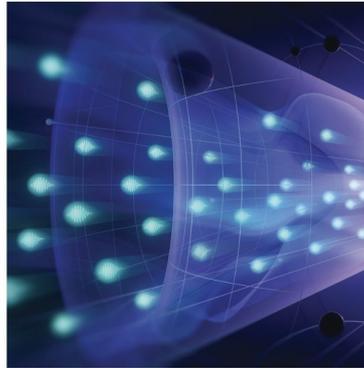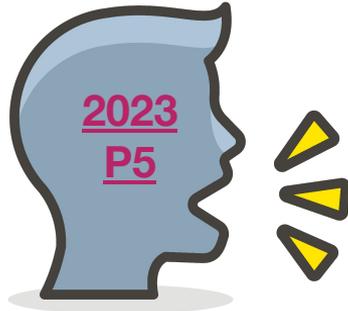# HFCC PED status & plans

Elizabeth Brost

October 10, 2025

Coordinating Panel on Advanced Detectors,
University of Pennsylvania

Brookhaven
National Laboratory

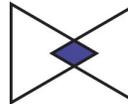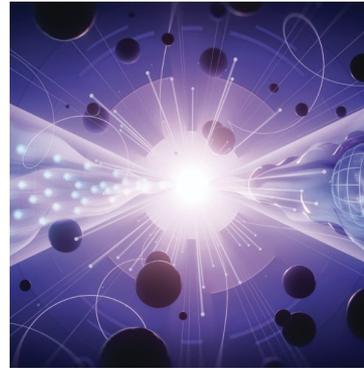# Towards a future Higgs Factory

2023 P5

Decipher the Quantum Realm

Elucidate the Mysteries of Neutrinos

Reveal the Secrets of the Higgs Boson
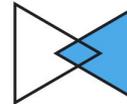
Explore New Paradigms in Physics

Search for Direct Evidence of New Particles

Pursue Quantum Imprints of New Phenomena

Illuminate the Hidden Universe

Determine the Nature of Dark Matter

Understand What Drives Cosmic Evolution

Recommendation: **"An offshore Higgs factory, realized in collaboration with international partners, in order to reveal the secrets of the Higgs boson…"**

Updates from the HFCC*

- *~~Higgs Factory Coordination Consortium~~ →
  Higgs Factory Circular Collider

  - Chaired by Tor Raubenheimer (Accelerators) and Srini Rajagopalan (Physics, Experiments, and Detectors)

- Per DOE request, shift focus to the **Future Circular Collider** (FCC-ee) at CERN

Updates from the HFCC

U.S. Higgs Factory Circular Collider Organization (presented by DOE 9/4/2025)

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Current HFCC PED structure

Introduce
L1 layer

Detector	Software & Computing	Physics	Outreach and Engagement
Tracker	Simulation	Theory	
Calorimeter	Core SW	Performance	
Muon	AI / ML	Physics studies	
TDAQ			
AIM			

Promote S&C to L1

Add "Physics" L1 area

Add "Outreach" L1 area

Workshops, communication, speakers…

(also reports to HFCC Accelerators)

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Future Circular Collider (FCC)

- Proposed 91 km collider near CERN
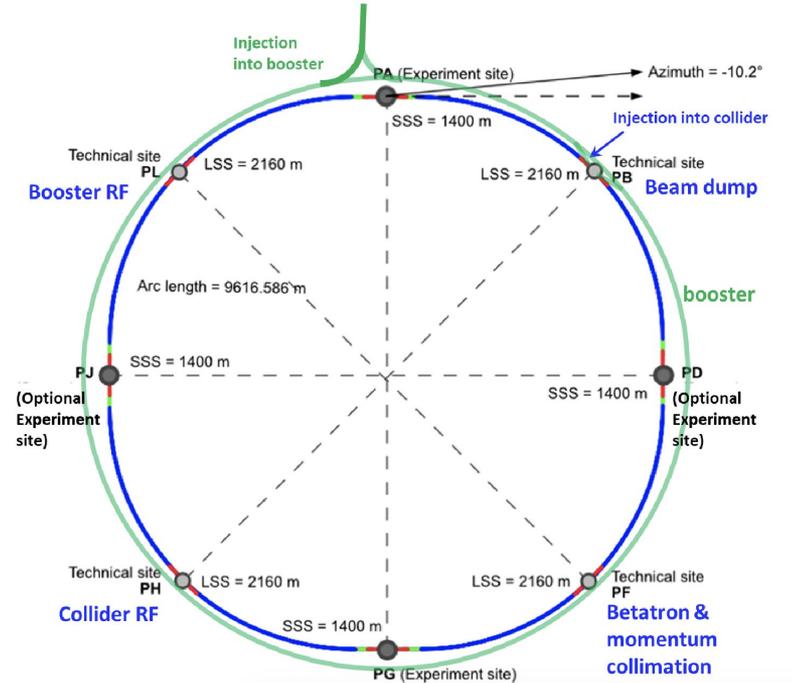 - 4 interaction points
- Planned to start shortly after HL-LHC operations
- Stage 1: e^+e^- Higgs (& electroweak & top) factory to run at 4(+) energy points
- Stage 2: O(100 TeV) proton-proton

