Physics at the FCCs

a story of synergy and complementarity

see recent metings:

FCC physics workshops

2017 https://indico.cern.ch/event/550509/

2018 https://indico.cern.ch/event/618254/

FCC week in Amsterdam

https://indico.cern.ch/event/656491/

Alain Blondel, University of Geneva

with many thanks to the FCC collaborators!

Photo J. Wenninger

The Future Circular Colliders
CDR and cost review to appear Q4 2018 for ESU

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*)**

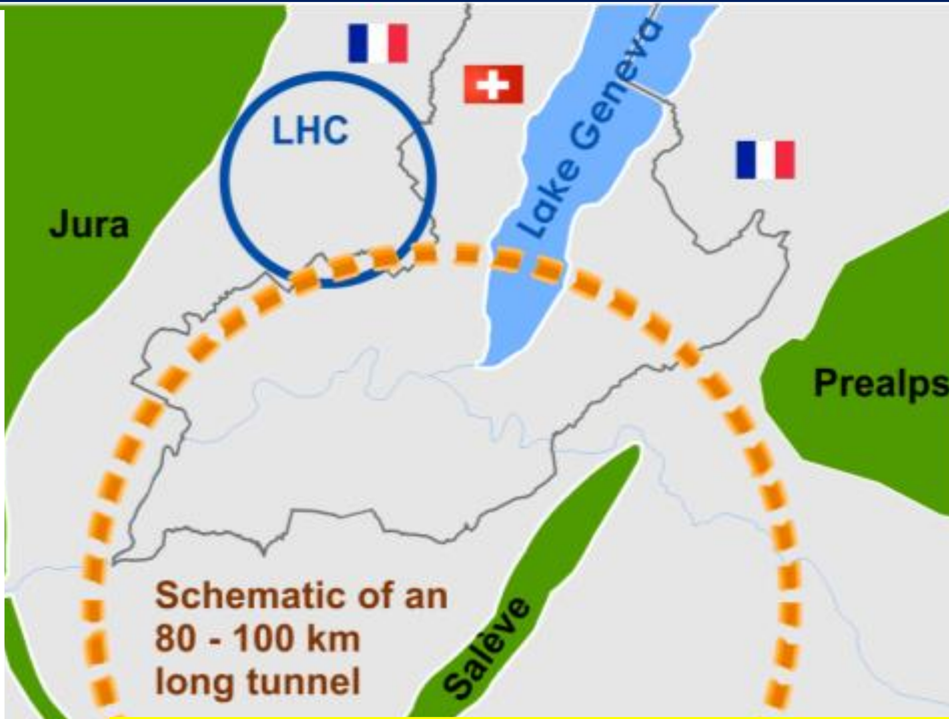
→ defining infrastructure requirements

Two 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 addition:

- ***p-e* (*FCC-he*) option**



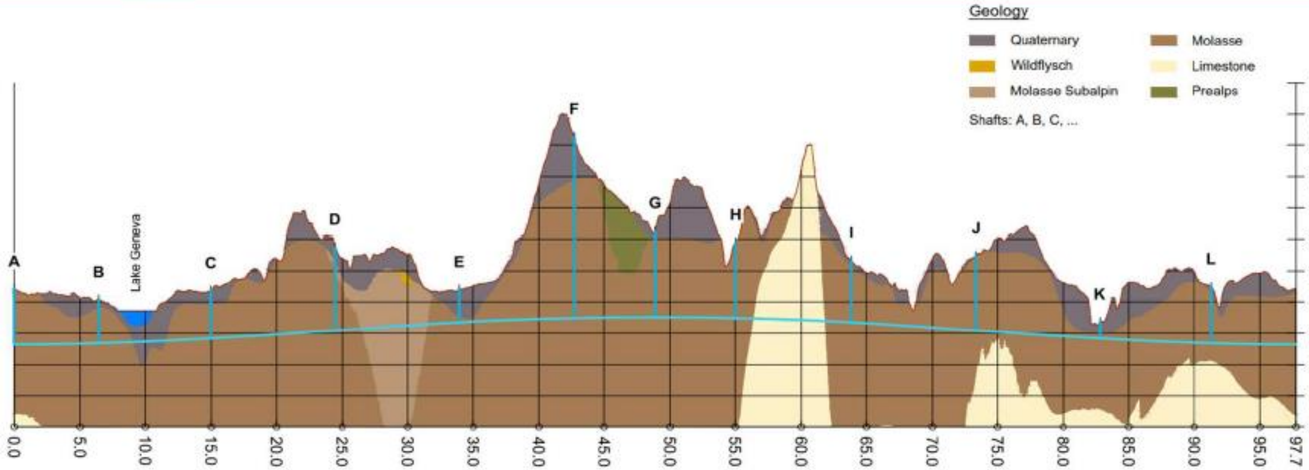
From what we know today :
the way by FCC-ee is probably the fastest and cheapest way to 100 TeV.
That combination also produces the most physics. It is the assumption in the following.

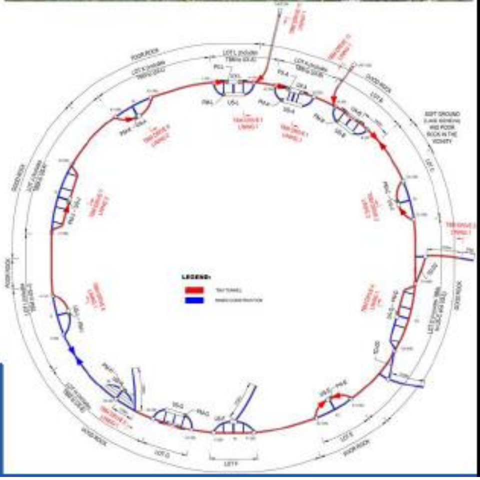
also a good start for μC!

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

SYNERGY

FCC implementation - footprint baseline





Present baseline position was established considering:

- lowest risk for construction
- fastest and cheapest construction
- feasible positions for large span caverns (most challenging structures)

next step: review of surface site locations and machine layout

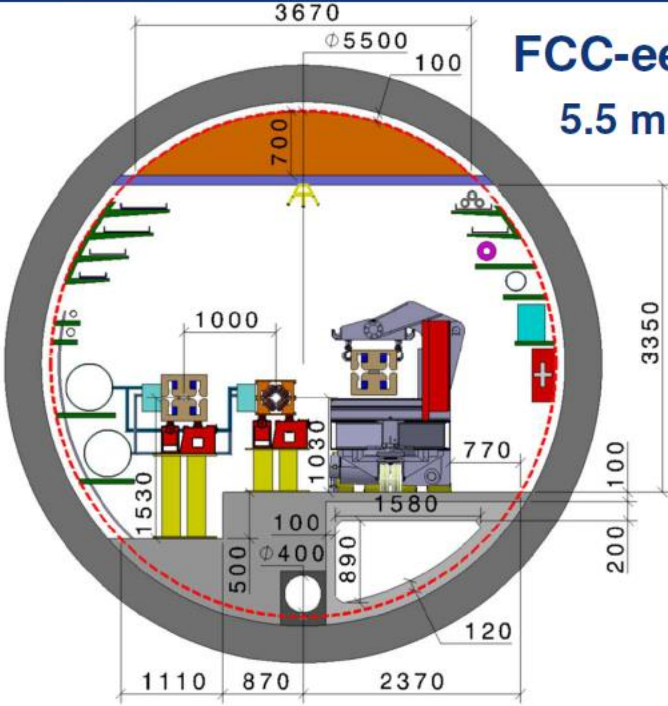
Future Circular Collider Study
Michael Benedikt
9th IPAC Vancouver, 3 May 2018

