

SUISSE

FRANCE

LHC

Genève

FCC

Annecy

The Future Circular Collider

Patrizia Azzi - INFN Padova

EPPSU Discussion Padova, 25/10/24

Why FCC Integrated project

Accessing two physics frontiers

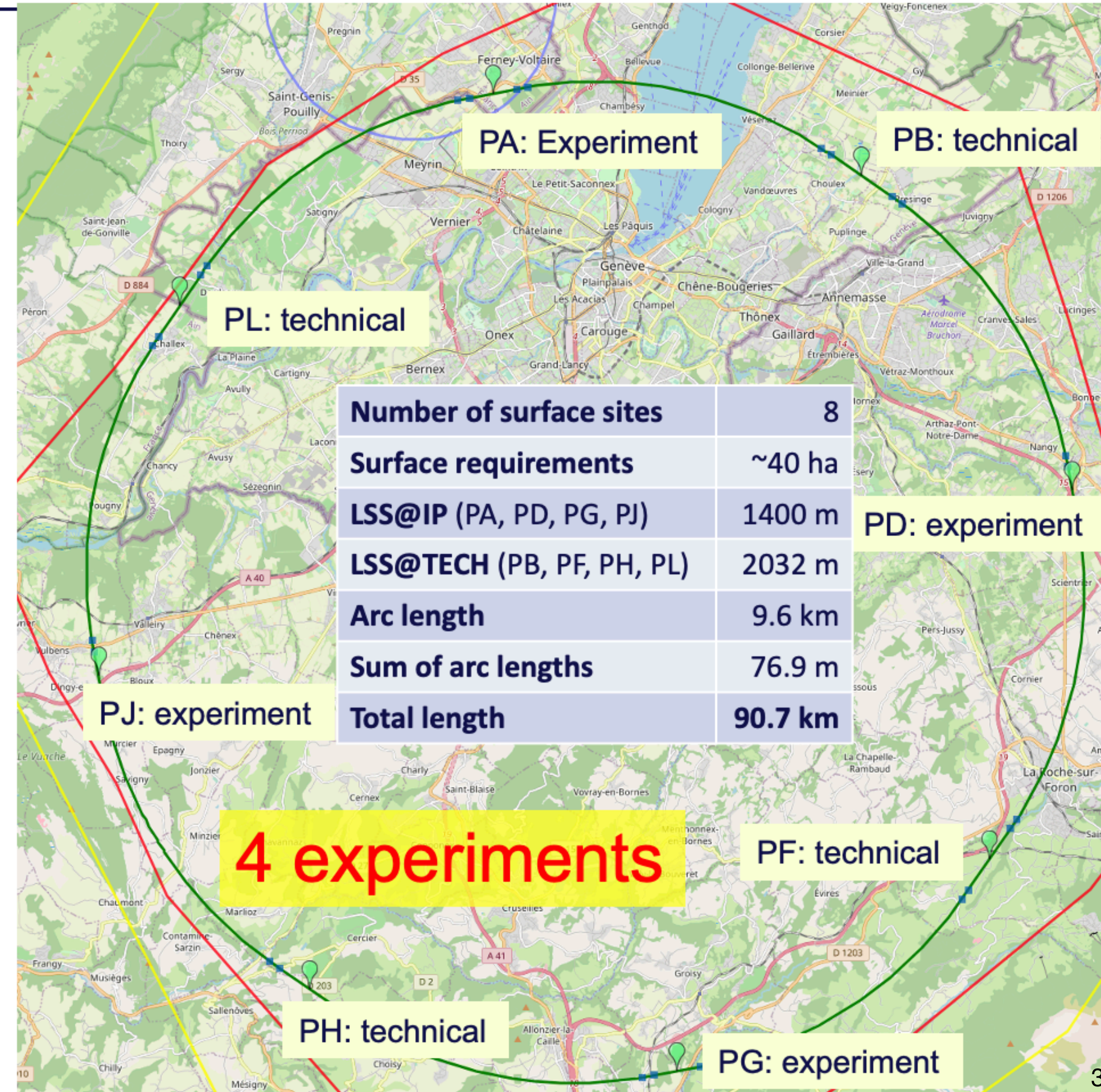
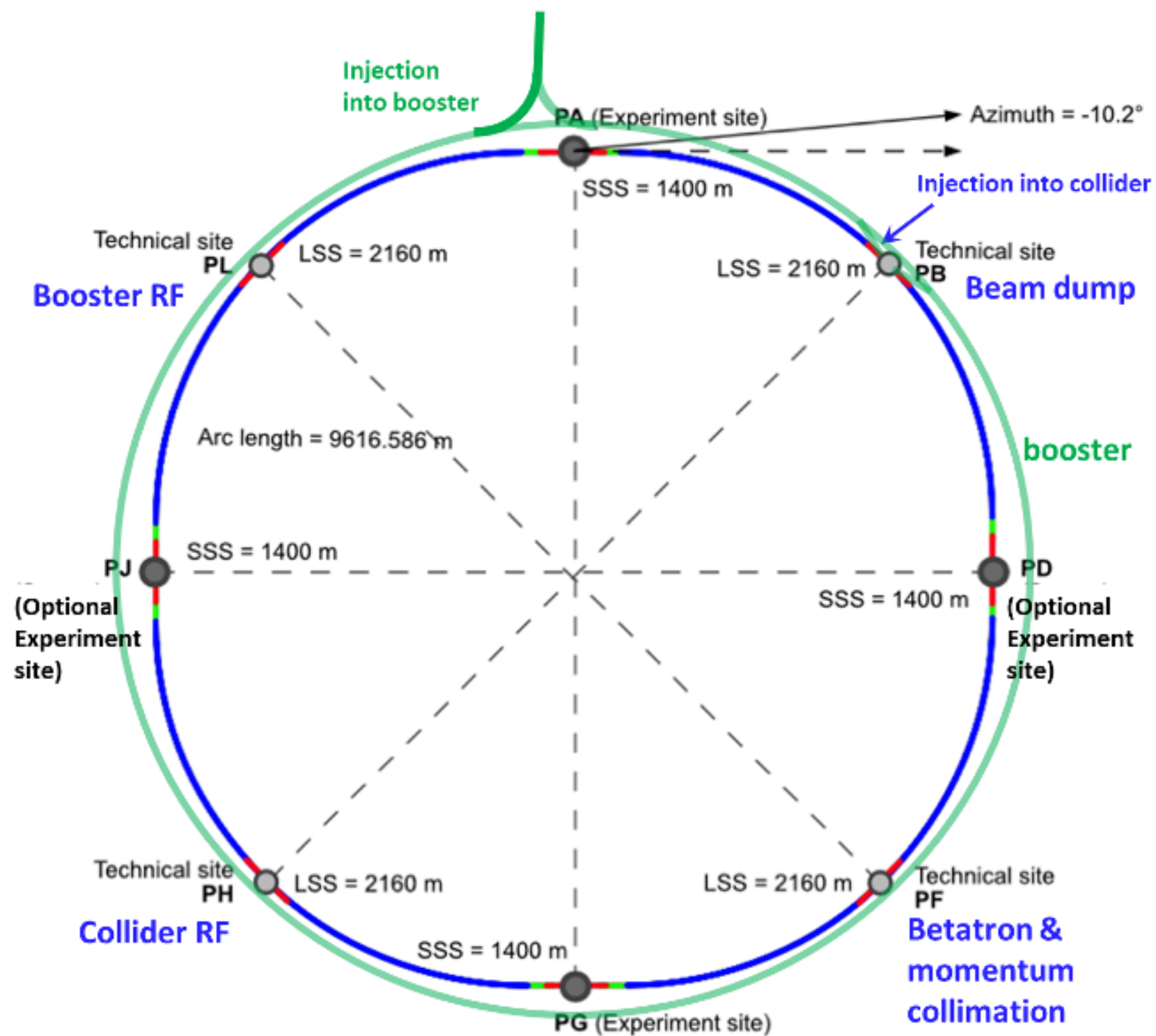
- **INTENSITY FRONTIER Precision (electron-positron)**
 - **1st stage collider, FCC-ee:** electron-positron collisions 90-365 GeV
 - Construction: 2033-2045 / Physics operation: **2048-2063**
 - *Stress-test the SM limits → Indirect / low mass BSM sensitivity*
- **ENERGY FRONTIER Discovery (hadron-hadron)**
 - **2nd stage collider, FCC-hh:** proton-proton collisions at ~100 TeV
 - Construction: 2058-2070 / Physics operation: ~ 2070-**2095**
 - *Maximizing potential for BSM discovery → Direct / high mass BSM sensitivity*

FCC baseline placement and layout for feasibility study

Layout chosen out of ~ 100 initial variants, based on **geology** and **surface constraints** (land availability, access to roads, etc.), **environment**, (protected zones), **infrastructure** (water, electricity, transport), **machine performance** etc.

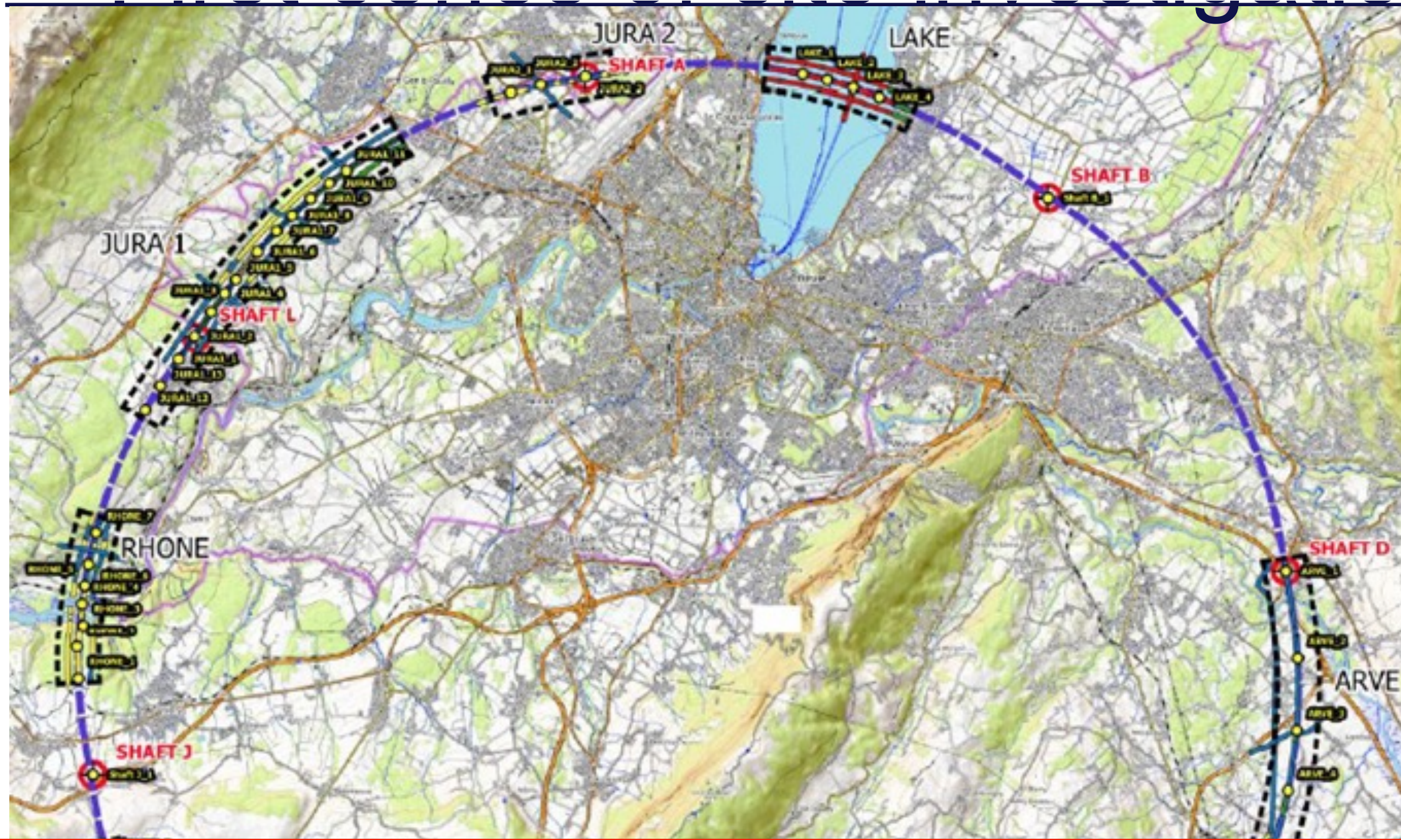
“**Avoid-reduce-compensate**” principle of EU and French regulations

Overall lowest-risk baseline: 90.7 km ring, 8 surface points,
Whole project now adapted to this placement



Feasibility study progress on implementation

Geology, drilling, logistics, politics...

