KPS Autumn Meeting
Jeju, October 22nd, 2026

The FCC program and the detector concepts for FCC-ee

Paolo Giacomelli
INFN Bologna and CERN

Outline

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- Complementarity between a lepton collider and a high energy pp collider

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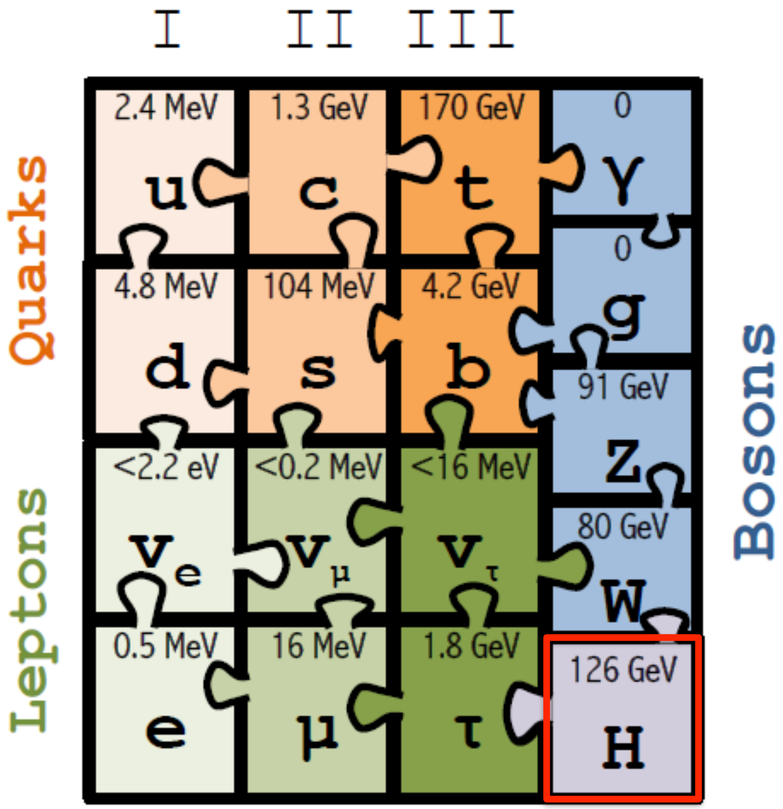
Disclaimer

To prepare these slides I used content from many friends and colleagues, whom I wholeheartedly wish to thank. Any mistake or misinterpretation is entirely my fault!

The Physics Landscape



P. Janot

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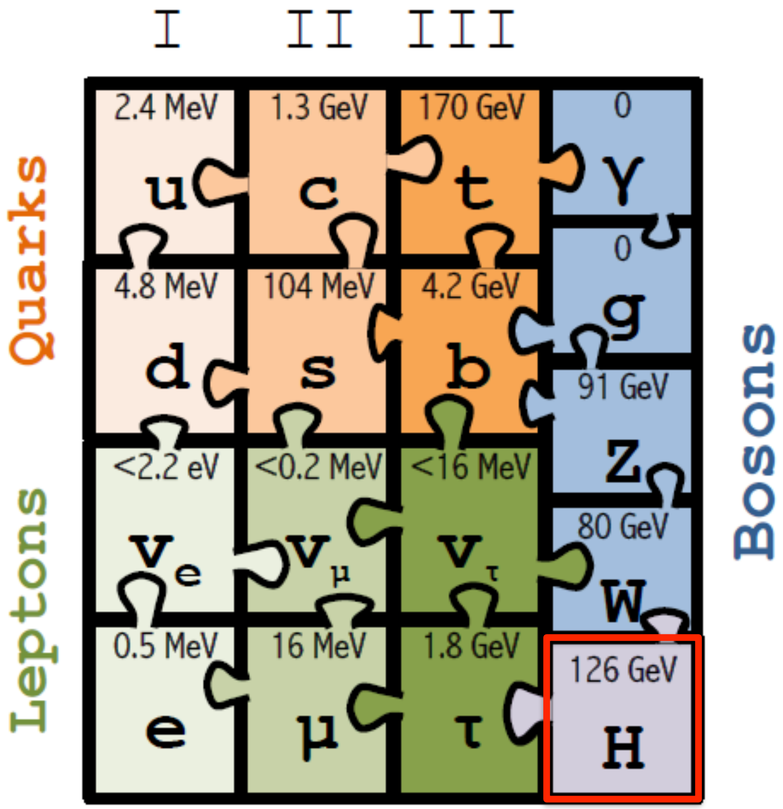

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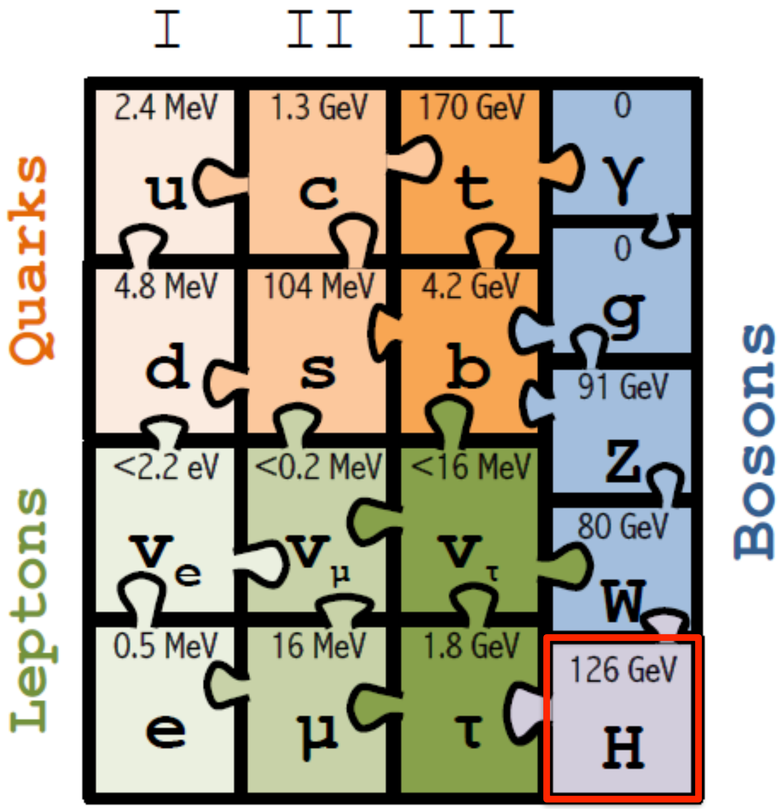

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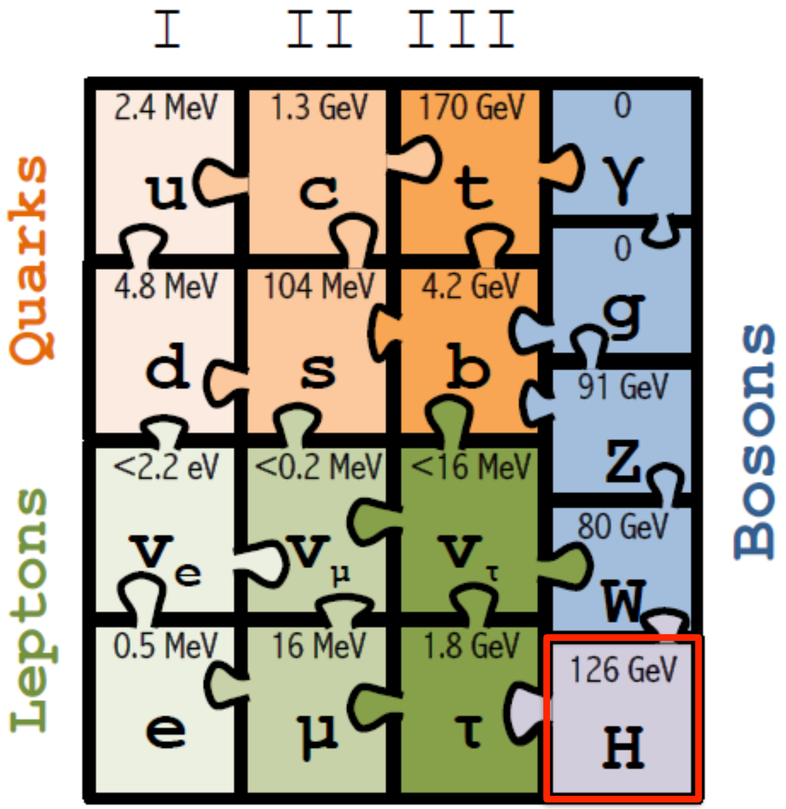

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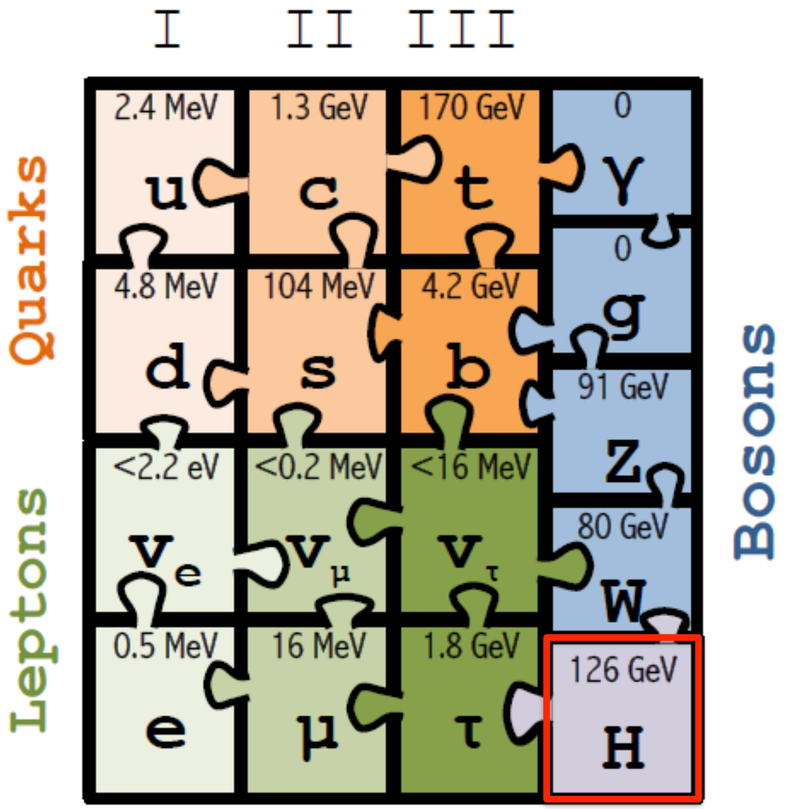

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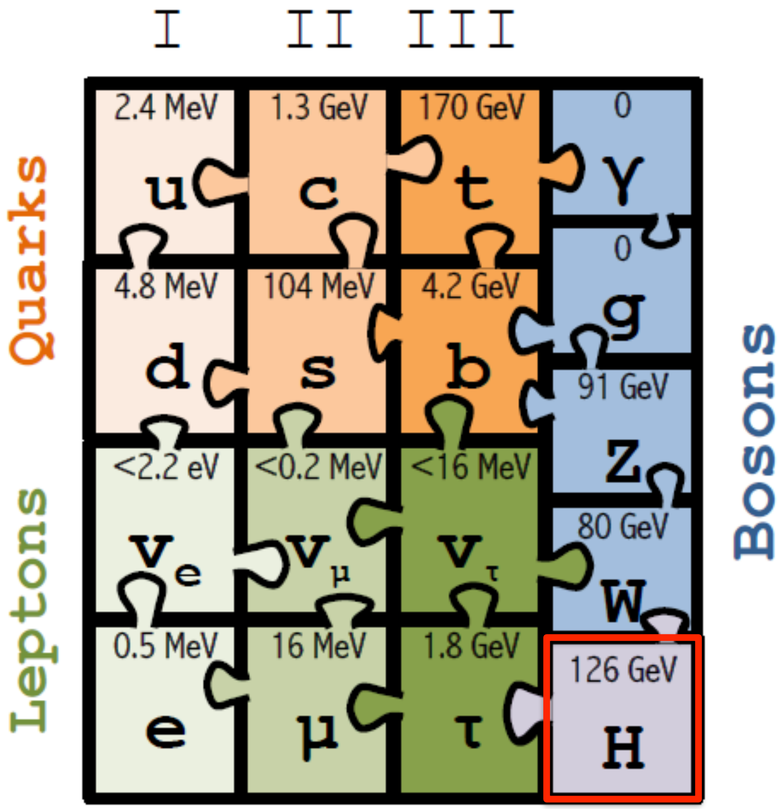

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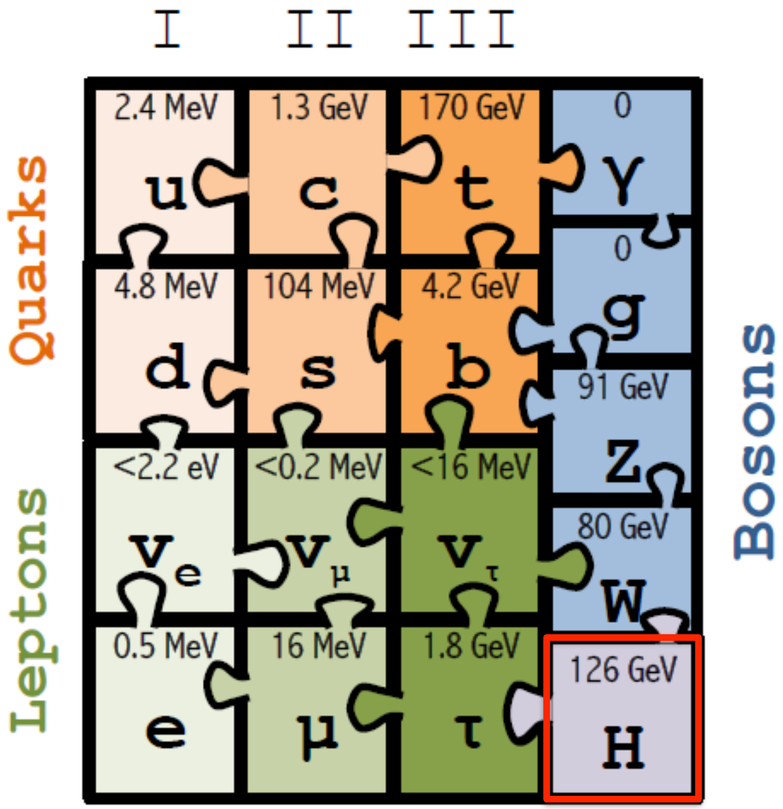

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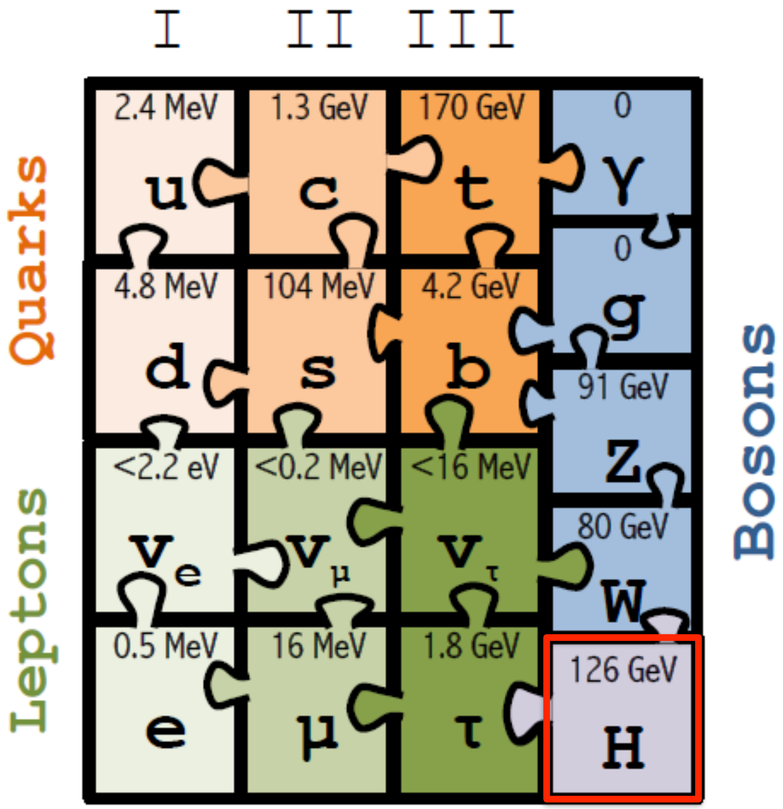

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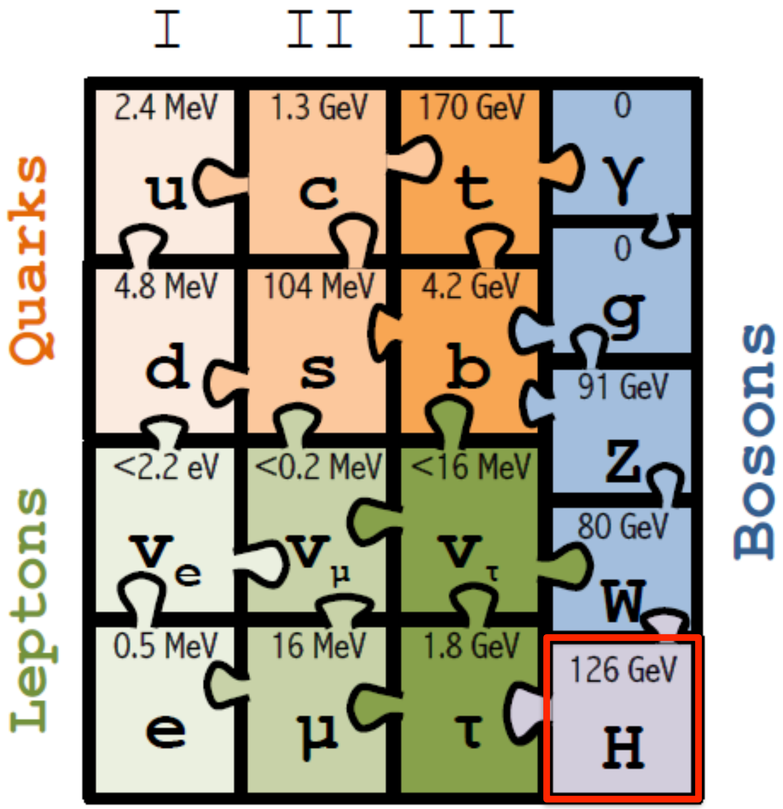

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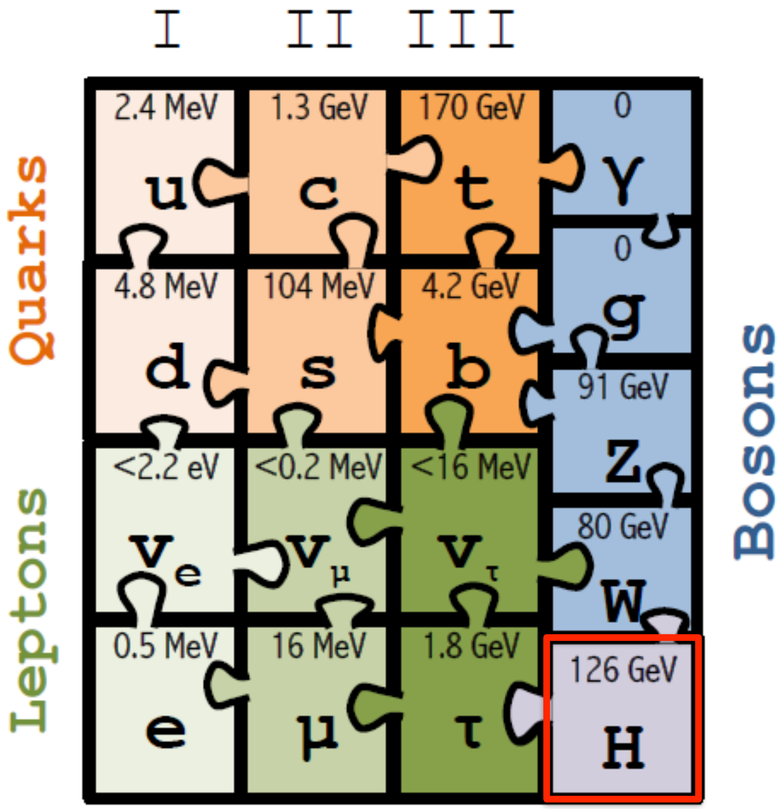

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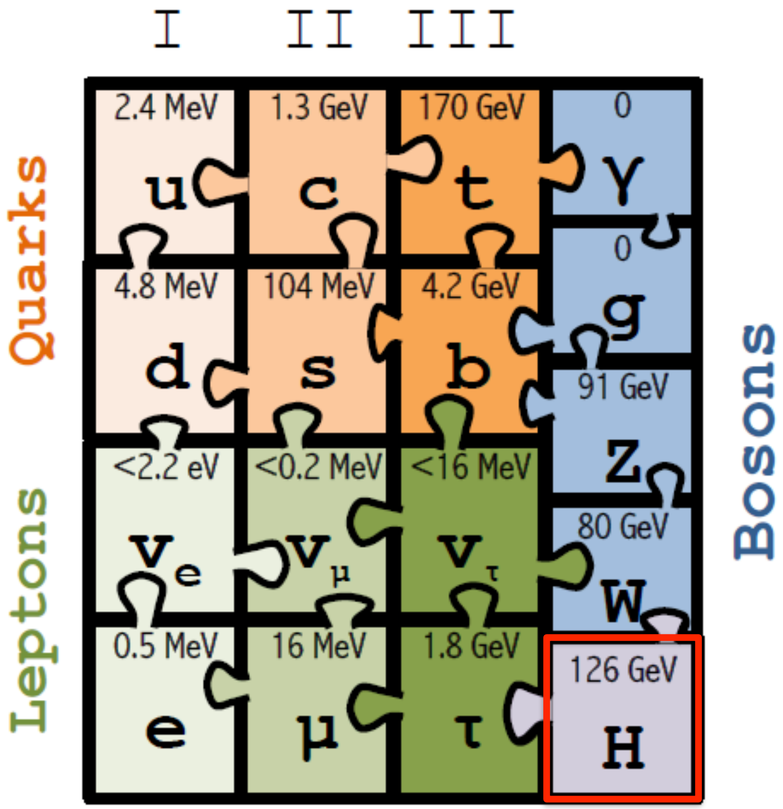

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- etc.

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Analogy: Explore new worlds (Star Trek)

We have now identified more than 6000 exoplanets.

Imagine one day we are ready to seek out new life and civilizations,

and dare to go where no one has gone before…

What would be your strategy?

F. Maltoni

Phase I : Observe

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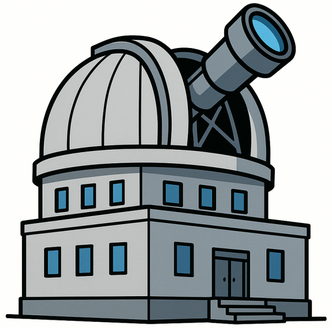

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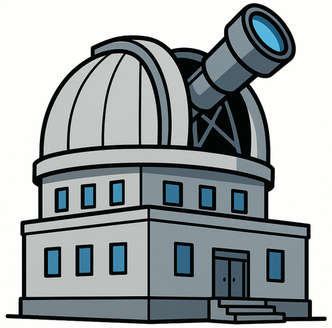

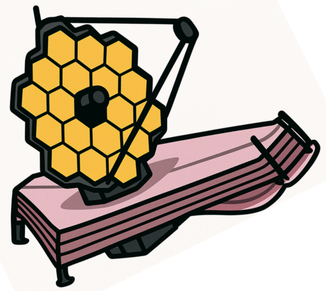

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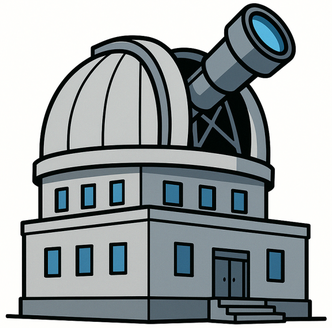
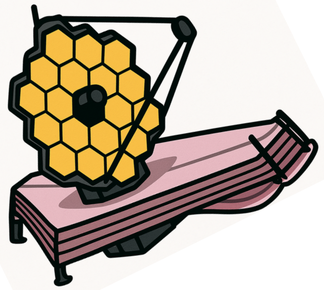
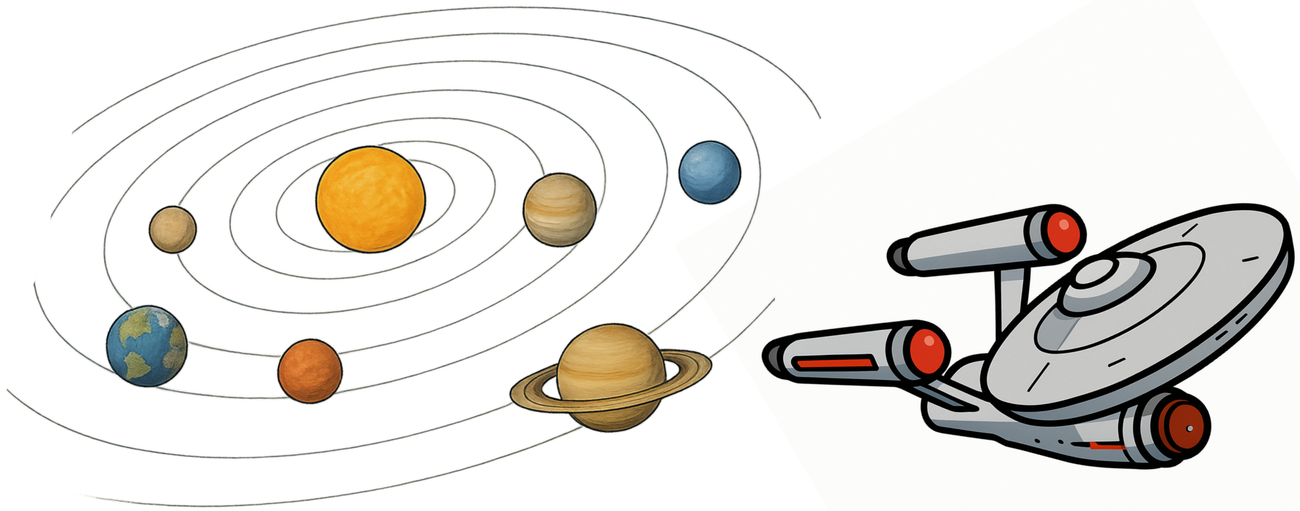




Build telescopes with better and better resolution to make the observations and identify the best candidates for life and civilizations…

F. Maltoni

Phase II : Go there!



Develop new technologies to allow space travel and then….

F. Maltoni

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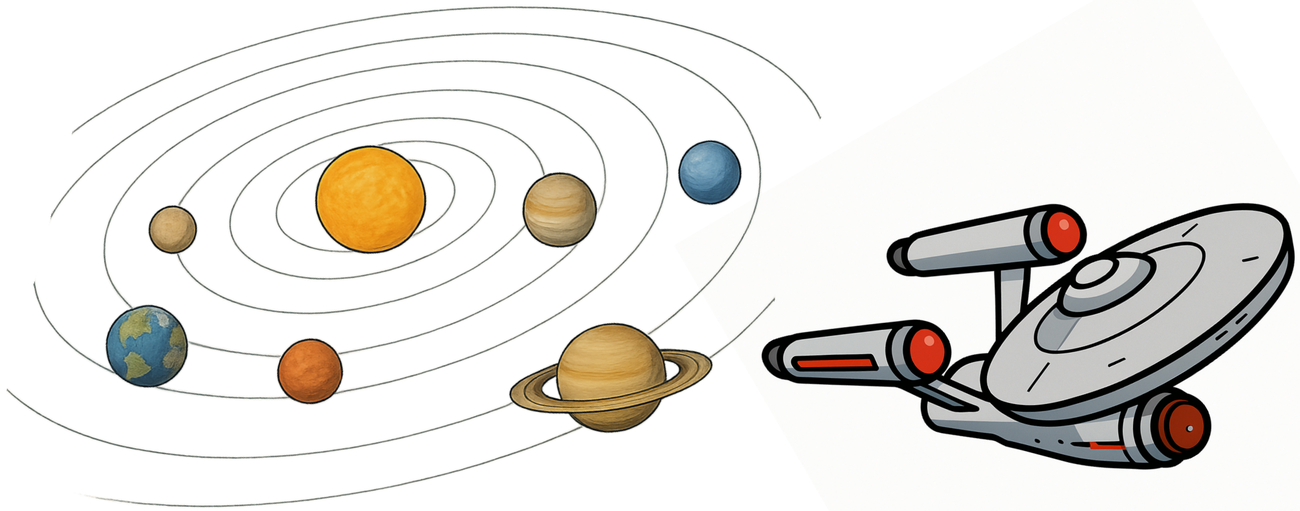

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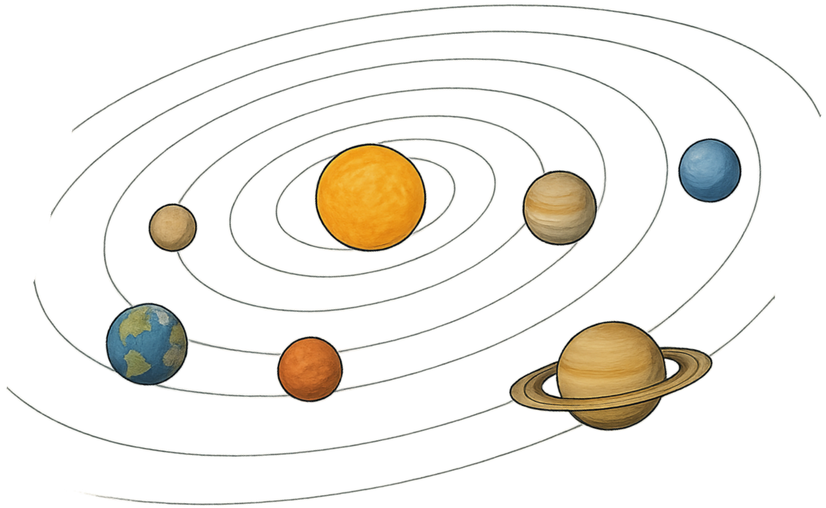

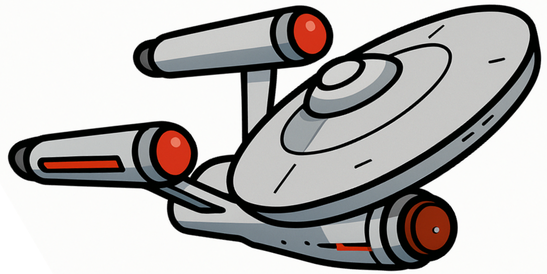

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Where do we go from here?

We are in an interesting situation

- No experimental hint to the origin of these observed phenomena
- No clear theoretical hint to indicate the best direction to go

We have no clear energy scale for new physics
We don't know its coupling strength to the SM particles

- Next facility must be versatile
  - With a reach as broad as possible

More Sensitivity, more Precision, more ENERGY

- A high precision, high intensity lepton collider, later followed by a high energy hadron collider offers the best solution

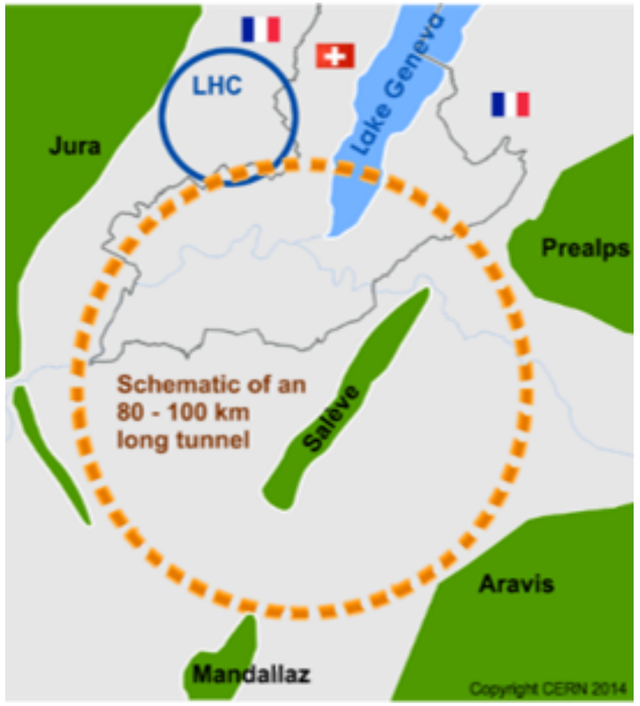
P. Janot

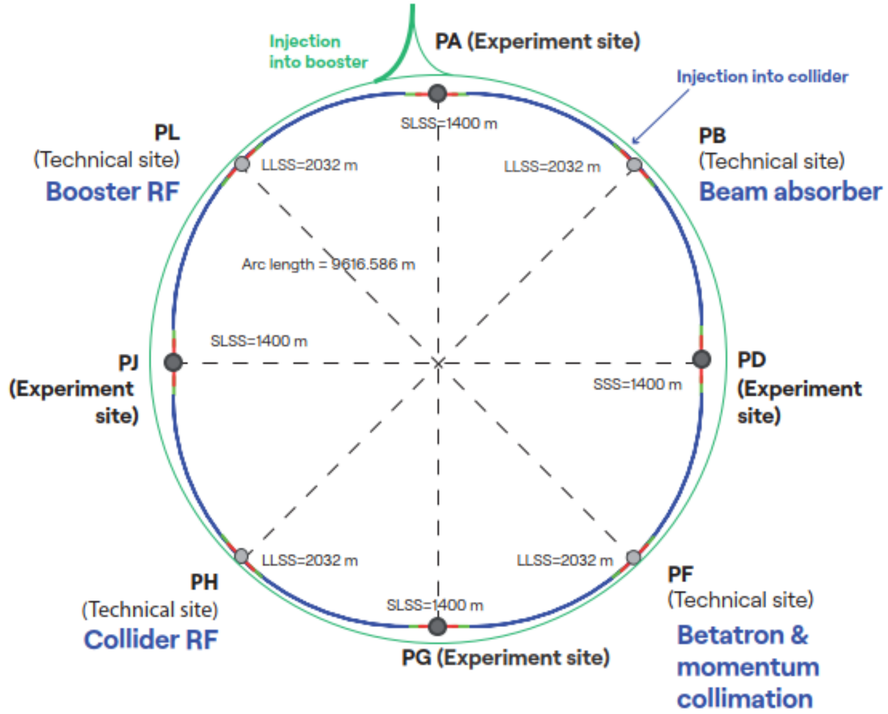
FCC Program

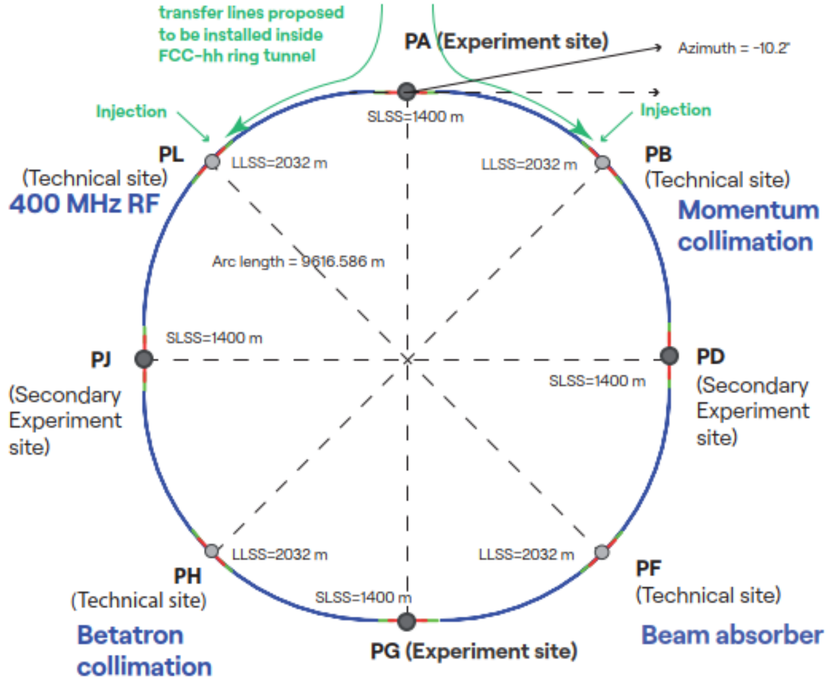
FCC-ee (Z, W, H, $t\bar{t}$): Higgs factory, electroweak & top factory at highest luminosities

