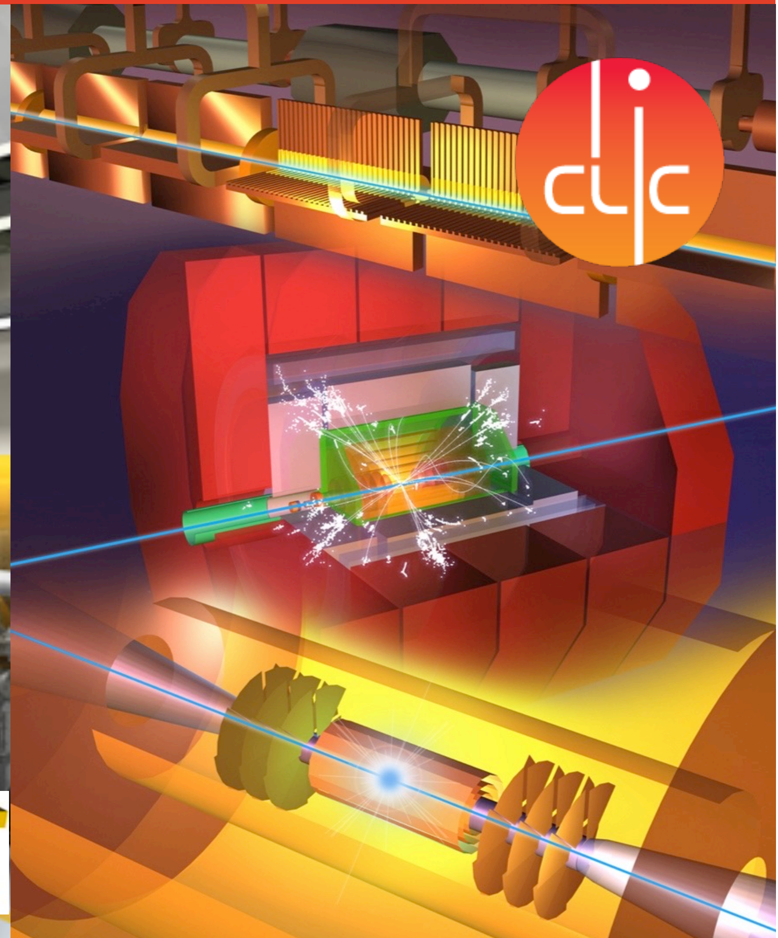
Higgs prospects at linear e^+e^- colliders

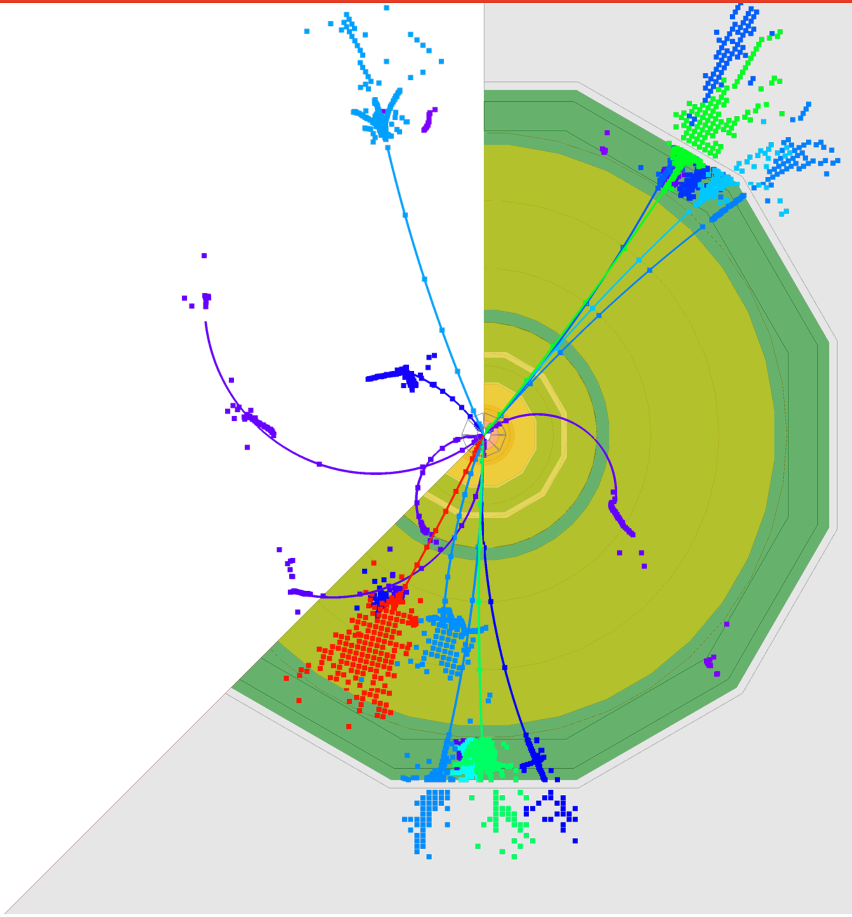


UK HEP Forum: "Completing the Higgs-saw Puzzle", 21 November 2023

Aidan Robson, University of Glasgow

Higgs prospects at linear e^+e^- colliders

- Why e+e– ?
- Why linear?
- Single Higgs
- Higgs pairs
- BSM physics in Higgs
- Status and outlook of projects
- ECFA Higgs/top/electroweak factory study



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

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- 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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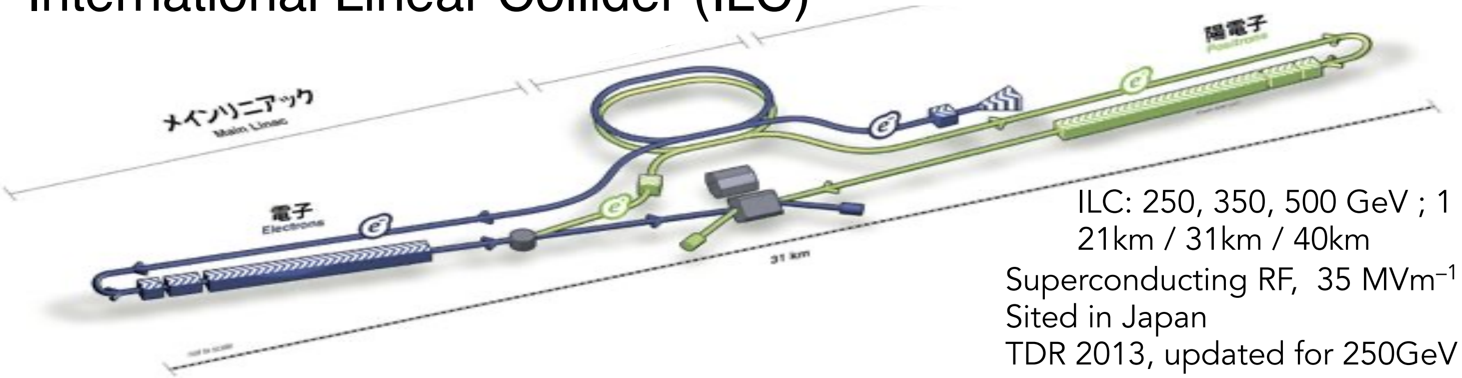
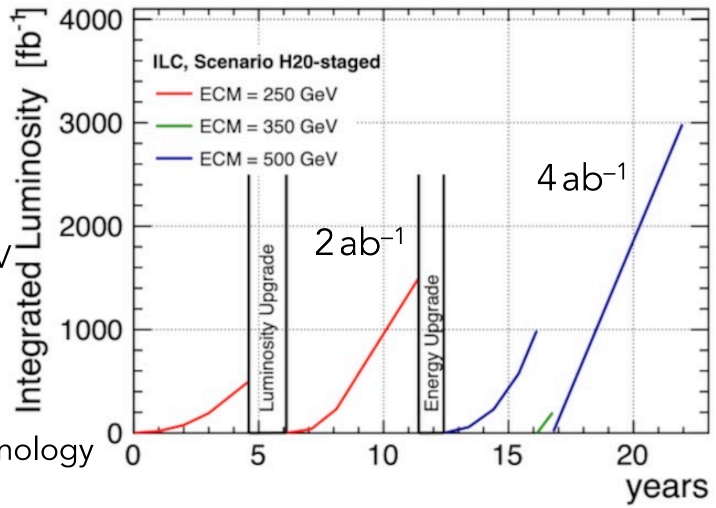
Higgs factory contenders (1): Linear Colliders

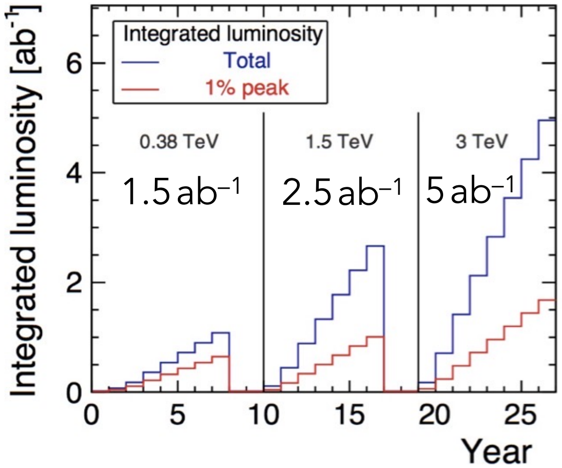
International Linear Collider (ILC)



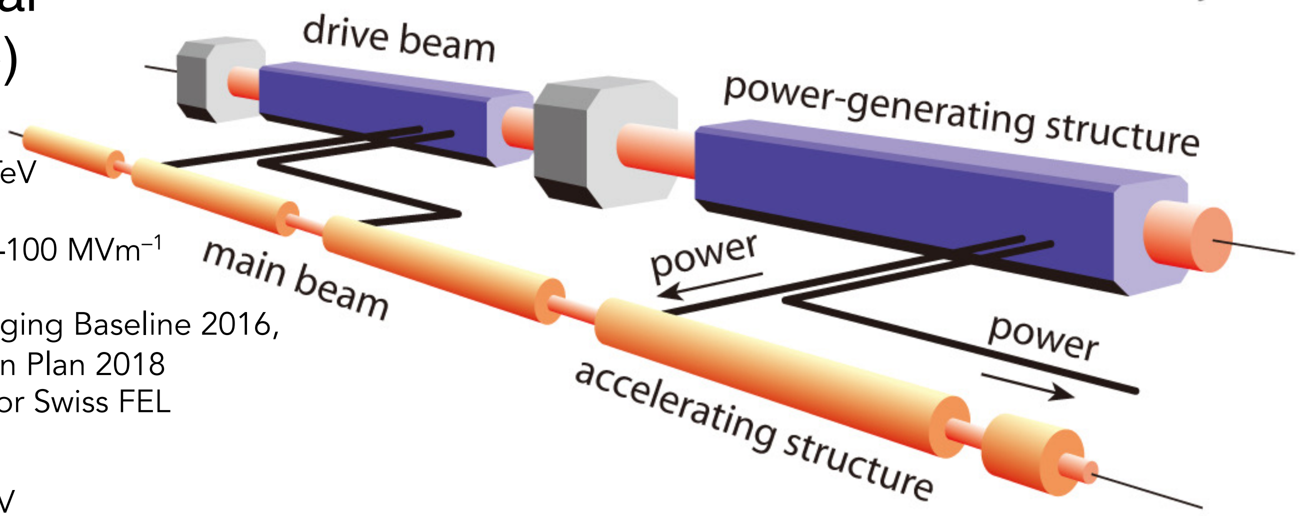
ILC: 250, 350, 500 GeV ; 1 TeV
21km / 31km / 40km
Superconducting RF, 35 MVm^{-1}
Sited in Japan
TDR 2013, updated for 250GeV
European XFEL demonstrates technology



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

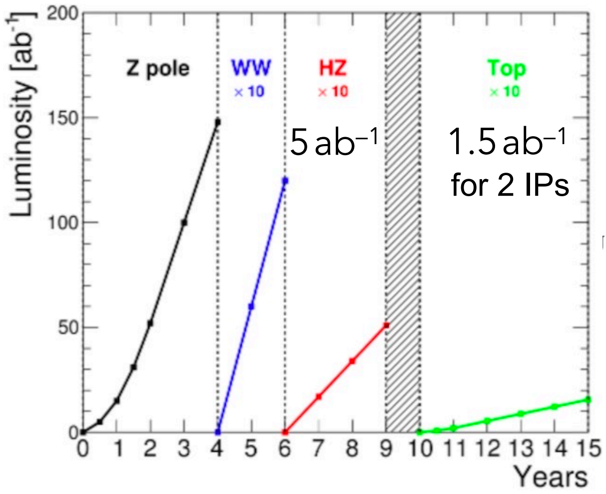
Hybrid Asymmetric Linear Higgs Factory (HALHF)

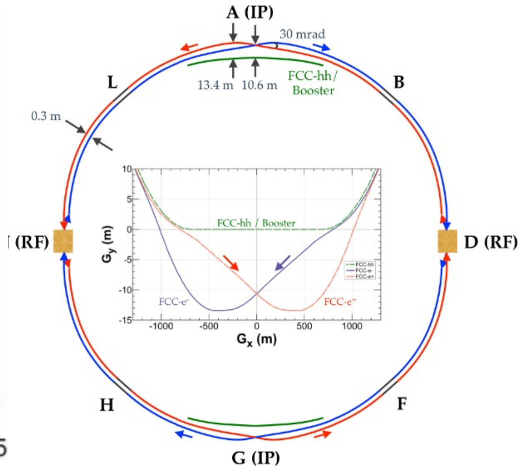
HALHF: 250 GeV (e^- 500GeV, e^+ 31GeV)
3.3km
25 MVm^{-1} conventional, 6.3GVm^{-1} plasma
Pre-CDR

Higgs factory contenders (2): Circular Colliders

Future Circular Collider (FCC-ee)

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

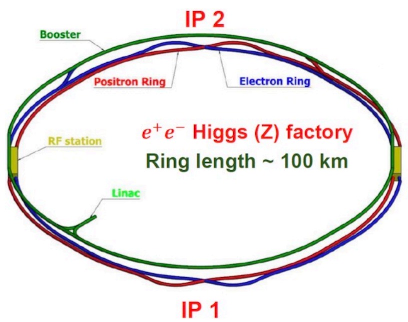




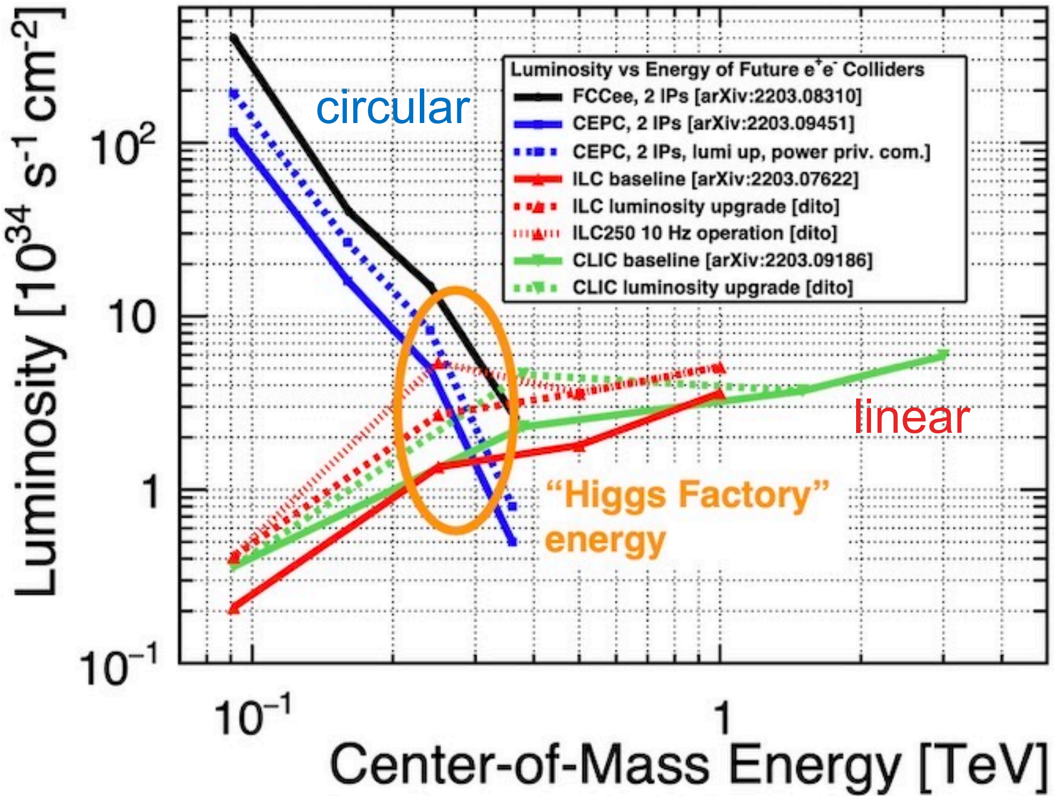
FCC: ~92k, ring
FCCee CDR 2019
Accelerator technology mostly proven >50yr

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 (1): Linear Colliders

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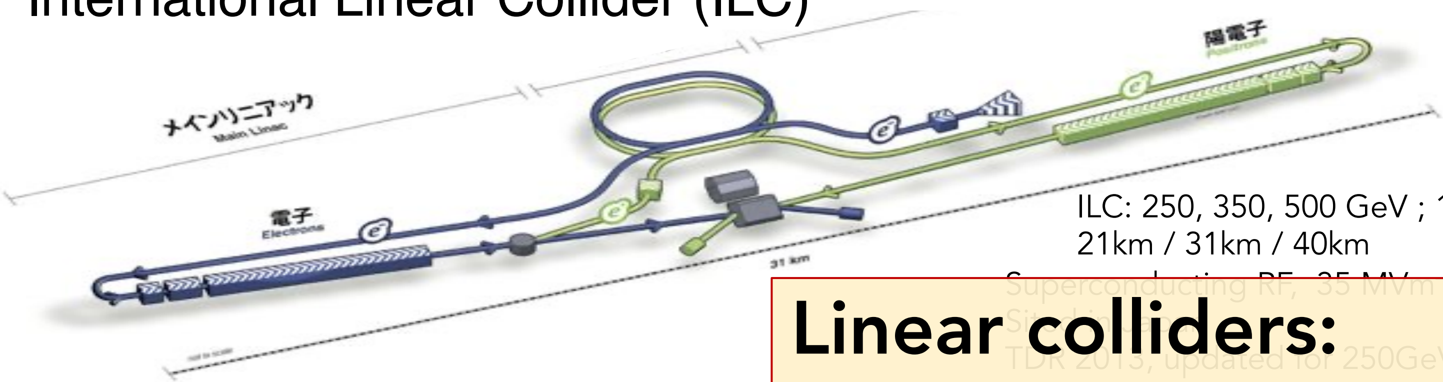

