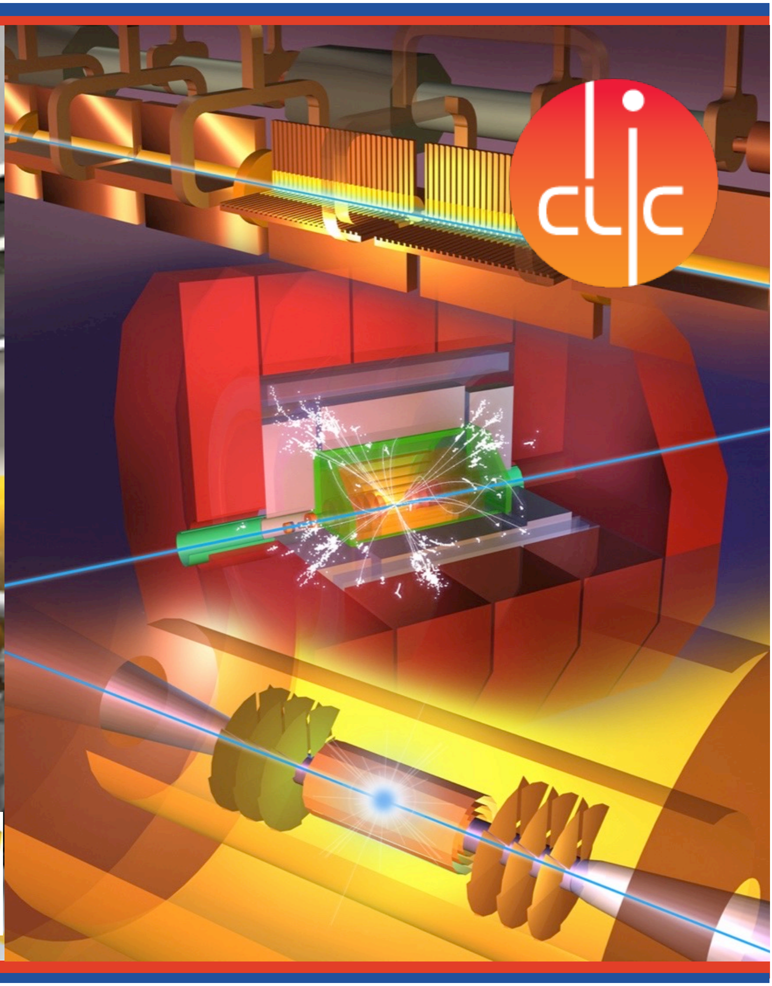
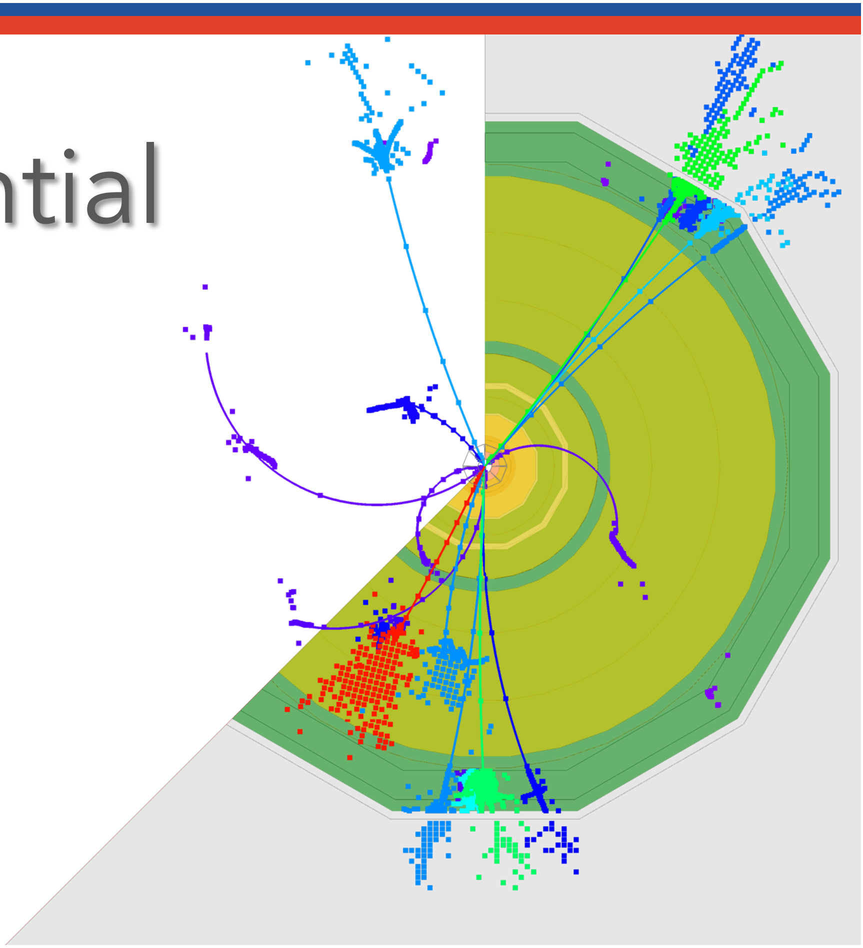
Linear collider physics potential



CLIC Mini Week, 11 December 2023

Aidan Robson, University of Glasgow

Linear collider physics potential



- Why a linear e+e– Higgs Factory
  with extension to high energies ?
- Single Higgs
- Higgs pairs
- BSM physics
- Top physics
- 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

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

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

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

=> small contributions -> need precise measurements!

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

=> discover and study di-Higgs production

The Higgs Factory mission

- Find out as much as we can about the 125-GeV Higgs
  - Basic properties:
    - **total production rate**, total width
    - decay rates to known particles
    - **invisible decays**
    - search for "exotic decays"
  - CP properties of couplings to gauge bosons and fermions
  - **self-coupling**
  - Is it the only one of its kind, or are there **other Higgs (or scalar) bosons**?

- To interpret these Higgs measurements, also need:
  - top quark: mass, Yukawa & electroweak couplings, their CP properties…
  - Z / W bosons: masses, couplings to fermions, triple gauge couplings, incl CP…

- Search for direct production of new particles – and determine their properties
  - Dark Matter? **Dark Sector**?
  - Heavy neutrinos?
  - SUSY? **Higgsinos**?
  - **The UNEXPECTED !**

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

  In particular:
  - low backgrounds
  - clean events
  - triggerless operation (LCs)

The Higgs Factory mission

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e+e– Higgs factory identified as highest-priority next collider, by European Strategy Update 2020 and US Snowmass / P5 2023

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

In particular:

- low backgrounds
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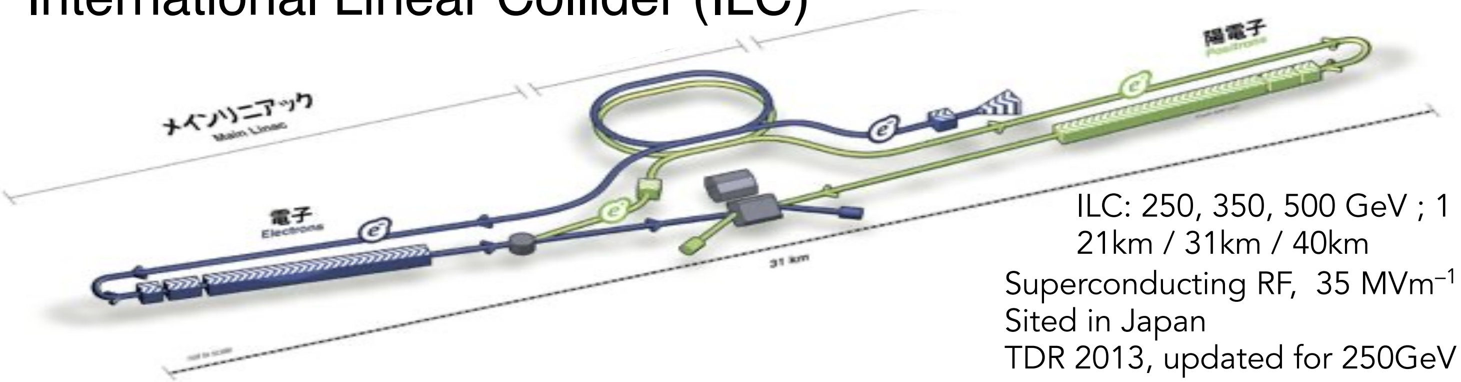
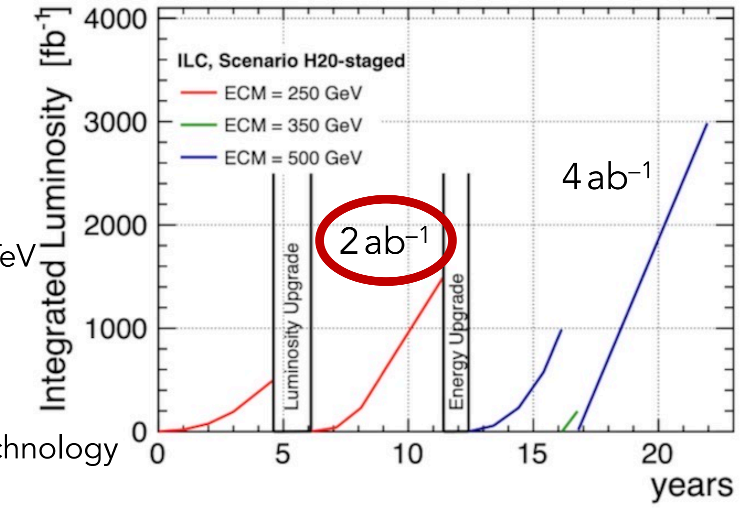
- triggerless operation (LCs)

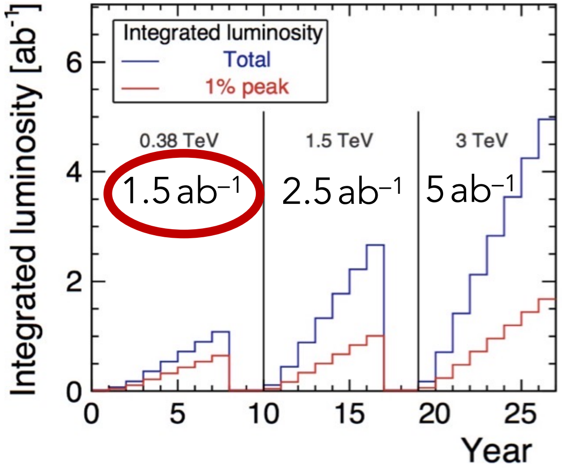
Higgs factory contenders (1): Linear Colliders

International Linear Collider (ILC)



