Higgs Factories: Present and Future

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Higgs Physics Beyond Discovery
April 26, 2013

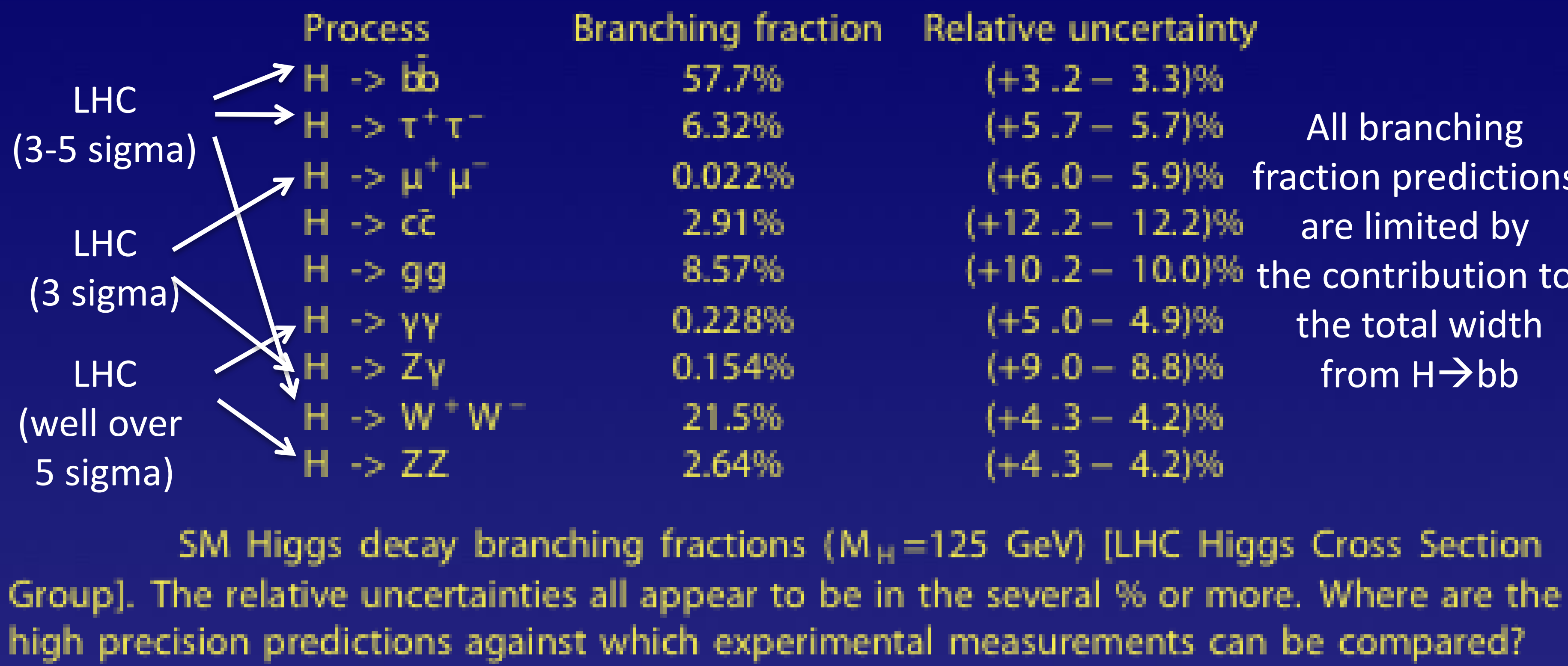
Higgs Physics in the Big Picture

- Will the detailed properties of the Higgs boson tell us more about the laws of physics?
  - What is the nature of dark matter?
    - Does dark matter interact with the Higgs boson?
  - Why is there a large-scale universe?
    - Are there symmetries or properties of space-time that made this possible and will such properties be discovered through the detailed study of the Higgs boson?
    - Why weren’t the elementary particles given heavy masses – this in itself is partly responsible for the large discrepancy in the strength of gravity relative to electroweak interactions? The universe is not a small dot – but seems like it should be.

Major Challenges for Higgs Physics

- The LHC at 14 TeV will probe new physics at and above the TeV scale in a broad sweep
  - Beyond further discoveries at the LHC, the most promising avenue for future exploration is via the Higgs boson properties through high precision measurement.
    - What constitutes a high precision test capable of exploring more physics than a broadband discovery machine like the LHC?
    - Higher precision in the Higgs sector alone is likely to be insufficient, a comprehensive program of order of magnitude improvements in all electroweak observable, the W boson and top quark mass are needed.
- The Higgs boson and the top quark were guaranteed discoveries based on exactly this strategy
  - The basis for the high precision measurements came from the Z factories (over **10^6** Z bosons produced on resonance and studied with polarized beams with ~10^5 Z bosons).

Some Predicted Higgs Boson Properties



LHC
(3-5 sigma)

LHC
(3 sigma)

LHC
(well over
5 sigma)

Process	Branching fraction	Relative uncertainty
H -> $b\bar{b}$	57.7%	(+3.2 − 3.3)%
H -> $\tau^+\tau^-$	6.32%	(+5.7 − 5.7)%
H -> $\mu^+\mu^-$	0.022%	(+6.0 − 5.9)%
H -> $c\bar{c}$	2.91%	(+12.2 − 12.2)%
H -> gg	8.57%	(+10.2 − 10.0)%
H -> $\gamma\gamma$	0.228%	(+5.0 − 4.9)%
H -> $Z\gamma$	0.154%	(+9.0 − 8.8)%
H -> W^+W^-	21.5%	(+4.3 − 4.2)%
H -> ZZ	2.64%	(+4.3 − 4.2)%

All branching
fraction predictions
are limited by
the contribution to
the total width
from H→bb

SM Higgs decay branching fractions (M_H =125 GeV) [LHC Higgs Cross Section Group]. The relative uncertainties all appear to be in the several % or more. Where are the high precision predictions against which experimental measurements can be compared?

- Additionally, the total width: Γ_H=4.07 MeV (+4.0-3.9)%
- ttH coupling, HHH self-coupling (and HHHH self-coupling)
- CP even and momentum dependence of couplings known

The Predicament

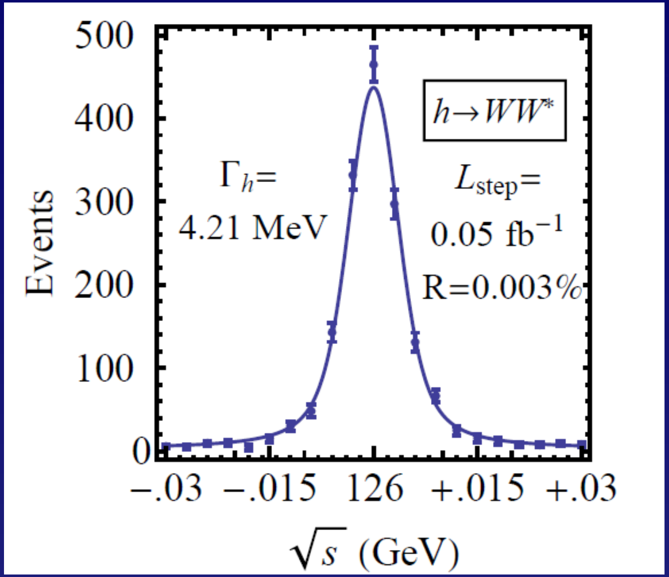
- The total width of the Higgs boson is not known, and the prediction from theory summing over visible modes is limited by H→bb to ~3%
  - This translates to a theoretical uncertainty on all branching fractions (5 sigma is ~15%)
  - There is not enough precision in the theory predictions to look for new physics beyond what the LHC can already probe
  - Ratios of branching fractions can yield higher precision, such as in Br(H→$\gamma\gamma$)/Br(H→ZZ), but a Higgs factory can't do these in any case – too few Higgs bosons compared to the LHC
- What is the point of a precision Higgs factory?
  - Any plan for going beyond the LHC has to include a way of creating high precision tests of theory and experiment

