ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

Istituto Nazionale di Fisica Nucleare

The Future Circular Collider
(The point of view of those involved)

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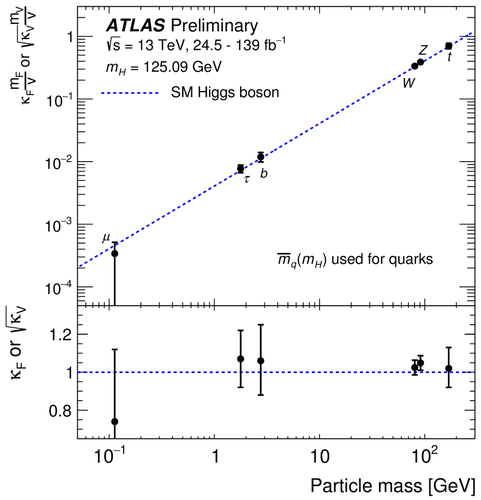
Università di Bologna
(With thanks to the RD_FCC group for the feedback)

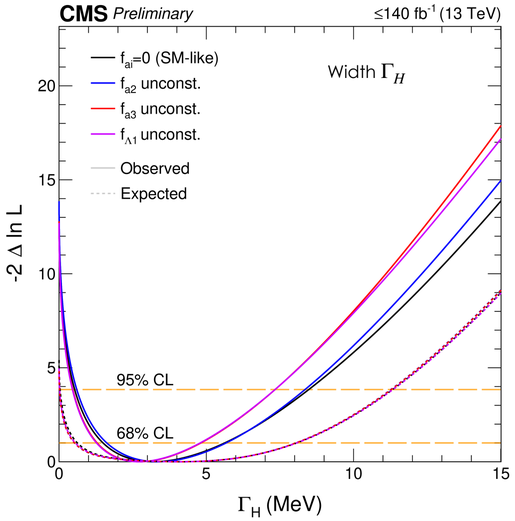
7 November 2024 - Workshop di Sezione - European Strategy for Particle Physics

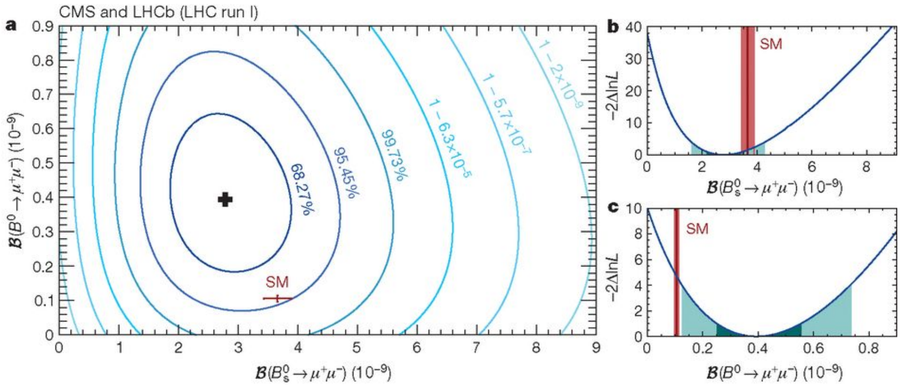
These projects have received funding from the European Union's Horizon Europe Research and Innovation programme under Grant Agreements No. 101004761 (AIDAinnova), 101057511 (EURO-LABS).

The physics we have

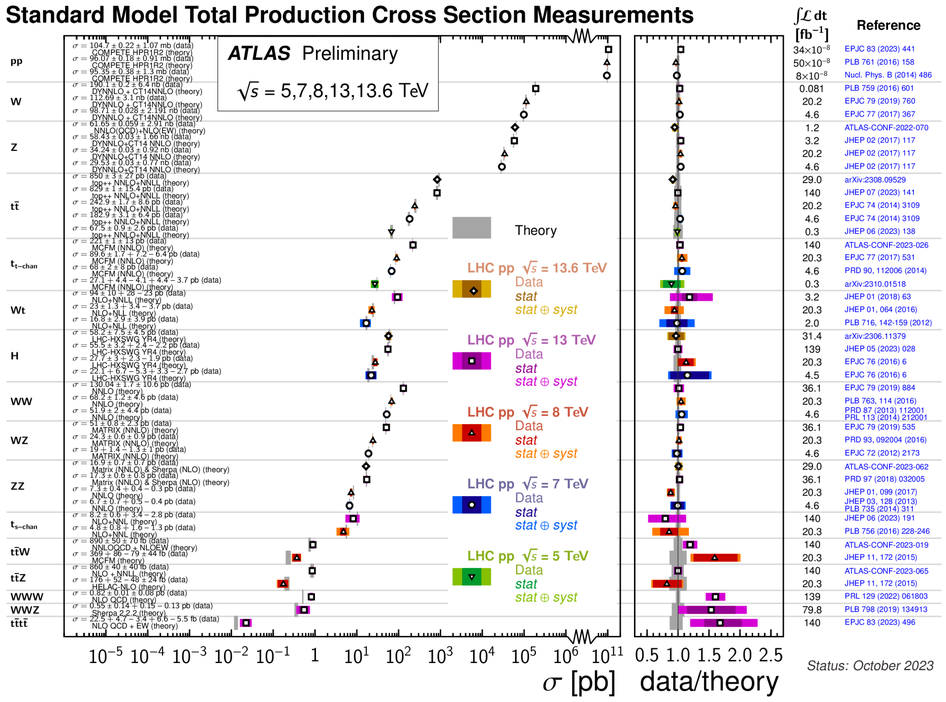
- The take-home message from the LHC so far: **this universe is very SM-like**.







No significant deviation from SM with 140 fb^{-1} of pp collisions (not promising for BSM at HL-LHC)



ESPP update - the next collider project at CERN

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- Where do we go from here?
  - I will be giving the input to the strategy of the Bologna RD_FCC group, counting (with its synergic projects) about 5 FTE, plus the national coordinator of RD_FCC (P. Giacomelli).
  - We believe that the output of the EPSS should be a **clear and unambiguous statement** on what the next collider project at CERN should be.
  - We believe that failing to do so will threaten the future of the field in Europe.
  - I am going to advocate that the option chosen **should be FCC** (ee + hh in the long term).
  - My feedback is structured along some of the 6 questions proposed by ECFA and listed at point 3) at this link.
  - To tackle the subject of today's workshop head-on, let me address (at least some of) those.

