The Future Circular Collider

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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*

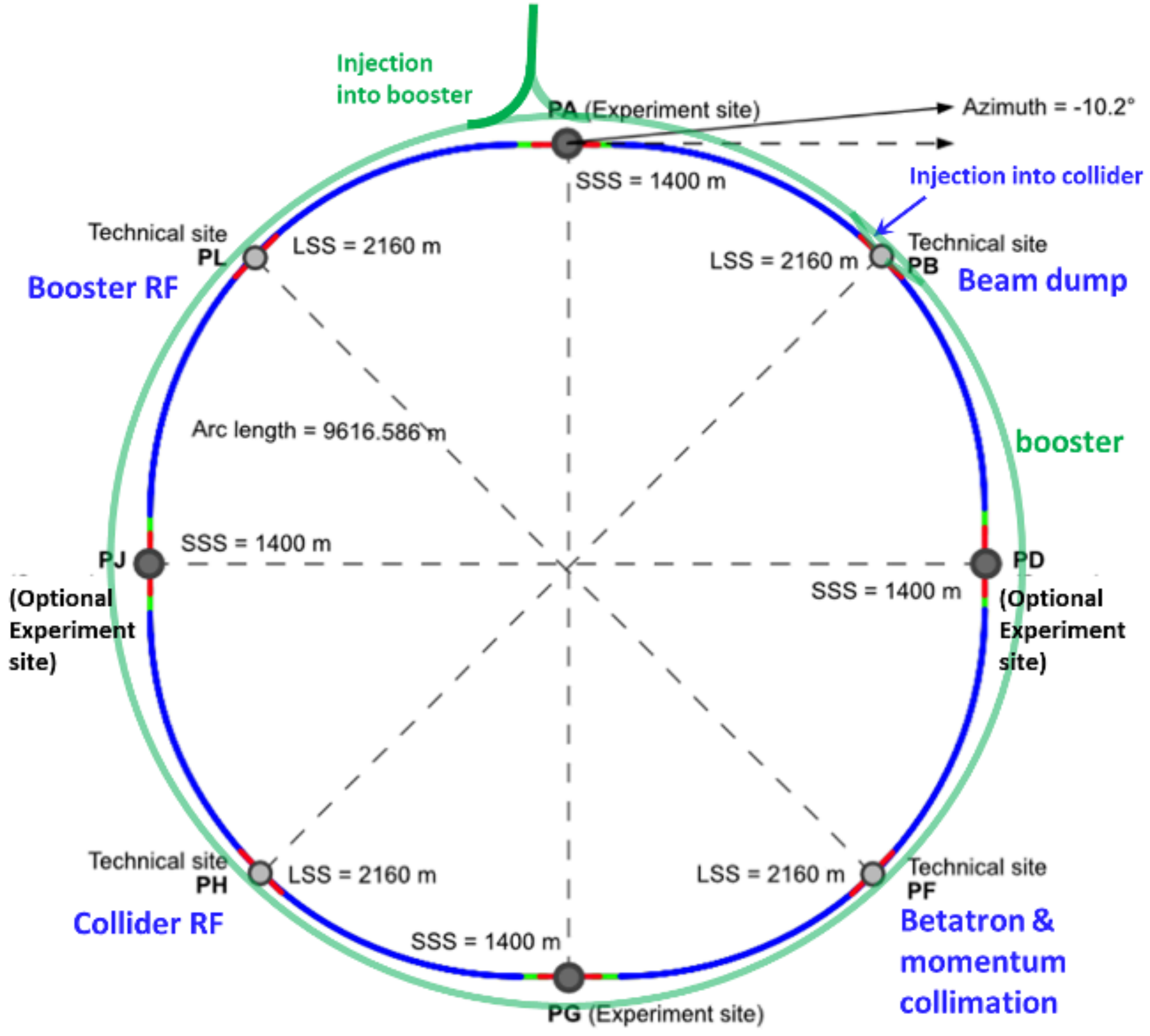
- **ENERGY FRONTIER Discovery (hadron-hadron)**
  - **2nd stage collider, FCC-hh:** proton-proton collisions at ~100 TeV
  - Construction: 2058-2070 / Physics operation: ~ 2070-**2095**
  - *Maximizing potential for BSM discovery → Direct / high mass BSM sensitivity*

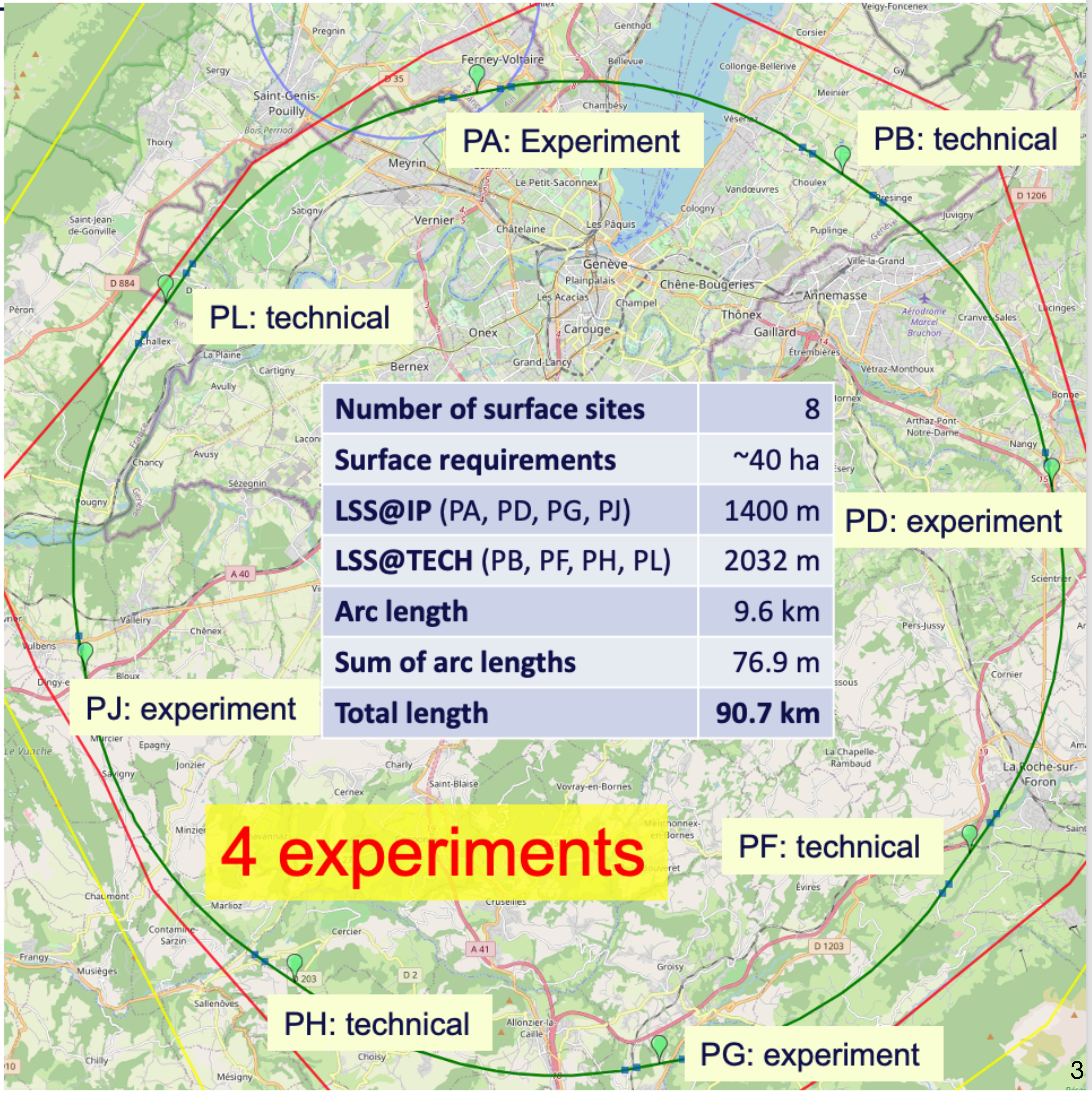
FCC baseline placement and layout for feasibility study

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

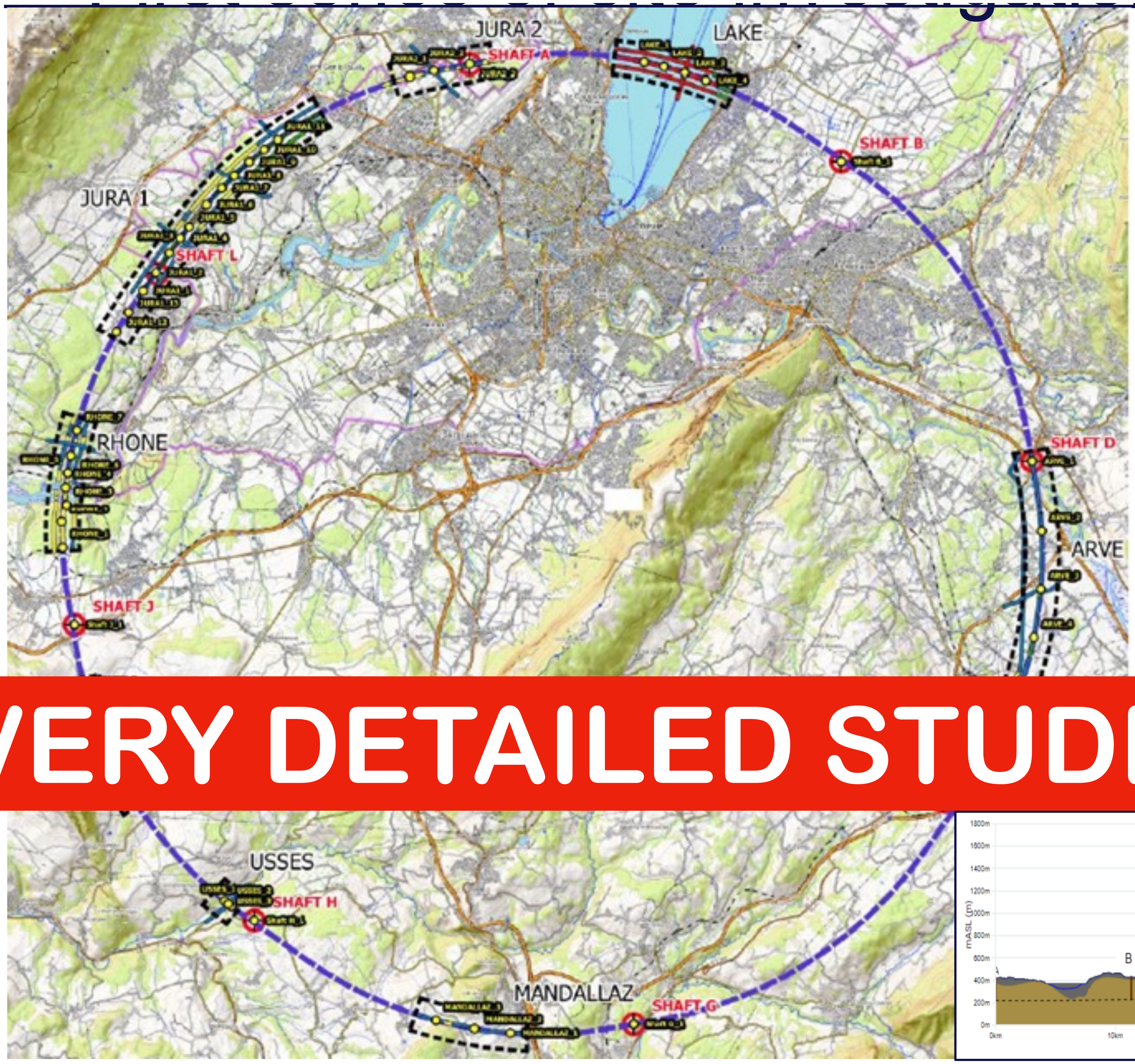




Number of surface sites	8
Surface requirements	~40 ha
LSS@IP (PA, PD, PG, PJ)	1400 m
LSS@TECH (PB, PF, PH, PL)	2032 m
Arc length	9.6 km
Sum of arc lengths	76.9 m
Total length	**90.7 km**

