Informal Forum of FCC-ee (PE&D) national contacts
Introduction

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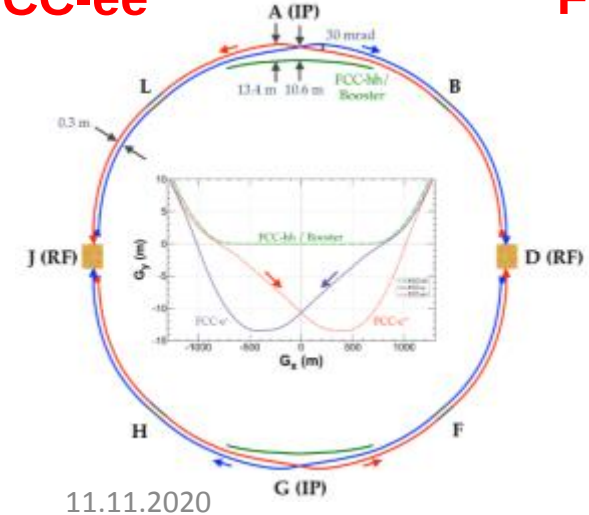
More information, physics, etc..
in the workshop and in spares

The FCC integrated program at CERN inspired by successful LEP – LHC (1976-203X) program

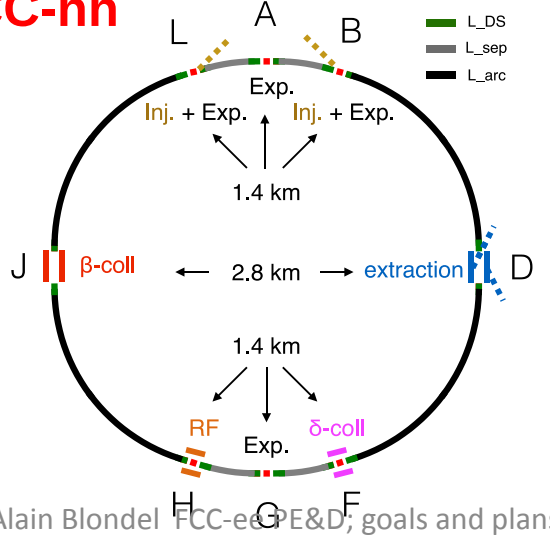
Comprehensive cost-effective program maximizing physics opportunities

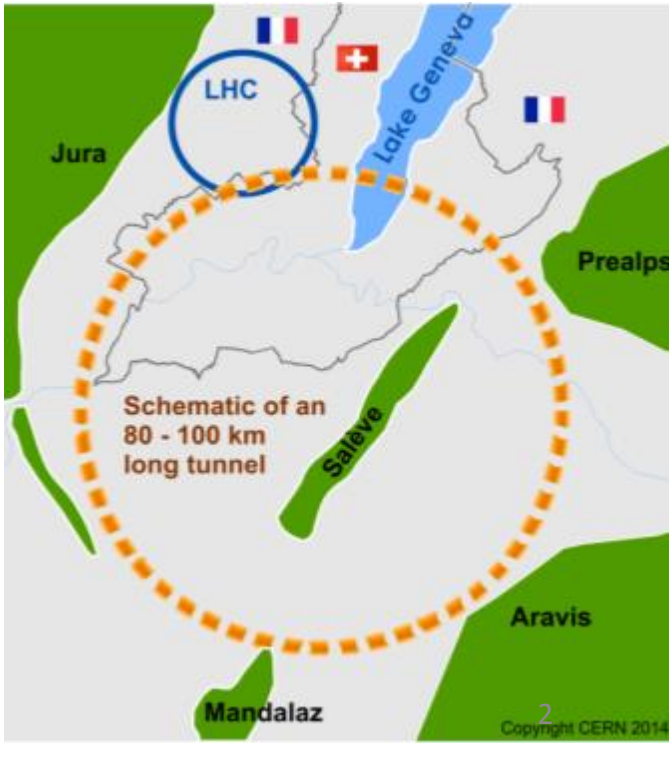
- **Stage 1: FCC-ee (Z, W, H, tt) as first generation Higgs EW and top factory at highest luminosities.**
- **Stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, with ion and eh options.**
- **Complementary physics**
- Integrating an ambitious high-field magnet R&D program
- Common civil engineering and technical infrastructures
- Building on and reusing CERN's existing infrastructure.
- **FCC-INT project plan is fully integrated with HL-LHC exploitation and provides for seamless continuation of HEP**

