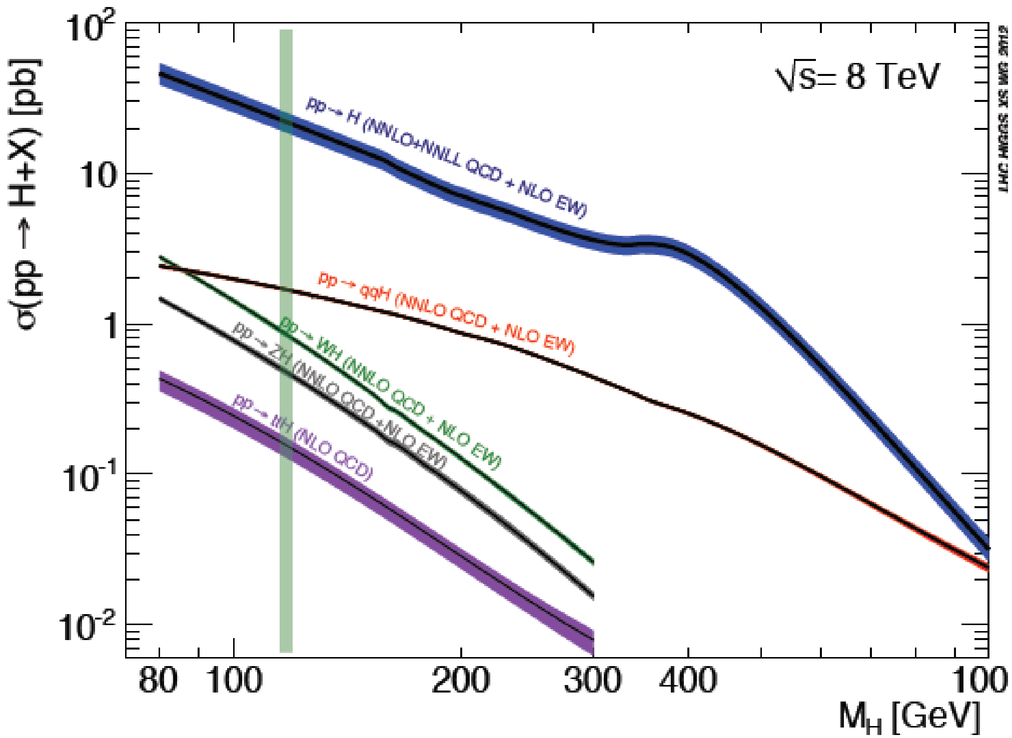
CIRCULAR HIGGS FACTORIES

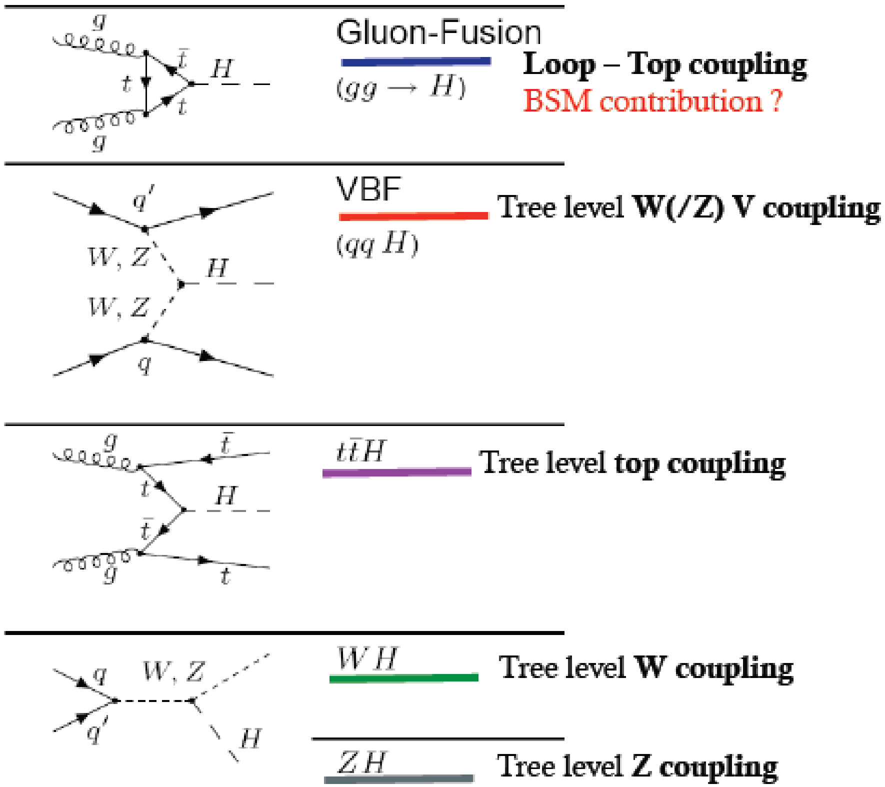
Why a Higgs factory?

Question 1: is the H(126) The Higgs boson
-- do we know well enough from LHC?
-- how precisely do we need to know before we are convinced?

Question 2: is there something else in sight?
-- known unknown facts need answer
 neutrino masses, (Dirac, and/or Majorana, sterile and right handed, CPV, MH..)
 non baryonic dark matter,
 Accelerated expansion of the Universe
 Matter-antimatter Asymmetry
-- can the Higgs be used as search tool for new physics that answer these questions?
-- precision measurements sensitive to the existence of new particles through loops
-- how precisely do we need to know before we are convinced?

Question 3: which Higgs factories ?
-- HL-LHC
-- (V)HE-LHC
-- mu+mu-
-- gamma-gamma
-- e+e- : linear and circular





The LHC is a Higgs Factory !

1M Higgs already produced – more than most other Higgs factory projects.
15 Higgs bosons / minute – and more to come (gain factor 3 going to 13 TeV)

Difficulties: several production mechanisms to disentangle and significant systematics in the production cross-sections σ_{prod} .
Challenge will be to reduce systematics by measuring related processes.

$$\sigma_{i\to f}^{observed} \propto \sigma_{prod} \frac{(g_{Hi})^2 (g_{Hf})^2}{\Gamma_H}$$

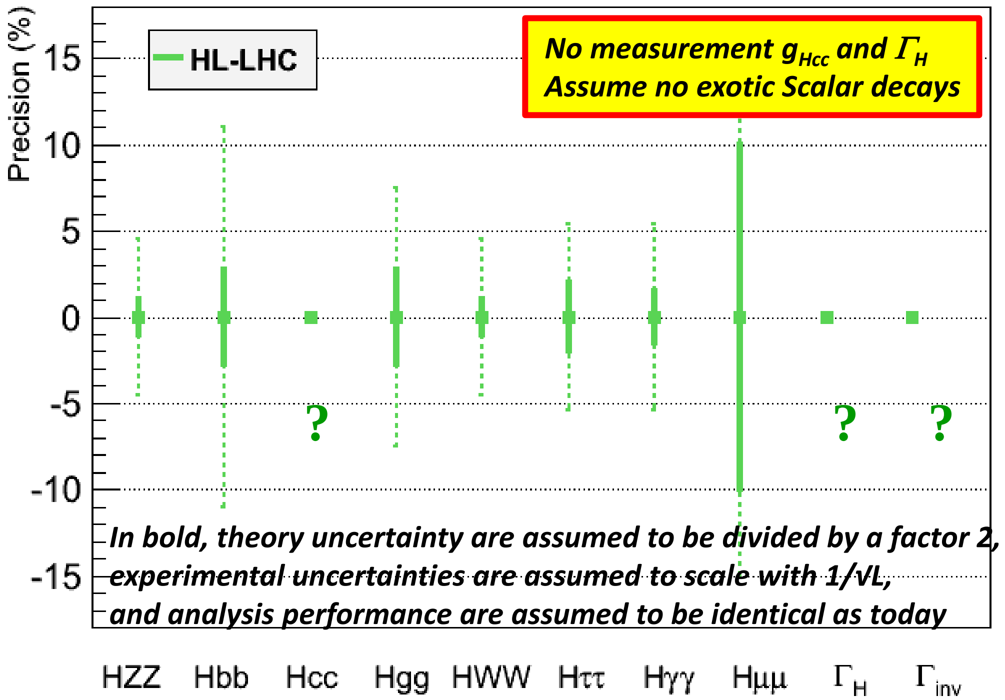
extract couplings to anything you can see or produce from if i=f as in WZ with H→ ZZ → absolute normalization

HL-LHC (≡3 ab^{-1} at 14 TeV):

Highest-priority recommendation from European Strategy

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

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



Coupling measurements with precision :

- in the range **6-15%** with LHC - 300 fb^{-1}
- in the range **1-4%** with HL-LHC - 3000 fb^{-1}

B. Mele

NB: at LEP theory errors improved by factor 10 or more….

Some guidance from theorists:

New physics affects the Higgs couplings

SUSY $\frac{g_{hbb}}{g_{h_{SM}bb}} = \frac{g_{h\tau\tau}}{g_{h_{SM}\tau\tau}} \simeq 1 + 1.7\% \left(\frac{1\ \mathrm{TeV}}{m_A}\right)^2$, for tanβ = 5

Composite Higgs $\frac{g_{hff}}{g_{h_{SM}ff}} \simeq \frac{g_{hVV}}{g_{h_{SM}VV}} \simeq 1 - 3\% \left(\frac{1\ \mathrm{TeV}}{f}\right)^2$

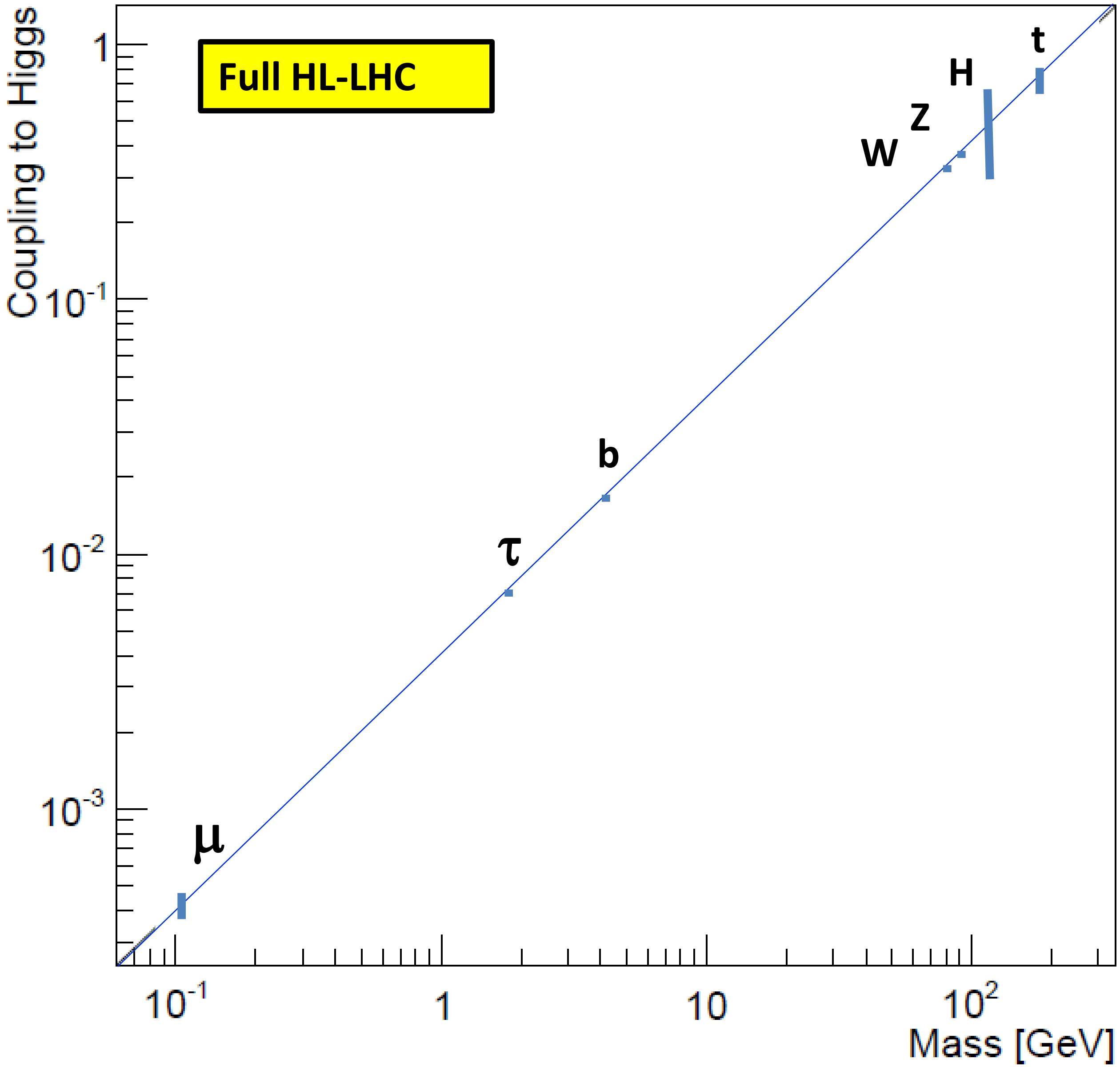
Top partners $\frac{g_{hgg}}{g_{h_{SM}gg}} \simeq 1 + 2.9\% \left(\frac{1\ \mathrm{TeV}}{m_T}\right)^2, \quad \frac{g_{h\gamma\gamma}}{g_{h_{SM}\gamma\gamma}} \simeq 1 - 0.8\% \left(\frac{1\ \mathrm{TeV}}{m_T}\right)^2$

Other models may give up to 5% deviations with respect to the Standard Model

Sensitivity to "TeV" new physics needs per-cent to sub-per-cent accuracy on couplings for 5 sigma discovery.