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

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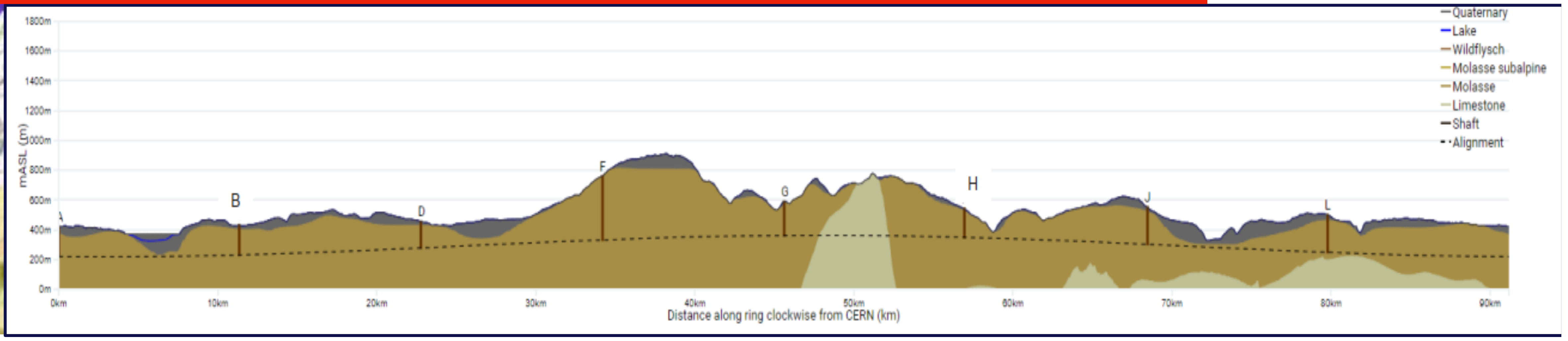
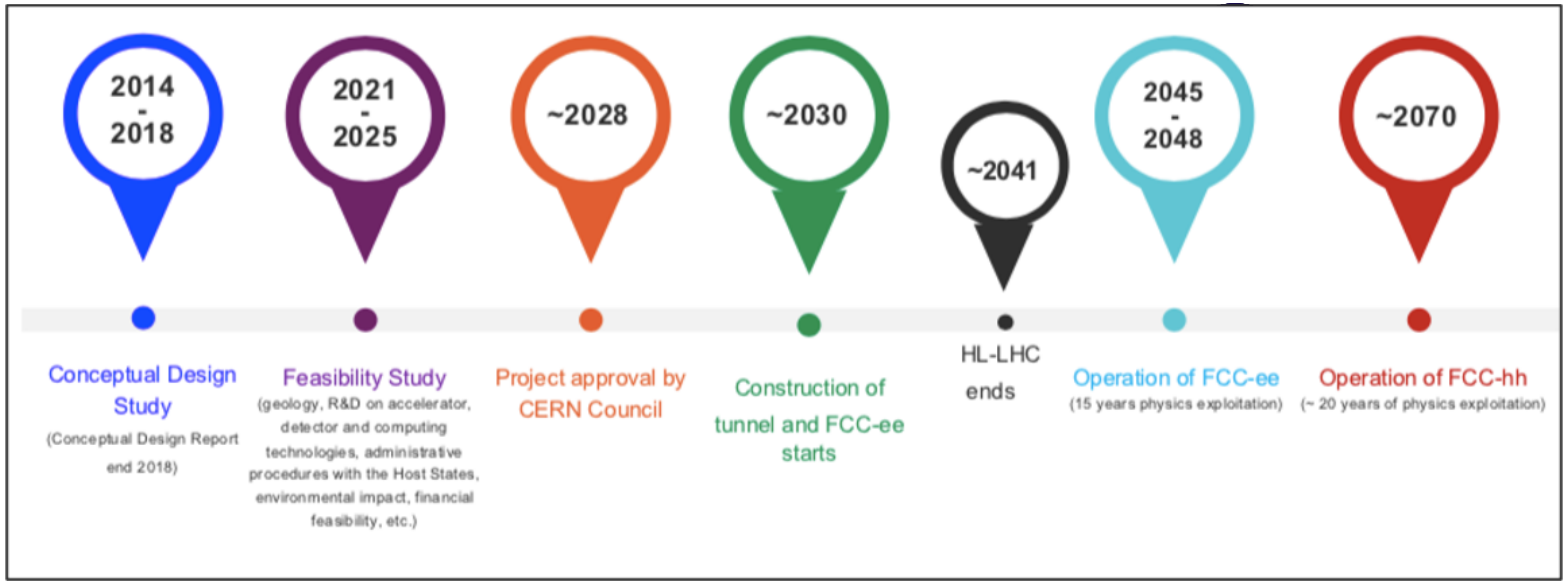
ks on the lake

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)
  - 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

More on timeline later

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

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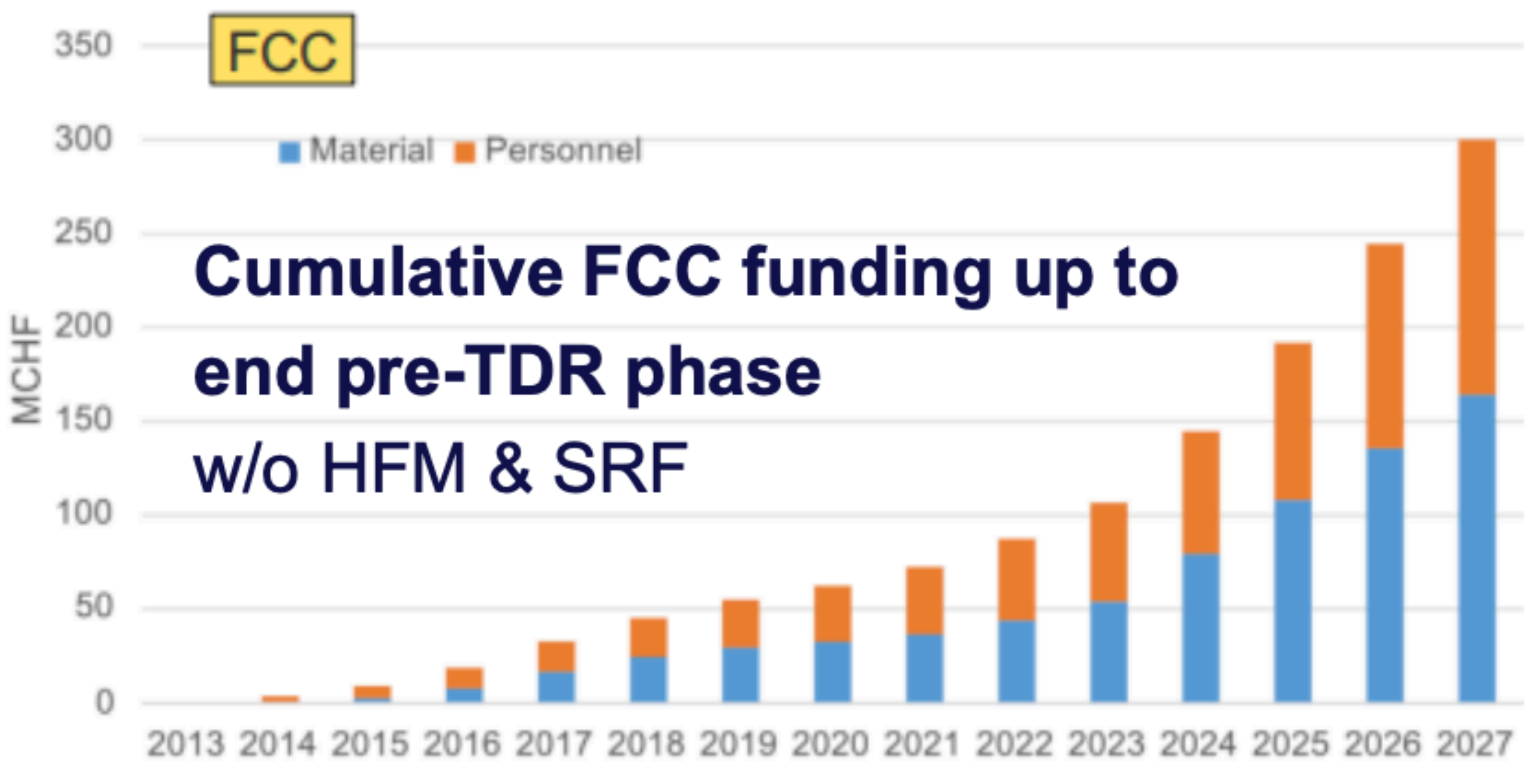
Recent decisions by CERN council

- **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**.

