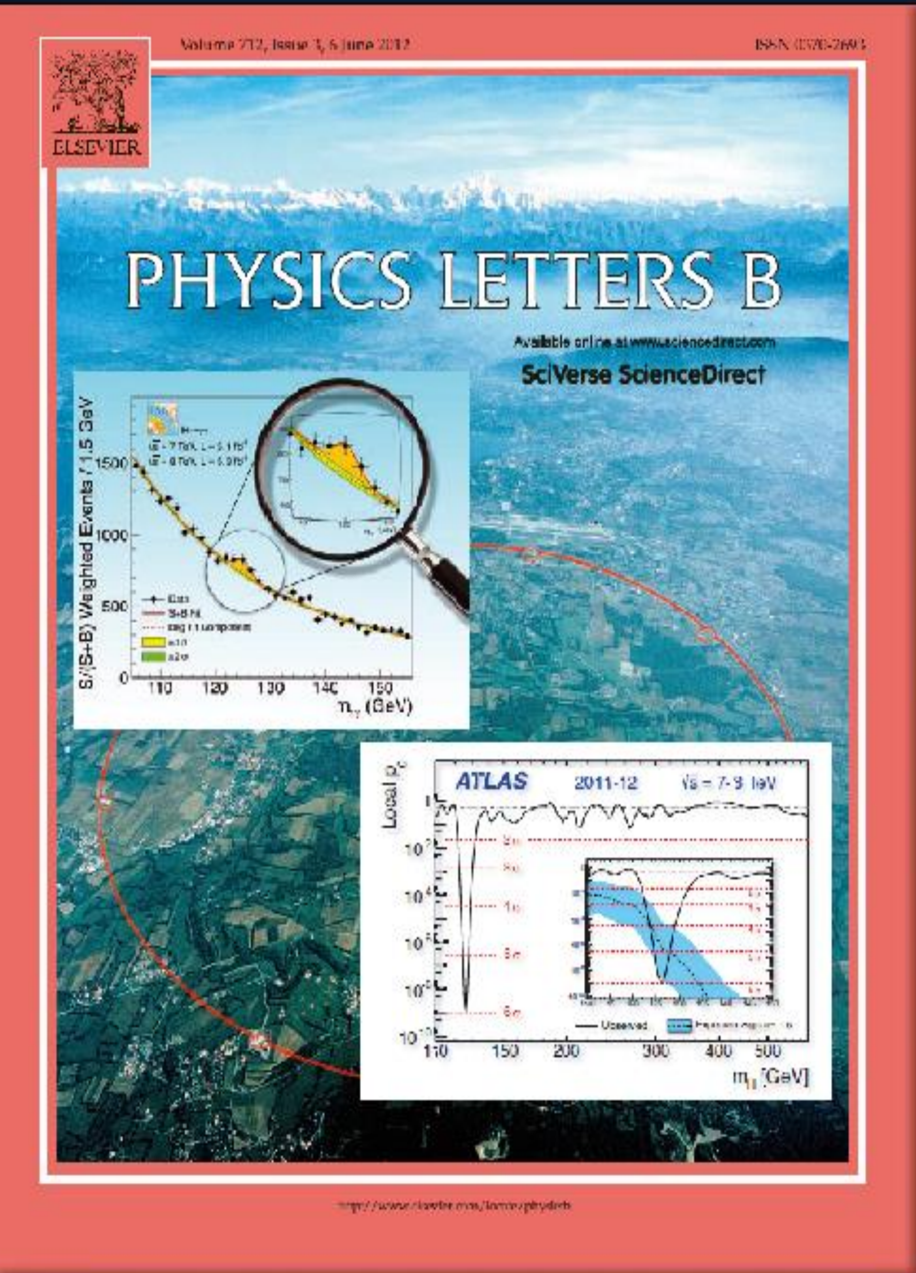
FUTURE COLLIDERS

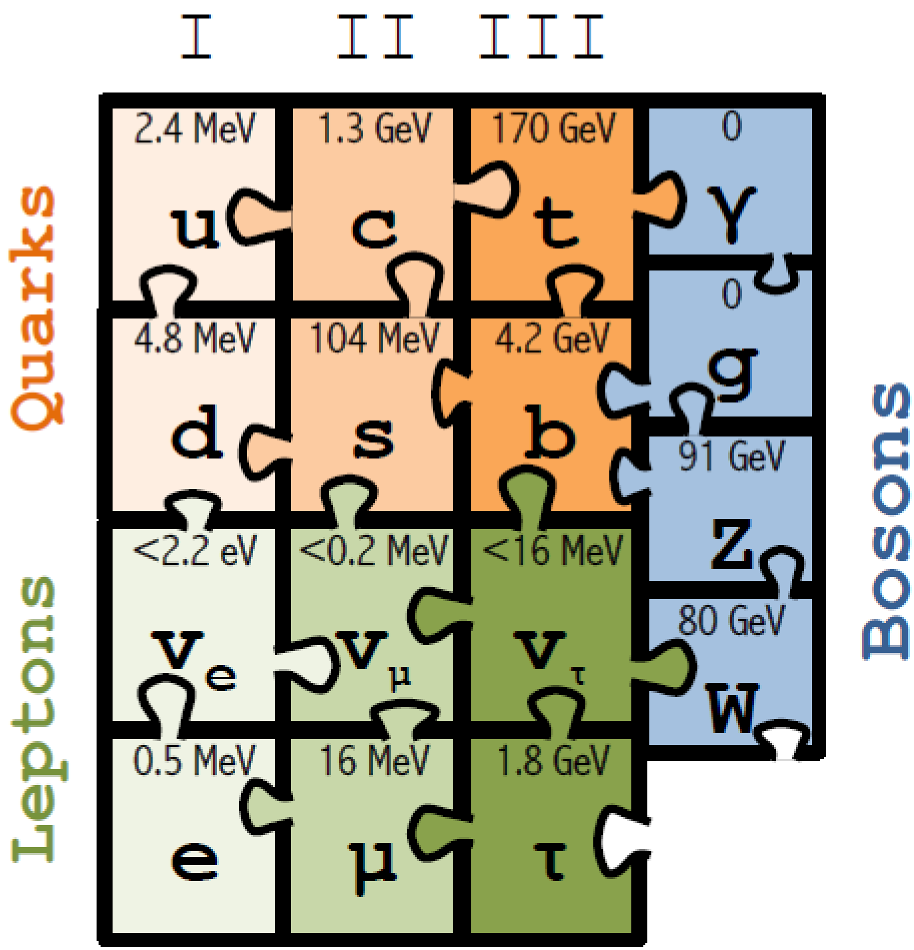
Skeikampen, 6 January 2018

Alain Blondel, University of Geneva, FCC coordination group

SIX YEARS AGO ALREADY



1994-1999: top mass predicted (LEP, mostly Z mass&width)
top quark discovered (Tevatron)
t'Hooft and Veltman get Nobel Prize

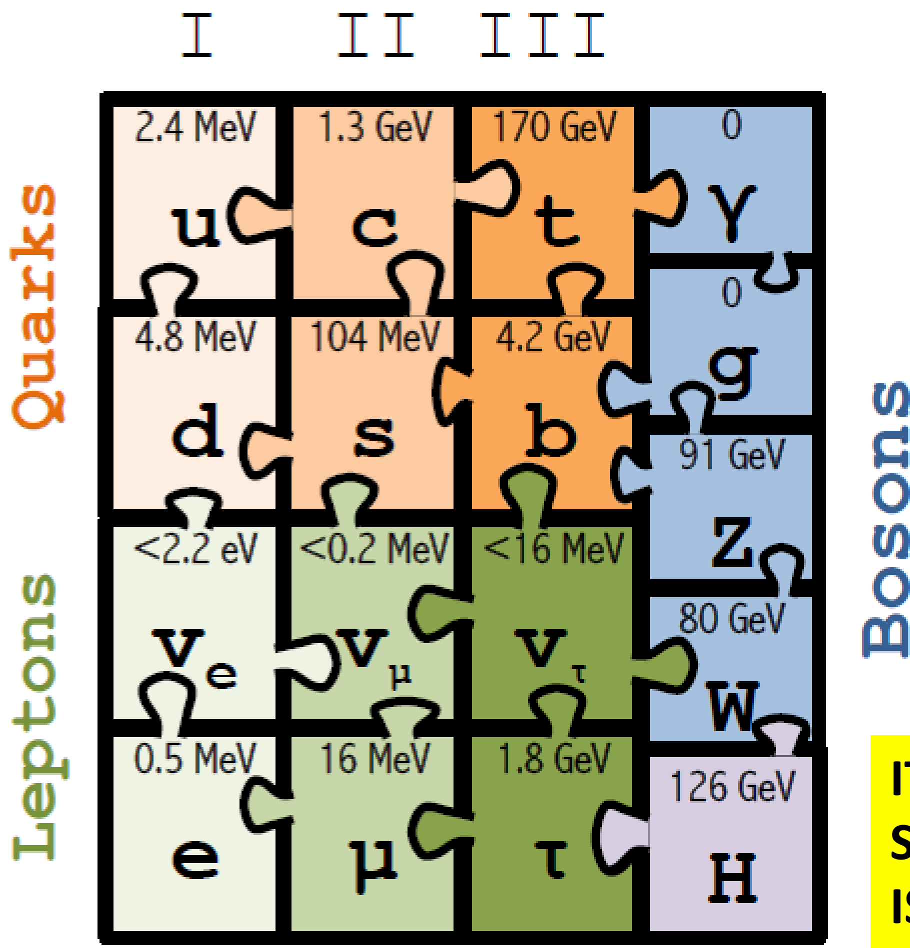


(c) Sfyrla

1997-2013 Higgs boson mass cornered (LEP H, M_Z etc +Tevatron m_t , M_W)

Higgs Boson discovered (LHC)

Englert and Higgs get Nobel Prize



IT LOOKS LIKE THE STANDARD MODEL IS COMPLETE.....

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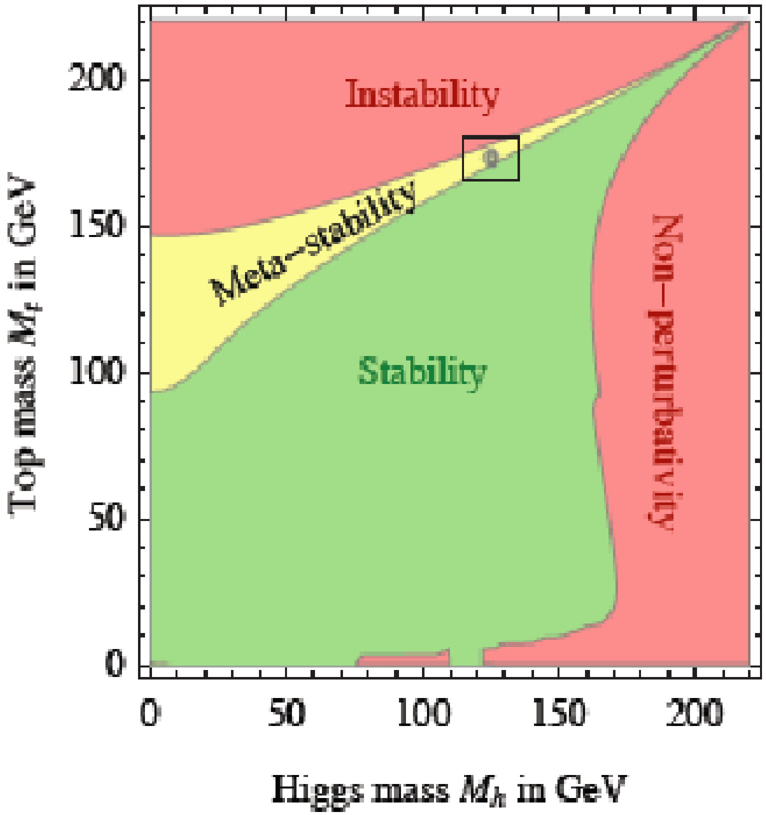
Is it the end?



Instability
Meta–stability
Stability
Non–perturbativity
Top mass M_t in GeV
Higgs mass M_h in GeV
0
50
100
150
200

Asymptotic safety of gravity and the Higgs boson mass

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12 January 2010

Abstract

There are indications that gravity is asymptotically safe. The Standard Model (SM) plus gravity could be valid up to arbitrarily high energies. Supposing that this is indeed the case and assuming that there are no intermediate energy scales between the Fermi and Planck scales we address the question of whether the mass of the Higgs boson m_H can be predicted. For a positive gravity induced anomalous dimension $A_\lambda > 0$ the running of the quartic scalar self interaction λ at scales beyond the Planck mass is determined by a fixed point at zero. This results in $m_H = m_{\min} = 126$ GeV, with only a few GeV uncertainty. This prediction is independent of the details of the short distance running and holds for a wide class of extensions of the SM as well. For $A_\lambda < 0$ one finds m_H in the interval $m_{\min} < m_H < m_{\max} \simeq 174$ GeV, now sensitive to A_λ and other properties of the short distance running. The case $A_\lambda > 0$ is favored by explicit computations existing in the literature.

Key words:
Asymptotic safety, gravity, Higgs field, Standard Model
PACS: 04.60.-m 11.10.Hi 14.80.Bn

Detecting the Higgs scalar with mass around 126 GeV at the LHC could give a strong hint for the absence of new physics influencing the running of the SM couplings between the Fermi and Planck/unification scales.

Is it the end?

Certainly not!

-- Dark matter

-- Baryon Asymmetry in Universe

-- Neutrino masses

are experimental proofs that there is more to understand.

We must continue our quest

HOW?

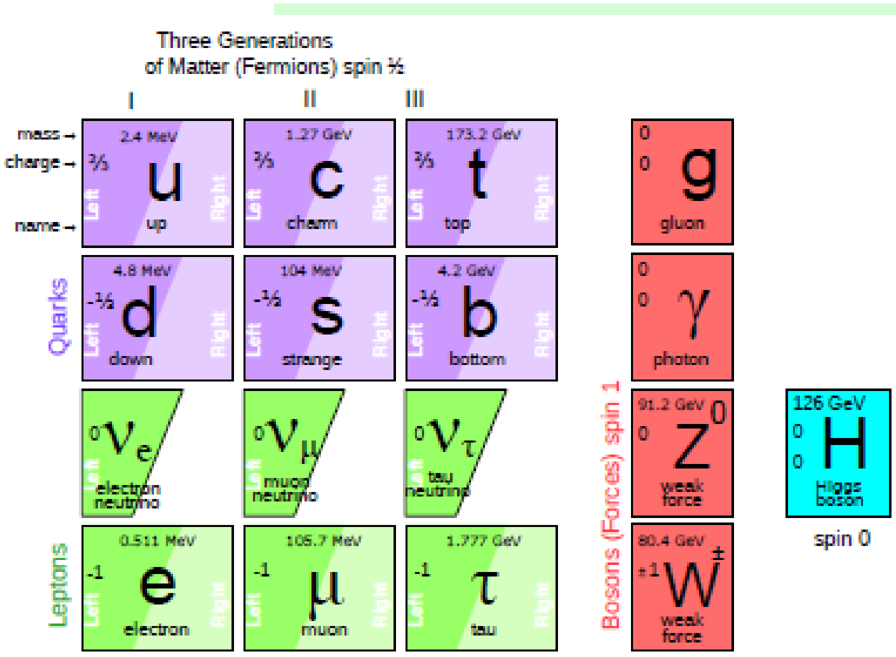
Direct observation of new particles **(but not only!)**

New phenomena **(Neutral currents, CP violation, neutrino oscillations…)**

Deviations from precise predictions

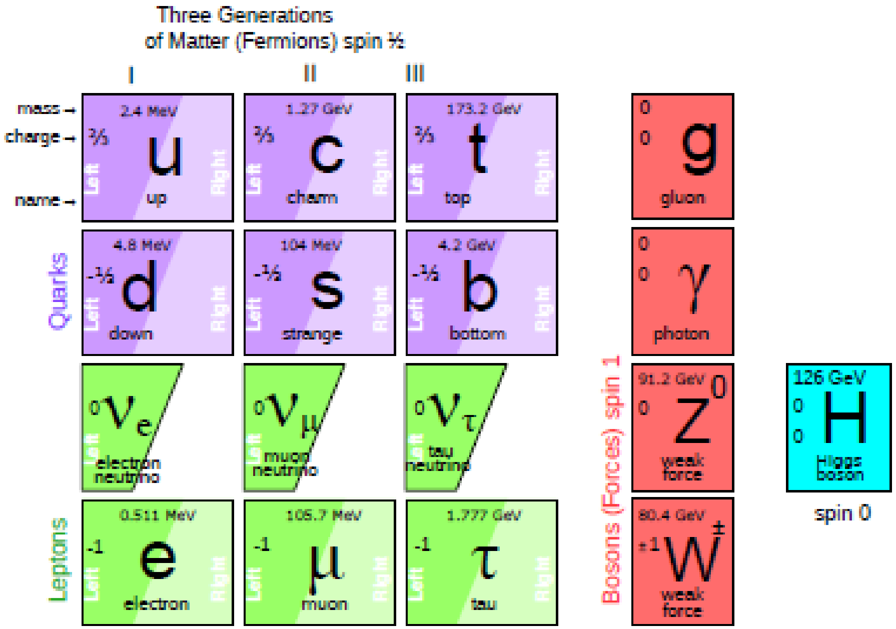
(ref. Uranus to Neptune, top and Higgs preds from LEP/SLC/Tevatron/B factories, g-2, etc…)

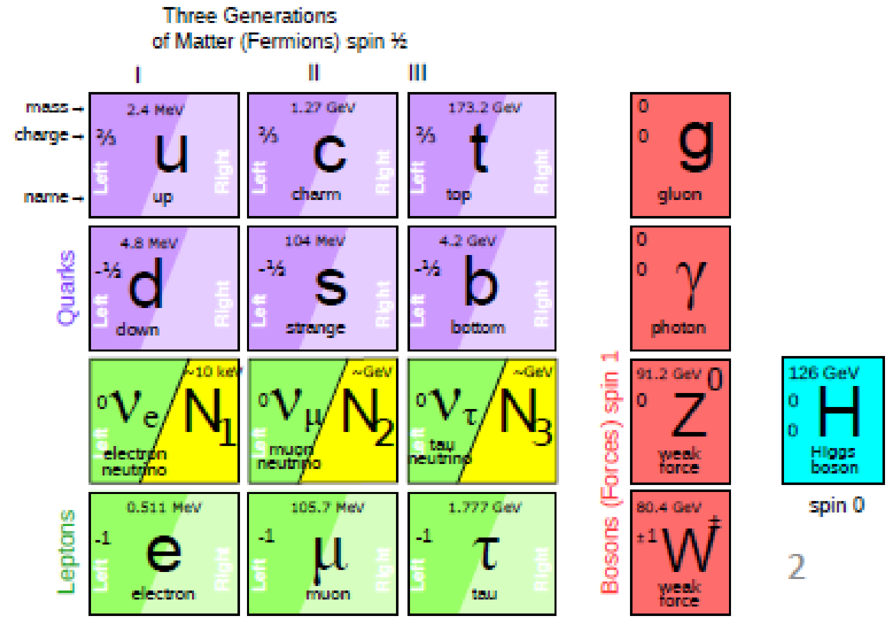
at least 3 pieces are still missing



Since 1998 it is established that neutrinos have mass and this very probably implies new degrees of freedom

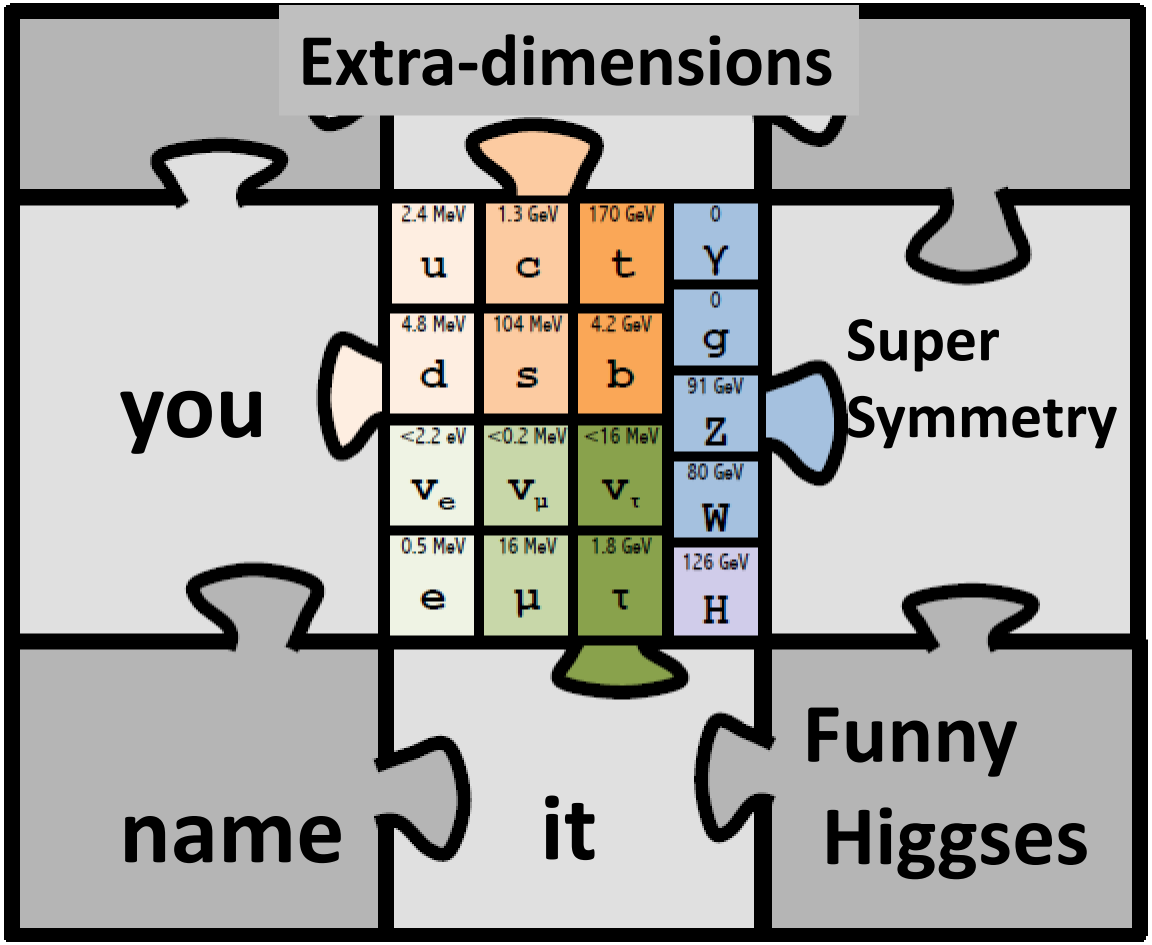
at least 3 pieces are still missing





Since 1998 it is established that neutrinos have mass
and this very probably implies new degrees of freedom
➔ «sterile», very small coupling to known particles
completely unknown masses (eV to ZeV), nearly impossile to find.
.... but could perhaps explain all: DM, BAU,ν-masses

or perhaps new world(s) of SM replicas




But Where Is Everybody?
Nima
At higher masses -- or at smaller couplings?

FUTURE ACCELERATORS

1. High Luminosity LHC (3000 fb^{-1} @ 14 TeV) → 2035

   An approved program

2. ILC/CLIC as Higgs and top factory and upgrades

   A very 'mature' study of a new technique

   'or'

2'. Circular e+e- Z,W,H,top factories (FCC)

   «Young» studies of a very mature technique

3. HE-LHC (FCC)

   apparently straightforward... but

   'or'

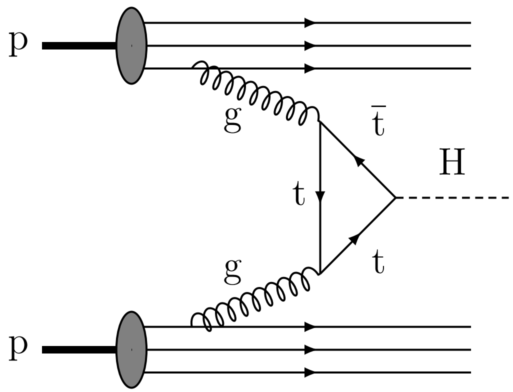
4. 100 TeV hadron collider (FCC)

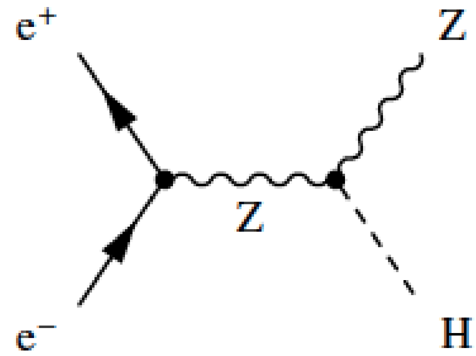
   The 'ultimate' energy exploration

4. muon collider (possibly FCC?)

   not so young but still no very mature (will briefly mention H width)

pp collisions / e^+e^- collisions





p-p collisions	e^+e^- collisions
Proton is compound object → Initial state not known event-by-event → Limits achievable precision	**e^+/e^- are point-like** → Initial state well defined (√s / polarisation) → High-precision measurements
High rates of QCD backgrounds → Complex triggering schemes → High levels of radiation	**Cleaner experimental environment** → Trigger-less readout → Low radiation levels
High cross-sections for **colored-states**	Superior sensitivity for **electro-weak states**
High-energy **circular** pp colliders feasible	High energy (>≈380 GeV) e^+e^- requires **linear** collider High precision (<≈380 GeV) best at **circular** collider

The Physics Landscape

1. we know that new physics beyond the SM is needed for
dark matter,
baryon asymmetry of the universe
neutrino masses
the fact that electron and proton have the same charge to 10^{-22} precision...
and more.

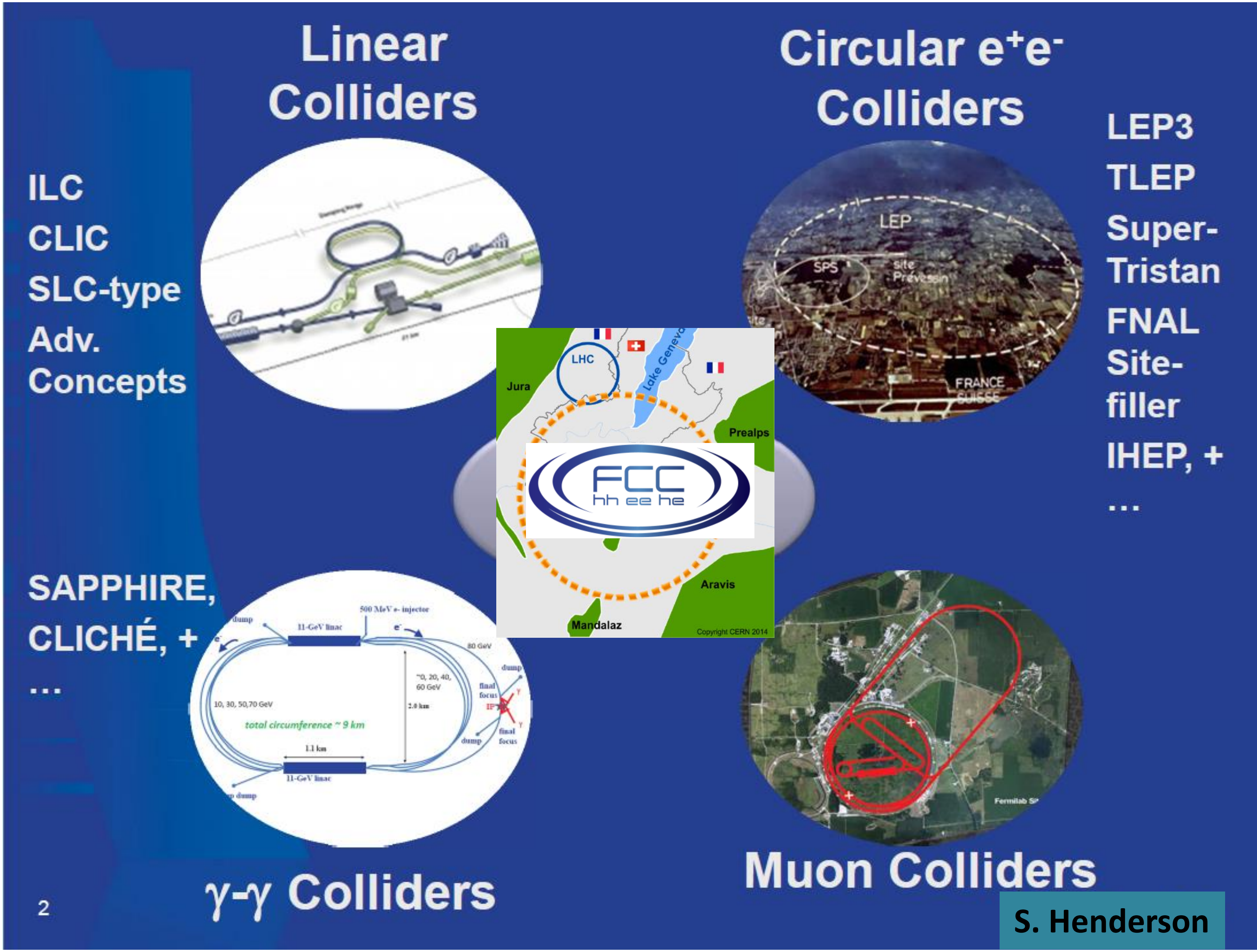
2. The Standard Model without any new particles with couplings .ge. the weak coupling works very well:
-- predicted the top and Higgs masses from m_Z vs m_W vs Γ_z vs $\sin^2\theta^{eff}_W$ etc..
-- and seems to extrapolate smoothly to the Planck scale.

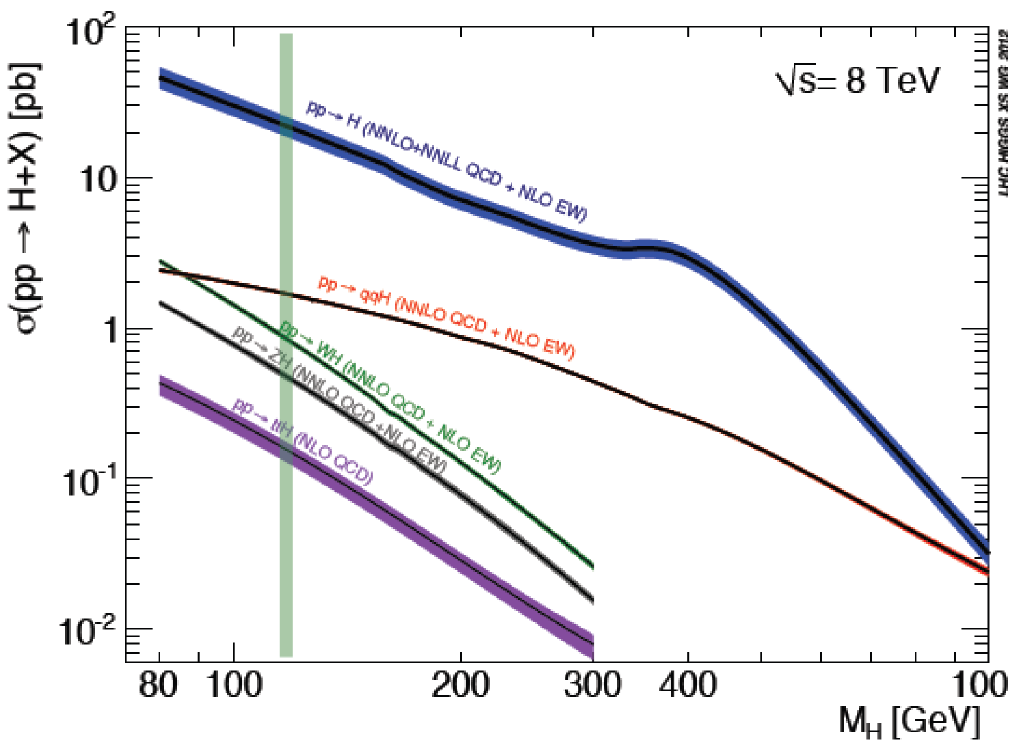
3. Fascinating situation: where to look and what will we find?

