Quote from Yesterday's Plenary

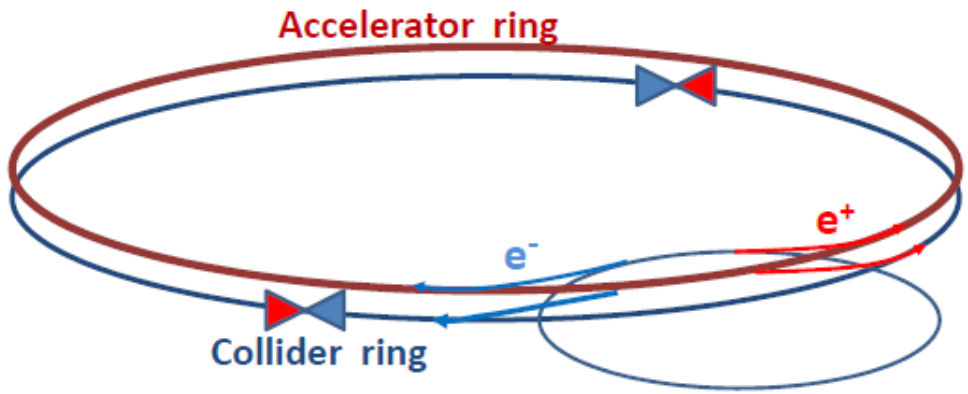
The Higgs must be studied
with the best precision we can muster

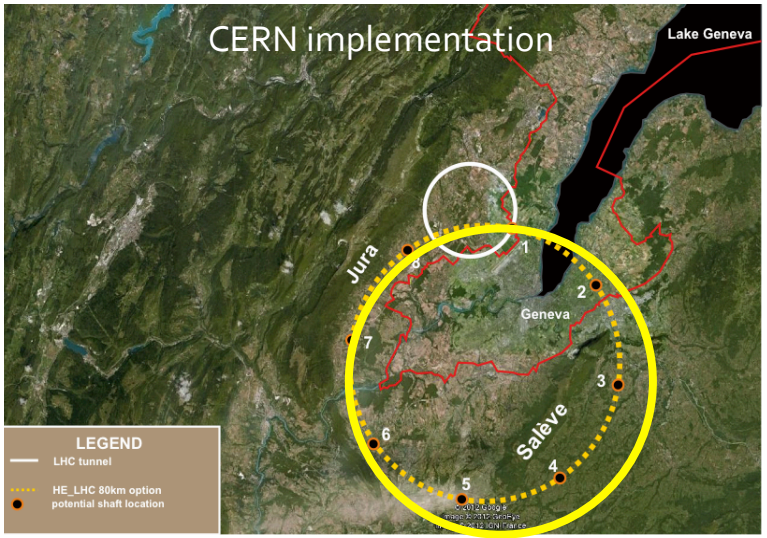
Nigel Lockyer, Fermilab Director
01-July-2013

The TLEP Physics Case : First Look

- **TLEP: An e^+e^- collider in a new 80-100 km tunnel with $\sqrt{s}$ up to 350 GeV**
  - **Supported by the recent European Strategy update**

A. Blondel



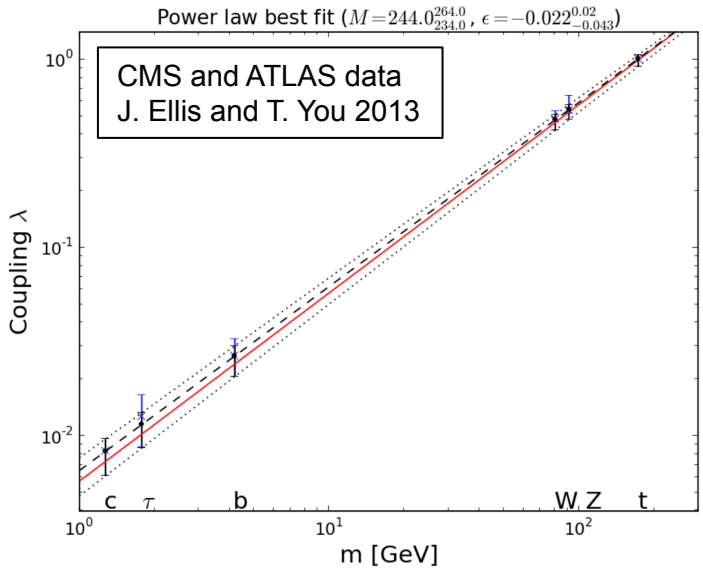


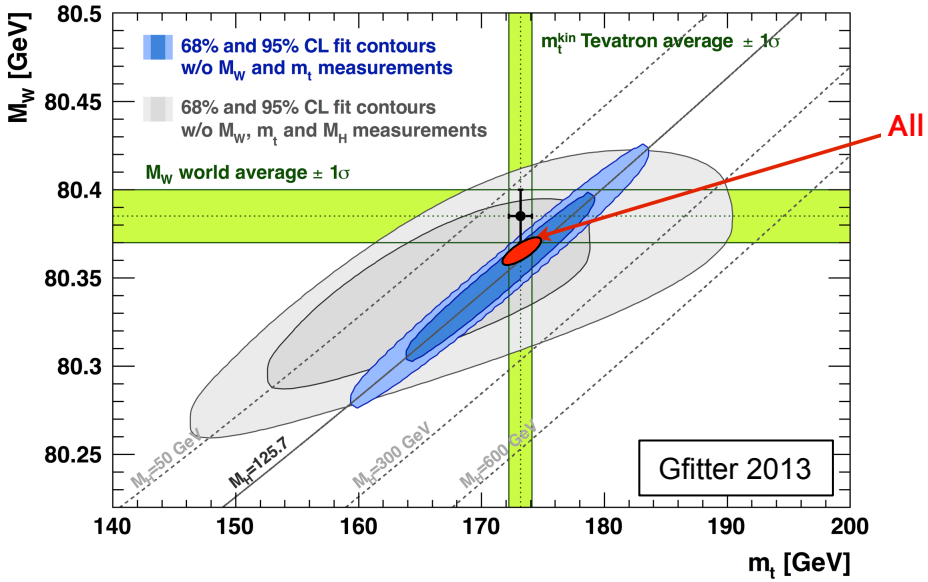
J. Osborne and C. Waajer

- **Now part of the CERN Medium Term Plan (2013-2018)**
  - ➨ **Approved by the CERN Council two weeks ago.**
- **Design Study Proposal :** http://tlep.web.cern.ch/
- **Next workshop 25-26 July 2013 ar FNAL (approved by the DOE)**
  https://indico.fnal.gov/internalPage.py?pageId=2&confId=6983

Scientific Motivation

- **Driven by today's experimental situation**
  - A (very) Standard Higgs boson and a (very) Standard Model



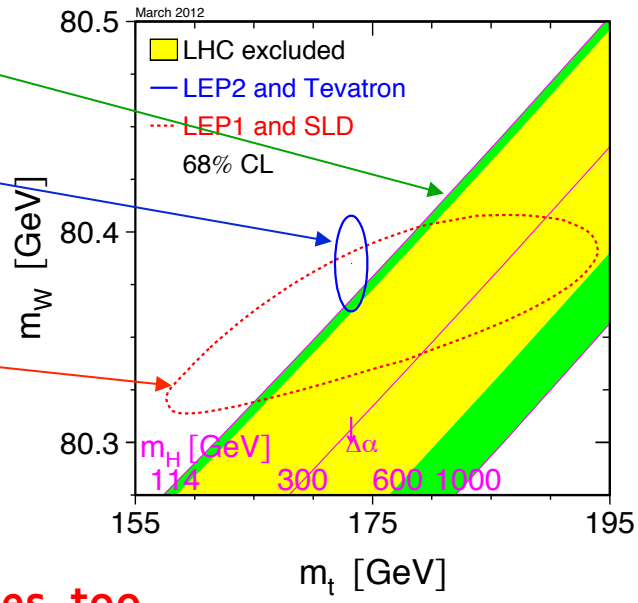


  - Need to measure Higgs properties and EWSB parameters with high(er) precision
    - "With the best precision we can muster"
  - No new physics all the way to several 100's GeV (SUSY) or several TeV (Resonances)
    - Next run at 14 TeV will extend the coverage to ~500 GeV (SUSY) or more
      - Very strong incentive to look for heavier New Physics

