A F(CC-ee)orward look

Rebeca Gonzalez Suarez - Uppsala University

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40 years from now

31 of October, 2063

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FUTURE CIRCULAR COLLIDER

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Is this a reality?

Is this a reality? It very well may be

FUTURE CIRCULAR COLLIDER

The (present) situation

What do we have?

- A relatively new particle that is very special, our newest **exploration tool**
- Decades of collider expertise to build on top of
- **The largest physics community we ever had**
- A few future collider options on the table: linear/circular, hadron/lepton(ee/μμ)
- And most of all: we have priorities

2020 European Strategy 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."

(European Strategy Update brochure)

Snowmass 2021

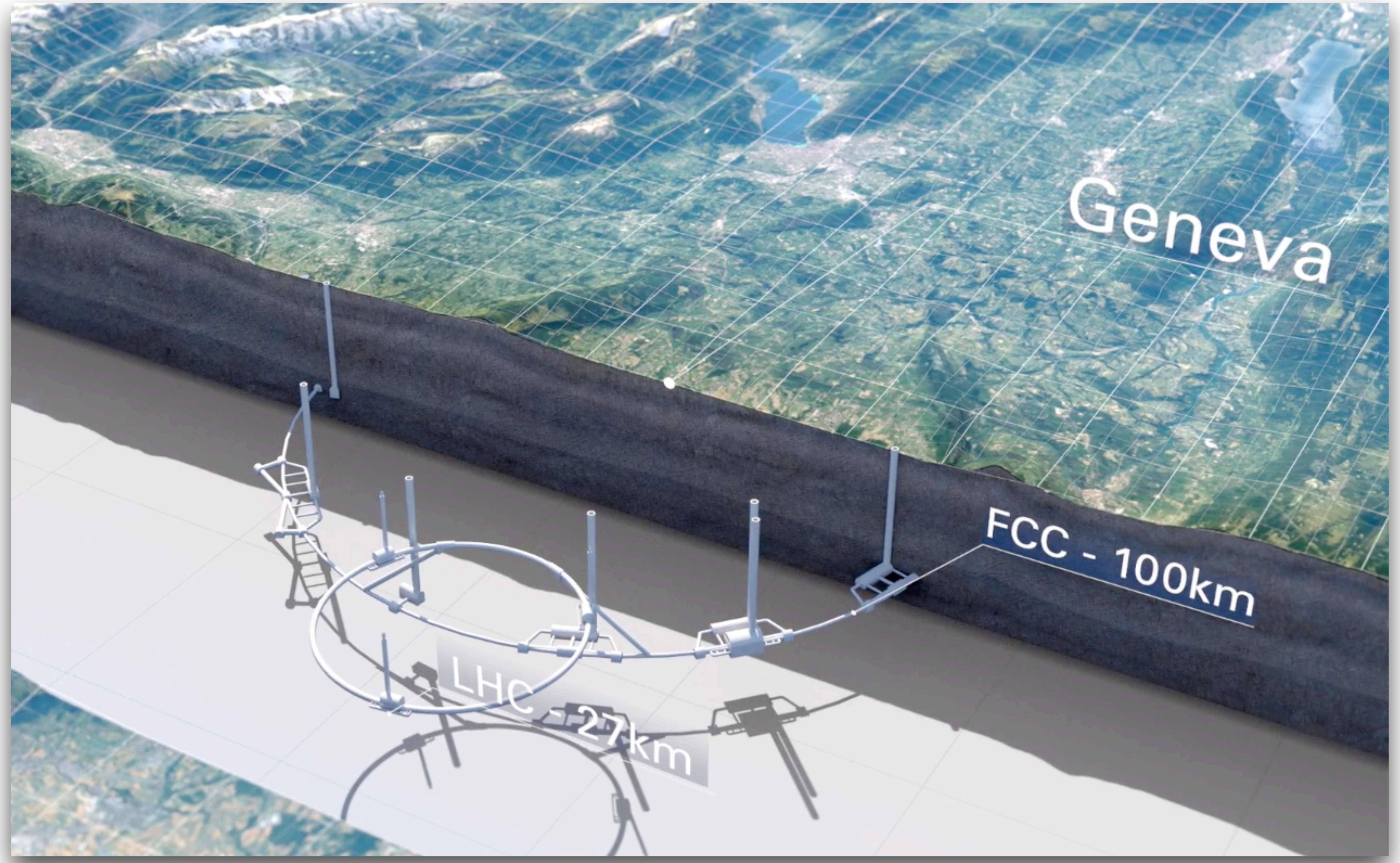
"The intermediate future is an e^+e^- Higgs factory, either based on a linear (ILC, C3) or circular collider (FCC-ee, CepC). In the long term EF envision a collider that probes the multi-TeV scale, up or above 10 TeV parton center-of-mass energy (FCC-hh, SppC, Muon Coll.)"

(Energy Frontier Plenary by Alessandro Tricoli)

When it comes to W and Z bosons

In e+e- Higgs factories

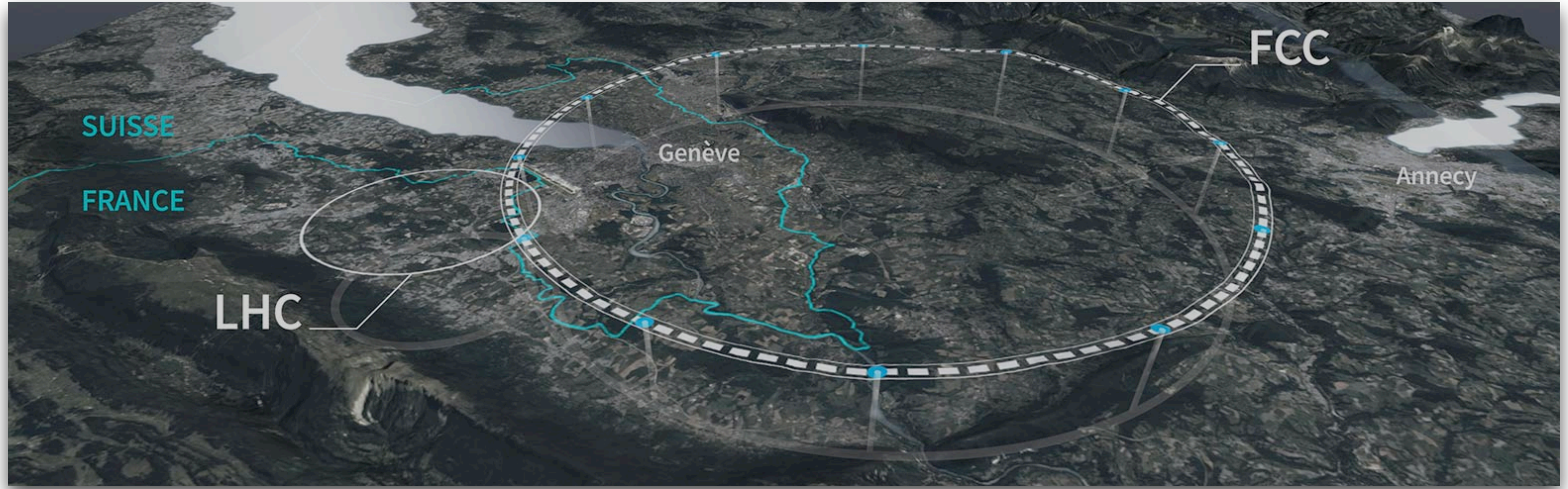
- There is one factory that has incredible potential
  - Part of a project that offers the best response to what we learnt from LHC: the combined exploration of the intensity and energy frontiers
  - and that is FCC-ee, here at CERN



FCC

Future Circular Collider at CERN

- 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



Two frontiers

get you a collider that can do both

- INTENSITY FRONTIER Precision and discovery
  - **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

