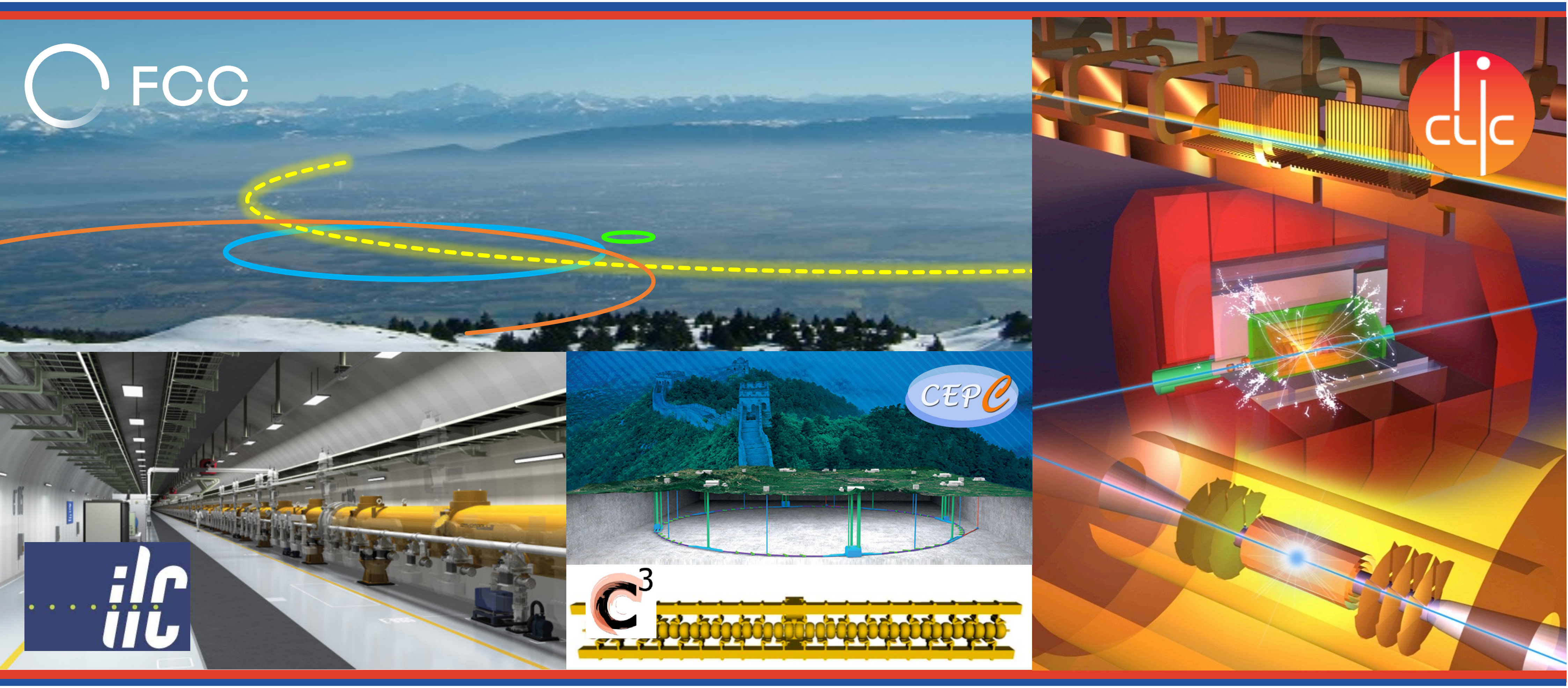
Future Colliders: e^+e^- Higgs Factories

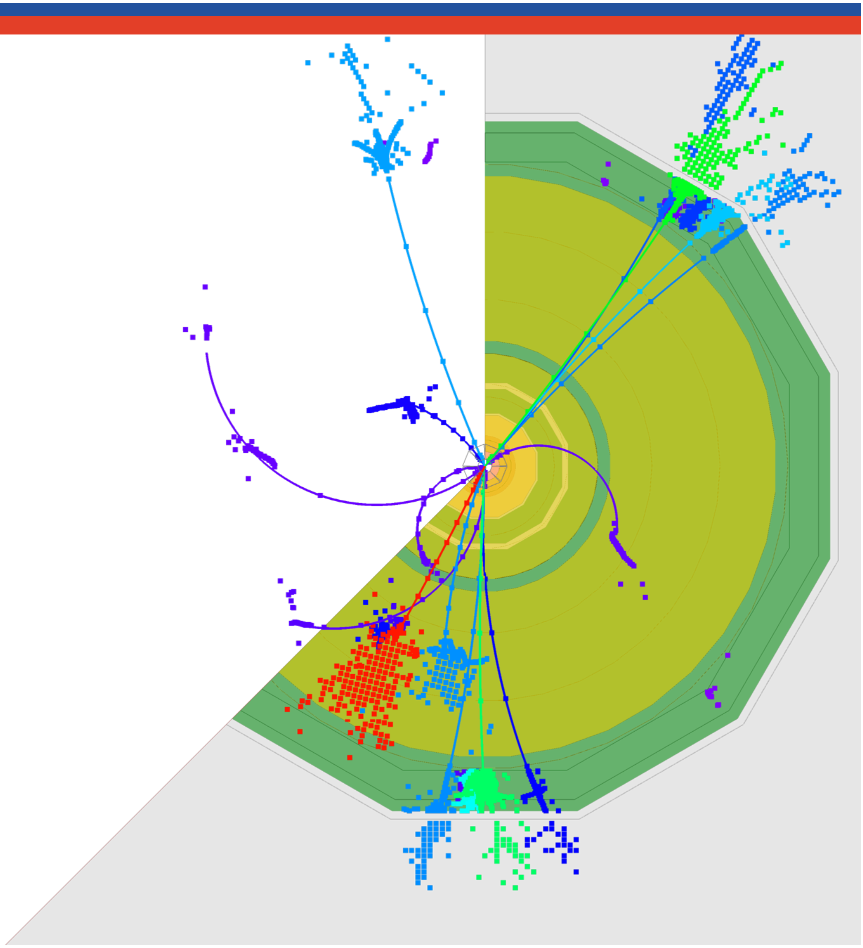


PPAP Community Meeting, 25 June 2024

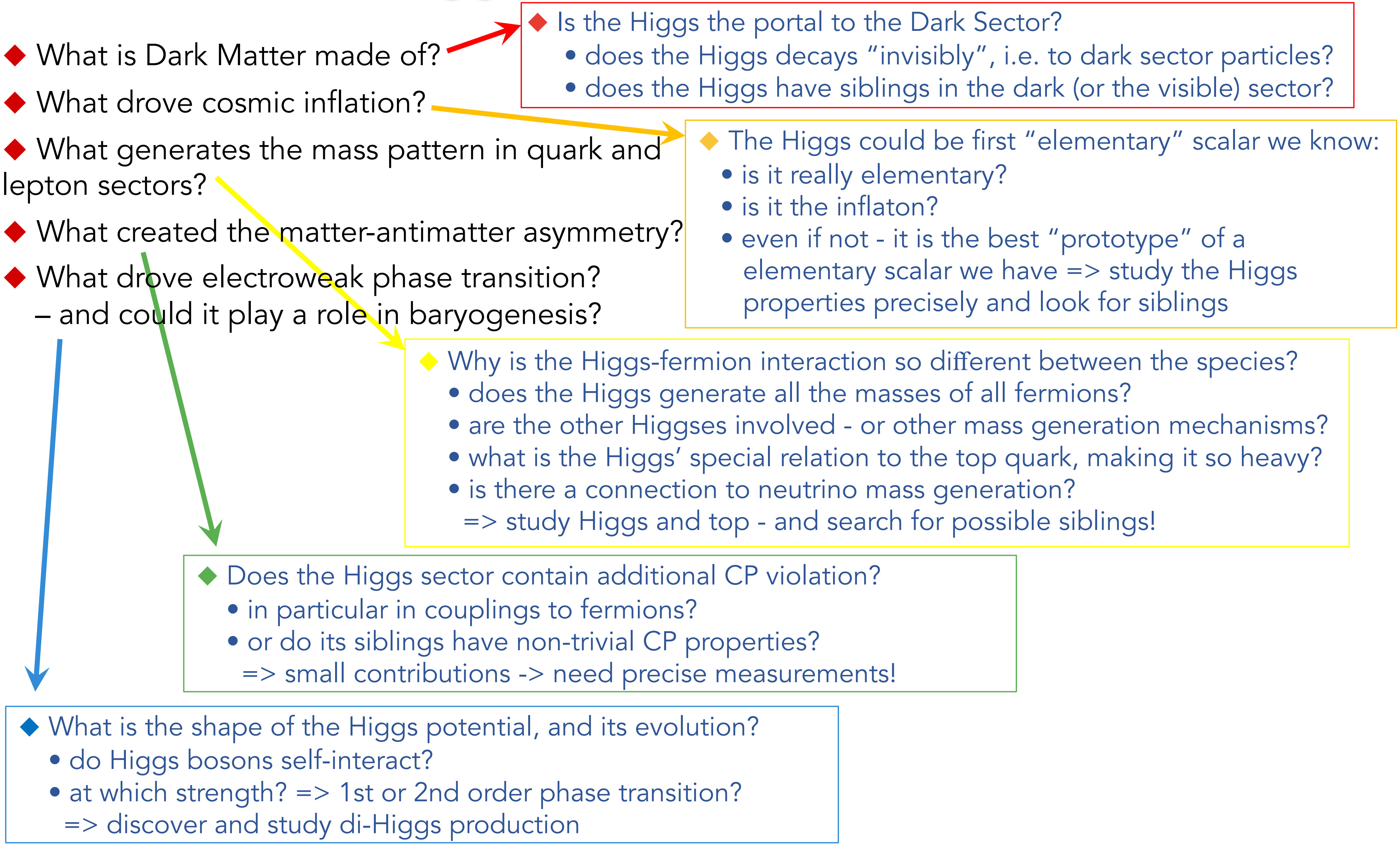
Aidan Robson, University of Glasgow

Higgs Factories

- Why e+e– ?
- Single Higgs
- Higgs self-coupling
- Top & BSM physics
- Status and outlook of projects
- Strategic considerations



The Higgs Boson and the Universe



◆ What is Dark Matter made of?

◆ What drove cosmic inflation?

◆ What generates the mass pattern in quark and lepton sectors?

◆ What created the matter-antimatter asymmetry?

◆ What drove electroweak phase transition?
– and could it play a role in baryogenesis?

◆ Is the Higgs the portal to the Dark Sector?
- does the Higgs decays "invisibly", i.e. to dark sector particles?
- does the Higgs have siblings in the dark (or the visible) sector?

◆ The Higgs could be first "elementary" scalar we know:
- is it really elementary?
- is it the inflaton?
- even if not - it is the best "prototype" of a elementary scalar we have => study the Higgs properties precisely and look for siblings

◆ Why is the Higgs-fermion interaction so different between the species?
- does the Higgs generate all the masses of all fermions?
- are the other Higgses involved - or other mass generation mechanisms?
- what is the Higgs' special relation to the top quark, making it so heavy?
- is there a connection to neutrino mass generation?

=> study Higgs and top - and search for possible siblings!

◆ Does the Higgs sector contain additional CP violation?
- in particular in couplings to fermions?
- or do its siblings have non-trivial CP properties?

=> small contributions -> need precise measurements!

◆ What is the shape of the Higgs potential, and its evolution?
- do Higgs bosons self-interact?
- at which strength? => 1st or 2nd order phase transition?

=> discover and study di-Higgs production

The Higgs Factory mission

◆ Find out as much as we can about the 125-GeV Higgs

- Basic properties:
  - **total production rate**, total width
  - decay rates to known particles
  - **invisible decays**
  - search for "exotic decays"
- CP properties of couplings to gauge bosons and fermions
- **self-coupling**
- Is it the only one of its kind, or are there **other Higgs (or scalar) bosons**?

◆ To interpret these Higgs measurements, also need:

- top quark: mass, Yukawa & electroweak couplings, their CP properties…
- Z / W bosons: masses, couplings to fermions, triple gauge couplings, incl CP…

◆ Search for direct production of new particles – and determine their properties

- Dark Matter? **Dark Sector**?
- Heavy neutrinos?
- SUSY? **Higgsinos**?
- **The UNEXPECTED !**

◆ Conditions at e+e- colliders very complementary to LHC;

In particular:

- low backgrounds
- clean events
- triggerless operation (LCs)

The Higgs Factory mission

◆ Find out as much as we can about the 125-GeV Higgs

- Basic properties:
  - **total production rate**, total width
  - decay rates to known particles
  - **invisible decays**
  - search for "exotic decays"
- CP properties of couplings to gauge bosons and fermions
- **self-coupling**
- Is it the only one of its kind, or are there **other Higgs (or scalar) bosons**?

e+e– Higgs factory identified as highest-priority next collider, by European Strategy Update 2020 and US Snowmass process 2023

◆ To interpret these Higgs measurements, also need:

- top quark: mass, Yukawa & electroweak couplings, their CP properties…
- Z / W bosons: masses, couplings to fermions, triple gauge couplings, incl CP…

◆ Search for direct production of new particles – and determine their properties

- Dark Matter? **Dark Sector**?
- Heavy neutrinos?
- SUSY? **Higgsinos**?
- **The UNEXPECTED !**

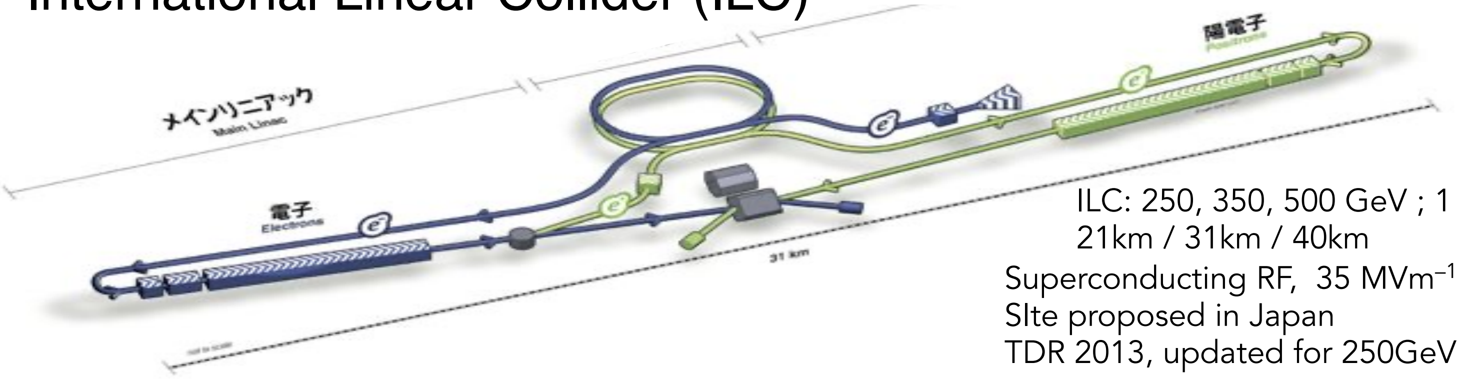
◆ Conditions at e+e- colliders very complementary to LHC;

In particular:

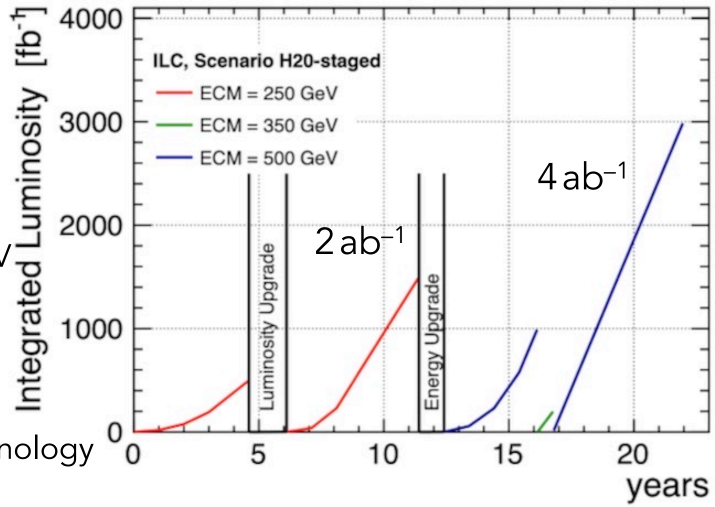
- low backgrounds
- clean events
- triggerless operation (LCs)

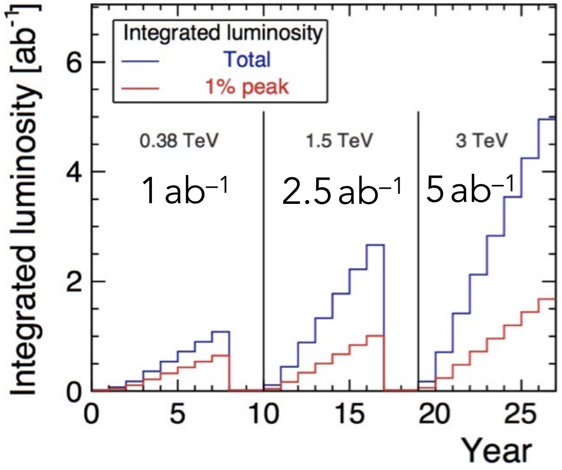
Higgs factory contenders (1): Linear Colliders

