First Look at the Physics Case of TLEP

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The TLEP Design Study Working Group

(See next pages for the list of authors)

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Abstract

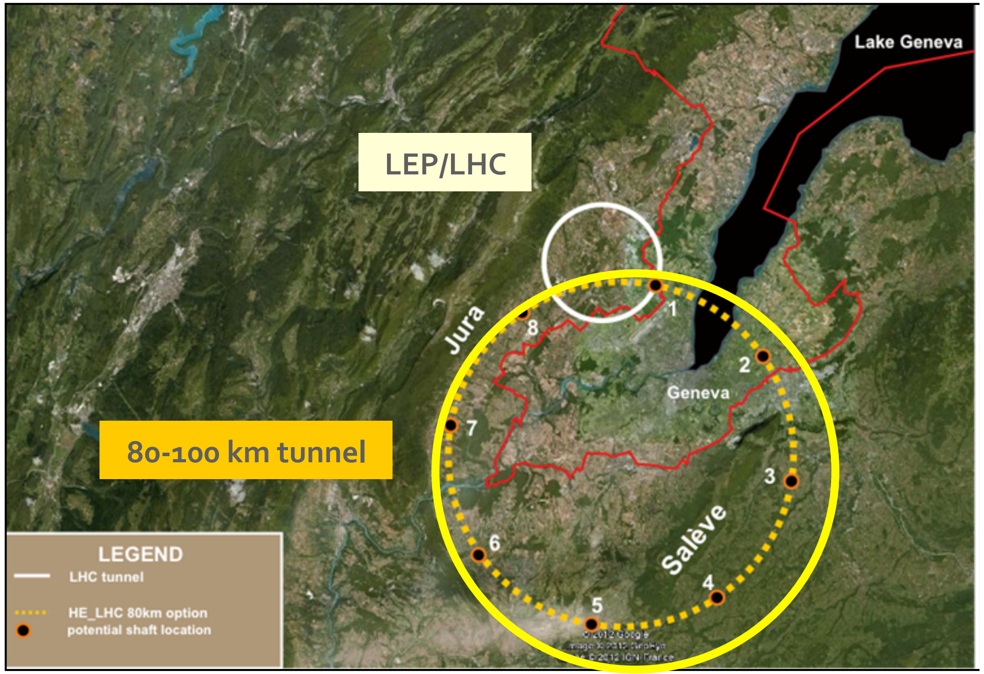
The discovery by the ATLAS and CMS experiments of a new boson with mass around 125 GeV and with measured properties compatible with those of a Standard-Model Higgs boson, coupled with the absence of discoveries of phenomena beyond the Standard Model up to scales of several hundred GeV, has triggered interest in ideas for future Higgs factories. A new circular e^+e^- collider hosted in a 80 to 100 km tunnel, TLEP, is among the most attractive solutions proposed so far. It has a clean experimental environment, produces high luminosity for top-quark, Higgs boson, W and Z studies, accommodates multiple detectors, and can reach energies up to the $t\bar{t}$ threshold and beyond. It will enable measurements of the Higgs boson properties and of Electroweak Symmetry-Breaking (EWSB) parameters with unequalled precision, offering exploration of physics beyond the Standard Model in the multi-TeV range. Moreover, being the natural precursor of the VHE-LHC, a 100 TeV hadron machine in the same tunnel, it builds up a long-term vision for particle physics. Altogether, the combination of TLEP and the VHE-LHC offers, for a great cost effectiveness, the best precision and the best search reach of all options presently on the market. This paper presents a first appraisal of the salient features of the TLEP physics potential, to serve as a baseline for a more extensive design study.

Submitted to the Journal of High Energy Physics

TLEP = Triple LEP (80 km) or Tetra LEP (100 km)

Precision physics at the EW scale

TeraZ, OkuW, MegaHiggs and MegaTops



Possible long-term strategy (>50 yrs) : FCCs

e^+e^- collisions with $\sqrt{s}$ up to 500 GeV (FEC)

pp collisions with $\sqrt{s}$ up to 100 TeV (FHC)

FCC Design Study has been launched

- Excerpt from the CERN Medium Term Plan (2014-2018) in May 2013

> • 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

- Approved by the CERN Council in June 2013
  - Conceptual Design Study officially launched at CERN by the CERN DG on Oct. 7th

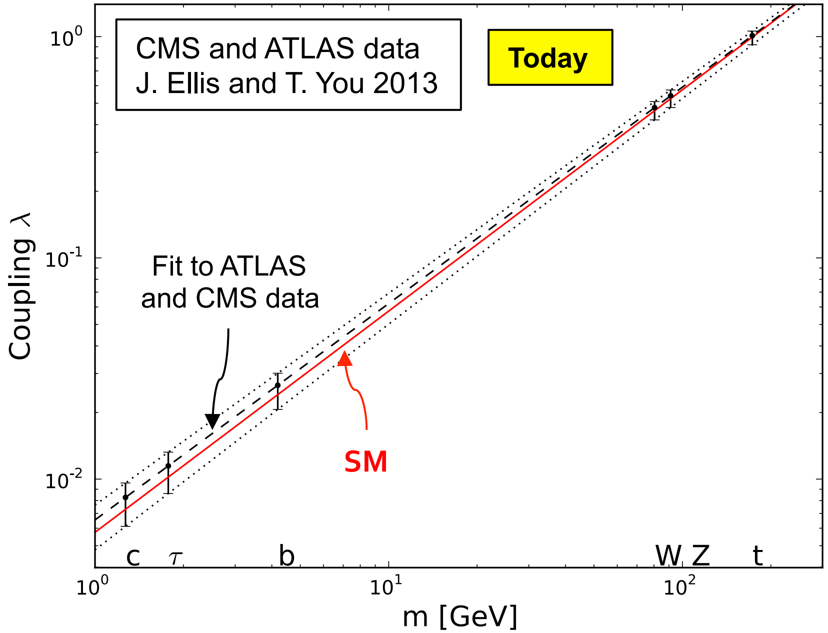
Future Circular Colliders - Conceptual Design Study
Study coordination, host state relations, global cost estimate
Benedikt, Zimmermann

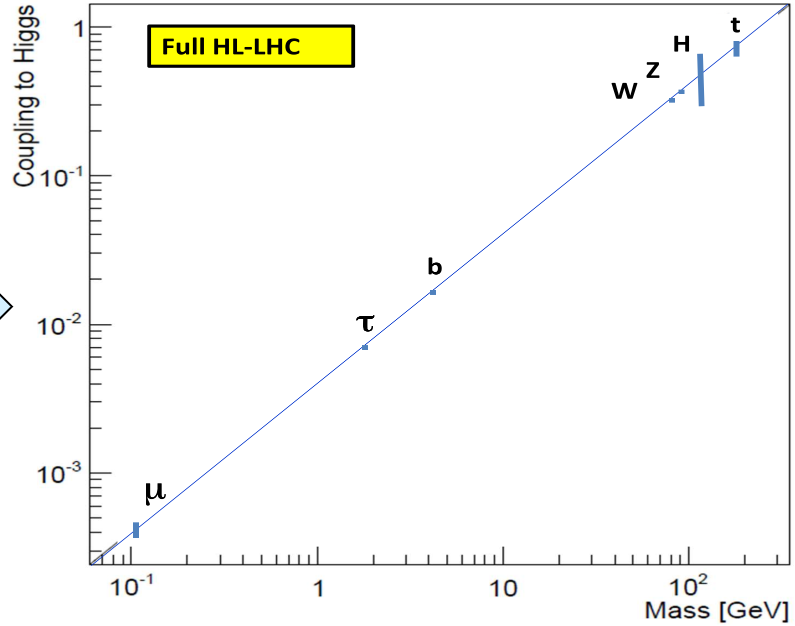
- **Hadron injectors** – **B. Goddard**
- **VL Hadron collider** – **D. Schulte**
- **Infrastructure, cost estimates** – **P. Lebrun**
- **e+ e- collider** – **J. Wenninger**
- High Field Magnets – **L. Bottura**
- Supercon-ducting RF – **E. Jensen**
- Cryogenics – **L. Tavian**
- Specific Technologies (MP, Coll, Vac BI, BT, PO) – **JM. Jimenez**
- **Physics and experiments**
  - Hadron physic Experiments, Infrastructure – **A. Ball, F. Gianotti, M. Mangano**
  - e+ e- exper., physics – **A. Blondel J.Ellis, P.Janot**
  - e- p physics + – **M. Klein**
- **e- p option** – Integration aspects **O. Brüning**
- **Operation aspects,** energy efficiency, OP & mainten., safety, environment. – **P. Collier**
- **Planning (Implementation roadmap, financial planning, reporting)** – **F. Sonnemann**

Unanimously approved by r-ECFA

Why an FCC Design Study now?

- **The LHC discovered H(126) and nothing else (so far)**
  - **Most standard scenario – including H(126) properties: We just entered the precision era**





  - **We are not done. We must keep looking for new physics with LHC at 13-14 TeV**
    - **We know for sure that new particles/phenomena exist (at an unknown scale)**
      - **Dark matter, absence of antimatter, small neutrino masses, m_H stabilisation…**
  - **LHC will give its answer in 2017 – we have to get prepared for the 2018 strategy update**
    - **We'll know if we need <u>more</u> precision, or <u>more</u> energy (what energy?), or both.**

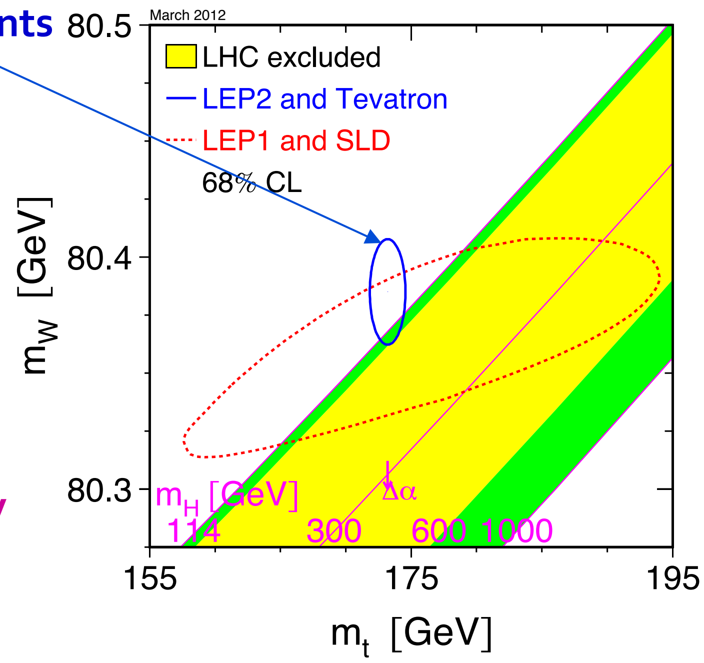
Why would we need more precision?