FCC-ee in pills

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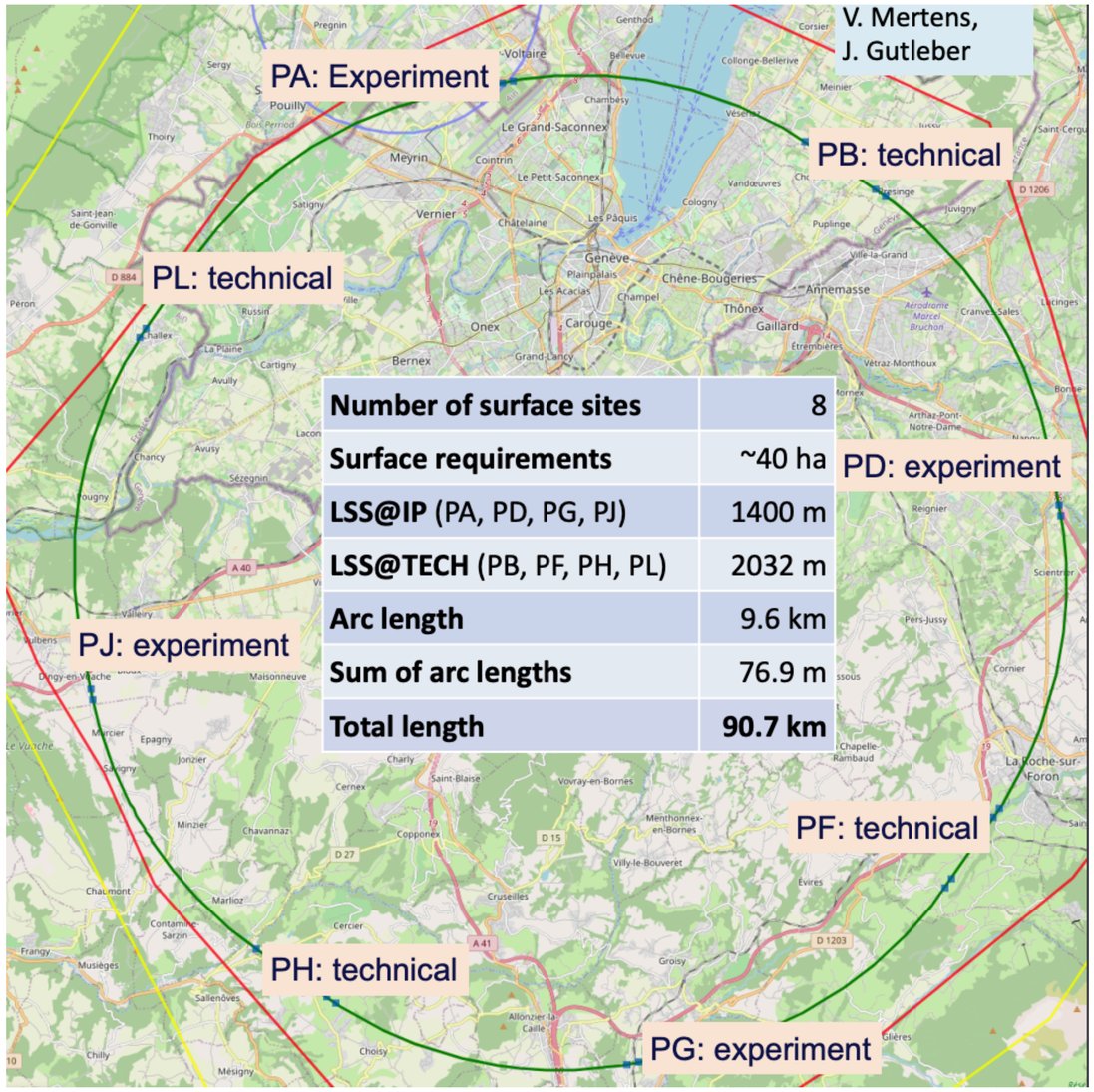
Which is the preferred next major/flagship collider project for CERN?

	Z pole	WW pole	ZH pole	Top pair pole
Beam energy (GeV)	45.6	80	120	182.5
Beam current (mA)	1270	137	26.7	4.9
Number of bunches	11200	1780	440	60
Luminosity (per IP - 10^{34} cm^{-2} s^{-1})	140	20	5	1.25
Integrated luminosity (per IP - ab^{-1}/year)	17	2.4	0.6	0.15
Planned running time (years)	4	2	3	5

Which translates in

- 5×10^{12} Z (LEP $\times 10^5$)
- $\sim 10^8$ WW (LEP $\times 10^4$)
- 2×10^6 H unprecedented at e^+e^-
- 2×10^6 $t\bar{t}$ unprecedented at e^+e^-

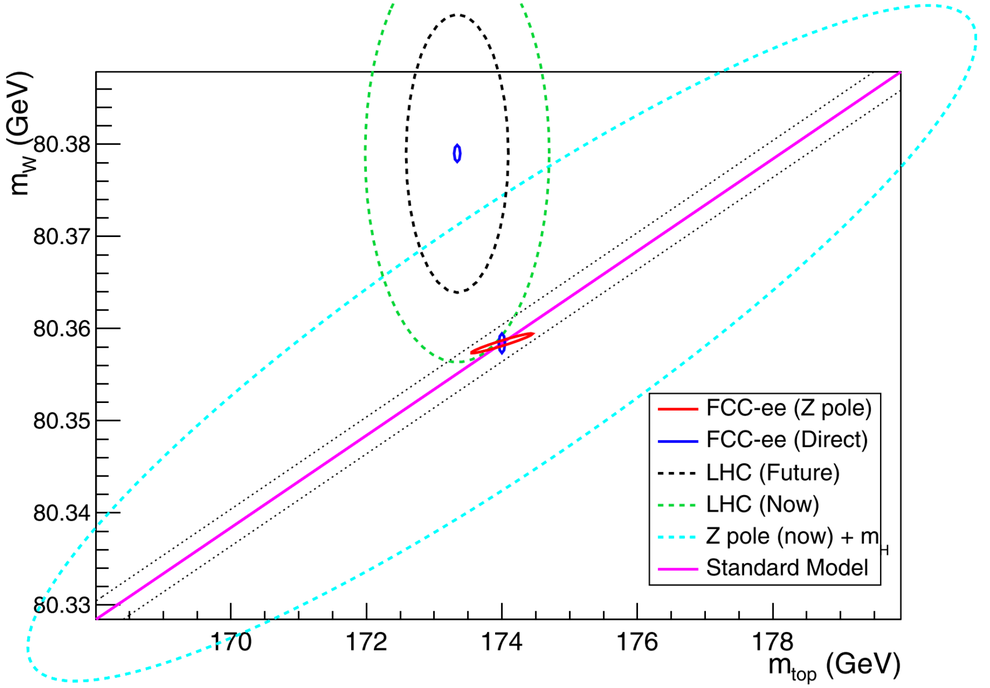
Not to mention ~10^{12} $b\bar{b}$ and $\tau\bar{\tau}$

