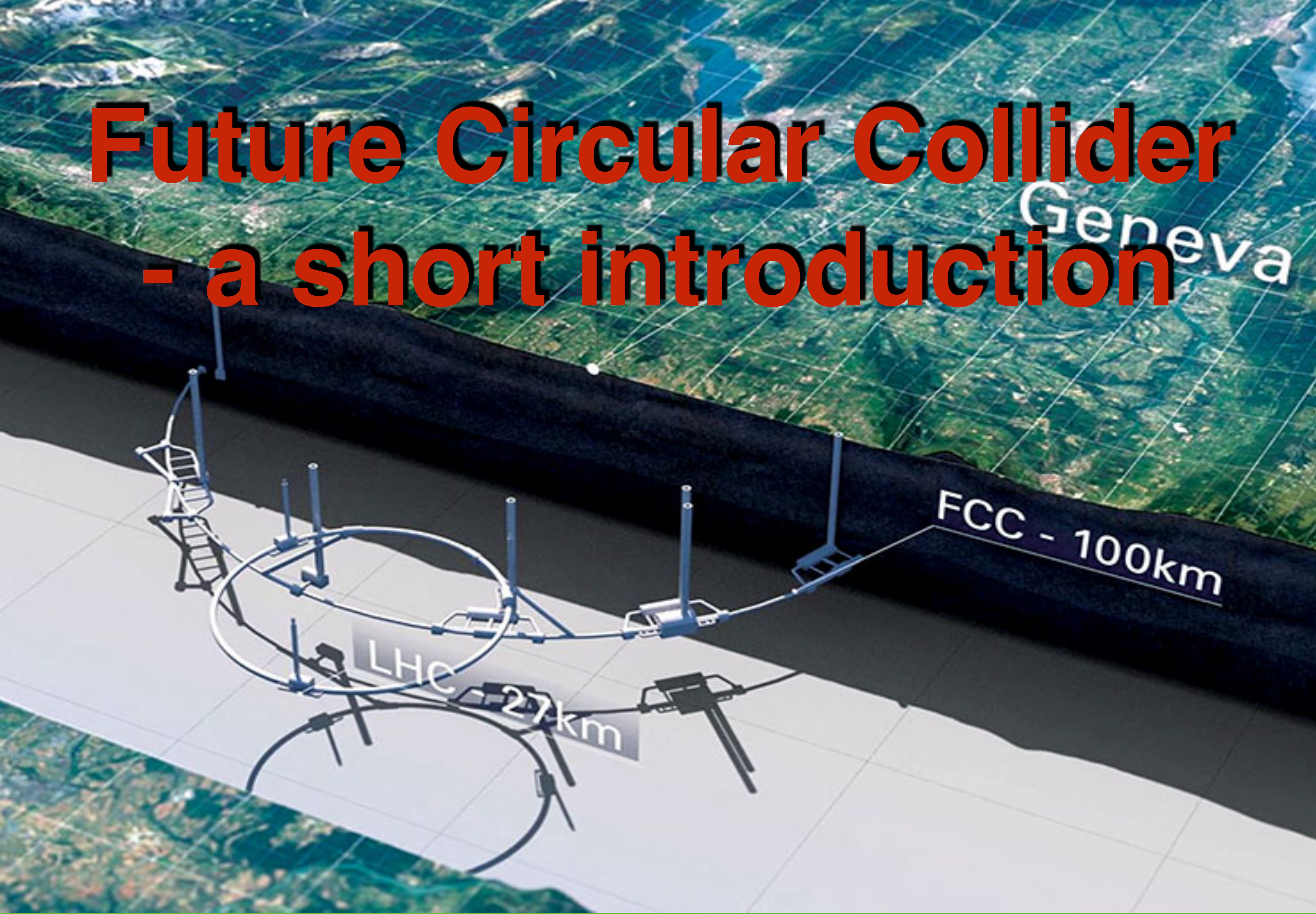
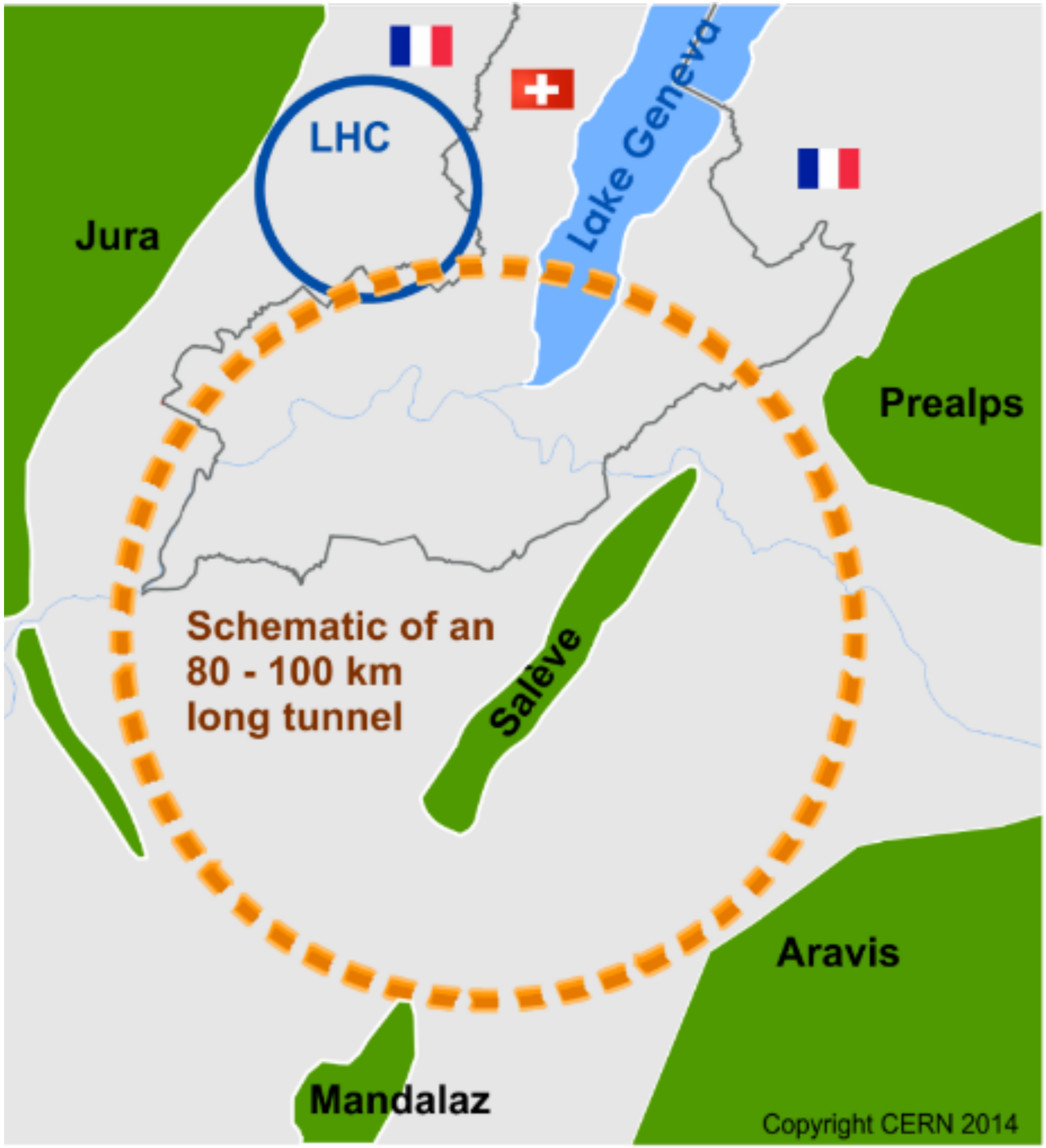
Future Circular Collider - a short introduction



