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 are called 'Higgs Factories' and considered to have similar performance**

2. With the underlying conclusion that probably only one needs to/ can be built

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

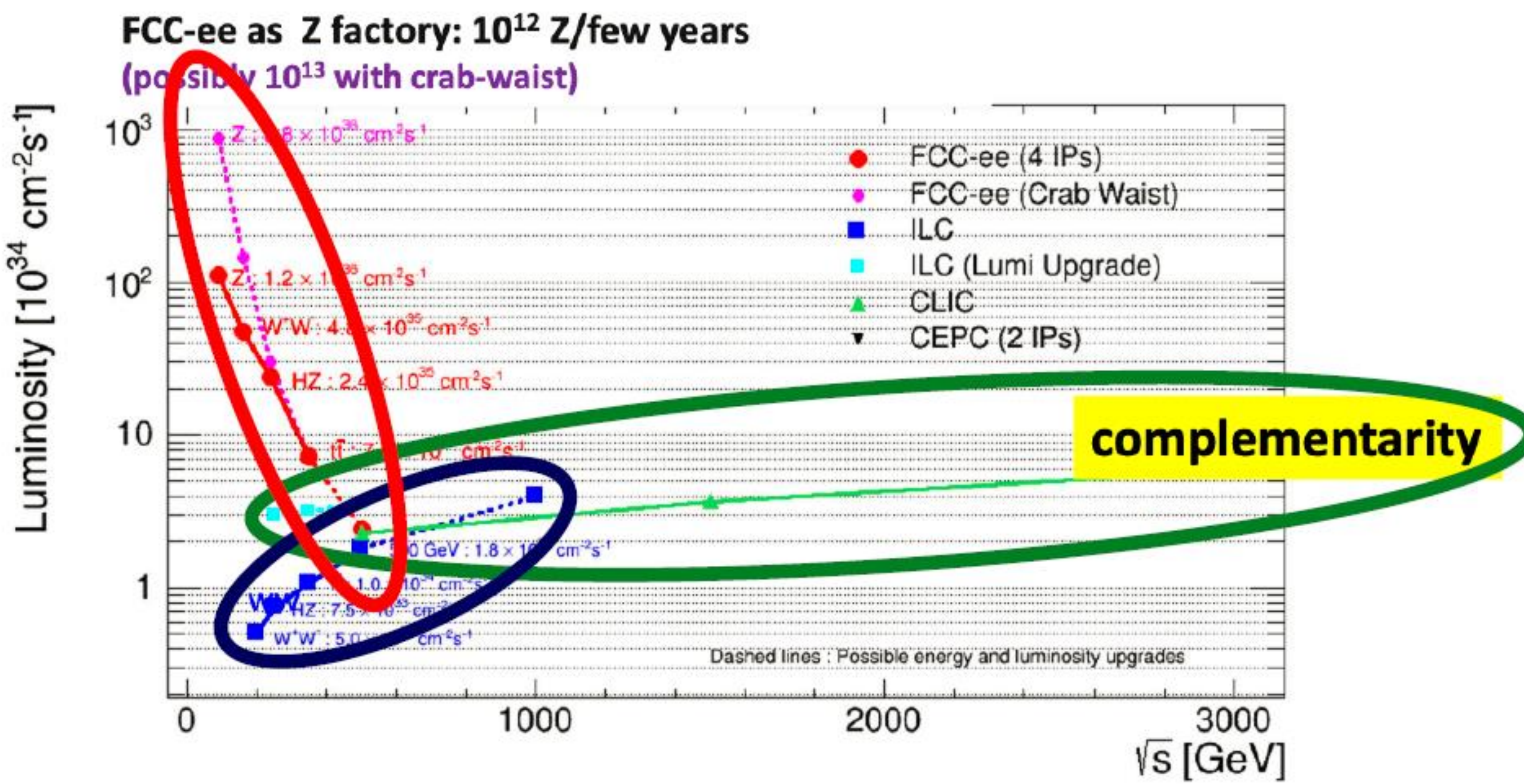
4. Given the very strong synergetic link between the FCC-ee and the FCC-hh
   ≥100 TeV p-p collisions provide the highest parton-E_{CM} for the foreseeable future.
   {ee + hh} → -- much more favorable funding profile + stronger physics case for 100km tunnel
   --considered best possible scenario in ESPP input by FCC collaboration.
   FCC (ee+hh) will probably be either fully build or fully dropped

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

5. **We investigate here the physics 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
If you prefer, replace by CC–A and LC--B

This remark was made since the beginning in 2012



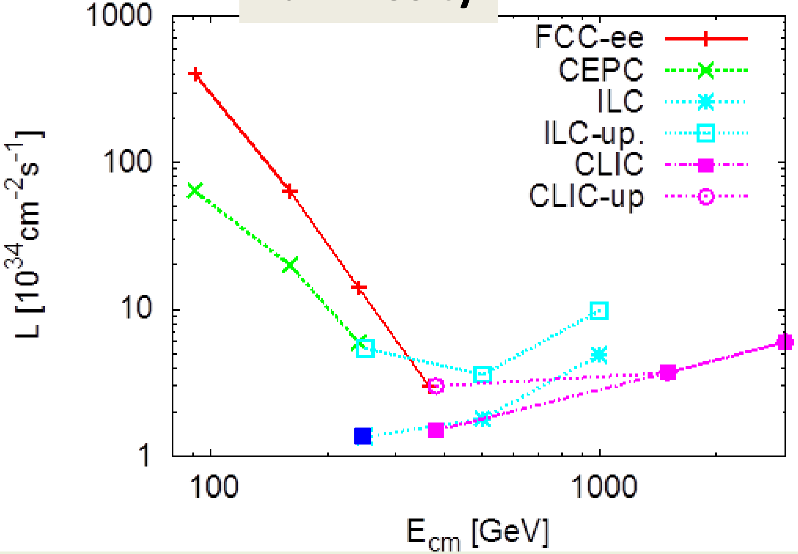
overlap in ~300 GeV region

A.B. HFACT 2014

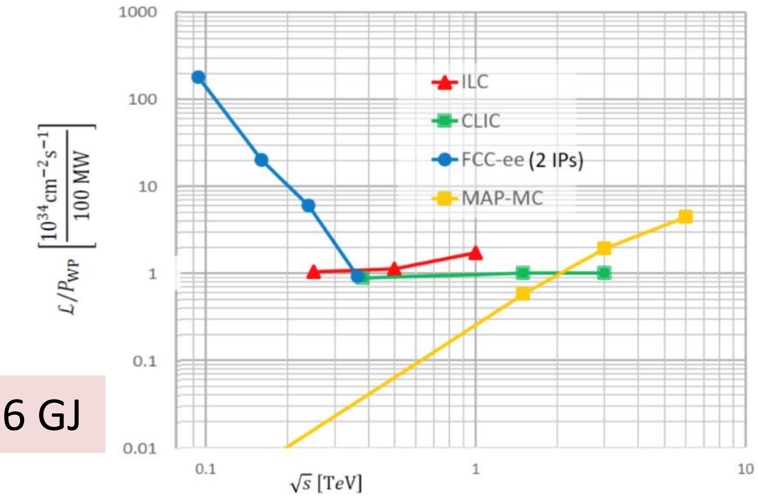
Operational Differences

plots from Briefing Book

Luminosity



Luminosity/Power → Energy efficiency



1 MW.h = 3.6 GJ

Luminosity vs Energy **circular below 350 GeV** **linear above 350 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% e+ ±30% → 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** *upgrades are not included in the cost*

