

Resistive Plate Chambers as charged-particle trigger detectors: from the HL- LHC to the FCC

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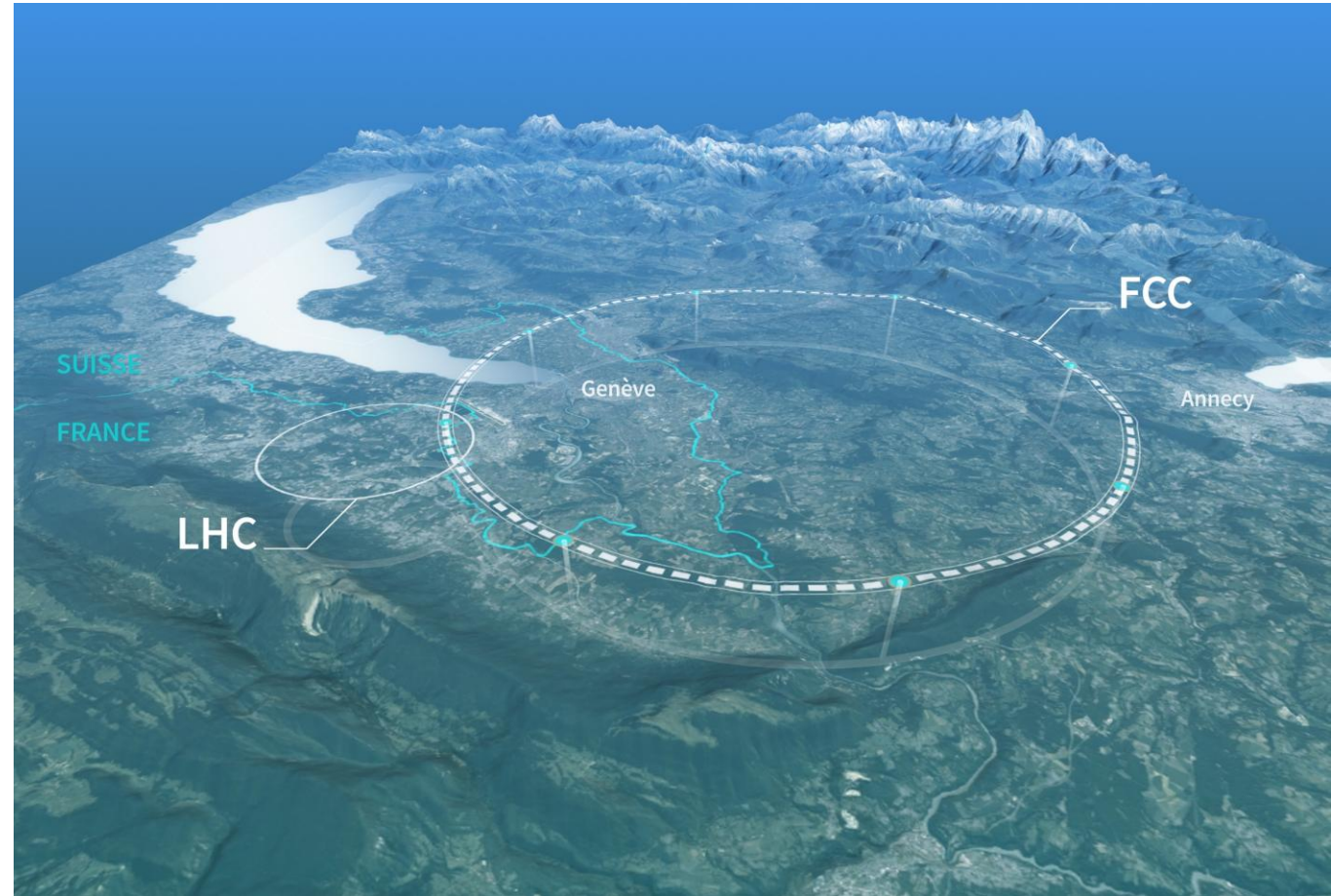
Outlook

- Introduction
- Reasons for the Future Circular Colliders
- RPCs for a muon-trigger detector at the FCC-ee
- RPCs for a muon-trigger detector at the FCC-hh
- Conclusion

