FCC Feasibility Study: Physics and Theory

Fourth FCC/DRD France workshop

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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

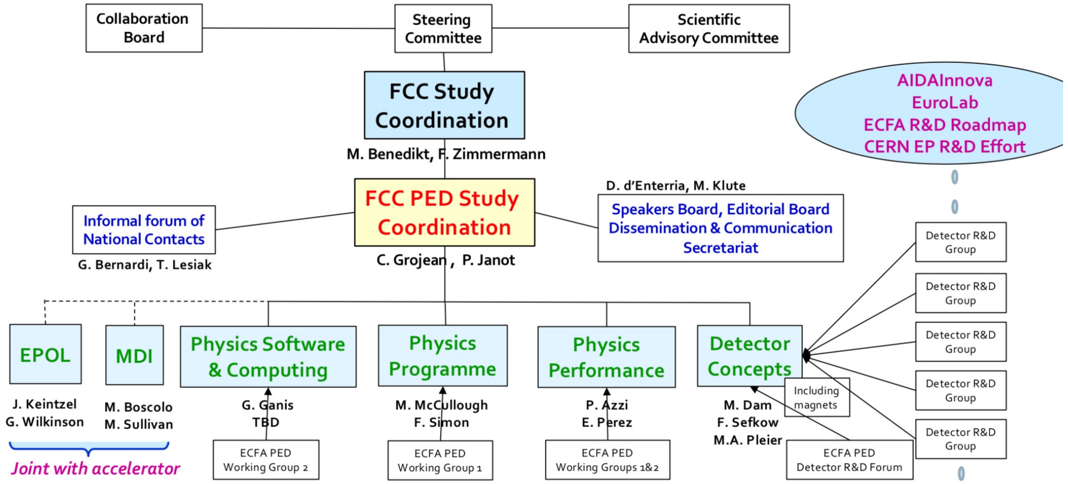
Physics, experiments, detectors:
- Documentation of FCC-ee and FCC-hh physics cases
- Plans for improved theoretical calculations to reduce theoretical uncertainties towards matching FCC-ee statistical precision for the most important measurements.
- First documentation of main detector requirements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

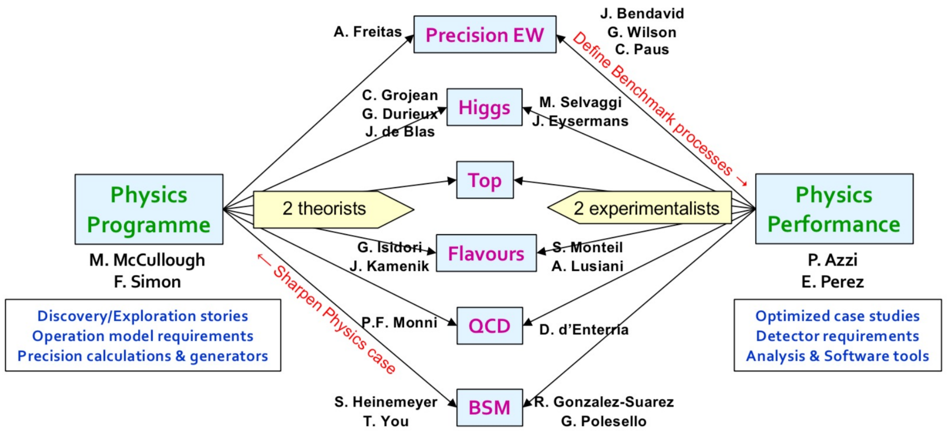
Organisation and financing:
- Overall cost estimate & spending profile for stage 1 project

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 SPC and FC on Nov. 21-22
- To be reviewed by Council Feb. 2

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

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 (8.2–8.4)

Content of the mid-term PED chapter (60 pages were expected)

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
  - 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)