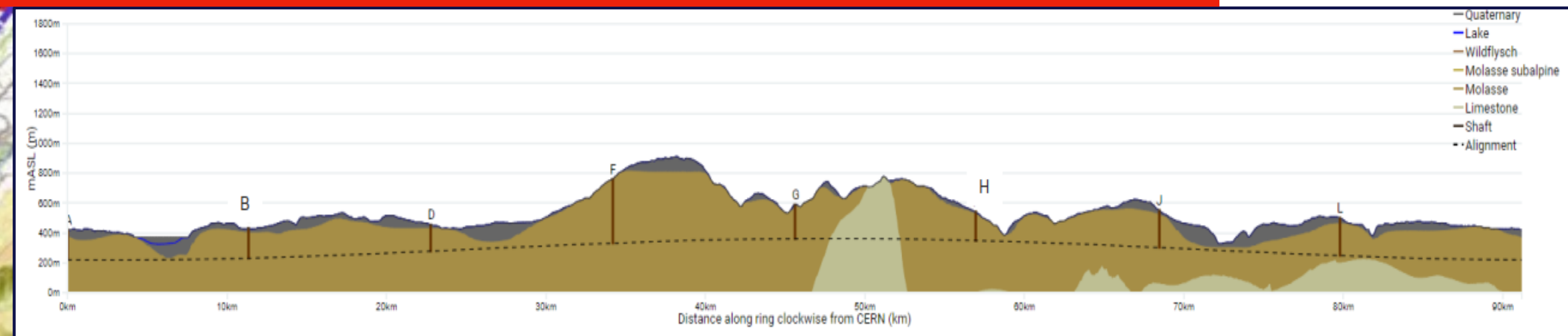


Site investigations to identify exact location of geological interfaces:

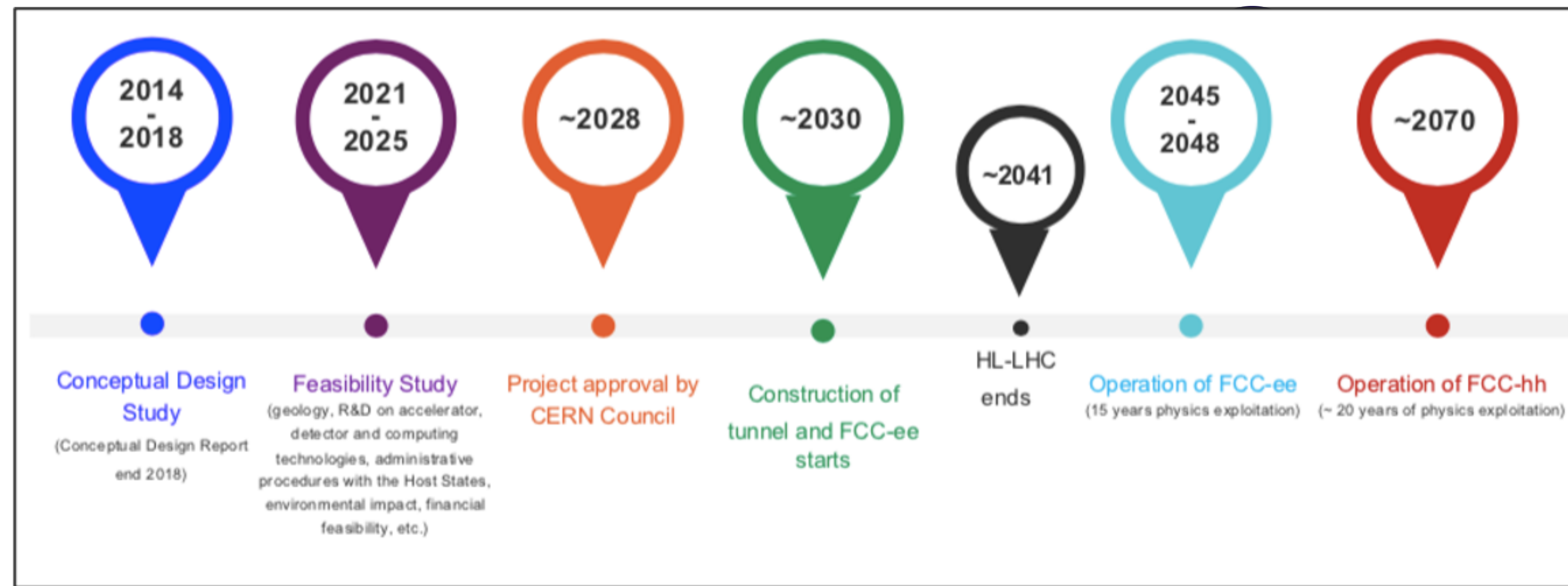
- Molasse layer vs moraines/limestone
- ~30 drillings and ~100 km seismic lines



VERY DETAILED STUDIES ONGOING



Strength In size and timescale

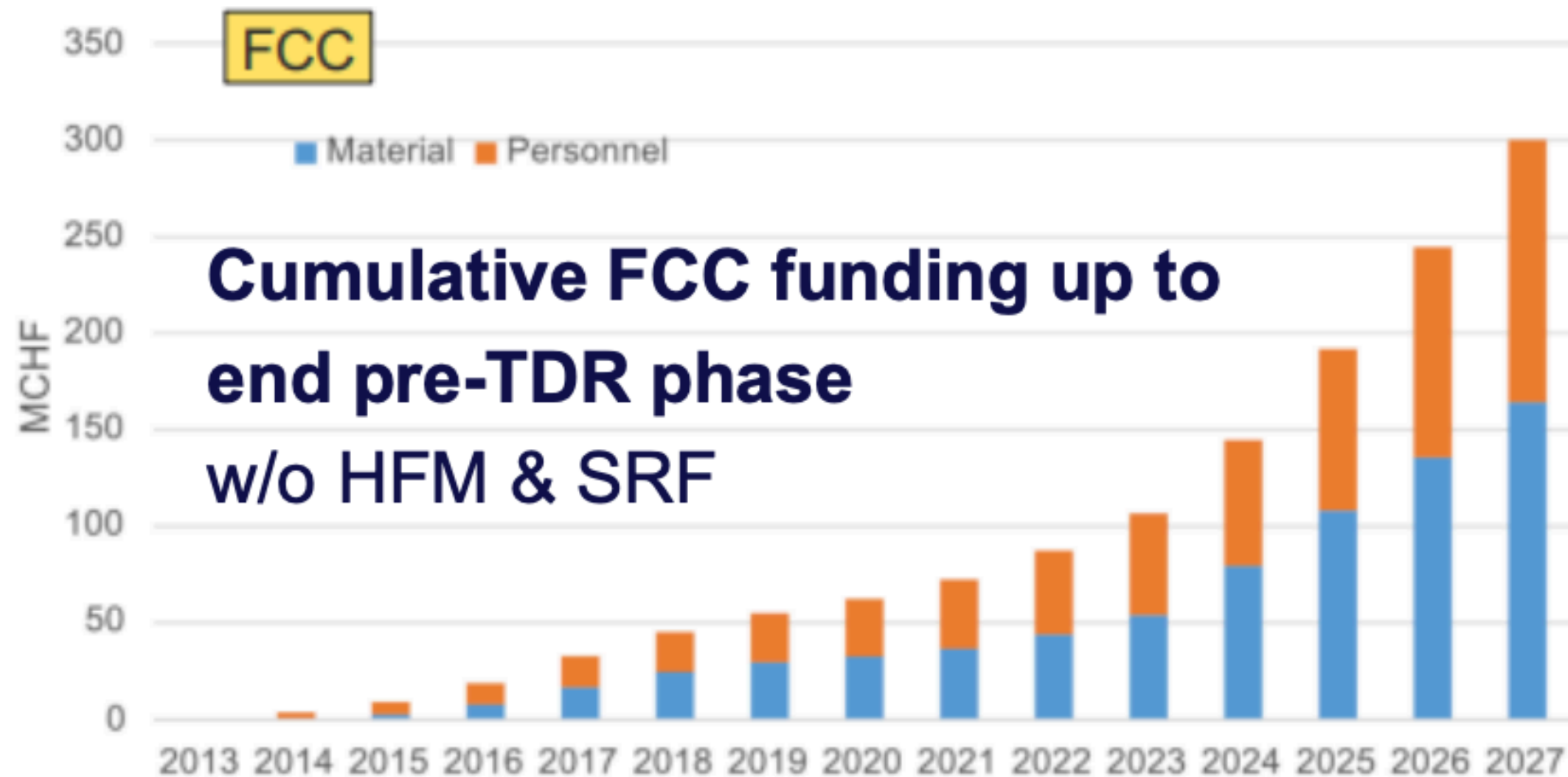


- FCC-ee technology is mature → construction in parallel to HL-LHC operation
- Physics a few years after the HL-LHC (2045-2048) ***More on timeline later***
 - Continuity of HEP guaranteed & only facility commensurate to size of community
- Two-stage approach:
 - Allows to spread the cost of the (more expensive) FCC-hh over more years
 - 20 years of R&D work towards affordable magnets
 - Optimization of overall investment by reusing civil engineering and large part of the technical infrastructure

New CERN EP-FCC group created from October 1st 2024

Recent decisions by CERN council

- **February 2024:** special Council meeting: **successful Mid-Term Review**; all objectives met, lots of praise & positive feedback, recommendations & guidance.
- **March 2024: ESPPU schedule 2025/2026** approved with input by March 2025, conclusions mid 2026; **compatible with “accelerated” FCC schedule.**
- **June 2024: approval of modified CERN Medium Term Plan (MTP), including more resources for FCC-FS completion and for FCC pre-TDR phase.**



Additional expenses in June 2024 MTP to prepare for CERN’s future.

Future Circular Collider (FCC)

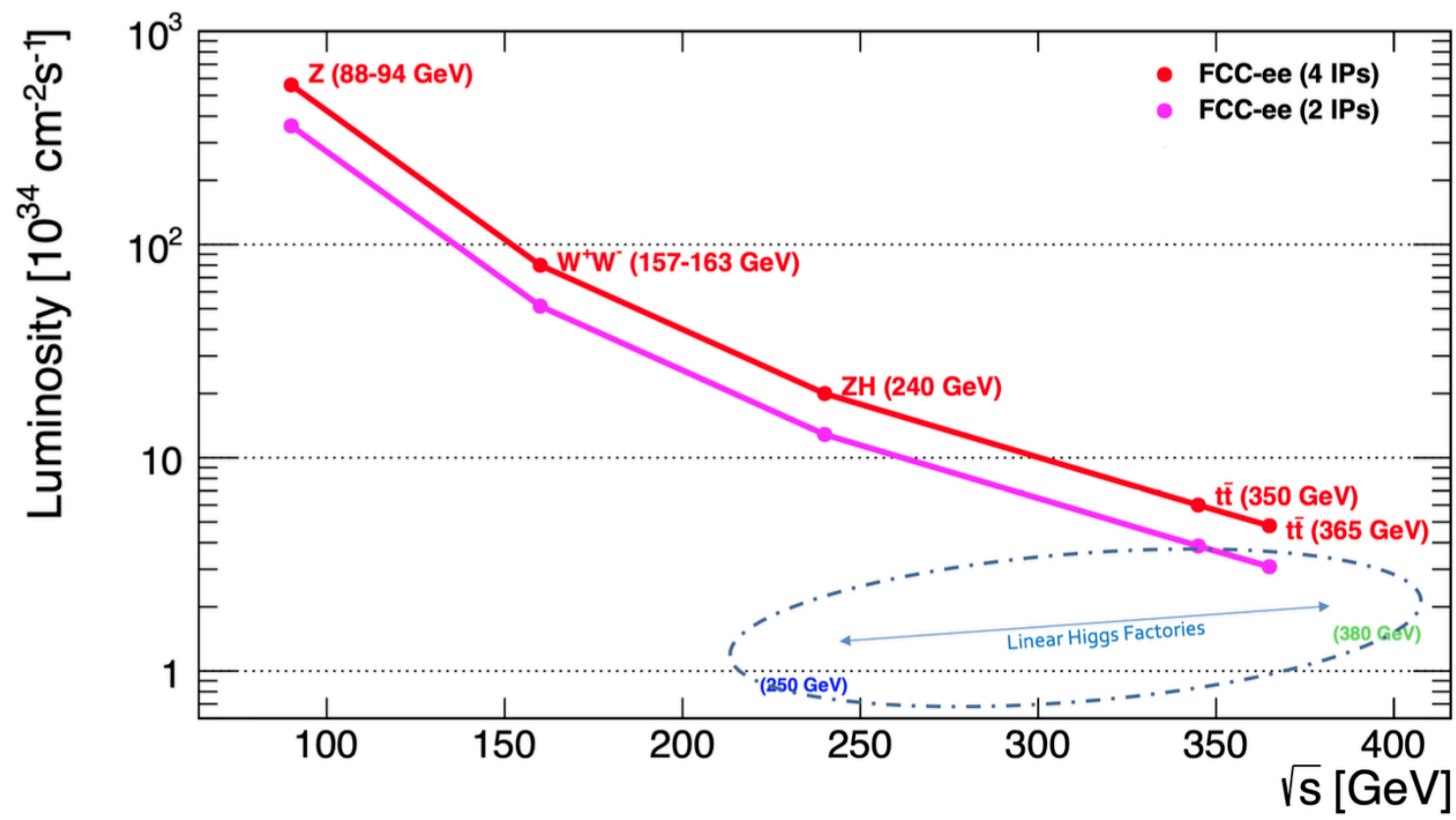
Additional resources for the Feasibility Study → 13 MCHF (until March 2025, when final report will be submitted)

Funding for “pre-TDR phase” → 82 MCHF (April 2025 - 2027)

Superconducting radiofrequency technology (SRF)

Ramp up R&D for future accelerators (until now 2.3 MCHF/year) → 9.7 MCHF (2025-2027)

FCC-ee Energy range & luminosity



LEP Data statistics accumulated every 2 minutes!

