Welcome to the 4th FCC Physics Meeting

FCC
hh ee he

It being the FCC-IS kick-off we will concentrate mainly on FCC-ee

FCC-ee PE&D Study; goals and plans

Alain BLONDEL, Patrick JANOT

Theory programme committee

- Ayres Freitas
- Janusz Gluza
- Christophe Grojean
- Sven Heinemeyer
- Michelangelo Mangano (co-chair)
- Matthew Mc Cullough
- Lian Tao Wang

Experiments and Detectors programme committee

- Alain Blondel (co-chair)
- Mogens Dam
- Patrick Janot
- Max Klein

International Programme Advisory committee for Experiments and Detectors

- Roy Aleksan
- Franco Bedeschi
- Stan Bentvelsen
- Greg Bernardi
- Richard Brenner
- Joel Butler
- Maria Chamizo
- Dmitri Denisov
- Jorgen D'Hondt
- Paula Eerola
- Sarah Eno
- Jorge Fernandez de Troconiz
- Paolo Giacomelli
- Beate Heinemann
- Christian Joram
- Mario Kadastik
- Young-Kee Kim
- Christos Leonidopoulos
- Tadeusz Lesiak
- Anna Lipniacka
- David Milstead
- Farid Ould-Sada
- Jochen Schieck
- Felix Sefkow
- Frank Simon
- Rainer Wallny

Conveners

FCC detectors I: Calorimeters

- Martin Aleksa (CERN)
- Franco Bedeschi (Universita & INFN Pisa (IT))

FCC detectors I: PID

- Guy Wilkinson (University of Oxford (GB))
- Stephane Monteil (Université Clermont Auvergne (FR))

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- Martin Aleksa (CERN)

FCC detectors I: FCC-eh detector

- Max Klein (University of Liverpool (GB))

FCC detectors I: TDAQ & Electronics

- Richard Brenner (Uppsala University (SE))
- Christos Leonidopoulos (The University of Edinburgh (GB))

Vertex detector

Auguste Besson (Strasbourg)
Paula Collins (CERN)
Andreas Jung (Fermilab)

Tracker

Dominik Dannheim (CERN)
Bernhard Ketzer (Bonn)
Franco Grancagnolo (Lecce)

MDI

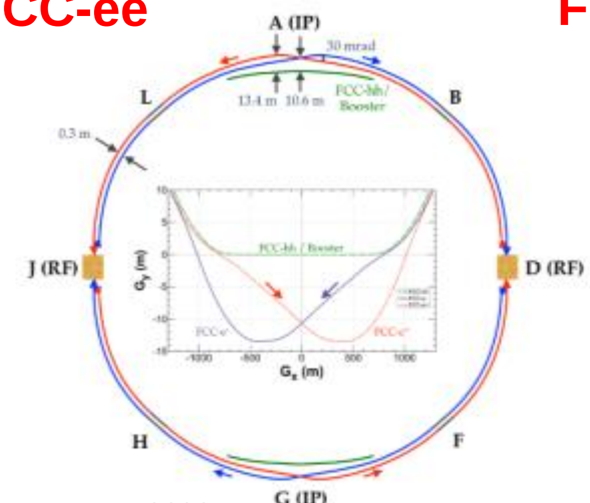
Nicola Bacchetta (CERN)
Manuela Boscolo (Frascati)
Angeles Faus-Golfe (Paris-Saclay)
Jorg Wenninger (CERN)

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

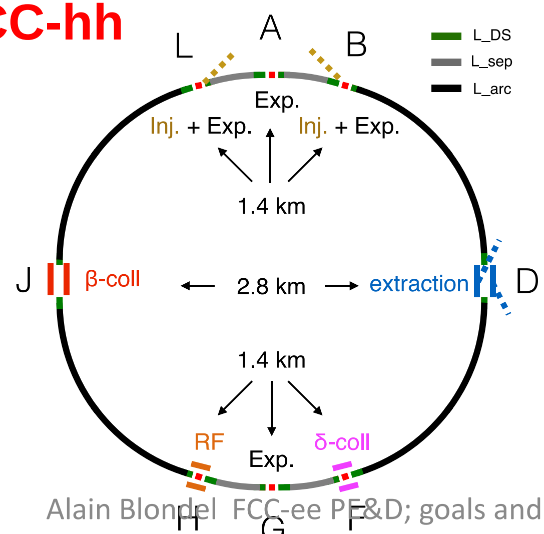
Comprehensive cost-effective program maximizing physics opportunities

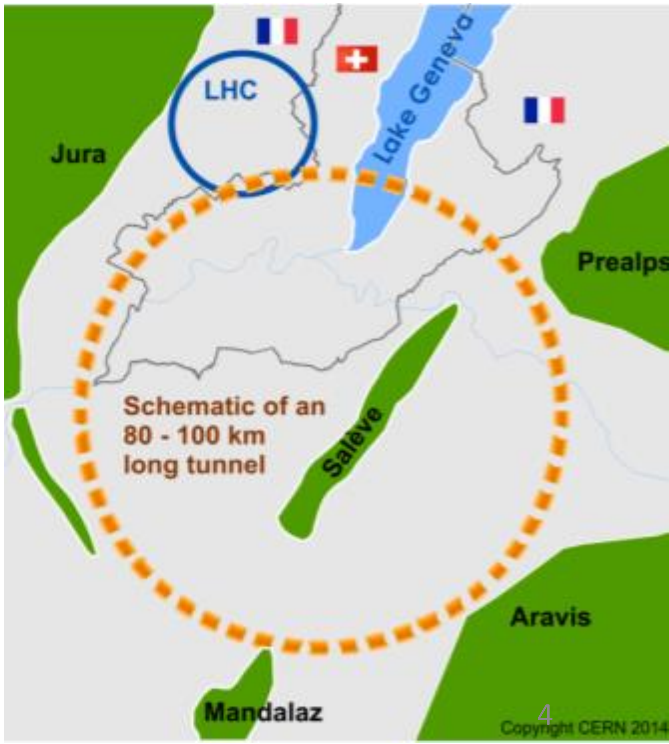
- **Stage 1: FCC-ee (Z, W, H, tt) as first generation Higgs EW and top factory at highest luminosities.**
- **Stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, with ion and eh options.**
- **Complementary physics**
- Integrating an ambitious high-field magnet R&D program
- Common 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





