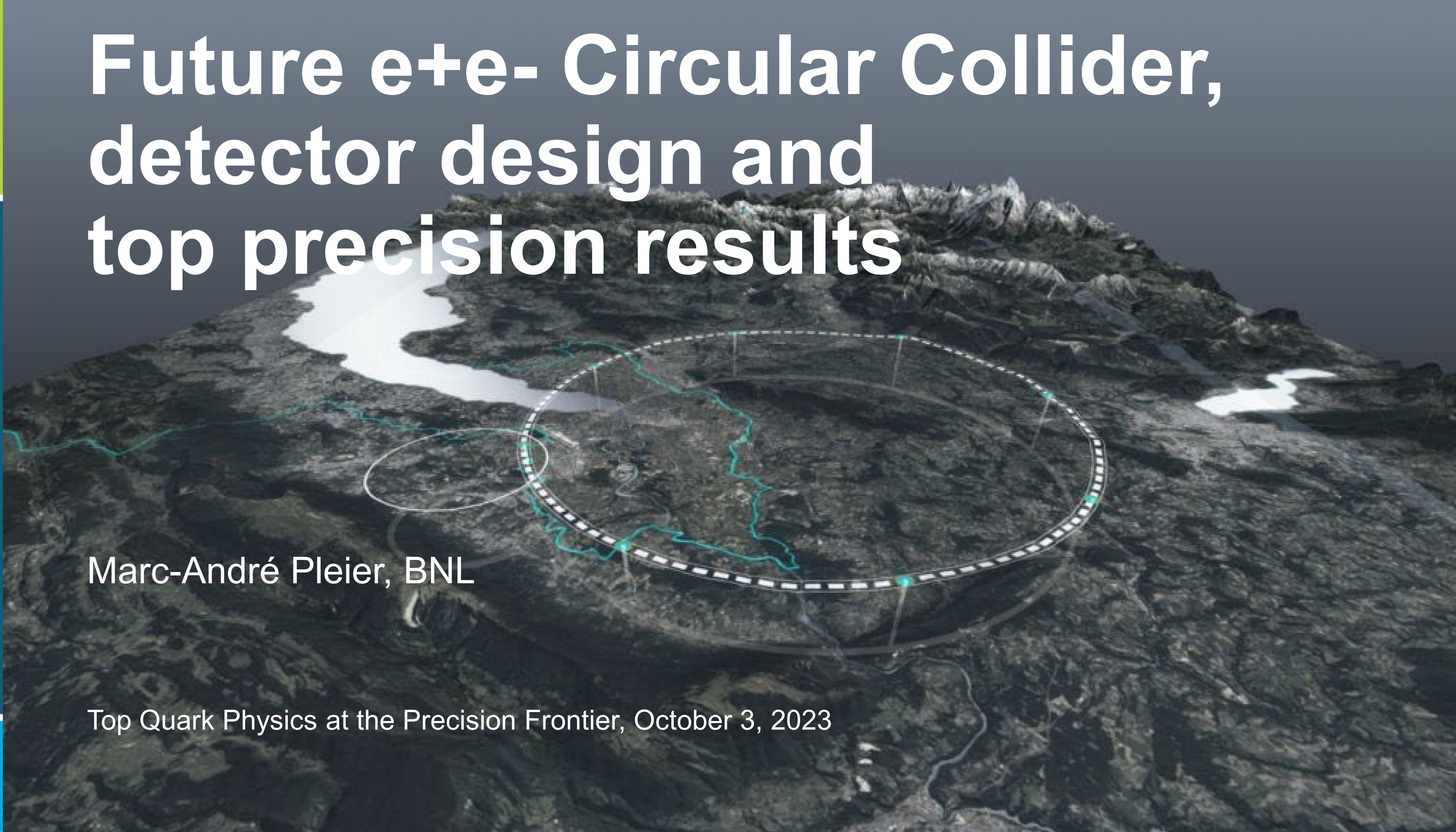
Future e+e- Circular Collider, detector design and top precision results



Marc-André Pleier, BNL

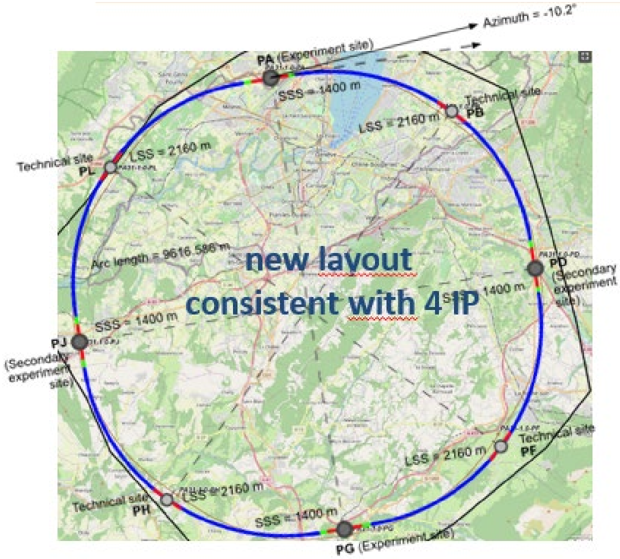
Top Quark Physics at the Precision Frontier, October 3, 2023

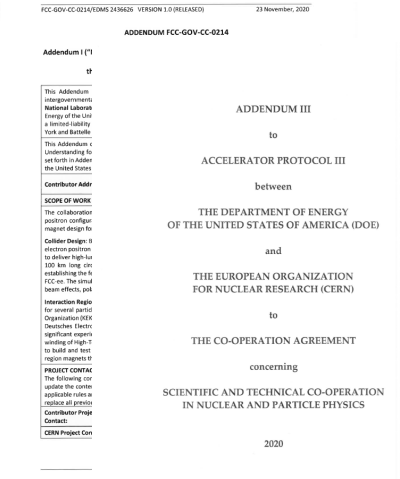
The Future Circular Collider (FCC)

- "**An electron-positron Higgs factory is the highest-priority next collider**…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*."
  [2020 Update of the European Strategy for Particle Physics]

- Addendum to **DOE-CERN coop agreement and CERN-BNL MoU are in place** since 2020 for FCC accelerator feasibility study, which started in 2021

- "ICFA reconfirms the international consensus on the importance of a **Higgs Factory as the highest priority** for realizing the scientific goals of particle physics."
  [International Committee for Future Accelerators, April '22]




FCC-GOV-CC-0214/EDMS 2436626 VERSION 1.0 (RELEASED) 23 November, 2020

ADDENDUM FCC-GOV-CC-0214

ADDENDUM III

to

ACCELERATOR PROTOCOL III

between

THE DEPARTMENT OF ENERGY
OF THE UNITED STATES OF AMERICA (DOE)

and

THE EUROPEAN ORGANIZATION
FOR NUCLEAR RESEARCH (CERN)

