Accelerator Needs from High Energy Physics for the next 50 years

-- or --

50 years in 15 minutes + questions

will concentrate on two main questions:
-- neutrinos
-- high energy exploration

Both saw revolutions in 2011-2012

Massive neutrinos: THE NEW PHYSICS there is

neutrino masses constitute a new question which has no unique answer in the Standard Model

-- while all other charged fermions receive 'Dirac' masses
neutrinos are neutral and could *also* receive 'Majorana' masses
which alllow a transition between neutrinos and antineutrinos
i.e. matter and anti-matter

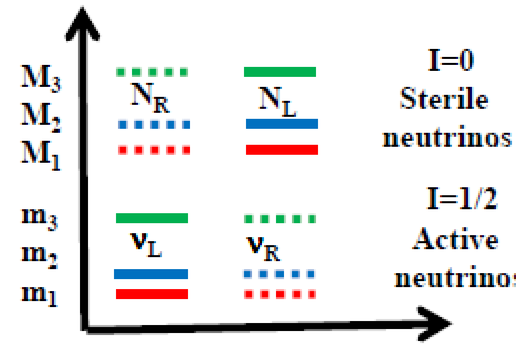
As a consequence, massive neutrinos could quite naturally have 'sterile' brothers … and contribute to the solution of several well known observations
None of which have an explanation within the Standard Model.

-- baryon asymmetry of the universe (CP asymmetry)

-- dark matter (sterile neutrinos)

-- and could contribute for a fraction of an additional degree of freedom in the early universe (CMB, Plank) depending on their mass.

Neutrinos : the New Physics there is… and a lot of it!

SM	Dirac mass term only	Majorana mass term only	Dirac AND Majorana Mass terms
ν_L $\bar{\nu}_R$ I= $\frac{1}{2}$ $\frac{1}{2}$	ν_L ν_R $\bar{\nu}_R$ $\bar{\nu}_L$ $\frac{1}{2}$ 0 $\frac{1}{2}$ 0	ν_L ν_R $\frac{1}{2}$ $\frac{1}{2}$ (a.k.a. $\bar{\nu}$)	
X 3 Families	X 3 Families	X 3 Families	
6 massless states	3 masses 12 states 3 active neutrinos 3 active antinu's 6 sterile neutrinos… 3 mixing angles 1 CP violating phase	3 masses 6 active states No steriles 3 mixing angles 3 CP violating phases 0νββ	6 masses 12 states 6 active states 6 sterile neutrinos… More mixing angles and CPV phases 0νββ → Leptogenesis and Dark matter

Mass hierarchies are all unknown except $m_1 < m_2$

Preferred scenario has both Dirac and Majorana terms …

… a bonanza of extreme experimental challenges

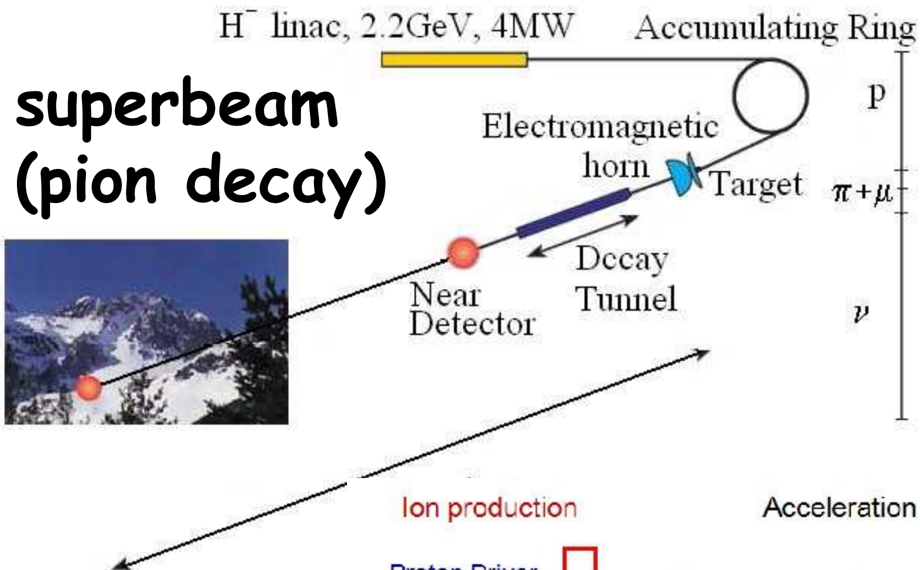
1998	Atmospheric neutrinos	$\|\Delta m^2_{32}\| = \| m^2_3 - m^2_2 \|$, θ_{23}.
2002	Solar neutrinos (SNO) reactor (KAMLAND)	$\Delta m^2_{21} = m^2_2 - m^2_1$, θ_{12}
2011-12	Accelerator (T2K (06/2011, MINOS 07/2011) and rectors (DChooz 12/2011, DayaBay 03/2012, Reno 04/2012)	θ_{13}

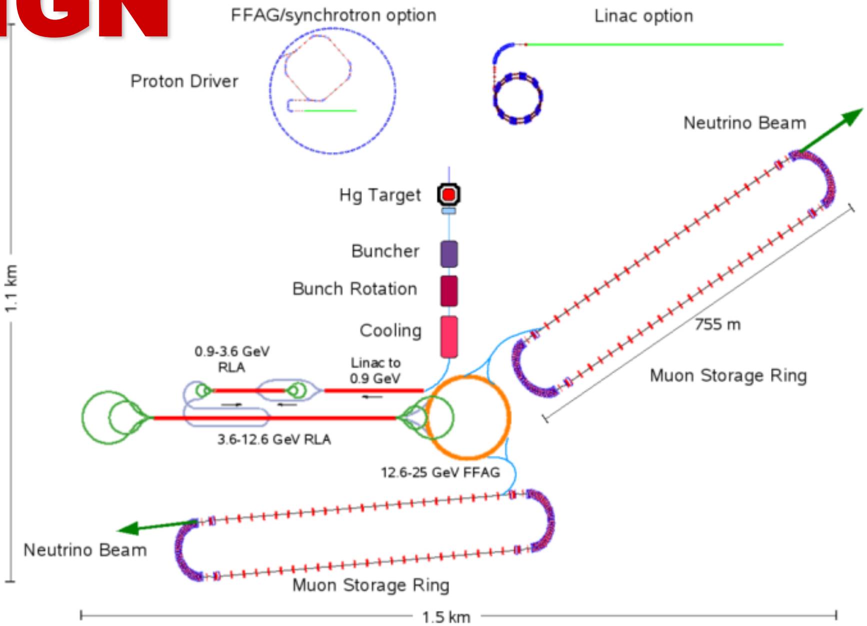
NOW

Time (Yrs)		
5-10	Do neutrinos follow the same *mass hierarchy* as all other fermions?	sign(Δm^2_{32})
10-20	Do ν's and $\bar{\nu}$'s oscillate the same? (CP violation)	δ_{CP}
10-20	Do neutrinos have a Majorana mass term?	$\beta\beta 0\nu > 0$
10-40	Do sterile neutrinos exist?	Precision measts of all the above, new oscillations or new neutral objects that interact only with gravity. except for small mixing with active ν's
50?	What are their masses (active and sterile)? (anywhere from $\leq\sim$eV to $\sim 10^{19}$eV!)	

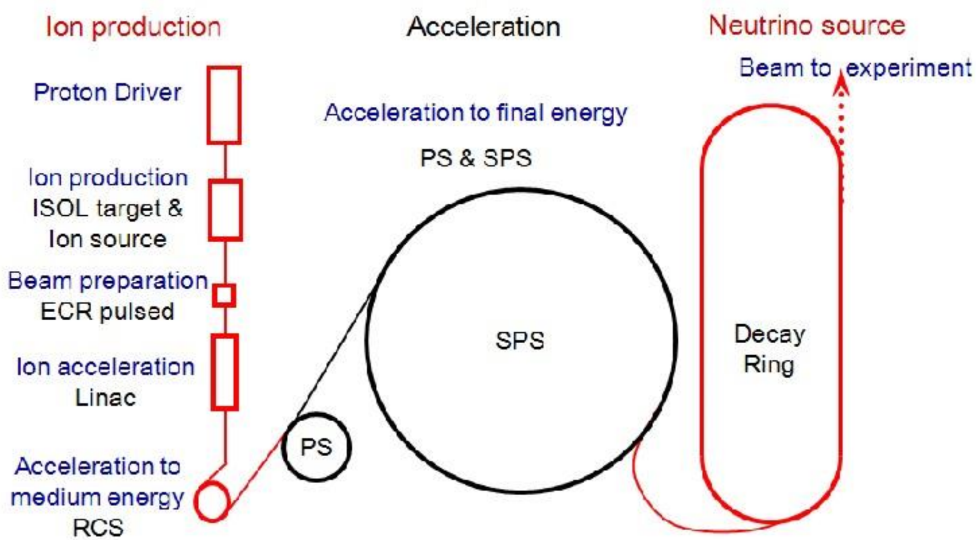
EUROν DESIGN STUDY

superbeam (pion decay)