Scientific differences / complementarity

First stage 'Higgs Factory' (E_{CM} ≤365 GeV)

- "All low-energy Higgs factories have similar performance, to 1st order"
  - ILC_{250} = $CLIC_{380}$ = $CEPC_{240}$ = FCC-$ee_{240\rightarrow365}$?
    - Not quite !

J. De Blas et al., arXiv:1905.03764

HL-LHC: alone requires total width assumptions, with e+e- → model indept

Kappa fit, without/with HL-LHC

LHC-dominated

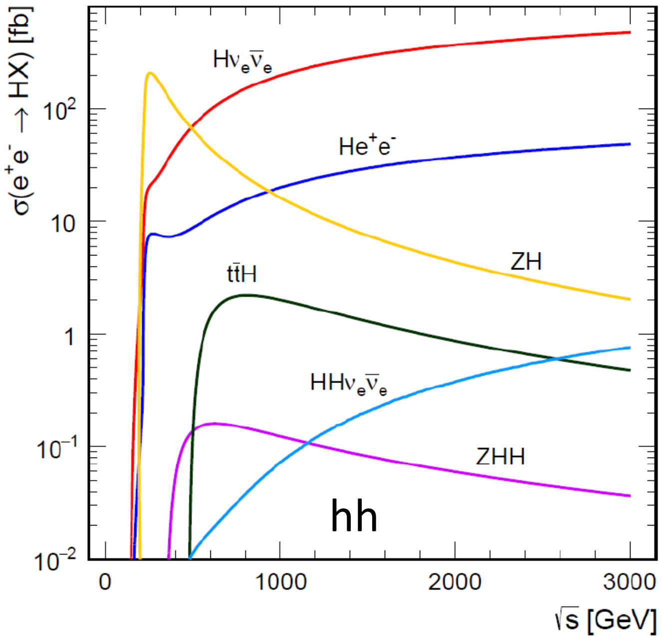
Global EFT fit, without/with HL-LHC

Collider	HL-LHC	ILC_{250}	$CLIC_{380}$	$CEPC_{240}$	FCC-$ee_{240\rightarrow365}$	
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	

Higher luminosity of circular collider --> more statistics, in less time
- TeraZ program helps (arXiv:1907.04311)
- longitudinal polarization helps little if HL-LHC or Giga-Z added

High energy Higgs factories: ILC500, CLIC3000, FCC-hh.

FCC-ee + FCC-hh is unbeatable



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.	±2(stat)±~3(syst)
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

ee

hh

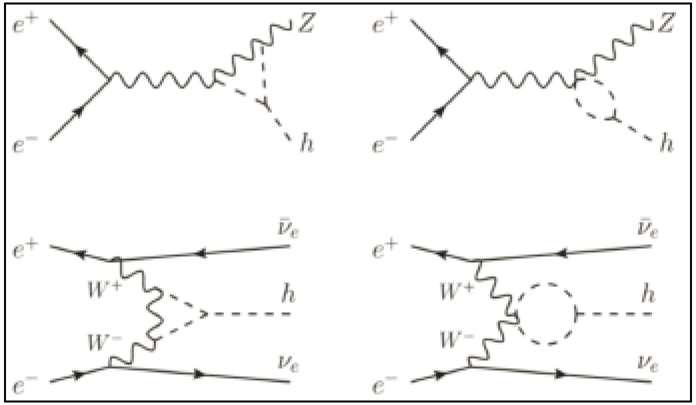
FCC-hh 10^{10} H produced, +
FCC-ee measurement of g_{HZZ}
→ g_{HHH} , $g_{H\gamma\gamma}$, $g_{HZ\gamma}$, $g_{H\mu\mu}$, BR_{inv}

(*)see M. Selvaggi, 3d FCC physics workshop,
9% precision in 3 years of FCC-hh running, 2004.03505v1