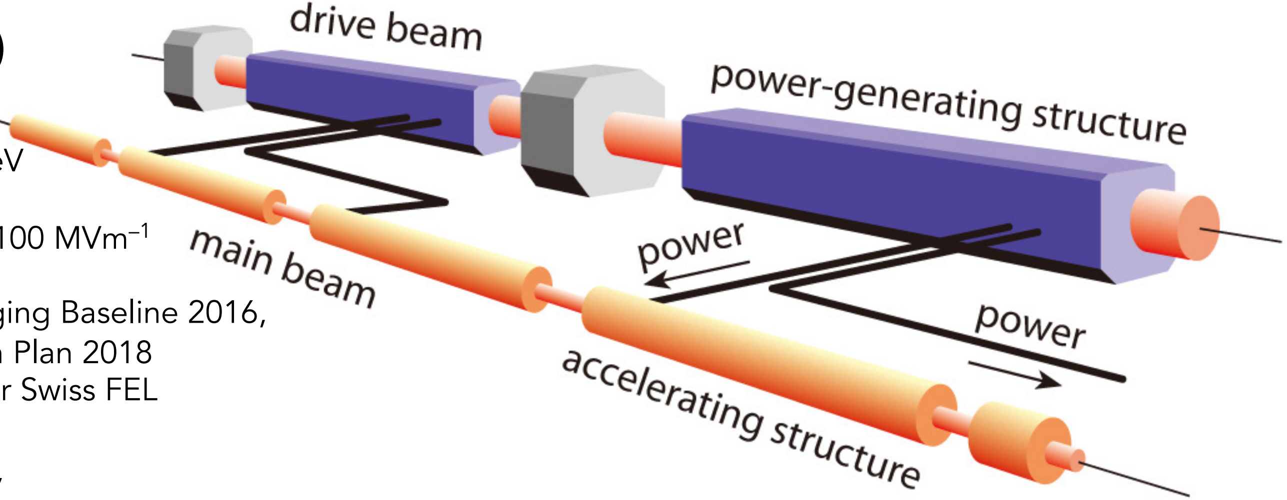
ILC: 250, 350, 500 GeV ; 1 TeV
21km / 31km / 40km
Superconducting RF, 35 MVm^{-1}
Sited in Japan
TDR 2013, updated for 250GeV
European XFEL demonstrates technology





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

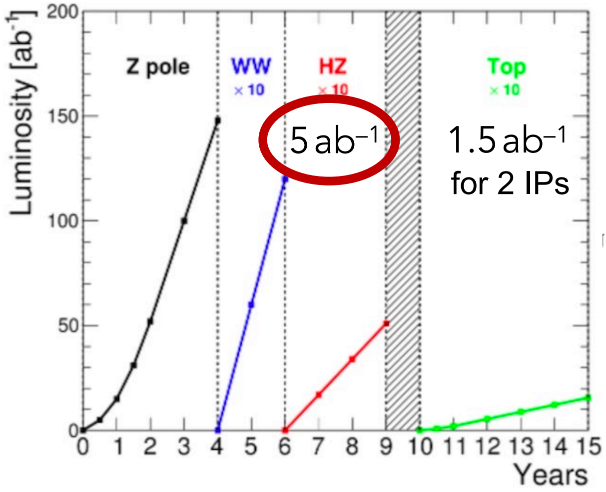
Hybrid Asymmetric Linear Higgs Factory (HALHF)

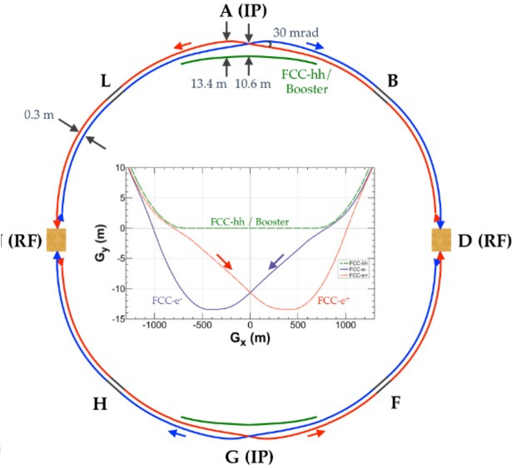
HALHF: 250 GeV (e$^-$ 500GeV, e$^+$ 31GeV)
3.3km
25 MVm^{-1} conventional, 6.3GVm^{-1} plasma
Pre-CDR

Higgs factory contenders (2): Circular Colliders

Future Circular Collider (FCC-ee)

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

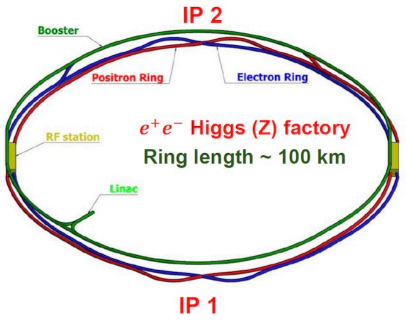




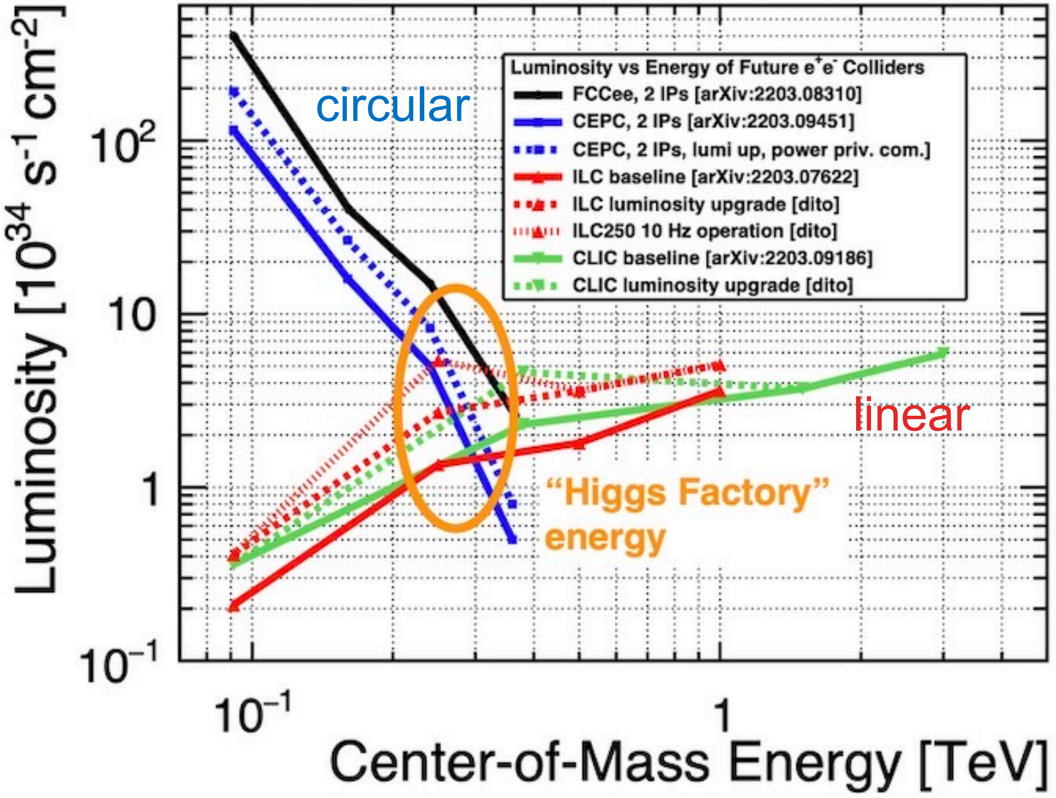
FCC: ~92k, ring
FCCee CDR 2019
Accelerator technology mostly proven >50yr

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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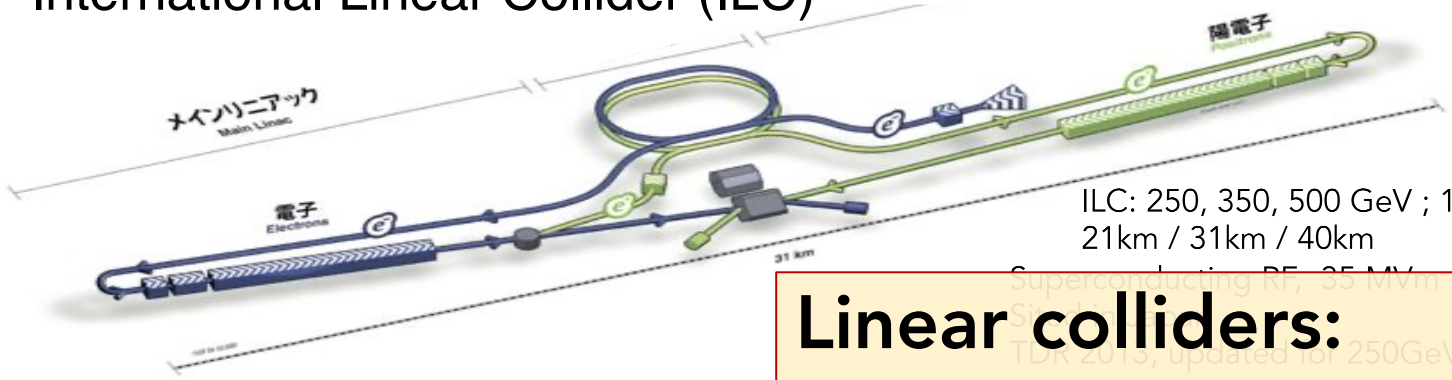

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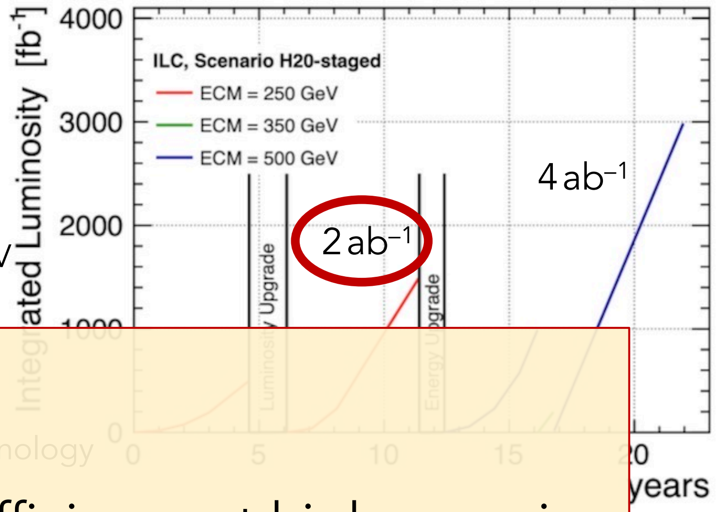