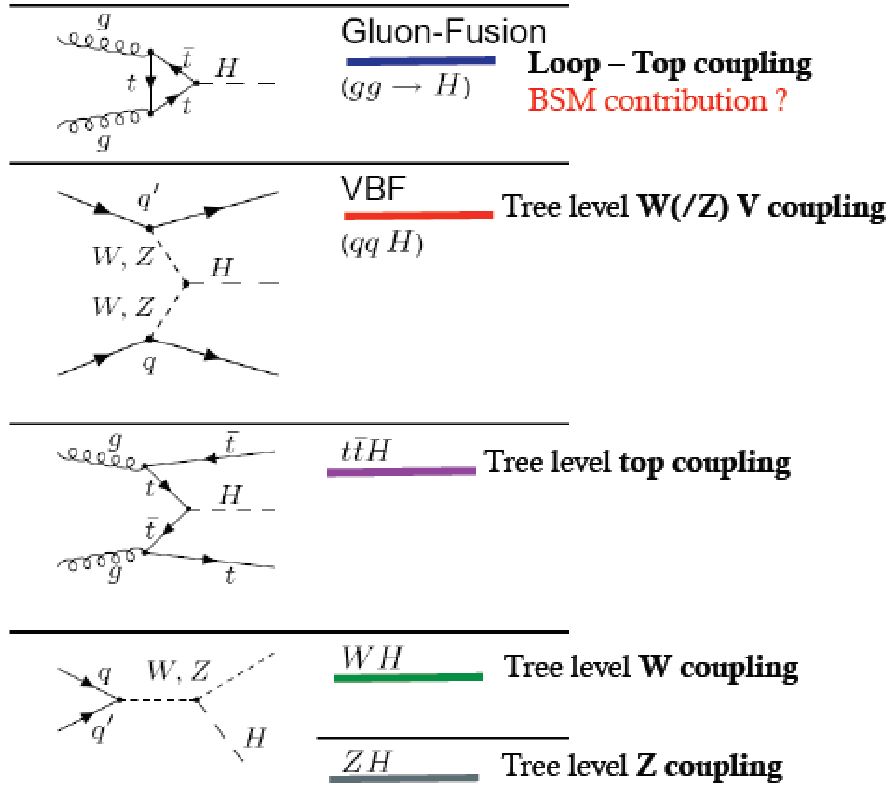
4. search must continue but tools must be as broad and powerful as possible, as there is no precise target.

HIGGS FACTORIES

Higgs provides a very good reason why we need e+e- (or $\mu\mu$) collider


Linear Colliders
ILC
CLIC
SLC-type
Adv. Concepts
Circular e+e- Colliders
LEP3
TLEP
Super-Tristan
FNAL Site-filler
IHEP, + …
LEP
SPS
site Prévessin
FRANCE
SUISSE
LHC
Jura
Lake Geneva
Prealps
FCC
hh ee he
Aravis
Mandalaz
Copyright CERN 2014
SAPPHIRE,
CLICHÉ, +
…
500 MeV e- injector
11-GeV linac
80 GeV
10, 30, 50, 70 GeV
total circumference ~ 9 km
1.1 km
2.0 km
final focus
IP
dump
Muon Colliders
2
γ-γ Colliders
S. Henderson





THE LHC is a Higgs Factory

several tens of Million Higgs already produced > than most Higgs factory projects.

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.

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

difficult to extract the couplings because σ_{prod} uncertain and Γ_H is unknown (invisible channels)

Why do we need a new machine after and in addition to HL-LHC?

1. the Higgs boson itself:

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

difficult to extract the couplings because σ_{prod} uncertain and Γ_H is unknown

also (g_{Hgluon} is sensitive to new physics…)

2. There might be other Higgs bosons or other generation of masses which modifiy the properties of the Higgs (126) by small amounts
-> want to measure H properties as well as possible (10^{-3})

3. New physics with small couplings is difficult to see at the LHC

4. Precision measurements are limited at LHC,
yet precision measurements at LEP were used to predict the top quark and Higgs boson masses
Can we improve the measurements by large factors?

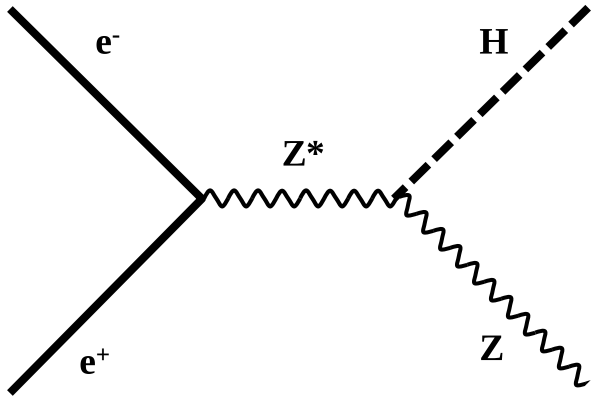
5. In the following we will examine what we can learn from a next e+e- collider

Higgs production mechanism

“higgstrahlung” process close to threshold

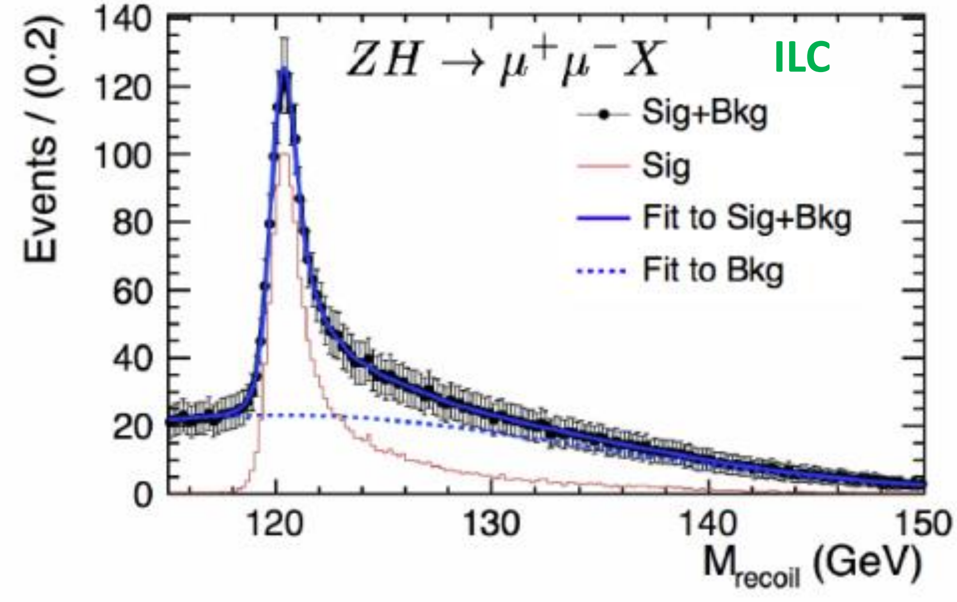
Production xsection has a maximum at near threshold ~200 fb

$10^{34}/cm^2/s$ ➔ 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 $\propto g_{HZZ}^2$

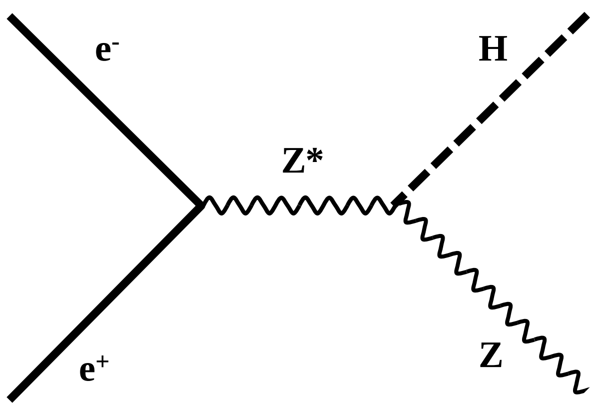
ZZZ final state $\propto g_{HZZ}^4 / \Gamma_H$

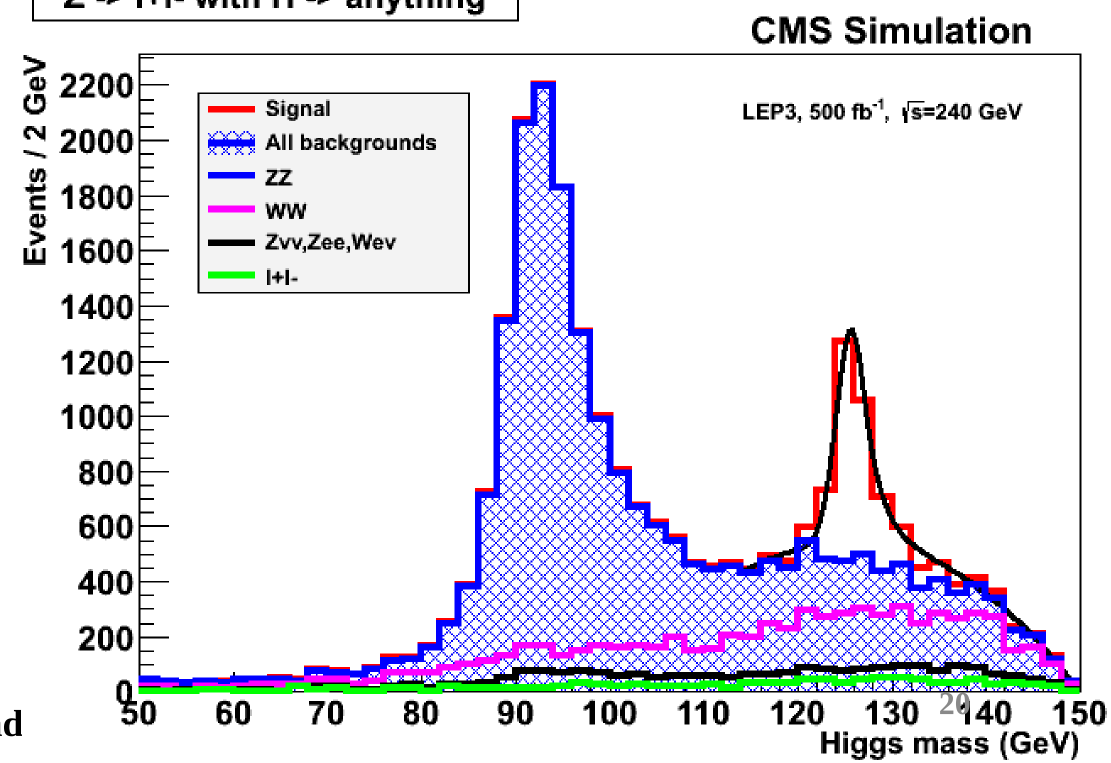
➔ measure total width Γ_H

empty recoil = invisible width

'funny recoil' = exotic Higgs decay

easy control below theshold

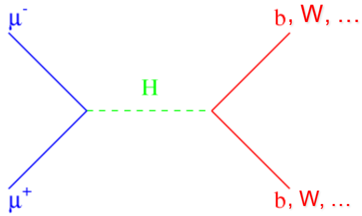




$\mu^+\mu^-$ Collider vs e^+e^- Collider ?

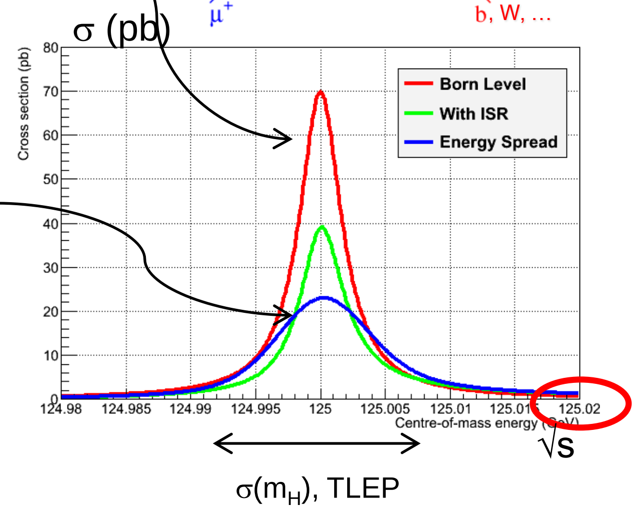
- **A $\mu^+\mu^-$ collider can do things that an e^+e^- collider cannot do** [16,17]
  - Direct coupling to H expected to be larger by a factor m_μ/m_e

$$\sigma(\mu^+\mu^- \to H) \approx 40000 \times \sigma(e^+e^- \to H)$$ [σ_{peak} = 70 pb at tree level]



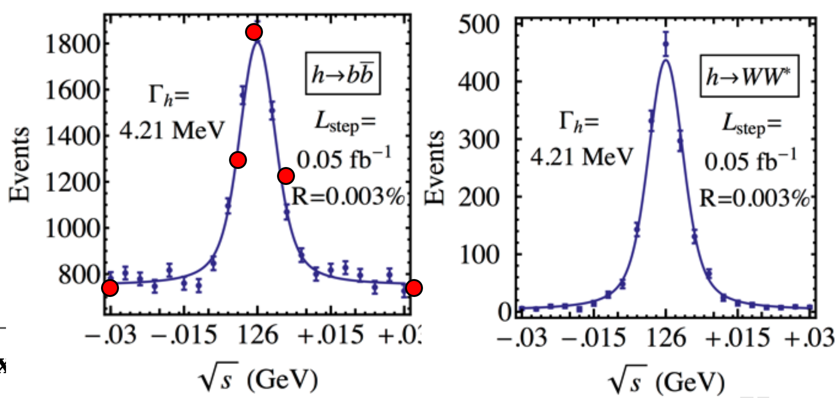
  - Beam energy spread δE/E may be reduced to 3×10^{-5}
    - 6D Cooling, no beamstrahlung, ~no bremsstrahlung
    - For δE/E = 0.003% (δE ~ 3.6 MeV, Γ_H ~ 4 MeV)
      - ➔ Corresponding luminosity ~ 10^{31} cm^{-2}s^{-1}

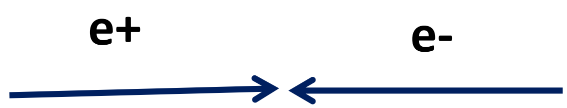
Expect 2300 Higgs events in 100 pb^{-1}/ year



  - Polarization, beam energy and energy spectrum
    - Can be measured with an exquisite precision
      - ➔ From the electrons of the muon decays
  - Then measure the lineshape of the Higgs at $\sqrt{s} \sim m_H$
    - Five-point scan, 50 + 100 + 200 + 100 + 50 pb^{-1}
      - ➔ Precision from H→bb and WW :

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





e+ e- colliders have a very rich history of discoveries

examples:

-- charm (1974-76) SPEAR at SLAC (USA)

-- gluon (1978) PETRA at DESY (Germany)

-- B mixing (1985) DORIS at DESY

-- Number of neutrinos is 3 LEP at CERN 1989

-- Prediction of top quark mass LEP 1994

-- Observation of tau neutrinos LEPII at CERN 1996

-- CP violation in the B system 1999 PEPII at SLAC and Belle at KEK (Japan)

and of precision measurements

ex:

tau mass at BEPC, Beijing $1776.99\ {+0.29}{-0.26}\ (1.5\ 10^{-4})$

J/ψ mass at Novosibirsk, 3096.916 ± 0.011 MeV (3.510^{-6})

Z mass and width at LEP $91.1876 \pm 0.0021\ (2\ 10^{-5})$

The e+e- colliders:

Circular e+e- colliders

Placed in a tunnel of circumference C and bending radius ρ ($2\pi\,\rho \sim 0.8$ C)

Acceleration occurs in a few RF sections around the ring.

total RF volts needed = energy loss by synchrotron radiation (scales as E^4/ρ)

Main limitation : power and ring size → cost + power + beam energy

Beams collide 10^6 to 10^7 times

Many e+e- storage rings and many successes: c and b factories, LEP

LEP = 27km circumference reached 209 GeV -- long believed to be the last at high energies. Luminosity of b factories has reached unexpected levels

Linear e+ e- colliders

Acceleration takes place once through a large set of RF cavities

total RF volts needed = center-of-mass Energy

e.g. 500 GeV Linear collider requires > 500 GV of RF voltage

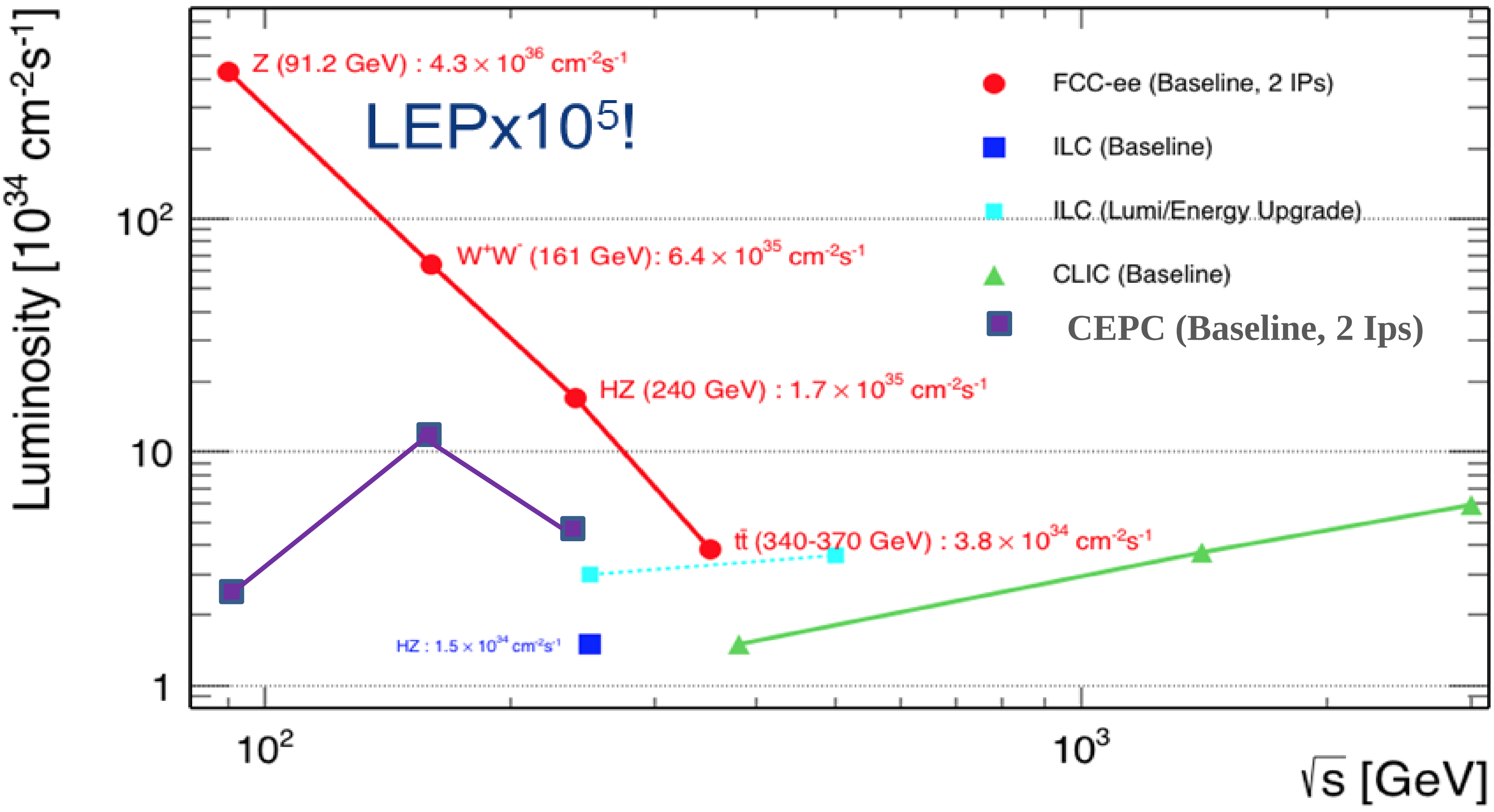
Main limitation = cost + power + beam energy

beam polarization is easy for electrons, feasible for positrons

beam energy spread few percent, beam energy calibration $\Delta E/E \sim 10^{-4}$

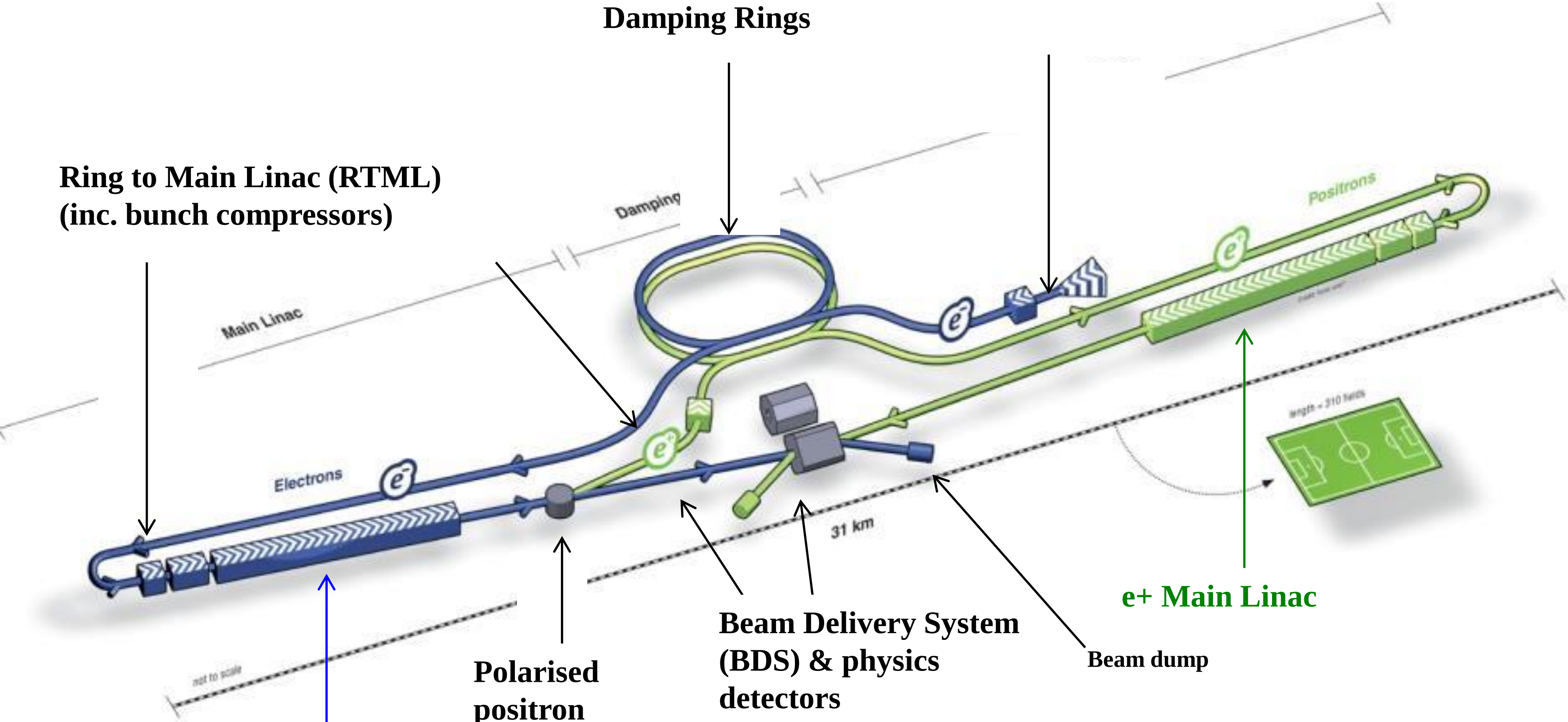
Beams collide only once

Only one example that worked: SLC at SLAC (1988-1998) -- not easy!



Overlap in Higgs/top region, but differences and complementarities between linear and circular machines:
Circ: High luminosity, experimental environment (up to 4 IP), E_{CM} calibration
Linear: higher energy reach, longitudinal beam polarization

ILC in a Nutshell



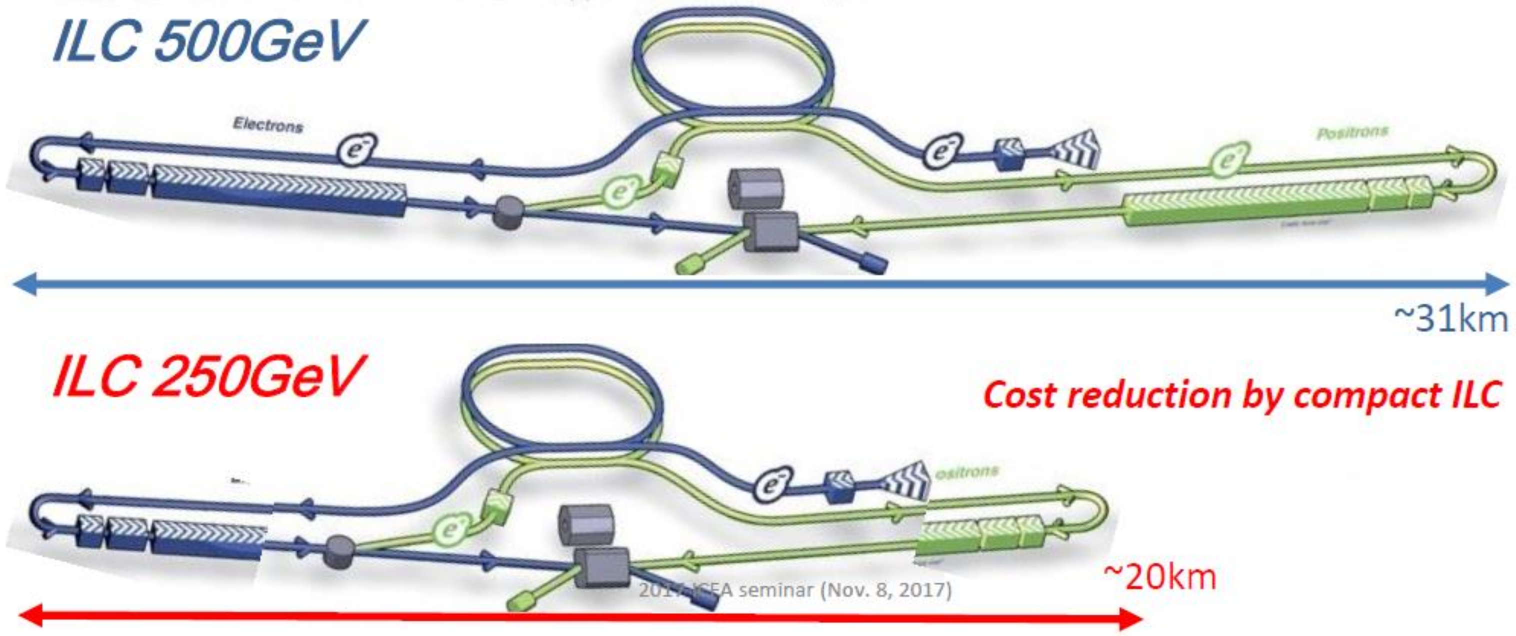
US-Japan cost reduction R&D

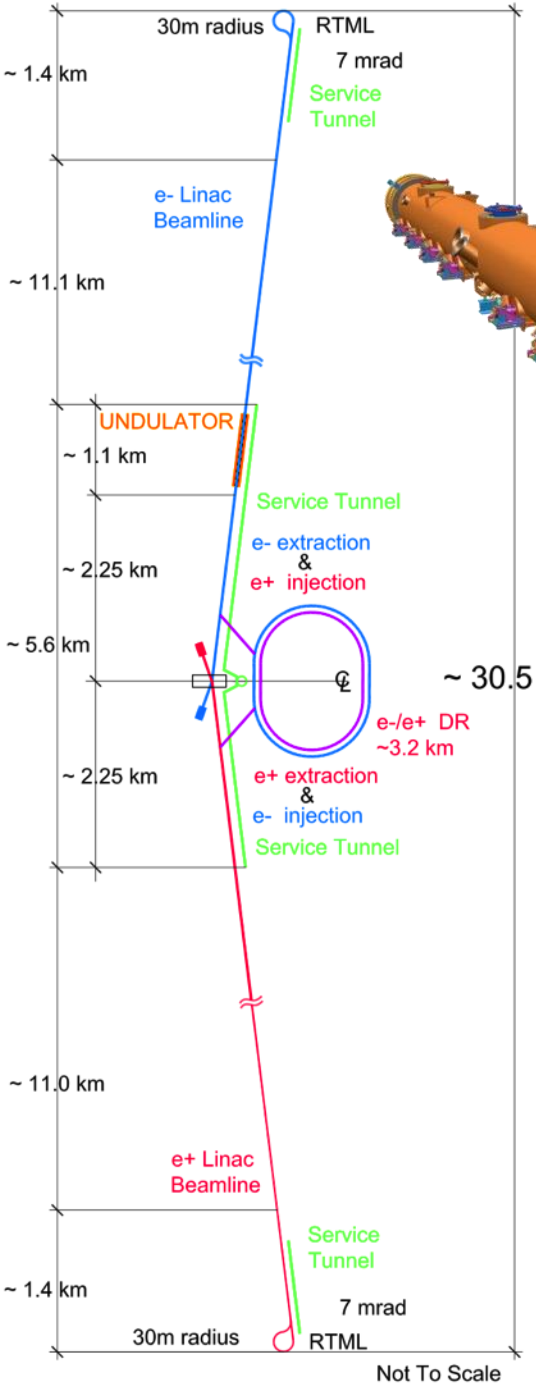
Cost reduction by technological innovation

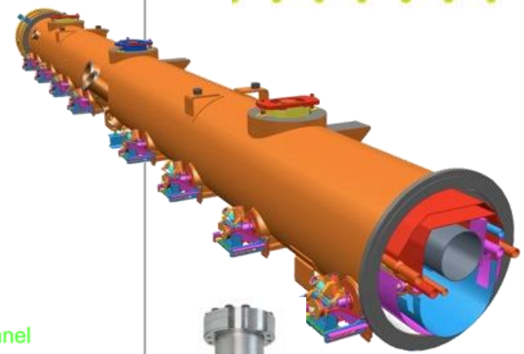
Innovation of Nb (superconducting) material process: decrease in material cost

Innovative surface process for high efficiency cavity (N-infusion): decrease in number of cavities

Staging







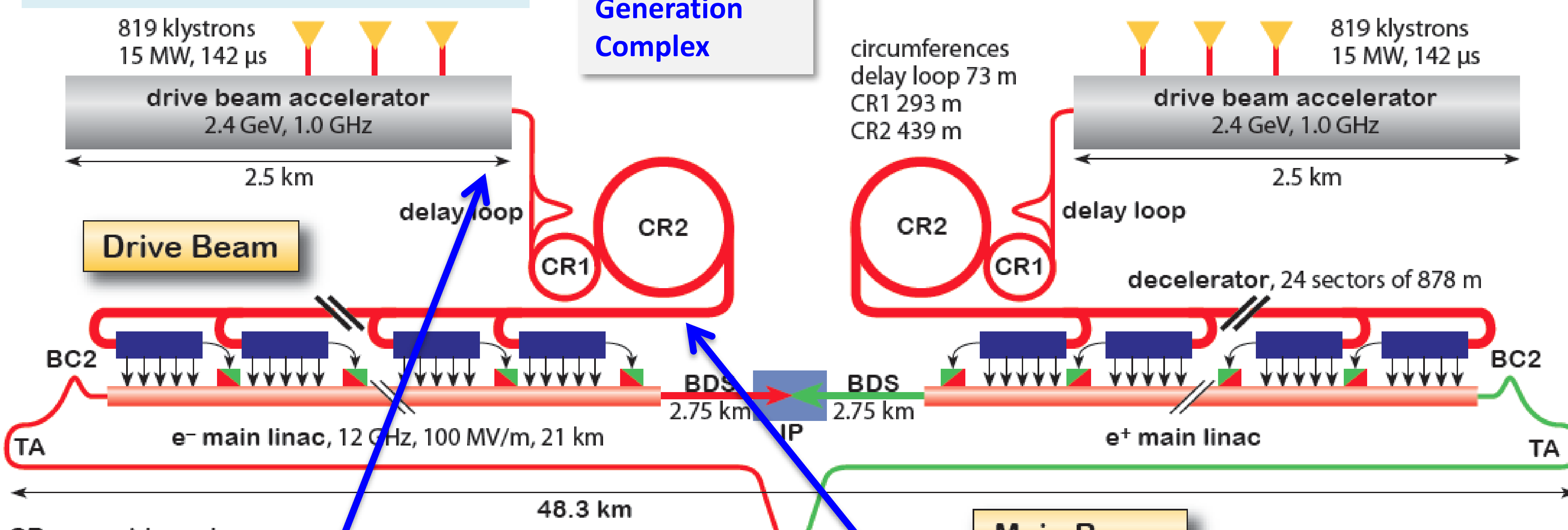
The ILC

- **200-500 GeV E_{cm} e^+e^- collider $L \sim 2\times10^{34}\ cm^{-2}s^{-1}$**
  - upgrade: ~1 TeV
- **SCRF Technology**
  - 1.3GHz SCRF with 31.5 MV/m
  - 17,000 cavities
  - 1,700 cryomodules
  - 2×11 km linacs
- **Developed as a truly global collaboration**
  - **G**lobal **D**esign **E**ffort – **GDE**
  - ~130 institutes
  - http://www.linearcollider.org