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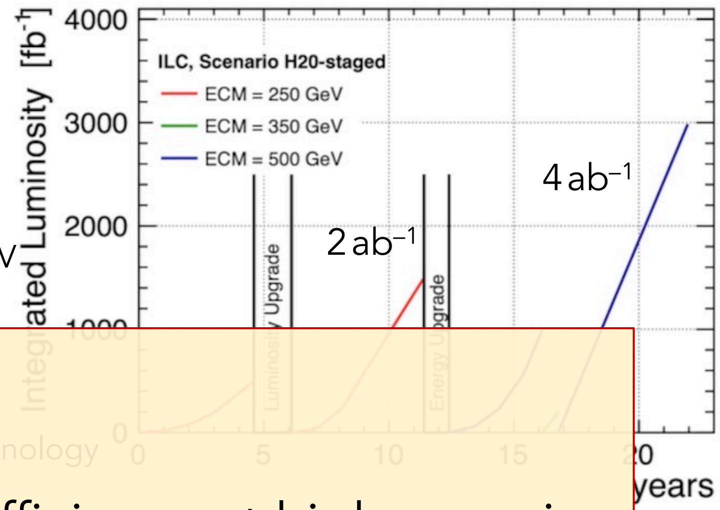

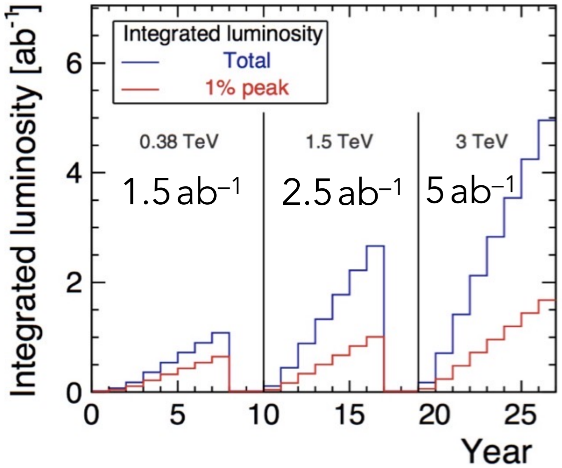

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Linear colliders:

- 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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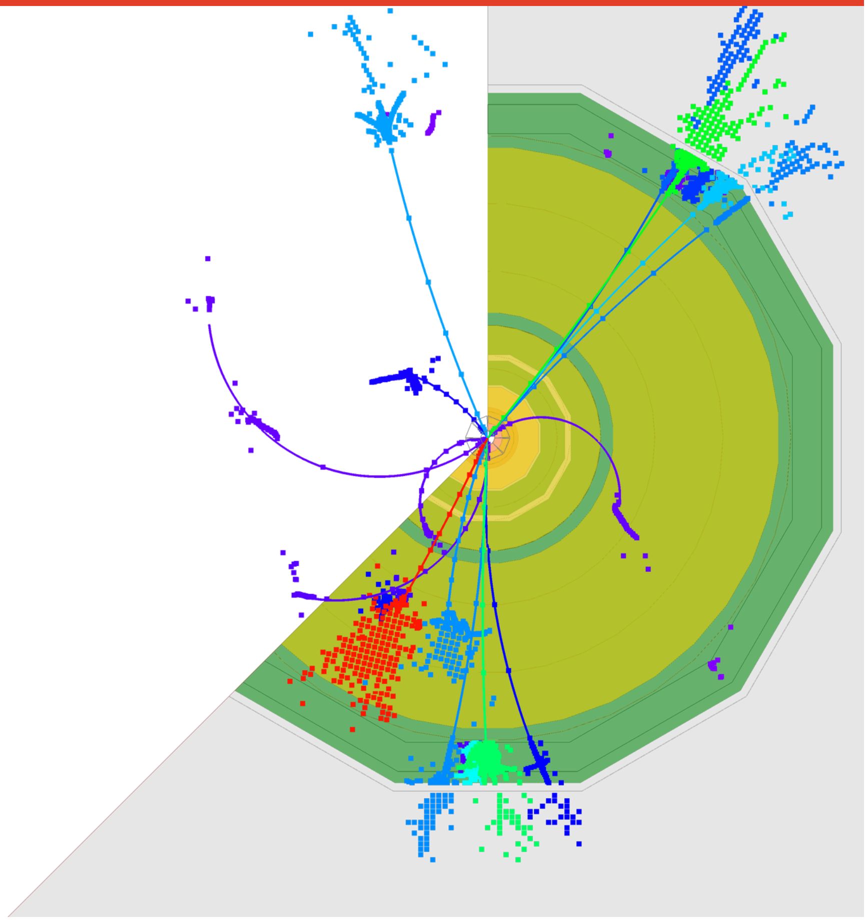
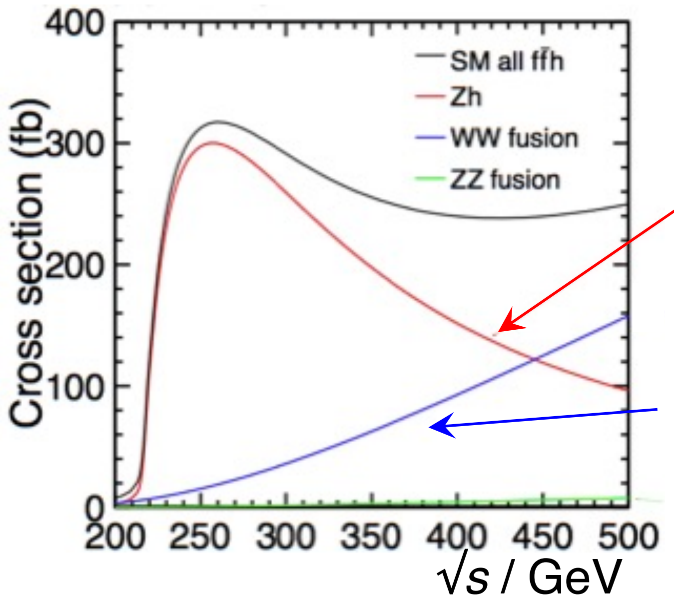
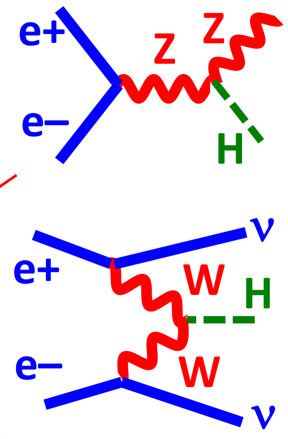
Higgs in e^+e^-



Higgs production in e^+e^-

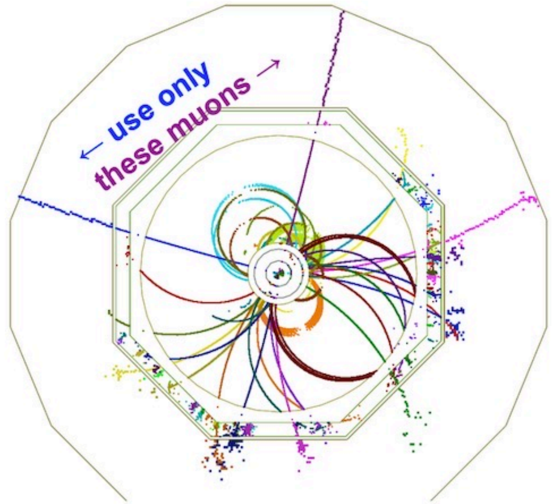




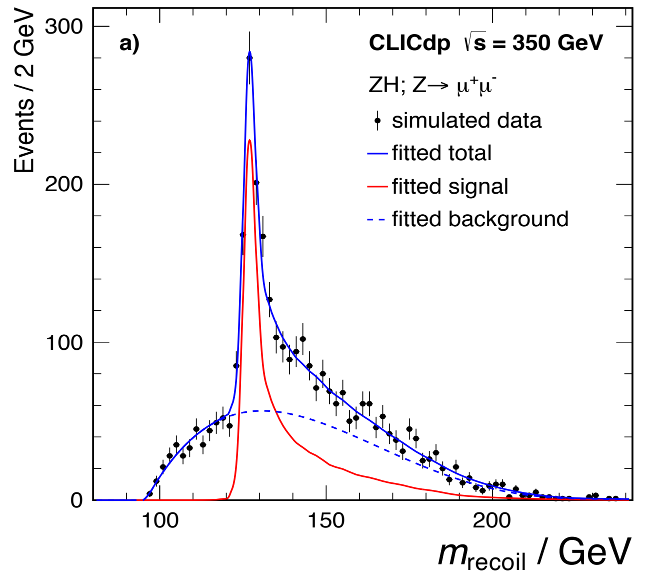
- ZH process allows reconstruction of H by looking exclusively at recoil of Z –> model-independent extraction of g_{HZZ} coupling

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

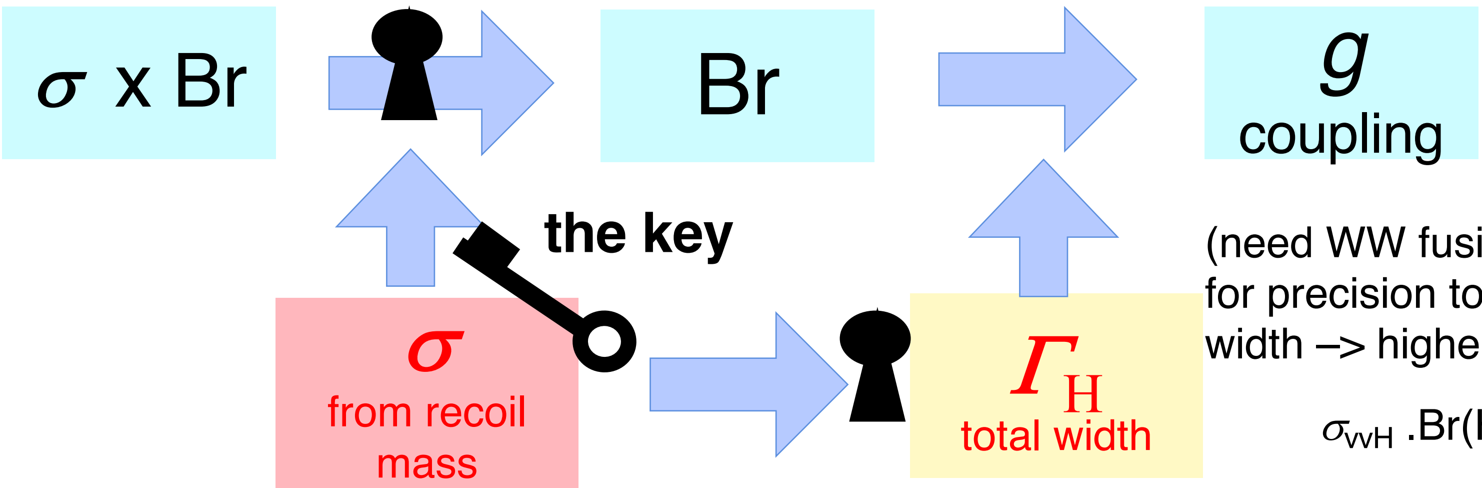
$$\frac{\sigma_{ZH}\,.\mathrm{Br(H\text{->}bb)}}{\sigma_{\nu\nu H}\,.\mathrm{Br(H\text{->}bb)}} \propto \frac{g^2_{HZZ}}{g^2_{HWW}}$$



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



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

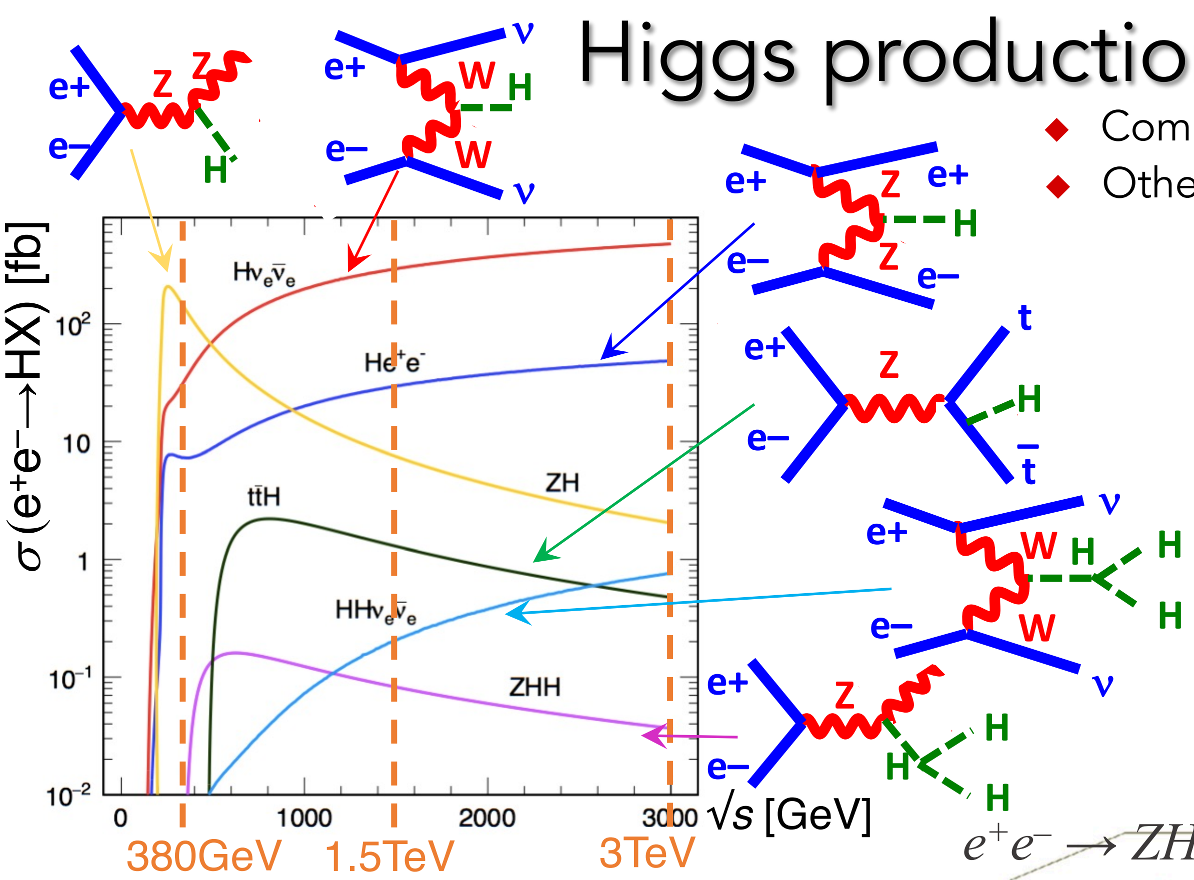


(need WW fusion for precision total width –> higher √s)

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

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

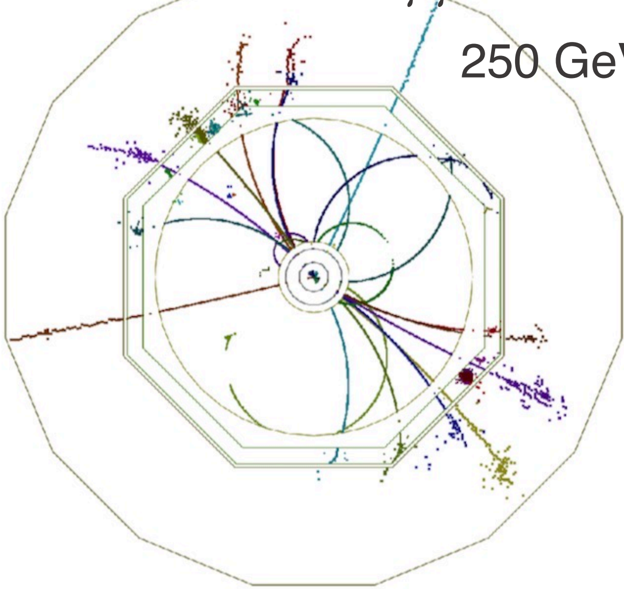
All projects have studied many channels

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	$\sigma(ZH)\times BR(H\to WW^*)$	$g^2_{HZZ}g^2_{HWW}/\Gamma_H$
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e)\times BR(H\to b\bar{b})$	$g^2_{HWW}g^2_{Hbb}/\Gamma_H$
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e)\times BR(H\to c\bar{c})$	$g^2_{HWW}g^2_{Hcc}/\Gamma_H$
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e)\times BR(H\to gg)$	

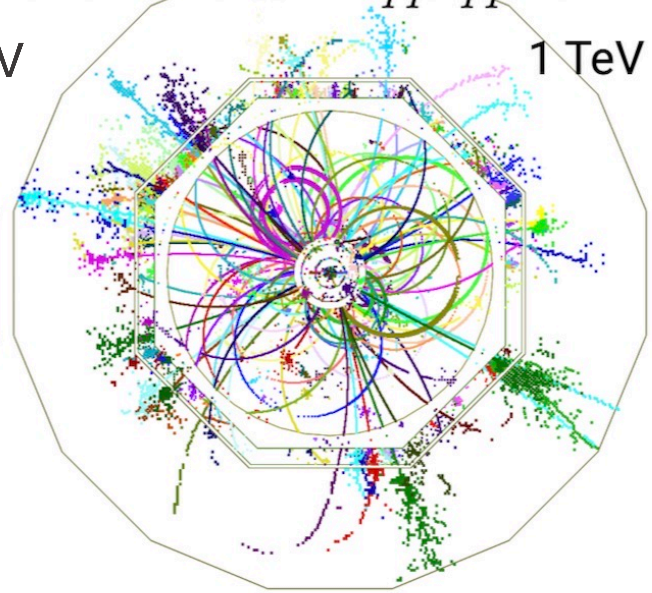
surement	Observable
ss distribution	m_H
$R(H\to b\bar{b})$	$g^2_{HZZ}g^2_{Hbb}/\Gamma_H$
$BR(H\to b\bar{b})$	$g^2_{HWW}g^2_{Hbb}/\Gamma_H$
$BR(H\to c\bar{c})$	$g^2_{HWW}g^2_{Hcc}/\Gamma_H$
$BR(H\to gg)$	
$BR(H\to \tau^+\tau^-)$	$g^2_{HWW}g^2_{H\tau\tau}/\Gamma_H$
$BR(H\to \mu^+\mu^-)$	$g^2_{HWW}g^2_{H\mu\mu}/\Gamma_H$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