Markus Klute (MIT)

Lepton Collider Workshop - April 22nd, 2020

Future Circular Collider Study

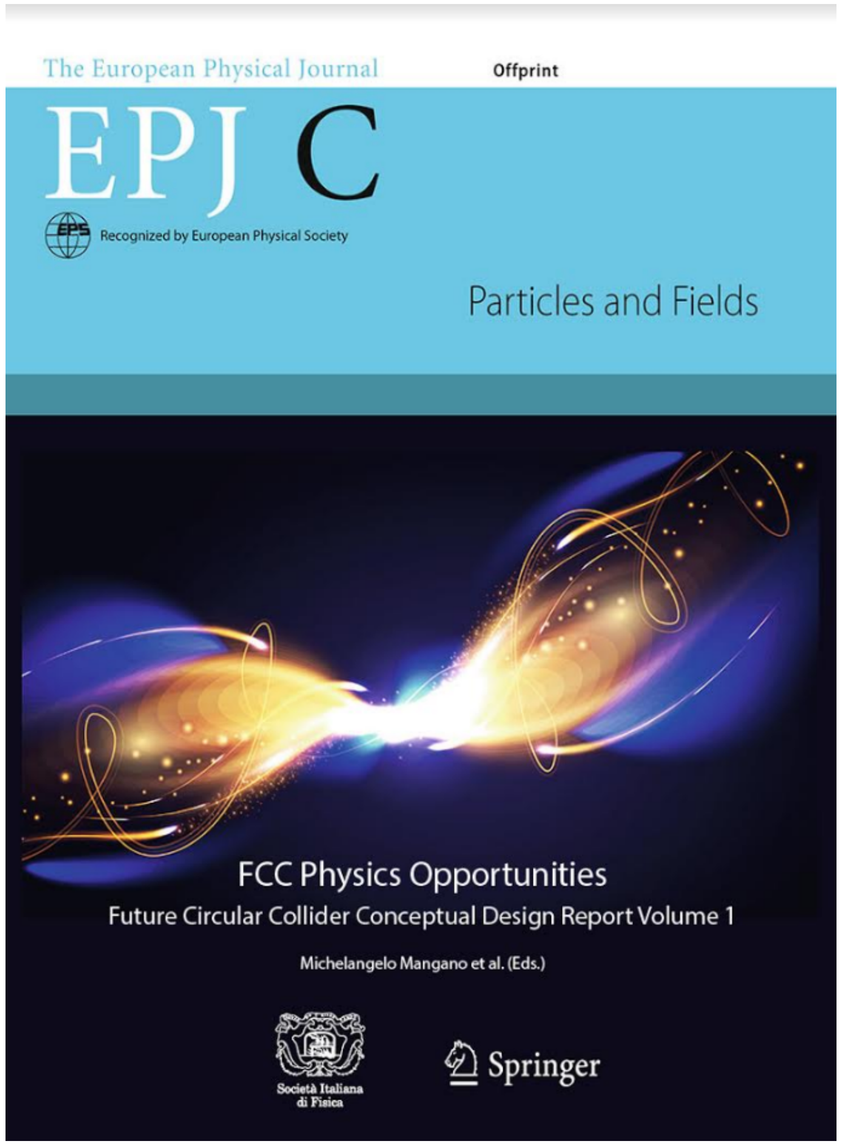


International FCC collaboration with CERN as host lab to study:

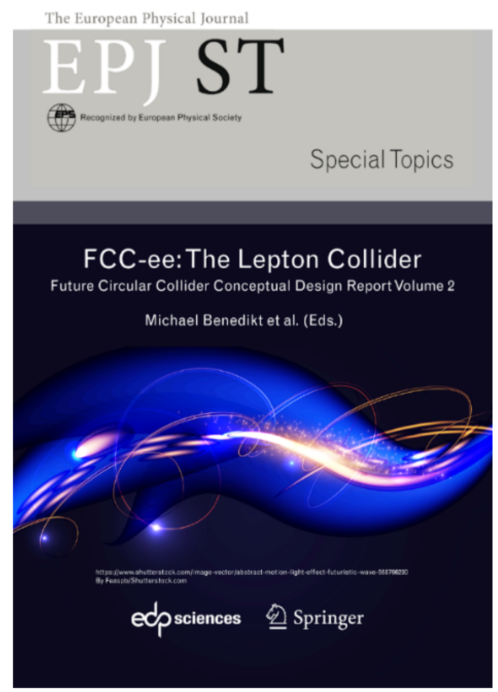
- ~100 km tunnel infrastructure in Geneva area and linked to CERN
- e^+e^- collider (FCC-ee) as potential first step
- pp-collider (FCC-hh) as long-term goal, defining the infrastructure requirements
  - ~16T => 100 TeV pp in 100 km
- HE-LHC with FCC-hh technology
- Ion and lepton-hadron options with hadron collider