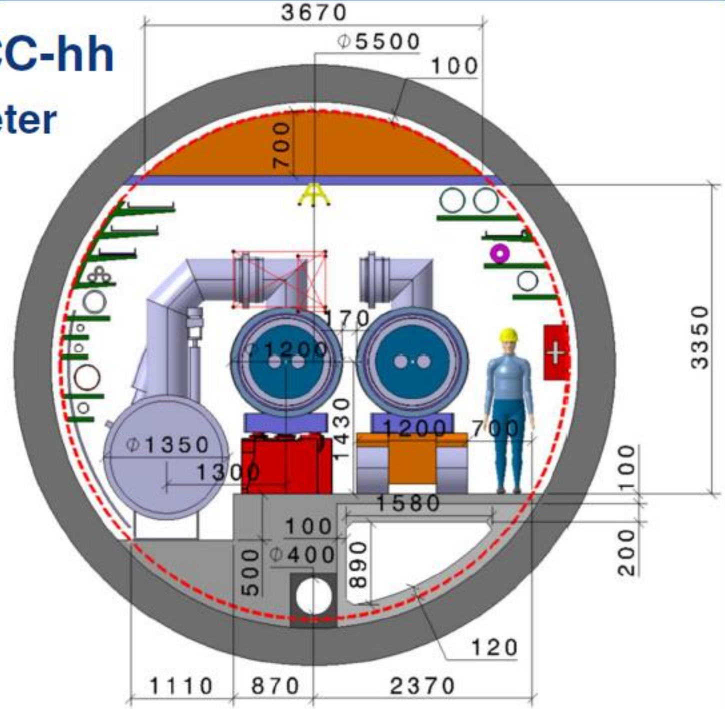
Sharing the same tunnel

FCC – tunnel integration in arcs

FCC-ee **FCC-hh**

5.5 m inner diameter





Future Circular Collider Study
Michael Benedikt
9th IPAC Vancouver, 3 May 2018

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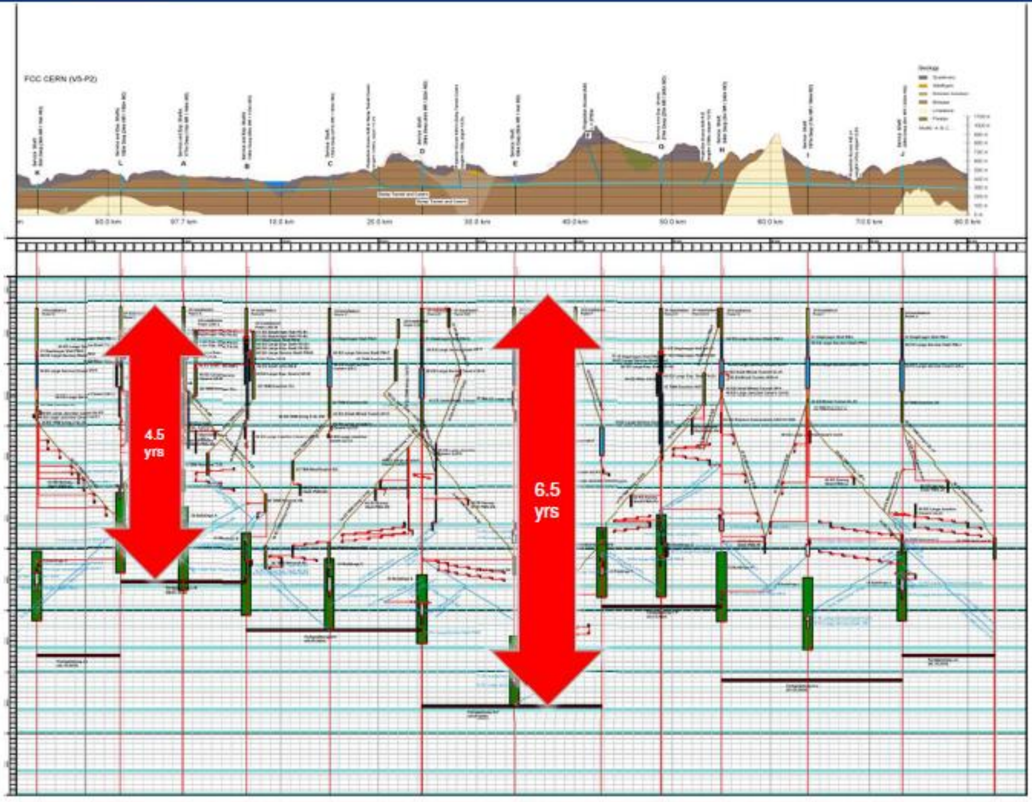
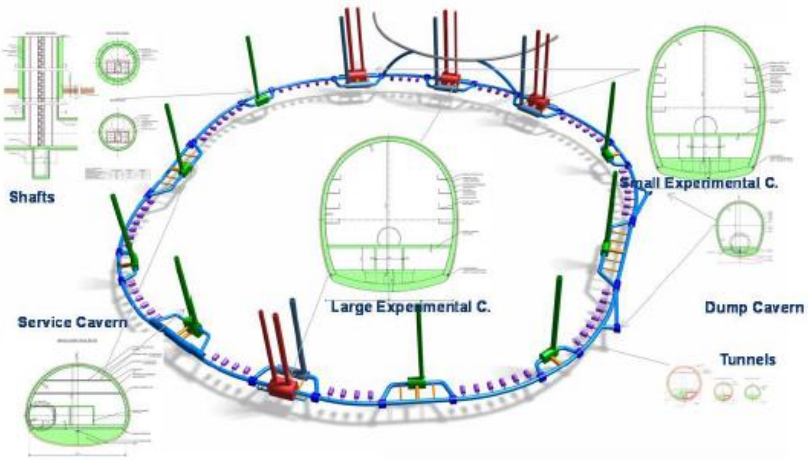
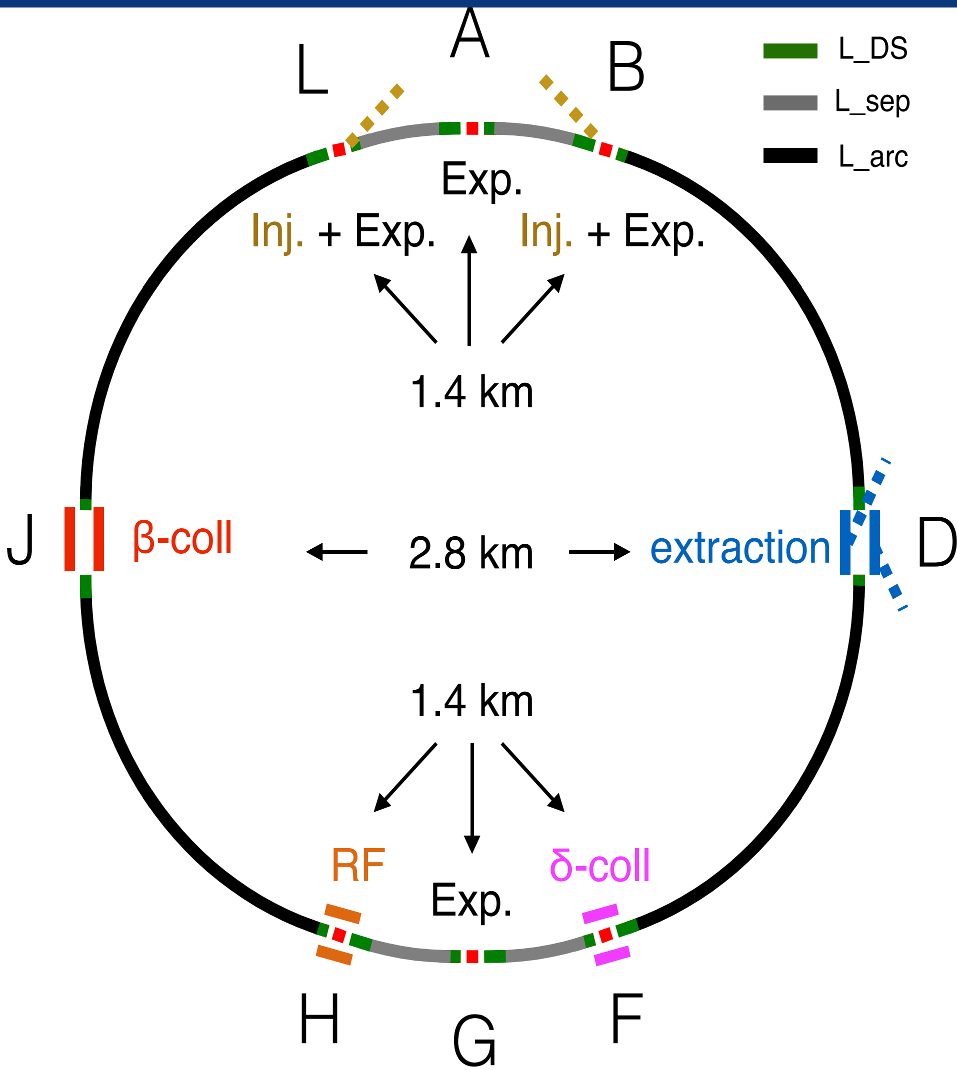
CE schedule studies

