - Possible timescale for LEP3
    - Conceptual design report at the end of 2014
    - If the case is still present, technical design report in 2019-2020
      - ➨ Decision to go ahead during LS2 (2017)
    - If the case is still present, installation starts at LS3 (2022)
      - ➨ LEP took 18 months to install
    - Physics could start around 2024, for 10 years (see physics programme next slides)
      - ➨ Fits well with the possibility of HE-LHC

        High-field magnets could be ready by 2032-2035

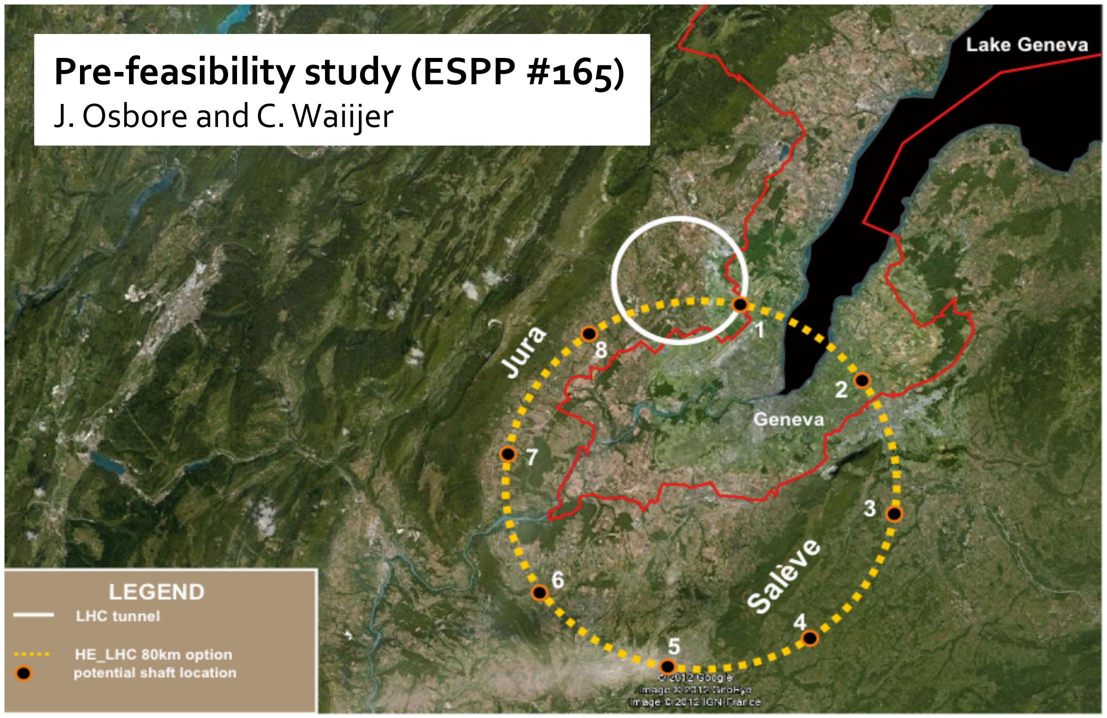
A LEP3 Primer : Why the LHC tunnel ?

- **Cost ! Cost ! Cost !**
  - For example :
    - The tunnel, the cooling infrastructure, the injectors, etc., exist
    - Two multi-purpose detectors (CMS/ATLAS) can be re-used
      - ➨ See later for the expected performance in e^+e^- collisions
  - Could build LEP3 for a canonical 1 billion $ (or CHF)
    - Factor ~10 smaller than a linear collider
  - Expect 100,000 Higgs bosons / detector over a period of 5 years
    - 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$, but twice more Higgs bosons to analyse
    - Basic investment in the ILC configuration : ~200 k$ / Higgs boson
      - ➨ 40 times more expensive than LEP3
    - Basic investment in the LHC configuration : ~50 k$ / detected Higgs boson
  - An interesting opportunity for Europe, for CERN … and for the LHC/ILC Collaborations

(Even if they don't fully realize it as we speak)

A TLEP Primer : What is TLEP ?

- **A long-term vision …**
  - A 80km tunnel around Geneva could be fit avoiding Jura, Saleve, Vuache



  - Could host a 350 GeV e+e- collider as a first step
    - Called TLEP

A TLEP Primer : Why TLEP ?

- **Three main physics arguments**
  - Reaches $\sqrt{s}$ = 350 GeV (top threshold) with L = 6.10^{33} $cm^{-2}s^{-1}$, same RF as LEP3
    - To measure the top mass precisely
    - To put precise constraints on α_s
    - To look for rare top decays
  - 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
      - ➨ Hence potentially more precise Higgs coupling measurements
      - ➨ With 2 or 4 detectors, up to 40 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 ?**
  - Tunnel and Collider would be the largest contributors : say 5 + 3 B$
  - Detectors would be next : say 2B$ for four detectors
  - Still less expensive than a linear collider, and tunnel can be re-used
    - Individual Higgs cost over a five-year period : ~ 5 k$ / Higgs boson

Parameter Table for LEP3 and TLEP

	LEP2	LHeC	LEP3	TLEP-Z	TLEP-H	TLEP-t
beam energy E_b [GeV]	104.5	60	120	45.5	120	175
circumference [km]	26.7	26.7	26.7	80	80	80
beam current [mA]	4	100	7.2	1180	24.3	5.4
#bunches/beam	4	2808	4	2625	80	12
#e–/beam [10^{12}]	2.3	56	4.0	2000	40.5	9.0
horizontal emittance [nm]	48	5	25	30.8	9.4	20
vertical emittance [nm]	0.25	2.5	0.10	0.15	0.05	0.1
bending radius [km]	3.1	2.6	2.6	9.0	9.0	9.0
partition number J_ε	1.1	1.5	1.5	1.0	1.0	1.0
momentum comp. α_c [10^{-5}]	18.5	8.1	8.1	9.0	1.0	1.0
SR power/beam [MW]	11	44	50	50	50	50
β^*_x [m]	1.5	0.18	0.2	0.2	0.2	0.2
β^*_y [cm]	5	10	0.1	0.1	0.1	0.1
σ^*_x [μm]	270	30	71	78	43	63
σ^*_y [μm]	3.5	16	0.32	0.39	0.22	0.32
hourglass F_{hg}	0.98	0.99	0.67	0.71	0.75	0.65
ΔE^{SR}_{loss}/turn [GeV]	3.41	0.44	6.99	0.04	2.1	9.3

Parameter Table for LEP3 and TLEP

	LEP2	LHeC	LEP3	TLEP-Z	TLEP-H	TLEP-t
$V_{RF,tot}$ [GV]	3.64	0.5	12.0	2.0	6.0	12.0
$\delta_{max,RF}$ [%]	0.77	0.66	4.2	4.0	9.4	4.9
ξ_x/IP	0.025	N/A	0.09	0.12	0.10	0.05
ξ_y/IP	0.065	N/A	0.08	0.12	0.10	0.05
f_s [kHz]	1.6	0.65	3.91	1.29	0.44	0.43
E_{acc} [MV/m]	7.5	11.9	20	20	20	20
eff. RF length [m]	485	42	600	100	300	600
f_{RF} [MHz]	352	721	1300	700	700	700
δ^{SR}_{rms} [%]	0.22	0.12	0.23	0.06	0.15	0.22
$\sigma^{SR}_{z,rms}$ [cm]	1.61	0.69	0.23	0.19	0.17	0.25
L/IP[10^{32}cm^{-2}s^{-1}]	1.25	N/A	107	10335	490	65
number of IPs	4	1	2	2	2	2
Rad.Bhabha b.lifetime [min]	360	N/A	16	74	32	54
Υ_{BS} [10^{-4}]	0.2	0.05	10	4	15	15
n_γ/collision	0.08	0.16	0.60	0.41	0.50	0.51
$\Delta\delta^{BS}$/collision [MeV]	0.1	0.02	33	3.6	42	61
$\Delta\delta^{BS}_{rms}$/collision [MeV]	0.3	0.07	48	6.2	65	95

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	Background	σ (pb)	Events	Rate (Hz)
$H \to b\bar{b}$	57.9	57,870	$e^+e^- \to Z^*/\gamma^* \to q\bar{q}$	50	25,000,000	0.50
$H \to W^+W^-$	21.6	21,630	$e^+e^- \to Z^*/\gamma^* \to \ell^+\ell^-$	12.5	6,250,000	0.12
$H \to gg$	8.19	8,200	$e^+e^- \to W^+W^-$	16	8,000,000	0.16
$H \to \tau^+\tau^-$	6.40	6,400	$e^+e^- \to ZZ$	1.3	650,000	0.01
$H \to c\bar{c}$	2.83	2,820	$e^+e^- \to We\nu$	1.35	700,000	0.01
$H \to ZZ$	2.62	2,620	$e^+e^- \to Ze^+e^-$	3.8	1,900,000	0.04
$H \to \gamma\gamma$	0.27	266	$e^+e^- \to Z\nu\bar{\nu}$	0.032	16,000	–
$H \to Z\gamma$	0.16	160	$e^+e^- \to e^+e^-$ (Bhabha)	5,000	$2.5\,10^9$	50
$H \to \mu^+\mu^-$	0.02	22	$\gamma\gamma \to \ell^+\ell^-, q\bar{q}$	15,000	$7.5\,10^9$	150

➨ Precise measurement of the e^+e^- → HZ cross section

Integrated lumi measured with Bhabha scattering to better than 0.1%

(cross section indicated for at least one electron above 5^o off the beam axis)

➨ Precise measurement of most branching fractions

Hence of couplings to fermions and gauge bosons

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 precise 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 Zγ 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 → 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
  - Interesting observation : Event rate
    - Z decays + Bhabha events (1^o) + $\gamma\gamma$ collisions add up to a rate of 25 kHz
      - CMS high-level trigger currently collects events at a rate of 1kHz

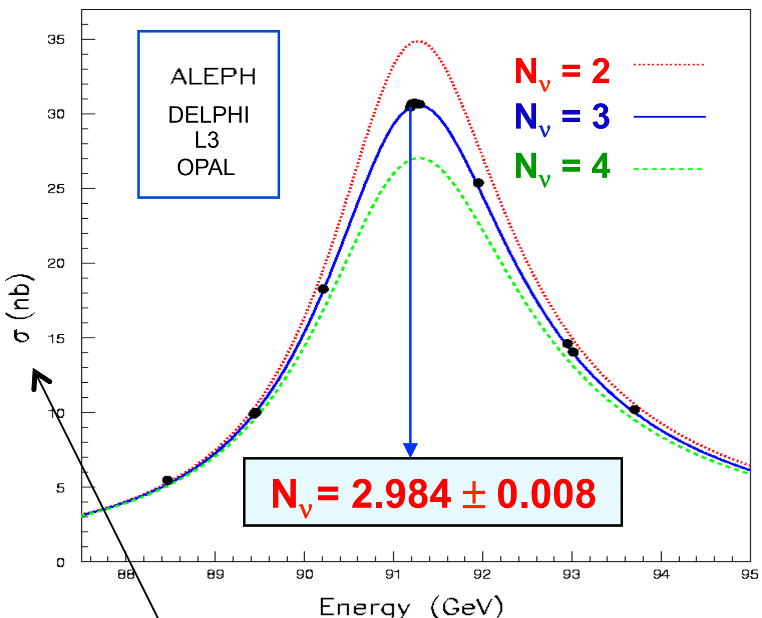
        A factor 25 to find ?
      - Luckily, CMS events at LHC are big and slow to process

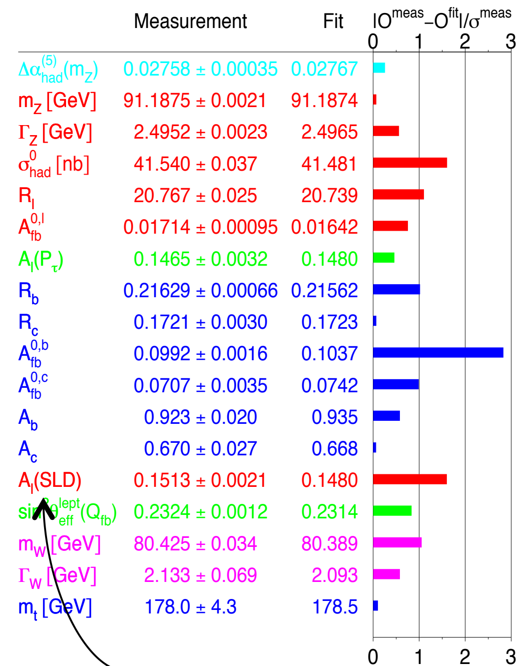
        Especially with 30-40 PU events

        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 : Requires 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 focussing quadrupoles
      - ➨ No specific study done for LEP3

        Negligible beamstrahlung is an 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
    - Polarization was lost in collision because of design flaws
      - ➨ Should be possible to maintain it with some care in the design
      - ➨ No specific study done for LEP3 yet
  - Polarization in situ measurement, together with A_{LR}
    - Scheme with alternate polarized and unpolarized bunches exists

