C^3, a "Cool" Route to the Higgs Boson and Beyond

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Thanks to Many for Contributions / Discussions

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SLAC NATIONAL ACCELERATOR LABORATORY

Acknowledgements

Snowmass LOI

C^3: An Advanced Concept for a High Energy e^+e^- Linear Collider

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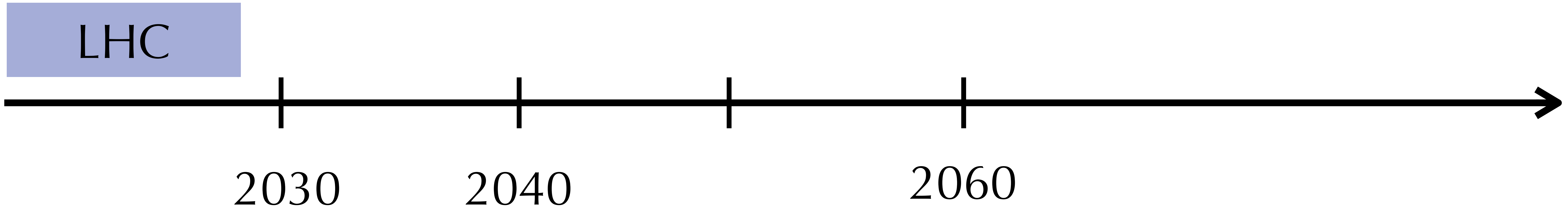
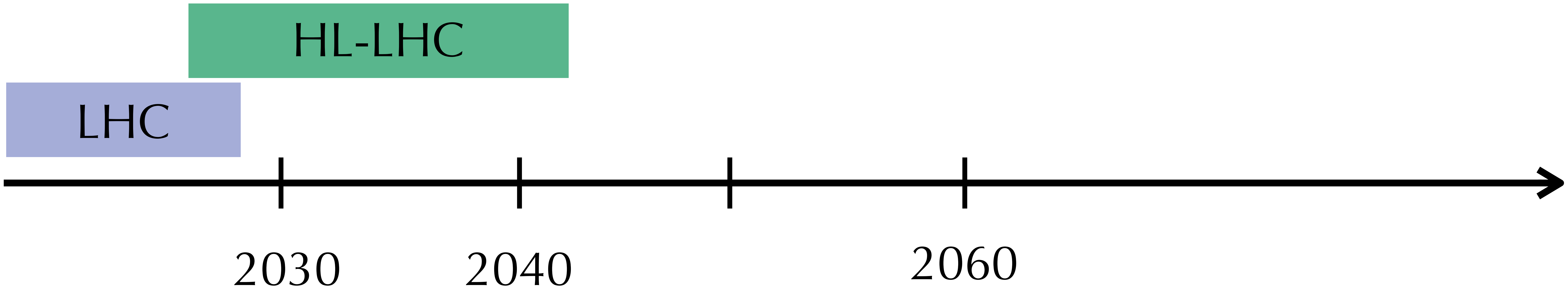
Where are we?



(some) Higgs boson couplings measured with O(5-10)% precision

Where are we?



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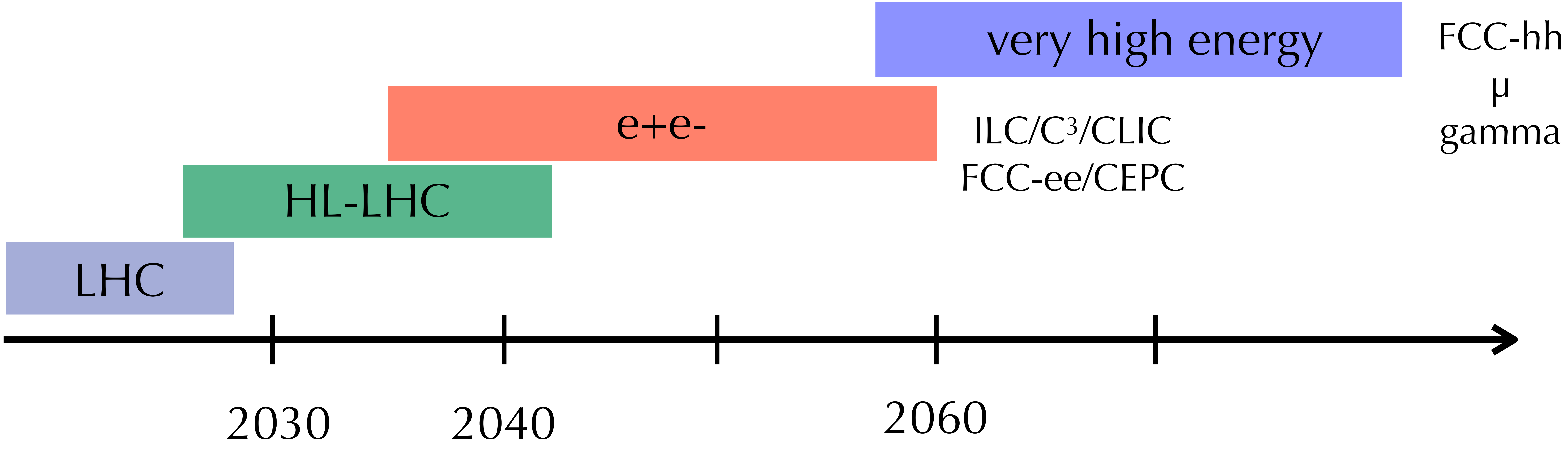
HL-LHC as a Higgs factory: 170M Higgs bosons - 120k HH pairs for 3/ab

Phase-2 HL-LHC detector upgrades are being built

What's next?

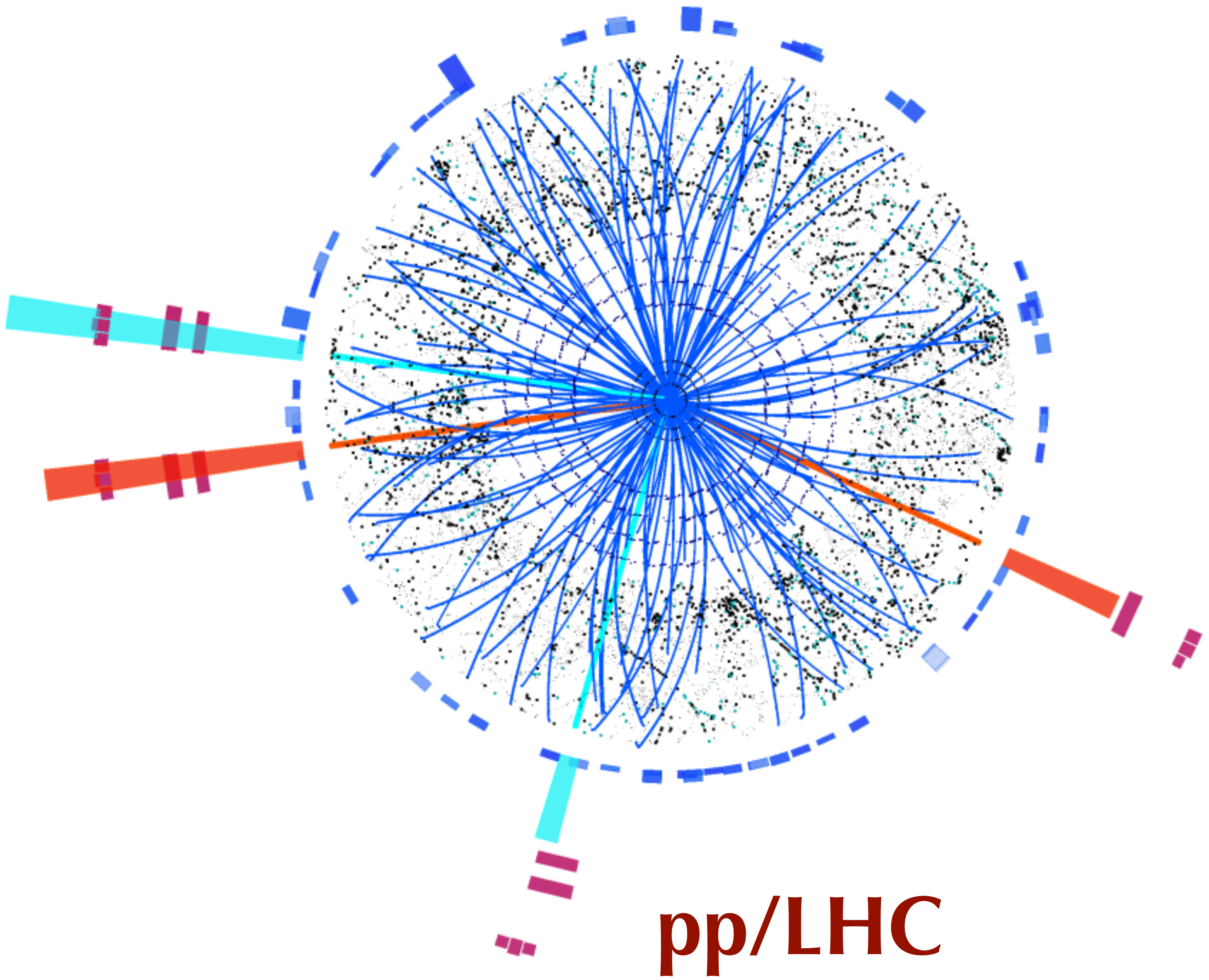


Wish list beyond HL-LHC:

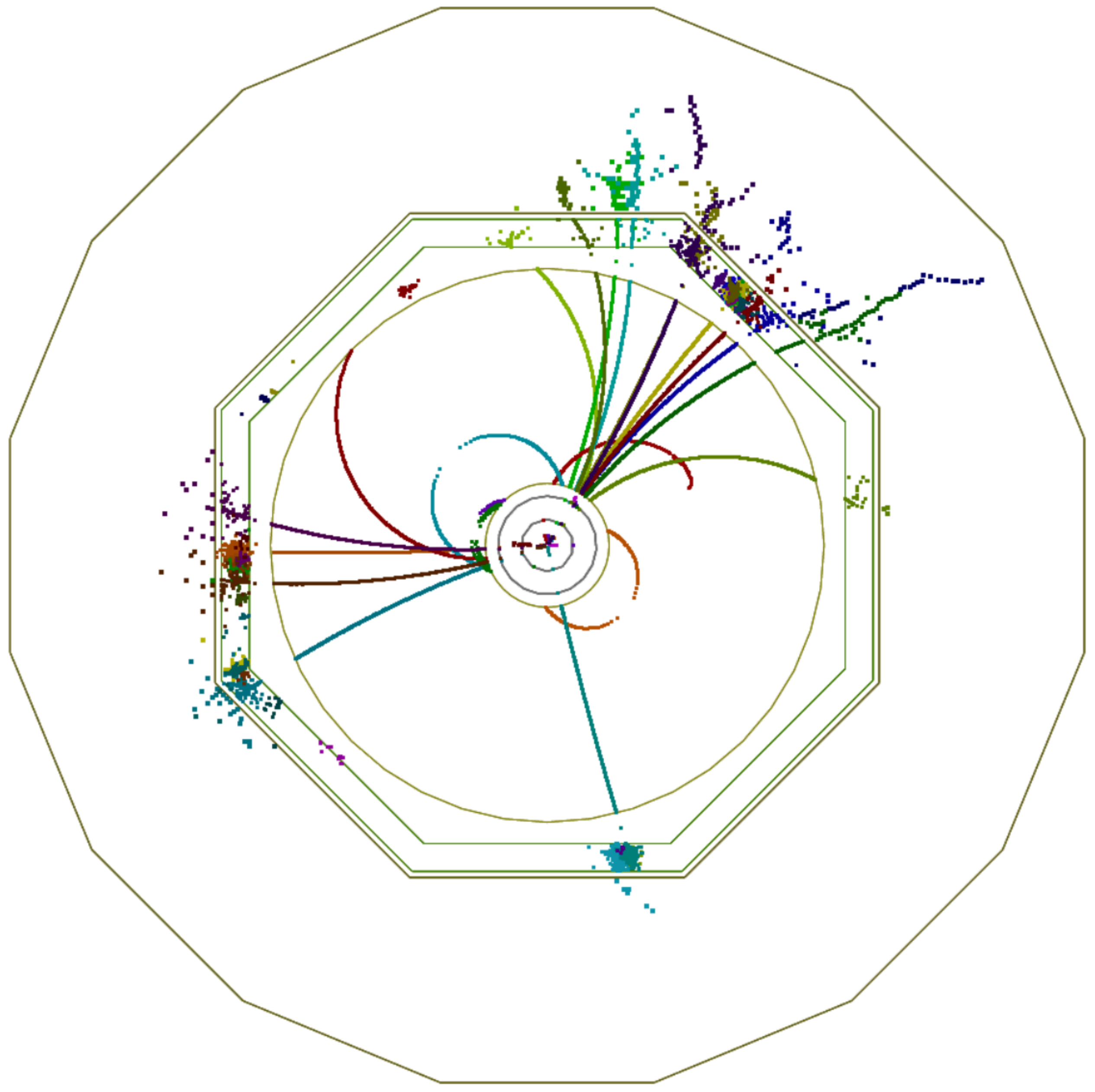
1. **Establish Yukawa couplings to light flavor $\Longrightarrow$ needs precision**
2. **Establish self-coupling $\Longrightarrow$ needs high energy**

Why e^+e^-?