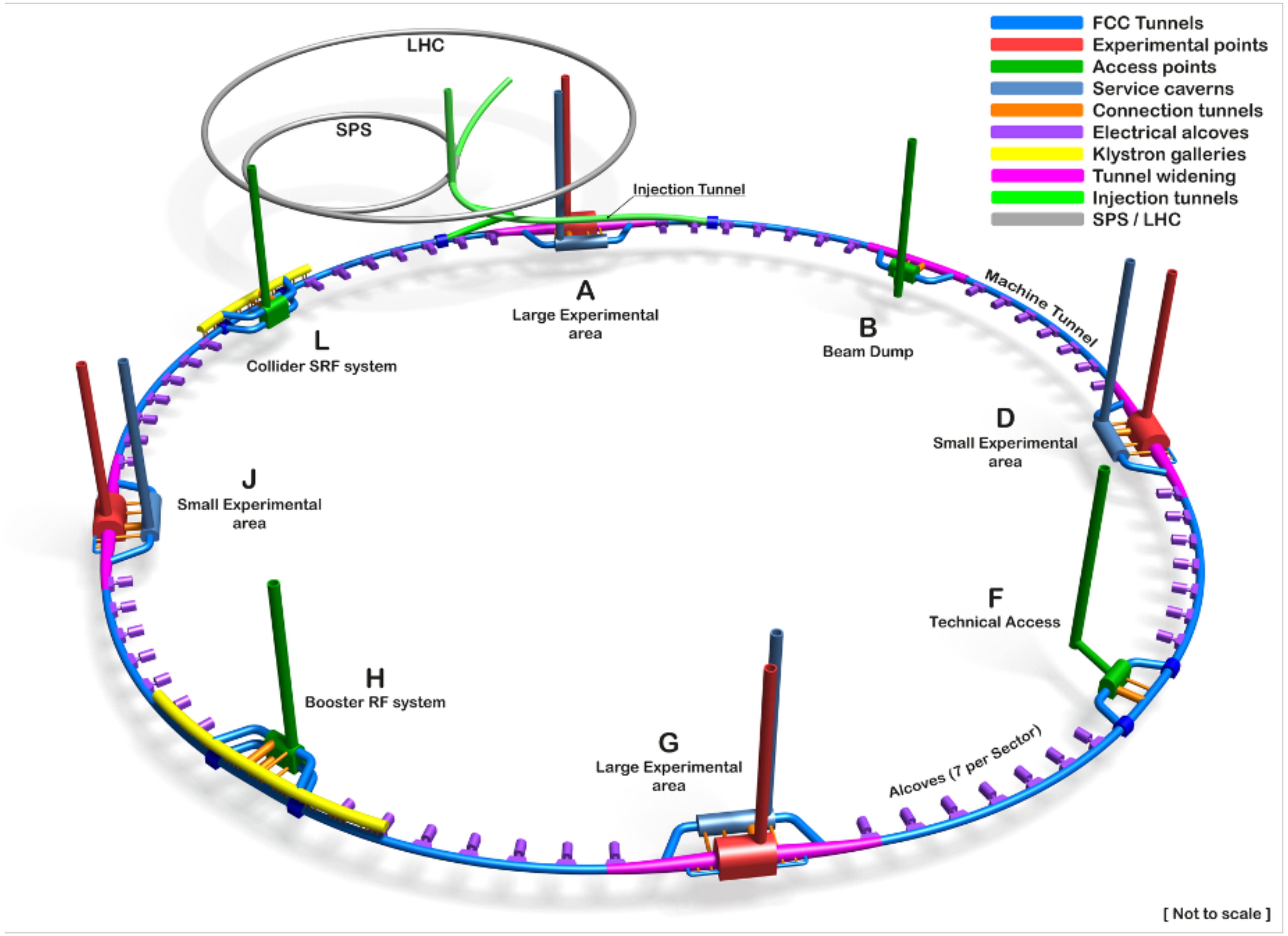
- ENERGY FRONTIER Discovery and precision
  - **2nd stage collider, FCC-hh:** proton-proton collisions at ≥ 100 TeV
  - Physics operation: ~ 2070-2095
  - Maximizing potential for BSM discovery → Direct high mass BSM sensitivity

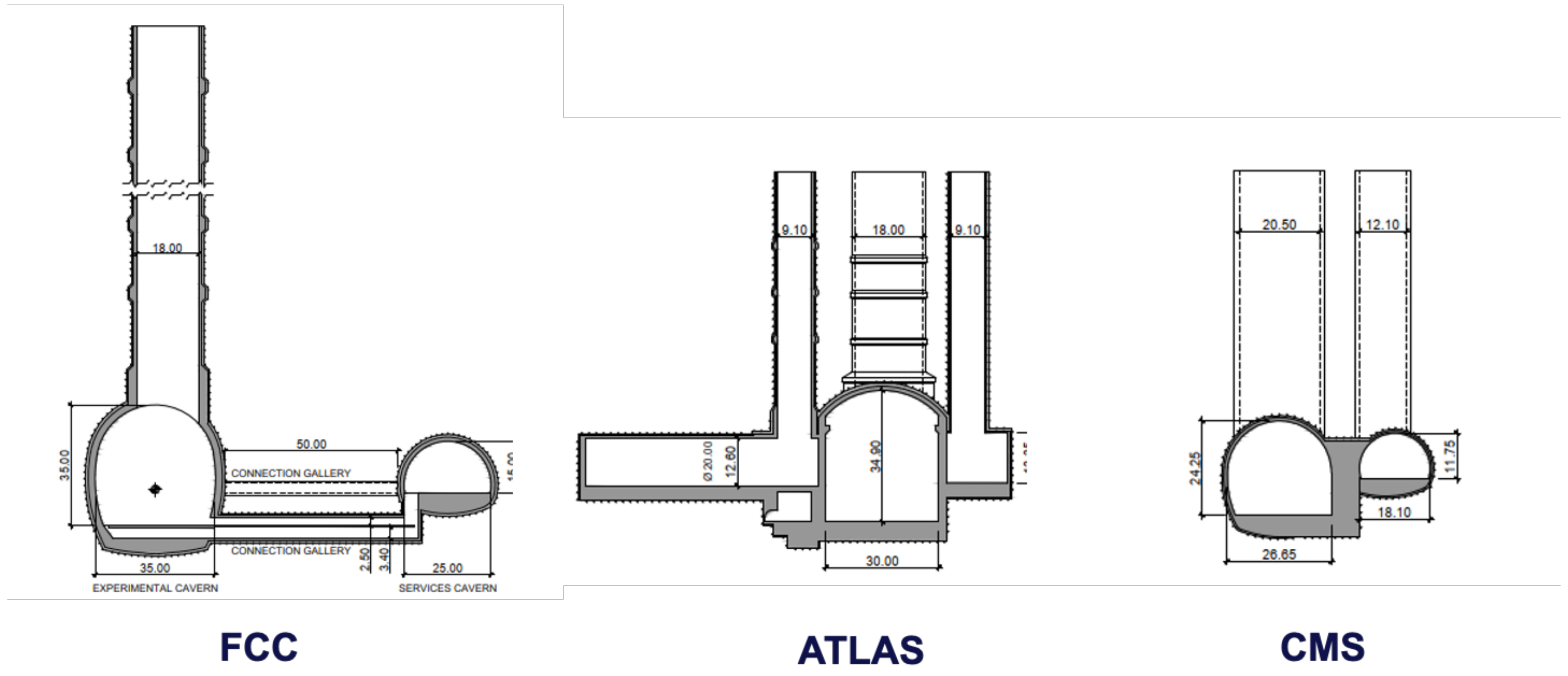
Complementary
Synergetic
All-in-one facility

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



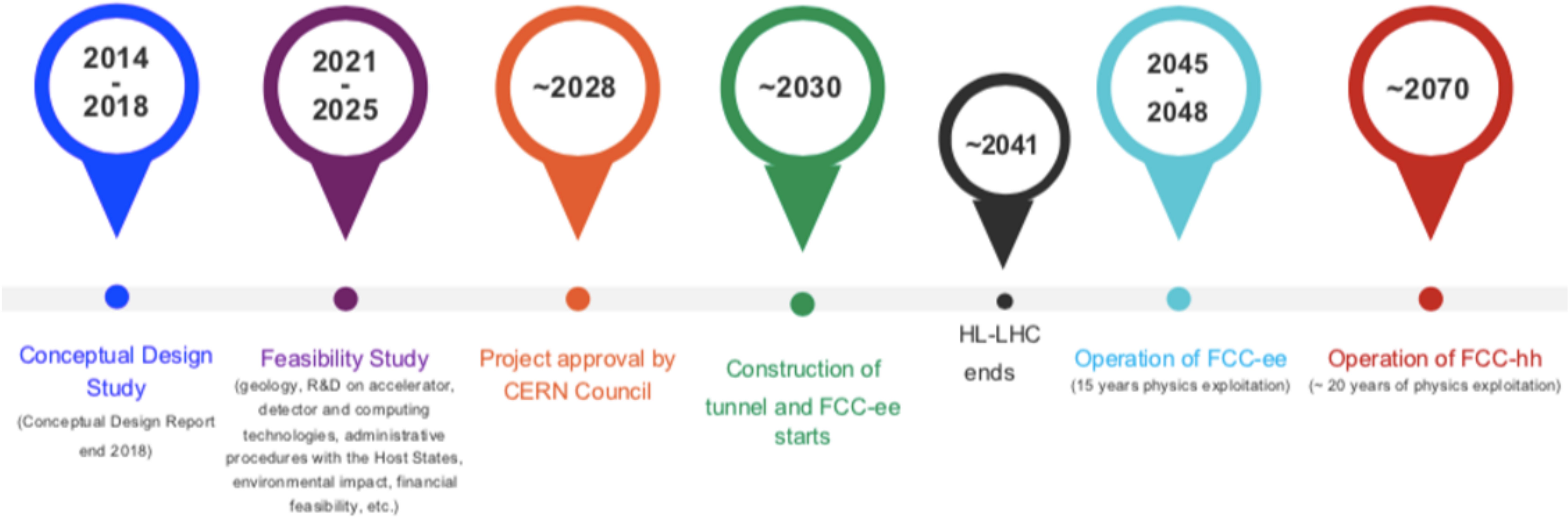


- **4 Experimental areas** 2 large (> ATLAS) & 2 small (~CMS)
- Deepest shaft: 400m
- Average shaft depth: 243m

