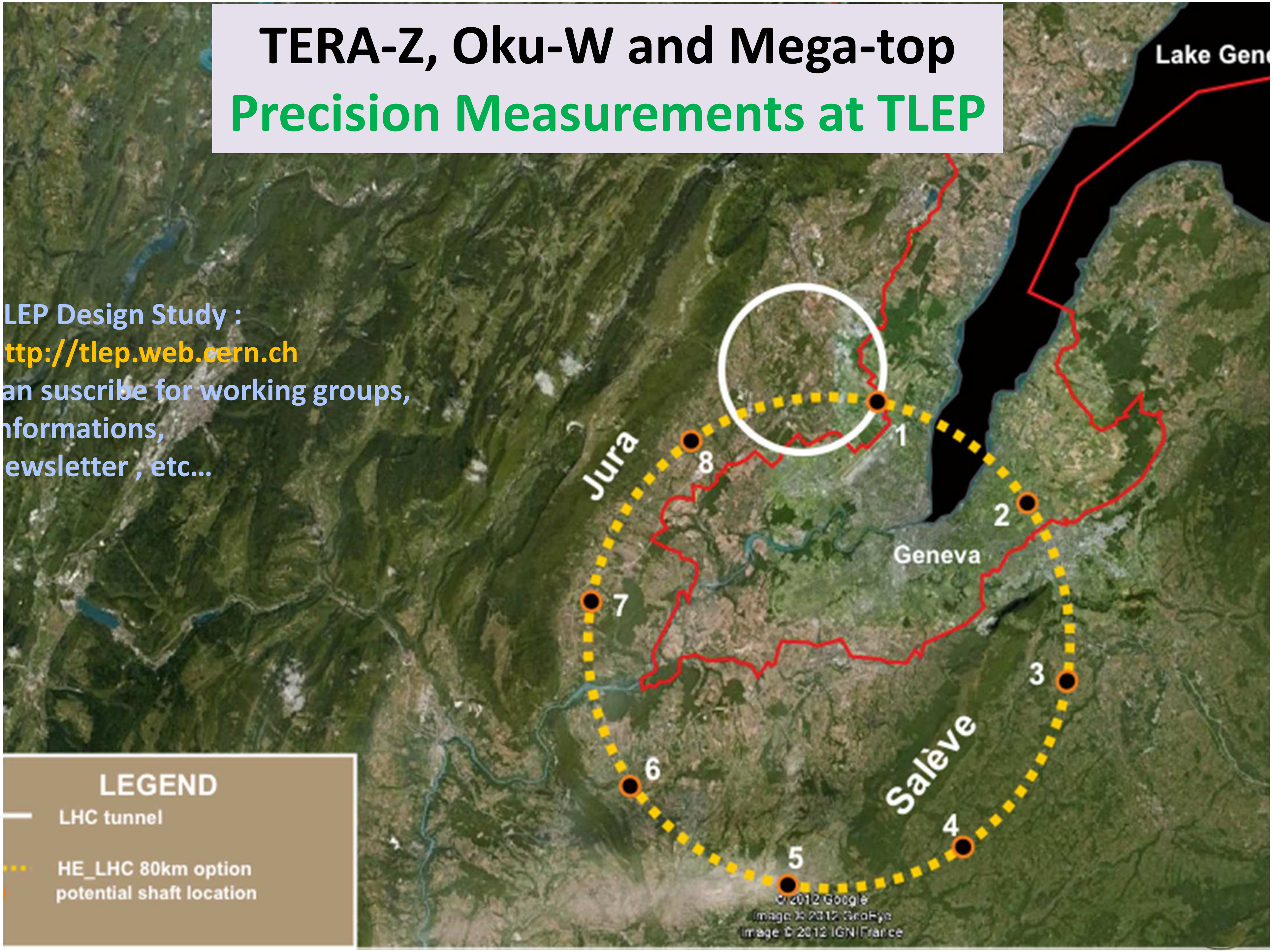
TERA-Z, Oku-W and Mega-top
Precision Measurements at TLEP

LEP Design Study :
ttp://tlep.web.cern.ch
an suscribe for working groups,
nformations,
ewsletter , etc…



FCC Study Scope and Structure

Future Circular Colliders - Conceptual Design Study for next European Strategy Update (2018)

Infrastructure

tunnels, surface buildings, transport (access roads), civil engineering, cooling ventilation, electricity, cryogenics, communication & IT, fabrication and installation processes, maintenance, environmental impact and monitoring,

Hadron injectors	Hadron collider	e+ e- collider
Beam optics and dynamics Functional specs Performance specs Critical technical systems Operation concept	Optics and beam dynamics Functional specifications Performance specs Critical technical systems Related R+D programs *HE-LHC comparison* Operation concept Detector concept Physics requirements	Optics and beam dynamics Functional specifications Performance specs Critical technical systems Related R+D programs Injector (Booster) Operation concept Detector concept Physics requirements

e- p option: Physics, Integration, additional requirements

Future Circular Colliders – Conceptual Design Stu
Michael Benedikt
6th TLEP Workshop - CERN– 16th October 2013

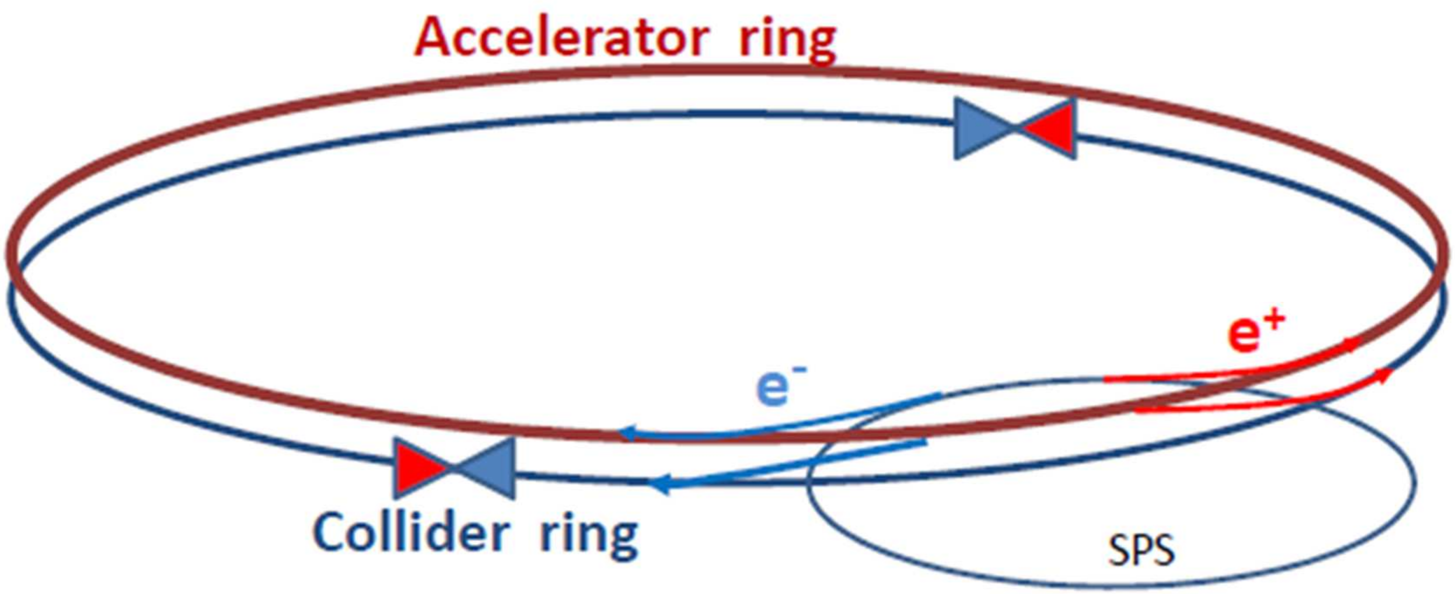
Michael Benedikt

The two pillars: pp and e+e-
mandate is to deliver full CDR for both machines with an extended cost review by ~2018
Kick Off meeting: Geneva 12-14 February 2014

A circular e+e- Higgs Factory, why not? LEP2 was not that far after all.
One year of LEP2 ➔ ~200pb^{-1} x 4 exp. -- need 1000fb^{-1}!
How can one increase over LEP 2 (average) luminosity by a factor 1000 without exploding the power bill?

