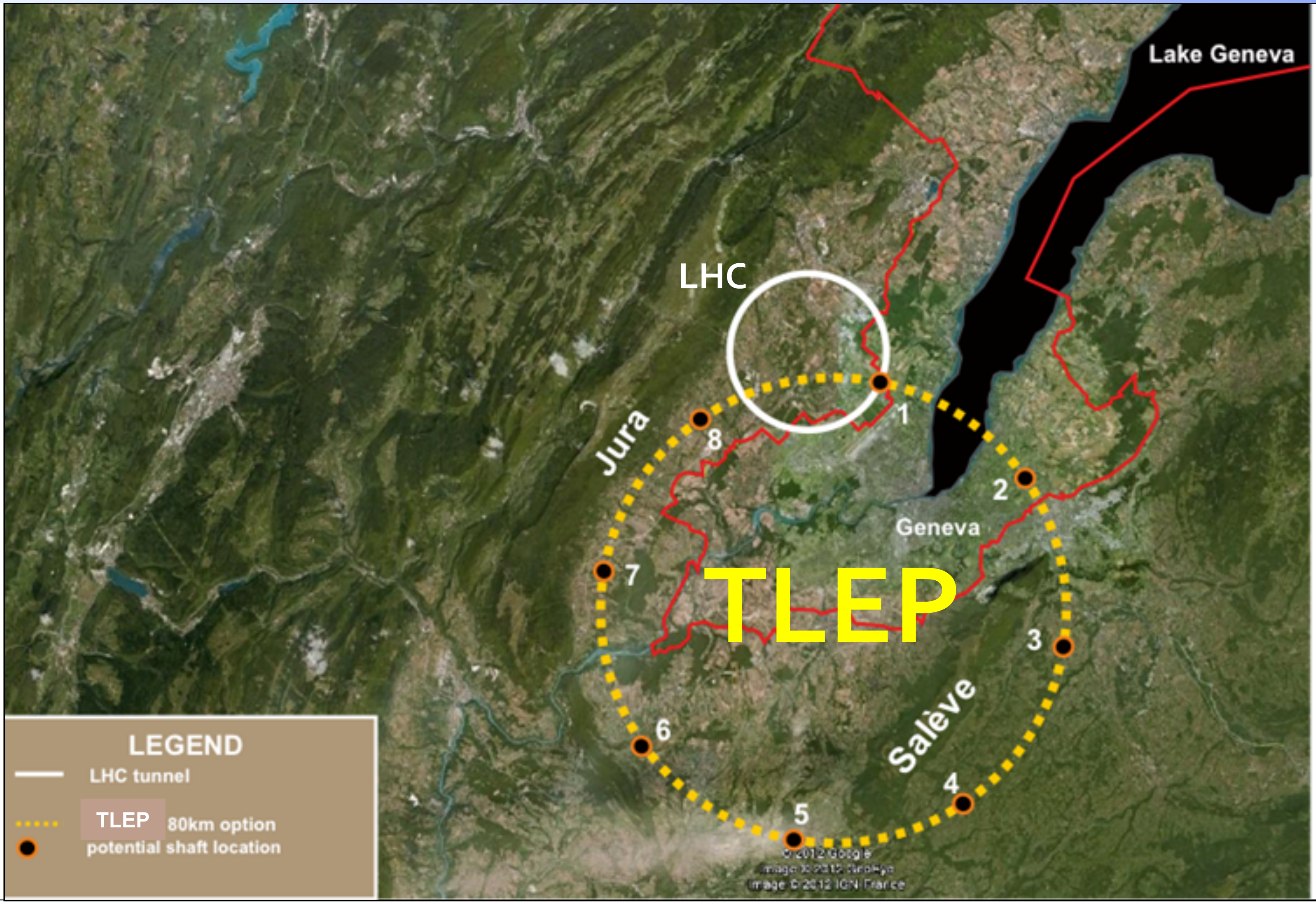
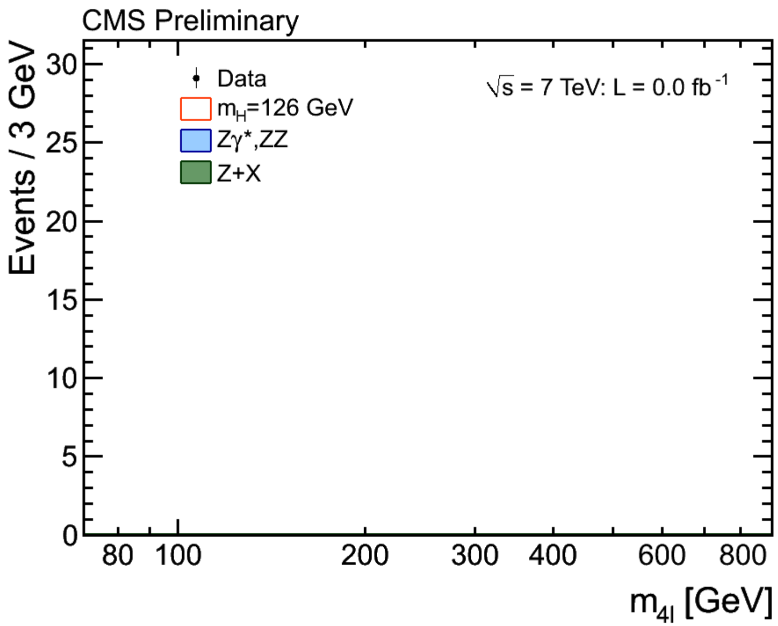
A first step in a long-term vision for HEP

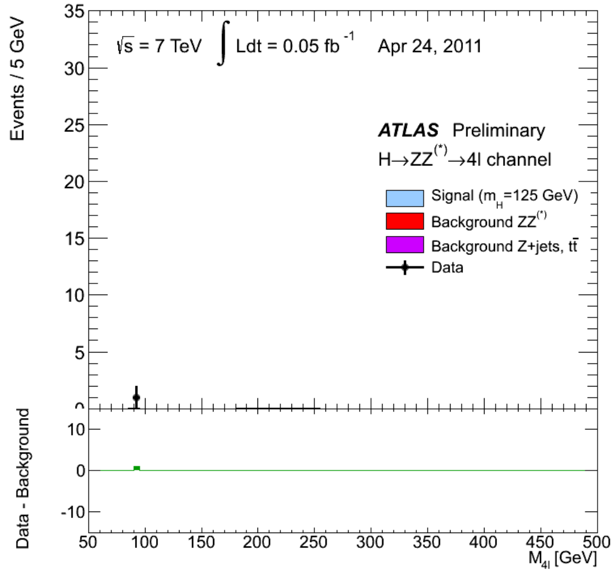


A new accelerator complex for HEP ?

Why ? Why now ? What ?



Moriond EW '13



Today…

- **At least four evidence for New Physics**
  - **Non Baryonic Dark Matter**
  - **Accelerated Expansion of the Universe**
  - **Baryon Asymmetry**
  - **Neutrino Masses**

Today…

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  - Baryon Asymmetry
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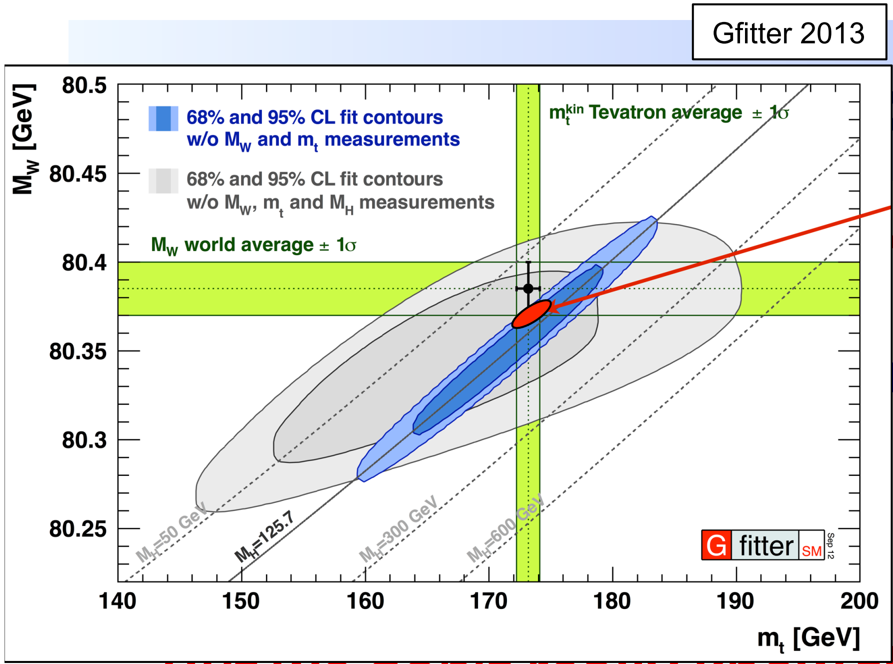
- **But we don't really know the New Physics energy scale(s)**
  - The Standard Model is as alive as ever



...oday...

...ew Physics

...niverse

- But we don't really know the New Physics energy scale(s)
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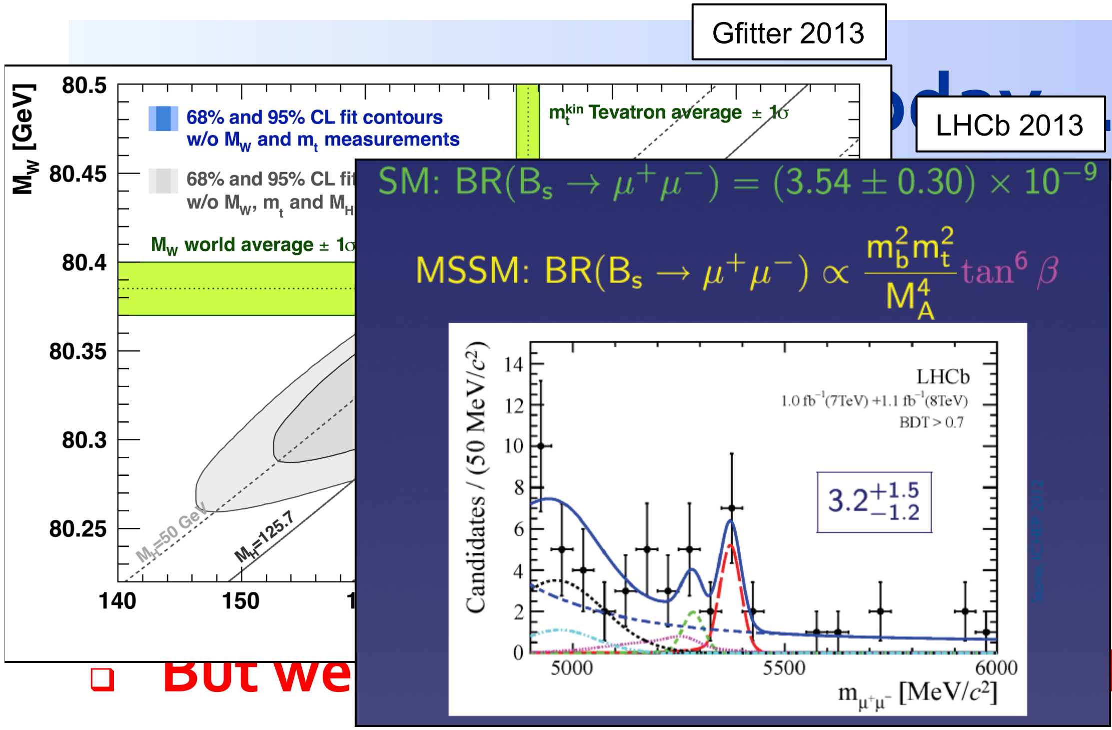
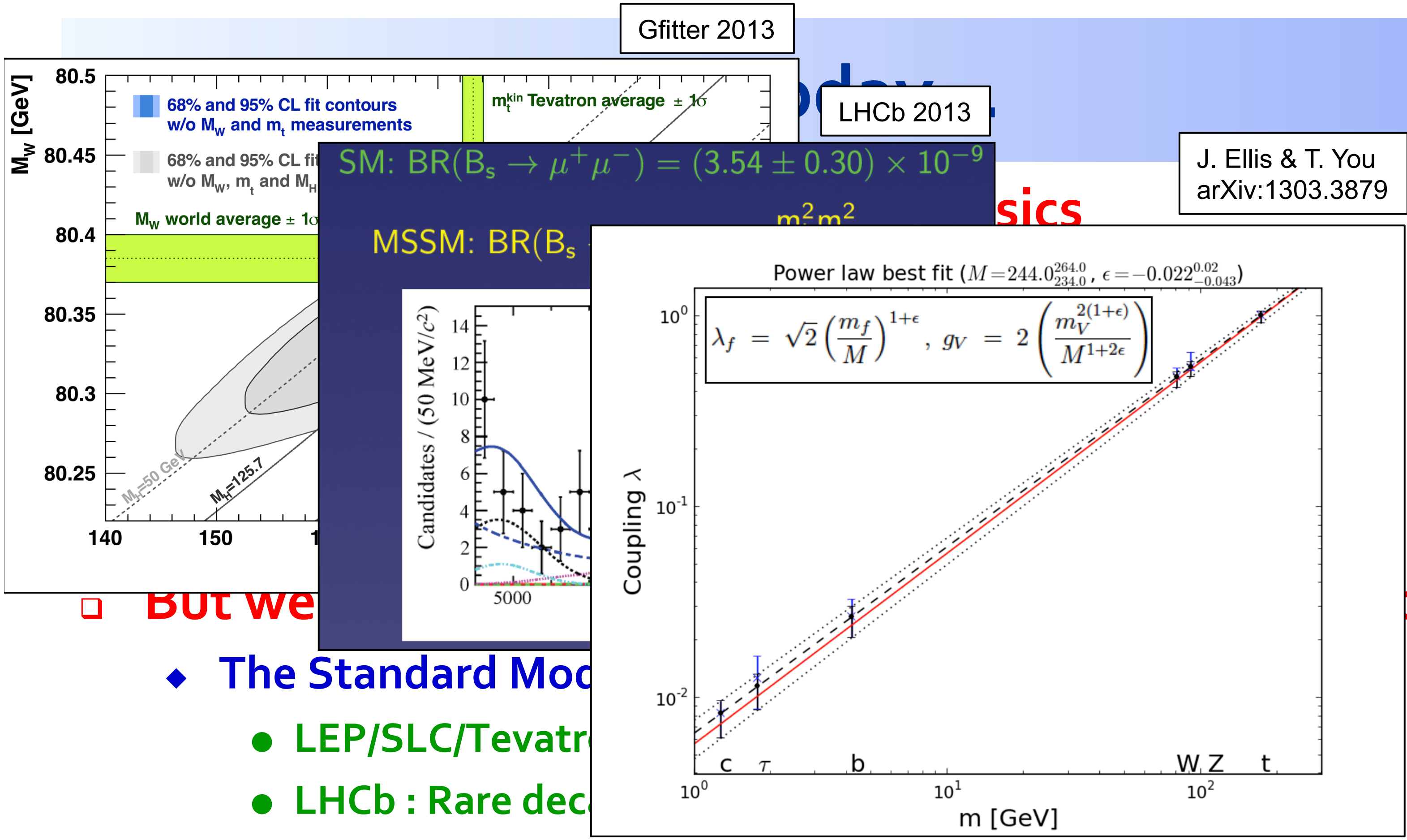
    - LEP/SLC/Tevatron : Electroweak precision measurements

…oday…

…sics



- But we … Physics energy scale(s)
  - The Standard Model is as alive as ever
    - LEP/SLC/Tevatron : Electroweak precision measurements
    - LHCb : Rare decays



…sics

- But we … cale(s)
  - The Standard Moc…
    - LEP/SLC/Tevatr…
    - LHCb : Rare dec…
    - CMS/ATLAS : A very standard scalar sector (so far)