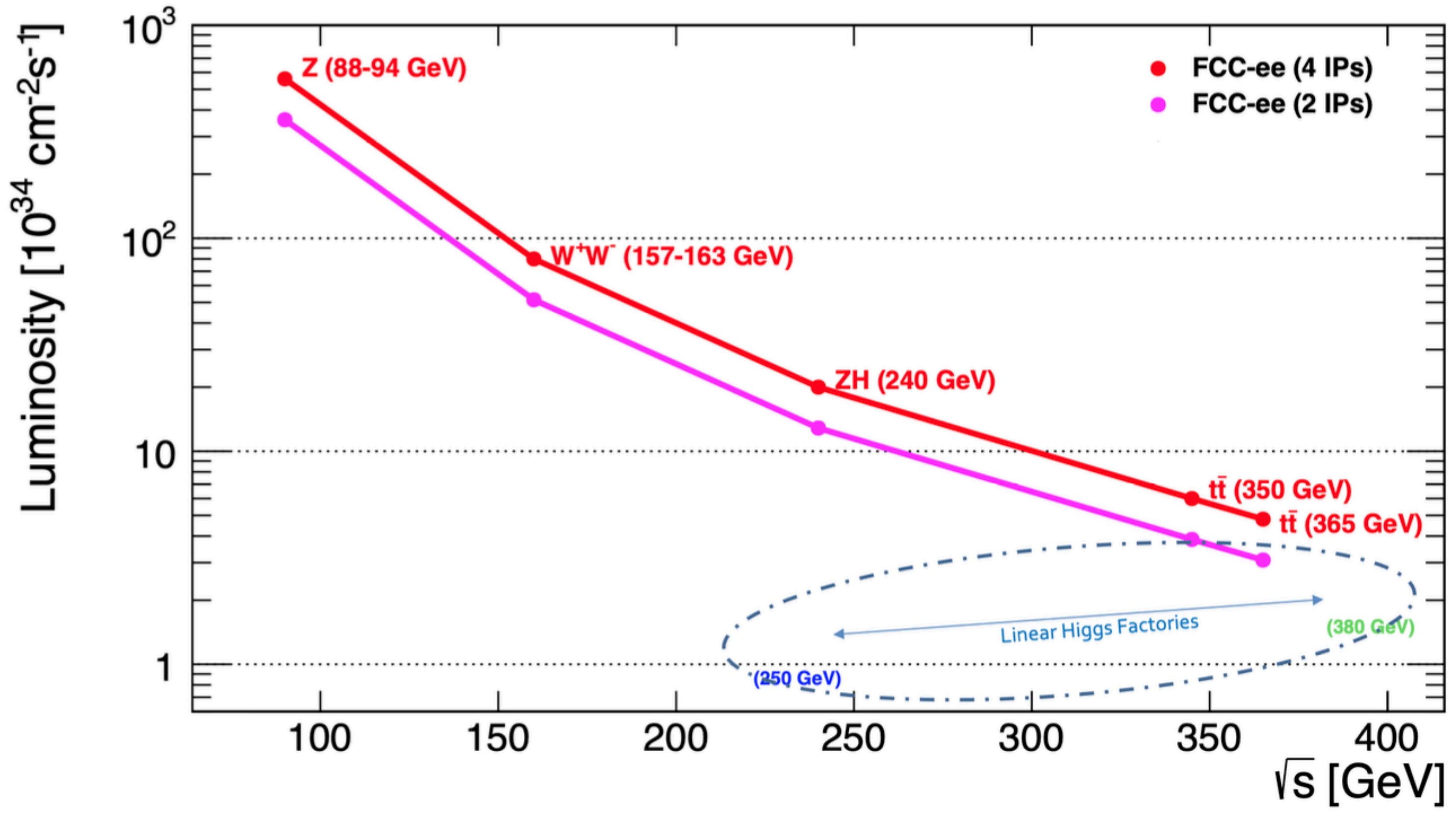


Additional expenses in June 2024 MTP to prepare for CERN's future.

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



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LEP Data statistics accumulated every 2 minutes!

In each detector:
10^5 Z/sec, 10^4 W/hour,
1500 Higgs/day, 1500 top/day

Working point	Z, years 1-2	Z, later	WW, years 1-2	WW, later	ZH	$t\bar{t}$	
$\sqrt{s}$ (GeV)	88, 91, 94		157, 163		240	340–350	365
Lumi/IP ($10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$)	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} $t\bar{t}$ +330k ZH +80k WW $\rightarrow$ H	

"Tera-Z"

New Optics developed - New numbers for European Strategy document
Up to 10.8/ab at √s=240GeV (3y)
and up to √s=3/ab at 365 GeV(5y)

Never produced before at a lepton collider!

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FCC-ee Extensive physics program

Flexible collider program

- **Opportunities** beyond the baseline plan (√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

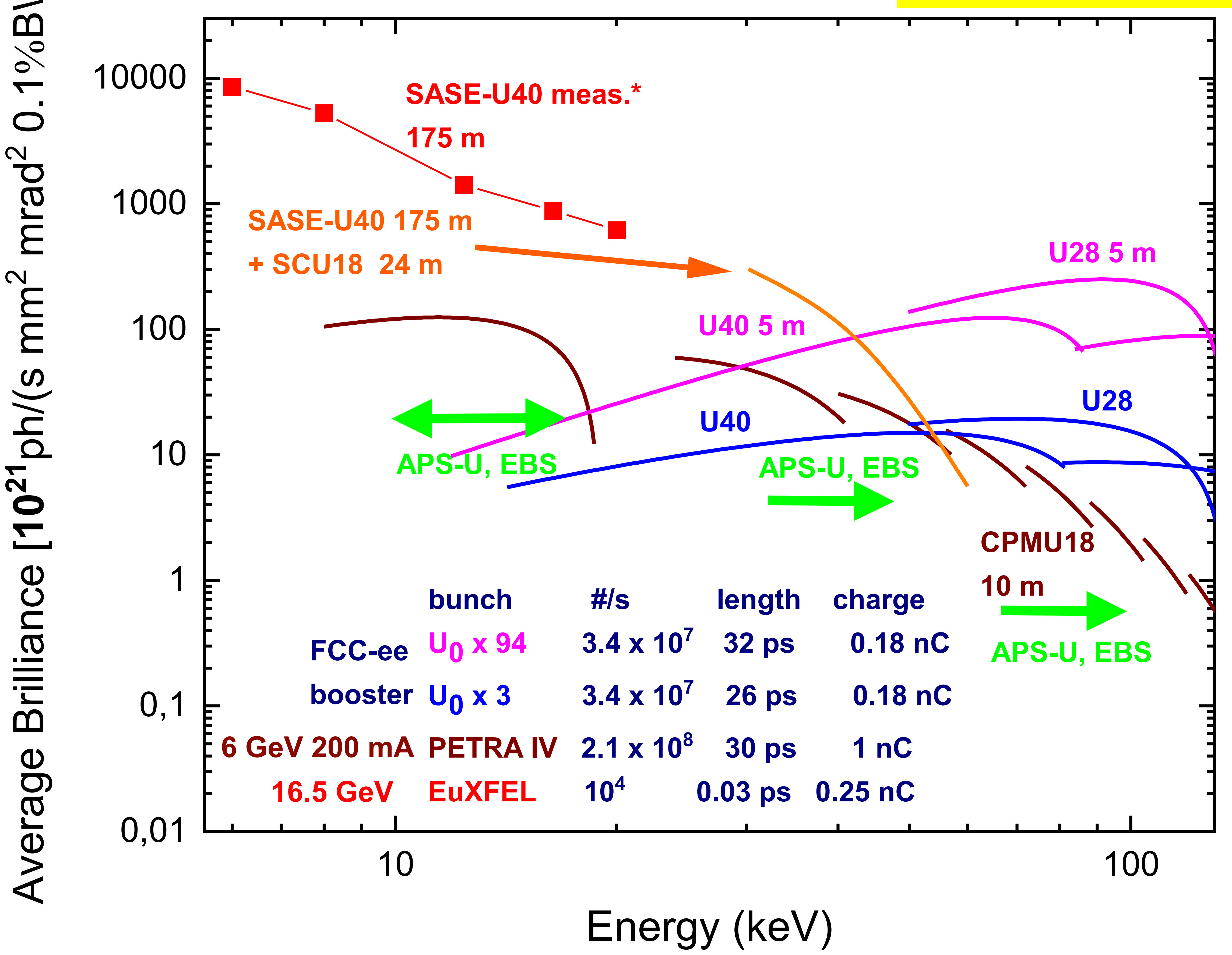
using beamstrahlung for **radionuclide production**

e^- beam driven **neutron source**

M. Calviani,
C. Duchemin

etc.

S. Casalbuoni



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

Some preliminary detector benchmarks for FCC-ee

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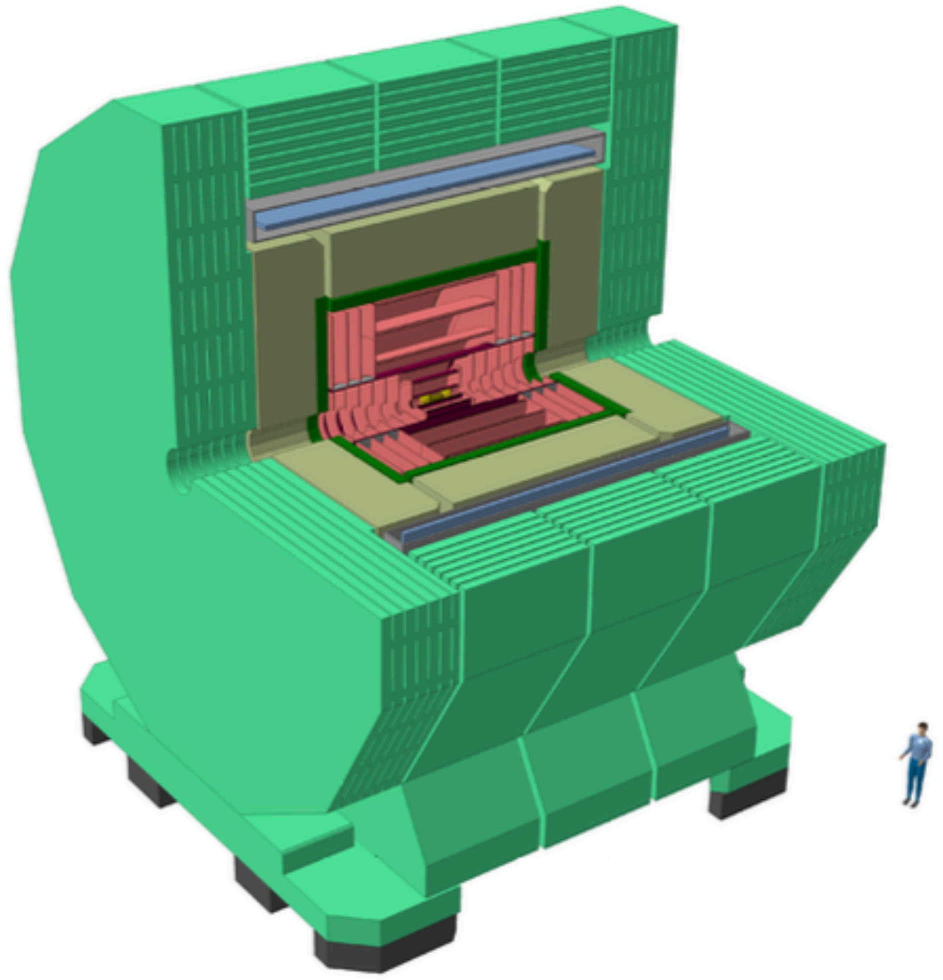
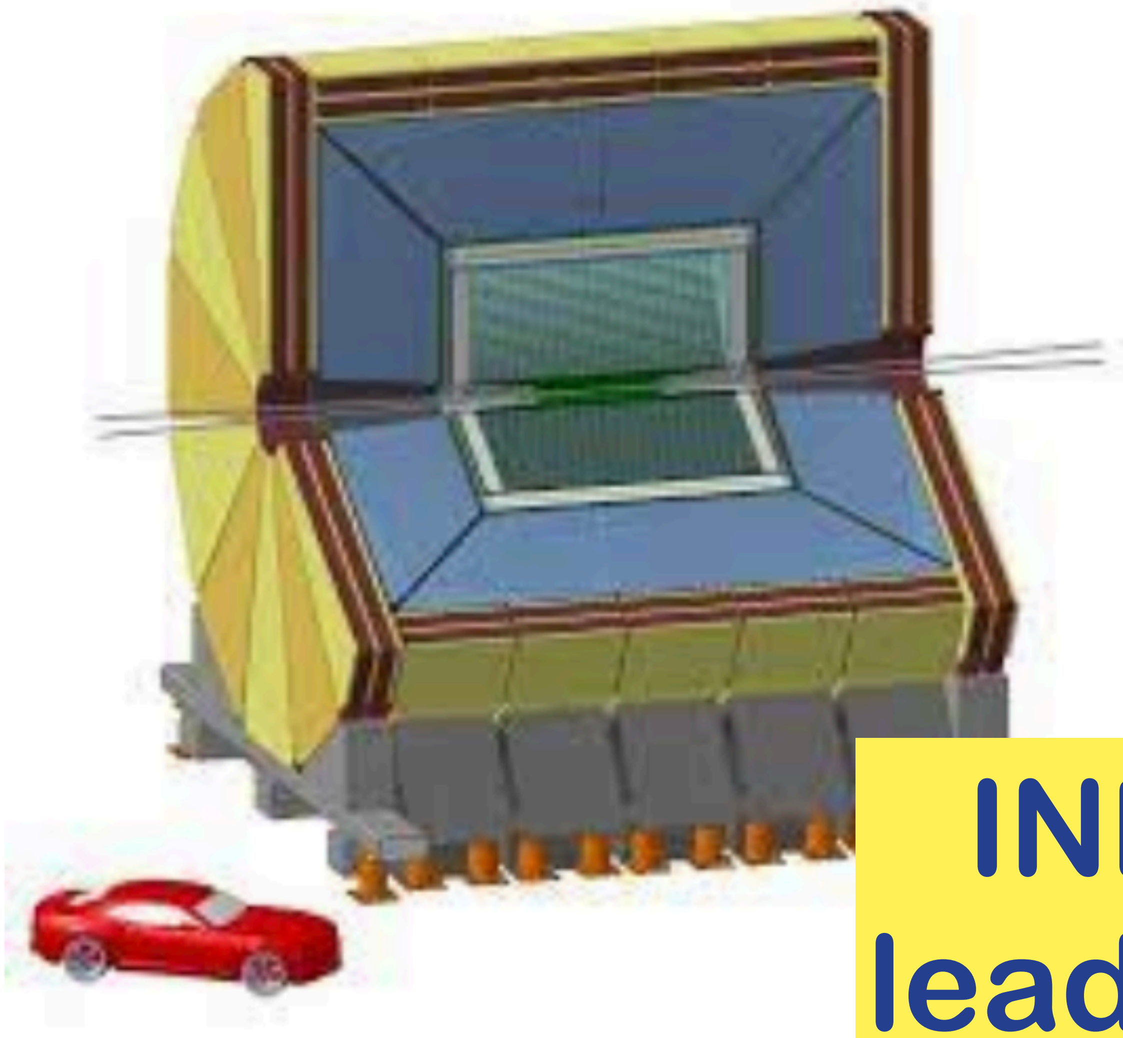
CLIC-like Detector (CLD)