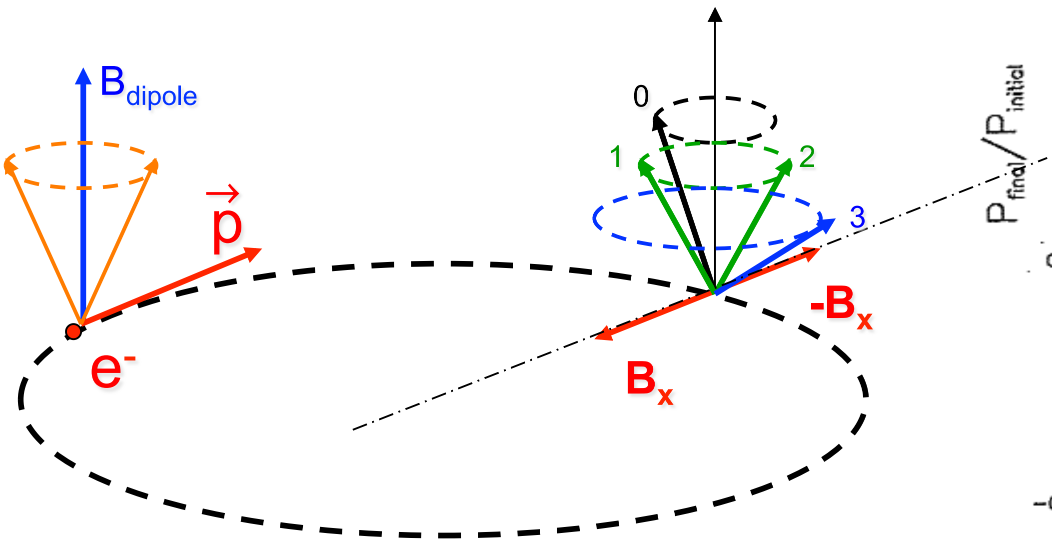
      A. Blondel, Phys.Lett. B202 (1988) 145, Erratum-ibid. 208 (1988) 531

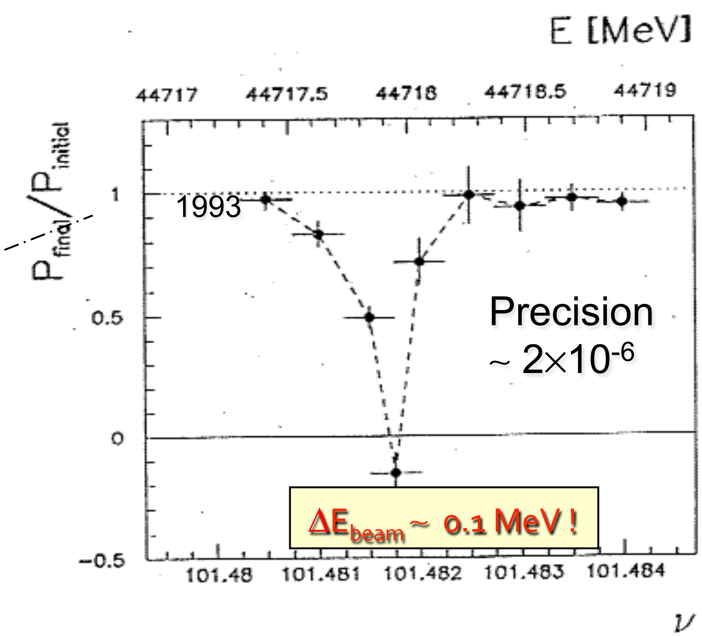
      "A scheme to measure the polarization at the Z pole at LEP"

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 !





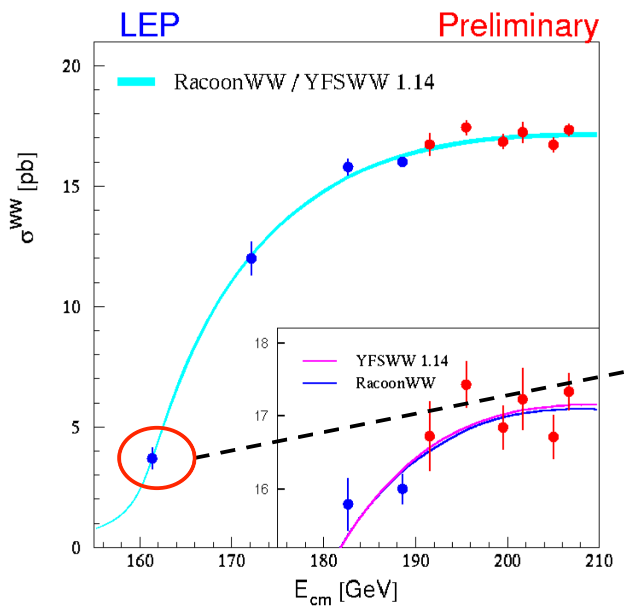
➨ **Ultimate precision better than 0.1 MeV**

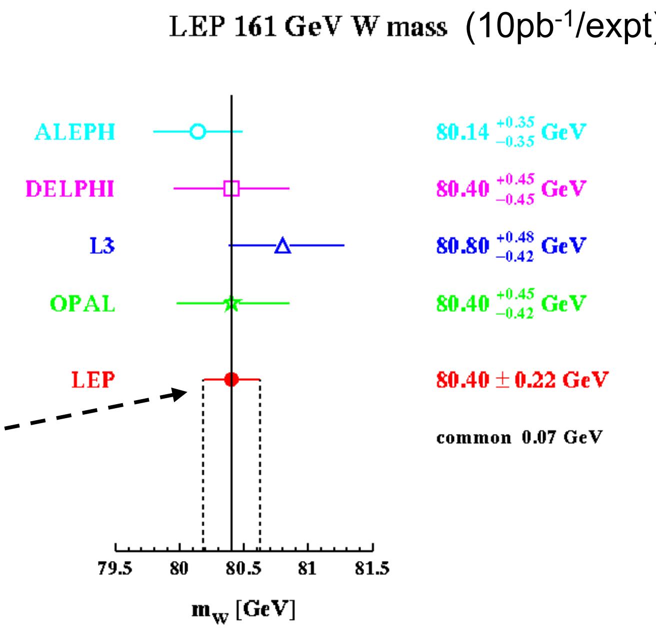
Measure Γ_Z to better than 0.1 MeV

(limited to 2 MeV @ LEP1: tidesl; 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

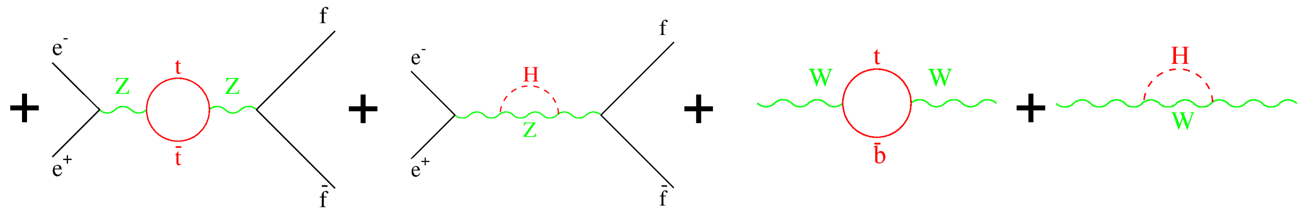
- With 10^{35} cm^{-2}s^{-1}, i.e., 1 ab^{-1} in a year (10^5 times larger data sample)
  - Δm_W reduced to 0.7 MeV per experiment (stat. only)
    - ➨ Grand combination with 240 GeV leads to a precision of 300 keV on m_W

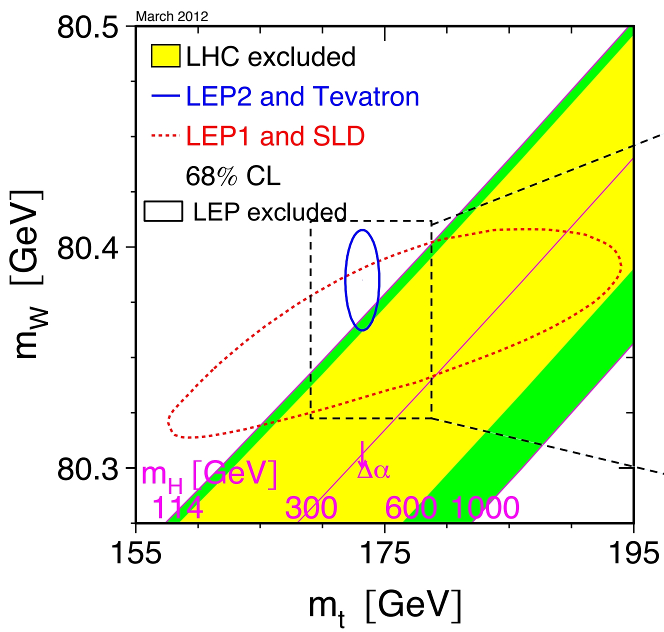
Note : Resonant depolarization needs to be operational at E_{beam} ~ 80 GeV

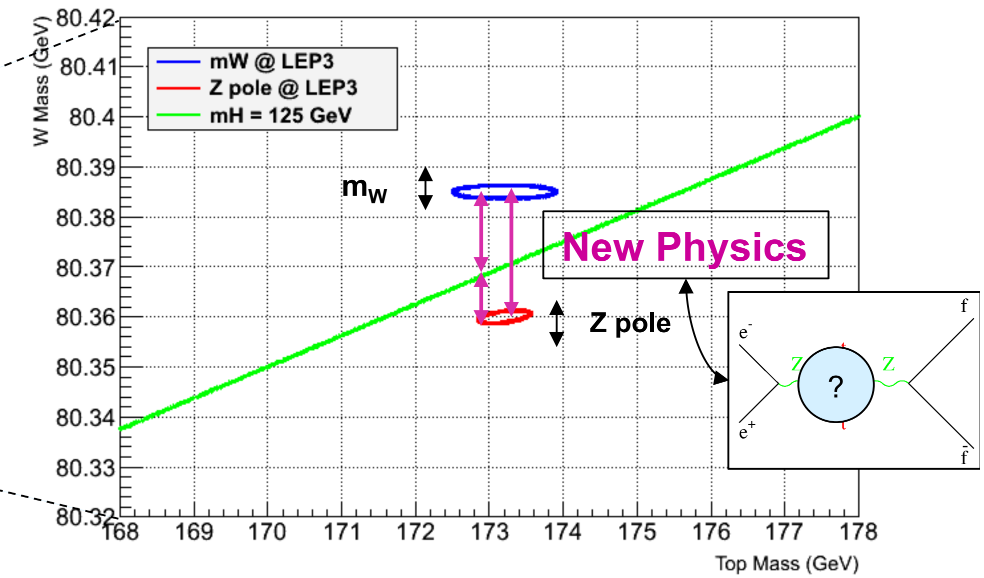
The LEP3 Physics Programme (8)

- **Opens a whole new book in EWSB precision measurements:**

$$m_W = m_Z \cos\theta_W + \ldots$$





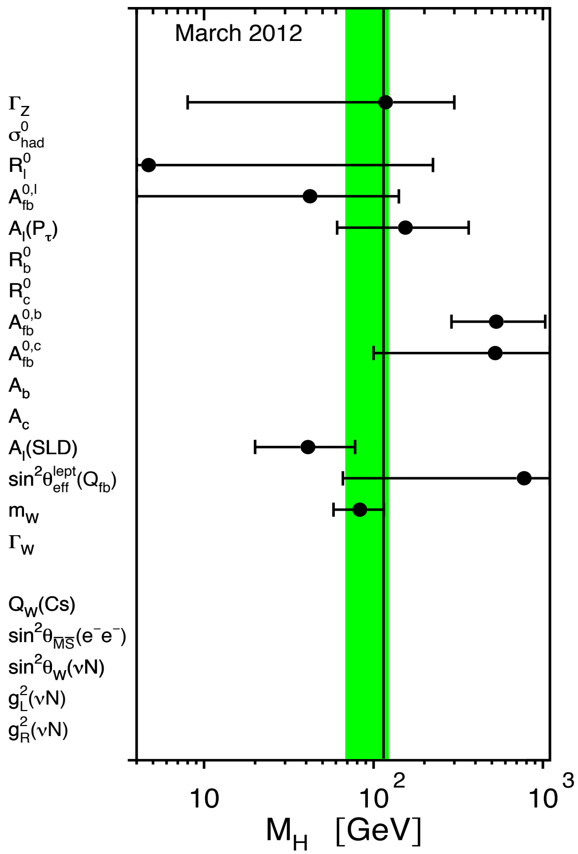


- **March 2012 (Moriond)**

After LHC + LEP3 (conservative)

