European Course to the High-Energy Frontier

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Abstract

- We review the capabilities of two projects that have been proposed as the next major European facility: CLIC and FCC.
- We focus on their physics potentials and emphasise the key differences between the linear or circular approaches.
- Largely based on arXiv:1912.13466

European Strategy for Particle Physics

- The Update of the European Particle Physics Strategy started with a broad consultation of the European particle physics community.
  - Open Symposium, Granada, May 2019
  - Briefing Book for the 2020 European Strategy Particle Physics Update (250 pages)
- The process culminated in a dedicated meeting of the European Strategy Group (ESG)
  - representatives of the CERN's Member States and of the major European laboratories
  - representatives of particle physics communities from outside Europe.
  - Strategy drafting meeting, Bad Honnef, Januray 2020
- The Strategy draft should be approved at a dedicated "European Strategy Session" of the CERN Council.
  - Due to the COVID-19 pandemic, the special session of CERN Council for approval of the strategy, originally scheduled for 25 May 2020, has been postponed.

Portuguese contribution to the Update of the European Strategy for Particle Physics

Citations from the Portuguese contribution (October 2019):

- We believe that the FCC programme presents the most promising and flexible way to achieve the right conditions for the exploration of the energy frontier.
- It has significant advantages with respect to linear collider options.
- We believe that the “FCC-all”, starting with the FCC-ee option, should get the highest priority.

Why this seminar?

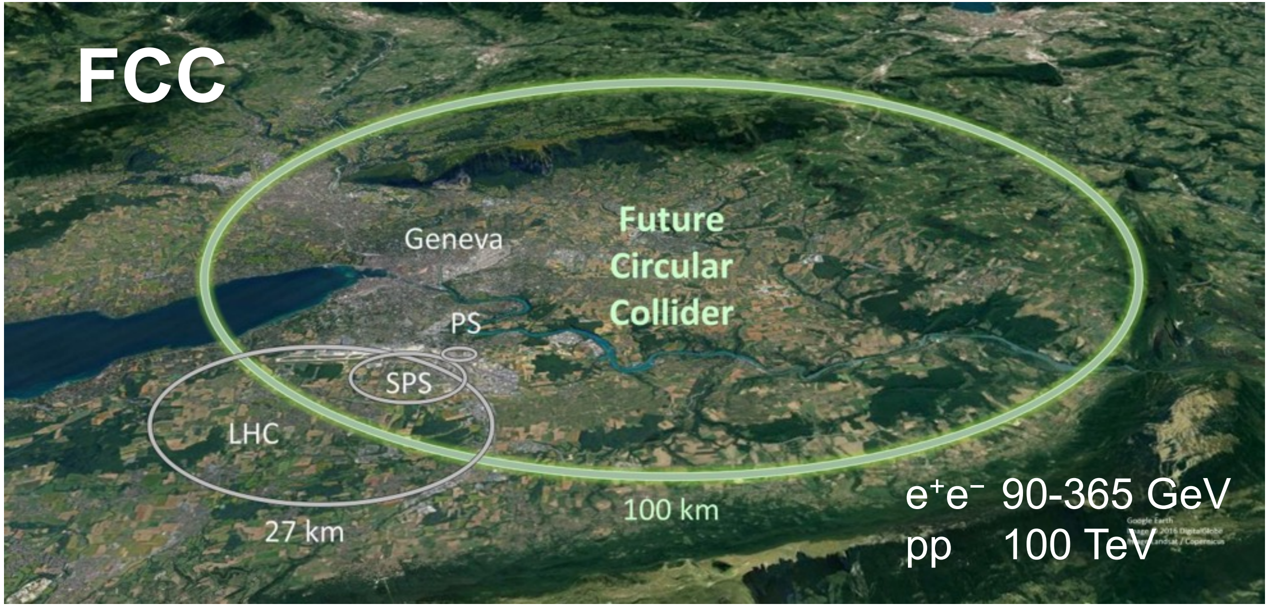
- Integrated in the LHC Physics Course
- It is a good occasion to summarize the physics motivations for the options on the table
- The Update to be approved by Council may leave options open…
- …the debate will be pursued until the next Update in 2027.