International Linear Collider (ILC)



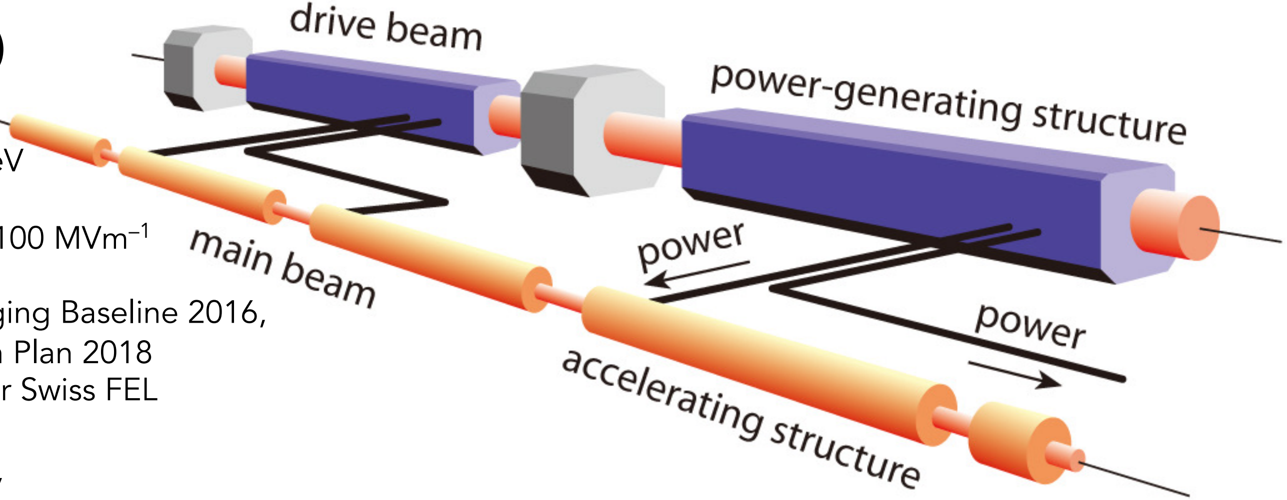
ILC: 250, 350, 500 GeV ; 1 TeV
21km / 31km / 40km
Superconducting RF, 35 MVm^{-1}
SIte proposed in Japan
TDR 2013, updated for 250GeV
European XFEL demonstrates technology





Compact Linear Collider (CLIC)

CLIC: 380 GeV ; 1.5, 3 TeV
11km / 29km / 50km
Room temperature, 72–100 MVm^{-1}
Site proposed at CERN
CDR 2012, Updated Staging Baseline 2016,
Project Implementation Plan 2018
Similar structures used for Swiss FEL



Cool Copper Collider (C^3)

C^3: 250, 550 GeV
8km / 8km
Operation temperature 77K, 70–120 MVm^{-1}
Proposed site at Fermilab
Pre-CDR

C^3 Beam delivery / IP identical to ILC
Damping rings / injector similar to CLIC
Physics output very similar to ILC

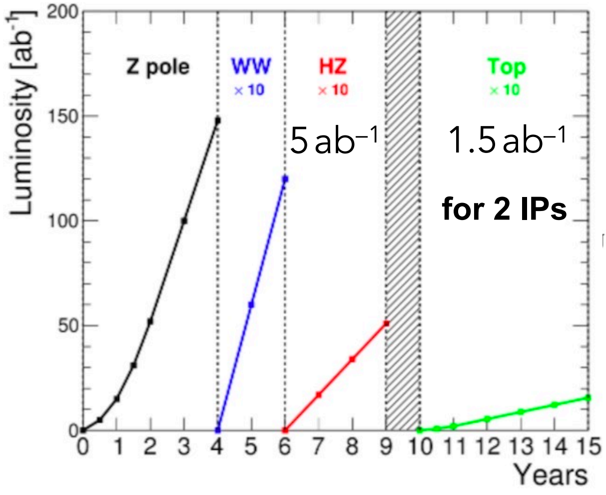
Hybrid Asymmetric Linear Higgs Factory (HALHF)

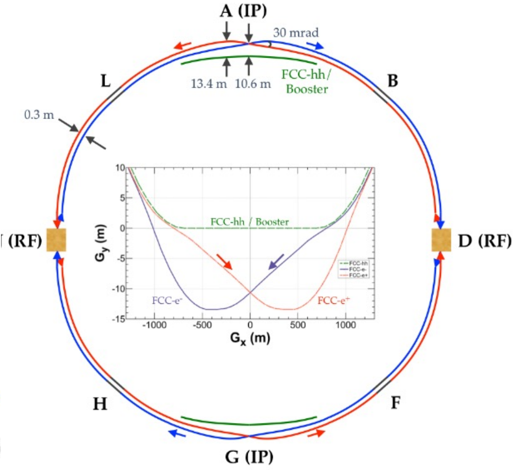
HALHF: 250 GeV (e^- 500GeV, e^+ 31GeV)
3.3km
25 MVm^{-1} conventional, 6.3GVm^{-1} plasma
Pre-CDR

Higgs factory contenders (2): Circular Colliders

Future Circular Collider (FCC-ee)

FCC-ee: 91, 160, 240, 360 GeV

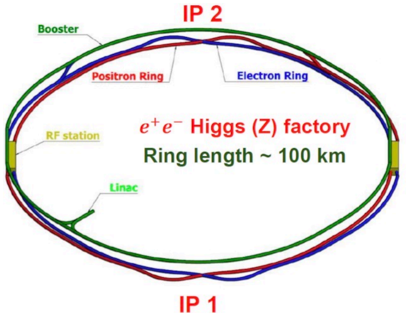




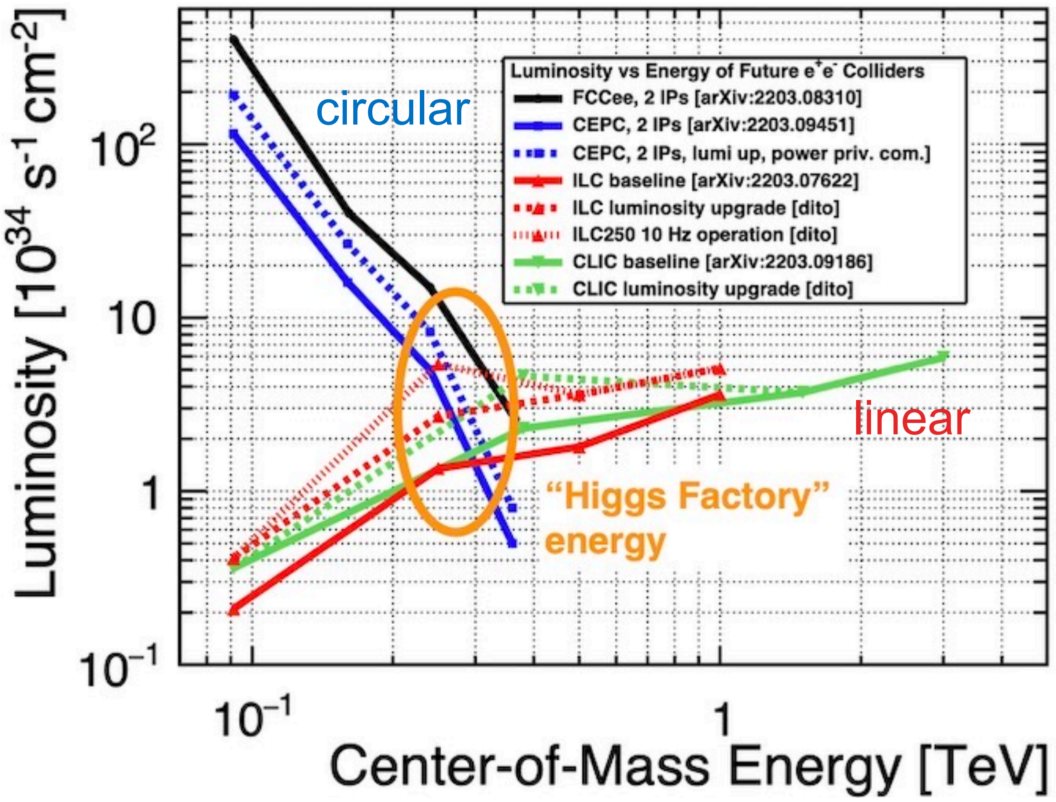
FCC: ~92km ring
FCCee CDR 2019
Accelerator technology mostly proven >50yr

Circular Electron Positron Collider (CEPC)

CEPC: 91, 160, 240 GeV
CEPC: ~100km ring
CEPC CDR 2018
3 years at Z/WW, 7 years at HZ, 5.6ab^{-1} for 2 IPs



◆ Key difference linear/circular: luminosity performance with energy

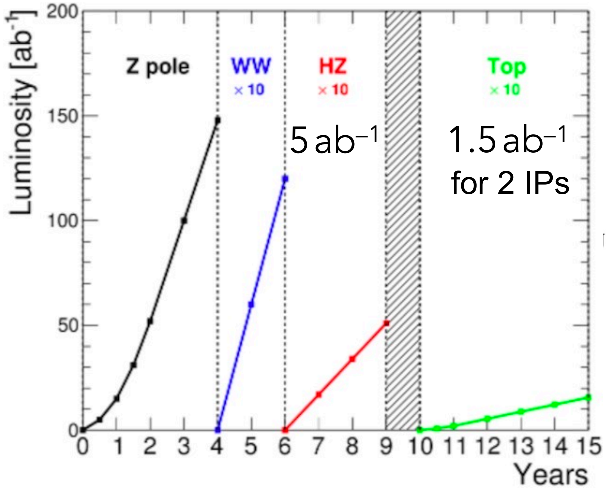


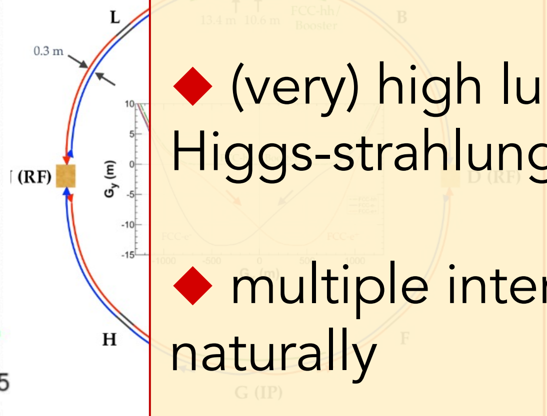
Best luminosity and power efficiency is at lower energies for circular machines; higher energies for linear machines

Higgs factory contenders (2): Circular Colliders

Future Circular Collider (FCC-ee)

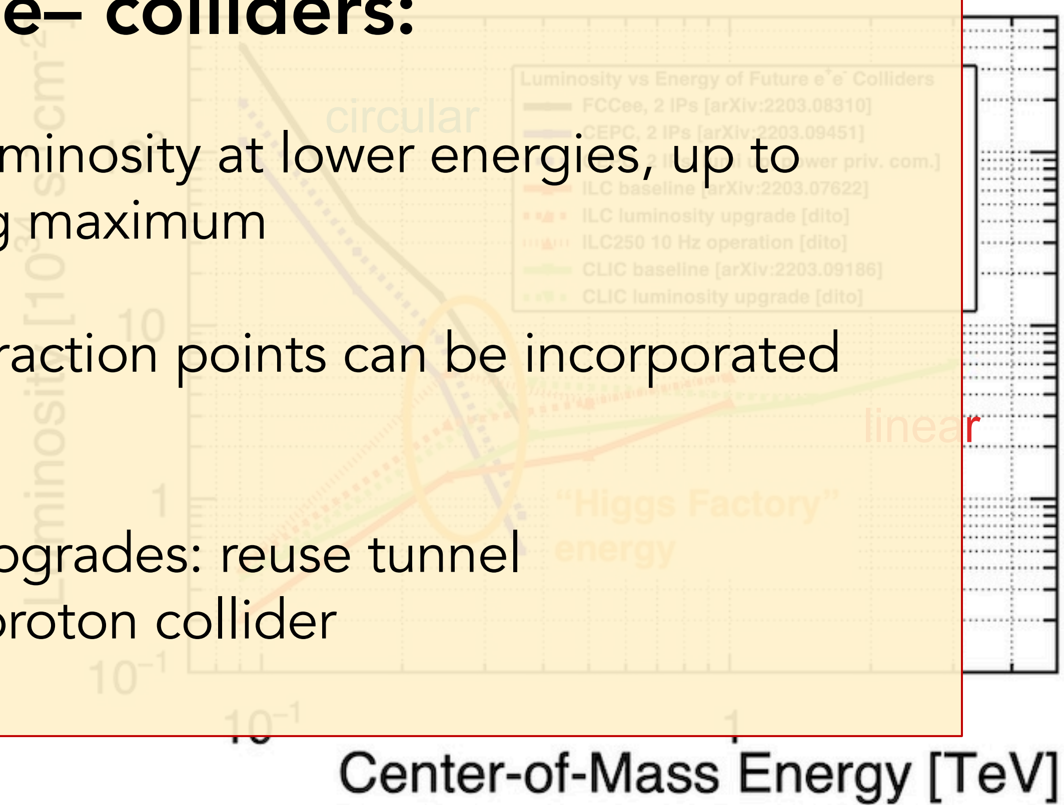
FCC-ee: 91, 160, 240, 360 GeV





FCC: ~92k, ring
FCCee CDR 2019
Accelerator technology mostly proven

◆ Key difference linear/circular:
luminosity performance with energy



Best luminosity and power efficiency is at lower energies for circular machines; higher energies for linear machines

Circular e+e– colliders:

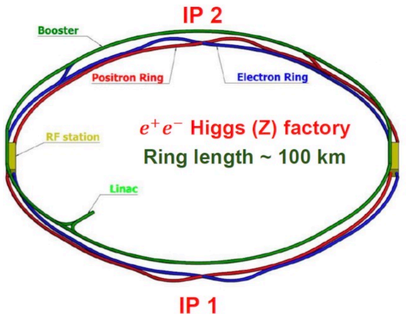
◆ (very) high luminosity at lower energies, up to Higgs-strahlung maximum

◆ multiple interaction points can be incorporated naturally

◆ Long-term upgrades: reuse tunnel
- e.g. proton-proton collider

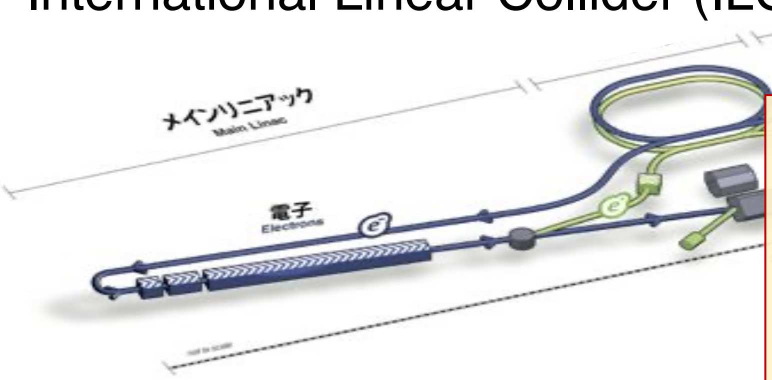
Circular Electron Positron Collider (CEPC)

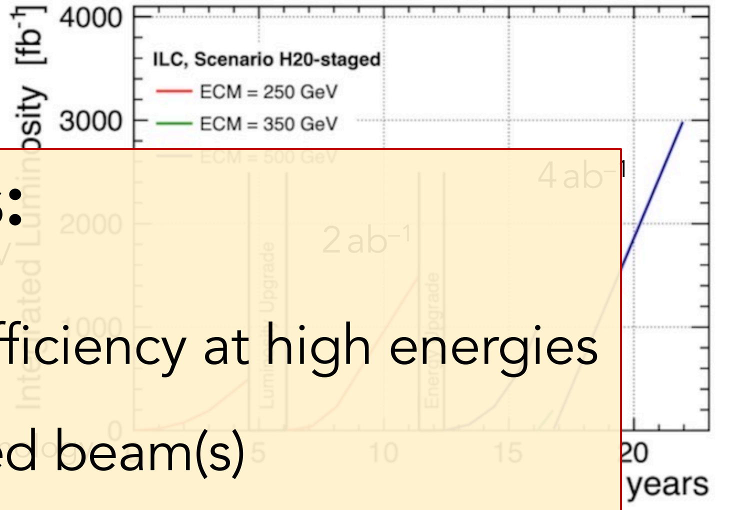
CEPC: 91, 160, 240 GeV
CEPC: ~100km ring
CEPC CDR 2018
3 years at Z/WW, 7 years at HZ, 5.6ab⁻¹ for 2 IPs



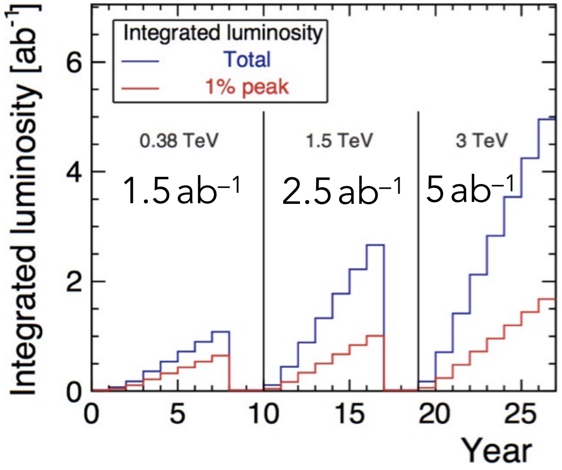
Higgs factory contenders (1): Linear Colliders