- **Because precision is a new physics discovery search**
  - From precise EW measurements, LEP could predict m_{top} through EW loops
    - Adding m_{top} and m_W precise measurements from Tevatron, LEP predicted m_H
  - LEP1 measurements are also sensitive to new physics at a scale of ~1 TeV
    - Could increase this sensitivity to 10 TeV with precision improved by a factor 100
      - NB: This corresponds to 10000 times more statistics, i.e., 10^{11} Z (!)
  - Match precision with direct m_W and m_{top} measurements
    - Improve by at least one order of magnitude
      - $\delta m_W < 1$ MeV and $\delta m_{top} < 50$ MeV
  - Higgs properties are also sensitive to new physics

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

H. Baer et al., ILC TDR

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

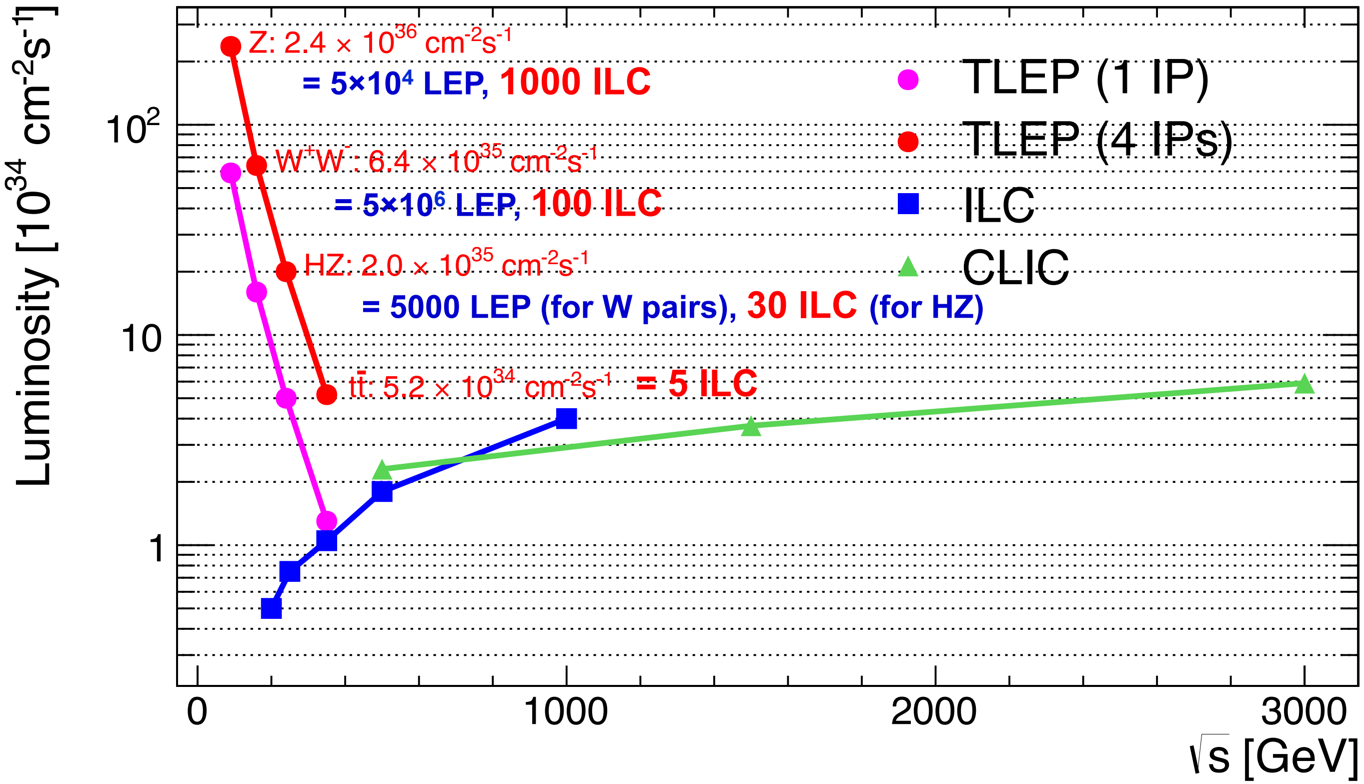


    - Need to measure couplings with 1% precision
      - For a 5σ discovery if new physics is at 1 TeV
    - … and to sub-per-cent precision for larger scales

- **Sum-up: Measure Z, W, H and top properties with ultimate precision**

Specificities of a circular e^+e^- machine (1)

- **High repetition rate and multiple detectors : Large luminosity**
  - e.g., 20 MHz at the Z pole; 200 kHz at √s = 240 GeV



- **Potential considerable improvements in the precision of EW observable measurements**
- **Possibility to measure the Higgs and top quark properties with unequalled accuracy**
- **Sensitivity to the rarest decays of the Z, W, top, Higgs, b, c, or τ**

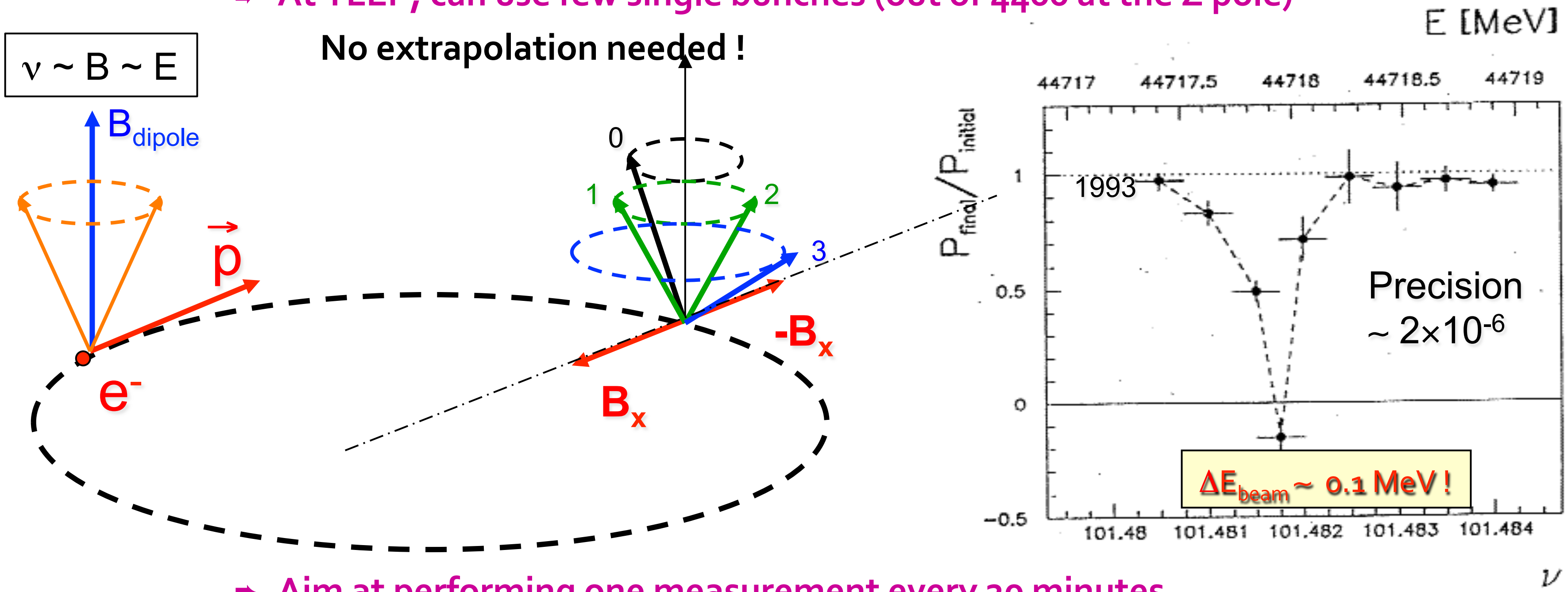
See L. Silvestrini's talk today for rare decays examples

See D. d'Enterria's talk tomorrow for the case for QCD studies

Specificities of a circular e^+e^- machine (2)

- **Natural beam transverse polarization up to $\sqrt{s} \sim 2\,m_W$**
  - **Exquisite beam energy measurement with resonant depolarization, unique to rings**
    - **Precision limited to 2 MeV at LEP1 by the extrapolation to collision conditions**
      - ➨ **At TLEP, can use few single bunches (out of 4400 at the Z pole)**

No extrapolation needed !



- ➨ **Aim at performing one measurement every 20 minutes**

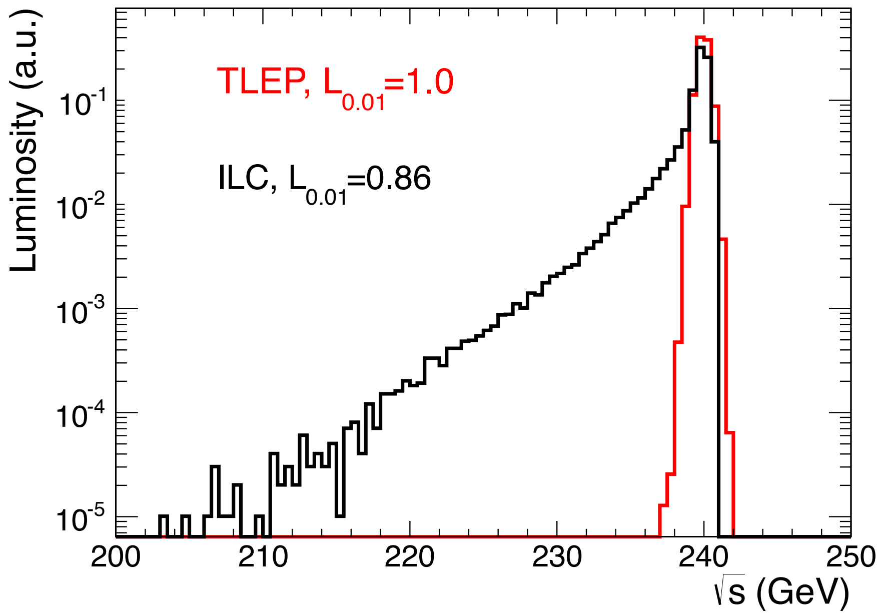
Ultimate precision better than 50 keV for m_Z and m_W measurements

- **For $\sqrt{s}$ above $2m_W$: use accurate W or Z masses in $e^+e^- \to Z(\gamma)$, WW, ZZ**
  - **Expected precision on the centre-of-mass energy: ~few MeV (for m_H, m_{top})**

