First Look at the Physics Case of TLEP

TLEP(*) : Precision Measurements at the EWSB scale

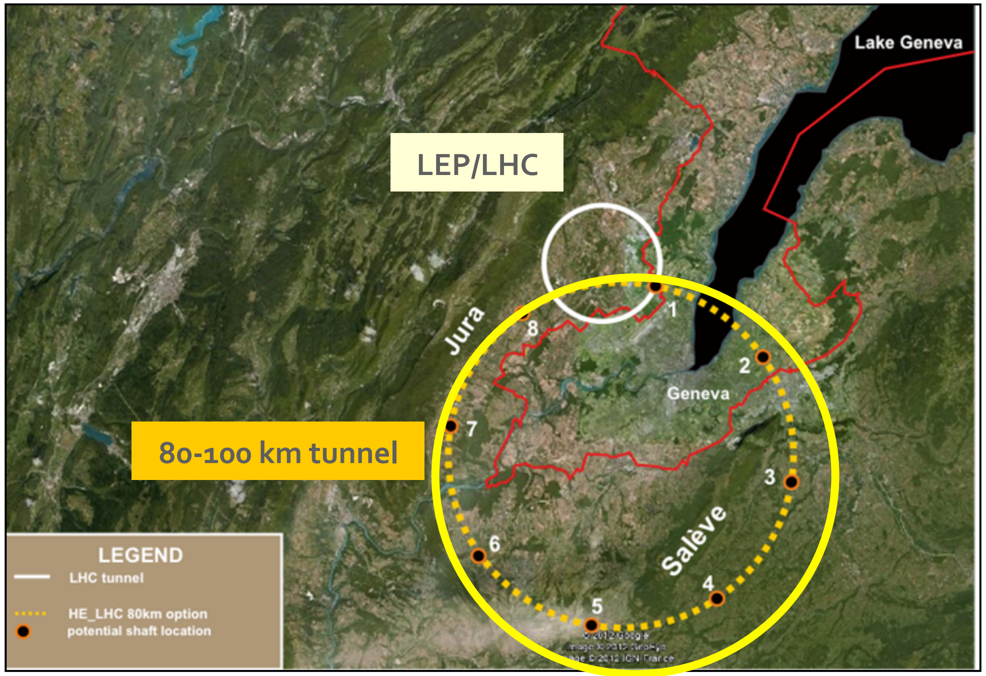
with TeraZ, OkuW, MegaHiggs, and MegaTop

(*) TLEP = Triple LEP

"The Higgs must be studied with the best precision we can muster"
Nigel Lockyer, Fermilab Director, Seattle, 01-July-2013

TLEP: A long-term strategy for HEP

- In a new 80-100 km circular tunnel :



First step

TLEP : e^+e^-, $\sqrt{s}$ up to 350 GeV++

- Tera-Z : $\sqrt{s} \sim m_Z$
- Oku-W : $\sqrt{s} \sim 2m_W$
- Mega-Higgs : $\sqrt{s} \sim 240$ GeV
- Mega-top : $\sqrt{s} \sim 2m_{top}$

Followed by

VHE-LHC : pp collisions,
$\sqrt{s} \sim 100$ TeV with 15T magnets

> 50 years of ee, pp, ep physics

- Follow the successful historical path for high-energy physics
  - TLEP Physics case: Precision measurements sensitive to multi-TeV New Physics
    - ➨ With luminosity 10-1000 × larger than projects of similar timescale and cost
  - VHE-LHC Physics case: Direct search for New Physics in the 10-100 TeV range
    - ➨ Also allows the HHH coupling to be measured to a few %

The TLEP Design Study has started !

- **Excerpt from the CERN Medium Term Plan (2014-2018):**

  - studies for high-energy proton-proton and electron-positron colliders in a new 80-100 km circular tunnel have already started. The aim is to have available Conceptual Design Reports by the time of the next update of the European Strategy for Particle Physics.

  CERN/SPC/1012
  CERN/FC/5747
  CERN/3069

  - … and another 14 mentions of the TLEP and VHE-LHC
    - Approved by the CERN Council about a month ago.
      - VHE-LHC / TLEP Design Study Coordinators : M. Benedikt, F. Zimmermann

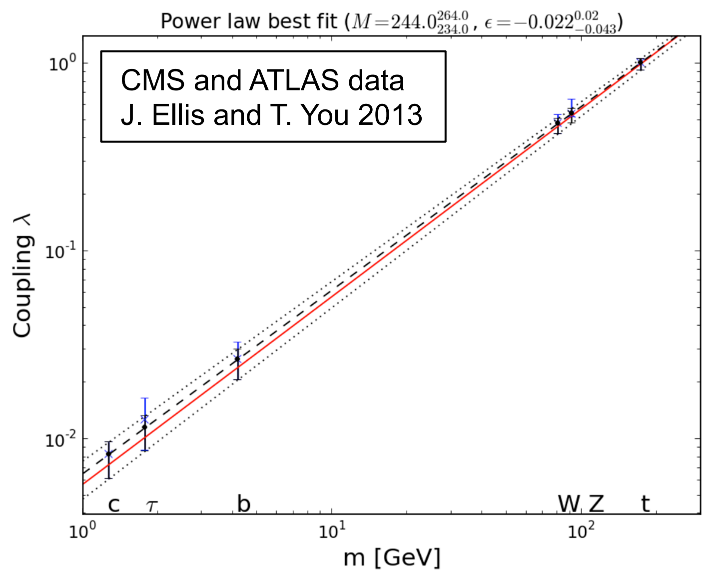
- **The 5th TLEP Workshop took place at Fermilab (25-26 July 2013)**
  - https://indico.fnal.gov/internalPage.py?pageId=2&confId=6983
    - 6th workshop at CERN, 16-18 Oct. 2013. Kick-off in Feb. 2014 (w/ VHE-LHC).
      - https://indico.cern.ch/conferenceDisplay.py?ovw=True&confId=257713

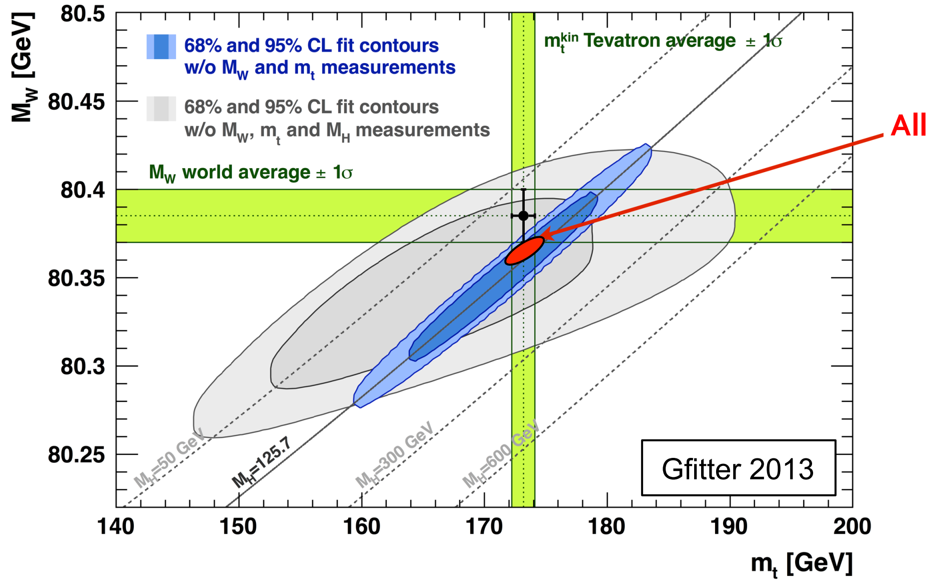
- **You can contribute to the design study in the next 4-5 years**
  - Join the study at http://tlep.web.cern.ch
    - Already 319 collaborators as of yesterday, and counting …
      - Physics Case article at http://arxiv.org/abs/1308.6176

        Hurry if you want to read and sign it …

TLEP + VHE-LHC : Scientific Motivation

- **A (very) Standard Higgs boson and a (very) Standard Model**





  - **Need to measure Higgs properties and EWSB parameters with high(er) precision**
    - **"With the best precision we can muster"**
      - ➨ **Linear colliders are limited in luminosity in the Higgs Factory / EWSB modes**
- **No new physics up to several 100's GeV (SUSY) or several TeV (Resonances)**
  - **Next run at 14 TeV will extend the coverage to ~500 GeV (SUSY) or more**
    - **Very strong incentive to look for and study heavier New Physics**
      - ➨ **Linear Colliders with √s = o(TeV) do not cover this Physics case**

TLEP : Precision Needed

- **Precision = sensitivity to New Physics**
  - Typical deviations of SM Higgs couplings:

$$\frac{g_{HXX}}{g_{HXX}^{SM}} \approx 1 + \delta \times \left(\frac{1\ \text{TeV}}{\Lambda_{NP}}\right)^2$$

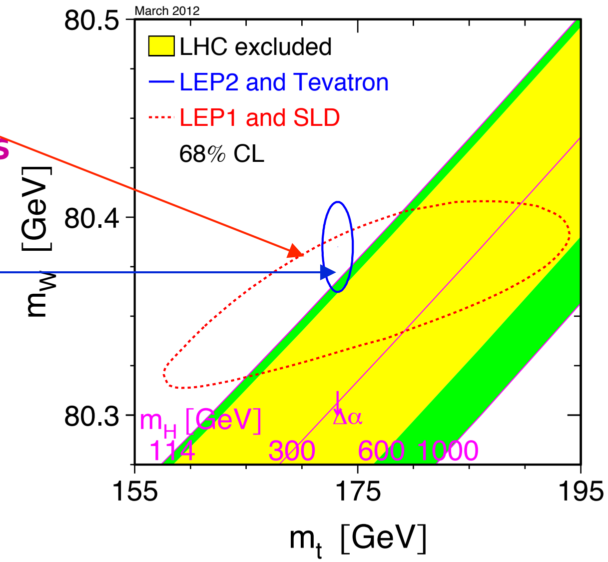
H. Baer et al., ILC TDR

with $|\delta| <\ \sim 5\%$

(Exact value of δ depend on model & coupling)

  - Need at least a per-cent accuracy for a 5σ observation if Λ_{NP} = 1 TeV
    - ➨ And a sub-per-cent accuracy for multi-TeV New Physics scale
  - Need <u>millions</u> of Higgs bosons

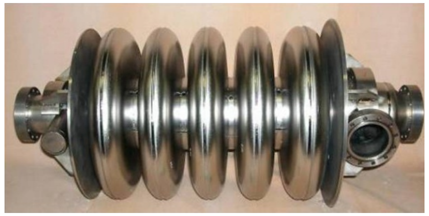
- Z pole measurements
  - LEP1 was sensitive to Λ_{NP} ~ 1 TeV with 10^7 Z
    - ➨ Sensitivity to 10 TeV w/ 100 times smaller errors
  - Need at least <u>10^{11} Z decays</u>
- Match precision with direct m_W and m_{top} measurements
  - Improve by at least one order of magnitude
    - ➨ δm_W < 1 MeV and δm_{top} < 50 MeV



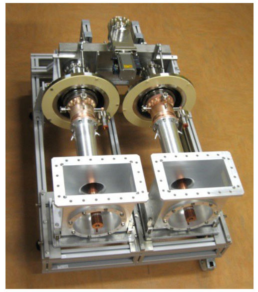
- **Need to reduce all systematic and theory uncertainties.**

Energy and Luminosity at TLEP (1)

- At 350 GeV, beams lose 9 GeV / turn by synchrotron radiation
  - Need 600 5-cell SC cavities @ 20 MV/m in CW mode
    - Much less than ILC (8000 9-cell cavities@ 31 MV/m)
    - Length ~900 m, similar to LEP (7 MV/m)
  - 200 kW/ cavity in CW : RF couplers are challenging
    - Heat extraction, shielding against radiation, …