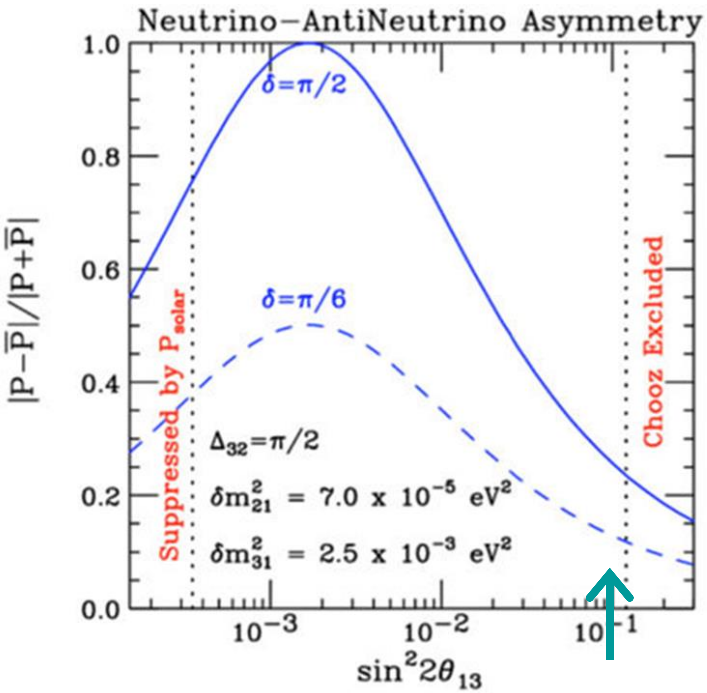
Neutrino Factory (muon decay)



Beta-beam rad-ion decay

Alain Blondel. EUCARD plenary 11-06-2013

Neutrino CP asymmetry



$$\frac{P(\nu_\mu \rightarrow \nu_e) - P(\overline{\nu}_\mu \rightarrow \overline{\nu}_e)}{P(\nu_\mu \rightarrow \nu_e) + P(\overline{\nu}_\mu \rightarrow \overline{\nu}_e)}$$

-- requires high intensity beam of both polarities
-- baseline of 500-1500km*E_ν(GeV)
-- large mass detector w e/μ separation
-- with θ_{13} large:
A_{CP} is small (max~20%)
background is low, but….

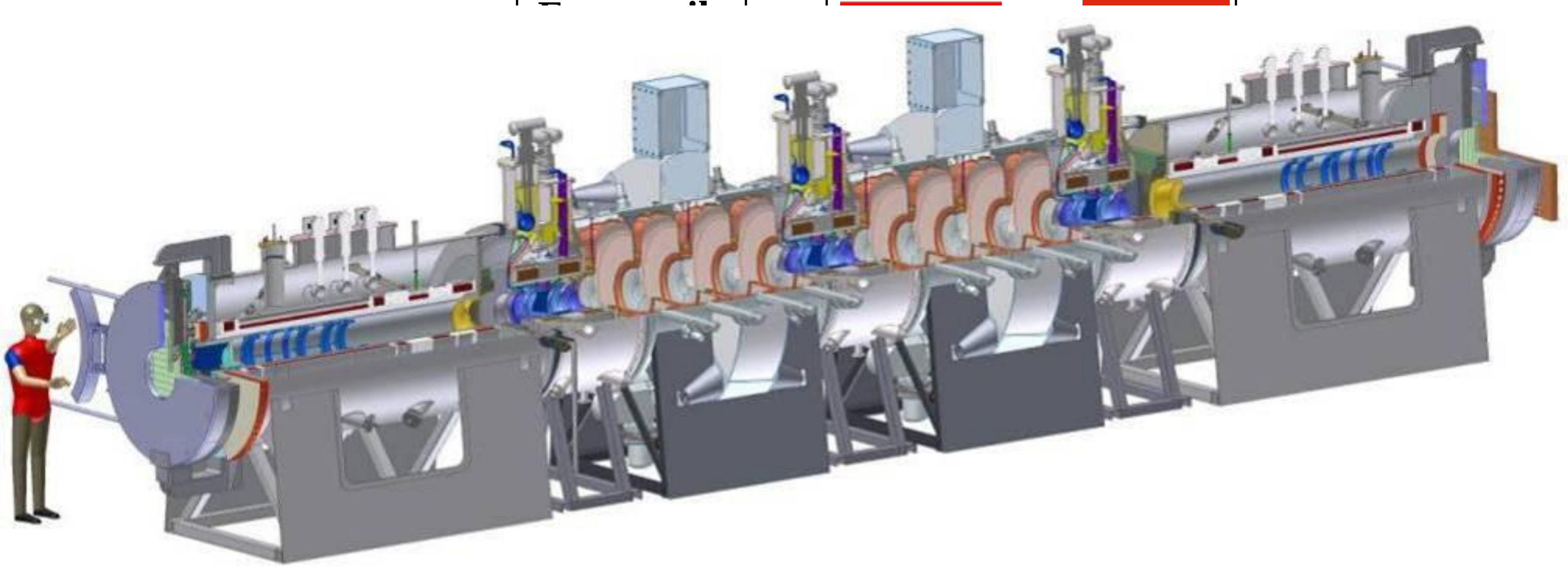
-- Sensitive to double ratio of cross-sections

$$RR = \frac{\nu_e/\nu_\mu}{\overline{\nu}_e/\overline{\nu}_\mu}$$ very poorly known presently

Probably requires combination of
-- a high statistics conventional beam (horn focused superbeam)
e.g. CERN→ Pyhasalmi, T2HK, Fermilab to DUSEL, ESS to ?
-- a precision cross-section experiment
-- eventually a facility that combines the two: neutrino factory

MICE Collaboration across the planet

Coupling Coils 1&2



Cherenkovs

Diffuser

Liquid Hydrogen absorbers 1,2,3

TOF 2, KL
EMR

Incoming muon beam

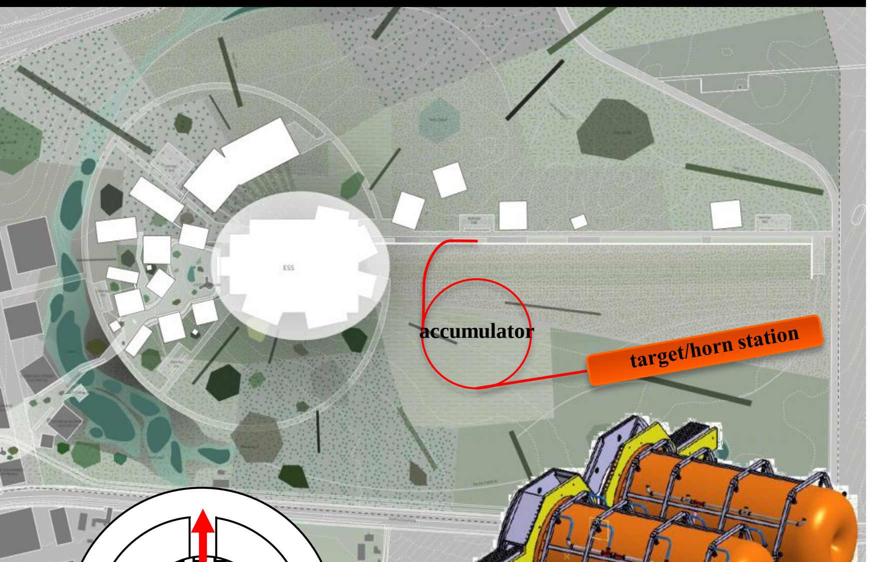
Trackers 1 & 2

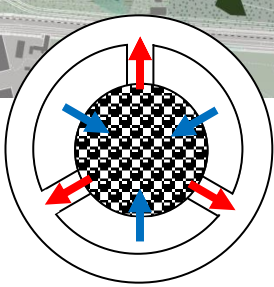
EuCARD

High statistics
= High beam power * high detector mass
2-4MW >50-100kton

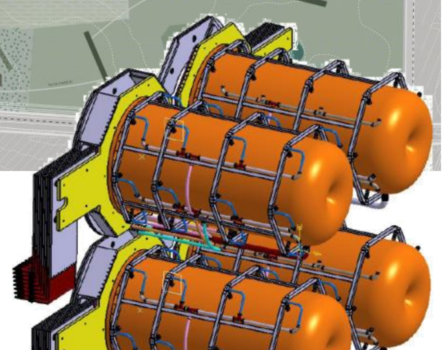
Get the beam power where it is
-- why not the 5MW ESS? (Ekelof, Dracos)
-- make a neutrino superbeam as in EUROnu

Get the Large Underground neutrino detector
-- why not one of LAGUNA options?