to

THE CO-OPERATION AGREEMENT

concerning

SCIENTIFIC AND TECHNICAL CO-OPERATION
IN NUCLEAR AND PARTICLE PHYSICS

2020

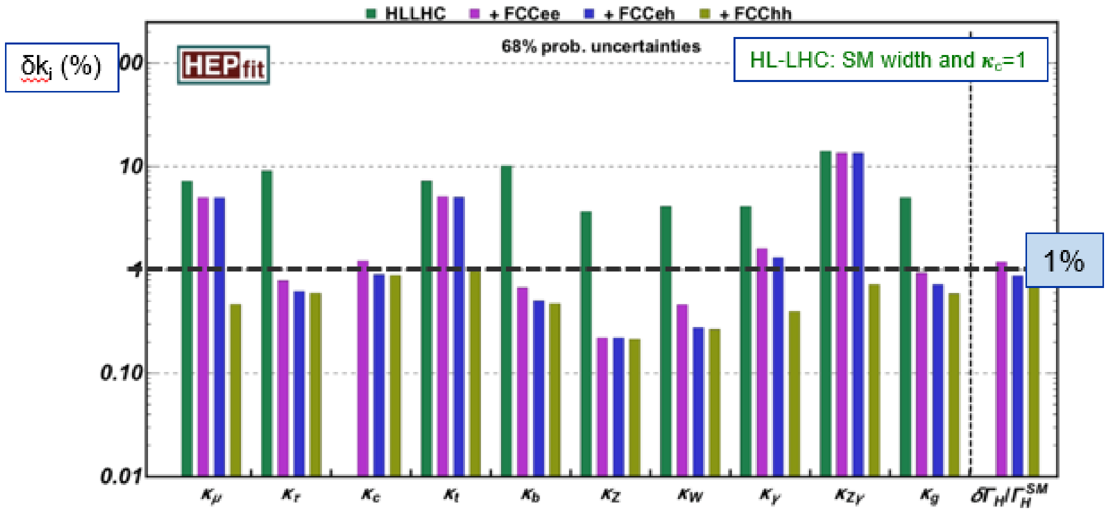
Brookhaven National Laboratory

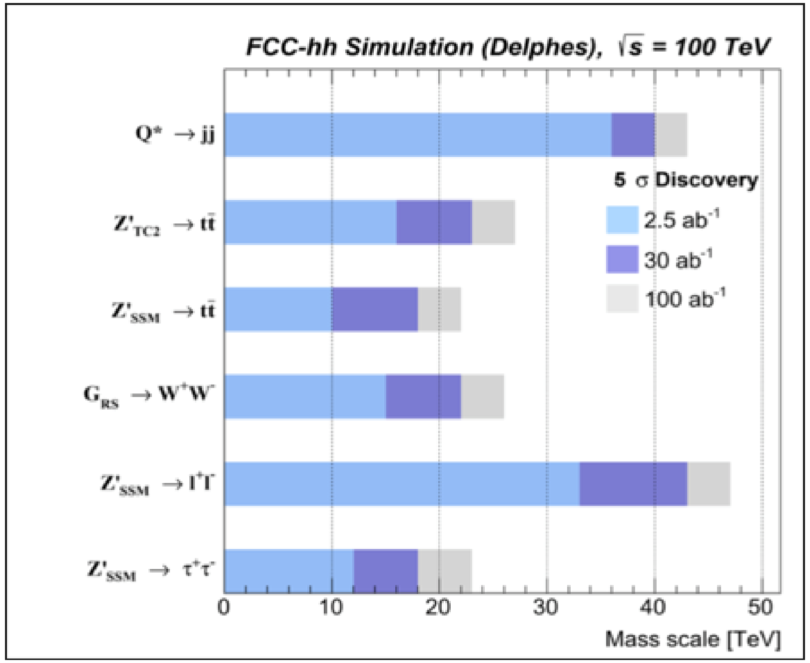
FCC physics potential

	$\sqrt{s}$	L /IP ($cm^{-2} s^{-1}$)	Int L/IP/y (ab^{-1})	Comments
e^+e^- FCC-ee	~90 GeV Z 160 WW 240 H ~365 top	182 x 10^{34} 19.4 7.3 1.33	22 2.3 0.9 0.16	2-4 experiments Total ~ 15 years of operation
pp FCC-hh	100 TeV	5-30 x 10^{34} 30	20-30	2+2 experiments Total ~ 25 years of operation
PbPb FCC-hh	$\sqrt{s_{NN}}$ = 39TeV	3 x 10^{29}	100 nb^{-1}/run	1 run = 1 month operation
ep Fcc-eh	3.5 TeV	1.5 10^{34}	2 ab^{-1}	60 GeV e- from ERL Concurrent operation with pp for ~ 20 years
e-Pb Fcc-eh	$\sqrt{s_{eN}}$ = 2.2 TeV	0.5 10^{34}	1 fb^{-1}	60 GeV e- from ERL Concurrent operation with PbPb

A multi-stage facility with immense physics potential (energy and intensity), operating until the end of the century.

- FCC-ee : highest luminosities at Z, W, ZH of all proposed Higgs and EW factories; indirect discovery potential up to ~ 70 TeV
- FCC-hh: direct exploration of next energy frontier (~ x10 LHC) and unparalleled measurements of low-rate and "heavy" Higgs couplings (ttH, HH)
- Also heavy-ion collisions and, possibly, ep/e-ion collisions
- Synergistic programme exploiting common civil engineering and technical infrastructure, building on and reusing CERN's existing infrastructure





Slide from Fabiola Gianotti

FCC-ee machine pars & physics potential

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 x 10^{12} Z LEP x 10^5	2 years > 10^8 WW LEP x 10^4	3 years 2 x 10^6 H	5 years 2 x 10^6 tt pairs

Currently assessing technical feasibility of changing operation sequence (e.g. starting at ZH energy)

- ❑ x 10-50 improvements on all EW observables
- ❑ up to x 10 improvement on Higgs coupling (model-indep.) measurements over HL-LHC
- ❑ x10 Belle II statistics for b, c, τ
- ❑ indirect discovery potential up to ~ 70 TeV
- ❑ direct discovery potential for feebly-interacting particles over 5-100 GeV mass range

Up to 4 interaction points → robustness, statistics, possibility of specialised detectors to maximise physics output

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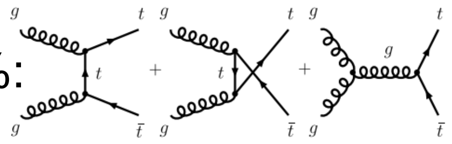
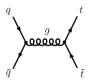
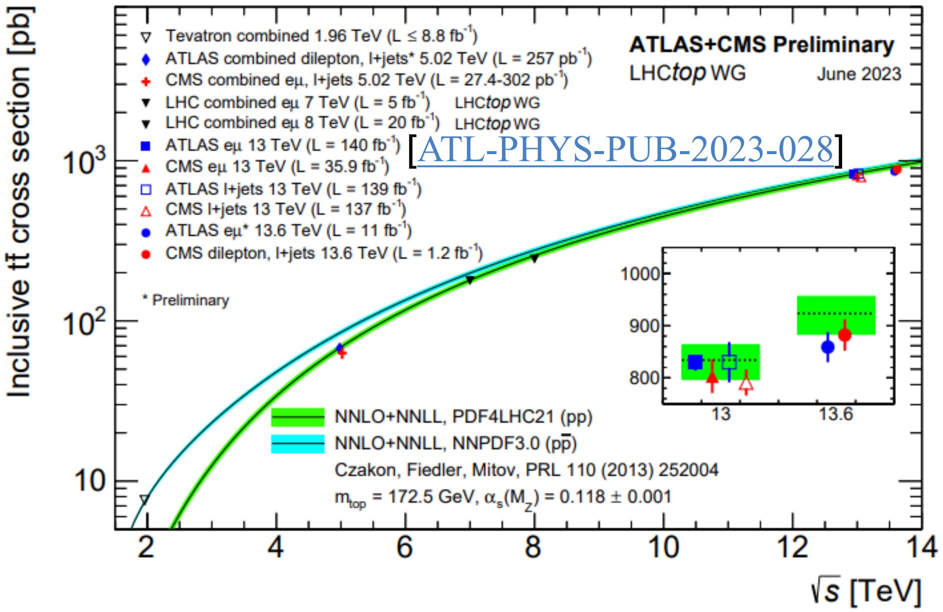
Slide from Fabiola Gianotti

FCC-ee and top quark precision physics

The (HL-) LHC is rightfully known as “top factory”

90%: 

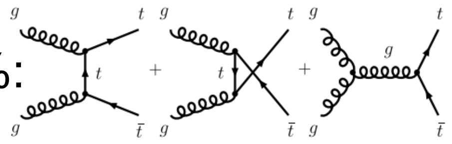
10%: 