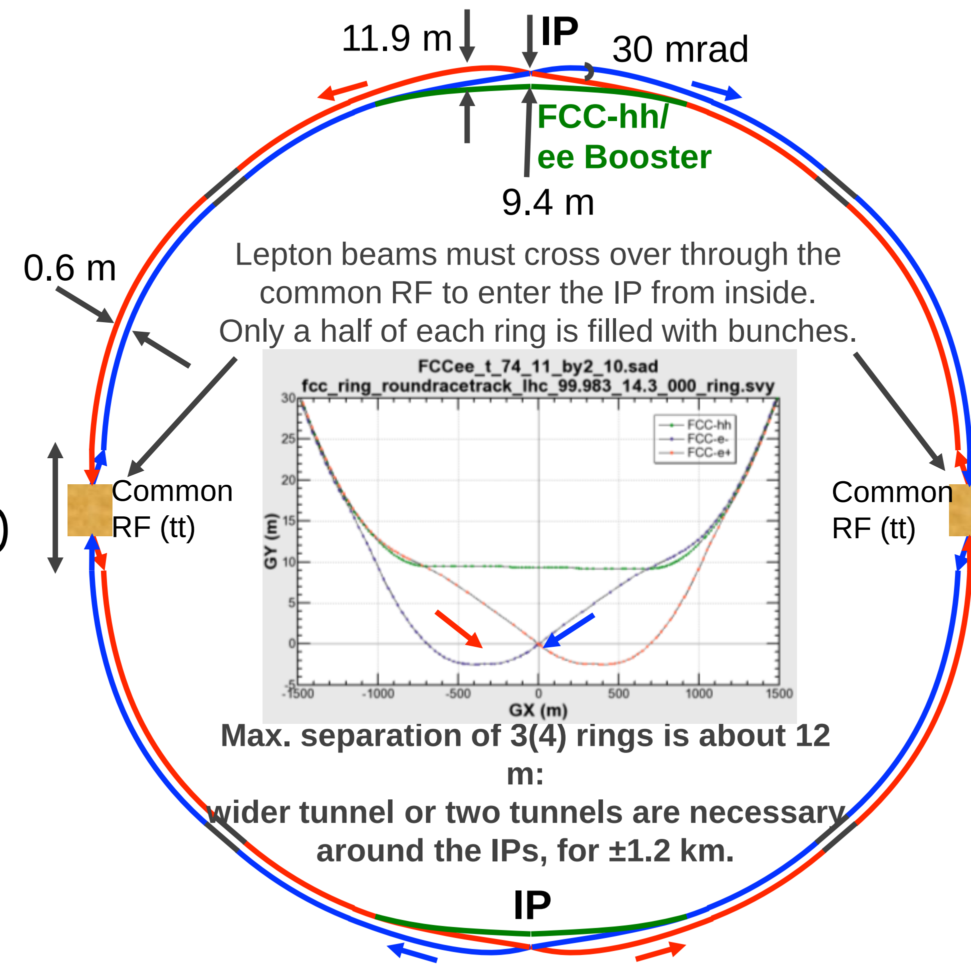




- Total construction duration 7 years
- First sectors ready after 4.5 years

common layouts for hh & ee





FCC-ee 1, FCC-ee 2,

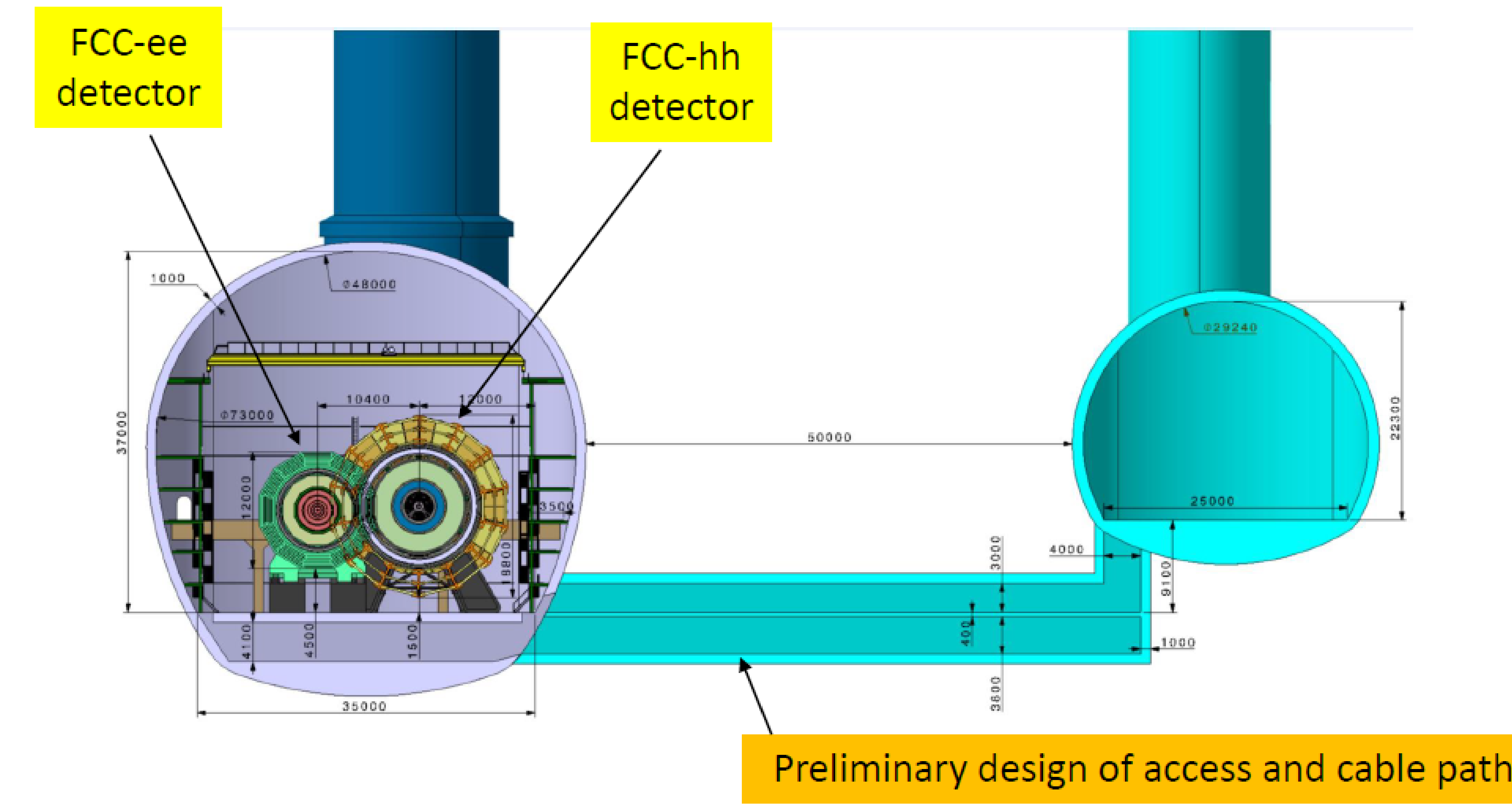
FCC-ee booster (FCC-hh footprint)

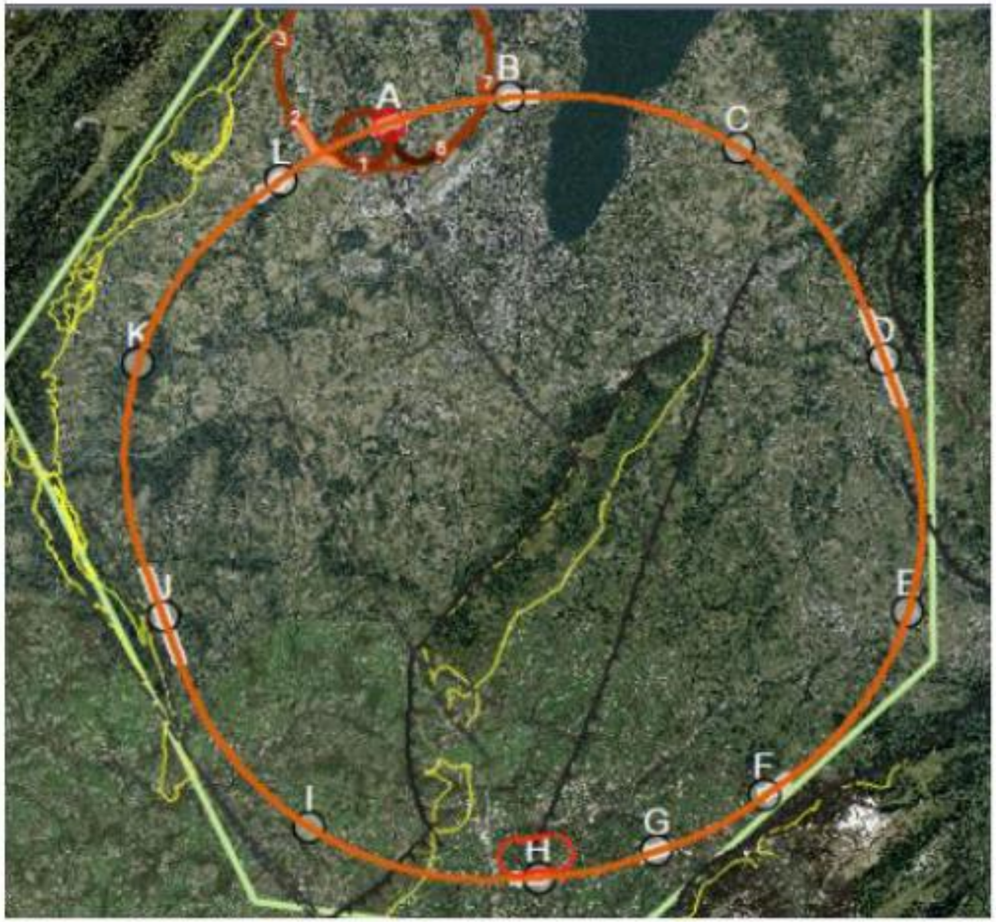
Asymmetric IR for ee, limits SR to expt

2 main IPs in A, G for both machines

The same caverns

Distance between detector cavern and service cavern 50 m.





FCC-eh

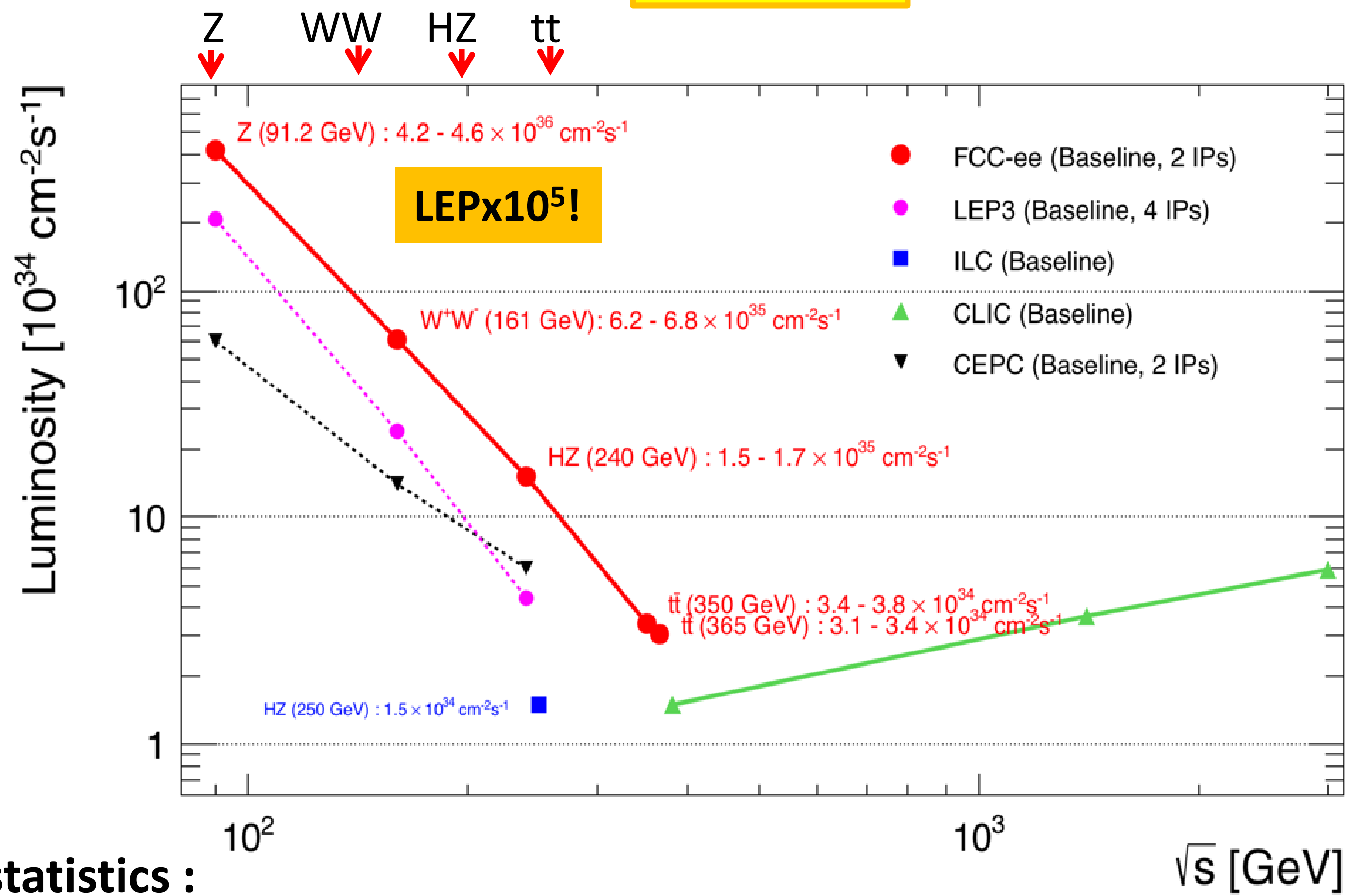
LHeC or FCC-eh function as an add-on to LHC or FCC-hh respectively:
additional 10km cicumference Electron Reciculating Linac ERL.

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**

COMPLEMENTARITY

FCC-ee



Event statistics :

				E_{CM} errors:
Z peak	E_{cm} : 91 GeV	$5\ 10^{12}$ e+e- → Z	LEP x 10^5	100 keV
WW threshold	E_{cm} : 161 GeV	10^8 e+e- → WW	LEP x 2.10^3	300 keV
ZH threshold	E_{cm} : 240 GeV	10^6 e+e- → ZH	Never done	1 MeV
$\bar{t}t$ threshold	E_{cm} : 350 GeV	10^6 e+e- → $\bar{t}t$	Never done	2 MeV

Great energy range for the heavy particles of the Standard Model.

