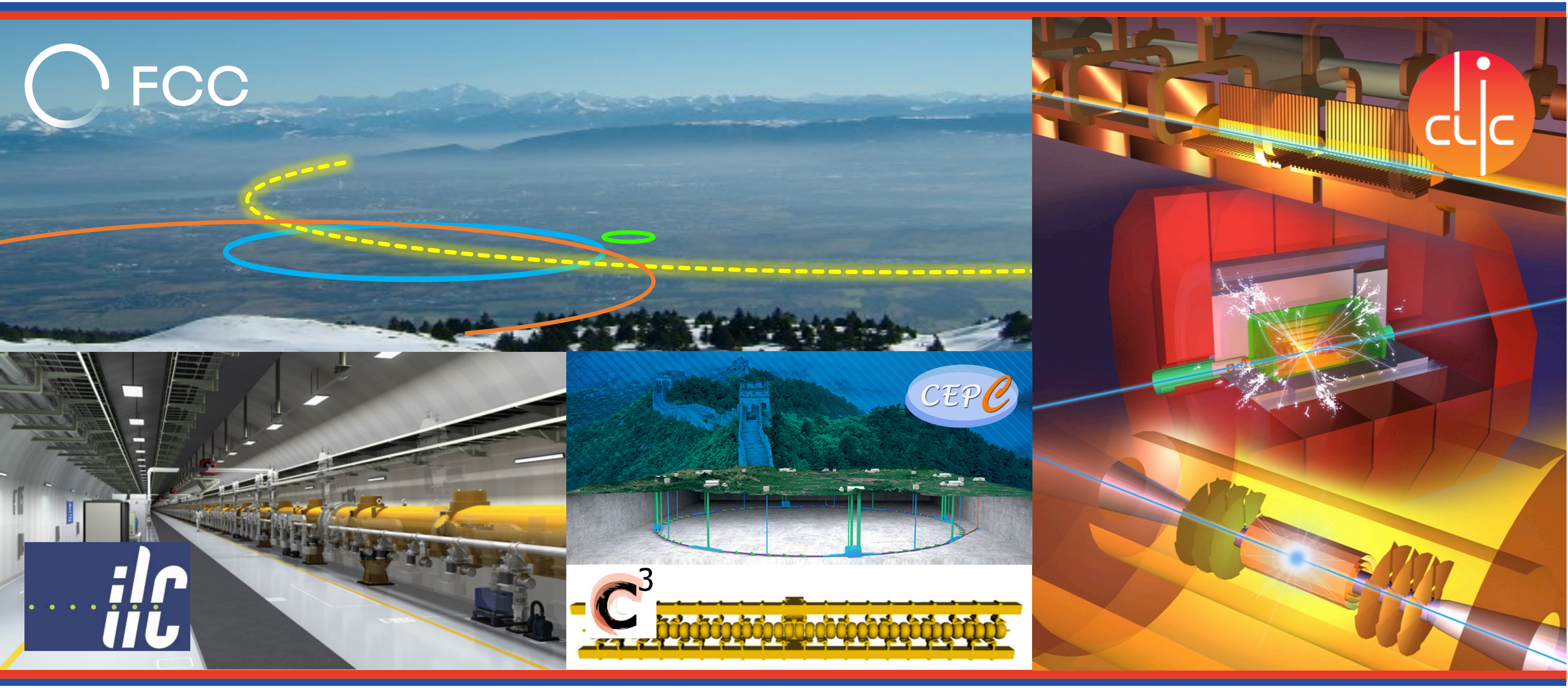
Higgs Factories

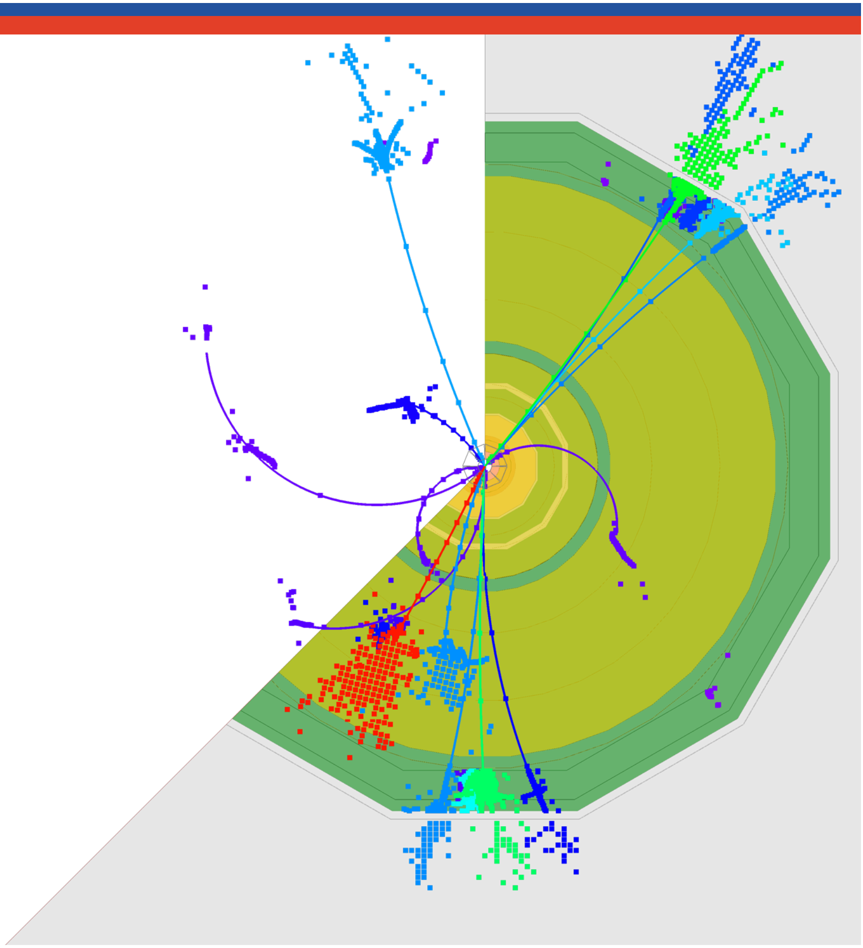


2nd Corfu Workshop on Future Accelerators, May 2024

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



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Important disclaimer! :

There are many related talks at this workshop and so in this talk I am NOT trying to be comprehensive, but am trying to avoid too much overlap with the others.

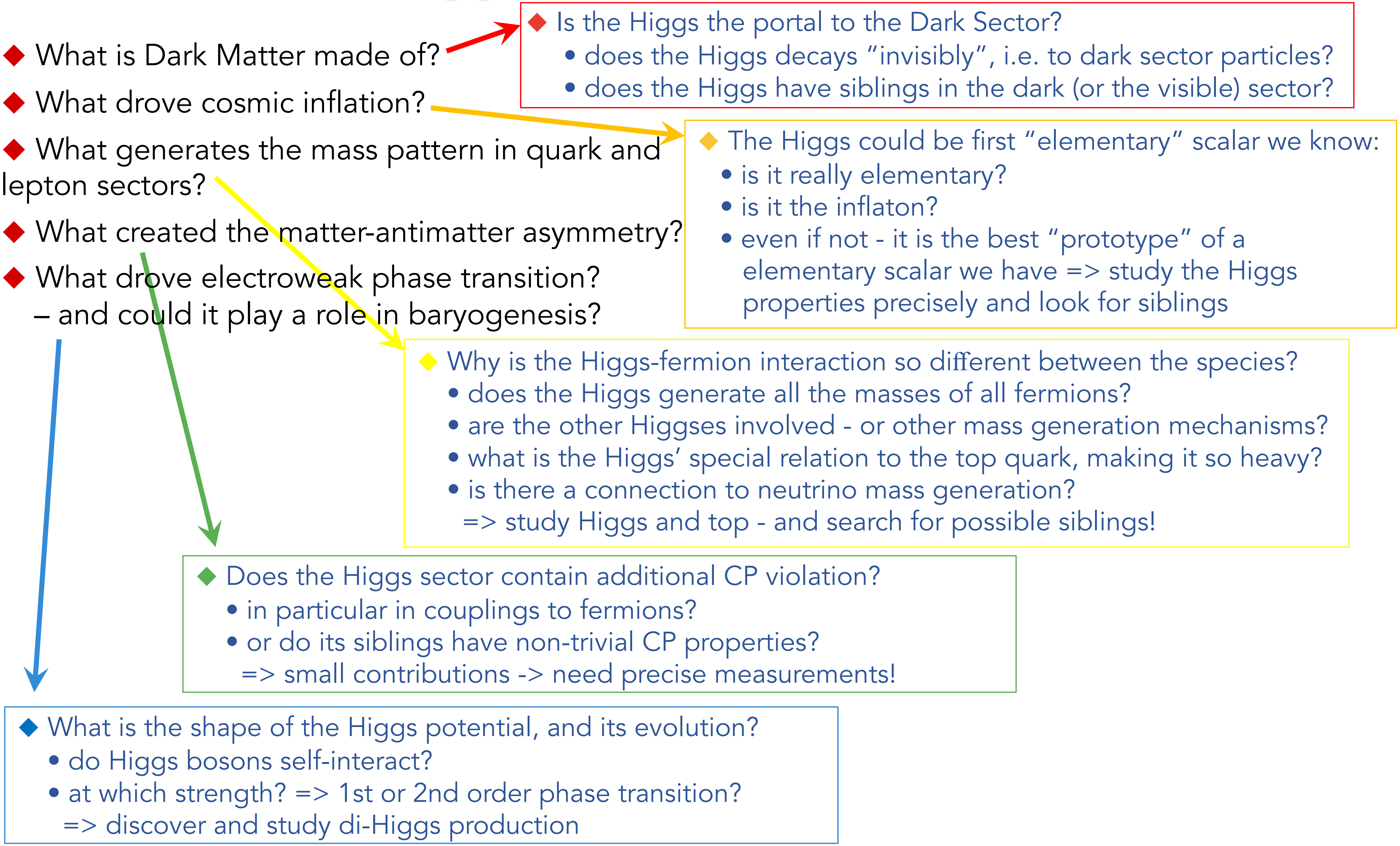
For the latest **FCC** status and programme see the talks from Christophe Grojean and Emmanuel Tsesmelis;

For detailed **physics** discussions see the talks from Georg Weiglein, Stefano Forte, Alex Mitov and others;

For **detector** considerations see the talks from Roberto Ferrari, Karsten Buesser, Mary-Cruz Fouz and others

For **advanced accelerator** concepts see the talks from Jens Osterhoff and others

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)

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

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

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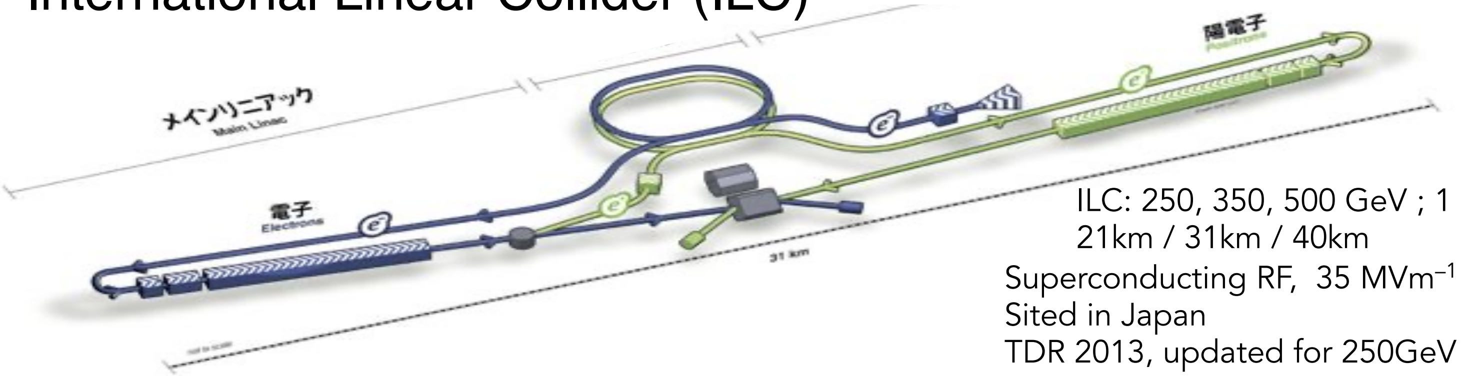
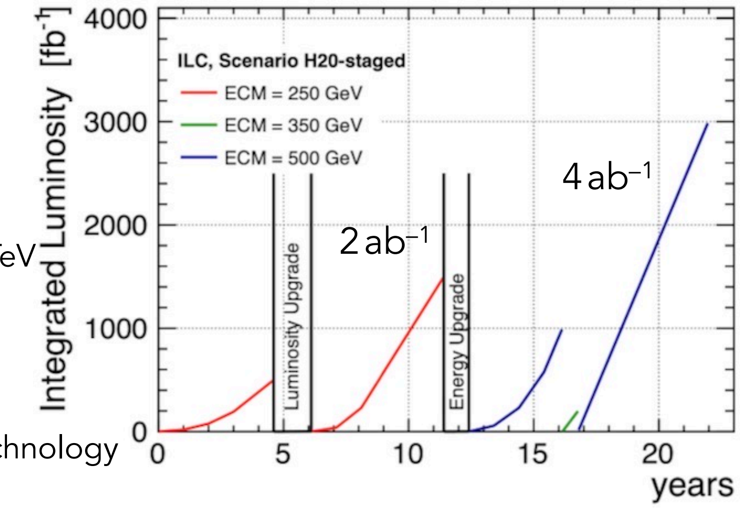
- triggerless operation (LCs)

Higgs factory contenders (1): Linear Colliders

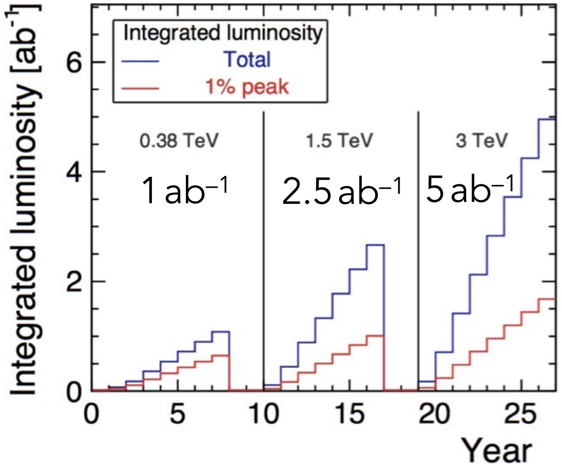
International Linear Collider (ILC)



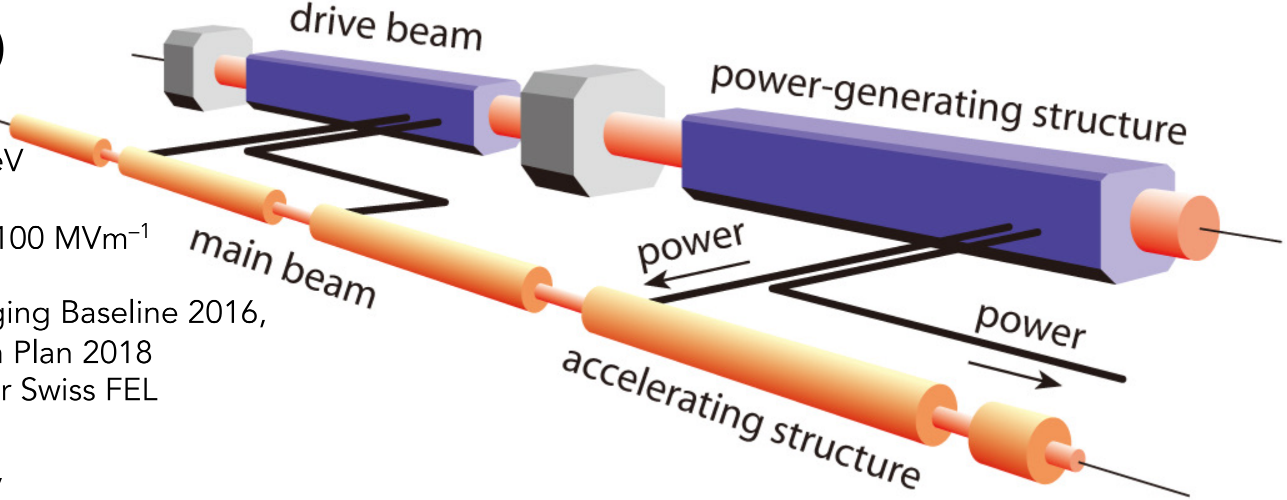
ILC: 250, 350, 500 GeV ; 1 TeV
21km / 31km / 40km
Superconducting RF, 35 MVm^{-1}
Sited in Japan
TDR 2013, updated for 250GeV
European XFEL demonstrates technology



Compact Linear Collider (CLIC)



CLIC: 380 GeV ; 1.5, 3 TeV
11km / 29km / 50km
Room temperature, 72–100 MVm^{-1}
Sited 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}
Sited at Fermilab
Pre-CDR

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

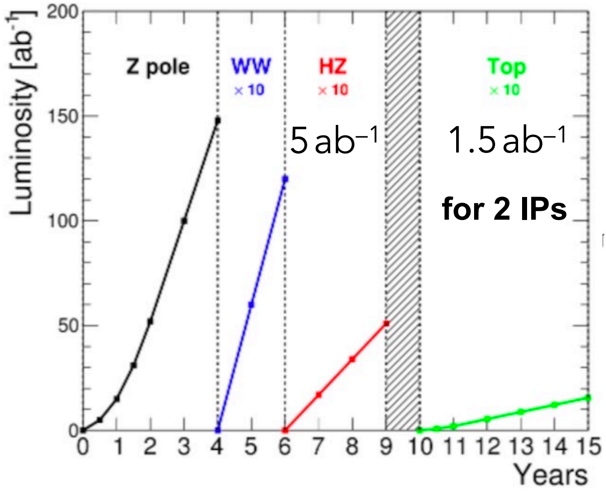
Hybrid Asymmetric Linear Higgs Factory (HALHF)

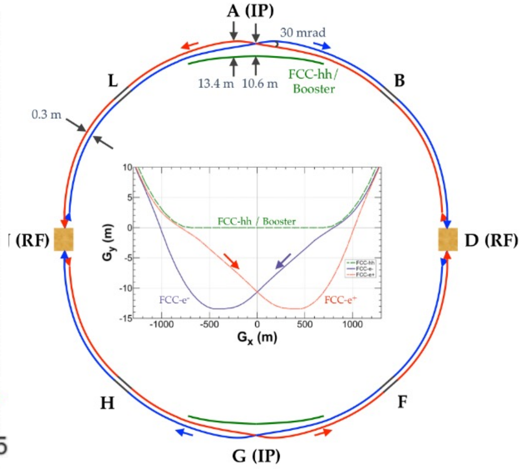
HALHF: 250 GeV (e^- 500GeV, e^+ 31GeV)
3.3km
25 MVm^{-1} conventional, 6.3GVm^{-1} plasma
Pre-CDR

Higgs factory contenders (2): Circular Colliders

Future Circular Collider (FCC-ee)

