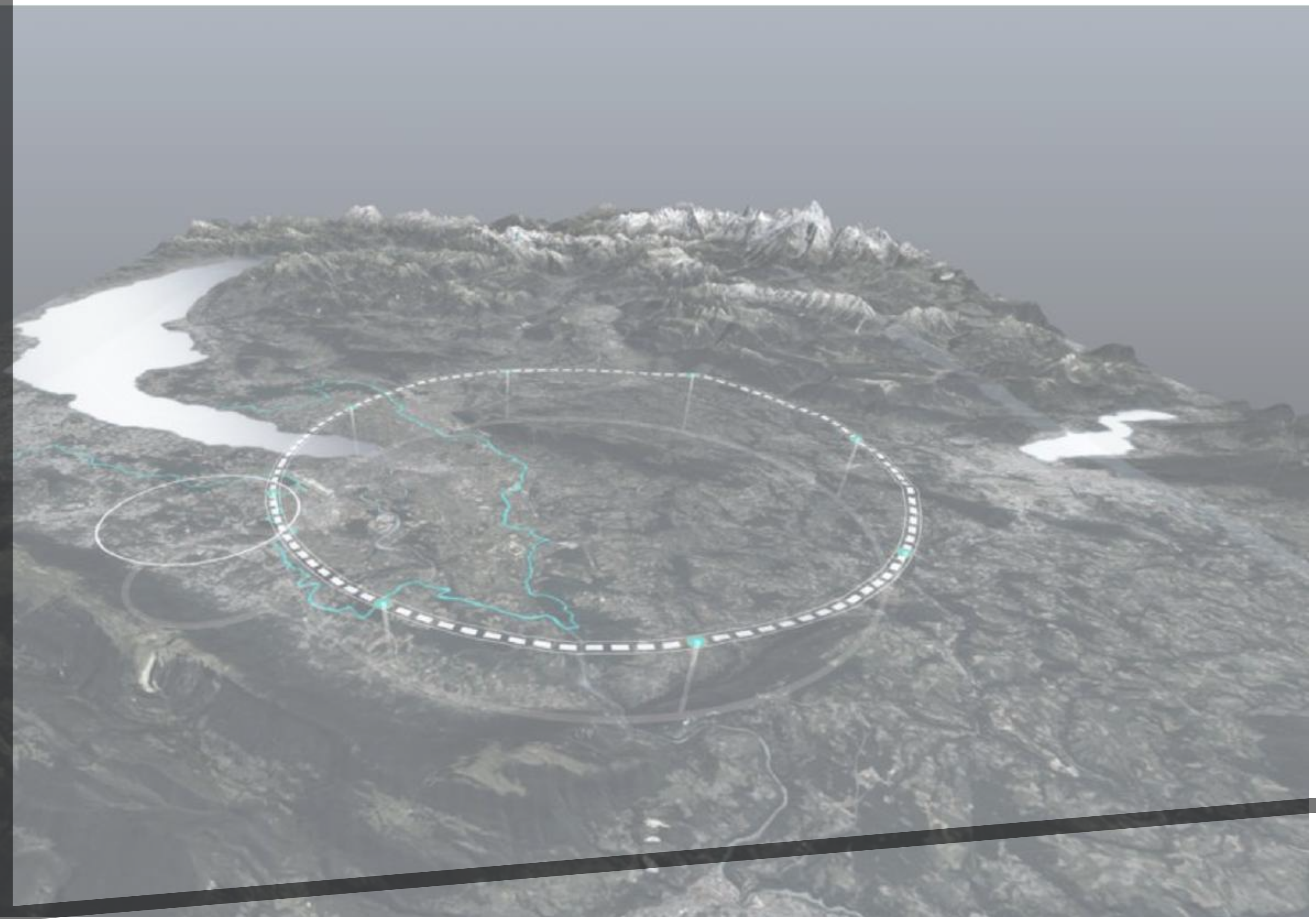
Future Circular Collider

III[rd] Latin American Strategy Forum for Research Infrastructure



Christophe Grojean

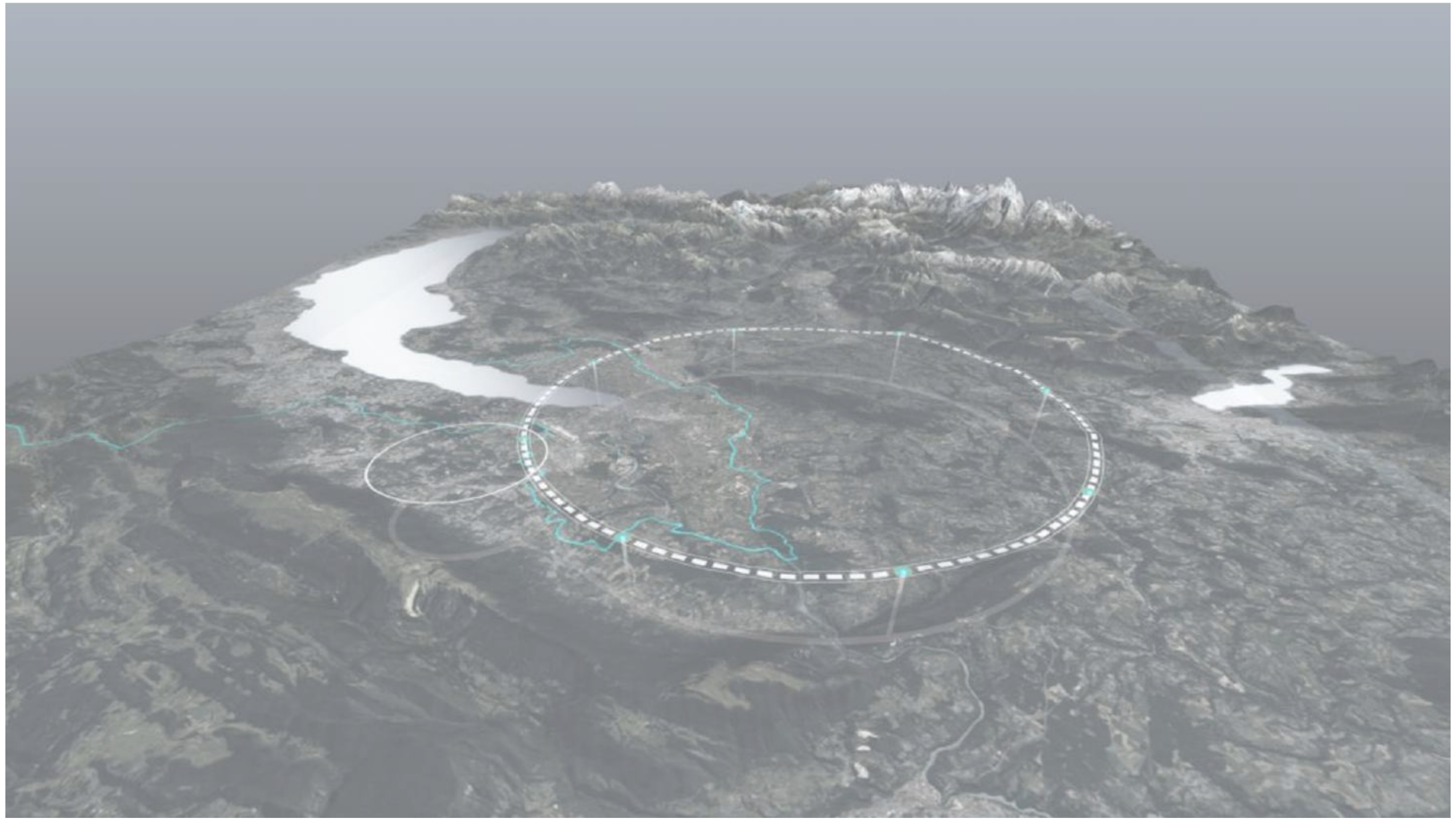
(christophe.grojean@desy.de)

— on behalf of the FCC team—

Future Circular Collider

- A versatile particle collider housed in a 91km underground ring around CERN.

- Implemented in several stages:
  - an e^+e^- “Higgs/EW/Flavour/top/QCD” factory running at 90-365 GeV ▶ **FCC-ee**
  - followed by a high-energy pp collider reaching 100 TeV ▶ **FCC-hh**



FCC on a Fast Track

After just over a decade of pioneering work, huge progress has been achieved:

- The first proposal of a high-luminosity e^+e^- circular collider to study the Higgs boson was made **thirteen years** ago (December 2011) and submitted to the 2012-13 European Strategy Update [A. Blondel & F. Zimmermann following discussions with P. Janot at CERN cafeteria on a bright 2011 summer night speculating on the rumours of a Higgs at **140 GeV**];

- The Future Circular Collider collaboration was created **ten years** ago, towards the conceptual design study of a **100 TeV pp collider**, with an e^+e^- Higgs factory as a potential intermediate step;

- The **Conceptual Design Reports** of the FCC physics case, and of the FCC-ee and FCC-hh colliders, were published **five years** ago and submitted to the 2018-19 European Strategy Update;

- The CERN Council updated the European Strategy **three years** ago, stating that an e^+e^- Higgs factory would be the highest priority next collider, to be followed by a proton-proton collider at the highest achievable energy;

- **Two years** ago, the CERN Council consequently initiated and funded a **technical and financial feasibility** study for FCC with focus on an e^+e^- electroweak and Higgs factory as a first stage, study to be completed by the time of the next European Strategy Update;

- **Ten months** ago, a 700+ pages **mid-term report** about the FCC feasibility was submitted to the CERN Council for a thorough review, with a conclusion expected at the beginning of 2024. Very positive feedback from CERN council in **Feb. 2.**

FCC-hh tunnel is great for FCC-ee.

- **80-100 km is needed to accelerate pp up to 100 TeV**
- **80-100 km is also exactly what is needed**
  - to get enough luminosity (5 times more than in 27 km) to maybe get sensitivity to the Higgs self coupling, the electron Yukawa coupling, or sterile neutrinos,
  - to make TeraZ a useful flavour factory,
  - for transverse polarisation to be available all the way to the WW threshold (allowing a precise W mass measurement)
  - for the top threshold to be reached and exceeded.

After the success of LHC, we need a broad, versatile and ambitious programme that
1. sharpens our knowledge of already discovered physics → **guaranteed deliverables**
2. pushes the frontiers of the unknown at high and low scales → **exploration**

— together FCC-ee & FCC-hh combine these 2 aspects —

more PRECISION and more ENERGY, for more SENSITIVITY to New Physics

Precision as a discovery tool.

Many historical examples

- Uranus anomalous trajectory ⇢ Neptune
- Mercury perihelion ⇢ General Relativity
- Z/W interactions to quarks and leptons ⇢ Higgs boson
- …

Sometimes, these discoveries were expected based on theoretical arguments
(e.g. Rayleigh-Jeans UV catastrophe for QM, unitarity breakdown for the Higgs)
but precision gave valuable additional clues.
In any case, experimentalists shouldn't lean too heavily on theorist priors/prejudices
(remember discovery of CP violation).
At times when we don't have a precise theoretical guidance, we need powerful experimental tools to make progress.

The FCC project offers unprecedented opportunities on many different fronts.
No LHC/SSC-like **no-lose theorem** but a **promise** of making significant steps forward in our understanding of the fundamental laws of Nature.

FCC feasibility study

The launch of the feasibility study.

"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."

— CERN council approved the Strategy and CERN management implemented it —

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

Mid-term review in 2023.

Objectives of FCC feasibility study.

- Demonstration of the **geological, technical, environmental and administrative feasibility** of the tunnel and surface areas and optimisation of placement and layout of the ring and related infrastructure.
- Pursuit, together with the Host States, of the preparatory **administrative processes** required for a potential project approval to identify and remove any showstopper.
- Optimisation of the design of the **colliders and their injector chains**, supported by R&D to develop the needed key technologies.
- Elaboration of a sustainable **operational model** for the colliders and experiments in terms of human and financial resource needs, as well as environmental aspects and energy efficiency.
- Development of a consolidated **cost estimate**, as well as the funding and organisational models needed to enable the project's technical design completion, implementation and operation.
- Identification of substantial **resources** from outside CERN's budget for the implementation of the first stage of a possible future project (**tunnel and FCC-ee**).
- Consolidation of the **physics case and detector concepts** for both colliders.

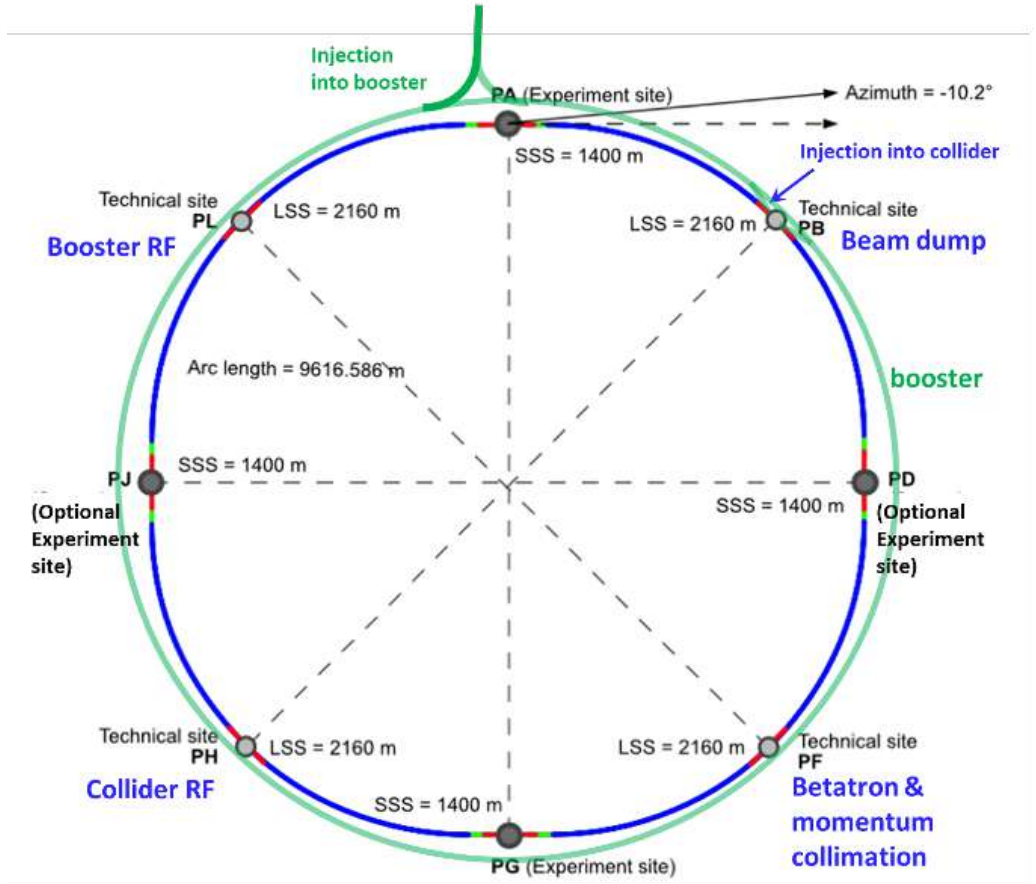
Optimized placement and layout.

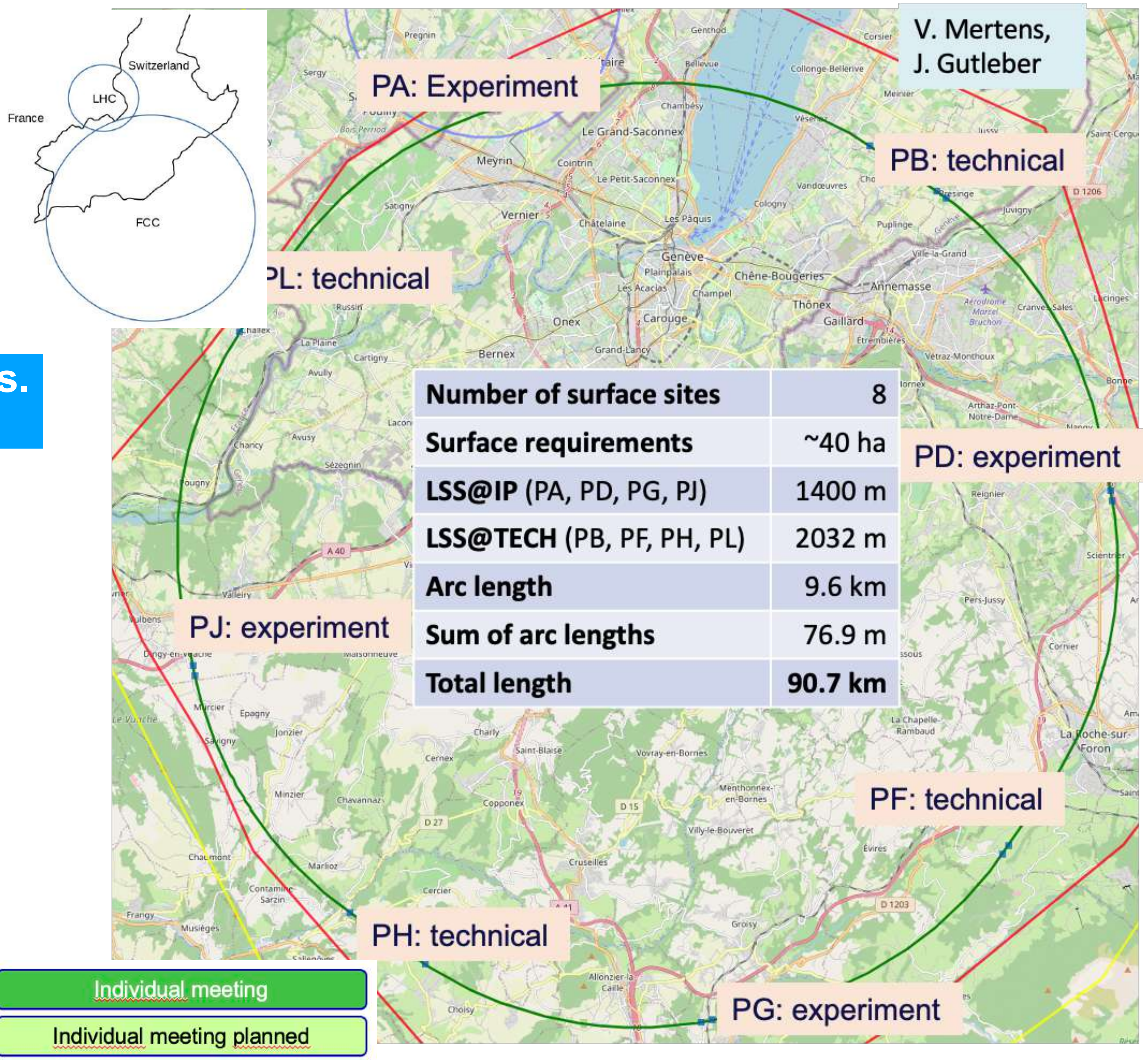
M. Benedikt @ CERN 13.02.24

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 regulation

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**

Individual meeting

Individual meeting planned

Collective meeting

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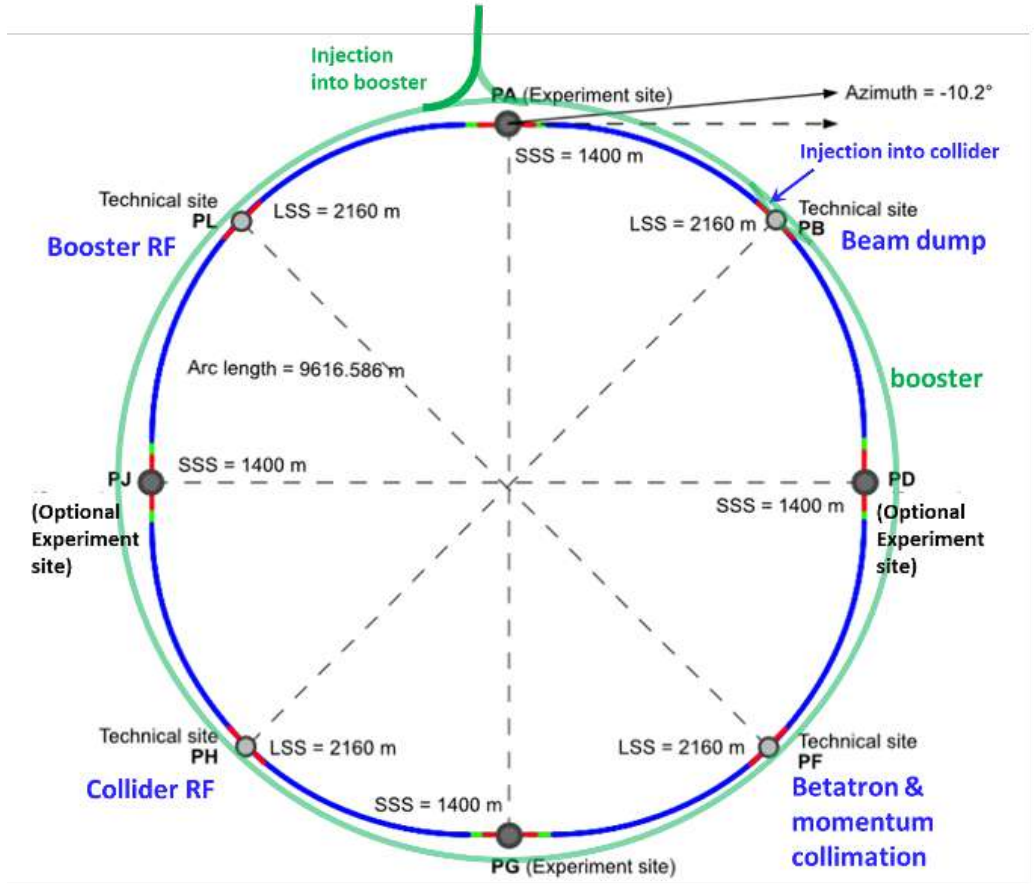