Scientific Complementarity: Higgs self - coupling

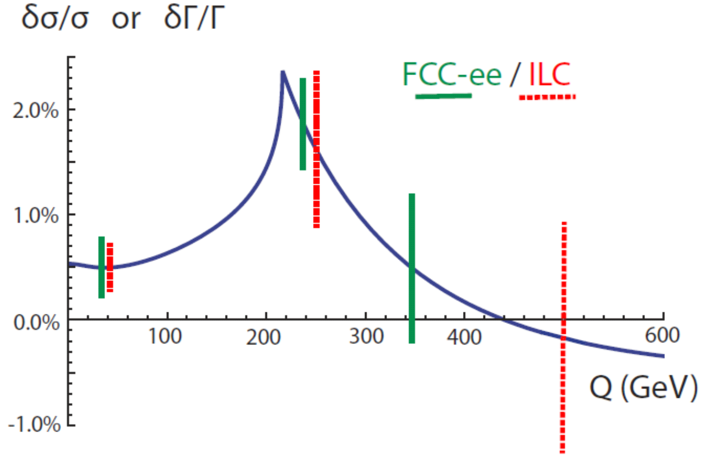
McCullough

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



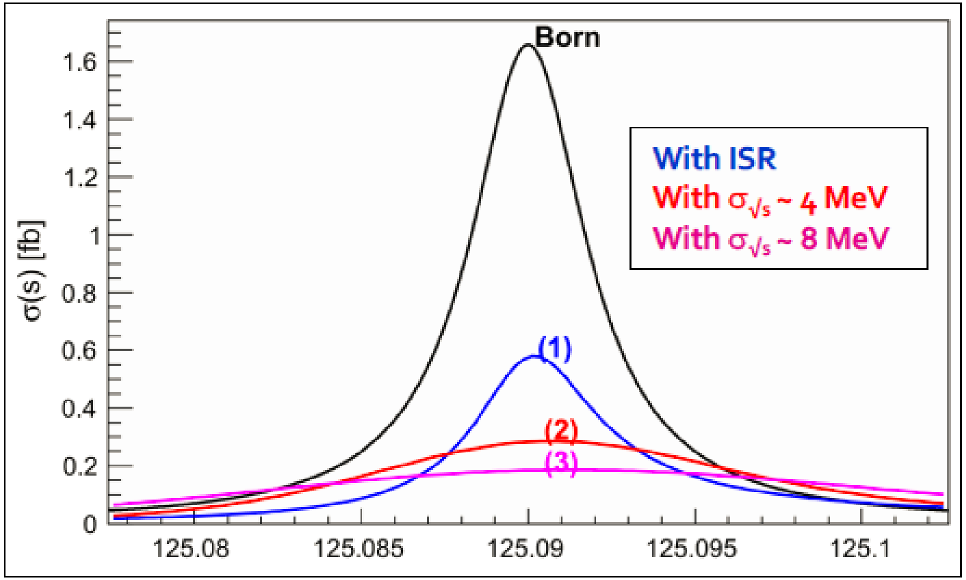
«Traditional» two-Higgs production can be performed
also, above 500 GeV by ILC, CLIC, FCC-hh

«the two are complementary, robust methods»
1910.00012v2 B. Di Mico et al
ILC500→ ±27%   FCC-ee (4IP) → ±27%

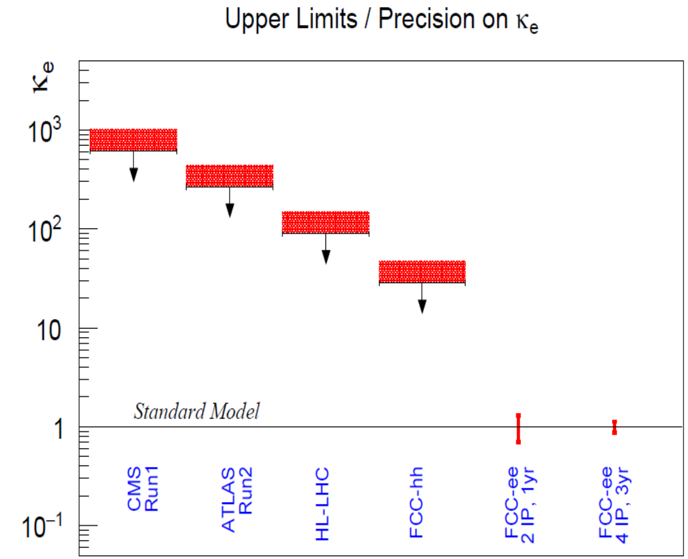


CLIC: ±9% from 380/1TeV/3TeV (2040+ 30 years)
FCC-hh: ±9% after 3-5 years (2040+ 30 years)
(± 2 ± ~3)% (50 years)

Something unique for FCC-ee: electron Yukawa coupling



Jadach & Kycia arXiv:1509.02406



e+e- → H @ 125.xxx GeV requires

-- Higgs mass to be known to <5 MeV from 240 GeV run (FCC: under study, CEPC group did it)

-- **Huge luminosity** (special single cell 400 MHz RF is foreseen for low energy runs)

-- **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 (also neutrino counting and rare Z decay)

Value of transverse polarization in circ. collider: Z line shape example

Beam energies can be monitored at 100 keV level regularly (every 10 minutes)
FCC «EPOL group» estimated the beam energy errors on line shape parameters.
arXiv:1909.12245

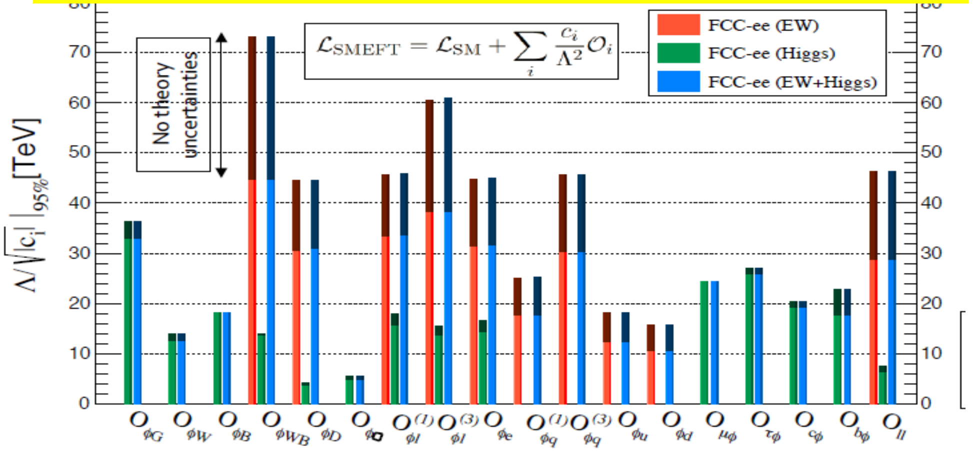
Table 15. Calculated uncertainties on the quantities most affected by the centre-of-mass energy uncertainties, under the final systematic assumptions.

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

From the three point scan extract hadron cross-sections and muon forward backward asymmetry as function of center-of-mass energies
→ m_Z, Γ_Z, $\sin^2\theta_W^{eff}$ and α_{QED}(mZ) from $A_{FB}{}^{\mu}$ (Pole) and the slope of AFB(s) (unique).

Precision EW measurements: is the SM complete?

Observable	present value ± error	FCC-ee Stat.	FCC-ee Syst.	Comment and leading exp. error
m_Z (keV)	91186700 ± 2200	**4**	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2495200 ± 2300	**4**	25	From Z line shape scan Beam energy calibration
R^Z_ℓ ($\times 10^3$)	20767 ± 25	**0.06**	0.2-1	ratio of hadrons to leptons **acceptance for leptons**
$\alpha_s(m_Z^2)$ ($\times 10^4$)	1196 ± 30	**0.1**	0.4-1.6	from R^Z_ℓ above
R_b ($\times 10^6$)	216290 ± 660	**0.3**	<60	ratio of $b\bar{b}$ to hadrons stat. extrapol. from SLD
σ^0_{had} ($\times 10^3$) (nb)	41541 ± 37	**0.1**	4	peak hadronic cross section luminosity measurement
N_ν($\times 10^3$)	2996 ± 7	**0.005**	1	Z peak cross sections Luminosity measurement
$\sin^2\theta_W^{eff}$($\times 10^6$)	231480 ± 160	**2**	2.4	from $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{QED}(m_Z^2)$($\times 10^3$)	128952 ± 14	**3**	small	from $A_{FB}^{\mu\mu}$ off peak QED&EW errors dominate
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 polarization asymmetry τ decay physics
m_W (MeV)	80350 ± 15	**0.25**	0.3	From WW threshold scan Beam energy calibration
Γ_W (MeV)	2085 ± 42	1.2	0.3	From WW threshold scan Beam energy calibration
$\alpha_s(m_W^2)$($\times 10^4$)	1170 ± 420	**3**	small	from R_ℓ^W
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	**17**	small	From $t\bar{t}$ threshold scan QCD errors dominate
Γ_{top} (MeV/c^2)	1410 ± 190	45	small	From $t\bar{t}$ threshold scan QCD errors dominate
$\lambda_{top}/\lambda_{top}^{SM}$	1.2 ± 0.3	**0.10**	small	From $t\bar{t}$ threshold scan QCD errors dominate
ttZ couplings	± 30%	0.5 – 1.5%	small	From $\sqrt{s} = 365$ GeV run



-^- EFT D6 operators (some assumptions)

-^- Higgs and EWPOs are complementary

-^- top quark mass and couplings essential!