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

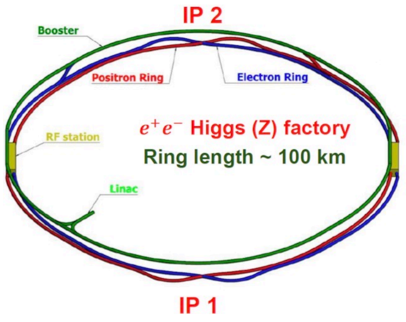




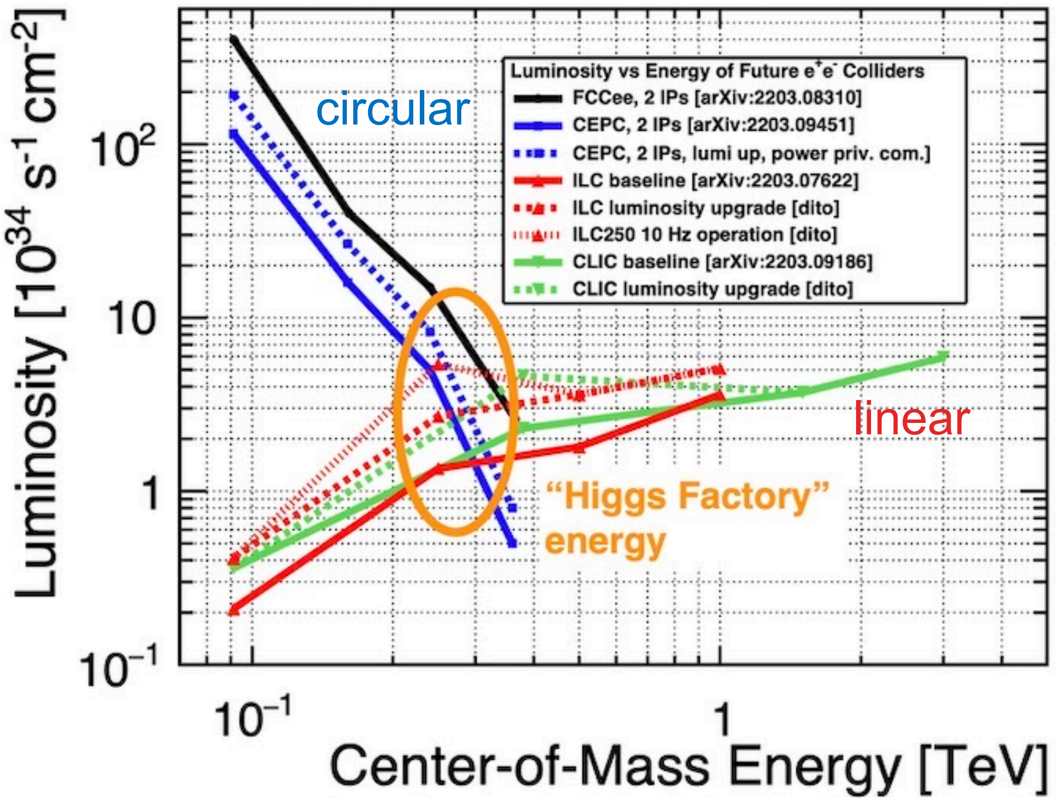
FCC: ~92km ring
FCCee CDR 2019
Accelerator technology mostly proven >50yr

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

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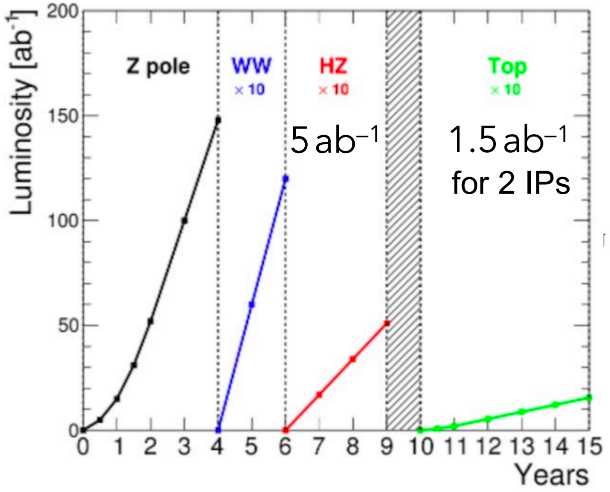

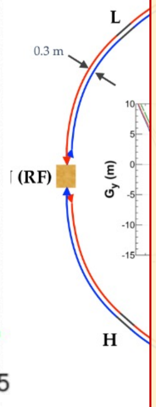

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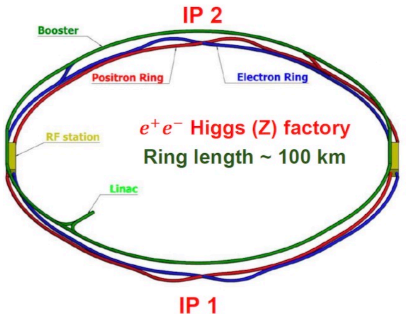

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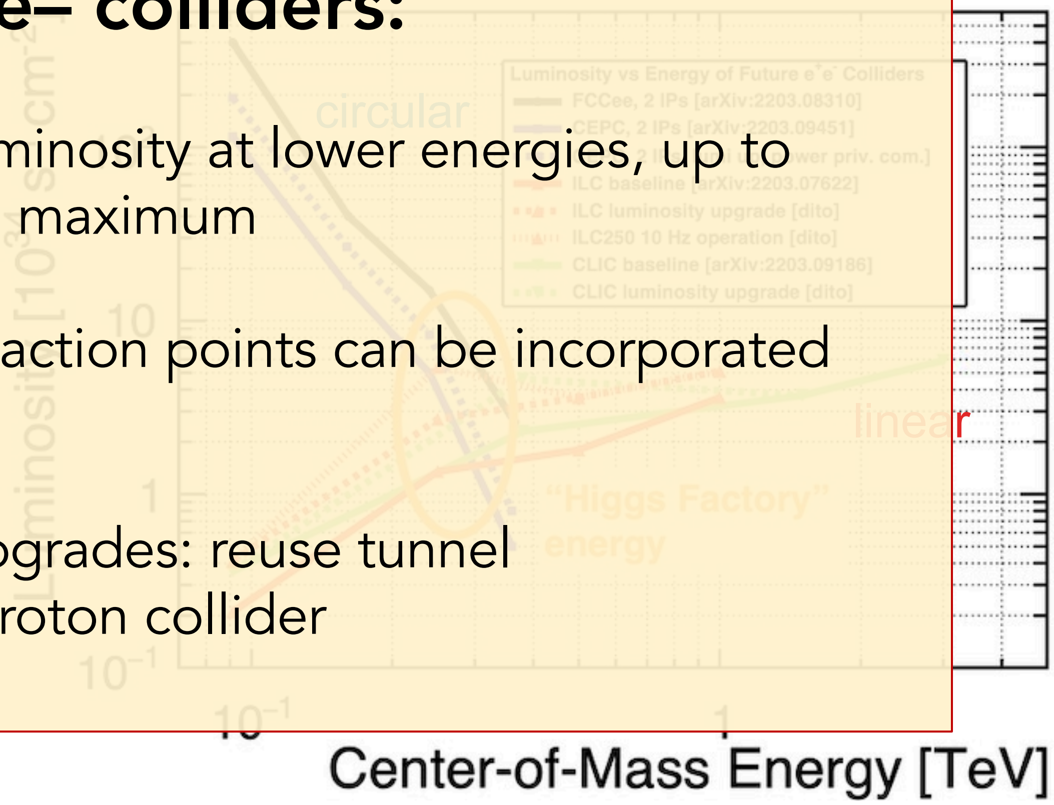

Best luminosity and power efficiency is at lower energies for circular machines; higher energies for linear machines

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

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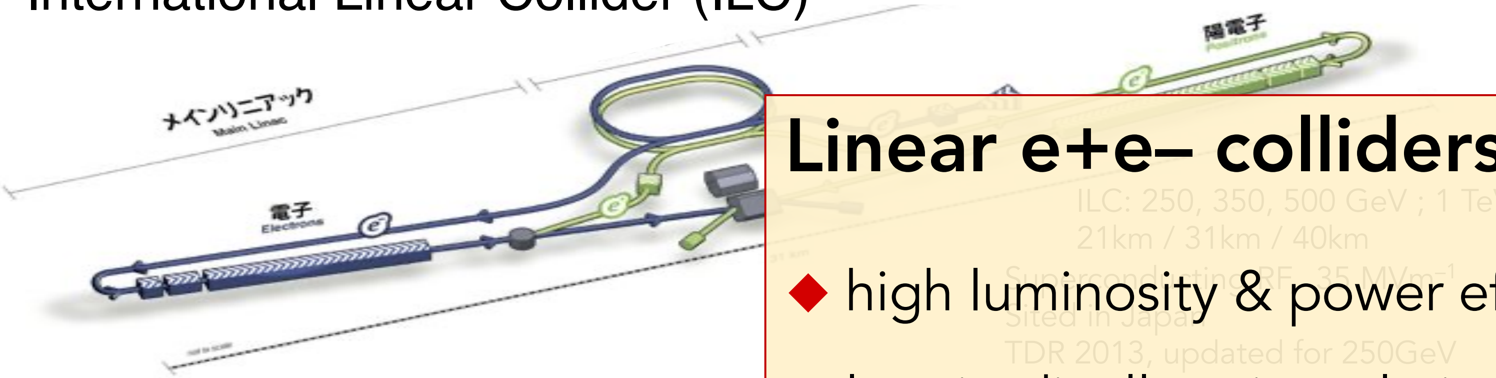
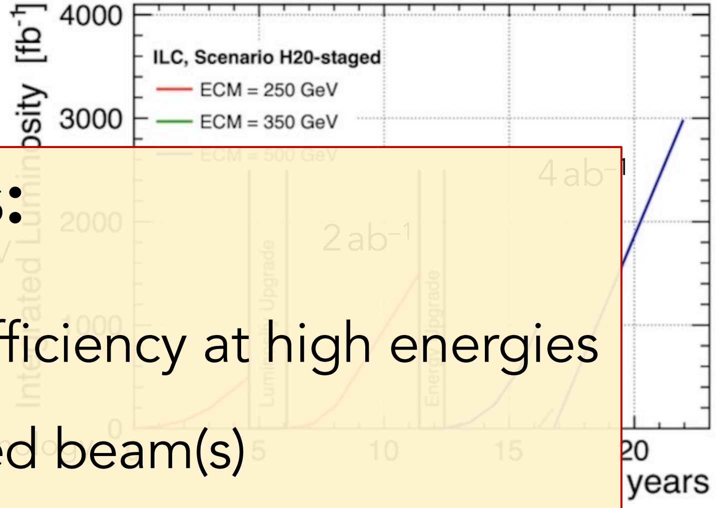
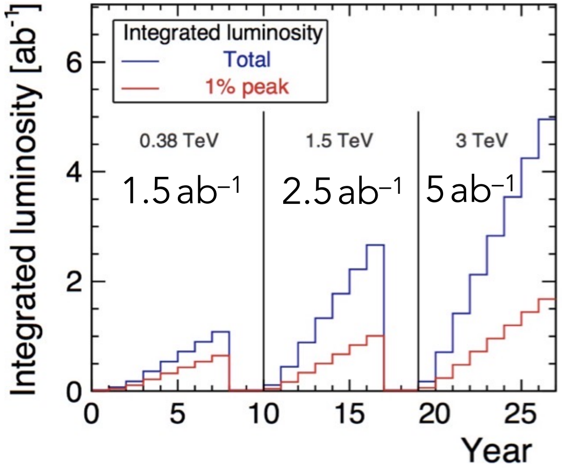


ILC: 250, 350, 500 GeV ; 1 TeV
21km / 31km / 40km
Superconducting RF, 35 MVm^{-1}
Sited in Japan
TDR 2013, updated for 250GeV



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?



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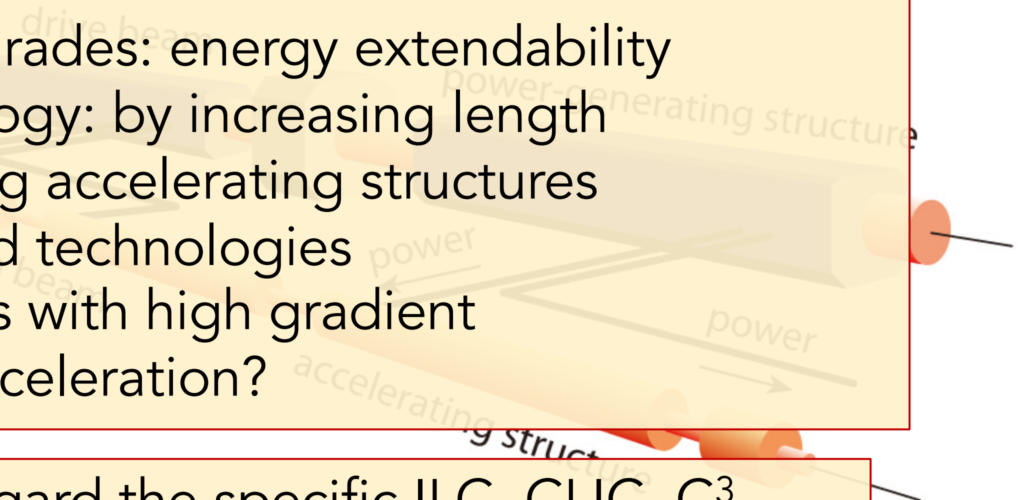


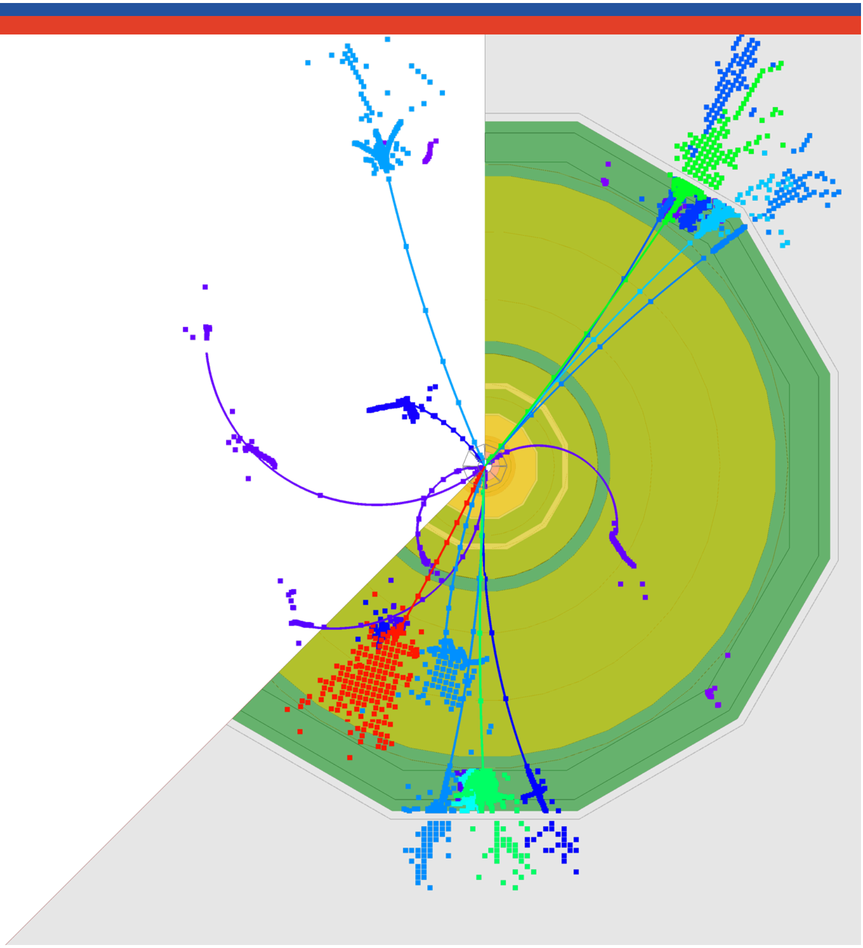
Cool Copper Collider (C^3)

◆ Important note: it's most useful to regard the specific ILC, CLIC, C^3 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. ILC-like machine at CERN; or CLIC-like machine at 250GeV elsewhere than CERN.

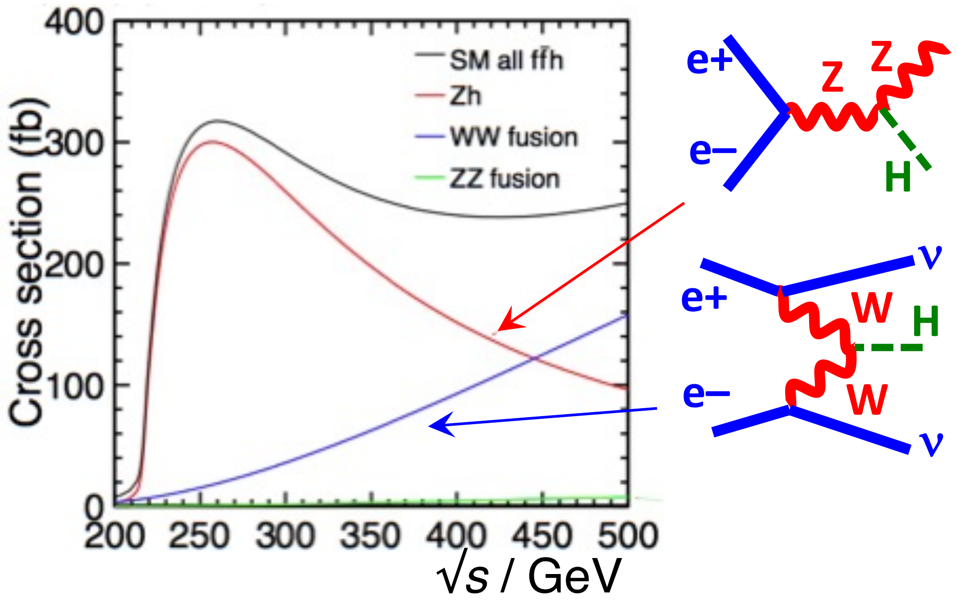
Hybrid Asymmetric Linear Higgs Factory (HALHF)

Pre-CDR

Higgs in e^+e^-



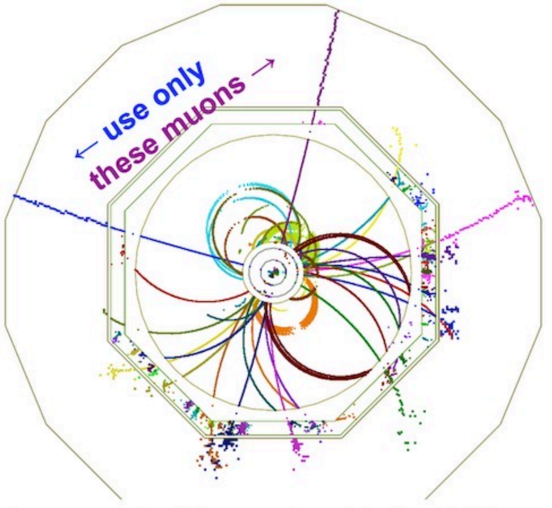
Higgs production in e^+e^-



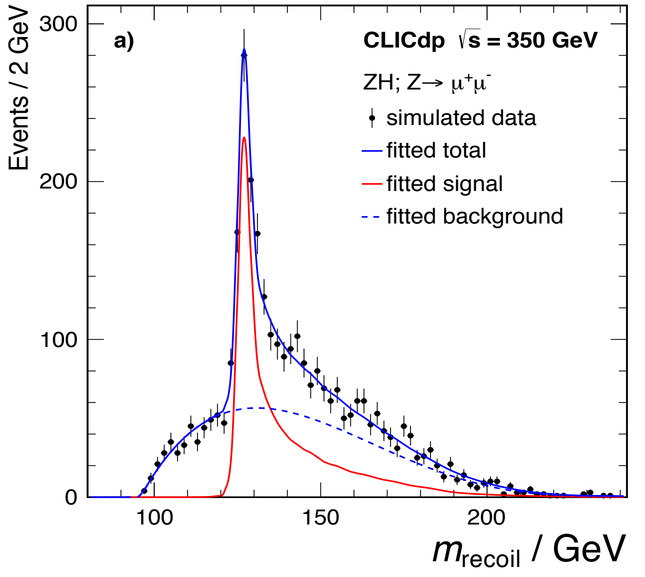
- ◆ ZH process allows reconstruction of H by looking exclusively at recoil of Z –> model-independent extraction of g_{HZZ} coupling

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

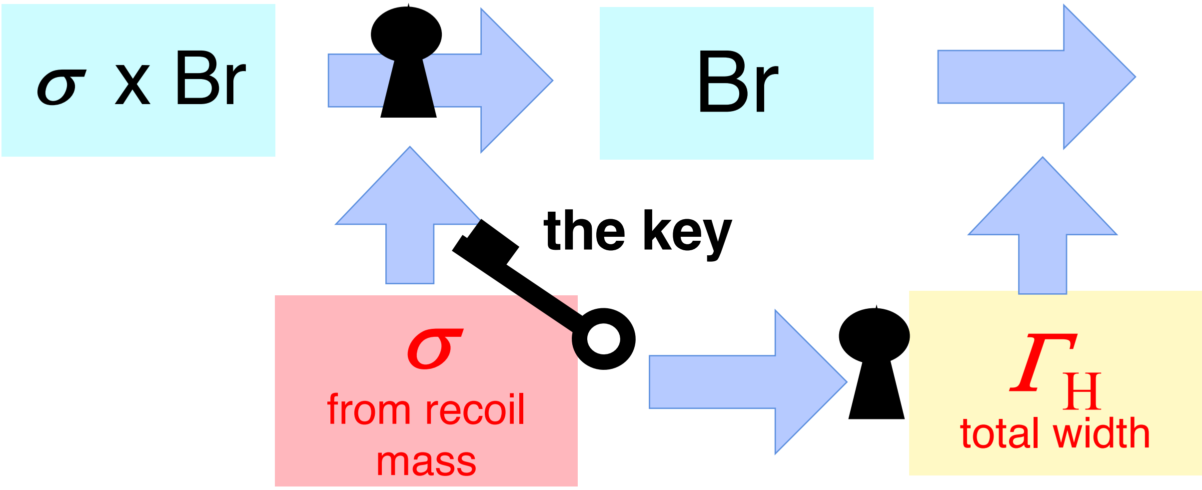
$$\frac{\sigma_{ZH}\,.\mathrm{Br}(H\text{->}bb)}{\sigma_{\nu\nu H}\,.\mathrm{Br}(H\text{->}bb)} \propto \frac{g^2_{HZZ}}{g^2_{HWW}}$$