International Linear Collider (ILC)

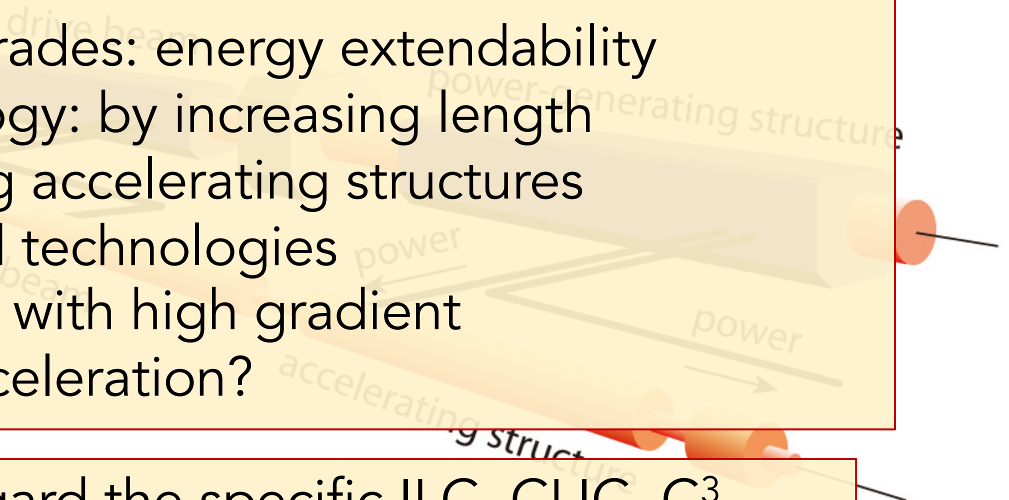




ILC: 250, 350, 500 GeV ; 1 TeV
21km / 31km / 40km
Superconducting RF, 35 MVm⁻¹
Sited in Japan
TDR 2013, updated for 250GeV
European XFEL demonstrat… technology



Compact Linear Collider (CLIC)



CLIC: 380 GeV ; 1.5, 3 TeV
11km / 29km / 50km
Room temperature, 72-100 MVm⁻¹
Sited at CERN
CDR 2012, Updated Staging Baseline 2016
Project Implementation Plan 2018
Similar structures used for SwissFEL

Linear e+e– colliders:

- high luminosity & power efficiency at high energies
- longitudinally spin-polarised beam(s)
- Long-term upgrades: energy extendability
  - same technology: by increasing length
  - or by replacing accelerating structures with advanced technologies
    - – RF cavities with high gradient
    - – plasma acceleration?

Cool Copper Collider (C³)

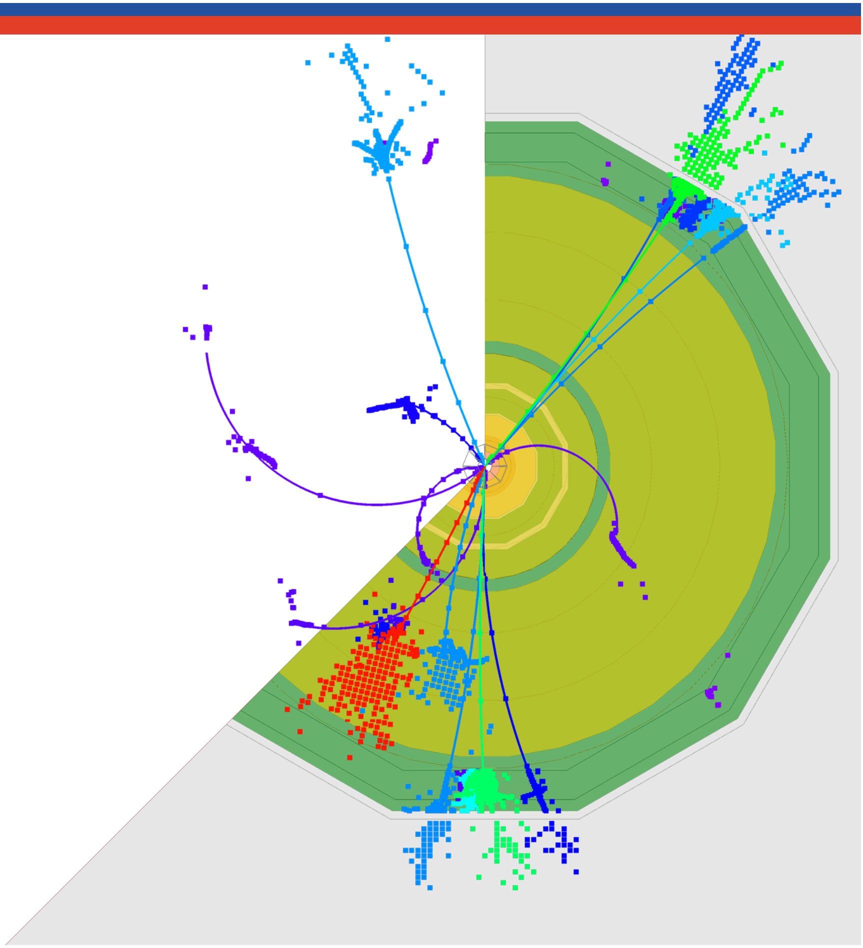
C³: 250, 550 GeV
8km / 8km
Sited at Fermilab
Pre-CDR
C³ Beam delivery / IP identical to ILC
Damping rings / injector similar to CLIC

Hybrid Asymmetric Linear Higgs Factory (HALHF)

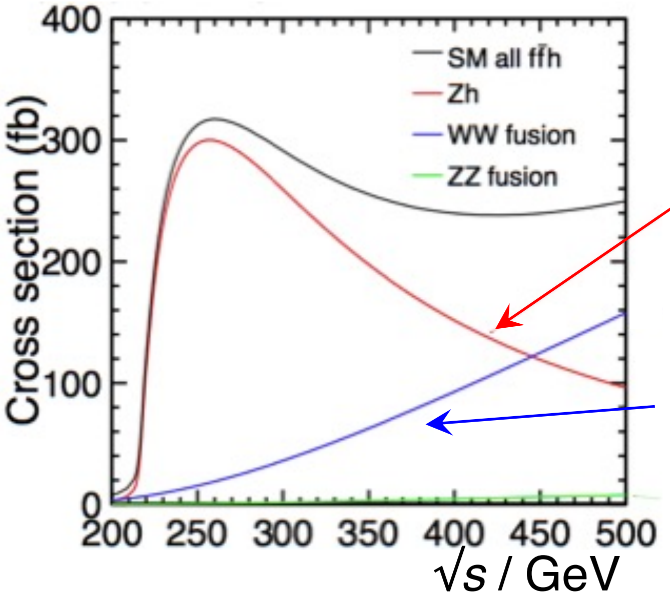
3.3km
25 MVm⁻¹ conventional, 6.3GVm⁻¹ plasma
Pre-CDR

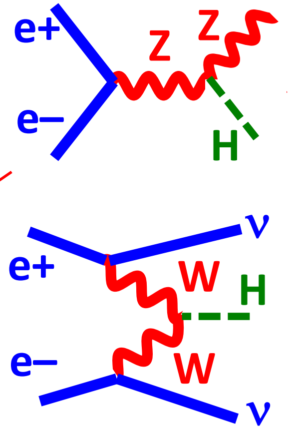
◆ Important note: it's most useful to regard the specific ILC, CLIC, C³ proposals as 'sampling the parameter space' of possible machines / locations. Other combinations of warm/cold accelerator, energy staging, and location are equally possible and should be considered, e.g. an ILC-like machine at CERN; or a CLIC-like machine at 250GeV or 500GeV etc.

Higgs in e^+e^-



Higgs production in e^+e^-

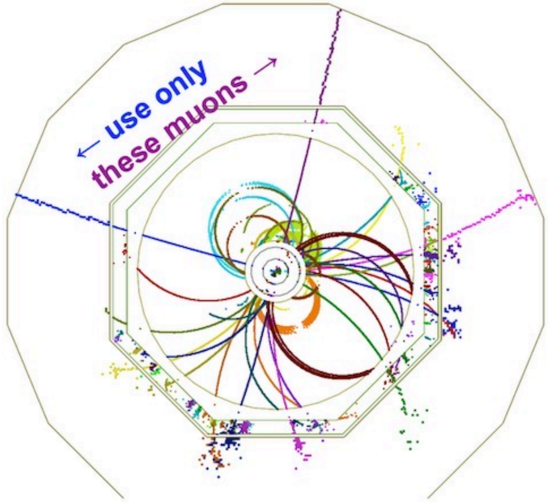




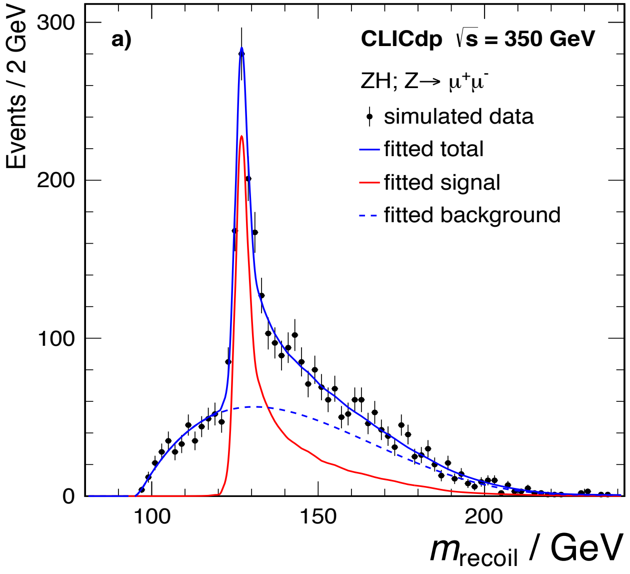
- ◆ ZH process allows reconstruction of H by looking exclusively at recoil of Z –> model-independent extraction of g_{HZZ} coupling

$$\sigma_{ZH} \propto g^2_{HZZ}$$

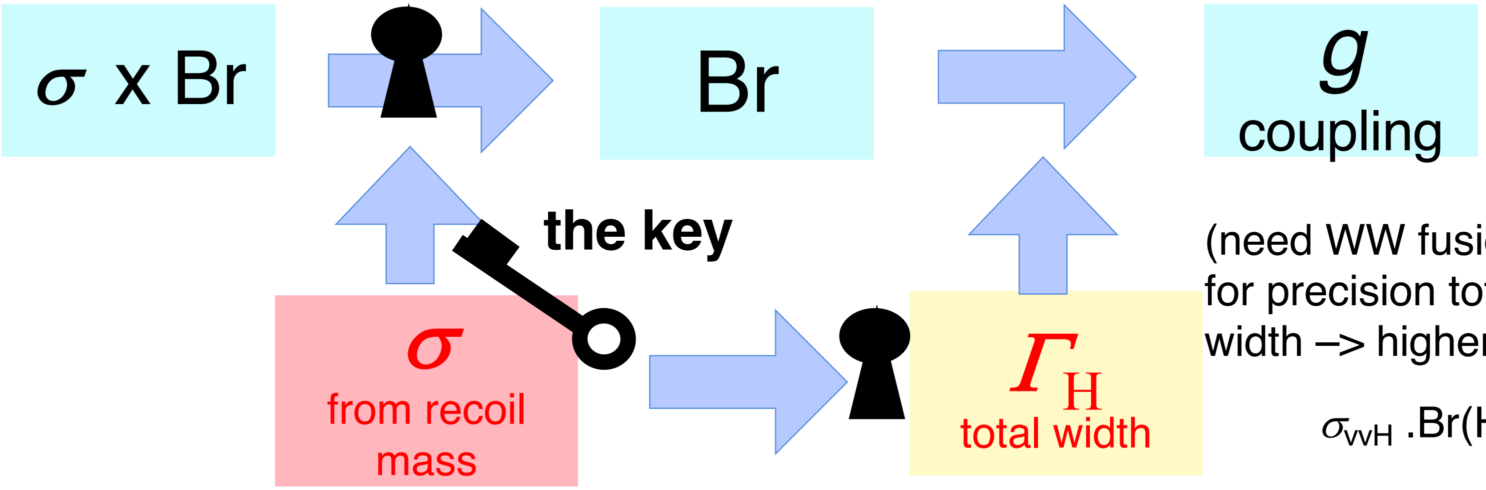
$$\frac{\sigma_{ZH}\,.\mathrm{Br}(H\text{->}bb)}{\sigma_{\nu\nu H}\,.\mathrm{Br}(H\text{->}bb)} \propto \frac{g^2_{HZZ}}{g^2_{HWW}}$$



$e^+e^- \rightarrow \mu^+\mu^- H \rightarrow \mu^+\mu^-$ bb in ILD



$$g^2_{HAA} \propto \Gamma(H \rightarrow AA) = \Gamma_H \cdot BR(H \rightarrow AA)$$



σ x Br

Br

g
coupling

the key

σ
from recoil mass

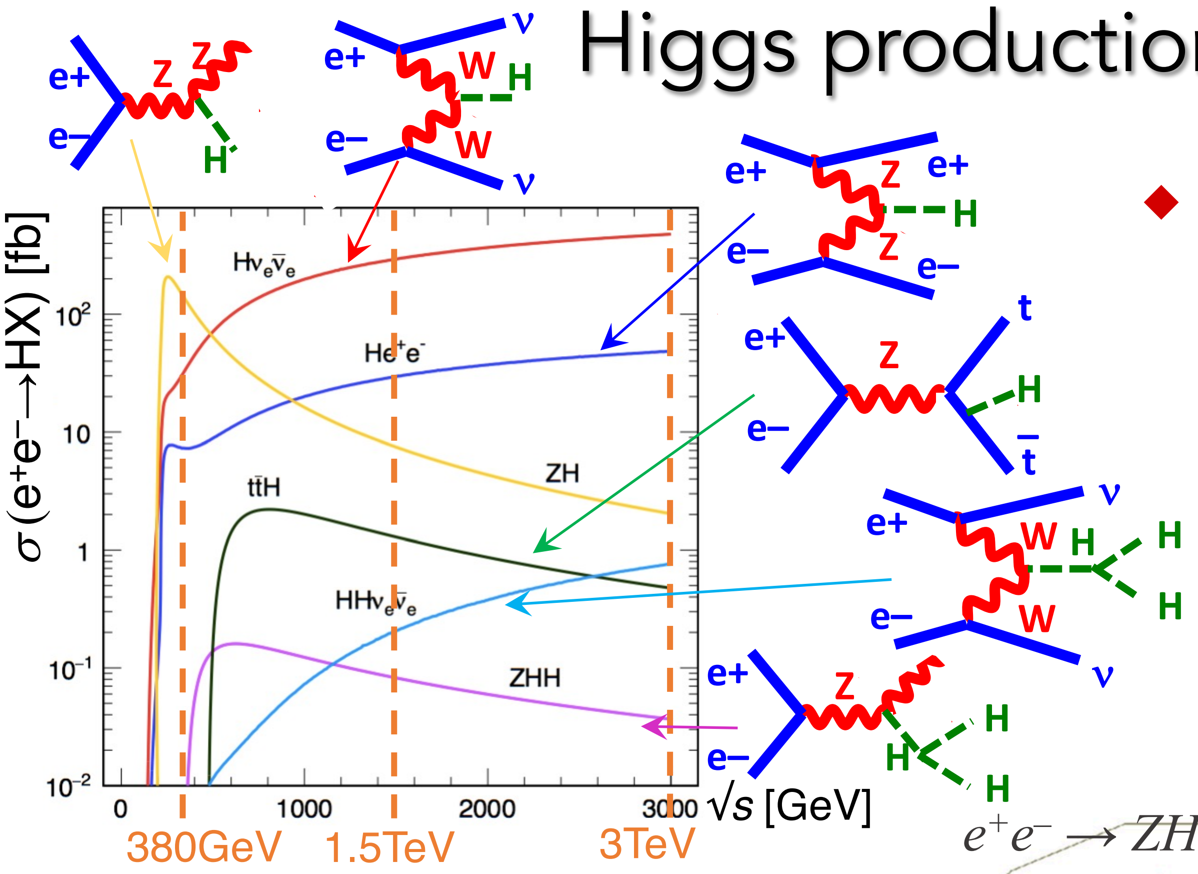
Γ_H
total width

(need WW fusion for precision total width –> higher √s)

$$\sigma_{\nu\nu H}\,.\mathrm{Br}(H\text{->}WW) \propto g^4_{HWW}/\Gamma_H$$

Yields model-independent absolute couplings – not possible at LHC!