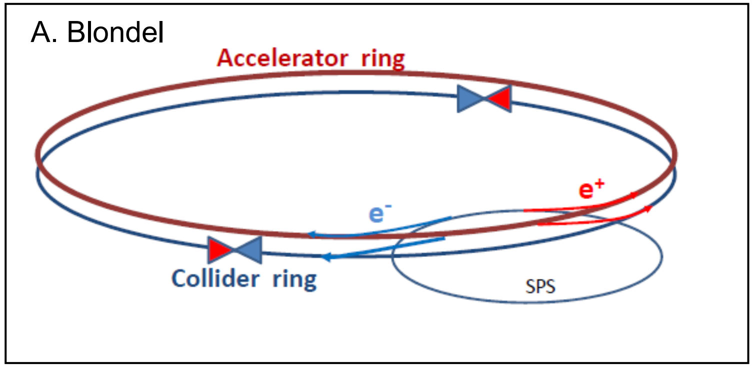


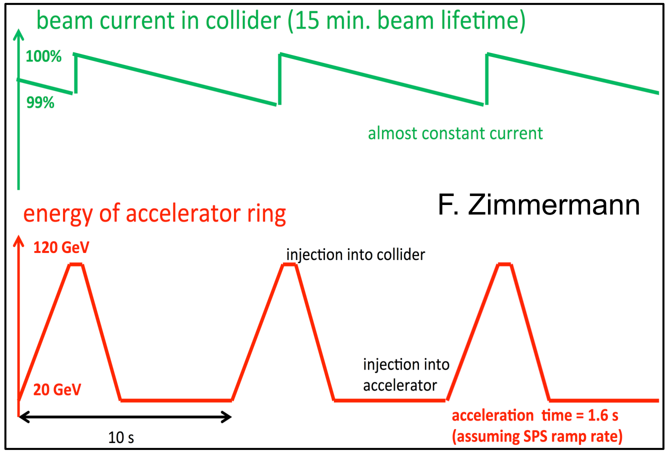
BNL 5-cell 700 MHz cavity



RF Coupler (ESS/SPL)

- Achieve luminosity with large rep. rate and small vertical beam size : σ_y ~ 100 nm
  - A factor 30 smaller than at LEP2, but much more relaxed than ILC (6-8 nm)
    - TLEP can deliver 1.3×10^{34} cm^{-2}s^{-1} per collision point at $\sqrt{s}$ = 350 GeV
- Small beam lifetime due to Bhabha scattering ~ 15 minutes
  - Need efficient top-off injection





M. Koratzinos

Energy and Luminosity at TLEP (2)

- At smaller √s, increase the number of bunches to saturate the RF power
  - Synchrotron radiation decreases like $1 / E^4$
    - Give much less energy to many more bunches

$$L \propto P_{tot} \times \frac{\rho}{E^3_{beam}}$$

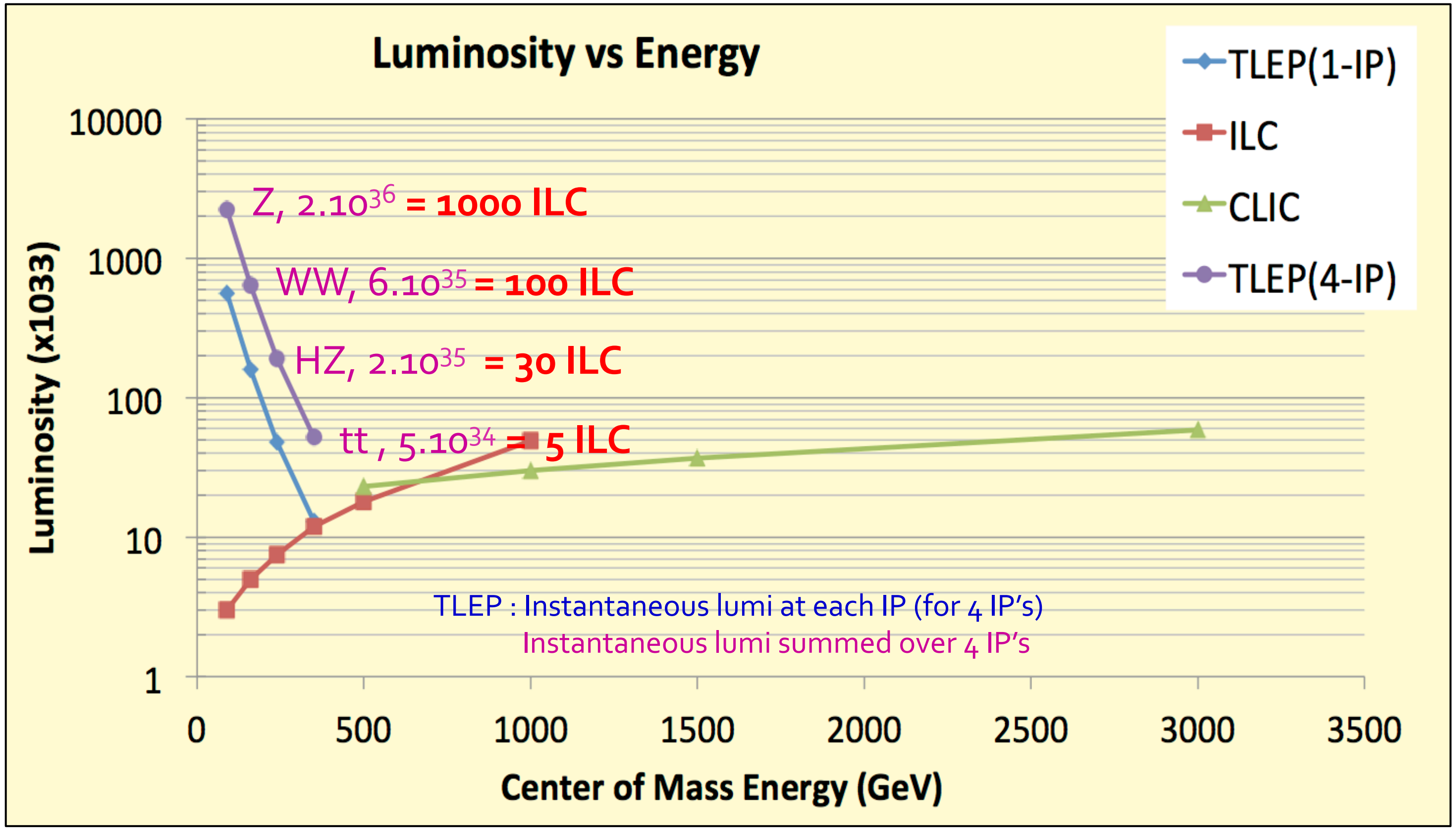
√s (GeV)	90	160	240	350
Luminosity ($\times 10^{34} cm^{-2} s^{-1}$)/IP	56	16	5	1.3
Vertical Beam Size (nm)	270	140	140	100
RF Cavity Gradient (MV/m)	3	3	10	20
Number of bunches	4400	600	80	12
Beam lifetime (mn)	67	25	16	27
Total AC power (MW)	250	250	260	284

M. Koratzinos et al.
arXiV:1305.6498

(Parameters just published – but already obsolete…)

Energy and Luminosity at TLEP (3)

- **Comparison with linear colliders**
  - **Bonus : circular colliders can have several IP's**

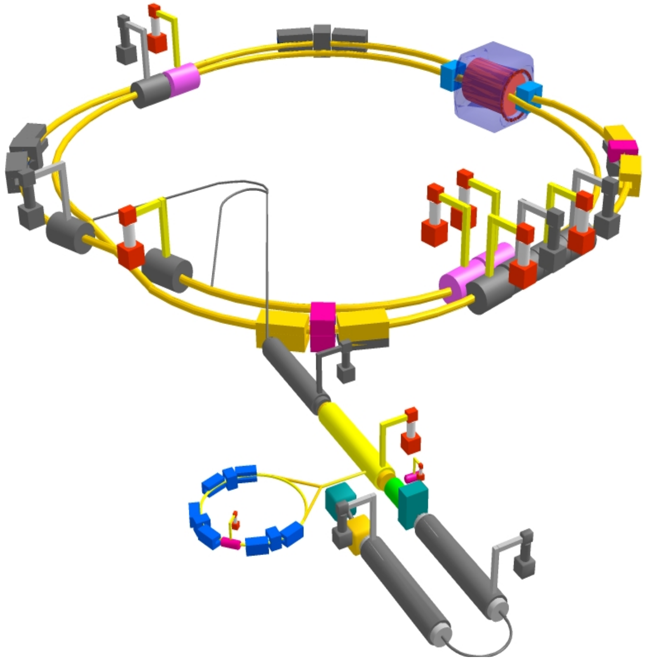


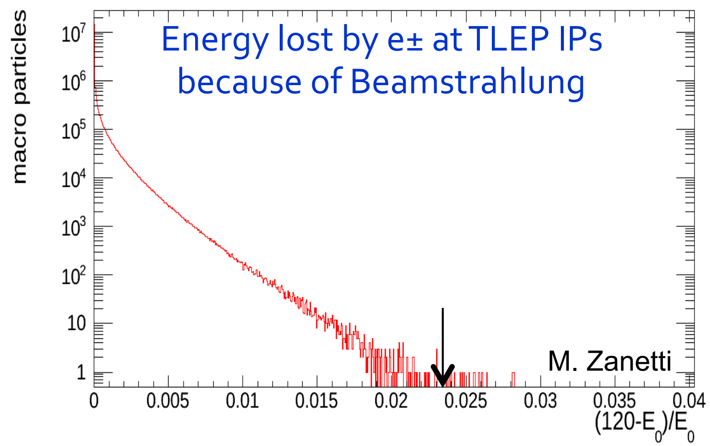
➨ **Ultimate precision measurements possible only at circular colliders**

Note : Luminosity upgrade now discussed for ILC (no cost estimate)

Energy and Luminosity at TLEP (4)

- **Find the extrapolations optimistic ?**
  - **SuperKEKB will be a TLEP demonstrator**
    - **Beam commissioning starts early 2015**
- **Some SuperKEKB parameters :**
  - **Lifetime : 5 minutes**
    - **TLEP : 15 minutes**
  - **β^*_y : 300 µm**
    - **TLEP : 1 mm**
  - **σ_y : 50 nm**
    - **TLEP : 100 nm**
  - **$\varepsilon_y/\varepsilon_x$: 0.25%**
    - **TLEP : 0.20%**
  - **Positron production rate : 2.5×10^{12} / s**
    - **TLEP : < 1×10^{11} / s**
  - **Off-momentum acceptance at IP : ±1.5%**
    - **TLEP : ±2.0 to ±2.5%**
      - ➨ **(because of Beamstrahlung at IP's)**





Energy and Luminosity at TLEP (5)

- Find the extrapolations optimistic ? (cont'd)

	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	× 1/30	× 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
  - Will also learn a lot from ATF2

- Lot of work ahead to reach ILC beam dimensions
- Estimates for circular colliders historically reliable

Energy and Luminosity at TLEP (5)

TLEP
$HZ^0W^-W^+t\bar{t}$

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- SuperKEKB will be an excellent test-bench fc
  - Will also learn a lot from ATF2

- Lot of work ahead to reach ILC beam dimens
- Estimates for circular colliders historically rel