FCC-ee baseline

FCC-ee run plan

Z (88-95 GeV) 205 ab^{-1}	WW (158-162 GeV) 19.2 ab^{-1}	ZH (240 GeV) 10.8 ab^{-1}	ttbar (345-365 GeV) 2.7 ab^{-1}

- **4 yrs @ Z (LEP1 data accumulated every 2 minutes - 10^{13} Z)**
  - Z mass, width, electroweak precision measurements, flavor

- **2 yrs @ WW (10^8 W)**
  - W mass, W width, electroweak precision measurements

- **3 yrs @ ZH (10^6 e$^+$e$^- \rightarrow$ ZH)**
  - Model-independent Higgs xs, Higgs couplings, Higgs self-coupling input

- **5 yrs @ ttbar (10^6 ttbar pairs)**
  - Top mass, top width, WW→H, Higgs self-coupling input

- **s-channel H? (5000 e$^+$e$^- \rightarrow$ H in 5? years)**

Higgs Factory

- **Major goals of the FCC-ee physics program:**
  - Model-independent measurement of the Higgs width
  - Higgs couplings to sub-percent precision
- Additional Higgs physics goals:
  - Precise Higgs mass measurement (few MeV)
  - Indirect access to Higgs self-coupling
  - Bonus: could measure electron Yukawa w/ dedicated Higgs pole run

240 GeV   **365 GeV**

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Higgs Boson decays

- H →μμ
- H →Zγ
- H →γγ
- H →ZZ
- H →cc
- H →ττ
- H →WW
- H →bb

muon system

hadron calorimeter

EM calorimeter

inner detector

muon   neutrino

b-jet
bottom quark   tau

electron   photon

Beyond a Higgs Factory

- **Tera-Z program = precision electroweak physics**
  - 10^5 increase in sample size compared to LEP
  - Improvement of ~200 on Γ_Z precision will be sensitive to new physics
- **Tera-Z will ALSO produce:**
  - A huge number of b hadrons in a very clean environment
  - An enormous sample of taus
- **Top physics @ ttbar run: top mass, width, EW couplings**
- **BSM (direct and indirect):**
  - Small deviations in SM measurements could point to new, heavy physics
  - Direct searches for e.g. long-lived particles

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Unprecedented dataset = unprecedented challenges

- **Theory systematics**
  - become a leading challenge, especially for the tera-Z program
  - beyond the scope of this talk (and this workshop); a major challenge for our theory colleagues

- **Experimental systematics**
  - need orders of magnitude better control than at LEP or LHC to complement the statistics of the tera-Z run

FCC-ee Detector Requirements

- **Higgs:**
  - Momentum resolution
  - Jet energy resolution (W/Z separation)
  - Impact parameter resolution / particle ID for b,c-tagging

- **Precision QCD, Electroweak:**
  - Luminosity determination
  - Momentum resolution

- **Heavy Flavor:**
  - Impact parameter resolution
  - ECAL resolution
  - π^0/γ separation, particle ID (K/π separation for b and τ physics)

- **BSM:**
  - Displaced tracking
  - Detector volume
  - Hermeticity

(current) FCC detector concepts

CLD

- Present in CDR;
- Based on CLIC design;
- Full-Si tracker.

IDEA

- Present in CDR;
- Drift chamber.

ALLEGRO

- New concept;
- Liquid-noble calorimeter.

ILD for FCC

- Very new concept;
- ILC design →
- TPC.