FCC Results

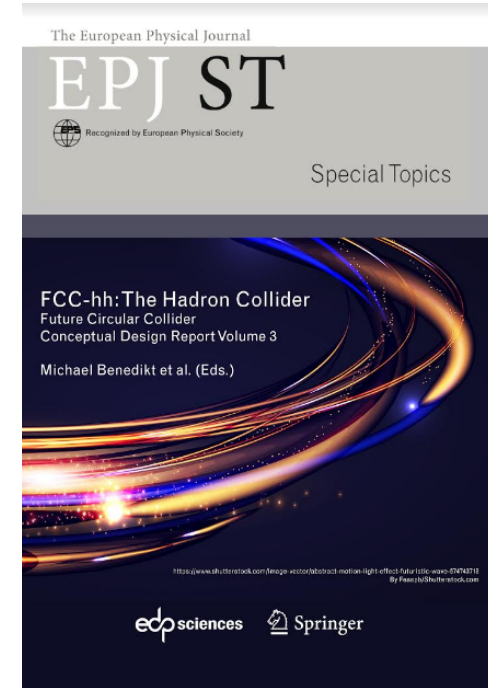
4 CDR volumes published in EPJ



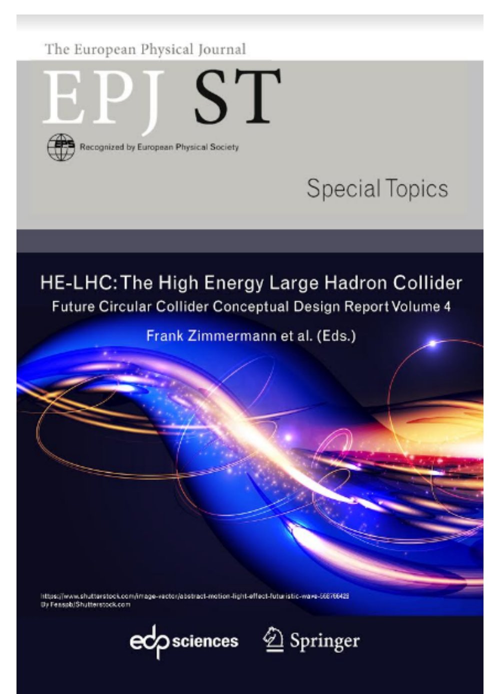
FCC Physics Opportunities



FCC-ee: The Lepton Collider



FCC-hh: The Hadron Collider

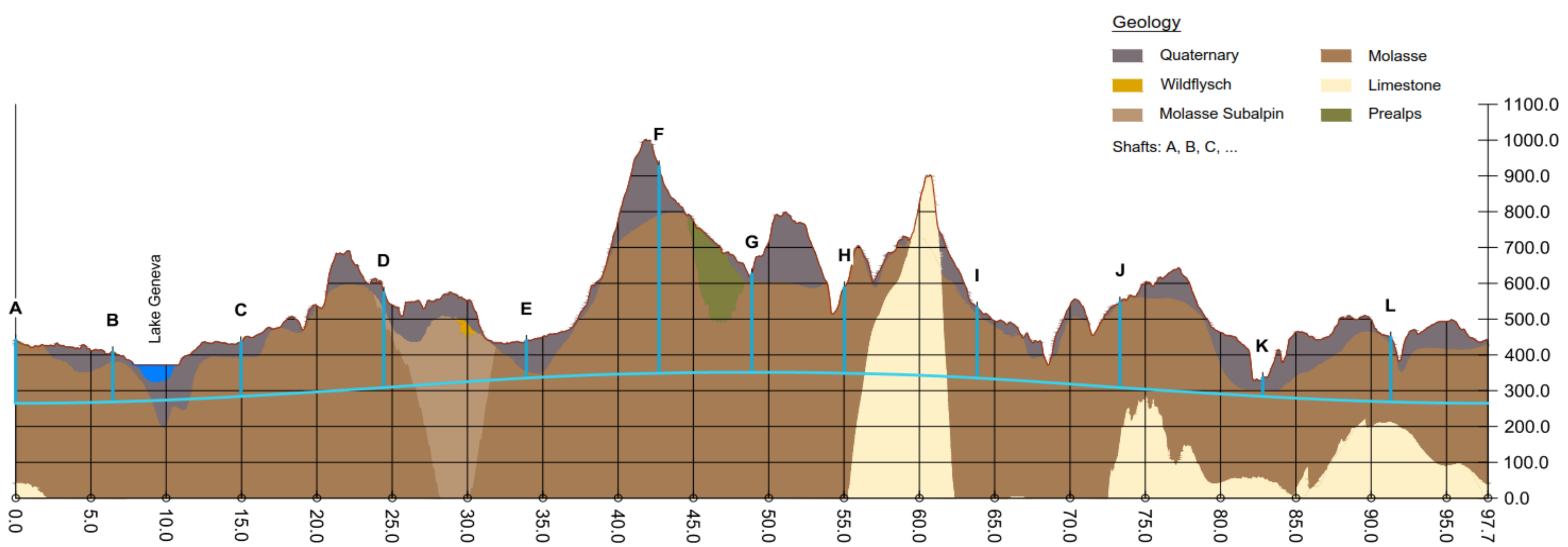


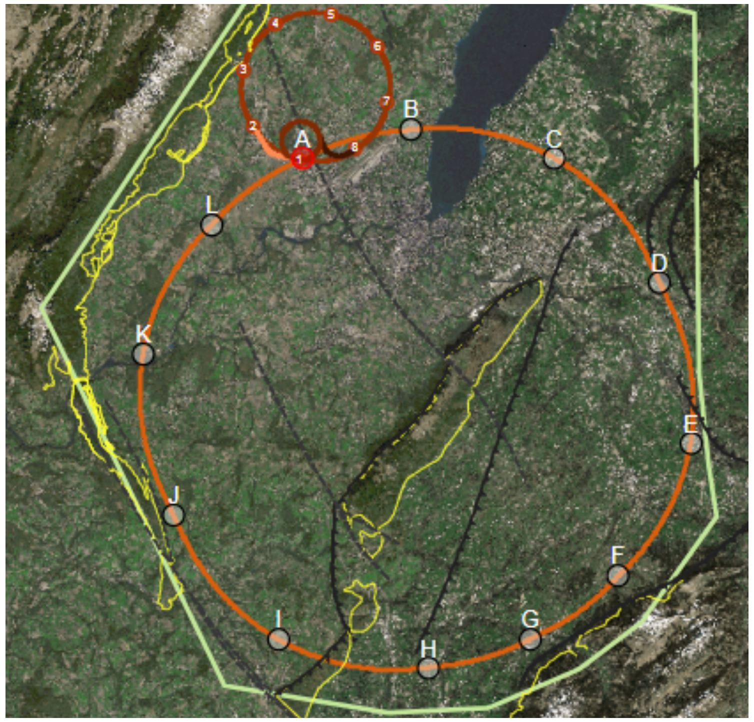
HE-LHC: The High Energy Large Hadron Collider