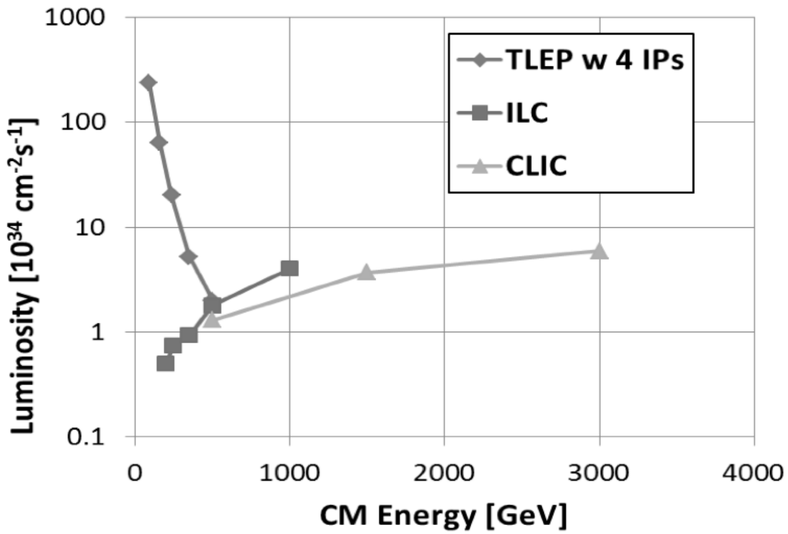
Parameter	Design LEP1 / LEP2	Achieved LEP1 / LEP2
Bunch current	0.75 mA	1.00 mA
Total beam current	6.0 mA	8.4 / 6.2 mA
Vertical beam-beam parameter	0.03	0.045 / 0.083
Emittance ratio	4.0 %	0.4 %
Maximum luminosity	16 / 27 10^{30} $cm^{-2}s^{-1}$	34 / 100 10^{30} $cm^{-2}s^{-1}$
IP beta function β_x	1.75 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

Energy and Luminosity at TLEP (6)

- **TLEP Upgrades : Energy and luminosity can be further increased**
  - Not in the baseline proposal
    - The design study will concentrate on a solid baseline
  - Example : Possible TLEP energy upgrade
    - Can reach $\sqrt{s}$ = 500 GeV, if justified by scientific arguments
      - ➨ By tripling the RF system (12 → 35 GV)

        1.7 km instead of 600 m of cavities
      - ➨ With a luminosity of 0.5×10^{34} $cm^{-2}s^{-1}$ per interaction point

        Hence similar to the ILC at $\sqrt{s}$ = 500 GeV

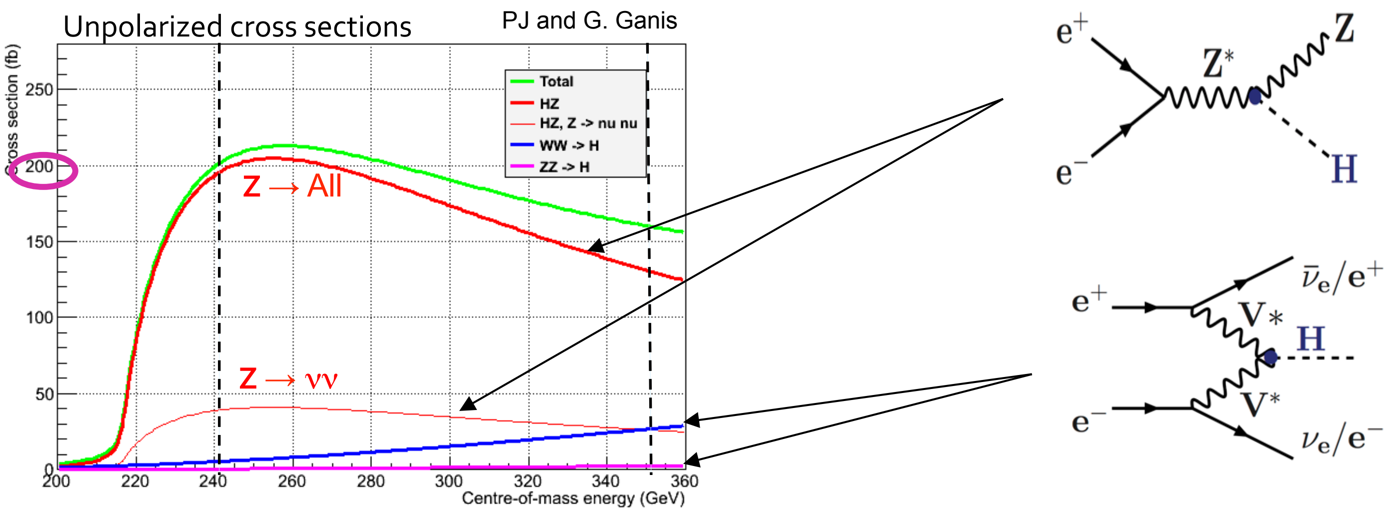


TLEP : Possible Physics Programme

- **Higgs Factory mode at $\sqrt{s}$ = 240 GeV: 5+ years**
  - Higgs boson properties, WW and ZZ production.
    - Periodic returns at the Z peak for detector and beam energy calibration
- **Top Threshold scan at $\sqrt{s}$ ~ 350 GeV: 5+ years**
  - Top quark mass, width, Yukawa coupling; top quark physics; more Higgs boson studies.
    - Periodic returns at the Z peak for detector and beam energy calibration
- **Z resonance scan at $\sqrt{s}$ ~ 91 GeV: 1-2 years**
  - Get ~10^{12} Z decays @ 15 kHz/IP. Repeat the LEP1 Physics Programme every 15 minutes.
    - Transverse polarization of "single" bunches for precise E_{beam} calibration
- **WW threshold scan at $\sqrt{s}$ ~ 161 GeV: 1-2 years**
  - Get ~10^8 W decays; Measure the W mass; Precise W studies.
    - Transverse polarization of single bunches and returns to the Z peak.
- **Longitudinally polarized beams at $\sqrt{s}$ = m_Z: 1 year**
  - Get ~10^{11} Z decays, and measure A_{LR}, A_{FB}^{pol}, etc.
    - Polarization wigglers, spin rotators
- **Luminosity, Energy, Polarization upgrades ?**
  - If justified by scientific arguments (with respect to the upgrade to VHE-LHC)

TLEP as a Mega-Higgs Factory (1)

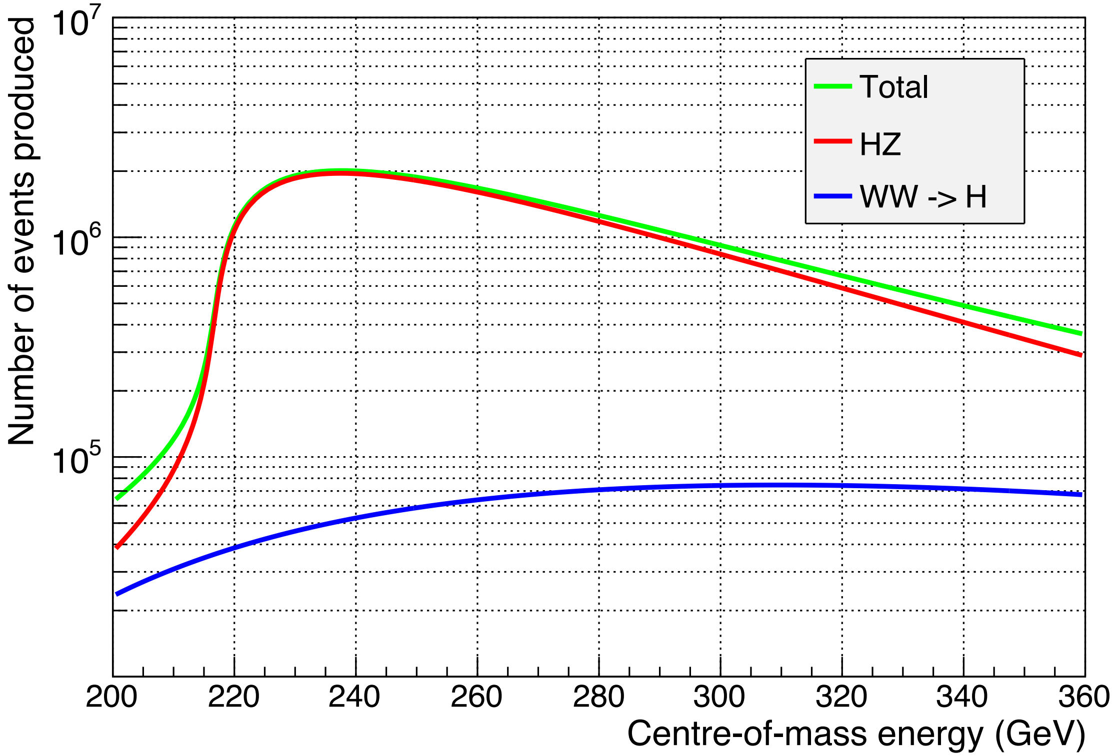
- Number of Higgs bosons produced at √s = 240-250 & 350 GeV



	ILC-250	TLEP-240	ILC-350	TLEP-350	
Lumi / 5 yrs	250 fb^{-1}	**10 ab^{-1}**	350 fb^{-1}	**2.6 ab^{-1}**	
Beam Polarization	80%, 30%	–	80%,30%	–	
# of HZ events	70,000	**2,000,000**	65,000	**325,000**	× 1.4
# of WW→H events	3,000	**50,000**	20,000	**65,000**	× 2.4

TLEP as a Mega-Higgs Factory (2)

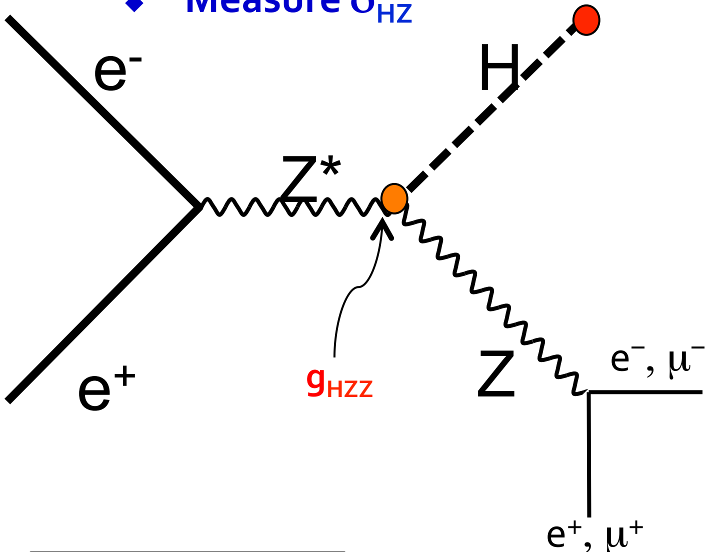
- **Choice of the centre-of-mass energy**
  - **Maximize the number of Higgs events expected for 5 years at 4 IP's**
    - **With the very specific luminosity profile of TLEP (in $1/E^3$)**

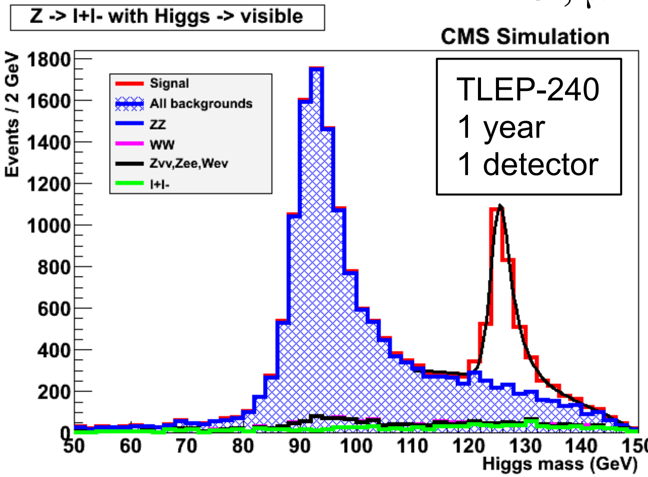


➨ **$\sqrt{s}$ = 240 GeV for HZ, $\sqrt{s}$ = 340-350 GeV for WW → H and the $t\bar{t}$ threshold scan**

TLEP as a Mega-Higgs Factory (3)

- **Example : $e^+e^- \rightarrow ZH \rightarrow l^+l^-$ + anything**
  - **Measure σ_{HZ}**





Summary of the possible measurements :

(TLEP : CMS Full Simulation + some extrapolations for cc, gg)