A Comprehensive Approach

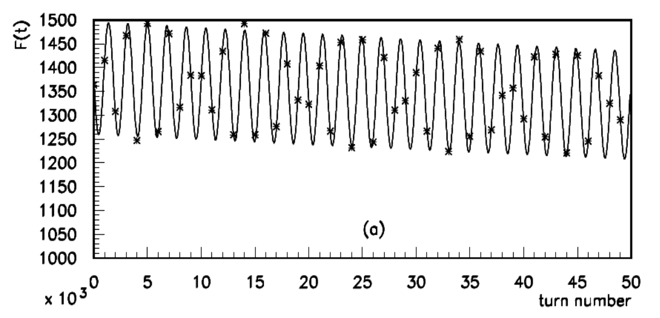
- Higgs factories create high precision theory and experiment simultaneously, first by increasing the precision by an order of magnitude on electroweak quantities, α_s, and the W and top masses
  - 10^9 or more Z bosons (91 GeV)
  - Threshold scan for the W mass (161 GeV)
  - Threshold scan for the top quark mass (350 GeV)
  - α_s from the Z data and several c-o-m energies
- Secondly, by improving the constraints on the total width
  - Direct measurement of H→bb will achieved a precision that supersedes the theory error and pushes down this contribution to sub-percent
  - Total width of the Higgs boson needs to be measured to better than 1% using high statistics from mass recoil method (much larger than considered so far) and line shape scans when possible

Muon Collider

- Resonant (s-channel) Higgs production
  - Compact ring structure fits at Fermilab
  - Beam energy spread of 0.4 MeV on the Higgs resonance, for two experiments on ring produces 80,000 bosons per year
  - 10^{34}cm^{-2}s^{-1} luminosity on the Z peak, with increasing luminosity from 1, 3, 6 TeV
  - High precision beam energy could be used to determine the most precise top quark mass from a thresholds scan and similary for the W boson pair production threshold
  - Will provide the highest precision H→μμ and this could have one of the most precise theory predictions
- Detector backgrounds
  - From secondary particles from beam dumps of off-momentum electrons from muon decay
  - Understood to be MeV-scale electron and out of time muons that can be removed with precision timing
- Challenging accelerator program
  - Requires several stages of development (20yrs)

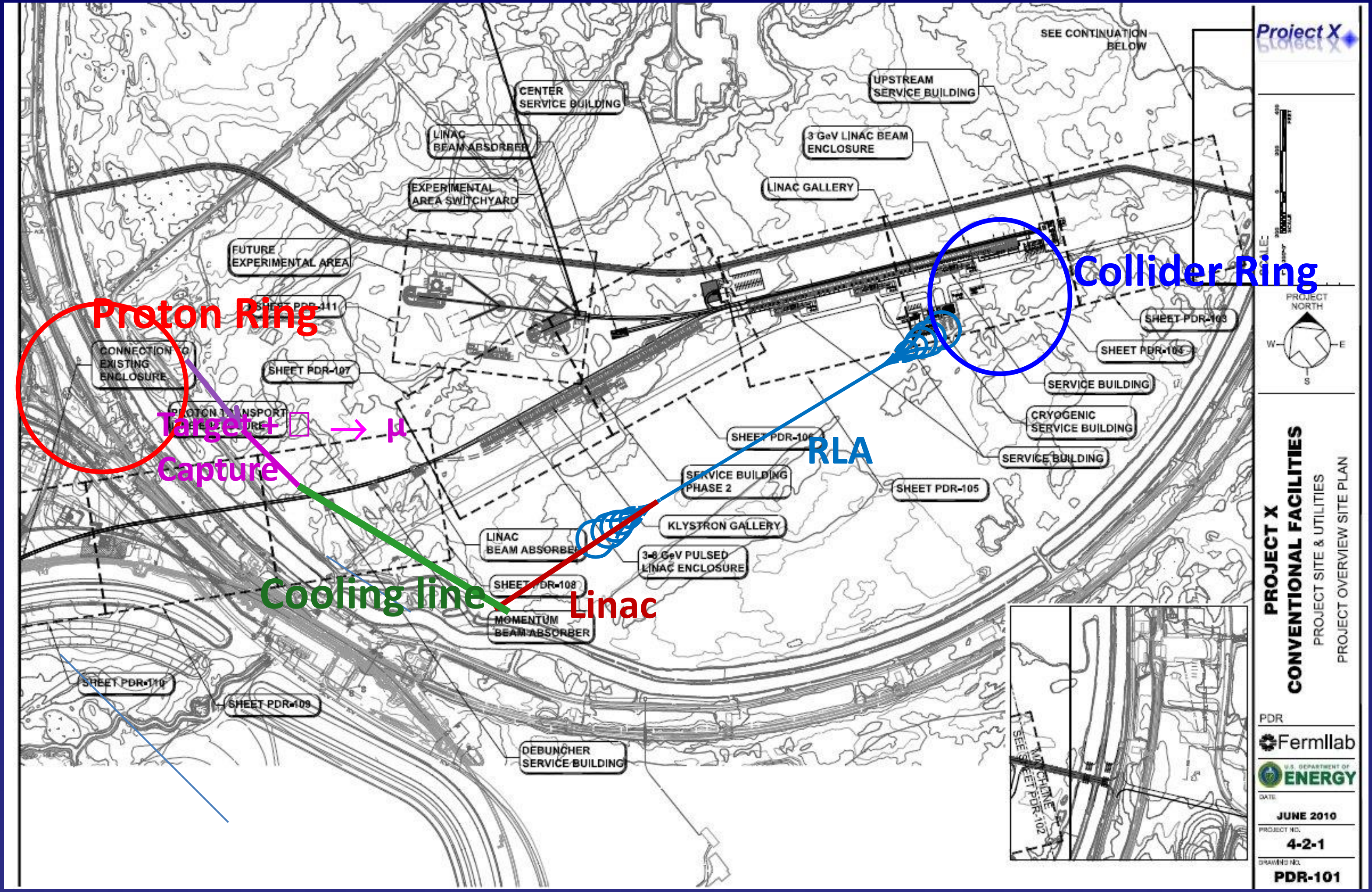


Direct line shape scan of Higgs boson (accurate to 0.2 MeV)