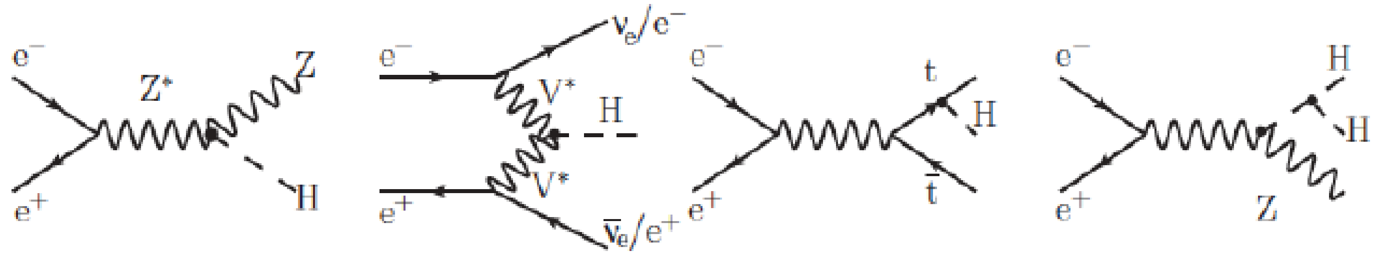
LHC discovery/(or not) at 13 TeV will be crucial to understand the strategy for future collider projects

R.S. Gupta, H. Rzehak, J.D. Wells, "How well do we need to measure Higgs boson couplings?", arXiv:1206.3560 (2012)
H. Baer et al., "Physics at the International Linear Collider", in preparation, http://lcsim.org/papers/DBDPhysics.pdf

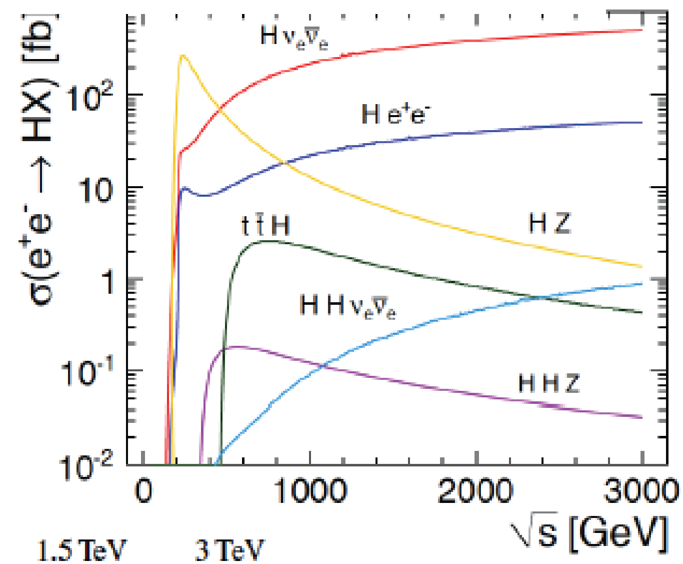

Full HL-LHC
Coupling to Higgs
1
10^{-1}
10^{-2}
10^{-3}
10^{-1}
1
10
10^{2}
Mass [GeV]
μ
τ
b
W
Z
H
t

Wyatt, Cracow

Higgs in e^+e^-



Many studies performed using full Geant-based MC

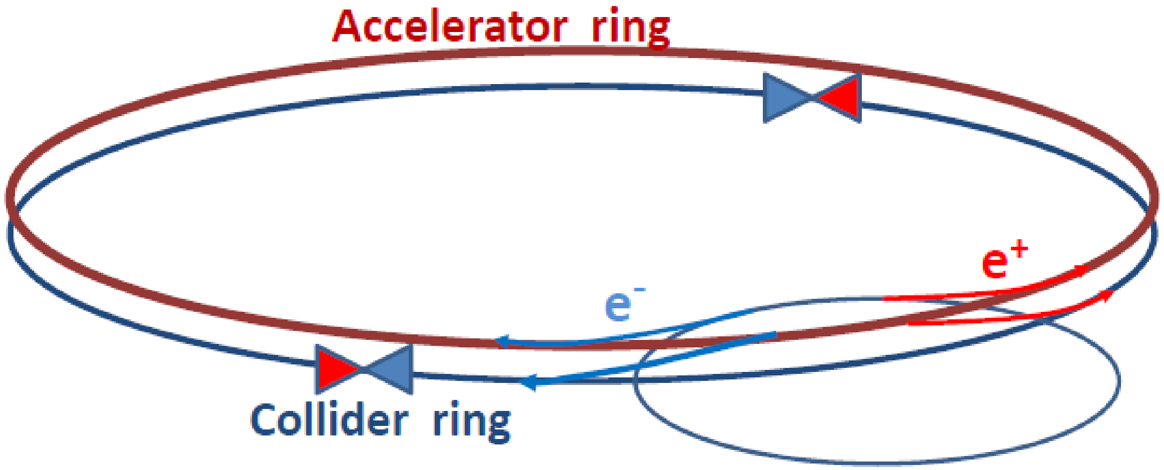


Integrated luminosity and numbers of events expected for initial 5 years running at each value of E_{cm}

ILC:

	250 GeV	350 GeV	500 GeV	1 TeV	1.5 TeV	3 TeV
$\sigma(e^+e^- \to ZH)$	240 fb	129 fb	57 fb	13 fb	6 fb	1 fb
$\sigma(e^+e^- \to H\nu_e\bar{\nu}_e)$	8 fb	30 fb	75 fb	210 fb	309 fb	484 fb
Int. $\mathcal{L}$	250 fb^{-1}	350 fb^{-1}	500 fb^{-1}	1000 fb^{-1}	1500 fb^{-1}	2000 fb^{-1}
# ZH events	60,000	45,500	28,500	13,000	7,500	2,000
# $H\nu_e\bar{\nu}_e$ events	2,000	10,500	37,500	210,000	460,000	970,000

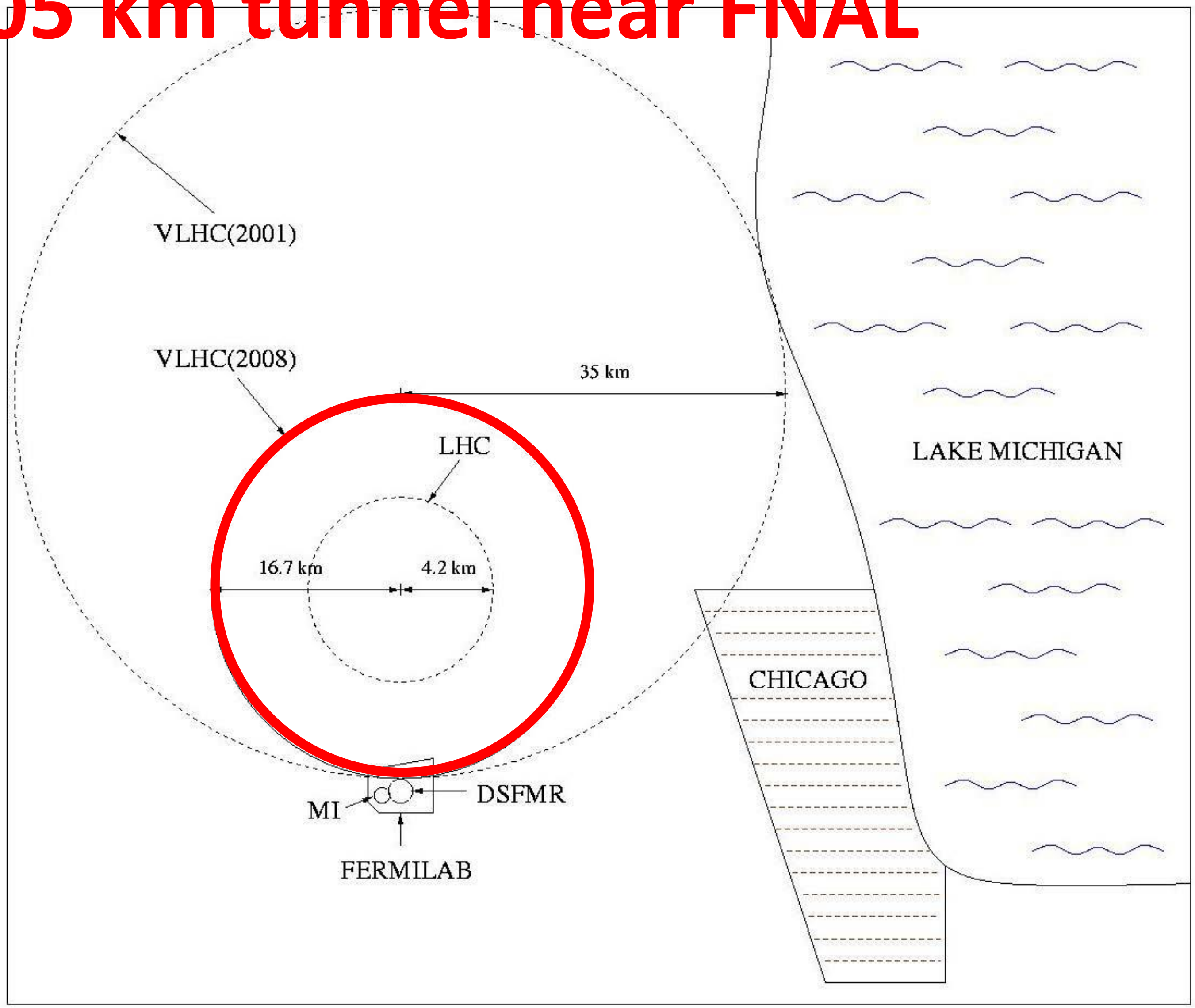
Circular e+e- colliders to study THE BOSON X(126)



a relatively young concept
(although there were many predecessors)

80 km ring in KEK area
12.7 km
KEK
Mt Tsukuba
筑波山
Tsutsujigaoka
つつじヶ丘
Miyawaki
宮脇
Mt Fuji
富士山
Ishioka
City Office
Makabe Branch
City Office
Chiyoda Branch
市役所千代田庁舎
City Office
Niihari Branch
Toyosato
Hospital
下館GC
丸山
足尾山
きのこ山
サミットGC
東筑波CC
フラワー
パーク
筑波国際CC
筑波東急GC
千代田PA
Map data ©2012 Google, ZENRIN

105 km tunnel near FNAL

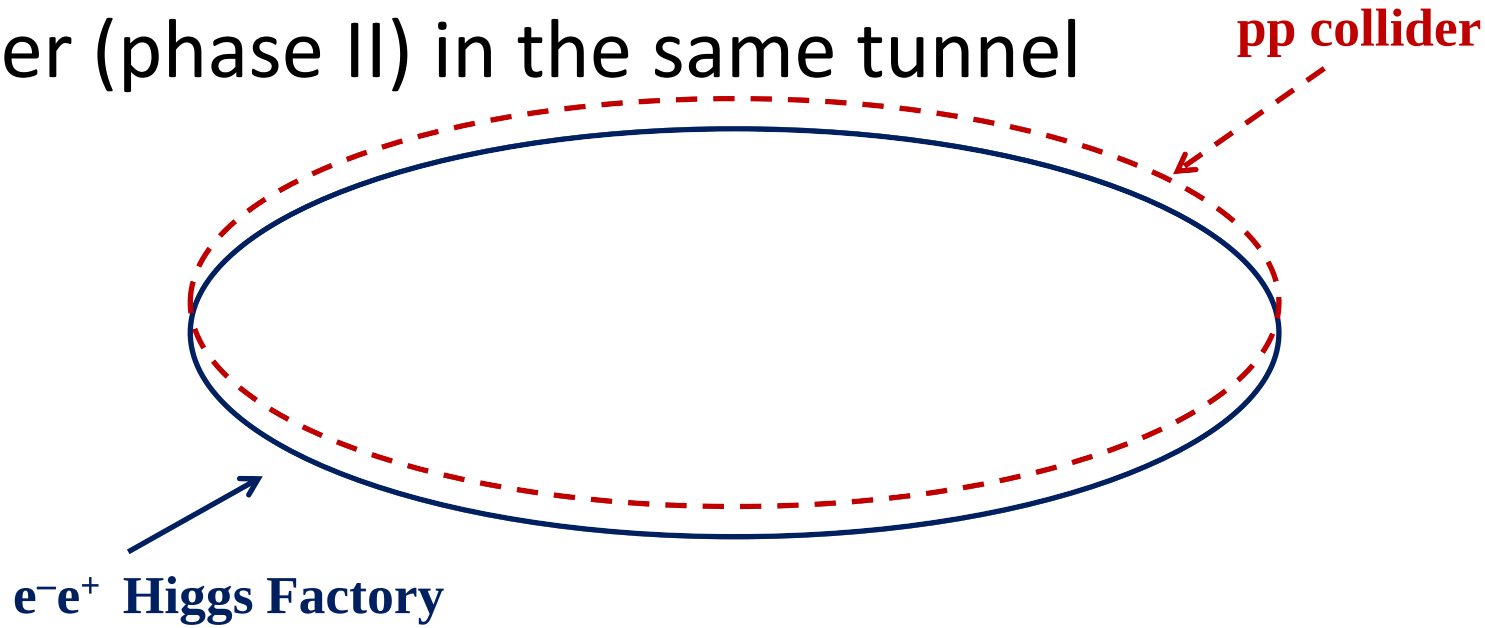


(+ FNAL plan B from R. Talman)