FCC-hh (~100 TeV) as potential second step: energy frontier, pp & AA collisions; e-h option

- focus on implementation of FCC-ee as first step; possible pathway to FCC-hh to be decided later
- Common civil engineering and technical infrastructures, building on and reusing CERN's existing infrastructure
- highly synergetic and complementary physics programme maximising the physics opportunities
- FCC-ee project would allow the start of a new, major facility at CERN within a few years of the end of HL-LHC



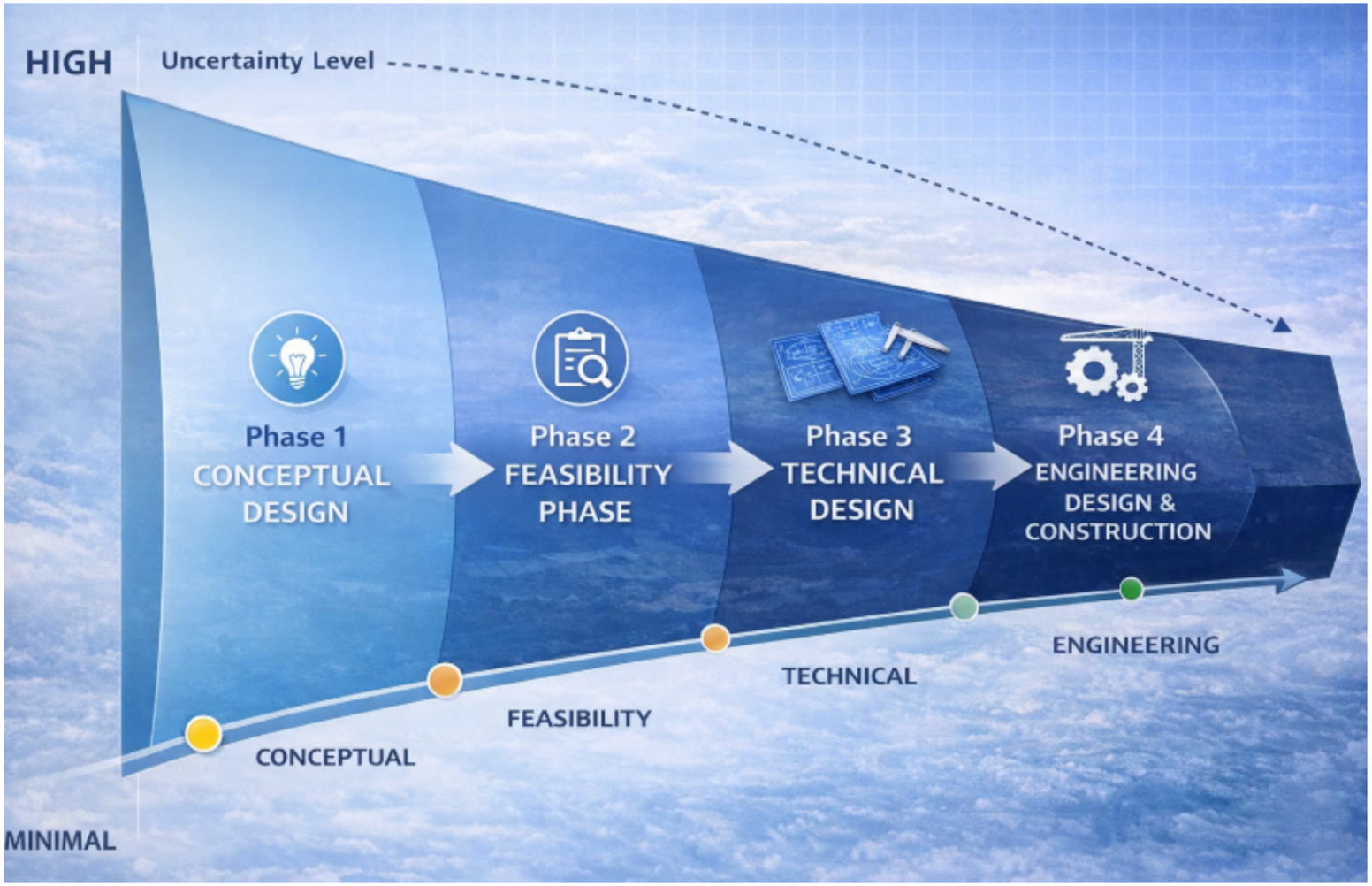




2020 - 2045 | **2048 - 2062** | **~2075 ?**

M. Benedikt

From Feasibility Study to Project Realisation



- Following the positive assessment of the Feasibility Study and Council approving the continuation, the FCC moves towards technical design.
- Expertise across CERN and from collaboration partners is required to be able to deliver an integrated technical design, with cost estimate and schedule, taking into account project authorisation processes, societal acceptance, procurement strategy.
- **2026-2028 Reference Design Phase**
- **2029-2032 Technical Design Phase**

Aiming for project decision by CERN Council after the Reference Design Phase

M. Benedikt

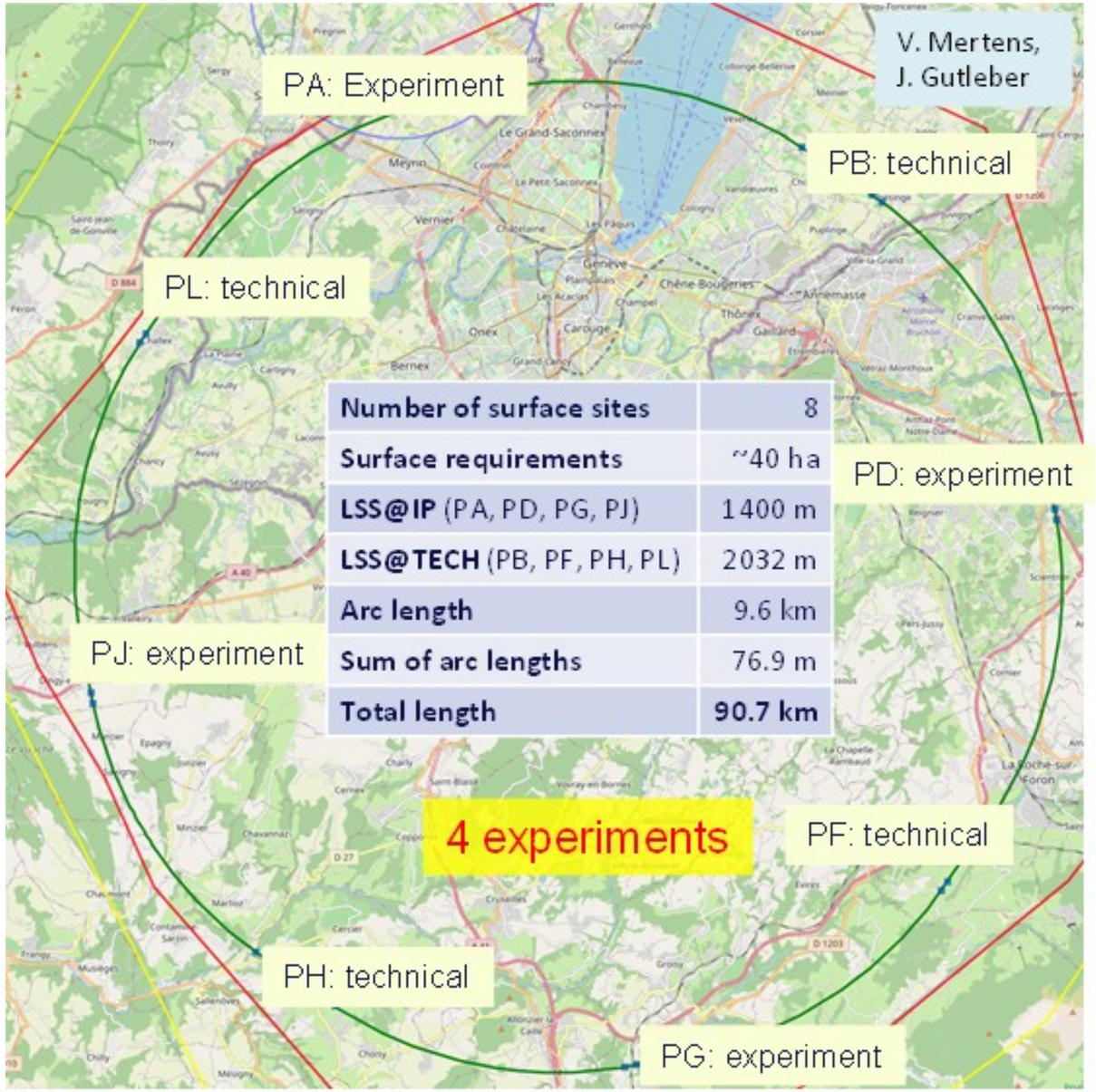
Reference layout and implementation:PA31 - 90.7 km

Layout chosen out of ~ 100 initial variants, based on several criterias:

- **geology,**
- **surface constraints** (land availability, urbanistic, etc.),
- **environment,** (protected zones),
- **infrastructure** (electricity, transport),
- **machine performance**

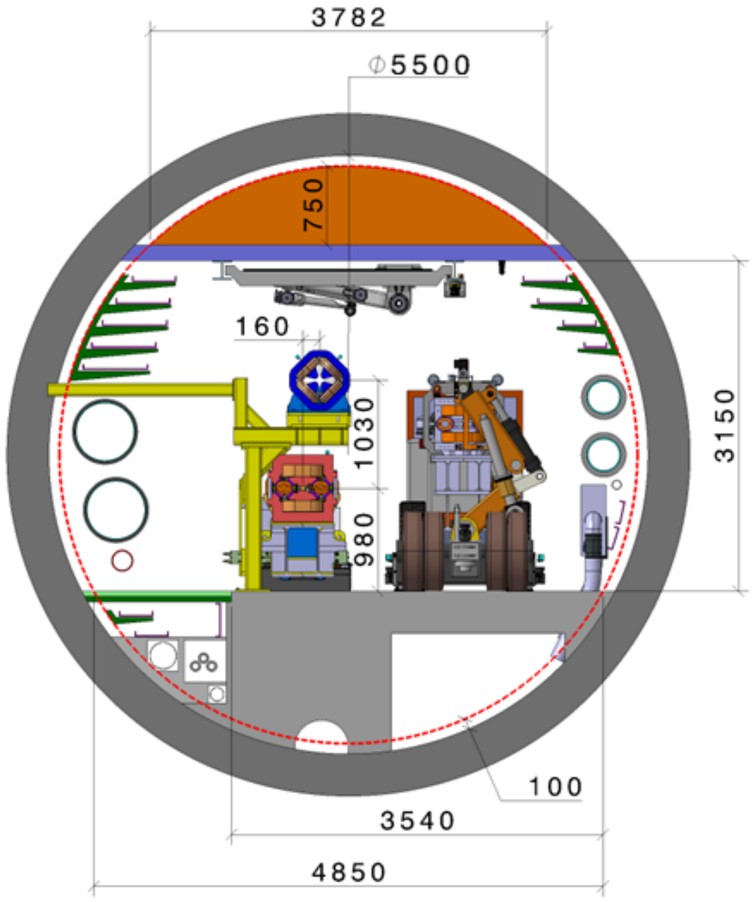
“Avoid-reduce-compensate” principle of EU and French regulations.

Overall lowest-risk baseline:
90.7 km ring, 8 surface points,
4-fold symmetry

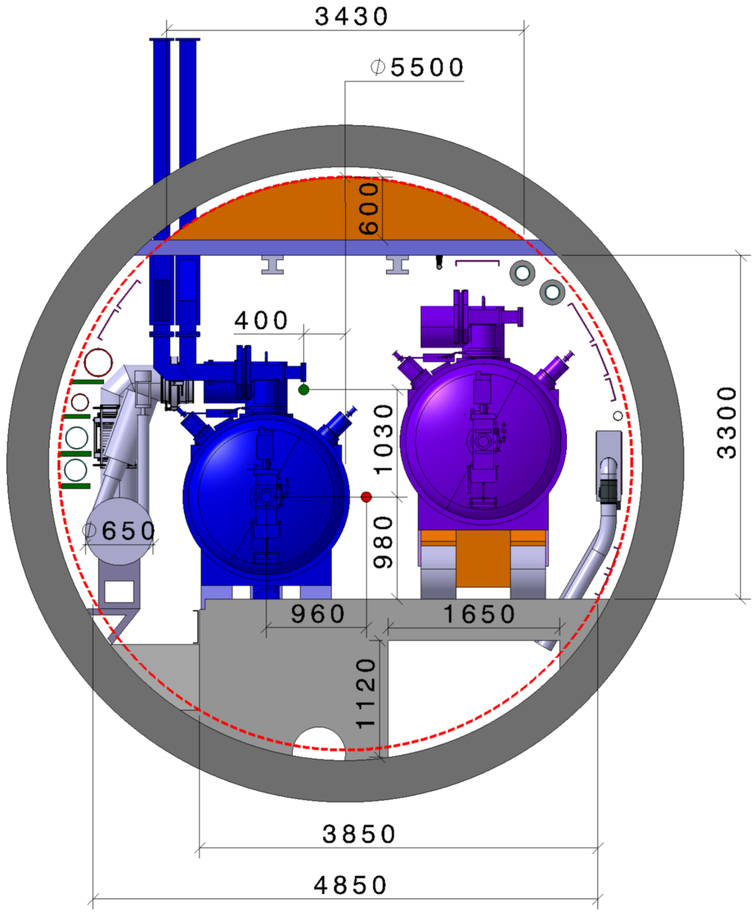


FCC – main tunnel integration – 5.5 m inner diameter

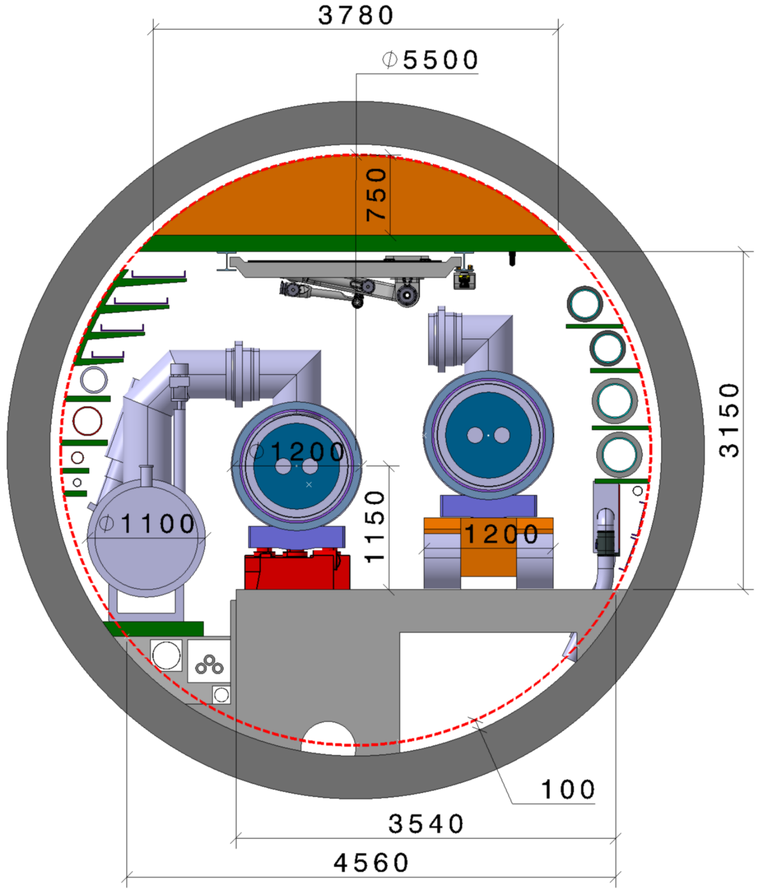
FCC-ee arc



FCC-ee 400 MHz RF section



FCC-hh arc



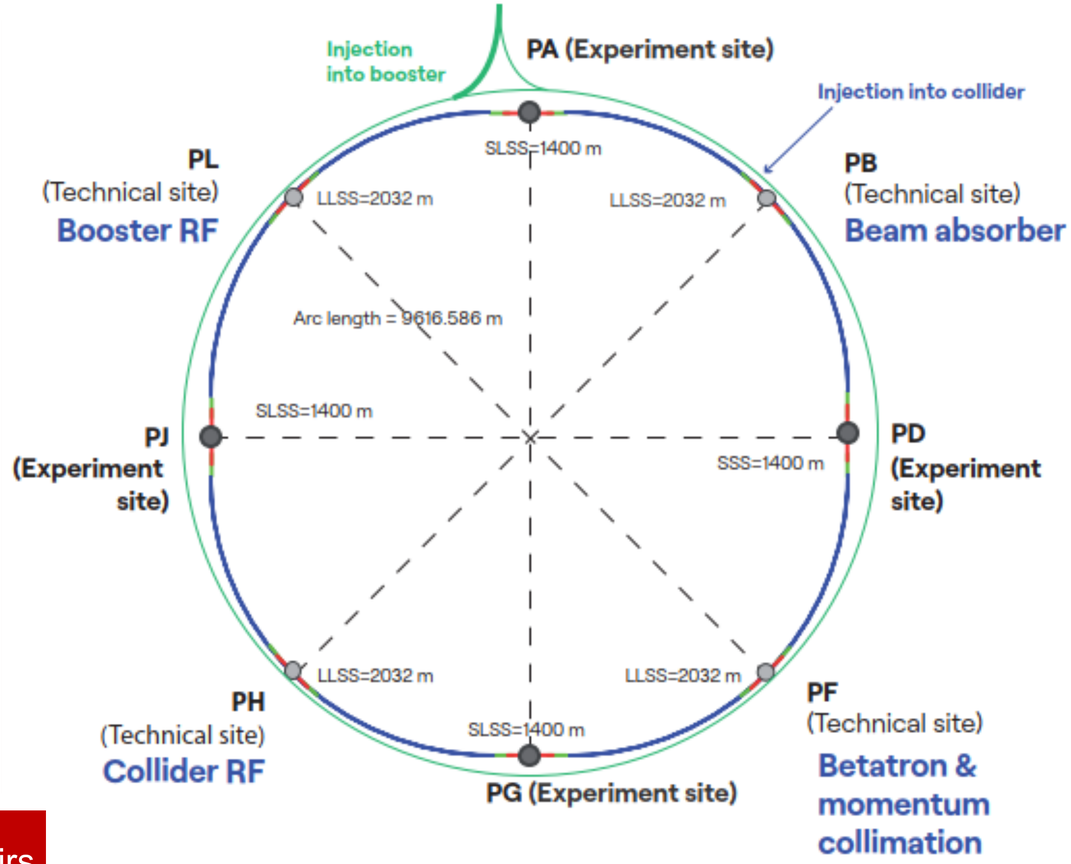
Integration & logistics studies for installation, safety concept reviewed, to confirm 5.5 m

Stage 1: e^+e^- collider FCC-ee

Consolidated main parameters

parameter	Z	WW	H (ZH)	
beam energy [GeV]	45.6	80	120	182.5
synchrotron radiation/beam [MW]	50	50	50	50
beam current [mA]	1294	135	26.8	5.1
number bunches / beam	11200	1852	300	64
total RF voltage 400/800 MHz [GV]	0.08 / 0	1.0 / 0	2.09 / 0	2.1 / 9.2
luminosity / IP [10^{34} cm^{-2}s^{-1}]	145	20	7.5	1.4
total integrated luminosity / IP / year [ab^{-1} / yr]	17	2.4	0.9	0.17
electrical power operation [MW]	250	275	297	381
electrical energy per year [TWh]	1.17	1.32	1.41	1.85
	4 years 6 x 10^{12} Z LEP x 10^5	2 years > 10^8 WW LEP x 10^4	3 years > 2x10^6 H	5 years 2 x 10^6 tt pairs

FCC-ee functional layout

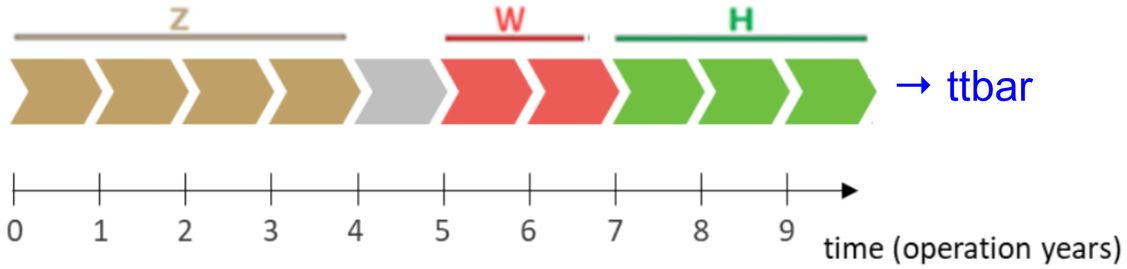


10^4 (@WW) - 10^5 (@Z) x luminosity/energy of LEP → sustainable physics

Operation modes for RF

- Physics at 4 different energy points:
  Z^0, W^+W^-, Higgs (ZH), t-tbar production
- Same SR power for all 4 modes

  P_{SR}= **50 MW** per beam



Lowest energy:
- Low RF voltage
- High beam current

- Few cavities
- Low voltage per cavity
- **High power** per cavity
- Significant HOM power
- Instabilities

- 1- or 2-cell cavities at low RF frequency (400MHz)

Highest energy:
- High RF voltage
- Low beam current

- Many cavities
- **High voltage** per cavity
- Low power per cavity
- Low HOM power
- High SR damping

- Multi-cell cavities at higher RF frequency (800MHz)

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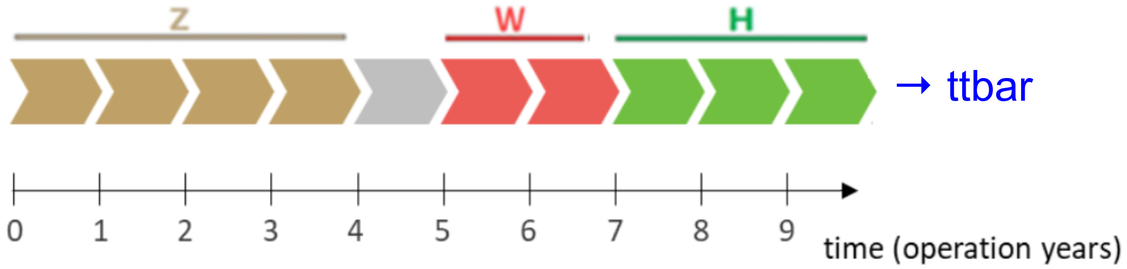

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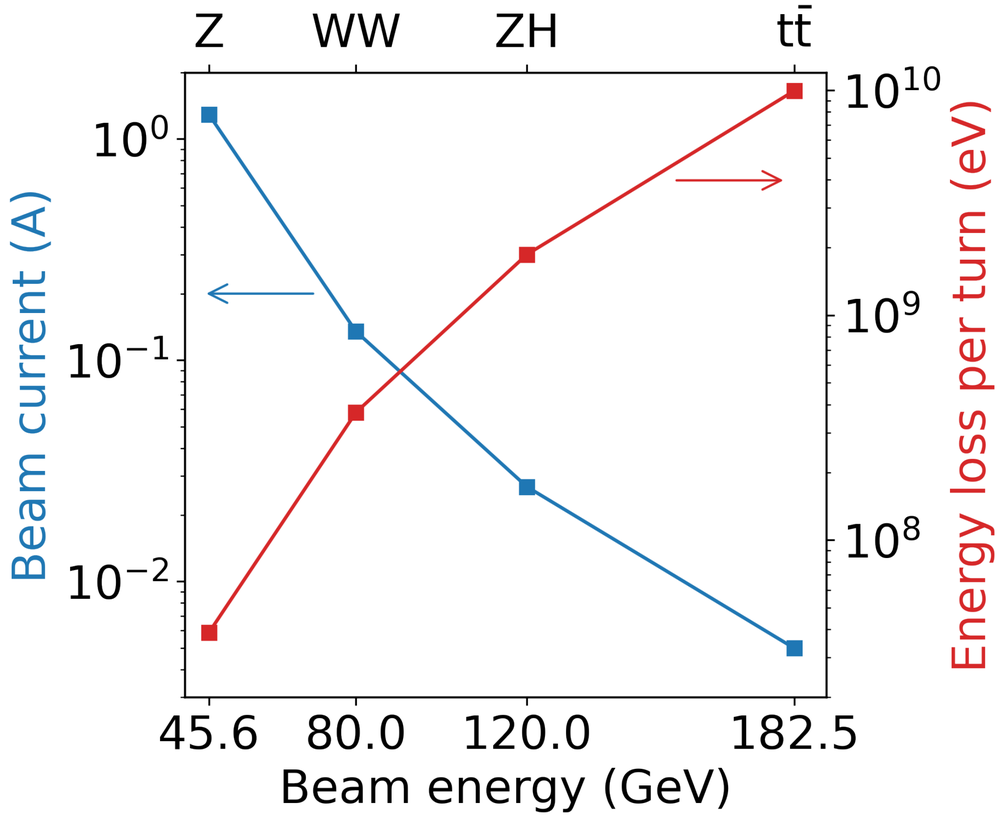
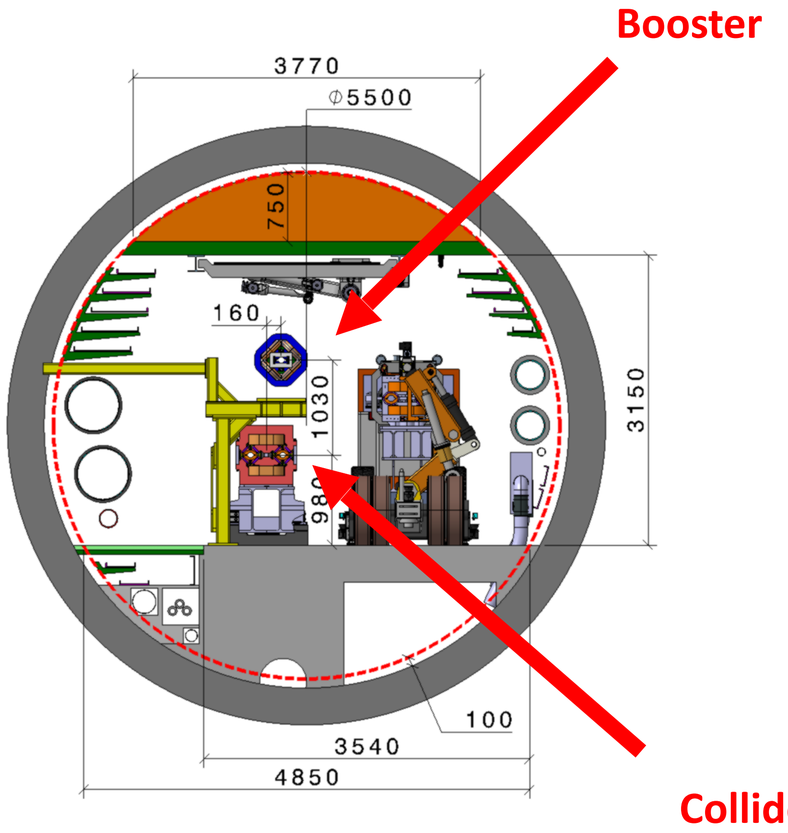
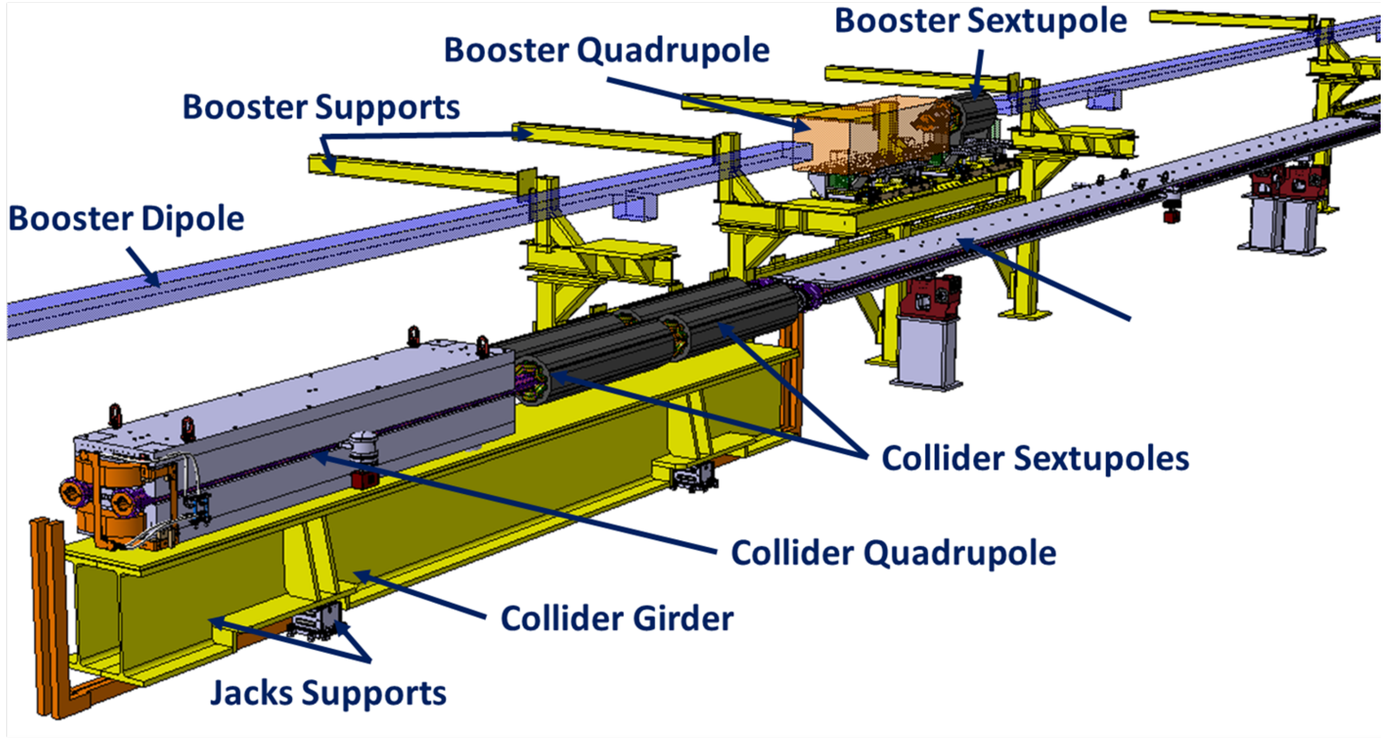


FCC-ee booster

full energy booster, ramping from 20 GeV to 46 GeV – 182.5 GeV; injection ~every minute to keep collider beam currents constant; booster intensity ~1% of collider; full RF voltage as in collider





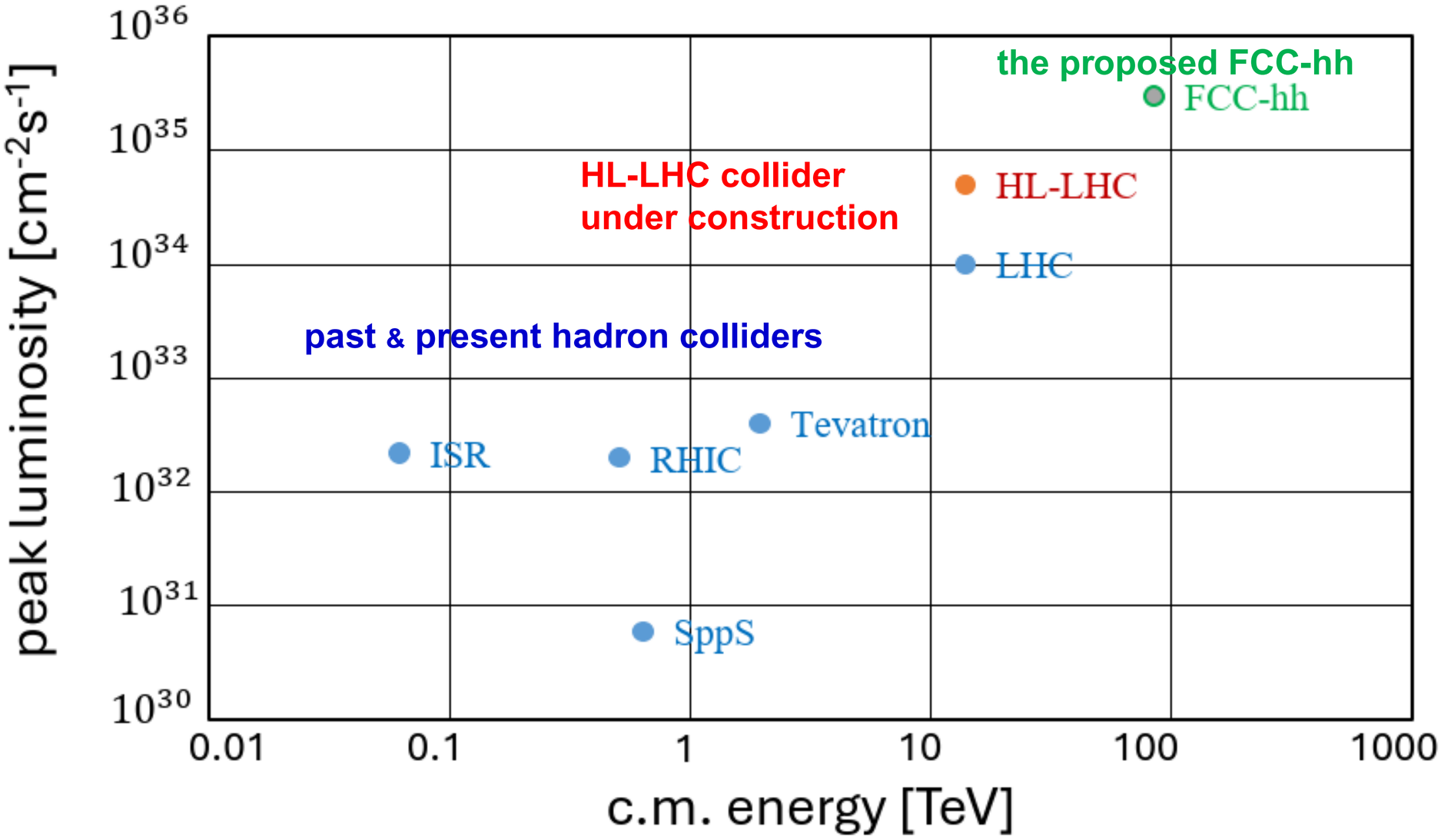
FCC-ee cost estimate (FSR 2025)

Capital cost (2024 CHF) for construction of the FCC-ee is summarised below. This cost includes construction of the entire new infrastructure and all equipment for operation at the Z, WW and ZH working points.

