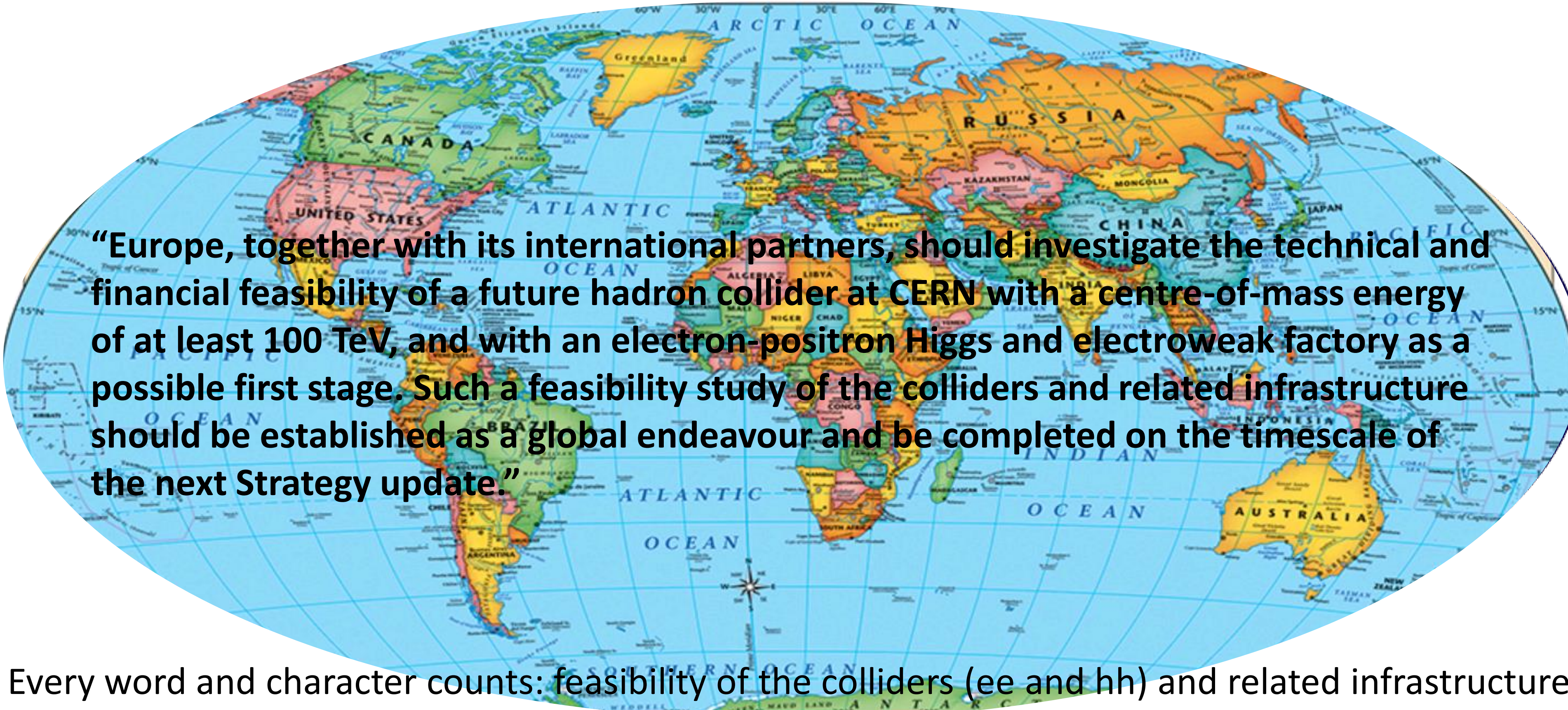
Brief News

CHIPP Road Map Meeting
27 August 2020

Our marching orders from ESPP 2020:



"Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV, and with an electron-positron Higgs and electroweak factory as a possible first stage. Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update."

Every word and character counts: feasibility of the colliders (ee and hh) and related infrastructure.

-- confirmed in meeting with DG on 14 July ➔ studies continue with 2013 mandate for now

-- **FCC is the highest priority for Europe and its international partners**

Feasibility study of FCC integrated program

Feasibility study to be delivered end 2025 as input for ESPP Update expected for 2026/2027:

- ***Feasibility study of the 100 km tunnel*** *(infrastructure aspects, administrative aspects, local authorities, environment, energy, etc.)*
- ***High-risk site investigations included****, to confirm principle feasibility*
- ***Host-state related processes*** *included to* ***allow start of construction begin 2030****.*
- ***CDR+ for colliders and injectors, including key technologies.***
- ***HFM intermediate milestones reached,*** *according to long-term R&D plan.*
- ***Physics and experiments CDR + for FCC integrated project.***
- ***Financing concept and operation model.***

➢ For all these activities the sequential nature of implementation of the colliders and the overall timeline needs to be taken into account!

⇑ FCC (ee, then hh)

M. Benedikt

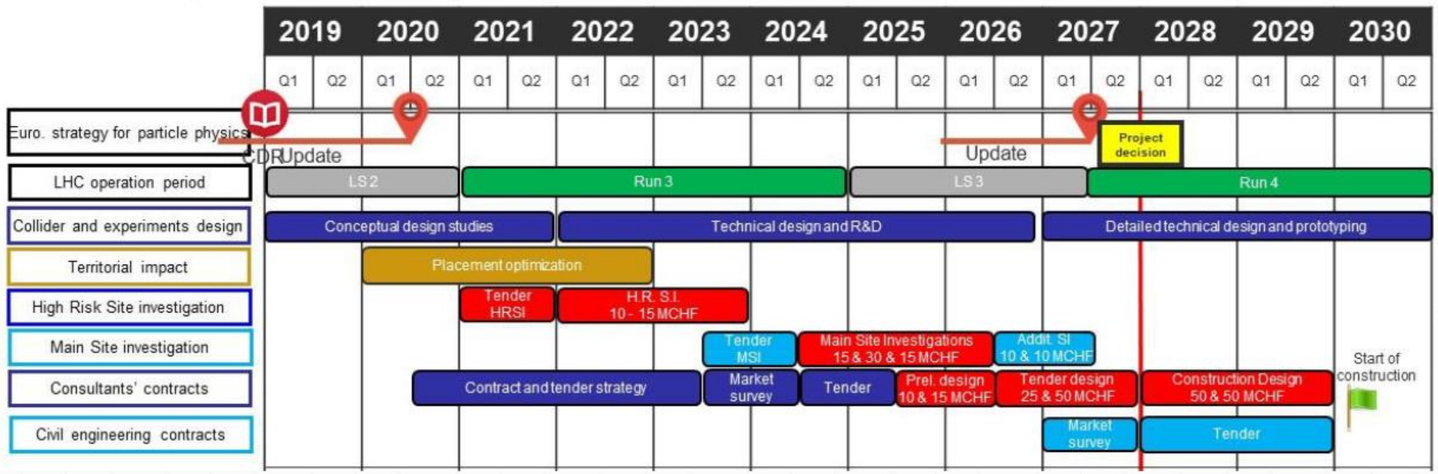
CERN MTP 2021-2025 for FCC

- Total material budget for FCC 75 MCHF, i.e. 15 MCHF/y
- Roughly 50% dedicated to host state activities, infrastructure preparations, implementation preparation out of which 10-15 MCHF for high-risk site investigations.
- Remainder for machine studies, technology R&D and technical infrastructure and related collaborations.
- Personnel: 30 CERN FTE, i.e 150 PY integral.
- New in MTP:
  - HFM line (16T program) with 75 MCHF M&P
  - Dedicated line for RF power source development (HE klystrons)

