Overview of the Future Circular Collider (FCC) Program

Heather M. Gray on behalf of the FCC collaboration

Berkeley
UNIVERSITY OF CALIFORNIA

BERKELEY LAB

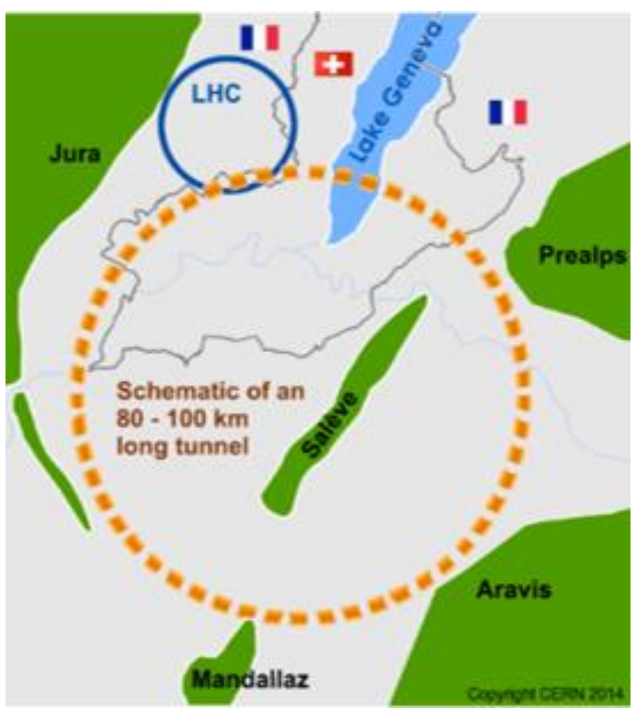
Lepton Photon 2023, Melbourne

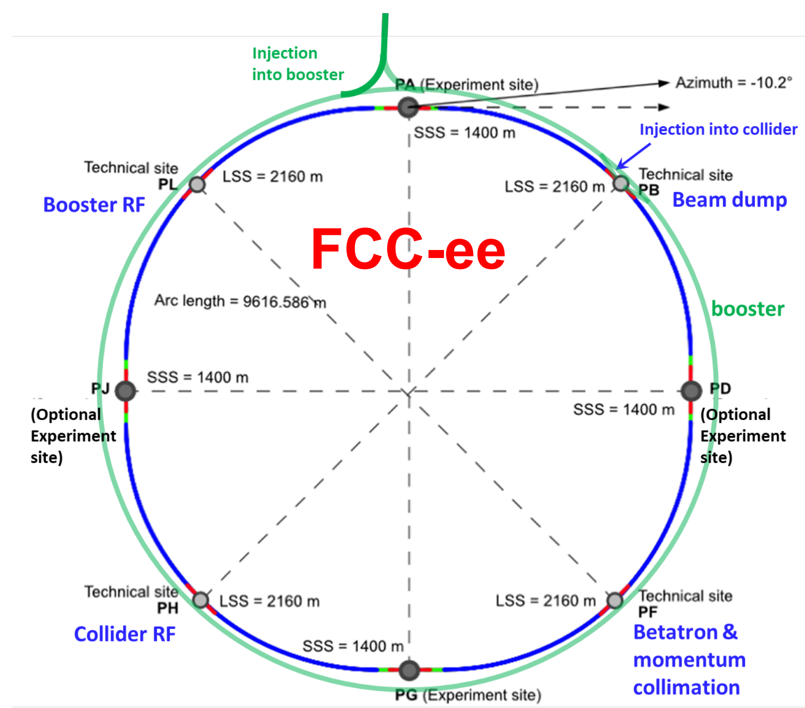
Introduction

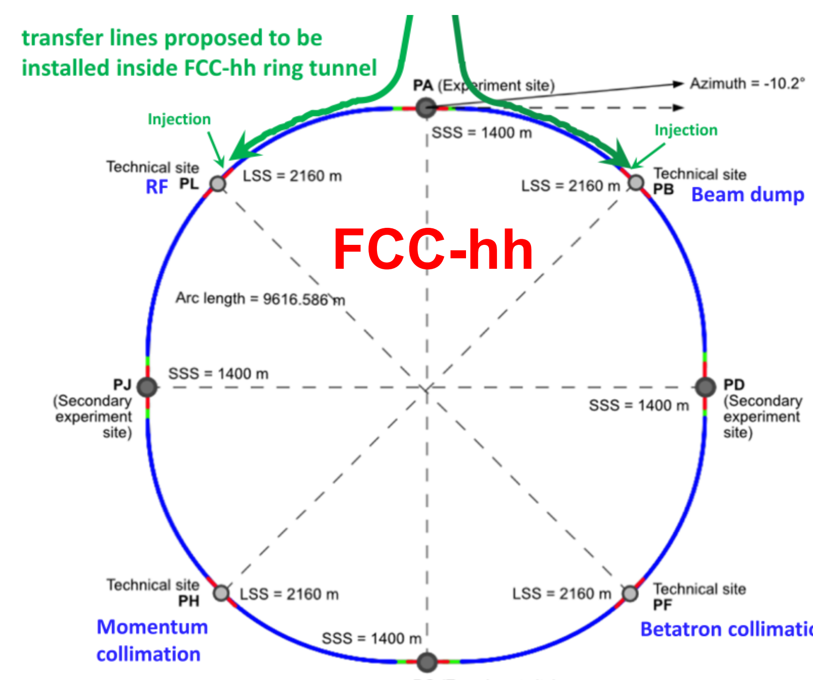
- Reminder: Outcome of the 2020 European Strategy Process
  - An electron-positron Higgs factory is the highest-priority next collider. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy.
  - Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage.
- Future Circular Collider (FCC) Feasibility Study launched in 2021
  - Mid-term review by end of 2023
  - Full Feasibility Study Report in 2025
- Outcome from the US Snowmass+P5 process expected soon