- Initial state well defined & polarization $\Longrightarrow$ High-precision measurements
- Higgs bosons appear in 1 in 100 events $\Longrightarrow$ Clean experimental environment and trigger-less readout

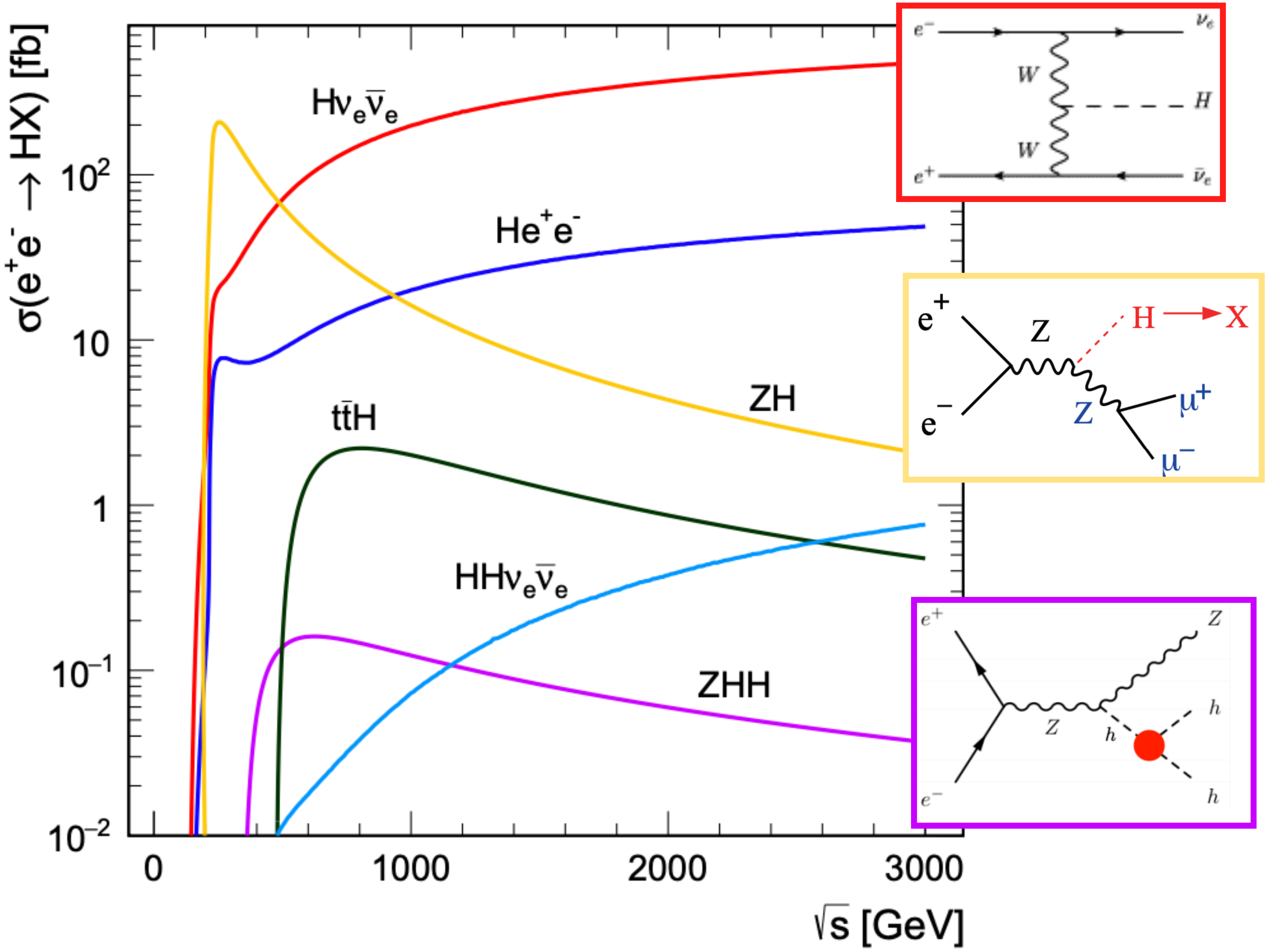


pp/LHC



e^+e^-

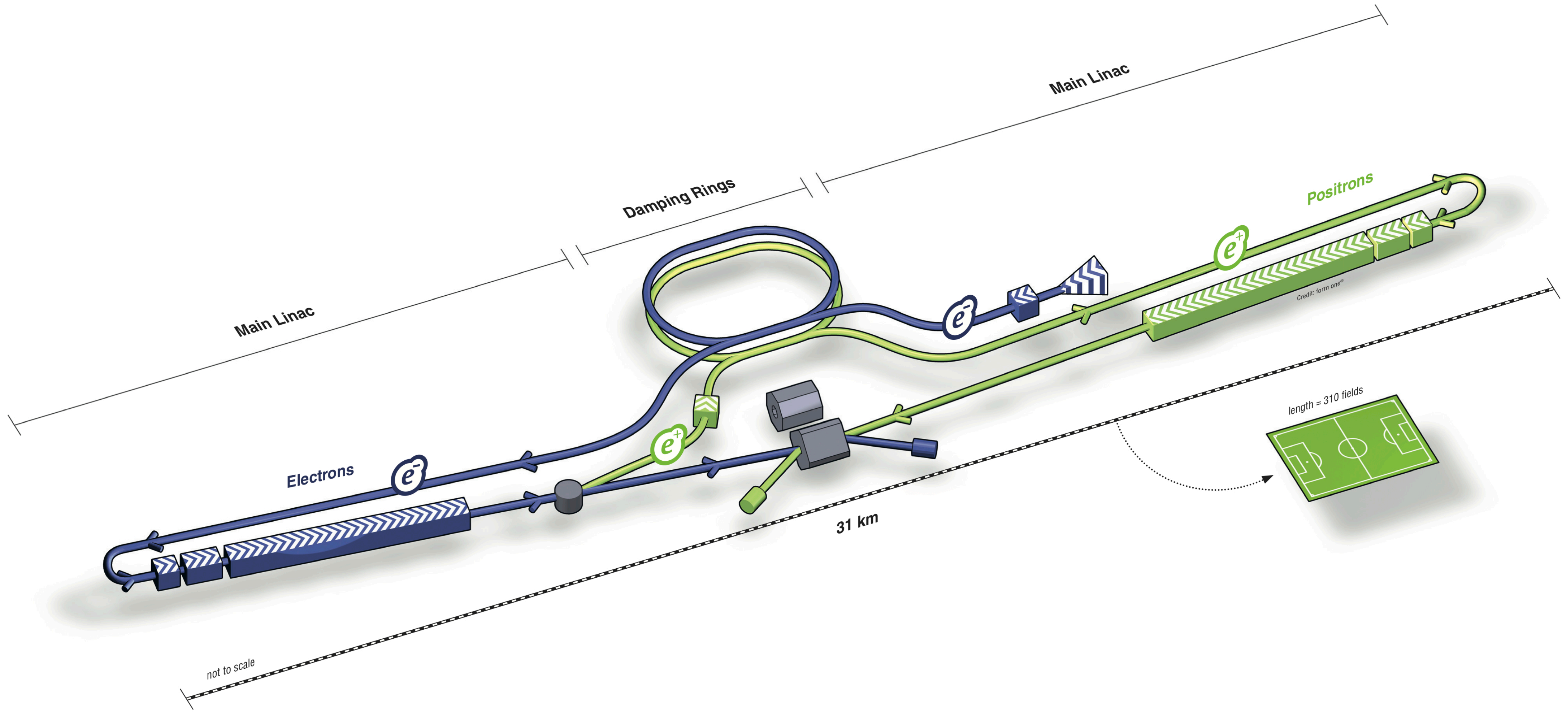
Higgs at e^+e^-

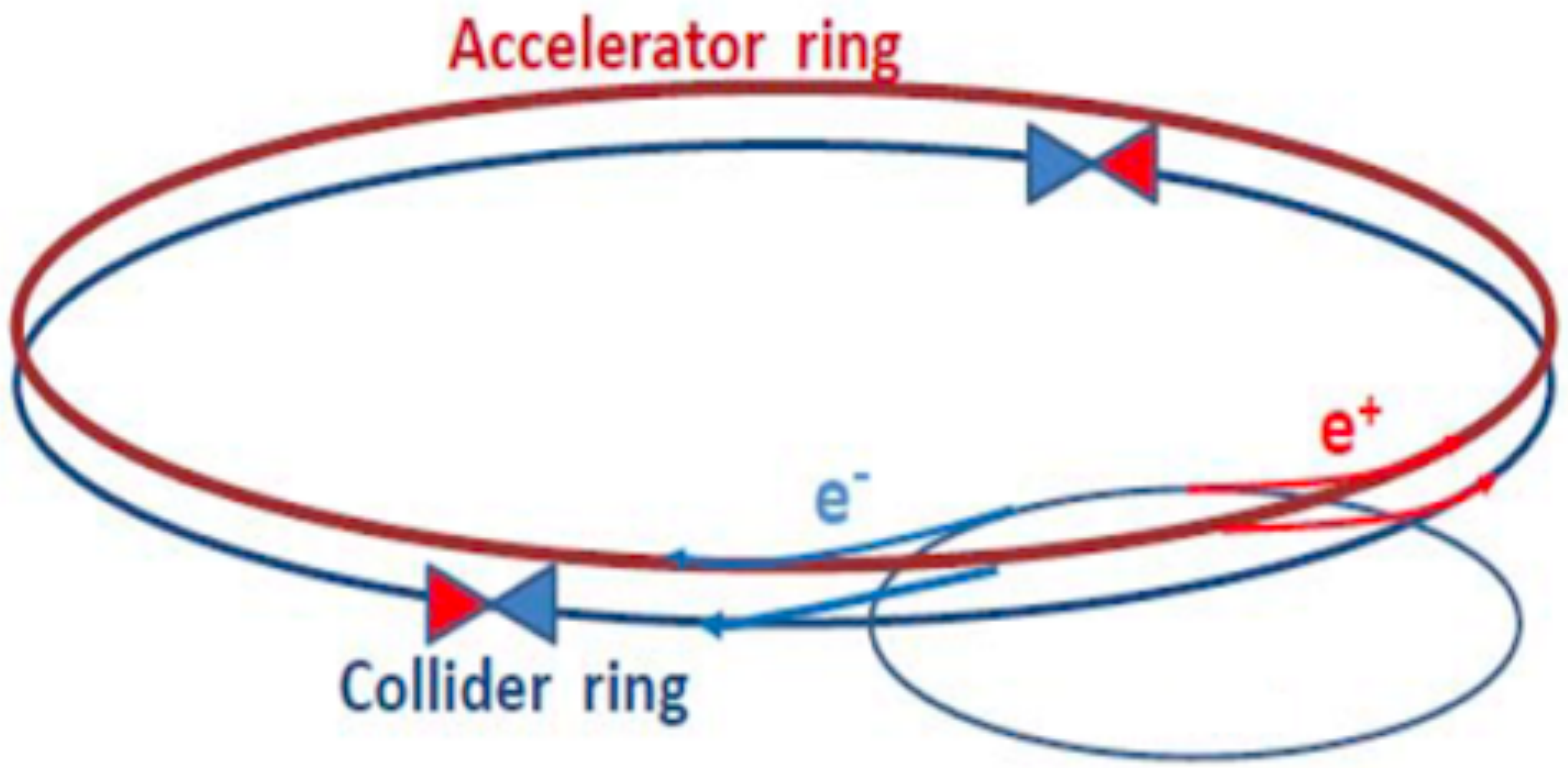


- ZH is dominant at **250 GeV**
- Above **500 GeV**
  - Hvv dominates
  - ttH opens up
  - HH production accessible with ZHH