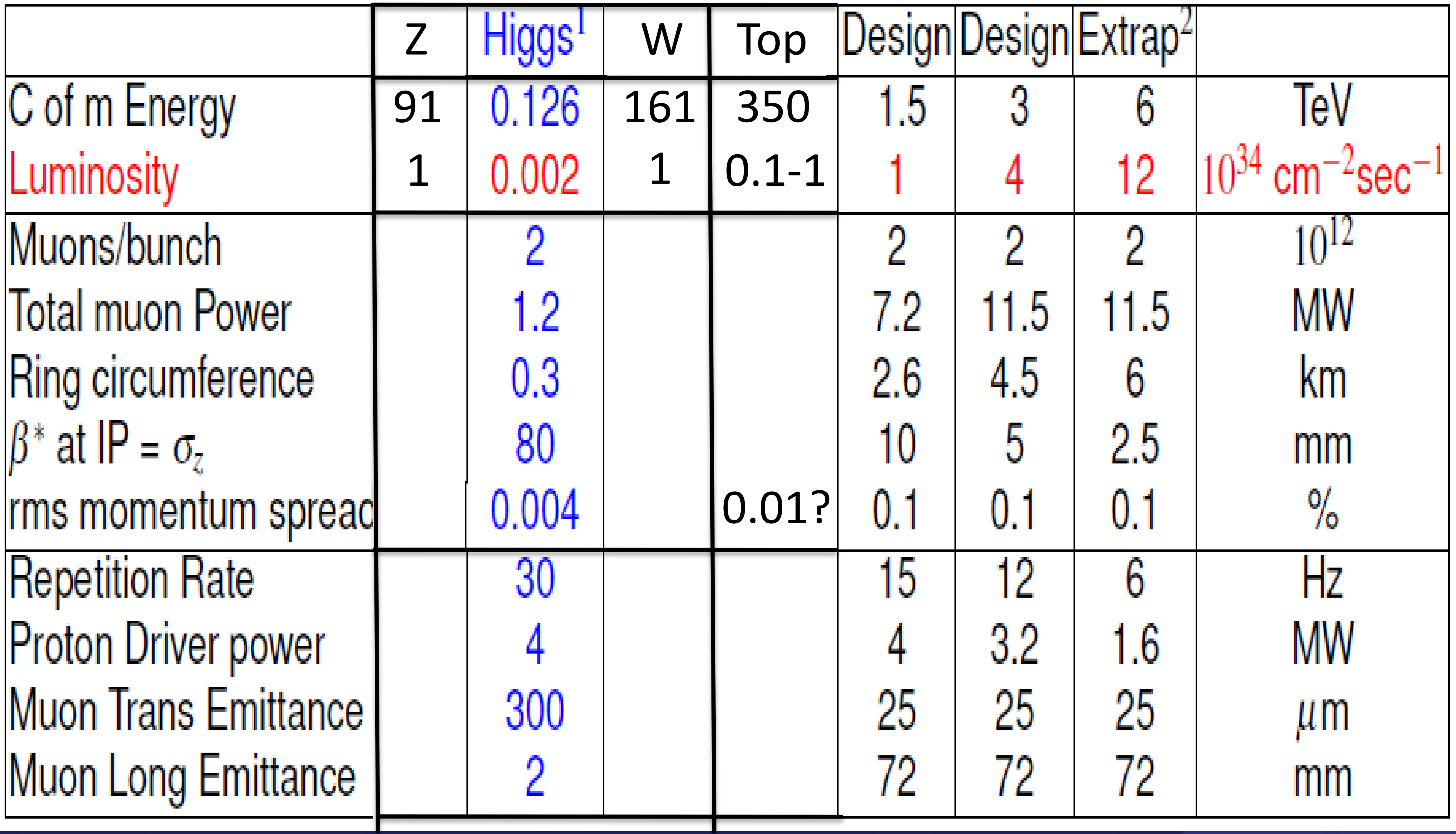


g-2 precession methods
for beam energy calibration to 10 keV

Scale of mu collider facility



Muon Collider parameters

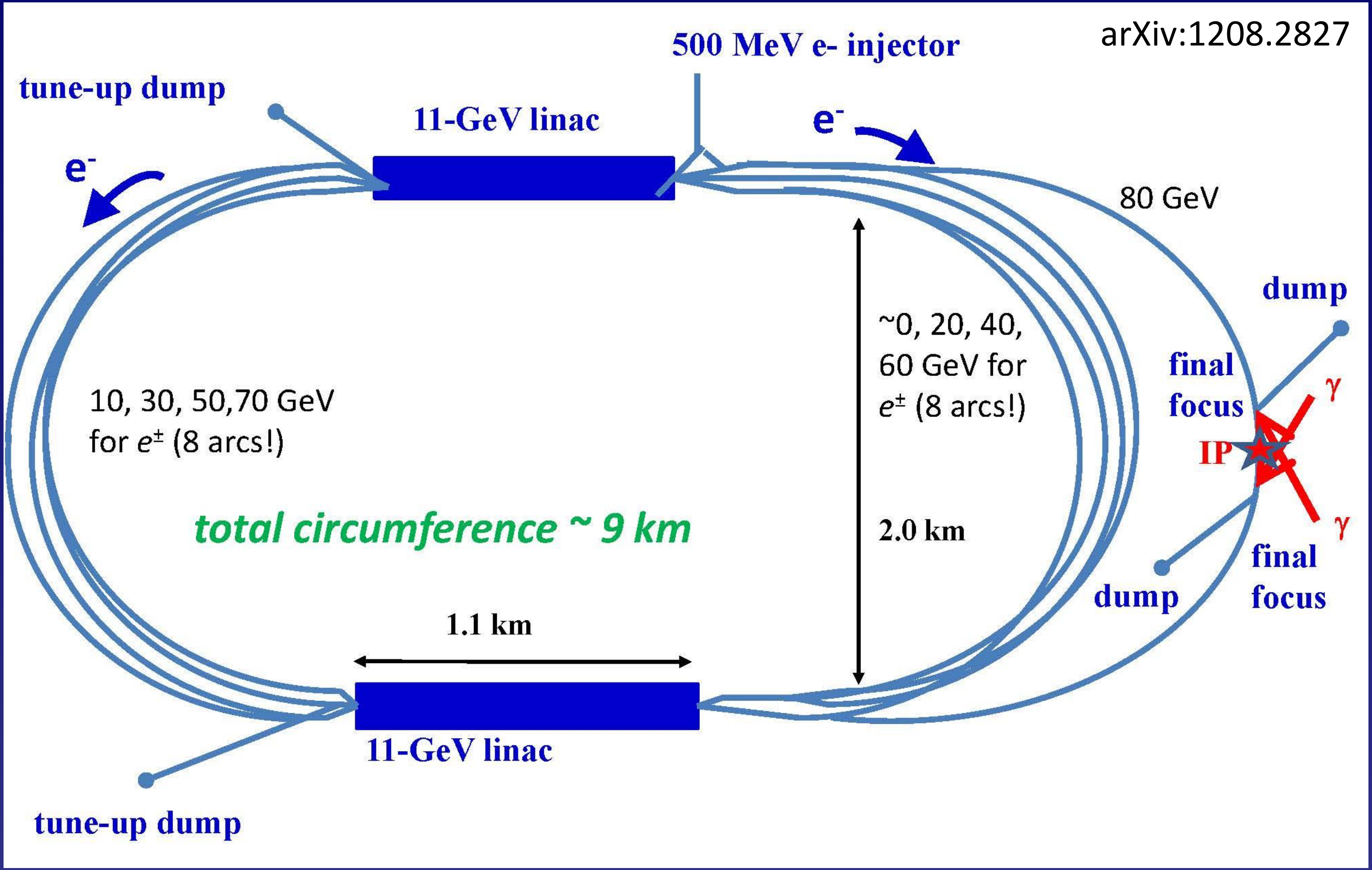


	Z	Higgs[1]	W	Top	Design	Design	Extrap[2]	
C of m Energy	91	0.126	161	350	1.5	3	6	TeV
Luminosity	1	0.002	1	0.1-1	1	4	12	10^{34} cm^{-2}sec^{-1}
Muons/bunch		2			2	2	2	10^{12}
Total muon Power		1.2			7.2	11.5	11.5	MW
Ring circumference		0.3			2.6	4.5	6	km
β^* at IP = σ_z		80			10	5	2.5	mm
rms momentum spread		0.004		0.01?	0.1	0.1	0.1	%
Repetition Rate		30			15	12	6	Hz
Proton Driver power		4			4	3.2	1.6	MW
Muon Trans Emittance		300			25	25	25	μm
Muon Long Emittance		2			72	72	72	mm