Copies can be requested at
http://get-fcc-cdr.web.cern.ch

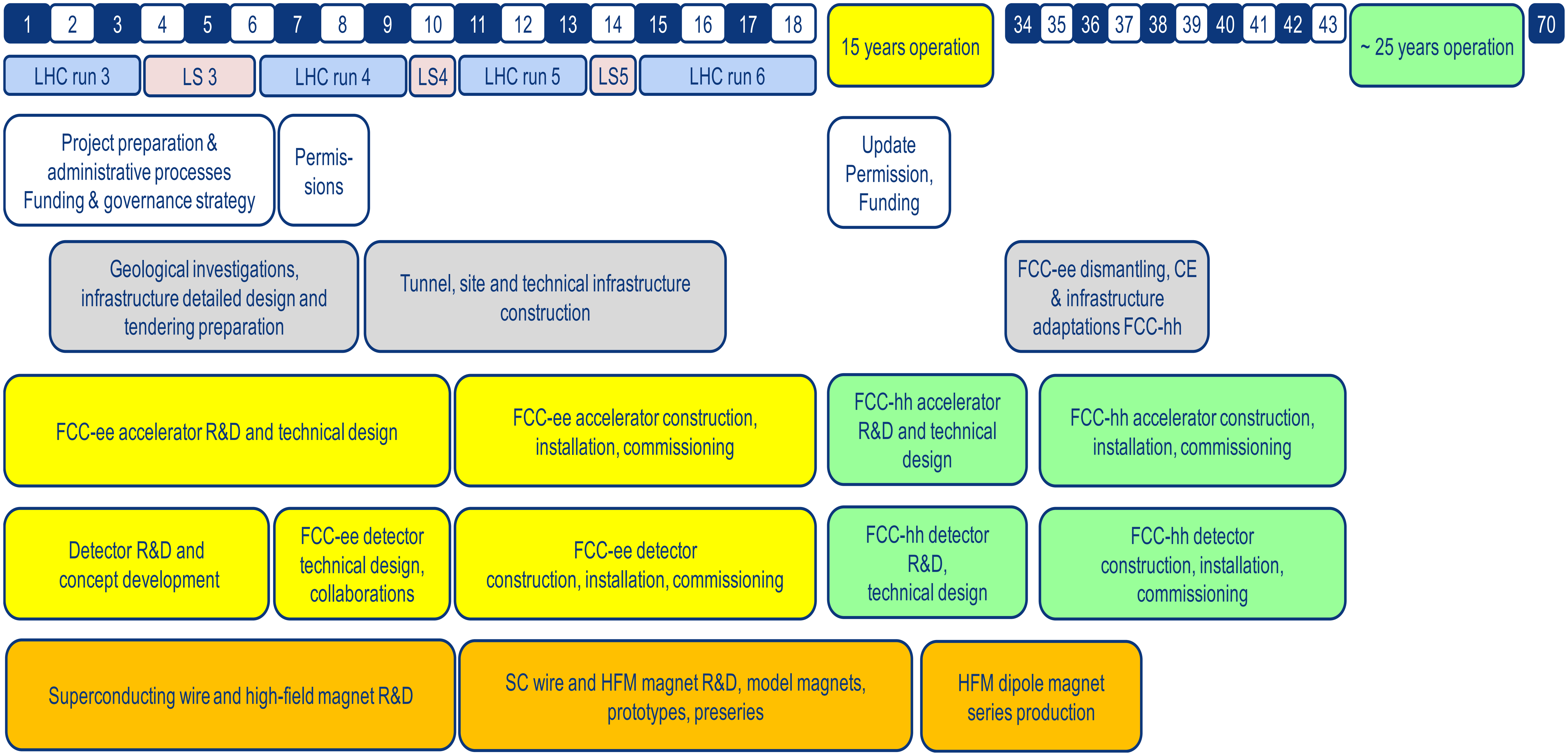
Program in two phase

- Phase 1: FCC-ee (Z, W, H, tt) as Higgs, EW and top factory at highest luminosities.
- Phase 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, with ion and eh options.





FCC Technical Schedule



FCC project plan is fully integrated with HL-LHC exploitation and provides seamless continuation of high energy physics at the energy frontier

FCC-ee Operations

➡ **A fantastic Higgs factory and much more**

➡ **Higgs factory**

- 10^6 $e^+e^- \to HZ$

➡ **EW & Top factory**

- 3×10^{12} $e^+e^- \to Z$
- 10^8 $e^+e^- \to W^+W^-$; 10^6 $e^+e^- \to tt$
- Transverse polarization
- Sensitive to NP up to 100 TeV