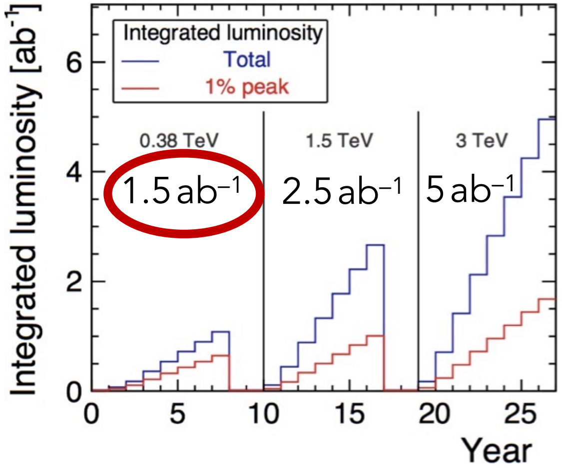

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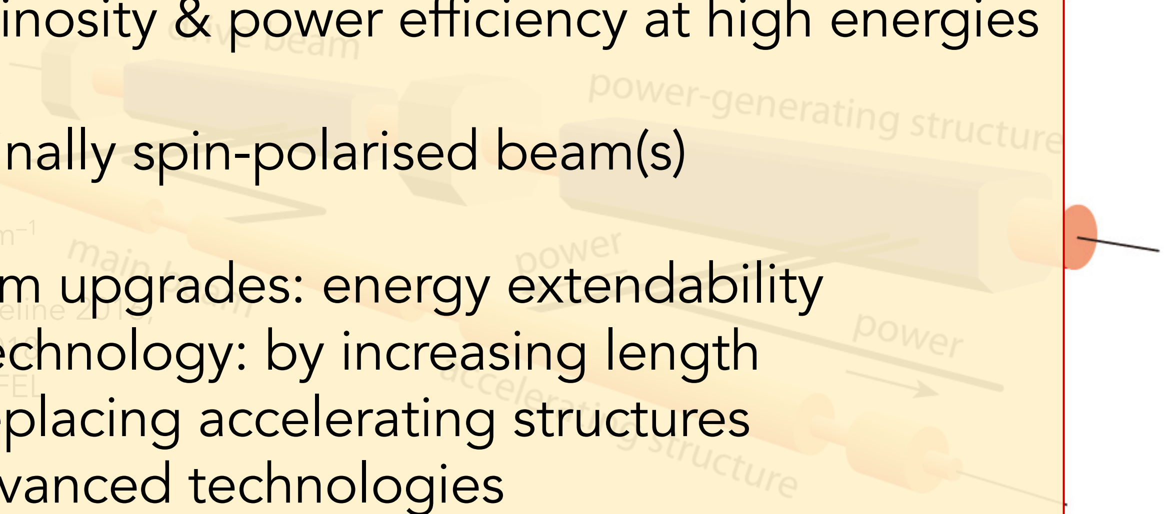

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HALHF: 250 GeV (e$^-$ 500GeV, e$^+$ 31GeV)
3.3km
25 MVm^{-1} conventional, 6.3GVm^{-1} plasma
Pre-CDR

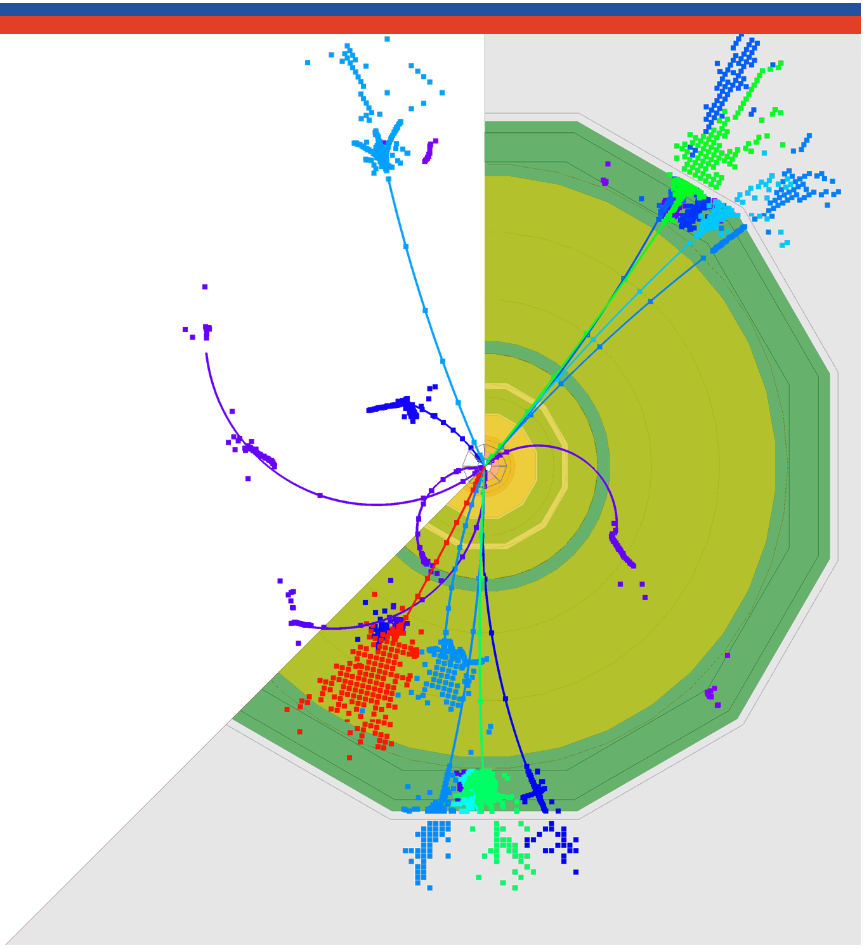
Linear colliders:

◆ high luminosity & power efficiency at high energies

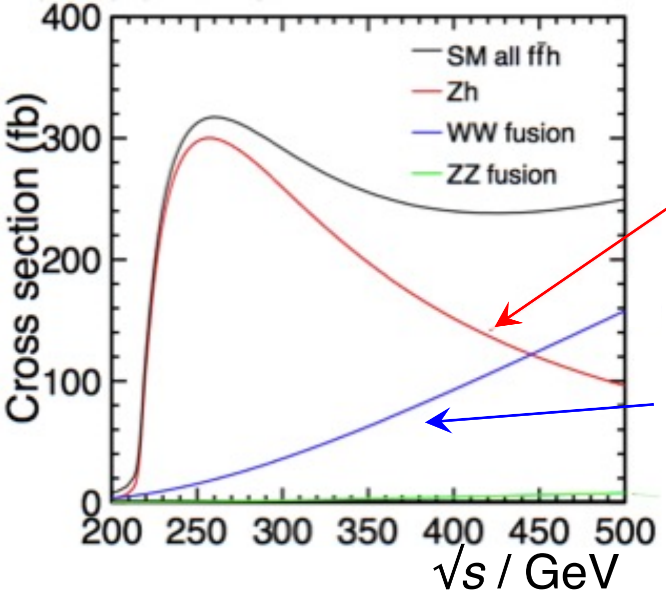
◆ longitudinally spin-polarised beam(s)

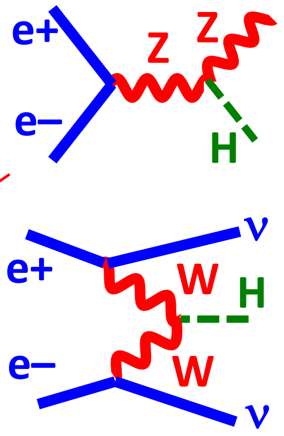
◆ Long-term upgrades: energy extendability
- same technology: by increasing length
- or by replacing accelerating structures with advanced technologies
  - – RF cavities with high gradient
  - – plasma acceleration?

Higgs in e^+e^-



Higgs production in e^+e^-

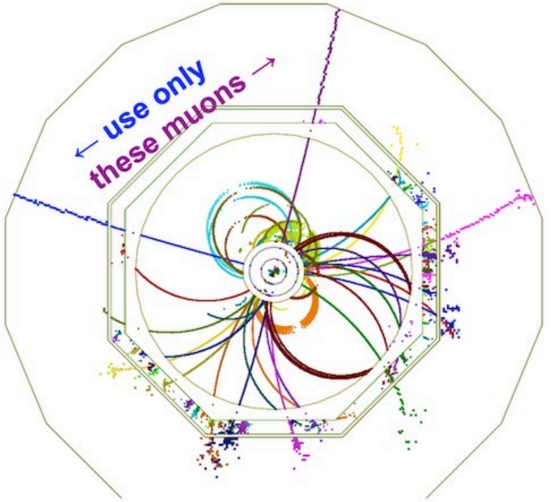




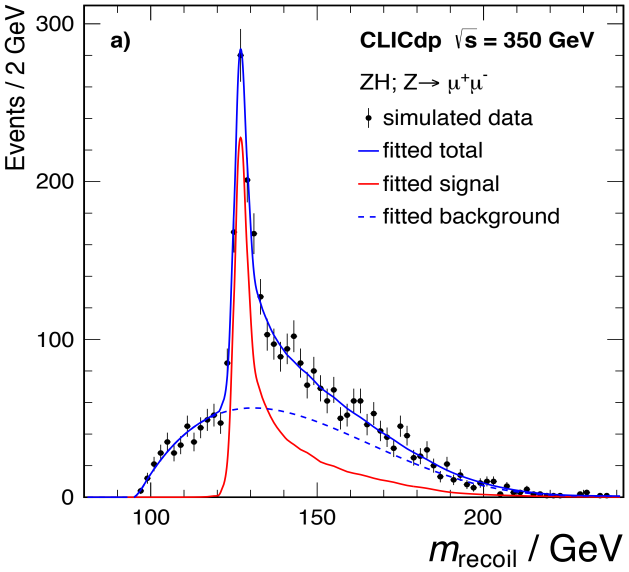
◆ ZH process allows reconstruction of H by looking exclusively at recoil of Z
–> model-independent extraction of g_{HZZ} coupling

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

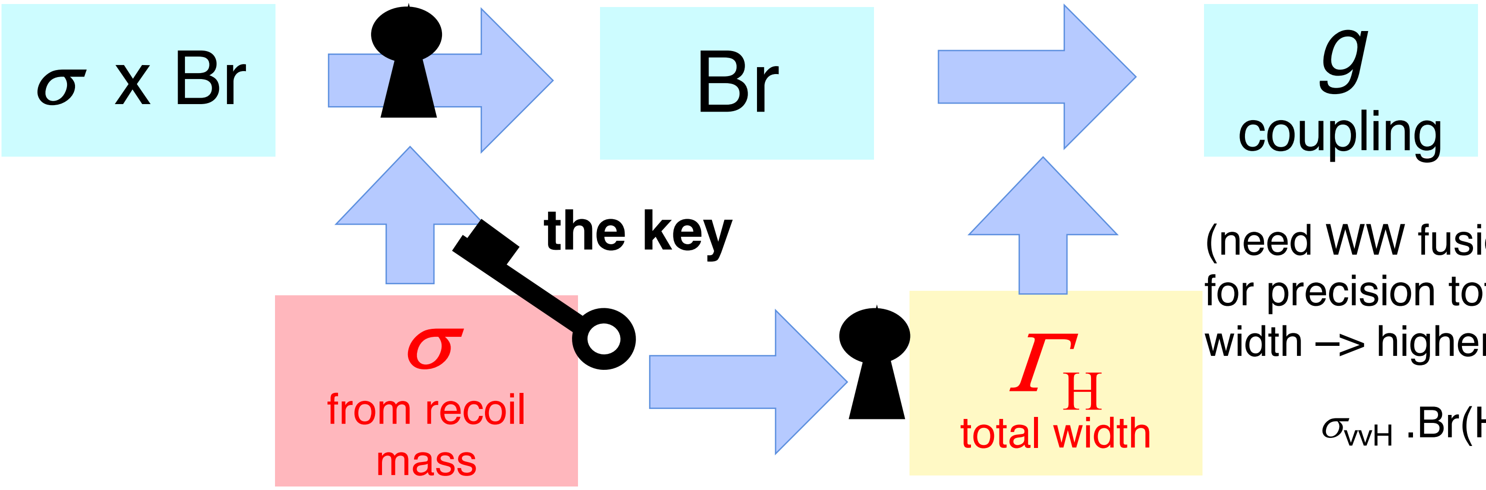
$$\frac{\sigma_{ZH}\ .\mathrm{Br(H\text{->}bb)}}{\sigma_{\nu\nu H}\ .\mathrm{Br(H\text{->}bb)}} \propto \frac{g^2_{HZZ}}{g^2_{HWW}}$$