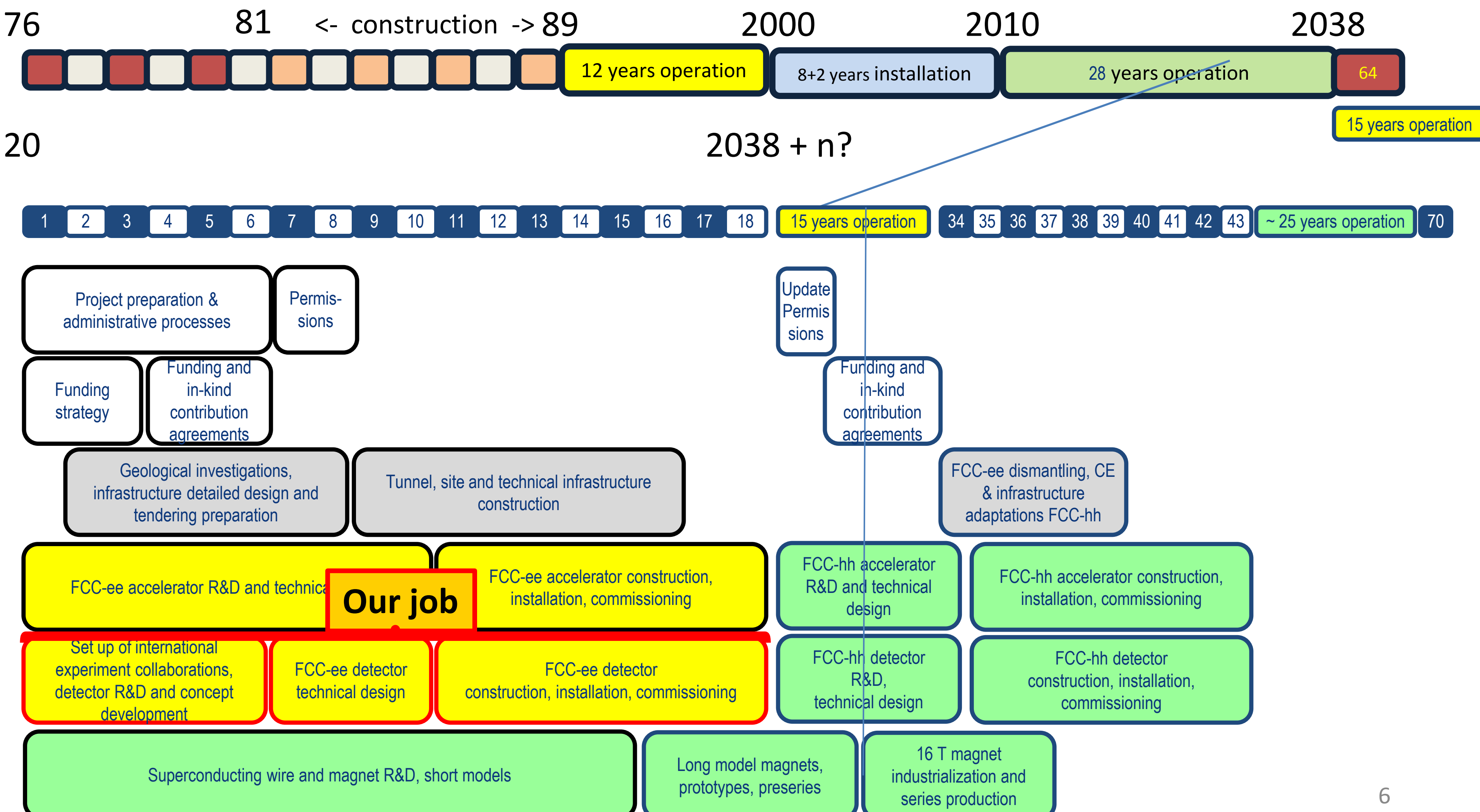
CDR + Documentation

- **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/

TIMELINE (Compare with LEP/LHC)