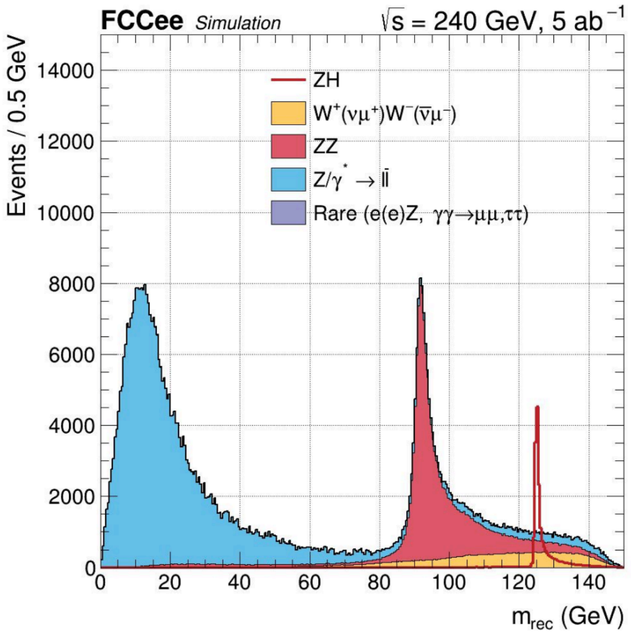


The physics we need

What are the most important elements in the response to the previous question?

- **Physics potential:** The **whole physics programme** (not just the “Higgs factory”) makes the difference
  - $\sin^2\theta_W^{\text{eff}}$, mainly from $A_{\text{FB}}^{\mu\mu}$.
  - m_W and width to $o(1\ \text{MeV})$.
  - m_{top} and width at $o(10-50\ \text{MeV})$.
  - Auxiliary measurements ($\alpha_{\text{QED}}(m_Z^2)$, Z boson mass and width, $\alpha_S^2(m_Z^2)$).
  - Model-independent Γ_H, Higgs couplings and Higgs to invisible.
  - BSM models (ALPs, dark photon, light dark matter, ….).





Taken from FCC-ee CDR

RD_FCC Bo input to the ESPP

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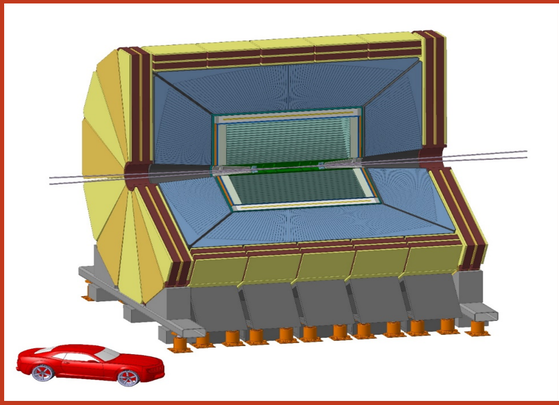
A **not-so-small group of colleagues** has worked to support a circular e^+e^- for a few years.

Most activities grouped under the **IDEA study group**, with contributions on:

- **Pre-shower and muon spectrometer** based on the μ Rwell technology (firmly placed within the DRD1 ECFA group)
- **Dual-readout calorimeter** based on optical fibres enclosed in capillary tubes (HIDRA project - DRD6)
- **Simulation** within the FCC software framework (k4geo)
- **Physics analysis** feasibility studies.
- **Theory/Phenomenology.**

IDEA (Innovative Detector for e^+e^- Accelerators)



2 T thin solenoid within calo
Si vertex detector
Tracking with ultra light drift chamber
Dual Readout Calorimeter + pre-shower
MPGD (µRwell) based Muon detector

A glimpse to our activities

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Beam pipe: R~1.0 cm

Vertex:

5 MAPS layers

R = 1.37-31.5 cm

Drift Chamber: 112 layers

4 m long, R = 35-200 cm

Outer Silicon wrapper:

R = 200-215 cm

DR crystal ecal: ~ 22 X_0

R = 215-250 cm

Superconducting solenoid coil:

3 T, R ~ 2.5-2.8 m

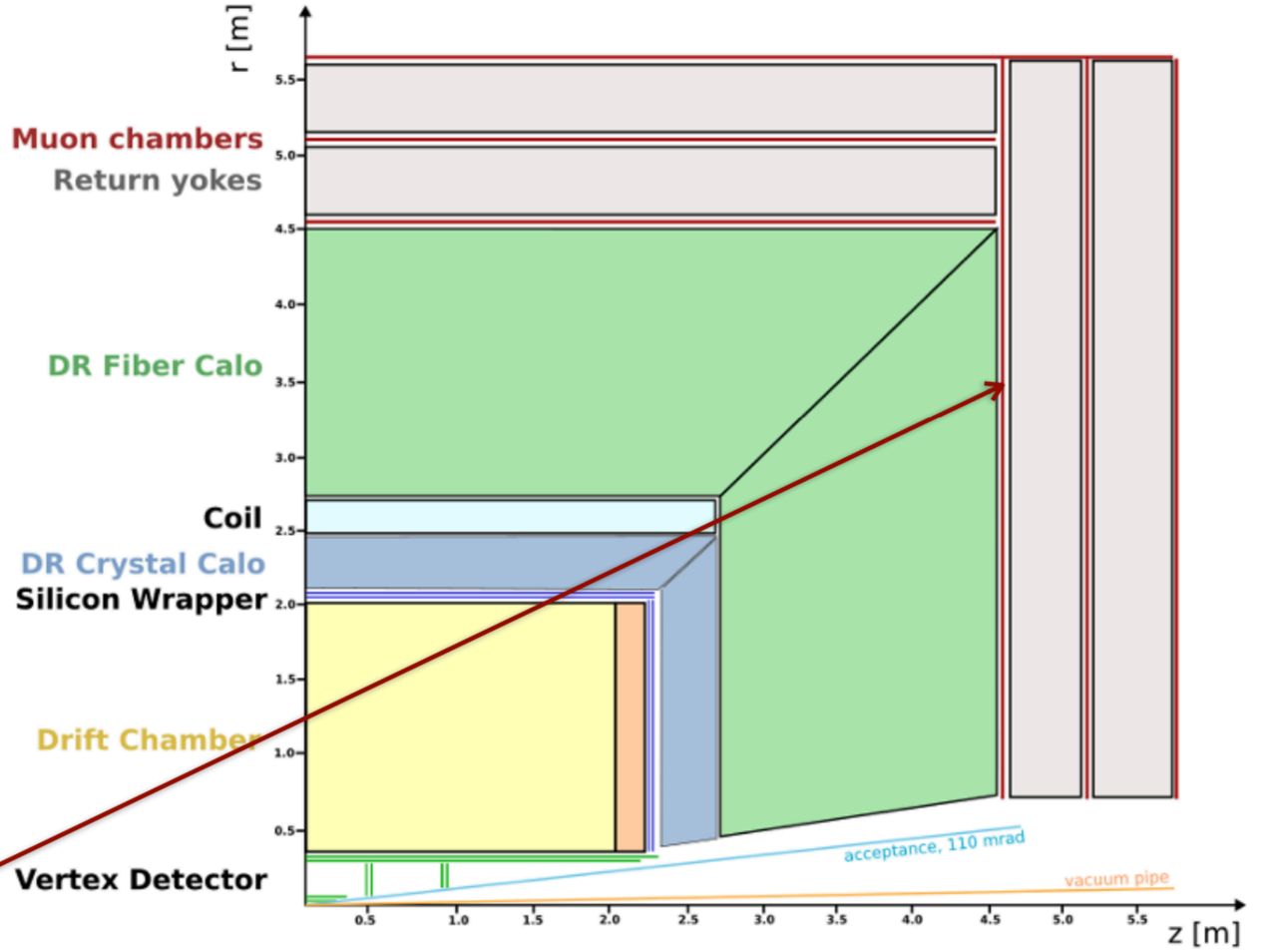
0.7 X_0, 0.16 λ @ 90°

Dual-Readout Calorimeter:

R = 280 -460 cm

Yoke + Muon chambers

R = 460 - 570 cm



Not just nice pictures

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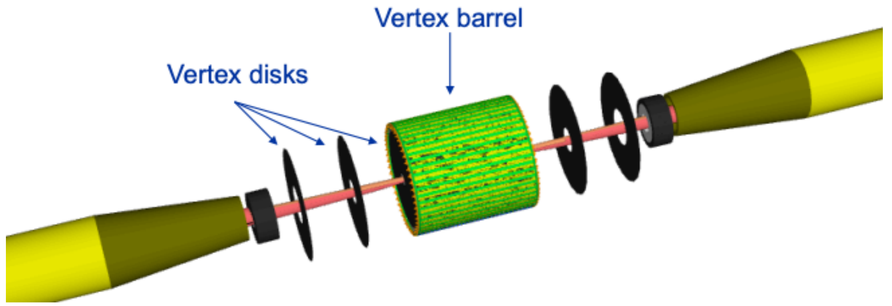
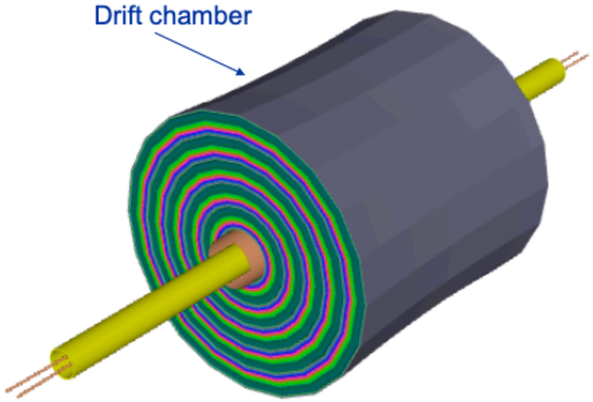
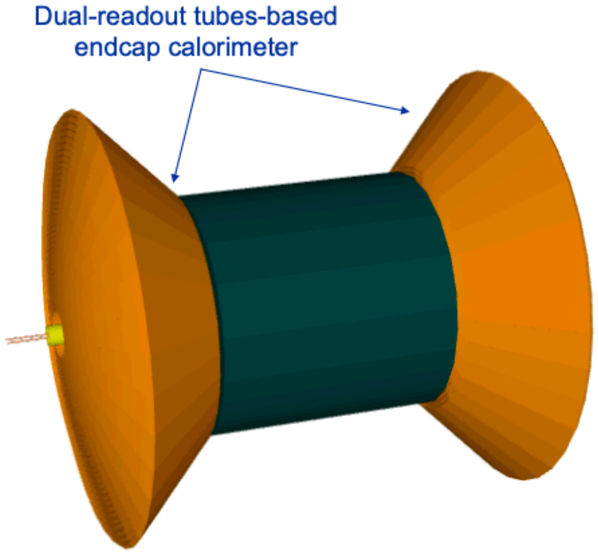
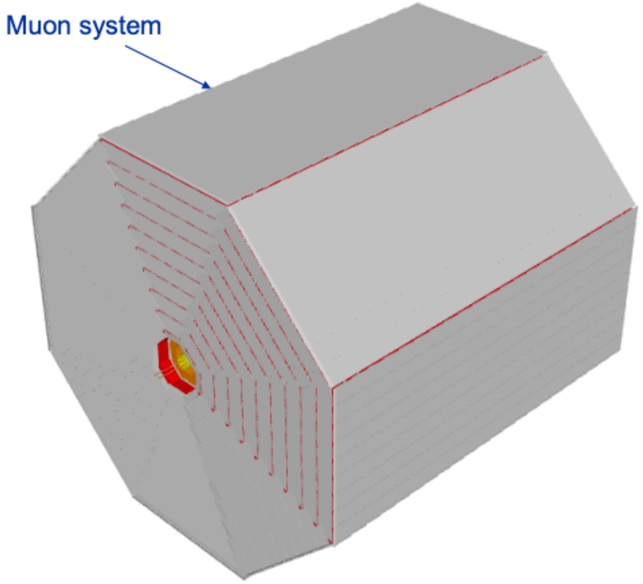
- Detector simulation integrated in the FCC software (k4geo + DD4hep)
- Running time and memory footprint reasonably under control.
- More work needed for digitisation/ reconstruction
- Contributors: M. Ali, S. Braibant, L. Pezzotti, IV