Higgs production in e^+e^-



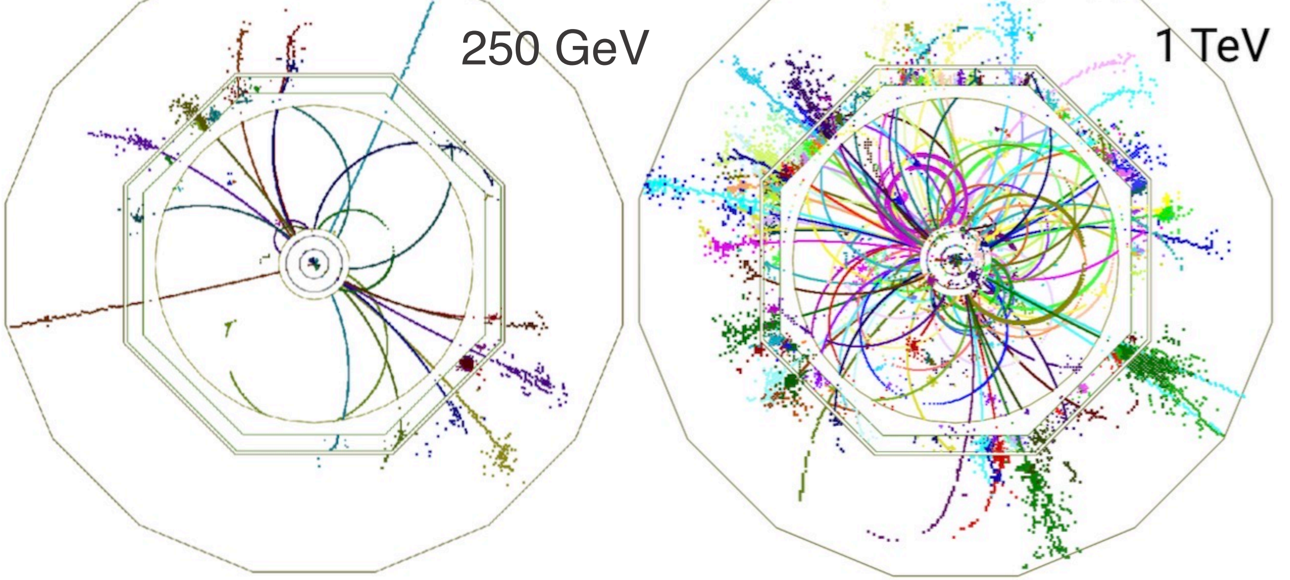
◆ Common to all projects:
ZH threshold at 250 / 380 GeV

◆ Other processes turn on at higher energies

◆ Core Higgs programme sets requirements on detector performance: momentum resolution, jet energy resolution, impact parameter resolution etc

◆ Imaging calorimetry approach allows e.g. H->bb/cc/gg separation

$e^+e^- \to ZH \to \mu\mu bb$ $\qquad$ $e^+e^- \to ttH \to q\bar{q}b\,q\bar{q}\bar{b}\,b\bar{b}$



Higgs couplings sensitivity

Standard Model

Dim-6 operators

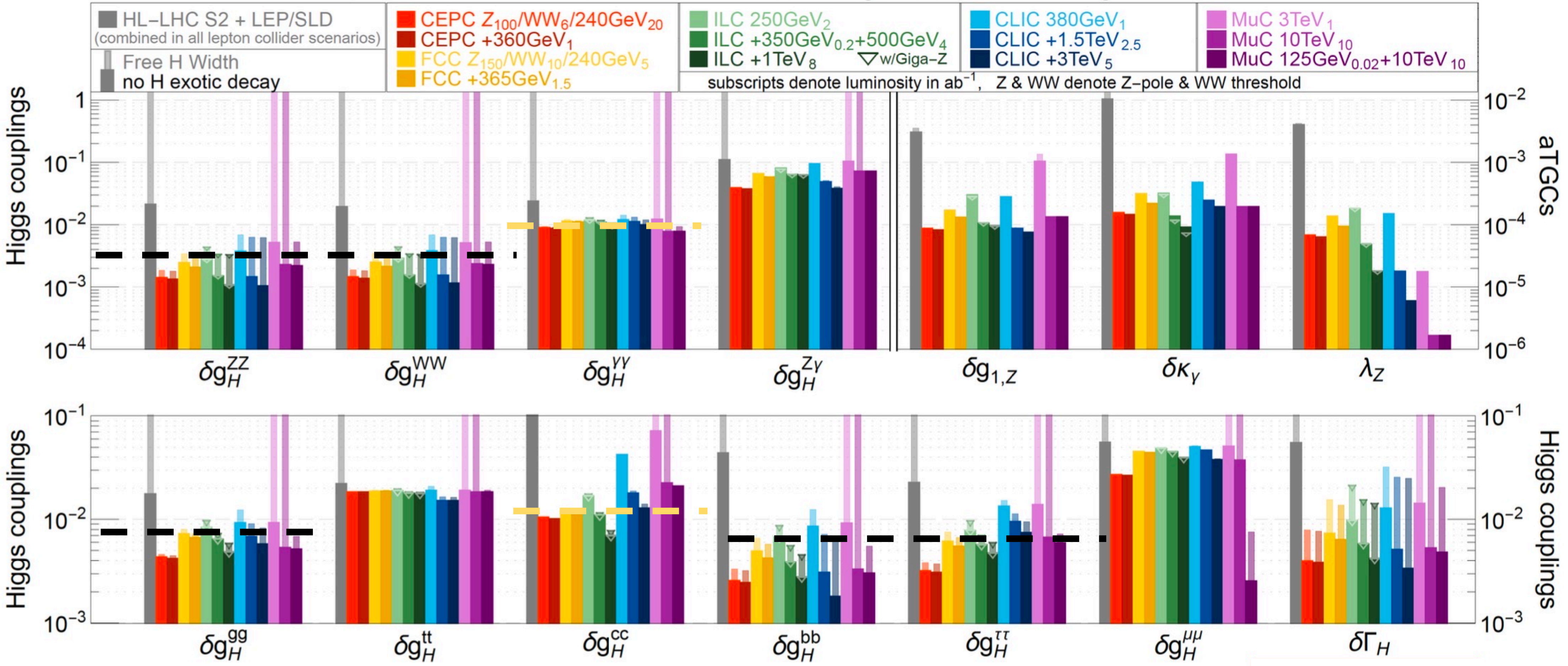
$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i$$

Scale of new decoupled physics

◆ Illustrative comparison of sensitivities (combined with HL-LHC)

Snowmass EFT couplings
arxiv: 2206.08326

precision reach on effective couplings from SMEFT global fit



◆ all e+e- colliders show very comparable performance for standard Higgs program despite quite different assumed integrated luminosities

- several couplings at few-0.1% level: Z, W, g, b, τ
- some more at ~1%: γ, c

Higgs couplings sensitivity

Standard Model

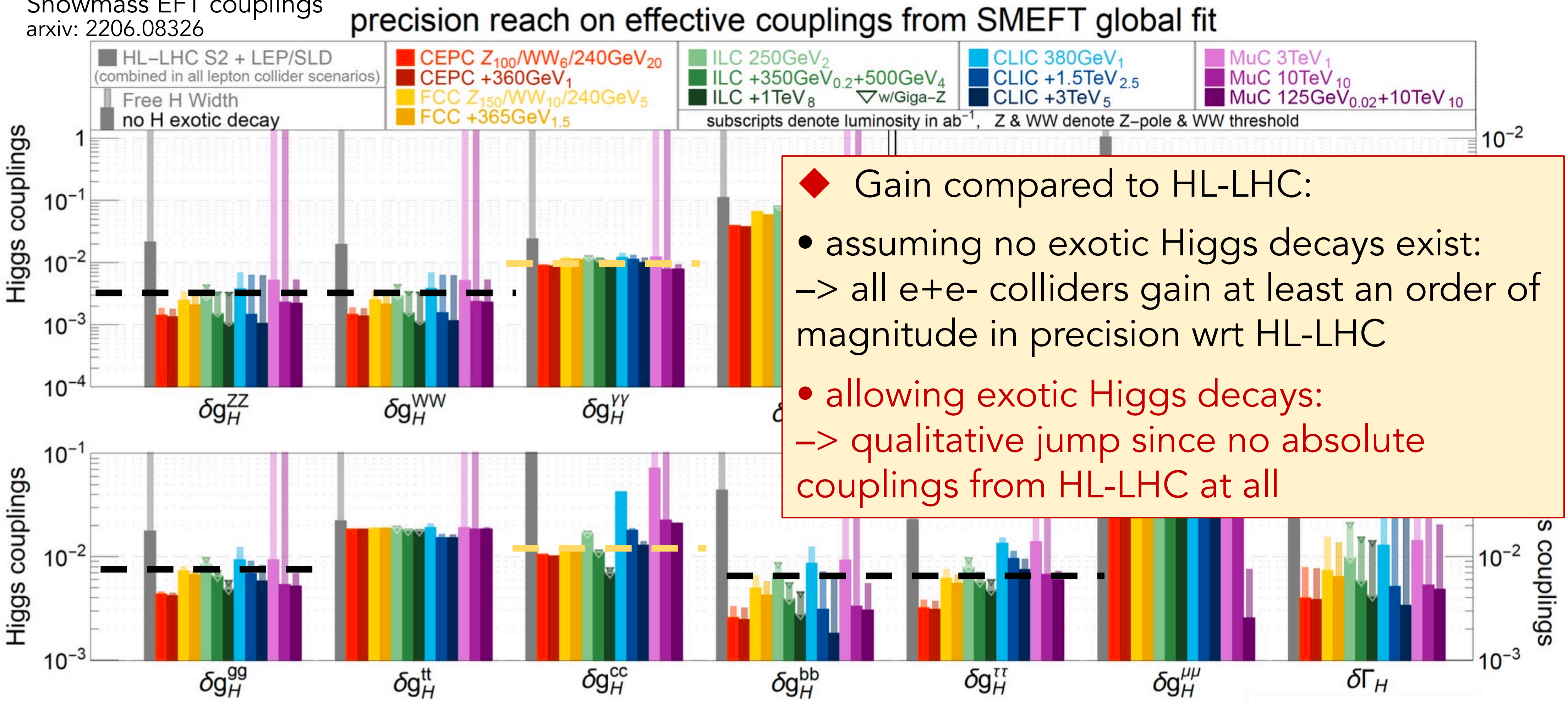
Dim-6 operators

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i$$

Scale of new decoupled physics

◆ Illustrative comparison of sensitivities (combined with HL-LHC)

Snowmass EFT couplings
arxiv: 2206.08326



◆ Gain compared to HL-LHC:

- assuming no exotic Higgs decays exist:
–> all e+e- colliders gain at least an order of magnitude in precision wrt HL-LHC
- allowing exotic Higgs decays:
–> qualitative jump since no absolute couplings from HL-LHC at all

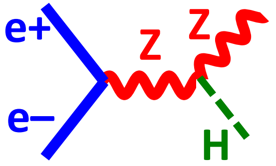
◆ all e+e- colliders show very comparable performance for standard Higgs program despite quite different assumed integrated luminosities

- several couplings at few-0.1% level: Z, W, g, b, τ
- some more at ~1%: γ, c

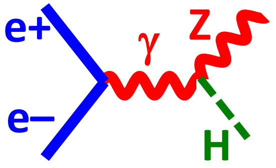
Polarisation

- why is the performance between projects so similar, given the very different integrated luminosities? *–> beam polarisation at linear colliders*

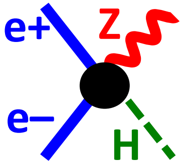
- Higgsstrahlung e+e– -> ZH is the key process at a Higgs factory
- Example: A_{LR} of Higgsstrahlung helps to disentangle different SMEFT operators



Only SM diagram
Flips sign under spin reversal $e_R \leftrightarrow e_L$

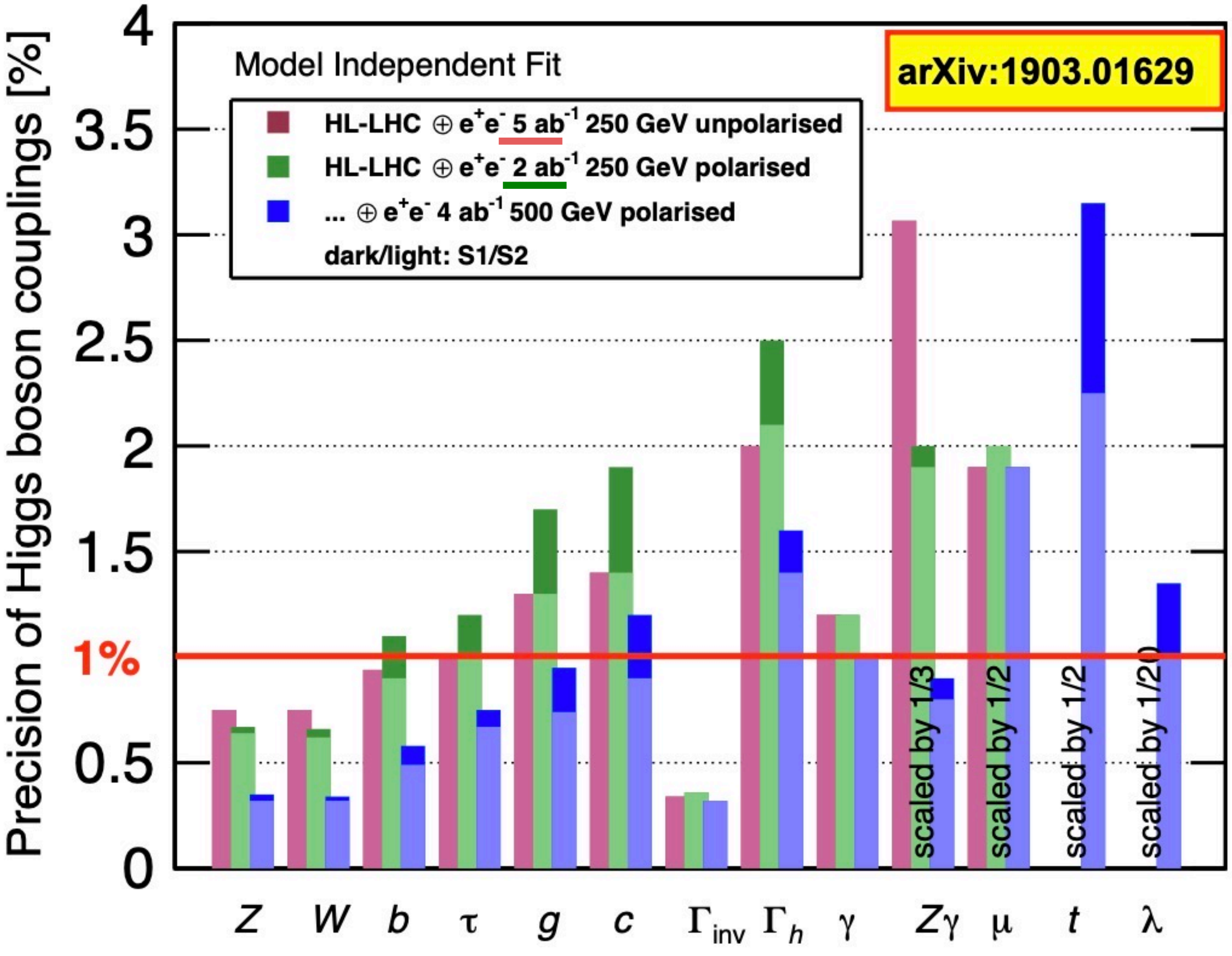


$\sim c_{WW}$
Keeps sign under spin reversal $e_R \leftrightarrow e_L$



Constrained by EWPOs

A_{LR} lifts degeneracy between operators

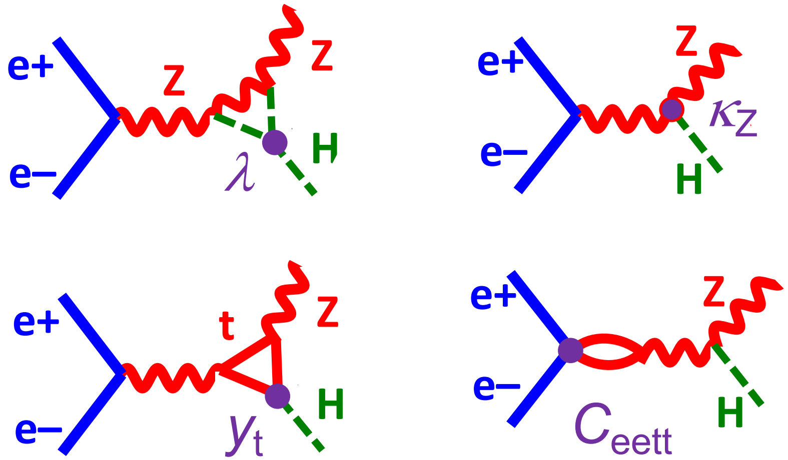


- 2 ab⁻¹ polarised ≈ 5 ab⁻¹ unpolarised
  –> the reason all e+e- Higgs factories perform so similarly

Higgs self-coupling: indirect access

◆ If λ deviates from SM, loop diagrams will give corrections to single-Higgs production and to Higgs decays

◆ e.g. (κ_λ–1)=1 increases σ(e$^+$e$^-$->ZH) by around 1.5% at $\sqrt{s}$=240GeV



◆ However, generic new physics tends to give deviations of the same size in several Higgs couplings so a fit to a larger model is needed and in this case contributions from λ are highly suppressed

