Intro

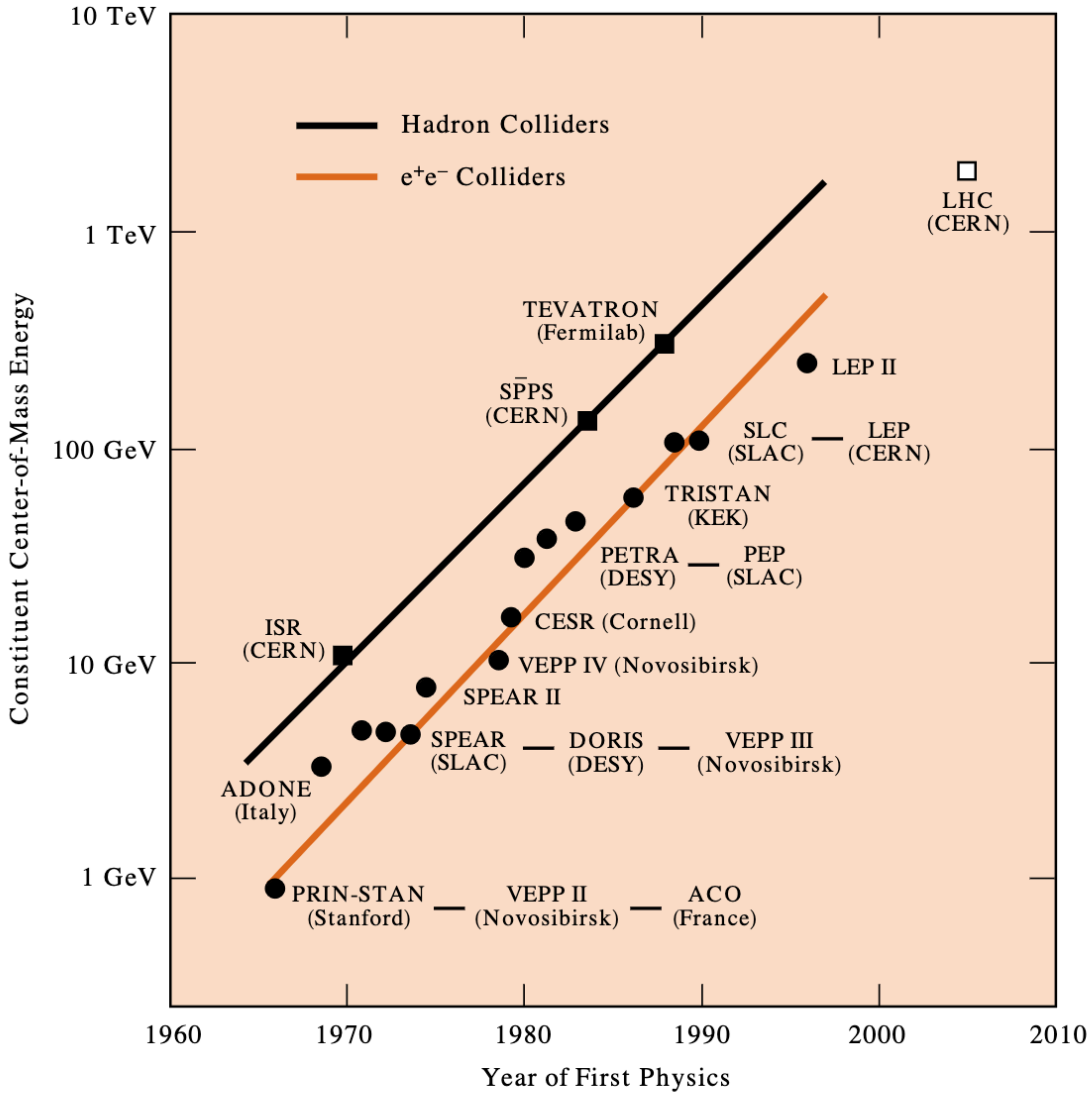
FCC information meeting

Rebeca Gonzalez Suarez - Uppsala University

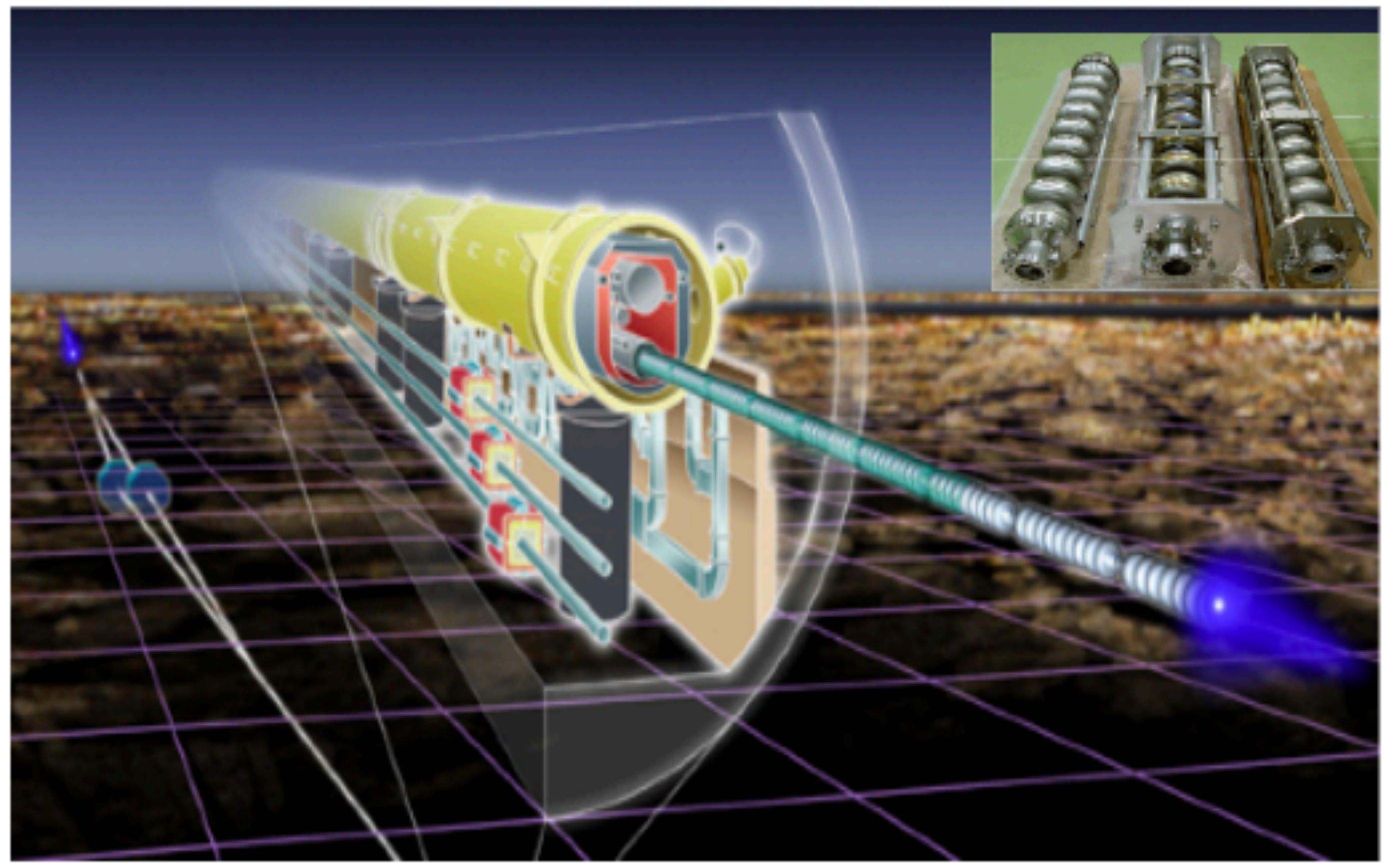
The 30th September 2011

The Tevatron closed

- Since then, we have the LHC and NOTHING else
  - Nothing else running
  - Nothing being built
- Which is not how it used to be
- And not what we thought it would be



ILC 2015 ? CLIC



Superconducting Linacs approach

1990 ***TESLA*** Collaboration
(over 40 Institutions)
TTF test Facility

2005 Decision: choice of SC technology

International Linear Collider
Worldwide collaboration

~2015 500 GeV c.m. → 1TeV

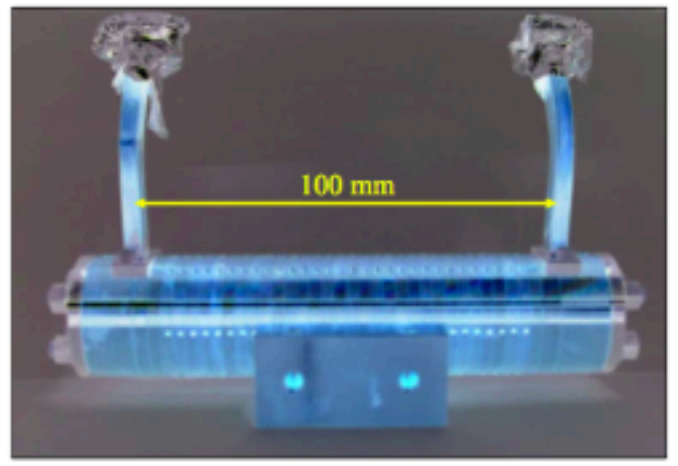
f_{RF} =1.5 GHz V_{acc}= 35 MV/m

Warm Linacs approach → **NLC**, SLAC-KEK Collaboration

CLIC
@ CERN

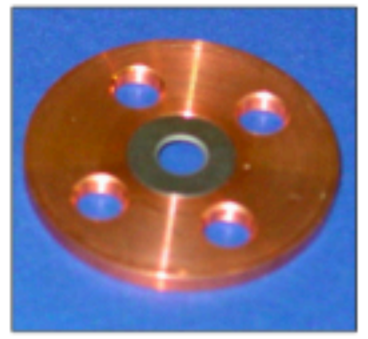
3 TeV c.m.

f_{RF} = 30 GHz V_{acc}~ 100 MV/m

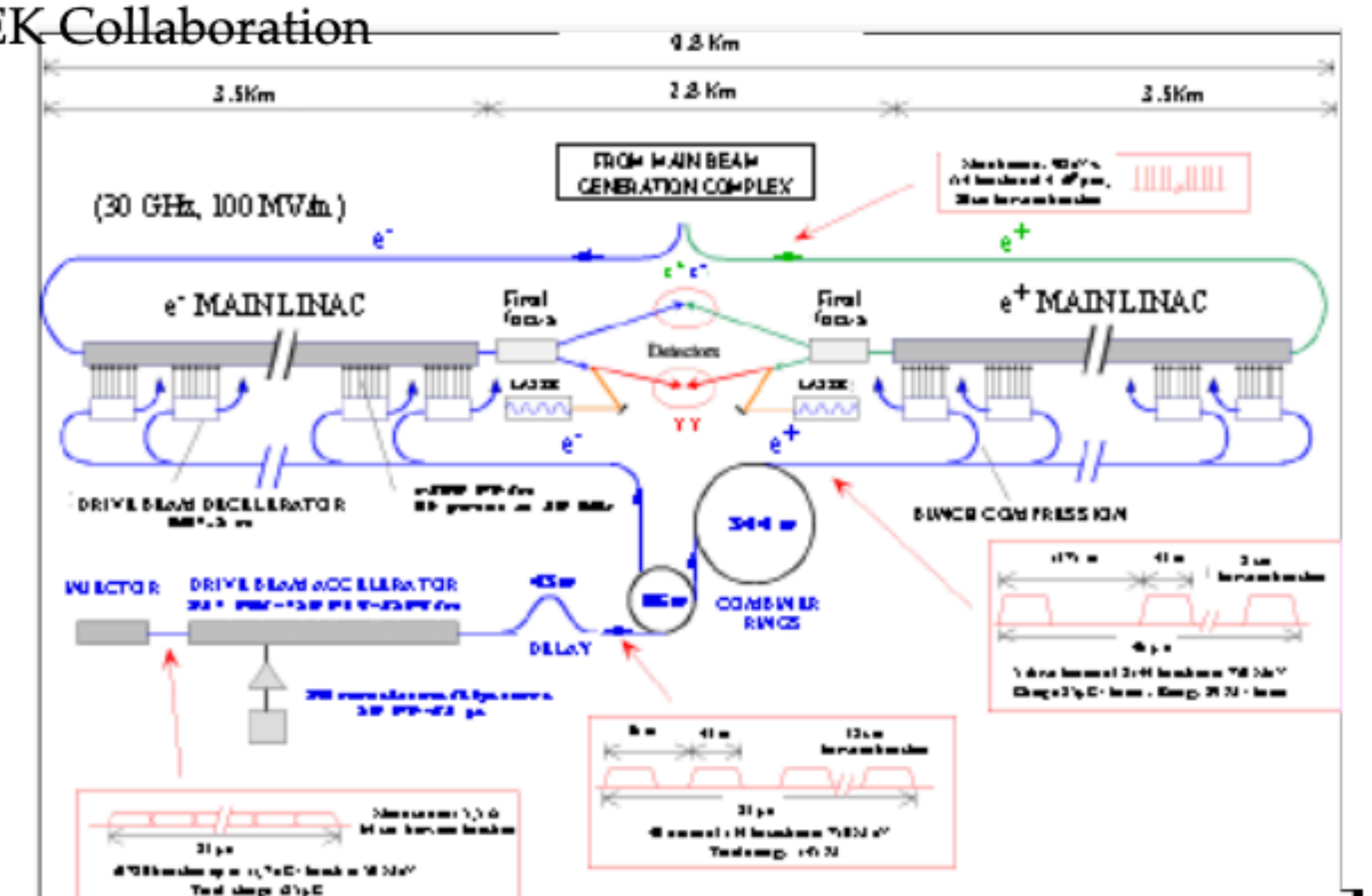


193 MV/m peak accelerating field
426 MV/m peak surface field

2π/3 phase advance
3.5 mm aperture
Es/<Eacc> = 2.84
4.6% v_g/c
T_{fill} 8.3 ns



CLIC Test Facility



OVERALL LAYOUT OF THE CLIC COMPLEX AT 500 GEV C.M.