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Upcoming work in the HFCC

Tracker (Carl Haber, Christoph Paus)

- Tracker **requirements**:
  - Momentum resolution (Higgs, flavor physics)
    - Tends to be dominated by multiple-scattering → controlling the material budget is crucial
  - Particle Identification
  - (bonus) Timing

- A variety of options under consideration for different detector concepts: silicon (**CLD**), drift chamber (**IDEA**), TPC (**ILD**)

- Tracking Detectors and software workshop in May

- Activity areas: Solid state, Gaseous, Mechanics

- ***High-priority work this year: Straw tube, MAPS, Tracker Simulation, Low Mass Mechanics***

Tracker

- ***Straw tube development***
  - [Optimization](#) of detector configuration, gas mixture through simulation + tests

- ***Monolithic Active Pixel Sensors (MAPS) development***
  - Low material budget: sensors and readout electronics are integrated on the same chip
  - Tradeoff: [power vs. timing resolution](#)

- ***Tracker simulation – beam background, occupancy***
  - Serves other groups, like TDAQ for event size estimates, sample production etc.

- ***Low mass mechanics***
  - Unique US contribution
  - Leveraging ongoing activity on CMS

Calorimeter (Michael Begel, Bob Hirosky)

- Activity areas: Dual Readout, Noble Liquid, Si-W, Tile-Sci

    - **IDEA detector concept:** Dual-readout fiber calorimeter behind solenoid, with crystal ECAL in front

    - **ALLEGRO detector concept:** High-granularity noble-liquid ECAL, with TileCal HCAL

    - **CLD detector concept:** Si-W ECAL, with steel/scintillating tile HCAL

- *High-priority work this year: DR Crystal and Fiber Calo, LAr design of turbine structures*

    Advice from Charlie Young this summer re: detector design: **"Special attention for calorimeters, which are expensive and rarely replaced / upgraded (except for electronics)"**

Calorimeter

- *Dual-Readout Crystal and Fiber*
    - Integration of AI/ML (for particle flow, Cherenkov/scintillation separation)
    - Planned test beams
    - Work on simulation and reconstruction (J. Wilson's talk this week)

- *"Turbine" Noble Liquid Endcap EM Calorimeter*
    - Initial studies of the turbine concept look promising
        - can attain reasonably large sampling fraction with required depth and frequency of sampling
        - variation of sampling fraction with radius can be controlled by tapering absorbers
    - Integrated into FCC simulation framework, allowing detailed performance studies

Muons (Marcus Hohlmann, Bing Zhou)

- Muon momentum will be well-measured by the trackers at FCC experiments, so the muon system must be:
  - Able to tag (identify) muons
  - Able to catch the tails of calorimeter showers
  - Cost-effective for the large area

- Bonus capabilities offered by some muon system concepts:
  - Good enough spatial resolution to perform tracking for long-lived particles
  - Fast timing (for triggers, LLP detection)

- Activity areas: Electronics, Drift Tubes, Micro-Pattern Gaseous Detectors (MPGDs)

- ***High-priority work this year: Drift Tubes + Scintillator Strips, Precision Muon Timing and ToF-based PID***

Muons

- A combination of **drift tubes and scintillators** for a muon system is a high precision, fast timing, robust, and cost-effective option

- Near-term R&D: Build a 2*6m module and front-end readout electronics, to demonstrate spatial and timing resolution performance with test beam experiments.

Precision Muon Timing and ToF-based PID with μRWELL-PICOSEC Technology

- Detection of delayed charged particles from long-lived particle decays in muon system
- Particle identification using time-of-flight (ToF) detector outside central tracker ("barrel timing wrapper")

Design, construction, and test of 10*10cm prototype with 100 channels @ test beam next summer

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TDAQ (Zeynep Demiragli, Sasha Paramonov)

- **Trigger and data acquisition** @ FCC-ee:
  - Need to understand data rates from the sub-detectors
  - Minimize data losses and inefficiencies

- 1st international [FCC-ee TDAQ workshop](#) November 6th at CERN

- ***High-priority work this year: Development of digitization framework***

  - Current roadblock for TDAQ studies - digitization of realistic detectors in Geant4 (top priorities: tracker, forward calorimeter)

  - This work will enable:
    - Calculation of event sizes and data rates
    - Exploration of AI/ML techniques for on-detector data processing
    - Characterization and optimization of detector performance

AIM (Julia Gonski, Jim Hirschauer)

- **AI/ML** for detector design, operation including on-detector AI/ML in custom hardware

- Cross-cutting topics targeting **Integrated Detector Concepts** including simulation-based studies for optimization of physics performance, holistic optimization of subsystems into a single detector concept/design

- New **Microelectronics** technologies, including general developments in CMOS nodes for next gen detectors, silicon photonics, analog compute, new materials, etc.

