Circular and Linear e+e- Colliders Another Story of Complementarity

Circular and Linear e^+e^- Colliders:
Another Story of Complementarity

Contribution to the European Strategy for Particle Physics Update, 2018–2020

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Abstract

The remarkable synergy and complementarity between the circular e^+e^- and pp colliders has been extensively discussed. In this short document, we investigate the complementarity between the proposed circular and linear e^+e^- colliders at the electroweak and TeV scale. This complementarity could be exploited on a world-wide scale, if both a large circular and a linear infrastructures were available. A possible implementation of such a complementary program is shown.

https://arxiv.org/abs/1912.11871

Motivation

1. All proposed e+e- colliders at Eletroweak Scale have been dubbed ‘Higgs Factories’ and considered to have similar performance

2. With the conclusion that only one needs to/could be built

3. The proponents of CC (resp. LC) protest that they can do **many things!** **that the other cannot do (or not as well at all)** (and they are right)

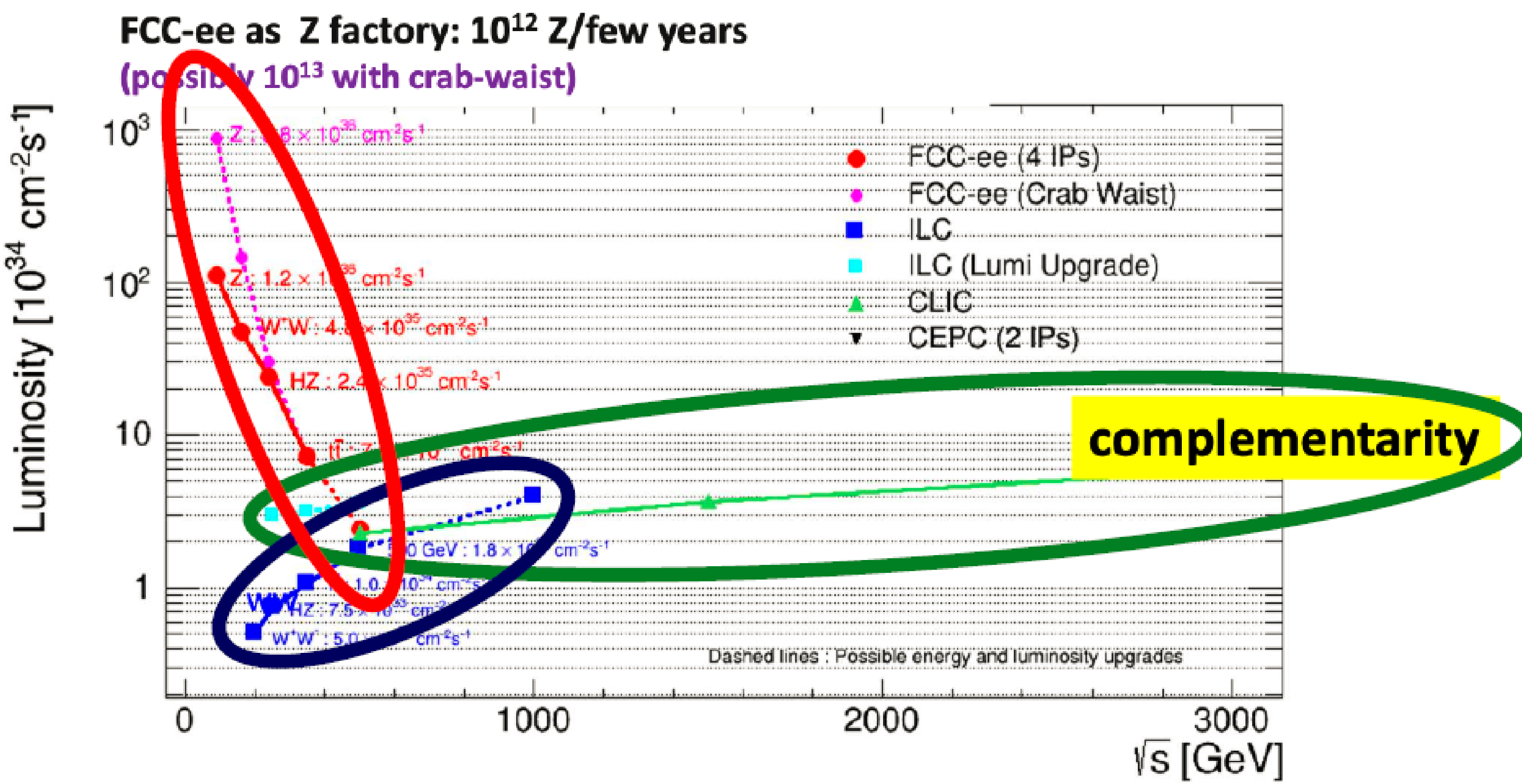
4. This creates an unnecessarily difficult strategic situation,
   esp. given the strong synergetic link between the FCC-ee and the FCC-hh:
   100 TeV p-p collisions provide the highest parton-E_{CM} for the foreseeable future.
   {ee + hh} → much more favorable funding profile and strong physics case for 100km tunnel

➔ **Will FCC-ee (or CEPC), while enabling 100TeV pp, kill the linear collider?**

5. Let us look at the differences (= complementarity) between circular and linear colliders, which have been overshadowed by the competitive comparisons.

In the following, for definiteness, we study the complementarity of FCC-ee and ILC and its possible expression as an advantageous run plan
If you prefer replace by CC–A and LC--B

This remark was made since the beginning in 2012



overlap in ~300 GeV region

A.B. HFACT 2014

Benefits

The FCC-INT programme by way of *synergy and complementarity* provides the best overall physics output as noted in the Physics Briefing Book

Yet the European Strategy Group needs to find a strategy

-- **That is excellent for Europe and CERN**

-- **That is positive on a global perspective**

Nearly impossible under the assumption that only one higgs factory will be built

Elaborating on differences, thus complementarity, between circular and linear e+e- colliders

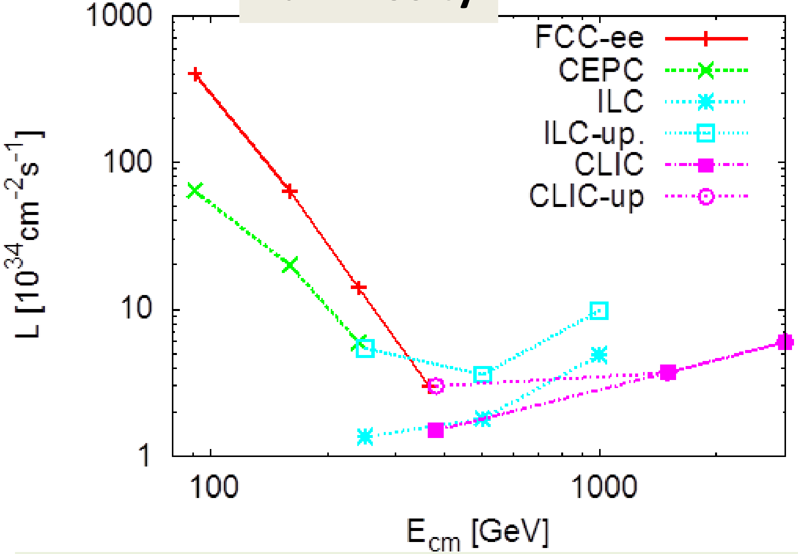
-- **allows for optimization of configurations and running plan**
in case both a circular and a linear infrastructures are available
cost (LC+CC-ee) < cost (LC) + cost (CC-ee)

-- **highlights uniqueness of each collider type (i.e. what do you lose if it is not done)**