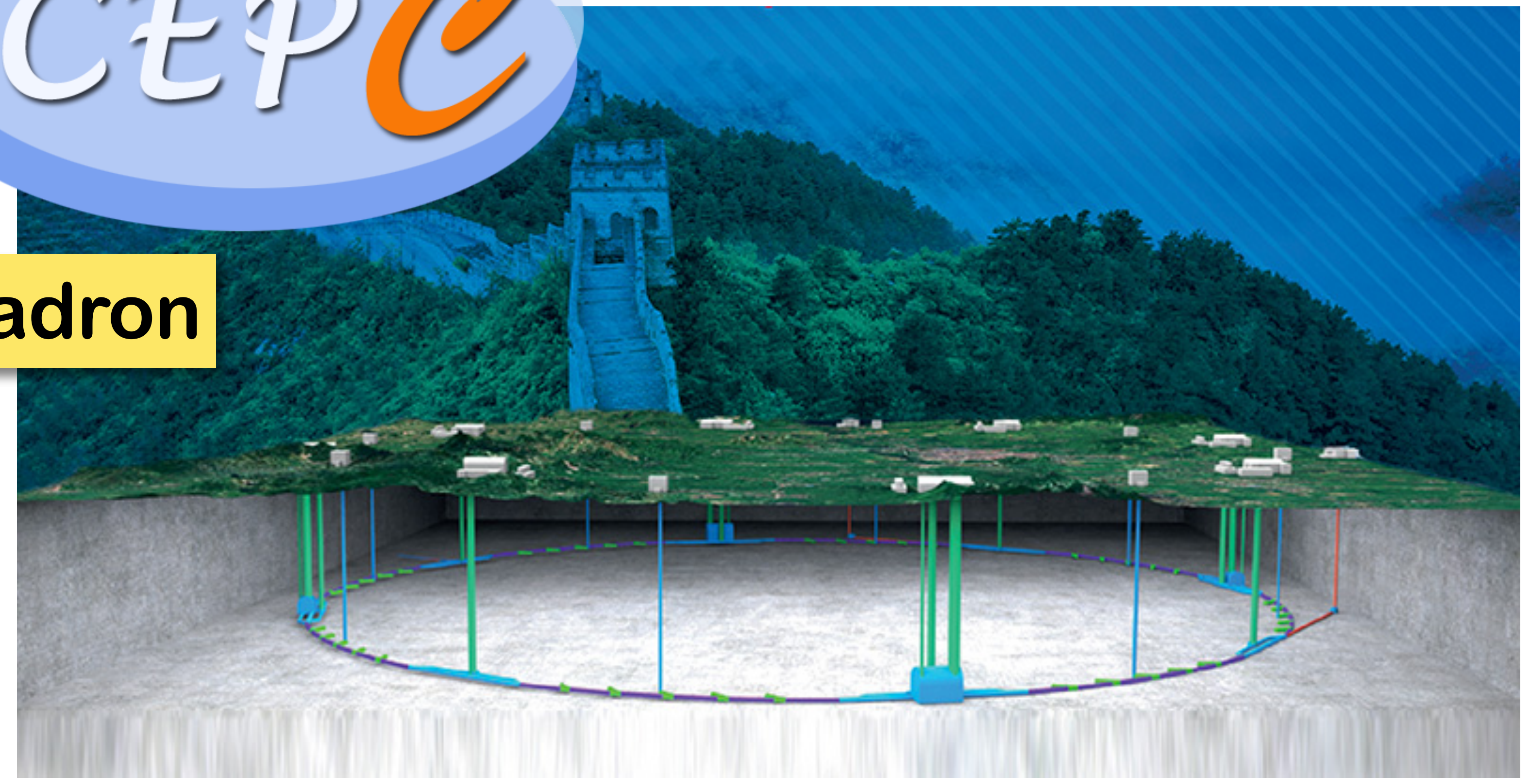
CAS - IC-2006

17

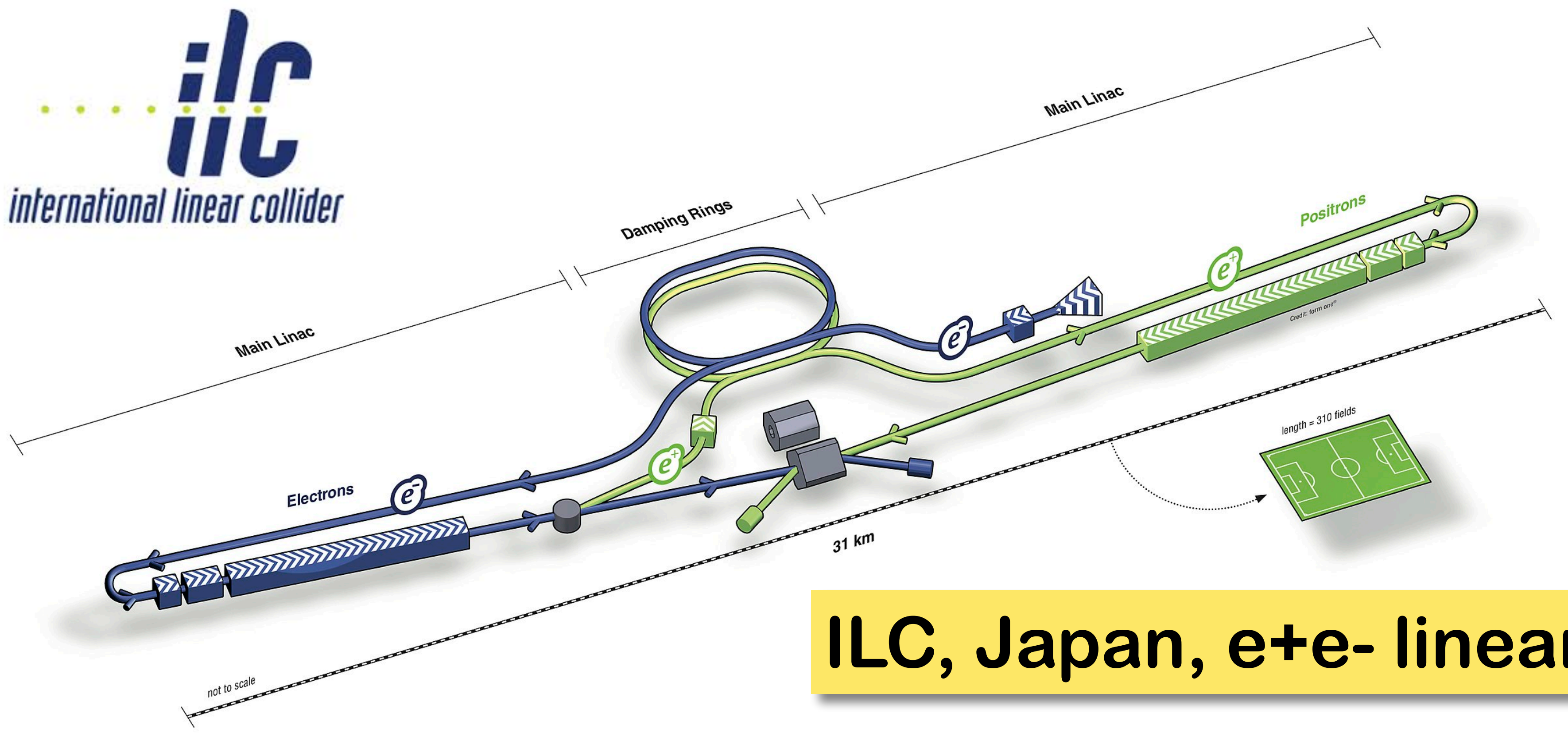
CAS slides from 2006

The options on the table

Are varied

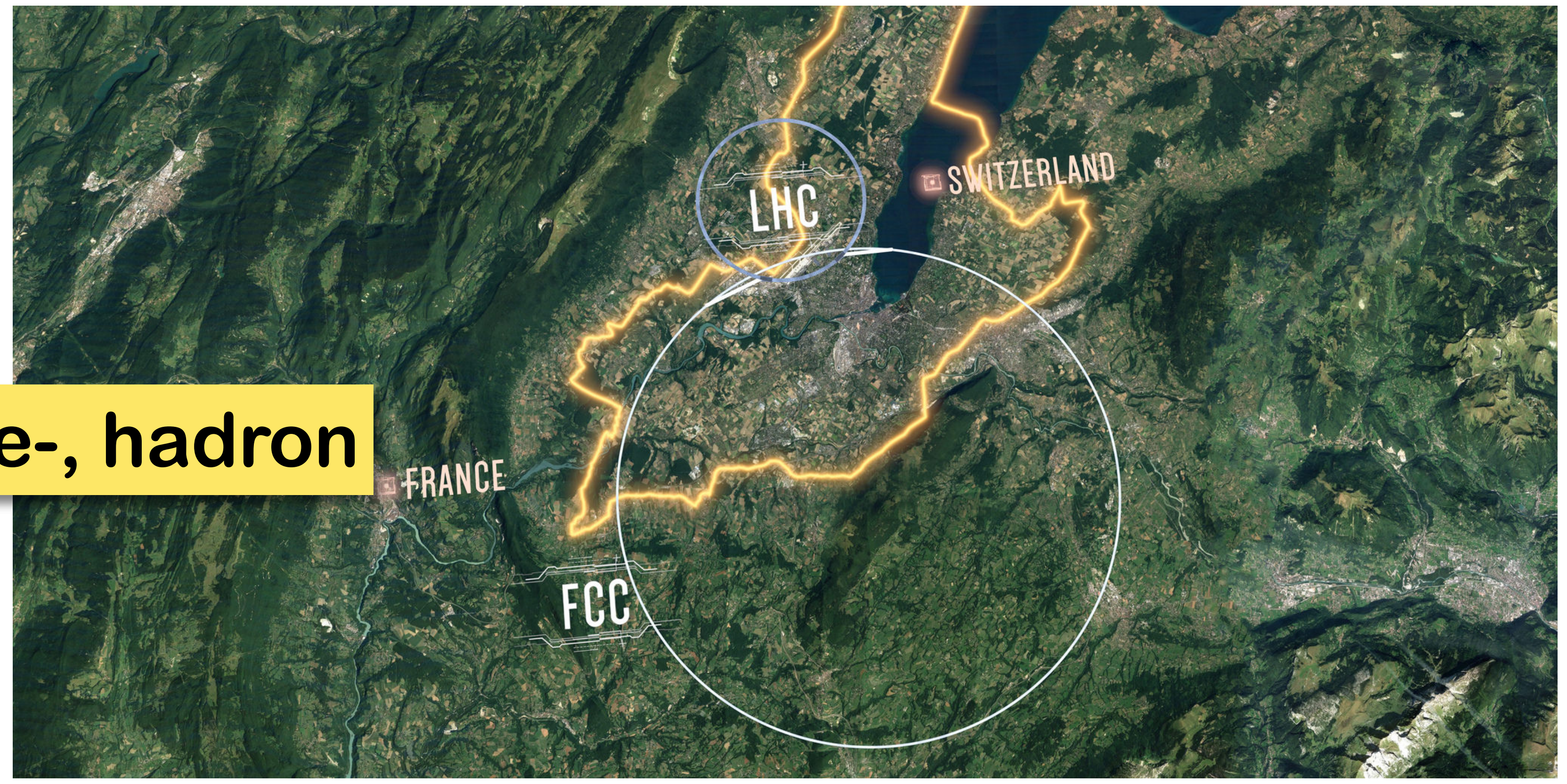


CEPC, China e+e-, hadron



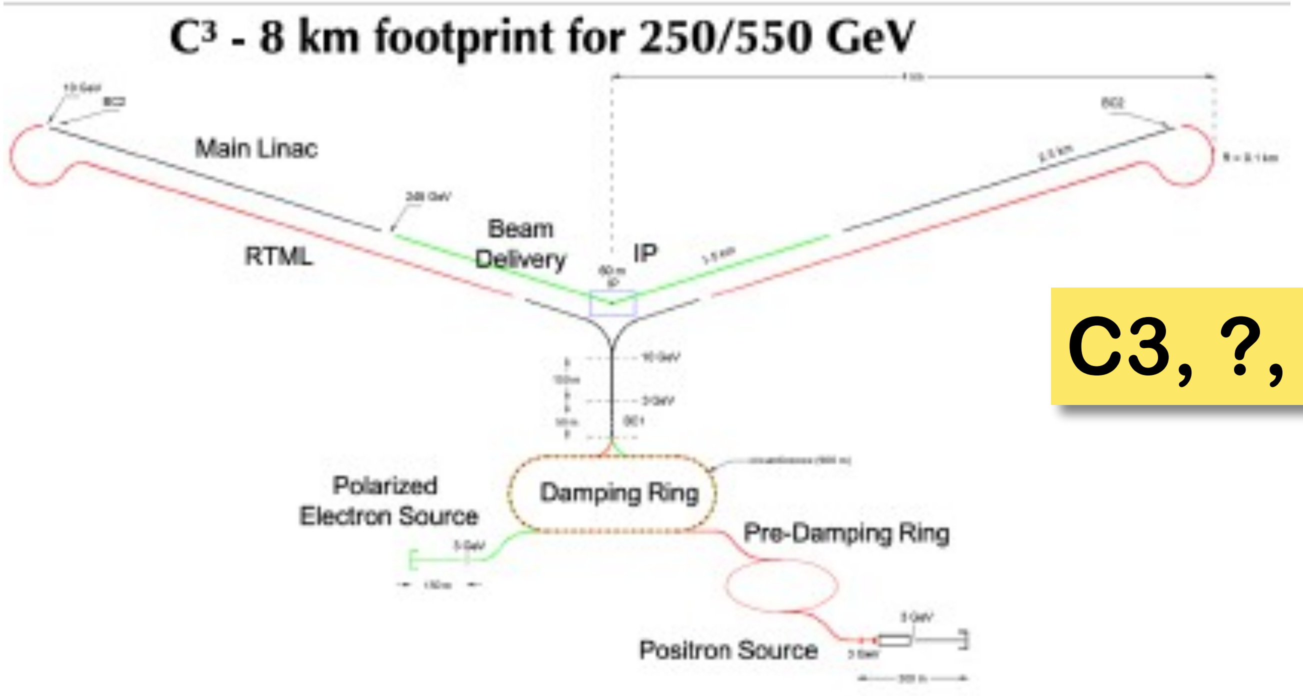
ILC, Japan, e+e- linear

FUTURE
CIRCULAR
COLLIDER

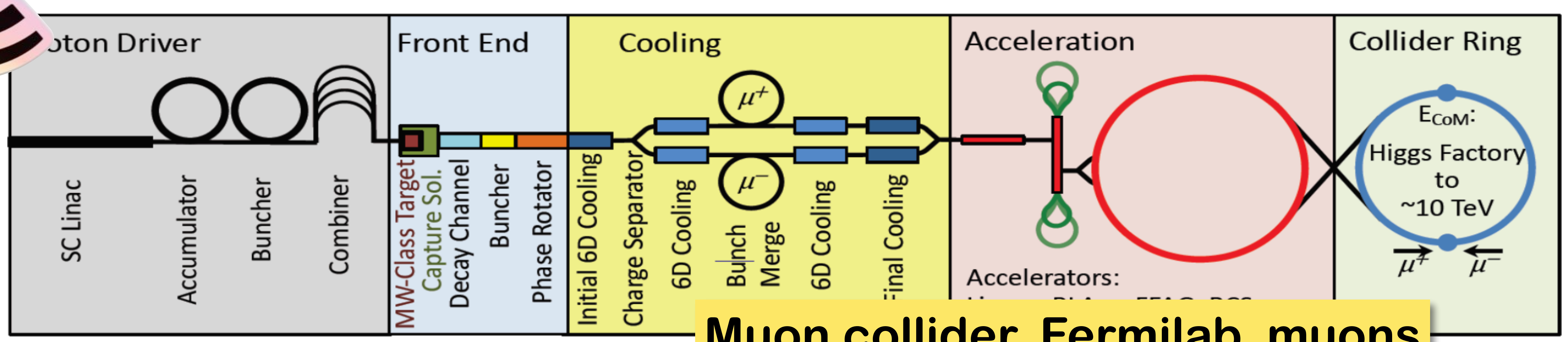


FCC, CERN e+e-, hadron

CLIC, CERN, e+e- linear



C3, ?, e+e- linear

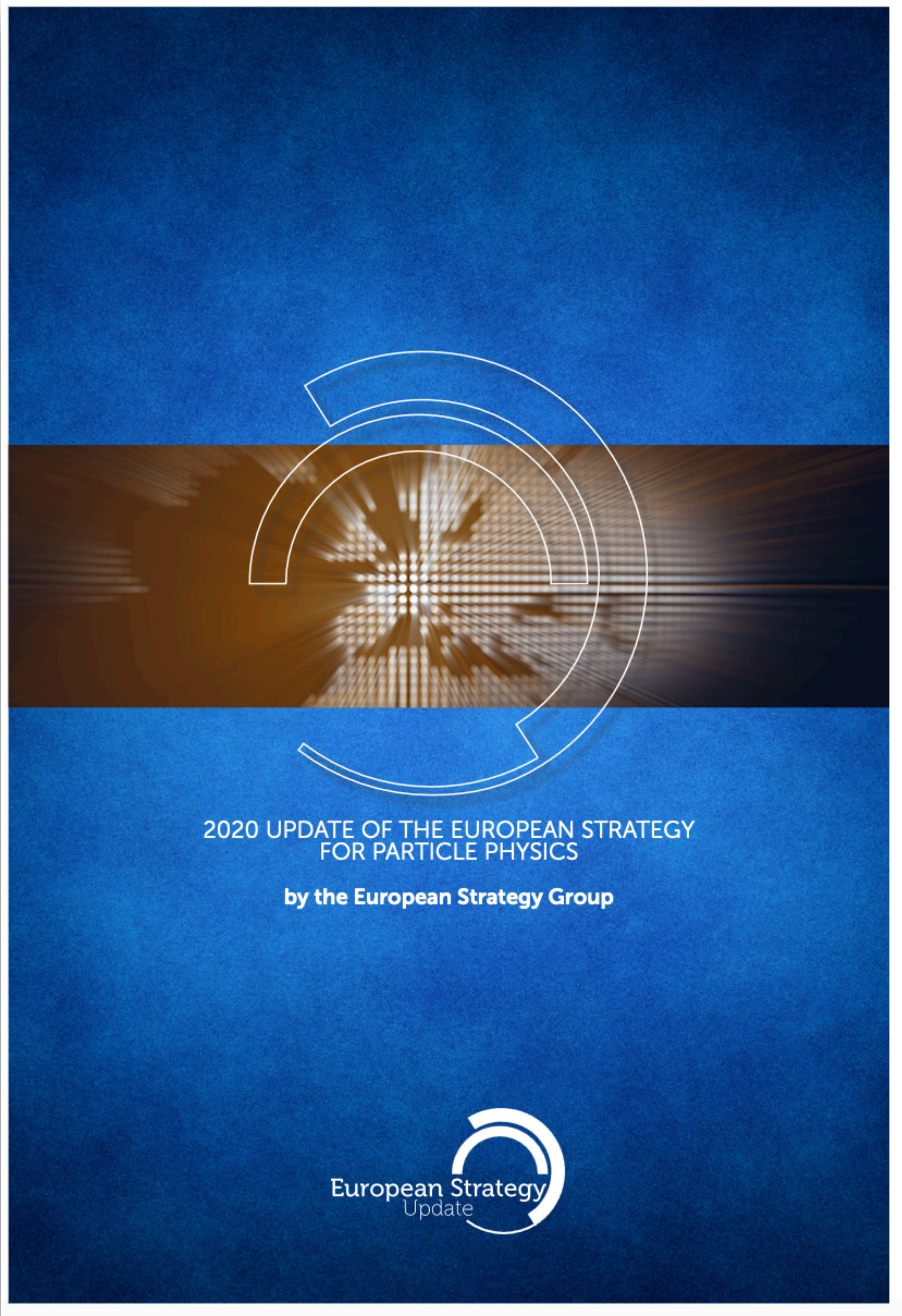


Muon collider, Fermilab, muons

Etc..

European Strategy for Particle Physics

2020 Update



"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."

Since then

FCC has become the clear CERN choice

- A versatile, next-generation particle collider housed in a 90km underground ring
- Linked to the LHC accelerator chain
- Implemented in stages, one e^+e^- machine, followed by a high-energy hadron collider

FCC pushes two frontiers

Intensity and Energy

Additional modes supported
Heavy ions, eh

- 1st stage collider, e+e-
  - **FCC-ee**
  - electron-positron collisions
  - 90-365 GeV
  - Higgs, EW, top factory
  - Construction starts: **2033**
  - Physics starts: 2048 (45 if accelerated)

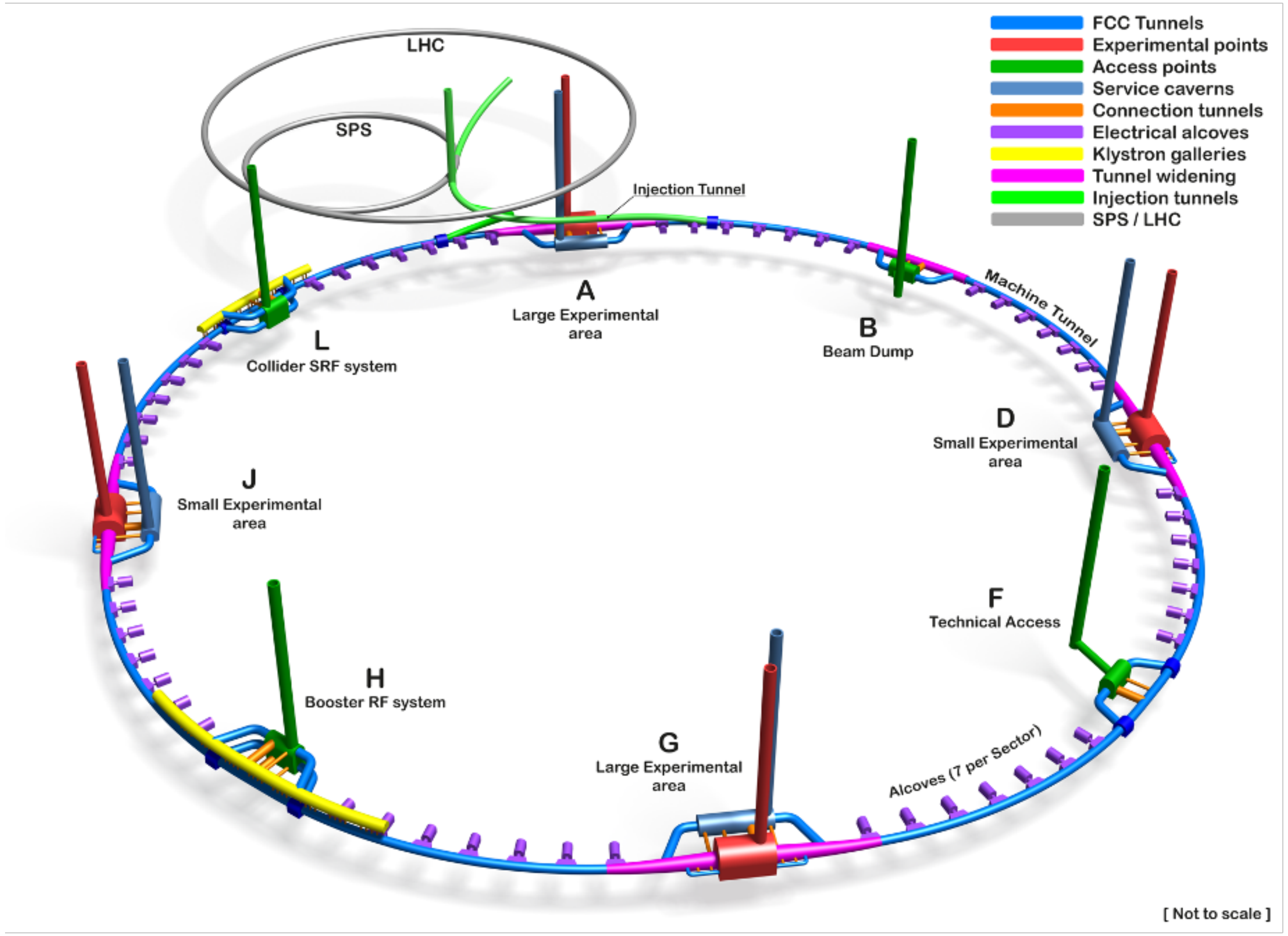
- 2nd stage collider, pp
  - **FCC-hh**
  - proton-proton collisions
  - ≥ 100 TeV
  - Discovery machine
  - Physics operation: ~ 2070

Complementary
Synergetic
All-in-one facility

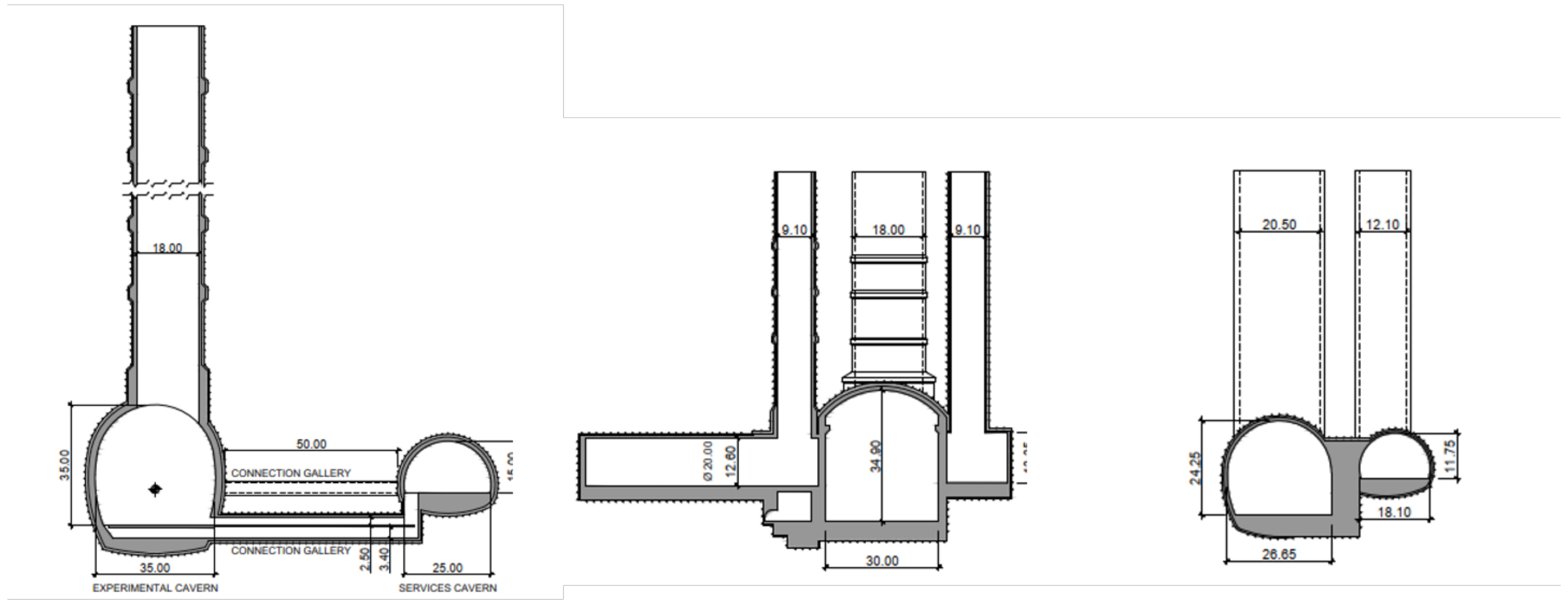
Strength

In shared infrastructure

- Making use of the current acceleration chain
- Using one tunnel (and one set of caverns) for both stages
  - 90.7 km ring, 8 surface points



- **4 Experimental areas** 2 large (> ATLAS) & 2 small (~CMS)
- Deepest shaft: 400m
- Average shaft depth: 243m

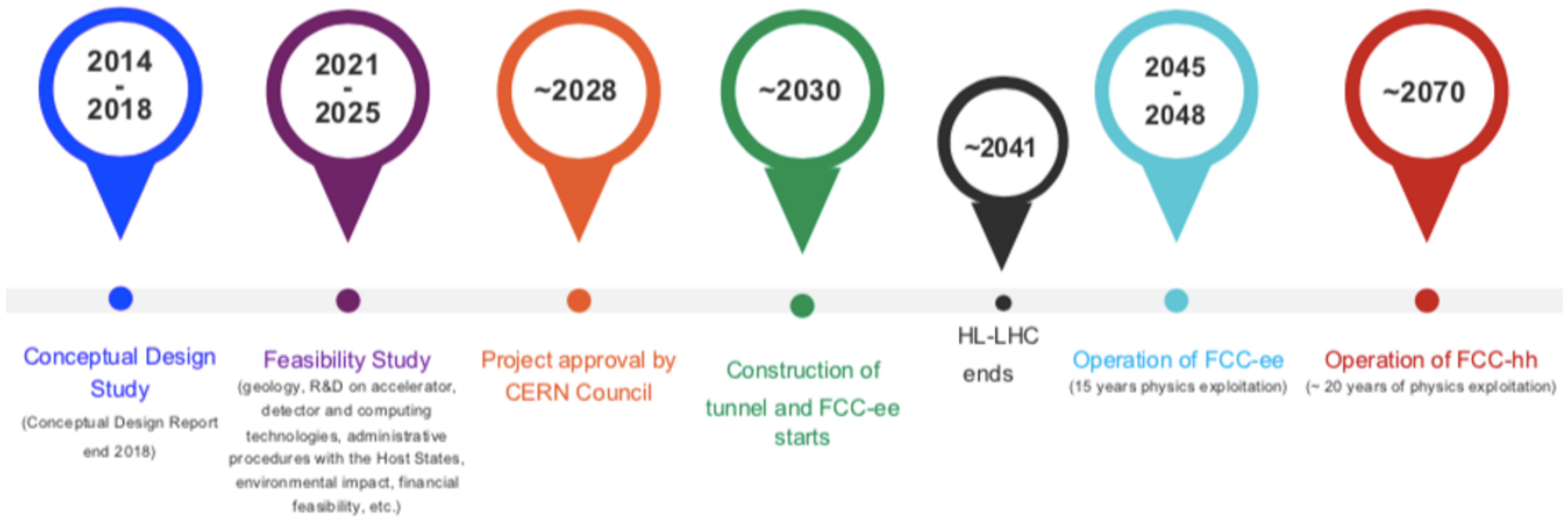


FCC ATLAS CMS

Strength

In size and timescale

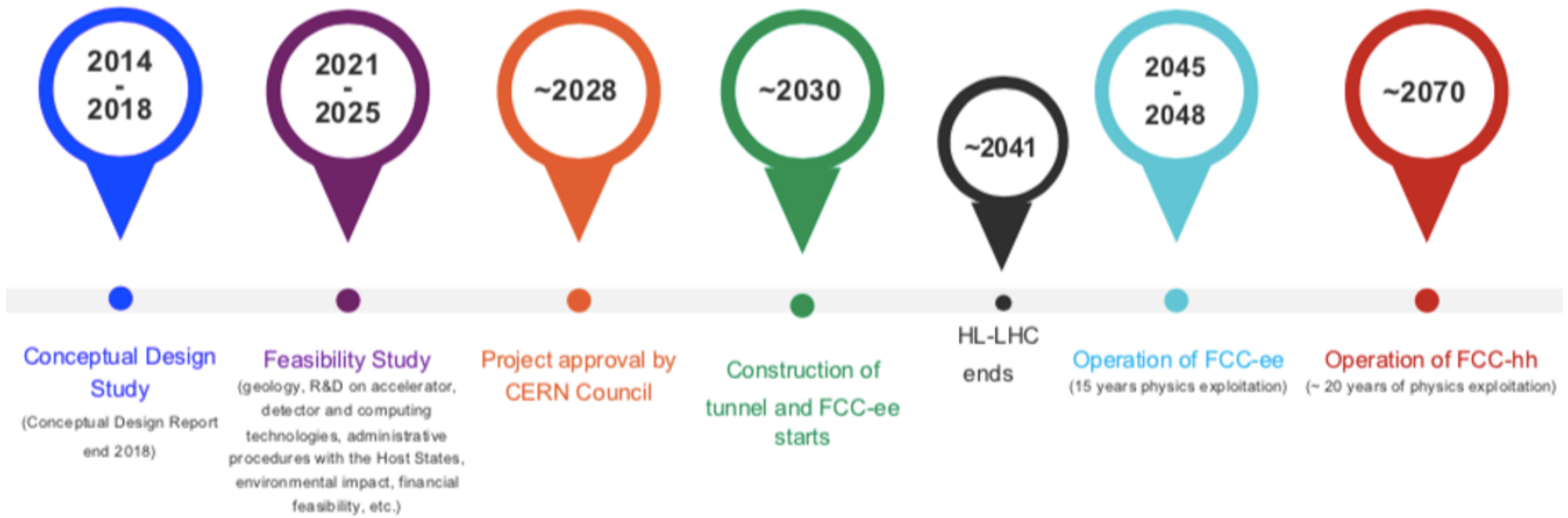
- FCC-ee technology is mature → construction in parallel to HL-LHC operation
- Physics a few years after the HL-LHC
  - Guarantees continuity for multiple generations of high energy physicists
  - **Only proposed facility that can accommodate the size of the CERN community**



Strength

In size and timescale

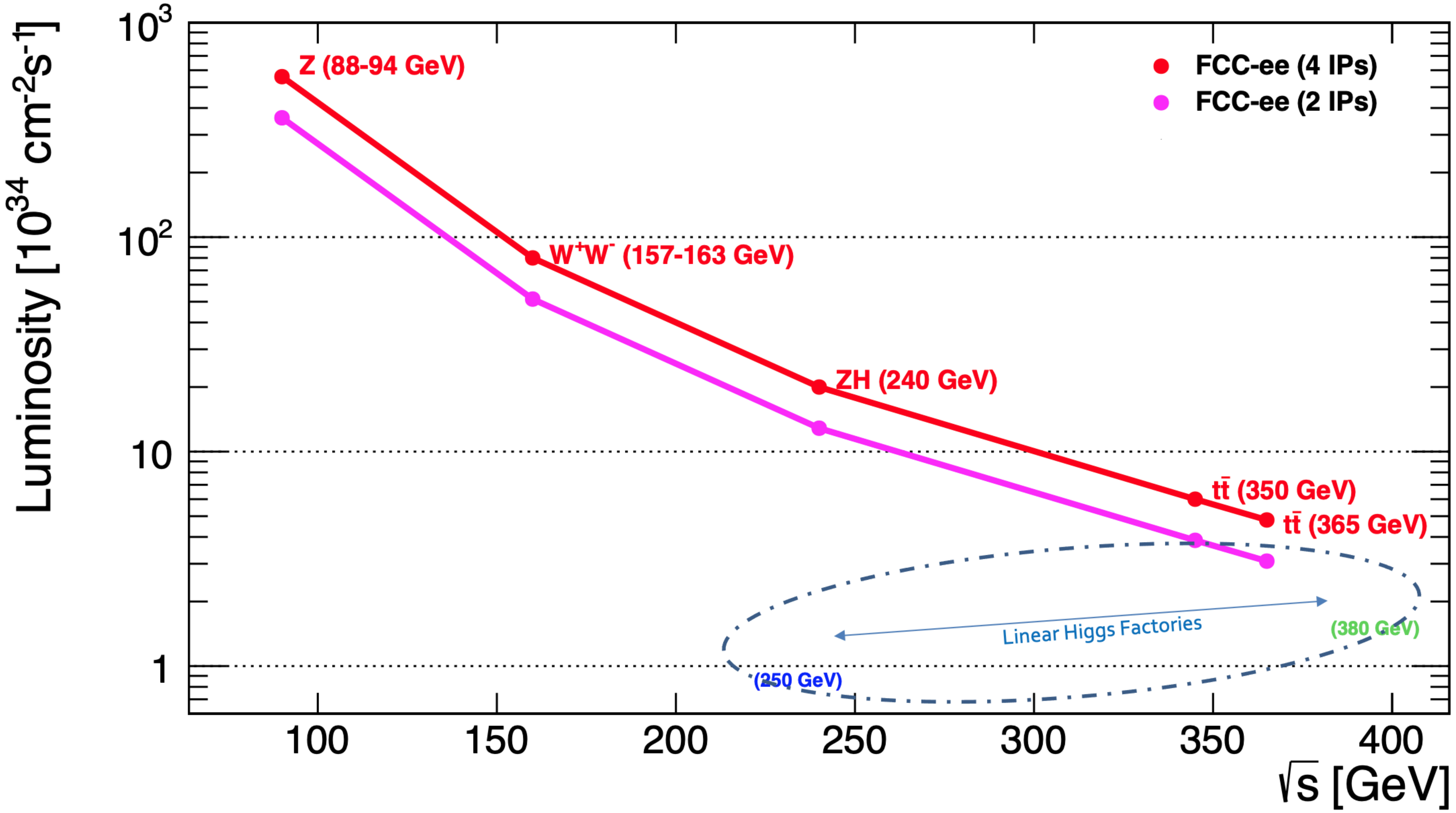
- Two-stage approach
  - Allows to **spread the cost** of the (more expensive) FCC-hh over more years
  - **20 years of R&D work towards optimal and affordable magnets**
  - Optimization of overall investment by reusing civil engineering and large part of the technical infrastructure



Strength

In physics potential

- **FCC-ee:** **highest luminosities of all proposed Higgs and EW factories,** clean experimental conditions, and a range of energies that cover Z, WW, ZH, and tt.