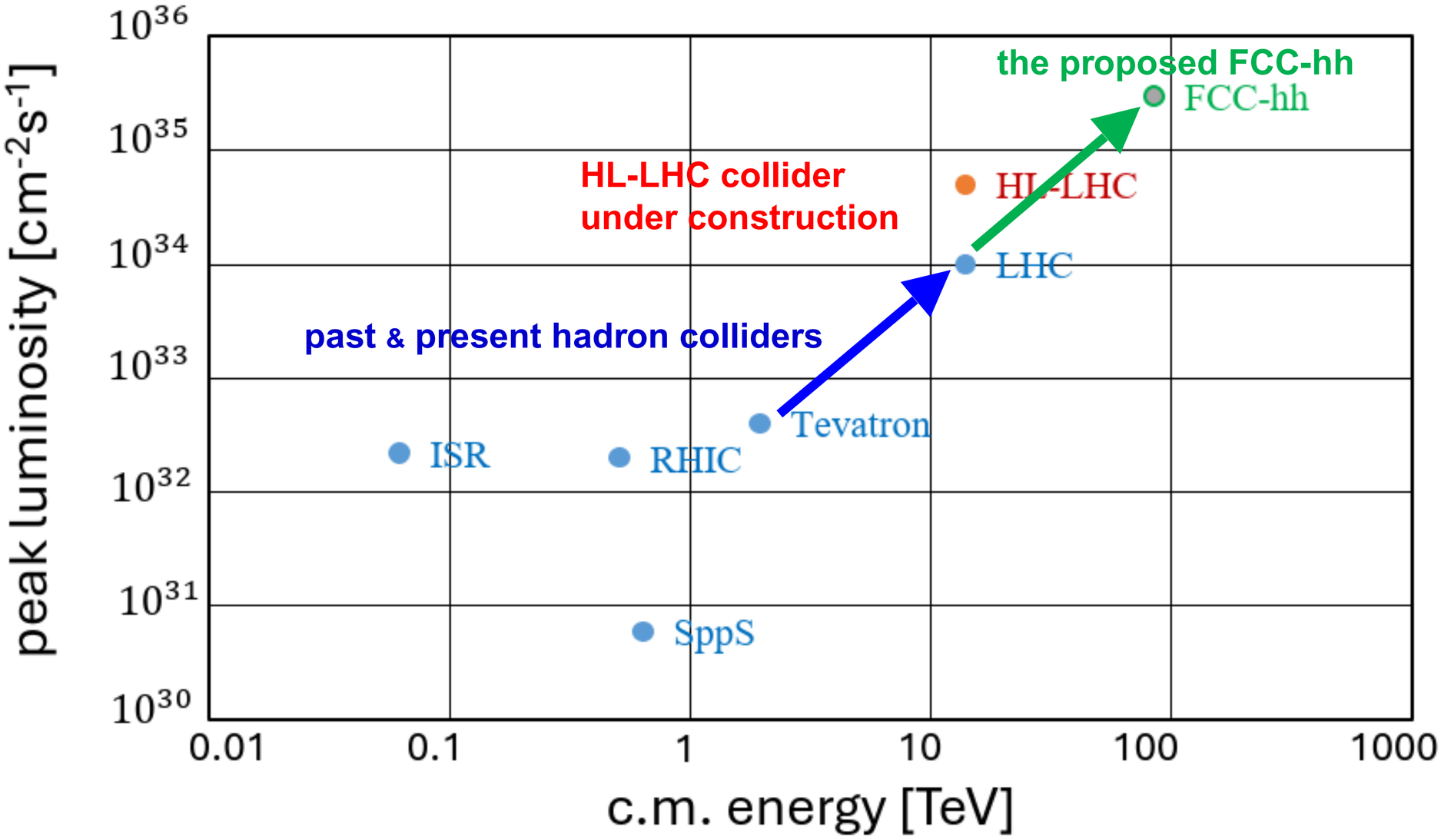
Domain	Cost [MCHF]
Civil engineering	6,160
Technical infrastructures	2,840
Injectors and transfer lines	590
Booster and collider	4,140
CERN contribution to four experiments	290
FCC-ee total	**14,020**
+ four experiments (non-CERN part)	1,300
FCC-ee total incl. four experiments	**15,320**

Note: Upgrade of SRF (800 MHz) & cryogenics for ttbar operation corresponds to additional cost of 1,260 MCHF.

Hadron collider peak luminosity vs. c.m. energy



Hadron collider peak luminosity vs. c.m. energy



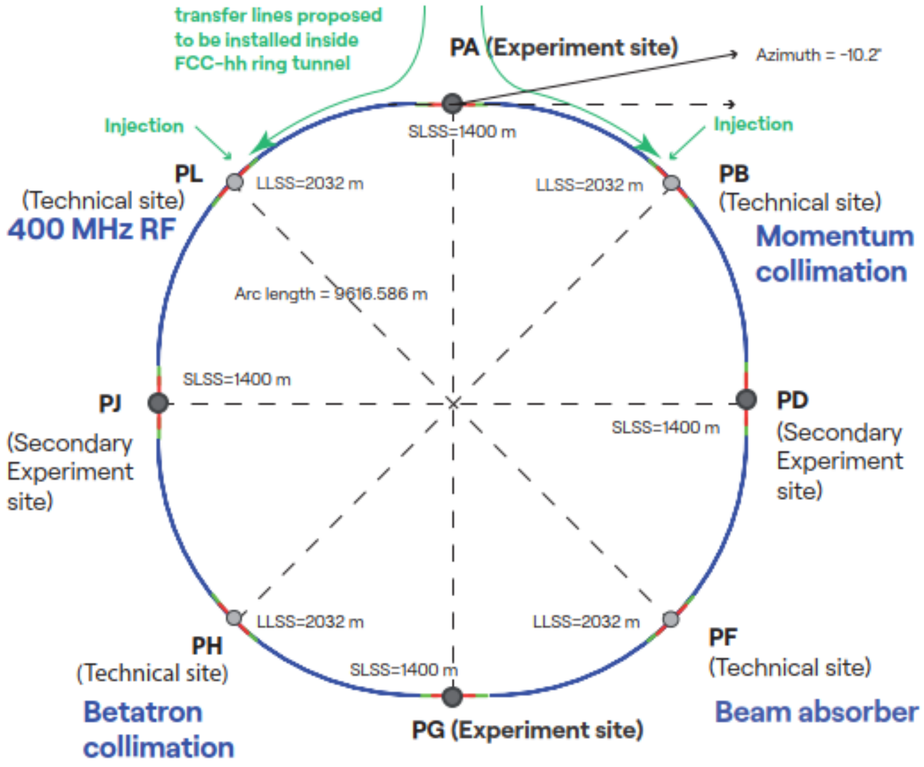
Stage 2: hadron collider FCC-hh

- Parameter optimization to lower electricity consumption (~max. consumption of FCC-ee)
- Magnetic field considered realistic with today's technologies (Nb_3Sn, ~14T, 1.9 K)

Main parameters FSR 2025

parameter	FCC-hh	FCC-hh CDR	HL-LHC
collision energy cms [TeV]	85	100	14
dipole field [T]	14	16	8.33
circumference [km]	90.7	97.8	26.7
beam current [A]	0.5	0.5	1.1
synchr. rad. per ring [kW]	1200	2400	7.3
peak luminos. [10^{34} cm^{-2}s^{-1}]	30	30	5 (lev.)
integr. luminosity / IP [fb^{-1}]	20000	20000	3000

FCC-hh functional layout

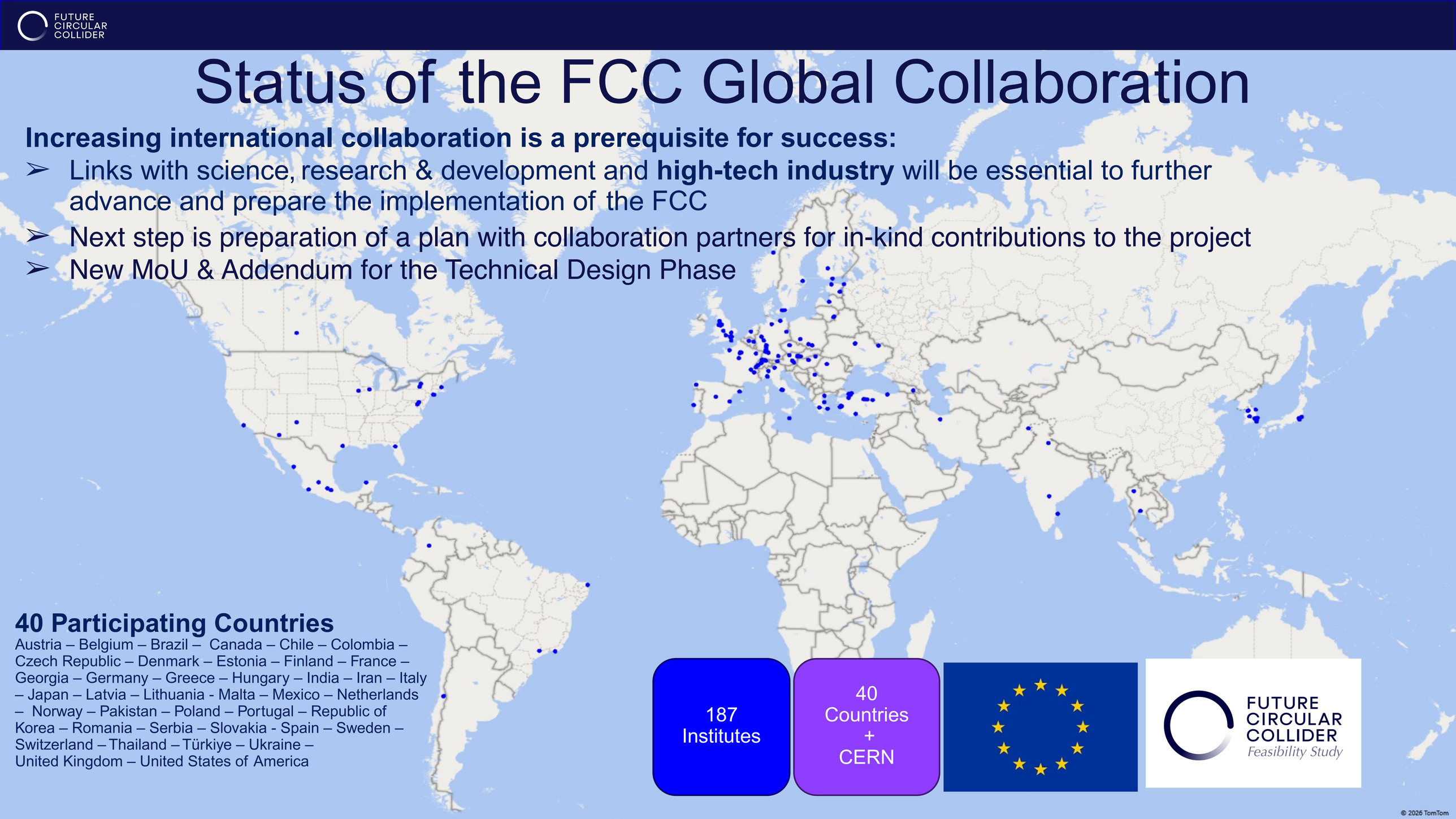


- **For Nb_3Sn @ 1.9 K: 355 MW el, consumption and 2.3 TWh/y**
- **For Nb_3Sn @ 4.5 K potential to reduce to ~1.8 TWh/y as FCC-ee.**

Status of the FCC Global Collaboration

Increasing international collaboration is a prerequisite for success:

- Links with science, research & development and **high-tech industry** will be essential to further advance and prepare the implementation of the FCC
- Next step is preparation of a plan with collaboration partners for in-kind contributions to the project
- New MoU & Addendum for the Technical Design Phase



40 Participating Countries

Austria – Belgium – Brazil – Canada – Chile – Colombia – Czech Republic – Denmark – Estonia – Finland – France – Georgia – Germany – Greece – Hungary – India – Iran – Italy – Japan – Latvia – Lithuania - Malta – Mexico – Netherlands – Norway – Pakistan – Poland – Portugal – Republic of Korea – Romania – Serbia – Slovakia - Spain – Sweden – Switzerland – Thailand – Türkiye – Ukraine – United Kingdom – United States of America

187 Institutes

40 Countries + CERN

FUTURE CIRCULAR COLLIDER *Feasibility Study*

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European Strategy for Particle Physics: 2026 Update

- Strategy process was initiated by the CERN Council in 2024

Motivation:
- Large progress towards future colliders at CERN (FCC feasibility study) and beyond
- International landscape of the field (CEPC, ILC, P5 in the US)
- Accomplishments in physics (LHC, HL-LHC and elsewhere)
- Long timescales (community engagement)

- *Aim: develop a **visionary and concrete plan** that greatly advances human knowledge in fundamental physics through the **realisation of the next flagship project at CERN**. This plan should attract and value **international collaboration** and should **allow Europe to continue to play a leading role in the field.***

- *The Strategy update should include the **preferred option for the next collider at CERN** and **prioritised alternative options** to be pursued if the chosen preferred plan turns out not to be feasible or competitive.*

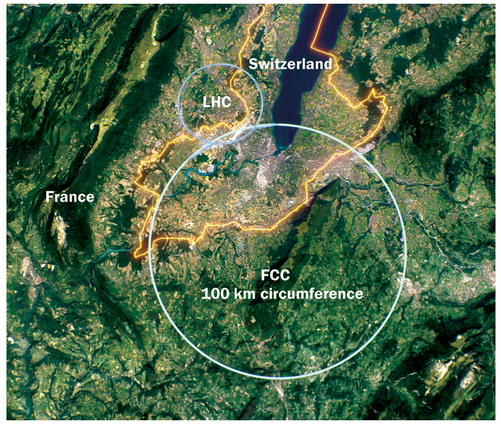
- *The Strategy update should also **indicate areas of priority for exploration complementary to colliders** and for other experiments to be considered at CERN and at other laboratories in Europe, as well as for participation in projects outside Europe.*

K. Jakobs

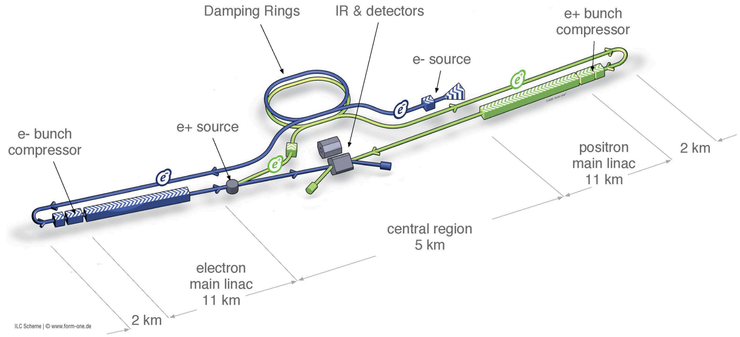
Proposed large-scale projects at CERN

e^+e^- colliders
("Higgs, Electroweak, Top and Flavor Factories factories")

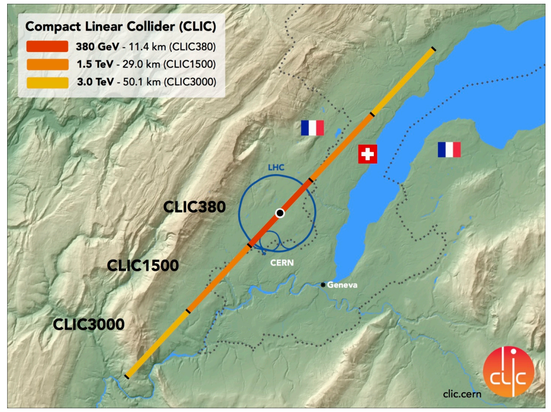
FCC-ee (e^+e^-, circular, 91 – 365 GeV)



LCF (e^+e^-, linear, 91 – 240, 550 GeV)



CLIC (e^+e^-, linear, 380 GeV, 1.5 TeV)

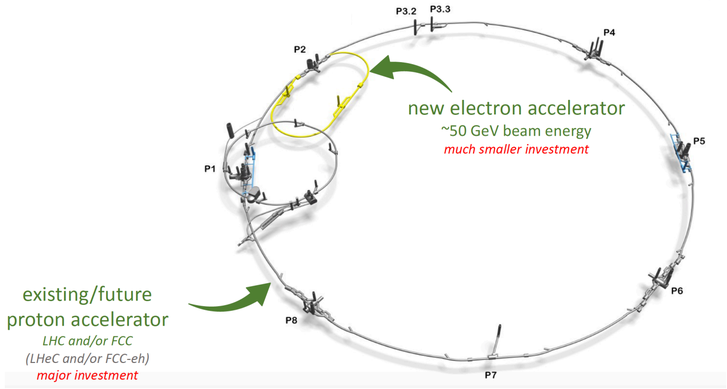


Intermediate projects

(Leave room (time, budget, resources) for further development of THE machine that can probe directly the energy frontier at the 10++ TeV parton center-of-mass scale)

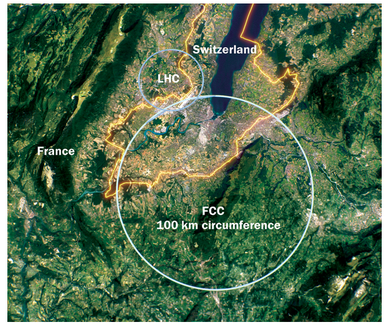
LEP3 (e^+e^-, circular, 91 – 230 GeV)

LHeC (ep, circular, electron ERL, 50 GeV e^-, > 1 TeV ep collisions)



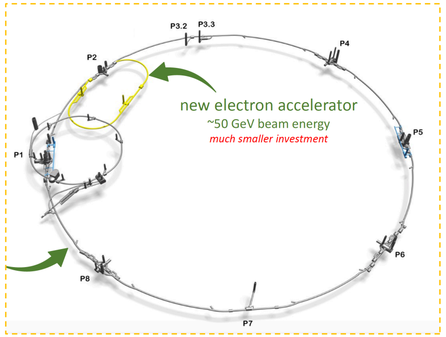
The vision: options for 10 TeV parton-cm energies

FCC-ee

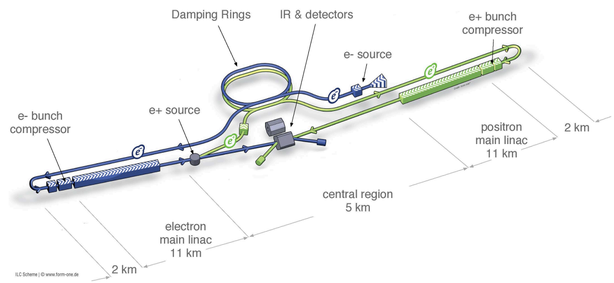


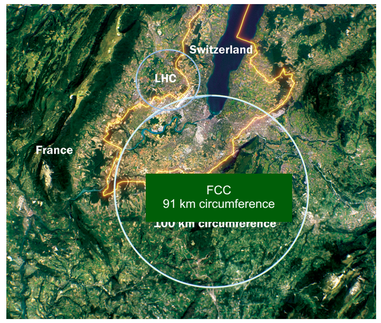
LEP3

LHeC

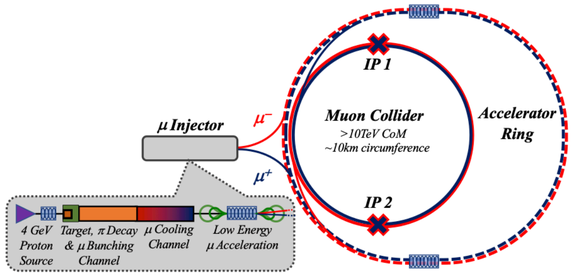


LCF, CLIC





FCC-hh,
baseline 85 TeV (→ 120 TeV)
+ possibility for HI collisions



Muon Collider (3, 10 TeV)

R&D

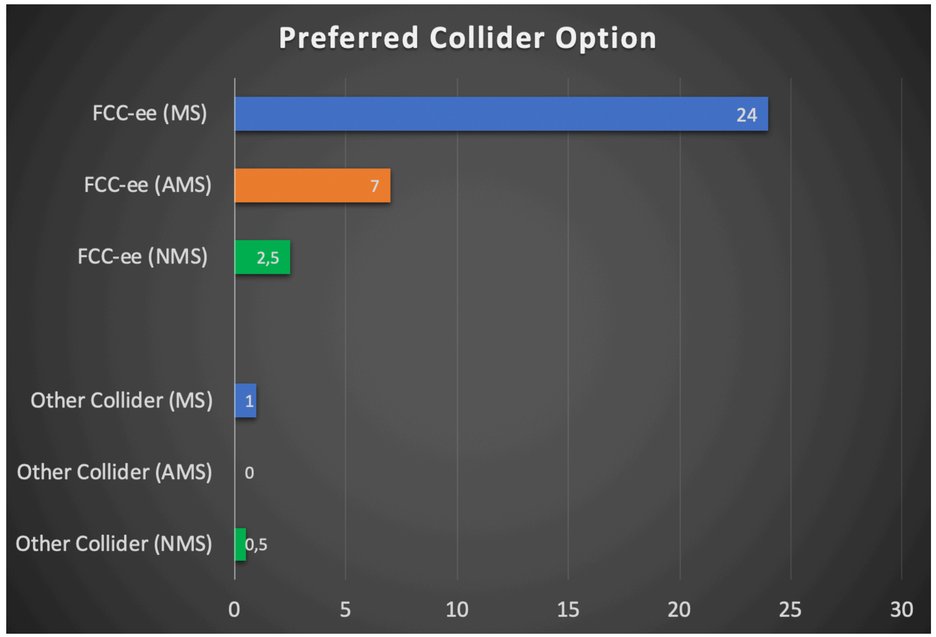
e^+e^- with improved acceleration technologies
LCF, **C³** (→ 1 TeV), **CLIC** (1.5 TeV), **HALHF**, …
→ plasma acceleration for higher energies
(can $\mathcal{O}(10)$ TeV be reached? on what timescale?)

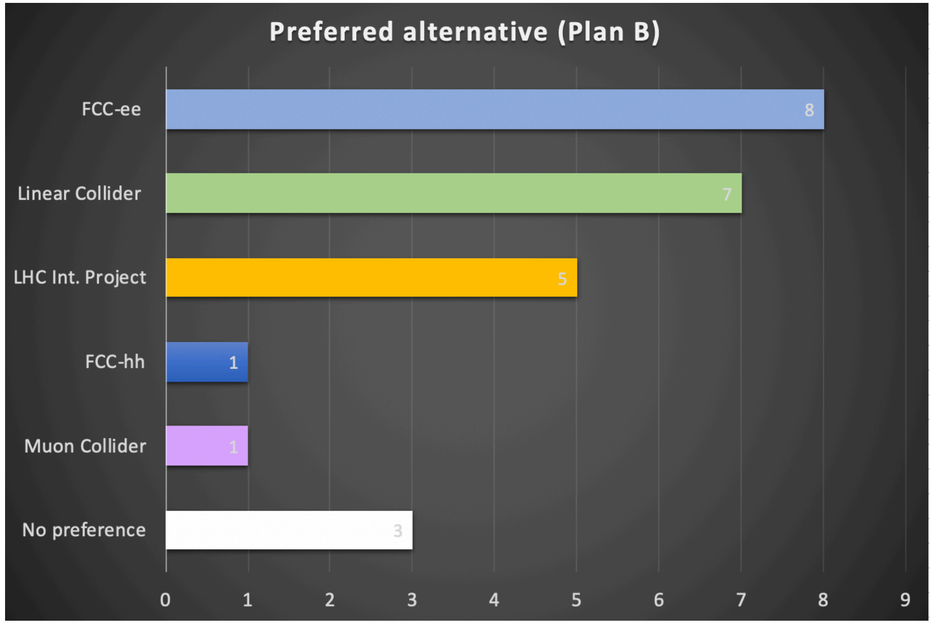
Final input from the national HEP communities

What is the preferred large-scale post-LHC accelerator at CERN?

CERN-ESU-2026-004

What is the preferred alternative if the preferred option would not be feasible?





- Overwhelming support (24/25 CERN Member State HEP communities) in favour of the FCC-ee programme
- Support as well from Associate Member States (AMS) and Non-Member States (NMS)

No consensus; **three main axes:**

- FCC (stretched in time, descoped, …)
- Linear Collider
- Intermediate project in LHC tunnel as bridge towards FCC-hh (10++ TeV scale)

P. Sphicas

Evaluation by the European Strategy Group

Assessment of large-scale accelerator projects at CERN
Report of ESG WG2a

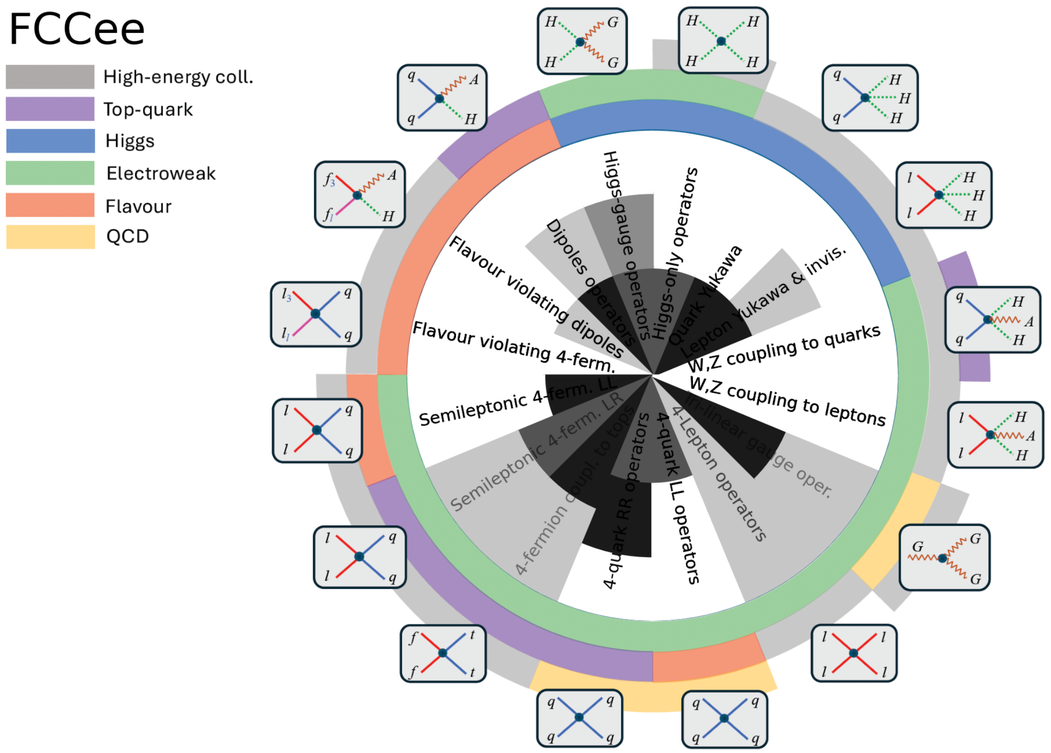
31 October 2025

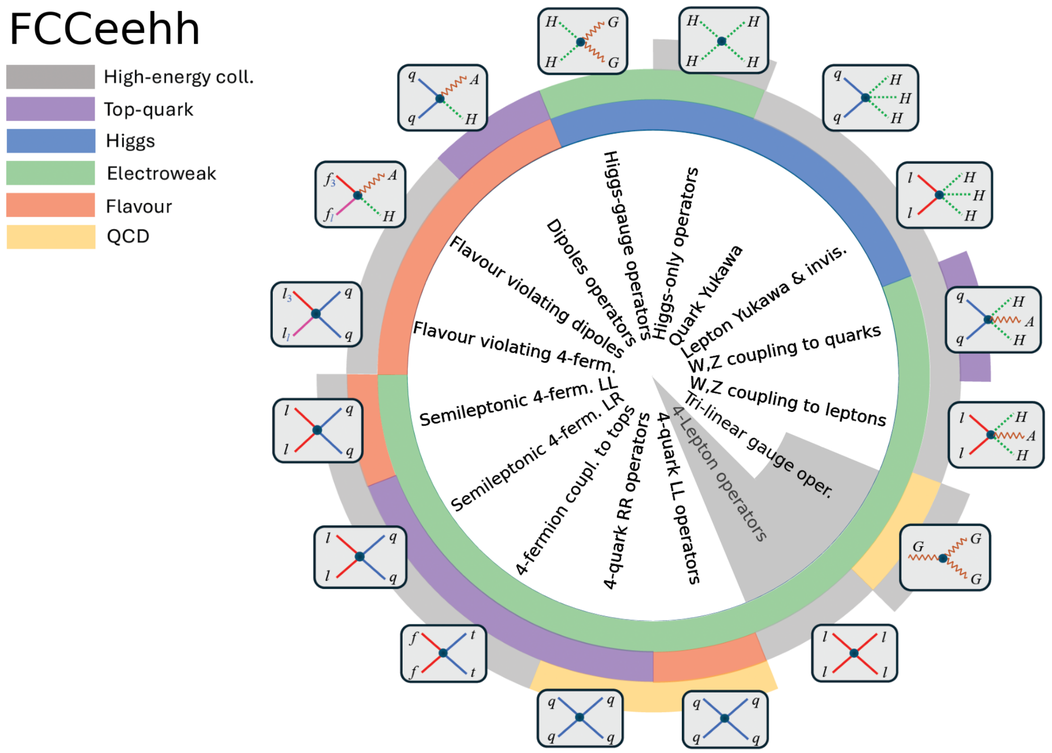
G. Arduini[1,a] (convener), F. Bordry[1] (co-opted accelerator expert), R. Brinkmann[2] (co-opted accelerator expert), P. Burrows[3,b] (convener), K. Desch[4], S. Farrington[5,6], F. Gianotti[1], K. Hanagaki[7], N. Holtkamp[8,9] (co-opted accelerator expert), J. Keintzel[1,c] (scientific secretary), B. Kilminster[10], T. Lesiak[11], L. Rivkin[12,13] (co-opted accelerator expert), F. Sabatié[14], M. Tuts[15], A. Zoccoli[16].

Project	Scope	TRL	R&D	Test facilities	Performance uncertainty	Site preparation	Schedule uncertainty	Cost uncertainty	Risk
CLIC 380 GeV, 1.5 TeV		4 - 6 / 5.2							
FCC-ee 91-365 GeV		4 - 7 / 6.0							
FCC-hh 85 TeV		4 - 7 (Nb_3Sn) / 4.3 2 - 7 (HTS) / 3.2							
FCC-hh - SA 85 TeV		4 - 7 (Nb_3Sn) / 5					Nb_3Sn		
LCF 250 - 550 GeV		5 - 7 / 5.5							
LEP3 91 - 230 GeV		3 - 6 / 4.0							
LHeC: HL-LHC + 50 GeV ERL		3 - 6 / 4.5							
MC 3.2 TeV, 7.6 TeV		3.2 TeV: 3 - 5 7.6 TeV: 2 - 5							

P. Sphicas

Coverage of the FCC integrated programme





Improvement factors in precision w.r.t. HL-LHC are evaluated and mapped on a log-scale covering the range 1 to 5

HL-LHC: 1 (gray scale 1 = black)

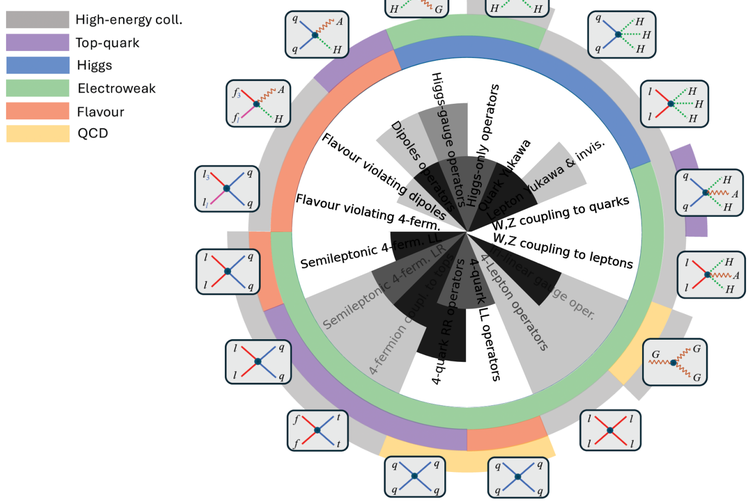
Best collider: 5 (gray scale 5 = white)

CERN-ESU-2026-006

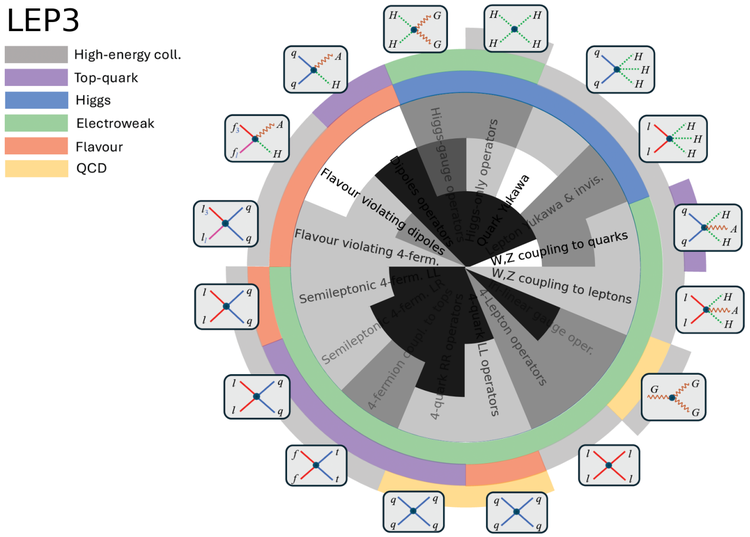
P. Sphicas

Coverage of first-stage e^+e^- colliders

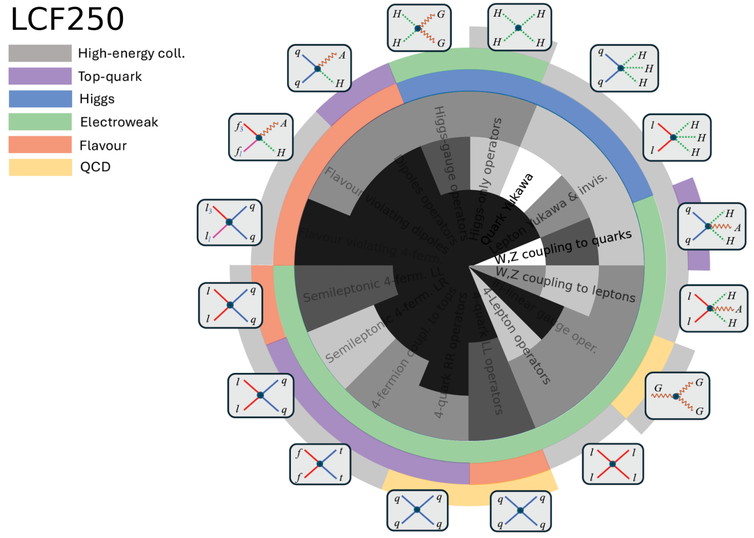
FCCee



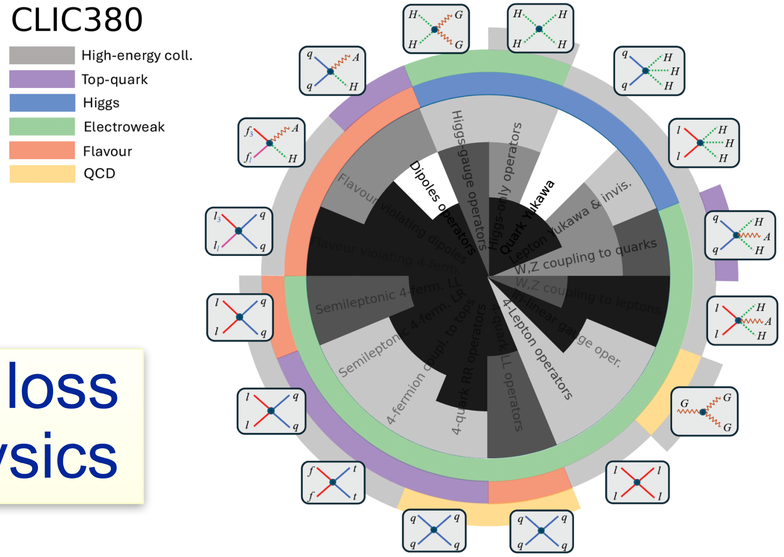
LEP3



LCF250



CLIC380



Major loss of physics

CERN-ESU-2026-006

P. Sphicas

Preferred next flagship collider: FCC-ee

- **The FCC-ee would deliver the world's broadest high-precision particle physics programme**
  - **Outstanding discovery potential through the Higgs, electroweak, flavour and top sectors, as well as advances in QCD**
  - **Its technical feasibility is demonstrated via the FCC feasibility study**
  - **Scope and costs are well defined, plausible funding models exist**
- **The FCC-ee would maintain European leadership in high-energy particle physics, also advancing technology and providing societal benefits**
- **The FCC-ee would also pave the way towards a hadron collider reusing the tunnel and much of the infrastructure, providing a direct discovery reach well beyond the 10 TeV parton energy scale**

FCC-ee: The preferred next CERN flagship project, which will allow Europe to play a leading role in the field.

But: Financial viability & potential **emergence of unforeseen challenges**, notably those associated with **tunnel construction**

Remaining question: what if this "plan A" is not feasible?
What is lost, if an alternative collider, other than the FCC, would be chosen?