FCC-ee



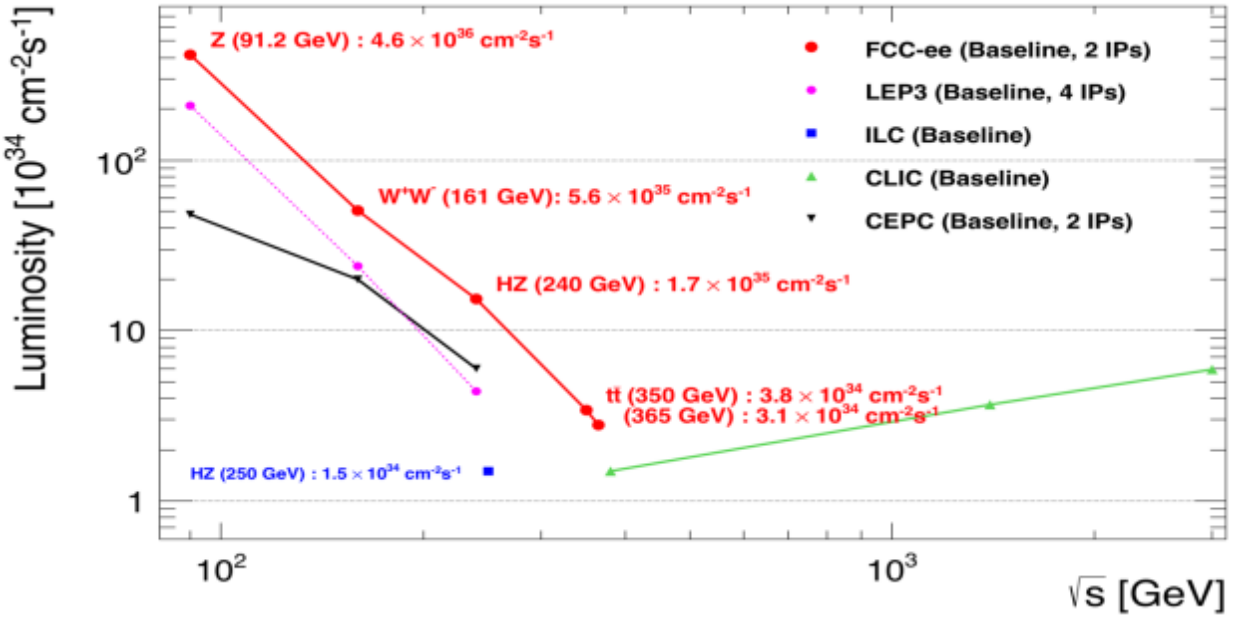
FCC-hh





FCC-ee

Z WW HZ tt

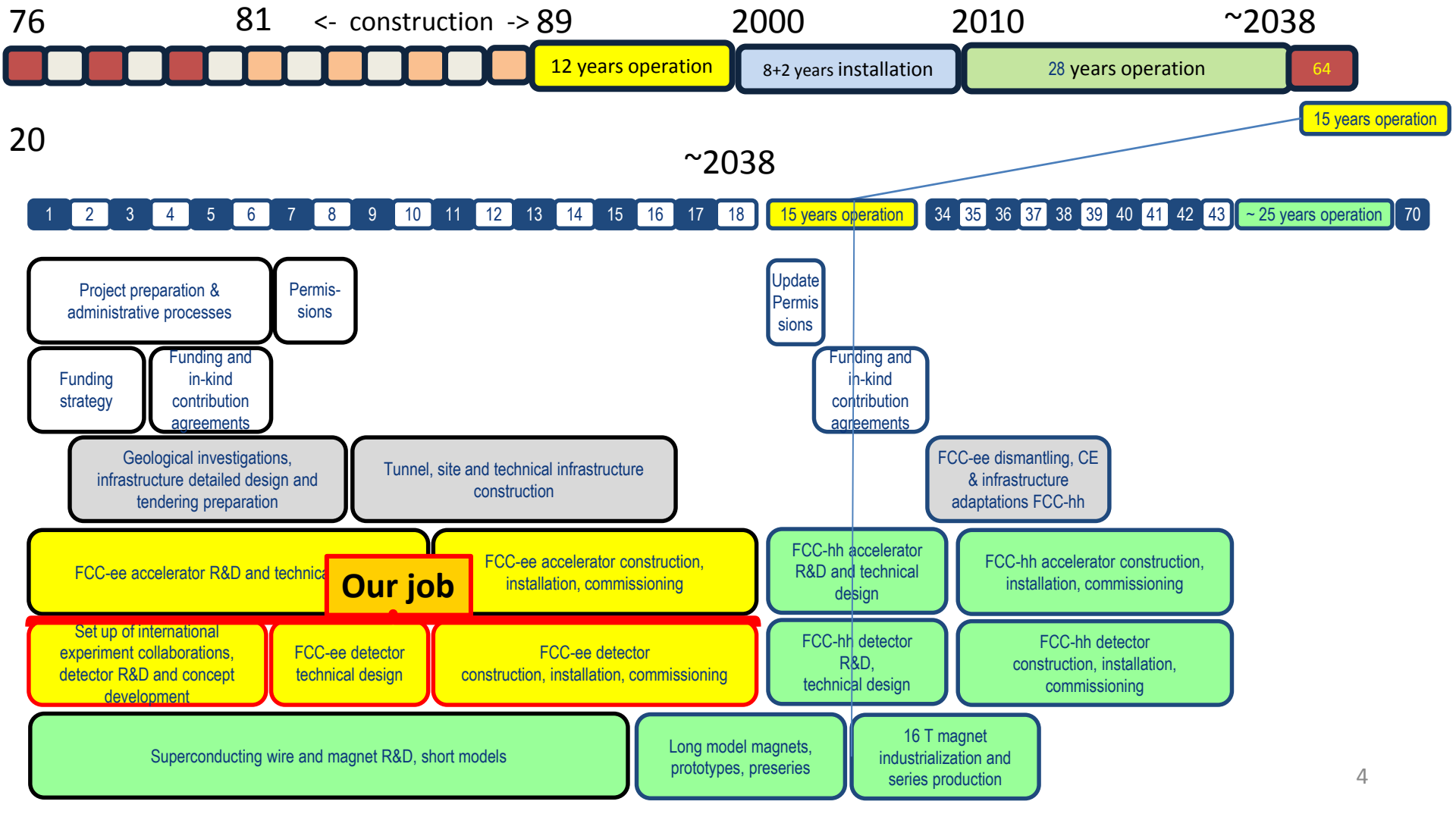


Event statistics :

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

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

TIMELINE (Compare with LEP/LHC)



CDR + Documentation

- **FCC-Conceptual Design Reports:**
  - **Vol 1 – Physics**
    Vol 2 – FCC-ee,
    Vol 3 – FCC-hh,
    Vol 4 – HE-LHC
    1338 authors

A public presentation of the CDR was given on 4-5 March at CERN https://indico.cern.ch/event/789349/
+ 3d FCC Phys. Workshop Jan'20 https://indico.cern.ch/event/838435/
4th FCC Phys workshop Nov'21 https://indico.cern.ch/event/932973/
→ many further details can/will be found there!

- Preprints since 15 January 2019 on http://fcc-cdr.web.cern.ch/ and INSPIRE
- **CDRs published in European Physical Journal C (Vol 1) and ST (Vol 2 – 4)**
- **ESPP summaries: FCC-integral, FCC-ee, FCC-hh, HE-LHC** http://fcc-cdr.web.cern.ch/
- FCC-ee «Your questions answered» https://arxiv.org/abs/1906.02693v1
- "Circular vs linear, another story of complementarity" arXiv:1912.11871v2
- LOIs to Snowmass, **challenges**: https://indico.cern.ch/event/951830/

The European Strategy

Preamble

The particle physics community is ready to take the next step towards even higher energies and smaller scales. The vision is to prepare a Higgs factory, followed by a future hadron collider with sensitivity to energy scales an order of magnitude higher than those of the LHC, while addressing the associated technical and environmental challenges.