❑ But we

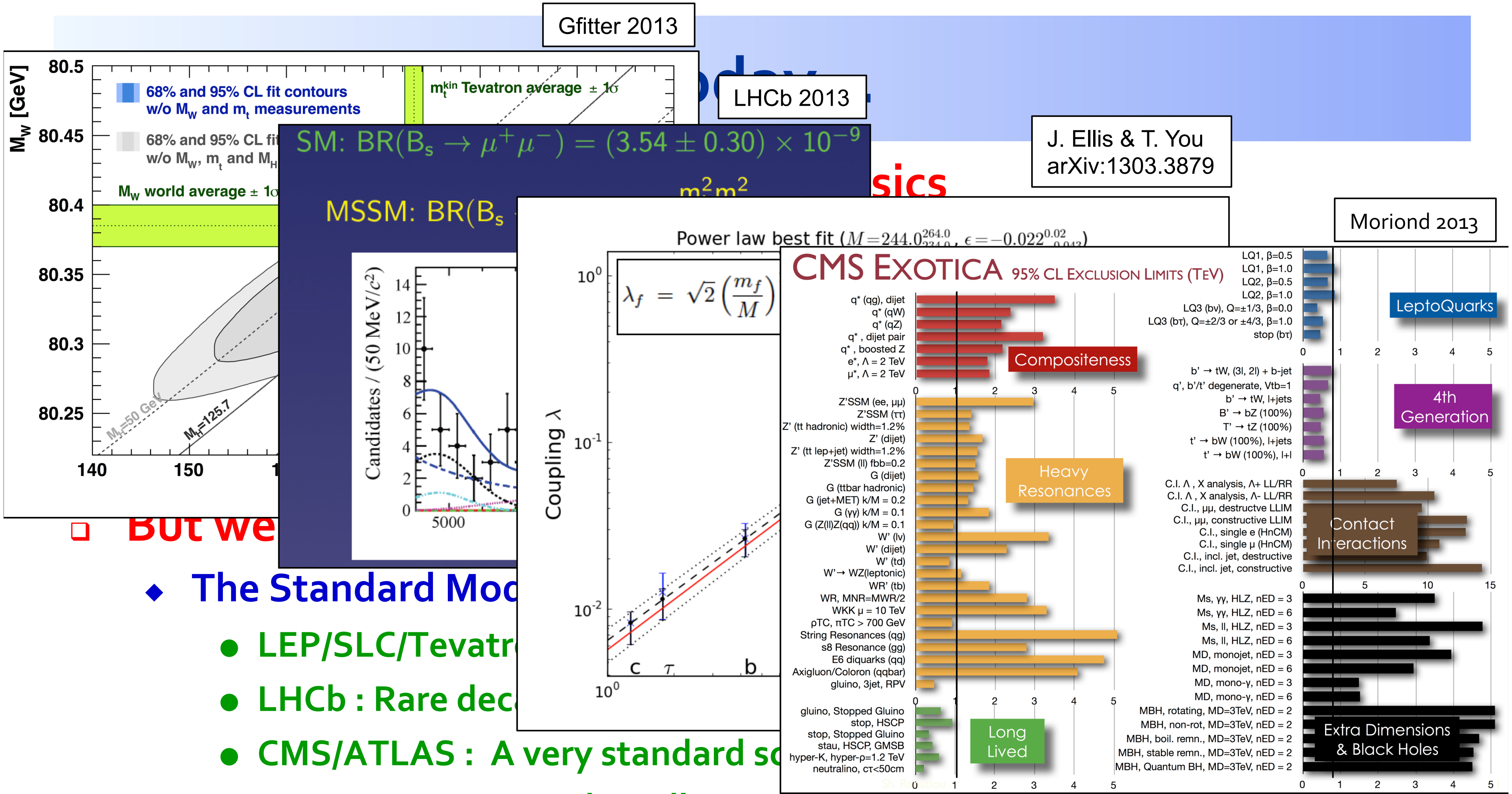
◆ The Standard Moc

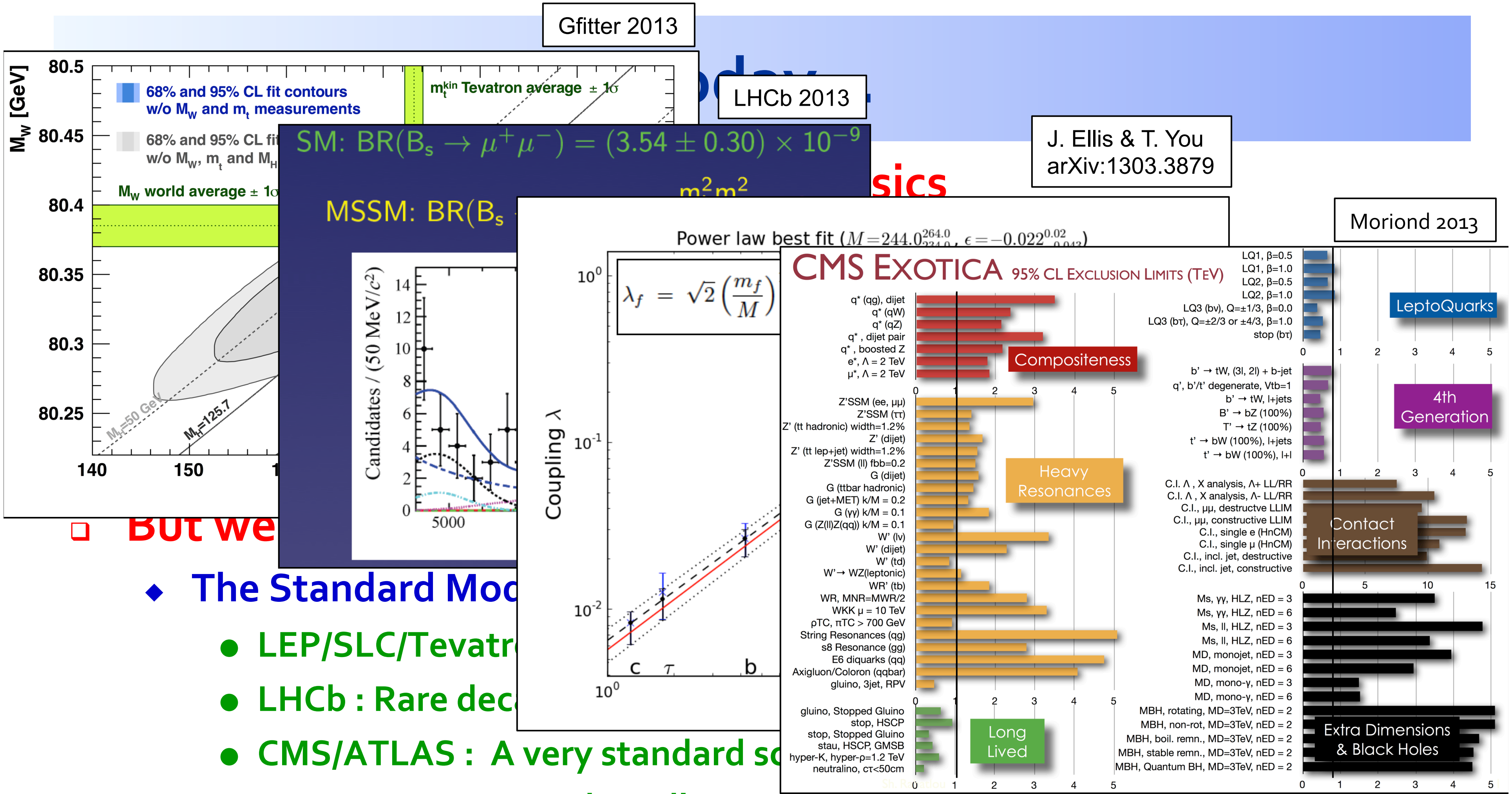
● LEP/SLC/Tevatr

● LHCb : Rare dec

● CMS/ATLAS : A very standard sc

● CMS/ATLAS : No (other) discovery below the ½ TeV range





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❑ **Question : Is Particle Physics at the Energy Frontier over ?**

◆ **If not : How do we look for the next energy scale ?**

Yesterday …

- A look to the past decades : what were the right machines ?
  - **1970-1990**
    - Precision measurements of neutral currents : predicted m_W and m_Z
    - The CERN Sp$\bar{p}$S (UA1, UA2) discovered the W and the Z
    - The CERN LEP (and SLC) nailed the gauge sector
  - **1990-2000**
    - Precision measurements of the gauge sector at LEP/SLC : predicted m_{top}
    - The FNAL Tevatron (CDF, D0) discovered the top
    - A collider to nail the top sector ? Does the LHC suffice ?
  - **1995-2015**
    - Precision measurements of m_W and m_{top} (LEP, TeVatron) : predicted m_H
    - The CERN LHC (CMS, ATLAS) discovered the SM Higgs boson
    - A collider to nail the scalar sector ? Does the LHC suffice ?

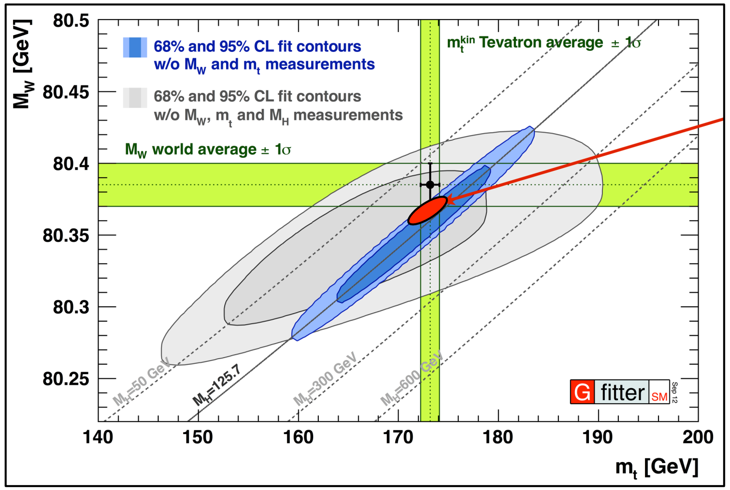
Tomorrow …

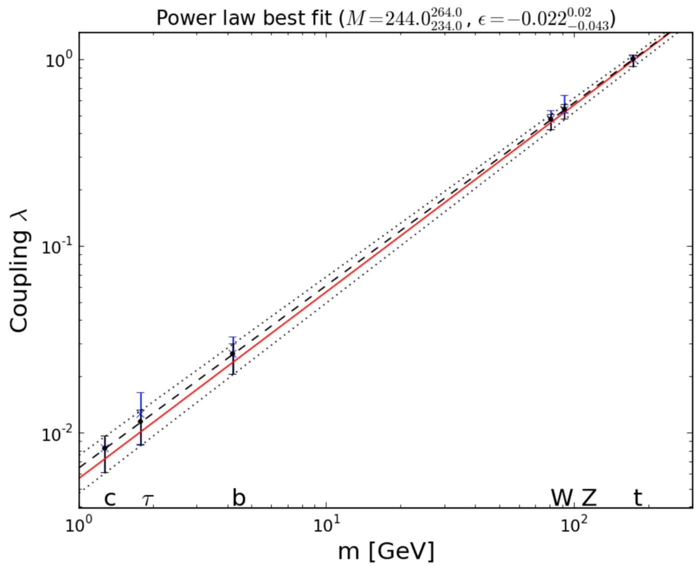
- **Perpetuating a 40-years-long tradition ?**
  - **2025-2050**
    - **Next Facility: Precision measurements of EWSB sector (W, Z, t, H)**
      - ➨ **Predict New Physics scale**
    - **Next-to-next facility : discover New Physics**
    - **Then, will need to nail this New Physics**

- **Questions :**
  - **What parameters should we measure to probe BSM Physics ?**
  - **What precision should we aim at ?**
  - **What energy scale should we then aim at to directly look for BSM Physics ?**
    - **… and have a reasonable chance to find it ?**
  - **What is (are) the best accelerator(s) to achieve these goals ?**
    - **Both for precision measurements and the BSM Physics direct search**
  - **… and when should we decide the right path ?**

Probing BSM Physics indirectly ?

What parameters ?
With what precision ?





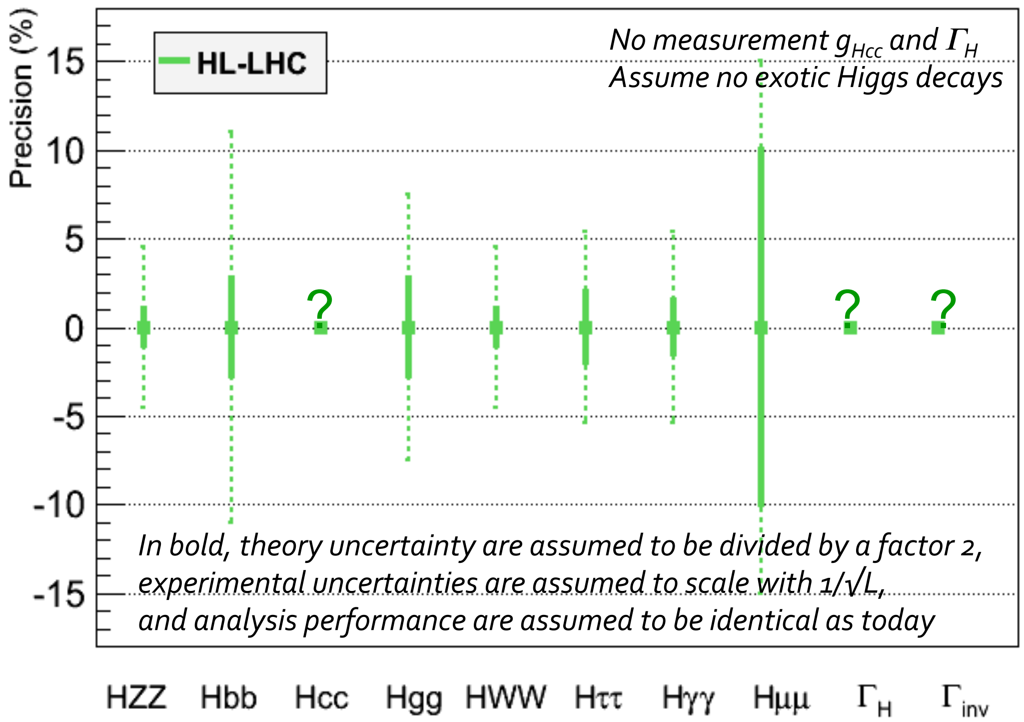
Parameters (I) : Higgs Properties

Highest-priority recommendation from European Strategy

c) The **discovery of the Higgs boson** is the start of a major programme of work to measure this particle's properties with the **highest possible precision for testing the validity of the Standard Model and to search for further new physics at the energy frontier**.

The LHC is in a unique position to pursue this programme.

	LHC	HL-LHC
End date	2021	2030-35?
N_H	1.7 x 10^7	1.7 x 10^8
Δm_H (MeV)	100	**50**
$\Delta g_{H\gamma\gamma}/g_{H\gamma\gamma}$	6.5 – 5.1%	5.4 – **1.5%**
$\Delta g_{Hgg}/g_{Hgg}$	11 – 5.7%	7.5 – **2.7%**
$\Delta g_{Hww}/g_{Hww}$	5.7 – 2.7%	4.5 – **1.0%**
$\Delta g_{HZZ}/g_{HZZ}$	5.7 – 2.7%	4.5 – **1.0%**
$\Delta g_{HHH}/g_{HHH}$	--	**< 30%**
$\Delta g_{H\mu\mu}/g_{H\mu\mu}$	<30%	<10%
$\Delta g_{H\tau\tau}/g_{H\tau\tau}$	8.5 – 5.1%	5.4 – **2.0%**
$\Delta g_{Hcc}/g_{Hcc}$	--	--
$\Delta g_{Hbb}/g_{Hbb}$	15 – 6.9%	11 – **2.7%**
$\Delta g_{Htt}/g_{Htt}$	14 – 8.7%	8.0 – **3.9%**



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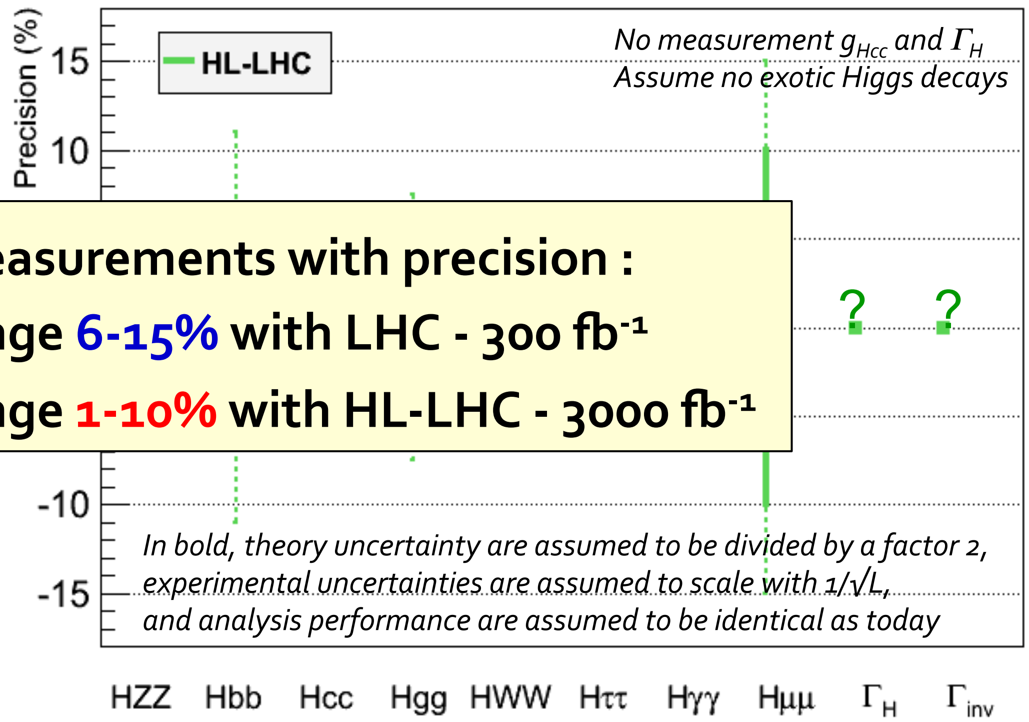


Coupling measurements with precision :

- **in the range 6-15% with LHC - 300 fb^{-1}**
- **in the range 1-10% with HL-LHC - 3000 fb^{-1}**

Precision Needed (I) : Higgs Properties

A few examples of BSM Physics

- Max. deviations to SM couplings, as a function of New Physics scale:

H. Baer, M. Peskin et al.

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

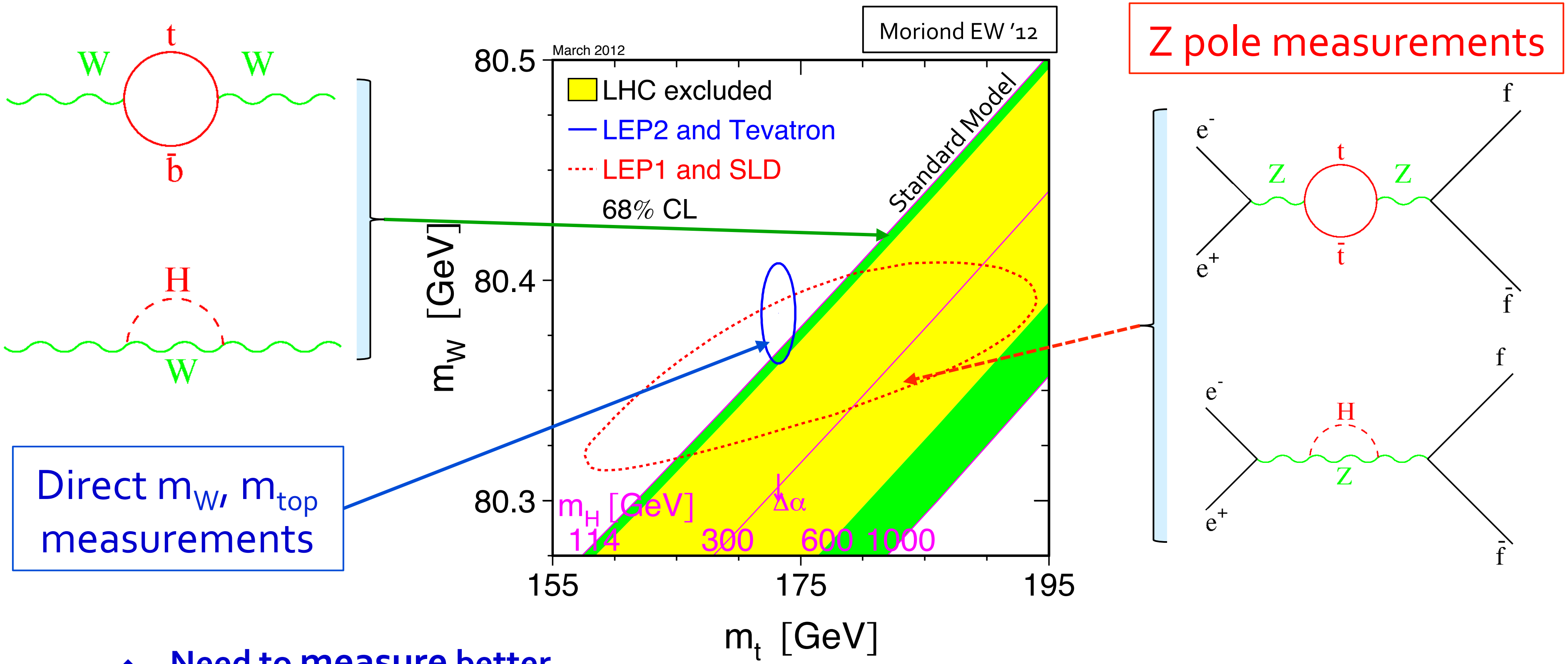
Precision needed

- Need at least a per-cent accuracy on couplings for a 5σ "observation"
  - And a sub-per-cent accuracy for a multi-TeV New Physics Scale
    - ➨ Hence colliders beyond (HL)-LHC

Towards a Precision Higgs Factory ?

Parameters (II) : EWSB Tests

- **Improve the precisions of all ESWB tests**



- **Need to measure better**
  - **m_W and m_{top}** — Reduce the size of the blue ellipse
  - **Z lineshape, Asymmetries, Cross section, Decay Rates, …** — and of the red potatoe
- **Need to compute better loop corrections to all these observables**

Precision needed (II) : EWSB Tests

- For a meaningful test of the SM closure to be done
  - Hence to become sensitive to heavier new physics
    - Reduce the size of the blue ellipse to approach the thickness of the green line
      - ➨ i.e., by one order of magnitude or more
    - Reduce the size of the red ellipse to that of the blue one
      - ➨ i.e., by two orders of magnitude or thereabout

- Numerically
  - m_W is known to 15 MeV (Tevatron), ultimately reduced to 10 MeV
    - … and maybe to 7 MeV when combined to forthcoming LHC measurements
  - m_{top} is know to 1 GeV (Tevatron + LHC), ultimately reduced to 500 MeV

Precision needed : m_W to better than 1 MeV and m_{top} to better than 50 MeV
(and reduce accordingly the relevant systematic and theory uncertainties)

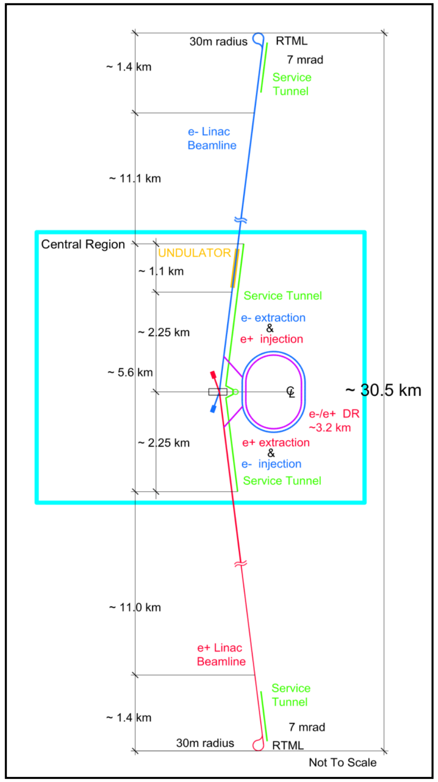
- Also need to increase the statistics at the Z pole significantly

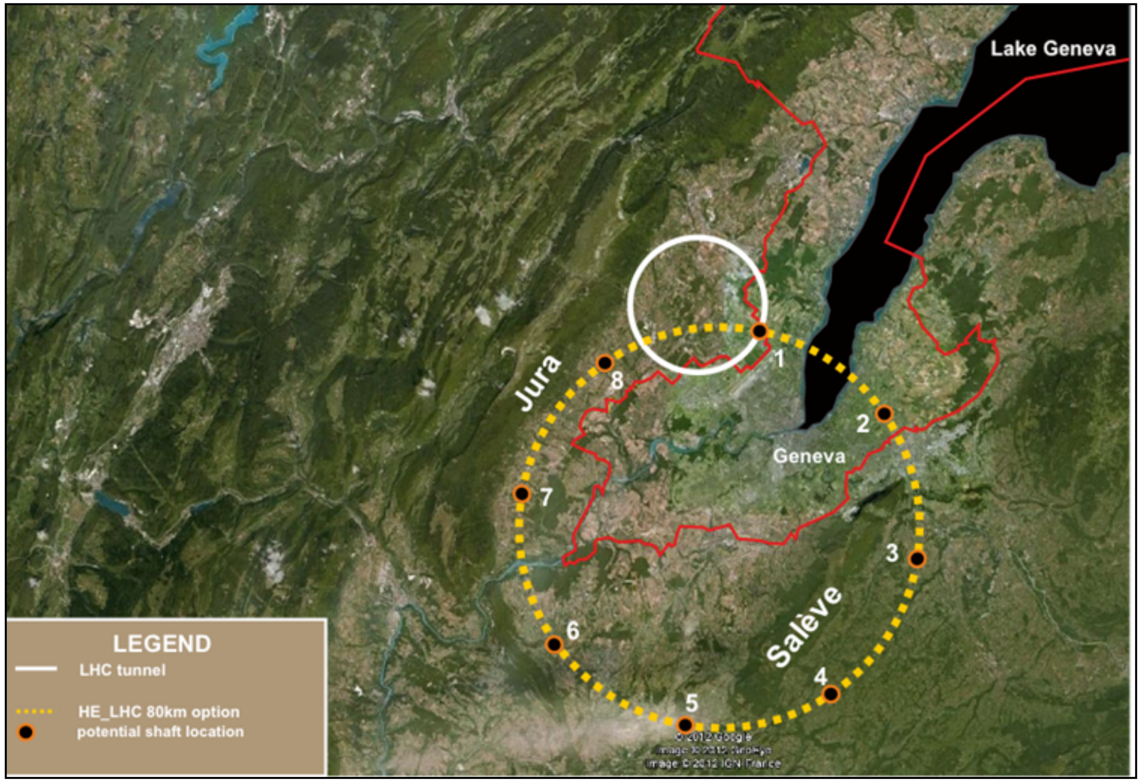
Statistics needed : 4 orders of magnitude above the LEP1 accumulated statistics
(and reduce accordingly the relevant systematic and theory uncertainties)

The Next Machine ?