(the 100km circumference is optimal for this)

<-- systematics are preliminary
(aim at reducing to systematics)

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

<-- complemented by high energy FCC-hh

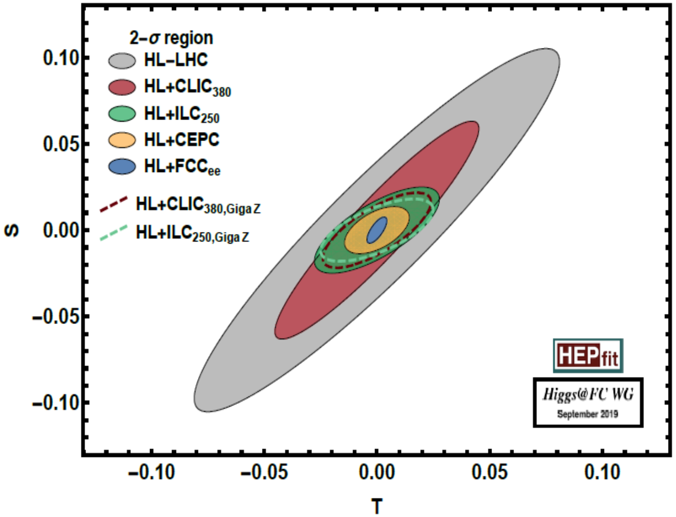
Theory work is critical and initiated *1809.01830*

d Line

Scientific Complementarity: Electroweak Physics

Low Energy: the realm of FCC-ee

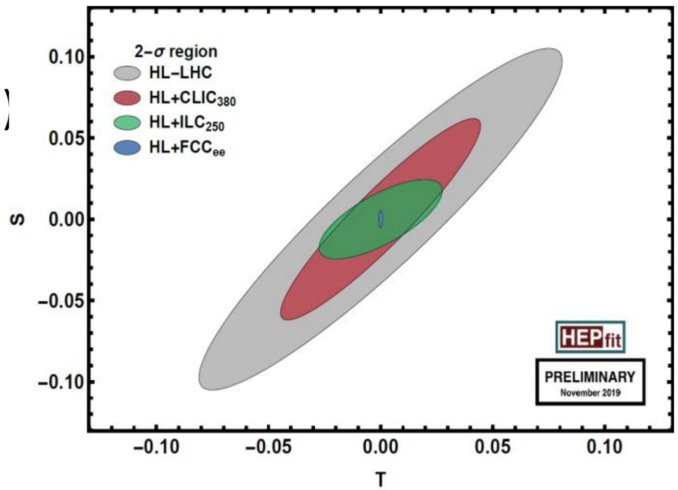
Highest luminosities at 91, 160 and 350 GeV
Transverse pol. at 91 and 160 GeV→Ecm calibration
m_Z (100 keV) Γ_Z (25 keV), m_W (<500 keV), $\alpha_{QED}(m_Z)$ (3.10^{-5})
Complete set of EW observables can be measured
Precision unique to FCC-ee + new physics sensitivity
➔ **a lot more potential than present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



ILC GigaZ or Zγ evts also interesting with longitudinal polar.
but **requiresboth polarized electrons <u>and</u> positrons**
P-violating asymmetries: A_{LR} A_{FB}^{Pol} (but no new information)

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 same ballpark as FCC-hh electroweak.



More on TeraZ

The Flavour Factory

Progress in flavour physics wrt SuperKEKb/BELLEII requires > 10^{11} b pair events,
FCC-ee(Z): will provide ~10^{12} b pairs. "**Want at least 5 10^{12} Z…"**

-- precision of CKM matrix elements
-- Push forward searches for FCNC, CP violation and mixing
-- Study rare penguin EW transitions such as $b \to s\ \tau^+ \tau^-$, spectroscopy (produce b-baryons, B_s …)
-- Test lepton universality with 10^{11} τ decays (with τ lifetime, mass, BRs) at 10^{-5} level, LFV to 10^{-10}
-- all very important to constrain / (provide hints of) new BSM physics.

need special detectors (PID); a story to be written!

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

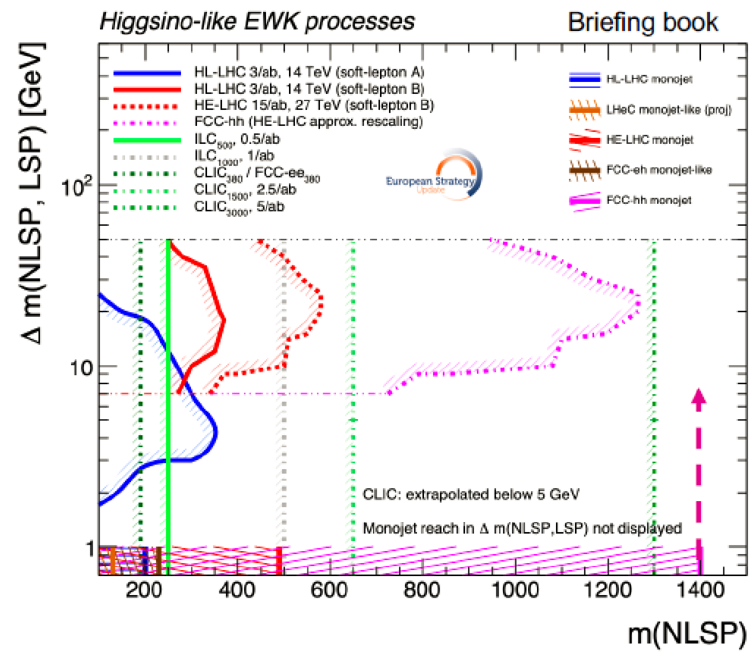
High-precision measurement of $\alpha_s(m_Z)$ with R_ℓ in Z and W decay, jet rates, τ decays, etc. : $10^{-3} \to 10^{-4}$
huge $\sqrt{s}$ lever-arm between 30 GeV and 1 TeV (FCC vs ILC), fragmentation, baryon production ….