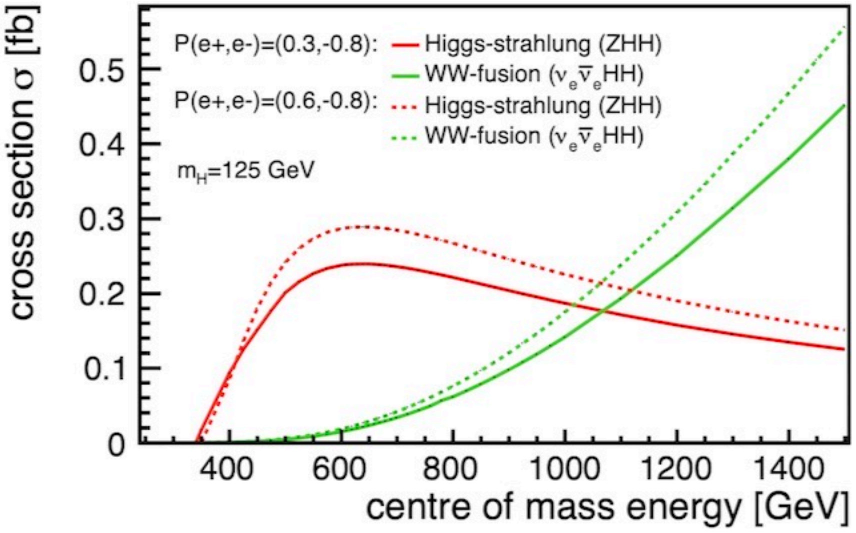
◆ ECFA Higgs@Future Colliders WG fitted single Higgs measurements, first to 1-parameter fit (SM modified only to shift of parameter κ_λ) – driven by ZH statistics

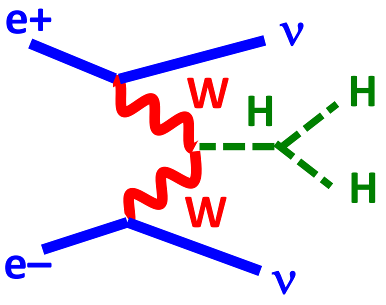
collider	1-parameter	full SMEFT
CEPC 240	18%	-
FCC-ee 240	21%	-
FCC-ee 240/365	21%	44%
FCC-ee (4IP)	15%	27%
ILC 250	36%	-
ILC 250/500	32%	58%
ILC 250/500/1000	29%	52%
CLIC 380	117%	-
CLIC 380/1500	72%	-
CLIC 380/1500/3000	49%	-

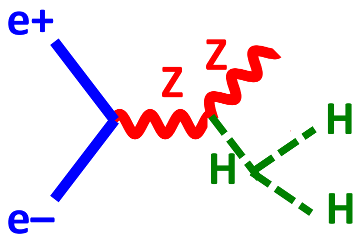
Higgs@Future Colliders 1905.03764 "-" means fit does not close

◆ theoretical work ongoing for disentangling contributions; very interesting to see how far this can go

Higgs self-coupling: direct double-Higgs production







- Two contributing direct production mechanisms: ZHH and $\nu\nu$HH
- ZHH becomes available at ILC 500 – studied in full sim with ILD detector Z->ll / Z->qq, HH->bbbb /HH->bbWW*
- If self-coupling λ is at SM value then double-Higgs process observable at 8σ, with 27% precision on λ
- Adding $\nu\nu$HH at 1TeV brings precision on λ to 10%

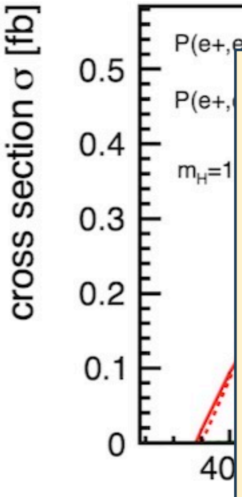
- ILC analysis used state-of-the-art reconstruction at the time (2016), but sensitivity very dependent on b-tagging performance, dijet mass resolution –> update is ongoing

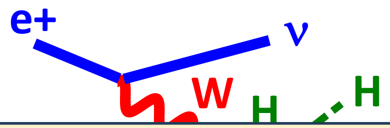
- CLIC studied sensitivity at 1.4TeV and 3 TeV
- at 1.4TeV rate-only analysis gives relative uncertainties –29% and +67% around SM value of g_{HHH}
- 3TeV differential measurement gives –8% and +11% assuming SM g_{HHWW}
- simultaneous measurement of triple and quartic couplings gives constraints below 4% in g_{HHWW} and below 20% in g_{HHH} for large modifications of g_{HHWW}

	1.4TeV	3TeV
$\sigma(HH\nu_e\bar{\nu}_e)$	>3σ EVIDENCE $\frac{\Delta\sigma}{\sigma}$ = 28%	>5σ OBSERVATION $\frac{\Delta\sigma}{\sigma}$ = 7.3%
$\sigma(ZHH)$	3.3σ EVIDENCE	2.4σ EVIDENCE
g_{HHH}/g_{HHH}^{SM}	1.4TeV: –29%, +67% rate-only analysis	1.4 + 3TeV: **–8%, +11%** differential analysis

Eur. Phys. J. C 80, 1010 (2020)

Higgs self-coupling: direct double-Higgs production





◆ Two contributing direct production mechanisms: ZHH and $\nu\nu HH$

0

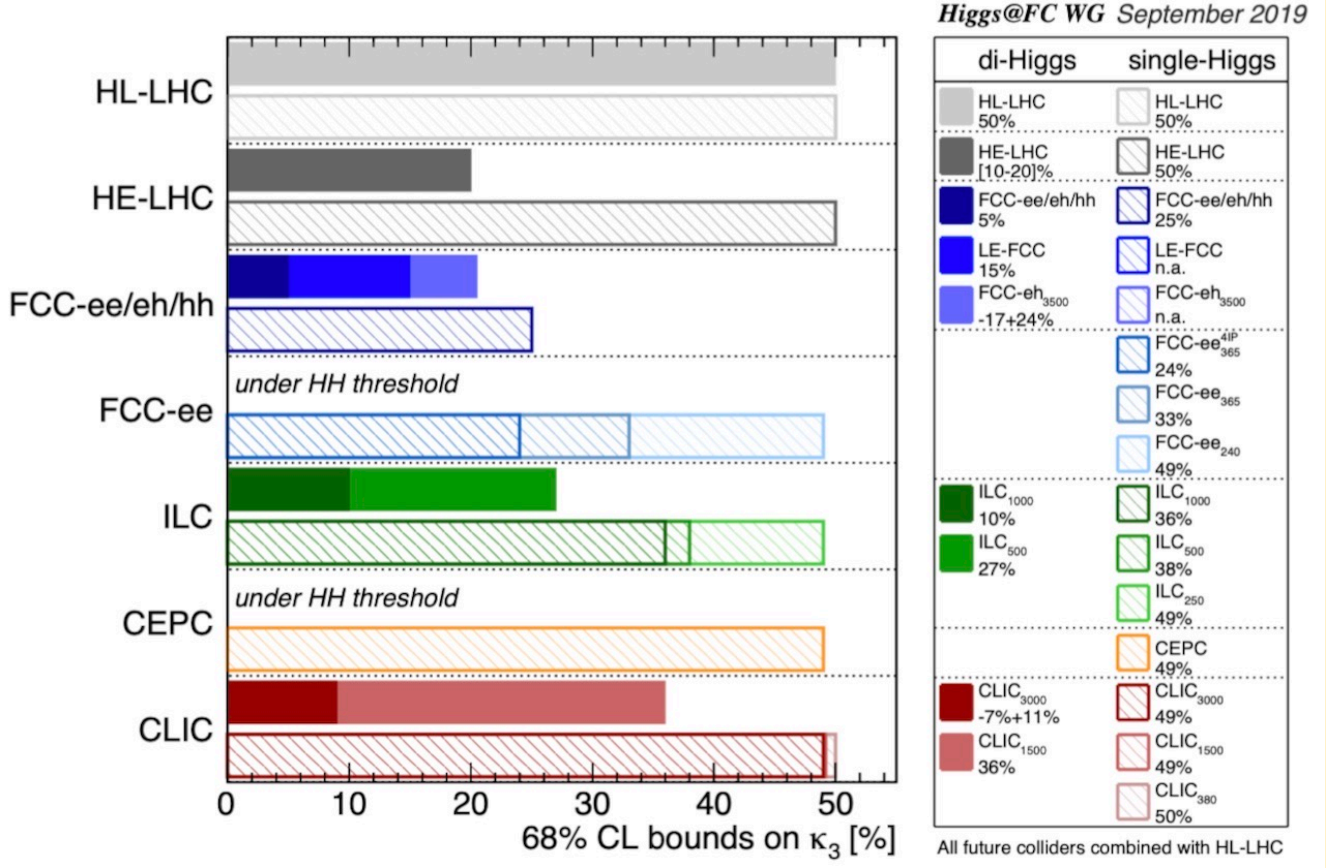
r

W*

en

8σ,

–> these are the entries in the summary plot on λ from the European Strategy Briefing Book arxiv:1910.11775



But… these sensitivities are only to the SM value of λ

◆ d

◆ CLIC s

◆ at 1.4T uncertain value of g

◆ 3TeV c –8% and

◆ simult quartic couplings gives constraints below 4% in g_{HHWW} and below 20% in g_{HHH} for large modifications of g_{HHWW}

ON

rate-only analysis

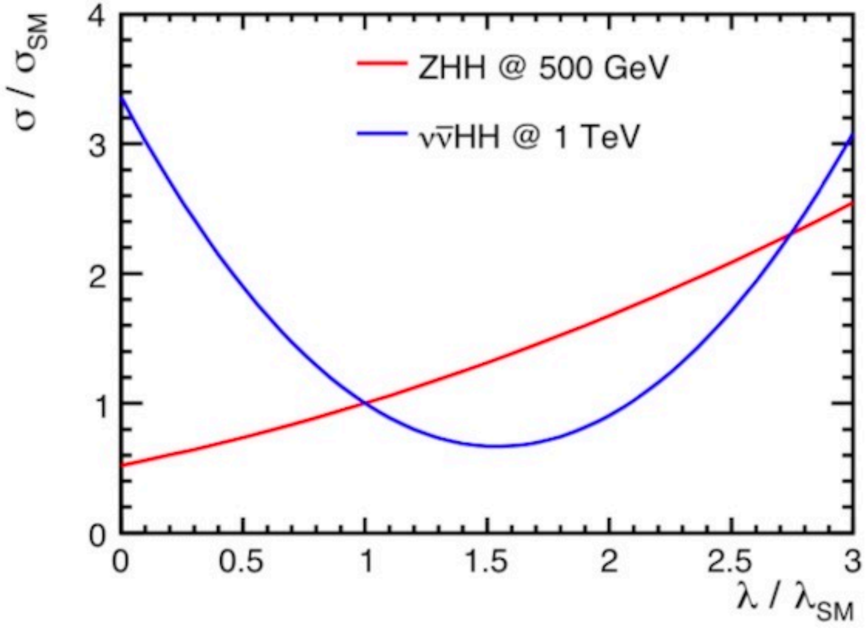
differential analysis

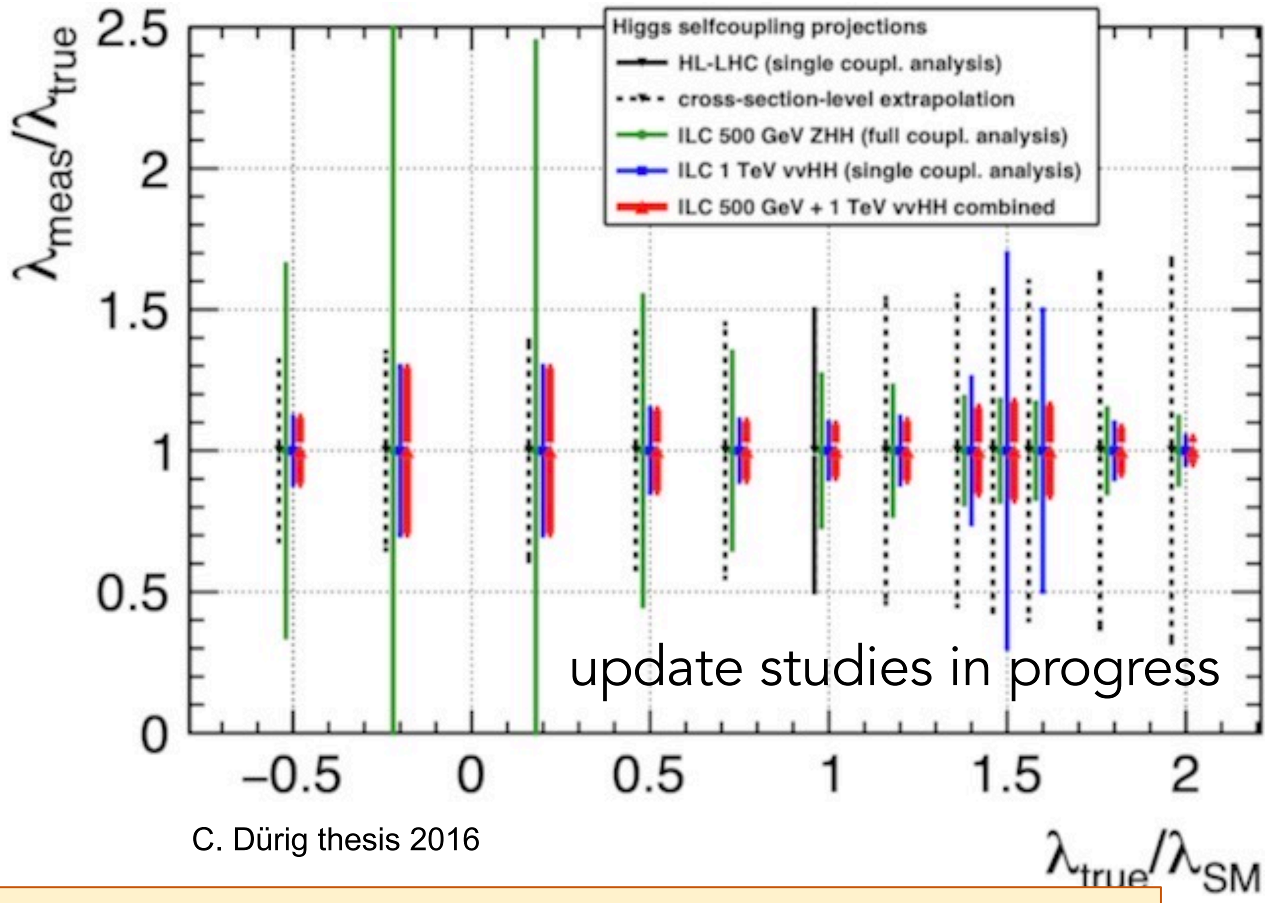
Eur. Phys. J. C 80, 1010 (2020)

Higgs self-coupling: non-SM case (0.5–1TeV)

- Most interesting case is when λ does NOT take SM value –> examine behaviour of production mechanisms

- Self-coupling diagram interferes constructively in ZHH and destructively in ννHH





update studies in progress

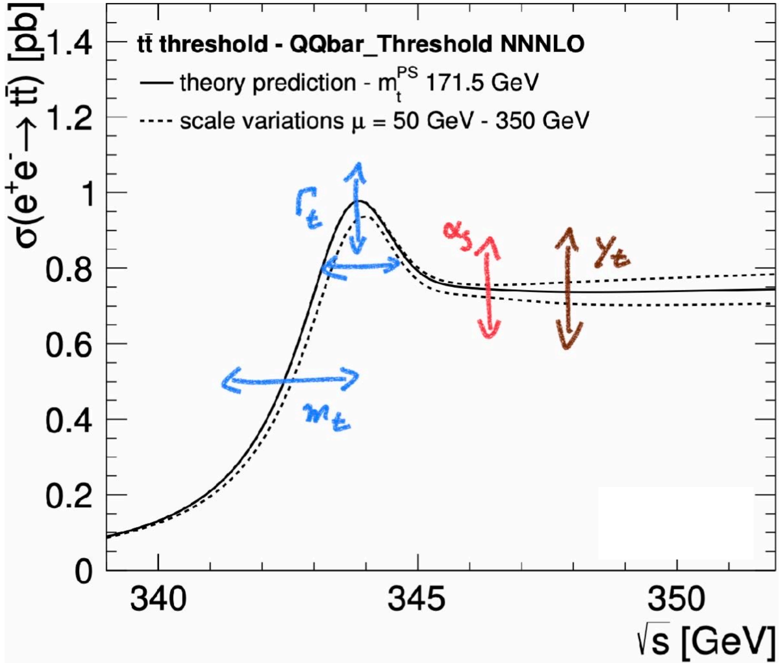
C. Dürig thesis 2016

- Owing to their different behaviours, combining ZHH and ννHH gives a measurement of λ at the level of 10–15% *for any value of λ* – **strong benefit of reaching √s ~550 GeV**

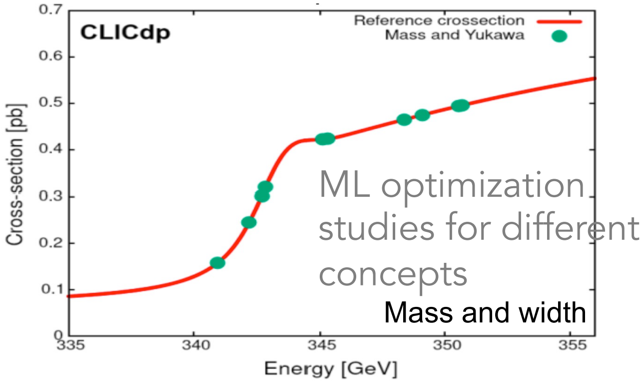
- e.g. 2HDM models where fermions couple to only one Higgs doublet allow $0.5 \lesssim \lambda/\lambda_{SM} \lesssim 1.5$, while EWK baryogenesis typically requires $1.5 \lesssim \lambda/\lambda_{SM} \lesssim 2.5$