P. Sphicas

Towards identifying a Plan B

- **All other collider options (i.e. not the FCC-ee) are considered as potential alternatives if the FCC-ee is not feasible.**
  - **All these alternatives do not present a concrete and visionary plan, by failing one or more of the requirements for the next flagship collider at CERN:**
    - **providing sufficient precision in the electron-positron collider program so as to be competitive with an FCC-ee-like machine running concurrently,**
    - **providing a sufficiently concrete plan due to pending demonstrations of key technology elements, or**
    - **providing a convincing vision for exploration of the highest achievable energies**

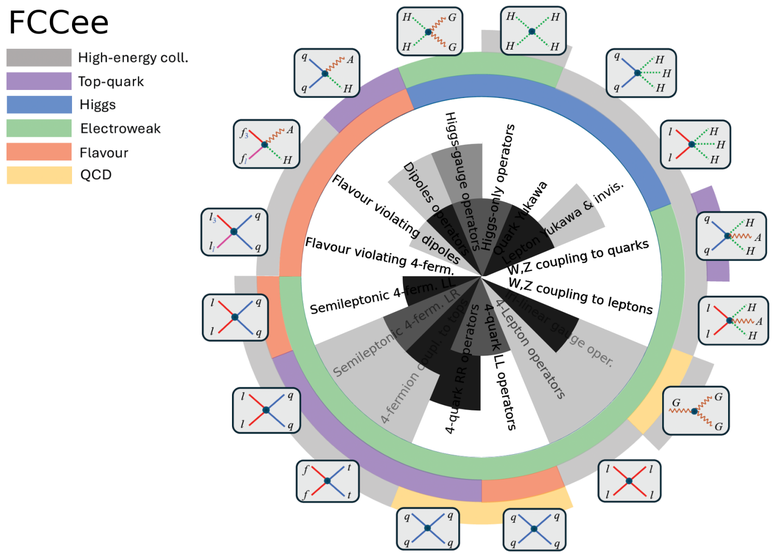
- **Given this analysis and the coherence of the input from the national HEP communities, ESPP update also considered possibility of a collider based on the FCC-ee concept but at a lower cost**
  - **Albeit with reduced physics capability.**

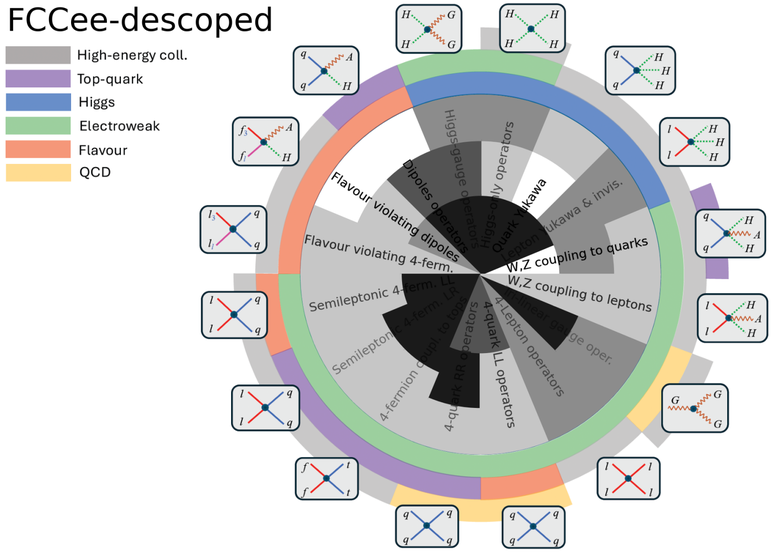
→ **An alternate option: a descoped FCC-ee has been investigated.**

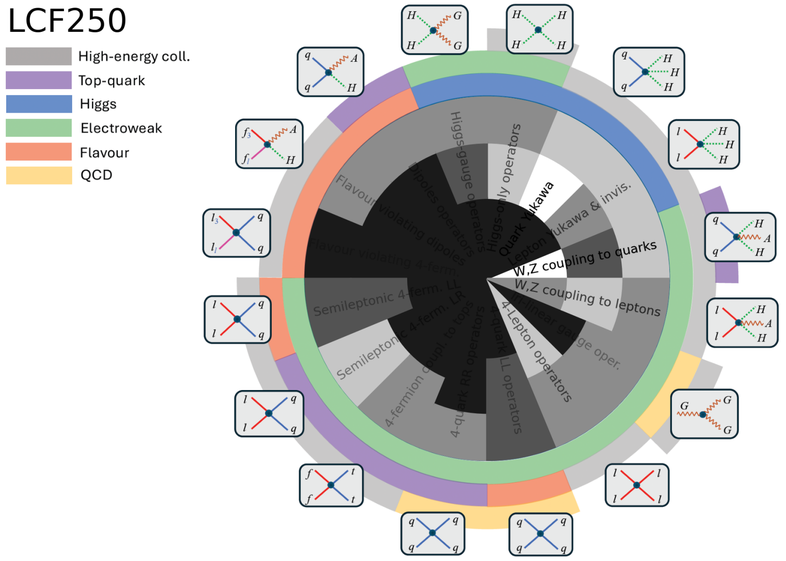
→ **Removing top-quark run (1.26 BCHF); two rather than four IPs/ experiments (0.80 BCHF); lower RF system power 50 MW ® 30 MW (0.35 BCHF); Luminosity: x0.36.**

P. Sphicas

Preferred next flagship collider: FCC-ee







Although an FCC-ee descope would have a significant impact on the breadth of the physics programme (top quark) and the precision achieved (luminosity), compared to alternative collider options, it would still provide

- A very strong physics programme and
- A viable path towards high energies (10++ TeV)
- Very importantly: Should additional resources become available, these descoping scenarios would be reversible.

P. Sphicas

Summary

Plan A

Plan B

Machine	Precision Physics	BSM physics	Physics vs CEPC	Technical readiness	Constr. cost (BCHF)	Time scale	Path to ≥10 TeV
FCC-ee	22	23			15.3	2046-2060	
Descoped FCC-ee	15	17			12.9	2046-2055	
LCF550	15	17			14.8	2045-2065	
CLIC1500	14	18			14.6	2045-2066	
LCF250	10	16			9.4	2045-2053	
CLIC380	10	16			7.5	2045-2054	
LEP3	15	17			4.1	2047-2062	
LHeC	8	7			2.1	2044-2051	

Plan A

Plan B

Physics: from WG2b (sum of precision/BSM physics)
Phys vs CEPC: competitiveness, assuming CEPC is running in parallel
Tech readiness: from WG2a
Construction cost: from proponents + exp. (CERN part)

P. Sphicas

Conclusion: next flagship collider

The electron–positron Future Circular Collider (FCC-ee) is recommended as the preferred option for the next flagship collider at CERN.

A descoped FCC-ee is the preferred alternative option for the next flagship collider at CERN

At this stage, without knowing the reasons for which the FCC-ee would not be feasible, other alternative options are not ranked.

This was a conscious decision and reflects the large gap in the overall physics reach and path to the future between the FCC-ee and the other options. Should the descoped FCC-ee turn out to be necessary: we can still get to the full FCC-ee if more resources are secured at a later stage.

P. Sphicas

The physics of FCC-ee

Following talk by David d'Enterria will give you much more detail

Detector hermeticity, flexibility

Tracking resolution (tagging), vertexing (flavour), jet resolution

Precision SM

- $m_Z, \Gamma_Z, N_\nu, R_l, A_{\mathrm{FB}}, m_W, \Gamma_W$
- α_s (with permille accuracy)
- Quark and gluon fragmentation
- NP QCD

BSM direct searches

Axion-like particles, dark photons, Heavy Neutral Leptons, LLPs

Higgs

Higgs physics

Higgs width, Higgs to invisible, couplings (including self-couplings)

Particle ID, detector resolution, systematics, stability

EW factory (Z,WW)

FCC-ee

Top

Top physics

$m_{\mathrm{top}}, \Gamma_{\mathrm{top}}$, EW top couplings

Flavour Physics

- 10^{11} $\tau\bar{\tau}$: tau-based EW observables, lepton universality
- 10^{12} $b\bar{b}/c\bar{c}$ pairs: flavour observables, flavour anomalies, CKM, CP, etc.

Vertexing, Particle ID (tracking,calo)

Physics requirements

Higgs Factory Programme

- At √s=240 and √s=365 GeV collect 2.6M HZ and 150k WW → H events
- Higgs couplings to fermions and bosons
- Higgs self-coupling (~4 σ) via loop diagrams
- Unique possibility: s-channel $e^+e^- \rightarrow H$ at 125 GeV

→

- **Momentum resolution $\sigma(p_T)/p_T \simeq 10^{-3}$ @ $p_T \sim 50$ GeV**
  - σ(p)/p limited by multiple scattering → minimise material
- **Jet σ(E)/E ≃ 3-4% in multijet events for Z/W/H separation**
- **Superior impact parameter resolution for b, c tagging**
- **Hadron PID for s tagging**

Precision EW and QCD Programme

- 6×10^{12} Z and 2×10^8 WW events
- × 500 improvement of statistical precision on EWPO: m_Z, Γ_Z, Γ_{inv}, $\sin^2\theta_W$, R_b, m_W, Γ_W, …
- 2×10^8 tt events: m_{top}, Γ_{top}, EW couplings
- Indirect sensitivity to new physics up to tens of TeV

→

- **Absolute normalisation of luminosity to 10^{-4}**
- **Relative normalisation to $\lesssim 10^{-5}$ (e.g. Γ_{had}/Γ_ℓ)**
  - Acceptance definition to $\mathcal{O}$(10 μm)
- **Track angular resolution < 0.1 mrad**
- **Stability of B field to 10^{-6}**

Heavy Flavour Programme

- 10^{12} bb, cc, 2×10^{12} ττ (clean and boosted): 10 × Belle II
- CKM matrix, CP measurements
- rare decays, CLFV searches, lepton universality

→

- **Superior impact parameter resolution**
- **Precise identification and measurement of secondary vertices**
- **ECAL resolution at few %/√E**
- **Excellent π^0/γ separation for τ decay-mode identification**
- **PID: K/π separation over wide p range** → dN/dx, RICH, timing

Feebly coupled particles Beyond SM

- Opportunity to directly observe new feebly interacting particles with masses below m_Z
- Axion-like particles, dark photons, Heavy Neutral Leptons
- Long-lifetime LLPs

→

- **Sensitivity to (significantly) detached vertices (mm → m)**
  - tracking: more layers, "continous" tracking
  - calorimetry: granularity, tracking capabilities
- **Precise timing**
- **Hermeticity**

M. Dam

Detector requirements

Table 13: Summary of detector requirements.

	Aggressive	Conservative	Comments
Beampipe	$X/X_0 < 0.5\%$	$X/X_0 < 1\%$	$B \to K^* \tau\tau$
Vertex	$\sigma(d_0) = 3 \oplus 15 \,/\, (p \sin^{3/2}\theta)\,\mu m$ $X/X_0 < 1\%$	–	$B \to K^* \tau\tau$ R_c
	$\delta L = 5$ ppm	–	$\delta\tau_\tau < 10$ ppm
Tracking	$\sigma_p/p < 0.1\%$ for $\mathcal{O}(50)$ GeV tracks	$\sigma_p/p < 0.2\%$ for $\mathcal{O}(50)$ GeV tracks	$\delta M_H = 4$ MeV $\delta\Gamma_Z = 15$ keV $Z \to \tau\mu$
	t.b.d.	$\sigma_\theta < 0.1$ mrad	$\delta\Gamma_Z(\text{BES}) < 10$ keV
ECAL	$\sigma_E/E = 3\%/\sqrt{E}$	$\sigma_E/E = 10\%/\sqrt{E}$	$Z \to \nu_e\bar{\nu}_e$ coupling, B physics, ALPs
	$\Delta x \times \Delta y =$ $2 \times 2\,\text{mm}^2$	$\Delta x \times \Delta y =$ $5 \times 5\,\text{mm}^2$	τ polarisation boosted π^0 decays bremsstrahlung recovery
	$\delta z = 100\,\mu$m, $\delta R_{\text{min}} = 10\,\mu\text{m}$ ($\theta = 20°$)	In-situ constraint with dilepton/diphoton events	alignment tolerance for $\delta\mathcal{L} = 10^{-5}$ with $\gamma\gamma$ events
HCAL	$\sigma_E/E = 30\%/\sqrt{E}$	$\sigma_E/E = 50\%/\sqrt{E}$	$H \to s\bar{s}$, $c\bar{c}$, gg, invisible HNLs
	$\Delta x \times \Delta y =$ $2 \times 2\,\text{mm}^2$	$\Delta x \times \Delta y =$ $20 \times 20\,\text{mm}^2$	$H \to s\bar{s}$, $c\bar{c}$, gg
Muons	low momentum ($p < 1$ GeV) ID	–	$B_s \to \nu\bar{\nu}$
Particle ID	$3\,\sigma$ K/π $p < 40$ GeV	$3\,\sigma$ K/π $p < 30$ GeV	$H \to s\bar{s}$ $b \to s\nu\bar{\nu}, \ldots$
LumiCal	tolerance $\delta z = 100\,\mu$m, $\delta R_{\text{min}} = 1\,\mu$m acceptance 50–100 mrad	–	$\delta\mathcal{L} = 10^{-4}$ target (Bhabha)

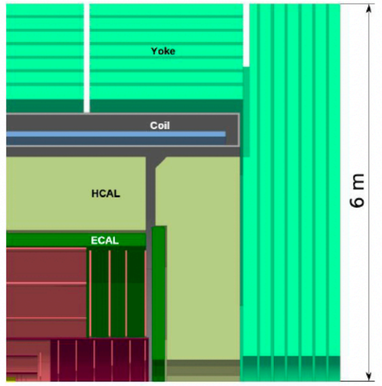
Detector requirements

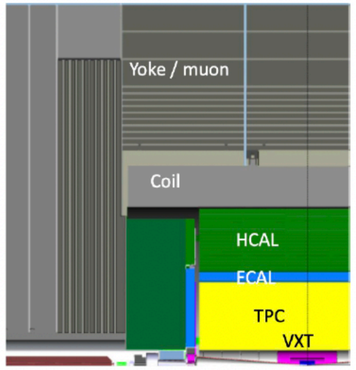
Table 13: Summary of detector requirements.

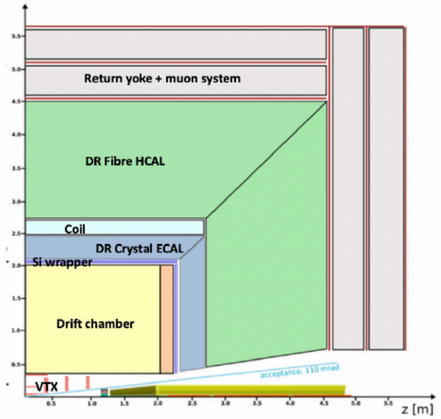
	Aggressive	Conservative	Comments
Beampipe	$X/X_0 < 0.5\%$	$X/X_0 < 1\%$	$B \to K^* \tau\tau$
Vertex	$\sigma(d_0) = 3 \oplus 15 \,/\, (p \sin^{3/2}\theta)\,\mu m$ $X/X_0 < 1\%$	–	$B \to K^* \tau\tau$ R_c
	$\delta L = 5$ ppm	–	$\delta\tau_\tau < 10$ ppm
Tracking	$\sigma_p/p < 0.1\%$ for $\mathcal{O}(50)$ GeV tracks	$\sigma_p/p < 0.2\%$ for $\mathcal{O}(50)$ GeV tracks	$\delta M_H = 4$ MeV $\delta\Gamma_Z = 15$ keV $Z \to \tau\mu$
	t.b.d.	$\sigma_\theta < 0.1$ mrad	$\delta\Gamma_Z(\text{BES}) < 10$ keV
ECAL	$\sigma_E/E = 3\%/\sqrt{E}$	$\sigma_E/E = 10\%/\sqrt{E}$	$Z \to \nu_e\bar{\nu}_e$ coupling, B physics, ALPs
	$\Delta x \times \Delta y =$ $2 \times 2\,\text{mm}^2$	$\Delta x \times \Delta y =$ $5 \times 5\,\text{mm}^2$	τ polarisation boosted π^0 decays bremsstrahlung recovery
	$\delta z = 100\,\mu$m, $\delta R_{\text{min}} = 10\,\mu\text{m}$ ($\theta = 20°$)	In-situ constraint with dilepton/diphoton events	alignment tolerance for $\delta\mathcal{L} = 10^{-5}$ with $\gamma\gamma$ events
HCAL	$\sigma_E/E = 30\%/\sqrt{E}$	$\sigma_E/E = 50\%/\sqrt{E}$	$H \to s\bar{s}$, $c\bar{c}$, gg, invisible HNLs
	$\Delta x \times \Delta y =$ $2 \times 2\,\text{mm}^2$	$\Delta x \times \Delta y =$ $20 \times 20\,\text{mm}^2$	$H \to s\bar{s}$, $c\bar{c}$, gg
Muons	low momentum ($p < 1$ GeV) ID	–	$B_s \to \nu\bar{\nu}$
Particle ID	$3\,\sigma$ K/π $p < 40$ GeV	$3\,\sigma$ K/π $p < 30$ GeV	$H \to s\bar{s}$ $b \to s\nu\bar{\nu}, \ldots$
LumiCal	tolerance $\delta z = 100\,\mu$m, $\delta R_{\text{min}} = 1\,\mu$m acceptance 50–100 mrad	–	$\delta\mathcal{L} = 10^{-4}$ target (Bhabha)

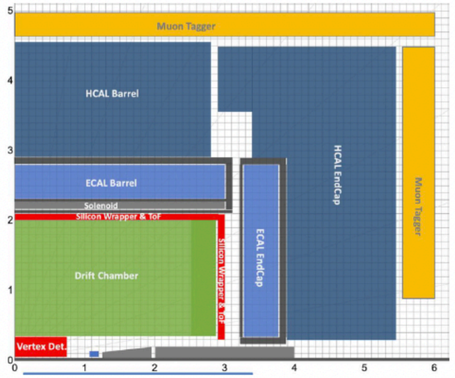
FCC-ee Detector concepts

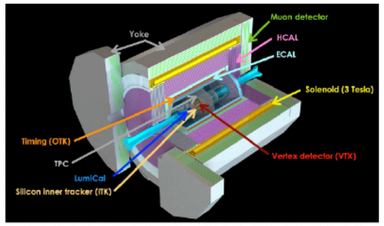
Six detector concepts so far, probably more coming











CLD
Full silicon tracking
High-granularity particle flow calorimetry

arXiV:1911.12230

ILD
Silicon vertex tracker
TPC tracker
High-granularity particle flow calorimetry

arxiv:1306.6329

IDEA
Ultra-light drift chamber
Dual-readout calorimetry

arxiv:2502.21223

ALLEGRO
Noble liquid (LAr) electromagnetic calorimetry

arxiv:2109.00391

ALFA
All-MAPS silicon tracker
Novel crystal grain calorimetry

AGORA
TPC tracker
Heavy-glass scintillating tile technology

arxiv:2510.05260

Common Subsystems
Cross-cutting R&D shared across all concept proposals

Particle ID
RICH, Cherenkov ARC
Tracker d*N*/d*x* and TOF

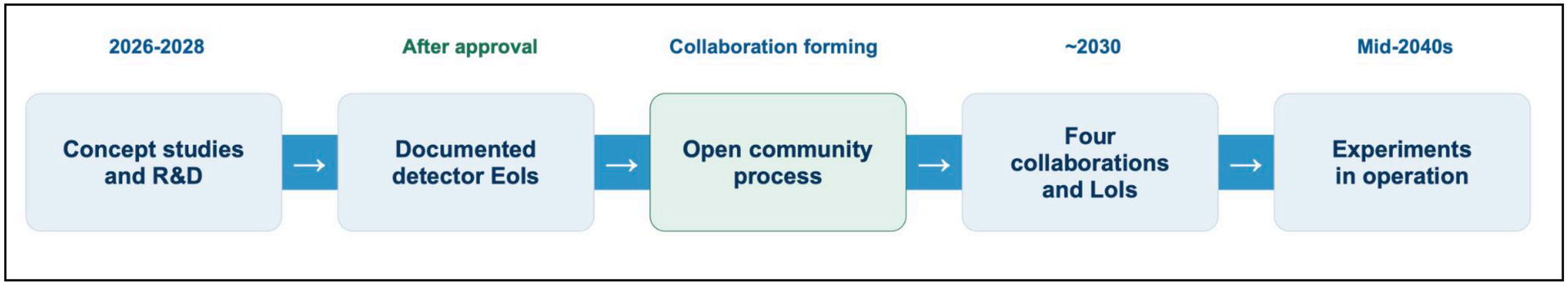
Magnetic fields
Up to 2 or 3 Tesla
Co-design with machine to avoid "emittance bow-up"

Aligning DRD Collaborations with FCC-ee Needs

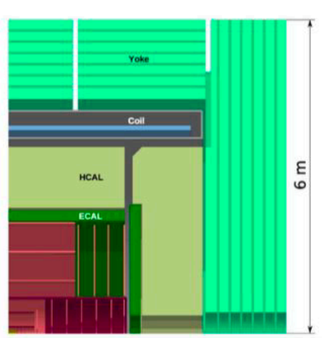
During the Reference Design Phase cooperation across detector concepts and technologies is highly encouraged

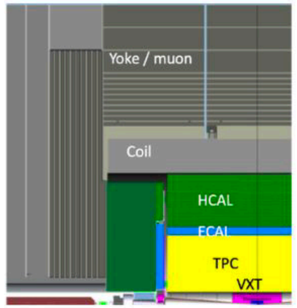
Reference Design Phase (RDP) seen from PED

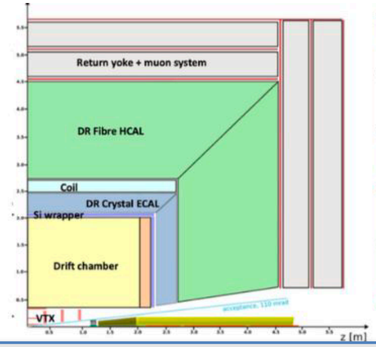
- The PED timeline is different from the rest of the study

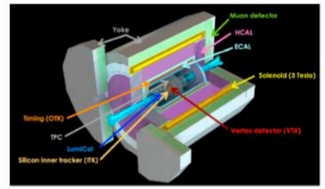


- Six detector concepts are studied today — hopefully more coming!









CLD	ILD	IDEA	ALLEGRO	ALFA	AGORA

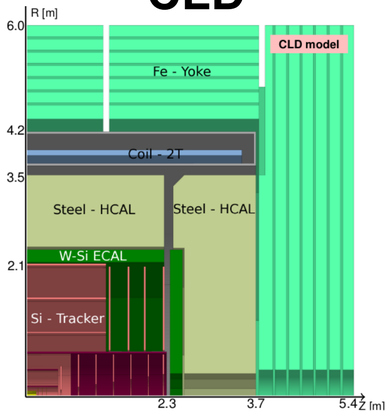
- Expression of interests will be called AFTER the approval (but prepared now)
- Collaboration forming (merging, etc.): Evian-like series of workshop in 2029-30
  - From 6+ detector concepts to four collaboration and four Letters of Intent in ~2030
- Detector CDRs in 2033-34; TDRs in 2036-37; Detectors ready in 2045-46.

PED coordination

Detector concepts - Tracking systems

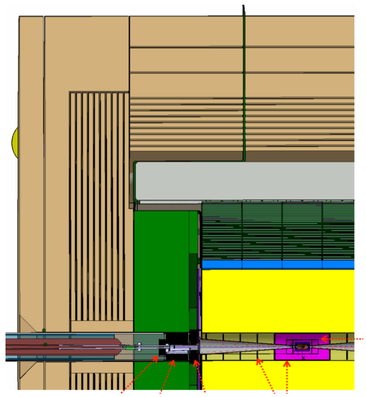
Legend: Inner Tracker, Outer Tracker, Wrappers

CLD



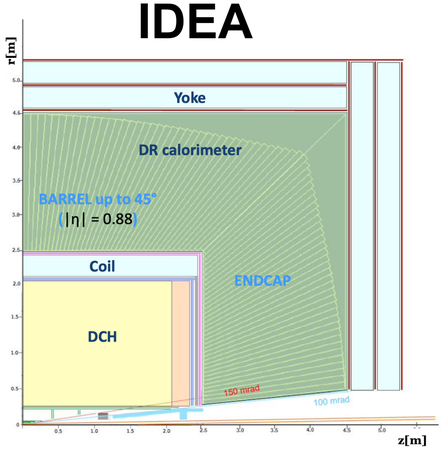
- Evolved from CLIC detector
- Silicon vertex with 25μm pixels
  - Geometry with ALICE ITS approximation → FCC-SEED
- Silicon tracker with 50μm strips
  - Sensors plus ASICs or monolithic structure or MAPS
- ARC (Array of RICH Cells) Lightweight with 20cm radial depth
  - Two radiators (gas + aerogel)

ILD



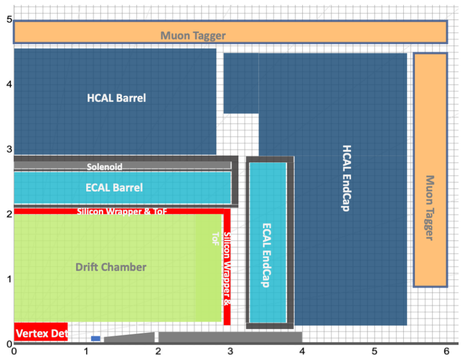
- Initial design for ILC
  - Significant changes for FCC-ee
- Silicon Vertex
  - Currently borrowed from CLD for simulations
- TPC as outer tracker
  - Studying different layouts varying the inner Radii
  - Pad or pixel electrode, GEM or Micromegas
- Silicon External Tracker for ToF + momentum resolution

IDEA



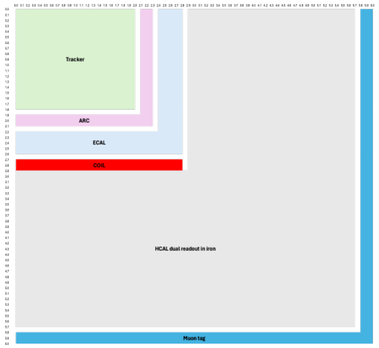
- Conceived for FCC-ee
- Silicon vertex tracker
  - Outer based on ATLASPix3 with 50x150μm pixels
  - Inner ARCADIA based 25x25 μm pixels
- Central tracker based on low mass Drift Chamber
  - 112 layers
  - 4m Long
  - R = 35-200cm
- Silicon wrapper
  - either with MAPS with ~10^{11} channels!
  - or CMOS-LGADs ~40ps

ALLEGRO



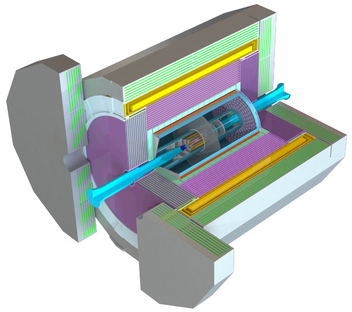
- Conceived for FCC-ee, started with a noble-liquid calorimeter
- Tracking system taken from IDEA
- Silicon Vertex with curved or straight sensors
- Outer tracker with
  - Extended Drift Chamber
  - Straw tubes
  - Scintillating Fiber Tracker (SciFi)
    - 5m Long
    - R = 35-200cm
- Silicon wrapper
  - Monolithic pixel or AC-LGADs

ALFA



- Newly Conceived project for FCC-ee
- MAPS tracker following ALICE ITS3 developments
  - Vertex curved MAPS 65 nm CMOS TPSCo 10x10 μm pixels
  - Outer tracker Reticle-size MAPS,
    - 25x32 mm^2 to 50x128 mm^2 module
- ARC (Array of RICH Cells) Lightweight with 20cm radial depth
  - Two radiators (gas + aerogel)

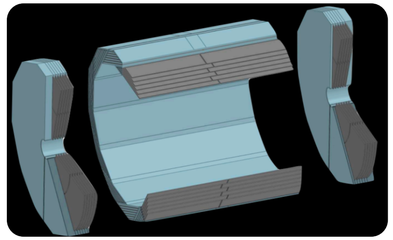
AGORA



- Newly Conceived project for CEPC
- MAPS tracker
  - Vertex curved MAPS 55 nm CMOS COFFEE3 pixels+stitching (4 single layers)
  - Inner tracker Si pixels CMOS MAPS 55 nm (2 double-sided conventional layers)
- Central tracker TPC with high granularity readout
  - 5.8 m long
  - 600 mm inner radius
- AC-LGAD ~40 ps

Detector concepts - Calorimetry

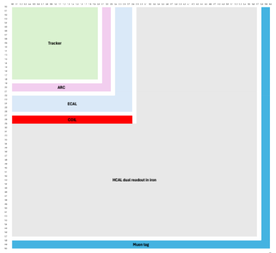
AGORA



ECAL: 4D transverse BGO crystal bars

HCAL: Heavy-glass (GFO) scintillating tile technology

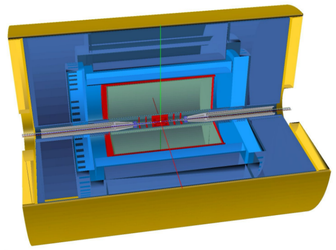
ALFA



ECAL: Grainita, crystal grains ($ZnWO_4$) immersed in a sodium-tungstate water solution

HCAL: DR fibres with Iron

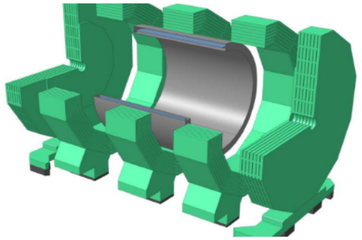
ALLEGRO



ECAL: High-granularity LAr (or LXe)

HCAL: High-granularity LAr

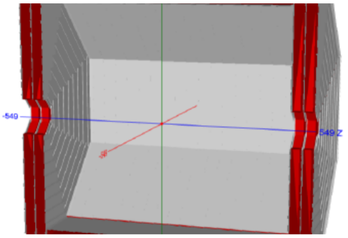
CLD



ECAL: High-granularity Si-W

HCAL: High-granularity Scintillator-steel

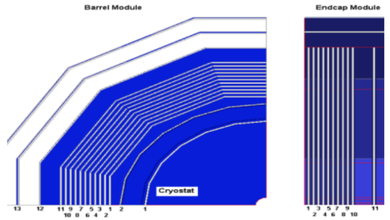
IDEA



ECAL: PWO or BS(G)O DR crystals (possible LYSO timing layer)

HCAL: DR fibres-steel

ILD



ECAL: High-granularity Si-W or Sci-W

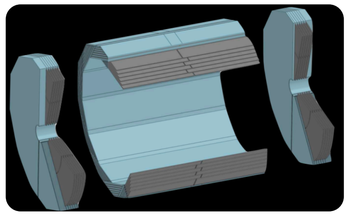
HCAL: High-granularity Scintillator-steel (analog) or RPC-steel (semi-digital)

Energy resolution ECAL: 2-3%/√E

Energy resolution HCAL: 30%/√E

Overview of Muon detection systems

AGORA

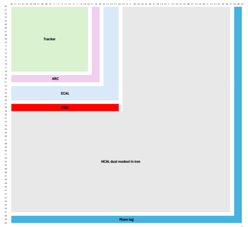


Tech: plastic scintillator strips

Layout: 6 layers in iron yoke

Purpose: tagging muon system

ALFA

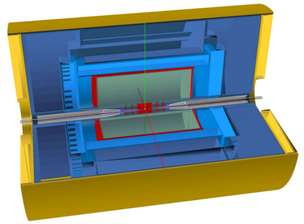


Tech: RPC or Scint. under discussion, possibly same HCAL

Layout: under discussion

Purpose: tagging muon system

ALLEGRO

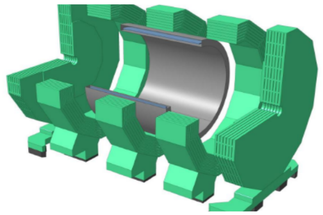


Tech: Squared drift tubes and Scintillator strips or Micromegas or Bigap RPCs

Layout: under discussion

Purpose: both tagging muon system and tracking muon system are considered

CLD

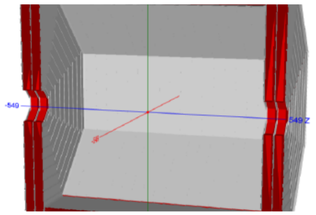


Tech: RPCs with 30x30 mm cells.

Layout: 6 equidistant layers embedded in yoke slots. and 1 extra layer behind solenoid as tail-catcher.

Purpose: high granularity tagging and calorimetry support.