➡ **Flavor factory**

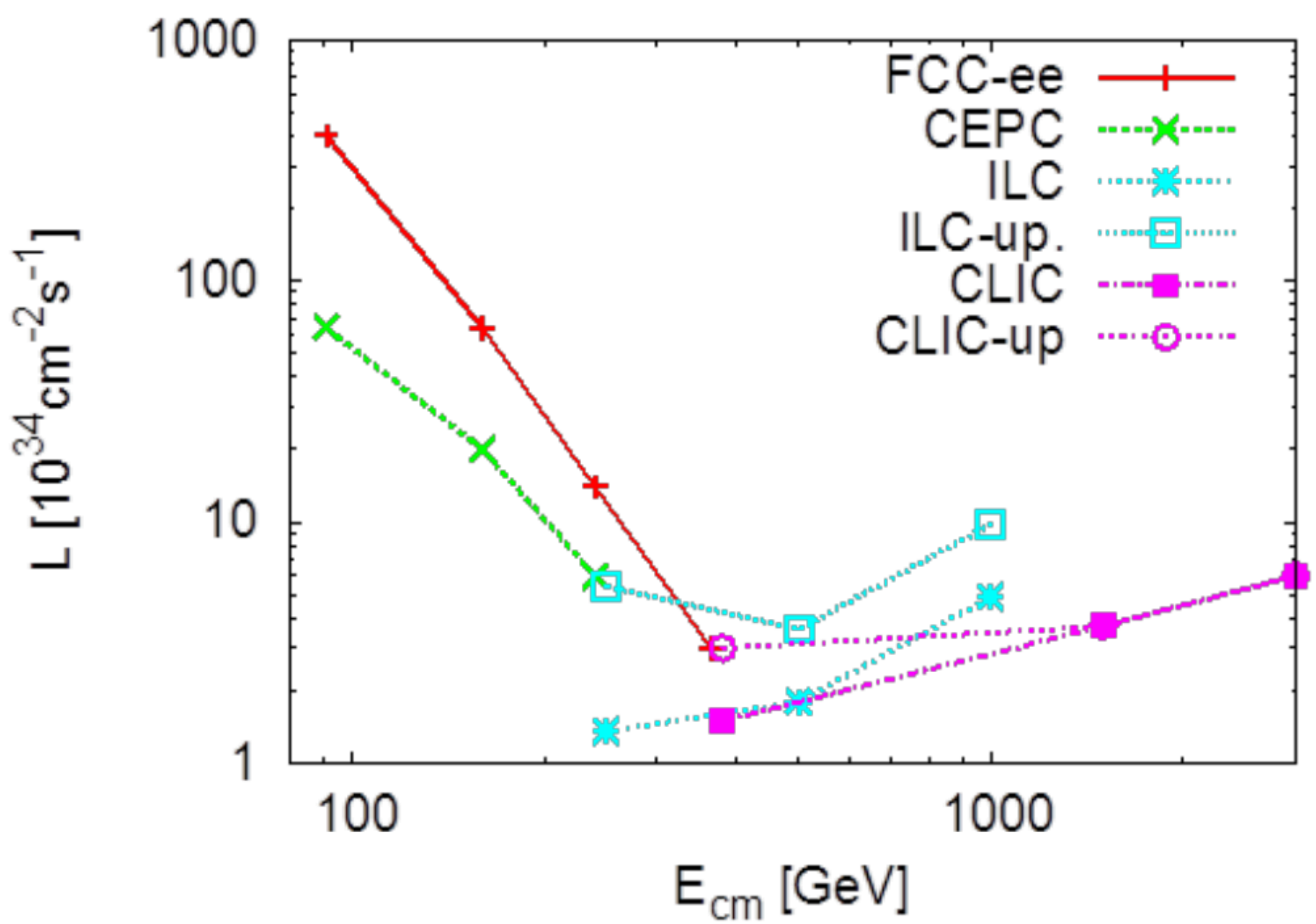
- 5×10^{12} $e^+e^- \to bb, cc$; 10^{11} $e^+e^- \to \tau^+\tau^-$

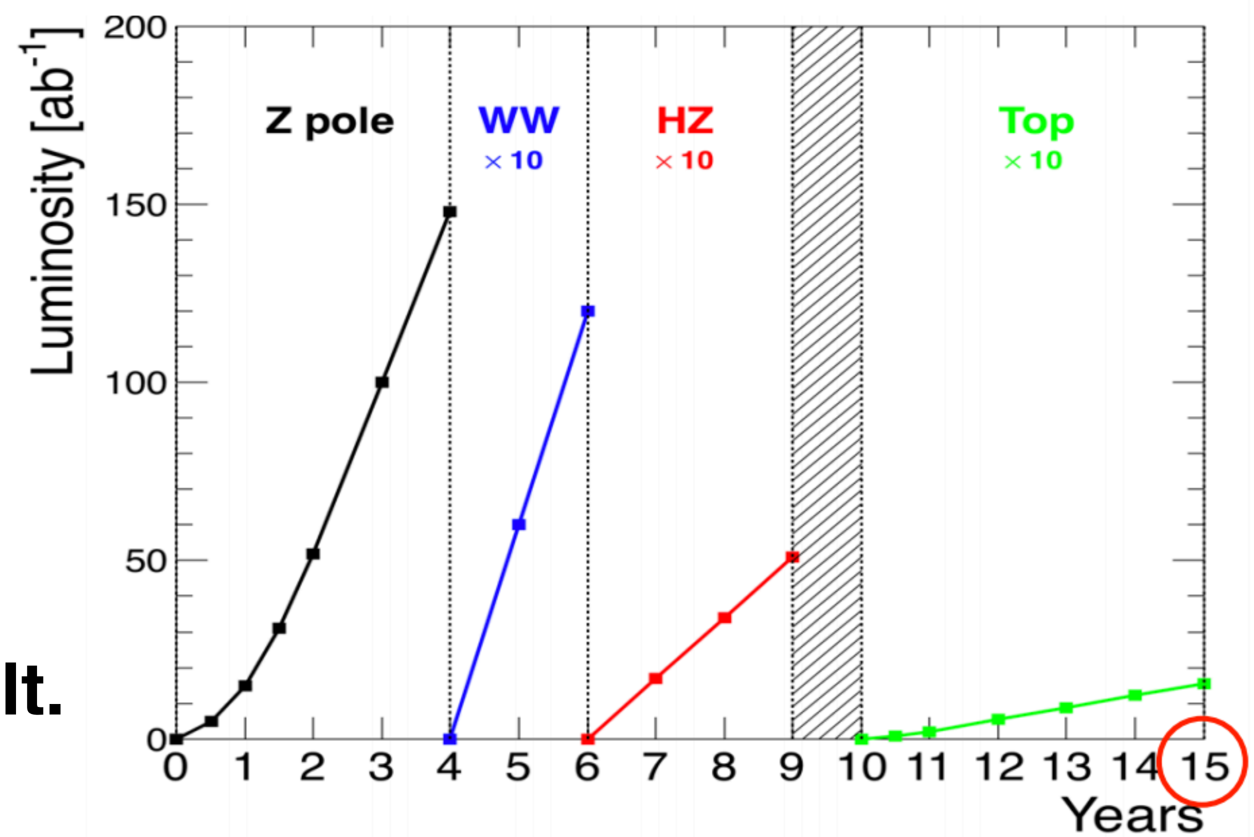
➡ **Precision tool**

- QED: (mZ), QCD (mZ), 10^5 $H \to gg$

➡ **Potential discovery of NP**

- ALPs, RH ν's, …





Schedule basis for CDR physics result. Can be modified or optimized!