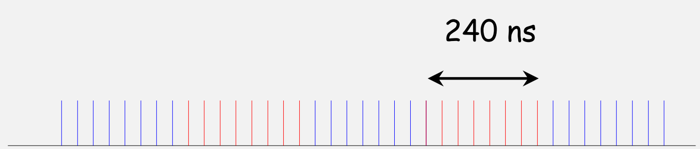
CLIC Layout at 3 TeV

Goal: Lepton energy frontier

Drive Beam Generation Complex

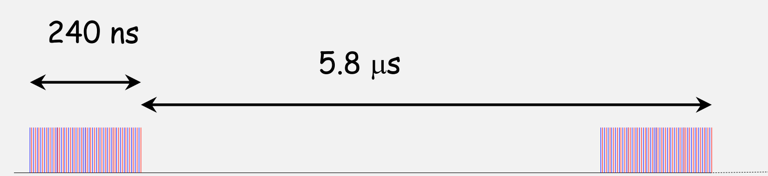


Drive beam time structure - initial



140 μs train length - 24 × 24 sub-pulses
4.2 A - 2.4 GeV – 60 cm between bunches

Drive beam time structure - final

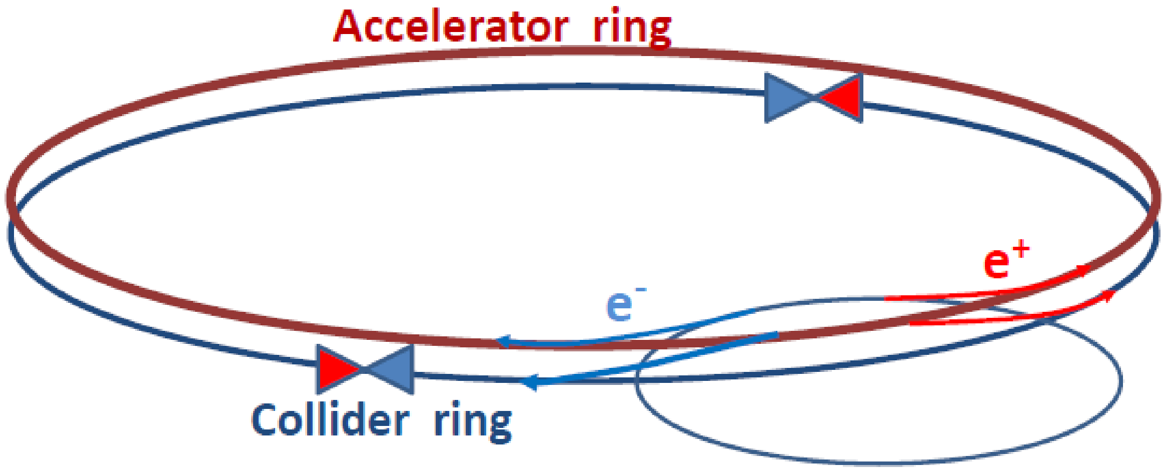


24 pulses – 101 A – 2.5 cm between bunches

Complex

LEP3, CEPC and TLEP/FCC-ee

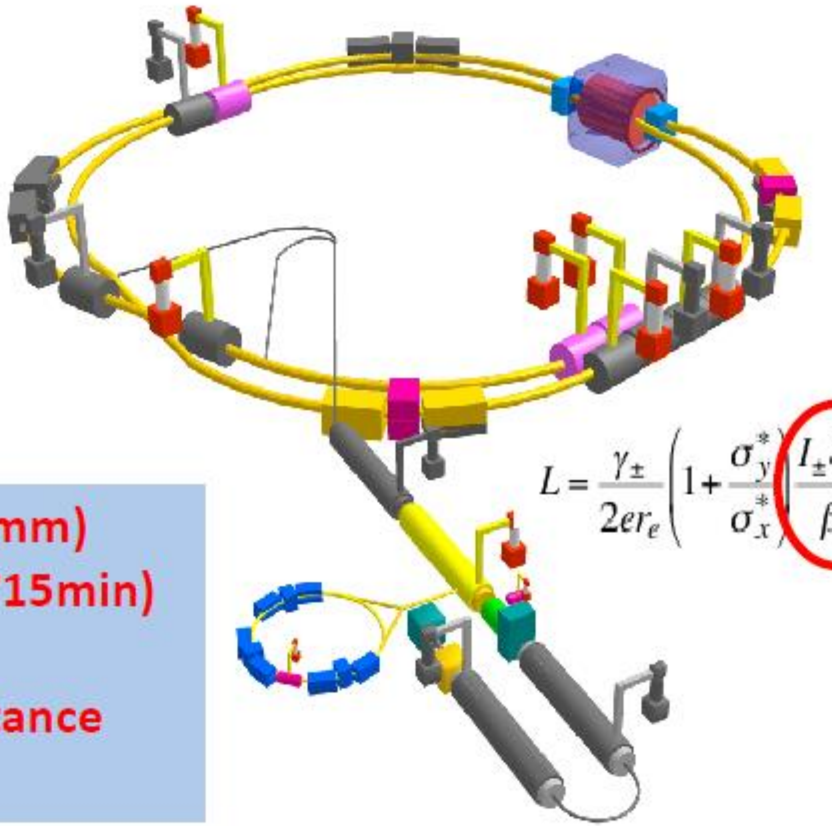
Circular e+e- colliders designed to study the Higgs boson but also Z, W and top factories



AB, F. Zimmermann
Dec. 13 2011

SuperKEKB – TLEP demonstrator!

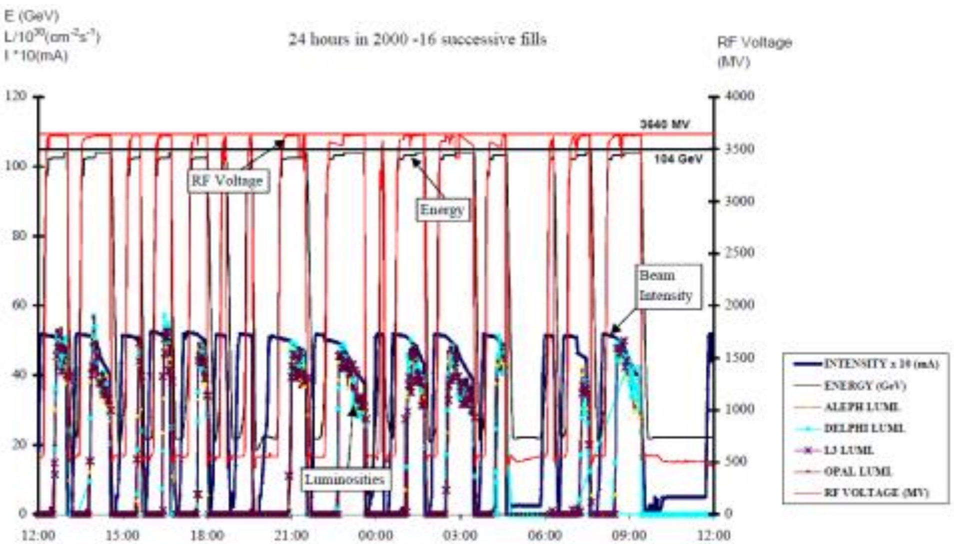
beam commissioning will start in **2016**



$$L = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_\pm \xi_{\pm y}}{\beta_y^*}\right)\left(\frac{R_L}{R_y}\right)$$

- β_y^*=300 μm (TLEP: 1 mm)
- lifetime 5 min (TLEP: ~15min)
- $\varepsilon_y/\varepsilon_x$=0.25% (~TLEP)
- off momentum acceptance
- e^+ production rate

Toping up ensures constant current, settings, etc... and greater reproducibility of system



LEP2 in 2000 (12th year!):
fastest possible turnaround but
average luminosity ~ 0.2 peak luminosity

B factory in 2006 with toping up
average luminosity ≈ peak luminosity

The Future Circular Colliders
CDR and cost review for the next ESU (2018)

International collaboration to Study Colliders fitting in a new ~100 km infrastructure, fitting in the *Genevois*

- ***Ultimate goal:*** **~16 T magnets**
  ***100 TeV pp*-collider (*FCC-hh*)**

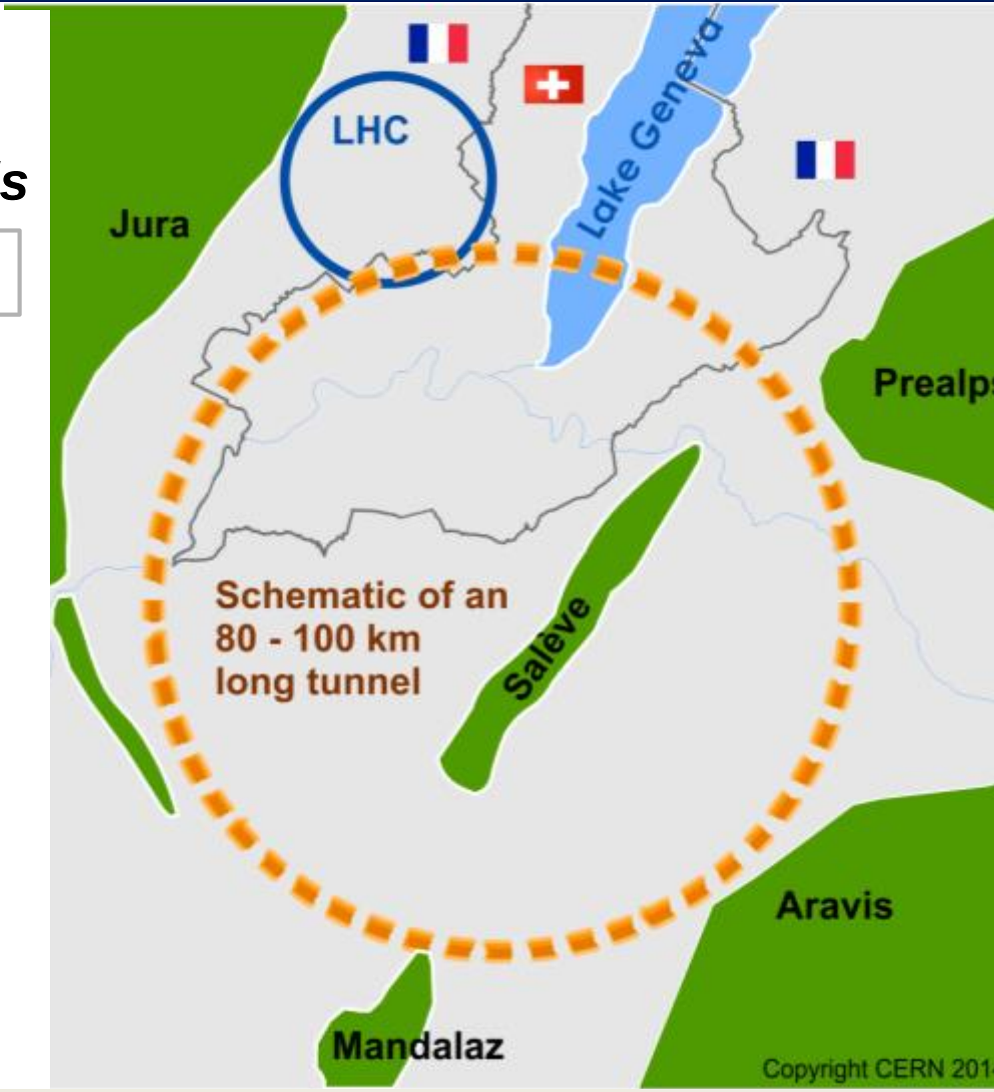
→ defining infrastructure requirements

Possible first steps:

- **e^+e^- collider (*FCC-ee*)**
  High Lumi, E_{CM} =90-400 GeV

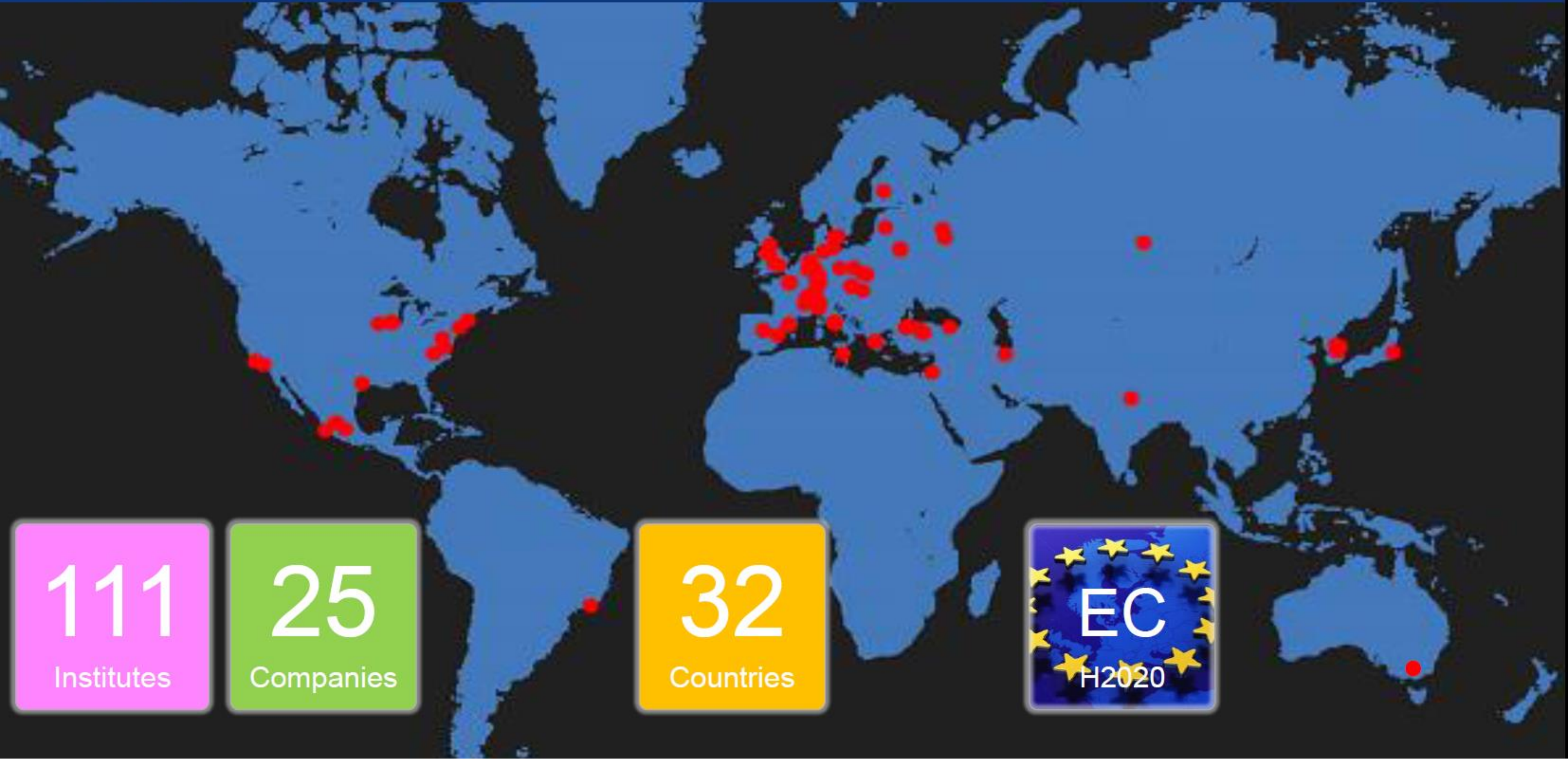
- ***HE-LHC* 16T ⇒ 28 TeV in LEP/LHC tunnel**

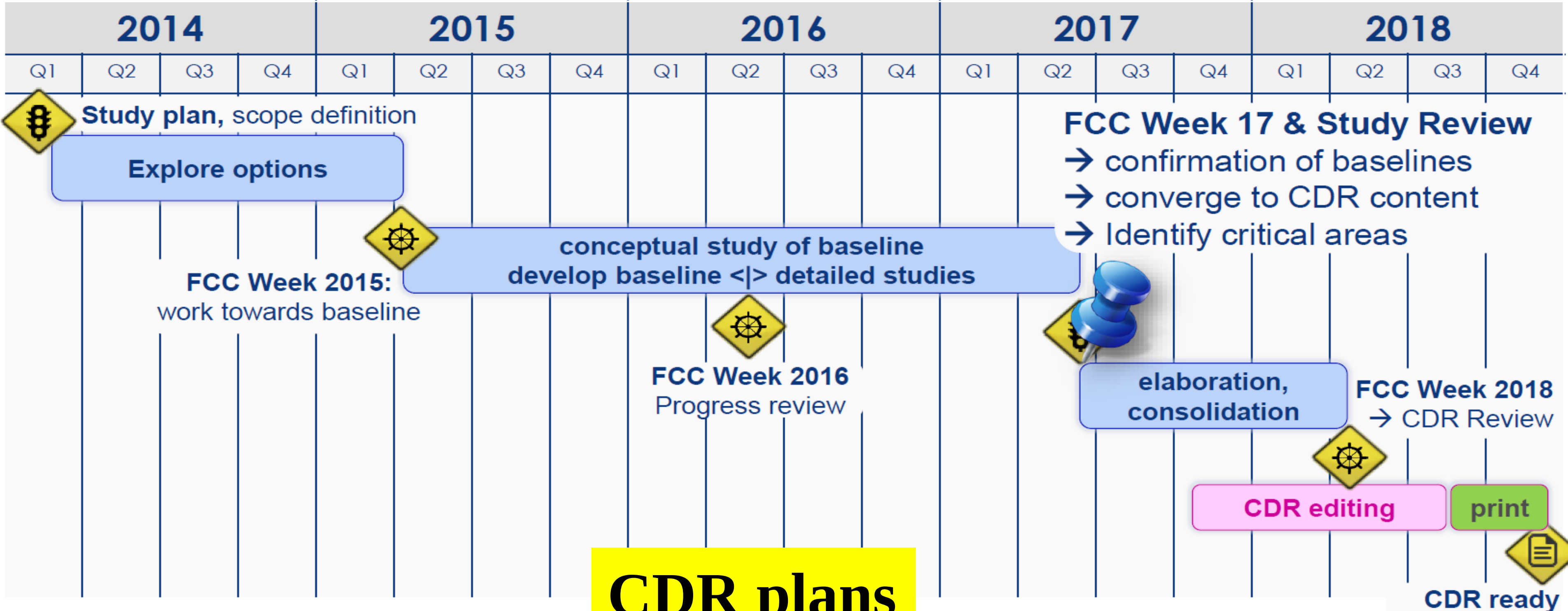
Possible add-on:



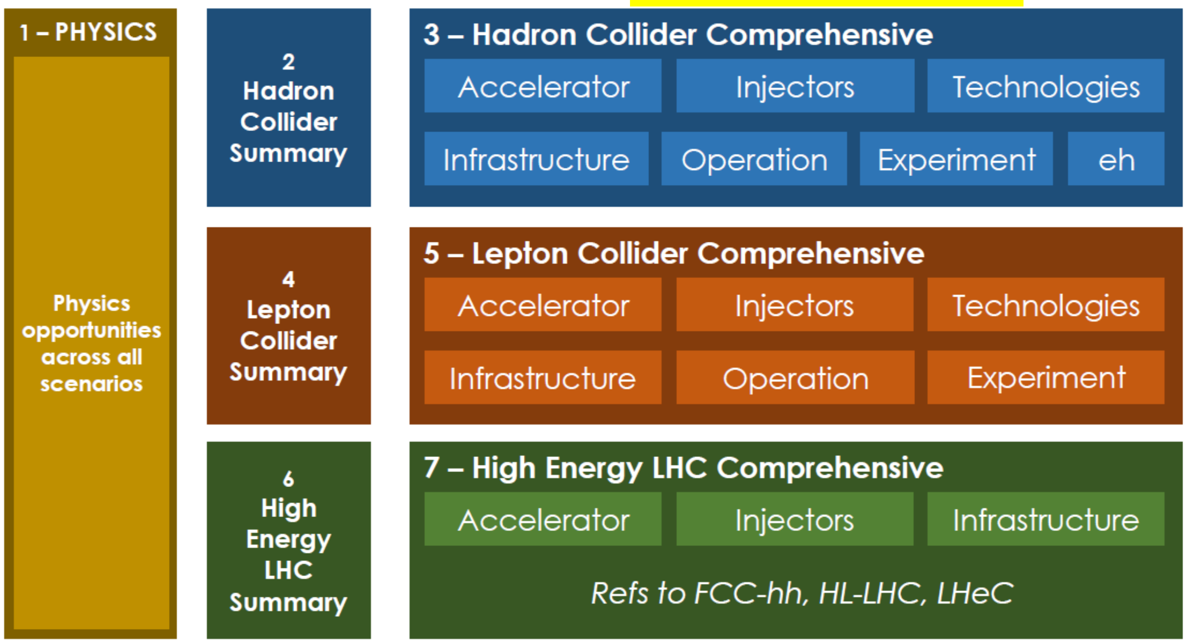
From European Strategy in 2013: "ambitious post-LHC accelerator project"
Study kicked-off in Geneva Feb 2014

Collaboration & Industry Relations



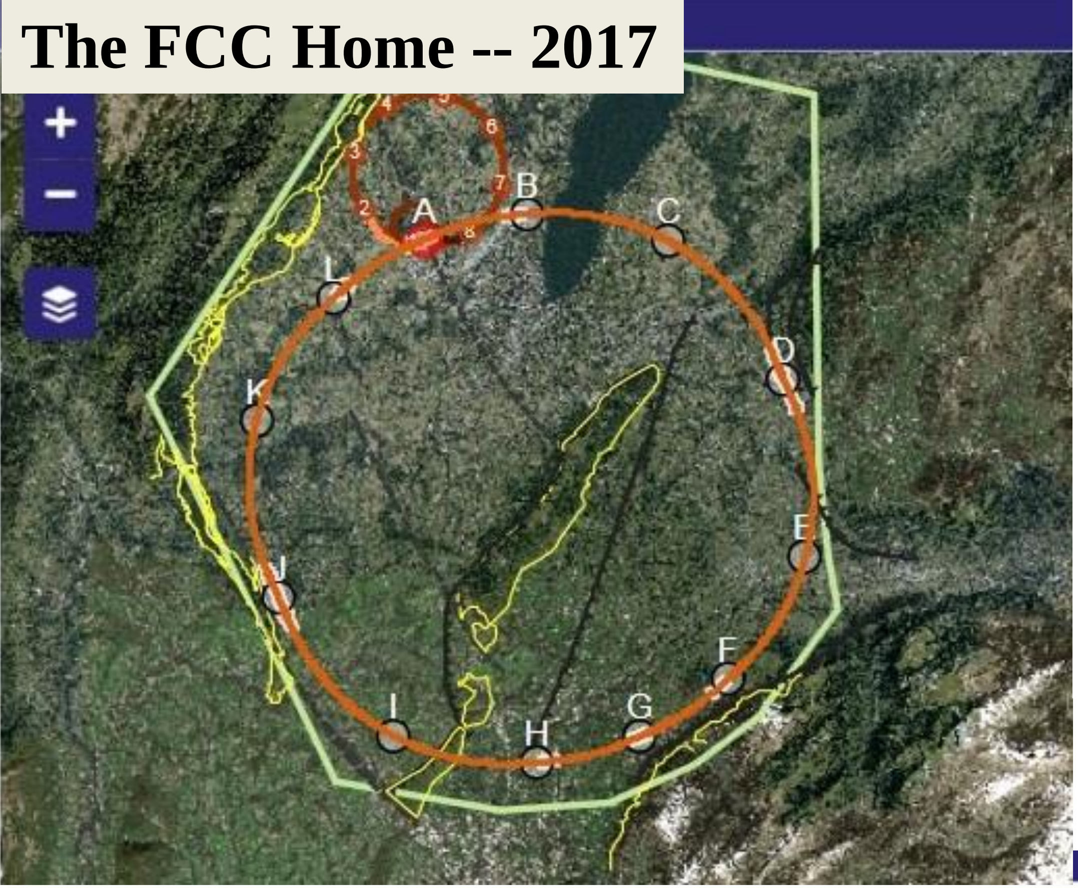


CDR plans



- **Required for end 2018, as input for European Strategy Update**
- **Common physics summary volume**
- **Three detailed volumes FCChh, FCCee, HE-LHC**
- **Three summary volumes FCChh, FCCee, HE-LHC**

The FCC Home -- 2017



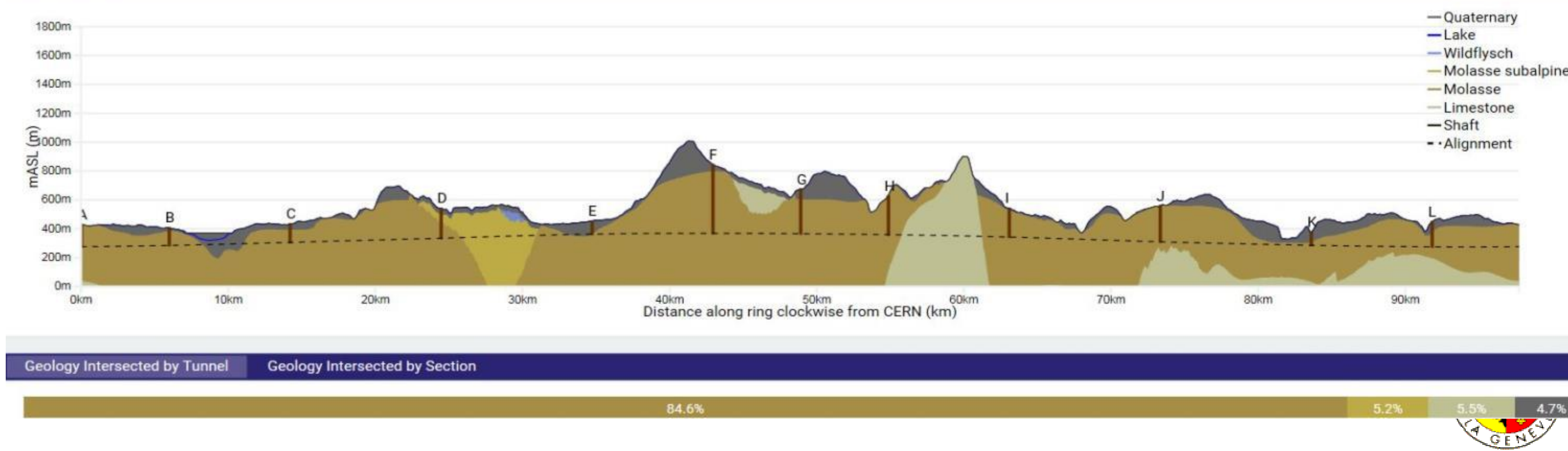
Optimisation in view of accessibility surface points, tunneling rock type, shaft depth, etc. optimum: 97.5 km

Tunneling

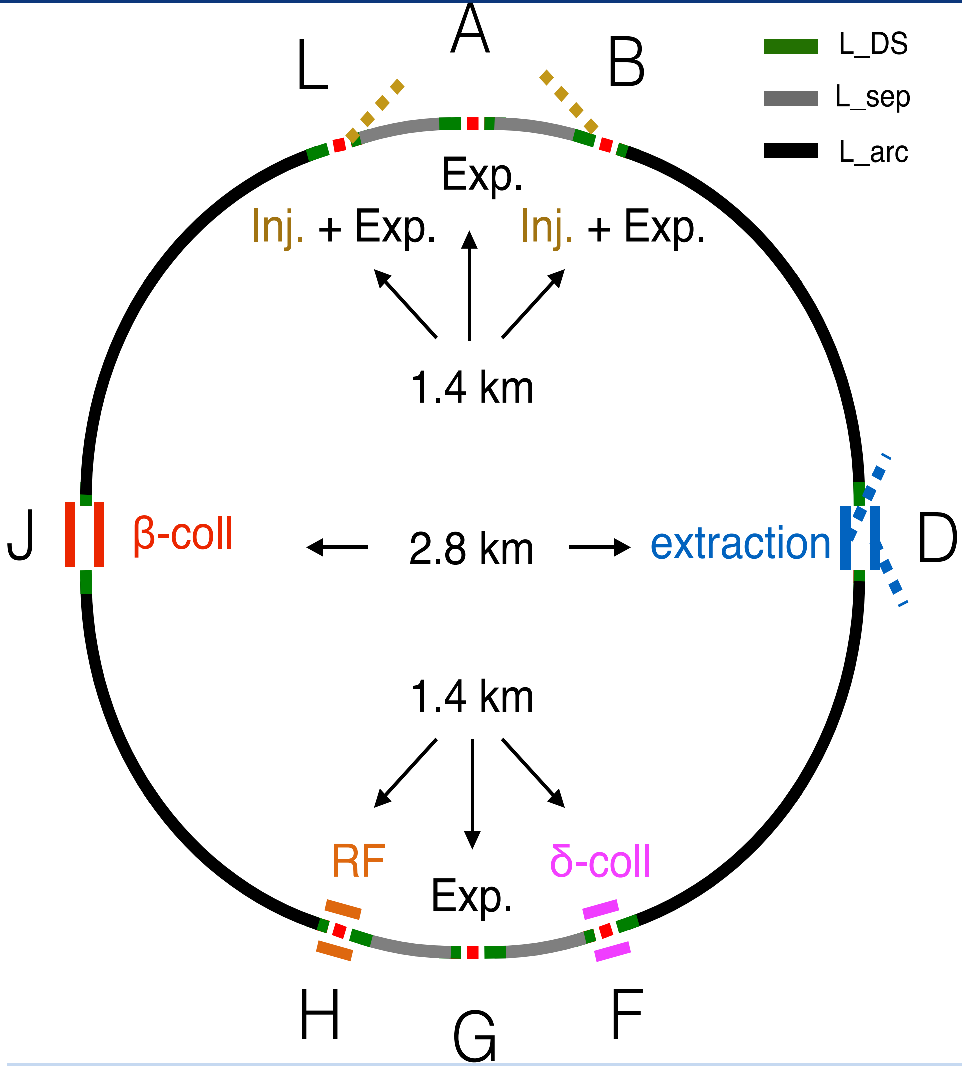
- **Molasse 90% (good rock),**
- **Limestone 5%, Moraines 5% (tough)**