$\gamma\gamma$ Collider

- Also s-channel production, but the beam energy spread is greater than the line shape width
  - Beams are produced using inverse Compton scattering of high power laser beams off electron beams (or positron beams for e^+e^- linear colliders)
  - Energy recovery linacs can compactly produced the beams necessary (fits anywhere – FNAL, JLab, DESY, CERN,…)
  - High power lasers such as those used for inertial confinement fusion (LIFE) and alternatively FELs provide the photons
- Polarized laser light allows for precision tests of CP violation and the most accurate $H \rightarrow \gamma\gamma$ measurement

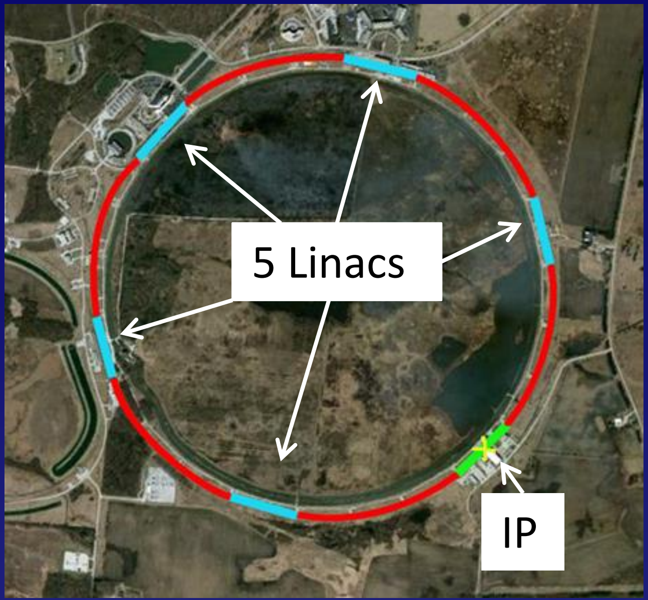
SAPPHiRE $\gamma\gamma$ Higgs Factory


arXiv:1208.2827

SAPPHiRE: Small Accelerator for Photon-Photon Higgs production using Recirculating Electrons

$\gamma\gamma$ Higgs Factory

LIFE beam line :
- **Pulses at 16 Hz**
- **8.125 kJ / pulse**
- **130 kW average power**
- **ns pulse width**

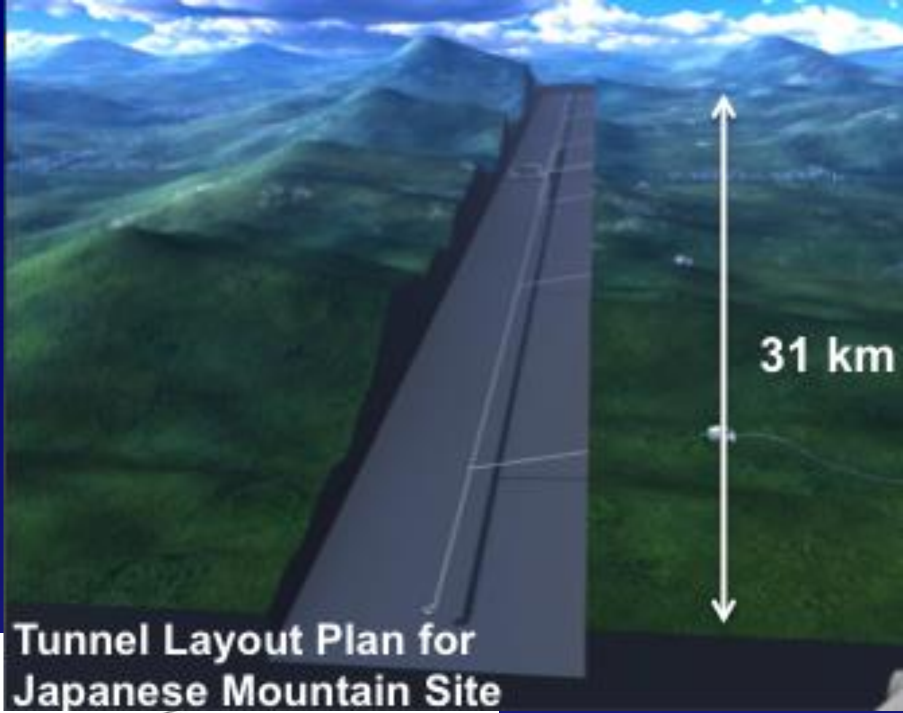


Top Energy	**80 GeV**	**80 GeV**
Turns	3	4
Magnet ρ	644.75 m	706.65 m
Linacs (5)	5.59GeV	4.23GeV
$\delta p/p$	$6.99\text{x}10^{-4}$	$7.2\text{x}10^{-4}$
ϵ_{nx} Growth	1.7μm	1.8μm

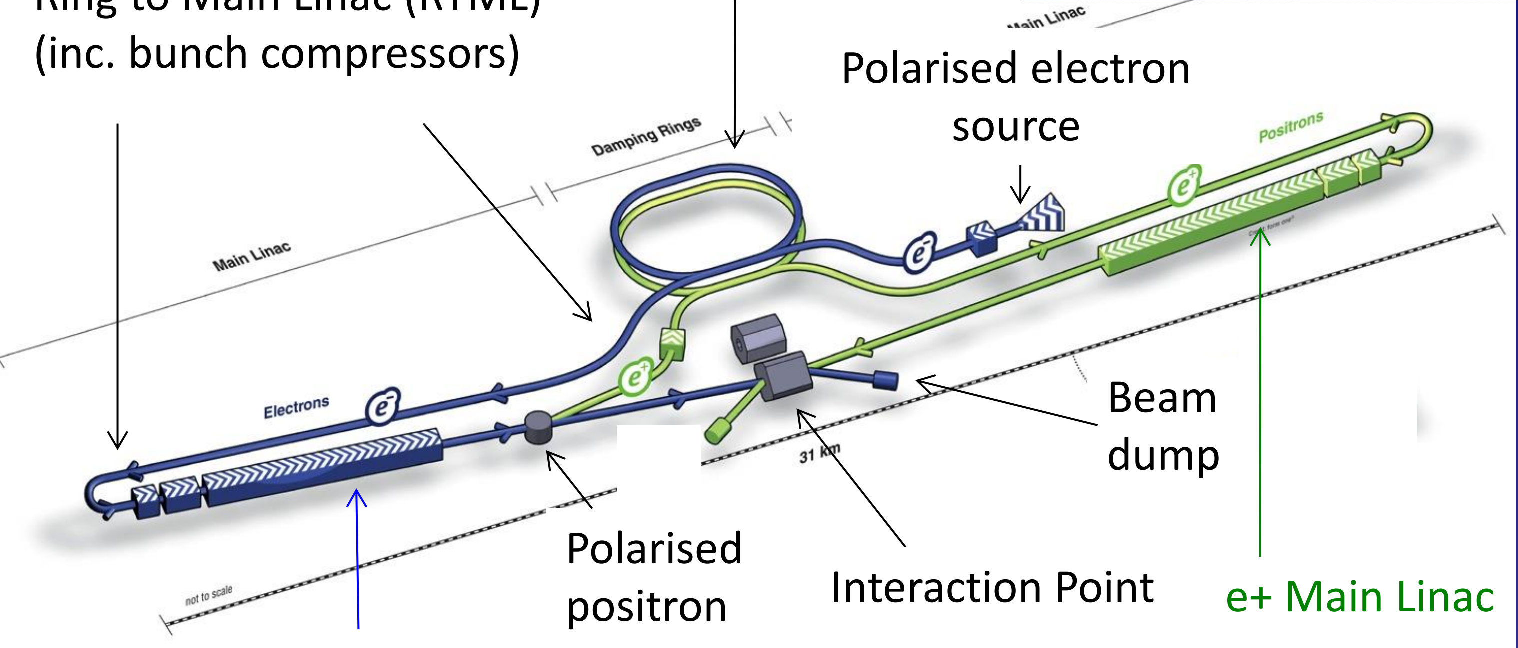
The Story of e^+e^- Colliders

- Began with a paper by Burt Richter, which drew the line (based on reasonable assumptions) on the maximum energy of circular e^+e^- colliders at ~200 GeV, beyond which linear e^+e^- must take over
  - Since that time, the KEK-B factory perfected the concept of dual high-energy beams which allows one ring to top off the other ring at full energy – this, not surprisingly, effectively doubles the maximum energy to ~350 GeV for a 80-100km circular ring
- Linear colliders have been designed to 1 TeV (ILC) and up to 3 TeV (CLIC) using a pair of collinear beams
  - Non-resonance production favors operating at 250 GeV for HZ mass recoil measurements with ~10,000 Higgs bosons per year
  - The Higgs boson measurements get most of their precision from their highest energy operation through VBF (~40,000/year)