A precision Higgs Factory

(+ Z, W, and top factories)

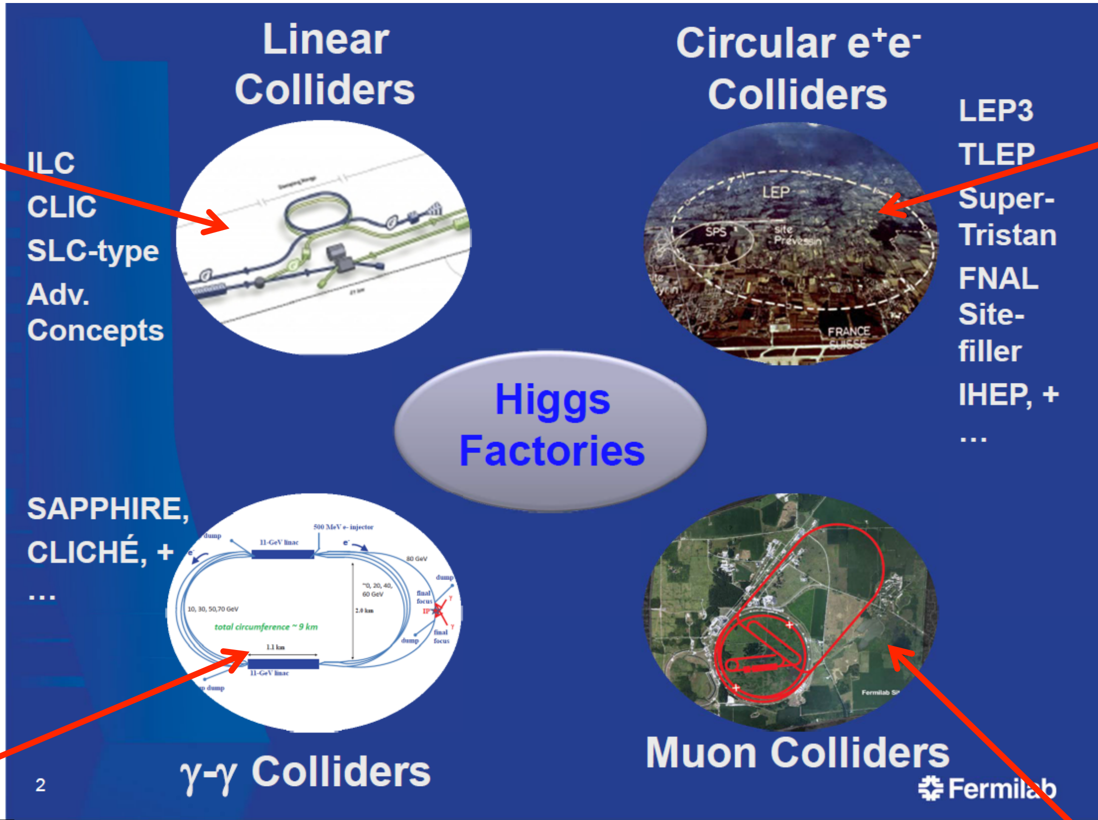




Possible Precision Higgs Factories

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

Studied for decades



More recent proposals
Known technology
Largest Luminosities

Smallest Physics Potential
No Z, W, top

Lots of R&D needed
Small luminosities
Not encouraged by European Strategy

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

Recommendation from European Strategy (1)

- **High-priority large-scale scientific activities**
  - **Second-highest priority, recommendation #2**

d) To stay at the forefront of particle physics, Europe needs to be in a position to propose an ambitious post-LHC accelerator project at CERN by the time of the next Strategy update, when physics results from the LHC running at 14 TeV will be available.

CERN should undertake design studies for accelerator projects in a global context, with emphasis on proton-proton and electron-positron high-energy frontier machines. These design studies should be coupled to a vigorous accelerator R&D programme, including high-field magnets and high-gradient accelerating structures, in collaboration with national institutes, laboratories and universities worldwide.

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- **Excerpt from the CERN Council deliberation document (22-Mar-2013)**

The two most promising lines of development towards the new high energy frontier after the LHC are proton-proton and electron-positron colliders. Focused design studies are required in both fields, together with vigorous accelerator R&D supported by adequate resources and driven by collaborations involving CERN and national institutes, universities and laboratories worldwide. The Compact Linear Collider (CLIC) is an electron-positron machine based on a novel two-beam acceleration technique, which could, in stages, reach a centre-of-mass energy up to 3 TeV. A Conceptual Design Report for CLIC has already been prepared. Possible proton-proton machines of higher energy than the LHC include HE-LHC, roughly doubling the centre-of-mass energy in the present tunnel, and VHE-LHC, aimed at reaching up to 100 TeV in a new circular 80km tunnel. A large tunnel such as this could also host a circular e^+e^- machine (TLEP) reaching energies up to 350 GeV with high luminosity.

Recommendation from European Strategy (2)

- **High-priority large-scale scientific activities**
  - **Third-highest priority, recommendation #3**

e) There is a strong scientific case for an electron-positron collider, complementary to the LHC, that can study the properties of the Higgs boson and other particles with unprecedented precision and whose energy can be upgraded.

The Technical Design Report of the International Linear Collider (ILC) has been completed, with large European participation. The initiative from the Japanese particle physics community to host the ILC in Japan is most welcome, and European groups are eager to participate.
Europe looks forward to a proposal from Japan to discuss a possible participation.

Recommendation from European Strategy (2)

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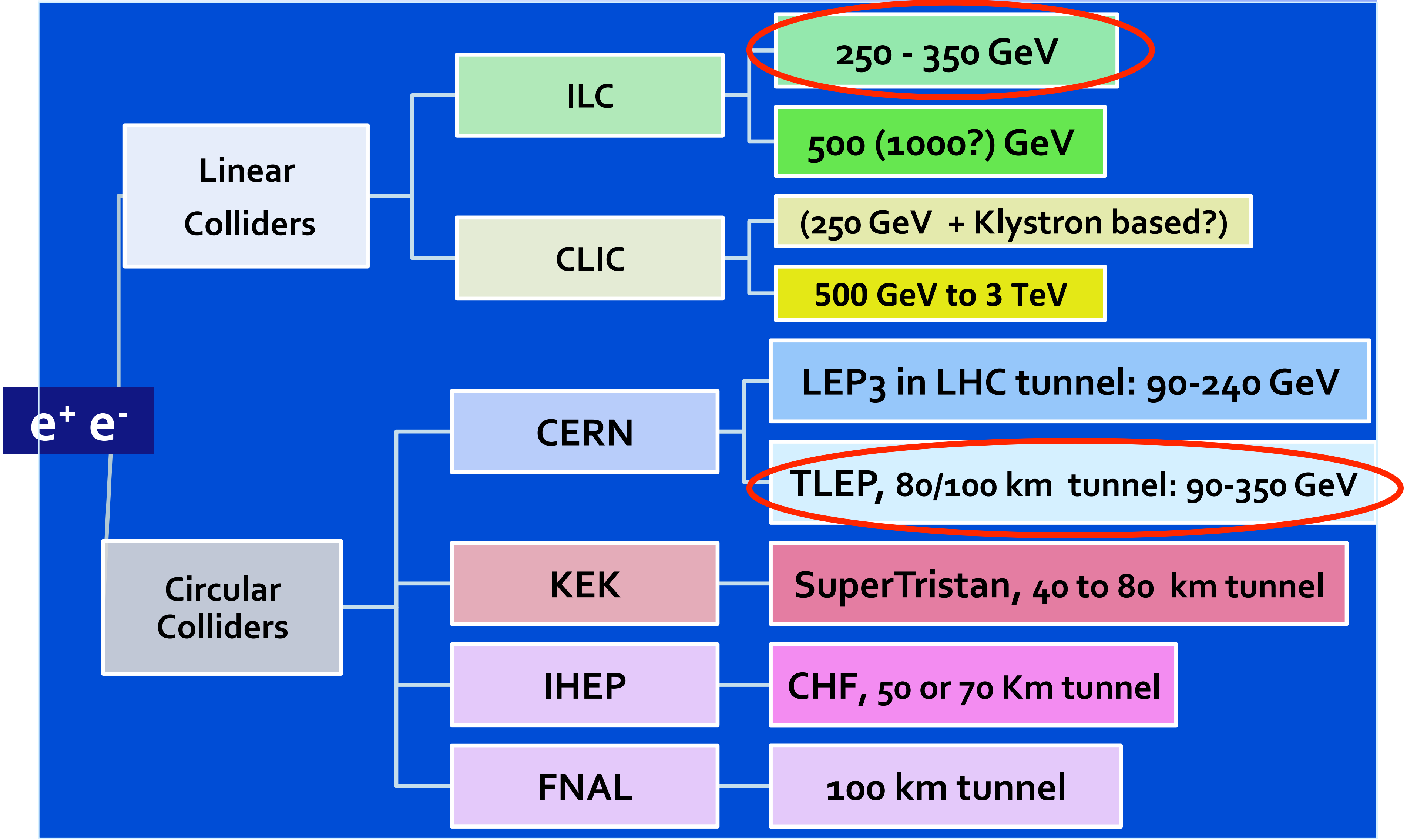
Most promising e^+e^- precision Higgs Factory options :

- **ILC @ 250-350 GeV**
- **TLEP @ 240-350 GeV**

Other e^+e^- Higgs Factories studies in the world



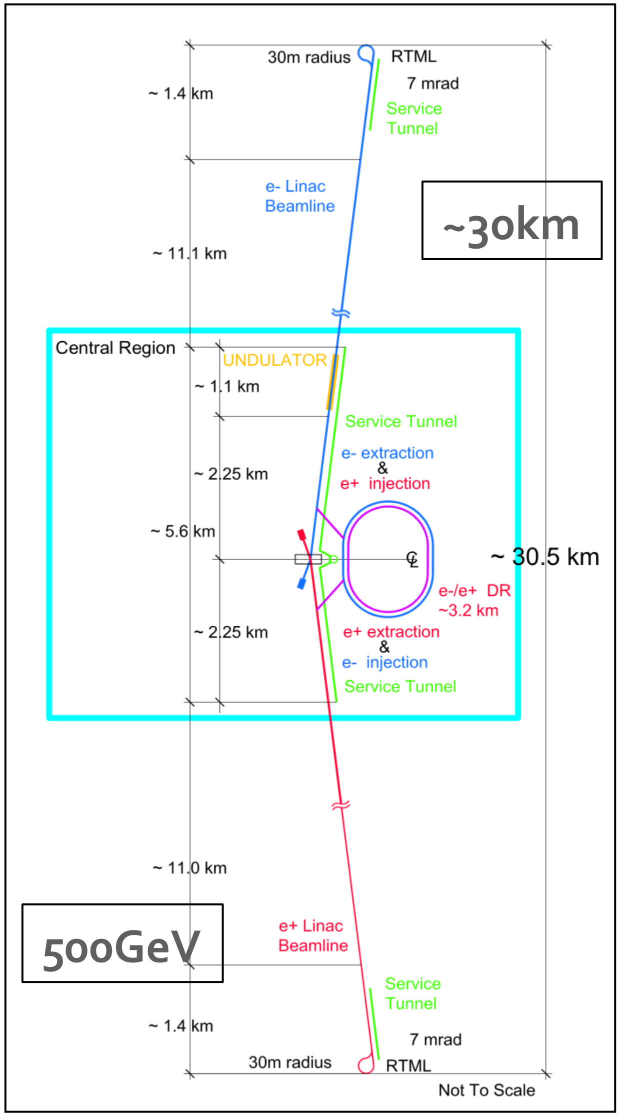
Some ILC Challenges (1)

- **Cost in Million $**

Region	Value (MILCU)
Americas	7,723
Asia	7,982
Europe	7,634

- About 8 Billion $ for the 500 GeV version
  - About 12 Billion $ for the 1 TeV version
- Does not cover a number of items
  - Detectors
    - About 1 Billion per detector
  - Site construction, infrastructure engineering
    - Including land acquisition, tunnel, …

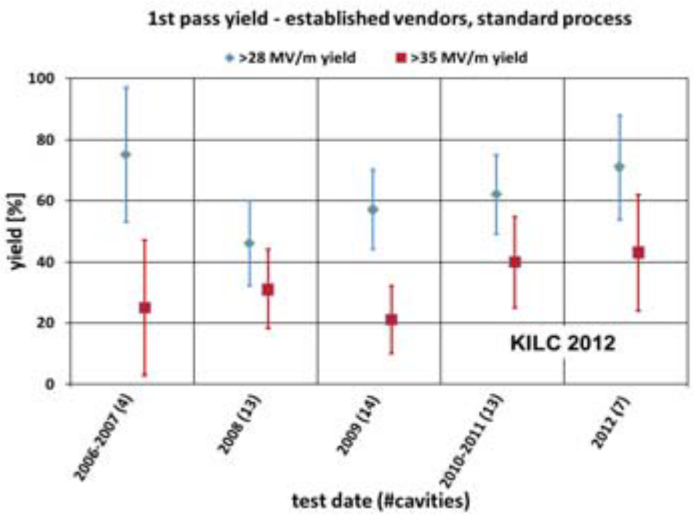
      Check-out the cost for CERN construction
  - Remaining R&D, prototyping, etc.
- Grand-total estimates err around 25 Billion $

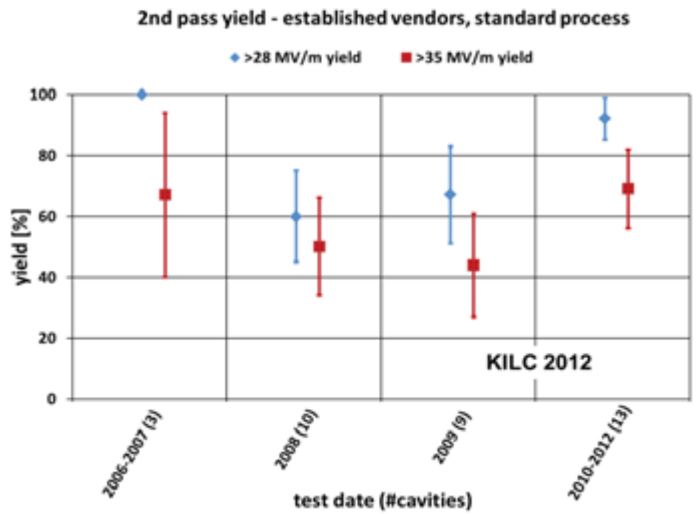


Some ILC Challenges (2)

- **Large-scale industrialization of technology**
  - **Example : RF Cavity production yield @ very high gradient**

Cavity Gradient (MV/m)	31.5
#9-Cell cavities	~16000
#Cryomodules (2K)	~1800
#RF units (10MW Kly)	~560





Some ILC Challenges (3)

- Achieve nano beam size (σ_y ~ 6 nm) with 2×10^{10} e / bunch
  - ATF2 operating since 2009 at KEK, objective 37 nm @ 1.28 GeV
    - Feb. 2012, reached 166 nm at nominal intensity
    - Dec. 2012, reached 72 nm at very low intensity (2×10^{9} e / bunch)
- Realization of very-low emittance damping rings
  - With ultra-fast kickers for beam extraction
- Produce the required positron rate : 3×10^{14} e^+ / second
  - Need 250 m of SC undulators on the 125 GeV electron beam
- Significant R&D ongoing
  - Several issues still being addressed
    - Years of R&D ahead

Energy CM (GeV)	250	500	1000
Luminosity ($\times10^{34}cm^{-2}s^{-1}$)	0.75	1.8	3.6
Beam size (σ_x/σ_y nm)	730/8	470/6	480/3
Pulse duration (ms)	0.75	0.75	0.9
Beam power (MW)	8.4	10.5	27.2
Total AC power (MW)	158	162	300

Some TLEP Challenges (1)

Cost in billion CHF

Bare tunnel	3.1 [(1)]
Services & Additional infrastructure (electricity, cooling, service cavern, RP, ventilation, access roads ...)	1.0[(2)]
RF system	0.9 [(3)]
Cryo system	0.2 [(4)]
Vacuum system & RP	0.5[(5)]
Magnet system for collider & injector ring	0.8[(6)]
Pre-injector complex SPS reinforcements	0.5
Total	**7.0**

(1): J. Osborne, Amrup study, June 2012

(2): Extrapolation from LEP

(3): O. Brunner, detailed estimate, 7 May 2013

(4): F. Haug, 4th TLEP Days, 5 April 2013

(5): K. Oide : factor 2.5 higher than KEK, estimated for 80 km ring

(6): 24,000 magnets for collider & injector; cost per magnet 30 kCHF (LHeC);

Note: detector costs not included – count 0.5 per detector (LHC)

Similar to ILC – but site exists already (if at CERN)

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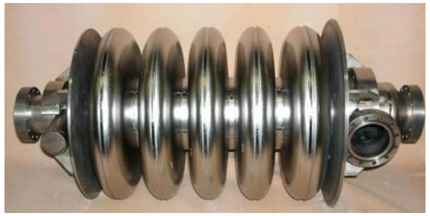
Similar to LEP – but site exists already (if at CERN)

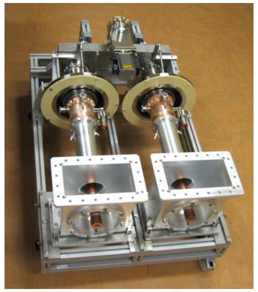
Preliminary
Not endorsed by anybody

Some TLEP Challenges (2)

- At 350 GeV, beams lose 9 GeV / turn by synchrotron radiation
  - Need 600 5-cell SC cavities @ 20 MV/m
    - Much less than ILC, but still a challenge
    - 200 kW/ cavity : RF couplers are an issue too
  - Heat extraction, shielding against radiation, …