$e^+e^- \rightarrow \mu^+\mu^- H \rightarrow \mu^+\mu^-$ 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

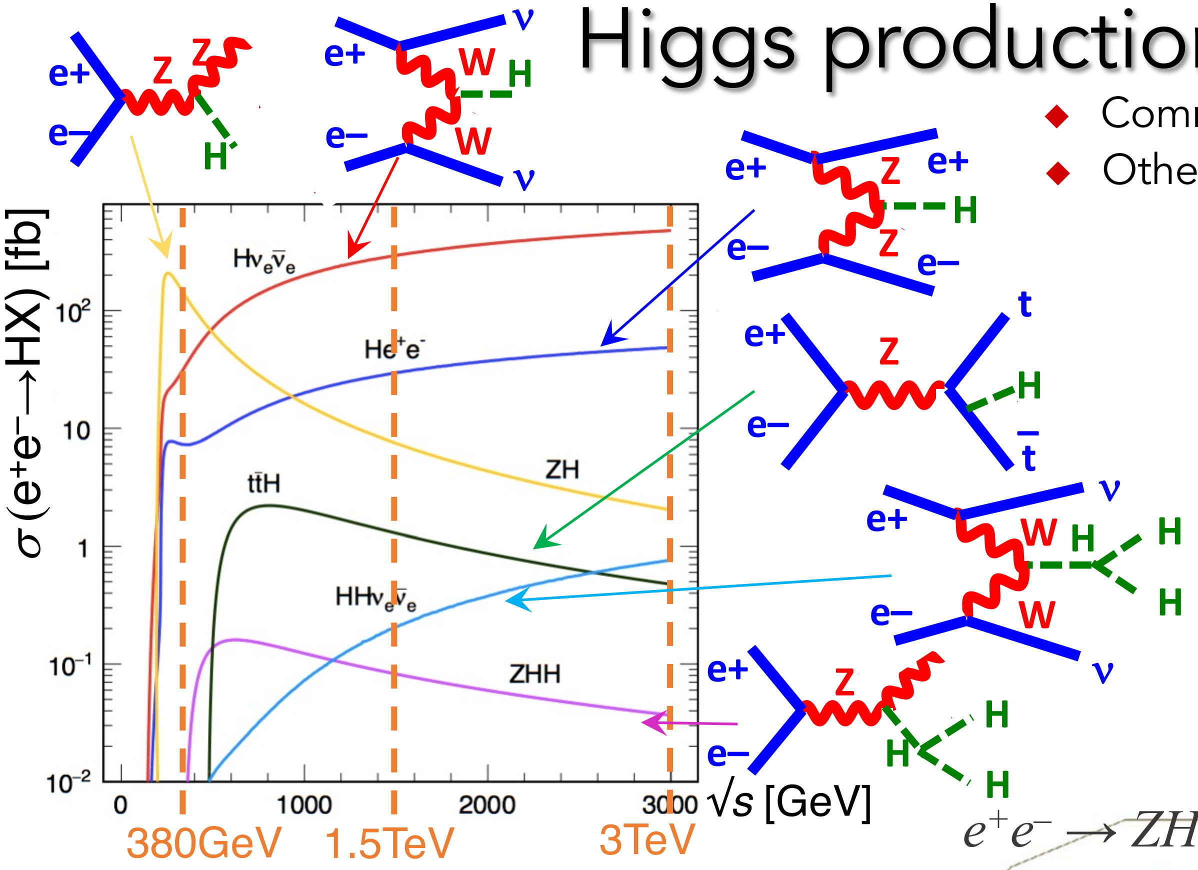
(need WW fusion for precision total width –> higher √s)

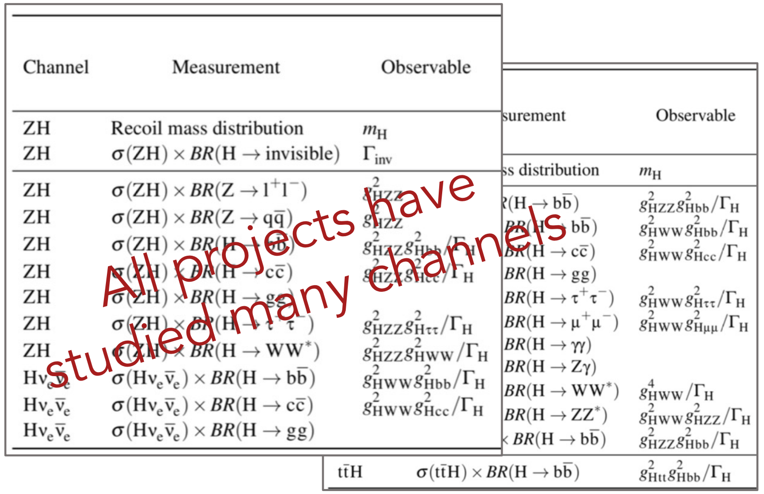
$$\sigma_{\nu\nu H}\,.\mathrm{Br}(H\text{->}WW) \propto g^4_{HWW}/\Gamma_H$$

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





Channel	Measurement	Observable
ZH	Recoil mass distribution	m_H
ZH	$\sigma(ZH) \times BR(H \to \text{invisible})$	Γ_{inv}
ZH	$\sigma(ZH) \times BR(Z \to l^+l^-)$	g^2_{HZZ}
ZH	$\sigma(ZH) \times BR(Z \to q\bar{q})$	g^2_{HZZ}
ZH	$\sigma(ZH) \times BR(H \to b\bar{b})$	$g^2_{HZZ}g^2_{Hbb}/\Gamma_H$
ZH	$\sigma(ZH) \times BR(H \to c\bar{c})$	$g^2_{HZZ}g^2_{Hcc}/\Gamma_H$
ZH	$\sigma(ZH) \times BR(H \to gg)$	
ZH	$\sigma(ZH) \times BR(H \to \tau^+\tau^-)$	$g^2_{HZZ}g^2_{H\tau\tau}/\Gamma_H$
ZH	$\sigma(ZH) \times BR(H \to WW^*)$	$g^2_{HZZ}g^2_{HWW}/\Gamma_H$
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to b\bar{b})$	$g^2_{HWW}g^2_{Hbb}/\Gamma_H$
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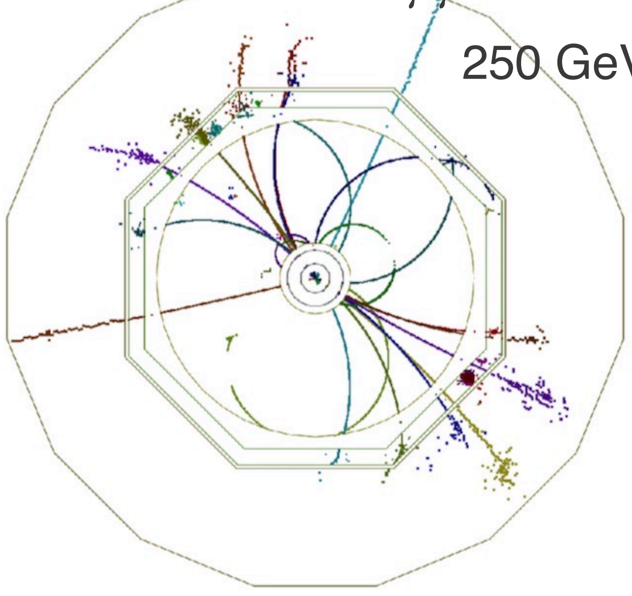
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to gg)$	

	surement	Observable
	ss distribution	m_H
	$(H \to b\bar{b})$	$g^2_{HZZ}g^2_{Hbb}/\Gamma_H$
	$BR(H \to b\bar{b})$	$g^2_{HWW}g^2_{Hbb}/\Gamma_H$
	$BR(H \to c\bar{c})$	$g^2_{HWW}g^2_{Hcc}/\Gamma_H$
	$BR(H \to gg)$	
	$BR(H \to \tau^+\tau^-)$	$g^2_{HWW}g^2_{H\tau\tau}/\Gamma_H$
	$BR(H \to \mu^+\mu^-)$	$g^2_{HWW}g^2_{H\mu\mu}/\Gamma_H$
	$BR(H \to \gamma\gamma)$	
	$BR(H \to Z\gamma)$	
	$BR(H \to WW^*)$	g^4_{HWW}/Γ_H
	$BR(H \to ZZ^*)$	$g^2_{HWW}g^2_{HZZ}/\Gamma_H$
	$\times BR(H \to b\bar{b})$	$g^2_{HZZ}g^2_{Hbb}/\Gamma_H$
$t\bar{t}H$	$\sigma(t\bar{t}H) \times BR(H \to b\bar{b})$	$g^2_{Htt}g^2_{Hbb}/\Gamma_H$

All projects have studied many channels

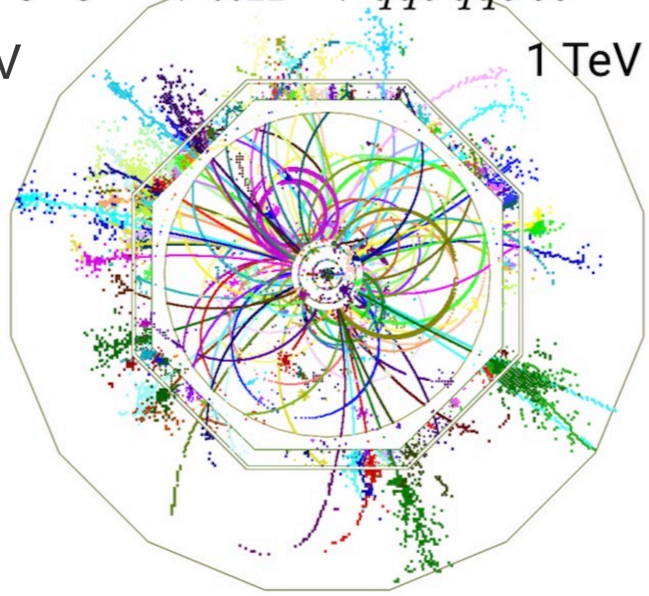
- ◆ ILC & CLIC: analyses in full GEANT simulation with beam backgrounds overlaid

$e^+e^- \to ZH \to \mu\mu bb$



250 GeV

$e^+e^- \to ttH \to q\bar{q}b\,q\bar{q}\bar{b}\,b\bar{b}$



1 TeV

- ◆ Experimental environment relatively 'clean' (consider VBF production, where Higgs decay is the only visible product)
- ◆ 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

Higgs couplings sensitivity

Standard Model

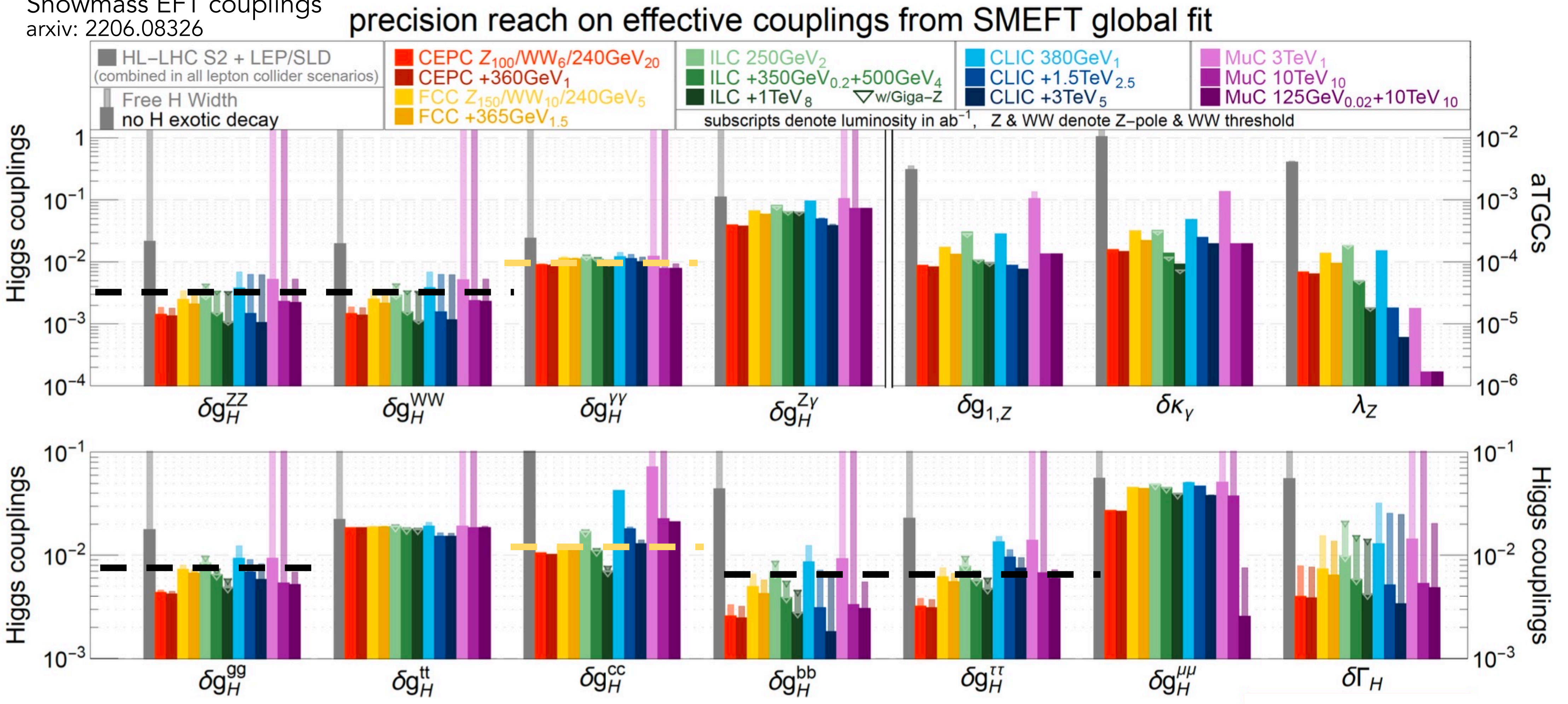
Dim-6 operators

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

Scale of new decoupled physics

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

Snowmass EFT couplings
arxiv: 2206.08326



◆ 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

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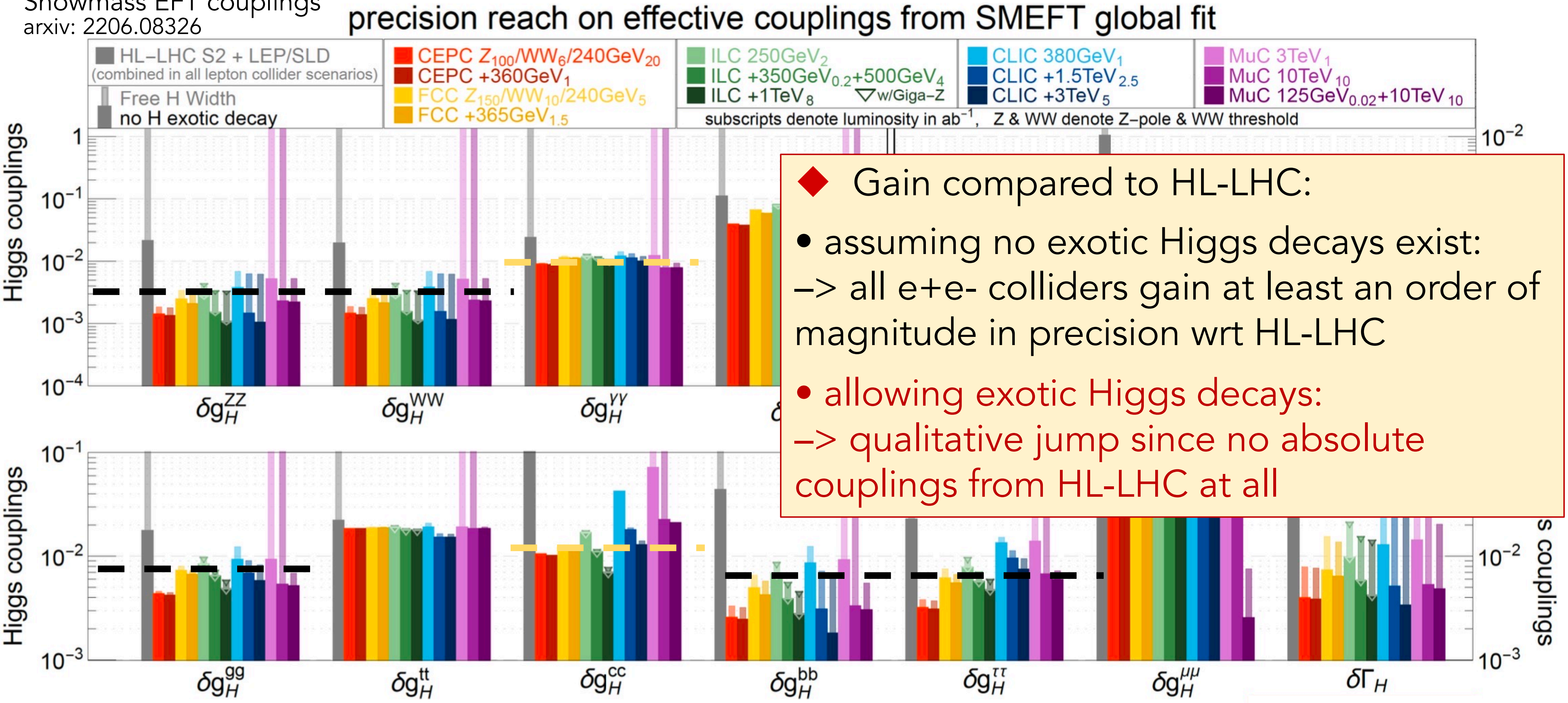


- Gain compared to HL-LHC:
  - assuming no exotic Higgs decays exist: –> all e+e- colliders gain at least an order of magnitude in precision wrt HL-LHC
  - allowing exotic Higgs decays: –> qualitative jump since no absolute couplings from HL-LHC at all

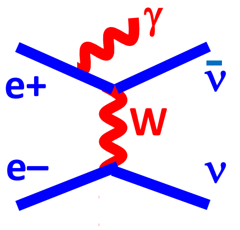
- all e+e- colliders show very comparable performance for standard Higgs program despite quite different assumed integrated luminosities
  - several couplings at few-0.1% level: Z, W, g, b, τ
  - some more at ~1%: γ, c

Polarisation

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

Background suppression:

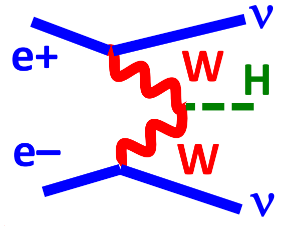
◆ e^+e^- -> WW / $\nu_e\nu_e$ strongly parity-dependent since *t*-channel only for $e^-_L e^+_R$



Signal enhancement:

◆ Many processes have strong polarisation dependence, e.g.:
- Higgs production in WW-fusion
- many BSM processes

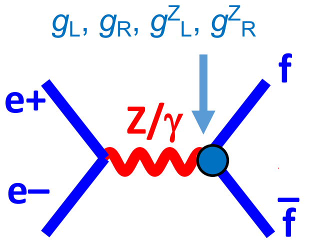
=> polarisation can give higher S/B



Chiral analysis:

◆ SM: Z and g differ in couplings to left- and right-handed fermions

◆ BSM: chiral structure unknown; needs to be determined



Redundancy & control of systematics:

◆ 'wrong' polarisation yields 'signal-free' control sample

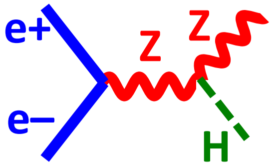
◆ flipping positron polarisation can control nuisance effects on observables relying on electron polarisation