The FCC Program

- Comprehensive long-term program with physics at the intensity and energy frontier:
  - Electron-positron collider: FCC-ee (Z, W, H, tt) as high-luminosity Higgs, EW + top factory
  - Hadron-hadron collider: FCC-hh (~100 TeV) to maximize energy to search for BSM physics and make precision measurements
    - includes pp, AA and eh options







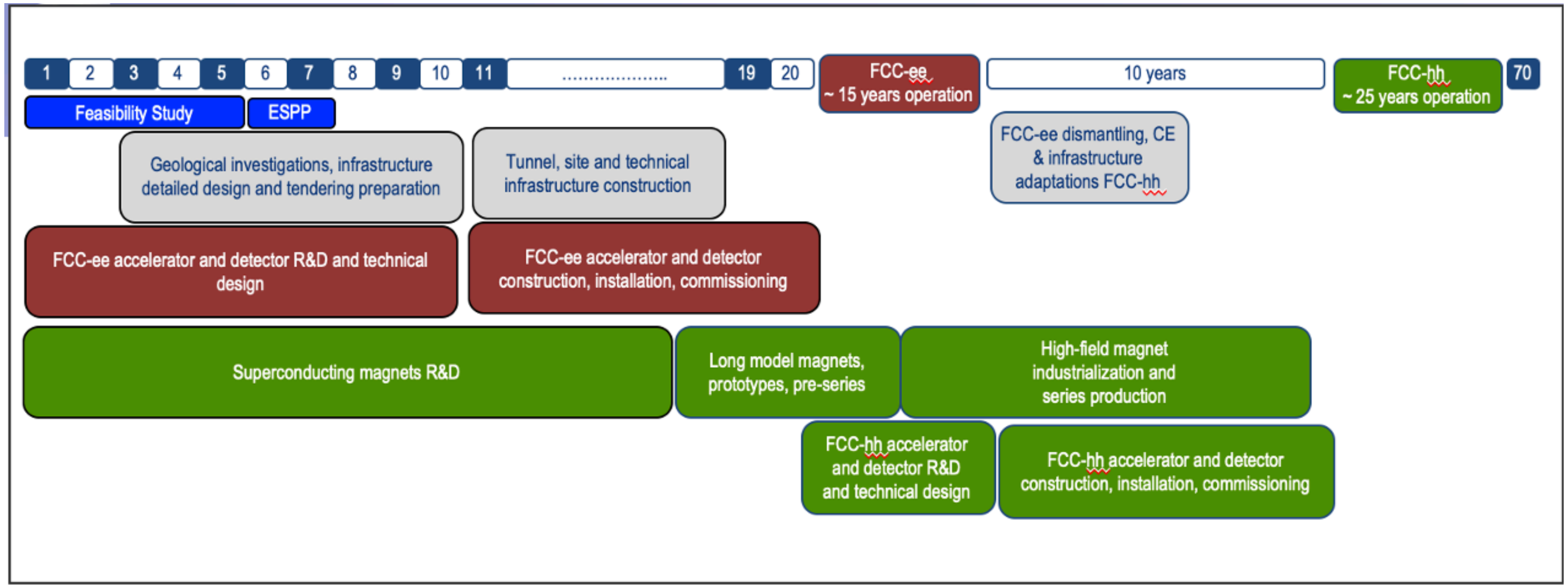
2020 - 2040 | 2045 - 2063 | 2070 - 2095

FCC Physics Case

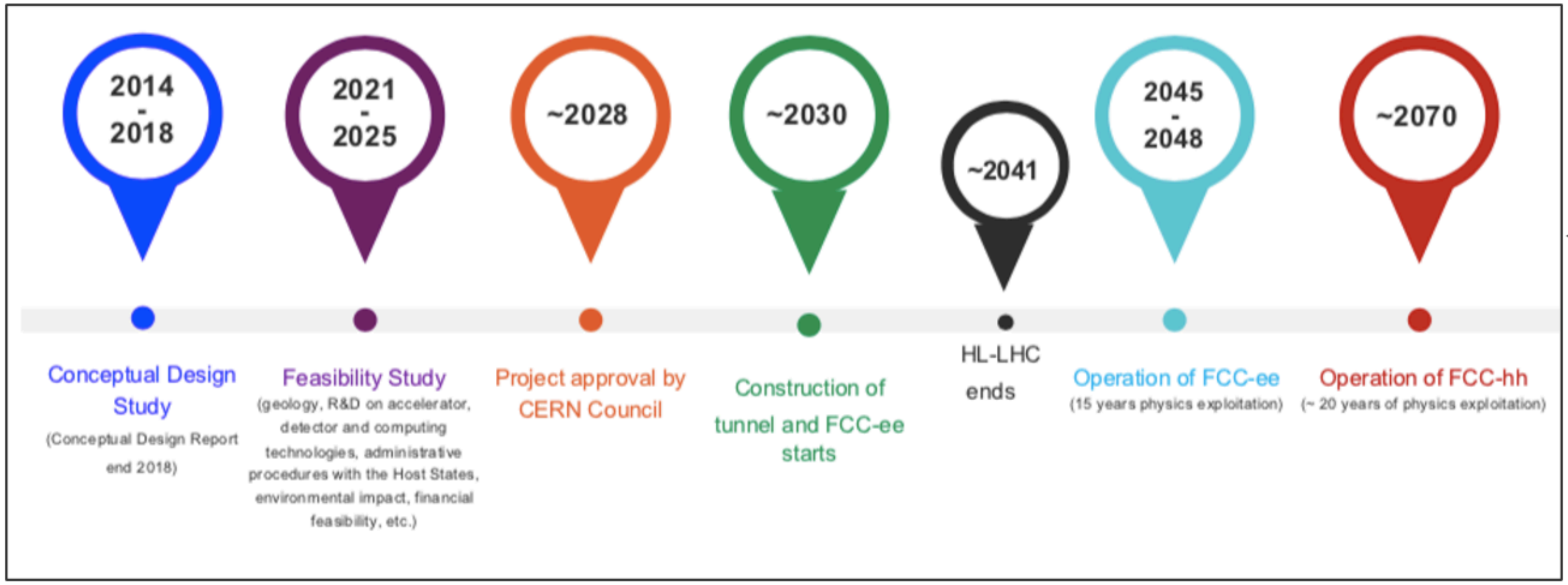
- Unbiased, high precision Higgs measurements
  - Higgs width (FCC-ee)