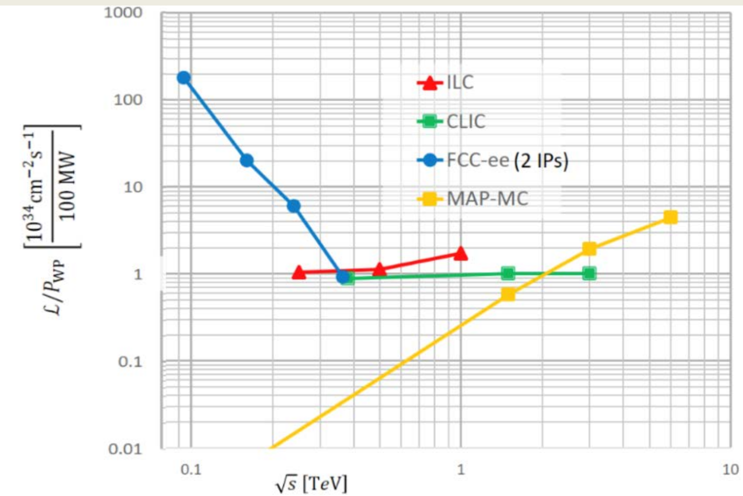
Operational Differences

plots from Briefing Book

Luminosity



Luminosity/Power → Energy efficiency



Luminosity vs Energy circular below 350 GeV linear above 250 GeV

Efficiency : 9 (5) GJ/Higgs at FCC-ee with 2(4)IP vs 50GJ/Higgs for ILC250 (first 15 years)

Beam polarization: circular: transverse → ppm beam energy calibration
linear: longitudinal : e- ±80% easy, (e+ ±30% difficult → additional d.o.f

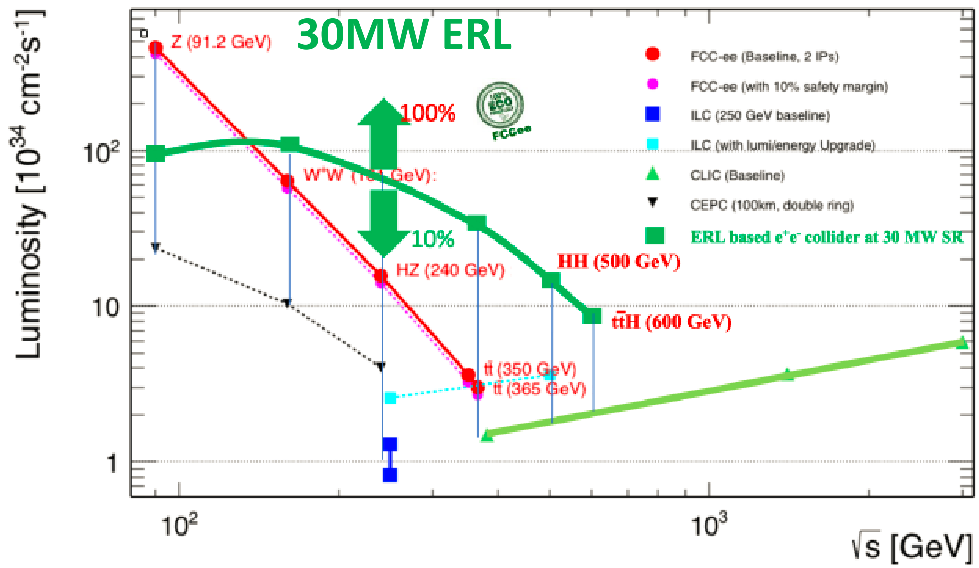
Long term energy upgrade circular: pp collider linear: High energy lepton collisions

Interaction points circular: 2-4 linear: 1

Run limited in time by arrival of hadron collider Run is open ended

Turn FCC into an ERL ?

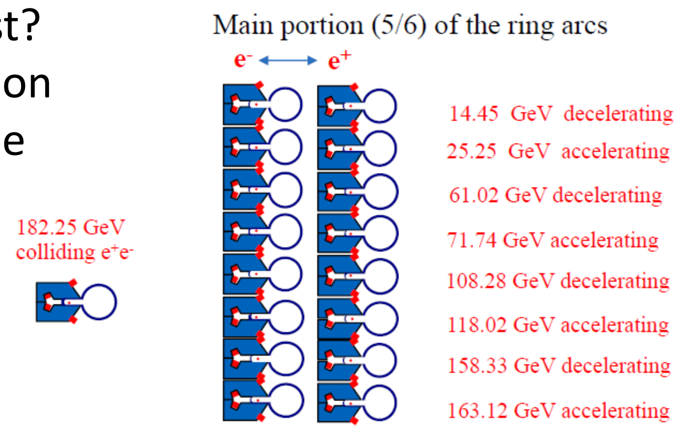
paper study by Litvinenko et al
- --could improve energy efficiency!
- -- No stable transverse polarization:
  - → not for Z and W!
- -- improve performance by large factors
  - -- higher Lumi for Higgs, top
  - -- can reach 600 GeV E_{CM}

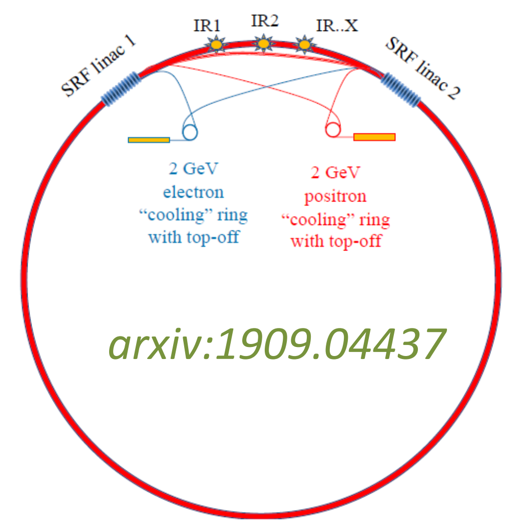


More rings, more RF Volts → cost?
- -- not ready enough for discussion

May not be feasible or affordable

Will be studied!





arxiv:1909.04437

Scientific differences / complementarity

First stage 'Higgs Factory' ($E_{CM} \lesssim$365 GeV)

- "All low-energy Higgs factories have similar performance, to 1st order"
  - $ILC_{250} = CLIC_{380} = CEPC_{240} = FCC\text{-}ee_{240\to365}$?
    - Not quite !

J. De Blas et al., arXiv:1905.03764

Collider	HL-LHC	ILC_{250}	$CLIC_{380}$	$CEPC_{240}$	$FCC\text{-}ee_{240\to365}$	
Lumi (ab^{-1})	3	2	1	5.6	5 + 0.2 + 1.5	
Years	10	11.5	8	7	3 + 1 + 4	
g_{HZZ} (%)	1.5	0.30 / 0.29	0.50 / 0.44	0.19 / 0.18	0.18 / 0.17	
g_{HWW} (%)	1.7	1.8 / 1.0	0.86 / 0.73	1.3 / 0.88	0.44 / 0.41	
g_{Hbb} (%)	5.1	1.8 / 1.1	1.9 / 1.2	1.3 / 0.92	0.69 / 0.64	
g_{Hcc} (%)	SM	2.5 / 2.0	4.4 / 4.1	2.2 / 2.0	1.3 / 1.3	
g_{Hgg} (%)	2.5	2.3 / 1.4	2.5 / 1.5	1.5 / 1.0	1.0 / 0.89	
$g_{H\tau\tau}$ (%)	1.9	1.9 / 1.1	3.1 / 1.4	1.4 / 0.91	0.74 / 0.66	2IP
$g_{H\mu\mu}$ (%)	4.4	15. / 4.2	– / 4.4	9.0 / 3.9	8.9 / 3.9	
$g_{H\gamma\gamma}$ (%)	1.8	6.8 / 1.3	– / 1.5	3.7 / 1.2	3.9 / 1.2	
$g_{HZ\gamma}$ (%)	11.	– / 10.	– / 10.	8.2 / 6.3	– / 10.	
g_{Htt} (%)	3.4	– / 3.1	– / 3.2	– / 3.1	10. / 3.1	
g_{HHH} (%)	50.	– / 49.	– / 50.	– / 50.	44./33. 2IP 27./24. 4IP	
Γ_H (%)	SM	2.2	2.5	1.7	1.1	
BR_{inv} (%)	1.9	0.26	0.65	0.28	0.19	2IP
BR_{EXO} (%)	SM (0.0)	1.8	2.7	1.1	1.1	

Kappa fit, without/with HL-LHC (g_{HZZ} … g_{Htt})

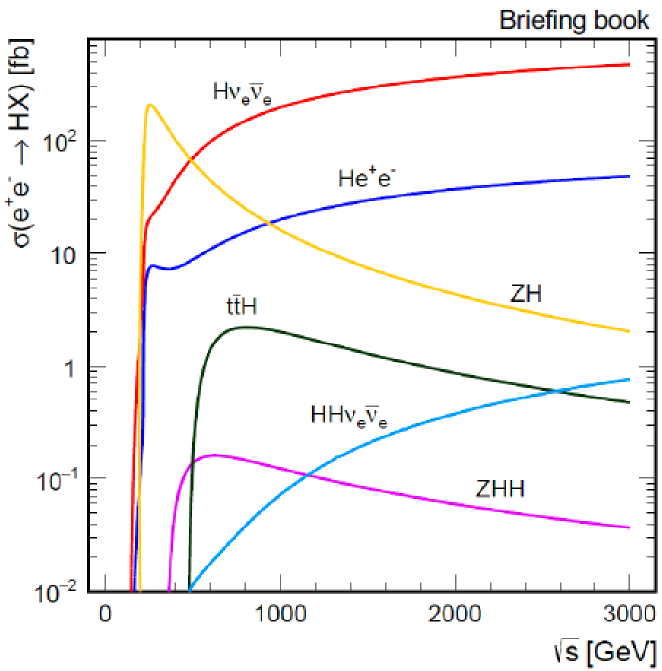
Global EFT fit, without/with HL-LHC → (g_{HHH})

Higher luminosity of circular collider --> more statistics
+ TeraZ program helps (de Blas)

High energy 'Higgs Factory' (E_{CM} >> 365 GeV)

5 10^{10} H!