Linear vs. Circular

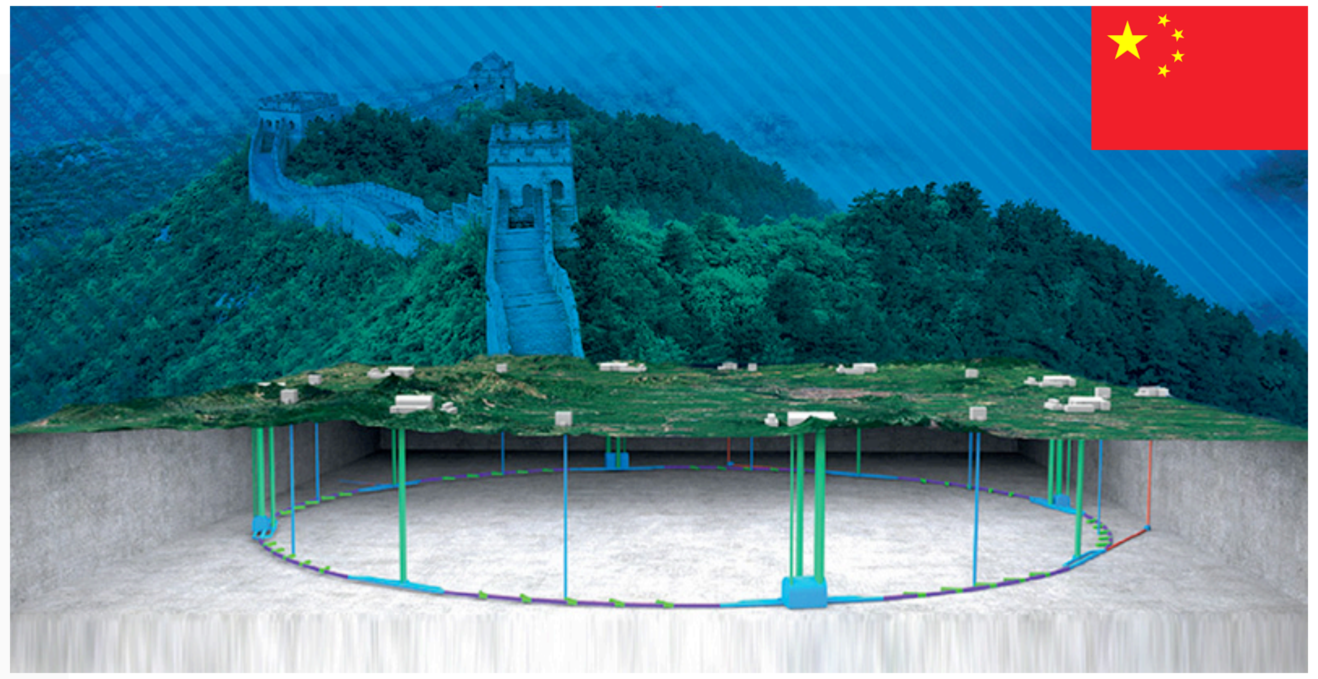
- **Linear** e^+e^- colliders: ILC, C^3, CLIC
  - Reach higher energies (~ TeV), and can use polarized beams
  - Relatively low radiation
  - Collisions in bunch trains
- **Circular** e^+e^- colliders: FCC-ee, CEPC
  - Highest luminosity collider at Z/WW/Zh
    - limited by synchrotron radiation above 350– 400 GeV
  - Beam continues to circulate after collision