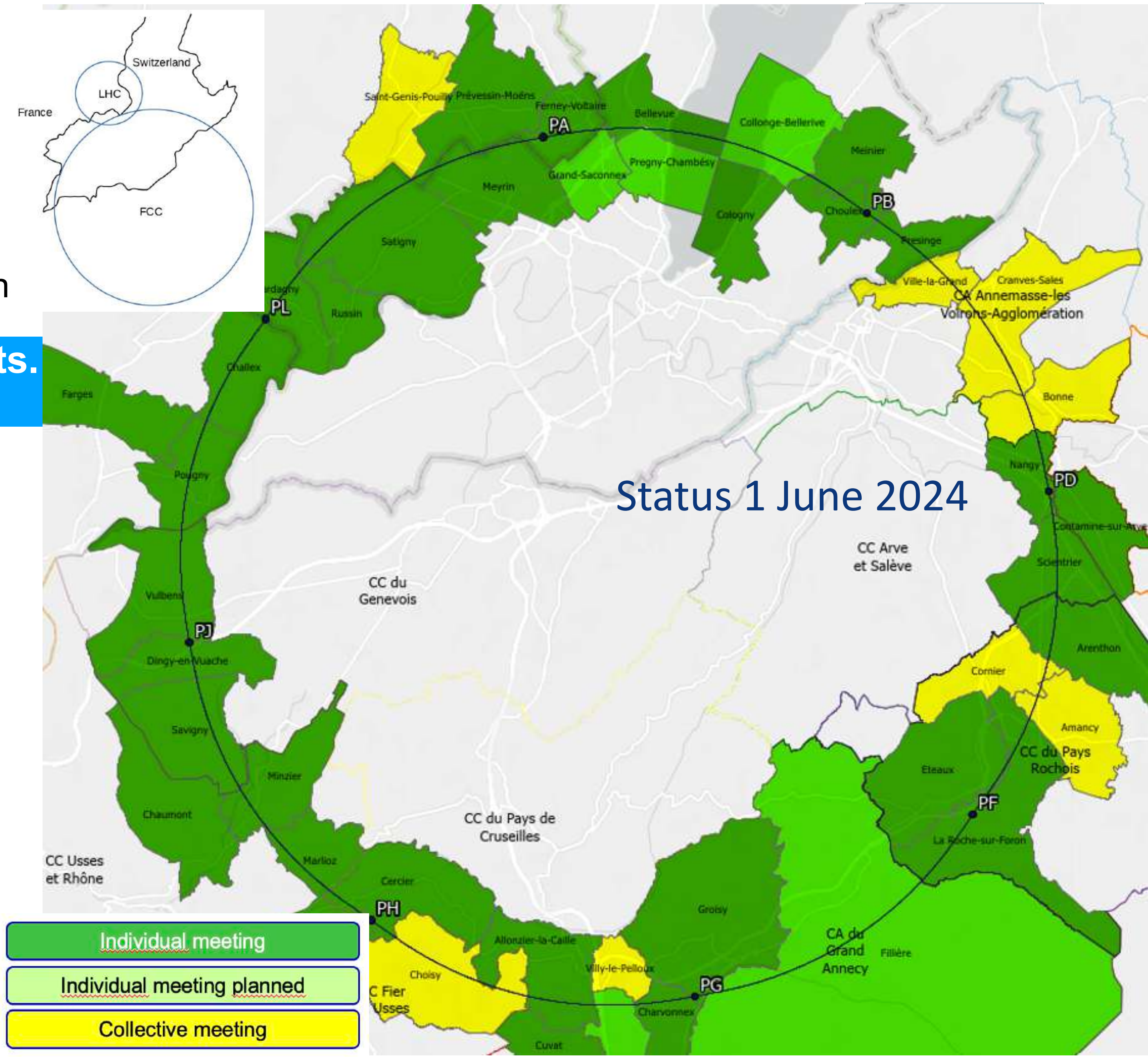

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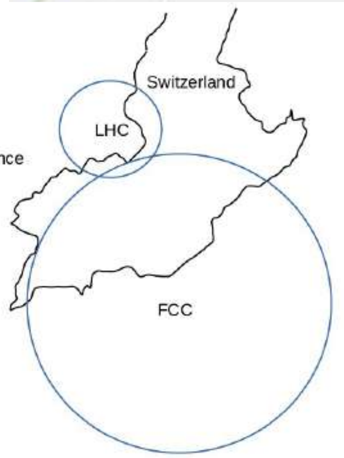
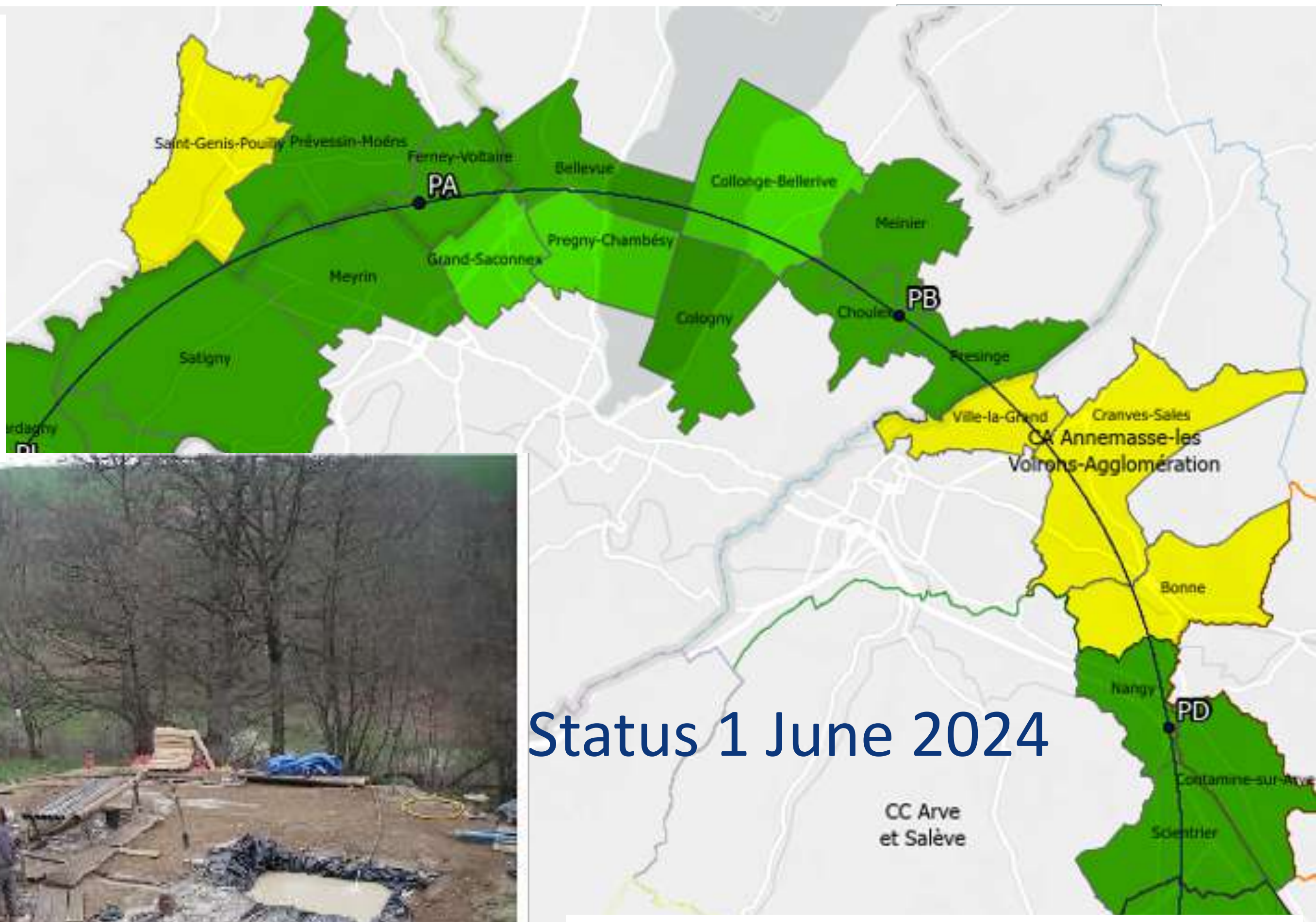
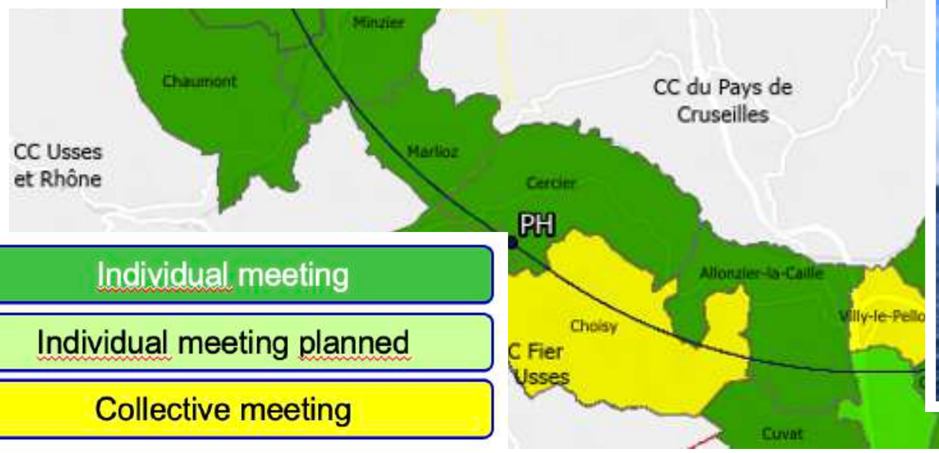
Whole project now adapted to this placement

- **Site investigations in areas with uncertain geological conditions:**
  - Optimisation of localisation of drilling locations ongoing with site visits since end 2022.
  - Alignment with FR and CH on the process for obtaining autorisation procedures. Ongoing for start of drillings in Q2/2024
- **Contracts Status:**
  - Contract for engineering services and role of Engineer during works, active since July 2022
  - Site investigations tendering ongoing towards contract placement in December 2023 and mobilization from January 2024





Sondage A89 (2007) incliné de 45° de 125 ml (surface plateforme estimée : 12 x 12 m soit environ 150 m²)



Individual meeting

Individual meeting planned

Collective meeting

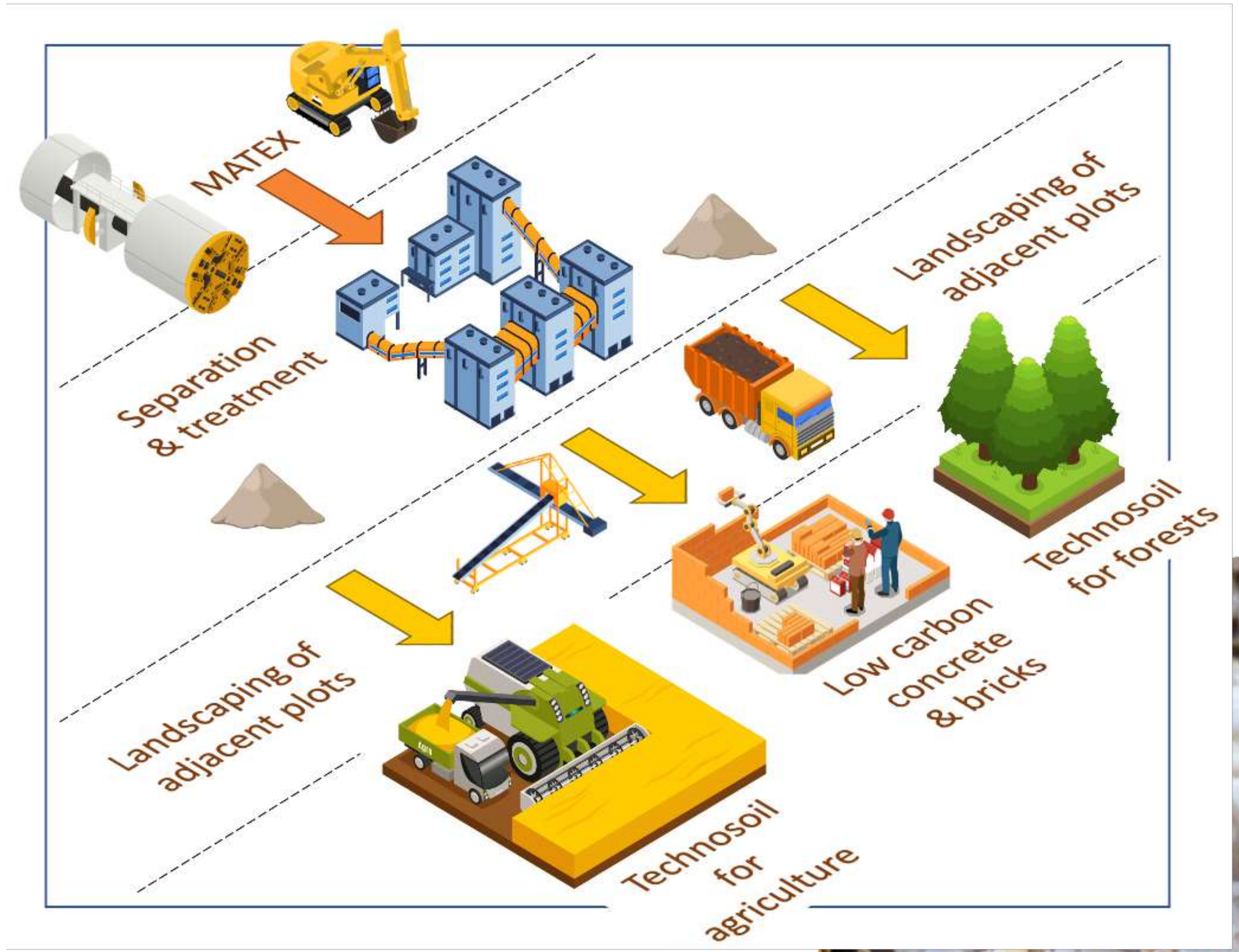
Drilling works on the lake

Environmental considerations.

M. Benedikt @ CERN 13.02.24

- **Excavated material** from FCC subsurface infrastructures: 6.5 Mm^3 in situ, 8.4 Mm^3 excavated
- **Priority : reuse, minimize disposal**
- 2021-2022: International competition **"Mining the Future"**, launched with the support of the EU Horizon 2020 grant, to find innovative and realistic ideas for the reuse of molasse (96% of excavated materials)
- 2023: **"OpenSky Laboratory"** project: Objective - Develop and test an innovative process to transform sterile "molasse" into fertile soil for agricultural use and afforestation. launched in Jan. 2024: 5500m^2 near LHC P5 in Cessy (FR). Trial with 5 000t of excavated local molasse → convert it to arable soil (agricultural/forestry)

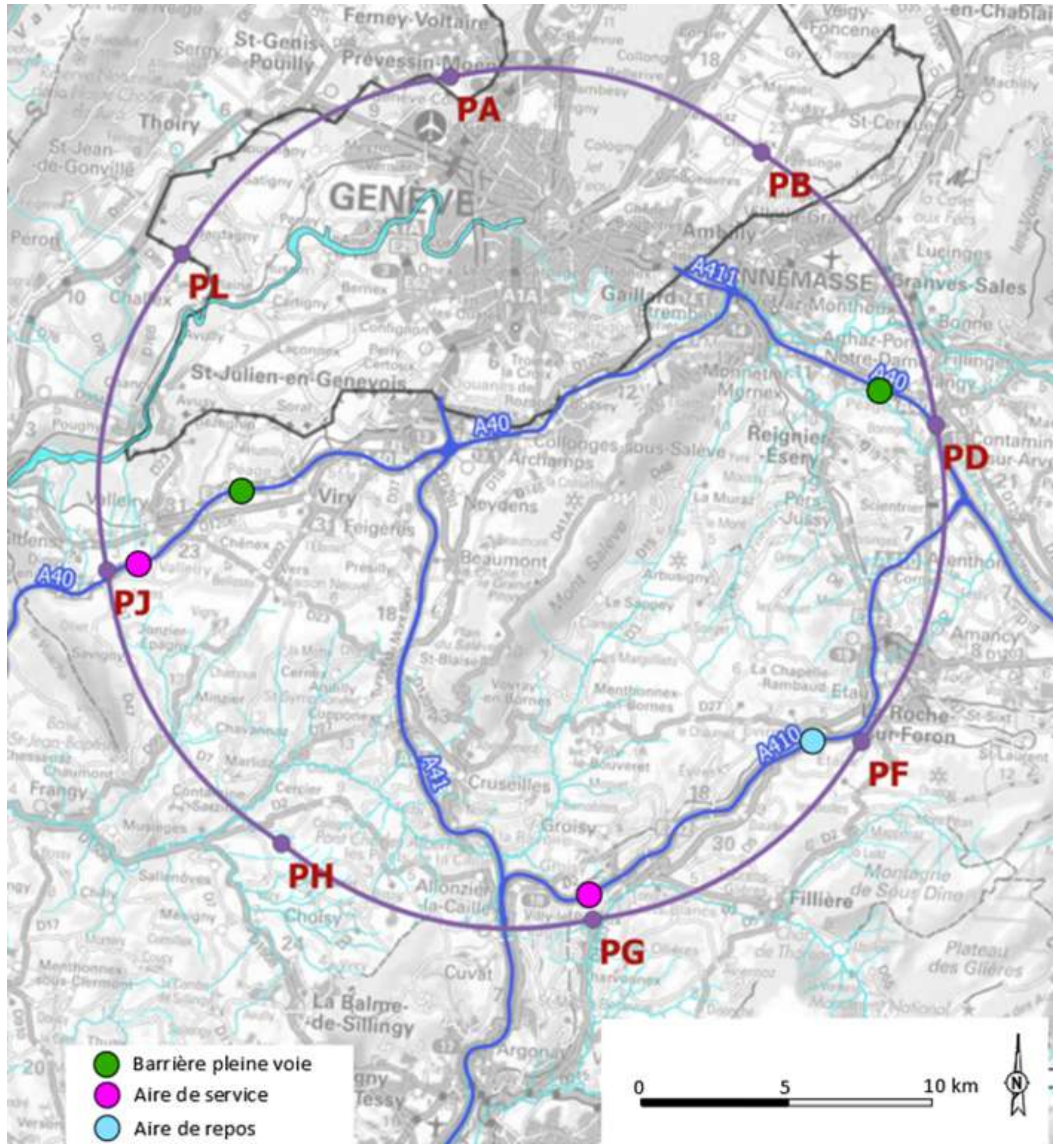
- **Heat:**
  - heating for local houses
  - cheese factories in Jura and Haute-Savoie expressed special interest



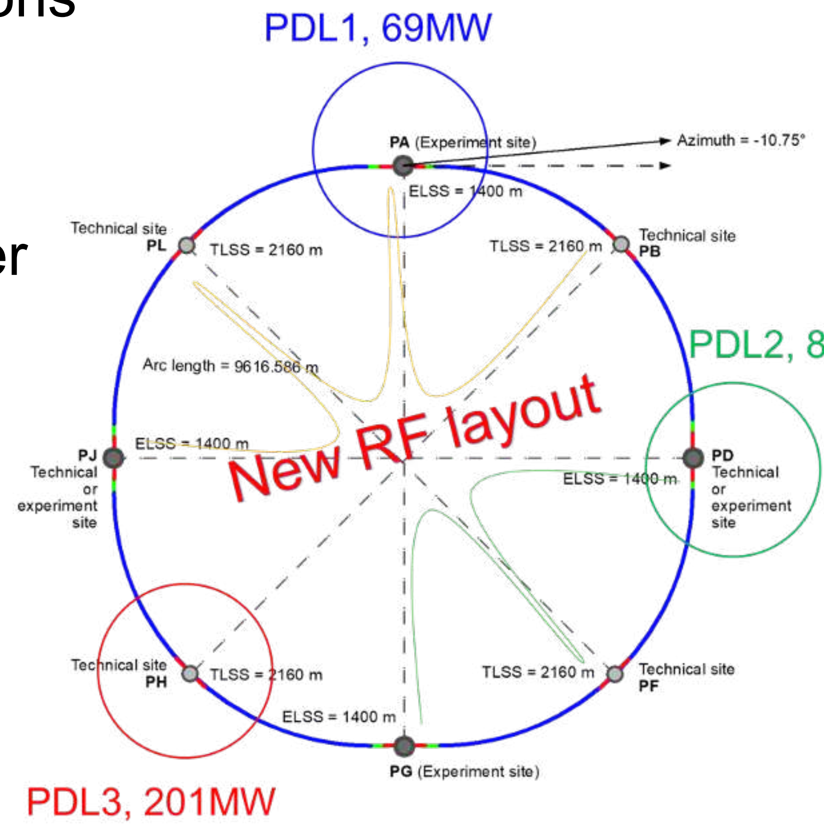
Connections with local infrastructre.