- **High-energy Higgs factories (ILC_{500} , ILC_{1000} , $CLIC_{3\,TeV}$, and FCC-hh)**
  - In combination with the low-energy standard candles (g_{HZZ}, Γ_H) and measurements



J. De Blas et al., arXiv:1905.03764

Collider	ILC_{500}	ILC_{1000}	CLIC	FCC-INT
g_{HZZ} (%)	0.24 / 0.23	0.24 / 0.23	0.39 / 0.39	0.17 / 0.16
g_{HWW} (%)	0.31 / 0.29	0.26 / 0.24	0.38 / 0.38	0.20 / 0.19
g_{Hbb} (%)	0.60 / 0.56	0.50 / 0.47	0.53 / 0.53	0.48 / 0.48
g_{Hcc} (%)	1.3 / 1.2	0.91 / 0.90	1.4 / 1.4	0.96 / 0.96
g_{Hgg} (%)	0.98 / 0.85	0.67 / 0.63	0.96 / 0.86	0.52 / 0.50
$g_{H\tau\tau}$ (%)	0.72 / 0.64	0.58 / 0.54	0.95 / 0.82	0.49 / 0.46
$g_{H\mu\mu}$ (%)	9.4 / 3.9	6.3 / 3.6	5.9 / 3.5	0.43 / 0.43
$g_{H\gamma\gamma}$ (%)	3.5 / 1.2	1.9 / 1.1	2.3 / 1.1	0.32 / 0.32
$g_{HZ\gamma}$ (%)	– / 10.	– / 10.	7. / 5.7	0.71 / 0.70
g_{Htt} (%)	6.9 / 2.8	1.6 / 1.4	2.7 / 2.1	1.0 / 0.95
g_{HHH} (%)	27.	10.	9.	~~5.~~ 3.-5.(*)
Γ_H (%)	1.1	1.0	1.6	0.91
BR_{inv} (%)	0.23	0.22	0.61	0.024
BR_{EXO} (%)	1.4	1.4	2.4	1.0

(*)see M. Selvaggi, 3d FCC physics workshop
9% precision in 3 years of running

HIGGS – COMMENTS

1. Circular colliders at 240 GeV are very efficient Higgs factories
   FCC-ee provides the most precise determination of gHZZ
   Best standard candle for all measurements in hadron collisions

2. At higher energies, linear colliders progressively get a better determination of gHWW
   Combination of circular and linear colliders offer the best gHZZ/gHWW determination
   This test of the SU(2) custodial could also be achieved by FCC-INT with the FCC-eh

3. Proton-proton collisions are more effective at high energy (5 10^{10} Higgs for FCC-hh)^
   Once HZZ and ttZ couplings are determined in an absolute manner,
   FCC-INT yields precisions better than 1% for all couplings of the previous table

Scientific Complementarity: Higgs self - coupling

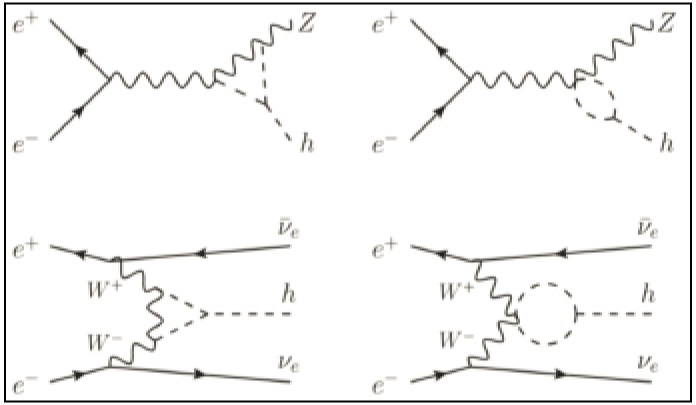
M Cullough

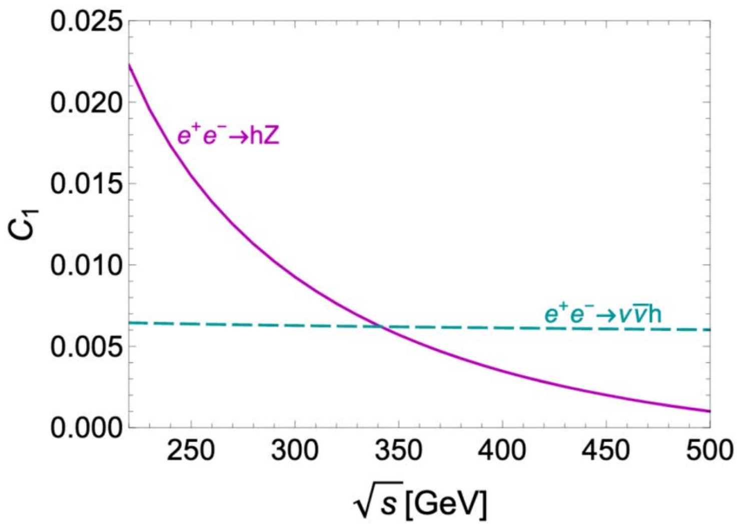
FCC-ee can determine (at 4 sigma)
the Higgs self-coupling by its effect on the
ZH cross-section vertex correction. →
This is thanks to having two energy points

Same can be done at ILC running at 250 and 500 GeV
but is less precise; fewer events at 250, decreasing σ(E)

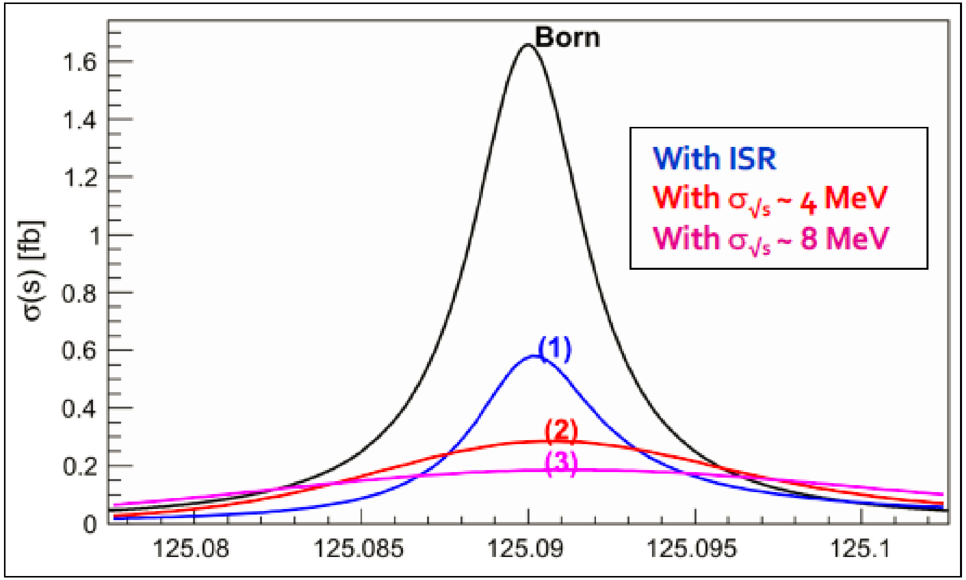
«Traditional» two-Higgs production can be performed also, above 500 GeV by ILC, CLIC
the two are complementary, robust methods
see arXiv:1910.00012v2 B. Di Mico et al