- *High-priority work this year: develop AI detector optimization pipelines*

Not AIM-led, but synergistic: Machine Learning for the Front End workshop this summer

AIM Community Detector Design/Optimization "Challenge"

Goals for the "Challenge":

- Inspire the US community to contribute to **international efforts** for Integrated Detector physics studies
- Lower the barrier to entry for new groups
- Inspire new optimization and design ideas

AI-based differentiable detector optimization workflow for full detector concept studies (W. Chung)

- [Optimize detector geometry and reconstruction](#) parameters simultaneously with ML methods

In collaboration with S&C

Software and Computing (Lothar Bauerdick, Mike Hance)

- **Common software for future colliders**: Key4HEP
  - GAUDI: Event processing
  - EDM4HEP: data model
  - DD4HEP: detector description toolkit
  - Reconstruction (digi, tracking, clustering, etc)
  - US scope: DD4HEP support (I. Osborne)

- Activity areas: simulation, core software, AI/ML techniques

- *High-priority work this year: Documentation and Training support, Core software in Key4HEP, MC Production*

Software and Computing

Commission FCC Monte Carlo simulation production at US Facilities

- Two approaches, pursued in parallel:
  - Deploy FCC production tools on US resources
  - Targeted improvements to Full-Sim implementations to speed up per-event resource needs
- Include overlay of non-collision (beam/MDI) backgrounds
- Feed any necessary modifications back into FCC infrastructure
- Target 10x improvement on existing throughput for Full-Sim (& Delphes) samples

High-priority for FCC-ee studies! (see talk by Stefan Höche)

Outreach and Engagement

- Workshops and trainings
  - Tutorials on MDI, beam physics, software, simulation
  - Hackathon - gather experts and newcomers for dedicated working time

- Outreach and Engagement panel at the HF-FCC meeting in April
  - Discussed barriers to growing the US community and how to address them

See me if you want an FCC-ee sticker!

Timeline to FCC-ee

- 2025: FCC Feasibility Study Report, **Collect detector Expressions of Interest**

- 2026-7: European Strategy update

3 years from now
- **2028: Formation of four collaborations**

- 2029: Completion of HL-LHC upgrade

6 years from now
- **2031: Submit four detector CDRs**

- **2035: Four detector TDRs**

~ 15 years from now
- **2041: Start detector installation**

- Early 2040s: end of HL-LHC operations

- **2045: Start detector commissioning**

- **2048: FCC operations**

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Conclusions & next steps

- Lots of exciting work ongoing in the US HFCC PED
- **Lots of room for new people to get involved!**
  - Get in touch with the relevant L2s (listed on the slides)
  - Join our monthly meetings
  - Join our mailing list - us-hfcc@cern.ch, us-hfcc-[L2 area]@cern.ch
  - Participate in our annual meetings - next one will be Fall 2026

Third annual meeting at FNAL&ANL, April 2025

BACKUP

HFCC PED charge

Charge (Physics, Experiments & Detectors), 5/28/2024

1. **Physics and technical feasibility studies**, including any associated design and R&D efforts, to **advance various experiment detector concepts** at a future Higgs factory;

2. **Prioritization and stewardship** of the national R&D efforts should funds be identified by DOE and/or NSF;

3. **Development of the pre-project detector R&D scope** that will be required prior to DOE and/or NSF initiating any detector project at a future e+e- collider;

4. Conceptualization of the **software and computing framework** that will be needed to advance physics studies and R&D efforts; and to collect, store, and analyze the large volumes of physics data at future collider experiments;

5. In consultation with DOE and NSF program managers, **develop various funding models** that will be required to support the R&D efforts described in items (3) and (4) above; and

6. **Ensure collaborations** by the U.S. with our partners are cost-effectively carried out to advance the future Higgs factory initiatives. (CPAD, ECFA, DRD, others).

