



# LCVision

## An alternative avenue to a future Higgs factory

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# Setting the scene

- We all know that the Standard Model is incomplete
  - Unfortunately despite decades of hard work no success in closing the gaps
- There are many ways to explore new physics
  - I'll concentrate on Higgs Factories
  - With a focus on  $e^+e^-$  - as I consider them the most mature
- I'll skip
  - Proton-Proton Energy frontier machines
  - Flavor factories
  - e-p Colliders
- Focus on opportunities at CERN
  - Currently the most realistic option to build a Higgs factory



# What now ?

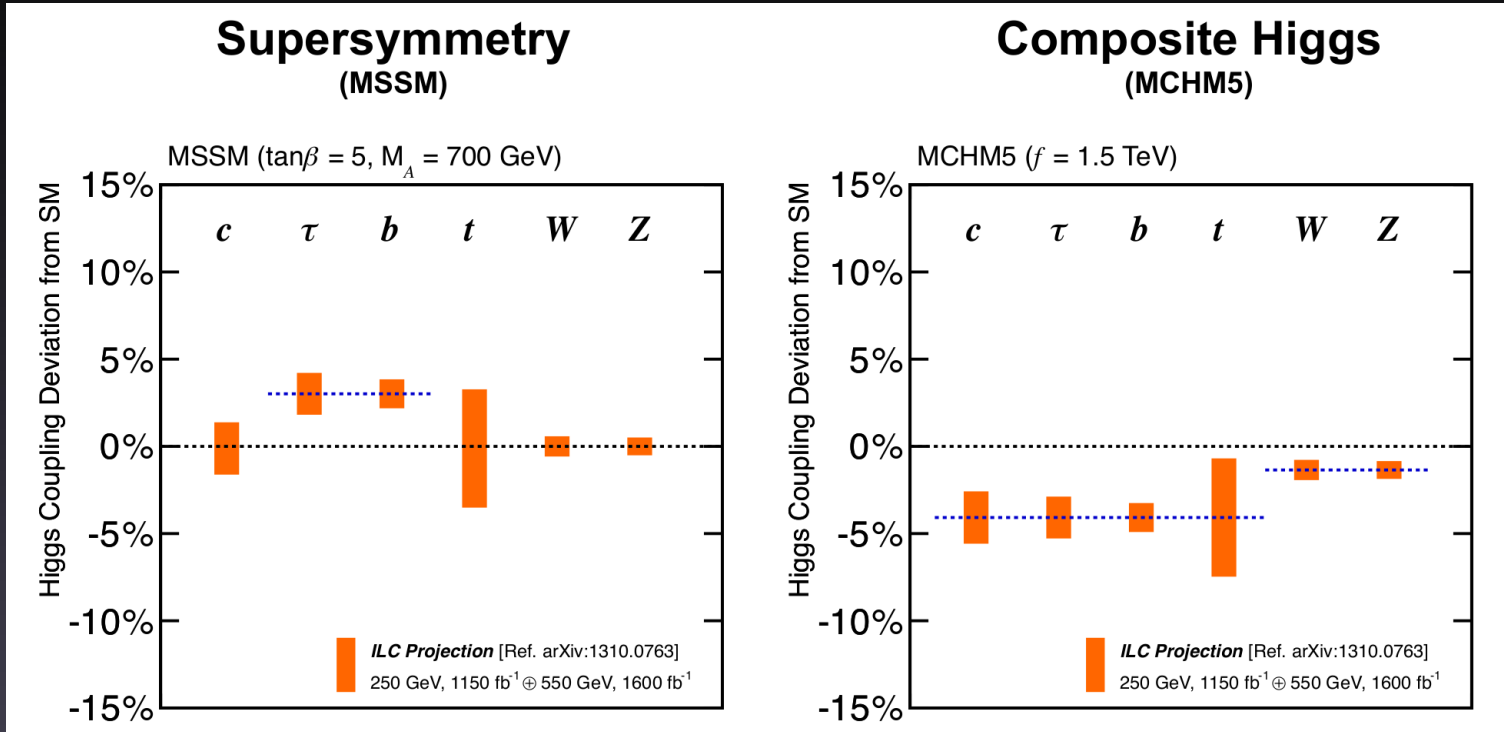
- LHC has not discovered evidence for new physics yet
  - A big surprise to many ...
- If new physics exists and is out of reach for the LHC or HL-LHC



- Explore the unknown new energy regime directly
  - Build a very high energy machine
  - Hope it has the necessary reach

- Explore small deviations to SM processes
  - $\sim 1/M_{\text{New Physics}}$
  - e.g. Higgs Branching Ratios are very sensitive
- Need 1% or better accuracy to fingerprint new physics

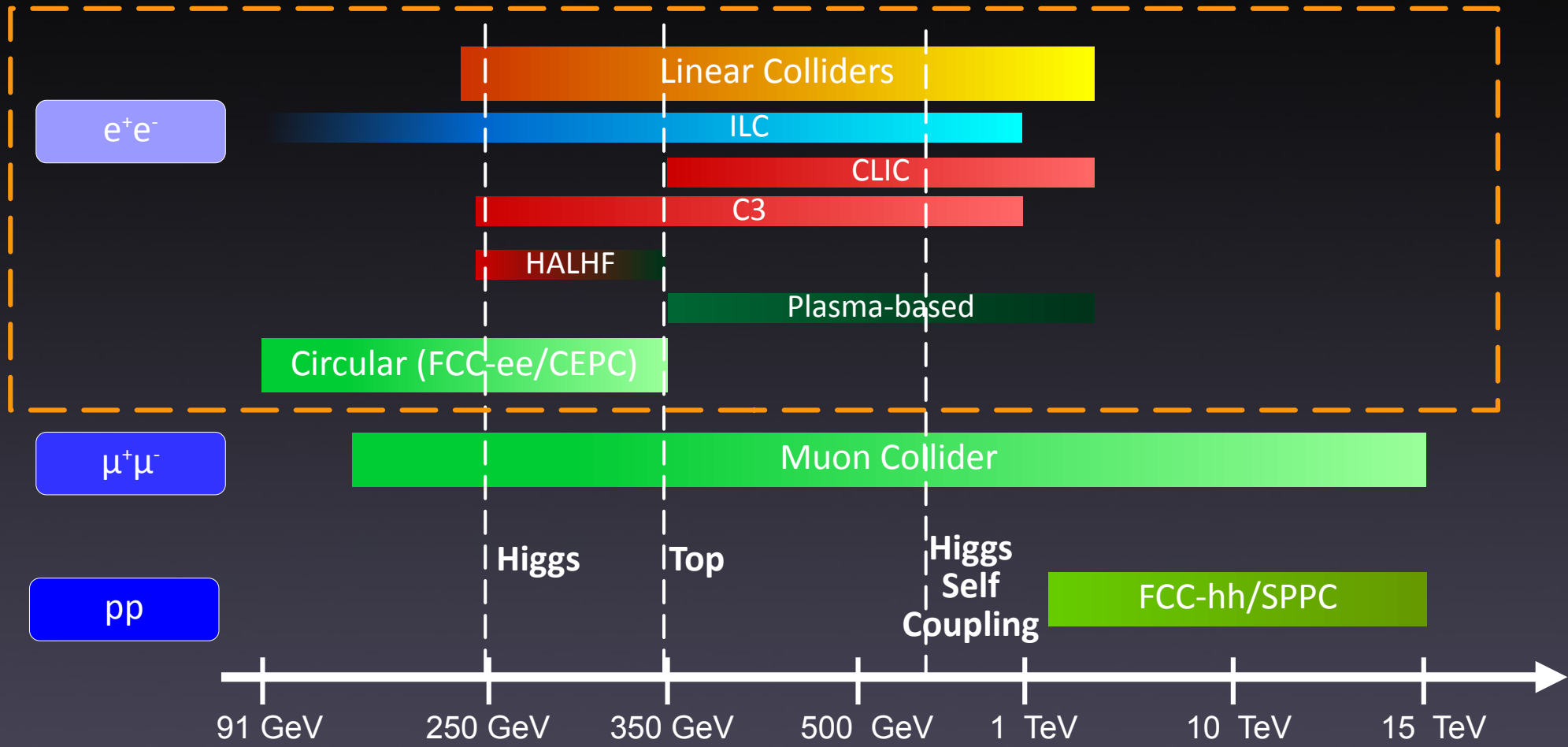
# Probing new physics



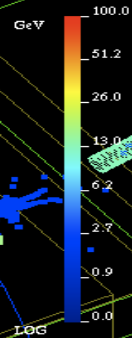
Percent-level accuracy on Higgs Couplings essential !



# Overview of the collider options



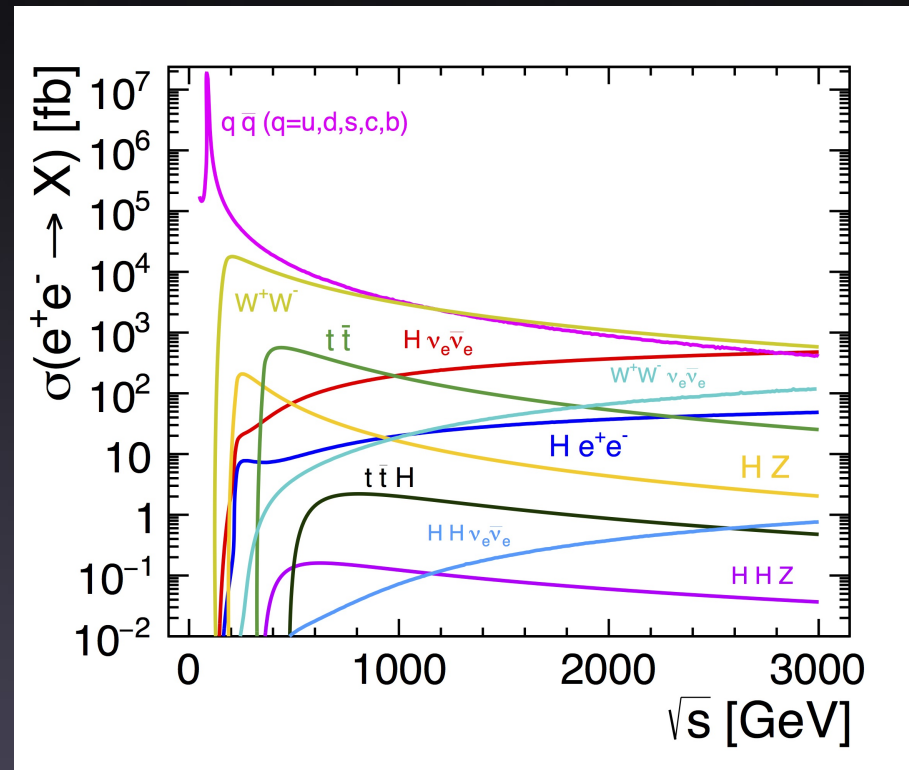
# $e^+e^-$ Higgs Factories





# $e^+e^-$ Factories

- Factories: High-Luminosity  $e^+e^-$  Colliders running at a resonance
- Well-known
  - B-factories  $\rightarrow$  (Super)-KEKB, PEP-II
  - Tau-Charm factories  $\rightarrow$  BES-III
- Now promoting Higgs factories
  - and top-factories, Z-factories
  - N.B. there is no accessible Higgs resonance (way too small)

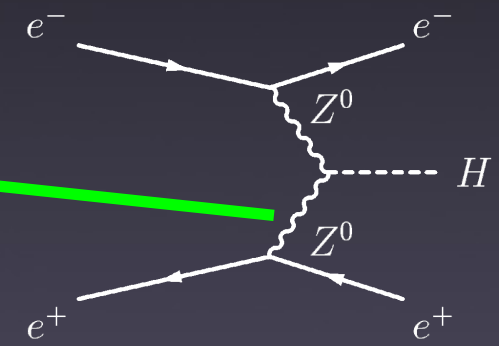
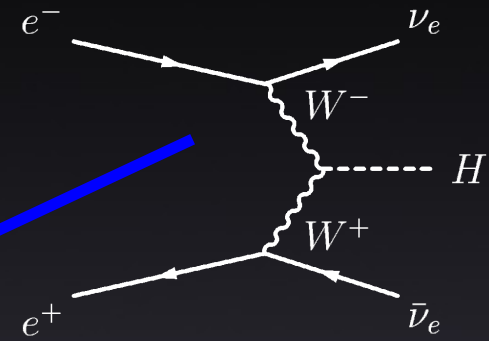
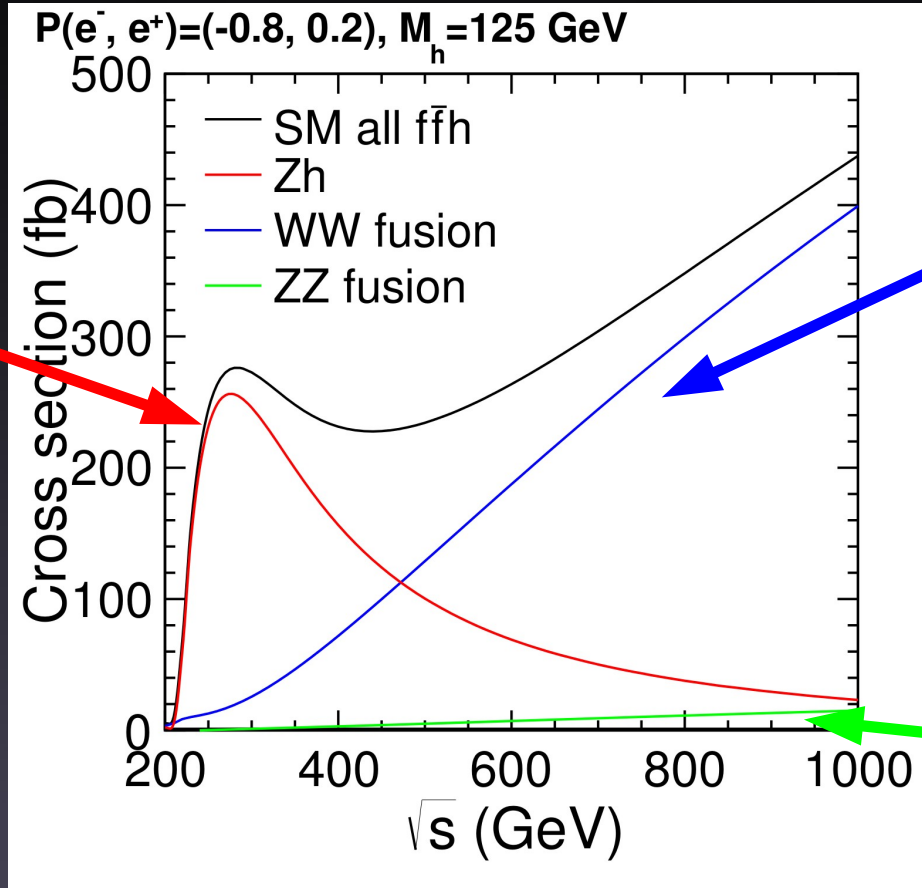
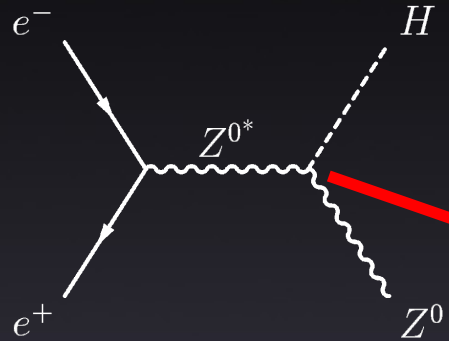