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



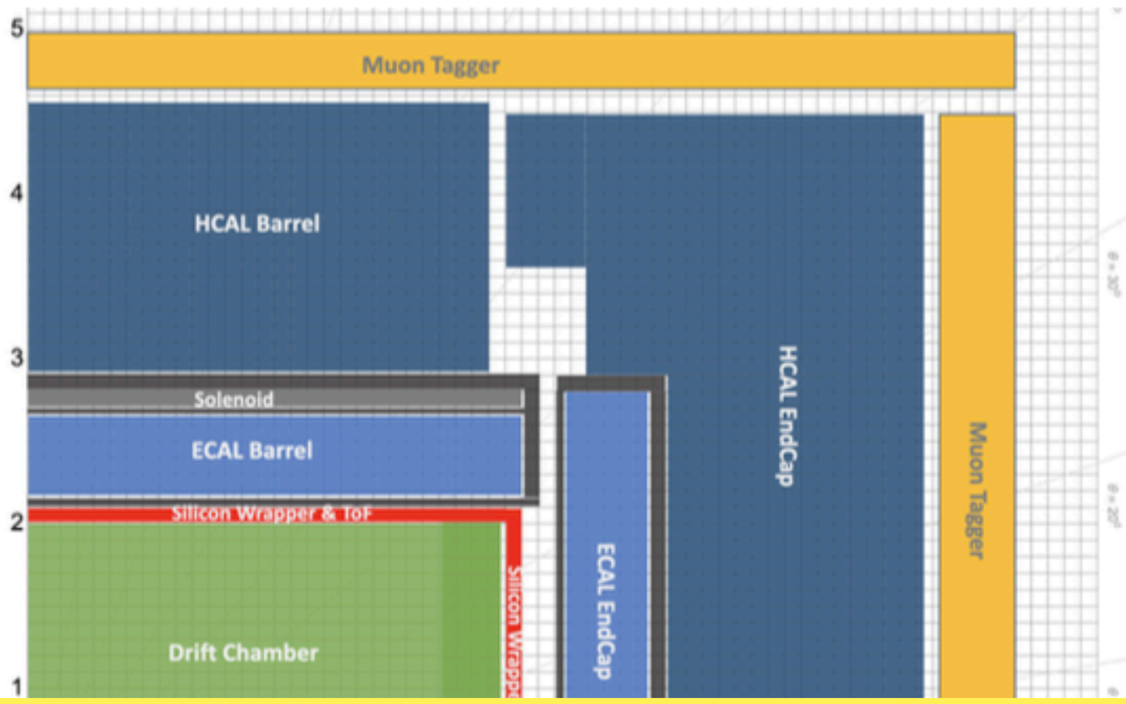
Innovative Detector for an Electron Positron Accelerator (IDEA)

- 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

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

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

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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**

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How long would it take?

Luminosity is key

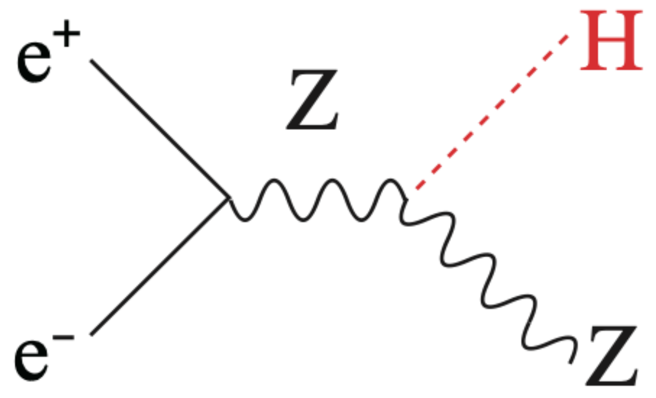
- Example for a precision on $k_Z = 0.14\,\%$
- For ILC@CERN need to rescale the years by 1.6/1.2

Collider	FCC-ee	ILC	CLIC
$\sqrt{s}$ (GeV)	240	250	380
Integrated luminostiy / 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}