–> ideally want to be able to reverse helicity quickly for both beams

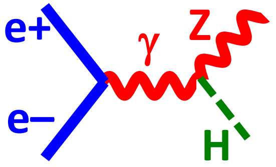
◆ many physics benefits from beam polarisation

Polarisation

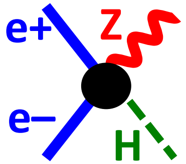
- Higgsstrahlung e+e– -> ZH is the key process at a Higgs factory
- A_{LR} of Higgsstrahlung helps to disentangle different SMEFT operators



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

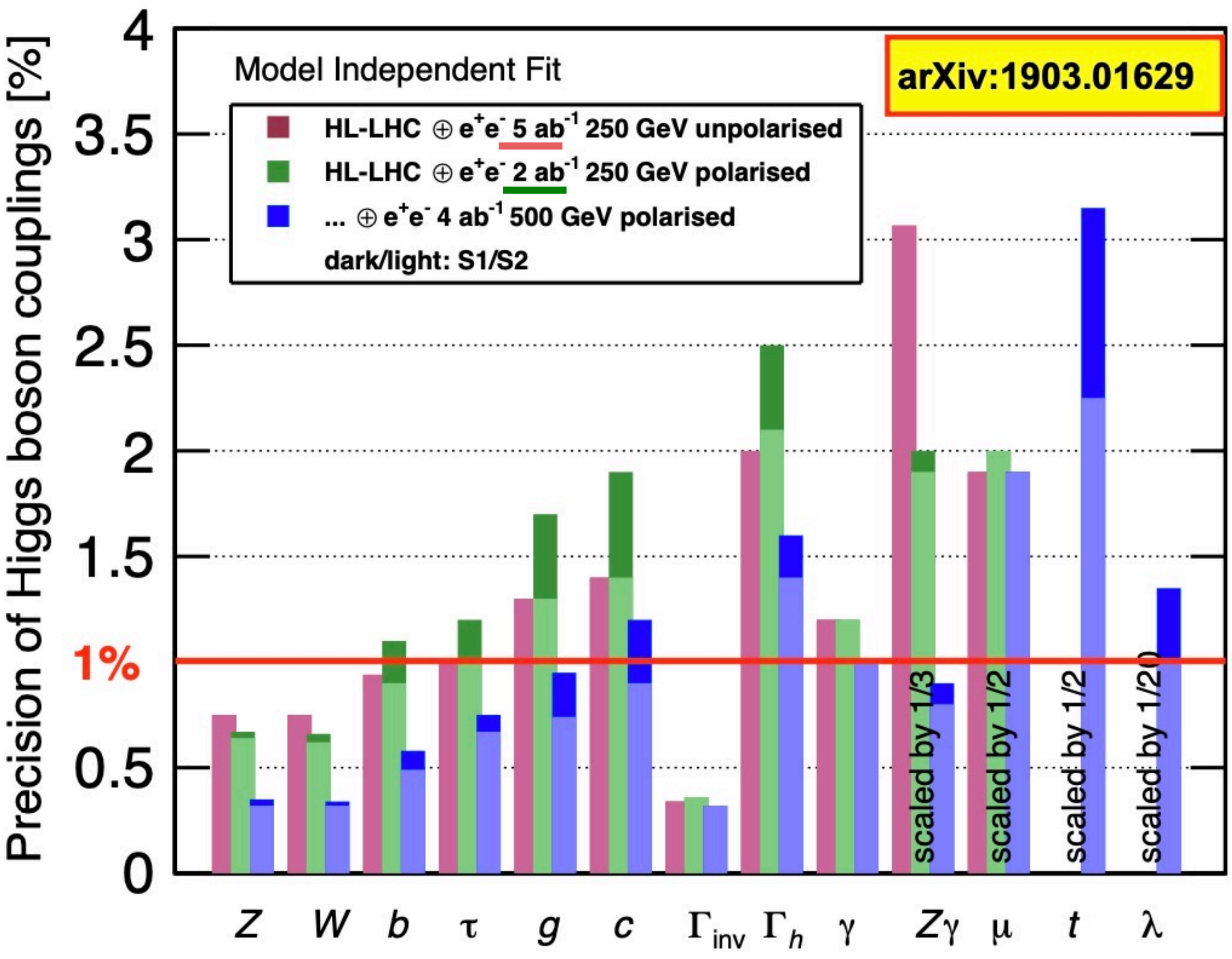


$\sim c_{WW}$
Keeps sign under spin reversal $e_R \leftrightarrow e_L$



Constrained by EWPOs

A_{LR} lifts degeneracy between operators



- **$2\ \mathrm{ab}^{-1}$ polarised** ≈ **$5\ \mathrm{ab}^{-1}$ unpolarised**
  => the reason all e+e- Higgs factories perform so similarly!

Higgs couplings sensitivity

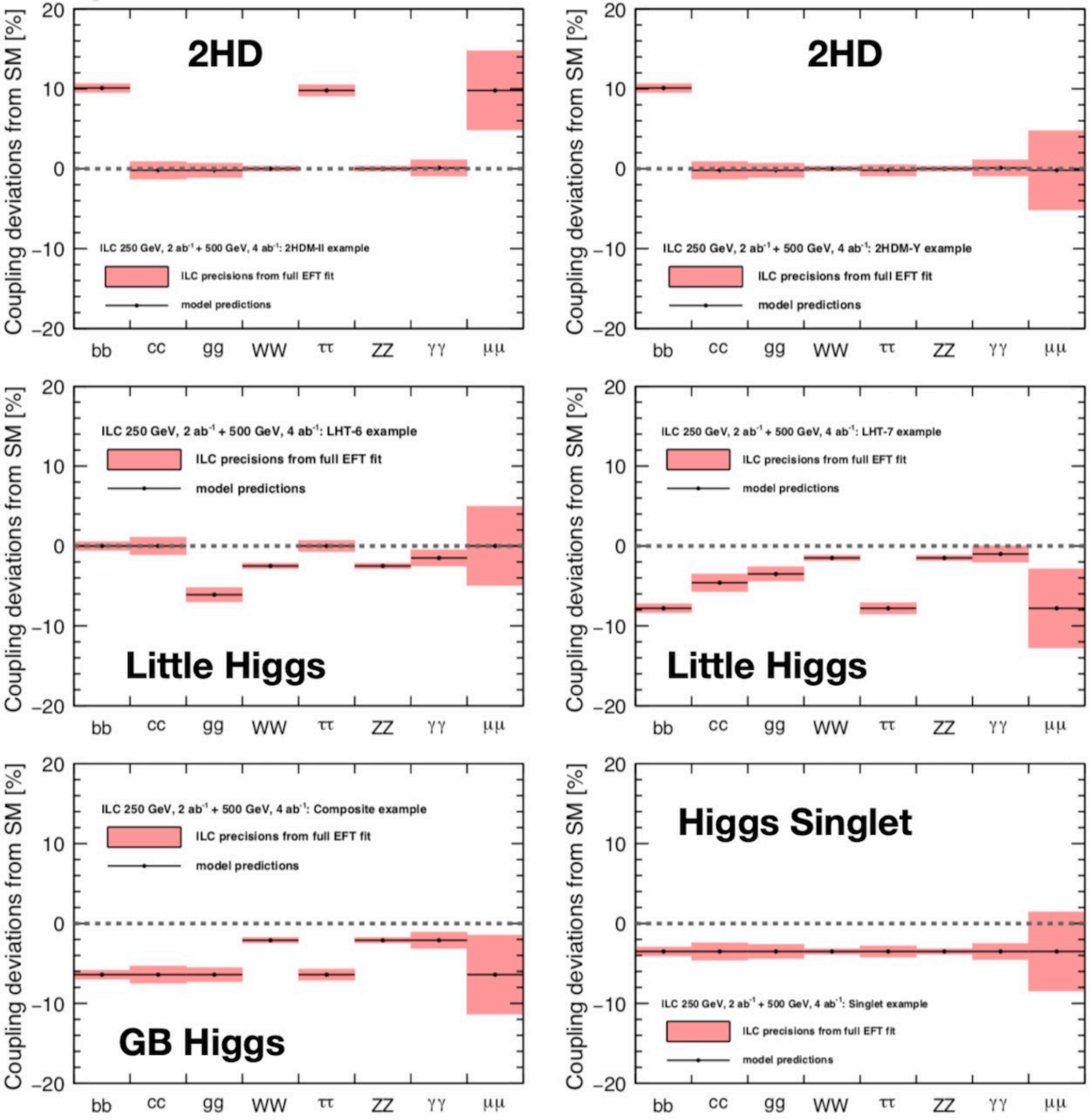
- Aim of precision Higgs measurements is to ***discover violation of the SM***

- Complementary to direct searches at LHC – these are examples with large coupling deviations due to new particles that are out of reach of HL-LHC, shown [just as an example] with projected ILC precisions at 500GeV

(Barklow et al. 1708.08912)

- A pattern of well-established deviations can point to a common origin

- Typical models give coupling deviations at 1% level; **e+e– factories can reach this sensitivity**

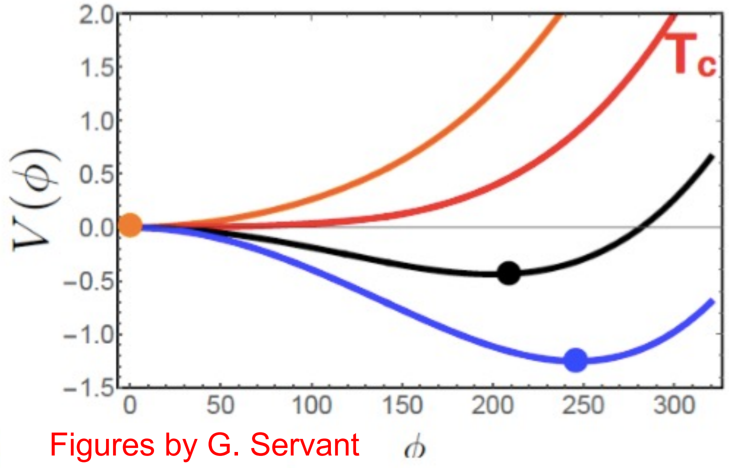


Barklow/Peskin

Higgs self-coupling

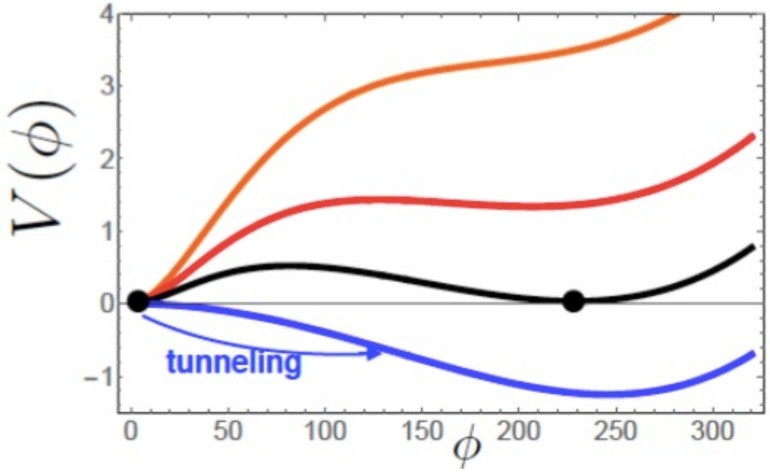
- The Higgs self-coupling gives access to the shape of the Higgs potential

Standard Model:

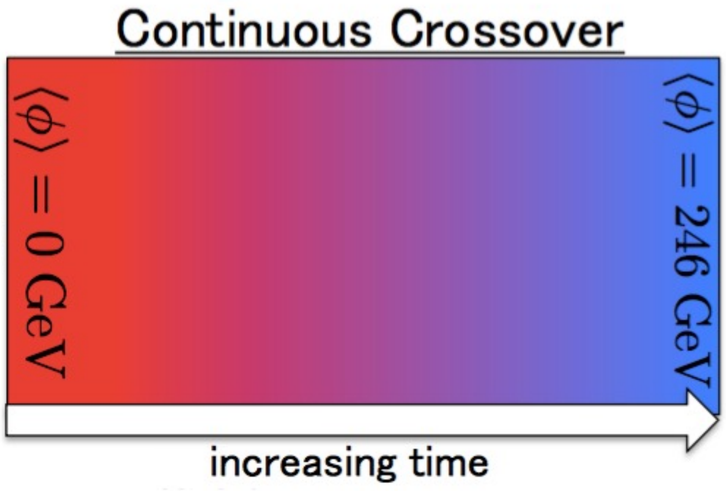


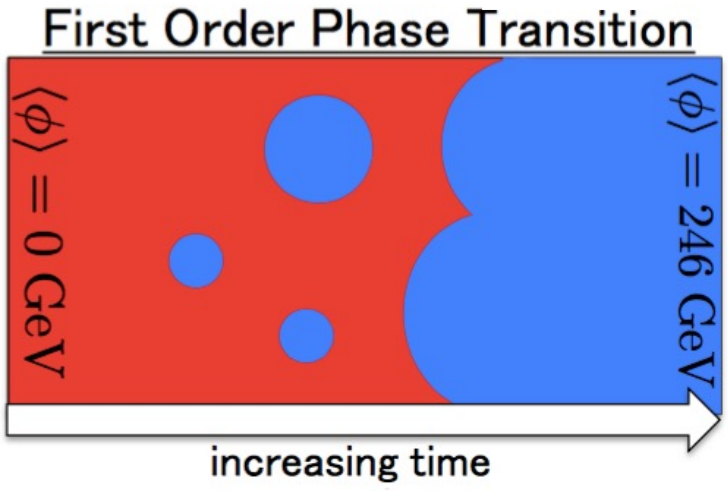
Figures by G. Servant

Possible alternative:



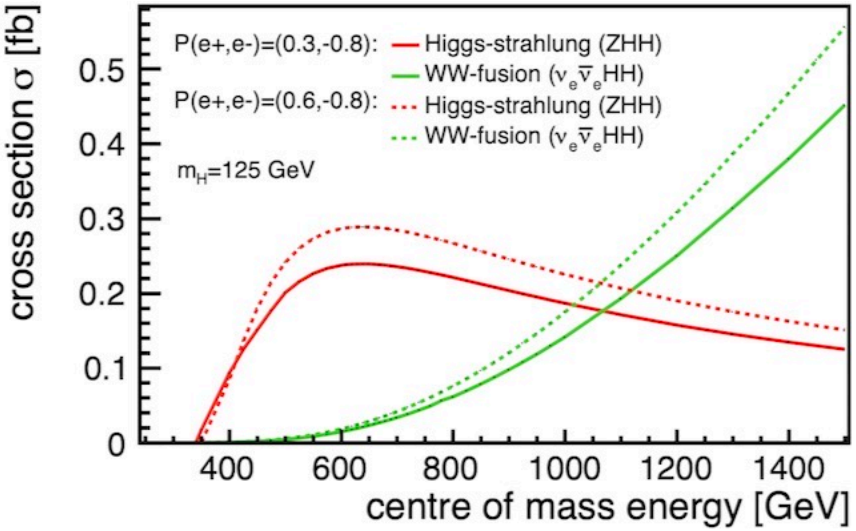
In this case, two phases can coexist:

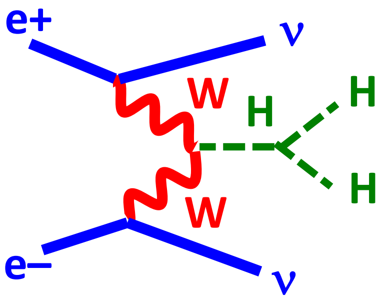


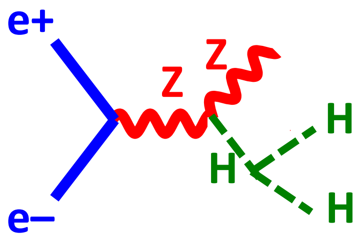


–> electroweak baryogenesis possible

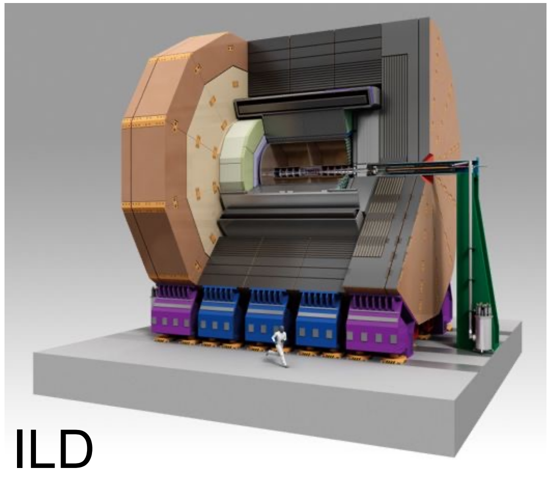
Higgs self-coupling: 0.5–1TeV

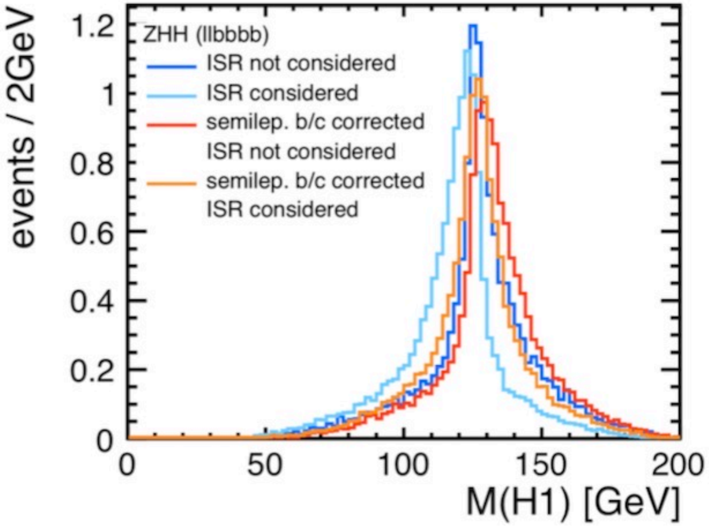




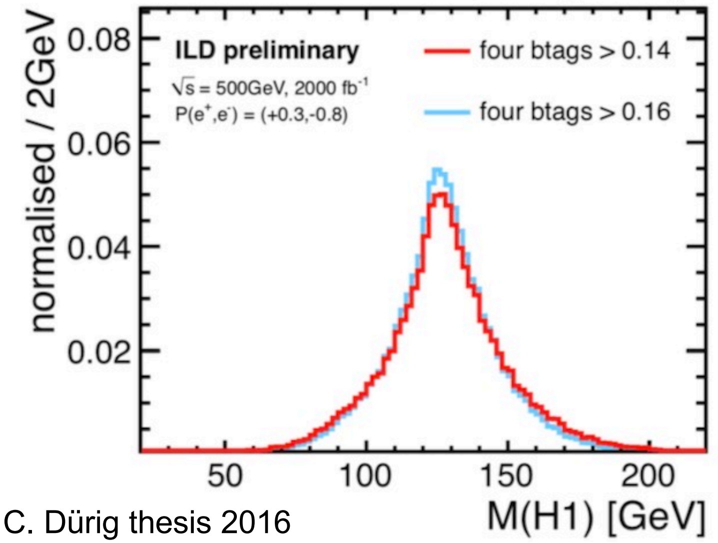


- ◆ Two contributing direct production mechanisms: ZHH and ννHH
- ◆ ZHH becomes available at ILC 500 – studied in full sim with ILD detector Z->ll / Z->qq, HH->bbbb /HH->bbWW*
- ◆ If self-coupling λ is at SM value then double-Higgs process observable at 8σ, with 27% precision on λ
- ◆ Adding ννHH at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