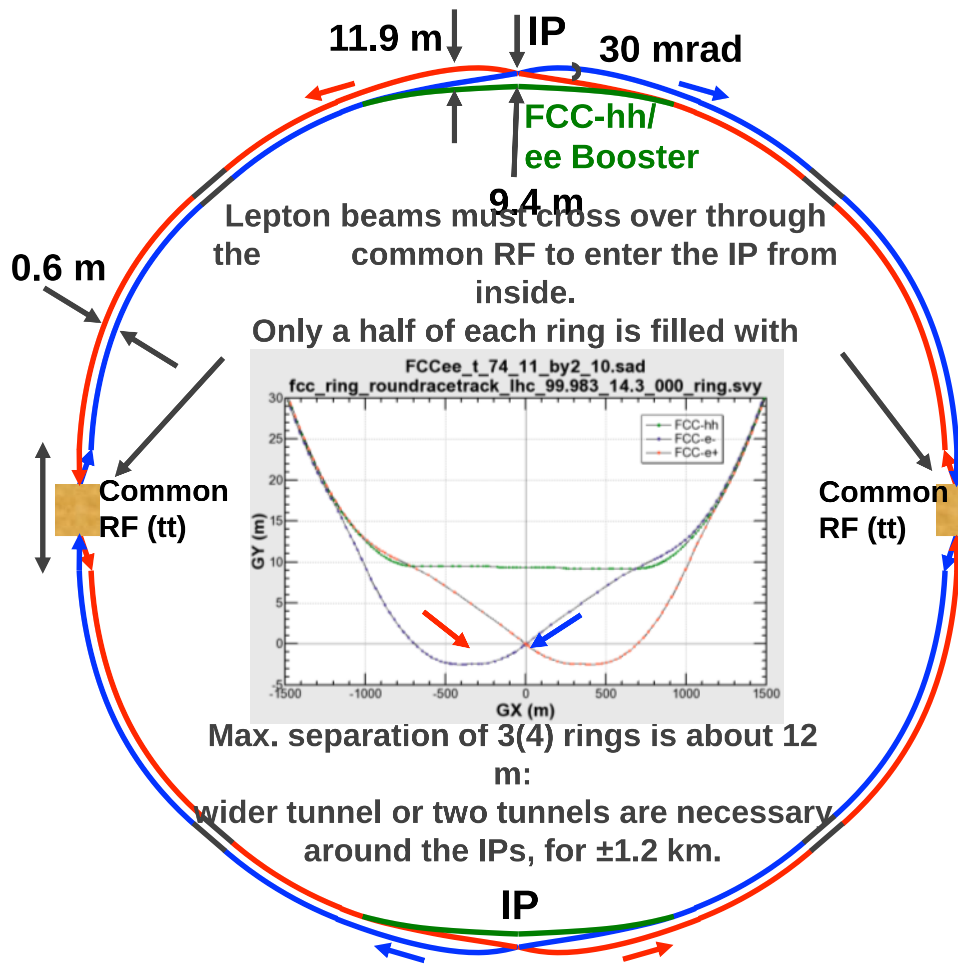
Shallow implementation

- **~ 30 m below Léman lakebed**
- **Reduction of shaft lengths etc...**
- **One very deep shaft F (476m) (RF or collimation), alternatives being studied, e.g. inclined access**



common layouts for hh & ee



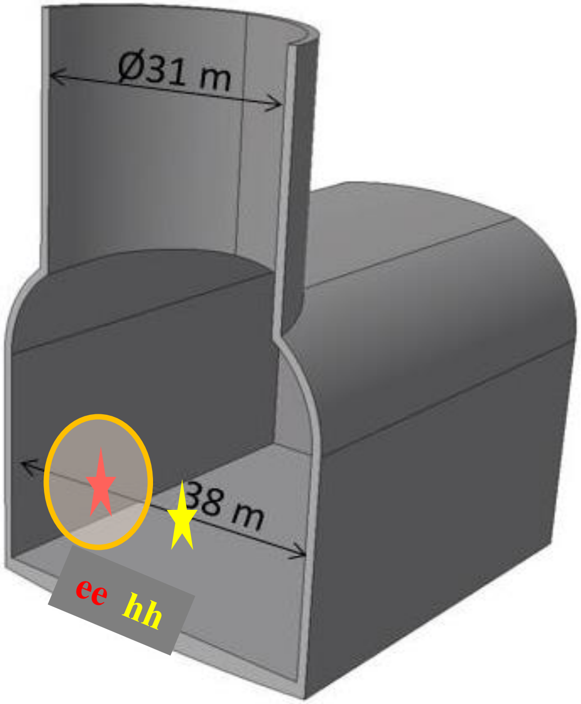


2 main IPs in A, G for both machines

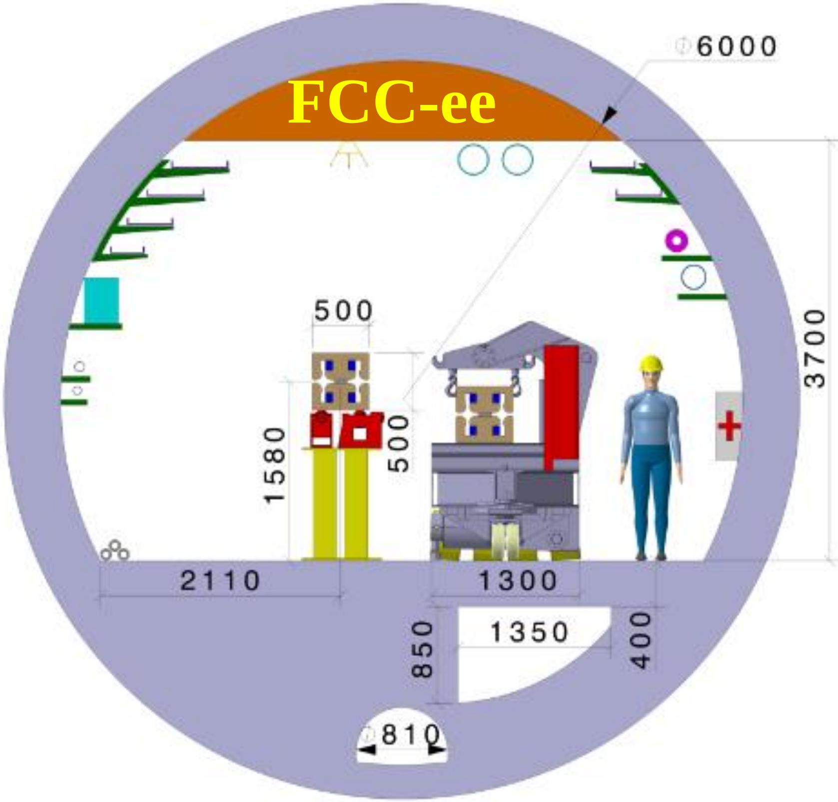
FCC-ee 1, FCC-ee 2,

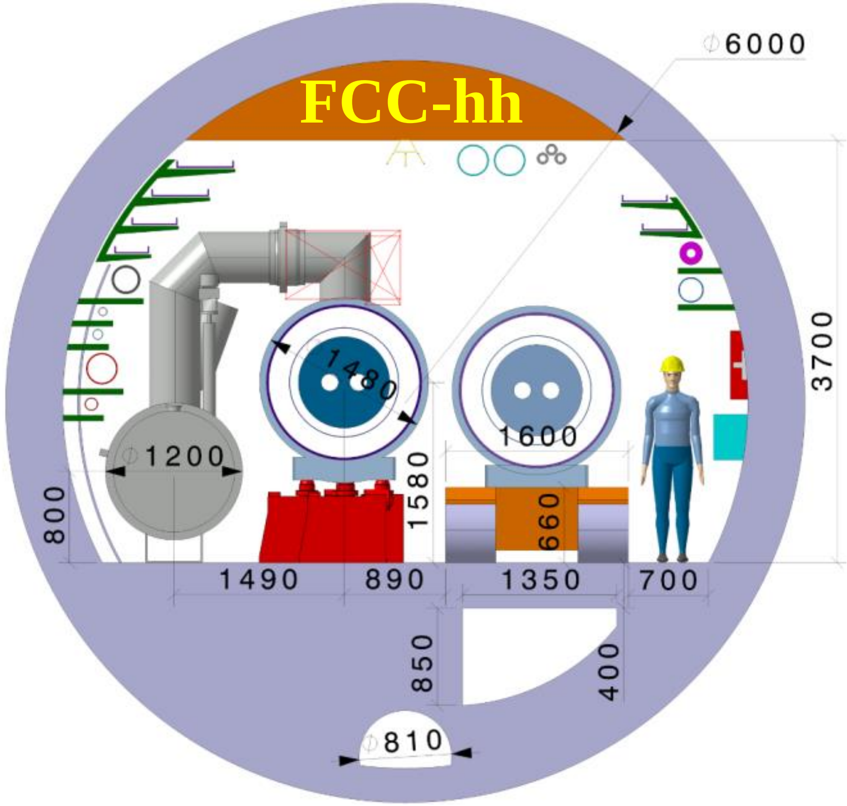
FCC-ee booster (FCC-hh footprint)

Asymmetric IR for ee, limits SR to expt



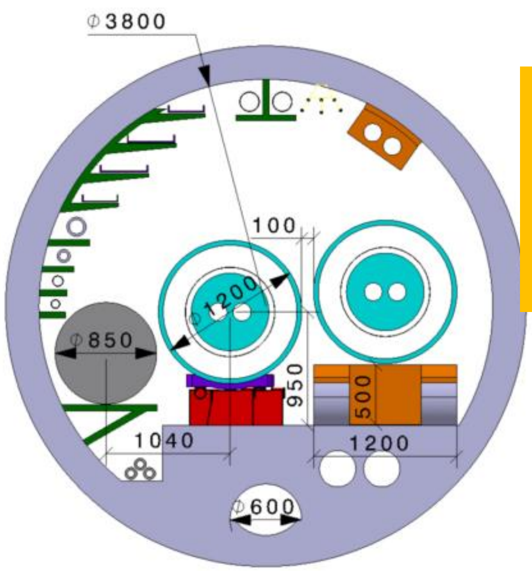
Sharing the FCC experimental caverns
(Prelim. layout as of FCC-Rome meeting)



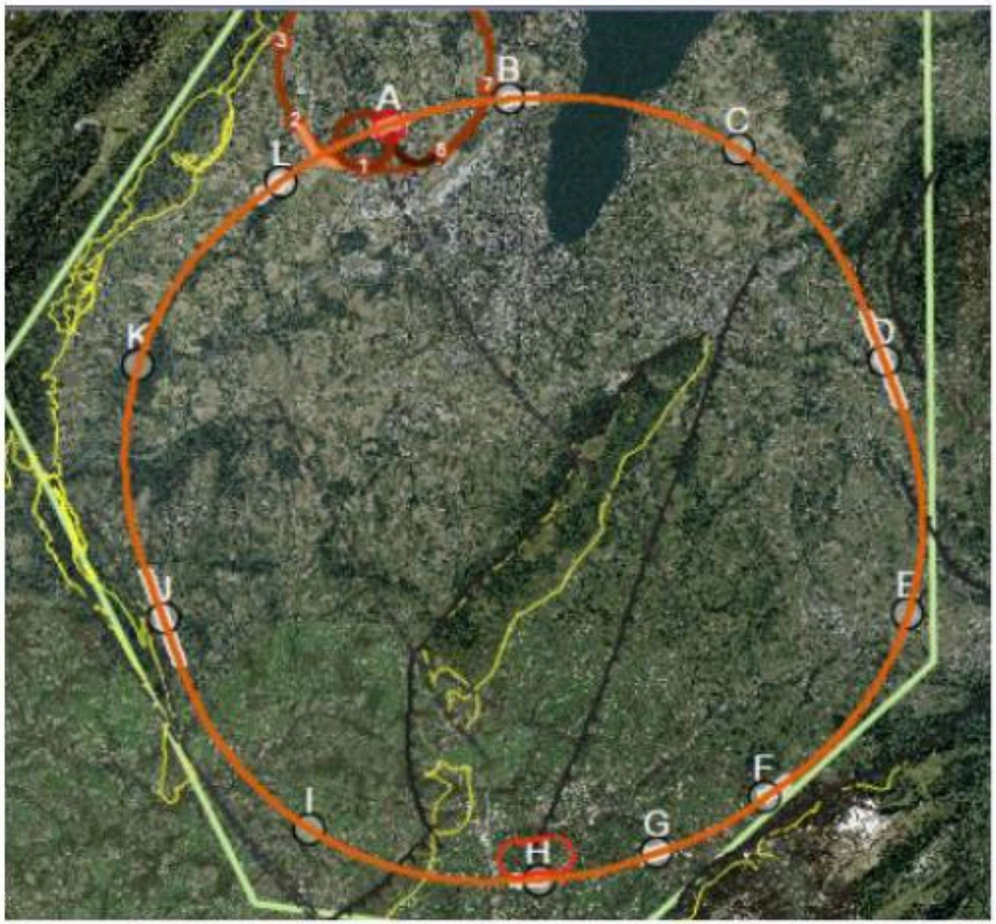


HE-LHC :
constraints:
No civil engineering, same beam height as LHC
→ Magnets OD ca. 1200 m max
QRL (shorter than FCC) OD ca. 850 mm (all included)

Magnet suspended during „handover“ from transport vehicle to installation transfer table
Compliant 16T magnet design ongoing (challenge)
+ still many items to study!



If HE-LHC can work in 3.8m ∅ ... it will feed-back to FCC tunnel design!



FCC-eh

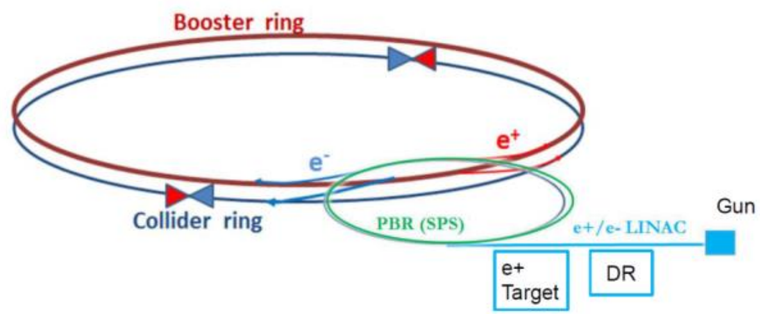
LHeC or FCC-eh function as an add-on to LHC or FCC-hh respectively:
additional 10km cicumference
Electron Reciculating Linac ERL.

The possibility to collide FCC-ee with FCC-hh is not considered in the framework of the study

In the case of FCC-eh it could profit from the -- then existing -- FCC-hh,
and, perhaps, from considerable RF of the -- then dismantled -- FCC-ee

FCC-ee

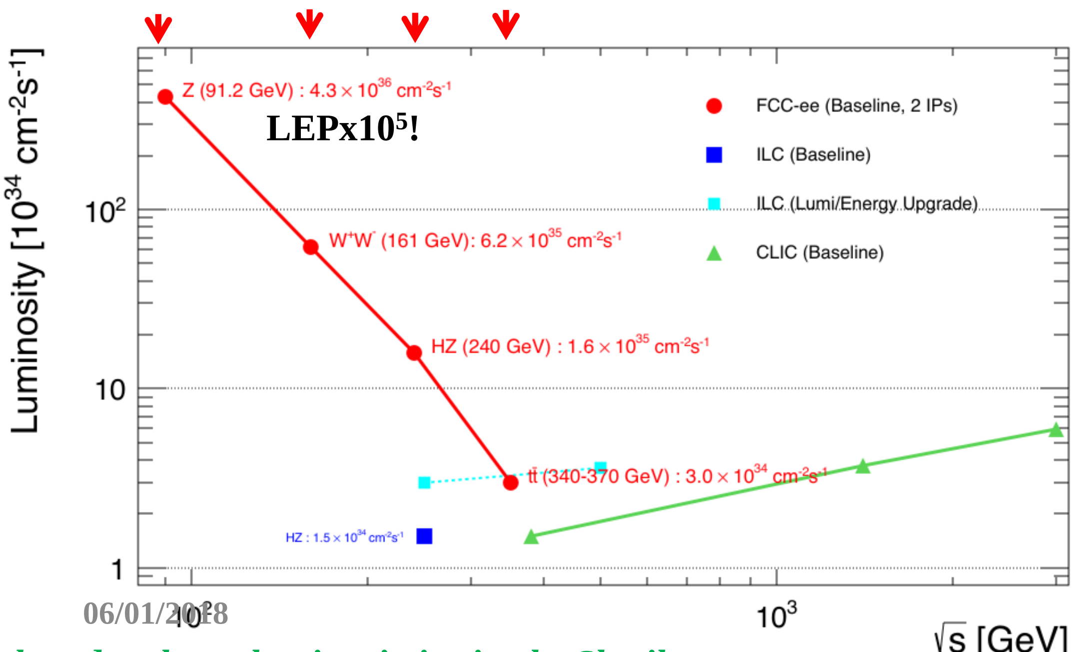
AB, F. Zimmermann 2011 **(LEP3@240 GeV)**



top-up injection for high duty factor
several schemes possible

Q: Why is luminosity so much higher than LEP?
A: inspired by b-factory designs
- -- continuous injection (high efficiency)
- -- e+ and e- separate (→many bunches)
- -- fix 100 MW Synchrotron Radiation at all E
- -- low β^*_y , O(1mm)
- -- larger ring ($P_{SR} \propto E^4/\rho$)
- -- beam cross at angle (30 mrad)
- -- crab waist crossing
- -- asymmetric IP to avoid SR → LEP levels

Z WW HZ tt



Luminosity performance dominated by
- -- at Z, WW, H energies: beam-beam instabilities → simulations
- -- at top energy: beamstrahlung depends on value of $\varepsilon_y/\varepsilon_x$
  - 0.2% assumed (0.25%@superKEKB)
  - 0.4% achieved at LEP
- -- limit from injector is much higher

based on latest lumi optimization by Shatilov

Recent FCC-ee parameter list

	Z	W	H	tt
Circumference [km]	97.750			
Bending radius [km]	10.747			
Beam energy [GeV]	45.6	80	120	175
Beam current [mA]	1390	147	29	6.4
Bunches / beam	18800	2000	375	45
Bunch spacing [ns]	15	150	455	6000
Bunch population [10^{11}]	1.5	1.5	1.6	2.9
Horizontal emittance ε [nm] Vertical emittance ε [pm]	0.267 1.0	0.26 1.0	0.61 1.2	1.33, 2.03 2.66, 3.1
Momentum comp. [10^{-6}]	14.79	7.31	7.31	7.31
Arc sextupole families	208	292	292	292
Betatron function at IP - Horizontal β^* [m] - Vertical β^* [mm]	 0.15 0.8	 0.20 1	 0.5 1.2	 1 2
Horizontal beam size at IP σ^* [μm] Vertical beam size at IP σ^* [nm]	6.3 28	7.2 32	17 38	45 79
Free length to IP l^* [m]	2.2			
Solenoid field at IP [T]	2			
Full crossing angle at IP [mrad]	30			
Energy spread [%] - Synchrotron radiation - Total (including BS)	 0.038 0.130	 0.066 0.153	 0.10 0.14	 0.145 0.194
Bunch length [mm] - Synchrotron radiation - Total	 3.5 11.2	 3.27 7.65	 3.1 4.4	 2.4 3.3
Energy loss / turn [GeV]	0.0356	0.34	1.71	7.7
SR power / beam [MW]	50			
Total RF voltage [GV]	0.10	0.44	2.0	9.5
RF frequency [MHz]	400			
Longitudinal damping time [turns]	1281	235	70	23
Energy acceptance RF / DA [%]	1.9,	1.9,	2.4,	5.3, 2.5 (2.0)
Synchrotron tune Q_s	-0.025	-0.023	-0.036	-0.069
Polarization time τ_p [min]	15040	905	119	18
Interaction region length L_i [mm]	0.42	1.00	1.45	1.85
Hourglass factor $H(L_i)$	0.95	0.95	0.87	0.85
Luminosity/IP for 2IPs [10^{34} cm^{-2}s^{-1}]	215	31.0	7.9	**1.9**
Beam-beam parameter - Horizontal - Vertical	 0.004 0.134	 0.007 0.126	 0.033 0.141	 0.092 0.150
Beam lifetime rad Bhabha, BS [min]	72	54	42	47, 70 (12)

FCC-ee physics run

- **FCC-ee physics goals (sum of two IPs):**
  - 150 ab^{-1} at and around the Z pole (88, 91, 94 GeV)
  - 10 ab^{-1} at the WW threshold (~161 GeV with a +/- few GeV scan)
  - 5 ab^{-1} at the HZ maximum (~240 GeV)
  - 1.5 ab^{-1} at and above the ttbar threshold (a few 100 fb^{-1} with a scan from 340 to 350 GeV, and the rest at 365-370 GeV)
- **Assumptions:**
  - 200 scheduled physics days per year, i.e. 7 months – 13 days of MD/stops.
  - "Hübner factor" H=0.75 (lower than value achieved with top-up injection at KEKB, ~0.8).
  - Half the design luminosity in the first two years of Z operation, assuming machine starts with Z (similar to LEP-1; LEP-2 start up was much faster)
  - Machine configuration between WPs is changed during winter shutdowns (effective time of about 3 months/year)

IMPLEMENTATION AND RUN PLA

"Ampere-class" machine

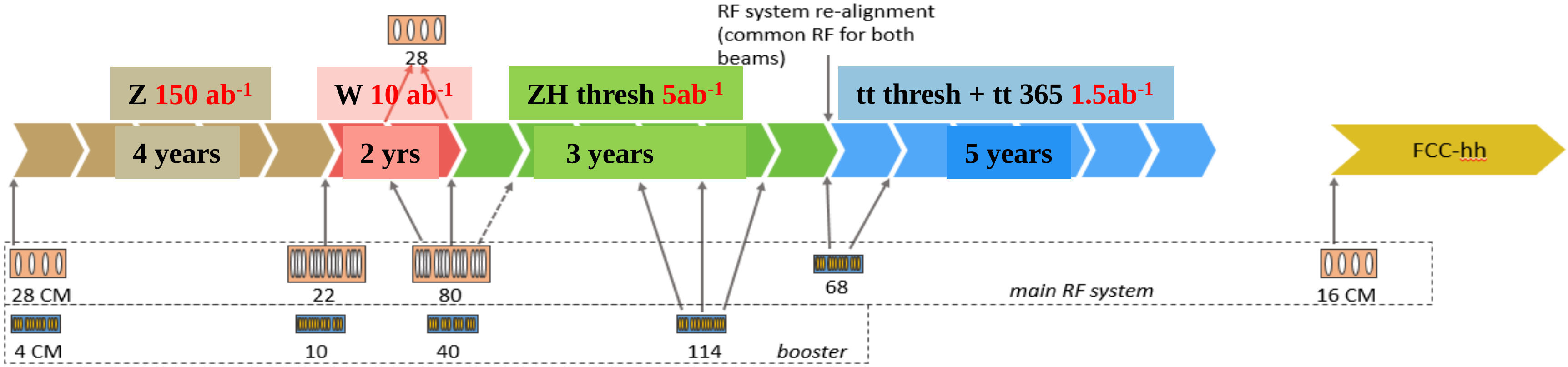
	V_tot (GV)	n_bunch	I_beam (mA)
Z	0.2	91500	1450
W	0.8	5260	152
H	3	780	30
t	10	81	6.6

"high gradient" machine

Three sets of RF cavities for FCCee & Booster:

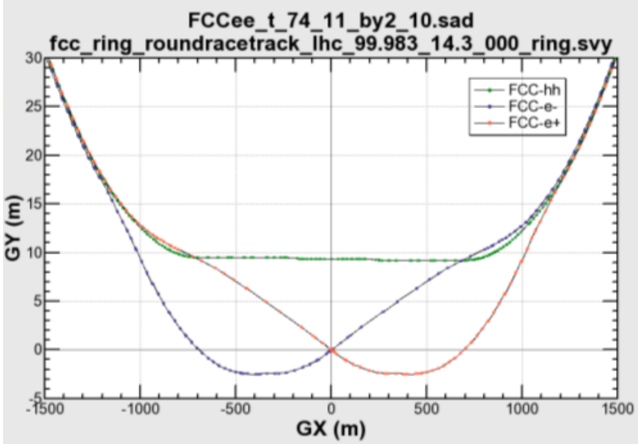
- **Installation as LEP (≈30 CM/winter)**
- **high intensity (Z, FCC-hh): 400 MHz mono-cell cavities, ≈ 1MW source**
- **high energy (W, H, t): 400 MHz four-cell cavities, also for W machine**
- **booster and t machine complement: 800 MHz four-cell cavities**
- **Adaptable 100MW, 400MHz RF power distribution system**

➔ **Spreads the funding profile**

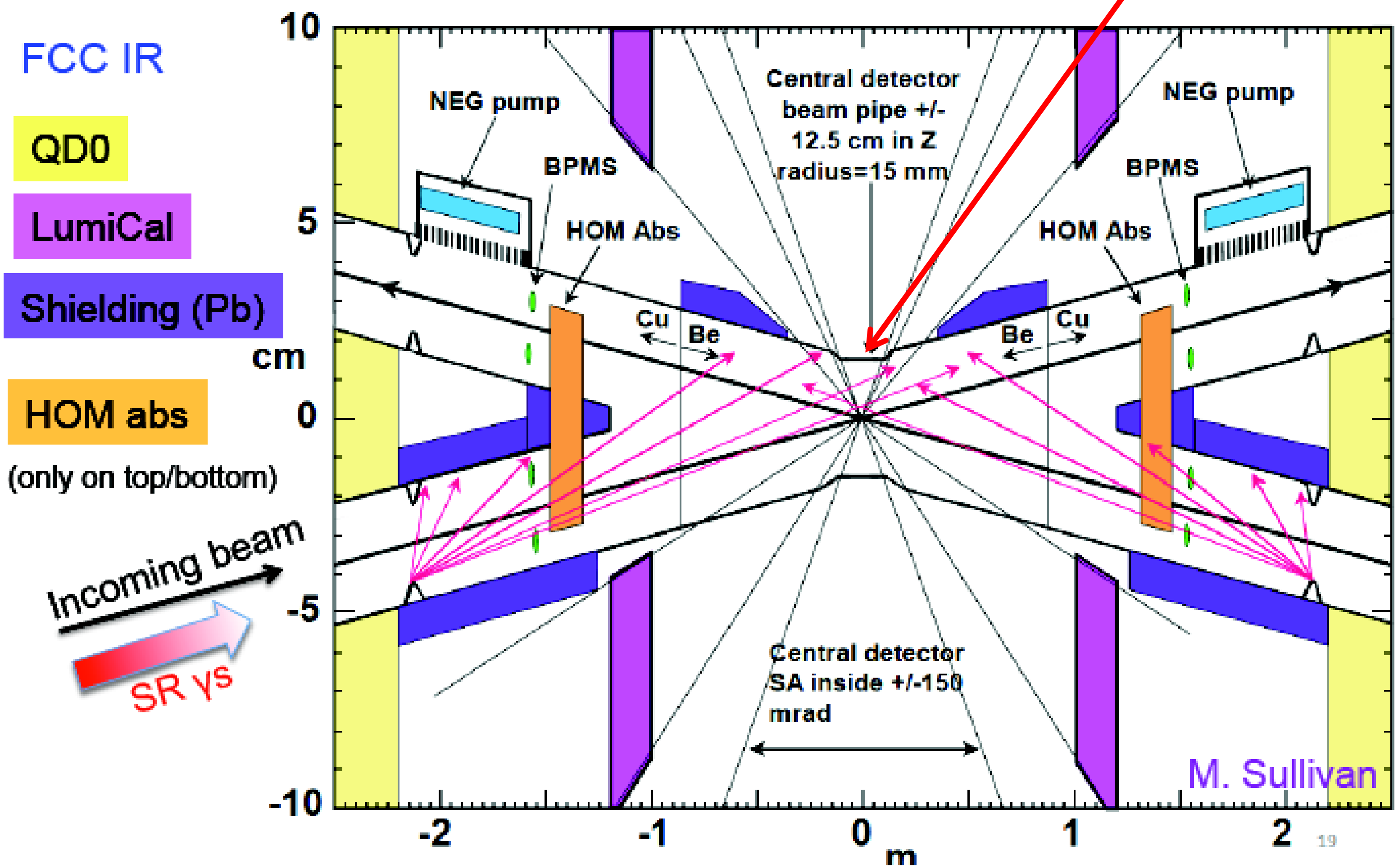


indicative: 2(comm) + 2 2 3 5 total ~14 years

Detailed layout of the Interaction Region



Beam pipe radius at IP is 15mm ☺



Beam Polarization and Energy calibration

First priority is to achieve transverse polarization for precision energy calibration in a way that allows continuous beam calibration by resonant depolarization (energy measurement every ~10 minutes on 'monitoring' single bunches)

- This is a unique feature of circular e+e- colliders
- baseline running scheme defined with monitoring bunches, wigglers, polarimeter
- the question of the residual systematic error requires further studies of the relationship between spin tune, beam energy at IRs, and center-of-mass energy

➔ target is **O(±100keV)** at Z and W pair threshold energies (averaged over data taking)

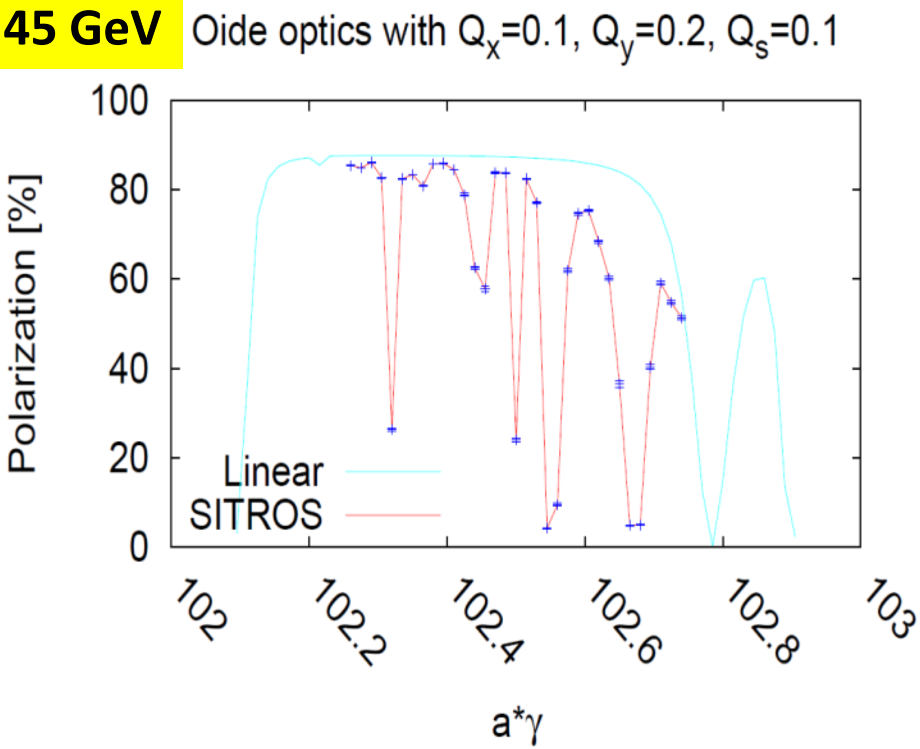
longitudinal polarization?

lower priority

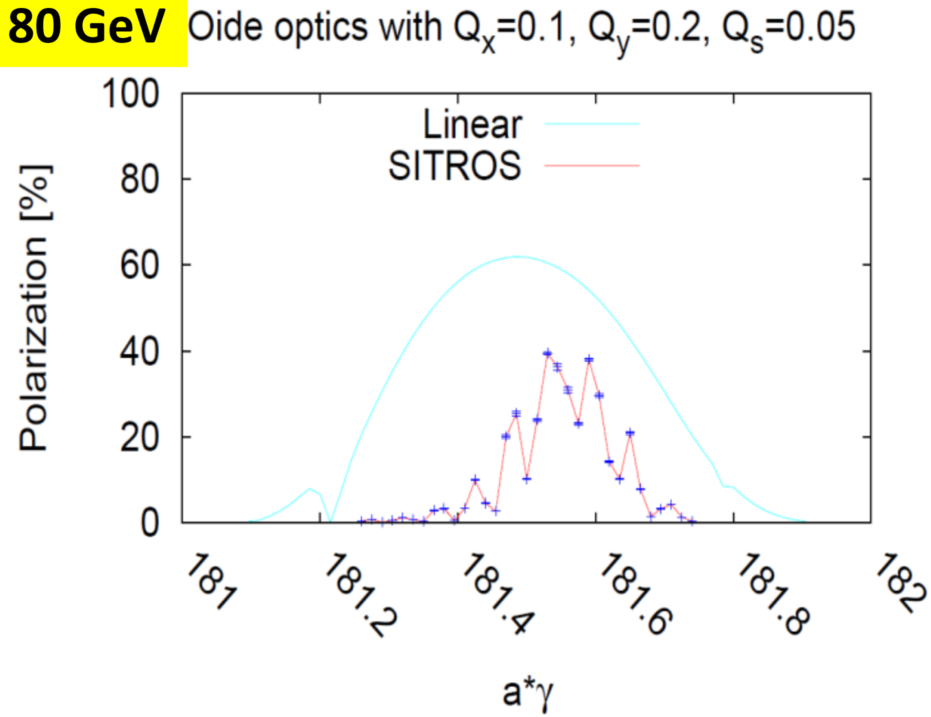
at Z, W, top: no information that we cannot obtain otherwise
from unpolarized A_{FB} asymmetries or final state polarization (top, tau)
+ too much loss of luminosity in present running scheme to provide gain in precision.