  - 10x improvement Higgs couplings (Mostly FCC-ee, some at FCC-hh)
  - Higgs self-coupling (Mostly FCC-hh)
- Searches for physics beyond the Standard Model
  - Indirect searches via precision measurements up to 70 TeV(FCC-ee)
  - Direct searches for new particles and new interactions (FCC-hh)
    - 10x reach of HL-LHC
- And many more
  - 10-50x improvement on EW observables
  - 10x Belle II statistics for b, c, tau

FCC Timeline

Technically-limited schedule



Realistic schedule



F. Gianotti, June 2023

FCC Ring Location

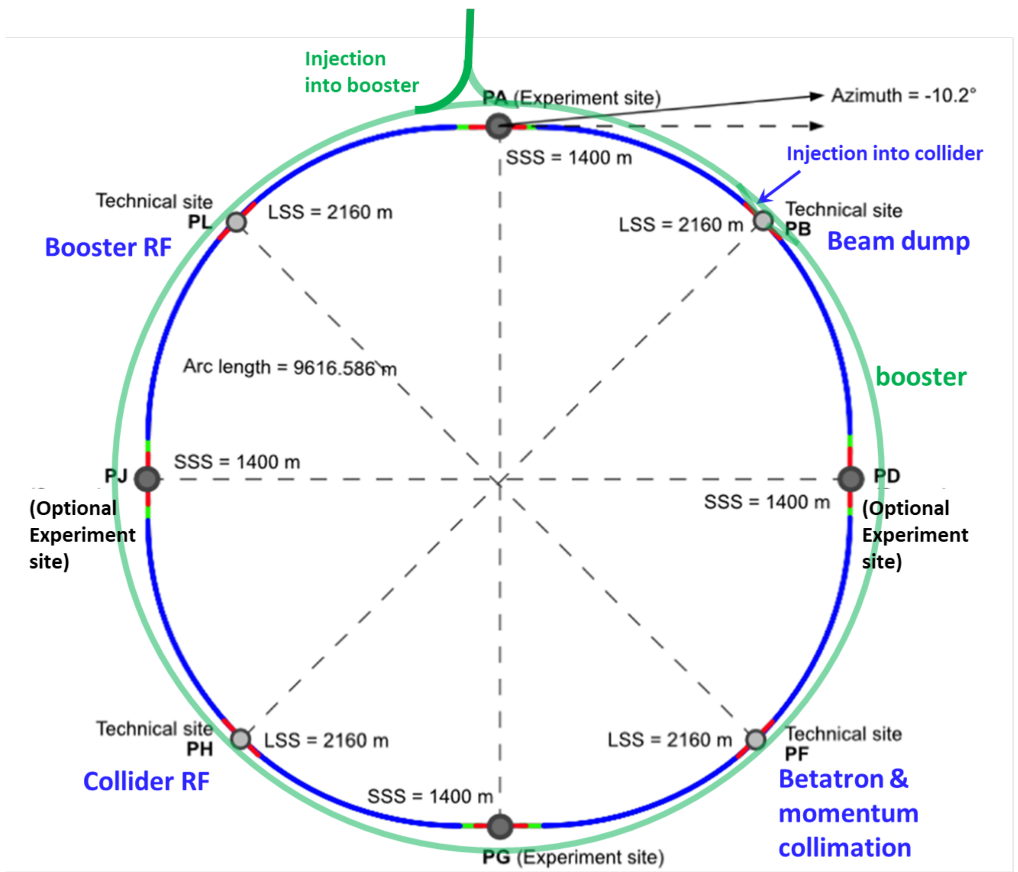
Major achievement: optimization of the ring placement