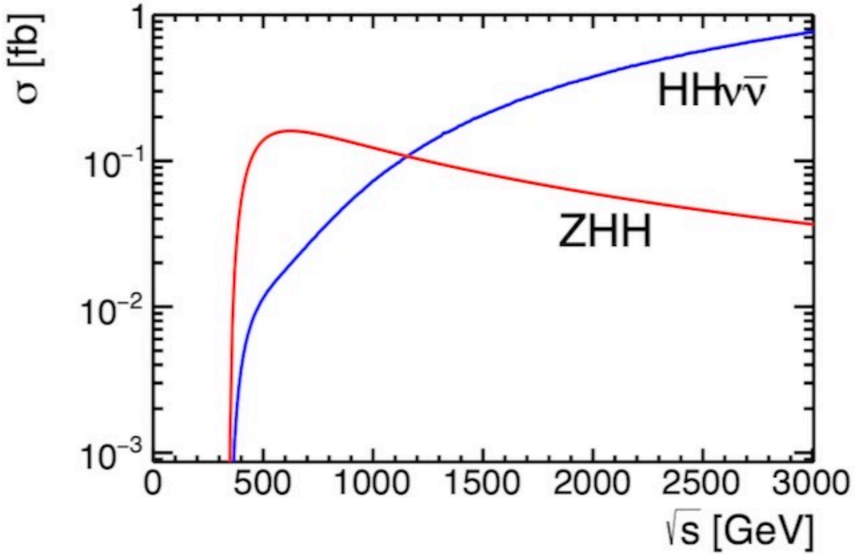
ZHH → qqHH analysis



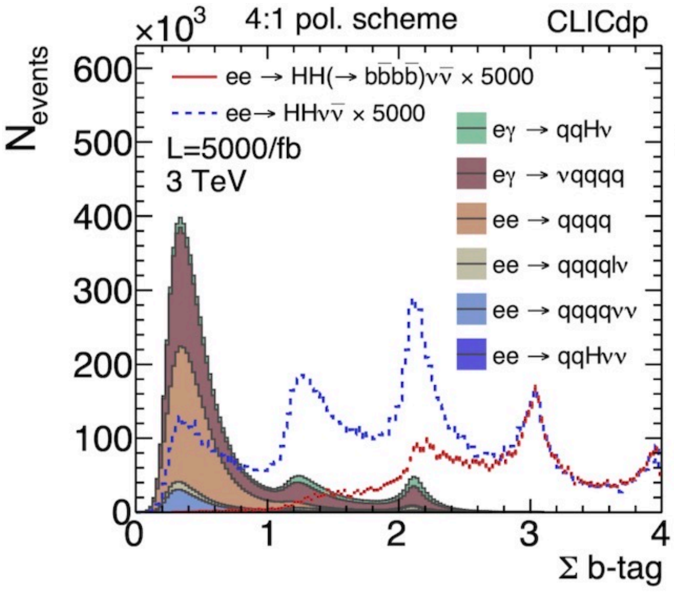
C. Dürig thesis 2016

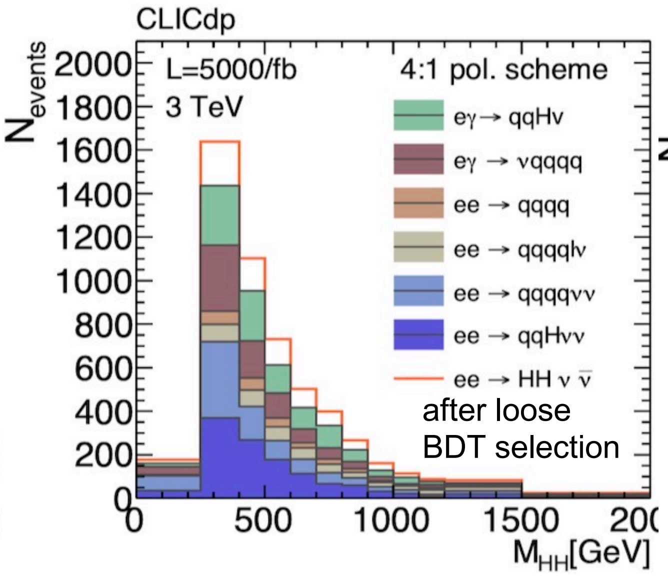
- ◆ used state-of-the-art reconstruction at the time (2016), but sensitivity very dependent on b-tagging performance, dijet mass resolution –> update is ongoing

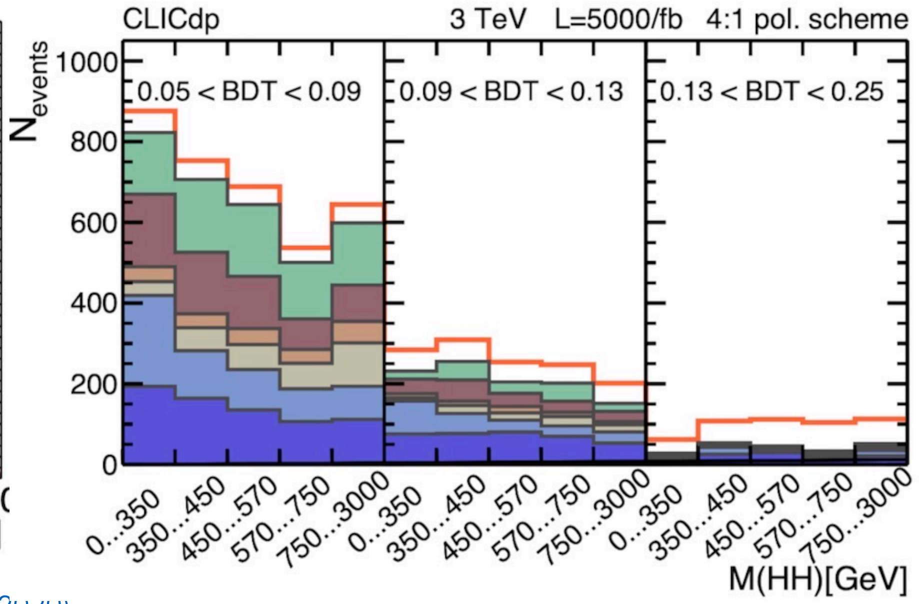
Higgs self-coupling: >1TeV



- νν̄HH dominates at both CLIC TeV stages
- studied in full sim with all processes & beam backgrounds using HH->bbbb /HH->bbWW* (all-hadronic)
- Σb-tag (trained on e^+e^- -> Zνν) used to separate bbbb and bbWW* channels
- main backgrounds: diboson and ZH production
- BDTs trained for 4-jet and 6-jet topologies
- 3.5σ observation, and 28% precision on σ, at 1.4TeV 7.3% precision on σ at 3TeV (and observation with 700fb^{-1})
- λ/λ_{SM} extracted from template fit to binned M_{HH} in bins of BDT response

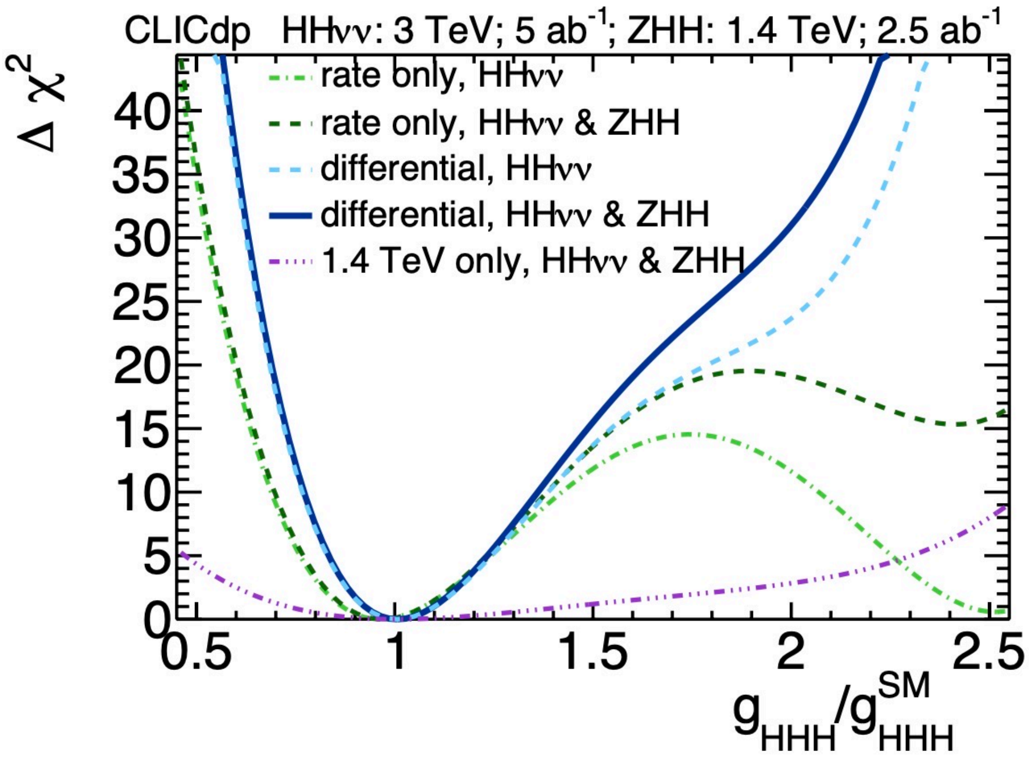


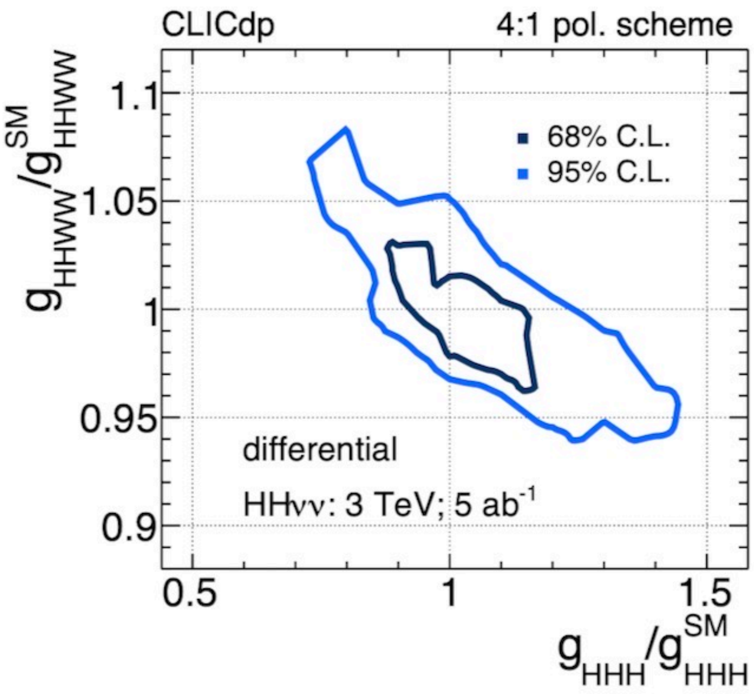




Eur. Phys. J. C 80, 1010 (2020)

Higgs self-coupling: >1TeV





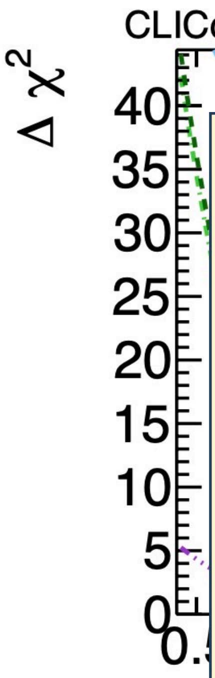
- at 1.4TeV rate-only analysis gives relative uncertainties –29% and +67% around SM value of g_{HHH}
- 3TeV differential measurement gives –8% and +11% assuming SM g_{HHWW}
- simultaneous measurement of triple and quartic couplings gives constraints below 4% in g_{HHWW} and below 20% in g_{HHH} for large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

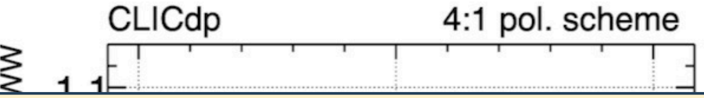
	1.4TeV	3TeV
$\sigma(HH\nu_e\bar{\nu}_e)$	>3σ EVIDENCE $\frac{\Delta\sigma}{\sigma}$ = 28%	>5σ OBSERVATION $\frac{\Delta\sigma}{\sigma}$ = 7.3%
σ(ZHH)	3.3σ EVIDENCE	2.4σ EVIDENCE
g_{HHH}/g^{SM}_{HHH}	1.4TeV: –29%, +67% rate-only analysis	1.4 + 3TeV: **–8%, +11%** differential analysis

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

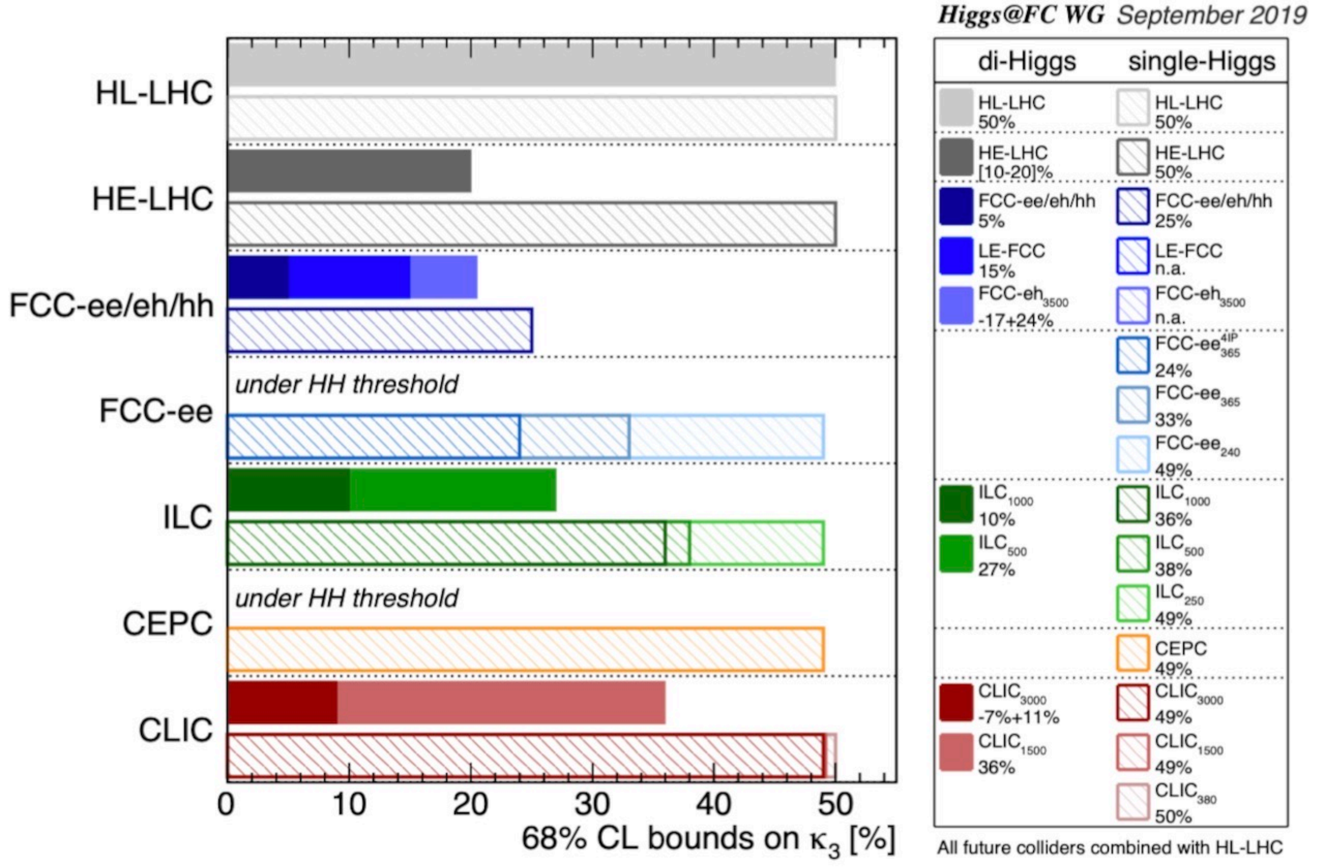
Higgs self-coupling: >1TeV

CLICdp HHνν: 3 TeV; 5 ab^{-1}; ZHH: 1.4 TeV; 2.5 ab^{-1}





–> 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

- at 1.4
uncertai
value of
- 3TeV
–8% and
- simul
quartic c
4% in g_{HHWW} and below 20% in g_{HHH} for large modifications of g_{HHWW}

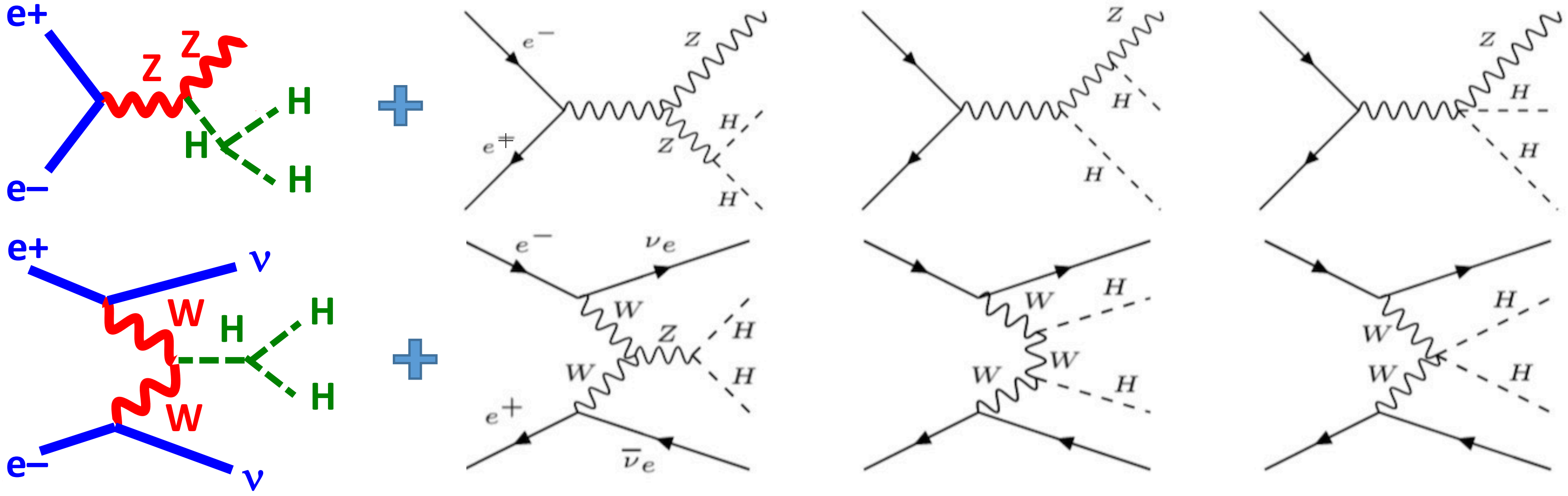
ON

rate-only analysis | differential analysis

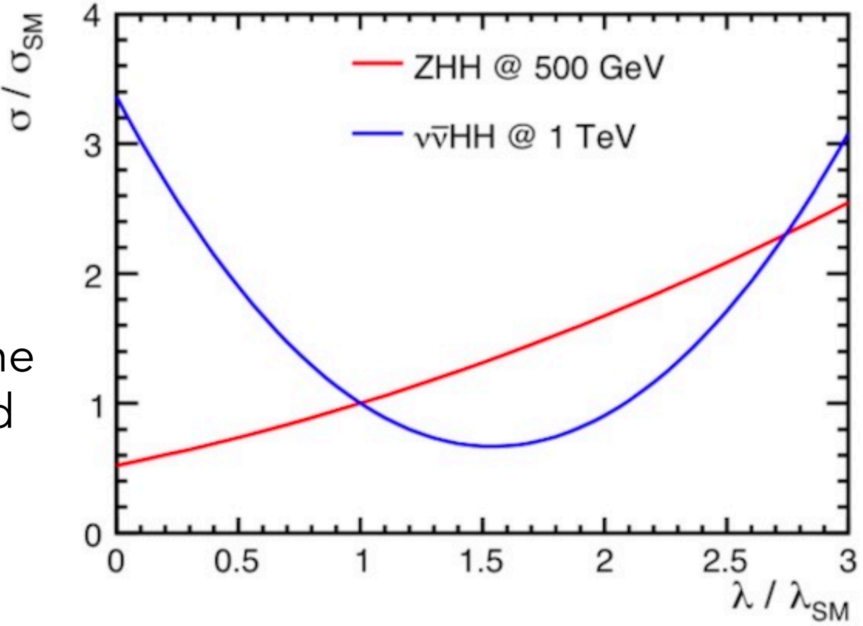
Eur. Phys. J. C 80, 1010 (2020)