IDEA

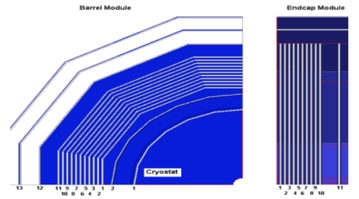


Tech: 50x50 cm^2 µ-RWELL chambers with 1.2 mm strip pitch

Layout: 4 stations interleaved with 30/50 cm iron yoke

Purpose: standalone tracking muon system for LLP

ILD



Tech: Scintillators (SiPM/WLS) or X-Y RPCs, possibly same HCAL

Layout: 14 active layers in barrel, 12 layers in endcap in iron yoke

Purpose: Robust tagging and 2D reconstruction

Performance: over 95% efficiency, under 1% µ fake rate

Coverage: over 98% solid angle

Resolution: 1 ns time resolution and 1 cm spatial for tagging muon system or 200 µm spatial for tracking muon system

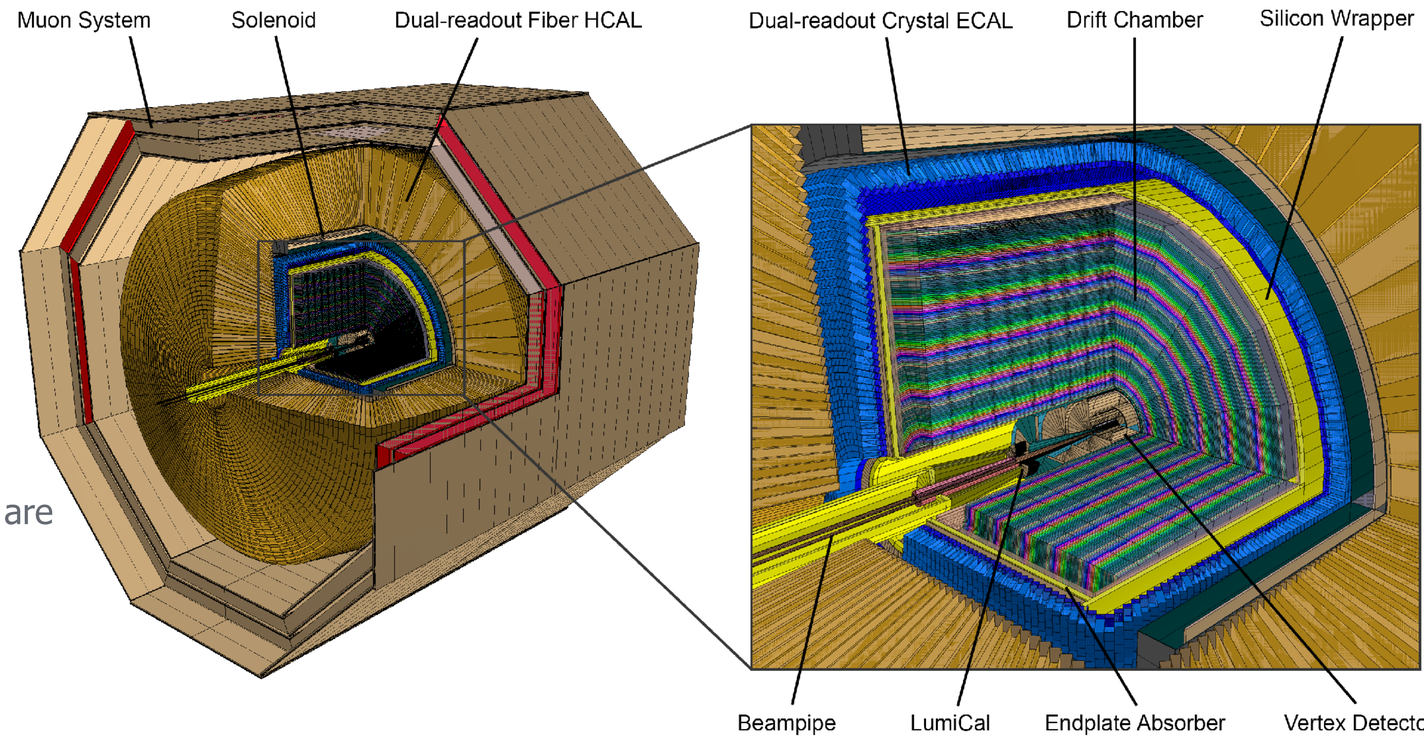
Rate: 50 Hz/cm^2 in the barrel and 10 kHz/cm^2 in the endcap

FCC-ee Detector concepts technologies

- **Vertex trackers** are very similar across the 6 detector concepts
  - MAPS with 3 μm position resolution (planar or curved geometry)
- **Central tracker**
  - Gaseous (Drift chamber, TPC) or silicon sensor based (MAPS or silicon-strip)
    - Straw tubes and Scintillating fiber tracker as other options
- **Wrapper**
  - Silicon-based (strips, MAPS, LGADs), ARC
- **Calorimeters**
  - **Ecal**
    - DR crystals, high-granularity particle flow, liquid Ar (or Xe), Grainita, heavy-glass scintillating tile
  - **Hcal**
    - DR fibers, high-granularity particle flow, liquid Ar
- **Muon detector**
  - MPGDs (μRWELL, Micromegas), RPCs, scintillators, DT, TGC

Innovative Detector for E^+e^- Accelerator (IDEA)

- **IDEA** is constituted geometrically of a barrel closed by two endcaps.
- It is made of (in increasing distance from the IP):
  - **A vertex detector with CMOS sensors**
    - 3 inner layers with 25x25 μm^2 pixels
    - 2 outer layers with 50x150 μm^2 pixels
  - **An ultra-light drift chamber**
    - Excellent PID capability with dN/dx
    - 112 independent measurements along a track
  - **An outer wrapper made of silicon strip detectors**
    - LGAD detectors with precision timing resolution (100 ps) are considered as an option
  - **A Dual Readout crystal electromagnetic calorimeter**
    - $\sigma_{EM} \approx 3\%/\sqrt{E}$ for photons/electrons
  - **HTS solenoid providing a magnetic field up to 3 T**
  - **A Dual Readout fibre calorimeter**
    - Provides an excellent hadronic jet energy resolution
  - **A muon detector composed of 4 stations of µRWELL detectors**
  - **Two Lumicals in the forward regions** to measure luminosity with high precision ($<=10^{-4}$)



References: The IDEA detector concept at FCC-ee, https://arxiv.org/abs/2502.21223, will soon appear in NIM

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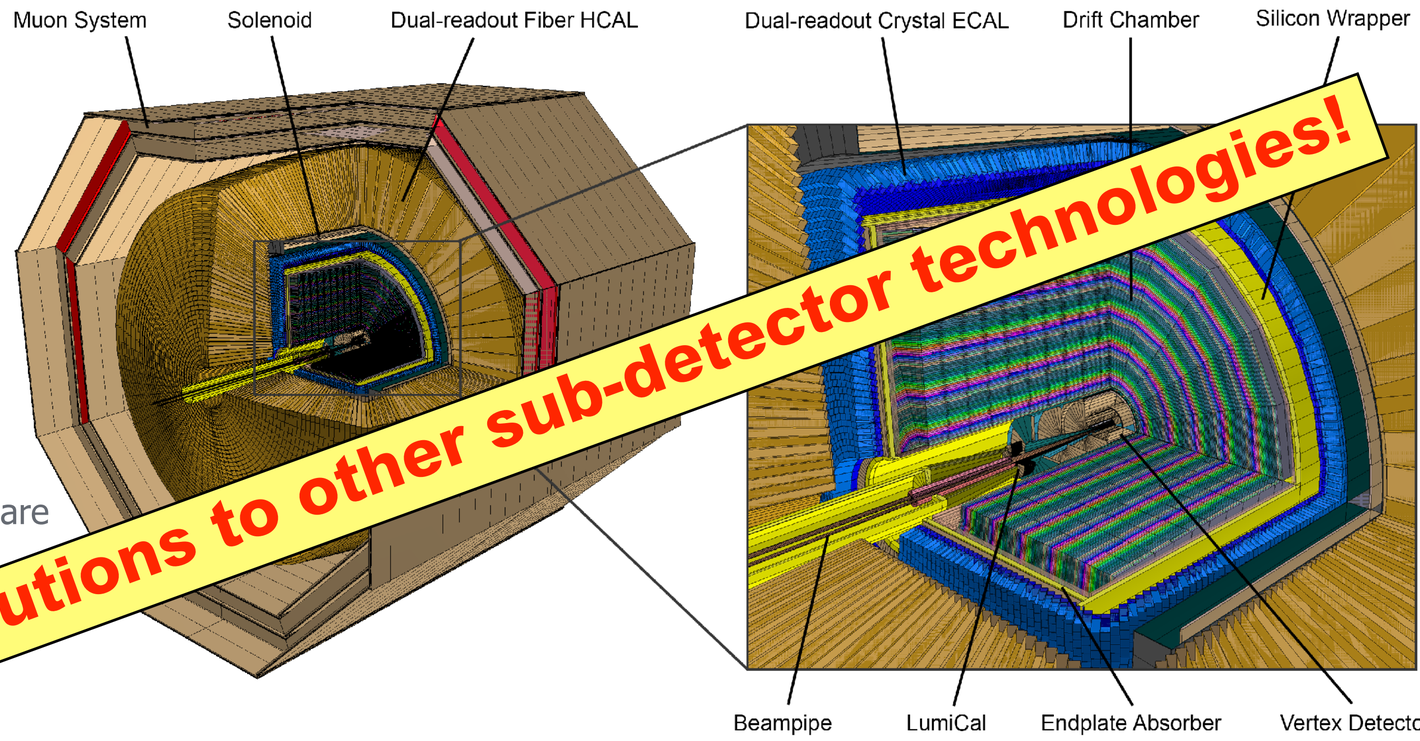
  - **HTS solenoid providing a m… …p to 3 T**
  - **A Dual Readout fi… …el**
    - Provid… …hadronic jet energy resolution
  - **…ector composed of 4 stations of µRWELL detectors**
  - **…o Lumicals in the forward regions** to measure luminosity with high precision (<=10^{-4})

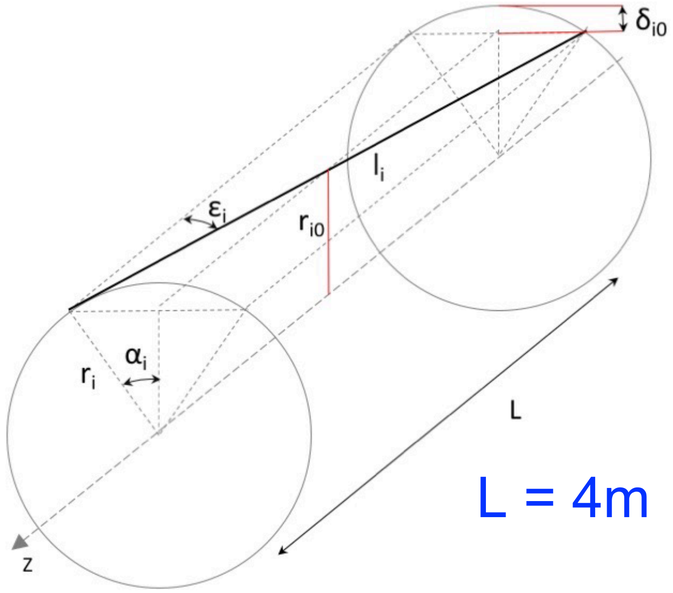


We are extremely open to contributions to other sub-detector technologies!

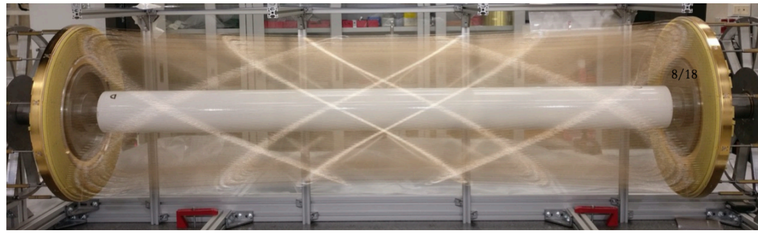
References: The IDEA detector concept at FCC-ee, https://arxiv.org/abs/2502.21223, will soon appear in NIM

Drift chamber

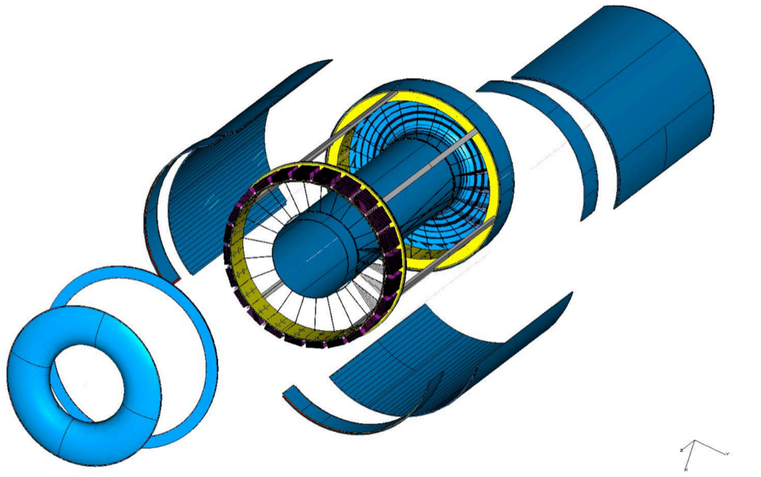
- IDEA: Extremely transparent Drift Chamber
  - Gas: 90% He – 10% iC_4H_{10}
  - Radius 0.35 – 2.00 m
  - Total thickness: 1.6% of X_0 at 90°
  - All stereo wires (56448 cells, 343968 wires)
    - Tungsten wires dominant contribution
  - 112 layers for each 15° azimuthal sector
  - max drift time: 350 ns

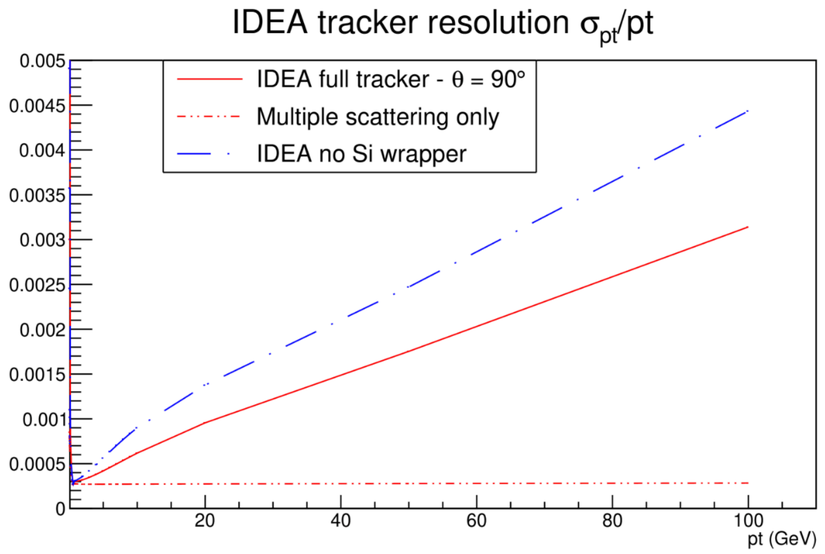


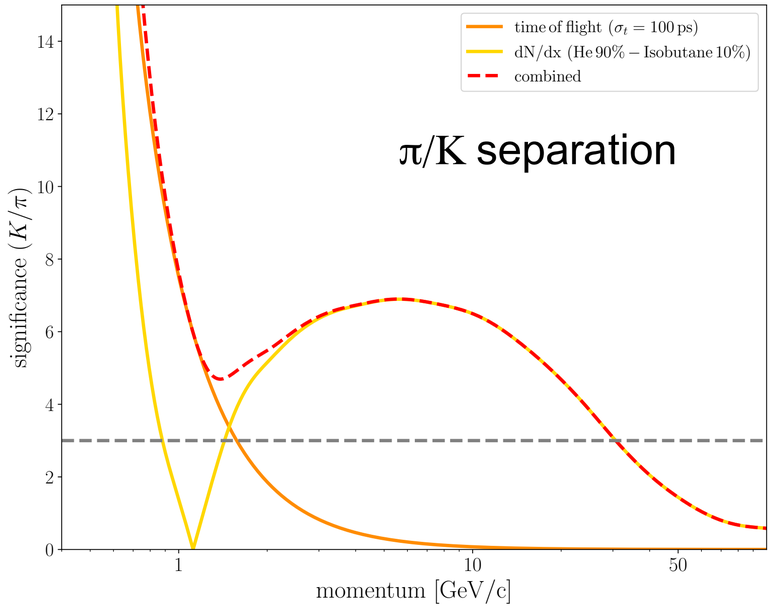
L = 4m



Excellent PID with cluster counting
JINST 20 P11019







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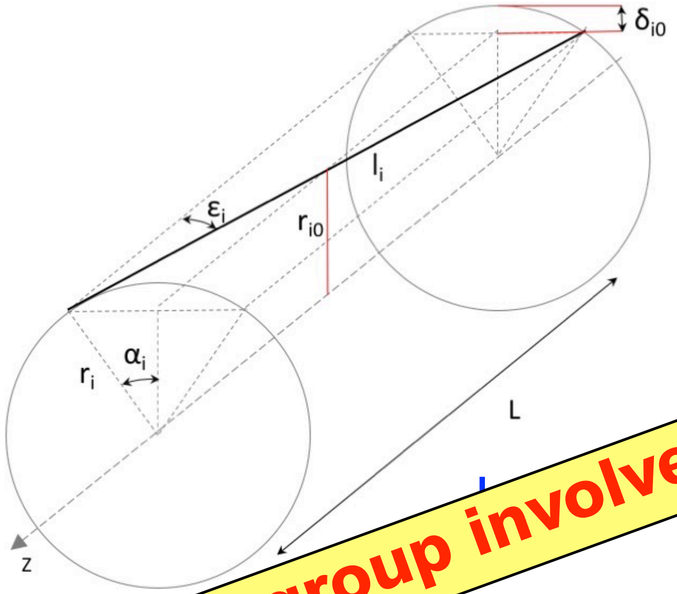
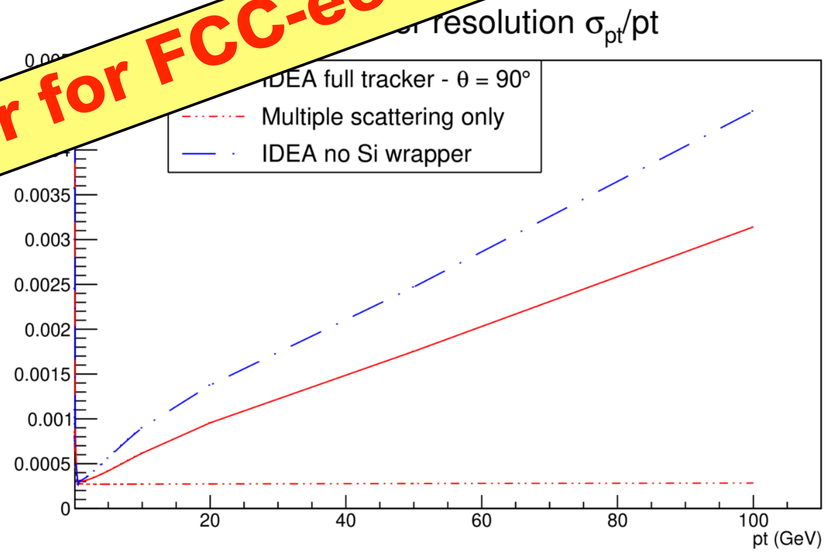
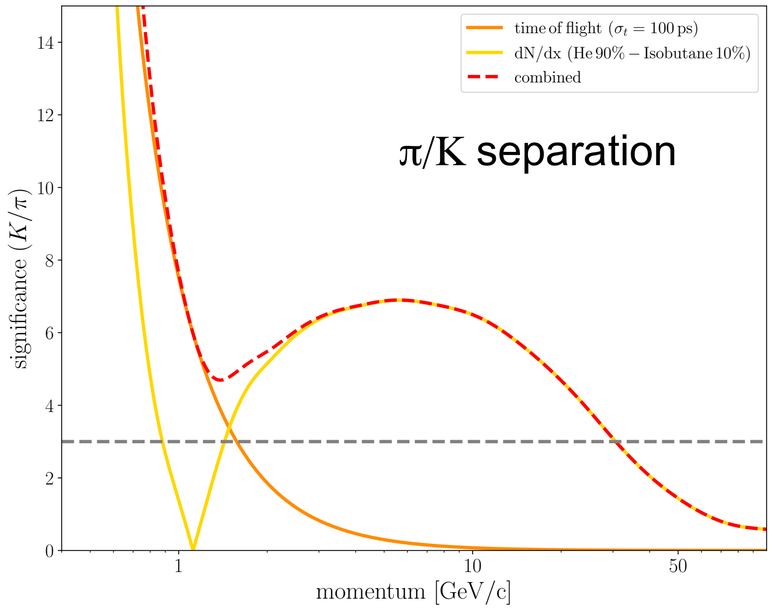


Best central tracker for FCC-ee but group involved needs to grow!

Excellent PID with cluster counting
JINST 20 P11019

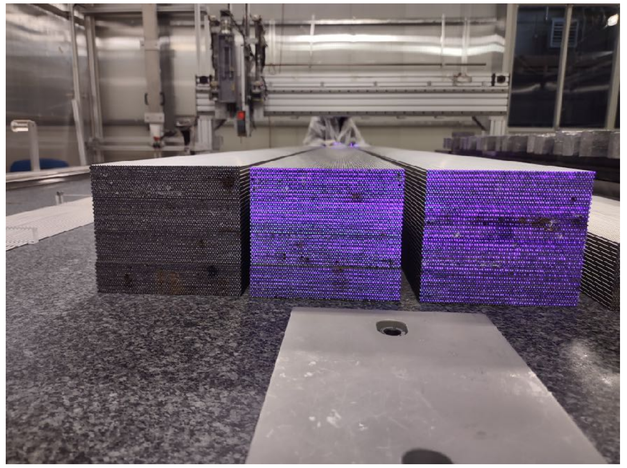


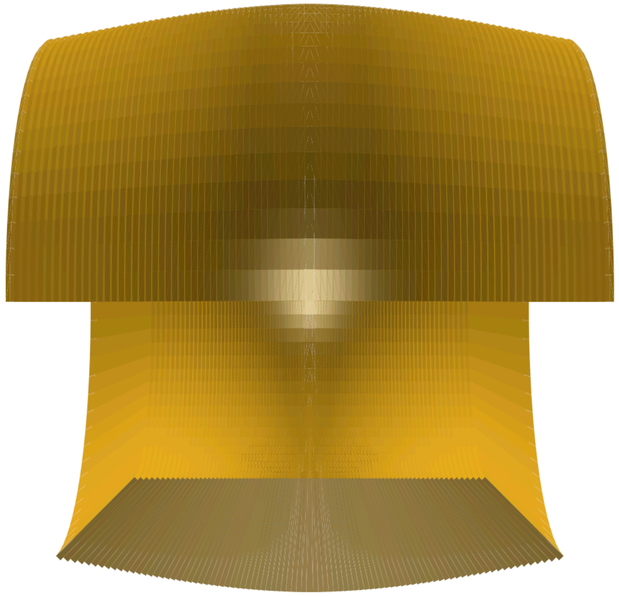


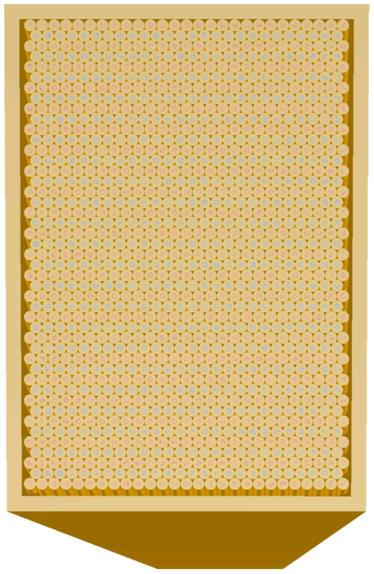
Hadronic DR fibre calorimeter

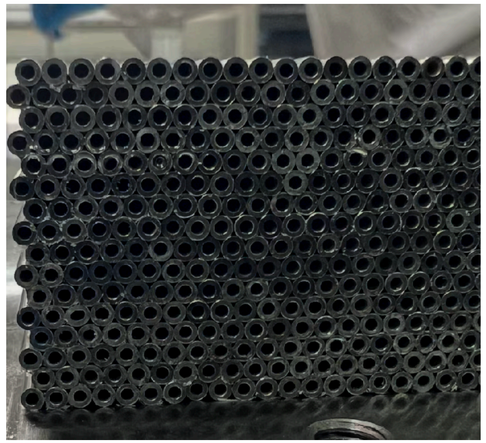
Bucatini-like, fibre-based, dual-readout calorimeter.

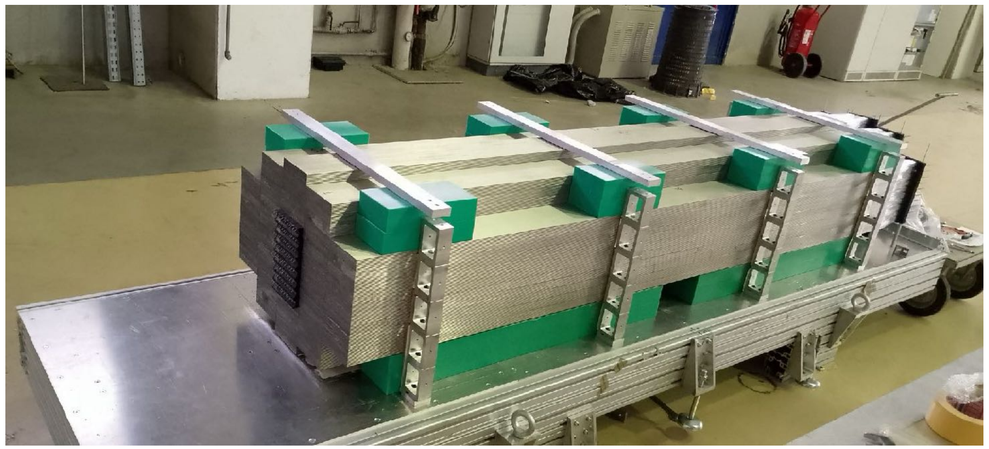
Readout based on **one SiPM per fibre**. SiPM signal **analogically summed** to obtain the desired granularity. Dual-readout achieved with **two different types of fibres (Cherenkov** and **scintillating)**.



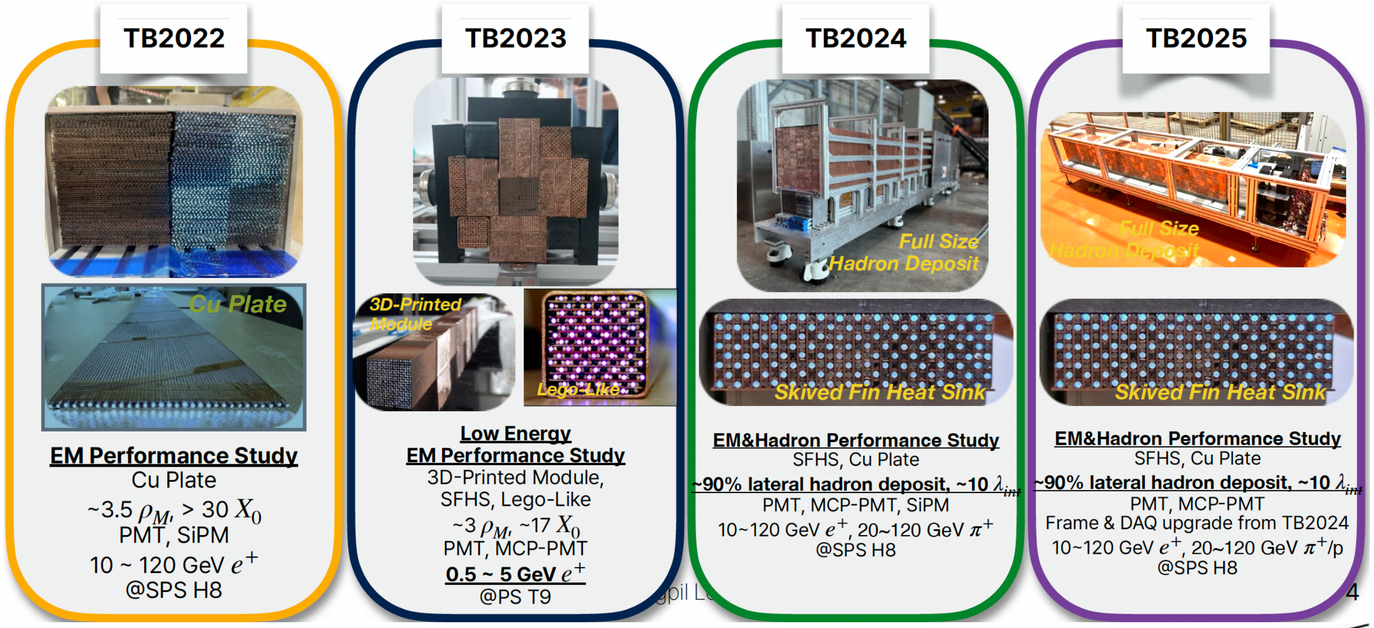


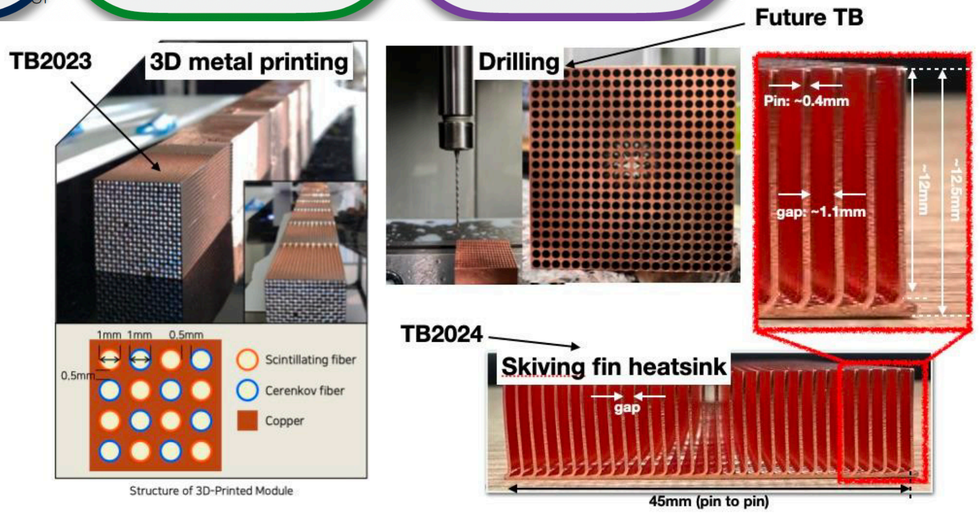






DR fibre calorimeter: Korea DRC



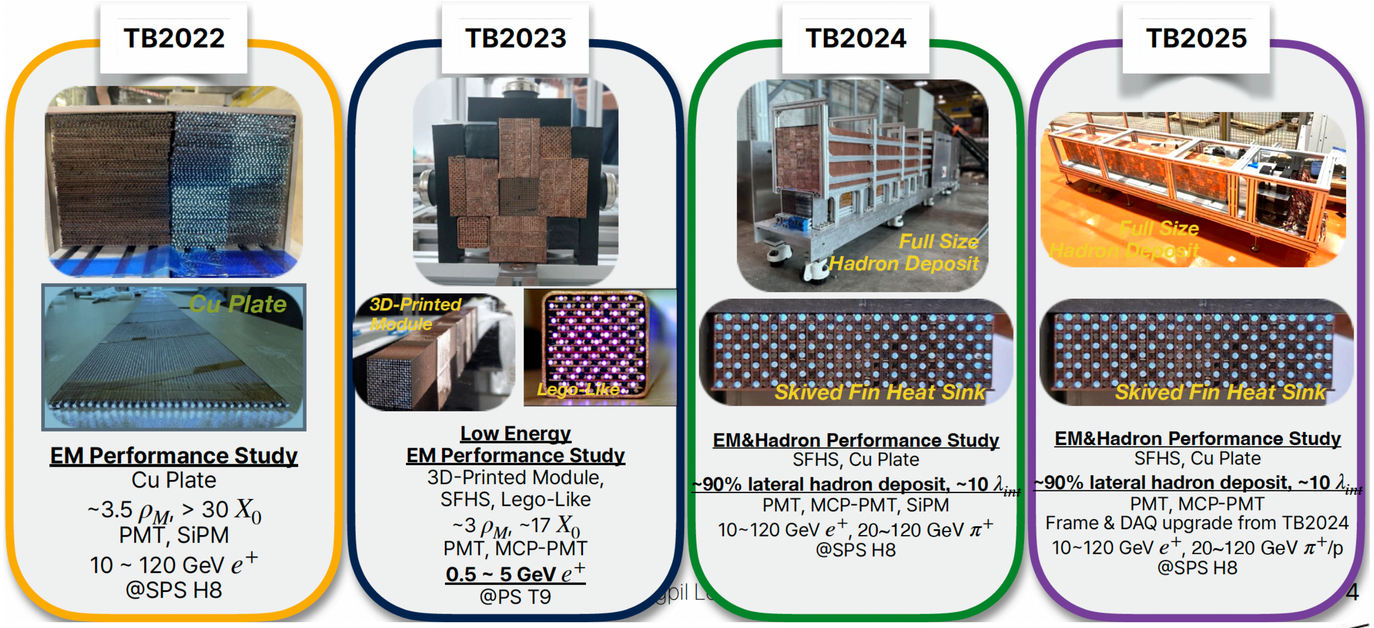


South Korea groups are exploring multiple manufacturing processes for the absorber material:

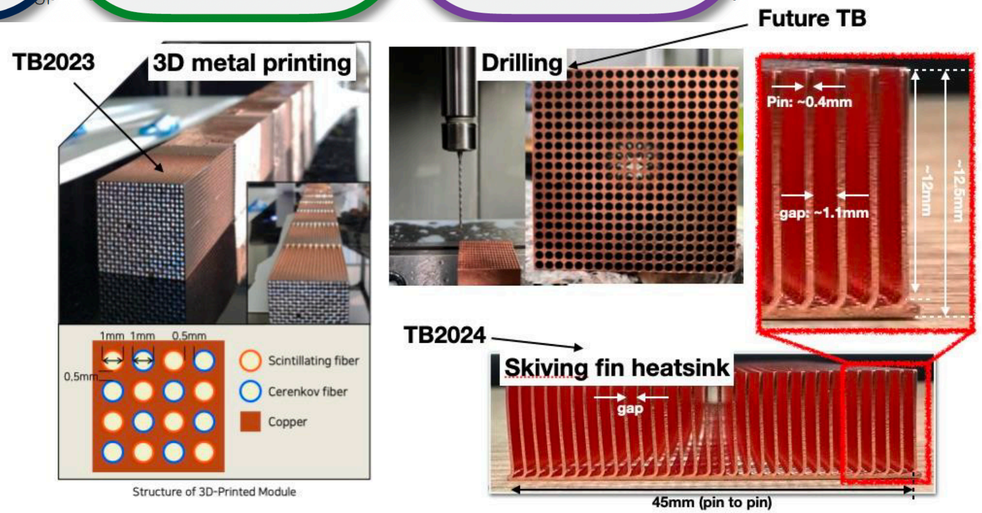
- 3d metal printing
- Drilling
- Skiving

Long standing expertise on DR calorimetry in Korea!
Collaborating with IDEA since several years

DR fibre calorimeter: Korea DRC



Will hear many more details about Korean activities in Prof. Hwidong's talk



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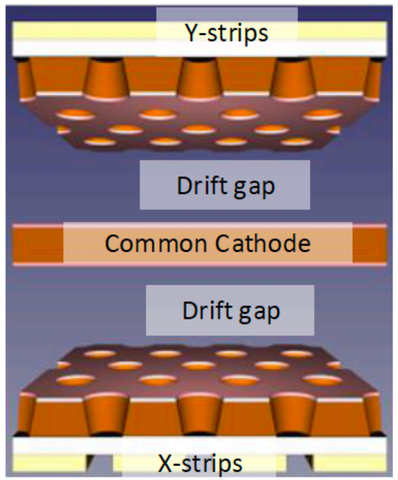
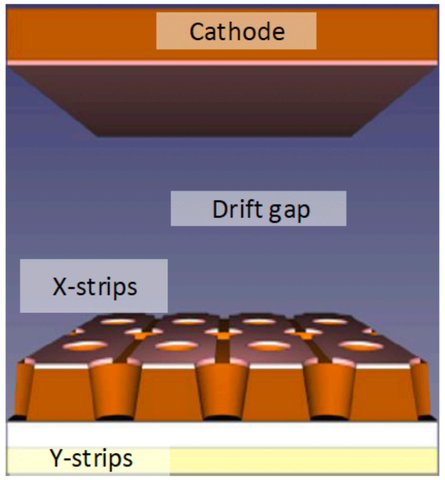
Muon detector: μ-RWELL technology

2×1D Layout



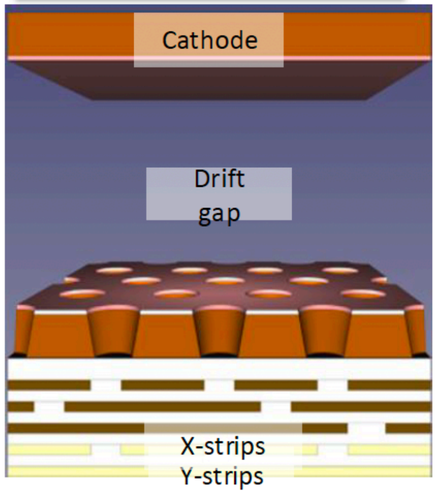
Lower gas gain w.r.t. the "COMPASS R/O" (X / Y are not sharing any charge)
Pitch strip: 0.8 mm

Top R/O Layout



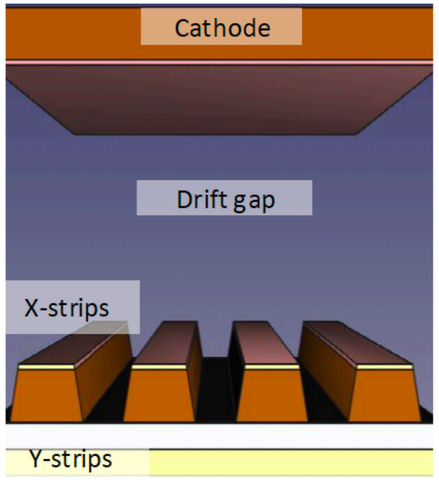
Lower gas gain w.r.t. the "COMPASS R/O" (X / Y are not sharing any charge)
The "Top" coordinate introduces dead zone in the active area
Pitch strip: 0.4 mm

Capacitive Sharing [*] Layout



Reduce the FEE channels
The charge is divided between X and Y → Higher gas gain required w.r.t. 1D
Pitch strip: 1.2 mm

μ-RGRoove (*) Layout

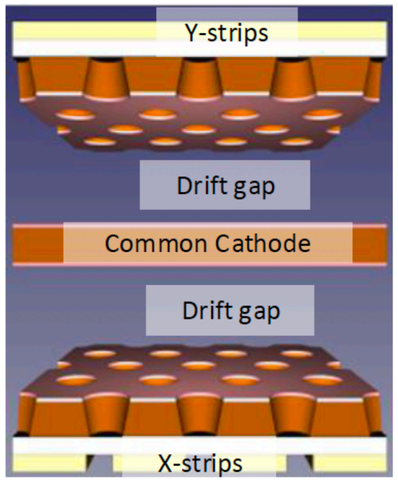


Lower gas gain w.r.t. the "COMPASS R/O" (X / Y are not sharing any charge)
No dead zone w.r.t the Top R/O lauout
Pitch strip: 0.4 mm