# Driving precision

- To complement the LHC/HL-LHC results a precision machine is required
  - an  $e^+e^-$  Higgs factory offer the required precision with sufficient statistics
- Basic Rule
  - Precision  $\sim 1/M_{\text{NewPhysics}}$
- $e^+e^-$  collider advantages
  - Well defined initial state and tunable  $E_{\text{CMS}}$
  - Clean environment, no large backgrounds from QCD like in  $pp/p\bar{p}$
  - Very low radiation environment
  - Technically feasible

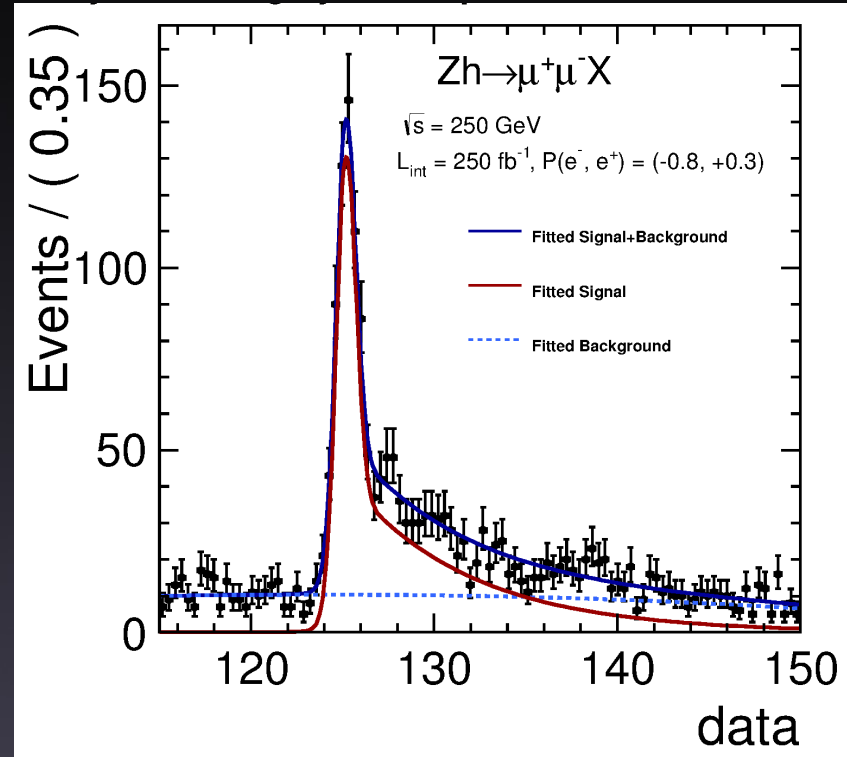
# Higgs Production at $e^+e^-$ colliders





# Higgs Precision Physics

- $e^+e^-$  will do everything the LHC/HL-LHC does
  - Couplings, Mass, Spin
- But  $e^+e^-$  does Model-independent measurements
  - No dependence on theory
- Unique at a Higgs factory
  - Total Higgs Width
  - $H \rightarrow c\bar{c}/g\bar{g}$
  - $H \rightarrow s\bar{s}$  maybe possible

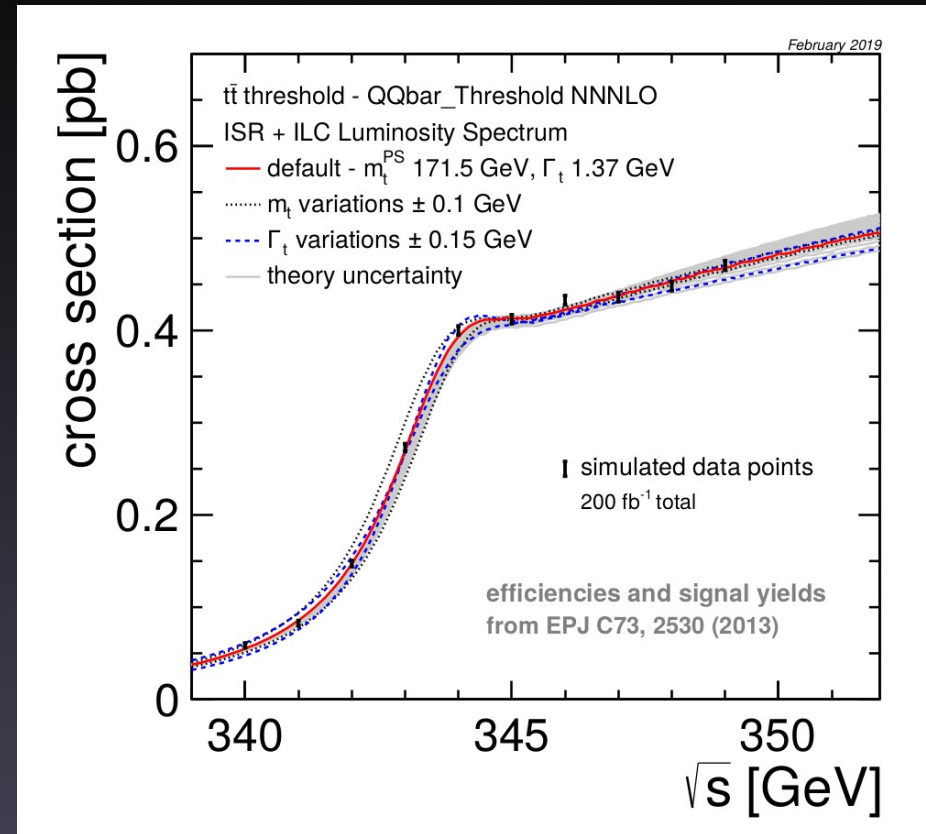


Model-independent Measurement  
of  $\sigma_{HZ}$  at 250 GeV



# A Top Factory

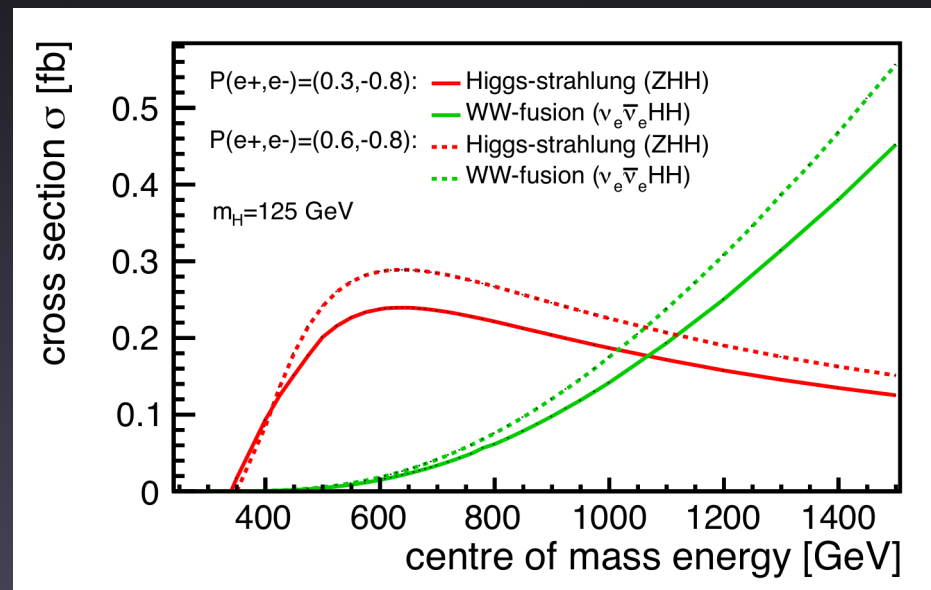
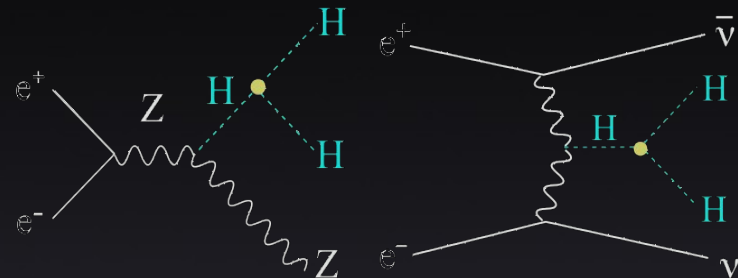
- Top Threshold scans
  - $\Delta m_{\text{top}} < 40 \text{ MeV}$
- Conversion to  $\overline{\text{MS}}$  scheme
  - Measured top mass at  $e^+e^-$  can easily be converted to  $\overline{\text{MS}}$  mass
  - This yields an total error of  $\Delta m_{\text{top}} \sim 50 \text{ MeV}$
  - Theory/  $\alpha_s$  limited
- Compared to LHC/HL-LHC
  - Accuracy  $\sim 500\text{-}800 \text{ MeV}$
  - Mass is “Monte-Carlo Mass”
  - Conversion is non-trivial



# Higgs Self-Coupling - Is it the Higgs ?



- This measurement is one of the most difficult ones at both LHC and at Higgs factories
  - Cross-section  $10^4$  smaller than the Higgs cross-section
- Clear discovery, but precision ultimately depends on luminosity
- Requires a machine with  $\sqrt{s} \sim 600$  GeV



# Two ways to a Higgs Factory



## Running in circles

- Two-ring synchrotron design
  - a “static” collider
  - A booster synchrotron
- Constant Top-Up to boost luminosity
- Superconducting RF
- More Interaction regions improve luminosity (but not linearly)
- Building on decades of successful synchrotrons
  - SuperKEKB being the exception

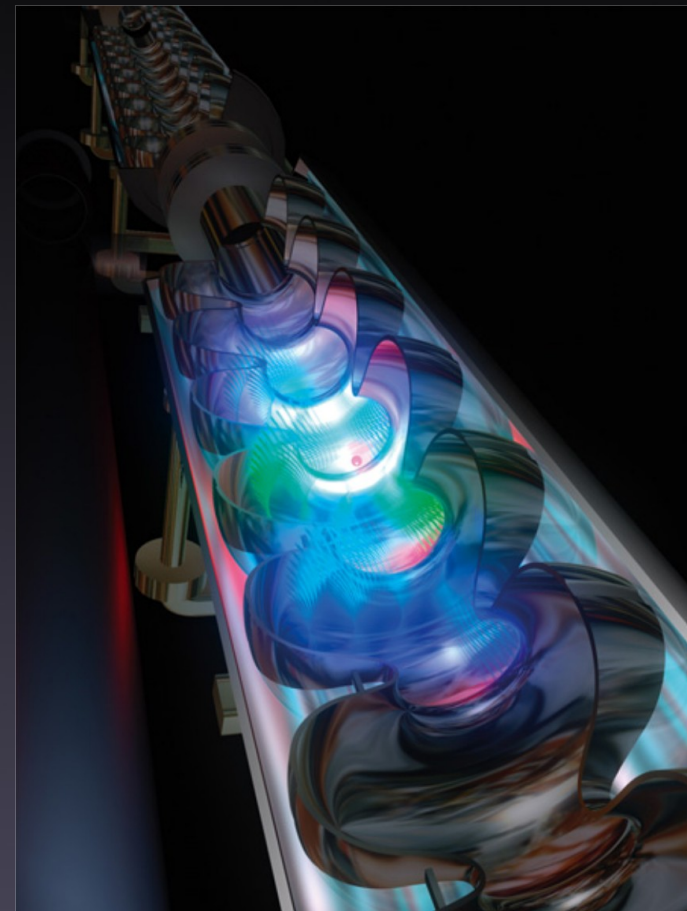
## Shooting straight

- Various technologies proposed
  - Cold → Superconducting RF → ILC style
  - Luke-warm (liquid N<sub>2</sub>) → C3
  - Warm copper → CLIC
- Beam control is more complex
- More Interaction regions divide Luminosity
- One one Linear Collider so far
  - SLC took a long time to reach design luminosity



# Linear vs. Circular

- Basic Limitations of all  $e^+e^-$  synchrotrons
  - Synchrotron radiation loss  $\sim E^4/r$
  - Synchrotron cost  $\sim$  quadratically with Energy (B. Richter 1980)
    - $E_{\text{CMS}} \sim 200$  GeV as upper limit for warm RF
    - $E_{\text{CMS}} \sim 300$  GeV as upper limit for cold RF
  - Above this limit power consumption & cost becomes prohibitive
- Linear Accelerators offer a simpler way to higher energy
  - Not limited by synchrotron radiation
  - Cost  $\sim$  linear with Energy
  - Polarization of both beams



# Power of polarization at linear colliders



- Linear colliders offers polarized  $e^-$  and  $e^+$  beams
- Extremely difficult for circular colliders
- Baseline
  - 80 % polarization for  $e^-$
  - 30 % polarization for  $e^+$
- Unique capabilities
  - Controlling Backgrounds
  - Enhancing Signal

**$W^+ W^-$  (Largest SM BG in SUSY searches)**

In the symmetry limit,  $\sigma_{WW} \rightarrow 0$  for  $e_R^-$  !