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

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>

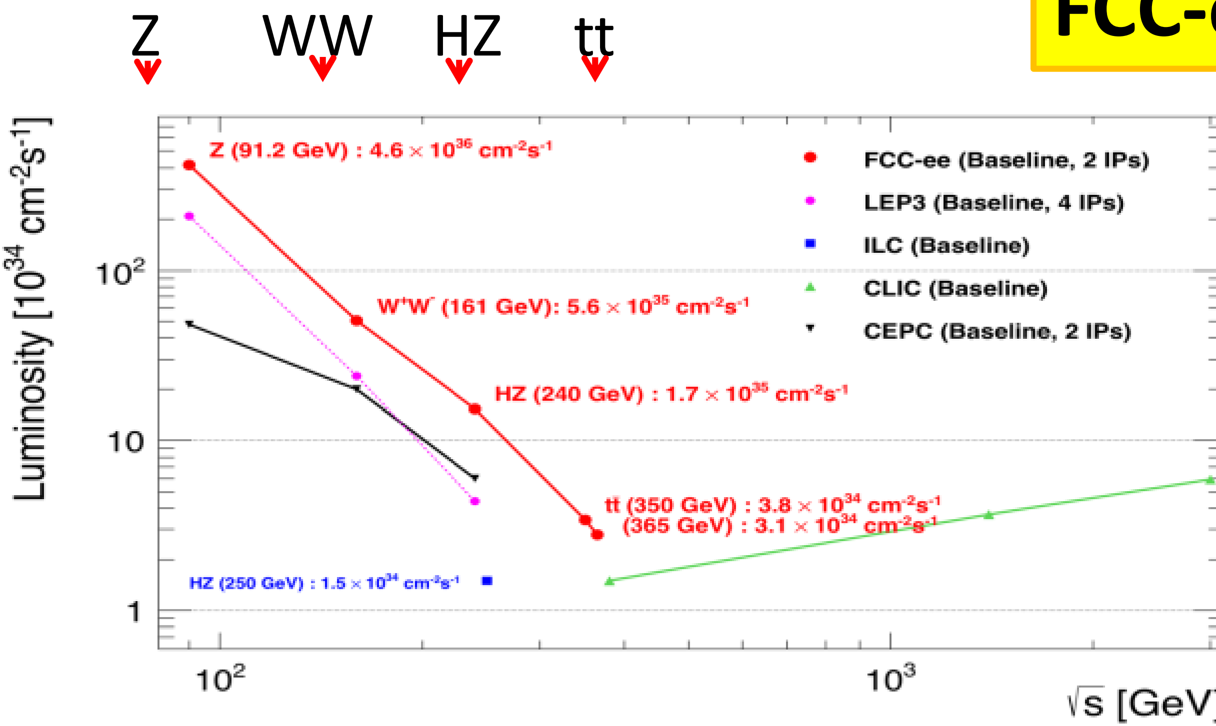
FCC , thanks to synergies and complementarities, offers the most versatile and adapted response to today's physics landscape

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} $q\bar{q}$ $\bar{2}$0% bb ; 1.7 10^{11} each of e^+e^-, $\mu\mu$, $\tau\tau$; 10^{12} $\bar{\nu}\nu$)
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-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	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.

FCC-ee run plan

Table 2.1: Run plan for FCC-ee in its baseline configuration with two experiments. The number of WW events is given for the entirety of the FCC-ee running at and above the WW threshold.

from the CDR

Phase	Run duration (years)	Center-of-mass Energies (GeV)	Integrated Luminosity (ab^{-1})	Event Statistics
FCC-ee-Z	4	88-95	150	3×10^{12} visible Z decays
FCC-ee-W	2	158-162	12	10^8 WW events
FCC-ee-H	3	240	5	10^6 ZH events
FCC-ee-tt	5	345-365	1.5	10^6 $t\bar{t}$ events

1. **Order of Z,W and H points (and duration) can (and probably will) be changed in due time**

Meanwhile we all work on the same run plan.

2. A layout with the possibility of 4 IPs is being considered

→ Would lead to total integrated luminosity x 1.7, energy consumption per event reduced accordingly

3. e+e- → H ($E_{CM} = m_H$) unique, not in the schedule so far, must be after both Z and H.

3. Transerse polarization → precision beam energy calibration at Z and W
Longitudinal possible (for both beams) but not in CDR by choice

Physics at FCC-ee

1. HIGGS FACTORY

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

2. ELECTROWEAK PRECISION (10^{-3} today → 10^{-5})

Z + WW + top required!

This is a test of the completeness of the SM

existence of weakly interacting new particles

3. Z FACTORY (5 10^{12} Z)

High statistics for Heavy Flavours and Search for Feebly Coupled Particles

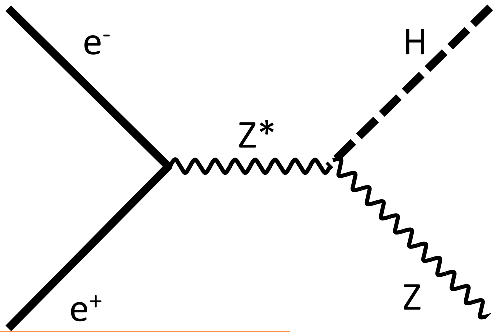
The place for 'direct discovery'