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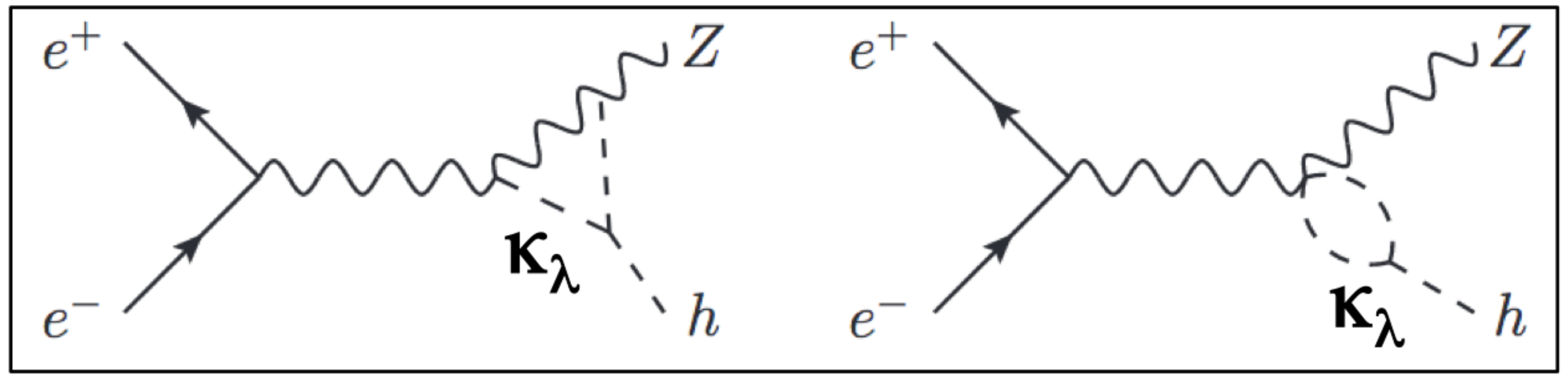
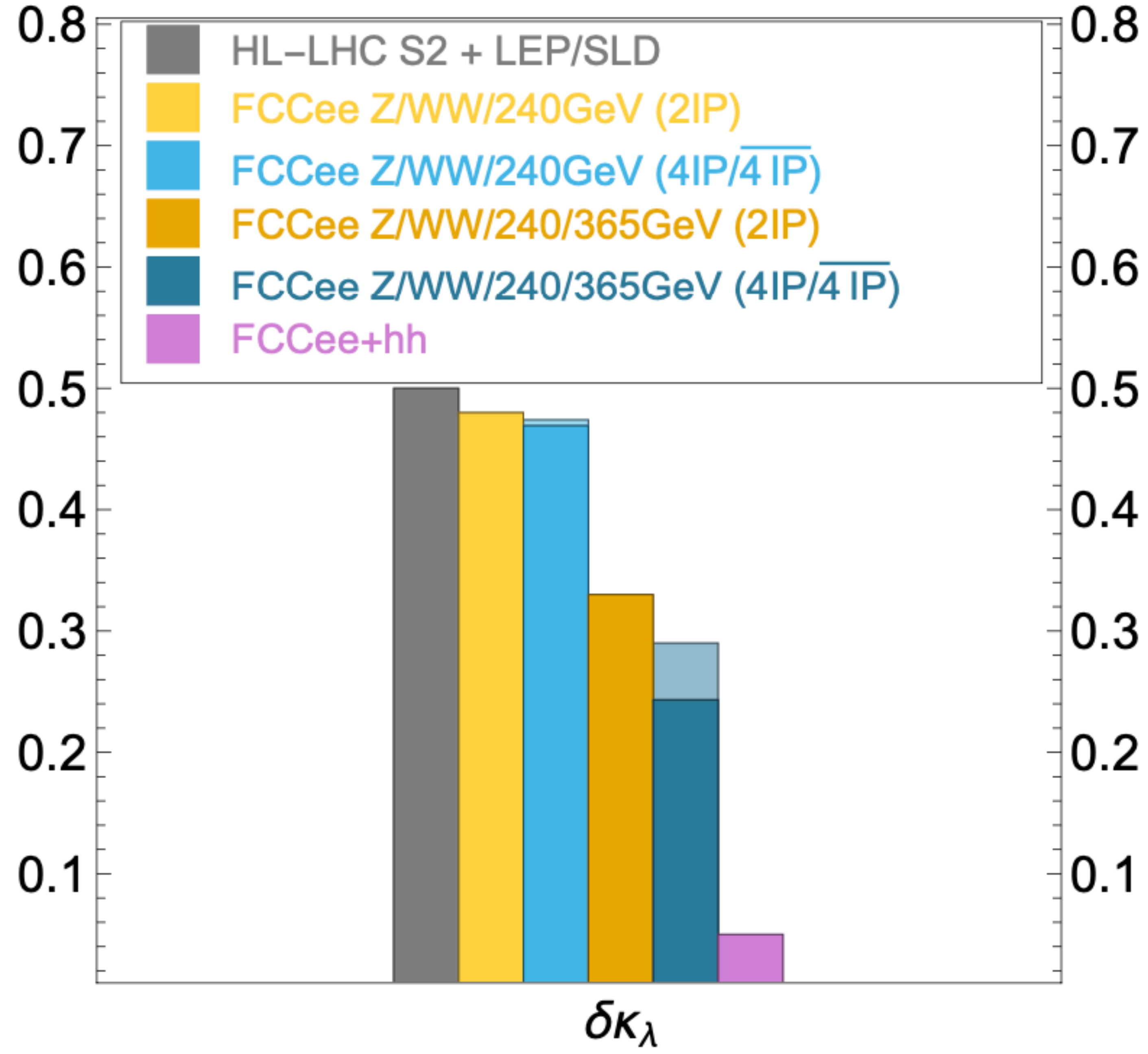
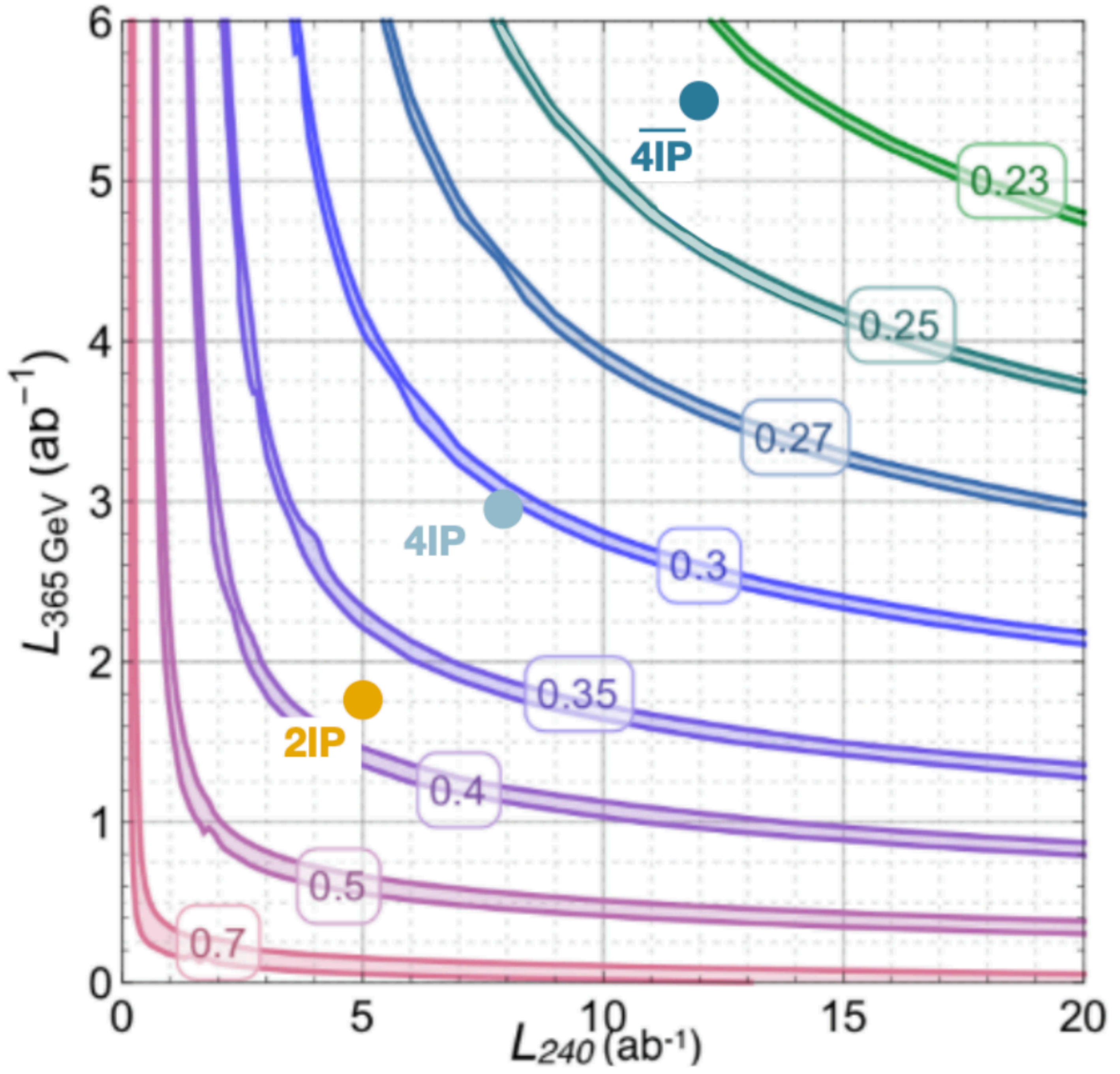


$$\Sigma_{\rm NLO} = Z_H \Sigma_{\rm LO}(1 + \kappa_\lambda C_1) \qquad \kappa_\lambda \equiv \frac{\lambda_3}{\lambda_3^{\rm SM}}$$





- 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)

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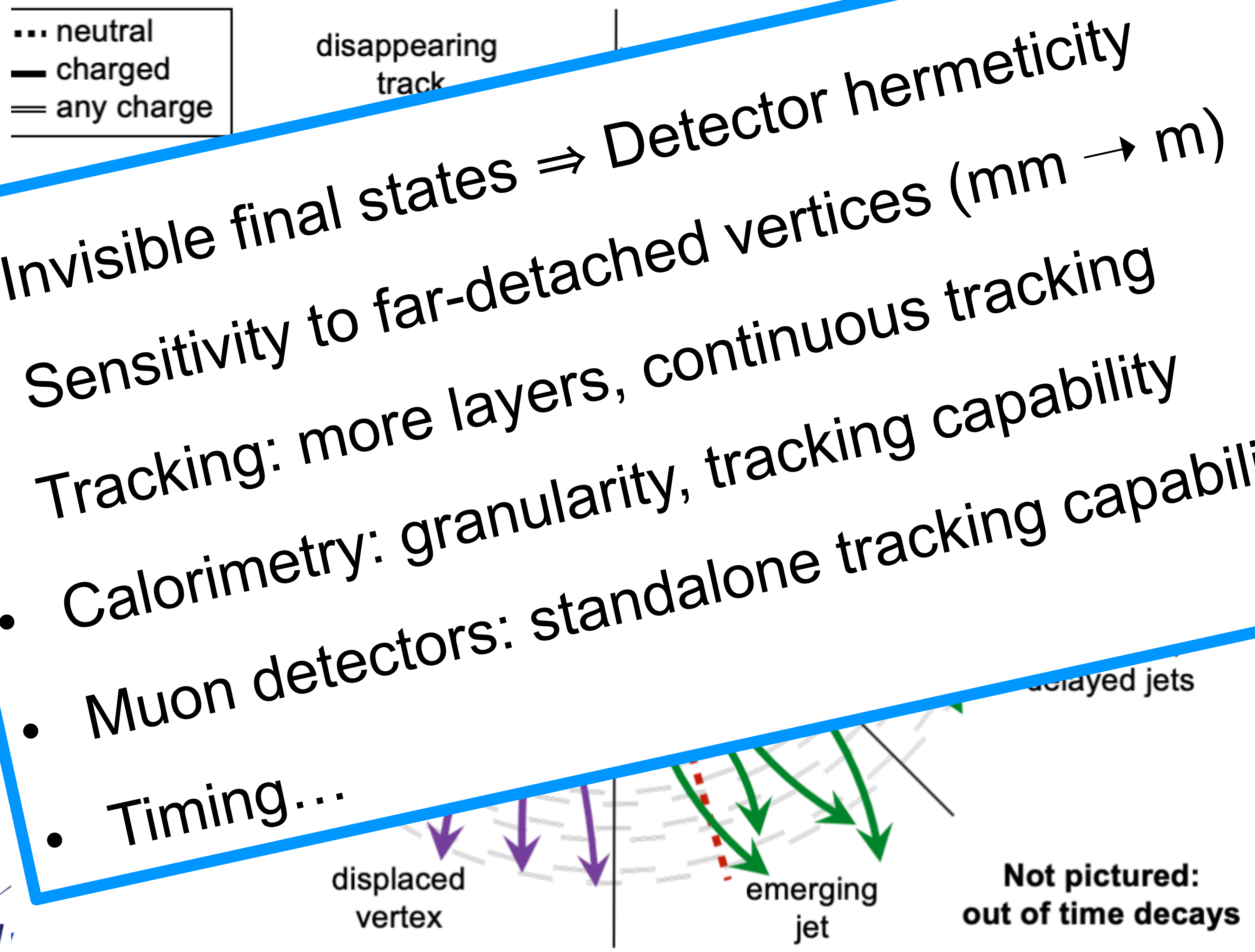
Direct search for Feebly Interacting Particles