M. Benedikt @ CERN 13.02.24

- **Road accesses** developed for all 8 surface sites
  - Four possible highway connections defined
  - Less than 4 km new departmental roads required

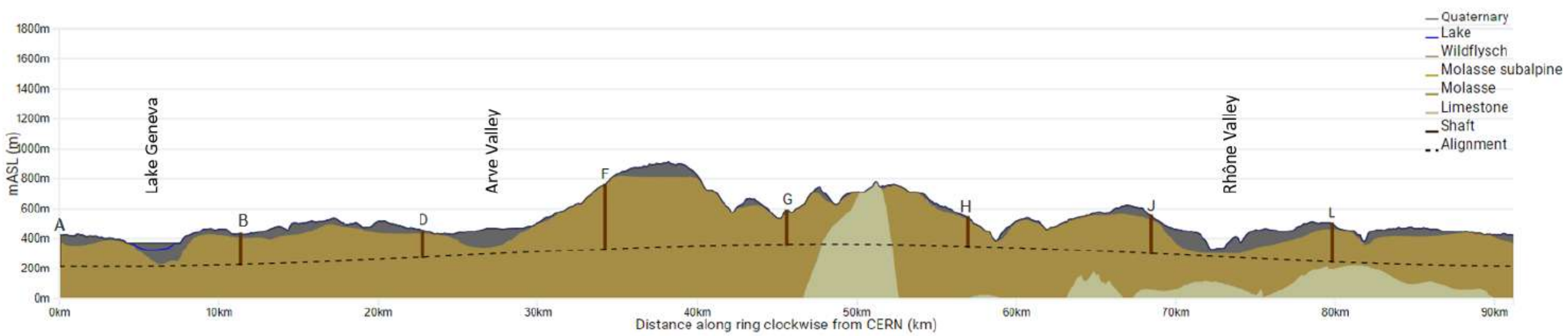


- **Connections to electrical grid**
  - Electrical connection concept studied by RTE (French electrical grid operator) → requested loads have no significant impact on grid
  - Powering concept and power rating of the three sub-stations compatible with FCC-hh
  - R&D efforts aiming at further reduction of the energy consumption of FCC-ee and FCC-hh



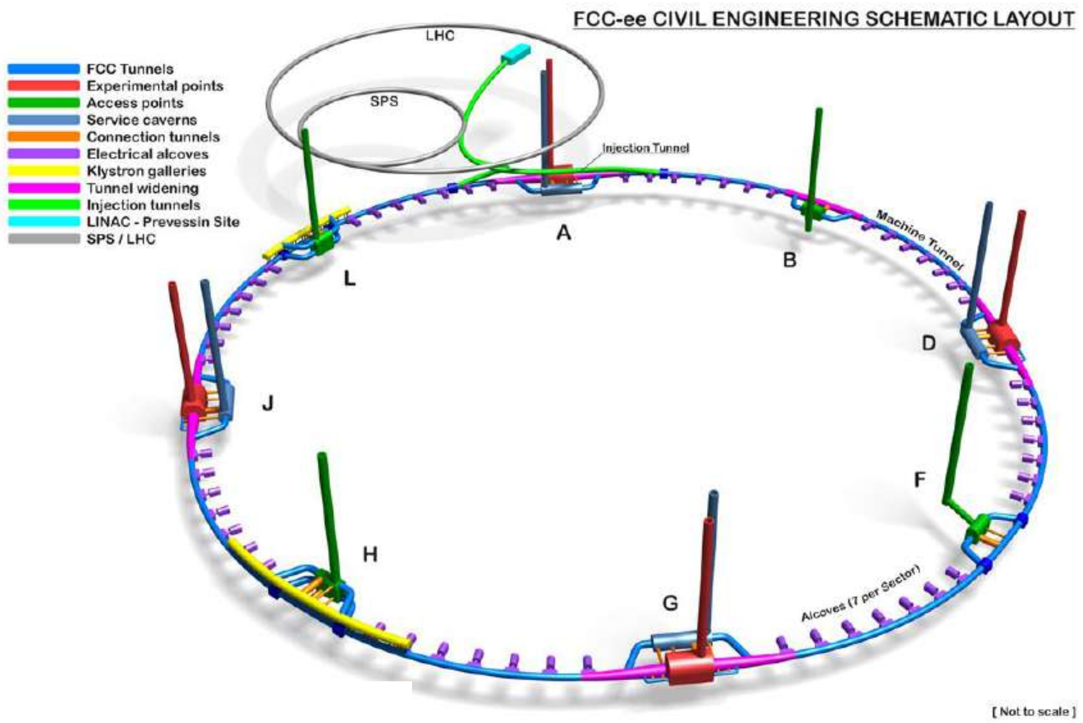
Civil engineering

T. Watson @ Annecy FCC Physics ‘24



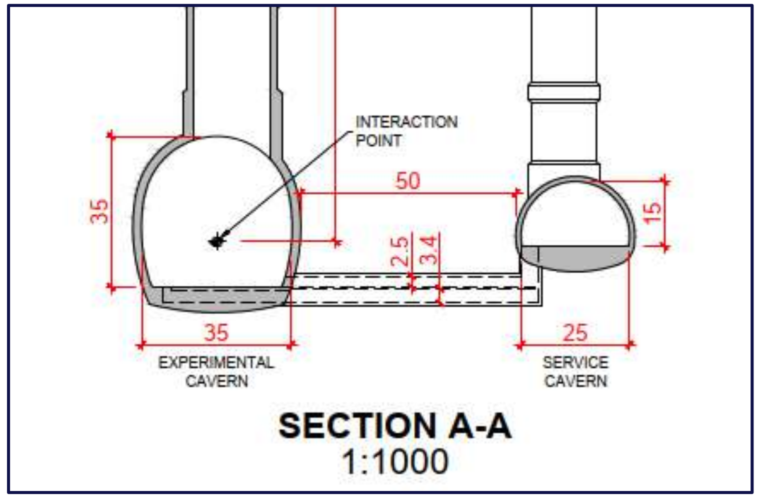
Shaft depths:

A: 201 m B: 201 m D: 181 m F: 400 m G: 226 m H: 235 m J: 253 m L: 250 m

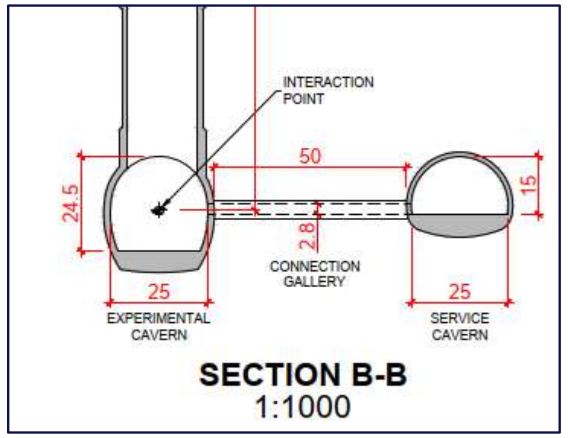


Tunnel Boring Machine (TBM)

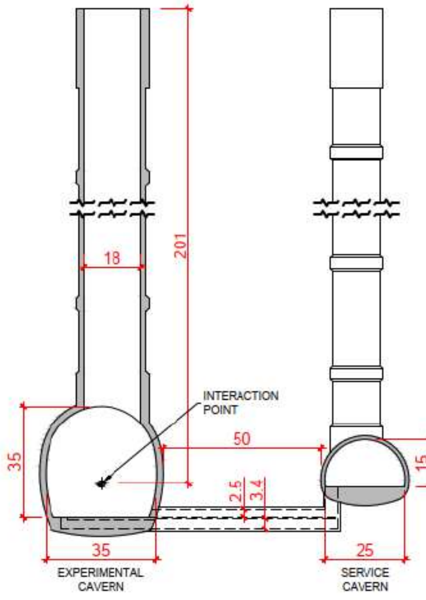
- Tunnel Boring Machines (TBMs) are designed to work almost continuous 24/7 other than periodic maintenance. Rate of 18m/day in the Molasse → 8 years.
- 13 shafts
- 2/2 large/small caverns



large cavern complex



small cavern complex



shaft @ exp. site

Civil engineering

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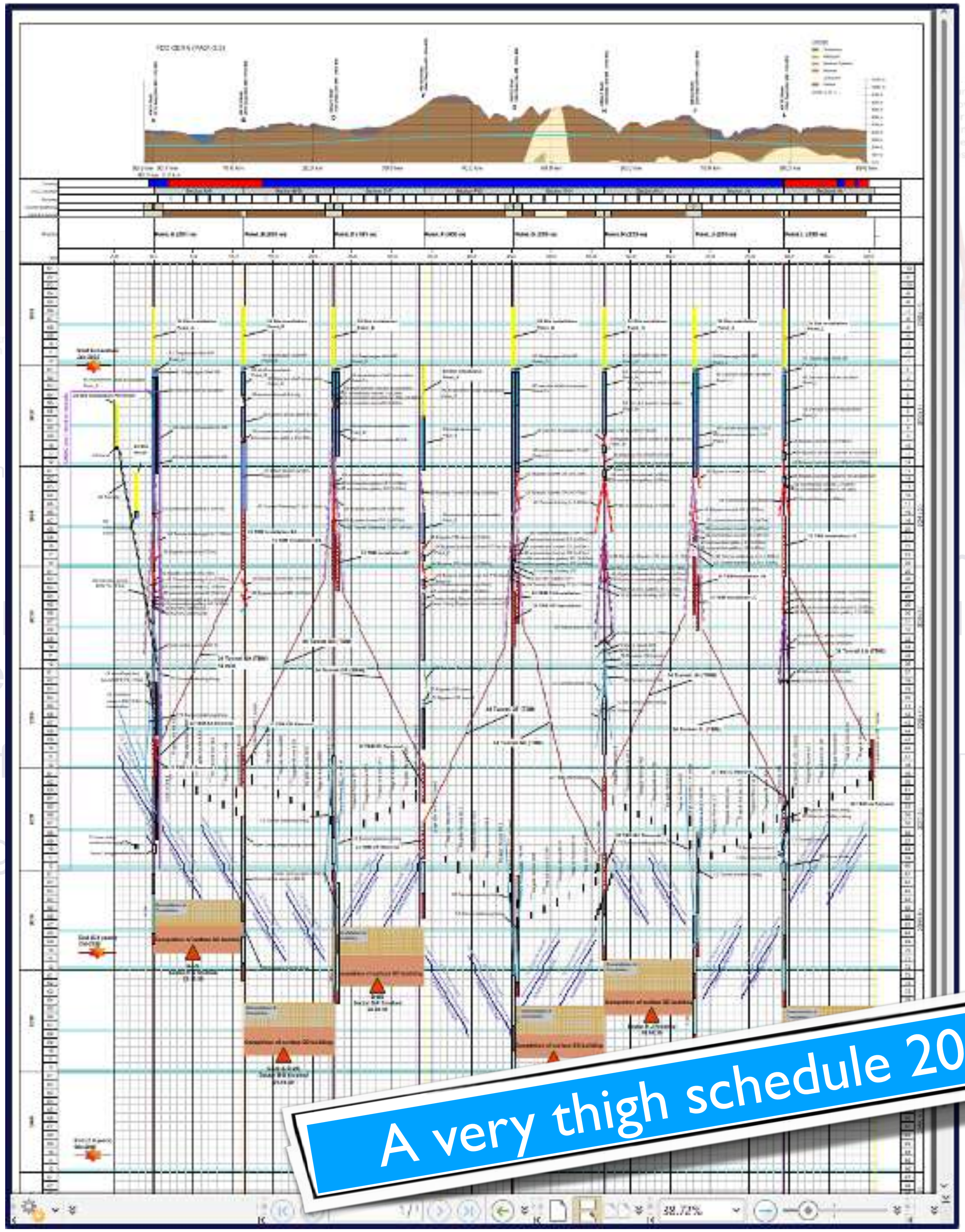
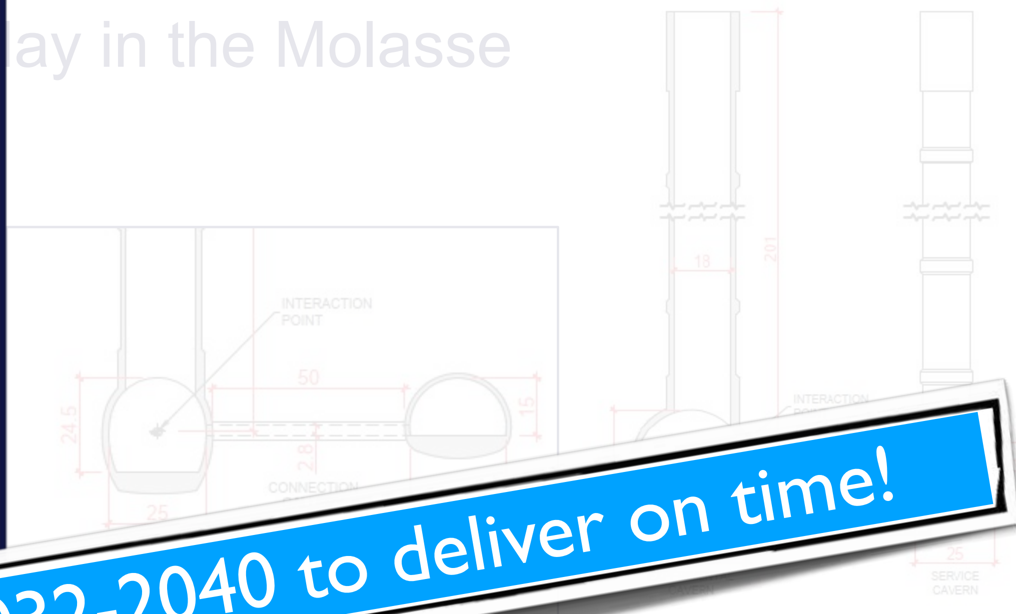
Tunnel Boring Machine (TBM)

- Tunnel ... k almost continuous 24/7 ot... ay in the Molasse → 8 ye...
- 13 sha...
- 2/2 larg...





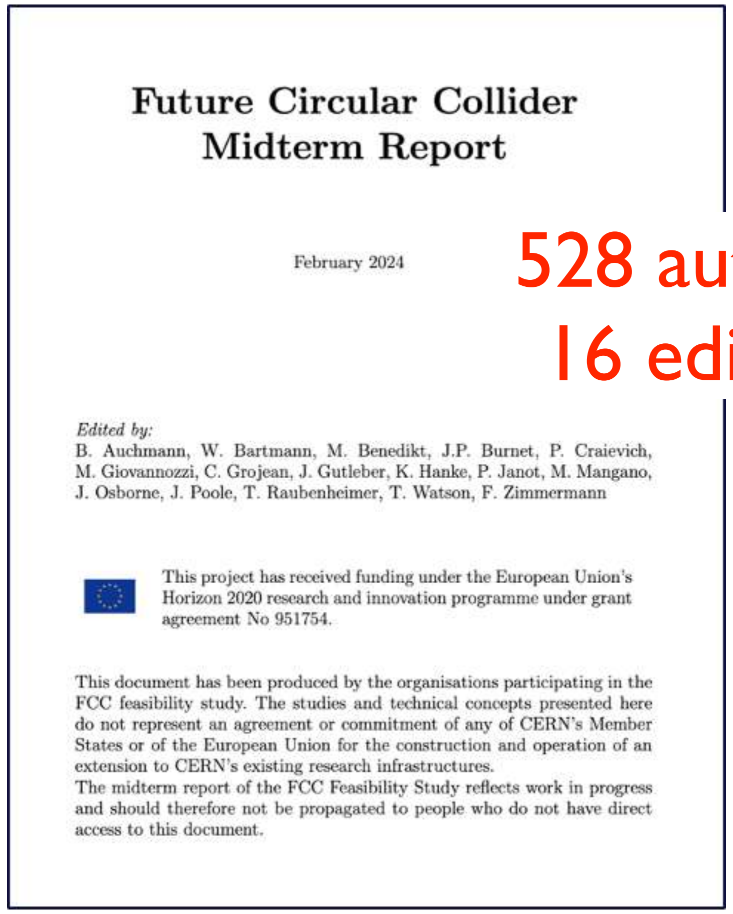
shaft @ exp. site

small cavern complex

A very thigh schedule 2032-2040 to deliver on time!

FCC feasibility mid-term report.

- **703 pages**: 7 chapters (cost and financial feasibility is a separate document) + refs.
    - 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
    - Scientific Policy Committee and Financial Committee on Nov. 21-22
    - CERN Council Feb. 2


Future Circular Collider
Midterm Report

February 2024

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

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This document has been produced by the organisations participating in the FCC feasibility study. The studies and technical concepts presented here do not represent an agreement or commitment of any of CERN's Member States or of the European Union for the construction and operation of an extension to CERN's existing research infrastructures.
The midterm report of the FCC Feasibility Study reflects work in progress and should therefore not be propagated to people who do not have direct access to this document.

528 authors
16 editors

confidential documents
(work in progress)
available
to CERN personnel

Physics, Experiments, Detectors.

- FCC Feasibility Study PED deliverables for mid-term review

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.

deliverables explicitly requested from SPC & Council (8.2–8.4)

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

Feedback.

Andy **Parker** (SAC chair), Norbert **Holtkamp** (CRP chair), Hugh **Montgomery** (SPC chair), Laurent **Salzarulo** (FC chair), Eliezer **Rabinovici** (Council president)

"many thanks for the work done, congratulations for the results, impressive quality of the study…"

"Financial Committee underlines the need to make the project attractive from the physics viewpoint and takes the view that it would be unfortunate to sacrifice the attractiveness of the physics for the sake of reducing costs."

"Si j'ai voulu venir là aujourd'hui c'est pour témoigner ma confiance aux équipes et notre volonté, notre ambition de conserver la première place dans ce domaine."

["My visit here bears witness to my trust in CERN personnel and France's will and ambition to keep the leadership in this domain."]