Linear Colliders with √s = o(TeV) do not cover this Physics case

Precision Needed

- **Higgs couplings : directly sensitive to New Physics**
  - Expected deviations to SM couplings depend on the New Physics scale
    - Typically : $$\frac{g_{HXX}}{g_{HXX}^{SM}} \approx 1 + \delta \times \left(\frac{1\ \text{TeV}}{\Lambda_{\text{NP}}}\right)^2$$ with $\delta < 5\%$ - (Exact value depend on model & coupling)
      - ➨ Need at least a per-cent accuracy for a 5σ observation if $\Lambda_{NP} = 1$ TeV
        And a sub-per-cent accuracy for multi-TeV New Physics scale
      - ➨ Need millions of Higgs bosons
- **EWSB parameters : Stringent SM closure test**
  - 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
  - Z pole measurements
    - Improve by at least two orders of magnitude
      - ➨ Need > 10^4 times LEP1 statistics



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

The solution : TLEP + VHE-LHC

- 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 : $\sqrt{s} \sim 2m_{top}$

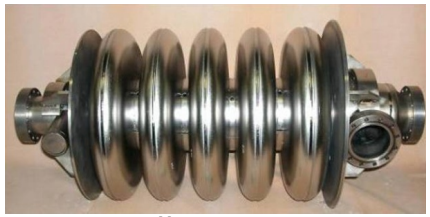
Followed by

VHE-LHC : pp collisions,
$\sqrt{s}$ ~ 100 TeV with 16T magnets

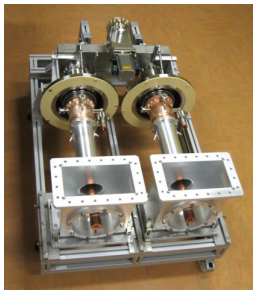
- Follow the successful historical path for high-energy physics
  - TLEP Physics case: Precision measurements sensitive to multi-TeV New Physics
    - ➨ With luminosity 10-1000 × larger than projects of similar timescale and cost
  - VHE-LHC Physics case: Direct search for New Physics in the 10-100 TeV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

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
    - Much less than ILC (16000 9-cell @ 31.5 MV/m)
    - 200 kW/ cavity : RF couplers are an issue too
  - Heat extraction, shielding against radiation, …



BNL 5-cell 700 MHz cavity



RF Coupler (ESS/SPL)

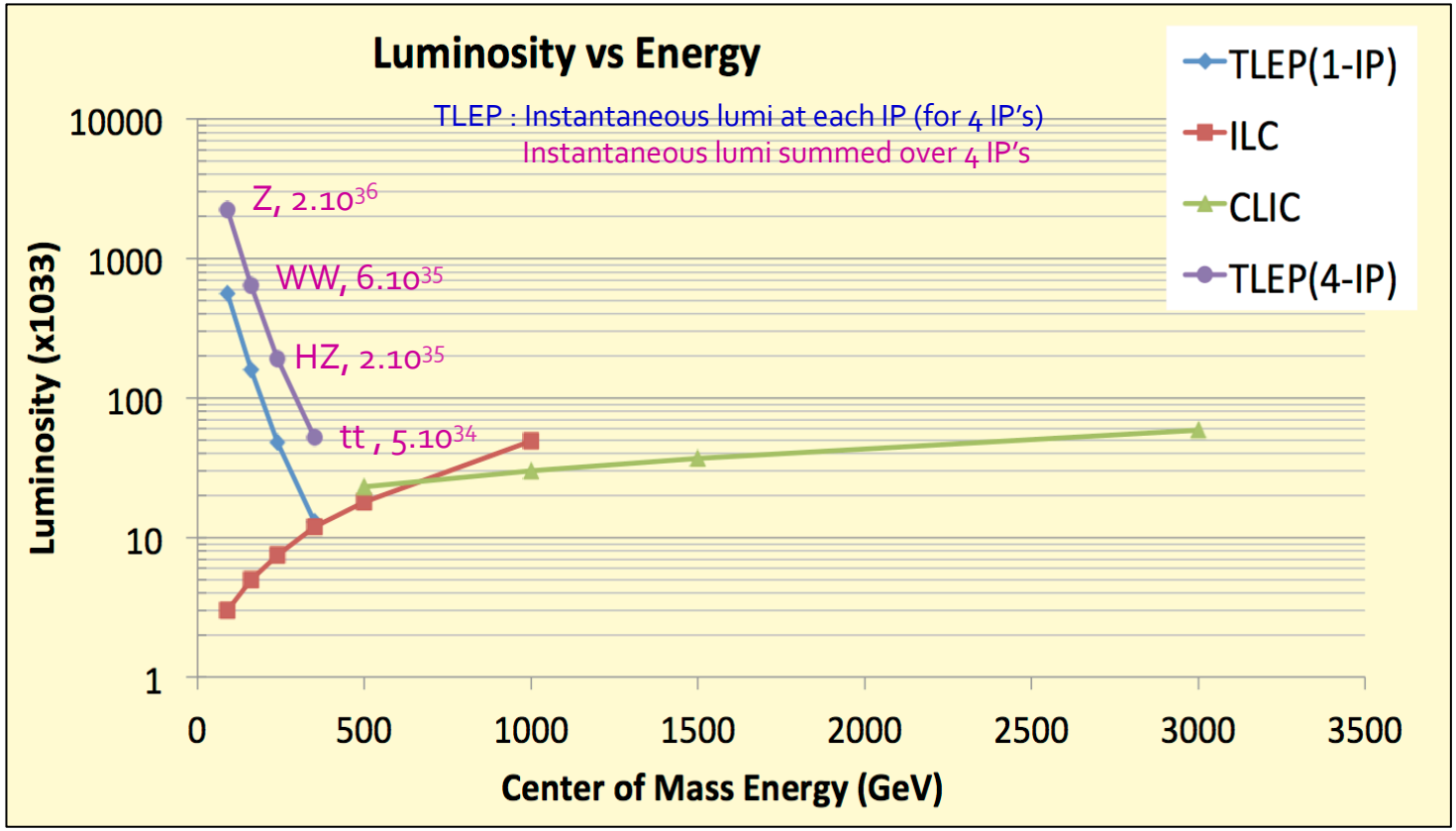
- Achieve luminosity with small vertical beam size : σ_y ~ 100 nm
  - A factor 30 smaller than at LEP2, but a factor 2 larger than SuperKEKB
    - Much more relaxed than ILC (6-8 nm), hence negligible beamstrahlung for physics
- At smaller √s, increase the number of bunches to saturate the RF power

√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

Energy and Luminosity at TLEP (2)

- Luminosity increases when √s decreases at circular colliders
  - By optimal use of the RF power

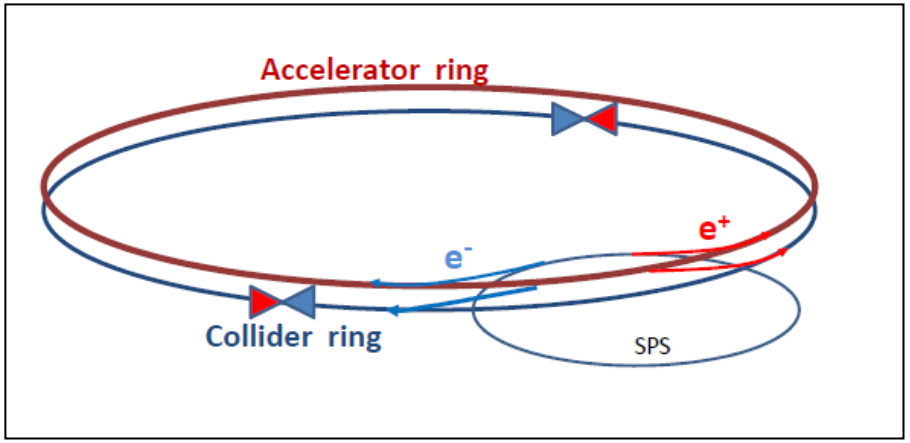


- And circular colliders can have several IP's
  - ➨ Ultimate precision measurements possible only at circular colliders

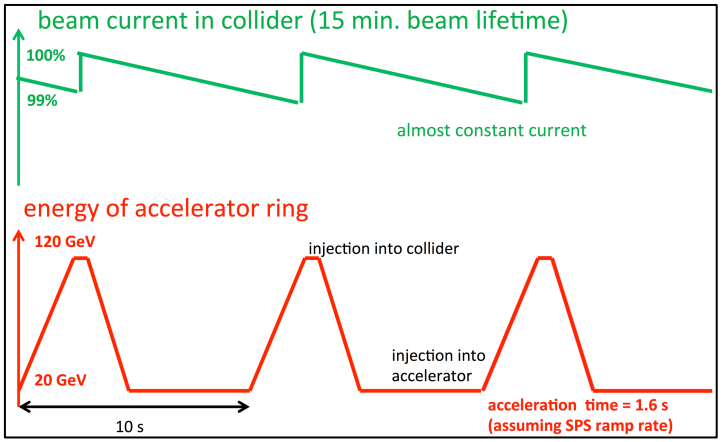
Why only 10^{32} $cm^{-2}s^{-1}$ at LEP2 ?