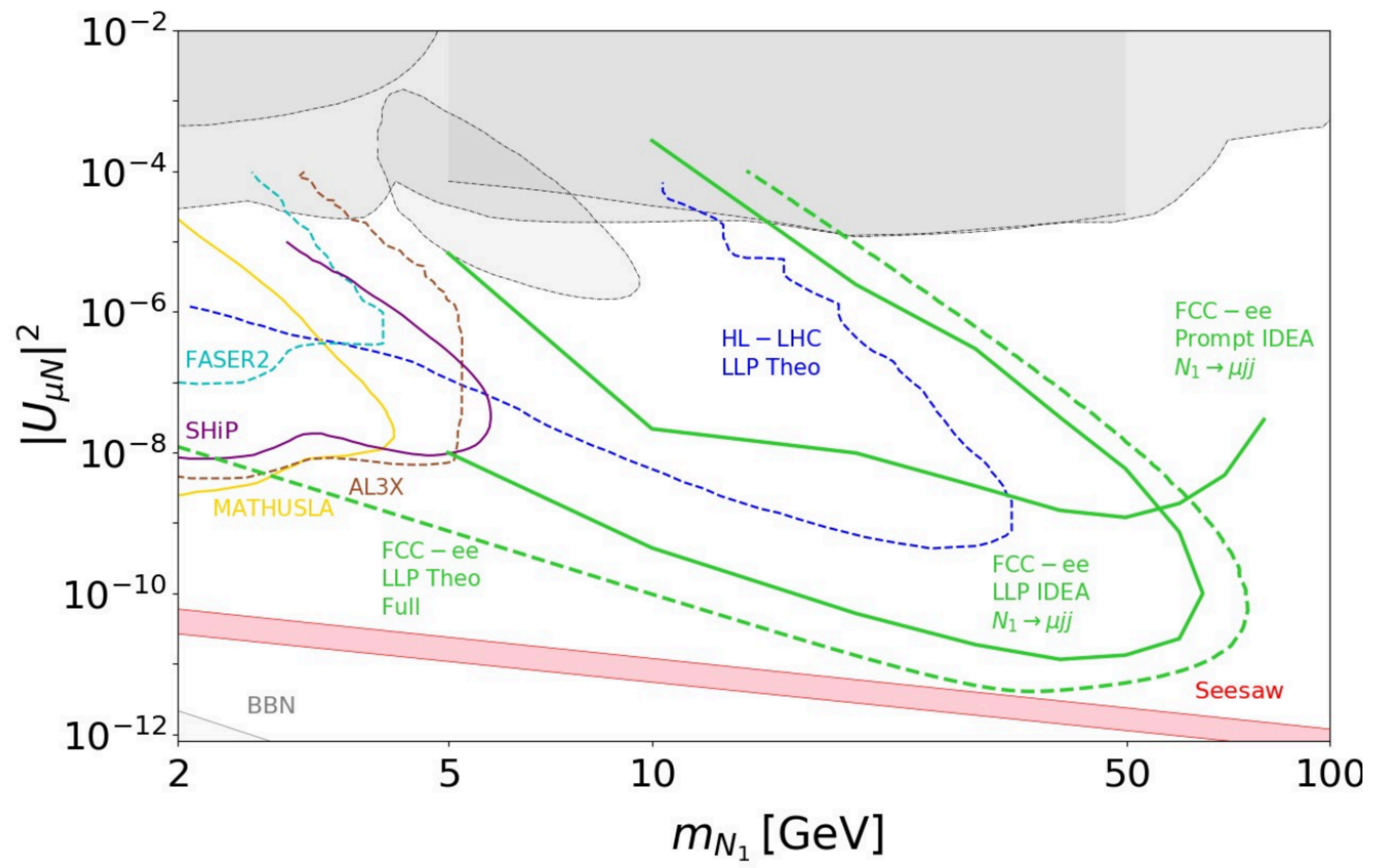
Intensity frontier at Tera-Z offers the opportunity to directly observe new feebly interacting particles in a very clean environment

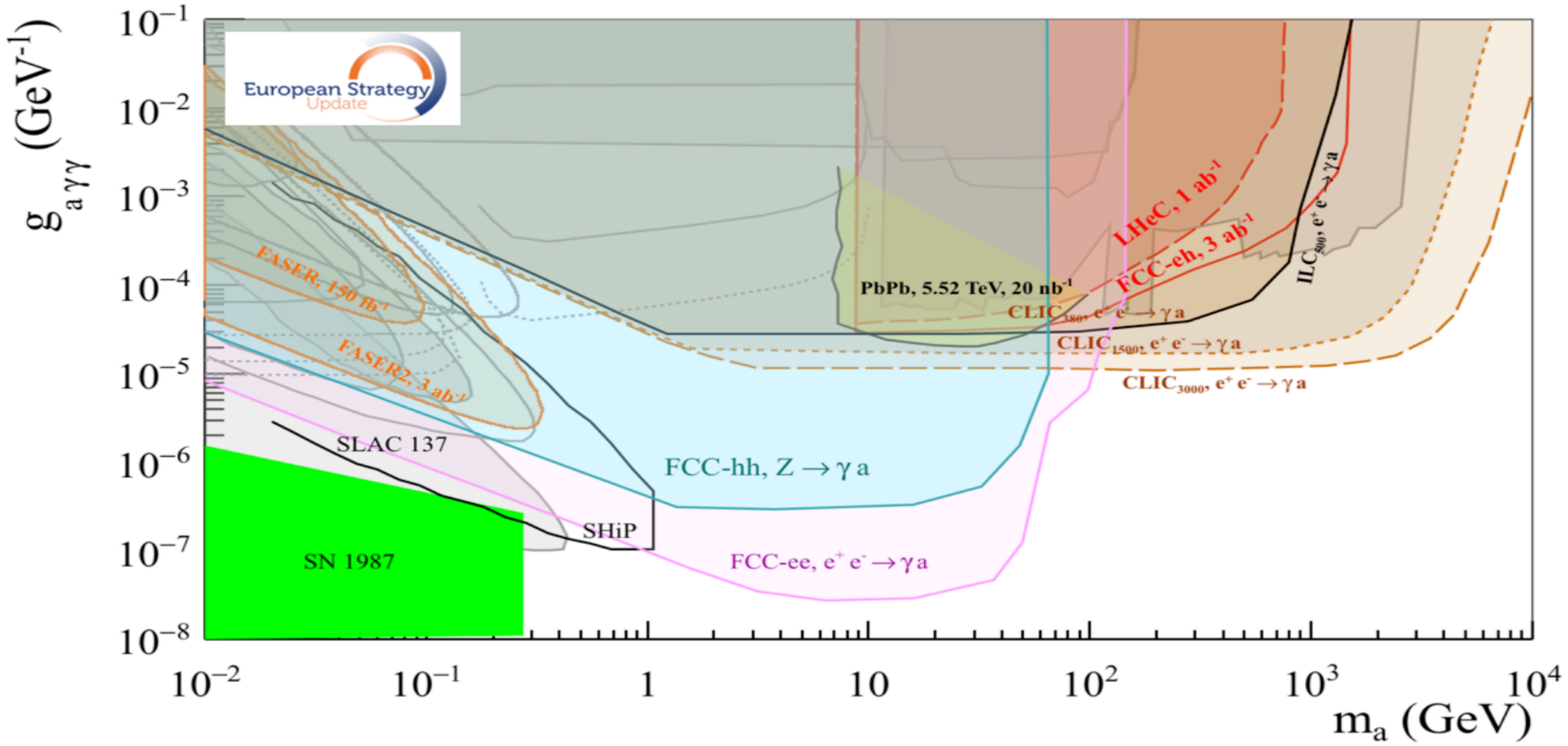
Signatures driven by search for unusual final states

Novel detector requirement to fully exploit possibilities



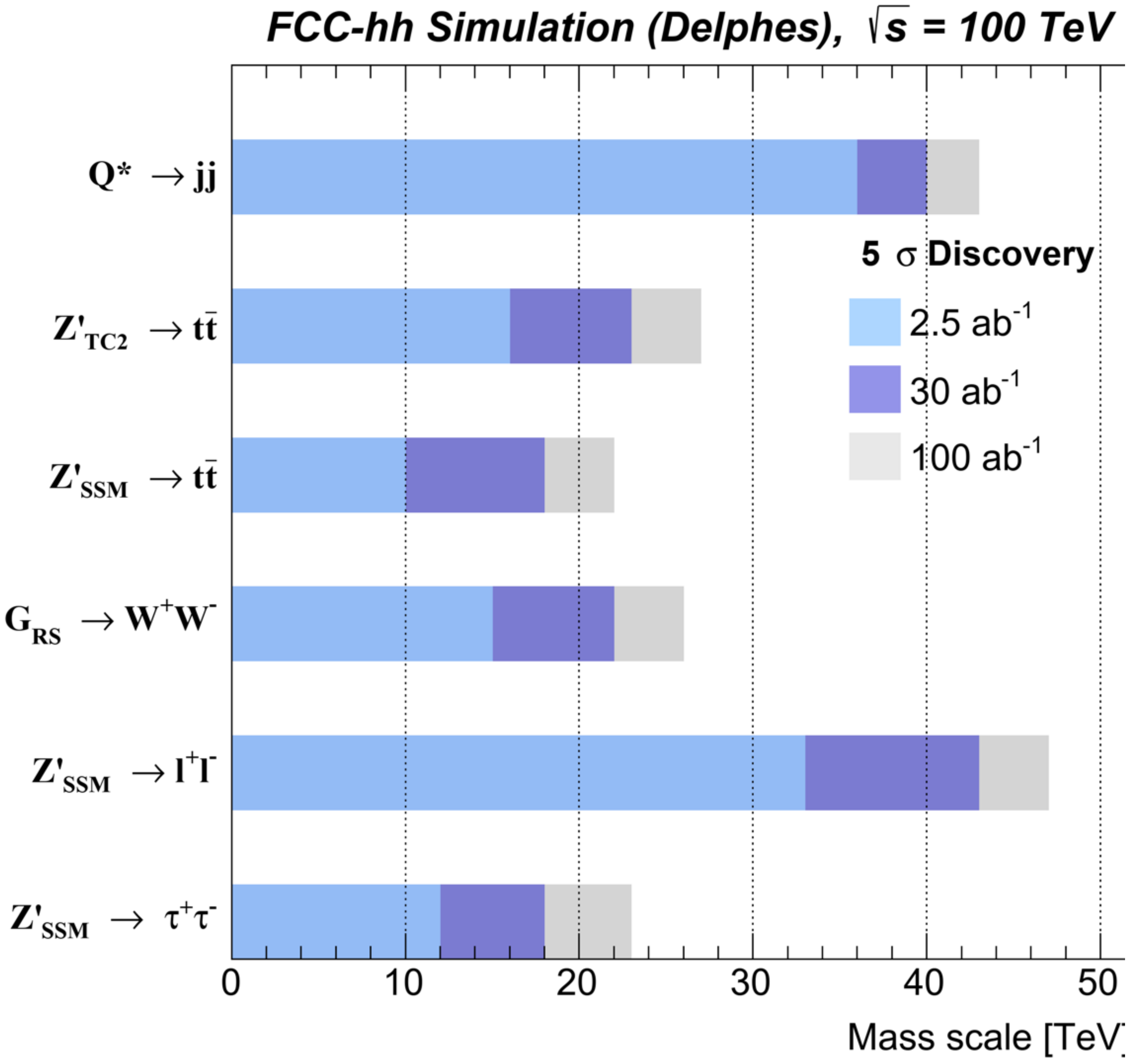
- Invisible final states ⇒ Detector hermeticity
- Sensitivity to far-detached vertices (mm → m)
- Tracking: more layers, continuous tracking
- Calorimetry: granularity, tracking capability
- Muon detectors: standalone tracking capability
- Timing…





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

di Fisica Nucleare

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:

a. **Documentation on Cost Estimate – Funding Models**

b. **Environmental Report**

EU competitiveness report

edited by Mario Draghi, and officially handed over to Ursula von der Leyen in September 2024

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

https://commission.europa.eu/topics/strengthening-european-competitiveness/eu-competitiveness-looking-ahead_en