Answer is in the B-factory design: a very low vertical emittance ring with higher intrinsic luminosity

electrons and positrons have a much higher chance of interacting
➔ much shorter lifetime (few minutes), beamstrahlung limit;
➔ feed beam continuously with a ancillary accelerator



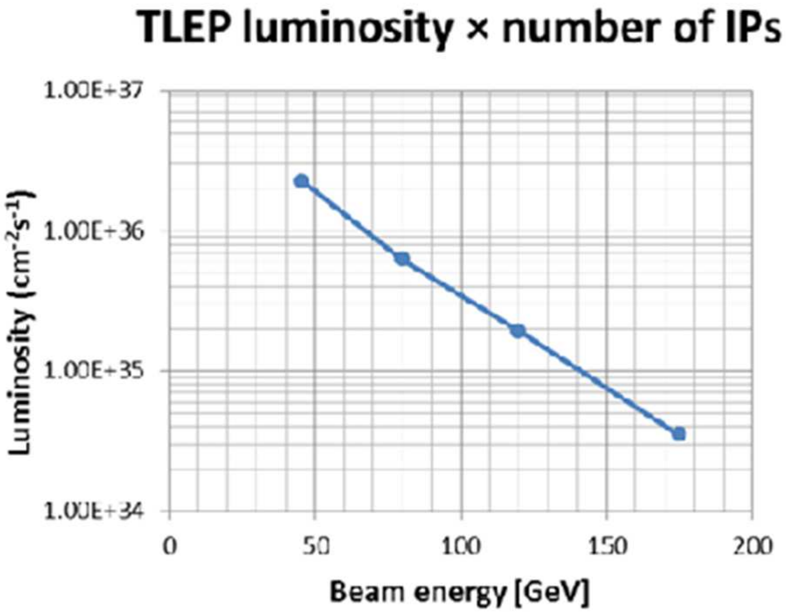
TLEP: A HIGH-PERFORMANCE CIRCULAR e^+e^- COLLIDER TO STUDY THE HIGGS BOSON

M. Koratzinos, A.P. Blondel, U. Geneva, Switzerland; R. Aleksan, CEA/Saclay, France; O. Brunner, A. Butterworth, P. Janot, E. Jensen, J. Osborne, F. Zimmermann, CERN, Geneva, Switzerland; J. R. Ellis, King's College, London; M. Zanetti, MIT, Cambridge, USA.

http://arxiv.org/abs/1305.6498.

Table 1: TLEP parameters at different energies

	TLEP Z	TLEP W	TLEP H	TLEP t
E_{beam} [GeV]	45	80	120	175
circumf. [km]	80	80	80	80
beam current [mA]	1180	124	24.3	5.4
#bunches/beam	4400	600	80	12
#e–/beam [10^{12}]	1960	200	40.8	9.0
horiz. emit. [nm]	30.8	9.4	9.4	10
vert. emit. [nm]	0.07	0.02	0.02	0.01
bending rad. [km]	9.0	9.0	9.0	9.0
κ_ε	440	470	470	1000
mom. c. α_c [10^{-5}]	9.0	2.0	1.0	1.0
$P_{loss,SR}$/beam [MW]	50	50	50	50
β^*_x [m]	0.5	0.5	0.5	1
β^*_y [cm]	0.1	0.1	0.1	0.1
σ^*_x [μm]	124	78	68	100
σ^*_y [μm]	0.27	0.14	0.14	0.10
hourglass F_{hg}	0.71	0.75	0.75	0.65
E^{SR}_{loss}/turn [GeV]	0.04	0.4	2.0	9.2
V_{RF},tot [GV]	2	2	6	12
$\delta_{max,RF}$ [%]	4.0	5.5	9.4	4.9
ξ_x/IP	0.07	0.10	0.10	0.10
ξ_y/IP	0.07	0.10	0.10	0.10
f_s [kHz]	1.29	0.45	0.44	0.43
E_{acc} [MV/m]	3	3	10	20
eff. RF length [m]	600	600	600	600
f_{RF} [MHz]	700	700	700	700
δ^{SR}_{rms} [%]	0.06	0.10	0.15	0.22
$\sigma^{SR}_{z,rms}$ [cm]	0.19	0.22	0.17	0.25
$\mathcal{L}$ /IP[10^{32}cm^{-2}s^{-1}]	5600	1600	480	130
number of IPs	4	4	4	4
beam lifet. [min]	67	25	16	20



CONSISTENT SET OF PARAMETERS FOR TLEP TAKING INTO ACCOUNT BEAMSTRAHLUNG

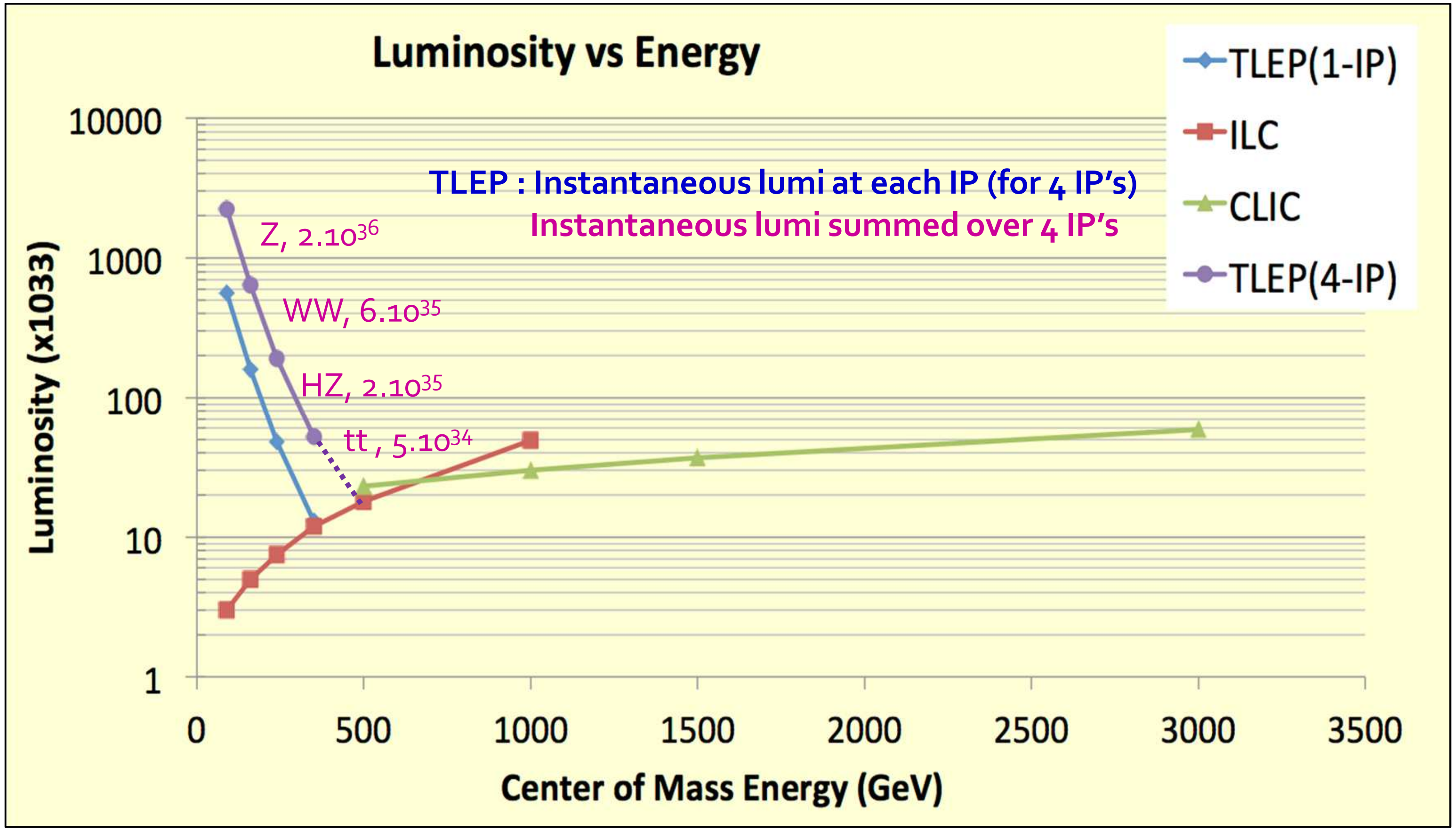
Presently: designing the optics. aim at new parameter set in Q1'14.