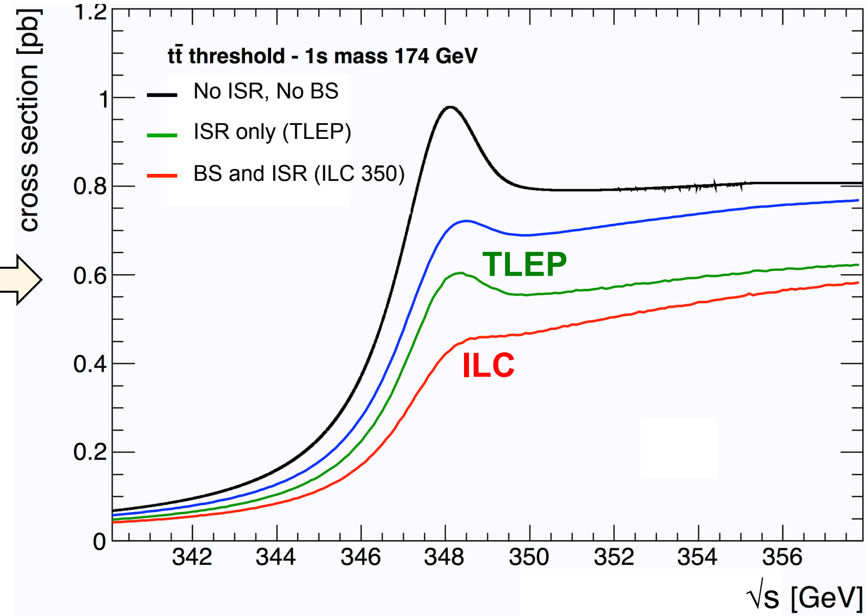
Specificities of a circular e^+e^- machine (3)

- **Little beamstrahlung at the interaction points**
  - Excellent centre-of-mass energy definition (and small EM backgrounds)

Luminosity E Spectrum



Effect on top threshold

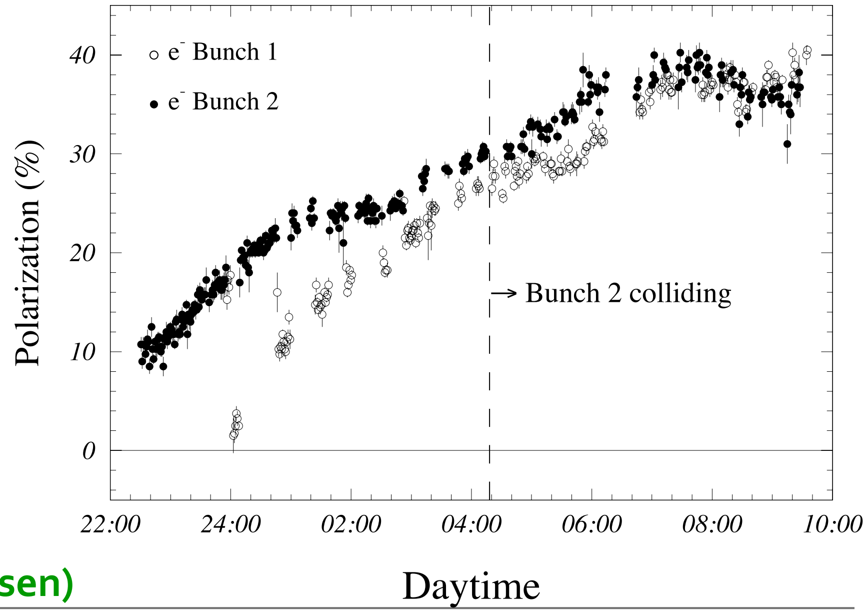


  - No need to measure the luminosity spectrum
  - No beam energy bias. Beam energy spread of ~0.1%.
  - Beam energy calibration to few MeV from $e^+e^- \rightarrow Z(\gamma)$, WW and ZZ
    - Small experimental uncertainty on m_{top}

Specificities of a circular e^+e^- machine (4)

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

- **Longitudinal polarization is not automatic**
  - Large polarization levels needed: probably possible only at $\sqrt{s} \sim m_Z$
  - Polarization wigglers needed to reduce the polarization time
  - Top-up injection needs to be minimized: run at reduced luminosity
  - Spin rotators (a la HERA) needed to rotate transverse polarization
    - Dedicated study is necessary to establish feasibility and optimize settings
  - Once established, longitudinal polarization must be kept in collisions
    - Successfully achieved at LEP (with transverse polarization)
      - Pol. > 40% reached
      - Kept in collisions for 5 hours
      - No Pol. reduction with respect to non-colliding bunches
  - Would allow A_{LR} measurement
- **Polarization at higher $\sqrt{s}$?**
  - Not crucial for the physics case
    - (mostly cross-section increase by factors between 1.5 and 2.5, when the proper beam polarization are chosen)



TLEP : Possible Physics Programme

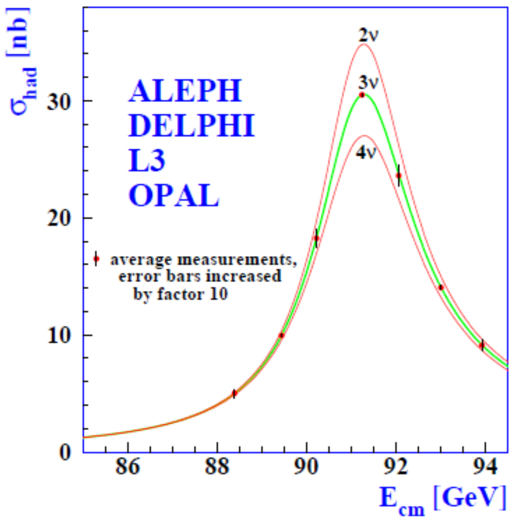
TLEP $HZ^0W^-W^+t\bar{t}$

- **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, reduced lumi
- **Luminosity, Energy, Polarization upgrades ?**
  - If justified by scientific arguments (with respect to the upgrade to VHE-LHC)

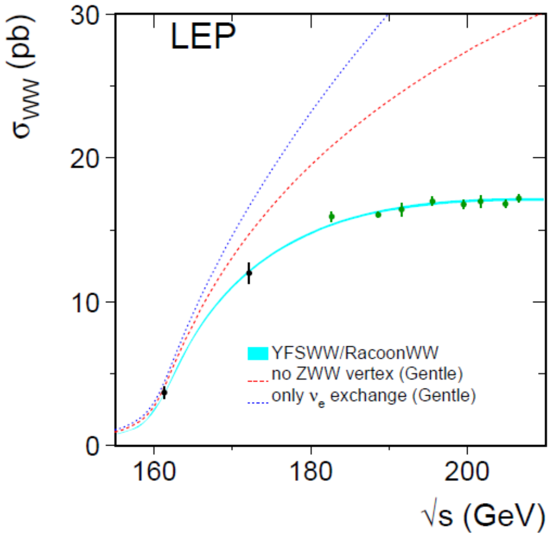
TLEP as a TeraZ and OkuW Factories (1)

- **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**

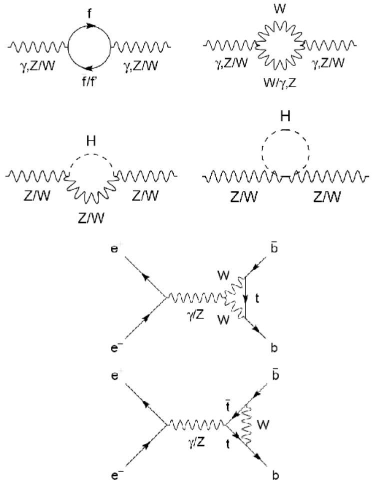
Z lineshape, asymetries



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 TeraZ and OkuW Factories (2)

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

- The study is just beginning : errors might get better with increasing understanding
  - ➨ Used LEP knowledge so far. Will be revisited with TLEP experimental cross-checks.

    Most serious issue is the theory uncertainty on the luminosity measurement (N_ν)
- 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 TeraZ and OkuW Factories (3)

❑ Measurements with Oku-W

See C. Schwinn's talk tomorrow for the WW threshold scan

- 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.	Challenge
m_W (MeV)	Threshold scan	80385 ± 15	0.3	< 0.5	QED Corrections
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	CKM Matrix

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

See G. Dissertori's and A. Pich's talks tomorrow for comments on α_s studies

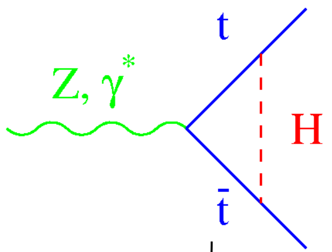
❑ Measurement with longitudinal polarization

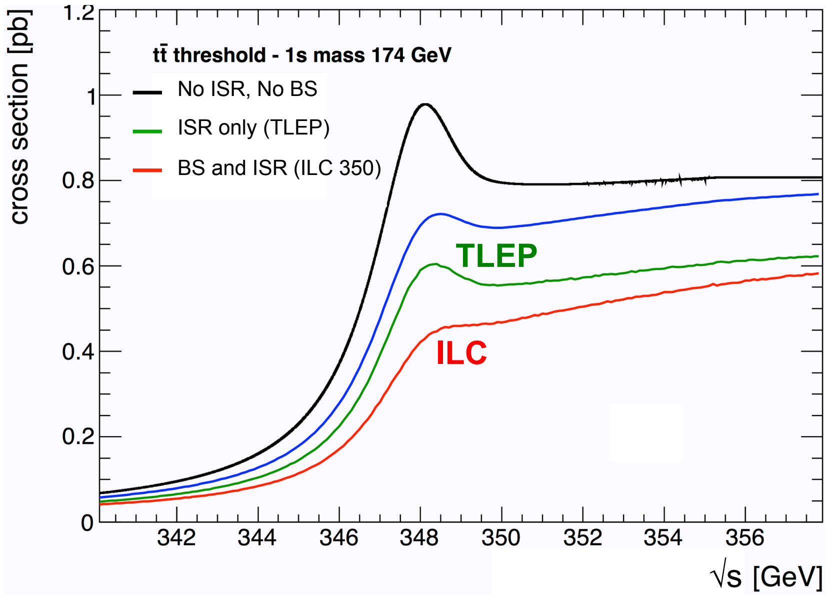
- One year with luminosity reduced to 20% of nominal (requires spin rotators + wigglers)
  - 40% beam longitudinal polarization assumed. (Cf. polarization in collisions at LEP)

