7th FCC Physics Workshop
Introduction - Goals of the workshop

Annecy, January 29, 2024

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FCC case reloaded

1. The **Higgs boson** was discovered in 2011/2012
2. The **mass of the Higgs** boson is optimal for a study in e+e-
3. The **b-factories** had proven that very high luminosities could be reached in **circular colliders** (hence the tentative revamp of LEP into LEP3 in 2012)
4. In 2012, CERN management proposed instead to fit this e+e- collider into a **80-100 km tunnel** primarily meant for a 100 TeV pp collider
5. 80-100 km was exactly what was needed for the **top threshold** to be reached and exceeded; for **transverse polarisation** to be available all the way to the WW threshold (allowing a precise W mass measurement); to get enough **luminosity** (5 times more than LEP3) to maybe get sensitivity to the **Higgs self coupling** or to **sterile neutrinos**; to make TeraZ a useful **flavour factory**; to optimally fit in the **Geneva basin**, etc
6. LHC had not seen anything in the **TeV range** (and still hasn't), making the case for 500-1000 GeV much weaker;
7. The **HF magnet technology** is unavailable today (both technically and financially), and FCC-ee is the best (and only) way to get FCC-hh eventually done at CERN.

FCC Feasibility Study in Response to ESUPP2020

F. Gianotti@P5-BNL

"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."

"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."

↓

FCC Feasibility Study (FS) started in 2021 → will be completed in 2025

Synergy between Physics and Technological developments

"The European particle physics community should develop an accelerator R&D roadmap focused on the critical technologies needed for future colliders" …. "The technologies under consideration include high-field magnets, high-temperature superconductors, plasma wakefield acceleration and other high-gradient accelerating structures, bright muon beams, energy recovery linacs."

↓

Accelerator R&D roadmap developed (→ now being executed). CERN pursue R&D on high-field magnets, SCRF, proton-driven plasma wakefield acceleration, and R&D and design studies for CLIC and muon colliders to prepare alternative options to FCC if the latter is not pursued.

Slide from Michael Benedikt's presentation, FCC Week 2023

Mid-term review deliverables as defined in CERN/3654/Rev.2, September 2022

Infrastructure & placement
- Preferred placement and progress with host states (territorial matters, initial states, dialogue, etc.)
- Updated civil engineering design (layout, cost, excavation)
- Preparations for site investigations

Technical Infrastructure
- Requirements on large technical infrastructure systems
- System designs, layouts, resource needs, cost estimates

Accelerator design FCC-ee and FCC-hh
- FCC-ee overall layout with injector
- Impact of operation sequence: Z, W, ZH, $t\bar{t}$ vs start at ZH
- Comparison of the SPS as pre-booster with 10-20 GeV linac
- Key technologies and status of technology R&D program
- FCC-hh overall layout & injection lines from LHC and SC-SPS

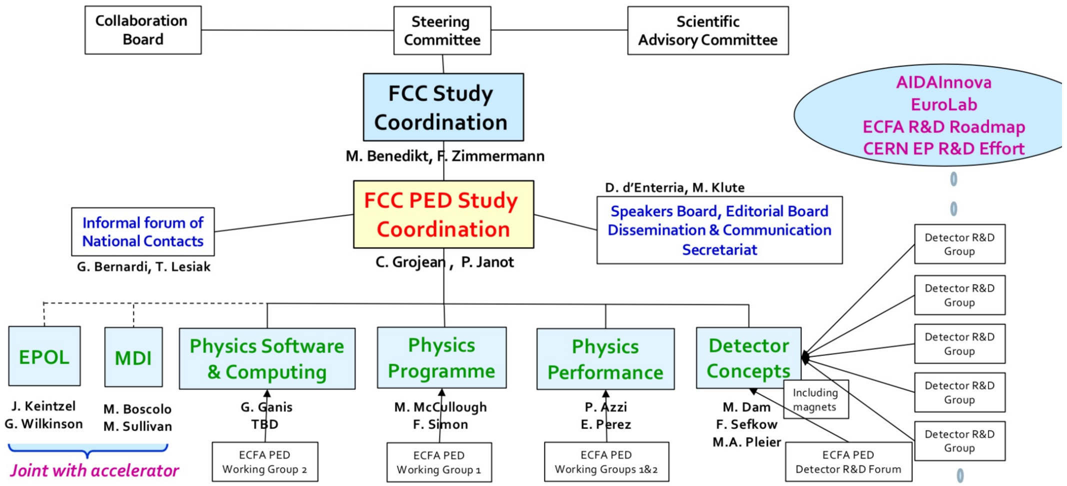
Physics, experiments, detectors:
- Documentation of FCC-ee and FCC-hh physics cases
- Plans for improved theoretical calculations to reduce theoretical uncertainties towards matching FCC-ee statistical precision for the most important measurements.
- First documentation of main detector requirements to fully exploit the FCC-ee physics opportunities