TLEP: PARAMETERS & STATISTICS

(e^+e^- -> ZH, $e^+e^- \rightarrow W^+W^-$, $e^+e^- \rightarrow$ Z,[$e^+e^- \rightarrow t\bar{t}$])

	TLEP-4 IP, per IP	statistics
circumference	80 km	
max beam energy	175 GeV	
no. of IPs	4	
Luminosity/IP at 350 GeV c.m.	1.3×10^{34} $cm^{-2}s^{-1}$	10^6 $t\bar{t}$ pairs
Luminosity/IP at 240 GeV c.m.	4.8×10^{34} $cm^{-2}s^{-1}$	2 10^6 ZH evts
Luminosity/IP at 160 GeV c.m.	1.6×10^{35} $cm^{-2}s^{-1}$	10^8 WW pairs
Luminosity/IP at 90 GeV c.m.	5.6 10^{35} $cm^{-2}s^{-1}$	10^{12} Z decays

Performance of e+ e- colliders

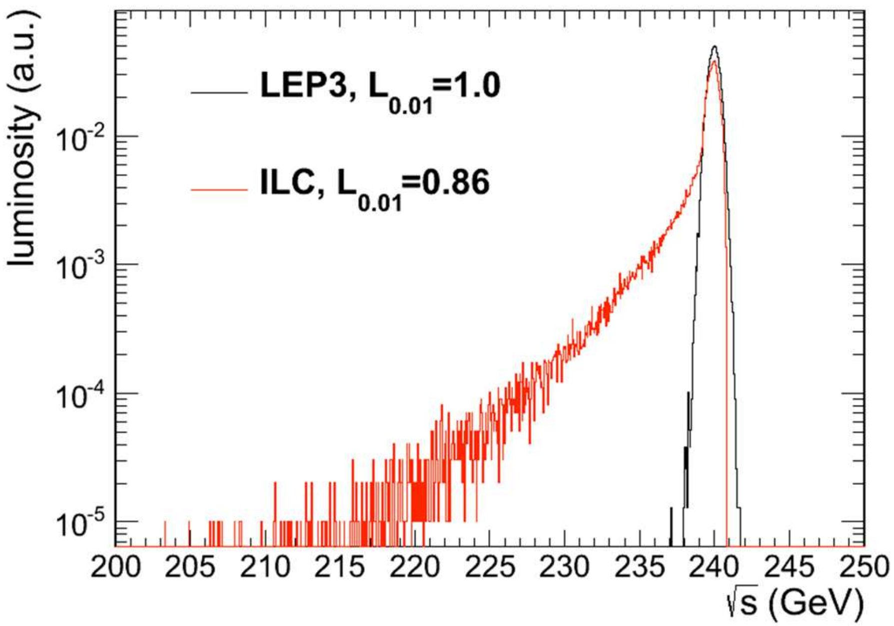


- **Luminosity : Crossing point between circular and linear colliders ~ 4-500 GeV**

  As pointed out by H. Shopper in 'The Lord of the Rings' (Thanks to Superconducting RF…)
- **Circular colliders can have several IP's**
- *use 4 IP machine as more reliable predictions using LEP experience*
- *Maximum TLEP energy somewhere between 350 and 500 GeV (at cost of more RF cavities)*

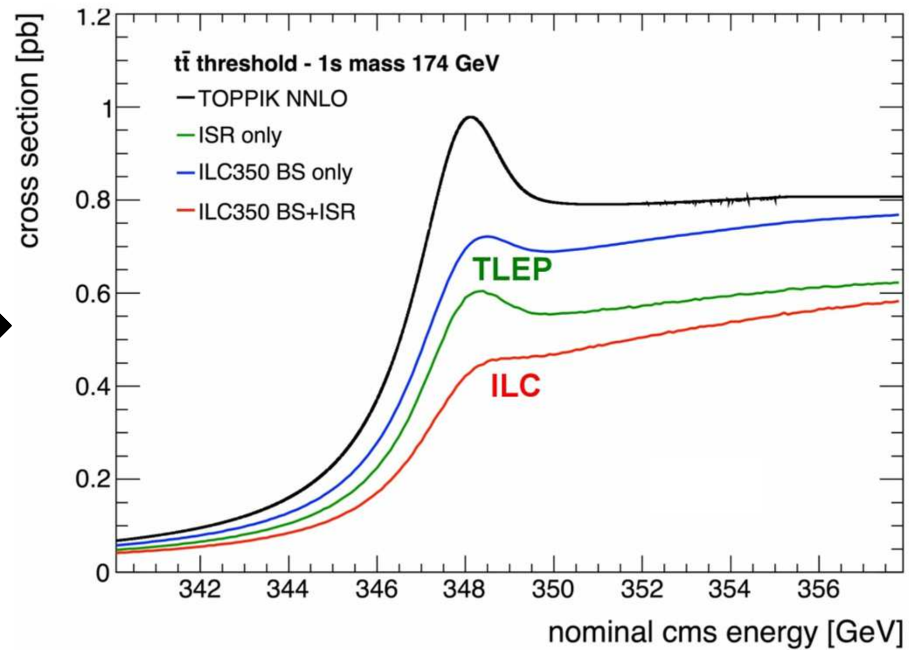
BEAMSTRAHLUNG

Luminosity *E* spectrum



➔

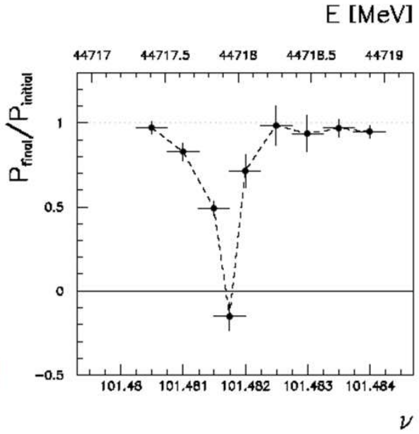
Effect on top threshold



Beamstrahlung @TLEP is important for machine design, ...but benign for experimentation : particles are either lost or recycled on a synchrotron oscillation

➔ some increase of energy spread (10-30% of 1-2 10^{-3})
but no change of average energy
Little EM background in the experiment.