Various proposals …

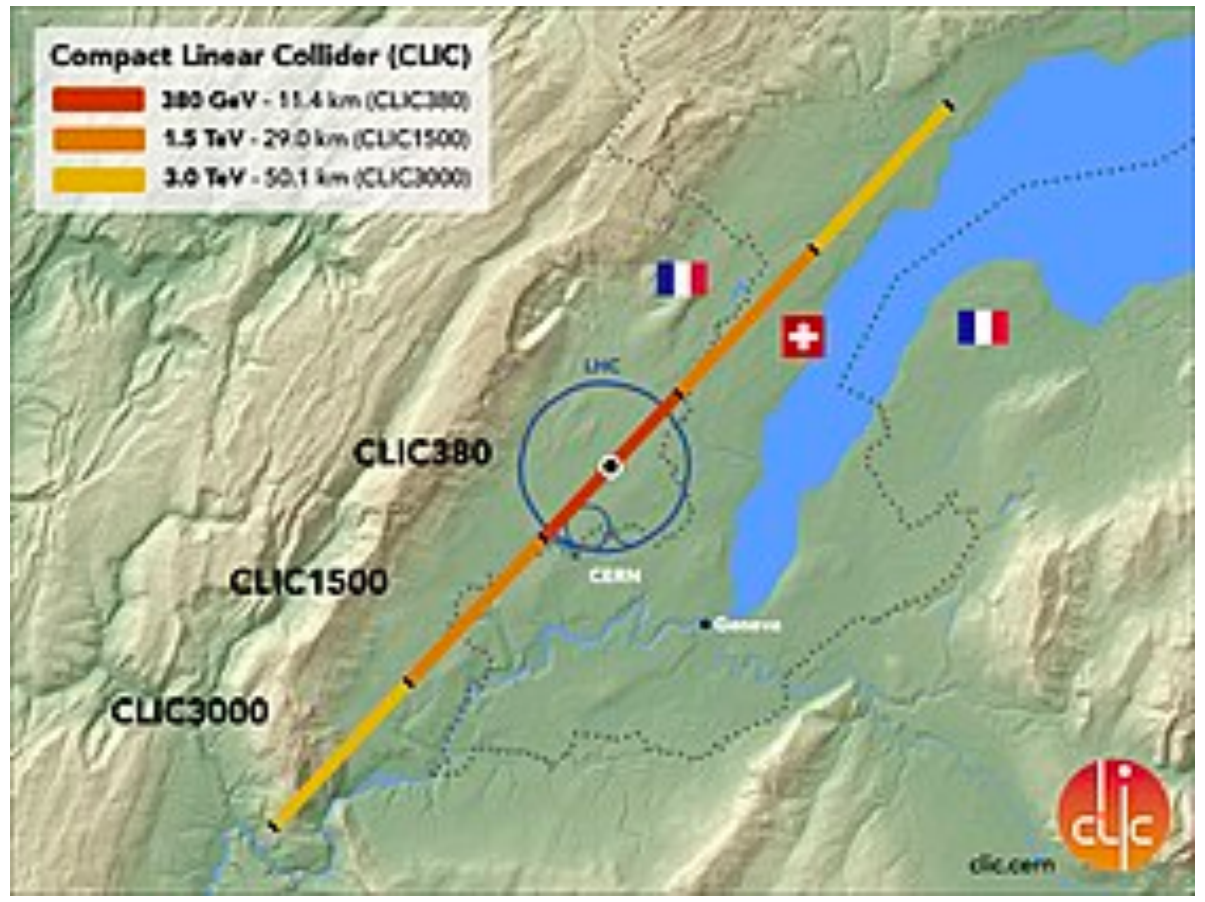
250/500 GeV

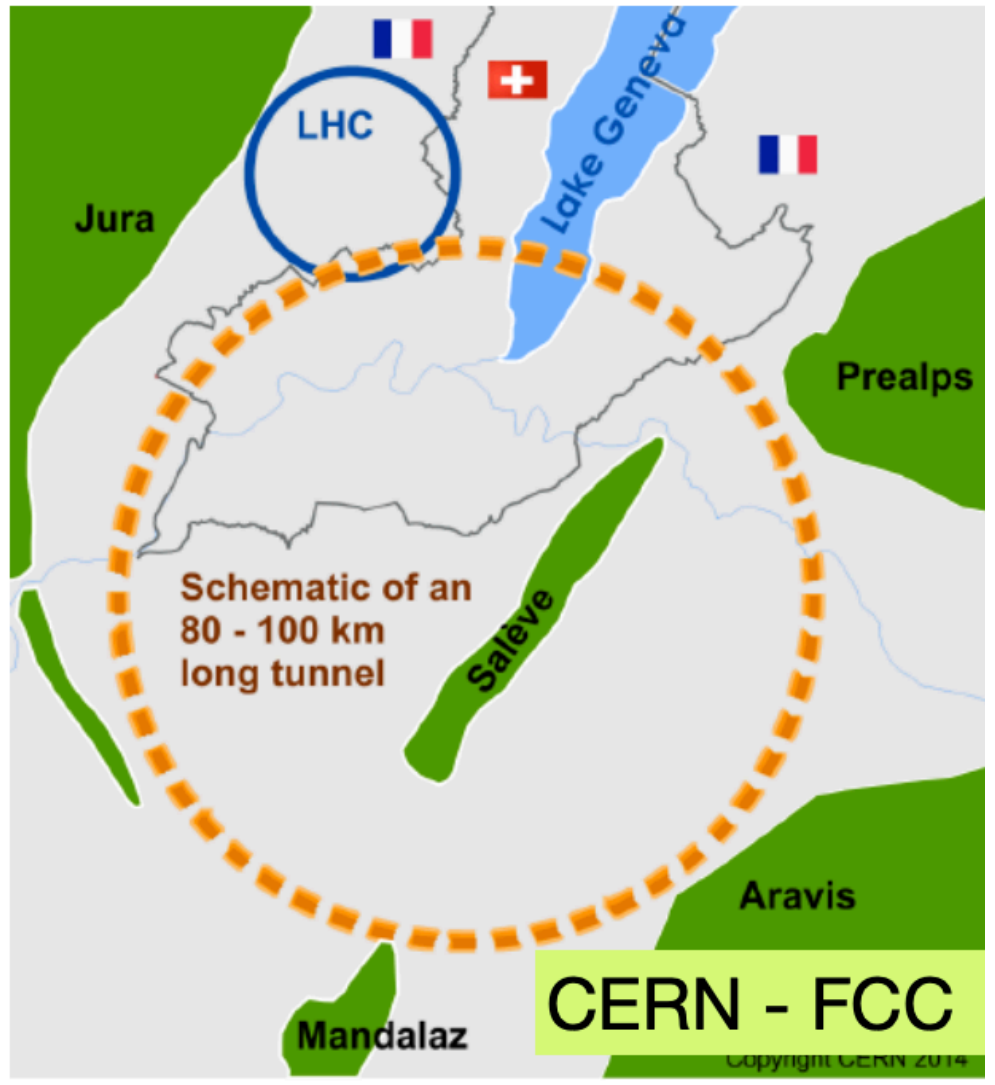


CEPC 240 GeV

250/550 GeV
… > TeV

CLIC 380/1500/3000 GeV





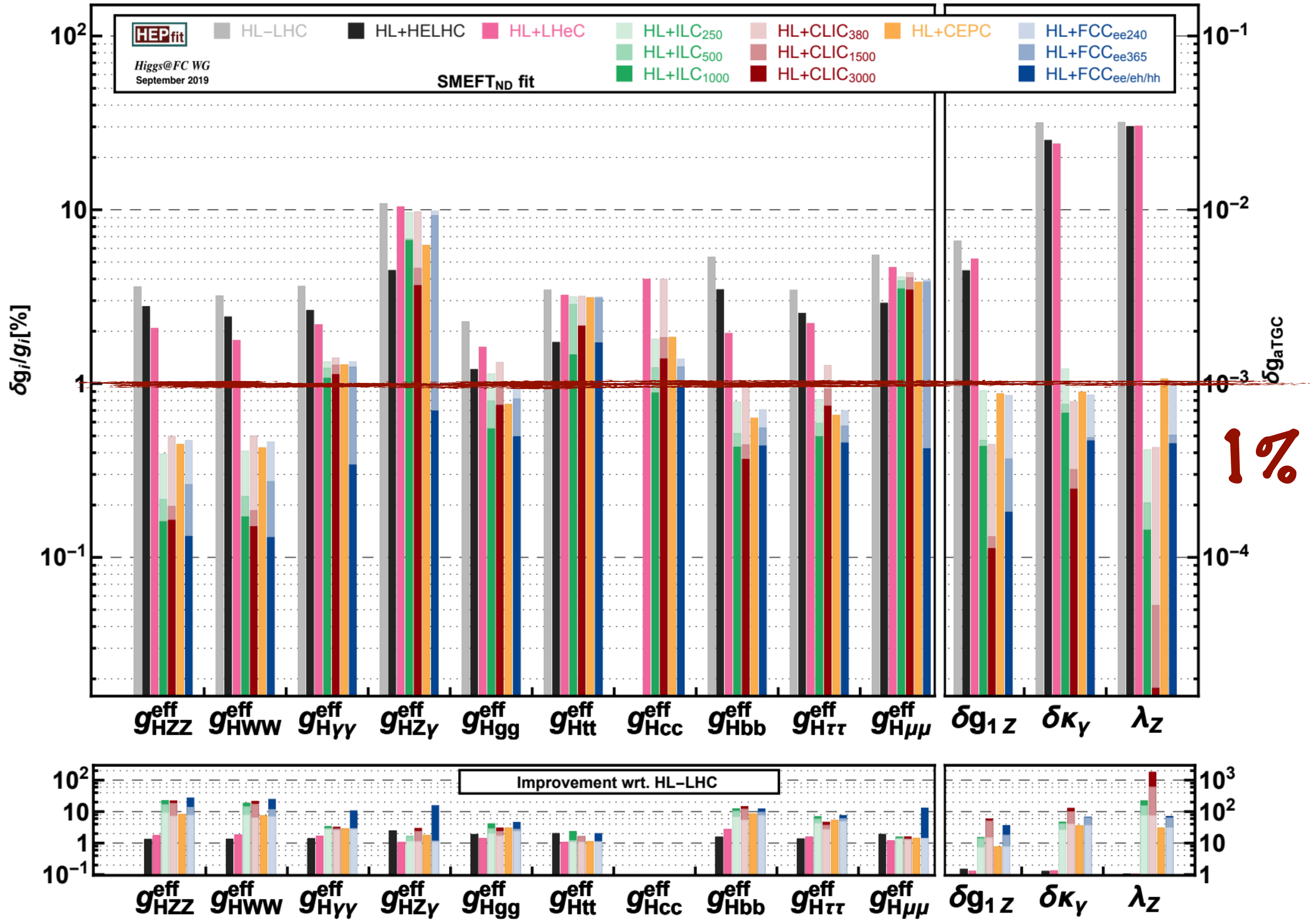
FCC-ee
240/365 GeV

Higgs couplings at future colliders

arXiv:1910.11775,arXiv:1905.03764

CERN-LPCC-2018-04

- **Coupling to W and Z** would be measured with an accuracy of few 0.1%
- **Coupling to charm and b** quarks could be measured with an accuracy of ~1% at future e+e- machines
- **Couplings to μ/γ/Zγ** benefit the most from the large dataset available at HL-LHC and not really improved at future colliders



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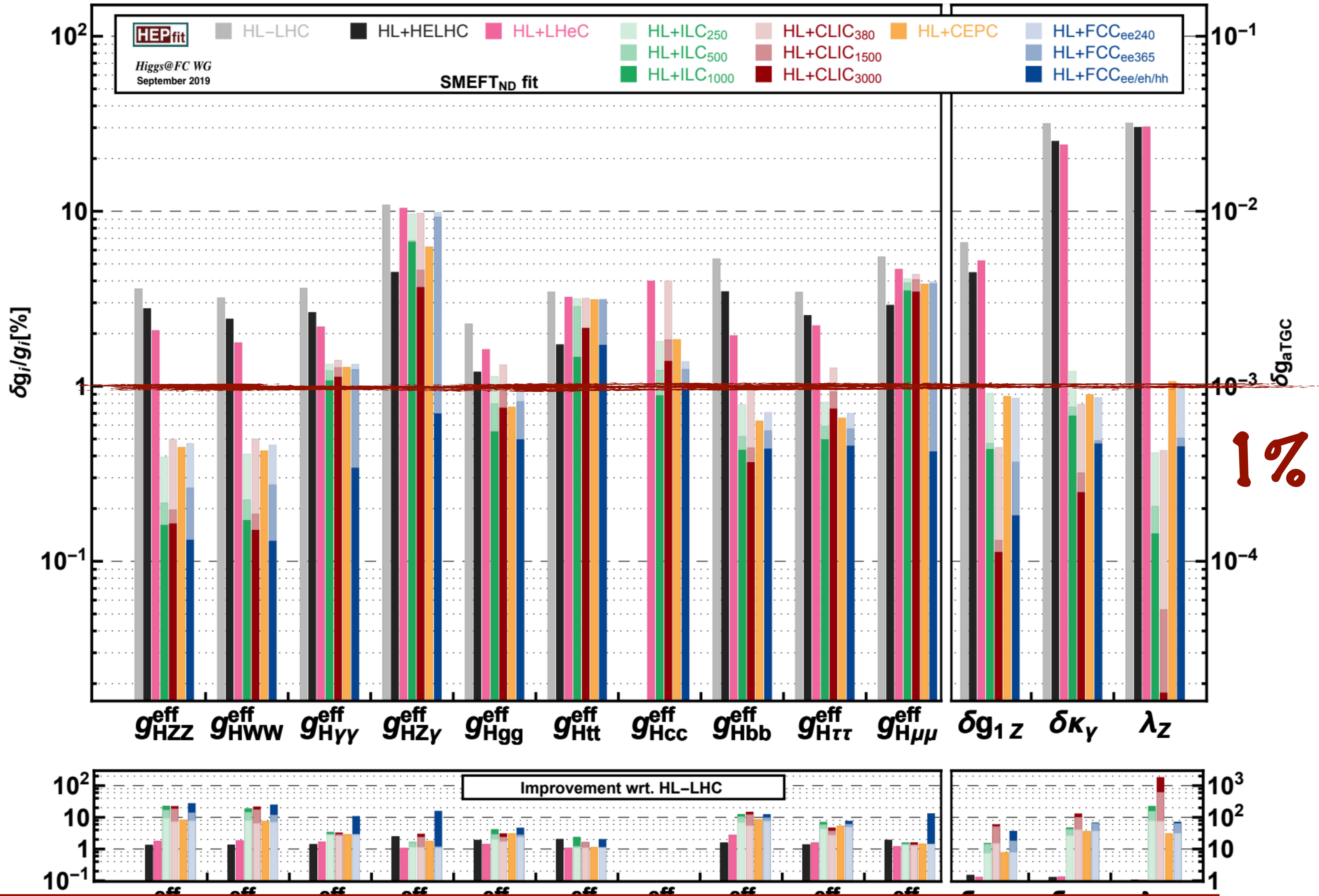
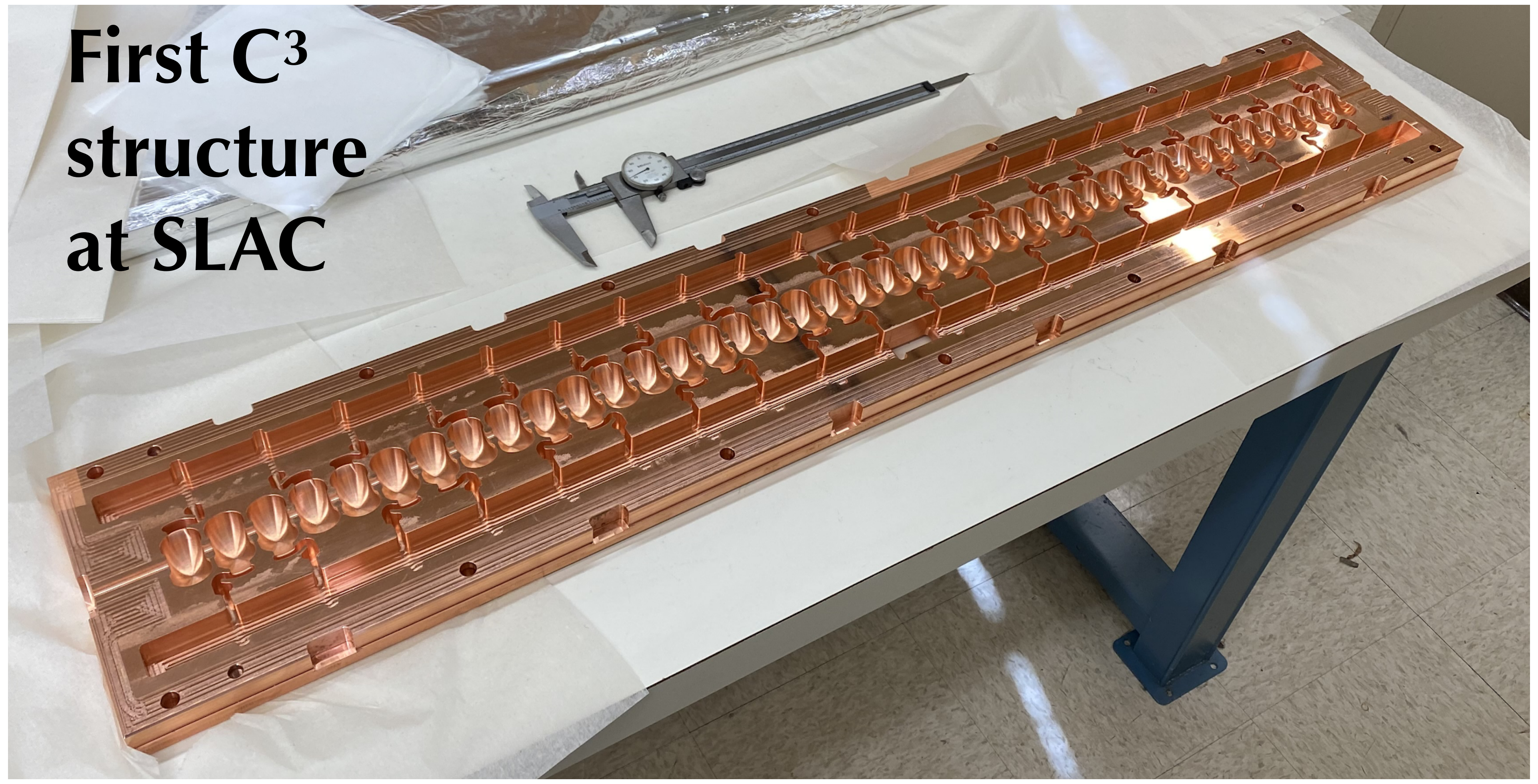