IMPLEMENTATION AND RUN PLAN

"Ampere-class" machine

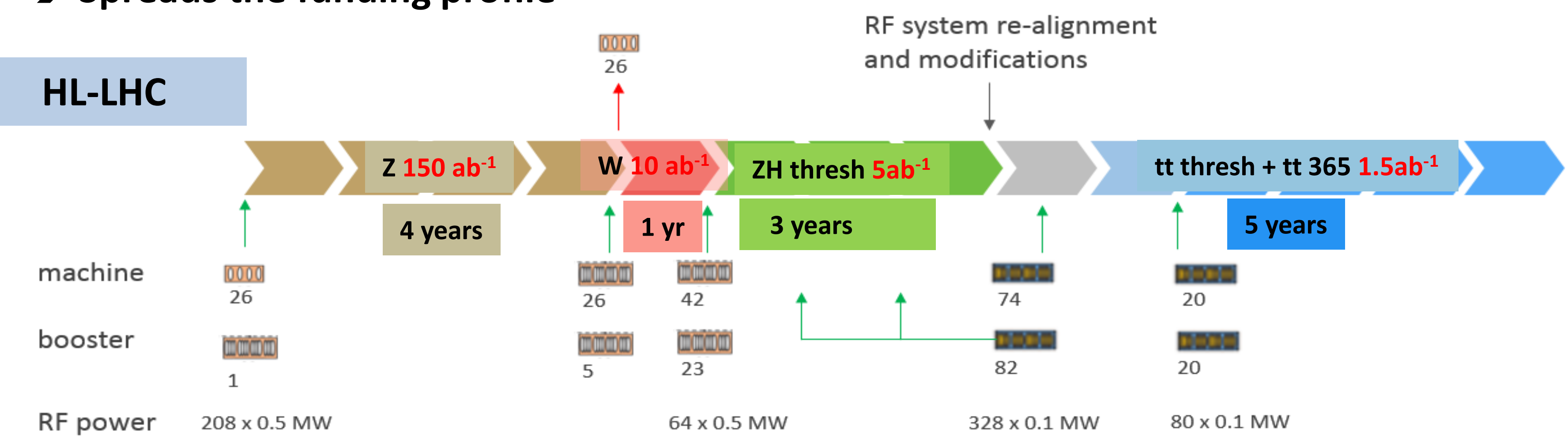
	V_tot (GV)	n_bunch	I_beam (mA)
Z	0.2	91500	1450
W	0.8	5260	152
H	3	780	30
t	10	81	6.6

"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 +High effciency**

➔ **Spreads the funding profile**



indicative: total ~15 years

O(1/3) of the machine cost comes O(10) years after start

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 , α_{QED} (m_z) α_s (m_z m_W m_τ), Higgs and top quark couplings

DISCOVER a violation of flavour conservation or universality and unitarity of PMNS @10^{-5}
-- ex FCNC (Z --> $\mu\tau$, eτ) in 5 10^{12} Z decays and τ BR in 2 10^{11} Z→ $\tau\tau$
+ flavour physics (10^{12} bb events) (B→s $\tau\tau$ 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 (H→ gg) etc….

NB Not only a «Higgs Factory», «Z factory» and «top» are important for 'discovery potential'

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

«First look of the physics case of TLEP» (original name of FCC-ee): 398 quotes today

HEP 398 records found 1 - 25 jump to record: 1

1. **Probing TeV scale origin of neutrino mass at lepton colliders**
P.S. Bhupal Dev, Rabindra N. Mohapatra, Yongchao Zhang. Mar 29, 2018. 48 pp.
e-Print: **arXiv:1803.11167 [hep-ph]** | PDF
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service
Detailed record

2. **Review of top and EW physics at future colliders**
Marcel Vos (Valencia U., IFIC). 2017. 10 pp.
Published in **PoS EPS-HEP2017 (2017) 471**
Conference: C17-07-05 Proceedings
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
Link to PoS server; Link to Fulltext
Detailed record

3. **Electroweak Physics at Future e^+e^- Colliders**
Elizabeth Locci (Saclay), On Behalf Of The Fcc Design Study Group. 2018. 10 pp.
Published in **PoS EPS-HEP2017 (2018) 449**
Conference: C17-07-05 Proceedings
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
Link to PoS server; Link to Fulltext
Detailed record

4. **Muon g-2 and dark matter in models with vector-like fermions**
Enrico Maria Sessolo (NCBJ, Warsaw), Kamila Kowalska (Tech. U., Dortmund (mai
Published in **PoS EPS-HEP2017 (2017) 338**
Conference: C17-07-05 Proceedings
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
Link to PoS server; Link to Fulltext
Detailed record

Much more than a Higgs factory!

HEP 430 records found 1 - 25 jump to record: 1

1. **Future Circular Collider Study (FCC)**
Tobias Golling (Geneva U.). 2016. 6 pp.
Conference: C15-08-31.1, p.559-564 Proceedings
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
Link to Fulltext
Detailed record

2. **A Deeper Probe of New Physics Scenarii at the LHC**
A. Djouadi (Orsay, LPT). 2017. 12 pp.
Conference: C17-07-09.3, p.44-55 Proceedings
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
Link to Fulltext
Detailed record

3. **Effective Field Theory Approaches to Particle Physics Beyond the Standard Model**
Zhengkang Zhang (Michigan U.). 2018. 246 pp.
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
Link to Fulltext; Link to Fulltext
Detailed record

4. **Measuring the triple Higgs self-couplings in two Higgs doublet model**
Nasuf Sonmez. Jun 23, 2018. 15 pp.
17-FEN-054, 17-FEN-054
e-Print: **arXiv:1806.08963 [hep-ph]** | PDF
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service
Detailed record

5. **Doubly-Charged Scalars in the Type-II Seesaw Mechanism: Fundamental Symmetry Tests and High**
P.S. Bhupal Dev (McDonnell Ctr. Space Sci.), Michael J. Ramsey-Musolf (Massachusetts U., Amherst & Caltech, Kellogg Lab), Yo
ACFI T18-10, ACFI-T18-10
e-Print: **arXiv:1806.08499 [hep-ph]** | PDF
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service
Detailed record

6. **The Higgs boson decays with the lepton flavor violation**
O.M. Boyarkin, G.G. Boyarkina, D.S. Vasileuskaya (Belarus State U.). 2018. 18 pp.
Published in **Int.J.Mod.Phys. A33 (2018) no.17, 1850103**
DOI: 10.1142/S0217751X18501038
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
Detailed record

7. **α_s status and perspectives (2018)**
David d'Enterria. Jun 15, 2018. 5 pp.
Conference: C18-04-16.1
e-Print: **arXiv:1806.06156 [hep-ex]** | PDF
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote

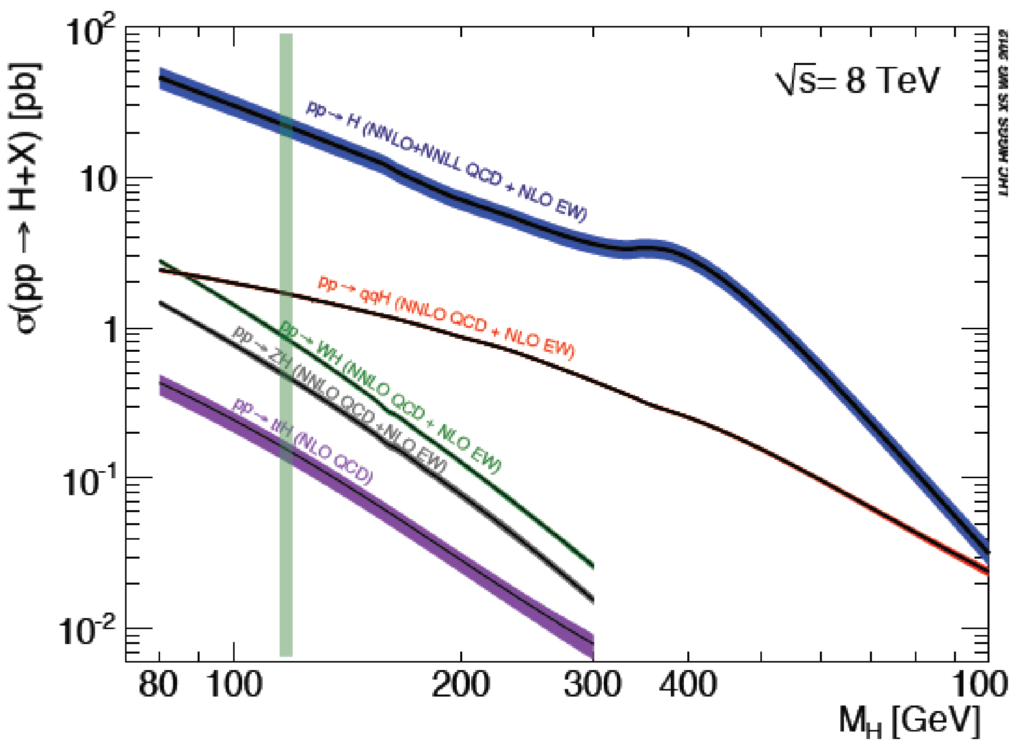
A sample of observables (more coming)

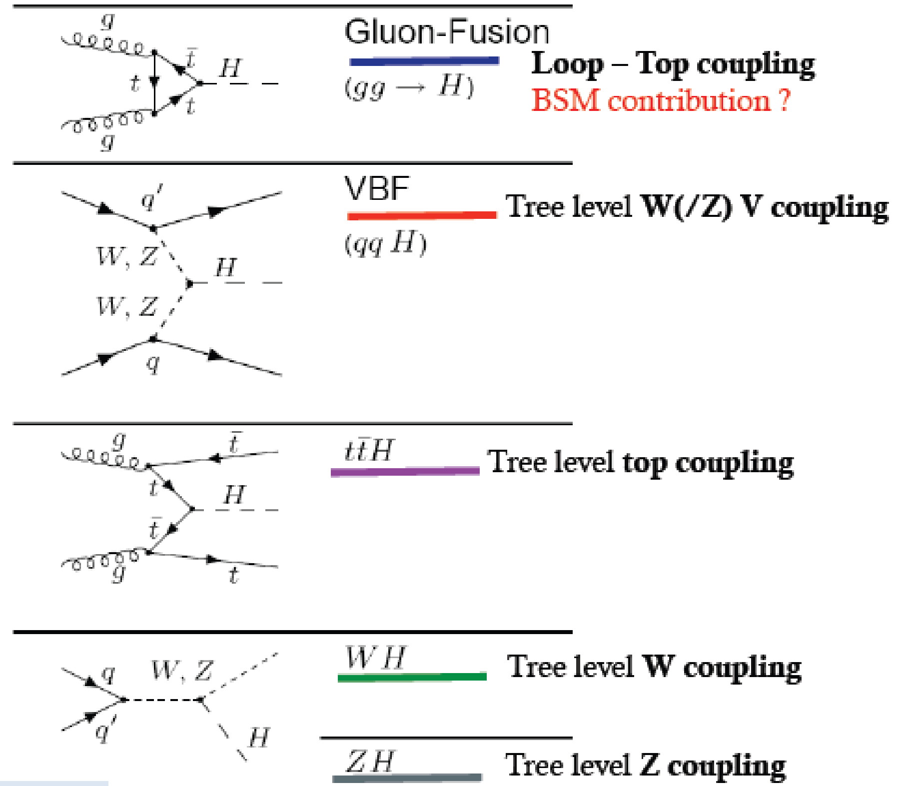
Observable	Measurement	Current precision	FCC-ee stat.	Possible syst.	Challenge
m_Z (MeV)	Lineshape	91187.5 ± 2.1	0.005	< 0.1	QED corr.
Γ_Z (MeV)	Lineshape	2495.2 ± 2.3	0.008	< 0.1 *	QED / EW
R_l	Peak	20.767 ± 0.025	0.001	< 0.001	Statistics
R_b	Peak	0.21629 ± 0.00066	0.000003	< 0.00006	g → bb
N_ν	Peak	2.984 ± 0.008	0.00004	< 0.004	Lumi meast
$\sin^2\theta_W^{eff}$	$A_{FB}^{\mu\mu}$ (peak)	0.23148 ± 0.00016	0.000003	<0.000005 *	Beam energy
$1/\alpha_{QED}(m_Z)$	$A_{FB}^{\mu\mu}$ (off-peak)	128.952 ± 0.014	0.004	< 0.004	QED / EW
$\alpha_s(m_Z)$	R_l	0.1196 ± 0.0030	0.00001	<0.0002	New Physics
m_W (MeV)	Threshold scan	80385 ± 15	0.6	< 0.6	EW Corr.
Γ_W (MeV)	Threshold scan	2085 ± 42	1.5	<1.5	EW Corr.
N_ν	$e^+e^- \to \gamma Z, Z \to \nu\nu$, ll	2.92 ± 0.05	0.001	< 0.001	?
$\alpha_s(m_W)$	$B_{had} = (\Gamma_{had}/\Gamma_{tot})_W$	B_{had} = 67.41 ± 0.27	0.00018	< 0.0001	CKM Matrix
m_{top} (MeV)	Threshold scan	173340 ± 760 ± 500	20	<40	QCD corr.
Γ_{top} (MeV)	Threshold scan	?	40	<40	QCD corr.
λ_{top}	Threshold scan	μ = 1.2 ± 0.3	0.08	< 0.05	QCD corr.
ttZ couplings	√s = 365 GeV	~30%	~2%	<2%	QCD corr