Facilities under consideration

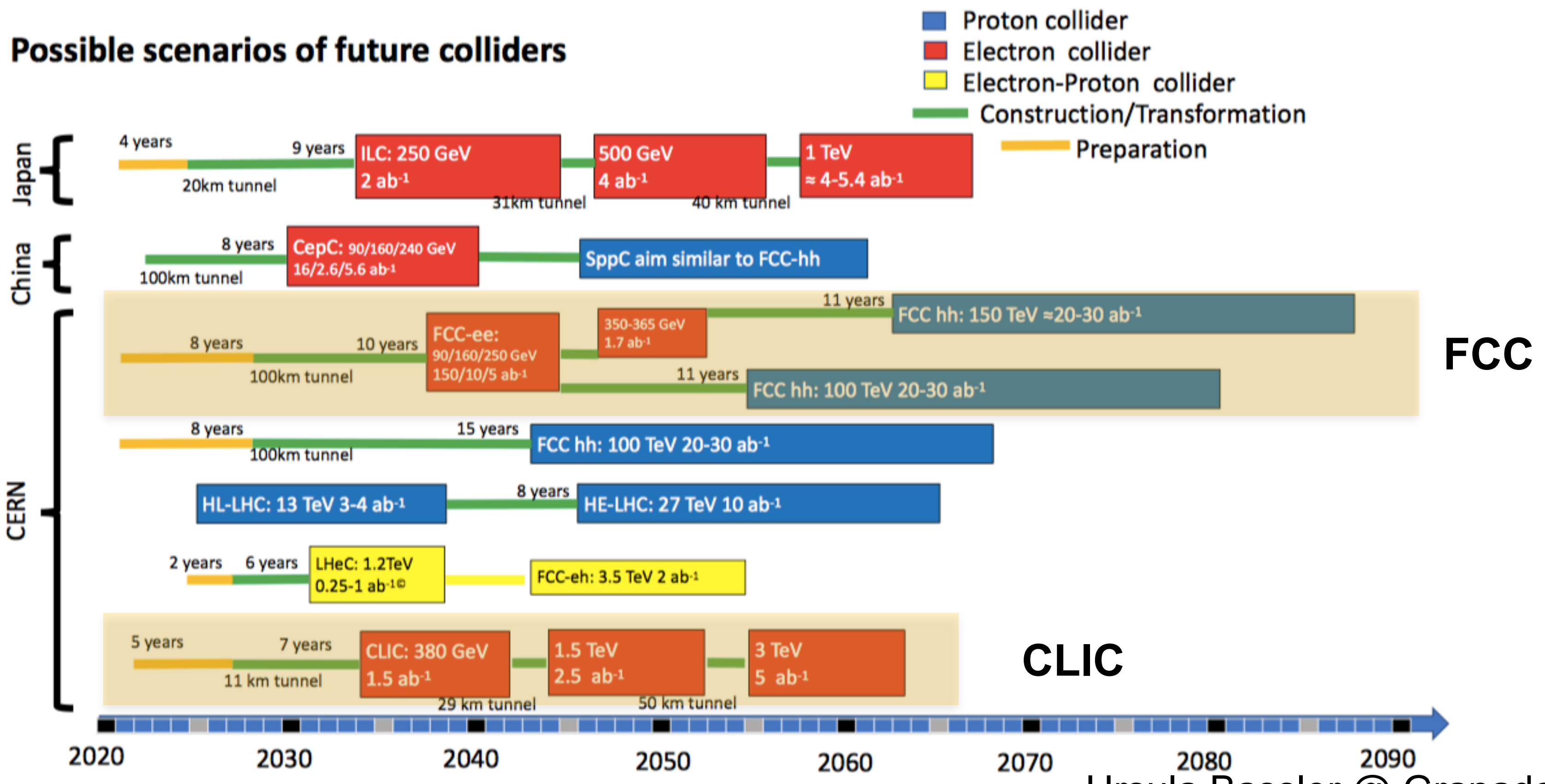
- Linear e^+e^- colliders staged in energy
  - CLIC in Europe, ILC in Japan

- Circular colliders with an e^+e^- phase followed by a hadron collider phase using the same infrastructure
  - FCC in Europe, CEPC in China

Possible future machines at CERN



Possible scenarios



Ursula Bassler @ Granada

Project phases

- Stage 1:
  - **There is overwhelming consensus on an e^+e^- collider with energy up to about 400 GeV, above the ttbar threshold, as the next high-energy facility.**
    - CLIC 380 GeV
    - FCC-ee from the Z Peak to 365 GeV

- Stage 2:
    - CLIC 1500/ 3000 GeV
    - FCC-hh 100 TeV

Accelerator technology

RF accelerating technology

- RF technologies are ready for **lepton colliders** (ILC, CLIC, FCC-ee, CEPC), focusing on the **construction of an Higgs Factory beginning in > ~5 years.**

- **SRF accelerating technology is well matured** including cooperation with industry.

- Continuing R&D effort for higher performance is very important for future project upgrades.
  - **Nb-bulk, 40–50 MV/m**: ~ 5 years for single-cell R&D and the following 5–10 years for 9 cell cavities statistics. Ready **for the upgrade**, **10 ~ 15 years.**

A. Yamamoto, Granada 2019

SC magnet technology

- Nb_3Sn superconducting magnet technology for hadron colliders still requires development to reach **14-16 T**.
- It would require the following **time-line** :
  - **Nb_3Sn**, **12~14 T:** 5~10 years for short-model R&D, and the following 5~10 years for prototype/pre-series with industry. It will result in **10 – 20 yrs** for the construction to start,
  - **Nb_3Sn**, **14~16 T:** 10-15 years for short-model R&D, and the following 10 ~ 15 years for protype/pre-series with industry. It will result in **20 – 30 yrs** for the construction to start, (consistently to the FCC-integral time line).

Caterina Biscari, EPS-HEP 2019

HL-LHC : 11 T magnets

HiLumi HL-LHC PROJECT

11 T in full swing production: LS2 installation in 2020!
Great care given the stress sensitivity of Nb_3Sn

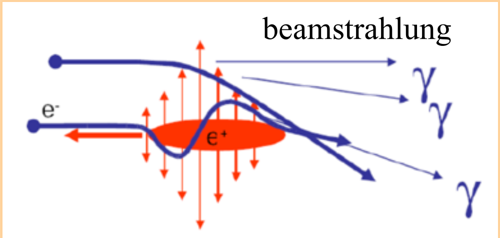
F. Bordry

Challenges of Linear Colliders Higgs Factories

$$\mathcal{L} \propto H_D \frac{N}{\sigma_x} N n_b f_r \frac{1}{\sigma_y}$$

~10^{34}

Luminosity Spectrum
(Physics)



- Grows with E: 40% of CLIC lumi >1% of $\sqrt{s}$

Beam Current
(RF power limited, beam stability)

- Challenging *e+* production (two schemes)
- CLIC high-current drive beam bunched at 12 GHz

(klystrons option adds 1.4 BCHF)