Preparing CERN's future

Driven by the **2020 Update of the European Strategy for Particle Physics**

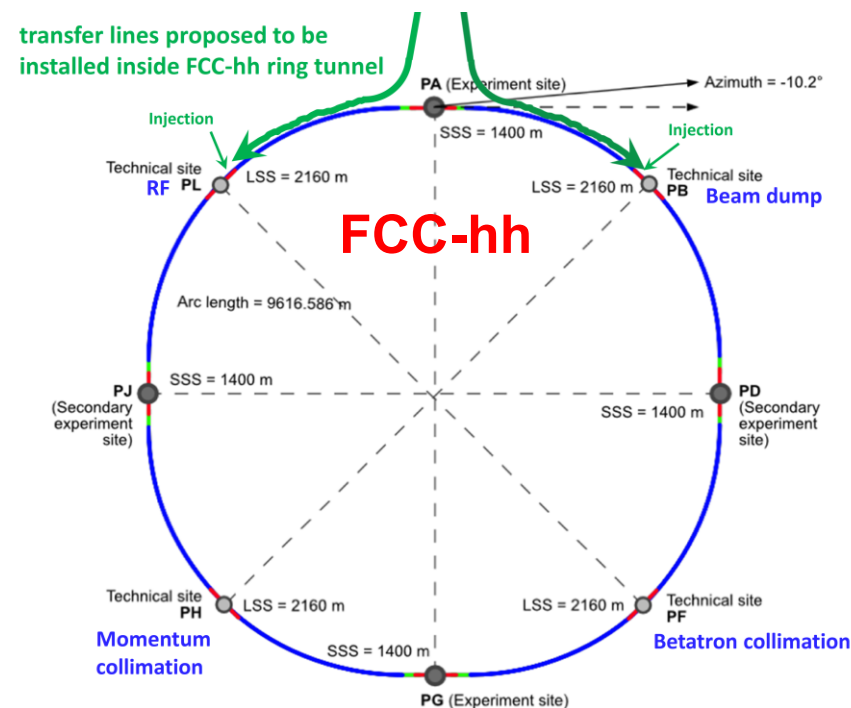
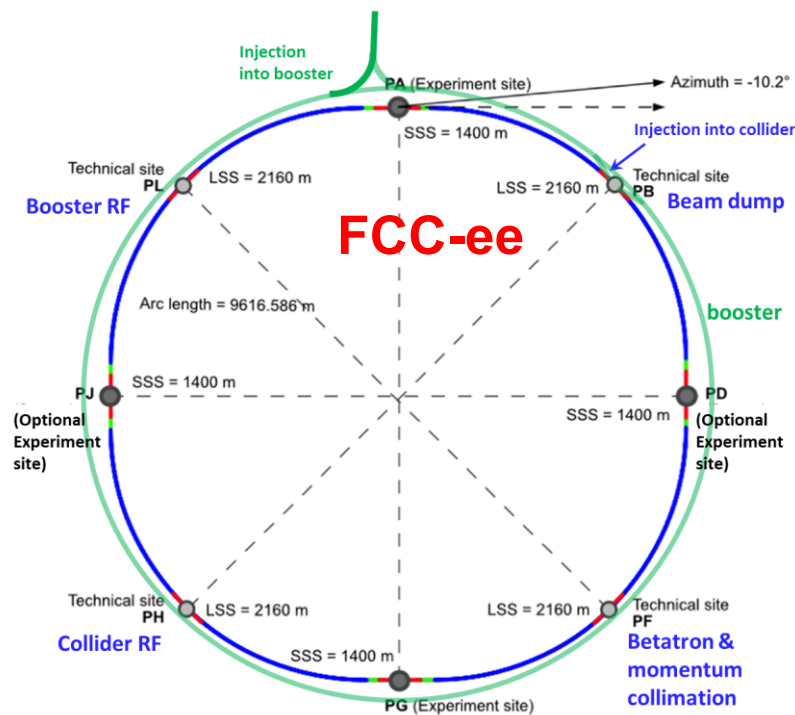
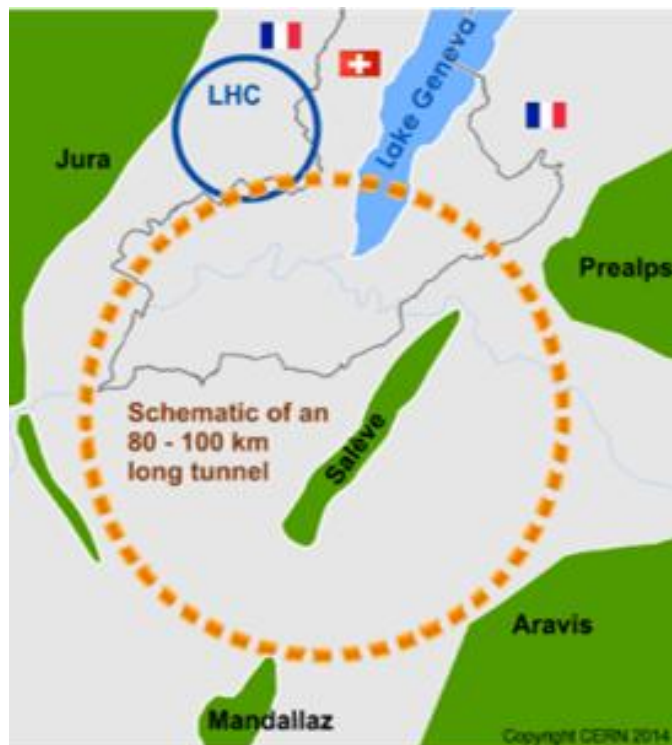
- Technical and financial feasibility study of a Future Circular Collider (report in 2025)
- Accelerator R&D to develop technologies for FCC and for alternative options
- Detector and computing R&D
- Maintain and expand a compelling scientific diversity programme
- Continue to support other projects around the world