**$WW$ -fusion Higgs Prod.**

Pol ( $e^-$ )	ILC
Pol ( $e^+$ )	-0.8
Pol ( $e$ )	+0.3
$(\sigma/\sigma)$	$1.8 \times 1.3 = 2.34$

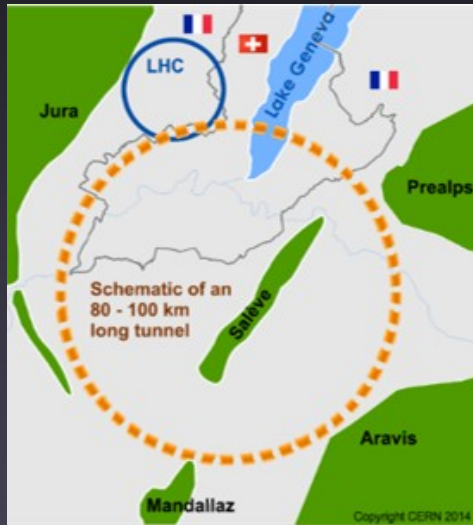
# The FCC



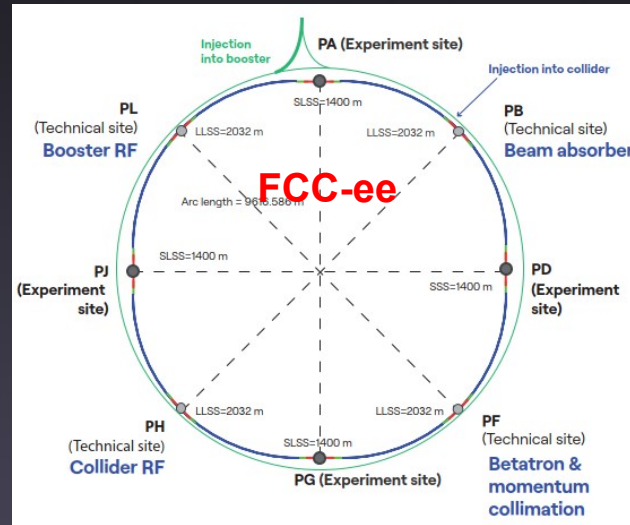


# The FCC programme

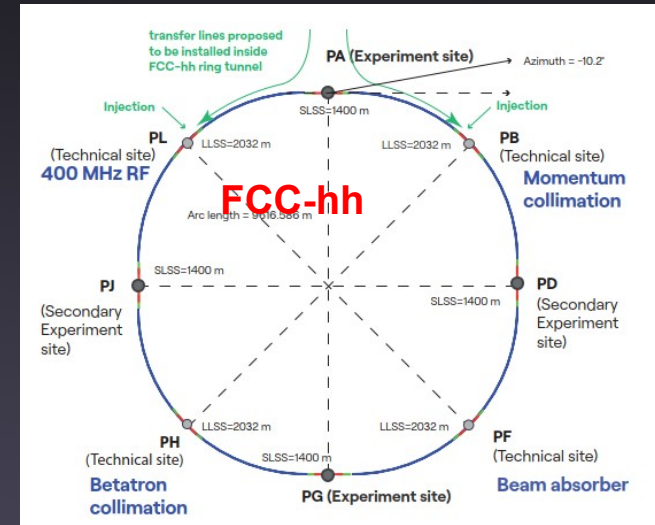
- Integrated program for an O(100km) large circular collider
  - Stage 1: FCC-ee (Z, W, H, tt) as Higgs and electroweak factory
  - Stage 2: FCC-hh (~100 TeV) as energy frontier machine, technology for magnets not there yet!
- Use of common infrastructure (tunnel!)
  - Technical schedule foresees start within years after completion of HL-LHC



2020 - 2045



2046 - 2065



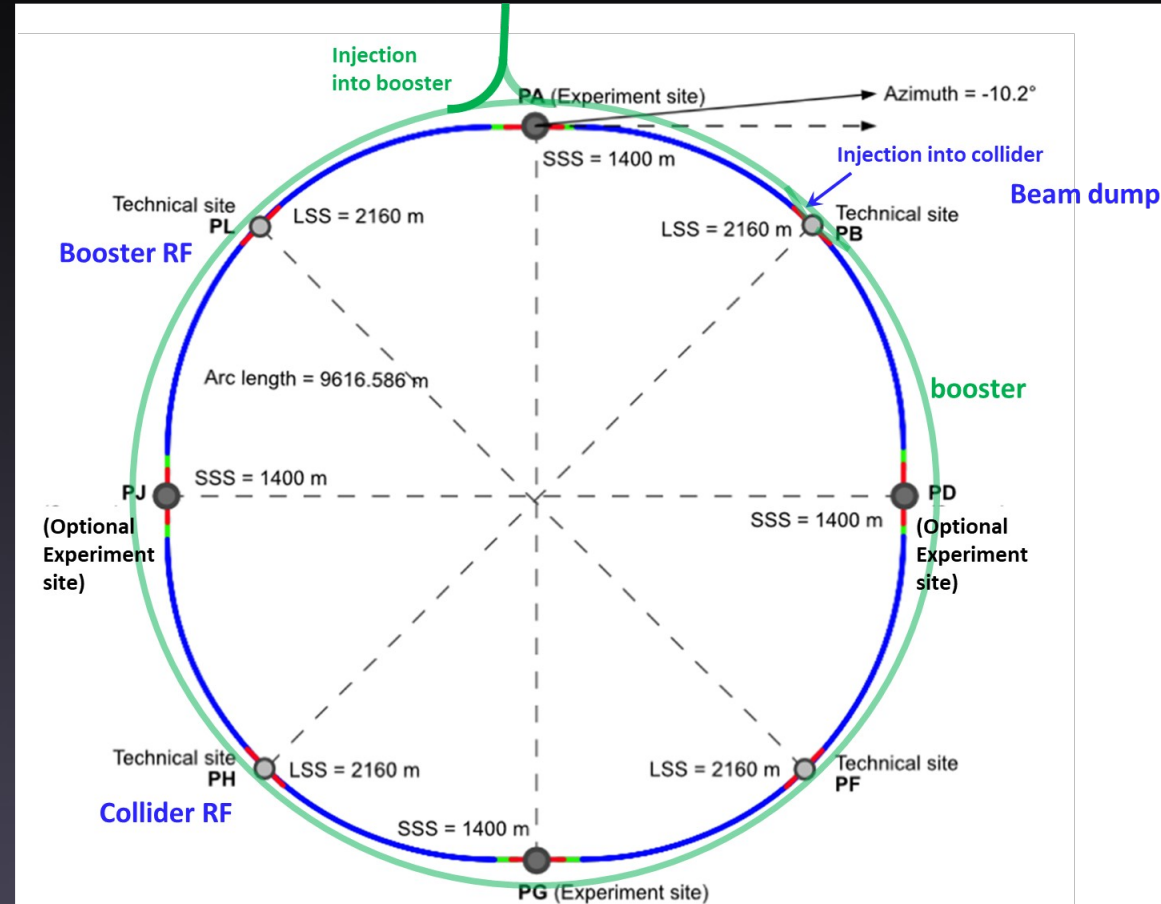
2070 - 2100



# FCC-ee – Easy, it's just like LEP ?



- LEP (1989-2000)
  - 27 km
  - 22  $\mu\text{s}$  Bunch spacing
  - $L=1.0 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$
- FCC-ee
  - 91 km
  - Down to 5 ns Bunch spacing
  - $144 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
- Two accelerators
  - Storage ring at full energy
  - Booster ring for top-up
  - 20 GeV Injector
- 50 MW energy loss per beam !



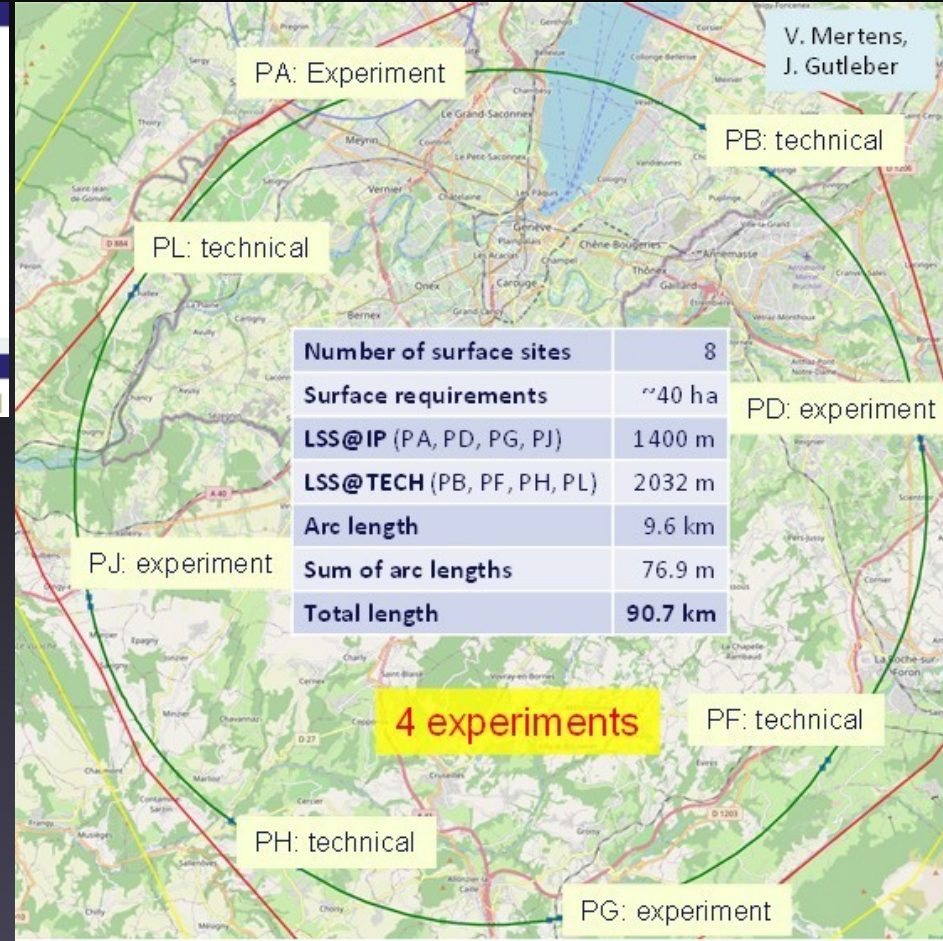
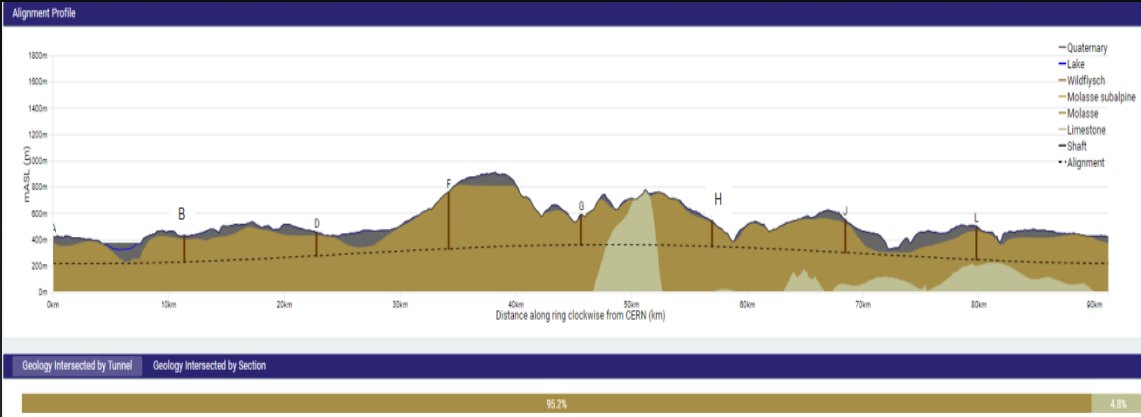
# FCC Parameters



Parameter	Z	WW	H (ZH)	tt	
Collision energy vs [GeV]	88, 91, 94	157, 163	240	340-350	365
Synchrotron radiation/beam [MW]	50	50	50	50	50
beam current [mA]	1294	135	26.8	6	5.1
number bunches / beam	11200	1852	300	70	64
total RF voltage 400 / 800 MHz [GV]	0.08 / 0	1.0 / 0	2.1 / 0	2.1 / 7.4	2.1 / 9.2
luminosity / IP [ $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ ]	144	20	7.5	1.8	1.4
luminosity / year [ $\text{ab}^{-1}$ ]	68	9.6	3.6	0.83	0.67
run time (including lumi ramp-up) [years]	4	2	3	1	4
total integrated luminosity [ $\text{ab}^{-1}$ ]	205	19.2	10.8	0.4	2.7
total number of events	$6 \cdot 10^{12}$ Z	$2.4 \cdot 10^8$ WW (incl. WW at higher vs)	$2.2 \cdot 10^6$ ZH 65k WW → H	$2 \cdot 10^6$ tt +370k ZH +92k WW→ H	
Peak power during beam operation [MW]	250	275	297	391	
Total FCC-ee yearly consumption [TWh]	1.2	1.3	1.4	1.85	