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

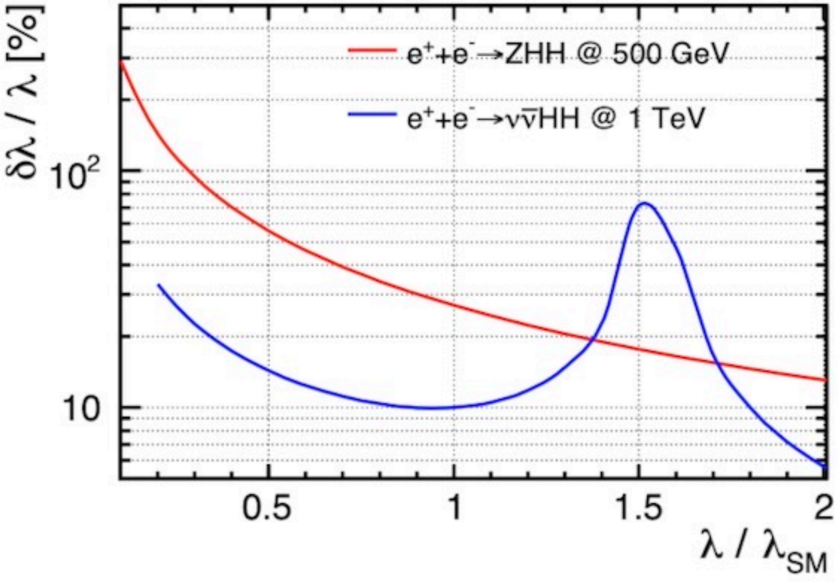


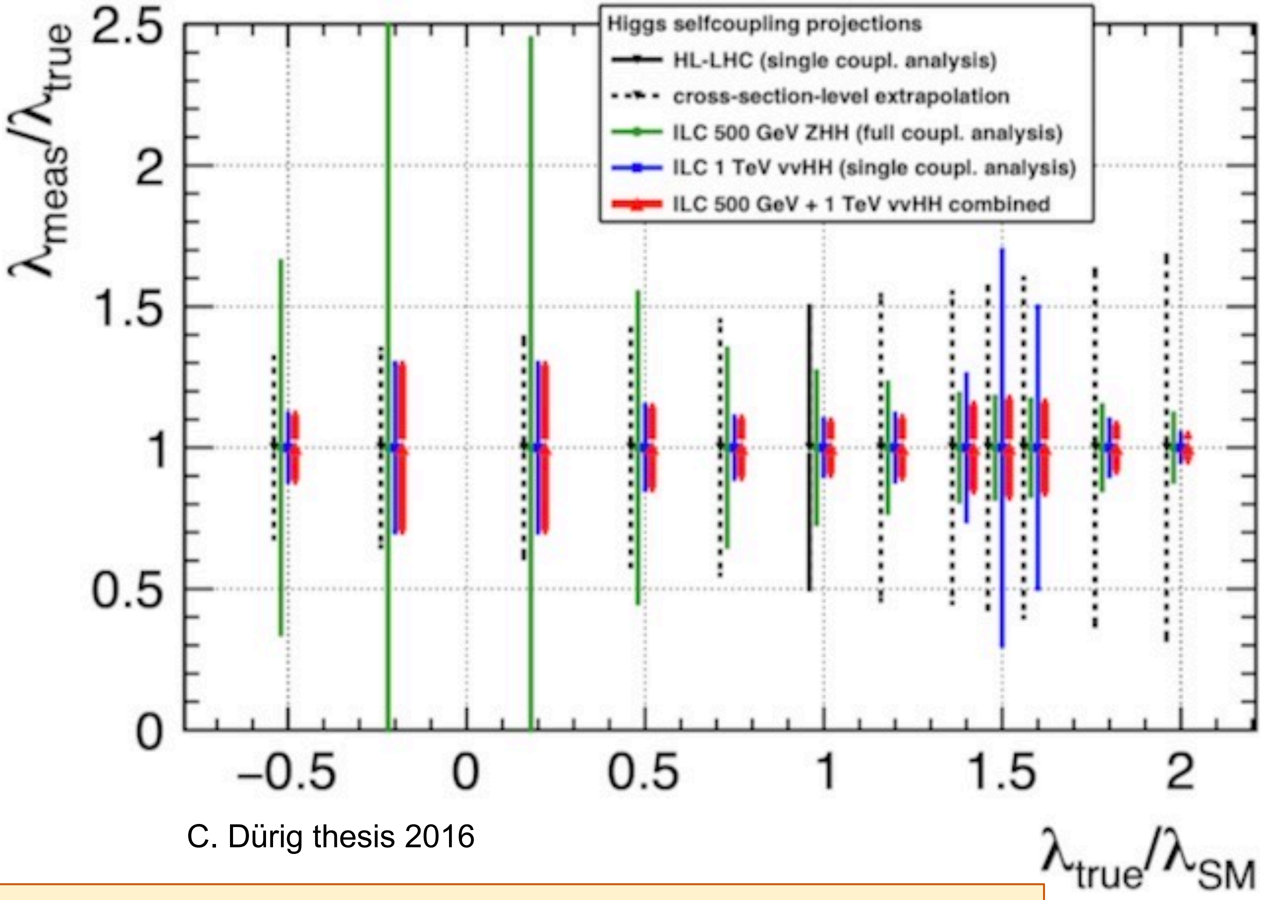
- Self-coupling diagram interferes constructively in ZHH and destructively in ννHH – whatever the sign of the deviation of κ_λ from 1, one of the processes will have an increased cross-section (and increased statistical sensitivity)



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

- Full simulation results from $\sqrt{s}$=500 GeV and 1TeV extrapolated to other energies, accounting for total cross-sections and interference contributions
- -> converted into precision on λ at highly enhanced or suppressed values



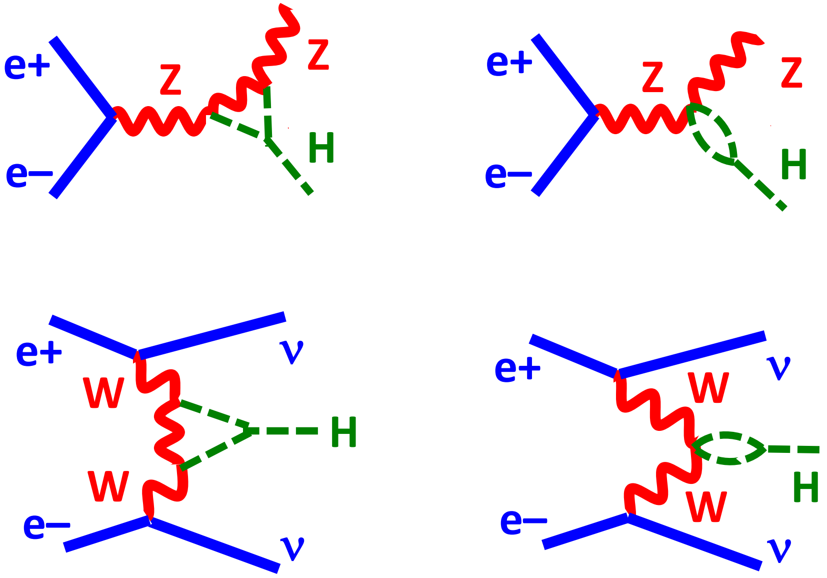


C. Dürig thesis 2016

- 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***
- 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 $1.5 \lesssim \lambda/\lambda_{SM} \lesssim 2.5$

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. $(\kappa_\lambda-1)=1$ increases $\sigma(e^+e^- \rightarrow ZH)$ by around 1.5% at $\sqrt{s}=240$GeV
- 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



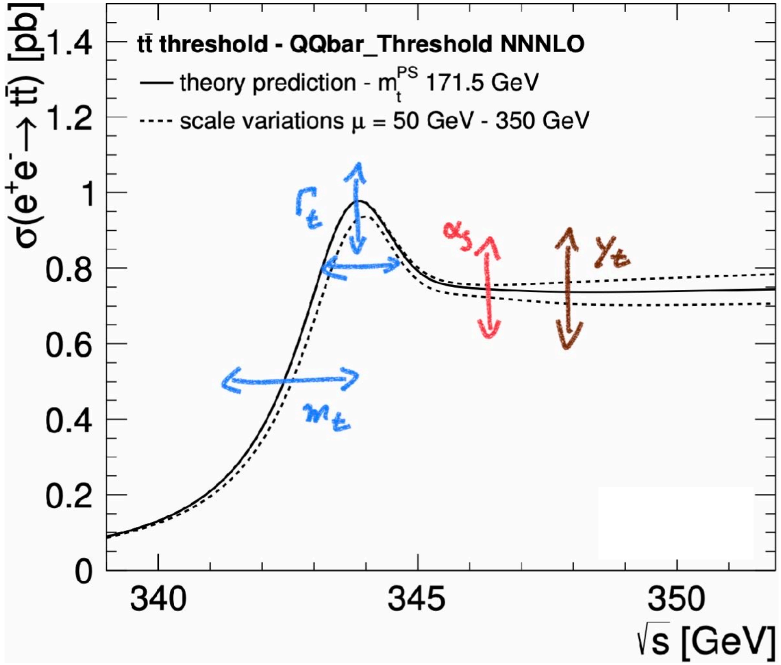
collider	1-parameter	full SMEFT
CEPC 240	18%	-
FCC-ee 240	21%	-
FCC-ee 240/365	21%	44%
FCC-ee (4IP)	15%	27%
ILC 250	36%	-
ILC 250/500	32%	58%
ILC 250/500/1000	29%	52%
CLIC 380	117%	-
CLIC 380/1500	72%	-
CLIC 380/1500/3000	49%	-

Higgs@Future Colliders 1905.03764 “-” means fit does not close

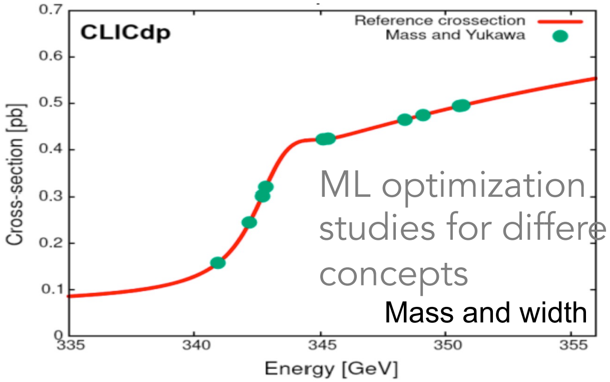
- However, generic new physics tends to give deviations of the same size in several Higgs couplings so a fit to a larger model is needed and in this case contributions from λ (c_6) are highly suppressed
- need runs at several energies to disentangle –> 27% at FCC-ee (4IP)
- there are ideas for addressing this at 240GeV by separating observables by their *Q*-values
- very interesting to see how far this can go

Top-quark physics

- ◆ Threshold scan – proposed by all projects



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

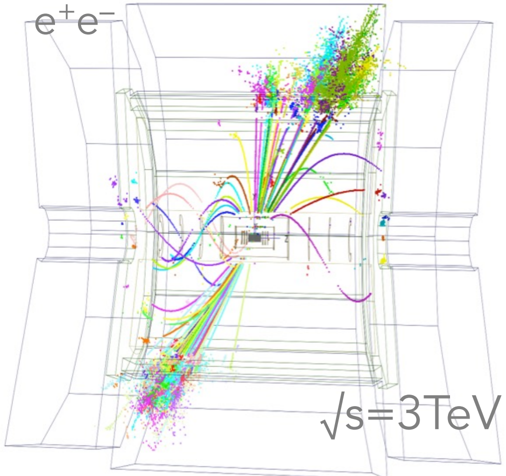


ML optimization studies for different concepts

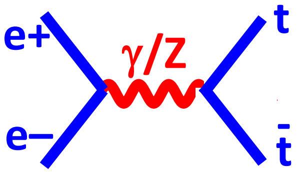
- ◆ Pair-production – benefits from higher √s and multiple stages

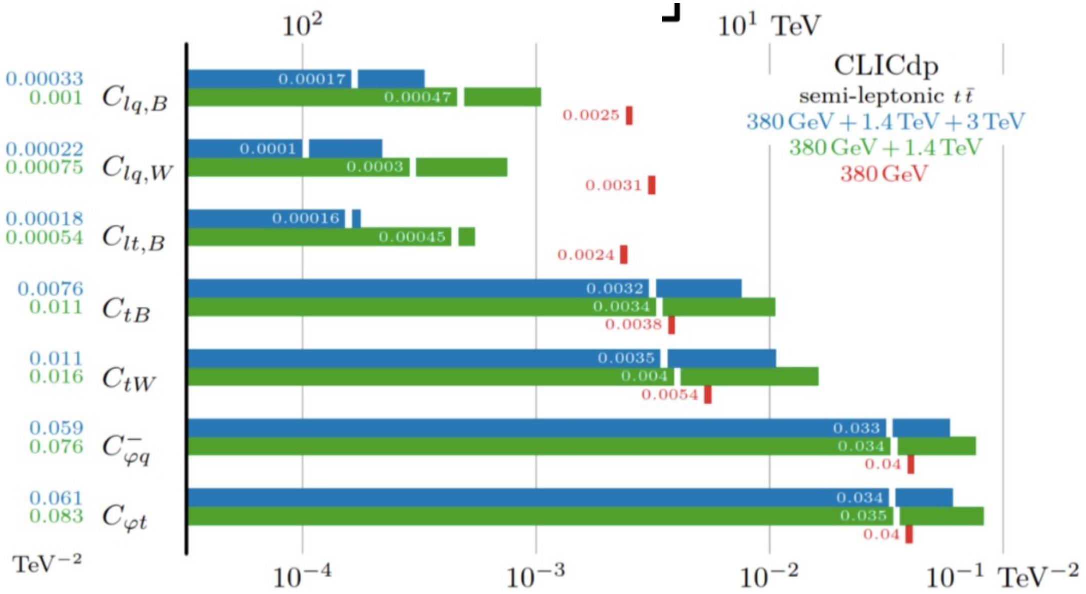
- ◆ Top cross-sections, both polarisations
- ◆ Top forward-backward asymmetries
- ◆ Statistically optimal observables for top EWK couplings; more than one energy stage allows global fit

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



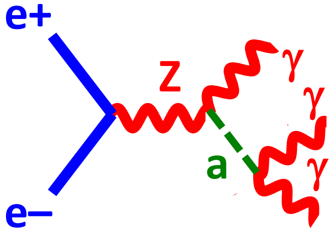
$e^+e^- \to t\bar{t} \to q\bar{q}q\bar{q}b\bar{b}$

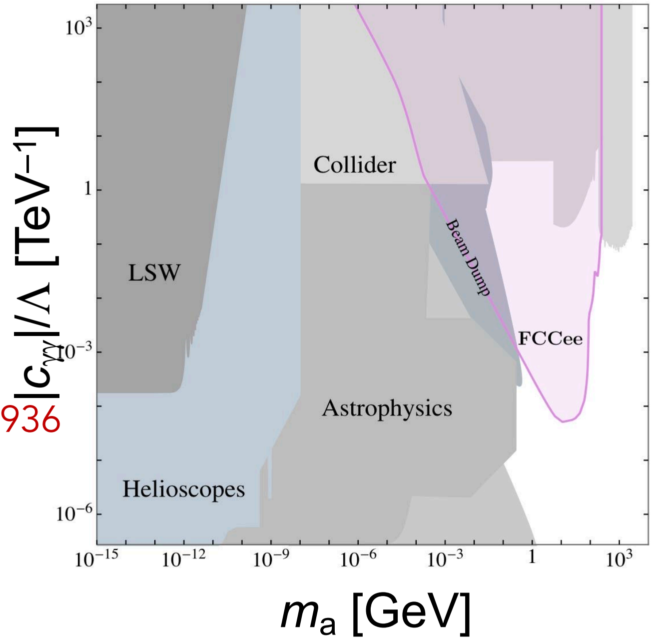




BSM physics

◆ **Rare decay signatures:**





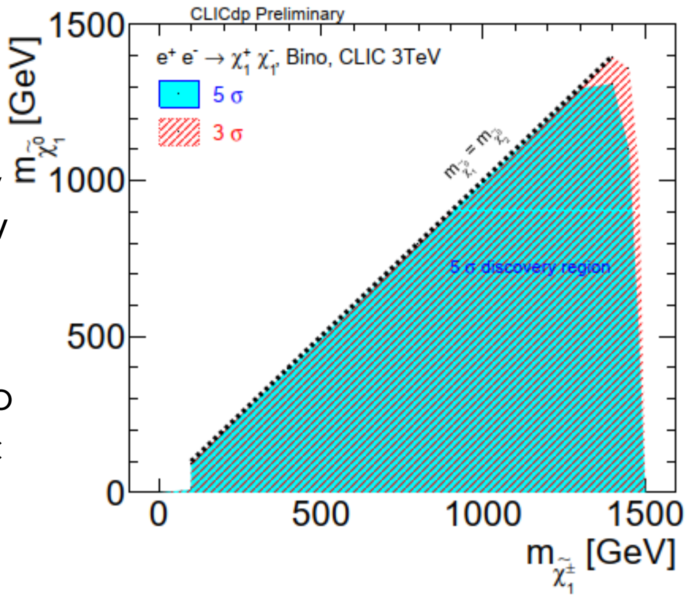
EPJ Plus (2021) 136:936

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

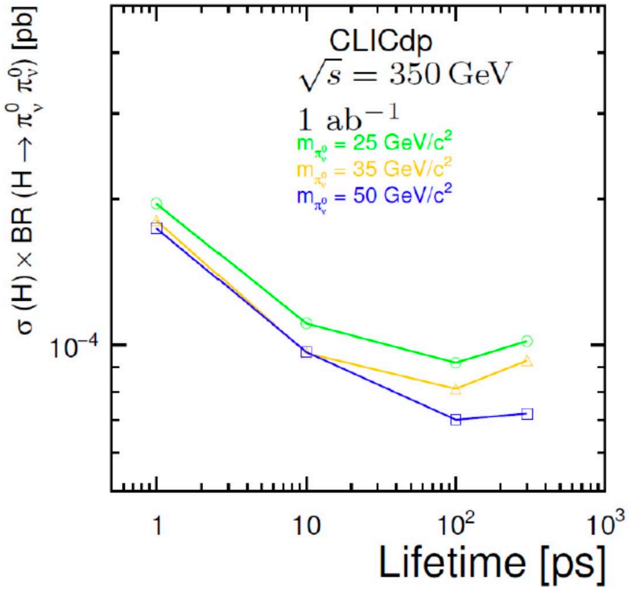


General benefit of searches in e^+e^-: avoiding 'holes' in parameter space

◆ **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^-



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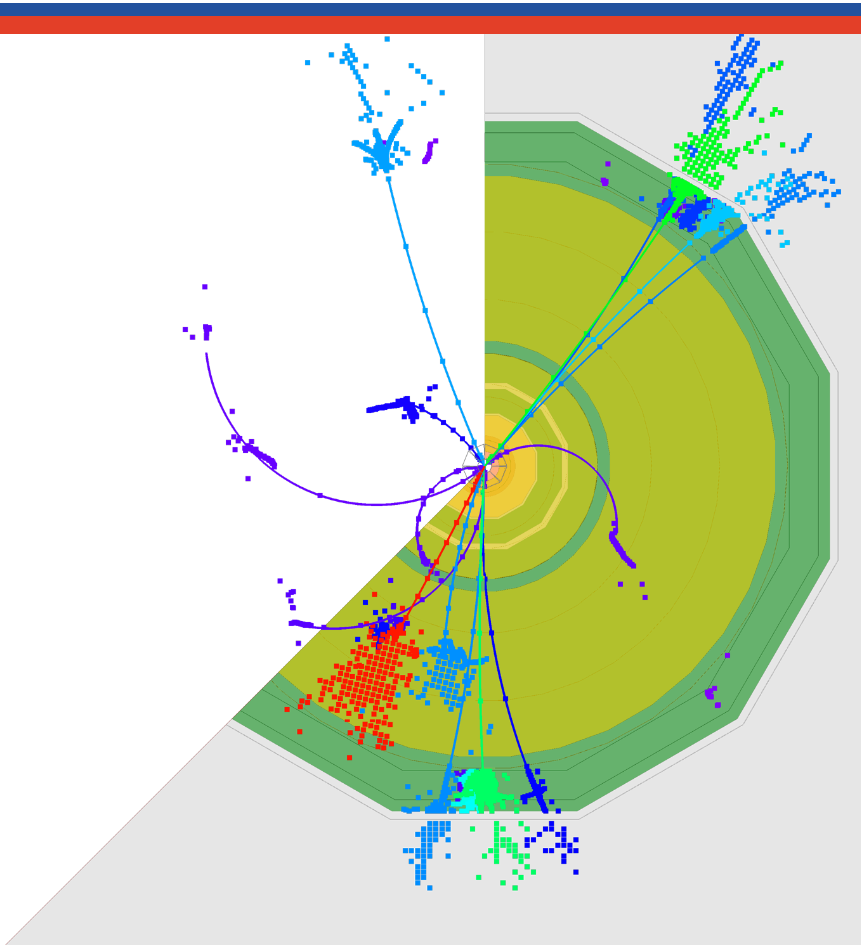
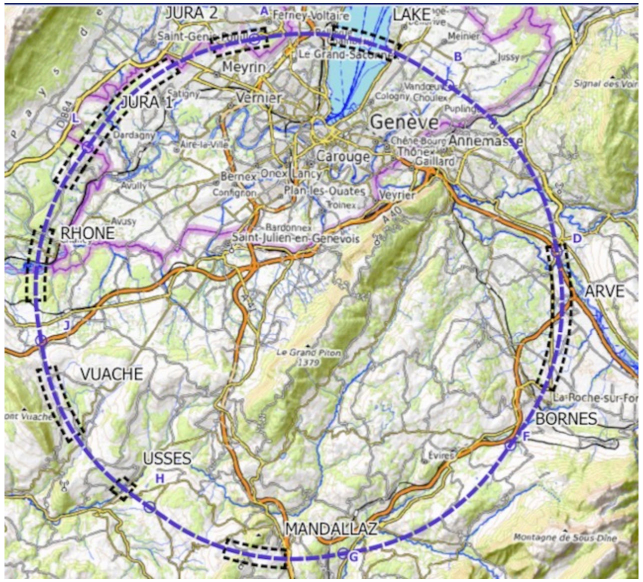
◆ **Plus BSM interpretations of precision measurements / EFT fits –> e.g. compositeness limits**