E. Macron, CERN 16.11.2023

US Statement of Intent

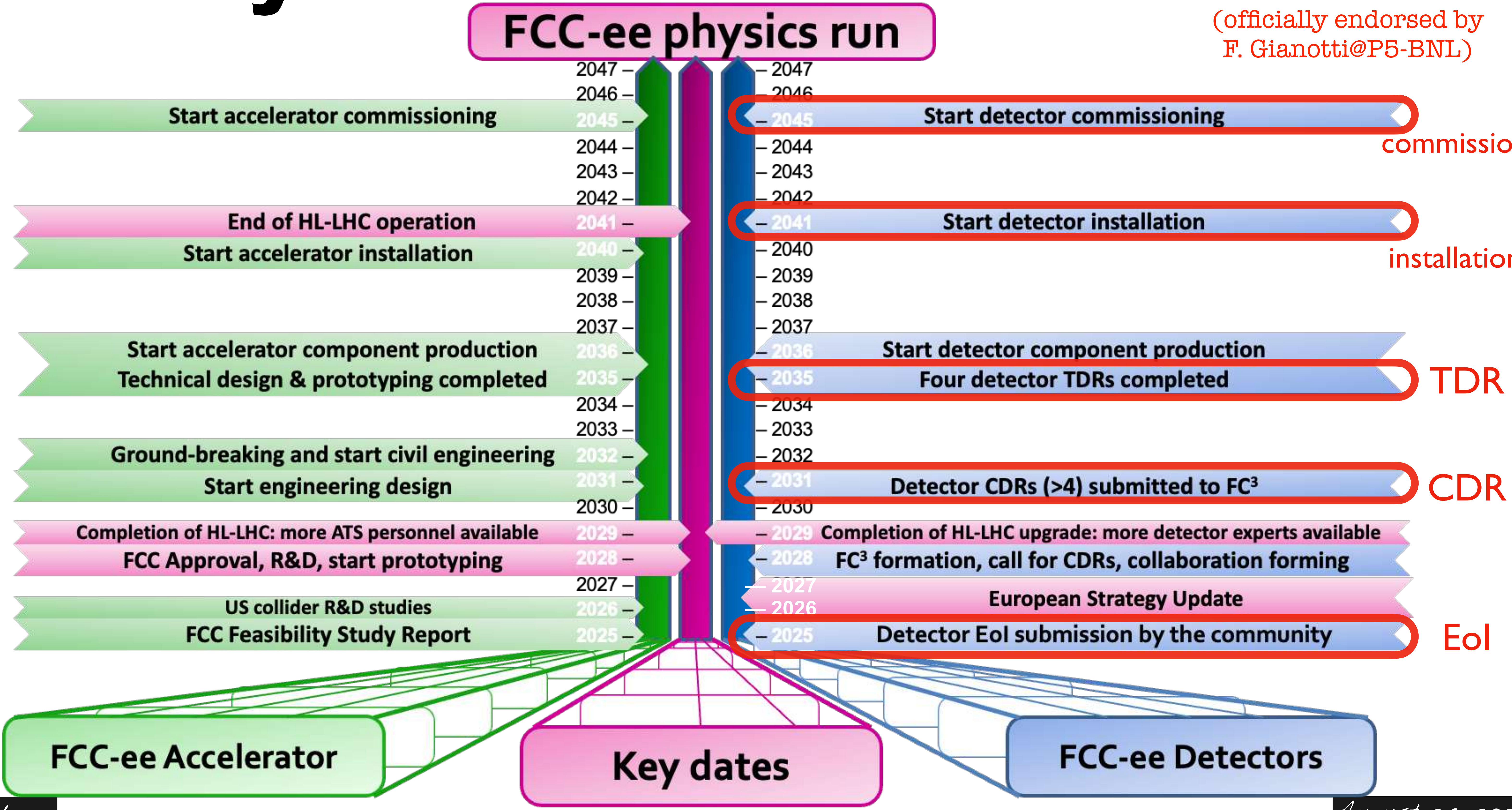
Deirdre Mulligan Fabiola Gianotti

"Should the CERN Member States determine the FCC-ee is likely to be CERN's next world-leading research facility following the high-luminosity Large Hadron Collider, the United States intends to collaborate on its construction and physics exploitation, subject to appropriate domestic approvals."

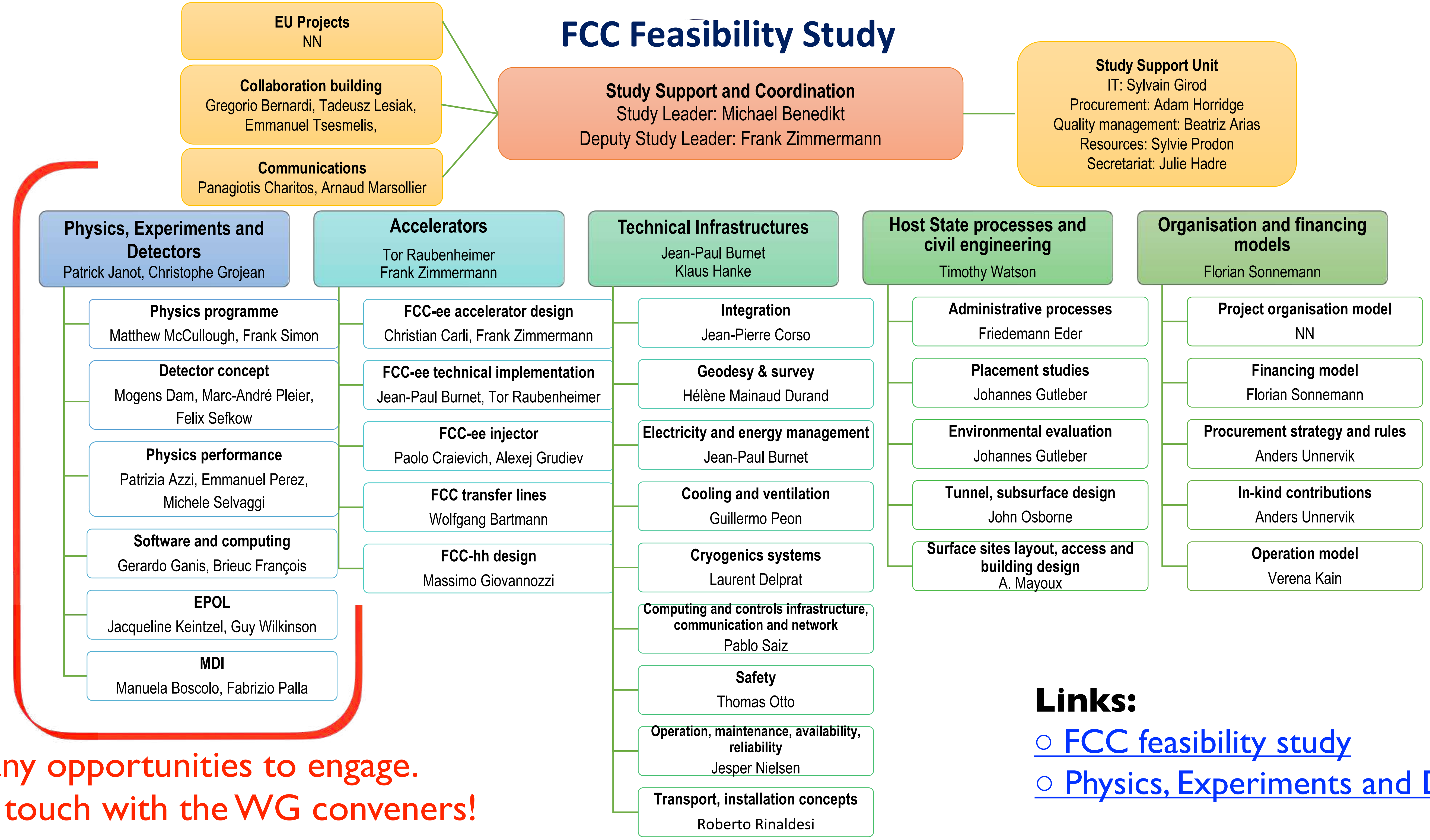
White House, April 26, 2024

The way forward.

P. Janot
(officially endorsed by
F. Gianotti@P5-BNL)



FCC Feasibility Organisation Chart.

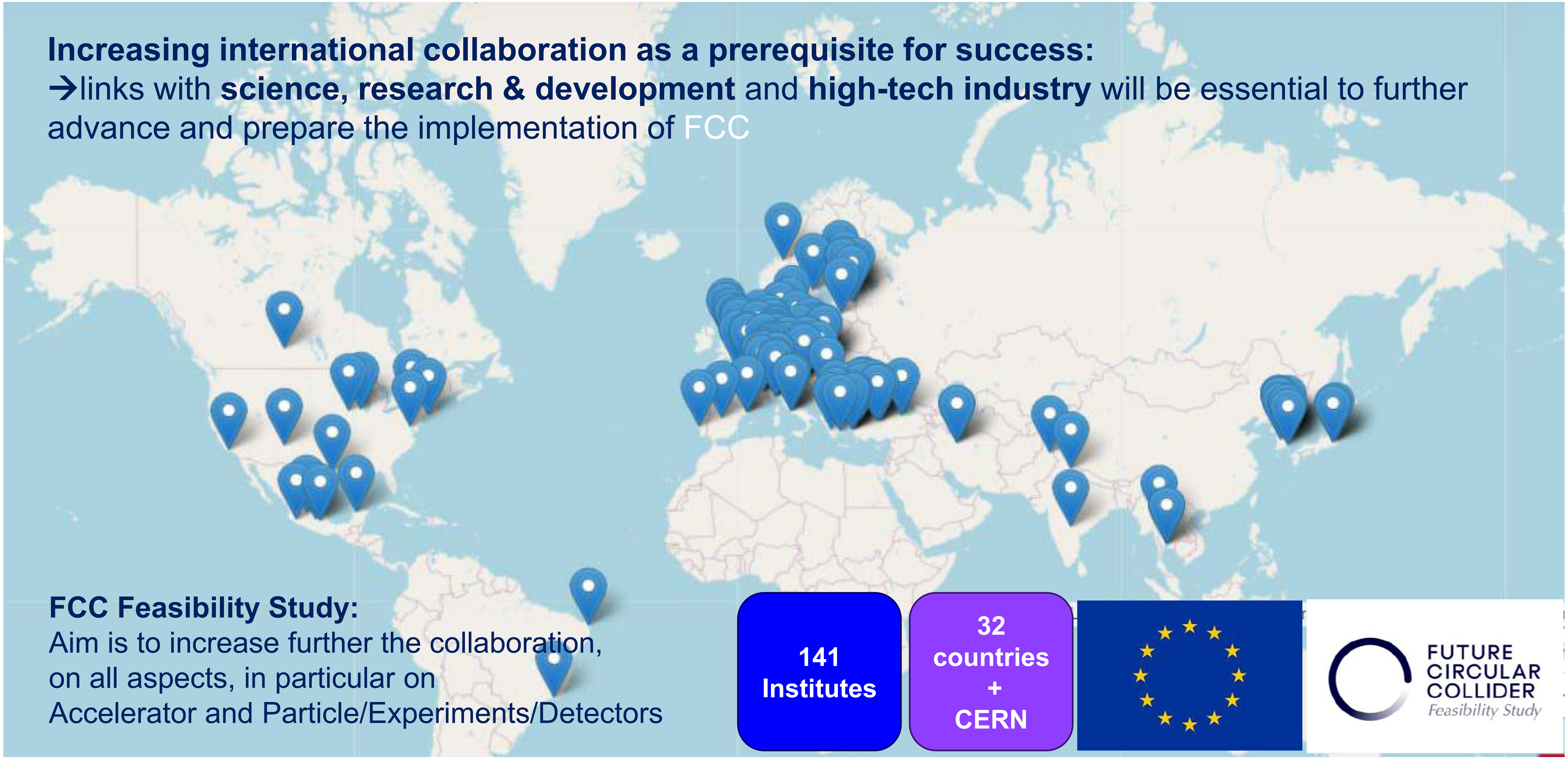


Many opportunities to engage.
Get in touch with the WG conveners!

Links:
- [FCC feasibility study]
- [Physics, Experiments and Detectors (PED)]

FCC: an international enterprise.

Increasing international collaboration as a prerequisite for success:
→links with **science, research & development** and **high-tech industry** will be essential to further advance and prepare the implementation of FCC



FCC Feasibility Study:
Aim is to increase further the collaboration, on all aspects, in particular on Accelerator and Particle/Experiments/Detectors

141 Institutes

32 countries + CERN

FUTURE CIRCULAR COLLIDER
Feasibility Study

Physics @ FCC

FCC-ee Run Plan.

LEP1 data accumulated in **every 2 mn**. Exciting & diverse programme with different priorities every few years.

(order of the different stages still subject to discussion/optimisation)

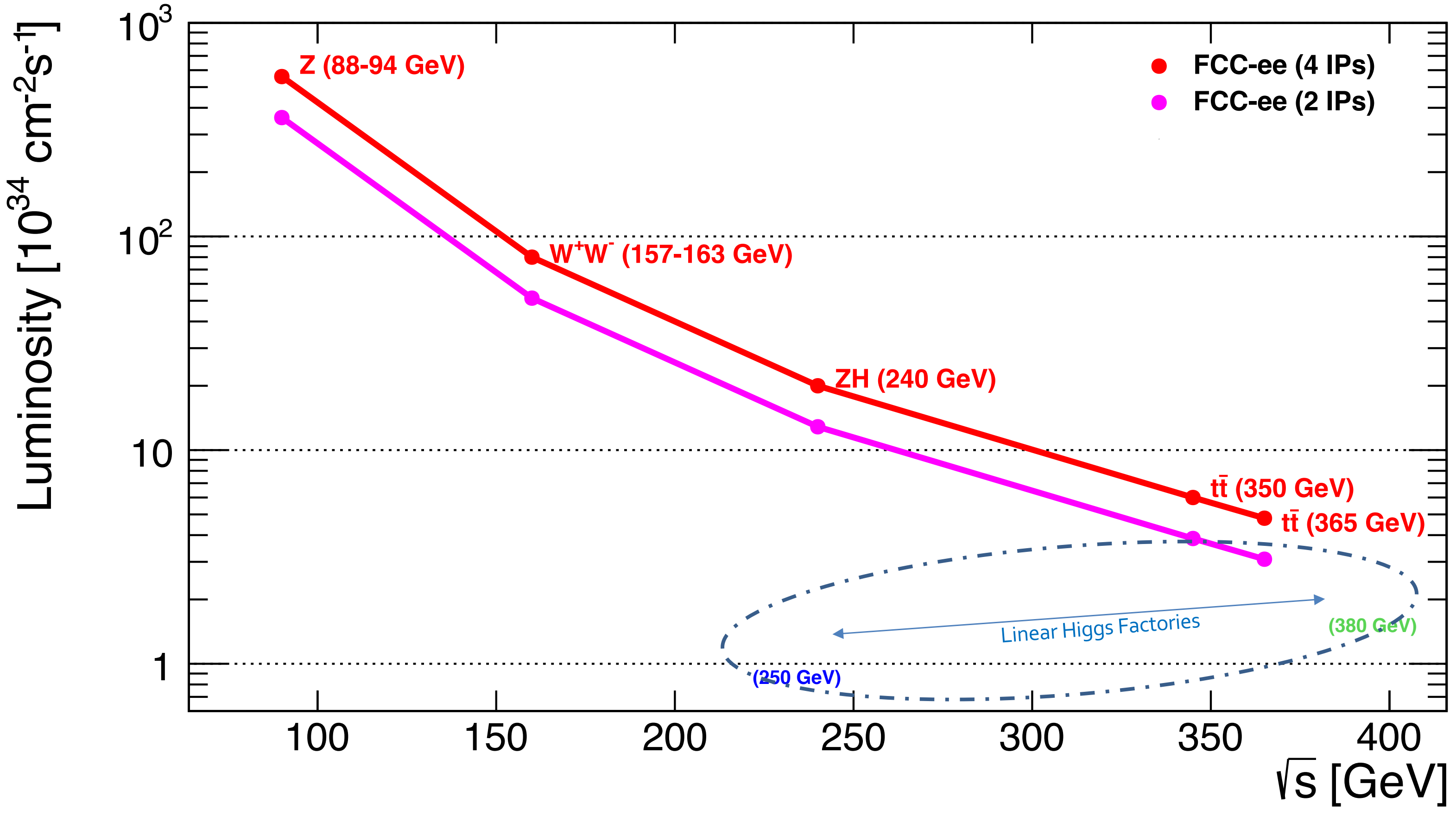
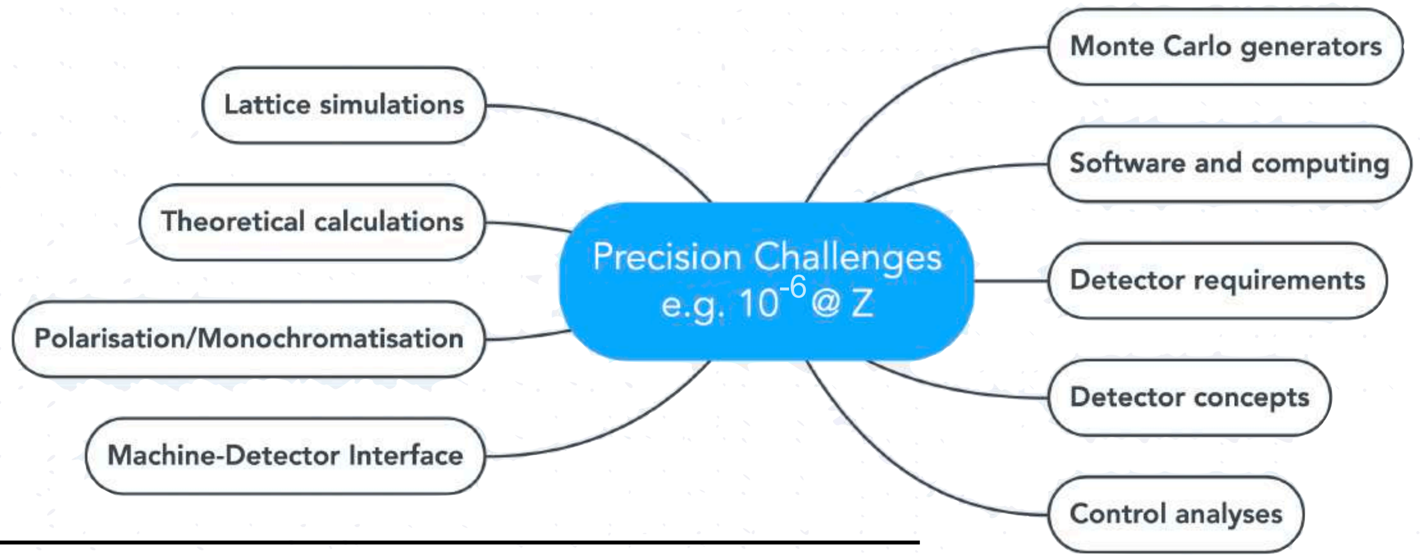


Fig. to be updated: new optics design (May 2024) gives 50% more lumi @ 240 GeV.