ILC
(International Linear e^+e^- Collider)



Tunnel Layout Plan for Japanese Mountain Site



Ring to Main Linac (RTML) (inc. bunch compressors)

Damping Rings

Polarised electron source

Beam dump

Polarised positron source

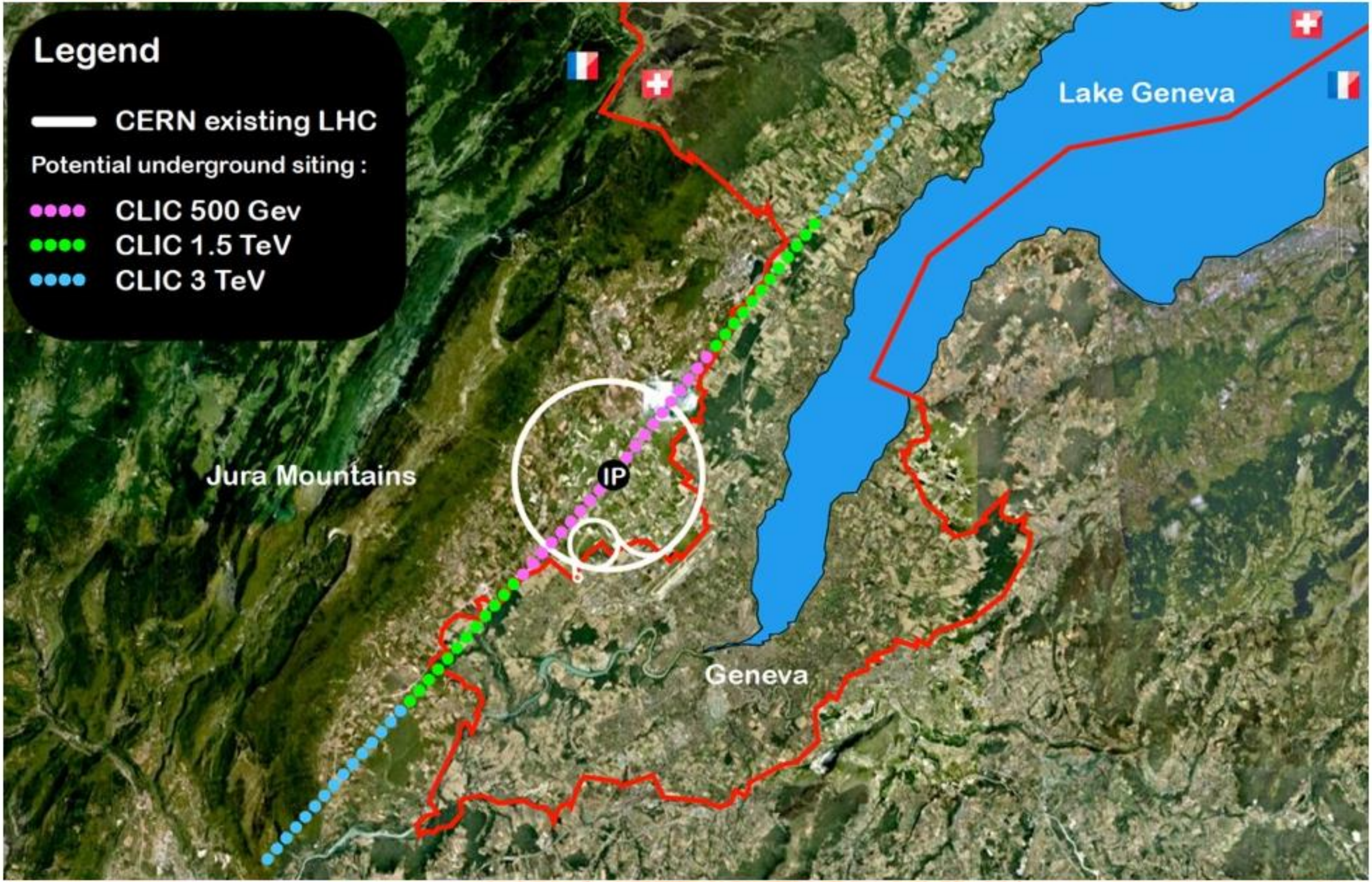
Interaction Point

e+ Main Linac

e- Main Linac

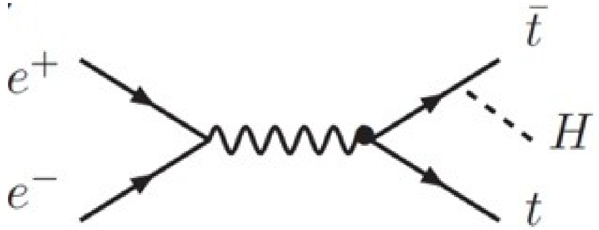
not too scale

CLIC - Possible Implementation at CERN

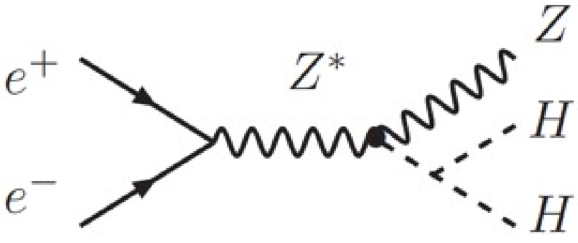


Higgs Production at e^+e^- Colliders

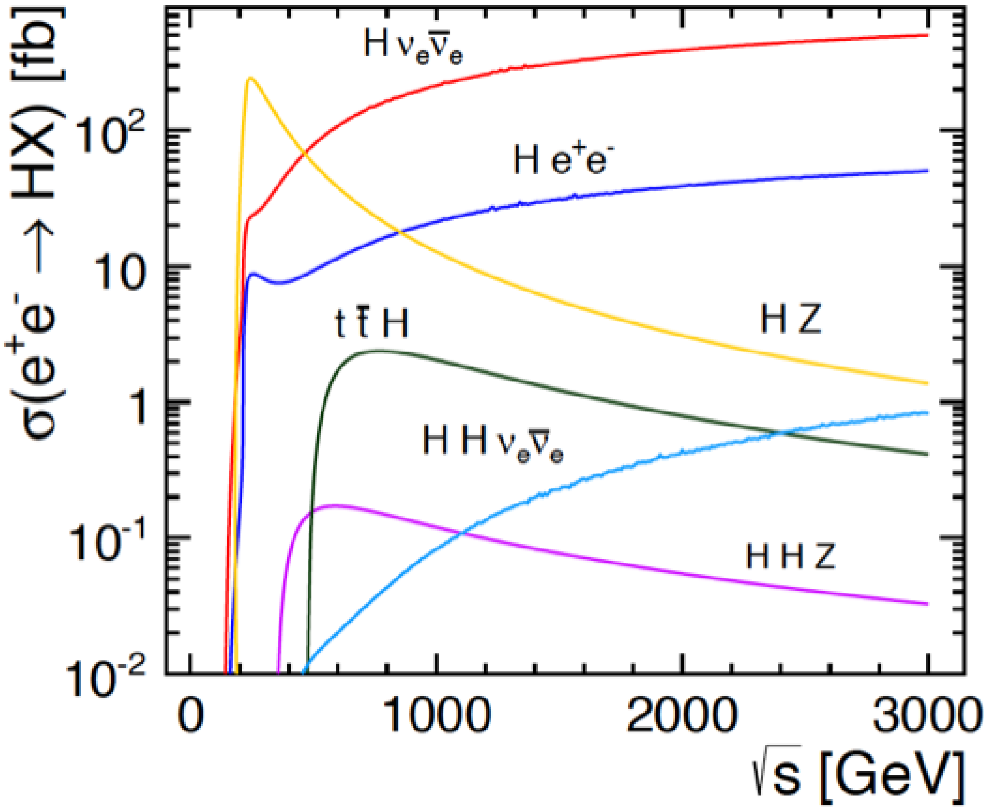