Testing running of α_s to excellent precision

BSM exploration at high energy: ILC/CLIC (E≥500 GeV)

- 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

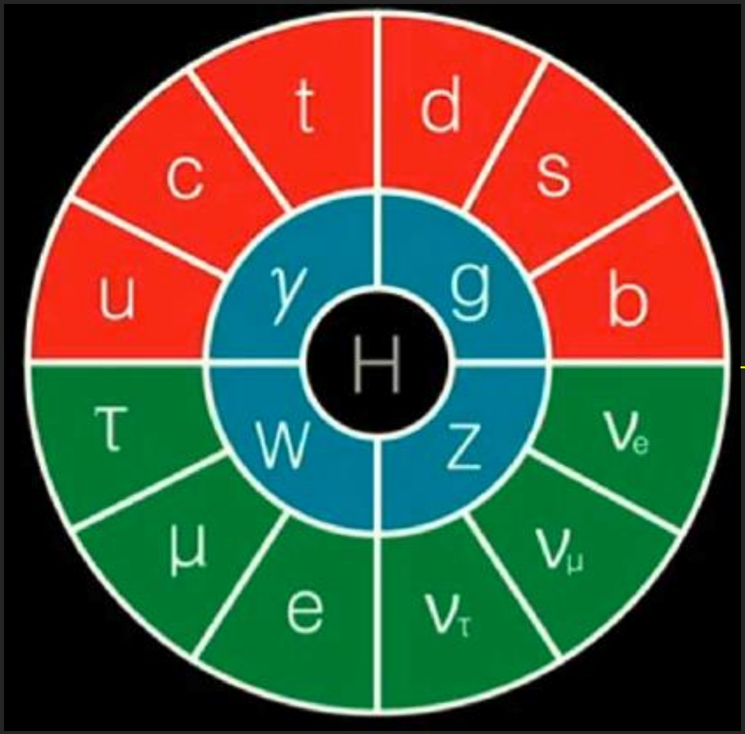


- Observation of heavier particles (5 → 50 TeV)
  - Require a 100 TeV hadron collider
    - Coloured particles
    - Higgs bosons
    - WIMPs

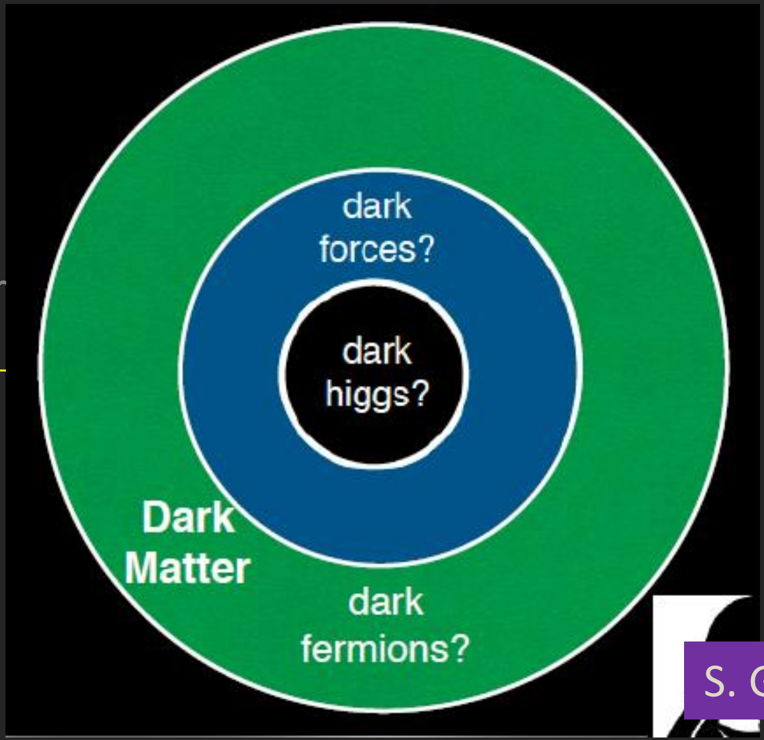
- A complete coverage require all colliders (FCC-ee, ILC, FCC-hh)

Dark Sector at Z factory

With the Higgs discovery SM works perfectly, yet we need new physics to explain the baryon asymmetry of the Universe, the dark matter etc… without interfering with SM rad. corr.



mediator
or
mixing



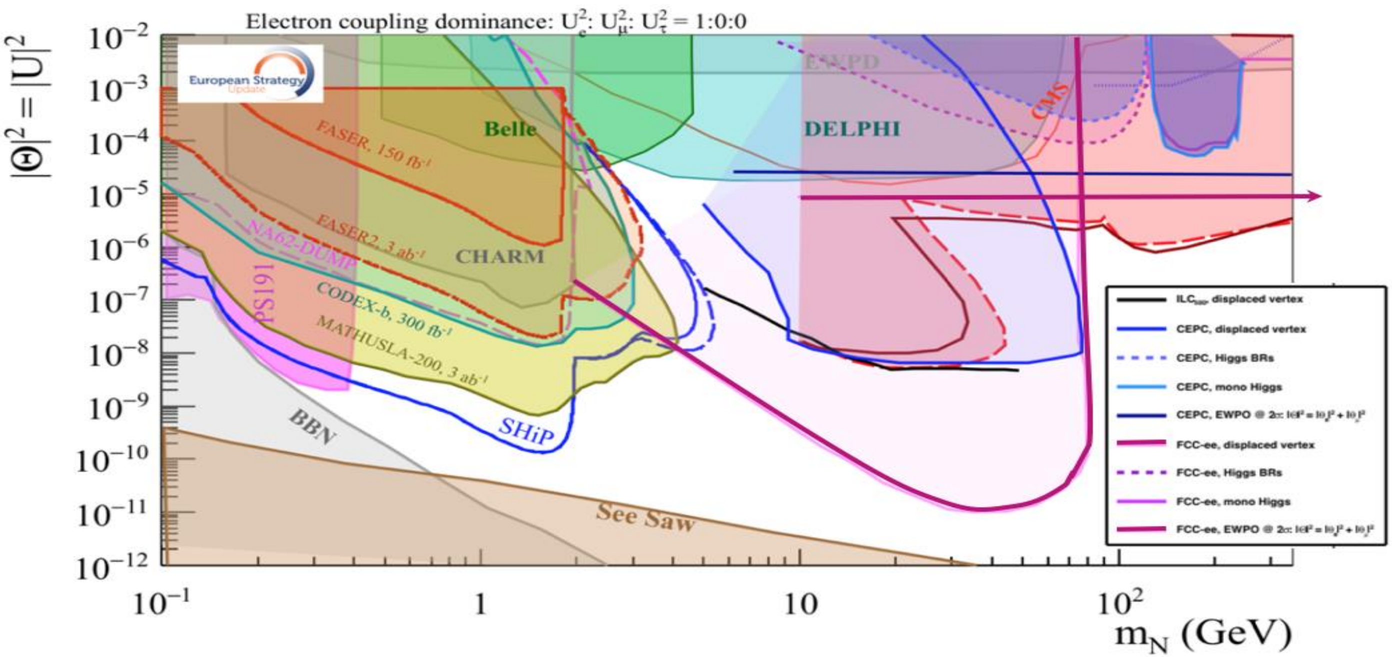
S. Gori

Dark photons, axion like particles, sterile neutrinos, all *feebly coupled* to SM particles

This picture is relevant to Neutrino, Dark sectors and High Energy Frontiers.