Beam Polarization and Energy calibration

45 GeV



80 GeV



At the Z obtain excellent polarization level but too slow for polarization in physics need wigglers for Energy calibration – OK as long as σ_{Eb}< ~55 MeV

$\sigma_{Eb} \propto E_b^2/\rho$

At the W expectation similar to LEP at Z → enough for energy calibration

Simulations by Eliana Gianfelice

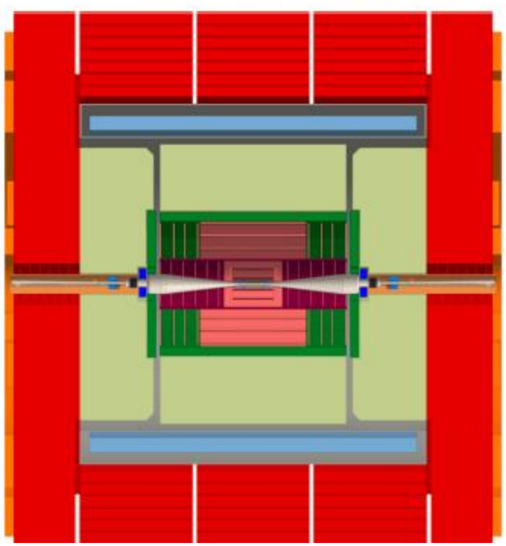
FCC-ee Detectors

Two integration, performance and cost estimates ongoing:

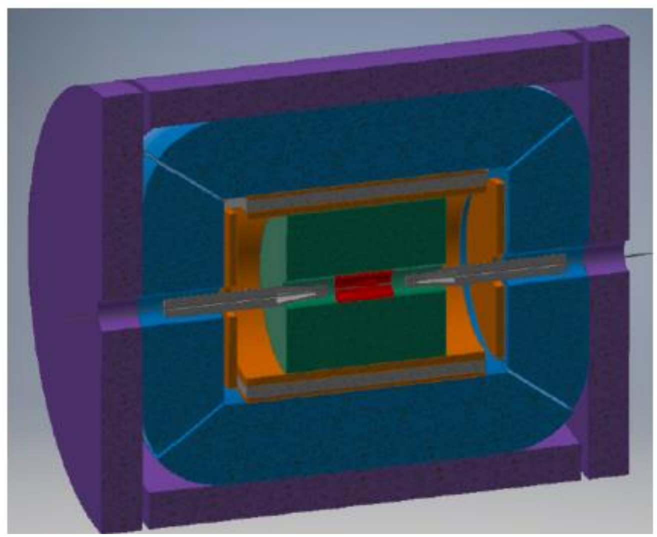
-- Linear Collider Detector group at CERN has undertaken the adaption of CLIC-SID detector for FCC-ee

-- new IDEA, detector specifically designed for FCC-ee (and CEPC)

"CLIC-detector revisited"



"IDEA"



- Vertex detector: ALICE **MAPS**
- Tracking: MEG2
- Si Preshower
- Ultra-thin solenoid (2T)
- Calorimeter: DREAM
- Equipped return yoke

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First look at the physics case of TLEP

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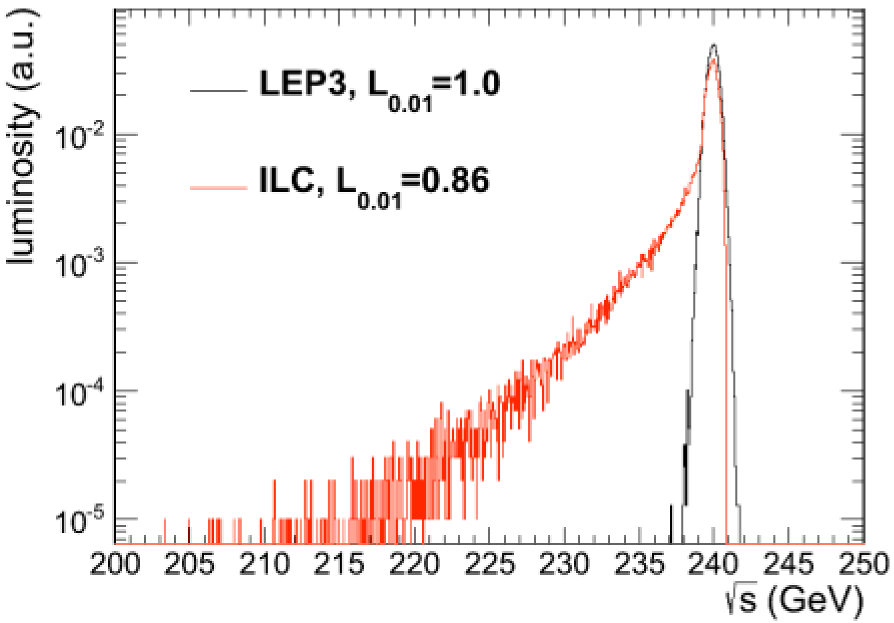
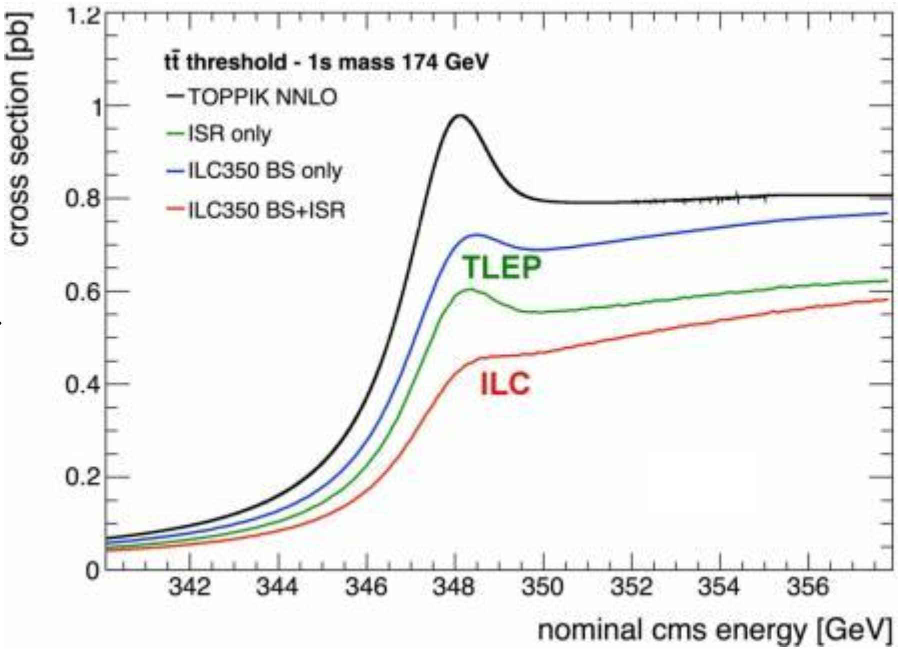
Luminosity *E* spectrum



Effect on top threshold



Beamstrahlung @TLEP is benign: particles are either lost or recycled on a synchrotron oscillation

➔ some increase of energy spread
but no change of average energy
Little EM background in the experiment.

FCC-ee discovery potential

Today we do not know how nature will surprise us. A few things that FCC-ee could discover :

EXPLORE 10-100 TeV energy scale (and beyond) with Precision Measurements

-- ~20-50 fold improved precision on many EW quantities (equiv. to factor 5-7 in mass)
$m_{Z,}$ m_W, m_{top} , $\sin^2\theta_w^{eff}$, R_b , $\alpha_{QED}(m_z)$ $\alpha_s(m_z\, m_W\, m_\tau)$, Higgs and top quark couplings

DISCOVER a violation of flavour conservation or universality
-- ex FCNC (Z --> $\mu\tau$, eτ) in 5 10^{12} Z decays.
+ flavour physics (10^{12} bb events) (B→s τ τ etc..)

DISCOVER dark matter as «invisible decay» of H or Z or in LHC loopholes.

DISCOVER very weakly coupled particle in 5-100 GeV energy scale
such as: Right-Handed neutrinos, Dark Photons etc…

+ an enormous amount of clean, unambiguous work on QCD etc….

NB the «Z factory» plays an important role in the 'discovery potential'

"First Look at the Physics Case of TLEP", JHEP 1401 (2014) 164,

100 TeV

Hadron collider parameters

parameter	FCC-hh		HE-LHC* *tentative	(HL) LHC
collision energy cms [TeV]	100		>25	14
dipole field [T]	16		16	8.3
circumference [km]	100		27	27
# IP	2 main & 2		2 & 2	2 & 2
beam current [A]	0.5		1.12	(1.12) 0.58
bunch intensity $[10^{11}]$	1	1 (0.2)	2.2	(2.2) 1.15
bunch spacing [ns]	25	25 (5)	25	25
beta* [m]	1.1	0.3	0.25	(0.15) 0.55
luminosity/IP $[10^{34}\ cm^{-2}s^{-1}]$	5	20 - 30	>25	(5) 1
events/bunch crossing	170	<1020 (204)	850	(135) 27
stored energy/beam [GJ]	8.4		1.2	(0.7) 0.36
synchrotr. rad. [W/m/beam]	30		3.6	(0.35) 0.18

Performance easier to achieve with 25 ns second spacing… 5ns preferred by expts!

16 T magnets

FCC goal is 16 T operating field
- Requires to use Nb_3Sn technology
- At 11 T used for HL-LHC

⇒ Strong synergy with HL-LHC

Key cost driver
16 T demonstrated in coil
Hope for US model test early 2018: 14-15 T
Short magnet models in 2018 – 2023
12 T for HL-LHC

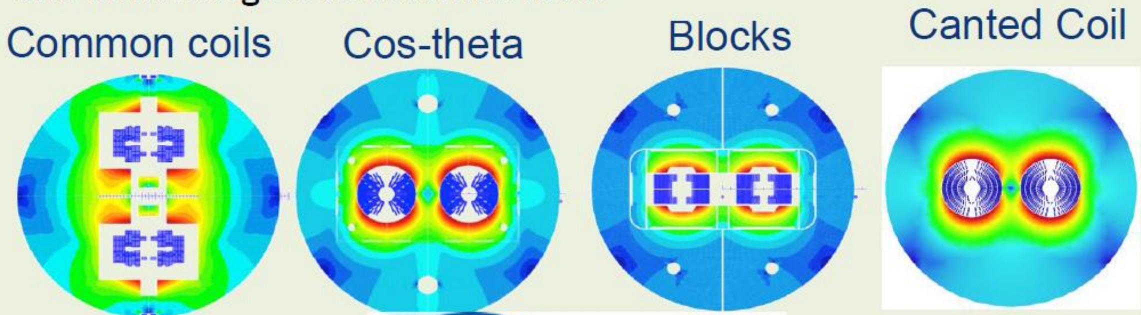
R&D on cables in test stand at CERN

Target: $J_C > 2300$ A/mm^2 at 1.9 K and 16 T (**50% above HL-LHC**)

Industrial fabrication:
Target cost: 3.4Euro/kAm

Magnet design to **minimise material** use and limit margins to essential level

D. Tommasini at al.



CIEMAT, CEA, INFN

EuroCirCol
A key to New Physics

Swiss contribution via PSI

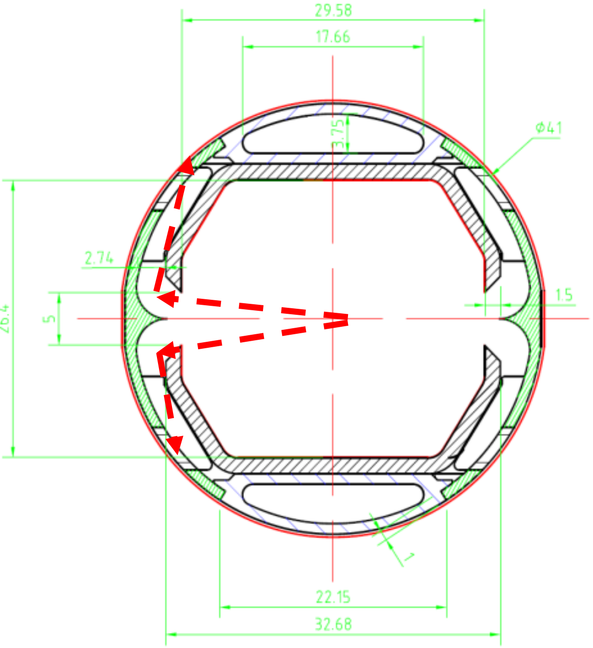
D. Schulte, EPS'17

-- possible shorter term application SCSPS or HE-LHC
-- For longer timescale HTS is also studied → 20T

Cryogenic beam vacuum system

One of the most critical elements for FCC-hh

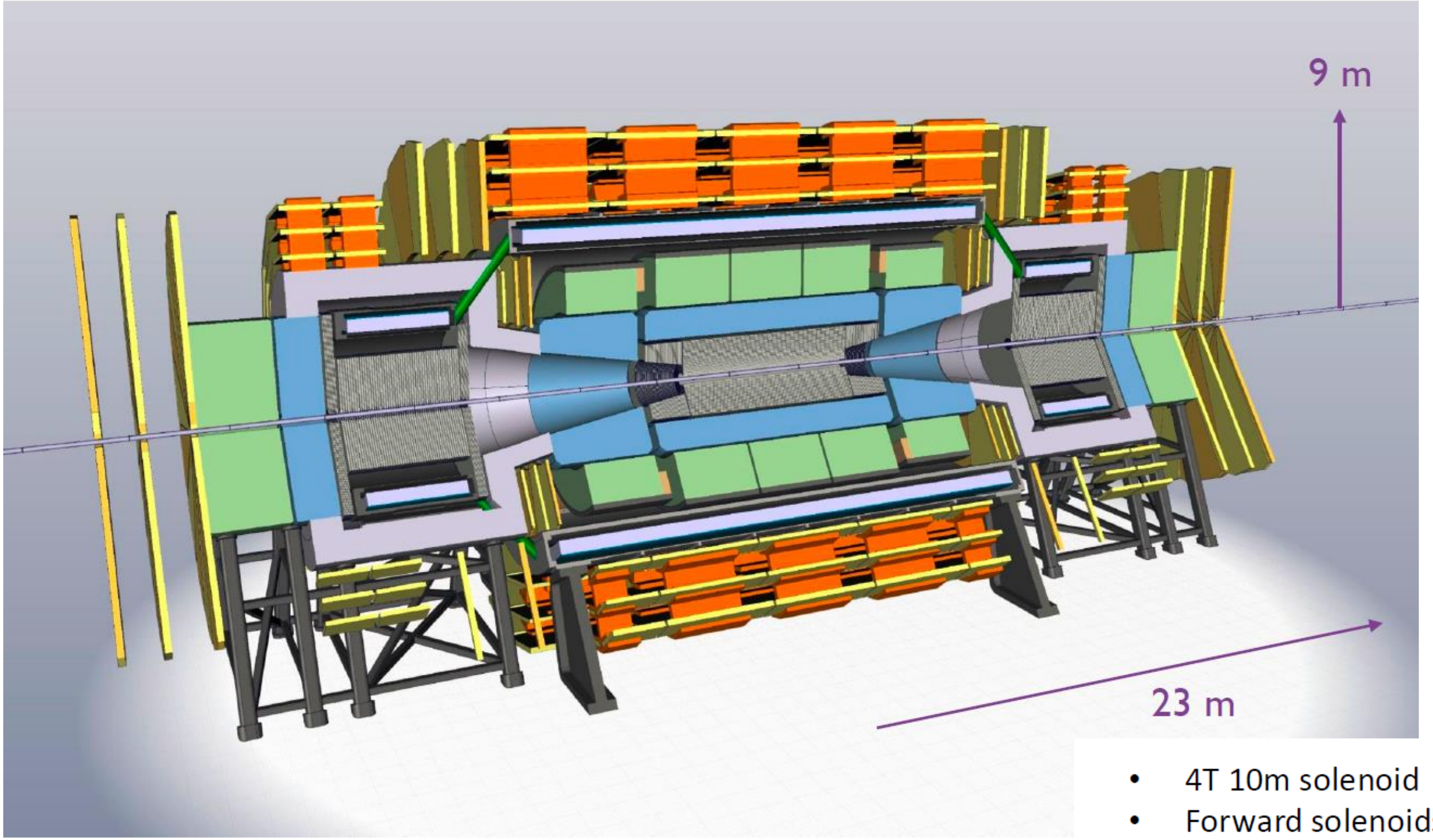
- **Absorption of synchrotron radiation at ~50 K for cryogenic efficiency (5 MW total power)**
- **Provision of beam vacuum, suppression of photo-electrons, electron cloud effect, impedance, etc.**



FCC Beamscreen prototype for test at ANKA:

External copper rings for heat transfer to cooling tubes

FCC-hh reference detector



- 4T 10m solenoid
- Forward solenoids
- Silicon tracker
- Barrel ECAL Lar
- Barrel HCAL Fe/Sci
- Endcap HCAL/ECAL LAr
- Forward HCAL/ECAL LAr

Solenoids in Central *and* forward areas no flux return.

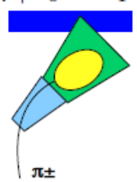
Object reconstruction and performances

✦ *Particle Flow Reconstruction*

- Using charged hadrons, muons, electrons and calorimeter towers to build particle-flow objects
- Tracks from pile-up are rejected if $|Z_0 - Z_{\mathrm{PV}}| > \sqrt{\sigma^2(Z_0) + \sigma^2(Z_{\mathrm{PV}})}$

✦ *Jets*

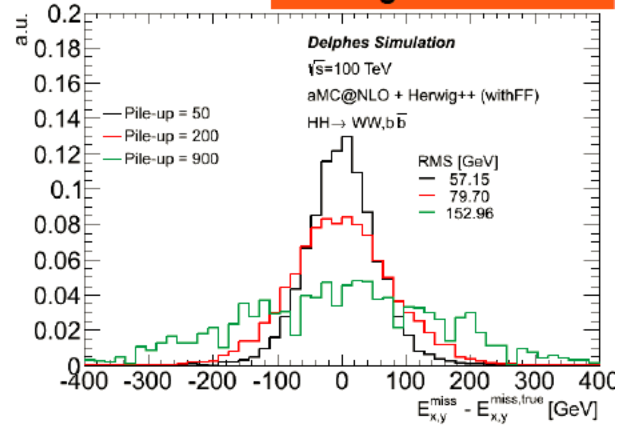
- Anti-Kt (Fast Jet) algorithm
- particle-flow objects as inputs
- R = 0.4
- Jet Area pile-up correction:
- private calibration to particle level $p_T^{\mathrm{corrected}} = p_T^{\mathrm{raw}} - \rho \cdot \mathrm{JetArea}$
- $p_T^{\mathrm{jet}} > 20$ GeV



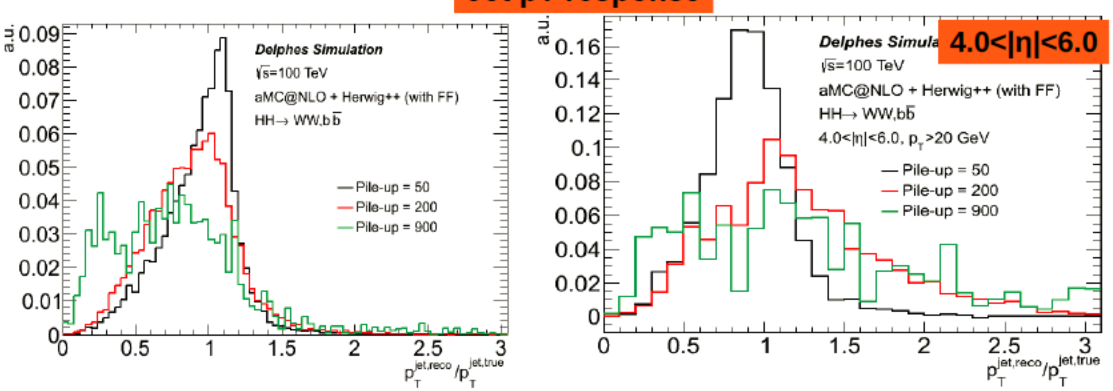
✦ *Missing Transverse Energy*

- Anti-Kt (Fast Jet) algorithm
- negative vector sum of Jets, after pile-up correction and calibration

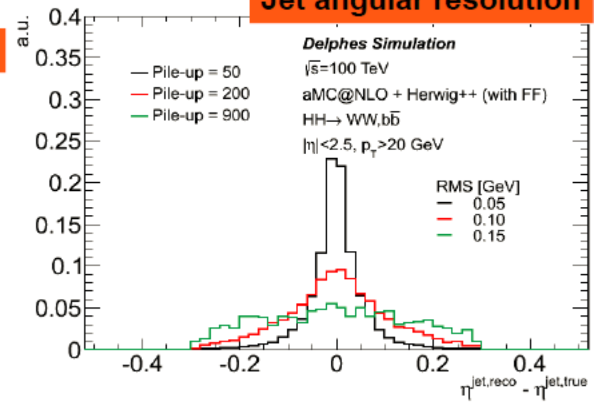
Missing ET resolution



Jet pT response



Jet angular resolution



FCC-hh discovery potential
Highlights

FCC-hh is a HUGE discovery machine (if nature …), but not only.

FCC-hh physics is dominated by three features:

-- Highest center of mass energy –> a big step in high mass reach!

ex: strongly coupled new particle up to 50 TeV

Excited quarks, Z', W', up to ~tens of TeV

Give the final word on natural Supersymmetry, extra Higgs etc.. reach up to 5-20 TeV

Sensitivity to high energy phenomena in e.g. WW scattering

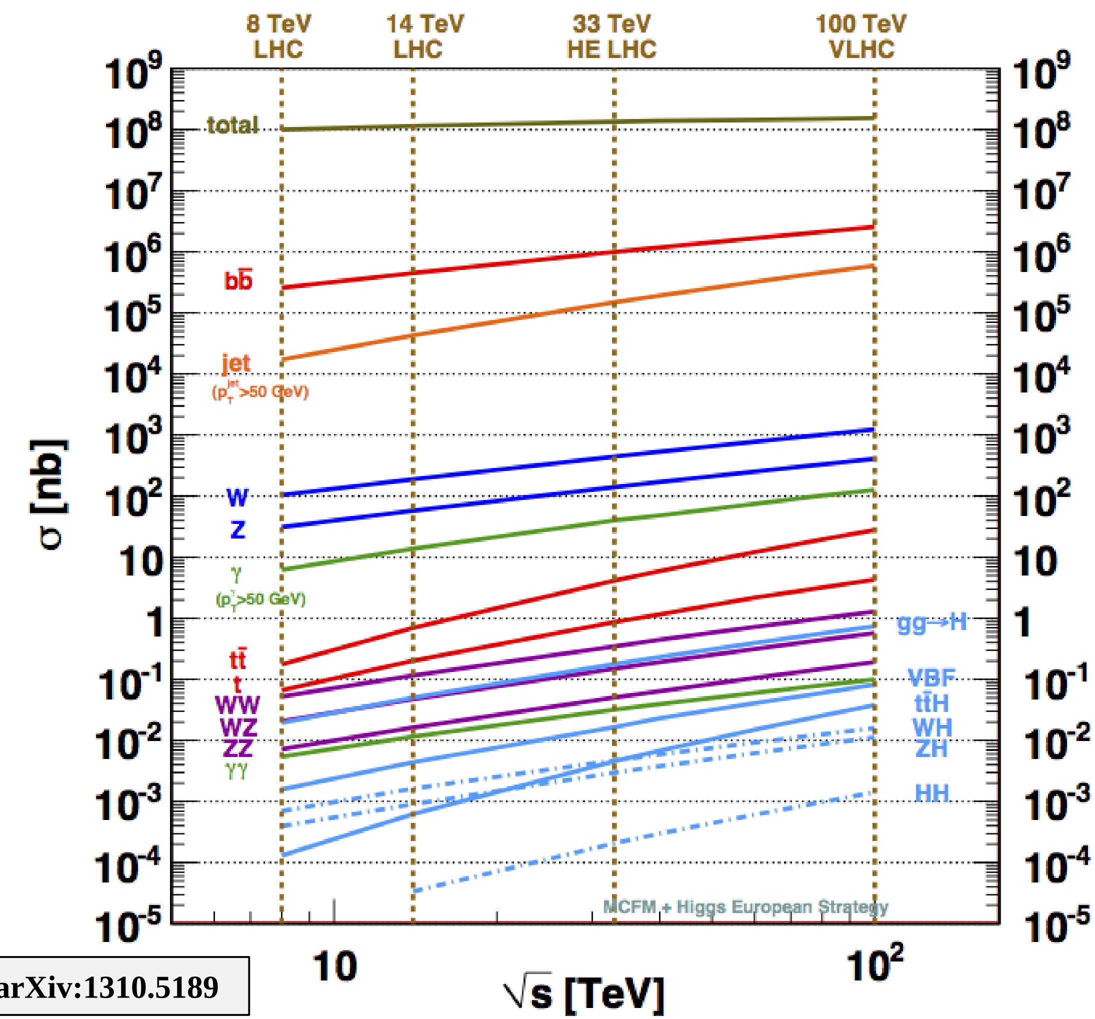
-- HUGE production rates for single and multiple production of SM bosons (H,W,Z) and quarks

- **-- Higgs precision tests using ratios to e.g. $\gamma\gamma/\mu\mu/\tau\tau/ZZ$, ttH/ttZ @% level**
- **-- Precise determination of triple Higgs coupling (~3% level) and quartic Higgs coupling**
- **-- detection of rare decays $H \rightarrow V\gamma$ ($V = \rho, \varphi, J/\psi, \Upsilon, Z\ldots$)**
- **-- search for invisibles (DM searches, RH neutrinos in W decays)**
- **-- renewed interest for long lived (very weakly coupled) particles.**
- **-- rich top and HF physics program**

-- Cleaner signals for high Pt physics

-- allows clean signals for channels presently difficult at LHC (e.g. $H \rightarrow bb$)

Hadron colliders: direct exploration of the "energy frontier"



arXiv:1310.5189

Gianotti

Process	σ (100 TeV)/σ (14 TeV)
Total pp	1.25
W	~7
Z	~7
WW	~10
ZZ	~10
tt	~30
H	~15 (ttH ~60)
HH	~40
stop (m=1 TeV)	~10^3

With 40/ab at √s=100 TeV expect: ~10^{12} top, 10^{10} H bosons, 10^5 m=8 TeV gluino pairs, …

If new (heavy) physics discovered at the LHC → completion of spectrum is a "no-lose" argument for future ~ 100 TeV pp collider: extend discovery potential up to m~50 TeV

FCC-hh discovery potential

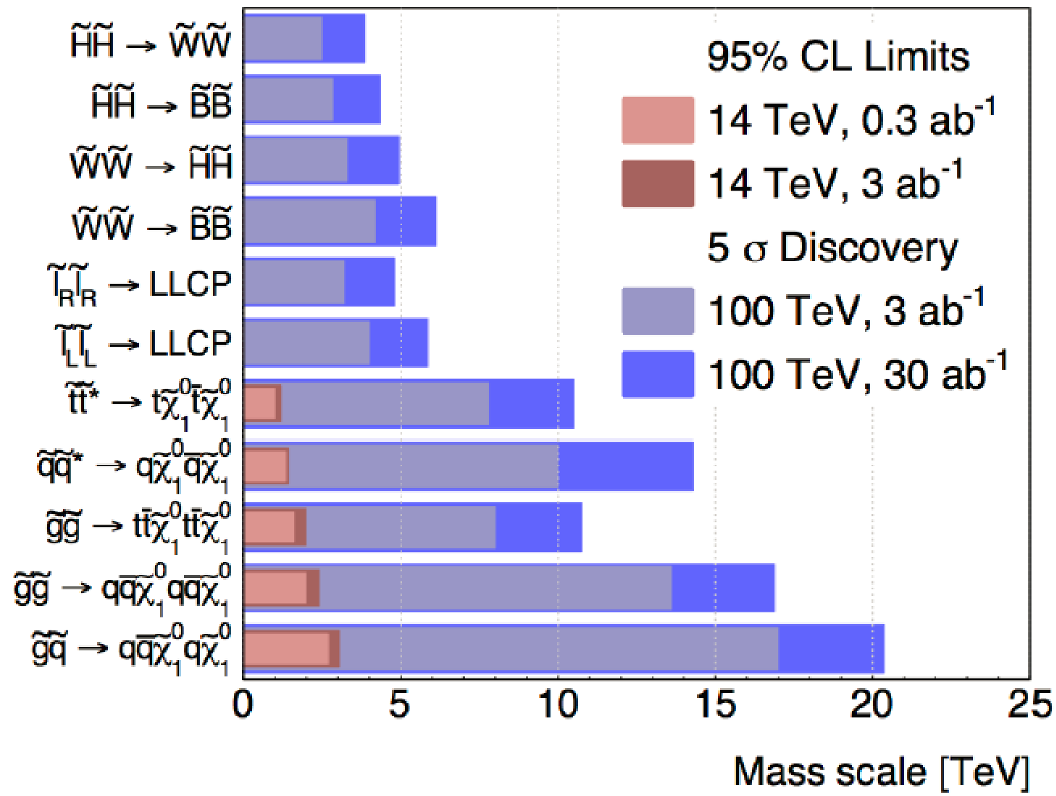
Physics at a 100 TeV pp collider: CERN Yellow Report (2017) no.3

1) Standard Model processes: https://arxiv.org/pdf/1607.01831v1.pdf
2) Higgs and EW symmetry breaking studies: https://arxiv.org/pdf/1606.09408v1.pdf
3) Beyond the Standard Model phenomena: https://arxiv.org/abs/1606.00947
4) Heavy ions at the Future Circular Collider: https://arxiv.org/abs/1605.01389

Now proceeding to ascertain these cross-section calculations with real detector and simulations…

Supersymmetry

Summary from FCC Report:



The paradigm of low energy supersymmetry has dominated ideas in physics beyond the Standard Model for decades. FCC-hh would provide the final word, by pushing far beyond the naturalness paradigm.