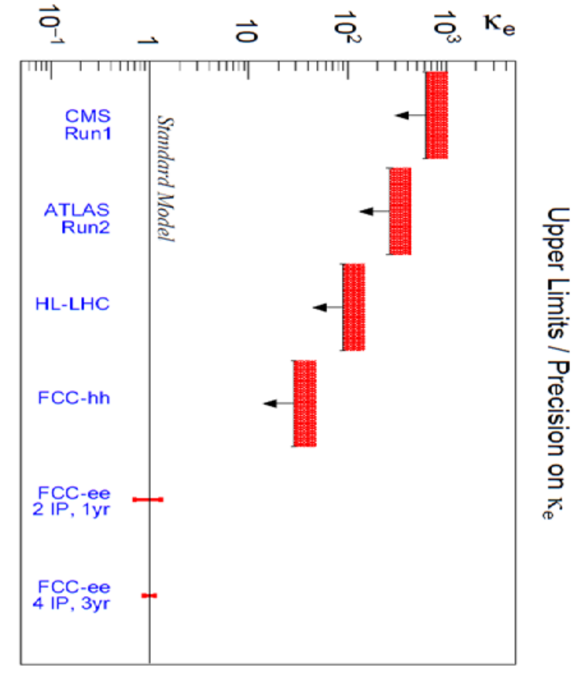
CLIC can achieve ±9% from 380/1TeV/3TeV (30 years)
FCC-hh will reach this precision after 3-5 years
(30 years of FCC) and (± 2 ± 2.5 - 4)% (50 years)
Again quite different environment.





Something unique!





e+e- → H @ 125.xxx GeV requires

-- Higgs mass to be known to <5 MeV from 240 GeV run (CEPC group almost there)

-- **Huge luminosity**

-- **monochromatization** (opposite sign dispersion using magnetic lattice) to reduce σ_{ECM}

-- **continuous monitoring and adjustment of E_{CM}** to MeV precision (transv. Polar.)

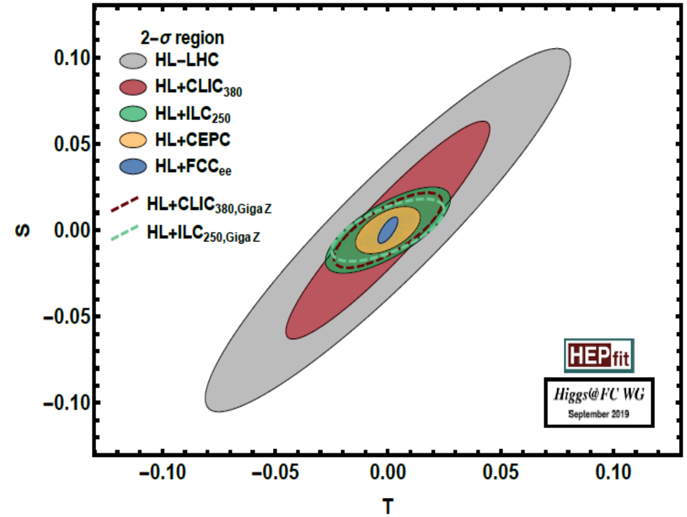
-- an extremely sensitive event selection against backgrounds

-- a generous lab director to spend 3 years doing this and neutrino counting

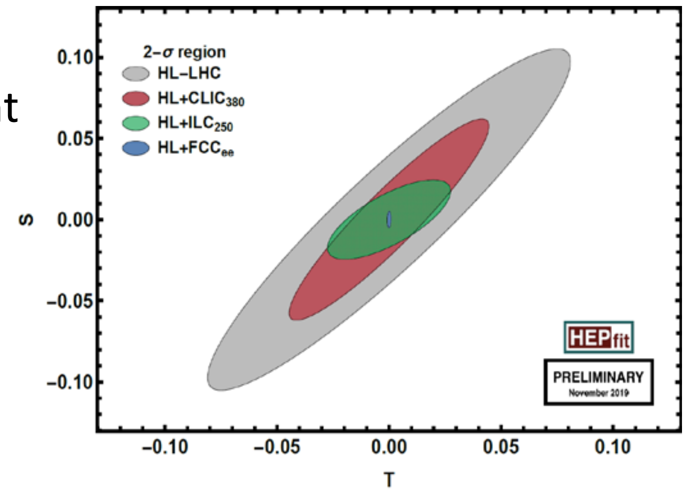
Scientific Complementarity: Electroweak Physics

Low Energy: the realm of FCC-ee

Highest luminosities at 91, 160 and 350 GeV
Transverse polar. at 91 and 160 GeV
m_Z (100 keV) Γ_Z (25 keV), m_W (<500 keV), $\alpha_{QED}(m_Z)$ (3.10^{-5})
Complete set of EW observables can be measured
Precision unique to FCC-ee + new physics sensitivity
➔ **a lot more potential than present treatment**.



ILC GigaZ or Zγ evts also interesting with long. polar.
but **requires polarized eletrons <u>and</u> positrons**
P-violating asymmetries: A_{LR} A_{FB}^{Pol} less precise but different



High Energy: the realm of ILC, CLIC

cross-sections and beam polarization asymmetries
for all charged leptons and quarks, WW, ZZ..etc.
Sensitivity at 3 TeV similar to FCC-hh electroweak.

Z line shape example

from the work of the «EPOL group» we estimated the beam energy related errors on the line shape parameters.

Table 15. Calculated uncertainties on the quantities most affected by the centre-of-mass energy uncertainties, under the final systematic assumptions.

Observable	statistics	$\Delta\sqrt{s}_{\text{abs}}$ 100 keV	$\Delta\sqrt{s}_{\text{syst-ptp}}$ 40 keV	calib. stats. 200 keV / $\sqrt{N^i}$	$\sigma_{\sqrt{s}}$ 85 ± 0.05 MeV
m_Z (keV)	4	100	28	1	–
Γ_Z (keV)	4	2.5	22	1	10
$\sin^2\theta_W^{\text{eff}} \times 10^6$ from $A_{FB}^{\mu\mu}$	2	–	2.4	0.1	–
$\frac{\Delta\alpha_{QED}(m_Z^2)}{\alpha_{QED}(m_Z^2)} \times 10^5$	3	0.1	0.9	–	0.1

from the three point scan we extract hadron cross-sections and muon forward backward asymmetry as function of ECM.

→ m_Z, Γ_Z, $A_{FB}{}^{\mu}$ (Pole) and α_{QED}(mZ) from the slope of AFB(s)

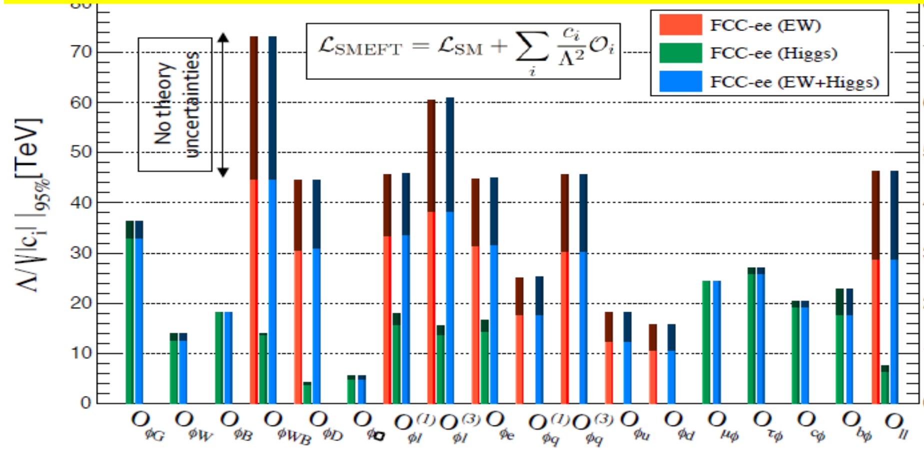
These are only the beam energy related errors must add lumi errors.

One of the ways to reduce the point to point errors is to use the muon momentum distribution.

Pecision EW measurements:
is the SM complete?

Table 3.1: Measurement of selected electroweak quantities at the FCC-ee, compared with the present precisions.