Strength

In size and timescale

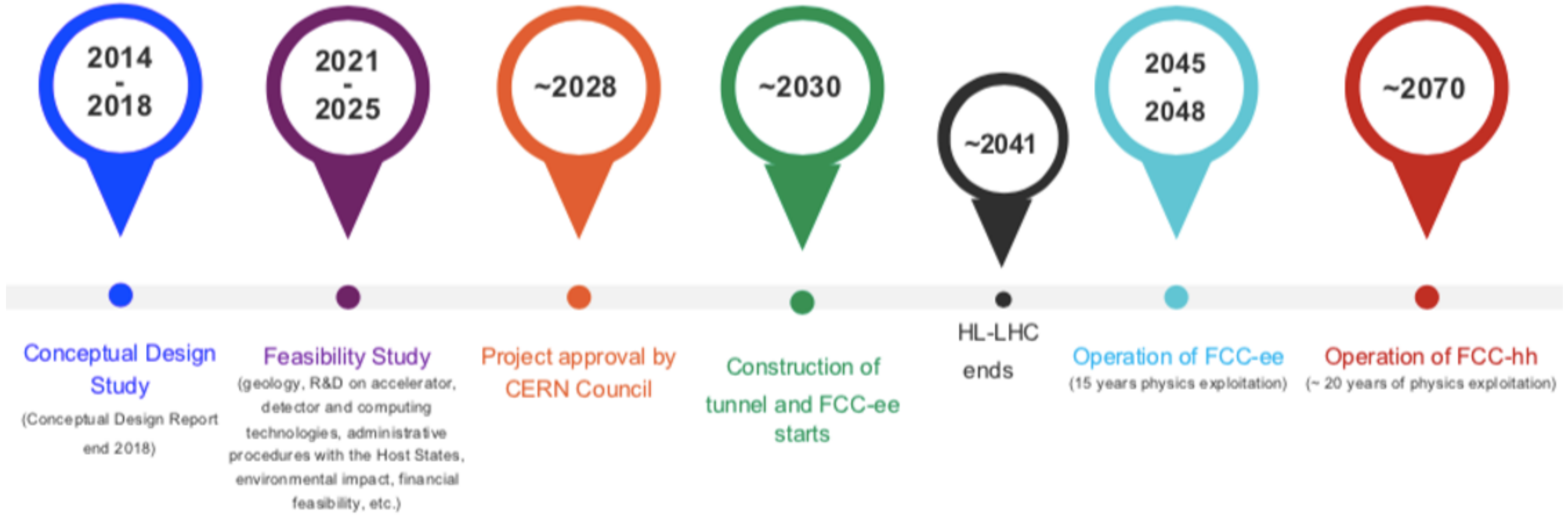
- FCC-ee technology is mature → construction in parallel to HL-LHC operation
- Physics a few years after the HL-LHC
    - Guarantees continuity for multiple generations of high energy physicists
    - **Only proposed facility that can accommodate the size of the CERN community**



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

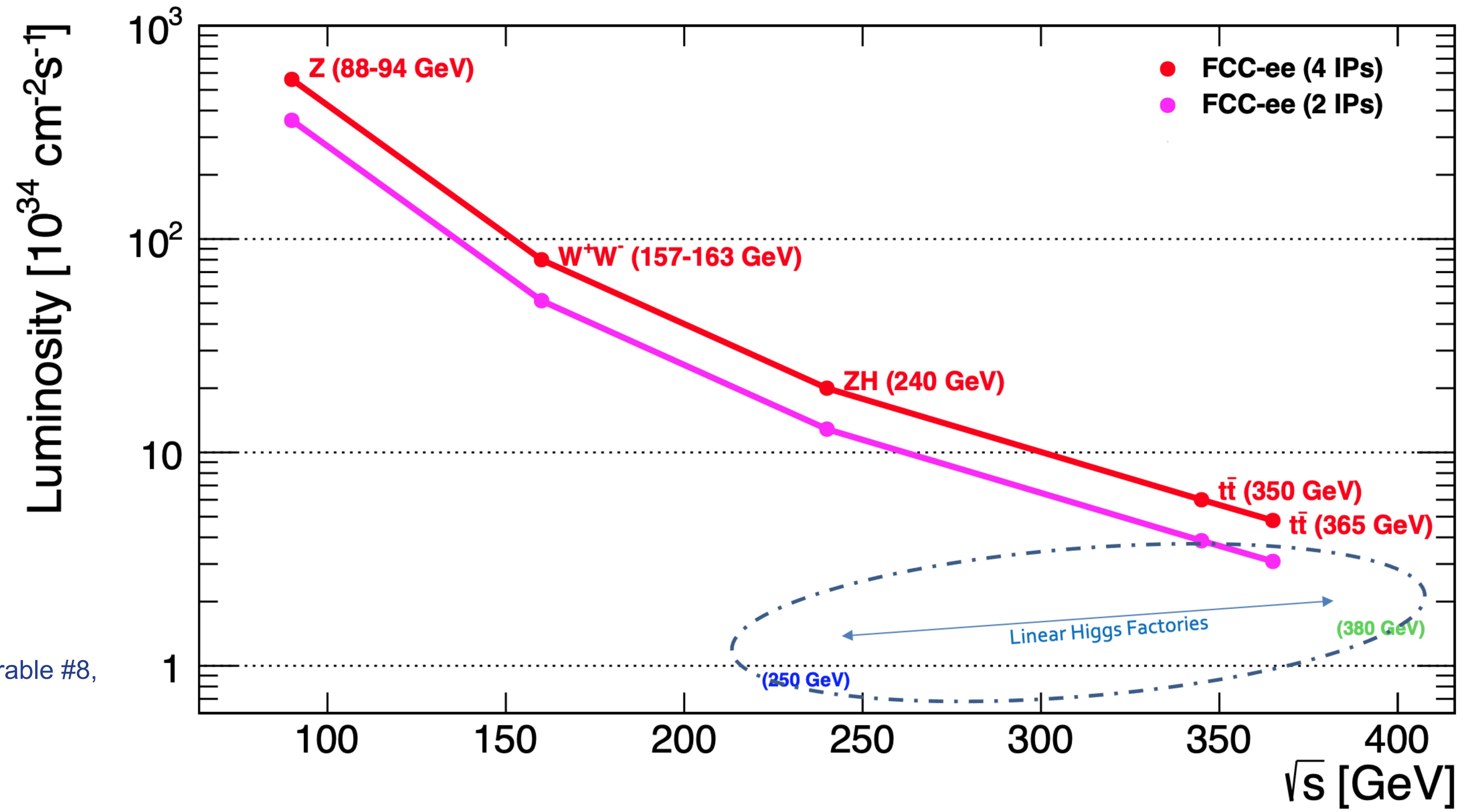


Let’s focus on FCC-ee

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

FCC-ee

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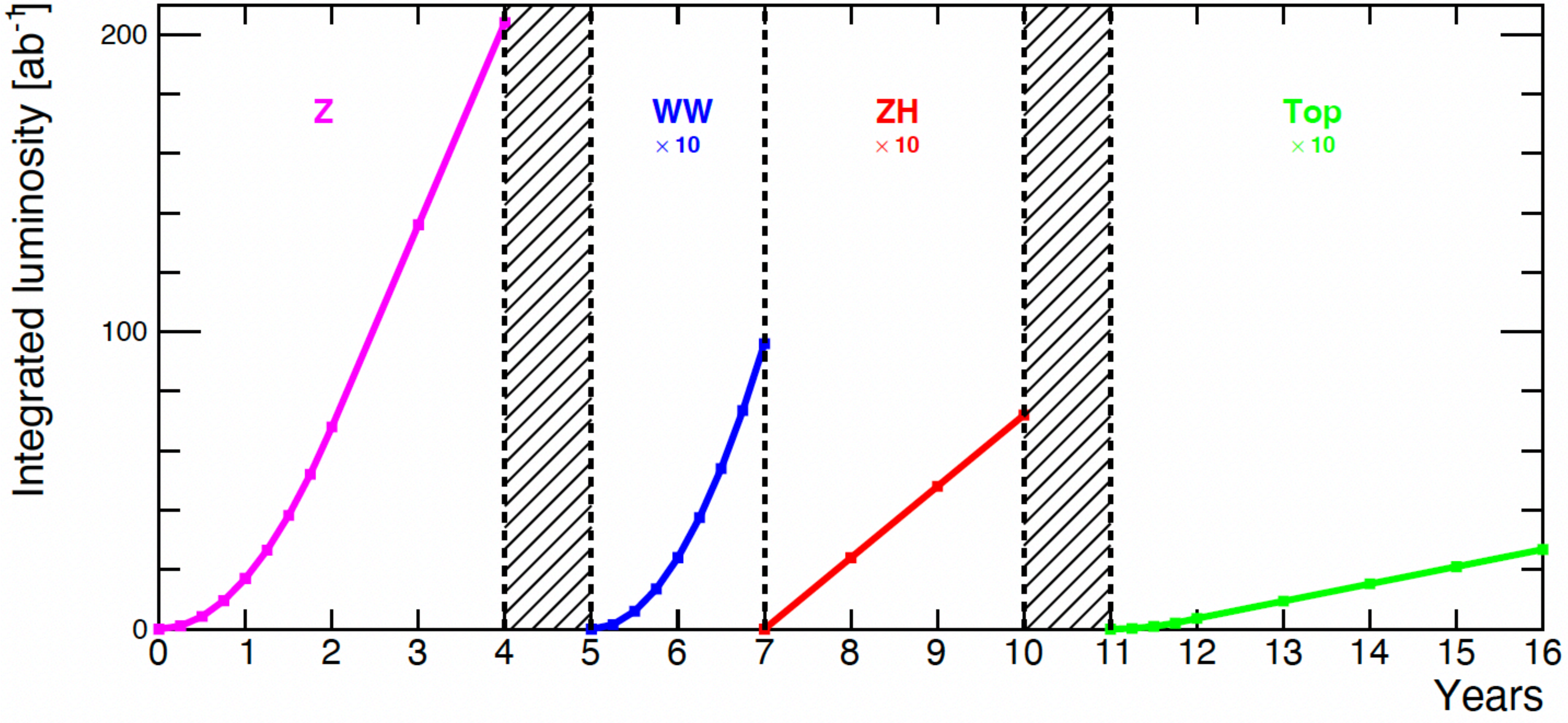
FCC feasibility Mid-term report - Deliverable #8, physics and Experiments

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 ($10^{34}\,\text{cm}^{-2}\text{s}^{-1}$)	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 → H	$1.9 \times 10^{6}\ t\bar{t}$ +330k ZH +80k WW → H	

all the data of LEP1 in minutes

What can we do with it?