# FCC layout



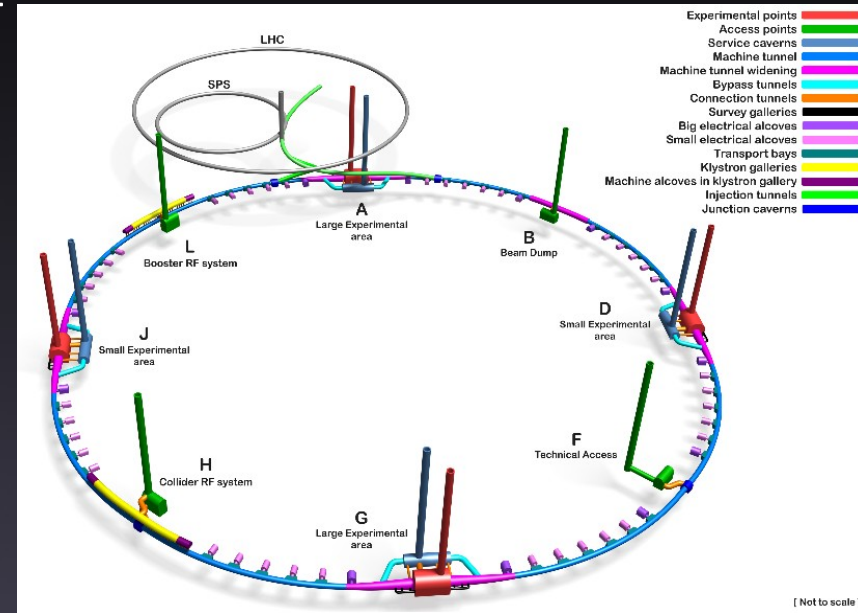
- Present baseline implementation
  - Tunneling mainly in molasse layer (soft rock), well suited for fast, low-risk TBM construction.
  - 6 million m<sup>3</sup> excavated volume c.f. 8.5 million m<sup>3</sup> excavation material on surface
  - CE Designs of all underground structures developed
  - Average shaft depths ~240 m
  - To fix the vertical position of the tunnel, interfaces between geological layers have to be known
- Site investigations ongoing to verify geological conditions:
  - ~40-50 drills, 100 km of seismic lines



# Key Construction Details



- 90.7 km main tunnel with an internal diameter of 5.5 m
  - Depth varies between 50 m and 560 m
  - 12 shafts up to 400 m deep and 18 m in diameter
- Caverns
  - 2 larger experiment caverns (35 m span)
  - 2 smaller experiment caverns (span 25 m)
  - >70 small caverns.
- 5 km transfer tunnel from the surface.
- 3 km of klystron gallery tunnels.
- Technical buildings on 8 surface sites
- Injector FCC-ee: high-energy linac at CERN Preveessin site



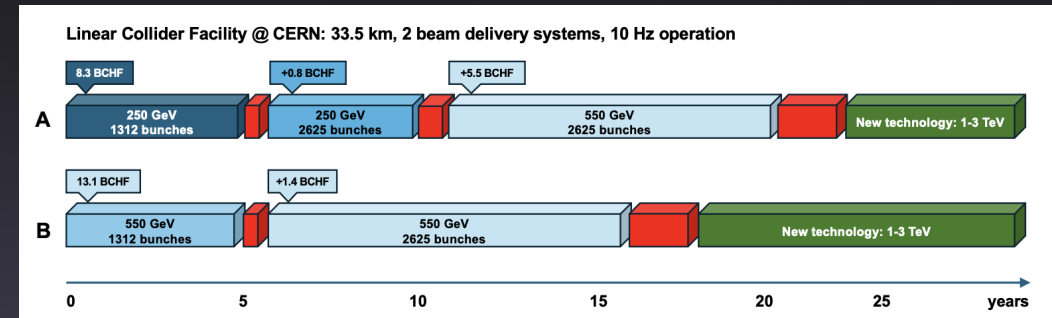
# The LCF at CERN



# A Linear Collider Facility at CERN



- Energy reach and flexibility:
  - Physics opportunities from Z-pole to TeV(s)
  - Flexible (E,L,cost, power) to adapt to development in physics and technology
- Footprint, cost, power
  - Lower cost to get to Higgs and top than a circular machine (initial machine)
  - Power similar to LHC, or lower, for initial configuration
  - Footprint (length/location) similar to LHC
- Provide many opportunities and increased flexibility for the future:
  - Own upgrade opportunities
  - Does not determine footprint of future energy frontier machines
  - Encourage accelerator and detector R&D

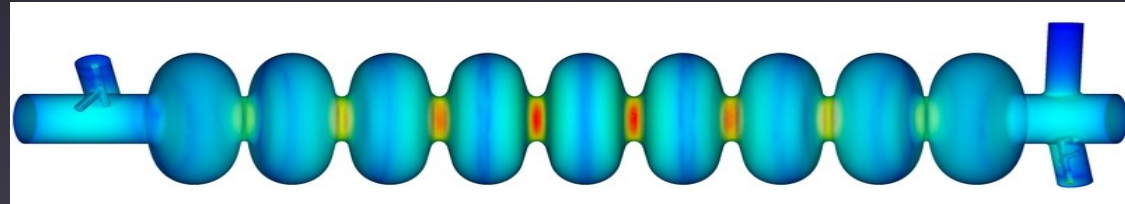


Note: tunnel extension to allow a 550 GeV upgrade is included in the initial programme

# Benefits of going cold...



- High RF -> Beam-power efficiency
  - low-loss cavities
- Ease of RF power generation
  - low frequency (1.3 GHz)
  - Long pulses / fill time (1 ms / 0.6 ms)
  - Long pulses allow intra-train feedback
- Emittance preservation
  - Large cavity iris
  - low transverse and longitudinal wakefields

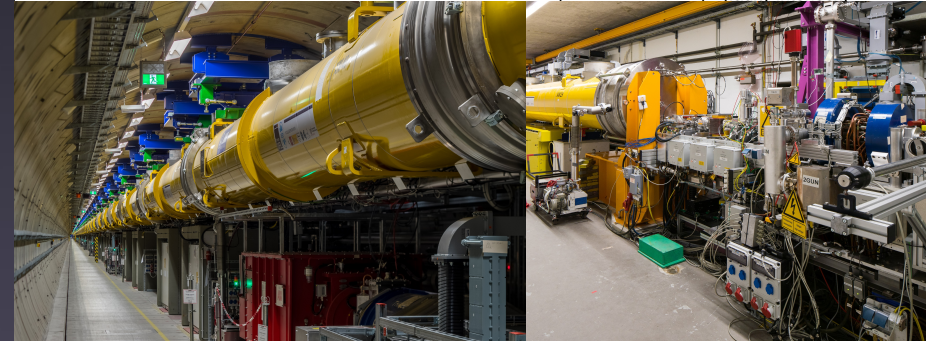
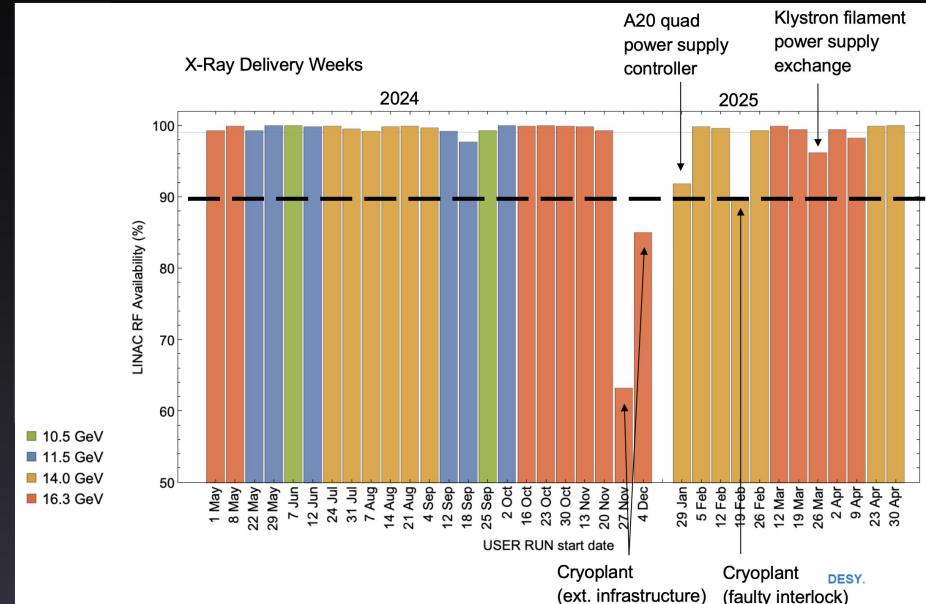


# The case for superconducting RF



- Several Free Electron Laser Linacs are using SCRF
  - European XFEL, LCLS-II, SHINE
  - Mature technical design and industrialization
  - Excellent performance and up-time
- Can be upgraded in Energy and Luminosity
- Worldwide interest in technology
  - Large technology interest in Europe (European XFEL and several other projects), and leading industries in Europe
- Simplifies in-kind contribution
  - Especially for non-member states

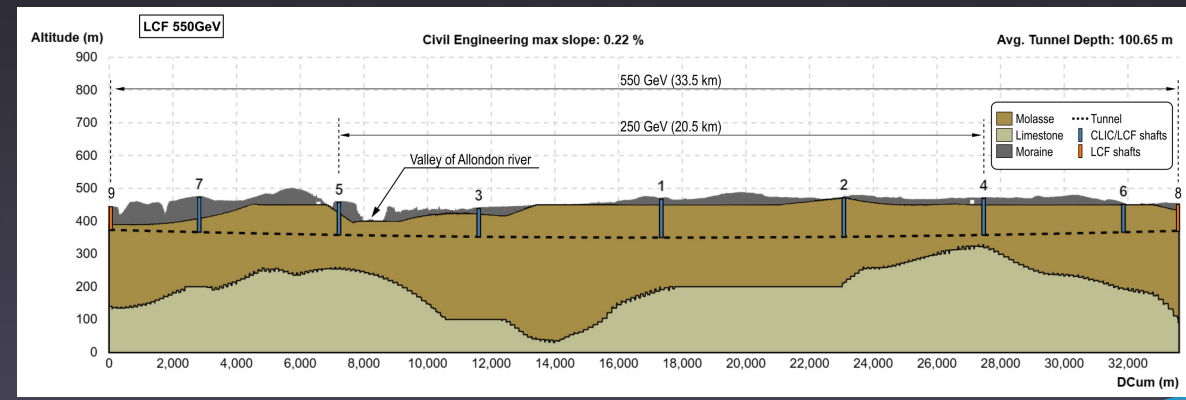
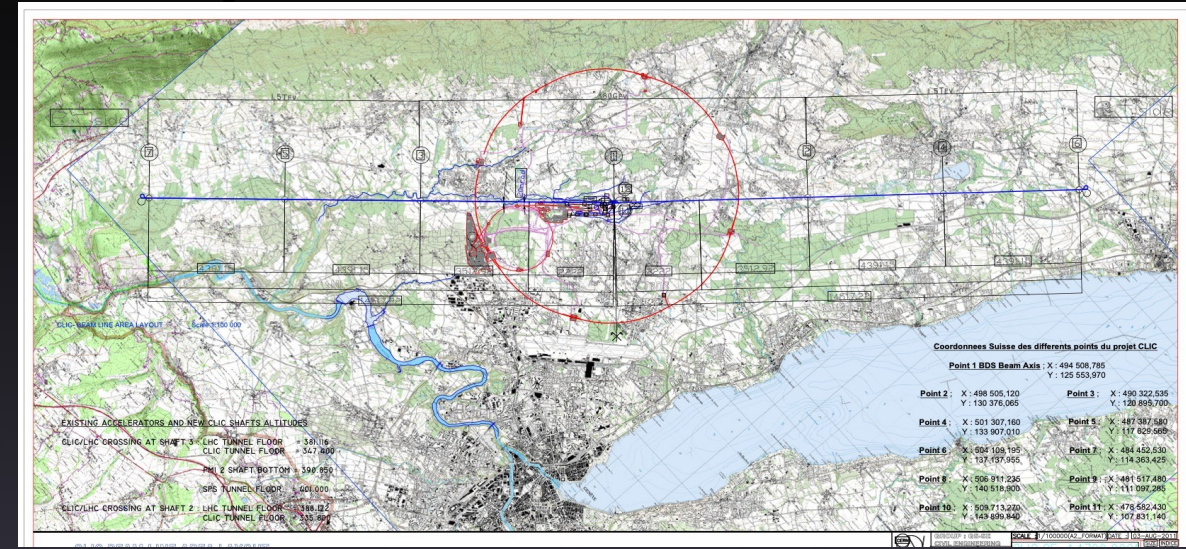
**Go Cold !**





# LCF Layout


- LCF Tunnel
  - 33.5 km for 550 GeV
  - 250 GeV requires only 20.5 km
  - 5.5 m diameter
- 2 Interaction regions
  - With full Beam delivery system
- Location of the IP's at the Prevezsin site





# LCF Parameters

Parameter	250 LP	250 FP	550 LP	550 FP
Collision energy $\sqrt{s}$ [GeV]	250	250	550	550
Synchrotron radiation/beam [MW]	-	-	-	-
Polarization [%/%]	80/30	80/30	80/30	80/60
Repetition frequency [Hz]	10	10	10	10
Bunches per pulse	1312	2625	1312	2625
beam current per pulse [mA]	5.8	8.8	5.8	8.8
luminosity / IP [ $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ ]	2	4	7.5	1.8
total integrated luminosity [ $\text{ab}^{-1}$ ]	1	2	2	4
Peak power during beam operation [MW]	143	182	250	322
Total yearly consumption [TWh]	0.8	1.0	1.4	1.8