Complementarity between HL-LHC and future colliders** (depending on their timeline) **will be the key to explore the Higgs sector

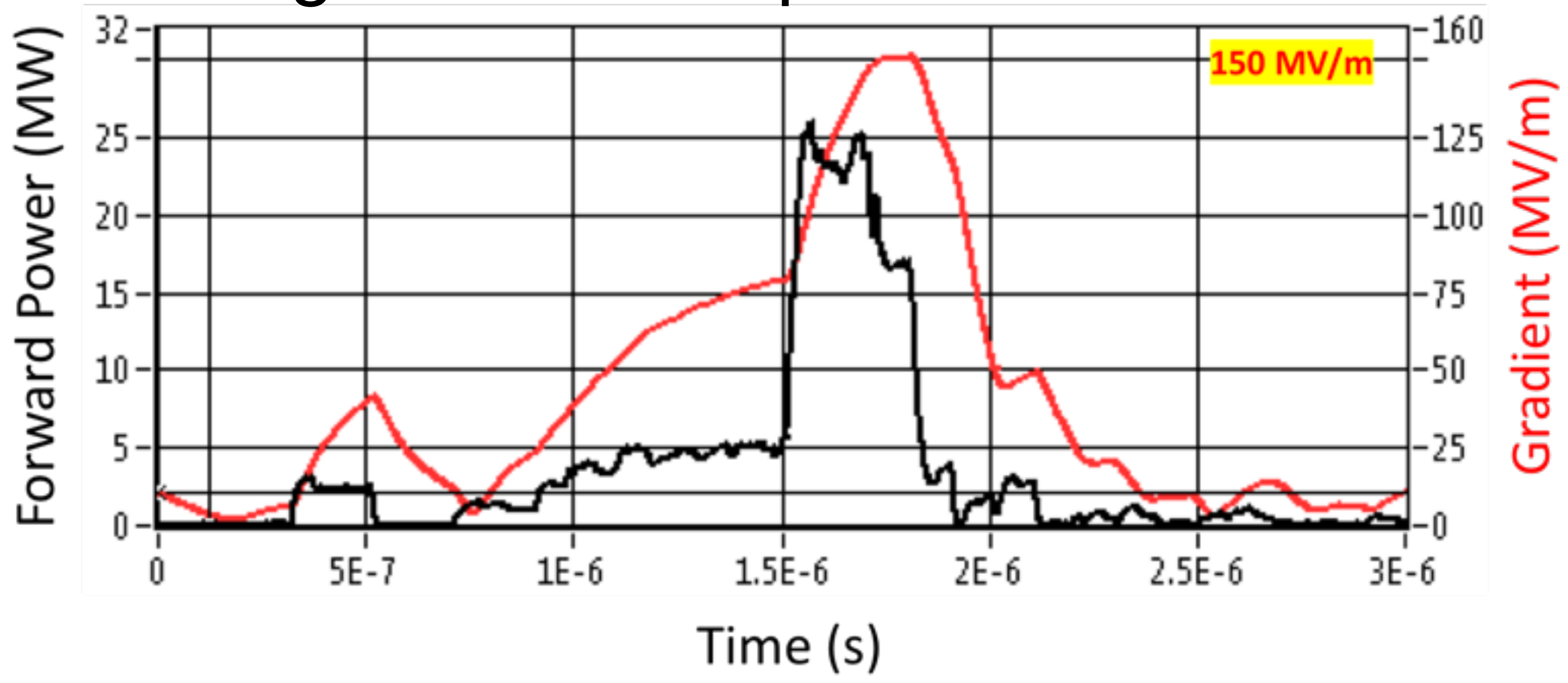
An alternative to ILC for a linear e+e- collider…

C^3 - Cool Copper Collider

- C^3 is based on a new SLAC technology
  - dramatically improving efficiency and breakdown rate
- distributed power to each cavity from a common RF manifold
- operation at cryogenic temperatures (LN2 ~80K)
- robust operations at high gradient: 120~MeV/m
- scalable to multi-TeV operation



High Gradient Operation at 150 MV/m



Why 550 GeV?

arXiv:1908.11299

We propose **250** GeV with a relatively inexpensive upgrade to **550** GeV on the same 8 km footprint.

- 550 GeV will offer an orthogonal dataset to cross-check a deviation from the SM predictions observed at 250 GeV
- O(20%) precision on the Higgs self-coupling would allow to exclude/ demonstrate at 5σ models of electroweak baryogenesis
- From 500 to 550 GeV a factor 2 improvement to the top-Yukawa coupling

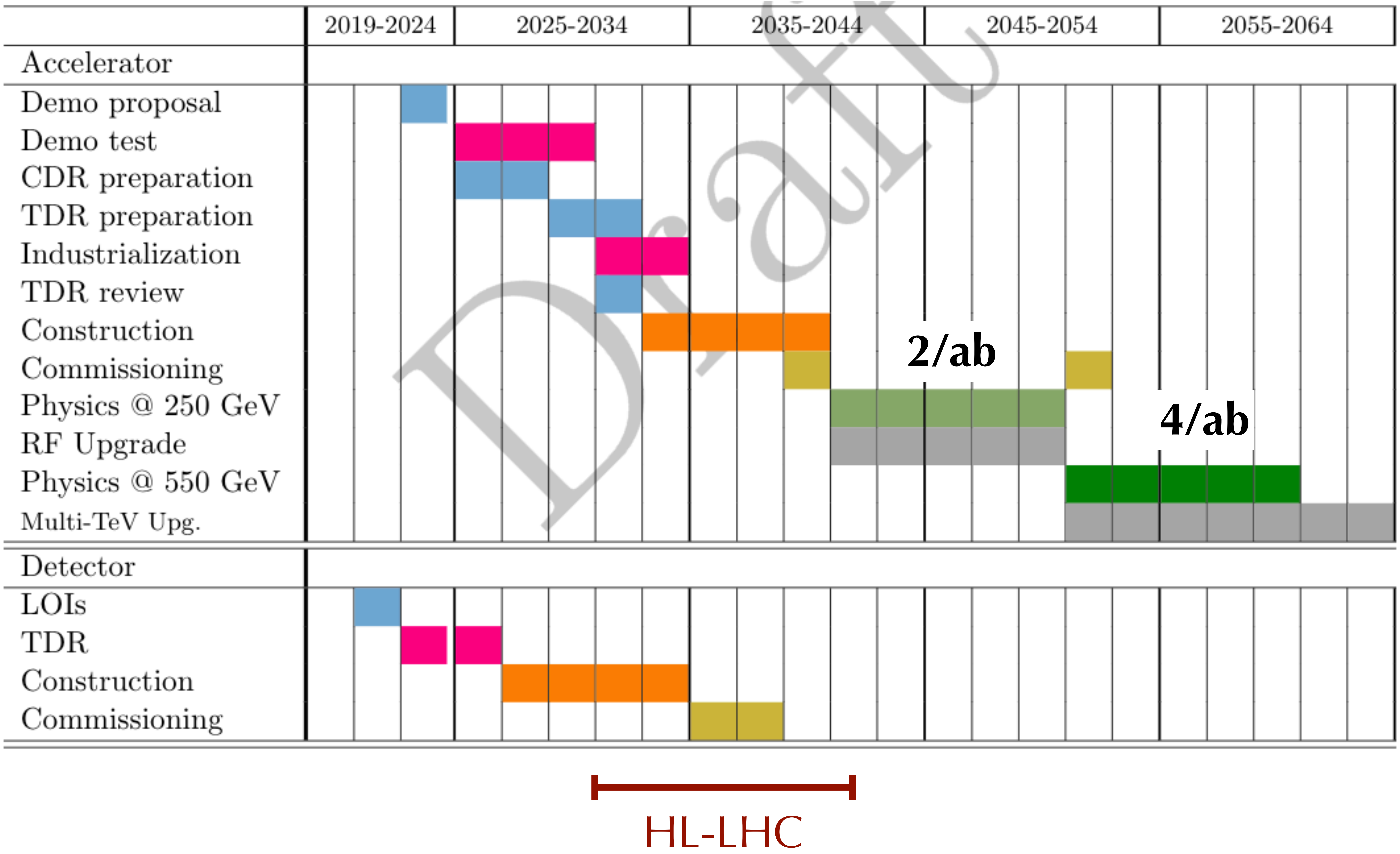
Collider Luminosity Polarization	HL-LHC 3 ab^{-1} in 10 yrs -	C^3 /ILC 250 GeV 2 ab^{-1} in 10 yrs $\mathcal{P}_{e^+} = 30\%$ (0%)	C^3 /ILC 500 GeV + 4 ab^{-1} in 10 yrs $\mathcal{P}_{e^+} = 30\%$ (0%)
g_{HZZ} (%)	3.2	0.38 (0.40)	0.20 (0.21)
g_{HWW} (%)	2.9	0.38 (0.40)	0.20 (0.20)
g_{Hbb} (%)	4.9	0.80 (0.85)	0.43 (0.44)
g_{Hcc} (%)	-	1.8 (1.8)	1.1 (1.1)
g_{Hgg} (%)	2.3	1.6 (1.7)	0.92 (0.93)
$g_{H\tau\tau}$ (%)	3.1	0.95 (1.0)	0.64 (0.65)
$g_{H\mu\mu}$ (%)	3.1	4.0 (4.0)	3.8 (3.8)
$g_{H\gamma\gamma}$ (%)	3.3	1.1 (1.1)	0.97 (0.97)
$g_{HZ\gamma}$ (%)	11.	8.9 (8.9)	6.5 (6.8)
g_{Htt} (%)	3.5	–	3.0 (3.0)*
g_{HHH} (%)	50	49 (49)	22 (22)
Γ_H (%)	5	1.3 (1.4)	0.70 (0.70)

One note on polarization

- There are extensive comparisons between the FCC-ee plan and the C3/ILC runs that show they are rather **compatible to study the Higgs Boson**
- When analyzing Higgs couplings with SMEFT, 2 ab^{-1} of polarized running is essentially equivalent to 5 ab^{-1} of unpolarized running.
  - **Electron polarization is essential** for this. But, there is almost no difference in the expectation with and without positron polarization.
  - Positron polarization allows more cross-checks of systematic errors. We may wish to add it later.
  - Positron polarization brings a large advantage in multi-TeV running, where the most important cross sections are from $e^-_L e^+_R$

coupling	2/ab-250 pol.	+4/ab-500 pol.	5/ab-250 unpol.	+ 1.5/ab-350 unpol
HZZ	0.50	0.35	0.41	0.34
HWW	0.50	0.35	0.42	0.35
Hbb	0.99	0.59	0.72	0.62
$H\tau\tau$	1.1	0.75	0.81	0.71
Hgg	1.6	0.96	1.1	0.96
Hcc	1.8	1.2	1.2	1.1
$H\gamma\gamma$	1.1	1.0	1.0	1.0
$H\gamma Z$	9.1	6.6	9.5	8.1
$H\mu\mu$	4.0	3.8	3.8	3.7
Htt	-	6.3	-	-
HHH	-	27	-	-
Γ_{tot}	2.3	1.6	1.6	1.4
Γ_{inv}	0.36	0.32	0.34	0.30
Γ_{other}	1.6	1.2	1.1	0.94