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

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



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



- 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

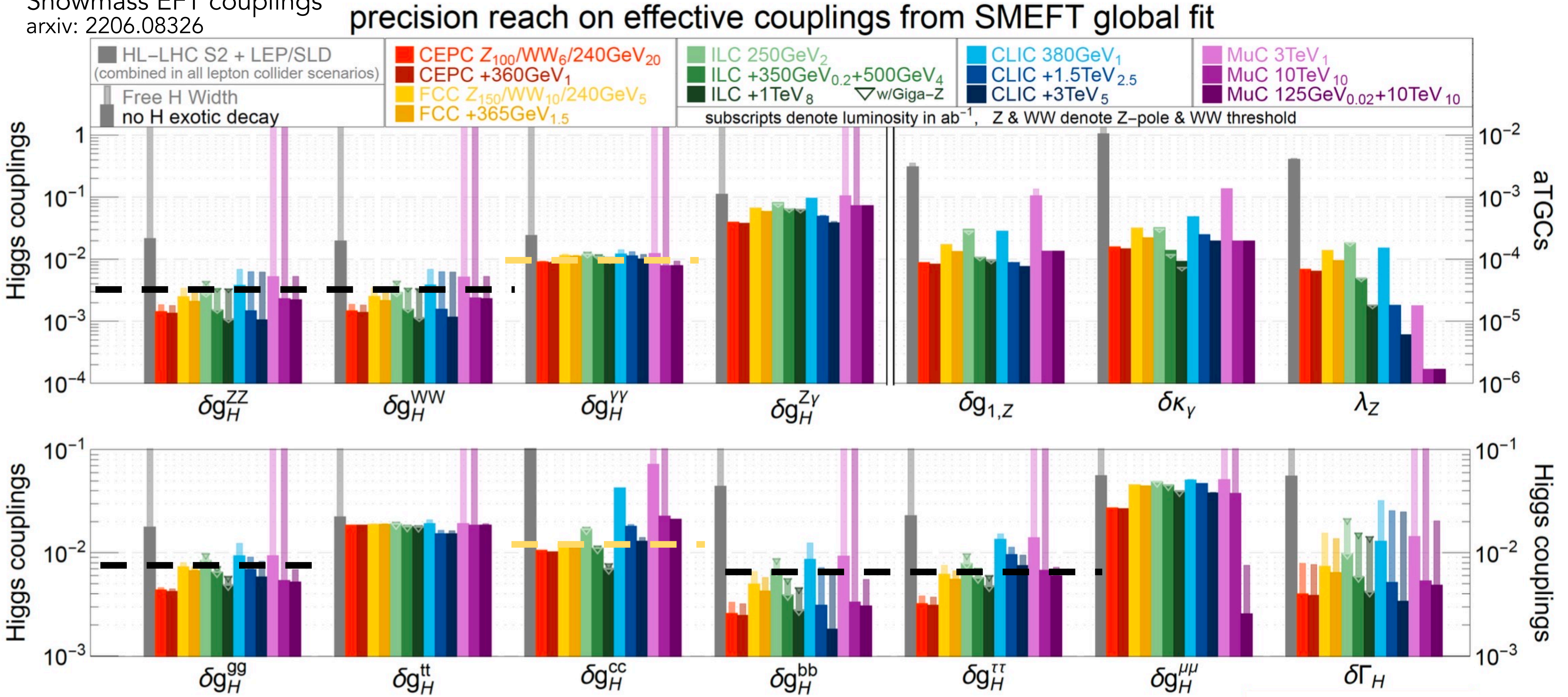
Dim-6 operators

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

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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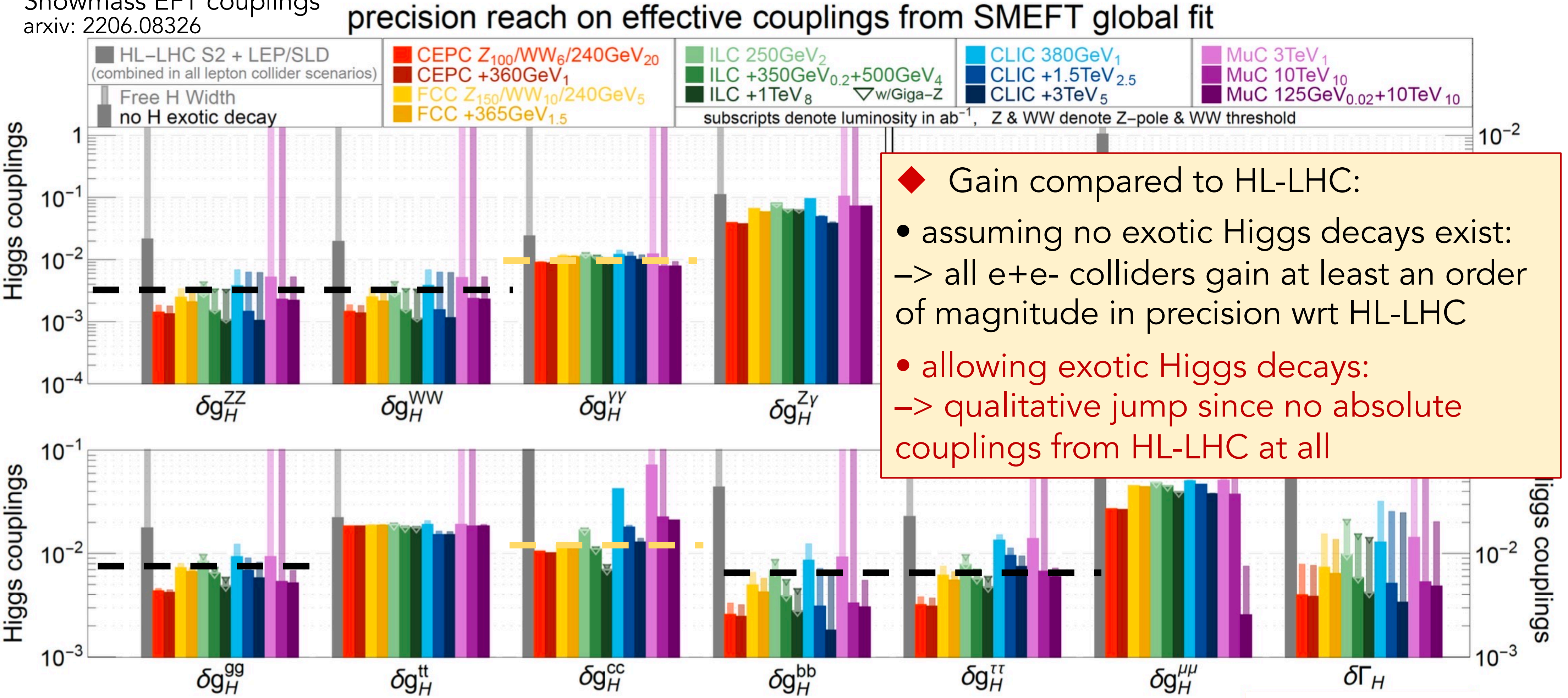


- Gain compared to HL-LHC:
  - assuming no exotic Higgs decays exist: –> all e+e- colliders gain at least an order of magnitude in precision wrt HL-LHC
  - allowing exotic Higgs decays: –> qualitative jump since no absolute couplings from HL-LHC at all

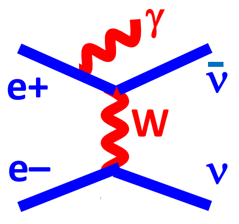
- all e+e- colliders show very comparable performance for standard Higgs program despite quite different assumed integrated luminosities
  - several couplings at few-0.1% level: Z, W, g, b, τ
  - some more at ~1%: γ, c

Polarisation

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

Background suppression:

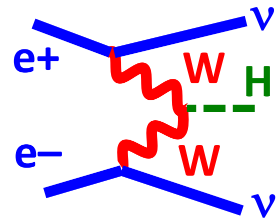
- e^+e_- -> WW / $\nu_e\nu_e$ strongly parity-dependent since *t*-channel only for $e^-_L e^+_R$



Signal enhancement:

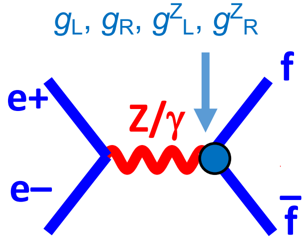
- Many processes have strong polarisation dependence, e.g.:
  – Higgs production in WW-fusion
  – many BSM processes

=> 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:

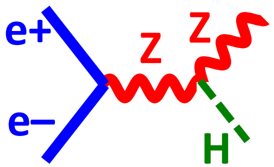
- ‘wrong’ polarisation yields ‘signal-free’ control sample
- flipping positron polarisation can control nuisance effects on observables relying on electron polarisation

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

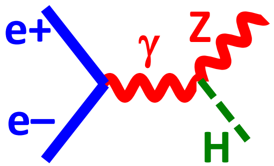
- many physics benefits from beam polarisation

Polarisation

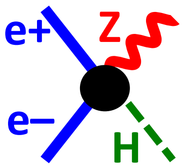
- Higgsstrahlung e+e– -> ZH is the key process at a Higgs factory
- A_{LR} of Higgsstrahlung helps to disentangle different SMEFT operators



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

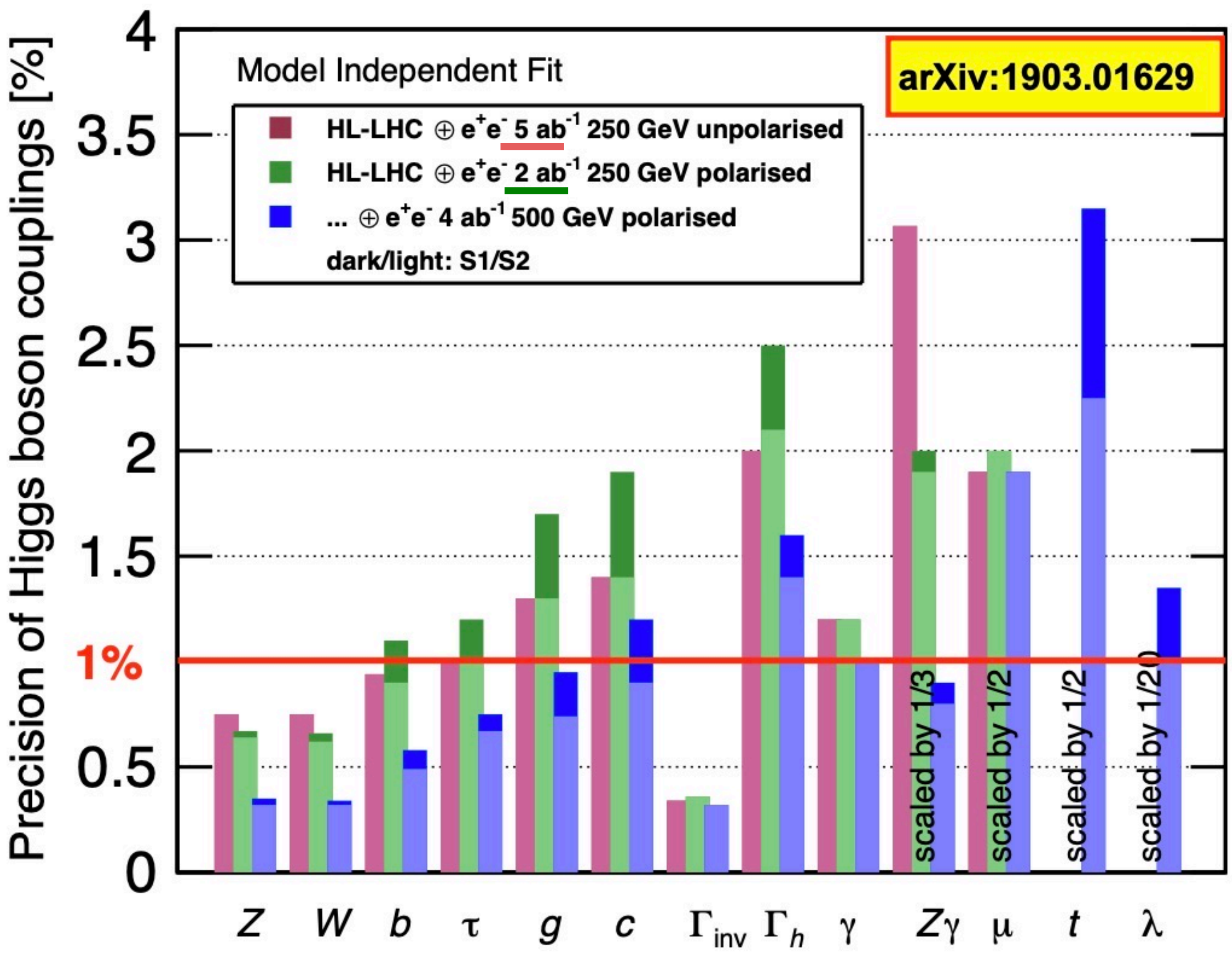


$\sim c_{WW}$
Keeps sign under spin reversal $e_R \leftrightarrow e_L$



Constrained by EWPOs

A_{LR} lifts degeneracy between operators



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

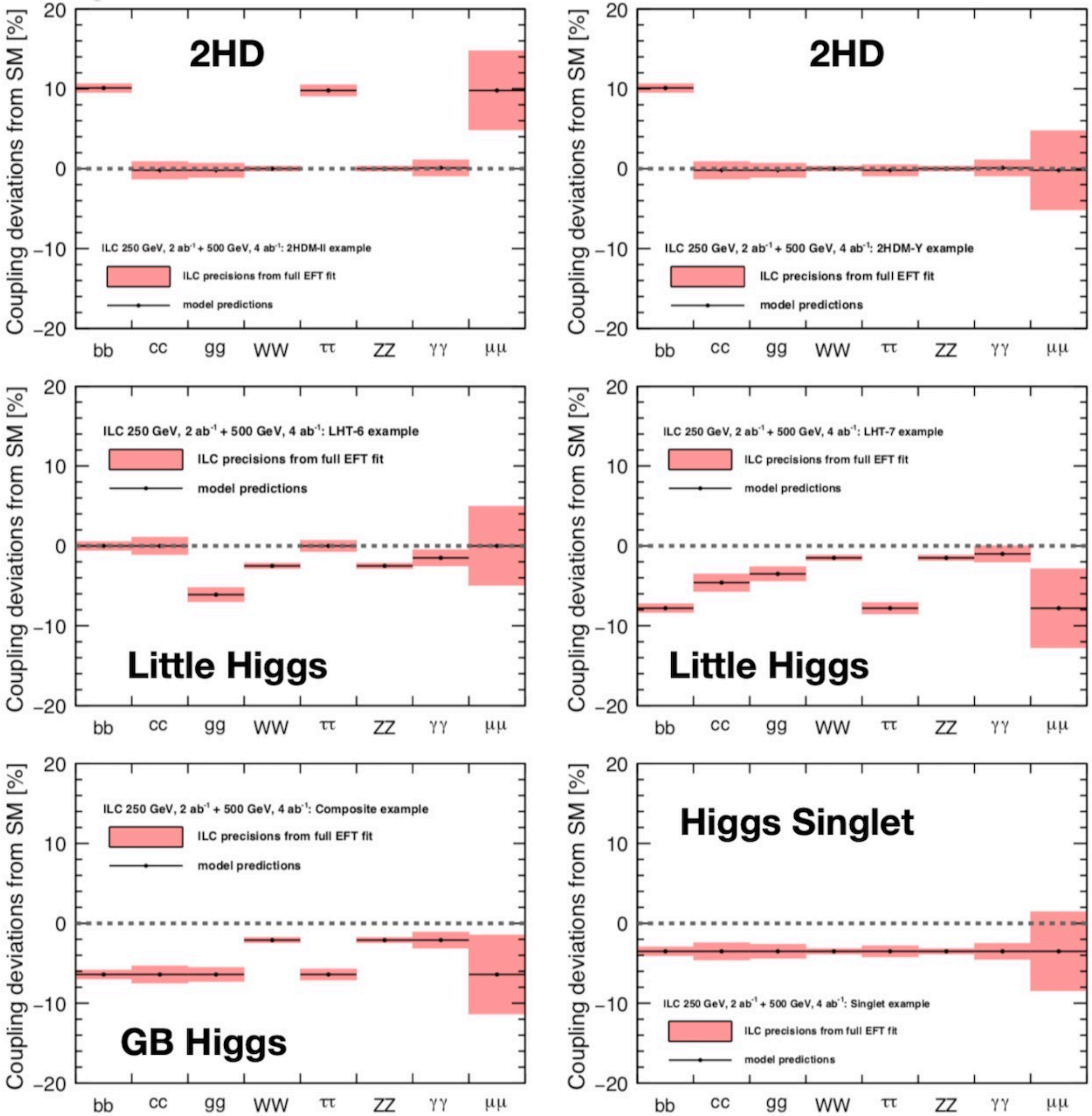
Higgs couplings sensitivity

- 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 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

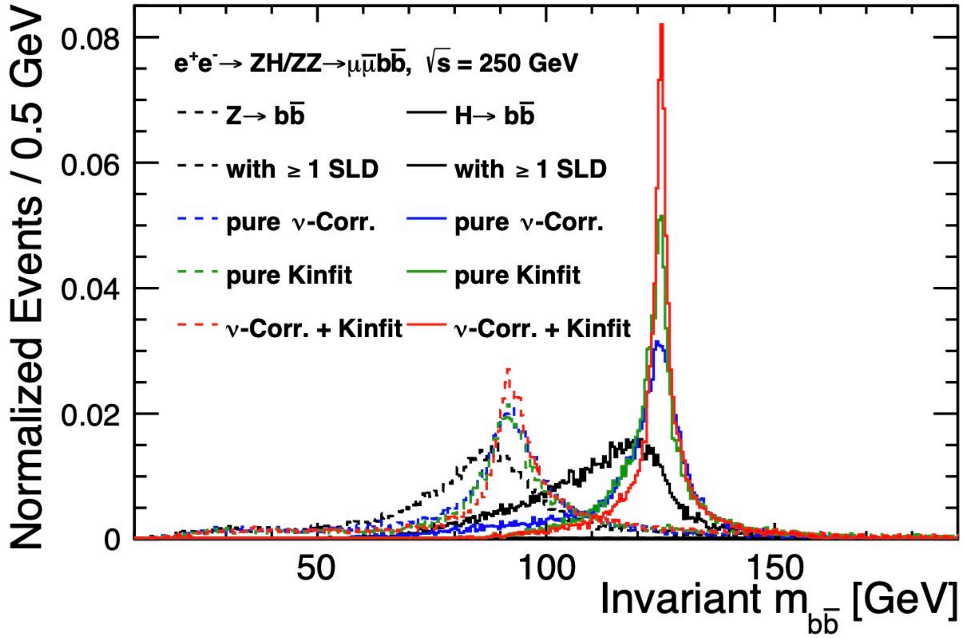
Single Higgs – recent work / room for improvement

Improvements in reconstructing Z/H -> bb

- correct semi-leptonic b/c decays
  - identify leptons in b- / c-jets
  - associate them with secondary/tertiary vertex
  - reconstruct neutrino kinematics (2-fold ambiguity)
- estimate jet-by-jet covariance matrix from particle flow
- use both in kinematic fit

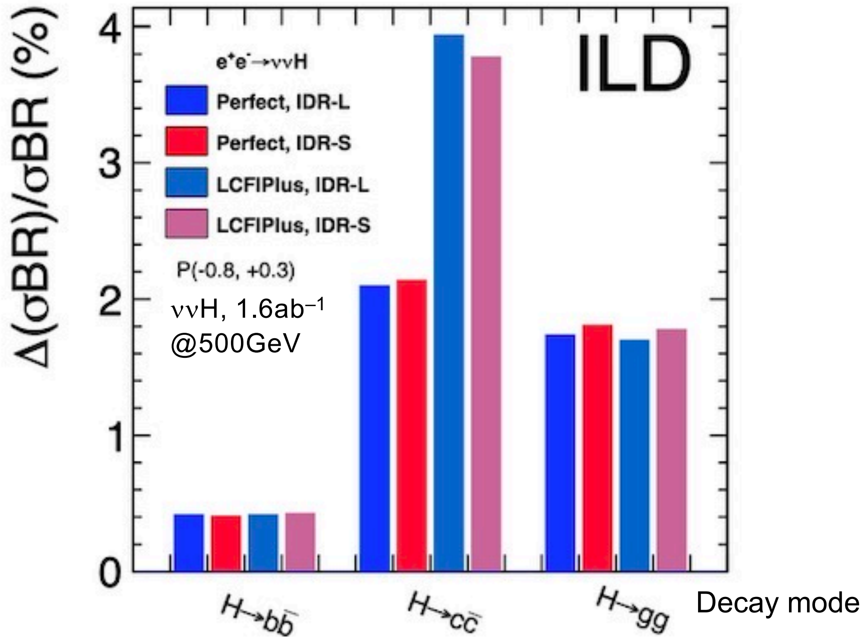
=> significant improvement in H->bb/cc and Z->bb/cc reconstruction; ready to propagate to sensitivity analyses

arxiv:2111.14775

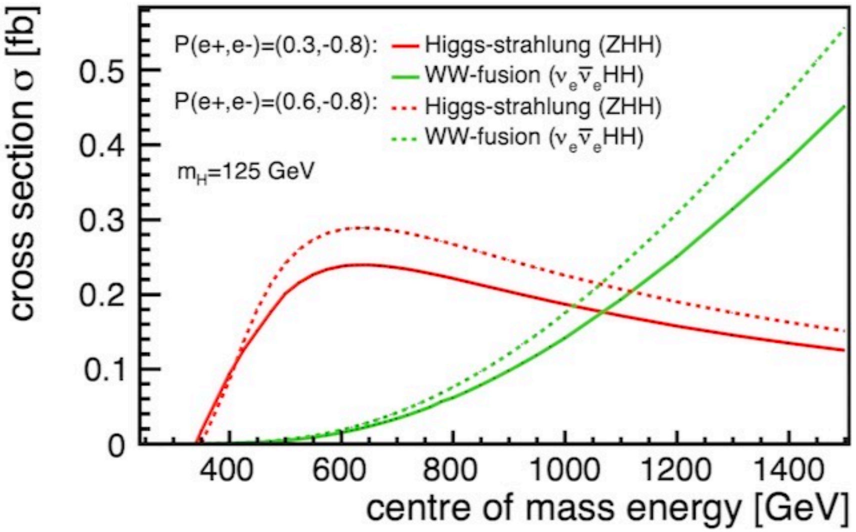


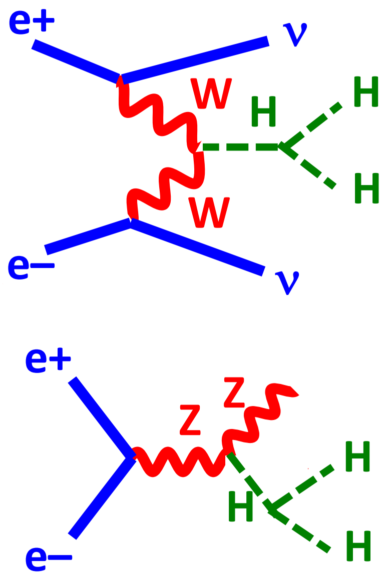
Improvements in flavour tagging

- σ x Br(cc) shows a lot of scope for improved flavour tagging!