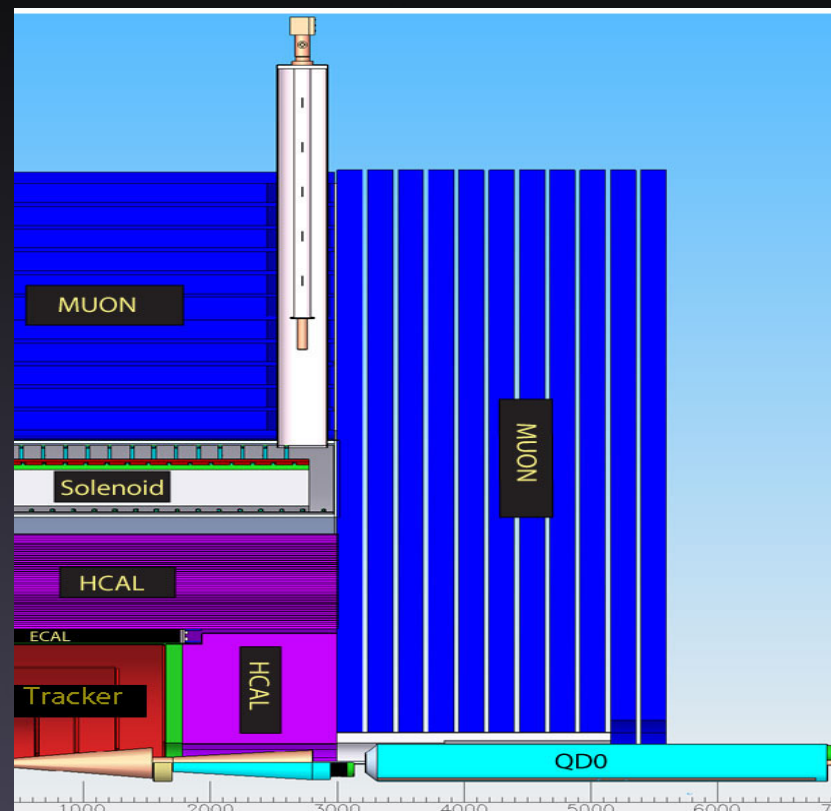
A detailed 3D cutaway rendering of a particle detector, likely for a Higgs boson factory. The image shows a complex, multi-layered structure with various components. In the center, there are two large, cylindrical detector modules, possibly calorimeters or tracking detectors, arranged symmetrically. The surrounding structure consists of numerous layers of material, likely for shielding or particle identification. The overall design is highly technical and precise. The text "Higgs Factory Detectors" is overlaid in a large, bold, yellow font with a black outline, centered over the detector components.

# Higgs Factory Detectors

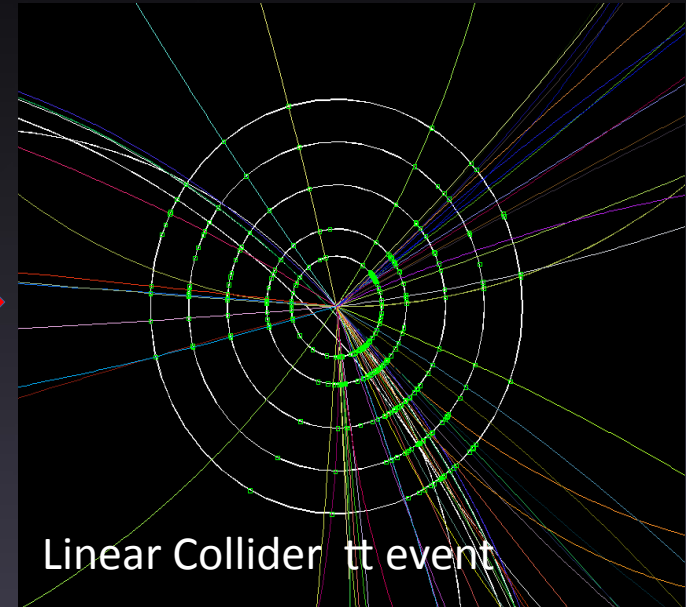
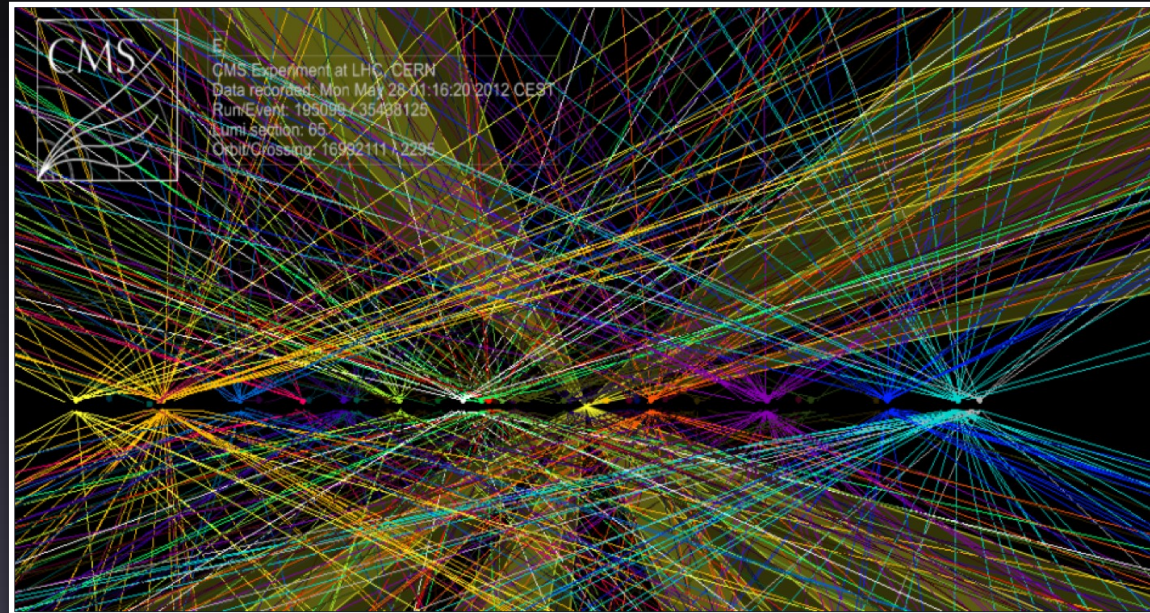
# A few words on detectors



- Higgs Factory detector studies have been becoming very mature
  - Thanks to over a decade of ILC/CLIC Detector R&D
- Most but not all detectors based on particle-flow paradigm
- Implies
  - Calorimeter inside the solenoid
  - Highly-granular calorimetry
  - Low material tracking

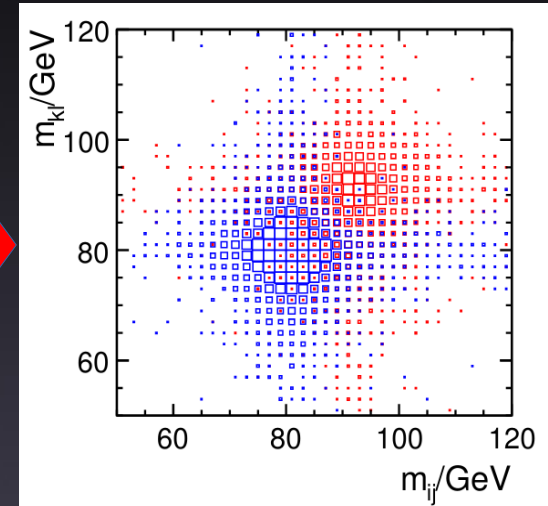
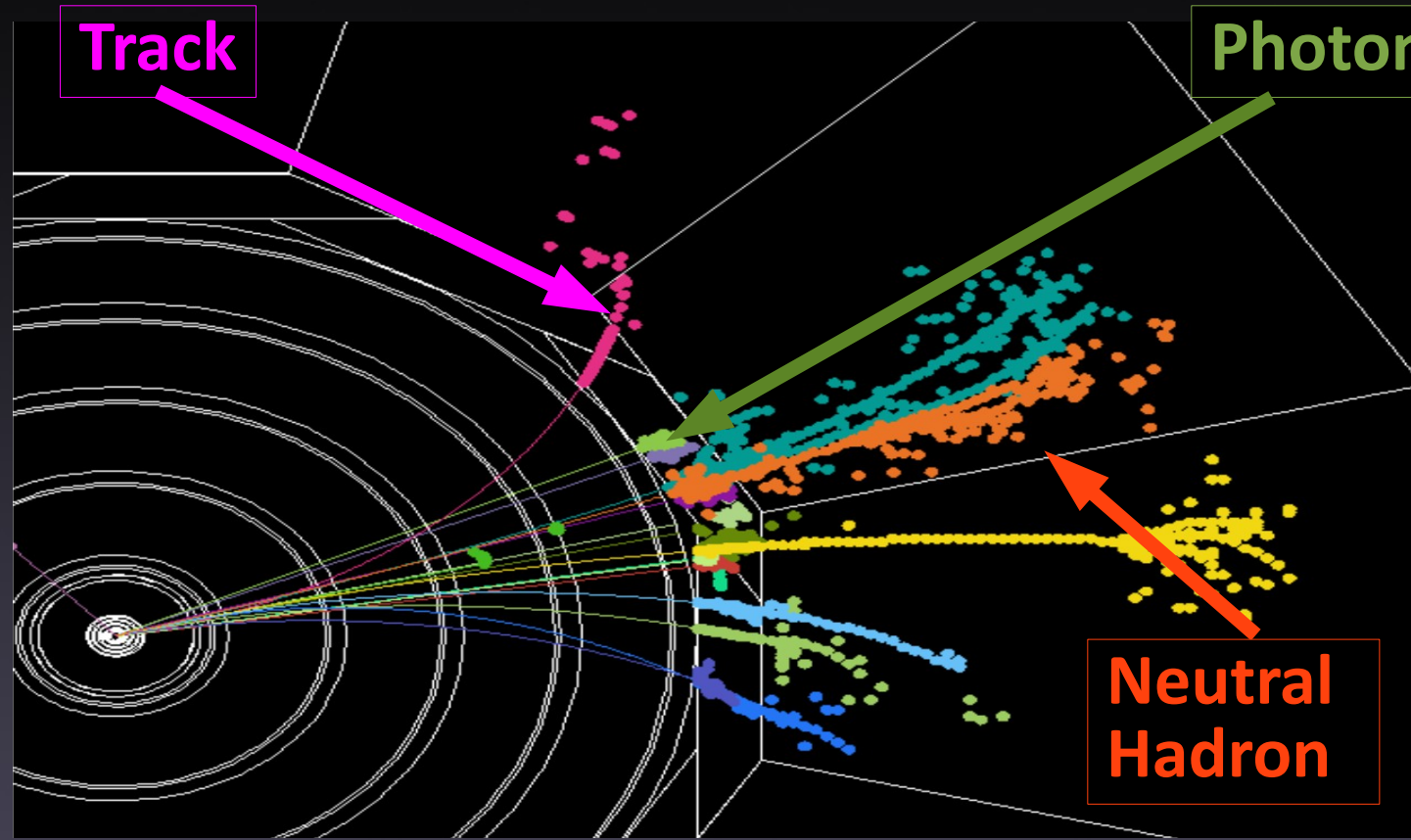


# From HL-LHC to ILC



- Moving from 140 interactions per crossing to  $\sim 1$  event in several crossings
- Occupancy driven by beam background

# PFA Reconstruction in a nutshell



# Linear Collider Specialties

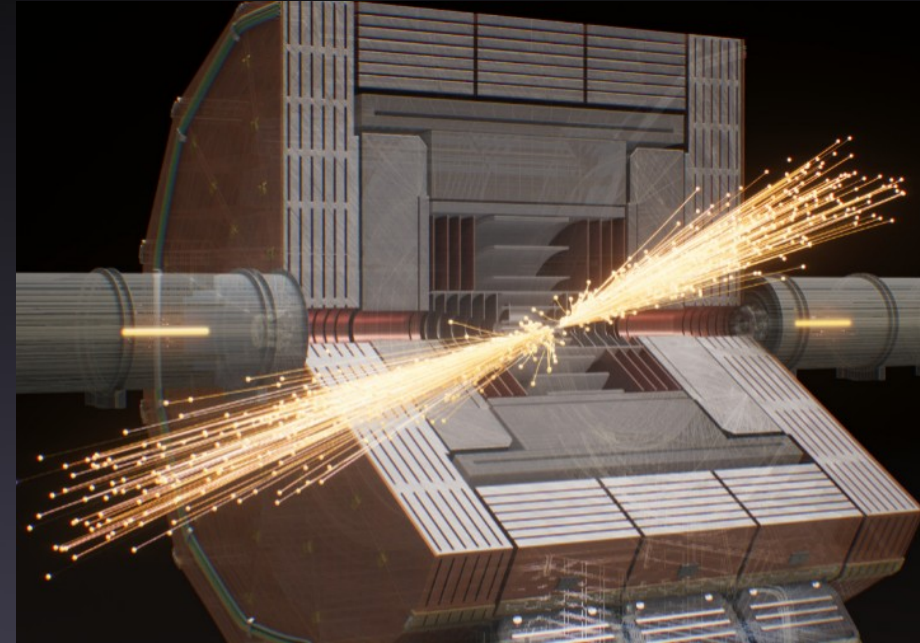


- Cold LCF environment is very different compared to LHC
  - Bunch spacing of  $\sim 554$  ns (baseline)
  - 1312 bunches in a 1 ms long pulse (train)
  - 199 ms quiet time
- Occupancy dominated by beam background & noise
  - $\sim 1$  hadronic Z ( $e^+e^- \rightarrow Z \rightarrow q\bar{q}$ ) per train ...
- Readout during quiet time possible  $\rightarrow$  so-called Power pulsing
- Warm machines have shorter pulses
  - e.g. CLIC 50 Hz 312 bunches, 0.5 ns spacing