FCC Integrated Programme

Comprehensive long-term programme maximising physics opportunities

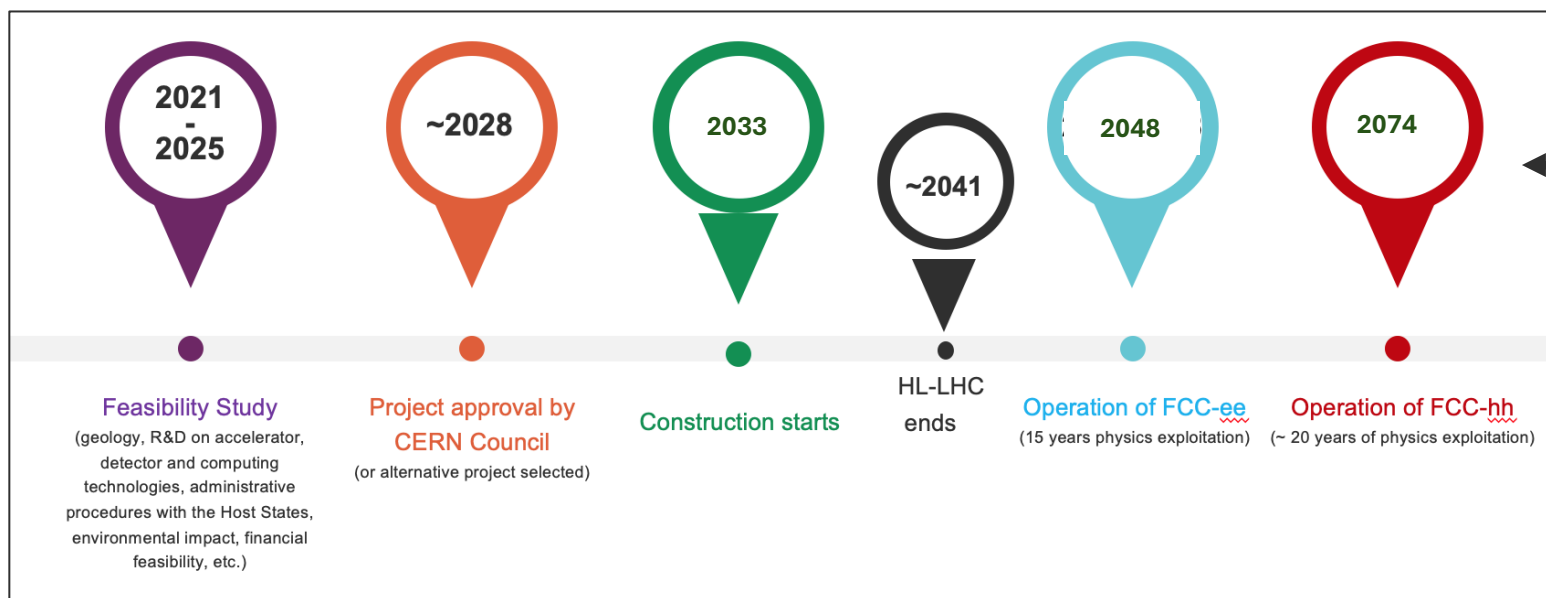
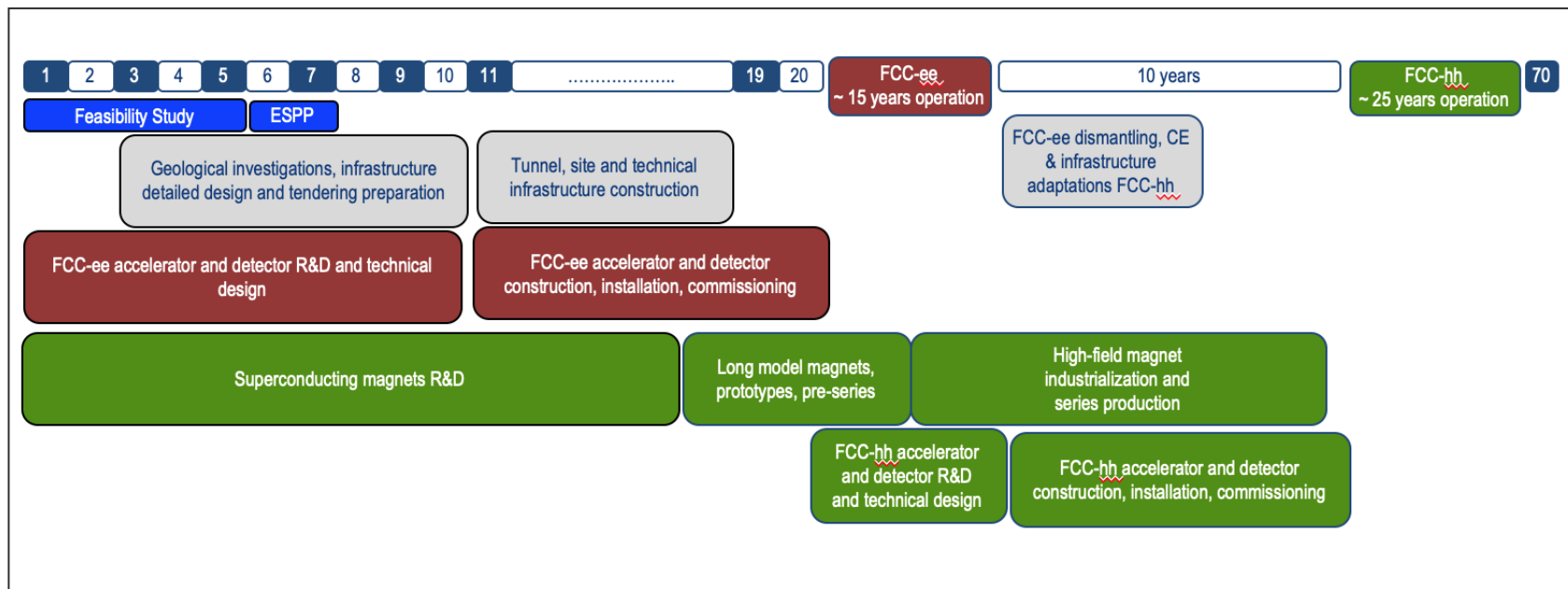
- Stage 1: FCC-ee (Z, W, H, $t\bar{t}$) as Higgs factory, electroweak & top factory at highest luminosities
- Stage 2: FCC-hh (~ 100 TeV) as natural continuation at energy frontier, pp & AA collisions; e-h option
- Highly synergetic and complementary programme boosting the physics reach of both colliders
- Common civil engineering and technical infrastructures, building on and reusing CERN's existing infrastructure
- FCC integrated project allows the start of a new, major facility at CERN within a few years of the end of HL-LHC



FCC Integrated Programme - Timeline

Note: FCC Conceptual Design Study started in 2014 leading to CDR in 2018

FCC construction can proceed in parallel with HL-LHC operation.



“Realistic” schedule taking into account:

- ☐ past experience in building colliders at CERN
- ☐ approval timeline: ESPP, Council decision
- ☐ that HL-LHC will run until 2041

Can be accelerated if more resources available

FCC-ee: Main Machine Parameters

Parameter	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45.6	80	120	182.5
beam current [mA]	1270	137	26.7	4.9
number bunches/beam	11200	1780	440	60
bunch intensity [10^{11}]	2.14	1.45	1.15	1.55
SR energy loss / turn [GeV]	0.0394	0.374	1.89	10.4
total RF voltage 400/800 MHz [GV]	0.120/0	1.0/0	2.1/0	2.1/9.4
long. damping time [turns]	1158	215	64	18
horizontal beta* [m]	0.11	0.2	0.24	1.0
vertical beta* [mm]	0.7	1.0	1.0	1.6
horizontal geometric emittance [nm]	0.71	2.17	0.71	1.59
vertical geom. emittance [pm]	1.9	2.2	1.4	1.6
horizontal rms IP spot size [μm]	9	21	13	40
vertical rms IP spot size [nm]	36	47	40	51
beam-beam parameter ξ_x / ξ_y	0.002/0.0973	0.013/0.128	0.010/0.088	0.073/0.134
rms bunch length with SR / BS [mm]	5.6 / 15.5	3.5 / 5.4	3.4 / 4.7	1.8 / 2.2
luminosity per IP [$10^{34} \text{ cm}^{-2}\text{s}^{-1}$]	140	20	5.0	1.25
total integrated luminosity / IP / year [ab^{-1}/yr]	17	2.4	0.6	0.15
beam lifetime rad Bhabha + BS [min]	15	12	12	11