FCC feasibility Mid-term report - Deliverable #8, physics and Experiments

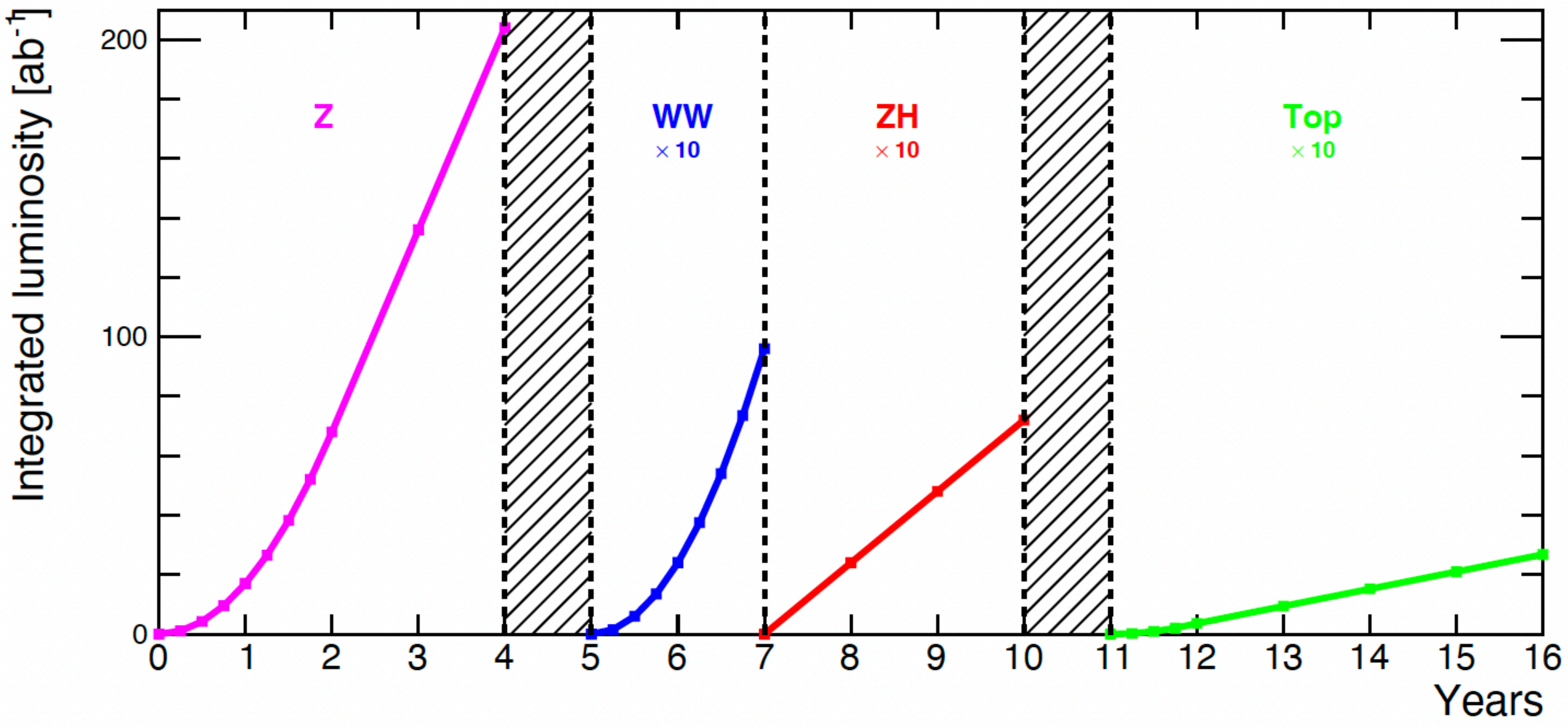
combining successful ingredients of several recent colliders → highest luminosities & energies

FCC-ee

FCC feasibility Mid-term report - Deliverable #8, physics and Experiments

The baseline

- 16 years, **4 IPs**
- **Flexibility in the run scenario:** in order and operation periods.
  - Additional runs, e.g. 125GeV possible
- **Stringent experimental requirements**



integrated luminosity per year summed over 4 IPs corresponding to 185 days of physics per year and 75% efficiency

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} cm^{-2}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 → H	1.9×10^6 $t\bar{t}$ +330k ZH +80k WW → H	

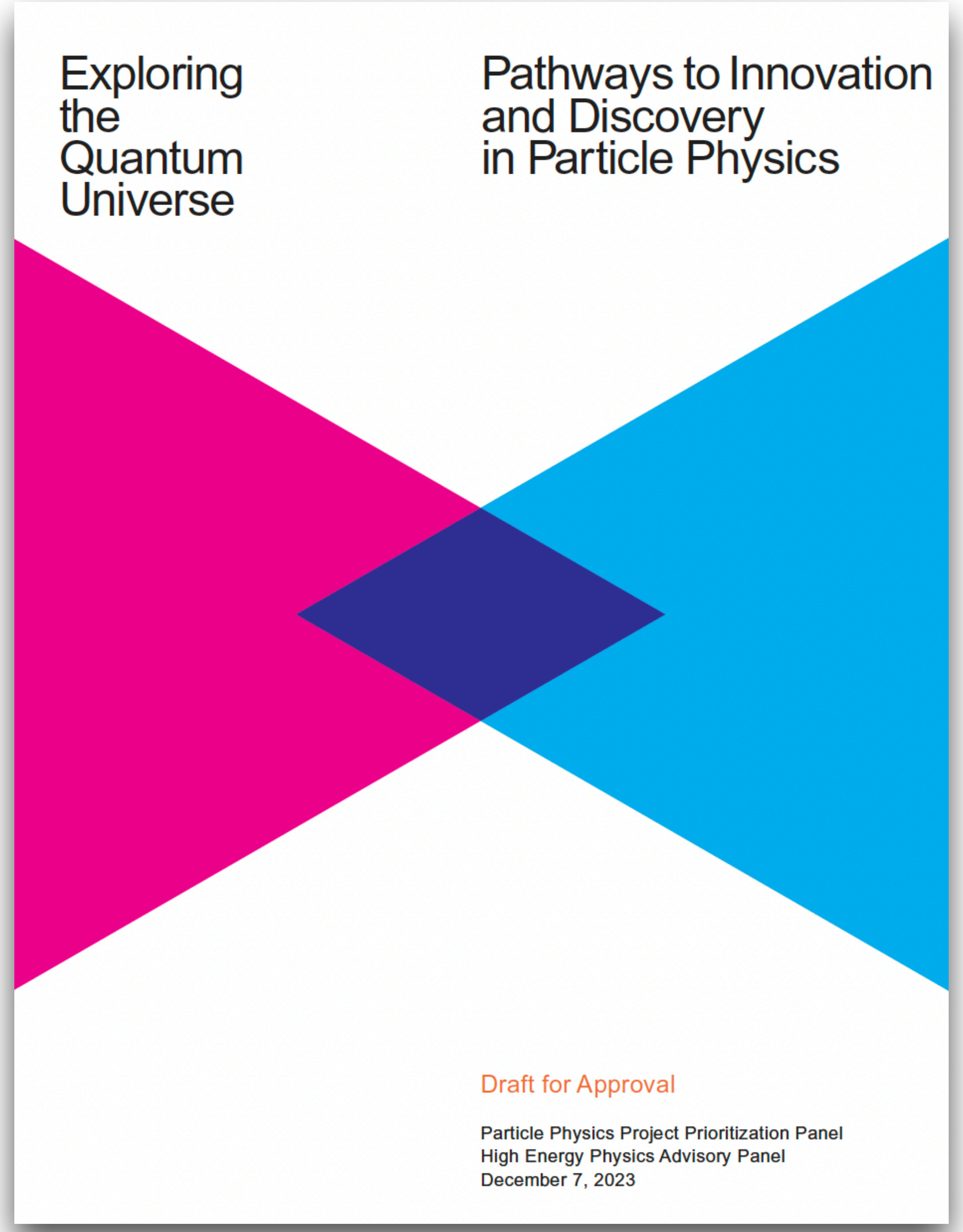
all the data of LEP1 in minutes

Lately

US P5 report

2023, following Snowmass

Advocates for substantial US participation and effort to support development of an offshore Higgs factory, with the goal of leading and potentially hosting a muon collider beyond it.



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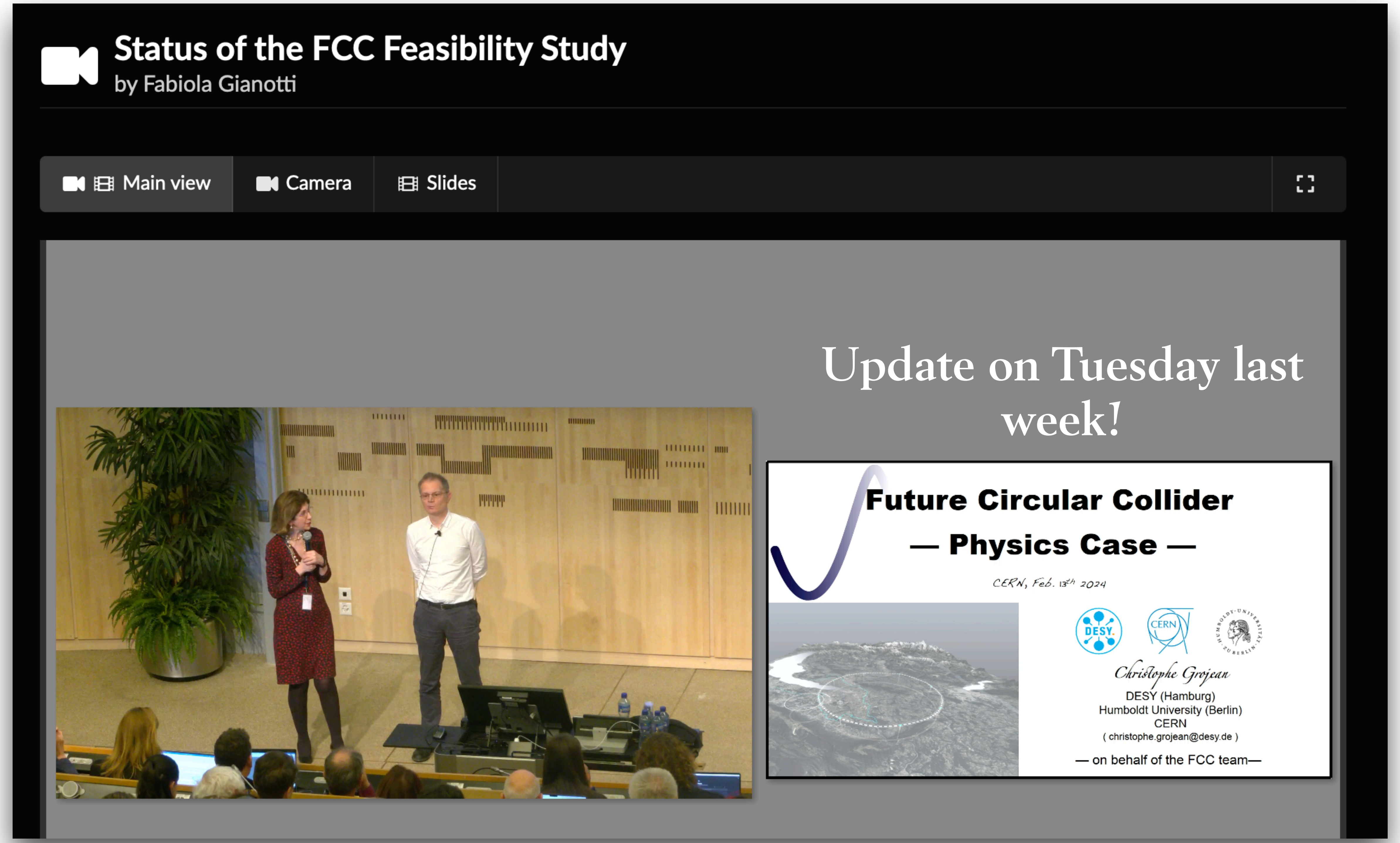
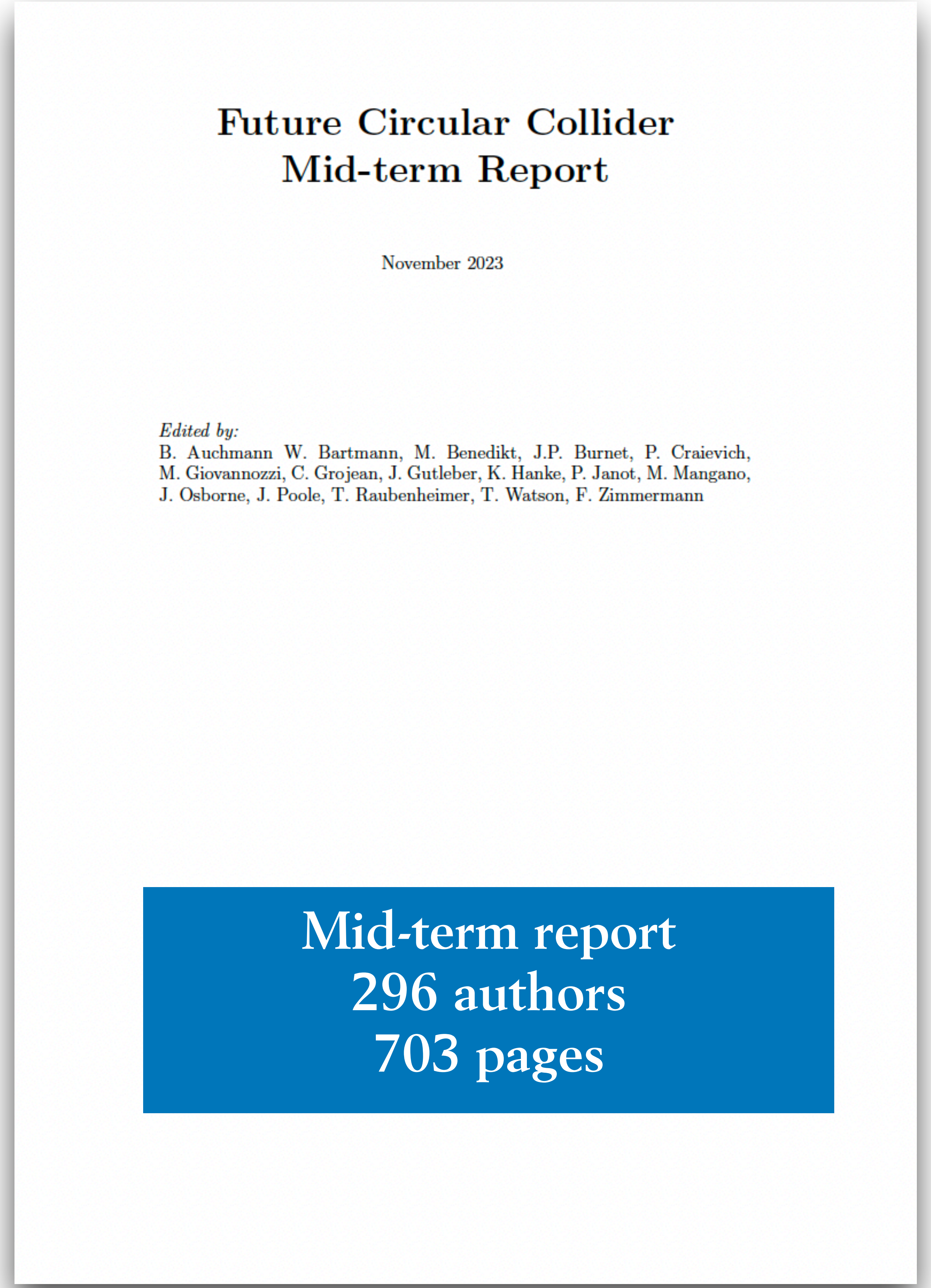
The mid-term report

Was reviewed by the CERN council





Locally in Sweden

Some news!

- Following the **mid-term report**, Vetenskapsrådet, the main funding body of Sweden, created a reference group to follow the FCC process and European Strategy Update:
  - **Sara Strandberg**, Lars Böjesson, Anders Karlhede, Lisbeth Olsson and Mattias Marklund.
  - Some initial feedback on the report focuses on:
    - Physics case, cost-estimates, environmental issues

Physics goals need to be made crystal clear to reviewers who are not particle physicists!

- In connection with the RECFA visit to Sweden (Lund, May 16-17) → **future colliders discussion (ECSB) + FCC dedicated discussion on May 14, 2024**
  - https://indico.cern.ch/event/1373946/
  - Register and join!

Locally in Uppsala

We've been working in FCC since 2019

Rebeca and Richard

- Convening the BSM Physics Performance group since 2022
- FCC National contact for Sweden since 2020
- Coordinator of the FCC-ee LLP case study [2020-2022]
- …

Master theses:
- Rohini Sengupta
- Lovisa Rygaard
- Magdalena Vande Voorde

Projects: Nils Eriksson, Lovisa Ryagaard, Rohini Sengupta, Olga Sunneborn Gudnadottir

- Contributions to the FCC Midterm Report - 8. Physics & Experiments (analysis and editing the report)
- Report of the Topical Group on Physics Beyond the Standard Model at Energy Frontier for Snowmass 2021
- The Present and Future Status of Heavy Neutral Leptons (J. Phys. G: Nucl. Part. Phys. 50 020501) - Snowmass 2021
- The Future Circular Collider: a Summary for the US 2021 Snowmass Process - Snowmass 2021
- Searches for long-lived particles at the future FCC-ee - Snowmass 2021
- Hunt for rare processes and long-lived particles at FCC-ee (Eur. Phys. J. Plus 136, 1056 (2021))

The future is now

- **We need to approve and build the next collider ASAP to guarantee the future of HEP beyond HL-LHC**
  - We need something for which technology is mature today → e+e-
  - We need something that is big enough to keep all our people → FCC is the only option big enough
  - We need a Higgs factory and to explore the SM thoroughly to inform the high energy to come → FCC-ee offers the highest luminosity, broadest energy range
  - We need to maximize our resources and bet on options that can be exploited long term → While FCC-ee is built and runs we can do R&D needed to hit the next energy frontier cheaper, maybe to have a muon collider (we realistically COULD have both hh and μμ)
- The interest in FCC has ramped up significantly in the last year, but there is MUCH to do in terms of
  - **Accelerators, detectors, physics → In Uppsala we can cover each area**
- 2025 marks the next Update for the European Strategy for particle physics → the time to join is now!

Backup

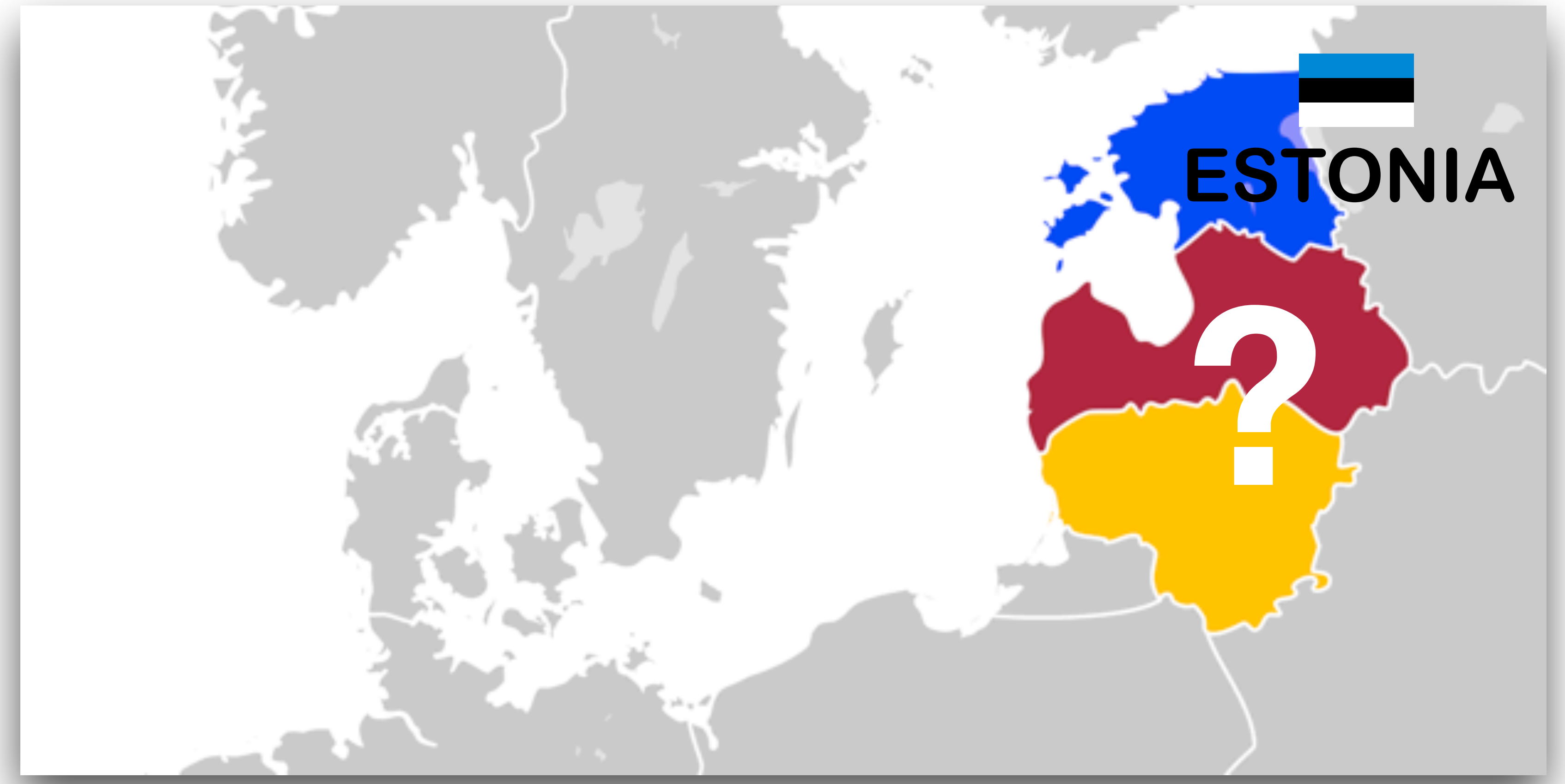
FUTURE CIRCULAR COLLIDER

Last update: April 2023

Nordics and FCC

Denmark, Norway, Sweden, Finland

- From the usual nordics we are missing Iceland
- Sometimes the Baltics are also counted in the nordics
  - We know there is **work ongoing in Estonia**
  - Do we have any presence in Latvia and Lithuania?



Is a "nordic cluster" something we want to pursue?

Denmark

The OG Nordic country in FCC

(National contact, institute contact)

- **Mogens Dam** ↔ Niels Bohr Institute, University of Copenhagen
  - **Co-convenership of the Detector Concept effort**
  - Key involvement in **luminosity measurement, contact to the MDI group**
  - **Convenership of the working group on detector costing** → input to the midterm report
  - **Two MSc students**, one working on LumiCal simulation the other on aspects of tau lifetime measurements.
- **Jørgen Beck Hansen** + **one MSc student** working on top studies.
- No efforts on other future colliders.

no dedicated funding for future collider efforts

Norway

Heidi Sandaker

(National contact)

- There are no activities on FCC at the moment, but there is very much interest.
  - **Part of the permanent staff worked on e+e- and/or is interested in Higgs physics.**
- Most permanent staff follow the FCC development to various degrees, but there are **no ongoing research projects now or planned in the near future.**
- Increased activities on the technology side may be of interest to FCC such as CO2 cooling; groups for robotics or civil engineering could be interested.
- There is no dedicated funding for FCC, the ongoing discussion is to secure funding for the lifetime of the HL-LHC.
  - The current funding for general experimental activities related to CERN is given as a Norwegian Centre-for CERN-related research.
  - Currently in the process of writing a **Norwegian roadmap for CERN-related research**, which will be used to secure future funding.
- The Norwegian community is and has been involved in CLIC, ILC, ESS (in-kind contributions) and various fundamental accelerator research activities.

Uppsala

Master theses: Rohini Sengupta, Lovisa Rygaard, M. Vande Voorde

(National contact, institute contact)

- **Rebeca Gonzalez Suarez**
- Work continues around BSM options
  - **Co-convenership of BSM group**
  - Contribution to mid-term report
  - Contribution to notes for mid-term report
  - Related convener position in **ECFA** Higgs factories WG1
- **Richard Brenner** involved in detector development
- **Postdoc** partly funded to work on FCC (Giulia Ripellino)
- **PhD student** (Axel Gallén) working on Exotic Higgs with Giulia and Magda (from KTH), **visiting PhD student** (Baibhab Pattnaik)

KTH

(Institute contact)

- **Christian Ohm**
  - Sweden National contact for ECFA Detector R&D Roadmap
- Interest in the group ramping up
- **One PhD student** (Magdalena Vande Voorde) working on exotic Higgs decays to LLPs
  - **Presentation this week, working towards a paper [link to the talk]**

Also presenting this week! [link to the talk]

Stockholm University

(Institute contact)

- **Christophe Clément**
- **Postdoc position to be announced before the summer**
- **Expecting at least one master student 2024**
- Interest in detector layout studies and BSM Higgs sector physics with multiple neutral scalars

Lund

(Institute contact)

- **Else Lytken**
- FCC not under discussion at the moment

Finland

Kenneth Osterberg

(National contact,
institute contact)

- No PED activities and no concrete plans.
- **No funding for PED activities**, difficult to motivate people to join.
- Currently doing **strategy planning for Particle Physics in Finland, ending Spring 2025**.
  - FCC PED activities to be brought up to see whether support and funding can be dedicated for FCC PED activities.
- **Some FCC accelerator-related activities** → material science for thin film deposits on superconducting cavities.
- Finland has still some connection to CLIC on physics modelling of the RF cavity surfaces under high electric and magnetic fields, but this is much smaller than it used to 5-10 years ago.
- No other future collider activity in Finland.