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

TLEP as a MegaTops Factory

- **Scanning the $t\bar{t}$ threshold at $\sqrt{s}$ ~ 350 GeV**



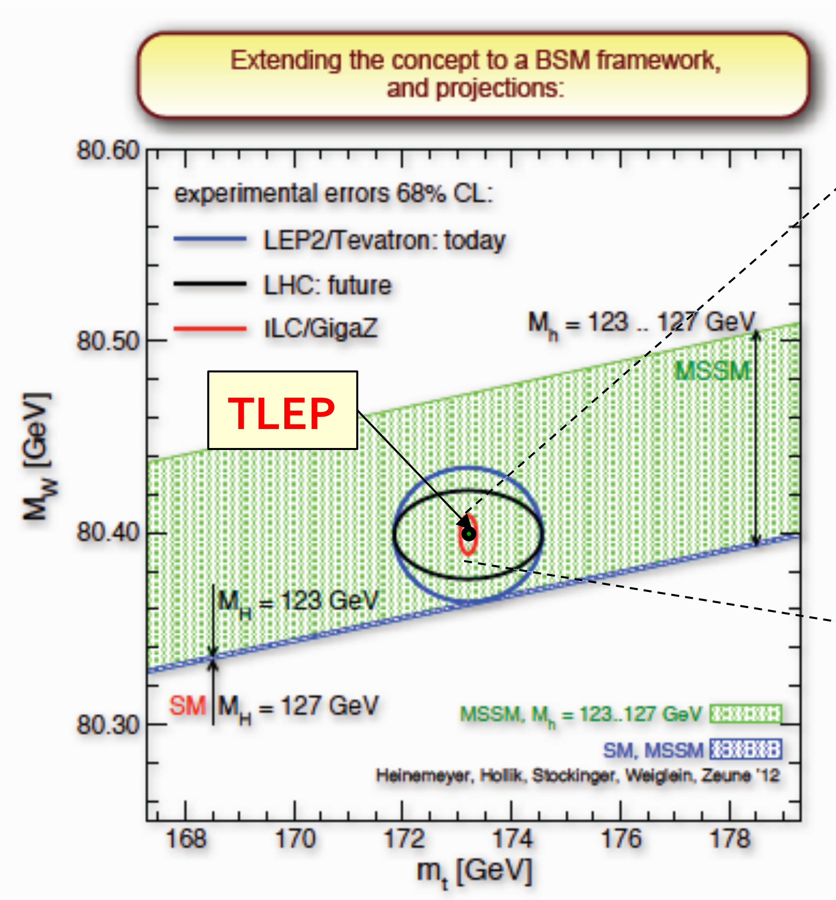


- **With about 1 million top pairs in 5 years :**

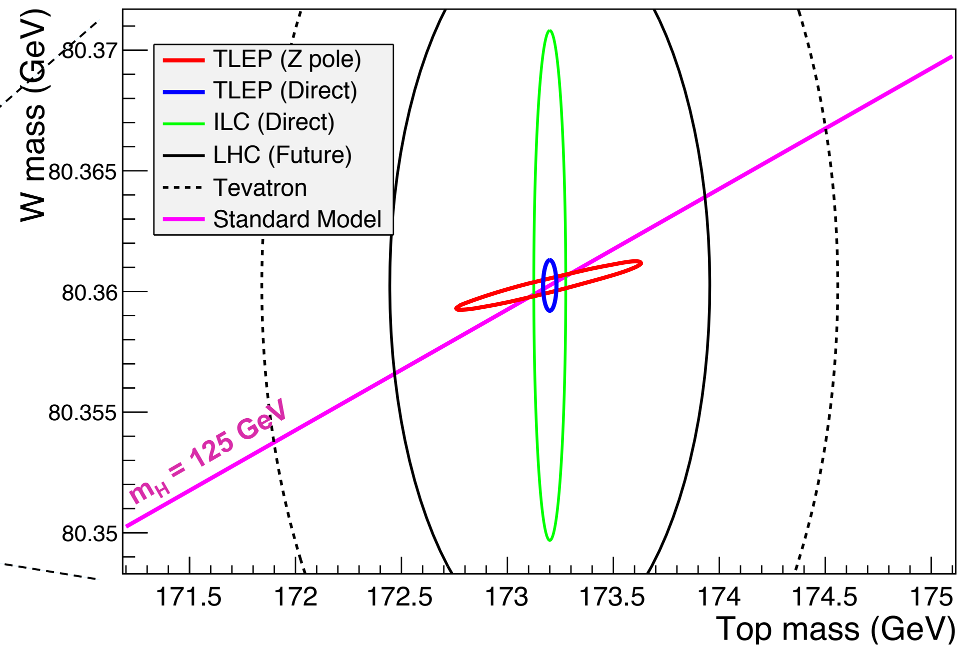
Observable	Measurement	Current precision	TLEP stat.	Possible syst.	Challenge
m_{top} (MeV)	Threshold scan	173200 ± 900	10	10	QCD corrections (~40 MeV)
Γ_{top} (MeV)	Threshold scan	?	12	?	$\alpha_s(m_Z)$
λ_{top}	Threshold scan	μ = 2.5 ± 1.05	13%	?	$\alpha_s(m_Z)$

Global EW fit with TLEP (1)

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



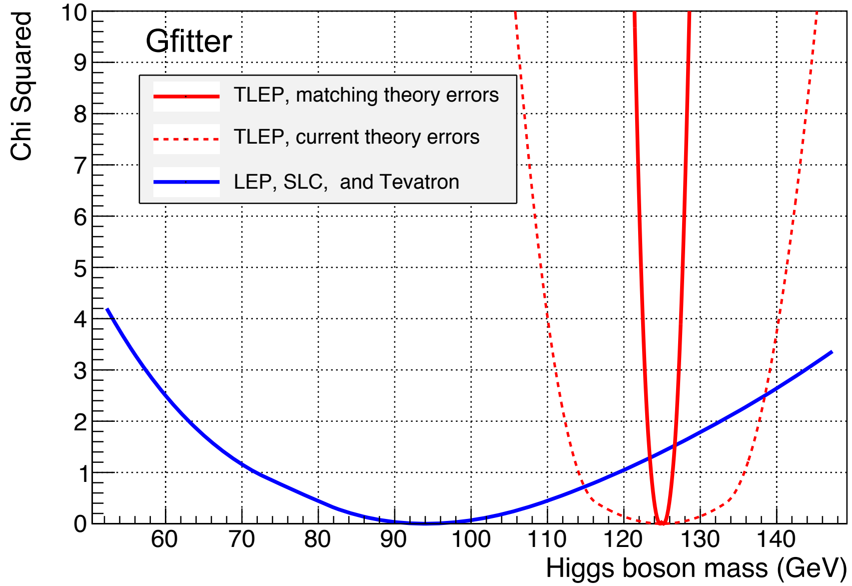
Obtained with Gfitter
(with matching theory uncertainties)



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

Global EW fit with TLEP (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)



See M. Baak's talk tomorrow for more Gfitter studies

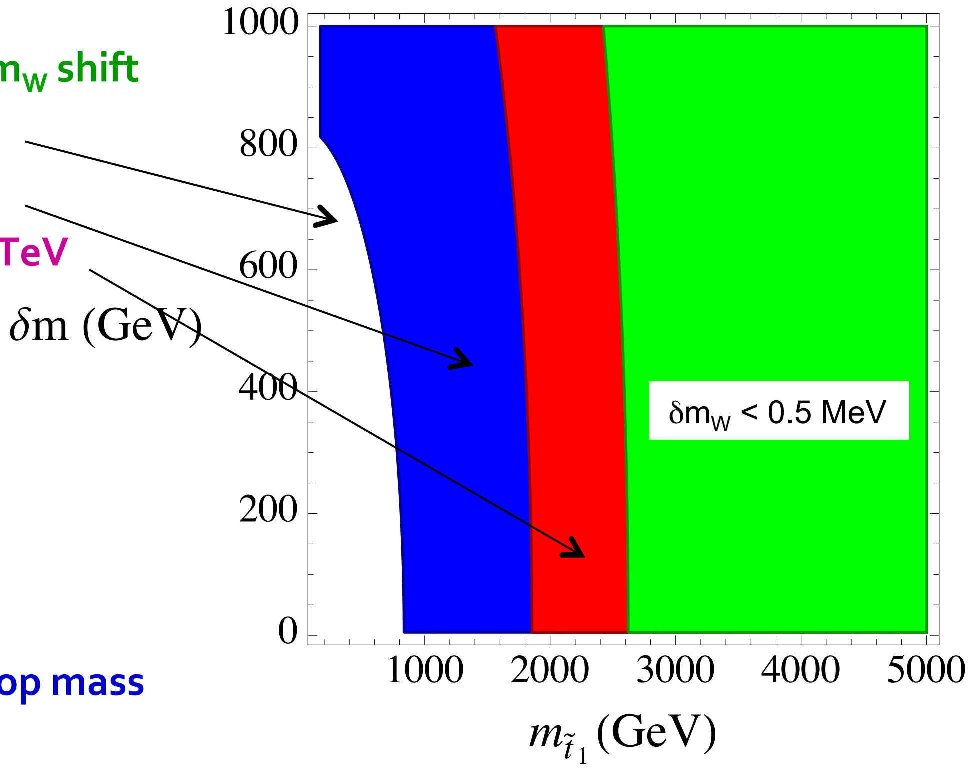
  - Needs order of magnitude reduction of EW calculations uncertainties
    - Within reach on the timescale required by TLEP ?
  - As well as uncertainties on all SM parameters
    - TLEP improved precision on m_Z and m_{top} will greatly help
      - ➨ Needs better accuracy of m_{top} prediction from σ_{tt} (nonperturbative QCD)
    - Also require a factor 5 improvement of the $alpha_{QED}(m_Z)$ precision

See J. Kuehn's talk tomorrow for comments on theory uncertainties

Constraints on new physics

- **To be evaluated with concrete examples, case by case**
  - For example, in natural SUSY
    - Presence of light stops creates a m_W shift
      - $\delta m_W > 5$ MeV if $m_{stop} < 1$ TeV
      - $\delta m_W > 1$ MeV if $m_{stop} < 2$ TeV
      - $\delta m_W > 0.5$ MeV if $m_{stop} < 2.6$ TeV

V. Sanz et al.

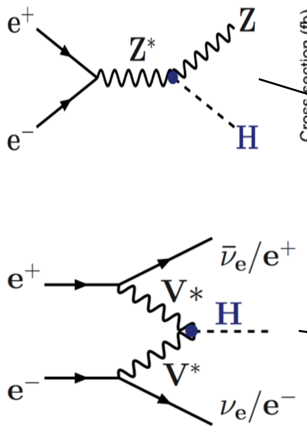


- TLEP would set a lower limit on the stop mass
  - With the sole m_W measurement
  - Far above what could be detected at LHC
    - Analysis needs to be repeated in the global fit.