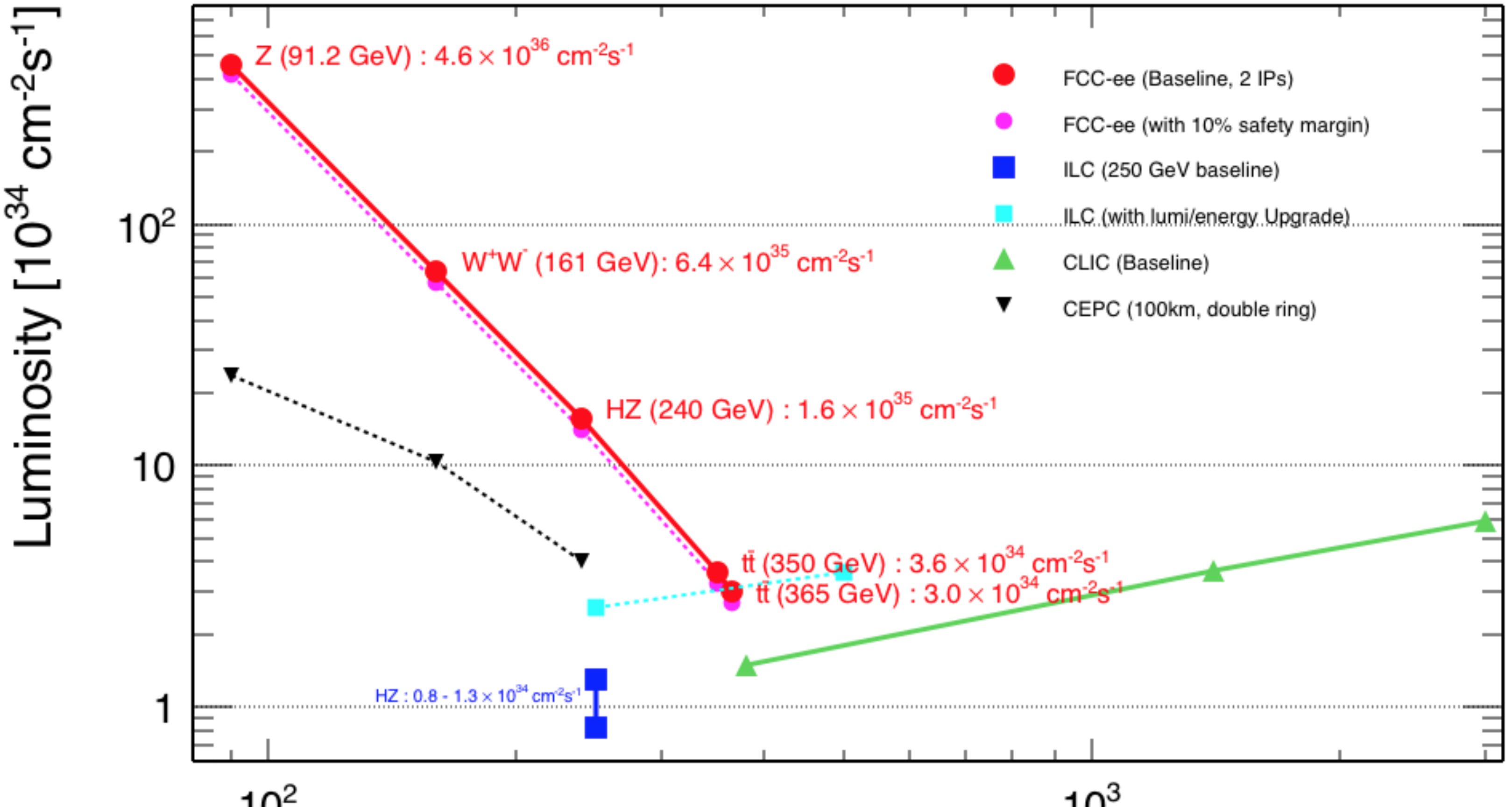
Beam Quality
(Many systems)

- Record small DR emittances
- 0.1 µm BPMs
- IP beam sizes

CLIC 3nm/150nm

Caterina Biscari, EPS-HEP 2019

Luminosity of e+e- machines



Other accelerator options

- Muon collider
  - Conceivably, a 3 TeV muon collider could become an attractive alternative to CLIC at 3 TeV, and it has been suggested that a 14 TeV muon collider might be a viable alternative to FCC-hh at 100 TeV.
  - However, considerable R&D will be required to demonstrate the feasibility of a muon collider, and its physics potential depends strongly on the expected luminosity.

- Wake-field acceleration
  - Novel accelerator concepts like wake-field acceleration may provide a breakthrough in a more distant future
  - However these concepts are very many years away from the maturity of the CLIC and FCC proposals.
  - They require very ambitious accelerator R&D, which obviously must be pursued.

Stage 1

The Higgs Boson is Special

Higgs = **new forces** of different nature than the gauge interactions known so far

- No underlying local symmetry
- No quantised charges
- Deeply connected to the space-time vacuum structure

The knowledge of the values of the **Higgs couplings**
is essential to our understanding of the deep structure of matter

- Up- and Down-quark Yukawa's decide if $m_{proton} < m_{neutron}$ i.e. stability of nuclei
- Electron Yukawa controls the size of the atoms (and thus the size of the Universe?)
- Top quark Yukawa decides (in part) of the stability of the EW vacuum
- The Higgs self-coupling controls the (thermo)dynamics of the EW phase transition ($t \sim 10^{-10}$s)
(and therefore might be responsible of the dominance of matter over antimatter in the Universe)

Higgs precision program is very much wanted
to probe BSM physics

Christophe Grojean,
EPS-HEP 2019

Precision is the name of the game!