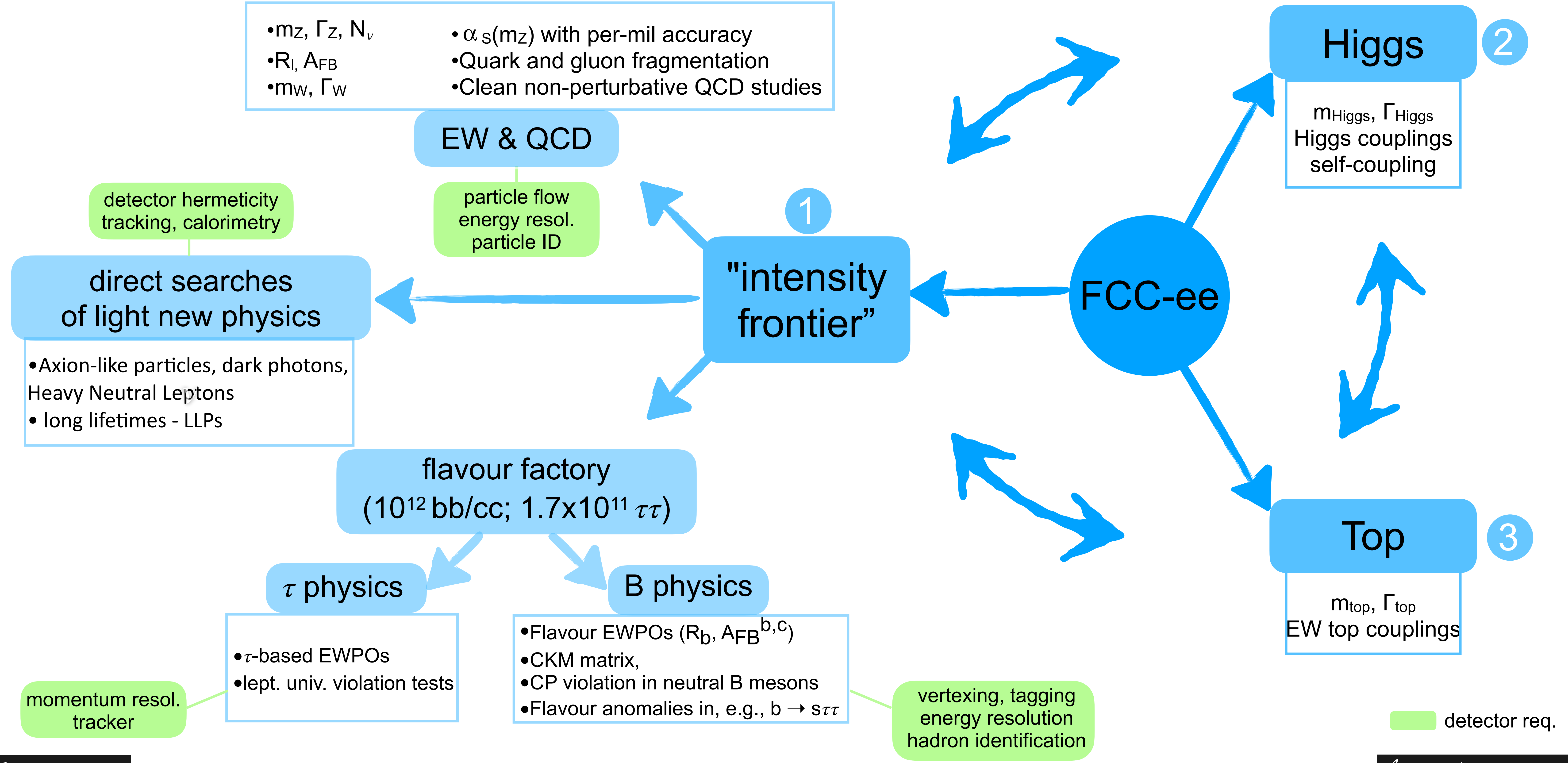
— Superb statistics achieved in only 15 years —

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

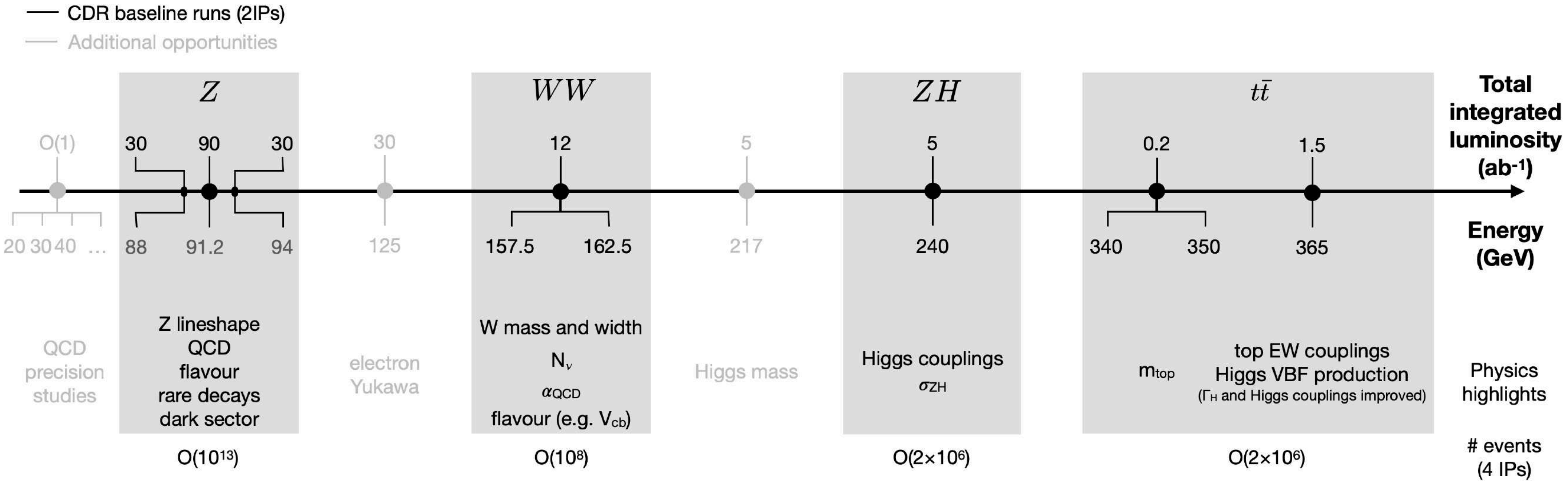


Working point	Z, years 1-2	Z, later	WW, years 1-2	WW, later	ZH	$t\bar{t}$	
$\sqrt{s}$ (GeV)	88, 91, 94		157, 163		240	340–350	365
Lumi/IP ($10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$)	70	140	10	20	5.0	0.75	1.20
Lumi/year (ab^{-1})	34	68	4.8	9.6	2.4	0.36	0.58
Run time (year)	2	2	2	–	3	1	4
Number of events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

FCC-ee Physics Programme.



Collider Programme (and beyond).



- **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.

FCC-LS: Powerful light source for very hard X-rays

The peak and average brilliance can be roughly 1000 times higher than at the proposed future storage ring light source PETRA IV in the very hard X ray regime, and coherent wavelengths down by a factor 100, opening up new areas of science.

ultimate photon source at ~100 keV energies

	w/o wiggler	U_0 x3	U_0 x94	XFEL	PETRA IV
beam energy [GeV]	20	20	20	17.5	6
average beam current [mA]	50	50	50	0.03	200
bunch population [10^{10}]	2	2	2		
RF voltage [MV]	60	65	190		
beta at wiggler /undulator [m]	1.6	1.6	1.6		
wiggler field [T]		1	1		
wiggler period [cm]	-	4	4		
wiggler unit length [m]	-	6.4	5		
undulator field [T]		0.71-0.32	0.71-0.32	0.44-1.0	0.3-1.1
undulator period [cm]		2.8	2.8	4	1.8
undulator unit length [m]		5	5	5	10
magnetic gap	10	10	10	10	6
energy loss / turn [MeV]	1.33	4	126	-	4
SR power at 0.15 A [MW]	0.2	0.6	19	-	
total length of wiggler [m]	**-**	**6.4**	**264**	**-**	
horizontal emittance [nm]	**0.046**	**0.015**	**0.0005**	**0.04 (slice)**	**0.02**
vertical emittance [pm]	**<5**	**<1.5**	**<0.05**	**40 (slice)**	**4**
wiggler photon energy 1st harmonic [keV]	10-50	**10-50**	**10-50**	-	
undulator photon energy 1st harmonic [keV]	50-100	50-100	50-100	9.1-30.7	7-16.8
coherence limit [Å]	**5.8** (2.1 keV)	**1.9** (6.5 keV)	**0.06** (200 keV)	**5** (2.5 keV)	**1.5** (8.3 keV)
peak brilliance [ph/s/0.1%bw/mm²/mrad²]					
@ 12 keV					
@25 keV		4.2×10^{22}	2×10^{25}	5×10^{33}	3×10^{24}
@50 keV		1.1×10^{23}	7.9×10^{25}	4×10^{33}	1.4×10^{24}
@100 keV		**1.0×10^{26}**	**3×10^{26}**	**N/A**	**3.8×10^{23}**
		1.1×10^{26}	**5.2×10^{26}**	**N/A**	**3×10^{22}**
average brilliance [ph/s/0.1%bw/mm²/mrad²]					
simulations for the FCC-ee injector with SPECTRA [4]					
@ 12 keV		4.2×10^{22}	8.2×10^{22}	1.6×10^{25}	8×10^{22}
@25 keV		1.1×10^{23}	3.2×10^{23}	2.5×10^{24}	3.8×10^{22}
@50 keV		**2.2×10^{23}**	**1.2×10^{24}**	**N/A**	**1×10^{22}**
@100 keV		**2.5×10^{23}**	**2.1×10^{24}**	**N/A**	**8×10^{20}**

FCC-ee: strong field QED

The FCC-ee injector complex can generate high rates of high-energy photons either by sending bunches from the linac against a target via bremsstrahlung, as in the proposed LUXE experiment [5], or, via laser Compton backscattering off bunches in the booster. These high-energy photons are then collided with low energy photons from a laser and pairs of electrons and positrons are created via the Schwinger process. The intensity of the laser is varied, e.g., between 5×10^{18} W/cm^2 and 1×10^{20} W/cm^2 (parameters from LUXE) and the rate of electron/positron pairs is measured as function of this intensity, The rate should be proportional to E^2 e $(-E_S/E)$ where E is the electric field of the laser.

Comparison of FCC-ee QED explorer configurations and the European XFEL's LUXE proposal.

	LUXE [5]	**FCC-ee linac**	**FCC-ee booster**
Beam energy [GeV]	14 (17)	20	20 or 45.6
Conversion	bremsstrahlung	bremsstrahlung	laser Compton (See Table 2)
Bunch charge [nC]	0.25 (1)	**3**	3 (only fraction converted to γ)
Number of bunches	1	2 or 4	up to 16,000
Repetition rate [Hz]	1 (10)	200	3,000
Rms spot size [μm]	5	3 (1 cm β)	30

FCC-ee: new source of e+/Positronium

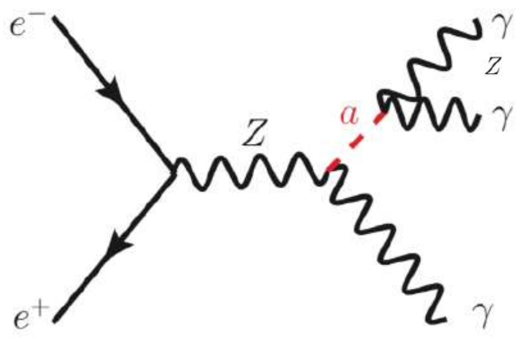
- e^+ source
  - New precision QED measurements feasible, with colder Ps sources
  - Positronium-Bose Einstien Condensate annihilation : 511 keV Gamma ray laser!
  - Non-destructive nanoprobes in material science

FCC-ee: Explore & Discover.

- **ALPs@ colliders**

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

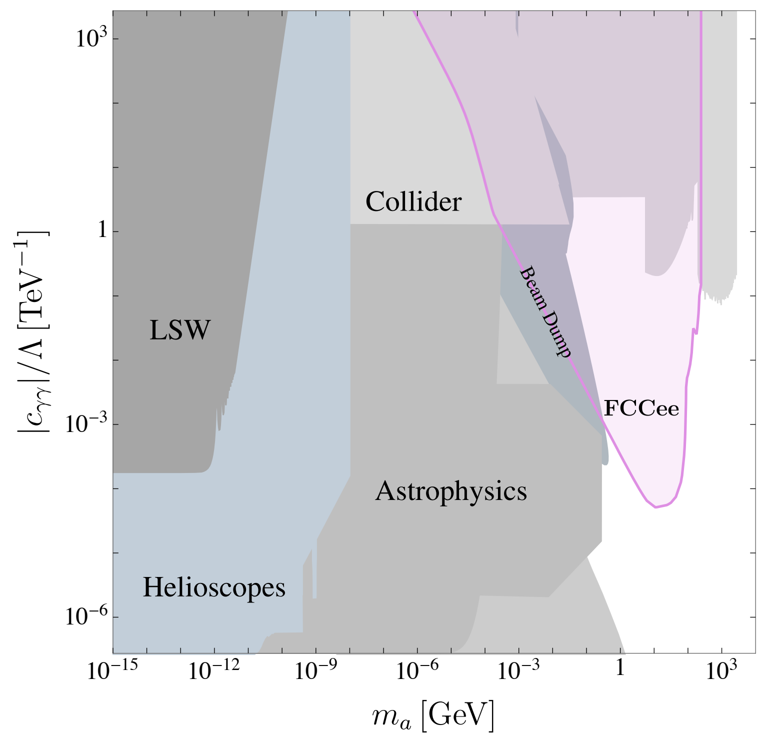
  $e^+e^- \to ha$



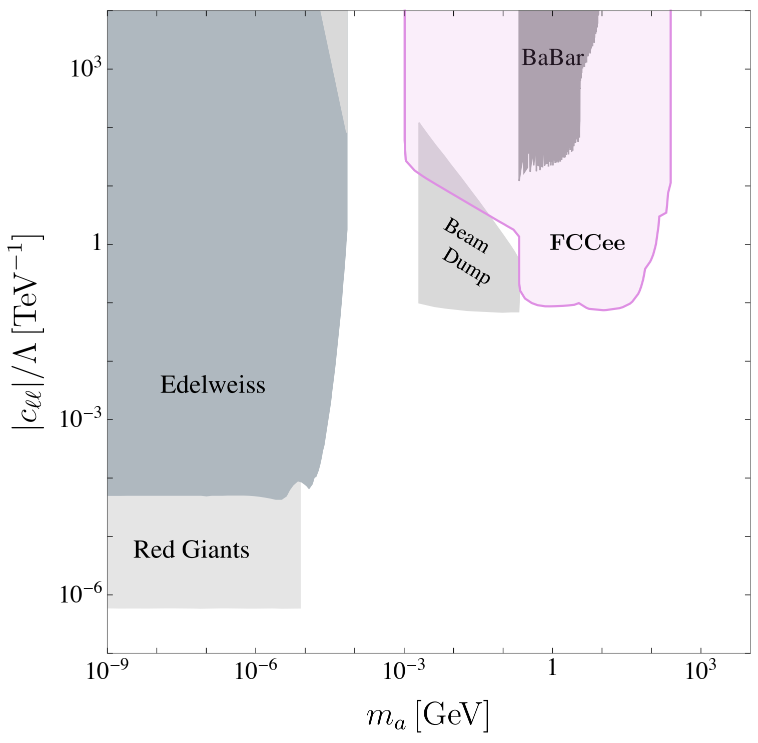
Knapen, Thamm arXiv:2108.08949

Astro/Cosmo → long-lived ALPs
colliders → short-lived ALPs MeV+

ALP coupling to photons

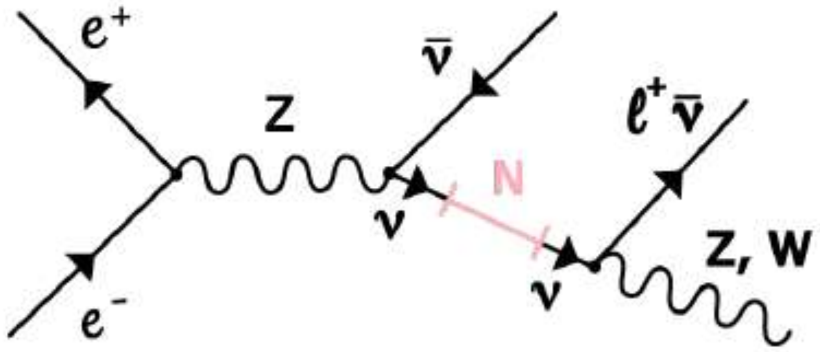


ALP coupling to electrons



- **Search for ν_{RH}.**

Direct observation
in Z decays
from LH-RH mixing



mixing active-sterile neutrinos

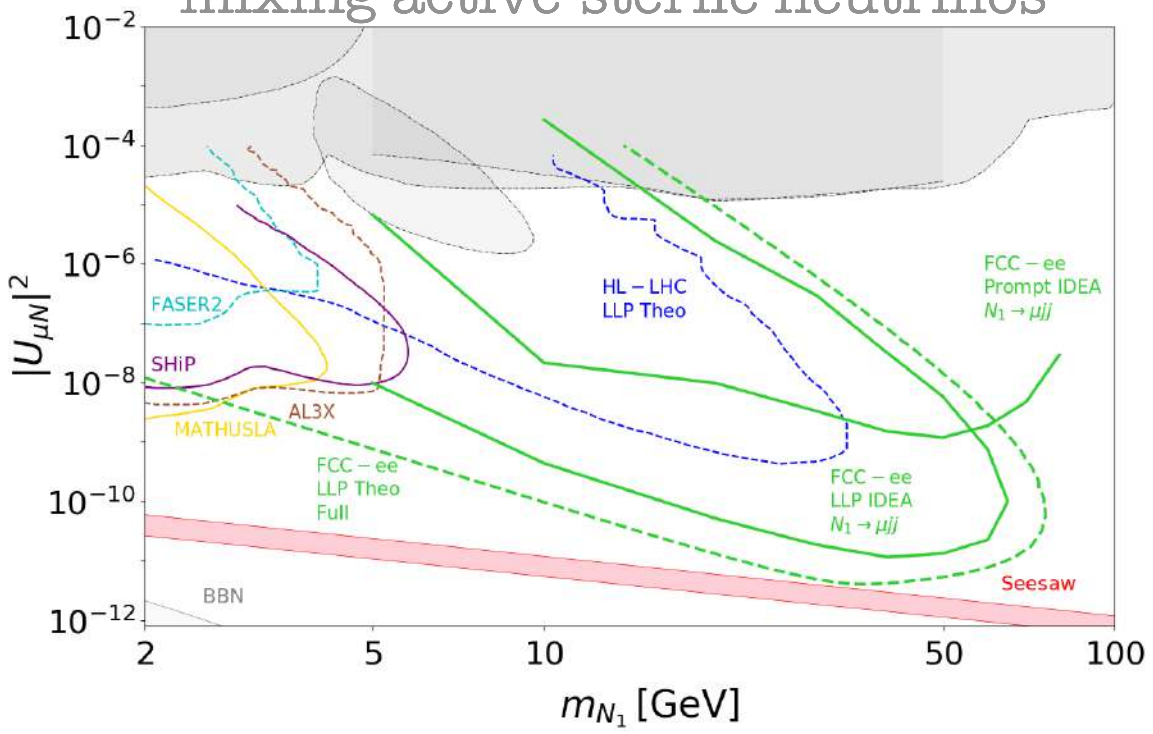
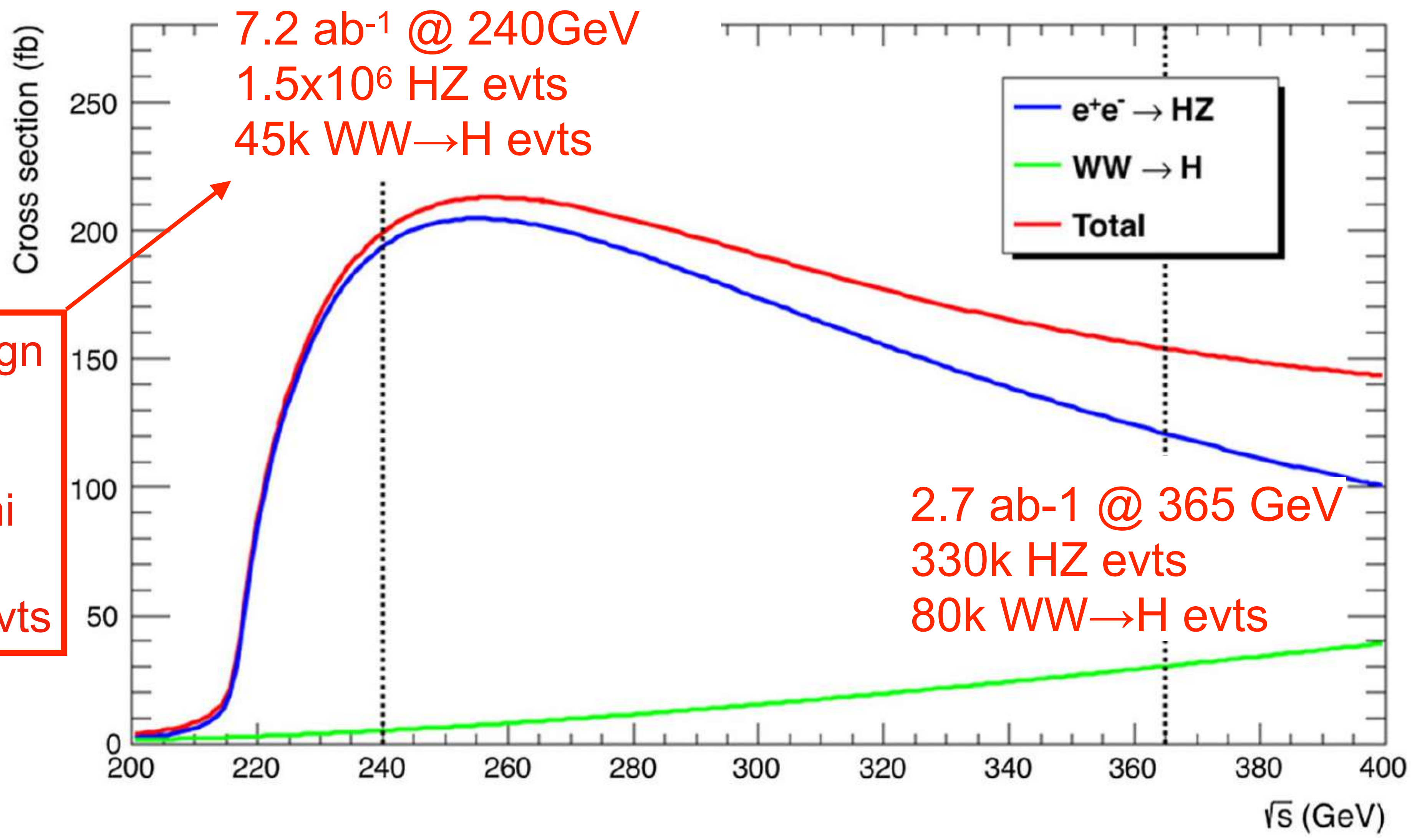


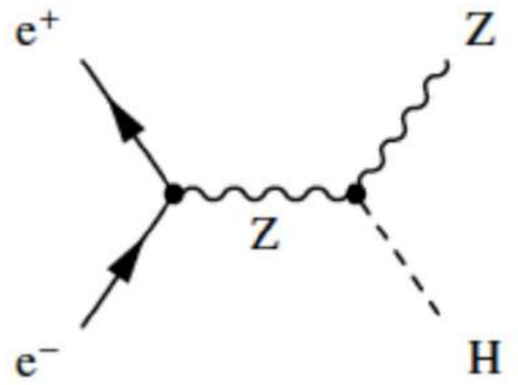
Fig. from mid-term report

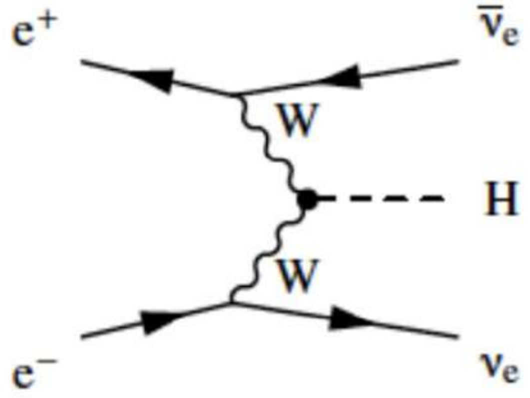
Higgs @ FCC-ee.