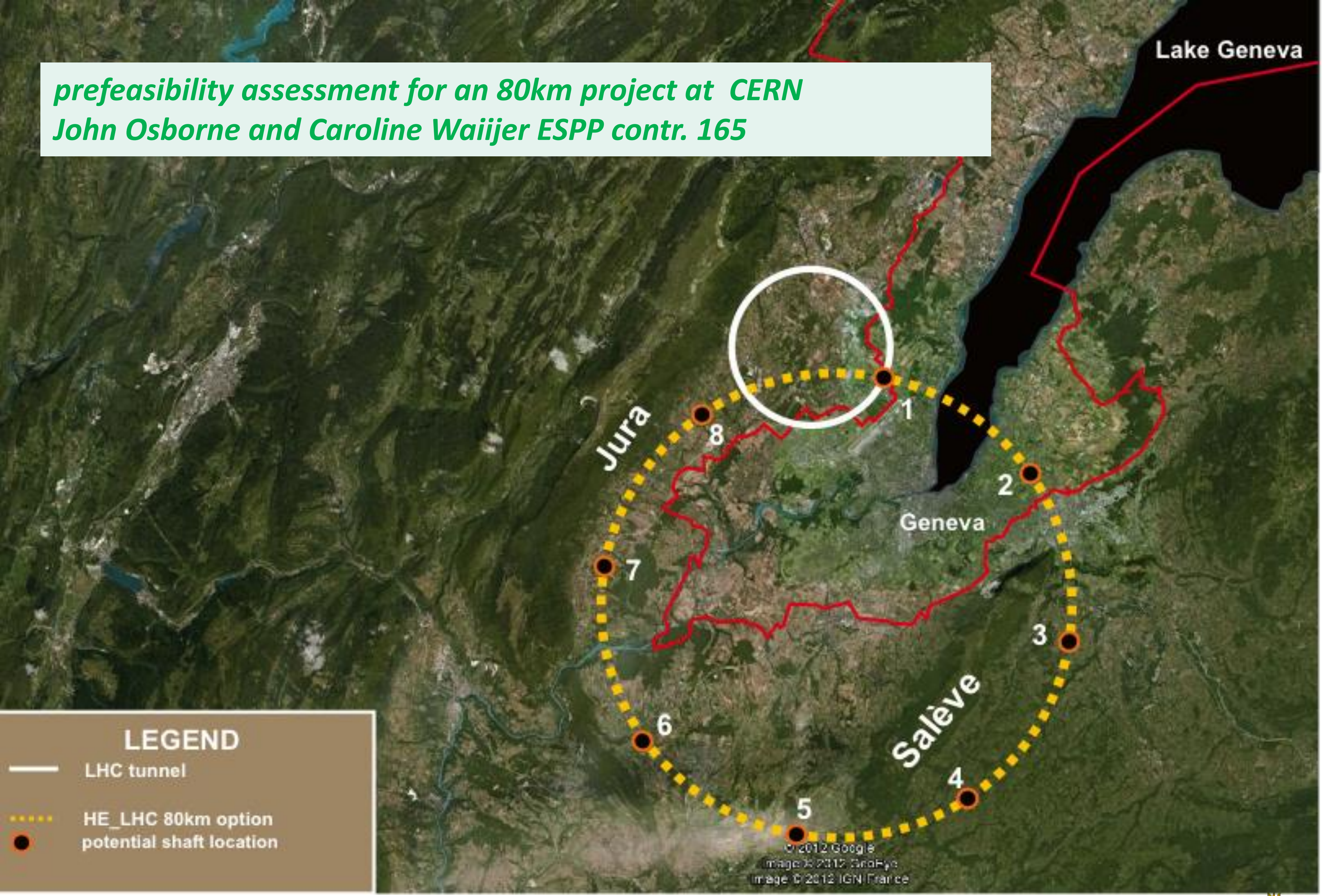
H. Piekarz, "… and … **path to the future of high energy particle physics**," JINST 4, P08007 (2009)

What is a (CHF + SppC)

Circular Higgs factory (phase I) + super pp collider (phase II) in the same tunnel



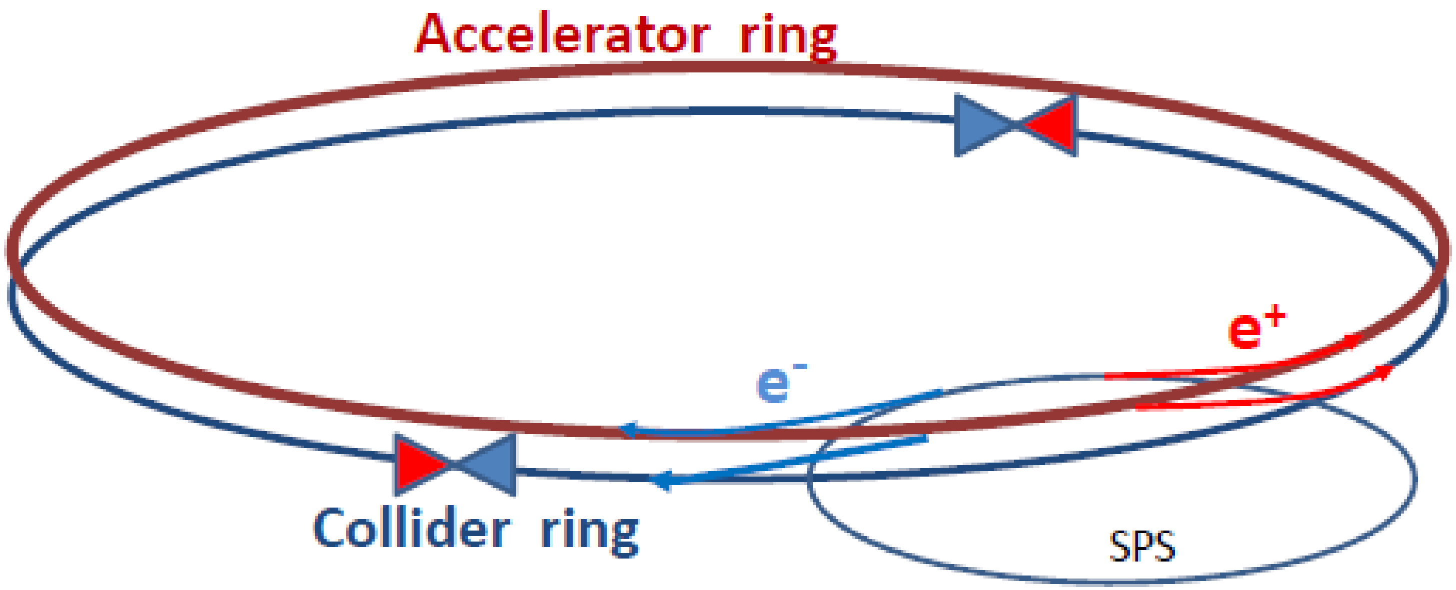
prefeasibility assessment for an 80km project at CERN
John Osborne and Caroline Waiijer ESPP contr. 165



How can one increase over LEP 2 (average) luminosity by a factor 500 without exploding the power bill?

Answer is in the B-factory design: a very low vertical emittance ring with higher intrinsic luminosity and a small value of β_y*

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



Storage ring has separate beam pipes for e+ and e- for multibunch operation

circular e^+e^- Higgs factories LEP3 & TLEP

option 1: installation in the LHC tunnel **"LEP3"**

- **+ inexpensive (only pay for new accelerator -- <~2B CHF)**
- **+ tunnel exists**
- **+ reusing ATLAS and CMS detectors**
- **+ reusing LHC cryoplants**
- **- interference with LHC and HL-LHC**

option 2: in new 80-km tunnel **"TLEP"**

- **+ higher energy reach, 5-10x higher luminosity**
- **+ decoupled from LHC/HL-LHC operation & construction**
- **+ tunnel can later serve for VHE-LHC 100 TeV machine long term vision**
- **- more expensive because of tunnel**

LEP3, TLEP

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

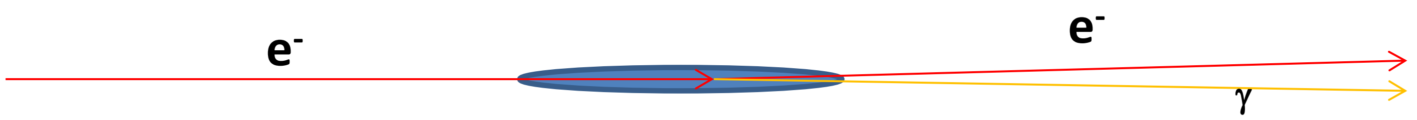
key parameters

	LEP3	TLEP
circumference	26.7 km	80 km
max beam energy	120 GeV	175 GeV
max no. of IPs	4	4
Luminosity/IP at 350 GeV c.m.	-	1.3×10^{34} cm^{-2}s^{-1}
Luminosity/IP at 240 GeV c.m.	**2-8 times ILC lumi at ZH thresh.**	**10-40 times ILC lumi at ZH thresh.**
Luminosity/IP at 160 GeV c.m.		
Luminosity/IP at 90 GeV c.m.		

at the *Z* pole repeat the LEP physics programme in a few minutes…

Luminosity estimates, limitations … and solutions

Going to higher intensities and small bunch length leads to higher beamstrahlung (beam particles radiate energy in the EM field of the colliding bunch)



This is well known for linear colliders where it limits the resolution and precision in center-of mass energy

Here it causes loss of beam particles which lose more than a certain momentum acceptance and reduces the beam lifetime. ***(Telnov)***

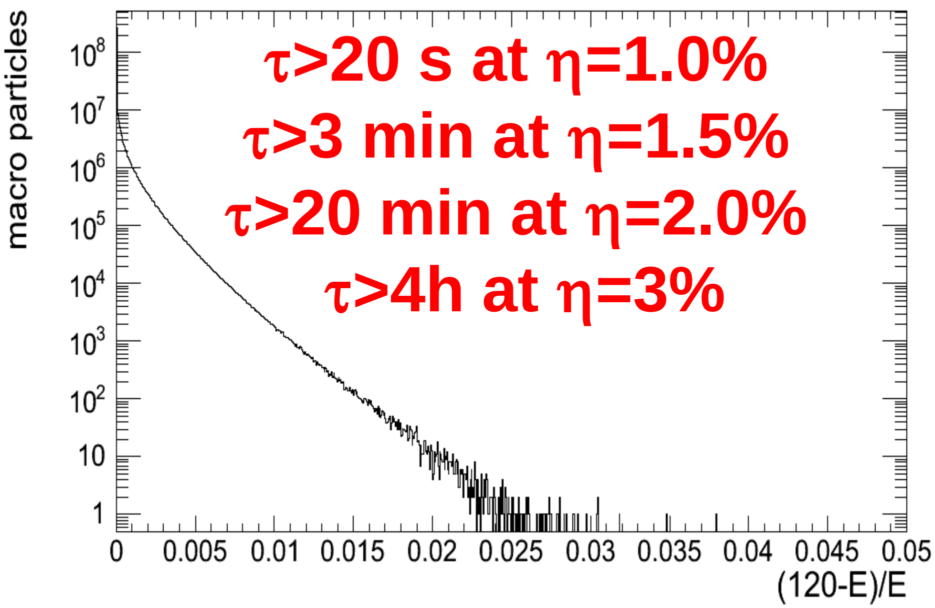
To keep the beams colliding 12000 times per second (in TLEP with 4 IP) for 100 seconds one needs to lose less than 10^{-6} particle per collision.

In a circular machine, the energy spread is increased by ~30% of a few permil and the central energy is essentially unchanged.

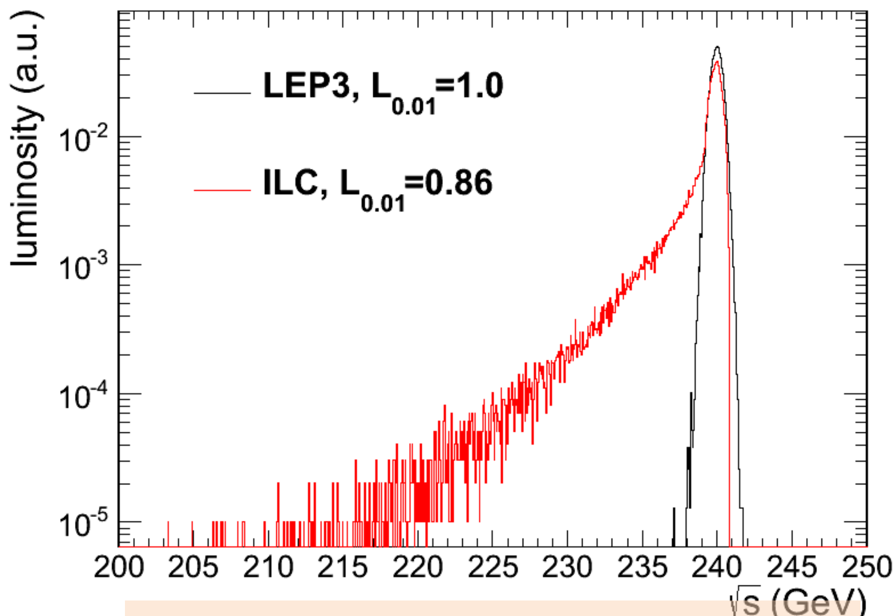
Ring HFs – beamstrahlung

- simulation w 360M macroparticles (guinea-pig)
- τ varies exponentially with momentum acceptance η