See Emmanuel's talk

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

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

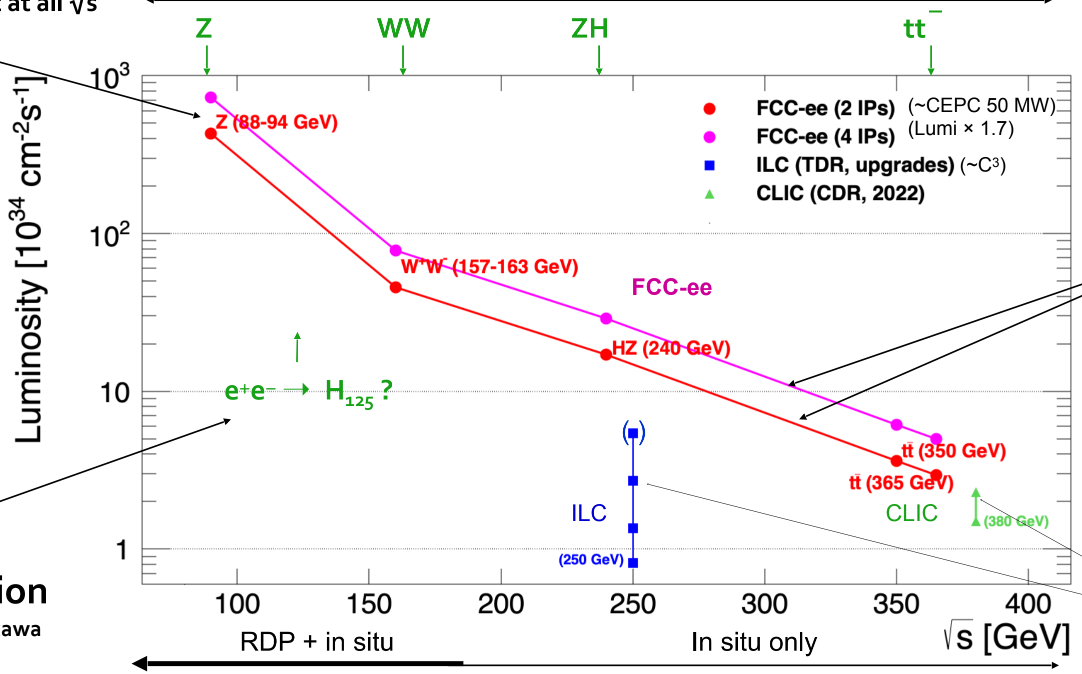
The Uniqueness of FCC-ee

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)



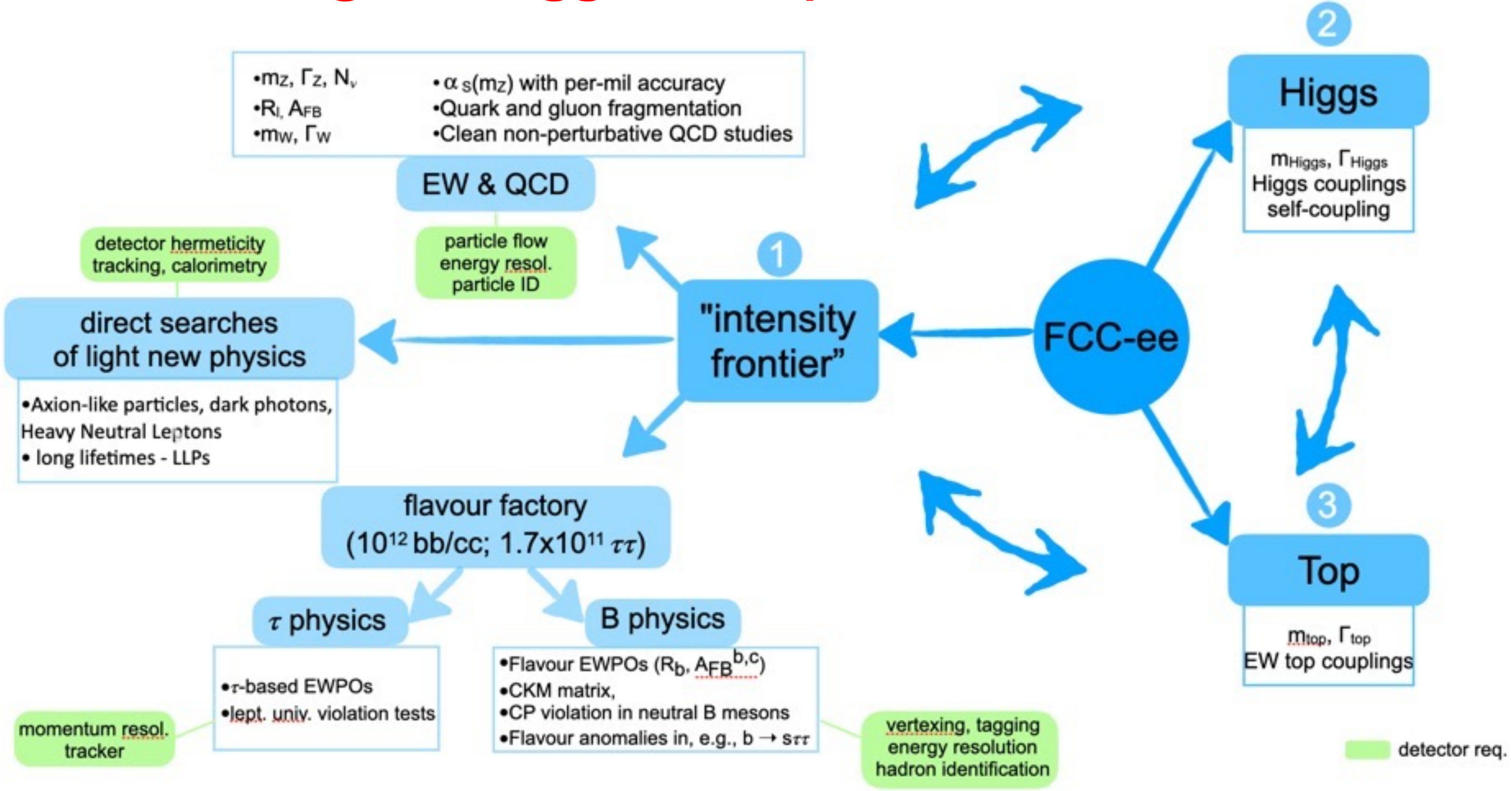
√s Monochromatisation
Unique opportunity for electron Yukawa