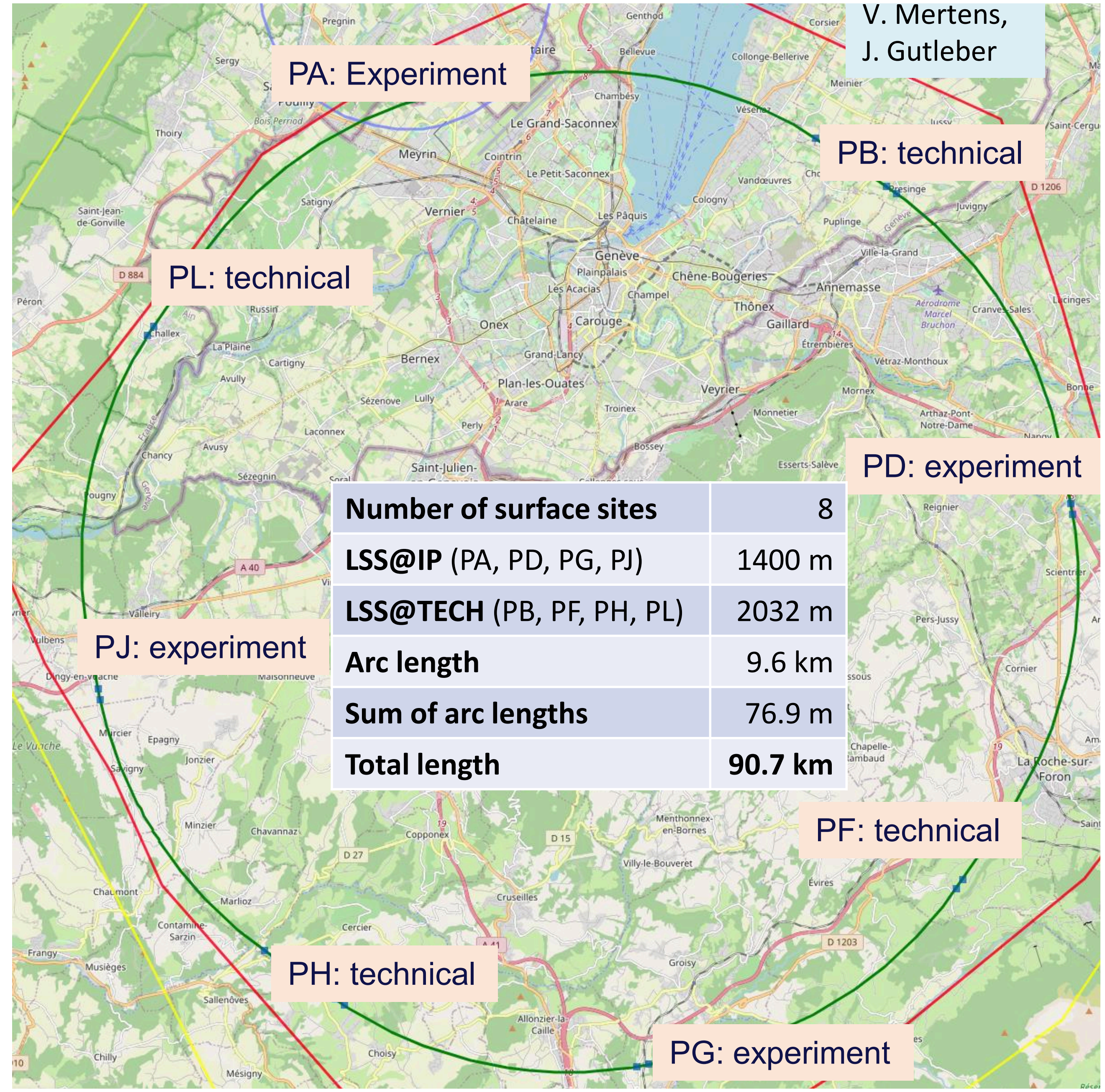
Layout chosen out of ~ 100 initial variants, based on geology and surface constraints (land availability, access to roads, etc.), environment (protected zones), infrastructure (water, electricity, transport), etc.