**In each detector:
10⁵ Z/sec, 10⁴ W/hour,
1500 Higgs/day, 1500 top/day**

Working point	Z, years 1-2	Z, later	WW, years 1-2	WW, later	ZH	tt
\sqrt{s} (GeV)	88, 91, 94		157, 163		240	340–350, 365
Lumi/IP ($10^{34} \text{ cm}^{-2} \text{ s}^{-1}$)	70	140	10	20	5.0	0.75, 1.20
Lumi/year (ab^{-1})	34	68	4.8	9.6	2.4	0.36, 0.58
Run time (year)	2	2	2	0	3	1, 4
Number of events	6×10^{12} Z		2.4×10^8 WW		1.45×10^6 ZH + 45k WW \rightarrow H	1.9×10^6 tt +330k ZH +80k WW \rightarrow H

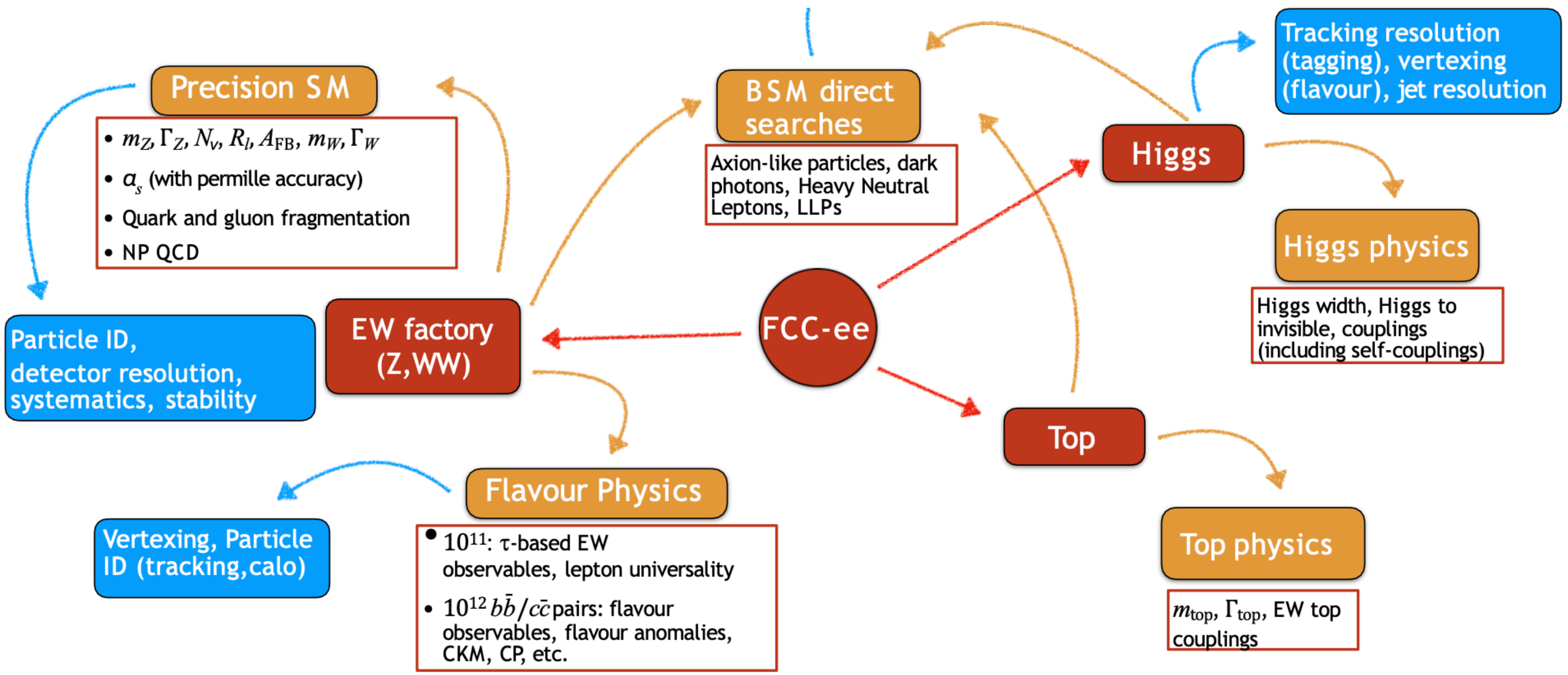
“Tera-Z”

**New Optics developed - New numbers for European Strategy document
Up to 10.8/ab at $\sqrt{s}=240\text{GeV}$ (3y)
and up to $\sqrt{s}=3/\text{ab}$ at 365 GeV(5y)**

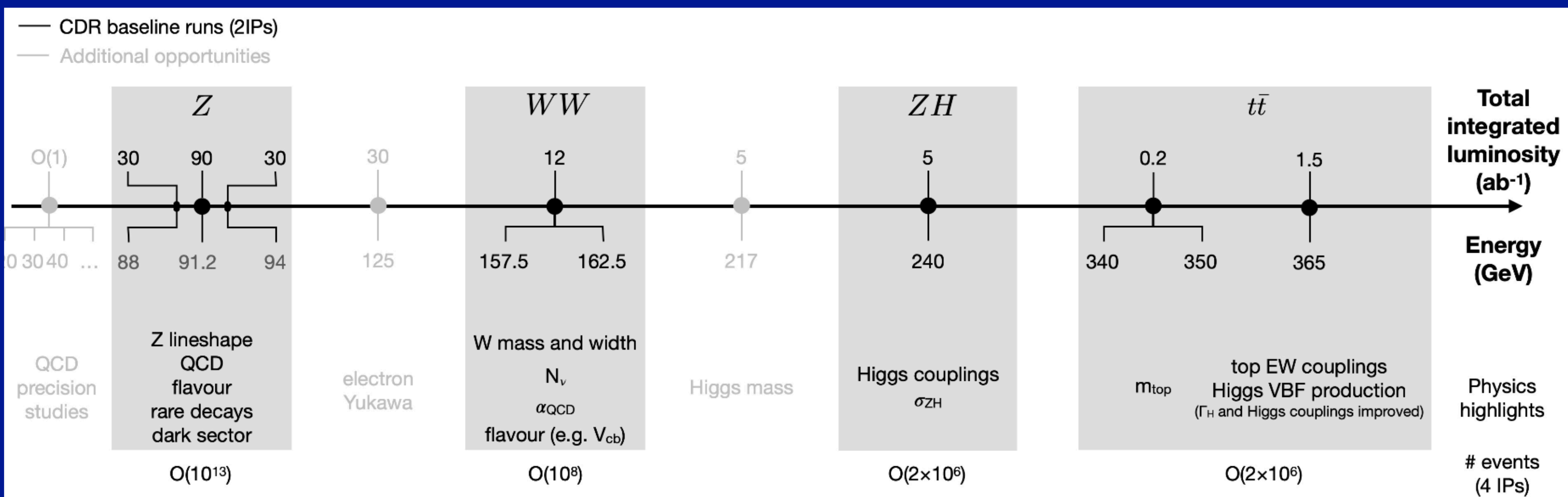
Never produced before at a lepton collider!

FCC-ee Extensive physics program

Detector hermeticity, flexibility



Flexible collider program



- **Opportunities** beyond the baseline plan (\sqrt{s} below Z, 125GeV, 217GeV; larger integrated lumi...)
- **Opportunities** to exploit FCC facility differently (to be studied more carefully):
 - using the electrons from the injectors for beam-dump experiments,
 - extracting electron beams from the booster,
 - reusing the synchrotron radiation photons.

other FCC science applications under study

for example:

FCC-ee booster as diffraction limited storage ring with coherent synchrotron radiation down to 0.1 Å

FCC-ee injector as the world's **ultimate positron source** for material studies and paving a path towards the first **Bose-Einstein condensation of Ps** (511-keV gamma-ray laser)

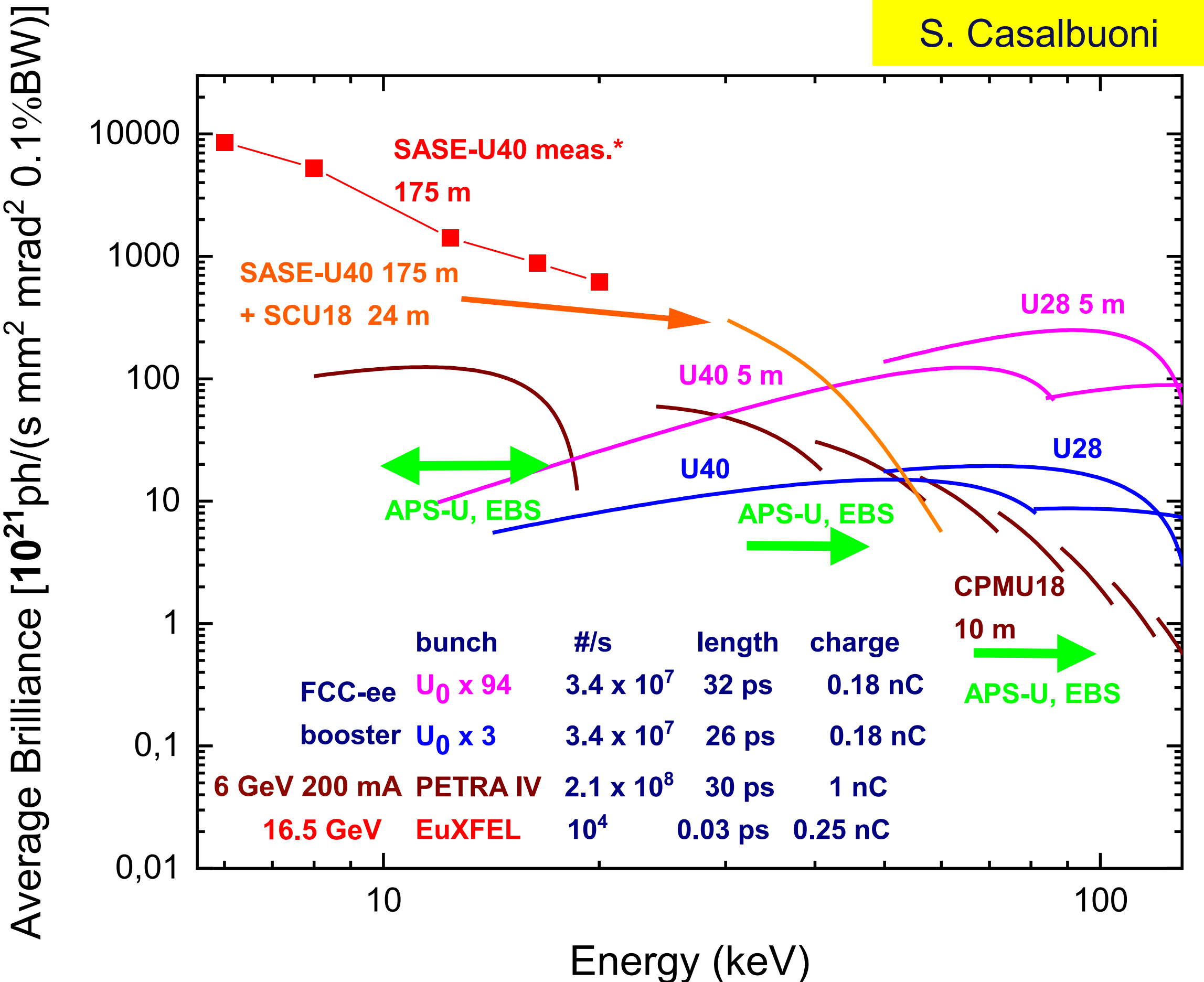
M. Doser,
B. Rienäcker

using beamstrahlung for **radionuclide production**

e⁻ beam driven **neutron source**

M. Calviani,
C. Duchemin

etc.