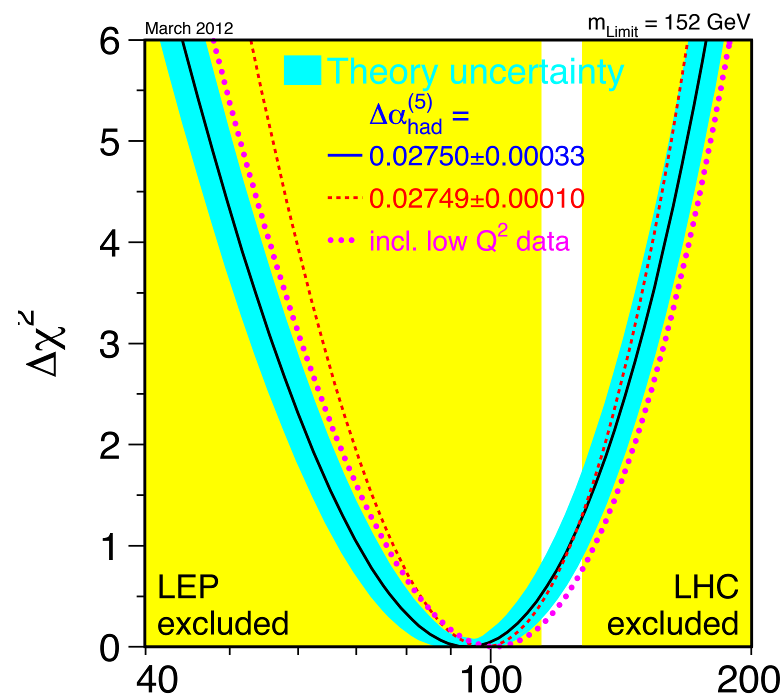
1 MeV for m_W, factor 25 at the Z pole (+500 MeV for m_{top})

- Will pave the way towards future facilities at the energy frontier
  - Many other projections can help on this way
    - For example :



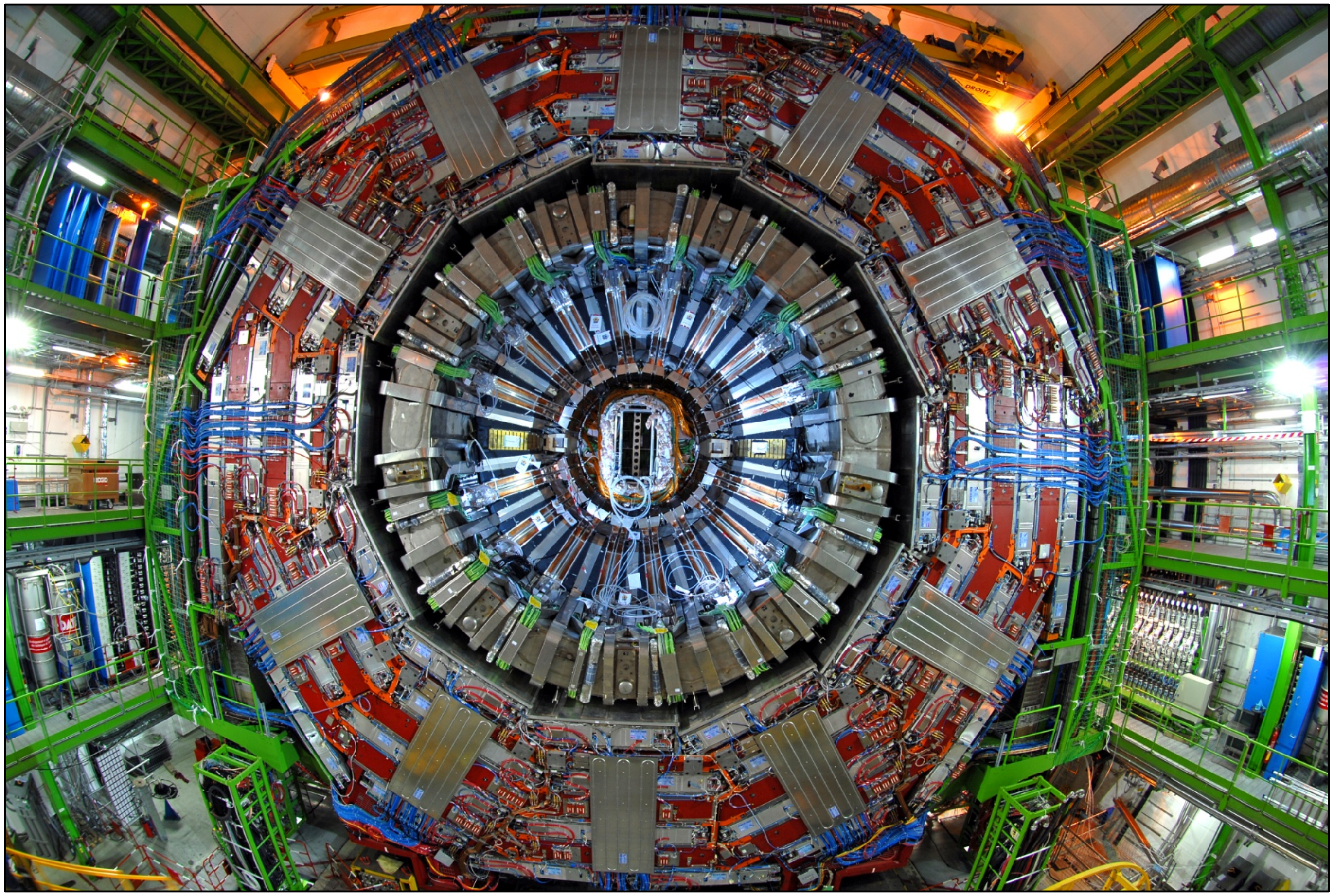
$$m_H = 94^{+29}_{-24}\ \text{GeV}/c^2$$

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



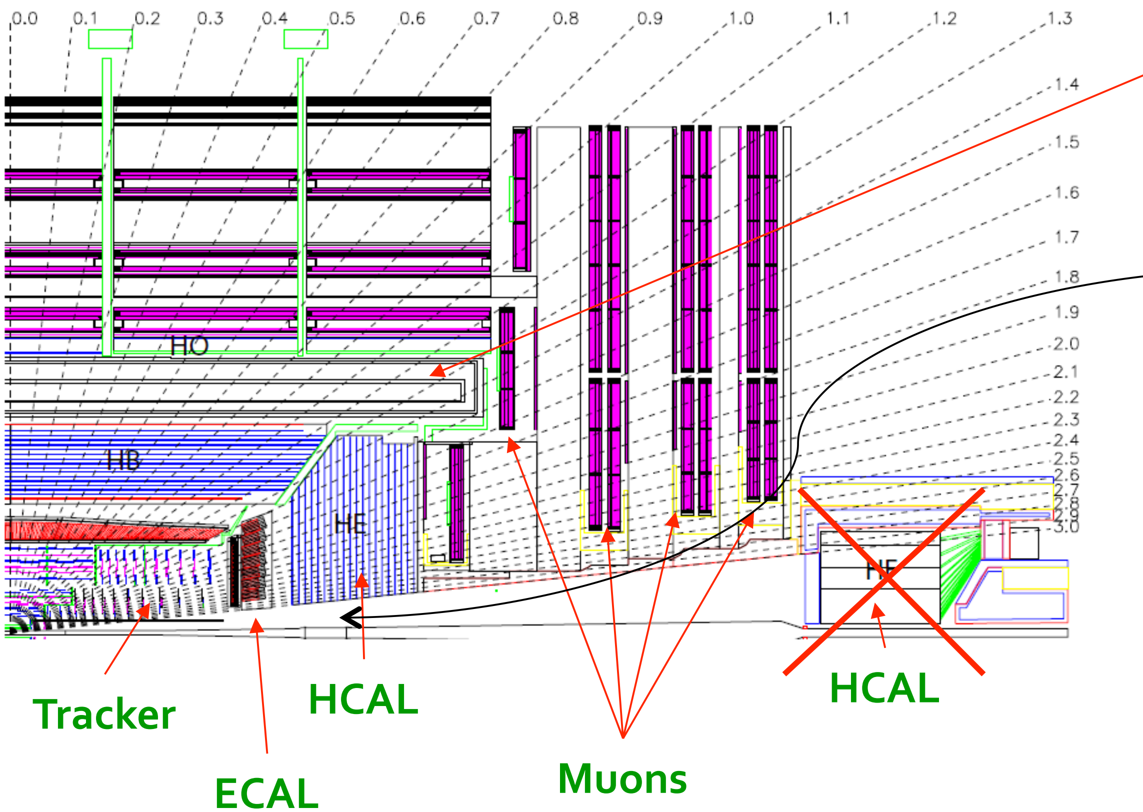
The CMS Detector And Performance

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

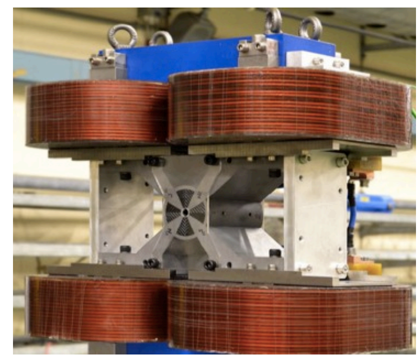


The CMS Detector

- Longitudinal view



LEP3 needs focusing quadrupoles at ±4m

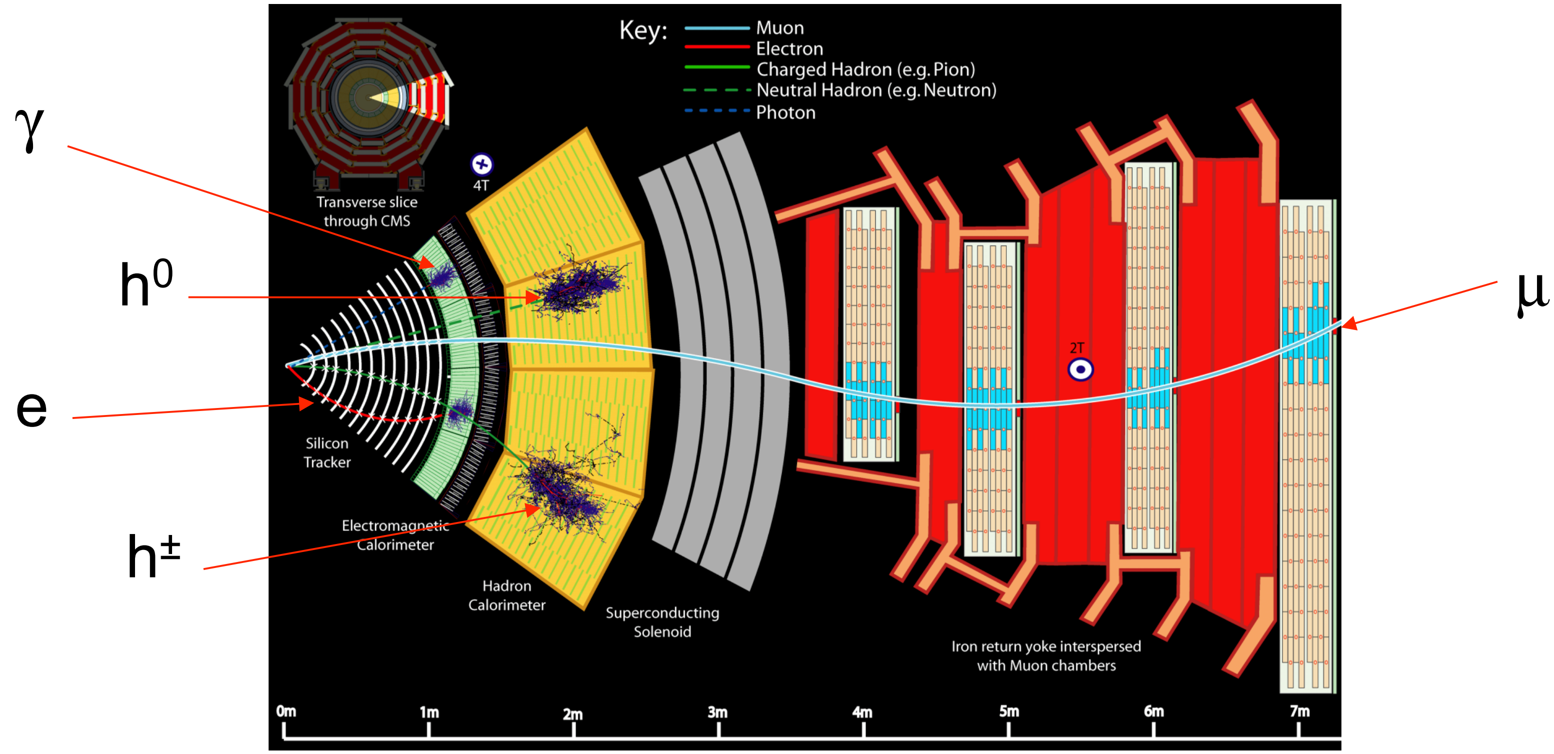


Very small CLIC prototypes exist and would fit !