FCC-ee (Z) compared to the other machines for right-handed (sterile) neutrinos

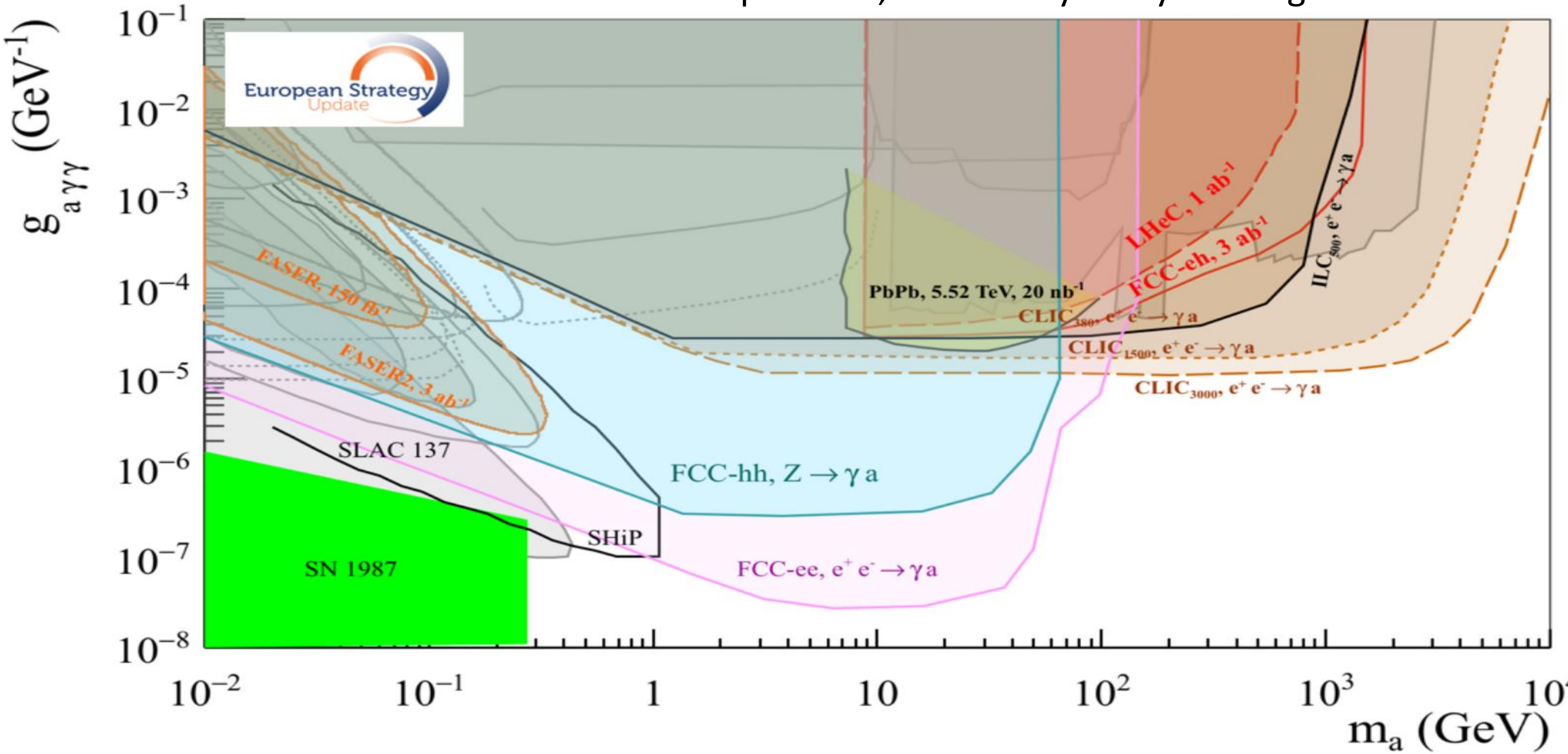
How close can we get to the 'see-saw limit'?



-- the purple line shows the reach for observing **heavy neutrino decays** (here for 10^{12} Z),

-- the horizontal line represents the sensitivity to **mixing of neutrinos** to the dark sector, using EWPOs (G_F vs $\sin^2\theta_W^{eff}$ and m_Z, m_W, tau decays) which extends sensitivity to 10^{-5} mixing all the way to very high energies (60 TeV at least).

Similar situation for Axion-like-particles; Luminosity is key to the game



Complementarity with High energy lepton collider,

Much more left to explore at FCC-ee-Z and FCC-hh!

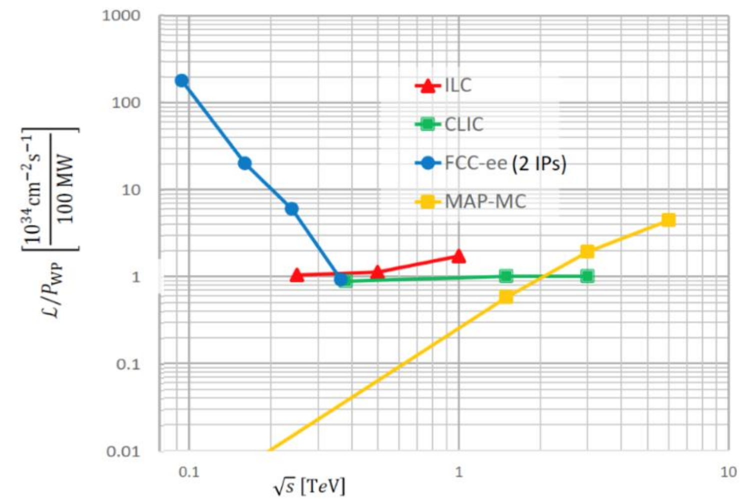
BSM Physics: what if?

A high energy e+ e- collider might become «urgent» (like the 'Higgs Factories' today) if a SM coupled new particle is found at a hadron collider (HL-LHC, FCC-hh), for which missing information precludes essential knowledge to be gathered.