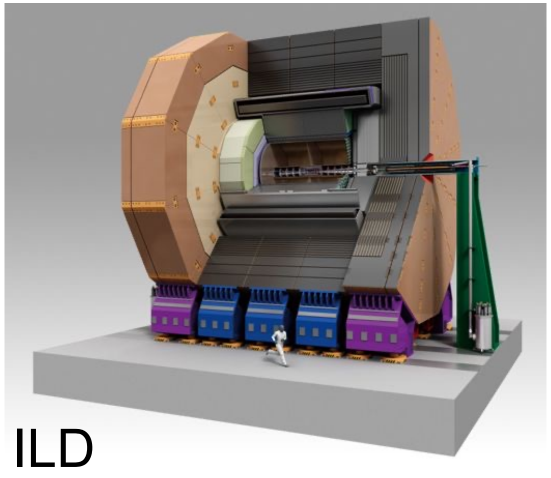


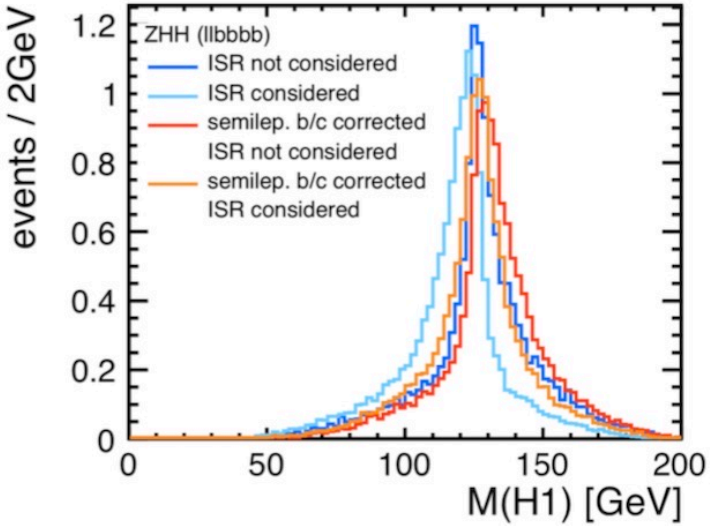
Higgs self-coupling: 0.5–1TeV

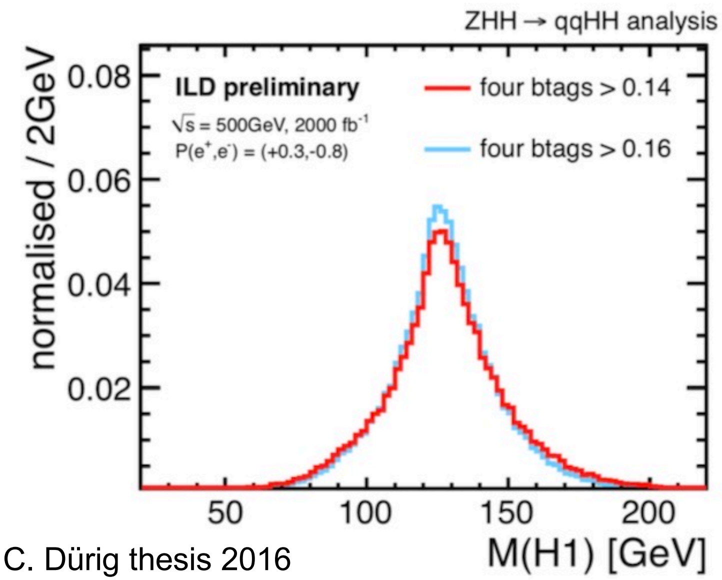




- Two contributing direct production mechanisms: ZHH and ννHH
- ZHH becomes available at ILC 500 – studied in full sim with ILD detector Z->ll / Z->qq, HH->bbbb /HH->bbWW*
- If self-coupling λ is at SM value then double-Higgs process observable at 8σ, with 27% precision on λ
- Adding ννHH at 1TeV brings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



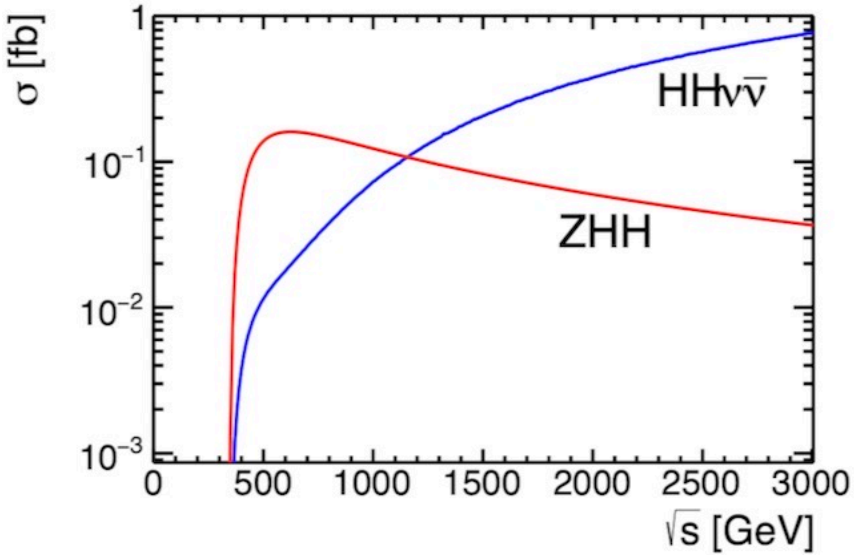




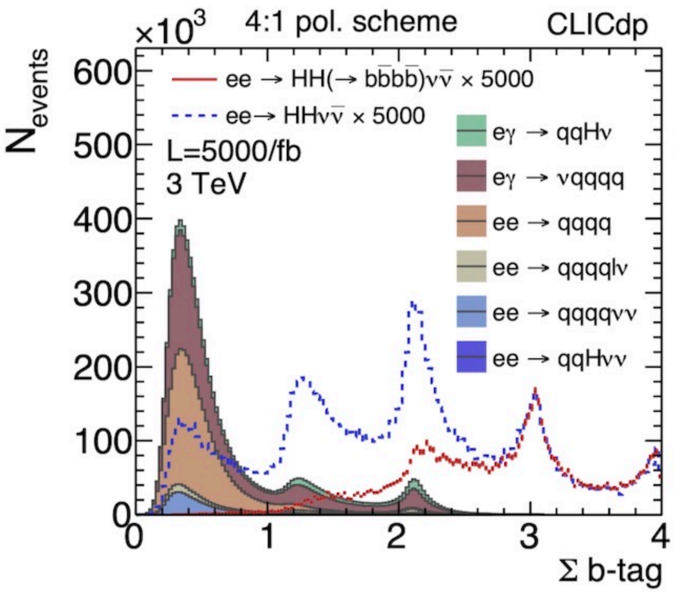
C. Dürig thesis 2016

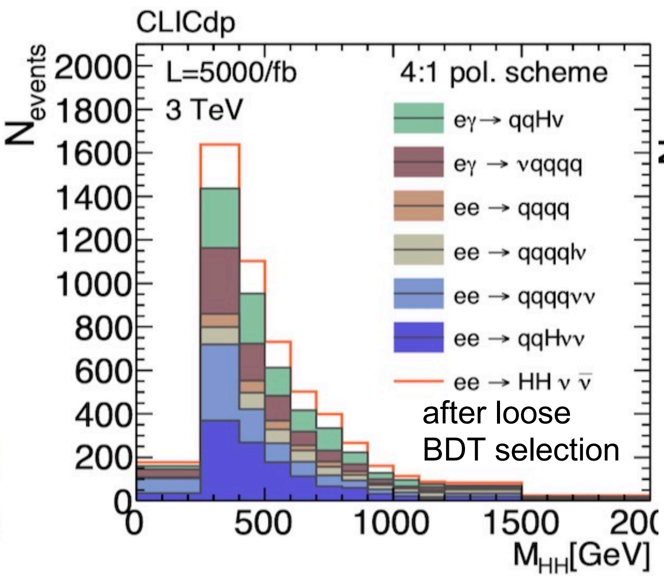
- used state-of-the-art reconstruction at the time (2016), but sensitivity very dependent on b-tagging performance, dijet mass resolution –> update is ongoing

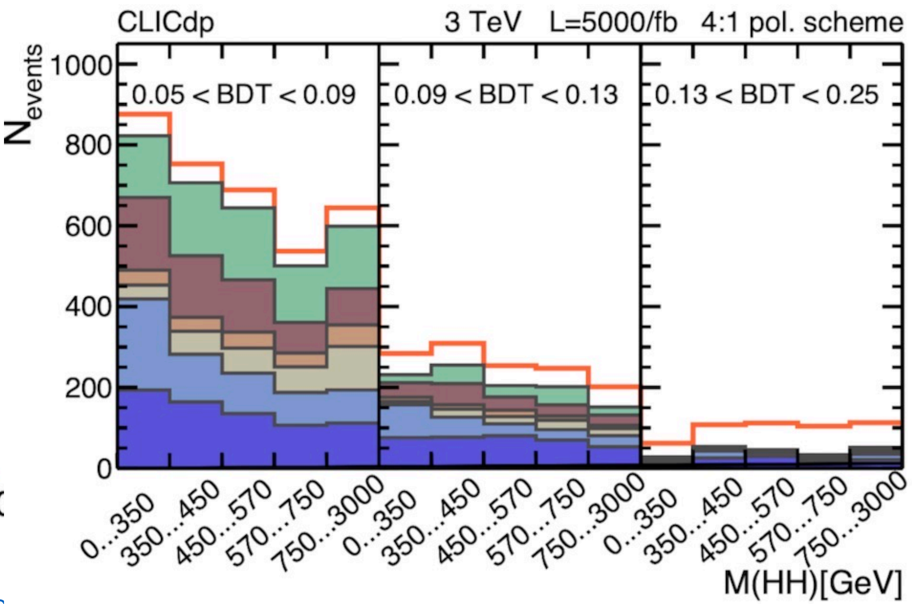
Higgs self-coupling: >1TeV



- ννHH 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

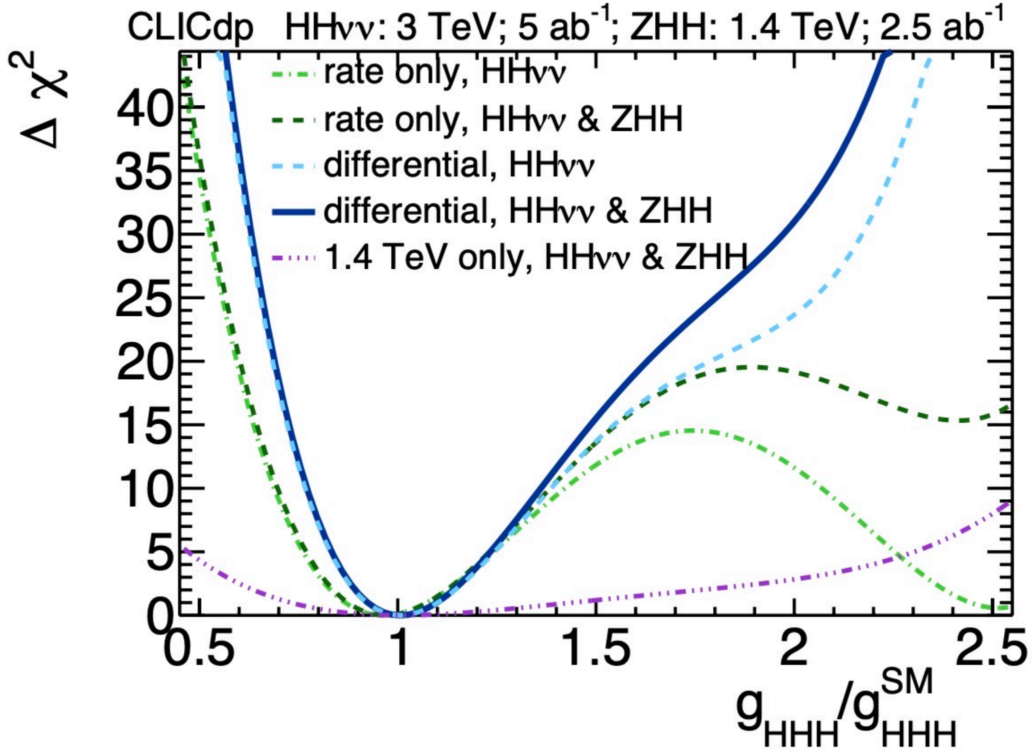


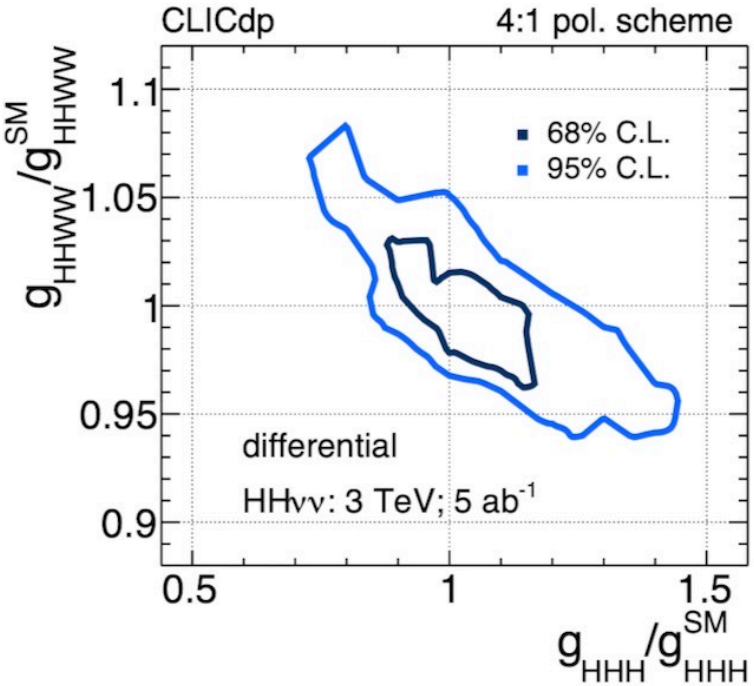




Eur. Phys. J. C 80, 1010 (2020)

Higgs self-coupling: >1TeV



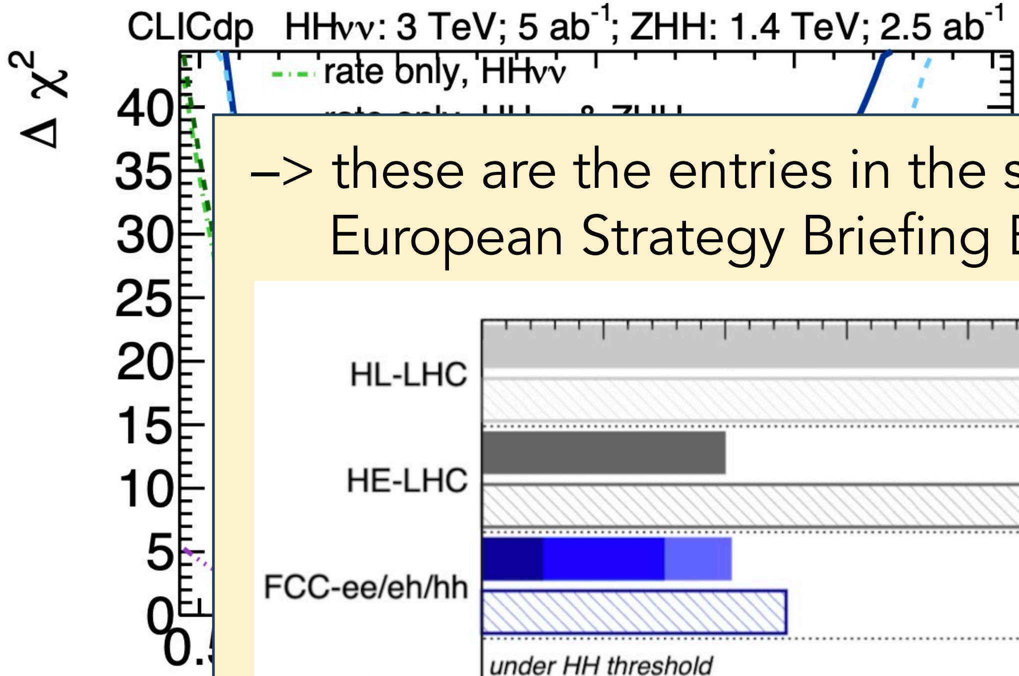


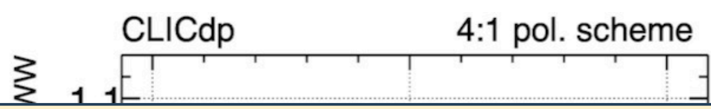
- at 1.4TeV rate-only analysis gives relative uncertainties –29% and +67% around SM value of g_{HHH}
- 3TeV differential measurement gives –8% and +11% assuming SM g_{HHWW}
- simultaneous measurement of triple and quartic couplings gives constraints below 4% in g_{HHWW} and below 20% in g_{HHH} for large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