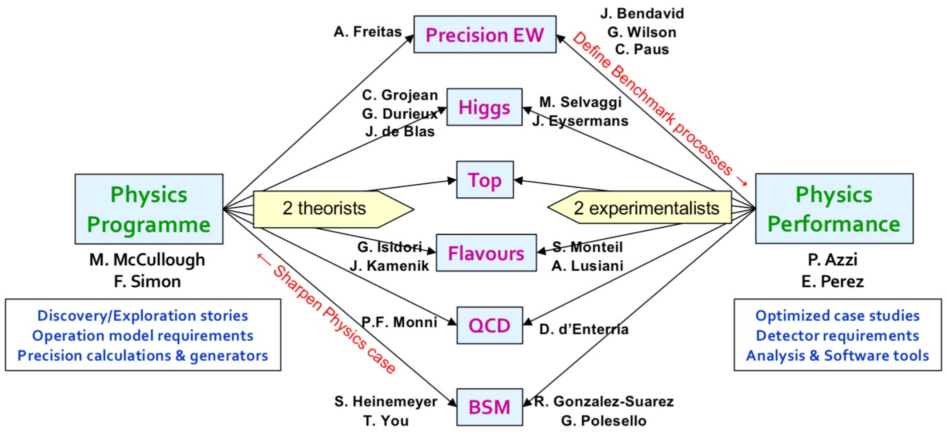
Organisation and financing:
- Overall cost estimate & spending profile for stage 1 project

Environmental impact, socio-economic impact:
- Initial state analysis, carbon footprint, management of excavated materials, etc.
- Socio-economic impact and sustainability studies

Feasibility Study and PED Team

- **"Technical and Financial Feasibility Study"** requested by CERN council after ESUPP2020.
- Mid-term evaluation in Oct./Nov. 2023
- **8th deliverables**: "Consolidation of the physics case and detector concepts for both colliders" But **PED** is not the top priority (because the physics case was already strong and well-documented?) therefore no dedicated resources!
- Progress by active participation of motivated volunteers only. **International Forum of National Contacts** is helping in structuring the community with special action towards young people.





Full Mid-Term Report

- 703 pages: 7 chapters (cost and financial feasibility is a separate document)
  - Placement scenario (75 pages)
  - Civil engineering (50 pages)
  - Implementation with the host states (45 pages)
  - Technical infrastructure (110 pages)
  - FCC-ee collider design and performance (170 pages)
  - FCC-hh accelerator (60 pages)
  - (Cost and financial feasibility)
  - Physics and experiments (110 pages)
  - References (70 pages)
- Executive summary: 44 pages
- Reviewed by Scientific Advisory Committee and Cost Review Panel on Oct. 16-18
- Reviewed by Scientific Policy Committee and Financial Committee on Nov. 21-22
- To be reviewed by Council Feb. 2 ⇒ might decide to publicly release the report/its summary
- Presentation of FCC mid-term report @ CERN on Feb. 13

296 authors

Future Circular Collider
Mid-term Report

Still confidential documents
Not yet public.

Edited by:
B. Auchmann W. Bartmann, M. Benedikt, J.P. Burnet, P. Craievich, M. Giovannozzi, C. Grojean, J. Gutleber, K. Hanke, P. Janot, M. Mangano, J. Osborne, J. Poole, T. Raubenheimer, T. Watson, F. Zimmermann

Supporting Notes

- **Supporting FCC Notes available in the new CDS**
  - 30 notes available
  - Appropriately referred to in the report
  - Available to everyone enrolled in a FCC-PED mailing list (need to log in to have access to the files)
  - Some were prepared in response to earlier comments/questions from Scientific Advisory Comm.

1/ Tau Physics Prospects at FCC-ee Lusiani, Alberto

2/ FCC-ee Detector requirements: geometric acceptance requirements for dilepton and diphoton events at Z pole energies Blondel, Alain & Dam, Mogens

3/ Reconstructed exclusive b-hadron decays as hemisphere jet charge tagger and its application for the measurement of R_b and A_{FB}^b Kroeninger, Kevin & Madar, Romain & Monteil, Stéphane

4/ Study of the feasibility of the observation of $B^0 \to K^{*(892)} \tau^+\tau^-$ at FCC-ee and related vertex detector performance requirements Miralles, Tristan & Monteil, Stéphane

5/ Prospects of searches for $b \to s\nu\nu$ decays at FCC-ee Kenzie, Matthew & Wiederhold, Aidan & Ahmis, Yasmine

6/ Bottom quark forward-backward asymmetry at the future electron-positron collider FCCee Toffolin, Leonardo & Cobal, Marina & Pinamonti, Michele

7/ Higgs to invisible at the FCC-ee Mehta, Andrew & Rompotis, Nikolaos

8/ Measurement of Higgs boson hadronic decays with $Z(\to\nu\nu/ll)$ H events at FCC-ee at $\sqrt{s}$ = 240 GeV Del Vecchio, Andrea & Gouskos, Loukas & Marchiori, Giovanni

9/ Higgs boson mass and model-independent ZH cross-section at FCC-ee in the di-electron and di-muon final states Eysermans, Jan & Bernardi, Gregorio & Ang, Li

10/ Sensitivity of the FCC-ee to decay of an HNL into a muon and two jets Polesello, Giacomo & Valle, Nicolò

11/ The FCC-ee interaction region, design and integration of the machine elements and detectors, machine induced backgrounds and key performance indicators Boscolo, Manuela & Palla, Fabrizio & Abramov, Andrey

12/ Particle Physics considerations for the FCC-ee choice and sequence of running energies Blondel, Alain & Grojean, Christophe & Janot, Patrick

13/ Accelerator and physics requirements for the calibration of the collision energy Aßmann, Ralph & Bauche, Jeremie & Barber, Desmond

14/ Long-Lived Particles from exotic Higgs decays at the FCC-ee Vande Voorde, Magdalena & Ripellino, Giulia & Gonzalez Suarez, Rebeca

15/ A selection of benchmark studies at FCC-ee The FCC PED Coordination group

16/ Recovery of bremsstrahlung photons in a FCC-ee detector Perez, Emmanuel & Selvaggi, Michele