Will include CERN-PH FCC group

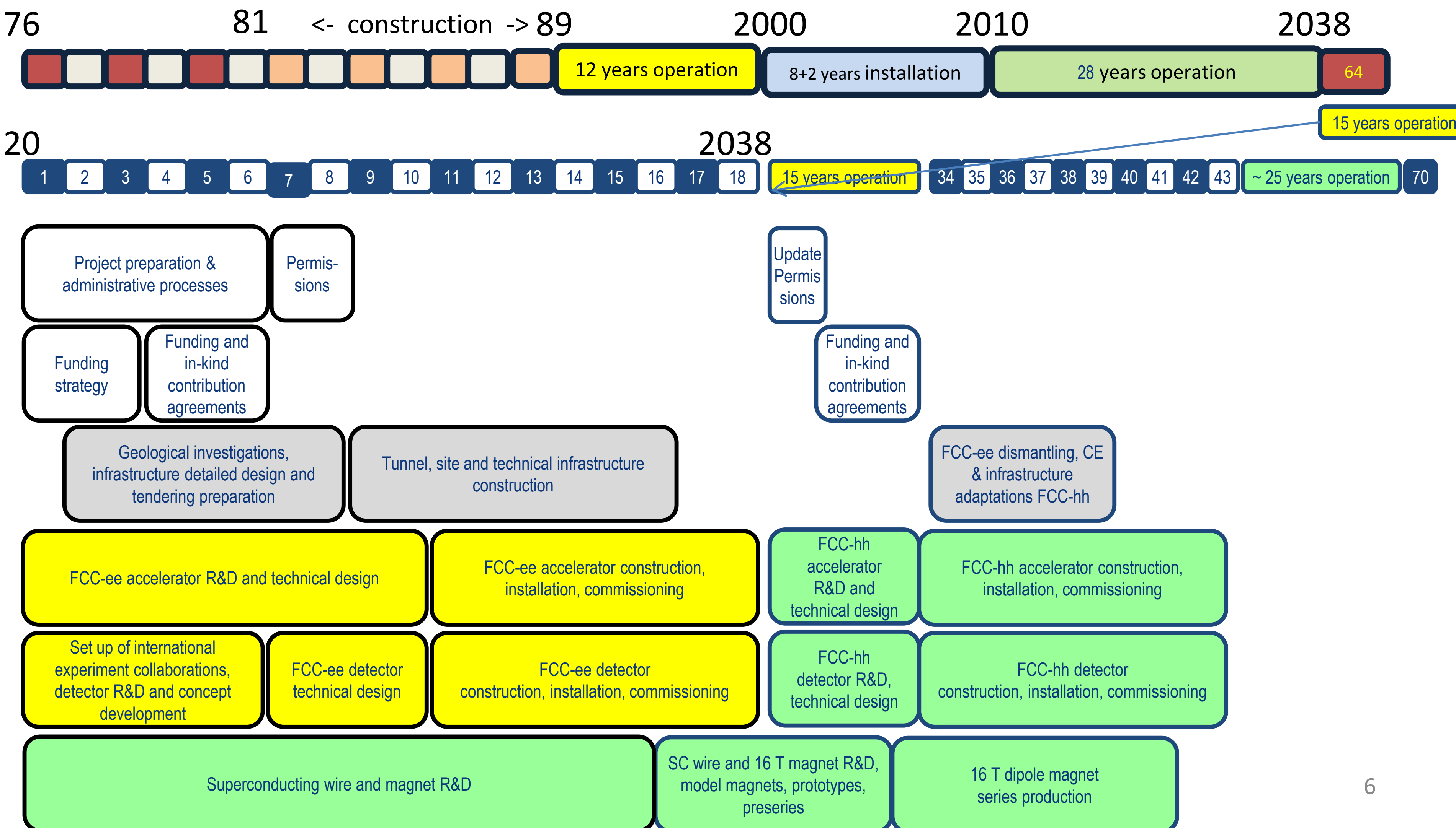
Feasibility study tunnel – updated planning

Timeplan CE project preparation 2019 – 2030



- Schedule of major processes leading to **start of construction begin 2030.**
- **For proof of principle feasibility: High risk site investigations 10 - 15 MCHF in the period 2022/23.**
- **Additional CE investments will be required in MTP period to allow start of construction in 2030: MSI 45 MCHF, PD 10 MCHF: Total of 55MCHF.**

Compare with LEP/LHC



Swiss Accelerator Research and Technology
CHART Collaboration

Commitments from SERI, ETHs, PSI, UniGE and CERN for a total sum of 40 MCHF to fund these activities for the next 5 years

Main activities:

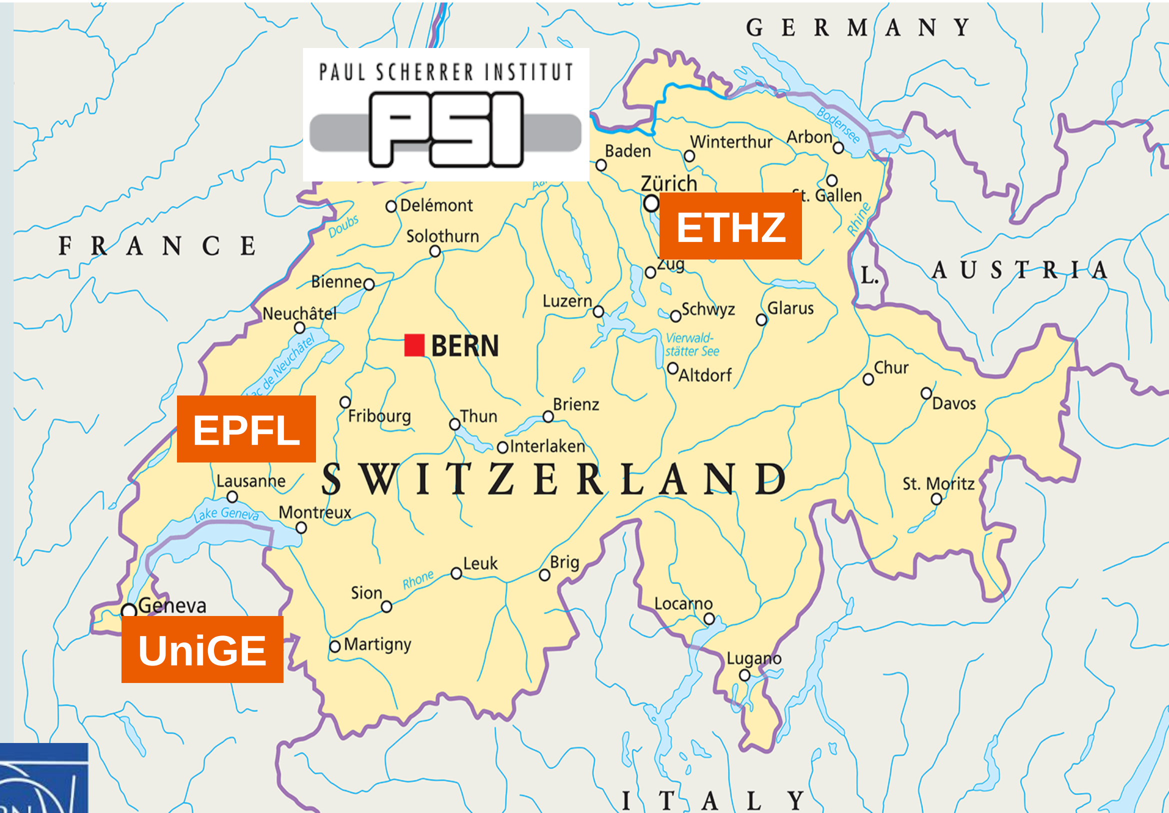
-High field magnets (Nb3Sn and HTS)

-FCC-ee injector study, including a positron target exp't at Swiss FEL PSI

-3D geology model of the Geneva basin (Geology department of UNIGE)

-Geodesy and Survey concepts for FCC (ETHZ, Swisstopo, HEIG Vaud)

-Beam dynamics for FCC-ee and FCC-hh



Securing the future of CERN beyond LHC

L. Rivkin, M. Seidel

Swiss Institute of Particle Physics

Presently setting up collaborations via the LOIs for SNOWMASS

Monochromatized direct s-channel Higgs production at 125 GeV

M. Benedikt (CERN), A. Blondel (U. Geneva and CNRS), A. Bogomyagkov (BINP), J. Butler (FNAL), Y. Cai (SLAC), D. d'Enterria (CERN), A. Faus-Golfe (IJCLab), P. Janot (CERN), M. Klute (MIT), E. Levichev (BINP), Y. Nosochkov (SLAC), K. Oide (CERN and KEK), D. Shatilov (BINP), S. Sinyatkin (BINP), M.A. Valdivia Garcia (U. Guanajuato & CERN), J. Wenninger (CERN), A. Zholents (ANL), F. Zimmermann (CERN)

Abstract

The FCC-ee could allow the measurement of ... in a dedicated run at ~125 GeV centre-of-mass energy, provided that the ... to about 5– 10 MeV to be comparable to the width of the ...

Precision Energy Calibration for a Future Circular Electron-Positron Collider

R. Assmann (DESY), D. Barber (DESY and UNM), M. Benedikt (CERN), O. Beznosov (UNM), A. Blondel (U. Geneva and CNRS), A. Bogomyagkov (BINP), Y. Cai (SLAC), T. Charles (U. Liverpool), J. Ellison (UNM), E. Gianfelice-Wendt (FNAL), K. Heinemann (UNM), P. Janot (CERN), M. Klute (MIT), I. Koop (BINP), M. Koratzinos (MIT), E. Levichev (BINP), N. Muchnoi (BINP), A.-S. Müller (KIT), S. Nikitin (BINP), Y. Nosochkov (SLAC), V. Ptitsyn (BNL), K. Oide (CERN and KEK), T. Roser (BNL), R. Rossmanith (KIT), D. Sagan (Cornell), A. Seryi (JLab), S. Sinyatkin (BINP), J. Wenninger (CERN), U. Wienands (ANL), F. Zimmermann (CERN)

Abstract

...ture Circular Collider integrated project foresees as a first stage a high-lum... collider (FCC-ee). A key component of the FCC-ee physics prog... ation of the collision energy. On the Z pole and around the W p... rgy needs to be measured with extremely high precision (ppm... depolarization. At higher energies the polarimeter infrastr...