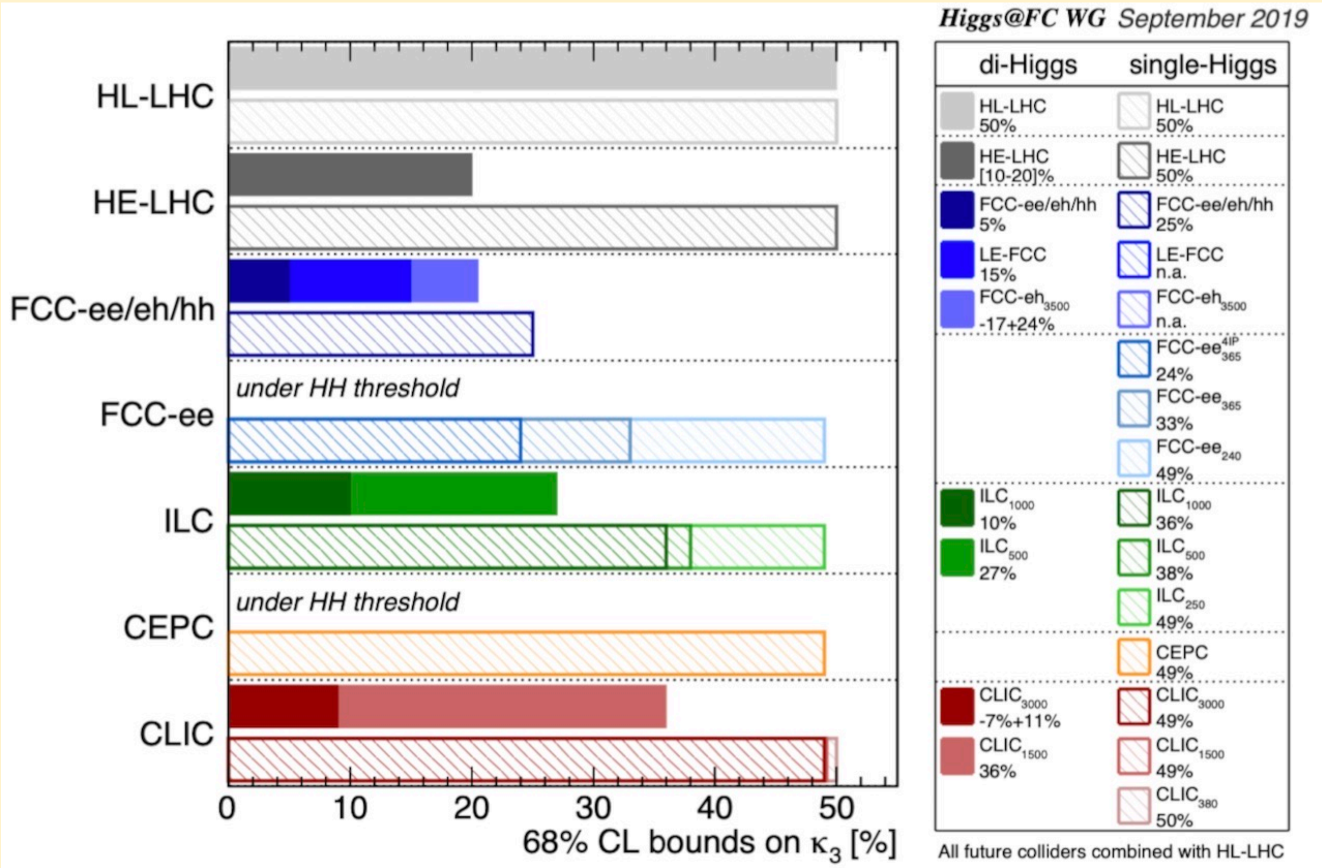
Eur. Phys. J. C 80, 1010 (2020)

Higgs self-coupling: >1TeV





–> 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

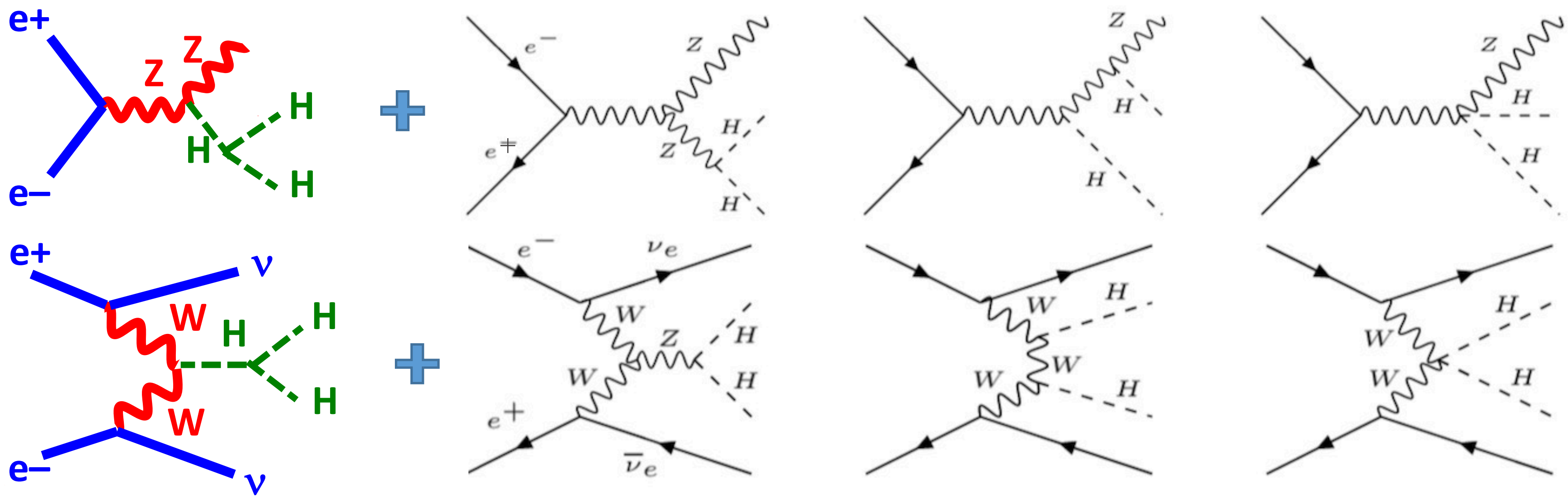
- at 1.4 … uncertai… value of …
- 3TeV … –8% and …
- simul… quartic c… 4% in g_{HHWW} and below 20% in g_{HHH} for large modifications of g_{HHWW}

	ON	
	rate-only analysis	differential analysis

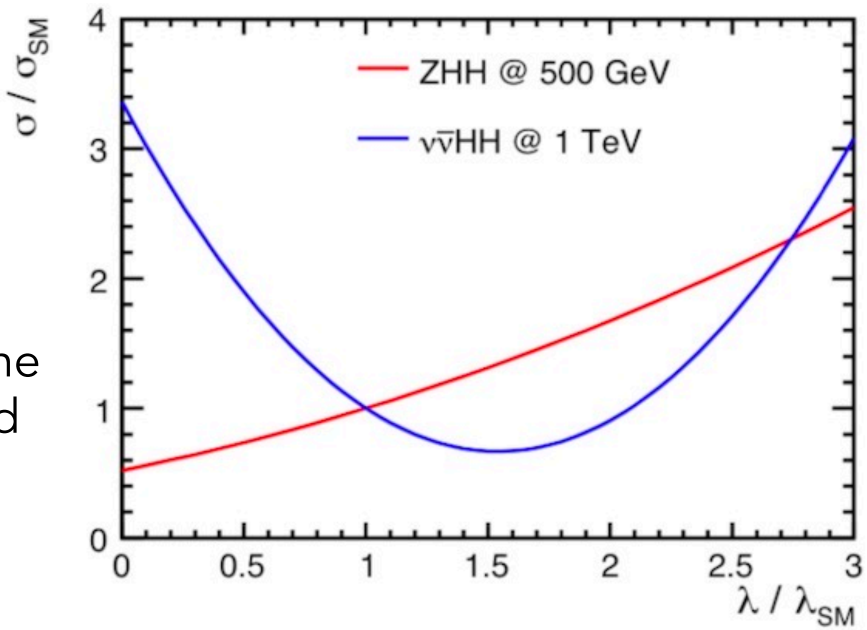
Eur. Phys. J. C 80, 1010 (2020)

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

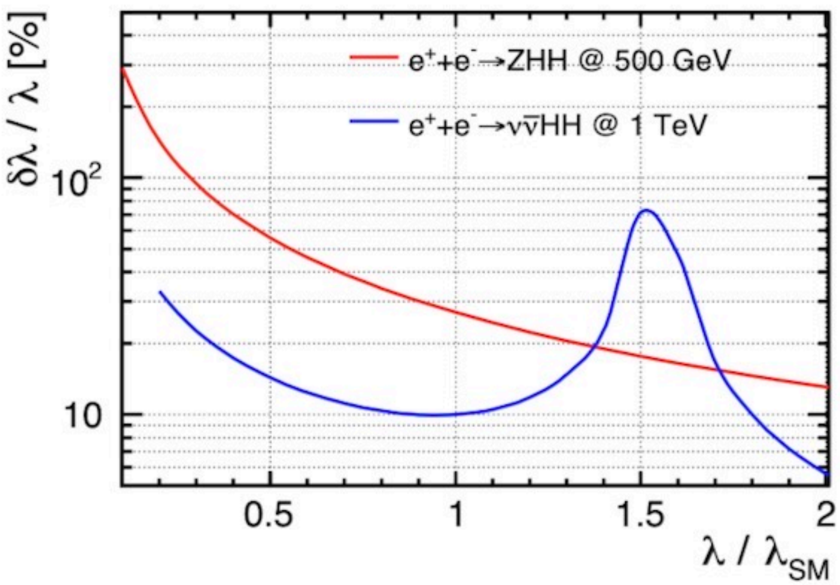


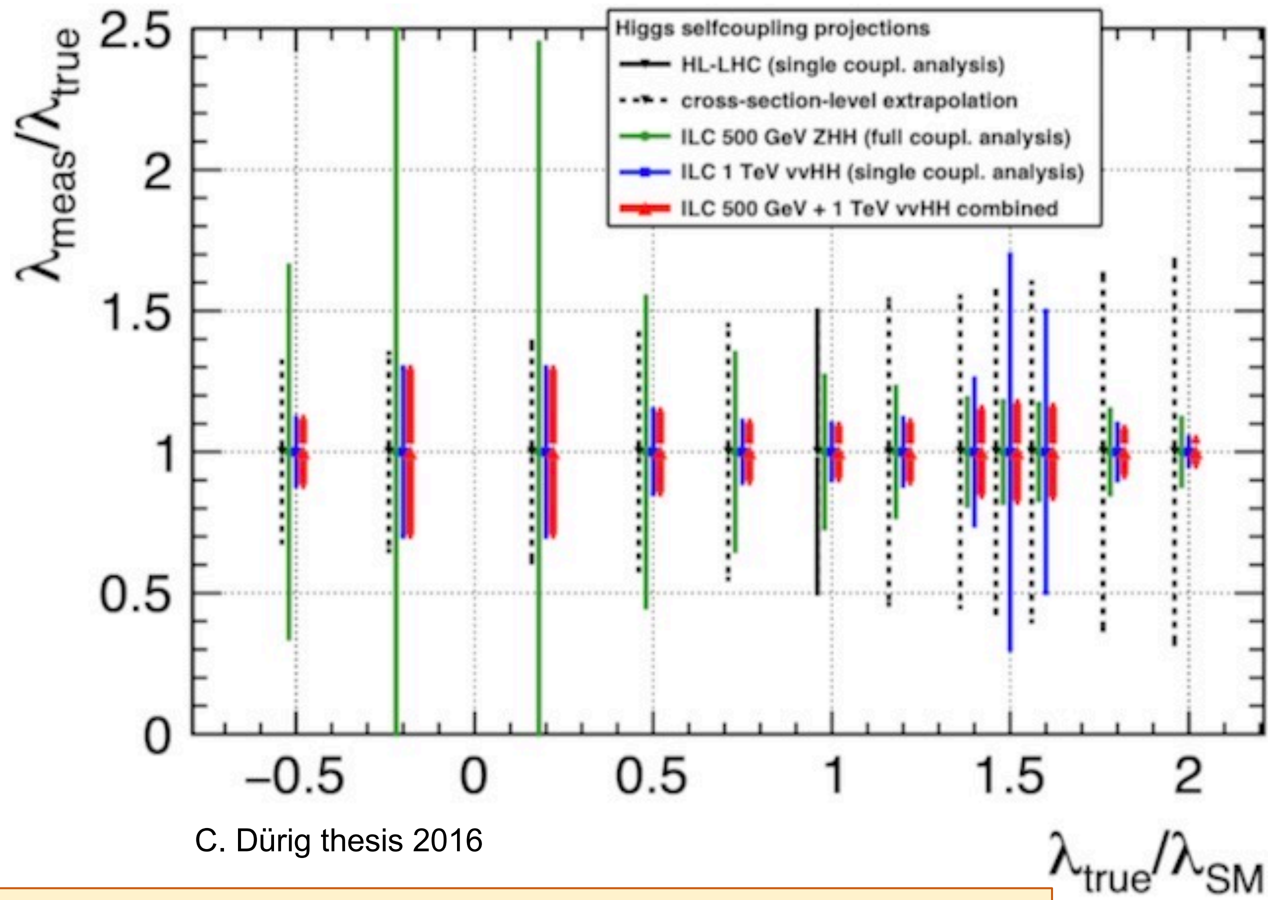
- Self-coupling diagram interferes constructively in ZHH and destructively in ννHH – whatever the sign of the deviation of κ_λ from 1, one of the processes will have an increased cross-section (and increased statistical sensitivity)



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





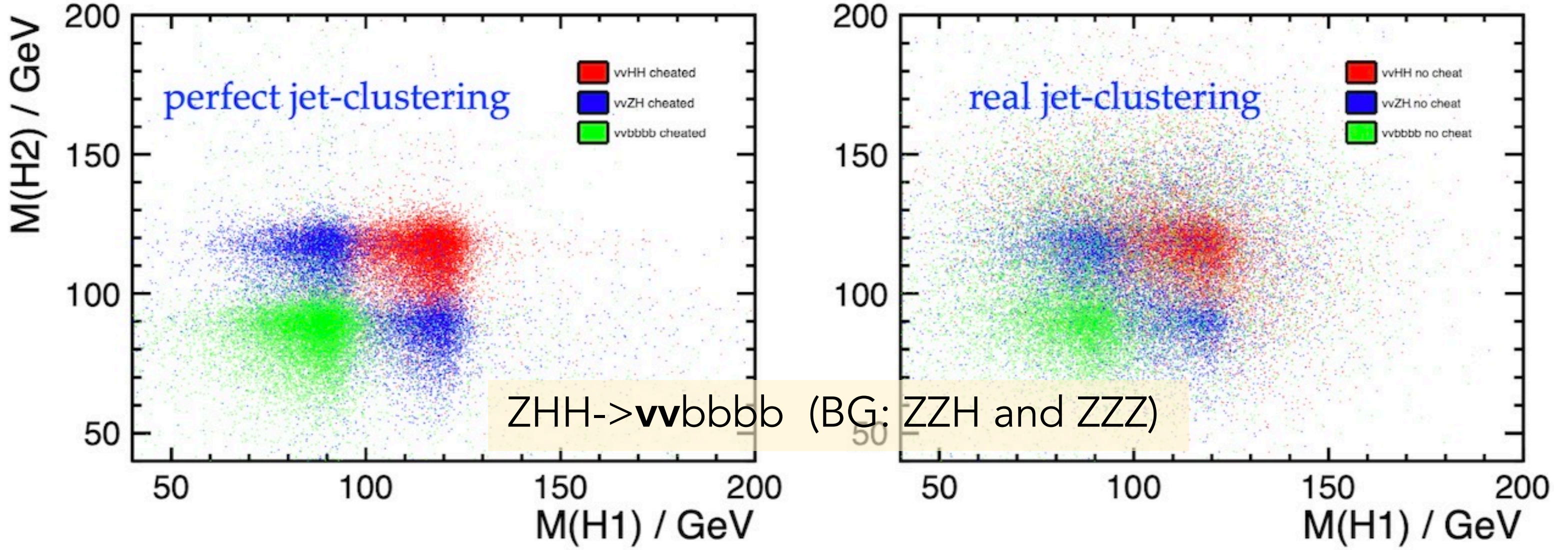
C. Dürig thesis 2016

- 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***

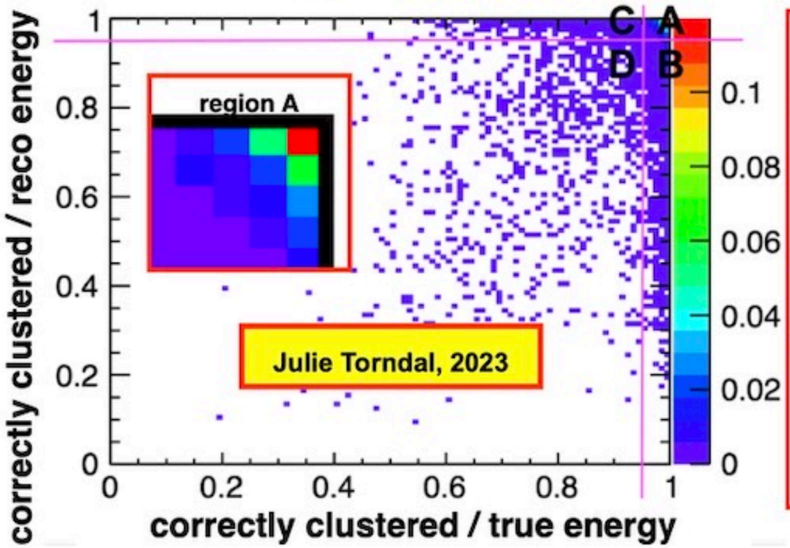
- e.g. 2HDM models where fermions couple to only one Higgs doublet allow $0.5 \lesssim \lambda/\lambda_{SM} \lesssim 1.5$, while EWK baryogenesis typically requires $1.5 \lesssim \lambda/\lambda_{SM} \lesssim 2.5$

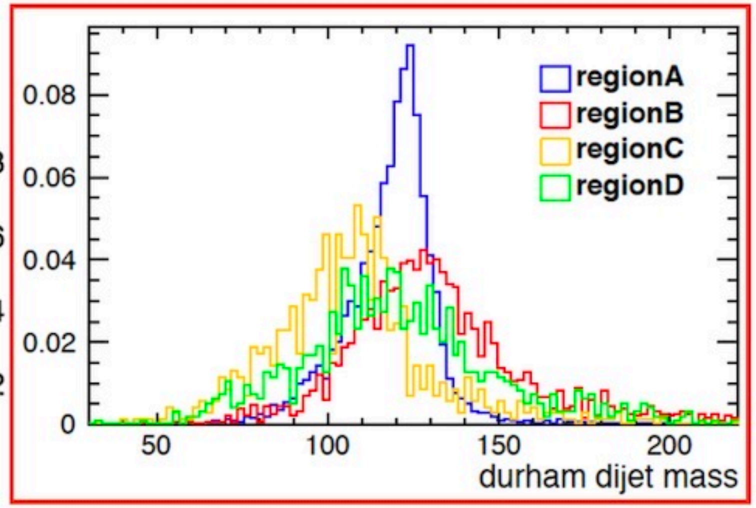
Higgs pairs – recent work / room for improvement

- mis-clustering of particles significantly degrades the separation between signal and BG!