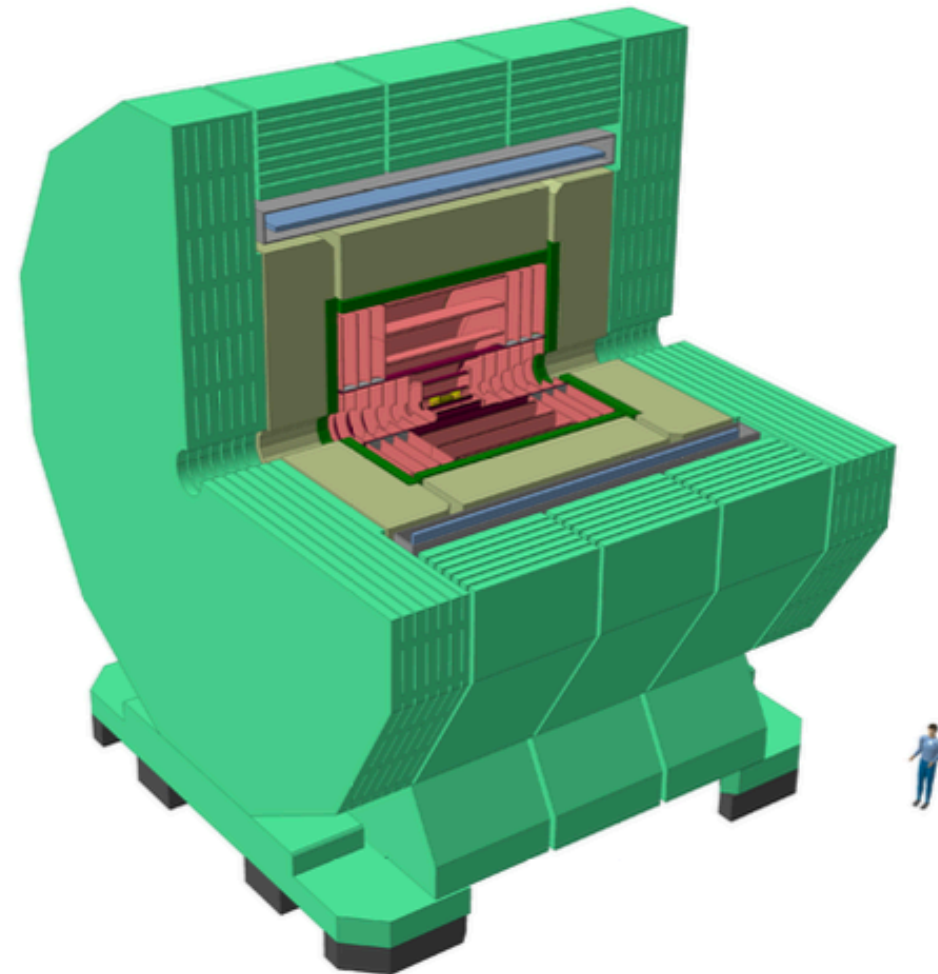


“Other Science Opportunities at the FCC-ee” 28/29 November
<https://indico.cern.ch/event/1454873/>

Some preliminary detector benchmarks for FCC-ee

CLIC-like Detector (CLD)

- Full silicon vertex-detector + tracker
- 3D high-granularity calorimeter
- Solenoid outside calorimeter



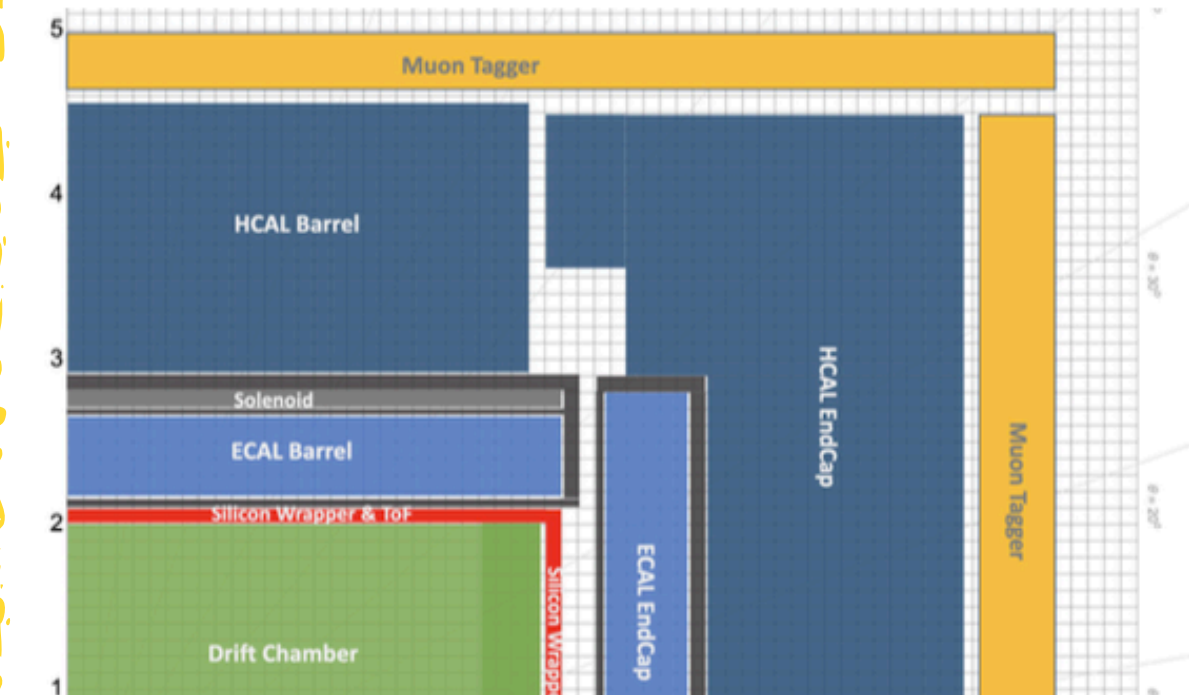
Innovative Detector for an Electron Positron Accelerator (IDEA)

- Silicon vertex detector
- Short-drift chamber tracker
- Dual-readout calorimeter (solenoid inside)



Noble Liquid

- High-granularity noble liquid calorimeter
- LAr or Lar + Lead or Tungsten absorber
- Newest proposal



INFN RD-FCC proponent and leader in the development of the IDEA concept

PD molto coinvolta in R&D per MAPS anche per sinergie con ALICE, EiC e MuColl

- In the process of extracting the requirement on the detector
- With 4IP, opportunity to have detector optimised for
- Spoiler: “Higgs factory” requirements are not the most

Higgs coupling precision expectations

Model independent

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

Table from mid-term report

- **FCC-ee: Model-independent coupling determination. Up to 10x better than LHC****
- **FCC-hh: produces over 10^{10} Higgs bosons, 10^8 ttH and 2×10^7 HH pairs:**
 - Improved precision on g_{Htt} , g_{HHH}
 - Access to Rare Decays: $\mu\mu$, $\gamma\gamma$, $Z\gamma$
- **FCC-ee + FCC-hh outstanding:**
 - All accessible couplings with per-mil precision
 - Self-coupling with few per-cent precision

****LHC is reevaluating estimates based on Run2+3 for the European Strategy**

How long would it take?

Luminosity is key

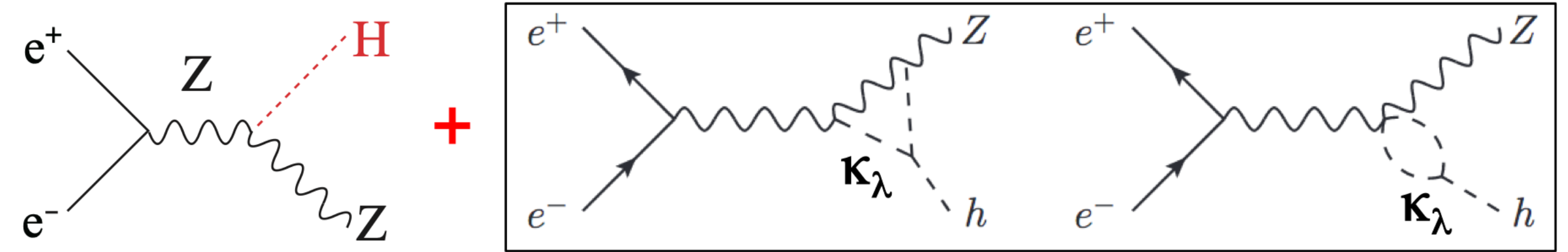
- Example for a precision on $k_Z = 0.14\%$
- For ILC@CERN need to rescale the years by 1.6/1.2

Collider	FCC-ee	ILC	CLIC
\sqrt{s} (GeV)	240	250	380
Integrated luminosity / year (ab^{-1} , all IPs)	3.6	0.21 – 0.42	0.28
Electricity consumption / year (TWh)	1.33	0.8 – 1.0	0.6
Years of operation [baseline]	3	11.5	8
Total integrated luminosity (ab^{-1}) [baseline]	10.8	2	1.5
Total energy consumption (TWh) [baseline]	4.0	10.0	4.8
Precision on κ_Z (%) [baseline]	0.14	0.31	0.42
Years of operation for a κ_Z precision of 0.14%	3	30	43
Electricity consumption for a κ_Z precision of 0.14% (TWh)	4	29	26

Higgs self-coupling with single Higgs

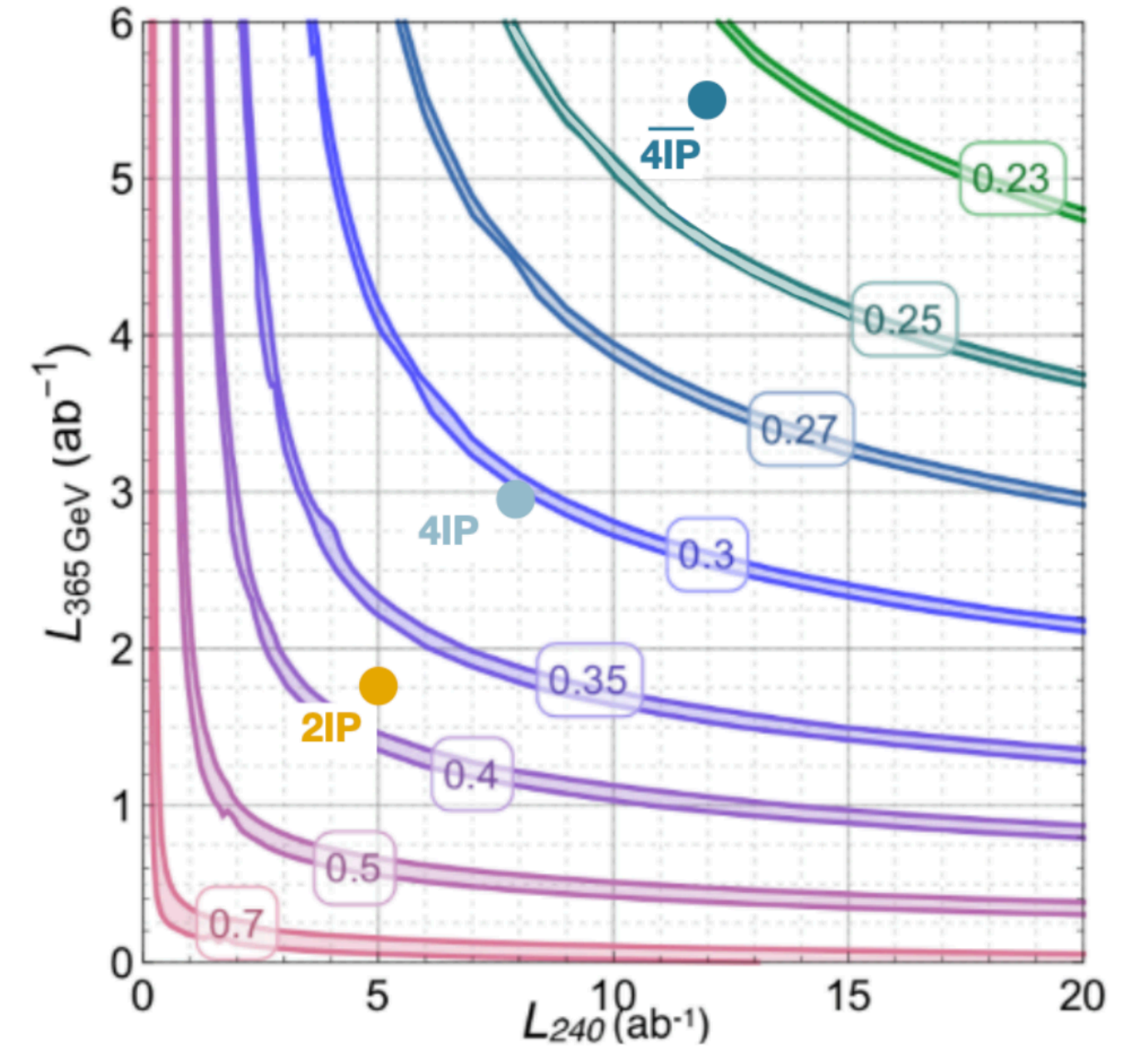
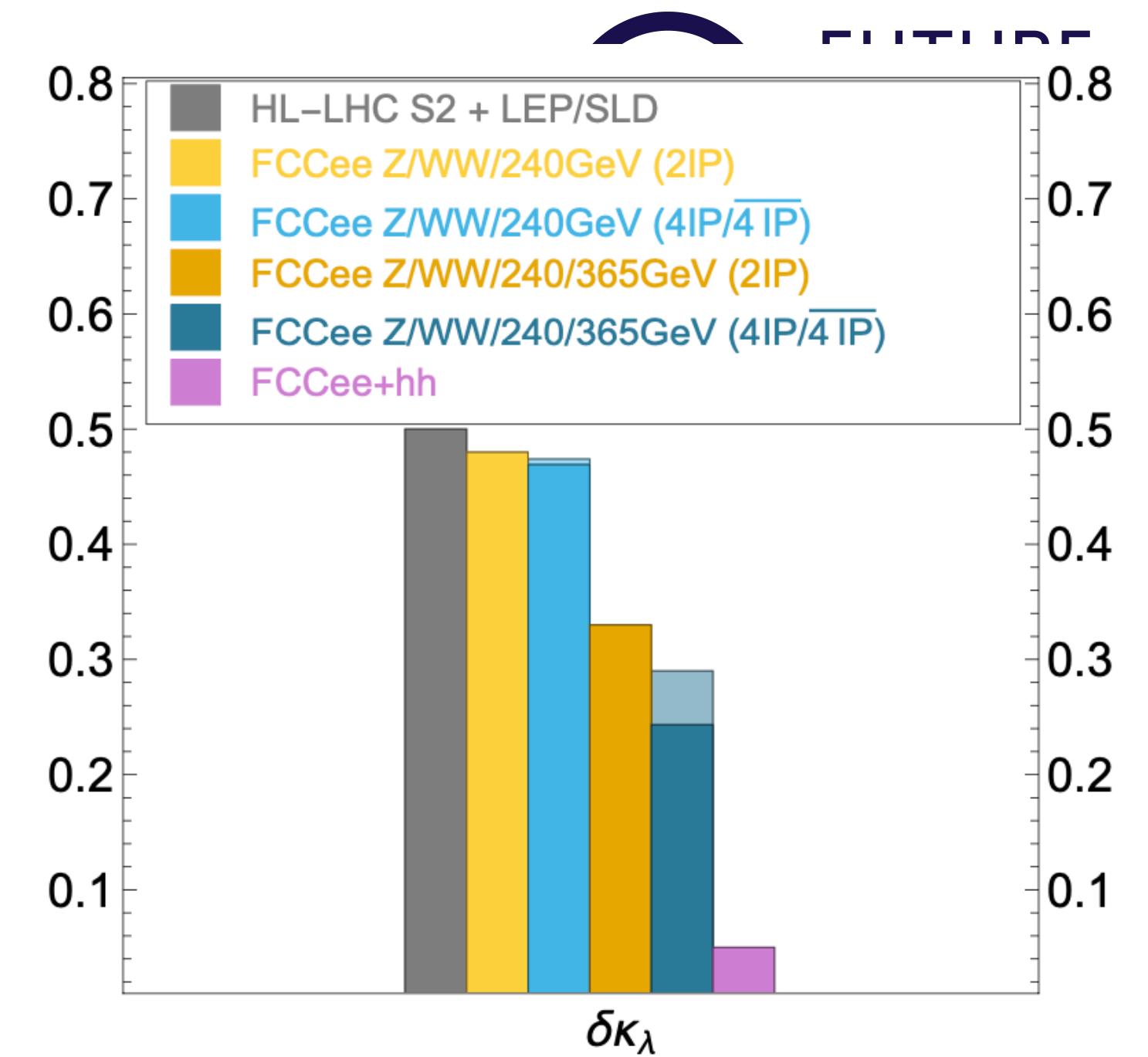
M. McCullough
arXiv:1312.3322