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

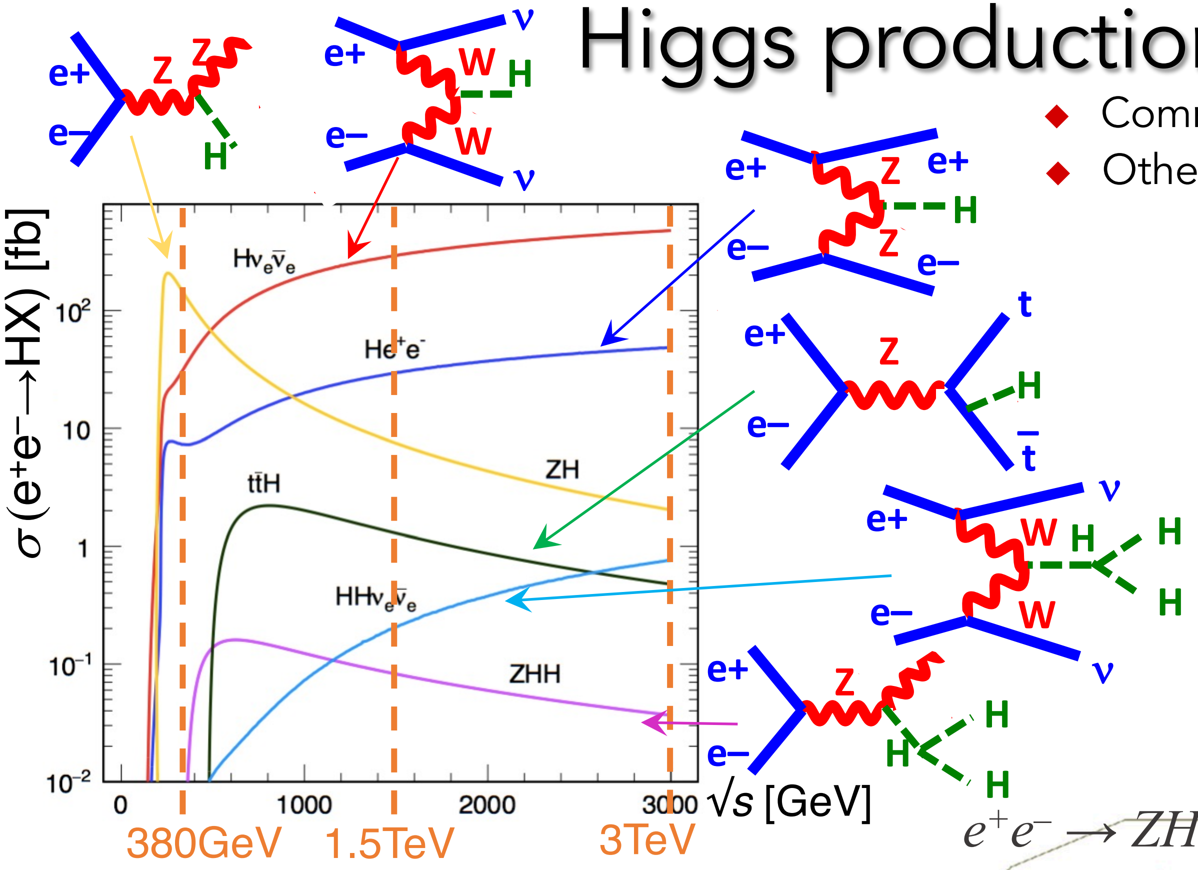
Γ_{H}
total width

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

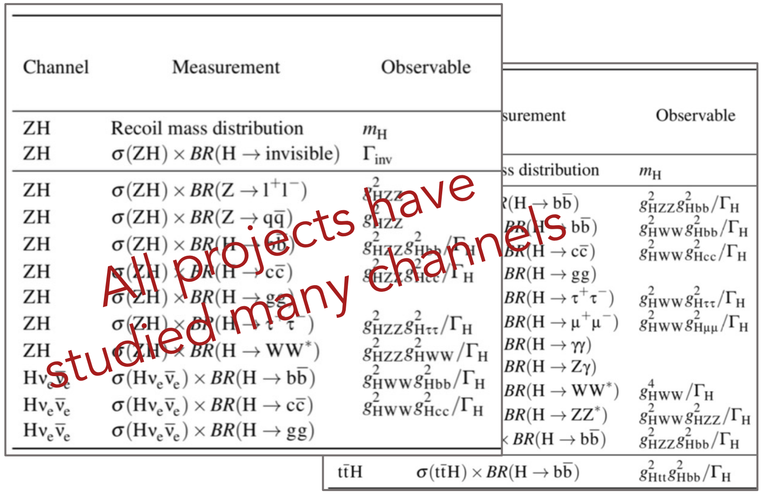
$\sigma_{\nu\nu H}$ .Br(H->WW) $\propto g^4_{HWW}/\Gamma_H$

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



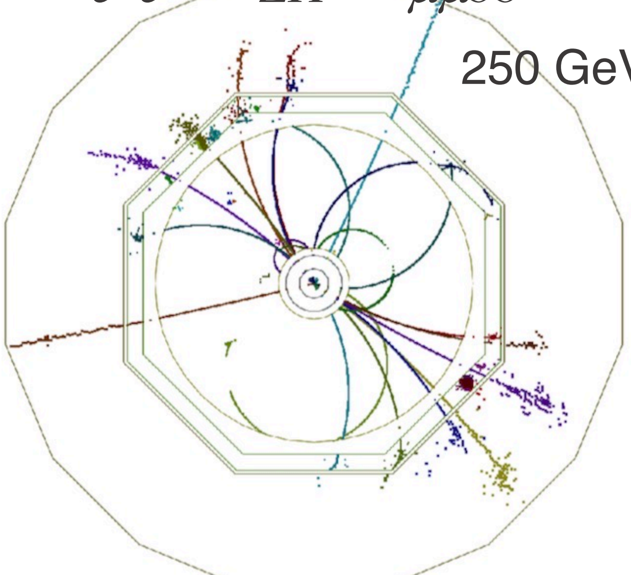
Channel	Measurement	Observable
ZH	Recoil mass distribution	m_H
ZH	$\sigma(ZH)\times BR(H\to \text{invisible})$	Γ_{inv}
ZH	$\sigma(ZH)\times BR(Z\to l^+l^-)$	g^2_{HZZ}
ZH	$\sigma(ZH)\times BR(Z\to q\bar{q})$	g^2_{HZZ}
ZH	$\sigma(ZH)\times BR(H\to b\bar{b})$	$g^2_{HZZ}g^2_{Hbb}/\Gamma_H$
ZH	$\sigma(ZH)\times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

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

All projects have studied many channels

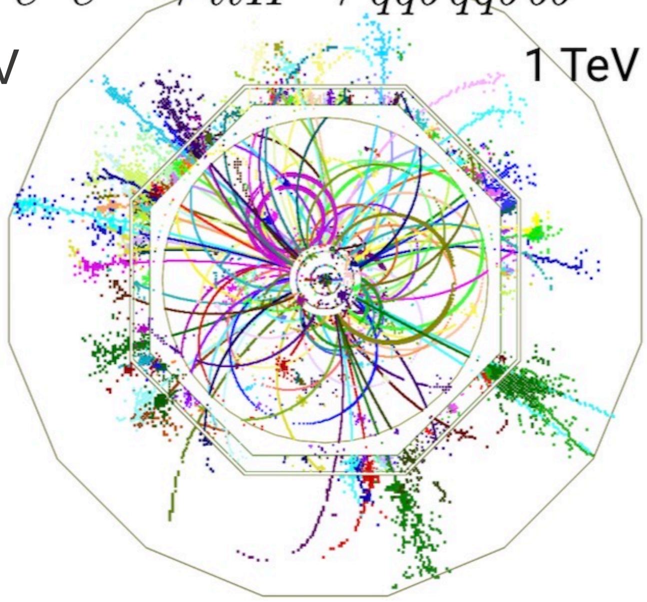
- ILC & CLIC: analyses in full GEANT simulation with beam backgrounds overlaid