High-priority future initiatives

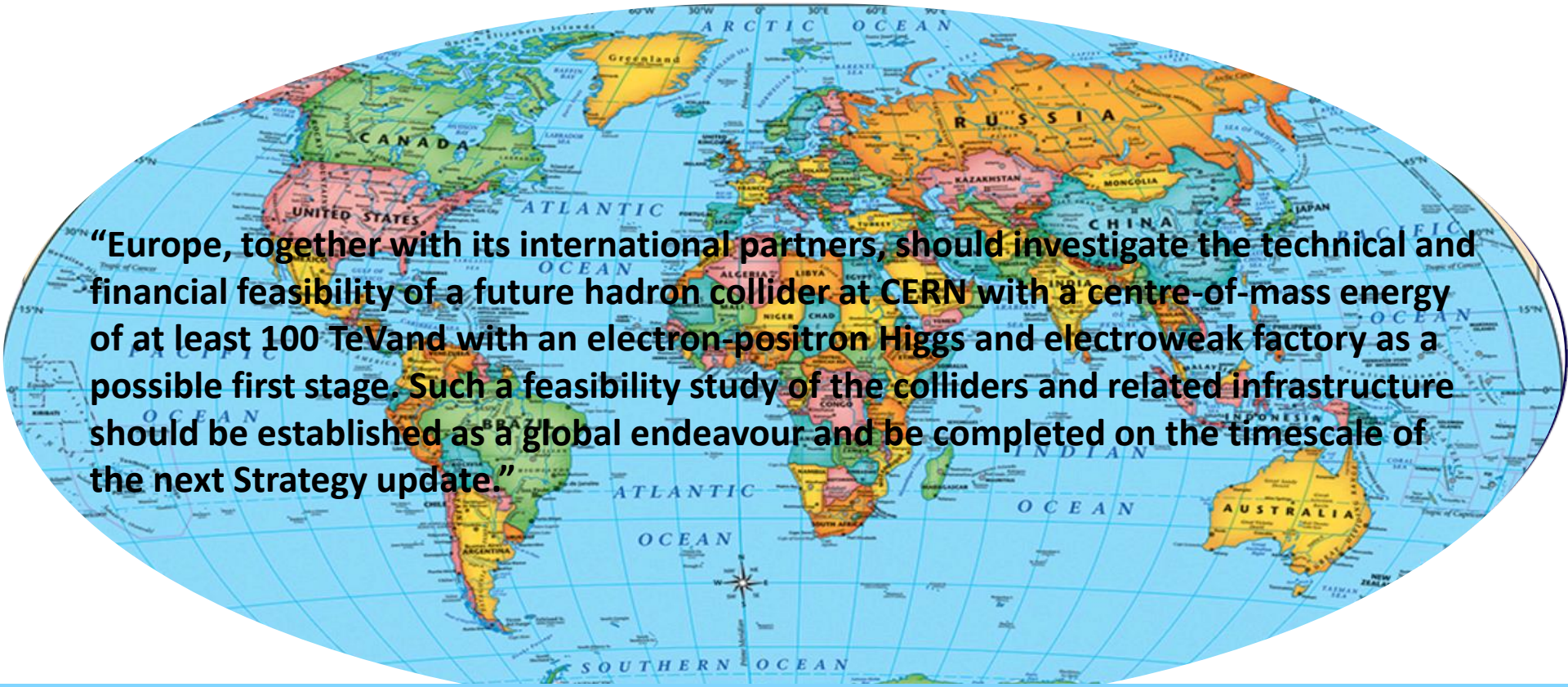
An electron-positron Higgs factory is the highest-priority next collider. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy. Accomplishing these compelling goals will require innovation and cutting-edge technology:

the particle physics community should ramp up its R&D effort focused
· on advanced accelerator technologies, in particular that for high-field superconducting magnets, including high-temperature superconductors;

· 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.

The timely realisation of the electron-positron International Linear Collider (ILC) in Japan would be compatible with this strategy and, in that case, the European particle physics community would wish to collaborate.

Our marching orders:



"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 TeVand 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.

--

-- **FCC is the highest priority for Europe and its international partners → reach out!**

Many opportunities…

-- Starts at the end of HL-LHC
-- Huge luminosities
-- Excellent running conditions
-- low SR, Gaussian beams, ∅20mm beam pipe, 100mrad low angle MDI limit
-- A beam of Higgs bosons!
-- Centre-of-mass energy calibration at Z and W runs
-- A Z factory! 5 TeraZ (3.5 10^{12} $q\bar{q}$ 20% $b\bar{b}$; 1.7 10^{11} each of e^+e^-, $\mu\mu$, $\tau\tau$; 10^{12} $\nu\bar{\nu}$)
Line-shape/EW/QCD/Fragmentation/Heavy Flavours/LLPs/LFV/LNV….

-- full coverage of EWPO input parameters
-- Several IPs → more than one detector/answer to challenges
-- two of the detector caverns are fit for FCC-hh detectors and could host large e+e- detectors

-- and the first step towards FCC-hh!

…and many challenges

FCC PE&D
Bottom-up actions to widen the community support

"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 FCC 'lepton collider' submission to ESPP)

1. **Building a network of national contacts in Europe and international partners**
2. **CERN will put in place dedicated effort in experimental and theoretical physics**
3. **Restart physics studies from Physics Performance effort**

… more to come!

FCC PE&D National Contacts

Very important for us at a time when we want to reach out to international partners, to circulate Information, encourage and nominate people to participate in the study.

Thanks to Gregorio Bernardi and Tadeusz Lesziak for calling this meeting and assembling Information

As collaboration builds up, participation is formalized by Memorandum of Understanding (MOU) prepared and signed either by National Institute (INFN, IN2P3, STFC, etc..)
or single institution (University or Laboratory)
A manpower participation to Physics studies and a deliverable work plan are completely eligible to a valid MOU for a University group.

Getting started

1. **See Tuesday morning introductory sessions at this workshop:**
   4th FCC Phys workshop Nov'21 https://indico.cern.ch/event/932973/

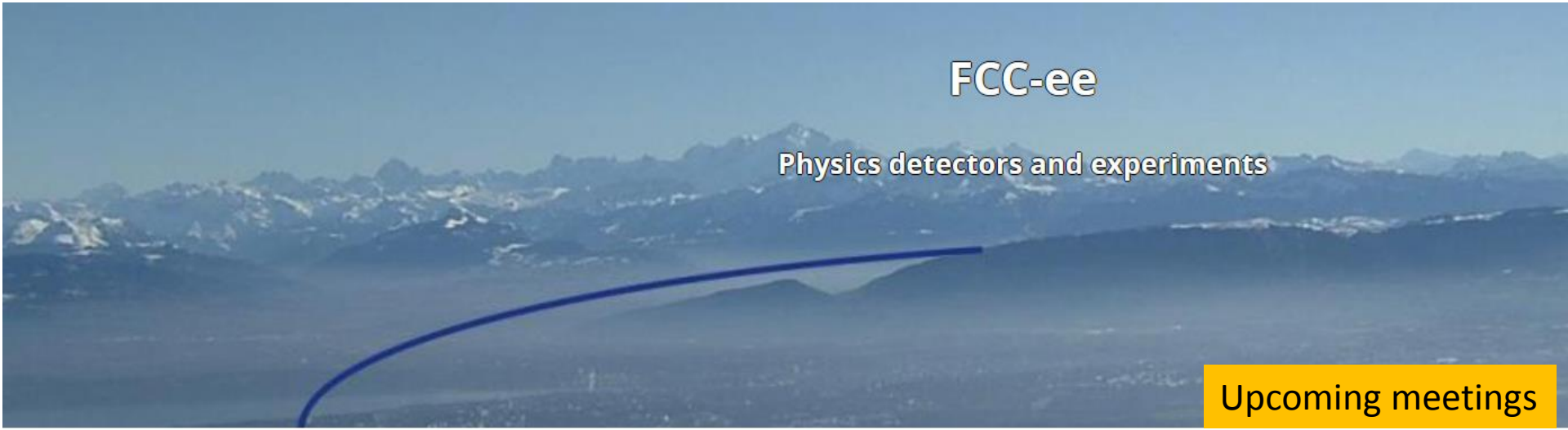
2. Register

Whether you just want to remain up-to-date on the FCC physics and experiments activities, or if you plan to participate in the study, please register to the mailing lists at the following urls:
https://simba3.web.cern.ch/simba3/SelfSubscription.aspx?groupName=fcc-experiments-lepton
and
https://simba3.web.cern.ch/simba3/SelfSubscription.aspx?groupName=fcc-experiments-hadron