- **Next challenge : Accelerator beam pass-through !**
  - **Or common beam pipe + different RF buckets ? Or a bypass ?**

The CMS Particle Detection

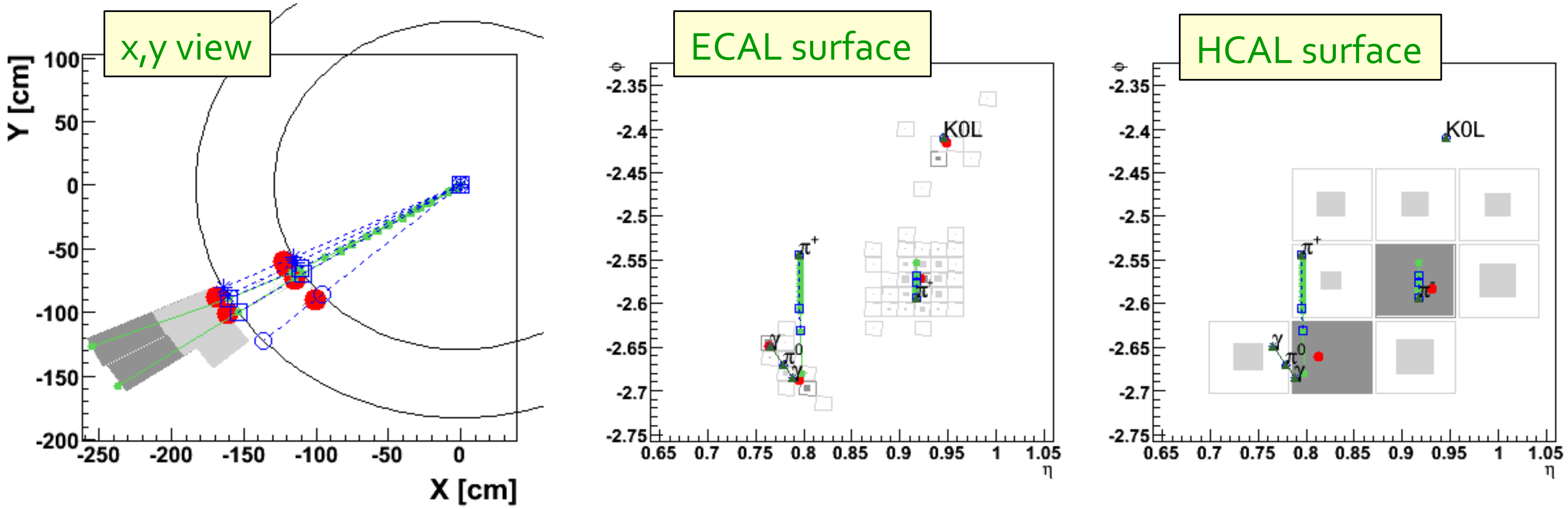
- An octant in the transverse view



- 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)

The CMS Particle Flow Reconstruction

- **Example of a simple jet with p_T ~ 50 GeV/c (full simulation)**
  - **Particle content : π^+, π^-, π^0 and K^0_L**

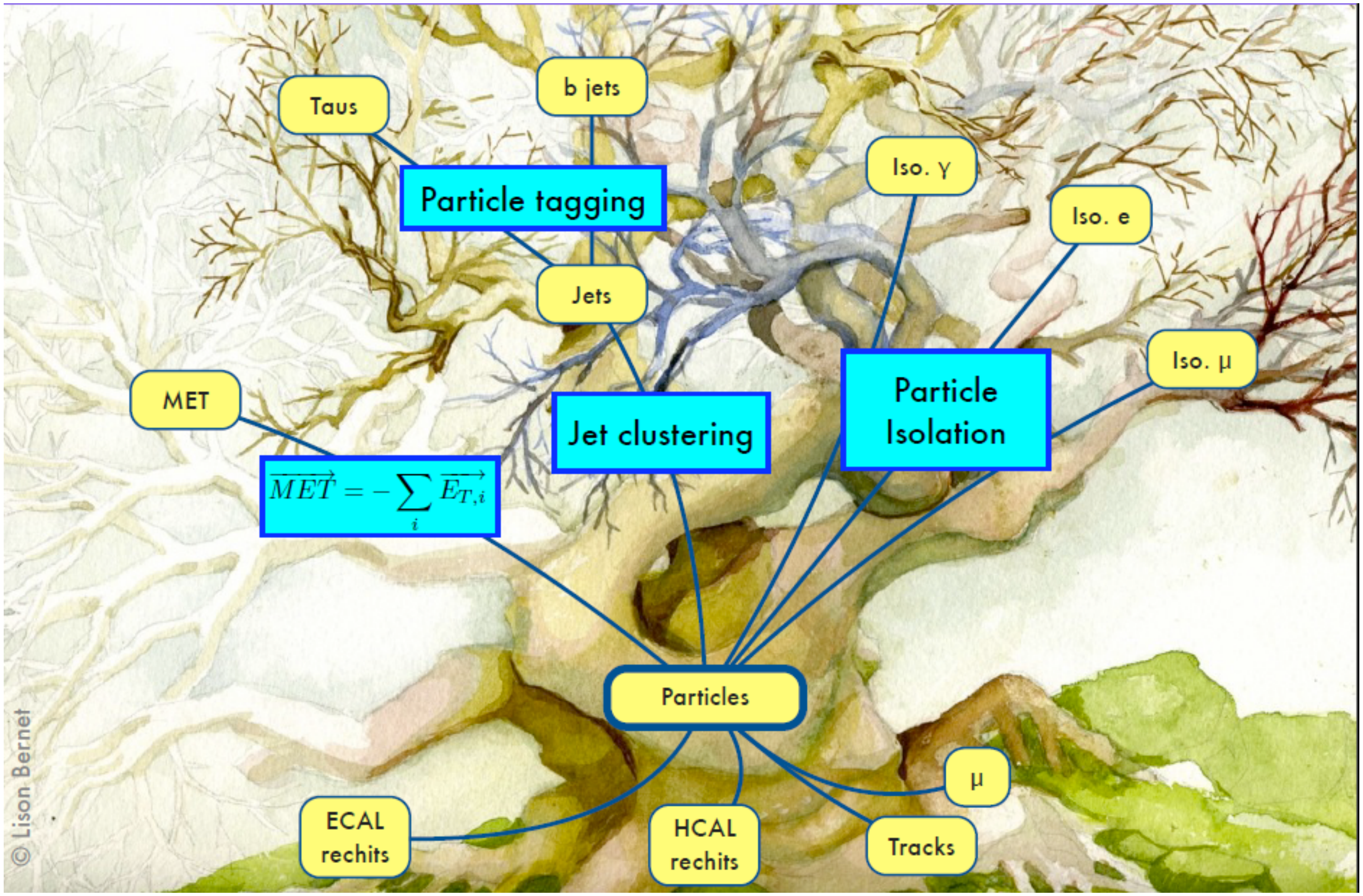


- **Clustering in calorimeters finds all three hadrons, and the two photons from the π^0**
- **Track-Cluster link associates the tracks to the right cluster(s)**
- **Check calorimeter energy excess for neutral hadrons**
  - **Reconstructed particle content : $\pi^+, \pi^-, \gamma, \gamma$ (from the π^0) and γ**

(Here, the K^0_L made it to a photon, no HCAL cluster associated…)

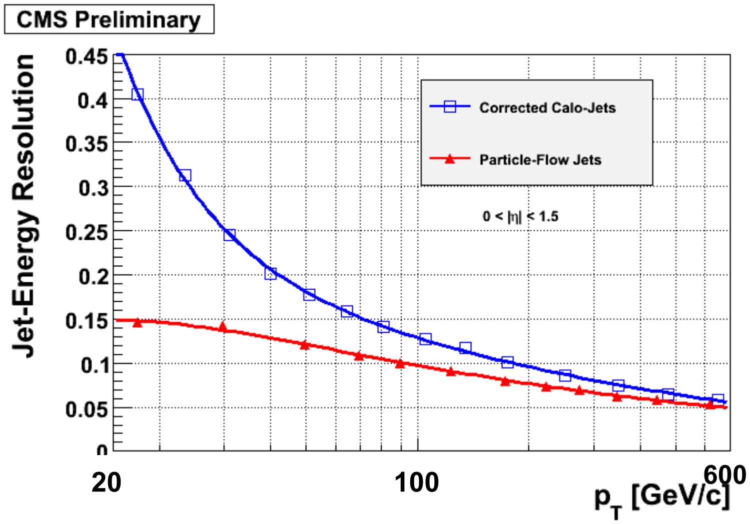
The CMS Particle Flow Reconstruction

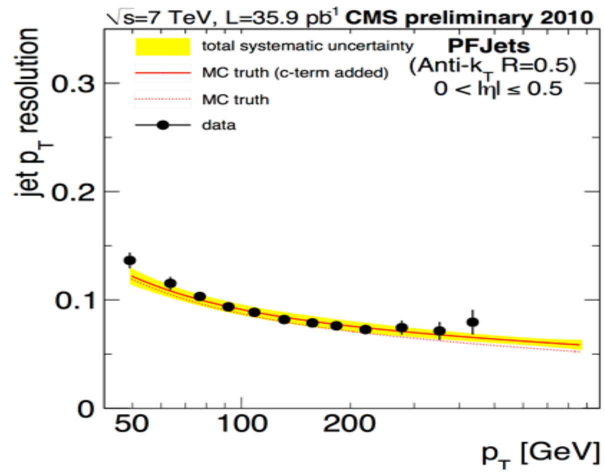
- **A global event description :**



Performance for Jets (1)

- **Jet energy resolution**

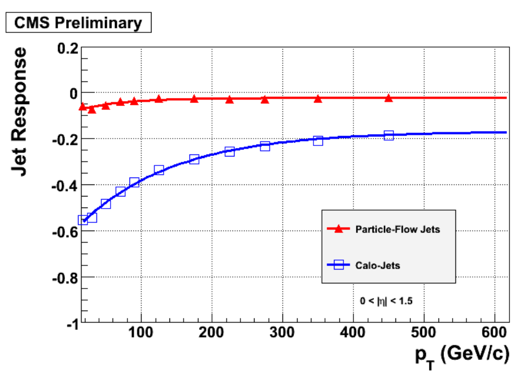


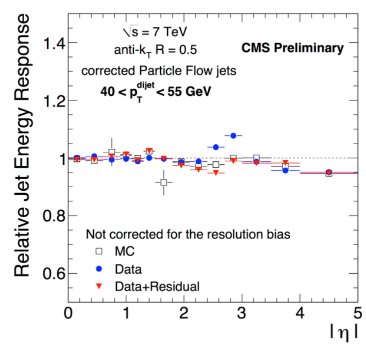


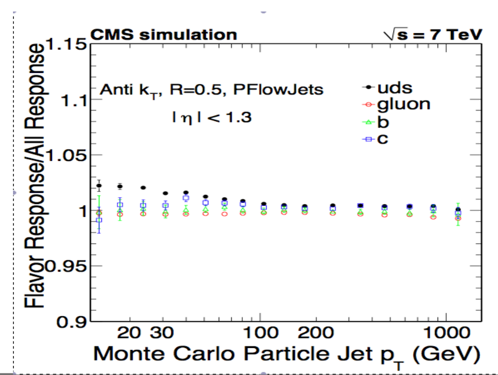
$$\frac{\sigma_E}{E} = \frac{50\%}{\sqrt{E}} \oplus 4\%$$

Nice data/simulation agreement

- **… and response**

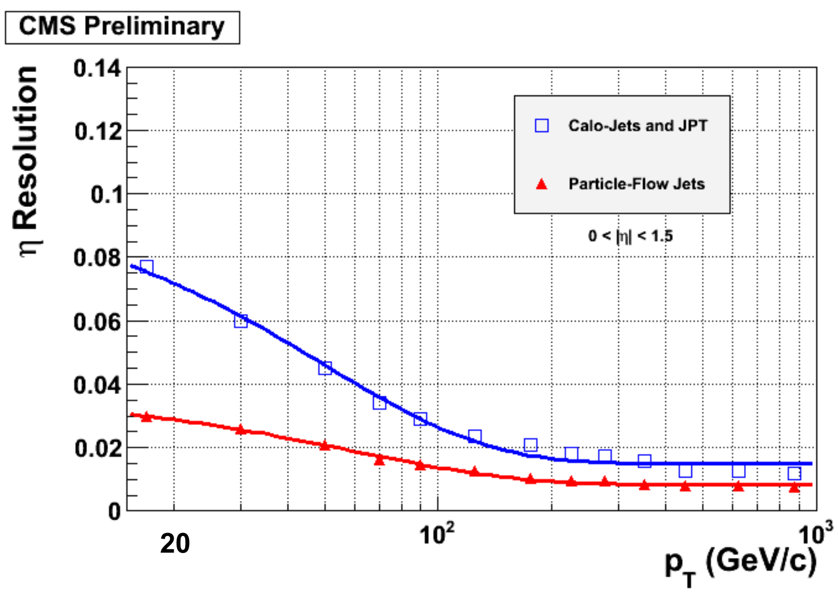


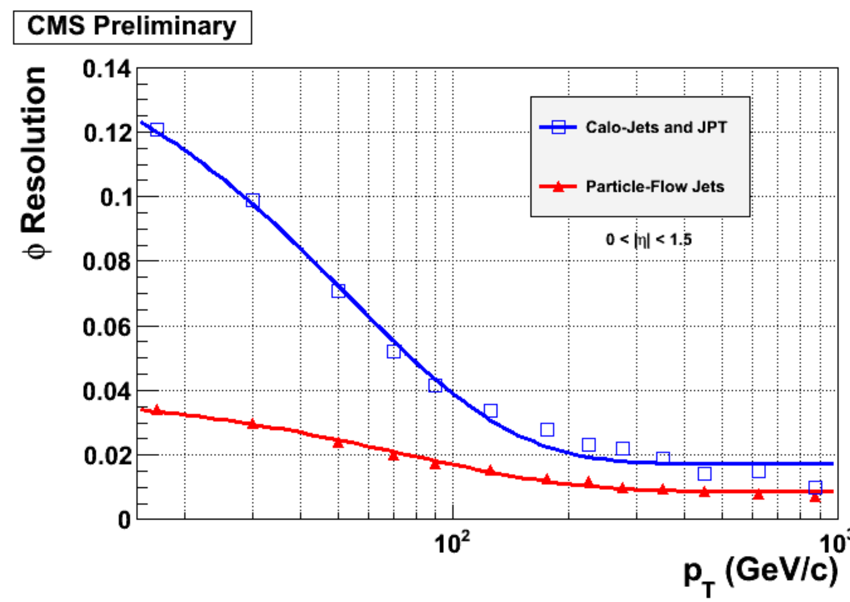




Performance for Jets (2)