ILC TDR

From P. Azzi et al. arXiV:1208.1662

	ILC-250	TLEP-240
σ_{HZ}	2.5%	0.4%
$\sigma_{HZ}\times BR(H\rightarrow bb)$	1.1%	0.2%
$\sigma_{HZ}\times BR(H\rightarrow cc)$	7.4%	1.2%
$\sigma_{HZ}\times BR(H\rightarrow gg)$	9.1%	1.4%
$\sigma_{HZ}\times BR(H\rightarrow WW)$	6.4%	0.9%
$\sigma_{HZ}\times BR(H\rightarrow \tau\tau)$	4.2%	0.8%
$\sigma_{HZ}\times BR(H\rightarrow ZZ)$	19%	3.1%
$\sigma_{HZ}\times BR(H\rightarrow \gamma\gamma)$	35%	3.0%
$\sigma_{HZ}\times BR(H\rightarrow \mu\mu)$	100%	13%
Γ_{INV} / Γ_H	< 1%	< 0.2%
m_H	40 MeV	8 MeV

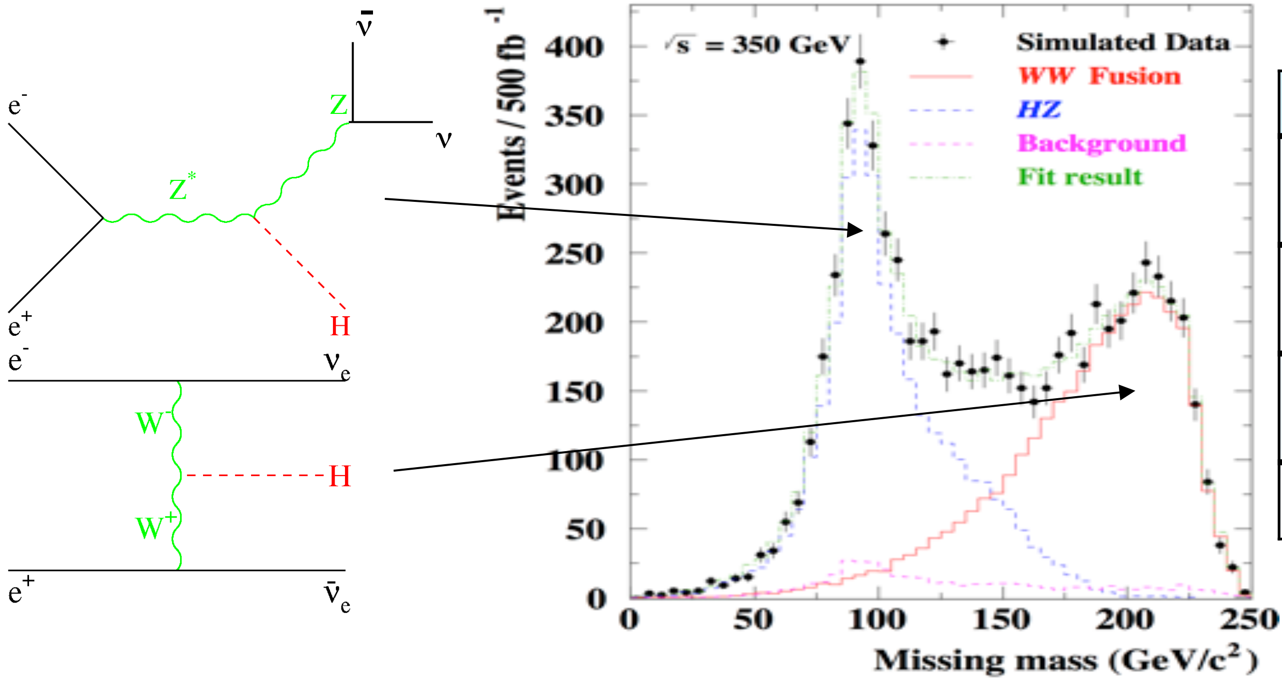
TLEP as a Mega-Higgs Factory (4)

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

$$\Gamma_H = \Gamma(H \to ZZ)\ /\,\mathrm{BR}(H \to ZZ)\ \propto\ \sigma_{HZ}\,/\,\mathrm{BR}(H \to ZZ)$$

  - From the bbνν final state at √s = 350 GeV (and 240 GeV)

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



Γ_H from:	ILC	TLEP
HZ→ZZZ @ 240	20%	3.2%
WW→H @240	12%	2.4%
WW→H @350	7%	1.2%
Combined	5.8%	1.0%

Note : μμ collider
$\Delta\Gamma_H/\Gamma_H$ ~ 5%

Global fit of the Higgs couplings (1)

TLEP $HZ^0W^-W^+t\bar{t}$

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

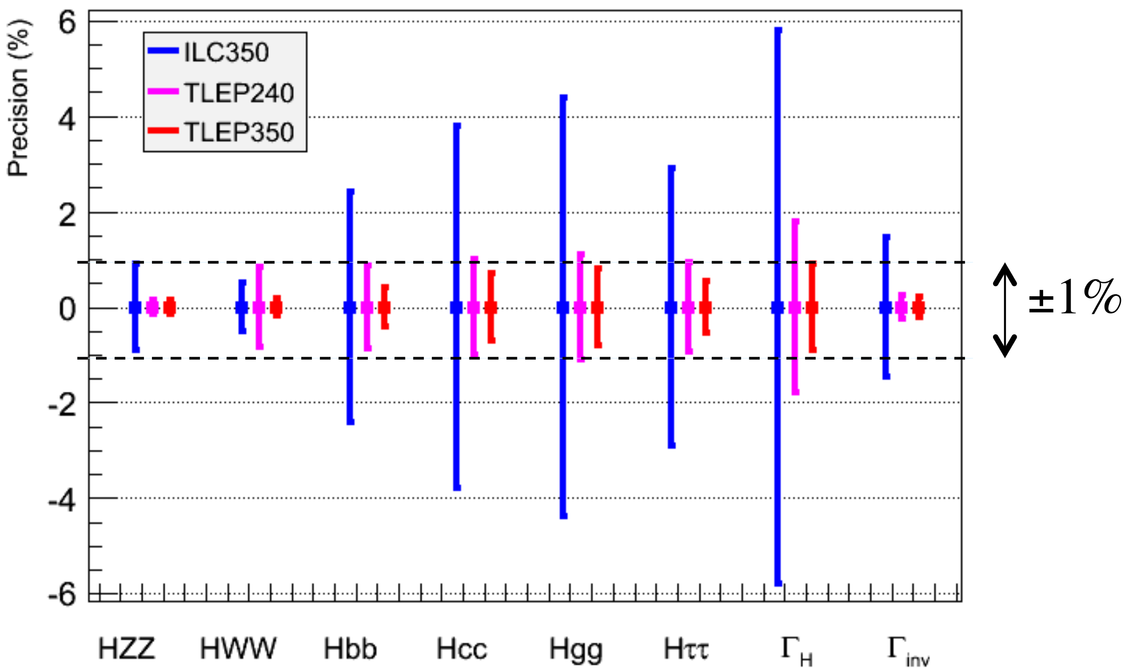
> The 80 km tunnel envisioned for TLEP can also host a hadron collider (TLHC). This might well be the future of particle physics in Europe.
>
> I will now discuss the estimates of Higgs measurement capabilities of these machines and the conversion of those estimates to measurement errors on the Higgs 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.

Global fit of the Higgs couplings (2)

- **Model-independent fit**

M. Bachtis

Coupling	g_Z	g_W	g_b	g_c	g_g	g_τ	g_μ	g_γ	BR_{exo}
LEP-240	0.16%	0.85%	0.88%	1.0%	1.1%	0.94%	6.4%	1.7%	0.48%
LEP-350	0.15%	0.19%	0.42%	0.71%	0.80%	0.54%	6.2%	1.5%	0.45%
ILC-350	0.9%	0.5%	2.4%	3.8%	4.4%	2.9%	45%	14.5%	2.9%



Facility	ILC	TLEP (4 IP)
Energy (GeV)	500	350
$\int \mathcal{L}dt$ (fb^{-1})	+500	+1400
$\Delta\Gamma_h/\Gamma_h$	6.0%	1.0%
$\mathcal{B}_{\rm inv}$	< 0.69%	< 0.1%
$\Delta g_\gamma/g_\gamma$	8.4%	1.5%
$\Delta g_{Z\gamma}/g_{Z\gamma}$	?	?
$\Delta g_g/g_g$	2.5%	0.8%
$\Delta g_W/g_W$	1.4%	0.19%
$\Delta g_Z/g_Z$	1.3%	0.15%
$\Delta g_\mu/g_\mu$	–	6.2%
$\Delta g_\tau/g_\tau$	2.5%	0.54%
$\Delta g_c/g_c$	3.0%	0.71%
$\Delta g_b/g_b$	1.8%	0.42%
$\Delta g_t/g_t$	18%	13%

Snowmass 2013

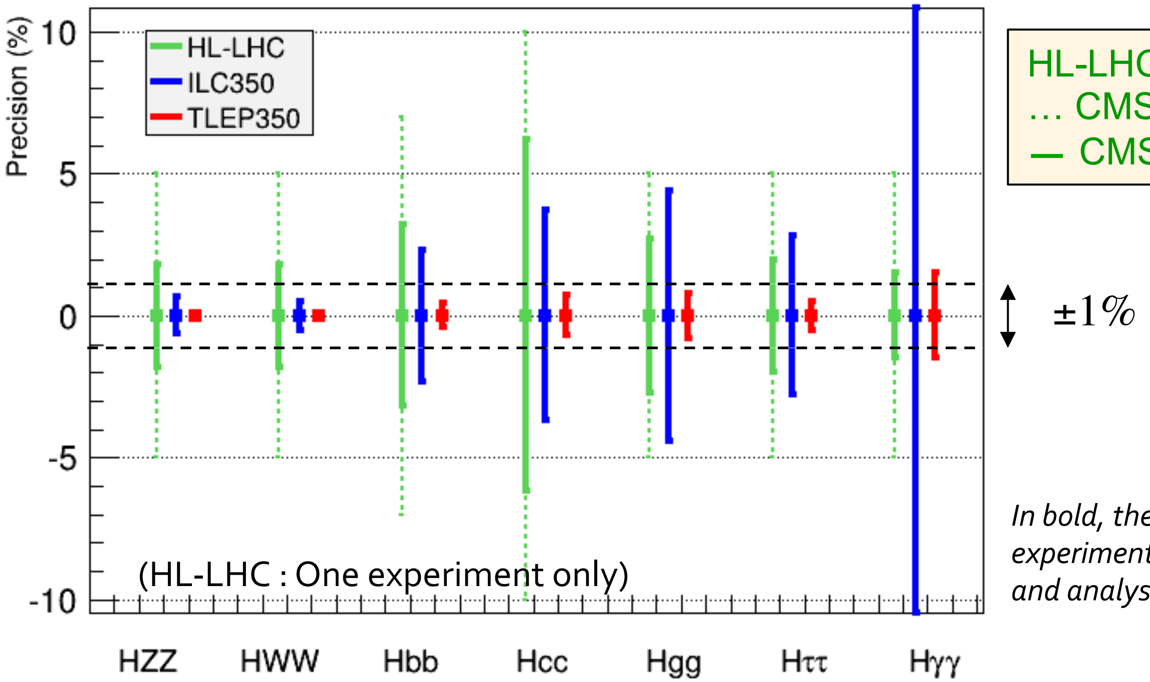
- **NB : Theory uncertainties must be worked out.**

Global fit of the Higgs couplings (3)