If you wish to provide more information on your desired participation in the FCC-ee design study, and thus be registered to the corresponding mailing lists, you can also fill the form https://fcc-ee.web.cern.ch/contribute-to-the-design-study **(BEST!)**

Web site

https://fcc-ee.web.cern.ch/



Upcoming meetings

Indico threads
of important meetings
Monthly:
-- physics performance
-- general physics meeting

Stay aware

- **The general FCC physics, experiments, detectors and WG** all past and upcoming FCCee Physics groups meetings
- **FCC-ee physics performance** past and upcoming Physics Performance meetings
- **FCC-ee monthly physics meetings** past and upcoming FCCee physics meetings
- **FCC conferences and workshops** past and upcoming Conferences & Workshops

The FCC-ee in a few words

The idea of a large circular e+e- collider as Higgs Factory came from a conjunction of circumstances: i) the need of a large tunnel for the continuation of the high energy exploration after the LHC; ii) the new 'nano-beam' designs proposed for the 'super' B factories; iii) and of course the discovery of the Higgs boson with a mass that could have been reached (with efforts) at LEPII. The idea of such a machine as a first step toward a 100TeV pp collider was submitted to the ESPP2013/13 and led to the FCC study, launched in 2014. The study concluded in its FCC-int submission to the ESPP2020 that the *"The most effective and comprehensive approach to thoroughly explore the open questions in modern particle physics is a staged research programme, integrating in sequence lepton (FCC-ee) and hadron (FCC-hh) collisions"*.

The ESPP concluded: ***"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."***

The FCC-ee is a high-luminosity, high-precision e-e- circular collider. Two separate e+ and e- storage rings with very strong focusing, fed by a full size continuous injector, provide e+e- collision luminosities ranging from (per interaction point) 230 10^{34} /cm2 /s at the Z pole, 8 10^{34} /cm^2 /s at the ZH production

Next events

FCC-ee Related Events
Informal Forum of FCC-ee national contacts
Wed, 11/11/2020 - 17:25

Conferences and Workshops
4th FCC Physics and Experiments Workshop
Tue, 11/10/2020 - 09:00

FCC-ee Physics, Experiments, and Detectors General Meetings
FCC-ee physics zoom meeting -
Mon, 11/30/2020 - 15:00

IMPORTANT MILESTONES AND EVENTS

-- reach out to all 'European and International Partners' **NOW**
-- complete organization of physics conveners within the next two months
  -- nominations and volunteers welcome (contact AB and PJ)
  -- we have other open roles (see next slides)

-- completion of first case study(es) in spring 2021 → detector requirements
-- decide on FCC Layout (compatible with 4 IRs or not) by summer 2021

Yearly meetings

-- FCC week in Mai-June 2021 (hopefully in person!) then annual event.
-- FCC-IS Physics Workshop in Winter 2022 in Liverpool
-- FCC-IS Physics Workshop in Winter 2023 in Poland
-- FCC-IS Physics Workshop in Winter 2024 in France

-- delivery of Physics and Experiments CDR ++ → END 2024

-- to serve as support for experimental proto-collaborations → EOI/LOIs for next ESPP

Physics Performance effort & conveners

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

Patrizia Azzi Patrizia.Azzi@cern.ch Emmanuel Perez Emmanuel.Perez@cern.ch
have agreed to serve as coordinators

operation (see next slide)

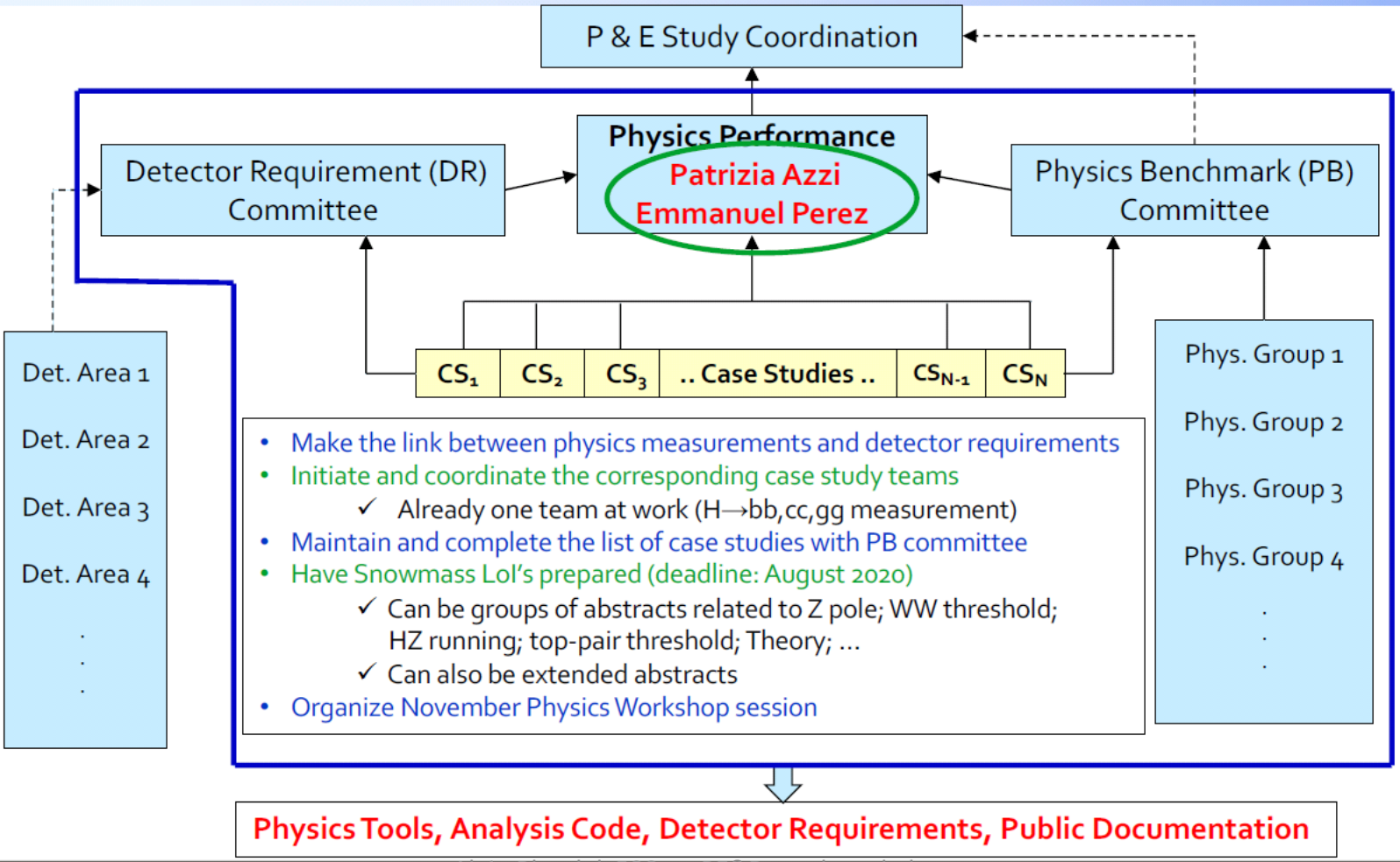
1. Physics working groups (conveners) → establish list of BENCHMARK MEASUREMENTS
- **-- each can correspond to several case studies**
- **-- group case studies from different measurements for efficiency/consistency**

2. Case study teams establish DETECTOR REQUIREMENTS for optimizing measurement, and in particular matching exp. systematics with the expected statistical precision.
- **-- one team well advanced since July: c vs b/g jets in Higgs (and Z) decays**
- **-- several others started, monthly meetings**

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

4. Working towards a first complete case study analysed by spring 2021

Hot News: Physics Performance coordinators



Physics groups: Nominations wanted !