FCC-ee Higgs Couplings

➡Unique measurements at highest precision

Collider	HL-LHC	ILC_{250}	$CLIC_{380}$	FCC-ee			FCC-eh
Luminosity (ab^{-1})	3	2	0.5	5 @ 240 GeV	+ 1.5 @ 365 GeV	+ HL-LHC	2
Years	25	15	8	3	+ 4	–	20
$\delta\Gamma_H/\Gamma_H$ (%)	SM	3.6	4.7	2.7	**1.3**	1.1	SM
$\delta g_{HZZ}/g_{HZZ}$ (%)	1.5	0.30	0.60	0.2	**0.17**	0.16	0.43
$\delta g_{HWW}/g_{HWW}$ (%)	1.7	1.7	1.0	1.3	**0.43**	0.40	0.26
$\delta g_{Hbb}/g_{Hbb}$ (%)	3.7	1.7	2.1	1.3	**0.61**	0.56	0.74
$\delta g_{Hcc}/g_{Hcc}$ (%)	SM	2.3	4.4	1.7	**1.21**	1.18	1.35
$\delta g_{Hgg}/g_{Hgg}$ (%)	2.5	2.2	2.6	1.6	**1.01**	0.90	1.17
$\delta g_{H\tau\tau}/g_{H\tau\tau}$ (%)	1.9	1.9	3.1	1.4	**0.74**	0.67	1.10
$\delta g_{H\mu\mu}/g_{H\mu\mu}$ (%)	4.3	14.1	n.a.	10.1	**9.0**	3.8	n.a.
$\delta g_{H\gamma\gamma}/g_{H\gamma\gamma}$ (%)	1.8	6.4	n.a.	4.8	**3.9**	1.3	2.3
$\delta g_{Htt}/g_{Htt}$ (%)	3.4	–	–	–	–	3.1	1.7
BR_{EXO} (%)	SM	< 1.8	< 3.0	< 1.2	$< \mathbf{1.0}$	< 1.0	n.a.

➡Uncertainties not limited by experimental or theoretical uncertainties. Statistics sets the floor.

➡Indirect sensitivity to Higgs self-coupling

FCC-ee EW & Top Physics Program

Table 3.1 Measurement of selected electroweak quantities at the FCC-ee, compared with the present precisions

Observable	Present value ± error	FCC-ee Stat.	FCC-ee Syst.	Comment and dominant exp. error
m_Z (keV)	$91{,}186{,}700 \pm 2200$	5	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	$2{,}495{,}200 \pm 2300$	8	100	From Z line shape scan Beam energy calibration
R_ℓ^Z $(\times 10^3)$	$20{,}767 \pm 25$	0.06	0.2–1.0	Ratio of hadrons to leptons acceptance for leptons
α_s (m_Z) $(\times 10^4)$	1196 ± 30	0.1	0.4–1.6	From R_ℓ^Z above [43]
R_b $(\times 10^6)$	$216{,}290 \pm 660$	0.3	< 60	Ratio of $b\bar{b}$ to hadrons stat. extrapol. from SLD [44]
σ_{had}^0 $(\times 10^3)$ (nb)	$41{,}541 \pm 37$	0.1	4	Peak hadronic cross-section luminosity measurement
N_ν $(\times 10^3)$	2991 ± 7	0.005	1	Z peak cross sections Luminosity measurement
$\sin^2\theta_W^{eff}$ $(\times 10^6)$	$231{,}480 \pm 160$	3	2–5	From $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{QED}$ (m_Z) $(\times 10^3)$	$128{,}952 \pm 14$	4	Small	From $A_{FB}^{\mu\mu}$ off peak [34]
$A_{FB}^{b,0}$ $(\times 10^4)$	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 Polarisation and charge asymmetry τ decay physics
m_W (MeV)	$80{,}350 \pm 15$	0.5	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
α_s (m_W) $(\times 10^4)$	1170 ± 420	3	Small	From R_ℓ^W [45]
N_ν $(\times 10^3)$	2920 ± 50	0.8	Small	Ratio of invis. to leptonic in radiative Z returns
m_{top} (MeV)	$172{,}740 \pm 500$	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	0.1	Small	From $t\bar{t}$ threshold scan QCD errors dominate
ttZ couplings	$\pm 30\%$	0.5–1.5%	Small	From $E_{CM} = 365$ GeV run