*“**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.”*

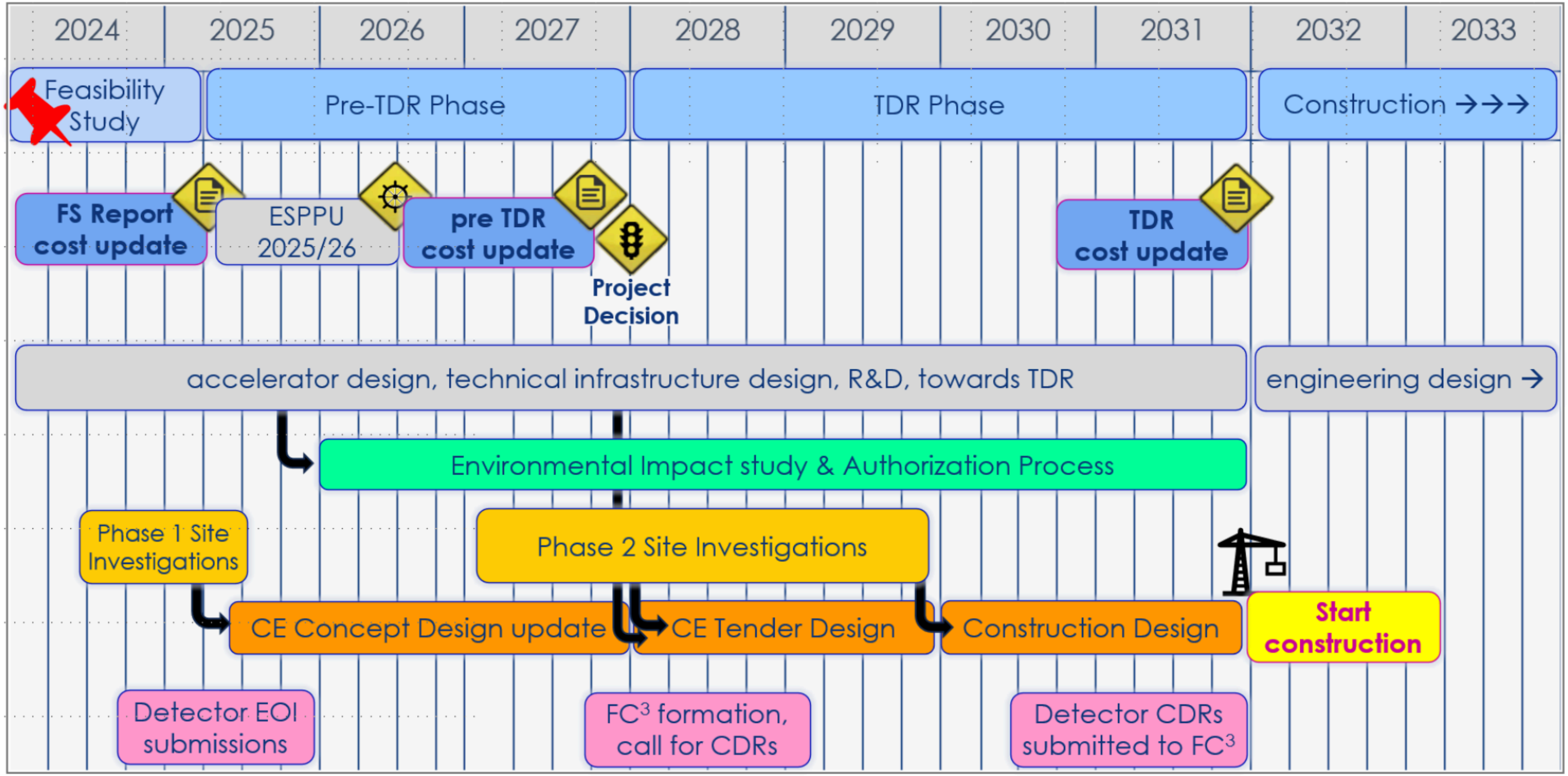
Plans for European Strategy

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



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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

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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 $\sqrt{s}$=240GeV
  - some civil enginnering needed, more RF cavities. more power etc.
  - running at top threshold probably not viable or very very expensive
  - no trasverse 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 alphaQED)
  - 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 MCH
  - 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

MLM https://agenda.infn.it/event/42594

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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)

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

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

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

100 TeV	s I	s II	s III
stat	3.0	4.1	5.6
syst	1.6	3.0	5.4
tot	3.4	5.1	7.8

80 TeV	s I	s II	s III
stat	3.5	4.7	6.4
syst	1.6	3.0	5.4
tot	3.8	5.6	8.4

120 TeV	s I	s II	s III
stat	2.6	3.6	4.9
syst	1.6	3.0	5.4
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%

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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

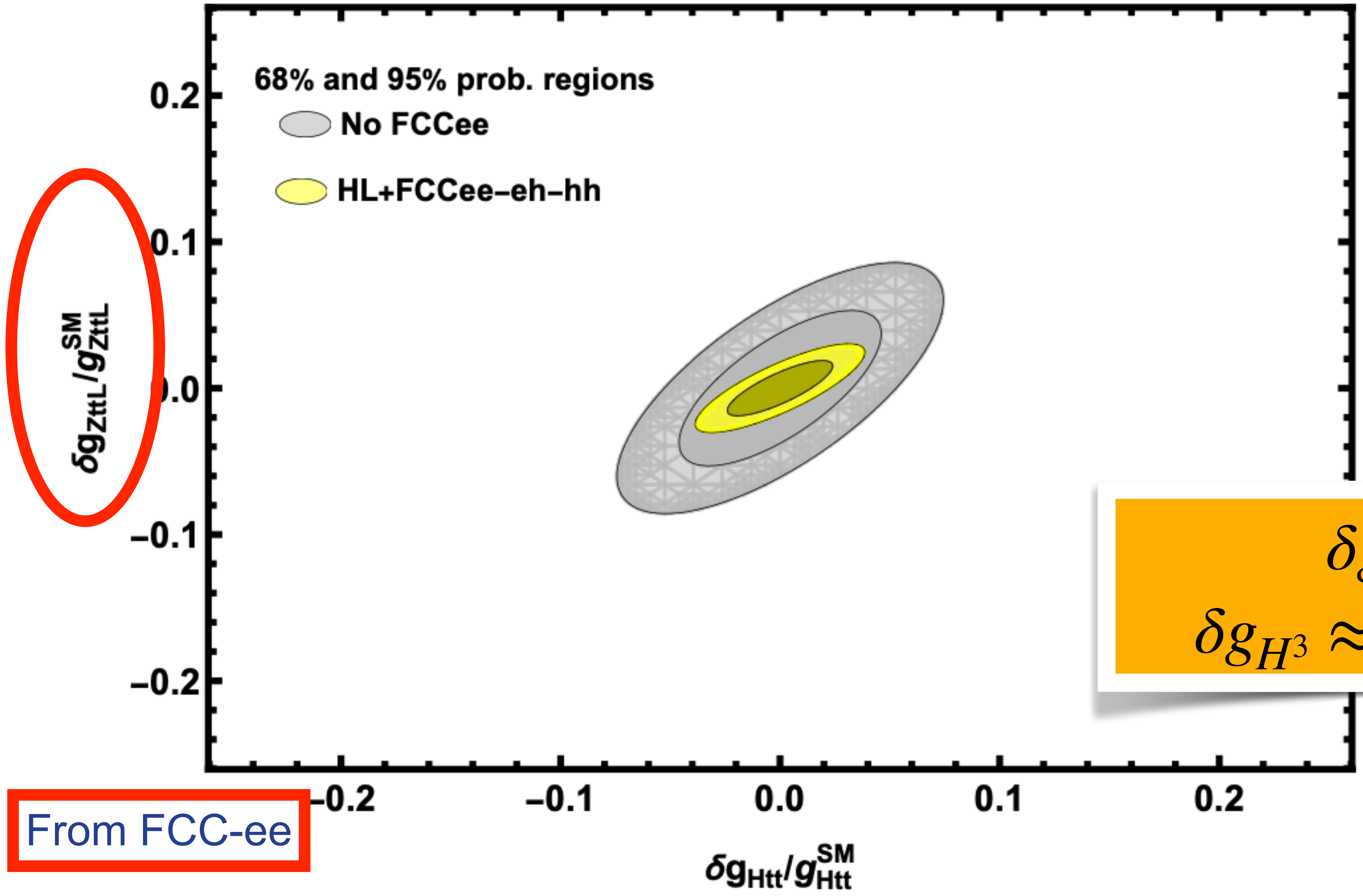
- Discovery reach at the largest masses vary at the level of –20% to +15% for the 80 and 120 TeV options. No obvious case today of critical thresholds to push for, or exclude, either option.

  ➡ 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 …

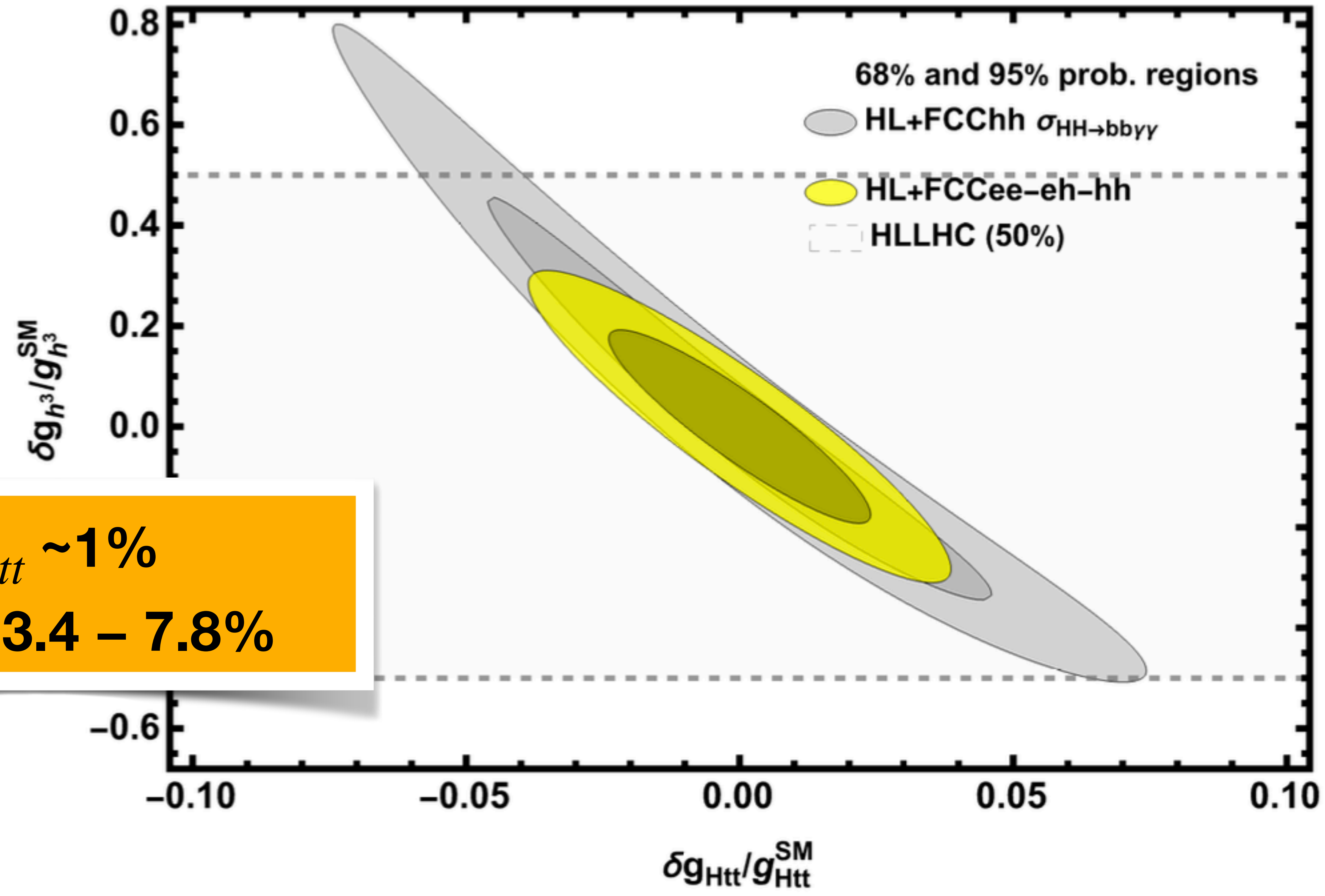
  ➡ the decision of 80 vs 120 vs 100 is probably final, and unlikely to lead to an upgrade path