+ synergy and complementarity of FCC-ee hh and eh

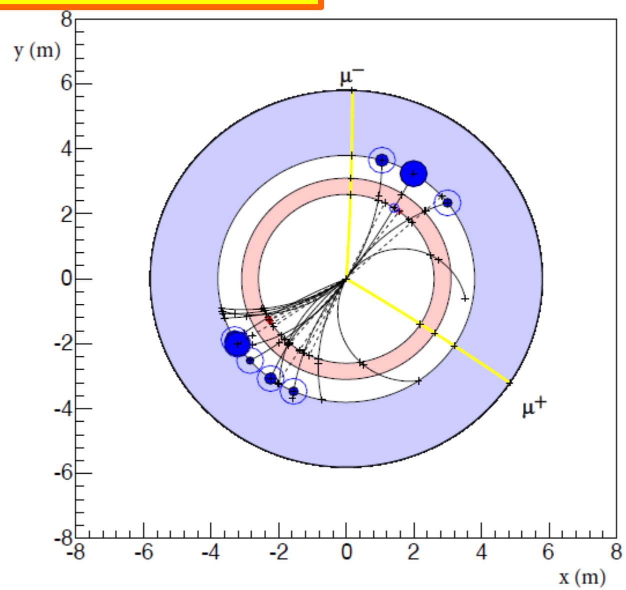
e+e- : Z – tagging by missing mass

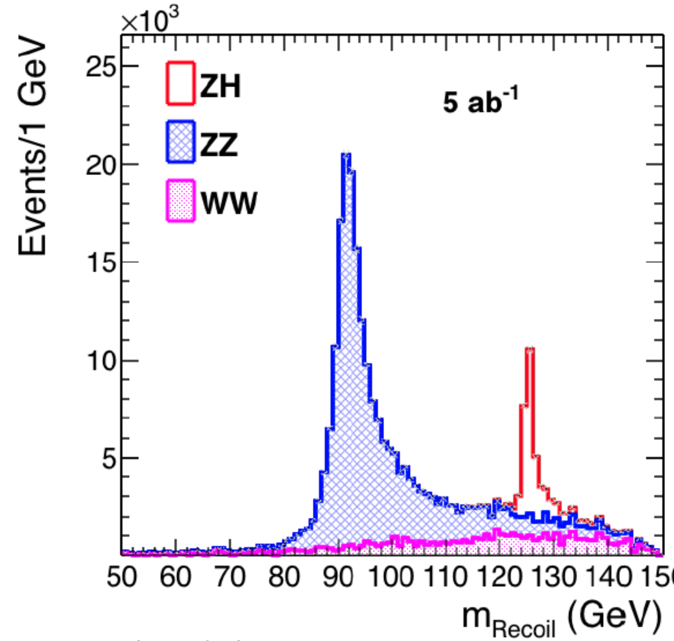
total rate $\propto g_{HZZ}^2$
ZZZ final state $\propto g_{HZZ}^4 / \Gamma_H$
➔ **measure total width** Γ_H

g_{HZZ} to ±0.2% and many other partial widths
empty recoil = invisible width
'funny recoil' = exotic Higgs decay
easy control below theshold



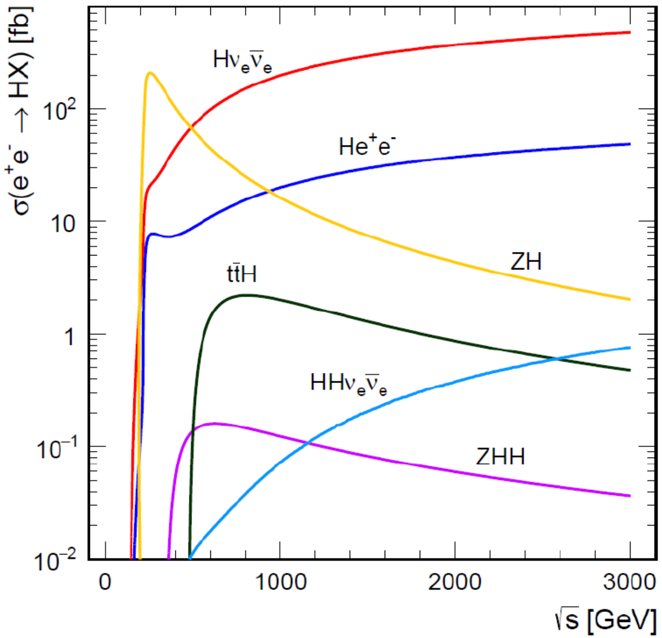
A "beam" of Higgs bosons





High energy Higgs factories: ILC500, CLIC3000, FCC-hh.

FCC-ee + FCC-hh is unbeatable!

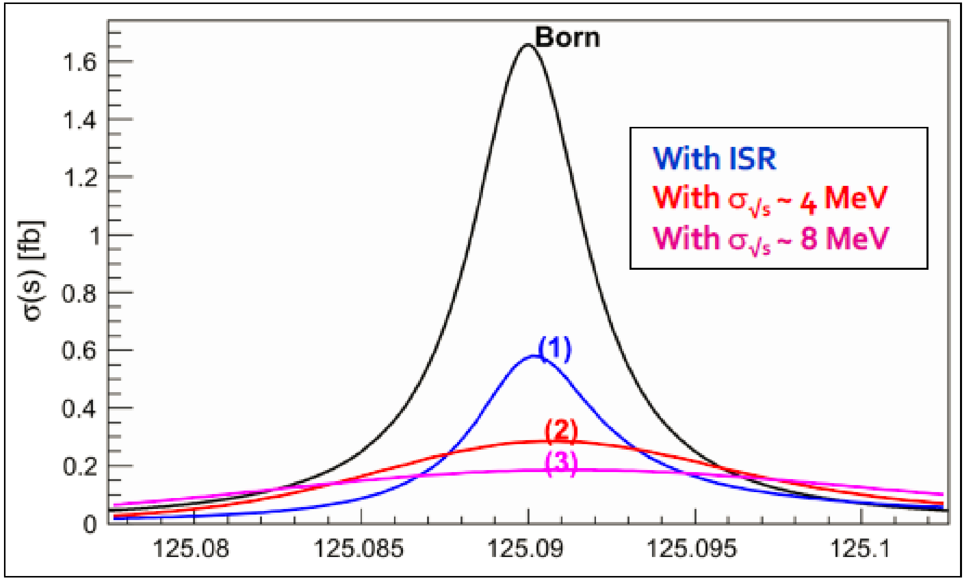


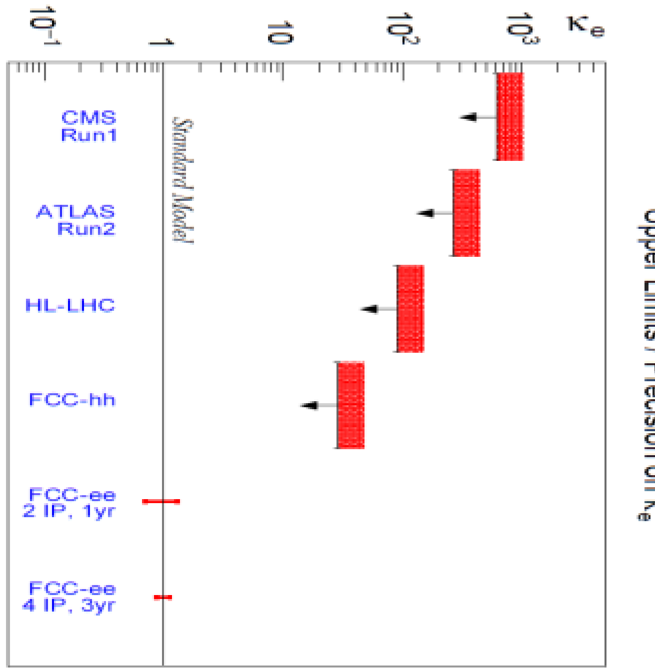
Collider	ILC_{500}	ILC_{1000}	CLIC	FCC-INT	
g_{HZZ} (%)	0.24 / 0.23	0.24 / 0.23	0.39 / 0.39	0.17 / 0.16	ee
g_{HWW} (%)	0.31 / 0.29	0.26 / 0.24	0.38 / 0.38	0.20 / 0.19	ee
g_{Hbb} (%)	0.60 / 0.56	0.50 / 0.47	0.53 / 0.53	0.48 / 0.48	ee
g_{Hcc} (%)	1.3 / 1.2	0.91 / 0.90	1.4 / 1.4	0.96 / 0.96	ee
g_{Hgg} (%)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