Muon detector: μ-RWELL technology

[20] R. Farinelli et al 2025 JINST 20 C06064

2×1D Layout



Lower gas gain w.r.t
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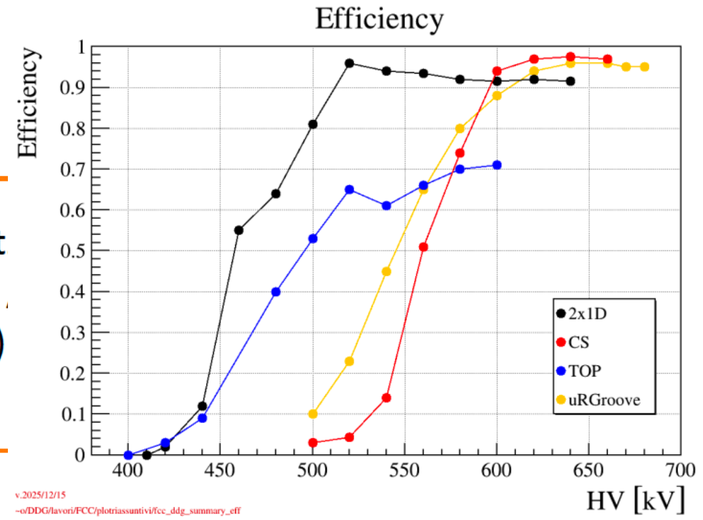
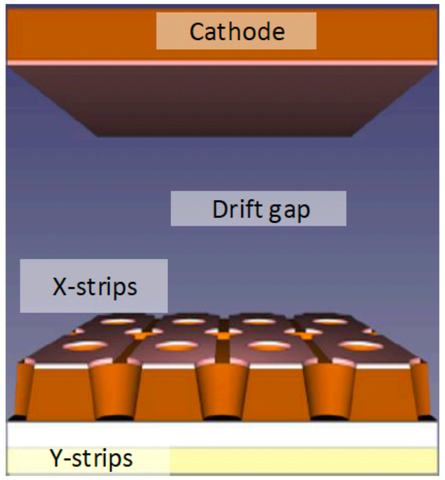
Pitch strip: 0.8 mm



ne "COMPASS
aring any charge)
introduces dead
a

Top R/O Layout



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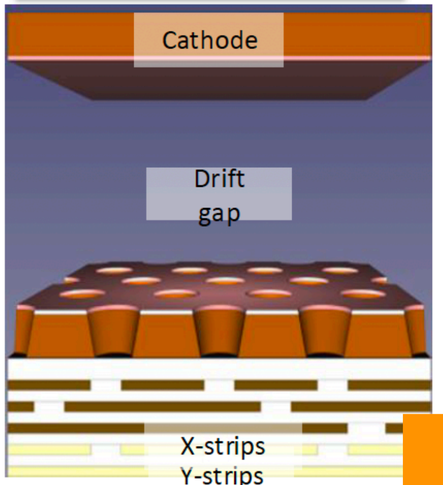

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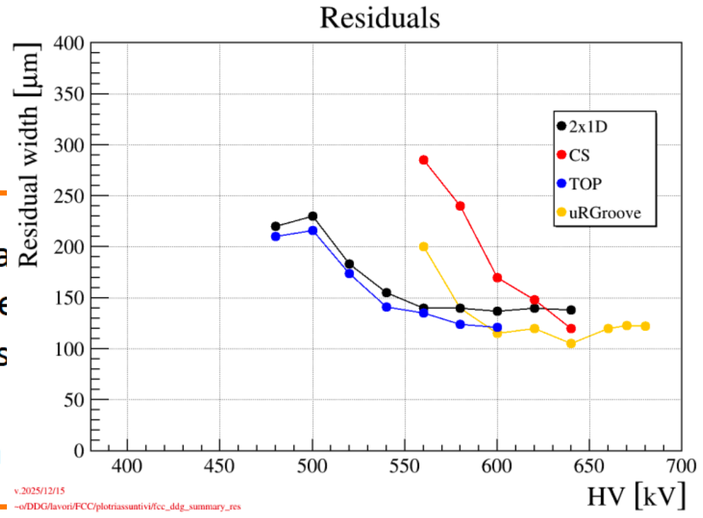

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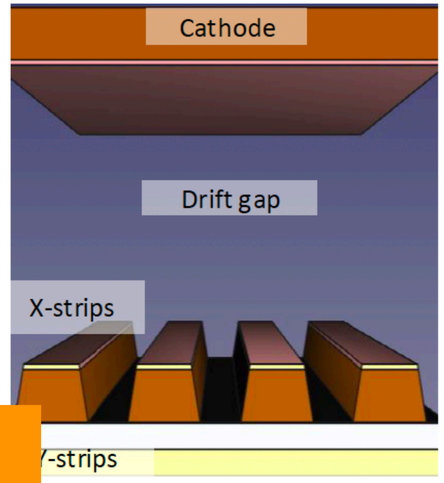


The results are promising and the layouts already satisfy the performance requirements, although some optimisations are possible

Muon detector: μ-RWELL technology

- μ-RWELL is a simplification of the GEM technology with a single-stage charge amplification
  - Korea has a lot of expertise on GEMs (CMS muon detector)
  - Korea has a lot of expertise on RPCs (CMS muon detector) which are considered for muon detection systems in several FCC-ee detector concepts

RPC activities in Korea

- Goals: **Large sized timing RPCs (glass electrodes) to identify heavy particles from muons at endcap yokes**
  - ✓ Time resolution ~ 150 ps with the rate capability ~ a few hundreds Hz cm^{-2}
  - ✓ 2D position resolution **~ 3 mm with a 10-mm strip pitch (with simple digitization) and < 5 mm along the strips**
- For proper gas circulation, use thin spacers (by a molding method) instead of fishing rod.
- **Intrinsic time resolution of gaps → with 300 μm (~ 100 ps) or 500 μm (~ 150 ps) thick single-gap thicknesses**

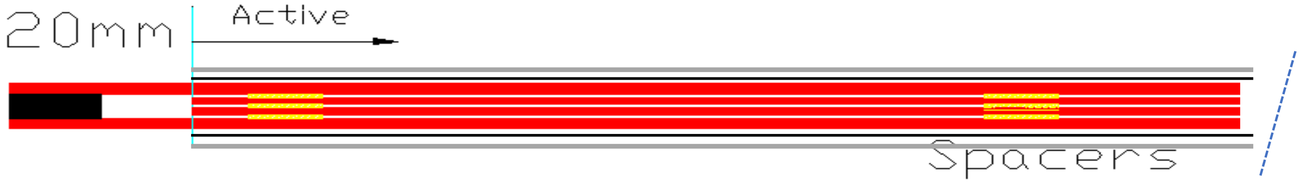
  Use of spacers instead of fishing rod for relevant gas circulation and preventing aging

  → **Productivity of gluing gas-gap envelopes with spacers is much higher**

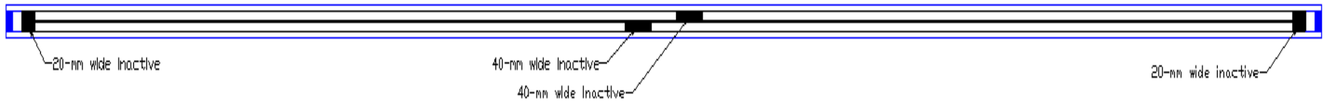
  → Structure-wise, strip readout is lying outside (free from) the gas volumes
- Maximum ~ 1 m long strips to allow dispersion of signals ~ 50 ps.

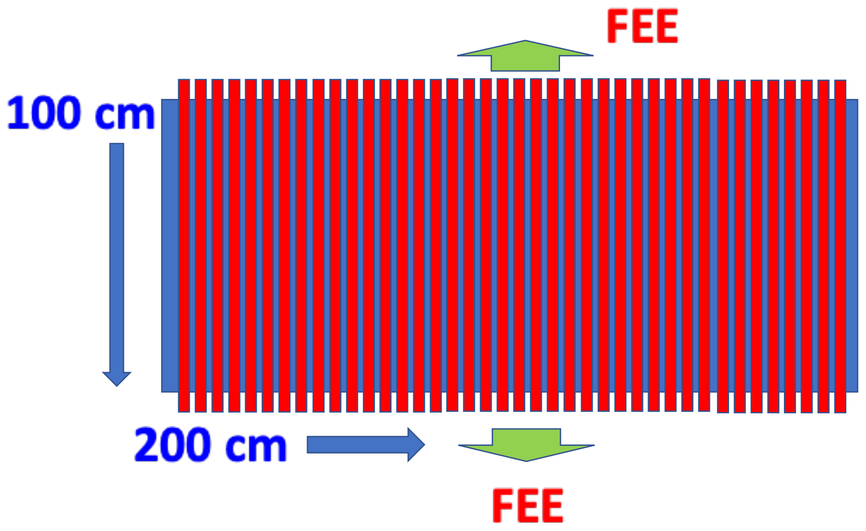
→ 1-m detector width will be maximum to get σ_t **~ 150 ps (300-μm six gaps)** and ~ **200 ps (500-μm four gaps)**

Korea model



A single detector composed of 4 triple-gap gas envelopes (no geometrical inefficiency)





RPC activities in Korea

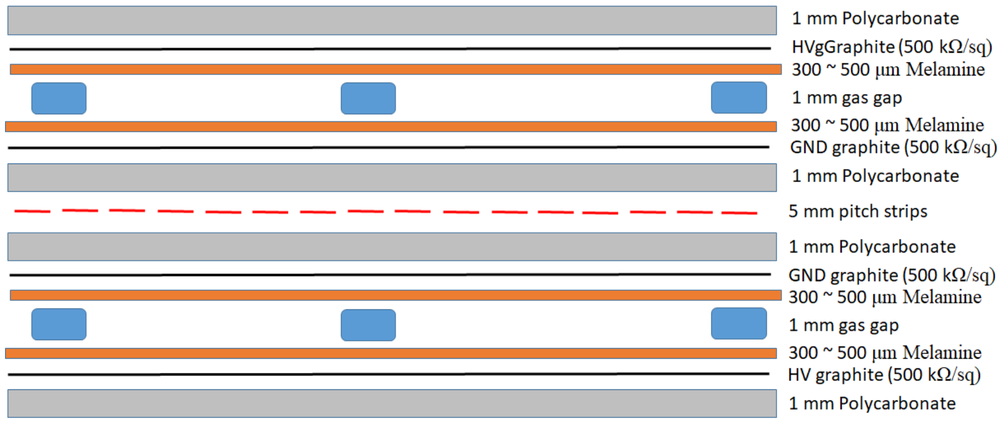
New RPC electrodes, for better position and time resolutions with a higher rate capability

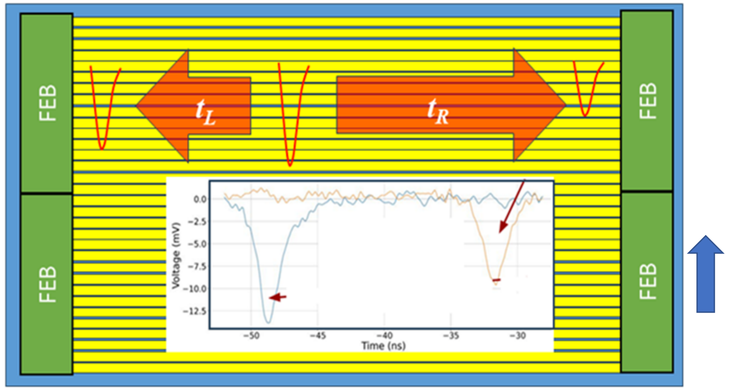
Goals: **Development of trigger as well as tracking RPCs like MPGDs**
(resolution for muon p_T is most important for the Higgs factory program)

- ✓ **Time resolution ~ 300 ps** with a 1-mm thick gas gap thickness
- ✓ **Position resolution ~ 500 µm** (with simple digitization using 1.6 mm pitch strips)
- ✓ **Rate capability better than 5 kHz cm^{-2}**

Use thin melamine-based HPL electrodes (0.35 and 0.5 mm)

- Double-gap RPCs with 1-mm gaps for time resolution ~ 300 ps)
- **Use thinner anode-side electrodes to lower lateral dispersion of signals**
- Oil varnishing required for low noise and better longevity (aging)
- Thin melamine-Phenol electrodes + PC support
  → **better stiffness and then uniformity of gas gaps**





y

ρ ~ 1.5 x 10^{11} Ω cm

200 µm Melamine + 150 µm Phenol

Graphite coating on a PC plate

Published NIMA **1082** 170983 (February 2026)

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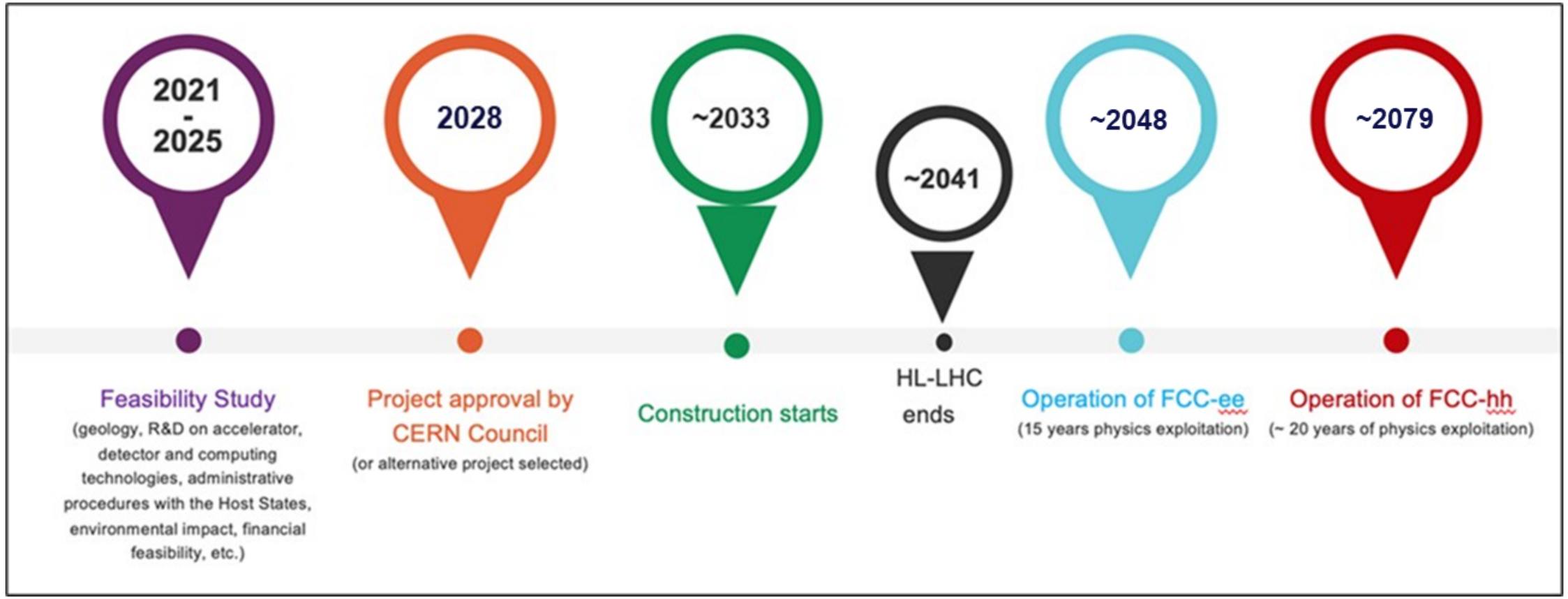
- We are living in very interesting times, especially for our young collaborators
- We are open to cooperation and collaboration, there are plenty of opportunities

Backup

FCC integrated program – timeline

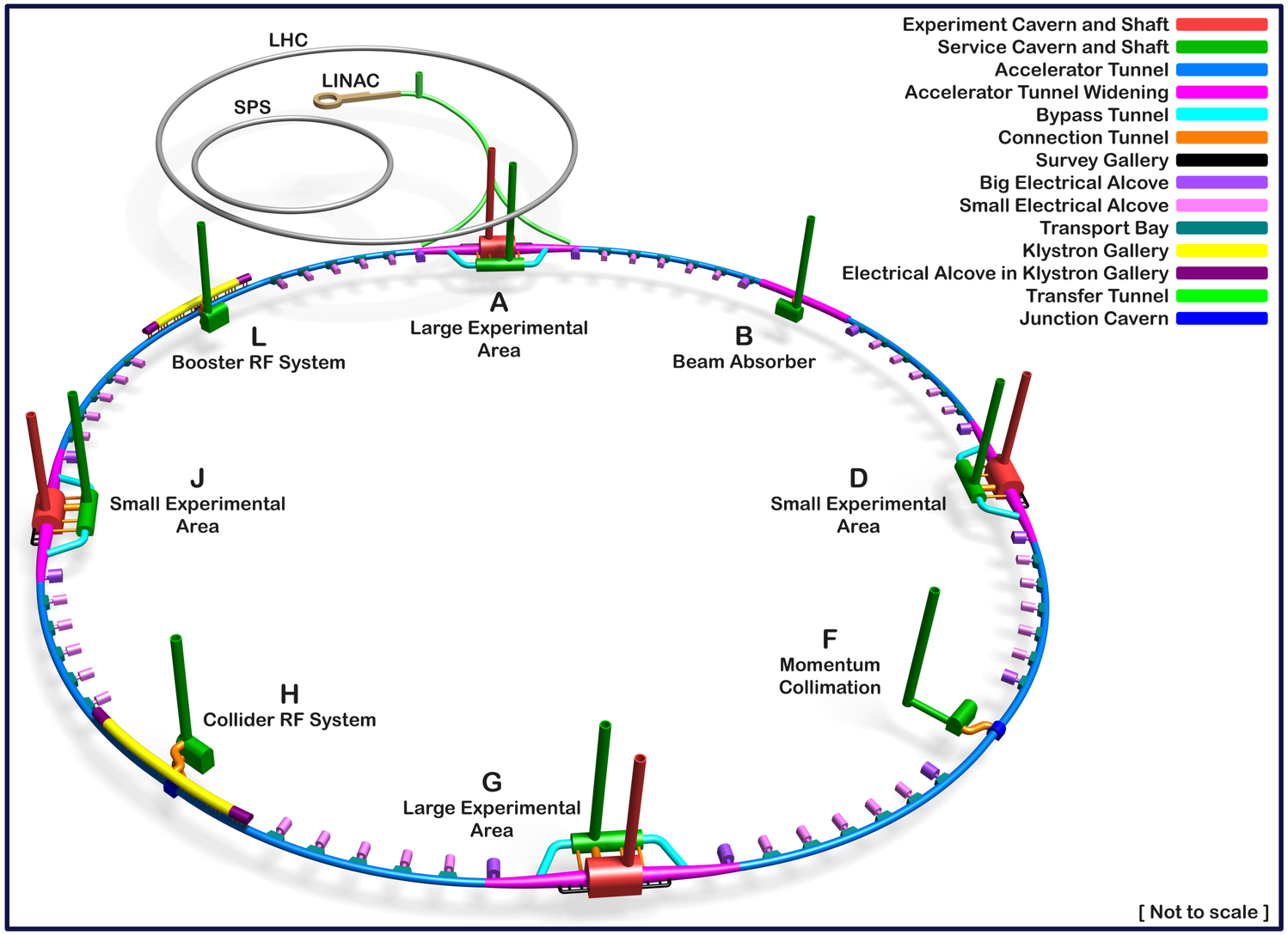


Ambitious schedule taking into account:

- ❑ past experience in building colliders at CERN
- ❑ approval timeline: ESPP, Council decision
- ❑ that HL-LHC will run until 2041
- ❑ **constraints imposed by present assumptions in funding model**
- ❑ **project preparatory phase with adequate resources immediately after Feasibility Study**

Key features of the Underground Civil Engineering Baseline

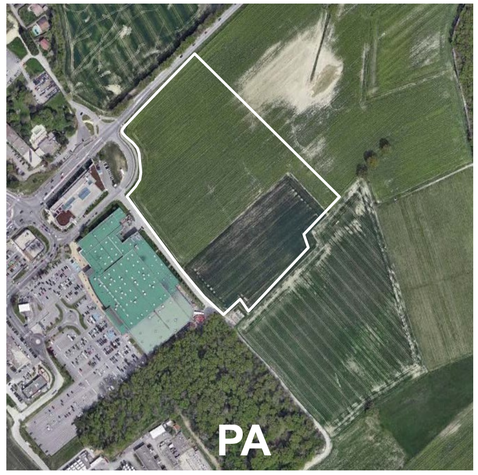
- Tunnel Circumference: 90.7 km
- Excavated vol: 6.25M m^3 (*in-situ* volume)
- Access shafts: 12
- Construction shafts: 1
- Large experiment sites: 2
- Small experiment sites: 2
- Technical sites: 4
- Deepest shaft: 400m
- Average shaft depth: 243m
- Total concrete volume: 2 M m^3

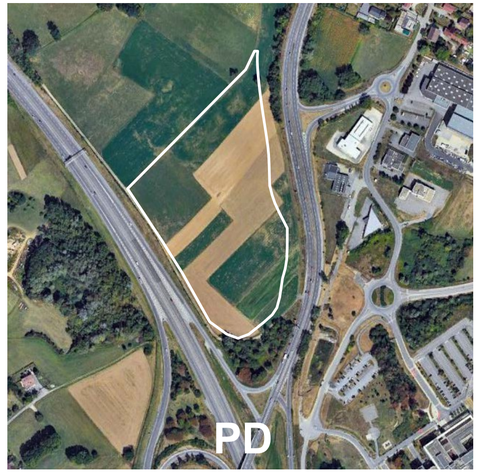


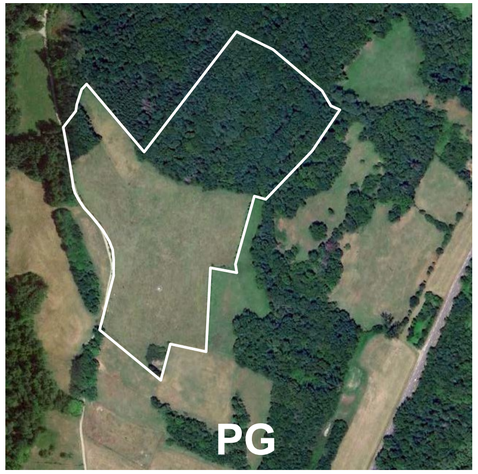
Schematic of FCC-ee Baseline Underground Civil Engineering

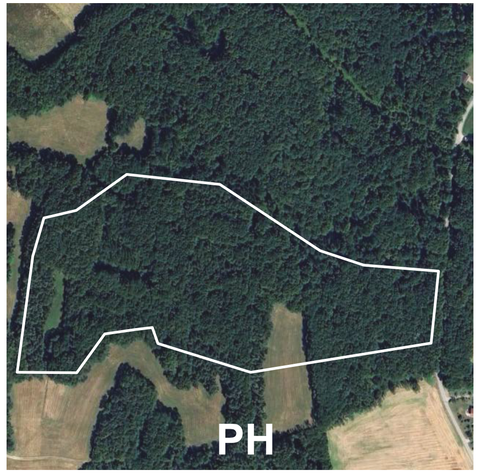
Surface site locations 7 FR and 1 CH

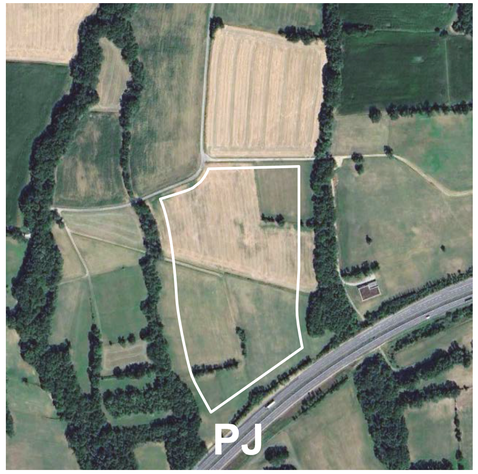
Optimisation done with communes











- land plot needs communicated to Host States,
- process in FR: «prise en consideration», landplot in CH owned by Canton of Geneva

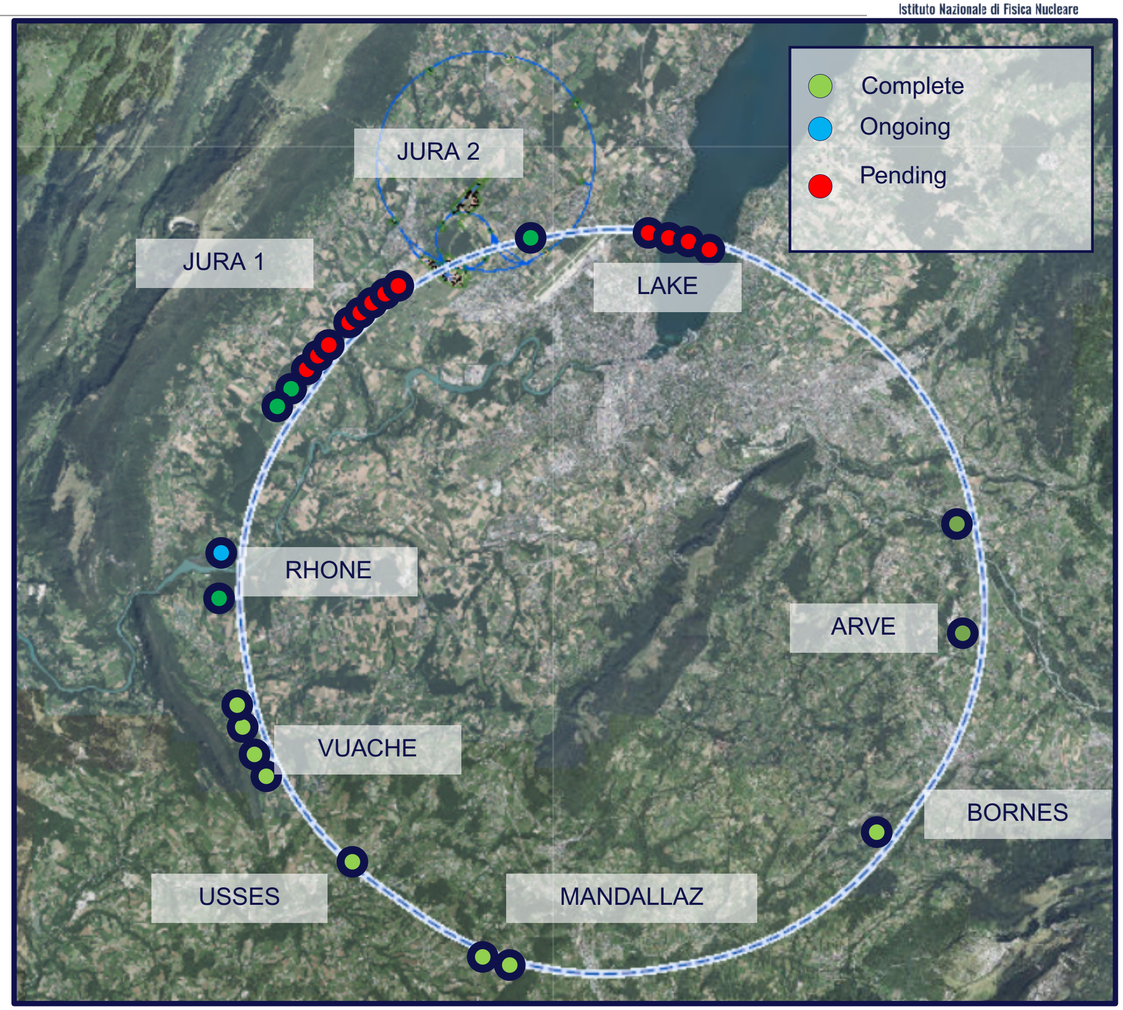
Site Investigation Phase 1

South-western work package SGS3

- Works began in October 2024
- Geophysics acquisition complete and interpretation ongoing
- Drilling activities complete for all 10 boreholes
- Testing complete and report preparation ongoing

North-eastern work package GEOTEC-IOI

- Works began in France in April 2025
- Two boreholes completed and one ongoing
- Geophysics 25% complete
- 4 lake drillings starting and permits for last 8 boreholes imminent.

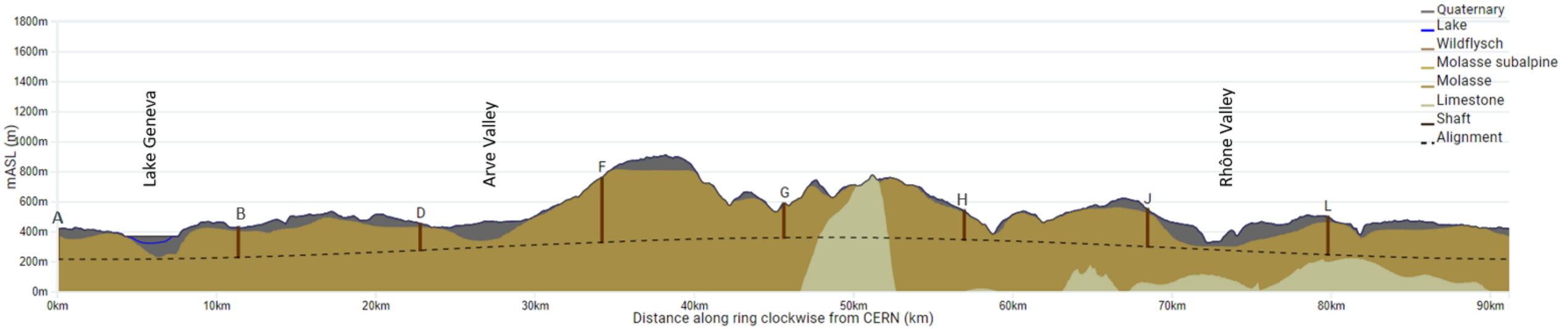


Status of drilling 1/09/2025

Preliminary results

- Results to date do not indicate any deviation from the baseline assumptions made for the rock conditions and the location of the moraine/molasse interface and molasse/limestone interface being as expected or more favourable.
- The length of tunnel in the Mandallaz limestone is now expected to be close to 3 km compared to 5 km as assumed prior to the phase 1 site investigation.

Optimum placement of FCC tunnel and geology



Tunnelling mainly in molasse layer (soft rock), well suited for fast, low-risk TBM construction.

6 million m³ excavated volume → 8.5 million m³ excavation material on surface

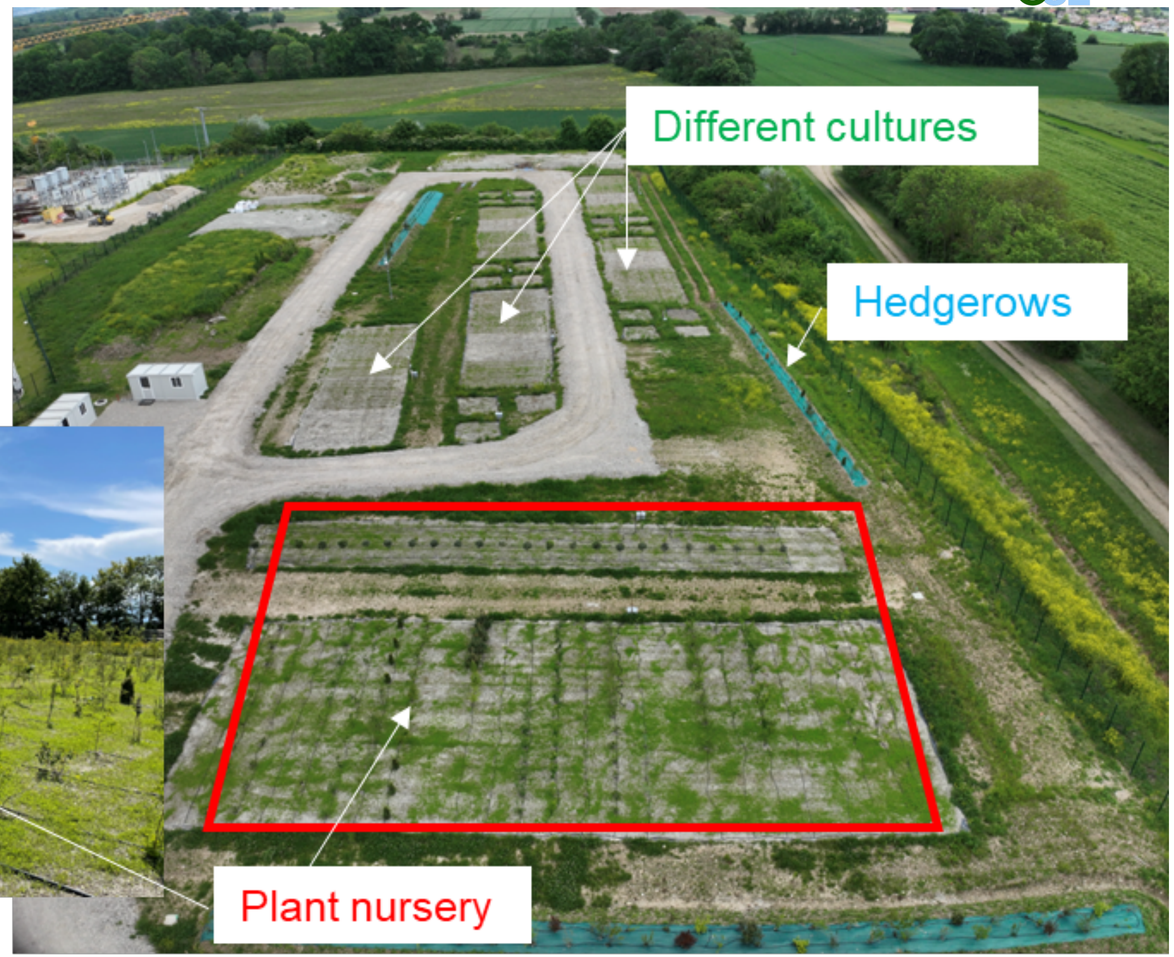
CE Designs of all underground structures developed

Average shaft depths ~240 m

To fix the vertical position of the tunnel, interfaces between geological layers have to be known

Reuse of excavated materials: OpenSkyLab project

- Develop a quality-managed process to transform excavated materials into fertile soil
- Permit reuse in renaturalisation, agriculture, etc.
- Additives as compost etc. in various mixtures
- Location: 1 ha field, LHC P5 CMS Cessy (FR)
- Applicable to entire alpine molasse region!