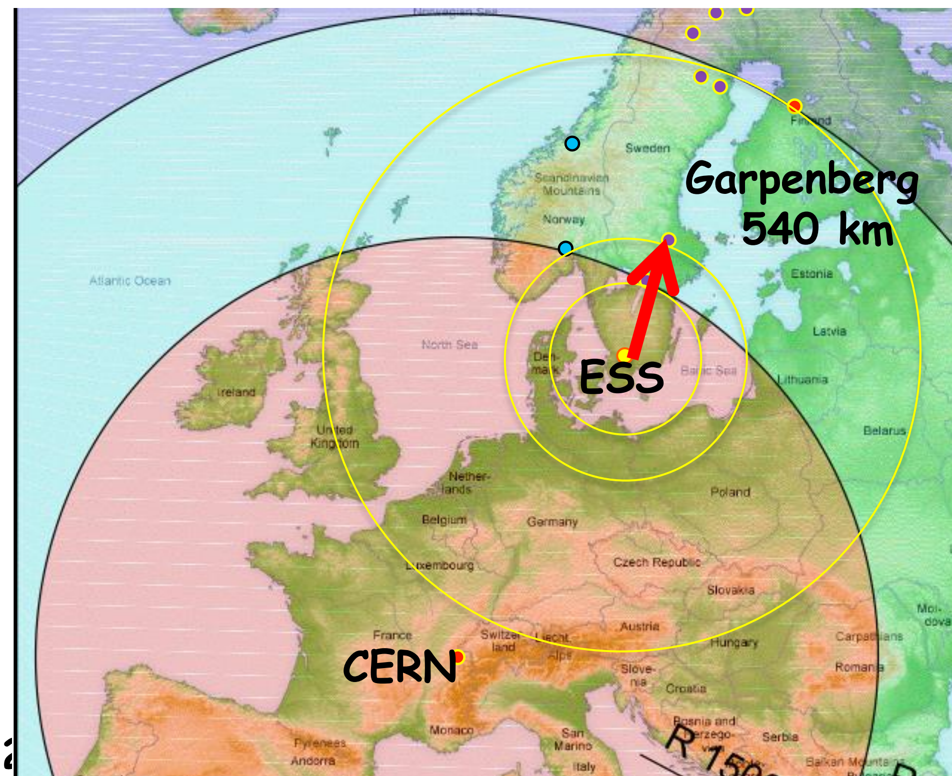




Helium cooled ball target

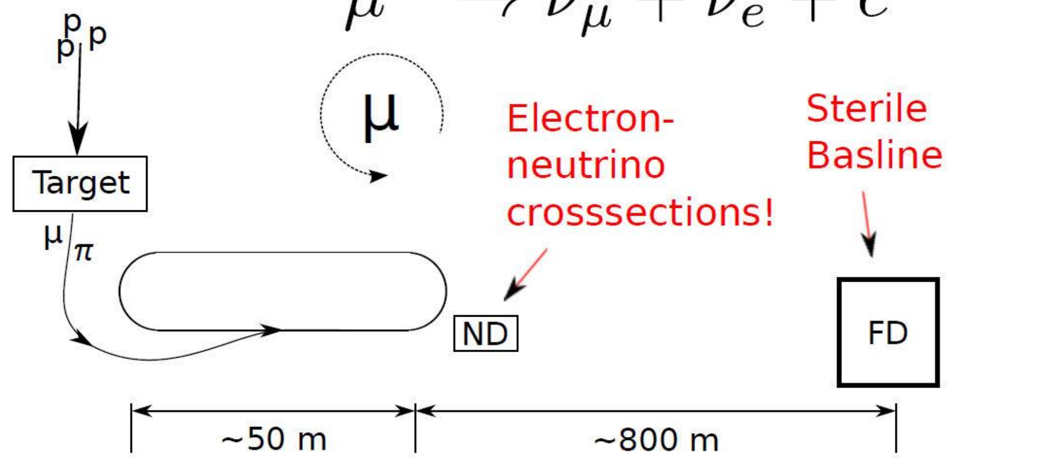


4-horn neutrino beam



νSTORM: neutrinos from stored muons
➔ first step towards neutrino factory and muon collider

$$\mu^+ \rightarrow \bar{\nu}_\mu + \nu_e + e^+$$

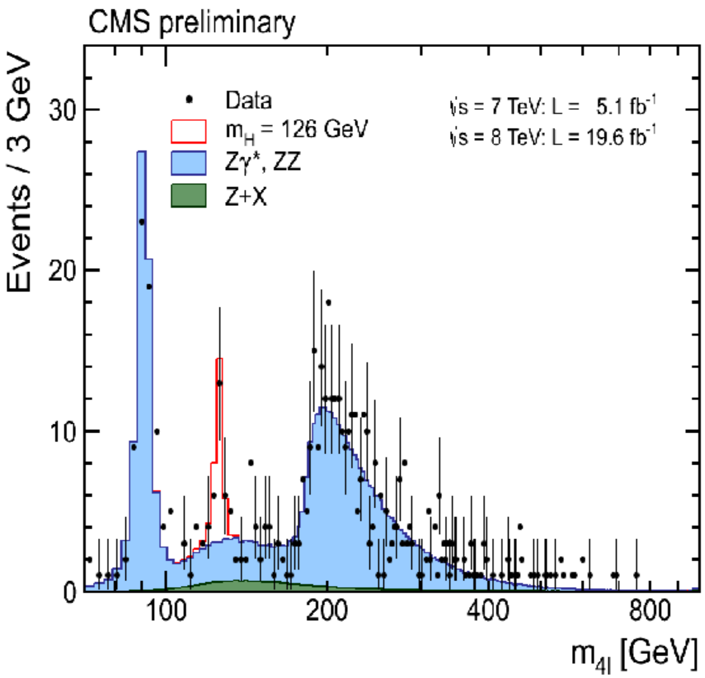


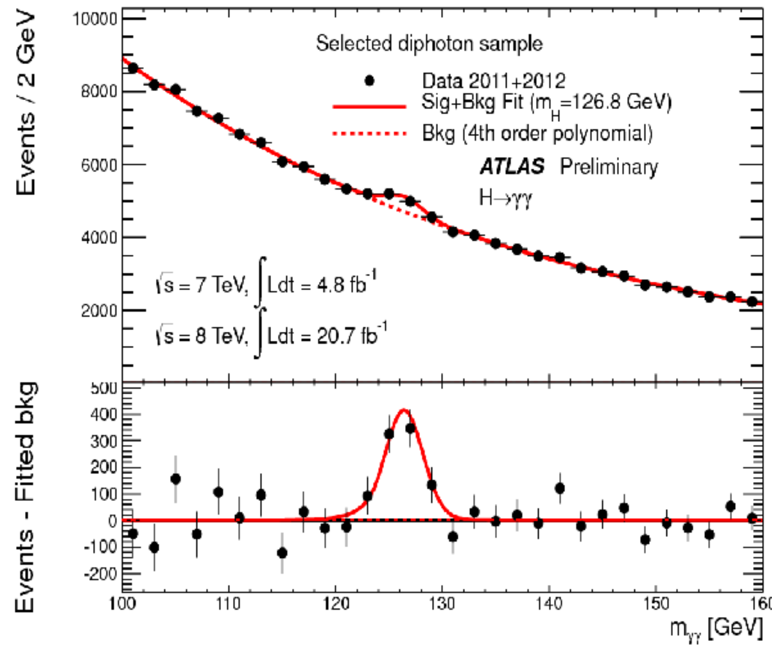
Clean solution of LSND 'sterile neutrino'

Precision measurements of cross-sections (E=0.5-3 GeV)