17/ Integrated Luminosities and Sequences of Events to be used in the Mid-Term Report Janot, Patrick & Benedikt, Michael & Zimmermann, Frank

Breakthroughs from Mid-Term Review

- 4 IPs is now the baseline design (and facility layout now optimised for FCC-ee)
- Importance to remain flexible in the run sequence is well appreciated
- Rich physics with possible additional runs (below Z, at the Higgs pole…)
- Consider additional science that could increase the user base, i.e. diversity programme / dark sector searches etc
- Running FCC-ee longer than originally planned is not a taboo topic (to adjust to FCC-hh schedule/readiness)
- Understanding that resources are needed (at CERN and beyond)
- Discussion to establish a theory FCC center
- General feeling that "FCC is on its way".

PED Mid-Term Report

❑ FCC Feasibility Study PED deliverables for mid-term review

Excerpt from https://twiki.cern.ch/FCC/MidtermReview

8. Physics & Experiments	C. Grojean, P. Janot, M. Mangano	8.1 Overview
		8.2. Documentation of the specificities of the FCC-ee and FCC-hh physics cases.
		8.3 Strategic plans for the improved theoretical calculations.
		8.4 FCC-ee Detector Requirements.

} explicit requests from SPC & Council

◆ Content of the mid-term PED chapter (60 pages were expected → 110 pages delivered)

1 Overview 3
- 1.1 FCC-ee: A great Higgs factory, and so much more 4
- 1.2 FCC-hh: The energy-frontier collider with the broadest exploration potential 13

2 Specificities of the FCC physics case 15
- 2.1 Characterisation of the Higgs boson: role of EW measurements and of FCC-hh 16
- 2.2 Discovery landscape 24
- 2.3 Flavour advancement 34
- 2.4 FCC-hh specificities compared to lepton colliders 36

3 Theoretical calculations 42
- 3.1 Electroweak corrections 44
- 3.2 QCD precision calculations 46
- 3.3 Monte Carlo event generators 50
- 3.4 Organization and support of future activities to improve theoretical precision 53

4 Detector requirements 54
- 4.1 Introduction 54
- 4.2 Machine-detector interface 55
- 4.3 The current detector concepts 56
- 4.4 Measurement of the tracks of charged particles 58
- 4.5 Requirements on the vertex detector 64
- 4.6 Requirements on charged hadron particle identification 73
- 4.7 Requirements on electromagnetic calorimetry 78
- 4.8 Requirements on the hadronic calorimeter 88
- 4.9 Requirements on the muon detector 93
- 4.10 Precise timing measurements 93

5 Outlook and further steps 96
- 5.1 Software and Computing 98
- 5.2 Physics Performance 99
- 5.3 Detector Concepts 101
- 5.4 Centre-of-mass energy calibration, polarisation, monochromatisation (EPOL) 103
- 5.5 Machine-Detector Interface (MDI) 104
- 5.6 Physics Programme 105
- 5.7 FCC-hh 106

What is inside the report?

- **Does not repeat FCC CDR**
  - where the physics case was already well documented/motivated,
  - overview section insists the synergy/complementarity of large circular ee and pp colliders
- **Focuses on new studies:**
  - New phenomenological ideas
  - Identification of **synergy** between FCC-ee and FCC-hh and with other machines
    $\longrightarrow$ FCC-ee is not there simply to wait for FCC-hh to be ready; going straight to FCC-hh is not an option
  - Case studies with proper detector simulations
  - Understanding of detector challenges and requirements
  - Development of analysis software framework
    - software and computing codes themselves will be a deliverable of final report and beyond (resource allowing)
  - Study of centre-of-mass energy calibration, polarisation, monochromatisation (EPOL)
  - Optimisation of Machine-Detector Interface (MDI)