We are not in that situation today, but we never know.

ILC or CLIC cover the high energy e+e- in the energy range from 400 to 3000 GeV.
the CLIC and Muon collider R&D will be continued at CERN.

THIS…
IS A STRONG ARGUMENT TO KEEP LINEAR e+e- ALIVE



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	$\propto E_{\mathrm{beam}}^{-3.5} \times$ Radius $\times$ Power $\times$ #IP	$\propto E_{\mathrm{beam}} \times$ 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
$\mathrm{t\bar{t}}$ and above	10^{6} $\mathrm{t\bar{t}}$ at 365 GeV	3.10^{6} $\mathrm{t\bar{t}}$ 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	–	$\pm$ 27% (500 GeV), $\pm$ 10% (1 TeV)
Electroweak	m_Z, Γ_Z, m_W (100, 25, 600 keV) $\sin^2\theta_W^{\mathrm{eff}} (3.10^{-6})$ $\Delta\alpha_{\mathrm{QED}} (3.10^{-5})$ 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

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

Summary

Between 250 and 380 GeV : ILC and/or FCC-ee

FCC-ee

↓

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 or CLIC *(but competition from hadron collider)*

- 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

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 $\sqrt{s} = m_H$, → electron Yukawa coupling
Essential synergy with the ≥100 TeV hadron collider

For ILC:

Unique ability to explore lepton collisions above 365 GeV to fill interesting gaps left by LHC (or if a new particle is discovered at LHC in the suitable mass range).

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

And indeed…

Preamble

The particle physics community is ready to take the next step towards even higher energies and smaller scales. The vision is to prepare a Higgs factory, followed by a future hadron collider with sensitivity to energy scales an order of magnitude higher than those of the LHC, while addressing the associated technical and environmental challenges.

High-priority future initiatives

An electron-positron Higgs factory is the highest-priority next collider. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy. Accomplishing these compelling goals will require innovation and cutting-edge technology:

the particle physics community should ramp up its R&D effort focused
· on advanced accelerator technologies, in particular that for high-field superconducting magnets, including high-temperature superconductors;

· Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage. Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update.

The timely realisation of the electron-positron International Linear Collider (ILC) in Japan would be compatible with this strategy and, in that case, the European particle physics community would wish to collaborate.

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SPARE SLIDES

Financial Complementarity

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

-- Two facilities?

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

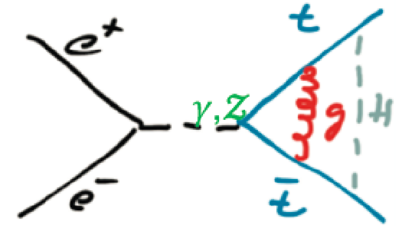
-- the simplest way is to run each facility in its best domain of performance e.g. let the FCC take the data at and below 240 GeV and ILC start at 250 and take data at and above 380 GeV

Scientific Complementarity: Top physics

- **Top-pair threshold scan and just above: $\sqrt{s}$ = 340 – 380 GeV**

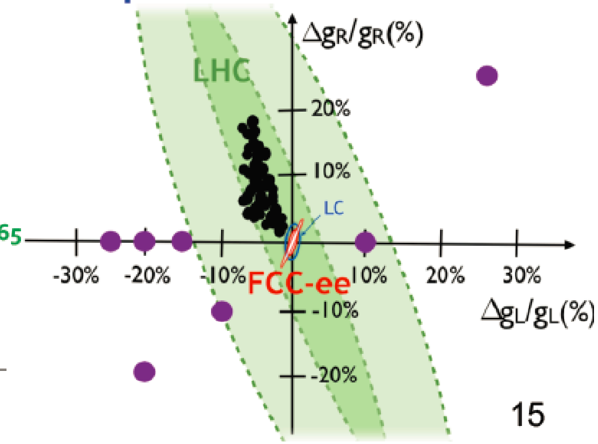
André H. Hoang

  - 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



Patrick Janot

3rd FCC Physics Workshop
17 Jan 2020

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Top Physics at High Energies

More general EFT analysis of top EW couplings with 10 independent form factors
G. Durieux et al 1807.02121

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

Longitudinal polarization adds to the info but also given by observables resulting from top polarization analysed by V-A decay, having high energy point is more important!

need high energy (≥500 GeV) lepton collider

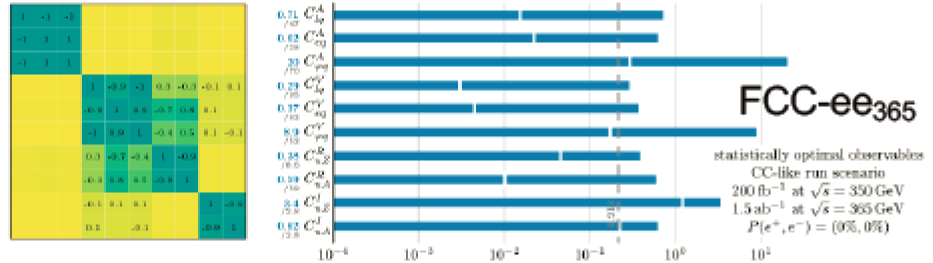


Figure 23. Global one-sigma constraints and correlation matrix deriving from the measurements of statistically optimal observables in a circular collider (CC-)like benchmark run scenario.