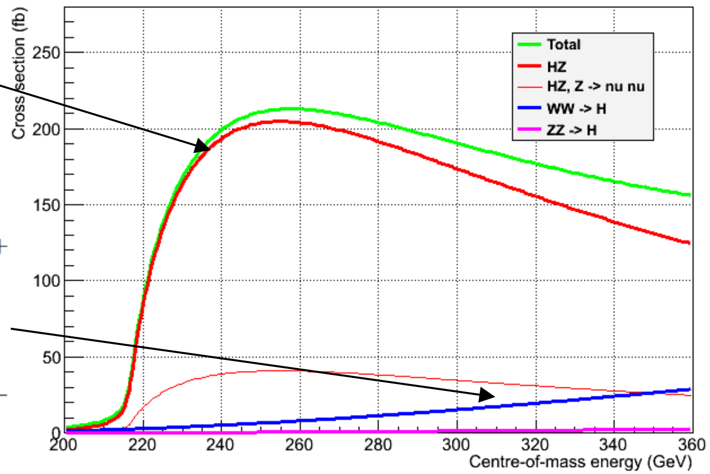
See S. Mishima's talk today for more examples

TLEP as a MegaHiggs Factory (1)

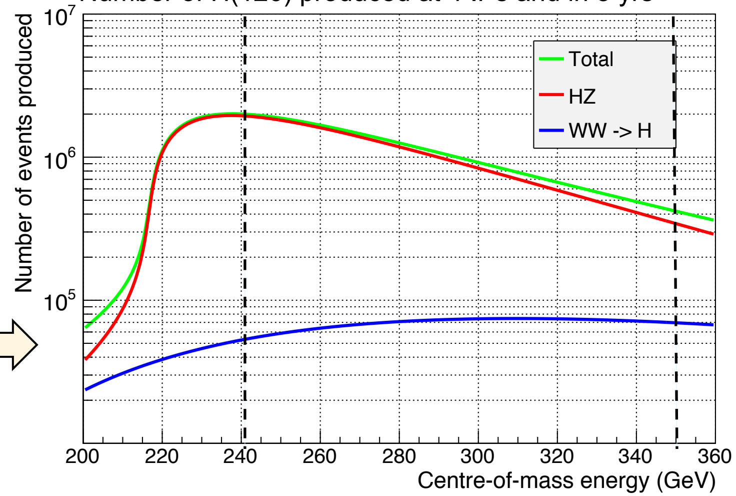
- Choice of the centre-of-mass energy : maximize # of Higgs events



Unpolarized cross sections



Number of H(126) produced at 4 IPs and in 5 yrs



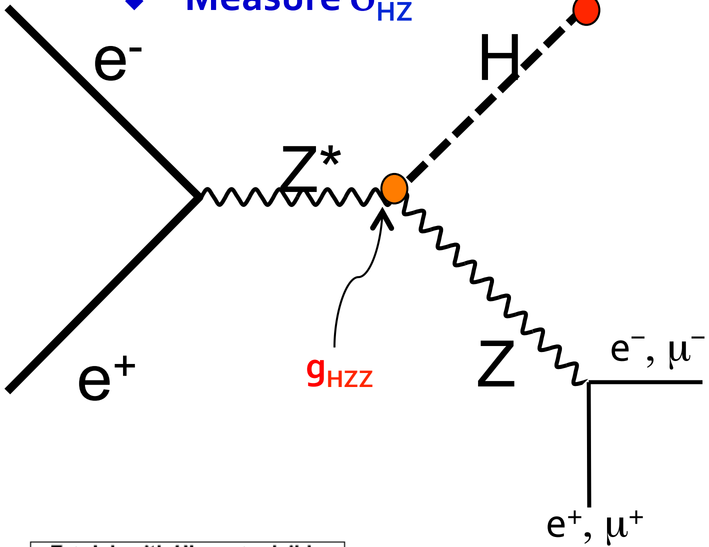
- For each IP and per year at TLEP: 500 fb^{-1} at $\sqrt{s}$ = 240 GeV ; 130 fb^{-1} at $\sqrt{s}$ = 350 GeV
  - Total production cross section ~ 200 fb at maximum

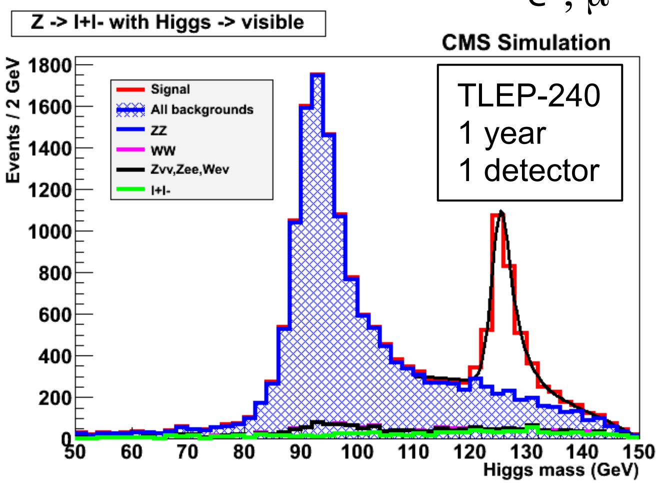
	Lumi / 5 yrs / 4 IPs	# of HZ events	# of WW→H events
TLEP 240	10 ab^{-1}	2,000,000	50,000
TLEP 350	2.6 ab^{-1}	325,000	65,000

➨ Enough events for measurements at the sub-per-cent level

TLEP as a MegaHiggs Factory (2)

- **Example #1 : $e^+e^- \rightarrow ZH \rightarrow l^+l^-$ + anything**
  - **Measure σ_{HZ}**





Summary of the possible measurements @ 240 GeV

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

	TLEP-240
σ_{HZ}	0.4%
$\sigma_{HZ} \times BR(H\rightarrow bb)$	0.2%
$\sigma_{HZ} \times BR(H\rightarrow cc)$	1.2%
$\sigma_{HZ} \times BR(H\rightarrow gg)$	1.4%
$\sigma_{HZ} \times BR(H\rightarrow WW)$	0.9%
$\sigma_{HZ} \times BR(H\rightarrow \tau\tau)$	0.8%
$\sigma_{HZ} \times BR(H\rightarrow ZZ)$	3.1%
$\sigma_{HZ} \times BR(H\rightarrow \gamma\gamma)$	3.0%
$\sigma_{HZ} \times BR(H\rightarrow \mu\mu)$	13%
Γ_{INV} / Γ_H	< 0.2%
m_H	8 MeV

See M. Thomson's talk today
for comments on detector issues
and synergies with CLIC/ICL studies

TLEP as a MegaHiggs Factory (3)

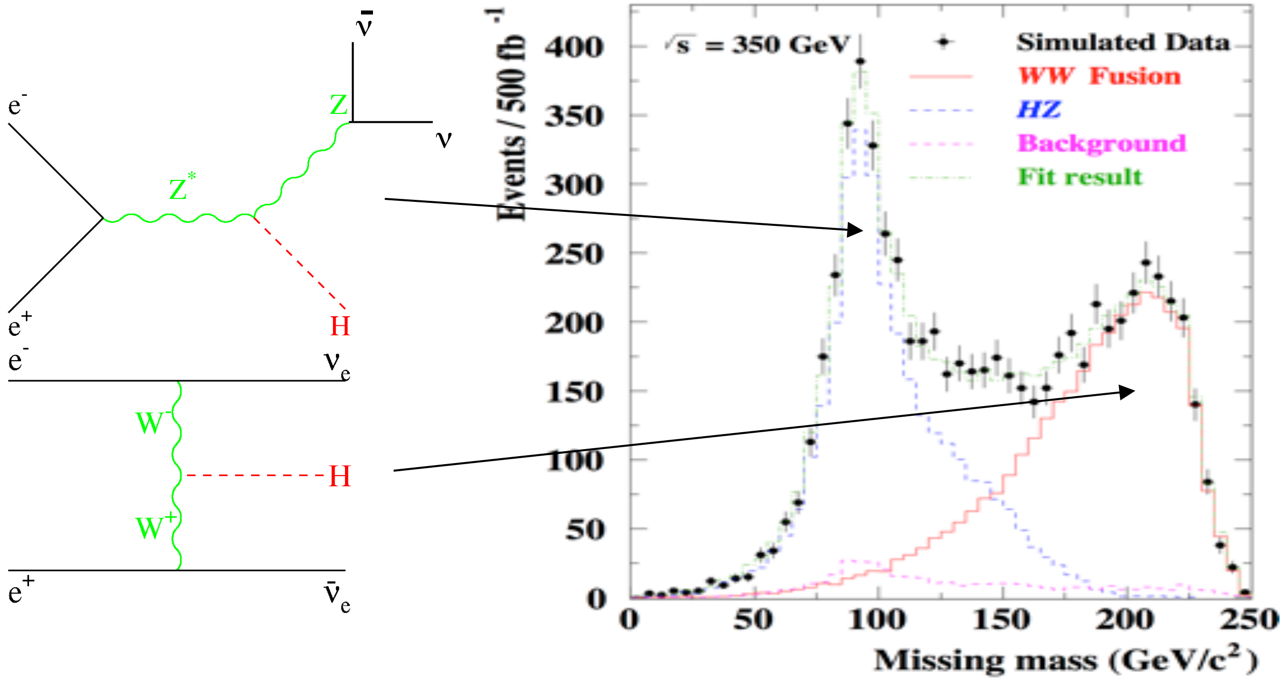
TLEP $HZ^0W^-W^+t\bar{t}$

- **Example #2 : 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:	TLEP
HZ→ZZZ @ 240 GeV	3.2%
WW→H @240 GeV	2.4%
WW→H @350 GeV	1.2%
Combined	**1.0%**

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

Global fit of the Higgs couplings (1)

From Snowmass'13 : Model-independent fit

Table 1-16. *Uncertainties on coupling scaling factors as determined in a completely model-independent fit for different e^+e^- facilities. Precisions reported in a given column include in the fit all measurements at lower energies at the same facility, and note that the model independence requires the measurement of the recoil HZ process at lower energies. ‡ILC luminosity upgrade assumes an extended running period on top of the low luminosity program and cannot be directly compared to TLEP and CLIC numbers without accounting for the additional running period. ILC numbers include a 0.5% theory uncertainty. For invisible decays of the Higgs, the number quoted is the 95% confidence upper limit on the branching ratio.*