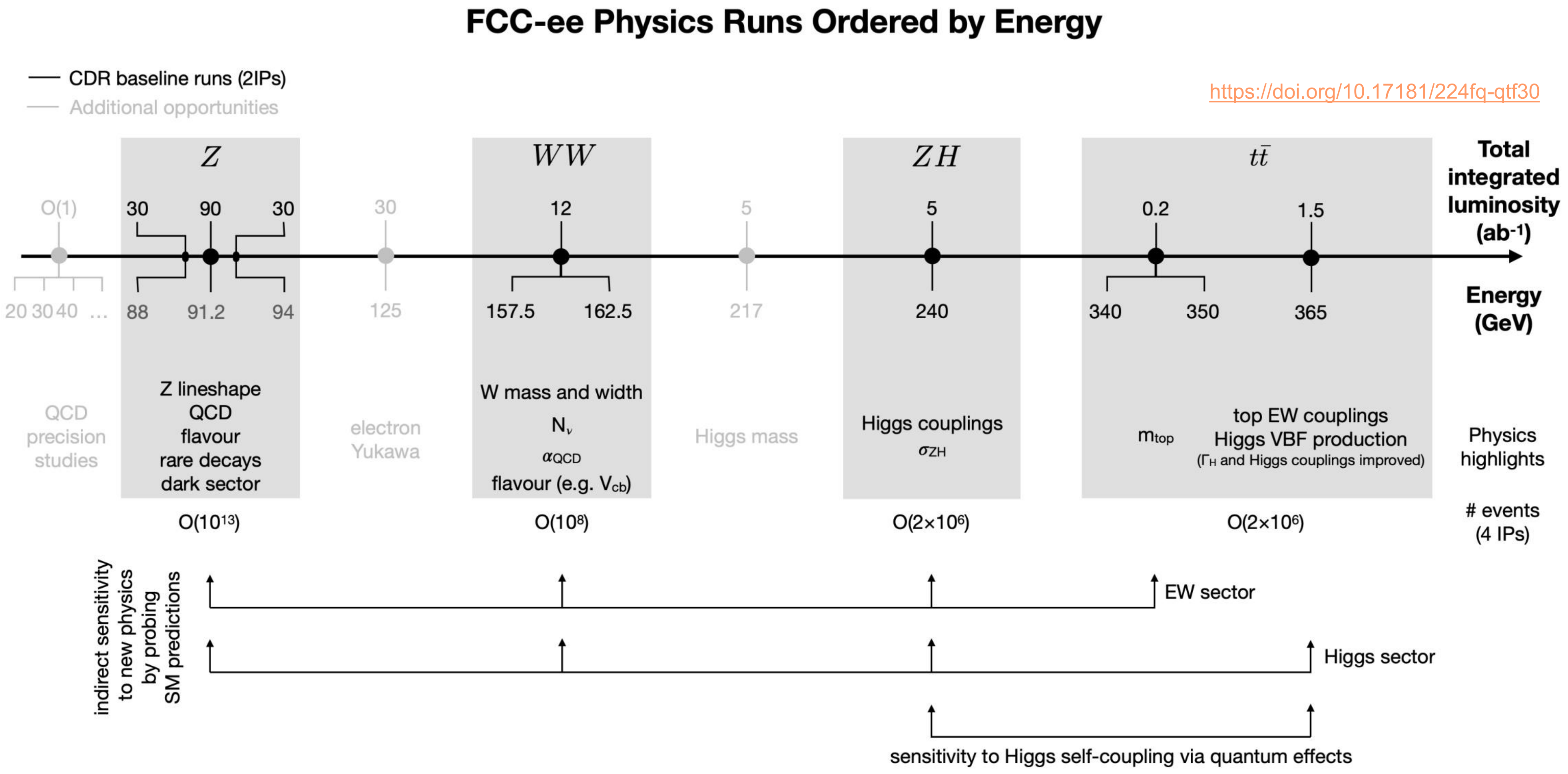
Joint PED-ACC efforts (included in D5 chapter)

FCC in perspective

Precision & Exploration at both ee/pp colliders

- **FCC-ee: more than a Higgs factory thanks to 80-100 km tunnel:**
  - Top-pair production threshold
  - High instantaneous luminosity in energy range tailored for the study of the four heaviest SM particles
  - Control of centre-of-mass energy by resonant depolarisation (up to WW threshold)
  - Multi-TeraZ run: EPWO, flavour programme, light and feebly BSM
  - 4 IPs allowing for multi-purposed and dedicated experiments
  - Electron Yukawa accessible
- **FCC-hh: the perfect energy upgrade**
  - Extension of Higgs property measurements (ttH, HH, rare decays…)
  - EW dynamics well above the scale of EW symmetry breaking
  - Study of behaviour of high-density and high-temperature strongly interacting plasmas
  - Direct exploration of the multi-TeV energy scale

A Possible Extended Physics Programme



Way Ahead

- **Physics Programme requires dedicated work to complete the Feasibility Study and beyond:**
  - Design and initiate a concept to develop worldwide a theory community around FCC
    - Towards, e.g., achieving the required precision with theoretical calculations and MC generators
  - Complete the physics case in a number of areas
    - Scientific outcome and challenges of the TeraZ programme
    - Flavour observable SM prediction
    - Interplay between the Z, W, Higgs and top programmes
    - Potential of other energy settings ? Of more luminosity ? Global aspirations for FCC-ee.
  - Study specific BSM models that could address (or not) the big open questions of HEP
    - To understand FCC-ee capability to exclude or discover (or confirm previous observations)
  - FCC-hh
    - Interplay between EFT sensitivity at FCC-ee and direct discovery potential at FCC-hh
    - Interplay between precision at FCC-ee and precision at FCC-hh, and added value of FCC-hh
    - Scientific outcome of sensitivity to centre-of-mass energy (80-100-120 TeV)
    - More about FCC-hh vs muon colliders

See Patrick's concluding talk on Friday

Conclusion

- **On the basis of feedback received so far from SAC/CRP/SPC, it was confirmed that**
  - **The quality and quantity of work done is highly recognized and appreciated**
  - **The FCC will address fundamental scientific questions**
  - **The FCC will maintain CERN's global leadership in particle physics**
  - **The FCC-ee cost estimates (including detectors) are fair and robust**
  - **The final feasibility deliverables are achievable**
  - **No (technical or non-technical) immediate showstoppers were identified**

    Even if several aspects that are on the critical path will need to be attended urgently.
- **The mid-term review may have been seen by some as an opportunity to stop the feasibility study early.**
- **The impression is, instead, that the mid-term review report will reinforce the validity of the FCC project altogether, that it might facilitate building consensus in view of the ESUPP, and therefore accelerate the final approval.**

Let's get ready and build the Future.

Why are we here? aka Goals of the Workshop

- Take stock of where we are
- List the resources needed to move forward
- Understand how to accelerate the schedule
- Increase outside participation
- Build the community
- … discuss the physics that will be done at FCC.

Have a nice week! Enjoy the workshop!

Bonuses

Why FCC?