Beam polarization and E-calibration @ TLEP



Precise meast of E_{beam} by resonant depolarization
~100 keV each time the meast is made

At LEP transverse polarization was achieved routinely at Z peak.
instrumental in 10^{-3} measurement of the Z width in 1993
led to prediction of top quark mass (179+- 20 GeV) in March 1994

Polarization in collisions was observed *(40% at BBTS = 0.04)*

At LEP beam energy spread destroyed polarization above 60 GeV
$\sigma_E \propto E^2/\sqrt{\rho}$ ➔ At TLEP transverse polarization up to at least 80 GeV

TLEP: use 'single' bunches to measure the beam energy continuously
no interpolation errors due to tides, ground motion or trains etc…
feasible scenario with polarization wigglers

<< 100 keV beam energy calibration around Z peak and W pair threshold.
Δm_Z ~0.1 MeV, $\Delta\Gamma_Z$ ~0.1 MeV, Δm_W ~ 0.5 MeV

TLEP: a new member of the e+ e- family

ILC CLIC TLEP

main differences:

-- luminosity vs energy dependence
-- high energy reach
-- upgrade path
-- resolution and precision in center-of-mass energy
-- ILC is linear and «ready»
-- TLEP is circular and <u>begins design study</u>

main common quality: e+e- → Z H (Higgs tag by recoil mass to Z decay)

First Look at the Physics Case of TLEP

The TLEP Design Study Working Group

(See next pages for the list of authors)

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

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.

A possible TLEP running programme

1. ZH threshold scan and 240 GeV running (200 GeV to 250 GeV)
   5+ years @2 10^35 /cm2/s => 210^6 ZH events
   ++ returns at Z peak with TLEP-H configuration
   for detector and beam energy calibration

Higgs boson HZ studies
+ WW, ZZ etc..

2. Top threshold scan and (350) GeV running
   5+ years @2 10^35 /cm2/s ➔ 10^6 ttbar pairs ++Zpeak

Top quark mass
Hvv Higgs boson studies

3. Z peak scan and peak running , TLEP-Z configuration ➔ 10^12 Z decays
   → transverse polarization of 'single' bunches for precise E_beam calibration
   2 years

M_Z, Γ_Z R_b etc…
Precision tests and rare decays

4. WW threshold scan for W mass measurement and W pair studies
   1-2 years ➔ 10^8 W pairs ++Zpeak

M_W, and W properties etc…

5. Polarized beams (spin rotators) at Z peak 1 year at BBTS=0.01/IP => 10^{11} Z decays.

A_{LR}, A_{FB}^{pol} etc

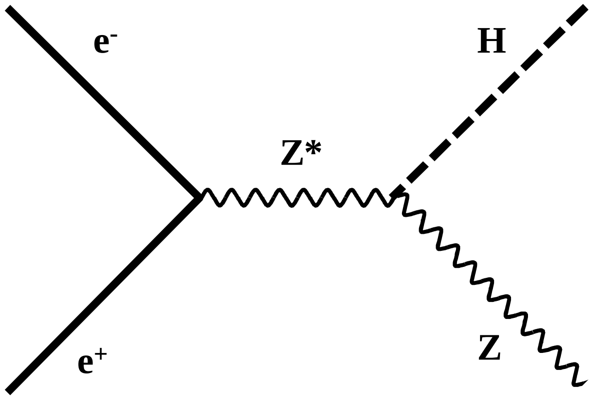
NB accelerator configuration possibly different for TLEP-Z , W vs TLEP-H and TLEP-t

Higgs production mechanism

In e^+e^- the Higgs is produced by "higgstrahlung" close to threshold

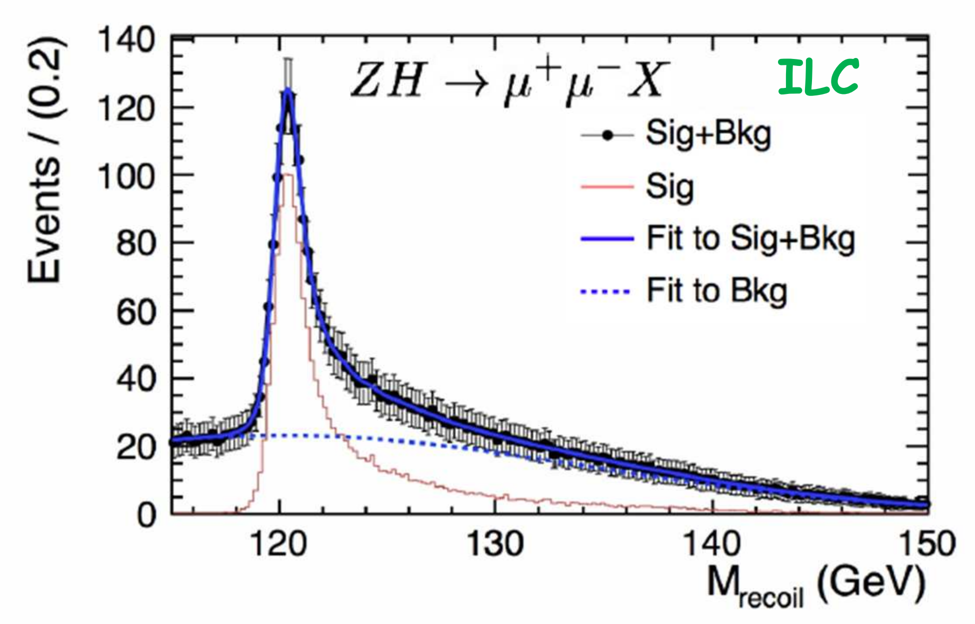
Production xsection has maximum near threshold ~200 fb