4 years
 5×10^{12} Z
 LEP $\times 10^5$

2 years
 $> 10^8$ WW
 LEP $\times 10^4$

3 years
 2×10^6 H

5 years
 2×10^6 tt pairs

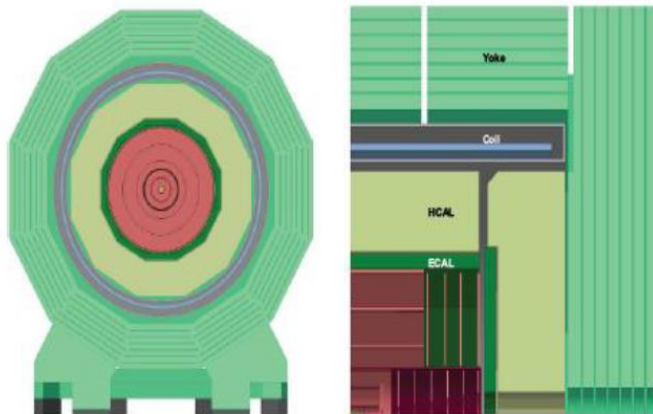
Design and parameters dominated by the choice to allow for 50 MW synchrotron radiation per beam.

- Up to x2000 improvement on all EW observables
- Up to x10 improvement on Higgs coupling (model-indep.) measurements over HL-LHC
- x10 Belle II statistics for b, c, τ
- indirect discovery potential up to ~ 70 TeV
- direct discovery potential for feebly-interacting particles over 5-100 GeV mass range

Up to 4 interaction points $\rightarrow$ robustness, statistics, possibility of specialised detectors to maximise physics output

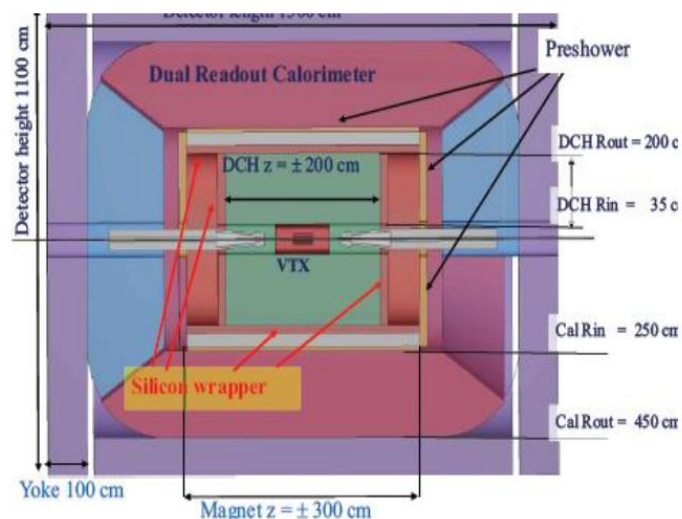
Detectors Under Study for FCC-ee

CLD



- conceptually extended from the CLIC detector design
- full silicon tracker
- 2T magnetic field
- high granular silicon-tungsten ECAL
- high granular scintillator-steel HCAL
- instrumented steel-yoke with RPC for muon detection

IDEA



- explicitly designed for FCC-ee/CepC
- silicon vertex
- low X_0 drift chamber
- drift-chamber silicon wrapper
- MPGD/magnet coil/lead preshower
- dual-readout calorimeter: lead-scintillating/cerenkov fibers

Noble Liquid ECAL



- explicitly designed for FCC-ee, recent concept, under development
- silicon vertex
- Low X_0 drift chamber
- Thin Solenoid before the Calorimeter
- High Granularity Liquid Argon Calorimetry

But several other options like Crystal Calorimetry (active in US, Italy), are under study (similarly for tracking, muons and particle ID) and Time Projection Chamber (TPC) of ILD

With potentially 4 experiments, many complementary options will be implemented, Definitely a place to contribute

Muon detection at FCC-ee

- The Muon detector requirements at FCC-ee are not extreme
- Existing technologies can do the job, but further development can improve the physics reach
- Proposals at the various detector concepts mostly reflect the expertise/R&D of interested Institutes
- At LHC experiments the Muon system are mostly based on gaseous detectors



- ALICE
 - CSC
 - MWPC
 - RPC
 - Timing RPC

- ATLAS
 - MDT
 - CSC
 - TGC, sTGC
 - RPC
 - Micromegas

- CMS
 - DT
 - CSC
 - RPC
 - GEM

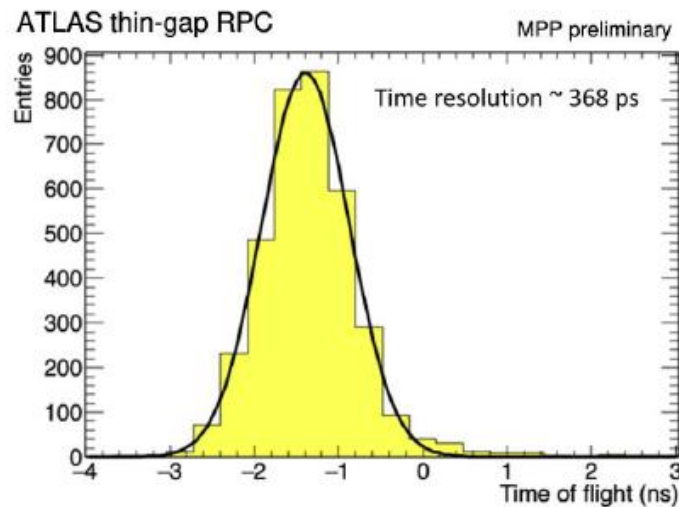
- LHCb
 - MWPC
 - GEM

Gaseous detectors at the 4 large LHC experiments,
(Run1, Run2 and Run3)