In some case leading in the development or “tuning” of the new tools

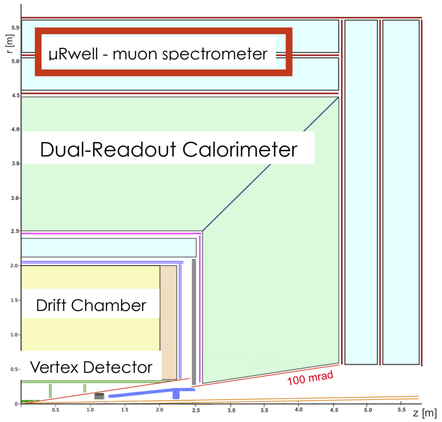




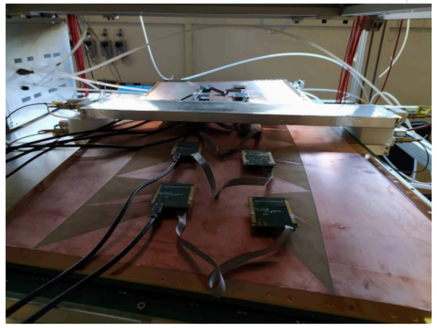


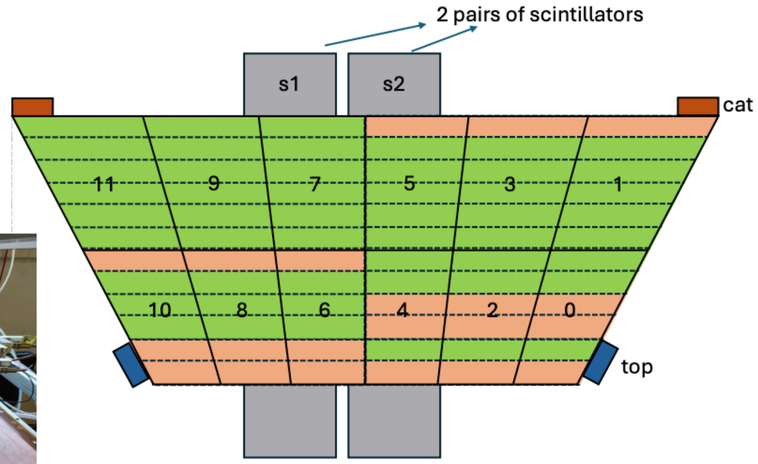


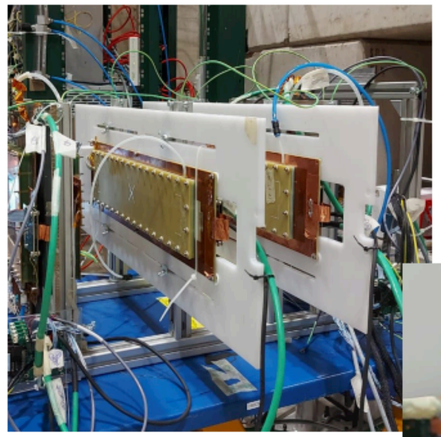
A glimpse to our activities



- MPGD - μRwell technology:
  - Testing different configurations for the wells over the years 2020-2023.
  - 2024 test beam: testing TIGER chip (110 nm CMOS, simultaneous time and charge measurement) + GEMROC (voltage level distribution, data concentrator for TIGER) and evaluate performance.
  - Simulation of TiGER performance
  - Test-bed also available in Berti-Pichat using cosmics
- Main contributors: F. Chiapponi, R. Farinelli, P. Giacomelli.

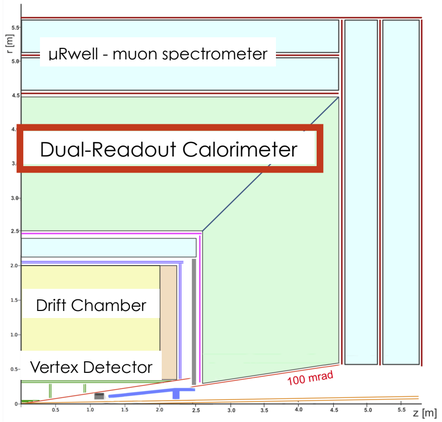




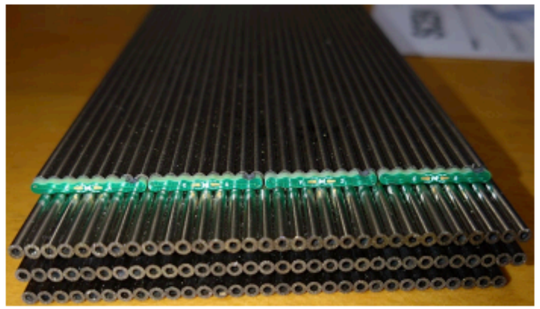


A glimpse to our activities

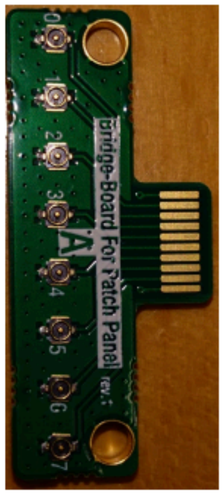
- HiDRa: High-granularity Dual-ReAdout calorimeter.