Status of e+e– projects



FCC Project and CEPC

FCC



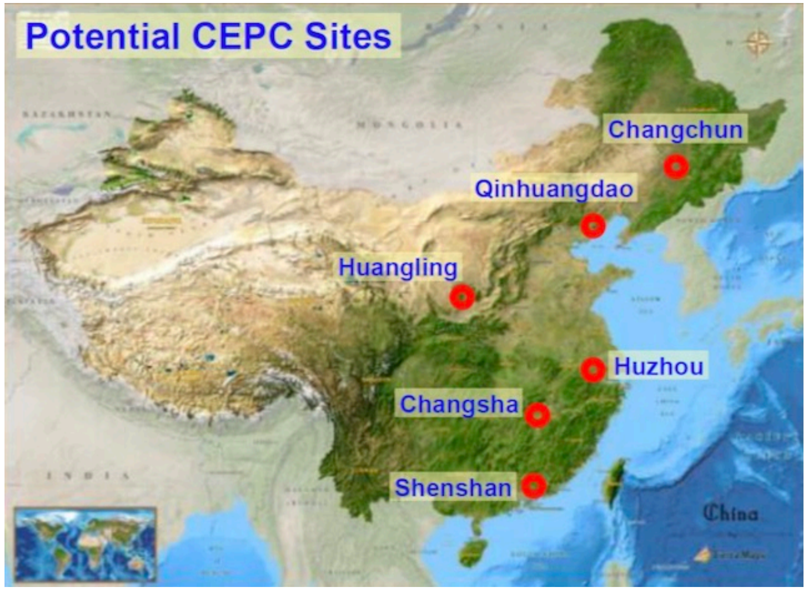
- Following last ESPP Update, FCC is CERN's "Plan A".
- Feasibility study 2021-25 concentrates on:

– 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)

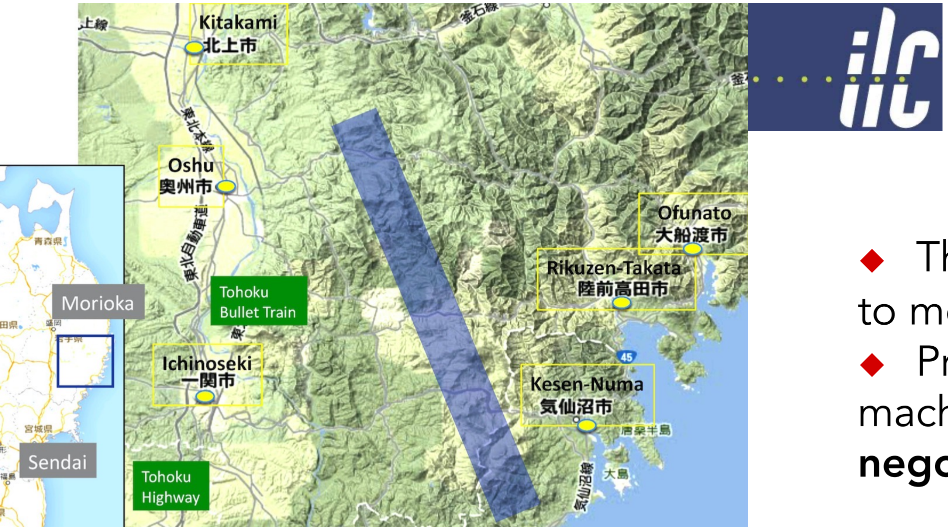
- Mid-term report published 2024 – well-received by CERN committees.
- Final Feasibility Study Report brought forward to March 2025
- Tentative timeline laid out for FCC-ee detectors:
  CDRs 2031; TDRs 2035; Installation 2041; Commissioning 2035

CEPC

- CEPC pursuing key technology R&D
- Prototype dipole modules produced
- TDR published 2023
- Chinese Academy of Sciences recently ranked CEPC top priority in the relevant subcommittee
- Seeking approval in the 15th 5-Year Plan (runs 2026–30)



ILC Project



- 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
- Pre-lab envisaged to complete **engineering designs** for machine and civil construction and support **intergovernmental negotiation of organisation, governance, cost-sharing**

- Latest:
ILC International Technology Network (ITN) launched in July 2023
- Global collaboration programme focusing on time-critical accelerator R&D

SRF
e- & e+ Sources } Synergy with
Nano-beam } other colliders

- KEK budget for this R&D significantly increased and activity started since April 2023; ITN allows flow of funds through bilateral agreements with regional host labs (and onwards)
- Some progress on discussing 'global project' governance etc

APPENDIX 26
KR5783/ATSAPPENDIX26-to-ICA-J

to

The Agreement on Collaborative Work (ICA-JP-0103)

between

THE HIGH-ENERGY ACCELERATOR RESEARCH ORGANIZATION (KEK)

and

Signed 7/7/23 at CERN by KEK and CERN DGs

THE EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

concerning

Support for the European International Linear Collider (ILC) Technology Network

2023

ILC International Technology Network (ITN)

◆ 17 ITN Work Packages →

SRF	WPP	1	Cavity production
	WPP	2	CM design
	WPP	3	Crab cavity
e-, e+ Sources	WPP	4	E- source
	WPP	6	Undulator target
	WPP	7	Undulator focusing
	WPP	8	E-driven target
	WPP	9	E-driven focusing
	WPP	10	E-driven capture
	WPP	11	Target replacement
Nano-Beam	WPP	12	DR System design
	WPP	14	DR Injection/extraction
	WPP	15	Final focus
	WPP	16	Final doublet
	WPP	17	Main dump

◆ 5 European areas of activity:

A1 SRF
- SRF: Cavities, and Cryomodule
- Crab-cavities
- Main Linac quads and cold BPMs

A2 Sources
- Pulsed magnet
- Wheel/target

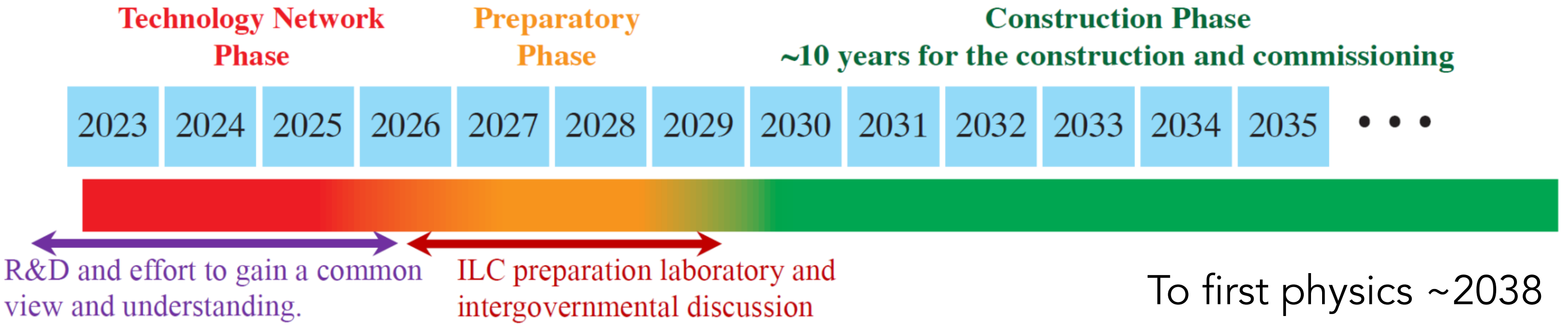
A3 Damping Ring including kickers
- Low Emittance Ring lab

A4 ATF activities for final focus, nanobeams, MDI

A5 Implementation including Project Office
- Dump, CE, Cryo
- Sustainability
- EAJADE started (EU funding)

Synergies also with CLIC

◆ Updated working timeline:



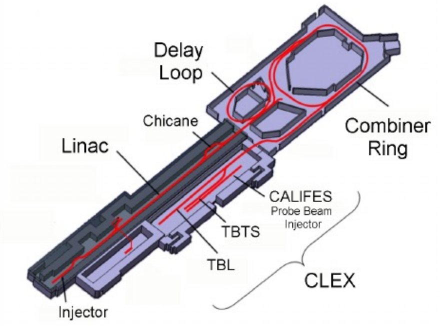
To first physics ~2038

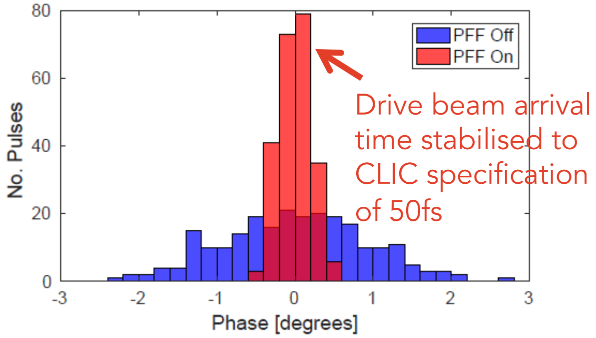
◆ Federation of Diet Members for the ILC has been reactivated, April 2023

CLIC Project

High-current drive beam bunched at 12 GHz

Produced at CLIC Test Facility CTF3





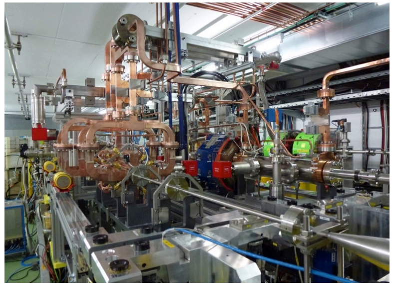
Drive beam arrival time stabilised to CLIC specification of 50fs

~100 MV/m gradient in main-beam cavities

Achieved in structures produced by different sources

Power transfer + main-beam acceleration

Demonstrated 2-beam acceleration



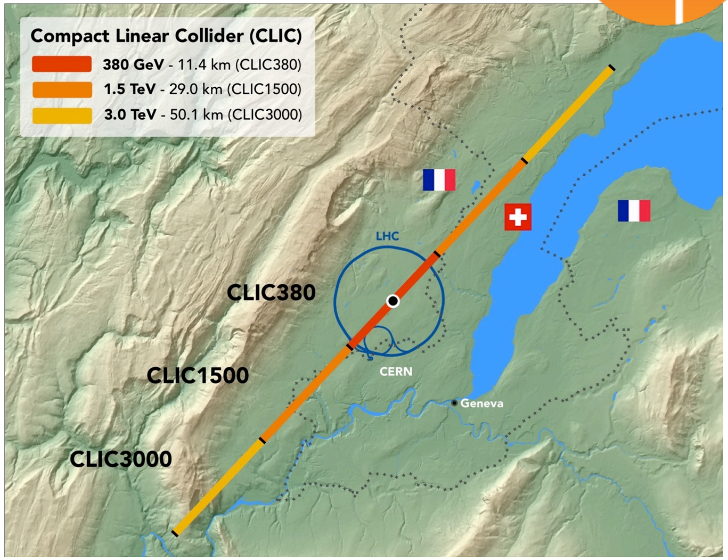
Alignment & stability

The CLIC strategy:

- Alignment; vibration damping; good beam measurement and feedback
- Tests in small accelerators of equipment and algorithms (FACET at Stanford, ATF2 at KEK, CTF3, Light-sources)

–> Key accelerator technologies have been demonstrated

CDR 2012 –> Updated Staging Baseline 2016 –> Project Implementation Plan 2018

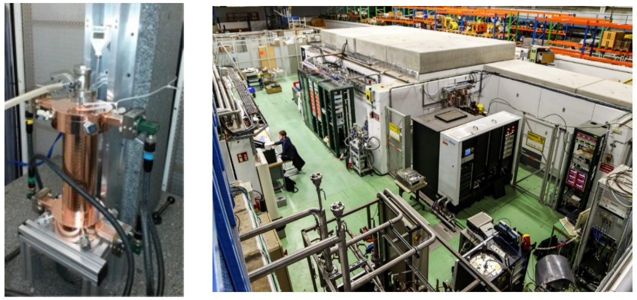


◆ Following the European Strategy Update, CLIC is maintained at CERN –> if the FCC feasibility study is not conclusive then CLIC could be implemented in an expeditious way

◆ 2021-25 programme continues CLIC as an option for a Higgs/top accelerator facility at CERN, and is pursuing high-gradient R&D and nanobeam technology more generally with a focus on non-particle physics applications

◆ A Project Readiness Report will be developed for 2025

CLIC Technologies & Developments



X-band technology:

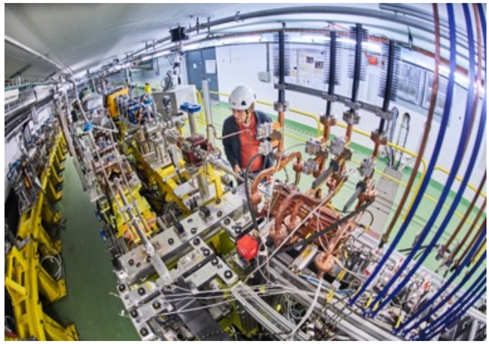
- Design and manufacturing of X-band structures and components
- Study structures breakdown limits and optimization, operation and conditioning
- Baseline verification and explore new ideas
- Assembly and industry qualification
- Structures for applications, FELs, medical, etc

Technical and experimental studies, design & parameters:

- Module studies
- Beam dynamics and parameters
- Tests in CLEAR (wakefields, instrumentation) and other facilities (e.g. ATF2)
- High efficiency klystrons
- Injector studies suitable for X-band linacs

Luminosity margins and increases at 380 GeV

- Initial estimates of static and dynamic degradations from damping ring to IP gave: 1.5 x 10^{34} cm^{-2} s^{-1}
- Simulations taking into accord static and dynamic effects with corrective algorithms give 2.8 on average, and 90% of the machines above 2.3 x 10^{34} cm^{-2} s^{-1}



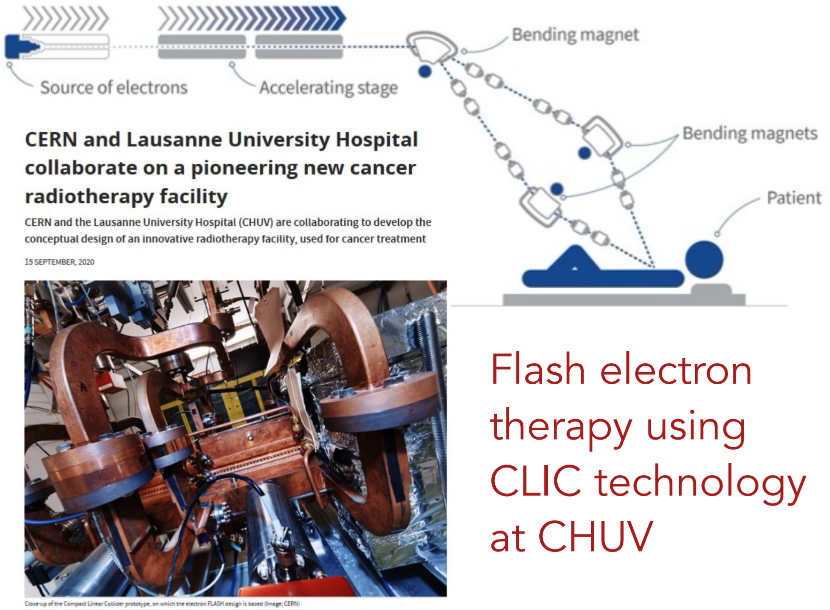
◆ **X-band technology readiness for the 380 GeV CLIC initial phase - more and more driven by use in small compact accelerators**

Application of X-band technology (examples):

- A compact FEL (CompactLight: EU Design Study 2018-21)
- Compact Medical linacs (proton and electrons)
- Inverse Compton Scattering Source (SmartLight)
- 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 etc towards a collider



CERN and Lausanne University Hospital collaborate on a pioneering new cancer radiotherapy facility

CERN and the Lausanne University Hospital (CHUV) are collaborating to develop the conceptual design of an innovative radiotherapy facility, used for cancer treatment

15 SEPTEMBER, 2020

Close-up of the Compact Linear Collider prototype, on which the electron FLASH design is based (Image: CERN)

Flash electron therapy using CLIC technology at CHUV

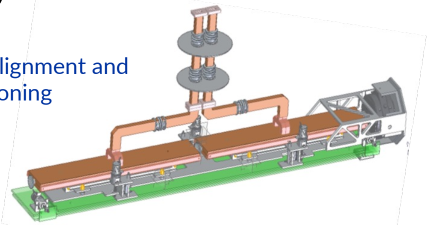
C^3 studies

8 km footprint for 250/550 GeV CoM ⟹ 70/120 MeV/m

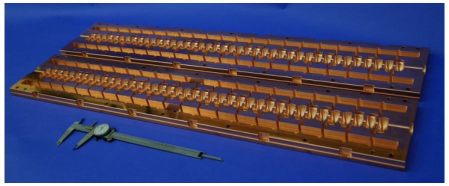
Large portions of accelerator complex are compatible between LC technologies

- 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
- Reliant on work done by CLIC and ILC to make progress

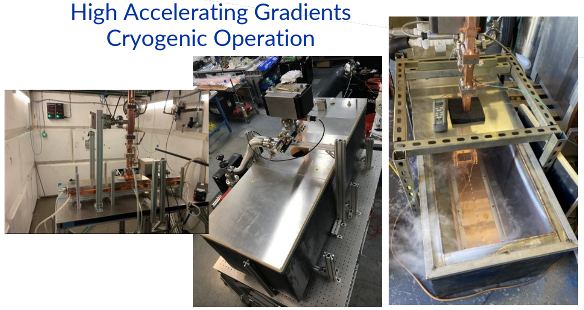
Ongoing work:



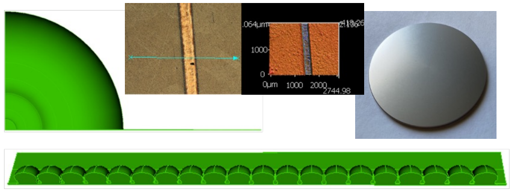
Preliminary Alignment and Positioning



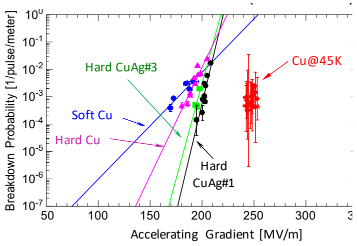
Modern Manufacturing Prototype One Meter Structure