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

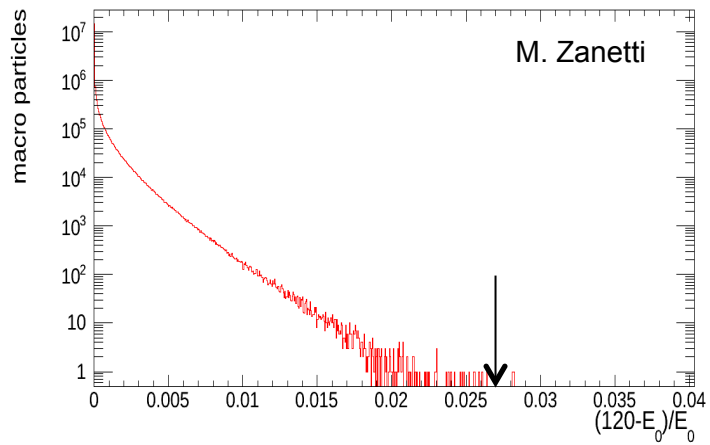
A. Blondel



F. Zimmermann



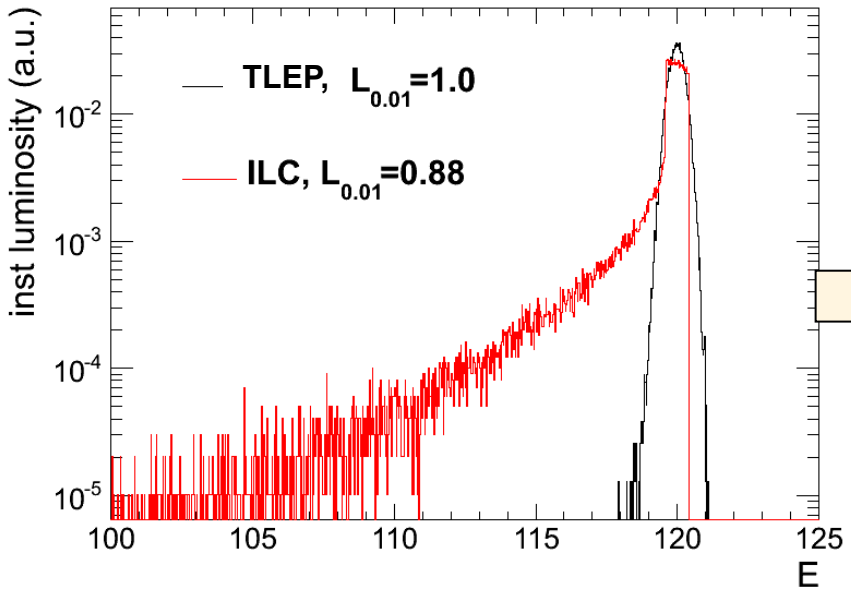
- **Lifetime further reduced by beamstrahlung**
  - **Radiating $e^{\pm}$ pushed outside the acceptance**
  - **Need to design an achromatic optics at the IPs**
    - **with 2-3% momentum acceptance**

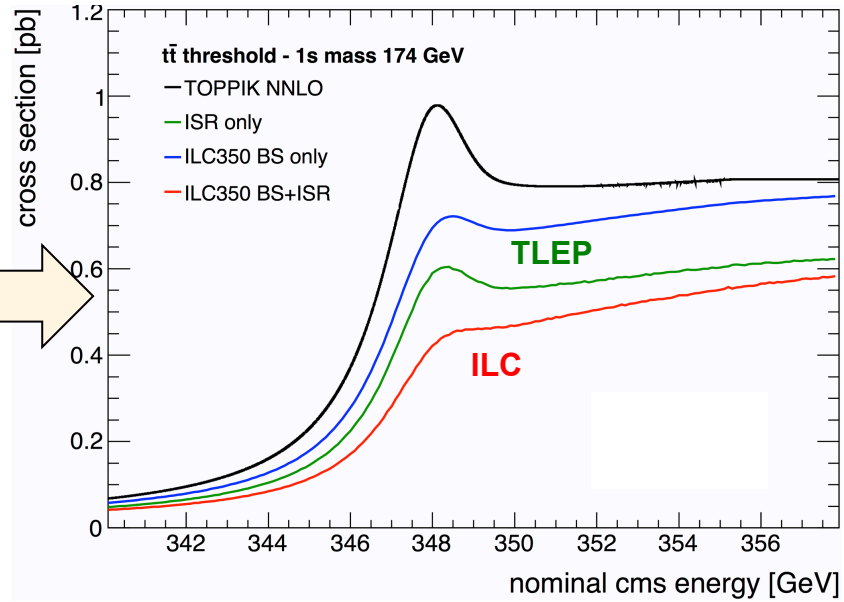


Negligible Beamstrahlung for Physics

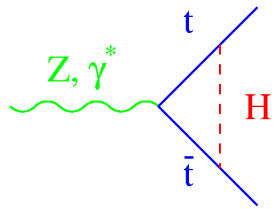
- **Many positive consequences : backgrounds, kin. fits, lumi measurement…**
  - **In particular: Beam energy spectrum is narrower and better known**

M. Zanetti





	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%



- **CLIC study: m_{top} uncertainty of 75 MeV for a 20% uncertainty on the luminosity peak RMS**
- **Current theory uncertainty ~ 100 MeV**

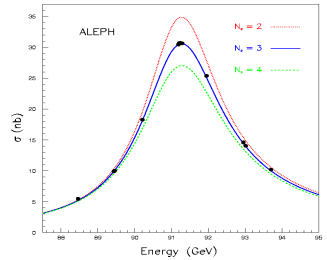
Precision tests of EWSB at TLEP (1)

- **See Alain Blondel's talk on Sunday for more details**

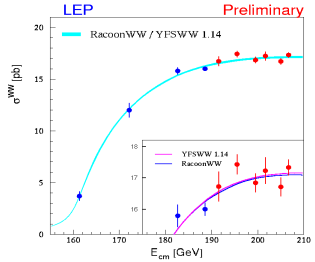
	LEP	ILC	TLEP
$\sqrt{s} \sim m_Z$	Mega-Z	Giga-Z	**Tera-Z**
#Z / year Polarization Precision vs LEP1 Error on m_Z, Γ_Z	2×10^7 Yes (T) 1 2 MeV	Few 10^9 Easy 1/5 to 1/10 Few MeV	**10^{12} (>10^{11} b,c,τ)** Yes (T,L) ~1/100 < 0.1 MeV
$\sqrt{s} \sim 2m_W$			
#W pairs / year Polarization Error on m_W	Few dozens No 220 MeV	2×10^5 Easy 6 MeV	**2.5×10^7** Yes (T) 0.5 MeV
$\sqrt{s}$ = 180-250 GeV			**Oku-W**
# W pairs / 5 years Error on m_W	4×10^4 33 MeV	4×10^6 7 MeV	**2×10^8** 1 MeV
$\sqrt{s} \sim 350$ GeV			**Mega-Top**
# top pairs / 5 years Error on m_{top}	– –	100,000 30 MeV	**1,000,000** 10 MeV

- **Bottom line : Only TLEP meets the precision requirements**

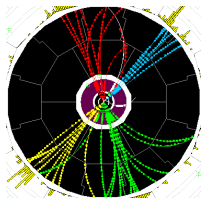
Asymmetries, Lineshape



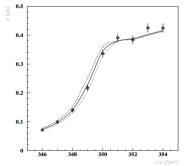
WW threshold scan

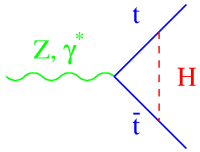


WW production



$t\bar{t}$ threshold scan





Precision tests of WSB at TLEP (1)

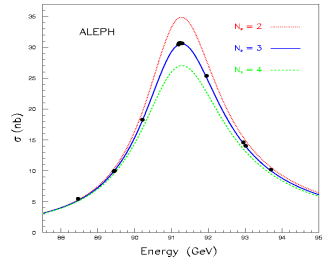
- See Alain Blondel's talk for more details

TLEP : Repeat the LEP1 physics programme every 15 min
Transverse polarization up to the WW threshold
- Exquisite beam energy determination (10 keV)
- m_Z, Γ_Z to better than 100 keV, m_W to 0.5 MeV
Longitudinal polarization at the Z pole
- Measure $\sin^2\theta_W$ to 2.10^{-6} from A_{LR}