Estonia

Mario Kadastik & Joosep Pata

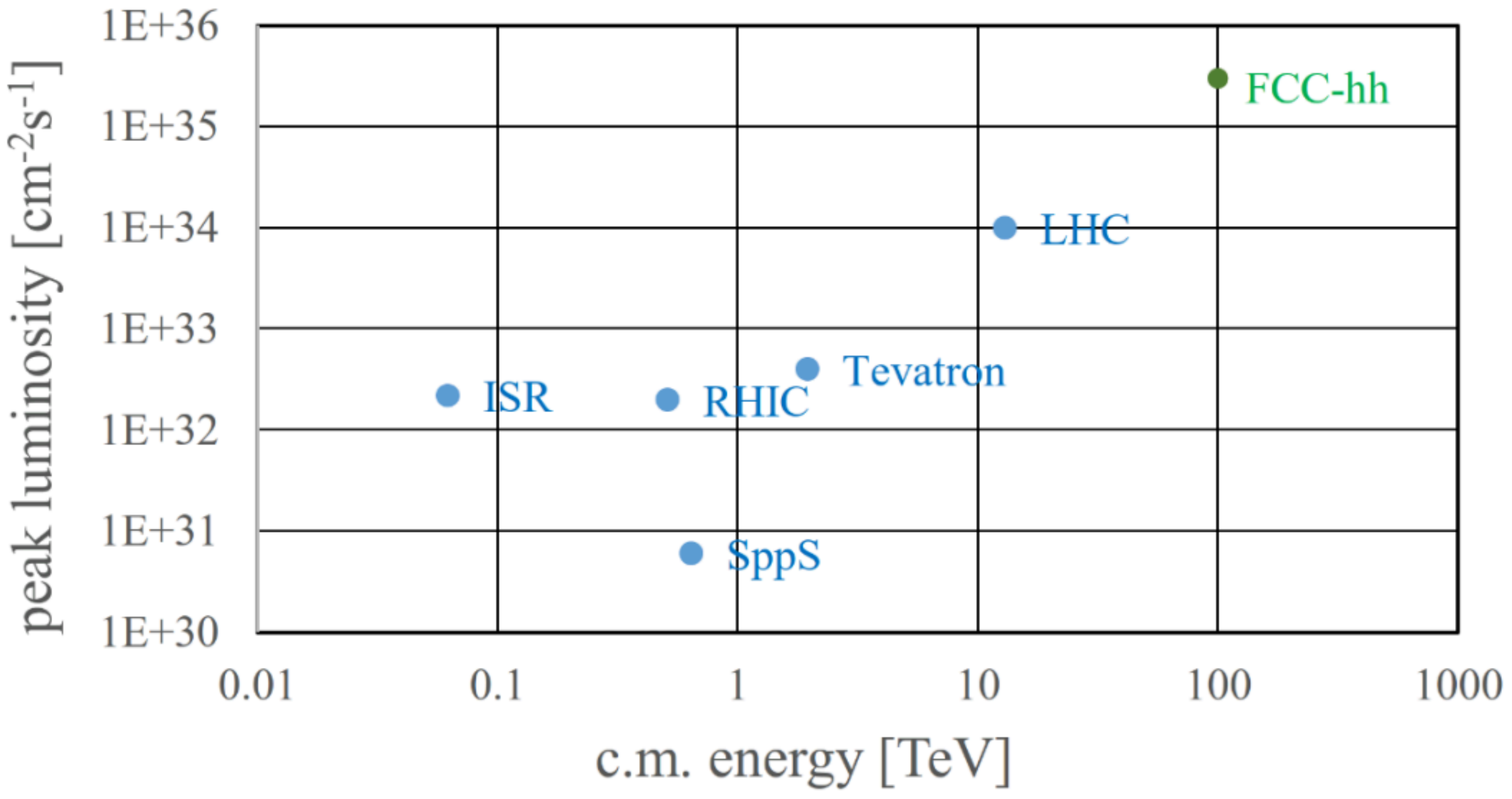
Laboratory of High Energy and Computational Physics (HEPC)

- Getting started, **no students or postdocs on FCC yet** but there is intention to change that
- Experience built with **Key4HEP sim+reco**
- Plans to participate / help out with FCC software development, specifically taggers and reconstruction.
  - Two recent, relevant papers that rely on Key4HE done with the CLIC setup:
    - ML-based tau reco: https://authors.elsevier.com/a/1iTX12OInroMt
    - ML-based PF reco: https://arxiv.org/abs/2309.06782
    - These studies will be re-done for FCC soon
- Will soon start participating in the working groups

Strength

In physics potential

- **FCC-hh:** Able to directly reach the next energy frontier (~ x10 LHC)
  - order of magnitude performance increase in both energy & luminosity wrt the LHC

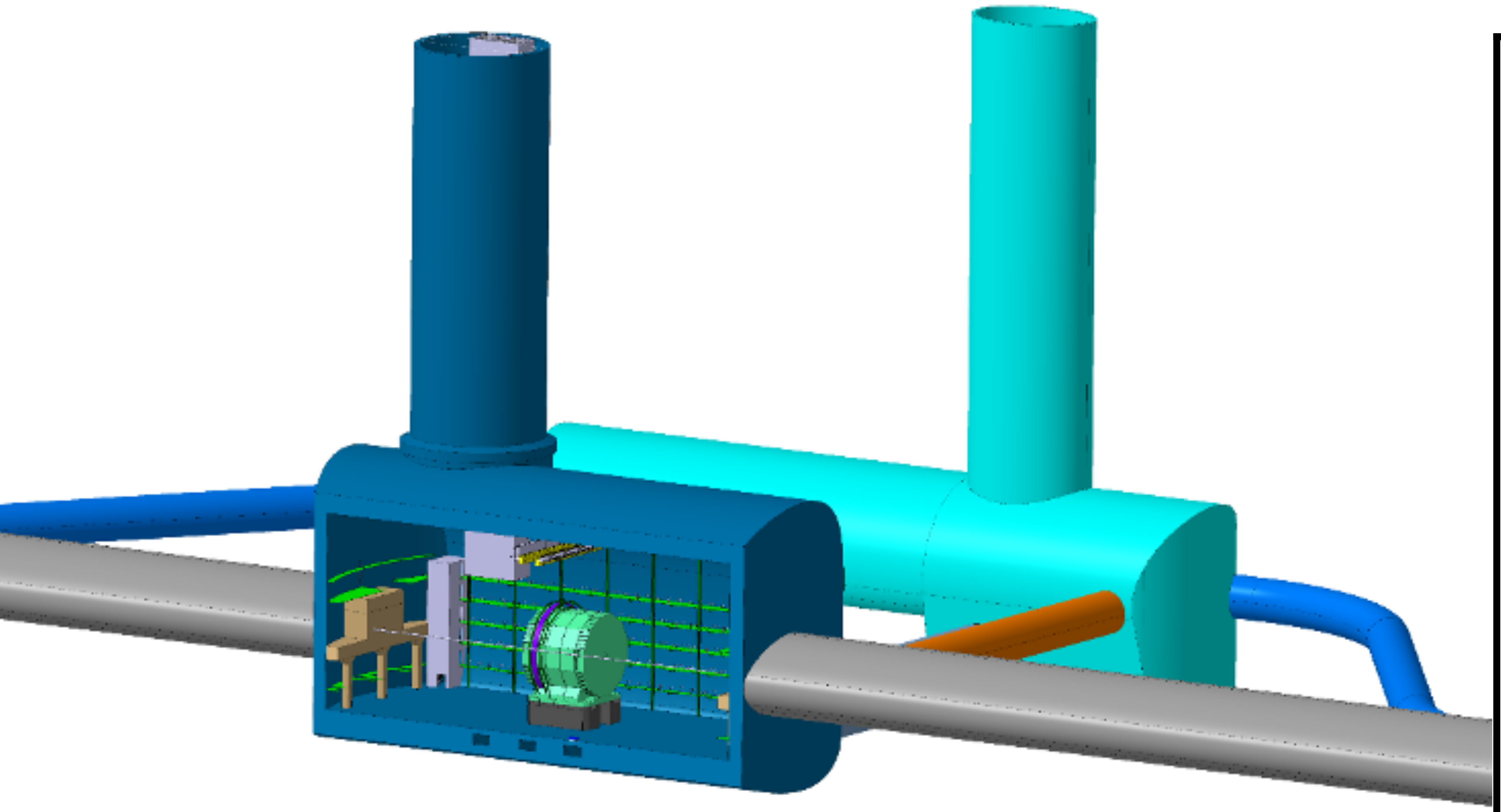


parameter	FCC-hh	HL-LHC	LHC
collision energy cms [TeV]	84 - 119	14	
dipole field [T]	14 - 20	8.33	
circumference [km]	90.7	26.7	
Integrated luminosity/main IP [fb^{-1}]	20000	3000	300

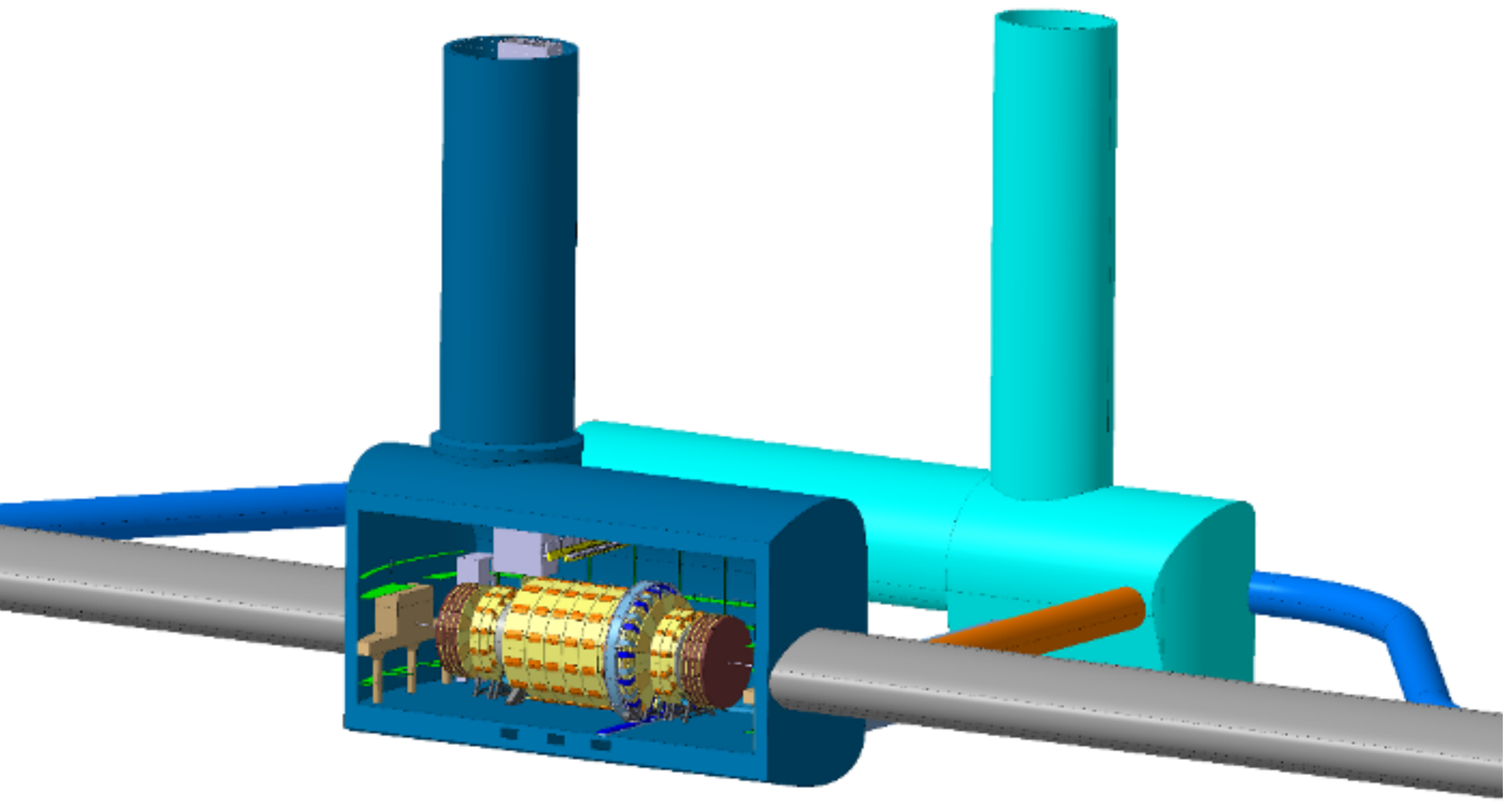
Frank Zimmermann - ICFA Seminar 2023

That's not all!
Heavy-ion collisions and, possibly, ep/e-ion collisions, additional experiments and e.g. a FPF could be there from the beginning

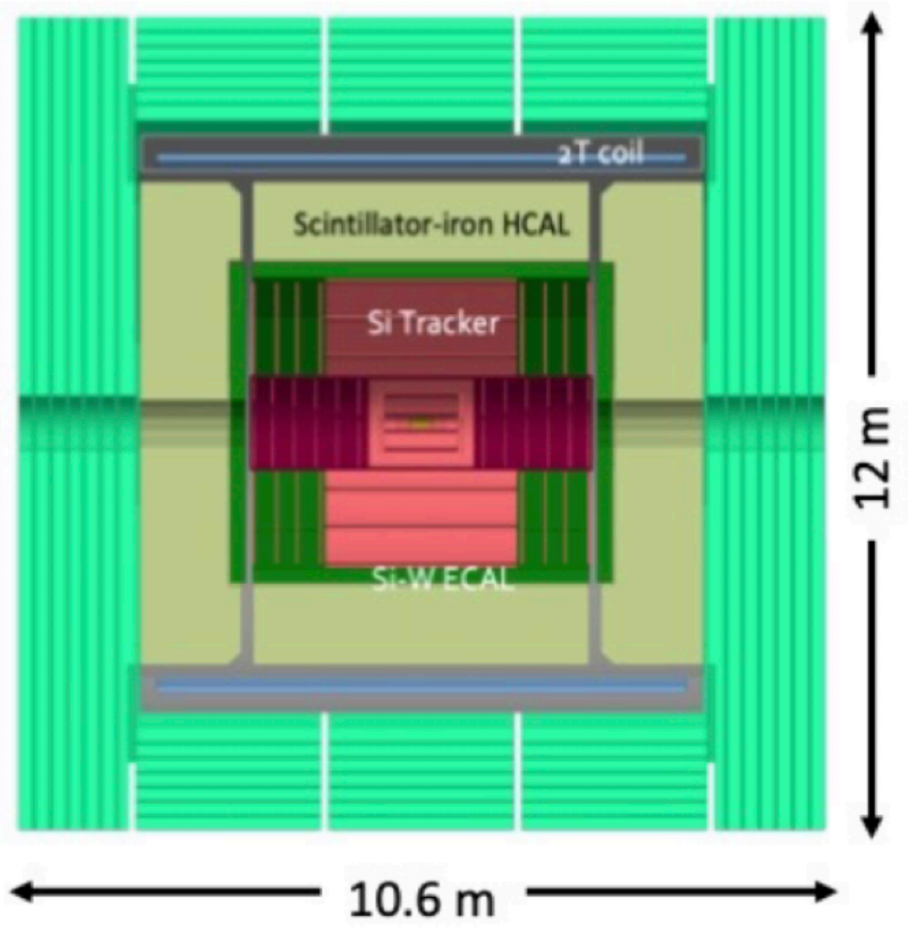
Detector concepts

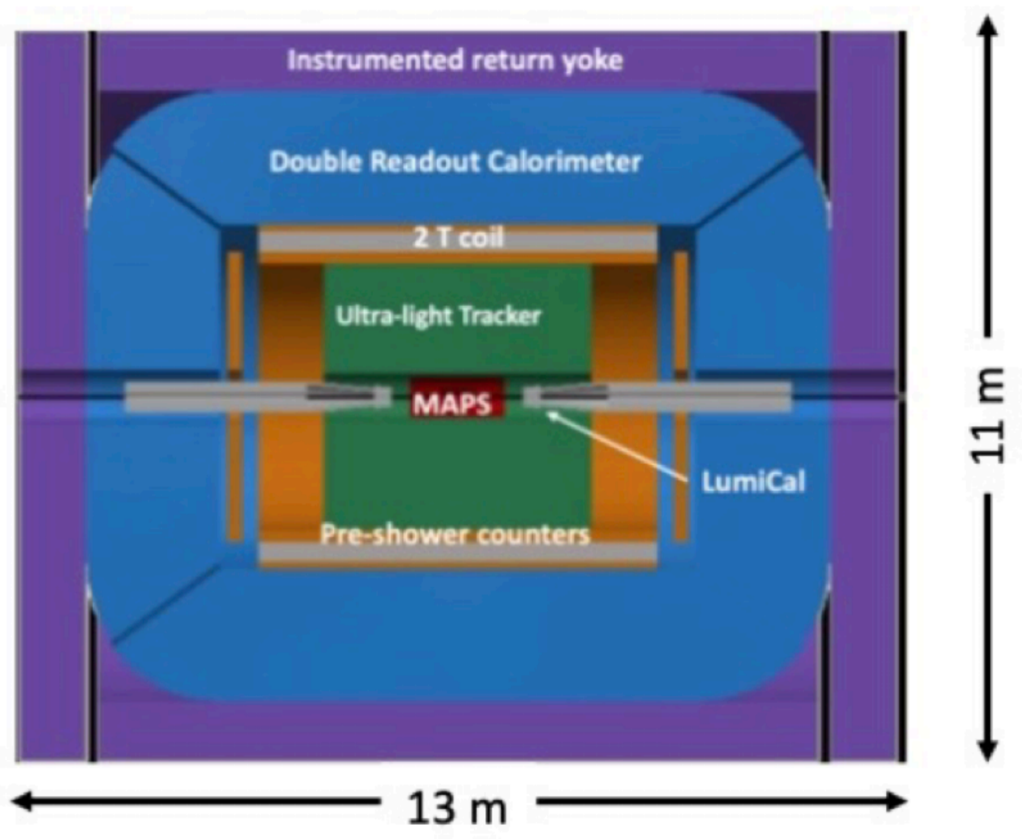


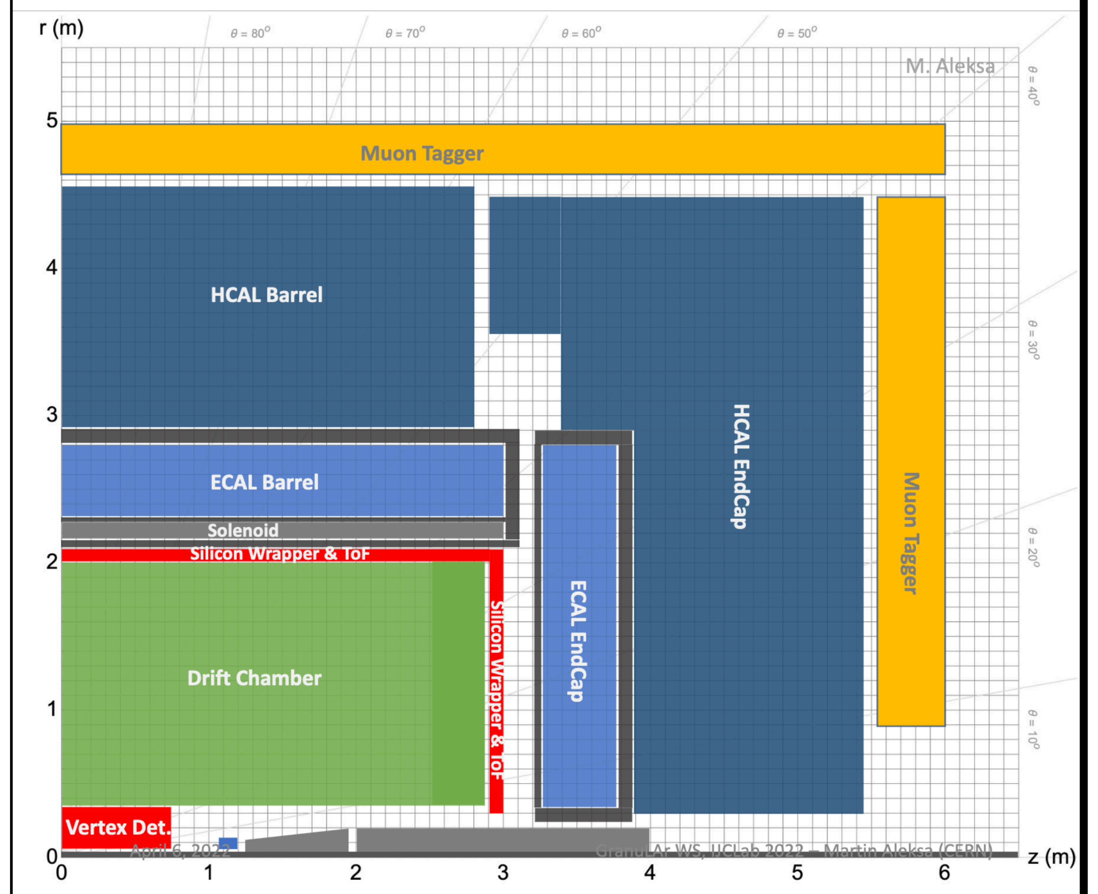
FCC-ee



FCC-hh







CLD	IDEA	ALLEGRO
Based on CLIC detector design, arXiv:1911.12230 Full silicon vertex detector and tracker 3D-imaging highly-granular calorimeter system Coil outside calorimeter system	Innovative, possibly cheaper than CLD https://pos.sissa.it/390/819 Baseline in many ongoing studies Silicon vertex detector Short-drift, ultra-light wire chamber Dual-readout calorimeter Thin and light solenoid coil inside calorimeter system	GranuLAr WS, IJCLab 2022 – Martin Aleksa Highly granular noble-liquid calorimeter Thin 2T solenoid in the calorimeter cryostat.

More complementary options possible (4 IP!) → Can we optimize detector designs for the complete physics program? Yes! opportunities to contribute

Covered with detail by Michele Selvaggi yesterday

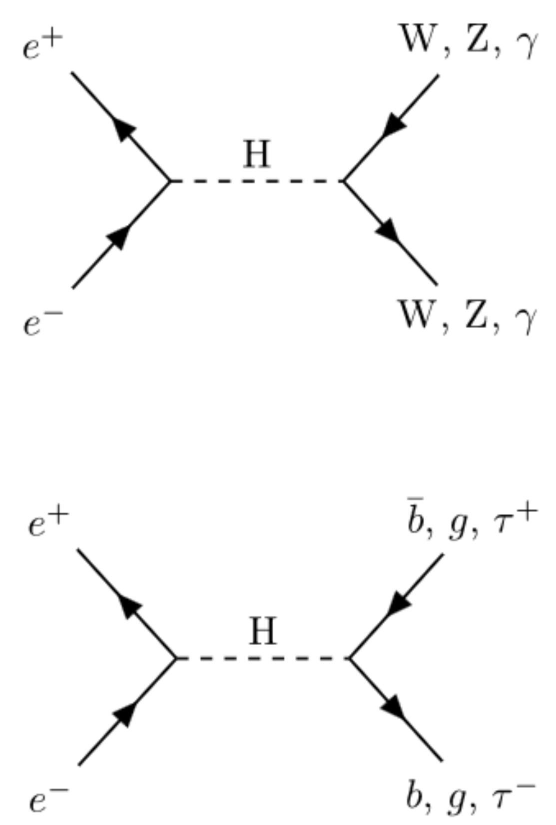
Higgs

Under the microscope

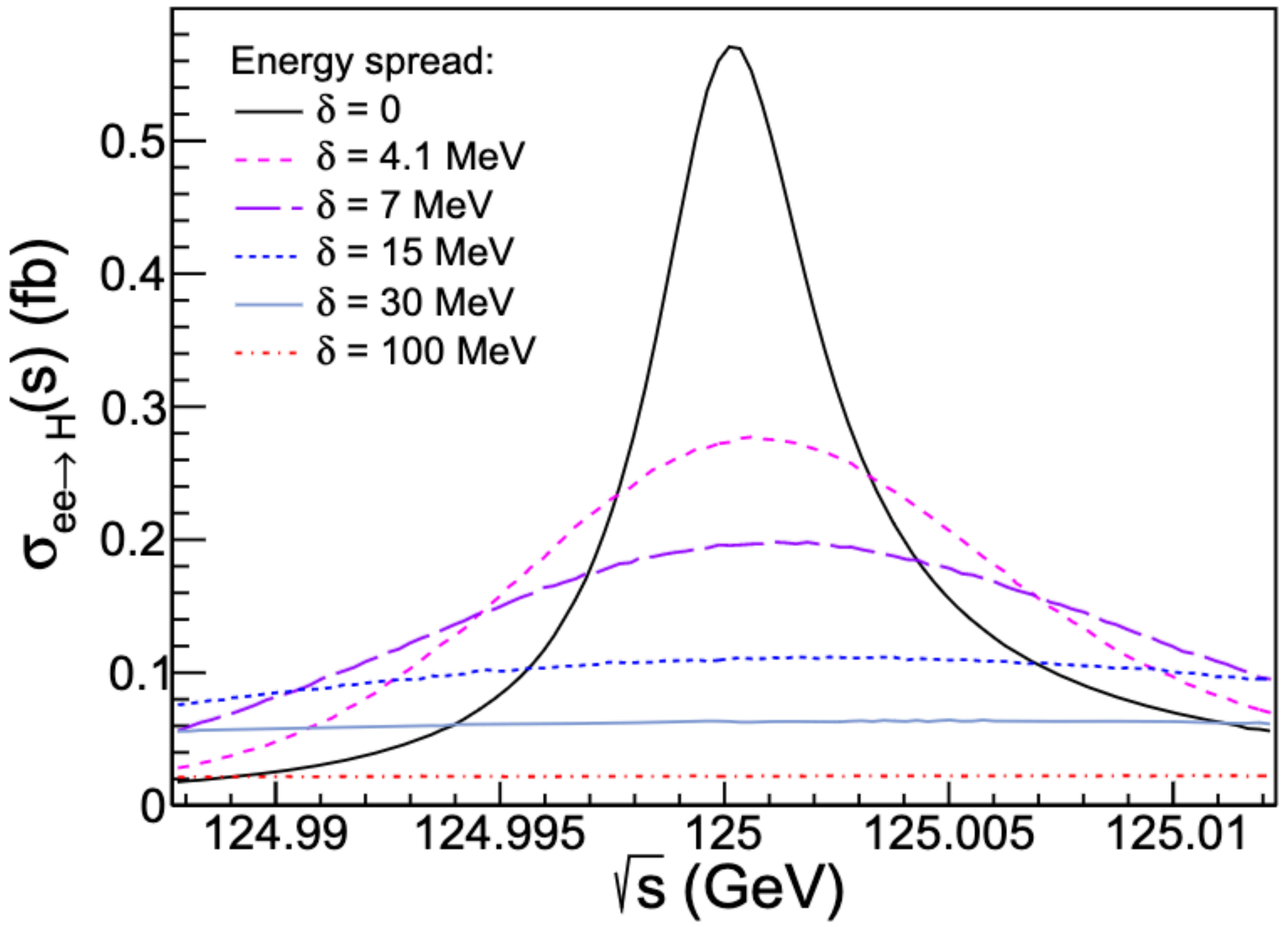
- We will be able to map all its properties with great accuracy. Peeking into the formation of the Higgs vacuum field, picoseconds after the Big Bang.
- Improvement in the precision of several Higgs boson couplings of about one order of magnitude wrt the end of the HL-LHC
- sub-% measurement of couplings to W, Z, b, τ , % to gluon and charm
- absolute measurement width/couplings
- Recoil method
- **Access to direct Higgs production at 125GeV**