"Éviter, reduire, compenser" principle of EU and French regulations

Lowest-risk baseline: 90.7 km ring, 8 surface points, 4-fold superperiodicity, possibility of 2 or 4 IPs

Whole project now adapted to this placement





Number of surface sites	8
LSS@IP (PA, PD, PG, PJ)	1400 m
LSS@TECH (PB, PF, PH, PL)	2032 m
Arc length	9.6 km
Sum of arc lengths	76.9 m
Total length	**90.7 km**

M. Benedikt, July 2023

Beam Parameters

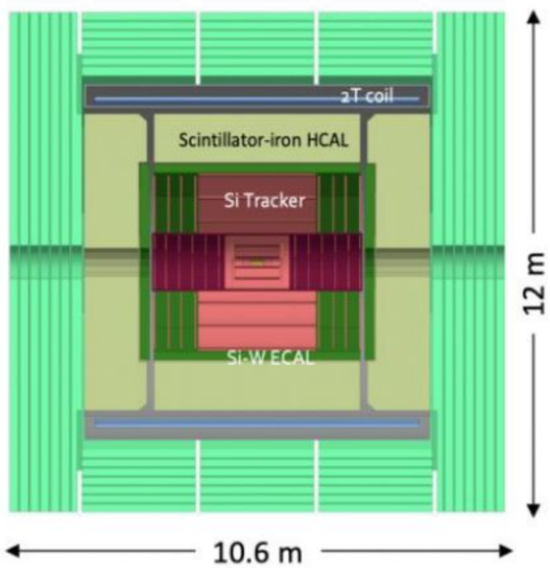
Parameter	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45	80	120	182.5
beam current [mA]	1280	135	26.7	5.0
number bunches/beam	10000	880	248	36
bunch intensity [10^{11}]	2.43	2.91	2.04	2.64
SR energy loss / turn [GeV]	0.0391	0.37	1.869	10.0
total RF voltage 400/800 MHz [GV]	0.120/0	1.0/0	2.08/0	4.0/7.25
long. damping time [turns]	1170	216	64.5	18.5
horizontal beta* [m]	0.1	0.2	0.3	1
vertical beta* [mm]	0.8	1	1	1.6
horizontal geometric emittance [nm]	0.71	2.17	0.64	1.49
vertical geom. emittance [pm]	1.42	4.34	1.29	2.98
horizontal rms IP spot size [μm]	8	21	14	39
vertical rms IP spot size [nm]	34	66	36	69
luminosity per IP [10^{34} $cm^{-2}s^{-1}$]	182	19.4	7.3	1.33
total integrated luminosity / year [ab^{-1}/yr] 4 IPs	87	9.3	3.5	0.65
beam lifetime (rad Bhabha + BS+lattice)	8	18	6	10
	4 years 5×10^{12} Z LEP x 10^5	2 years > 10^8 WW LEP x 10^4	3 years 2×10^6 H	5 years 2×10^6 tt pairs

Currently assessing feasibility to change order, i.e. start with ZH

F. Gianotti, June 2023

Detector Concepts for FCC-ee

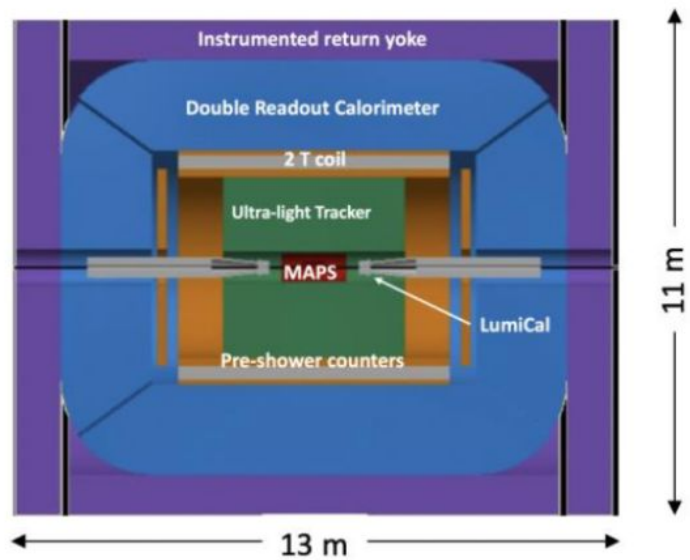
CLD



- Well established design
  - ILC -> CLIC detector -> CLD
- Full Si vtx + tracker;
- CALICE-like calorimetry;
- Large coil, muon system
- Engineering still needed for operation with continuous beam (no power pulsing)
  - Cooling of Si-sensors & calorimeters
- Possible detector optimizations
  - σ_p/p, σ_E/E
  - PID ($\mathcal{O}$(10 ps) timing and/or RICH)?