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
arxiv:2004.03505v1
10% precision in 2-5 years of FCC-hh running

Something unique!





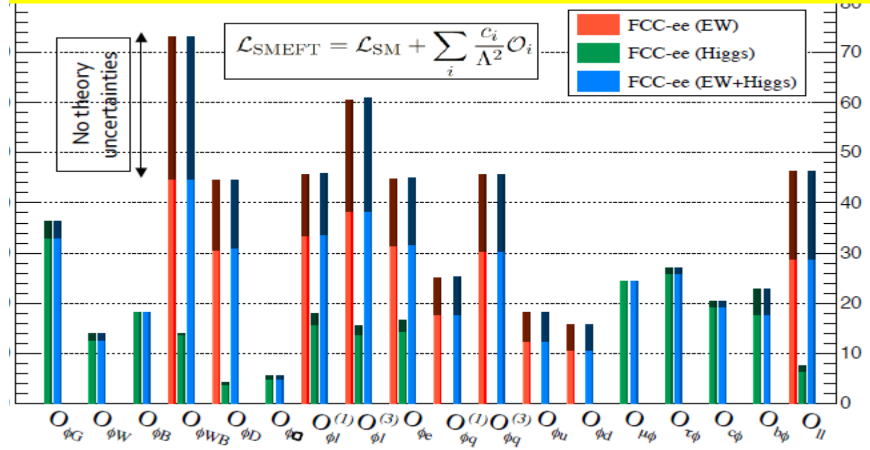
HUGE CHALLENGE

e+e- → H @ 125.xxx GeV requires
-- Higgs mass to be known to <5 MeV from 240 GeV run (CEPC group almost there)
-- **Huge luminosity**
-- **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
-- a generous lab director to spend 3 years doing this and neutrino counting

D. d'Enterria
wednesday

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
$\sin^2\theta_W^{eff} (\times 10^6)$	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
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
σ_{had}^0 $(\times 10^3)$ (nb)	41541 ± 37	**0.1**	4	peak hadronic cross section luminosity measurement
$N_\nu (\times 10^3)$	2996 ± 7	**0.005**	1	Z peak cross sections Luminosity measurement
R_b $(\times 10^6)$	216290 ± 660	**0.3**	< 60	ratio of $b\bar{b}$ to hadrons stat. extrapol. from SLD
$A_{FB}^b, 0$ $(\times 10^4)$	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
τ lifetime (fs)	290.3 ± 0.5	**0.001**	0.04	radial alignment
τ mass (MeV)	1776.86 ± 0.12	**0.004**	0.04	momentum scale
τ leptonic $(\mu\nu_\mu\nu_\tau)$ B.R. (%)	17.38 ± 0.04	**0.0001**	0.003	e/μ/hadron separation
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
$N_\nu (\times 10^3)$	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

Precision EW measurements: is the SM complete?



-^- 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

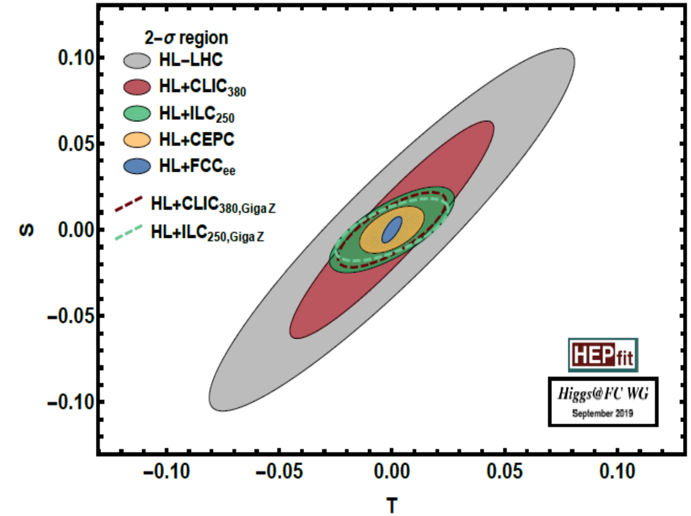
<-- complemented by high energy FCC-hh

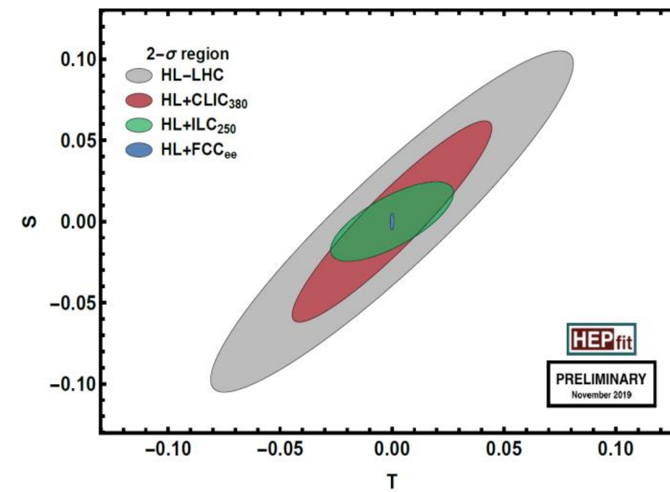
Theory work is critical and initiated *1809.01830*