▪ Prepare the groundwork to respond to the P5 Recommendation 6a: "[Convene a targeted panel to review] the level and nature of US contribution in a specific Higgs factory including an evaluation of the associated schedule, budget, and risks once crucial information becomes available"

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HFCC PED charge

Role of the L2/L3 coordinators

- Engage the U.S. community
  - Regular meetings with community to define, prioritize and justify the U.S. scope and make the case for appropriate level of funding.
    - Organize meetings, workshops and training events as relevant.
  - Oversee the U.S. effort to meet the respective objectives and milestones.
    - ❖ Ensuring proposed work scope is cost effective and justified and exploits US strengths and capabilities.
    - ❖ Synergies with international and other partners
    - ❖ Tracking milestones and overseeing R&D efforts

- Engage the external partners
  - Coordinate the efforts with the respective DRD coordinators, other international partners incl FCC detector concepts and software/computing groups.
    - Ensure U.S. efforts are aligned with international efforts
  - Collaborate and communicate with CPAD/RDC and DRD groups.

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Updates from the HFCC

U.S. Higgs Factory Circular Collider Organization

- **U.S. FCC Joint Steering Committee:**
  - Co-Chaired by PED and ACC
  - Responsible for coordinating the strategic partnership with CERN and other major stakeholders as well as addressing issues common to ACC and PED.
- **U.S. FCC ACC (PED):**
  - ACC and PED each led by a co-Chair: Appointed by DOE
  - Each co-Chair may appoint a deputy and other members to their team as they deem appropriate.
  - Responsible for overseeing the U.S. technical efforts in Accelerator (Physics, Experiments, Detectors) and coordinating with relevant stakeholders.
  - Oversee the ACC (PED) Steering Committee respectively.
- **FCC ACC (PED) Advisory Committee:**
  - Advises ACC and PED Chairs on a number of issues including scope, prioritization, requirements and other community needs. Members appointed by respective ACC/PED chairs.
- **PED (ACC) External Stakeholders:** Additional stakeholders specific to PED and ACC.
- **U.S. – CERN FCC Coordination Committee:** Interface group to address scientific and technical R&D, priorities, and direction between the U.S. and CERN FCC managements.
- **Laboratory Coordination Group (LCG):** may be common or split PED/ACC, as needed for engagement and coordination with the DOE national laboratories.

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FCC-ee detector requirements

Performance indicator	Requirement	Physics motivation
Vertex hit resolution and material budget	$\approx 3\,\mu m$; $\approx 0.1\%\ X_0$ per layer	B-meson, Higgs-boson and τ lepton physics
Momentum resolution	$\sigma(p_T)/p_T \approx 2 \times 10^{-5} \cdot p_T(\text{GeV}) \oplus 0.2\%$	$\delta M_H = 4\,\text{MeV};\ \delta M_Z = 15\,\text{keV}$
ECAL	$\sigma(E)/E \approx \text{few}\%/\sqrt{E(\text{GeV})}$ and high granularity	B-meson, τ and EW physics, π^0 and γ reconstruction
Jet energy resolution	$\approx 30\%/\sqrt{E(\text{GeV})}$	Higgs and multi-jet events
Magnetic field stability/mapping	better than 10^{-6}	Point-to-point energy uncertainty in $\delta\Gamma_Z$
Timing resolution	tens to $100\,\text{ps}$ per track	Particle identification; δM_{HNL}
Particle identification	> 3 standard deviation π–K separation $1\,\text{GeV}$ to $30\,\text{GeV}$; standalone muon ID	$H \to s\bar{s}$; $b \to s\nu\bar{\nu}$; long-lived particle searches
Luminosity detector alignment	Position along beam line: $\delta z = 110\,\mu m$; Inner radius: $\delta R_{\min} = 1\,\mu m$	$\delta\mathscr{L} = 10^{-4}$ from Bhabha events at the Z pole energy
Data acquisition and trigger	$50\,\text{MHz}$ trigger rate and up to $25\,\text{Gbit}\,\text{s}^{-1}$ module readout	Processing of beam-induced backgrounds at the Z pole

Differences w.r.t. ILC

Although there are many things in common, there are sufficient key differences that mean we cannot merely take an ILC detector design and re-use it at FCC-ee.