ZHH->**vv**bbbb (BG: ZZH and ZZZ)

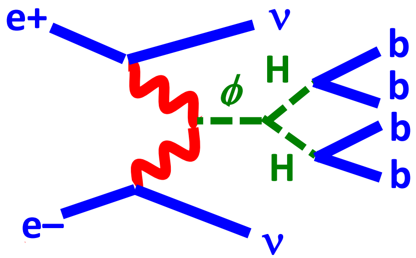


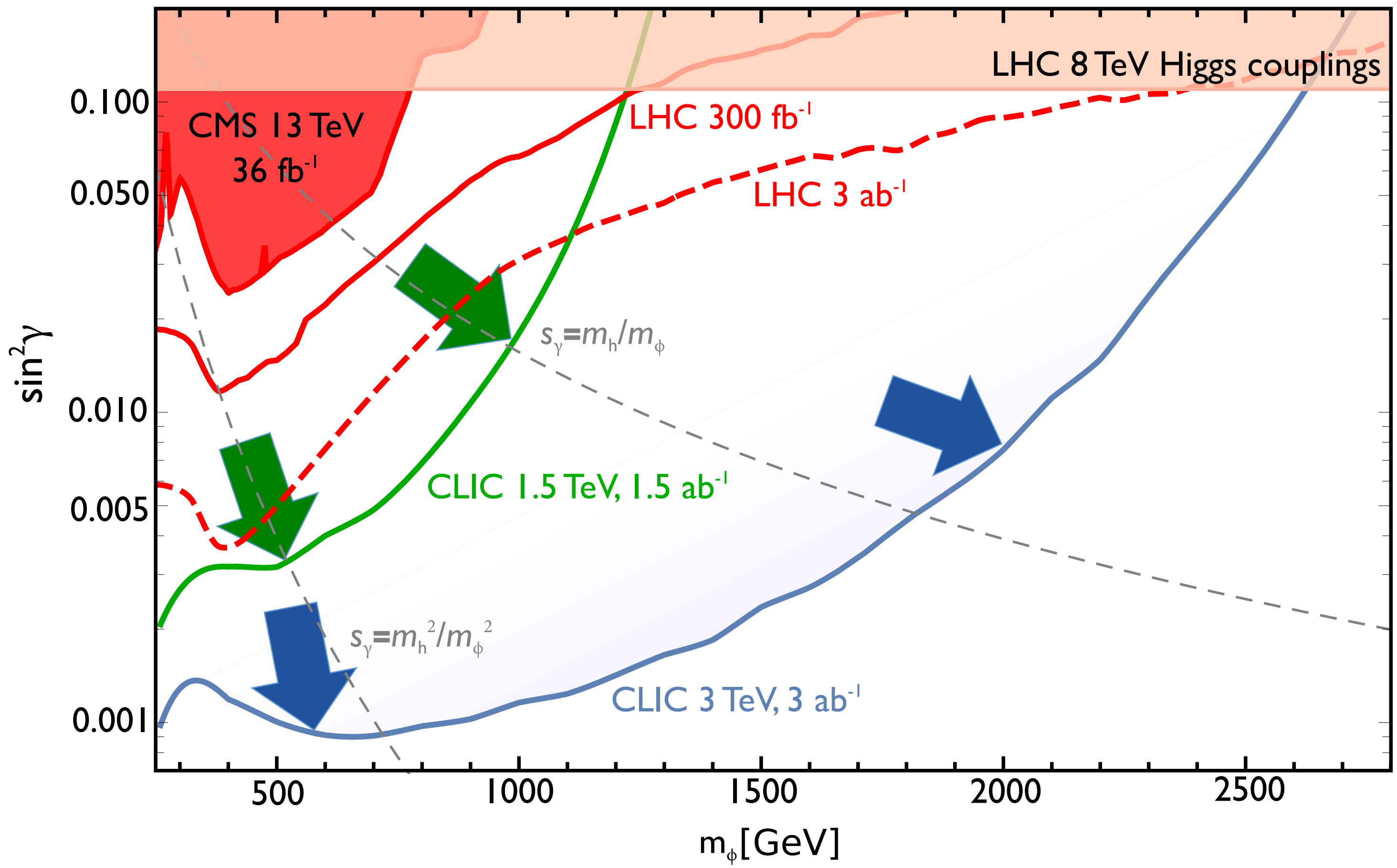


- Improvement would translate into improved sensitivity to λ.
  Study ongoing; could be helped by advanced jet clustering / ML / ... ?

BSM Models: Higgs + heavy singlet

Direct search for real scalar singlet ϕ:





arXiv:1807.04743 – Buttazzo, Redigolo, Sala, Tesi
arXiv:1812.02093 The CLIC Potential for New Physics

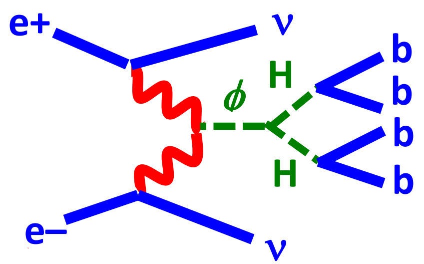
$$h = h_0 \cos\gamma + S \sin\gamma$$

$$\phi = S \cos\gamma - h_0 \sin\gamma$$

γ is mixing angle of SM-like Higgs (m_h=125GeV), and singlet-like state ϕ

BSM Models: Higgs + heavy singlet

Direct search for real scalar singlet ϕ:



Complementary:

Indirect search using Higgs couplings

arXiv: 1608.07538

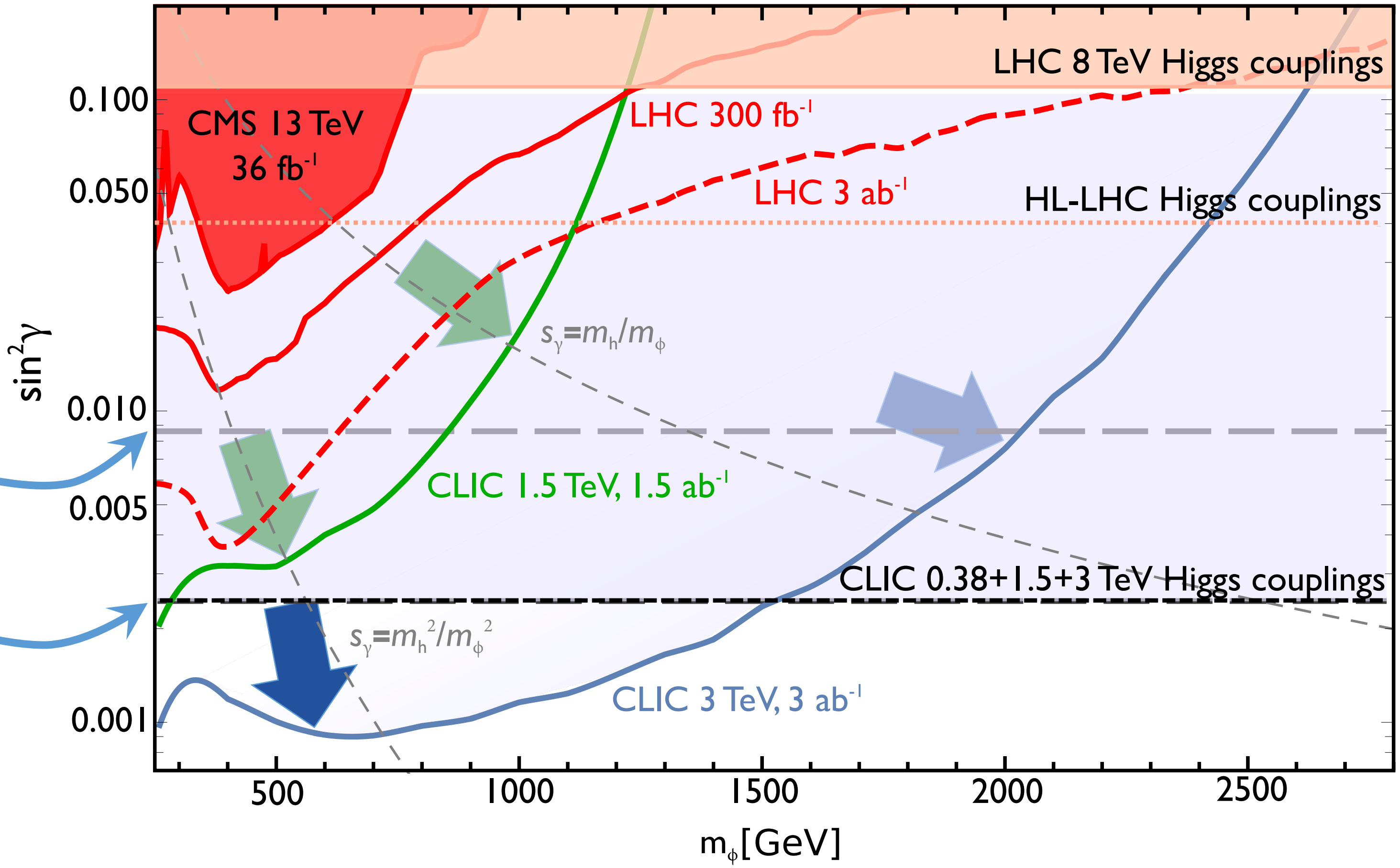
$\sin^2\gamma<0.9\%$ 95% CL (380GeV)

$\sin^2\gamma<0.24\%$ 95% CL (380GeV+1.5TeV+3TeV)

$$h = h_0 \cos\gamma + S \sin\gamma$$

$$\phi = S\cos\gamma - h_0 \sin\gamma$$

γ is mixing angle of SM-like Higgs (m_h=125GeV), and singlet-like state ϕ



arXiv:1807.04743 – Buttazzo, Redigolo, Sala, Tesi

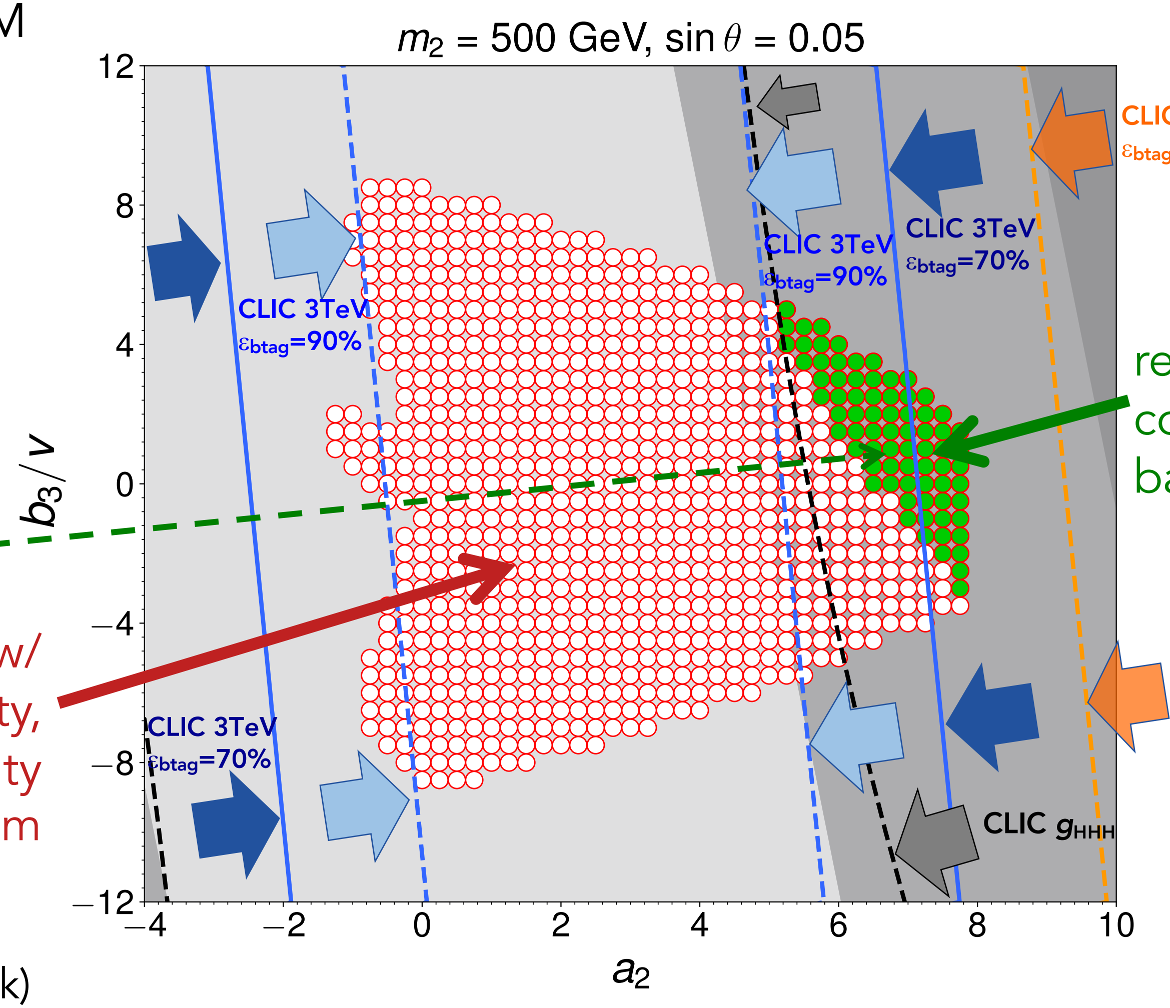
arXiv:1812.02093 The CLIC Potential for New Physics

BSM Models: Baryogenesis

- We observe a matter-dominated universe
- For baryogenesis to account for this, need to add something to the SM
- EW phase transition required to be first order
- Explored for CLIC in the Higgs+singlet model:
  resonant di-Higgs searches
  Higgs self-coupling g_{HHH}
- Sensitive to the interesting region

arXiv:1807.04284 No, Spannowsky

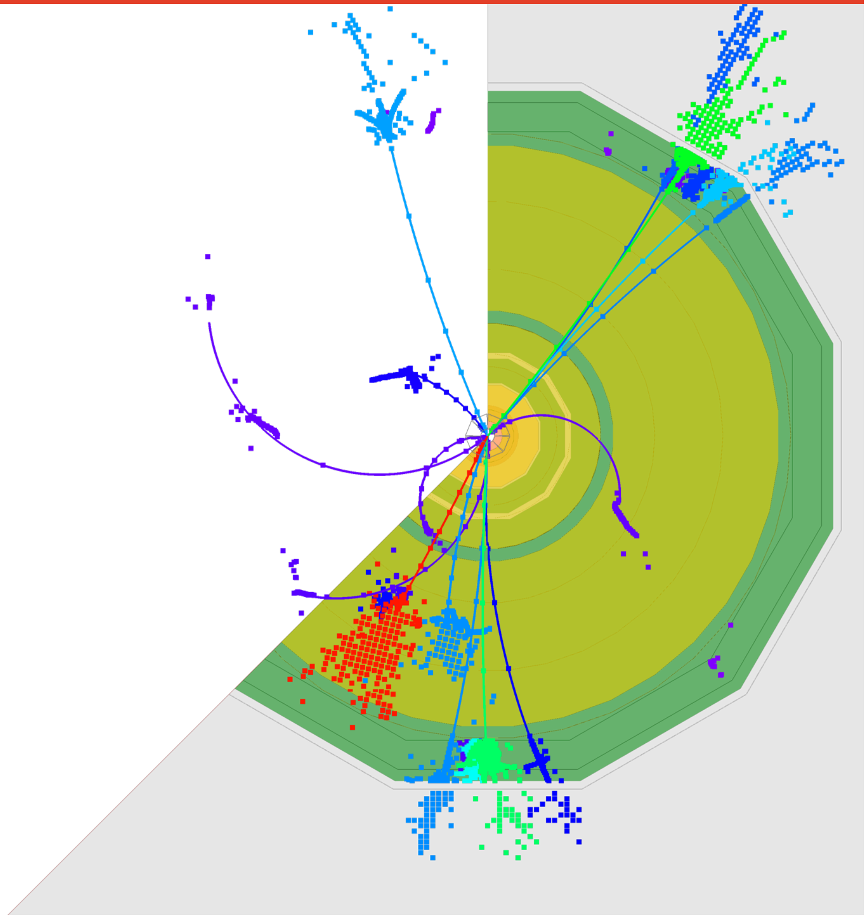
arXiv:1812.02093 The CLIC Potential for New Physics



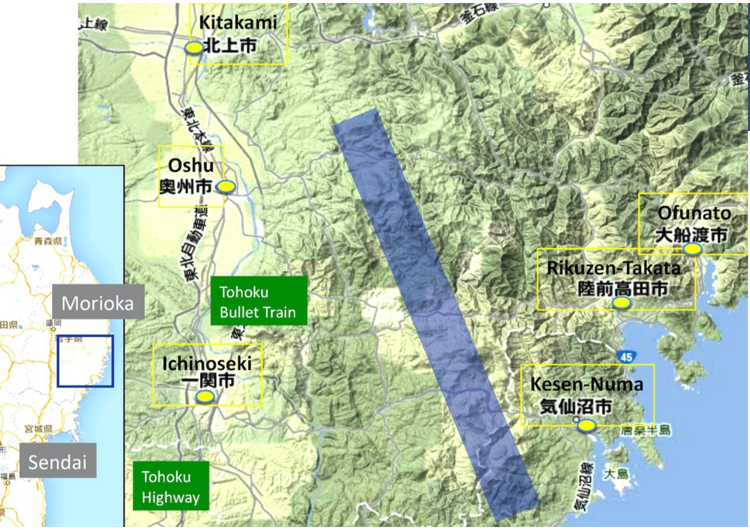
a_2 and b_3/v are parameters of the temperature-dependent effective potential; m_2 and θ are the singlet mass and mixing

well-constrained by CLIC Higgs self-coupling (black) and CLIC resonant di-Higgs searches at 1.5TeV and 3 TeV

Status of e+e– projects



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
  –> UK representation Brian Foster, Phil Burrows, Aidan Robson
- 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 this year and activity started since April; 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

THE EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

concerning

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

2023

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

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:

Main UK interests

A1 SRF
- SRF: Cavities, and Cryomodule
- Crab-cavities → Daresbury; activity coordinated by UK
- Main Linac quads and cold BPMs

A2 Sources
- Pulsed magnet
- Wheel/target → Prototype rotating wheel done in UK

A3 Damping Ring including kickers → Strong synergy with Diamond 2 upgrade
- Low Emittance Ring lab

A4 ATF activities for final focus, nanobeams, MDI → John Adams Inst

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

Synergies also with CLIC

- Updated working timeline:

Technology Network Phase				Preparatory Phase			Construction Phase ~10 years for the construction and commissioning						
2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	• • •

R&D and effort to gain a common view and understanding.