* work to do: check if we cant improve

HIGGS FACTORY

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





THE LHC is a Higgs Factory…BUT

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

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

relative error scales with 1/purity and 1/√efficiency of signal

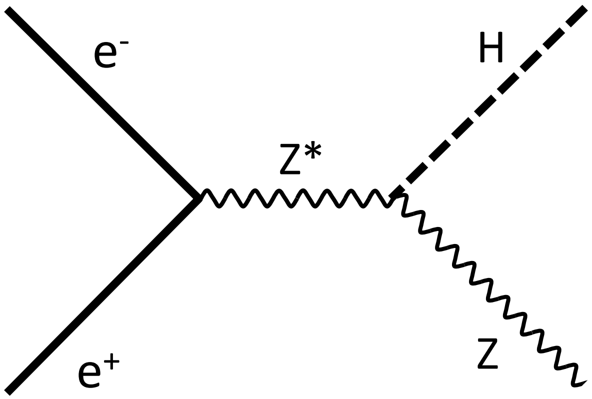
difficult to extract the couplings because σ_{prod} uncertain and Γ_H is unknown (invisible channels) → must do physics with ratios.

Higgs production mechanism

"higgstrahlung" process close to threshold

Production xsection has a maximum at near threshold ~200 fb

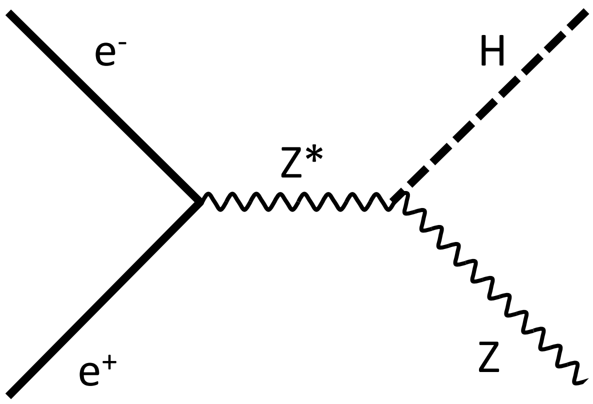
$10^{34}/cm^2/s$ ➔ 20'000 HZ events per year.



Z – tagging
by missing mass

For a Higgs of 125GeV, a centre of mass energy of 240-250 GeV is optimal
➔ kinematical constraint near threshold for high precision in mass, width, selection purity

e+e- : Z – tagging by missing mass



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

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

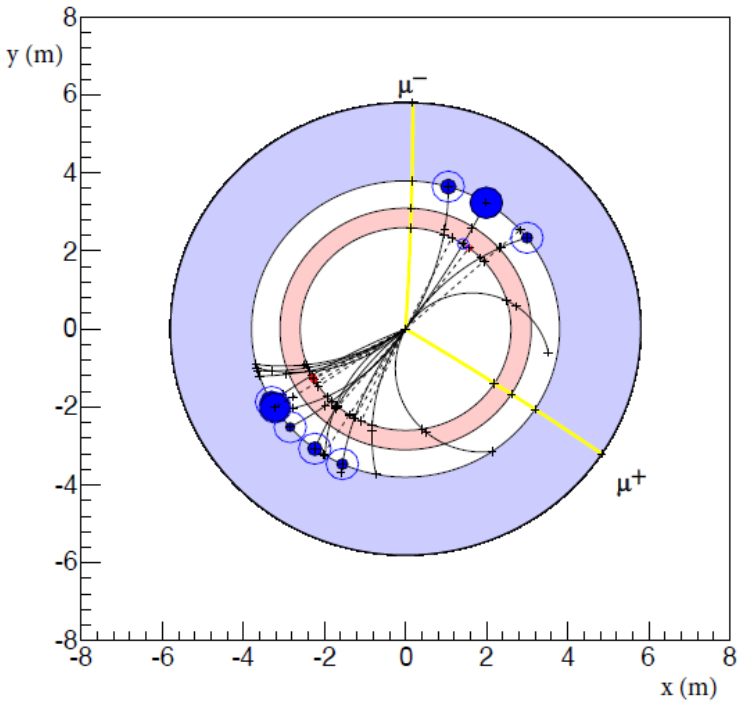
➔ **measure total width** Γ_H

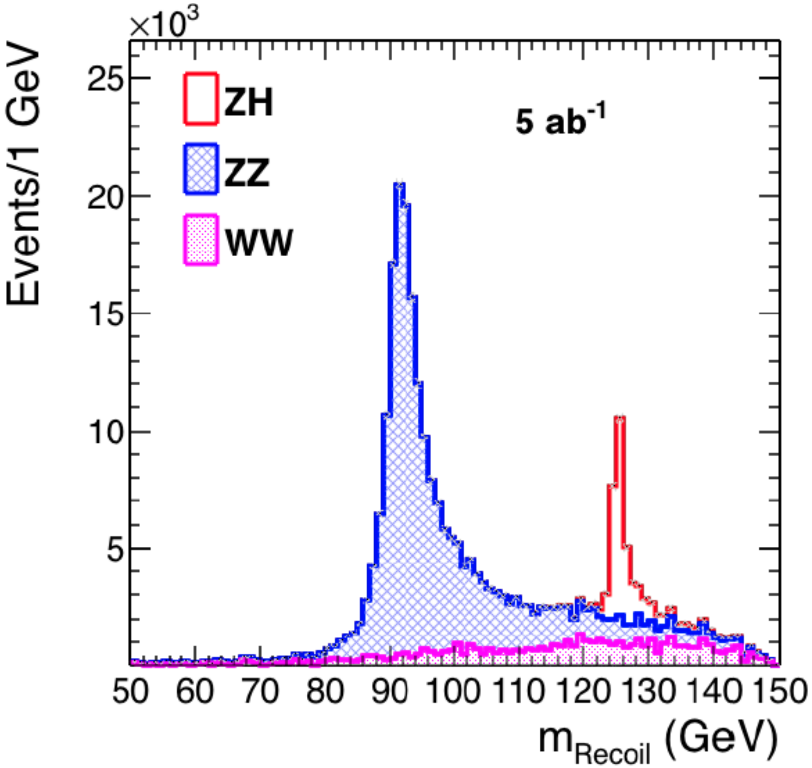
g_{HZZ} to ±0.2% and many other partial widths

empty recoil = invisible width

'funny recoil' = exotic Higgs decay

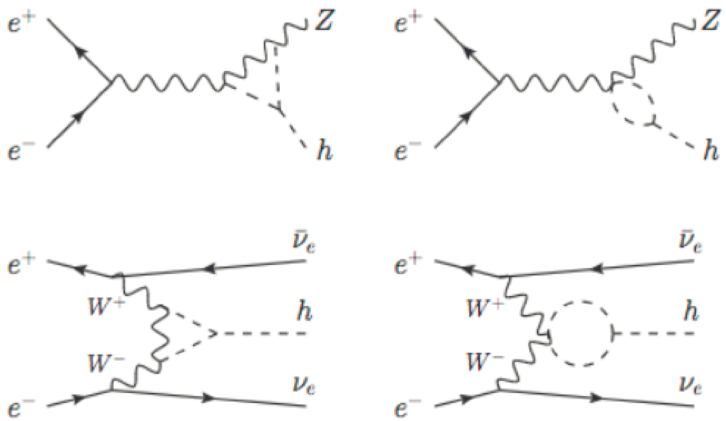
easy control below theshold

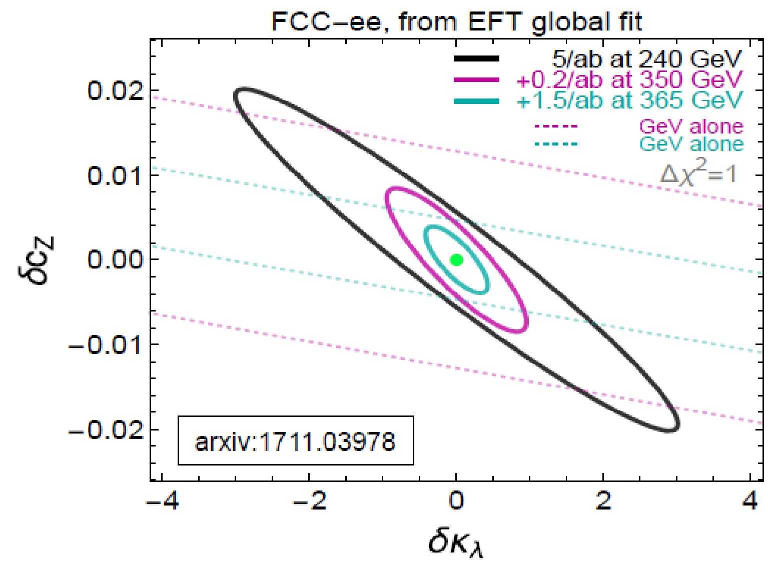




The FCC-ee does not produce pairs of Higgses from which one can extract λ_H but the ZH cross-section receives a E_{cm} - dependent correction from it.