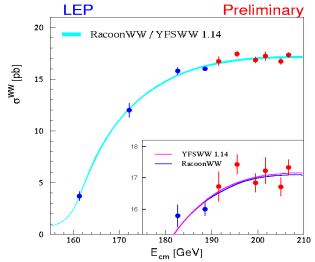
			TLEP
			Tera-Z
	2 MeV	few 10^9 Easy 1/5 to 1/10 Few MeV	10^{12} (>10^{11} b,c,τ) Yes (T,L) ~1/100 < 0.1 MeV
W pairs / year Polarization Error on m_W	Few dozens No 220 MeV	2×10^5 Easy 6 MeV	2.5×10^7 Yes (T) 0.5 MeV
√s = 180-250 GeV			Oku-W
# W pairs / 5 years Error on m_W	4×10^4 33 MeV	4×10^6 7 MeV	2×10^8 1 MeV
√s ~ 350 GeV			Mega-Top
# top pairs / 5 years Error on m_{top}	– –	100,000 30 MeV	1,000,000 10 MeV

- **Bottom line : TLEP meets the precision requirements**

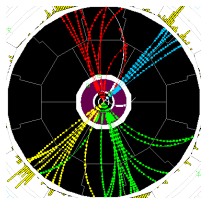
Asymmetries, Lineshape



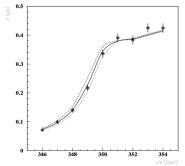
WW threshold scan

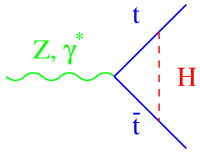


WW production

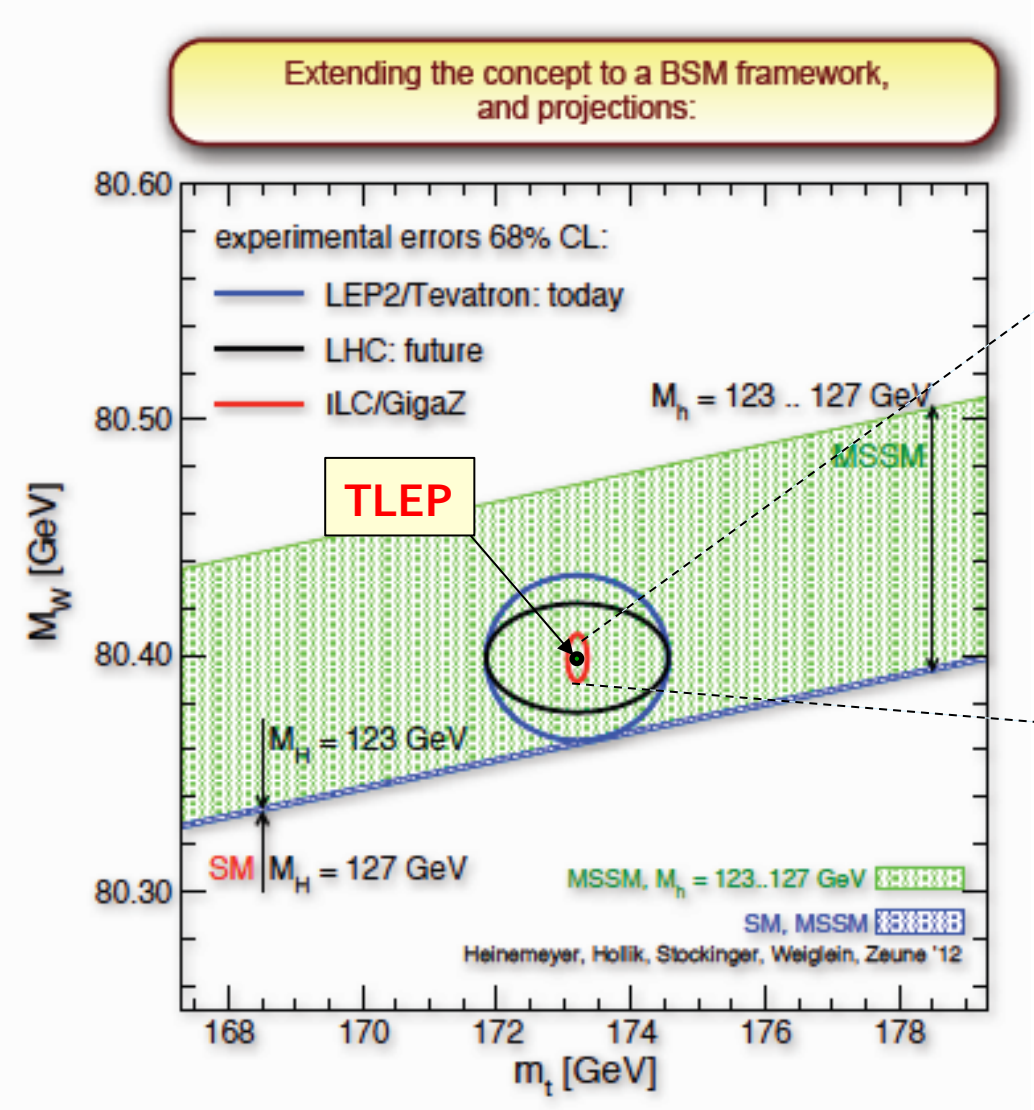


$t\bar{t}$ threshold scan

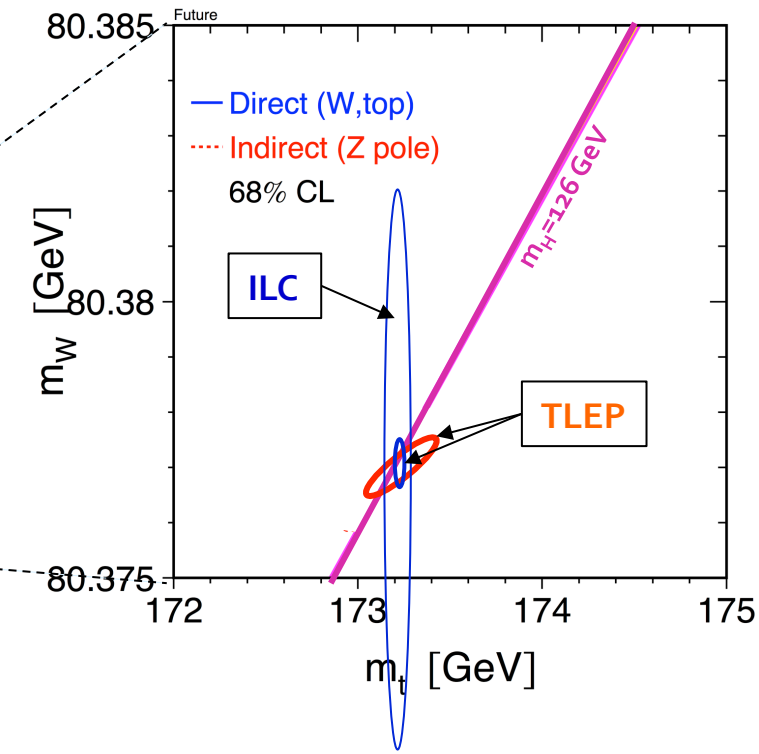




Precision tests of EWSB at TLEP (2)



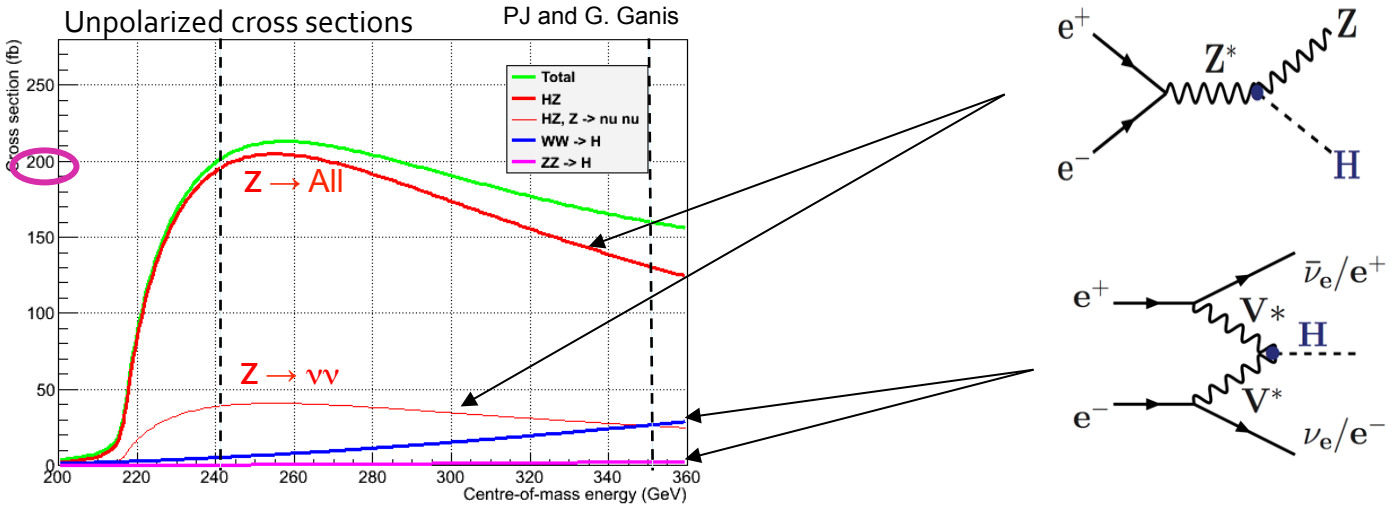
Warning : indicative only.
Complete study being done