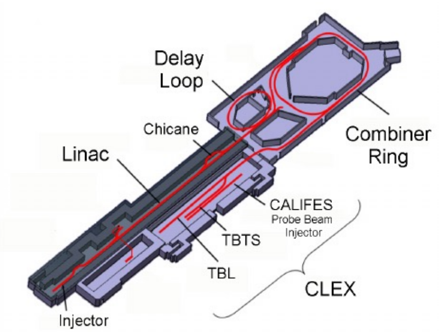
ILC preparation laboratory and intergovernmental discussion

To first physics ~2038

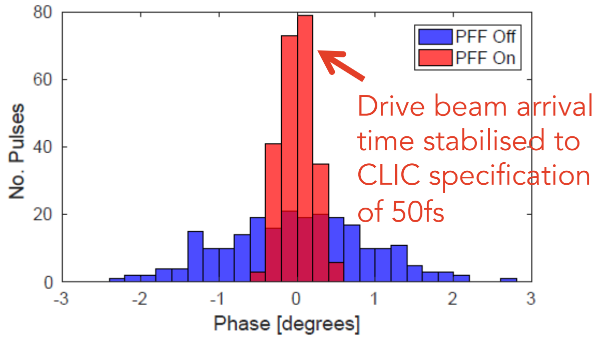
- Federation of Diet Members for the ILC has been reactivated, April 2023

CLIC Project

High-current drive beam bunched at 12 GHz



Produced at CLIC Test Facility CTF3

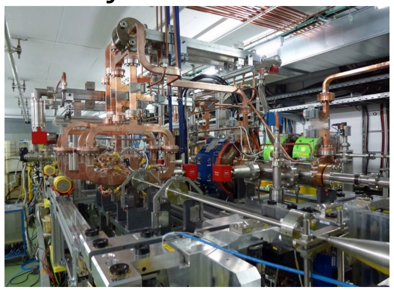


~100 MV/m gradient in main-beam cavities

Achieved in structures produced by different sources

Power transfer + main-beam acceleration

Demonstrated 2-beam acceleration



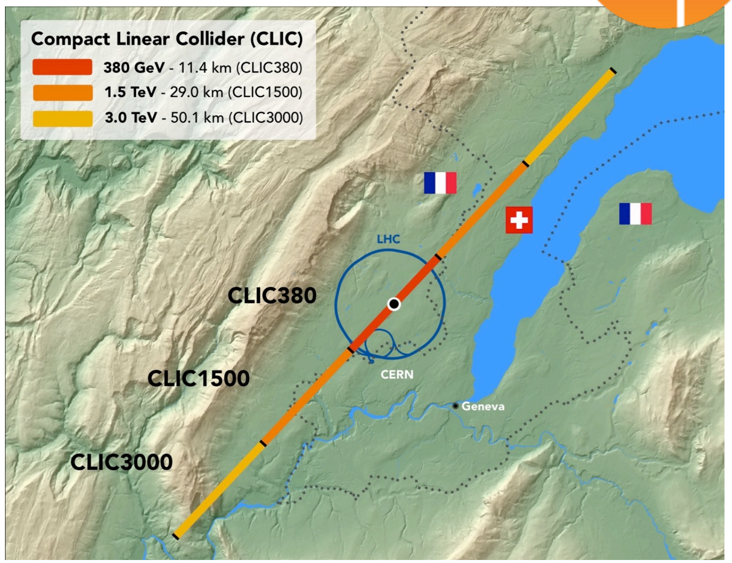
Alignment & stability

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



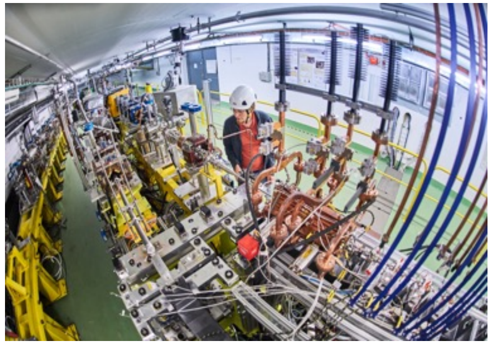
- Following the European Strategy Update, CLIC is maintained at CERN –> if the FCC feasibility study is not conclusive then CLIC could be implemented in an expeditious way
- 2021-25 programme continues CLIC as an option for a Higgs/top accelerator facility at CERN, and is pursuing high-gradient R&D and 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: 1.5×10^{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 2.3×10^{34} cm^{-2} s^{-1}

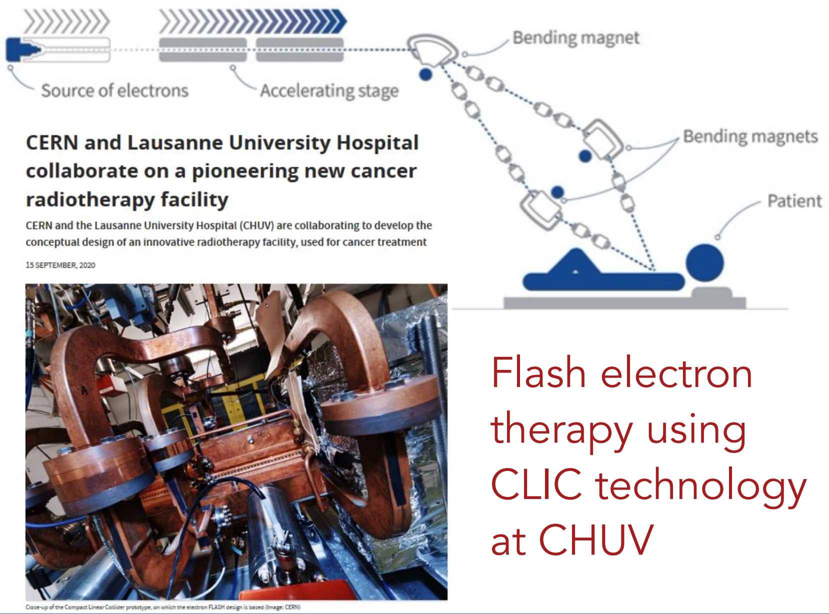


◆ X-band technology readiness for the 380 GeV CLIC initial phase - more and more driven by use in small compact accelerators

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



Flash electron therapy using CLIC technology at CHUV

C^3 studies

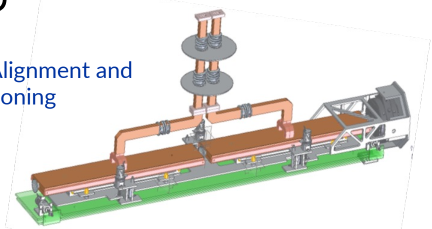
8 km footprint for 250/550 GeV CoM ⟹ 70/120 MeV/m

Large portions of accelerator complex are compatible between LC technologies

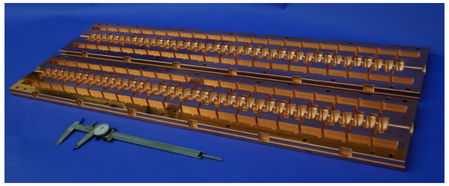
- Beam delivery and IP modified from ILC (1.5 km for 550 GeV CoM)
- Damping rings and injectors to be optimized with CLIC as baseline
- Reliant on work done by CLIC and ILC to make progress

Ongoing work:

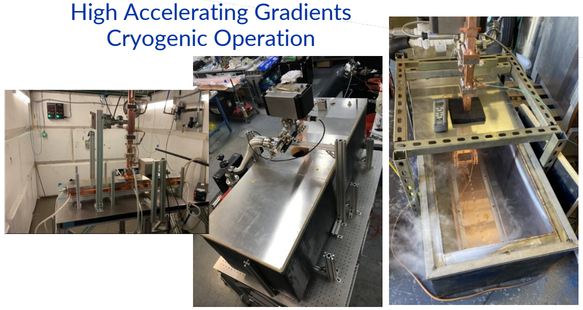
Preliminary Alignment and Positioning



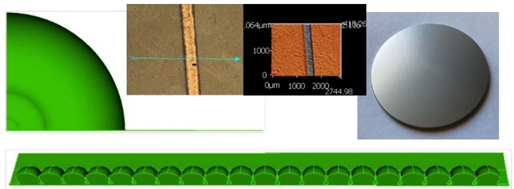
Modern Manufacturing Prototype One Meter Structure

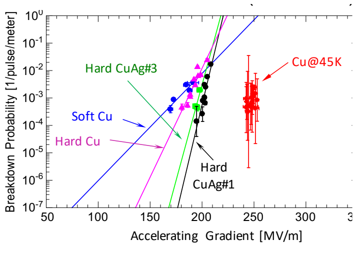


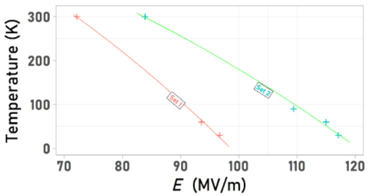
High Accelerating Gradients Cryogenic Operation



Integrated Damping Slot Damping with NiChrome Coating

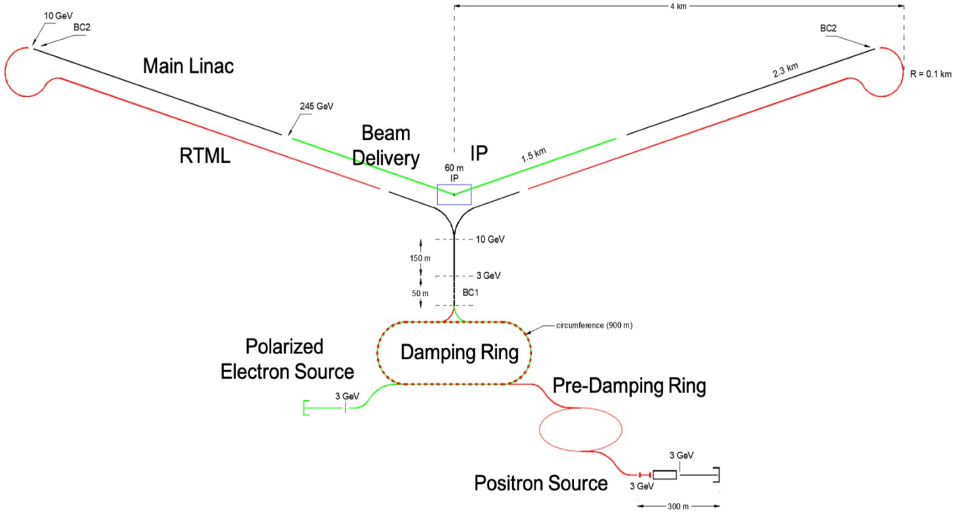






Cryo-cooled copper

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



C^3 Parameters

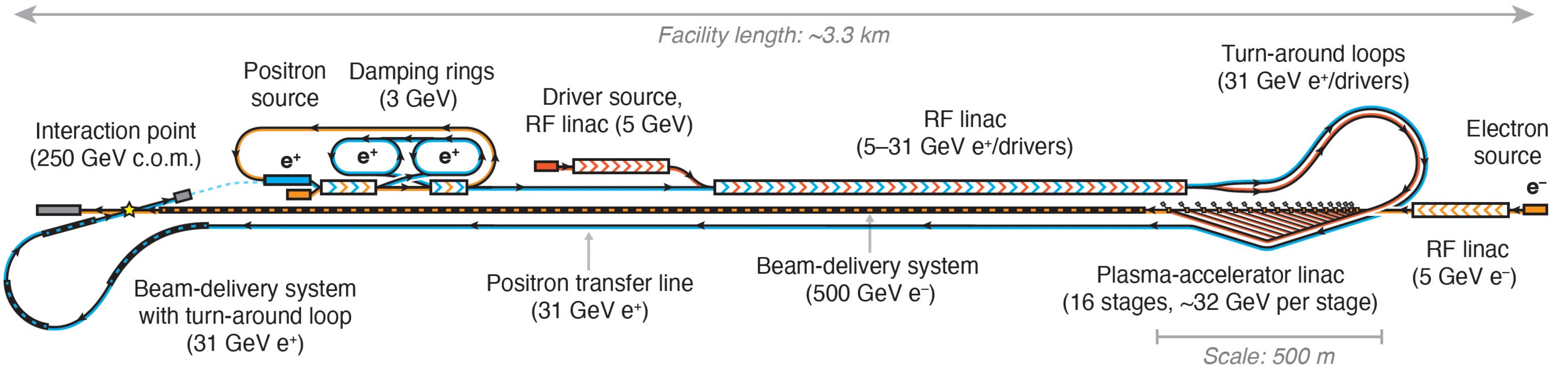
Collider	C^3	C^3
CM Energy [GeV]	250	550
Luminosity [x10^{34}]	1.3	2.4
Gradient [MeV/m]	70	120
Effective Gradient [MeV/m]	63	108
Length [km]	8	8
Num. Bunches per Train	133	75
Train Rep. Rate [Hz]	120	120
Bunch Spacing [ns]	5.26	3.5
Bunch Charge [nC]	1	1
Crossing Angle [rad]	0.014	0.014
Site Power [MW]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

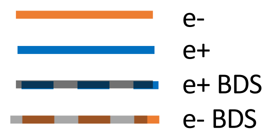
- Currently looking for R&D support recommendation from US P5 committee
- Optimistic scenario: construction 2030; first collisions 2040

HALHF

Hybrid Asymmetric Linear Higgs Factory

https://arxiv.org/2303.10150





- 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

Flexibility

- Key advantage of linear machines is flexibility in run scenarios
  –> allows to adapt to external factors (physics landscape / budgetary)

  - Options studied in detail:
    ILC at 250, (350), 500 GeV; 1 TeV
    CLIC at 380 GeV, 1.5 TeV, 3 TeV

  - ***But*** these are 'just' benchmarks;
    CLIC could be built with initial stage at 250, or a stage at 500;
    ILC could be built at 380
    –> these are physics choices to be made

  - And e.g. ILC could also 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
$g^{eff}_{HZZ}[\%]$	$SMEFT_{ND}$	3.6	0.3	0.2	0.5	0.3
$g^{eff}_{HWW}[\%]$	$SMEFT_{ND}$	3.2	0.3	0.2	0.5	0.3
$g^{eff}_{H\gamma\gamma}[\%]$	$SMEFT_{ND}$	3.6	1.3	1.3	1.3	1.2
$g^{eff}_{HZ\gamma}[\%]$	$SMEFT_{ND}$	11.	9.3	4.6	9.8	9.3
$g^{eff}_{Hgg}[\%]$	$SMEFT_{ND}$	2.3	0.9	1.0	1.0	0.8
$g^{eff}_{Htt}[\%]$	$SMEFT_{ND}$	3.5	3.1	2.2	3.1	3.1
$g^{eff}_{Hcc}[\%]$	$SMEFT_{ND}$	–	2.1	1.8	1.4	1.2
$g^{eff}_{Hbb}[\%]$	$SMEFT_{ND}$	5.3	0.6	0.4	0.7	0.6
$g^{eff}_{H\tau\tau}[\%]$	$SMEFT_{ND}$	3.4	1.0	0.9	0.7	0.6
$g^{eff}_{H\mu\mu}[\%]$	$SMEFT_{ND}$	5.5	4.3	4.1	4.	3.8
$\delta g_{1Z}[\times 10^2]$	$SMEFT_{ND}$	0.66	0.027	0.013	0.085	0.036
$\delta \kappa_\gamma[\times 10^2]$	$SMEFT_{ND}$	3.2	0.032	0.044	0.086	0.049
$\lambda_Z[\times 10^2]$	$SMEFT_{ND}$	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

Sustainability

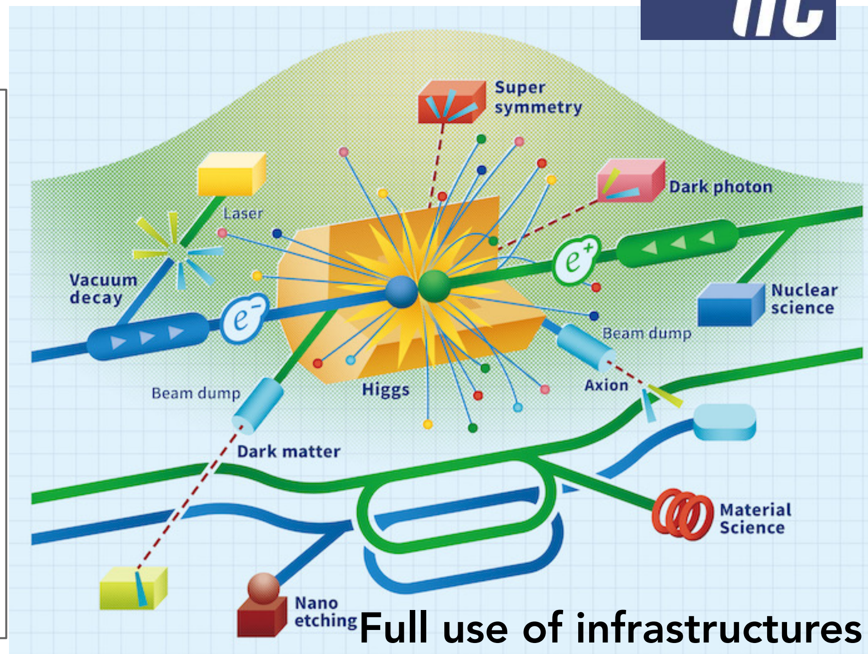
CLIC Power Efficiency:

Improving power efficiency for both initial phase & high energies

Power estimate bottom up (concentrating on 380 GeV systems)

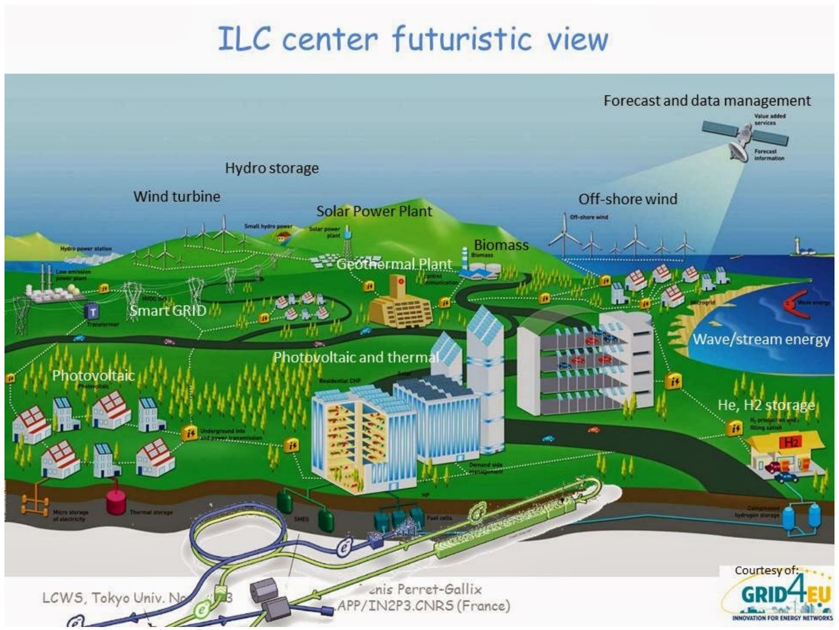
- Very large reductions since CDR, much more optimized drivebeam complex and more efficient klystrons, injectors more optimized, main target damping ring RF significantly reduced, recent L-band klystron studies, and also better estimates of nominal settings.