Facility		ILC		ILC(LumiUp)	TLEP (4 IP)			CLIC	
$\sqrt{s}$ (GeV)	250	500	1000	250/500/1000	240	350	350	1400	3000
$\int \mathcal{L}dt$ (fb^{-1})	250	+500	+1000	1150+1600+2500‡	10000	+2600	500	+1500	+2000
$P(e^-, e^+)$	$(-0.8, +0.3)$	$(-0.8, +0.3)$	$(-0.8, +0.2)$	(same)	$(0, 0)$	$(0, 0)$	$(-0.8, 0)$	$(-0.8, 0)$	$(-0.8, 0)$
Γ_H	12%	5.0%	4.6%	2.5%	1.9%	1.0%	9.2%	8.5%	8.4%
κ_γ	18%	8.4%	4.0%	2.4%	1.7%	1.5%	–	5.9%	<5.9%
κ_g	6.4%	2.3%	1.6%	0.9%	1.1%	0.8%	4.1%	2.3%	2.2%
κ_W	4.9%	1.2%	1.2%	0.6%	0.85%	0.19%	2.6%	2.1%	2.1%
κ_Z	1.3%	1.0%	1.0%	0.5%	0.16%	0.15%	2.1%	2.1%	2.1%
κ_μ	91%	91%	16%	10%	6.4%	6.2%	–	11%	5.6%
κ_τ	5.8%	2.4%	1.8%	1.0%	0.94%	0.54%	4.0%	2.5%	<2.5%
κ_c	6.8%	2.8%	1.8%	1.1%	1.0%	0.71%	3.8%	2.4%	2.2%
κ_b	5.3%	1.7%	1.3%	0.8%	0.88%	0.42%	2.8%	2.2%	2.1%
κ_t	–	14%	3.2%	2.0%	–	13%	–	4.5%	<4.5%
BR_{inv}	0.9%	$< 0.9\%$	$< 0.9\%$	0.4%	0.19%	$< 0.19\%$			

The 10B$ ILC, 10 years

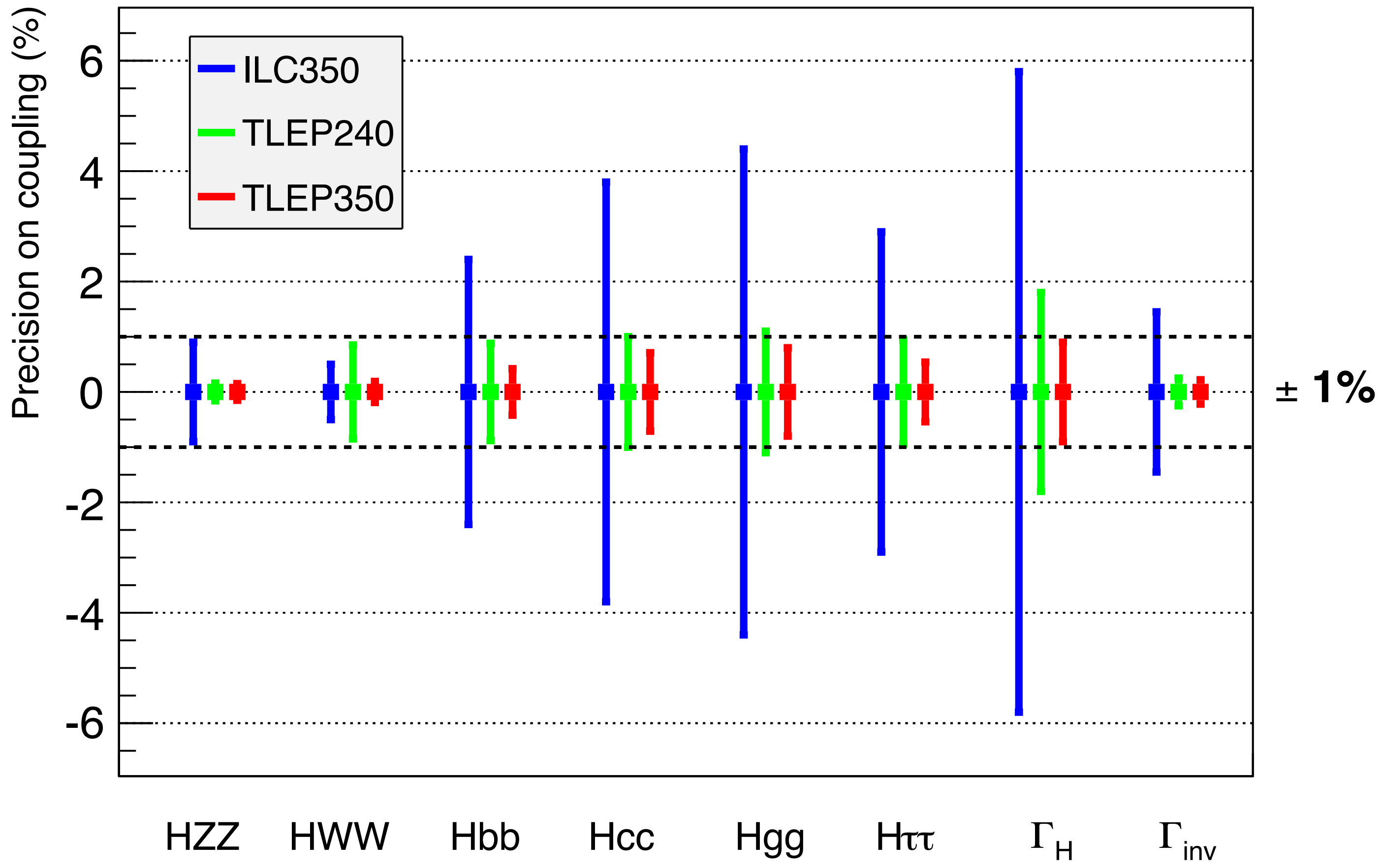
Price?
30 years+

TLEP, 10 years

Global fit of the Higgs couplings (2)

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

From Snowmass'13 : Model-independent fit (cont'd)



- **Sub-per-cent coupling measurements possible at TLEP**
  - **Potential sensitivity to multi-TeV new physics**

Global fit of the Higgs couplings (3)

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

From Snowmass'13 : Seven-parameter fit

Table 1-20. *Expected precisions on the Higgs couplings and total width from a constrained 7-parameter fit assuming no non-SM production or decay modes. The fit assumes generation universality ($\kappa_u \equiv \kappa_t = \kappa_c$, $\kappa_d \equiv \kappa_b = \kappa_s$, and $\kappa_\ell \equiv \kappa_\tau = \kappa_\mu$). The ranges shown for LHC and HL-LHC represent the conservative and optimistic scenarios for systematic and theory uncertainties. ILC numbers assume (e^-, e^+) polarizations of $(-0.8, 0.3)$ at 250 and 500 GeV and $(-0.8, 0.2)$ at 1000 GeV. CLIC numbers assume polarizations of $(-0.8, 0)$ for energies above 1 TeV. TLEP numbers assume unpolarized beams.*

Facility	LHC	HL-LHC	ILC500	ILC500-up	ILC1000	ILC1000-up	CLIC	TLEP (4 IPs)
$\sqrt{s}$ (GeV)	14,000	14,000	250/500	250/500	250/500/1000	250/500/1000	350/1400/3000	240/350
$\int \mathcal{L}dt$ (fb^{-1})	300/expt	3000/expt	250+500	1150+1600	250+500+1000	1150+1600+2500	500+1500+2000	10,000+2600
κ_γ	5 – 7%	2 – 5%	8.3%	4.4%	3.8%	2.3%	–/5.5/<5.5%	1.45%
κ_g	6 – 8%	3 – 5%	2.0%	1.1%	1.1%	0.67%	3.6/0.79/0.56%	0.79%
κ_W	4 – 6%	2 – 5%	0.39%	0.21%	0.21%	0.2%	1.5/0.15/0.11%	0.10%
κ_Z	4 – 6%	2 – 4%	0.49%	0.24%	0.50%	0.3%	0.49/0.33/0.24%	0.05%
κ_ℓ	6 – 8%	2 – 5%	1.9%	0.98%	1.3%	0.72%	3.5/1.4/<1.3%	0.51%
$\kappa_d = \kappa_b$	10 – 13%	4 – 7%	0.93%	0.60%	0.51%	0.4%	1.7/0.32/0.19%	0.39%
$\kappa_u = \kappa_t$	14 – 15%	4 – 10%	2.5%	1.3%	1.3%	0.9%	3.1/1.0/0.7%	0.69%

HL-LHC

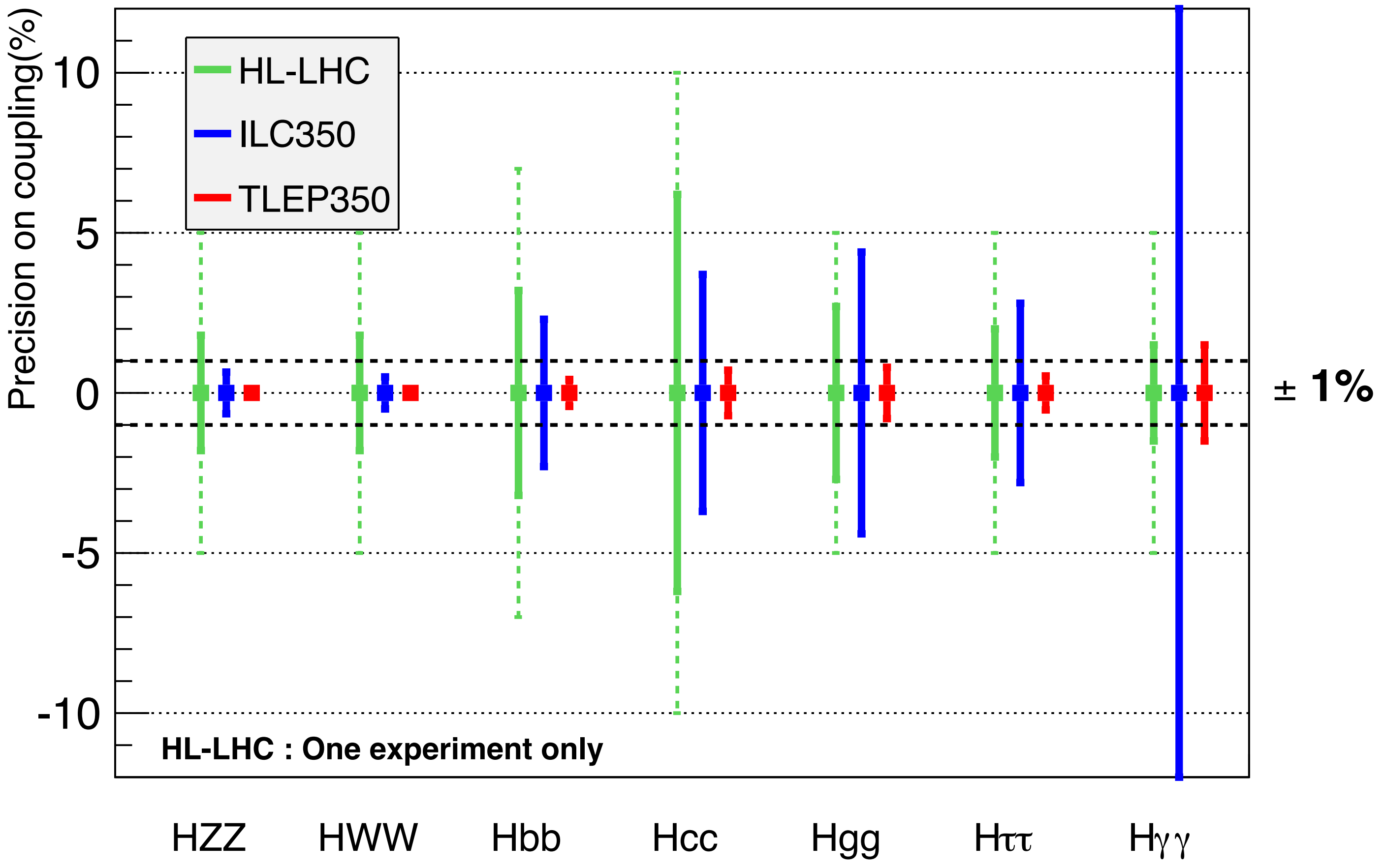
The 10B$ ILC

TLEP

See G. Petrucciani's talk tomorrow for the ttH coupling measurement at (HL-)LHC

Global fit of the Higgs couplings (4)