- 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)

Black = exp.
White = 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, S. Heinemeyer	Global Analysis Synergies J. De Blas	Precision Calculations J. Gluza, A. Freitas

- By 15 September, we would like to receive
  - Your proposals of new physics groups (tau, LLP, ...)
  - Your nominations (including self) 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

Thanks for your proposals, more are welcome, esp. for theorists!
We will also request proposals from national contacts.

Important tasks of Physics Groups conveners

Mandate in preparation

For each Physics Group, one or two experimentalists, and one or two phenomenologists

1. Gather community

-- with help from FCC national contacts

-- using their own relations

-- as needed organize well advertised kick-off mini-workshops or meetings

-- collect a first set of Benchmark measurements

existing list can be found here https://www.overleaf.com/read/dyjpdszrqxhz

list of submissions to Snowmass https://indico.cern.ch/event/951830/

2. With high priority should focus on participating to the Physics Performance effort

via the Physics Benchmark Committee

-- Benchmark measurements → case studies leading to detector requirements

➔ **common Physics Tools, Analysis Code, Detector Requirements, Public Documentation**

NB independently of physics groups, volunteers are welcome in PP effort!

2'. Scope thoroughly the physics capabilities,

develop new measurements, event generators, understand th. uncertainties etc.

investigate New Physics sensitivities **towards physics CDR**

The Physics Performance coordinators are good contact points for those desiring to start FCC-PE&D work by one of the case studies, at the interface between physics benchmarks and the detector requirements, and using/creating the physics software tools.

<u>This should be advertised to the various countries.</u>

Other important roles

We are seeking volunteers for

-- **FCC PE&D conference committee**
a few more members from exp. and th.
-- **General Physics Meetings Organizer**
one Exp. Physicist to replace P. Azzi

Nominate or Volunteer

FCC PE&D Conference committee

New member(s) are sought for FCC PE&D conference committee
Existing members: P. Azzi (to be replaced), A.Blondel, P. Giacomelli, C. Grojean, M. Klute (chair)
(did I forget somebody?) An online interface exists (Markus)

Dissemination is an important task for the collaboration!

-- beneficial to communicate on the project (physics capacities, plans, performance etc…) to wider audiences
-- beneficial to entrust FCC presentations to active members as well as new/young interested members
    -- even if it goes somewhat beyond their own area of expertise
-- write-ups are also very useful

Tasks

-- collect and disseminate information, deadlines for abstracts etc… on upcoming conferences
-- collect suggestions for topics and seek suggestions/nominations for speakers
-- sometimes discuss directly with conference organizers/conveners etc.
-- ensure abstracts are reasonably consistent and coherent and that important topics are not absent.

Meetings: so far as needed but will seek a regular monthly meeting.

Seeking: at least one more member to replace Patrizia
Mandate: two years

Organizer of FCC PE&D monthly general meetings

Context: These meetings have been taking place since TLEP times.
Patrizia Azzi and Matthew McCullough are jointly organizing them at present.
Patrizia having accepted the task of Physics Performance Coordinator, she has asked to be relieved
-- thanks Patrizia for excellent and lively organization!

The object of the general meeting is as follows
-- inform the design study members – and whoever has registered on the mailing list – of the progress of the study
-- discuss new results of the study
-- as appropriate proceed to make them official results.

Content *typically* comprises:
-- General news, news pertaining to common working environment
-- Important new results from any of the working groups
++ Experiment
-- accelerator performance
-- MDI
-- physics performance results , i.e. detector requirements from case studies
-- detector simulation or test beam results
-- new detector ideas
++ Theory:
-- new results from theoretical calculations
-- new ideas for measurements that can be done at FCC-ee
-- before big conference cycles, special general meetings can be organized for review of the presentations

We want to help you make sure that your country and your compatriots will be able to participate and contribute to this scientific adventure.

We would like to know from you what you will wish/need

SPARES

CHALLENGE 1 : why do we need a new accelerator after the LHC?

➔ See round table discussion yesterday

The Physics Landscape

We found the Higgs … the SM is 'complete' – but unexplained facts remain!

We are in a fascinating situation: where to look and what will we find?

For the first time since Fermi theory, <u>WE HAVE NO SCALE</u> (that is known)

The next facility must be versatile with as broad and powerful reach as possible, as there is no precise target

➔ <u>more Sensitivity, more Precision, more Energy</u>

FCC(ee & hh) , thanks to synergies and complementarities, offers the most versatile and adapted response to today's physics landscape

FCC-ee Collider Parameters

parameter	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45	80	120	182.5
beam current [mA]	1390	147	29	5.4
no. bunches/beam	16640	2000	393	48
bunch intensity [10^{11}]	1.7	1.5	1.5	2.3
SR energy loss / turn [GeV]	0.036	0.34	1.72	9.21
total RF voltage [GV]	0.1	0.44	2.0	10.9
long. damping time [turns]	1281	235	70	20
horizontal beta* [m]	0.15	0.2	0.3	1
vertical beta* [mm]	0.8	1	1	1.6
horiz. geometric emittance [nm]	0.27	0.28	0.63	1.46
vert. geom. emittance [pm]	1.0	1.7	1.3	2.9
bunch length with SR / BS [mm]	3.5 / 12.1	3.0 / 6.0	3.3 / 5.3	2.0 / 2.5
luminosity per IP [10^{34} $cm^{-2}s^{-1}$]	230	28	8.5	1.55
beam lifetime rad Bhabha / BS [min]	68 / >200	49 / >1000	38 / 18	40 / 18

FCC-ee discovery potential and Highlights

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

-- ~20-100 fold improved precision on many EW quantities (equiv. to factor 5-10 in mass)

m_Z, m_W, m_{top} , $\sin^2 \theta_w^{eff}$, R_b , α_{QED} (m_z) α_s $(m_z\, m_W\, m_\tau)$, Higgs and top quark couplings

model independent g_{HZZ}«fixed candle» for Higgs measurements, ee-H coupling.