σ_{HZ}



$$\Sigma_{\text{NLO}} = Z_H \Sigma_{\text{LO}} (1 + \kappa_\lambda C_1) \quad \kappa_\lambda \equiv \frac{\lambda_3}{\lambda_3^{\text{SM}}}$$

- The precision of FCC-ee on the ZH cross section measurement (0.1%) allows to exploit the higher order effects from the Higgs self-coupling
- Measurements at $\sqrt{s}=240$ and 365GeV help lift degeneracy on C_1
- $\delta k_\lambda \approx 28\%$ with 4IPs (optimised scenario)



Direct search for Feebly Interacting Particles

Intensity frontier at Tera-Z offers the opportunity to directly observe new feebly interacting particles in a very clean environment

Signatures driven by search for unusual final states
Novel detector requirement to fully exploit possibilities

- Invisible final states \Rightarrow Detector hermeticity
- Sensitivity to far-detached vertices (mm \rightarrow m)
- Tracking: more layers, continuous tracking
- Calorimetry: granularity, tracking capability
- Muon detectors: standalone tracking capability
- Timing...

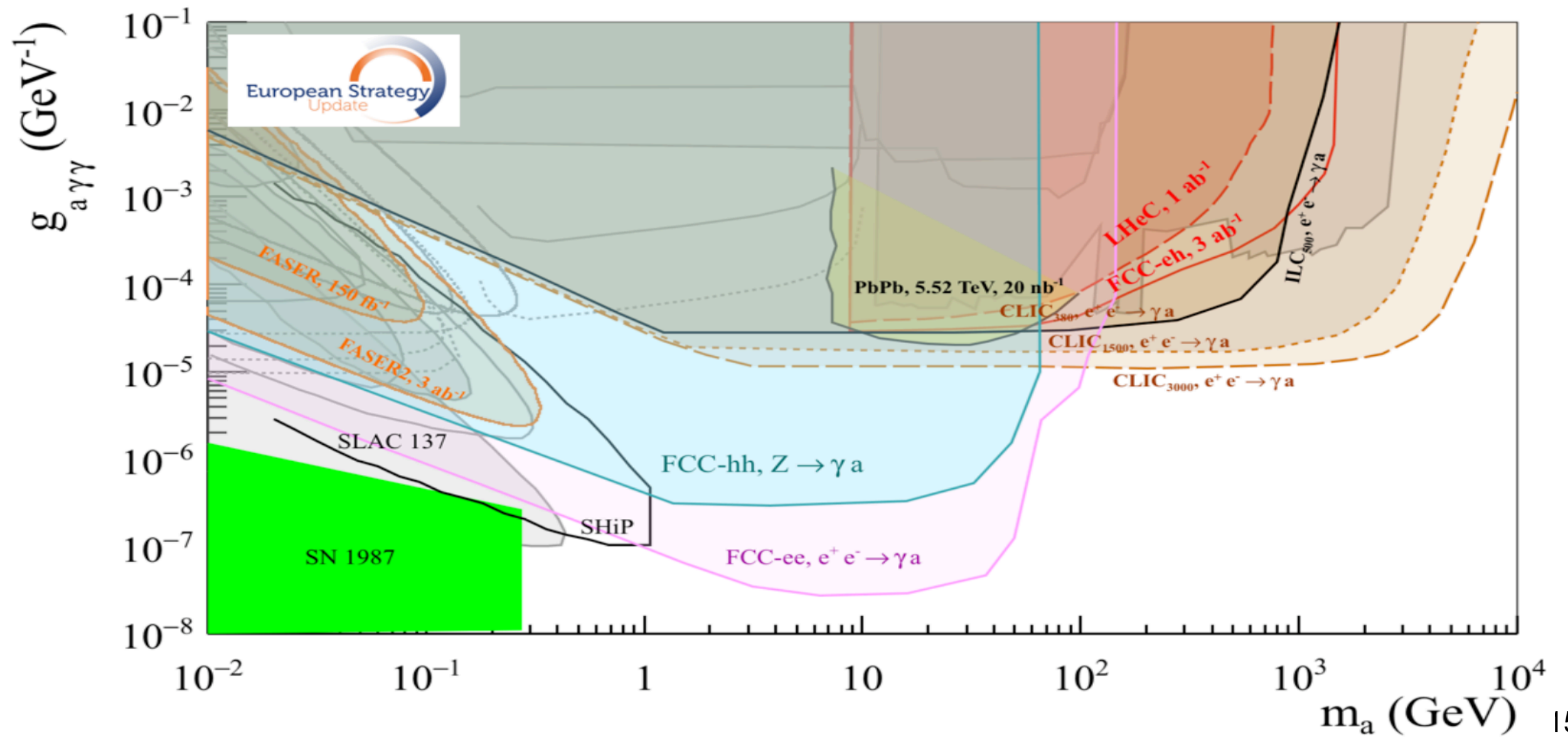
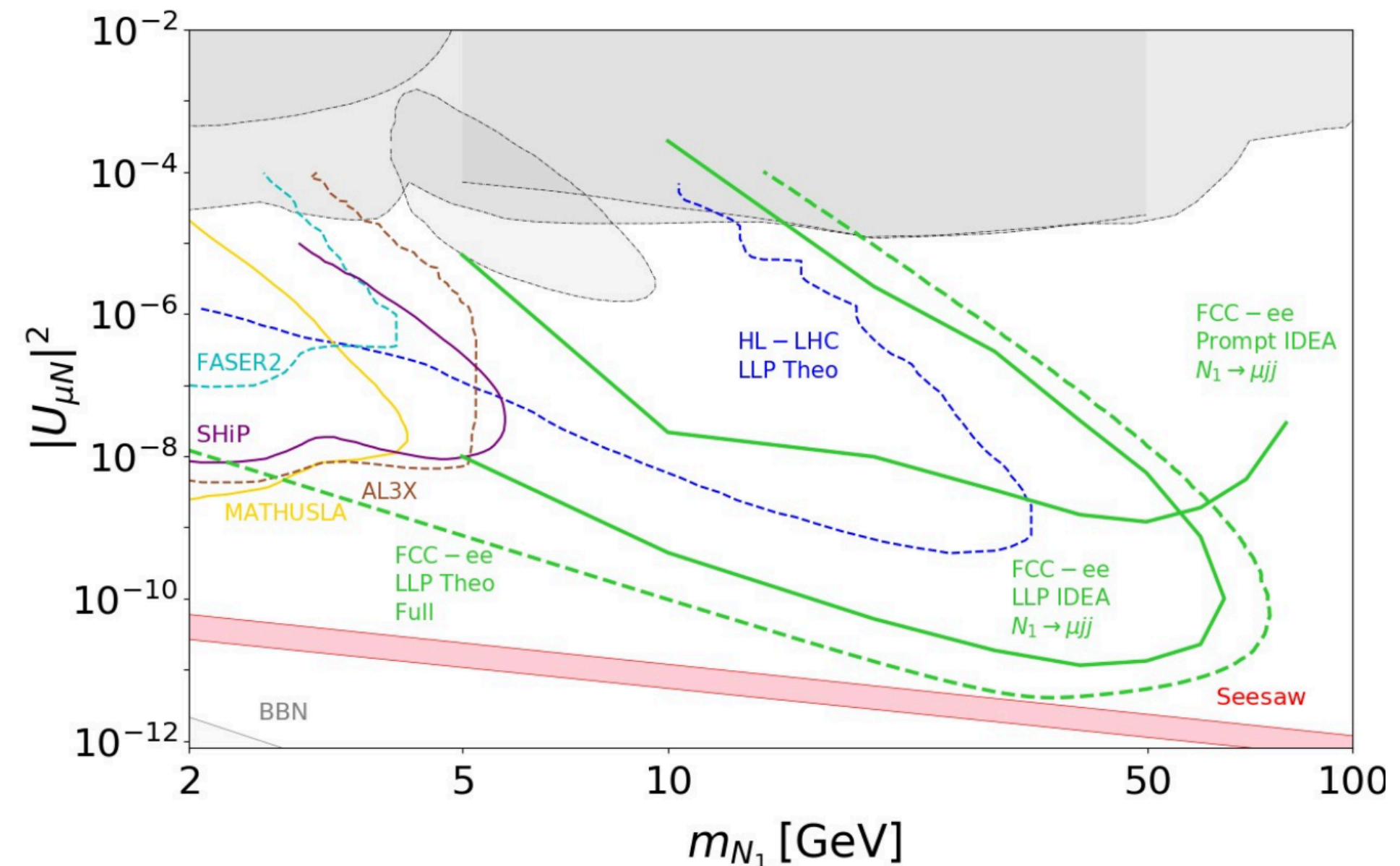
--- neutral
— charged
= any charge