Three broad goals

That make the physics case for FCC-ee

- Put the Higgs, W, and Z bosons under the microscope and map all their properties with great accuracy.
  - Sensitive e.g. to processes leading to the formation of today's Higgs vacuum field, picoseconds after the Big Bang.
- Understand much better known particle physics phenomena: **precise EWK, QCD, flavor, tau, Higgs, and top measurements.**

  best flavour factory ever!
  - Sensitive to the tiniest deviations from the SM predictions, probing energy scales far beyond the direct kinematic reach.
- Improve by orders of magnitude the **sensitivity to rare phenomena at low energies**, including the possible discovery of light particles with very small couplings.

  Long-lived particles, new scalars!

In terms of W and Z

We can do a lot

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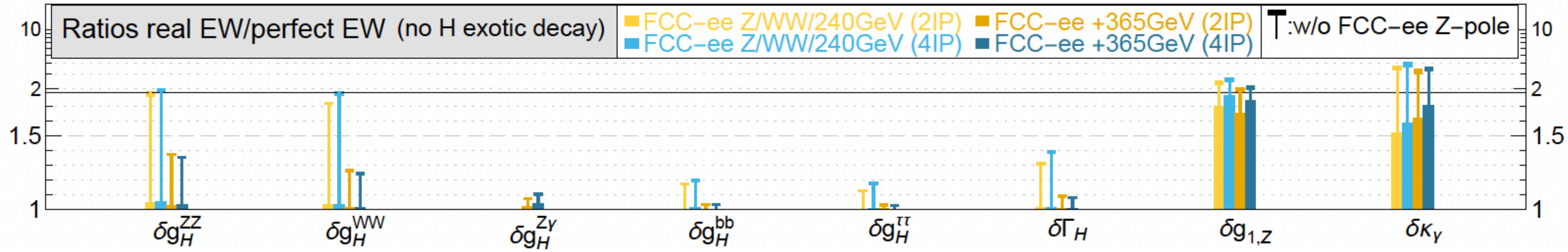
- Dedicated W and Z runs with unprecedented statistics
  - **Z pole run → LEP Statistical uncertainties divided by ~1000**
- Comprehensive measurements of the Z lineshape and many Electroweak Precision Observables
  - **50x improved precision**
- Direct and uniquely precise determinations of $\alpha_{QED}(m_Z)$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

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

Ultimate precision

A profound test of the SM

- Which translates into indirect BSM sensitivity (EFT operators dim 6 and up):
  - factor 50 in precision → factor 7 in energy scale, a step towards discovery similar to that from LHC to FCC-hh
  - **Any inconsistency will become a smoking gun of new physics**
- **Complements** the rest of the FCC physics program
  - Example: without a FCC-ee Z-pole run we would have a limited knowledge of EW couplings that in turn will limit how precisely we can measure Higgs couplings



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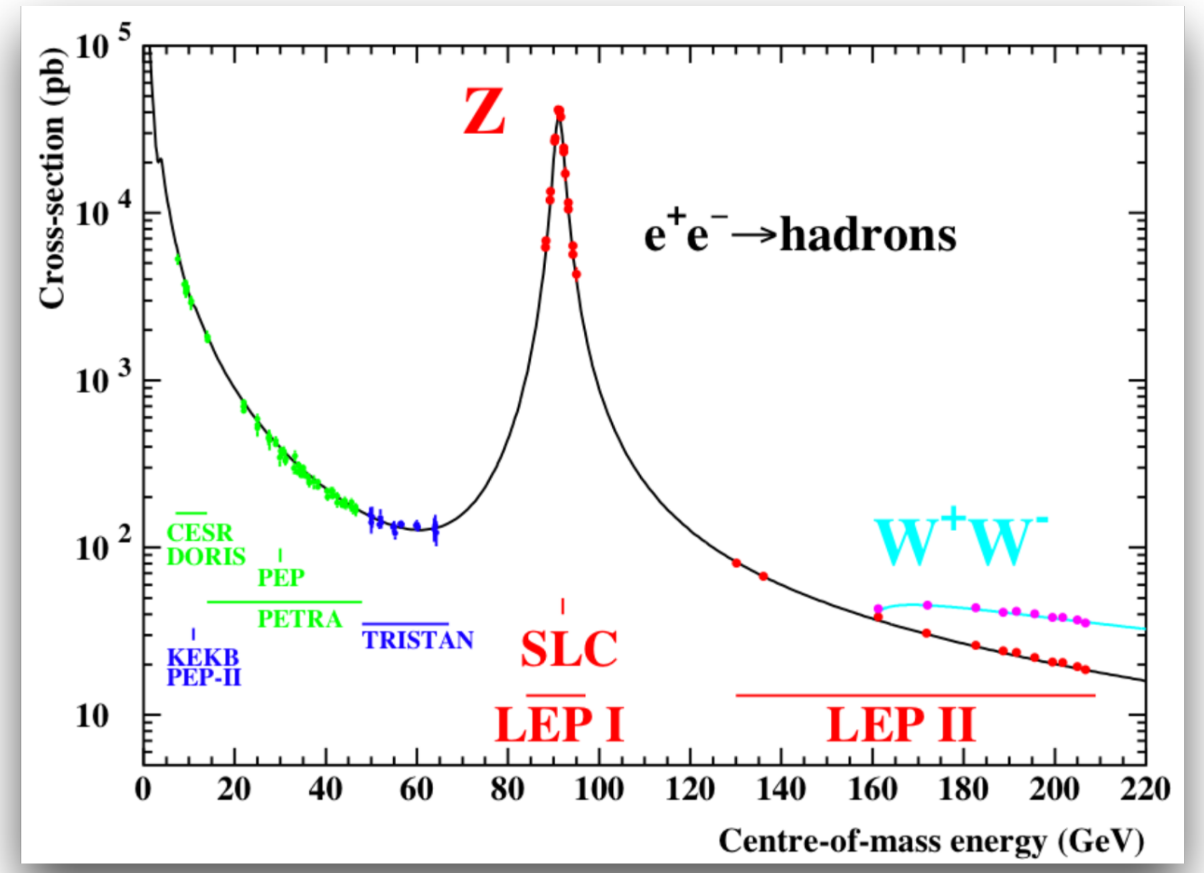
arXiv:2206.08326

Central parameters

CM energy



- Crucial to extract the best physics
  - **Statistical precision of 25 keV for Z mass and width**
  - At the Z pole, the centre-of-mass energy should be known to 1 ppm or better with a point-to-point residual uncertainty of 40 keV, and its spread to a couple per mil→ key inputs to the electroweak precision programme