- Sub-leading processes - top Yukawa coupling, self-coupling

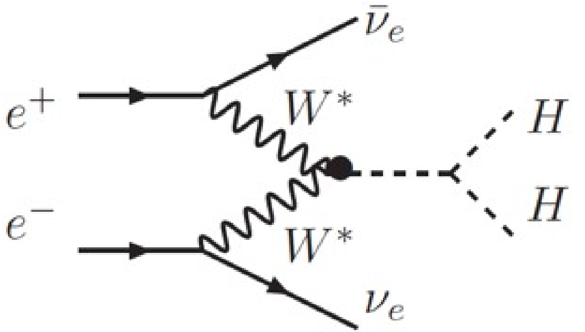


Higgs Strahlung off top quarks (s-channel)



Double Higgs production in Higgs-Strahlung(s-channel)



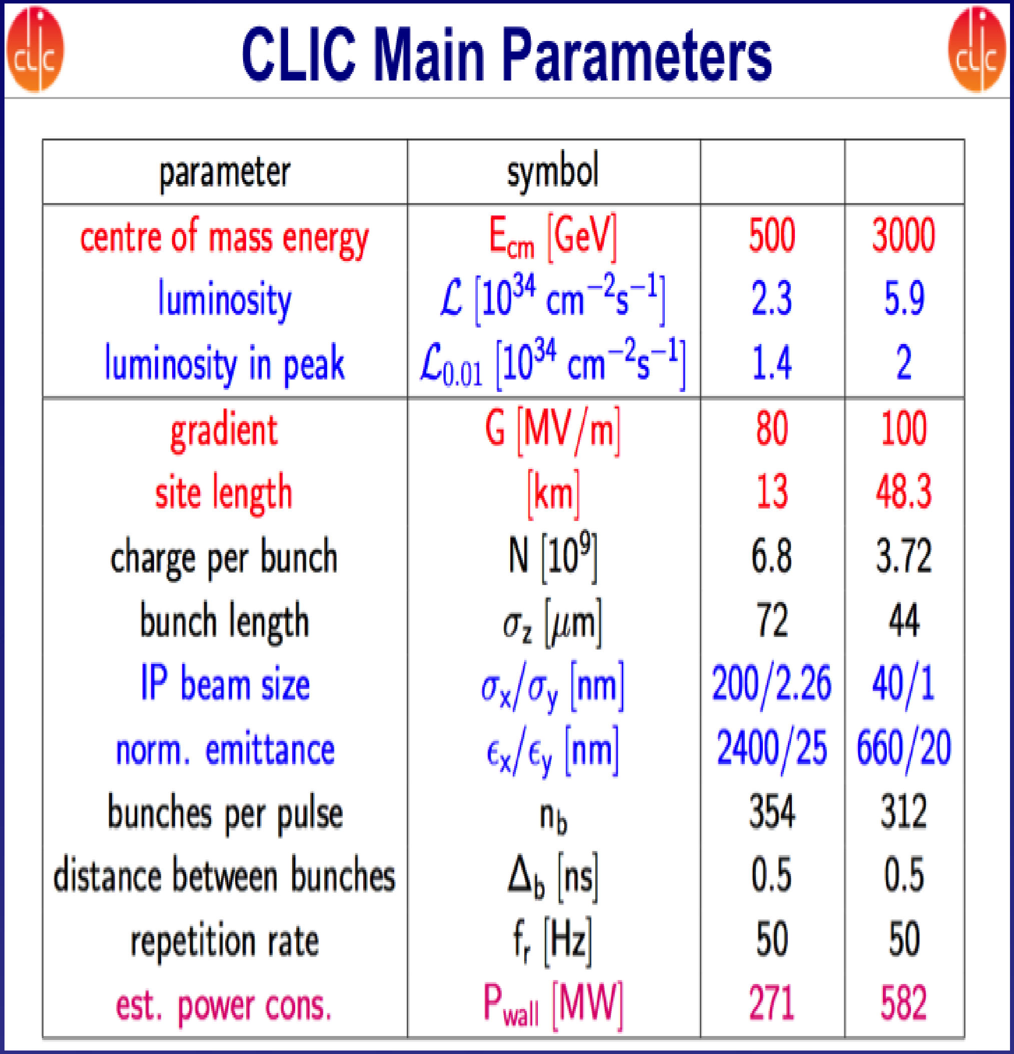


Double Higgs production in vector boson fusion (t-channel)

e^+e^- Linear Collider Parameters

ILC Collision rate	Hz	5
Number of bunches		1312
Bunch charge	$\times10^{10}$	2
Bunch separation	ns	554
RMS bunch length	mm	0.3
Electron polarisation	%	80
Positron polarisation	%	30