DISCOVER a violation of flavour conservation or universality and unitarity of PMNS @10^{-5}

-- ex FCNC (Z --> $\mu\tau$, $e\tau$) in 5 10^{12} Z decays and τ lifetime & BR in 2 10^{11} Z→ $\tau\,\tau$

+ flavour physics (10^{12} bb events) (B→K $\tau\,\tau$ 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, ALPS, etc…

+ and many opportunities in – e.g. QCD (α_s @ 10^{-4}, fragementations, H→ gg) etc….

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

First stage 'Higgs Factory' ($E_{CM} \leq 365$ GeV)

- "All low-energy Higgs factories have similar performance, to 1st order"
  - ILC_{250} = $CLIC_{380}$ = $CEPC_{240}$ = FCC-$ee_{240\to365}$?
    - Not quite !

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

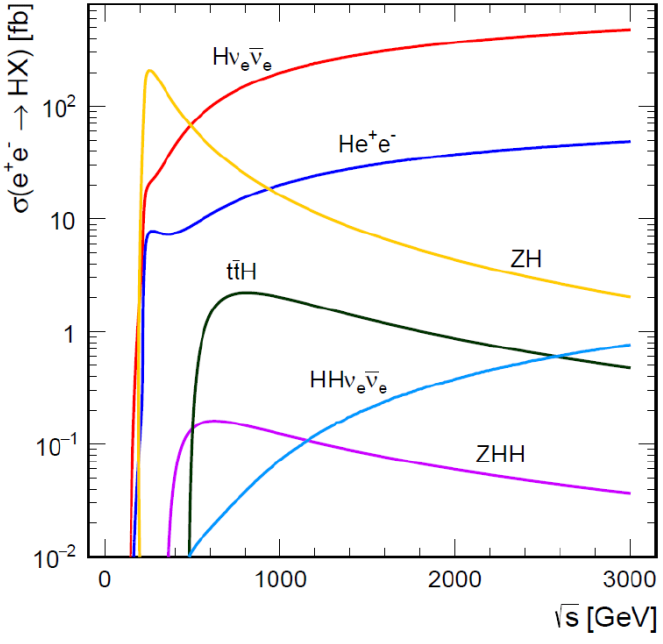
J. De Blas et al., arXiv:1905.03764

Collider	HL-LHC	ILC_{250}	$CLIC_{380}$	$CEPC_{240}$	FCC-$ee_{240\to365}$	
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

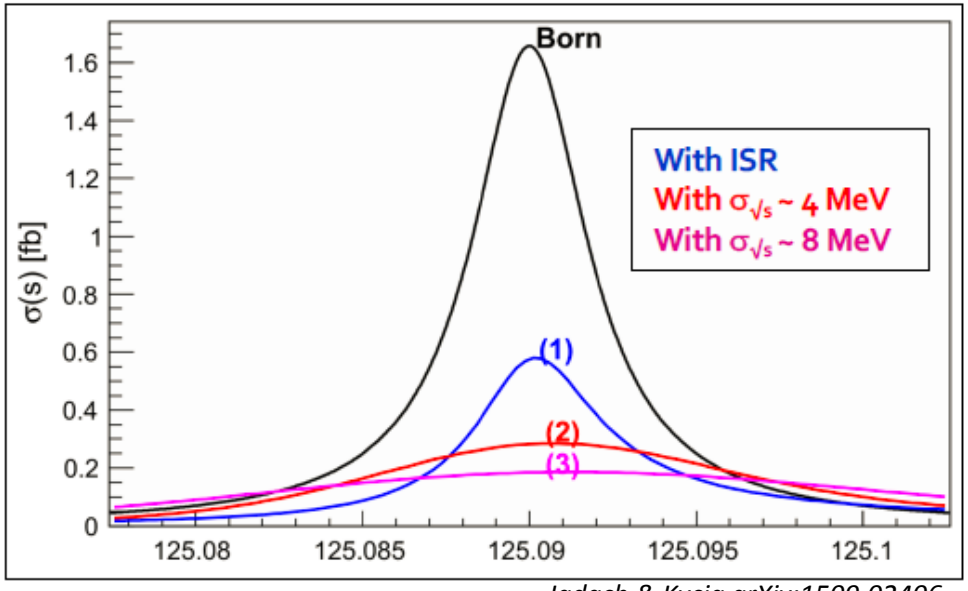
ee

hh

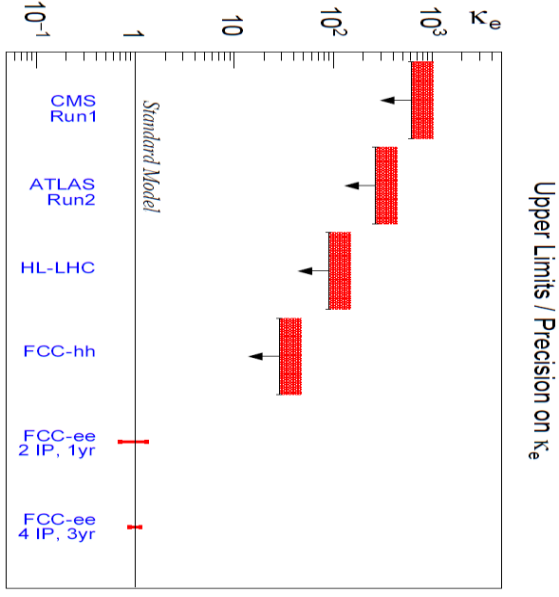
FCC-hh (> 10^{10} H produced)
+FCC-ee measurement of g_{HZZ}
→ g_{HHH} , $g_{H\gamma\gamma}$, $g_{HZ\gamma}$, $g_{H\mu\mu}$, BR_{inv}

(*)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}

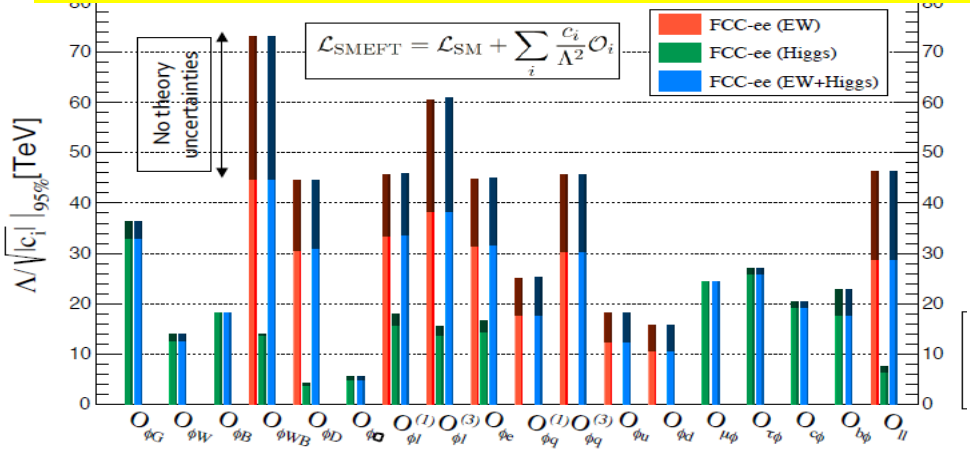
-- **continuous monitoring and adjustment of E_{CM}** to MeV precision (transv. Polar.)