PHYSICS COMPLEMENTARITY

Some examples

Higgs Physics -- ee → ZH fixes Higgs width and HZZ coupling , (and many others)
-- FCC-hh gives huge statistics of HH events for Higgs self-coupling

Search for Heavy Physics
-- ee gives precision measurements (m_Z m_W to < 0.5 MeV, m_{top} 10 MeV, etc…)
sensitive to heavy physics up to … 100 TeV
-- FCC-hh gives access to direct observation at unprecedented energies
Also huge statistics of Z,W and top → rare decays

QCD -- ee gives $\alpha_s \pm 0.0002$ (R_{had})
also H→gg events (gluon fragmentation!)
-- ep provides tructure functions and $\alpha_s \pm 0.0002$
-- all this improves the signal and background predictions
for new physics signals at FCC-hh

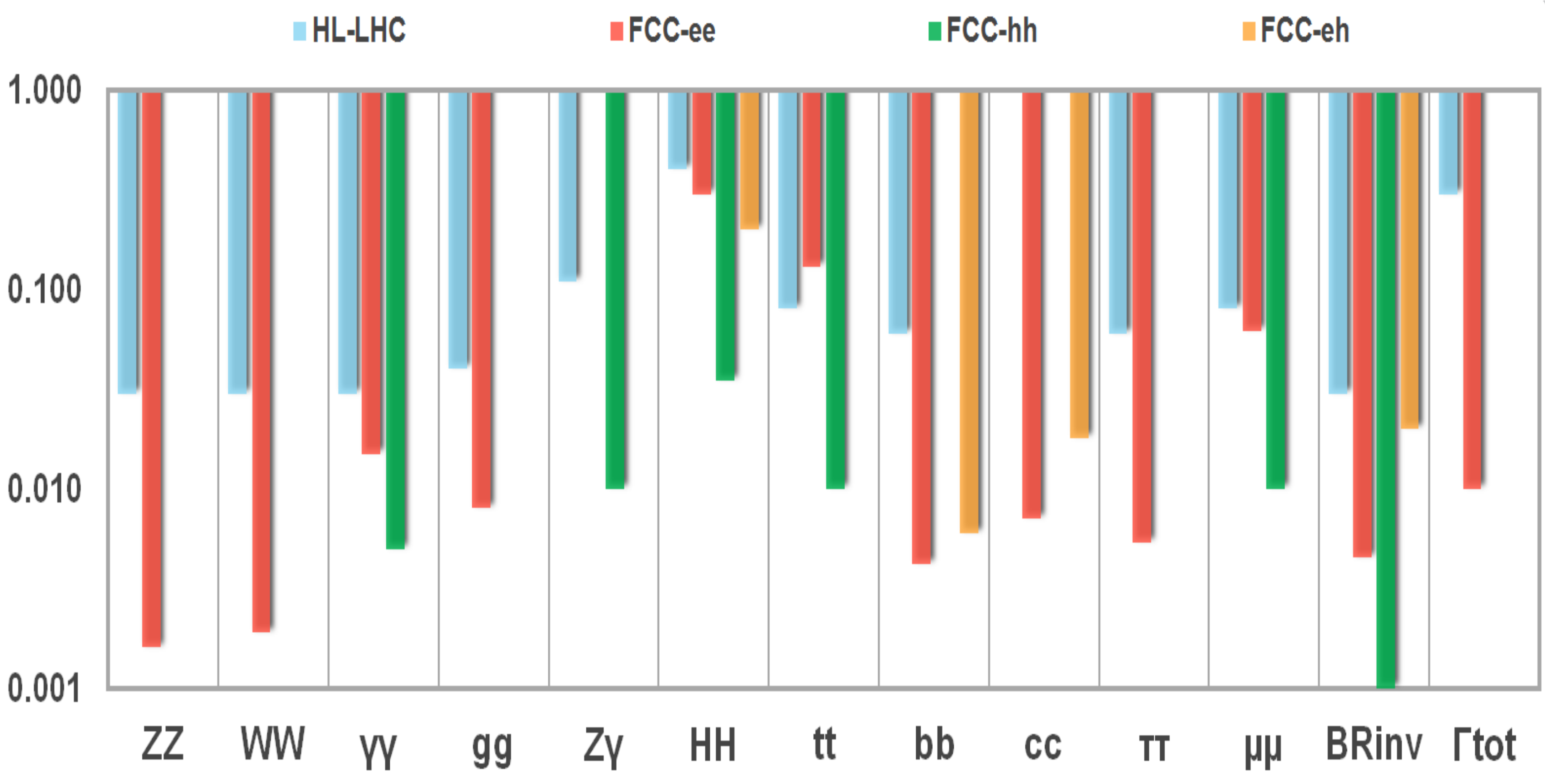
Heavy Neutrinos -- ee: very powerful and clean, but flavour-blind
-- hh and eh more difficult, but potentially flavour sensitive
NB this is very much work in progress!!

HIGGS PHYSICS

Higgs couplings g_{Hxx} precisions

hh, eh precisions assume SM or ee measurements

g_{Hxx}	FCC-ee	FCC-hh	FCC-eh
ZZ	**0.15 %**		
WW	**0.20%**		
Γ_H	**1%**		
$\gamma\gamma$	1.5%	**<1%**	
$Z\gamma$	--	**1%**	
tt	13%	**1%**	
bb	**0.4%**		0.5%
$\tau\tau$	**0.5%**		
cc	**0.7%**		1.8%
$\mu\mu$	6.2%	**2%**	
uu,dd	$H \rightarrow \rho\gamma$?	$H \rightarrow \rho\gamma$?	
ss	$H \rightarrow \phi\gamma$?	$H \rightarrow \phi\gamma$?	
ee	**ee → H**		
HH	30%	**~3%**	20%
inv, exo	<0.45%	**10^{-3}**	5%



NB this is an ‘impression plot’ not the consistent result of a Higgs coupling fit!

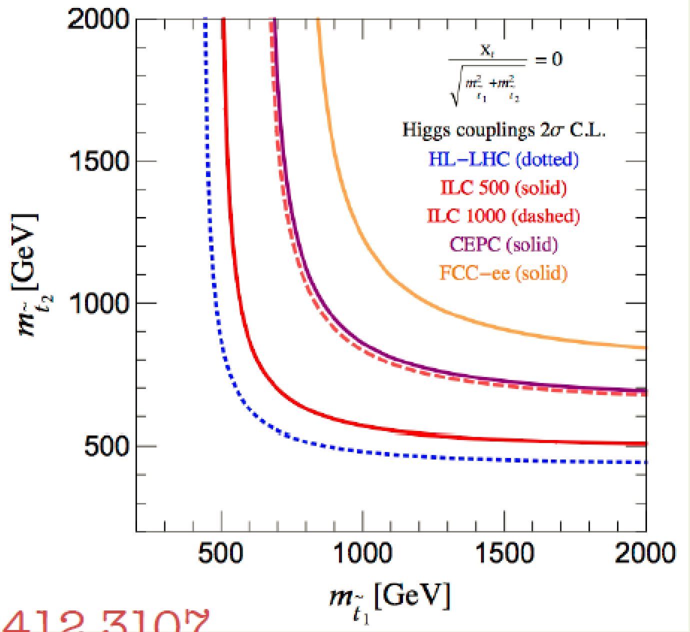
hh, eh precisions assume SM or ee measurements!

Supersymmetry

In supersymmetry top partner is "stop squark".

FCC-ee

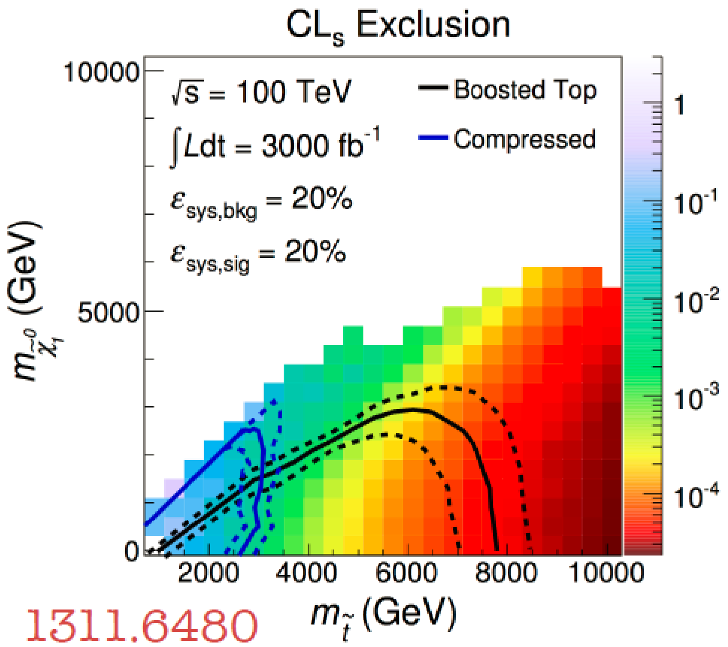
Coloured and charged, stops modify Higgs couplings:



1412.3107

FCC-hh

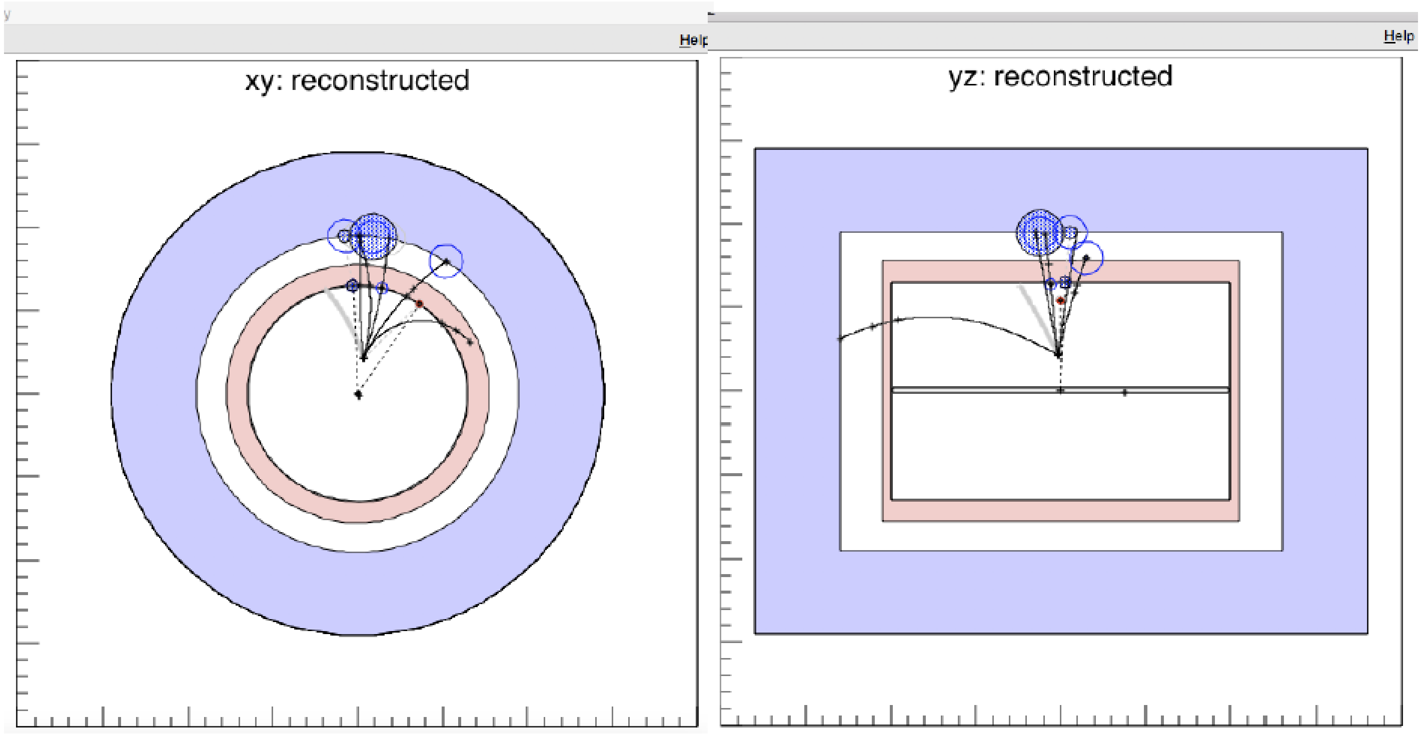
And show up directly at hadron colliders:



1311.6480

FCC-ee: Indirect, but more "spectrum independent", for a model.
FCC-hh: Direct confirmation, but direct might be hidden.

Simulation of heavy neutrino decay in a FCC-ee detector

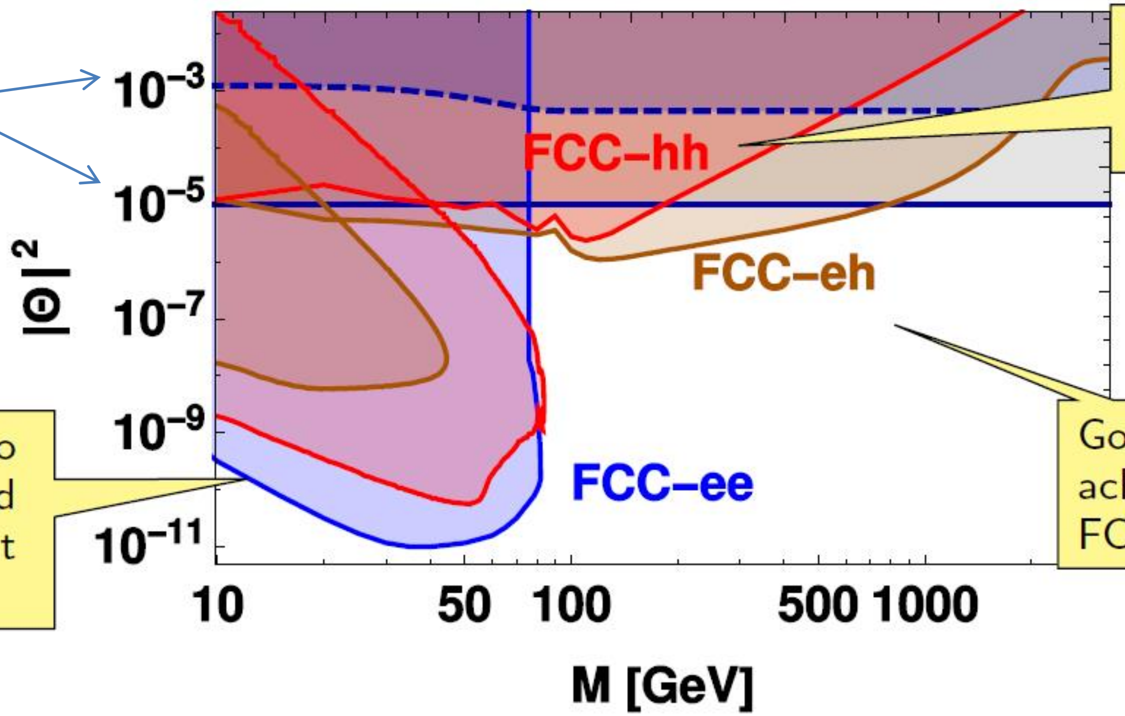


Summary

Another example of Synergy and complementarity
while ee covers a large part of space very cleanly ,
its either 'white' in lepton flavour or the result of EWPOs etc
Observation at FCC –hh or eh would test flavour mixing matrix!

- Systematic assessment of heavy neutrino signatures at colliders.
- First looks at FCC-hh and FCC-eh sensitivities.
- Golden channels:
  - **FCC-hh:** LFV signatures and displaced vertex search
  - **FCC-eh:** LFV signatures and displaced vertex search
  - **FCC-ee:** Indirect search via EWPO and displaced vertex search

EWPO sensitivity up to very high mass scales



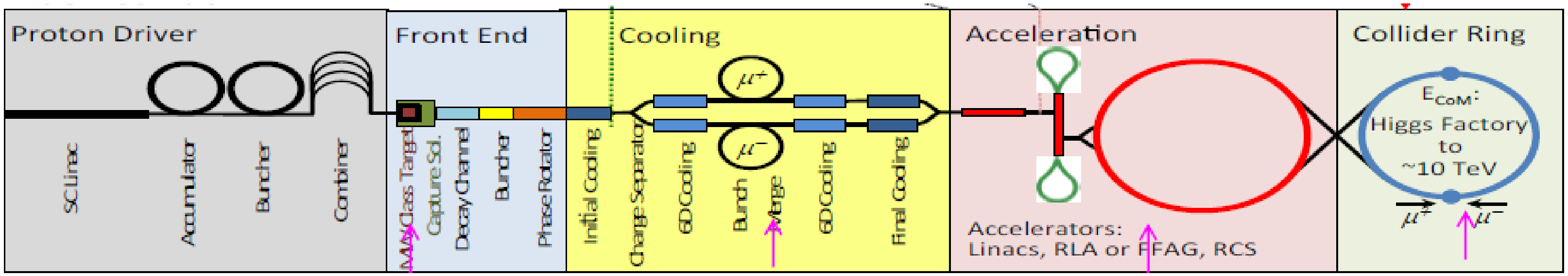
FCC-hh able to test all flavour combinations.

Best sensitivity to $|\theta|^2$ from displaced vertex searches at the FCC-ee.

Good sensitivity reach from FCC-hh & FCC-eh.

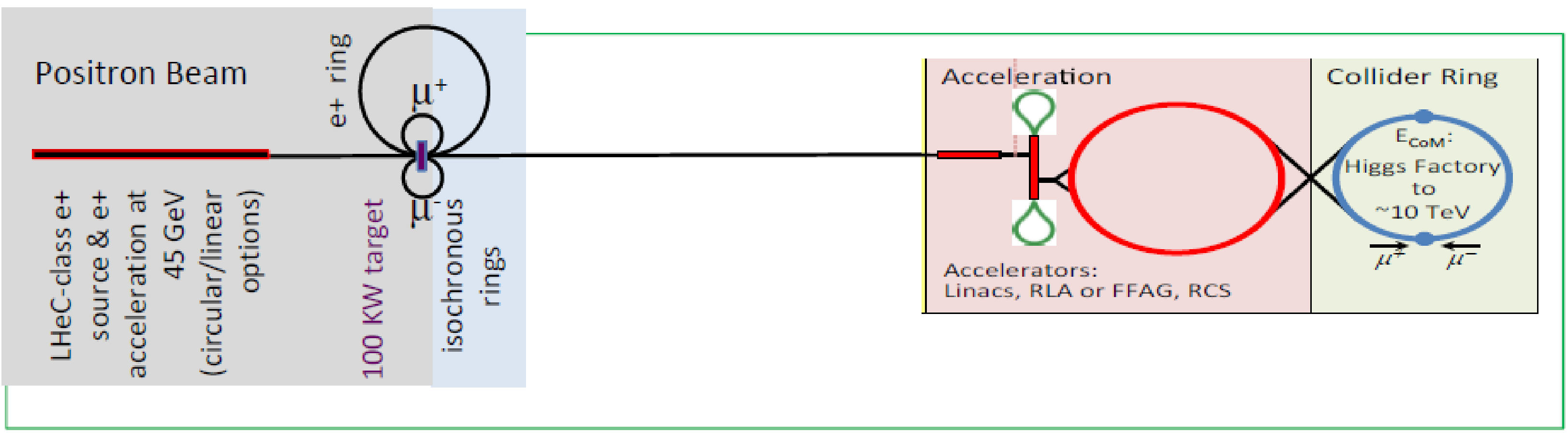
detailed study required for all FCCs – especially FCC-hh to understand feasibility at all

from US-MAP (2015) to Italian μ-collider (2017)



key challenges

~10^13-10^14 μ / sec tertiary particle p→π→μ:	fast cooling (τ=2μs) by 10^6 (6D)	fast acceleration mitigating μ decay	background from μ decay



key challenges: ~10^{11} μ / sec from $e^+e^- \rightarrow \mu+\mu-$

key R&D: 10^{15} e+/sec, 100 kW class target, NON destructive process in e+ ring

M. Antonelli, M. Boscolo, P. Raimondi et al.

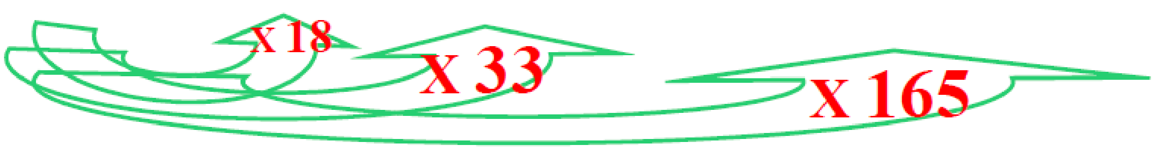
μ production by e⁺ annihilation

threshold e⁺ energy for μ production in e⁺ annihilation on static e⁻: $E_{e^+,\mathrm{thr}} = \frac{4m_\mu^2c^4 - 2m_e^2c^4}{2m_ec^2}$ =43.7 GeV

→ we could use the FCC-ee e⁺ ring or the FCC-ee top-up booster as μ accumulation & internal target ring!

e⁺ production rates achieved (SLC) or needed

	S-KEKB	SLC	CLIC (3 TeV)	ILC (*H*)	FCC-ee (*Z*)	Italian μ collider
10^{12} e⁺ / s	**2.5**	**6**	**110**	**200**	**5**	**1000**



LHC based Gamma Factory could provide 100x more e⁺/s than needed!

recipe for affordable high-energy colliders

- ✓ reduce SC/magnet cost
- ✓ select site with existing injector complex
- ✓ staging

e^+e^- 1st, *pp* 2nd, and $\mu^+\mu^-$ 3rd?

FCC-ee FCC-hh "FCC-μμ"?!

V. Shiltsev

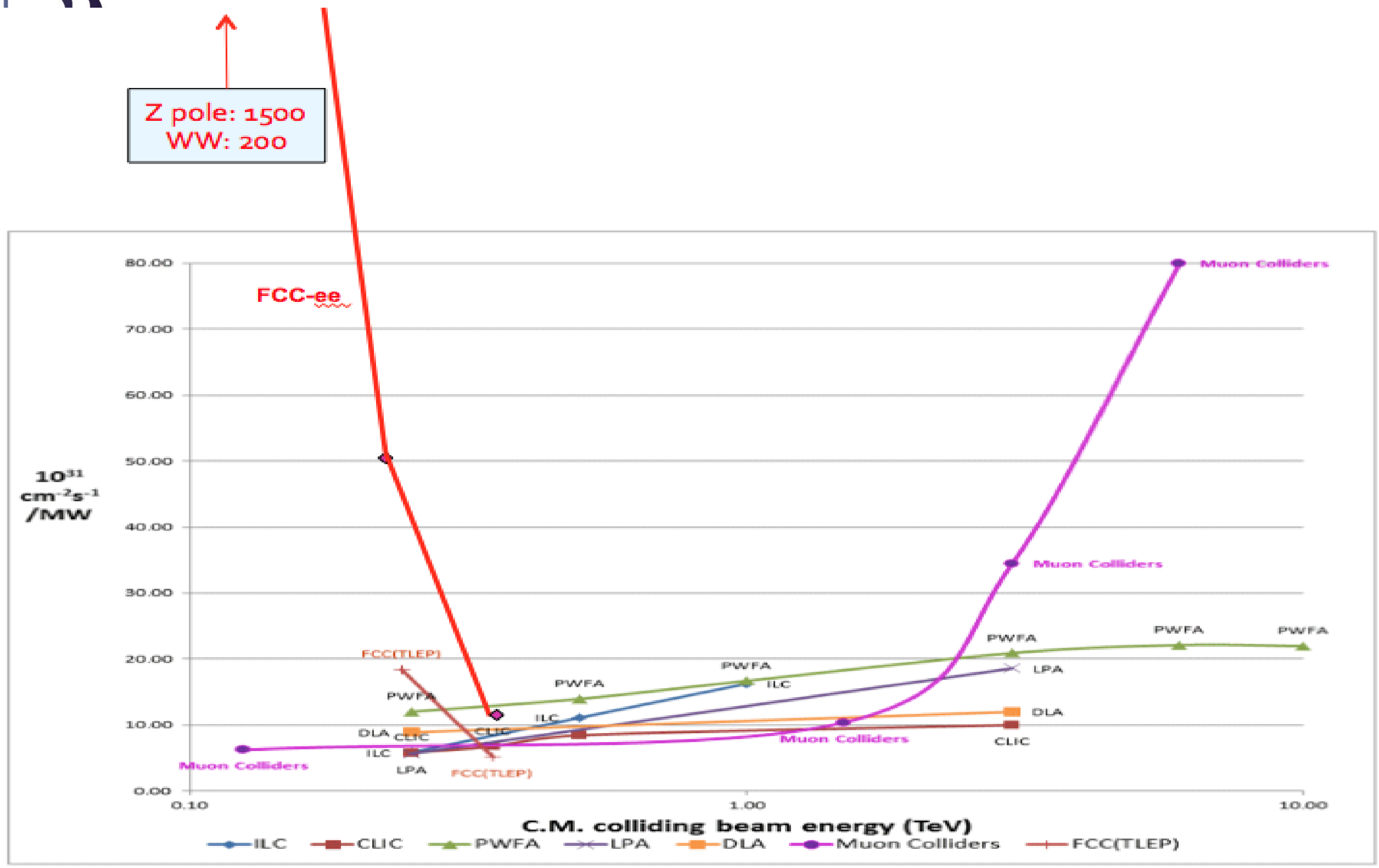


Figure 2: Luminosity per wall plug power consumption for various lepton collider technologies. The FCC-ee figure of merit has been updated with respect to the original paper to include the luminosity from two interaction points, the latest luminosity and power consumption figures, and the WW threshold and Z pole working points (well outside the frame of the plot).

FCC CONCLUSIONS

-- The FCC design study is establishing the feasibility or the path to feasibility of an ambitious set of colliders after LEP/LHC, at the cutting edge of knowledge and technology.

-- Both FCC-ee and FCC-hh have outstanding physics cases

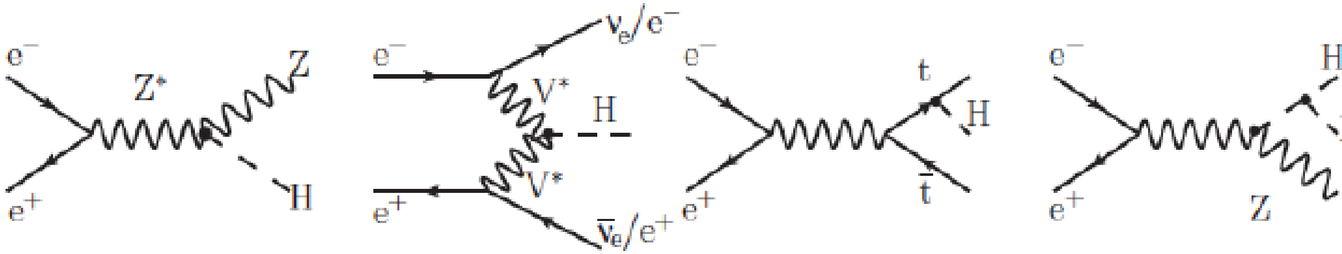
-- each in their own right

-- the sequential implementation of FCC-ee, FCC-hh, FCC-eh would maximise the physics reach

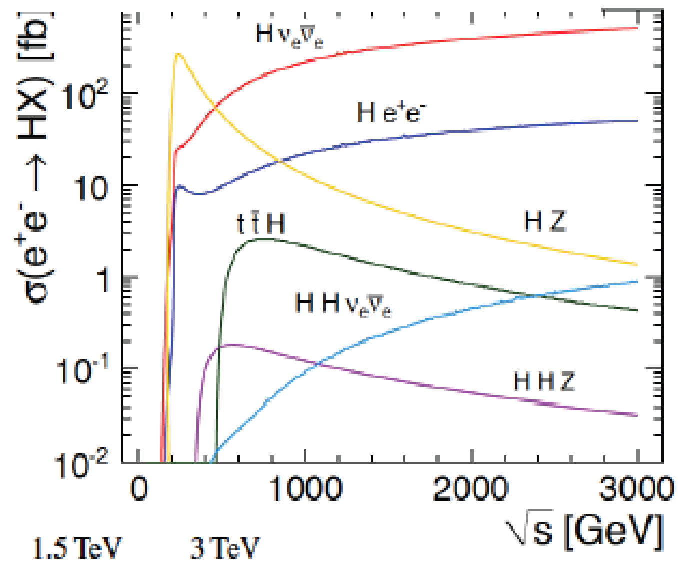
-- Attractive scenarios of staging and implementation (budget!) cover more than 50 years of exploratory physics, taking full advantage of the synergies and complementarities.