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

TLEP as a Higgs Factory

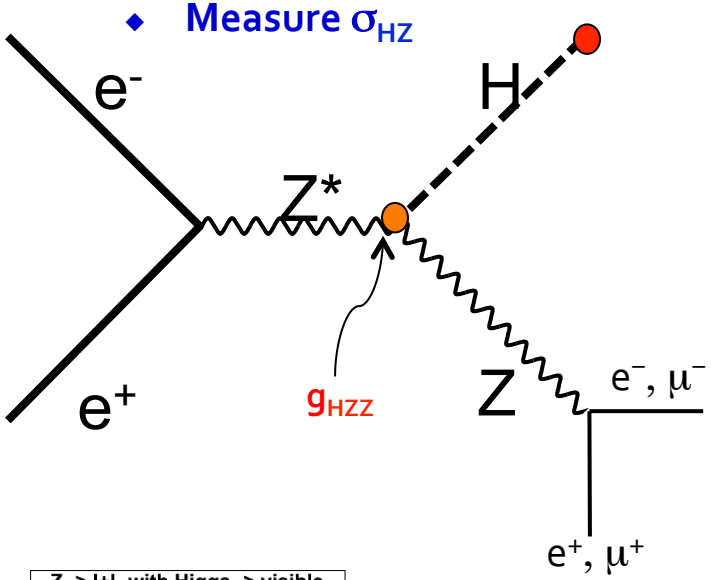
- **Number of Higgs bosons produced at √s = 240-250 & 350 GeV**

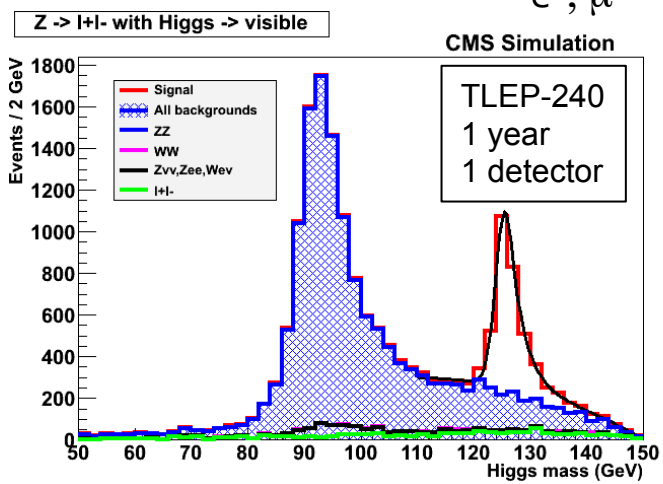


	ILC-250	**TLEP-240**	ILC-350	**TLEP-350**
Lumi / IP / year	50 fb^{-1}	**500 fb^{-1}**	70 fb^{-1}	**130 fb^{-1}**
Lumi / 5 yrs	250 fb^{-1}	**10 ab^{-1}**	350 fb^{-1}	**2.6 ab^{-1}**
Beam Polarization	80%, 30%	–	80%,30%	–
# of HZ events	70,000	**2,000,000**	65,000	**325,000**
# of WW→H events	1,500	**50,000**	12,000	**65,000**

Measurements at $\sqrt{s}$ = 240-250 GeV

- **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

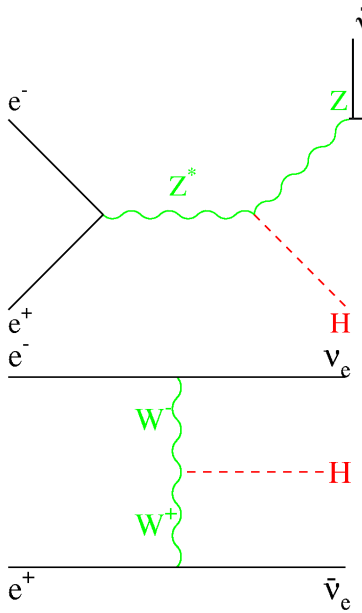
Measurements at √s = 350 GeV

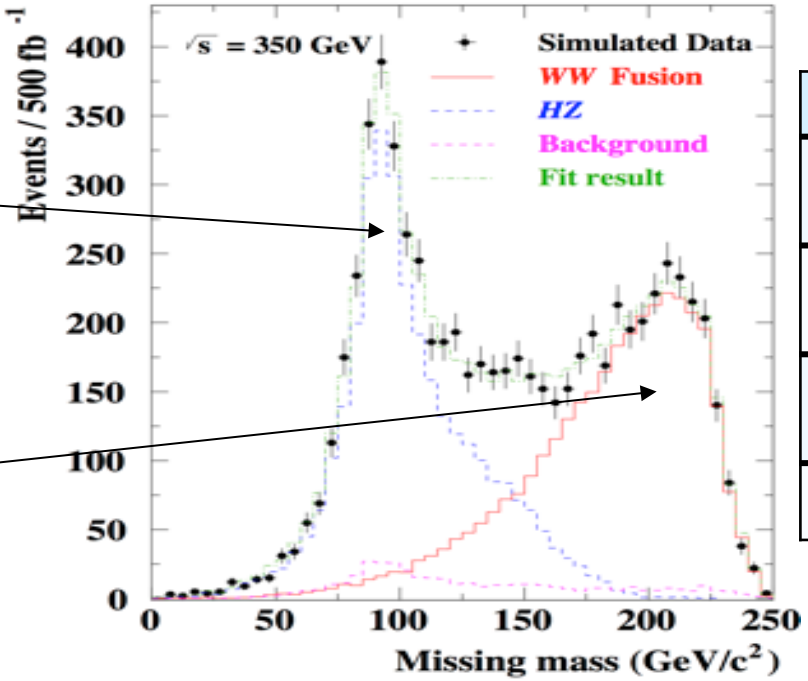
- More $\sigma_{HZ} \times BR(H \rightarrow XX)$ and … Determination of the total width
  - From the number of HZ events and of ZZZ events at √s = 240 GeV