F. Gianotti, Jan. 24

1) Physics : best overall physics potential of all proposed future colliders; matches the vision of the 2020 European Strategy: "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."

- ❑ FCC-ee : ultra-precise measurements of the Higgs boson, indirect exploration of next energy scale (~ x10 LHC)
- ❑ FCC-hh : only machine able to explore next energy frontier directly (~ x10 LHC)
- ❑ Also provides heavy-ion collisions and, possibly, ep/e-ion collisions
- ❑ 4 collision points → robustness; specialized experiments for maximum physics output

2) Timeline

- ❑ FCC-ee technology is "mature" → construction can start in the ealry 2030s and physics a few years after the end of HL-LHC operation (currently 2048, earlier if more resources available) → This would keep the community, in particular the young people, engaged and motivated.
- ❑ FCC-ee before FCC-hh would also allow:
  - cost of the (more expensive) FCC-hh machine to be spread over more years
  - 20 years of R&D work towards affordable magnets providing the highest achievable field (high-T superconductors!)
  - optimization of overall investment : FCC-hh will reuse same civil engineering and large part of FCC-ee technical infrastructure

3) It's the only facility commensurate to the size of the CERN community (4 major experiments)

Is it feasible? Isn't it too ambitious?
- Ongoing Feasibility Study showing spectacular progress
- FCC is big, audacious project, but so were LEP and LHC when first conceived → they were successfully built and performed far beyond expectation → demonstration of capability of our community to deliver on very ambitious projects
- FCC is best project for future of CERN (for above reasons) → we have to work to make it happen

The Alignment of Stars towards FCC

P. Janot @ CERN-SPC

- **Discovery of a light Higgs boson – m_H = 125 GeV, just above LEP limit**
  - Higgs boson can be produced at e^+e^- centre-of-mass energies accessible at circular colliders

- **Progress in e^+e^- circular collider technology (B factories)**
  - Makes it possible to exceed 10^{35} $cm^{-2}s^{-1}$ at the $e^+e^- \to ZH_{125}$ cross section max. (~240 GeV)

- **No BSM physics found (yet) in the TeV range at LHC (+ ttH/HH sensitivity at HL-LHC)**
  - Greatly limits the physics potential of TeV-class e^+e^- linear colliders
  - Forces to think differently about BSM physics to explain the big open questions
    - Dark matter, Neutrinos, BAU, Flavour, Hierarchy problem, …
  - Solutions to these open questions can be at even higher energy
    - Higgs compositeness is among the most popular avenues
  - But often include light and very-weakly-coupled structures
    - Axion-like particles, dark photons, heavy neutral leptons, long-lifetime particles

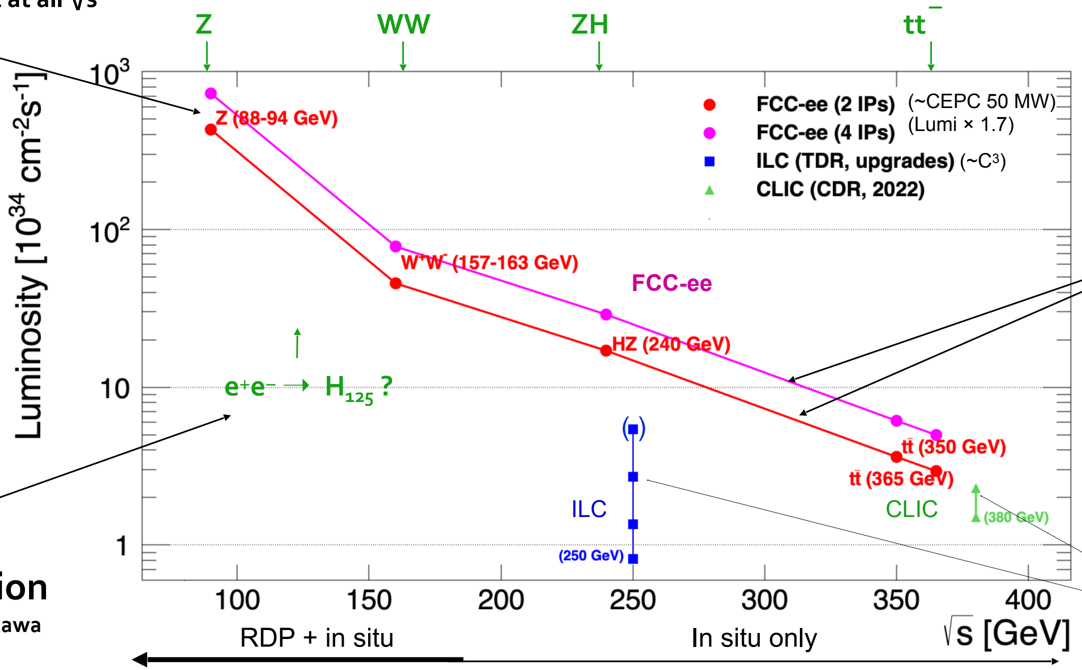
The Uniqueness of FCC-ee

Optimal energy range for SM particles
Sharpen and challenge our knowledge of already existing physics

LEP1 statistics in a few minutes
Detector calibration/alignment at all √s

Highest luminosities
Less running time for a given physics outcome
Better physics outcome for a given running time
Increase discovery potential

Serve up to 4 interaction points
Net overall gain in MW/ab-1 or CO2-eq/ab-1
Essential redundancy for precision measurements
May satisfy all detector requirements
Increase discovery potential
Enhance the community (FCC/CERN clients)



√s Monochromatisation
Unique opportunity for electron Yukawa

Motivates the competition
Luminosity is the name of the game

Precise and continuous √s, √s spread, boost determination
Both with resonant depolarisation (RDP) and with collision events in up to four detectors
Essential for precision measurements

FCC - PED Feasibility Study: Physics Case

LHC@10 changed HEP landscape/priorities:

- no evidence of new physics below 1TeV to directly explore
- need for a versatile machine to probe both the intensity and energy frontiers (search for light feebly coupled particles and search for heavy particles)

FCC = general-purpose particle observatory whose objective is to explore the fundamental origins of our universe by looking inwards toward the smallest scales, in new regimes of precision and energy.