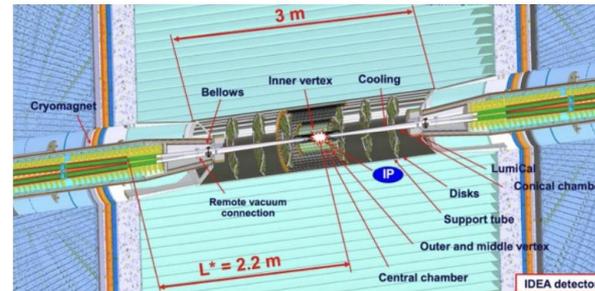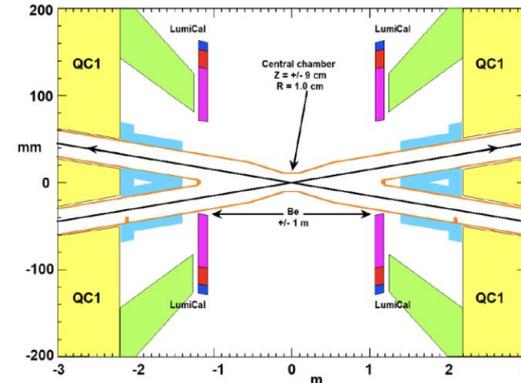30 mrad crossing angle leads to tightly packed MDI * region and limits B-field to 2T and ~100 mrad acceptance;

`Continuous' beams, with spacing down to 20 ns, means no power-pulsing and active cooling required;

Event rates of up to 100 kHz have consequences for detector response, occupancies, backgrounds *etc.*;

Higher luminosities at HZ than ILC demands better systematic control…

…which is an even greater concern at the Z, with lumis of ~10^{36} cm^{-2} s^{-1} ;
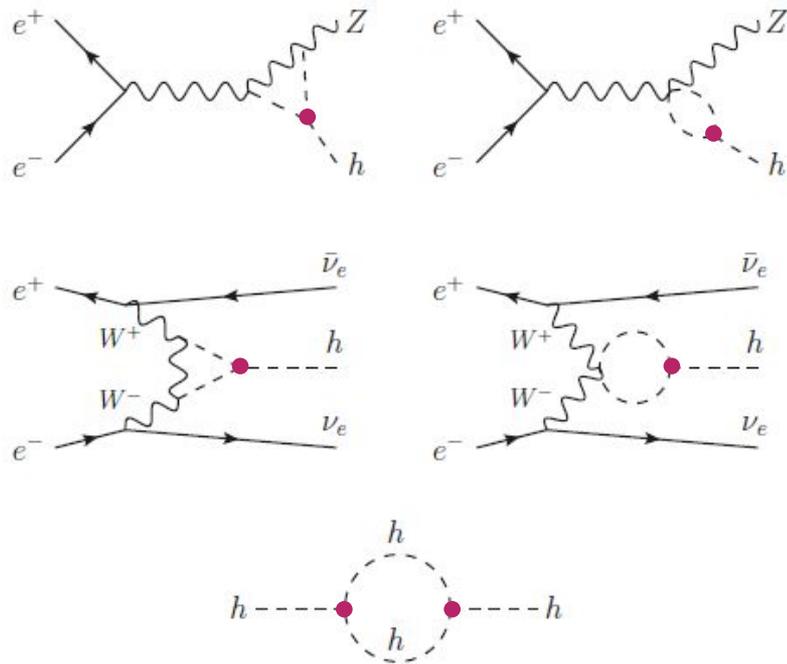
Tera-Z run, in particular, opens up many other areas of physics (*e.g.* flavour), each with their own requirements.

* MDI = machine-detector interface

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How to indirectly measure the self-coupling at a low-energy Higgs Factory?

- The FCC-ee self-coupling measurement depends mainly on measurements of the ZH and WW→H production cross sections and Higgs decays to boson pairs (ZZ and WW)

  - For example, if $\kappa_\lambda = 0$, ZH cross section increases by ~1.5% at 240 GeV

- Requires running at multiple energies (365 GeV is a must!)

Self-coupling constraints the FCC-ee

- Global fit (SMEFT)

- FCC-ee nominal run plan (incl. both the 240 and 365 GeV runs) results in 28% standalone precision on SM self-coupling

- Combining with the HL-LHC results: 18%

- Hypothetical scenario with doubled luminosity "HL-4IP" improves precision further

FCC Feasibility Study Report