Central goal of FCC-ee: model-independent measurement of Higgs width and couplings with (<)% precision. Achieved through operation at two energy points.

new optics design (May 2024) gives 50% more lumi @ 240 GeV ⇒ 2.5x10⁶ HZ evts







Sensitivity to both processes very helpful in improving precision on couplings.

Complementarity with 365GeV on top of 240GeV
improvement factor: ∞/3/2/1.5/1.2 on $\kappa_\lambda / \kappa_W / \kappa_b / \kappa_g, \kappa_c / \kappa_\gamma$ (plot in bonus)

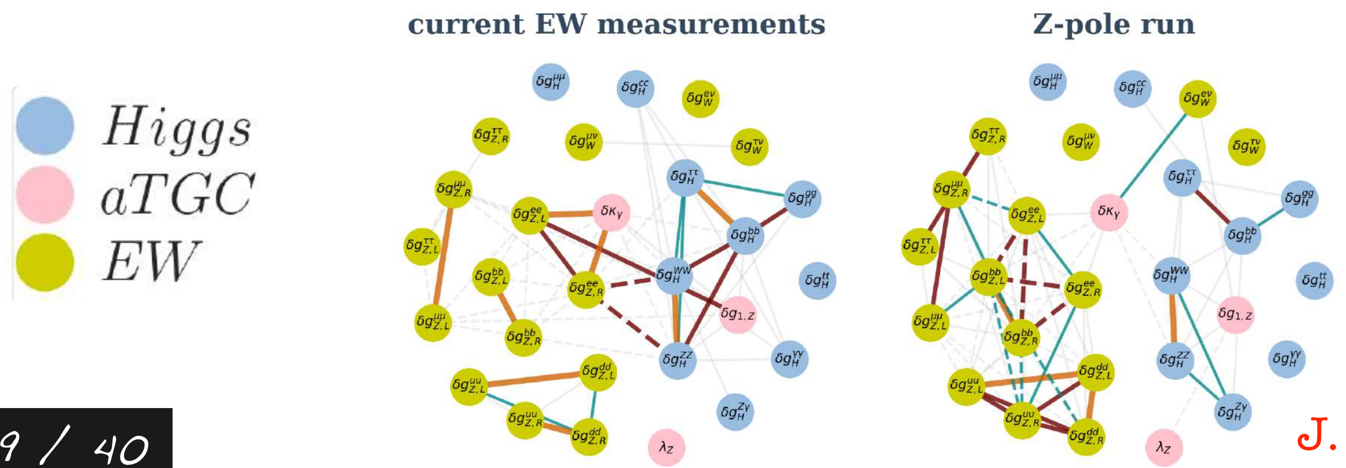
Higgs @ FCC-ee.

- Absolute normalisation of couplings (by recoil method). The LHC fit doesn't converge w/o making any assumption.
- Measurement of width (from ZH>ZZZ* and WW>H)
- $\delta\Gamma_H \sim 1\%, \delta m_H \sim 3\,\mathrm{MeV}$ (resp. 25%, 30 MeV @ HL-LHC)
- Model-independent coupling determination and improvement factor up to 10 compared to LHC
- (Indirect) sensitivity to new physics up to 70 TeV (for maximally strongly coupled models)

$$(\delta\kappa_X = v^2/f^2 \quad \& \quad m_{\mathrm{NP}} = g_{\mathrm{NP}} f)$$

- Unique access to electron Yukawa

— Higgs programme needs Z-pole —



Higgs coupling sensitivity

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
$\mathrm{BR}_{\mathrm{inv}}$ (<%, 95% CL)	1.9*	0.20 / 0.15
$\mathrm{BR}_{\mathrm{unt}}$ (<%, 95% CL)	4*	1.0 / 0.88

Table from mid-term report (new luminosity at 240GeV will further improve the coupling reach, e.g. 0.11% for κZ)

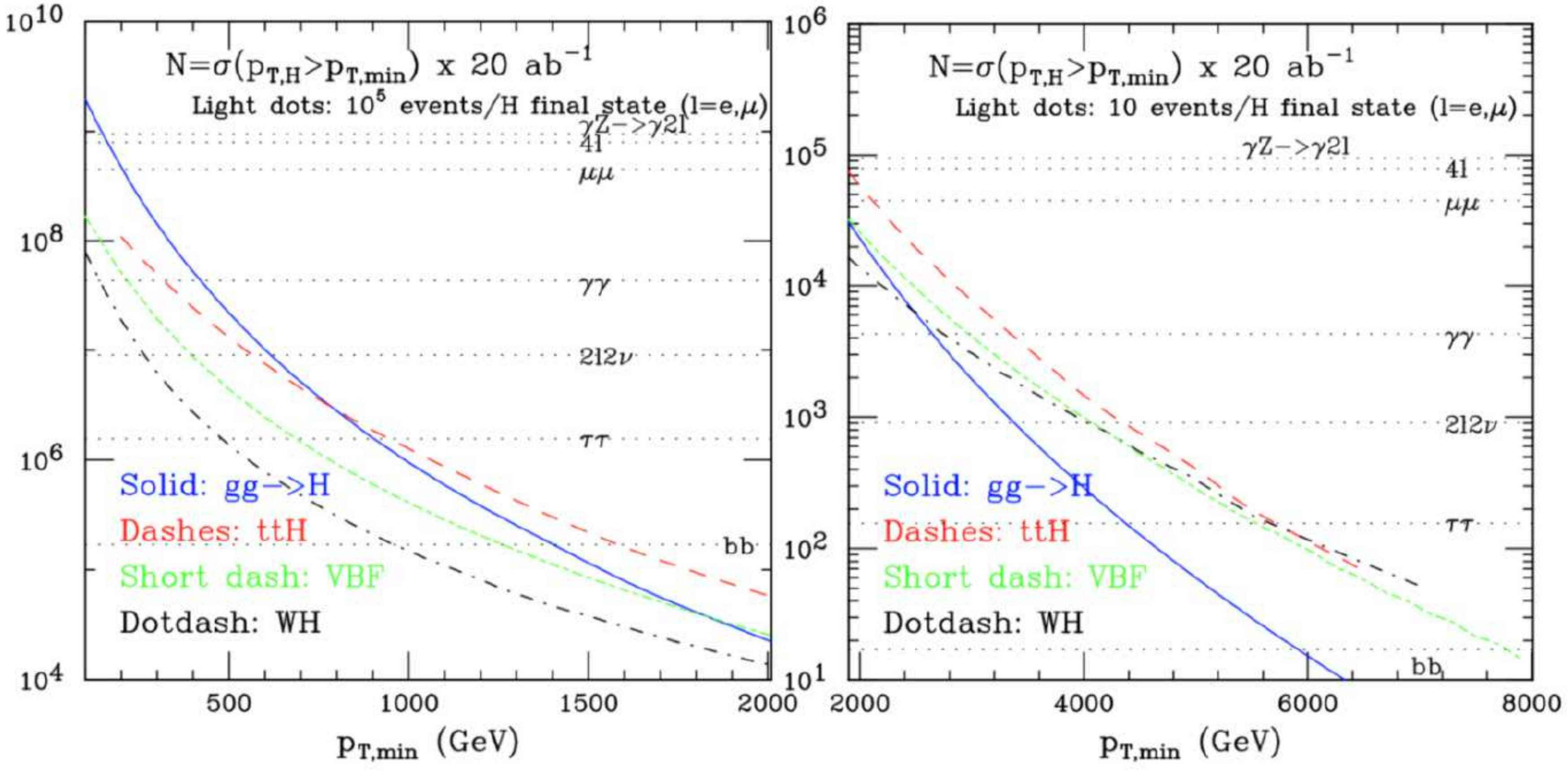
$$\kappa_X = \frac{g_{hXX}}{g_{hXX}^{\mathrm{SM}}}$$

J. De Blas et al. 1907.04311

Higgs @ FCC-hh.

	ggH (N^3LO)	VBF (N^2LO)	WH (N^2LO)	ZH (N^2LO)	$t\bar{t}$H (N^2LO)	HH (NLO)
N100	24×10^9	2.1×10^9	4.6×10^8	3.3×10^8	9.6×10^8	3.6×10^7
N100/N14	180	170	100	110	530	390

$(\mathrm{N100} = \sigma_{100\,\mathrm{TeV}} \times 30\,\mathrm{ab}^{-1} \;\; \& \;\; \mathrm{N14} = \sigma_{14\,\mathrm{TeV}} \times 3\,\mathrm{ab}^{-1})$



- Large rate ($> 10^{10}$H, $> 10^7$ HH)
  - unique sensitivity to rare decays
  - few % sensitivity to self-coupling
- Explore extreme phase space:
  - e.g. 10^6 H w/ pT>1 TeV
  - clean samples with high S/B
  - small systematics

Observable	present value	±	error	FCC-ee **Stat.**	FCC-ee Syst.	Comment and leading error
m_Z (keV)	91186700	±	2200	**4**	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2495200	±	2300	**4**	25	From Z line shape scan Beam energy calibration
$\sin^2\theta_W^{eff}(\times10^6)$	231480	±	160	**2**	2.4	From $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{QED}(m_Z^2)(\times10^3)$	128952	±	14	**3**	small	From $A_{FB}^{\mu\mu}$ off peak QED&EW errors dominate
R_ℓ^Z $(\times10^3)$	20767	±	25	**0.06**	0.2-1	Ratio of hadrons to leptons Acceptance for leptons
$\alpha_s(m_Z^2)$ $(\times10^4)$	1196	±	30	**0.1**	0.4-1.6	From R_ℓ^Z
σ^0_{had} $(\times10^3)$ (nb)	41541	±	37	**0.1**	4	Peak hadronic cross-section Luminosity measurement
$N_\nu(\times10^3)$	2996	±	7	**0.005**	1	Z peak cross-sections Luminosity measurement
R_b $(\times10^6)$	216290	±	660	**0.3**	<60	Ratio of $b\bar{b}$ to hadrons Stat. extrapol. from SLD
$A_{FB}^b, 0$ $(\times10^4)$	992	±	16	**0.02**	1-3	b-quark asymmetry at Z pole From jet charge
$A_{FB}^{pol,\tau}$ $(\times10^4)$	1498	±	49	**0.15**	<2	τ polarization asymmetry τ decay physics
τ lifetime (fs)	290.3	±	0.5	**0.001**	0.04	Radial alignment
τ mass (MeV)	1776.86	±	0.12	**0.004**	0.04	Momentum scale
τ leptonic $(\mu\nu_\mu\nu_\tau)$ B.R. (%)	17.38	±	0.04	**0.0001**	0.003	e/μ/hadron separation
m_W (MeV)	80350	±	15	**0.25**	0.3	From WW threshold scan Beam energy calibration
Γ_W (MeV)	2085	±	42	**1.2**	0.3	From WW threshold scan Beam energy calibration
$\alpha_s(m_W^2)(\times10^4)$	1010	±	270	**3**	small	From R_ℓ^W
$N_\nu(\times10^3)$	2920	±	50	**0.8**	small	Ratio of invis. to leptonic in radiative Z returns
m_{top} (MeV)	172740	±	500	**17**	small	From $t\bar{t}$ threshold scan QCD errors dominate
Γ_{top} (MeV)	1410	±	190	**45**	small	From $t\bar{t}$ threshold scan QCD errors dominate
$\lambda_{top}/\lambda_{top}^{SM}$	1.2	±	0.3	**0.10**	small	From $t\bar{t}$ threshold scan QCD errors dominate
ttZ couplings		±	30%	**0.5 – 1.5 %**	small	From $\sqrt{s} = 365$ GeV run

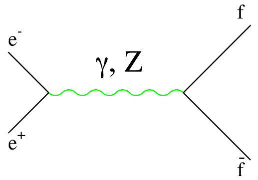
EW Precision Measurements at FCC-ee

Experimental (statistical and systematic) precision of a selection of measurements accessible at FCC-ee, compared with the present world-average precision. FCC-ee syst. scaled down from LEP estimates. Room for improvement with dedicated studies. Note that syst. go down also with stat. (e.g. beam energy determination from ee→Z/γ thus goes down with luminosity).

Table from mid-term report

Example of EW measurements @ Tera Z

measure $\sigma(e^+e^- \to \mu^+\mu^-)$ and $A_{FB}^{\mu\mu}$ at (a) judicious $\sqrt{s}$



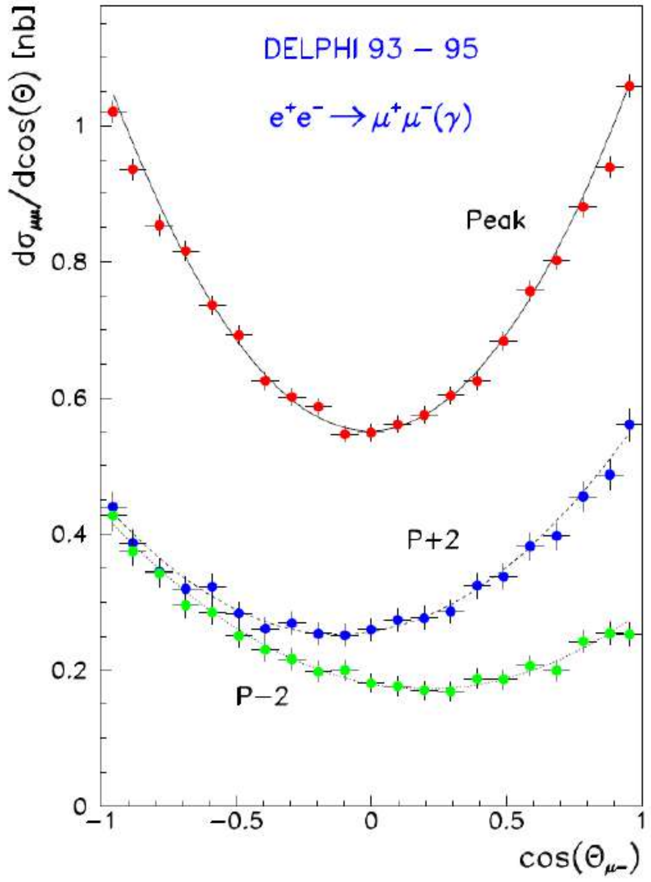
The γ exchange term is proportional to $\alpha^2_{QED}(\sqrt{s})$
The Z exchange term is proportional to G^2_F, hence independent of α_{QED}
The γZ interference is proportional to $\alpha_{QED}(\sqrt{s}) \times G_F$

Excellent experimental control of off-peak di-muon asymmetry motivates campaign to collect 50-80 ab^{-1} off peak to gain highest sensitivity to Z-γ interference

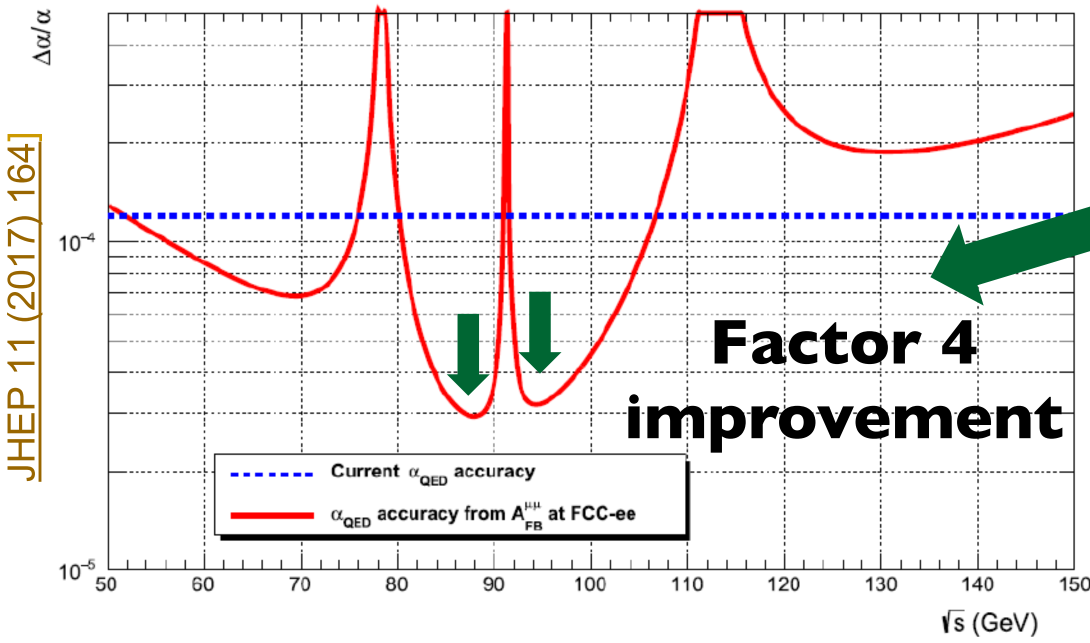
strongly depends on $\sqrt{s}$ ←
direct measurement of $\alpha_{QED}(s)$ at $\sqrt{s}$!= m_Z ←
measure $\sin^2\theta_W$ to high precision ←

$$A_{FB}^{\mu\mu}(s) \simeq \frac{3}{4} \mathcal{A}_e \mathcal{A}_\mu \times \left[1 + \frac{8\pi\sqrt{2}\alpha_{QED}(s)}{m_Z^2 G_F \left(1 - 4\sin^2\theta_W^{eff}\right)^2} \frac{s - m_Z^2}{2s} \right]$$

Allows for clean determination of $\alpha_{QED}(m_Z^2)$, which is a *critical* input for m_W closure tests (see later).



relative α_{QED} uncertainty with 80 ab^{-1}



P.Janot '16
[JHEP 02 (2016) 053, JHEP 11 (2017) 164]

This dependence, & location of half-integer spin tunes, guides the choice of off-peak energies: 87.8 & 93.9 GeV.