BNL 5-cell 700 MHz cavity



RF Coupler (ESS/SPL)

- Achieve luminosity with small vertical beam size : σ_y ~ 100 nm
  - A factor 30 smaller than at LEP2, but a factor 2 larger than SuperKEKB
    - Much more relaxed than ILC (6-8 nm)
  - At smaller √s, increase the number of bunches to saturate the RF power

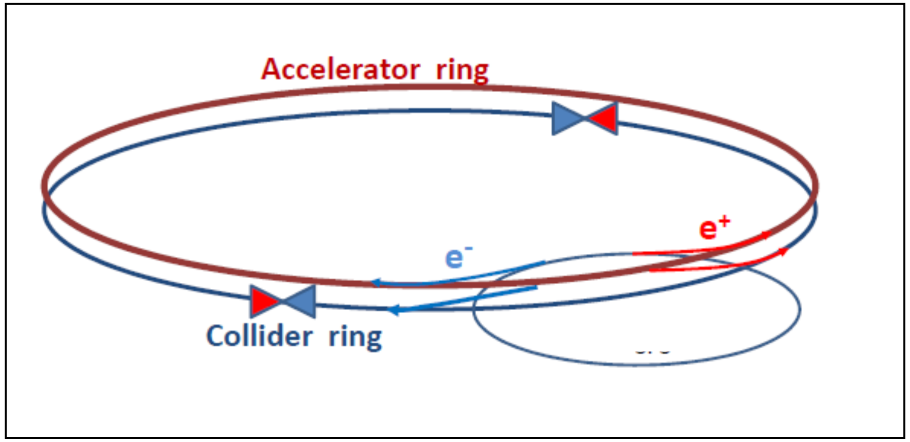
√s (GeV)	90	160	240	350
Luminosity ($\times 10^{34} cm^{-2}s^{-1}$)/IP	56	16	5	1.3
Vertical Beam Size	270	140	140	100
RF Cavity Gradient	3	3	10	20
Number of bunches	4400	600	80	12
Beam lifetime (mn)	67	25	16	27
Total AC power (MW)	250	250	260	284

A. Blondel et al.
arXiV:1305.6498

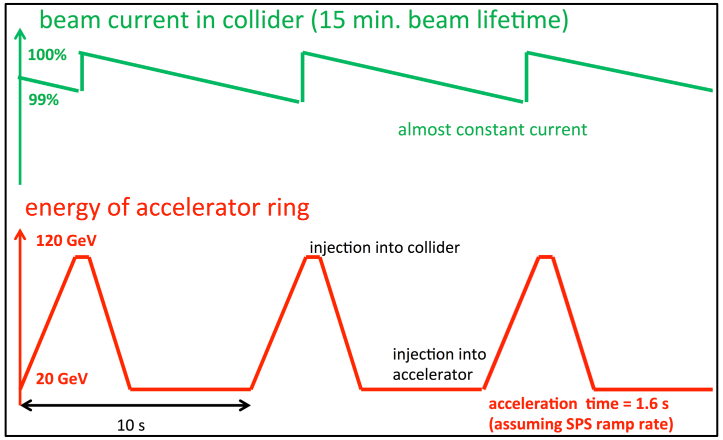
Some TLEP Challenges (3)

- Beam lifetime due to Bhabha scattering ~ 15 minutes
  - Will be ~ 5 minutes at SuperKEKB
    - Need to design an efficient top-up injector

A. Blondel

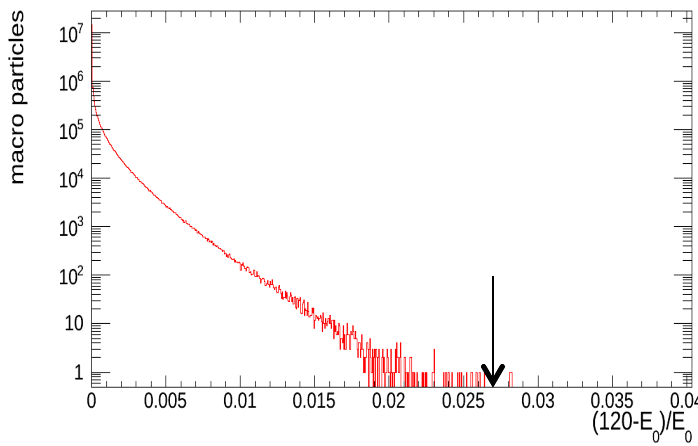


F. Zimmermann



- Beam lifetime further reduced by beamstrahlung
  - Radiating $e^{\pm}$ pushed outside the acceptance
  - Need to design an achromatic optics at the IPs
    - with 2-3% momentum acceptance
- Operation at the Z pole : 1.2 A / beam
  - Need 2×10^{12} e^{+} / second from positron source
    - Large, but 100 times smaller than ILC

M. Zanetti



ILC/TLEP Extrapolations

- Extrapolation from past experience

F. Zimmermann

	LEP2→TLEP-H	SLC→ILC 250
peak luminosity	× 400	× 2500
energy	× 1.15	× 2.5
vertical geom. emittance	× 1/5	× 1/400
vert. IP beam size	× 1/20	× 1/150
e^+ production rate	× 0.5 !	× 65
RF System Length	× 0.8 !	× 10
commissioning time	<1 year → ?	>10 years →?

- SuperKEKB will be an excellent test-bench for TLEP
  - In many respects
- Will also learn a lot from ATF2
- Lot of work ahead to reach ILC beam dimensions

Example : beam size @ IP

LEP2	3500
KEKB	940
SLC	500
LEP3	*320*
TLEP-H	*140*
ATF2, FFTB	72, 65
SuperKEKB	*50*
SAPPHiRE	*18*
ILC	*5 – 8*
CLIC	*1 – 2*

ILC/TLEP Extrapolations

Extrapolation from past experience

F. Zimmermann

	LEP2→TLEP-H	SLC→ILC 250
peak luminosity	× 400	× 2500
energy	× 1.15	× 2.5
vertical geom. emittance	× 1/5	× 1/400
vert. IP be		
e⁺ produc		
RF Syster		
commissi		→?

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

- Su ... EP
- W
- Lo
- Estimates for circular colliders historically reliable

Example : beam size @ IP

LEP2	3500
KEKB	940
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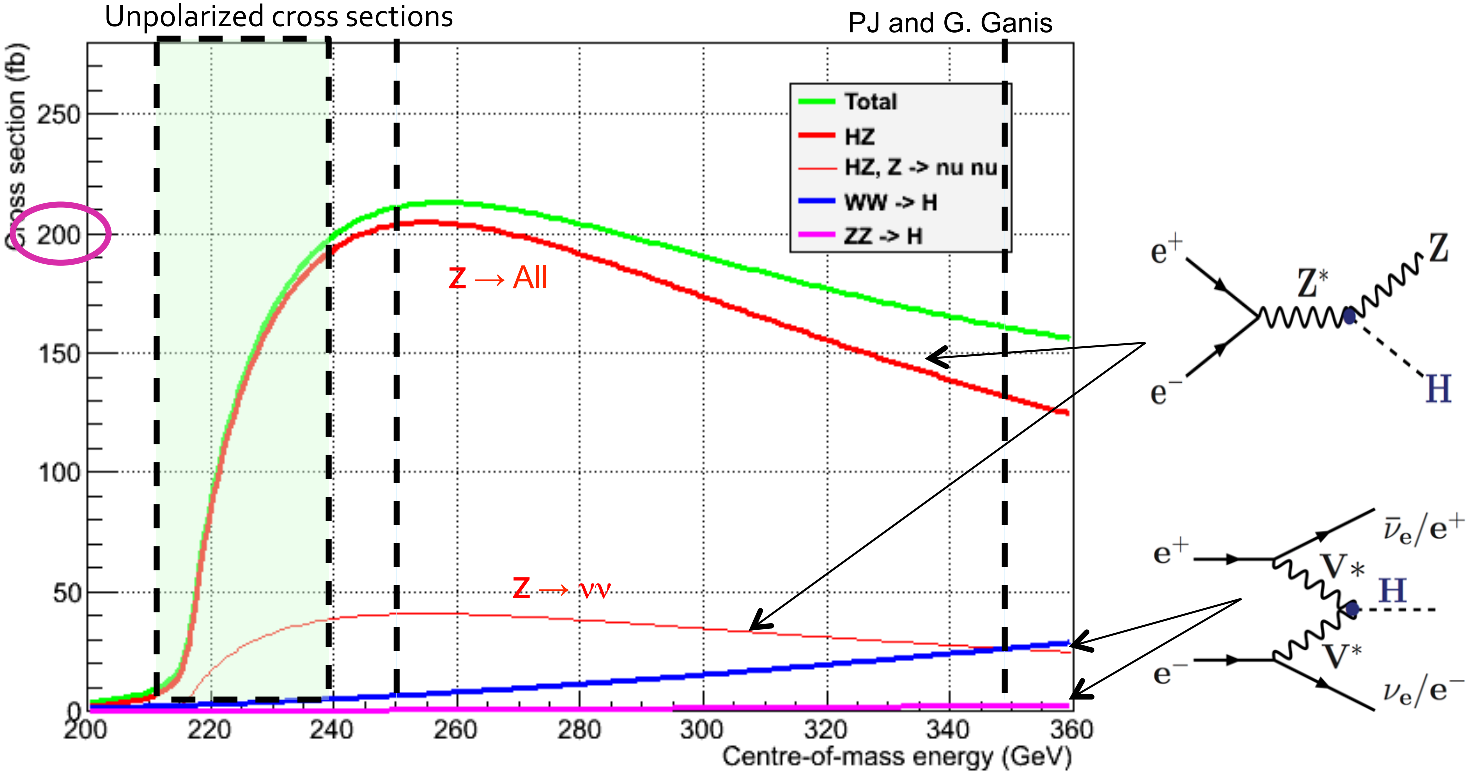
LEP3	*320*
TLEP-H	*140*
ATF2, FFTB	72, 65
SuperKEKB	*50*
SAPPHiRE	*18*
ILC	*5 – 8*
CLIC	*1 – 2*

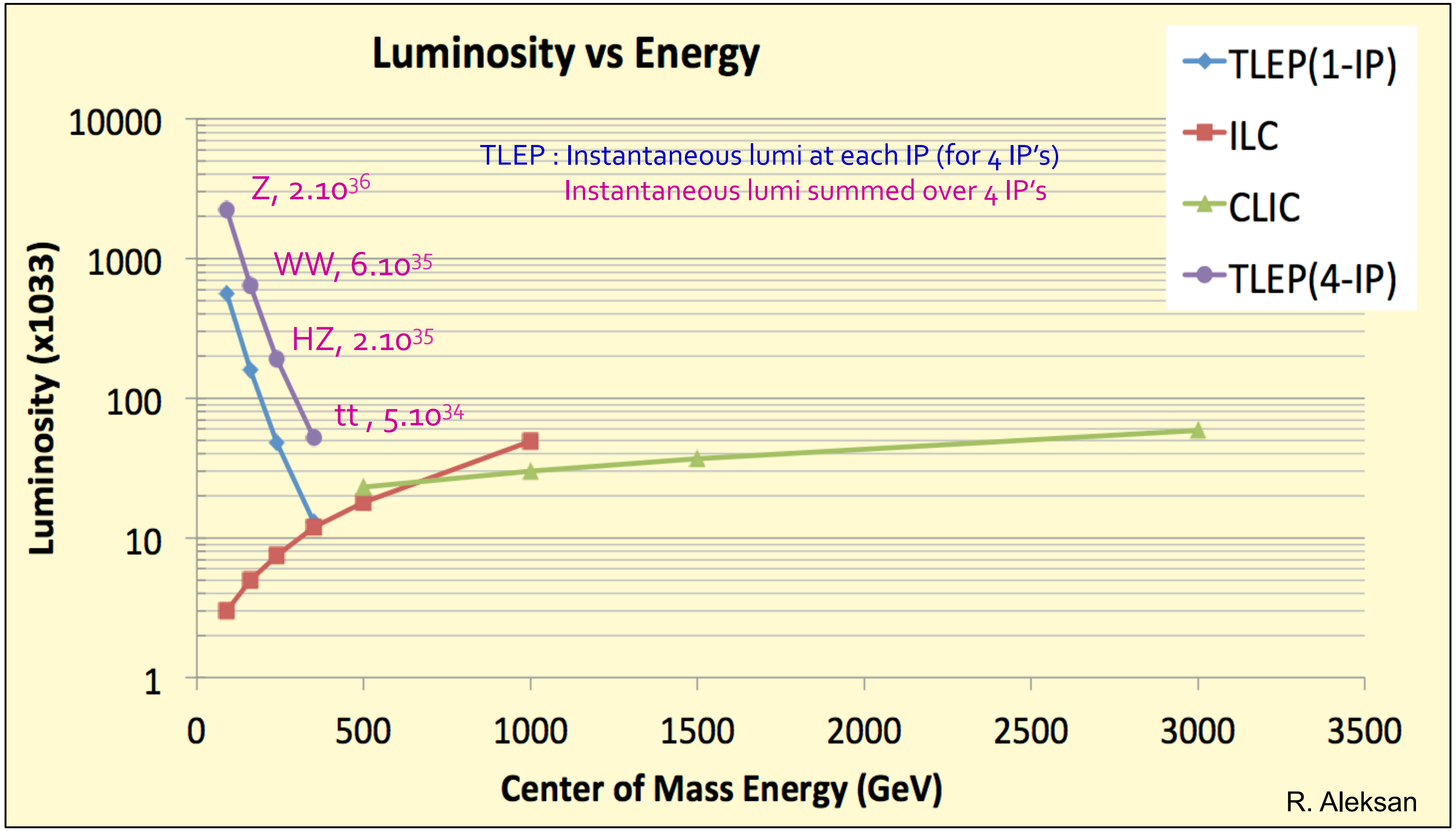
Performance Comparison (1)

- Physics case as a Higgs Factory
  - Similar : Not driven by the fact that the collider is linear or circular
    - Scan of the HZ threshold : √s = 210-240 GeV — Spin
    - Maximum of the HZ cross section : √s = 240-250 GeV — Mass, σ_{HZ}, BRs, Width, …
    - Just below or at the tt threshold : √s ~ 340-350 GeV — Width



Performance Comparison (2)

- **Luminosity : Circular colliders can have several IP's**



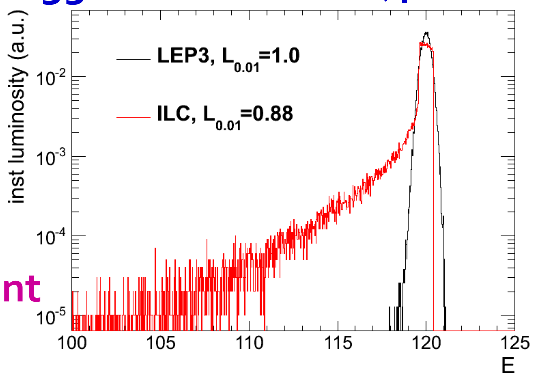
- **Note : Lumi upgrade (×3) now envisioned at ILC : luminosity is the key at low energy !**
  - **Crossing point between circular and linear colliders ~ 450 GeV**

Performance Comparison (3)

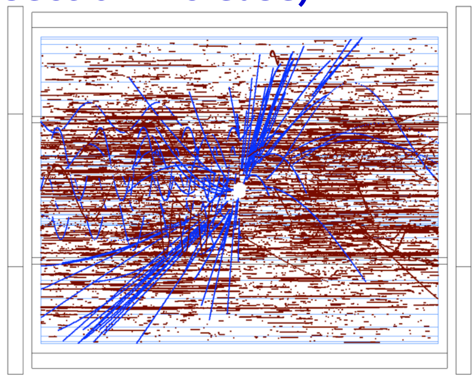
- Number of Higgs Bosons produced at $\sqrt{s}$ = 250 & 350 GeV

	ILC-250	TLEP-240	ILC-350	TLEP-350
Lumi / IP / 5 yrs	250 fb^{-1}	2.5 ab^{-1}	350 fb^{-1}	650 fb^{-1}
# IP	1	4	1	4
Lumi / 5 yrs	250 fb^{-1}	10 ab^{-1}	350 fb^{-1}	2.5 ab^{-1}
Beam Polarization	80%, 30%	–	80%,30%	–
$L_{0.01}$ (beamstrahlung)	88%	100%	80%	100%
# of HZ events	70,000	2,000,000	65,000	325,000
# of WW→H events	1,500	50,000	12,000	65,000

- Beam polarization not critical for Higgs boson studies (40% cross section increase)
  - Beamstrahlung is critical
    - Beam energy
    - γγ Pileup
    - Beam backgrounds
    - Luminosity measurement
    - ...



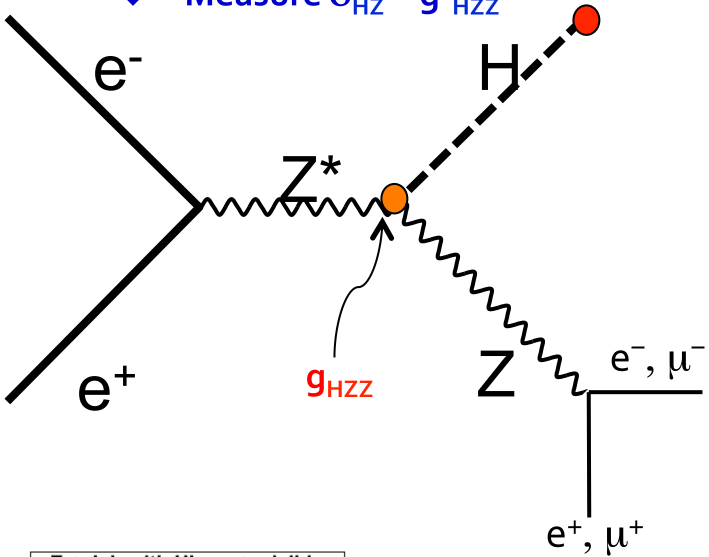
M. Zanetti

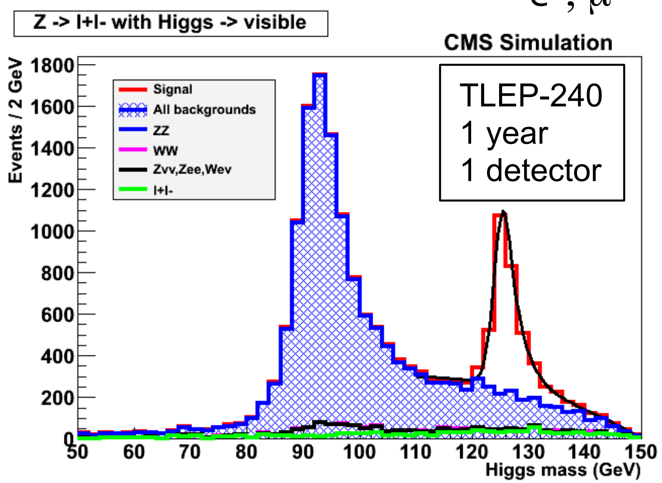


ILD TPC at 500 GeV

Performance Comparison (4)

- **Example : $e^+e^- \rightarrow ZH \rightarrow l^+l^-$ + anything**
  - Measure $\sigma_{HZ} \sim g^2_{HZZ}$





Summary of measurements

	ILC-250	TLEP-240
σ_{HZ}	2.5%	0.4%
$\sigma_{HZ} \times BR(H \rightarrow bb)$	1.0%	0.1%
$\sigma_{HZ} \times BR(H \rightarrow cc)$	6.9%	1.3%
$\sigma_{HZ} \times BR(H \rightarrow gg)$	8.5%	1.4%
$\sigma_{HZ} \times BR(H \rightarrow WW^*)$	8.0%	0.9%
$\sigma_{HZ} \times BR(H \rightarrow \tau\tau)$	5.0%	0.9%
$\sigma_{HZ} \times BR(H \rightarrow ZZ^*)$	28%	3.1%
$\sigma_{HZ} \times BR(H \rightarrow \gamma\gamma)$	27%	3.0%
$\sigma_{HZ} \times BR(H \rightarrow \mu\mu)$	–	13%
Γ_{INV} / Γ_H	< 1.5%	< 0.3%
m_H	40 MeV	8 MeV
	ILC-350	TLEP-350
$\sigma_{WW \rightarrow H}$	3%	0.5%
Γ_H	5.5%	1.1%