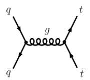


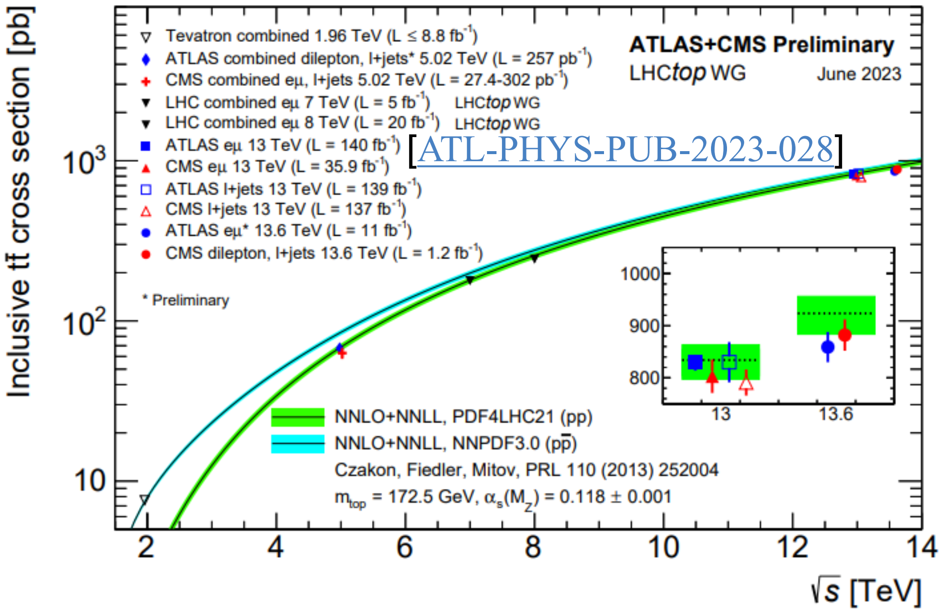
[ATL-PHYS-PUB-2023-028]

FCC-ee and top quark precision physics

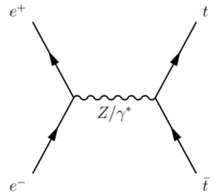
The (HL-) LHC is rightfully known as "top factory"

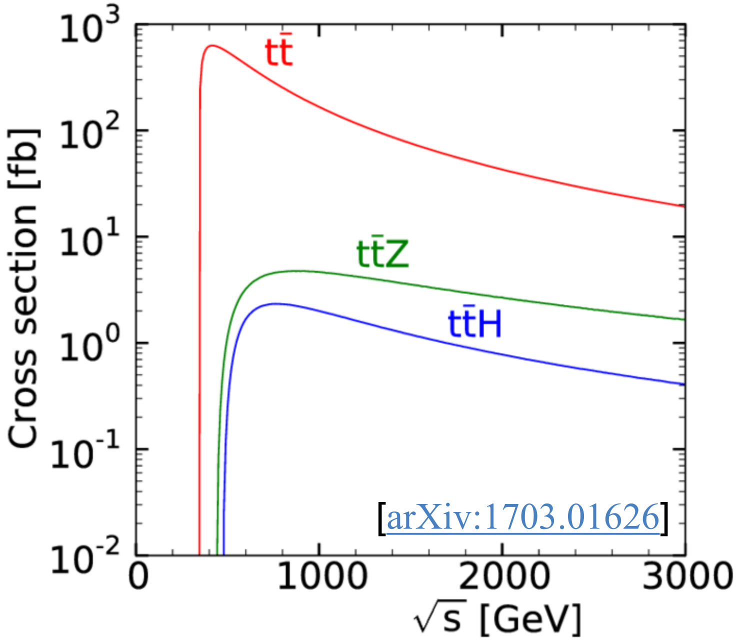
90%: 

10%: 



What about the FCC-ee?





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FCC-ee and top quark precision physics

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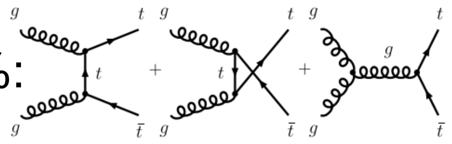
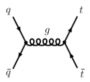
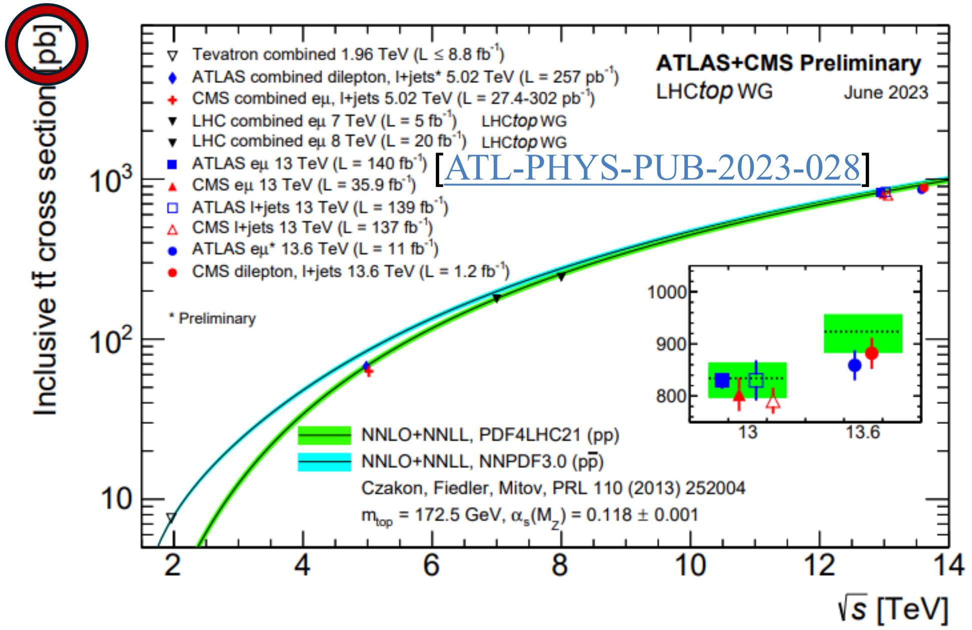
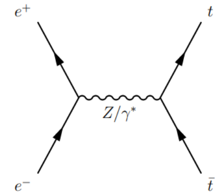
90%: 

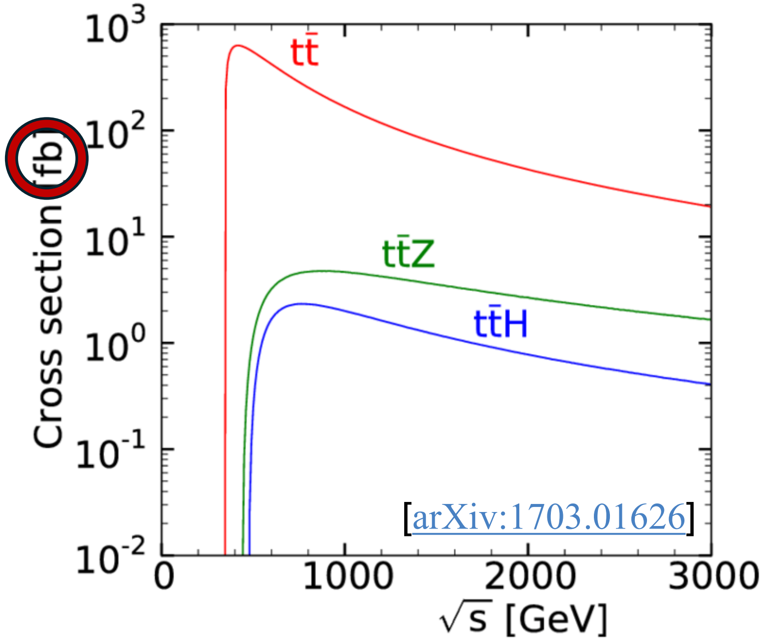
10%: 



[ATL-PHYS-PUB-2023-028]

What about the FCC-ee?