-- the FCC are shaping up as the most natural, complete and powerful aspiration of HEP for its long-term future

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}

	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

🡐 baseline ILC/CLIC as of ESPP

The Higgs at a e+e- Collider has been studied for many years (Tesla, ILC, CLIC)

At a given Ecm and Luminosity, the physics has marginally to do with the fact that the collider is *linear or circular*

--specifics:

- **-- e- polarization is easy at the source in LC, (not critical for Higgs)**
- **-- EM backgrounds from beam disruption at LC**
- **-- knowledge and definition of beam energy at CC**
- **-- one IP (LC) vs several IPs (CC)**
- **-- Dependence of Luminosity on Center-of-mass energy →**

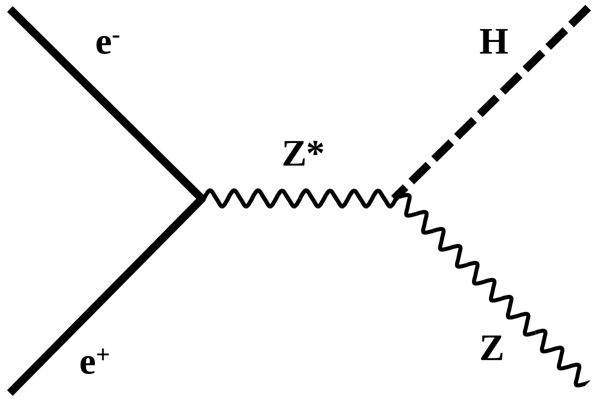
-- detectors are likely to be very similar

Higgs production mechanism

"higgstrahlung" process close to threshold

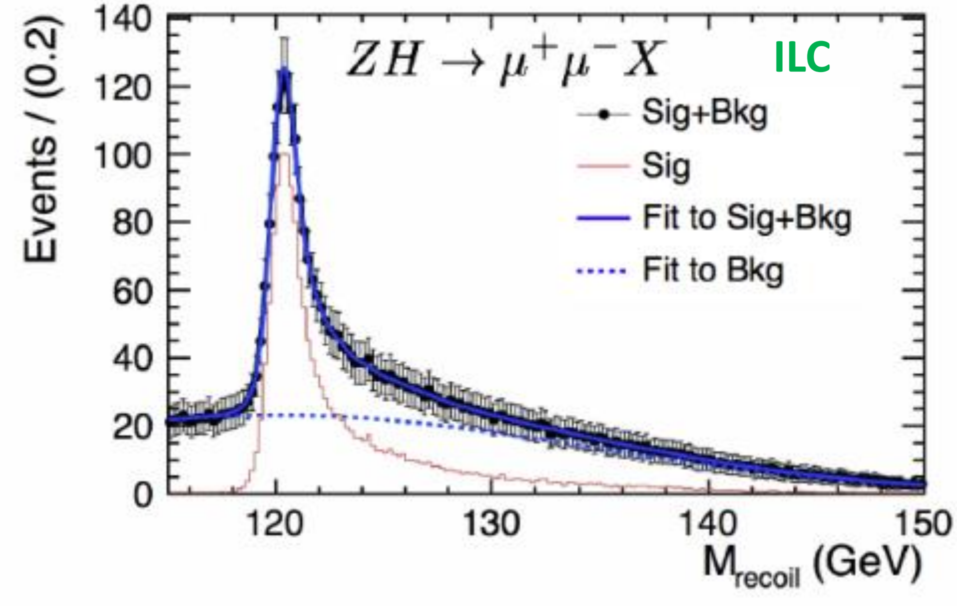
Production xsection has a maximum at near threshold ~200 fb

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



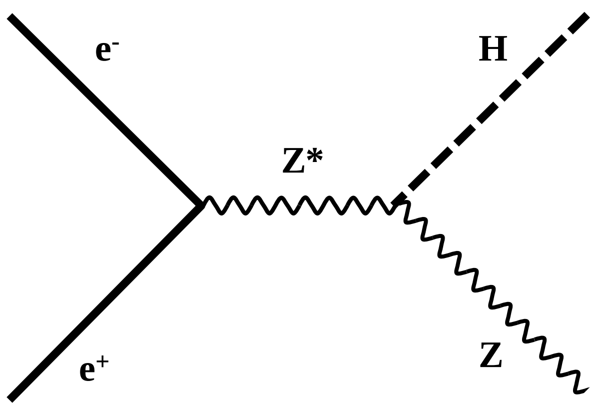
Z – tagging
by missing mass

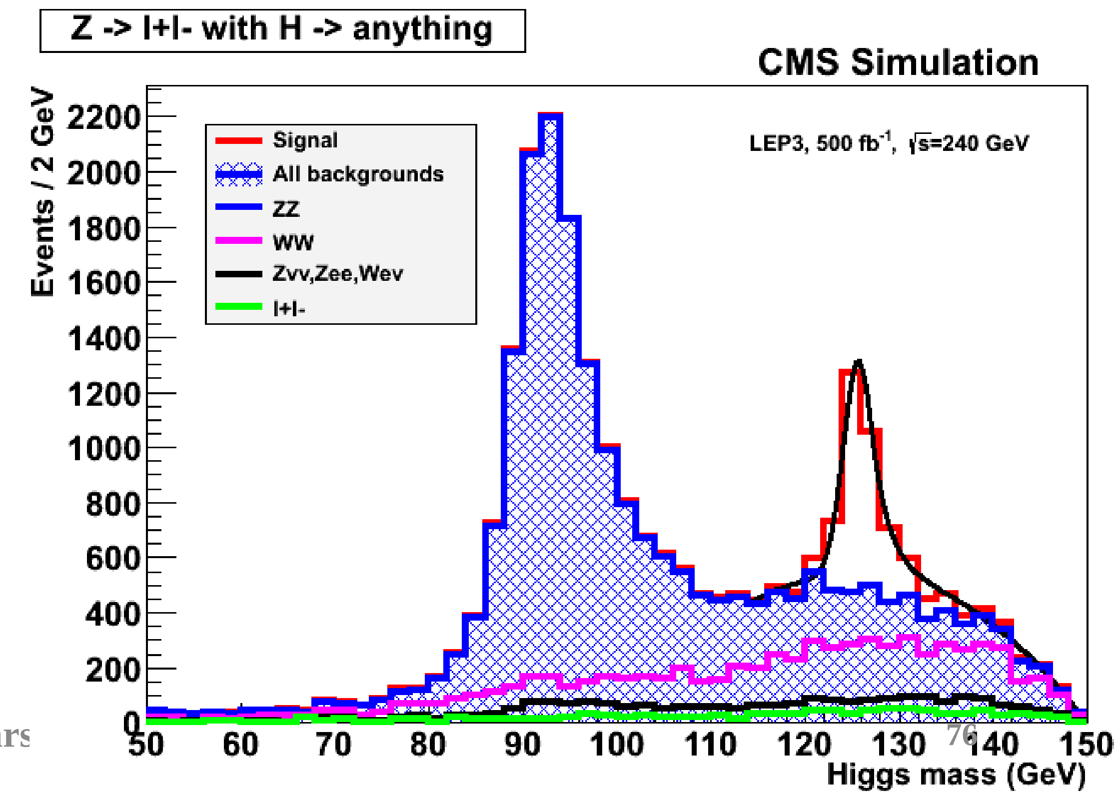
For a Higgs of 125GeV, a centre of mass energy of 240GeV is sufficient
➔ kinematical constraint near threshold for high precision in mass, width, selection purity



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

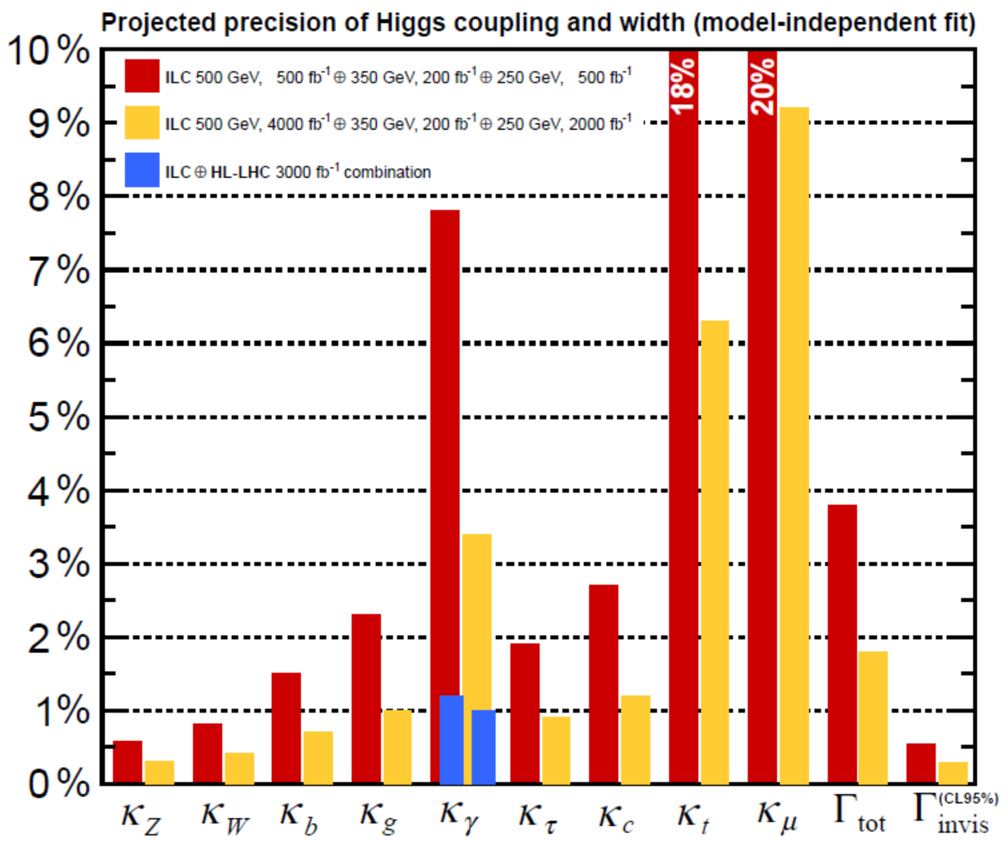




ILC new running scenarios including upgrade of luminosity

Topic	Parameter	Initial Phase	Full Data Set	units	ref.
Higgs	m_h	25	15	MeV	[15]
	$g(hZZ)$	0.58	0.31	%	[2]
	$g(hWW)$	0.81	0.42	%	[2]
	$g(hb\bar{b})$	1.5	0.7	%	[2]
	$g(hgg)$	2.3	1.0	%	[2]
	$g(h\gamma\gamma)$	7.8	3.4	%	[2]
		1.2	1.0	%, w. LHC results	[17]
	$g(h\tau\tau)$	1.9	0.9	%	[2]
	$g(hc\bar{c})$	2.7	1.2	%	[2]
	$g(ht\bar{t})$	18	6.3	%, direct	[2]
		20	20	%, $t\bar{t}$ threshold	[34]
	$g(h\mu\mu)$	20	9.2	%	[2]
	$g(hhh)$	77	27	%	[2]
	Γ_{tot}	3.8	1.8	%	[2]
	Γ_{invis}	0.54	0.29	%, 95% conf. limit	[2]

ILC new running scenarios including upgrade of luminosity



10 yrs (1.6 10^7s/yr) TDR lumi, incl. ramp-up

20 yrs (1.6 10^7s/yr) lumi upgrade incl. ramp-up

Figure 5: Relative precisions for the various Higgs couplings extracted from a model-independent fit to expected data from the ILC. The notation is as in Fig. 4.

arxiv:1506.07830
arxiv:1506.05992

FCC-ee as Higgs factory

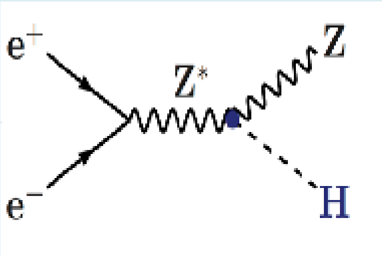
(constrained fit including 'exotic')

	4 IPs TLEP	(2 IPs)
g_{HZZ}	0.05%	(0.06%)
g_{HWW}	0.09%	(0.11%)
g_{Hbb}	0.19%	(0.23%)
g_{Hcc}	0.68%	(0.84%)
g_{Hgg}	0.79%	(0.97%)
$g_{H\tau\tau}$	0.49%	(0.60%)
$g_{H\mu\mu}$	6.2%	(7.6%)
$g_{H\gamma\gamma}$	1.4%	(1.7%)
BR_{exo}	0.16%	(0.20%)

➔ ***total width*** **<1%**

HHH (best at FCC-hh) 28% → from HZ thresh

H*tt* (best at FCC-hh) 13% → from tt thresh



$2\ 10^6$ ZH events in 5 years

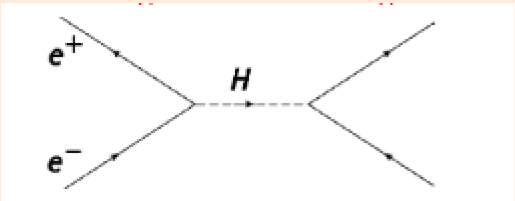
«A tagged Higgs beam».

sensitive to new physics in loops

incl. invisible = (dark matter?)
NB leptonic tag only.
Will improve with Hadronic Z tag

A big challenge, but unique:

Higgs s-channel production at $\sqrt{s} = m_H$



10^4 events per year. limits or signal?

monochromators?

Aleksan, D'Enterria, Woijcik

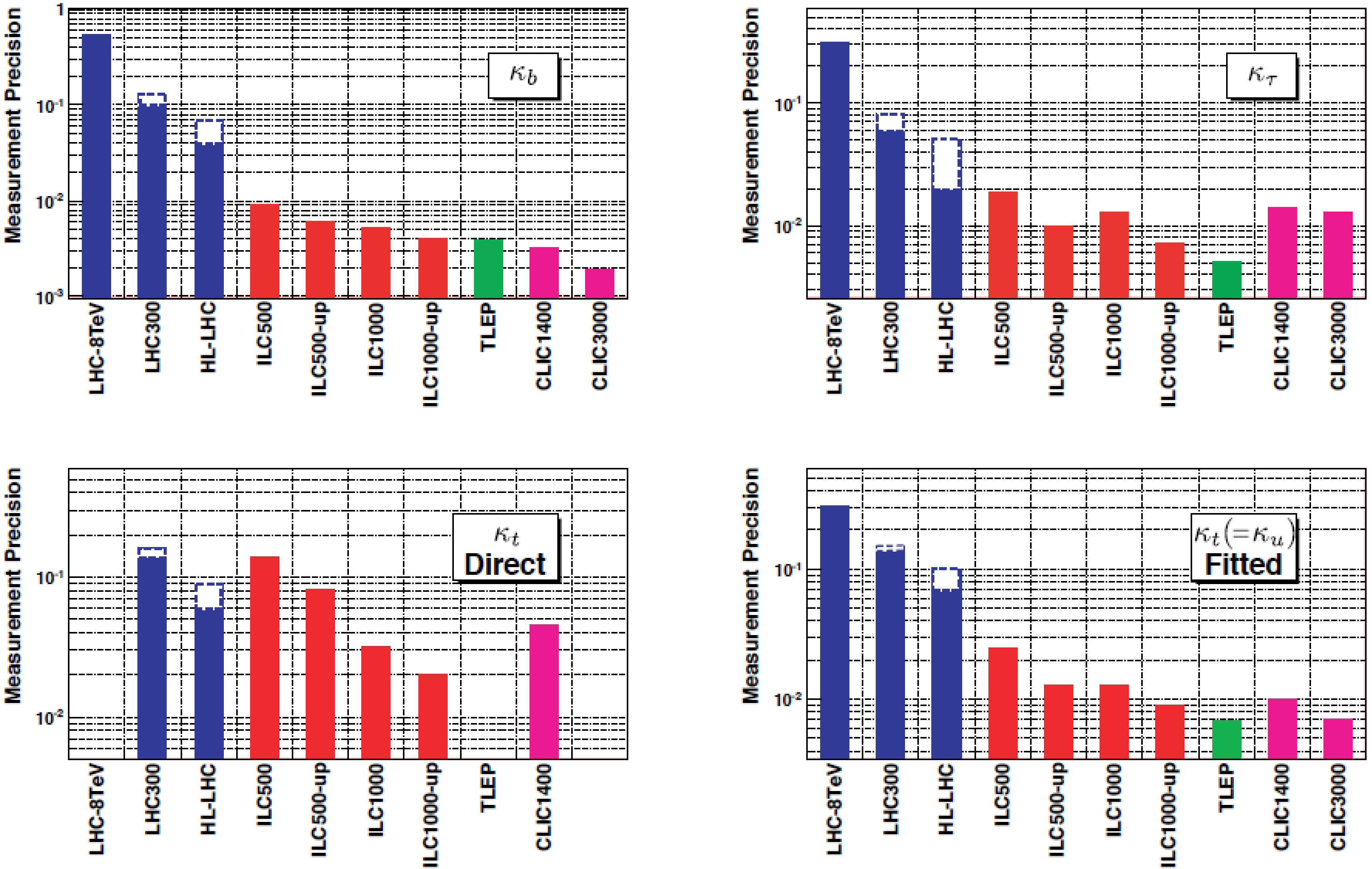


Figure 1-4. *Measurement precision on κ_b, κ_τ, and κ_t measured both directly via $t\bar{t}H$ and through global fits at different facilities.*

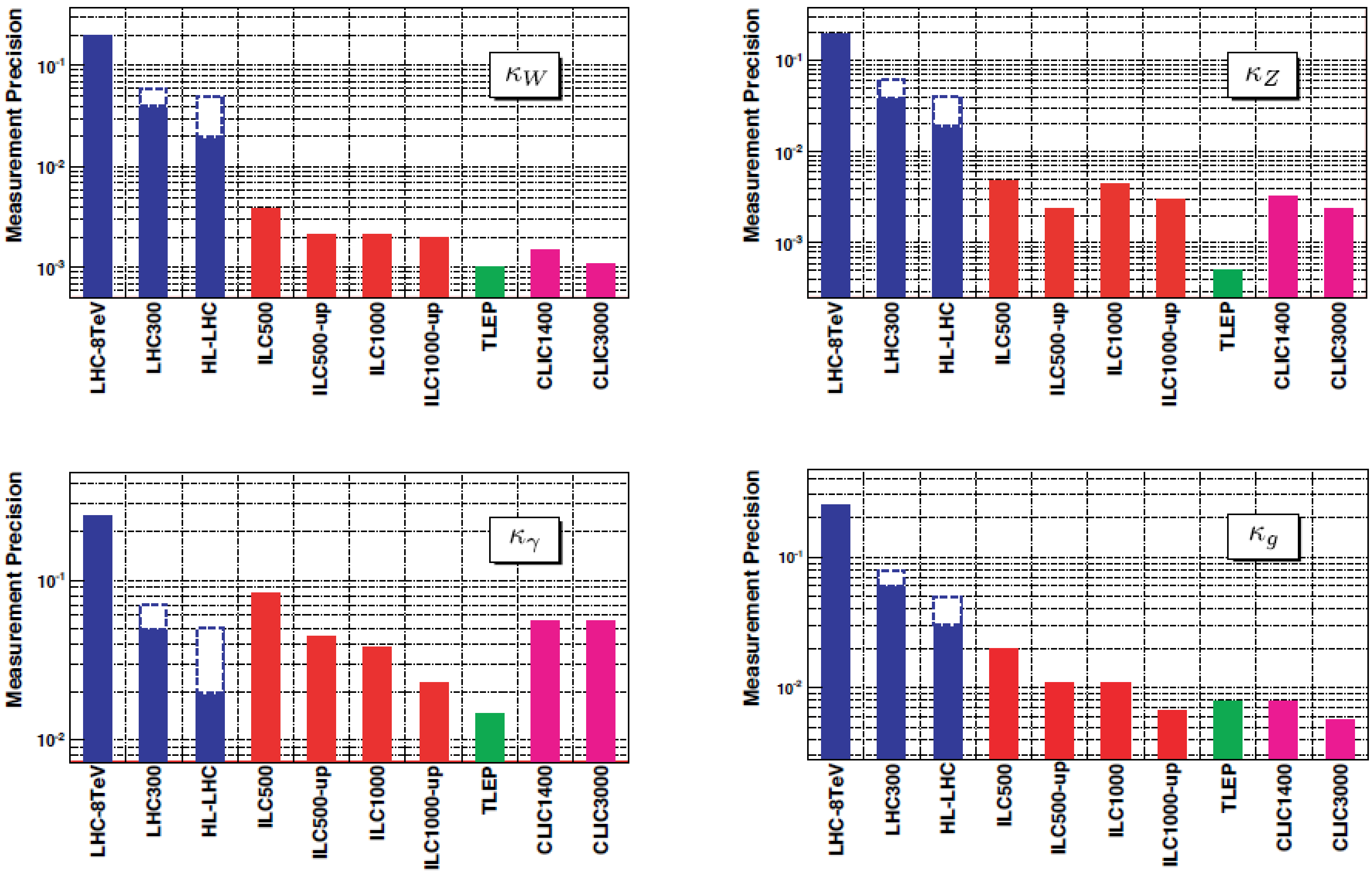
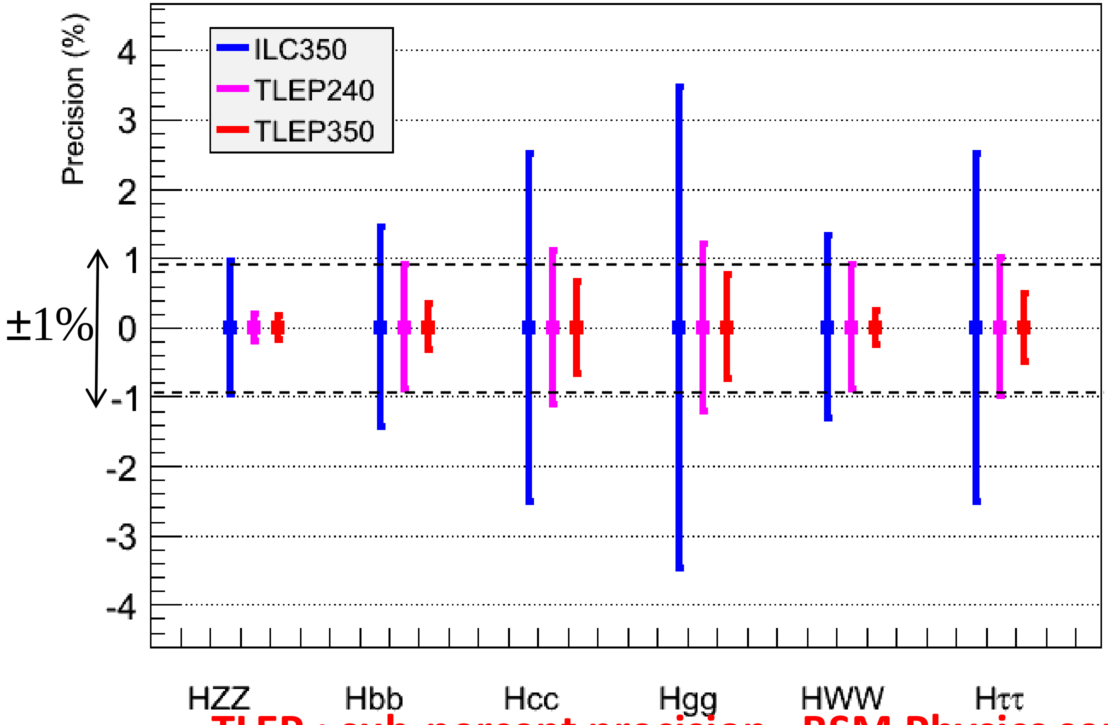


Figure 1-3. *Measurement precision on κ_W, κ_Z, κ_γ, and κ_g at different facilities.*

Performance Comparison

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

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

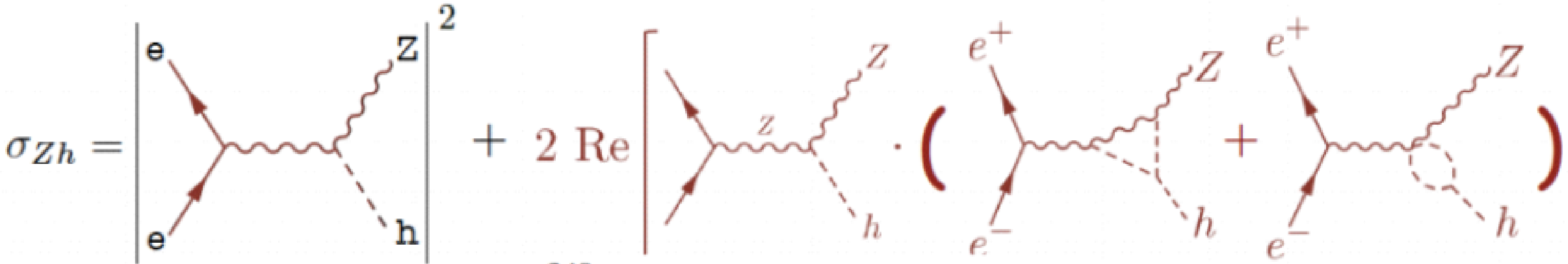


Expected precision on the total width

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

TLEP : sub-percent precision, BSM Physics sensitivity beyond several TeV

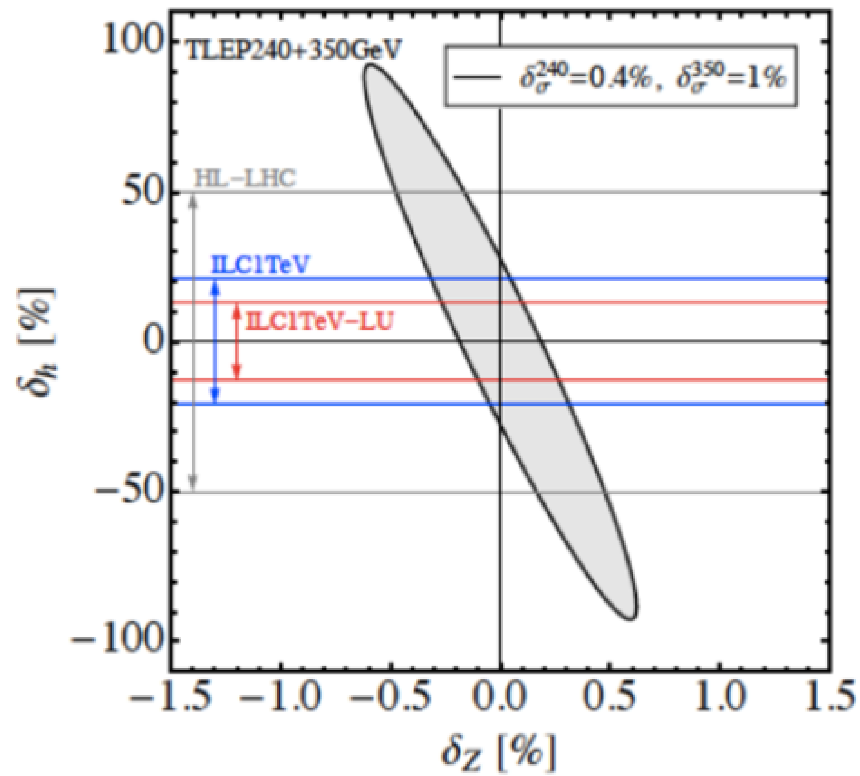
very accurate precision on threshold cross-section sensitive to loop corrections



$$\delta_\sigma^{240} = 100\,(2\delta_Z + 0.014\delta_h)\,\%$$

arxiv:1312.3322

- ➡ Very large datasets at high energy allow extreme precision g_{ZH} measurements
- ➡ Indirect and model-dependent probe of Higgs self-coupling
- ➡ Note, the time axis is missing from the plot

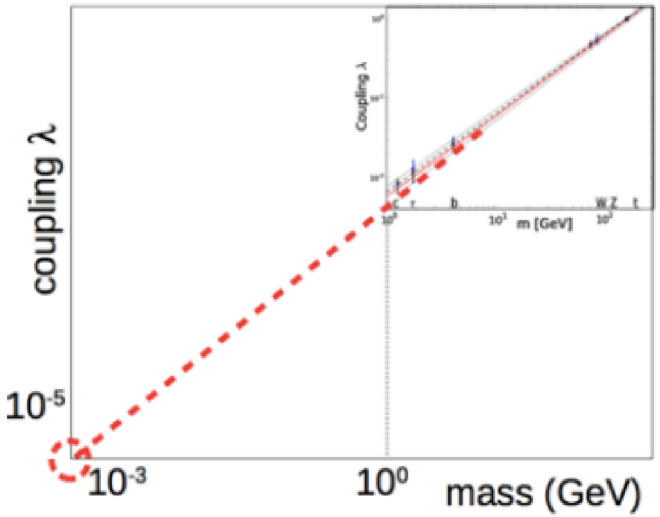


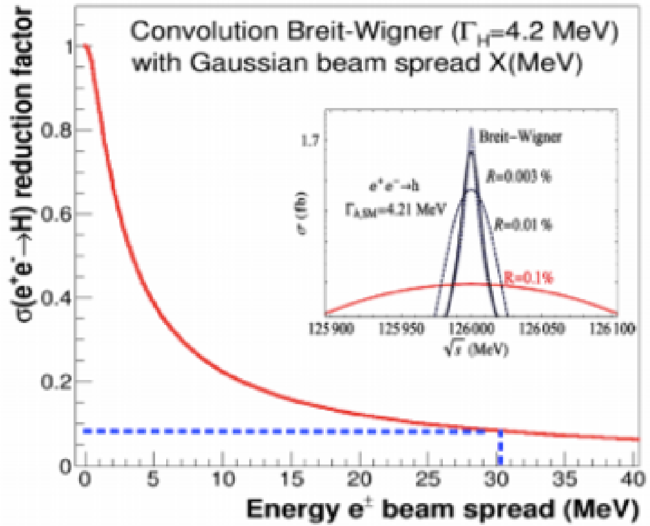
19

First generation couplings

➡ **s-channel Higgs production**

- Unique opportunity for measurement close to SM sensitivity
- Highly challenging; σ(ee→H) = 1.6fb; 7 Higgs decay channels studied





Preliminary Results

L = 10 ab^{-1}

κ_e < 2.2 at 3σ

➡ **Work in progress**

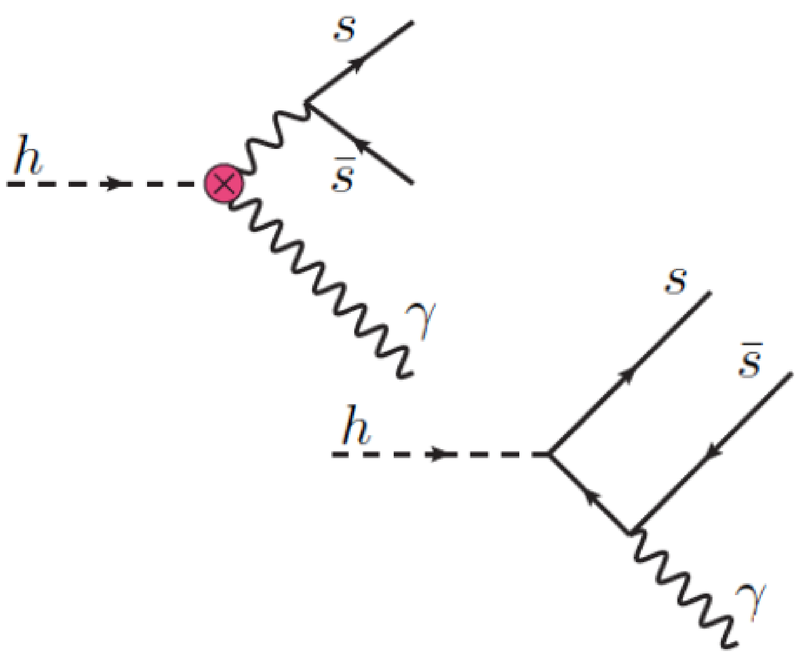
- How large are loop induced corrections? How large are BSM effects?
- Do we need an energy scan to find the Higgs?
- How much luminosity will be available for this measurement? By how much is the luminosity reduced by monochromators?