# FCC-ee Detectors



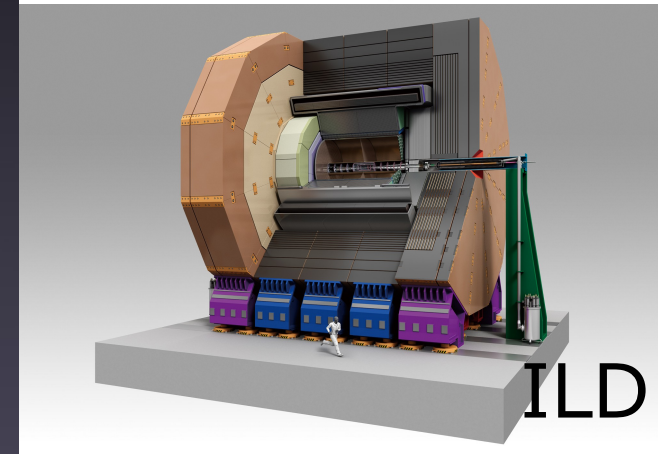
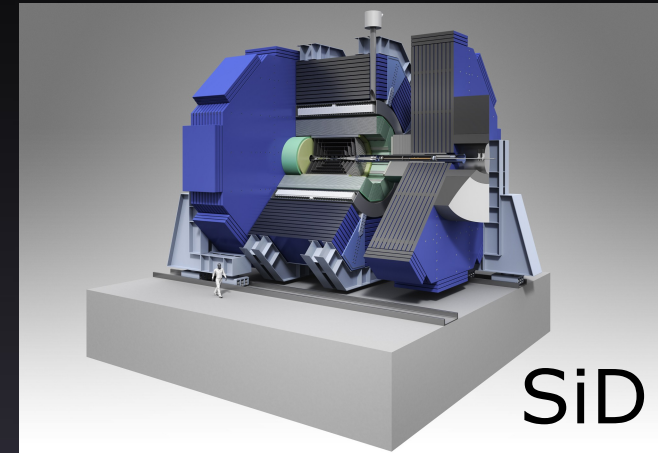
- There are two major challenges
  - Bunch spacing at the Z  $\rightarrow$  requires fast detectors
  - Continuous operation  $\rightarrow$  stress on power & material budget
- Depending on the physics needs, an FCC-ee detector maybe not be optimal for all energies
  - Decent particle ID requires dedicated subsystem  $\rightarrow$  conflicts with PFA
  - While Z run has very stringent timing requirements, 250 GeV and above is way more relaxed
  - Given the field limits of 2 T at FCC-ee, higher energy performance will be affected



# The LCF Detectors

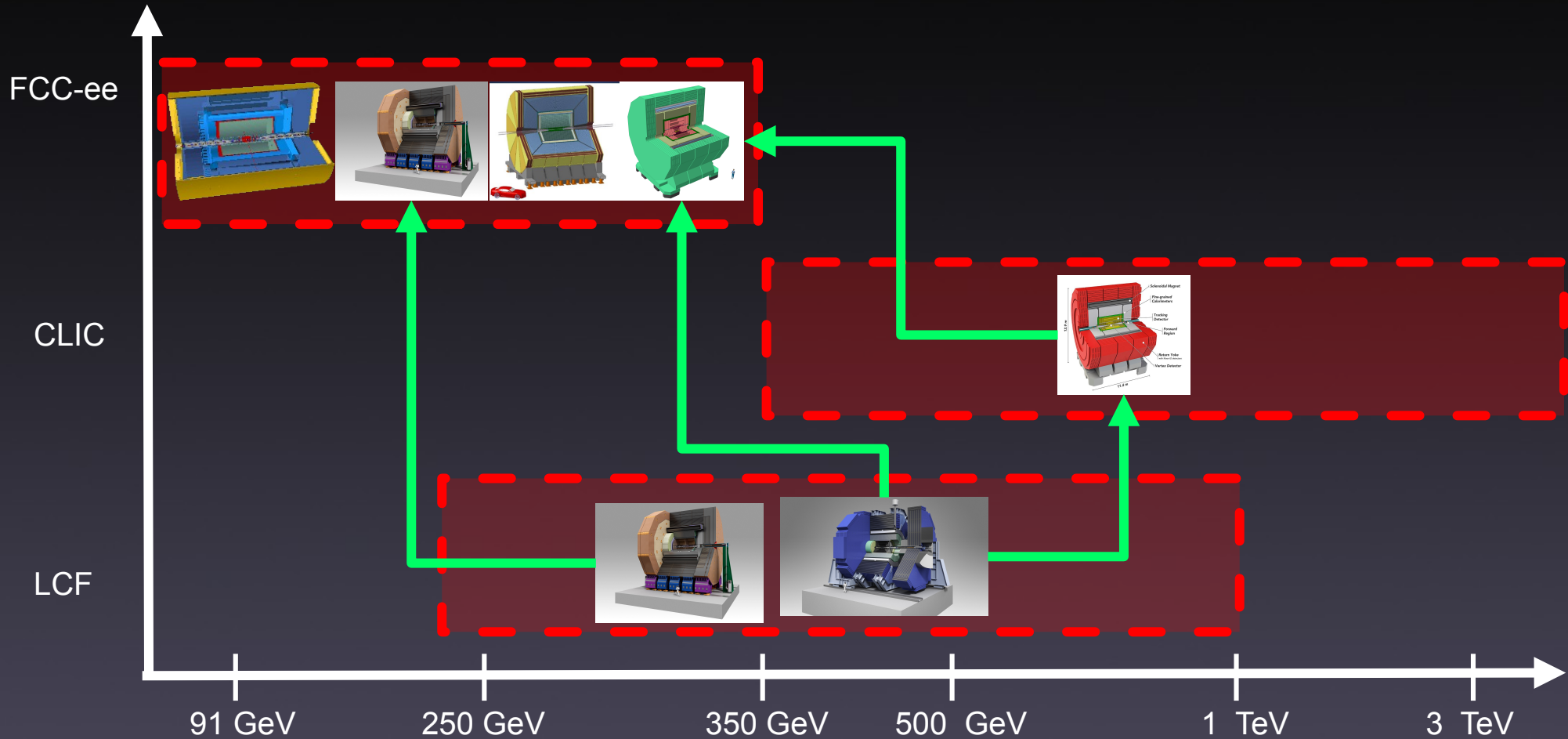


- LCF detectors are currently all based
  - PFA with highly granular calorimetry
  - Power pulsing
  - Pretty High fields (4 -5 T)
  - Main difference is tracking TPC versus all-silicon
- Well-studied since ILC days
  - Full simulation
  - Lots of R&D went into designs
- But to be fair, they need some face-lift





# A complex relation



# An overview



	SiD	ILD	CLICDET	CLD	ALLEGRO	IDEA
<b>Target</b>	LCF	LCF	CLIC	FCC-ee	FCC-ee	FCC-ee
<b>Vertexing</b>	MAPS	MAPS	MAPS	MAPS	MAPS	MAPS
<b>Tracking</b>	Silicon	TPC	Silicon	Silicon	Gaseous + Silicon	Gaseous
<b>PiD</b>	-	TPC	-	RICH Option	RICH	
<b>Calorimetry</b>	Silicon +Scintillator	Silicon + Scintillator	Silicon +Scintillator	Silicon +Scintillator	Noble liquids	Dual-Readout
<b>Coil</b>	5 T	4 T	4 T	2 T	2 T	2 T
<b>Muon System</b>	Scintillator	Scintillator	Gaseous RPC	Gaseous	Gaseous	Gaseous

Main ideas are fixed, but lots of room for improving

# Common Challenges

The image features a 3D rendered white fiber optic cable that is the central focus. The cable is shown in a looped configuration, with one end having a connector housing. A section of the cable is cut away to reveal the internal structure, including a central core and multiple surrounding cladding layers. The background is a complex, glowing blue digital landscape. It consists of a grid of lines and nodes, resembling a circuit board or a data network map, with various labels and patterns. The overall aesthetic is futuristic and technological, with a dark blue color palette and bright yellow highlights.



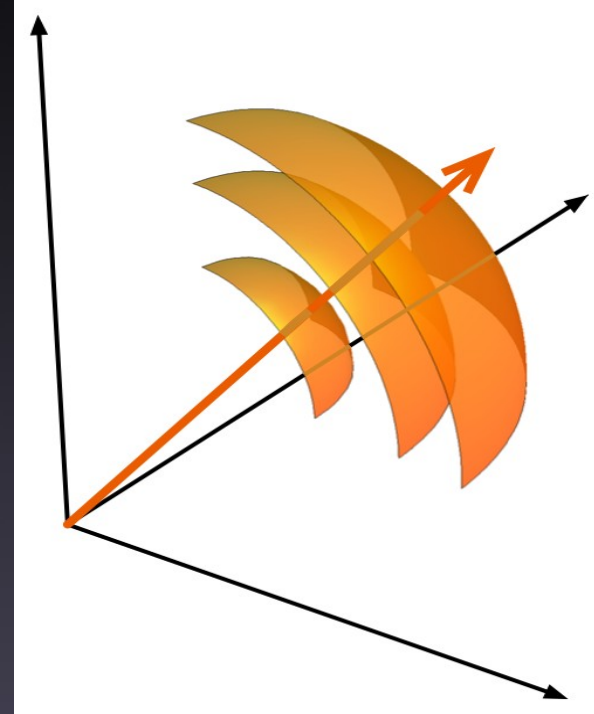
# Initial thoughts

- The European Strategy for Particle Physics identified an electron-positron Higgs Factory as the **highest priority** for the next collider and I am convinced that Future Circular Collider (FCC) is scientifically the best option. **The main question is cost and affordability.**  
**Mark Thomson** (Incoming CERN DG)
- **Having a tunnel is everything**  
**Lyn Evans** LHC Project Leader

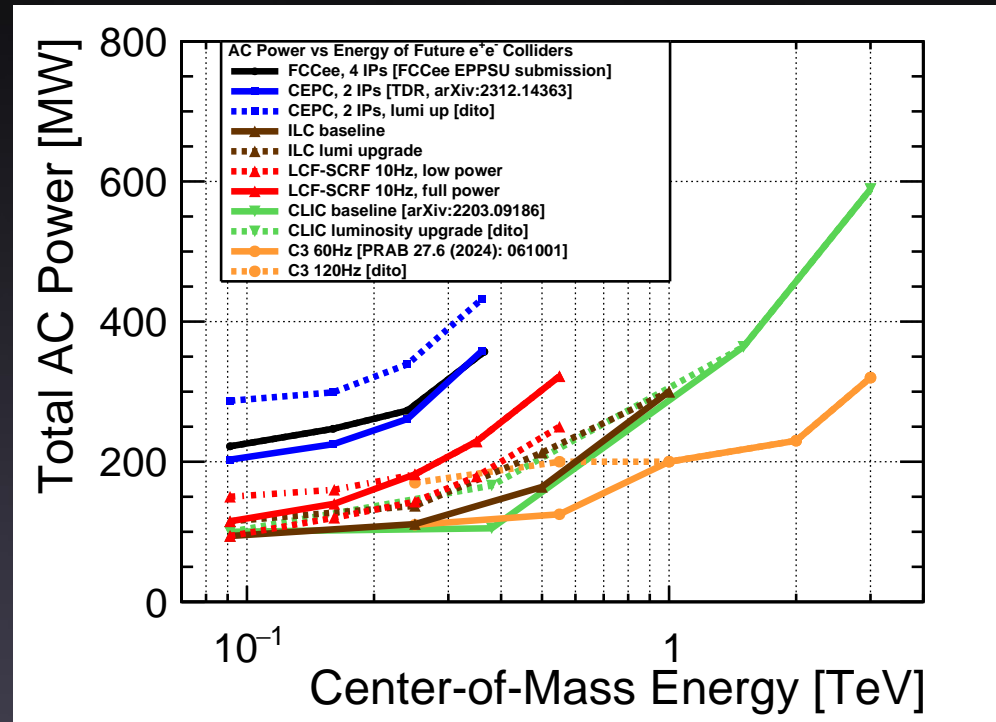
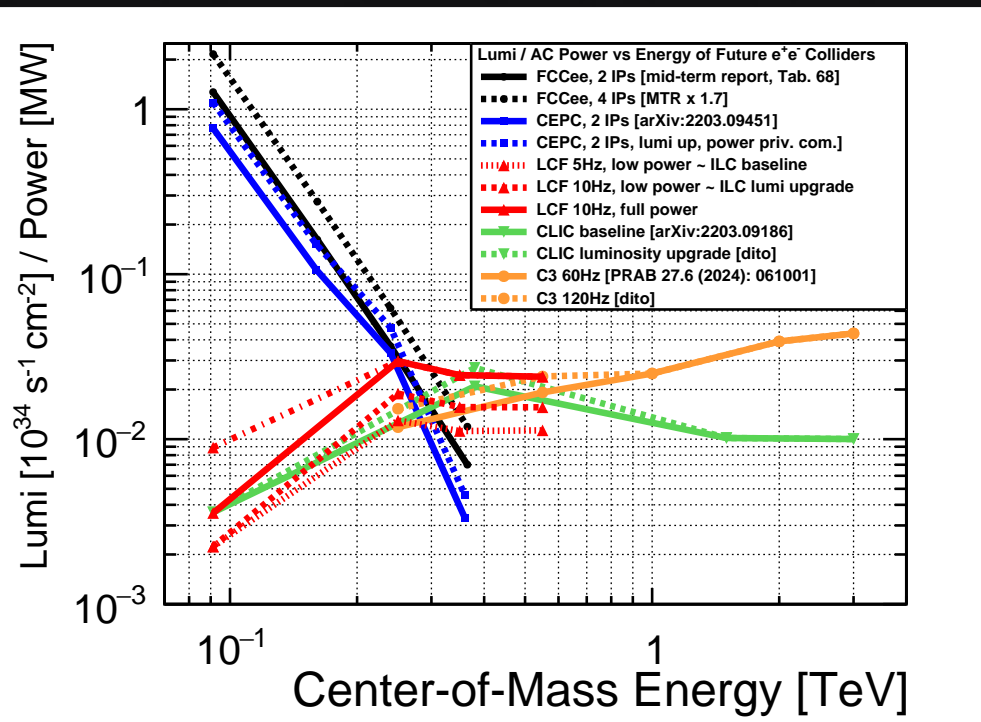
# What are these challenges ?