Observable	present value ± error	FCC-ee Stat.	FCC-ee Syst.	Comment and dominant exp. error
m_Z (keV/c^2)	91186700 ± 2200	5	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2495200 ± 2300	8	100	From Z line shape scan Beam energy calibration
R_ℓ^Z ($\times 10^3$)	20767 ± 25	0.06	0.2-1	ratio of hadrons to leptons acceptance for leptons
$\alpha_s(m_Z)$ ($\times 10^4$)	1196 ± 30	0.1	0.4-1.6	from R_ℓ^Z above [29]
R_b ($\times 10^6$)	216290 ± 660	0.3	<60	ratio of $b\bar{b}$ to hadrons stat. extrapol. from SLD [30]
σ^0_{had} ($\times 10^3$) (nb)	41541 ± 37	0.1	4	peak hadronic cross-section luminosity measurement
N_ν ($\times 10^3$)	2991 ± 7	0.005	1	Z peak cross sections Luminosity measurement
$\sin^2\theta_W^{eff}$ ($\times 10^6$)	231480 ± 160	3	2 - 5	from $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{QED}(m_Z)$ ($\times 10^3$)	128952 ± 14	4	small	from $A_{FB}^{\mu\mu}$ off peak [20]
$A_{FB}^{b,0}$ ($\times 10^4$)	992 ± 16	0.02	1-3	b-quark asymmetry at Z pole from jet charge
$A_{FB}^{pol,\tau}$ ($\times 10^4$)	1498 ± 49	0.15	<2	τ polarisation and charge asymmetry τ decay physics
m_W (keV/c^2)	80350000 ± 15000	600	300	From WW threshold scan Beam energy calibration
Γ_W (keV)	2085000 ± 42000	1500	300	From WW threshold scan Beam energy calibration
$\alpha_s(m_W)$ ($\times 10^4$)	1170 ± 420	3	small	from R_ℓ^W [31]
N_ν ($\times 10^3$)	2920 ± 50	0.8	small	ratio of invis. to leptonic in radiative Z returns
m_{top} (MeV/c^2)	172740 ± 500	20	small	From $t\bar{t}$ threshold scan QCD errors dominate
Γ_{top} (MeV/c^2)	1410 ± 190	40	small	From $t\bar{t}$ threshold scan QCD errors dominate
$\lambda_{top}/\lambda_{top}^{SM}$	1.2 ± 0.3	0.08	small	From $t\bar{t}$ threshold scan QCD errors dominate
ttZ couplings	± 30%	<2%	small	From E_{CM} = 365GeV run



-^- EFT D6 operators (some assumptions)

-^- Higgs and EWPOs are complementary

-^- top quark mass and couplings essential!

(the 100km circumference is optimal for this)

<-- many systematics are preliminary and should improve with more work.

<-- tau b and c observables still to be added

<-- complemented by high energy FCC-hh

Theory work is critical and initiated

More on TeraZ

The flavour factory

Progress in flavour physics wrt SuperKEKb requires > 10^{11} b pair events, FCC-ee(Z): 10^{12}

-- Challenge precision of CKM matrix elements
-- Push forward searches for FCNC, CP violation and mixing
-- Study rare penguin EW transitions such as $b \rightarrow s\tau^+\tau^-$
-- Test lepton universality with 10^{11} τ decays (with τ lifetime, mass, BRs)

a story to be written!

The 3.5 × 10^{12} hadronic Z decay also provide precious input for QCD studies

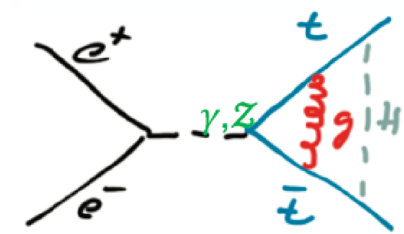
High-precision measurement of $\alpha_s(m_Z)$ with R_ℓ in Z and W decay jet rates, τ decays, etc. : $10^{-3} \rightarrow 10^{-4}$
huge $\sqrt{s}$ lever-arm between 30 GeV and 1 TeV (FCC vs ILC)

Testing running of α_s to excellent precision

Scientific Complementarity: Top physics

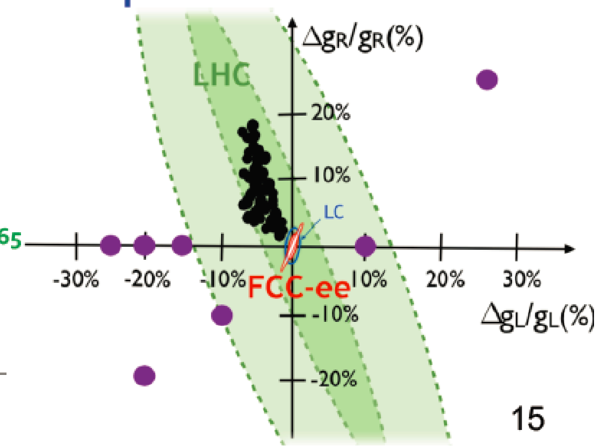
André H. Hoang

- **Top-pair threshold scan and just above: $\sqrt{s}$ = 340 – 380 GeV**
  - Similar luminosity and energy efficiency at FCC-ee and ILC
  - First main output: measurement of the top mass with precision ~20 MeV (stat)
    - Essential input to reduce parametric uncertainties in EWPO
    - Today's $\alpha_S(m_Z)$ uncertainty is a limiting factor: δm_{top} = 70 MeV
      - → Precise $\alpha_S(m_Z)$ @ FCC-ee helps: δm_{top} < 10 MeV
    - Complementary: Effective threshold scan with ISR
      - → Best result at 365/380 GeV (~100 MeV)



  - Second main output: measurement of the top EW couplings with % precision
    - Can determine four couplings: $g_{L,R}(Z,\gamma)$
      - → Either with longitudinal beam polarization (LC)
      - → Or with final-state top-quark polarization (CC and LC)

        With lepton / b-quark angular and energy distributions
    - Figure shows similar sensitivity for $g_{L,R}(Z)$ @ ILC_{500} and $FCC\text{-}ee_{365}$
      - → Similar result with $CLIC_{380}$
    - Only a first look for FCC-ee: still much understanding to gain



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Top Physics at High Energies

More general EFT analysis of top EW couplings with 10 independent form factors

Requires two energies 365/380 GeV + e.g. 500

Longitudinal polarization adds to the info also given by observables resulting from top polarization analysed by V-A decay

need high energy (>500 GeV) lepton collider

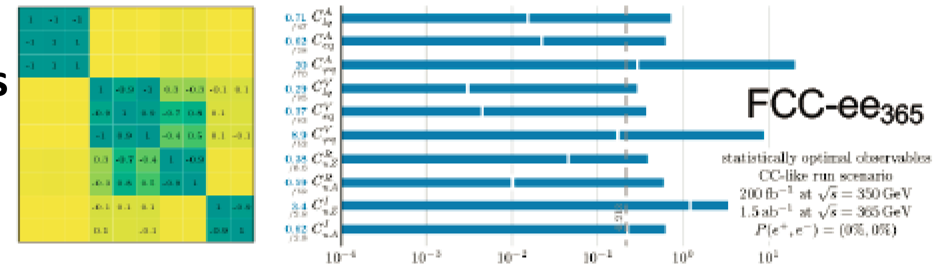


Figure 23. Global one-sigma constraints and correlation matrix deriving from the measurements of statistically optimal observables in a circular collider (CC-)like benchmark run scenario.