FCC-ee as Z, W and H factory

I. Agapov (DESY), R. Assmann (DESY), M. Benedikt (CERN), A. Blondel (U. Geneva and CNRS), A. Bogomyagkov (BINP), M. Boscolo (INFN), Y. Cai (SLAC), T. Charles (U. Liverpool), E. Gianfelice-Wendt (FNAL), P. Janot (CERN), M. Klute (MIT), M. Koratzinos (MIT), E. Levichev (BINP), C. Milardi (INFN), A.-S. Müller (KIT), Y. Nosochkov (SLAC), A. Novokhatski (SLAC), K. Ohmi (KEK), K. Oide (CERN and KEK), D. Sagan (Cornell), A. Seryi (JLab), J. Seeman (SLAC), D. Shatilov (BINP), M. Sullivan (SLAC), R. Wanzenberg (DESY), J. Wenninger (CERN), U. Wienands (ANL), F. Zimmermann (CERN)

Abstract

The Future Circular Collider integrated project foresees, as a first stage, a high-luminosity electron-positron collider (FCC-ee), to study with high precision the Z, W, and Higgs bosons, with samples of $5 \cdot 10^{12}$ Z bosons, 10^8 W pairs, and 10^6 Higgs bosons. Optionally, the FCC-ee could then be upgraded to higher energy for top quark production, before later be followed by a highest-energy hadron collider (FCC-hh) installed in the same tunnel. The FCC-ee should be designed with maximum energy-efficiency with regard to hardware, operational scenarios, and parameters. The beam parameters are limited by several, partly new effects, such as beamstrahlung in collision, a coherent beam-beam instability with large crossing angle, the available top-up injection rate, and instabilities related to the large ring circumference. Luminosity optimization must consider these effects along with numerous other constraints. The number of collision points is a further variable.

FCC-ee upgrade to top factory

I. Agapov (DESY), R. Assmann (DESY), M. Benedikt (CERN), A. Blondel (U. Geneva and CNRS), A. Bogomyagkov (BINP), M. Boscolo (INFN), Y. Cai (SLAC), T. Charles (U. Liverpool), E. Gianfelice-Wendt (FNAL), P. Janot (CERN), M. Klute (MIT), M. Koratzinos (MIT), E. Levichev (BINP), C. Milardi (INFN), A.-S. Müller (KIT), Y. Nosochkov (SLAC), A. Novokhatski (SLAC), K. Ohmi (KEK), K. Oide (CERN and KEK), D. Sagan (Cornell), A. Seryi (JLab), J. Seeman (SLAC), D. Shatilov (BINP), M. Sullivan (SLAC), R. Wanzenberg (DESY), J. Wenninger (CERN), U. Wienands (ANL), F. Zimmermann (CERN)

FCC Physics and Experiments

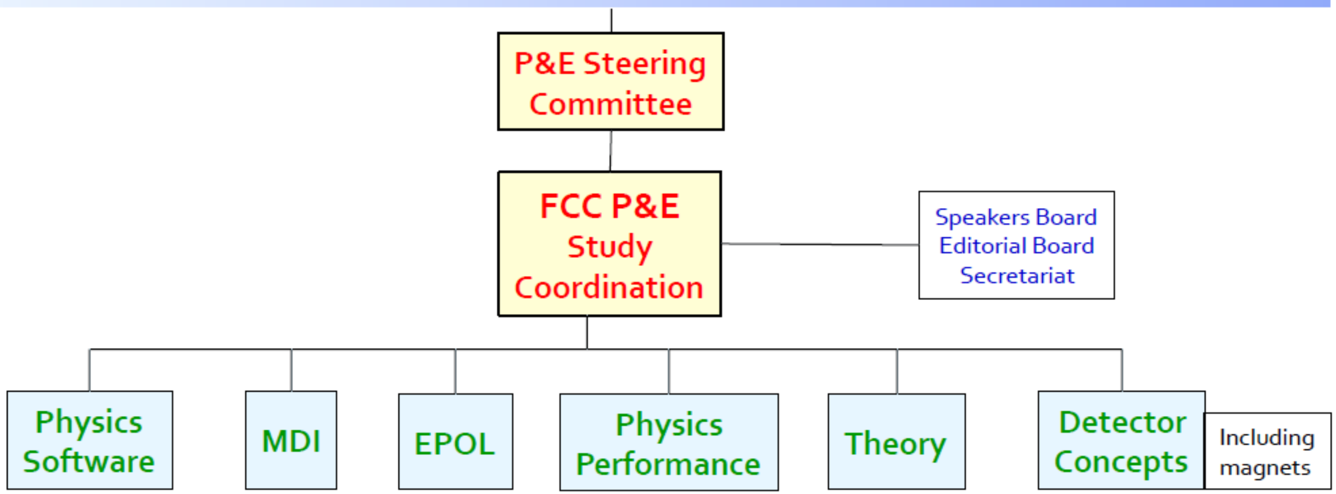
In 2012-2019 the physics landscape and detector feasibility for FCC (ee&hh) was established, by a relatively small group of people.
Best/unique for a very broad program (a Higgs factory and **much more**) well matched to the present physics landscape. (see spares)
Higgs (ee and hh) /Electroweak Precision (10^{-5})/flavours/QCD/BSM feeble (ee) High Mass (hh)

The greatest remaining challenge is the creation of a world-wide consortium of scientific contributors who reliably commit resources to the development and preparation of the FCC-ee science project from 2020 onwards. ***(from the FCC submission to the ESPP2020)***

We thus concentrate now on detector design and collaboration forming for FCC-ee in view of ***protocollaborations by 2023 (→ LOIs for the next strategy)***

Detectors for FCC-ee are similar to the ILC or CLIC concepts but the requirements are much broader and more demanding on systematic precision

P&E Organization in 2020-2026



Swiss Institute of Particle Physics

Physics Performance group & conveners

The FCC-ee PE&D SG approved a proposal for a Physics Performance group.

Patrizia Azzi and Emmanuel Perez have agreed to serve as coordinators

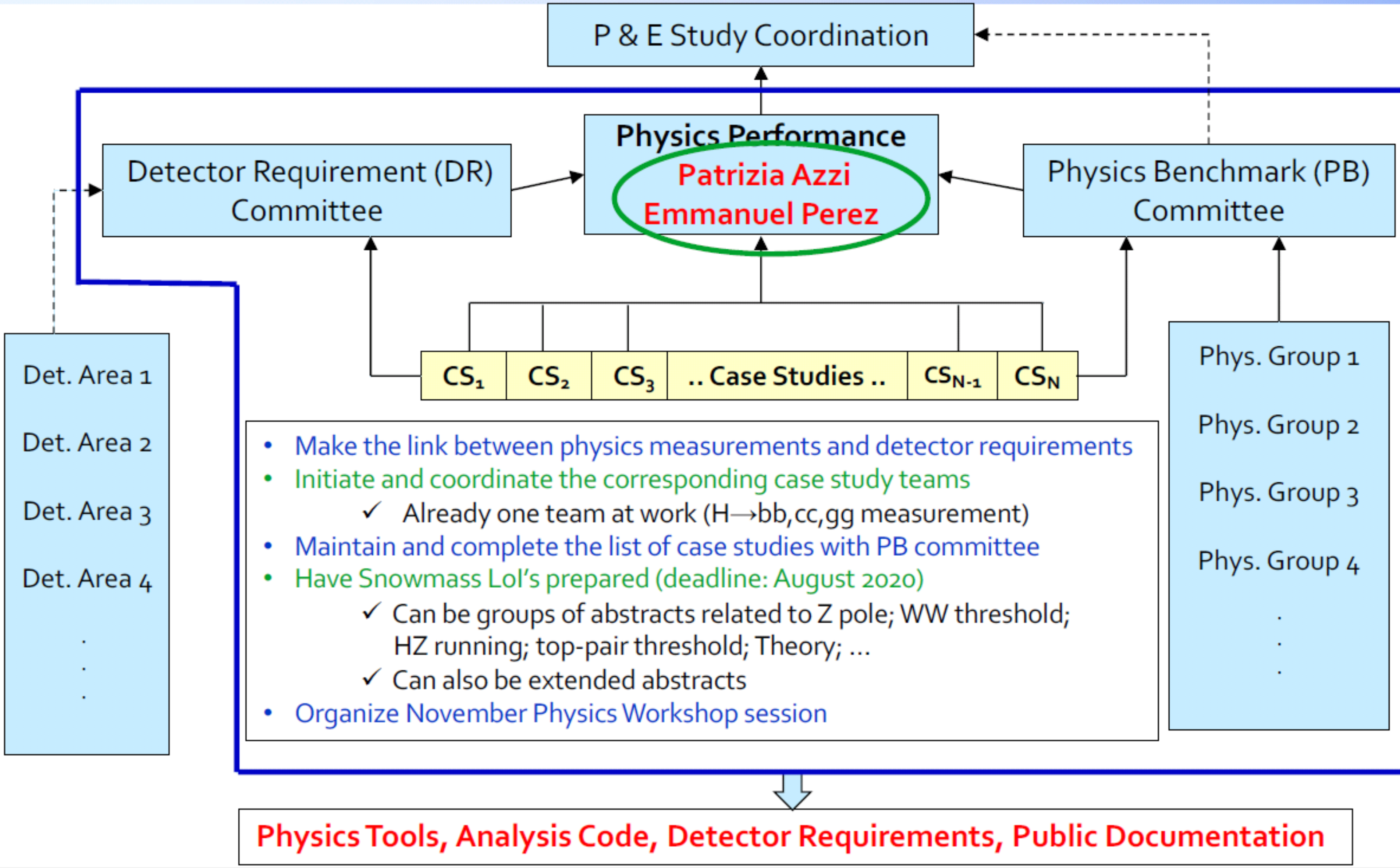
operation (see next slide)