Power 110MW; energy consumption ~0.6 TWh yearly, CERN is currently (when running) at 1.2 TWh (~90% in accelerators)



Full use of infrastructures

Towards 'Green ILC':



Lifecycle assessment:

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

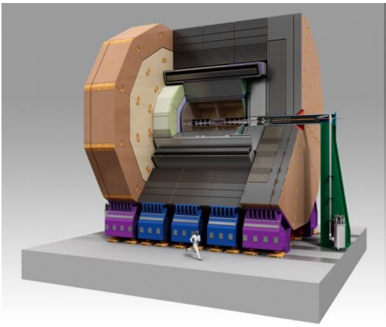
Assesses Global Warming Potential of underground civil engineering – raw materials, transport, construction activities (not the accelerator components). Bottom line:

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

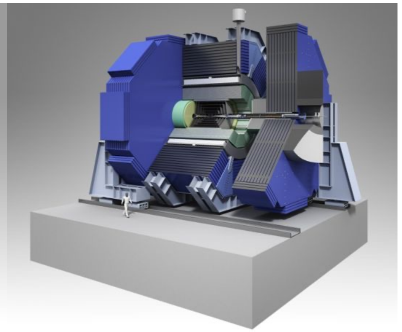
ILC 250GeV:
266kton CO2-eq

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

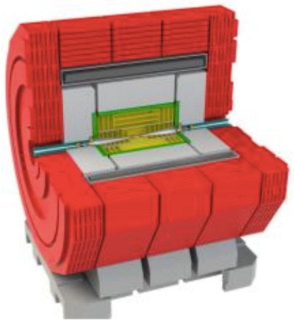
Detectors & software



ILD



SiD



CLICdet

ILC & CLIC have well-developed detector concepts – Individual specific requirements from accelerator environment, but also many common aspects:

- detector concepts
- detector technologies
- software tools
- physics studies

UK has strong history & ongoing participation in ILD, SiD, CLICdp

- almost all LC studies based on Pandora C++ software development kit (Cambridge/Warwick)
- almost all LC studies use LCFIVertex flavour-tagging s/w (written in UK, now maintained in Japan)
- physics studies e.g. ZH hadronic recoil -> critical staging choices for linear colliders
- provided new ECAL simulation model for ILD
- provided complete new simulation model for SiD

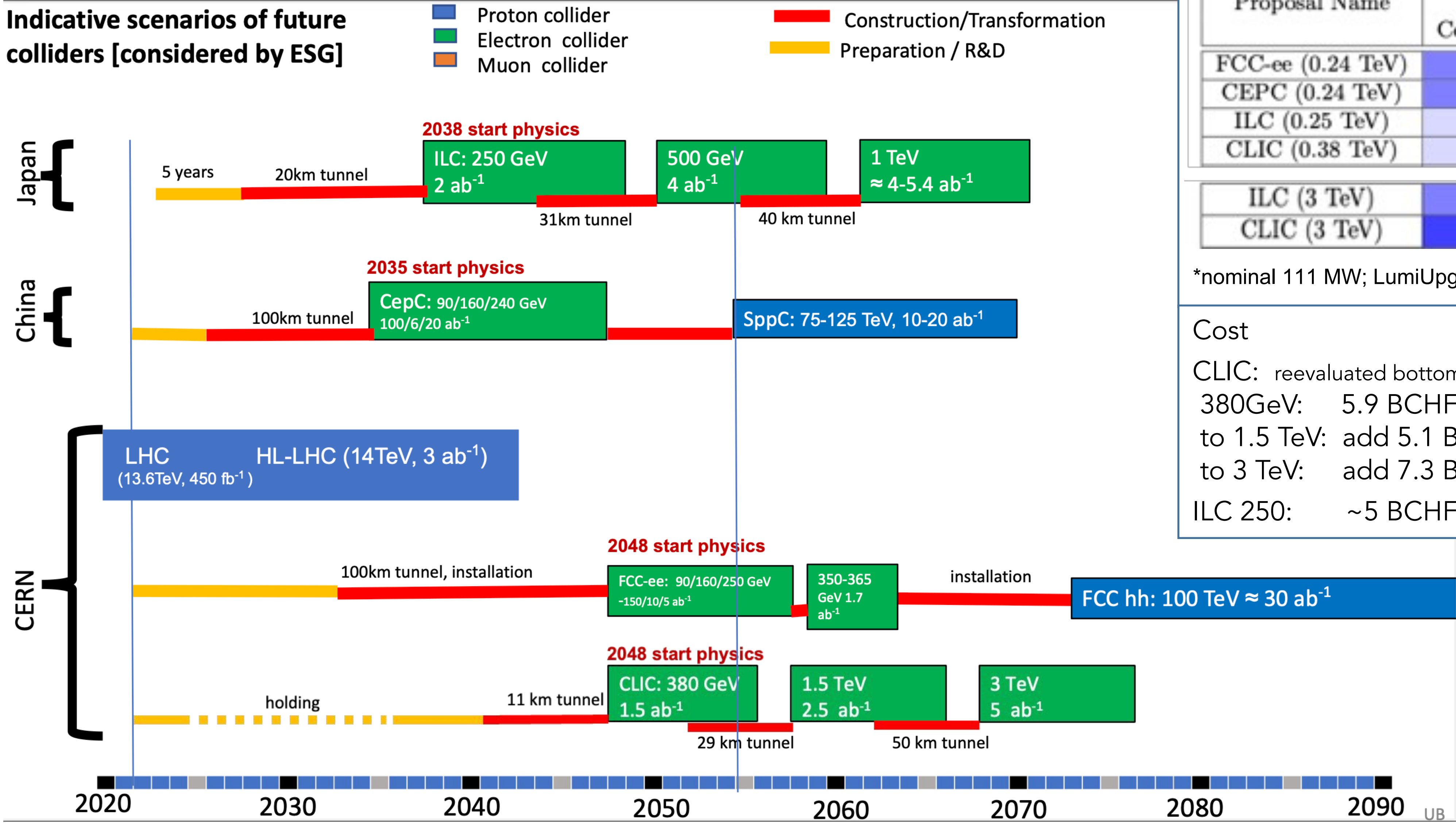
Recent focus on linked efforts: via DRDs on hardware and via ECFA to identify commonalities and complementarities, and to share expertise

UK aligned hardware interests in silicon vertexing/tracking, calorimetry, DAQ

– contact maintained through loose 'LCUK' collaboration with representative from (almost) every UK group

- PhDs in last 6 years in Linear Colliders from:
  Cambridge [reconstruction, calorimeter optimization, Higgs & EWK studies]
  Edinburgh [Higgs studies]
  Glasgow [CLICpix]
  Sussex [DAQ & Higgs studies]
  Birmingham [digital calorimetry & top studies]
  Oxford [accelerator physics]

Timeline, cost, power



Power
from Snowmass implementation taskforce

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

*nominal 111 MW; LumiUpgrade 138MW

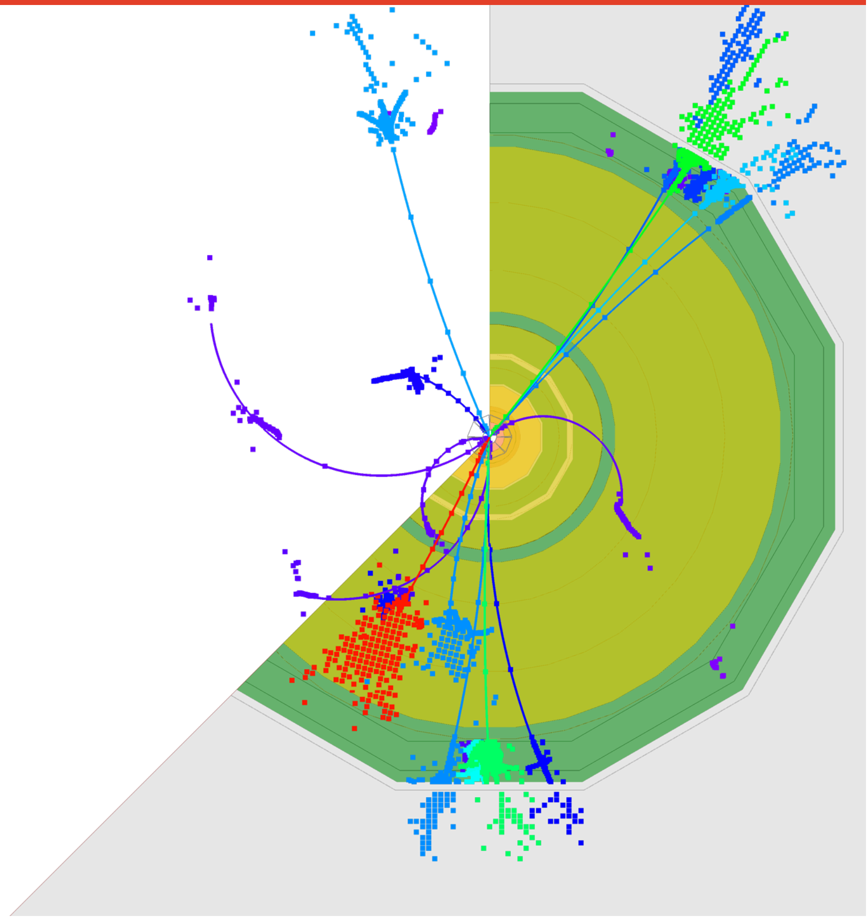
Cost

CLIC: reevaluated bottom-up 2017–18
380GeV: 5.9 BCHF
to 1.5 TeV: add 5.1 BCHF
to 3 TeV: add 7.3 BCHF

ILC 250: ~5 BCHF

- 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

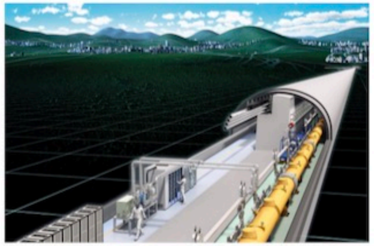
ECFA study

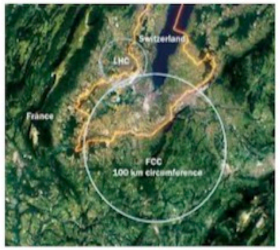


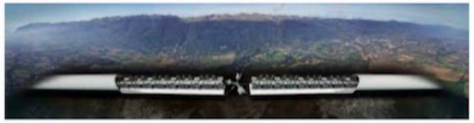
ECFA Study on Higgs/top/electroweak factories

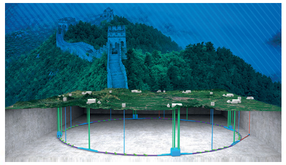
- Study mandated by ECFA to respond coherently to the European Strategy's statement on the highest-priority next collider – ***working together cross-project***

> *ECFA recognizes the need for the experimental and theoretical communities involved in physics studies, experiment designs and detector technologies at future Higgs factories to gather.* ***ECFA supports a series of workshops*** *with the aim to* ***share challenges and expertise, to explore synergies in their efforts*** *and to respond coherently to this priority in the European Strategy for Particle Physics (ESPP).*
>
> *Goal: bring the entire e^+e^- Higgs factory effort together, foster cooperation across various projects; collaborative research programmes are to emerge*



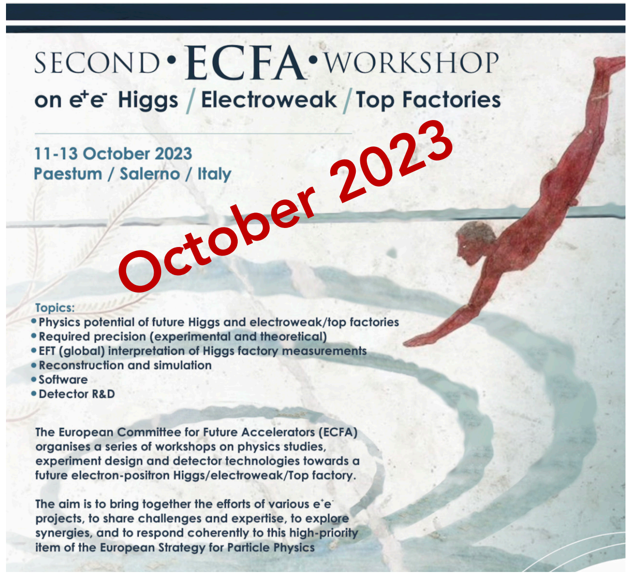






–> Build on previous coherent efforts
e.g. Higgs@FutureColliders working group
for last European Strategy Update

- Structure of the study:
  - Activities organised via three Working Groups
  - Two major workshops so far
  - ECFA Report as input to next European Strategy



ECFA Study on Higgs/top/electroweak factories

- Major element of 2023 workshop: converging on definition of 14 ***Focus Topics***

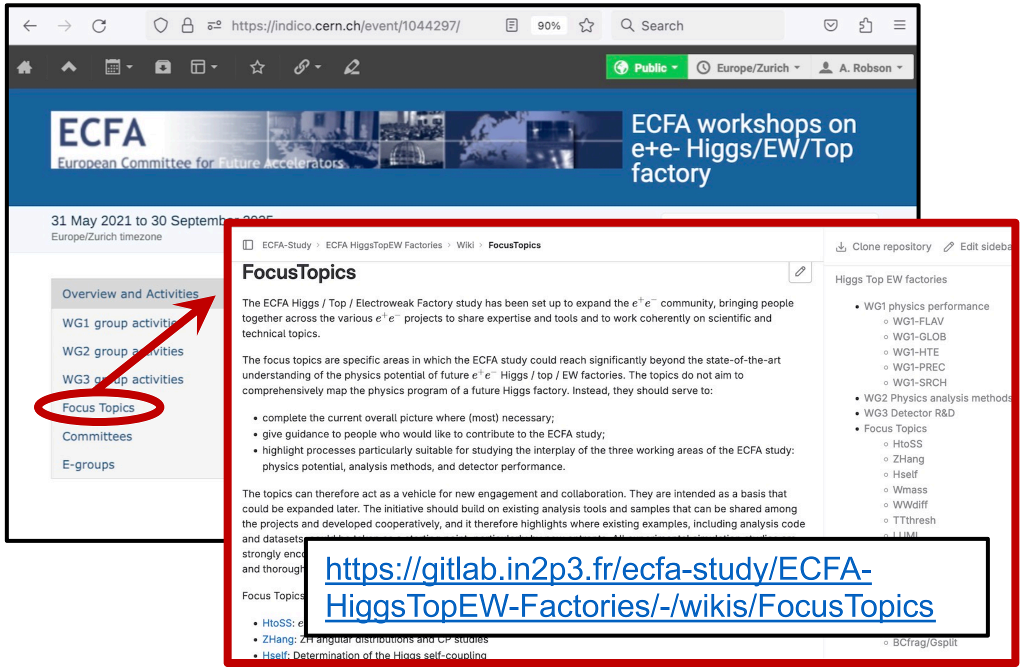
> Focus topics are intended to encompass a wide range of activities spanning theory & experiment, analysis & algorithm development, and detector requirements & optimisation

- Overall aim: accumulate critical mass working on each topic, reaching publications on timescale of ECFA study
  –> excellent place to join if you would like to start working on e+e–

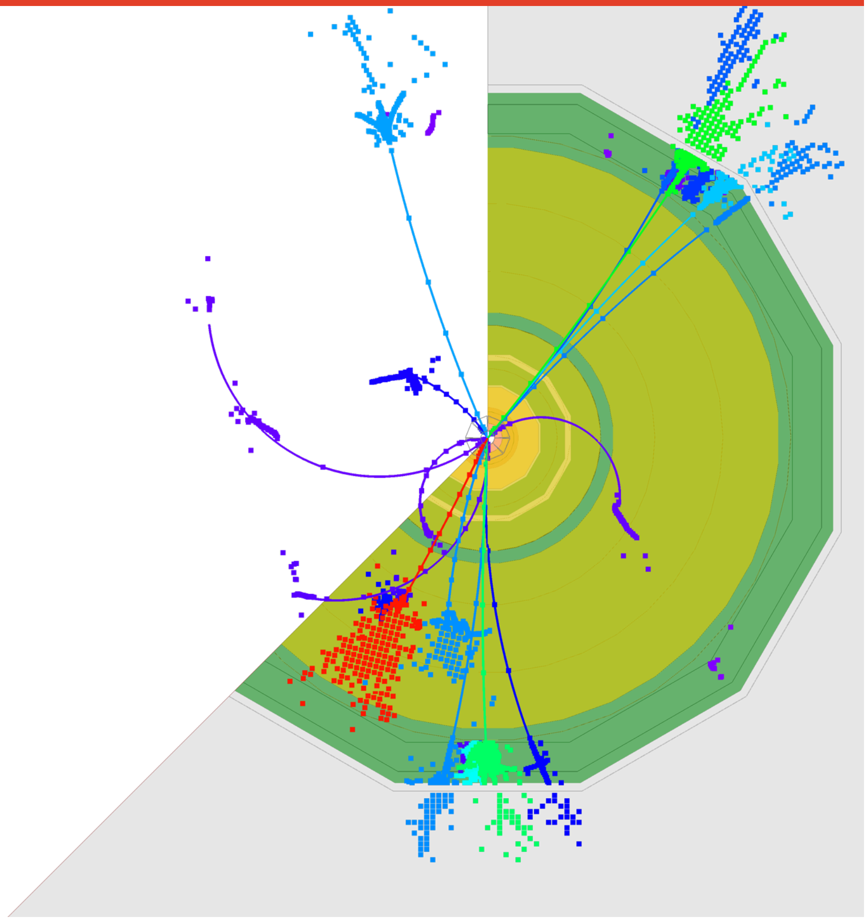
- HtoSS: $e^+e^- \to Zh$: $h \to ss$
- ZHang: ZH angular distributions and CP studies
- Hself: Determination of the Higgs self-coupling
- Wmass: Mass and width of the W boson
- WWdiff: Full studies of WW and evW
- TTthresh: Top threshold - detector-level studies of $e^+e^- \to t\bar{t}$
- LUMI: Precision luminosity measurement
- EXscalar: New exotic scalars
- LLPs: Long-lived particles
- EXtt: Exotic top decays
- CKMWW: CKM matrix elements with on-shell and boosted W decays
- BKtautau: $B^0 \to K^{0*}\tau^+\tau^-$
- TwoF: EW precision - 2-fermion final states
- BCfrag/Gsplit: Measurement of b- and c-fragmentation functions and hadronisation rates and measurement of gluon splitting to bb / cc

Planning a UK meeting in spring 2024; for now all information on web:

https://indico.cern.ch/event/1044297/



Summary



Linear Colliders vision

- ILC and CLIC are mature options for a Higgs factory; C^3 and HALHF could be interesting alternatives
- Flexibility with a LC:
  - Starting from initial Linear Collider: can be followed 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
- User community:
  - One or two main collider experiments (ILC baseline is push-pull; CLIC380 has studied two IPs)
  - "Diversity programme" using injectors, single beams, "long range" effects for axion searches / LLPs etc (much more to explore)

The LC "vision" is a balanced programme over the next 20-30 years for:

- a Higgs factory as soon as possible, upgradable
- R&D for the machine beyond, no constraints imposed by the LC
- a strong diversified programme using the LC complex
- and HL-LHC of course!