disappearing track

displaced vertex

emerging jet

Not pictured:
out of time decays

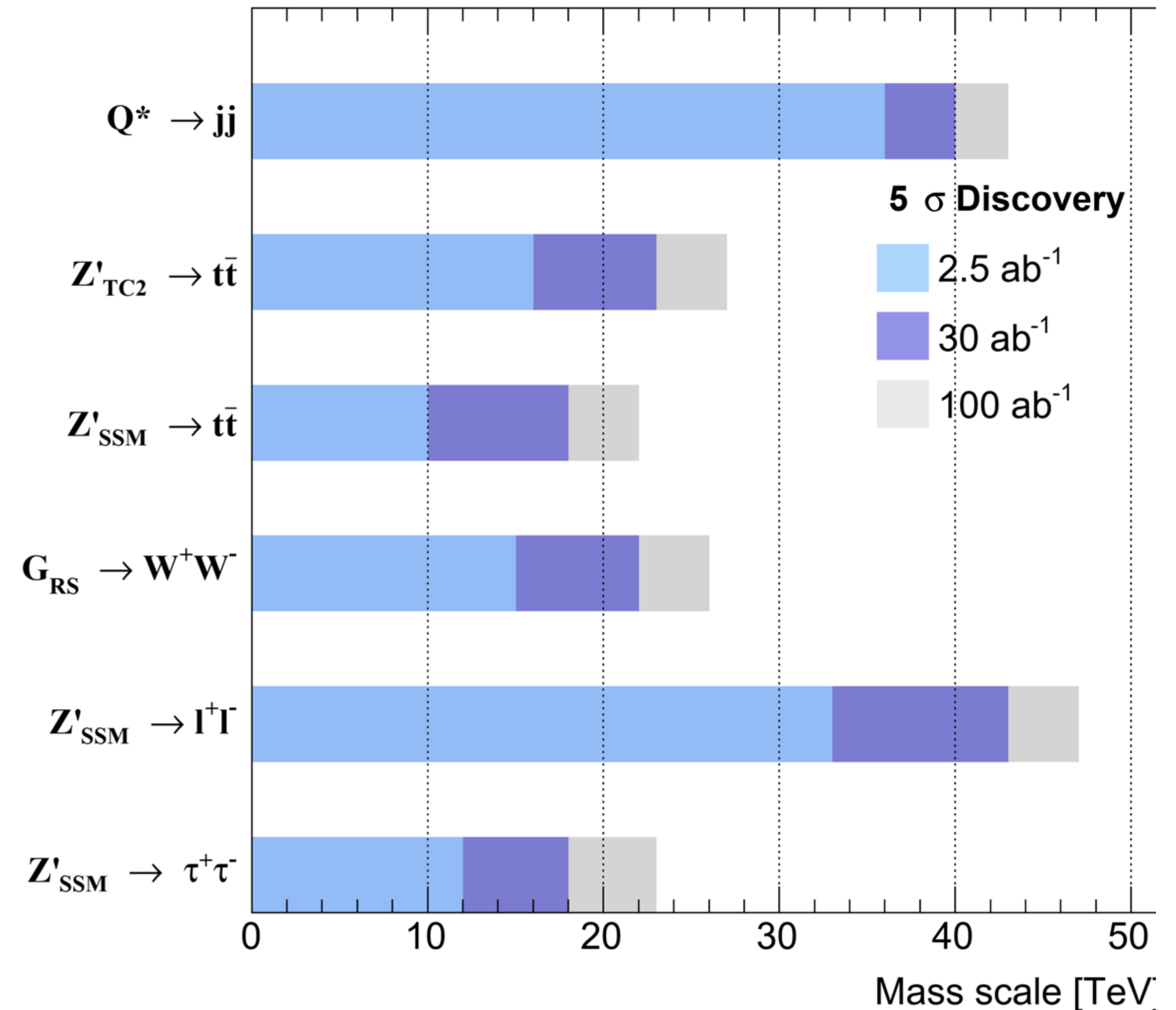


FCC-hh Direct discovery potential

- Higher parton centre-of-mass energy → high mass reach:
- Strongly coupled new particles, new gauge bosons (Z' , W'), excited quarks: up to 40 TeV!
- Extra Higgs bosons: up to 5-20 TeV
- High sensitivity to high energy phenomena, e.g., WW scattering, DY up to 15 TeV

about x6 LHC mass reach at high mass, well matched to reveal the origin of deviations indirectly detected at the FCC-ee

FCC-hh Simulation (Delphes), $\sqrt{s} = 100$ TeV



Feasibility Study Report for March 2025

Structure: Three Volumes

- *Vol. 1: Physics, Experiments and Detectors (~200 pages)*
- *Vol. 2: Accelerators, Technical Infrastructures, Safety Concepts (~400 pages)*
- *Vol. 3: Civil Engineering, Implementation & Sustainability (~200 pages)*
- **Executive Summary of the FCC Feasibility Study: ~40 pages**

Input for Update of European Strategy for Particle Physics

to be prepared with Overleaf & published by EPJ (Springer-Nature) – FCCIS members



In addition:

- Documentation on Cost Estimate – Funding Models**
- Environmental Report**

The future of European competitiveness

Part B | In-depth analysis and recommendations

Strong statement of support for CERN mission; explicit mention of the FCC Project

“One of CERN’s most promising current projects, with significant scientific potential, is the construction of the Future Circular Collider (FCC): a 90-km ring designed initially for an electron collider and later for a hadron collider. Chinese authorities are also considering constructing a similar accelerator in China, recognising its scientific potential and its role in advancing cutting-edge technologies. If China were to win this race and its circular collider were to start working before CERN’s, Europe would risk losing its leadership in particle physics, potentially jeopardising CERN’s future.

Refinancing CERN and ensuring its continued global leadership in frontier research should be regarded as a top EU priority, given the objective of maintaining European prominence in this critical area of fundamental research, which is expected to generate significant business spillovers in the coming years.”

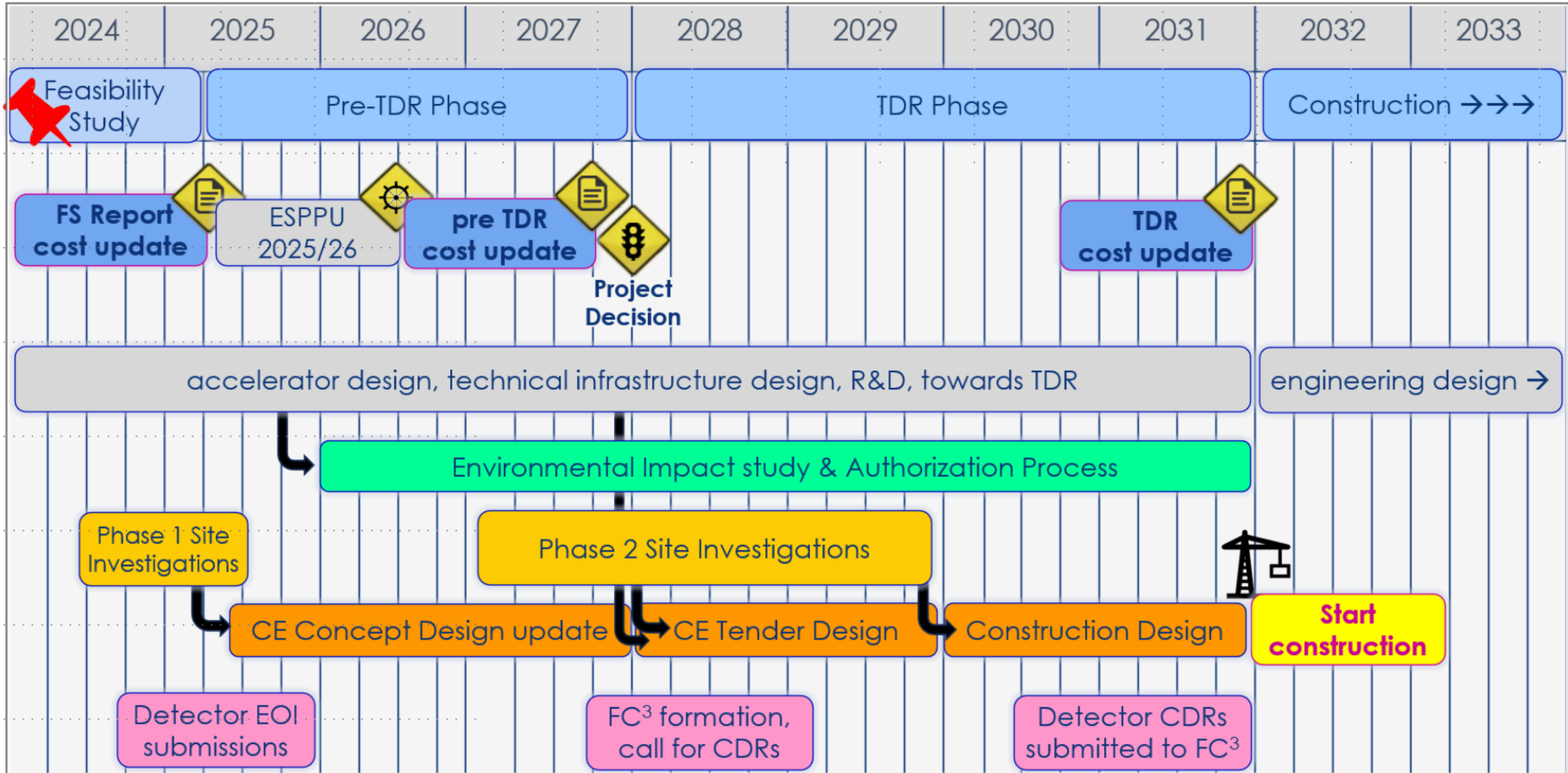
Plans for European Strategy concerning FCC

- RD-FCC:
 - EOIs for the IDEA detector concept and each of the subdetectors
- FCC (CERN)
 - Final Report of the Feasibility Study
 - Accompanied by publication of papers on analyses, software tools etc.
 - Additional studies on variations for FCC-hh energies in progress <https://indico.cern.ch/event/1439072/>
- ECFA Workshop on e+e- Factories
 - Final Report on Physics, Software and Detectors which includes contributions from FCC, ILC, CLIC, C3 etc.
- **INFN Workshop on "Future Lepton Colliders" LNF, January 22-24, 2025**



BACKUP

Tentative timeline



More questions???

- <https://arxiv.org/abs/1906.02693> “FCC-ee: Your Questions Answered”
 - Document being updated with the latest questions, such as:
 - 1) How many interaction points?
 - 2) how important are the data at and beyond the tt threshold?
 - 3) Would an ee collider inside the LHC tunnel be a viable alternative?
- 26 questions already answered. Don't hesitate to send us your own!
- Also check out the CERN Courier article: <https://cds.cern.ch/record/2893513>

SUPERCON, Inc.
Superconducting Wire Products
Standard and Speciality designs are available to meet your most demanding superconductor requirements.

SUPERCON, Inc. has been producing niobium-based superconducting wires and cables for 58 years. We are the original SUPERCON – the world's first commercial producer of niobium-alloy based wire and cable for superconducting applications.

<p>Standard SC Wire Types</p> <ul style="list-style-type: none"> NbTi Wires Nb₃Sn – Bronze Nb₃Sn – Internal Tin CuNi resistive matrix wires Fine diameter SC Wires Aluminum clad wire Wire-in-Channel Innovative composite wires 	<p>Product Applications</p> <ul style="list-style-type: none"> Magnetic Resonance Imaging Nuclear Magnetic Resonance High Energy Physics SC Magnetic Energy Storage Medical Therapeutic Devices Superconducting Magnets and Coils Crystal Growth Magnets Scientific Projects
---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------	-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------

“We deliver when you need us!”
www.SUPERCON-WIRE.com

A mission of impactful scientific fundamental research

STAY CONNECTED WITH A UNIQUE, DIVERSE, SUPPORTIVE AND LIKE-MINDED COMMUNITY

Approachable, collaborative, with a shared experience

Join now!
alumni.cern

The High Energy Physics Division
The Hadron Accelerator Division

CERN COURIER  **IOP Publishing**

VOLUME 64 NUMBER 2 MARCH/APRIL 2024

FEATURE FCC FEASIBILITY STUDY

Studies show that the FCC would deliver benefits that outweigh its costs

Taking into account the time needed to construct and operate FCC-ee and, in parallel, to develop the high-field dipole magnet technology, it is estimated that FCC-hh could begin physics operations in the early 2030s.

The cost of an FCC-ee with four interaction points is estimated to be CHF 15 billion, around a third of which is taken up by the tunnel. The reliability of the FCC-ee cost estimate will be improved following further development of the various accelerator systems and equipment required, along with the subsurface investigations starting in 2024. The final feasibility study report will also address risk management and the personnel resources required from project development to construction.

Power consumption is another topic of interest. The FCC-ee will be the largest particle accelerator ever built, with its RF, magnet and cryogenic systems drawing the main loads. The total CERN energy consumption throughout the FCC-ee scientific programme is estimated to vary between 2.0 and 2.8 TWh/year depending on the energy mode, to be compared with about 1.6 TWh/year during the High-Luminosity LHC era. The figures are hoped to be lowered as R&D (for example, to improve the performance of superconducting cavities and the efficiency of power sources) advances. The FCC study team is also working with regional authorities to identify ways in which part of this energy may be re-used for heating in local industries and public infrastructures.

Electrical power would be provided from the French electricity grid, and the system is designed such that no new sub-stations will need to be constructed between the different FCC-ee energy stages. Studies carried out in conjunction with McKinsey and Accenture indicate that by the time the FCC comes into operation, a low carbon footprint can be achieved with an energy mix that contains a large fraction of energy from renewable sources.

Return on investment

Beyond the generation of new knowledge, studies undertaken within the European Union co-funded FCC Innovation Study show that the FCC would deliver benefits that outweigh its cost. Impacts on industry from high-tech developments, the sustained training of early-stage researchers and engineers, the development of open and free software, the creation of spin-off companies, cultural goods and other factors lead to an estimated benefit-to-cost ratio of 1.66. The FCC project is linked to the creation of around 800,000 person-years of jobs, states the mid-term report, and the FCC-ee scientific programme is estimated to generate an overall local economic impact of more than €6 billion.