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

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

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



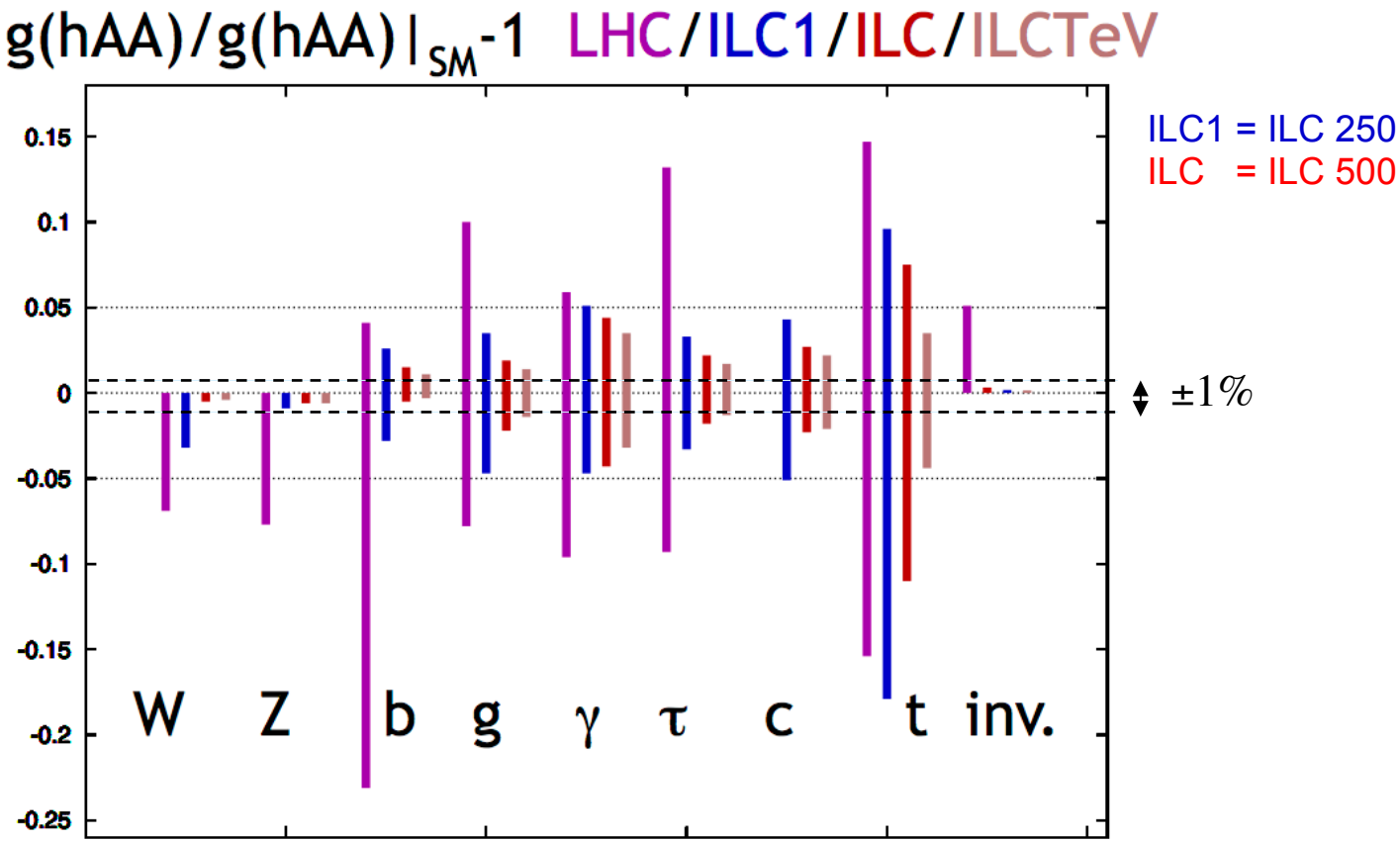


Γ_H from:	ILC	TLEP
HZ→ZZZ @ 240	20%	3.2%
WW→H @240	12%	2.3%
WW→H @350	7%	1.1%
Combined	5.8%	0.9%

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

Global fit of the Higgs couplings (1)

- **Follows the lines Michael Peskin's fit** (arXiV:1207.2516v3)



- A number of interesting features in this plot
  - LHC error bars; g_t measurement from ILC250; asymmetric error bars; …

Global fit of the Higgs couplings (2)

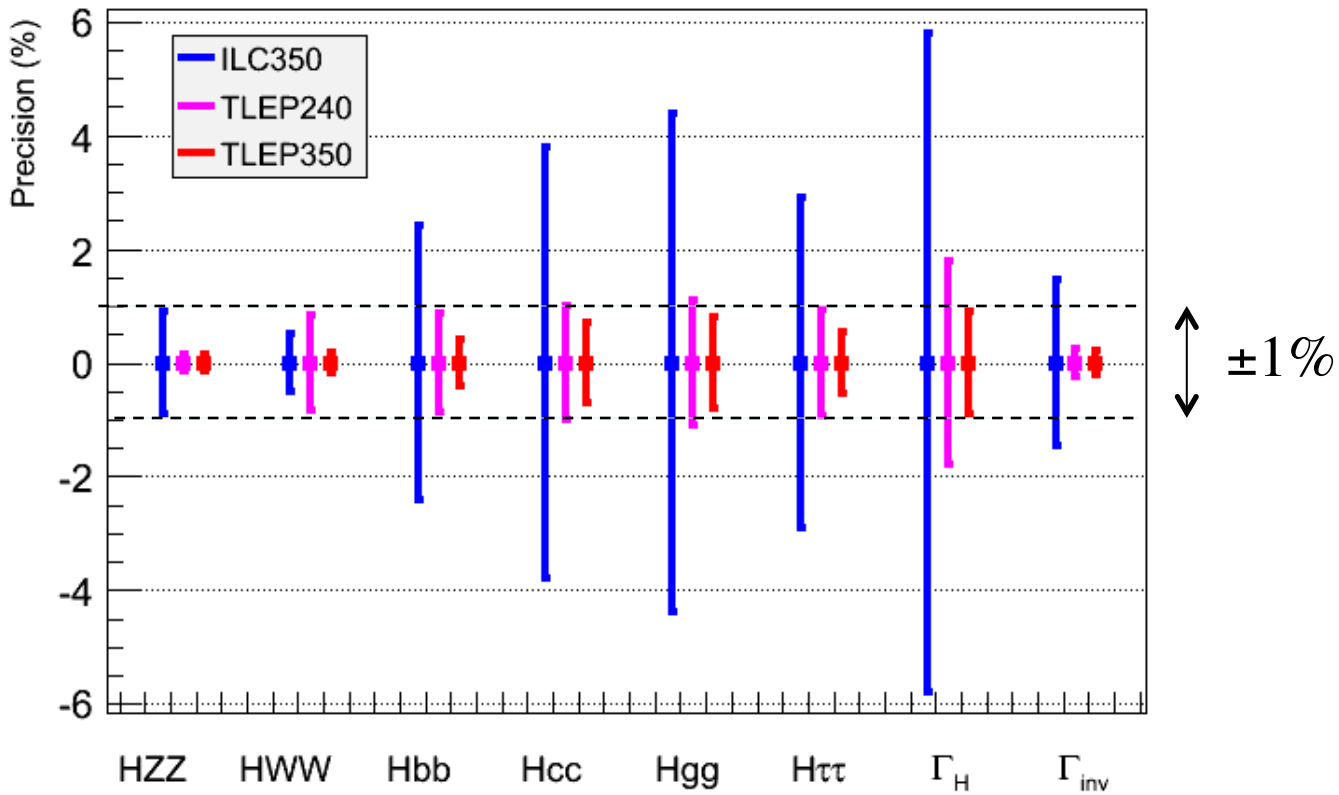
- **Follows the lines Michael Peskin's fit** (arXiV:1207.2516v3)
  - With three minor differences
    - No combination with LHC in the estimate of the ILC physics potential
    - No model-dependent assumption on g_W and g_Z
      - ➨ Assumed to be bounded from above by their SM value in arXiV:1207.2516v3
    - No assumption on the Higgs exotic decays
      - ➨ Assumed to be saturated by the measured invisible decays in arXiV:1207.2516v3
  - … thus making the fit truly model-independent
    - And truly representative of the lepton-collider potential
  - Of course, the fit was also made with the same assumptions as in arXiV:1207.2516v3
    - And could reproduce Michael's results
- **Result of the 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%

Global fit of the Higgs couplings (3)

- Graphically …

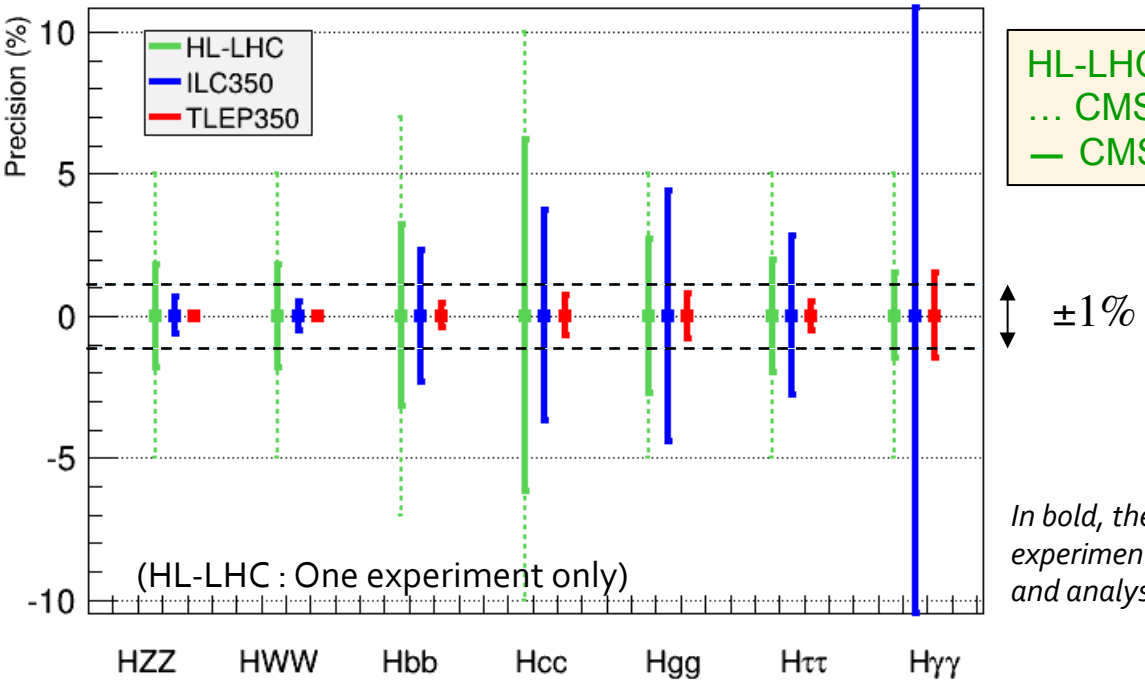


- Only TLEP can reach the desired sub-per-cent accuracy
  - Needed to reach (multi-)TeV New Physics sensitivity
    - ➨ Theoretical work essential to reduce theory errors accordingly.