TLEP at 240 GeV post-collision
***E* tail → lifetime τ**



luminosity *E* spectrum



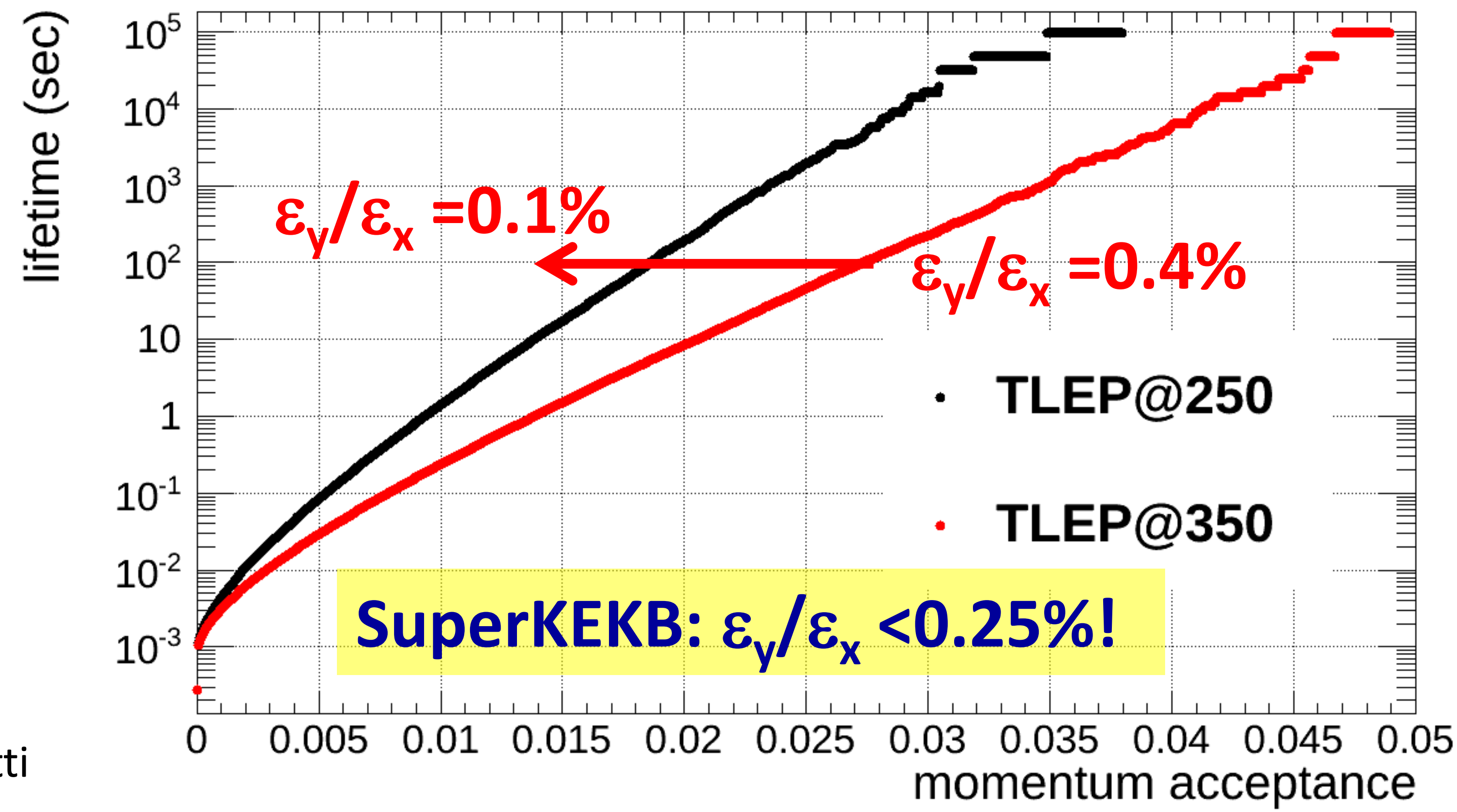
R-HF beamstrahlung more benign than for linear collider

M. Zanetti (MIT)

beamstrahlung lifetime

- simulation w 360M macroparticles
- τ varies exponentially w energy acceptance η
- post-collision *E* tail → lifetime τ

beam lifetime versus acceptance δ_{max} for 4 IPs:



M. Zanetti

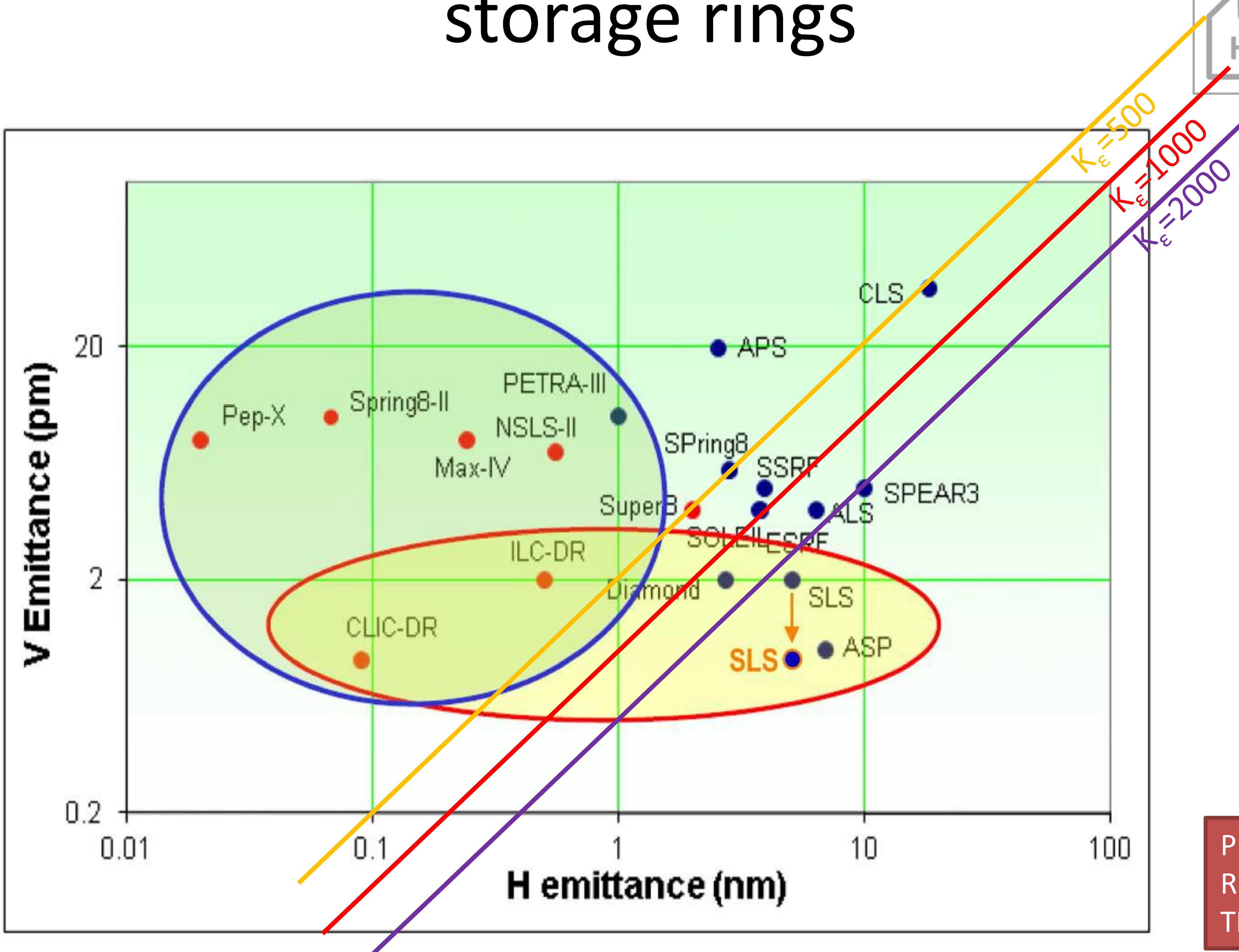
Luminosity estimates, limitations … and solutions

Just like in the LC the mitigation of beamstrahling is to increase the horizontal beam size while keeping a constant beam area
➔ increase ratio of emittances $\varepsilon_x / \varepsilon_y$ ➔flat beams!

parameter	LEP2	Ring Higgs Factory @240 GeV		
β_y^*	5cm	1mm		
RF frequency	352MHz	~700 MHz		
Energy loss per turn	3 GeV	2 (TLEP) -7 (LEP3) GeV		
Beam lifetime from Bhabha scattering	6hrs	16 min		
Emittance ratio $\varepsilon_x / \varepsilon_y$	**200**	**200**	**400**	**800**
Beamstrahlung life time	Very long	100s	100s	100s
Required Momentum Acceptance	uncritical	4% **difficult**	2.7% ~OK	1.9% **good☺**

← Fix this For good performance

Existing (blue) and future (red) storage rings



Plot from L. Rivkin, 2nd TLEP3 day

Conclusions on beamstrahlung and luminosity

The effect must be understood by analytical calculations (Telnov) as well as simulations (Zanetti).

We have now a consistent set of parameters achieving 2 10^{35}/cm^2/s @240 GeV

Improvement in the emittance ratio w.r.t. LEP2 desirable from about 250 up to >500 .. Set aim at 1000.

Synchrotron light sources (Diamond, SLS) routinely achieve ratio better than 1000

Topping up is key to success:
at LEP optics corrections had to be repeated at each fill.

➔ Smart orbit corrections (y and D_y corrections, coupling etc..) have to be included at design level

NB: Chinese colleagues are working on designing optics with larger mom. acceptance. (Wang et al., IPAC'13)

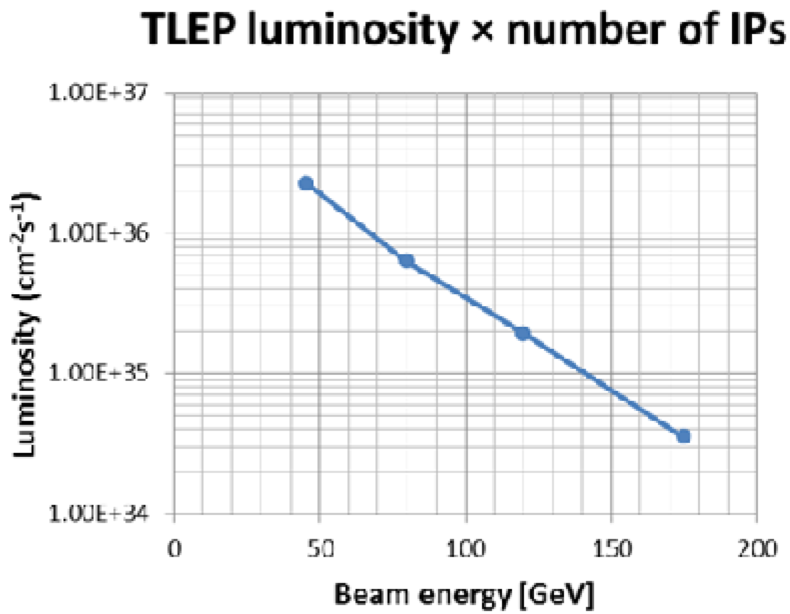
TLEP: A HIGH-PERFORMANCE CIRCULAR e^+e^- COLLIDER TO STUDY THE HIGGS BOSON

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



Note: we consistently use 4 IPs as this is the least extrap from LEP2
It is expected that luminosity grows like sqrt(N_{IP})

So total luminosity for a machine with 2 IP should be

$$\mathcal{L}(2.IP) = \mathcal{L}(4.IP)/\text{sqrt}(2)$$

This will need to be verified by proper simulation.

Full facility power consumption (except detectors)

Table 2: Preliminary RF power consumption

	TLEP 120	TLEP 175
RF systems	173-185 MW	
cryogenics	10 MW	34 MW
top-up ring	3 MW	5 MW
Total RF	186-198 MW	212-224 MW

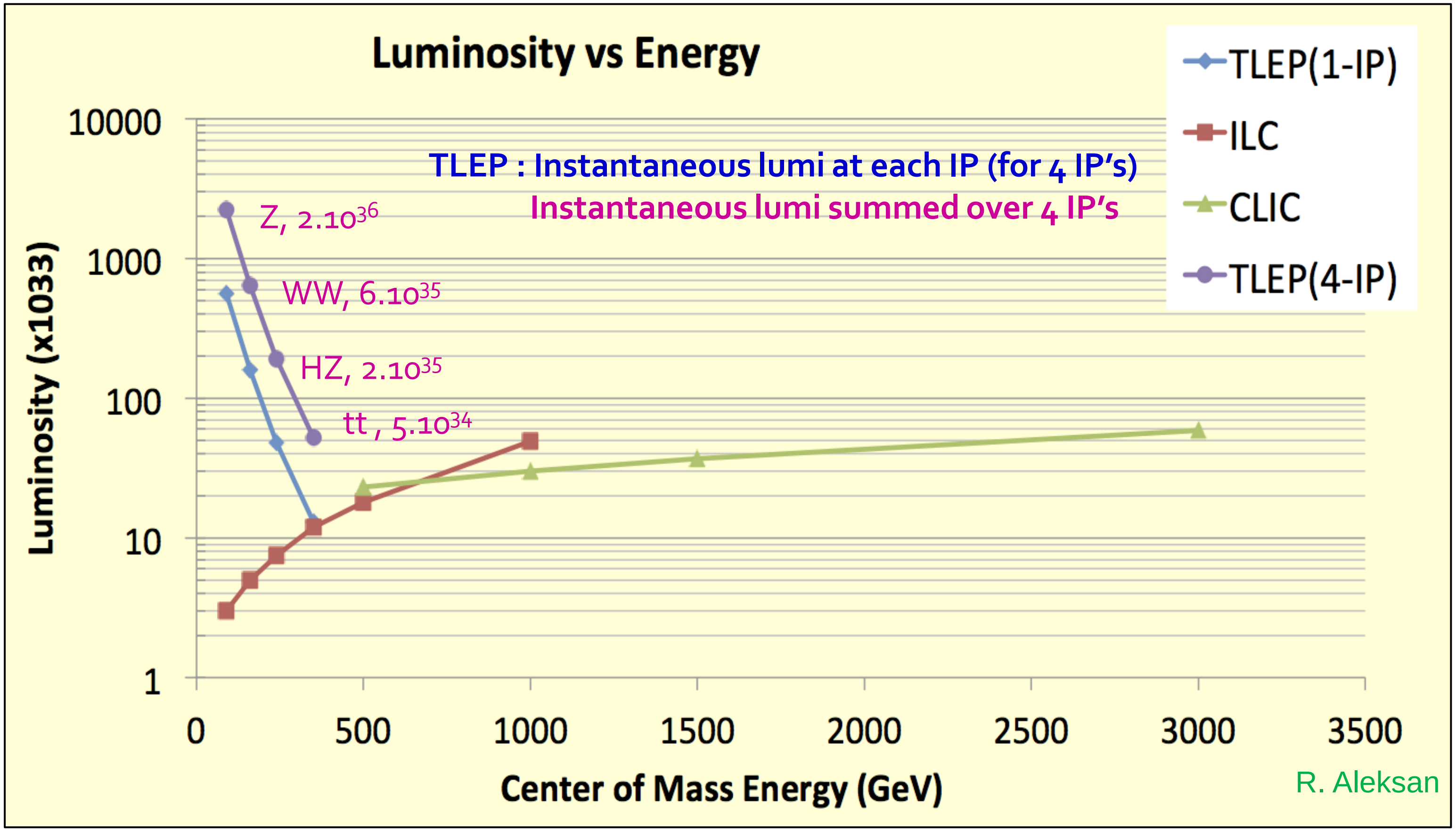
Table 3: Preliminary TLEP power consumption at 175 GeV