TLEP
$HZ^0W^-W^+t\bar{t}$

Model-dependent (seven-parameter) fit a-la-LHC

- Assume no exotic Higgs decays, and $\kappa_c = \kappa_t$



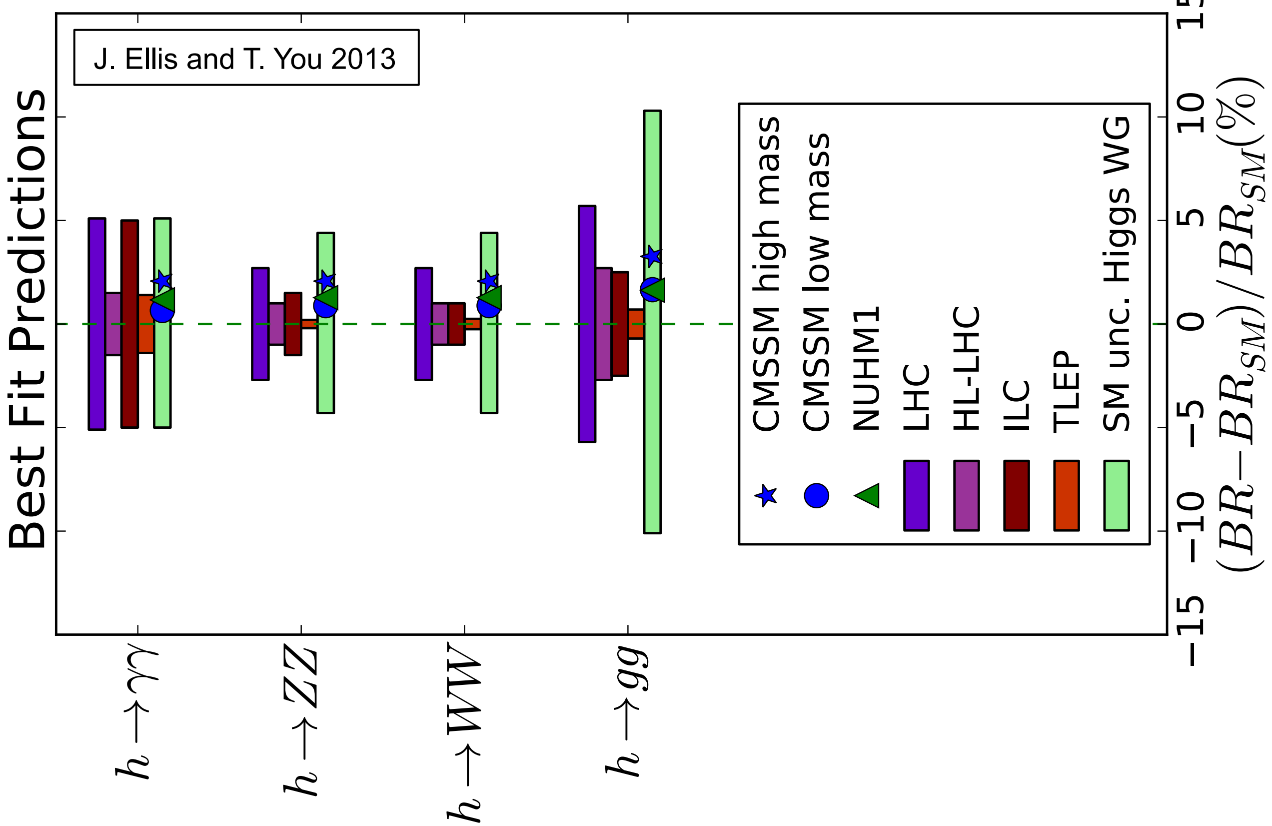
HL-LHC : One experiment only
… CMS Scenario 1
— CMS Scenario 2 CMS, July 13

In bold, theory uncertainty are assumed to be divided by a factor 2, experimental uncertainties are assumed to scale with 1/√L, and analysis performance are assumed to be identical as today

- Quantitative added value from ILC – wrt HL-LHC – does not stick out clearly.
  - In contrast, sub-per-cent TLEP potential is striking for all couplings
    - ➨ Only TLEP is sensitive to (multi-)TeV new physics with Higgs measurements
- Much theoretical progress is needed to reduce accordingly theory uncertainties

Global fit of the Higgs couplings (4)

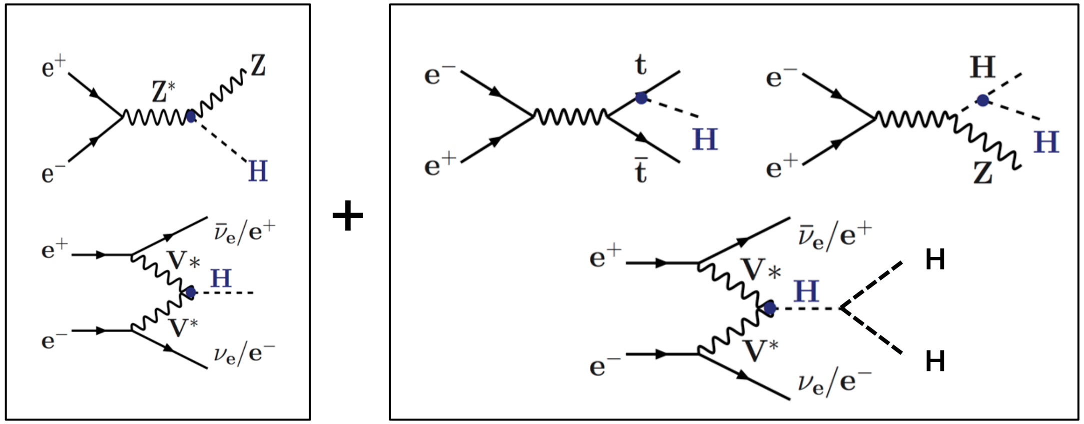
- **Sensitivity to new physics and theory uncertainties**

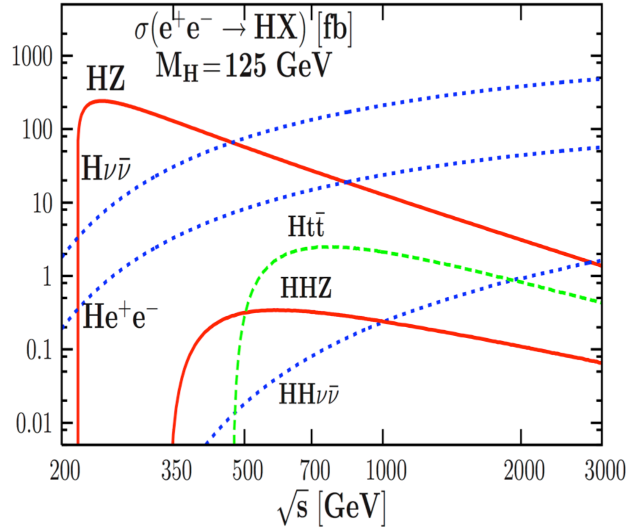


- **Sensitivity to new physics needs TLEP**
  - It also requires a substantial theoretical effort
    - ➨ To reduce the uncertainties in the theoretical calculation of Higgs properties

Higgs Physics with $\sqrt{s}$ > 350 GeV ? (1)

- **Signal cross sections in e^+e^- collisions**





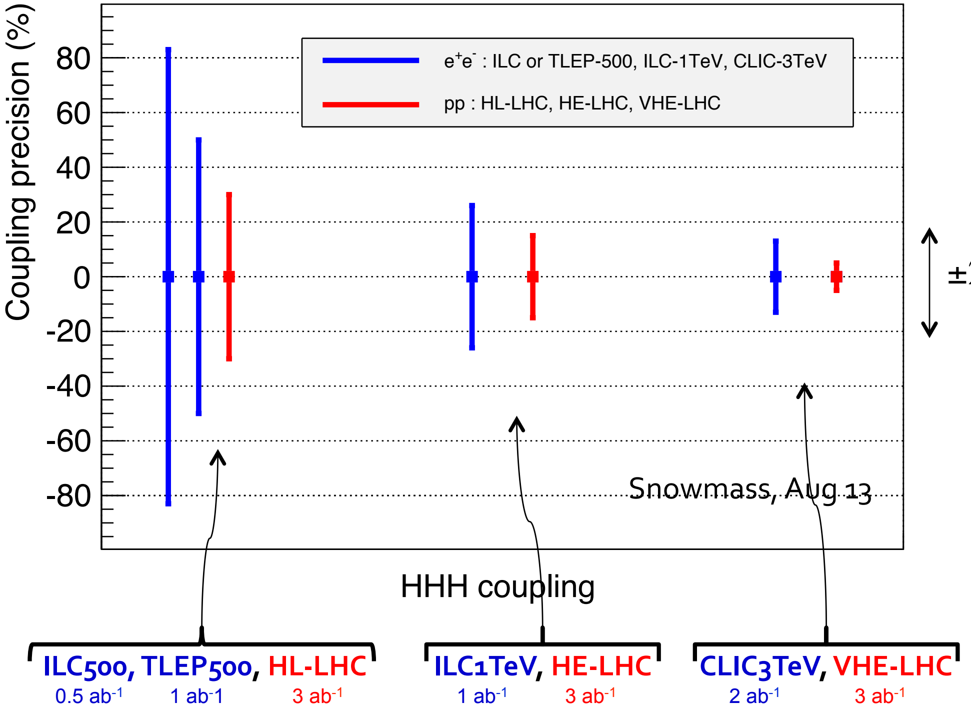
- **Measurements at higher energy**
  - $\sqrt{s}$ > 350 GeV does not do much for couplings to c, b, g, Z, W, γ, μ and Γ_{tot}. (slide 15)
    - Invisible width best done at $\sqrt{s}$ = 240 GeV
  - The ttH coupling benefits from higher energy
    - TLEP 350 : 13% ; TLEP 500 : 10%
    - ILC 500 : 14% ; ILC 1 TeV : ~4% ; CLIC : ~4%
  - The HL-LHC will already do the measurement with 5% precision (and improving)
    - Sub-per-cent precision will need the ultimate pp machine at 100 TeV : VHE-LHC

Higgs Physics with $\sqrt{s}$ > 350 GeV ? (2)

TLEP $HZ^0W^-W^+t\bar{t}$

Measurements at higher energy (cont'd)

- Higgs tri-linear self coupling λ very difficult for all machines



J. Wells et al.
arXiV:1305.6397

Particularly difficult for $\sqrt{s}$ < 2-3 TeV

Few per-cent precision will need VHE-LHC

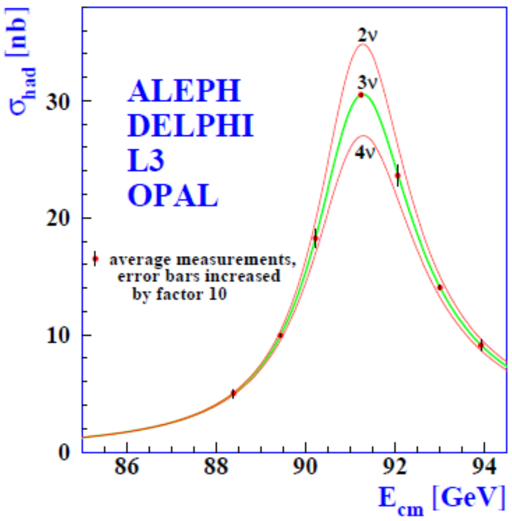
Summary

- For the study of H(126), the case for e^+e^- collisions above 350 GeV is not compelling.
  - A stronger motivation will exist if a new particle found (or inferrred) at LHC
    - ➨ *IF e^+e^- collisions can bring substantial new information about it*

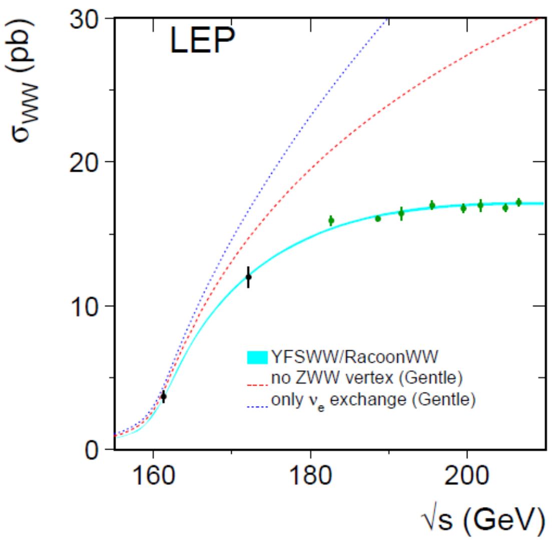
TLEP as a Tera-Z and Oku-W Factories (1)

- **TLEP repeats the LEP1 physics programme every 15 minutes**
  - **Transverse polarization up to the WW threshold**
    - **Exquisite beam energy determination with resonant depolarization**
      - ➨ **Up to 50 keV precision or less – unique at circular e^+e^- colliders**
  - **Measure m_Z, m_W, Γ_Z, … with unequalled accuracy**

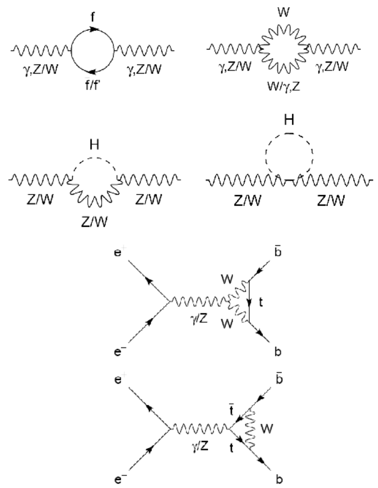
Z lineshape, asymetries



WW threshold scan



New Physics in loops ?