-- 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 bb to hadrons stat. extrapol. from SLD
σ_{had}^0 ($\times 10^3$) (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 tt threshold scan QCD errors dominate
Γ_{top} (MeV/c^2)	1410 ± 190	45	small	From tt threshold scan QCD errors dominate
$\lambda_{top}/\lambda_{top}^{SM}$	1.2 ± 0.3	**0.10**	small	From tt threshold scan QCD errors dominate
ttZ couplings	± 30%	0.5 – 1.5%	small	From $\sqrt{s} = 365$ GeV run



-^- 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

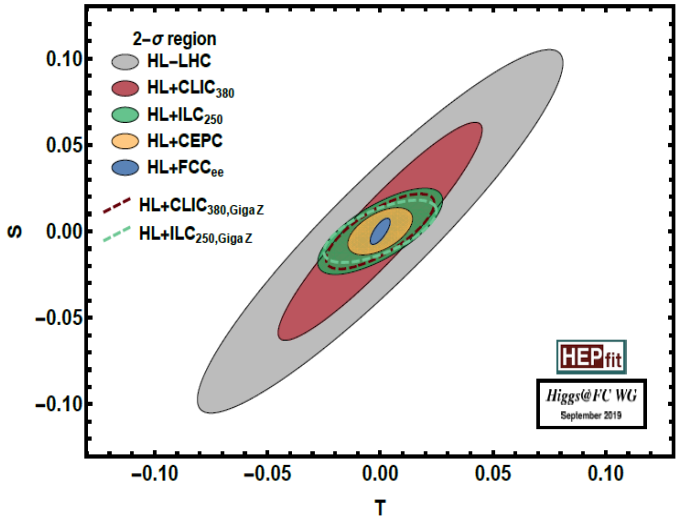
<-- complemented by high energy FCC-hh

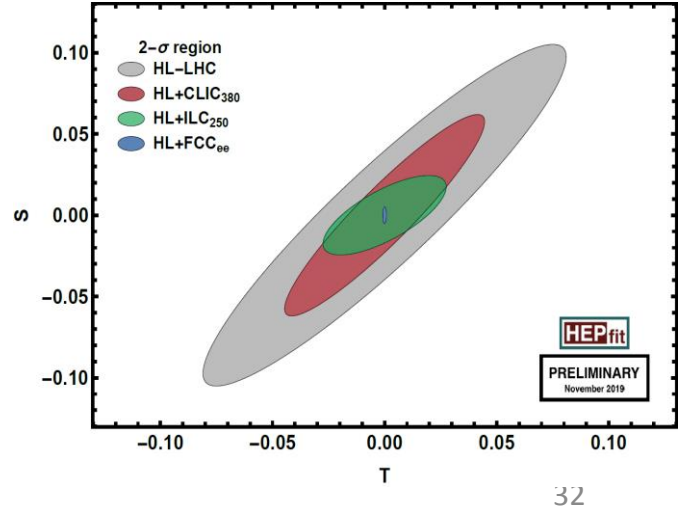
Theory work is critical and initiated *1809.01830*

At EW scale: 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





More on TeraZ

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 →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!

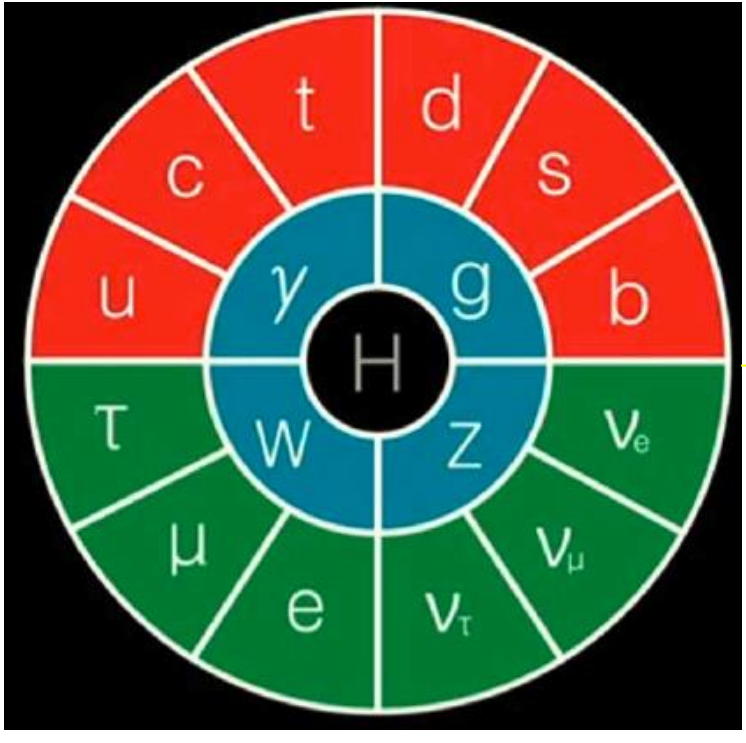
The 3.5 × 10^{12} hadronic Z decay also provide precious input for QCD studies

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

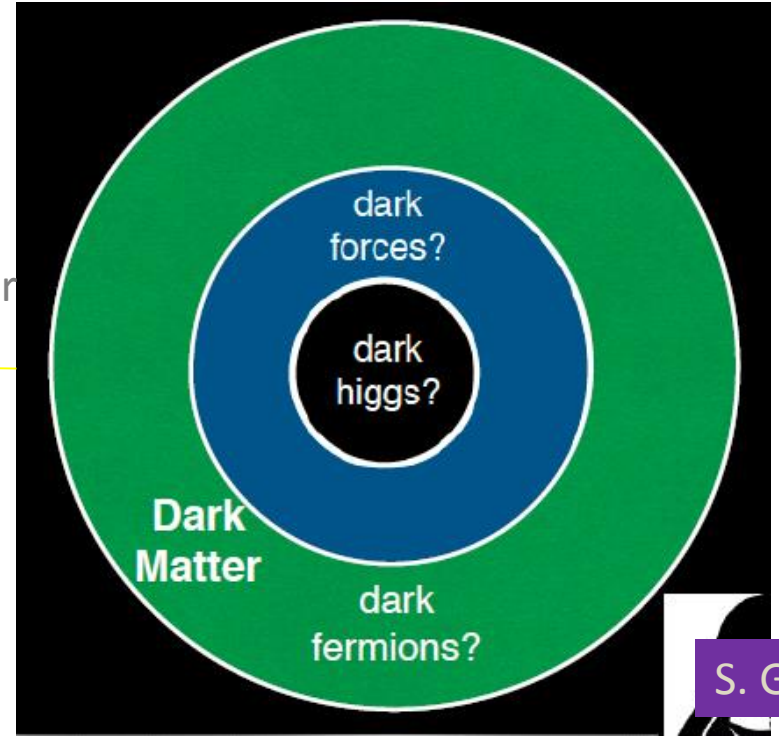
Testing running of α_s to excellent precision

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.