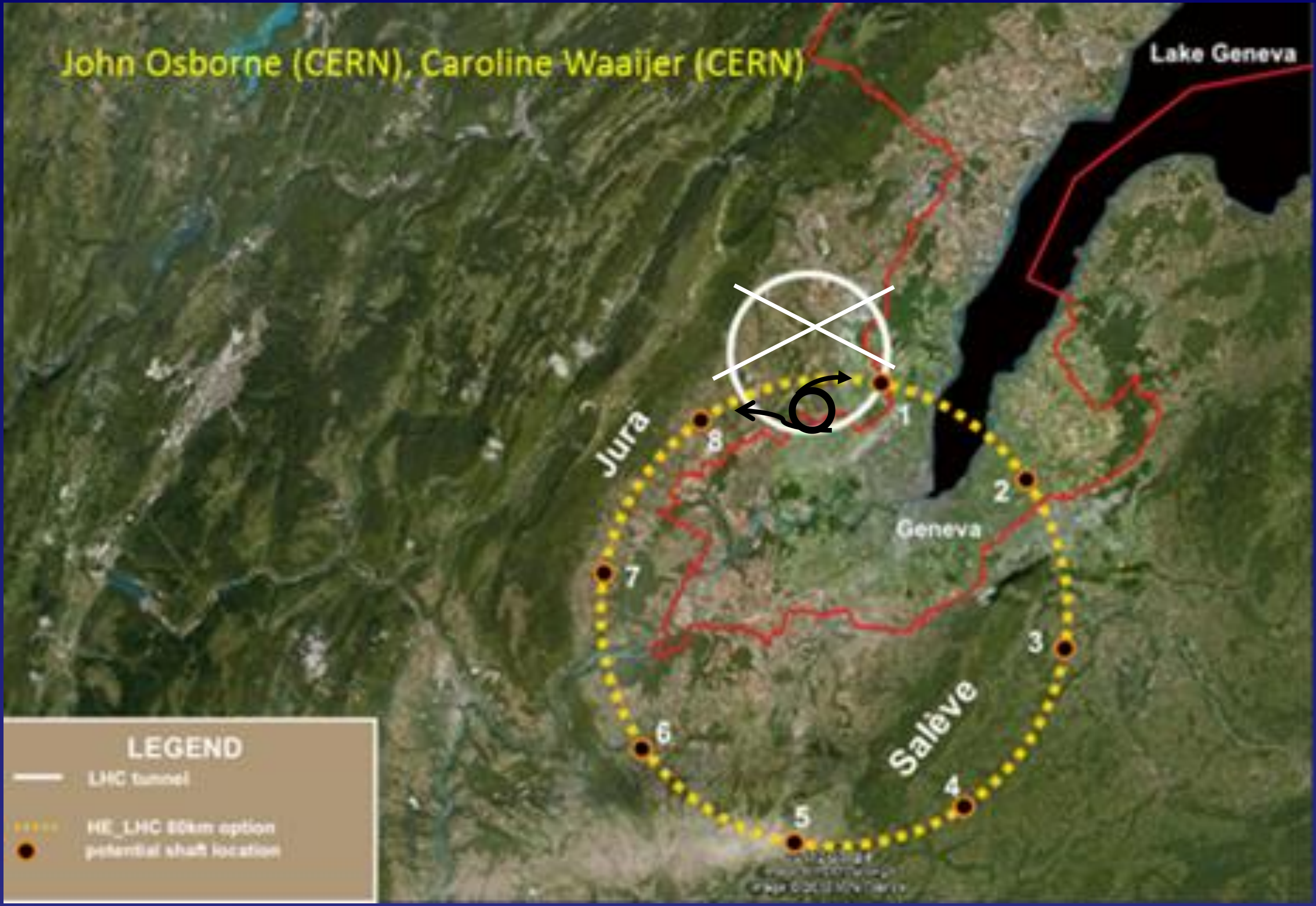
ILC Centre-of-mass energy	**GeV**	**250**	**350**	**500**
Electron RMS energy spread	%	0.19	0.16	0.12
Positron RMS energy spread	%	0.15	0.10	0.07
IP RMS horizontal beam size	nm	700	662	474
IP RMS veritcal beam size	nm	8.3	7.0	5.9
Luminosity	**$\times10^{34}$ cm^{-2}s^{-1}**	**0.75**	**0.93**	**1.8**
% luminosity in top 1% ΔE/E		84%	79%	63%
Average energy loss		1%	2%	4%
Total pair energy / BX	TeV	51	108	344



CLIC Main Parameters

parameter	symbol		
centre of mass energy	E_{cm} [GeV]	500	3000
luminosity	$\mathcal{L}$ [10^{34} cm^{-2}s^{-1}]	2.3	5.9
luminosity in peak	$\mathcal{L}_{0.01}$ [10^{34} cm^{-2}s^{-1}]	1.4	2
gradient	G [MV/m]	80	100
site length	[km]	13	48.3
charge per bunch	N [10^9]	6.8	3.72
bunch length	σ_z [μm]	72	44
IP beam size	σ_x/σ_y [nm]	200/2.26	40/1
norm. emittance	ϵ_x/ϵ_y [nm]	2400/25	660/20
bunches per pulse	n_b	354	312
distance between bunches	Δ_b [ns]	0.5	0.5
repetition rate	f_r [Hz]	50	50
est. power cons.	P_{wall} [MW]	271	582

TLEP and VHE-LHC in 80-100km tunnel


John Osborne (CERN), Caroline Waaijer (CERN)

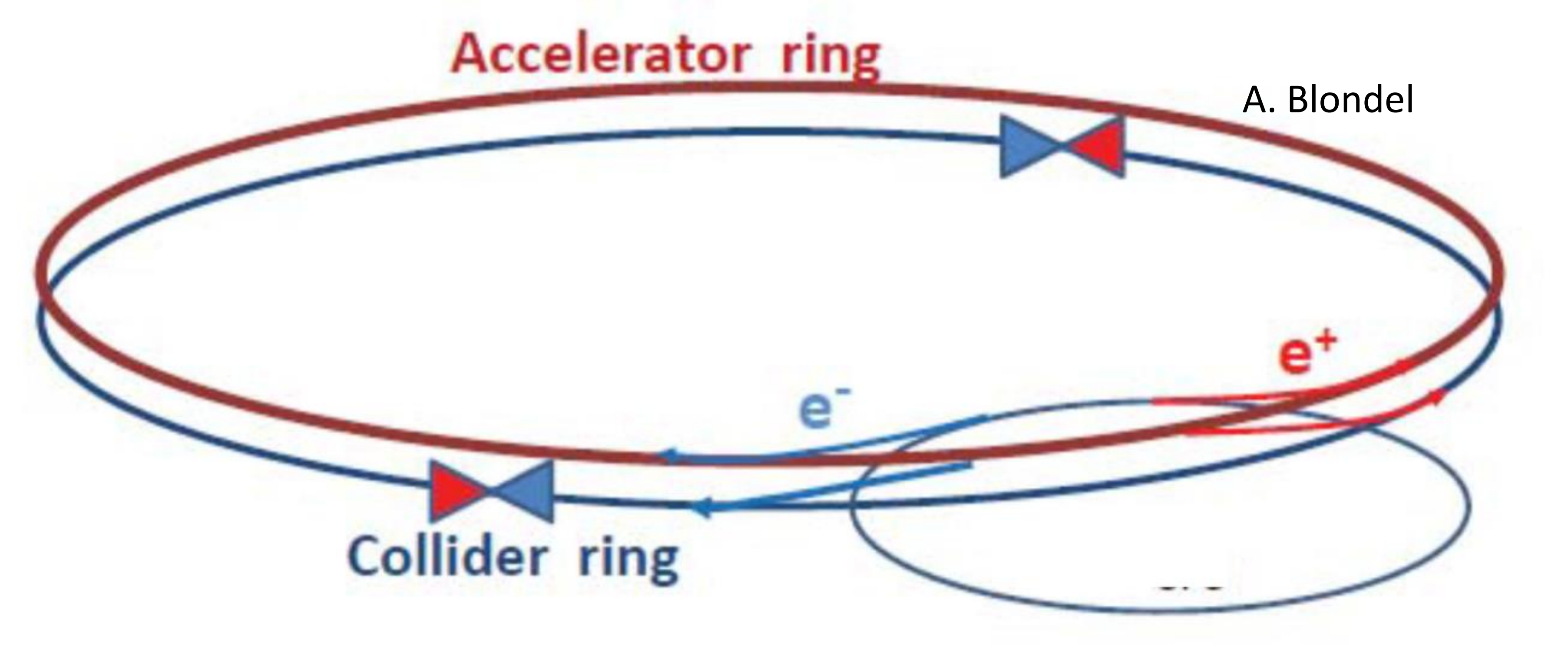
injection scheme: SPS+ →LHC → VHE-LHC too expensive (50 MW power for cryo)