$10^{35}/cm^2/s$ ➔ 1'000'000 HZ events in 5 years



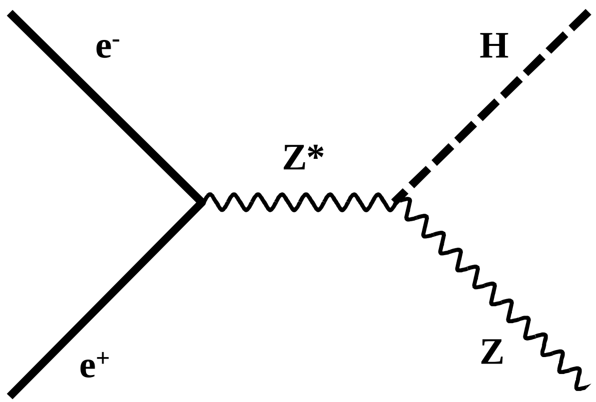
H – tagging by missing mass to Z decay

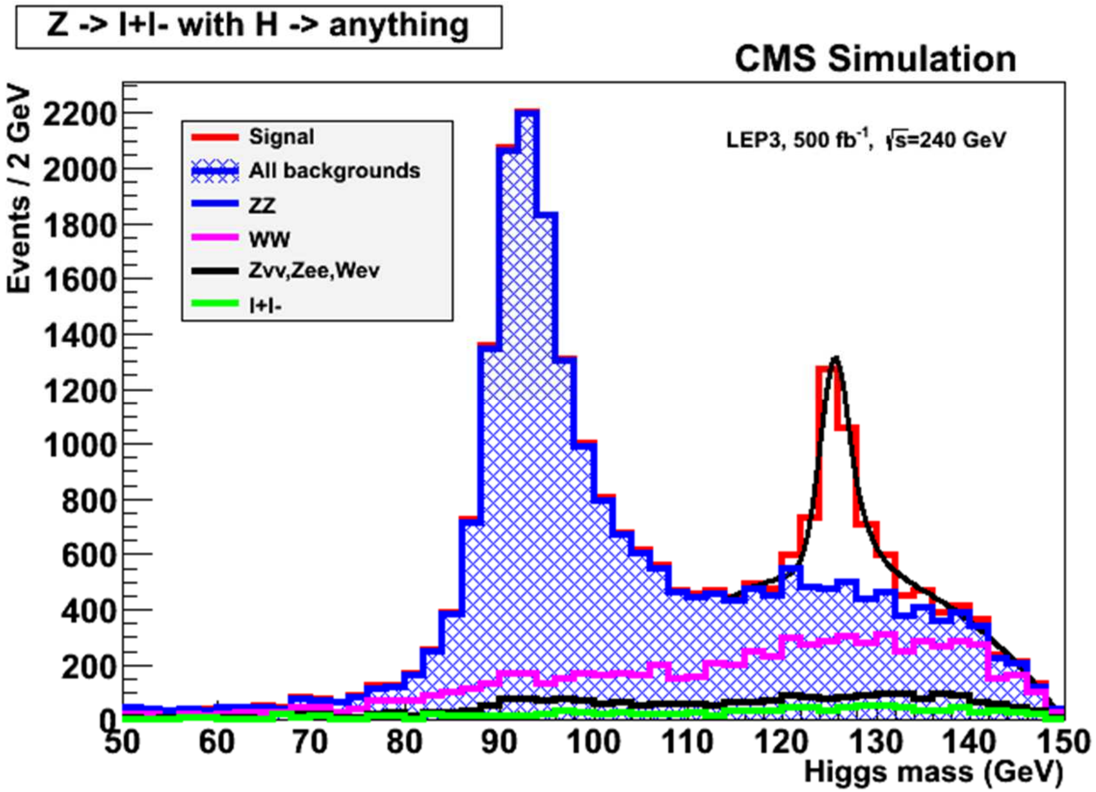
For a Higgs of 125GeV, a centre of mass energy of ~240GeV is best
➔ kinematical constraint near threshold for high precision in mass, width, selection purity



Z – tagging
by missing mass

total rate $\propto g_{HZZ}^2$
ZZZ final state $\propto g_{HZZ}^4 / \Gamma_H$
➔ measure total width Γ_H
empty recoil = invisible width
'funny recoil' = exotic Higgs decay
easy control below theshold





HF2012

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%	7 − 10%	2.5%	1.3%	1.3%	0.9%	3.1/1.0/0.7%	0.69%

baseline ILC

TLEP

NB : this is not a very good comparison with LHC as correlation between channels
➔ some ratios of BRs being can be more precise observables than the couplings themselves.
NBB: recent ttH analyses indicate LHC pecision in 3-4% range for ttH coupling

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%			

Baseline ILC, 10 years

Price?
30 years+

TLEP, 10 years

My personal favorite: invisible Higgs width (dark matter!), dominated by statistics at 240 GeV

SUMMARY

Hans Kuehn
"Precision calculations for TLEP"

- theory predictions do not (yet?) fulfill TLEP requirements,
- missing corrections are presumably feasible (QCD),
- important experimental input from low-energy e^+e^- annihilation:

  $m_b, m_c, \Delta\alpha, (\alpha_s?)$, (SuperKEKb, TLEP – guidance needed for $\Delta\alpha$)
- m_b determiantion $\Rightarrow \Gamma(H \to bb)$

  usage of $m_b(pole)$ is strongly disfavoured compared to $m_b(10\text{ GeV})$

perspectives: (assume $\delta\alpha_s = 2 \times 10^{-4}$)

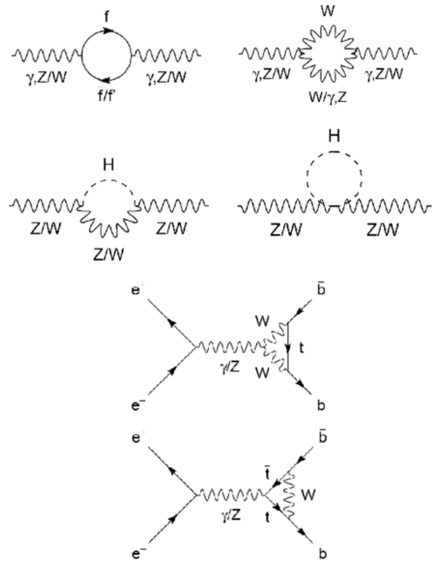
$\delta m_b(10\text{GeV})/m_b \sim 10^{-3}$ conceivable (dominated by $\delta\Gamma(\Upsilon \to e^+e^-)$)

$\Rightarrow \frac{\delta\Gamma_b}{\Gamma_b} = \pm 2 \times 10^{-3}|_{m_b} \pm 1.3 \times 10^{-3}|_{\alpha_s,\text{running}} \pm 1 \times 10^{-3}|_{\text{theory}}$

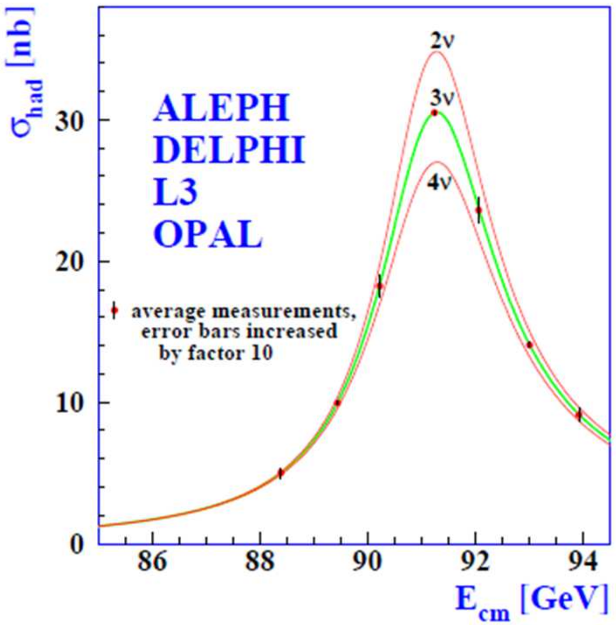
Aim at
$\Delta\kappa_b \sim 0.4\%$
at TLEP

TLEP6 workshop 16-18 October 2013 CERN
see tlep.web.cern.ch web site

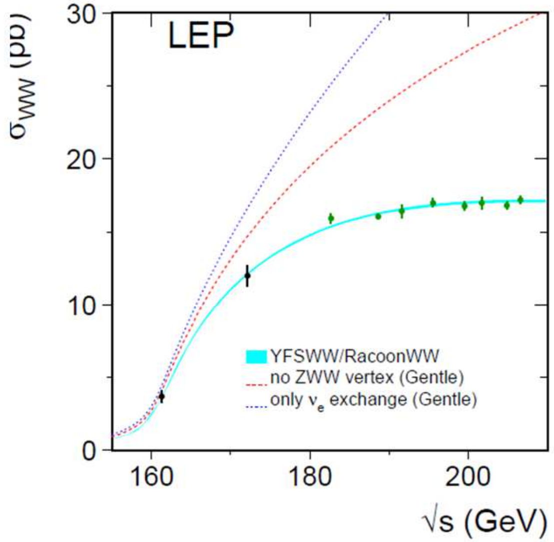
Precision measurements of EW observables

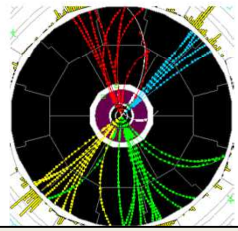


Z pole asymmetries, lineshape

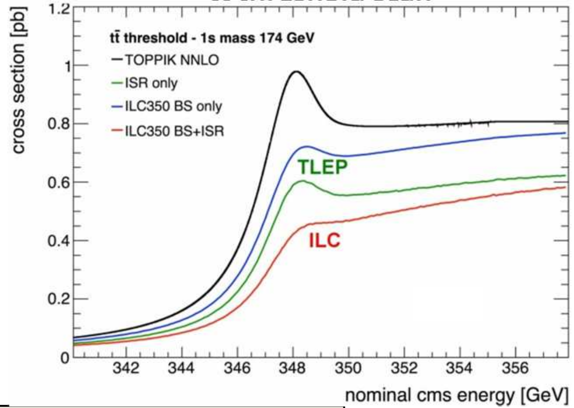


WW threshold scan





tt threshold scan



TLEP : Repeat the LEP1 physics programme every 15 mn

STATISTICS!