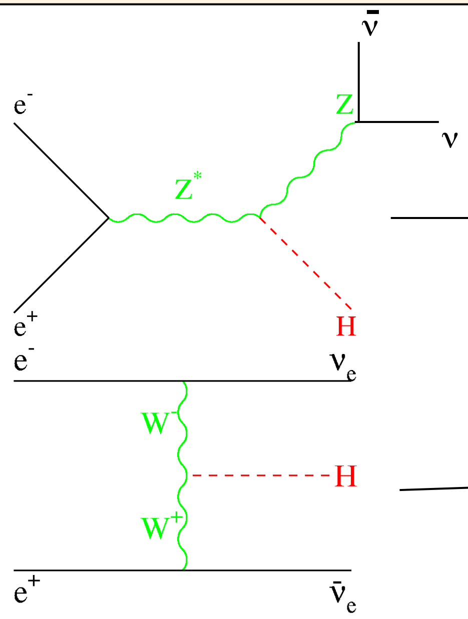
Performance Comparison (5)

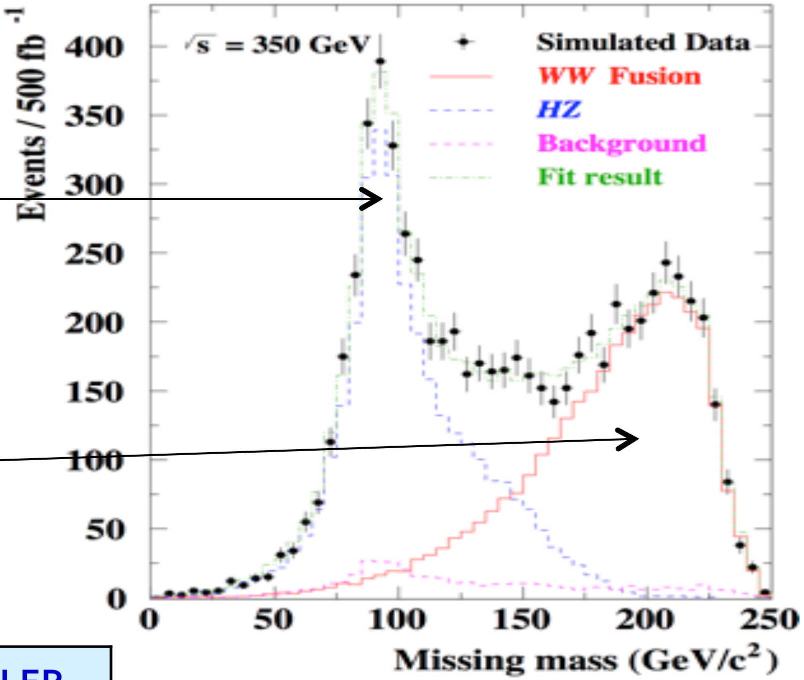
- **Determination of the total width**
  - From the number of HZ events and of ZZZ events at √s = 240 GeV

$$\sigma_{HZ} \propto g_{HZZ}^2, \text{ and } \sigma_{HZ} \times \mathrm{BR}(H \to ZZ) \propto g_{HZZ}^4 / \Gamma_H \Rightarrow \Gamma_H \propto \sigma_{HZ}^2 / \sigma_{HZ} \times \mathrm{BR}(H \to ZZ)$$

  - From the bbνν final state at √s = 350 GeV

$$\Gamma_H \propto \sigma_{WW\to H} / \mathrm{BR}(H \to WW) = \sigma_{WW\to H\to bb} / \mathrm{BR}(H \to WW) \times \mathrm{BR}(H \to bb)$$





	ILC	TLEP
Γ_H	5.5%	1.1%

Performance Comparison (6)

- Precision on couplings, cross sections, mass, width, …
  - Summary of the ICFA HF2012 workshop (FNAL, Nov. 2012)

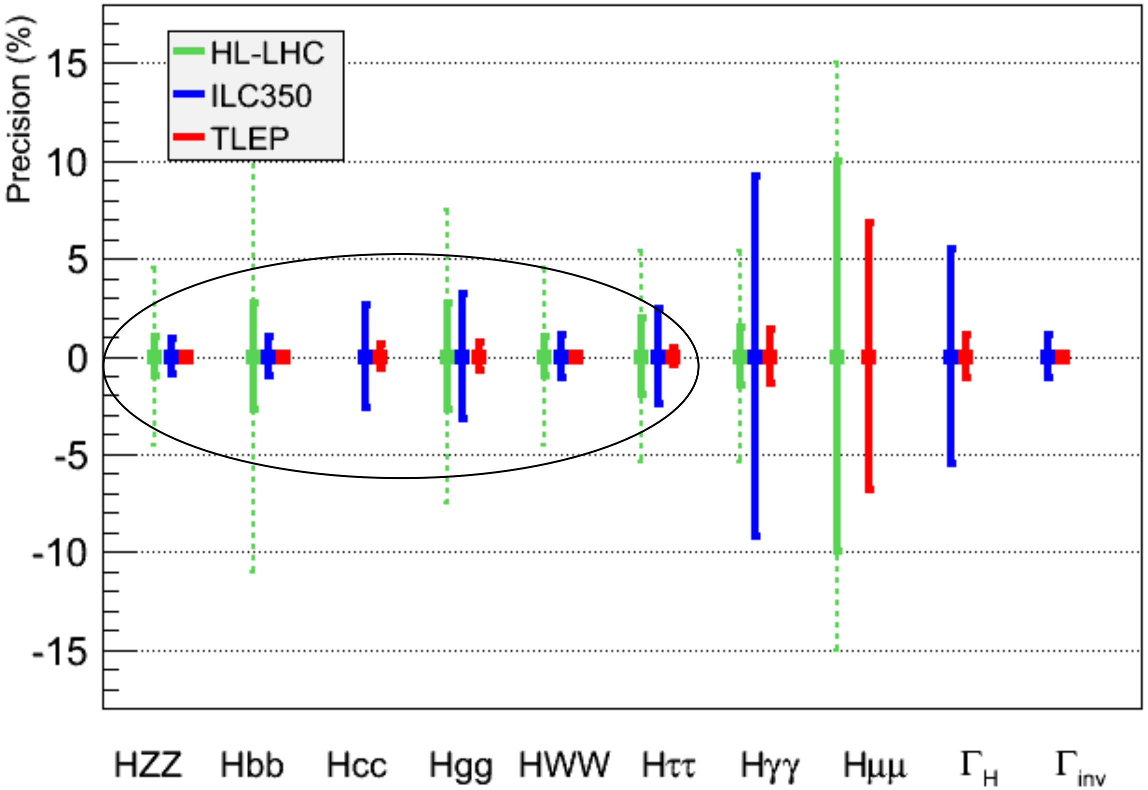
Table 2.1: Expected performance on the Higgs boson couplings from the LHC and e^+e^- colliders, as compiled from the Higgs Factory 2012 workshop. CLIC numbers from Ref [11-12].

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

Best precision

Performance Comparison (7)

- **Same assumptions as for HL-LHC for a sound comparison**
  - **Assume no exotic decay for the Higgs boson**



- **ILC complementary to HL-LHC (g_{Hcc}, Γ_H, Γ_{inv})**

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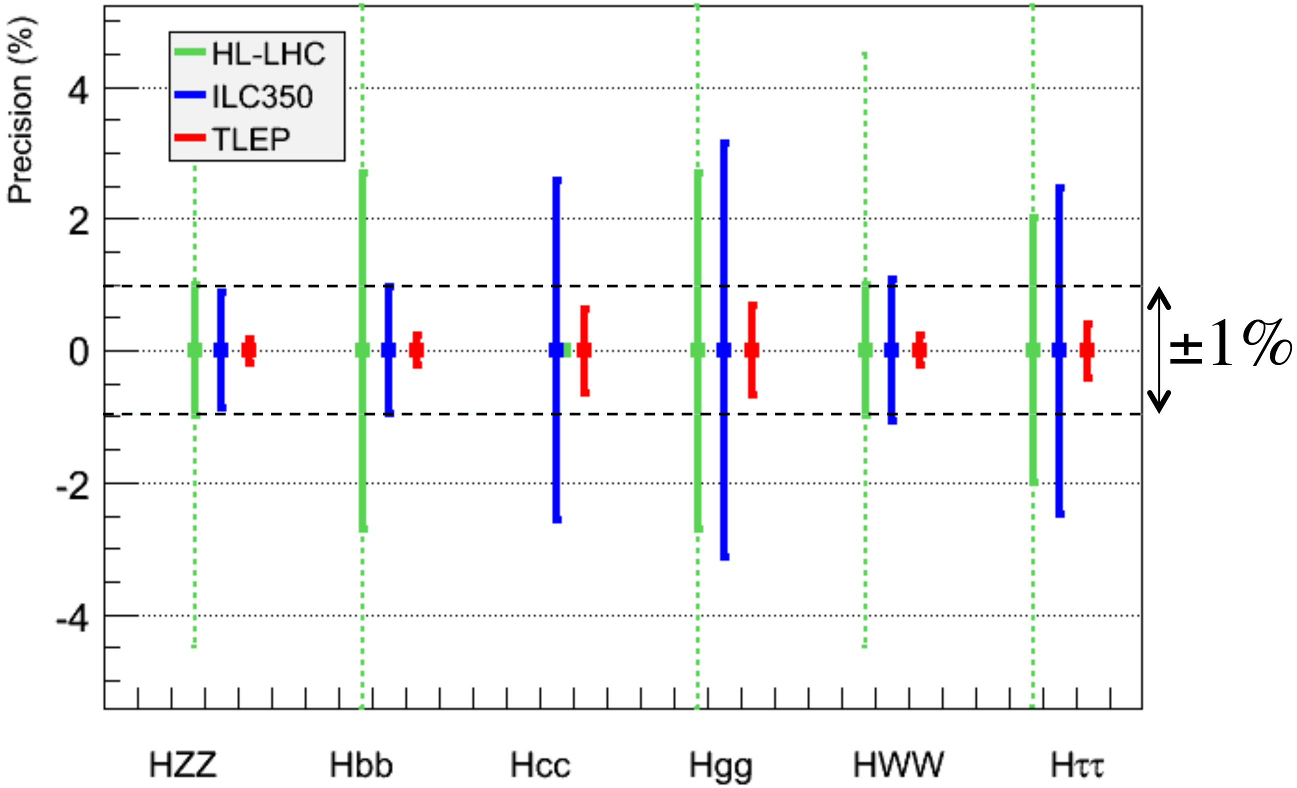

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  - ➨ **TLEP reaches the sub-per-cent precision (>1 TeV BSM Physics)**

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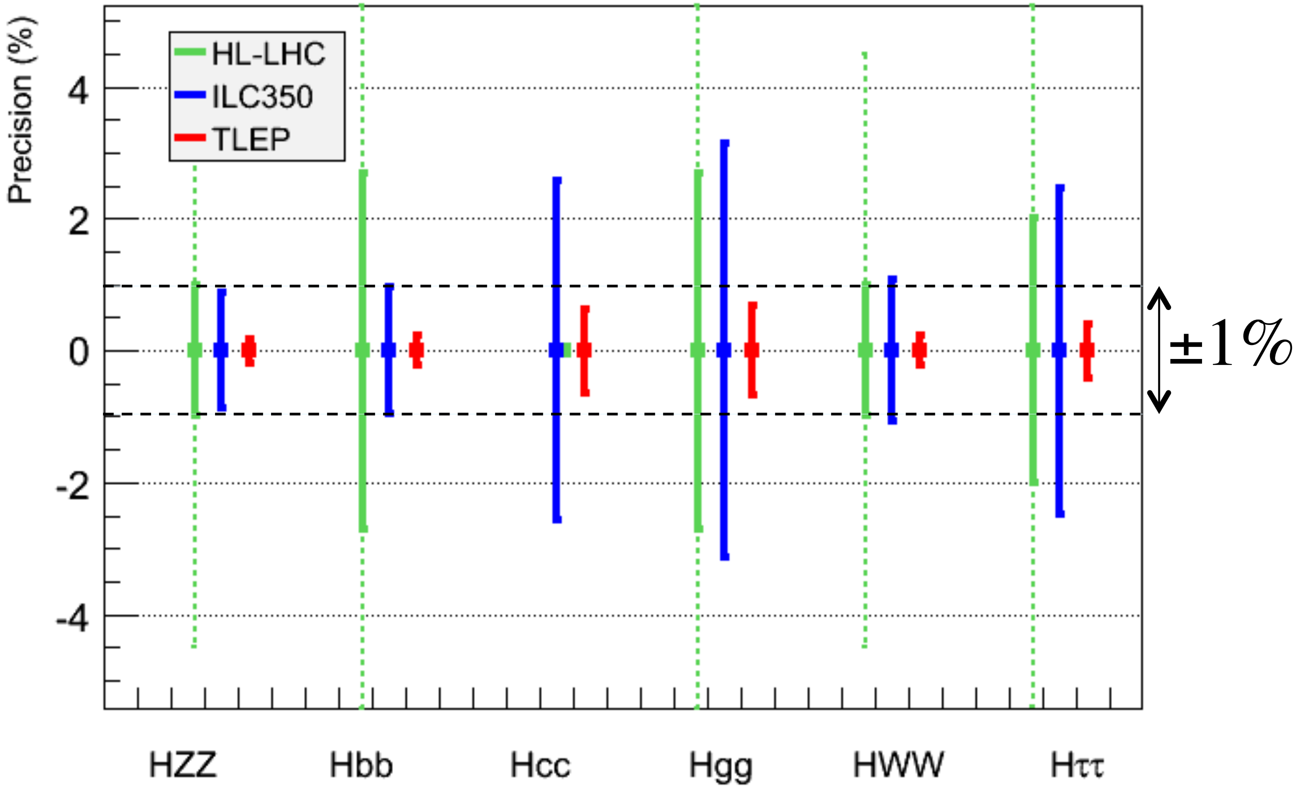
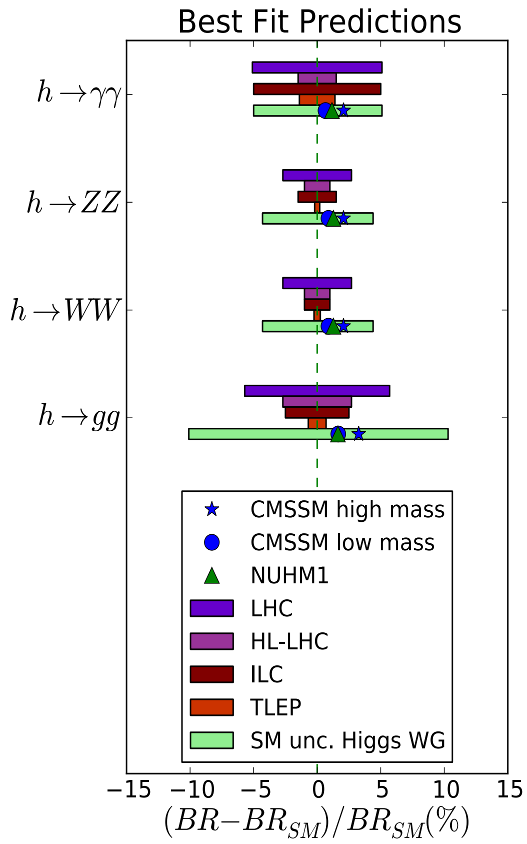




J. Ellis et al.

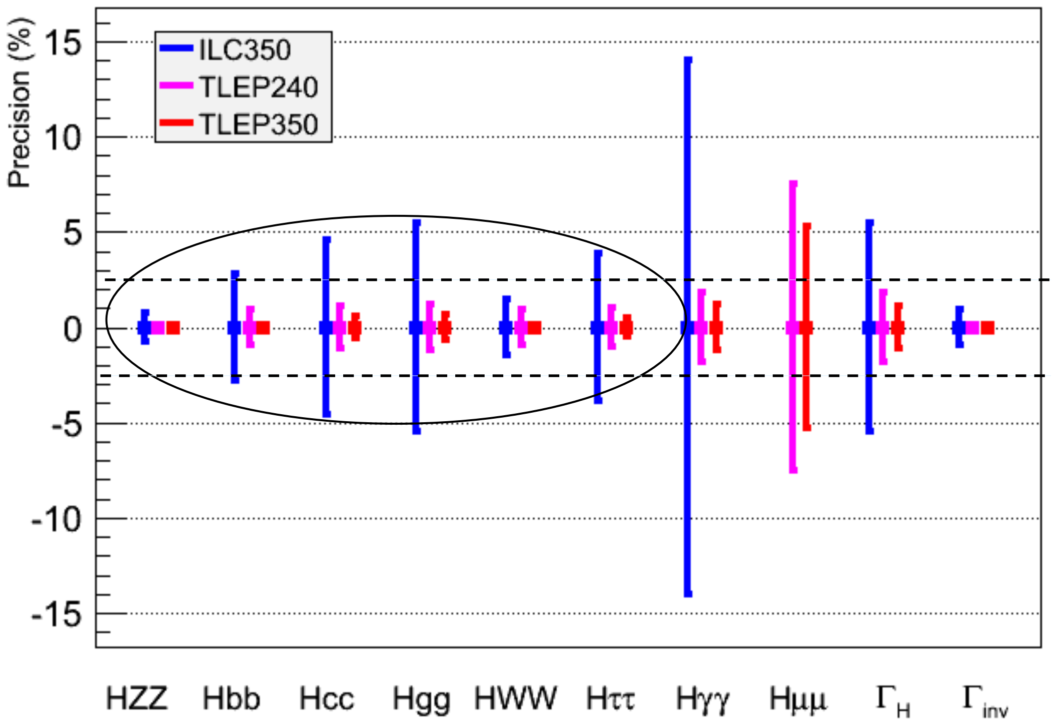
- ILC complementary to HL-LHC (g_{Hcc}, Γ_H, Γ_{inv})
  - ➨ TLEP reaches the sub-per-cent precision (>1 TeV BSM Physics)

Progress on the theoretical side also needed

Performance Comparison (8)

- **Conclusion reinforced when Γ_H is a free parameter in the fit**

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



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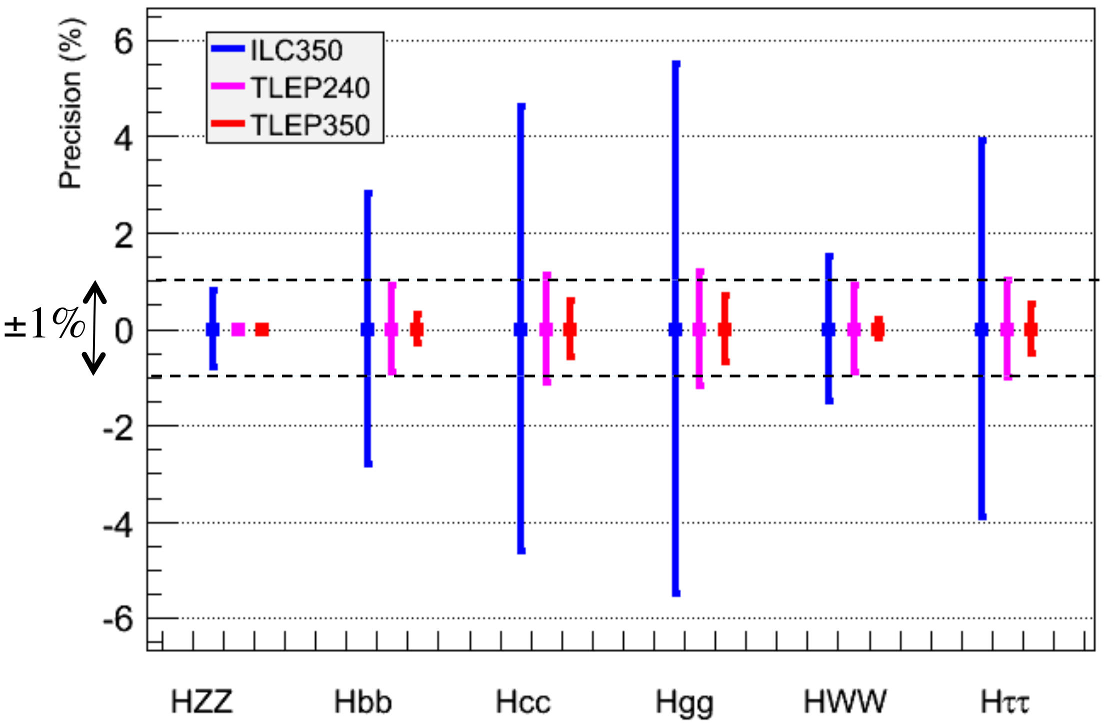