L. Rossi

TLEP

double ring with top-up injection

supports short lifetime & high luminosity



A. Blondel

top-up experience: PEP-II, KEKB, light sources

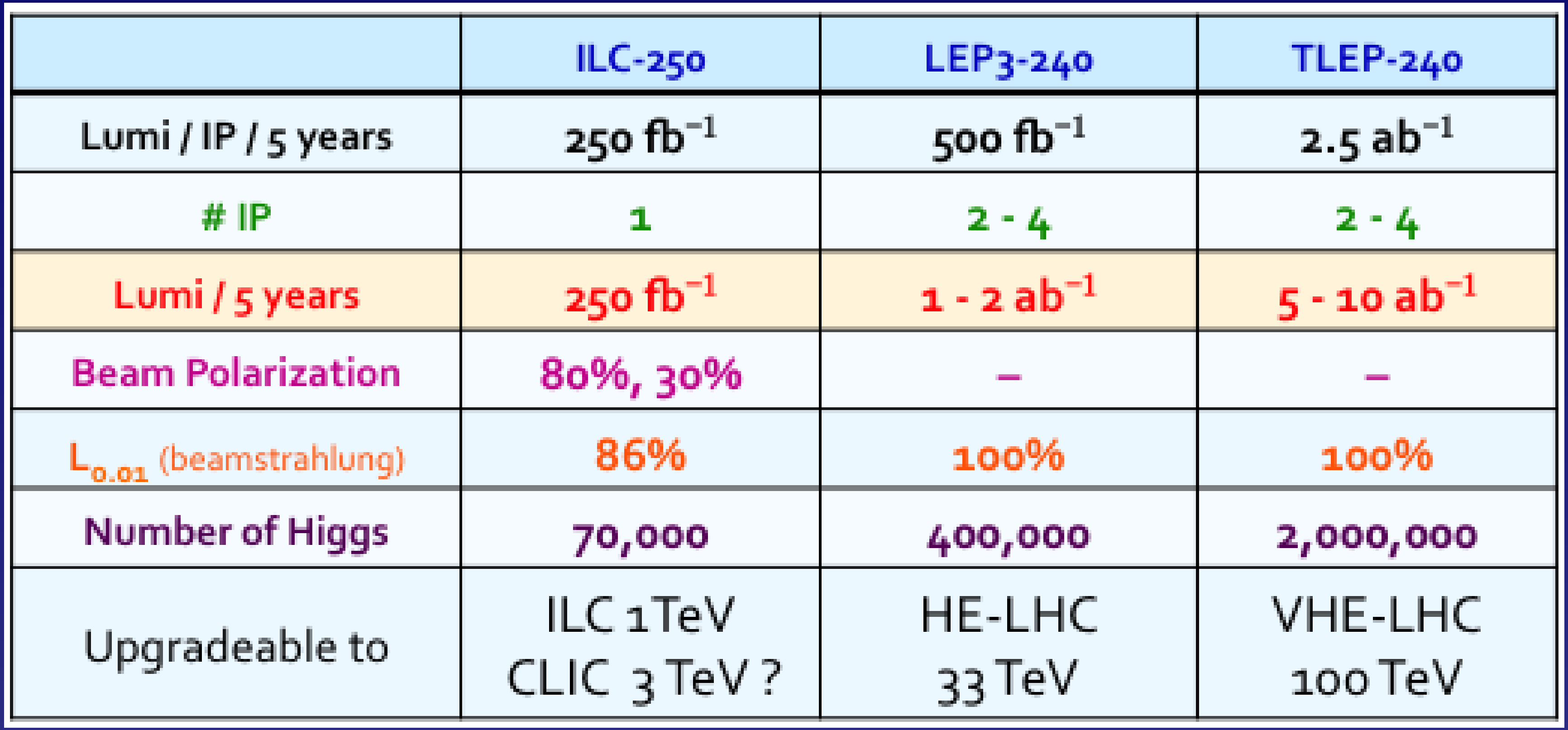
LEP3 and TLEP

key parameters

	LEP3	**TLEP**
circumference	26.7 km	80 km
max beam energy	120 GeV	175 GeV
max no. of IPs	4	4
luminosity at 350 GeV c.m.	-	0.7×10^{34} $cm^{-2}s^{-1}$
luminosity at 240 GeV c.m.	10^{34} $cm^{-2}s^{-1}$	5×10^{34} $cm^{-2}s^{-1}$
luminosity at 160 GeV c.m.	5×10^{34} $cm^{-2}s^{-1}$	2.5×10^{35} $cm^{-2}s^{-1}$
luminosity at 90 GeV c.m.	2×10^{35} $cm^{-2}s^{-1}$	10^{36} $cm^{-2}s^{-1}$

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

Comparison of ZH Higgs production rates for linear and circular e^+e^-



	ILC-250	LEP3-240	TLEP-240
Lumi / IP / 5 years	250 fb^{-1}	500 fb^{-1}	2.5 ab^{-1}
# IP	1	2 - 4	2 - 4
Lumi / 5 years	250 fb^{-1}	1 - 2 ab^{-1}	5 - 10 ab^{-1}
Beam Polarization	80%, 30%	–	–
$L_{0.01}$ (beamstrahlung)	86%	100%	100%
Number of Higgs	70,000	400,000	2,000,000
Upgradeable to	ILC 1 TeV CLIC 3 TeV ?	HE-LHC 33 TeV	VHE-LHC 100 TeV

Higgs Factories

- The only two resonance production methods for the Higgs boson ($\mu^+\mu^-$ and $\gamma\gamma$) involve technologies that we have not developed yet
  - But we do believe they will be developed eventually.
- The other directions for high precision Higgs studies involve accelerators that are themselves new energy frontier machines or in some way are designed to expand into new energy frontier machines
  - Since these machines use non-resonant processes, the Higgs boson measurements get most of their precision from their highest energy operation
  - By choosing these machine technologies we are effectively choosing the future direction of the energy frontier before having decisive constraints to guide us.
  - That might be the only answer, but it would choose between:
    - linear e^+e^- up to 1 TeV or 3 TeV – here there are two accelerator technologies
    - circular e^+e^- up to 240 GeV (350 GeV) followed by pp at 33 TeV (100 TeV) – where the 33 TeV program is HE-LHC in the existing LEP tunnel
    - And it should be noted that $\mu^+\mu^-$ could be extended up to at least 3 TeV
    - And that $\gamma\gamma$ could be included in a linear e^+e^- energy frontier machine

Summary

- A precision search for new physics in the Higgs sector requires precision theory prediction to compare against
  - There is not sufficiency precision in the Higgs sector without improvements in electroweak precision quantities, α_s, the W boson and top quark masses, or, alternatively,
  - a precision measurement of H→bb to supersede the theory uncertainty on the total width or measurements of the total width to better than 1% such as from high statistics recoil mass method and possibly a line shape scan when possible
- The potential future directions for Higgs physics are being amply fueled by impressive new capabilities in accelerator and detector technologies
  - The list of alternatives is understood
- There may be a case for a new machine at this time, but what is clear is that the enabling technologies need continued and dedicated pursuit, and that:
  - Potential discoveries at the 14 TeV LHC is the most immediate and direct route to new discoveries at this time

ILC = Complete Higgs factory program (1 TeV)
- (more precision needed on total width)

CILC = ILC + HHH + 3 TeV

mu collider = ILC + higher rates + s-channel line shape + HHH
+ over 3 TeV + $H\mu\mu$ + higher precision beam energy
- (detector backgrounds) – (low beam pol)

LEP3 = ILC + higher rates + 33 TeV HE-LHC (+HHH+$H\gamma\gamma$)
- (ttH) - (top mass) - (beam pol)

TLEP = ILC + much higher rates + 100 TeV VHE-LHC (+ttH+HHH+$H\gamma\gamma$)
- (beam pol)

Possible Linear Combinations: (some one will do $\gamma\gamma$ collider)
ILC/CLIC/mu collider + 33 TeV LHC
TLEP + 100 TeV LHC