Proposal at Fermilab last week and at CERN 25 June

HIGH ENERGY FRONTIER

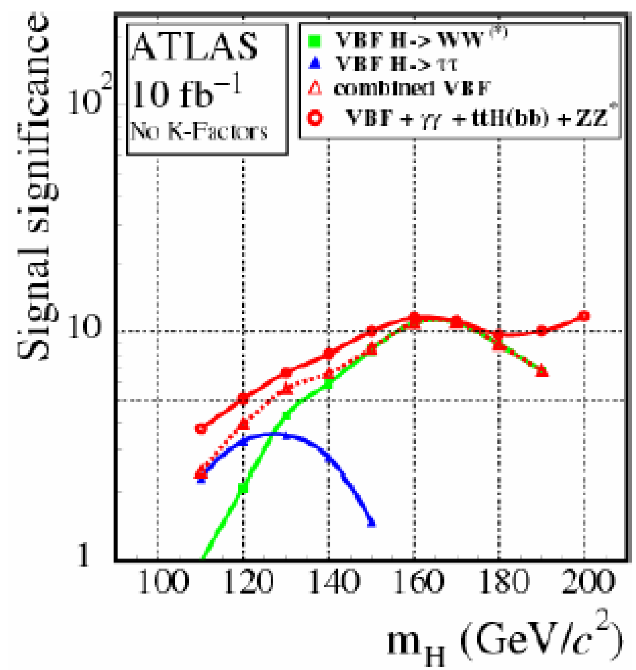


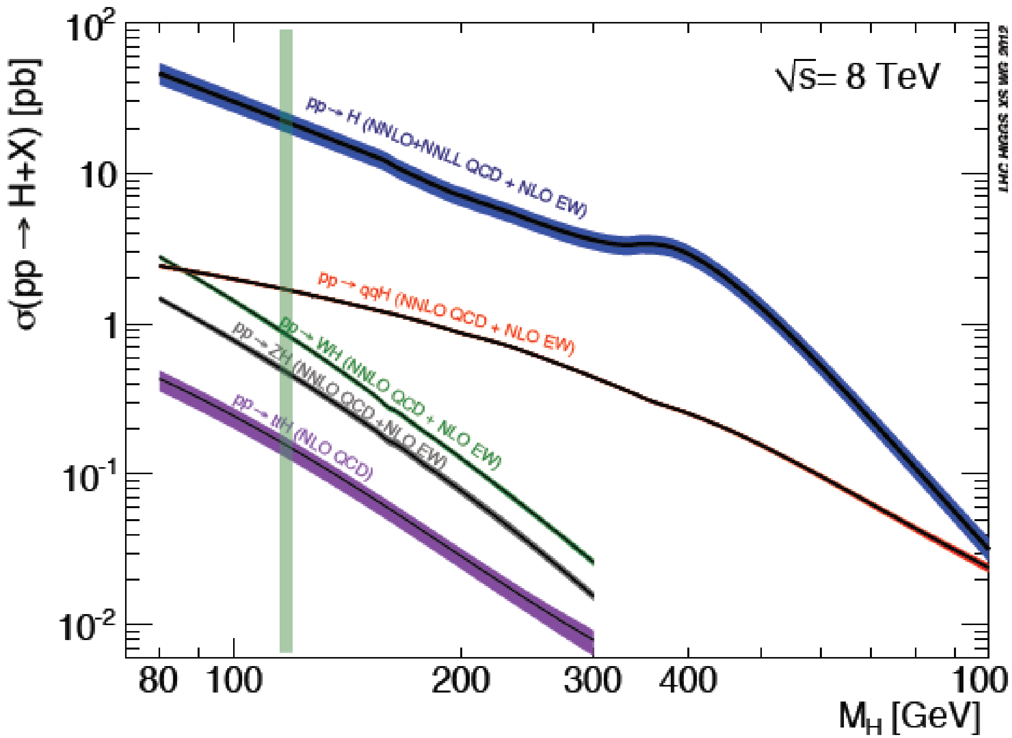


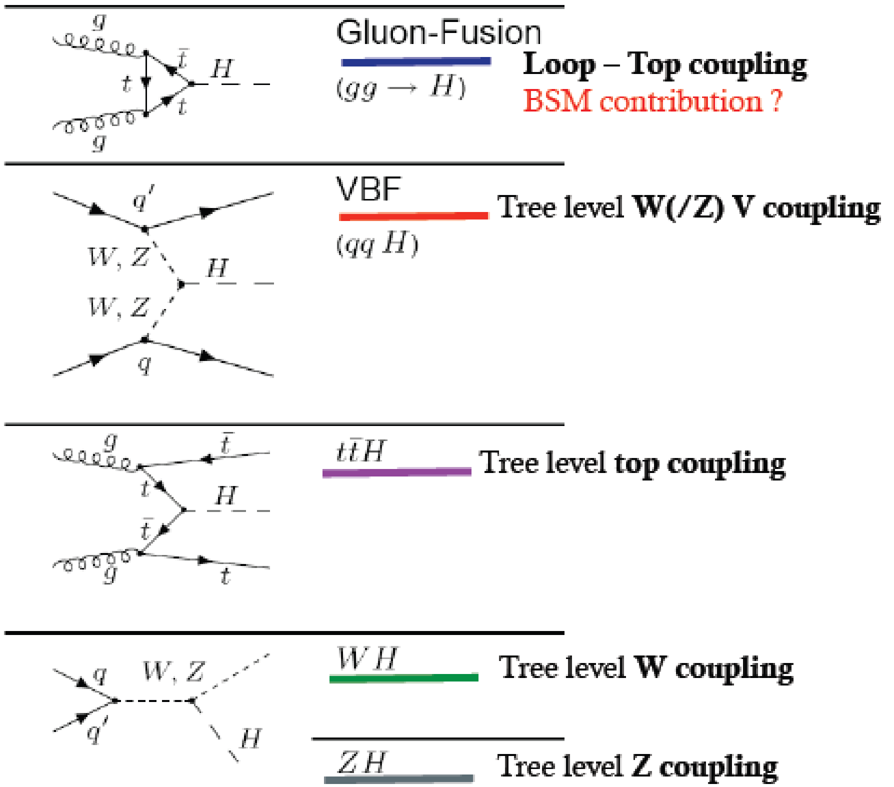
1. Scalar boson H(126) has been discovered!

2. LHC detectors have done much better than projected →

here is a plot from ATLAS in 2005, expected 3-4σ with 10fb-1 at 14TeV







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.

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

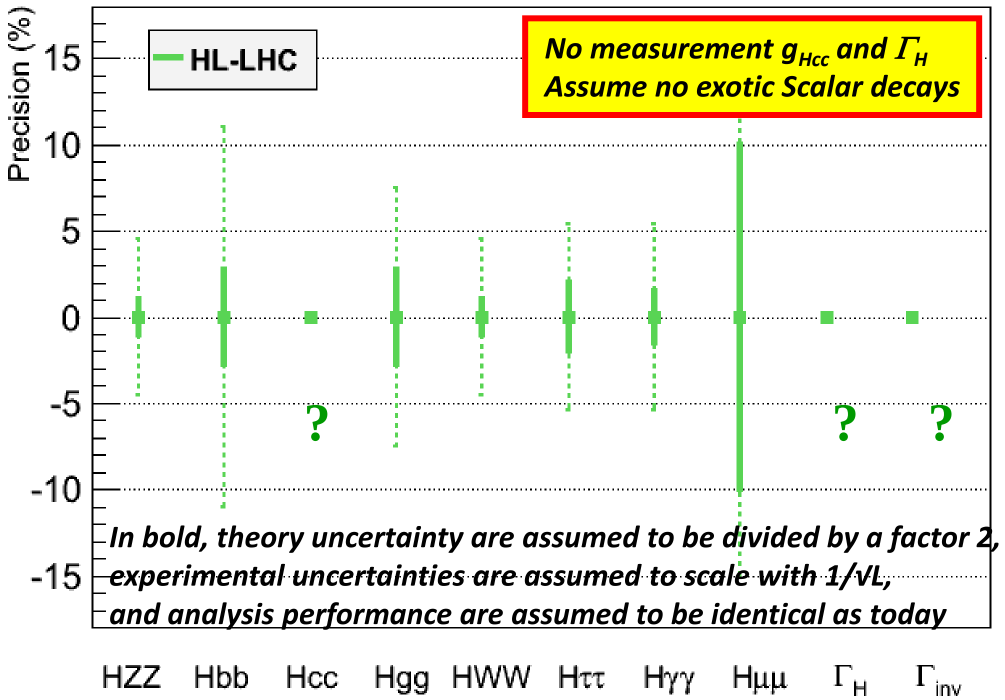
extract couplings to anything you can see or produce from if i=f as in WZ with H→ ZZ → absolute normalization

HL-LHC (≡3 ab^{-1} at 14 TeV):

Highest-priority recommendation from European Strategy

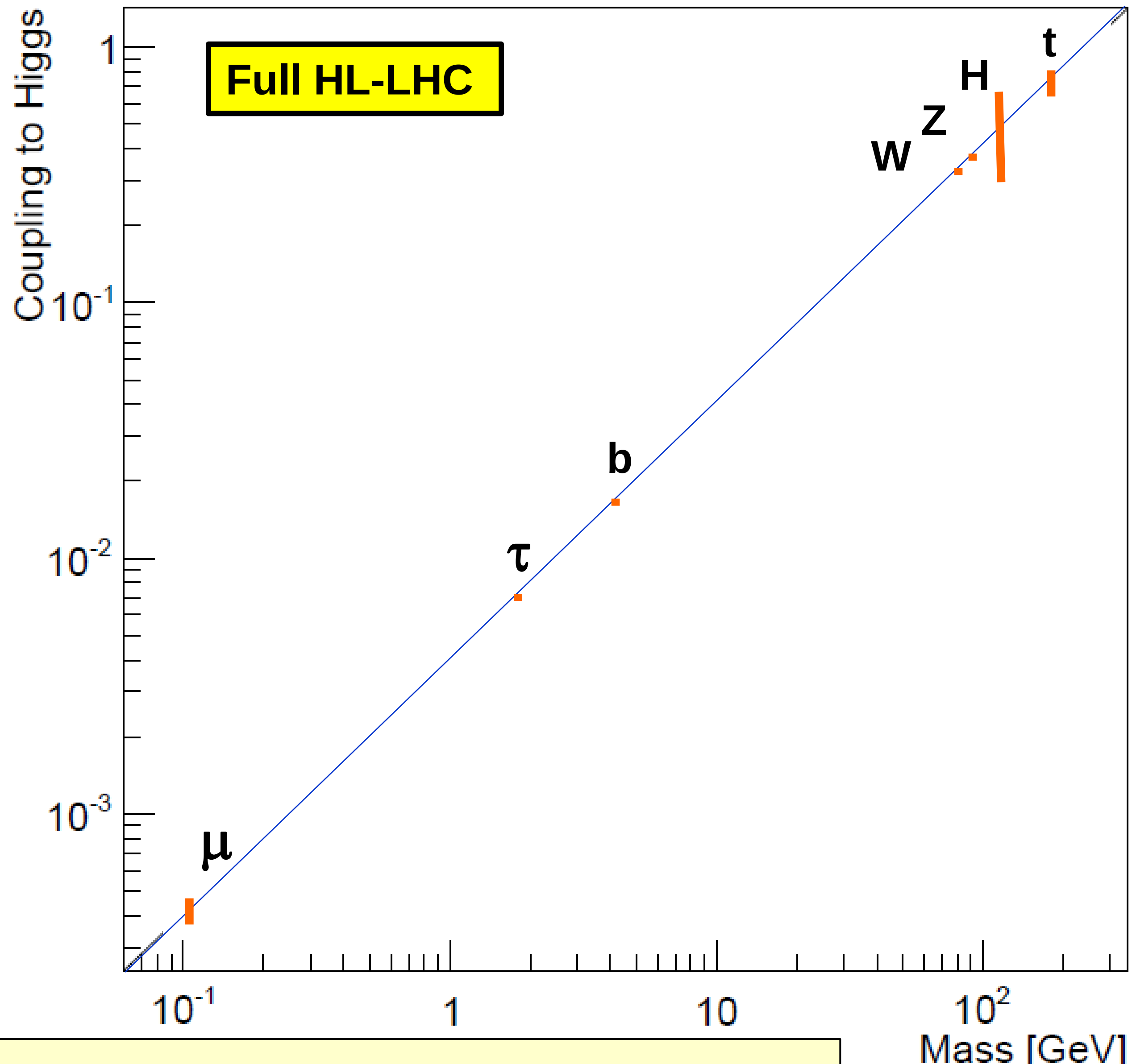
c) The discovery of the Higgs boson is the start of a major programme of work to measure this particle's properties with the highest possible precision for testing the validity of the Standard Model and to search for further new physics at the energy frontier.
The LHC is in a unique position to pursue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