Luminosity scenarios in stage 1

- CLIC 380
  - instantaneous luminosity of 1.5 × 10^{34} cm^{-2} s^{-1} at 380 GeV,
  - integrated luminosity of 1 ab^{-1} in 8 years (**160,000 Higgs bosons**)
  - CLIC could provide 0.0025 ab^{-1} per year at the Z pole (or 0.045 if modified)
- FCC-ee
  - operation at the Z peak, at the WW threshold, at the HZ cross-section maximum and at the ttbar threshold
  - 14 years of data taking

Working point	Z, years 1-2	Z, later	WW	HZ	$t\bar{t}$	
$\sqrt{s}$ (GeV)	88, 91, 94		157, 163	240	340 - 350	365
Lumi/IP (10^{34} $cm^{-2}s^{-1}$)	115	230	28	8.5	0.95	1.55
Lumi/year (ab^{-1}, 2 IP)	24	48	6	1.7	0.2	0.34
Physics goal (ab^{-1})	150		10	5	0.2	1.5
Run time (year)	2	2	2	3	1	4
Number of events	5×10^{12} Z		10^8 WW	10^6 HZ + 25k $WW \to H$	$10^6 t\bar{t}$ +200k HZ +50k $WW \to H$	

Higgs couplings

- Potential deviations from the Standard Model (SM) Higgs boson properties described by multiplicative coupling strength modifiers, known as the κ framework.
  - a systematic description of new physics situated at a higher energy scale is better treated with an effective Lagrangian approach (EFT)

- **For all Higgs couplings the precision achieved with FCC-ee is better than with CLIC 380**
- Precision of the total Higgs width from a global fit to the κ parameters: FCC-ee 1.0 % and CLIC 2.7 %
- By measuring the HZ cross section at two different centrer-of-mass energies (240 and 365 GeV), FCC-ee can extract the Higgs self-coupling κ_λ through quantum effects with a precision of ±25% (combining 4 experiments)

Coupling modifier (precision in %)	HL-LHC +	
	$CLIC_{380}$	$FCC\text{-}ee_{365}$
κ_W	0.73	0.41
κ_Z	0.44	0.17
κ_g	1.5	0.90
κ_γ	1.4 *	1.3
$\kappa_{Z\gamma}$	10 *	10 *
κ_c	4.1	1.3
κ_t	3.2	3.1
κ_b	1.2	0.64
κ_μ	4.4 *	3.9
κ_τ	1.4	0.66
BR_{inv} (< %, 95% CL)	0.63	0.19
BR_{unt} (< %, 95% CL)	2.7	1.0

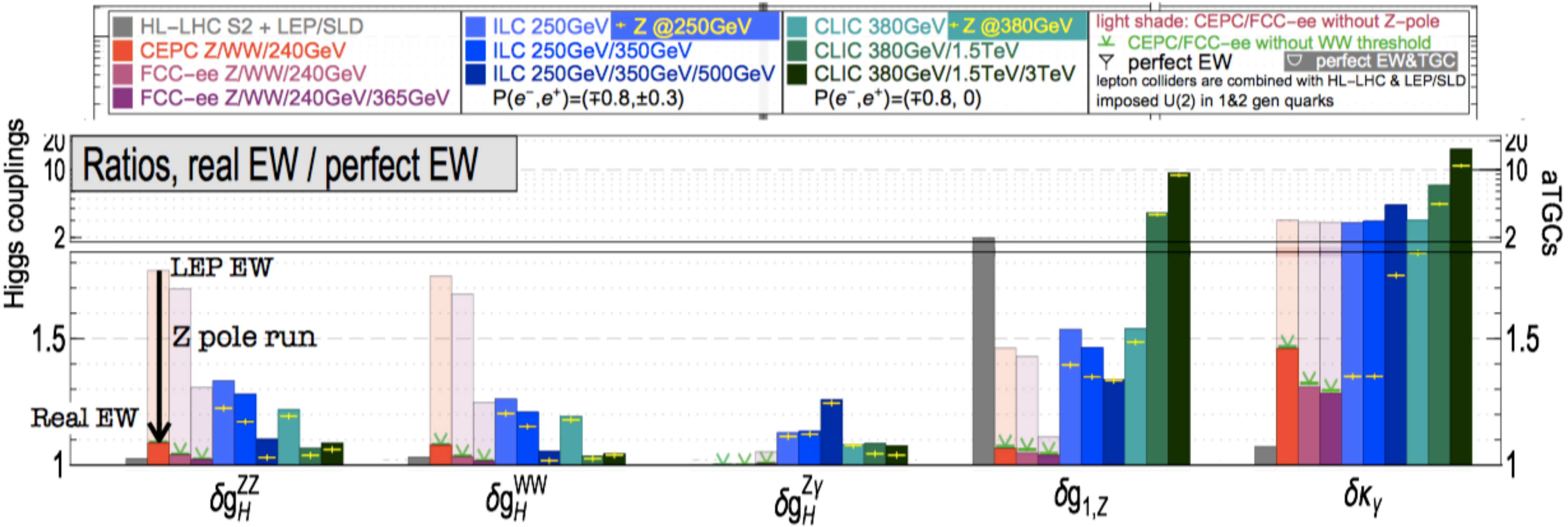
Z and WW programme

- **Unique to FCC-ee: very high luminosity at the Z peak (about 10^5 times the LEP statistics: 5×10^{12} Z decays) and at the WW threshold (with 10^8 pairs of W bosons)**
  - outstanding programme of EW, QCD and flavour physics
  - EW measurements closely linked to the study of properties of the Higgs boson
- A high precision (<100 keV) absolute determination of the CM energy
  - from transverse polarisation and resonant depolarisation
- Very high precision of EW parameters:
  - Precision on α_{em} (M_Z) improved by factor 4
  - Uncertainty in $\sin^2\theta_W$ to be reduced by a factor of 30 to 50.
  - Accuracy of 0.001 in the effective number of neutrino species (0.008 at LEP)
  - Uncertainty in the W mass reduced to 0.5 MeV (~15 MeV at LHC)
- A dedicated theoretical effort is required to match the expected experimental accuracy