- $\sqrt{s}$ dependence of the "effective" g_{HZ} and g_{HW} to the Higgs self-coupling
  - Accessible from the high-precision runs at 240, (350), and 365 GeV
    - Arising from Higgs-triangle and -loop diagrams





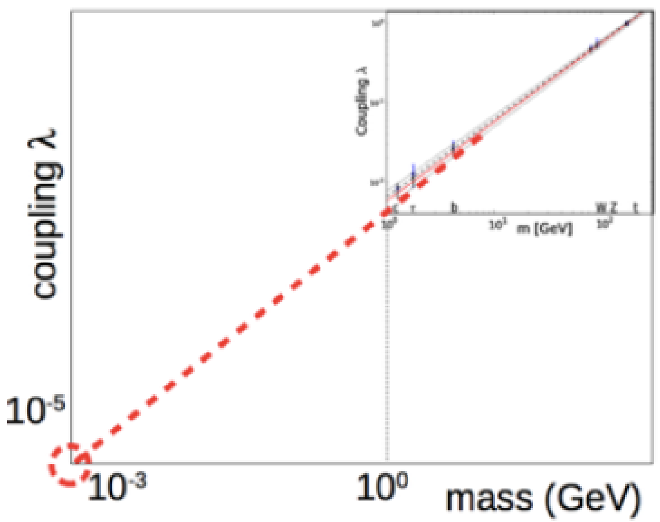
- Higgs self-coupling precision at FCC-ee : ~40%
  - Improved to ~20% if g_{HZ} is fixed to its SM value
- Unique FCC-ee synergy between the runs at 240 and 365 GeV
  - Calls for the highest luminosity (4IP's ? Longer runs ?)

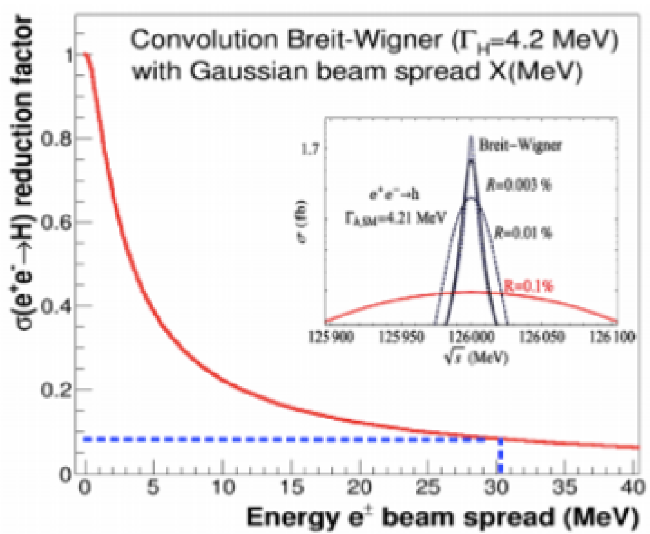
investigating now : the possibility of reaching 5σ observation of Higgs self coupling at FCC-ee:
4 detectors
+ recast of running scenario

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?

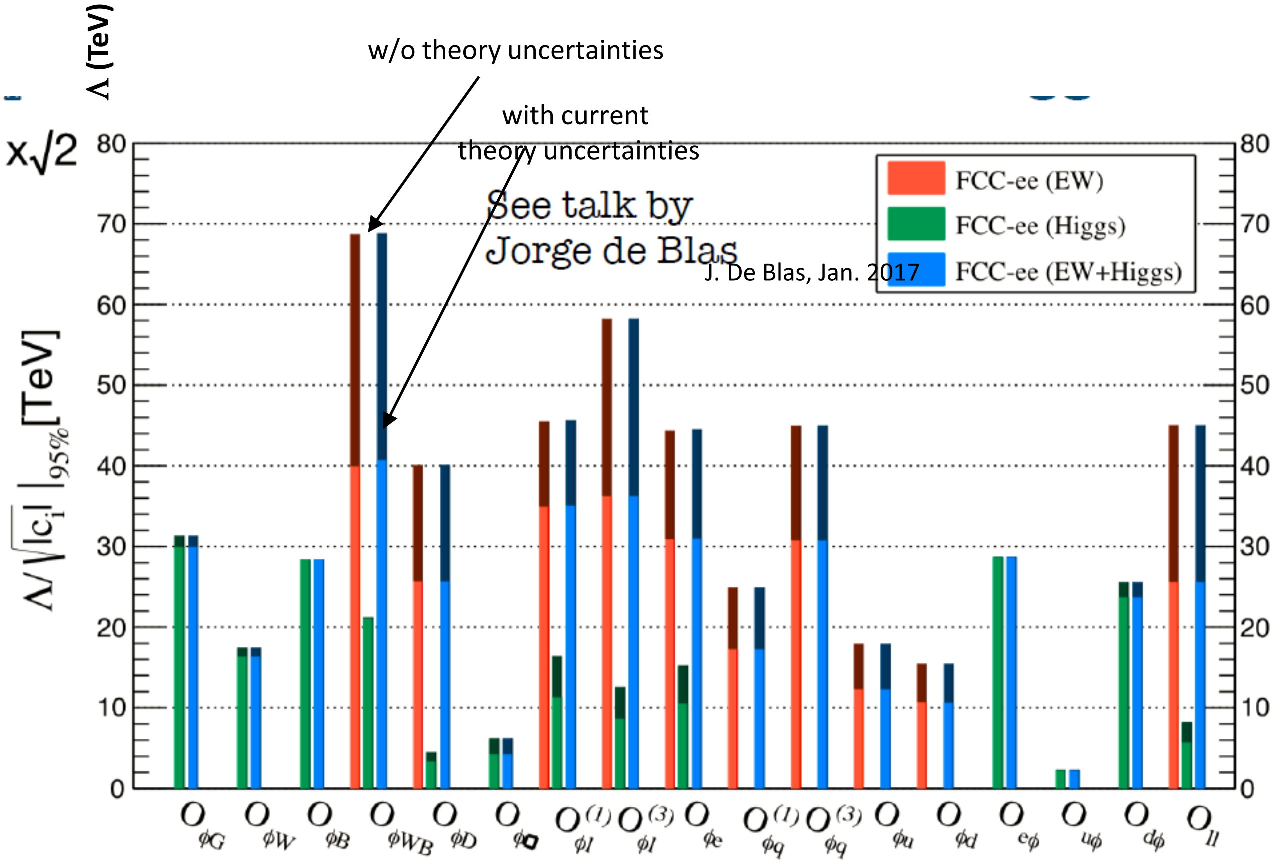
Result of the coupling (a.k.a. κ) fit

- Comparison(*) with other lepton colliders at the EW scale (up to 380 GeV)

13	μ Coll$_{125}$	ILC$_{250}$	CLIC$_{380}$	LEP3$_{240}$	CEPC$_{250}$	FCC-ee$_{240}$	FCC-ee$_{365}$
Years	6	15	5	6	7	3	+4
Lumi (ab^{-1})	0.005	2	0.5	3	5	5	+1.5
δm_H (MeV)	0.1	t.b.a.	110	10	5	7	6
$\delta\Gamma_H / \Gamma_H$(%)	6.1	3.8	6.3	3.7	2.6	2.8	1.6
$\delta g_{Hb} / g_{Hb}$ (%)	3.8	1.8	2.8	1.8	1.3	1.4	0.70
$\delta g_{HW} / g_{HW}$ (%)	3.9	1.7	1.3	1.7	1.2	1.3	0.47
$\delta g_{H\tau} / g_{H\tau}$(%)	6.2	1.9	4.2	1.9	1.4	1.4	0.82
$\delta g_{H\gamma} / g_{H\gamma}$ (%)	n.a.	6.4	n.a.	6.1	4.7	4.7	4.2
$\delta g_{H\mu} / g_{H\mu}$ (%)	3.6	13	n.a.	12	6.2	9.6	8.6
$\delta g_{HZ} / g_{HZ}$ (%)	n.a.	0.35	0.80	0.32	0.25	0.25	0.22
$\delta g_{Hc} / g_{Hc}$ (%)	n.a.	2.3	6.8	2.3	1.8	1.8	1.2
$\delta g_{Hg} / g_{Hg}$ (%)	n.a.	2.2	3.8	2.1	1.4	1.7	1.0
Br$_{invis}$ (%)$_{95\%CL}$	SM	<0.3	<0.6	<0.5	<0.15	<0.3	<0.25
BR$_{EXO}$ (%)$_{95\%CL}$	–	<1.8	<3.0	<1.6	<1.2	<1.2	<1.1

(*) Green = best
Red = worst

many EFTs



Conclusion from Precision Calculations Mini-Workshop in January 2018:
The necessary theoretical work is doable in 5-10 years perspective, due to steady progress in methods and tools, including the recent completion of NNLO SM corrections to EWPOS. This statement is conditional to a strong support by the funding agencies and the overall community. Appropriate financial support and training programs for these precision calculations are mandatory.

Several EFTs will achieve sensitivity exceeding 50 TeV (decoupling physics!)

junction with FCC-hh EFTs under progress by Jorge de Blas

100 TeV

Hadron collider parameters (*pp*)

parameter	FCC-hh		HE-LHC	(HL) LHC
collision energy cms [TeV]	100		27	14
dipole field [T]	16		16	8.3
circumference [km]	100		27	27
beam current [A]	0.5		1.12	(1.12) 0.58
bunch intensity [10^{11}]	1 (0.5)		2.2	(2.2) 1.15
bunch spacing [ns]	25 (12.5)		25 (12.5)	25
norm. emittance $\gamma\varepsilon_{x,y}$ [μm]	2.2 (1.1)		2.5 (1.25)	(2.5) 3.75
IP $\beta^*_{x,y}$ [m]	1.1	0.3	0.25	(0.15) 0.55
luminosity/IP [10^{34} cm^{-2}s^{-1}]	5	30	28	(5) 1
peak #events / bunch Xing	170	1000 (500)	800 (400)	(135) 27
stored energy / beam [GJ]	8.4		1.4	(0.7) 0.36
SR power / beam [kW]	2400		100	(7.3) 3.6
transv. emit. damping time [h]	1.1		3.6	25.8
initial proton burn off time [h]	17.0	3.4	3.0	(15) 40

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 >30 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 $H\rightarrow V\gamma$ ($V=\rho,\varphi,J/\psi,\Upsilon,Z$…)**
- **-- 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. $H\rightarrow bb$)