1. Physics working groups (conveners) → establish list of BENCHMARK MEASUREMENTS
   -- each can correspond to several case studies
   -- group case studies from different measurements for efficiency/consistency
   -- will start with the Z (as in the run plan)

2. Case study teams establish DETECTOR REQUIREMENTS for optimizing measurement, and in particular matching exp. systematics with the expected statistical precision.
   -- one team already started: c vs b/g jets in Higgs (and Z) decays

3. This requires simulations of detector setup (fast sim or full sim as appropriate) with help/guidance from detector experts

Hot News: Physics Performance coordinators



A first selection of Benchmark studies (mostly experimental, some theory) has already been prepared.
A list of abstracts is here:
https://www.overleaf.com/read/dyjpdszrqxhz
it will be regularly updated

This was also submitted to the SNOWMASS process. https://snowmass21.org/ as LOI

If you are interested in contributing this is a great way to start.

Now writing these up as LOIs by 31 August

A first list of benchmark studies

1. Towards an ultimate measurement of $R_\ell = \frac{\sigma(Z\to \text{hadrons})}{\sigma(Z\to \text{leptons})}$
2. Towards an ultimate measurement of the Z total width Γ_Z
3. Towards an ultimate measurement of the Z peak cross section
4. Direct determination of $\sin^2\theta^\ell_{\rm eff}$ and of $\alpha_{\rm QED}(m_Z^2)$ from muon pair asymmetri
5. Determination of the QCD coupling constant $\alpha_S(m_Z^2)$
6. Tau Physics, Lepton Universality, and Lepton Flavour Violation
7. Tau exclusive branching ratios and polarization observables
8. Z-pole Electroweak observables with heavy quarks
9. Long lived particle searches
10. Measurement of the W mass
11. Measurement of the Higgs boson coupling to the c quark
12. Measurement of the ZH production cross section
13. Measurement of the Higgs boson mass - Part I
14. Measurement of the Higgs boson mass - Part II
15. Inferring the total Higgs boson decay width - Part I
16. Inferring the total Higgs boson decay width - Part II
17. Determination of the HZγ effective coupling
18. Electron Yukawa via s-channel $e^+e^- \to H$ production at the Higgs pole
19. Measurement of top properties at threshold and above
20. Search for FCNC in the top sector
21. Theory Needs for FCC-ee
22. Beyond MFV: constraints on RH charged currents and on dipole operators
23. Construction of CP-odd observables to probe CP-violating Higgs couplings
24. Combined fit of Higgs and top data

Tera Z

τ, b,c

WW

H fact

ee→H

top

theory

This table presents the **statistical** errors for EWPOs, as given by the run plan.

It represents the real potential of FCC-ee

Systematics are 'just a start'
and next challenge will be to
-- design detectors and analysis
and
--improve calculations/simulations

so that systematics ≈≤ statistics

One common mistake in all the previous studies was to underestimate …. the ability of a real group of collaborators to exploit real data to reduce systematics

Table 5: Measurement of selected EWPOs at FCC-ee, compared with present precision. The systematic uncertainties are initial estimates, aim is to improve down to statistical errors. This set of measurements, together with those of the Higgs properties, achieves indirect sensitivity to new physics up to a scale Λ of 70 TeV in a description with dim 6 operators, and possibly much higher in specific new physics (non-decoupling) models.

Observable	present value ± error	FCC-ee Stat.	FCC-ee Syst.	Comment and leading exp. error
m_Z (keV)	91186700 ± 2200	**4**	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2495200 ± 2300	**4**	25	From Z line shape scan Beam energy calibration
R_ℓ^Z ($\times 10^3$)	20767 ± 25	**0.06**	0.2-1	ratio of hadrons to leptons **acceptance for leptons**
$\alpha_s(m_Z^2)$ ($\times 10^4$)	1196 ± 30	**0.1**	0.4-1.6	from R_ℓ^Z above
R_b ($\times 10^6$)	216290 ± 660	**0.3**	<60	ratio of bb to hadrons stat. extrapol. from SLD
$\sigma^0_{\rm had}$ ($\times 10^3$) (nb)	41541 ± 37	**0.1**	4	peak hadronic cross section luminosity measurement
N_ν($\times 10^3$)	2996 ± 7	**0.005**	1	Z peak cross sections Luminosity measurement
$\sin^2\theta_W^{\rm eff}$($\times 10^6$)	231480 ± 160	**2**	2.4	from $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{\rm QED}(m_Z^2)$($\times 10^3$)	128952 ± 14	**3**	small	from $A_{FB}^{\mu\mu}$ off peak QED&EW errors dominate
A_{FB}^b,0 ($\times 10^4$)	992 ± 16	**0.02**	1-3	b-quark asymmetry at Z pole from jet charge
$A_{FB}^{pol,\tau}$ ($\times 10^4$)	1498 ± 49	**0.15**	<2	τ polarization asymmetry τ decay physics
m_W (MeV)	80350 ± 15	**0.25**	0.3	From WW threshold scan Beam energy calibration
Γ_W (MeV)	2085 ± 42	1.2	0.3	From WW threshold scan Beam energy calibration
$\alpha_s(m_W^2)$($\times 10^4$)	1170 ± 420	**3**	small	from R_ℓ^W
N_ν($\times 10^3$)	2920 ± 50	**0.8**	small	ratio of invis. to leptonic in radiative Z returns
$m_{\rm top}$ (MeV/c^2)	172740 ± 500	**17**	small	From $t\bar{t}$ threshold scan QCD errors dominate
$\Gamma_{\rm top}$ (MeV/c^2)	1410 ± 190	45	small	From $t\bar{t}$ threshold scan QCD errors dominate
$\lambda_{\rm top}/\lambda_{\rm top}^{\rm SM}$	1.2 ± 0.3	**0.10**	small	From $t\bar{t}$ threshold scan QCD errors dominate
ttZ couplings	± 30%	0.5 – 1.5%	small	From $\sqrt{s} = 365$ GeV run

FCC-IS kick-off meeting and 4th Physics workshop

9-13 November https://indico.cern.ch/event/932973/

You can register already and let us know if you wish to present something

Rainer Wallny is member of the international program advisory committee

Physics groups

- Current/Previous organization (not all conveners are active)

Physics and Experiment Studies coordination
A. Blondel, P. Janot (EXP), C. Grojean, M. McCullough, M. Mangano, J. Ellis (TH)

EW Physics with Z's and W's J. Alcaraz, P. Azzurri, E. Locci A. Freitas	Higgs properties M. Klute, K. Peters C. Grojean	Top quark physics P. Azzi, F. Blekman	ee → H D. d'Enterria

QCD and $\gamma\gamma$ physics D. d'Enterria P. Skands	Flavours physics S. Monteil J. Kamenik	New physics M. Pierini, C. Rogan M. McCullough	Global Analysis Synergies J. De Blas	Precision Calculations A. Freitas, J. Gluza S. Heinemeyer

- **By 15 September, we would like to receive**
  - Your proposals of new physics groups — *ex: tau physics, Long Lived Particles, (+FCC-hh)*
  - Your nominations for physics group conveners
    - ➔ Current conveners who want to continue should of course let us know

      Some have already said they could not continue as conveners
    - ➔ Most urgent part of the mandate will be to enlarge international participation

Patrick Janot & Alain Blondel — FCC Physics & Experiments Coordination meeting 23 July 2020 — 4

self-nominations as group member or convener are most welcome.