CDR

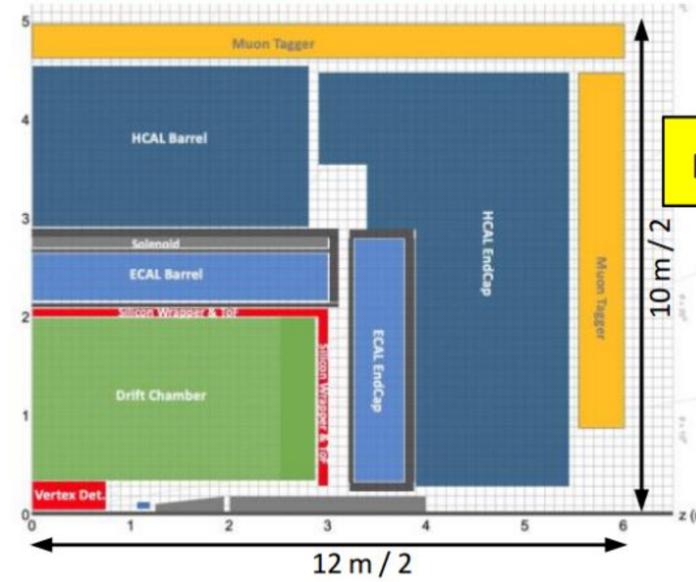
IDEA



- A bit less established design
  - But still ~15y history
- Si vtx detector; ultra light drift chamber w powerful PID; compact, light coil;
- Monolithic dual readout calorimeter;
  - Possibly augmented by crystal ECAL
- Muon system
- Very active community
  - Prototype designs, test beam campaigns, …

Noble Liquid ECAL based

new



- A design in its infancy
- Si vtx det., ultra light drift chamber (or Si)
- High granularity Noble Liquid ECAL as core
  - Pb/W+LAr (or denser W+LKr)
- CALICE-like or TileCal-like HCAL;
- Coil inside same cryostat as LAr, outside ECAL
- Muon system.
- Very active Noble Liquid R&D team
  - Readout electrodes, feed-throughs, electronics, light cryostat, …
  - Software & performance studies

M. Selvaggi

Physics Landscape

Higgs
factory

m_H, σ, Γ_H
self-coupling
H→ bb, cc, ss, gg
H→inv
ee→H
H→bs, ..

Top

m_{top}, Γ_{top}, ttZ, FCNCs

Flavor
"boosted" B/D/τ factory:

CKM matrix
CPV measurements
Charged LFV
Lepton Universality
τ properties (lifetime, BRs..)

$B_c \to \tau\nu$
$B_s \to D_s K/\pi$
$B_s \to K^* \tau\tau$
$B \to K^* \nu\nu$
$B_s \to \varphi \nu\nu$ …

QCD - EWK
most precise SM test

m_Z , Γ_Z , Γ_{inv}

$\sin^2\theta_W$, R^Z_ℓ, R_b, R_c

$A_{FB}^{b,c}$, τ pol.

α_S ,

m_W, Γ_W

BSM
feebly interacting particles

Heavy Neutral Leptons
(HNL)

Dark Photons Z_D

Axion Like Particles (ALPs)

Exotic Higgs decays

Detector Requirements

Higgs
factory

track momentum resolution (low X_0)

IP/vertex resolution for flavor tagging

PID capabilities for flavor tagging

jet energy/angular resolution (stochastic and noise) and PF

Flavor
"boosted" B/D/τ factory:

track momentum resolution (low X_0)

IP/vertex resolution

PID capabilities

Photon resolution, pi0 reconstruction

QCD - EWK
most precise SM test

acceptance/alignment knowledge to 10 μm

luminosity

BSM
feebly interacting particles

Large decay volume

High radial segmentation
- tracker
- calorimetry
- muon

impact parameter resolution for large displacement

triggerless

M. Selvaggi

Precision EW at FCC-ee

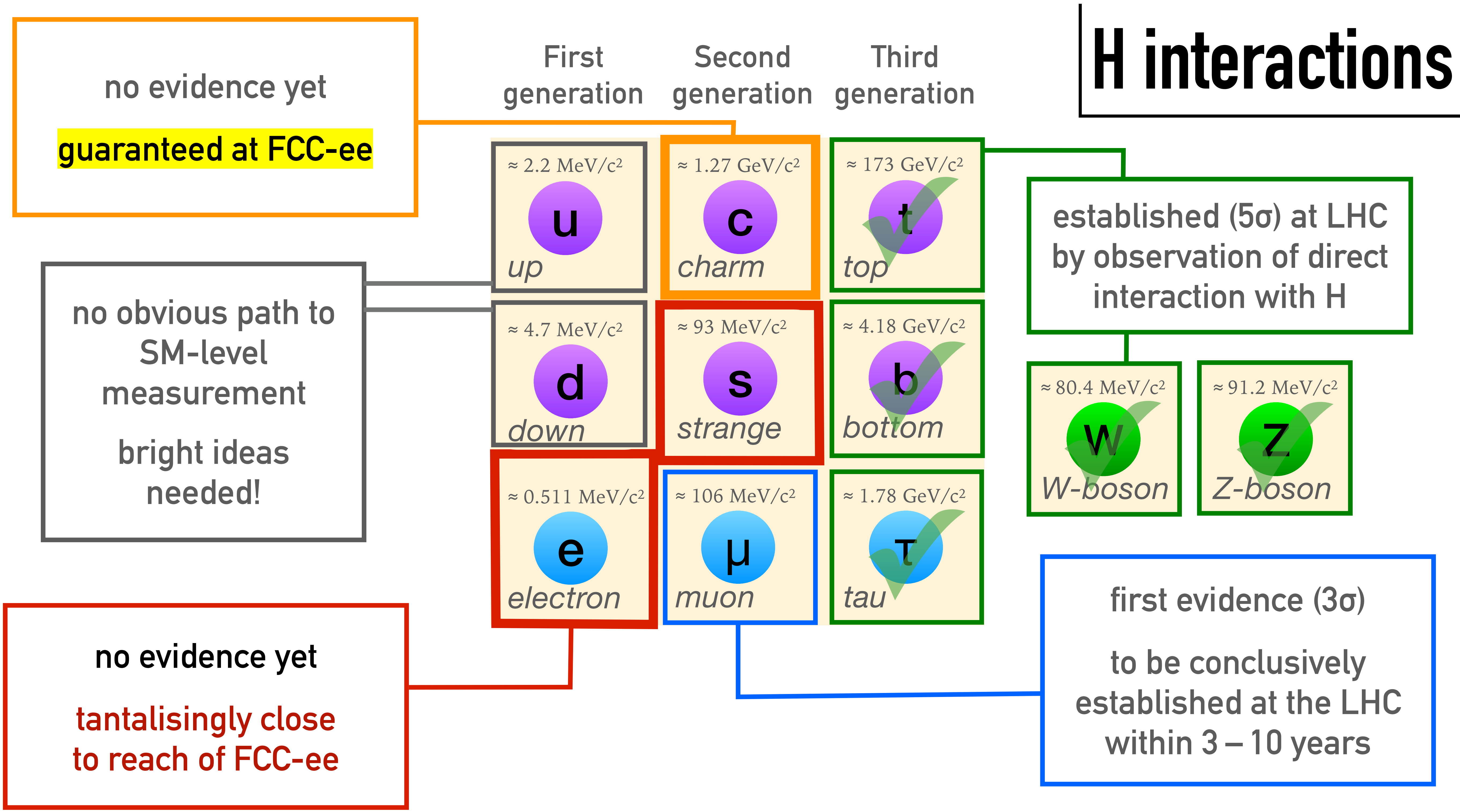
...a quantum leap in our understanding of electroweak physics...