Coupling measurements with precision :

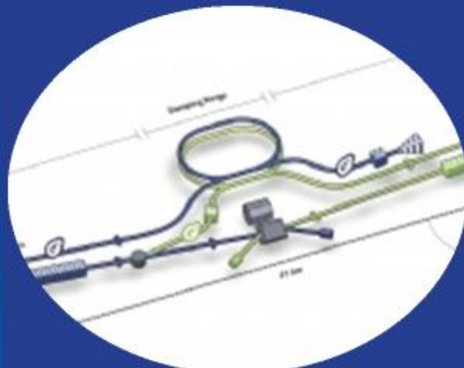
- **in the range 6-15% with LHC - 300 fb^{-1}**
- **in the range 1-4% with HL-LHC - 3000 fb^{-1}**

B. Mele

Higgs Factories

Linear Colliders

- ILC
- CLIC
- SLC-type
- Adv. Concepts

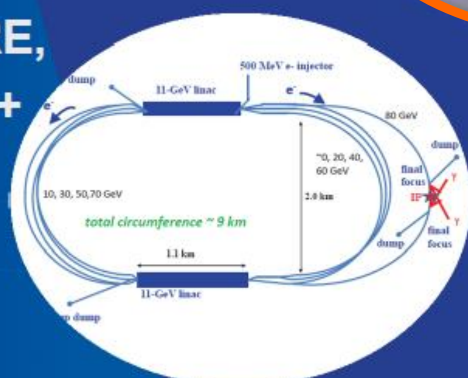


Circular e^+e^- Colliders

- LEP3
- TLEP
- Super-Tristan
- FNAL Site-filler
- IHEP, +
- …

γ-γ Colliders

- SAPPHIRE,
- CLICHÉ, +
- …



Muon Colliders

v

v

$\mu^+\mu^-$ Collider as Higgs Factory

- A $\mu^+\mu^-$ collider can do things that an e^+e^- collider cannot do
  - Direct coupling to H expected to be larger by a factor m_μ/m_e

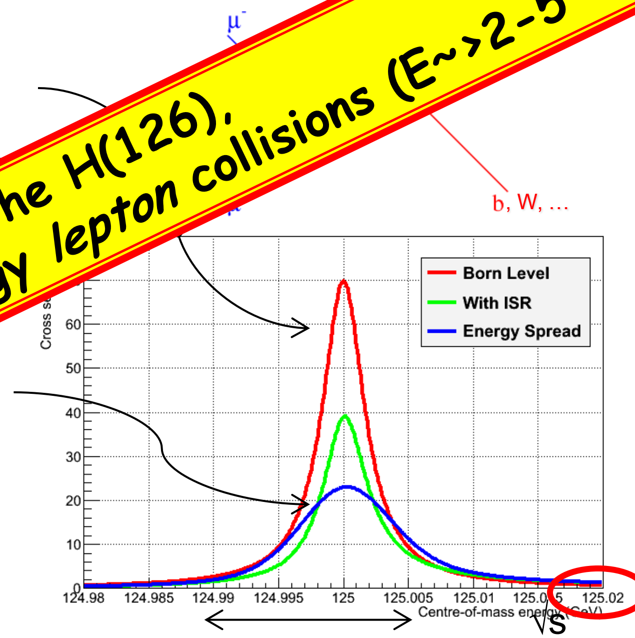
$$\sigma(\mu^+\mu^- \to H) \approx 40000 \times \sigma(e^+e^- \to H)$$

[σ_{peak} = 70 pb at tree level]

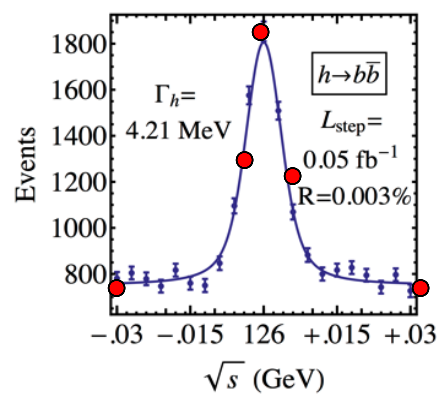
  - Can it be built + beam energy spread $\delta E/E$ be reduced to 3×1…
    - 4D+6D Cooling needed!
    - For $\delta E/E$ = 0.003% (δE ~ 3.6 MeV, Γ_H ~ 4…
    - no beamstrahlung, reduced brem…
      - Corresponding lumi… s^{-1}
      - Expect 2300… …s in 100 pb^{-1}/ year
  - Using g-2 prece… …and energy spectrum
    - Can… …exquisite precision (<10 keV)
    - …electrons of muon decays
    - …e the detailed lineshape of the Higgs at $\sqrt{s}$ ~ m_H
    - …ive-point scan, 50 + 100 + 200 + 100 + 50 pb^{-1}

m_H	σ_{Peak}	Γ_H
0.1 MeV	0.6 pb	0.2 MeV
10^{-6}	2.5%	5%

As will be seen e+e- collider can probably do the job for the H(126), but the muon collider remains the best road to high energy lepton collisions (E~>2-5 TeV)

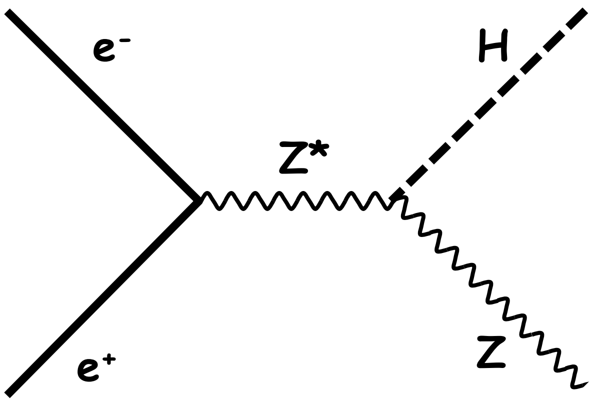


σ(m_H), TLEP



Higgs Production Mechanism in e+ e- collisions

H(126) 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.