- **Jet angular resolution**
  - Important in e^+e^- collisions
    - Jet directions used together with E,p conservation to determine jet energies

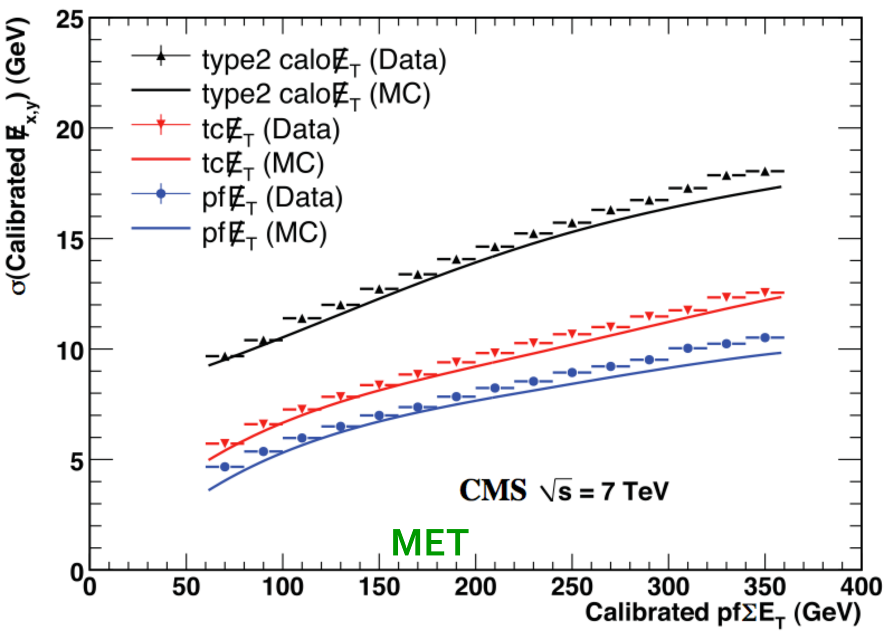




➨ Typically 20-30 mrad for the LEP3 range

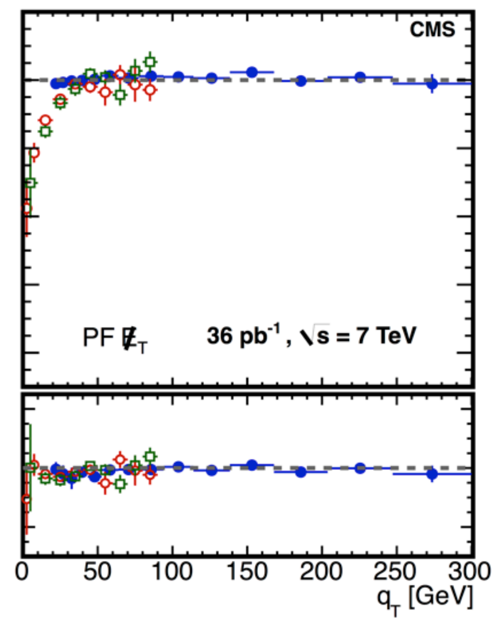
Performance for Missing Energy

- **Missing energy resolution …**
  - **From minbias and multijet events**



… and response :

From Z -> μμ events

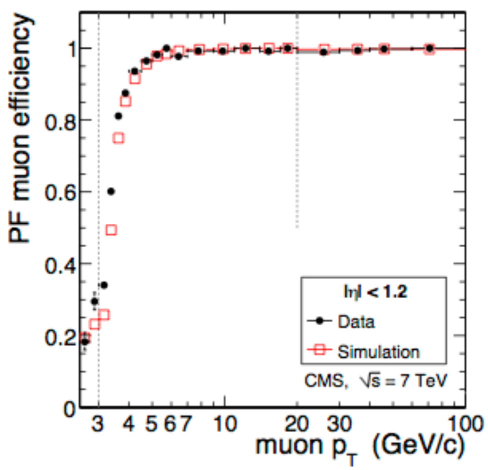


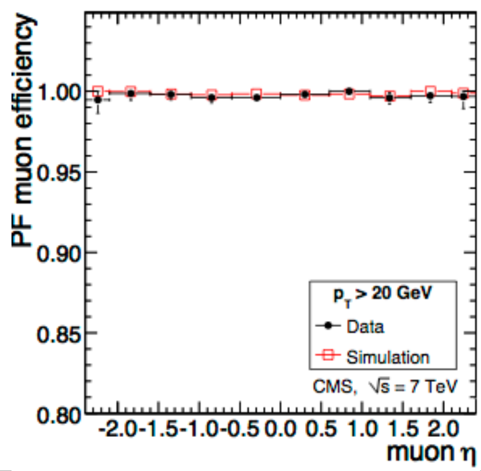
$$\sigma(MET) \approx 50\% \sum E_T$$

Nice data/simulation agreement

Performance for Muons

- **Muon Identification efficiency …** **and momentum determination**

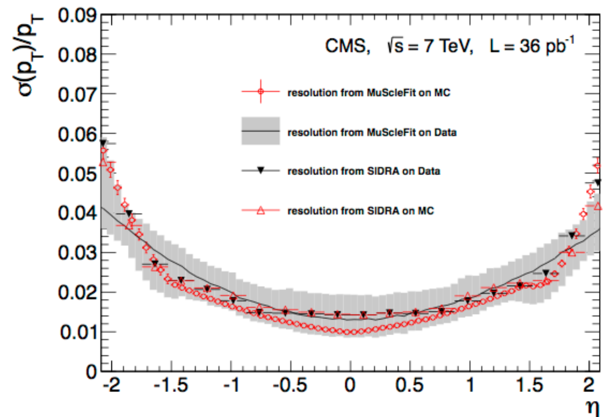


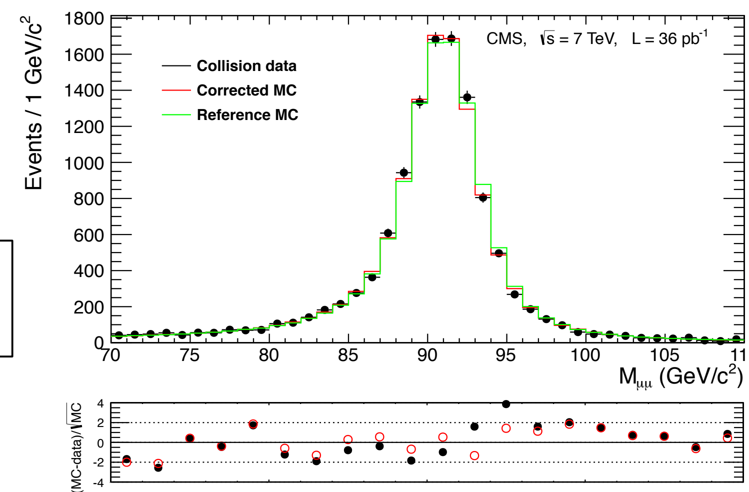


From Z -> μμ events

$$\sigma(p_T)/p_T \approx 2\%$$

Nice data/simulation agreement

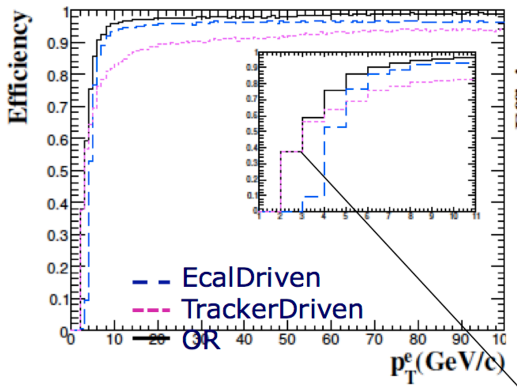




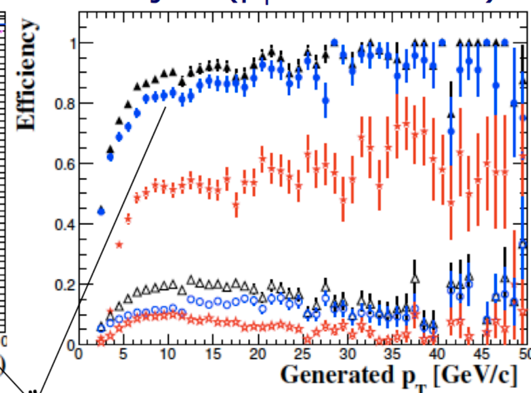
Performance for Electrons

- Electron Identification efficiency (ECAL-seeded or Tracker-seeded)

Z->ee



b-jets (p_T 20-120 GeV)

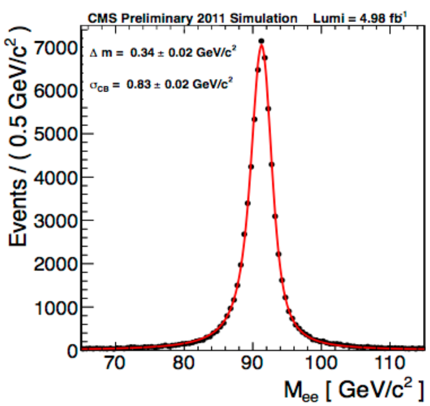


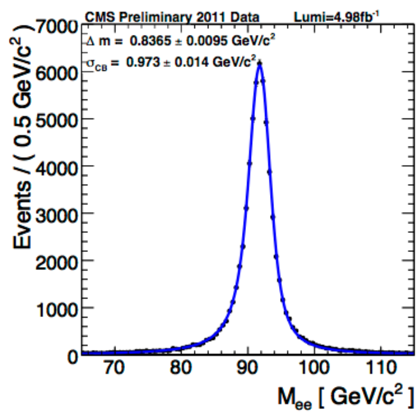
- OR
- Tracker Driven
- Ecal Driven

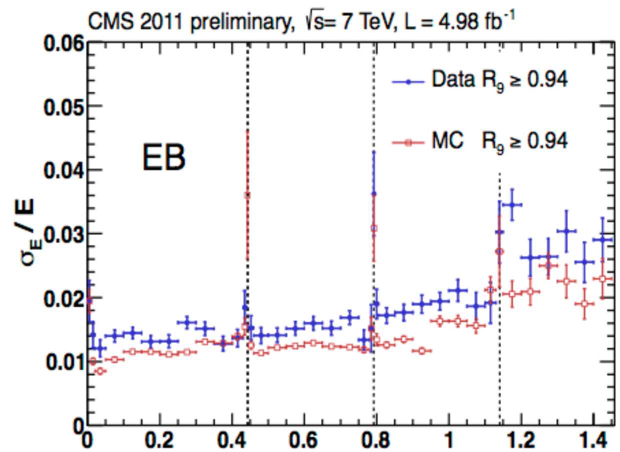
Improvements brought by the trakerDriven seeding