National FCC-groups for physics, experiments and detectors

Progress ongoing

-- FCC-FRANCE and ITALY: are well established already.
Contacts (G. Bernardi, R. Aleksan) (F. Bedeschi)

-- UK: lots of progress. Contacts in all HEP groups and at the two STFC lab sites (RAL and DL).
First meeting 11 September. (Christos Leonidopoulos, Guy Wilkinson)
-- Poland: (Tadeusz Lesiak) planning FCC information day at Epiphany conference in January 2021
-- Spain: starting within a national 'future colliders' structure (Juan Alcaraz)

-- CH well in the road map, CHART for accelerator (esp. ee injector complex, hh magnet R&D) discussions on towards effort FCC funding. CH unambiguously supported FCC-INT project. Rainer Wallny has agreed to serve as contact for the next workshop organization.

-- Begium and Netherlands (just starting, contact Freya Blekman)
-- Contacts with Germany (Heinemann, Simon), USA, Austria, Estonia etc..
have been initiated – to be followed.

SUMMARY

With all its careful writing the strategy gives CERN and its international partners an unambiguous mandate:

Financial and technical feasibility study of the FCC colliders and infrastructure.

National groups are steadily being formed and seeking their own visibility/resources.

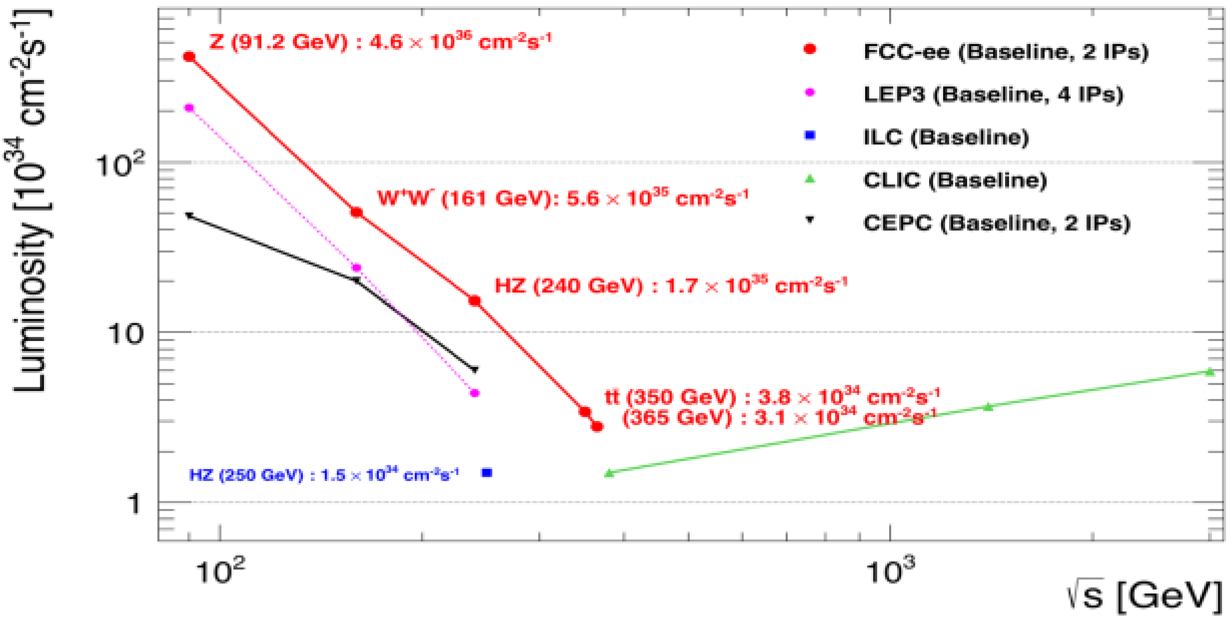
Organizing FCC-CH should be discussed for a scientific contribution matching/supporting the already large infrastructure/accelerator contribution.

Mark the 4th Physics workshop in your calendars and join.

Time to go into high gear!

FCC-ee

Z WW HZ tt



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	2 MeV
$\bar{t}t$ threshold	E_{cm} : 350 GeV	10^6	e+e- → $\bar{t}t$	Never done	5 MeV

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

Swiss Institute of Particle Physics

First stage 'Higgs Factory' (E_{CM} ≤365 GeV)

- "All low-energy Higgs factories have similar performance, to 1st order"
  - $ILC_{250} = CLIC_{380} = CEPC_{240} = FCC\text{-}ee_{240\rightarrow365}$?
    - Not quite !

J. De Blas et al., arXiv:1905.03764

HL-LHC: alone requires total width assumptions, with e+e- → model indept

Kappa fit, without/with HL-LHC

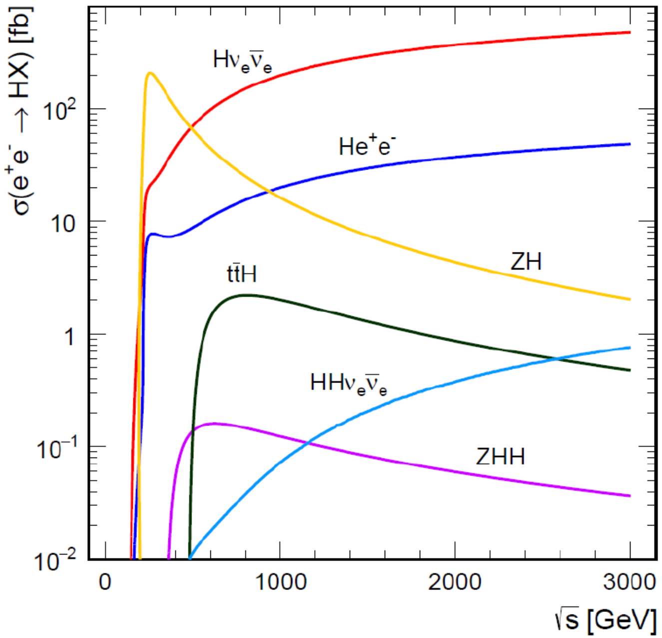
LHC-dominated

Global EFT fit, without/with HL-LHC

Collider	HL-LHC	ILC_{250}	$CLIC_{380}$	$CEPC_{240}$	$FCC\text{-}ee_{240\rightarrow365}$	
Lumi (ab^{-1})	3	2	1	5.6	5 + 0.2 + 1.5	
Years	10	11.5	8	7	3 + 1 + 4	
g_{HZZ} (%)	1.5	0.30 / 0.29	0.50 / 0.44	0.19 / 0.18	0.18 / 0.17	
g_{HWW} (%)	1.7	1.8 / 1.0	0.86 / 0.73	1.3 / 0.88	0.44 / 0.41	
g_{Hbb} (%)	5.1	1.8 / 1.1	1.9 / 1.2	1.3 / 0.92	0.69 / 0.64	
g_{Hcc} (%)	SM	2.5 / 2.0	4.4 / 4.1	2.2 / 2.0	1.3 / 1.3	
g_{Hgg} (%)	2.5	2.3 / 1.4	2.5 / 1.5	1.5 / 1.0	1.0 / 0.89	
$g_{H\tau\tau}$ (%)	1.9	1.9 / 1.1	3.1 / 1.4	1.4 / 0.91	0.74 / 0.66	2IP
$g_{H\mu\mu}$ (%)	4.4	15. / 4.2	– / 4.4	9.0 / 3.9	8.9 / 3.9	
$g_{H\gamma\gamma}$ (%)	1.8	6.8 / 1.3	– / 1.5	3.7 / 1.2	3.9 / 1.2	
$g_{HZ\gamma}$ (%)	11.	– / 10.	– / 10.	8.2 / 6.3	– / 10.	
g_{Htt} (%)	3.4	– / 3.1	– / 3.2	– / 3.1	10. / 3.1	
g_{HHH} (%)	50.	– / 49.	– / 50.	– / 50.	44./33. 2IP 27./24. 4IP	
Γ_H (%)	SM	2.2	2.5	1.7	1.1	
BR_{inv} (%)	1.9	0.26	0.65	0.28	0.19	2IP
BR_{EXO} (%)	SM (0.0)	1.8	2.7	1.1	1.1	