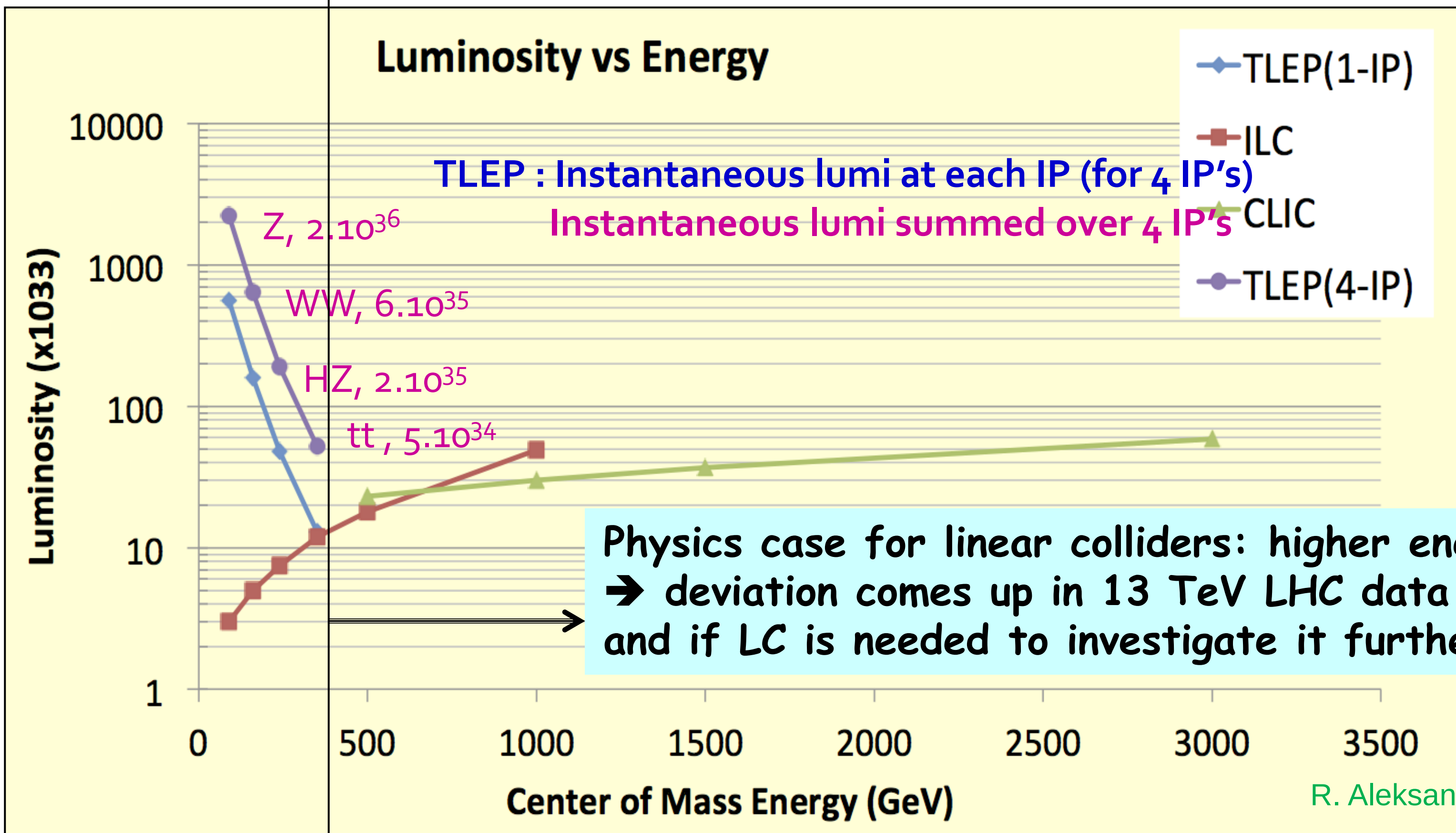
Z – tagging by missing mass
➔ a beam of Higgs bosons

Precision ➔ 1M events ➔ 5 years * $10^{35}/cm^2/s$

Sensitivity to exotic/invisible decays (dark matter?)

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

Performance of e+ e- colliders



Physics case for linear colliders: higher energy!
➔ deviation comes up in 13 TeV LHC data
and if LC is needed to investigate it further.

Physics case for circular colliders
Measure precisely (e.g. masses to fraction of MeV)
known particles (TeraZ, OkuW, MegaH and tops)
to see evidence for new phenomena.

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. CLIC numbers from Ref [11-12].

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}) 500 GeV (500 fb^{-1}) 1.4 TeV (2 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} 3 yrs (*)
N_H	1.7×10^7	1.7×10^8	6×10^4 ZH	10^5 ZH 1.4×10^5 Hνν		4×10^5 ZH	2×10^6 ZH
m_H (MeV)	100	50	35	35	~70	26	7
$\Delta\Gamma_H / \Gamma_H$	--	--	10%	3%	6%	4%	1.3%
$\Delta\Gamma_{inv} / \Gamma_H$	Indirect (30%?)	Indirect (10% ?)	1.5%	1.0%	--	0.35%	0.15%
$\Delta g_{H\gamma\gamma} / g_{H\gamma\gamma}$	6.5 – 5.1%	5.4 – 1.5%	--	5%	N/A	3.4%	1.4%
$\Delta g_{Hgg} / g_{Hgg}$	11 – 5.7%	7.5 – 2.7%	4.5%	2.5%	N/A	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%	~20%	--	--
$\Delta g_{H\mu\mu} / g_{H\mu\mu}$	< 30%	< 10%	--	--	15%	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%	4%	2.0%	0.65%
$\Delta g_{Hbb} / g_{Hbb}$	15 – 6.9%	11 —2.7%	1.4%	1%	2%	0.7%	0.22%
$\Delta g_{Htt} / g_{Htt}$	14 – 8.7%	8.0 – 3.9%	--	15%	3%	--	30%

HL-LHC ~ as good as LCs

Best precision

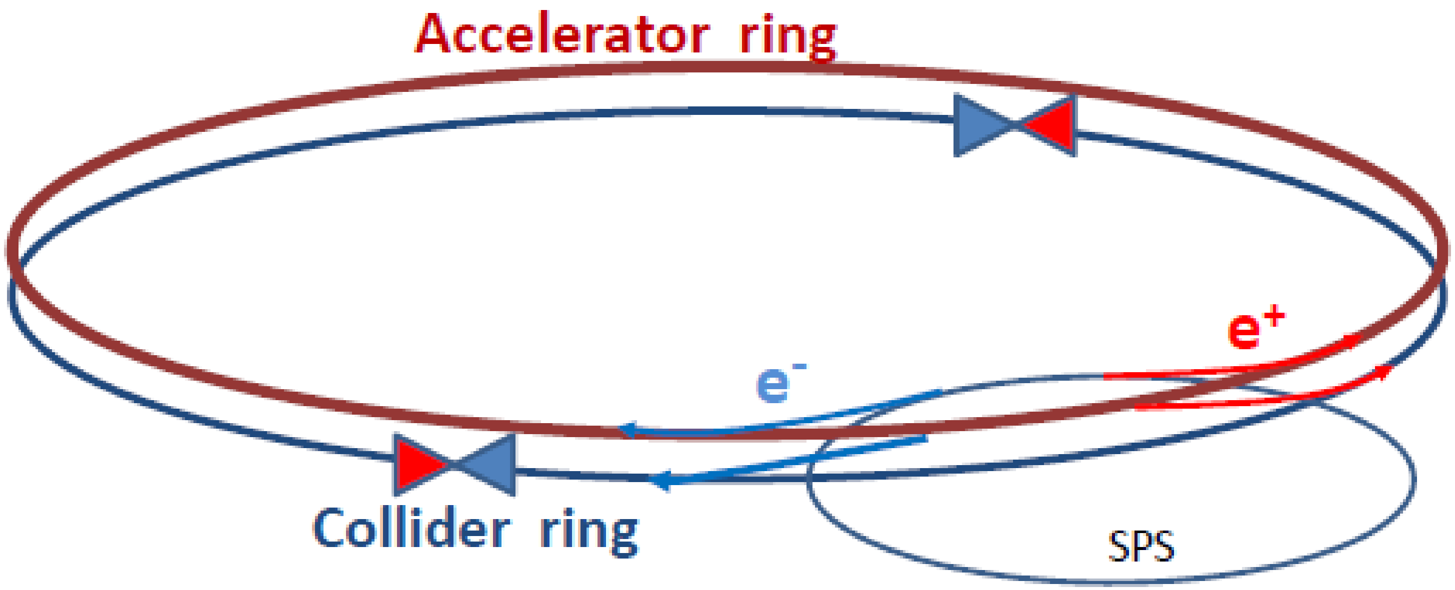
How can one increase over LEP 2 (average) luminosity by a factor 500 without exploding the power bill?

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)