Top-quark physics

- Threshold scan
  – proposed by all projects

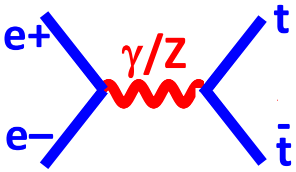


sensitive to top mass, width, coupling
reach Δm_t around level of 10MeV (stat)



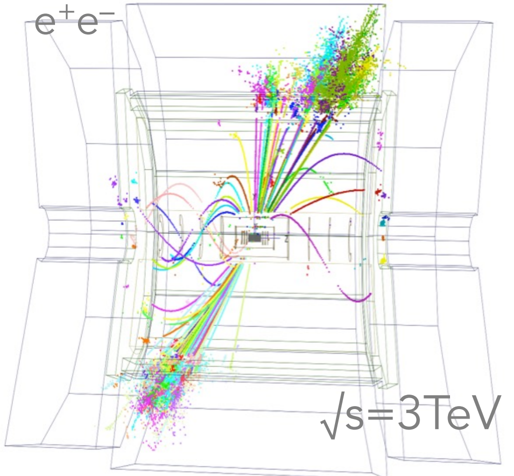
ML optimization studies for different concepts

- Pair-production
  – benefits from higher √s and multiple stages



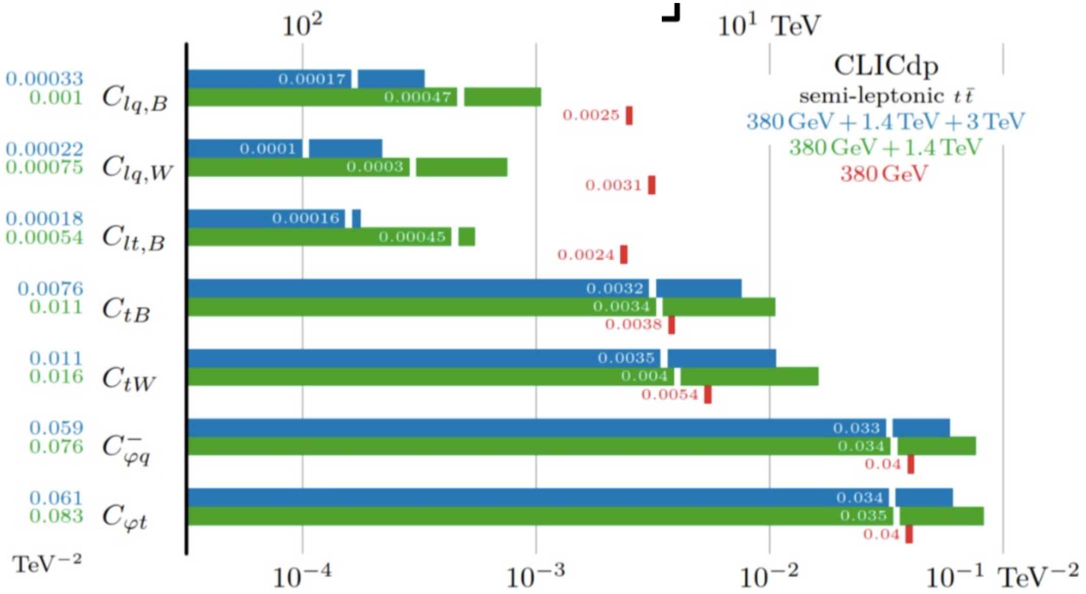
- Top cross-sections, both polarisations
- Top forward-backward asymmetries
- Statistically optimal observables for top EWK couplings; more than one energy stage allows global fit

First study of boosted top production in e^+e^-



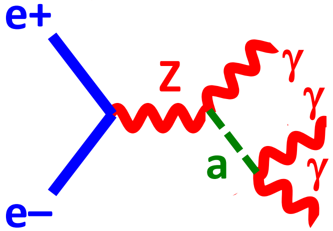
√s=3TeV

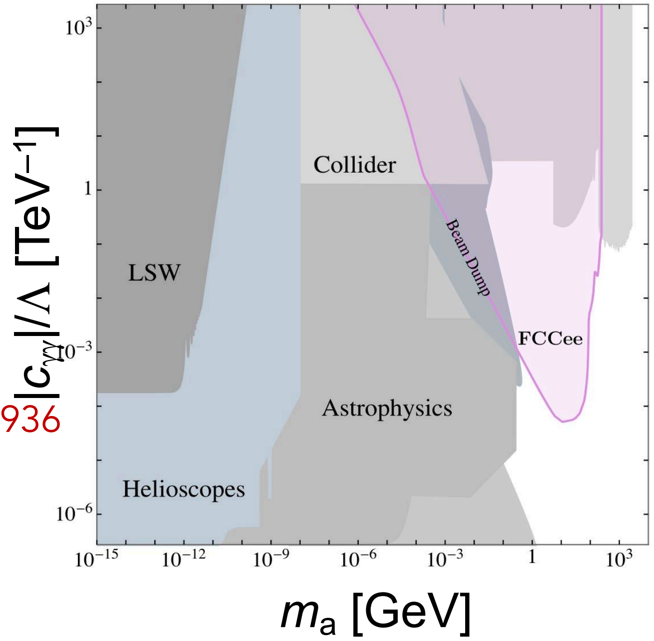
e^+e^- -> tt̄ -> qq̄qq̄bb̄



BSM physics

- **Rare decay signatures:**





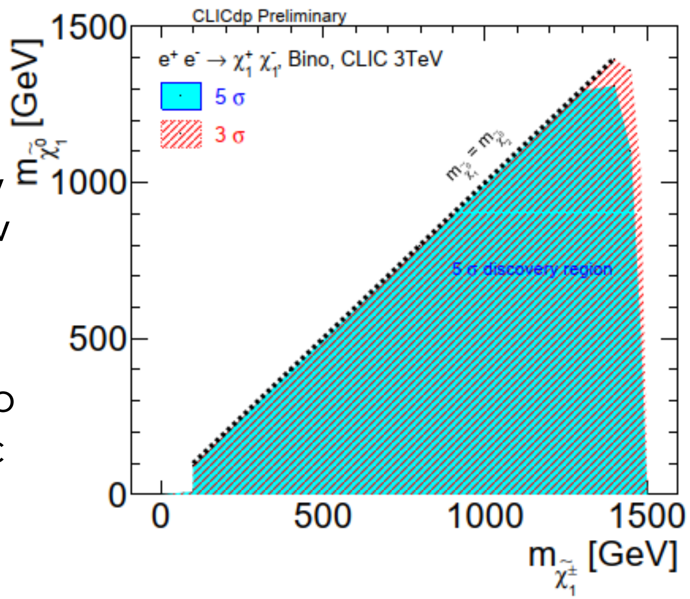
EPJ Plus (2021) 136:936

Axion-like particle search in FCC-ee TeraZ

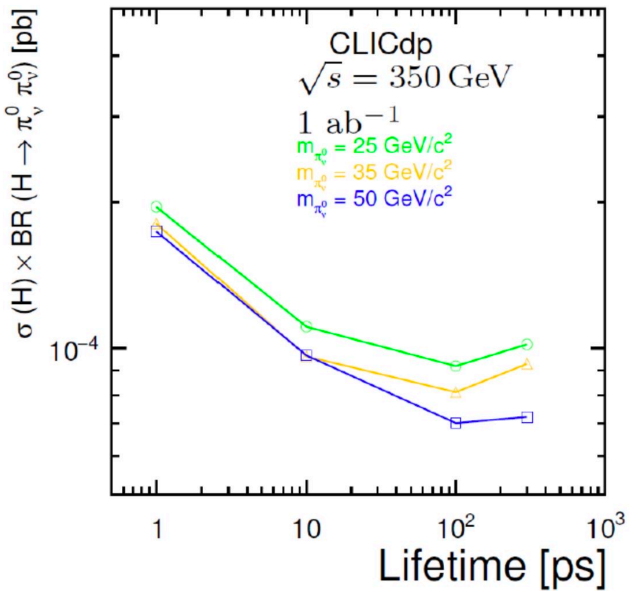
- **SUSY signatures:**

$e^+e^- \rightarrow \chi_1^+ \chi_1^-$
with $\chi_1^\pm \rightarrow \chi_1^0 W^\pm$
and $W^+W^- \rightarrow qqqq$
or $W^+W^- \rightarrow e^-\mu^+\nu\nu$
or $e^+\mu^-\nu\,\nu$

Scan of parameter space in R-parity conserving scenario –> larger kinematic coverage; difficult to access at LHC



General benefit of searches in e^+e^-: avoiding ‘holes’ in parameter space



- **Exotic signatures:**

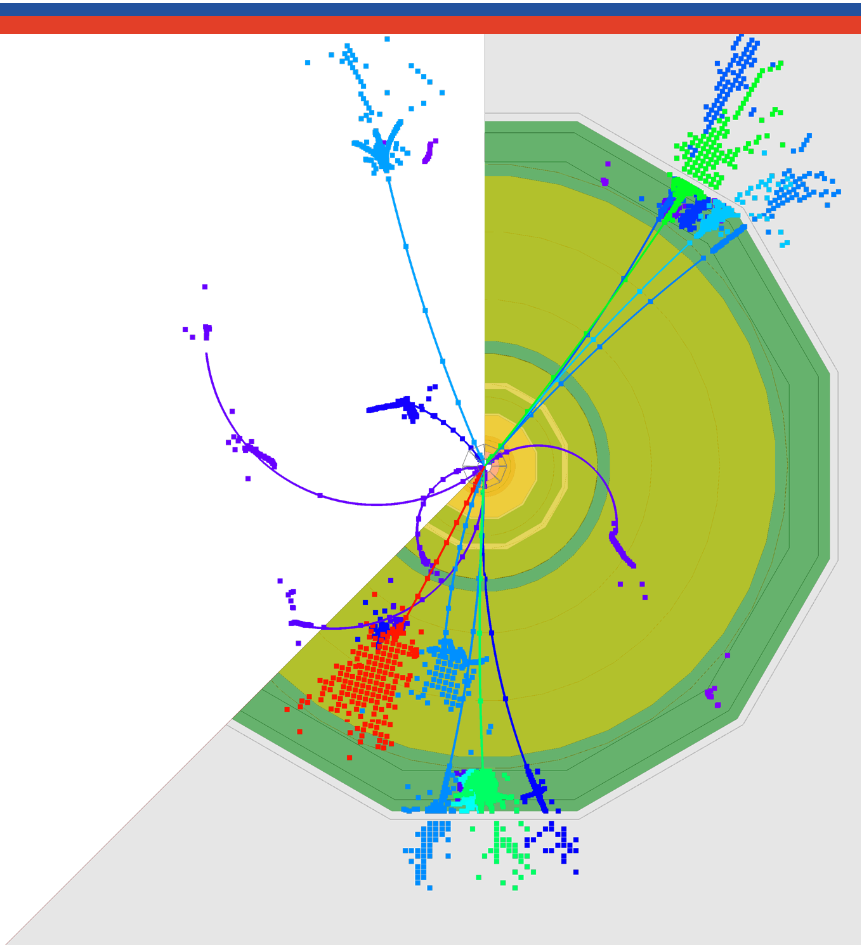
Long-lived particles; displaced vertices
– hidden valley H –> $\pi_V^0\pi_V^0$ –> bbbb

General benefit of ‘clean environment’ in e^+e^-

JHEP 03 (2023) 131

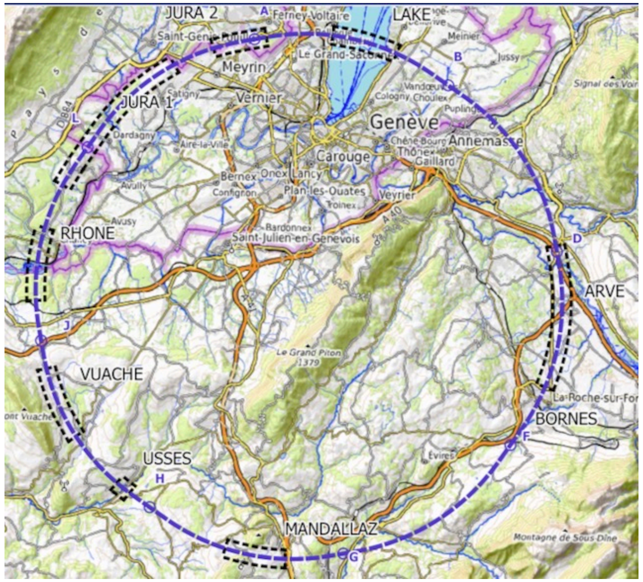
- **Plus BSM interpretations of precision measurements / EFT fits –> e.g. compositeness limits**

Status of e+e– projects



FCC Project and CEPC

FCC



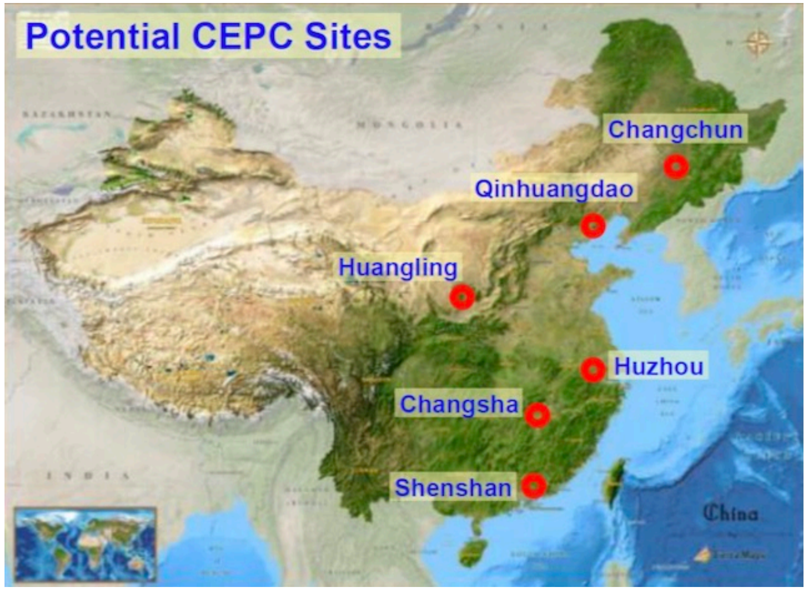
- Following last ESPP Update, **FCC** is CERN's "Plan A".
- Feasibility study 2021-25 concentrates on:

– technical & administrative feasibility of tunnel & surface areas
– optimisation of collider designs
– elaboration of a sustainable operational model
– development of a consolidated cost estimate
– identification of substantial resources from outside CERN's budget for the implementation of the first stage (tunnel & FCC-ee)

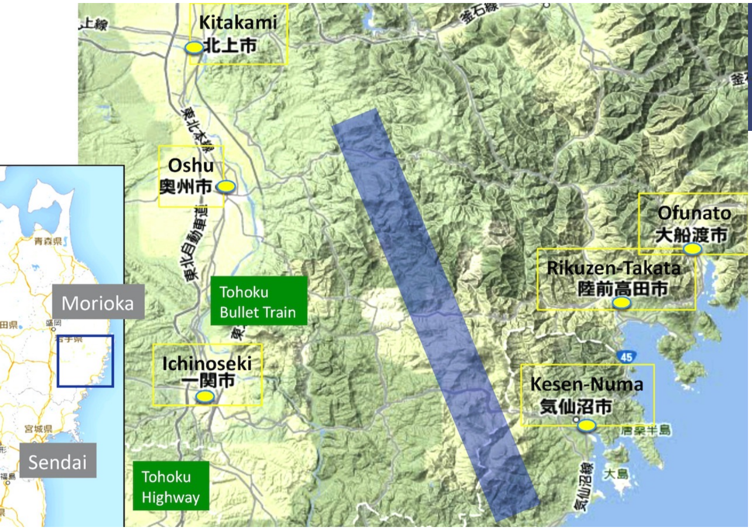
- Mid-term report published 2024 – well-received by CERN committees.
- Final Feasibility Study Report brought forward to March 2025
- Tentative timeline laid out for FCC-ee detectors:
  CDRs 2031; TDRs 2035; Installation 2041; Commissioning 2045

CEPC

- **CEPC** pursuing key technology R&D
- Prototype dipole modules produced
- TDR published 2023
- Chinese Academy of Sciences recently ranked CEPC as top priority in the relevant subcommittee
- Next steps towards approval:
- Chinese Academy of Sciences decides whether to submit CEPC project request to 5-year plan (~autumn this year)
- Funding decisions made in 2025 for 15th 5-Year Plan (runs 2026–30)