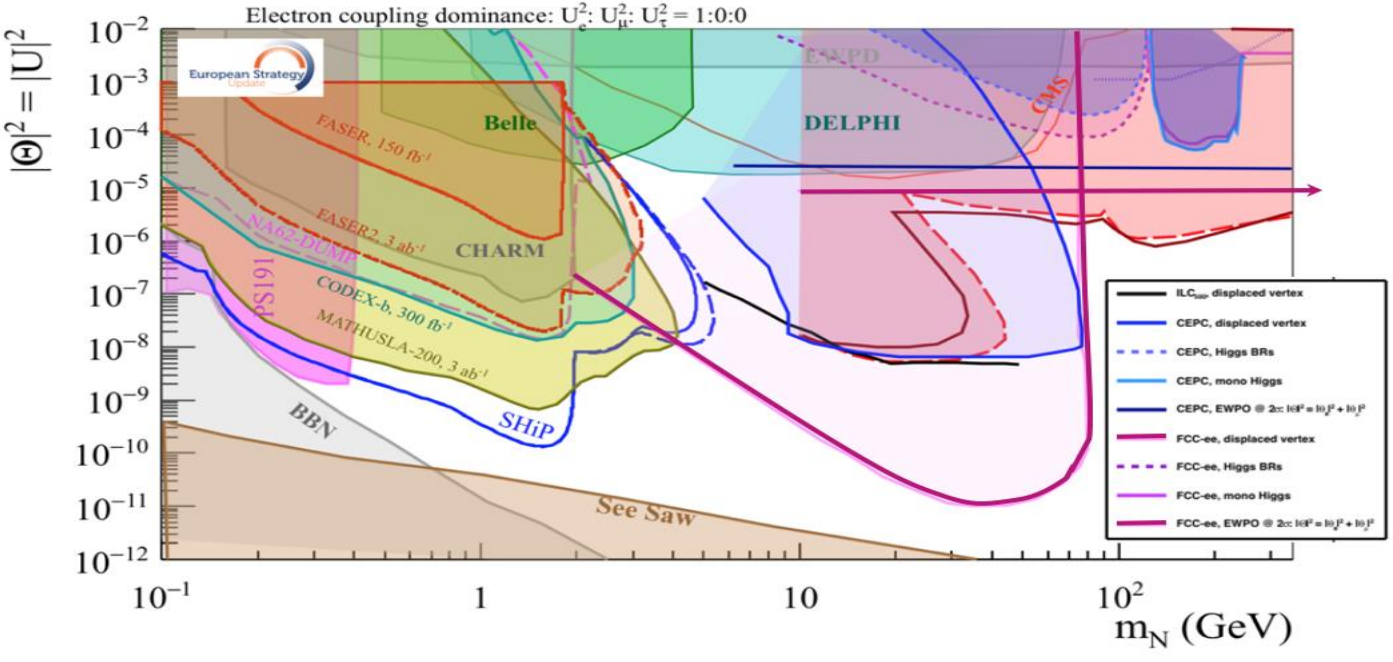
mediator or mixing



S. Gori

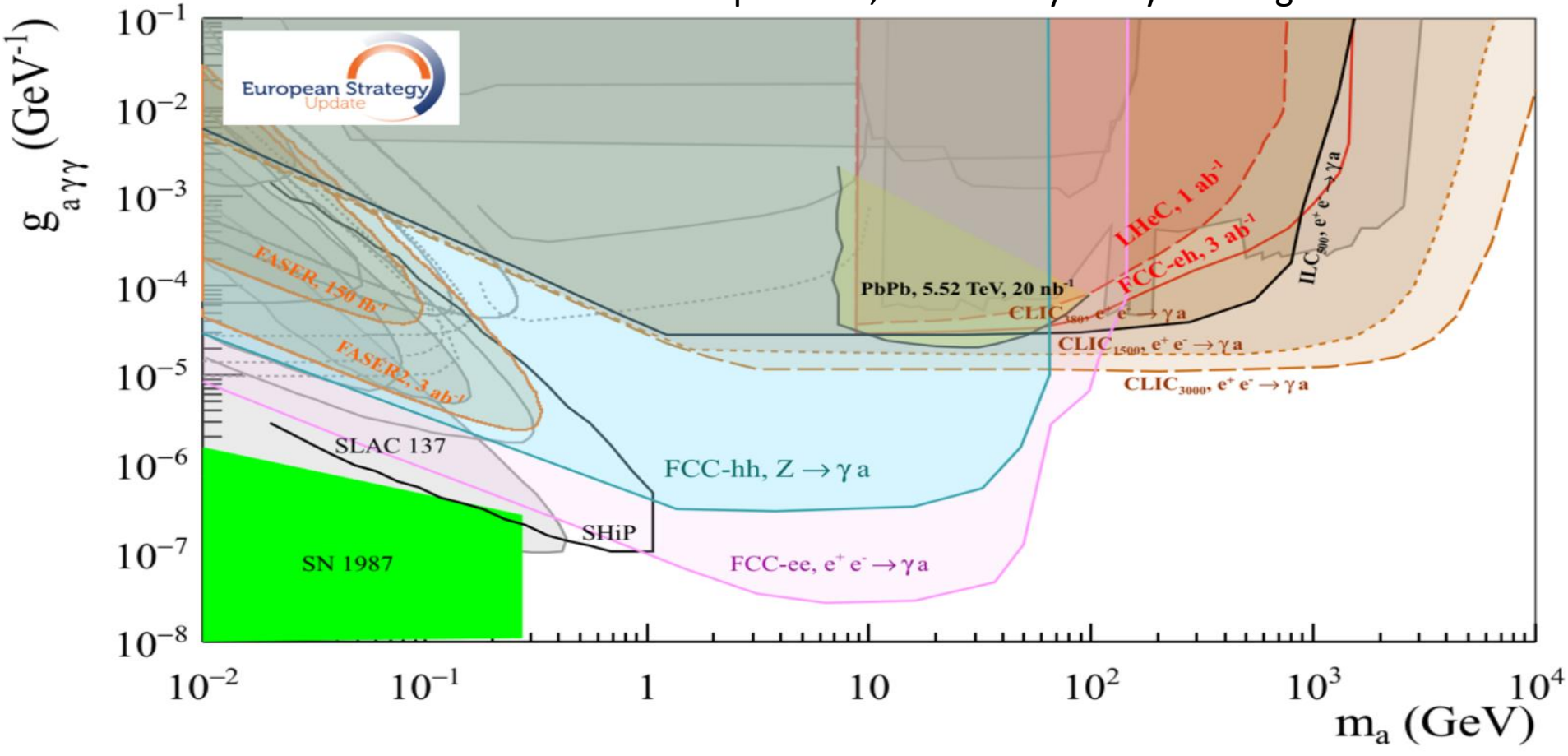
Dark photons, axion like particles, sterile neutrinos, all *feebly coupled* to SM particles

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!