Impact of Z-pole measurements

J. De Blas, G. Durieux, C. Grojean, J. Gu, A. Paul 1907.04311

Comparing 3 EW scenarios: LEP/SLD, actual EW measurements, perfect EW measurements



FCC-ee benefits a lot (>50% on HVV) from Z-pole run

LEP EW measurements are a limiting factor (~30%) for Higgs precision at CLIC

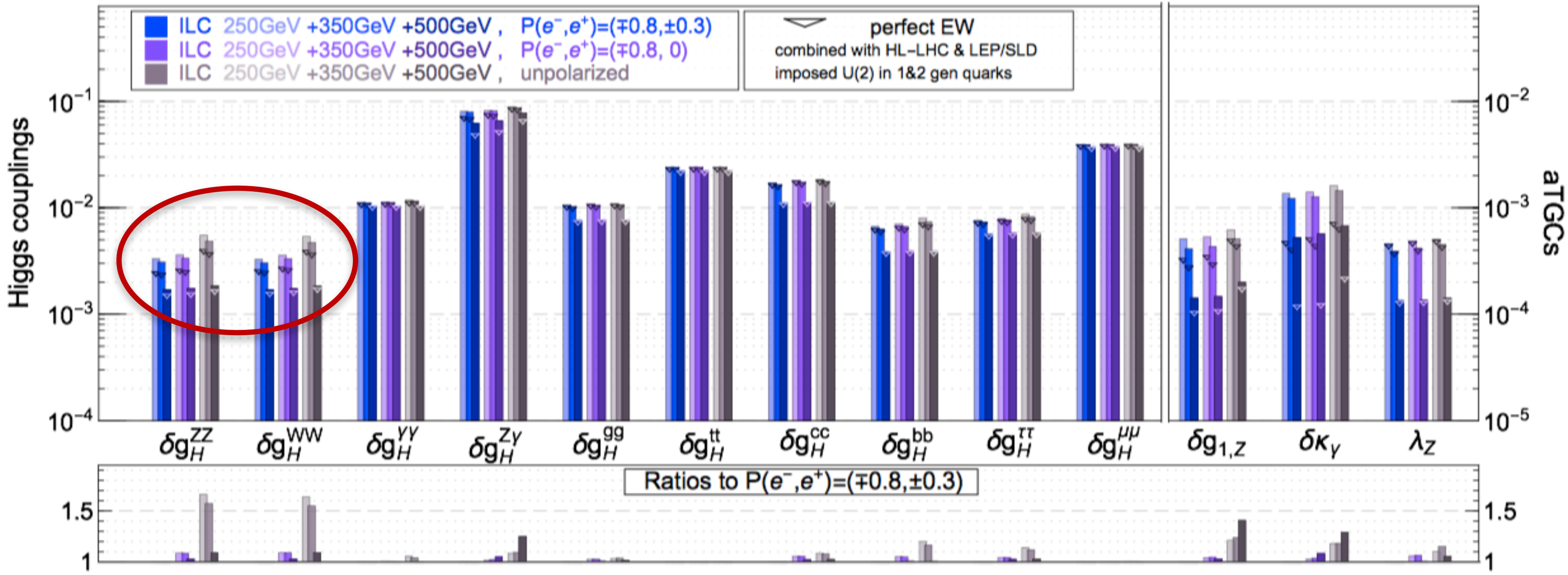
Beam longitudinal polarization

- Available at CLIC
  - helps to improve measurements and partially compensates lower luminosity

- Not available at FCC-ee
  - but helicity effects in the final state, e.g., of the τ in $Z \to \tau^+ \tau^-$, will provide similar information.

Impact of Beam Polarisation

J. De Blas, G. Durieux, C. Grojean, J. Gu, A. Paul 1907.04311



- If low energy runs: electron polarisation improves significantly (>50%) HVV determination
- Polarisation-benefit diminishes when other runs at higher energies are added

Top physics

- The luminosities of CLIC at 380 GeV and FCC-ee per IP at 365 GeV are comparable
  - a priori similar performance
- The top mass is extracted from the energy dependence of the cross-section
  - Statistical uncertainties: 17 MeV at FCC-ee, 20 MeV at CLIC-380.
  - The total uncertainty is about 50 MeV
    - dominated by the scale uncertainties of the NNNLO QCD prediction for the top threshold region
    - ultimate precision at HL-LHC is 200 MeV
- Top Yukawa coupling with similar precision as HL-LHC
  - through quantum level effects on the ttbar cross-section
- The lack of beam polarisation at FCC-ee is compensated by measuring the polarisation of the top quarks
- FCC-ee has the advantage of having 2 or more experiments

General Issues for CLIC 380 and FCC-ee

- CLIC 380
  - Linear tunnel of 11.4 km length. **The vertical beam size at final focus is 2.9 nm.**
  - Achieving the luminosity, needs control of beam size, machine parameters and stability at the nm scale. **This is a major technological challenge and concern.**
    - The only linear e^+e^- collider ever built, the SLC (1989), achieved 40% of its design luminosity after 10 years of operation, with a vertical size at the IP of about 600 nm.
  - The reliability of CLIC results must be achieved with a single detector.
  - The cost ranges from 5.9 BCHF (drive beam option) to 7.3 BCHF (klystron option)
- FCC-ee
  - Circular tunnel of 100 km circumference
    - Would provide an invaluable infrastructure, offering the perspective of the integrated programme of FCC-ee followed by FCC-hh
  - This circular machine is also quite demanding, but profits from the vast experience accumulated with previous circular e^+e^- colliders,
  - The cost of the civil engineering for the FCC-ee is 5.4 BCHF. The complete FCC-ee programme with two experimental caverns will require a total investment of 11.6 BCHF.