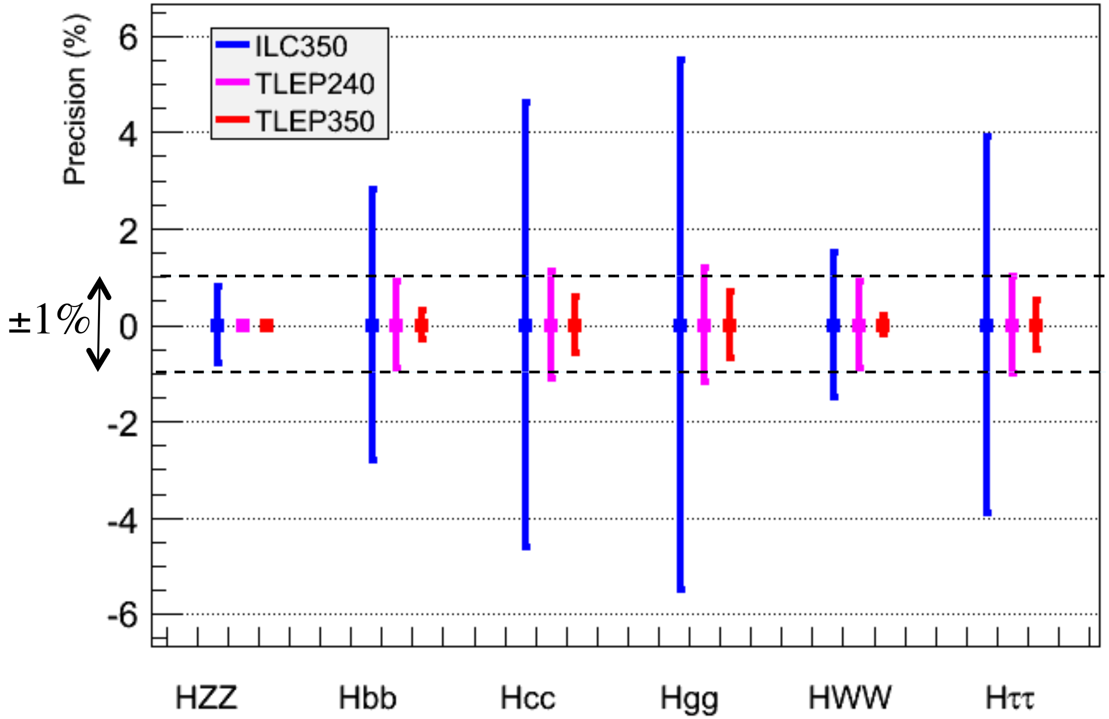
- **TLEP : sub-percent precision, adequate for BSM Physics sensitivity beyond 1 TeV**

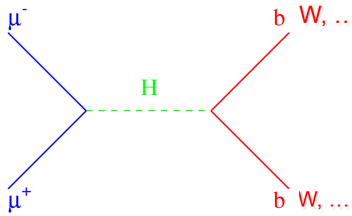
Performance Comparison (8)

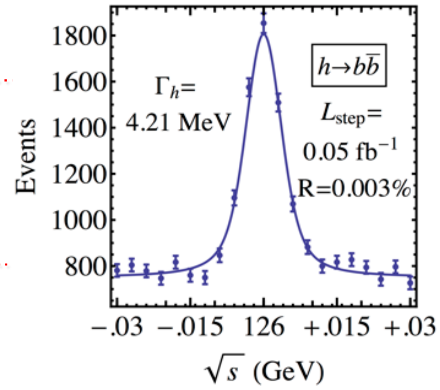
- **Conclusion reinforced when Γ_H is a free parameter in the fit**

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

Note : Determination of the total width better with e^+e^- collider than with $\mu^+\mu^-$ collider







Expected precision on the total width

$\mu^+\mu^-$	ILC350	ILC1000	TLEP240	TLEP350
5%	5%	3%	2%	1%

- **TLEP : sub-percent precision, adequate for BSM Physics sensitivity beyond 1 TeV**

Performance Comparison (9)

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

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

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

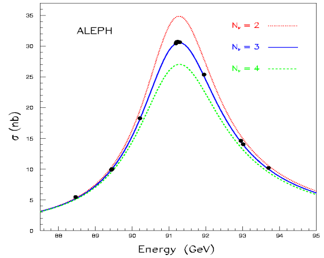
It will be obvious that - weighting all claims equally - TLEP has the best capabilities. It has the highest luminosity, can plausibly support multiple detectors, and can reach energies well above the Higgs threshold. In the following, I will omit the comparison with TLEP in the figures. The final errors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

Performance Comparison (10)

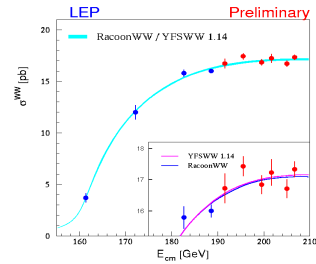
❑ Precision tests of EWSB

	LEP	ILC	TLEP
$\sqrt{s} \sim m_Z$	Mega-Z	Giga-Z	**Tera-Z**
#Z / year Polarization **Precision vs LEP1** **Error on m_Z, Γ_Z**	2×10^7 Yes (T) **1** **2 MeV**	Few 10^9 Easy **1/5 to 1/10** **–**	**10^{12} (>10^{11} b,c,τ)** Yes (T,L) **~1/100** **< 0.1 MeV**
$\sqrt{s} \sim 2m_W$			
#W pairs / year Polarization **Error on m_W**	Few dozens No **220 MeV**	2×10^5 Easy **7 MeV**	**2.5×10^7** Yes (T) **0.5 MeV**
$\sqrt{s}$ = 240 GeV			**Oku-W**
# W pairs / 5 years **Error on m_W**	4×10^4 **33 MeV**	4×10^6 **3 MeV**	**2×10^8** **0.5 MeV**
$\sqrt{s} \sim 350$ GeV			**Mega-Top**
# top pairs / 5 years **Error on m_{top}** **Error on λ_t**	– **–** **–**	100,000 **30 MeV** **40%**	**500,000** **13 MeV** **15%**

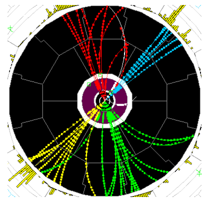
Asymmetries, Lineshape



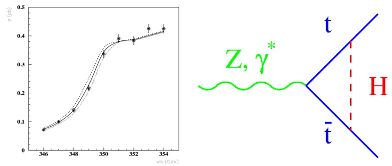
WW threshold scan



WW production

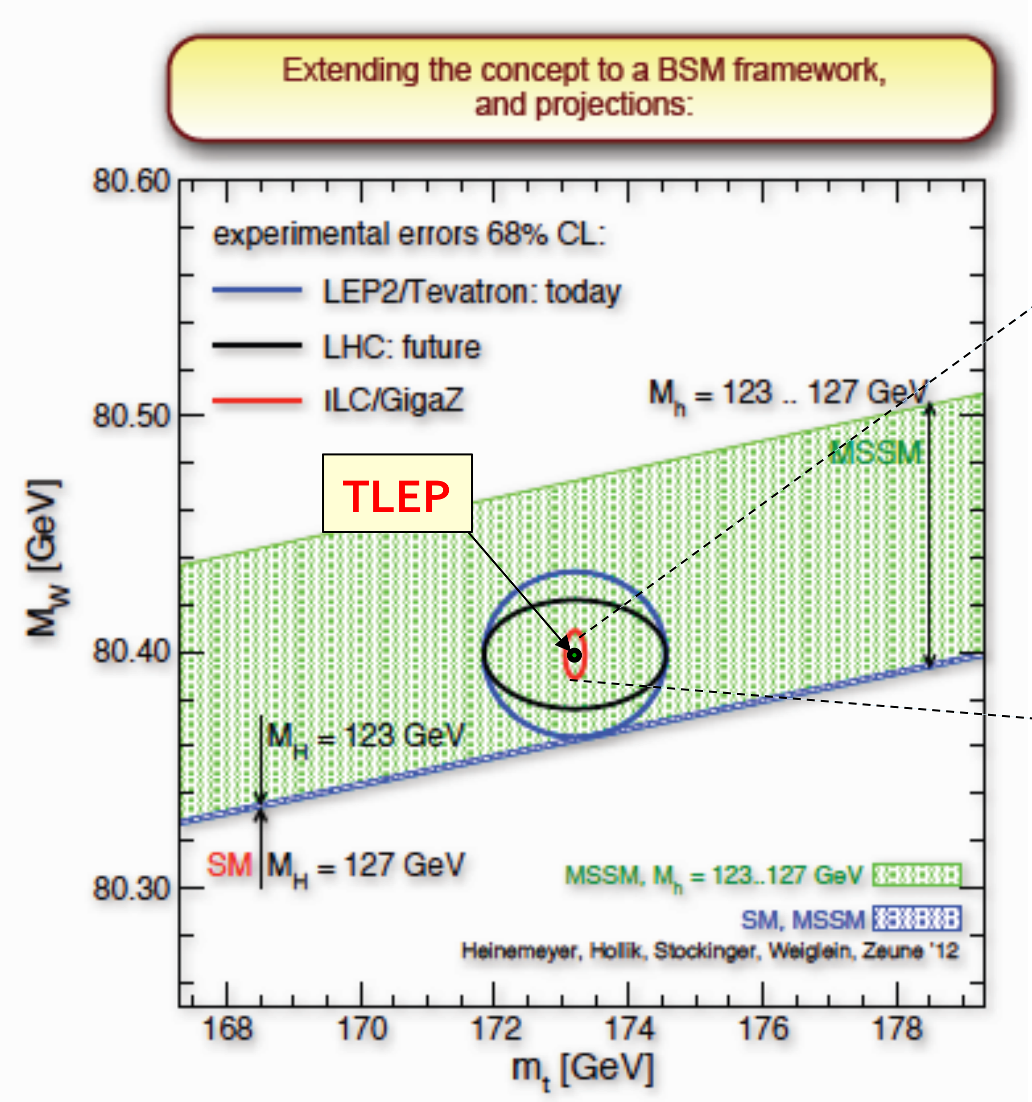


$t\bar{t}$ threshold scan

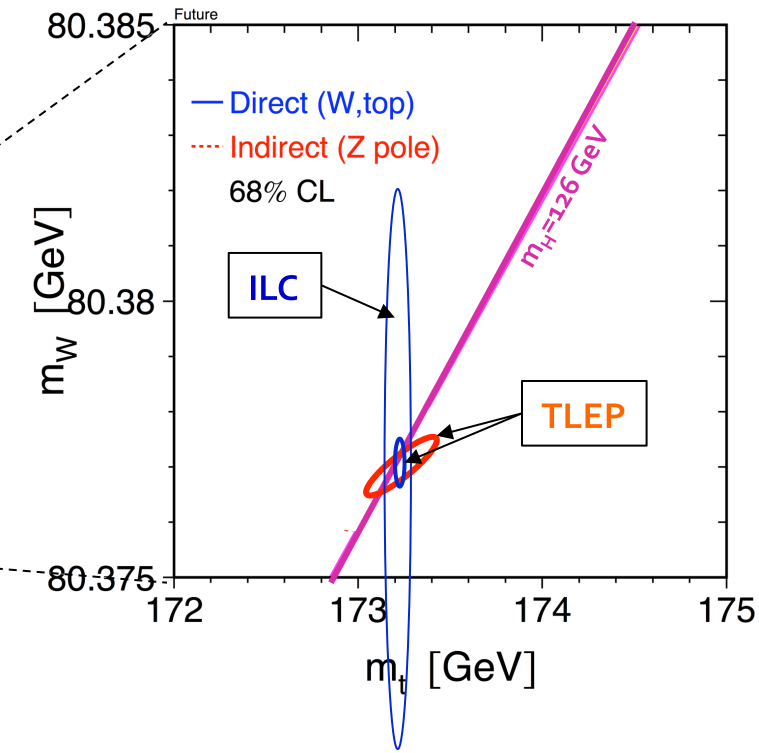


- ◆ **TLEP meets the precision requirements (slide 8)**

Performance Comparison (11)



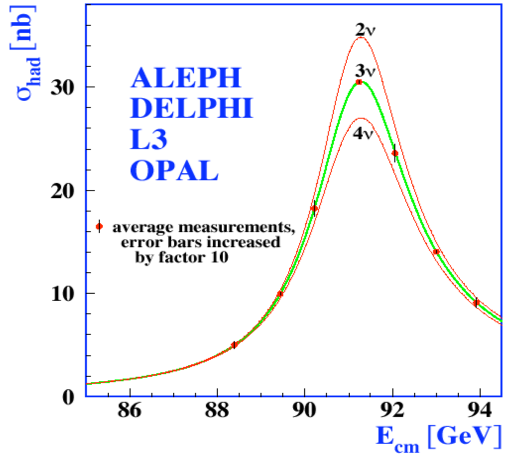
Warning : indicative only.
Complete study being done



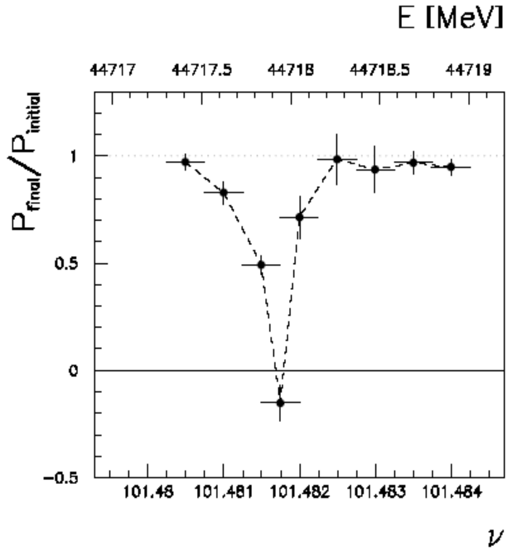
Very stringent SM closure test.
Sensitivity to weakly-interacting multi-TeV BSM Physics.

TLEP-Z , TLEP-W: A few remarks (1)

- **TLEP-Z : Hadronic Z event rate ~ 15 kHz in each detector**
  - Trigger rate 15 times larger than in LHC experiments
    - Event size / reconstruction time 20 times smaller
  - Bunch crossing rate similar to LHC (4000 bunches over 80km)
    - Need similarly fast detector / electronics
  - LEP1 physics programme can be repeated every 15 minutes
    - A trillion Z decays (10^{12}) in one year
    - A great tool for detector calibration for higher $\sqrt{s}$ runs

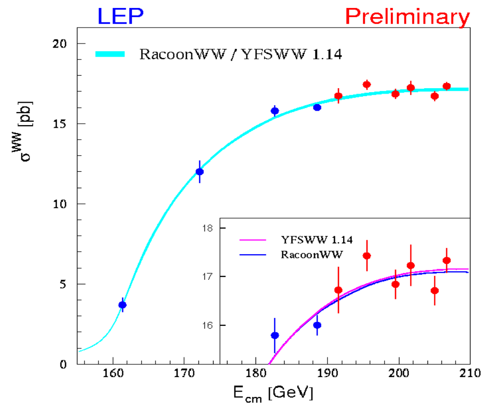


- **Ultra-precise beam energy measurement is required**
  - Resonant depolarization unique @ circular machines
    - Intrinsic precision ~ 100 keV (LEP1) / measurement
      - ➨ Decreases like 1 / √#(Measurements)
  - Requires beam transverse polarization
    - In one non-colliding bunch, during operations
      - ➨ Continuous energy measurement
      - ➨ No extrapolation needed (tides, trains, rain…)
  - Can measure m_Z and Γ_Z to better than 0.1 MeV
    - To be compared to 2 MeV at LEP1



TLEP-Z , TLEP-W: A few remarks (2)

- **TLEP-Z : Measurement of A_{LR} requires longitudinal polarization**
  - Will require spin rotators, polarimeters
    - And the real challenge : keep the polarization during collisions
      - A dedicated run with lower luminosity is envisioned
      - Towards measuring $\sin^2\theta_W$ with a precision of 2.10^{-6}
- **TLEP-W : Measurement of m_W requires transverse polarization too**
  - Towards the precise measurement of the beam energy
    - Statistical precision on m_W of 0.5 MeV is at hand
  - Straight extrapolations from LEP show that it's possible
    - Got 5% polarization at E_{beam} = 60 GeV
      - With 80 km, can have 5% at 81 GeV
  - E_{beam} measurement at higher $\sqrt{s}$ will use ZZ and $Z(\gamma)$ events

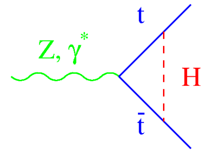


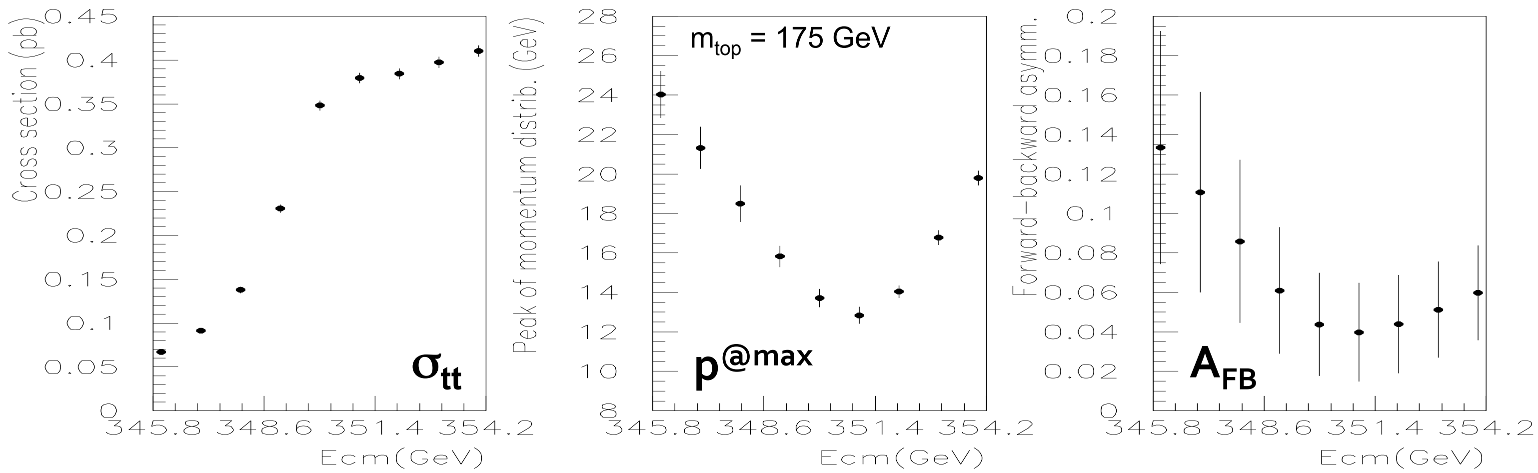
- **A lot of work to be done**
  - On the theoretical side
  - On the experimental systematic effects
    - To match theory and experimental uncertainties to the statistical uncertainties

TLEP-t : A few remarks

337 339 341 343 345 347 349 351 (m_{top} = 172.5 GeV)

- **Scan of the tt threshold**
  - Observables σ_{tt}, A_{FB} and <$p^{@max}$> sensitive to m_{top}, Γ_{top}, and λ_{top} (ttH Yukawa coupling)
    - Experimental precision for ILC with 100,000 $t\bar{t}$ events
      - ➨ No beamstrahlung and 500,000 $t\bar{t}$ events at TLEP