- Physics reach
- Construction
  - Cost
  - Sustainability
  - Infrastructure needs
- Operating Costs
  - Power Budget
  - Maintenance
- Future Potential



# Setting the scene ...



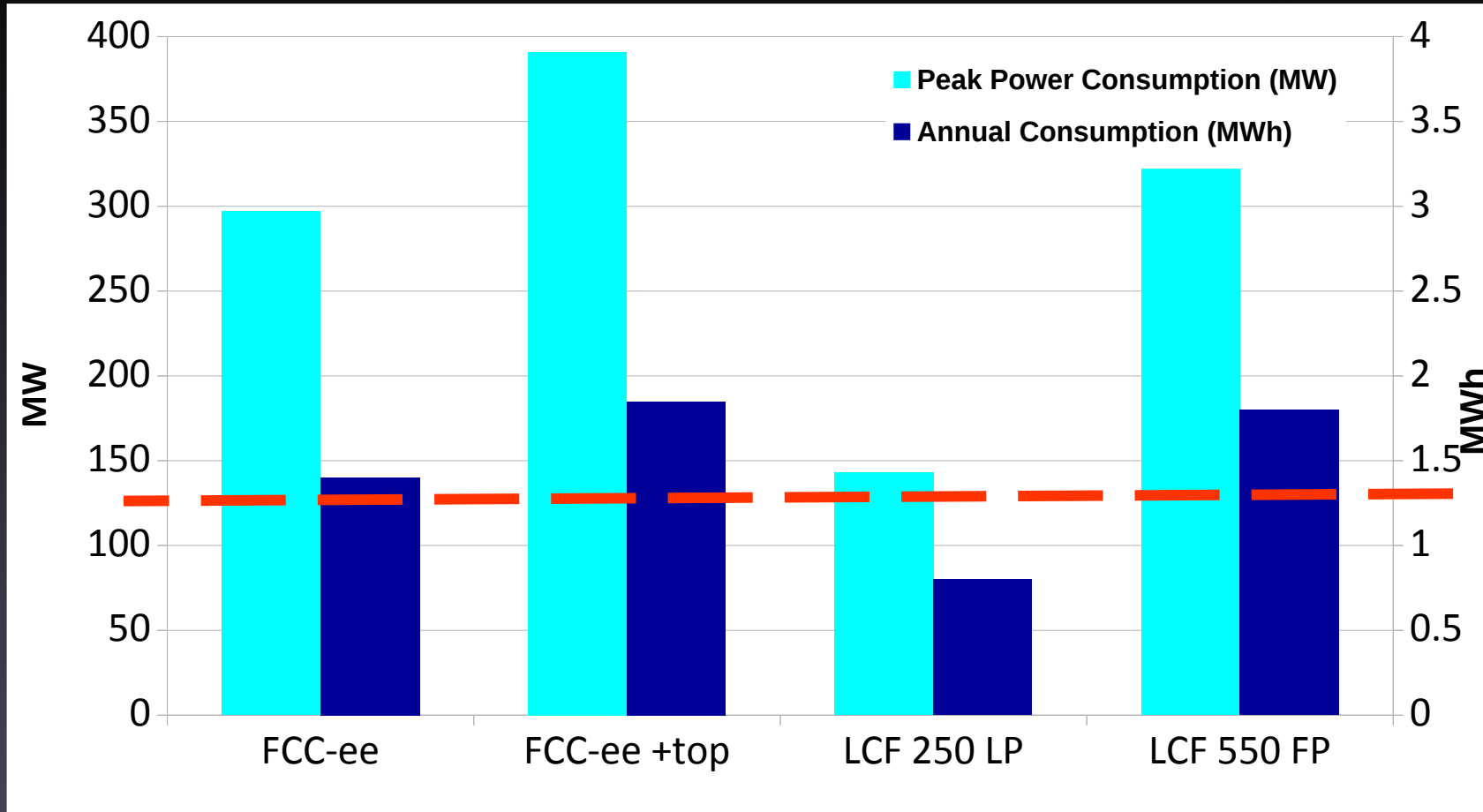
# Construction Cost comparison



	FCC-ee	FCC-ee +top	LCF 250 LP	LCF 550 FP
<b>Max Centre-of-mass energy [GeV]</b>	240	365	250	550
<b>Tunnel length [km]</b>	91	91	31	31
<b>Civil Engineering</b>	6160	6160	2338	2338
<b>Technical Infrastructure</b>	2840	2840	1109	2283
<b>Injector complex</b>	590	590	1181	1267
<b>Collider</b>	4140	5400	3864	8068
<b>Total Cost Accelerator</b>	13730	14990	8492	13956
<b>Number of Experiments</b>	4	4	2	2
<b>Total Cost experiments</b>	1590	1590	795	795
<b>Total Project</b>	15320	16580	9287	14751



# Power Consumption



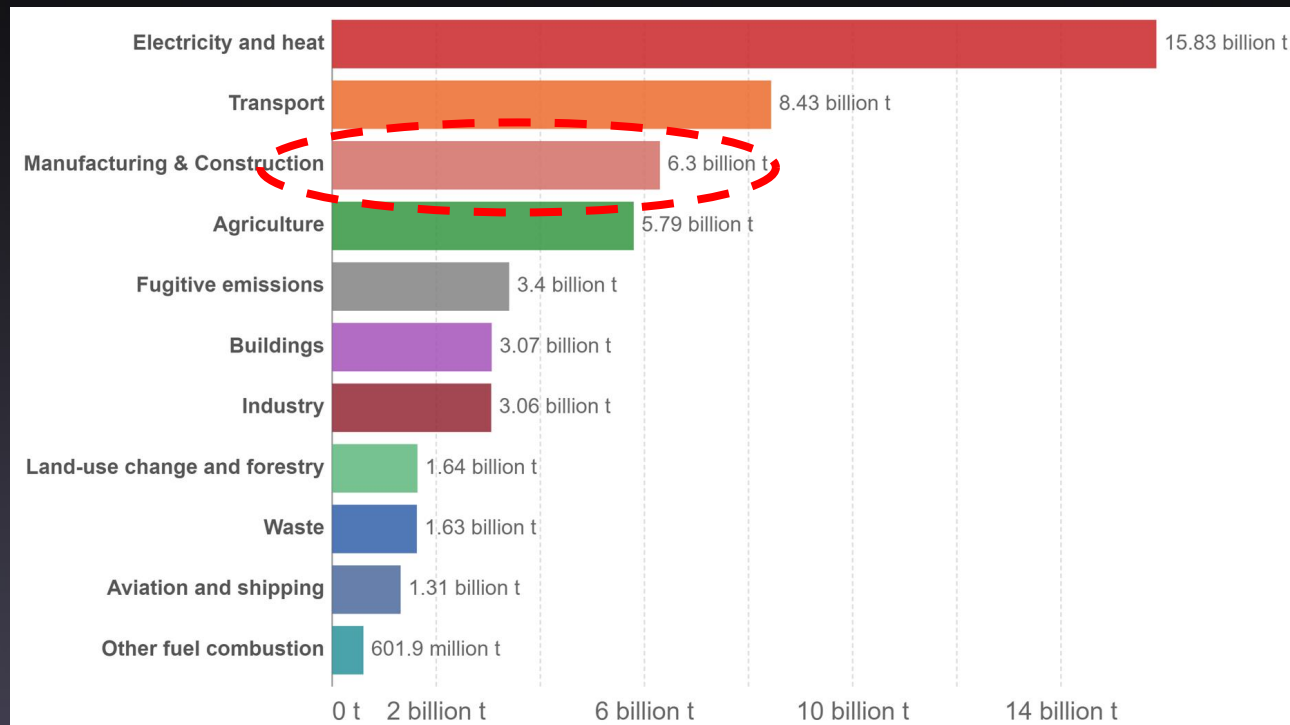
**CERN  
today**





# Sustainability

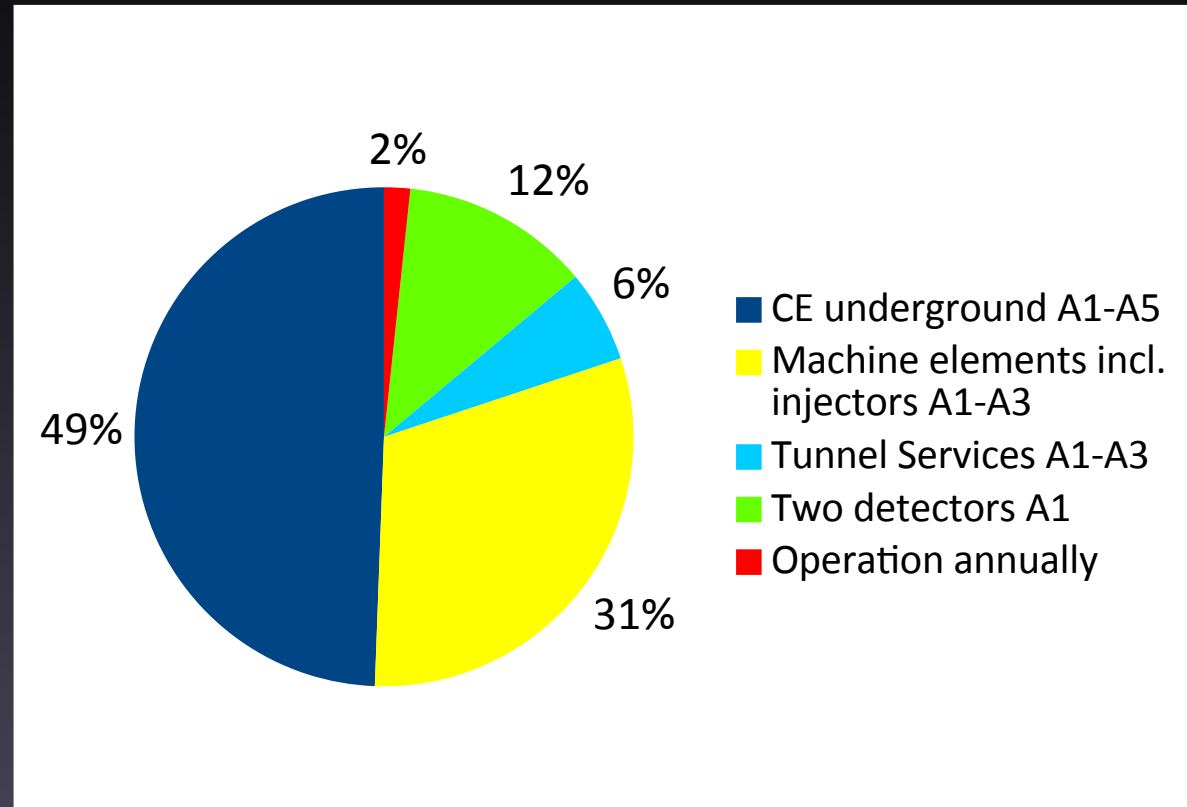
- A topic that has become more and more important
- Construction has major impact
- Life-cycle analysis
  - Looks at entire Carbon footprint of a project
  - From first excavation to close-out





# Sustainability Results

- Following ISO 14040:2006
- Tunneling is “bad” for CO<sub>2</sub>
  - Driven by Concrete and Steel
- Contrary to “naive” expectations
  - Power consumption is not the major culprit
  - Power generation in 2050 will be almost CO<sub>2</sub> free
- Rule of thumb
  - 1 km of construction corresponds to 1 year of operating
- Full report [here](#)