Stage 2

Stage 2: CLIC 1500/ 3000 or FCC-hh

- The possibility to increase the CM energy in stages is a key advantage of a linear e+e− collider
  - CLIC 1500 (29 km tunnel, 364 MW); CLIC 3000 (50 km tunnel, 589 MW)
- There is presently no indication of new physics in this energy range
  - CLIC 1500 and 3000 are mostly motivated by precision measurements in the Higgs, top, QCD and EW sectors.

- The 100 TeV FCC-hh will represent a major step in energy compared to LHC
- FCC-hh programme includes ion-ion and possibly electron-hadron collisions
  - which offer new insights into the collective behaviour of hadronic matter
- FCC-hh power requirement close to 600 MW (similar to CLIC 3000)
  - obviously needs a special, environmentally sound and probably radical solution

Cost in BCHF:

CLIC [a] Total	380 GeV	1500 GeV	3000 GeV
	5.9 (drive beam)	11.0	18.3
	7.3 (klystron)	12.4	20.1
FCC-ee [d] Total	250 GeV	365 GeV	FCC-hh (100 TeV) [e]
	10.5	11.6	28.6

FCC-hh physics prospects

- Possibility of discoveries in an unchartered mass range
- Integrated luminosity of 30 ab^{-1} (10x HL-LHC)
  - 3×10^{10} Higgs, ~ 4×10^{7} Higgs pairs, 10^{13} top quark pairs,
- Increase in production cross-section with respect to the LHC:
  - factor of ≈10 for VH (V = W, Z) associated production
  - factor of ≈ 60 for the ttH channel
- Rate increase is much higher for large transverse momentum phenomena
  - particularly interesting for probing heavy new physics.
- Very large kinematical range over which production of the Higgs boson and the top quark can be explored

Top physics at stage 2

- The top Yukawa coupling is required for the understanding of the Higgs potential
  - The top Yukawa coupling determination at HL-LHC will be limited to a model-dependent accuracy of around 3.4%

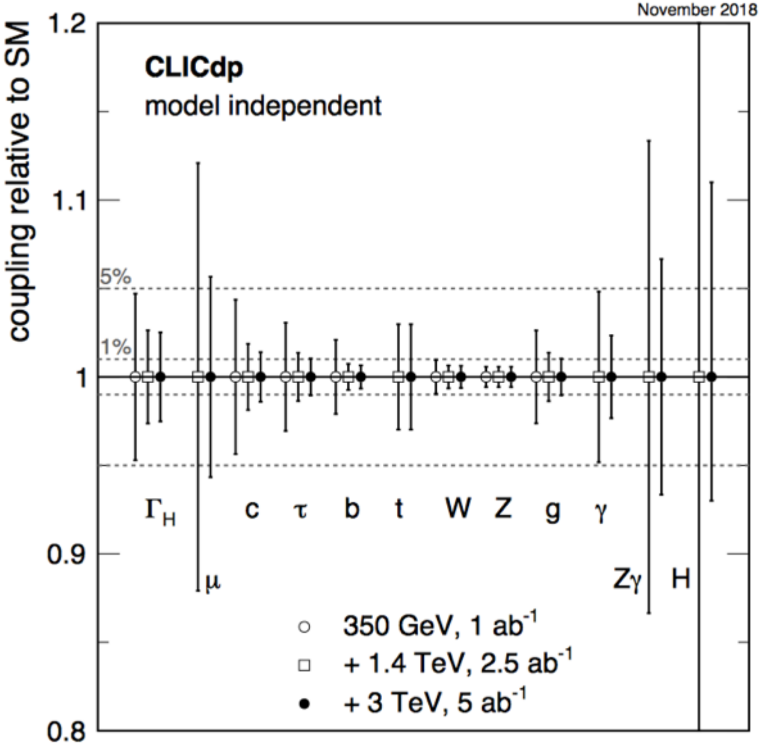
- Effective field theory (EFT) analysis of ttbar production at all CLIC energies
  - Operation at high energy improves the sensitivities to the 4-fermion operator coefficients, which approach the level of 10^{-4} TeV^{-2} .
  - At CLIC 1500, ttH production gives direct access to the top-quark Yukawa coupling with an expected accuracy of 2.9%.

- At FCC-hh the top-quark Yukawa coupling will be inferred at FCC with an accuracy of about 1.5%

Higgs physics at CLIC stage 2

- Model-independent global fit at the three energy stages
  - Accuracy on g_{HZZ} of 0.6% from the total HZ cross-section.
  - The precision for other couplings such as g_{HWW} and g_{Hbb} reach a similar level.
  - The g_{Hcc} coupling can be obtained with percent-level accuracy
  - Total Higgs width with 2.5% accuracy.