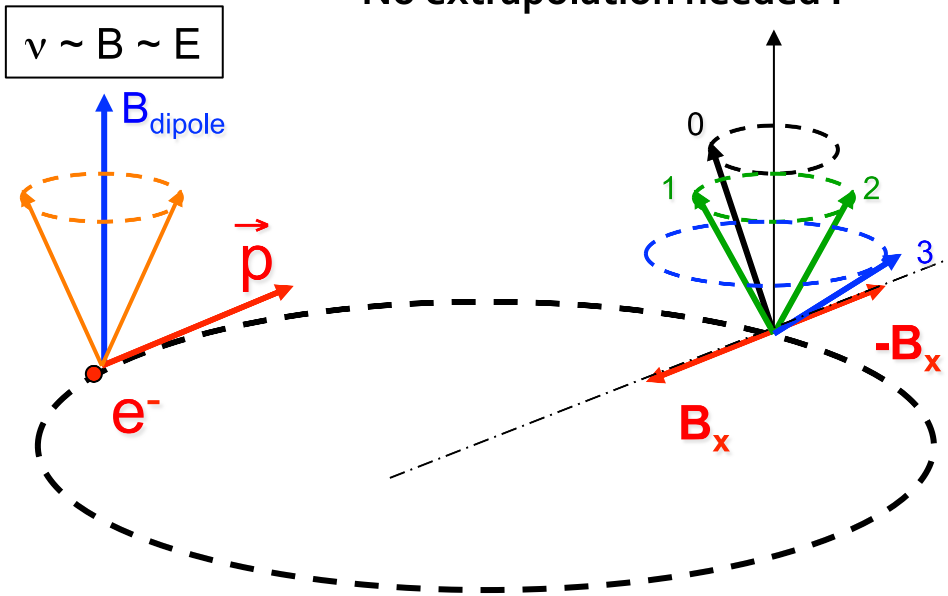
  - **EW loops sensitive to the existence of weakly-coupled heavy particles**
    - **For example, LEP predicted m_{top} = 172 ± 20 GeV in 1994**
      - ➨ **The top was discovered at FNAL; EW measts now predict m_H = 100 ± 25 GeV**

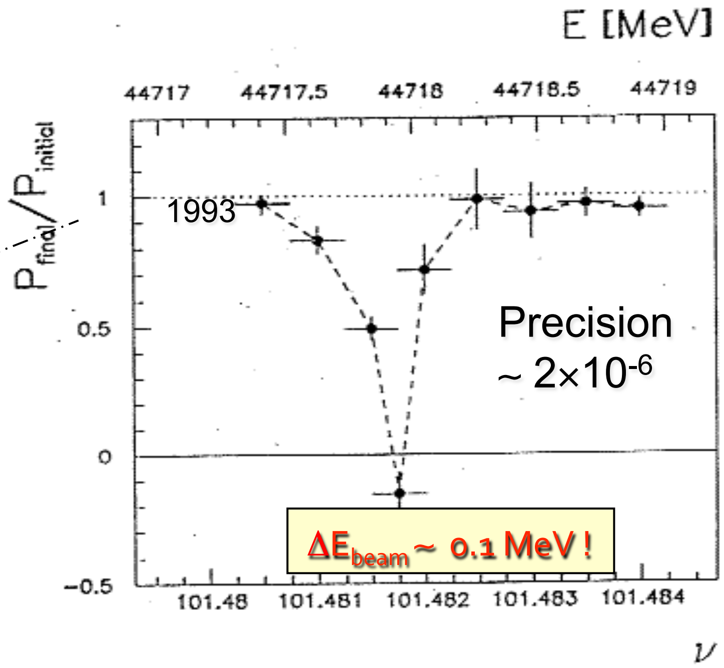
No beamstrahlung
is a clear advantage

TLEP as a Tera-Z and Oku-W Factories (2)

- **Beam energy measurement at TLEP**
  - Ultra-precise resonant depolarization method, unique to a ring
    - Precision limited to 2 MeV at LEP1 by the extrapolation to collision conditions
      - ➨ At TLEP, can use few single bunches (out of 4400)

No extrapolation needed !





- ➨ Ultimate precision better than 0.1 MeV

  (limited to 2 MeV @ LEP1: tides; TGV, rain; + extrapolation)
- ➨ Aim at performing one measurement every 20 minutes

TLEP as a Tera-Z and Oku-W Factories (3)

TLEP $HZ^0W^-W^+t\bar{t}$

Measurements with Tera-Z

- **Caution : TLEP will have 5×10^4 more Z than LEP**
  - Predicting achievable accuracies with 250 times smaller statistical precision is difficult

Observable	Measurement	Current precision	TLEP stat.	Possible syst.	Challenge
m_Z (MeV)	Lineshape	91187.5 ± 2.1	0.005	< 0.1	QED corrections
Γ_Z (MeV)	Lineshape	2495.2 ± 2.3	0.008	< 0.1	QED corrections
R_l	Peak	20.767 ± 0.025	0.0001	< 0.001	Statistics
R_b	Peak	0.21629 ± 0.00066	0.000003	< 0.00006	$g \rightarrow bb$
N_ν	Peak	2.984 ± 0.008	0.00004	< 0.004	Lumi meast
$\alpha_s(m_Z)$	R_l	0.1190 ± 0.0025	0.00001	0.0001	New Physics

NB: ILC limited to a factor > 30 larger errors

- The study is just beginning : errors might get better with increasing understanding
  - ➡ Used LEP knowledge so far. Will be revisited with the design study.
- Much more to do at the Z peak
  - ➡ e.g., asymmetries, flavour physics (> 10^{11} b, > 10^{11} c, > 10^{10} t), rare Z decays, …

TLEP as a Tera-Z and Oku-W Factories (4)

TLEP $HZ^0W^-W^+t\bar{t}$

Measurements with Oku-W

- **Caution : TLEP will have 5×10^6 more W than LEP at the WW threshold**
  - **Predicting achievable accuracies with 1000 times smaller statistical precision is difficult**

Observable	Measurement	Current precision	TLEP stat.	Possible syst.	ILC precision
m_W (MeV)	Threshold scan	80385 ± 15	0.3	< 0.5	7
N_ν	Radiative returns $e^+e^-\to\gamma Z$, $Z\to\nu\nu$, ll	2.92 ± 0.05	0.001	< 0.001	?
$\alpha_s(m_W)$	$B_{had} = (\Gamma_{had}/\Gamma_{tot})_W$	B_{had} = 67.41 ± 0.27	0.00018	< 0.0001	0.002

  - **Much more W physics to do at the WW threshold and above**
    - **e.g., Γ_W, λ_W, rare W decays, diboson couplings, …**

Measurement with longitudinal polarization

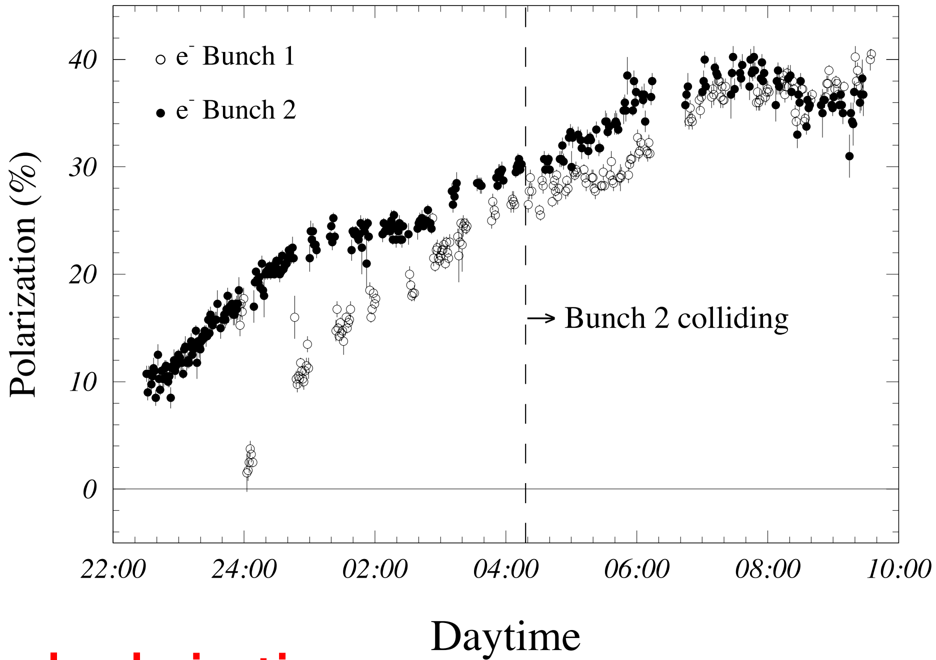
- **One year with luminosity reduced to 20% of nominal (requires spin rotators + wigglers)**
  - **40% beam longitudinal polarization assumed – NB: kept polarization in collisions at LEP**

Observable	Measurement	Current precision	TLEP stat.	Possible syst.	Challenge
A_{LR}	Z peak, polarized	0.1514 ± 0.0022	0.000015	< 0.000015	Design Experiment

NB: ILC limited to a factor 10 larger errors

TLEP as a Tera-Z and Oku-W Factories (5)

- **Polarization in collisions**
  - Often claimed to be impossible in e^+e^- rings because of depolarizing effects
    - It was actually achieved at LEP, and kept for several hours

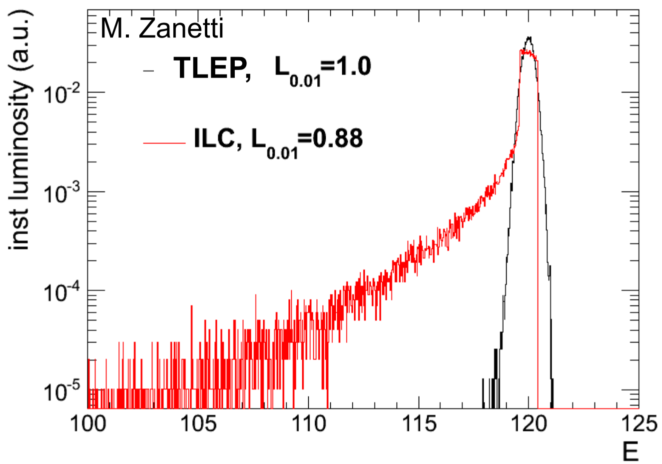


- **Longitudinal polarization**
  - Was achieved at HERA with dedicated spin rotators
    - The feasibility at TLEP needs to be studied
      - ➨ Challenges : continuous top-up injection, large natural polarization time