Higher luminosity of circular collider --> more statistics, in less time
- TeraZ program helps (arXiv:1907.04311)
- longitudinal polarization helps little if HL-LHC or Giga-Z are added

Higgs factories: FCC-ee + FCC-hh is unbeatable



Collider	ILC_{500}	ILC_{1000}	CLIC	FCC-INT
g_{HZZ} (%)	0.24 / 0.23	0.24 / 0.23	0.39 / 0.39	0.17 / 0.16
g_{HWW} (%)	0.31 / 0.29	0.26 / 0.24	0.38 / 0.38	0.20 / 0.19
g_{Hbb} (%)	0.60 / 0.56	0.50 / 0.47	0.53 / 0.53	0.48 / 0.48
g_{Hcc} (%)	1.3 / 1.2	0.91 / 0.90	1.4 / 1.4	0.96 / 0.96
g_{Hgg} (%)	0.98 / 0.85	0.67 / 0.63	0.96 / 0.86	0.52 / 0.50
$g_{H\tau\tau}$ (%)	0.72 / 0.64	0.58 / 0.54	0.95 / 0.82	0.49 / 0.46
$g_{H\mu\mu}$ (%)	9.4 / 3.9	6.3 / 3.6	5.9 / 3.5	0.43 / 0.43
$g_{H\gamma\gamma}$ (%)	3.5 / 1.2	1.9 / 1.1	2.3 / 1.1	0.32 / 0.32
$g_{HZ\gamma}$ (%)	– / 10.	– / 10.	7. / 5.7	0.71 / 0.70
g_{Htt} (%)	6.9 / 2.8	1.6 / 1.4	2.7 / 2.1	1.0 / 0.95
g_{HHH} (%)	27.	10.	9.	±2(stat)±~3(syst)
Γ_H (%)	1.1	1.0	1.6	0.91
BR_{inv} (%)	0.23	0.22	0.61	0.024
BR_{EXO} (%)	1.4	1.4	2.4	1.0

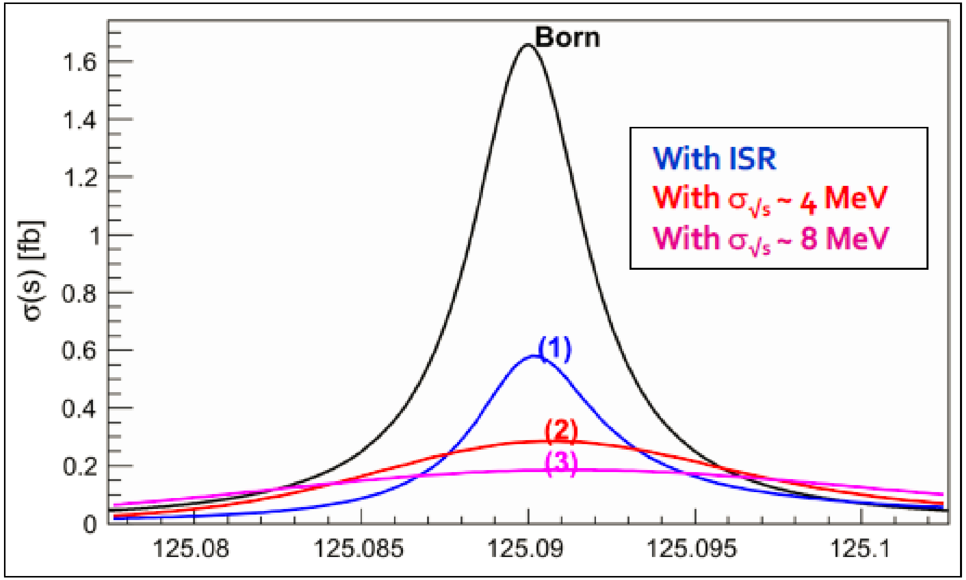
ee

hh

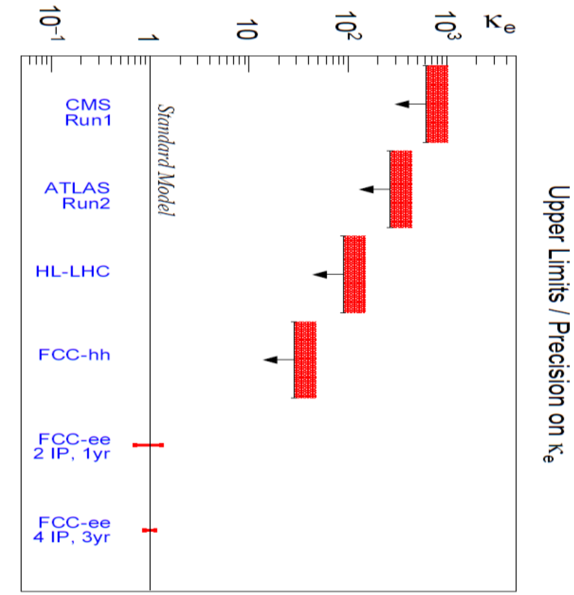
FCC-hh (> 10^{10} H produced)
+FCC-ee measurement of g_{HZZ}
→ g_{HHH}, $g_{H\gamma\gamma}$, $g_{HZ\gamma}$, $g_{H\mu\mu}$, BR_{inv}

(*)see M. Selvaggi, 3d FCC physics workshop,
9% precision in 3 years of FCC-hh running, 2004.03505v1

Something unique for FCC-ee: electron Yukawa coupling



Jadach & Kycia arXiv:1509.02406



e+e- → H @ 125.xxx GeV requires

-- Higgs mass to be known to <5 MeV from 240 GeV run (FCC: under study, CEPC group did it)

-- **Huge luminosity** (special single cell 400 MHz RF is foreseen for low energy runs)

-- **monochromatization** (opposite sign dispersion using magnetic lattice) to reduce σ_{ECM}

-- **continuous monitoring and adjustment of E_{CM}** to MeV precision (transv. Polar.)

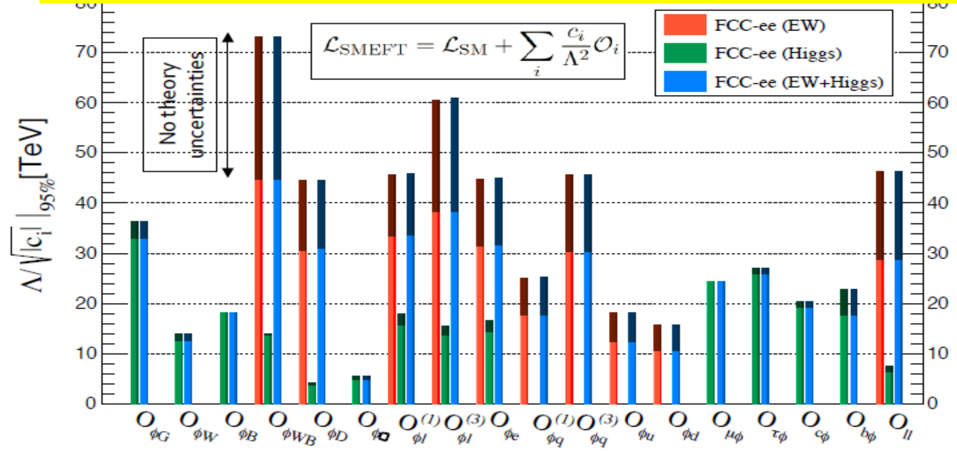
-- an extremely sensitive event selection against backgrounds

-- typically 3 years doing this (also neutrino counting+ rare Z decay search with γtagged $Z\gamma$ evts)

Precision EW measurements:
is the SM complete?