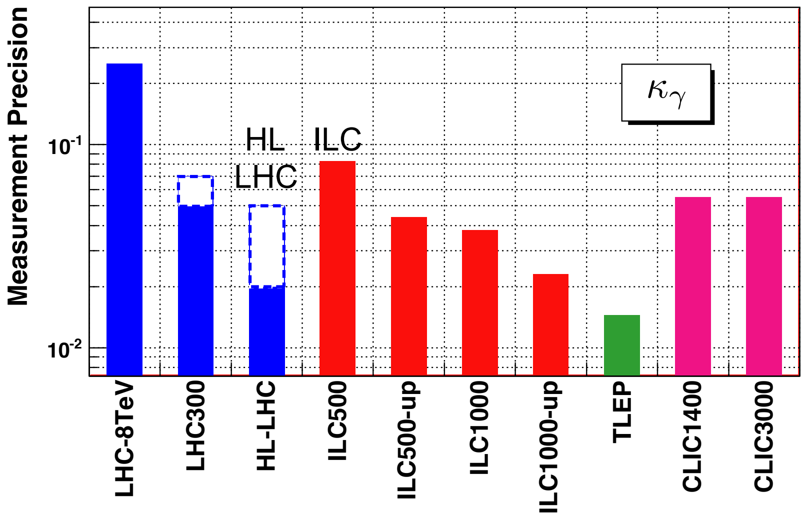
- From Snowmass'13 : Seven-parameter fit (cont'd)

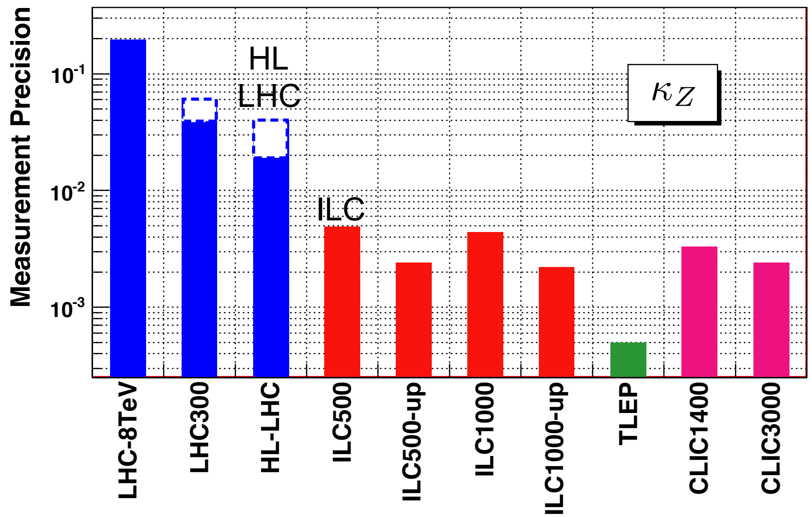


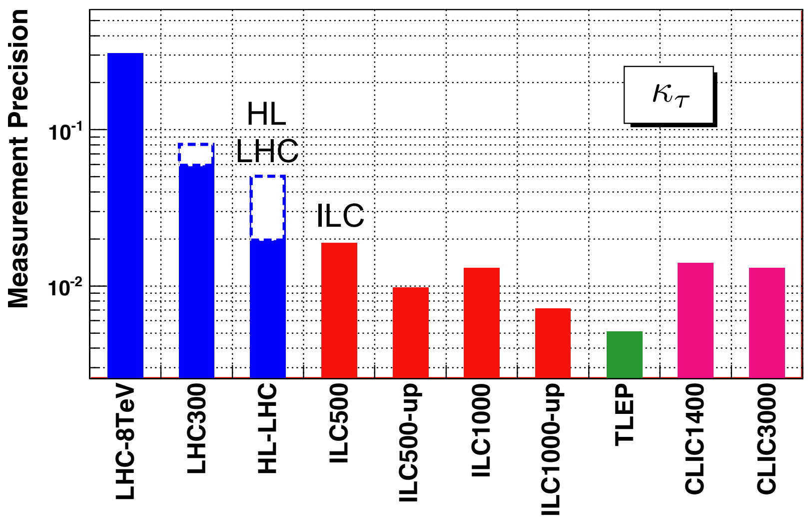
- TLEP potentially improves very significantly over HL-LHC projected precisions

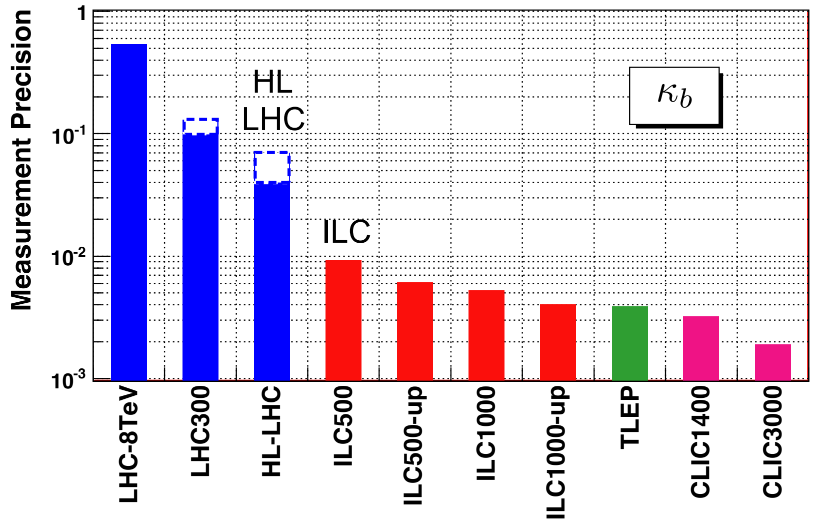
Global fit of the Higgs couplings (5)

- From Snowmass'13 : Seven-parameter fit (cont'd)



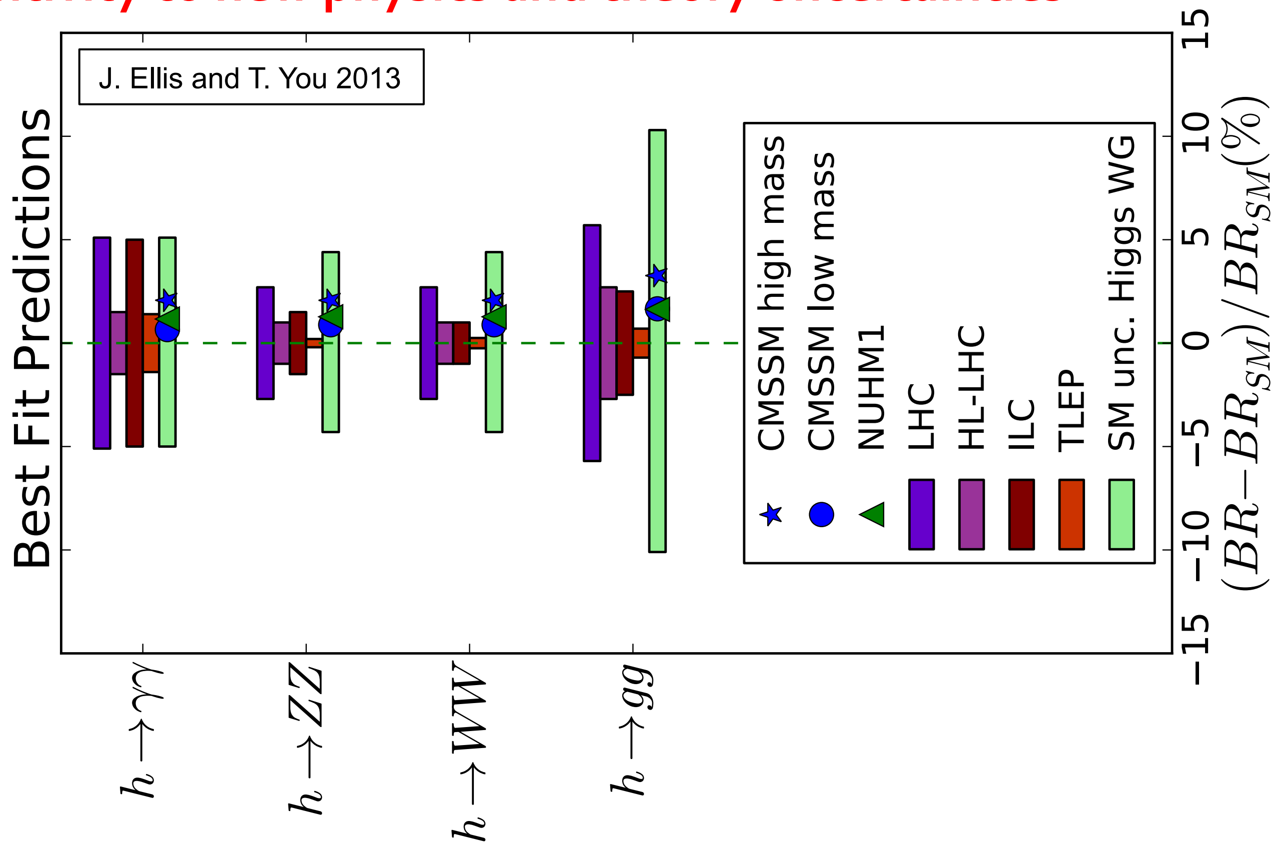






Global fit of the Higgs couplings (6)