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

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

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

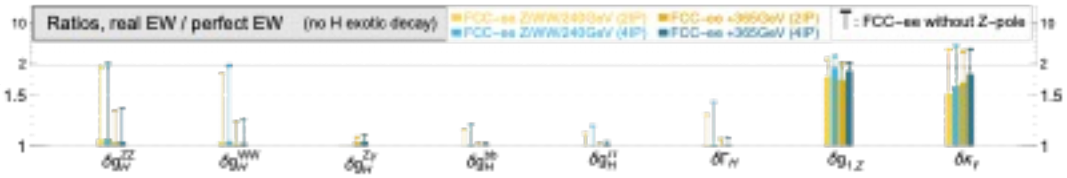
Higgs

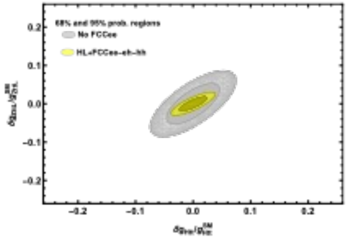
FCC-ee = best Higgs factory

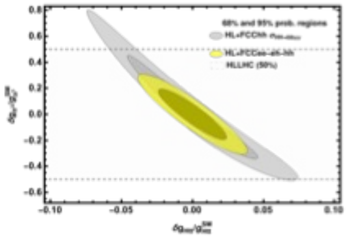
Coupling	HL-LHC	linear colliders (250 or 380 GeV)	circular colliders (240–365 GeV) 2 IPs / 4 IPs
κ_W [%]	1.5*	0.73	0.43 / 0.33
κ_Z[%]	1.3*	0.29	0.17 / 0.14
κ_g[%]	2*	1.4	0.90 / 0.77
κ_γ [%]	1.6*	1.4	1.3 / 1.2
$\kappa_{Z\gamma}$ [%]	10*	10	10 / 10
κ_c [%]	–	2.0	1.3 / 1.1
κ_t [%]	3.2*	3.1	3.1 / 3.1
κ_b [%]	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