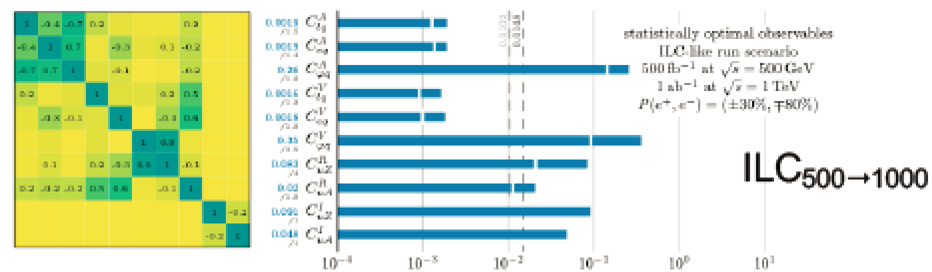
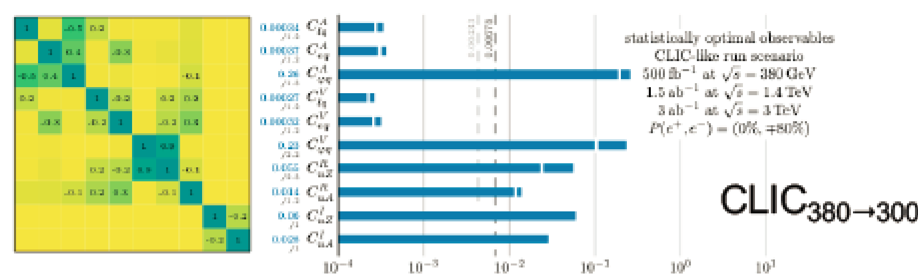


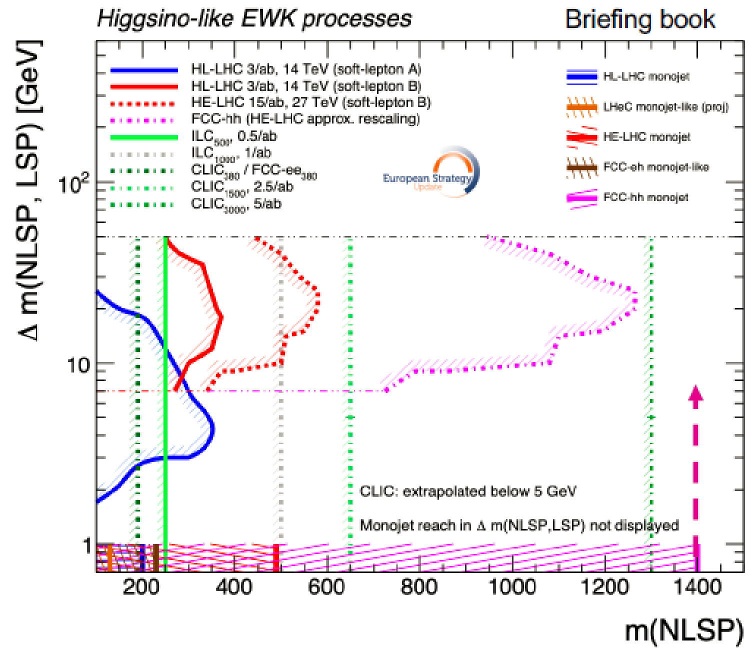
Figure 24. Global one-sigma constraints and correlation matrix deriving from the measurements of statistically optimal observables, in an ILC-like benchmark run scenario.



Scientific Complementarity: BSM Physics

- Observation of WIMPs (with masses m_χ of a few 100 GeV, and small ΔM with LSP)
  - Such particles may have escaped LHC and may continue to escape HL-LHC/FCC-hh
    - Could affect EWPO: Z pole run of FCC-ee
    - Directly produced at linear colliders if $m_\chi < \sqrt{s}/2$
    - May also be found at FCC-hh in the same mass range
      - → LHC analyses show that it is possible

CMS Coll., arXiv:1905.13059, Fig. 6

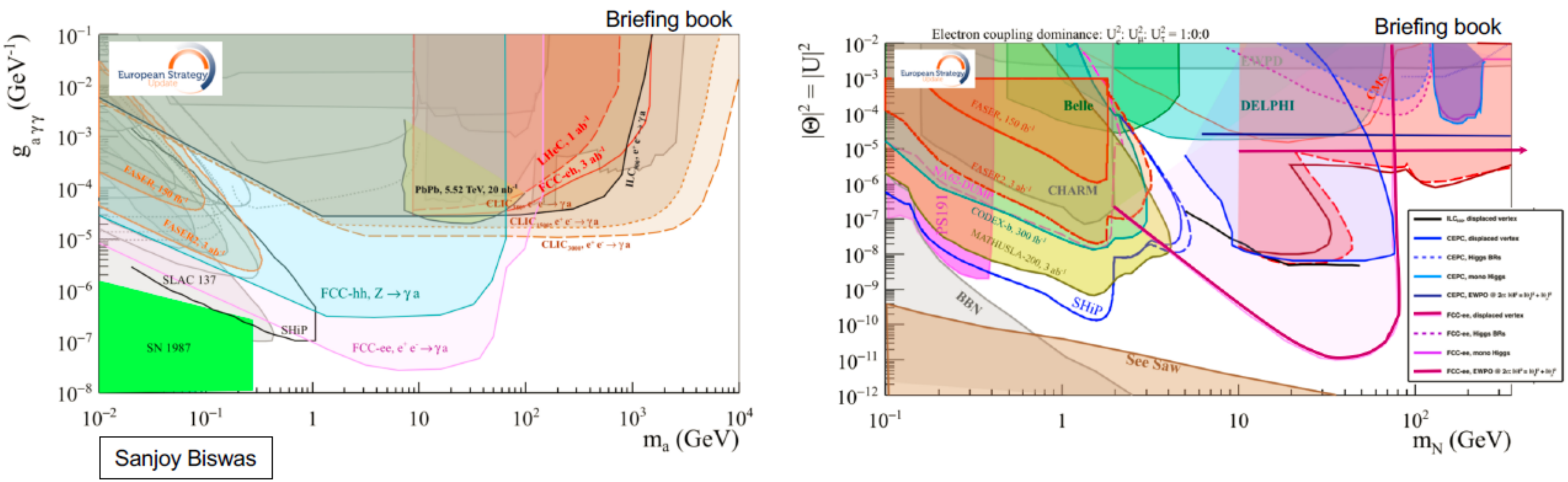


- Observation of heavier particles (5 → 50 TeV)
  - Require a 100 TeV hadron collider
    - Coloured particles
    - Higgs bosons
    - WIMPs

- A complete coverage require all colliders (FCC-ee, ILC, FCC-hh)

Scientific Complementarity: BSM Physics

- Direct observation of new feebly-interacting particles
  - For example, axion-like particles, dark photons, right-handed heavy neutrinos
    - Best odds to find such particles below the Z mass with FCC-ee running at the Z pole



    - Higher-energy machines can see them at higher masses if their couplings are larger

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BSM Physics: what if?

A high energy e+ e- collider might become an urgent must (like the 'Higgs Factories' today) if a new particle is found at a hadron collider (HL-LHC, FCC-hh) and missing information precludes essential knowledge to be gathered.
We are not in that situation, but we might be, one day!

This was the case for the Z and W bosons: at the S $\bar{p}$ p S or Tevatron colliders the number of neutrino families could not be determined fault of an independent tag of W or Z production or of the Z width. This was solved in 3 weeks of running at LEP in 1989.

Similarly we need to measure the Higgs width and coupling in absolute term → lepton collider

<u>We must ensure that even if FCC-ee or CEPC proceeds, the high energy e+e- door is not closed.</u>
➔ at least complete the R&D to ensure that a linear collider can be build…
if we are in the lucky position to need one.

Similar remarks for circular collider for e.g. feebly coupled particles from Z decay except…
CC would have to discover them…

Summary of complementary qualities

Table 3: Summary of complementary qualities of the proposed circular and linear colliders FCC-ee and ILC. Notes: [1] single-parameter sensitivity, full program; [2] multi-parameter sensitivity up to 365/500 GeV; LFUV: Lepton Flavour Universality Violation; LNV: Lepton Number Violation.