The mid-term report addresses the challenging R&D for the high-field FCC-hh magnets. A key deliverable of the feasibility study is a summary of R&D plans based on Nb₃Sn, high-temperature superconductors (HTS) and hybrid

FEATURE FCC FEASIBILITY STUDY

MACHINE MATTERS

From the latest accelerator designs to their estimated cost and long-term societal returns, the *Courier* gathers the key takeaways so far from the Future Circular Collider feasibility study.



It's exactly 50 years since 350 physicists and engineers met at the University of Geneva to kick-off the Future Circular Collider (FCC) study. A response to the 2013 European strategy for particle physics, the study initially examined options for an energy frontier collider in a new 80-100km-circumference tunnel. By late 2018 a conceptual design report (CDR) integrating the physics, detector, accelerator and infrastructure of a staged lepton (FCC-ee) and hadron (FCC-hh) collider was published. Two years of lengthy deliberations later, the 2020 European strategy recommended that the community 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 e+e- Higgs and electroweak factory as a possible first stage. After three years of work, mobilising the expertise of physicists and engineers from around the world, a mid-term report of the FCC feasibility study was completed in December 2023. Numerous technical documents and a 700-page overview of the results demonstrate significant progress across all project deliverables, including physics opportunities, the placement and implementation of the ring, civil engineering, technical infrastructure, accelerators, detectors and cost. No technical showstoppers have been identified, and the results were received positively by the CERN Council during a special session on 2 February. Here and in the following pages, the *Courier* gathers the key take-aways.

A collider for the times

The scientific backdrop to the FCC is the existence of a 125 GeV Higgs boson together with nearly 95% of new elementary particles at the TeV scale – transformational discoveries by the LHC that call for a broad and versatile exploration tool with unprecedented precision, sensitivity and energy reach (p96). An untold amount of work has led to an optimal placement of the FCC ring, surface sites and project implementation with CERN's host states (p27). The 90.7 km FCC tunnel, constituting a major global civil-engineering project in its own right, is well understood (p55). Assuming a decision to advance to the next

Scalar adventure

A sketch of the FCC-ee accelerator in its tunnel. (Credit: Polar Medici)

THE AUTHOR
Matthew Chalmers editor

FEATURE FCC FEASIBILITY STUDY

WHERE AND HOW?

An update on the latest progress in optimising the placement of the FCC ring, taking into account scientific output, territorial compatibility and implementation risks.

Designing a next-generation collider with a performance that meets the scientific demands of the particle-physics community is one thing. Ensuring its territorial compatibility, technical feasibility and cost control is quite another. A core element of the FCC feasibility study is therefore the placement of the ring and the necessary surface sites, for which an iterative approach in collaboration with CERN's host states, France and Switzerland, has been adopted from the outset.

Territorial compatibility requires numerous natural, technical, urban and cultural constraints to be identified and considered. The goal is to limit the consumption of land, keep the quantity of excavated materials to a minimum and re-use as much as possible, minimise the consumption of resources such as electricity and water, avoid visibility, noise and dust nuisances, and create synergies with future neighbours where possible. Following eight years of intense study, one configuration was identified out of some 100 variants as being particularly suitable. This scenario has a circumference of about 90.7 km, eight surface sites and permits the installation of up to four experiments.

During 2023 this reference scenario was reviewed out of its integrated geographicality with the existing CERN accelerator complex, with beam transfer possible from either the LHC or via the SPS tunnel.

The feasibility study, carried out with relevant consultancy companies, confirms the technical feasibility of all eight surface sites and the underground works. Working meetings with all the municipalities affected in France and Switzerland have not revealed any showstoppers so far, even if decisions by municipalities and the host states are yet to be taken. Next steps include the detailed integration of the surface sites in the environment.

Timescales are critical to be able to continue with such studies. By the end of the feasibility study in 2025, all land plots that are required by the project need to be communicated to the host states. In addition, a formal environmental evaluation phase in both France and Switzerland is necessary for the authorisation procedures. These activities rely on an agreement between CERN and the host states on the steps to be made by each stakeholder, including the associated legal and regulatory conditions.

Throughout all studies, CERN has been accompanied by the services of the Swiss and French authorities as dif-



In the zone

More than 100 placement scenarios with different layout geometries and surface sites have been analysed.

Is a LEP3 viable option?

An e⁺e⁻ in the LHC tunnel

- In principle it is possible to run at the Z, WW, Higgs, up to $\sqrt{s}=240\text{GeV}$
 - some civil engineering needed, more RF cavities. more power etc.
 - running at top threshold probably not viable or very very expensive
 - no transverse polarization for beam calibration possible
- Conclusion (main points):
 - the EWK precision program ~not possible (without the improvements on the parametric uncertainty on top mass, W mass and α_{QED})
 - Higgs self-coupling from single Higgs at 24% not possible as need run at a second \sqrt{s}
 - Reduction in luminosity: 16years FCC --> 80 years LEP3 significantly reduces the "Z pole" sensitivity
- Additional drawback:
 - LEP3 would not start earlier than a FCC in a new tunnel the LHC tunnel (bc of the needed civil engineering work)
 - the LHC would not be a possible injector for a higher energy hadron collider

FCC Feasibility Study Midterm Cost Estimate

- Total cost for Z, W, and ZH run with two IPs estimated to 12,801 MCHF
 - Accelerator: 3,847 MCHF
 - Injector & transfer lines: 585 MCHF
 - Civil engineering: 5,538 MCHF
 - Technical infrastructure: 2,490 MCHF
 - Territorial development 191 MCHF
 - CERN contribution to experiments: 150 MCHF

- Additional cost for two further IPs is estimated to 710 MCHF

- To operate FCC-ee at the top-pair threshold would require an additional investment in RF equipment and cryogenics of 1,465 MCHF



Additional studies for various FCC-hh configurations

Higgs couplings beyond precision reach of H factory

Coupling precision	100 TeV CDR baseline	80 TeV	120 TeV
$\delta g_{H\gamma\gamma} / g_{H\gamma\gamma} (\%)$	0.4	0.4	0.4
$\delta g_{H\mu\mu} / g_{H\mu\mu} (\%)$	0.65	0.7	0.6
$\delta g_{HZ\gamma} / g_{HZ\gamma} (\%)$	0.9	1.0	0.8

Higgs self-coupling

Det performance/systematics scenarios

<https://arxiv.org/abs/2004.03505>

- I. Target det performance: LHC Run 2 conditions
- II. Intermediate performance
- III. Conservative: extrapolated HL-LHC performance, with today's algo's (eg no timing, etc)

$$\frac{\sigma_{HH}(80\text{TeV})}{\sigma_{HH}(100\text{TeV})} \sim 0.72 \Rightarrow \text{reduce } \delta_{\text{stat}} \text{ by } 15\%$$

$$\frac{\sigma_{HH}(120\text{TeV})}{\sigma_{HH}(100\text{TeV})} \sim 1.3 \Rightarrow \text{increase } \delta_{\text{stat}} \text{ by } 15\%$$

$\delta\kappa_{HHH} (\%)$

100 TeV	s I	s II	s III	80 TeV	s I	s II	s III	120 TeV	s I	s II	s III
stat	3.0	4.1	5.6	stat	3.5	4.7	6.4	stat	2.6	3.6	4.9
syst	1.6	3.0	5.4	syst	1.6	3.0	5.4	syst	1.6	3.0	5.4
tot	3.4	5.1	7.8	tot	3.8	5.6	8.4	tot	3.1	4.7	7.3

Remarks:

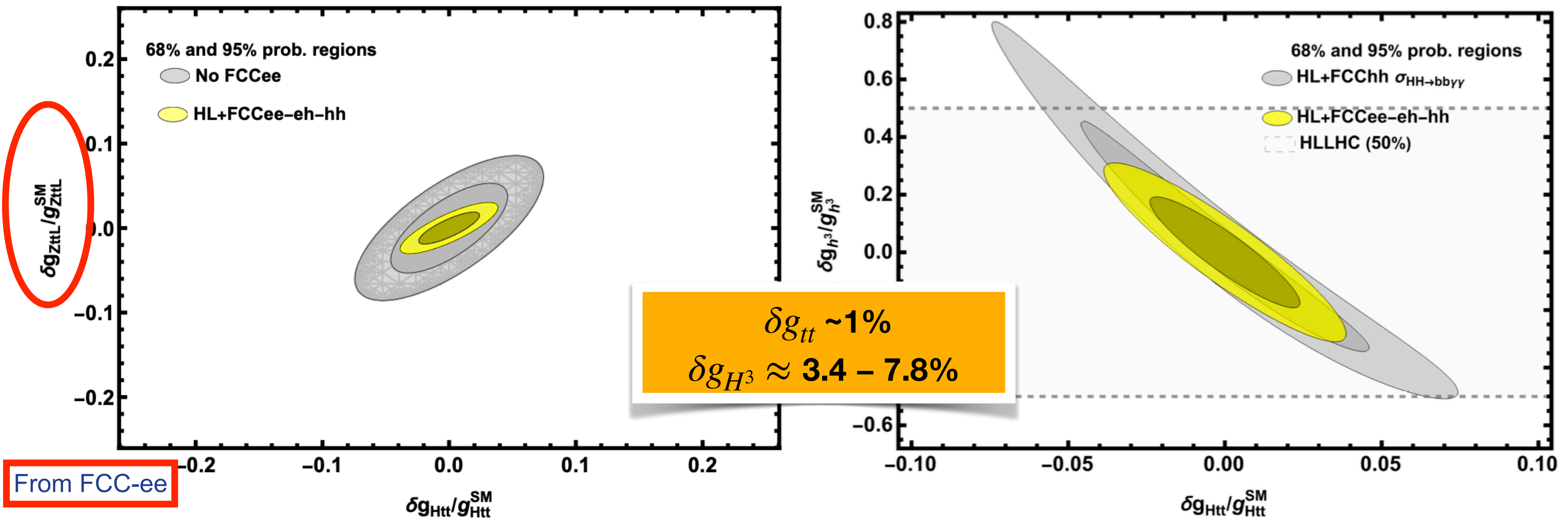
- Similar +/- 15% changes for Htt coupling
- Differences within the uncertainty range of detector performance. **Run 2 performance** keeps $\delta\kappa_{HHH}$ well below 5%

100 vs 80 vs 120: remarks

- For the key “guaranteed deliverables”, the difference between 100 and 80 TeV is comparable to the detector performance projection uncertainties. The loss in rate is in the range of 20-30% for key observables, with minor impact on measurements that by and large tend to be systematics-dominated
 - ➔ **improving detector performance brings more than increasing E**
- Discovery reach at the largest masses vary at the level of -20% to $+15\%$ for the 80 and 120 TeV options. No obvious case today of critical thresholds to push for, or exclude, either option.
 - ➔ unless a specific BSM case arises, the upgrade from 80 (or 100) to 120 TeV doesn't lead to clear progress justifying the potential cost and refurbishment time loss: running at 80(100) TeV longer might be wiser ...
 - ➔ **the decision of 80 vs 120 vs 100 is probably final, and unlikely to lead to an upgrade path**

FCC-ee & FCC-hh complementarity - k_t and k_λ

- The determination of the Ztt couplings from $e^+e^- \rightarrow t\bar{t}$ during the 365 GeV run of the FCC-ee, in conjunction with the ttH/ttZ FCC-hh would help to **reduce the few per-cent uncertainty on δg_{tt} from the HL-LHC to $\sim 1\%$** .
- Current estimates suggest that a precise determination of the self-coupling with an uncertainty of 3.4 – 7.8% would be within the reach of the 100 TeV pp collider

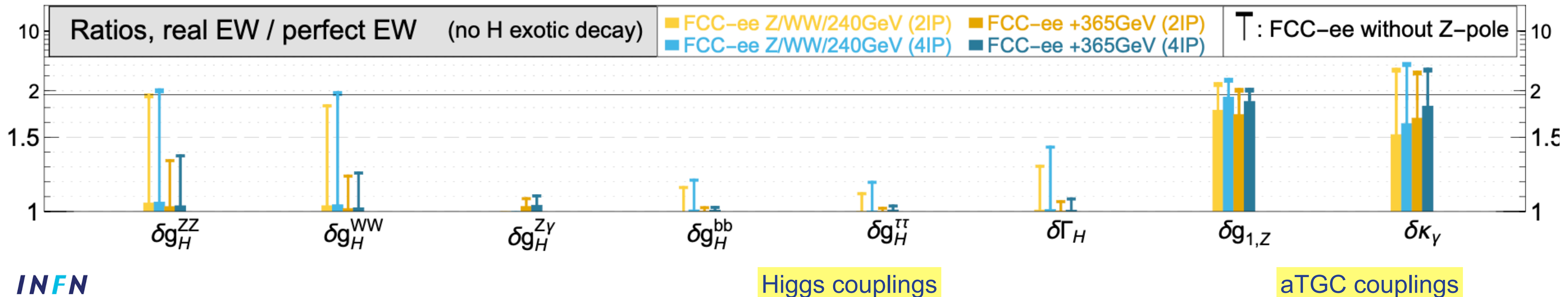


Higgs program NEEDS precision EWK measurements

J. de Blas, G. Durieux, C. Grojean, J. Gu, A. Paul <https://arxiv.org/abs/1907.04311>

$$\mathcal{L}_{\text{Eff}} = \mathcal{L}_{\text{SM}} + \sum_{d>4} \frac{1}{\Lambda^{d-4}} \mathcal{L}_d, \quad \mathcal{L}_d = \sum_i c_i^{(d)} \mathcal{O}_i^{(d)}.$$

- Fit to new physics effects parameterised by dimension 6 SMEFT operators
- The precision measurements of the Z pole run affect significantly Higgs operators: almost ideal if present, and a factor 2 worse if absent!