Z pole

WW

tt

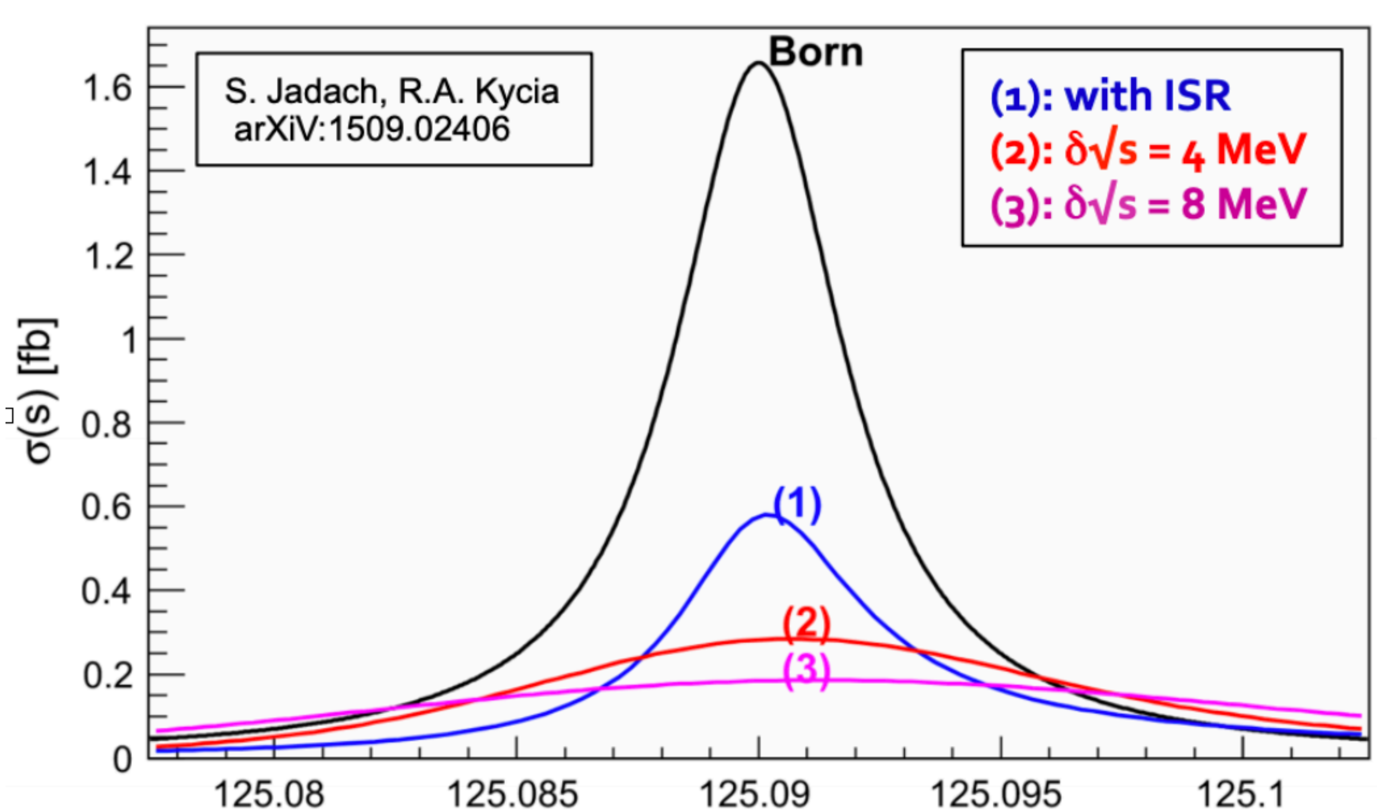
➡ First set of main observables

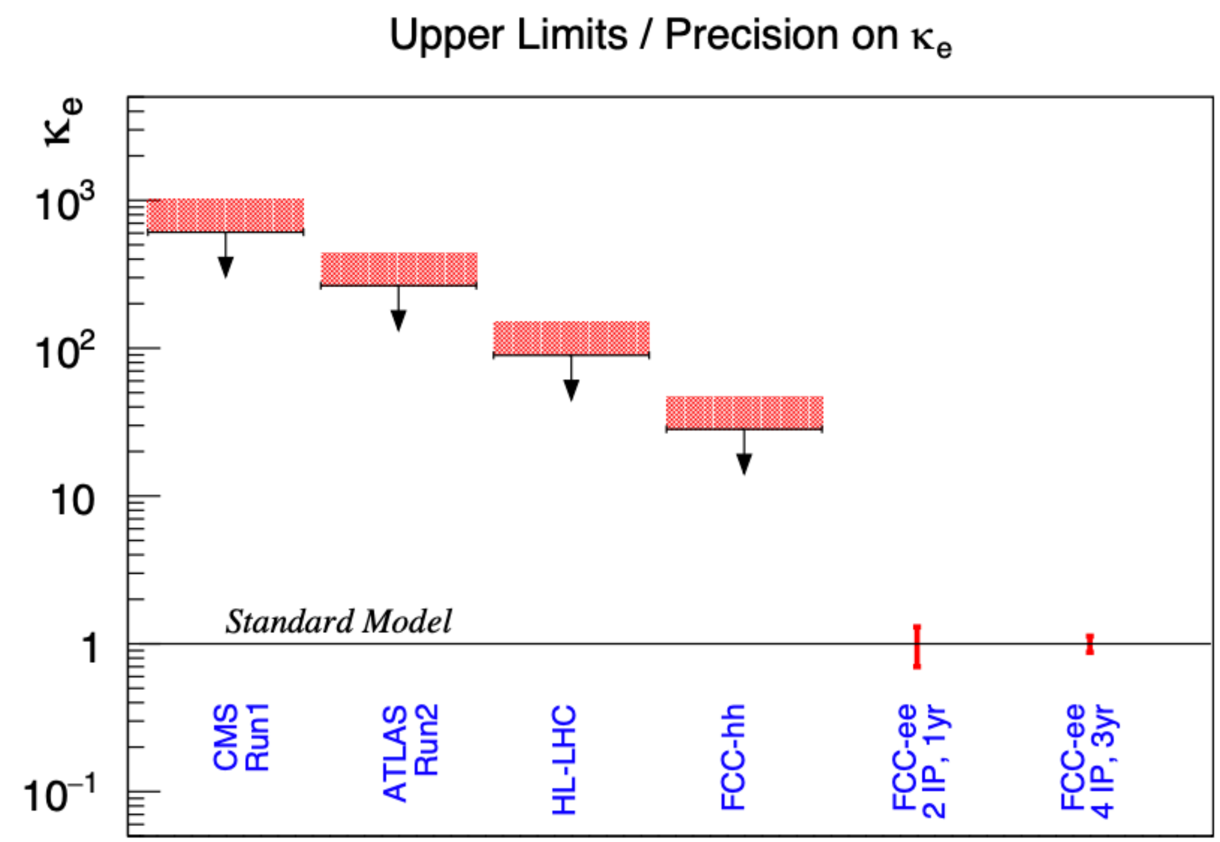
- **Statistical precision follows straight forward**
- **For Z and W boson mass, center-of-mass energy uncertainty will dominate**
- **For cross-section measurements the luminosity measurement will be limiting**
- **Possible experimental uncertainties are indicative**

Unique measurement at FCC-ee

➡ First generation Higgs couplings

- **Not part of baseline run plan but a few years at √s = mH with high luminosity is an interesting add-on**
- **Expected signal significance of 0.4σ / √ year in option 1 and 2 (see below)**
  - **Set a electron Yukawa coupling upper limit: k_e < 2.5 @95% CL**
  - **Reaches SM sensitivity after 5 years**





Physics Results (FCC-ee) Landscape

➡ **Possible FCC-ee discoveries**

➡ Exploring 10-100 TeV energy scale with **precision measurements**

➡ "Model independent" Higgs couplings

➡ Higgs self couplings

➡ m_Z, m_W, m_{top}, $\sin^2\Theta_w^{eff}$, R^b, $\alpha_{QED}(m_Z,m_W,m_\tau)$, top quark couplings