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

Notes: 1. In a circular machine the RF is operated in standing wave (CW)
this is more efficient (55-60%) than pulsed mode
2. The RF power system is the main cost
this is independent on the size of the ring
➔ Except for the tunnel, all ring machines have similar costs!
3. total power consemption <300 MW (or other value)
is design parameter

Performance of e+ e- colliders

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



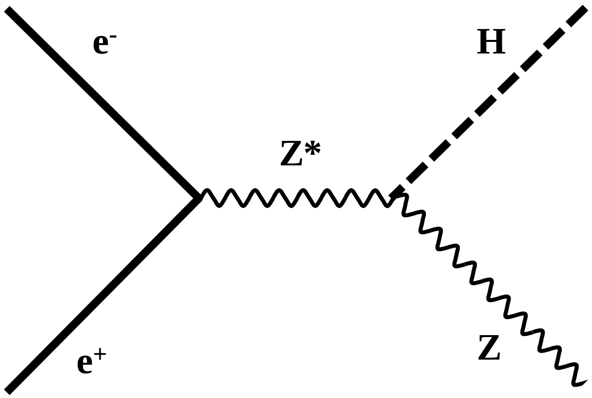
- Lumi upgrade (×3) now envisioned at ILC : luminosity is the key at low energy!
- Crossing point between circular and linear colliders ~ 400 GeV
- With fewer IP's expect luminosity of facility to scale approx as $(N_{IP})^{0.5-1}$

Higgs Production Mechanism in e+ e- collisions

For a light Higgs it is produced by the “higgstrahlung” process close to threshold

Production xsection has a maximum at near threshold ~200 fb

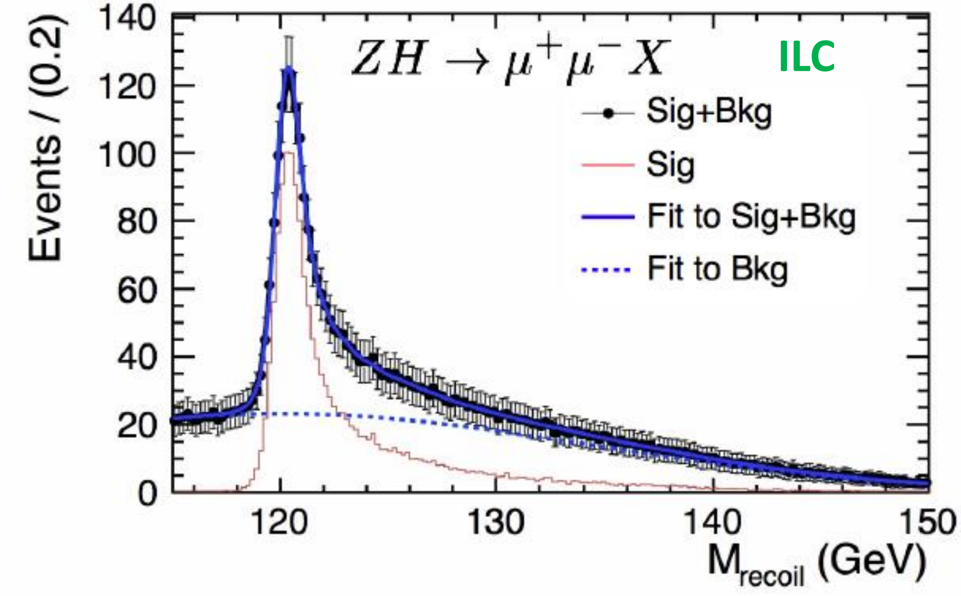
$10^{34}/cm^2/s$ ➔ 20’000 HZ events per year.



Z – tagging

by missing mass

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



Z – tagging by missing mass

total rate $\propto g_{HZZ}^2$

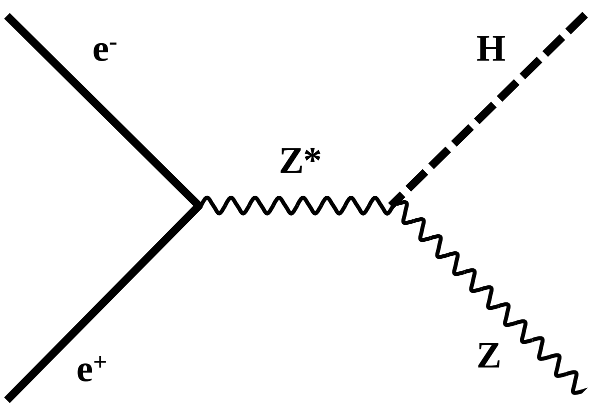
ZZZ final state $\propto g_{HZZ}^4 / \Gamma_H$

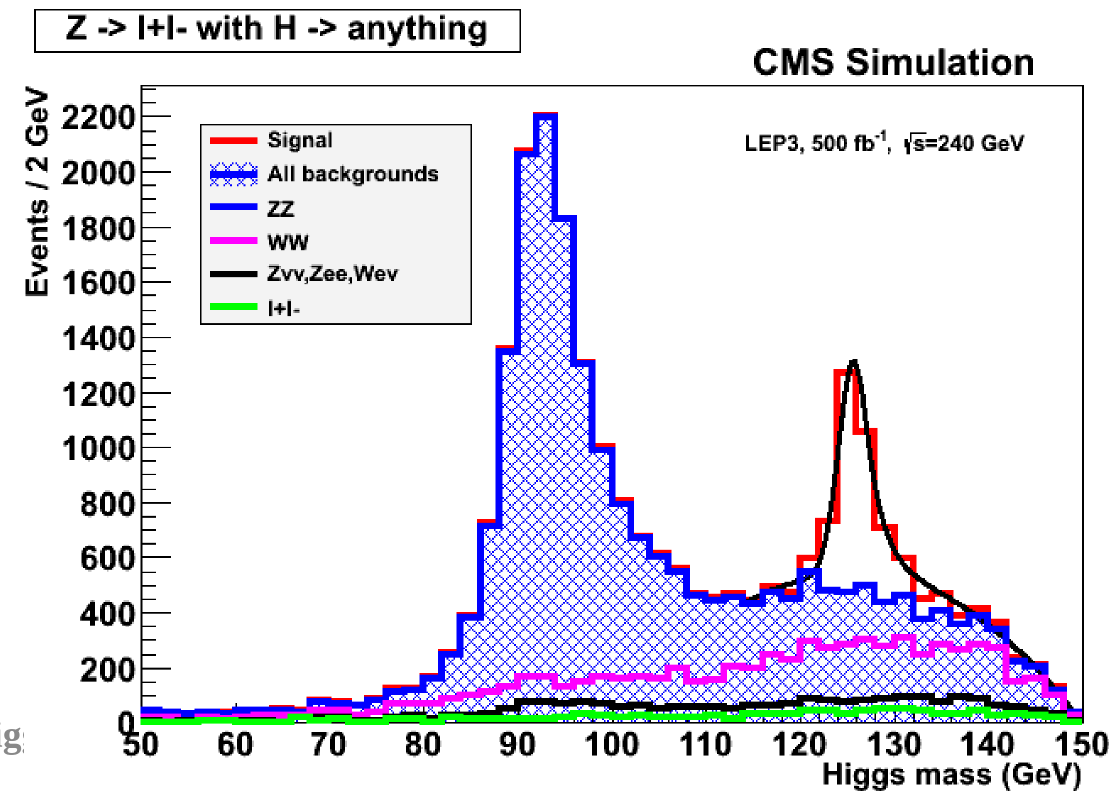
➔ measure total width Γ_H

empty recoil = invisible width

'funny recoil' = exotic Higgs decay

easy control below theshold





Higgs Physics with e^+e^- colliders above 350 GeV

1. Similar precisions to the 250/350 GeV Higgs factory for W,Z,b,g,tau,charm, gamma and total width. Invisible width best done at 240-250.

2. ttH coupling possible with similar precision as HL-LHC (4%)

3. Higgs self coupling also very difficult… precision

   30% at 1 TeV similar to HL-LHC prelim. estimates

   10-20% at 3 TeV (CLIC)

   ➔ percent-level precision might need to wait for a 100 TeV machine

➔ **<u>For the study of H(126) alone</u>, and given the existence of HL-LHC, an e+e- collider with energy above 350 GeV is not compelling w.r.t. one working in the 240 GeV – 350 geV energy range.**

➔ **The stronger motivation for a high energy e+e- collider will exist if new particle found (or inferrred) at LHC, *for which e+e- collisions would bring substantial new information***

Higgs factory performances

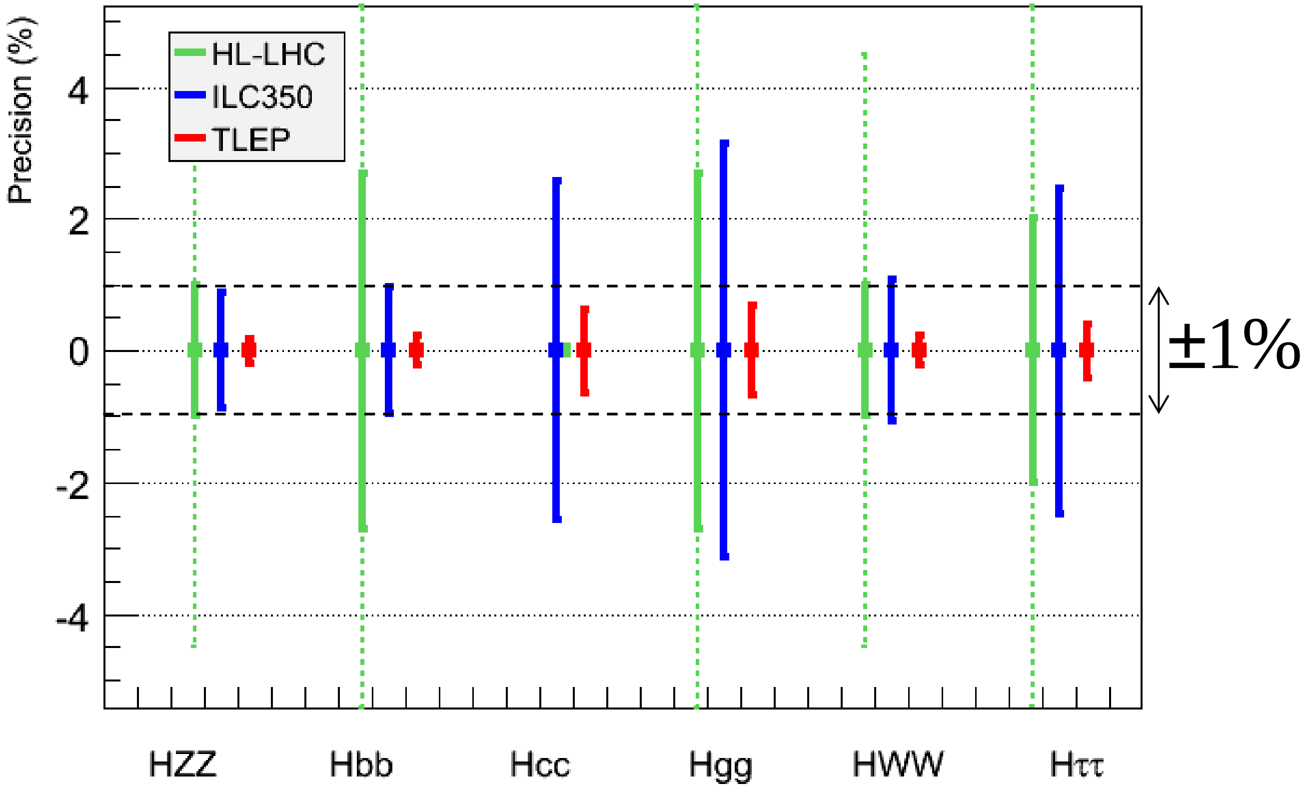
Precision on couplings, cross sections, mass, width, Summary of the ICFA HF2012 workshop (FNAL, Nov. 2012) arxiv1302:3318

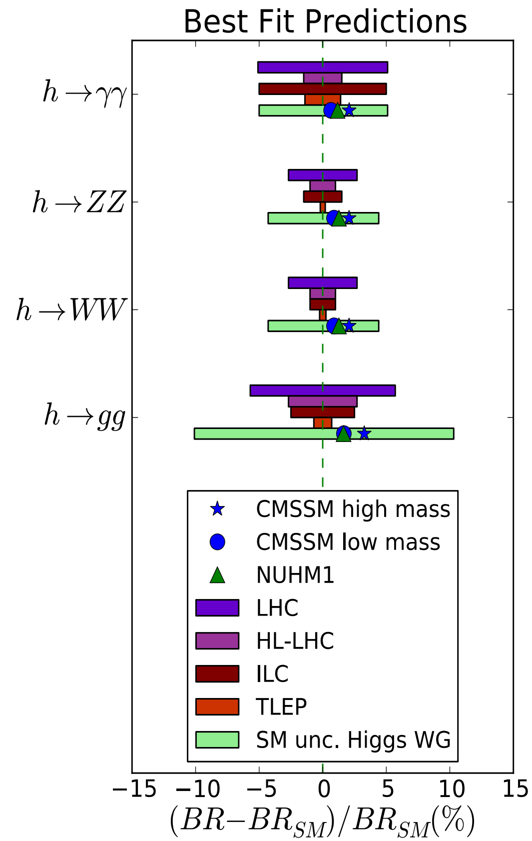
Table 2.1: Expected performance on the Higgs boson couplings from the LHC and e^+e^- colliders, as compiled from the Higgs Factory 2012 workshop. Many studies are quite recent and still ongoing.