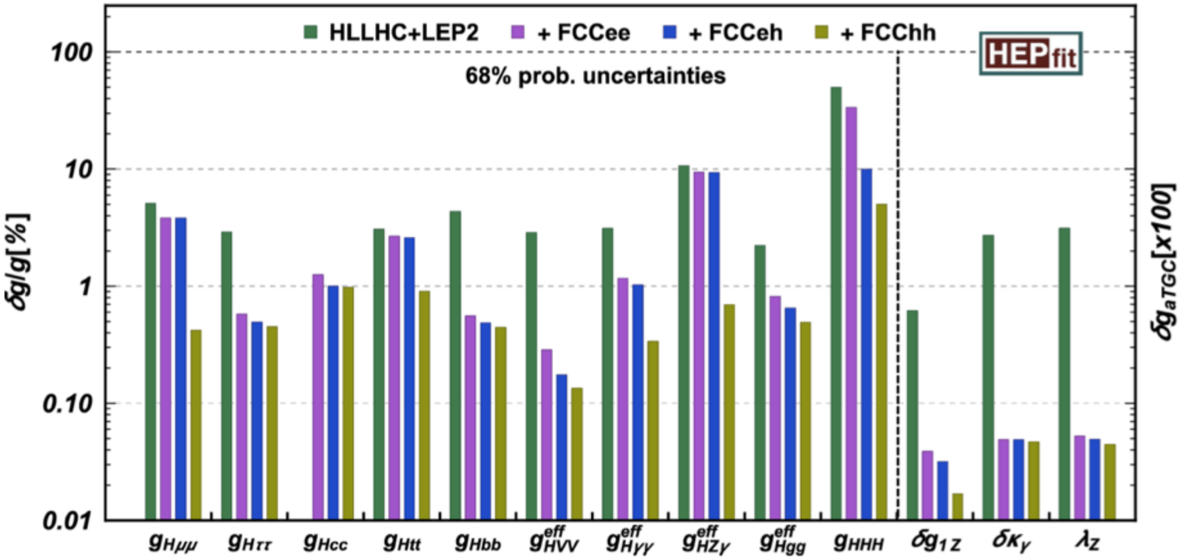
- Assuming the absence of non-SM Higgs decays, a global fit constrains several Higgs couplings to per mille-level accuracy



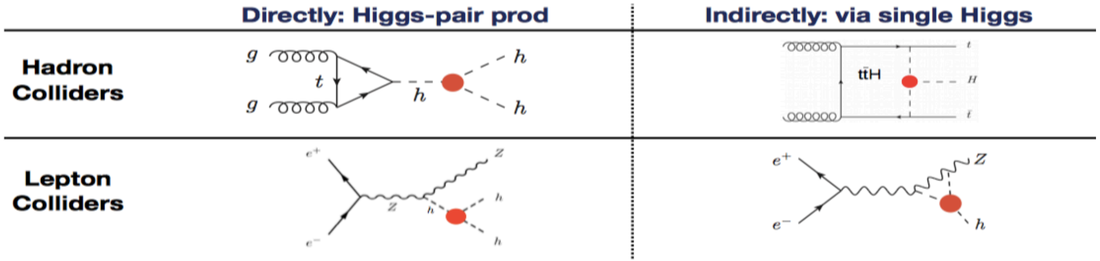
Model-independent global fit at the three energy stages

Higgs physics at FCC-hh

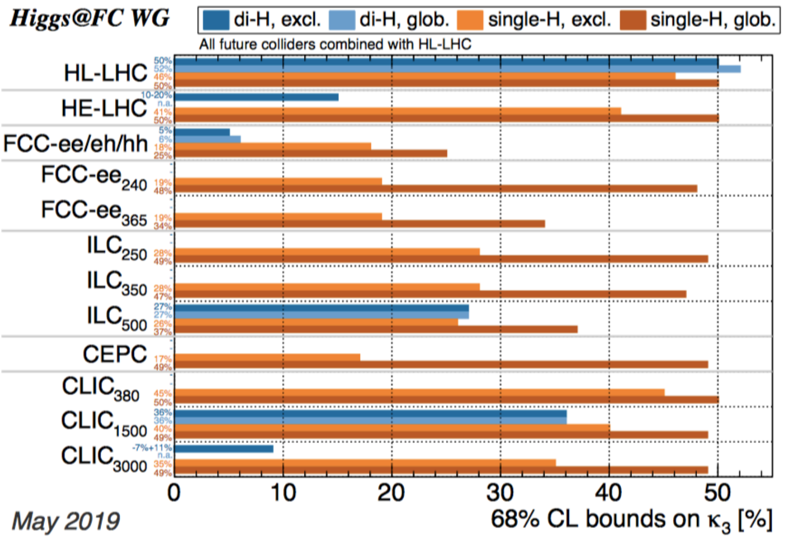
- At FCC-hh, the large statistics allow for precision in new kinematic regimes and give access to rare decay channels, complementary to FCC-ee.
- Percent or sub-percent accuracy on "rare" couplings, such as $H \rightarrow \mu^+\mu^-$, γγ and Zγ



Higgs self-coupling



	di-Higgs	single-H
exclusive	**1. di-H, excl.** • Use of σ(HH) • only deformation of κλ	**3. single-H, excl.** • single Higgs processes at higher order • only deformation of κλ
global	**2. di-H, glob.** • Use of σ(HH) • deformation of κλ + of the single-H couplings (a) do not consider the effects at higher order of κλ to single H production and decays (b) these higher order effects are included	**4. single-H, glob.** • single Higgs processes at higher order • deformation of κλ + of the single Higgs couplings