[arXiv:1703.01626]

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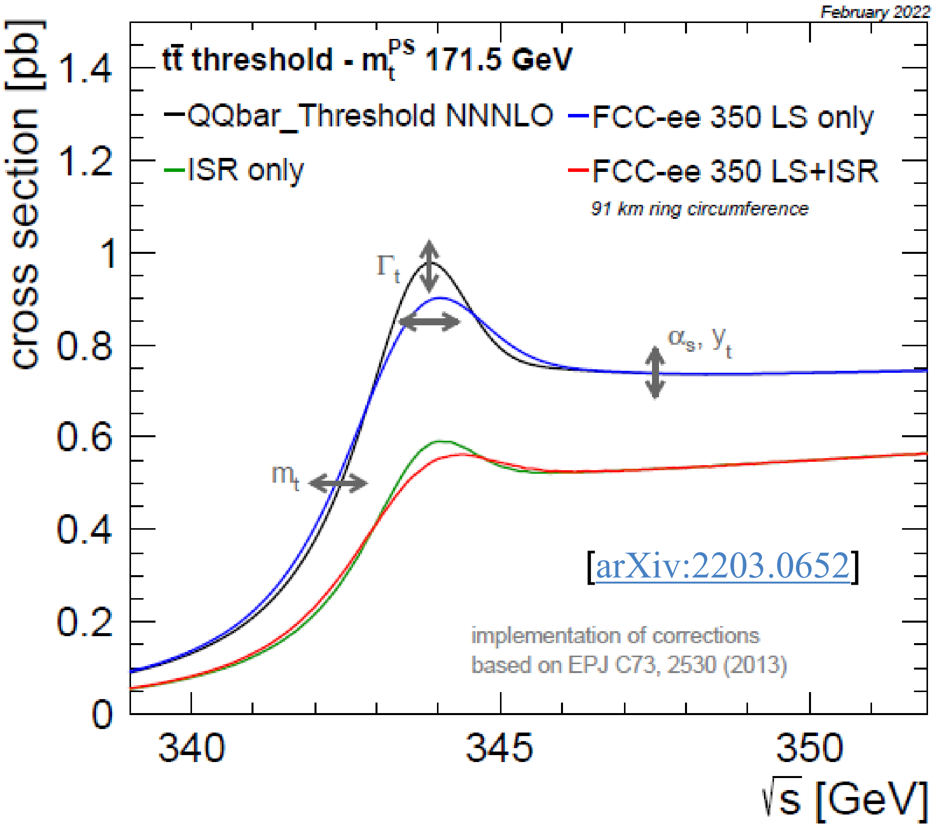
FCC-ee and top quark precision physics

- Expect ~2M ttbar events near & above the production threshold (first time ever at e^+e^-!)
- << HL-LHC, but clean environment & can **scan** sqrt(s)!
- Ultimate precision for top quark properties: mass, width, and Yukawa coupling
  - Can use measurement of cross section shape around threshold to extract m_t, Γ_t, y_t (and α_s)
  - m_t, Γ_t simultaneous fit expected stat uncertainties: ±17 MeV (m_t), ±45 MeV (Γ_t)
    - Systematic uncertainties dominated by theory, e.g. 45 MeV for m_t!
  - Current top mass average (LHC + Tevatron): 172.69±0.3 GeV
- Probe probe the electroweak couplings $tt\gamma$ and ttZ at production vertex.
- Search for Flavor-changing neutral current interactions above threshold (365 GeV)



FCC-ee - Technical Readiness

- TRL1: Basic principles observed and reported
- TRL2: Technology concept and/or application formulated
- TRL3: Analytical and experimental critical function and/or characteristic proof of concept.
- TRL4: Component and/or breadboard validation in laboratory environment.
- TRL5: Component and/or breadboard validation in relevant environment.
- TRL6: System/subsystem model or prototype demonstration in a relevant environment.
- TRL7: System prototype demonstration in an operational environment.
- TRL8: Actual system completed and qualified through test and demonstration.
- TRL9: Actual system has proven through successful mission operations.

Technical Risk Factor	Score	Color Code
TRL = 1,2	4	
TRL = 3,4	3	
TRL = 5,6	2	
TRL = 7,8	1	

I - TDR complete, II - CDR complete, III - substantial documentation; IV - limited documentation and parameter table; V - parameter table.

TRL = Technical Readiness Level

Tier 1 = lower overall technical risk

Proposal Name (c.m.e. in TeV)	Collider Design Status	Lowest TRL Category	Technical Validation Requirement	Cost Reduction Scope	Performance Achievability	Overall Risk Tier
FCCee-0.24	II					1
CEPC-0.24	II					1
ILC-0.25	I					1
CCC-0.25	III					2
CLIC-0.38	II					1
CERC-0.24	III					2
ReLiC-0.24	V					2
ERLC-0.24	V					2
XCC-0.125	IV					2
MC-0.13	III					3

Snowmass 21 Collider Implementation Task Force [arXiv:2208.06030]

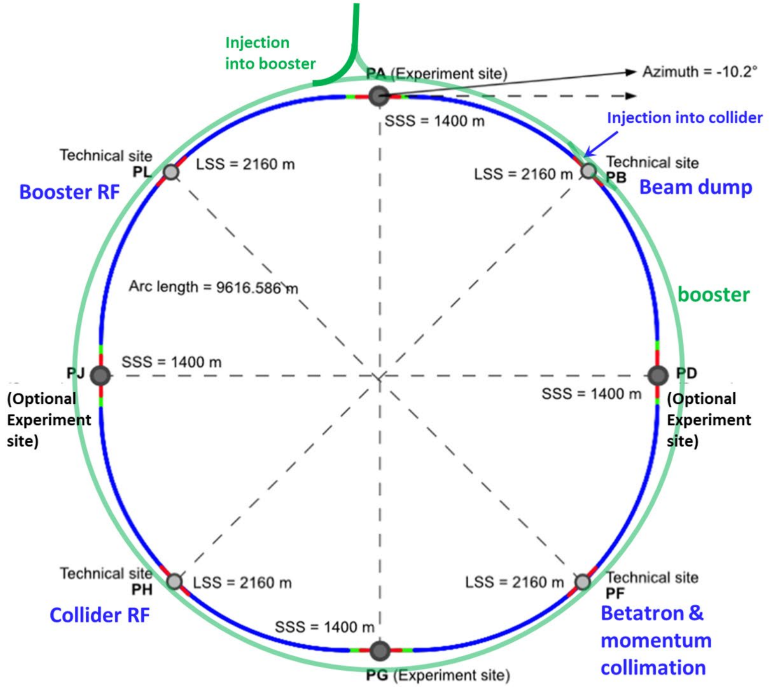
FCC ring placement (I)

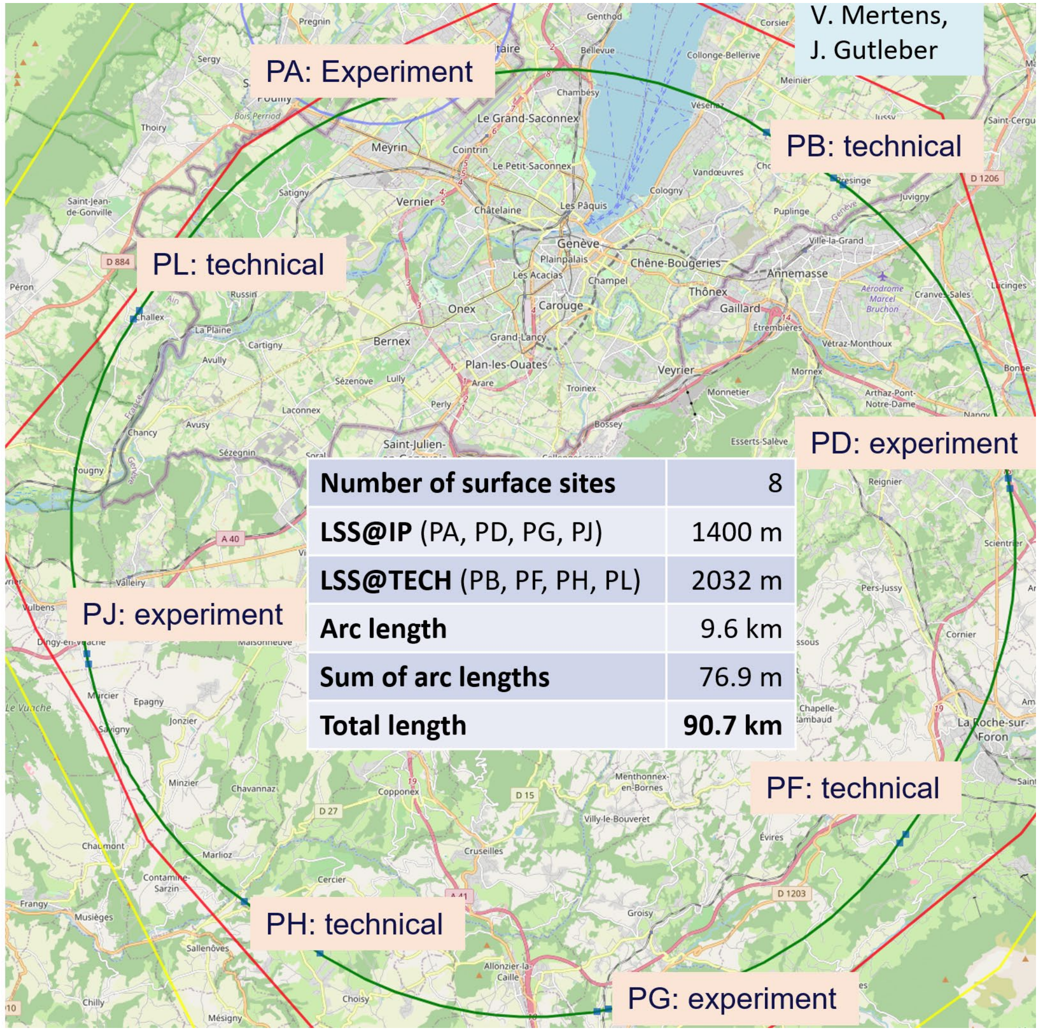
Major achievement: optimization of the ring placement