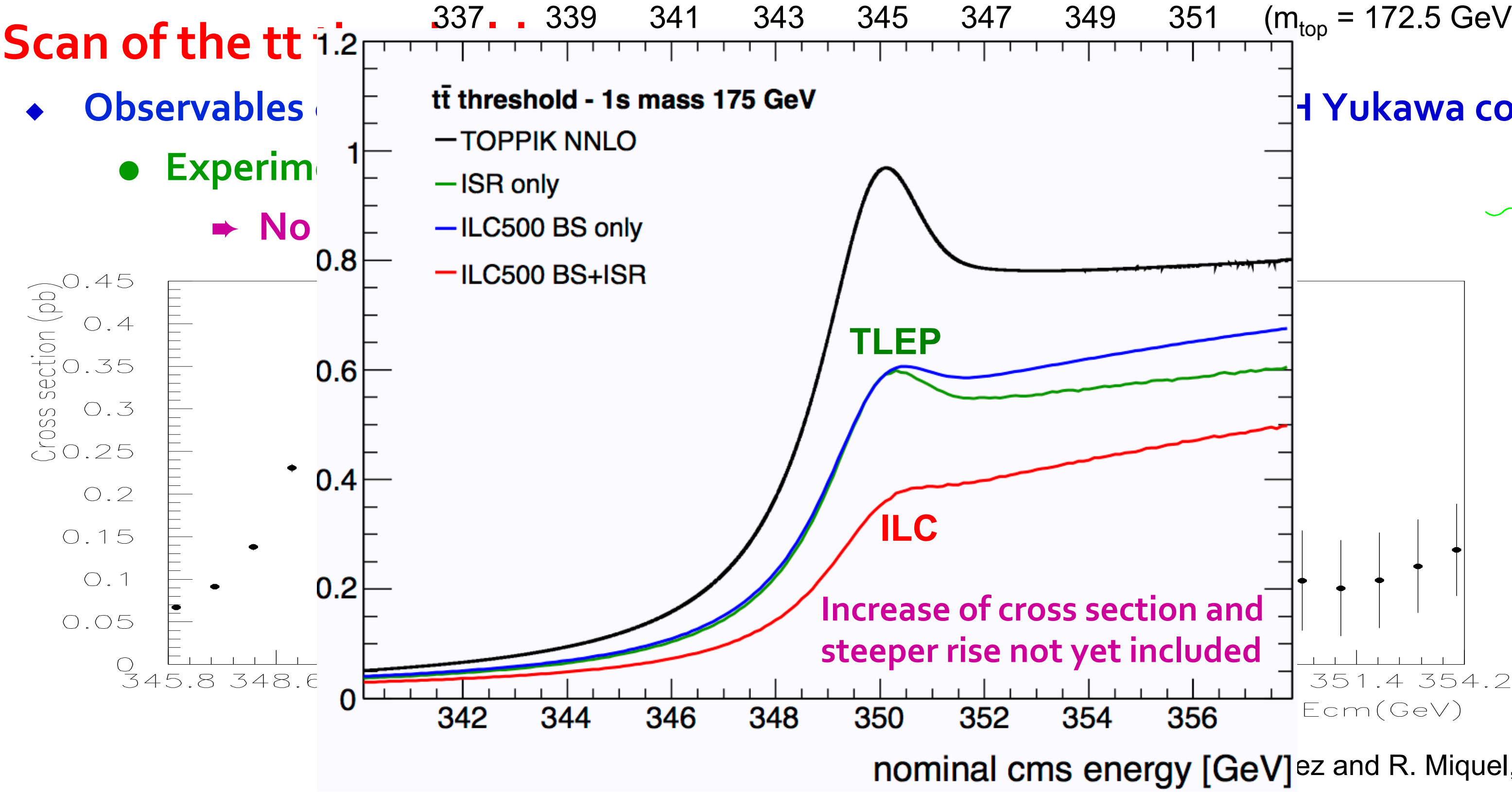
M. Martinez and R. Miquel, 2003

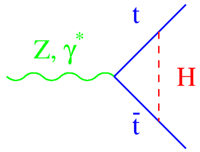
- Expected sensitivity for TLEP (full study to be done) and ILC

	Δm_{top}	$\Delta\Gamma_{top}$	$\Delta\lambda_{top}/\lambda_{top}$
TLEP	15 MeV	17 MeV	15%
ILC	30 MeV	35 MeV	40%

TLEP-t : A few remarks

- Scan of the tt t...
  - Observables ... H Yukawa coupling)
    - Experim...
      - ➨ No





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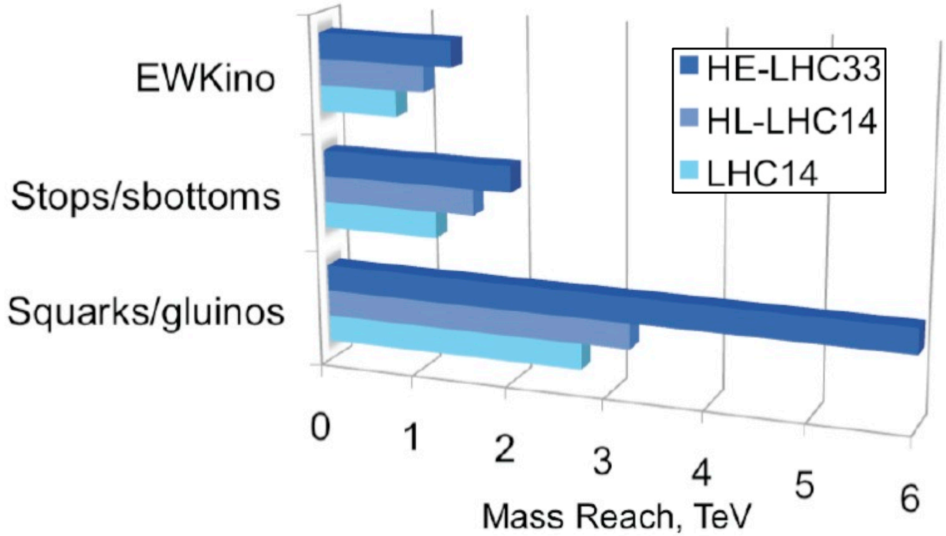
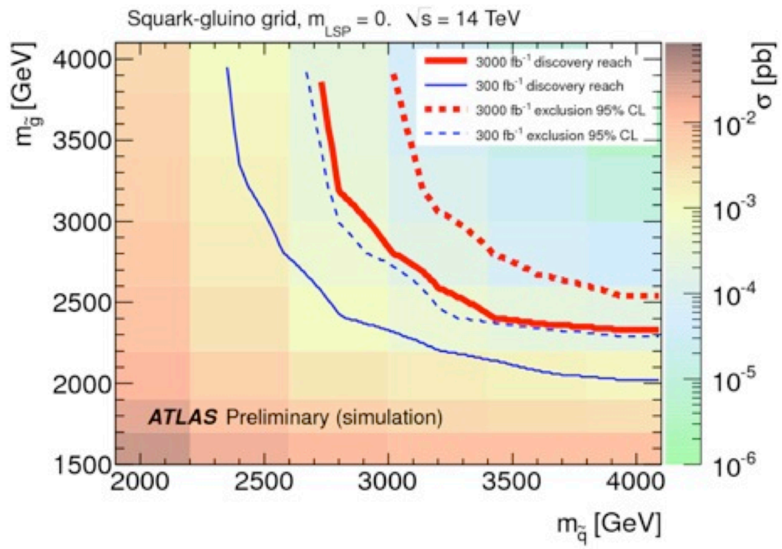
The Next-to-Next Facility (1)

- **Geared towards New Physics Discovery (hinted at by precision studies?)**
  - All existing projects do have an energy-frontier upgrade programme
- **LHC 7 TeV will be upgraded to LHC 14 TeV in 2015**
  - And possibly to HL-LHC (14 TeV) in ~2025





- Take-home (simplified) messages :
  1) Absence of discovery at LHC-14 wipes out SUSY below 700 GeV+
     - ➨ And below several TeV for non-SUSY New Physics
  2) No excess at LHC-14 makes a discovery quite unlikely at HL-LHC
  3) Energy does better than luminosity for direct search for New Physics

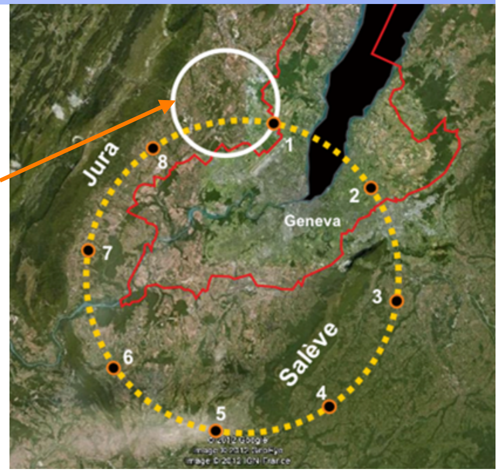
The Next-to-Next Facility (2)

- ILC350 can be upgraded to ILC500
  - And possibly to ILC1000
    - Could discover New Physics below 500 GeV (via pair production)
      - ➨ Air might get extremely thin after three years with LHC-14.
  - Take-home messages
    - New Physics discovery potential of ILC will be quite limited, even at 1 TeV
    - It is essential to wait for the LHC-14 results before engaging in ILC
      - ➨ Appropriate decision time is the next European Strategy update
  - Discoveries at LHC-14 might point to the need of a 3-TeV e^+e^- machine (CLIC)
    - Only if some kind of New Physics is found below 1.5 TeV
    - Lots of R&D still needed towards a TDR
      - ➨ 100 MV/m accelerating gradient
      - ➨ Very small beam size (1 nm)
      - ➨ Very short bunches (150 ns)
      - ➨ Ultra-precise alignment
      - ➨ Magnet stabilization
      - ➨ Large wall plug power (600 MW)
      - ➨ …

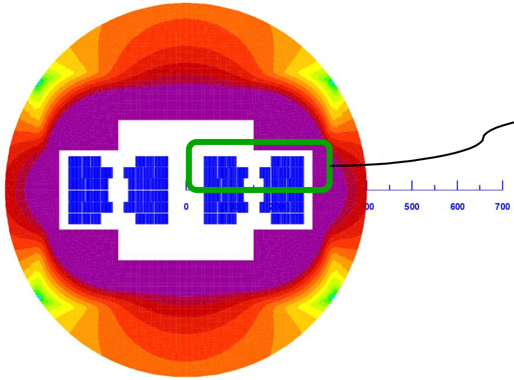
Energy CM (GeV)	500	3000
Luminosity ($\times 10^{34}$ cm^{-2}s^{-1})	2.3	5
Beam size (σ_x/σ_y nm)	202/2.3	40/1
Pulse duration (ns)	177	155
Beam power (MW)	4.9	14
Total AC power (MW)	270	589

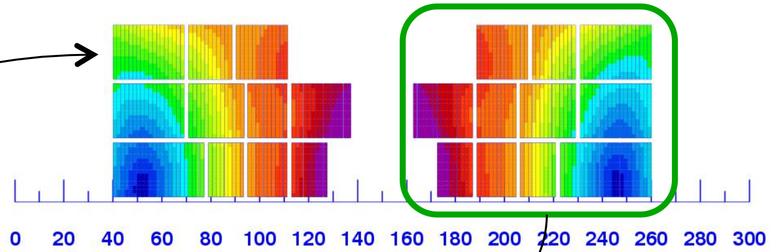
The Next-to-Next Facility (3)

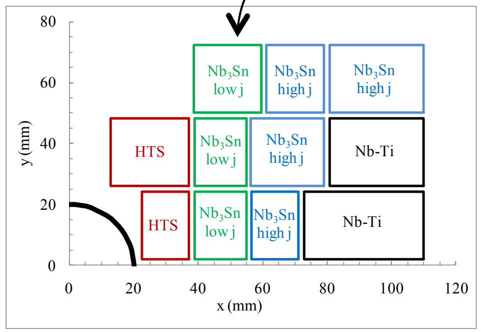
- **TLEP can be upgraded to VHE-LHC**
  - Re-use the 80 km tunnel to reach 80-100 TeV pp collisions
    - Or re-use the LHC tunnel to reach 27-33 TeV pp collisions
  - In both cases, need to develop 16-20 T SC magnets
    - Needs lots of R&D and time (TLEP won't delay VHE-LHC)
  - First consistent conceptual design
    - Using multiple SC materials



L. Rossi







Material	N. turns	Coil fraction	Peak field	$J_{overall}$ (A/mm^2)
Nb-Ti	41	27%	8	380
Nb3Sn (high Jc)	55	37%	13	380
Nb3Sn (Low Jc)	30	20%	15	190
HTS	24	16%	20.5	380

20 T field!

The Next-to-Next Facility (3)

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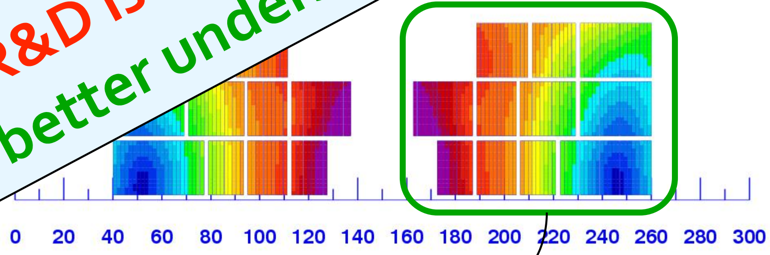
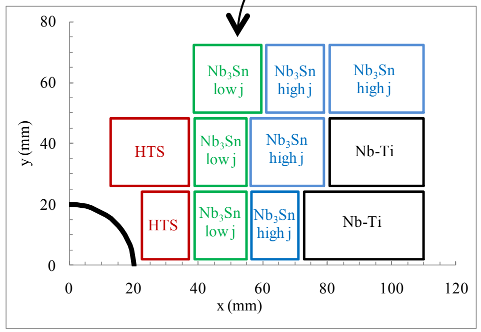


Could explore higher-energy regions (up to 10 TeV and more)
Detailed conceptual study of the machine is needed
Intense collaborative R&D is necessary
Physics case must be better understood

		...ak field	$J_{overall}$ (A/mm^2)
		8	380
	...7%	13	380
	20%	15	190
24	16%	20.5	380

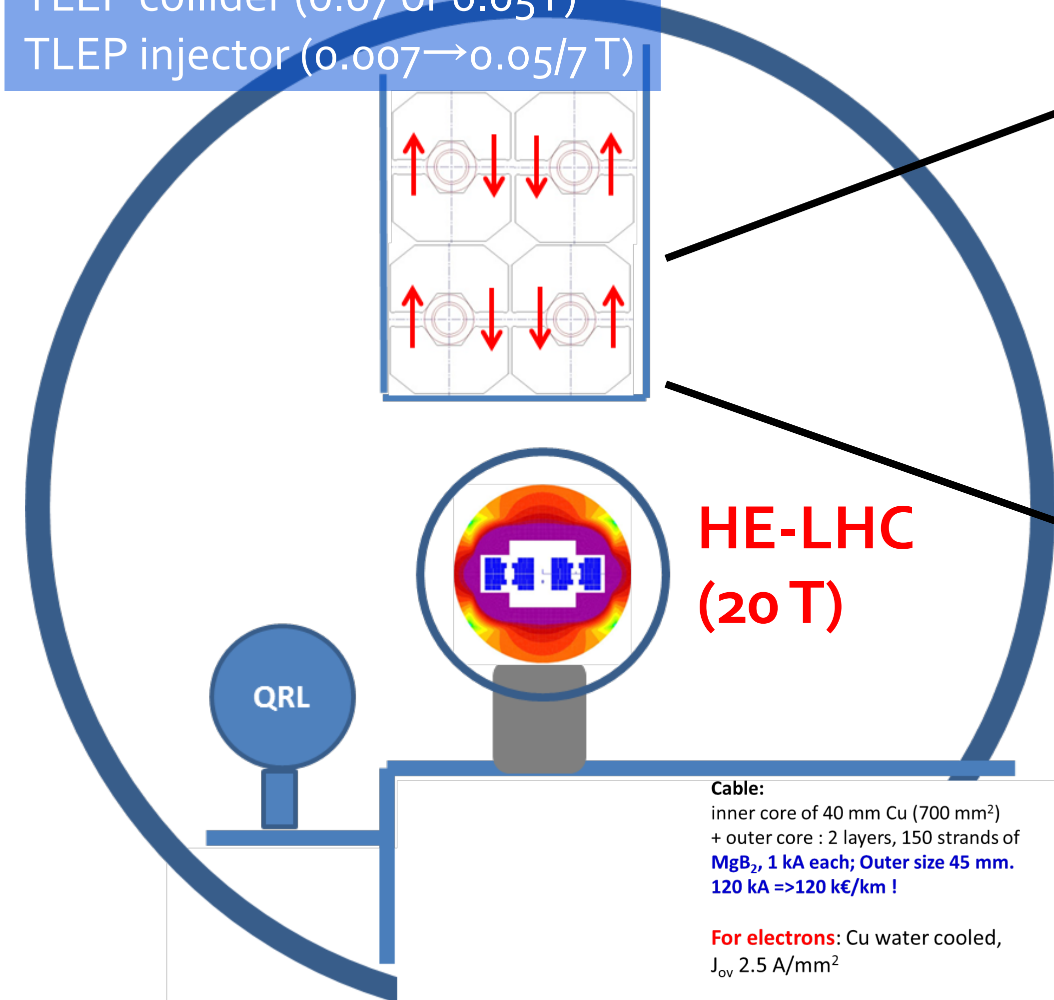
20 T field!



VHE-LHC + TLEP

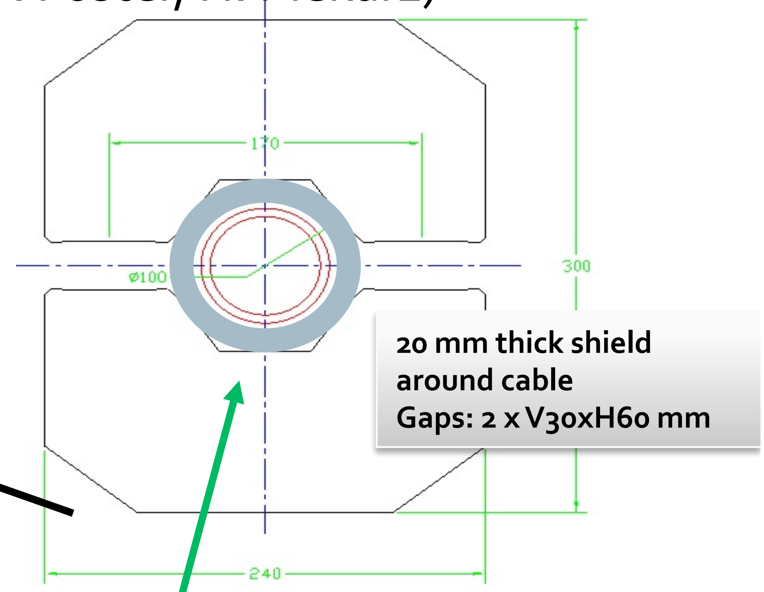
L. Rossi

HE-LHC-LER (0.17→1.5 T)
TLEP collider (0.07 or 0.05T)
TLEP injector (0.007→0.05/7 T)



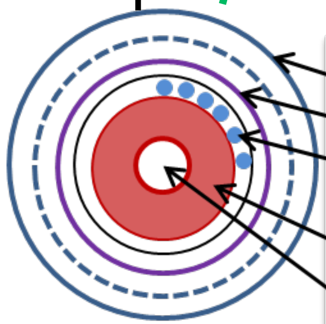
multipurpose tunnel

transmission line magnet
(B. Foster, H. Piekarz)



20 mm thick shield around cable
Gaps: 2 x V30xH60 mm

super-resistive cable



Cryostat : 60 mm
He envelope : 50 mm
SC part: 2 layers MgB_2 (Bi2212)150x∅1mm
Cu inner core 40 mm
Cooling hole: 10 mm

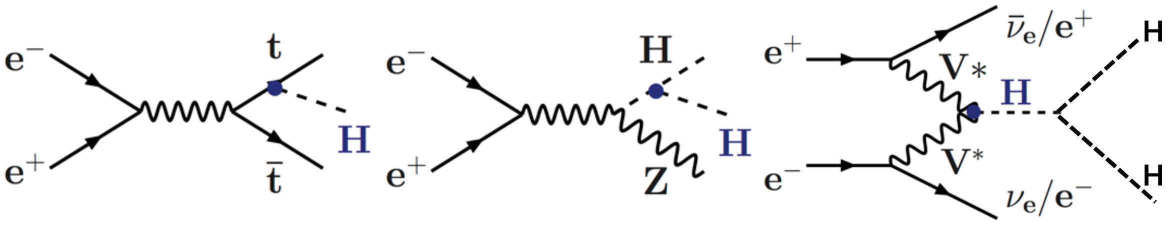
Cable:
inner core of 40 mm Cu (700 mm²)
+ outer core : 2 layers, 150 strands of
MgB_2, 1 kA each; Outer size 45 mm.
120 kA =>120 k€/km !