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 365GeV 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 ~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



From FCC-ee



δg_{tt} ~1%

$\delta g_{H^3} \approx$ 3.4 – 7.8%

Higgs program NEEDS precision EWK measurements

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

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

- 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

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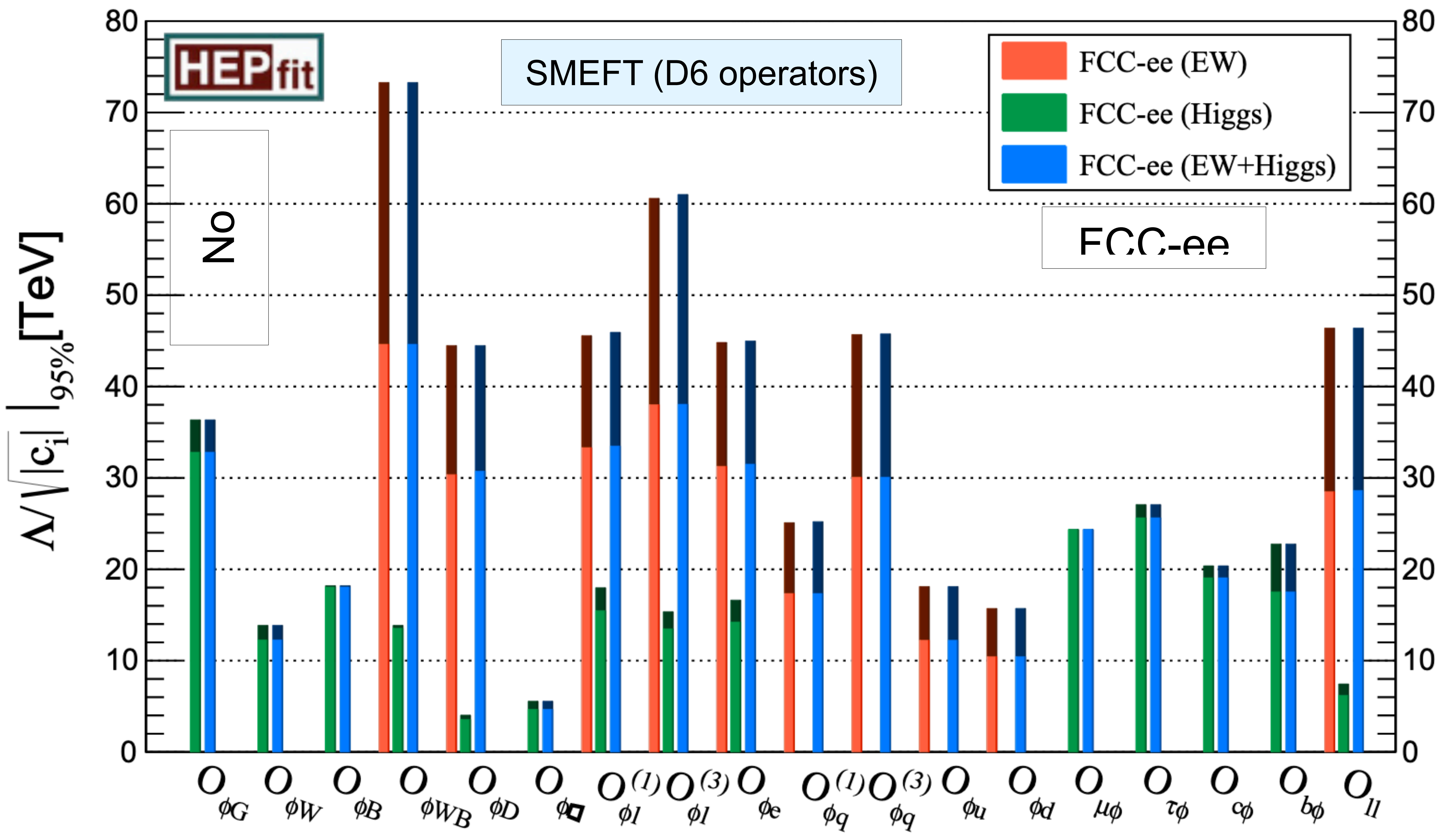
arXiv:2106.13885

- Target: reduce systematic uncertainties to the level of statistical
- Exquisite √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 Γ_Z $\sin^2\theta^{\ell}_{\rm eff}$	2.1 MeV 2.3 MeV 1.6×10^{-4}	0.004 (0.1) MeV 0.004 (0.025) MeV $2(2.4)\times10^{-6}$	non-resonant $e^+e^-\to f\bar{f}$, initial-state radiation (ISR)	NLO, ISR logarithms up to 6th order	NNLO for $e^+e^-\to f\bar{f}$
m_W	12 MeV	0.25 (0.3) MeV	lineshape of $e^+e^-\to WW$ near threshold	NLO ($ee\to 4f$ or EFT framework)	NNLO for $ee\to WW$, $W\to f\bar{f}$ in EFT setup
HZZ coupling	—	0.2%	cross-sect. for $e^+e^-\to ZH$	NLO + NNLO QCD	NNLO electroweak
$m_{\rm top}$	100 MeV	17 MeV	threshold scan $e^+e^-\to t\bar{t}$	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

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Flavour/Tau physics with the Tera-Z run

FUTURE CIRCULAR COLLIDER

Particle production (10^9)	B^0	B^-	B^0_s	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				
$B^0 \to K^*(892)e^+e^-$	~ 2000	~ 150	~ 5000	~ 200000
$\mathcal{B}(B^0 \to K^*(892)\tau^+\tau^-)$	~ 10	–	–	~ 1000
$B_s \to \mu^+\mu^-$	n/a	~ 15	~ 500	~ 800
$B^0 \to \mu^+\mu^-$	~ 5	–	~ 50	~ 100
$\mathcal{B}(B_s \to \tau^+\tau^-)$				
Leptonic decays				
$B^+ \to \mu^+\nu_{mu}$	5%	–	–	3%
$B^+ \to \tau^+\nu_{tau}$	7%	–	–	2%
$B_c^+ \to \tau^+\nu_{tau}$	n/a	–	–	5%
CP / hadronic decays				
$B^0 \to J/\Psi K_S$ ($\sigma_{\sin(2\phi_d)}$)	$\sim 2.*10^6$ (0.008)	41500 (0.04)	$\sim 0.8 \cdot 10^6$ (0.01)	$\sim 35 \cdot 10^6$ (0.006)
$B_s \to D_s^\pm K^\mp$	n/a	6000	~ 200000	$\sim 30 \cdot 10^6$
$B_s(B^0) \to J/\Psi\phi$ (σ_{ϕ_s} rad)	n/a	96000 (0.049)	$\sim 2.10^6$ (0.008)	$16 \cdot 10^6$ (0.003)

Out of reach at LHCb/Belle

boosted b's/τ's

at FCC-ee

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

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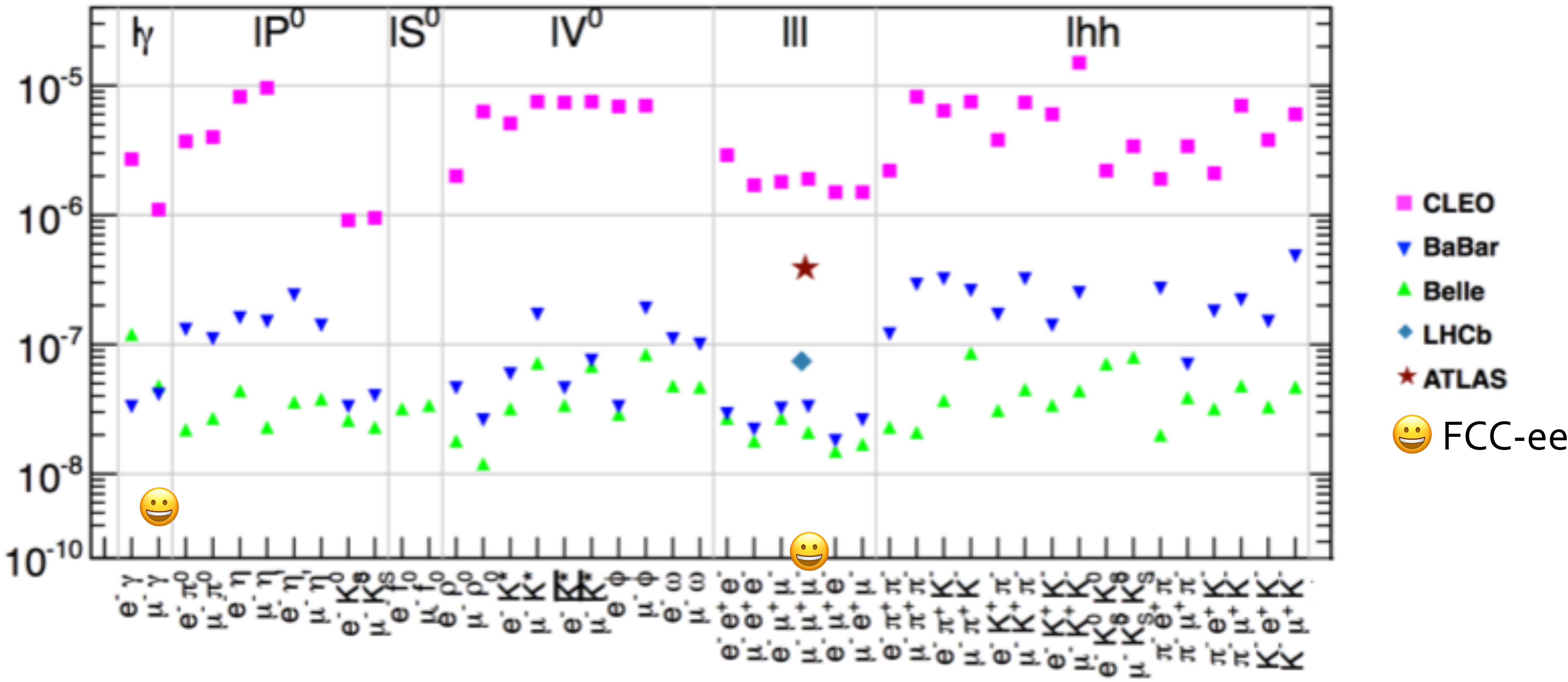
~10 times Belle's stat

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