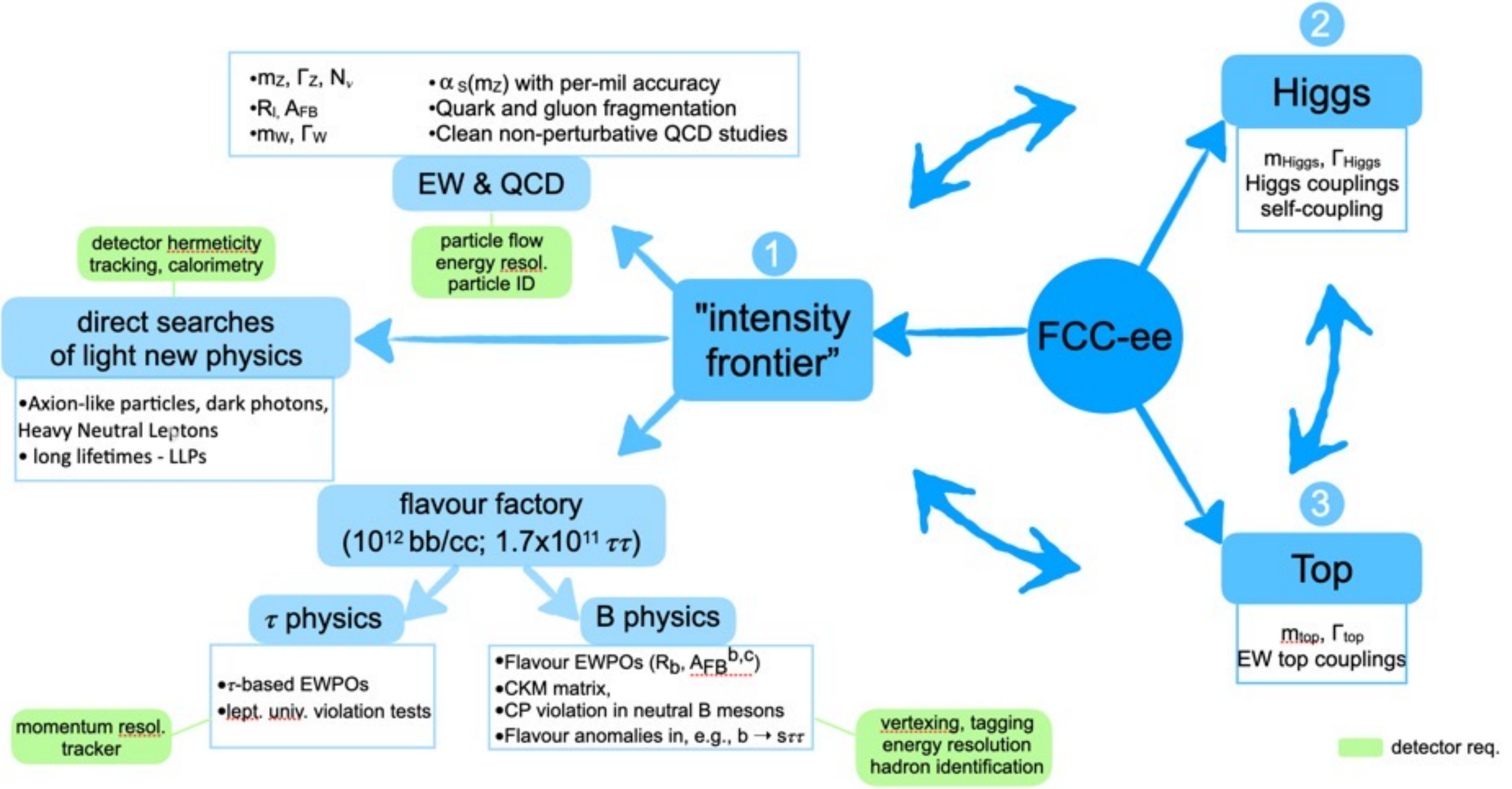
- What is the origin of the Higgs boson?
- What is the origin of matter?
- What is the origin of mass and flavour?
- What are the origins of dark matter and neutrino masses?
- What is the origin of the Standard Model?
- What are the origins of exotic astrophysical and cosmological signals

Physics Programme

- Here too, a great deal of ground work remains
  - Theoretical calculations
  - Additional physics opportunities, observables, data-driven methods, …
    - Complementary detectors for exotic signatures
    - Full exploration of the Tera-Z programme
    - Flavour measurements and SM predictions
  - Study specific BSM models to address/explain the great open questions of particle physics
    - Work out what would be the impact of FCC-ee/hh in discovering/excluding them
    - Evaluate what FCC could learn about these models, if discovered
    - Would put concrete faces in front of so-far abstract EFT and Wilson coefficients
  - Complete the list of benchmark processes for detector requirements
  - Revisit the CDR baseline choice of collision energies, luminosities, and running sequence
    - See FCC Note: https://doi.org/10.17181/224fq-qtf30
    - The list of opportunities (and challenges) is only becoming richer as the investigations deepen
      - ➔ It is becoming clear that more energy settings and luminosity would expand the FCC science value

FCC - PED Feasibility Study: Physics Case

FCC-ee: a great Higgs factory, and so much more



FCC - PED Feasibility Study: Physics Case

FCC-ee: a great Higgs factory, and so much more

Higgs
factory

m_H, σ, Γ_H
self-coupling
H→ bb, cc, ss, gg
H→inv
ee→H
H→bs, ..