Electroweak Physics

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), m_{top} (20 MeV)
$\alpha_{QED}(m_Z)$ (3.10^{-5} rel) and $\sin^2\theta_w$ (3.10^{-6} abs)

Complete set of EW observables can be measured
Precision unique to FCC-ee + new physics sensitivity
→ a lot more potential to exploit
requires dedicated detector design

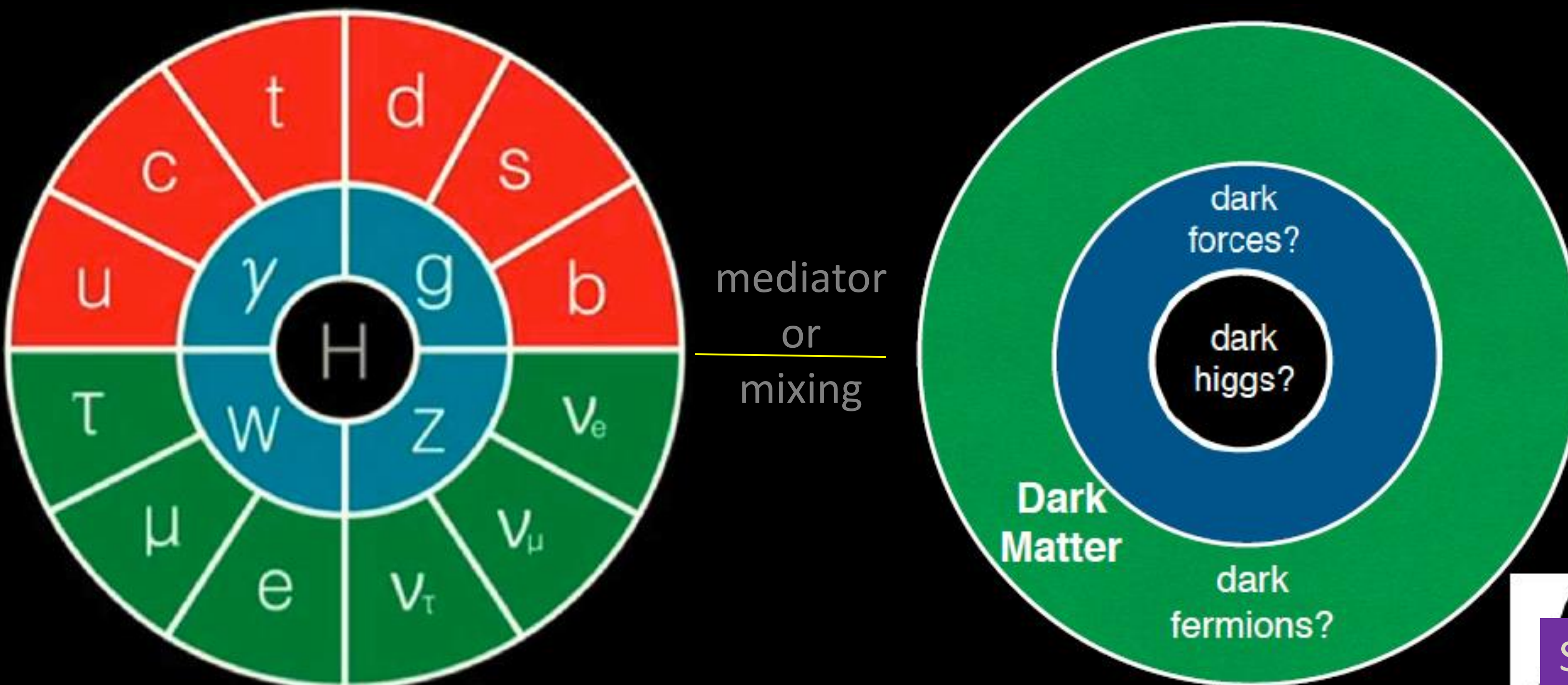




Can be seen on LEP, LHC etc…
A common error of many 'studies' of the past was to underestimate how well a group of dedicated (and well prepared) physicists can deconstruct a systematic error problem to the precision level of statistics. → Use statistical error as target!

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.