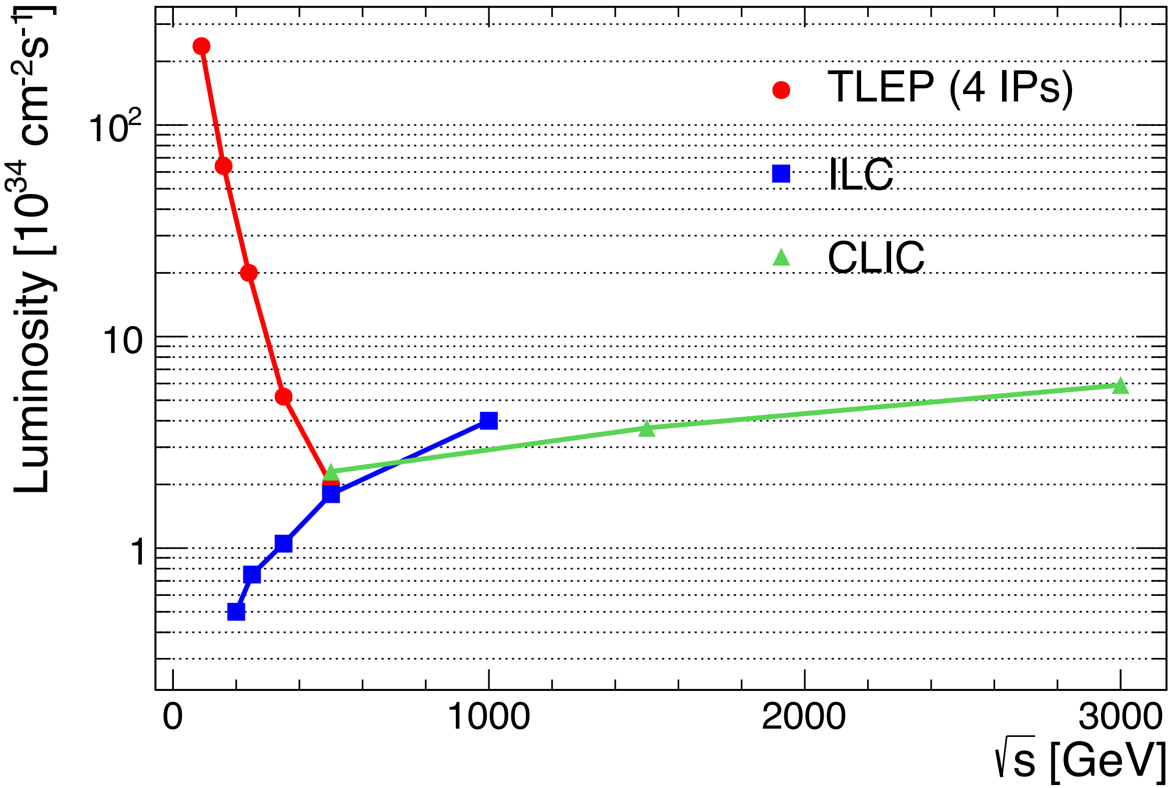
- **Sensitivity to new physics and theory uncertainties**



- 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)

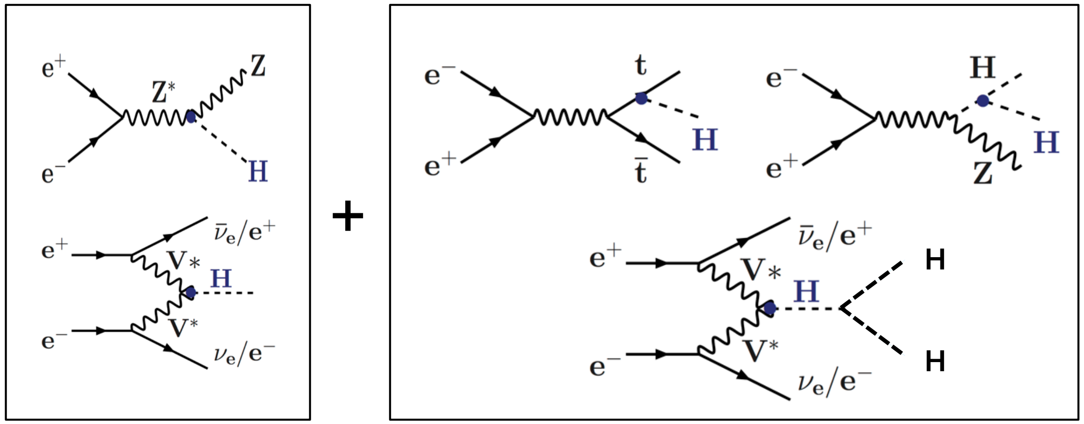
- **TLEP can possibly be upgraded up to $\sqrt{s}$ ~ 500 GeV**
  - By tripling the RF system (12 → 35 GV) : 1.7 km instead of 600 m of cavities
    - With a luminosity of 0.5×10^{34} cm^{-2}s^{-1} per interaction point

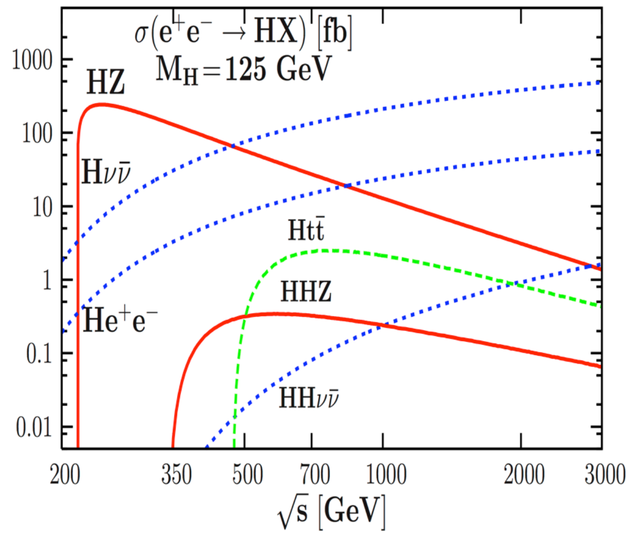


  - Question : is it justified by scientific arguments ?

Higgs Physics with √s > 350 GeV ? (2)

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



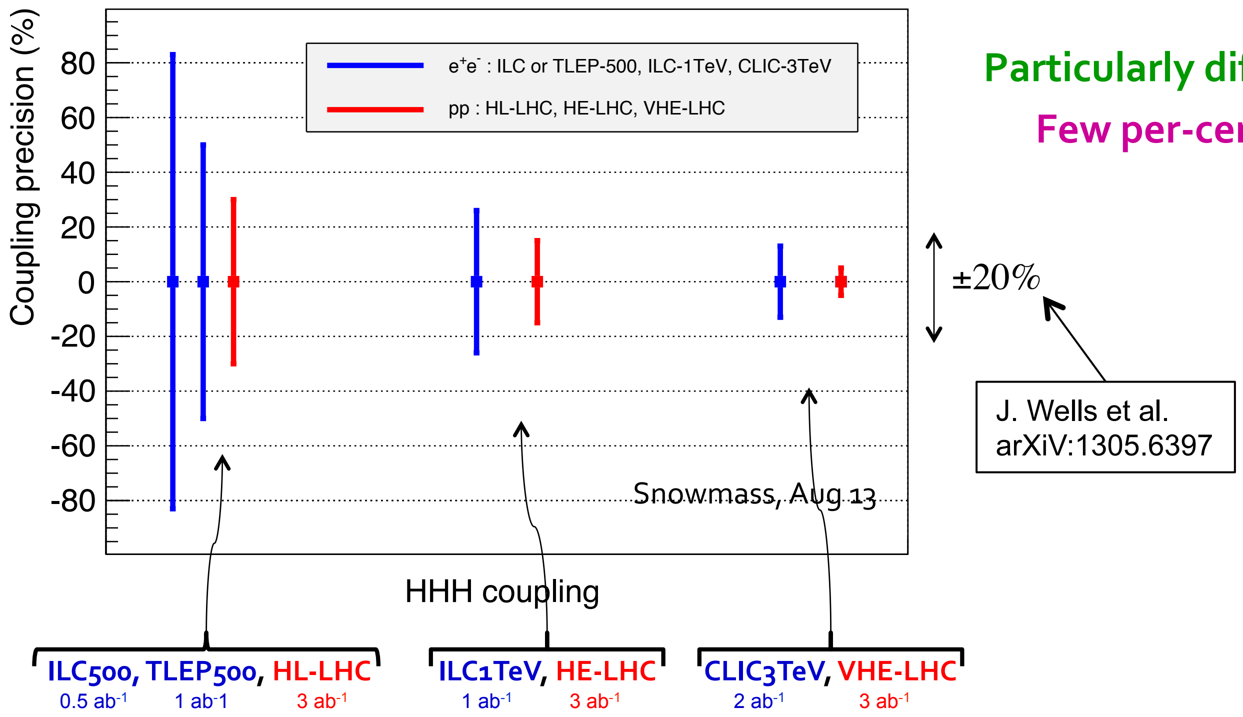


- Measurements at higher energy
  - √s > 350 GeV does not do much for couplings to c, b, g, Z, W, γ, μ and Γ_{tot}. (slide 15)
    - Invisible width best done at √s = 240 GeV
  - The ttH coupling benefits from higher energy
    - TLEP 350 : 13% ; TLEP 500 : 10%
    - ILC 500 : 14% ; ILC 1 TeV : ~4% ;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

Higgs Physics with √s > 350 GeV ? (3)

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

- **Measurements at higher energy (cont'd)**
  - Higgs tri-linear self coupling λ very difficult for all machines



Particularly difficult for √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*

Concluding Remarks

- 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 new (likely beyond ILC reach)
- The results of the LHC Run2 will be a precious input to the strategy
  - The next machine must bring order(s) of magnitude improvement wrt LHC
    - Both in precision measurements and in discovery potential
- 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; …
      - ➨ A considerable challenge for theoretical predictions

See V. Sanz's talk today for direct search for NP at TLEP

  - Most mature technology : supported by progress of e^+e^- factories for 20 years
    - SuperKEKB will be a precious demonstrator
  - 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
- The Future Circular Collider (FCC) design study is being organized
  - Towards a decision to be taken in Europe by 2018.

Backup Slides

First look at cost and power consumption

TLEP HZ⁰W⁻W⁺tt̄

Cost in billion CHF

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

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);

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

Very cost-effective : about 2-3 billion CHF

TLEP less expensive than the LHC.

Power Consumption in MW

Power consumption	TLEP 175
RF including cryogenics	224MW
cooling	5MW
ventilation	21MW
magnet systems	14MW
general services	20MW
Total	~280MW

Much to gain in plug-to-beam efficiency

Dedicated R&D on high-power RF needed

(55% assumed in the current estimate)

Design Study (2013 – 2018) : Structure

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

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