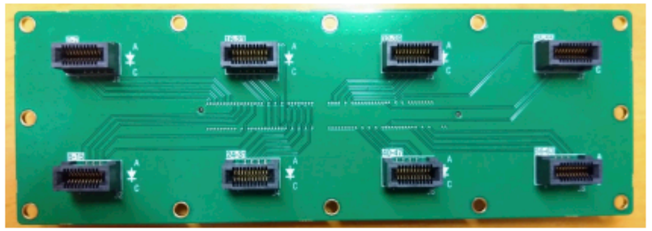
Absorber + front-end board

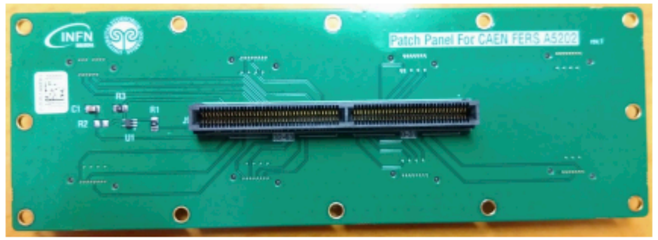


10 front-end board



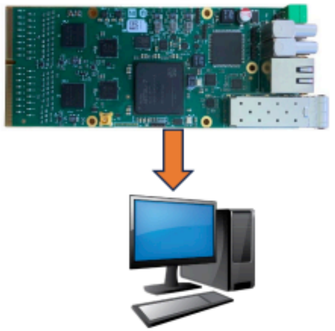
50 adapter board

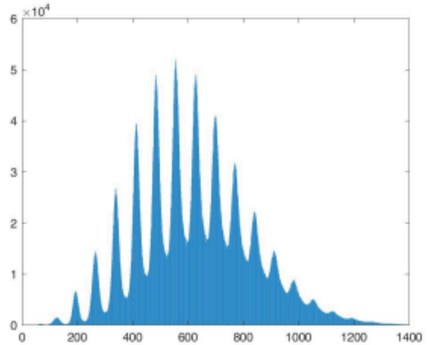




4 patch panel

CAEN FERS

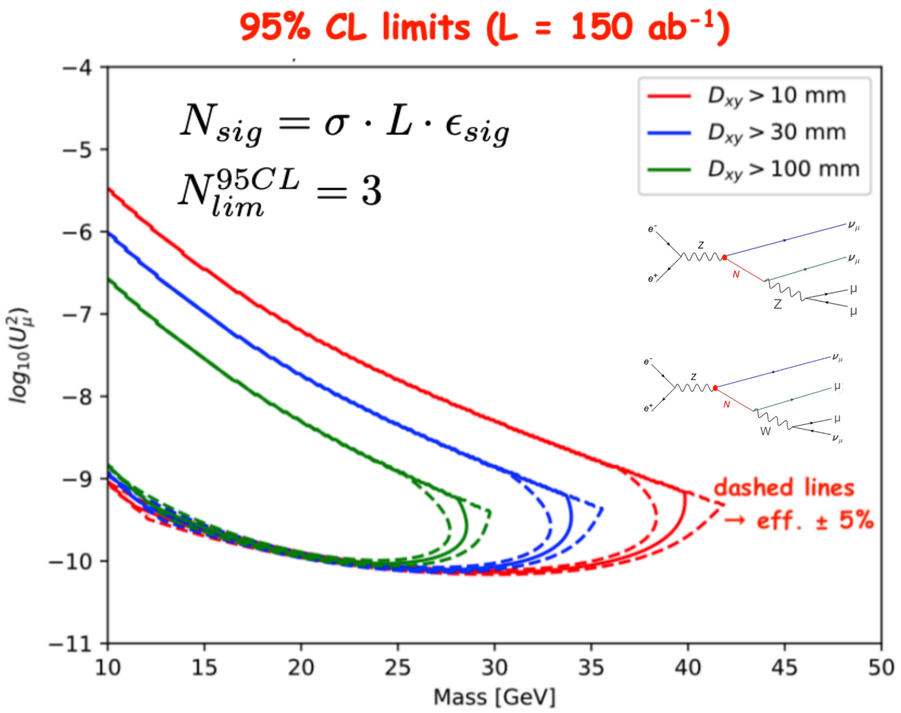




Arrays of **optical fibres** embedded in capillary tubes. Each fibre is read out by a single SiPM. The **analog signal from 8 SiPMs** is summed and distributed through a **patch panel to the FE electronics**.
INFN Bologna has designed and built the system with U. Insubria.
Main contributors: D. Falchieri, A. Gabrielli, P. Giacomelli, IV

A glimpse to our activities

- Physics feasibility studies in a few different scenarios:
  - Higgs recoil studies and quality of the recoil reconstruction (fast simulation)
  - Search for heavy neutral leptons (long-lived with decays in two muons and missing momentum).
  - Main contributors: M. Ali, L. Bellagamba, S. Braibant
- And, on the theory/phenomenology side:
  - Work on MC (MadGraph5_aMC@NLO) + precision NLO EW predictions
    - Main contributors F. Maltoni, D. Pagani



Quantum tops at circular lepton colliders 2404.08049

Quantum information and CP measurement in H→τ+τ- at future lepton colliders 2211.10513

Improving methods and predictions at high-energy e++e– – colliders within collinear factorisation 2207.03265

One-loop electroweak Sudakov logarithms: a revisitation and automation 2110.03714

Lepton collisions in MadGraph5_aMC@NLO 2108.10261

The automation of next-to-leading order electroweak calculations 1804.10017

RD_FCC Bo input to the ESPP

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What are the most important elements in the response to the previous question?

Long-term perspective: unlike other options on the table, FCC-ee is an obvious investment for FCC-hh and the exploration of the tens-of-TeV scale.

Financial and human resources: requirements and effect on other projects: unlike other options on the table, **a funding model for FCC-ee exists**, and, with a relatively modest investment on top of the standard CERN funding scheme, **it is credible**.

Careers and training: stretching a bit the question - CERN isn't DESY, or Fermilab. It is a world-level **lab-hub**, with a community of **~ 10-20k scientists** attached to it. Unlike other options, with 4 interaction points and the possibility of the FCC-hh, **FCC-ee guarantees the continuation of CERN's role**.

RD_FCC Bo input to the ESPP

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What are the most important elements in the response to the previous question?