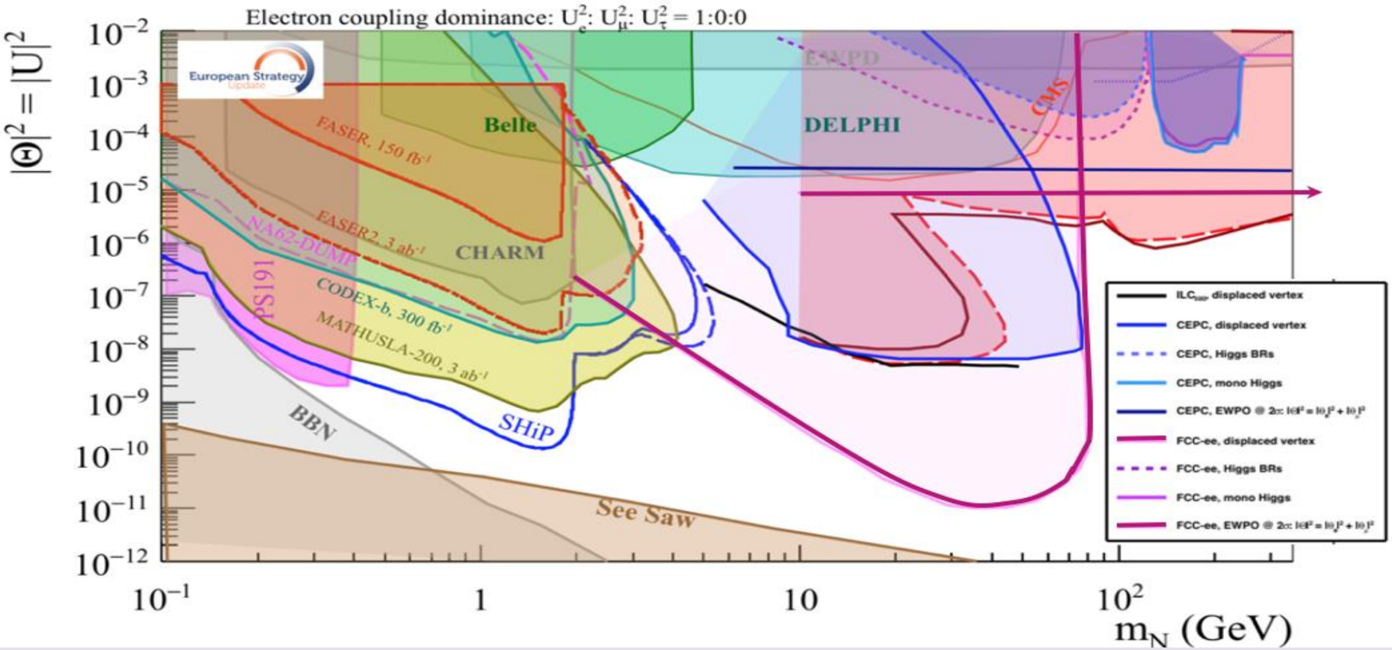
S. Gori

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

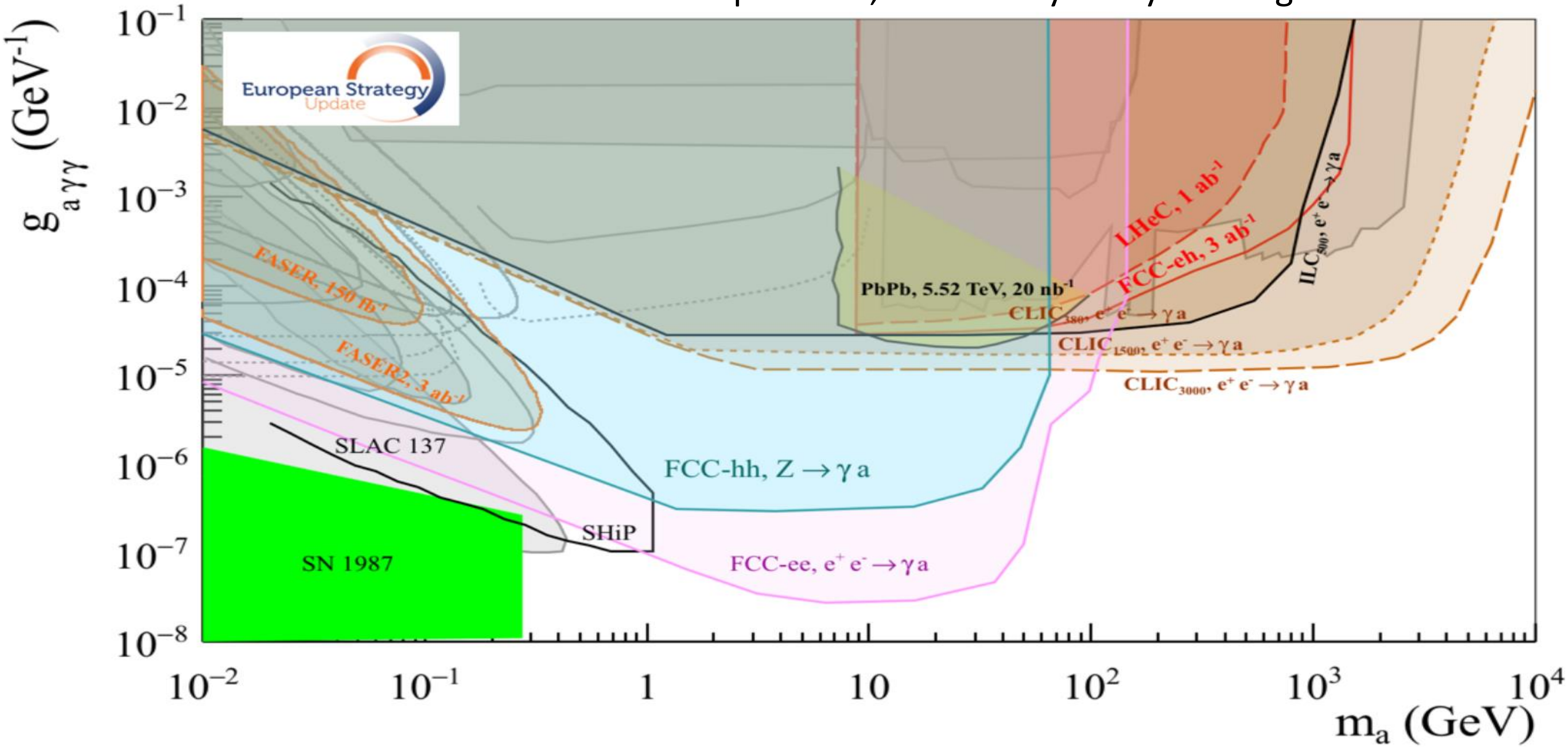
How close can we get to the 'see-saw limit'?



-- 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!

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 $b \to s\, \tau^+ \tau^-$, 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. : $10^{-3} \to 10^{-4}$

huge √s lever-arm between 30 GeV and 1 TeV (FCC vs ILC), fragmentation, baryon production ….