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…

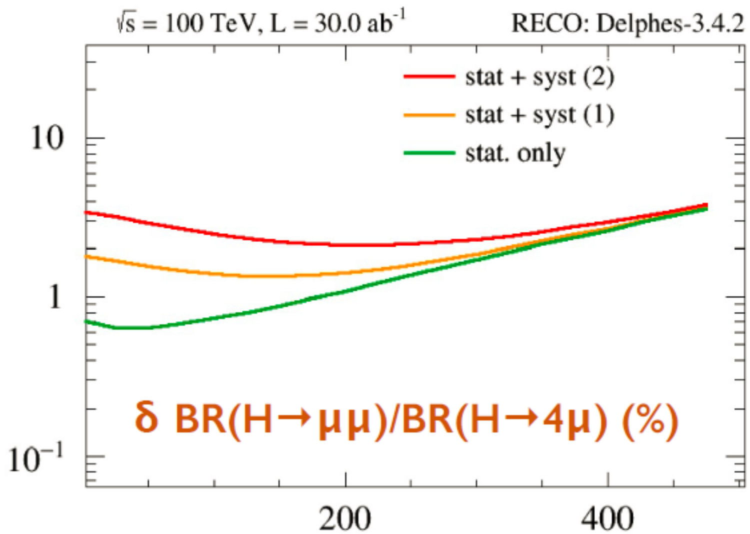
SM Higgs: event rates at 100 TeV

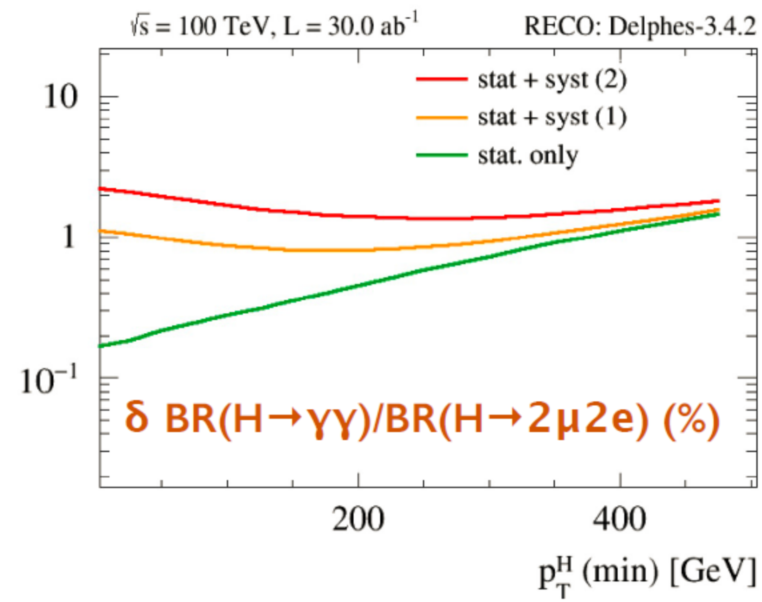
	gg→H	VBF	WH	ZH	ttH	HH
N_{100}	24 x 10^9	2.1 x 10^9	4.6 x 10^8	3.3 x 10^8	9.6 x 10^8	3.6 x 10^7
N_{100}/N_{14}	180	170	100	110	530	390

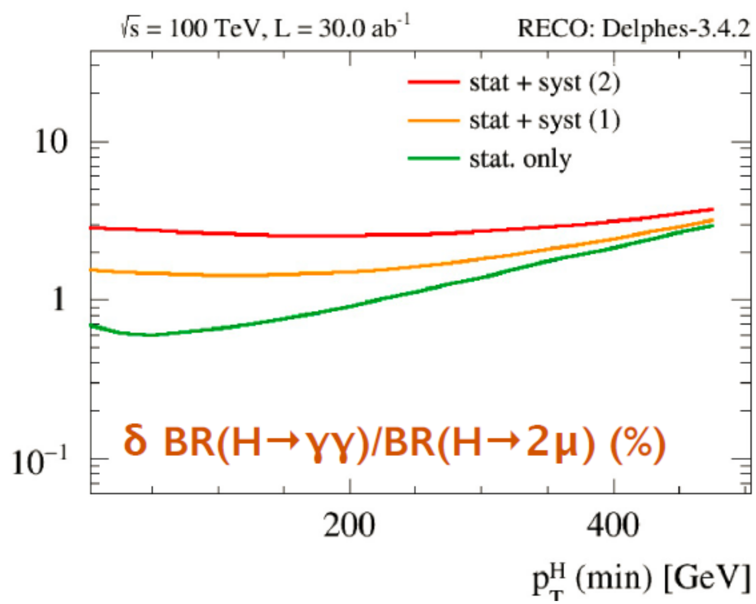
$N_{100} = \sigma_{100\,\mathrm{TeV}} \times 30\ \mathrm{ab}^{-1}$

$N_{14} = \sigma_{14\,\mathrm{TeV}} \times 3\ \mathrm{ab}^{-1}$

For rare decays ($\mu\mu$, $\gamma\gamma$, γZ) normalize to H→ ZZ well measured at FCC-ee





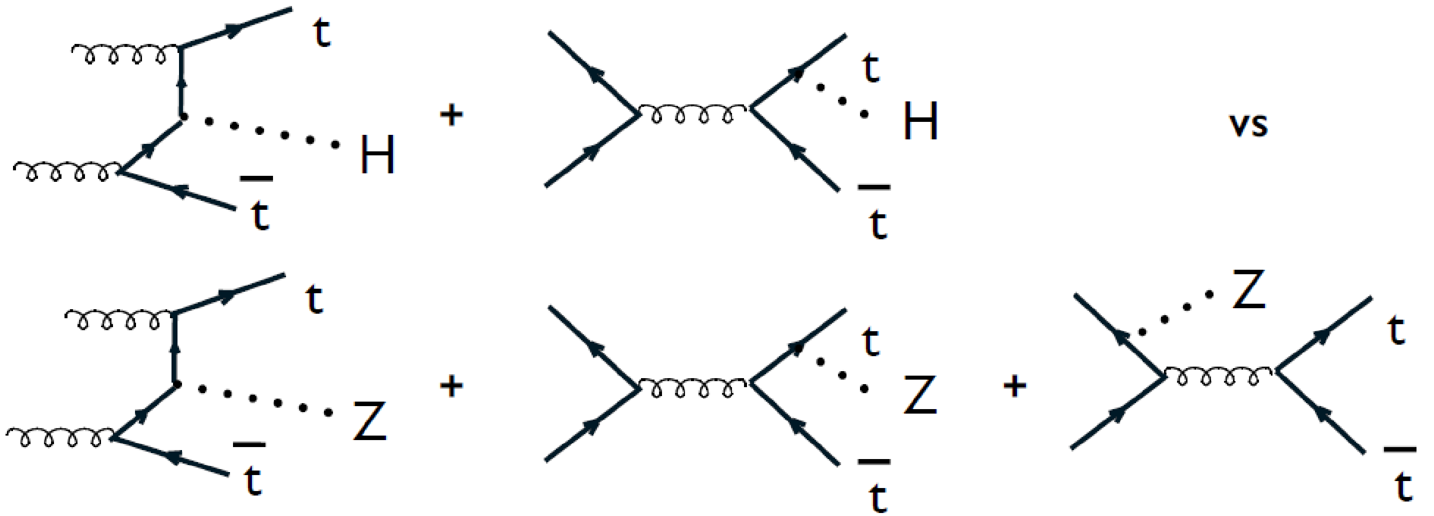


Normalize to BR(4l) from ee at 1% level => absolute sub-% for couplings

M.Selvaggi

13

Top Yukawa coupling from σ(ttH)/σ(ttZ)



To the extent that the qqbar → tt Z/H contributions are subdominant:

- Identical production dynamics:

  o correlated QCD corrections, correlated scale dependence
  o correlated α_S systematics

- $m_Z \sim m_H \Rightarrow$ almost identical kinematic boundaries:

  o correlated PDF systematics
  o correlated m_{top} systematics

For a given y_{top}, we expect σ(ttH)/σ(ttZ) to be predicted with great precision

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- δy_t (stat + syst $_{TH}$) ~ 1%

Higgs at FCC-hh

λ_H at the few percent level

Table 1.2: Target precision for the parameters relative to the measurement of various Higgs couplings, the Higgs self-coupling λ, Higgs branching ratios B and ratios thereof. Notice that lagrangian couplings have a precision that is typically half that of what is shown here, since all rates and branching ratios depend quadratically on the couplings.

Observable	Parameter	Precision (stat)	Precision (stat+syst)
$\mu = \sigma(H) \times B(H \to \mu\mu)$	$\delta\mu/\mu$	0.5%	0.9%
$\mu = \sigma(H) \times B(H \to \gamma\gamma)$	$\delta\mu/\mu$	0.1%	1%
$\mu = \sigma(H) \times B(H \to 4\mu)$	$\delta\mu/\mu$	0.2%	1.6%
$\mu = \sigma(t\bar{t}H) \times B(H \to b\bar{b})$	$\delta\mu/\mu$	1%	tbd
$\mu = \sigma(HH) \times B(H \to \gamma\gamma)B(H \to b\bar{b})$	$\delta\lambda/\lambda$	3.5%	5.0%
$R = B(H \to \mu\mu)/B(H \to 4\mu)$	$\delta R/R$	0.6%	1.3%
$R = B(H \to \gamma\gamma)/B(H \to 2e2\mu)$	$\delta R/R$	0.17%	0.8%
$R = B(H \to \gamma\gamma)/B(H \to 2\mu)$	$\delta R/R$	0.6%	1.4%
$B(H \to \text{invisible})$	B@95%CL	1×10^{-4}	2.5×10^{-4}

To reach a precision on λ_H at the few percent level requires a linear collider of at least 3TeV (ILC 500 GeV can obtain a $\pm$30% indication and CLIC 3TeV estimate is $\pm$10%)

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 and ttH and rare decays, including invisible.

Search for Heavy Physics
-- ee gives precision measurements (m_Z m_W to < 0.6 MeV, m_{top} 10 MeV, etc…) sensitive to heavy physics up to … 100 TeV (for weak couplings)
-- FCC-hh gives access to direct observation at unprecedented energies
Also huge statistics of Z,W H and top → rare decays

QCD -- ee gives $\alpha_s \pm 0.0002$ (R_{had} at Z, W and taus)
also H→gg events (gluon fragmentation!)
-- ep provides structure 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
FCC-hh : H→ ZZ to serve as cross-normalization

for ttH, combination of ±4% (model dependent)HL-LHC with FCC-ee will lead to ttH coupling to ± 3%... model independent!

for g_{HHH} investigating now : the possibility of reaching 5σ obsservation at FCC-ee:
4 detectors
+ recast of running scenario

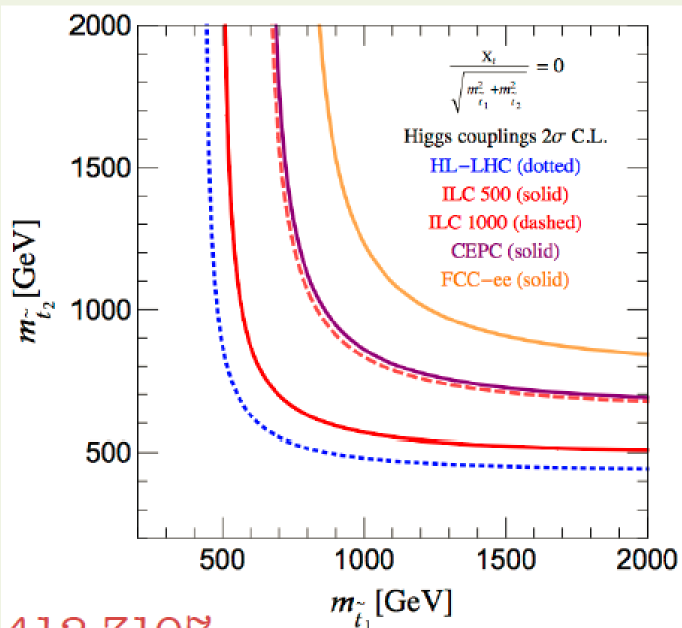
g_{Hxx}	FCC-ee	FCC-hh	FCC-eh
ZZ	**0.22 %**	**< 1% ***	
WW	**0.47%**		
Γ_H	**1.6%**		
γγ	4.2%	**<1%**	
Zγ	--	**1%**	
ttH	13%	**1%**	
bb	**0.7%**		0.5%
ττ	**0.8%**		
cc	**0.7%**		1.8%
gg	**1.0%**		
μμ	8.6%	**1-2%**	
uu,dd	H→ ργ?	H→ ργ?	
ss	H→ φγ ?	H→ φγ ?	
ee	**ee → H**		
HH	40%	**~3-5%**	20%
inv, exo	<0.55%	**10^{-3}**	5%

Supersymmetry

In supersymmetry top partner is “stop squark”.