Observable	Present value	±	error	FCC-ee (statistical)	FCC-ee (systematic)
m_Z (keV/c^2)	91 186 700	±	2200	5	100
Γ_Z (keV)	2 495 200	±	2300	8	100
R_ℓ^Z ($\times 10^3$)	20 767	±	25	0.06	1
$\alpha_s(m_Z)$ ($\times 10^4$)	1196	±	30	0.1	1.6
R_b ($\times 10^6$)	216 290	±	660	0.3	<60
σ^0_{had} ($\times 10^3$) (nb)	41 541	±	37	0.1	4
N_ν($\times 10^3$)	2991	±	7	0.005	1
$\sin^2\theta_W^{eff}$($\times 10^6$)	231 480	±	160	3	2–5
$1/\alpha_{QED}(m_Z)$($\times 10^3$)	128 952	±	14	4	Small
$A_{FB}^{b,0}$ ($\times 10^4$)	992	±	16	0.02	<1
$A_{FB}^{pol,\tau}$ ($\times 10^4$)	1498	±	49	0.15	<2
m_W (keV/c^2)	803 500	±	15 000	600	300

Compare these columns.

M. McCullough

Higgs Couplings at FCC-ee



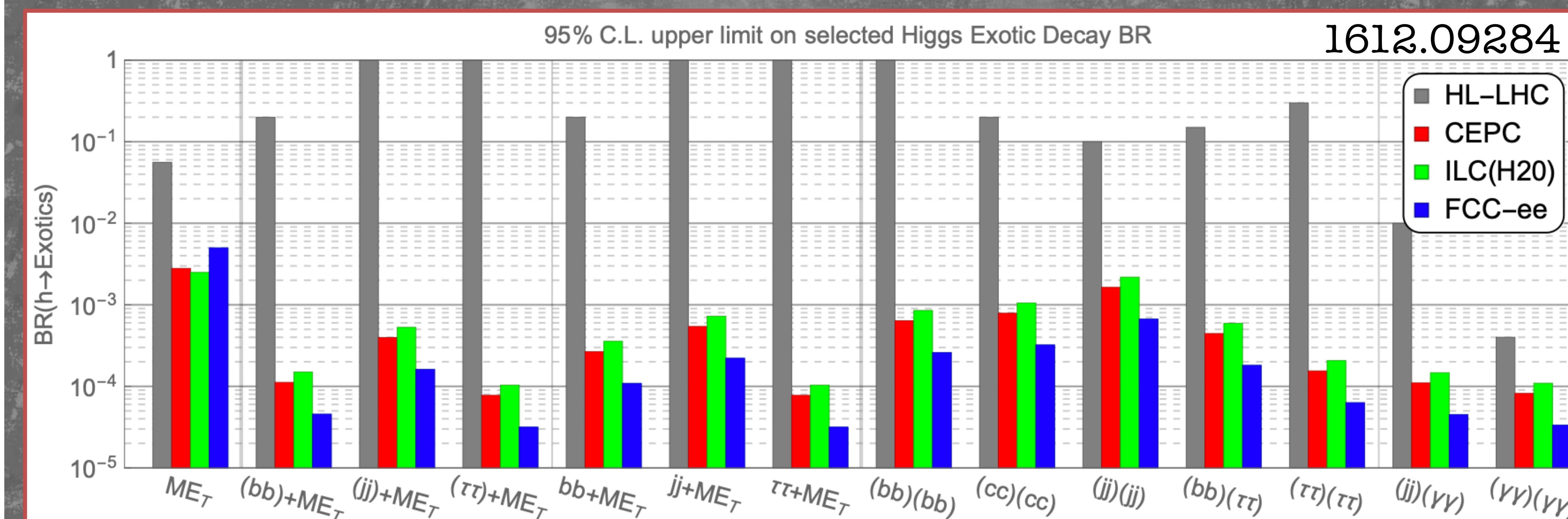
G. Salam

+20% on κ_λ

Dark Sector at FCC-ee

Our Dark Future

Would not be surprised if first dark world discovery is of light states which are not necessarily the dark matter itself, but are connected with dark sectors.