ILC and CLIC Projects



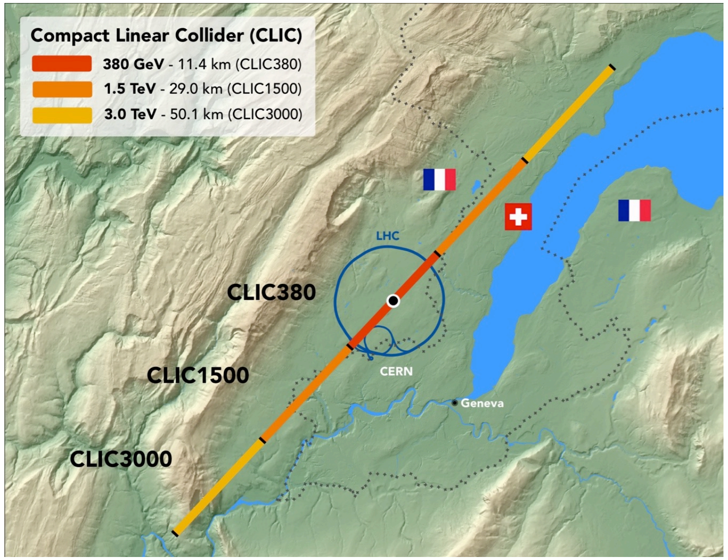
- **ILC** TDR 2013, several updates since then
- Site well understood; geological surveys done
- European XFEL demonstrated industrial cavity production
- Local support for hosting at Kitakami

- The International Development Team (IDT) was set up in 2020 to move towards the ILC Pre-lab
- **International Technology Network (ITN)** launched in July 2023
- Global collaboration programme focusing on time-critical accelerator R&D; funds flowing to Europe through KEK–CERN agreement

SRF
e- & e+ Sources
Nano-beam

} Synergy with other colliders

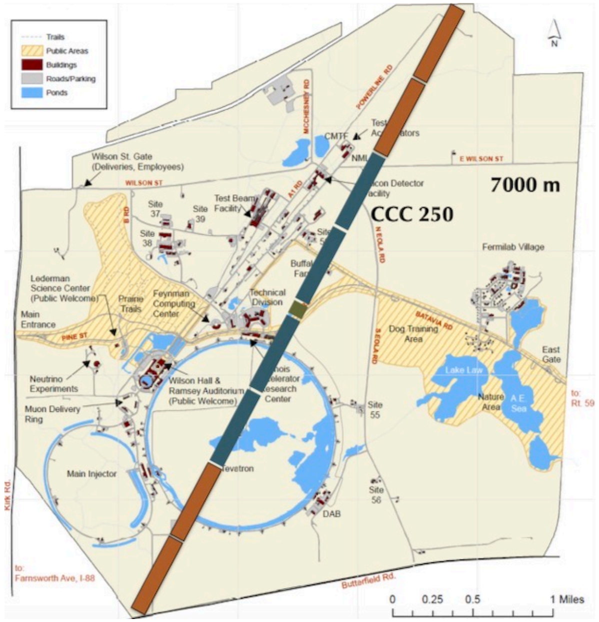
- **CLIC** key technologies demonstrated; site well understood
- X-band technology readiness for the 380 GeV CLIC initial phase increasingly driven by use in small compact accelerators
  - A compact FEL (CompactLight: EU Design Study 2018-21)
  - Compact Medical linacs e.g. flash electron therapy at CHUV (Lausanne)
  - Linearizers and deflectors in FELs (PSI, DESY, more)
  - 1 GeV X-band linac at LNF; SwissFEL uses CLIC-like structures at C-band –> helping to include industrial partners towards a collider
- Technical & experimental studies on design and parameters continue
  - Module studies; Beam dynamics and parameters
  - Tests in CLEAR; High efficiency klystrons
- Preparing 'Readiness Report' for 2025



C^3 and HALHF Projects

C^3: 8 km footprint for 250/550 GeV CoM ⟹ 70/120 MeV/m

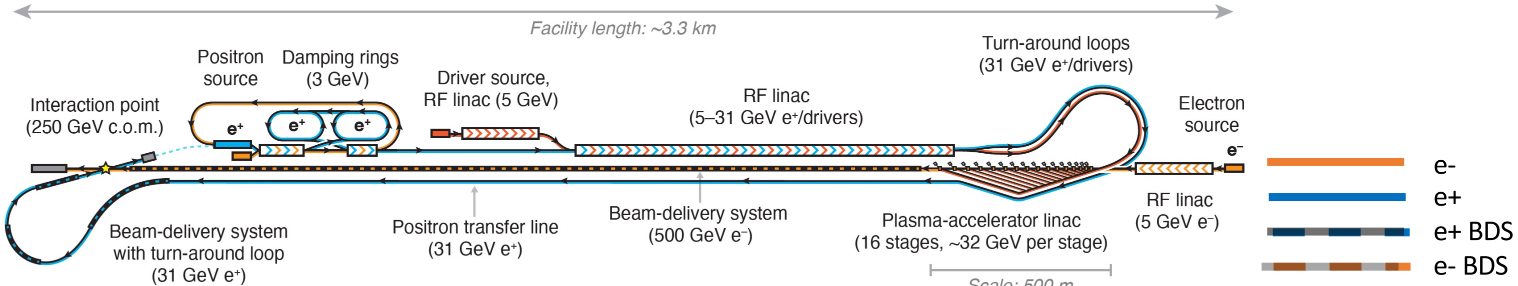
- Large portions of accelerator complex are compatible between LC technologies
  - –Beam delivery and IP modified from ILC (1.5 km for 550 GeV CoM)
  - –Damping rings and injectors to be optimized with CLIC as baseline
- R&D received some support from US P5 committee
- Moving towards CDR
- Could also be used as upgrade technology for ILC



- **HALHF** needs around 10 years R&D (driven by plasma cell R&D)
- very rough cost estimate extrapolating from ILC
  ~1.5bn ILCU (compare ~5bn ILCU for ILC)
  => towards single-country scale
- could build in ~2 years

Overall HALHF facility length ~ 3.3 km – which will fit on ~any of the major particle physics labs.

- considering configurations also for 380 and 550 GeV
- also considering options for upgrading ILC from 250 to 550
- initial studies of detector requirements for asymmetric configuration ongoing



https://arxiv.org/2303.10150

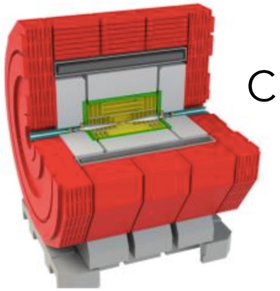
Detectors & software

Different projects have individual specific requirements from accelerator environments, but also many common aspects:

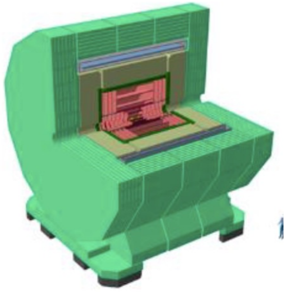
– detector concepts
– detector technologies
– software tools (& physics studies)

◆ Well-developed detector concepts extending from linear to circular projects

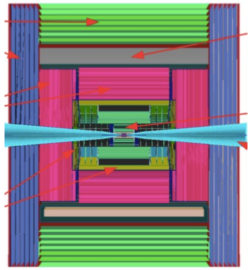
ILD SiD



CLICdet



CLD
for FCC-ee

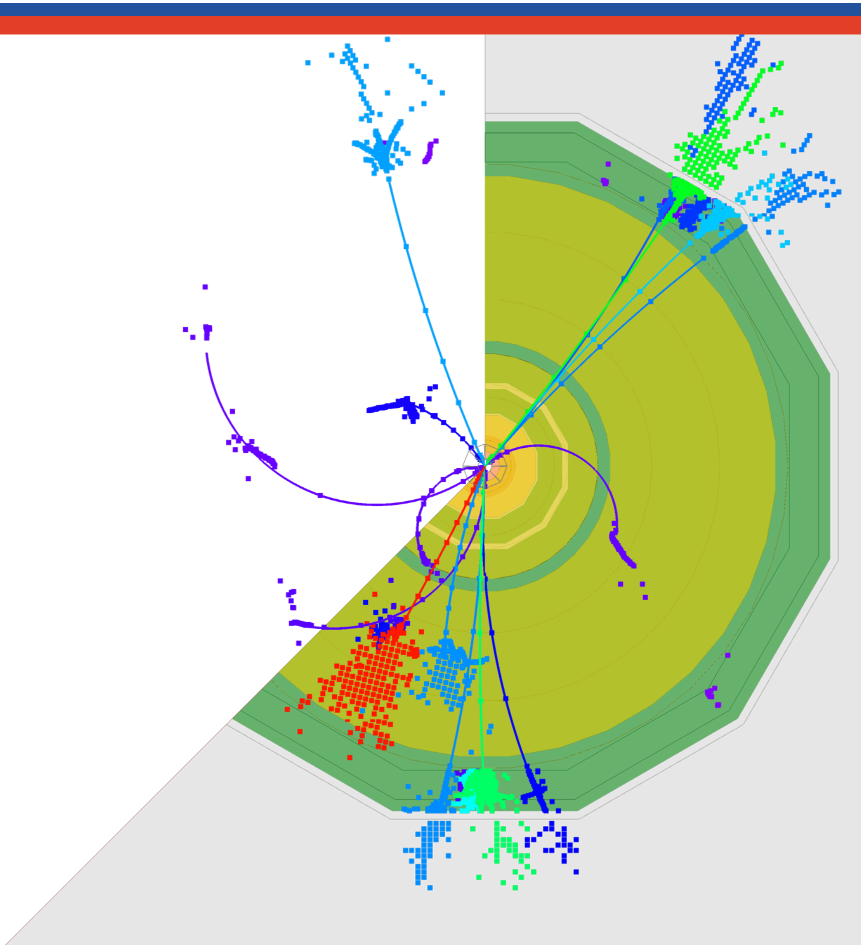


(CLICdet
adapted for
muon
collider!)

◆ Shared effort in analysis tools
– amplified through ECFA Higgs Factory study, identifying commonalities and complementarities, and sharing expertise

Detector	Collider	SW name	SW status	SW future
ILD	ILC	iLCSoft	Full sim/reco	Key4hep
SiD	ILC	iLCSoft	Full sim/reco	
CLICdet	CLIC	iLCSoft	Full sim/reco	
CLD	FCC-ee	iLCSoft	Full sim/reco	
IDEA	FCC-ee	FCC-SW	Fast sim/reco	
IDEA	CEPC	FCC-SW	Fast sim/reco	
CEPCbaseline	CEPC	iLCSoft branch-off	Full sim/reco	

Strategic considerations



Menu of physics to be covered?

- 91 GeV –> precision EW
- (160 GeV –> m_W from WW threshold)
- 250 GeV –> precision Higgs mass and Higgs branching fractions
- 350 GeV –> precision top quark mass (threshold scan)
- 550–600 GeV –> double Higgs-strahlung
  -> ZHH, top electroweak couplings, precision WW –> H fusion
- 800–1000 GeV –> double Higgs from WW fusion
  -> ννHH, precision top Yukawa and CP
- beyond: Higgs quartic coupling, and exploration…

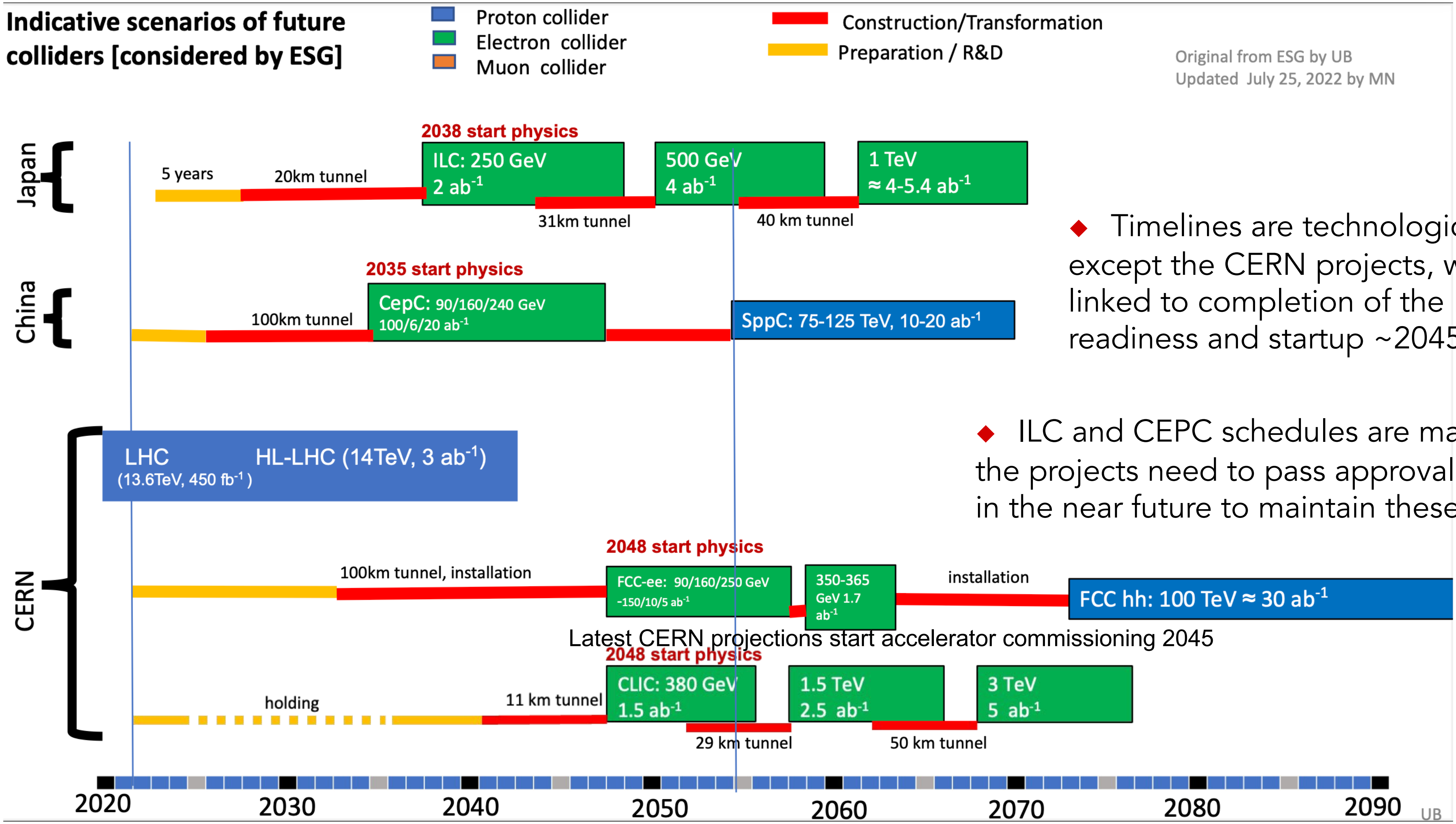
Broad agreement that we want to do all of this physics

Different proposals take different approaches:
ILC/C^3 proposal runs at each energy;
CLIC proposal consolidates Higgs & top to 380GeV then >1TeV;
FCC puts some parts with hh.

- **Strategic question 1:**
  – how much of the programme should be done with the next machine (e^+e^-) ?
  – or are we prepared to wait for the next-to-next (hh or μμ) ?

Timelines?

- **Strategic question 2:**
  – how long are we prepared to wait for aspects of the physics programme?



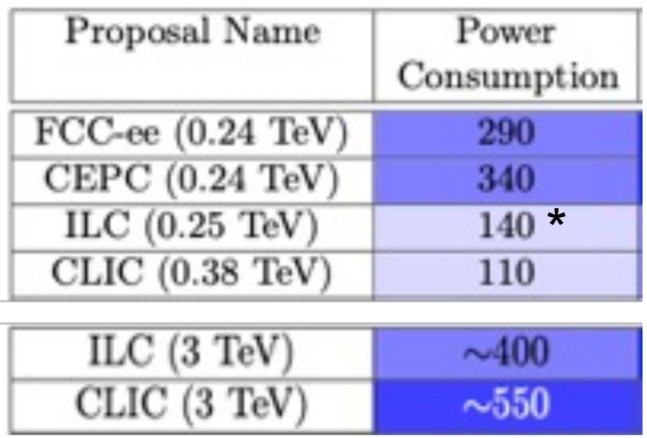
- Timelines are technologically limited except the CERN projects, which are linked to completion of the HL-LHC; readiness and startup ~2045-48

- ILC and CEPC schedules are mature, but the projects need to pass approval processes in the near future to maintain these schedules

Sustainability?

◆ **Strategic question 3:**
– when/how to fold in environmental considerations?