- **Statistics, statistics: 10^{10} tau pairs, 10^{11} bb pairs, QCD and QED studies etc…**

Transverse polarization up to the WW threshold

- **Exquisite beam energy determination (100 keV each time) for M_Z Γ_Z M_W**

Longitudinal polarization at the Z pole

- **Measure $\sin^2\theta_W$ to 2.10^{-6} from A_{LR}**

$\Delta\rho$: $\equiv \varepsilon_1$

$$\Gamma_\ell = (1+\Delta\rho)\,\frac{G_F\, M_Z^3}{24\pi\sqrt{2}}\left(1+\left(\frac{g_{V\ell}}{g_{A\ell}}\right)^2\right)\left(1+\frac{3}{4}\frac{\alpha}{\pi}\right)$$

ε_3

$$\sin^2\theta_W^{eff}\cos^2\theta_W^{eff} = \frac{\pi\alpha(M_Z^2)}{\sqrt{2}\,G_F\,m_Z^2}\;\frac{1}{1+\Delta\rho}\;\frac{1}{1-\frac{\varepsilon_3}{\cos^2\theta_W}}$$

δ_{vb}

$$\Gamma_b = (1+\delta_{vb})\,\Gamma_d\left(1-\text{mass corrections } \propto m_b^2/M_Z^2\right)$$

ε_2

$$M_W^2 = \frac{\pi\alpha(M_Z^2)}{\sqrt{2}\,G_F\sin^2\theta_W^{eff}}\cdot\frac{1}{(1-\varepsilon_3+\varepsilon_2)}$$

$\sin^2\theta_W^{eff}$ is defined from

$$\sin^2\theta_W^{eff} = \frac{1}{4}\left(1-\frac{g_{V\ell}}{g_{A\ell}}\right) = \sin^2\theta_W^{eff}{}_{lept}$$

obtained from asymmetries at the Z.

also

Δr

$$m_W^2 = \frac{\pi\alpha}{\sqrt{2}\,G_F}\cdot\frac{1}{\left(1-\frac{M_W^2}{M_Z^2}\right)}\;\frac{1}{(1-\Delta r)}$$

$$\Delta r = \Delta\alpha - \frac{\cos^2\theta_W}{\sin^2\theta_W}\Delta\rho + 2\frac{\cos^2\theta_W}{\sin^2\theta_W}\varepsilon_3 + \frac{c^2-s^2}{s^2}\varepsilon_2$$

EWRCs

relations to the well measured

G_F m_Z α_{QED}

at first order:

$\Delta\rho = \alpha/\pi\;(m_{top}/m_Z)^2$

$-\;\alpha/4\pi\;\log\,(m_h/m_Z)^2$

$\varepsilon_3 = \cos^2\theta_W\;\alpha/9\pi\;\log\,(m_h/m_Z)^2$

$\delta_{vb} = 20/13\;\alpha/\pi\;(m_{top}/m_Z)^2$

complete formulae at 2d order including strong corrections are available in fitting codes

e.g. ZFITTER , GFITTER

Will need to be improved for TLEP!

$\Delta\rho$: $\equiv \varepsilon_1$

$$\Gamma_\ell = (1+\Delta\rho)\,\frac{G_F\, M_Z^3}{24\pi\sqrt{2}}\left(1+\left(\frac{g_{V\ell}}{g_{A\ell}}\right)^2\right)\left(1+\frac{3}{4}\frac{\alpha}{\pi}\right)$$

ε_3

$$\sin^2\theta_W^{eff}\cos^2\theta_W^{eff} = \frac{\pi\alpha(M_Z^2)}{\sqrt{2}\,G_F\,m_Z^2}\;\frac{1}{1+\Delta\rho}\;\frac{1}{1-\frac{\varepsilon_3}{\cos^2\theta_W}}$$

δ_{vb}

$$\Gamma_b = (1+\delta_{vb})\,\Gamma_d\,\left(1 - \text{mass corrections } \alpha\, m_b^2/M_Z^2\right)$$

ε_2

$$M_W^2 = \frac{\pi\alpha(M_Z^2)}{\sqrt{2}\,G_F\,\sin^2\theta_W^{eff}}\cdot\frac{1}{\ldots}$$

$\sin^2\theta_W^{eff}$ is defined fr…

$\sin^2\theta^{eff}$ … g_{Ae} … $= \sin^2\theta_W^{eff}{}_{lept}$

…ed from asymmetries at the Z.

also

Δr

$$\ldots = \frac{\pi\alpha}{\sqrt{2}\,G_F}\cdot\frac{1}{\left(1-\frac{M_W^2}{M_Z^2}\right)}\;\frac{1}{(1-\Delta r)}$$

$$\Delta r = \Delta\alpha - \frac{\cos^2\theta_W}{\sin^2\theta_W}\Delta\rho + 2\,\frac{c^2\theta_W}{\sin^2\theta_W}\,\varepsilon_3 + \frac{c^2-s^2}{s^2}\,\varepsilon_2$$

EWRCs

relations to the well measured

G_F m_Z α_{QED}

at first o…

… $(m_{top}/m_Z)^2$

… $\alpha/4\pi$ log $(m_h/m_Z)^2$

$\varepsilon_3 = \cos^2\theta_W\;\alpha/9\pi\;\log\,(m_h/m_Z)^2$

$\delta_{vb} = 20/13\;\alpha/\pi\;(m_{top}/m_Z)^2$

complete formulae at 2d order including strong corrections are available in fitting codes

e.g. ZFITTER , GFITTER

Will need to be improved for TLEP!

There is much more than M_W and $\sin^2\theta_W^{eff}$

Example (from Langacker& Erler **PDG 2011**)

$\Delta\rho = \varepsilon_1 = \alpha(M_Z)\ .\ T$

$\varepsilon_3 = 4\sin^2\theta_W\ \alpha(M_Z)\ .\ S$

$\Delta\rho$ today = 0. 0004+0.0003−0.0004

-- is consistent with 0 at 1σ

-- is sensitive to non-conventional Higgs bosons (e.g. in SU(2) triplet with 'funny v.e.v.s)

-- is sensitive to Isospin violation such as $m_t \neq m_b$

$$\rho_0 = 1 + \frac{3\,G_F}{8\sqrt{2}\pi^2}\sum_i \frac{C_i}{3}\,\Delta m_i^2\ , \qquad (10.63)$$

where the sum includes fourth-family quark or lepton doublets, $\binom{t'}{b'}$ or $\binom{E^0}{E^-}$, right-handed (mirror) doublets, non-degenerate vector-like fermion doublets (with an extra factor of 2), and scalar doublets such as $\binom{\tilde{t}}{\tilde{b}}$ in Supersymmetry (in the absence of L–R mixing).

Present measurement implies

$$\sum_i \frac{C_i}{3}\,\Delta m_i^2 \leq (52\ \text{GeV})^2.$$

Most e.g. SUSYmodels have these symmetries embedded from the start (natural?)

Similarly:

$$S = \frac{C}{3\pi}\sum_i \Big(t_{3L}(i) - t_{3R}(i)\Big)^2,$$

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$\Delta\rho = \varepsilon_1 = \alpha(M_Z) \,.\, T$

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-- is sensitive to Isospin violation such as m ...

$$\rho_0 = 1 + \frac{3 G_F}{8 \ldots} \qquad (10.63)$$

where the sum includes fourt... ...n doublets, $\binom{t'}{b'}$ or $\binom{E^0}{E^-}$, right-handed (mirror) doublets, non-d... ...ermion doublets (with an extra factor of 2), and scalar doub... ...ersymmetry (in the absence of L–R mixing).