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**

Slide from Michael Benedikt

Brookhaven National Laboratory

FCC ring placement (II)

Meetings with municipalities concerned in France (31) and Switzerland (10)

PA – Ferney Voltaire (FR) – site experimental

PB – Présinge/Choulex (CH) – site technique

PD – Nangy (FR) – site technique et experimental

PF – Roche sur Foron/Etaux (FR) – site technique

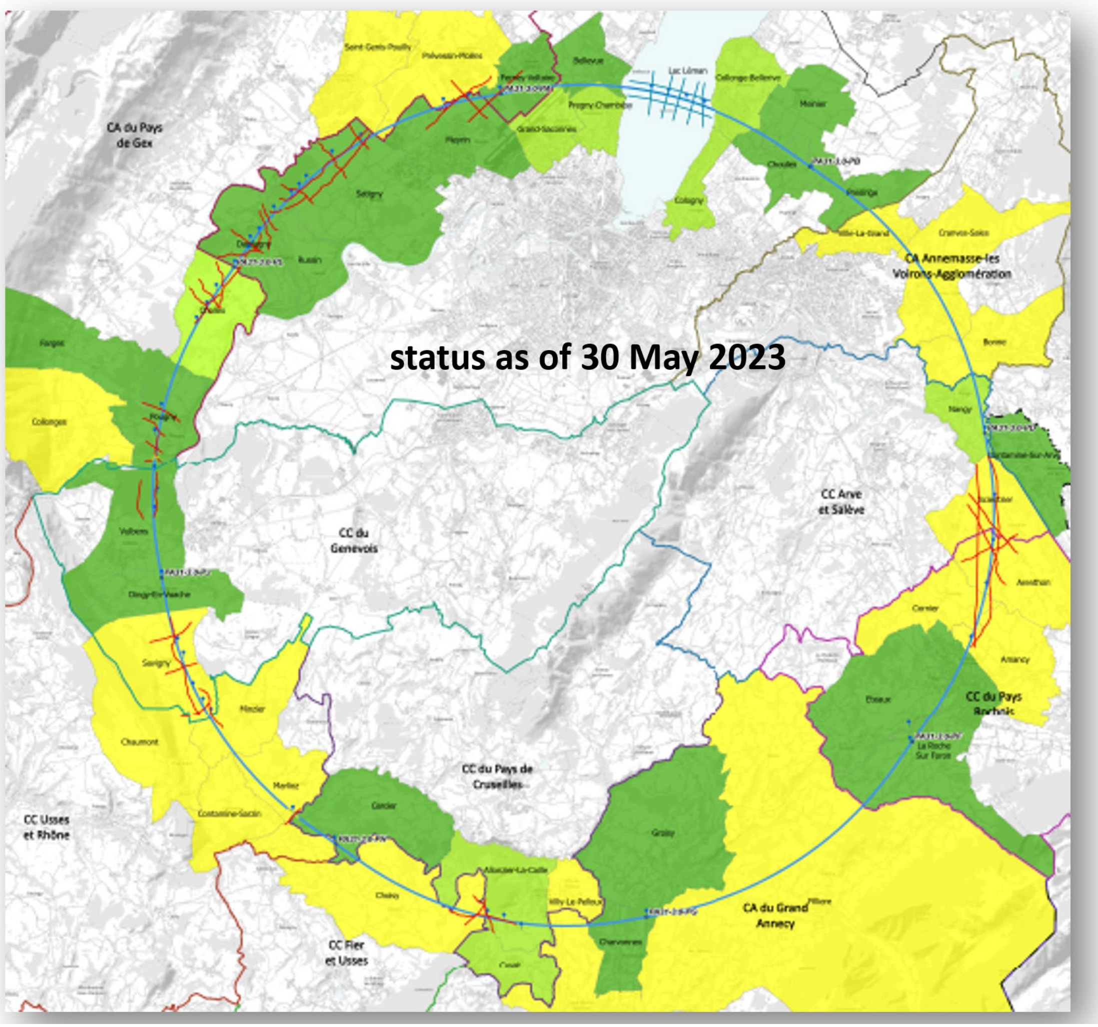
PG – Charvonnex/Groisy (FR) – site experimental

PH – Cercier (FR) – site technique

PJ – Vulbens/Dingy en Vuache (FR) site technique et experimental

PL – Challex (FR) – site technique

- Rencontrée individuellement
- Rendez-vous proposé / programmé
- Rencontre collective



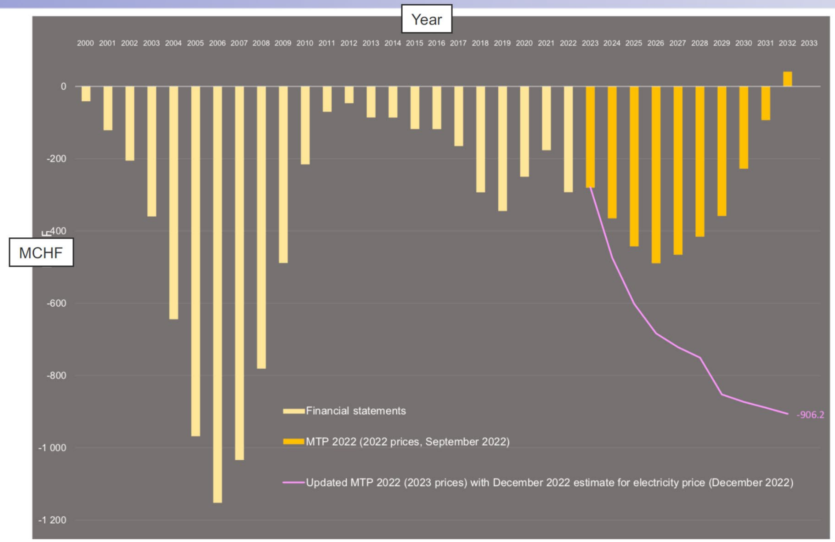
Environmental studies and preparation of geological investigations (drillings and seismics) ongoing since February 2023

Brookhaven National Laboratory

Slide from Michael Benedikt

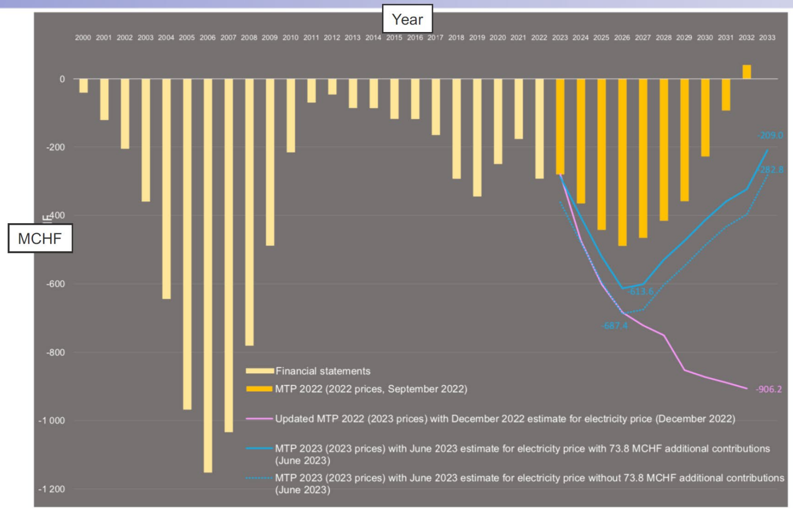
FCC and the CERN budget

Cumulative budget deficit (CBD) before 2023 MTP



Yellow bars: CBD before current financial challenges: "healthy" shape, with deficit decreasing at the end of HL-LHC construction in 2026 and going to zero in ~ 2031 → (big) investment in a new facility at CERN can start in early '30s
Pink curve: CBD in Dec 2022: it includes 2023 inflation and very high electricity tariff forecast at the end of 2022