Quality	FCC-ee	ILC
Energy Range (GeV)	88 to 240, up 365	(91) 240 up 500, 1000
Interaction points	2–4	1
Luminosity	$\propto E_{\rm beam}^{-3.5}$ × Radius × Power × #IP	$\propto E_{\rm beam}$ × Power
Main statistics		
Z	5.10^{12} Z	5.10^{9} Z
WW	3.10^{8} WW	10^{7} WW
HZ	10^{6} H	4.10^{5} H
$t\bar{t}$ and above	10^{6} $t\bar{t}$ at 365 GeV	3.10^{6} $t\bar{t}$ at 500 GeV
Beam Polarisation	Transverse	Longitudinal
For	e^+ and e^-	$e^-(\pm 80\%)$, $e^+(\pm 30\%)$
Beam Energies	up to WW threshold	all energies
Use	$\sqrt{s}$ ppm calibration	helicity cross-sections
Monochromatisation	$\sigma_{\sqrt{s}} = 4 - 10$ MeV	no
Use	s-channel H production	
Higgs Physics		
Hee Coupling	SM $(m_e) \pm$ 15-50%	–
HHH Coupling:		
from $\sigma(e^+e^- \to ZH)$	$\pm 14^1 - 33^2\%$	$\pm 25^1 - 38^2\%$
from HH production	–	± 27% (500 GeV), ± 10% (1 TeV)
Electroweak	m_Z, Γ_Z, m_W (100, 25, 600 keV) $\sin^2\theta_W^{\rm eff}(3.10^{-6})$ $\Delta\alpha_{\rm QED}(3.10^{-5})$ LFUV g_A (10^{-5}), g_V (10^{-5}) EFT operators up to 70 TeV	High-energy polarised Cross sections and asymmetries for leptons, quarks and bosons contact interactions up to 100 TeV
Flavour Physics	$e/\mu/\tau$ LNV 10^{-10} LFUV $< 10^{-5}$ b and c hadrons properties rare decays and CPV	
QCD	30-365 GeV jet systems hadronisation α_s in Z,W,τ (10^{-4})	240-1000 GeV jet systems hadronisation
New particle search	in Z decays: Feebly coupled particles RH neutrinos, ALPs etc.	up to 500 GeV pair production searches in gaps left by hadron collider

Summary

Between 30 and 240 GeV: FCC-ee

- High luminosity for Z, Hee, WW, HZ;
- Exquisite energy calibration at the Z, Hee, WW;
- Monochromatisation at $\sqrt{s} = m_H$;
- Z and W factory with 5.10^{12}Z and 3.10^8 WW, enabling electroweak measurements, α_{QED} and α_{QCD} determination, flavour (b, c, τ) studies, QCD physics, searches for SM symmetry violations and feebly coupled particles: RHnu, ALPS, etc;
- s-channel Higgs production: g_{Hee} coupling

Between 240 and 380 GeV: FCC-ee and ILC

- Higgs main couplings determined from copious decay modes in a model-independent way, with clear advantage for FCC-ee at 240 GeV due to 5-to-10 times higher luminosity;
- Higgs self-coupling inferred from ZH cross section energy dependence, also benefiting from larger luminosities (up to 4σ significance for FCC-ee);
- Measurements of m_{top} to better than 20 MeV. Determination of top neutral-current couplings, with some specificity for ILC because of beam polarization.

Above 380 GeV: ILC

- Determination of Higgs self-coupling from double Higgs production;
- Searches for new particles in the gaps left by hadron colliders. May be essential if a new particle is discovered at the hadron collider in ILC energy range;
- High energy EW processes: lepton, quarks and boson pairs, with polarised beams

Financial Complementarity

The complementarity for physics is well established can we make use of it to gain financial advantage?

-- Two facilities?

The cost of FCC-ee + cost of ILC ≈ incremental cost of FCC-hh as step 2

Having both facilities raises the profile of the community at the level needed for the following step.

-- lFF we are in that situation we could optimize the run plan and the set-up to minimize cost (LC+CC-ee) < cost (LC) + cost (CC-ee)

-- the simplest way would be to e.g. let the FCC take the data at and below 240 GeV and ILC take 250 also and all data above 380 GeV

Financial complementarity

- **Potential savings and optimizations**
  - On the colliders, with a coordinated distribution of tasks
  - On the detectors, with a narrower domain of energies to cover
    - e.g. less calorimeter granularity / thickness needed at $\sqrt{s}$ = 240 GeV than at $\sqrt{s}$ = 1 TeV
- **Example of monetary savings**
  - The FCC-ee upgrade to the top-pair threshold is estimated to 1.1 BCHF
  - Several opportunities on the ILC side
    - Re-arrangement for GigaZ
    - Extra work and investment for positron polarization at low energy
    - Detector push-pull
      - → Could add up to the best part of a billion USD
  - Further optimization of the run plans can be envisioned, taking into account e.g.
    - The integrated power to produce a Higgs boson
    - The best centre-of-mass energies for the Higgs self-coupling measurement
    - …

Sociological and regional complementarity

- **Sociological**
  - Competition and cross motivation
    - Remember LEP and SLC
    - Similar cross motivation between ILC and FCC-ee during the past seven years
      - → Maximal FCC-ee energy increased to 365 GeV

        To get similar top EW couplings and Higgs self coupling precision as ILC_{500}
      - → Seven-fold ILC luminosity increase at 250 GeV from 0.85 to $5.4\times10^{34}\ cm^{-2}s^{-1}$

        To approach FCC-ee Higgs coupling precision in a reasonable time
  - **!** ILC operation to 500 and 1000 GeV is expected to span over many decades
    - Would cover the 10-years physics gap between the end of FCC-ee and the beginning of FCC-hh
      - → Ensures continuous data taking at the high-energy frontier for the next 70 years
- **Regional**
  - Creation of two new infrastructures in two different parts of the works
    - Promising scope for development of complementary/synergistic programs
      - → With a long-term, worldwide, vision of high-energy frontier colliders

A complementary FCC-ee / ILC operation plan ?

Disclaimer

Presented operation models are hypothetical, for illustration purpose.

The real run plan will be discussed in due time by users and committees of both facilities

Assumptions

ILC is (soon) approved by the Japanese government → ILC starts in 2030's (no "maybe"!)

Required to allow for run plans logistics early enough

ILC claimed (upgraded) luminosities can be demonstrated

To reach luminosities similar to FCC-ee at and above the top-pair threshold

Luminosity upgrade occurs after 5 years of running at a given energy

FCC tunnel studies and FCC-INT TDR encouraged by the 2020 European Strategy

For FCC-ee to start in 2038, seamlessly after HL-LHC

FCC-ee designed and run with four IPs, maximise energy efficiency (more Higgs / GJ)

→ factor 1.7 with respect to CDR values

√s monochromatisation can be achieved at FCC-ee (Hee coupling measurement at √s = mH)

A would-be FCC-ee operation model complementary to ILC

principle: do not run at 350/365

NB this makes a big difference and should be known very soon

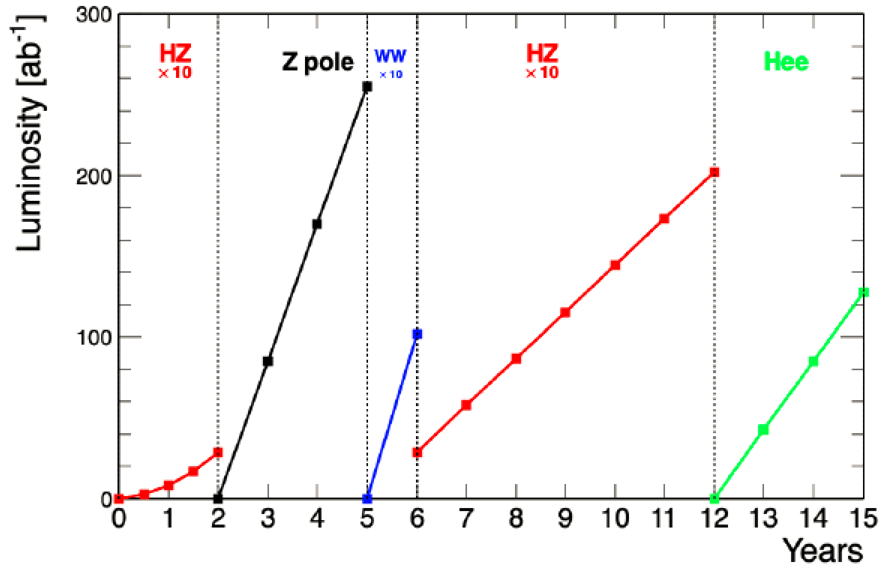
Use the six years saved by not operating at the top-pair threshold and above