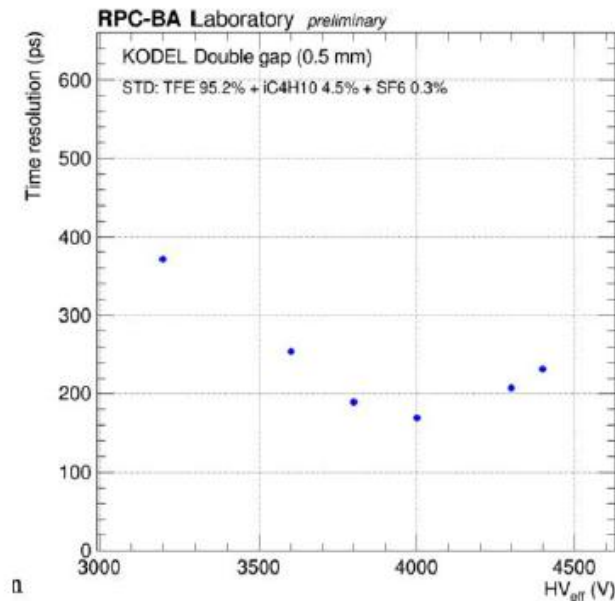
- Same for FCC-ee, but not exclusively:
 - Micro Pattern Gaseous Detectors (MPGD): μ RWELL and Micromegas
 - RPC
 - Drift tubes
 - Scintillators bars with SiPM

Resistive Plate Chambers

- Improved RPC with the aim to reach 100 ps time resolution (Eol [link](#))
 - Reduced gas gap: 1 mm or less
 - Low-threshold (down to 1 fC), low-noise FE elx
 - ~100 ps reachable with bi-gap configuration



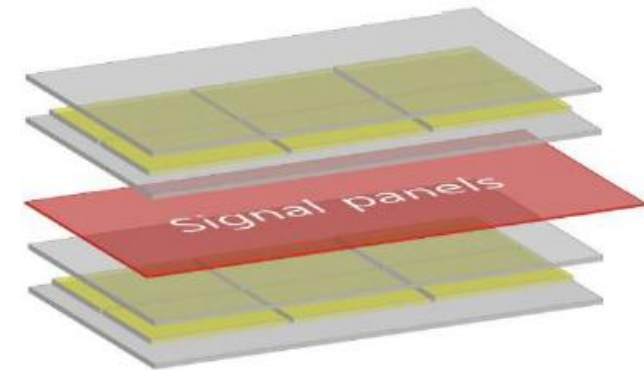
ATLAS Phase-II RPC prototype:
400 ps time resolution



Kodel bi-gap RPC: <200 ps time
resolution



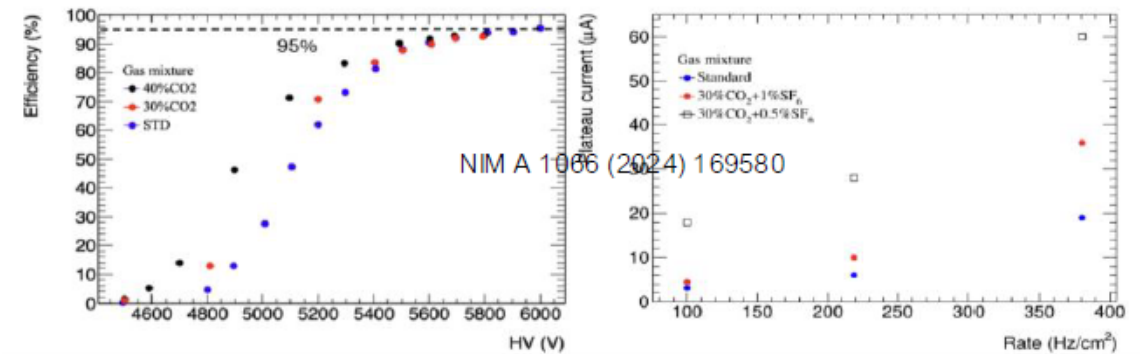
Small-gap RPC used in ATLAS and
CMS Phase-II upgrade



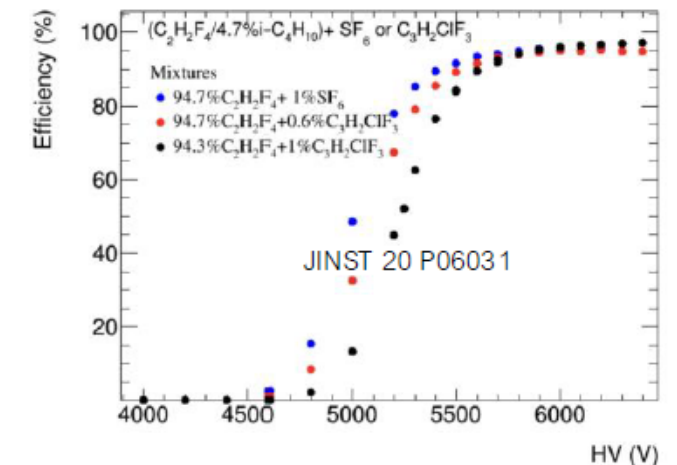
Bi-gap RPC: one signal panel
sandwiched between two gas gaps

RPCs: search for eco-gas replacements

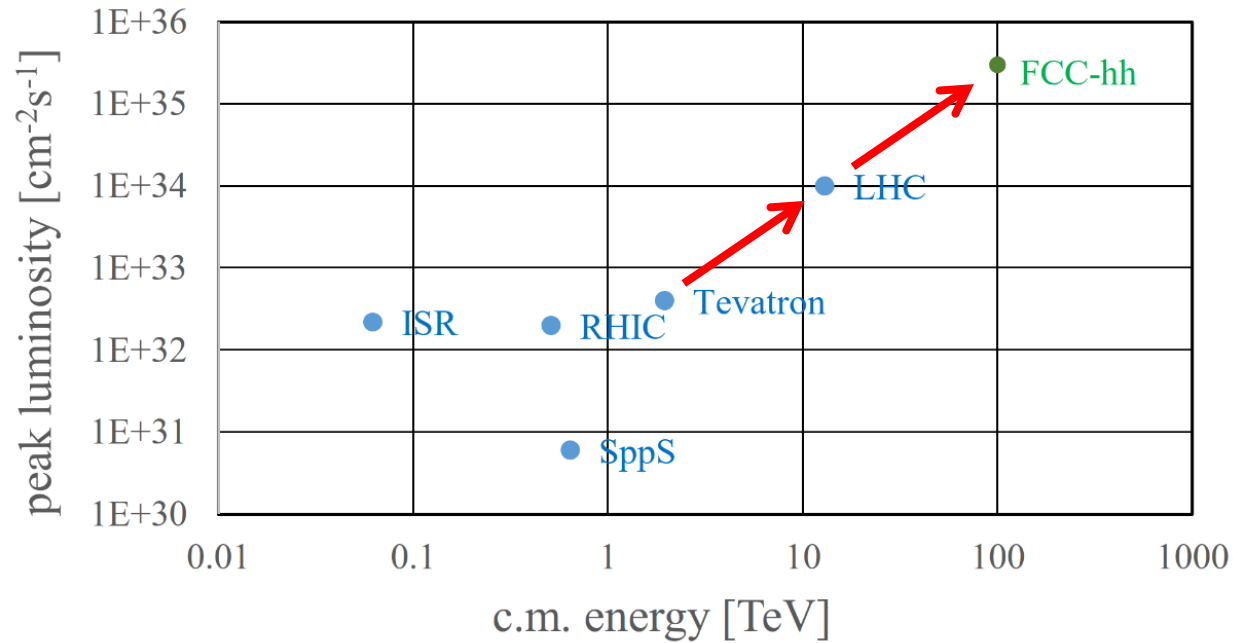
- Modern HEP must face regulation for the environmental sustainability
- The RPC at LHC use high global warming power (GWP) gases: TFE (R134a) and SF₆
- Regulations evolve with time: the current 'standard mixture' was identified as an alternative to freon (ozone depleting gas) used in LEP experiments
- Intense efforts ongoing to find eco-friendly gases
 - ATLAS replaced 30% of TFE with CO₂ in Run3
 - HFOs are being explored as alternative to TFE, but could undergo the PFAS ban in a near future
 - Promising alternative to SF₆ is under test
 - Back to LEP mixture: Ar/isobutane + 6% TFE? ...