Observable	present value ± error	FCC-ee Stat.	FCC-ee Syst.	Comment and leading exp. error
m_Z (keV)	91186700 ± 2200	**4**	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2495200 ± 2300	**4**	25	From Z line shape scan Beam energy calibration
R_ℓ^Z ($\times 10^3$)	20767 ± 25	**0.06**	0.2-1	ratio of hadrons to leptons **acceptance for leptons**
$\alpha_s(m_Z^2)$ ($\times 10^4$)	1196 ± 30	**0.1**	0.4-1.6	from R_ℓ^Z above
R_b ($\times 10^6$)	216290 ± 660	**0.3**	<60	ratio of $b\bar{b}$ to hadrons stat. extrapol. from SLD
σ^0_{had} ($\times 10^3$) (nb)	41541 ± 37	**0.1**	4	peak hadronic cross section luminosity measurement
N_ν($\times 10^3$)	2996 ± 7	**0.005**	1	Z peak cross sections Luminosity measurement
$\sin^2\theta_W^{eff}$($\times 10^6$)	231480 ± 160	**2**	2.4	from $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{QED}(m_Z^2)$($\times 10^3$)	128952 ± 14	**3**	small	from $A_{FB}^{\mu\mu}$ off peak QED&EW errors dominate
A_{FB}^b, 0 ($\times 10^4$)	992 ± 16	**0.02**	1-3	b-quark asymmetry at Z pole from jet charge
$A_{FB}^{pol,\tau}$ ($\times 10^4$)	1498 ± 49	**0.15**	<2	τ polarization asymmetry τ decay physics
m_W (MeV)	80350 ± 15	**0.25**	0.3	From WW threshold scan Beam energy calibration
Γ_W (MeV)	2085 ± 42	1.2	0.3	From WW threshold scan Beam energy calibration
$\alpha_s(m_W^2)$($\times 10^4$)	1170 ± 420	**3**	small	from R_ℓ^W
N_ν($\times 10^3$)	2920 ± 50	**0.8**	small	ratio of invis. to leptonic in radiative Z returns
m_{top} (MeV/c^2)	172740 ± 500	**17**	small	From $t\bar{t}$ threshold scan QCD errors dominate
Γ_{top} (MeV/c^2)	1410 ± 190	45	small	From $t\bar{t}$ threshold scan QCD errors dominate
$\lambda_{top}/\lambda_{top}^{SM}$	1.2 ± 0.3	**0.10**	small	From $t\bar{t}$ threshold scan QCD errors dominate
ttZ couplings	± 30%	0.5 – 1.5%	small	From $\sqrt{s} = 365$ GeV run

ircular
pleme



-^- EFT D6 operators (some assumptions)

-^- Higgs and EWPOs are complementary

-^- top quark mass and couplings essential!

(the 100km circumference is optimal for this)

<-- systematics are preliminary
(aim at reducing to systematics)

<-- tau, b, and c observables still to be added

<-- complemented by high energy FCC-hh

Theory work is critical and initiated *1809.01830*

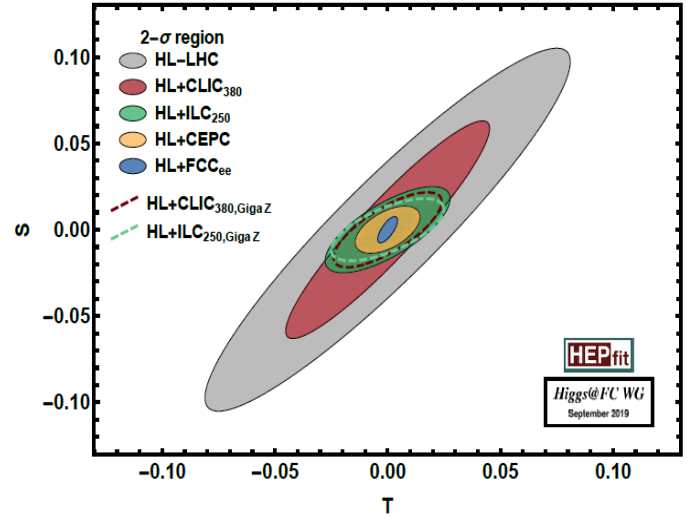
Swiss Institute of Particle Physics

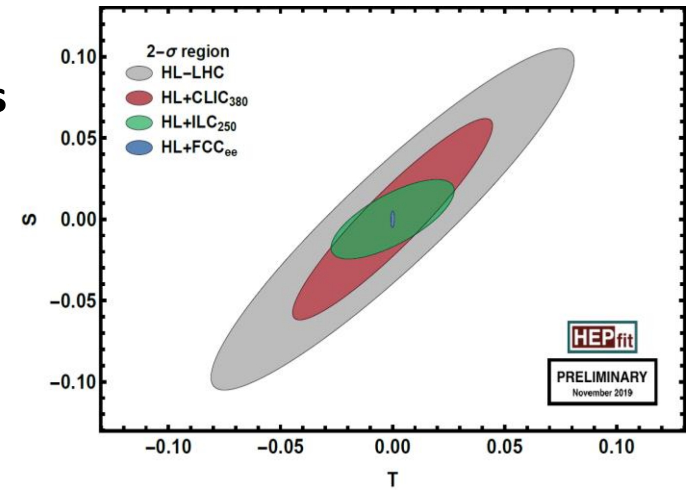
Electroweak Physics

Low Energy: the realm of FCC-ee

Highest luminosities at 91, 160 and 350 GeV
Transverse pol. at 91 and 160 GeV → Ecm calibration
m_Z (100 keV) Γ_Z (25 keV), m_W (<500 keV), $\alpha_{QED}(m_Z)$ (3.10^{-5}) and $\sin^2\theta_w$ at 310^{-6}

Complete set of EW observables can be measured
Precision unique to FCC-ee + new physics sensitivity
➔ a lot more potential to exploit
with good detector design than present treatment suggests





The Flavour Factory

Progress in flavour physics wrt SuperKEKb/BELLEII requires > 10^{11} b pair events,
FCC-ee(Z): will provide ~10^{12} b pairs. "**Want at least 5 10^{12} Z…"**

-- precision of CKM matrix elements
-- Push forward searches for FCNC, CP violation and mixing
-- Study rare penguin EW transitions such as $b \rightarrow s\, \tau^+ \tau^-$, spectroscopy (produce b-baryons, B_s …)
-- Test lepton universality with 10^{11} τ decays (with τ lifetime, mass, BRs) at 10^{-5} level, LFV to 10^{-10}
-- all very important to constrain / (provide hints of) new BSM physics.

need special detectors (PID); a story to be written!

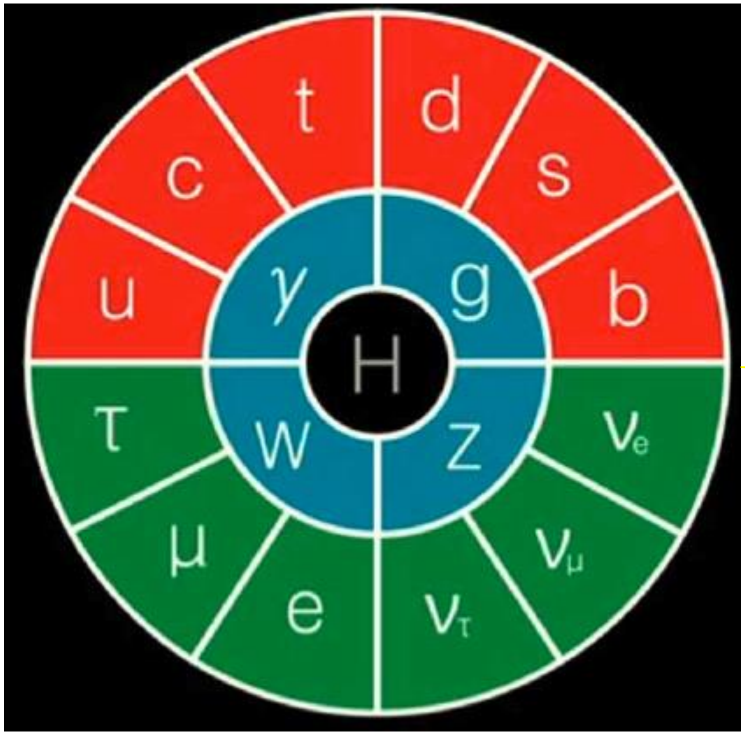
The 3.5 × 10^{12} hadronic Z decay also provide precious input for QCD studies

High-precision measurement of $\alpha_s(m_Z)$ with R_ℓ in Z and W decay, jet rates, τ decays, etc. : $10^{-3} \rightarrow 10^{-4}$
huge $\sqrt{s}$ lever-arm between 30 GeV and 1 TeV (FCC vs ILC), fragmentation, baryon production ….