arXiv:2107.00616

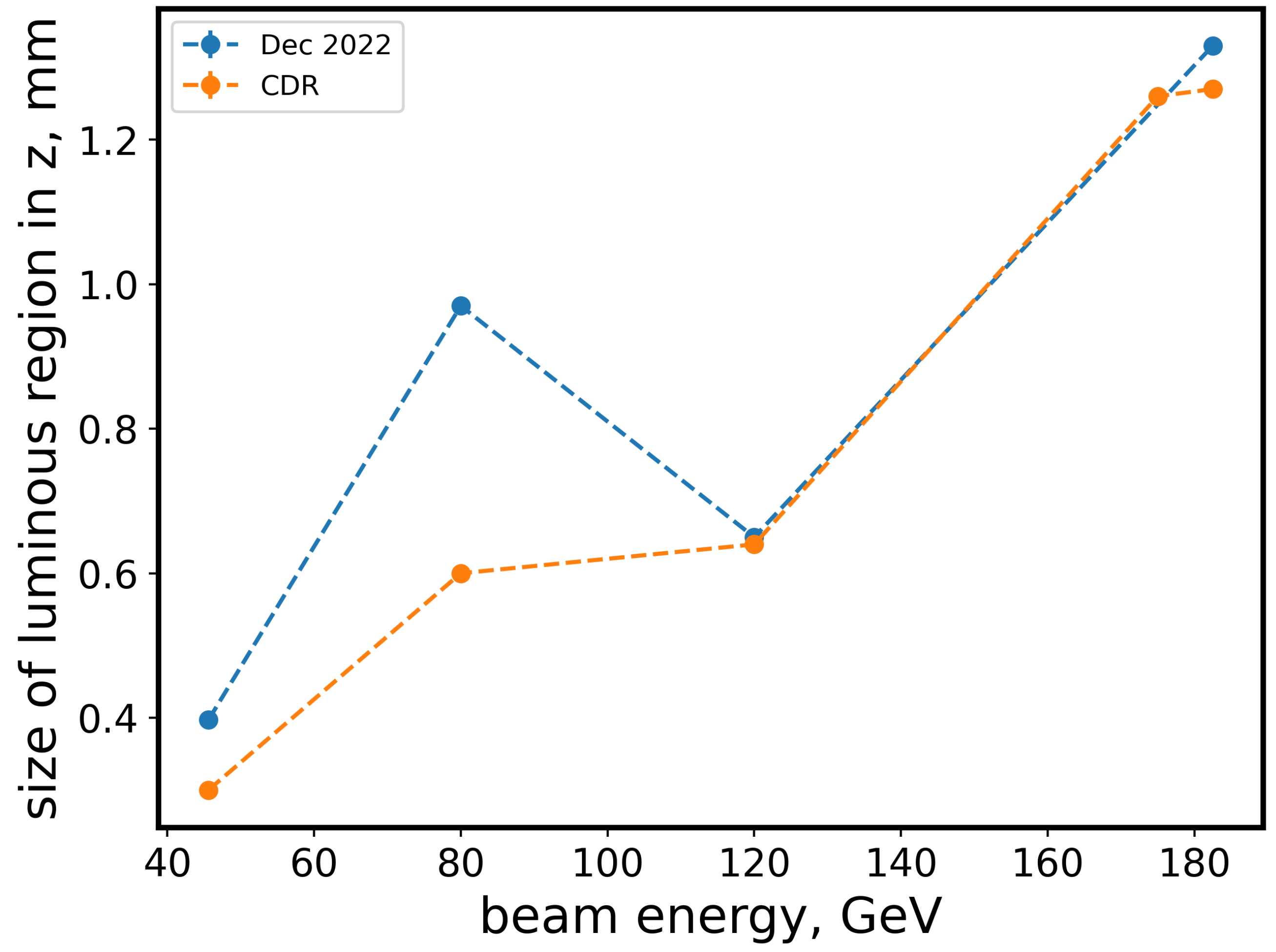
- Main calibration idea from LEP, but much more precise
  - **In-situ measurements of the beam energy** by resonant depolarization of pilot bunches
- Beam energy spread determined with dimuons/dilectrons
  - important for Z width and $\alpha_{QED}(m_Z)$

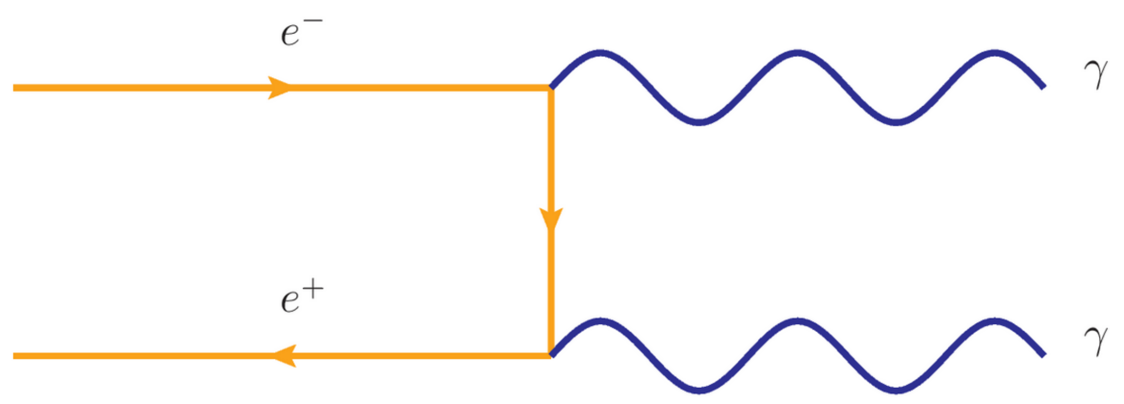
arXiv:1909.12245

Central parameters

Luminosity

- Luminosity: photon pairs and Bhabha scattering
  - $e^+e^- \rightarrow \gamma\gamma$: precise prediction, no Z dependence, clean, accuracy $O(10^{-5})$
    - Used as overall normalization
  - Small angle Bhabha scattering ($e^+e^- \rightarrow e^+e^-$) like in LEP, with large stats
    - Requires control of the geometry, $O(10^{-4})$ precision, and improvements on theory. Used to extrapolate across CM energies.
- Luminous region: **0.4 mm at Z pole**
- Well focused beam & pristine vertex reconstruction (**µm**) → no beam crossing angle issues
- Event pileup (two Z's in the same bunch crossing) at about 2/1000 events → **cleanly** identified





arXiv:1912.02067

Eur.Phys.J.Plus (2022) 137:81

The challenge

Important theoretical challenges

- To get to the right level of precision, work required:
  - Calculation of QED (mostly), EW, and QCD corrections to (differential) cross sections to convert experimental measurements to pseudo-observables*, precise calculation of the pseudo-observables*
  - Accurate **event generators** will be essential
  - Much theoretical work needed in general, two examples:

Leptonic ratios:
Acceptance at FCC-ee is substantially improved w.r.t. LEP, coverage much larger, angular & vertex resolutions much improved
Expected uncertainty on R_ℓ of 0.001 needs theory uncertainty to improve by a factor of 4 to approximate exp. precision

Forward backward asymmetries:
(Decouples from cross section, no luminosity uncertainty)
Needs accurate MC for ISR, FSR and IFI
QED/SM corrections crucial

(*if they can be used at that level of precision)

The challenge

Not only theory needs to step up

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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 **sub-MeV precision**	lineshape of $e^+e^-\to WW$ near threshold	NLO ($ee\to 4f$ or EFT frame-work)	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

Systematic uncertainties (from theory predictions but also experimental) need to catch up!

- Careful **experimental work** is needed too:
  - Detector concepts and specifications, mode of operation…
    - e.g. di-lepton and di-photon events require precise knowledge of the central tracker and calorimeter acceptance → accurate mechanical construction and in-situ alignment of the luminometer and detector end-caps

Work ongoing in all areas!

In Summary

FCC-ee is the future of W and Z physics

- FCC is a particle physics facility that will enter completely new regimes of precision and energy
    - FCC-ee is its first stage, a e+e- collider with an **incomparable electroweak precision programme**
        - **Dedicated W and Z runs (masses, widths, couplings, angular distributions, ratios, asymmetries…)**
        - Dividing by 1000 the statistic uncertainty from LEP at the Z pole run
        - **Factor of 50 in precision** → 7x jump in indirect sensitivity to BSM effects
        - **Complementarity** with a rich physics program at FCC-ee (Higgs, top, BSM), and FCC-hh

All of this brings exciting challenges: accelerator R&D, machine-detector interface, detector design, software development, theory calculations…
If we want to make it happen, NOW is the time to join and contribute!!

"This project is supported from the European Union's Horizon 2020 research and innovation programme under grant agreement No 951754."

Credits/Gratitude to (in no particular order): Christophe Grojean, Patrick Janot, Ayres Freitas, Christoph Paus, Roberto Tenchini, Patrizia Azzi, Fabiola Gianotti, Sarah Williams, Juliette Alimena, Frank Zimmermann, Michele Selvaggi, Matthew McCullough

Backup

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 ab^{-1} at 88 GeV, 125 ab^{-1} at 91.2 GeV, and 40 ab^{-1} at 94 GeV (5 ab^{-1} at 157.5 GeV, and 5 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 ($10^{34}\,cm^{-2}s^{-1}$)	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	