FCC feasibility Mid-term report - Deliverable #8, physics and Experiments

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



Eur. Phys. J. Plus (2022) 137:201



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Electroweak

Precision

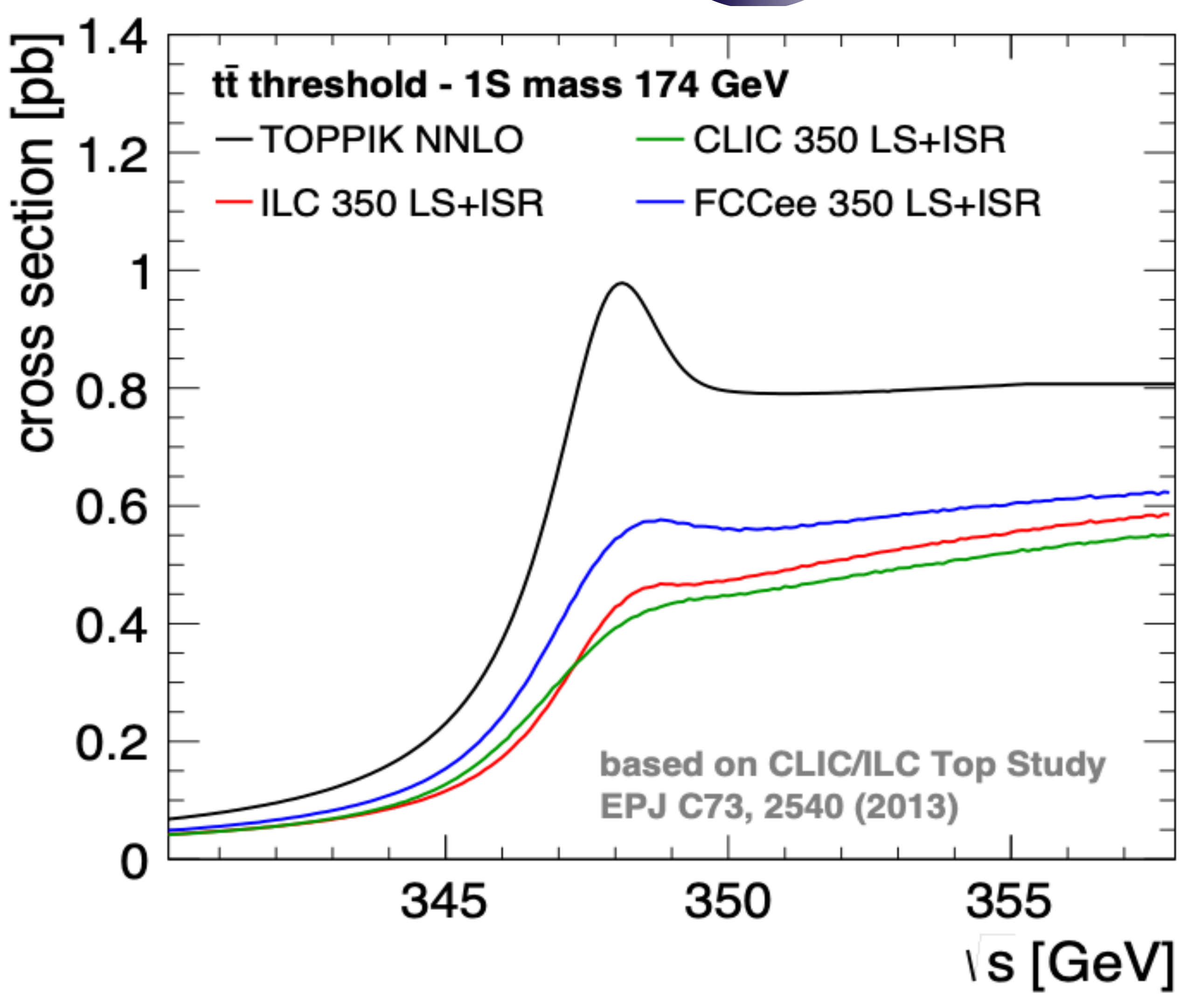
- Dedicated W and Z runs with unprecedented statistics
    - **Z pole run → LEP Statistical uncertainties divided by ~1000**
- Comprehensive measurements of the Z lineshape and many Electroweak Precision Observables
    - **50x improved precision→ 7x jump in indirect sensitivity to BSM effects**
- Direct and uniquely precise determinations of $\alpha_{QED}(m_Z)$ (for the first time) and $\alpha_S(m_Z)$

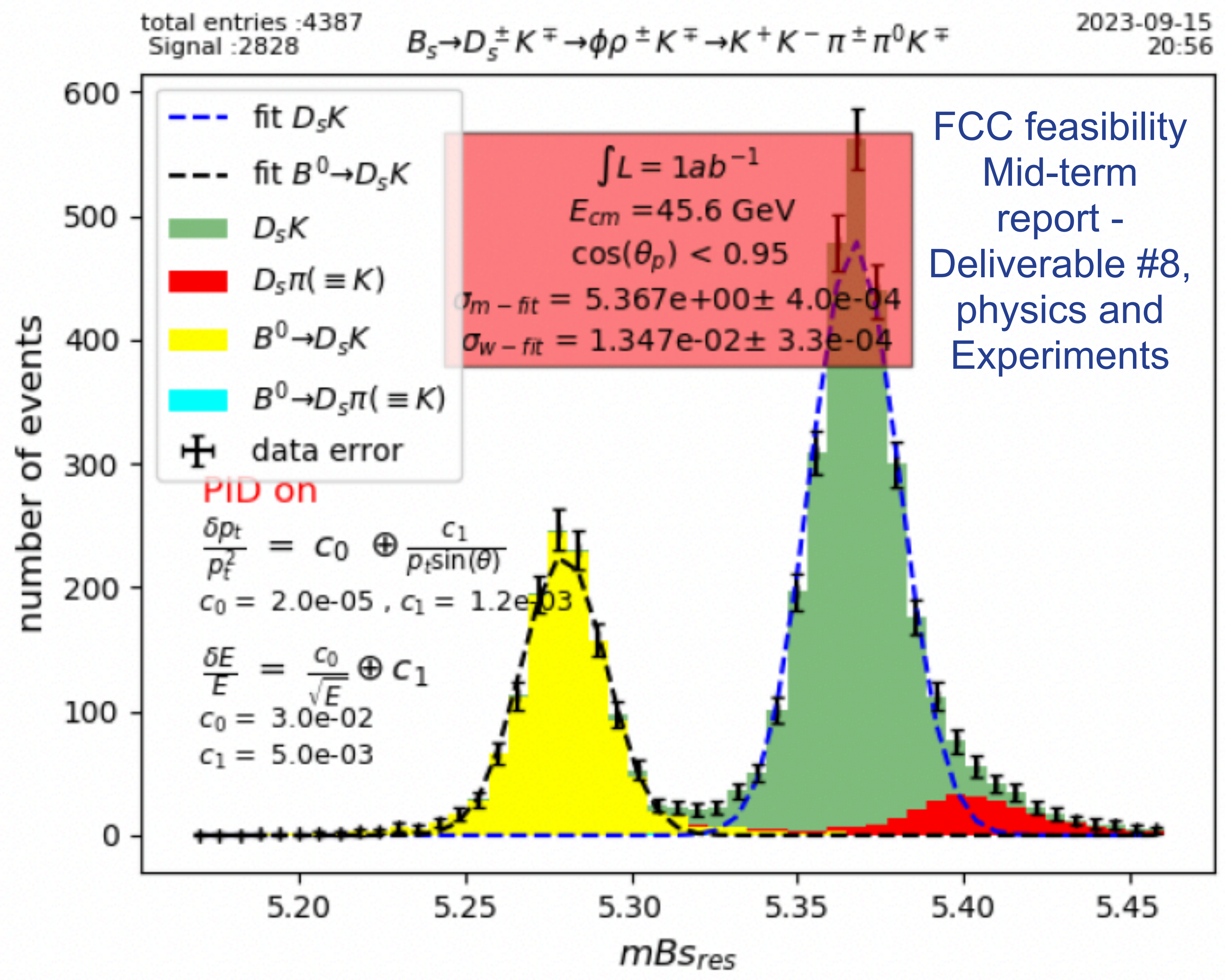
Come back to the talk of Christoph Paus for all the details!

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
$\sin^2\theta_W^{eff}(\times 10^6)$	231480	±	160	**2**	2.4	From $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{QED}(m_Z^2)(\times 10^3)$	128952	±	14	**3**	small	From $A_{FB}^{\mu\mu}$ off peak QED&EW errors dominate
R_ℓ^Z $(\times 10^3)$	20767	±	25	**0.06**	0.2-1	Ratio of hadrons to leptons Acceptance for leptons
$\alpha_s(m_Z^2)$ $(\times 10^4)$	1196	±	30	**0.1**	0.4-1.6	From R_ℓ^Z
σ_{had}^0 $(\times 10^3)$ (nb)	41541	±	37	**0.1**	4	Peak hadronic cross section Luminosity measurement
$N_\nu(\times 10^3)$	2996	±	7	**0.005**	1	Z peak cross sections Luminosity measurement
R_b $(\times 10^6)$	216290	±	660	**0.3**	<60	Ratio of $b\bar{b}$ to hadrons Stat. extrapol. from SLD
$A_{FB}^b, 0$ $(\times 10^4)$	992	±	16	**0.02**	1-3	b-quark asymmetry at Z pole From jet charge
$A_{FB}^{pol,\tau}$ $(\times 10^4)$	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

Top and flavor

- Threshold region: most precise measurements of **top quark mass, width**
- **A fantastic flavour factory!** Clean environment, precise momentum of pair-produced b/c/τ from Z decays (like in B-factories), ~**10 times more bb/cc than final Belle-II statistics**
- **Much potential in Boosted b/τ** →Higher efficiency than at B factories for modes with missing energy (especially multi-ν) and inclusive modes, and smaller uncertainties in lepton ID efficiencies.
- **Interesting opportunities**: e.g. decays of: Rare b-hadron with ττ pairs in the final state and charged-current b-hadrons with τν in the final state; lepton flavour violating τ decays, or lepton-universality tests in τ decays.



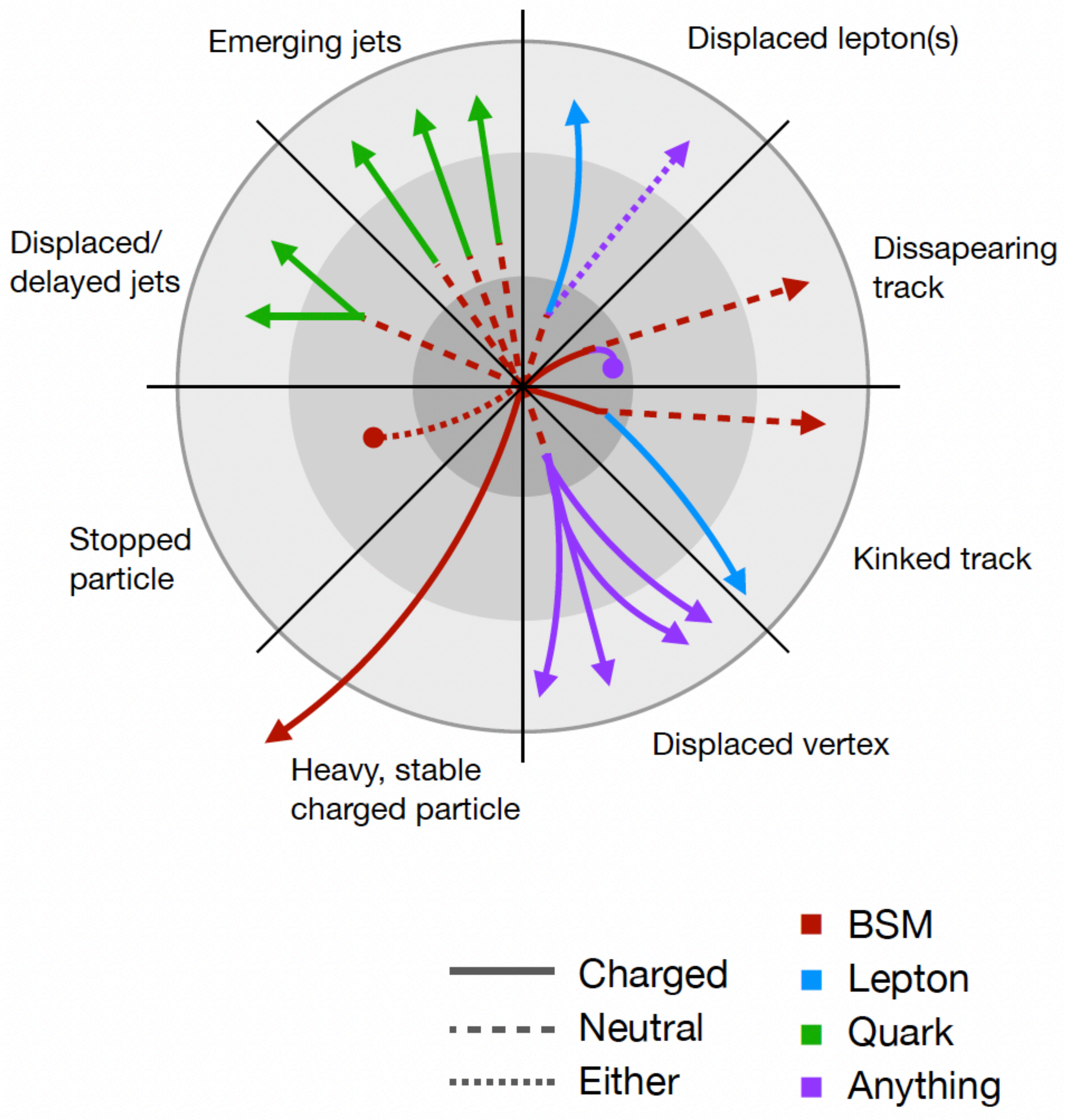


FCC feasibility Mid-term report - Deliverable #8, physics and Experiments

Reconstructed Bs system, 3% energy resolution in the calorimeter

Beyond the standard model

Direct sensitivity to new physics



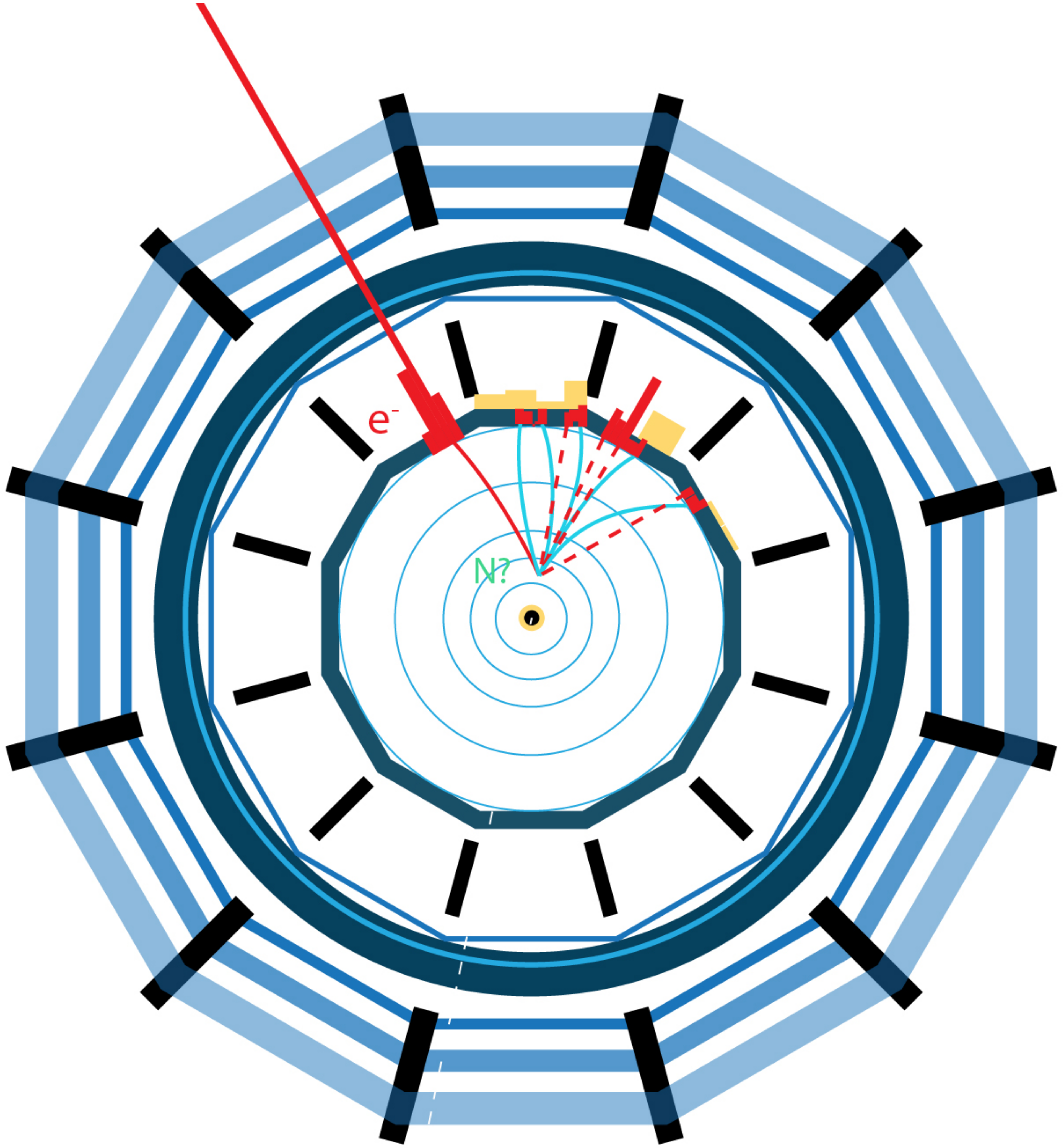
G. Ripellino

- Beyond the potential for indirect BSM exploration through the SMEFT, and other precision/search cases
- Direct searches:
  - **Clean environment, high luminosity, and large acceptance, direct scrutiny of O(1-100) GeV mass range for new particles**
  - Dark/hidden sectors that connect feebly to the SM via mediators (dark photon)
  - Exotic decays of the Z or Higgs boson
  - Specially interesting are **signature-driven searches for non-mainstream signals**

The flagship

Heavy Neutral Leptons

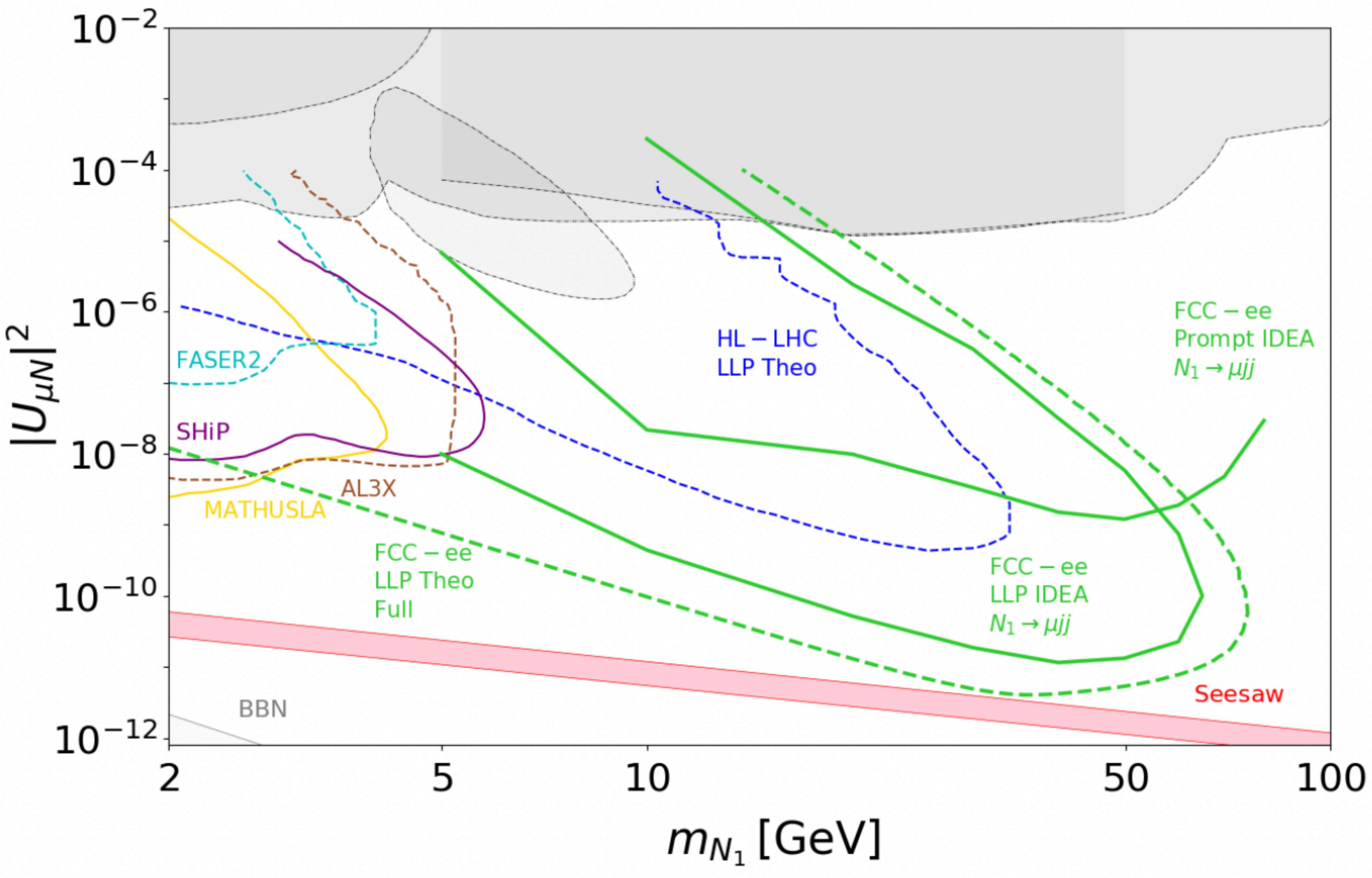
- Sterile/right-handed neutrinos
  - Could give many answers: neutrino masses, DM, BAU
- Many of the current limits cover large neutrino mixing angles. For small values of the mixing angle, the decay length of the HNL can be significant → LLP signature (displaced vertex search)
- **The FCC-ee will offer an unbeatable reach for HNL at the Z-Pole**
  - **FCC will probe space not constrained by astrophysics or cosmology, complementary to other dedicated experiments**



Heavy Neutral Leptons

Ongoing experimental studies

- Work in progress towards a complete sensitivity analysis implemented in FCC software
- **Work ongoing in a few chanels** (eeν, μjj, μμν), prompt and long-lived, Dirac/Majorana