$$\sigma(p_T)/p_T \approx 2\%$$

- ... and momentum determination



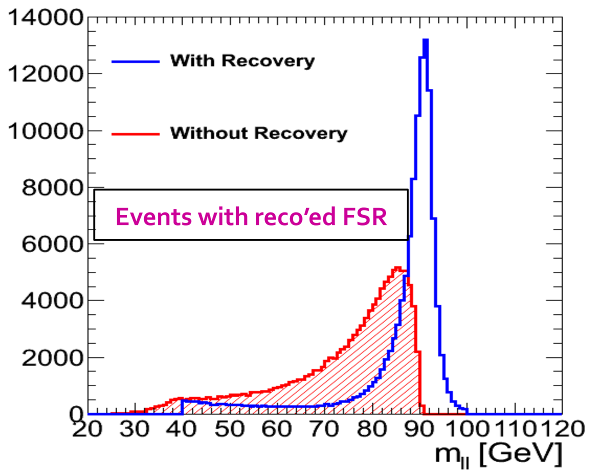


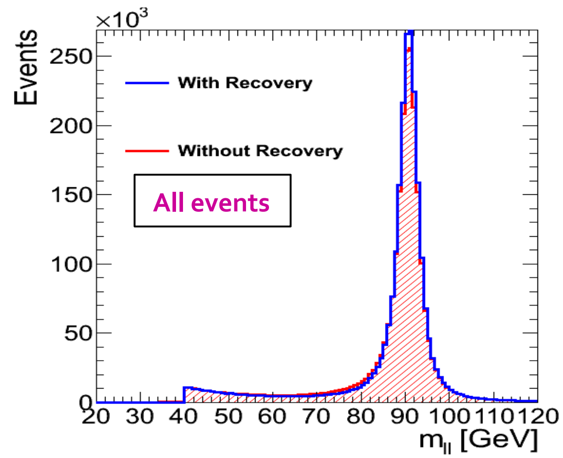


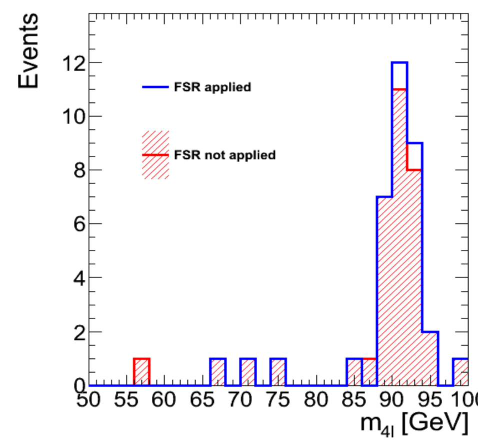
Nice data/simulation agreement

Performance for Photons

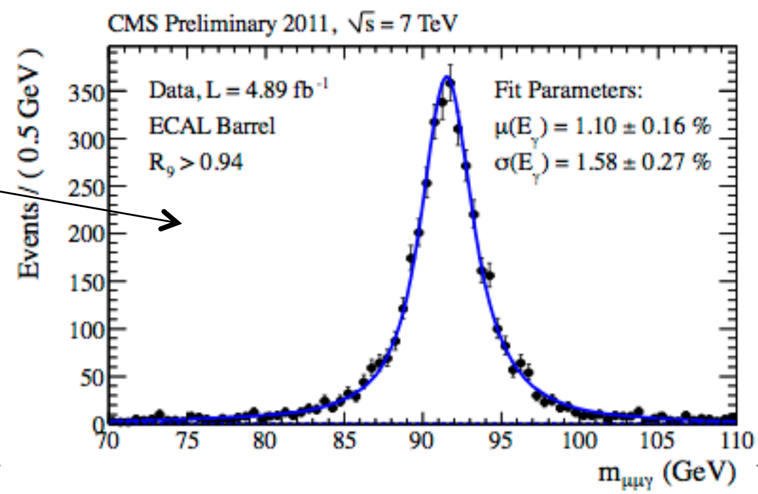
- Bremsstrahlung photons for Z -> $\mu\mu\gamma$ events … … and $\mu\mu\mu\mu\gamma$ events
  - $p_T(\gamma) > 2$ GeV/c







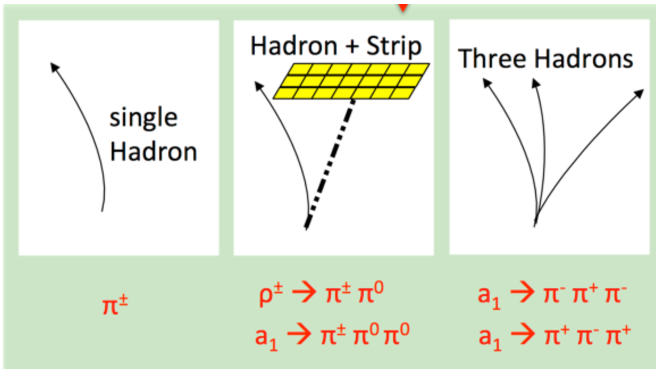
  - $p_T(\gamma) > 25$ GeV/c

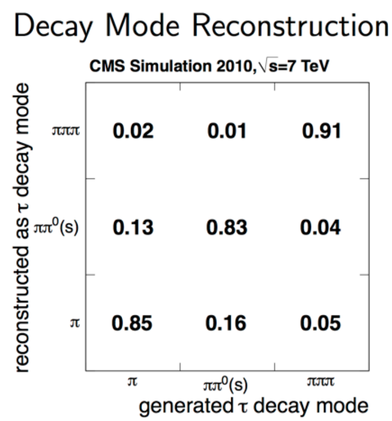


All plots with data !
Photon energy scale
and resolution as expected

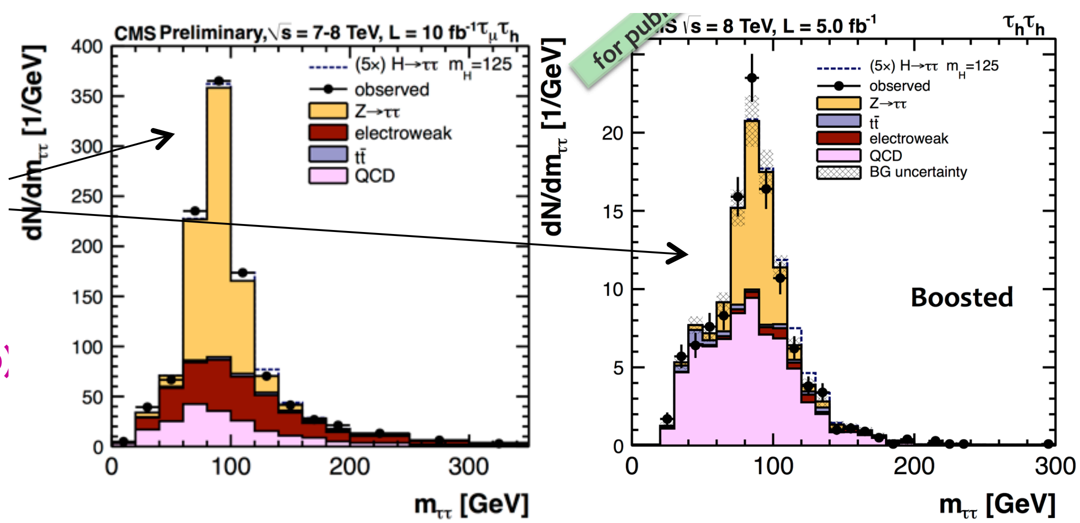
Performance for Taus

- Tau identification start from all charged hadrons and photons :





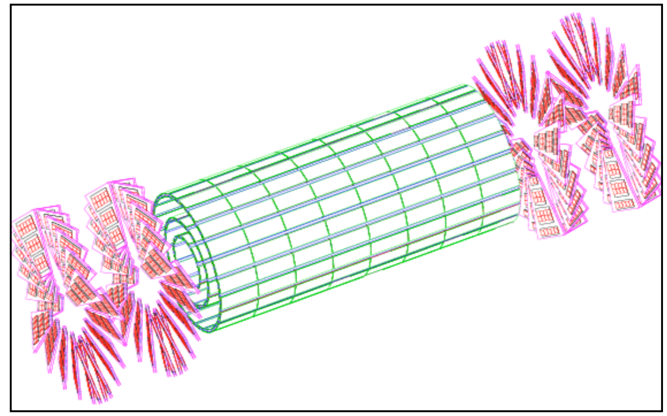
- Efficiency ~ 70%
- Energy scale and resolution
  - From Z -> ττ events
    - (contains MET info)

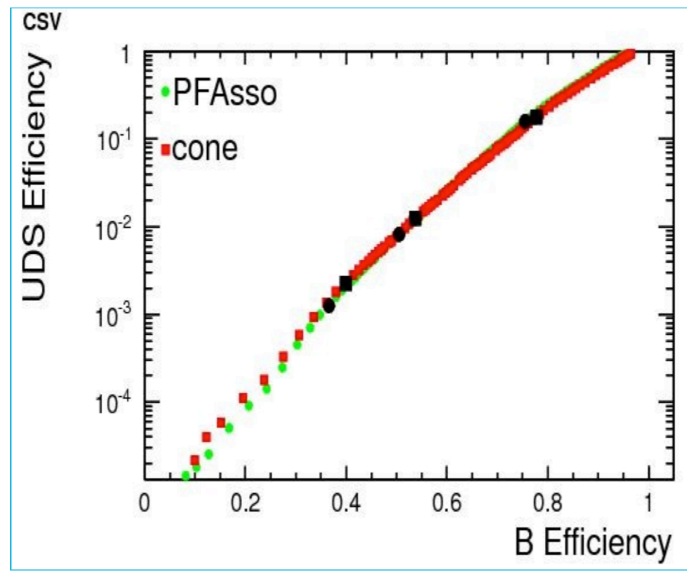


Performance for Heavy Flavours

- **b tagging efficiency**
  - Based on lifetime information only so far
    - $\sigma(d_0) \sim 20\ \mu m$ @ 10 GeV
    - With a bb efficiency of 30%
      - ➨ ~10^{-4} fake rate from light jet pairs
  - Soft-lepton tagging algorithms exist
    - For both muons and electrons
      - ➨ … but have not been used here

        (room for improvement!)





- **c tagging ? gluon tagging ?**
  - Not attempted yet

- **Note : Pixel detector soon upgraded**
  - To 4 barrel layers and 3 end-cap disks
    - … and with less material thickness
      - ➨ better b/c tagging performance

CMS Performance Summary

- **Comparison with a typical LC detector**

Object	CMS	LC
Jets	50%/√E+6%	25-30%/√E
Missing energy	50%ΣE	25%ΣE
Muon momentum	2-3%	0.2%
Electron energy	1-2%	0.2%
b tagging	30%	50%

- **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 (LEP3 vs LC)**

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

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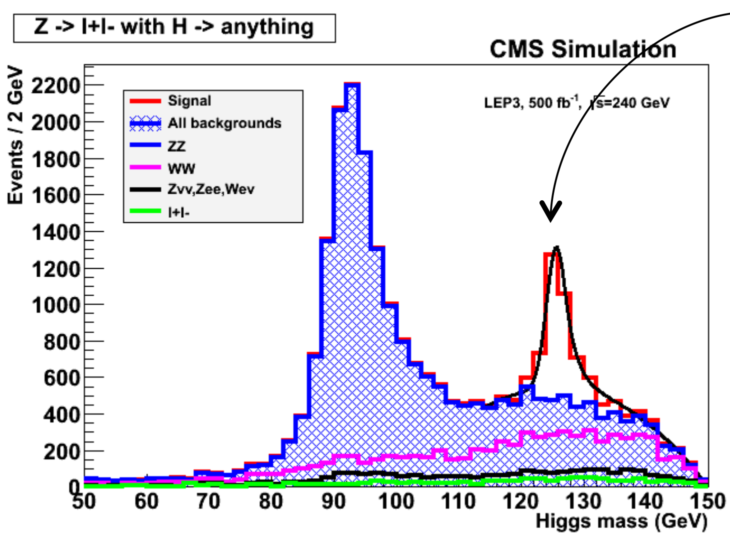
Examples that follow to be taken as illustration only