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



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

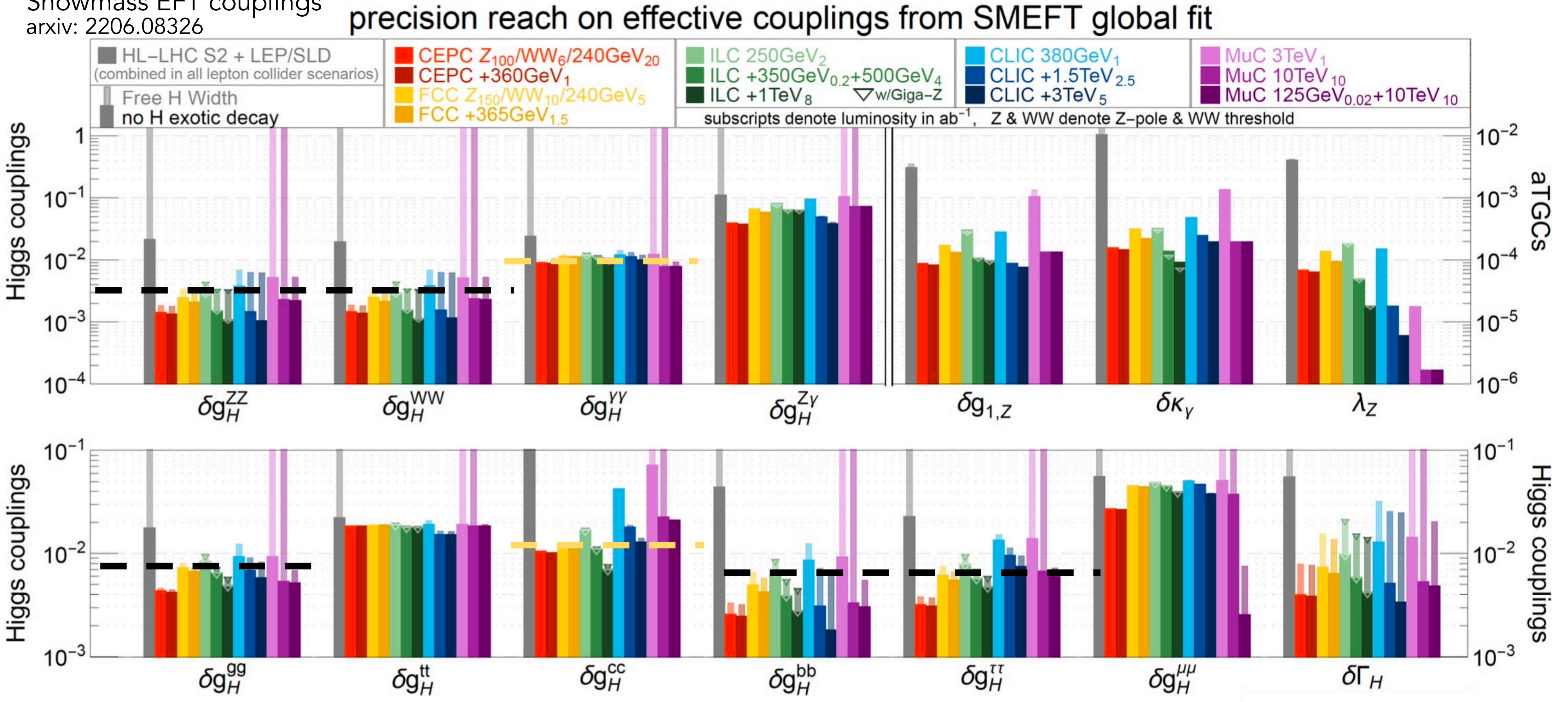
Dim-6 operators

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

Scale of new decoupled physics

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

Snowmass EFT couplings
arxiv: 2206.08326



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

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

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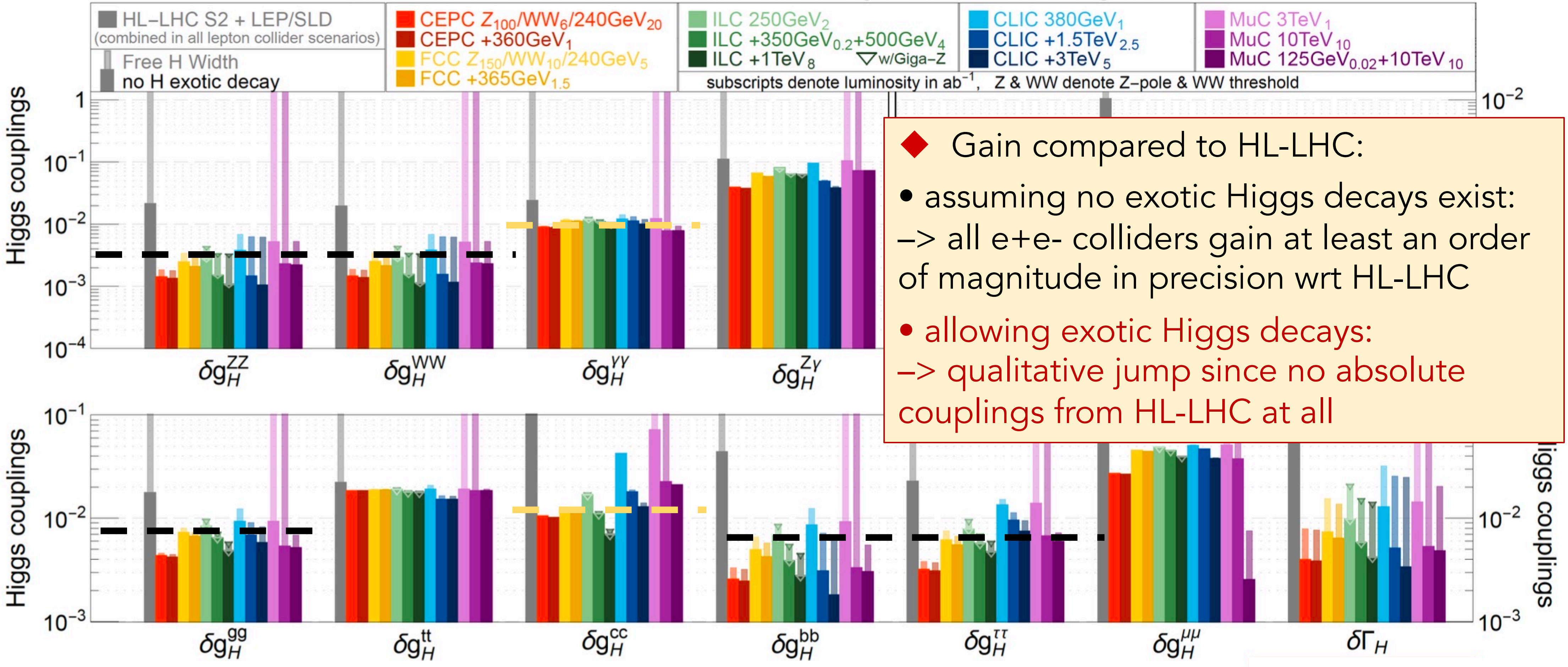
precision reach on effective couplings from SMEFT global fit



◆ 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

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

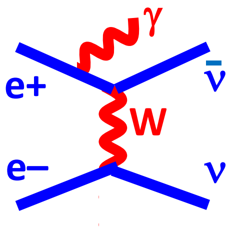
◆ all e+e- colliders show very comparable performance for standard Higgs program despite quite different assumed integrated luminosities

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 $e^-_L e^+_R$

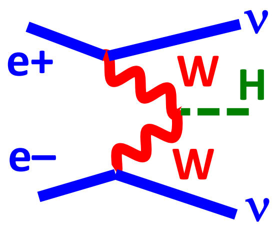


Signal enhancement:

◆ Many processes have strong polarisation dependence, e.g.:

- Higgs production in WW-fusion
- many BSM processes

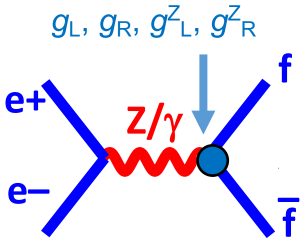
=> polarisation can give higher S/B



Chiral analysis:

◆ SM: Z and γ 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

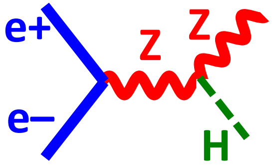
◆ flipping positron polarisation can control nuisance effects on observables relying on electron polarisation

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

◆ there are many physics benefits from beam polarisation

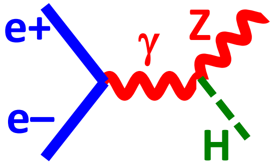
Polarisation

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



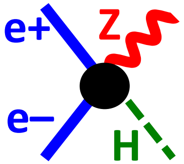
[The only SM diagram]