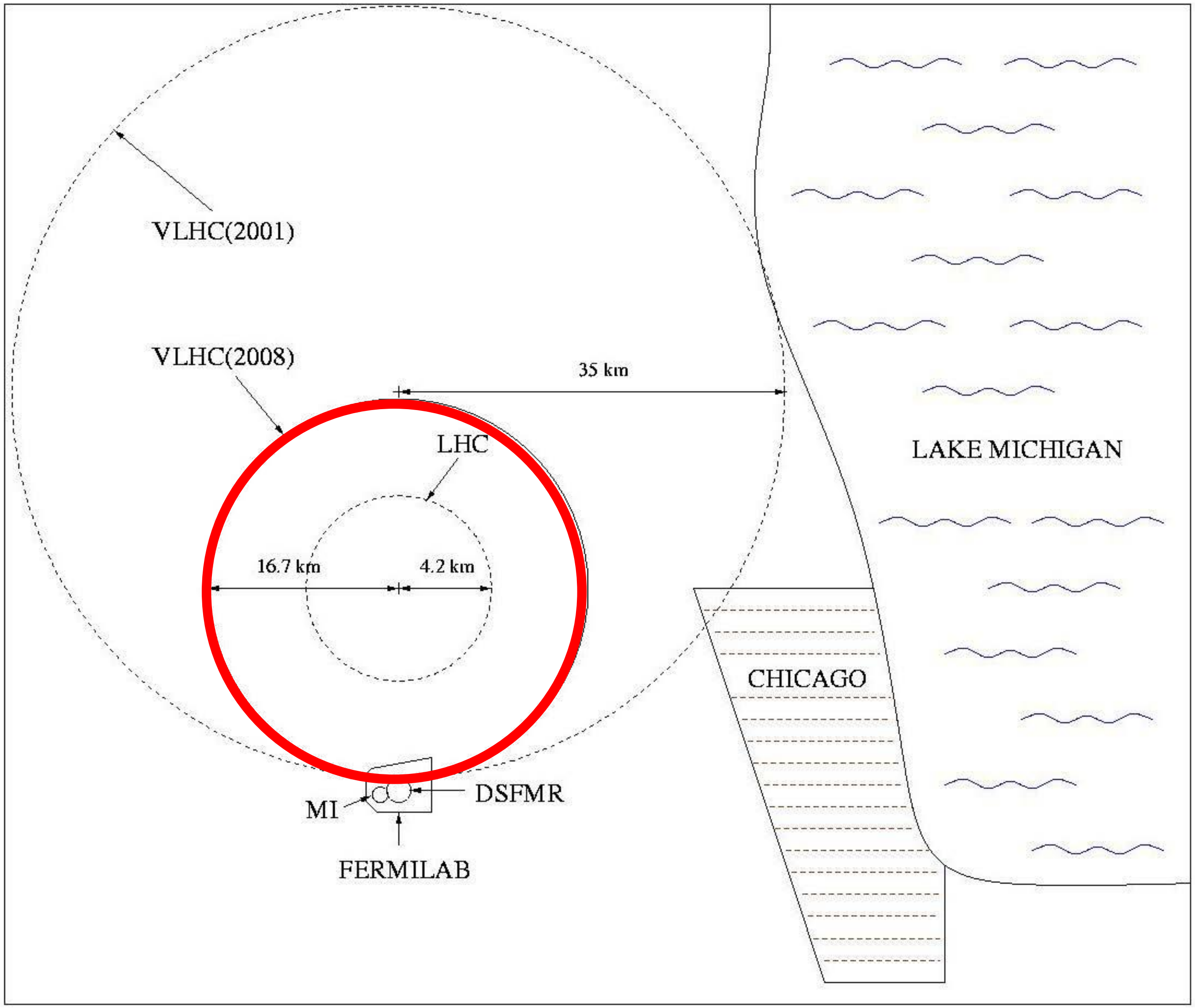
➔ feed beam continuously with a ancillary accelerator



Storage ring has separate beam pipes for e+ and e- for multibunch operation
Going to even higher luminosities with charge compensation?

80 km ring in KEK area

105 km tunnel near FNAL

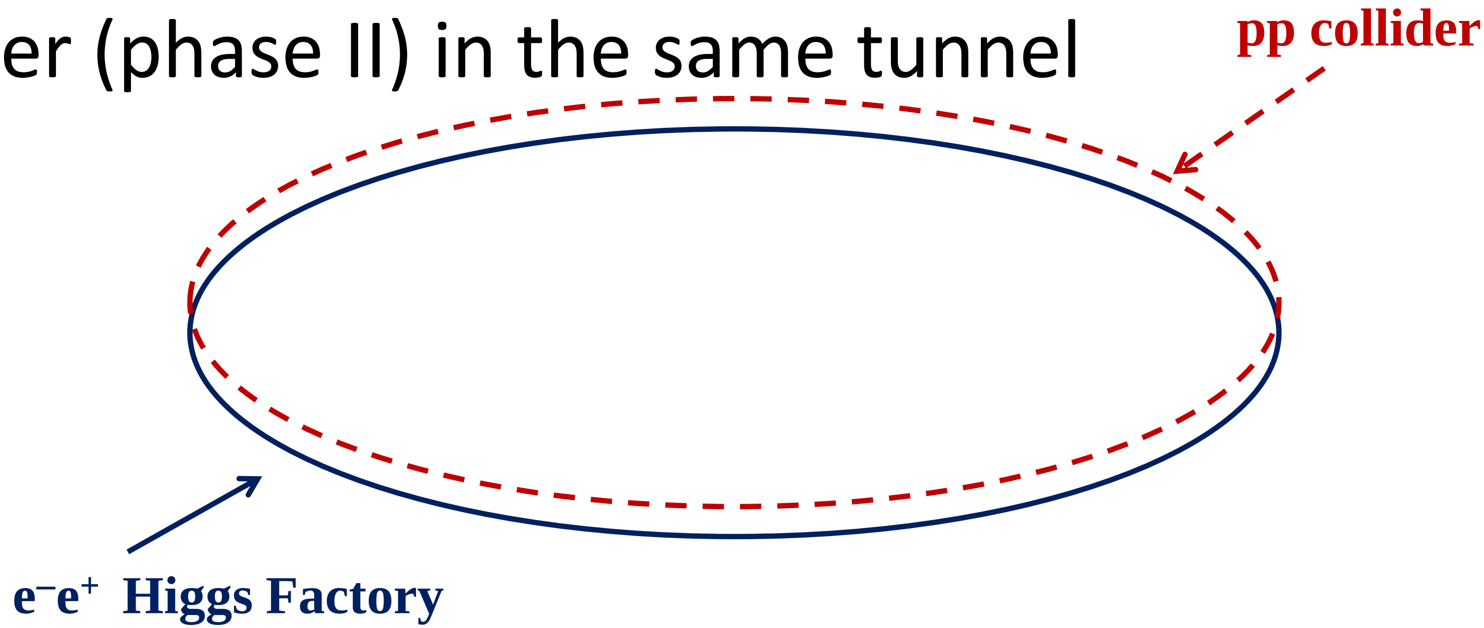


(+ FNAL plan B from R. Talman)

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

What is a (CHF + SppC)

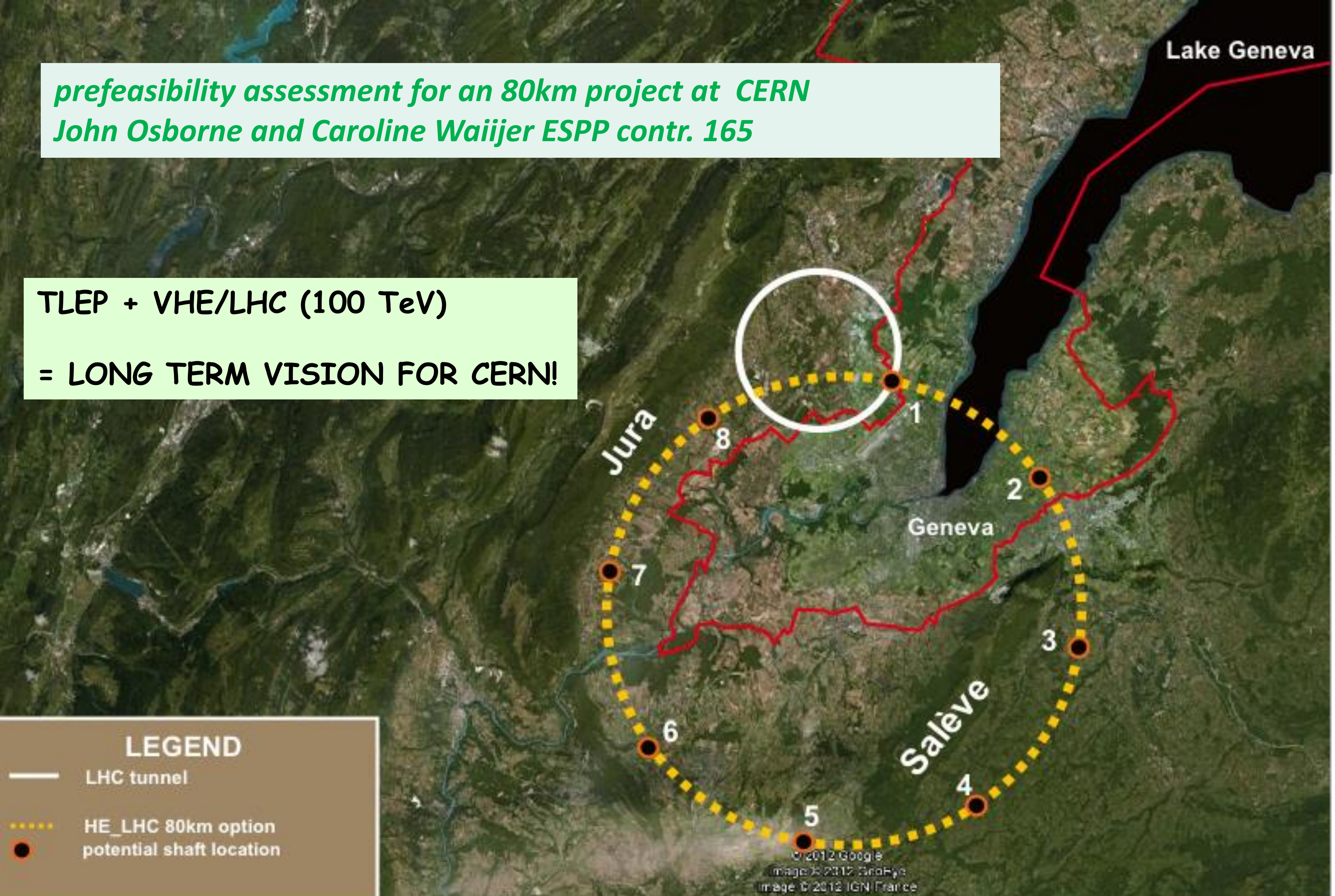
Circular Higgs factory (phase I) + super pp collider (phase II) in the same tunnel