FCC feasibility Mid-term report - Deliverable #8, physics and Experiments

Master theses: Sissel Bay Nielsen, Rohini Sengupta, Lovisa Rygaard, Tanishq Sharma, Dimitri Moulin

arXiv:2203.05502

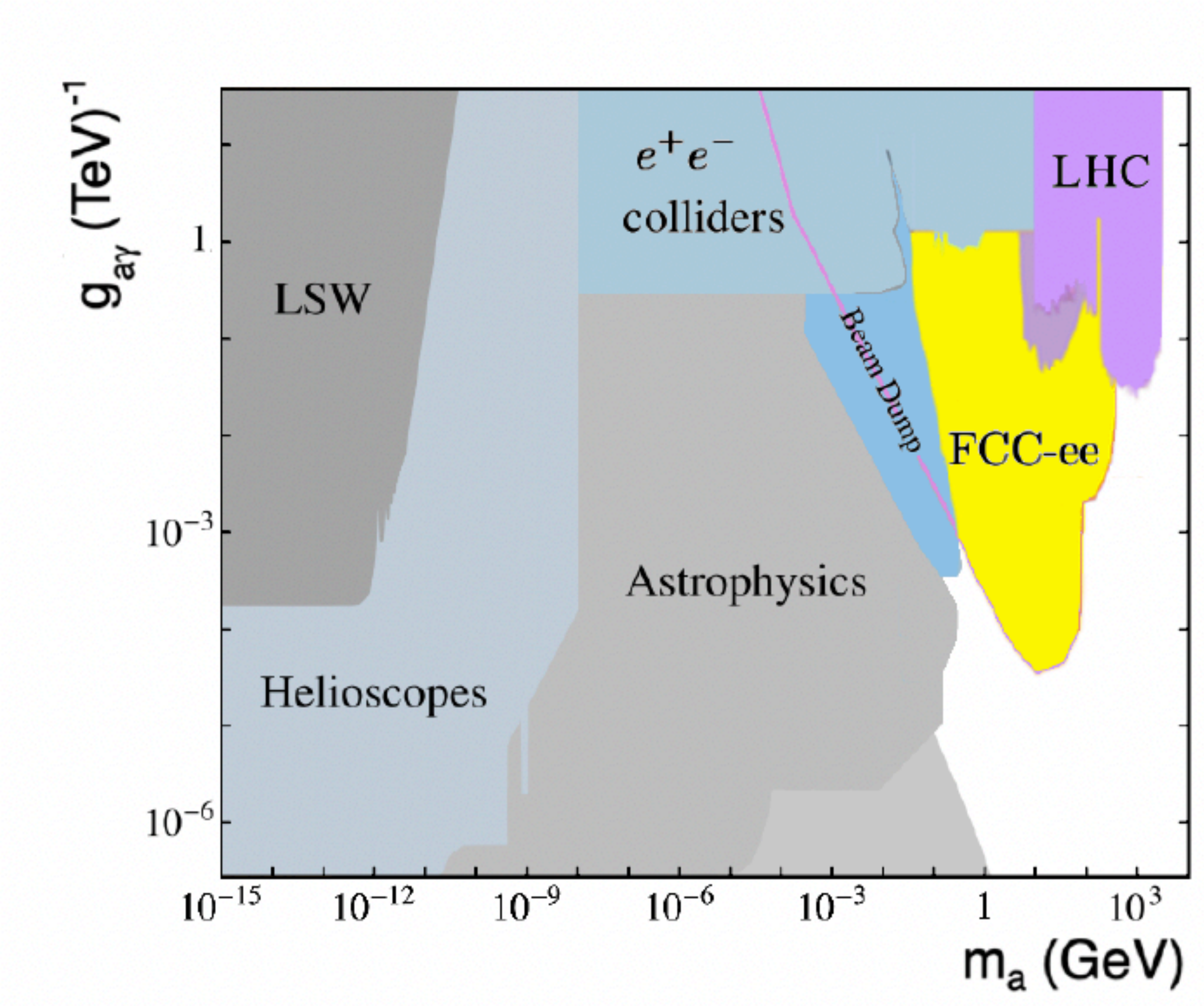
Axion-like particles

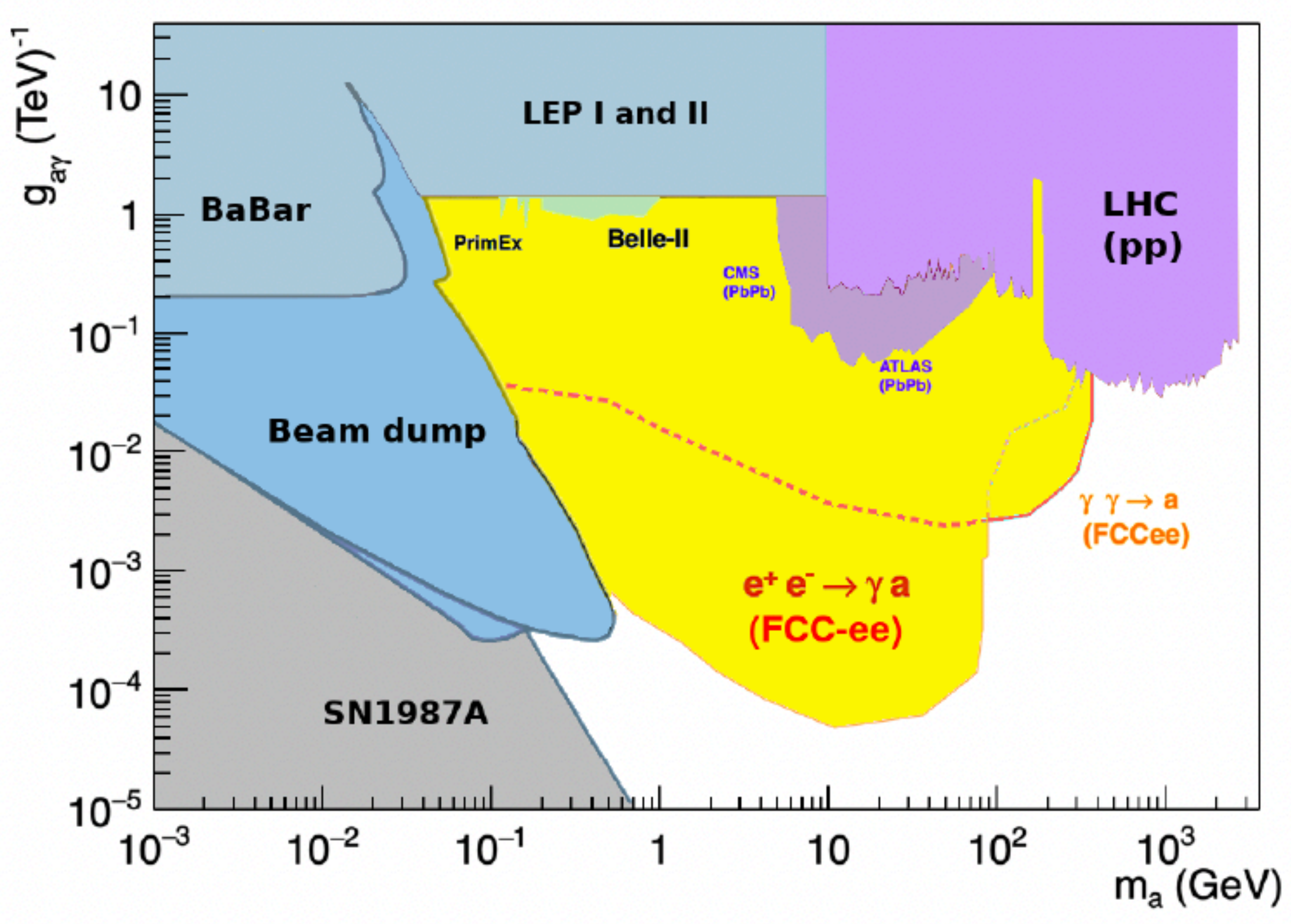
ALPs

extending current limits > than 3 orders of magnitude

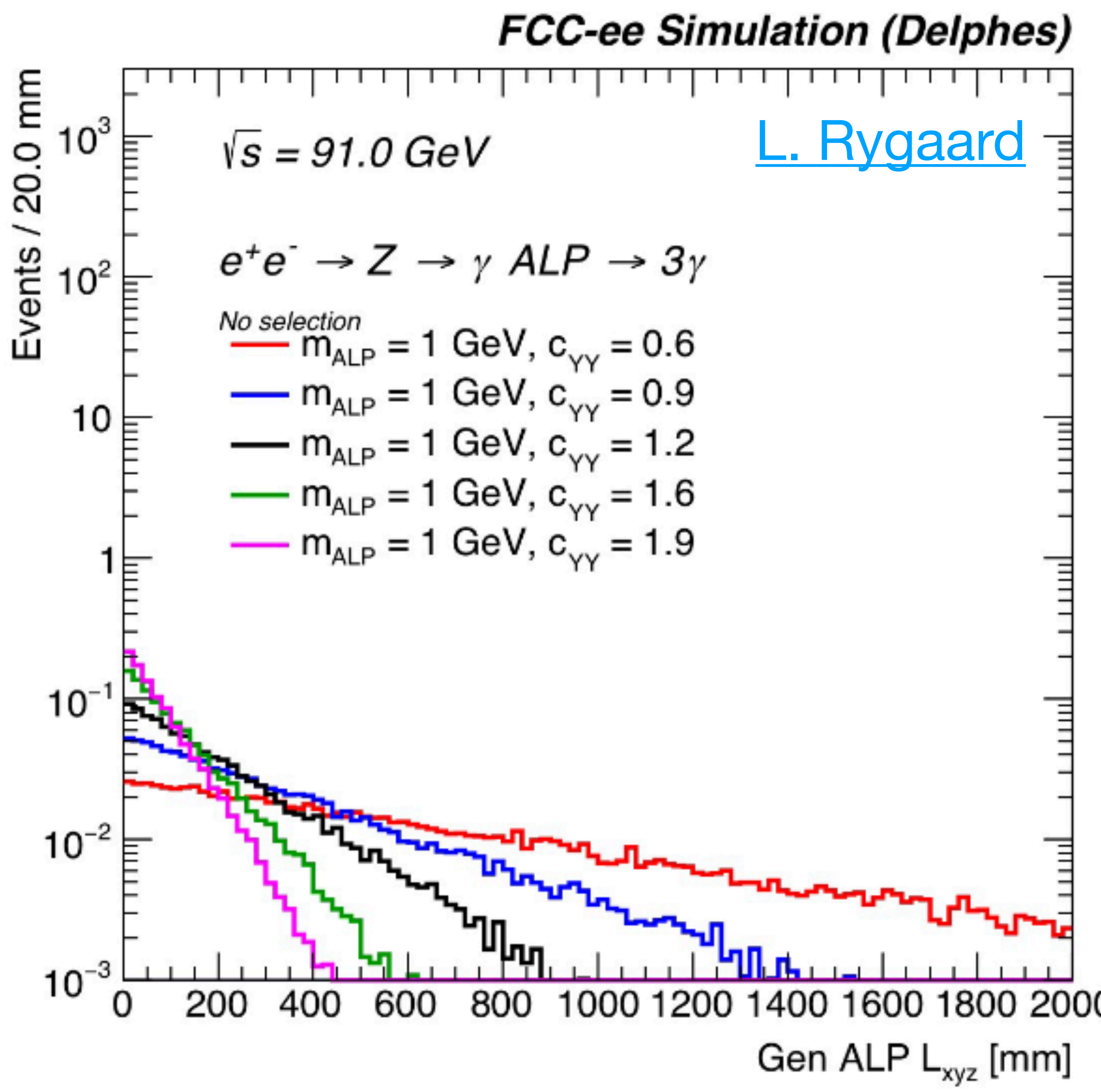
- Unconstrained mass range (0.1 – 100 GeV) accessible via e+e– → aγ and e+e–→ a, a → γγ. Sensitivity to couplings to < 10–4 TeV^{-1}
- At small coupling values → macroscopic decay lengths

First generation studies with FCC software available





FCC feasibility Mid-term report - Deliverable #8, physics and Experiments

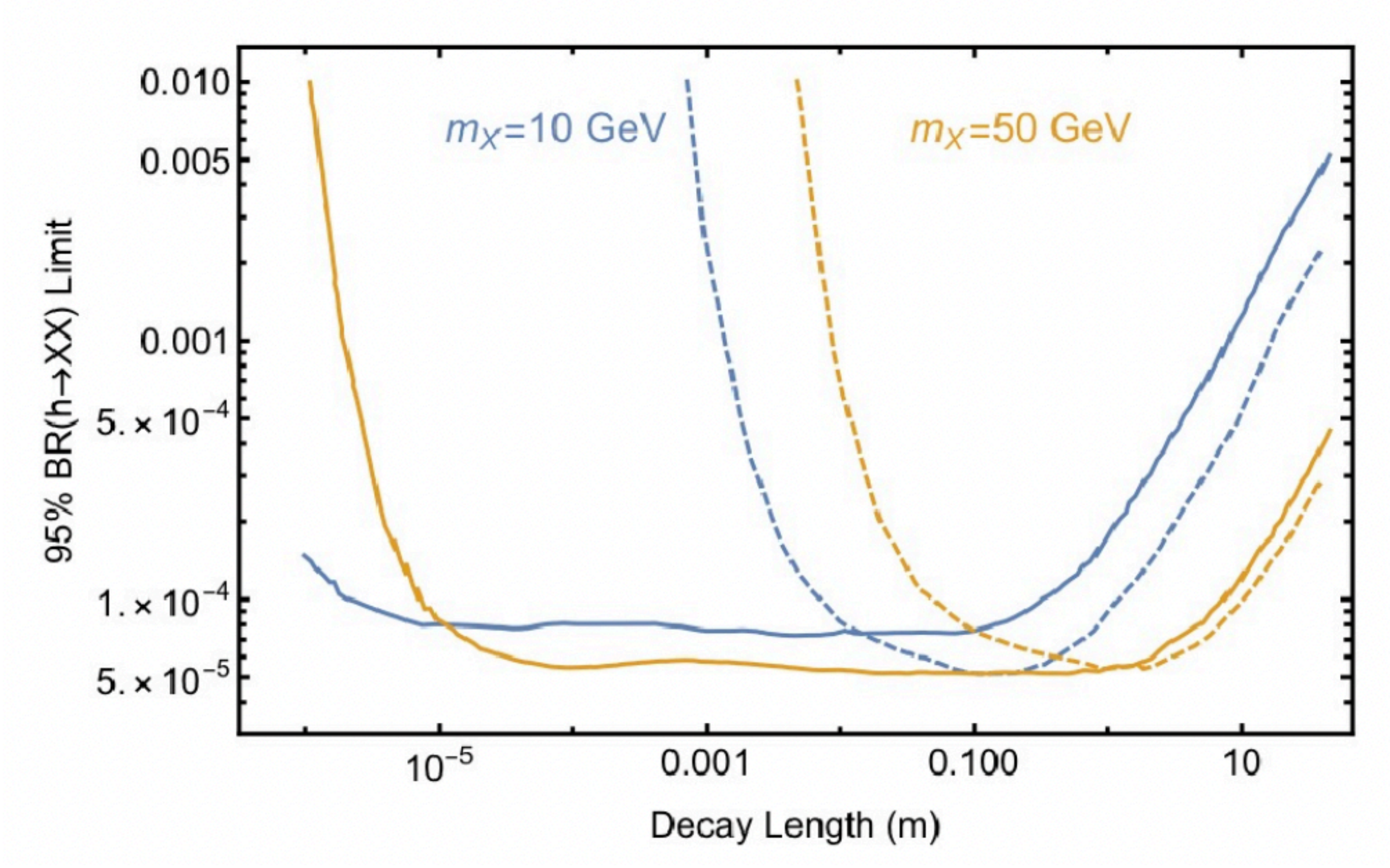


Truth-level decay length of the ALP

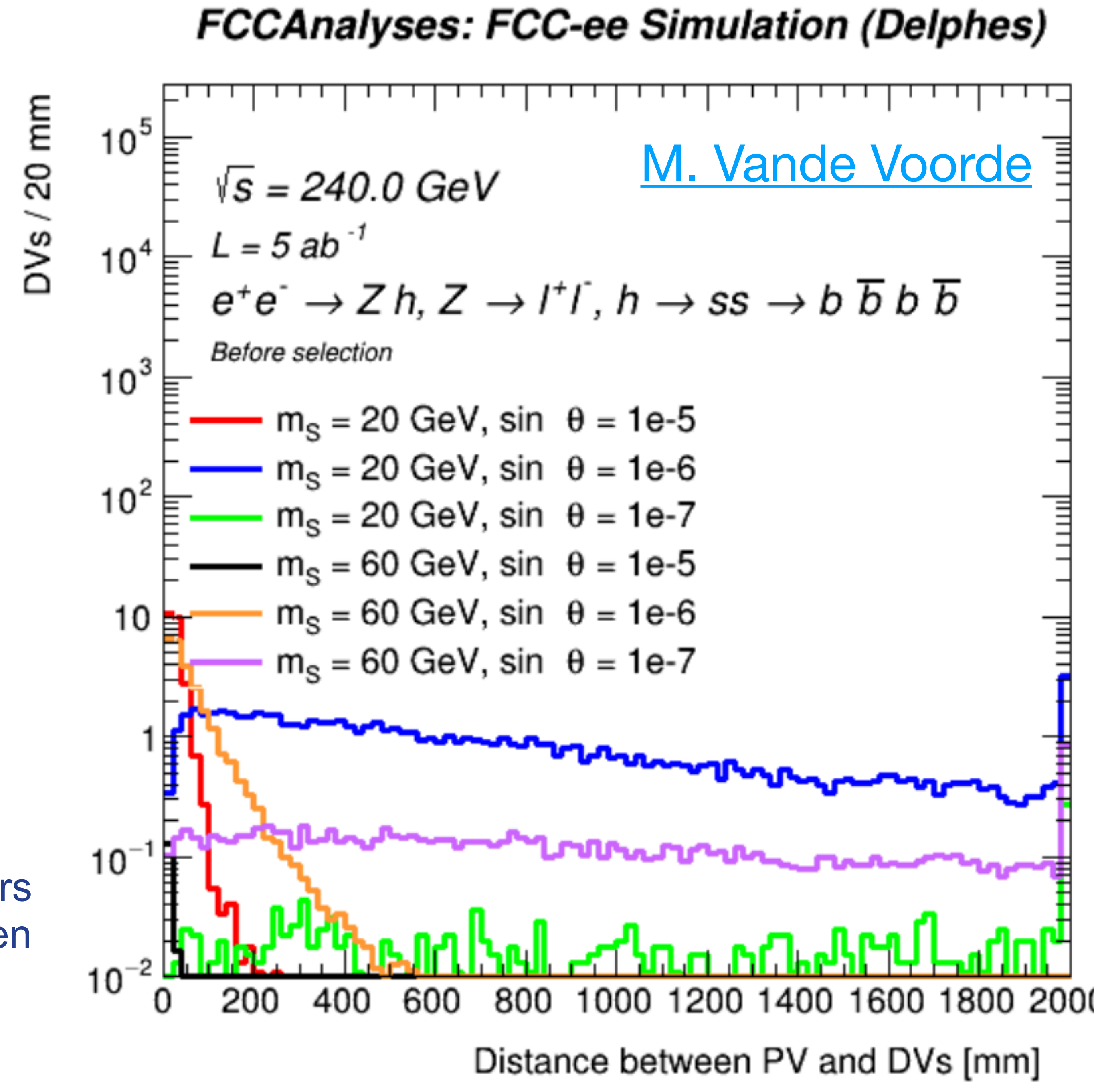
Exotic Higgs boson decays

Into LLPs

- Possible and present in many models:
  - SM extensions with scalars/fermions/ vectors, MSSM, NMSSM, Hidden Valleys, Twin Higgs (arXiv:1312.4992, arXiv:1812.05588, arXiv:1712.07135)



FCC feasibility Mid-term report - Deliverable #8, physics and Experiments

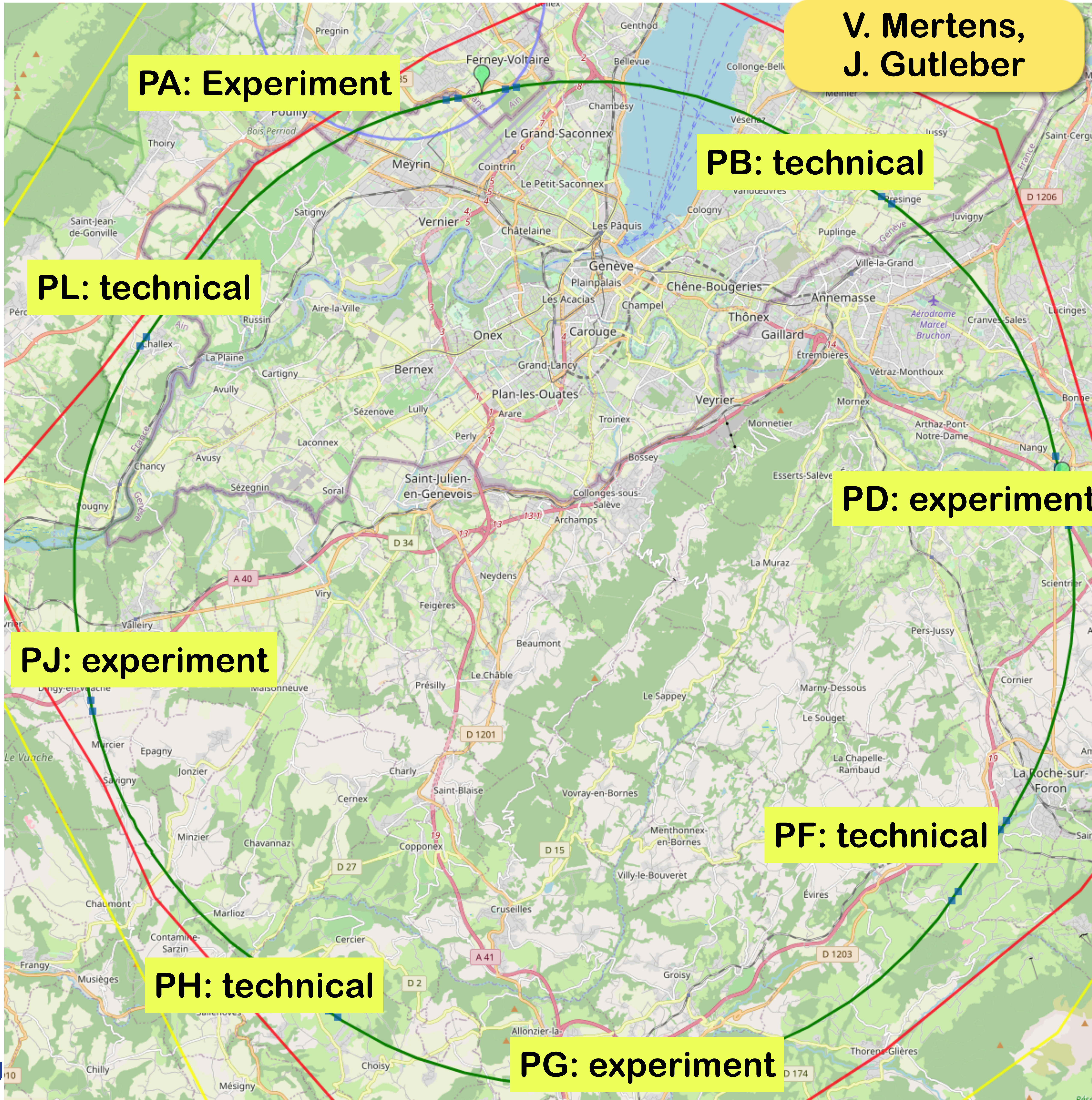


SM + S model (arXiv:1312.4992, arXiv:1412.0018) Long-lived scalars for sufficiently small mixing between the Higgs and the scalar

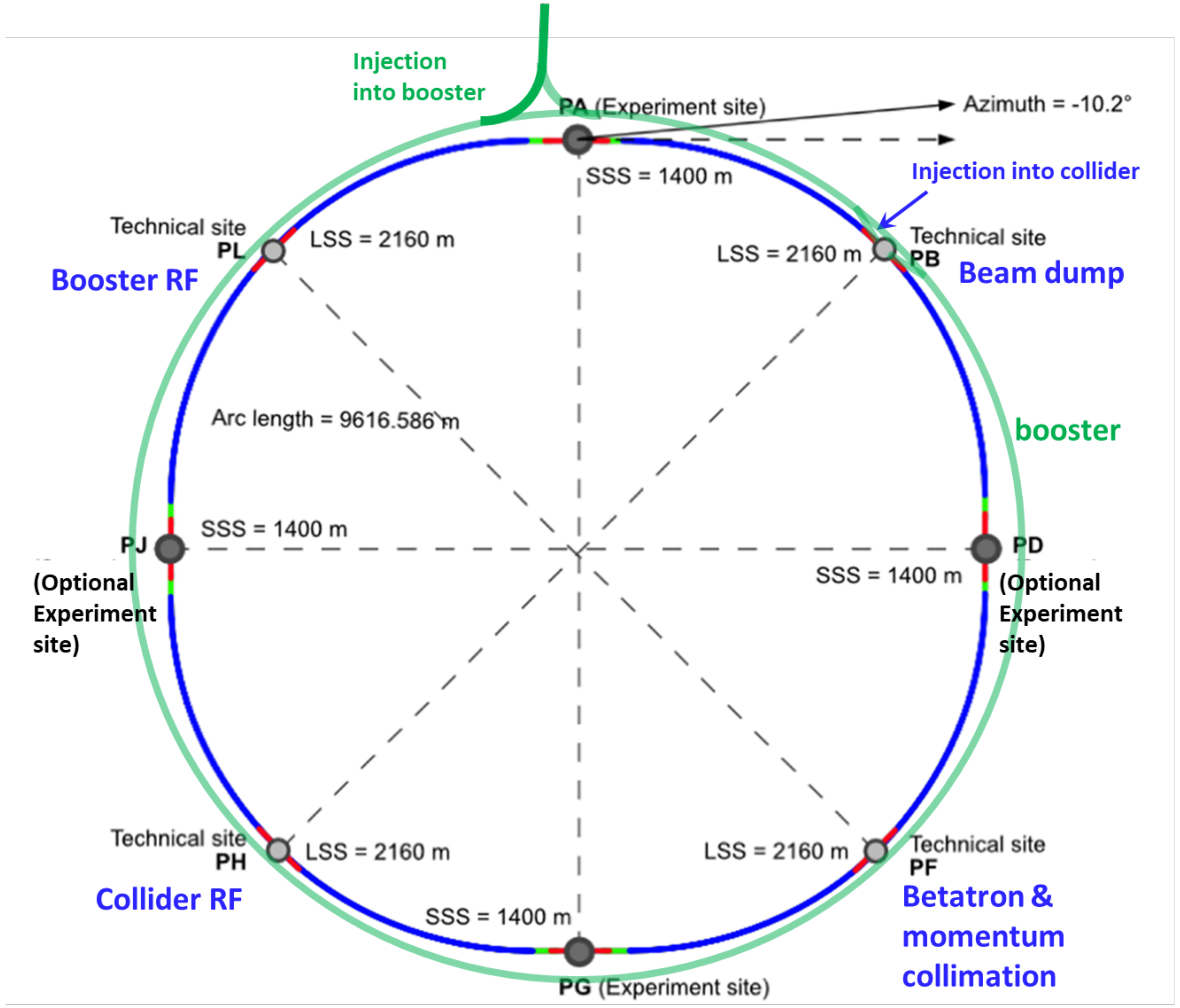
First experimental studies ongoing

Optimized placement and layout

- 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.
- Meetings with municipalities concerned
- in France (31) and Switzerland (10)
- Overall lowest-risk baseline: 90.7 km ring, 8 surface points,
- Whole project now adapted to this placement



Optimized placement and layout for feasibility study



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**

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Progress with implementation baseline

Meetings with municipalities concerned in France (31) and Switzerland (10)