Component	GWP	Vol conc. (%) STD	Vol conc. (%) 30% CO ₂ , 1% SF ₆	Vol conc. (%) 30% CO ₂ , 0.5% SF ₆	Vol conc. (%) 1% C ₃ H ₂ ClF ₃
C ₂ H ₂ F ₄ (R-134A)	1430	94.7	64	64.5	64
iC ₄ H ₁₀	3	5	5	5	5
SF ₆	22800	0.3	1	0.5	0
CO ₂	1	0	30	30	30
C ₃ H ₂ ClF ₃	4.5	0	0	0	1
Mixture GWP		1481	1266	1107	~950

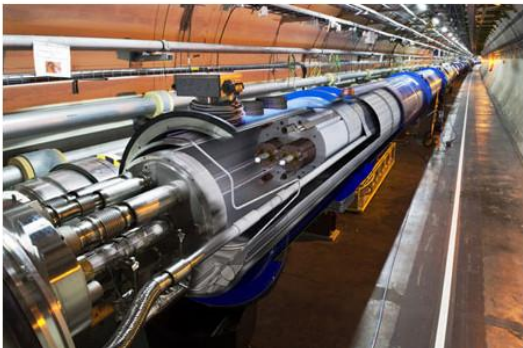


FCC-hh: Highest Collision Energies

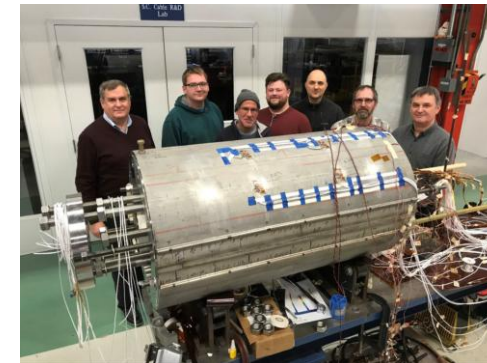


- **Order of magnitude performance increase** in both **energy & luminosity**
- **100 TeV collision energy** (vs 14 TeV for LHC)
- **20 ab^{-1} per experiment collected over 25 years** of operation (vs 3 ab^{-1} for LHC)
- Similar performance increase as from Tevatron to LHC
- **Key technology: high-field magnets**

from
LHC technology
8.3 T NbTi dipole



via
HL-LHC technology
12 T Nb_3Sn quadrupole



FNAL dipole
demonstrator
14.5 T Nb_3Sn

FCC-hh – Main Machine Parameters

parameter	FCC-hh	HL-LHC	LHC
collision energy cms [TeV]	81 - 115	14	
dipole field [T]	14 - 20	8.33	
circumference [km]	90.7	26.7	
arc length [km]	76.9	22.5	
beam current [A]	0.5	1.1	0.58
bunch intensity [10^{11}]	1	2.2	1.15
bunch spacing [ns]	25	25	
synchr. rad. power / ring [kW]	1020 - 4250	7.3	3.6
SR power / length [W/m/ap.]	13 - 54	0.33	0.17
long. emit. damping time [h]	0.77 – 0.26	12.9	
peak luminosity [$10^{34} \text{ cm}^{-2}\text{s}^{-1}$]	~30	5 (lev.)	1
events/bunch crossing	~1000	132	27
stored energy/beam [GJ]	6.1 - 8.9	0.7	0.36
Integrated luminosity/main IP [fb^{-1}]	20000	3000	300

With FCC-hh after FCC-ee:

Significantly more time for high-field magnet R&D aiming at highest possible energies

Formidable challenges:

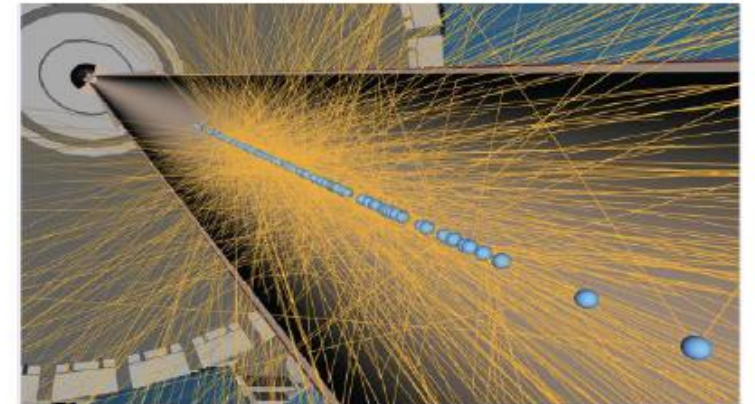
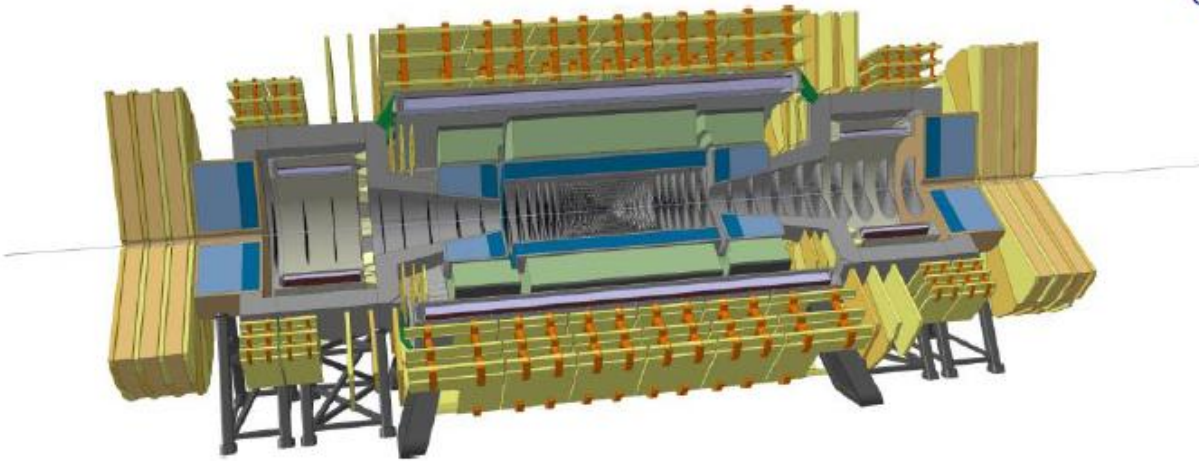
- ❑ high-field superconducting magnets: 14 - 20 T
- ❑ power load in arcs from synchrotron radiation: 4 MW → cryogenics, vacuum
- ❑ stored beam energy: ~ 9 GJ → machine protection
- ❑ pile-up in the detectors: ~1000 events/xing
- ❑ energy consumption: 4 TWh/year → R&D on cryo, HTS, beam current, ...

Formidable physics reach, including:

- ❑ Direct discovery potential up to ~ 40 TeV
- ❑ Measurement of Higgs self to ~ 5% and ttH to ~ 1%
- ❑ High-precision and model-indep (with FCC-ee input) measurements of rare Higgs decays ($\gamma\gamma$, $Z\gamma$, $\mu\mu$)₁₂
- ❑ Final word about WIMP dark matter

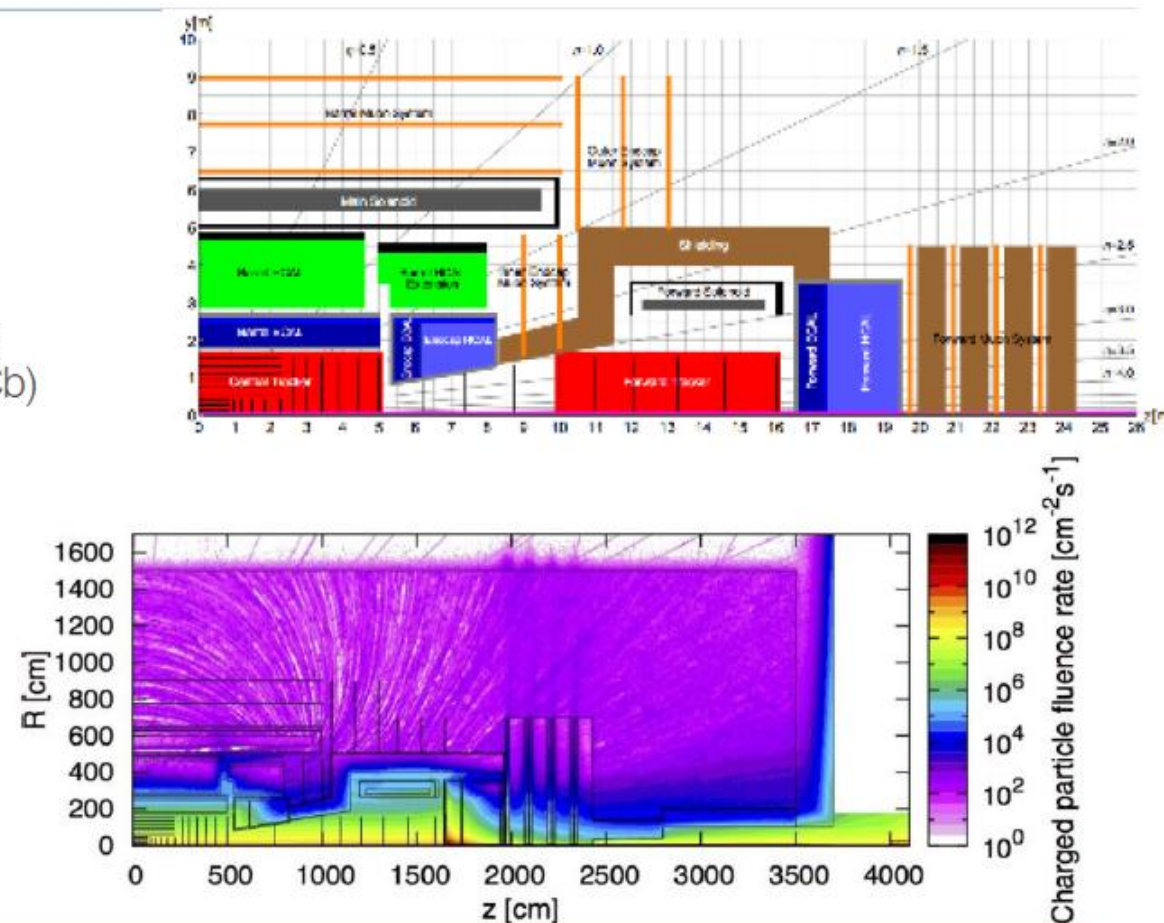
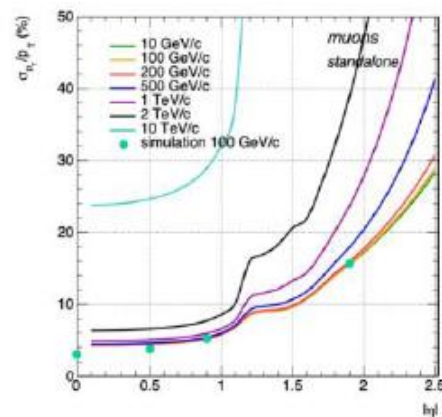
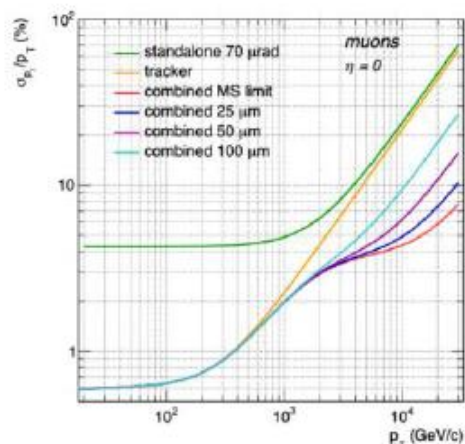
Muon System at the FCC