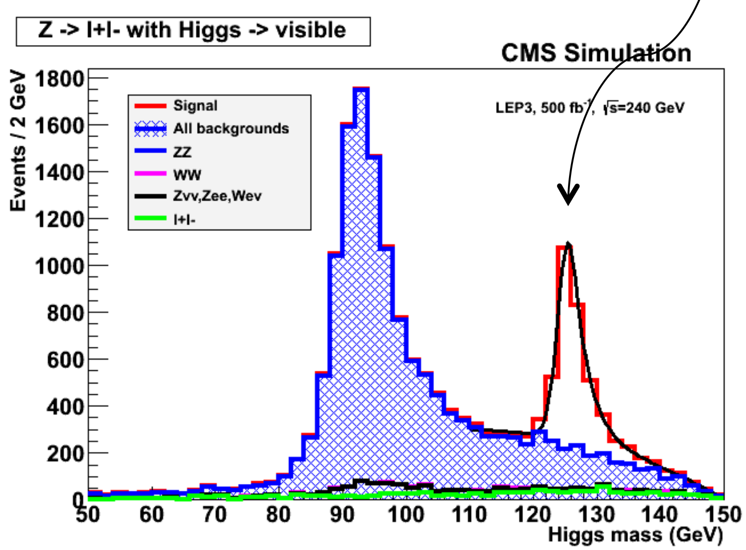
Room for very substantial improvements

See arXiv:1208.1662 for more details

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

- Model-independent measurement with $Z \to e^+e^-, \mu^+\mu^-$
  - 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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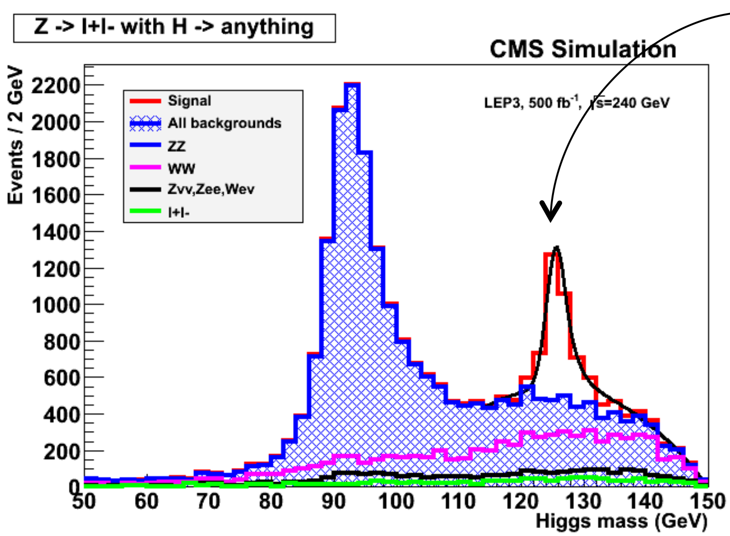
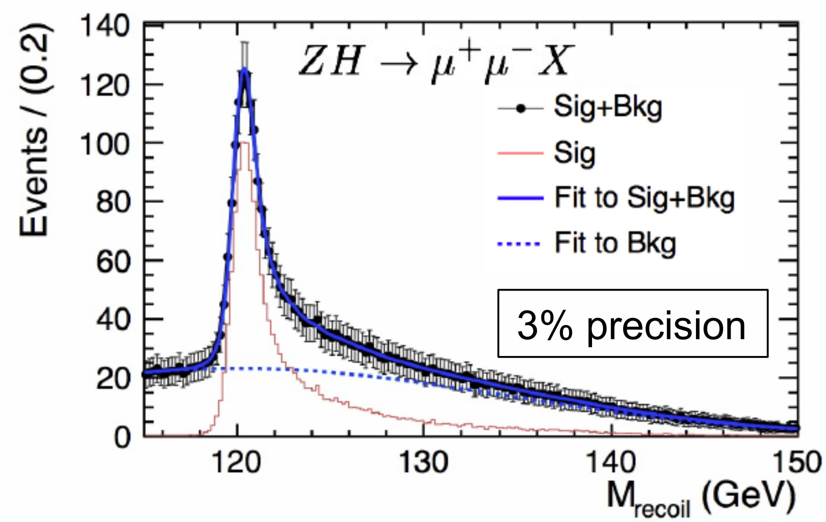
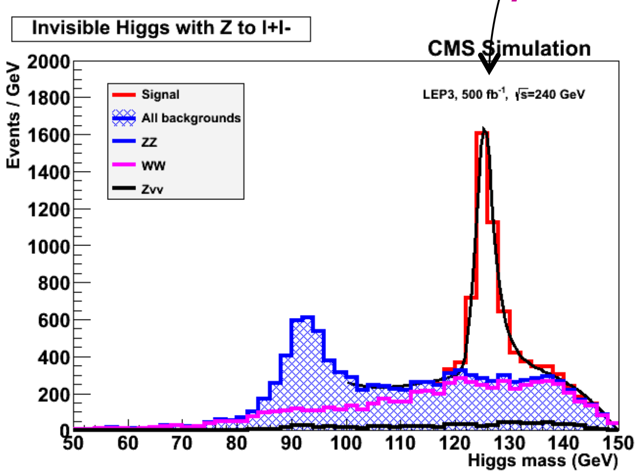


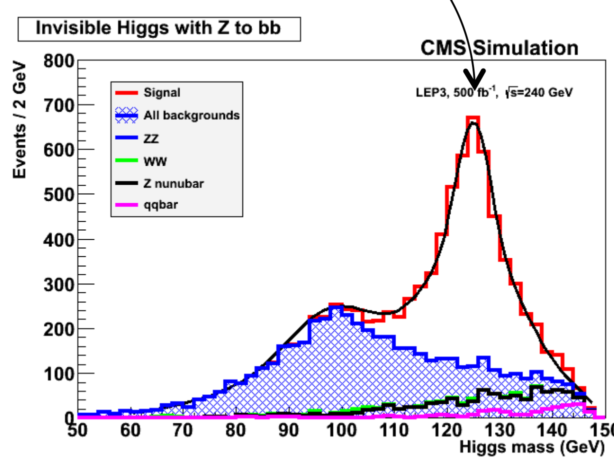
Comparison with ILC studies



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

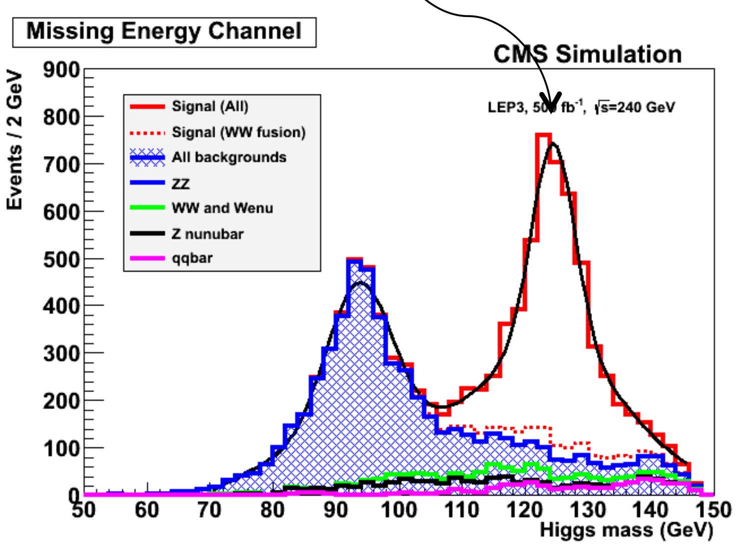
- **Same approach as before**
  - With the requirement that the event consists of only the two leptons (+Brem)
    - Display the mass recoiling against the two leptons (with BR_{invis} = 100%)
  - Complete the analysis with Z -> b bbar
    - Force the events to form two jets, and apply very pure b tagging 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)

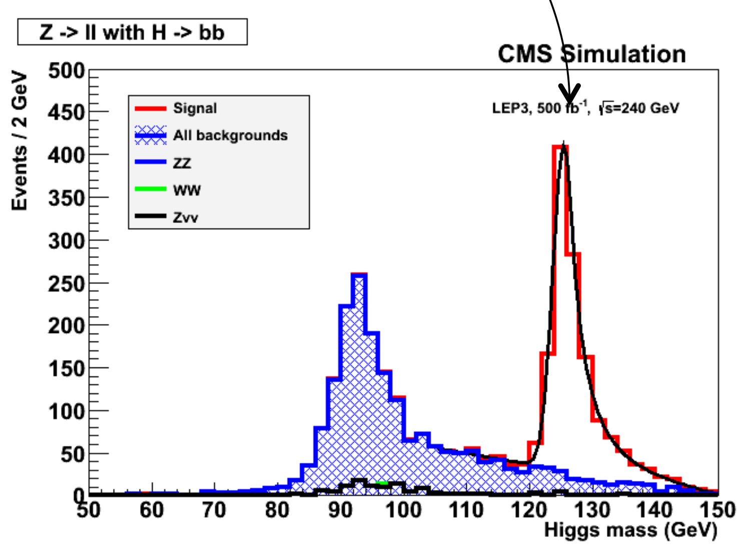




Measurement of σ_{HZ} x BR(H→bb)

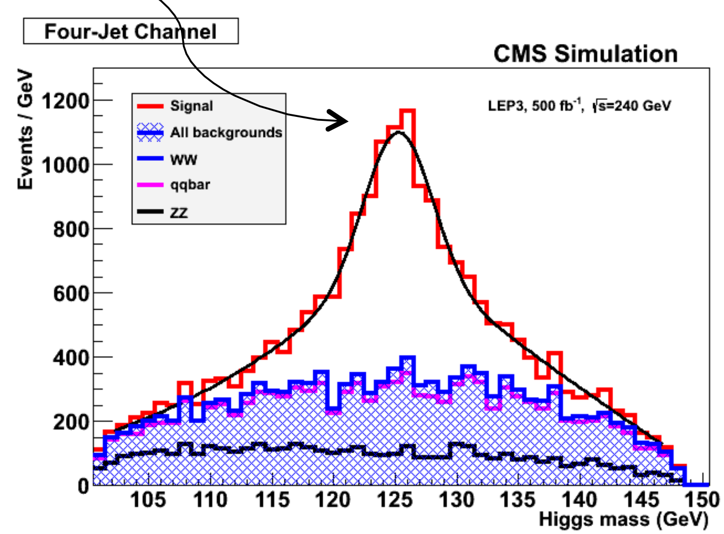
- **Leptonic final state : Z -> e^+e^-, $\mu^+\mu^-$**
  - Exact same selection as for the σ_{HZ} measurement
    - Force the rest of the event to form two jets, and apply a tight b tagging
      - ➨ Precision of 3.1% on σ_{HZ} x BR(H→bb)
- **Missing energy final state : Z -> νν**
  - Exact same selection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

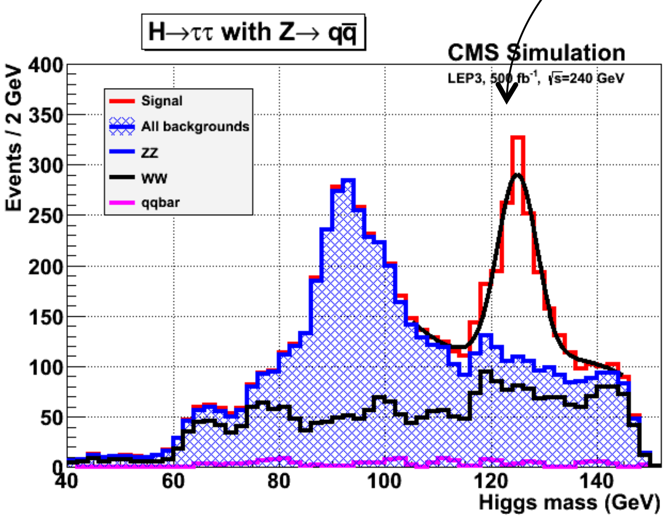
- **The four-jet channel : Z -> qq**
  - Force the event to form four jets, all identified as hadronic jets (particle multiplicty)
  - No significant missing energy : visible mass > 180 GeV
  - Four jet energies rescaled to satisfy E,p conservation (directions unchanged)
    - Distance to ZZ and WW hypotheses 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)

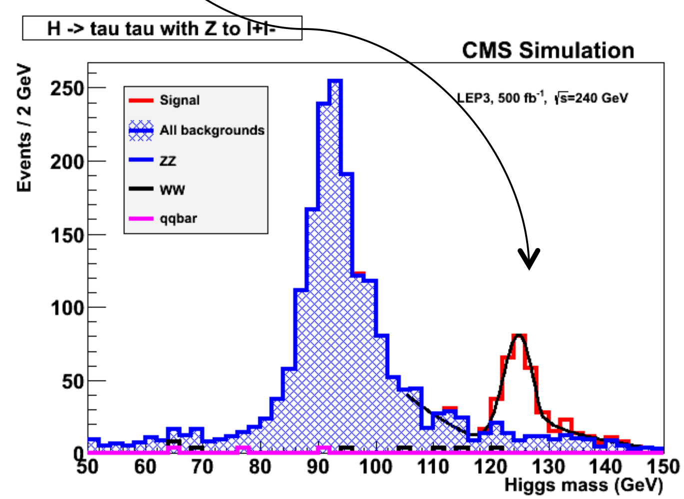


- **Combined precision : 1.0%**
  - Hot news : 5C and 6C improve this by ~20%
    - Not displayed / not used here

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

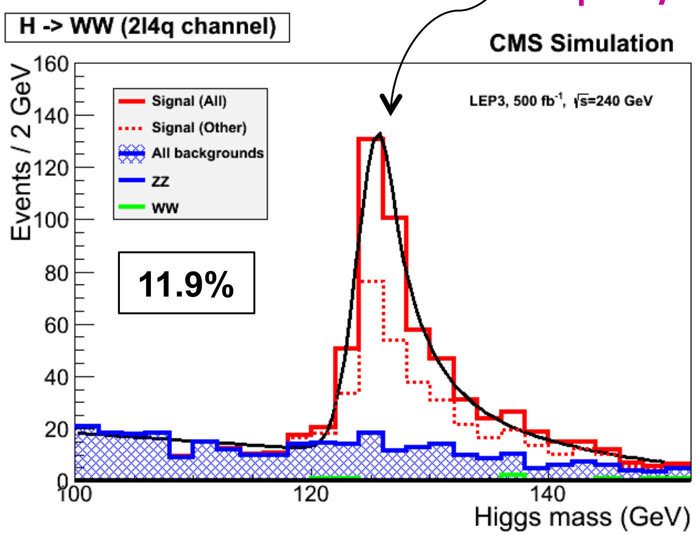
- **Important note : SM Branching Ratio already excluded by CMS**
  - (Can be a fluctuation)
- **Analysis similar to the bb decay**
  - Substitute tau tagging for b tagging
    - Addressed only the hadronic and leptonic Z decays
      - ➨ No mass determination in the missing energy channel
- **Combined precision of 4.3% on σ_{HZ} x BR($H \rightarrow \tau\tau$)**

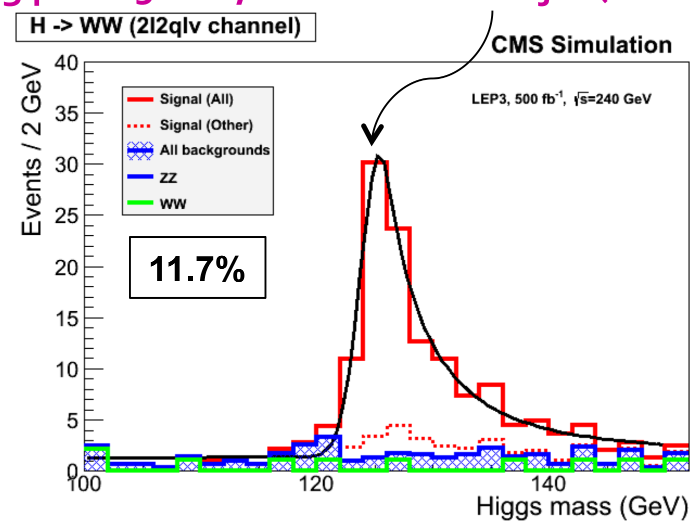




Measurement of σ_{HZ} x BR(H→W^+W^-)