To run 2x longer at the HZ maximum

To run 3 years at √s = 125 GeV

start at ZH point

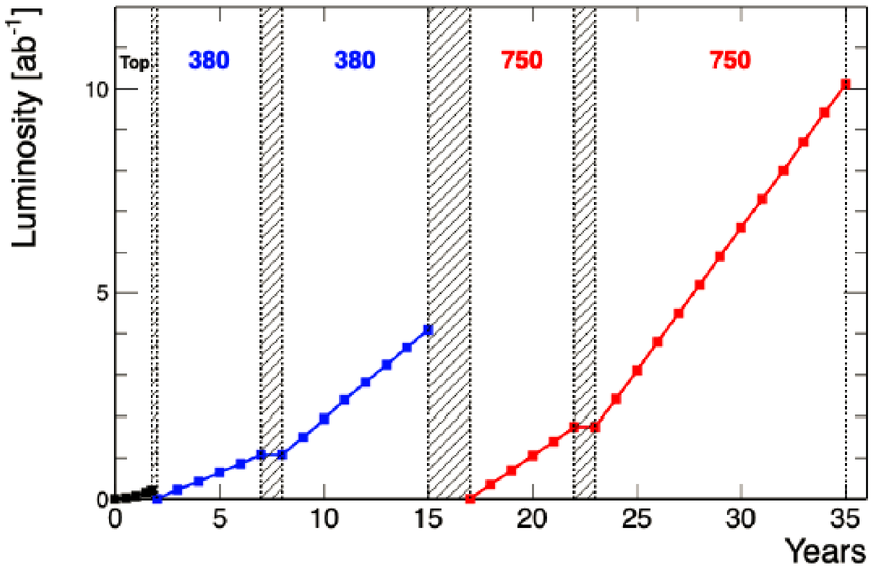
- With 4 IPs, accumulate
  - 2.9 ab^{-1} at 240 GeV in the first 2 years
    - ~600,000 Higgs in 2040
  - 20 ab^{-1} in at 240 GeV over a decade
    - Total: 4 million Higgs
  - 250 ab^{-1} around the Z pole in 3 years
    - Almost 10^{13} Z produced
  - 10 ab^{-1} at the WW threshold in 1 year
  - 130 ab^{-1} at $\sqrt{s}$ = 125 GeV in 3 years
    - ~15-30 ab^{-1} with 6-10 MeV monochromatization: 15% precision on Hee



A would-be ILC operation model complementary to FCC-ee

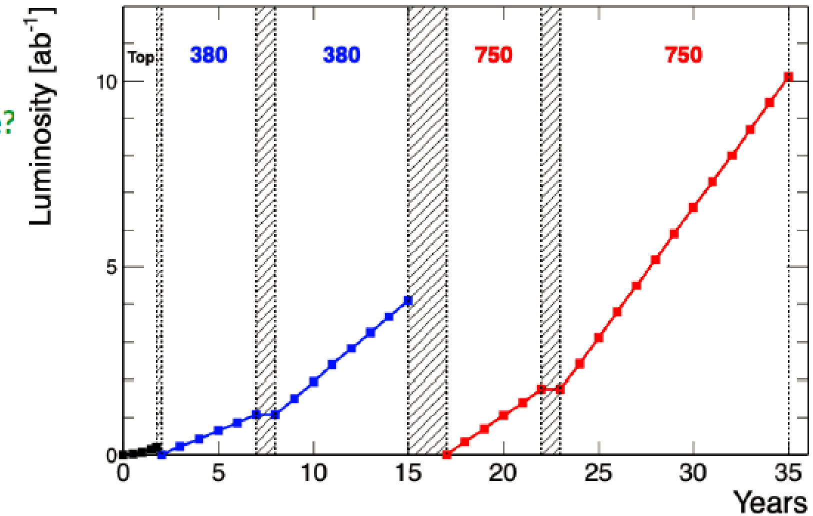
- In the time initially foreseen at √s = 250 GeV (400,000 Higgs bosons in 2040-45)
  - Run instead at the top threshold and just above
    - Two years at 340-350 GeV for the threshold scan : 0.2 ab^{-1}
    - 4 ab^{-1} at 380 GeV (best compromise between top and Higgs physics)
      - → Top mass and EW couplings
      - → Higgs complementary to FCC-ee
      - → Couplings as precise as FCC-$ee^{4IP}_{240-365}$
    - Note: Detector calibration at the Z pole?

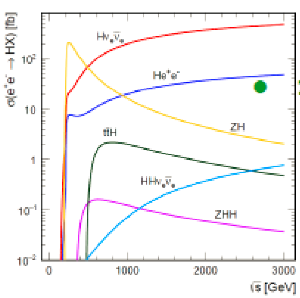
Collider	FCC-ee^{4IP}_{240}	ILC_{380}	Combin.
g_{HZZ} (%)	0.11	0.25	0.11
g_{HWW} (%)	0.65	0.43	0.31
g_{Hbb} (%)	0.67	0.80	0.41
g_{Hcc} (%)	0.87	2.2	0.67
g_{Hgg} (%)	0.83	1.2	0.59
$g_{H\tau\tau}$ (%)	0.71	1.3	0.47
g_{HHH} (%)	–	–	24.
Γ_H (%)	0.9	1.3	0.8
BR_{inv} (%)	0.11	0.33	0.10
BR_{EXO} (%)	0.60	1.4	0.55



A would-be ILC operation model complementary to FCC-ee (II)

- In the time initially foreseen at $\sqrt{s}$ = 250 GeV (400,000 Higgs bosons in 2040-45)
  - Run instead at the top threshold and just above
    - Two years at 340-350 GeV for the threshold scan : 0.2 ab^{-1}
    - 4 ab^{-1} at 380 GeV (best compromise between top and Higgs physics)
      - → Top mass and EW couplings
      - → Higgs complementary to FCC-ee
      - → Couplings as precise as $\text{FCC-ee}^{4IP}_{240\text{-}365}$
    - Drawback: Detector calibration at the Z pole?
  - High energy operation for HHH and ttH
    - 500 GeV and 1 TeV not optimal
      - → ZHH maximum around 600 GeV
      - → WW→ HH ≃ (Z→νν)HH around 700 GeV
      - → ttH maximum around 800 GeV
    - 10 ab^{-1} at 750 GeV in ~20 years
      - → ttH precision ~1.5% (tbc)
      - → HHH precision ~ 10% (tbc)





3rd FCC Physics Workshop
17 Jan 2020

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Complementary remarks

FCC-hh would further improve Higgs couplings

Rare decays (H $\rightarrow$Zg, gg, $\mu\mu$, …)

Top Yukawa coupling to better than 1% ; Higgs self-coupling to 3-5%.

With 10^{13} Z produced, the sensitivity of searches for rare processes would improve

ALPs, RH neutrinos, rare Z, b, τ decays, etc.

The run at √s = 125 GeV would provide Nν with a precision of 0.0005 (vs 0.0074 today)

With the measurement of the ratio $\sigma(e+e- \rightarrow \gamma\nu\bar{\nu})/\sigma(e+e- \rightarrow \gamma\mu+\mu-)$

A combination of FCC-INT (at CERN) and CLIC (in Japan) might be attractive.
Similar coordinations and omplementarities including CEPC, CLIC etc
will I am sure be considered

In general, the best solution is to enphasize the energies where each facility is unique.

Conclusions

The 'Higgs factories' are not 'all the same' !

Significant domains of physics exist, in which either FCC-ee or ILC is unique

For FCC-ee

High luminosity and exquisite energy calibration at the Z, WW, and ZH energies
Unique opportunities of multitude of EW measurements, flavour physics, searches of SM symmetry violations and feebly coupled particles.
Possibility of monochromatisation at $\sqrt{s} = mH$
Unique chance of measuring the electron Yukawa coupling

For ILC

Unique ability to explore lepton collisions above 365 GeV
Interesting in gaps left by LHC (or if a new particle is discovered at LHC in the suitable mass rang

This complementarity can be exploited with a suitable modification of the run plans
Leading to substantial global cost saving and overall improvement of physics performance compared to the simple addition of the original run plans

Conclusions (II)

If the European Strategy decides to support FCC-INT (FCC-ee, then FCC-hh)

The physics motivation for high-energy linear colliders remains

(If their performance claims are demonstrated)

➔ Plans and R&D for such colliders in other regions should thus be pursued.

If sufficient support is found to build a linear collider in Japan (or not)

FCC-ee remains the most pragmatic, safest, and most effective way toward FCC-hh

-- essential synergies between FCC-ee and FCC-hh

-- extremely strong FCC-ee physics case on its own right

-- The full FCC-INT programme is a formidable tool of investigation

A continuation of a worldwide plane including both circular and linear machine would certainly pose considerable challenges, but … offers complementary programmes with a long-term vision of the high-energy frontier