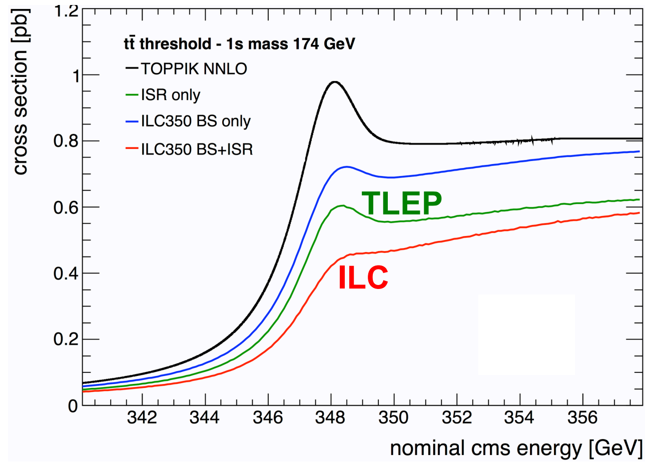
TLEP as a Mega-Top Factory

- Scanning the $t\bar{t}$ threshold at $\sqrt{s}$ ~ 350 GeV
  - Much smaller beamstrahlung at TLEP than at Linear Colliders (relaxed beam size)

Luminosity E Spectrum



Effect on top threshold

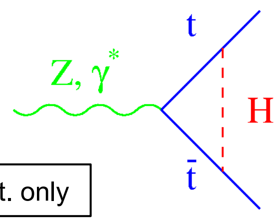


  - No need to measure the luminosity spectrum @ TLEP : no associated m_{top} uncertainty
  - Slightly larger cross section @ TLEP : reduced statistical uncertainty
  - Beam energy calibration to 5 MeV from $e^+e^- \rightarrow$ WW and Z(γ); α_s from Z and W leptonic decays.
  - Still need to work on theoretical predictions (~50 MeV uncertainty on m_{top})

	Lumi / 5 years	# top pairs	Δm_{top}	$\Delta\Gamma_{top}$	$\Delta\lambda_{top}/\lambda_{top}$
TLEP	4 × 650 fb⁻¹	1,000,000	10 MeV	12 MeV	13%
ILC	350 fb⁻¹	100,000	30 MeV	35 MeV	40%

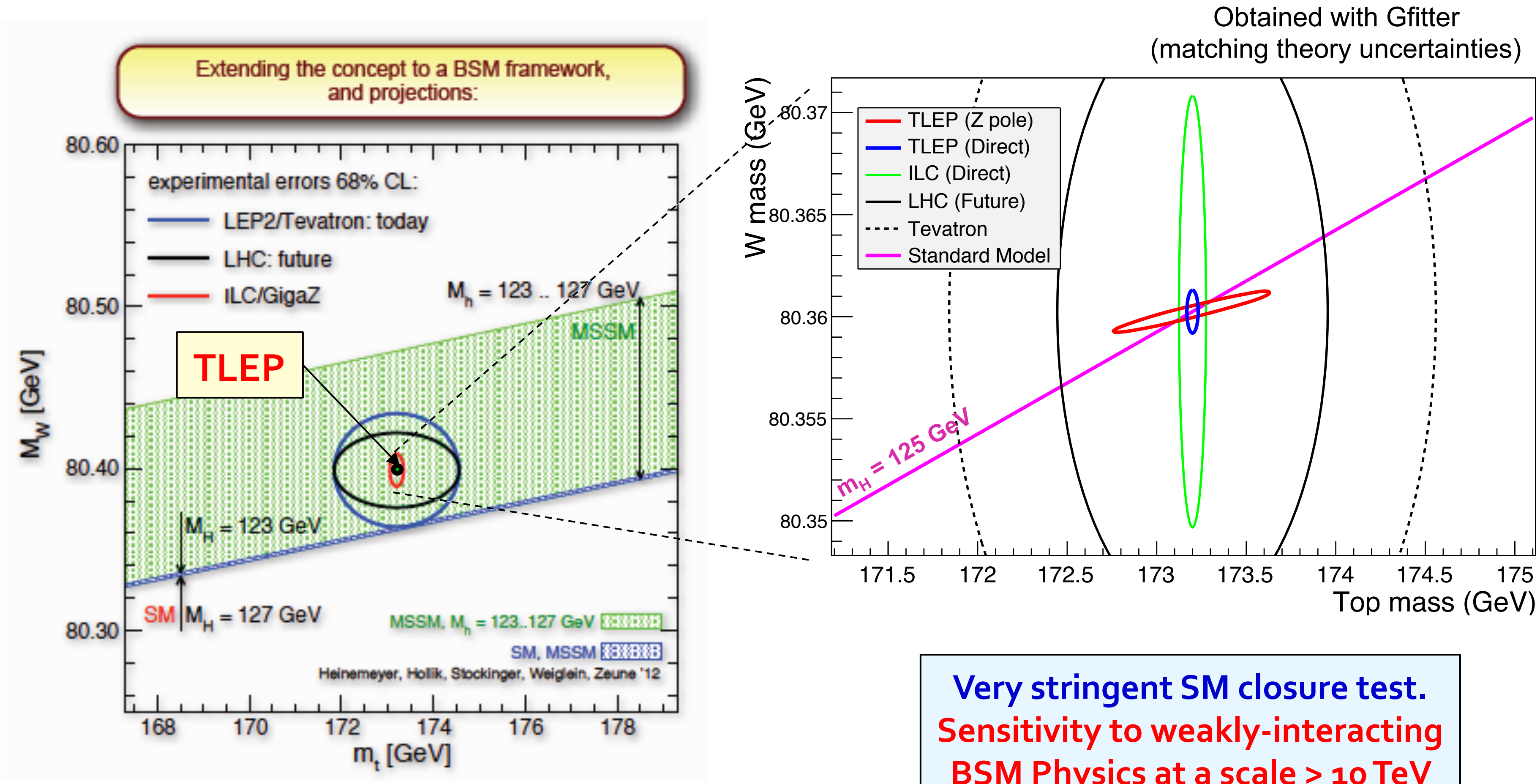
Stat. only

Rare decays !



EWSB Precision test at TLEP: Summary (1)

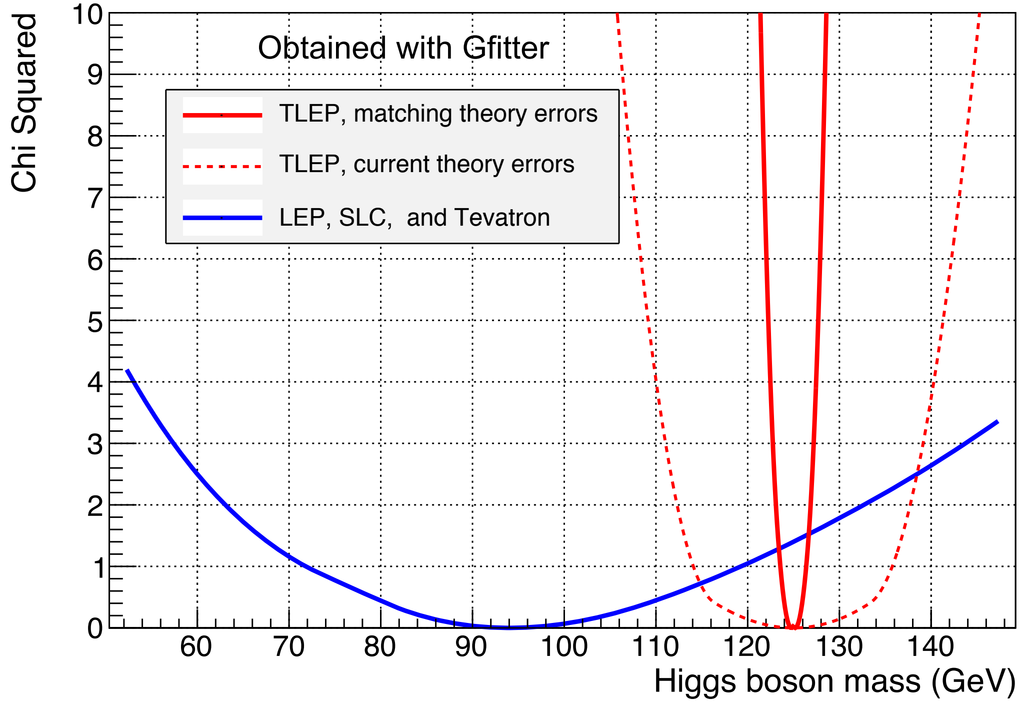
- When m_W, m_{top} and m_H are known with precision …
  - … The standard model has nowhere to go !



Very stringent SM closure test.
Sensitivity to weakly-interacting BSM Physics at a scale > 10 TeV

EWSB Precision test at TLEP: Summary (2)

- **Another viewpoint : m_H prediction from all EW measurements in the SM**
  - **$\sigma(m_H)$ would decrease from ±25 GeV (today) to ±1.4 GeV (with TLEP)**



- **Needs order of magnitude reduction of EW calculations uncertainties**
  - ➨ **And factor 5 improvement of the $\text{alpha}_{QED}(m_Z)$ precision**

Within reach at the timescale of TLEP (see later)

TLEP Cost (Very Preliminary) Estimate

Cost for the 80 km version : the 100 km version might be cheaper.)

❑ 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, 4^{th} 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);

As a self-standing project :

Same order of magnitude as LHC

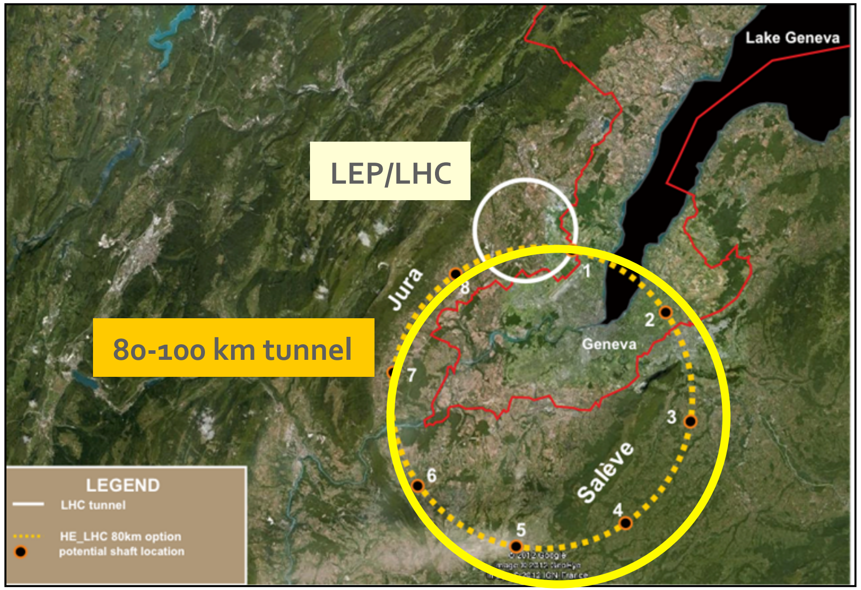
As an add-on to the VHE-LHC project :

Very cost-effective : about 2-3 billion CHF

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

Cost per Higgs boson : 1 - 3 kCHF / Higgs

(ILC cost : 150 k$ / Higgs) [NB : 1CHF ~ 1$]



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- **Cost in billion CHF**

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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**