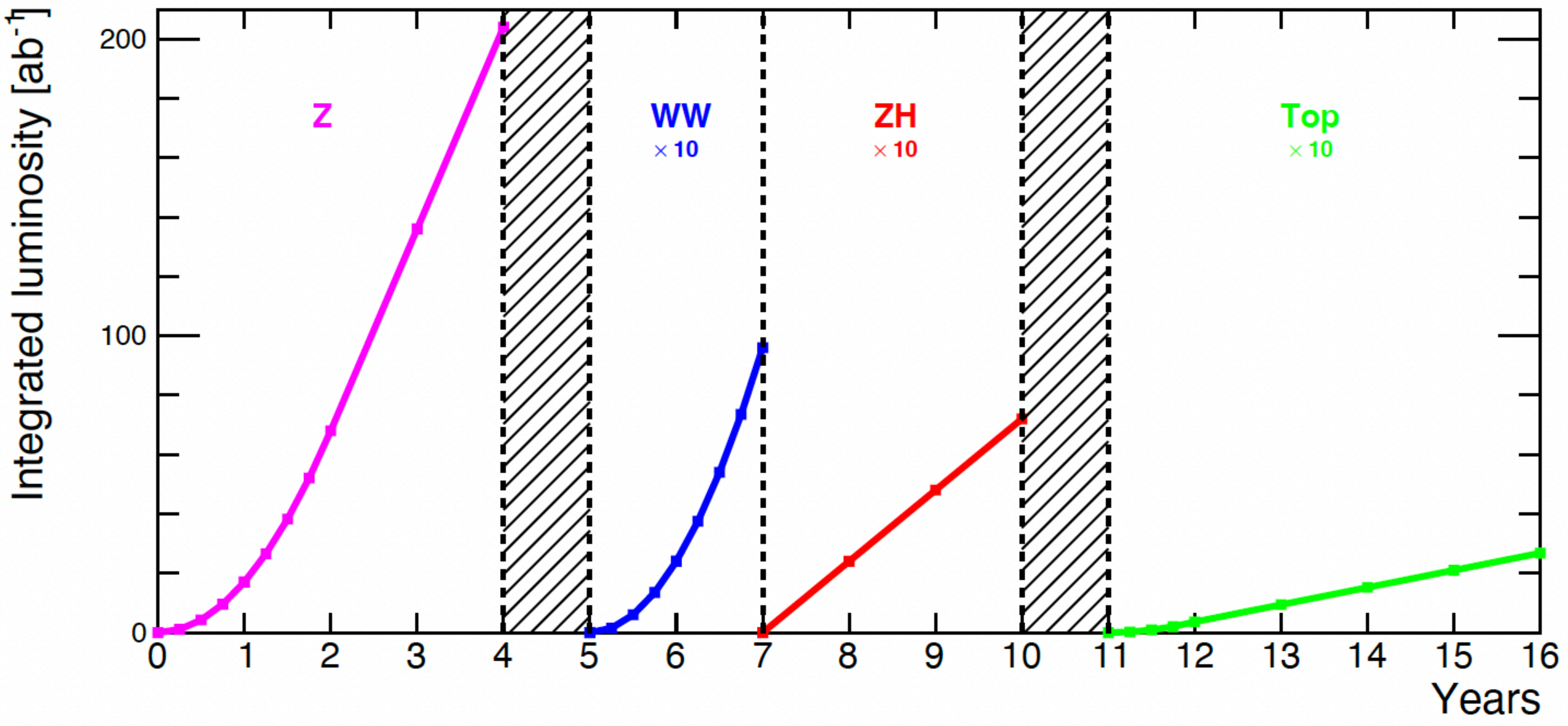


Fig. 2 Baseline operation model for FCC-ee with four interaction points, showing the integrated luminosity at the Z pole (pink), the WW threshold (blue), the Higgs factory (red), and the top-pair threshold (green) as a