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

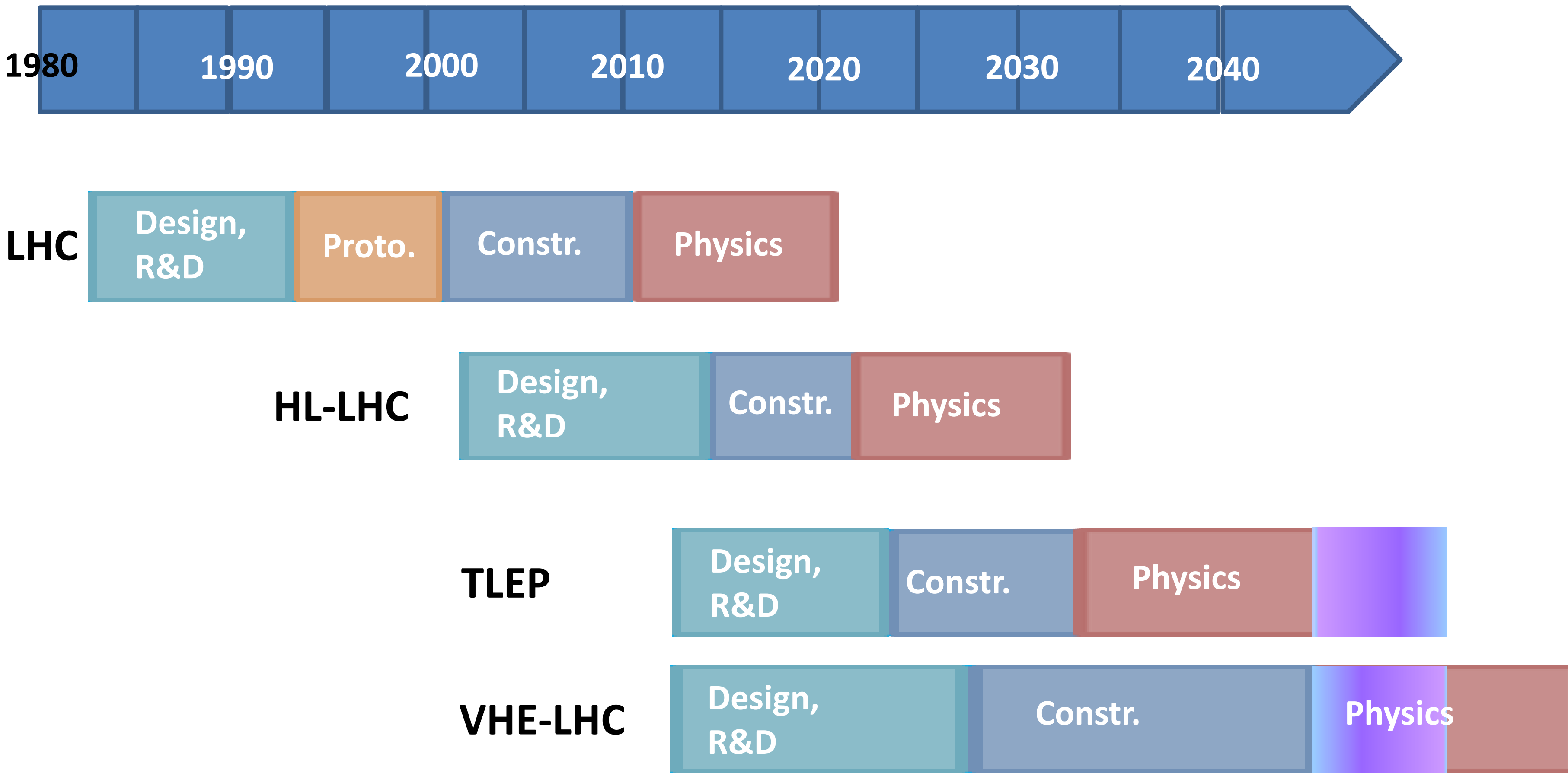
TLEP + VHE/LHC (100 TeV)

= LONG TERM VISION FOR CERN!



tentative time line

Zimmermann, Rossi, Aleksan etc…



At the moment we do not know 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!

Conclusions and outlook (my own view)

Particle physics with accelertors for the next 50 years

The last two years have seen two major discoveries in particle physics

The discovery of large θ_{13} $\nu_\mu \rightarrow \nu_e$ transitions (T2K, Daya Bay)

-- opens the way for a long term future in neutrino physics

→Mass hierarchy, CP violation, sterile neutrino search in a wide mass range.

-- intense and precise neutrino sources will be required

Superbeam, vSTORM, (possibly) Neutrino Factory, etc…

➔ 50 Years of neutrino experiments to come!

The discovery of the H(126) scalar boson opens the way to precise investigations

-- HL-LHC

-- a lepton collider of sufficient luminosity

-- best performance with an e+e- circular machine TLEP in a large (80km) tunnel that could pave the way to a Very Large Hadron Collider (100 TeV)

-- but is limited in energy reach

-- recommend choice vs LC when LHC results at 13 TeV available → 2017-18

in 2035 the LEP/LHC tunnel will have been used for 46 years….

the TLEP/VHE-LHC tunnel would be used for > 50 years!

Accelerator R&D is more than ever crucial to keep options open,

keeping an open mind that final choice of project

will depend on physics arguments and circumstances

Alain Blondel. EUCARD plenary 11-06-2013

Sterile neutrino search a global view:

Detected by mixing between sterile and active neutrino

ideal experiments:

source

known process

$\nu_{active,\ \alpha}$

detector

known process

$\nu_{sterile}$

$\nu_{active,\ \beta}$

if $\nu_{sterile}$ cannot be produced (too heavy) apparent **deficit in decay rate**

Heavy flavour decays… could even be Z or H invisible width (high energy research)

1. disappearance, not necessarily oscillatory best is **NC disappearance**

2. $\nu_\alpha \rightarrow \nu_\beta$ **appearance** (at higher order)

These will be precision experiments
-- high intensity (protons, targets)
-- precisely known flux (neutrino factories)
-- all energies concerned

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, <u>in collaboration with national institutes, laboratories and universities worldwide</u>.

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 <u>in both fields</u>, together with vigorous accelerator R&D supported by <u>adequate resources and driven by collaborations involving CERN and national institutes, universities and laboratories worldwide</u>. 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. <u>A large tunnel such as this could also host a circular e^+e^- machine (TLEP) reaching energies up to 350 GeV with high luminosity</u>.

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 14

The first 200 subscribers:

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

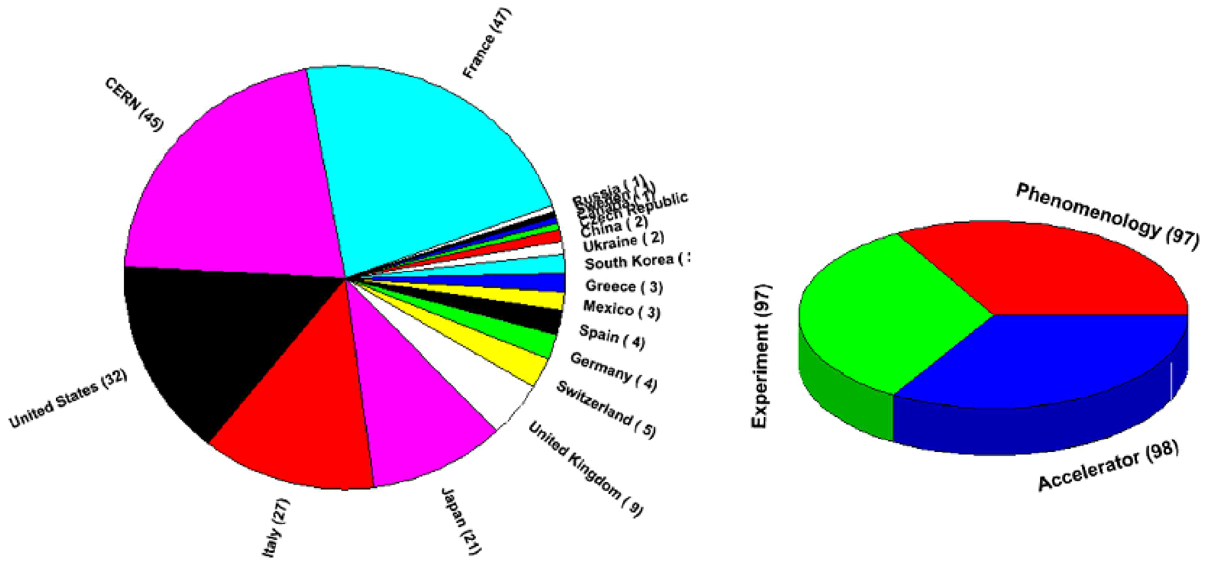


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Figure 1 Left : distribution of the first 200 subscribers on the basis of the institute's country. Right: distribution between accelerator, experiment and phenomenology.

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

J.Ellis

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