C^3 timeline

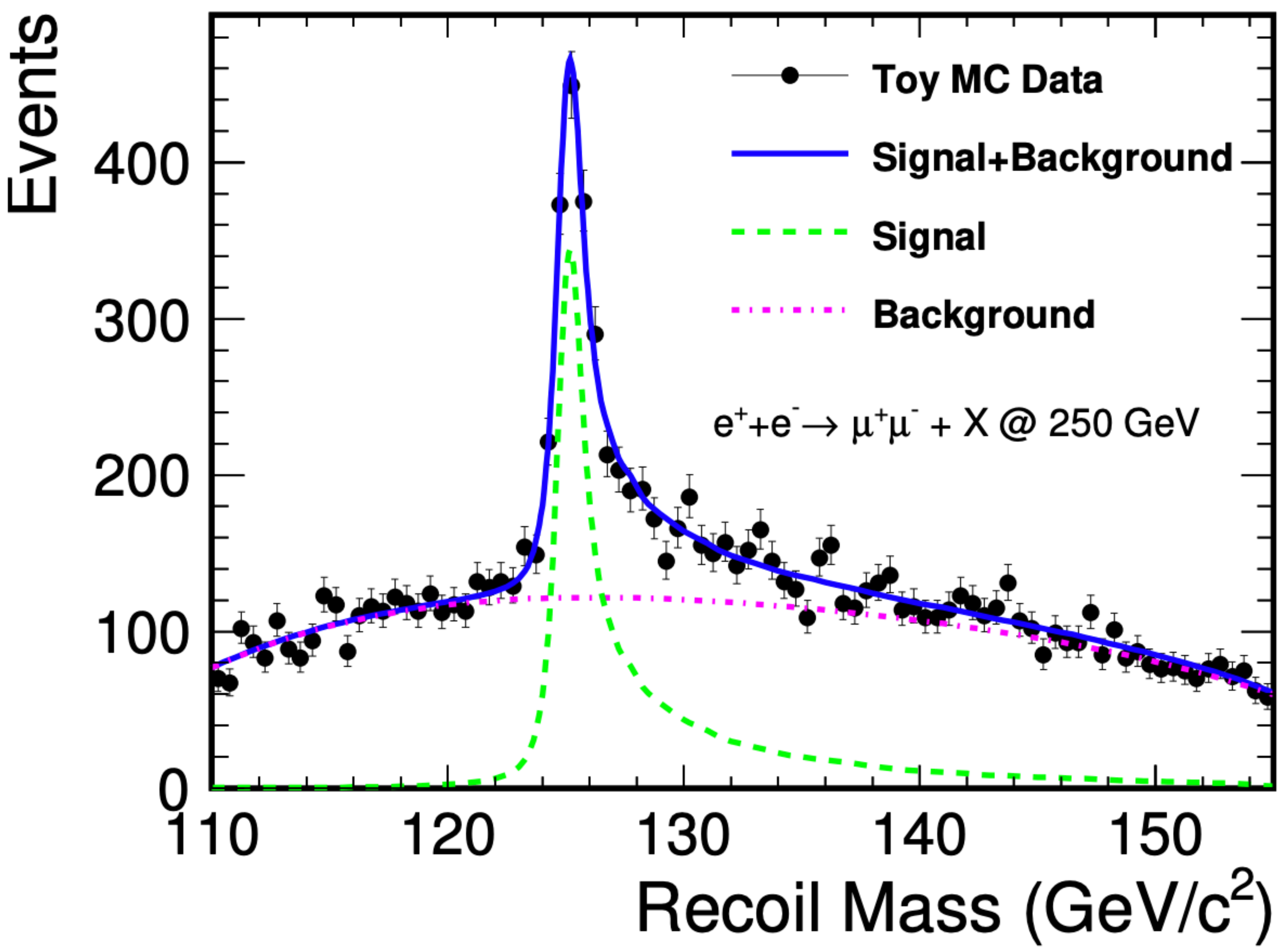


2019-2024
2025-2034
2035-2044
2045-2054
2055-2064
Accelerator
Demo proposal
Demo test
CDR preparation
TDR preparation
Industrialization
TDR review
Construction
Commissioning
Physics @ 250 GeV
RF Upgrade
Physics @ 550 GeV
Multi-TeV Upg.
Detector
LOIs
TDR
Construction
Commissioning
2/ab
4/ab
Draft
HL-LHC

Physics requirements for tracking detectors

arXiv:2003.01116

- **ZH process**: Higgs recoil reconstructed from Z →μμ
  - Drives requirement on charged track momentum and jet resolutions
  - Sets need for high field magnets and high precision / low mass trackers
  - **Bunch time structure allows high precision trackers with very low X_0 at linear e^+e^- colliders**
- **Higgs → bb/cc decays**: Flavor tagging & quark charge tagging at unprecedented level
  - Drives requirement on charged track impact parameter resolution → **low mass trackers near IP**
    - <0.3% X0 per layer (ideally 0.1% X_0) for vertex detector



Need new generation of ultra low mass vertex detectors with dedicated sensor designs

Detector Design Requirements

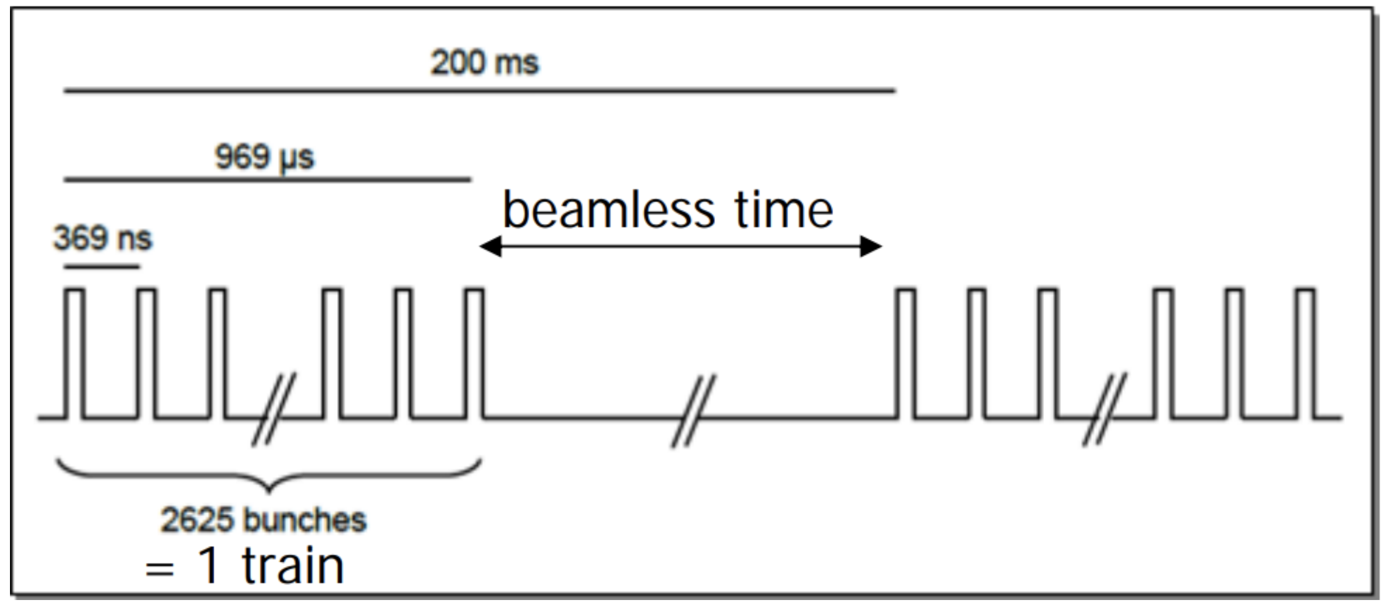
ILC timing structure: Fraction of a percent duty cycle

- **Power pulsing possible**, significantly reduce heat load
    - Factor of 50-100 power saving for FE analog power
- Tracking detectors **don't need active cooling**
    - Significantly reduction for the material budget
- **Triggerless readout** is the baseline

C^3 time structure is compatible with SiD-like detector overall design and ongoing optimizations.

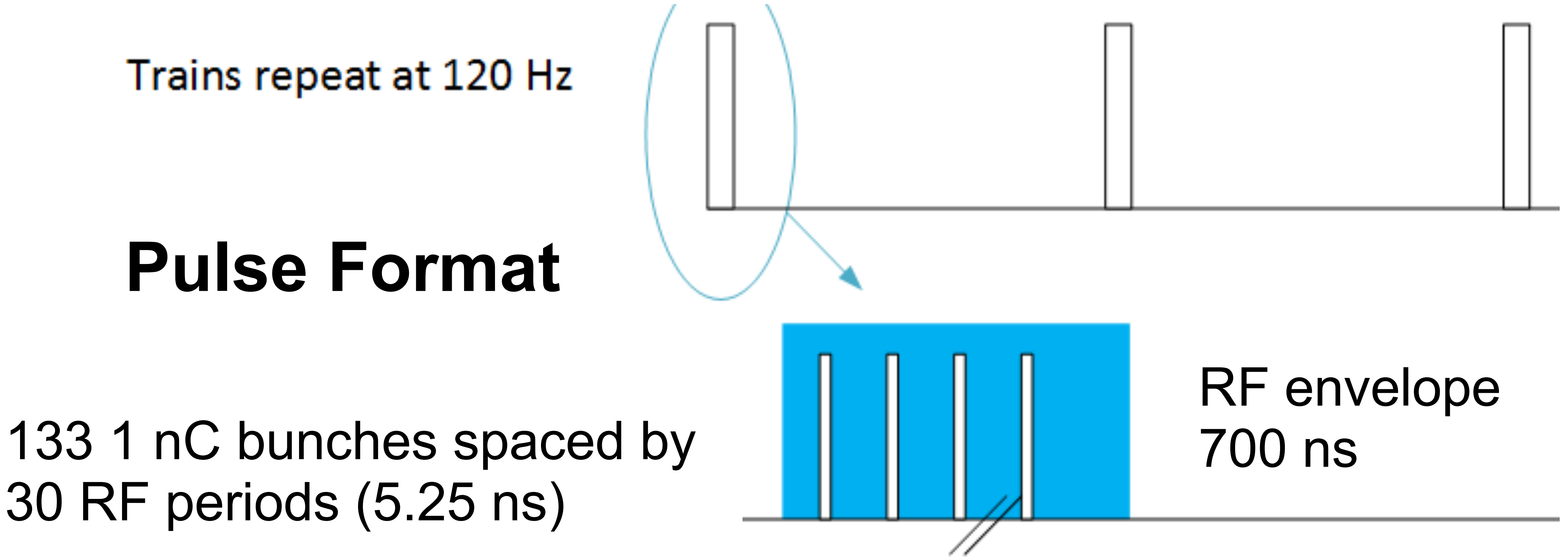
Collider	ILC	CCC
σ_z	300 μm	100 μm
β_x	8.0 mm	13 mm
β_y	0.41 mm	0.1 mm
ϵ_x	500 nm/rad	900 nm/rad
ϵ_y	35 nm/rad	20 nm/rad
N bunches	1312	133
Repetition rate	5 Hz	120 Hz
Crossing angle	0.014	0.020
Crab angle	0.014/2	0.020/2