Estimate of reuse quantities:

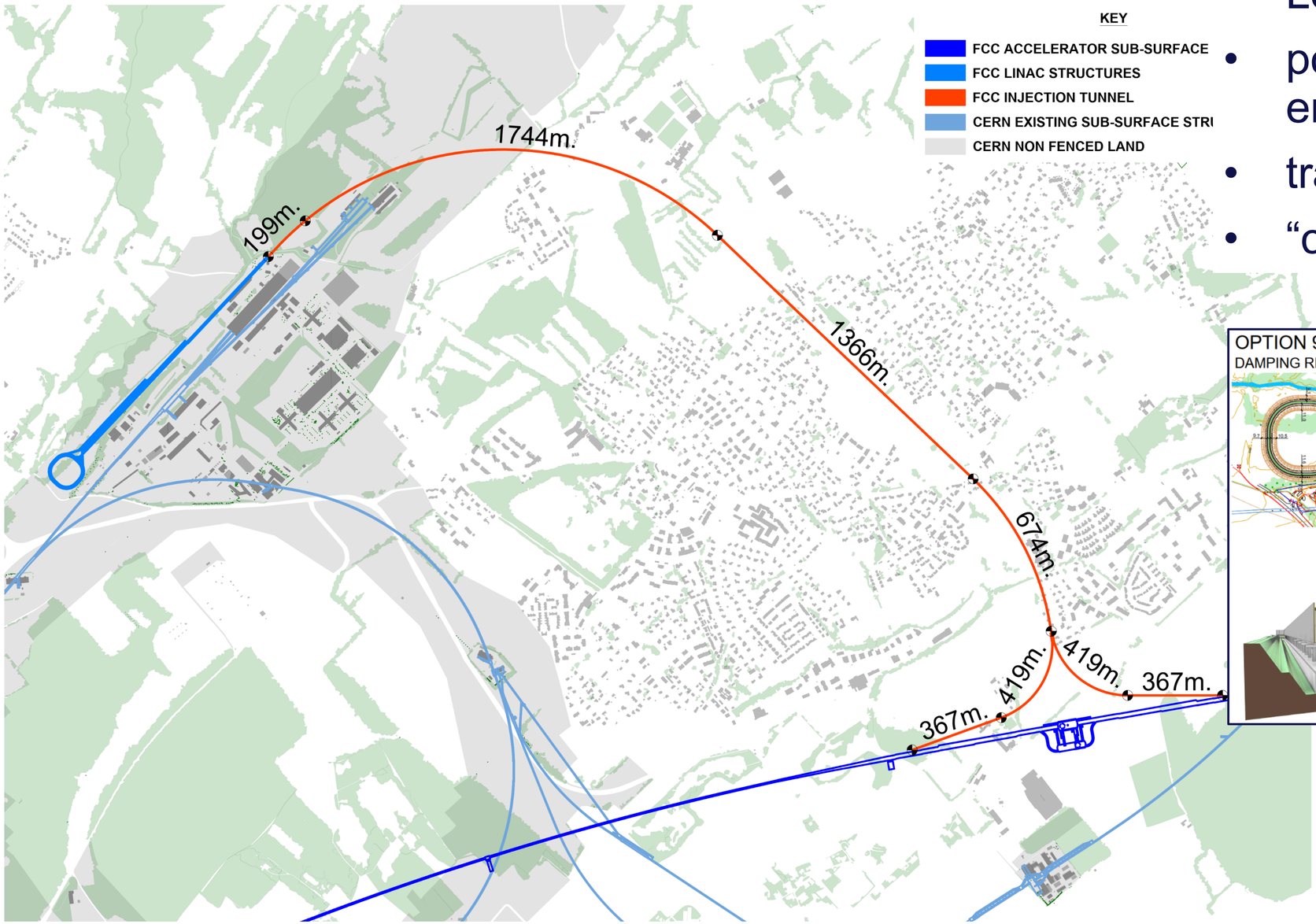
40% refill of quarries (~ 7.5 Mt)

25% reconstituted soil (~ 4 Mt)

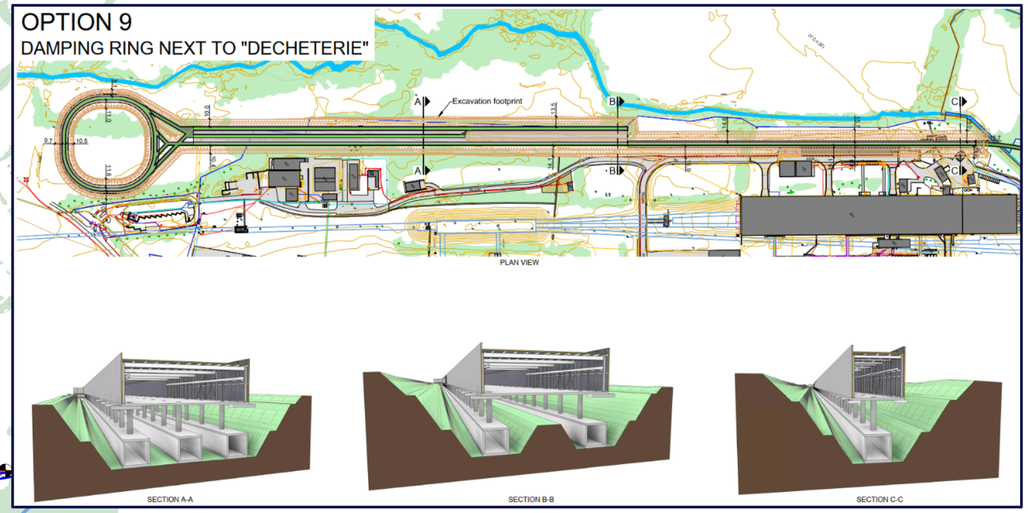
30% deposit (~ 5 Mt)

5% other reuse

FCC-ee injector with HE Linac



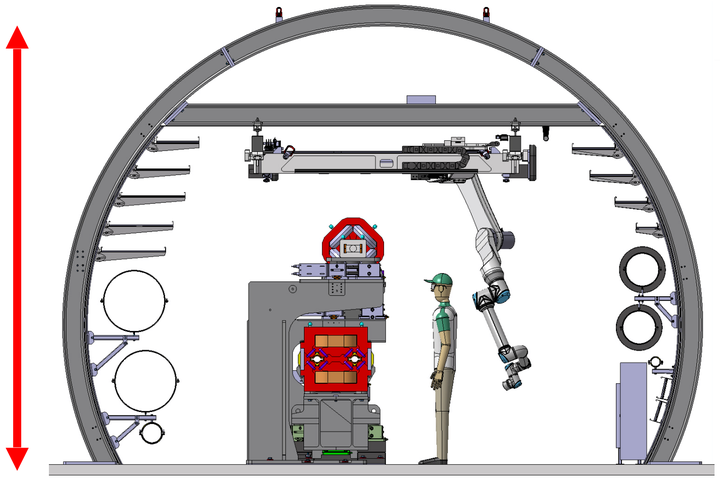
- Located on CERN Prévessin site
- possible connection to North Area to enable non-collider physics
- transfer line to FCC PA (LHC P8)
- “cut and cover” construction

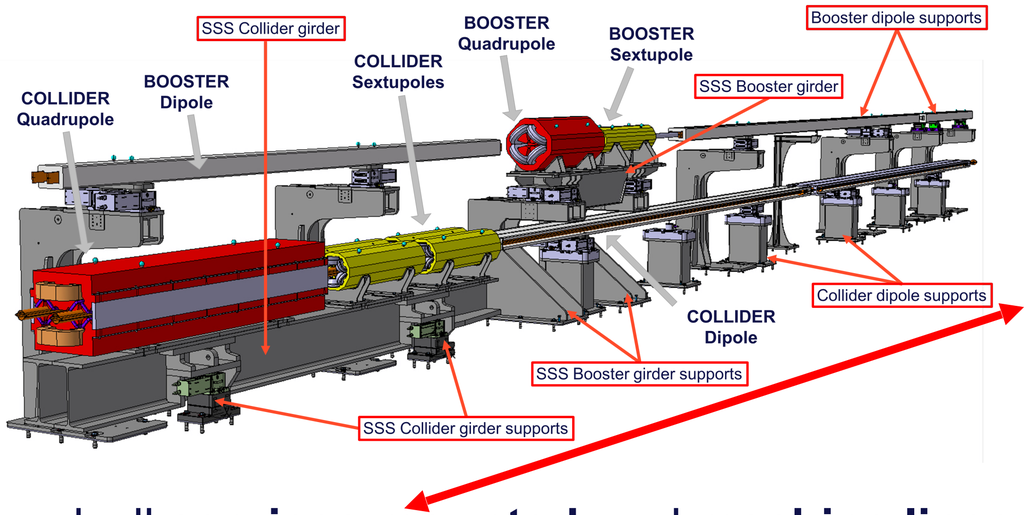


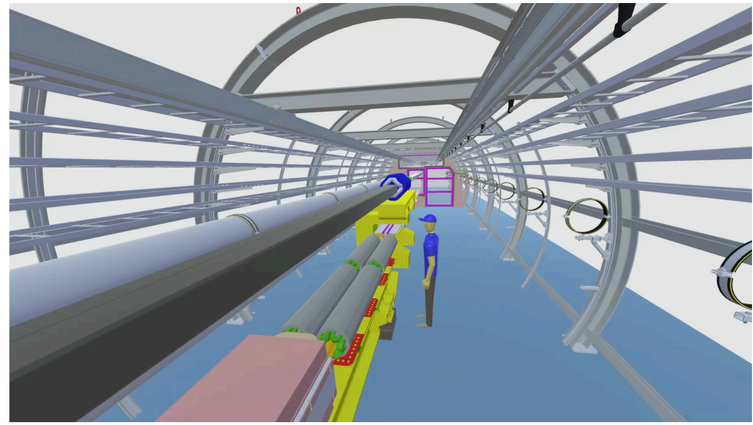
- Since MTR overall parameter optimization to reduce electrical power to < 30 MW

M. Benedikt - F. Zimmermann

Arc half-cell mockup



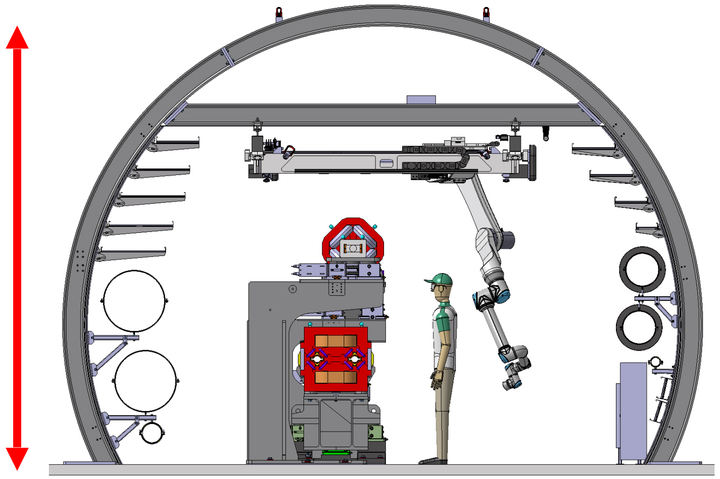


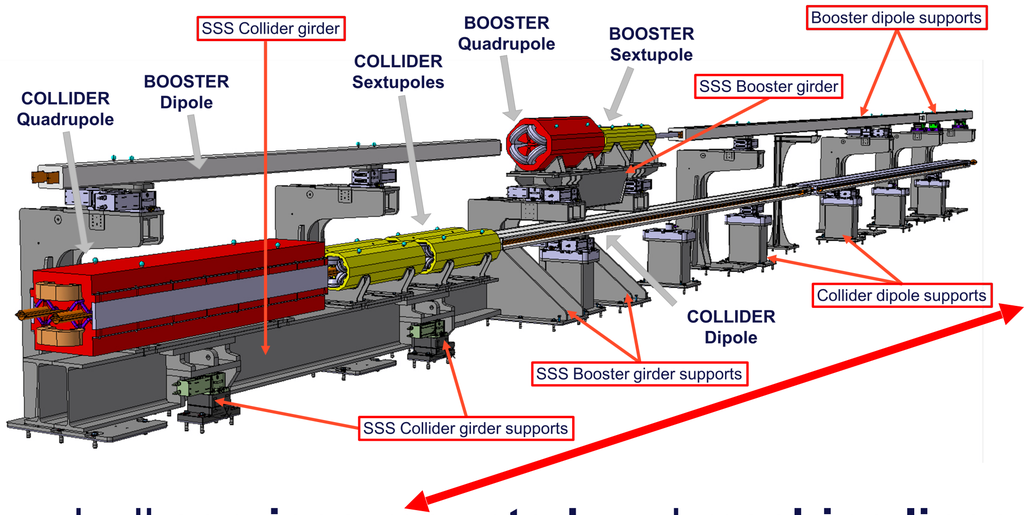


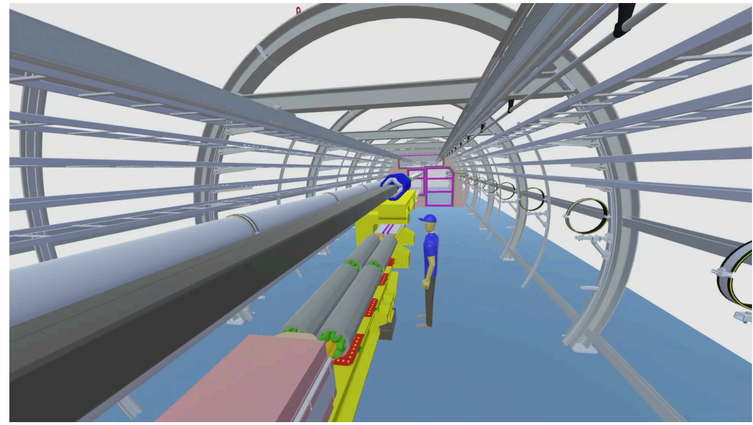
Mock-up installation well advanced, all **services mounted**, and **machine lines currently being installed !**

Key input for optimising 80 km FCC arc sections w.r.t. installation, integration, transport, robotics, etc.

Arc half-cell mockup







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Key input for optimising 80 km FCC arc sections w.r.t. installation, integration, transport, robotics, etc.

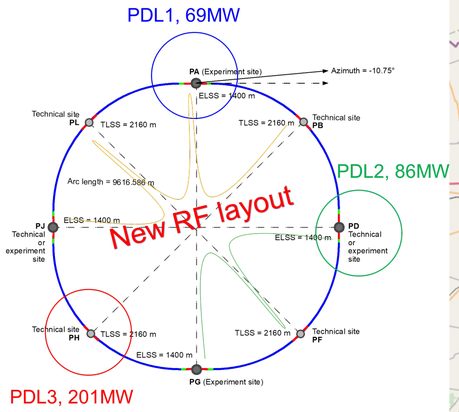
Resource needs & connections to regional infrastructure

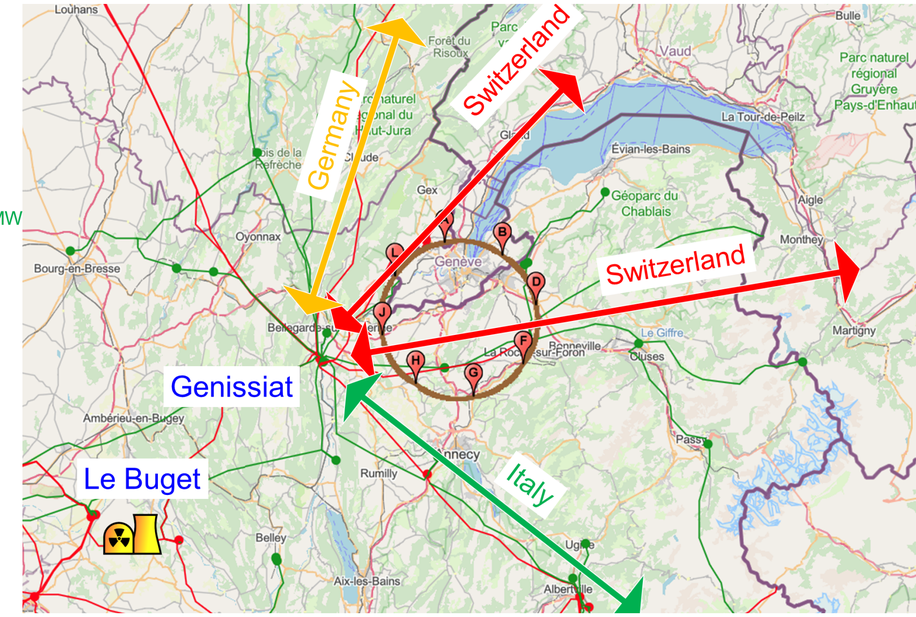
Electricity consumption 1.1 – 1.8 TWh/year

Three supply points

- Two new substations from existing HV grid
- Reuse of present CERN station

Feasibility confirmed with RTE (FR operator)





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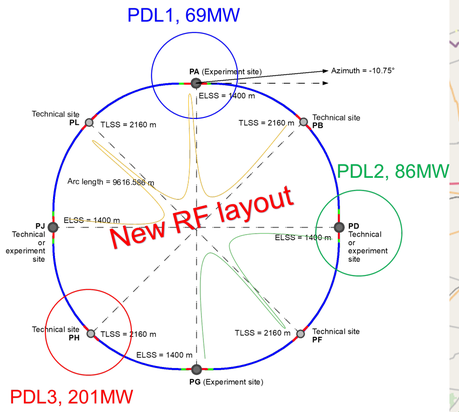

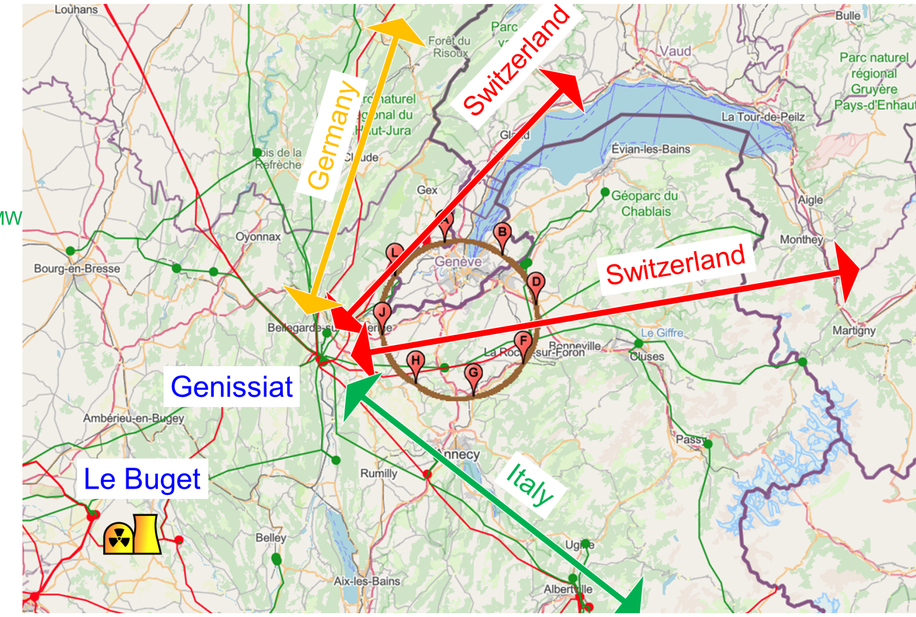

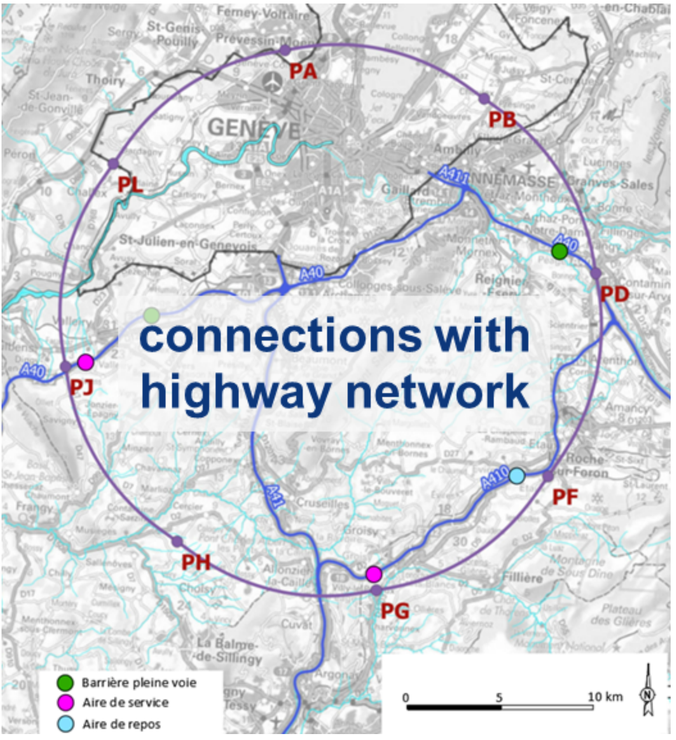

Road access

developed for all 8 surface sites

Four possible highway connections defined

Less than 4 km of new roads required

Resource needs & connections to regional infrastructure

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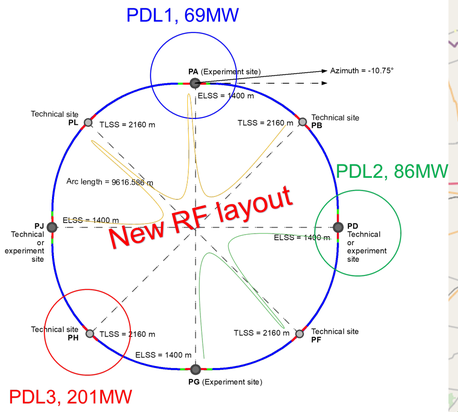

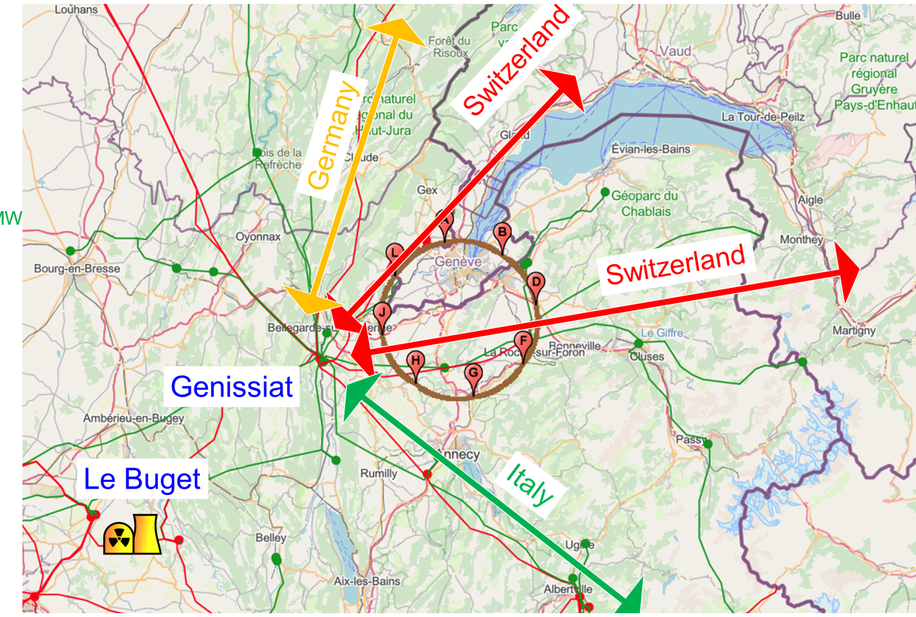

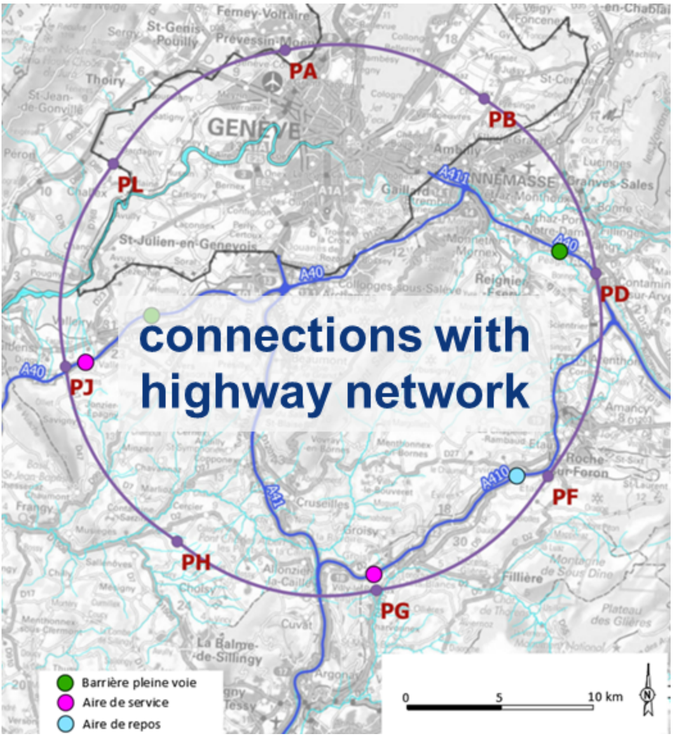

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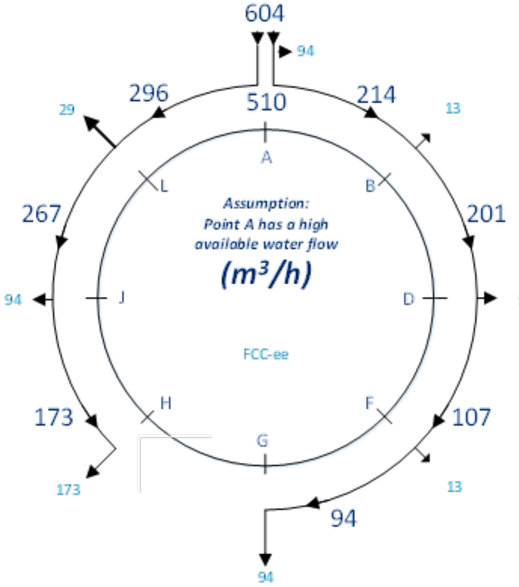
Raw water need:

1 – 3 million m^3/year

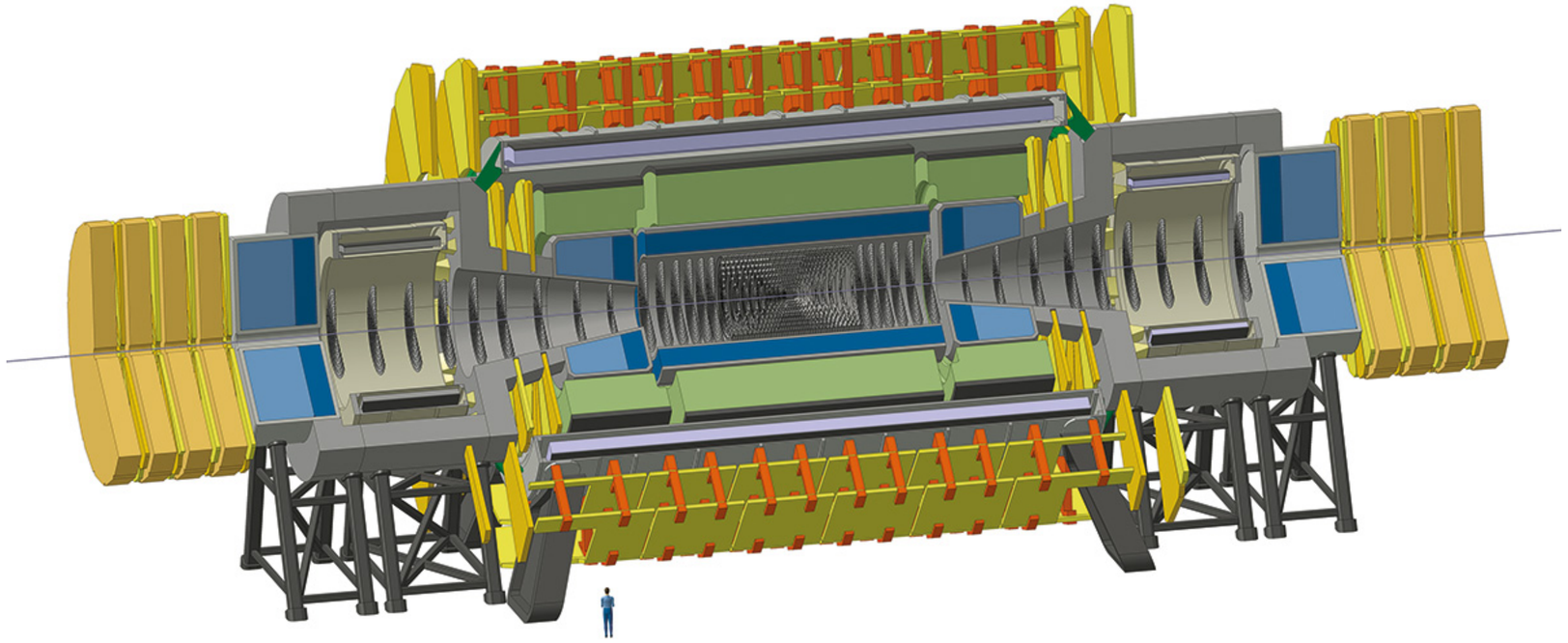
Water supply from lake Geneva via existing SIG supply to CERN

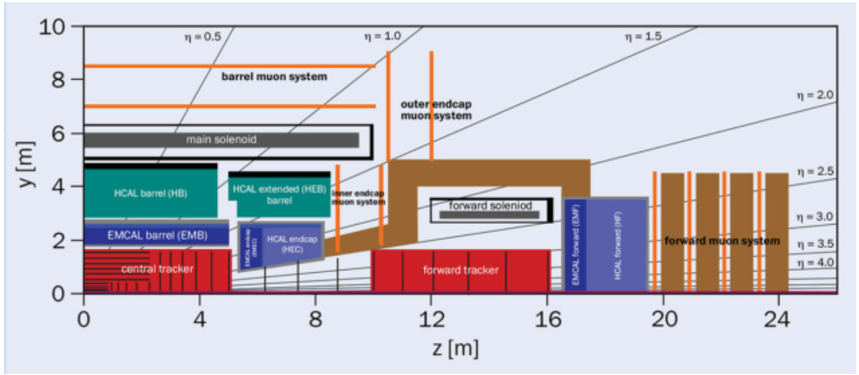
Distribution via tunnel



FCC-hh detector concept

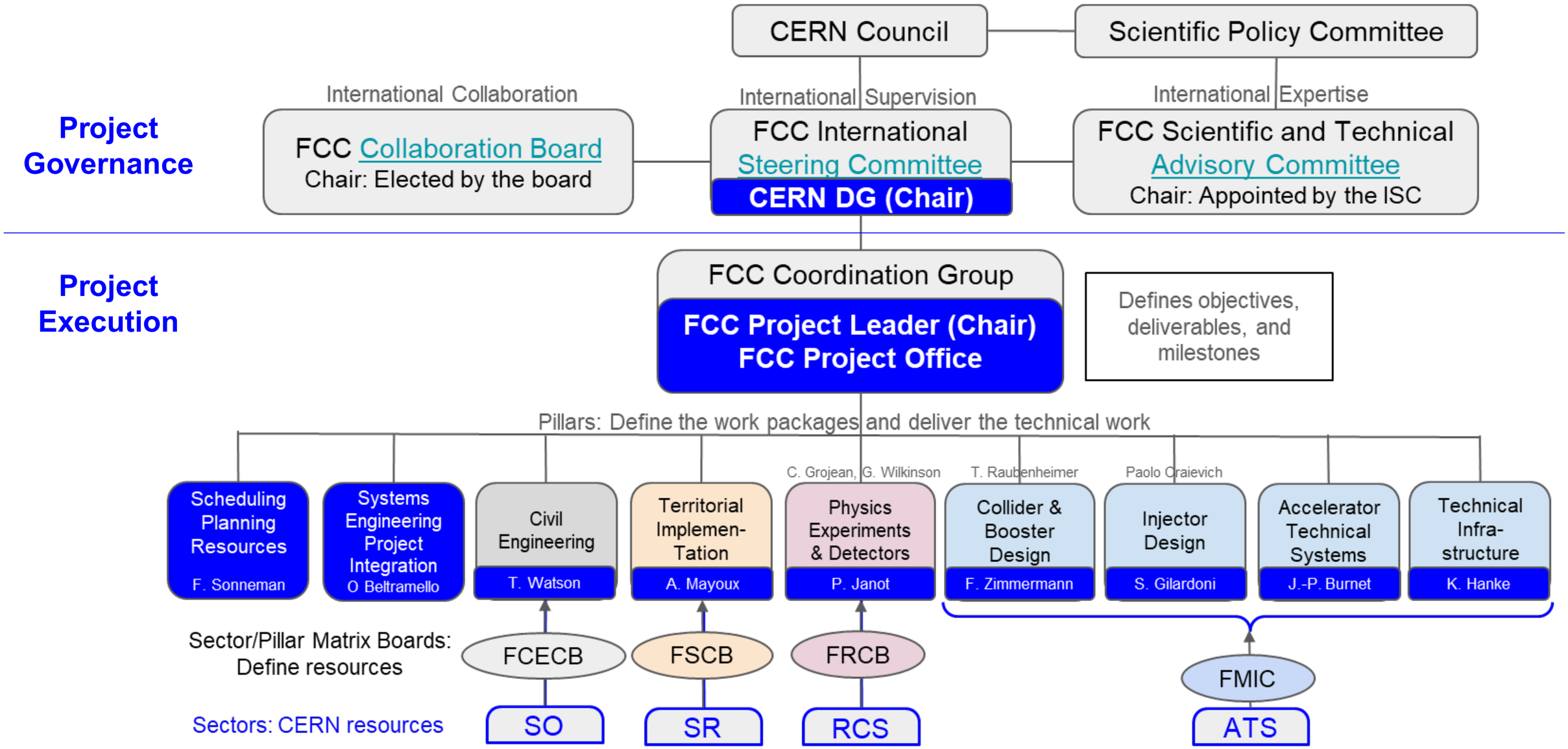
- pp collisions at $\sqrt{s} > 100$ TeV, luminosity up to 3 x 10^{35} cm^{-2} s^{-1} (up to 1000 pileup events)
- Central detector houses tracking, e.m. and hadron calorimetry inside a 4T solenoid with a free bore of 10 m diameter
- Forward parts are displaced by 10m from the interaction point, with two forward magnet coils
- The muon system is placed outside the magnet coils
- Overall length ~50m, diameter ~20m



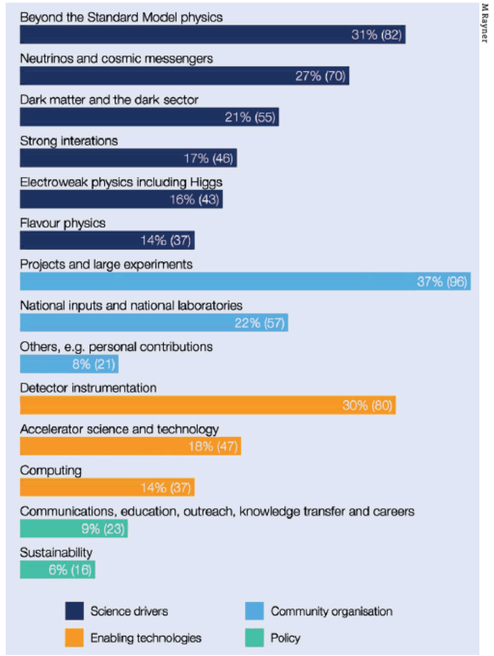


→ No field return yoke for FCC-hh reference detector

FCC Organisation for Reference Design Phase



European Strategy for Particle Physics: 2026 Update



266 submissions received
- Major flagship projects
- Many projects in other physics areas
- Input from national HEP communities
- National labs
- Early career researchers
- …

Timeline for the update of the European Strategy for Particle Physics

End September 2024
Council appointment of the members of the **PPG** and decision on the venue for the **Open Symposium**

December 2024
Council decision on the venue for the **ESG Strategy Drafting Session**

31 March 2025
Deadline for the submission of main input from the community

26 May 2025
Deadline for the submission of additional national input in advance of the **Open Symposium**

23-27 June 2025
Open Symposium

End September 2025
Submission of the "Briefing Book" to the **ESG**

14 November 2025
Deadline for the submission of final national input in advance of the **ESG Strategy Drafting Session**

1-5 December 2025
ESG Strategy Drafting Session

End January 2026
Submission of the draft strategy document to the Council

March and June 2026
Discussion of the draft strategy document by the Council and **updating of the Strategy**

More details on ESPP web page: https://europeanstrategyupdate.web.cern.ch/

P. Sphicas

Open Symposium in Venice

https://agenda.infn.it/event/44943/overview

ESPP and CERN Council

A very clear and strong message from the European Strategy Group:

All efforts (by Council and CERN management)
should be made to make FCC a reality
The baton is now with CERN management and Council

The ESPP was updated by CERN Council
in a dedicated meeting in Budapest on 22 May 2026