Global fit of the Higgs couplings (4)

- **Comparison between HL-LHC, ILC and TLEP**
  - **Need additional (model-dependent) assumptions**
    - **No exotic Higgs decays (no Γ_H at LHC)**
    - **c- and t-quark couplings are correlated (no H → cc at LHC)**

LC qualitative added value
(LC = Lepton Collider)



HL-LHC : One experiment only
… CMS Scenario 1
— CMS Scenario 2
J. Olsen

±1%

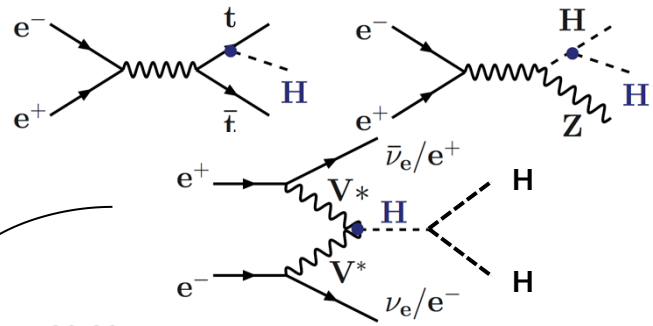
In bold, theory uncertainty are assumed to be divided by a factor 2, experimental uncertainties are assumed to scale with 1/√L, and analysis performance are assumed to be identical as today

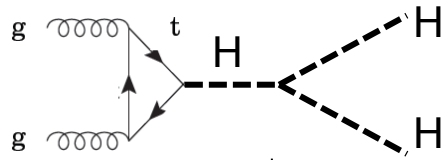
  - **Quantitative added value from ILC (wrt HL-LHC) does not stick out clearly.**
    - **In contrast, sub-per-cent TLEP potential is striking for all couplings**

Other Higgs Couplings : Energy-Frontier Upgrades (1)

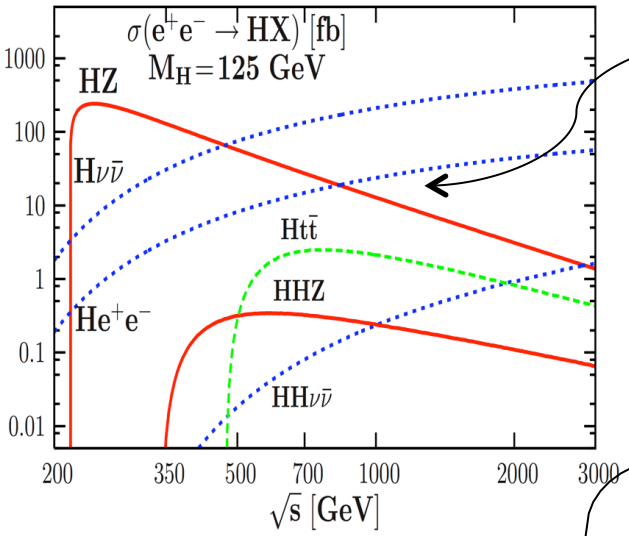
- **Both Higgs factories have upgrade paths to larger √s**
  - To discover New Physics in a direct manner
  - To measure more difficult Higgs coupling : g_{HHH} (and g_{Htt})
    - ILC250 can be upgraded to ILC500 (ILC1TeV) – or shall we go to CLIC (3 TeV) ?
    - TLEP can be upgraded to VHE-LHC (100 TeV)

Already well measured at HL-LHC





Cross sections in e⁺e⁻ collisions



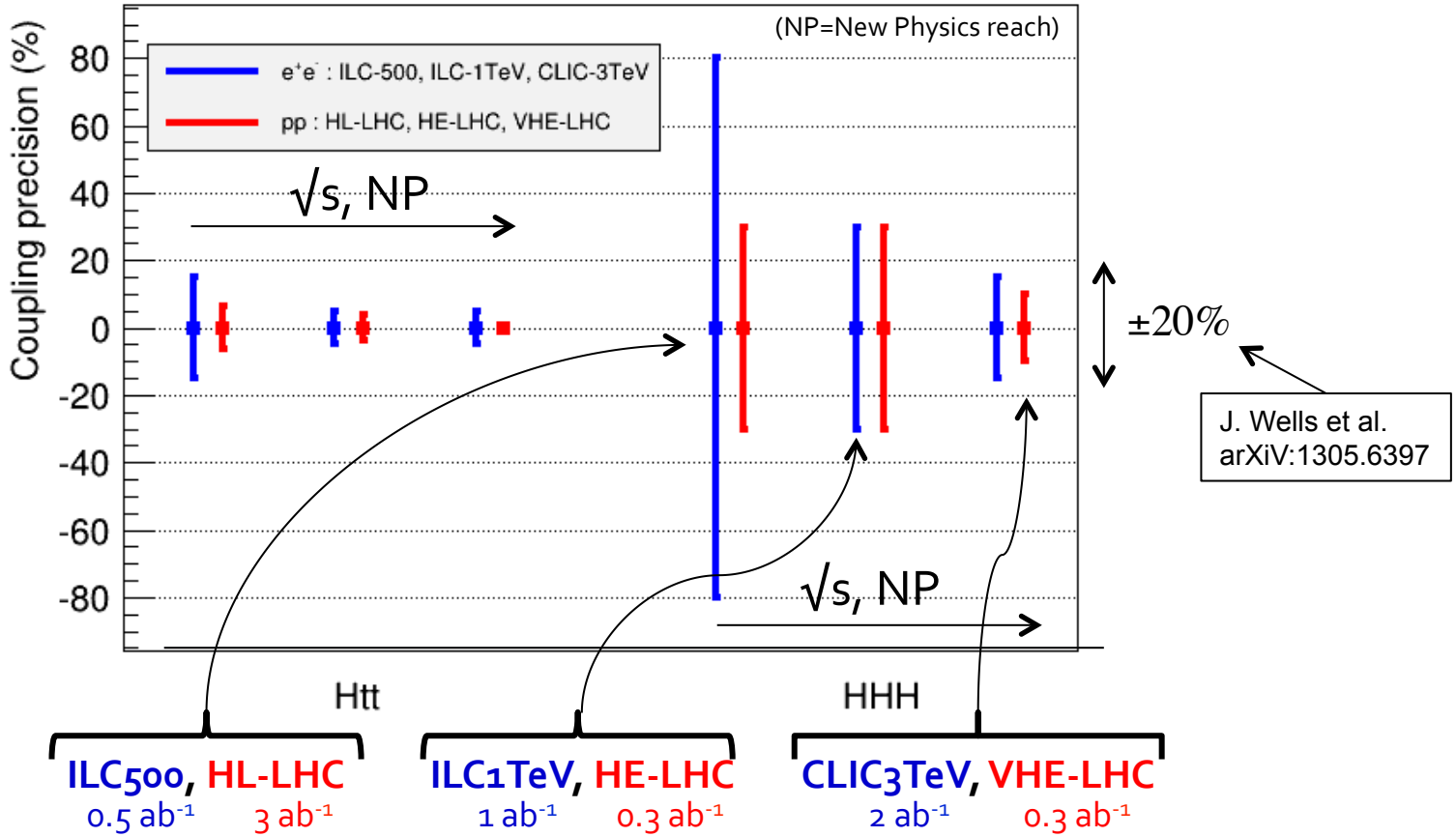
Cross sections in pp collisions

M. Mangano

	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

Other Higgs Couplings : Energy-Frontier Upgrades (2)

- **Performance comparison for Htt and HHH couplings**



- **VHE-LHC : largest New Physics reach and best potential for g_{HHH}**
  - **CLIC better suited than ILC for a meaningful measurement of g_{HHH}**
    - ➨ **The ILC1TeV added value to g_{Htt} wrt HL-LHC might not be worth 12 B$**

TLEP Cost (Very Preliminary) Estimate

- **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 ILC500 – but site exists already