function of time. In this baseline model, the sequence of events goes with increasing 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.

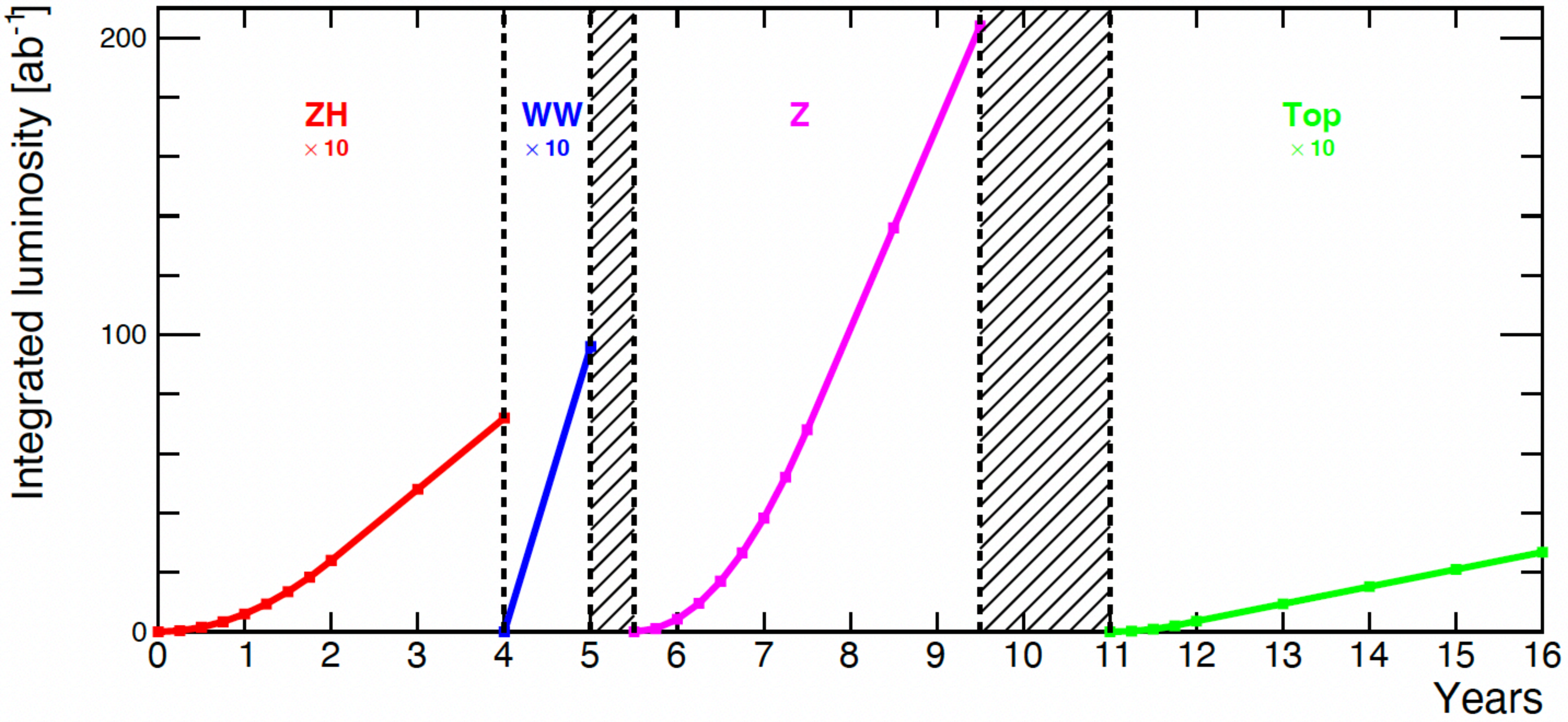
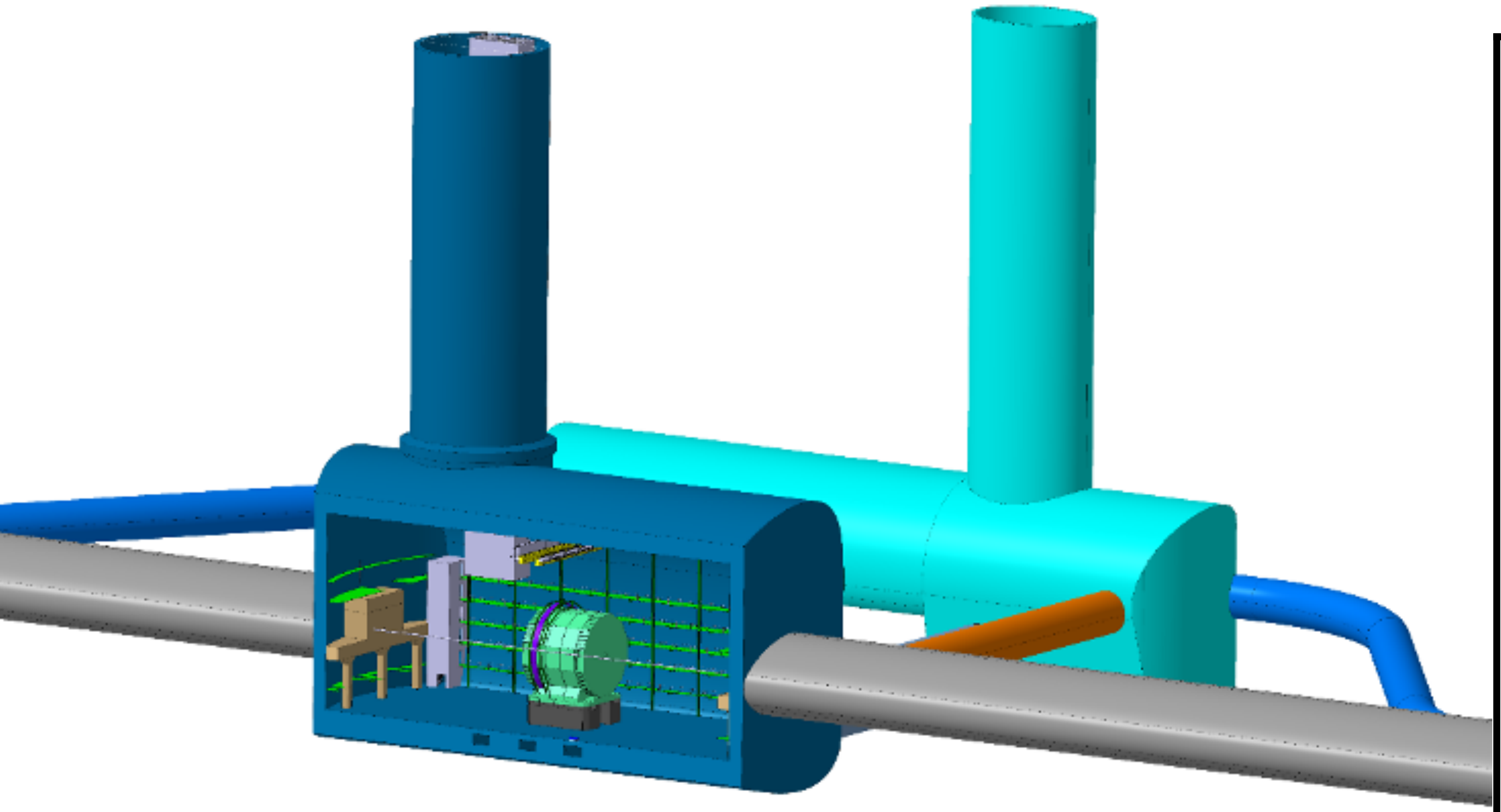
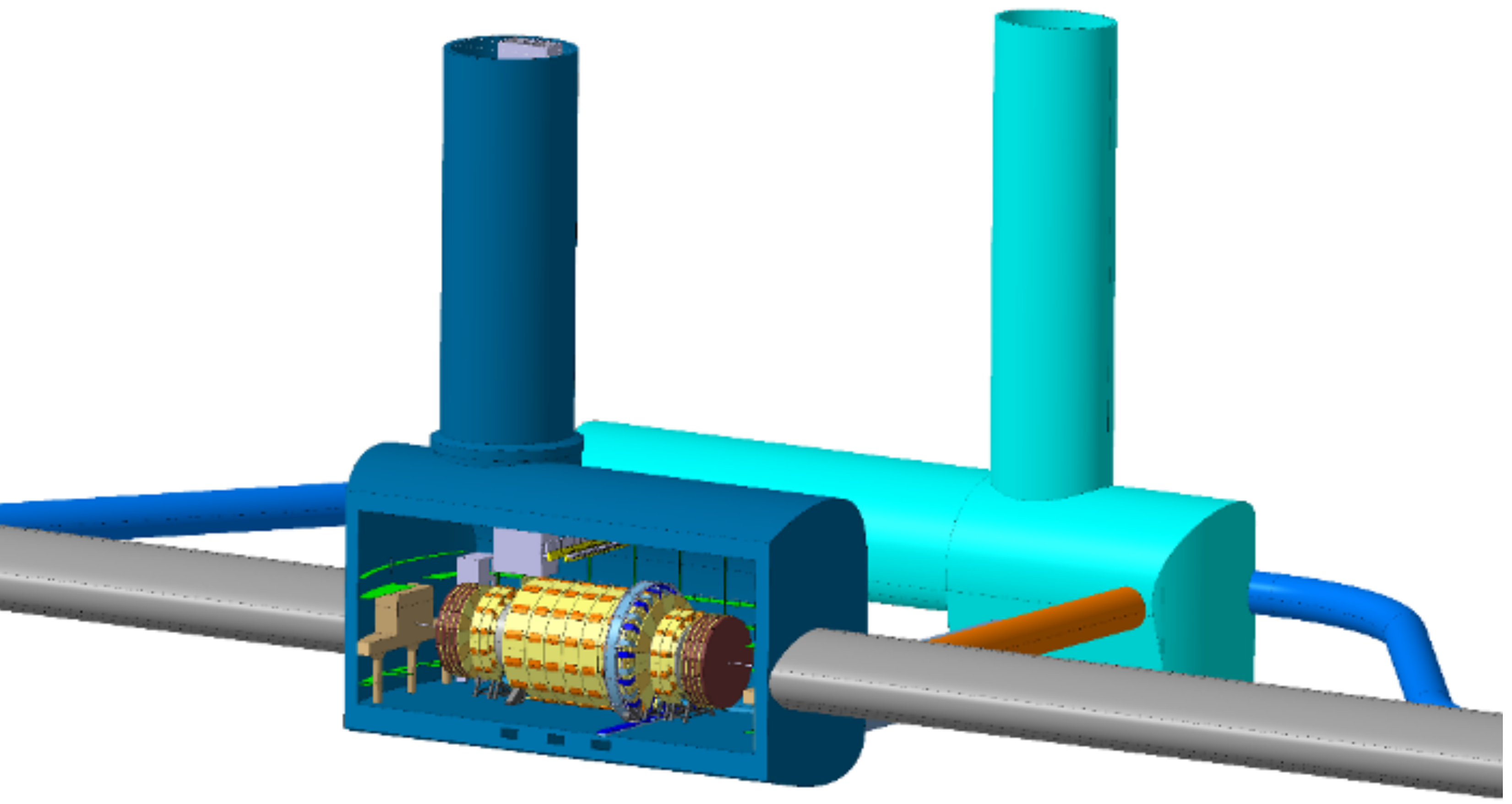