Flips sign under spin reversal $e_R \leftrightarrow e_L$



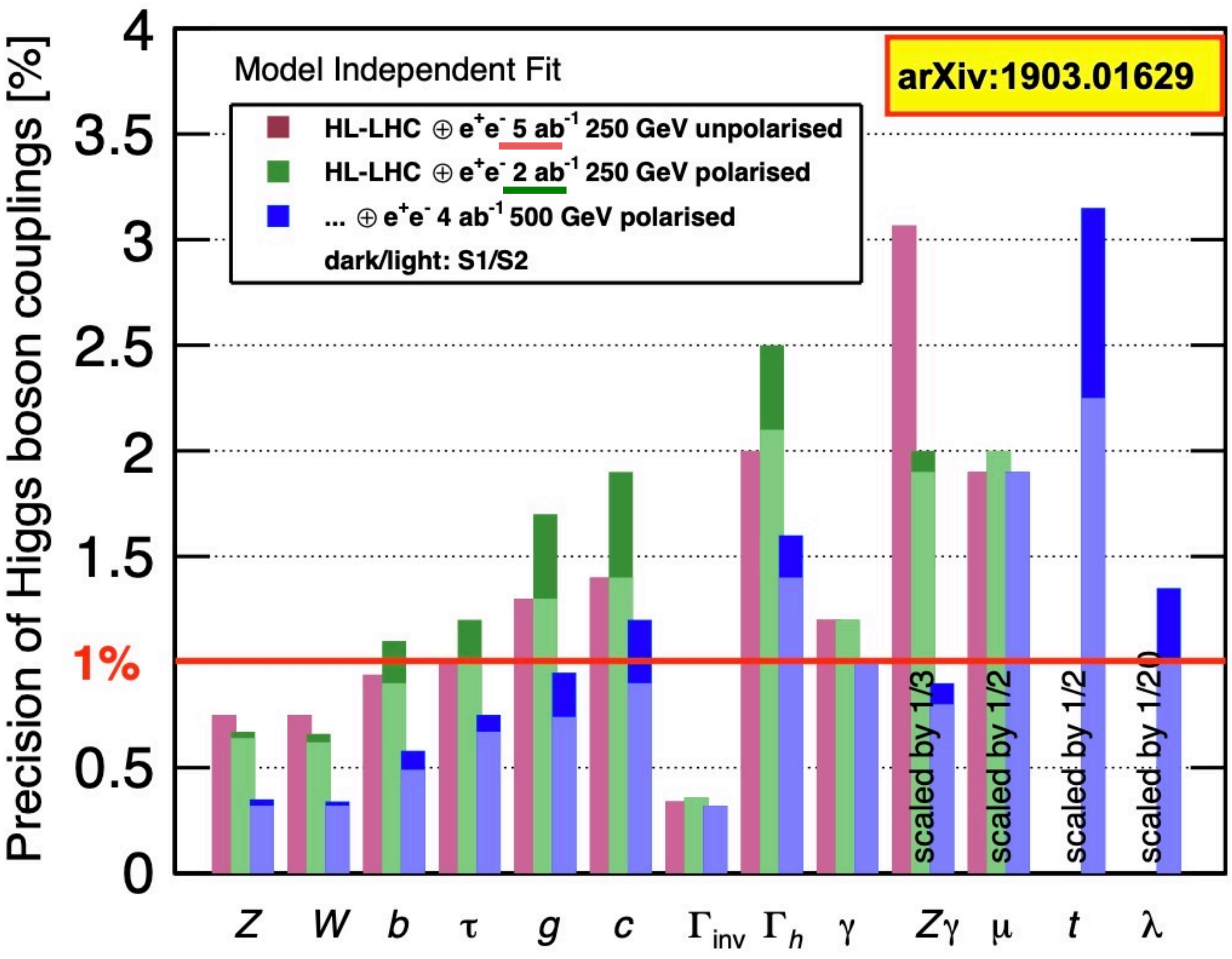
$\sim c_{WW}$

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

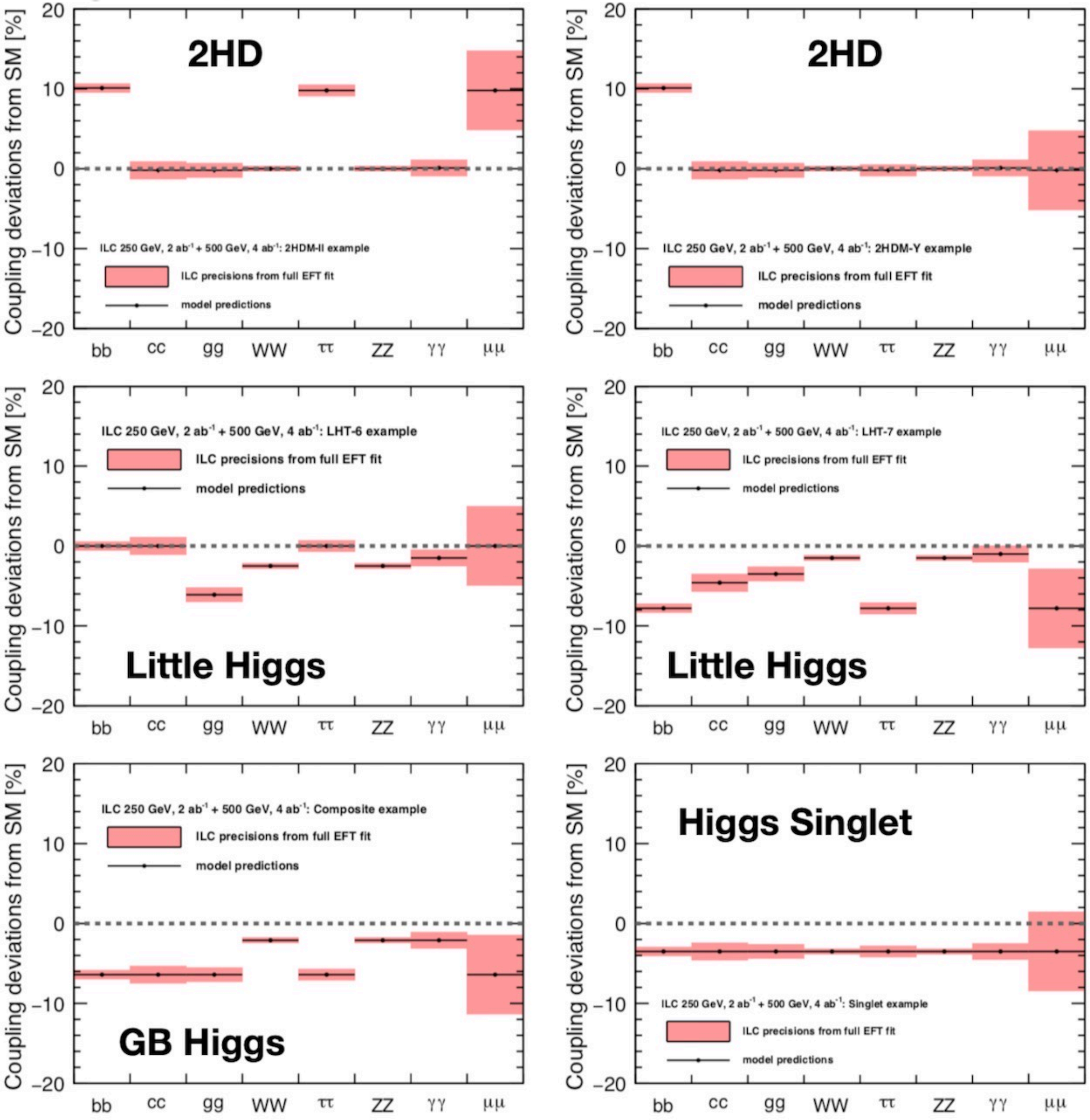
- Aim of precision Higgs measurements is to ***discover violation of the SM***

- 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

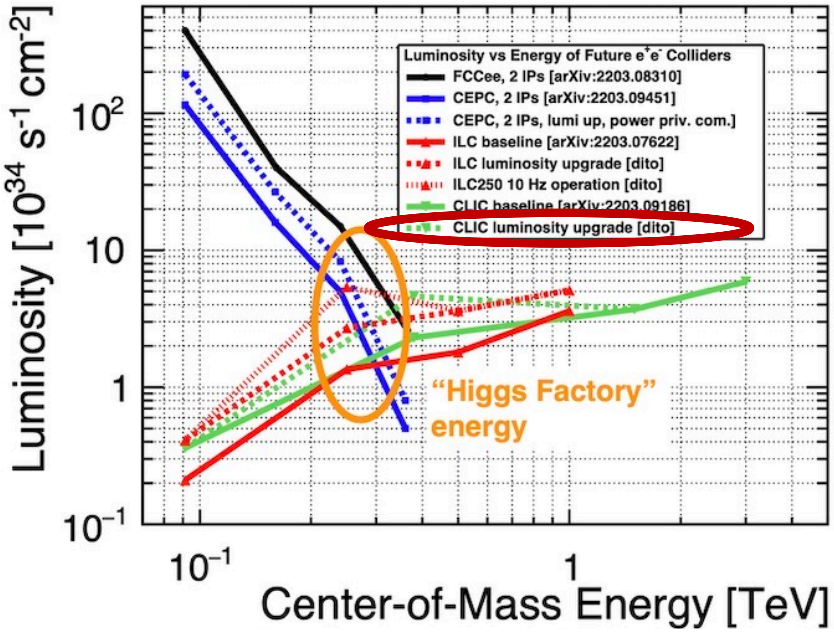
- Typical models give coupling deviations at 1% level; **e+e– factories can reach this sensitivity**



Barklow/Peskin

Alternative CLIC run scenario

- To illustrate the flexibility of the run-plan: two modifications with respect to the baseline staging:
- **Doubling bunch train repetition rate at initial stage from 50Hz to 100 Hz**
–> modest increase in cost and power
- **Increasing initial stage from 8 to 13 years** CERN-ACC-2019-0051
–> Integrated luminosity at 380GeV increases from 1ab^{-1} to 4ab^{-1}



	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
$g^{\text{eff}}_{HZZ}[\%]$	SMEFT_{ND}	3.6	0.3	0.2	0.5	0.3
$g^{\text{eff}}_{HWW}[\%]$	SMEFT_{ND}	3.2	0.3	0.2	0.5	0.3
$g^{\text{eff}}_{H\gamma\gamma}[\%]$	SMEFT_{ND}	3.6	1.3	1.3	1.3	1.2
$g^{\text{eff}}_{HZ\gamma}[\%]$	SMEFT_{ND}	11.	9.3	4.6	9.8	9.3
$g^{\text{eff}}_{Hgg}[\%]$	SMEFT_{ND}	2.3	0.9	1.0	1.0	0.8
$g^{\text{eff}}_{Htt}[\%]$	SMEFT_{ND}	3.5	3.1	2.2	3.1	3.1
$g^{\text{eff}}_{Hcc}[\%]$	SMEFT_{ND}	–	2.1	1.8	1.4	1.2
$g^{\text{eff}}_{Hbb}[\%]$	SMEFT_{ND}	5.3	0.6	0.4	0.7	0.6
$g^{\text{eff}}_{H\tau\tau}[\%]$	SMEFT_{ND}	3.4	1.0	0.9	0.7	0.6
$g^{\text{eff}}_{H\mu\mu}[\%]$	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 first stage

◆ CLIC baseline

From arXiv: 2001.05278

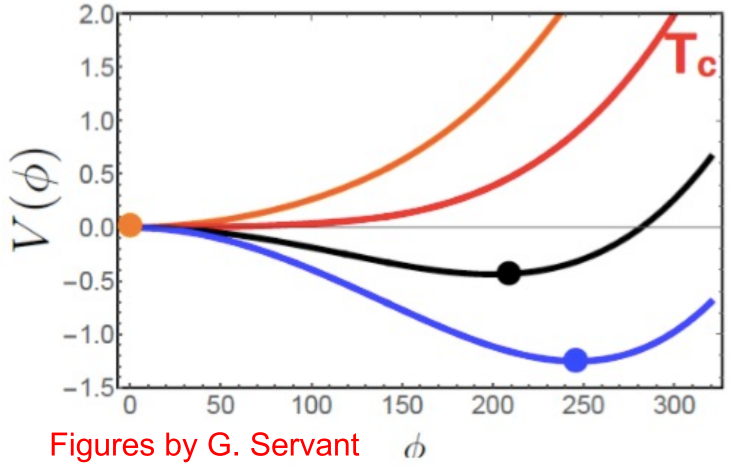
From European Strategy Briefing Book

- Either scenario (longer 1st stage, or baseline 1st+2nd stage) is very competitive
- We shouldn't forget that 1.5TeV and 3TeV are example benchmarking choices for CLIC – e.g. 500 / 550 GeV (etc) are not ruled out!

Higgs self-coupling

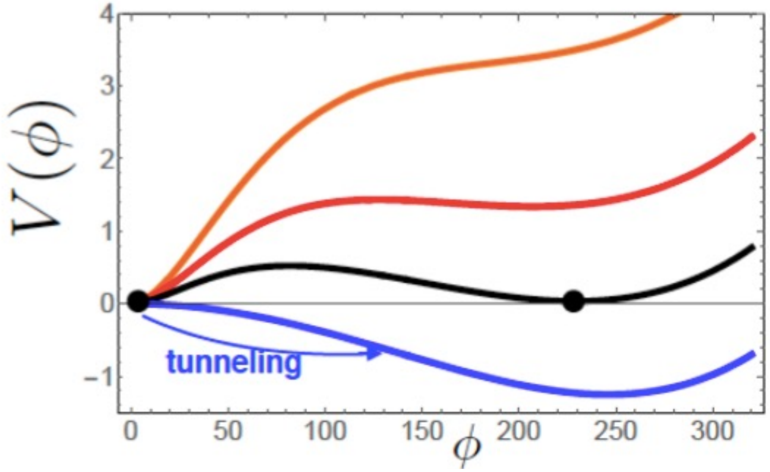
- The Higgs self-coupling gives access to the shape of the Higgs potential

Standard Model:



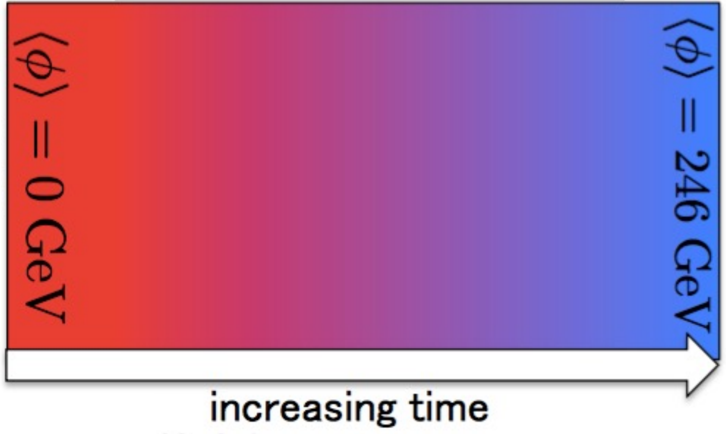
Figures by G. Servant

Possible alternative:

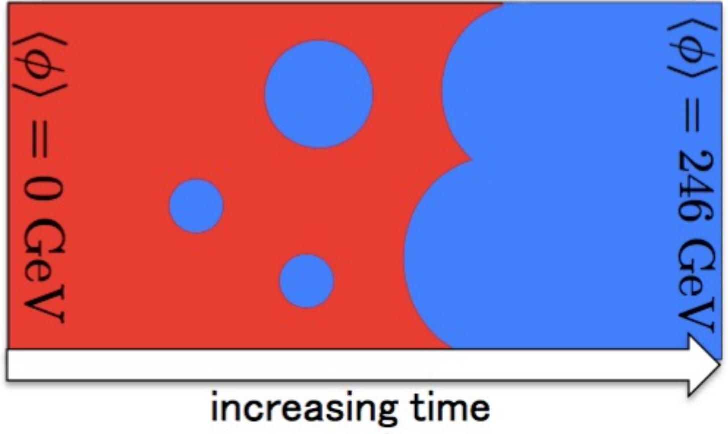


In this case, two phases can coexist:

Continuous Crossover

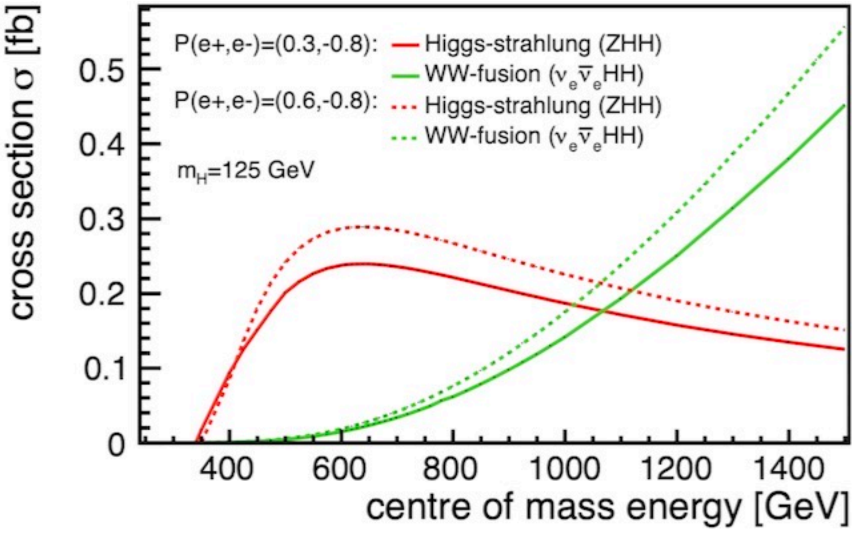


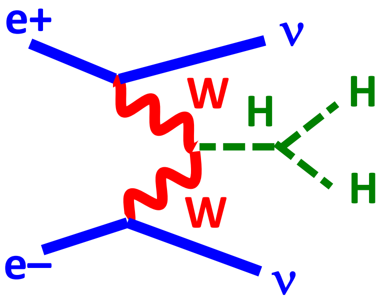
First Order Phase Transition

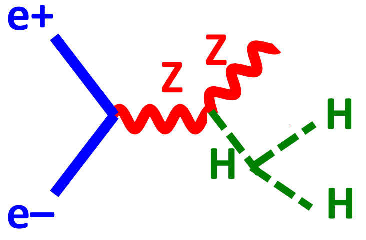


–> electroweak baryogenesis possible

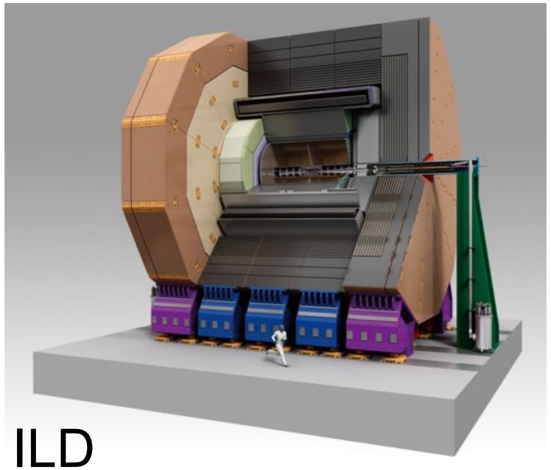
Higgs self-coupling: 0.5–1TeV



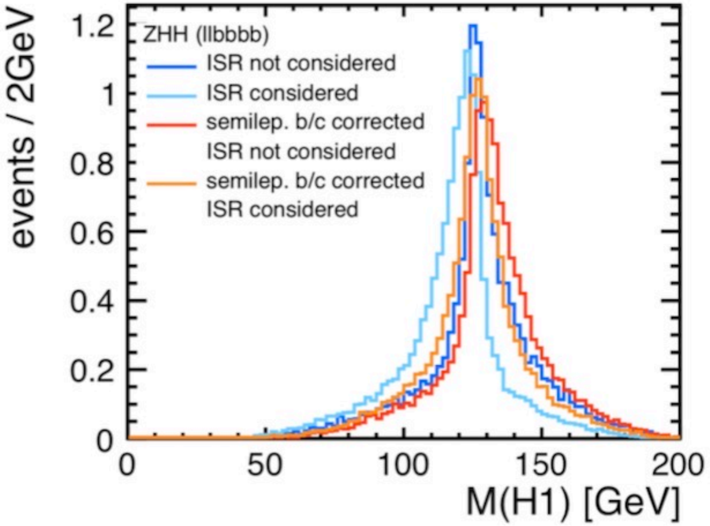


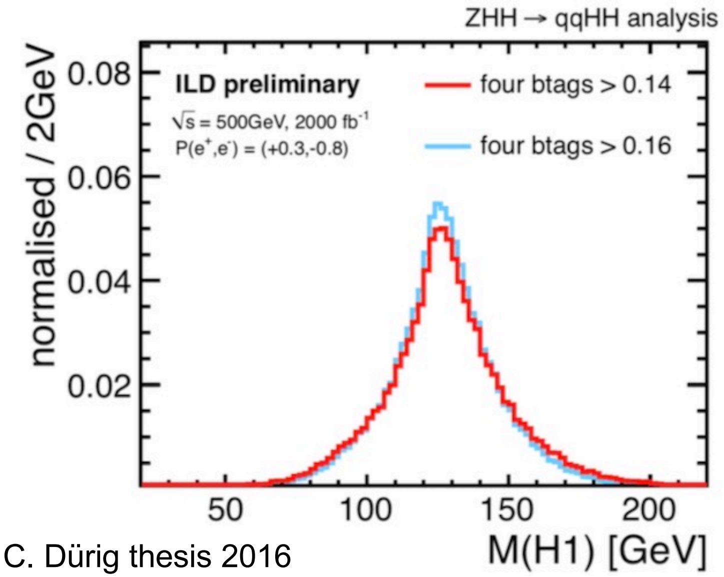


- ◆ Two contributing ***direct production*** mechanisms: ZHH and ννHH
- ◆ ZHH becomes available at ILC 500 – studied in full sim with ILD detector Z->ll / Z->qq, HH->bbbb /HH->bbWW*
- ◆ If self-coupling λ is at SM value then double-Higgs process observable at 8σ, with 27% precision on λ
- ◆ Adding ννHH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



ILD

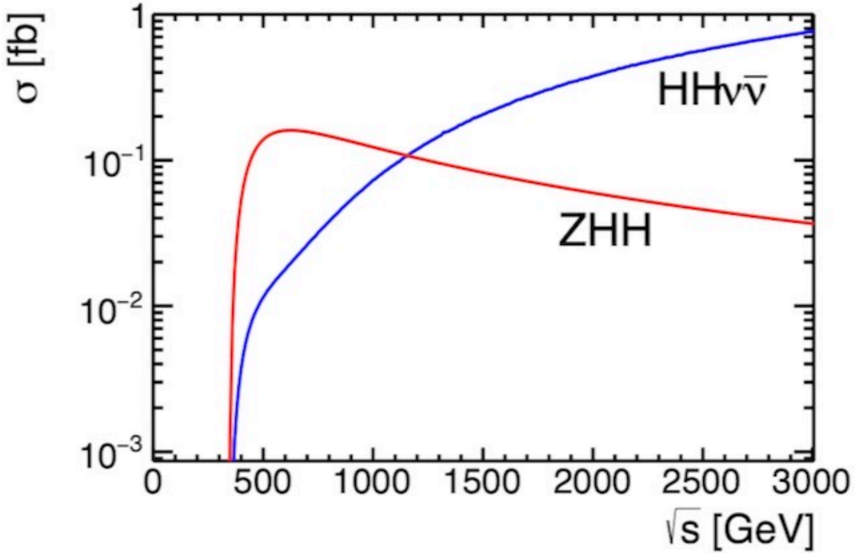




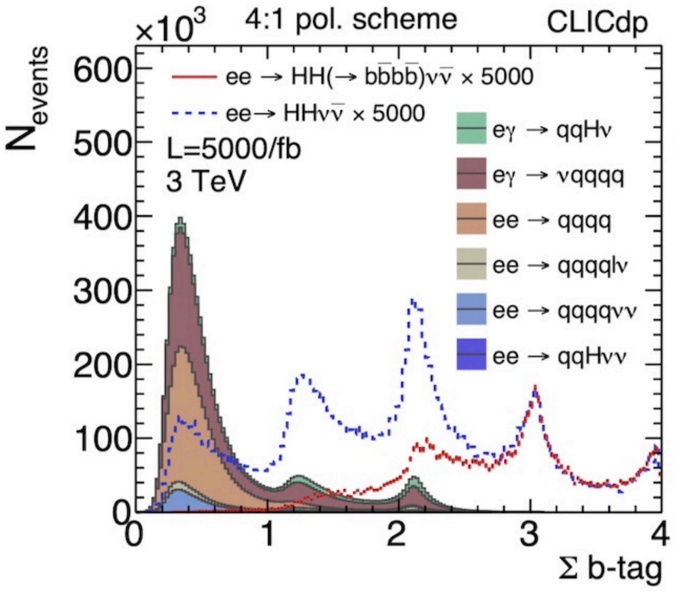
C. Dürig thesis 2016

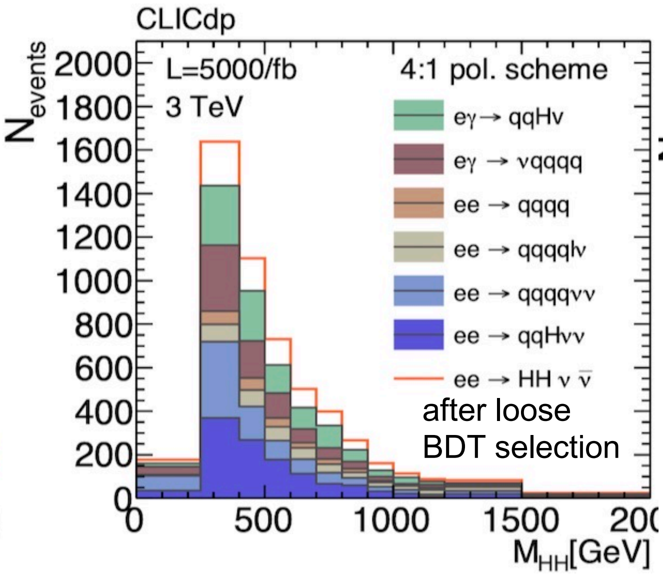
- ◆ used state-of-the-art reconstruction at the time (2016), but sensitivity very dependent on b-tagging performance, dijet mass resolution –> update is ongoing