Accelerator → Physical Quantity ↓	**LHC** 300 fb^{-1} /expt	**HL-LHC** 3000 fb^{-1} /expt	**ILC** 250 GeV 250 fb^{-1} 5 yrs	**Full ILC** 250+350+ 1000 GeV 5yrs each	**CLIC** 350 GeV (500 fb^{-1}) 1.4 TeV (1.5 ab^{-1}) 5 yrs each	**LEP3, 4 IP** 240 GeV 2 ab^{-1} (*) 5 yrs	**TLEP, 4 IP** 240 GeV 10 ab^{-1} 5 yrs (*) 350 GeV 1.4 ab^{-1} 5 yrs (*)
N_H	1.7×10^7	1.7×10^8	6×10^4 ZH	10^5 ZH 1.4×10^5 Hνν	7.5×10^4 ZH 4.7×10^5 Hνν	4×10^5 ZH	2×10^6 ZH 3.5×10^4 Hνν
m_H (MeV)	100	50	35	35	100	26	7
$\Delta\Gamma_H / \Gamma_H$	--	--	10%	3%	ongoing	4%	1.3%
$\Delta\Gamma_{inv} / \Gamma_H$	Indirect (30%?)	Indirect (10% ?)	1.5%	1.0%	ongoing	0.35%	0.15%
$\Delta g_{H\gamma\gamma} / g_{H\gamma\gamma}$	6.5 – 5.1%	5.4 – 1.5%	--	5%	ongoing	3.4%	1.4%
$\Delta g_{Hgg} / g_{Hgg}$	11 – 5.7%	7.5 – 2.7%	4.5%	2.5%	< 3%	2.2%	0.7%
$\Delta g_{Hww} / g_{Hww}$	5.7 – 2.7%	4.5 – 1.0%	4.3%	1%	~1%	1.5%	0.25%
$\Delta g_{HZZ} / g_{HZZ}$	5.7 – 2.7%	4.5 – 1.0%	1.3%	1.5%	~1%	0.65%	0.2%
$\Delta g_{HHH} / g_{HHH}$	--	< 30% (2 expts)	--	~30%	~22% (~11% at 3 TeV)	--	--
$\Delta g_{H\mu\mu} / g_{H\mu\mu}$	< 30%	< 10%	--	--	10%	14%	7%
$\Delta g_{H\tau\tau} / g_{H\tau\tau}$	8.5 – 5.1%	5.4 – 2.0%	3.5%	2.5%	≤ 3%	1.5%	0.4%
$\Delta g_{Hcc} / g_{Hcc}$	--	--	3.7%	2%	2%	2.0%	0.65%
$\Delta g_{Hbb} / g_{Hbb}$	15 – 6.9%	11 —2.7%	1.4%	1%	1%	0.7%	0.22%
$\Delta g_{Htt} / g_{Htt}$	14 – 8.7%	8.0 – 3.9%	--	5%	3%	--	30%

(*) The total luminosity is the sum of the integrated luminosity a

Circular Higgs Factory really goes to precision at few permil level.





Progress on the theoretical side also needed

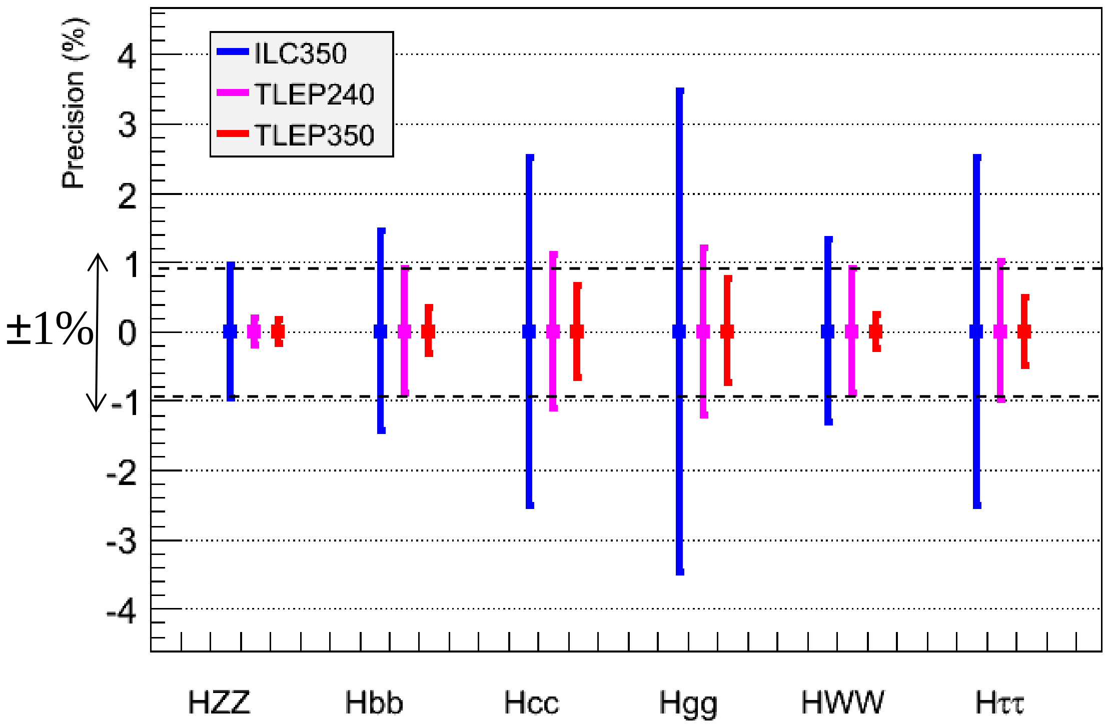
J. Ellis et al.

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

Performance Comparison

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

- Same conclusion when Γ_H is a free parameter in the fit



Expected precision on the total width

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

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

TERA-Z and Oku-W

Precision tests of the closure of the Standard Model

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

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

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

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

$\sin^2\theta_W^{eff}$ 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

TLEP

ZZZZZZZZ

Example (from Langacker& Erler PDG 2011)

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

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

From the EW fit

$\Delta\rho$ = 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).

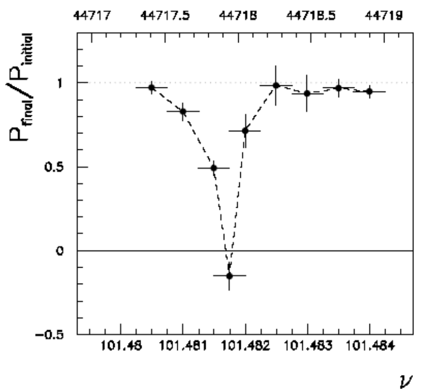
Present measurement implies

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

Similarly:

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

Beam polarization in Ring HF



Beam polarization is a crucial tool for precise measurement of the beam energy by resonant depolarization (~100 keV)

At LEP transverse polarization was achieved routinely at the Z peak and was intrumental in the 10^{-3} measurement of the Z width which led to the prediction of the top quark mass (179+- 20 GeV) for winter conf. 1994.

Polarization in beam collisions was observed only once (40% at BBTS = 0.04)

At high energy it was destroyed by the beam energy spread above 60 GeV
At TLEP (because radius is larger) this corresponcds to availability of transverse polarization for 80 GeV beams
We plan to use 'single' bunches (non-interacting) to measure the beam energy continuously and eliminate interpolation between measurements

➔ 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

EXPERIMENTS ON BEAM-BEAM DEPOLARIZATION AT LEP

R. Assmann*, A. Blondel*, B. Dehning, A. Drees°, P. Grosse-Wiesmann, H. Grote, M. Placidi, R. Schmidt, F. Tecker†, J. Wenninger

PAC 1995

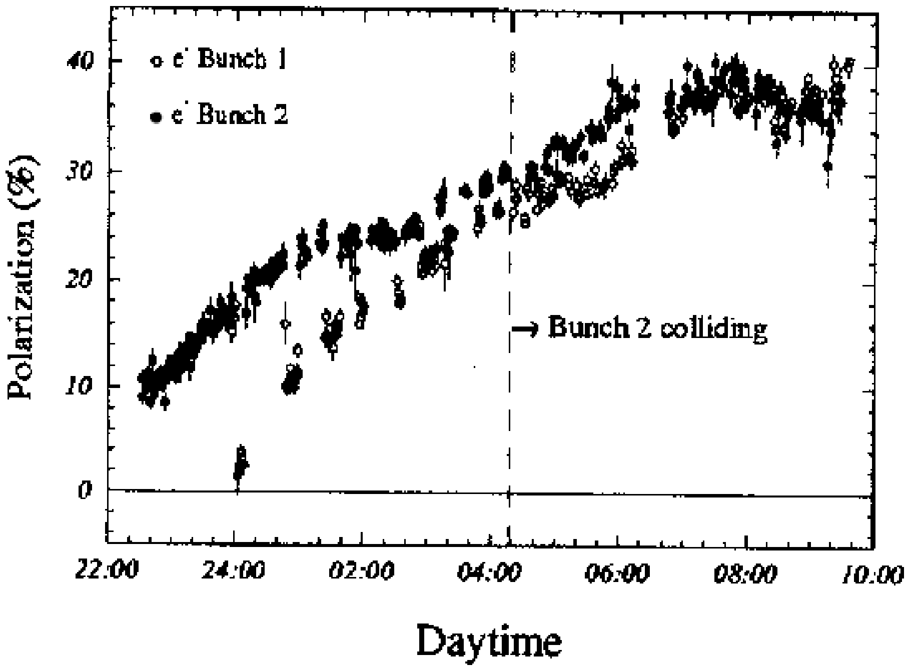


Figure. 3. Polarization level during third experiment

- With the beam colliding at one point, a polarization level of 40 % was achieved. The polarization level was about the same for one colliding and one non colliding bunch.
- It was observed that the polarization level depends critically on the synchrotron tune : when Q_s was changed by 0.005, the polarization strongly decreased.

experiment performed at an energy of 44.71 GeV the polarization level was 40 % with a linear beam-beam tune shift of about 0.04/IP. This indicates, that the beam-beam depolarization does not scale with the linear beam-beam tune shift at one crossing point. Other parameters as spin tune and synchrotron tune are also of importance.

This was only ever tried 3 times!
Best result: P = 40% , ξ^*_y= 0.04 , one IP
Assuming 4 IP and ξ^*_y= 0.01 ➔

reduce luminositiy x 10 still, 10^{11} Z @ P=40%

Measurement of A_{LR}

electron bunches	1⇐	2	3	4⇐
positron bunches	1	2⇒	3	4⇒
cross sections	σ_1	σ_2	σ_3	σ_4
event numbers	N_1	N_2	N_3	N_4

$$\sigma_1 = \sigma_u (1 - P^-_e A_{LR})$$

$$\sigma_2 = \sigma_u (1 + P^+_e A_{LR})$$

$$\sigma_3 = \sigma_u$$

$$\sigma_4 = \sigma_u [1 - P^+_e P^-_e + (P^+_e - P^-_e) A_{LR}]$$

Verifies polarimeter with experimentally measured cross-section ratios

statistics

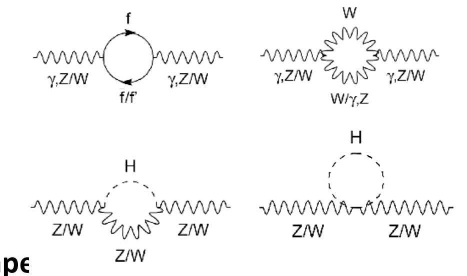
ΔA_{LR} = 0.0025 with about 10^6 Z^0 events,

ΔA_{LR} = 0.000015 with 10^{11} Z and 40% polarization in collisions.