Top

m_{top}, Γ_{top}, ttZ, FCNCs

Flavor
"boosted" B/D/**τ** factory:

CKM matrix
CPV measurements
Charged LFV
Lepton Universality
τ properties (lifetime, BRs..)

$B_c \to \tau \nu$
$B_s \to D_s K/\pi$
$B_s \to K^* \tau \tau$
$B \to K^* \nu \nu$
$B_s \to \varphi \nu \nu$ …

QCD - EWK
most precise SM test

m_Z , Γ_Z , Γ_{inv}

$\sin^2\theta_W$, R^Z_ℓ, R_b, R_c

$A_{FB}^{b,c}$, **τ** pol.

α_S ,

m_W, Γ_W

BSM
feebly interacting particles

Heavy Neutral Leptons (HNL)

Dark Photons Z_D

Axion Like Particles (ALPs)

Exotic Higgs decays

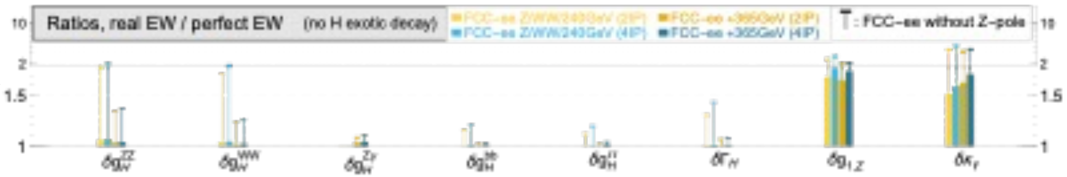
Higgs

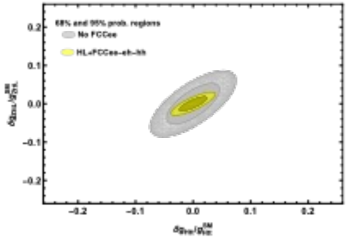
FCC-ee = best Higgs factory

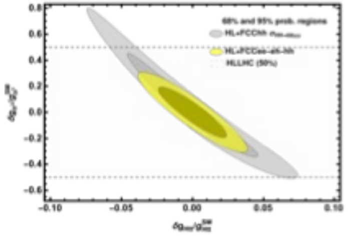
Coupling	HL-LHC	linear colliders (250 or 380 GeV)	circular colliders (240–365 GeV) 2 IPs / 4 IPs
κ_W [%]	1.5*	0.73	0.43 / 0.33
κ_Z[%]	1.3*	0.29	0.17 / 0.14
κ_g[%]	2*	1.4	0.90 / 0.77
κ_γ [%]	1.6*	1.4	1.3 / 1.2
$\kappa_{Z\gamma}$ [%]	10*	10	10 / 10
κ_c [%]	–	2.0	1.3 / 1.1
κ_t [%]	3.2*	3.1	3.1 / 3.1
κ_b [%]	2.5*	1.1	0.64 / 0.56
κ_μ [%]	4.4*	4.2	3.9 / 3.7
κ_τ [%]	1.6*	1.1	0.66 / 0.55
BR_{inv} (<%, 95% CL)	1.9*	0.26	0.20 / 0.15
BR_{unt} (<%, 95% CL)	4*	1.8	1.0 / 0.88

Reaches 1‰ in a record time and model-independent way (contrary to HL-LHC *)

- Interplay 240 and 365 GeV runs
- Interplay Z-pole run and Higgs measurements
- Complementarity and synergy ee/hh:
  - Rare production and decay channels
  - ttH/ttZ @ ee + ttH @ hh → top Yukawa
  - ttZ @ ee + HH @ hh → Higgs self-coupling