Cumulative budget deficit in 2023 MTP



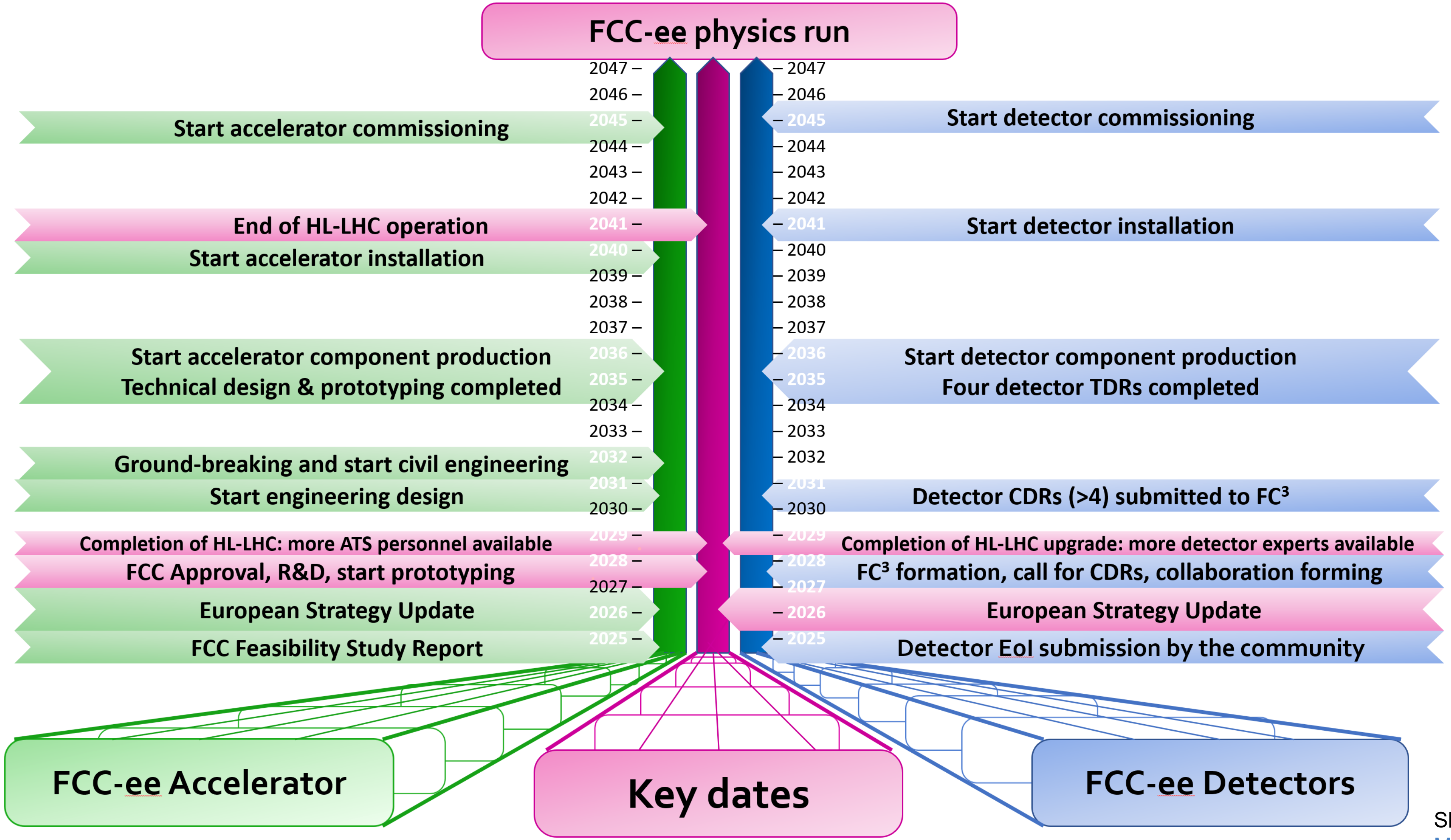
CBD in 2023 MTP is back to "healthy shape", thanks to the additional, exceptional contribution from Member and Associate Member States (73.8 M), significant savings from CERN's Budget (280 M, including 8.7 M crisis levy on staff basic salaries) and reduction of electricity costs (125 M over 2024-2028), which, all together, more than offset the additional expenses

(MTP = Medium-Term Plan)

Slides from [Fabiola Gianotti]

Brookhaven National Laboratory

FCC-ee timeline



Very approximate DOE Critical Decision steps (not official!)

CD-4 – Approve Start of Operations / Project Completion

CD-2/3 – Approve Performance Baseline & Start of Construction

CD-1 – Approve Alternative Selection and Cost Range

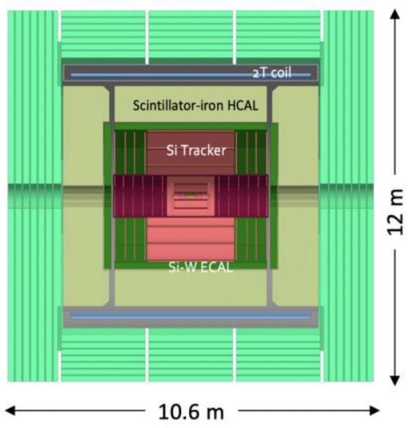
CD-0 – Approve Mission Need

Slide from [Michael Benedikt]

Brookhaven National Laboratory

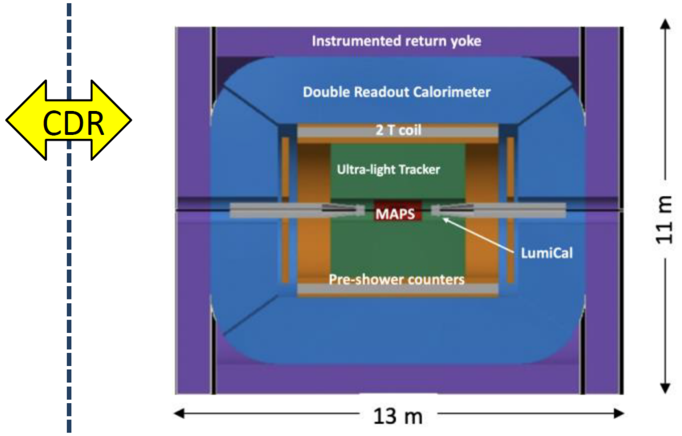
FCC-ee detectors

CLD



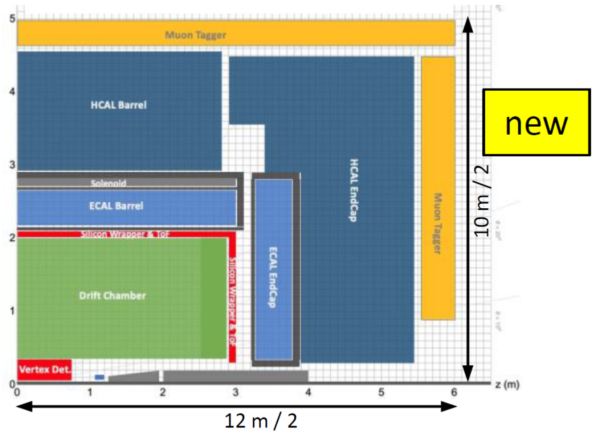
- Well established design
  - ILC -> CLIC detector -> CLD
- Full Si vtx + tracker;
- CALICE-like calorimetry;
- Large coil, muon system
- Engineering still needed for operation with continuous beam (no power pulsing)
  - Cooling of Si-sensors & calorimeters
- Possible detector optimizations
  - σ_p/p,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

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, …

ALLEGRO



- 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

FCC-ee CDR: https://link.springer.com/article/10.1140/epjst/e2019-900045-4

Strong synergies for U.S. detector R&D across e^+e^- colliders, see arXiv:2306.13567