→ Measure $\alpha_{QED}(m_Z^2)$ to 3×10^{-5} rel. precision (currently 1.1×10^{-4})
→ Stat. dominated; syst. uncertainties < 10^{-5} (dominated by $\sqrt{s}$ calib)
→ Theoretical uncertainties ~ 10^{-4}, higher order calcs needed

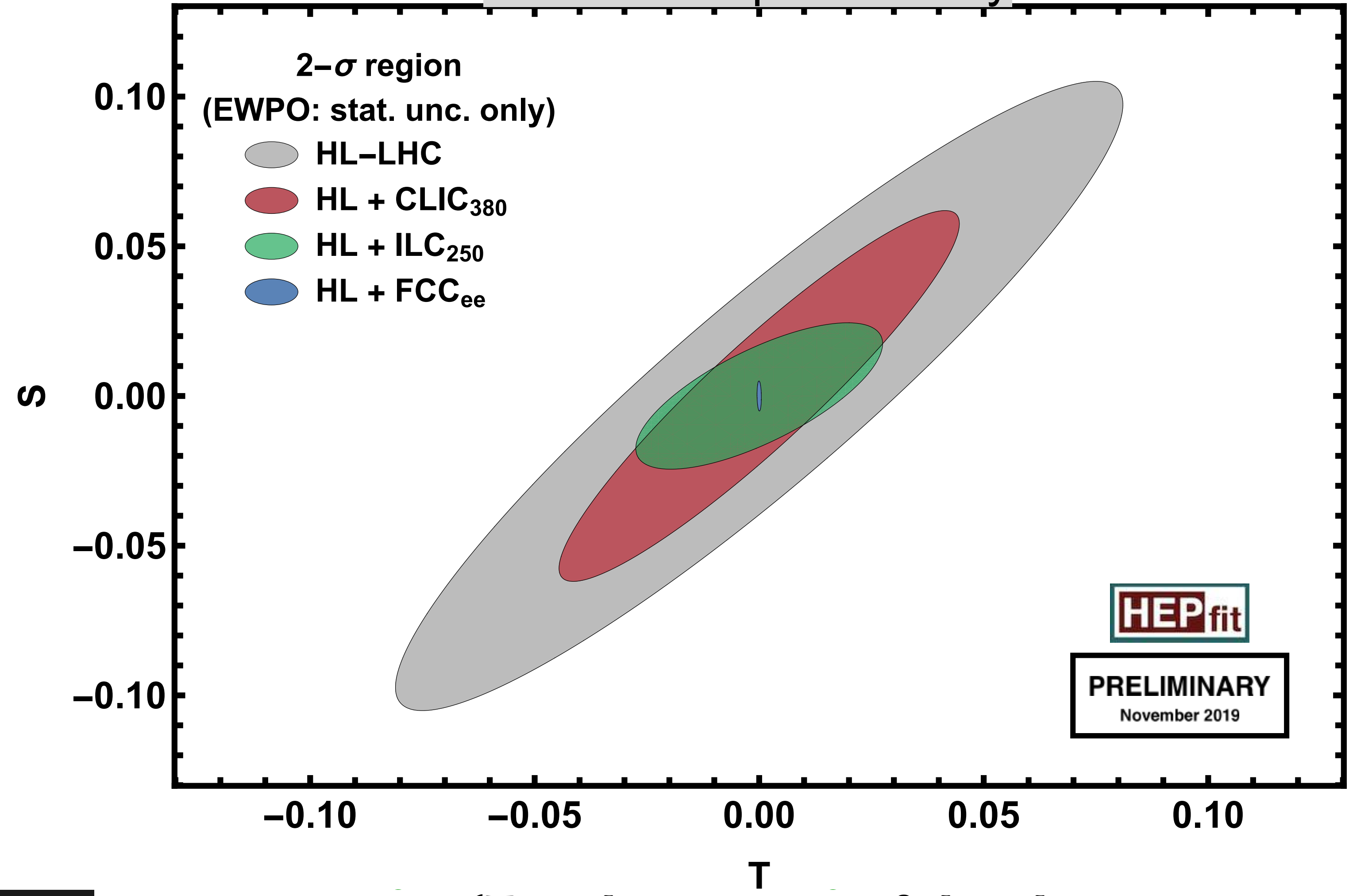
G. Wilkinson @ FCC week 2021

Tera-Z EW precision measurements.

- The target is to reduce syst. uncertainties to the level of stat. uncertainties.
  (exploit the large samples and innovative control analyses)
- Exquisite √s precision (100keV@Z, 300keV@WW) reduces beam uncertainties (EPOL)

➡ ~50 times better precision than LEP/LSD on EW precision observables
(stat. improvement alone is a factor **300-2'000** and innovative analyses/improved detectors can bring syst. down too)

w/ stat. and param. only



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

(For the impact of the theory uncertainties on the EW fit, see bonus slides)

Tera-Z EW precision measurements.

- The target is to reduce syst. uncertainties to the level of stat. uncertainties. (exploit the large samples and innovative control analyses)
- Exquisite √s precision (100keV@Z, 300keV@WW) reduces beam uncertainties (EPOL)

~50 times better precision than LEP/LSD on EW precision observables
(stat. improvement alone is a factor **300-2'000** and innovative analyses/improved detectors can bring syst. down too)

Need TH results to fully exploit Tera-Z

Table from mid-term report

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

New Physics Reach @ Z-pole.

There are 48 different types of particles that can have tree-level linear interactions to SM.

de Blas, Criado, Perez-Victoria, Santiago, arXiv: 1711.10391

Scalars

Name	$\mathcal{S}$	$\mathcal{S}_1$	$\mathcal{S}_2$	φ	Ξ	Ξ_1	Θ_1	Θ_3
Irrep	$(1,1)_0$	$(1,1)_1$	$(1,1)_2$	$(1,2)_{\frac{1}{2}}$	$(1,3)_0$	$(1,3)_1$	$(1,4)_{\frac{1}{2}}$	$(1,4)_{\frac{3}{2}}$
Name	ω_1	ω_2	ω_4	Π_1	Π_7	ζ		
Irrep	$(3,1)_{-\frac{1}{3}}$	$(3,1)_{\frac{2}{3}}$	$(3,1)_{-\frac{4}{3}}$	$(3,2)_{\frac{1}{6}}$	$(3,2)_{\frac{7}{6}}$	$(3,3)_{-\frac{1}{3}}$		
Name	Ω_1	Ω_2	Ω_4	Υ	Φ			
Irrep	$(6,1)_{\frac{1}{3}}$	$(6,1)_{-\frac{2}{3}}$	$(6,1)_{\frac{4}{3}}$	$(6,3)_{\frac{1}{3}}$	$(8,2)_{\frac{1}{2}}$			

Scalars

Fermions

Name	N	E	Δ_1	Δ_3	Σ	Σ_1	
Irrep	$(1,1)_0$	$(1,1)_{-1}$	$(1,2)_{-\frac{1}{2}}$	$(1,2)_{-\frac{3}{2}}$	$(1,3)_0$	$(1,3)_{-1}$	
Name	U	D	Q_1	Q_5	Q_7	T_1	T_2
Irrep	$(3,1)_{\frac{2}{3}}$	$(3,1)_{-\frac{1}{3}}$	$(3,2)_{\frac{1}{6}}$	$(3,2)_{-\frac{5}{6}}$	$(3,2)_{\frac{7}{6}}$	$(3,3)_{-\frac{1}{3}}$	$(3,3)_{\frac{2}{3}}$

Fermions

Vectors

Name	$\mathcal{B}$	$\mathcal{B}_1$	$\mathcal{W}$	$\mathcal{W}_1$	$\mathcal{G}$	$\mathcal{G}_1$	$\mathcal{H}$	$\mathcal{L}_1$
Irrep	$(1,1)_0$	$(1,1)_1$	$(1,3)_0$	$(1,3)_1$	$(8,1)_0$	$(8,1)_1$	$(8,3)_0$	$(1,2)_{\frac{1}{2}}$
Name	$\mathcal{L}_3$	$\mathcal{U}_2$	$\mathcal{U}_5$	$\mathcal{Q}_1$	$\mathcal{Q}_5$	$\mathcal{X}$	$\mathcal{Y}_1$	$\mathcal{Y}_5$
Irrep	$(1,2)_{-\frac{3}{2}}$	$(3,1)_{\frac{2}{3}}$	$(3,1)_{\frac{5}{3}}$	$(3,2)_{\frac{1}{6}}$	$(3,2)_{-\frac{5}{6}}$	$(3,3)_{\frac{2}{3}}$	$(\bar{6},2)_{\frac{1}{6}}$	$(\bar{6},2)_{-\frac{5}{6}}$

Vectors

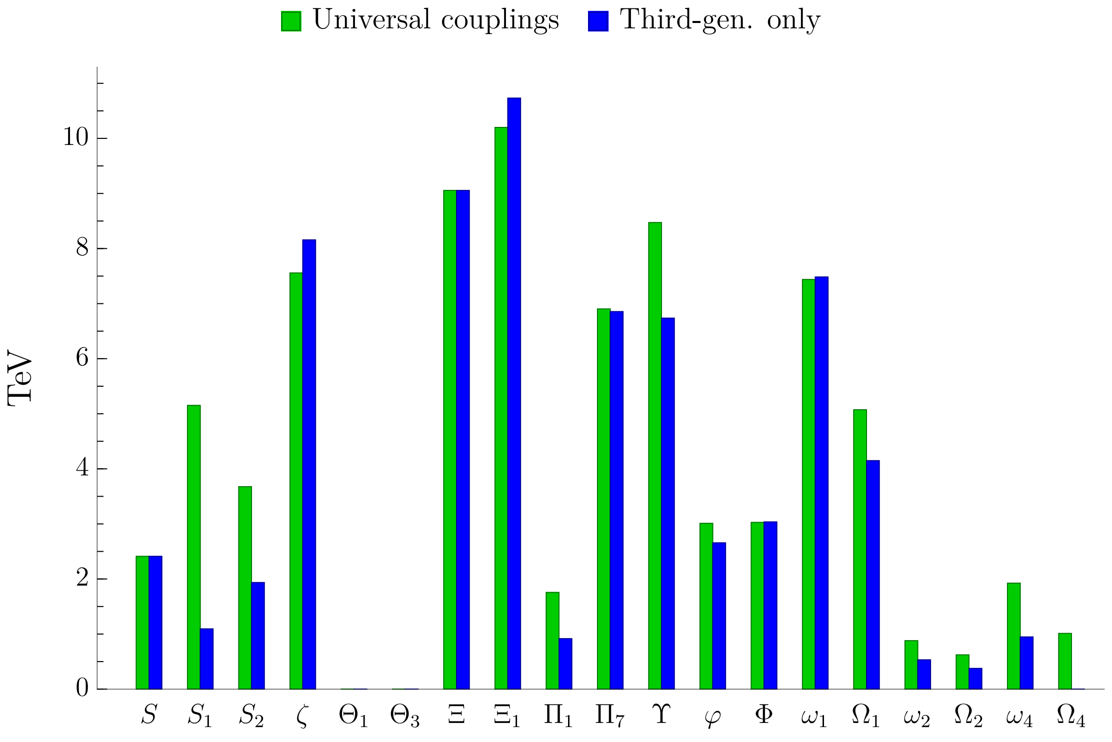
They are not all affecting EW observables at tree-level.

New Physics Reach @ Z-pole.

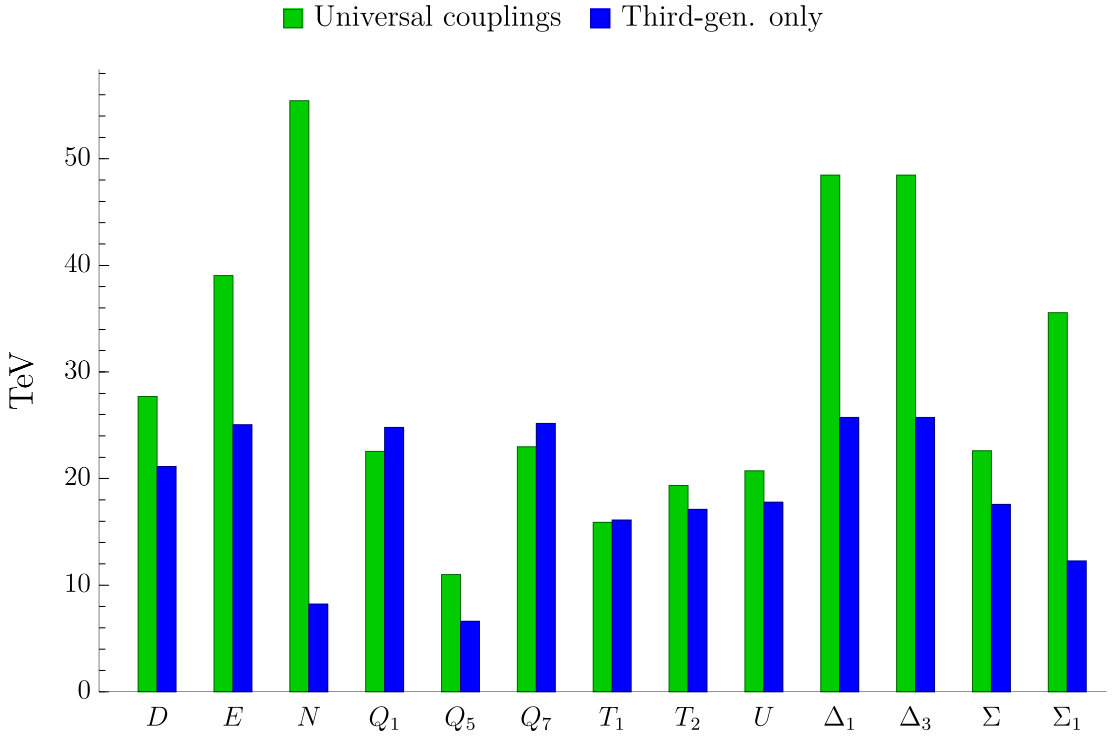
There are 48 different types of particles that can have tree-level linear interactions to SM.

They are not all affecting EW observables at tree-level.
However, all, but a few, have leading log. running into EW observables.

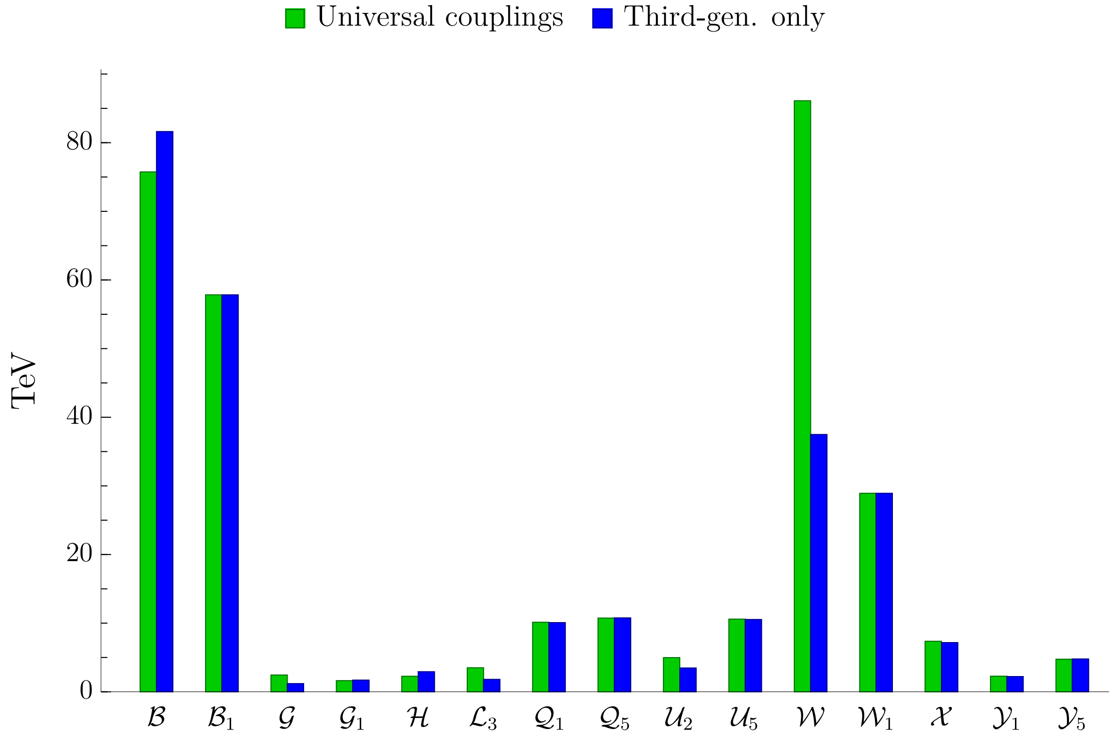
Allwicher, McCullough, Renner, arXiv: 2408.03992



Scalars



Fermions



Vectors

Tree-level matching and running from 1 TeV to Z mass.
W- and Z-pole observables only (no Higgs, no LEP-2 like observables)

Flavour potential.

At present (Z/h/NewPhysics) FCNCs mostly constrained by low energy observables.

The large statistics of FCC will open on-shell opportunities.

See S. Monteil, Flavour@FCC '22

Particle production (10^9)	B^0 / $\overline{B}^0$	B^+ / B^-	B^0_s / $\overline{B}^0_s$	Λ_b / $\overline{\Lambda}_b$	$c\overline{c}$	τ^-/τ^+
Belle II	27.5	27.5	n/a	n/a	65	45
FCC-*ee*	300	300	80	80	600	150

FCC-ee = 10 x Belle II

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)	$\sim 0.8\cdot10^6$ (0.01)	$\sim 35\cdot10^6$ (0.006)
$B_s \to D_s^{\pm}K^{\mp}$	n/a	6000	~ 200000	$\sim 30\cdot10^6$
$B_s(B^0) \to J/\Psi\phi$ (σ_{ϕ_s} rad)	n/a	96000 (0.049)	$\sim 2.10^6$ (0.008)	$16\cdot10^6$ (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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$\mathcal{B}(B^0 \to K^*(892)\tau^+\tau^-)$	~ 10			~ 1000
$B_s \to \mu$…				…800
$B^0 \to \mu$…				…100
$\mathcal{B}(B_s \to$…				
Leptoni…				
$B^+ \to$…				…%
$B^+ \to$…				…%
$B_c^+ \to$…				…%
CP / h…				
$B^0 \to J$…				…^{6} (0.006)
$B_s \to D$…				$\cdot 10^6$
$B_s(B^0)$…				(0.003)

out of reach at LHCb/Belle

Flavour @ FCC vs Belle/pp

Attribute	$\Upsilon(4S)$	pp	Z^0
All hadron species		✓	✓
High boost		✓	✓
Enormous production cross-section		✓	
Negligible trigger losses	✓		✓
Low backgrounds	✓		✓

boosted b's/τ's at FCC-ee

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

Flavour defines shared (vertexing, tracking, calorimetry) and specific (hadronic PID) detector requirements.

FCC-ee flavour opportunities.