ILC timing structure



1 ms long bunch trains at 5 Hz
2820 bunches per train
308ns spacing

C^3 timing structure

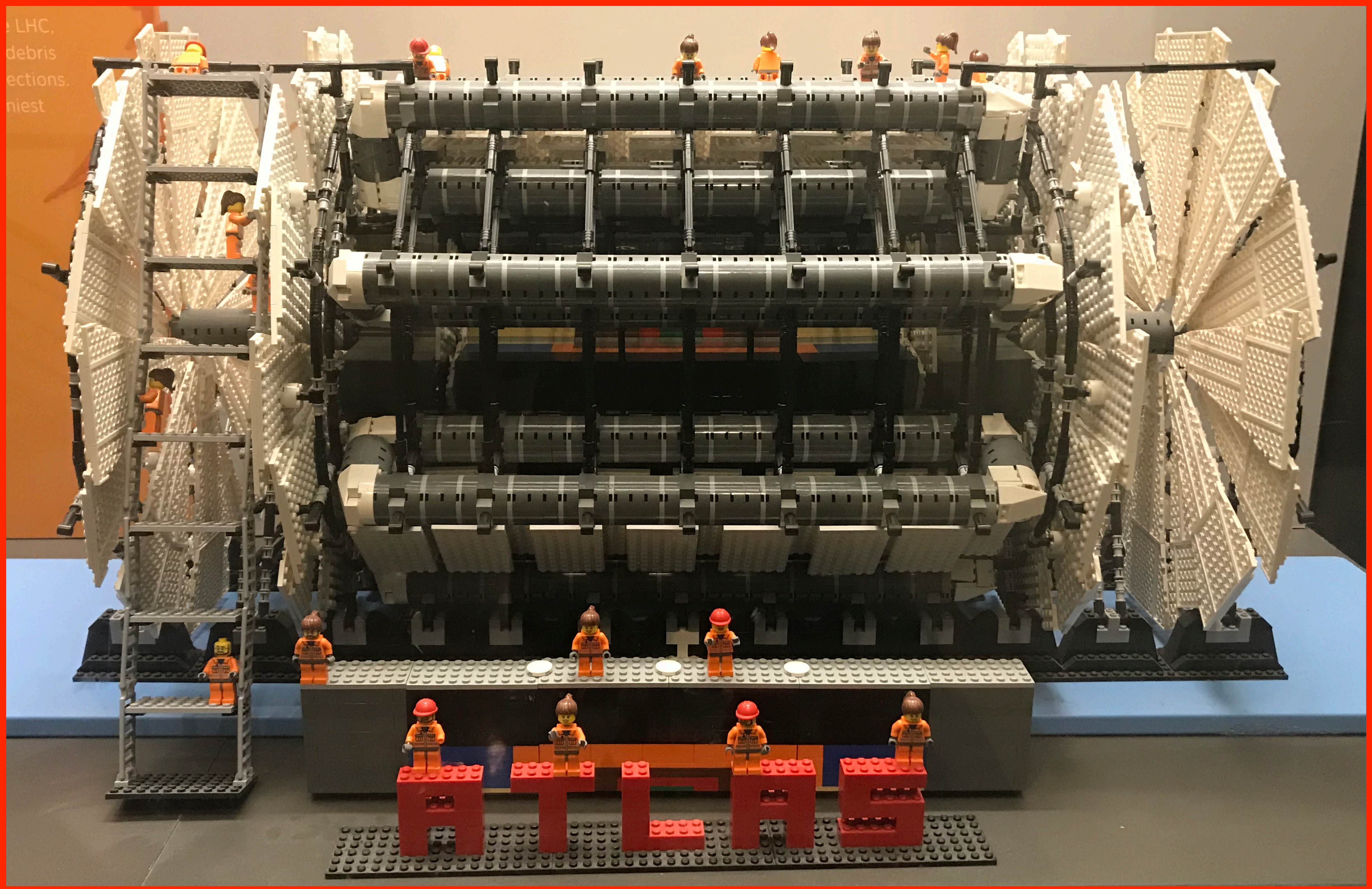


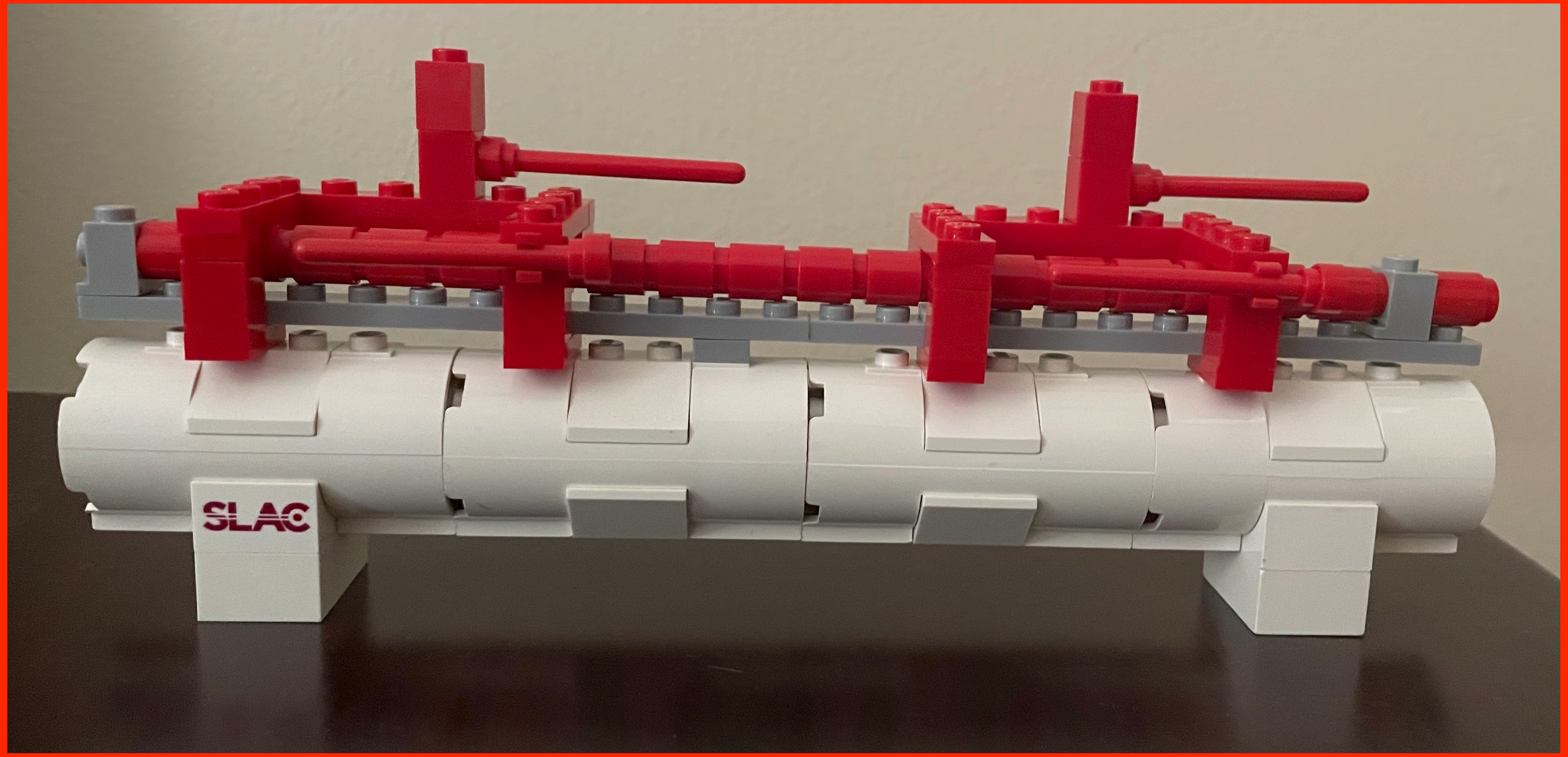
Demonstration concept

- We are proposing a demonstration facility to carry out a “string test” of three C^3 cryomodules.
- This step is included in our timeline. The cost is O(100) M$.
  - This demonstration directly benefits development of compact FELs for photon science.
- The other elements needed for a linear collider - the sources, damping rings, and beam delivery system - already have mature designs created for the ILC and CLIC.
  - Our current baseline uses these directly although we will look for further cost-optimizations for the specific needs of the C^3
- If the machine is constructed outward from the collision point, it may be possible to do physics at an intermediate stage in the construction at 91 GeV.
  - We do not consider this a part of our baseline, but we mention the possibility in case there is community interest for a Giga-Z (2 yrs) program.

Conclusions

- C^3 can provide a rapid route to precision Higgs physics with a compact 8 km footprint
  - ***Higgs physics run by 2040***
  - ***Possibly, a US-hosted facility***
- C^3 can be quickly and inexpensively upgraded to 550 GeV
- C^3 can be extended to a 3 TeV e^+e^- collider with capabilities similar to CLIC
- With new ideas, the C^3 lab can provide physics at 10 TeV and beyond

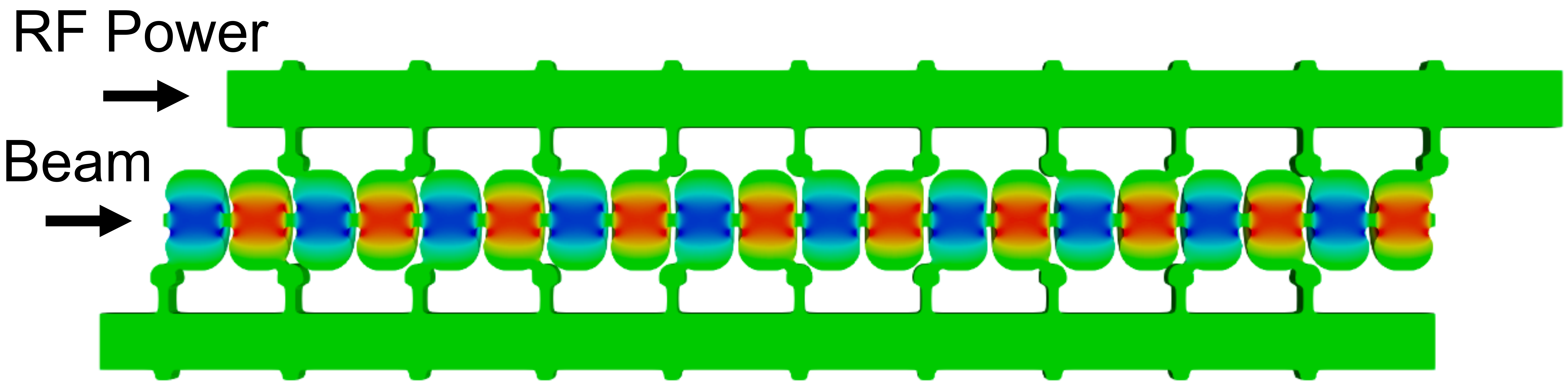




Extra

Breakthrough in the Performance of RF Accelerators

- RF power coupled to each cell – no on-axis coupling
- Full system design requires modern virtual prototyping



Electric field magnitude produced when RF manifold feeds alternating cells equally

- Optimization of cell for efficiency (shunt impedance)

  $R_s = G^2/P$ [MΩ /m]

- Control peak surface electric and magnetic fields
  - Key to high gradient operation

Tantawi, Sami, et al. "Design and demonstration of a distributed-coupling linear accelerator structure." *Physical Review Accelerators and Beams* 23.9 (2020): 092001.