Power:
Projects working on improving power efficiency

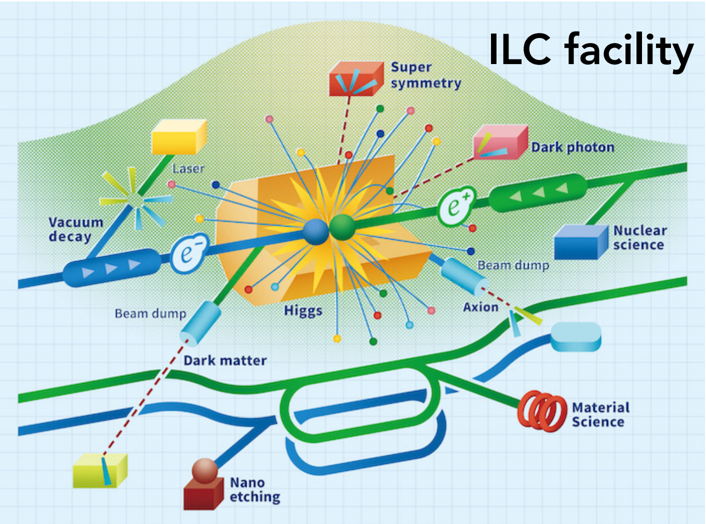


MW

Proposal Name	Power Consumption
FCC-ee (0.24 TeV)	290
CEPC (0.24 TeV)	340
ILC (0.25 TeV)	140 *
CLIC (0.38 TeV)	110
ILC (3 TeV)	~400
CLIC (3 TeV)	~550

from Snowmass implementation taskforce
*nominal 111 MW; LumiUpgrade 138MW

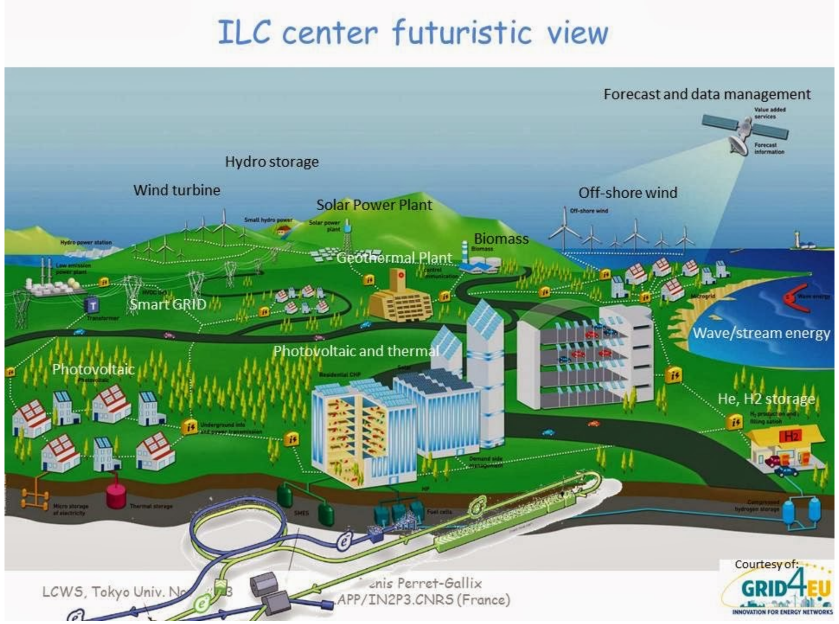
– what should be the metric?


ILC facility

Full use of infrastructures – all projects

FCCee considering:
– electrons from injector to beam-dump
– extracting electrons from booster
– use of synchrotron photons

Towards 'Green ILC': similarly @ CERN



Lifecycle assessment:
Study by Arup on carbon footprint and other environmental impacts, done to international standards

Assesses Global Warming Potential of underground civil engineering – raw materials, transport, construction activities

CLIC 380GeV:
127kton CO2-eq (two-beam option)
290kton CO2-eq (klystron option)

ILC 250GeV:
266kton CO2-eq

–> also points out potentials to reduce
Report released summer 2023

Now commissioning extended study to account for accelerator components & detectors

Flexibility?

- **Strategic question 4:**
  - how concrete is the plan / how important is flexibility?

- Looking ahead to the next-to-next machine:
  - are we ready to make the decision now on the next-to-next machine?
  - is FCC-hh definitely realisable at an achievable cost? (magnets?)
  - what is the timescale for currently-developing technologies to mature? and should we leave space for them to enter?

    (muon collider? plasma wakefield acceleration?)

Flexibility?

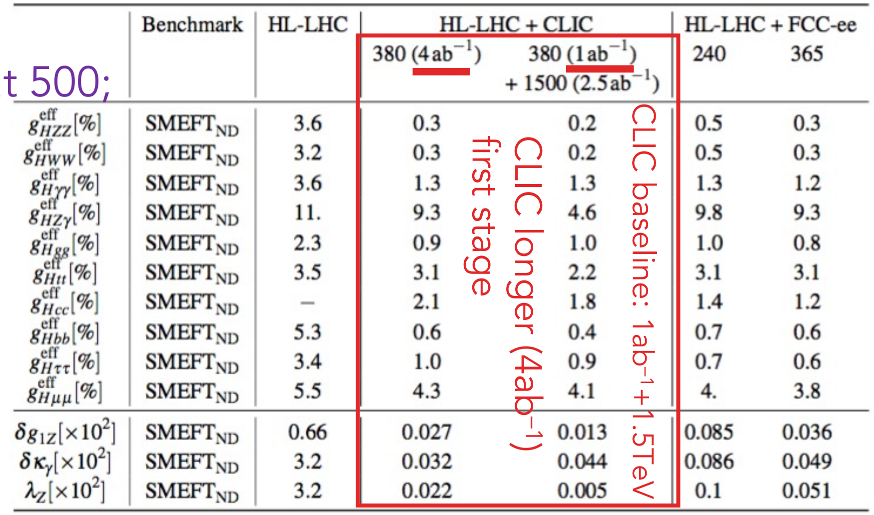
- **Strategic question 4:**
  – how concrete is the plan / how important is flexibility?

- Looking ahead to the next-to-next machine:
  - – are we ready to make the decision now on the next-to-next machine?
  - – is FCC-hh definitely realisable at an achievable cost? (magnets?)
  - – what is the timescale for currently-developing technologies to mature? and should we leave space for them to enter?
    (muon collider? plasma wakefield acceleration?)

- Linear machines are intrinsically flexibile in their run scenarios
  –> allows to adapt to external factors (physics landscape / budgetary)
  and postpone decision on next-to-next machine

- NB, linear options studied in detail are 'just' benchmarks;
  CLIC could be built with initial stage at 250, or a stage at 500;
  (or ILC could be built at 380)
  –> these are physics choices to be made
  And e.g. ILC could be built in Europe

Staging optimisation example:
CLIC baseline run plan is optimised to move to TeV energies quickly, but core Higgs coupling sensitivities can be achieved with CLIC just running longer at first stage



	Benchmark	HL-LHC	HL-LHC + CLIC		HL-LHC + FCC-ee	
			380 ($4\,ab^{-1}$)	380 ($1\,ab^{-1}$) + 1500 ($2.5\,ab^{-1}$)	240	365
$g^{\mathrm{eff}}_{HZZ}[\%]$	$\mathrm{SMEFT_{ND}}$	3.6	0.3	0.2	0.5	0.3
$g^{\mathrm{eff}}_{HWW}[\%]$	$\mathrm{SMEFT_{ND}}$	3.2	0.3	0.2	0.5	0.3
$g^{\mathrm{eff}}_{H\gamma\gamma}[\%]$	$\mathrm{SMEFT_{ND}}$	3.6	1.3	1.3	1.3	1.2
$g^{\mathrm{eff}}_{HZ\gamma}[\%]$	$\mathrm{SMEFT_{ND}}$	11.	9.3	4.6	9.8	9.3
$g^{\mathrm{eff}}_{Hgg}[\%]$	$\mathrm{SMEFT_{ND}}$	2.3	0.9	1.0	1.0	0.8
$g^{\mathrm{eff}}_{Htt}[\%]$	$\mathrm{SMEFT_{ND}}$	3.5	3.1	2.2	3.1	3.1
$g^{\mathrm{eff}}_{Hcc}[\%]$	$\mathrm{SMEFT_{ND}}$	–	2.1	1.8	1.4	1.2
$g^{\mathrm{eff}}_{Hbb}[\%]$	$\mathrm{SMEFT_{ND}}$	5.3	0.6	0.4	0.7	0.6
$g^{\mathrm{eff}}_{H\tau\tau}[\%]$	$\mathrm{SMEFT_{ND}}$	3.4	1.0	0.9	0.7	0.6
$g^{\mathrm{eff}}_{H\mu\mu}[\%]$	$\mathrm{SMEFT_{ND}}$	5.5	4.3	4.1	4.	3.8
$\delta g_{1Z}[\times 10^2]$	$\mathrm{SMEFT_{ND}}$	0.66	0.027	0.013	0.085	0.036
$\delta\kappa_\gamma[\times 10^2]$	$\mathrm{SMEFT_{ND}}$	3.2	0.032	0.044	0.086	0.049
$\lambda_Z[\times 10^2]$	$\mathrm{SMEFT_{ND}}$	3.2	0.022	0.005	0.1	0.051

CLIC longer ($4ab^{-1}$) first stage

CLIC baseline: $1ab^{-1}$+1.5TeV

2001.05278

European Strategy Briefing Book

Cost, community, and scenarios?

- **Strategic question 5:**
  - when/how to fold in cost considerations?
    - how to consider 'loss of opportunity' if money spent on one thing not others?

Cost

ILC 250: ~5 BCHF

CLIC:
380GeV: 5.9 BCHF
to 1.5 TeV: add 5.1 BCHF
to 3 TeV: add 7.3 BCHF

Cost

FCC-ee (to $\sqrt{s}$=365): ~11.6 BCHF

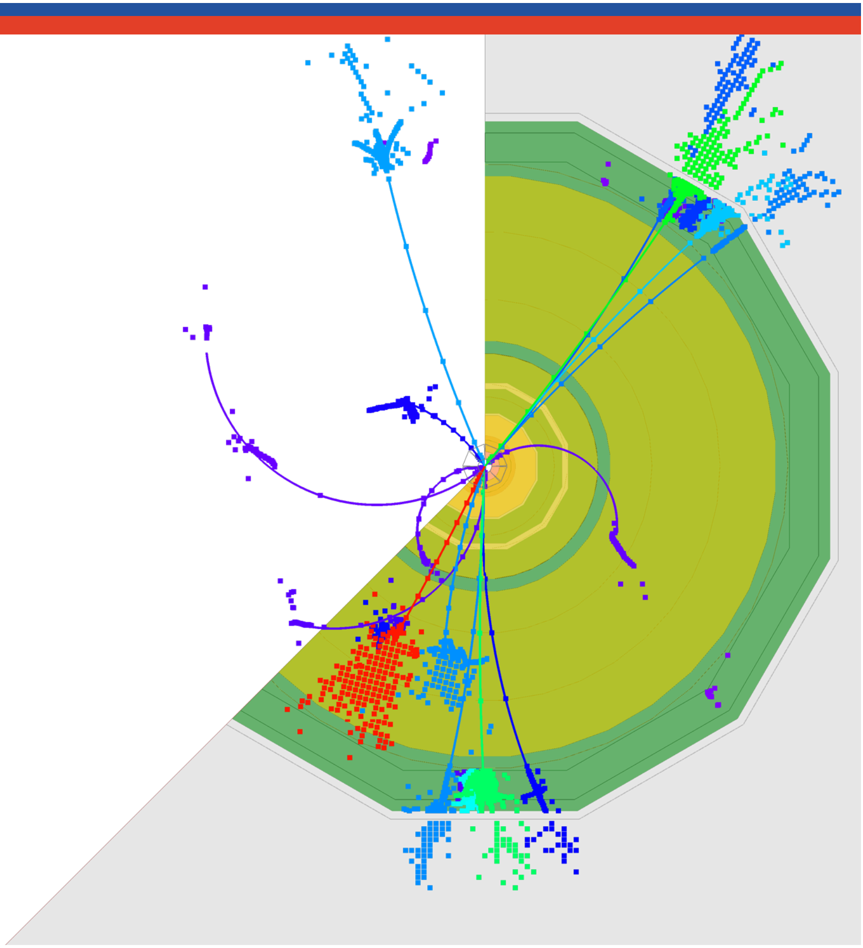
FCC-hh:
17 BCHF (if built after FCC-ee)
24 BCHF (if built standalone)

NB these are the costings presented at the last European Strategy; they are all being updated. This is a set of costings that can be compared

- **Strategic question 6:**
  - how to we wish to see the (collider) particle physics community evolving?
    - concentrated in one large project or allowing room for more, smaller experiments?
      - FCC-ee up to 4 IPs; LCs up to 2 expts via (ILC) push-pull or (CLIC) 2 IPs

- **Strategic question 7:**
  - what should Europe do in the case that CEPC goes ahead?
    - extent to which it would be possible to participate?
    - or enter into a 'race' for a circular machine?
    - or do something complementary e.g. higher $\sqrt{s}$ e+e– ?

Summary



Future visions

Broad agreement across community on the physics we want to do with a next collider – everyone involved would be delighted for ***any*** Higgs factory to be realised…

However, there can be different routes to the physics:

◆ **Linear Collider**

– a Higgs factory as soon as possible, upgradable

– R&D for the machine beyond in parallel; no constraints imposed by the LC

– a strong diversified programme using the LC complex

Initial Linear Collider can be followed (if funding permits) by energy increases and/or independent muon and/or hadron machines with radius and magnets to be determined – can also overlap in time with hadron/muon machines

In the longer future: the civil infrastructure can be used with novel acceleration techniques e.g. plasma

◆ **Circular Collider**

– an integrated programme of e^+e^- and pp

– R&D for FCC-hh magnets in parallel, but large-scale civil infrastructure secured at the first stage

– larger experimental community with up to 4 IPs

Initial Higgs Factory civil infrastructure reused (if funding permits) for hadron machine with radius fixed; magnets to be determined. Sequential progression.

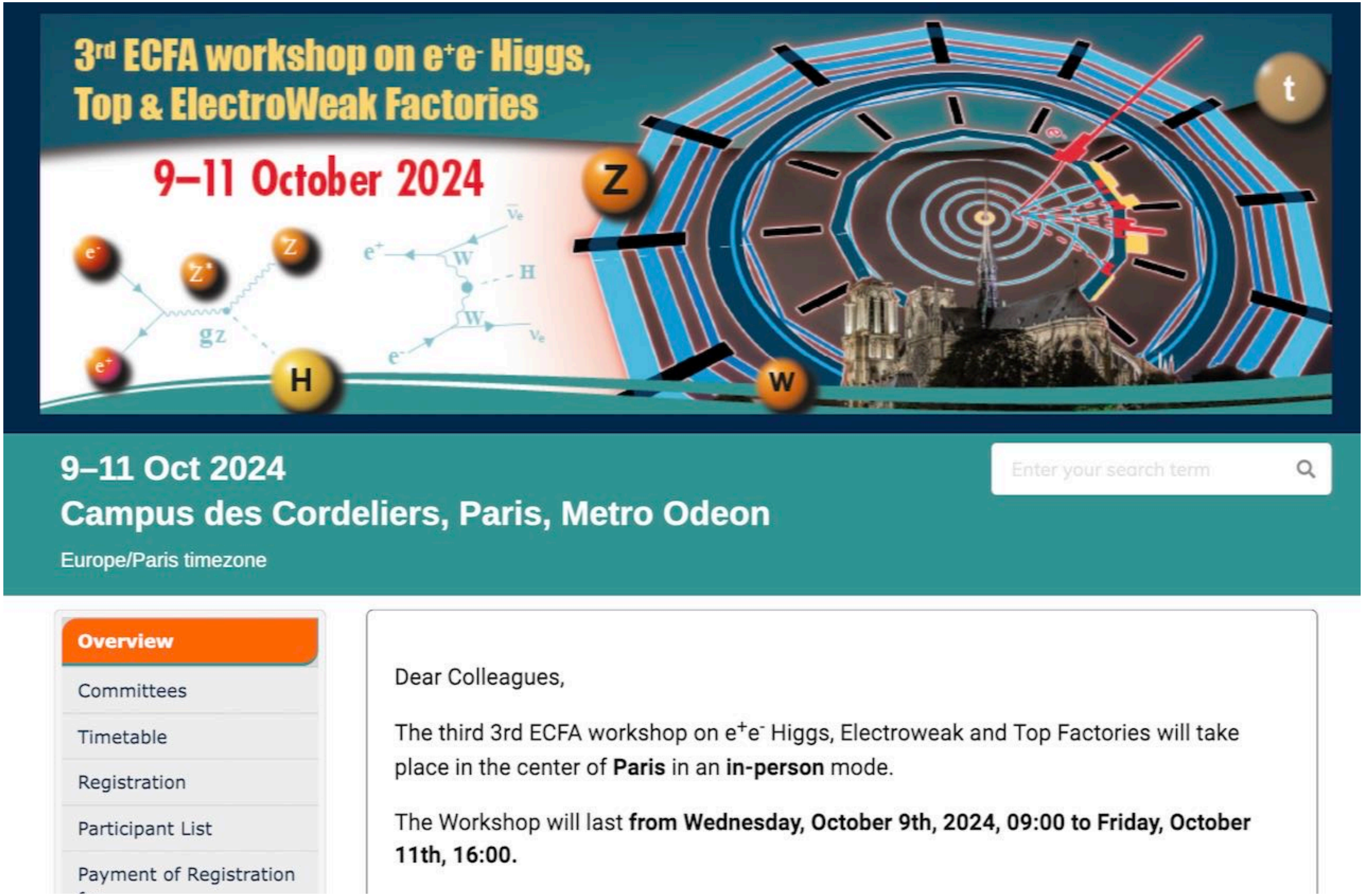
Programme fixed to ~2090s or beyond.

Needs careful thought about how best to achieve Higgs Factory and beyond
– trade-offs / risks

Hope for strong engagement in these discussions over the next ~year

3^{rd} ECFA Workshop on Higgs/Top/EWK factories

https://indico.in2p3.fr/event/32629/overview Registration & abstract submission OPEN



3rd ECFA workshop on e+e- Higgs, Top & ElectroWeak Factories

9–11 October 2024

9–11 Oct 2024

Campus des Cordeliers, Paris, Metro Odeon

Europe/Paris timezone

Dear Colleagues,

The third 3rd ECFA workshop on e^+e^- Higgs, Electroweak and Top Factories will take place in the center of **Paris** in an **in-person** mode.

The Workshop will last **from Wednesday, October 9th, 2024, 09:00 to Friday, October 11th, 16:00.**