ECFA Higgs study group ’19

Higgs self-coupling

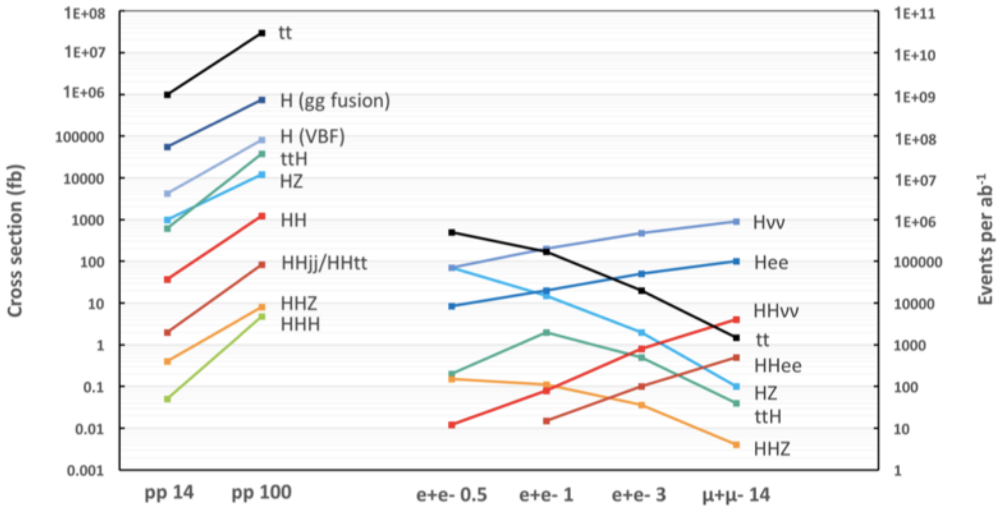
- At the HL-LHC, ATLAS and CMS in combination expect to find evidence for HH production at the 4-σ level, and to determine λ with an uncertainty of 50%.
- CLIC 3000 makes possible
  - a 5σ observation of the double Higgsstrahlung process $e^+e^- \rightarrow ZHH$ and provides evidence for the WW fusion process $e^+e^- \rightarrow HH\nu_e\nu_e$ at the 3.6σ level, if λ has the SM value.
  - **Overall one expects a precision on the Higgs self-coupling λ of [-7%, +11%] if it has the SM value.**
- At FCC-hh
  - High rate of double-Higgs production (a factor 40 more than at LHC) and high luminosity (another order of magnitude more than HL-LHC) allows the exploitation of several final states.
  - **Using the main HH → bbγγ channel plus a few secondary ones, a precision on the Higgs self-coupling of about 5% appears achievable**
  - FCC-hh is also the only machine giving access to the quartic Higgs coupling

Search for new physics

- Both machines will address several of the major, fundamental open questions of particle physics
  - possible composite nature of the Higgs,
  - solutions to the hierarchy problem,
  - baryogenesis and the electroweak phase transition,
  - the nature of dark matter,
  - the origin of neutrino mass,
  - the structure of flavour-changing neutral currents (FCNCs).
- These questions are most likely related to the scalar sector

Indirect discoveries

- The sensitivity to indirect discoveries is determined by the production rate of known processes.
- The smallness of most cross-section limits the statistics available with CLIC
- FCC-hh must extract the relevant signal from high backgrounds.



- A global fit to all FCC results will set constraints on NP up to a scale of ~ 20 to 100 TeV, and on NP coupled to the Higgs sector up to ~ 10 TeV.
- CLIC can discover indirectly a Z' with SM couplings and a mass up to 20 TeV.

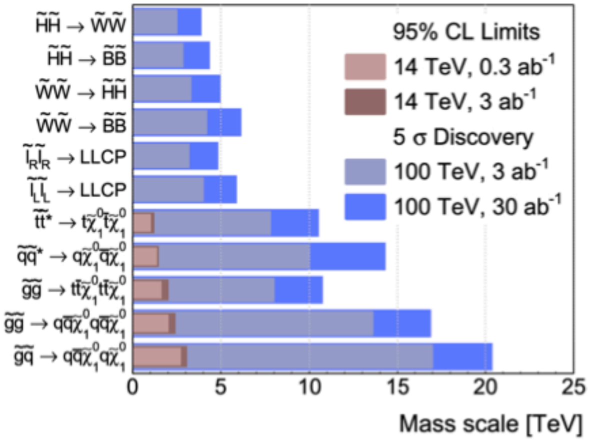
Direct discoveries

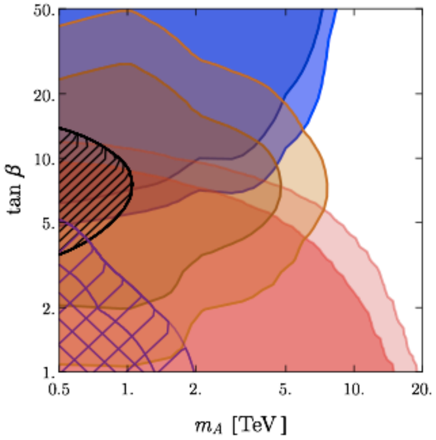
- CLIC 3000 can probe the existence of new particles interacting with the SM with EW-sized couplings, up to its kinematic limit of 1.5 (3.0) TeV, if they are pairwise (singly) produced.
- FCC-hh extends the reach for direct production of new heavy states up to tens of TeV, e.g., a new Z' or a new charged vector boson W' with a mass up to 40 TeV.

- At FCC-hh the huge increase in the production rate of light states like the Higgs, allows detecting exotic Higgs decays with tiny branching ratios smaller than 10^{-8}
- FCC-hh top quark FCNC searches are two orders of magnitude more sensitivity than the HL-LHC.

Susy at FCC-hh

- The mass reach for gluinos at FCC-hh varies from 11 TeV to 21 TeV (depending of main decay mode).
- Direct production of additional TeV-scale Higgs states will be a major physics goal of a 100 TeV collider (mass reach 5-10 TeV)





Overview of CLIC and FCC options

- CLIC at high CM energy offers very interesting precision physics, but CLIC will be restricted to e+e− collisions.
  - Given the cost and effort needed for CLIC, it will very likely preclude Europe from pursuing hadron collider physics beyond the LHC.
  - This fact, associated to the limited performance in direct searches and rare decays, the risks of the machine and the limitation to a single detector, do not favor the CLIC option
- FCC programme, with its combination of both e+e− and hh collision modes, has a much larger physics potential than CLIC.
  - This programme will offer both “guaranteed deliverables", i.e., high-quality precision measurements in all sectors at both the ee and pp stages,
  - and an increased reach for direct discovery at the highest masses.
- The combination of FCC-ee and FC-hh will provide a forefront scientific programme for CERN for many decades, just as the combination of LEP and LHC has done.

Thank you for your attention