Fig. 3 Alternative operation model for FCC-ee with four interaction points, showing the integrated luminosity at the Z pole (pink), the WW threshold (blue), the Higgs factory (red), and the top-pair threshold (green) as a function of time. In this model, the ZH run comes first, followed by the WW run. 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.

Detector concepts

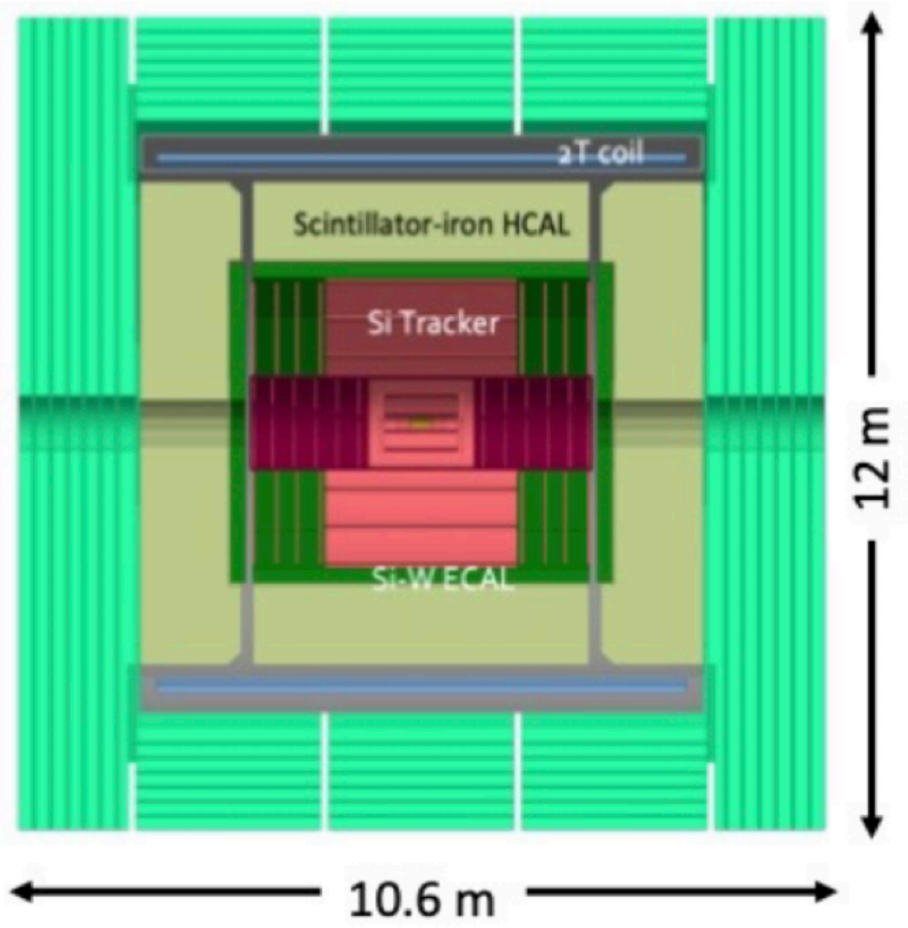


FCC-ee



FCC-hh

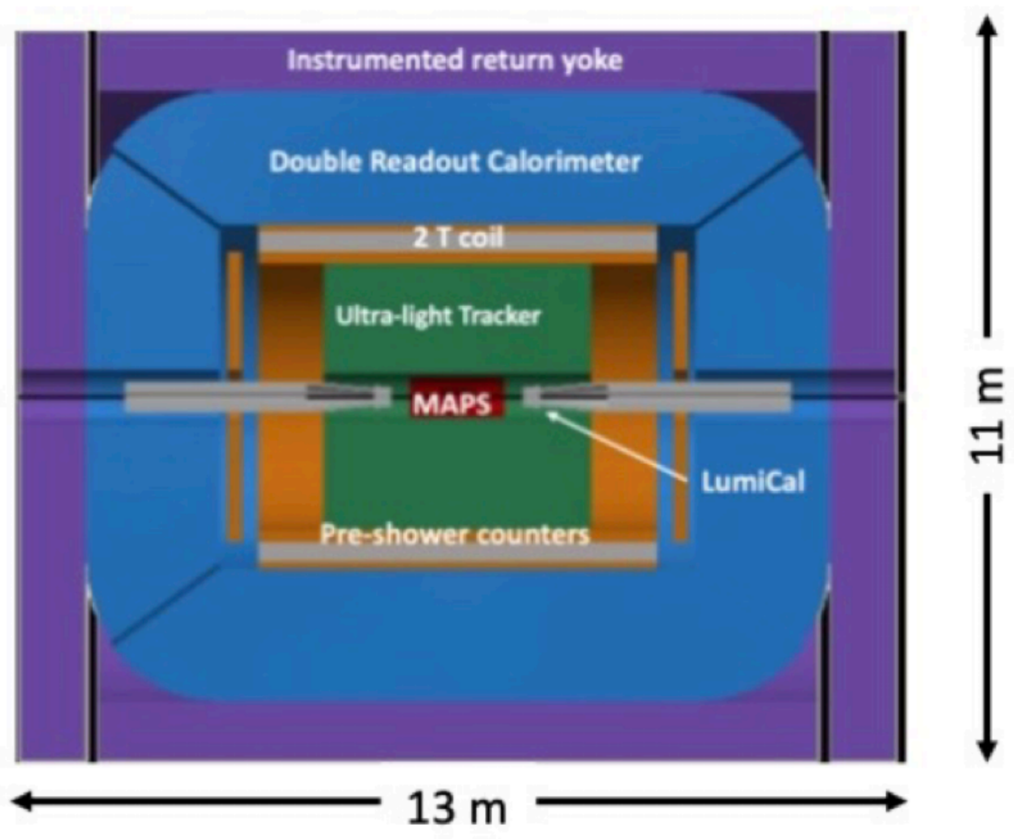
CLD



Based on CLIC detector design, arXiv:1911.12230

Full silicon vertex detector and tracker
3D-imaging highly-granular calorimeter system
Coil outside calorimeter system

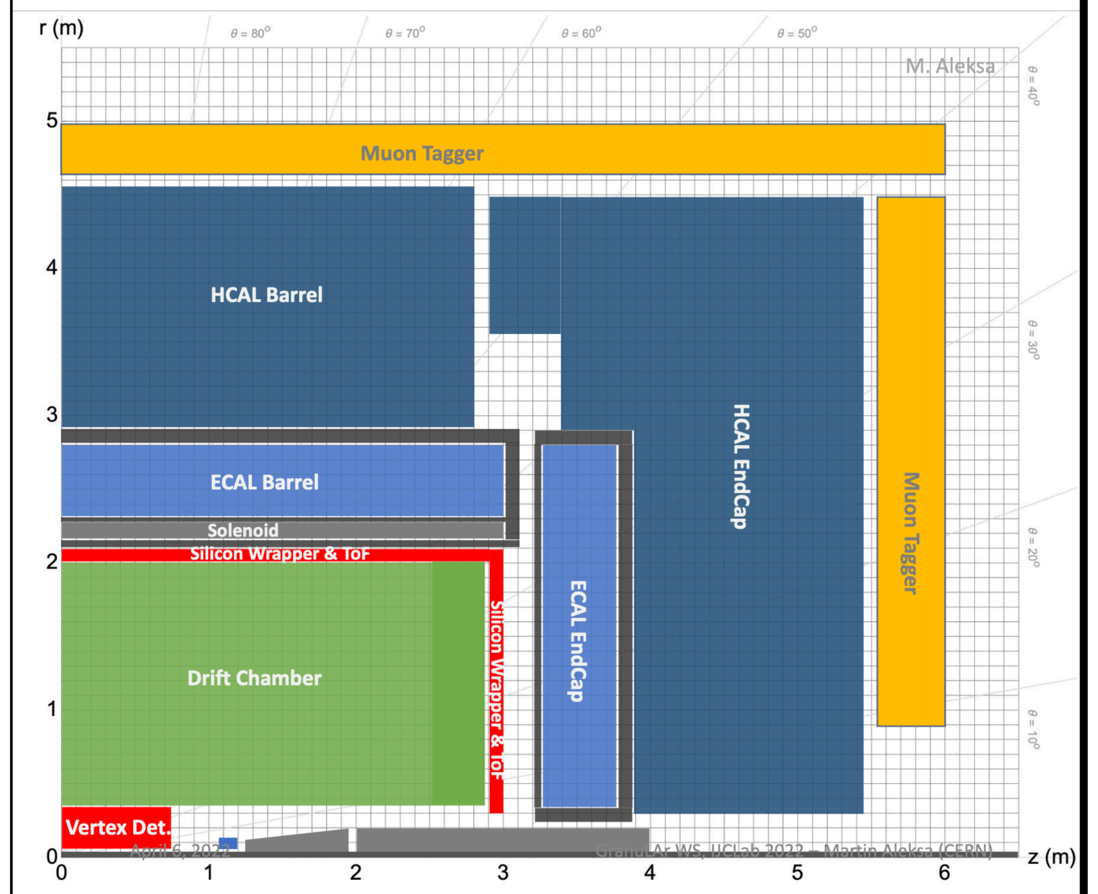
IDEA



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

ALLEGRO



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

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.

FUTURE CIRCULAR COLLIDER

Observable	present value	±	error	FCC-ee **Stat.**	FCC-ee Syst.	Comment and leading error
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$\alpha_s(m_Z^2)$ $(\times 10^4)$	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

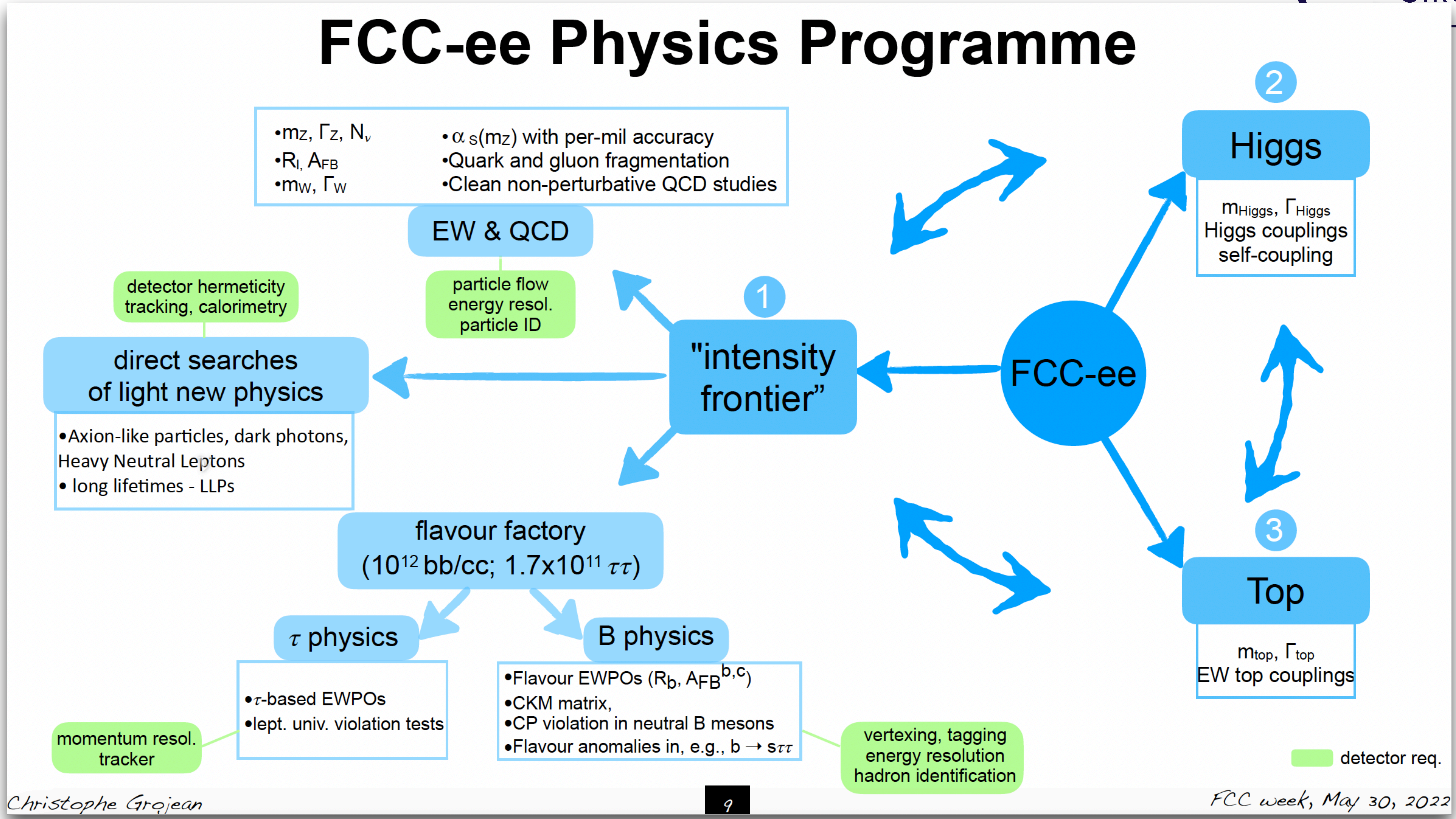
Table 131 A few sample precision quantities of interest for the FCC-ee programme, their current and projected experimental uncertainties, and the required theory input for their *extraction* from the data. The last two columns show the current state of the art for calculations of this theory input, and 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 framework)	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.

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

FUTURE CIRCULAR COLLIDER



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, CO2 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)