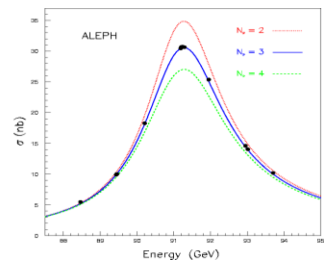
$\Delta \sin^2\theta_W^{eff}$ (stat) = O(2.10^{-6})

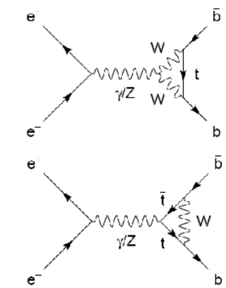
Precision tests of EWSB

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

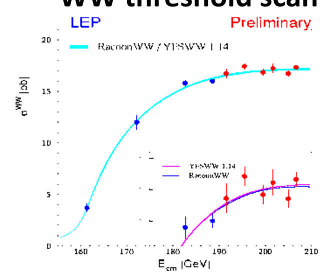


Asymmetries, Lineshape

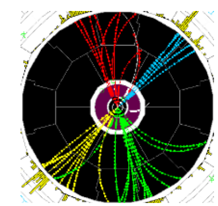




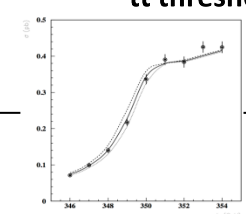
WW threshold scan

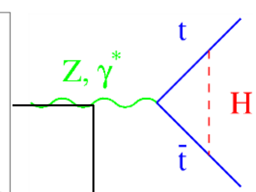


WW production



$t\bar{t}$ threshold scan





TLEP : Repeat the LEP1 physics programme every 15 mn

Transverse polarization up to the WW threshold

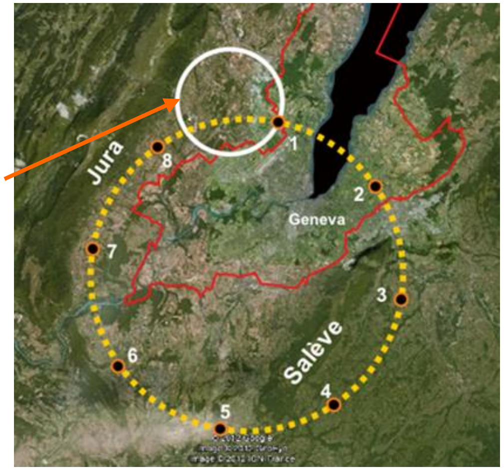
- **Exquisite beam energy determination (10 keV)**

Longitudinal polarization at the Z pole

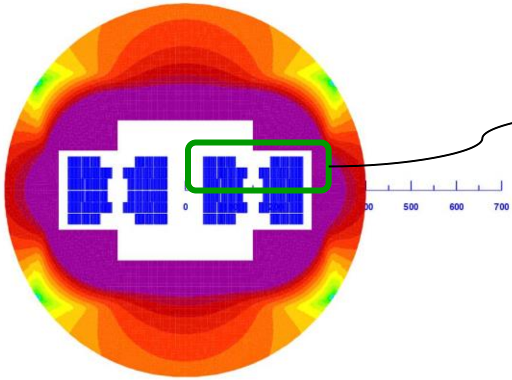
- **Measure $\sin^2\theta_W$ to 2.10^{-6} from A_{LR}**
- **Statistics, statistics …**

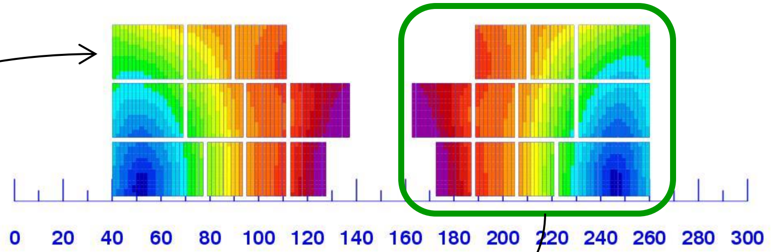
The Next-to-Next Facility

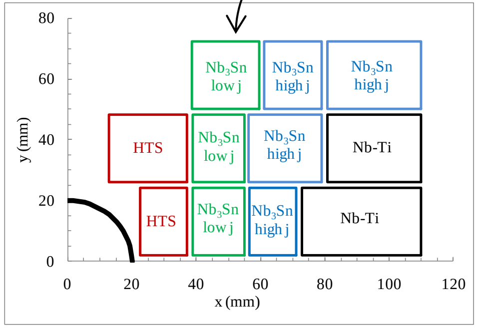
- TLEP can be upgraded to VHE-LHC
  - Re-use the 80 km tunnel to reach 80-100 TeV pp collisions
  - Need to develop 16-20 T SC magnets
    - Needs R&D and time (TLEP won't delay VHE-LHC)
  - Early conceptual design
    - Using multiple SC materials



L. Rossi





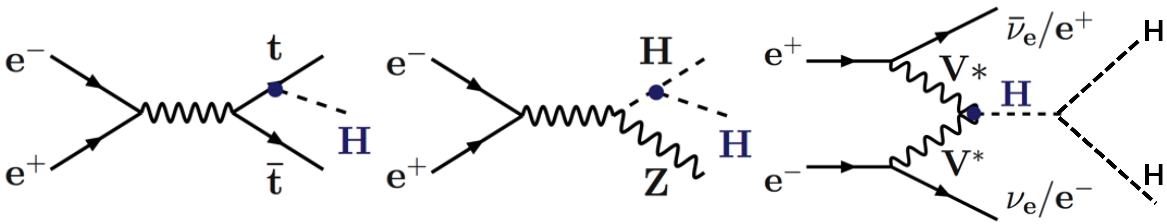


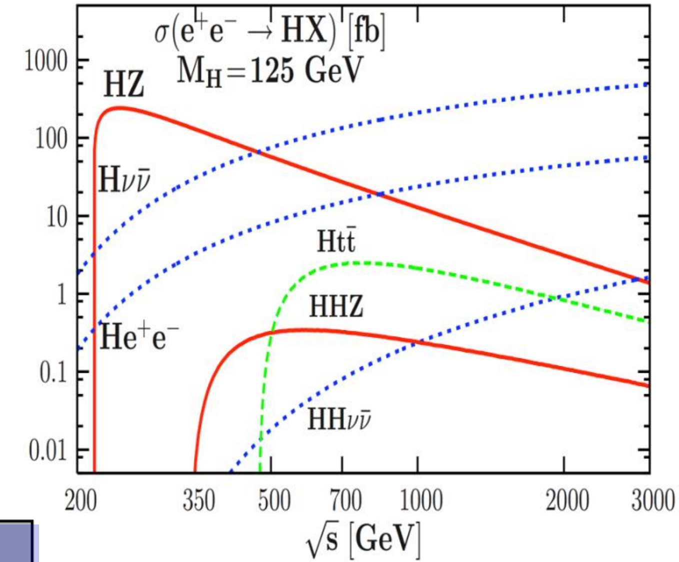
Material	N. turns	Coil fraction	Peak field	$J_{overall}$ (A/mm^2)
Nb-Ti	41	27%	8	380
Nb3Sn (high Jc)	55	37%	13	380
Nb3Sn (Low Jc)	30	20%	15	190
HTS	24	16%	20.5	380

20 T field!

The Next-to-Next Facility

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



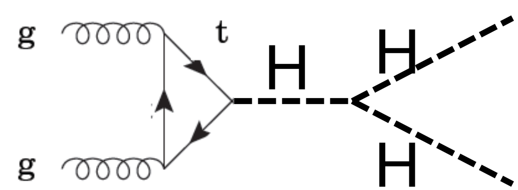


    - **In pp collisions**

M. Mangano

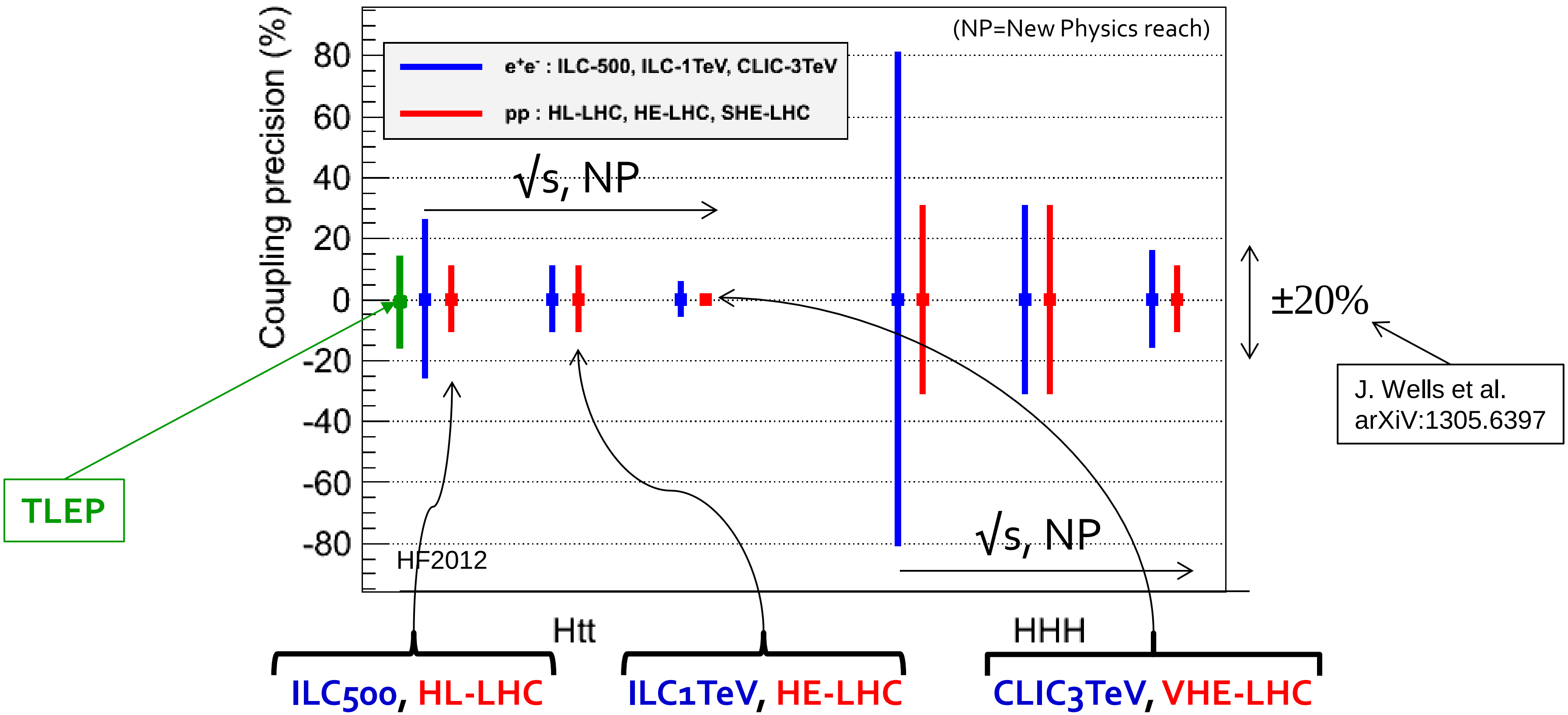
HE-LHC | VHE-LHC

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



The Next-to-Next Facility

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



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

At the moment we do not know for sure what is the most sensible scenario

LHC offered 3 possible scenarios: (could not lose)

Discover that there is nothing in this energy range.

➔ This would have been a great surprise and a **great discovery!**

NO

Discover SM Higgs Boson and that nothing else is within reach

➔ Most Standard scenario **great discovery!**

Discover many new effects or particles **great discovery!**

So far we are here

But….

Keep looking in 13/14 TeV data!

Also: understand scaling of LHC errors with luminosity

Answer in 2018

High precision

High energy

BE PREPARED!

Recommendation from European Strategy (2)

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

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

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

Design Study is now starting !

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

and suscribe for work, informations, newsletter

Global collaboration: collaborators from Europe, US, Japan, China →

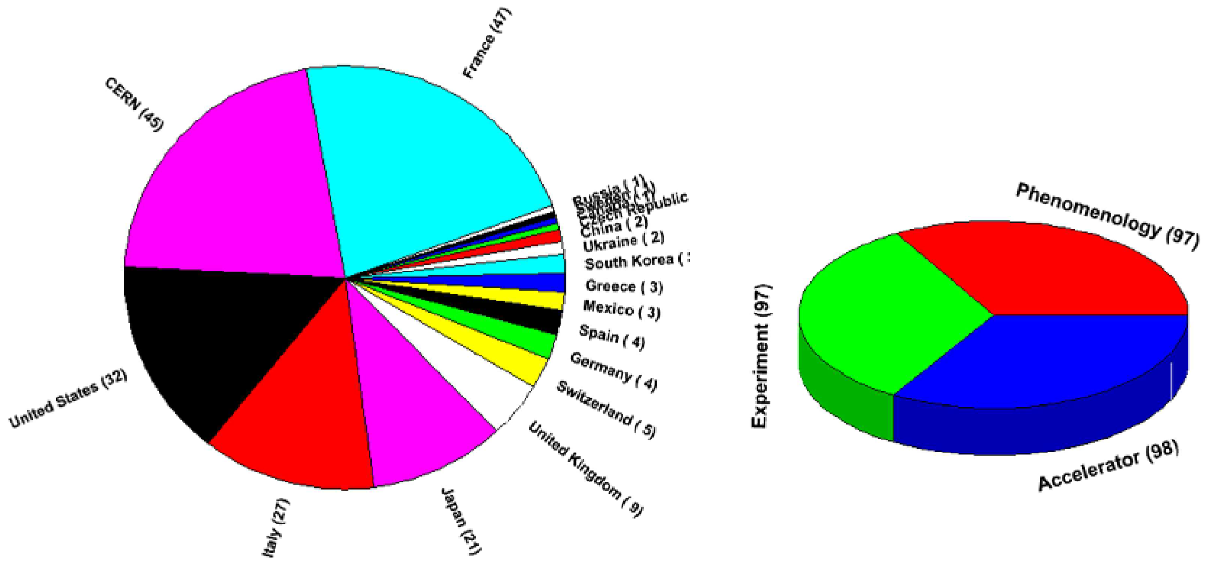
Next events: TLEP workshops 25-26 July 2013, Fermilab

16-18 October, CERN

Joint VHE-LHC+ TLEP kick-off meeting in February 2014

The first 200 subscribers:

Some interesting statistics can be found below. More details can be found on the TLEP web site.