Careers and training - my personal perspective: I started working on ATLAS as a PhD student in 2001. The production and commissioning phase of a big experiment is dense with learning experiences (often locked or screened away for those that have only seen a running experiment). The 15+ year-long ramp up phase (with HL-LHC largely running in parallel) should also be seen as an **opportunity.**

Timing: the accelerator options that are ~ready for physics are circular or linear e^+e^-. Muon collider should build a demonstrator - which does not address the question of maintaining the hub role of CERN.

Sustainability: Political and environmental sustainability are a concern (how to successfully engage with a global HEP project in a divided world with enormous climate/ energy-related issues?). **Similar concerns apply to other options on the table**.

RD_FCC Bo input to the ESPP

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Should CERN/Europe proceed with the preferred option set out in the previous question or should alternative options be considered

If Japan proceeds with the ILC in a timely way: yes, projects complementary in energy, luminosity, future prospects.

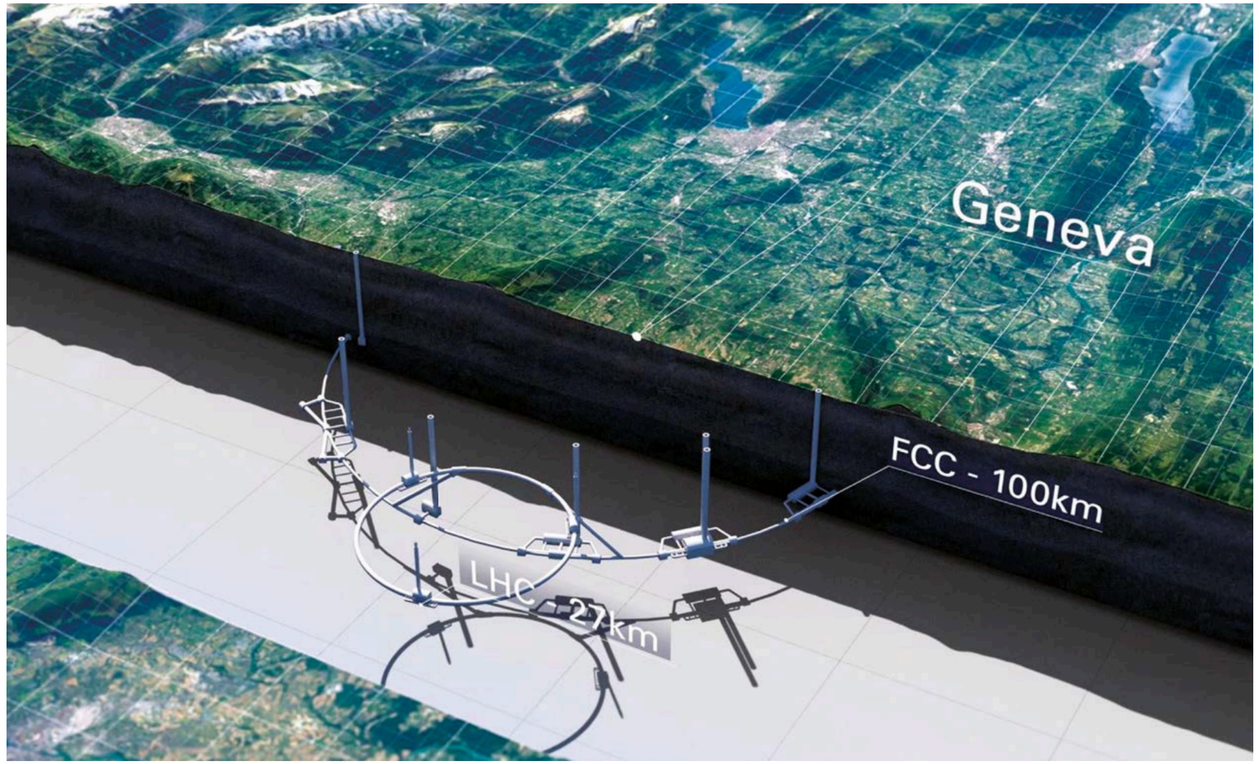
If the US proceeds with a muon collider: yes, projects completely orthogonal in timeline and physics reach.

If there are major new (unexpected) results from the HL-LHC or other HEP experiments: clearly, it depends on the results. Obviously yes, if the unexpected results arises from a scale accessible to FCC-ee.

If China proceeds with the CEPC on the announced timescale: the most difficult scenario - but the collaboration with China should be fostered, rather than limited. Avoiding competition cannot be the main argument in setting a 20+ year long strategy.

Summary

- Bologna is a key institute for RD_FCC.
- Effort concentrated on IDEA:
  - Muon spectrometer (with μRwell technology - DRD1).
  - Dual readout calorimeter (HiDRa - DRD6).
  - Simulation.
  - Physics analysis.
  - Phenomenology/theory.
- The field **has to converge** on a single proposal for the next big collider project at CERN.
- We advocate this should be FCC (ee, followed by hh)