Detector R&D needs for the next generation e^+e^- collider

A. Apresyan[i], M. Artuso[v], J. Brau[q], H. Chen[d], M. Demarteau[p], Z. Demiragli[c], S. Eno[n], J. Gonski[h], P. Grannis[u], H. Gray[e,m], O. Gutsche[i], C. Haber[m], M. Hohlmann[j], J. Hirschauer[i], G. Iakovidis[d], K. Jakobs[a], A.J. Lankford[g], C. Pena[i], S. Rajagopalan[d], J. Strube[r,q], C. Tully[s], C. Vernieri[t], A. White[w], G.W. Wilson[l], S. Xie[f], Z. Ye[k], J. Zhang[b], B. Zhou[o]

[a]Albert-Ludwigs-Universitat, Freiburg, [b]Argonne National Laboratory, [c]Boston University, [d]Brookhaven National Laboratory, [e]University of California, Berkeley, [f]California Institute of Technology, Pasadena, [g]University of California, Irvine, [h]Columbia University, New York, [i]Fermi National Accelerator Laboratory, [j]Florida Institute of Technology, Melbourne, [k]University of Illinois at Chicago, [l]University of Kansas, Lawrence, [m]Lawrence Berkeley National Laboratory, [n]University of Maryland, College Park, [o]University of Michigan, Ann Arbor, [p]Oak Ridge National Laboratory, [q]University of Oregon, Eugene, [r]Pacific Northwest National Laboratory, [s]Princeton University, [t]SLAC National Accelerator Laboratory, [u]Stony Brook University, [v]Syracuse University, [w]University of Texas at Arlington.

Abstract

The 2021 Snowmass Energy Frontier panel wrote in its final report "*The realization of a Higgs factory will require an immediate, vigorous and targeted detector R&D program*". Both linear and circular e^+e^- collider efforts have developed a conceptual design for their detectors and are aggressively pursuing a path to formalize these detector concepts. The U.S. has world-class expertise in particle detectors, and is eager to play a leading role in the next generation e^+e^- collider, currently slated to become operational in the 2040s. It is urgent that the U.S. organize its efforts to provide leadership and make significant contributions in detector R&D. These investments are necessary to build and retain the U.S. expertise in detector R&D and future projects, enable significant contributions during the construction phase and maintain its leadership in the Energy Frontier regardless of the choice of the collider project. In this document, we discuss areas where the U.S. can and must play a leading role in the conceptual design and R&D for detectors for e^+e^- colliders.

Slide from Martin Aleksa

Brookhaven National Laboratory

FCC – enthusiastic host lab support

Why FCC ?

1) Physics : best overall physics potential of all proposed future colliders
- FCC-ee : ultra-precise measurements of the Higgs boson, indirect exploration of next energy scale (~ x10 LHC)
- FCC-hh : only machine able to explore next energy frontier directly (~ x10 LHC)
- Also provides heavy-ion collisions and, possibly, ep/e-ion collisions
- 4 collision points → robustness; specialized experiments for maximum physics output

2) Timeline
- FCC-ee technology is mature → construction can proceed in parallel to HL-LHC operation and physics can start few years after end of HL-LHC operation (2045-2048) → This would keep the community, in particular the young people, engaged and motivated.
- FCC-ee before FCC-hh would also allow:
  - cost of the (more expensive) FCC-hh machine to be spread over more years
  - 20 years of R&D work towards affordable magnets providing the highest achievable field (high-T superconductors!)
  - optimization of overall investment : FCC-hh will reuse same civil engineering and large part of FCC-ee technical infrastructure

3) It's the only facility commensurate to the size of the CERN community (4 major experiments)

Is it feasible? Isn't it too ambitious?

-- Ongoing Feasibility Study showing spectacular progress → see next slide
-- FCC is big, audacious project, but so were LEP and LHC when first conceived → they were successfully built and performed far beyond expectation → demonstration of capability of our community to deliver on very ambitious projects
-- FCC is best project for future of CERN (for above reasons) → we have to work to make it happen

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Slide from Fabiola Gianotti

How to plug in? We are happy to help!!!

What are the next steps forward?

- sign up on US-FCC and FCC mailing lists
- Become an official FCC institution by signing an MOU (okay, I haven't done that yet)
- Get familiar with the existing documentation and structures
- Start to participate in some aspect as your current commitments allow. Even one meeting a month is enough to prepare for a bigger impact later.
- Try to send somebody from your group either to the winter "PED" meeting or to the June "FCC" meeting (which has strong accelerator-community attendance) or our new annual USFCC meeting..
- Think bold. Bored of what you are doing? Now is the opportunity to make a change. Why not think about drift chambers? cherenkov counters? doing flavour physics? doing precision measurements of the W, top, or Z mass? It can be fun to explore these things with undergrads. There are a few years here where you can get up to speed to make a course change
- Form a community to help ourselves make an impact despite our limited resources
- **and above all, get ready for a lot of fun!!**

Sarah Eno USFCC workshop

Good starting points for current status and where/how to plug in:

- US FCC workshop, April 23
- FCC Week London, June 23
- 7th FCC Physics Workshop, January 2024 in Annecy
- US FCC workshop March 24
- FCC Week in US, June 24

Slide from Sarah Eno

Brookhaven National Laboratory

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- US FCC workshop March 24
- FCC Week in US, June 24

Come talk with us!

Brookhaven National Laboratory

Conclusions

The FCC

- offers a rich physics potential **(including top quark precision physics)**,
- is based on mature technology,
- is financially achievable,
- offers a realistic schedule, compatible with HL-LHC commitments,
- is enthusiastically supported by CERN and invites US participation,
  - Fabiola at BNL P5: “FCC will only be possible with a strong US participation”
- provides a unique opportunity NOW for the next generation to shape FCC physics program, accelerator and detector technology

Backup

Impressions from the 1st US FCC Workshop

FCC-ee event yields with four IPs

Table 1 The baseline FCC-ee operation model with four interaction points, showing the centre-of-mass energies, instantaneous luminosities for each IP, integrated luminosity per year summed over 4 IPs corresponding to 185 days of physics per year and 75% efficiency, in the order Z, WW, ZH, $t\bar{t}$. The luminosity is assumed to be half the design value for machine commissioning and optimisation during the first two years at the Z pole, the first two years at the WW threshold, and the first year at the $t\bar{t}$ threshold. (Should the order of the sequence be modified to either Z, ZH, WW, $t\bar{t}$ or ZH, WW, Z, $t\bar{t}$, the ZH stage would start with two years at half the design luminosity followed by two years at design luminosity, while the WW stage would run afterwards for only one year but at design luminosity.) The luminosity at the Z pole (the WW threshold) is distributed as follows: 40 ab^{-1} at 88 GeV, 125 ab^{-1} at 91.2 GeV, and 40 ab^{-1} at 94 GeV (5 ab^{-1} at 157.5 GeV, and 5 ab^{-1} at 162.5 GeV). The number of WW events include all $\sqrt{s}$ values from 157.5 GeV up.

Working point	Z, years 1-2	Z, later	WW, years 1-2	WW, later	ZH	$t\bar{t}$	
$\sqrt{s}$ (GeV)	88, 91, 94		157, 163		240	340–350	365
Lumi/IP ($10^{34}\,cm^{-2}s^{-1}$)	70	140	10	20	5.0	0.75	1.20
Lumi/year (ab^{-1})	34	68	4.8	9.6	2.4	0.36	0.58
Run time (year)	2	2	2	0	3	1	4
Number of events	$6\,10^{12}$ Z		$2.4\,10^{8}$ WW		$1.45\,10^{6}$ HZ + 45k WW $\rightarrow$ H	$1.9\,10^{6}$ $t\bar{t}$ +330k HZ +80k WW $\rightarrow$ H	

FCC-ee in comparison

Snowmass 21 Collider Implementation Task Force Higgs Factory summary table

- Main parameters of the submitted Higgs factory proposals.
- The cost range is for the single listed energy.
- The superscripts next to the name of the proposal in the first column indicate:
  - (1) Facility is optimized for 2 IPs. Total peak luminosity for multiple IPs is given in parenthesis;
  - (2) Energy calibration possible to 100 keV accuracy for MZ and 300 keV for MW ;
  - (3) Collisions with longitudinally polarized lepton beams have substantially higher effective cross sections for certain processes