PA – Ferney Voltaire (FR) – experimental site

PB – Présinge/Choulex (CH) – technical site

PD – Nangy (FR) – experimental site

PF – Roche sur Foron/Etaux (FR) – technical site

PG – Charvonnex/Groisy (FR) – experimental site

PH – Cercier (FR) – technical site

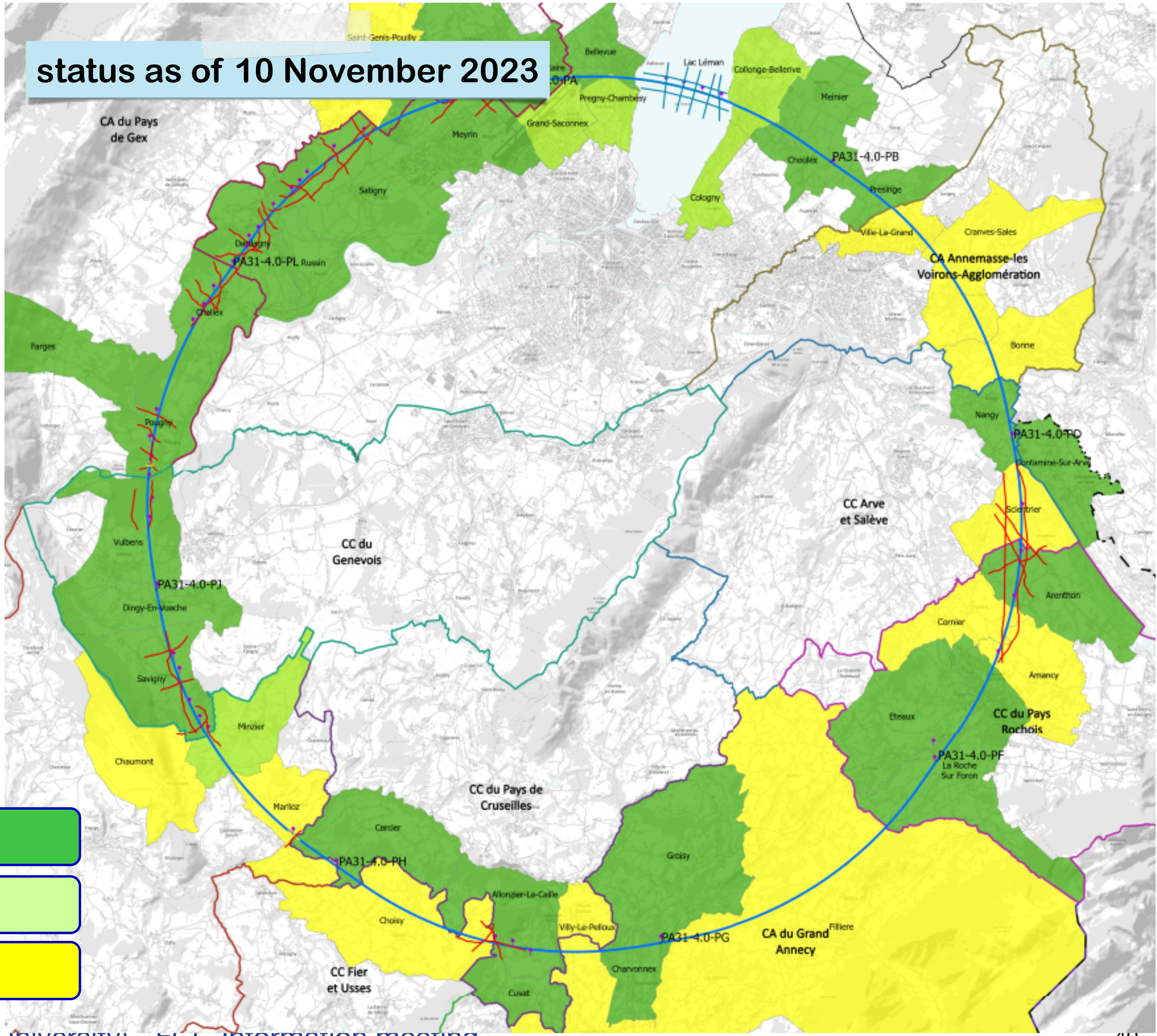
PJ – Vulbens/Dingy en Vuache (FR) experimental site

PL – Challex (FR) – technical site

Individual meeting

Individual meeting planned

Collective meeting



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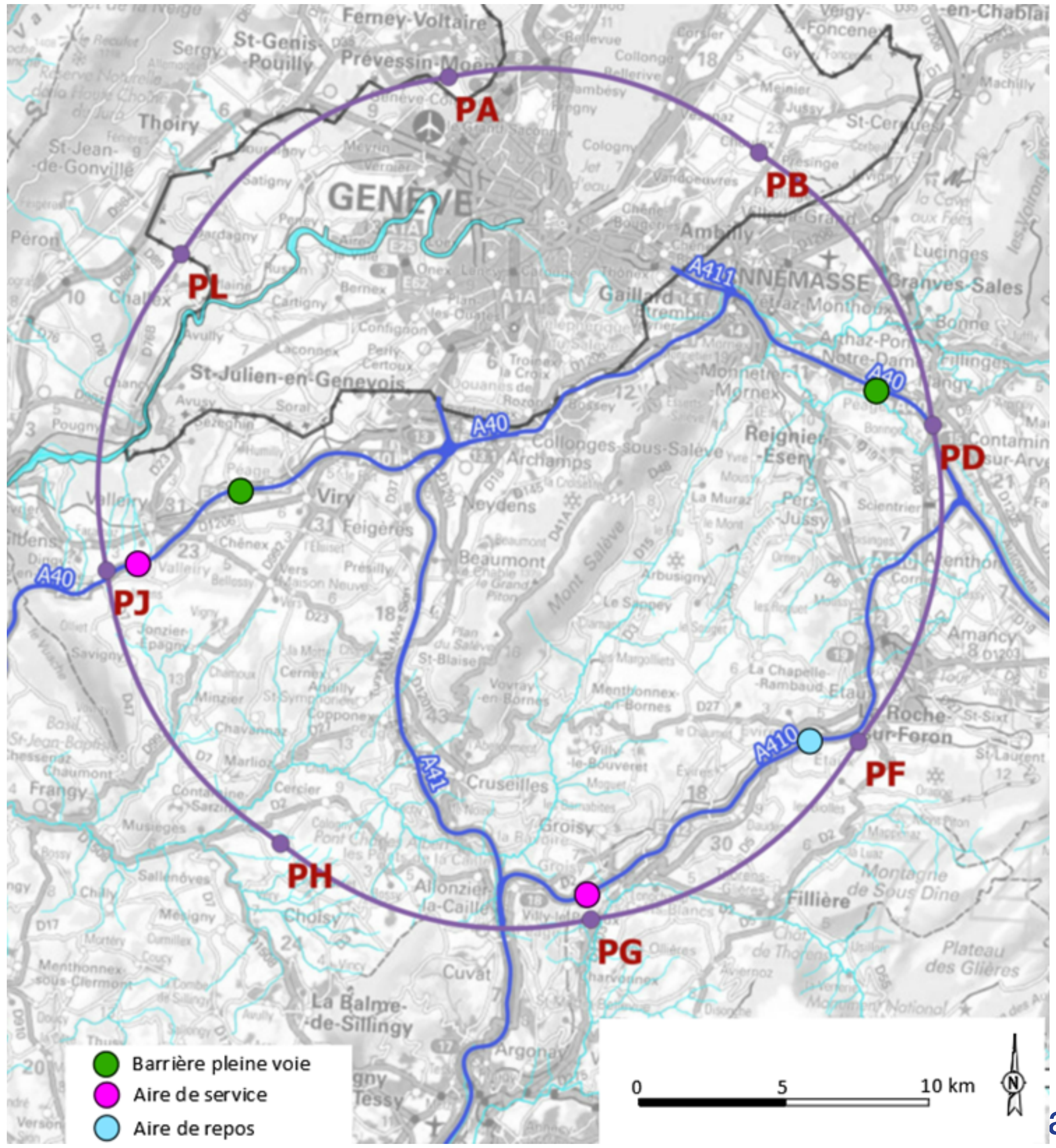
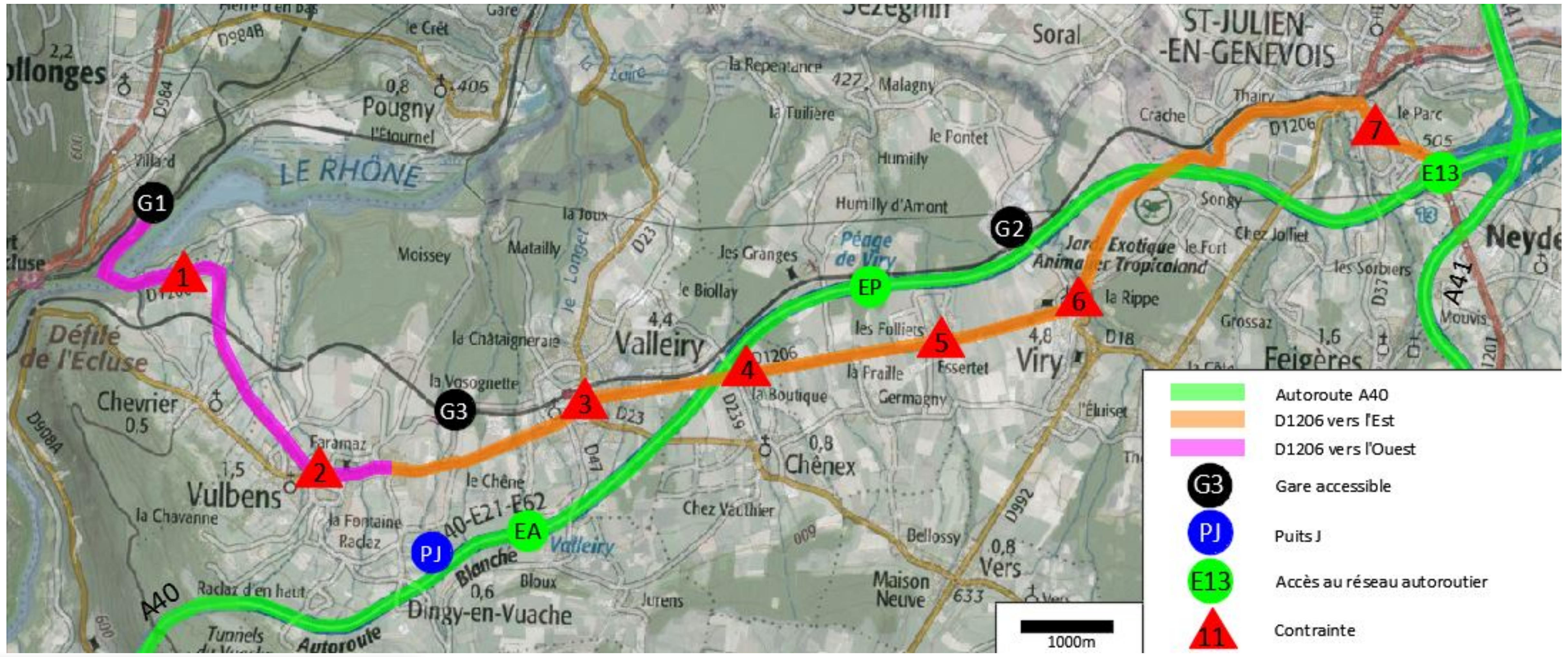
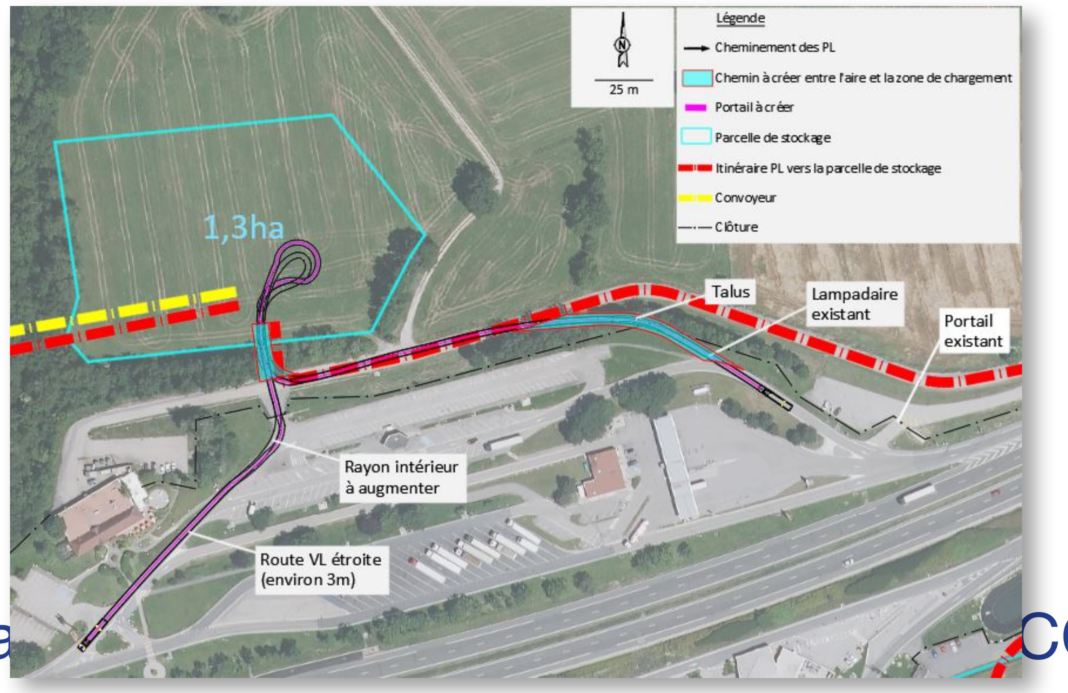
Connections to transport infrastructure

- Road accesses identified and documented for all 8 surface sites
- Four possible highway connections defined (material transport)
- Total amount of new roads required < 4 km (at departmental road level)







Tunnel implementation

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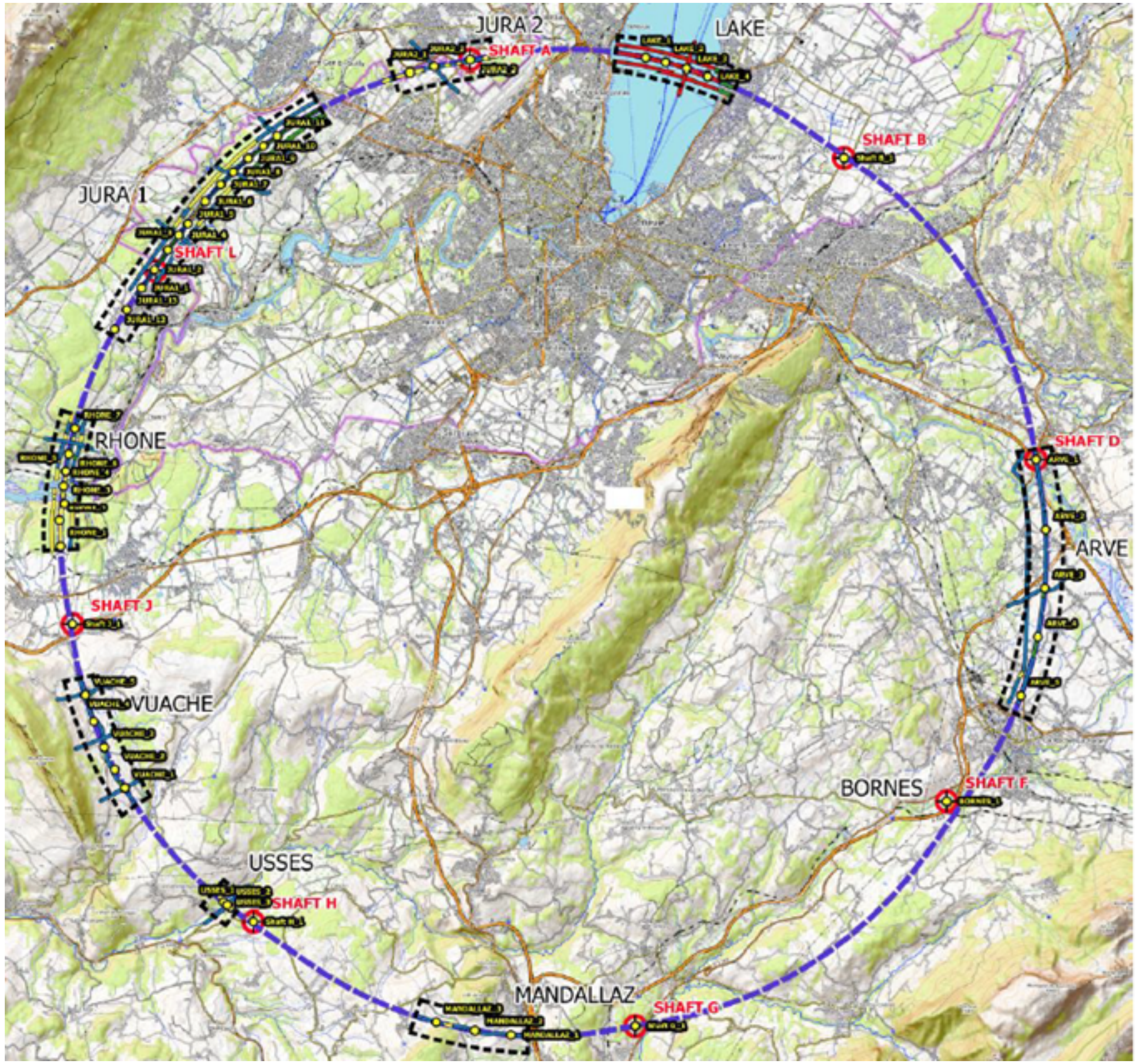
Status of site investigations



- 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 authorisation procedures. Planned start of drillings in Q2/2024
- Contract 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)

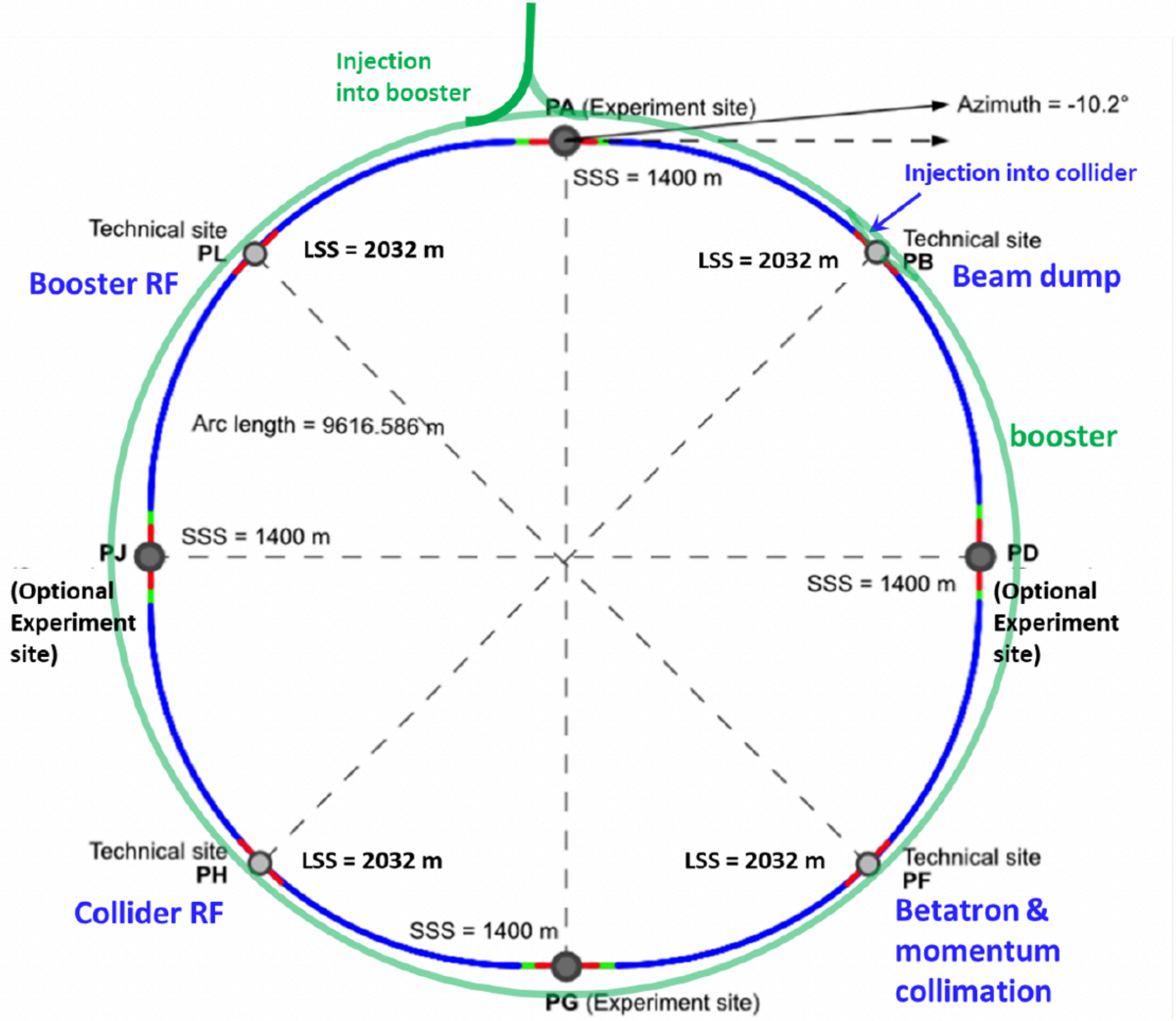


Fig. 186 The layout of the FCC-ee illustrating the 4 collision points in the SLSS and the four technical insertions at the LLSS.

Table 127 The baseline FCC-ee 16-years programme with four interaction points, showing the centre-of-mass energies, instantaneous luminosities for each IP, integrated luminosity per year summed over 4 IPs corresponding to 185 days of physics per year and 75% efficiency, in the order Z, WW, ZH, $t\bar{t}$. The luminosity is assumed to be half the design value for machine commissioning and optimisation during the first two years at the Z pole, the first two years at the WW threshold, and the first year at the $t\bar{t}$ threshold. (Should the order of the sequence be modified to either Z, ZH, WW, $t\bar{t}$ or ZH, WW, Z, $t\bar{t}$, the ZH stage would start with two years at half the design luminosity followed by two years at design luminosity, while the WW stage would run afterwards for only one year but at design luminosity.) The luminosity at the Z pole (the WW threshold) is distributed as follows: $40\,\text{ab}^{-1}$ at 88 GeV, $125\,\text{ab}^{-1}$ at 91.2 GeV, and $40\,\text{ab}^{-1}$ at 94 GeV ($5\,\text{ab}^{-1}$ at 157.5 GeV, and $5\,\text{ab}^{-1}$ at 162.5 GeV). The number of WW events include all $\sqrt{s}$ values from 157.5 GeV up.

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 ($10^{34}\,\text{cm}^{-2}\text{s}^{-1}$)	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	–	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	

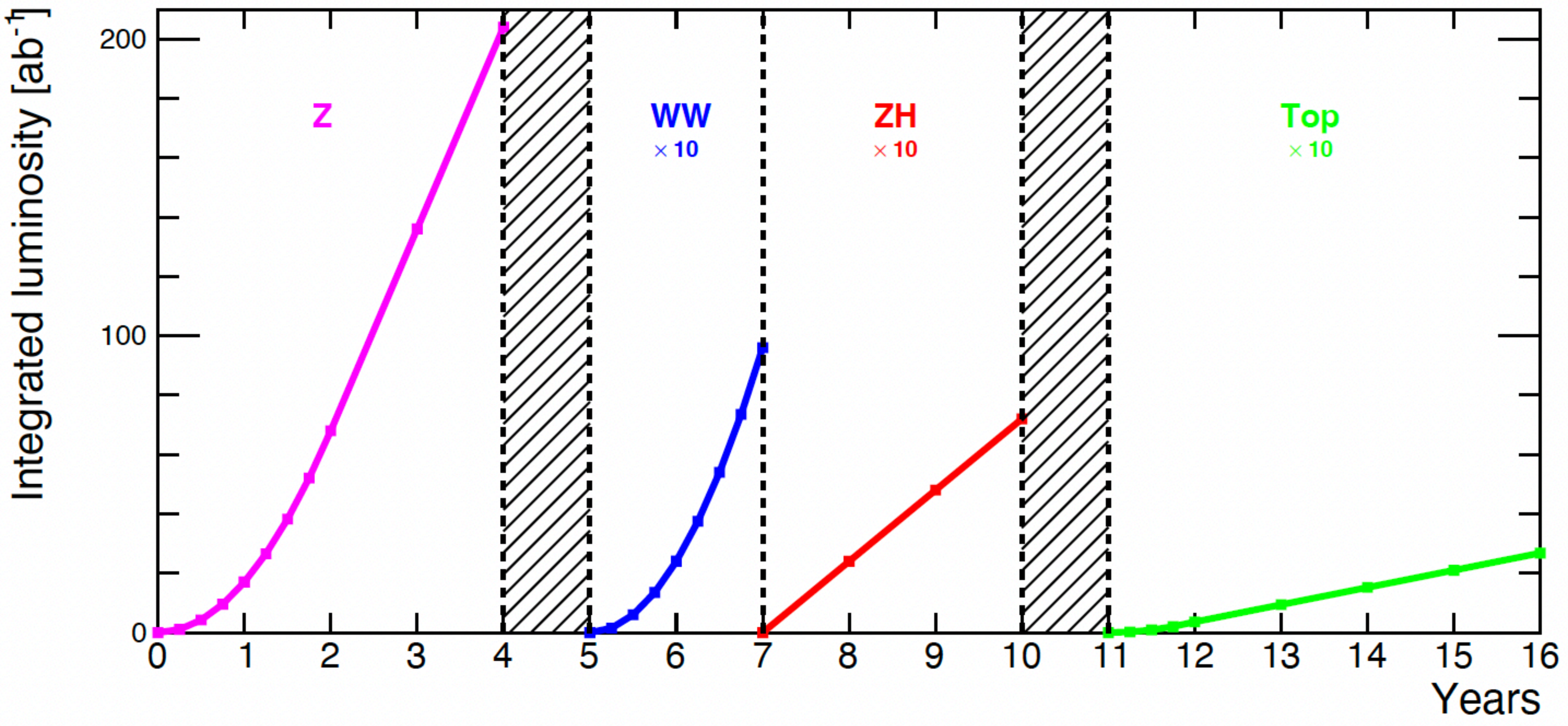


Fig. 2 Baseline operation model for FCC-ee with four interaction points, showing the integrated luminosity at the Z pole (pink), the WW threshold (blue), the Higgs factory (red), and the top-pair threshold (green) as a function of time. In this baseline model, the sequence of events goes with increasing centre-of-mass energy. The integrated luminosity delivered during the first two years at the Z pole and the WW threshold is half the annual design value. The hatched areas indicate the shutdown time needed to prepare the collider for the higher energy runs: one year prior to the WW and ZH runs, and one year prior to the top-pair threshold run.