- FCC-ee: Low background, high precision, focus on acceptance control and particle ID.
- FCC-hh: Extreme radiation environment, high rates (up to 30 kHz/cm²), and high-momentum resolution for TeV-scale muons.
- The leap to 100 TeV:
 - Muon rates increase by orders of magnitude
 - Requirement for trigger-less readout and ultra-fast timing to reject pile-up (up to ~1000)
 - Need for high-resolution tracking in the forward region ($\eta > 3$)
- Upgrades for HL-LHC are a good starting points, main challenges will be pushed further
 - High-dose, radiation, longevity...
 - High pile-up



Muon System at FCC-hh

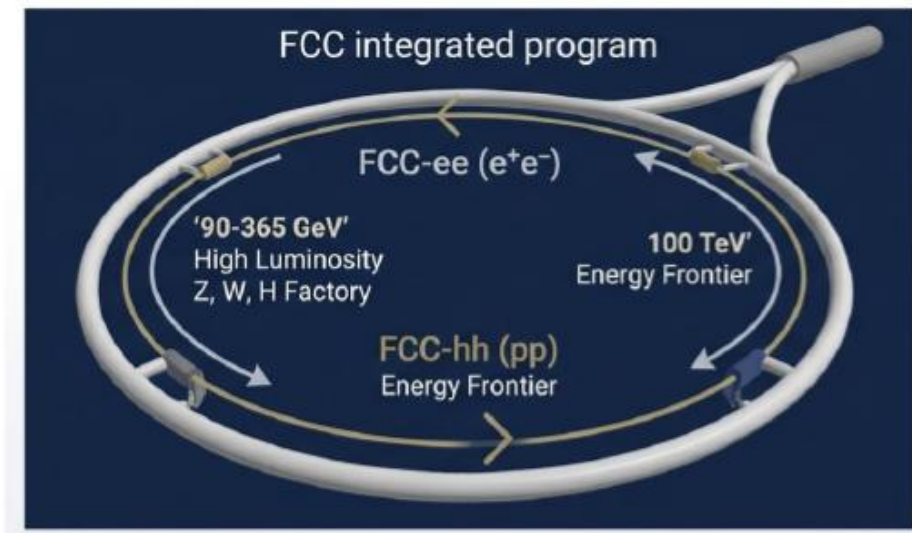
- No standalone muon performance required, but can help
→ minimum requirement: muon ID
- Requirement for combined muon momentum resolution:
10% for momenta of 20 TeV/c at $\eta = 0$.
- In forward muon system, muon measurement and triggering
can only be achieved with a forward dipole (like ALICE, LHCb)



- Gas detectors developed for HL-LHC are good candidates for the muon systems
- Different choices for Barrel&Outer EC and Inner EC
- Dedicated R&D needed to exploit recent trends in frontier detectors (sub-ns time res., $O(1)$ MHz/cm² rate capability, longevity, eco-friendly gas etc.)

Conclusion

- Muon detectors at future e^+e^- colliders must provide excellent muon identification capability to fully exploit the physics potential of the experiments
- Good timing and standalone measurement capability can extend the physics reach
- Most of the available technology have sufficient performance for the FCC-ee experiments
- Ongoing R&D oriented to
 - Consolidate the technologies
 - Simplification and cost-saving
 - Optimization for the specific detector design
- Redundancy and longevity keywords for long-term operations



- The FCCee detector concepts are in the exciting design phase
- Ideal environment for new ideas and to foster collaborations based on enthusiasm
- The effort must be synergic with the LHC upgrades

The detector community engaged in the LHC upgrades has the responsibility to maintain the high credibility of the field at the time when we are asking to build the largest machine ever

Conclusion

- An RPC-based muon-trigger system at FCC-hh will need more advances in the detector requirements, and specifically:
 - Higher rate capability due to the greater expected counting rate
 - Well-established operating gas mixture, totally eco-friendly (as low F-concentration as possible) and recyclable
 - Advanced read-out and trigger electronics to sustain the high speed and counting rate
 - A wide international scientific collaboration focused on building a subdetector about 10 times larger than the RPC systems installed in ATLAS and CMS
- I thank my colleague P. Iengo for fruitful discussion and support

Backup

FCC-ee in a Nutshell

- **High luminosity precision study of Z, W, H, and $t\bar{t}$**
 - $2 \times 10^{36} \text{ cm}^{-2}\text{s}^{-1}/\text{IP}$ at Z (or total $\sim 10^{37} \text{ cm}^{-2}\text{s}^{-1}$ with 4 IPs)
 - $7 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ at ZH, $1.3 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ at $t\bar{t}$
 - Unprecedented energy resolution at Z (<100 keV) and W (<300 keV)
- **Low-risk technical solution** based on 60 years of e^+e^- circular colliders and particle detectors ; R&D on components for improved performance, but no need for “demonstration” facilities; LEP2, VEPP-4M, PEP-II, KEKB, DAΦNE, or SuperKEKB already used many of the key ingredients in routine operation
- Infrastructure will support a **century of exciting physics of discovery**
 - FCC-ee $\rightarrow$ FCC-hh $\rightarrow$ FCC-eh and/or several other options (FCC- $\mu\mu$, Gamma Factory ..)
- **Utility requirements** similar to CERN existing use
- **Strong support** from CERN, partners & particle physics roadmaps (Europe, US)
- **Detailed multi-domain feasibility study underway** for next European Strategy