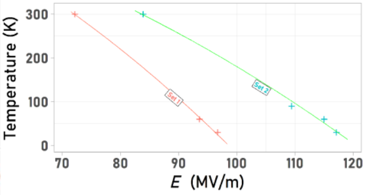


High Accelerating Gradients Cryogenic Operation



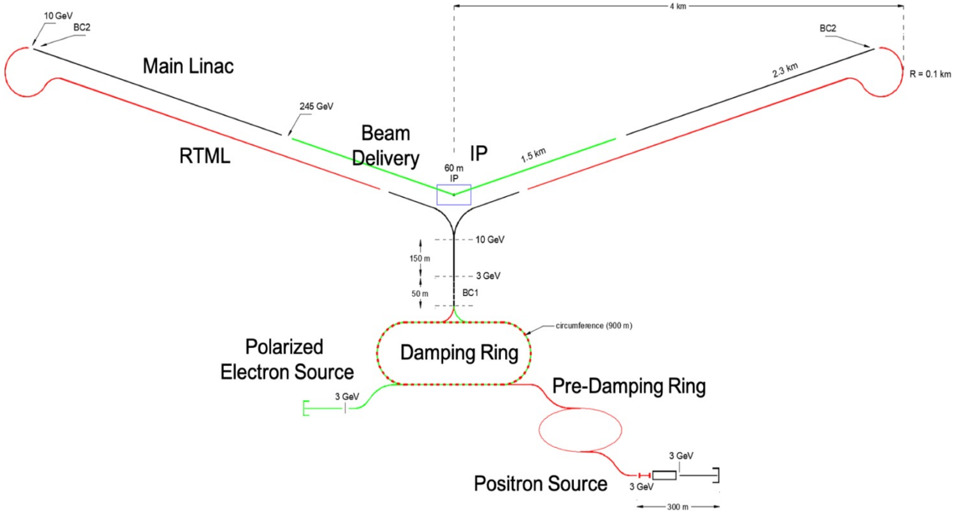
Integrated Damping Slot Damping with NiChrome Coating





Cryo-cooled copper

C^3 - 8 km Footprint for 250/550 GeV



C^3 Parameters

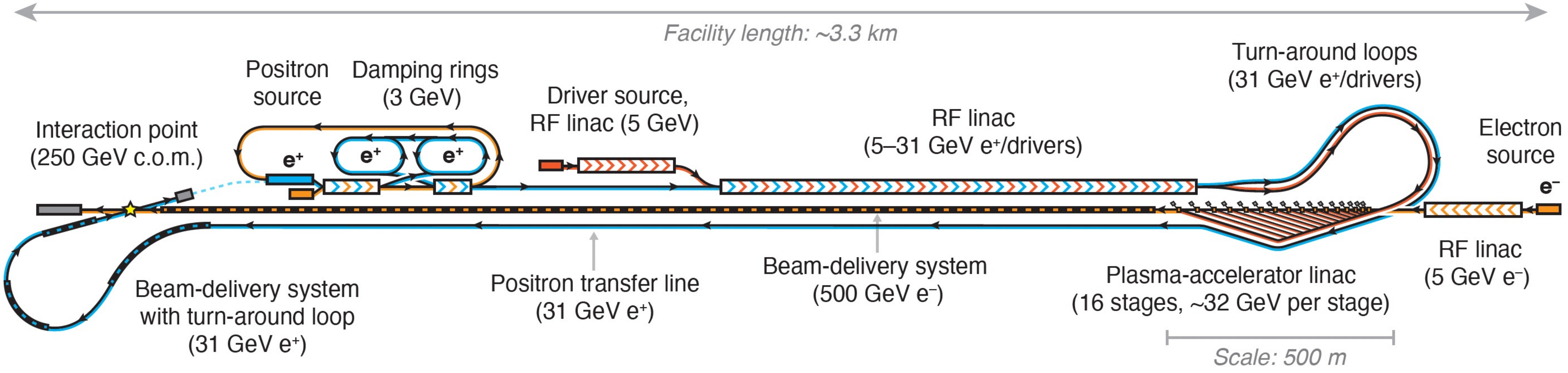
Collider	C^3	C^3
CM Energy [GeV]	250	550
Luminosity [x10^{34}]	1.3	2.4
Gradient [MeV/m]	70	120
Effective Gradient [MeV/m]	63	108
Length [km]	8	8
Num. Bunches per Train	133	75
Train Rep. Rate [Hz]	120	120
Bunch Spacing [ns]	5.26	3.5
Bunch Charge [nC]	1	1
Crossing Angle [rad]	0.014	0.014
Site Power [MW]	~150	~175
Design Maturity	pre-CDR	pre-CDR

- ◆ R&D received some support from US P5 committee
- ◆ Optimistic scenario: construction 2030; first collisions 2040

HALHF

Hybrid Asymmetric Linear Higgs Factory

https://arxiv.org/2303.10150



e-
e+
e+ BDS
e- BDS

- Overall facility length ~ 3.3 km – which will fit on ~ any of the major pp labs.

◆ 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

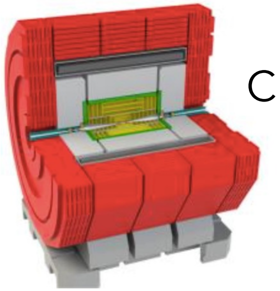
Detectors & software

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

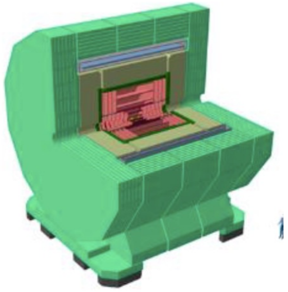
– detector concepts
– detector technologies
– software tools (& physics studies)

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

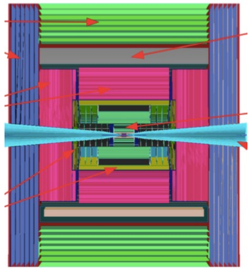
ILD SiD



CLICdet



CLD
for FCC-ee

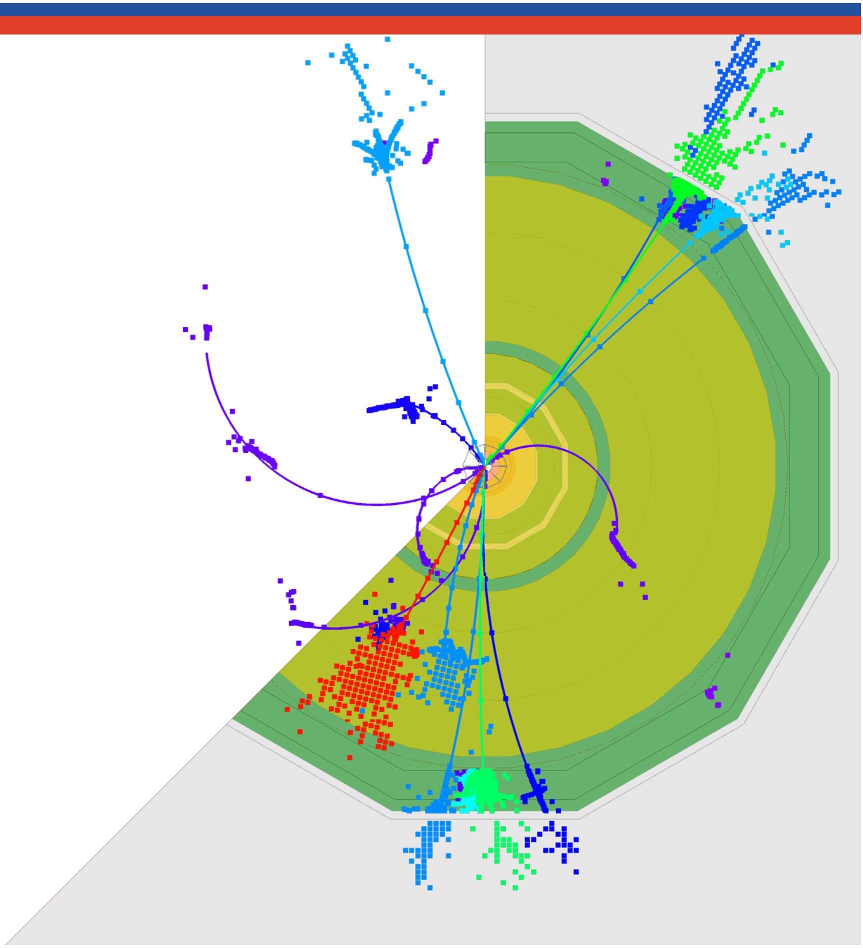


(CLICdet
adapted for
muon
collider!)

- ◆ 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
- 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: pure exploration

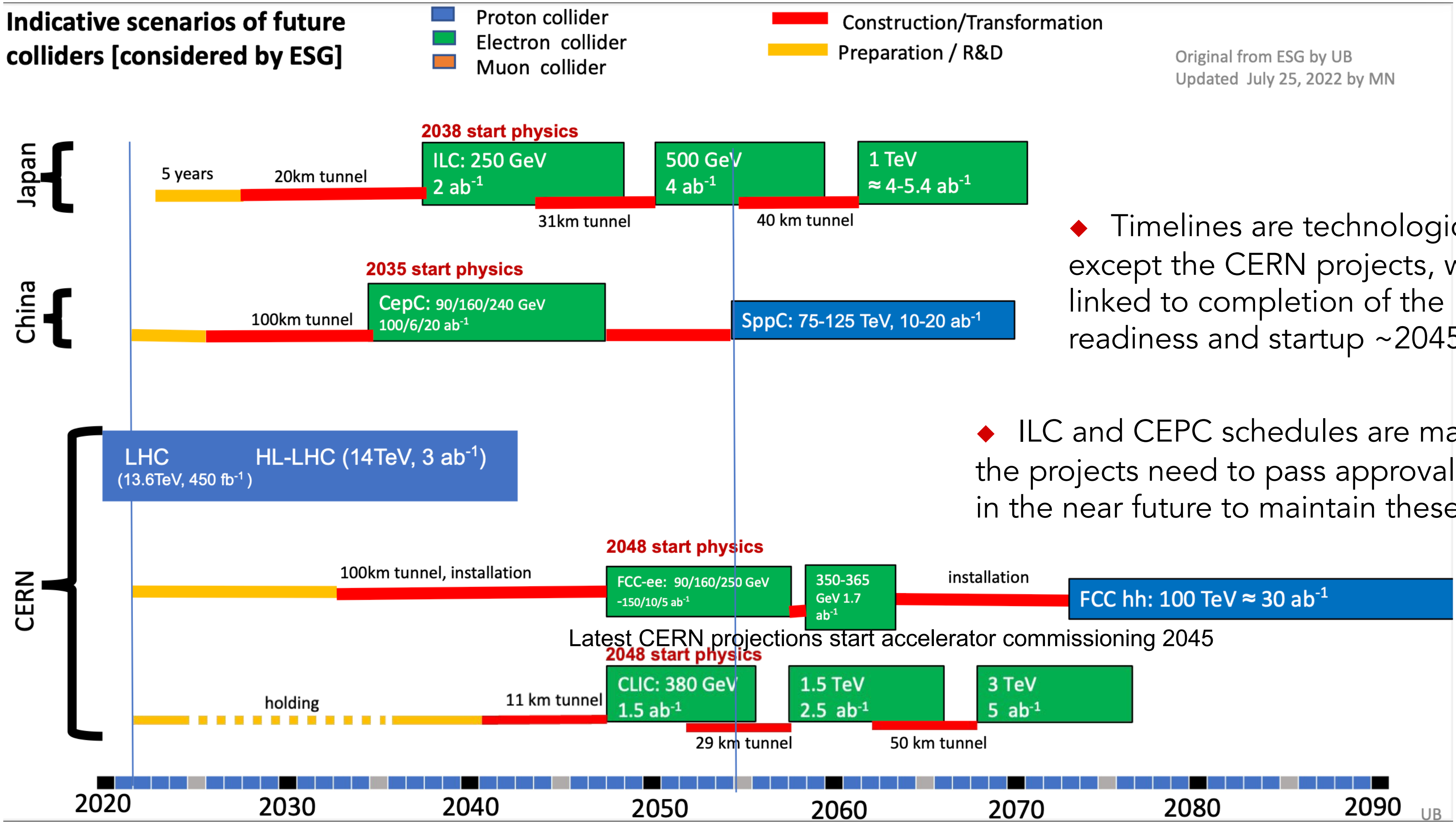
Broad agreement that we want to do all of this physics

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?



Latest CERN projections start accelerator commissioning 2045

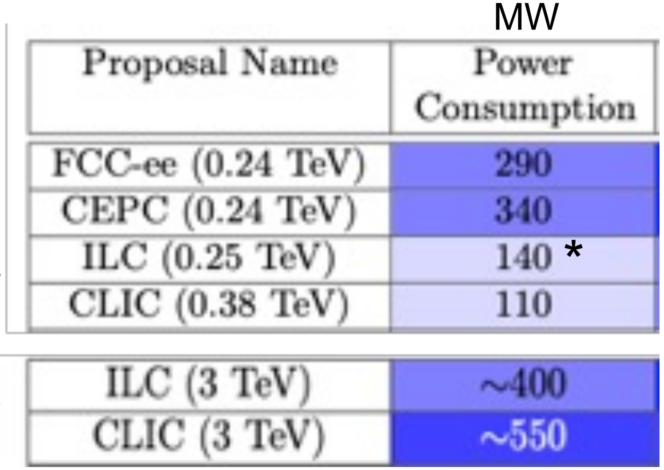
- Timelines are technologically limited except the CERN projects, which are linked to completion of the HL-LHC; readiness and startup ~2045-48

- 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?

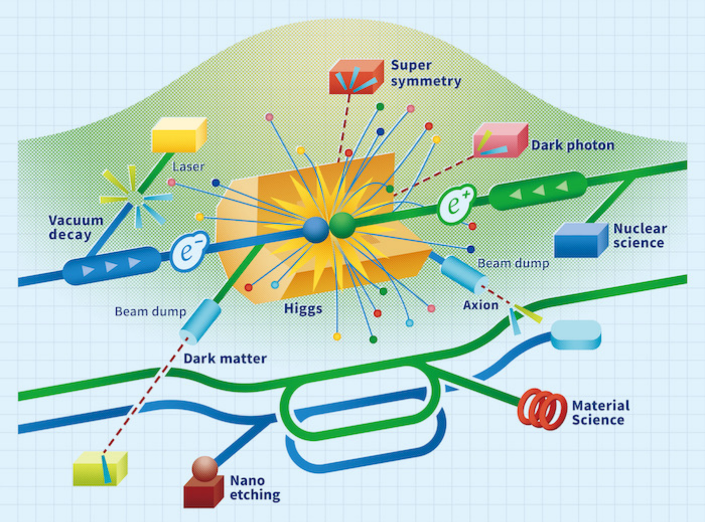
Power:
Projects working on improving power efficiency



Proposal Name	Power Consumption (MW)
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

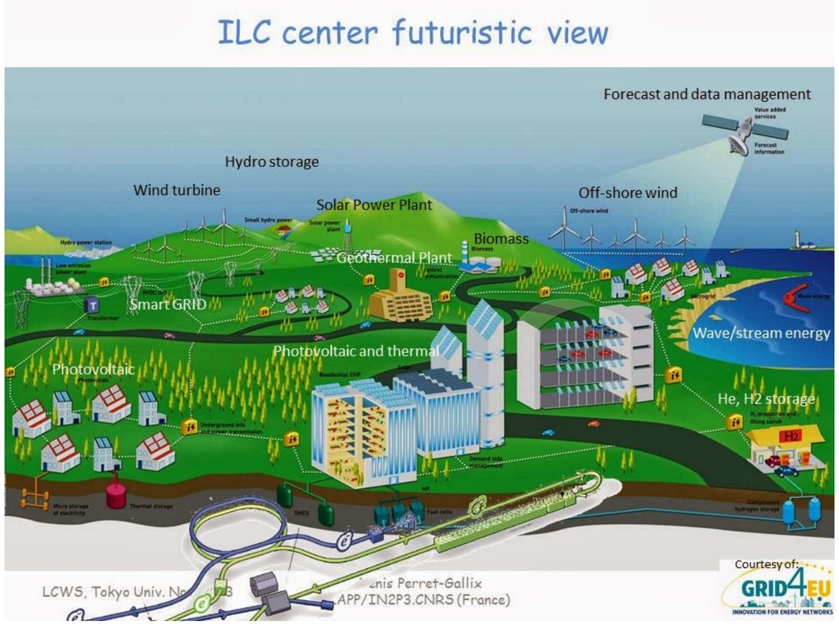
from Snowmass implementation taskforce
*nominal 111 MW; LumiUpgrade 138MW

– what should be the metric?



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?

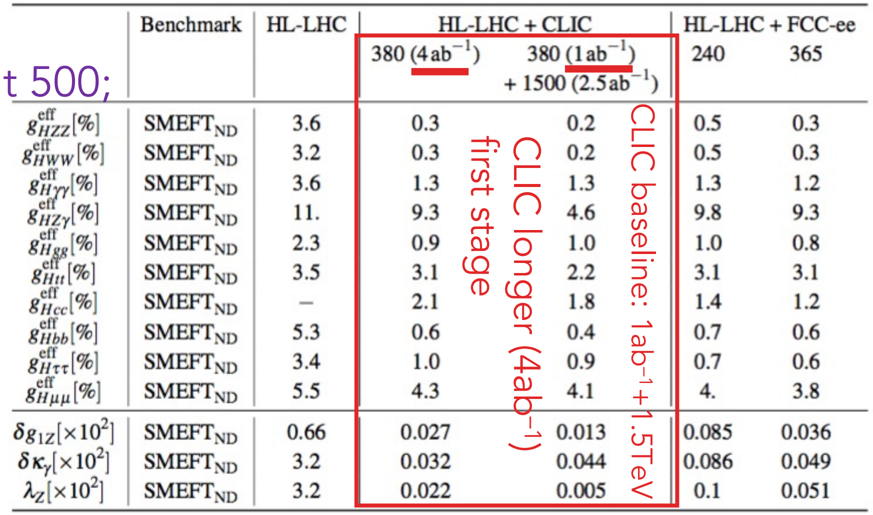
- **Strategic question 4:**
  – how concrete is the plan / how important is flexibility?

- 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

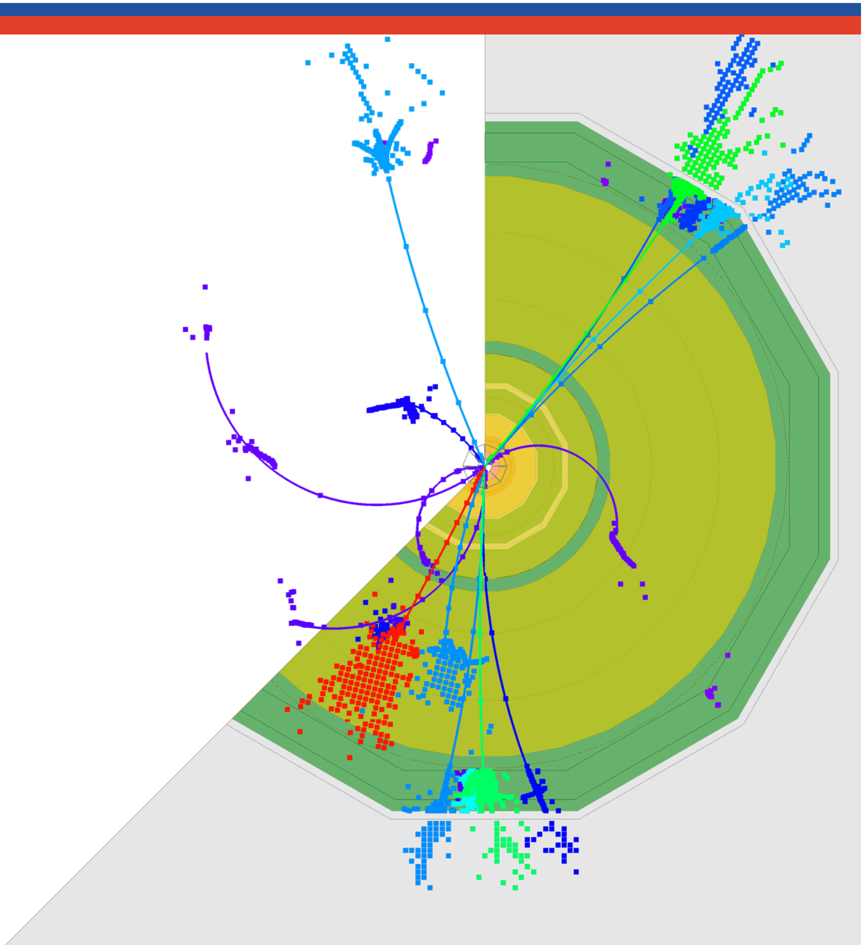
FCC-hh:
17 BCHF (if built after FCC-ee)
24 BCHF (if built standalone)

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