The Higgs self-coupling at future colliders

arXiv:1910.00012
arXiv:2004.03505

collider	single-H	HH	combined
HL-LHC	100-200%	50%	50%
$CEPC_{240}$	49%	–	49%
ILC_{250}	49%	–	49%
ILC_{500}	38%	27%	22%
ILC_{1000}	36%	10%	10%
$CLIC_{380}$	50%	–	50%
$CLIC_{1500}$	49%	36%	29%
$CLIC_{3000}$	49%	9%	9%
FCC-ee	33%	–	33%
FCC-ee (4 IPs)	24%	–	24%
HE-LHC	-	15%	15%
FCC-hh	-	5%	5%

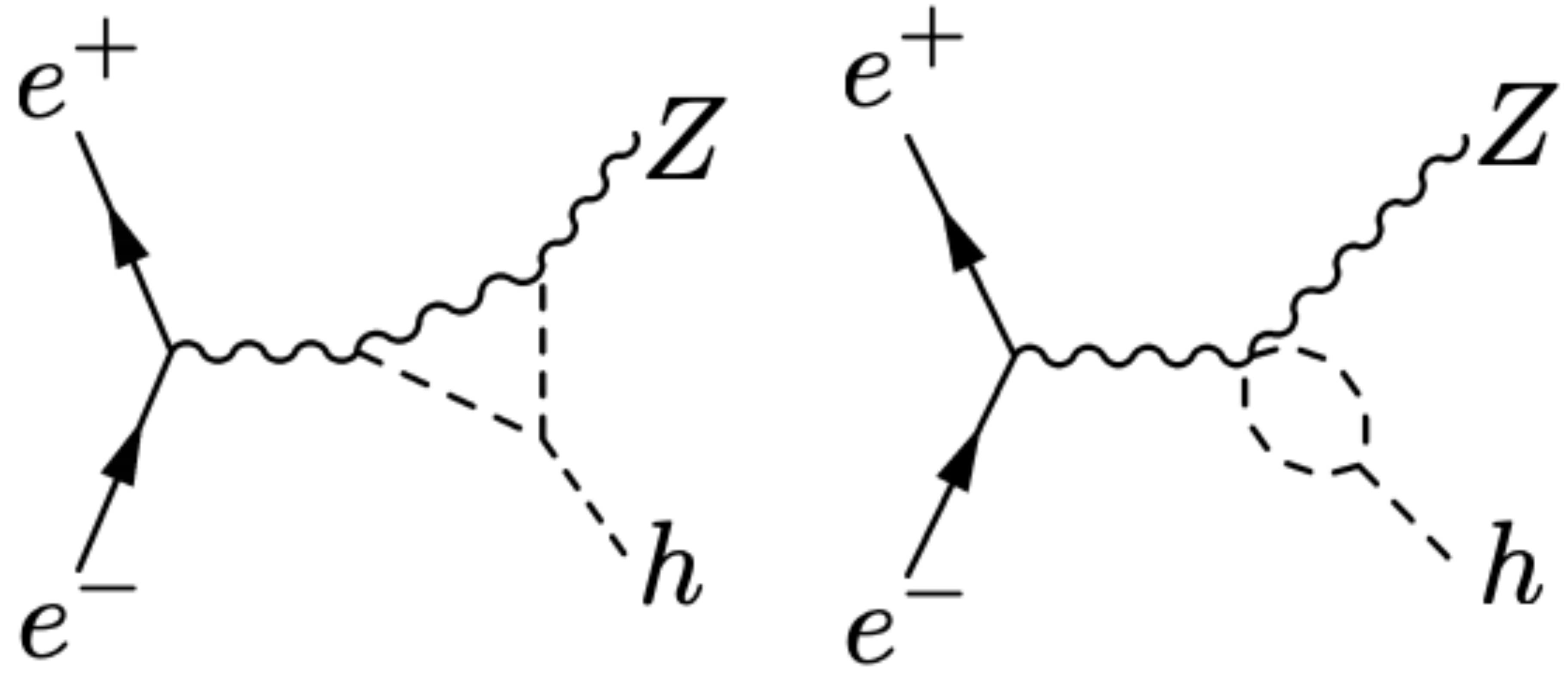
These values are combined with an independent determination of the self-coupling with uncertainty 50% from the HL-LHC.

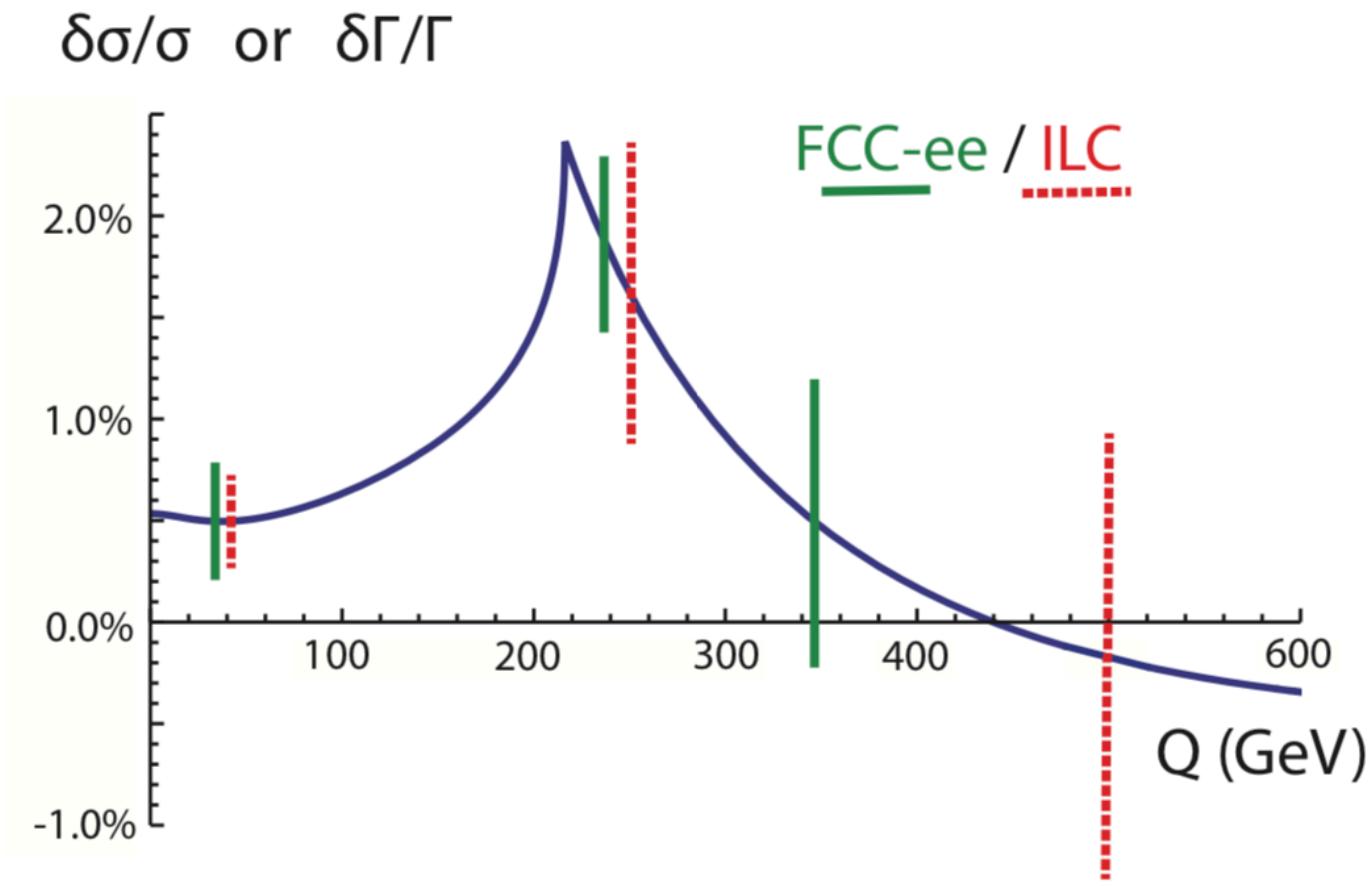
Self-coupling at e+e-

arXiv:1312.3322
arXiv:1910.00012

The self-coupling could be determined also through single Higgs processes

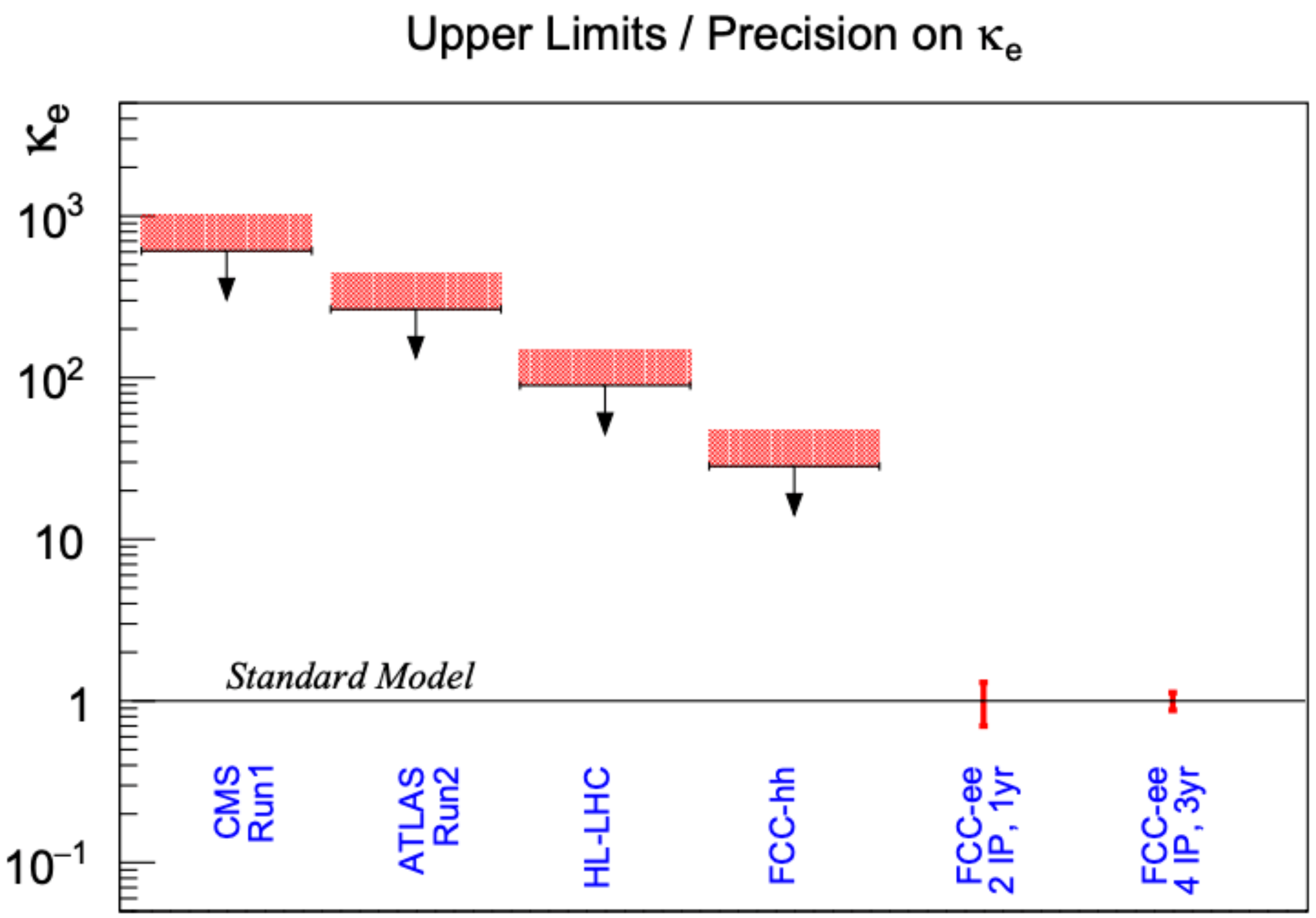
- Relative enhancement of the e+e− → ZH cross-section and the H→W+W− partial width
- Need multiple Q^2 to identify the effects due to the self-coupling





Higgs at e+e-

1912.11871



- Circular lepton colliders - FCC-ee - provide the highest luminosities at lower centre-of-mass energies
  - Unique opportunity to measure the Higgs boson coupling to electrons through the resonant production process e +e – → H at √ s = 125 GeV
  - FCC-ee running at H pole-mass with 20/ab would produce O(30.000) H's reaching SM sensitivity
    - Requires control of beam-energy spread