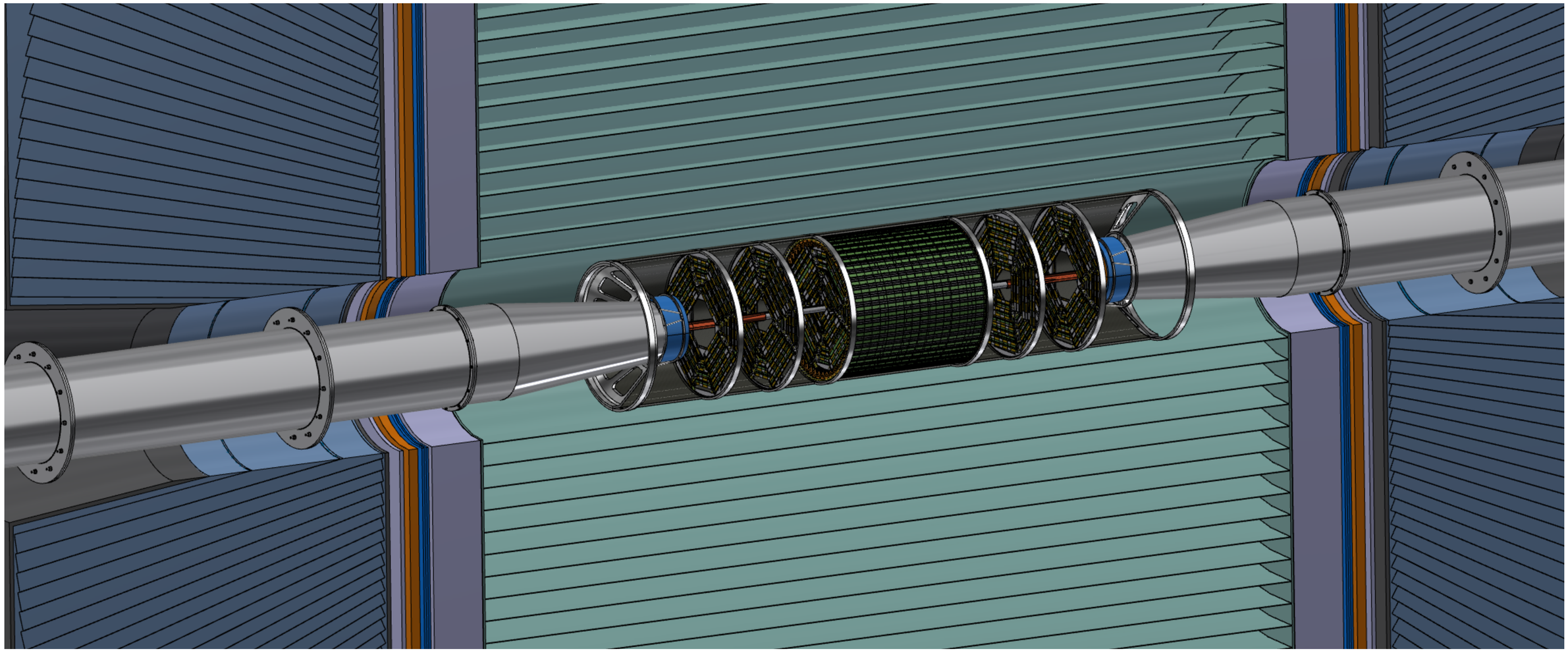
European Strategy
for Particle Physics

The baton is now with CERN management and Council

P. Sphicas

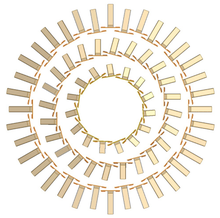
MDI and Vertex detector

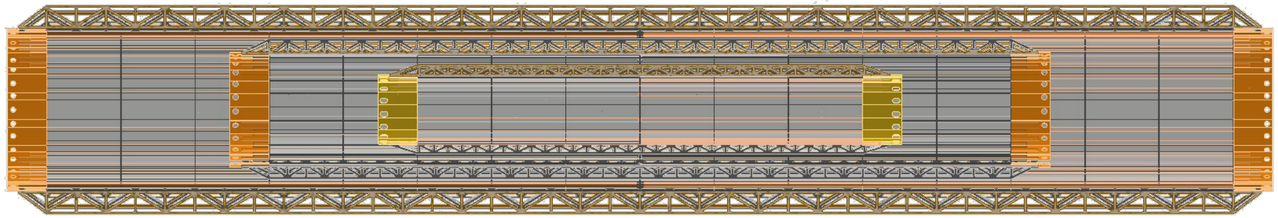
General integration



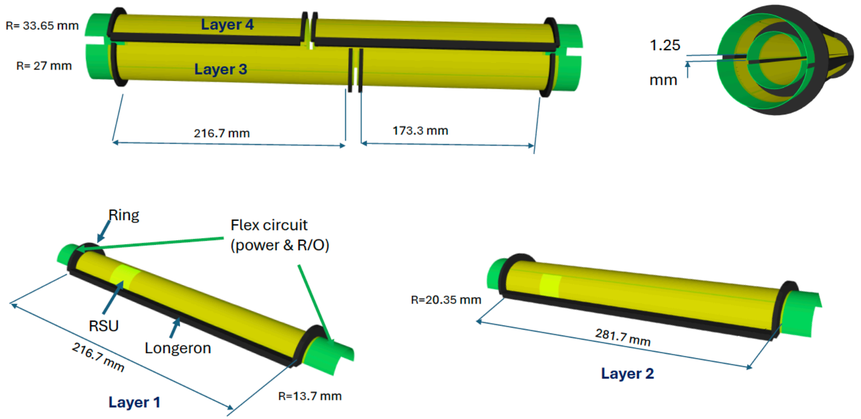
M. Boscolo

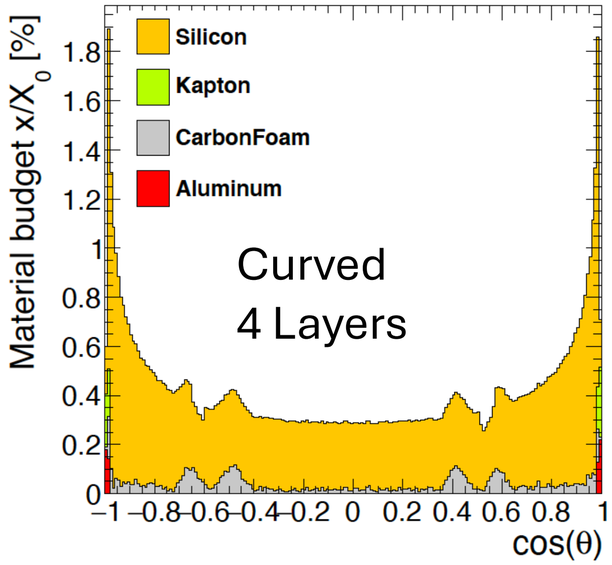
Silicon vertex tracker

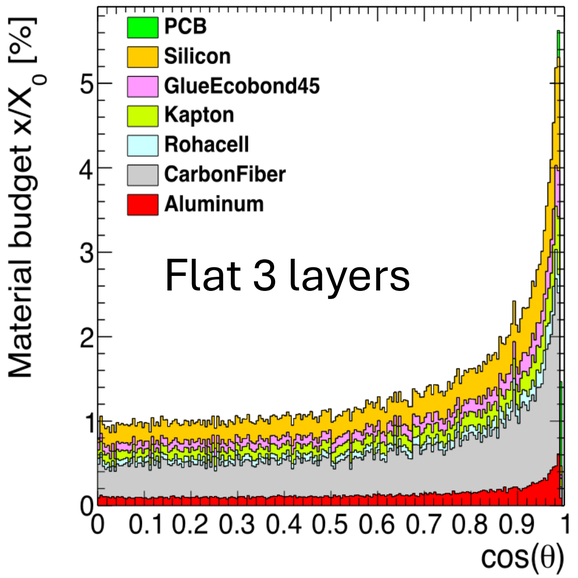




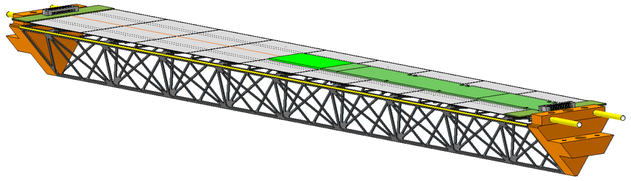
- Inner vertex. Air-cooled. Two layouts:
  - 3 barrel layers: ARCADIA based 25x25 μm²
  - 4 curved barrel layers: ITS3 inspired - ultralight

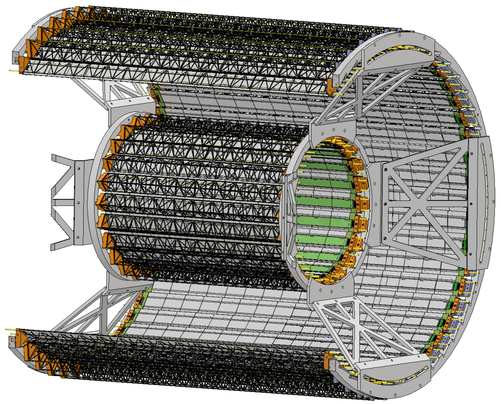


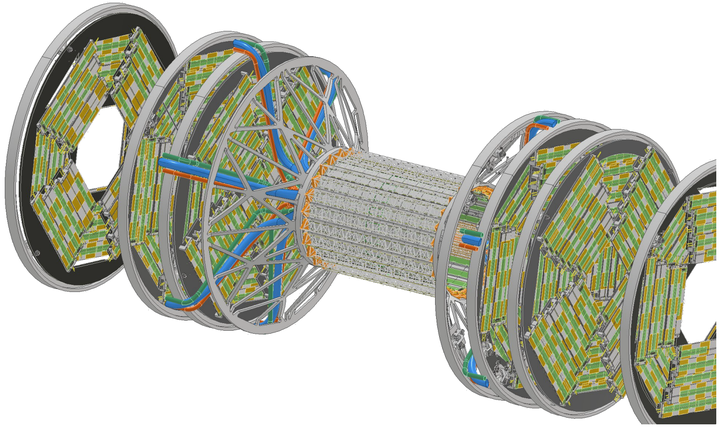




- Outer vertex and disks – water cooled (validation ongoing, see backup)
  - ATLASPix3 based 150 x 50 μm²







Silicon Wrapper

Instrumented surface:

- r = 2m:
- $|z| < 2.4$ m;
- $|\eta| < 2.6$

⟹ Total area for a single layer: ~90 m^2

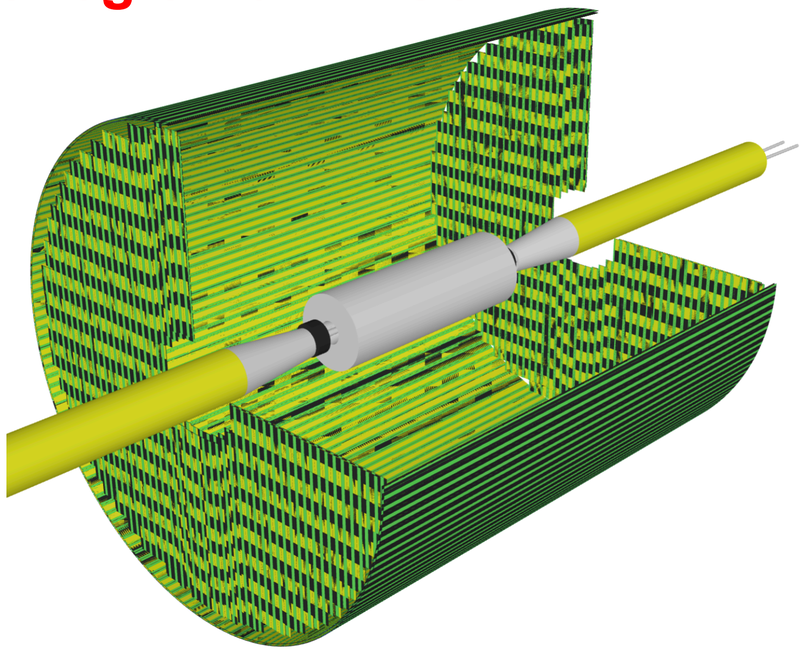
Baseline design uses same MAPS detectors as original vertex detector design:

- 50 µm x 150 µm pixel size → 7 µm x 45 µm resolution

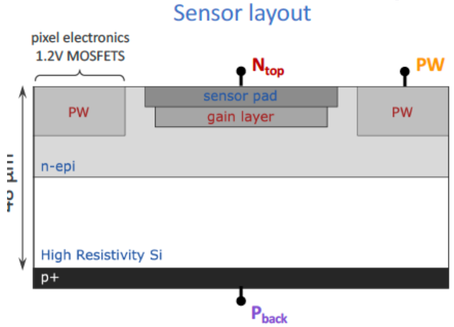
⟹ Total number of channels: ~ 12 × 10^9

- **Spatial resolution 10 µm**
- **Options under study**
  - **MAPS**
  - **Resistive LGAD**

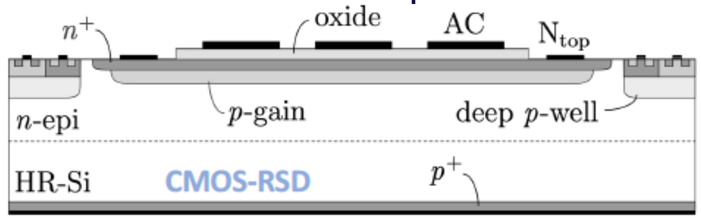
- **Enhances the momentum resolution**
- **and can provide PID in the region of ~1 GeV**



ARCADIA MADPIX
Time resolution ~80 ps



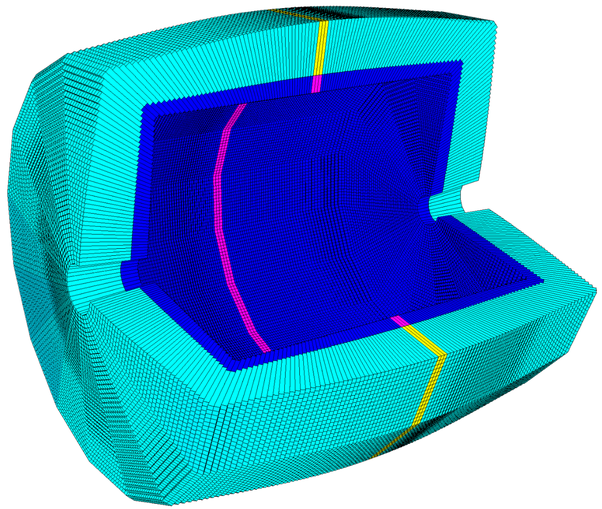
Monolithic CMOS AC-LGAD
Lower number of channels
Spatial resolution: 3% of the pitch
Time resolution ~20 ps

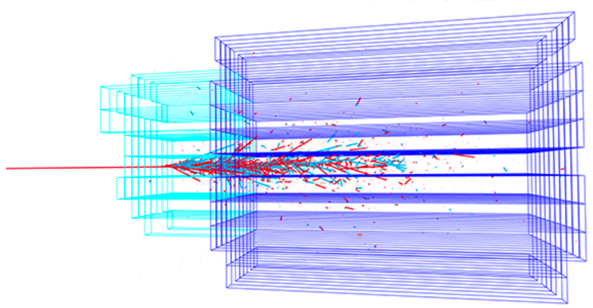


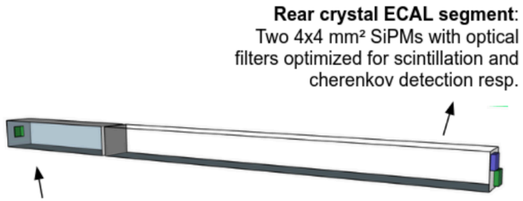
pending patent and extent of protection

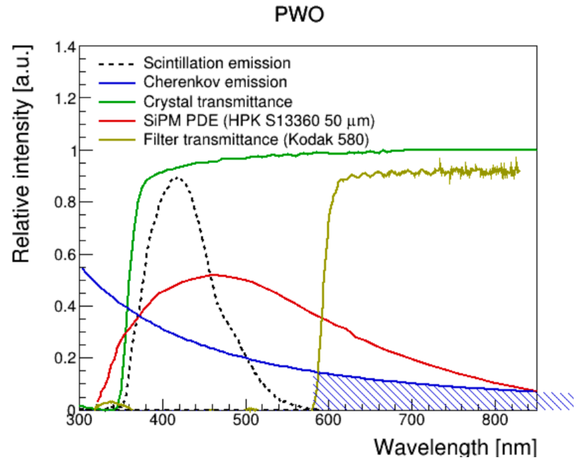
Ecal crystal DR calorimeter design

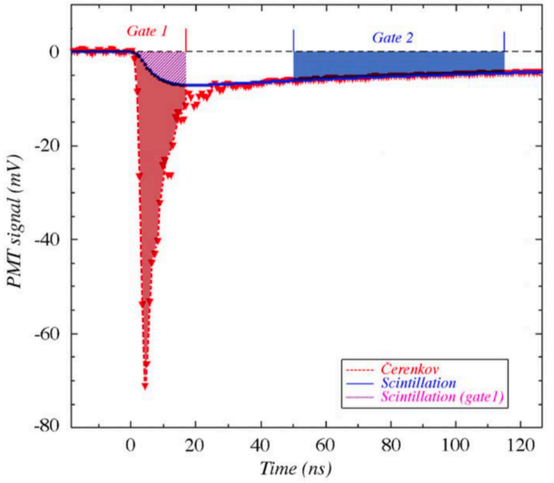
- Pseudo-projective, dual-readout **crystals** (baseline option $PbWO_4$, BGO and BSO under investigation). 10x10x50 mm^3 front crystals,14x14x160 mm^3 rear crystals. LYSO timing layer can be added.
- **Dual-readout** obtained either through separation of Cherenkov light in **wavelength or time** (or a combination of both). See how this works at a test beam here and here.
  - 14x14 mm^2 PWO crystals read with two 6x6 mm^2 SiPM (one with filter) put on beam in September 2025.









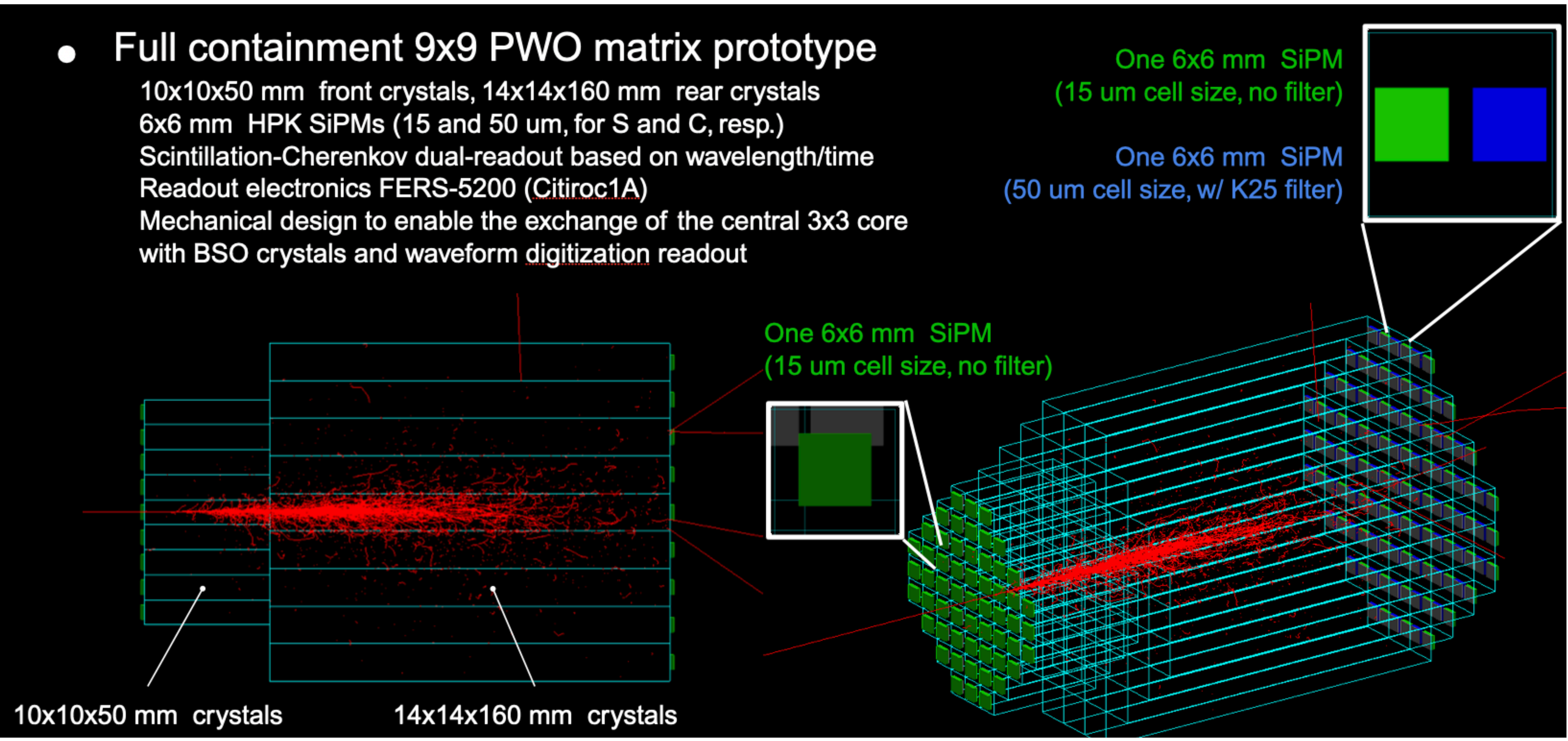


Ecal crystal DR calorimeter design

- Full containment 9x9 PWO matrix prototype
  - 10x10x50 mm front crystals, 14x14x160 mm rear crystals
  - 6x6 mm HPK SiPMs (15 and 50 um, for S and C, resp.)
  - Scintillation-Cherenkov dual-readout based on wavelength/time
  - Readout electronics FERS-5200 (Citiroc1A)
  - Mechanical design to enable the exchange of the central 3x3 core with BSO crystals and waveform digitization readout

One 6x6 mm SiPM
(15 um cell size, no filter)

One 6x6 mm SiPM
(50 um cell size, w/ K25 filter)



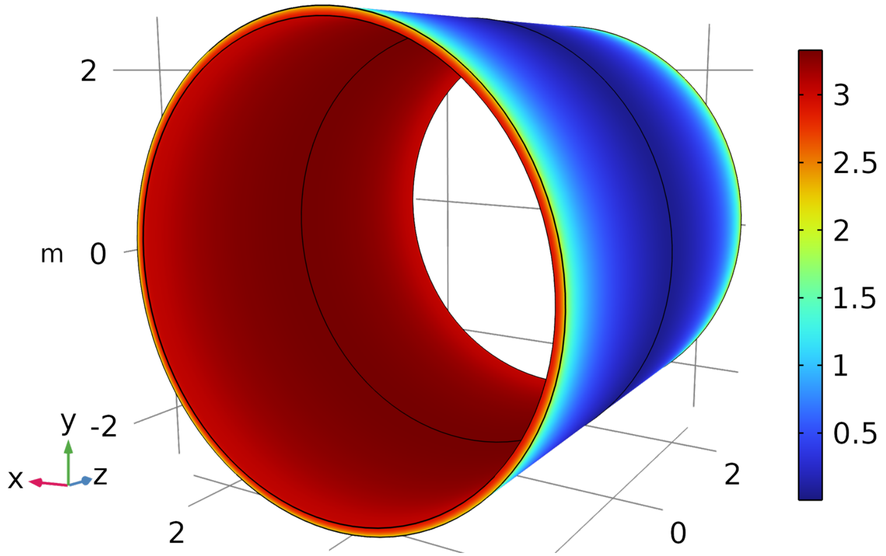
High temperature superconducting magnet

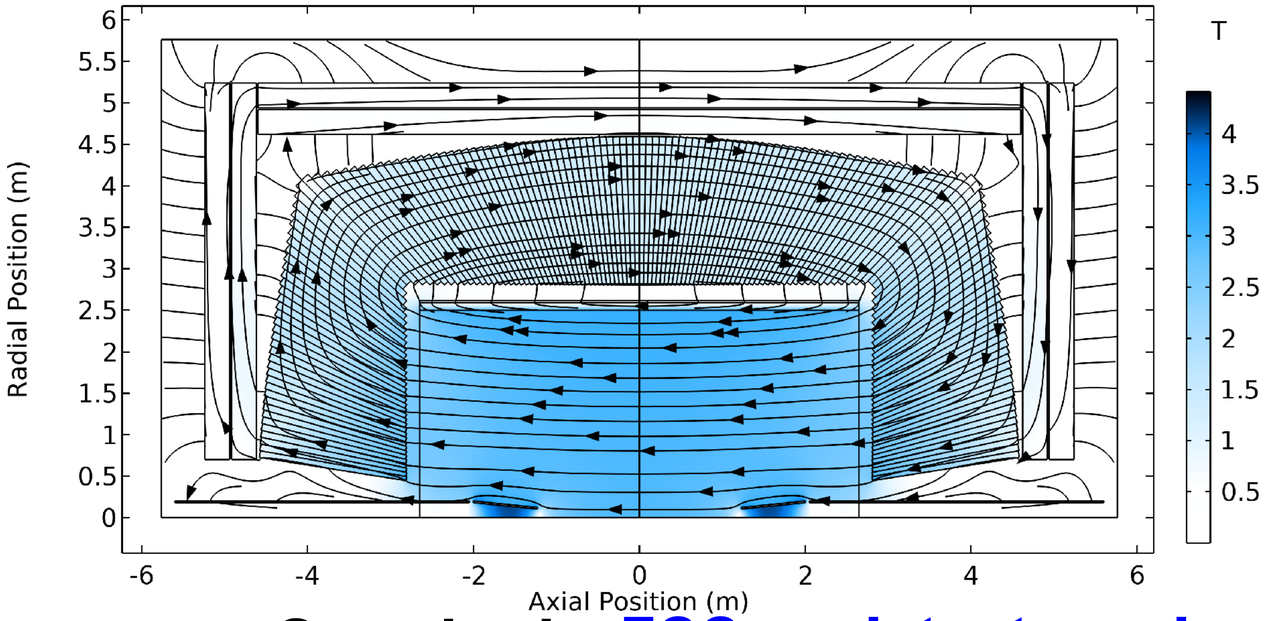
From analytical evaluations:

- B= 3 T, R_i=2.5 m e L=6 m → **18.65 MA-turns**

Peak field on the conductor equal to **3.37 T**
2D Rotational Symmetry Simulation in COMSOL

- Internal radius increased to allow for EM Calorimeter
- Coil thickness limited stress on conductor (100 MPa)
- Dual readout ferromagnetic HCal **implemented in the computation model!**





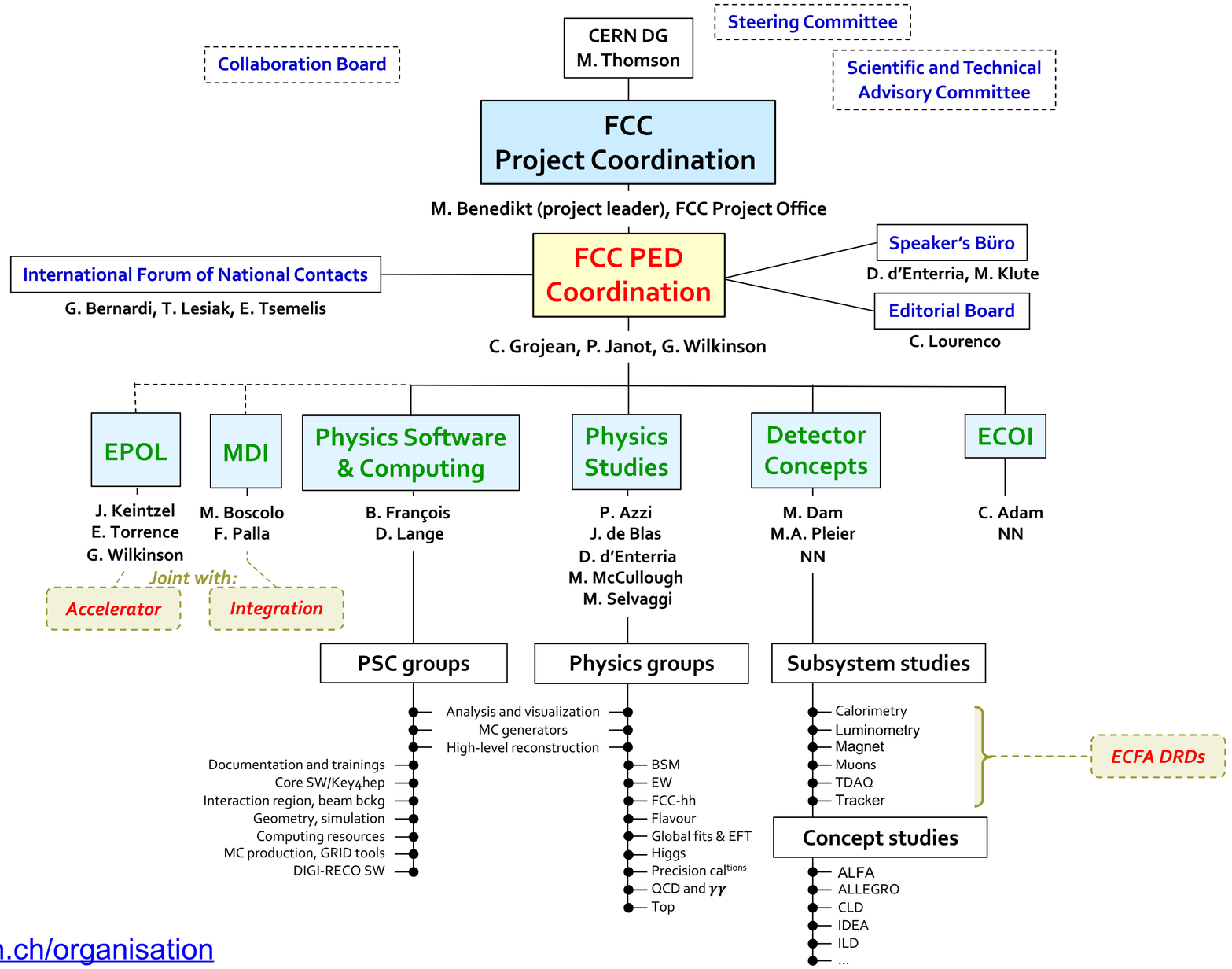
Parameter	Value
Bore Field	**3 [T]**
	8068 [A]
Coil Thickness	91.7 [mm]
Turns	1760 (220x8)
Inductance	12.4 [H]
Stored Energy	402 [MJ] 19.41 [kJ/kg]
Operating Temperature	**20 [K]**

Organised a FCC-ee detector solenoids workshop in LASA, Milan

IDEA's loosely (or not) covered areas

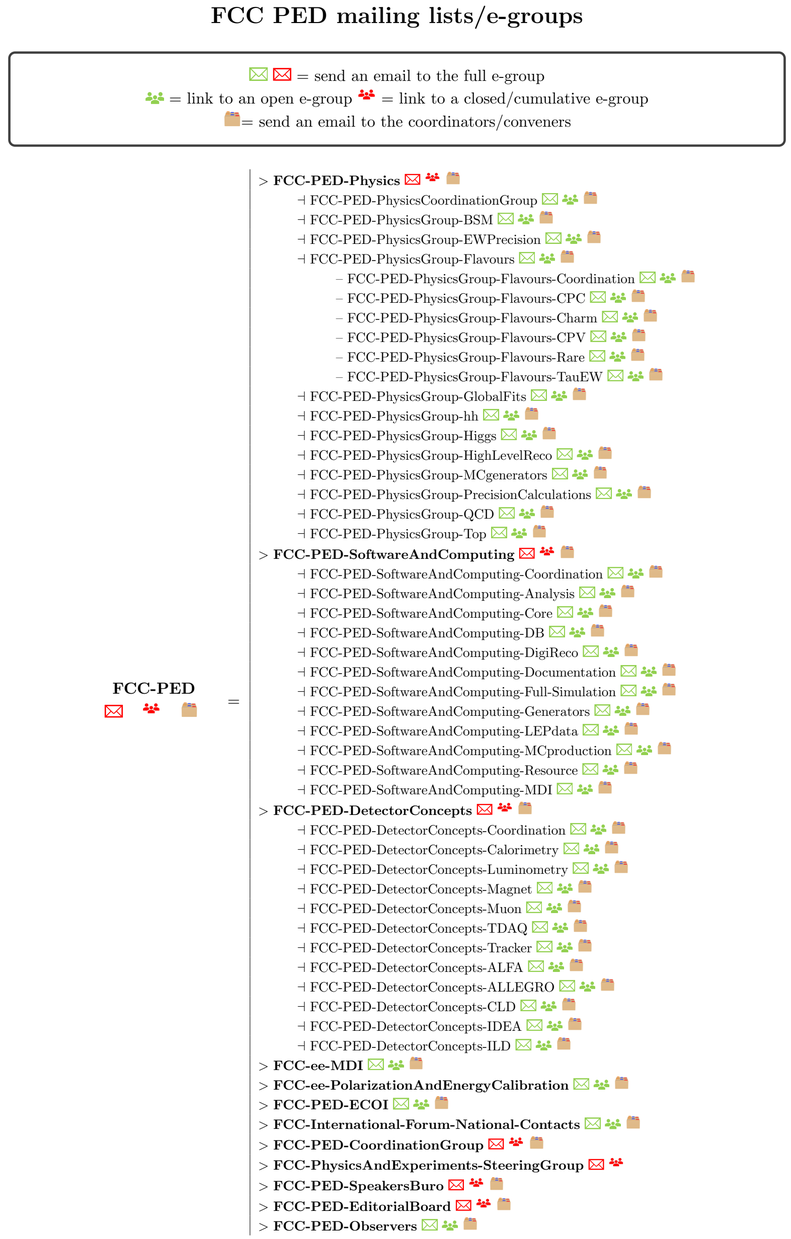
- **Lumical**
  - It is essential for precise determination of EW parameters
    - Absolute luminosity measurement required better than 10^{-4}
    - Nothing done yet, plenty of scope for contributions
- **Trigger and Data acquisition**
  - Aiming to have triggerless readout. Nothing done yet...
- **Software&Computing**
  - Plenty of scope for Korean contributions
- **Drift chamber**
  - Very large and challenging detector. Continuous tracking and outstanding PID
    - We definitely need more collaborators

FCC PED Organisation



https://fcc-ped.web.cern.ch/organisation

FCC PED mailing lists and links



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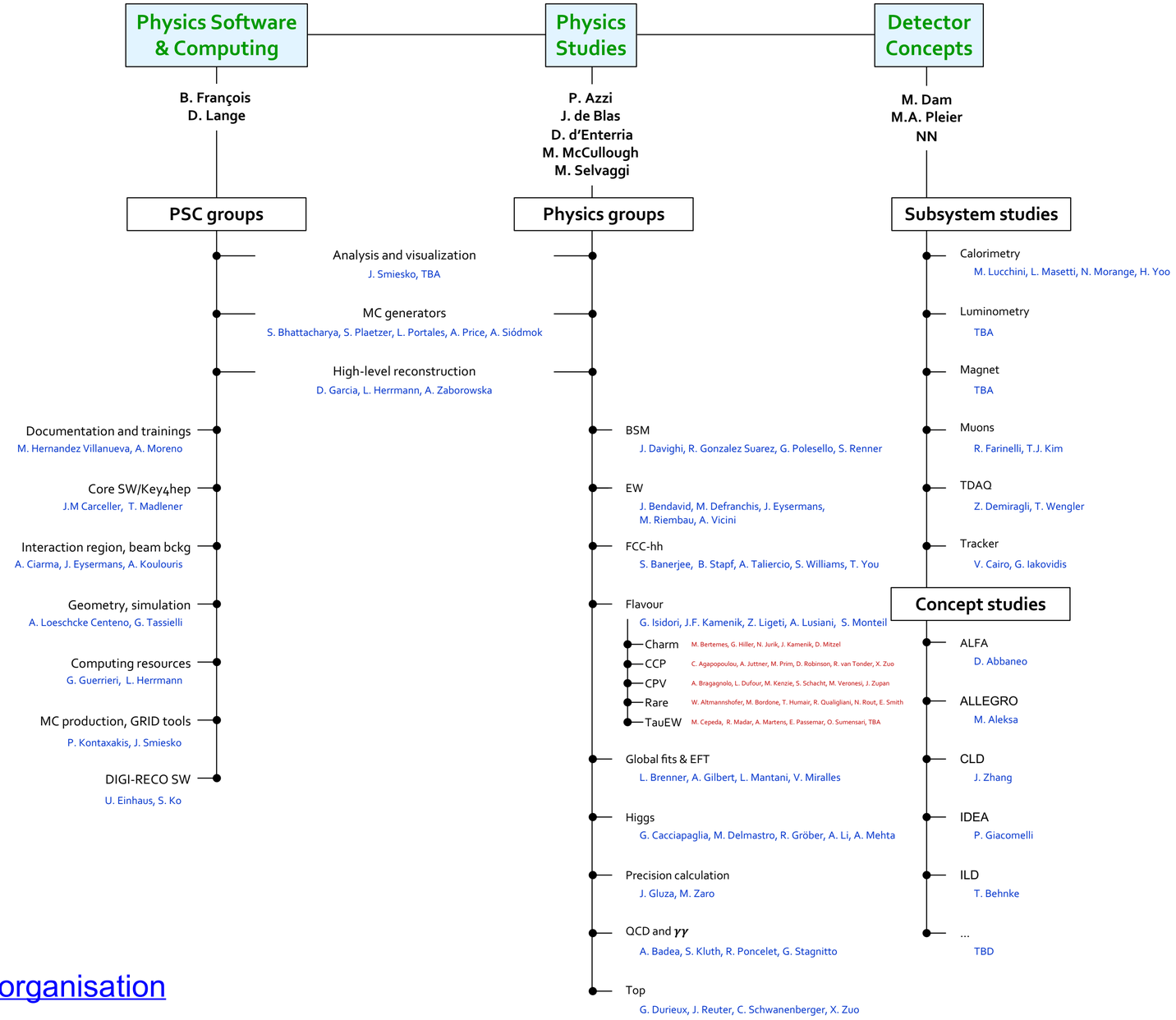
FCC PED Organisation



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