- **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)

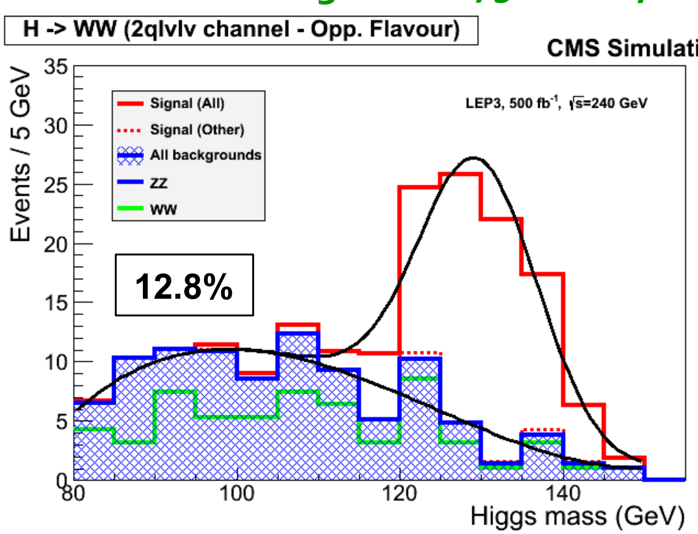


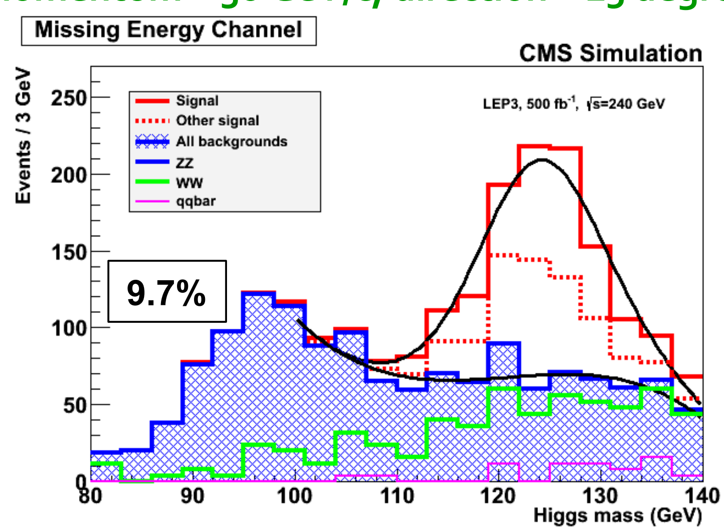


- Background from other Higgs decay channels significant
  - Take if from the SM for the time being. Will do a global fit eventually.

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

- **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/c²
    - Missing transverse momentum > 25 GeV/c
    - Recoiling system with N_{ch}>10 and compatible with the Z mass (±25 GeV/c²)
    - Same lepton flavours also studied, but statistically less interesting
  - 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/c², missing momentum > 30 GeV/c, direction > 25 degrees



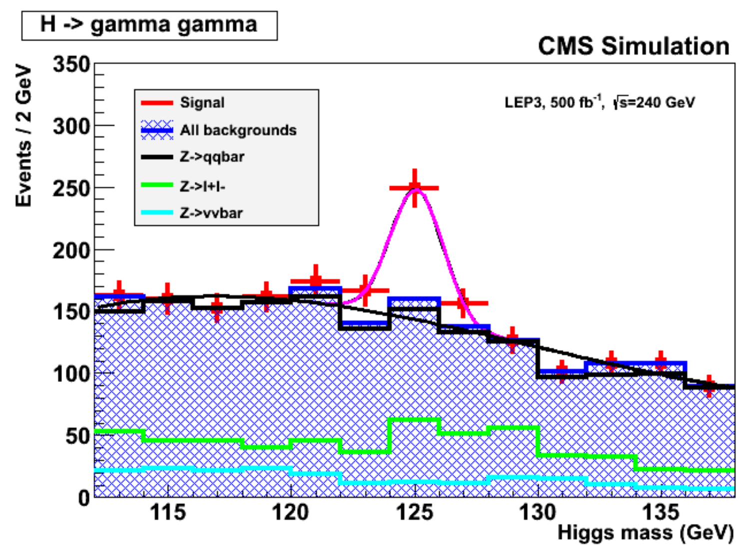


Measurement of σ_{HZ} x BR(H→W^+W^-)

- **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)

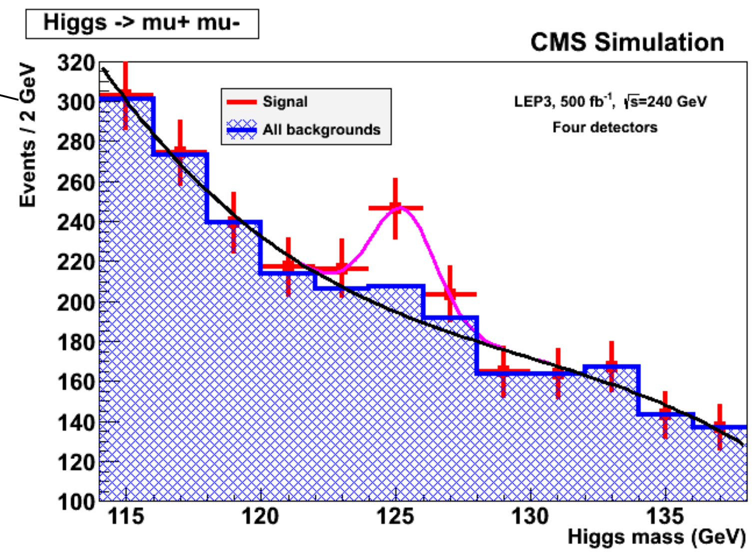
- **Quite rare a decay …**
  - About 250 H -> γγ events expected in 500 fb^{-1}
  - Main background consist of double radiative returns to the Z mass
    - e+e- ➔ ννγγ, eeγγ, μμγγ, ττγγ, and qqγγ (both photons in the detector acceptance)
  - Two photons with energy > 40 GeV, in the tracker acceptance, 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

Higgs Mass Measurement

- **Statistical precision from the various fits:**

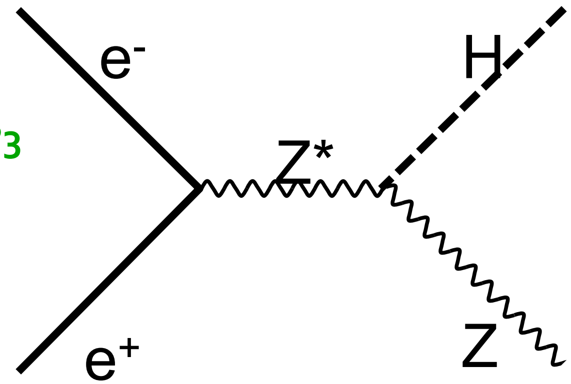
Table 2: The statistical precision on the Higgs boson mass in some of the channels studied in this Section, for an integrated luminosity of 500 fb^{-1} /

Final state	Accuracy (MeV/c^2)
$\ell^+\ell^-$ H	80
$q\bar{q}b\bar{b}$	109
$\nu\bar{\nu}b\bar{b}$	154
$q\bar{q}\tau^+\tau^-$	225
$\nu\bar{\nu}W^+W^-$	810
$H \rightarrow \gamma\gamma$	160
$H \rightarrow \mu^+\mu^-$	580

- Combined statistical uncertainty : 53 MeV/c^2
  - Small systematic bias (200 MeV/c^2)
    - ➨ Can be corrected with known methods (used for the W mass, the top mass...)
- Importance of a precise mass determination ?
  - Higgs total width variation : 4% / GeV
  - BR(H -> WW, bb) variations : 6% / GeV and 2% / GeV
    - ➨ A 100 MeV/c^2 precision seems good enough

Higgs Width Measurement

- **Direct measurement is not possible**
  - Higgs width (~ 4 MeV) is too small with respect to the mass resolution
  - Measure it indirectly
    - Total rate $\propto g_{HZZ}^2$
    - ZZZ rate $\propto g_{HZZ}^4/\Gamma_H$ - not yet addressed for LEP3
    - Alternatively, ZWW rate $\propto g_{HZZ}^4/\Gamma_H$
      - ➨ Assuming custodial symmetry
    - Hence $\Gamma_H \propto$ (Total Rate)^2 / ZWW (or ZZZ) rate

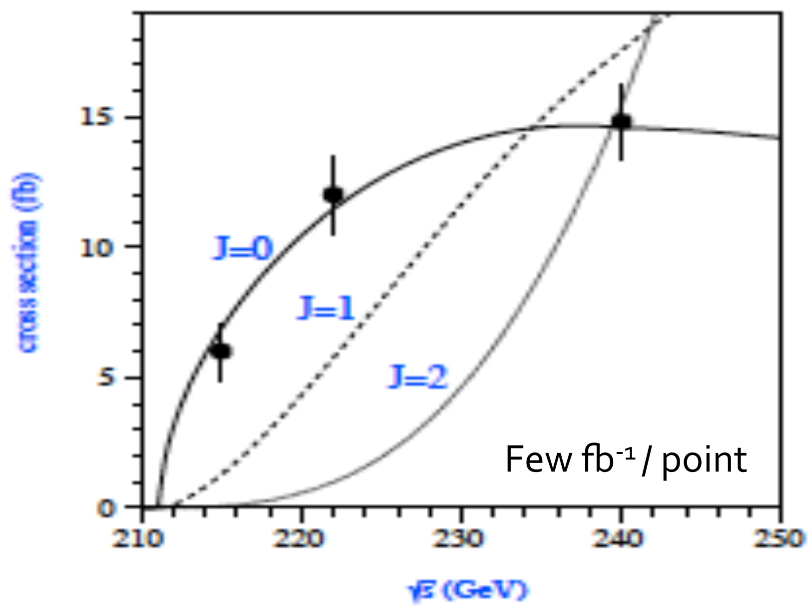


  - Expected precision on Γ_H ~ 6% (with WWW rate)
    - Reduced to 3% with four experiments
  - NB : Similar precision (2.5%) with a muon collider (direct measurement)
  - Importance of the width measurement
    - The observable most sensitive to new physics
      - ➨ Even if no exotic decays

Insteasd, branching ratios sensitivity suffers from cancellation in the ratio.

Spin and CP determination

- Nothing done specifically for LEP3 (yet)
  - Spin from threshold scan (from TESLA Physics TDR) with ll + X final state



  - CP from angular distributions

Summary of the measurements

- **Under the very conservative assumptions already stated :**
  - **LEP3 figures with 2 x CMS or 4 x CMS; LHC figures from SFitter; ILC figures from ESG.**

	ILC	LEP3 (2)	LEP3 (4)	LHC
σ_{HZ}	3%	1.9%	1.3%	–
$\sigma_{HZ} \times BR(H \to b\bar{b})$	1%	0.8%	0.5%	–
$\sigma_{HZ} \times BR(H \to \tau^+\tau^-)$	6%	3.0%	2.2%	–
$\sigma_{HZ} \times BR(H \to W^+W^-)$	8%	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}	1.5%	0.9%	0.6%	13%
g_{Hbb}	1.6%	1.0%	0.7%	21%
$g_{H\tau\tau}$	3%	2.0%	1.5%	13%
g_{Hcc}	4%	?	?	?
g_{HWW}	4%	2.0%	1.4%	11%
$g_{H\gamma\gamma}$	?	4.9%	3.4%	6%
$g_{H\mu\mu}$	–	–	14%	25%
m_H (MeV/c^2)	50	37	26	100

- **Typically uncertainties smaller by a factor 2-3 than the ILC**
  - ➨ **Divide by another factor 2 for TLEP.**

Conclusions (1)

- **LEP3 is exciting !**
  - It provides an economical (and even feasible) alternative to ILC
    - Everything is "off-the-shelf"
    - The money saved can be used for other exciting projects
  - The machine has many interesting challenges
    - But should safely achieved the predicted performance

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

Conclusions (2)

- **LEP3 issues**
  - Circular machine : not upgradeable to higher energies
    - But a 1 TeV LC cannot really improve on what LHC and HE-LHC can do
      - ➨ Need to understand how well the ttH and HHH couplings can be addressed
    - The choice really depends on the LHC findings in the next 5 years
      - ➨ What if there is no new physics that a 1 TeV LC would help characterizing ?
  - Fitting LEP3 in the LHC tunnel together with LHC is not easy
    - Need to weigh the relative merits of LEP3 + HE-LHC and of HL-LHC + HE-LHC
      - ➨ As an option for ATLAS and CMS
    - Again, the choice really depends on the LHC findings in the next 5 years
      - ➨ LEP3 timescale could be around 2024-2025, for 10 years
  - TLEP is a superior machine (energy and luminosity)
    - A tiny bit more expensive – although not as much as ILC
    - With a much longer timescale
    - "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

Next Event : LEP3 Workshop at CERN, IT Auditorium, 23 Oct.

https://indico.cern.ch/conferenceDisplay.py?confId=211018