Proposal Name	CM energy nom. (range) [TeV]	Lum./IP @ nom. CME [10^{34} cm^{-2}s^{-1}]	Years of pre-project R&D	Years to first physics	Construction cost range [2021 B$]	Est. operating electric power [MW]
FCC-ee[1,2]	0.24 (0.09-0.37)	7.7 (28.9)	0-2	13-18	12-18	290
CEPC[1,2]	0.24 (0.09-0.37)	8.3 (16.6)	0-2	13-18	12-18	340
ILC[3] - Higgs factory	0.25 (0.09-1)	2.7	0-2	<12	7-12	140
CLIC[3] - Higgs factory	0.38 (0.09-1)	2.3	0-2	13-18	7-12	110
CCC[3] (Cool Copper Collider)	0.25 (0.25-0.55)	1.3	3-5	13-18	7-12	150
CERC[3] (Circular ERL Collider)	0.24 (0.09-0.6)	78	5-10	19-24	12-30	90
ReLiC[1,3] (Recycling Linear Collider)	0.24 (0.25-1)	165 (330)	5-10	>25	7-18	315
ERLC[3] (ERL linear collider)	0.24 (0.25-0.5)	90	5-10	>25	12-18	250
XCC (FEL-based $\gamma\gamma$ collider)	0.125 (0.125-0.14)	0.1	5-10	19-24	4-7	90
Muon Collider Higgs Factory[3]	0.13	0.01	>10	19-24	4-7	200

Slide from Thomas Roser

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Peak lumi / IP vs sqrt(s) for Higgs Factories

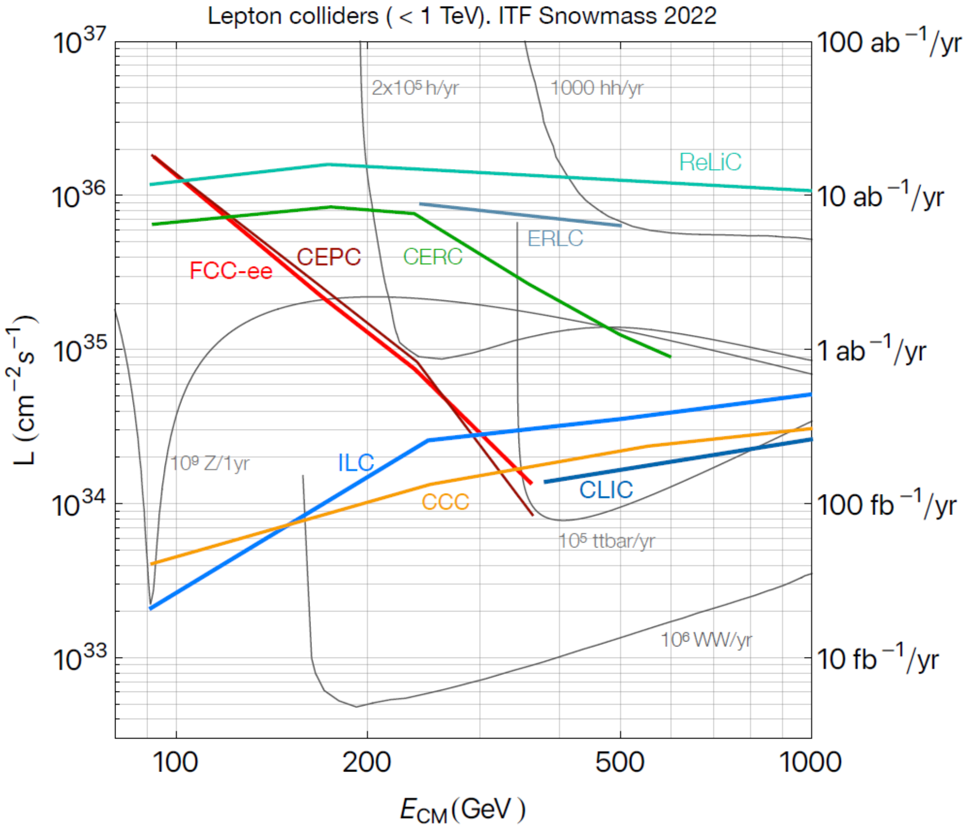

Figure 1. Peak luminosity per IP vs CM energy for the Higgs factory proposals as provided by the proponents. The right axis shows integrated luminosity for one Snowmass year (10^7 s). Also shown are lines corresponding to yearly production rates of important processes.

Snowmass 21 Collider Implementation Task Force [arXiv:2208.06030]

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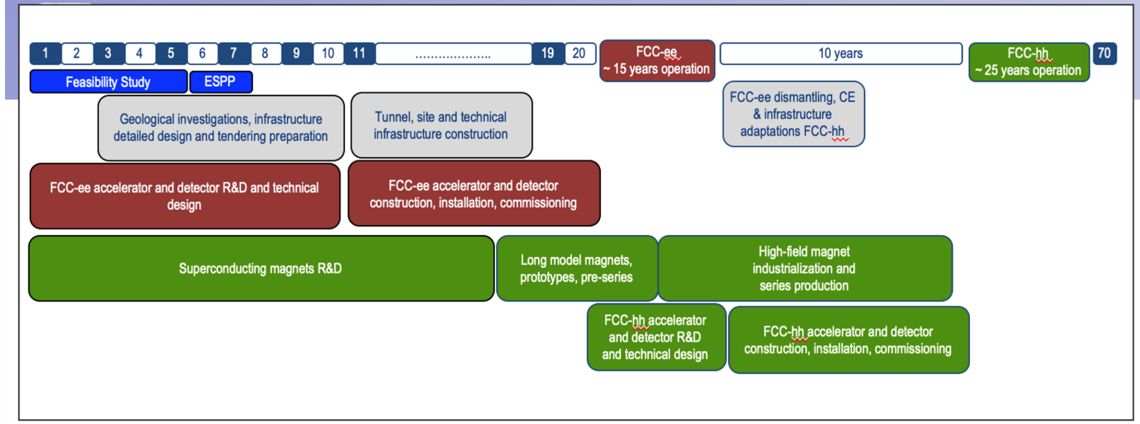
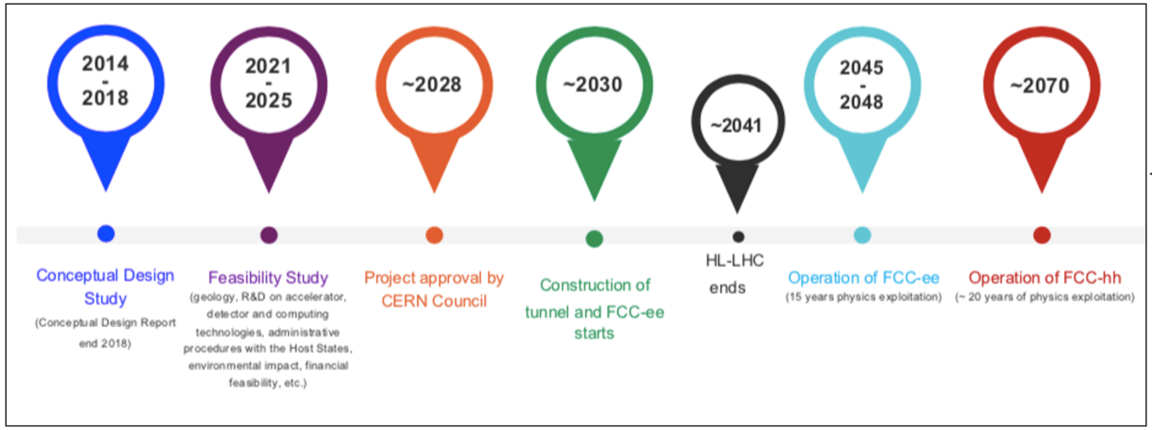
FCC timeline

FCC estimated timeline



Technical schedule:
FCC-ee could start physics operation **in 2040 or earlier**



"Realistic" schedule takes into account:

- ❑ past experience in building colliders at CERN
- ❑ approval timeline: ESPP, Council decision
- ❑ that 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)

1st stage collider, FCC-ee: electron-positron collisions 90-360 GeV
Construction: 2033-2045 → Physics operation: 2048-2063

2nd stage collider, FCC-hh: proton-proton collisions at ≥ 100 TeV
Construction: 2058-2070 → Physics operation: ~ 2070-2095

Care should be taken when comparing to other proposed facilities, for which in some cases only the (optimistic) technical schedule is shown

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Slide from [Fabiola Gianotti](#)