FCC-ee

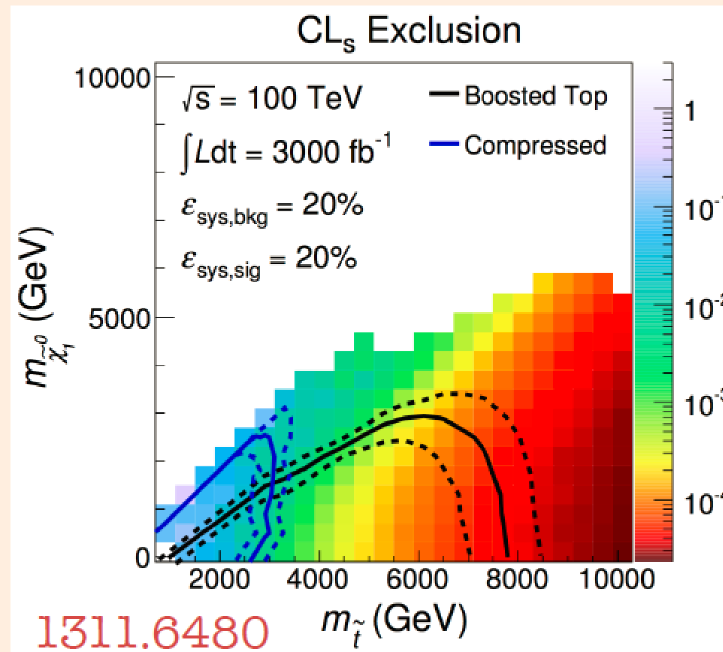
Coloured and charged, stops modify Higgs couplings:



1412.3107

FCC-hh

And show up directly at hadron colliders:

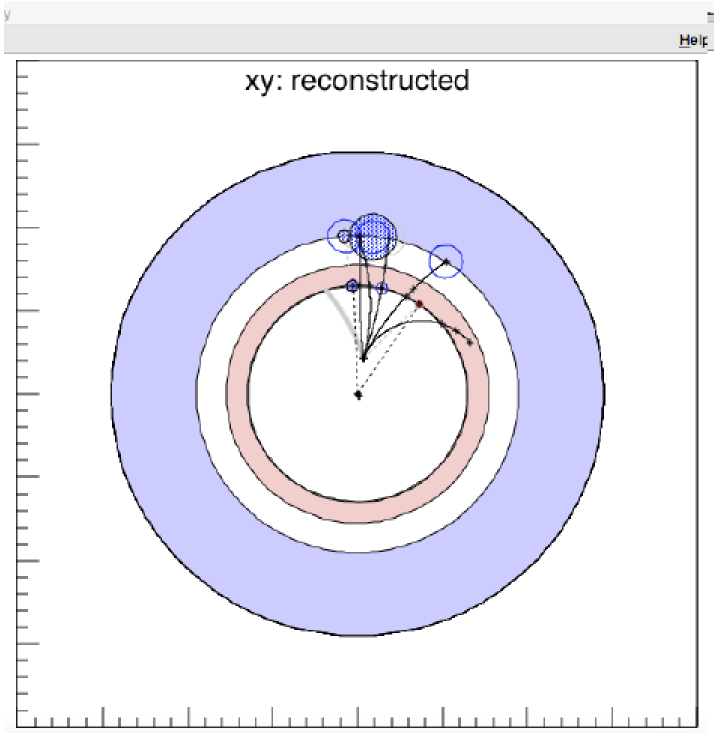


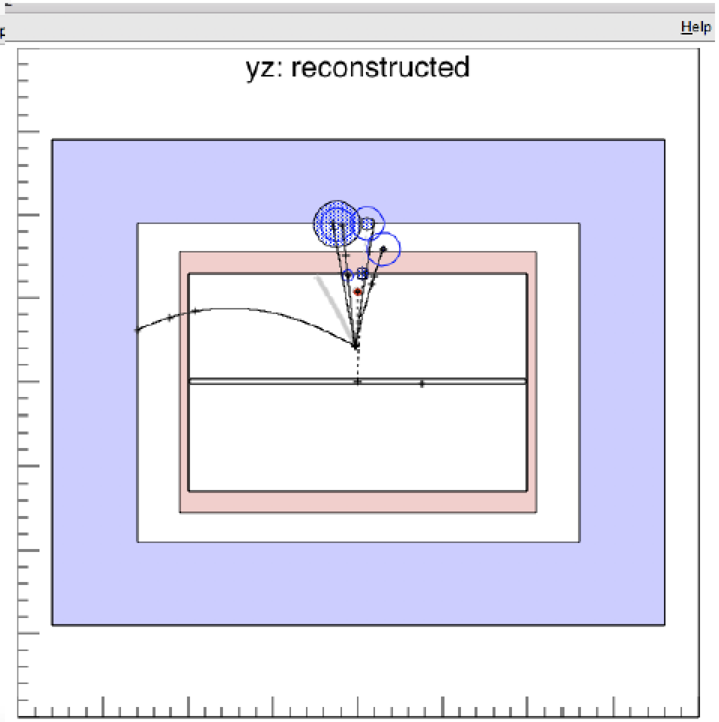
1311.6480

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

Very rare events

Simulation of heavy neutrino decay in a FCC-ee detector



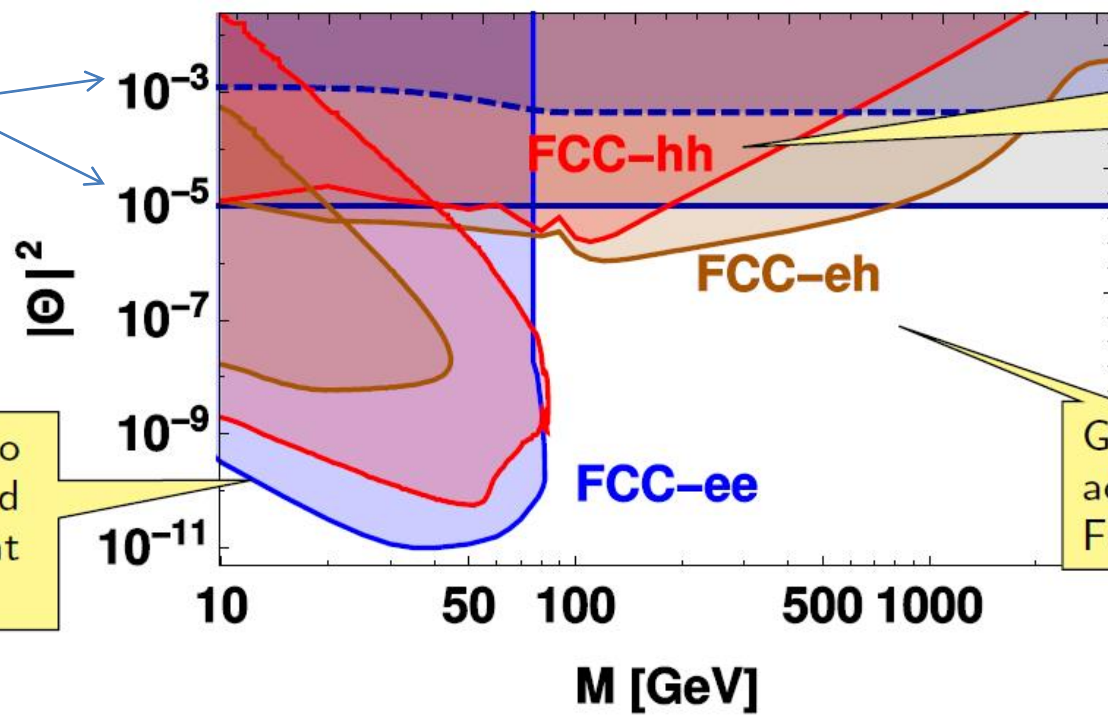


Summary

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.

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

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

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

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. **The CDR is on its way**

-- 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 maximises 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.

FCC (ee) could start seamlessly at the end of HL-LHC

A successful model!

PHYSICS WITH VERY HIGH ENERGY
e^+e^- COLLIDING BEAMS

CERN 76-18
8 November 1976

L. Camilleri, D. Cundy, P. Darriulat, J. Ellis, J. Field,
H. Fischer, E. Gabathuler, M.K. Gaillard, H. Hoffmann,
K. Johnsen, E. Keil, F. Palmonari, G. Preparata, B. Richter,
C. Rubbia, J. Steinberger, B. Wiik, W. Willis and K. Winter

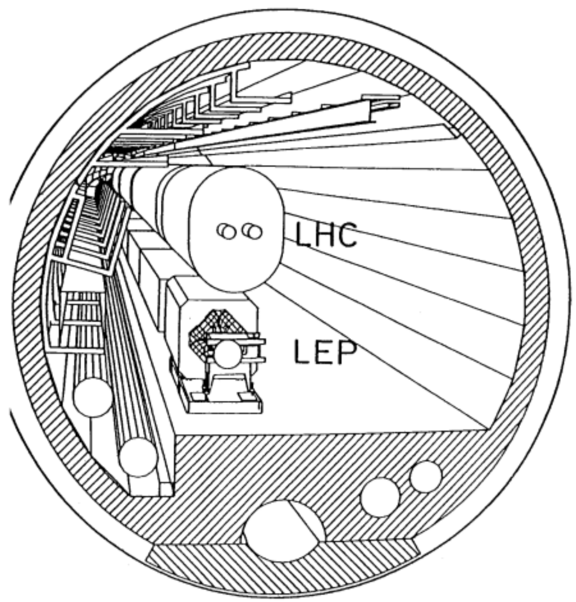
ABSTRACT

This report consists of a collection of documents produced by a Study Group on Large Electron-Positron Storage Rings (LEP). The reactions of

Did these people know that we would be running HL-LHC in that tunnel >**60 years later?**

ECFA 84/85
CERN 84-10
5 September 1984

e+e- 1989-2000



p p 2009-2039

LARGE HADRON COLLIDER
IN THE LEP TUNNEL

Vol. I

Let's not be SHY!