Dark Sectors

FCC-ee = Exploration of the Feebly Interacting Frontier

- Dark photons

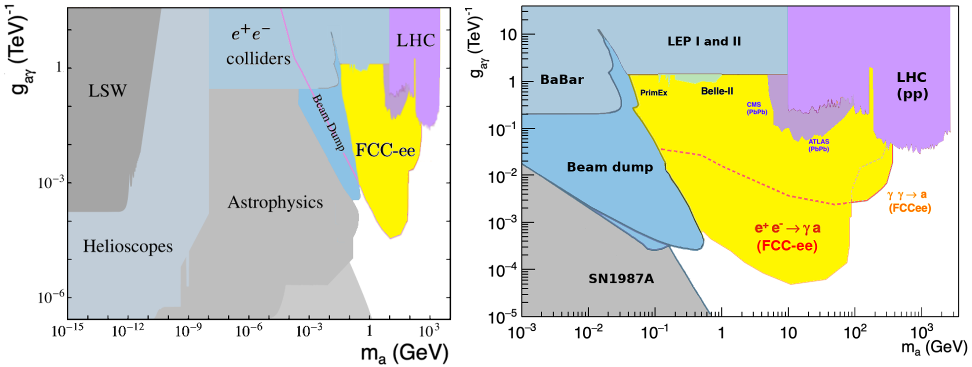
$$e^+e^- \to A'\gamma$$

$$e^+e^- \to A'H \text{ or } Z'H$$

- ALPs

$$e^+e^- \to a\gamma$$

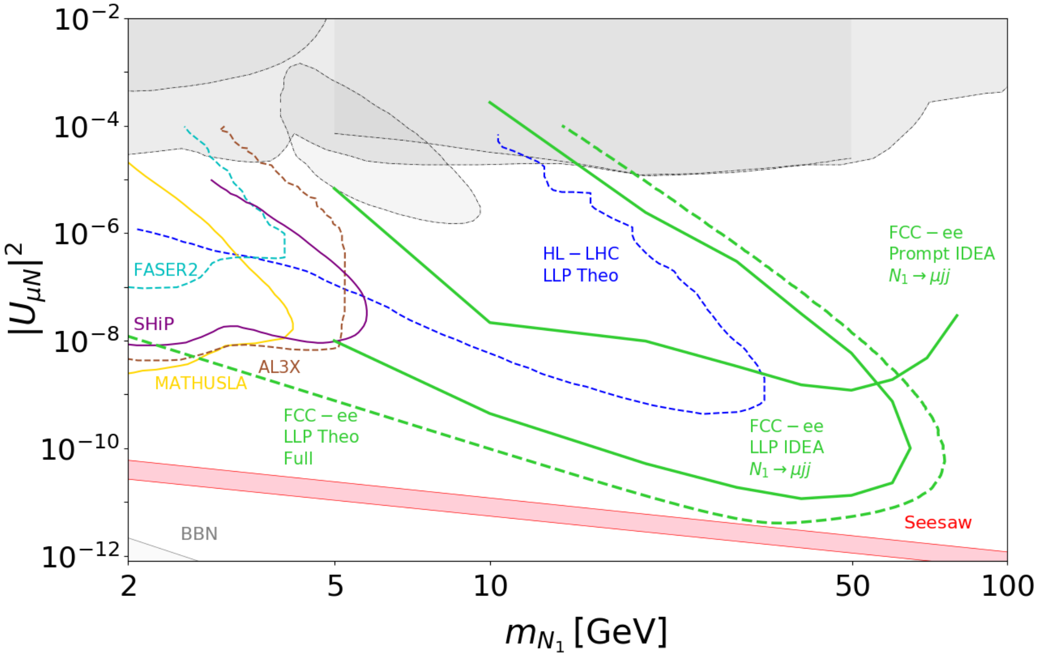
$$e^+e^- \xrightarrow{\gamma\gamma} a$$



Sensitivity to photon couplings down to < 10^{-4}–4 TeV^{-1}
(3 orders of magnitude improvement)

- LLPs from H/Z exotic decays

Heavy Neutral Leptons



New analysis:

HNL decays inside FCC-ee detector with a displacement larger than 0.4mm

(the search has been carried out for the first time with MC simulations in the μνjj final state, and seems to confirm the theoretical estimates we had before. This analysis can now be used for detector requirements).

Flavour

Tera-Z makes FCC a great Flavour Factory

Key features of flavour-physics programme at FCC-ee:

- Clean environment with precise momentum reconstruction
- Boosted b's and τ's ⟶ higher efficiency for channels with missing energy & smaller errors in lepton identification

Identification of classes of promising observables:

- Rare b-hadron decays with $\tau\bar{\tau}$ pairs in the final state.
- Charged-current b-hadrons decays with a τν pair in the final state.
- Lepton flavour violating τ decays
- Lepton-universality tests in τ decays.

High Energy Exploration

What should follow FCC-ee as a high energy exploration facility?

FCC-hh vs very high-energy lepton colliders

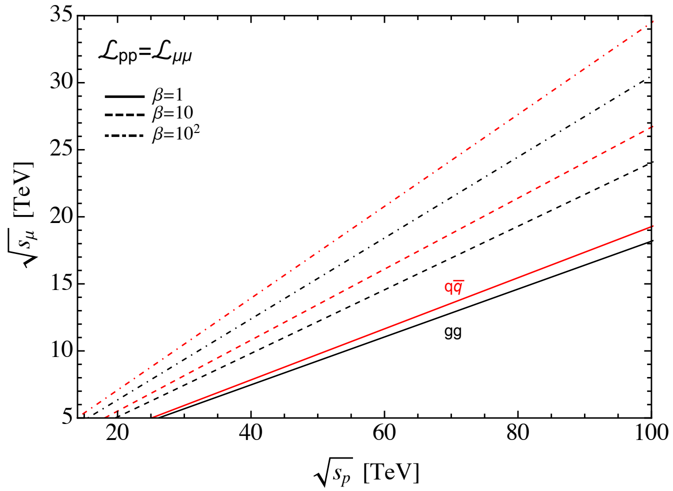


Fig. 19 Energies of equivalent event numbers, assuming equal integrated luminosities, between a high energy muon collider and a proton collider. $\beta = 1$ corresponds to the same partonic cross section between muons and proton partons. Larger values of β correspond to reduced partonic cross sections for muons, as would be the case for resonances coupled primarily to gluons or quarks.

pp@100TeV ≈ μμ@14 TeV
true only under specific assumptions

breadth of couplings that can be explored is a paramount consideration in planning for the future

pp colliders = array of production channels for discovery and exploration that is factorially greater than can be achieved by colliding single fundamental particles.