# But isn't FCC the plan for CERN

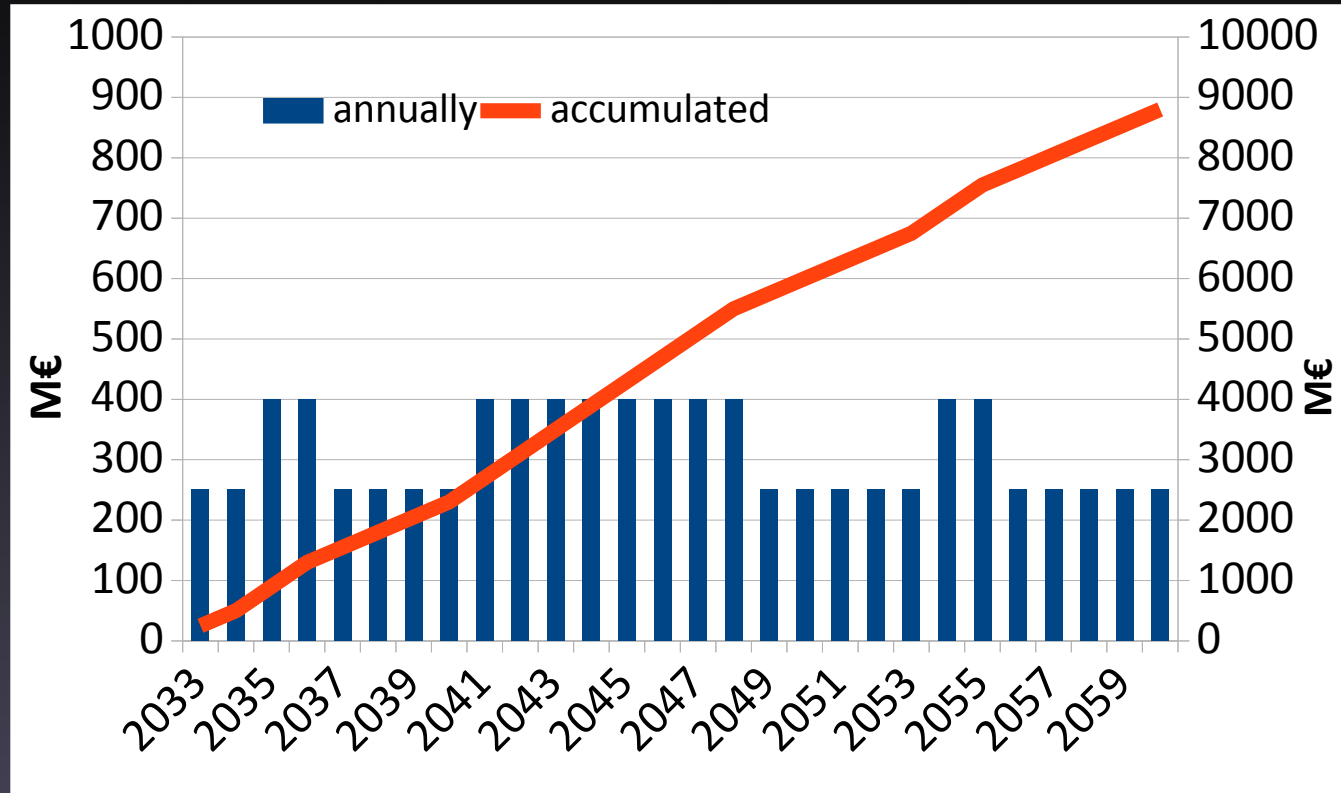


- Isn't FCC so fantastic, that we have to build it ?
  - It's the plan, not Plan A !
- European Strategy group explicitly asked for a Plan B
  - Also triggered by less than warm reception from council
  - Some major stakeholders had significant concerns e.g. [here](#)
- In the current political climate need to think about alternatives
  - Scientifically sound
  - More affordable

# A “Gedankenexperiment”



- What could CERN do on its own budget ?
  - 1.1 B€ per year
- Assume “free budget”
  - 250 M€ with running experiments
  - 400 M€ during shutdown
- Means ~ 9 B€ available till 2060



# This is where LCF comes in



- The LCF 250 could be done for 9.2 B€
  - Almost within the CERN budget
  - While still doing most of the FCC-ee programme
- There is an absolute barebone version of LCF 250
  - One interaction region, reduced luminosity, shorter tunnel that comes in at 6.8 B€
- The LCF has the advantage, that it can deliver a viable machine within the CERN budget
  - Additional external contributions then improve and extend the LCF
- Doesn't fix the next energy frontier machine
  - Can be pp or muons or ....



**Looking in the past**

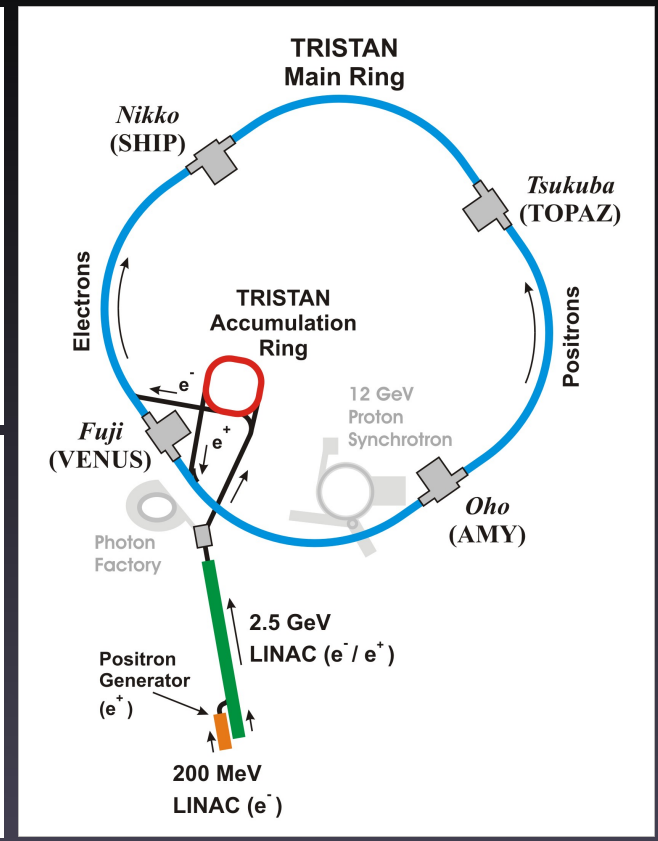
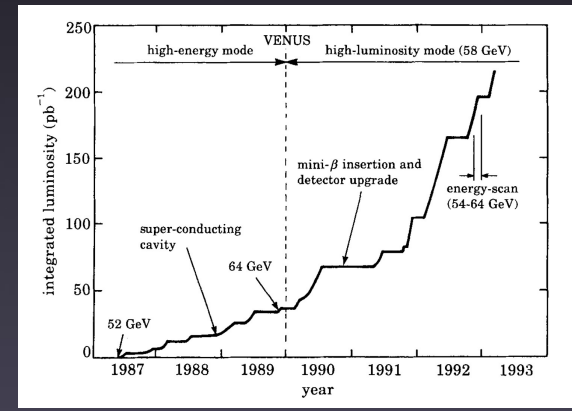
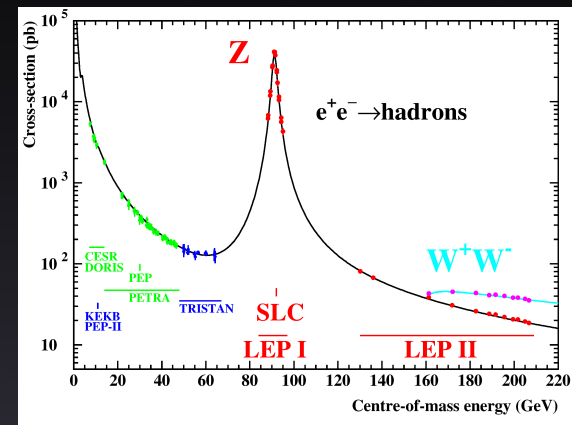
# Learning from the past

- The importance of the *no-loose theorem*
  - Accelerators that did not “deliver”
- Too big too fail ?
  - Accelerators aborted during construction
- Ahead of the game
  - Technologically ahead of its time
- Shovel-ready and still no construction
  - Projects with a complete Technical Design report



# TRISTAN

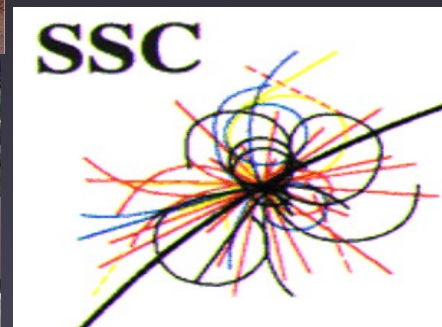
- Next generation collider after PETRA at DESY (Gluon discovery)
- Construction started in 1981
- Operating at KEK (1986-1994)
  - 3 km circumference
  - Centre-of-mass energy 50-64 GeV
  - 3 Experiments (TOPAZ, AMY, VENUS)
- Designed for finding the top-quark
  - Theory predictions:  $\sim 30$  GeV
  - Unfortunately the top was almost a factor 6 heavier



# The Superconducting Super Collider



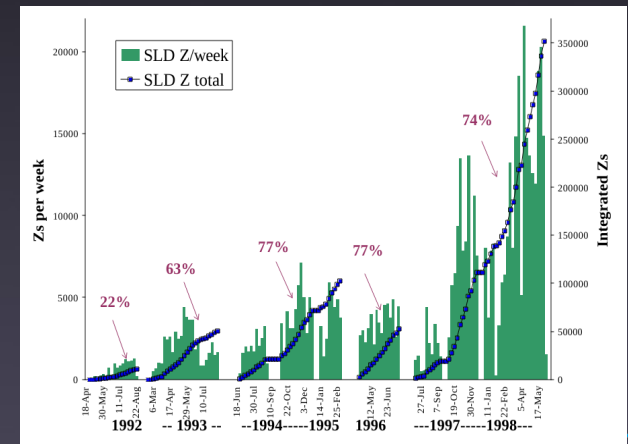
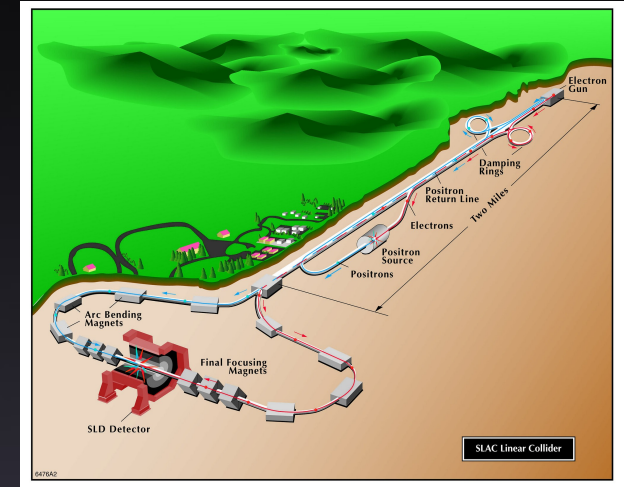
- SSC (1987-1993)
  - pp Collider
  - 87 km tunnel
  - 40 TeV center-of-mass energy
- Located in Waxahachie, Texas
  - Close to Dallas
- First physics in 1999
- US Congress terminated this project in 1993
  - After about a third of the tunneling was done
- Cost estimate 1993
  - 9 Billion US-\$
  - 2023 ~ 22 Billion US-\$



# The Stanford Linear Collider



- The world's first Linear Collider
  - Running on the Z pole an
- SLC was unquestionably the most difficult accelerator ever operated at the time
  - *The challenges were grossly underestimated the delusion of a quick, cheap triumph like SPEAR persisted for years in spite of overwhelming evidence to the contrary – N. Phinney*
- To make it work, it required new tools, new diagnostics, new control systems
  - By the time, it was working well, LEP was way ahead (350000 Z's vs. 20 million)
- All the lessons learned really pushed ILC/CLIC R&D



# ILC - Still shovel-ready

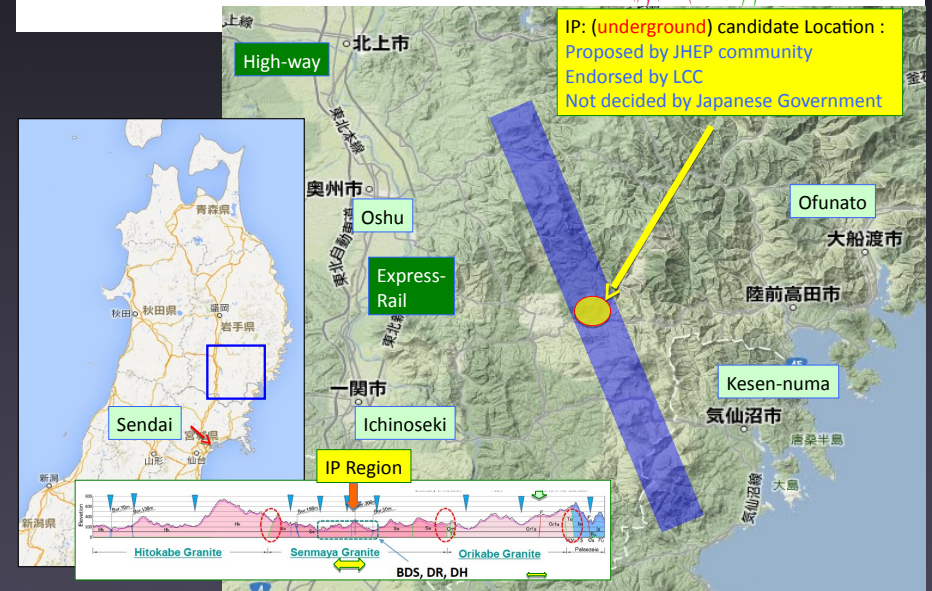


“As compared to other projects of similar scale (ITER, LHC, ATLAS, CMS, ALMA, XFEL, FAIR, ESS, SSC) the quality of the documentation presented by the GDE team is equal or superior to that utilized to launch into a similar process.”

The ILC is good to go!



- ILC TDR 2013
  - Five Volumes covering Physics, Accelerator & Detectors
  - Culmination of eight years of effort
  - Very favorable review
- Japan shows strong interest to host
- 2025 : Still no green light
- ILC PAC Chair 2014:
  - One can also kill the best project in the waiting room ...



# Personal Remarks



- The fastest and most future-proof way to  $e^+e^-$  collisions and a Higgs/Top-Factory is the LCF
  - Technically mature
  - It's also the most cost-effective and sustainable
  - And can be done within the CERN budget and CERN mechanisms
- Besides a “Throw deep” there is no physics-case for a ~~100~~ 85 TeV pp machine
  - It lacks the “no-loose” aspect of a Higgs factory
  - Besides magnets cannot be build right now and cost is “insane” 30 B€
  - Main motivation for a 91 km tunnel and FCC-ee
- It does not rely on funding miracles

# Conclusion



- To get a next generation Higgs factory going, it needs a joined effort from the entire community
  - Accept that there is no entitlement for HEP to get “its next toy”
  - *“Bickering scientists will get nothing”* S. Ritz US P5 Chair 2015
  - Smart young people to tackle the **real** problems
- Cost is the major obstacle
  - As is sustainability – which is more than just electricity
  - Some realism is in order – is HEP entitled to a 20 B€ investment ?
- Projects can fail for various reasons – important to look at the lessons learned