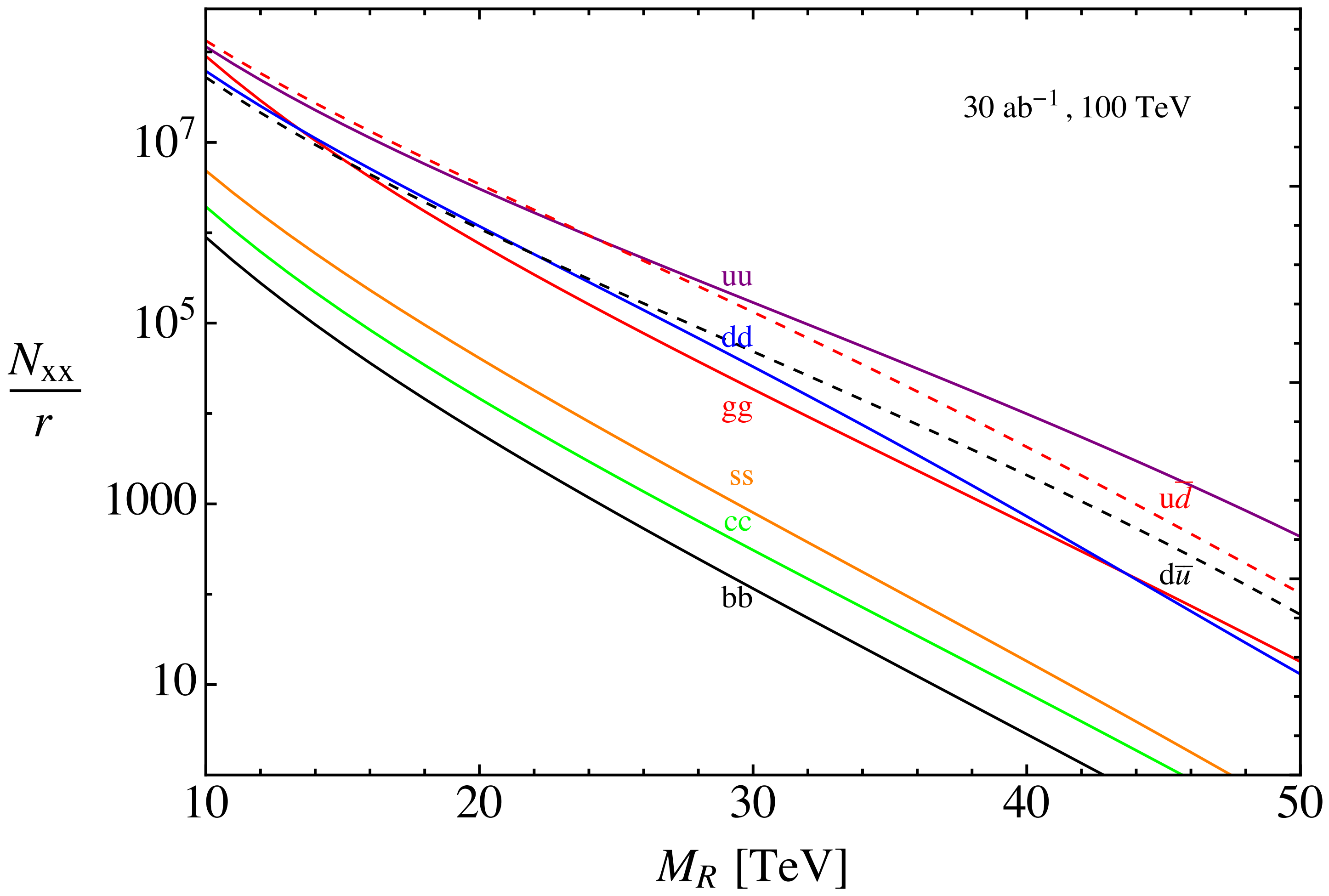
- **CKM element V_{cb}** (critical for normalising the Unitarity Triangle) from WW decays
- **Tau physics** (>10^{11} pairs of tau's produced in Z decays)
  - test of lepton flavour universality: G_F from tau decays @ 10 ppm @ FCC-ee (0.5 ppm from muon decays)
  - lepton flavour violation:
    - $\tau \rightarrow \mu\gamma$: $4\text{x}10^{-8}$ @Belle2021→10^{-9} @ FCC-ee
    - $\tau \rightarrow 3\mu$: $2\text{x}10^{-8}$ @Belle → $3\text{x}10^{-10}$ @BelleII → 10^{-11} @ FCC-ee
  - tau lifetime uncertainty:
    - 2000 ppm → 10 ppm
  - tau mass uncertainty:
    - 70 ppm → 14 ppm
- **Semi-leptonic mixing asymmetries** a^s_{sl} and a^d_{sl}
- …

Resonance production.

Protons are made of 5 quarks, gluons, photons, W/Z

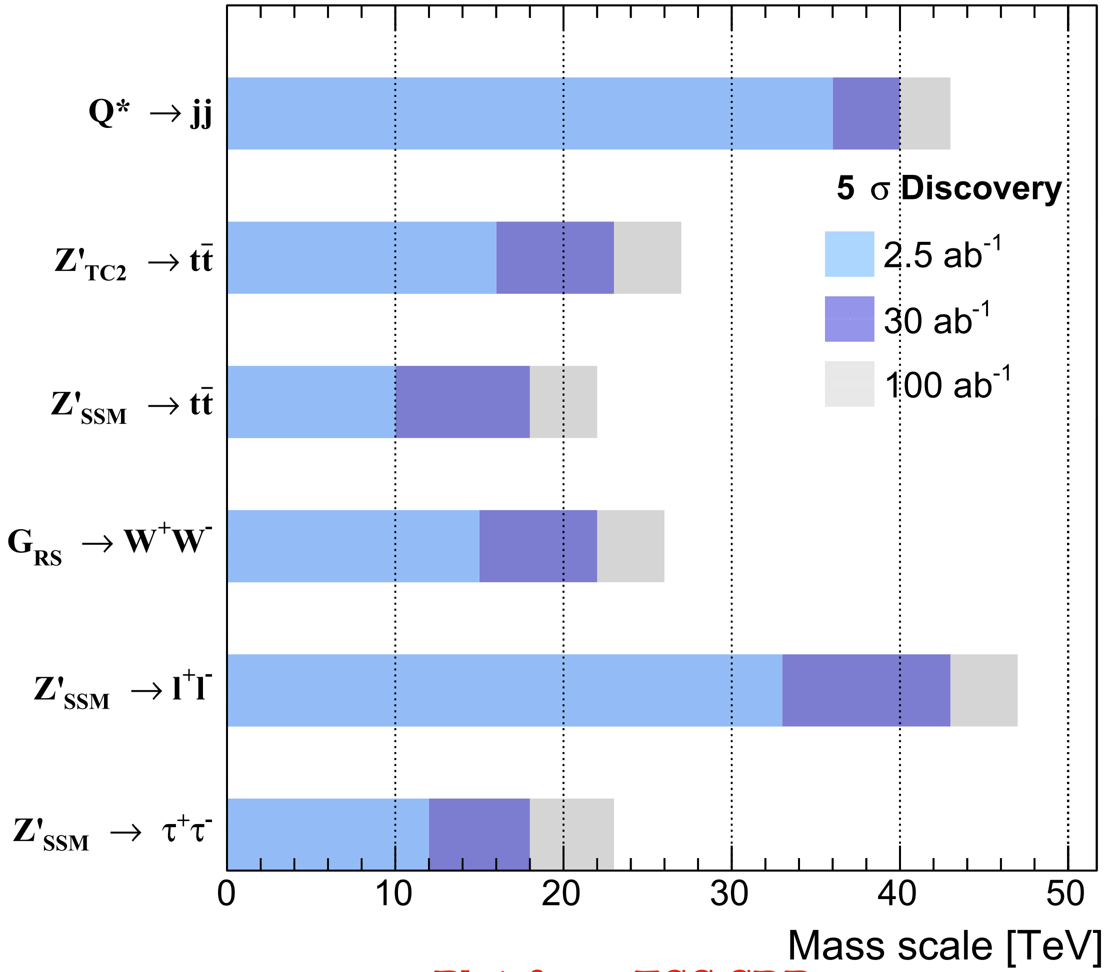
FCC-hh effectively collides 196 different initial states = perfect exploratory machine

resonances produced



Plot from mid-term report

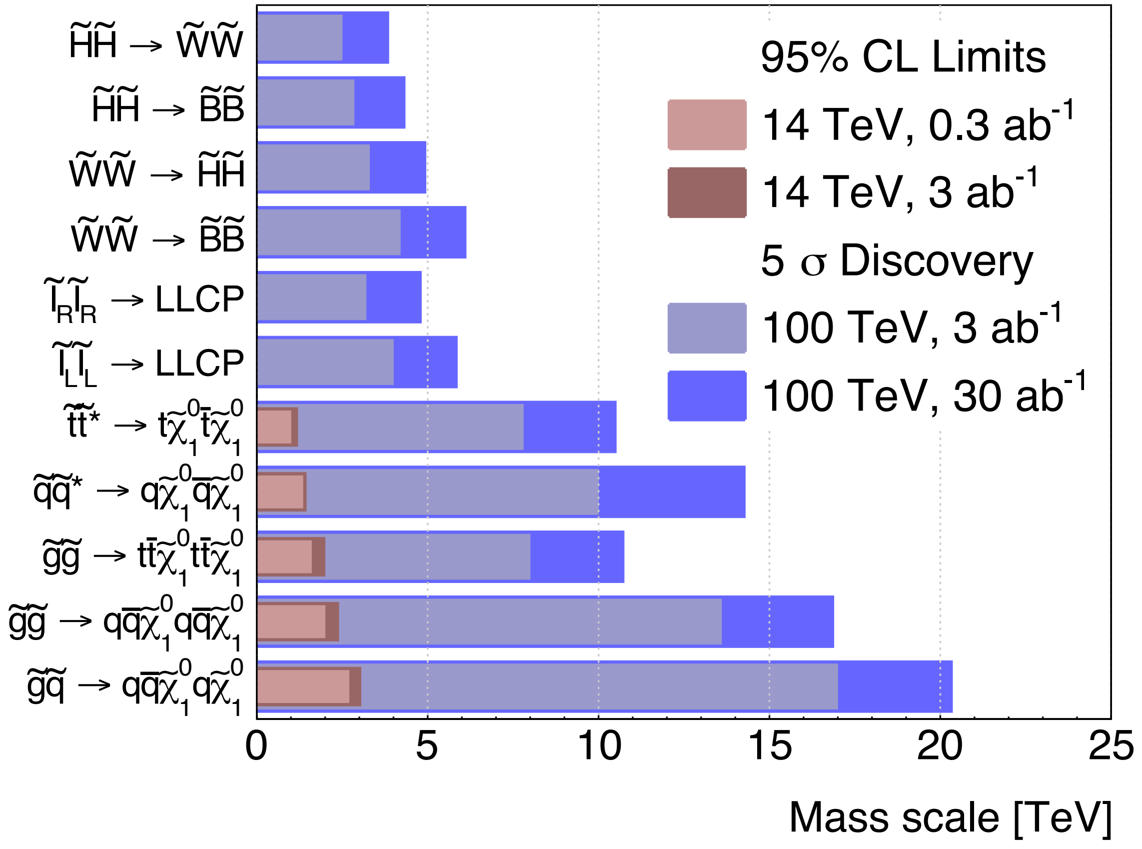
FCC-hh mass reach



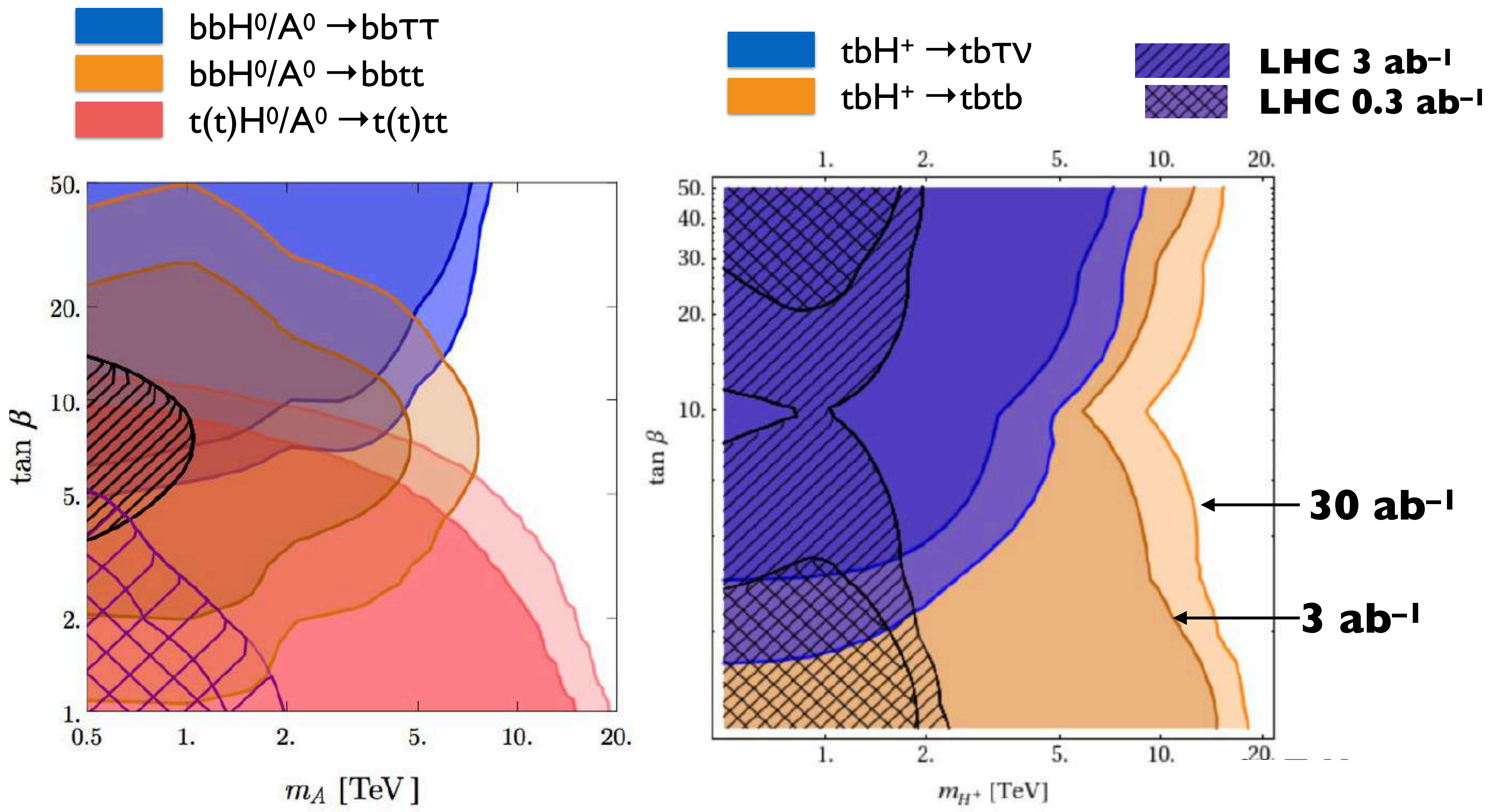
Plot from FCC CDR

FCC-hh allows the direct exploration of new physics at energy scales up to 40 TeV, including any physics that may be indirectly indicated by precision Higgs and EW measurements at FCC-ee.

Pushing limits of SUSY.



Plot from arXiv:1606.00947



Plot from arXiv:1605.08744 and arXiv:1504.07617

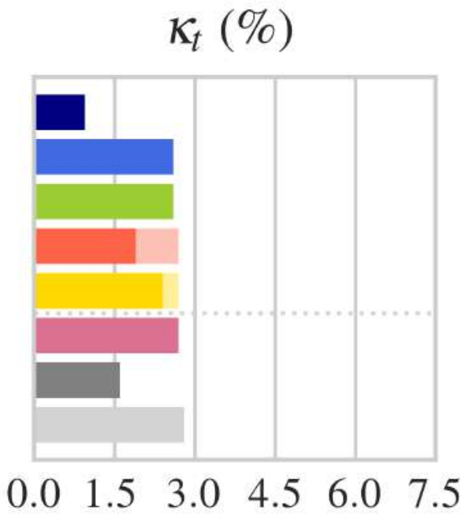
15-20TeV squarks/gluinos require kinematic threshold 30-40TeV: FCC-hh is more than a $\sqrt{\hat{s}}$~10TeV factory

Factor 10 increase on the HL-LHC limits.

Synergy ee↔hh.

1 FCC-hh without ee could bound BR_{inv} but it could say nothing about $BR_{untagged}$ (FCC-ee needed for absolute normalisation of Higgs couplings)

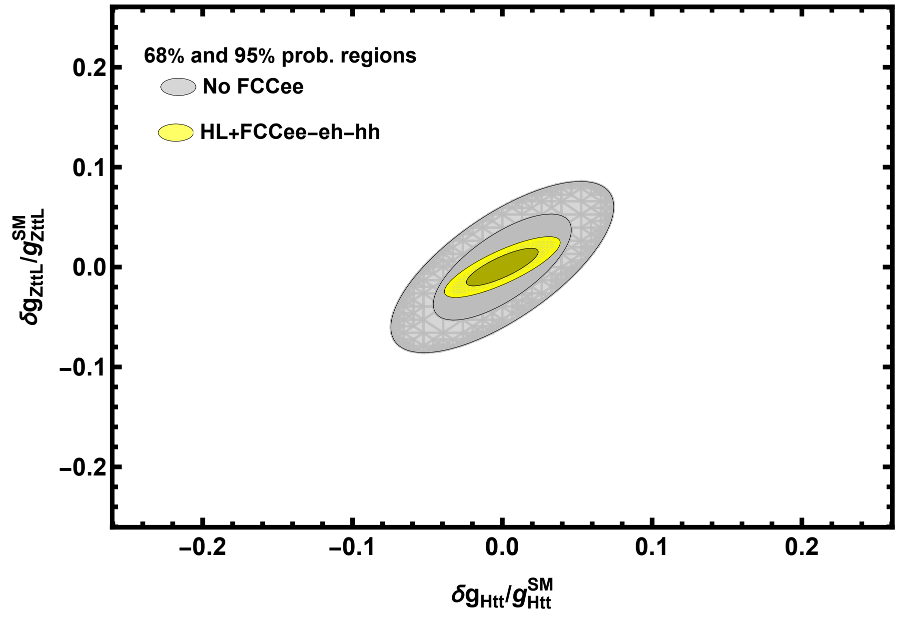
2 FCC-hh is determining top Yukawa through ratio tth/ttZ
So the extraction of top Yukawa heavily relies on the knowledge of ttZ from FCC-ee



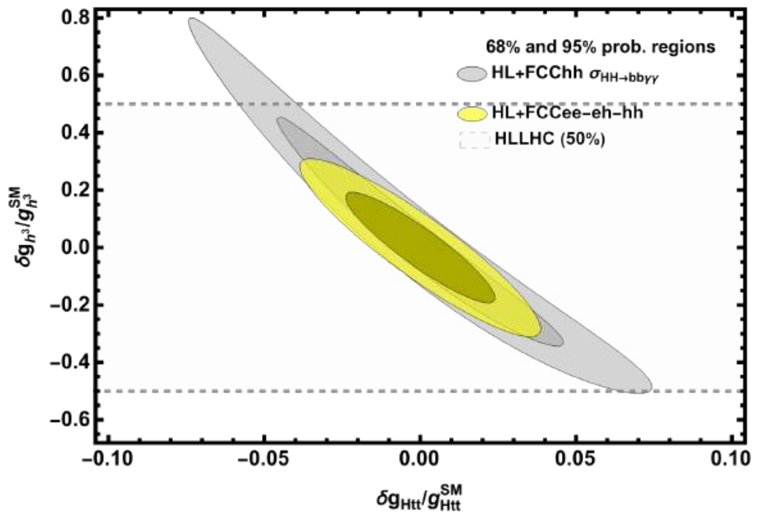
Mangano+ '15

	$\sigma(t\bar{t}H)$[pb]	$\sigma(t\bar{t}Z)$[pb]	$\frac{\sigma(t\bar{t}H)}{\sigma(t\bar{t}Z)}$
13 TeV	$0.475^{+5.79\%+3.33\%}_{-9.04\%-3.08\%}$	$0.785^{+9.81\%+3.27\%}_{-11.2\%-3.12\%}$	$0.606^{+2.45\%+0.525\%}_{-3.66\%-0.319\%}$
100 TeV	$33.9^{+7.06\%+2.17\%}_{-8.29\%-2.18\%}$	$57.9^{+8.93\%+2.24\%}_{-9.46\%-2.43\%}$	$0.585^{+1.29\%+0.314\%}_{-2.02\%-0.147\%}$

(uncertainty drops in ratio)



3 Subsequently, the 1% sensitivity on tth is essential to determine h^3 at O(5%) at FCC-hh



Plots from mid-term report

Let history repeat itself.

In the meantime, on the LHC machine side…

1991 December CERN Council:
'LHC is the right machine for advance of the subject and the future of CERN' (thanks to the great push by DG C Rubbia)

1993 December proposal of LHC with commissioning in 2002

Minister Boris Saltykov and DG Carlo Rubbia signing an updated Cooperation Agreement Russia and CERN (28 June 1993)

COMETA Colloquium, 27-5-2024
Peter Jenni (Freiburg and CERN)

Higgs Discovery Journey

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2028 December CERN Council:
'FCC is the right machine
for advance of the subject and the
future of CERN' (thanks to the great push by former DG F. Gianotti and current DG ??)

P. Jenni, May 27, 2024