Janot

Figure 1 Left : distribution of the first 200 subscribers on the basis of the institute's country. Right: distribution between accelerator, experiment and phenomenology.

The distribution of the country of origin reflects the youth of the TLEP project and the very different levels of awareness in the different countries.

The audience is remarkably well balanced between Accelerator, Experiment, and Phenomenology -- the agreement with the three colour model is too good to be a statistical fluctuation!

Conveners at interim.

TLEP design study –preliminary structure for discussion

Institutional board — **Steering group**: web site, mailing lists, speakers board, etc.. — **International Advisory board**

Accelerator — Zimmermann

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

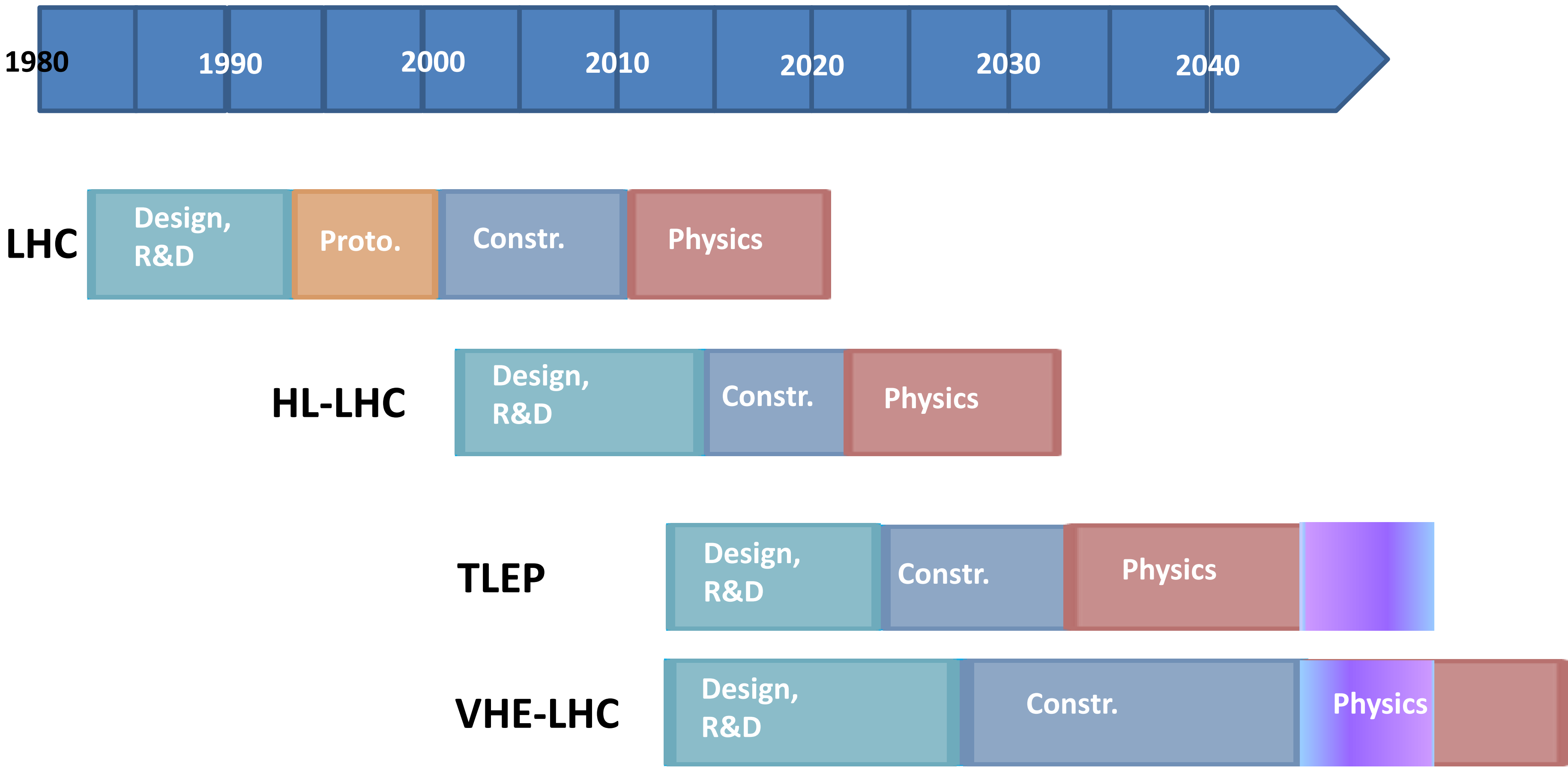
Experiments — Janot

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 — Janot

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

tentative time line



Conclusions

- **Discovery of H(126) focuses studies of the next machine**
  - News ideas emerging for Higgs factories and beyond
    - Prospects for the future look very promising
    - *The HL-LHC is already an impressive Higgs Factory*

- **It is important to choose the right machine for the future**
  - Cannot afford to be wrong for 10 billion CHF !
  - -- Must bring order of magnitude improvement wrt LHC

- **A large e+e- storage ring collider seems the best complement to the LHC**
  - Permil precision on Higgs Couplings
  - Unbeatable precision on EW quantities (m_Z, Γ_Z, m_W, A_{LR}, R_b etc, etc.....)
  - Most mature technology
  - A first step towards a 100 TeV proton proton collider and a long term vision.

The numbers speak for themselves!

- **Results of the LHC run at 14 TeV will be a necessary and precious input**
  - Towards an ambitious medium and long term vision
  - In Europe: Decision to be taken by 2018
  - -- Design study recommended and being organized
  - -- A circular H.F. in Japan would benefit from the great experience of KEK B factory!

LEP3/TLEP parameters -1

soon at SuperKEKB: β_x^*=0.03 m, β_Y^*=0.03 cm

	LEP2	LHeC	LEP3	TLEP-Z	TLEP-H	TLEP-t
beam energy E_b [GeV]	104.5	60	120	45.5	120	175
circumference [km]	26.7	26.7	26.7	80	80	80
beam current [mA]	4	100	7.2	1180	24.3	5.4
#bunches/beam	4	2808	4	2625	80	12
#e-/beam [10^{12}]	2.3	56	4.0	2000	40.5	9.0
horizontal emittance [nm]	48	5	25	30.8	9.4	20
vertical emittance [nm]	0.25	2.5	0.10	0.15	0.05	0.1
bending radius [km]	3.1	2.6	2.6	9.0	9.0	9.0
partition number J_ε	1.1	1.5	1.5	1.0	1.0	1.0
momentum comp. α_c [10^{-5}]	18.5	8.1	8.1	9.0	1.0	1.0
SR power/beam [MW]	11	44	50	50	50	50
β^*_x [m]	1.5	0.18	0.2	0.2	0.2	0.2
β^*_y [cm]	5	10	0.1	0.1	0.1	0.1
σ^*_x [μm]	270	30	71	78	43	63
σ^*_y [μm]	3.5	16	0.32	0.39	0.22	0.32
hourglass F_{hg}	0.98	0.99	0.59	0.71	0.75	0.65
ΔE^{SR}_{loss}/turn [GeV]	3.41	0.44	6.99	0.04	2.1	9.3

SuperKEKB: $\varepsilon_y/\varepsilon_x$=0.25%

even with 1/5 SR power (10 MW) still > L_{ILC}!

LEP3/TLEP parameters -2

LEP2 was not beam-beam limited

	LEP2	LHeC	LEP3	TLEP-Z	TLEP-H	TLEP-t
$V_{RF,tot}$ [GV]	3.64	0.5	12.0	2.0	6.0	12.0
$\delta_{max,RF}$ [%]	0.77	0.66	5.7	4.0	9.4	4.9
ξ_x/IP	0.025	N/A	0.09	0.12	0.10	0.05
ξ_y/IP	0.065	N/A	0.08	0.12	0.10	0.05
f_s [kHz]	1.6	0.65	2.19	1.29	0.44	0.43
E_{acc} [MV/m]	7.5	11.9	20	20	20	20
eff. RF length [m]	485	42	600	100	300	600
f_{RF} [MHz]	352	721	700	700	700	700
δ^{SR}_{rms} [%]	0.22	0.12	0.23	0.06	0.15	0.22
$\sigma^{SR}_{z,rms}$ [cm]	1.61	0.69	0.31	0.19	0.17	0.25
L/IP[10^{32}cm^{-2}s^{-1}]	1.25	N/A	94	10335	490	65
number of IPs	4	1	2	2	2	2
Rad.Bhabha b.lifetime [min]	360	N/A	18	37	16	27
Υ_{BS} [10^{-4}]	0.2	0.05	9	4	15	15
n_γ/collision	0.08	0.16	0.60	0.41	0.50	0.51
$\Delta\delta^{BS}$/collision [MeV]	0.1	0.02	31	3.6	42	61
$\Delta\delta^{BS}_{rms}$/collision [MeV]	0.3	0.07	44	6.2	65	95

LEP data for 94.5 - 101 GeV consistently suggest a beam-beam limit of ~0.115 (R.Assmann, K. C.)

beam-beam effect (single collision)

	TLEP-H	TLEP-t	ILC (250)	ILC (350)
beam energy [GeV]	120	175	125	175
disruption D_y	2.2	1.5	23.4	84.5
Υ_{BS} [10^{-4}]	15	15	207	310
n_γ/collision	0.50	0.51	1.17	1.24
$\Delta\delta^{BS}$/collision [MeV]	42	61	1265	2670
$\Delta\delta^{BS}_{rms}$/collision [MeV]	65	95	1338	2760

TLEP: negligible beamstrahlung apart for effect on beam lifetime

Number of Events										
	$Z \to q\bar{q}$					$Z \to \ell^+\ell^-$				
Year	A	D	L	O	LEP	A	D	L	O	LEP
1990/91	433	357	416	454	1660	53	36	39	58	186
1992	633	697	678	733	2741	77	70	59	88	294
1993	630	682	646	649	2607	78	75	64	79	296
1994	1640	1310	1359	1601	5910	202	137	127	191	657
1995	735	659	526	659	2579	90	66	54	81	291
Total	4071	3705	3625	4096	15497	500	384	343	497	1724

Table 1.2: The $q\bar{q}$ and $\ell^+\ell^-$ event statistics, in units of 10^3, used for Z analyses by the experiments ALEPH (A), DELPHI (D), L3 (L) and OPAL (O).

LEP = 16 Million hadronic Z decays, 1.7 Million leptonic decays,

10^{31} /cm^2/s → 0.3 Z events per second + 4 times that rate in Bhabhas = 1.5 events per second.

10^{36} /cm^2/s → 30'000 events per second **30KHz** …. 120 KHz with the Bhabhas

10^7 seconds → 3 10^{11} Z decays. TeraZ

CHALLENGE I design of detector and DAQ system to keep high precision in cross-section measurement

Small angle e+e- is necessary for luminosity determination as large angle e+e- is dominated by Z decays themselves

Table 1: Sample of TLEP Physics performance goals.

Physics region	E_{beam} (GeV)	E_{CM} (GeV)	Luminosity in each of 4 experiments $cm^{-2}s^{-1}$	Beam Polarization	Physics goals
Z peak	44-47	88-94	10^{36}	Transverse for energy calibration >5%	One year of data taking: $>3\times10^{11}$ Z decays per experiment $>6\times10^{10}$ $b\bar{b}$ pairs per experiment Z mass and width to 0.1 MeV/c^2 $\Delta\rho_\ell$ to $\leq 5 10^{-5}$; Improvements in R_{had} R_b Γ_{inv}, etc
Z peak	45.6	91.2	$>10^{35}$	Longitudinal: 50%	A_{LR} A_{FB}^{Pol} ; $\sin^2\theta_\ell^{eff}$ to $\leq 3 10^{-6}$
W pair threshold and maximum	80-90	160-180	2.10^{35}	Transverse for calibration >5% (useful, but not compulsory)	One year of data taking: W mass to <1 MeV/c^2
ZH threshold and cross-section maximum	110-125	220-250	5.10^{34}	Not required	5 years of data taking at ZH maximum (combined with 5 years at the $t\bar{t}$ threshold). W mass to $\leq$1 MeV/c^2 5×10^5 ZH events/expt m_H (MeV) 7 $\Delta\Gamma_H / \Gamma_H$ 1.3% $\Delta\Gamma_{inv} / \Gamma_H$ 0.15% $\Delta g_{H\gamma\gamma} / g_{H\gamma\gamma}$ 1.4% $\Delta g_{Hgg} / g_{Hgg}$ 0.7% $\Delta g_{Hww} / g_{Hww}$ 0.25% $\Delta g_{HZZ} / g_{HZZ}$ 0.2% $\Delta g_{H\mu\mu} / g_{H\mu\mu}$ 7% $\Delta g_{H\tau\tau} / g_{H\tau\tau}$ 0.4% $\Delta g_{Hcc} / g_{Hcc}$ 0.65% $\Delta g_{Hbb} / g_{Hbb}$ 0.22%
$t\bar{t}$ threshold and High Energy (E_{CM} > 340 GeV)	170-180	340-360	7.10^{33}	Not required	5 years of data taking: Top quark mass to 100 MeV/c^2 3.5 10^4 Hvv events