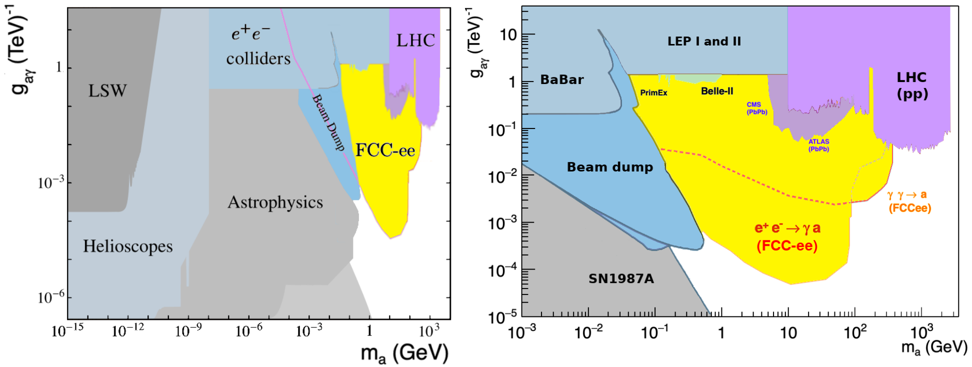
$$e^+e^- \to A'\gamma$$

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

- ALPs

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

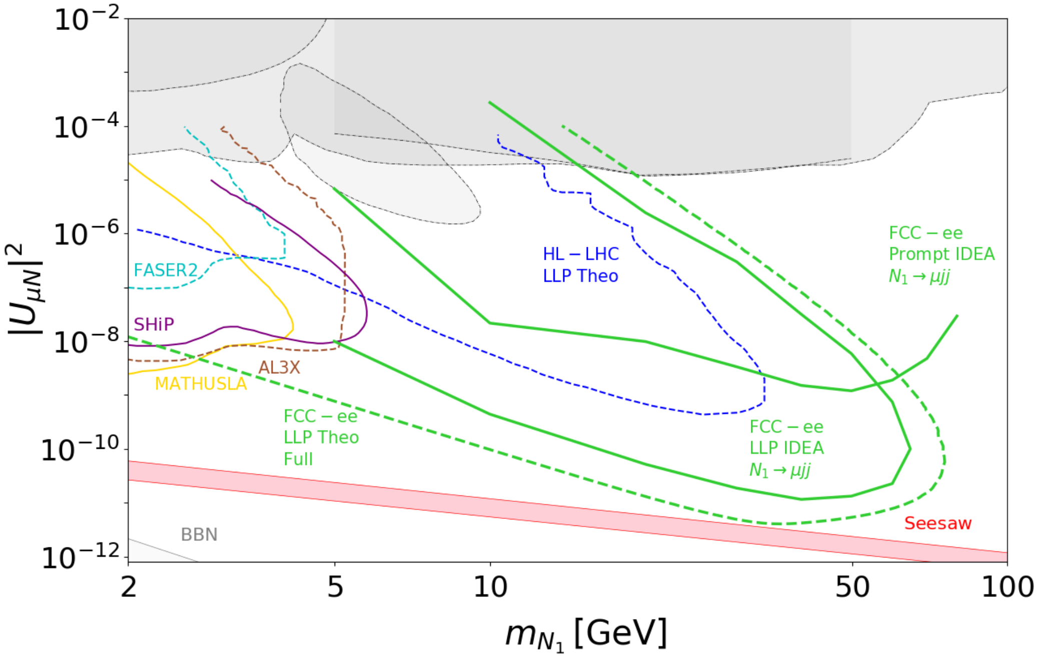
$$e^+e^- \xrightarrow{\gamma\gamma} a$$



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

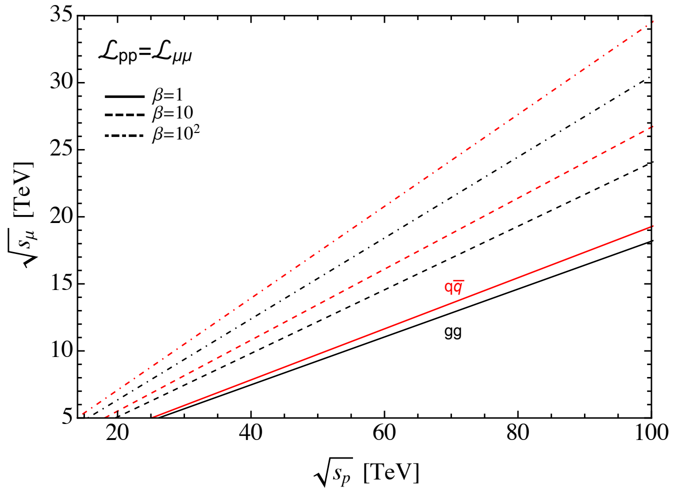


Fig. 19 Energies of equivalent event numbers, assuming equal integrated luminosities, between a high energy muon collider and a proton collider. $\beta = 1$ corresponds to the same partonic cross section between muons and proton partons. Larger values of β correspond to reduced partonic cross sections 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