Testing running of α_s to excellent precision

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_τ), Higgs and top quark couplings

model independent «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 BR in 2 10^{11} Z→ τ τ

+ 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, 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'

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

IMPORTANT MILESTONES AND EVENTS

-- reach out to all ‘European and International Partners’
-- complete organization of physics conveners within the next two months
  -- nominations and volunteers welcome (contact AB and PJ)
-- completion of first case study(es) in spring 2021 → detector requirements
-- decide on FCC Layout (compatible with 4 IRs or not) by summer 2021
-- 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

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 study from Physics Performance effort**

… more to come!

Physics Performance effort & conveners

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

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

2. Case study teams establish DETECTOR REQUIREMENTS for optimizing measurement, and in particular matching exp. systematics with the expected statistical precision.

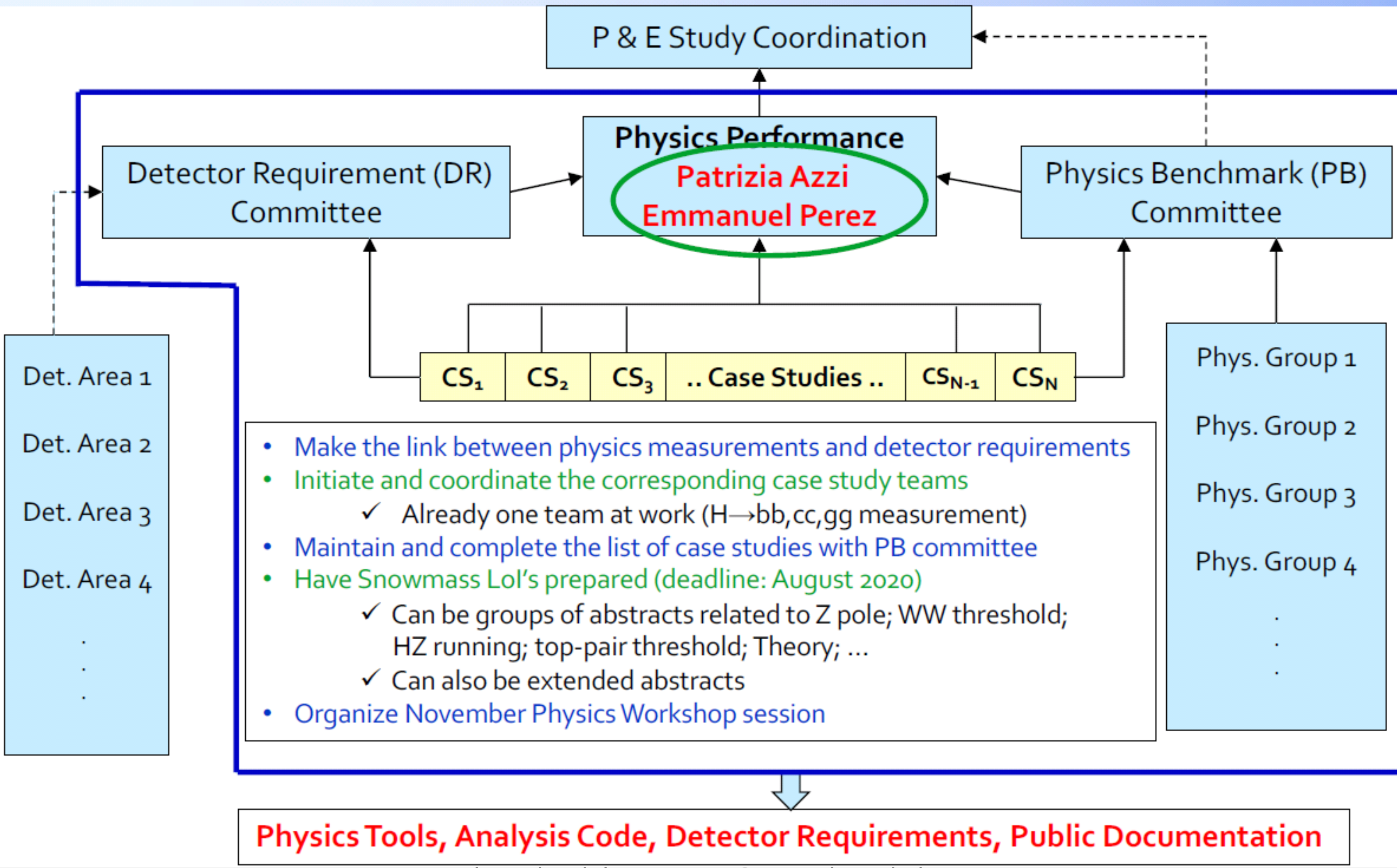
-- one team well advanced since July: c vs b/g jets in Higgs (and Z) decays

-- 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



- Make the link between physics measurements and detector requirements
- Initiate and coordinate the corresponding case study teams
  - ✓ Already one team at work (H→bb,cc,gg measurement)
- Maintain and complete the list of case studies with PB committee
- Have Snowmass LoI's prepared (deadline: August 2020)
  - ✓ Can be groups of abstracts related to Z pole; WW threshold; HZ running; top-pair threshold; Theory; …
  - ✓ Can also be extended abstracts
- Organize November Physics Workshop session

Notable sessions during the workshop

A fantastic program of phenomenology

In the PE&D :

Tuesday 11:00 Presentation of Physics Performance/Detector requirements/Software ("joining the study")

13:30 Joint session with accelerator: MDI (also Wednesday pm)

15:30 ECFA detector R&D road map/BELLEII/CEPC/AIDAInnovation

T **17h15 Round table discussion (will not be recorded)**

Wednesday pm -Thursday parallel sessions on detectors Calo/PID/TDAQ/VTX/Tracker

Thursday plenary 17:15 'Draw me a detector' session

Joint sessions exp-Pheno Wednesday & Friday morning

\+ Physics performance sessions in parallel with phenomenology afterwards.

Summaries on Friday afternoon + next steps and discussion end around 16:00.