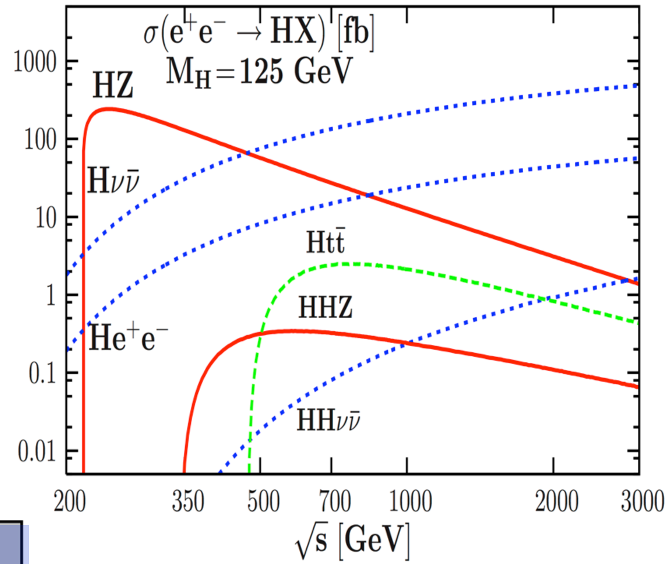
For electrons: Cu water cooled,
J_{ov} 2.5 A/mm²

For protons: 800 A/strands
120 kA (for >2.1 T); central copper acts as stabilizer

The Next-to-Next Facility (4)

- **Performance comparison for the SM Higgs boson**
  - **Measurement of the more difficult couplings : g_{Htt} (Yukawa) and g_{HHH} (self)**
    - **In e^+e^- collisions**



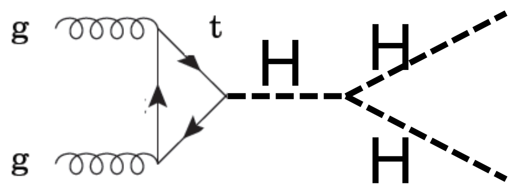


- **In pp collisions**

M. Mangano

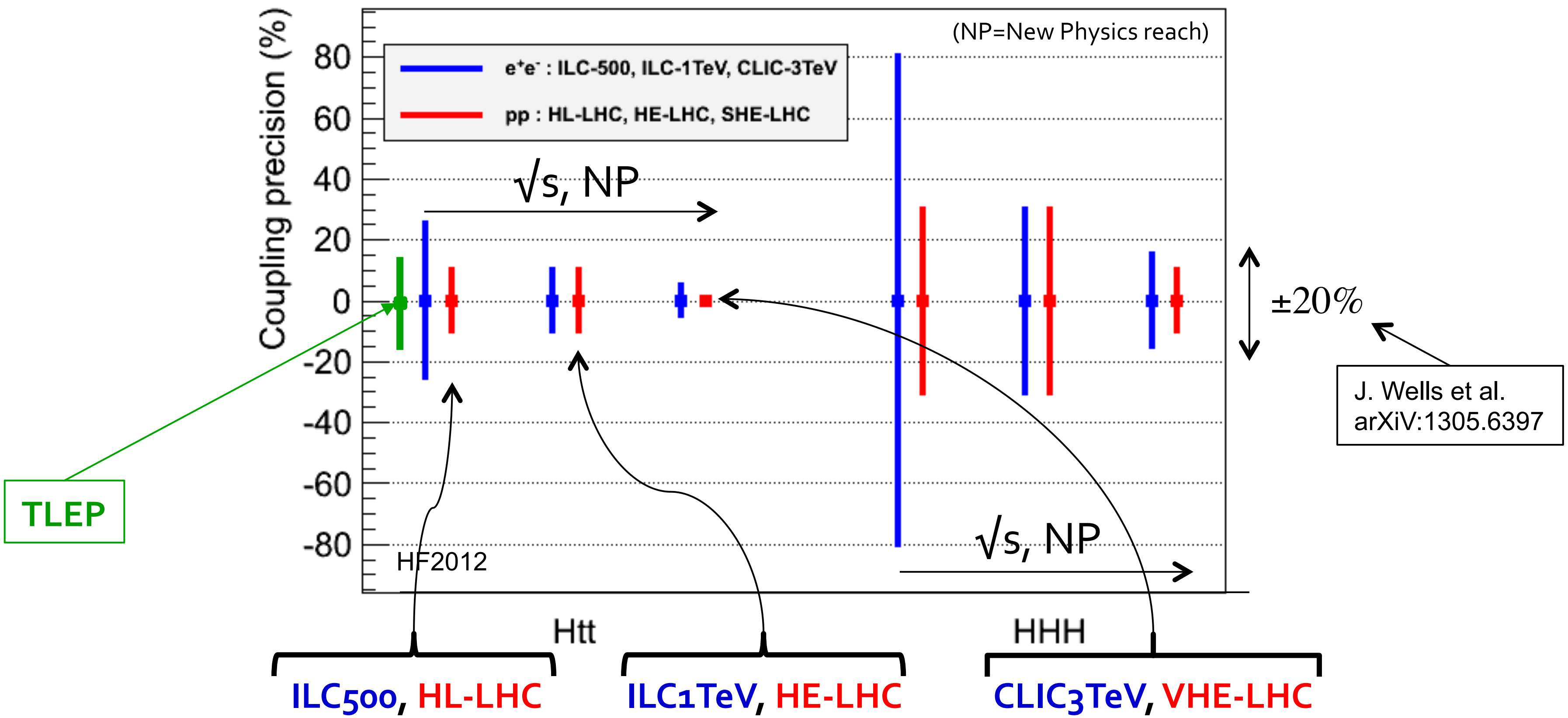
HE-LHC | VHE-LHC

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



The Next-to-Next Facility (5)

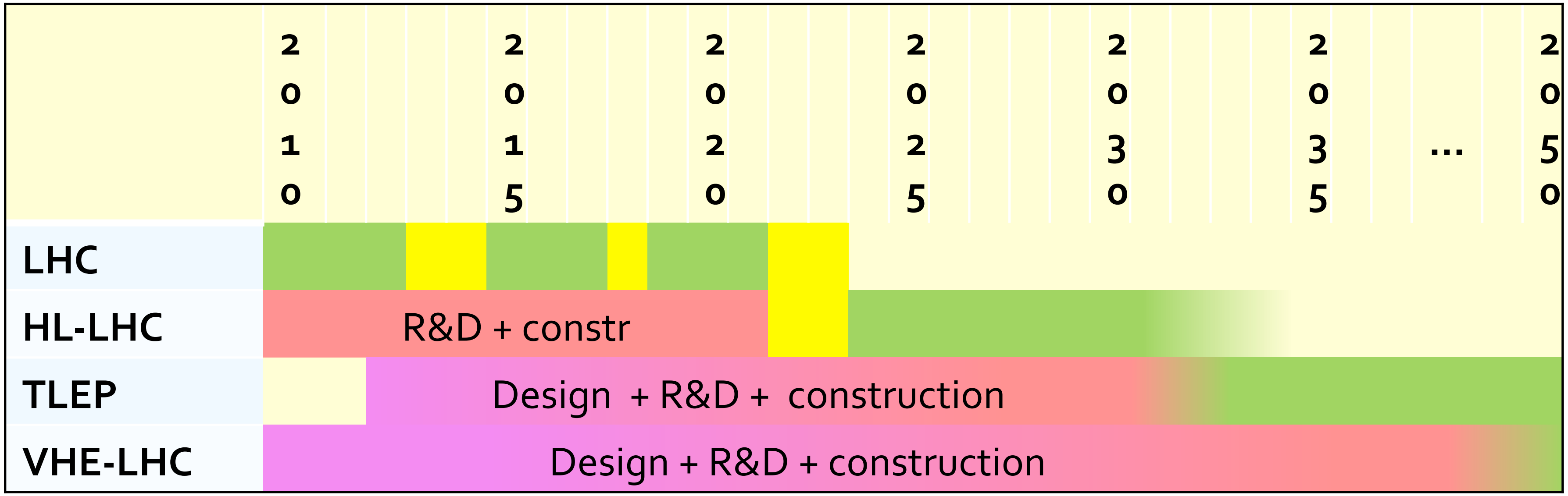
- **Performance comparison for the SM Higgs boson (cont'd)**
  - **Only ttH and HHH couplings**
    - **Other couplings benefit only marginally from high √s**



- **VHE-LHC : Largest New Physics reach and best potential for g_{Htt} and g_{HHH}**

Possible Timescale

- **Similar timescales for TLEP and ILC**
  - ILC aims for Physics in 2028-2030
- **TLEP**
  - Design study : 2013-2017
  - Next European Strategy Workshop : 2017-2018
  - Decision to go and start digging : 2018-2019
  - Start installation in parallel with HL-LHC running : 2023 - …
  - Start running at the end of HL-LHC running : 2030 - …



A light note on the cost

- **LEP3 : A cost-effective option in the LHC tunnel (limited to 240 GeV)**
  - Tunnel : 0 $ - Cryoplant : 0$
  - Two detectors : 0$ - Four detectors : 1 G$
  - RF + Magnets + Injector Ring : 1 G$

  } Total : 1 – 2 G$

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

- **TLEP : A long-term vision**
  - Tunnel : 4 G$
  - Four detectors : 2 G$
  - RF + Cryo + Magnet + Injector Ring : 3 G$

  } Total : 9 G$ — **of which 5 G$ in common With VHE-LHC**

  - 500,000 Higgs boson / detector / 5 years @ 240 GeV : < 4.5 k$ / Higgs boson

- **Comparison with ILC**
  - Total Cost : > 10 G$
  - 70,000 Higgs boson / 5 years @ 250 GeV

  } > 150 k$ / Higgs boson

Higgs Factories : Summary

Higgs Factories	Circular Collider	Linear Collider	γ−γ Collider	Muon Collider	Plasma Wakefield
Technical Maturity Proj launch/First beam	☺☺ 2020/2030	☺ 2018/2027	😐 2025/2035	☹ ?	☹☹ ?
Engineered design readiness	☹	☺☺ / ☹ ILC / CLIC	☹☹	☹☹	☹☹
Size (km)	☹ 27-80	☹ 13-50	☺ 10	☺☺ 1.5(0.3)	☺☺ 2.5
Cost (BCHF) [kCHF/Higgs]	😐 [☺] 7-8 [3]	☹ [☹] 8-10 + site [150]	?	?	?
Power (MW) Consumption	😐 280	😐 128-235	?	😐 200	☺ 133
EWSB Precision Measurements	☺☺	😐 / ☹☹ Limited / None	☹ None	☺	?
Higgs Precision Measurements	☺☺ Sub-per-cent	☺ / 😐 Few per-cent	😐 Limited	😐 Limited	?
Energy (TeV) Upgradability	☺☺ 100 p+	☹ / ☺ 0.5 - 1 / 3	☺ 1-2	☺☺ 3-6	☺☺ 3
Power @ Emax	😐 ~200	☹☹ ~600	?	😐 ~280	😐 ~320

Concluding Remarks

- Discovery of H(126) and European Strategy brought momentum
  - News ideas emerging for Higgs factories and beyond
    - Prospects for the future look very promising
- It is important to choose the right machine for the future
  - Cannot afford to be wrong for 10 billion CHF – it would be the end of HEP
- Results of the LHC run at 14 TeV will be a necessary and precious input
  - Towards an ambitious medium and long term vision for HEP and Europe
    - Decision to be taken by 2018

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    - Decision to be taken by 2018
- Today, I believe TLEP to be the best complementary machine to LHC
  - Unrivaled precision for Higgs properties and EWSB measurements
  - With low risk : Based on a very well-known technology
    - Supported by much progress in e^+e^- circular factories for 20 years (and counting)
  - A first ambitious step in a long-term vision for high-energy physics
  - With many synergies with VHE-LHC (pp collisions at 100 TeV)
    - Tunnel, accelerator, experiments, physics

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An intense design study must go on until 2018
Accelerator / Experiment / Phenomenlogy
Subscribe at http://tlep.web.cern.ch

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    - Tunn… celerator, experiments, physics
- **The goal is to have a technically-ready proposal by 2018**
  - And aim for Physics in 2030

An intense design study must go on until 2018
Accelerator / Experiment / Phenomenlogy
Subscribe at http://tlep.web.cern.ch

Design Study : 2013 – 2018 (1)

TLEP design study –preliminary structure for discussion

Institutional board

Steering group
web site, mailing lists

International Advisory board

R. Aleksan, A. Blondel, J. Ellis, P. Janot, M. Koratzinos, M. Zanetti, F. Zimmermann ad interim

Accelerator

F. Zimmermann ad interim

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

Experiments

P. Janot ad interim

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

Physics

J. Ellis ad interim

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

Design Study : 2013 – 2018 (1)

TLEP design study –preliminary structure

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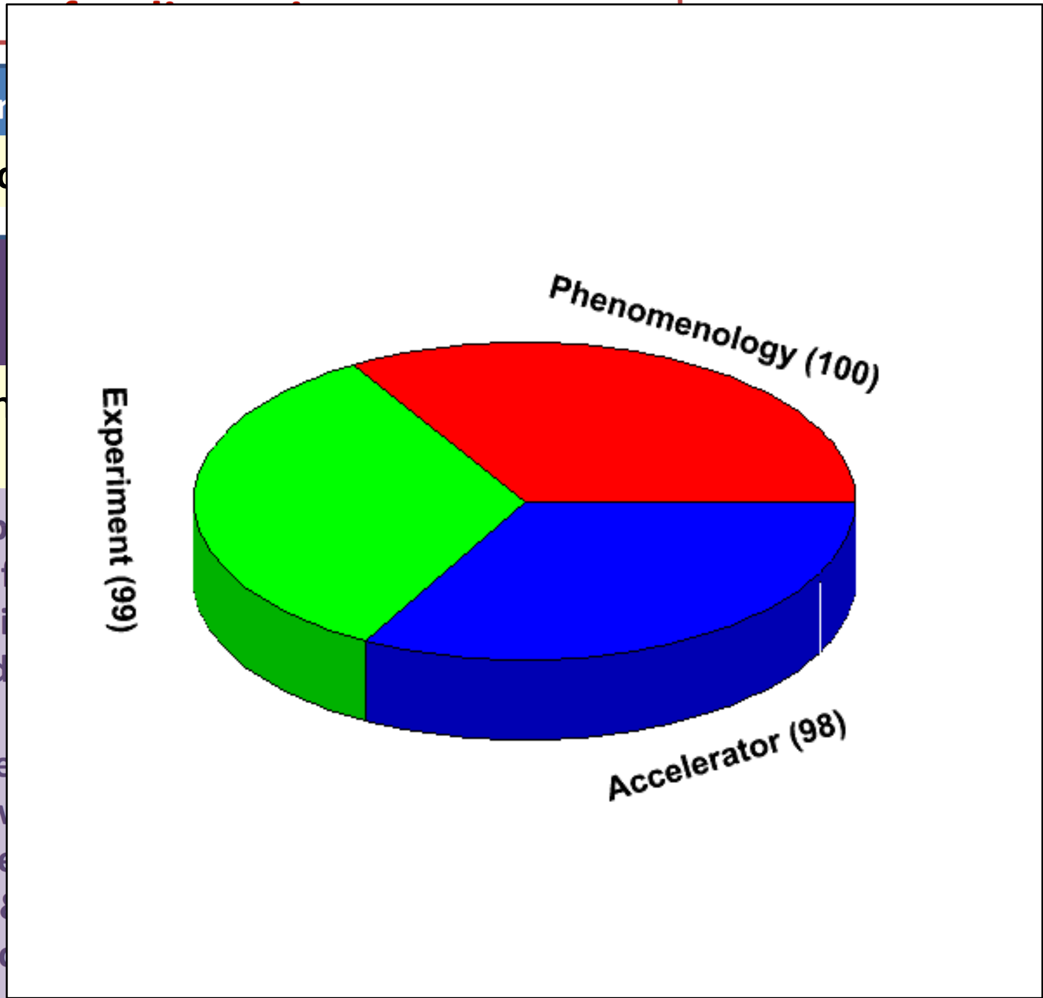

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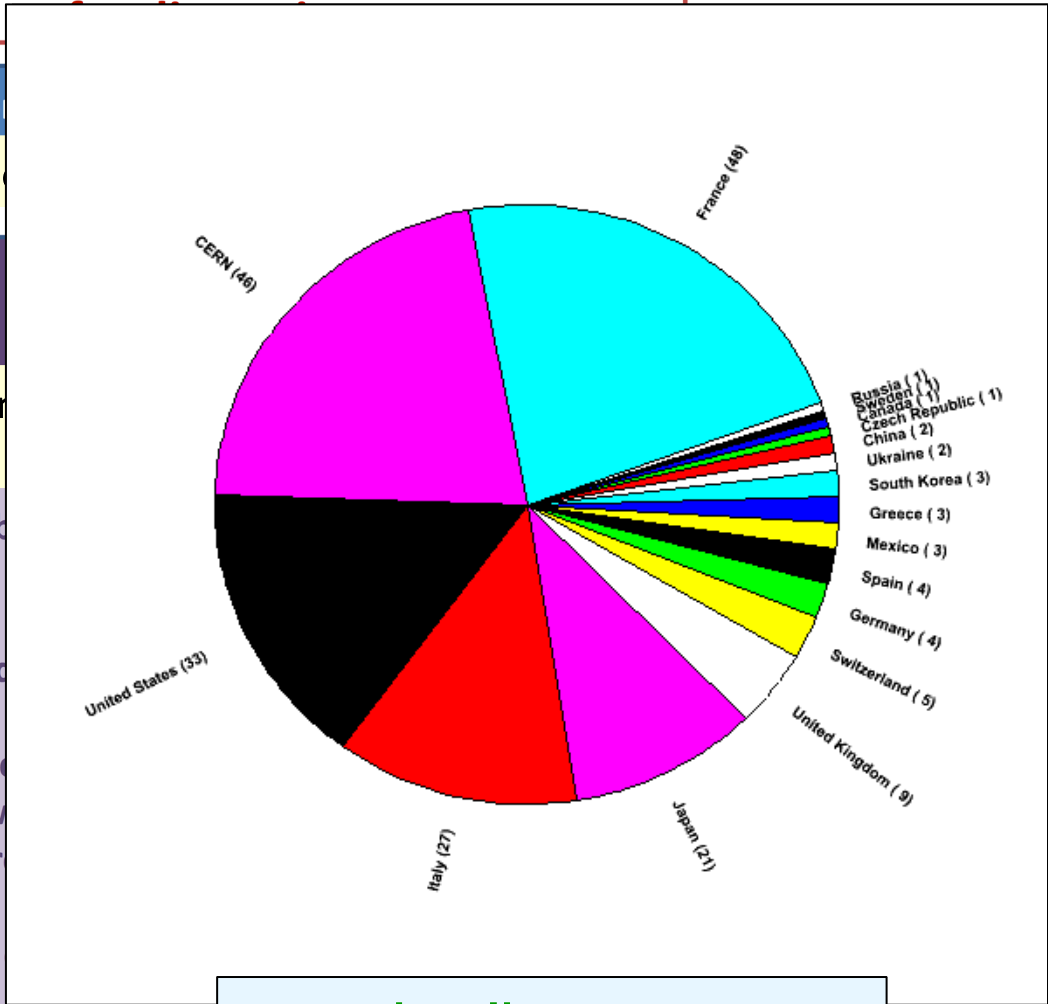

219 subscribers, 13-Jun-13

Design Study : 2013 – 2018 (2)

- **Experimental Studies : Preliminary Structure (Being discussed)**
  - 11 working groups
    - WG1 : Electroweak Physics at the Z pole
    - WG2 : Di-boson physics : W mass measurement, …
    - WG3 : H(126) properties
    - WG4 : Top Quark Physics
    - WG5 : b, c and τ physics
    - WG6 : QCD and γγ physics
    - WG7 : Rare Physics
    - WG8 : Experimental environment
    - WG9 : Offline software and computing
    - WG10 : Online software and computing
    - WG11 : Detector designs