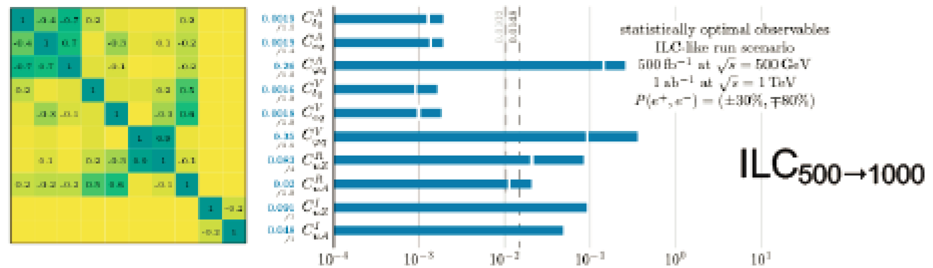
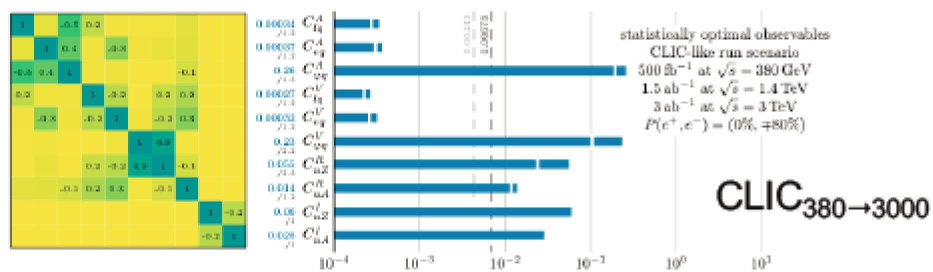
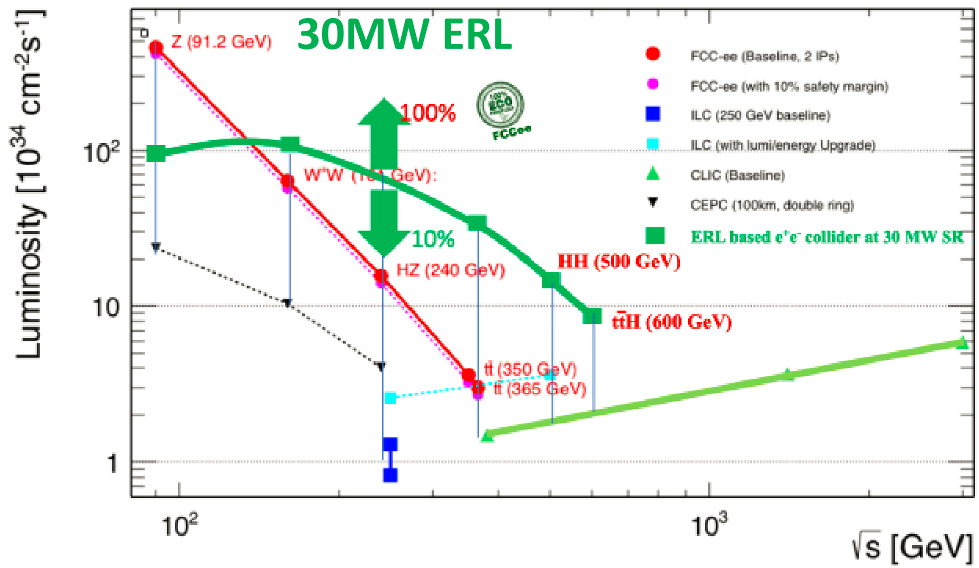


Figure 24. Global one-sigma constraints and correlation matrix deriving from the measurements of statistically optimal observables, in an ILC-like benchmark run scenario.



Turn FCC into an ERL ?

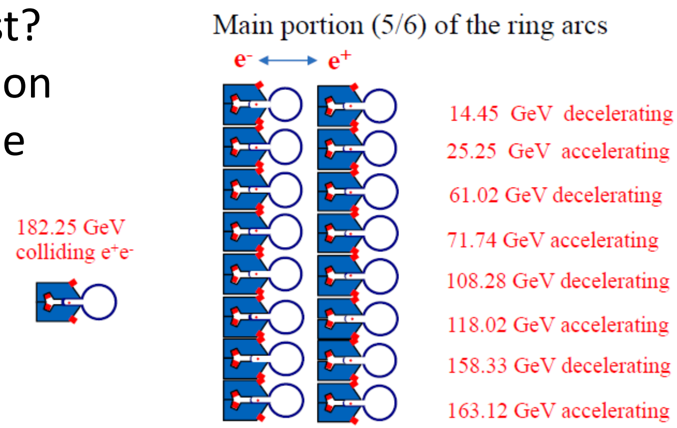
paper study by Litvinenko et al
- --could improve energy efficiency!
- -- No stable transverse polarization:
  - → not for Z and W!
- -- improve performance by large factors
  - -- higher Lumi for Higgs, top
  - -- can reach 600 GeV E_{CM}

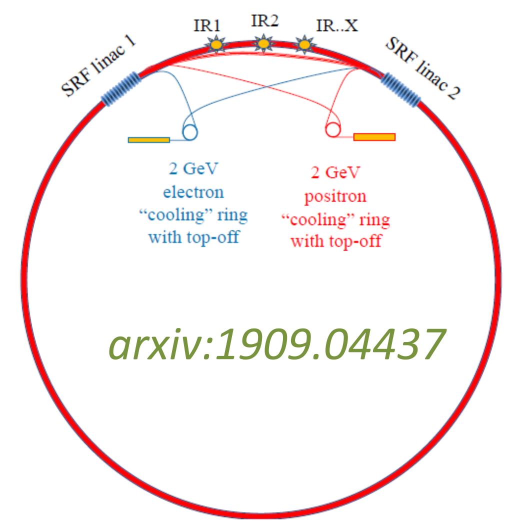


More rings, more RF Volts → cost?
- -- not ready enough for discussion

May not be feasible or affordable

Will be studied!





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

$\sqrt{s}$ monochromatisation can be achieved at FCC-ee (Hee coupling measurement at $\sqrt{s} = m_H$)

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

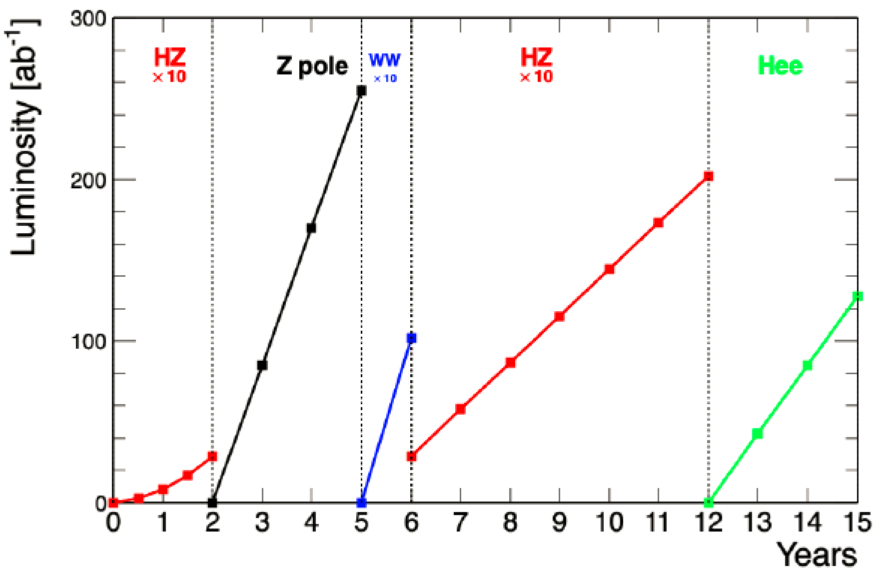
Use the six years saved by not operating at the top-pair threshold and above

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 $FCC\text{-}ee^{4IP}_{240\text{-}365}$
    - Note: Detector calibration at the Z pole?

Collider	$FCC\text{-}ee^{4IP}_{240}$	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