Absolutely Preliminary
Not endorsed by anybody

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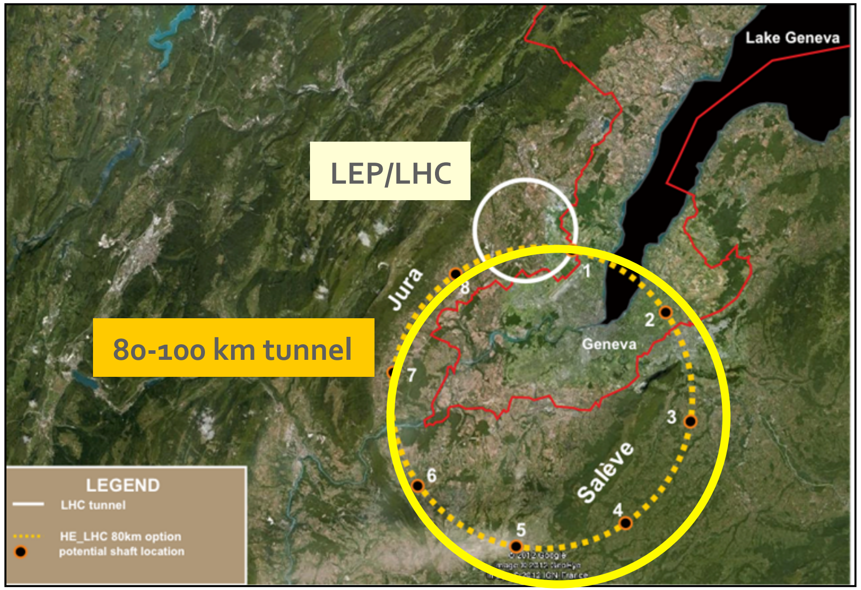
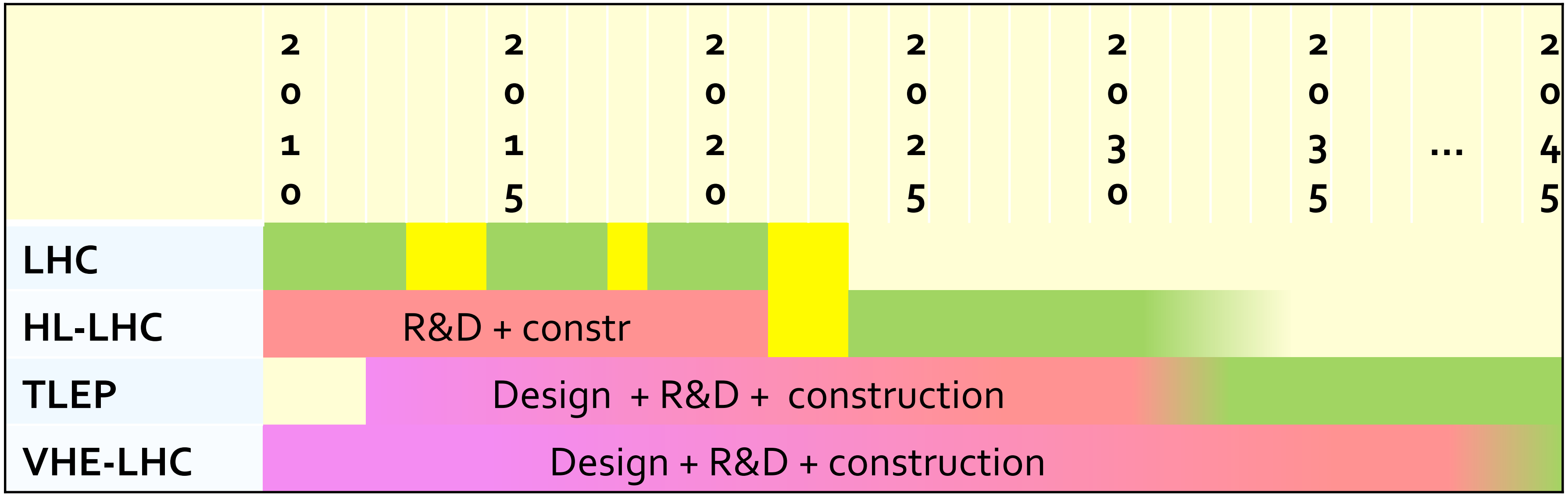


TLEP Possible Timescale

- **Similar timescales for TLEP and ILC**
  - ILC aims for Physics in 2027-2028
- **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 - …, for 12-15 years.

Now !



Design Study (2013 – 2018) : Structure

26 Working Groups: Accelerator / Experiment / Phenomenology

Institutional board

Steering group
web site, mailing lists,
speakers board, etc..

International Advisory board

Aleksan, Azzi, Blondel, Ellis, Janot, Klute, Koratzinos, Zanetti, Zimmermann

Accelerator — Zimmermann

1. Optics, low beta, alignment and feedbacks
2. Beam beam interaction
3. Magnets
4. RF system
5. Top-up injection
6. Injector system & sources
7. Integration w/(VHE)-LHC
8. MDI, Interaction region
9. Vacuum
10. Polarization &E-calib.
11. Civil Engineering
12. Elements of costing

Experiments — Janot

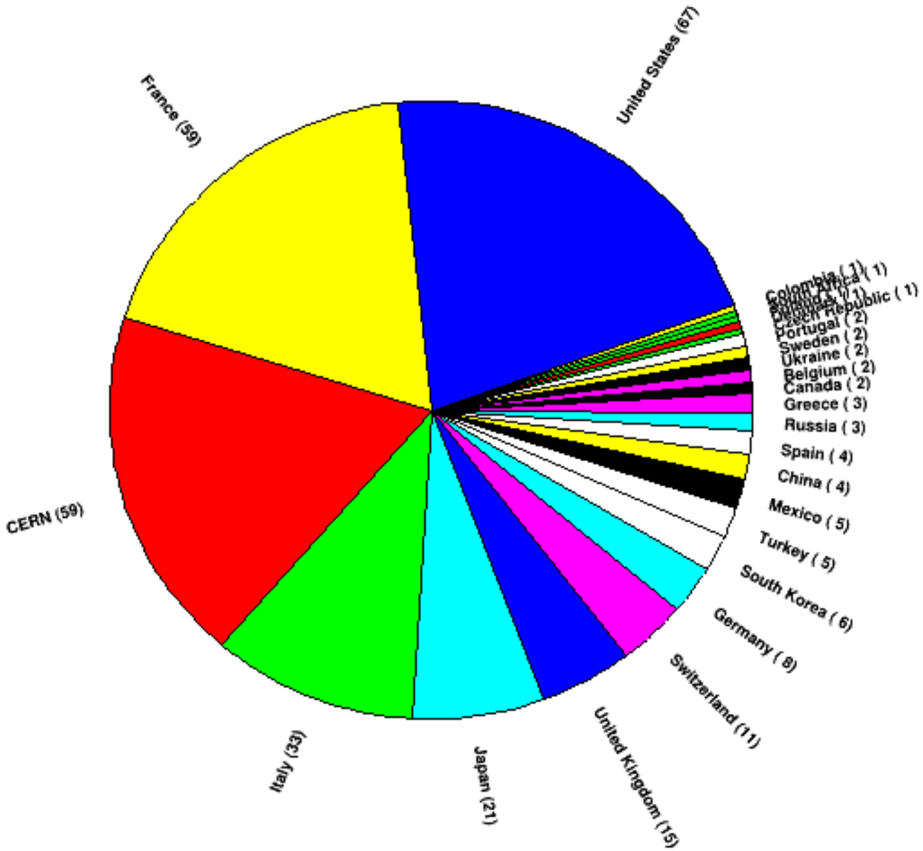
1. EW physics at Z pole
2. WW, ZZ, Zγ physics
3. H(126) properties
4. Top quark physics
5. Flavour (b,c, τ, ν) physics
6. QCD and γγ physics
7. rare decays & new physics
8. Experimental environment
9. offline computing
10. Online computing
11. Detector design

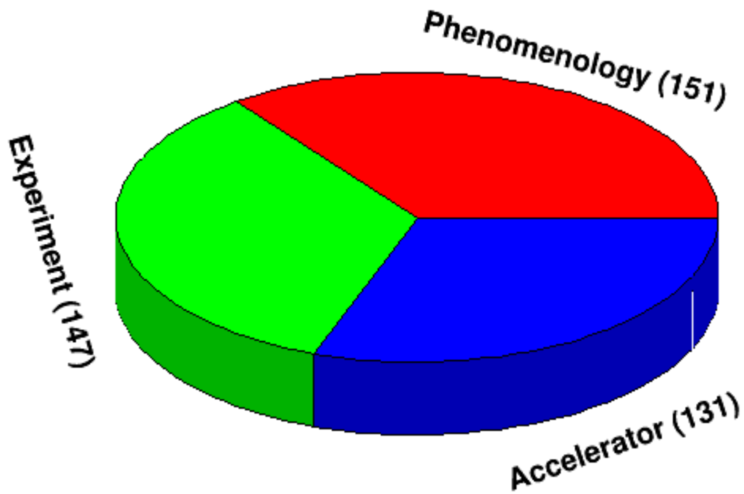
Phenomenology — Ellis

1. model building
2. Precision EW calculations
3. Flavour (b,c, τ, ν) physics
4. QCD and γγ physics
5. rare decays & new physics
6. Combination + complementarity with LHC and other machines ; global analysis

Design Study (2013 – 2018) : People

- **319 subscribers from 24 countries (+CERN)**
  - **Distribution reflects the level of awareness in the different countries**
    - **Subscribe at http://tlep.web.cern.ch !**





- **Remarkable balance between accelerator, experiment and phenomenolgy**

Design Study (2013 – 2018) : Next events

- http://tlep.web.cern.ch

- **Next event : Sixth TLEP workshop**
  http://indico.cern.ch/conferenceDisplay.py?ovw=True&confId=257713
- **Joint VHE-LHC + TLEP kick-off meeting in February 2014**

Concluding Remarks (1)

TLEP $HZ^0W^-W^+t\bar{t}$

- **The discovery of H(126) brought new light on the next large machine**
  - **Prospects for the next decade look very promising**
    - **The HL-LHC is already an impressive Higgs factory, with great potential**
    - **The coming run at 13 TeV may discover something else, likely beyond ILC reach**
- **It is important to choose the right machine for the future**
  - **It would be premature to mortgage the future of HEP before knowing the 13 TeV results**
    - **The right machine must bring order(s) of magnitude improvement wrt LHC**
      - **Both in precision measurements and in discovery potential**

The ILC project, for example, is limited in both aspects

- **A large e^+e^- circular collider seems to be the best complement to LHC**
  - **Per-mil precision on Higgs couplings; Unequalled precision on EWSB parameters**
    - **Rare W,Z,t,H decays; N_ν measurement to < 10^{-3}; Direct α_s measurement; …**
  - **Most mature technology : supported by progress of e^+e^- factories for 20 years**
    - **SuperKEKB will be a precious demonstrator**
    - **Based on this experience, cost, power, and luminosity predictions will be reliable**
  - **It is a first step towards a 100 TeV pp collider and a long-term vision for HEP**
    - **Together with VHE-LHC, it offers the best precision and search reach on the market**

Concluding Remarks (2)

TLEP $HZ^0W^-W^+t\bar{t}$

- The design study of TLEP has started
  - In close collaboration with the VHE-LHC design study
  - With worldwide collaboration (subscribers from Asia, Europe and USA)
  - With full support from the CERN Council
    - The study is now acted in the approved CERN MTP (2014-2018)

- The first proposed step is a design study report in 2015 …
  - … towards a CDR + cost estimate in 2018
    - For an informed decision to be taken in full knowledge of the LHC results
      And with operational experience with SuperKEKB

- A solid backbone exists for both the Design and the Physics case of TLEP
  - The physics case is very rich, but demanding
    - We need you for the many challenges, and their solutions

- TLEP could be ready for physics in 2030, if given enough support
  - It is time to join now and enjoy the work together.

Quote from Nima Arkani-Hamed

- **From 5th TLEP workshop (FNAL, 25-26 July 2013)**
  - **Title of the presentation : "Perspectives at a 100 TeV pp collider"**

(Slide 22) This alone fully justifies the march to 100 TeV, in my view

[Tera-Z @ TLEP plays very important complementary role]

(Slide 41) *EVERY student/post-doc/person with a pulse (esp. under 35) I know is ridiculously excited by even a glimmer of hope for a 100 TeV pp collider

These people don't suffer from SSC PTSD

- **Q : "What would you chose between a ILC at 1 TeV and a TLEP + VHE-LHC complex ?"**
  - **A : "It is so obvious !"**
- **Woit's blog after the workshop –** http://www.math.columbia.edu/~woit/wordpress/
  - **"Looking at the possibilities, I do think TLEP/VHE-LHC looks like the currently most promising route for the future for CERN and HEP physics"**