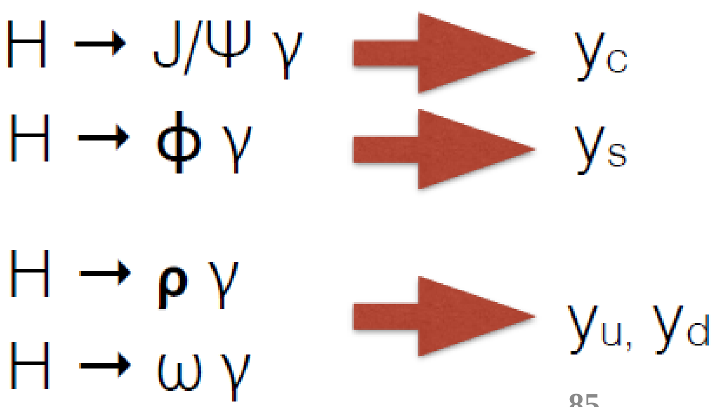
Exclusive Higgs boson decays

- ➡ First and second generation couplings accessible
  - Study of **ργ** channel most promising; expect ~50 evts.
  - Sensitivity to u/d quark Yukawa coupling
  - Sensitivity due to interference

$$\frac{\mathrm{BR}_{h\to\rho\gamma}}{\mathrm{BR}_{h\to b\bar{b}}} = \frac{\kappa_\gamma\left[(1.9\pm0.15)\kappa_\gamma - 0.24\bar{\kappa}_u - 0.12\bar{\kappa}_d\right]}{0.57\bar{\kappa}_b^2}\times 10^{-5}$$

- ➡ Also interesting to FCC-hh program
- ➡ Alternative H→MV decays should be studied (V= γ, W, and Z)

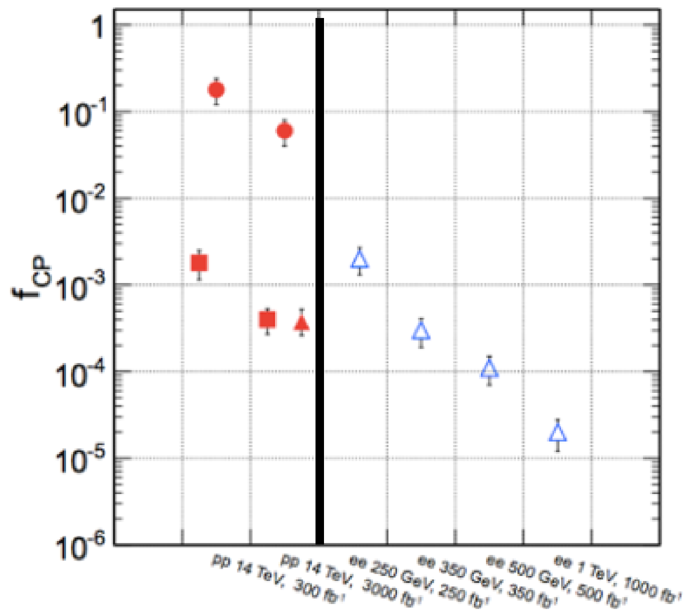




CP Measurements

- ➡ CP violation can be studied by searching for CP-odd contributions; CP-even already established
- ➡ Snowmass Higgs paper http://arxiv.org/abs/1310.8361
- ➡ Higgs to Tau decays of interest
- ➡ More detailed presentation by Felix Yu http://arxiv.org/abs/1308.1094

for HVV couplings



$$\mathcal{L}_{hff} \propto h\bar{f}(\cos\Delta + i\gamma_5 \sin\Delta)f$$

Colliders	LHC	HL-LHC	FCCee (1 ab^{-1})	FCCee (5 ab^{-1})	FCCee (10 ab^{-1})
Accuracy(1σ)	25°	8.0°	5.5°	2.5°	1.7°

Rare and Exotics Higgs Bosons

- 2,000,000 ZH events allow for detailed studies of rare and exotic decays
  - requires hadronic and invisible Z decays
  - set requirements for FCC-ee detector
- Coupling measurements have sensitivity to BSM decays
- Dedicated studies using specific final states improve sensitivity
- Example: Higgs to invisible, flavor violating Higgs, and many more
- Potential at the LHC (and HL-LHC) currently not fully explored
- Modes with of limited LHC sensitivity are of particular importance to FCC-ee program
  - currently under study
- FCC-ee might allow precision measurement of exotic Higgs decays
- Detailed discussion of exotic Higgs decays at Phys. Rev. D 90, 075004 (2014) More from David Curtin

$h \to \not{E}_T$

$h \to 4b$

$h \to 2b2\tau$

$h \to 2b2\mu$

$h \to 4\tau, 2\tau 2\mu$

$h \to 4j$

$h \to 2\gamma 2j$

$h \to 4\gamma$

$h \to ZZ_D, Za \to 4\ell$

$h \to Z_D Z_D \to 4\ell$

$h \to \gamma + \not{E}_T$

$h \to 2\gamma + \not{E}_T$

$h \to$ 4 ISOLATED LEPTONS $+ \not{E}_T$

$h \to 2\ell + \not{E}_T$

$h \to$ ONE LEPTON-JET $+ X$

$h \to$ TWO LEPTON-JETS $+ X$

$h \to b\bar{b} + \not{E}_T$

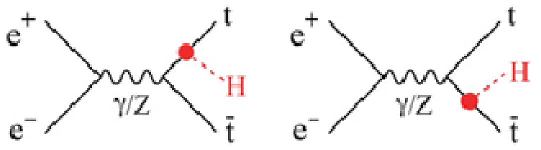
$h \to \tau^+\tau^- + \not{E}_T$

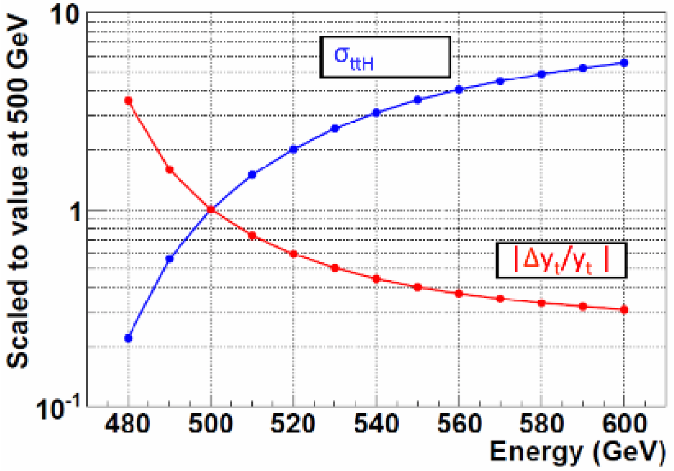
Top-Yukawa Coupling at 500 GeV

ILC Parameters Joint Working Group, arXiv:1506.07830v1 [hep-ex]

- top quark heaviest particle in SM
  - couples most strongly to Higgs sector
  - g_{Htt} could contain special effects
  - should be measured model-independently
- at ILC directly accessible through

$$e^+e^- \to t\bar{t}H \text{ (with } H \to b\bar{b})$$





- enhanced cross section at $\sqrt{s} = 500$ GeV
  - need full energy → close to production threshold
- at $\sqrt{s} = 550$ GeV better precision on g_{Htt}
  - by factor 4 enhanced cross section
  - main backgrounds decrease

$\Delta g_{Htt}/g_{Htt}$	ILC500	ILC500 LumiUP
500 GeV	18 %	6.3 %
550 GeV	$\sim$ 9 %	$\sim$ 3 %

increasing $\sqrt{s}$ by 10%, precision improves by factor two for same integrated luminosity

NB these are similar precisions as obtained from HL-LHC

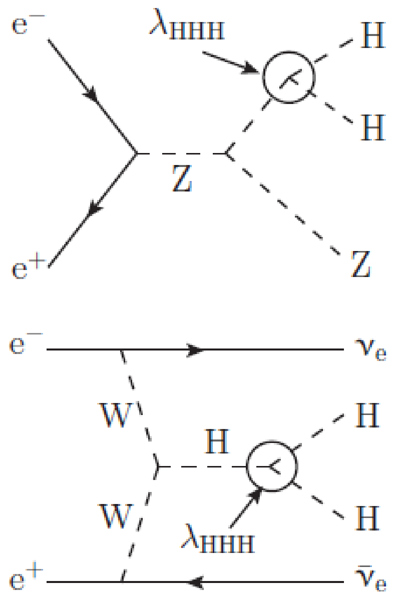
Higgs Self-Coupling Measurement at the ILC

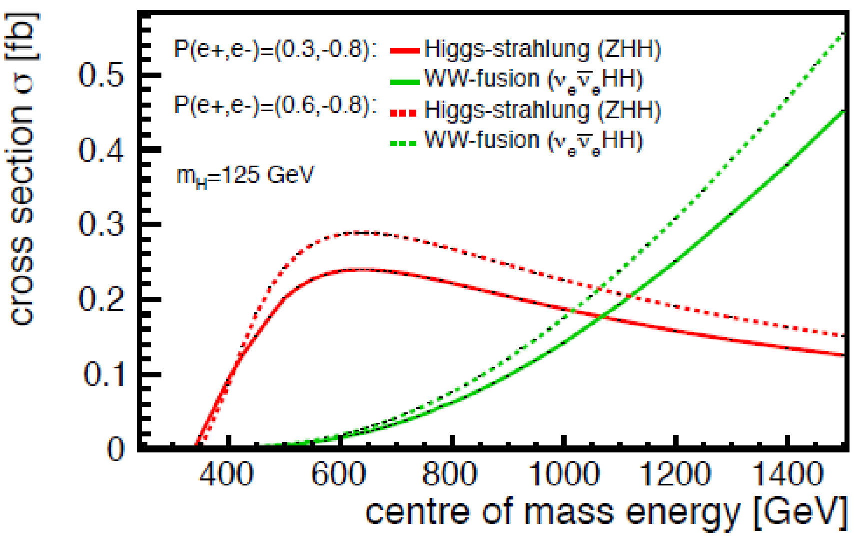
- precise measurement of SM Higgs potential via Higgs self-coupling

$$V(\eta_H) = \frac{1}{2} m_H^2 \eta_H^2 + \lambda v \eta_H^3 + \frac{1}{4} \lambda \eta_H^4$$

- existence of HHH coupling → direct evidence of vacuum condensation
- one must observe double Higgs production
- very challenging measurement

→ small production cross section, i.e. $\sigma(ZHH) \approx 0.2$fb at 500GeV
→ many jets in final state
→ interference terms due to irreducible diagrams





Claude Fabienne Dürig | Higgs program at the ILC | EPS-HEP Vienna, July 22-29 2015 | 10/13

Higgs Self-Coupling Measurement at the ILC

ILC Parameters Joint Working Group, arXiv:1506.07830v1 [hep-ex]

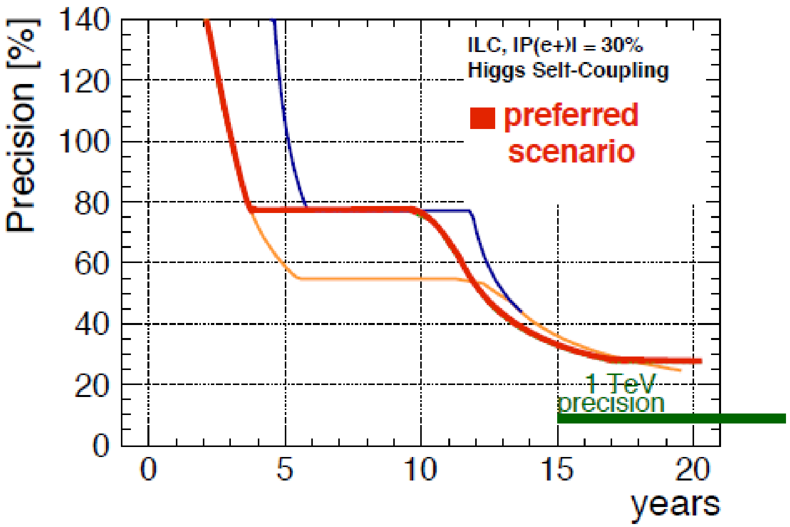
Existing full simulation analyses for $m_H = 125$ GeV

@ 500 GeV

- ZHH→Z(bb)(bb)
- ZHH→Z(bb)(WW)

@ 1 TeV

- ννHH →νν(bb)(bb)
- ννHH →νν(bb)(WW)



	500 GeV			500 GeV+1 TeV		
Scenario	A	B	C	A	B	C
Baseline	104%	83%	66%	26%	21%	17%
LumiUP	58%	46%	37%	16%	13%	10%

500 GeV: 500 (1600)fb^{-1} $P(e^+e^-)=(0.3,-0.8)$

1 TeV: 1000 (2500)fb^{-1} $P(e^+e^-)=(0.2,-0.8)$

Scenario A: HH → bbbb ✔

Scenario B: adding HH → bbWW ✔, expect 20% relative improvement

Scenario C: analysis improvement (jet-clustering, kinematic fit, flavor tagging, matrix element method, etc.), expect 20% relative improvement (**ongoing**)

HIGGS SELF COULING VERY DIFFICULT TO MEASURE PRECISELY AT LINEAR COLLIDERS

30% precision after 20 years

needs high energy (another 10-20 years) for 10% precision

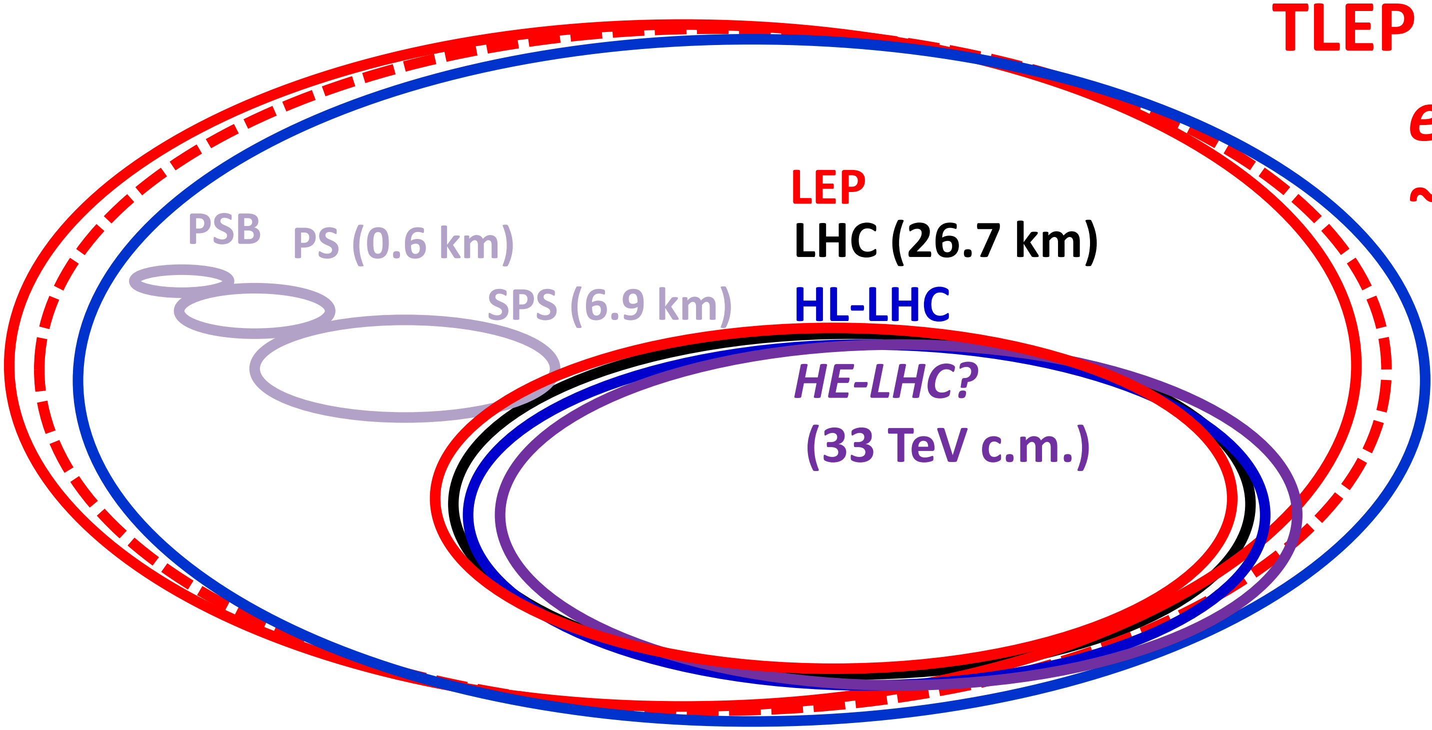
Measurements of most of Higgs physics and couplings, CP violation etc..
are best made with the ZH process at 240-350 GeV

Top quark and Higgs self couplings can be made with a linear collider of energy above 500 GeV (at least 550 GeV for ttH, at least 1 GeV for HHH).

However for ttH and HHH, similar precisions can be achieved by combining the HL-LHC with a 250-350 GeV e+e- machine.

And what about a higher energy pp collider?

possible long-term strategy



TLEP (80-100 km, e^+e^-, up to ~350 GeV c.m.)

VHE-LHC (*pp*, up to 100 TeV c.m.)

"same" detectors!?

& ***e***$^{\pm}$ **(120 GeV)–*p* (7, 16 & 50 TeV)** collisions (**[(V)HE-]TLHeC**)

≥60 years of *e*$^+$***e***$^-$**, *pp*, *ep/A* physics at highest energies**

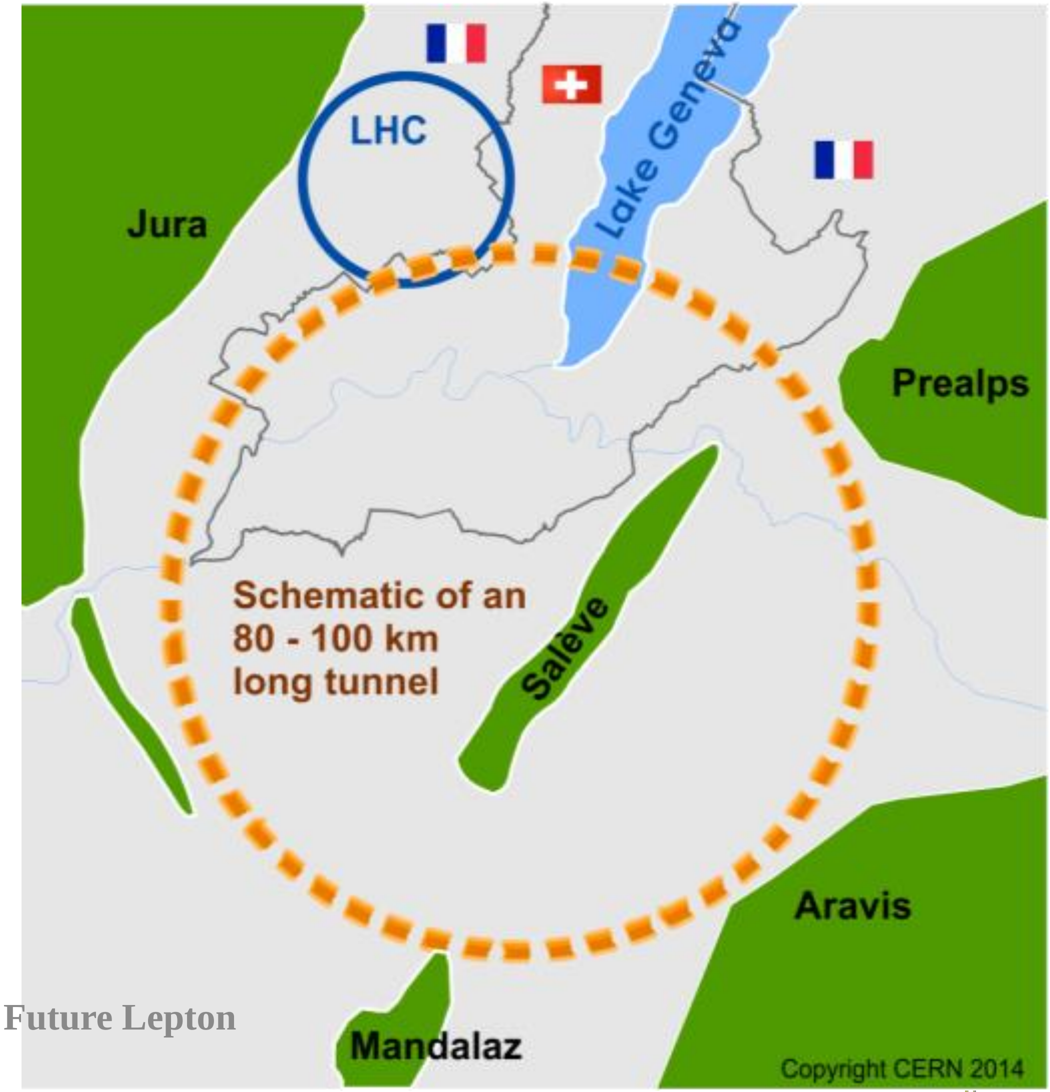
Future Circular Collider Study - SCOPE
CDR and cost review for the next ESU (2018)

Forming an international collaboration to study:

- ***pp*-collider (*FCC-hh*) → defining infrastructure**

~16 T ⇒ 100 TeV *pp* in 100 km
~20 T ⇒ 100 TeV *pp* in 80 km

- **e^+e^- collider (*FCC-ee*) as potential intermediate step ECM=90-400 GeV**
- ***p-e* (*FCC-he*) option**
- **80-100 km infrastructure in Geneva area**



FCC-hh parameters

parameter	FCC-hh		LHC	HL LHC
energy cms [TeV]	100		14	
dipole field [T]	16		8.3	
# IP	2 main & 2		2 main & 2	
bunch intensity [10^{11}]	1	1 (0.2)	1.1	2.2
bunch spacing [ns]	25	25 (5)	25	25
luminosity/Ip [10^{34} cm^{-2}s^{-1}]	5	20	1	5
events/bx	170	680 (136)	27	135
stored energy/beam [GJ]	8.4		0.36	0.7
synchr. rad. [W/m/apert.]	30		0.2	0.35

2.5 10^{35}cm^{-2}s^{-1} is the goal luminosity of FCC-hh

93km “optimised” racetrack

PRELIMINARY

Alignment | **Shaft Tools**

Choose alignment option

90km quasi-circular ▼

Tunnel depth at centre: 206mASL

Gradient Parameters

Azimuth (°): -15

Slope Angle x-x(%): 3

Slope Angle y-y(%): 0

CALCULATE

Alignment centre

X: 2493923 Y: 1105695

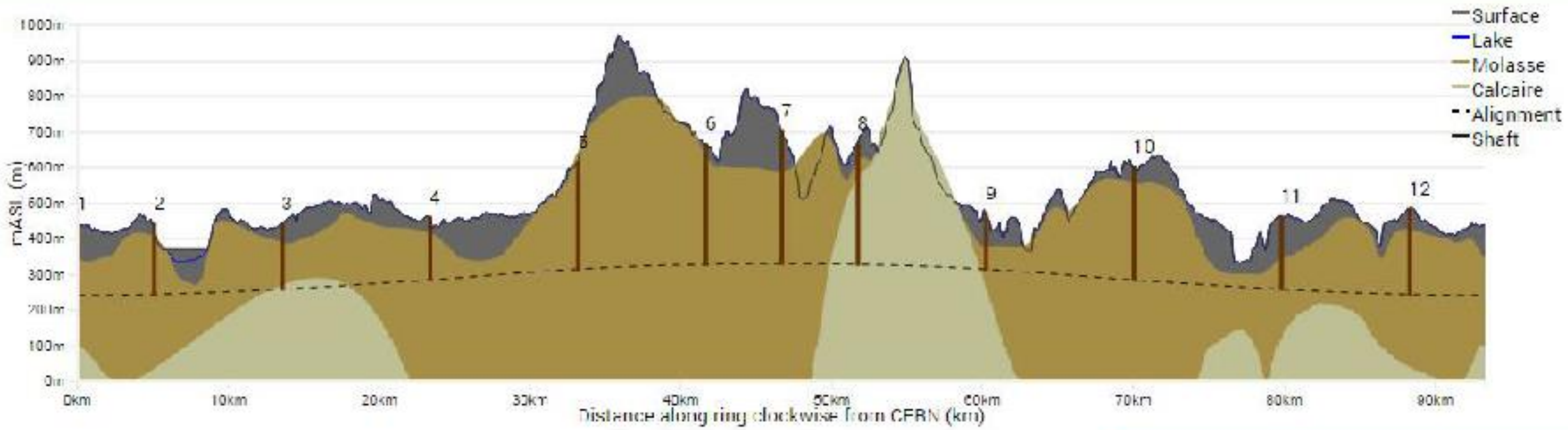
LHC Intersection	IP 1	IP 2
Angle	1°	-1°
Depth	542m	542m

Alignment Location

Geology Intersected by Shafts | **Shaft Depths**

Shaft	Shaft Depth (m) Actual	Min	Mean	Max	Geology (m) Moraine	Molasse	Calcaire
1	200	195	197	200	92	108	0
2	196	143	181	211	34	162	0
3	183	175	184	194	53	121	9
4	174	145	166	178	44	130	0
5	299	286	311	350	0	325	0
6	336	325	339	350	35	302	0
7	374	349	377	412	119	256	0
8	337	318	341	356	44	56	257
9	156	131	145	157	94	61	0
10	315	305	320	336	46	269	0
11	203	199	202	234	122	81	0
12	239	229	238	243	58	181	0
Total	3014	2801	3001	3211	741	2062	247

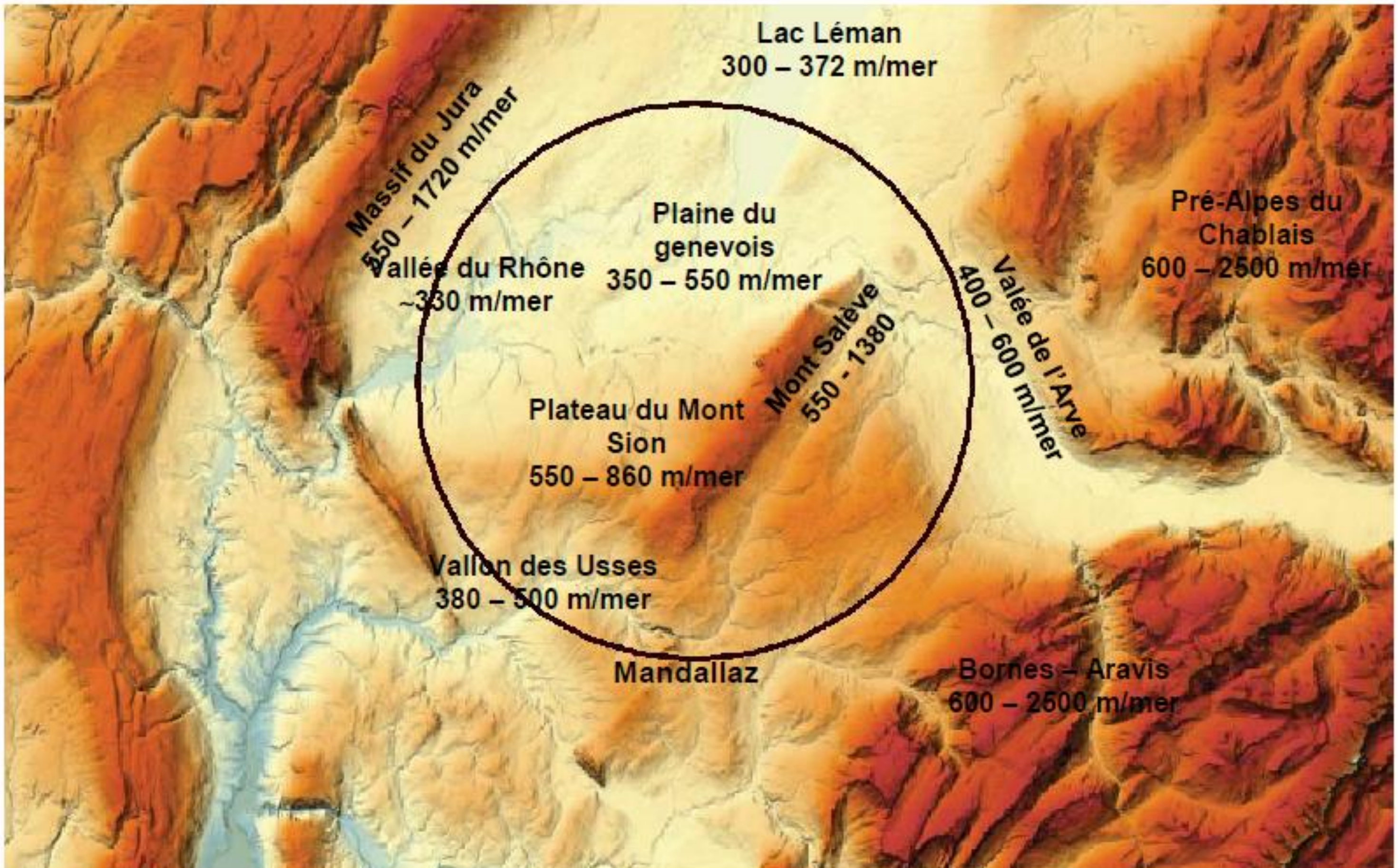
Alignment Profile



J. Osborne & C. Cook

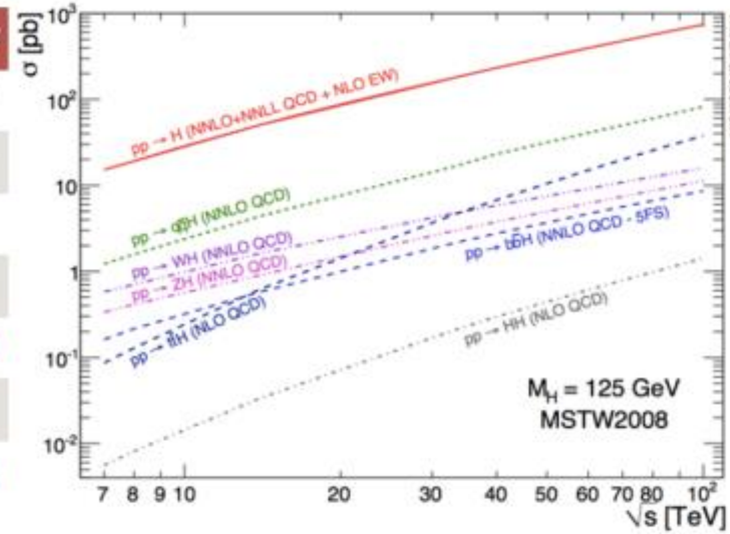
Tunnel location: topography [1/3]

- Minimize ground coverage
  - Hydrostatic pressure for TBM tunnelling
  - Shaft depth/cost



HIGGS AT FCC-pp

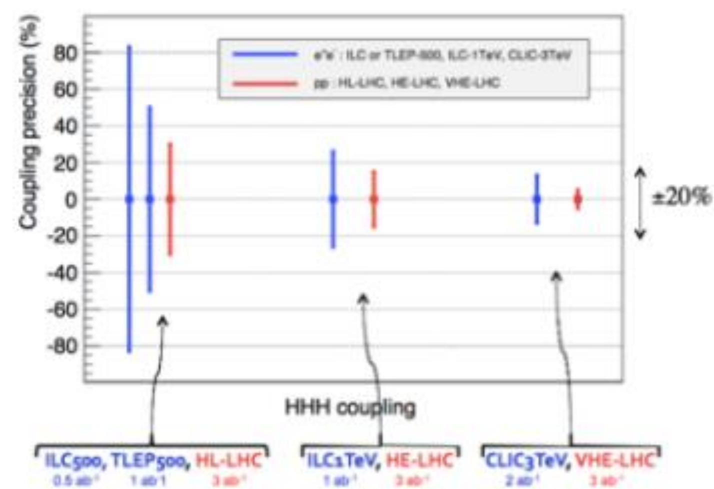
Process	8 TeV	14 TeV	100 TeV
gF	0.38	1	14.7
VBF	0.38	1	18.6
WH	0.43	1	9.7
ZH	0.47	1	12.5
ttH	0.21	1	61
bbH	0.34	1	15
gF to HH	0.24	1	42



Proton-proton Higgs datasets — **LHC Run I** → x300-600 → **HL LHC** → x10-400 → **FCC pp**

	HL-LHC	HE-LHC	VLHC
$\sqrt{s}$ (TeV)	14	33	100
$\int \mathcal{L}dt$ (fb^{-1})	3000	3000	3000
$\sigma \cdot \text{BR}(pp \to HH \to bb\gamma\gamma)$ (fb)	0.089	0.545	3.73
$S/\sqrt{B}$	2.3	6.2	15.0
λ (stat)	50%	20%	8%

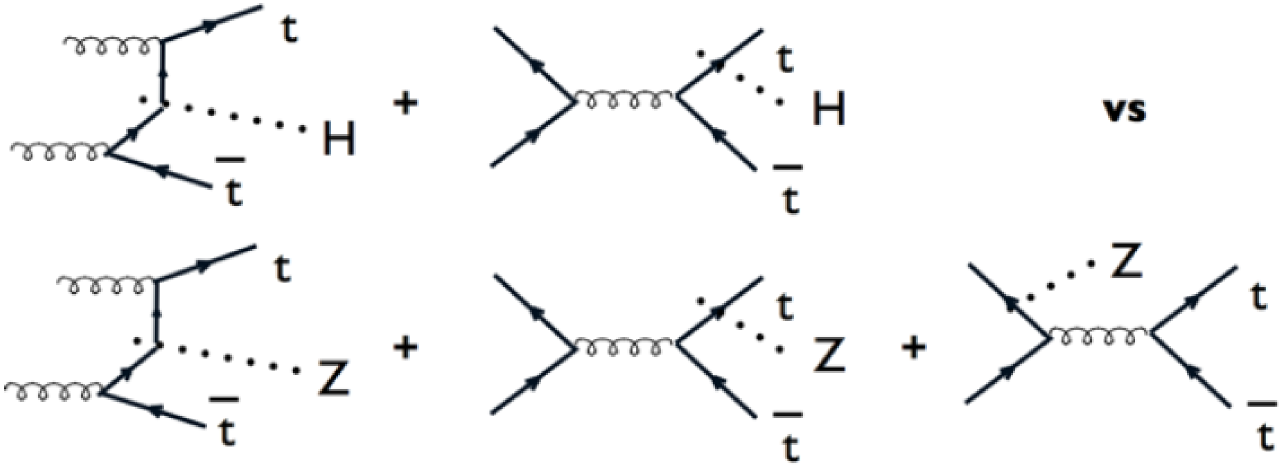
arXiv:1310.8361



10

➡ … but also new measurements not possible at the LHC/HL-LHC

ttH / ttZ



➡ Theoretical uncertainties cancel mostly

- PDF (CTEQ 6.6) ± 0.5%
- Missing higher orders ± 1.2%

➡ One can not conclude that one can measure the cross section ratio with ~2% ($\delta\lambda_{top} \cong$ 1%) precision. **More detailed studies are ongoing.**

➔ Lots of statistics and ideas for small systematics

FCC Higgs physics program

g_{HXY}	ZZ	WW	γγ	Zγ	tt	bb	ττ	cc	ss	μμ	uu,dd	ee	Γ_H	HH	BR_{exo}
FCC-ee	0.15	0.19	1.5			0.42	0.54	0.71	H→Vγ	6.2	H→Vγ	ee→H	0.9		0.45
FCC-hh			< 1?	1 ?	1 ?					2 ?				5 ?	$<10^{-6}$?

➡ Summary of FCC-ee studies and “guesses” for FCC-hh performance. Uncertainty in %.

➡ Almost perfect complementarity between FCC-ee and FCC-hh program

CONCLUSIONS for the HIGGS boson

1. The Higgs boson is the first spin 0 elementary particle ever found.

2. It plays a very particular role in linking a property of the vacuum (Higgs vev) with the masses of the SM particles
(NB what about the neutrinos?)

3. We must study it as well as we can!

4. Many Higgs factories have been discussed.
The best line seems to be the combination of
a High Luminosity, circular e+e- collider in 240-350 GeV region
and a High Energy High Luminosity pp collider (50-100 TeV Ecm)

➔ this is the philosophy of CEPC/SPPS and of the FCC (ee then pp) which, in combination, offer 'invincible' potential of investigation of the Higgs physics