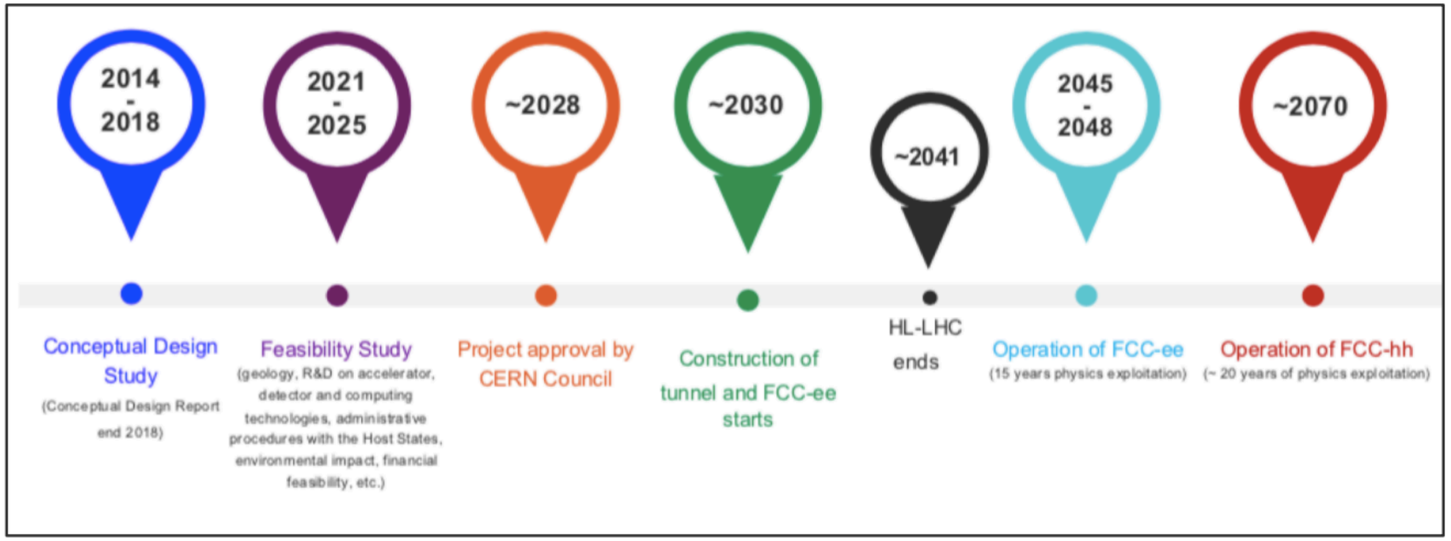


Backup

FCC timeline

F. Gianotti - FCC week
S. Francisco

10 June 2024



1st stage collider FCC-ee:
electron-positron collisions 90-360 GeV:
electroweak and Higgs factory
2nd stage collider FCC-hh:
proton-proton collisions at ~ 100 TeV

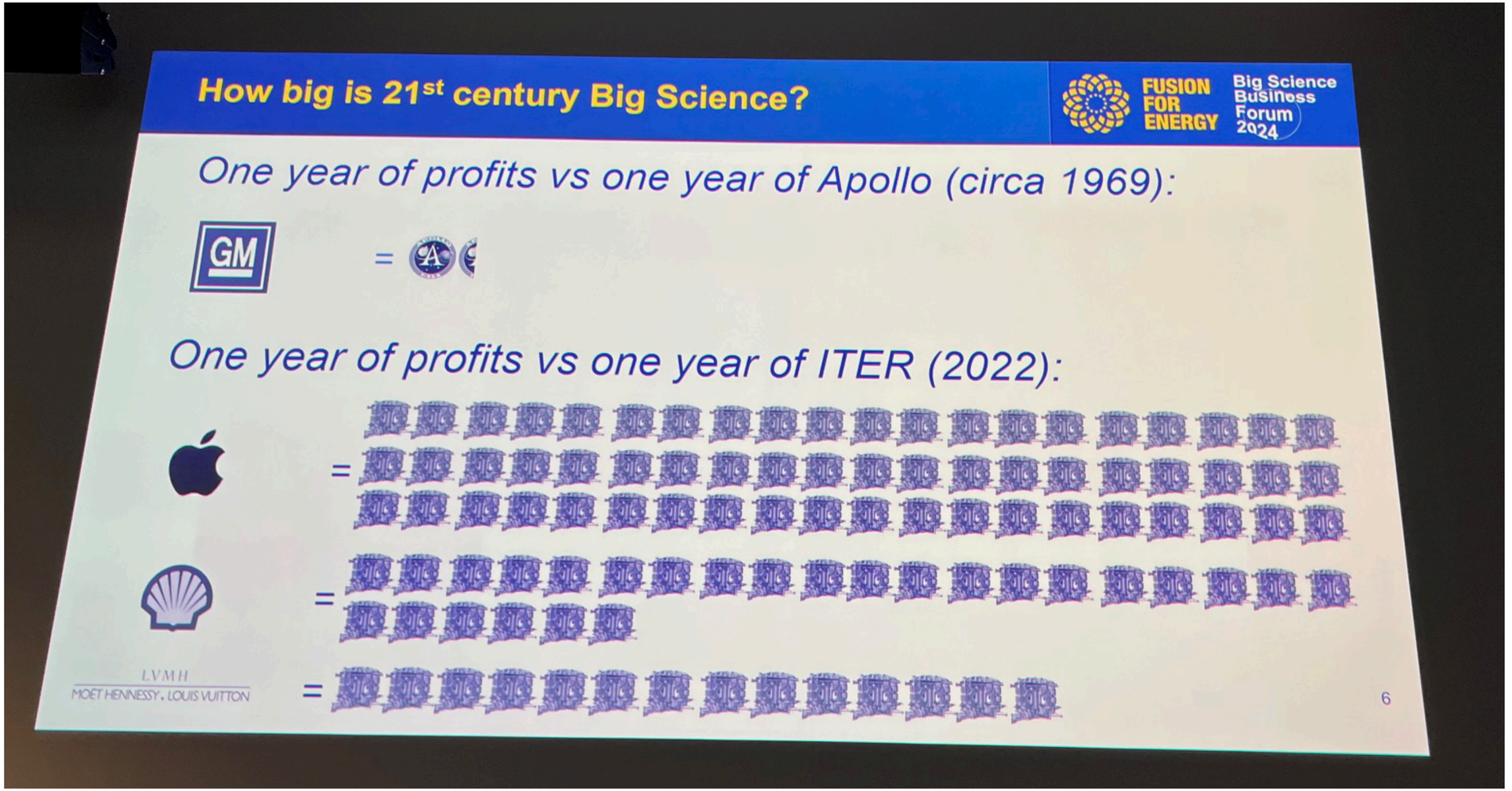
"Realistic" schedule taking into account:

- ❑ past experience in building colliders at CERN
- ❑ the various steps of approval process: ESPP update, CERN Council decision
- ❑ HL-LHC will run until ~ 2041

→ ANY future collider at CERN cannot start physics operation before ~ 2045 (but construction will proceed in parallel to HL-LHC operation)

Care should be taken when comparing to other proposed facilities, for which in most cases only the (optimistic) technical schedule is shown. In particular, studies related to **territorial implementation** (surface sites, roads, connection to water and electricty, environmental impact, admin procedures, etc.), which for FCC are being carried out in the framework of the Feasibility Studies, **take years.**

Shown by the CFO of ITER



Science business forum - Trieste