Present m...

$$\sum_i \frac{C_i}{3} \Delta m_i^2 \leq (52 \text{ GeV})^2.$$

Most e.g. SUSYmodels have these symmetries embedded from the start (natural?)

Similarly:

$$S = \frac{C}{3\pi} \sum_i \Big(t_{3L}(i) - t_{3R}(i) \Big)^2,$$

There is no decoupling in $(m/\Lambda)^n$ for particles which do not respect the SM symmetries

Quantity	Physics	Present precision		TLEP Stat errors	Possible TLEP Syst. Errors	TLEP key	Challenge
M_Z (keV)	**Input**	91187500 ±2100	Z Line shape scan	**5 keV**	**<100 keV**	E_cal	QED corrections
Γ_Z (keV)	**$\Delta\rho$ (T)** **(no $\Delta\alpha$!)**	2495200 ±2300	Z Line shape scan	**8 keV**	**<100 keV**	E_cal	QED corrections
R_ℓ	α_s, δ_b	20.767 ± 0.025	Z Peak	**0.0001**	**<0.001**	Statistics	QED corrections
N_ν	**PMNS Unitarity sterile ν's**	2.984 ±0.008	Z Peak	**0.00008**	**<0.004**		**Bhabha scat.**
N_ν	**PMNS Unitarity sterile ν's**	2.92 ±0.05	(γ+Z_inv) ($\gamma+Z\rightarrow \ell\ell$)	**0.001** (161 GeV)	**<0.001**	Statistics	
R_b	δ_b	0.21629 ±0.00066	Z Peak	**0.000003**	**<0.000060**	Statistics, small IP	Hemisphere correlations
A_{LR}	$\Delta\rho$, ε_3, $\Delta\alpha$ **(T, S)**	0.1514 ±0.0022	Z peak, polarized	**0.000015**	**<0.000015**	4 bunch scheme, > 2exp	Design experiment
M_W MeV/c2	$\Delta\rho$, ε_3, ε_2, $\Delta\alpha$ **(T, S, U)**	80385 ± 15	Threshold (161 GeV)	**0.3 MeV**	**<0.5 MeV**	E_cal & Statistics	QED corections
m_{top} MeV/c2	**Input**	173200 ± 900	Threshold scan	**10 MeV**	**<10MeV**	E_cal & Statistics	Theory interpretation 40 MeV?

Words of caution:

1. TLEP will have 5.10^4 more luminosity than LEP at the Z peak, 5.10^3 at the W pair threshold.
Predicting achievable accuracies with statistical errors decreasing by 250 is very difficult. The study is just beginning.

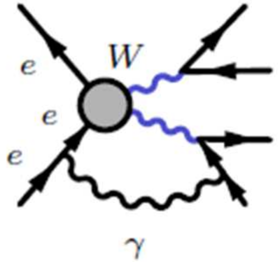
2. The previous table shows 'plausible' precisions based on experience and knowledge of the present limitations, most of which from higher order QED corrections (ex. production of additional lepton pairs etc..).
Many can have experimental cross-checks and errors may get better.

3. The most serious issue is the luminosity measurement which relies on the calculations/modeling of the low angle Bhabha scattering cross-section.
This dominates the measurement of the hadronic cross section at the Z peak thus the determination of N_ν (test of the unitarity of the PMNS matrix)

4. The table shhows only a sample of possibilities. With 10^{12} Z decays, there are many, many more powerful studies to perform at TERA-Z
e.g. flavour physics with 10^{11} $b\bar{b}$, $c\bar{c}$, 10^{10} $\tau\tau$ etc...

W-O-W!

$\Delta M_W = 0.5$ MeV ?



Future improvements of theory predictions?

Doable in principle:

- NNLO $\log\beta$, $\log(s/m_e^2)$ terms
- NNLO Coulomb corrections near threshold for distributions

Major effort, several years:

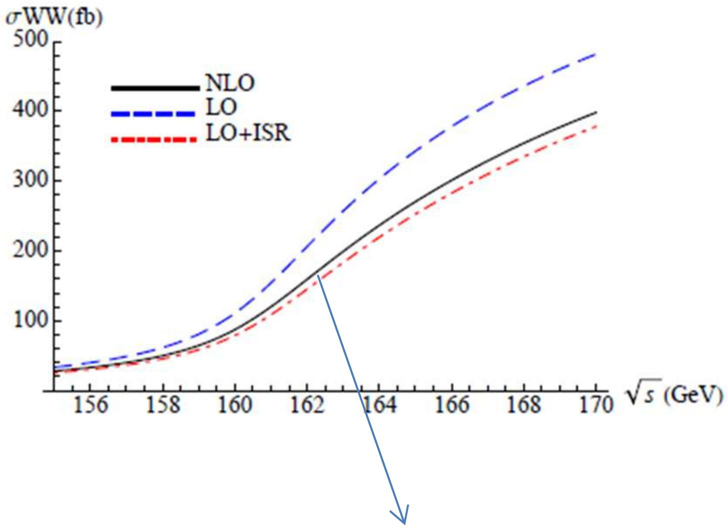
- NNLO EW corrections to on-shell $e^+e^- \to W^+W^-$

  (current frontier: first NNLO QCD $2 \to 2$ processes)

$\Rightarrow$ Input to full NNLO EFT calculation
Naive estimate for remaining uncertainty from cross-section calculation
$\Delta\sigma \sim \mathcal{O}(0.1‰)$, $\Delta M_W < 1$ MeV
ISR uncertainty?

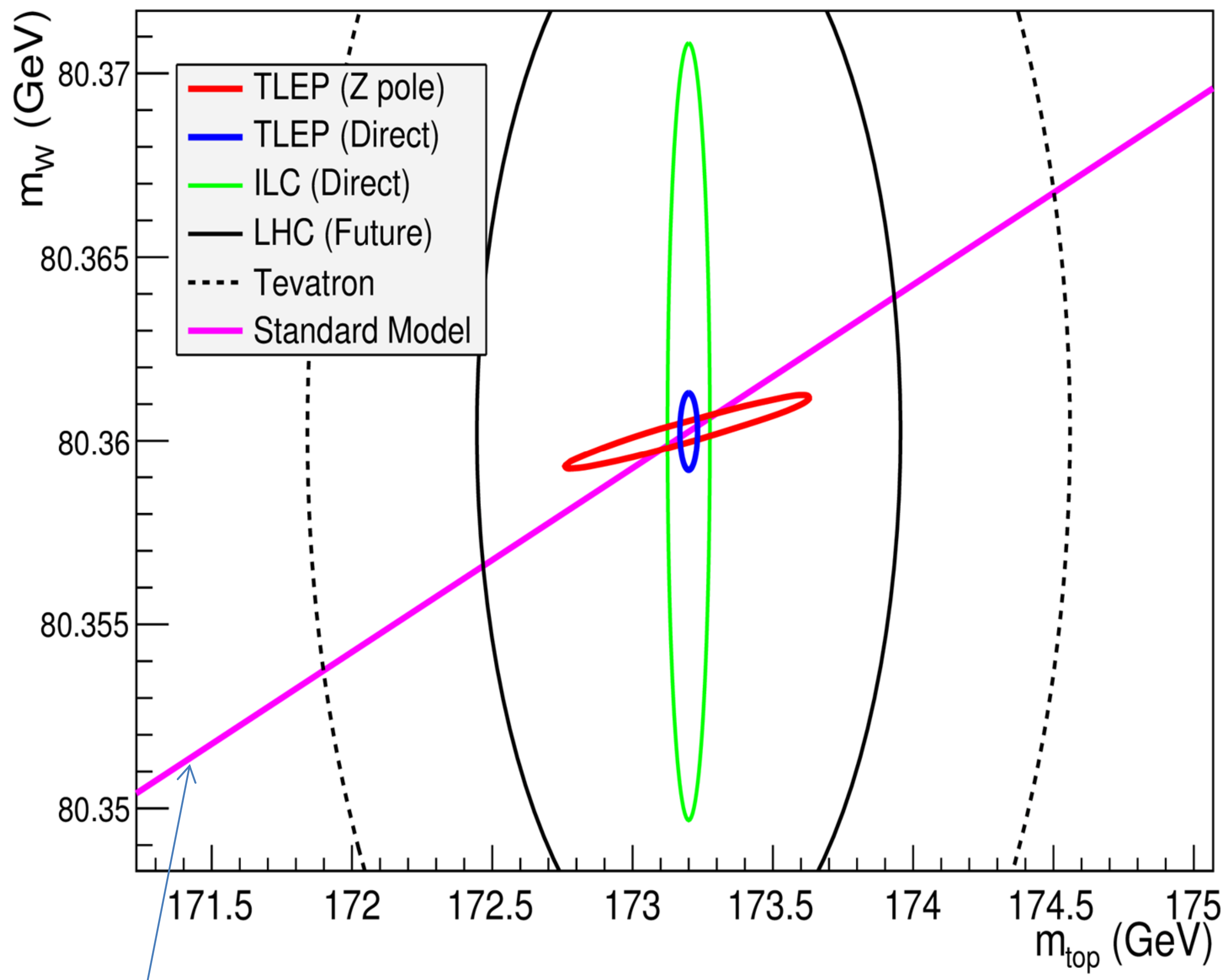
Completely new methods needed:

- NNLO EW corrections to $e^+e^- \to 4f$



maximum sensitivity :
near threshold's inflexion point.

present QED error on Z mass/width is 0.3 MeV



Janot

NB this is the Z mass really...

without TLEP the SM line would have a 2.2 MeV thickness

The marvels of statistics

many tricks to explore:

- measure m_b (Q^2) from Z → $\bar{b}b\gamma$ etc...

- measure α_s (Q^2) to ±2 10^{-4} from 3 different ways ***(Dissertori)***

i) $R_h = (\Gamma_{had} / \Gamma_{\ell\ell})$_Z

ii) $B_h= (\Gamma_{had} / \Gamma_{\ell\nu})$_W

iii) tau decays (spectral functions)

-- measure α_{QED} (Q^2) from e+e- → e+e- (t)

etc. etc... many ideas, not all will work

-

NEUTRINO CONNECTIONS

The only known BSM physics at the particle physics level is the existence of neutrino masses

-- There is no unique solution for mass terms: Dirac only? Majorana only? Both?

-- if Both, the existence of (2 or 3) families of massive right-handed (sterile) N_i , $\bar{N}_i$ neutrinos is predicted («see-saw» models) but masses are unknown (eV to 10^{10}GeV)

-- mixing with active neutrinos leads to various observable consequences

-- if very light (eV) , possible effect on neutrino oscillations

-- if mixing in % or permil level, possibly measurable effects on

-- PMNS matrix unitarity violation and deficit in Z invisible width

-- occurrence of Higgs invisible decays $H \rightarrow \nu_i \ \bar{N}_i$

-- violation of unitarity and lepton universality in W or τ decays

-- etc , etc.

-+- many more examples

At the end of LEP:

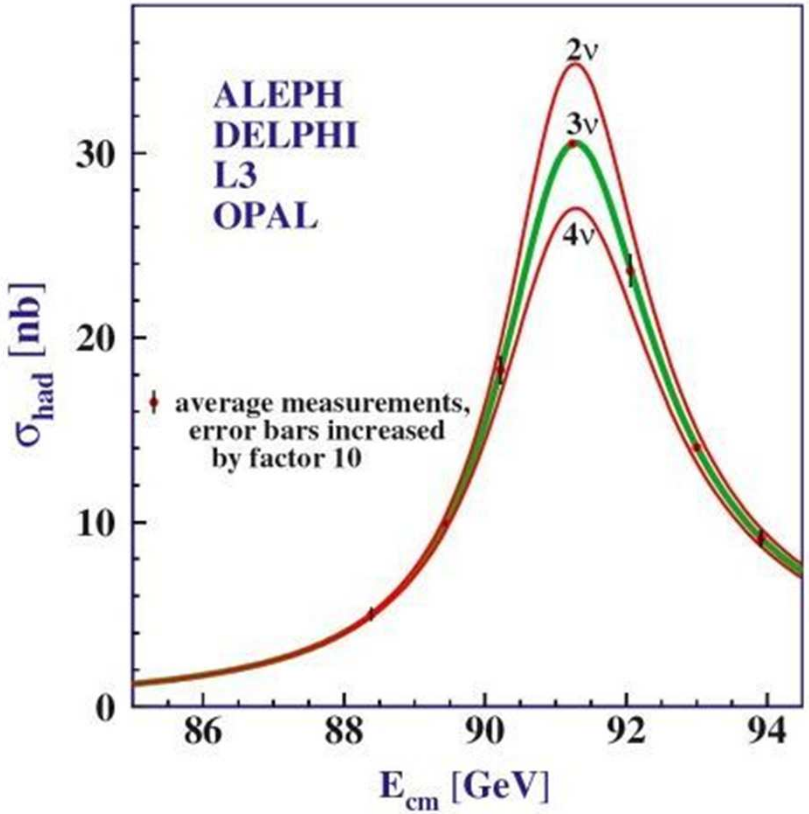
Phys.Rept.427:257-454,2006

N_ν = 2.984 ±0.008

- 2 σ :^) !!

This is determined from the Z line shape scan and dominated by the measurement of the hadronic cross-section at the Z peak maximum ➔

The dominant systematic error is the theoretical uncertainty on the Bhabha cross-section (0.06%) which represents an error of ±0.0046 on N_ν



Improving on N_ν by more than a factor 2 would require a large effort to improve on the Bhabha cross-section calculation!

Neutrino counting at TLEP

given the very high luminosity, the following measurement can be performed

$$N_\nu = \frac{\dfrac{\gamma Z(inv)}{\gamma Z \rightarrow ee, \mu\mu}}{\dfrac{\Gamma_\nu}{\Gamma e,\mu}\ (SM)}$$

The common γ tag allows cancellation of systematics due to photon selection, luminosity etc. The others are extremely well known due to the availability of $O(10^{12})$ Z decays.

The full sensitivity to the number of neutrinos is restored , and the theory uncertainty on $\frac{\Gamma_\nu}{\Gamma e}\ (SM)$ is very very small.

A good measurement can be made from the data accumulated at the WW threshold where $\sigma(\gamma Z(inv)) \sim 4$ pb for $|\cos\theta_\gamma| < 0.95$

161 GeV (10^7 s) running at $1.6 \times 10^{35}/cm^2/s$ x 4 exp → 3×10^7 $\gamma Z(inv)$ evts, $\Delta N_\nu = 0.0011$
adding 5 yrs data at 240 and 350 GeV .... $\Delta N_\nu = 0.0008$

A better point may be 105 GeV (20pb and higher luminosity) may allow $\Delta N_\nu = 0.0004$?

Conclusions

The search for the new phenomena
(required to e.g. explain dark matter or neutrino masses)
can go either to higher energies or smaller couplings.

With the mind-boggling statistics available, TLEP should be able
to provide great sensitivity to new physics by precision measurements of
Higgs but also Z W and top.

The statistics and experimental precisions need to be matched
by corresponding improvements in theoretical calculations ... and smart ideas.

This is only a beginning

The e+e- family has an important role to play in the FCC design study!

Team for kick-off and study preparation

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