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Preliminary

Not endorsed by anybody

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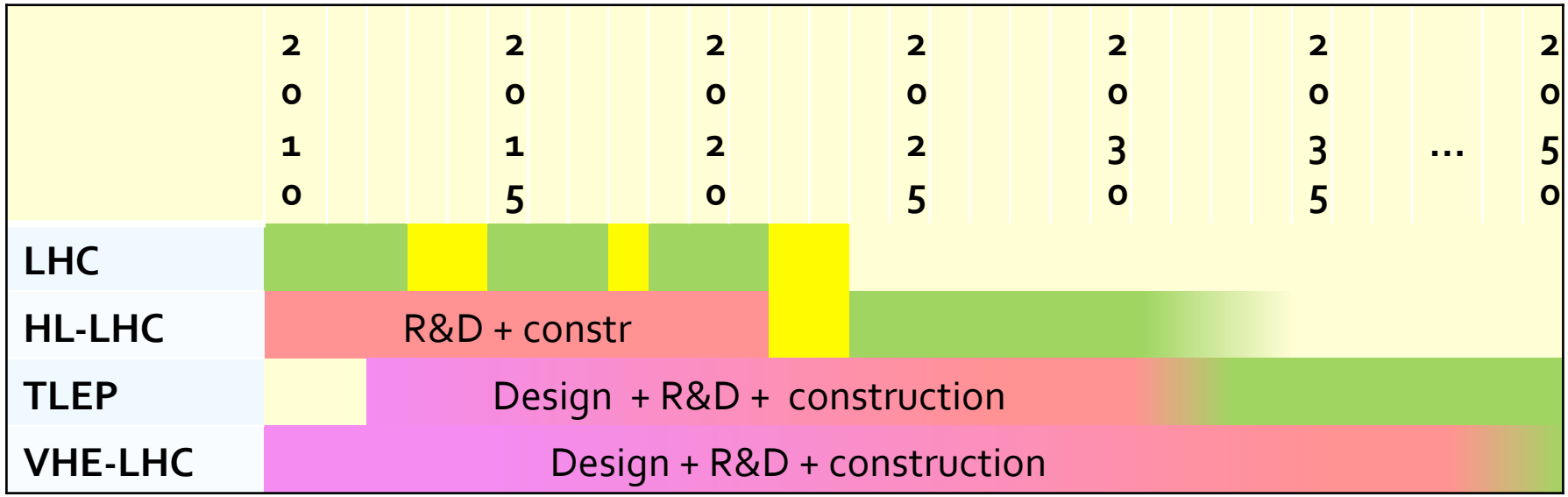
TLEP Possible Timescale

- **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.



Design Study (2013 – 2018) : Initiated

TLEP design study –preliminary structure for discussion

Institutional board — Steering group web site, mailing lists, — International Advisory board

R. Aleksan, A. Blondel (sp.), 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

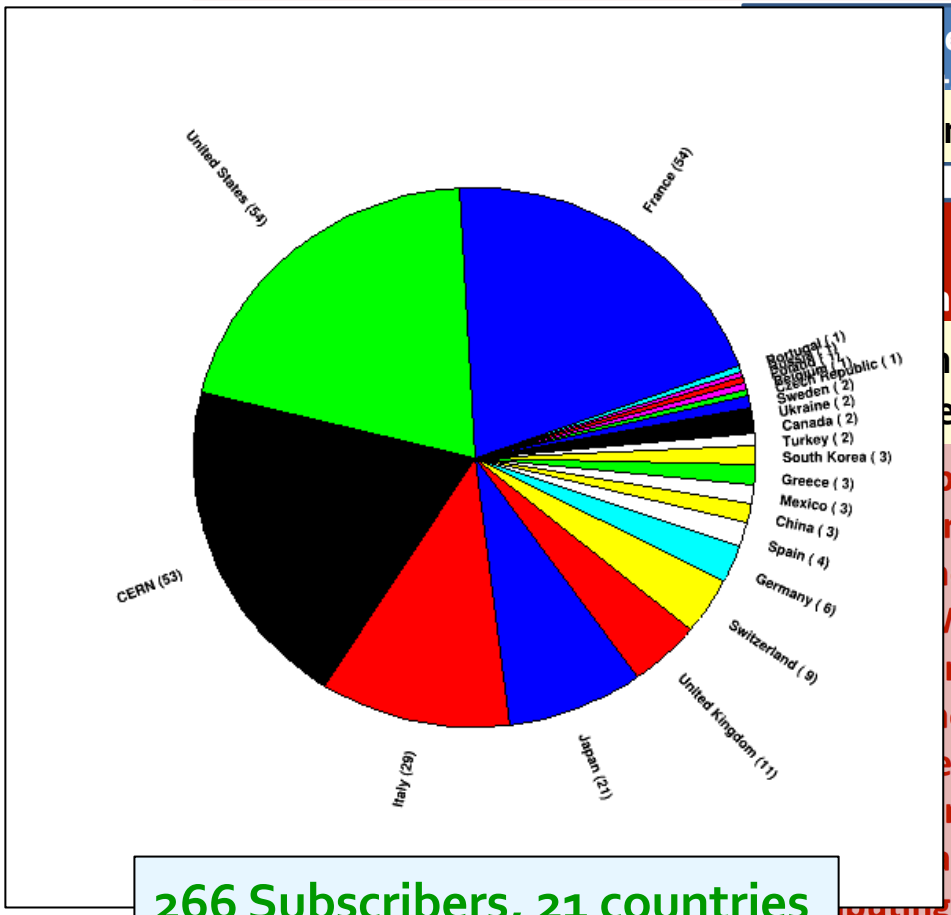
Physics

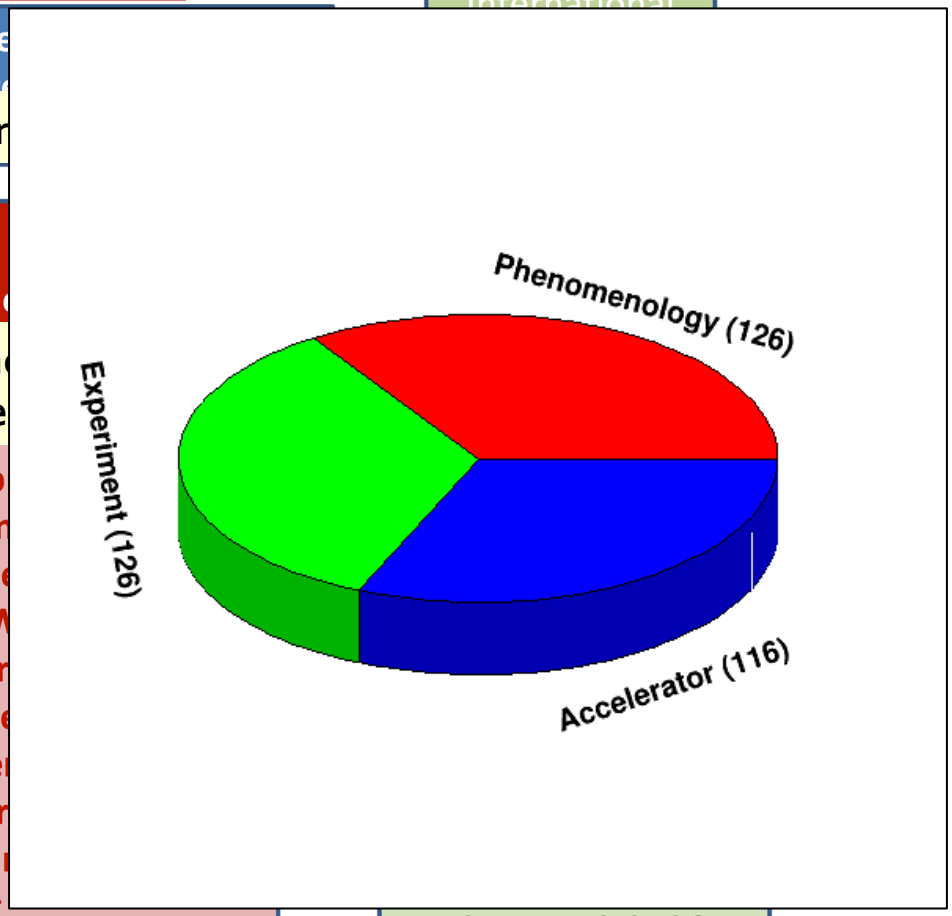
J. Ellis ad interim

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) : Initiated

TLEP design study –preliminary structure for discussion





266 Subscribers, 21 countries
Important US participation

machines ; global fits

Concluding Remarks

- It is important to choose the right machine for the future
  - Cannot afford to be wrong for a price of ~10 B$
- We believe TLEP to be the best complementary machine to LHC
  - Unbeatable precision for Higgs properties and EWSB parameters measurements
- TLEP is based on a low-risk, well-known technology
  - Supported by much progress in e^+e^- circular factories for 20 years (and counting)
    - LEP, LEP2, (super) b factories, synchrotron light sources
  - Based on this experience, luminosity, power and cost predictions will be reliable
- It is a first ambitious step in a long-term vision for high-energy physics
  - Many synergies with VHE-LHC : Tunnel, accelerator, experiments, physics
- The design study is starting up as we speak, acted in the CERN MTP
  - Join us at http://tlep.web.cern.ch
- The goal is to have a technically-ready proposal by 2018
  - So that the community can take a fully-informed decision
    - with the LHC Run2 results at $\sqrt{s}$ = 13-14 TeV in hand
- We aim for physics in 2030