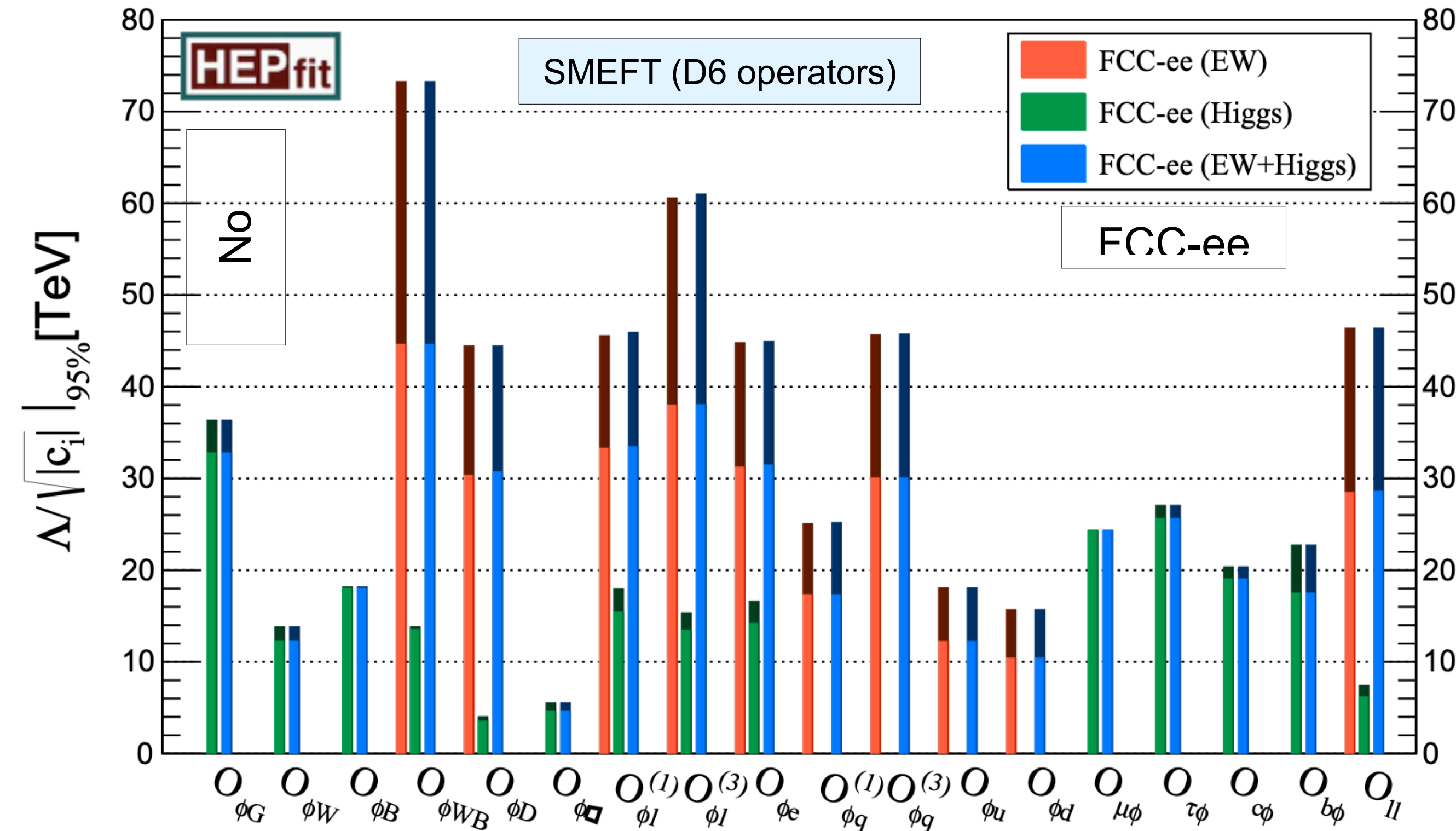
Indirect BSM sensitivity from EWPO

- Target: reduce systematic uncertainties to the level of statistical
- Exquisite \sqrt{s} precision (100keV@Z, 300keV@WW)
- ~50 times better precision than LEP/LSD on EW precision observables

Need TH results to fully exploit Tera-Z

Quantity	Current precision	FCC-ee stat. (syst.) precision	Required theory input	Available calc. in 2019	Needed theory improvement [†]
m_Z	2.1 MeV	0.004 (0.1) MeV	non-resonant $e^+e^- \rightarrow f\bar{f}$	NLO, ISR logarithms up to 6th order	NNLO for $e^+e^- \rightarrow f\bar{f}$
Γ_Z	2.3 MeV	0.004 (0.025) MeV	initial-state radiation (ISR)		
$\sin^2 \theta_{\text{eff}}^\ell$	1.6×10^{-4}	$2(2.4) \times 10^{-6}$			
m_W	12 MeV	0.25 (0.3) MeV	lineshape of $e^+e^- \rightarrow WW$ near threshold	NLO (ee \rightarrow 4f or EFT framework)	NNLO for ee \rightarrow WW, W \rightarrow ff in EFT setup
HZZ coupling	—	0.2%	cross-sect. for $e^+e^- \rightarrow ZH$	NLO + NNLO QCD	NNLO electroweak
m_{top}	100 MeV	17 MeV	threshold scan $e^+e^- \rightarrow t\bar{t}$	N ³ LO QCD, NNLO EW, resummations up to NNLL	Matching fixed orders with resummations, merging with MC, α_s (input)

[†]The listed needed theory calculations constitute a minimum baseline; additional partial higher-order contributions may also be required.



Indirect sensitivity
to 70TeV-scale sector
connected to EW/Higgs

Flavour/Tau physics with the Tera-Z run

Particle production (10^9)	B^0	B^-	B_s^0	Λ_b	$c\bar{c}$	$\tau^- \tau^+$
Belle II	27.5	27.5	n/a	n/a	65	45
FCC-ee	400	400	100	100	600	170

FCC-ee = 10 x BelleII

Decay mode/Experiment	Belle II (50/ab)	LHCb Run I	LHCb Upgr. (50/fb)	FCC-ee
EW/H penguins				
$B^0 \rightarrow K^*(892)e^+e^-$	~ 2000	~ 150	~ 5000	~ 200000
$\mathcal{B}(B^0 \rightarrow K^*(892)\tau^+\tau^-)$	~ 10	–	–	~ 1000
$B_s \rightarrow \mu^+\mu^-$	n/a	~ 15	~ 500	~ 800
$B^0 \rightarrow \mu^+\mu^-$	~ 5	–	~ 50	~ 100
$\mathcal{B}(B_s \rightarrow \tau^+\tau^-)$				
Leptonic decays				
$B^+ \rightarrow \mu^+\nu_{mu}$	5%	–	–	3%
$B^+ \rightarrow \tau^+\nu_{tau}$	7%	–	–	2%
$B_c^+ \rightarrow \tau^+\nu_{tau}$	n/a	–	–	5%
CP / hadronic decays				
$B^0 \rightarrow J/\Psi K_S (\sigma_{\sin(2\phi_d)})$	$\sim 2 \cdot 10^6 (0.008)$	41500 (0.04)	$\sim 0.8 \cdot 10^6 (0.01)$	$\sim 35 \cdot 10^6 (0.006)$
$B_s \rightarrow D_s^\pm K^\mp$	n/a	6000	~ 200000	$\sim 30 \cdot 10^6$
$B_s(B^0) \rightarrow J/\Psi\phi (\sigma_{\phi_s} \text{ rad})$	n/a	96000 (0.049)	$\sim 2 \cdot 10^6 (0.008)$	$16 \cdot 10^6 (0.003)$

boosted b's/ τ 's

at FCC-ee

Makes possible
a topological rec.
of the decays
w/ miss. energy

Flavour/Tau physics with the Tera-Z run

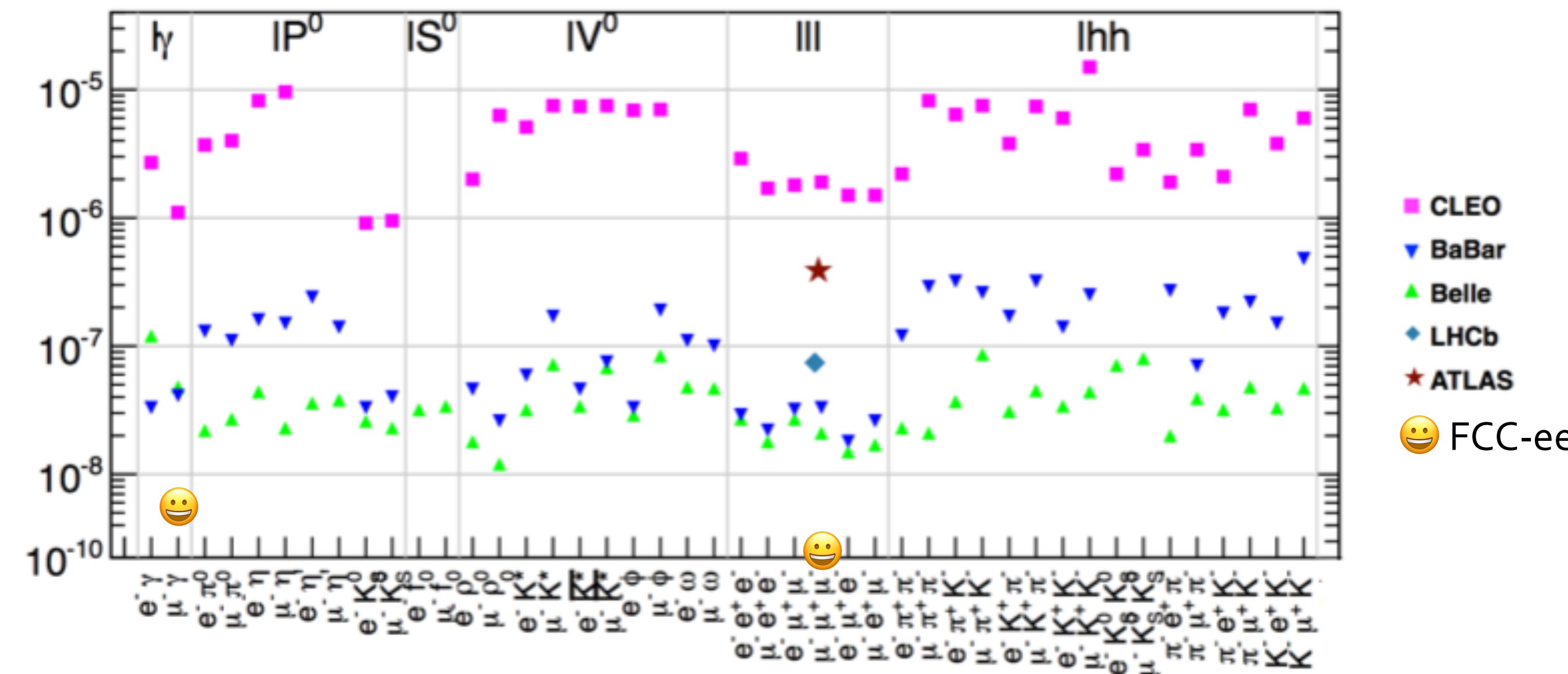
Particle production (10^9)	B^0	B^-	B_s^0	Λ_b	$c\bar{c}$	$\tau^-\tau^+$
Belle II	27.5	27.5	n/a	n/a	65	45
FCC- ee	400	400	100	100	600	170

~10 times Belle's stat
Boost at the Z!

- Lots of BSM searches/signatures from: rare decays, LFV/LFU tests

LFV tau decays

- **Enormous statistics 10^{12} $b\bar{b}$, $c\bar{c}$, 2×10^{11} $\tau\tau$ events**
- Clean environment
- Favourable kinematics -> boost
- Excellent vertexing/tracking/PID



FCC-ee: explore and discover

- **EXPLORE INDIRECTLY** the 10-100 TeV energy scale with precision measurements
 - From the correlated properties of the Z , b, c, τ , W, Higgs, and top particles
 - Up to 20-50-fold improved precision on ALL electroweak observables (EWPO)
 - Up to 10 × more precise and model-independent Higgs couplings (width, mass) measurements
- **DISCOVER** that the Standard Model does not fit
- **DISCOVER** a violation of flavour conservation/universality
- **DISCOVER** dark matter, e.g., as invisible decays of Higgs or Z
- **DISCOVER DIRECTLY** elusive (aka feebly-coupled) particles
 - in the 5-100 GeV mass range, such as right-handed neutrino