➡ Discovery of dark matter as invisible decays of H or others

➡ Discovery of very weakly coupled particles in 5-100 GeV range such as RH neutrinos, dark photons, ALPS, etc

➡ Discoveries in flavor physics and many more opportunities

➡ EW precision program essential to maximize Higgs factories potential

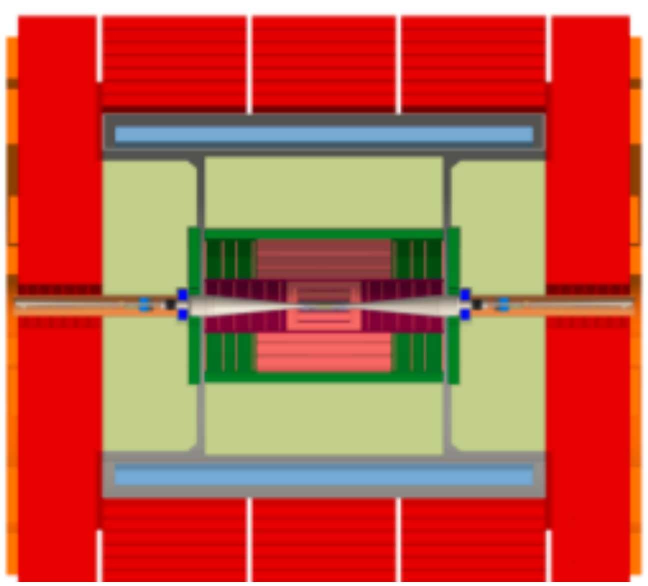
FCC-ee Detectors

Two detector concepts studied for integration, performance and cost estimates:

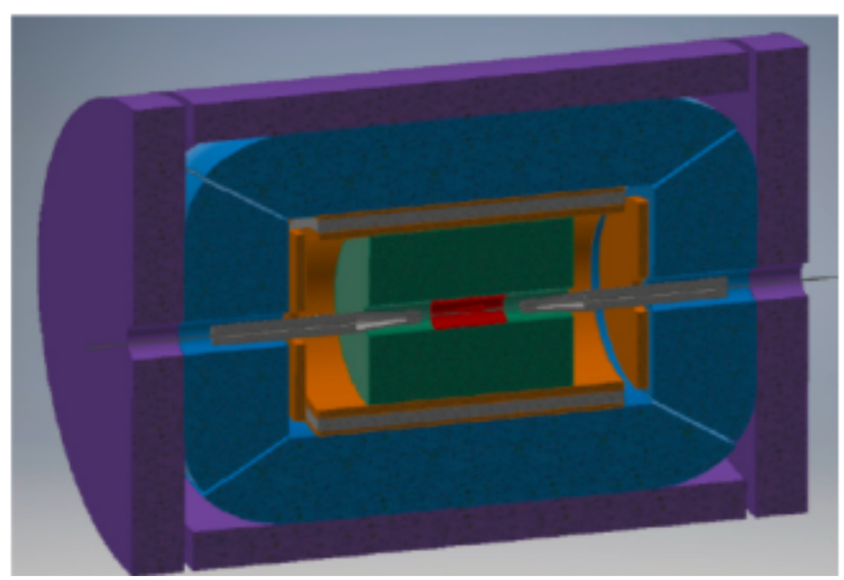
- Linear Collider Detector group at CERN has undertaken the adaption of CLIC-SID detector for FCC-ee
- IDEA, detector specifically designed for FCC-ee (and CEPC)

Next step is in optimizing detectors for physics

"CLIC-detector revisited"



"IDEA"



- Vertex detector: ALICE
- Tracking: MEG2
- Si Preshower
- Ultra-thin solenoid (2T)
- Calorimeter: DREAM
- Equipped return yoke

European Strategy

2013: To stay at the forefront of particle physics … CERN should undertake design studies … with emphasis on proton-proton and electron-positron high-energy frontier machines

2018/19: Physics Briefing book published as result of bottom-up community contributions https://arxiv.org/abs/1910.11775

2020: Recommendation discussed at March 15th CERN Council meeting **but** the meeting to endorse the strategy in May has been cancelled due to COVID-19

FCC Main Goals (2020-2026)

Overall goal

- Perform all necessary steps and studies to enable a definitive project decision by 2025/26, at the anticipated date for the next ESU, and a subsequent start of civil engineering construction by 2028/29.

This requires successful completion of the following four main activities

- Develop and establish a governance model for project construction and operation
- Develop and establish a financing strategy
- Prepare and successfully complete all required project preparatory and administrative processes with the host states (debat public, EIA, etc.)
- Perform site investigations to enable CE planning and to prepare CE tendering.

In parallel development preparation of TDRs and physics/ experiment studies

- Machine designs and main technology R&D lines
- Establish user communities, work towards proto-experiment collaboration by 2025/26.

Conclusion: FCC

- **International FCC study** focused on the conceptual design of high-performance **energy frontier circular colliders for the post-LHC era**.

- The **first phase of FCC conceptual design studies is completed**.

- Baseline machine designs and associated infrastructures, with performance matching the physics requirements, were established and are documented in **4 CDRs**.

- **Conditional on European Strategy recommendations**, the next steps will develop a concrete implementation plan in collaboration with host states, accompanied by machine optimization, physics studies and technology R&D.

Conclusion: FCC-ee

- ➡ FCC-ee is a Z, W, H, top (and NP) factory with exciting opportunities
- ➡ FCC-ee Higgs factory offers a unique dataset from 240 to 365 GeV
  - Delivers model-independent precision measurements of Higgs properties
  - Couplings including self-coupling, mass, CP, …
  - The floor is statistical
- ➡ EW and Higgs observables probe the scales to up to 50 TeV
  - Gain of 1-2 orders of magnitude in precision
  - EW precision measurements enable high accuracy Higgs program
- ➡ Synergy and complementarity to hadron collider physics programs (HL-LHC, FCC-hh)

References

- ➡ 4 CDR volumes
- ➡ First look at the physics case of TLEP
  - JHEP 1401 (2014) 164; > 500 citations
- ➡ FCC The Lepton Collider
  - Eur. Phys. JST (2019)
- ➡ FCC Physics Opportunities
  - Eur. Phys. J. C. (2019) 79:474
- ➡ FCC-ee: Your Questions Answered
  - arXiv:1906.02693
- ➡ Jan'20 FCC physics workshop
  - https://indico.cern.ch/event/838435/