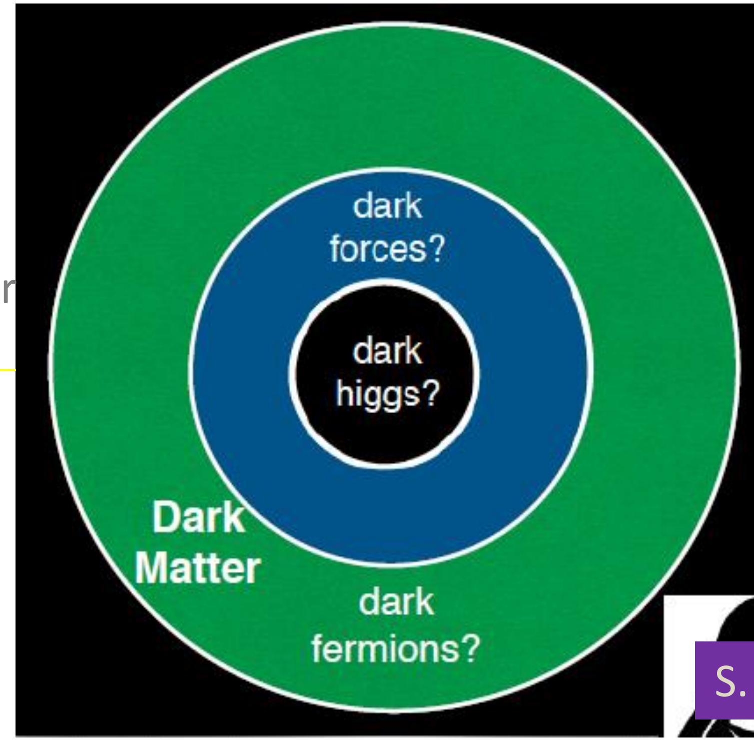
Testing running of α_s to excellent precision

Dark Sector at Z factory

With the Higgs discovery SM works perfectly, yet we need new physics to explain the baryon asymmetry of the Universe, the dark matter etc… without interfering with SM rad. corr.



mediator
or
mixing



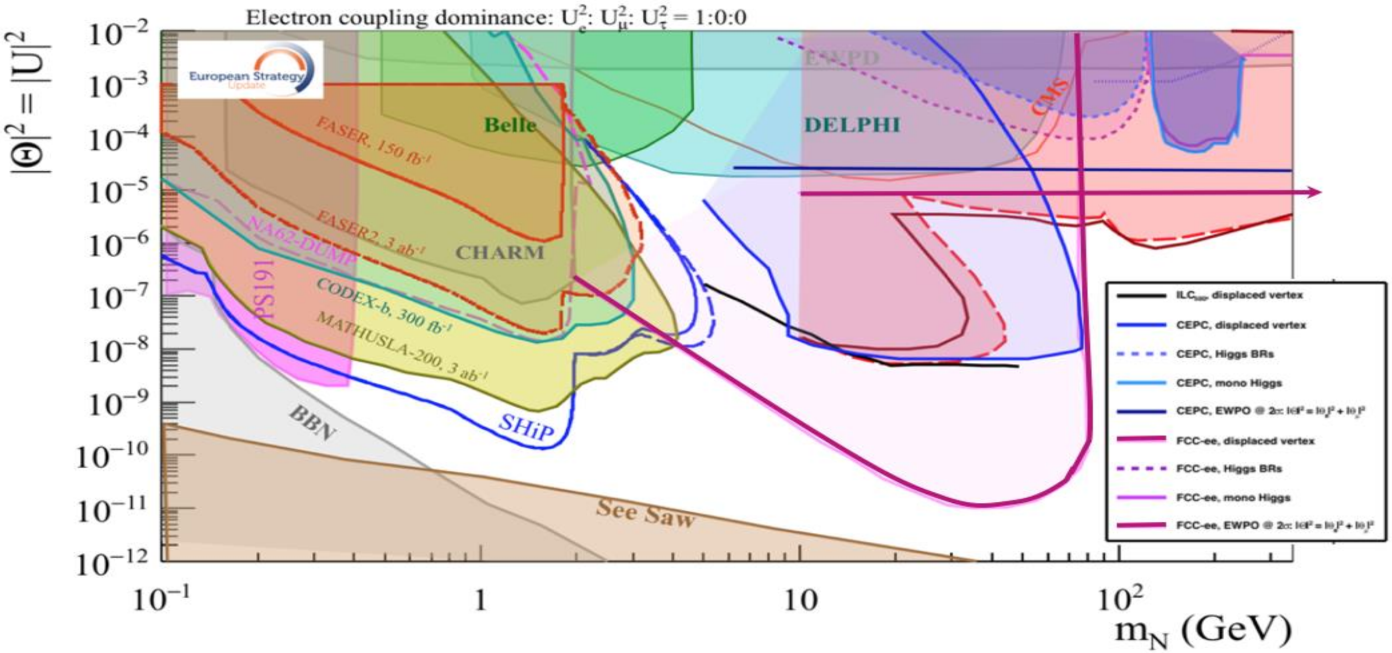
S. Gori

Dark photons, axion like particles, sterile neutrinos, all *feebly coupled* to SM particles

This picture is relevant to Neutrino, Dark sectors and High Energy Frontiers.

FCC-ee (Z) compared to the other machines for right-handed (sterile) neutrinos

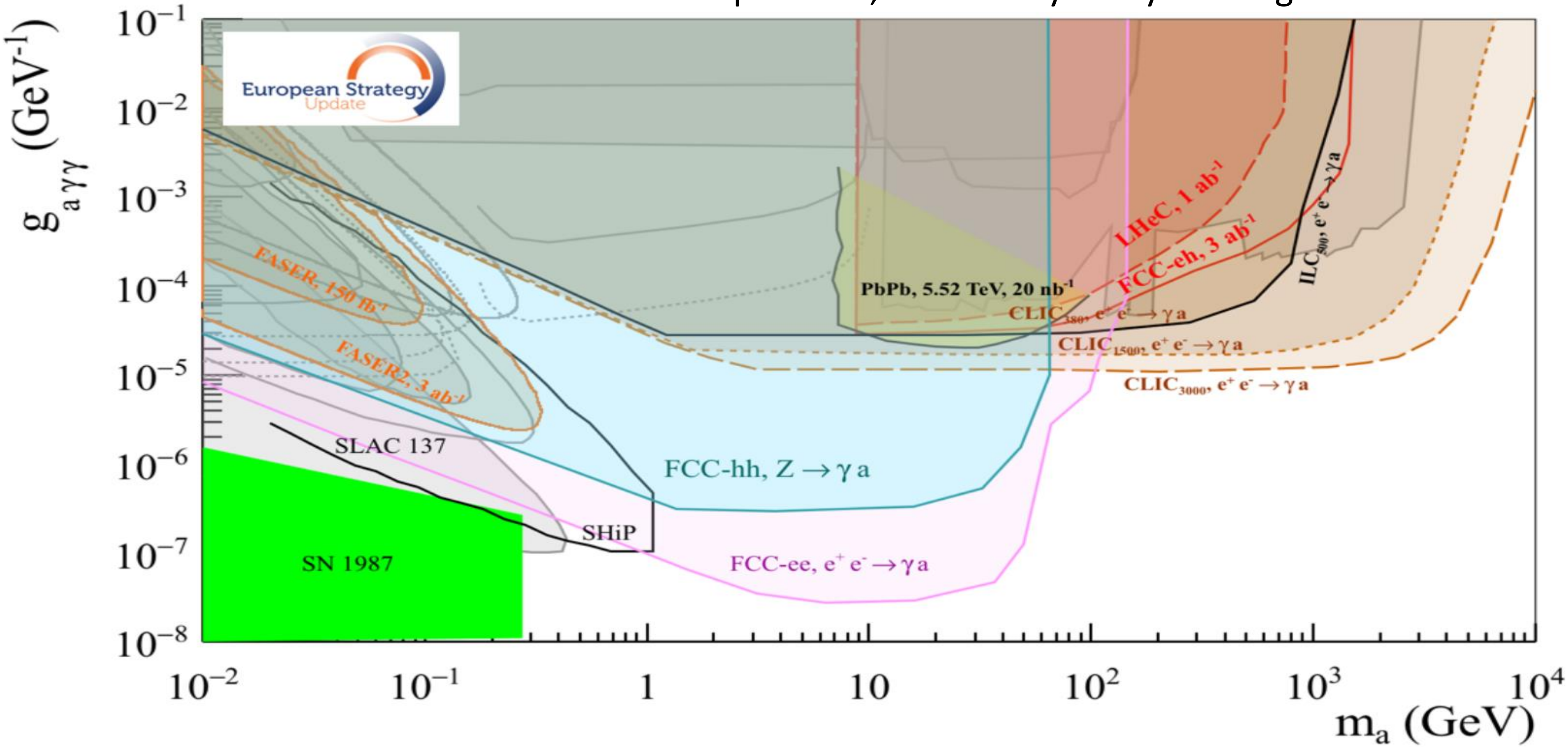
How close can we get to the ‘see-saw limit’?



-- the purple line shows the reach for observing **heavy neutrino decays** (here for 10^{12} Z),

-- the horizontal line represents the sensitivity to **mixing of neutrinos** to the dark sector, using EWPOs (G_F vs $\sin^2\theta_W^{eff}$ and m_Z, m_W, tau decays) which extends sensitivity to 10^{-5} mixing all the way to very high energies (60 TeV at least).

Similar situation for Axion-like-particles; Luminosity is key to the game



Complementarity with High energy lepton collider,

Much more left to explore at FCC-ee-Z and FCC-hh!