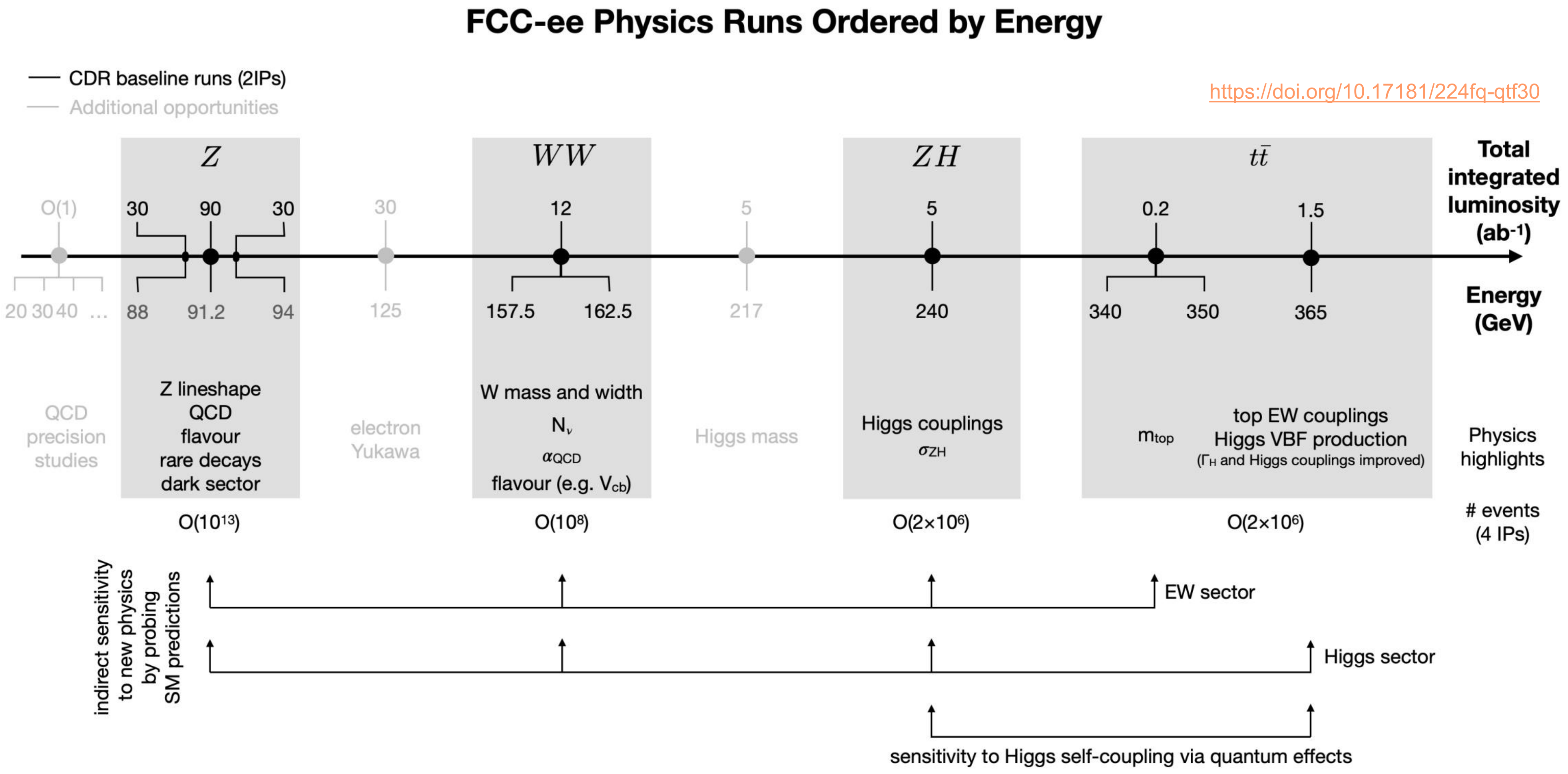
breadth of couplings that can be explored is a paramount consideration in planning for the future

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

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

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

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**
  - **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.**