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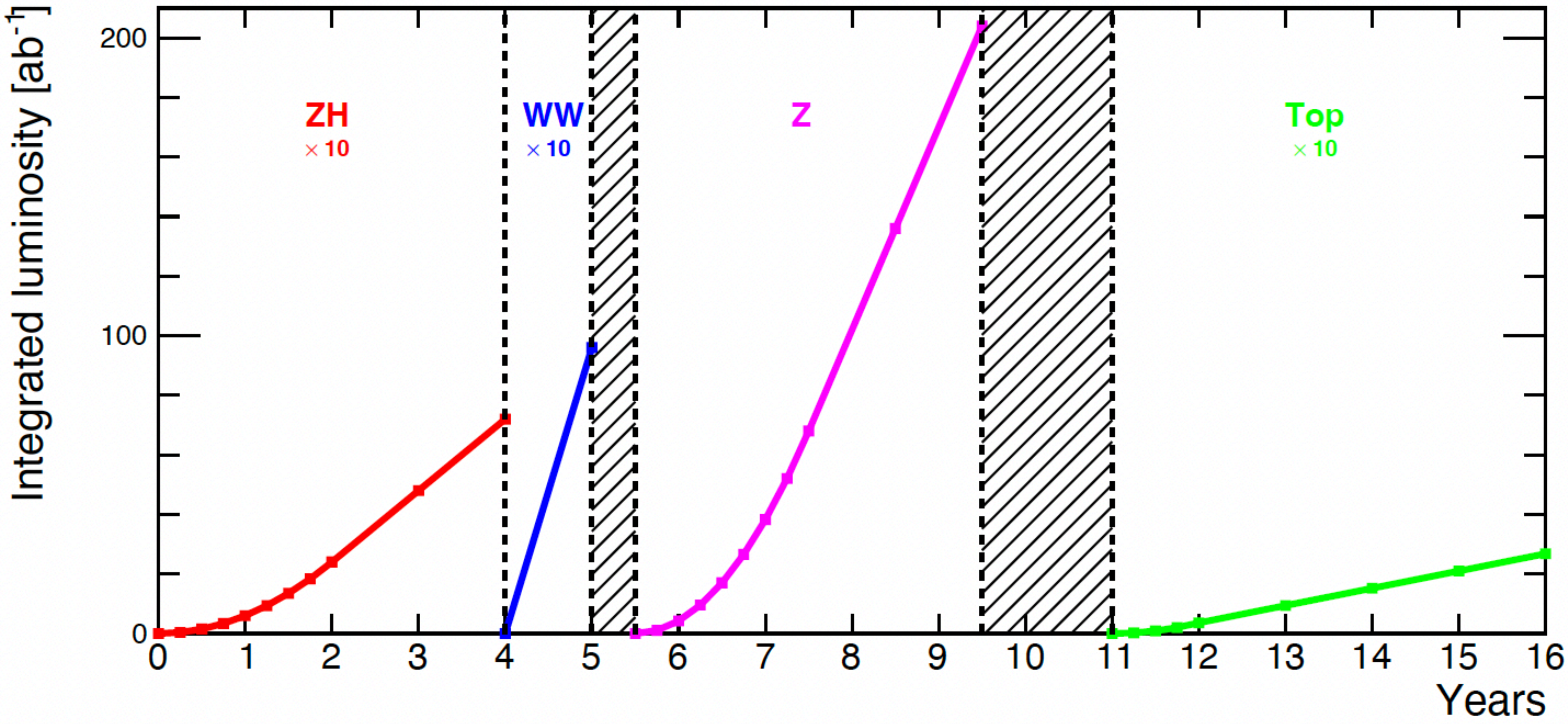

Fig. 3 Alternative operation model for FCC-ee with four interaction points, showing the integrated luminosity at the Z pole (pink), the WW threshold (blue), the Higgs factory (red), and the top-pair threshold (green) as a function of time. In this model, the ZH run comes first, followed by the WW run. The integrated luminosity delivered during the first two years at the Z pole and at the ZH cross-section maximum is half the annual design value. The hatched areas indicate the shutdown time needed to prepare the collider for the Z pole run and for the top-pair threshold run: six months prior to the Z pole run (which might happen during a longer winter shutdown), and one and a half year prior to the top-pair threshold run.

Table 128 Experimental (statistical and systematic) precision of a selection of measurements accessible at FCC-ee, compared with the present world-average precision. The FCC-ee experimental systematic errors (fourth column) are initial estimates from early 2021 [430], and aim at being improved down to statistical uncertainties (third column) with new ideas and innovative methods. This set of measurements, together with those of the Higgs boson properties, achieves indirect sensitivity to new physics up to a scale Λ of 70 TeV in an Effective Field Theory (EFT) description with dimension-6 operators (Section 8.2), and possibly much higher in specific new physics (non-decoupling) models.

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
$\sin^2\theta_W^{eff}(\times 10^6)$	231480	±	160	**2**	2.4	From $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{QED}(m_Z^2)(\times 10^3)$	128952	±	14	**3**	small	From $A_{FB}^{\mu\mu}$ off peak QED&EW errors dominate
R_ℓ^Z $(\times 10^3)$	20767	±	25	**0.06**	0.2-1	Ratio of hadrons to leptons Acceptance for leptons
$\alpha_s(m_Z^2)$ $(\times 10^4)$	1196	±	30	**0.1**	0.4-1.6	From R_ℓ^Z
σ_{had}^0 $(\times 10^3)$ (nb)	41541	±	37	**0.1**	4	Peak hadronic cross section Luminosity measurement
$N_\nu(\times 10^3)$	2996	±	7	**0.005**	1	Z peak cross sections Luminosity measurement
R_b $(\times 10^6)$	216290	±	660	**0.3**	< 60	Ratio of $b\bar{b}$ to hadrons Stat. extrapol. from SLD
$A_{FB}^b, 0$ $(\times 10^4)$	992	±	16	**0.02**	1-3	b-quark asymmetry at Z pole From jet charge
$A_{FB}^{pol,\tau}$ $(\times 10^4)$	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

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Table 131 A few sample precision quantities of interest for the FCC-ee programme, their current and projected experimental uncertainties, and the required theory input for their *extraction* from the data. The last two columns show the current state of the art for calculations of this theory input, and needed higher-order calculations to reach the FCC-ee precision target. See Ref. [435] for more details.

Quantity	Current precision	FCC-ee stat. (syst.) precision	Required theory input	Available calc. in 2019	Needed theory improvement†
m_Z Γ_Z $\sin^2\theta^{\ell}_{\text{eff}}$	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 frame-work)	NNLO for $ee \to WW$, $W \to ff$ in EFT setup
HZZ coupling	—	0.2%	cross-sect. for $e^+e^- \to ZH$	NLO + NNLO QCD	NNLO electroweak
m_{top}	100 MeV	17 MeV	threshold scan $e^+e^- \to t\bar{t}$	N^3LO 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.

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Table 68 Preliminary key parameters of FCC-ee (K. Oide), as evolved from the CDR parameters, now with a shorter circumference of 90.7 km, and a new arc optics for Z and W running. Luminosity values are given per interaction point (IP), for a scenario with 4 IPs in total. Both natural bunch lengths due to synchrotron radiation (SR) and collision values including beamstrahlung (BS) are shown. The FCC-ee has a combination of 400 MHz radiofrequency systems (at the first three energies, up to 2.1 GV) and 800 MHz (additional cavities for $t\bar{t}$ operation), with voltage strengths respectively indicated. For the integrated luminosity, 185 days of operation per year, and luminosity production at 75% efficiency with respect to the ideal top-up running is assumed, as in the report [14].

Running mode	Z	W	ZH	$t\bar{t}$
Number of IPs	4	4	4	4
Beam energy (GeV)	45.6	80	120	182.5
Bunches/beam	11200	1780	440	60
Beam current [mA]	1270	137	26.7	4.9
Luminosity/IP [10^{34} cm^{-2} s^{-1}]	141	20	5.0	1.25
Energy loss / turn [GeV]	0.0394	0.374	1.89	10.42
Synchrotron Radiation Power [MW]	100			
RF Voltage 400/800 MHz [GV]	0.08/0	1.0/0	2.1/0	2.1/9.4
Rms bunch length (SR) [mm]	5.60	3.47	3.40	1.81
Rms bunch length (+BS) [mm]	15.5	5.41	4.70	2.17
Rms horizontal emittance ε_x [nm]	0.71	2.17	0.71	1.59
Rms vertical emittance ε_y [pm]	1.9	2.2	1.4	1.6
Longitudinal damping time [turns]	1158	215	64	18
Horizontal IP beta β_x^* [mm]	110	200	240	1000
Vertical IP beta β_y^* [mm]	0.7	1.0	1.0	1.6
Hor. IP beam size σ_x^* [µm]	9	21	13	40
Vert. IP beam size σ_y^* [nm]	36	47	40	51
Beam lifetime (q+BS+lattice) [min.]	50	42	100	100
Beam lifetime (lum.) [min.]	22	16	14	12
Total beam lifetime [min.]	15	12	12	11
Int. annual luminosity / IP [ab^{-1}/yr]	17†	2.4†	0.6	0.15‡

† The integrated luminosity in the first two years is assumed to be half this value to account for the machine commissioning and beam tuning;

‡ The integrated luminosity in the first year, at a lower beam energy of about 173 GeV, is assumed to be about 65% of this value to account for the machine commissioning and beam tuning. The smaller time for commissioning compared with the lower energy running reflects the LEP/LEP-2 experience.

Table 70 A variant of parameters of FCC-ee collider. SR: synchrotron radiation, BS: beamstrahlung. The parameters for ZH and $t\bar{t}$ are pushed to higher luminosities compared with Table 68.

Beam energy	[GeV]	45.6	80	120	182.5
Layout		PA31-3.0			
# of IPs		4			
Circumference	[km]	90.658816			
Bend. radius of arc dipole	[km]	10.021			
Energy loss / turn	[GeV]	0.0391	0.374	1.88	10.29
SR power / beam	[MW]	50			
Beam current	[mA]	1279	137	26.7	4.9
Colliding bunches / beam		11200	1780	380	56
Colliding bunch population	[10^{11}]	2.14	1.45	1.32	1.64
Hor. emittance in collision ε_x	[nm]	0.71	2.17	0.67	1.57
Ver. emittance in collision ε_y	[pm]	1.6	2.2	1.0	1.6
Lattice ver. emittance $\varepsilon_{y,\mathrm{lattice}}$	[pm]	0.65	1.25	0.65	1.1
Arc cell		Long 90/90		90/90	
Momentum compaction α_p	[10^{-6}]	28.6		7.4	
Arc sext. families		75		146	
$\beta^*_{x/y}$	[mm]	100 / 0.7	220 / 1	240 / 1	800 / 1.5
Hor. tune Q_x		218.158	218.186	398.192	398.148
Ver. tune Q_y		222.200	222.220	398.360	398.216
Chromaticities $Q'_{x/y}$		0 / +5	0 / +2	0 / 0	0 / 0
Rms energy spread (SR/BS) σ_δ	[%]	0.039 / 0.111	0.070 / 0.109	0.103 / 0.152	0.159 / 0.201
Rms bunch length (SR/BS) σ_z	[mm]	5.60 / 15.8	3.46 / 5.09	3.40 / 5.09	1.85 / 2.33
RF voltage 400/800 MHz	[GV]	0.079 / 0	1.00 / 0	2.08 / 0	2.1 / 9.38
Harm. number for 400 MHz		121200			
RF frequency (400 MHz)	MHz	400.786684			
Synchrotron tune Q_s		0.0288	0.081	0.032	0.089
Long. damping time	[turns]	1158	219	64	18.3
RF acceptance	[%]	1.05	1.15	1.8	3.1
Energy acceptance (DA)	[%]	±1.0	±1.0	±1.6	-2.8/+2.5
Beam crossing angle at IP	[mrad]	±15			
Piwinski angle $(\theta_x \sigma_{z,\mathrm{BS}})/\sigma^*_x$		26.5	3.5	6.0	0.99
Crab waist ratio	[%]	70	55	50	40
Beam-beam ξ_x/ξ_y[1]		0.0019 / 0.103	0.013 / 0.128	0.010 / 0.088	0.066 / 0.144
Lifetime (q + BS + lattice)	[sec]	2800	4000	3500	3000
Lifetime (lum)[2]	[sec]	1240	970	660	650
Luminosity / IP	[10^{34}/cm^{2}s]	151	20	6.3	1.38
Luminosity / IP (CDR)	[10^{34}/cm^{2}s]	230	28	8.5	1.8

[1]incl. hourglass.

[2]only the energy acceptance is taken into account for the cross section

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"FCC physics case: the once, the now and the future" - Christophe Grojean

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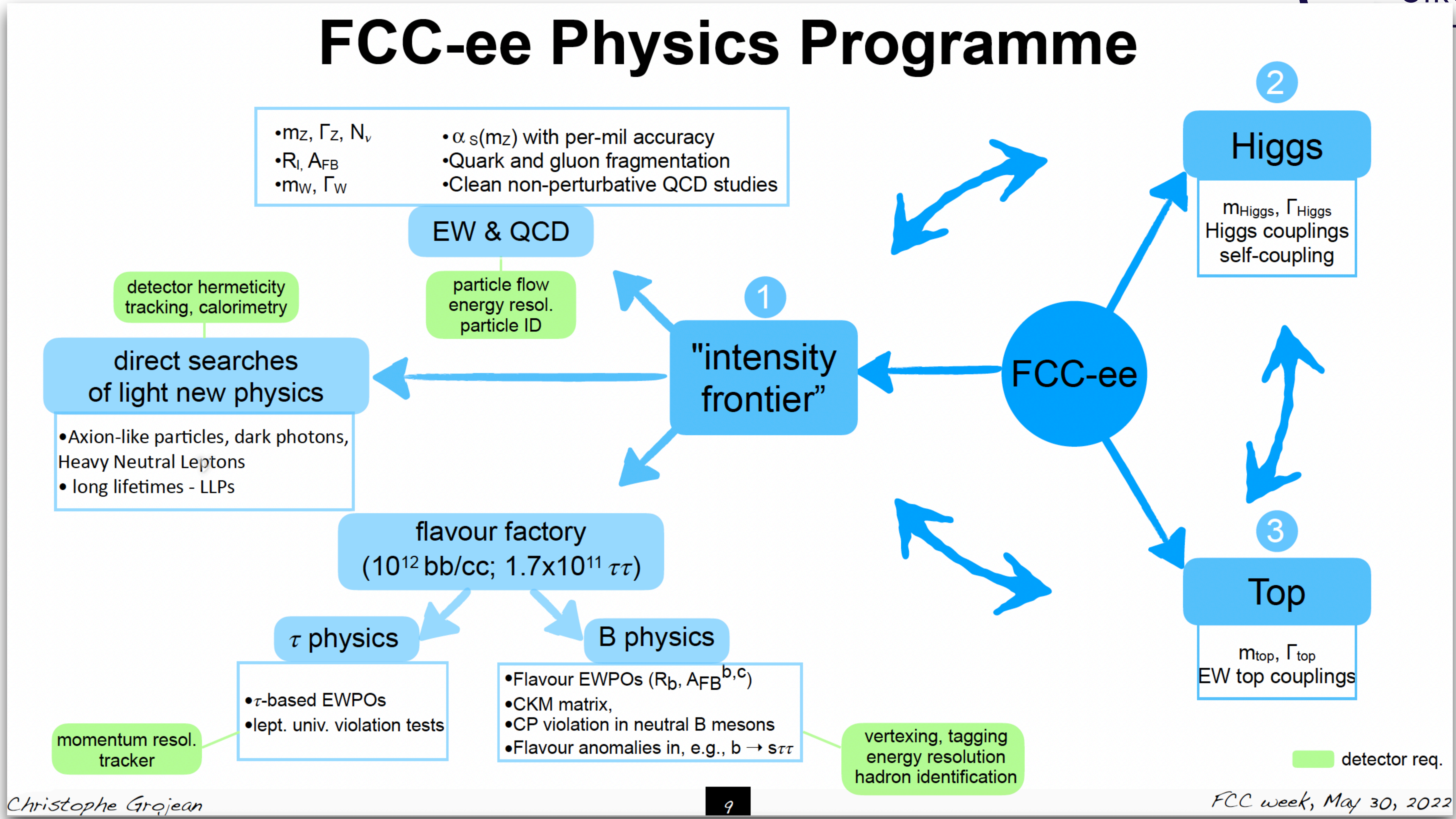

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Table 131 Expected 68%CL relative precision (%) of the κ parameters at HL-LHC and FCC-ee (combined with HL-LHC). The corresponding 95%CL upper limits on the untagged, BR_{unt}, and invisible, BR_{inv}, branching ratios are also given. As denoted with an asterisk (*), for the HL-LHC numbers, a bound on $|\kappa_V| \leq 1$ is applied since no direct access to the Higgs width is possible at hadron colliders. This restriction is lifted in the combination with FCC-ee (or other lepton colliders), since the latter ones provide the necessary access to the Higgs width. Cases in which a particular parameter has been fixed to the SM value due to lack of sensitivity are shown with a dash (−). Results from Ref. [452], updated with the 4-IPs scenario.

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

All this comes at a cost

More important than money

- While in some metrics, like energy consumption or carbon footprint per Higgs boson, FCC-ee is the most effective collider (due to the large luminosity) arXiv:2208.10466, FCC is a very large machine that will have an important environmental impact
- Sustainability is a key aspect of project
  - All designs and R&D are focused on energy savings to reduce the power demand and the energy consumption
  - Accelerator technologies (cavities, magnets...) will be designed with a focus on energy savings.
  - Other focus: reduction of water intake and treatment or reuse of excavated materials
  - FCC includes renewable energy supply

Energy and sustainability issues - Jean-Paul Burnet

Power during, in MW	Z	W	H	TT
shutdown	30	33	34	41
Technical stop	67	78	81	108
Downtime	67	78	81	108
Commissioning	144	163	177	233
Machine Development	96	121	147	231
Beam operation	222	247	273	357

Time to do the work to

Minimize impact on environment (Energy, CO_2 and water footprint, emissions, waste etc…) and availability of resources (e.g. less materials extracted)

Maximize not only physics but the value returned to society (included but not limited to training, technology and knowledge transfer)

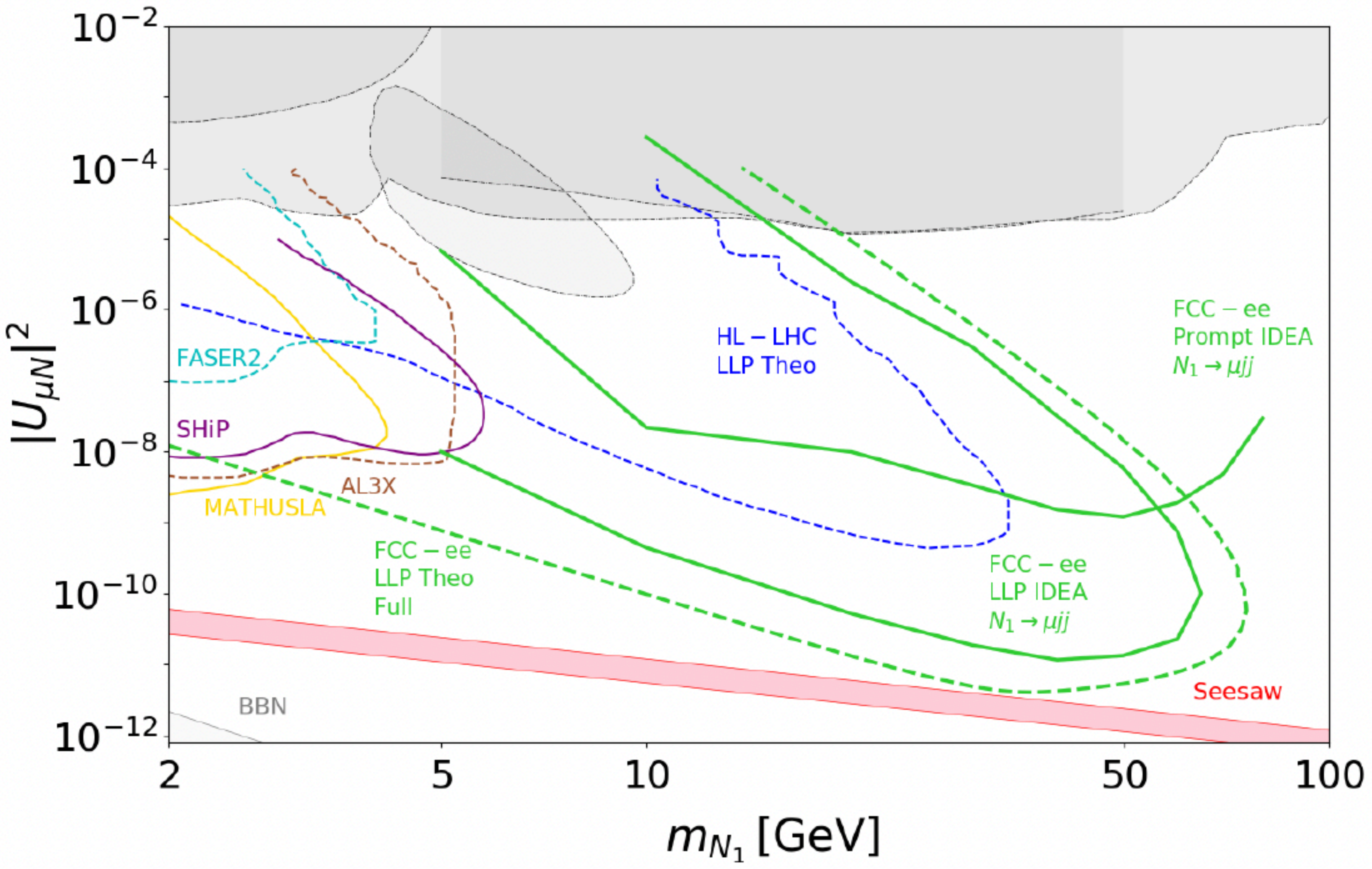

Fig. 360 Discovery potential in the $m_N - |U^2_{\mu N}|$ plane. The green full lines labelled FCC-ee are from the analysis described in [496], and are solely based on the study of the $\mu\nu jj$ final state when the HNL decays in a muon and a W. The dashed green line bounds the area with 4 HNL decays inside an FCC-ee detector with a displacement larger than 0.4 mm, based on the analytical formulas in [497]. The requirement to explain the light neutrino masses imposes a lower bound, indicated in red, on the total HNL mixing (summed over flavours). The width of this red band indicates the uncertainty in this lower bound due to the current lack of knowledge about the absolute scale and the ordering of the light neutrino masses. Light neutrino oscillation data can be explained anywhere above this band, in particular in models in which the neutrino masses are protected by a symmetry related to approximate lepton number conservation. Furthermore, this region could also accommodate the observed matter-antimatter asymmetry via a leptogenesis mechanism. The blue HL-LHC curve is a theoretical projection of the area which will be covered by the ATLAS experiment at the HL-LHC from [498]. The existing limits from experimental searches are given as shaded areas. The expected discovery potential of projected dedicated long-lived particle searches are taken from the web site accompanying the paper [499].

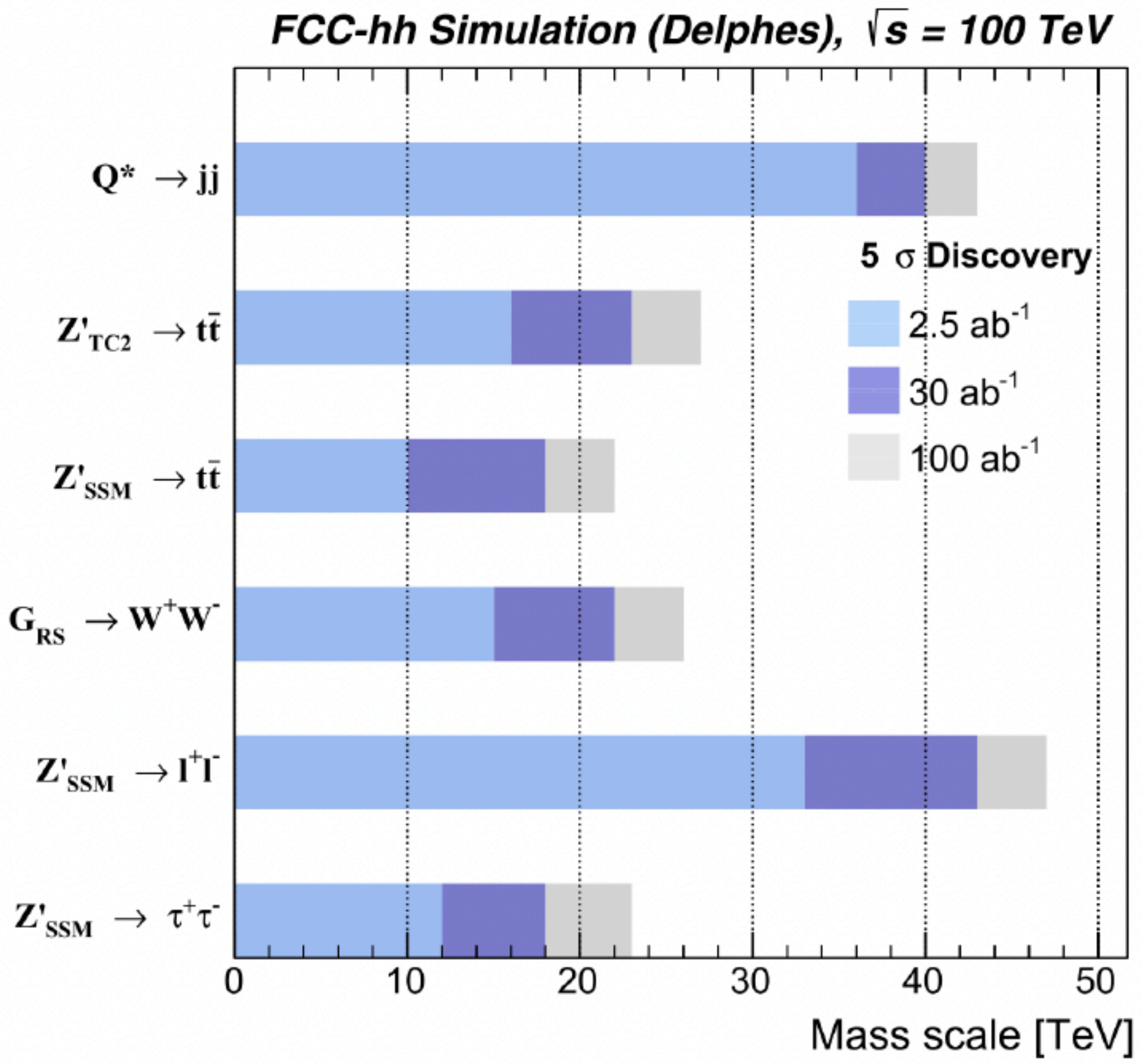

Fig. 361 Summary of the 5σ discovery reach as a function of the resonance mass for different luminosity scenarios. From [505].

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