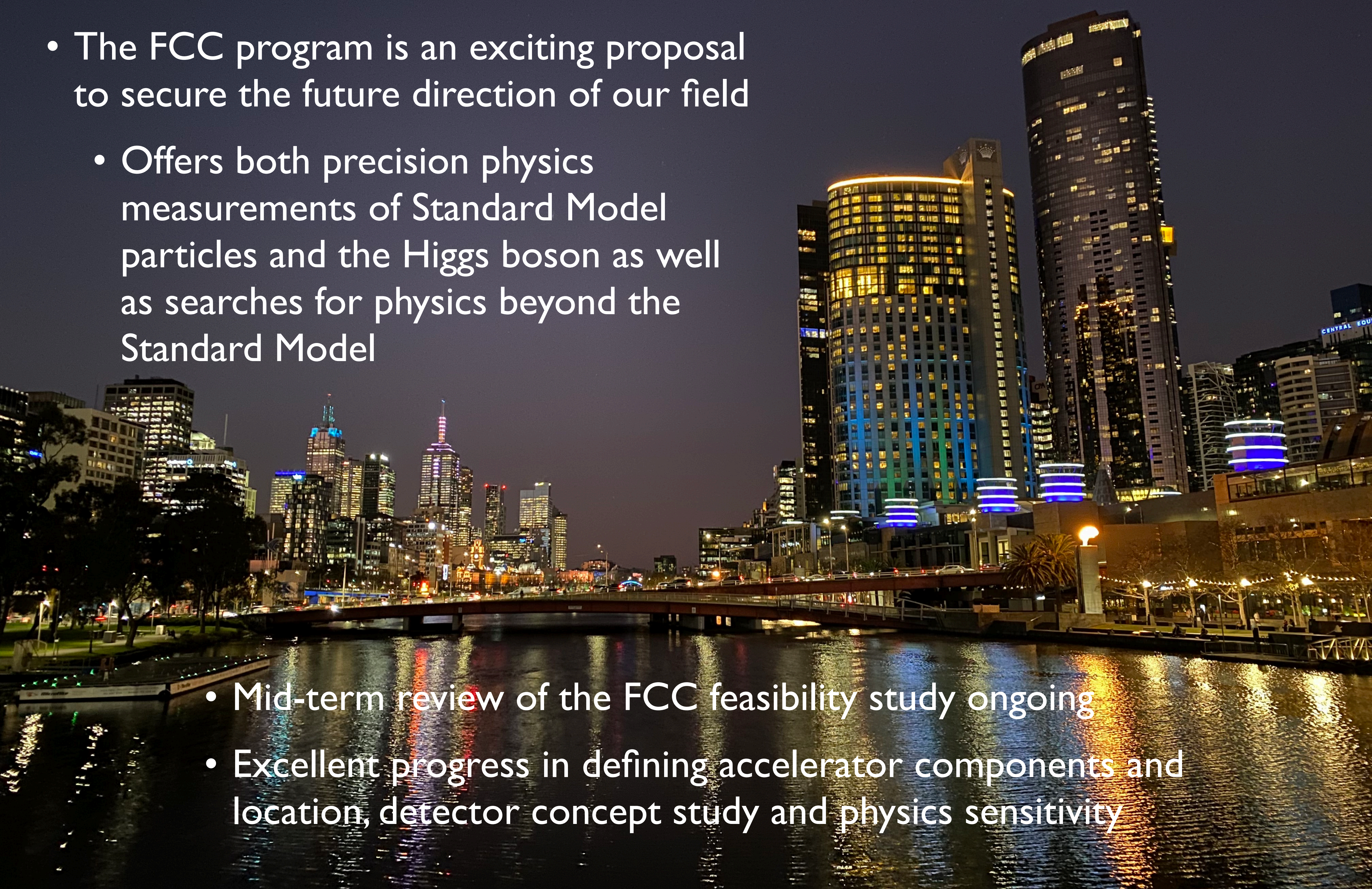


FCC-ee enables us to explore the richness of the dark sector with unprecedented breadth.

M. McCullough

Conclusion

- The FCC program is an exciting proposal to secure the future direction of our field
  - Offers both precision physics measurements of Standard Model particles and the Higgs boson as well as searches for physics beyond the Standard Model



- Mid-term review of the FCC feasibility study ongoing
- Excellent progress in defining accelerator components and location, detector concept study and physics sensitivity