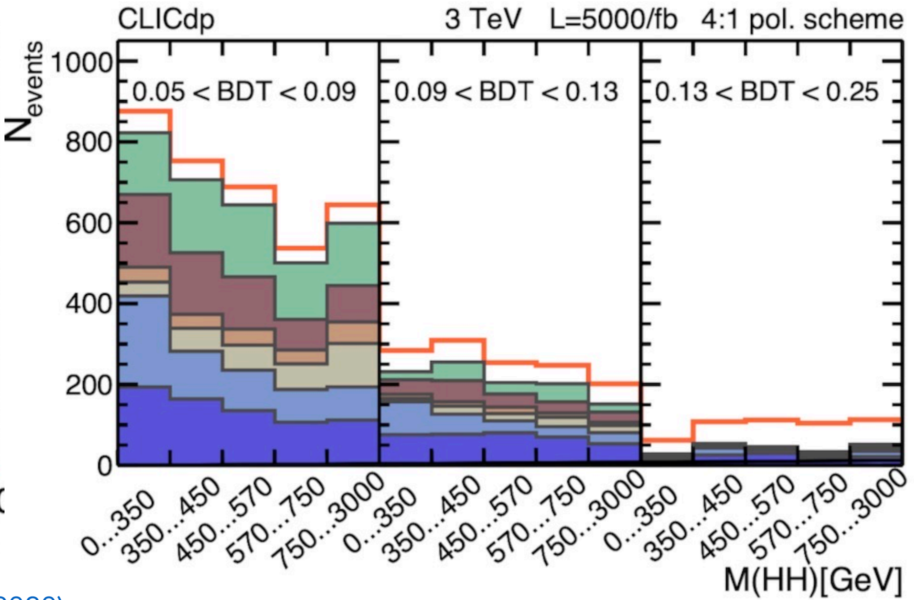
Higgs self-coupling: >1TeV



- $\nu\nu$HH 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^- -> Z$\nu\nu$) 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

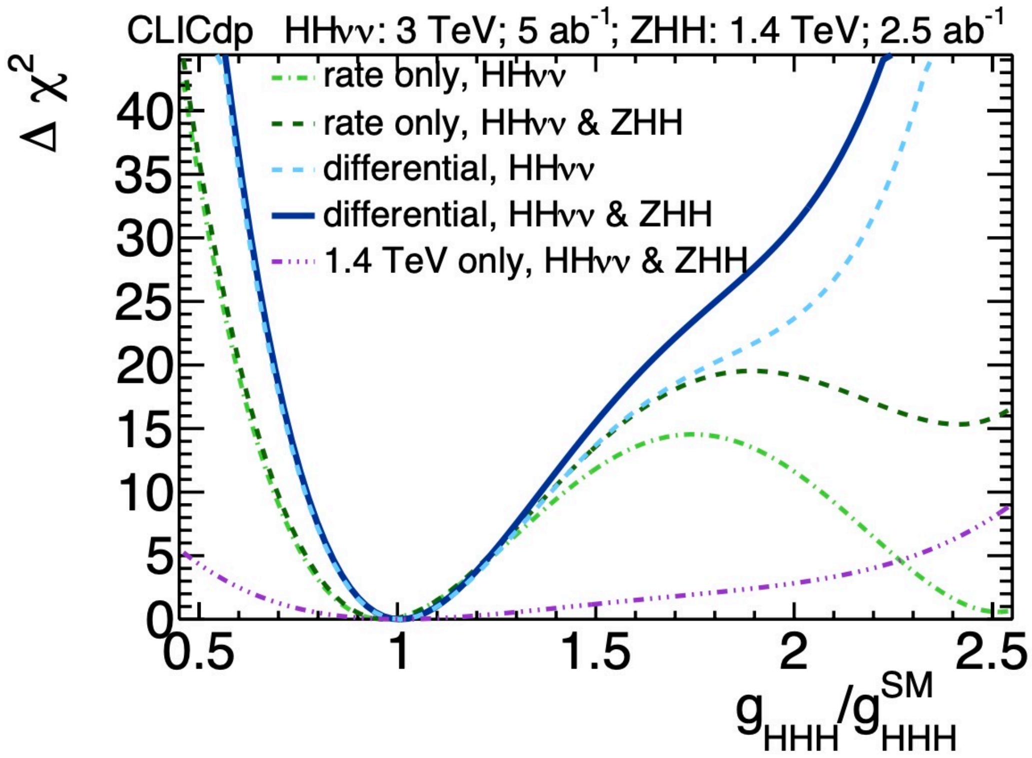


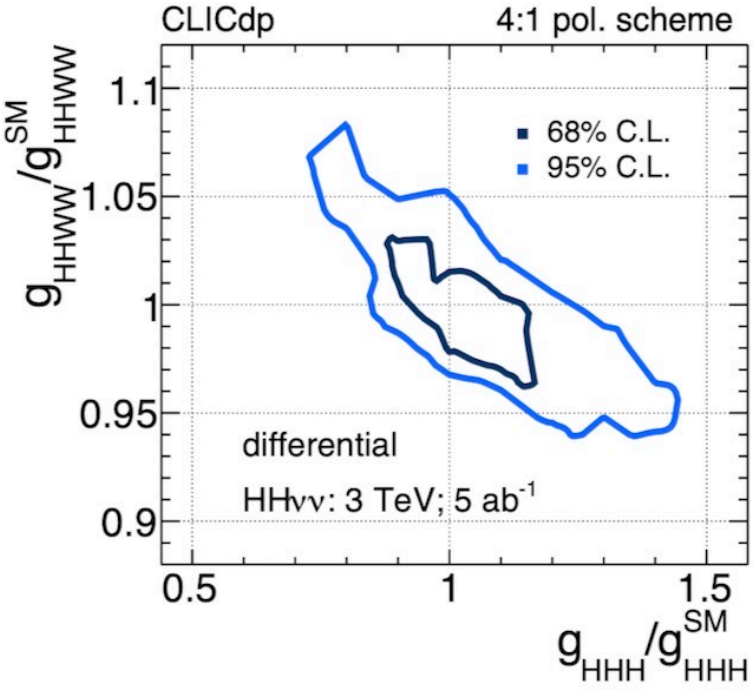




Eur. Phys. J. C 80, 1010 (2020)

Higgs self-coupling: >1TeV



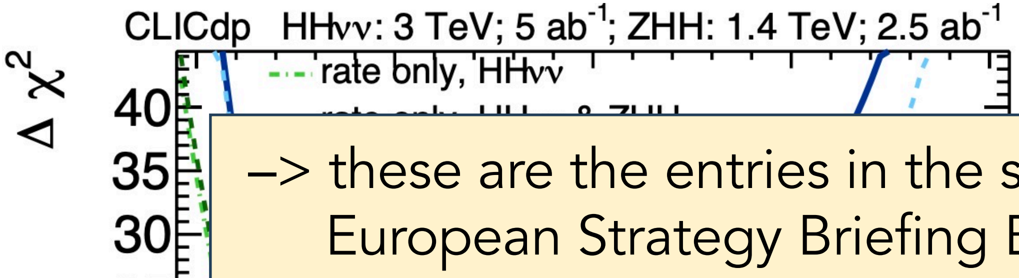


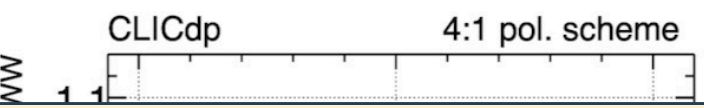
- at 1.4TeV rate-only analysis gives relative uncertainties –29% and +67% around SM value of g_{HHH}
- 3TeV differential measurement gives –8% and +11% assuming SM g_{HHWW}
- simultaneous measurement of triple and quartic couplings gives constraints below 4% in g_{HHWW} and below 20% in g_{HHH} for large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

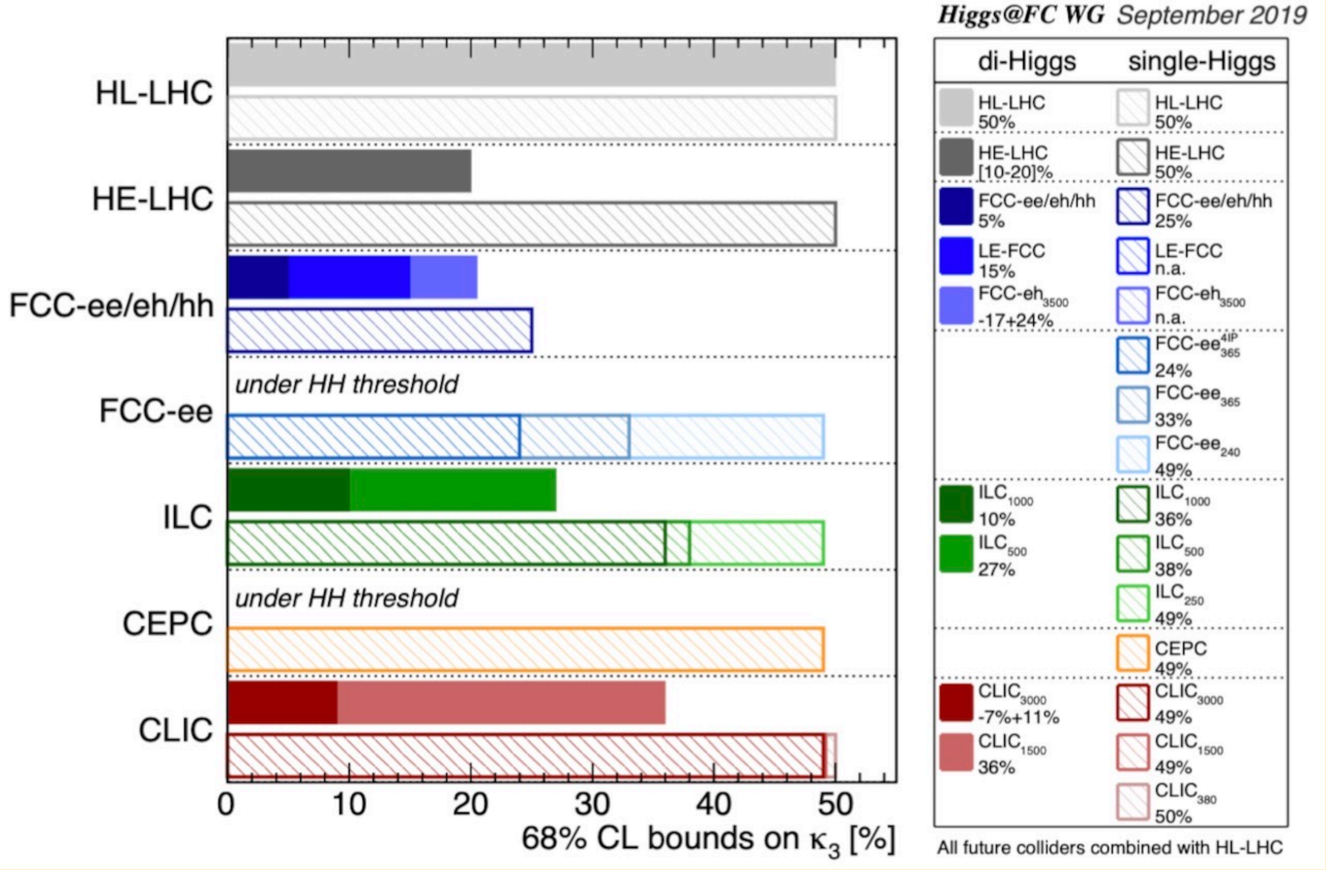
Eur. Phys. J. C 80, 1010 (2020)

Higgs self-coupling: >1TeV





–> 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

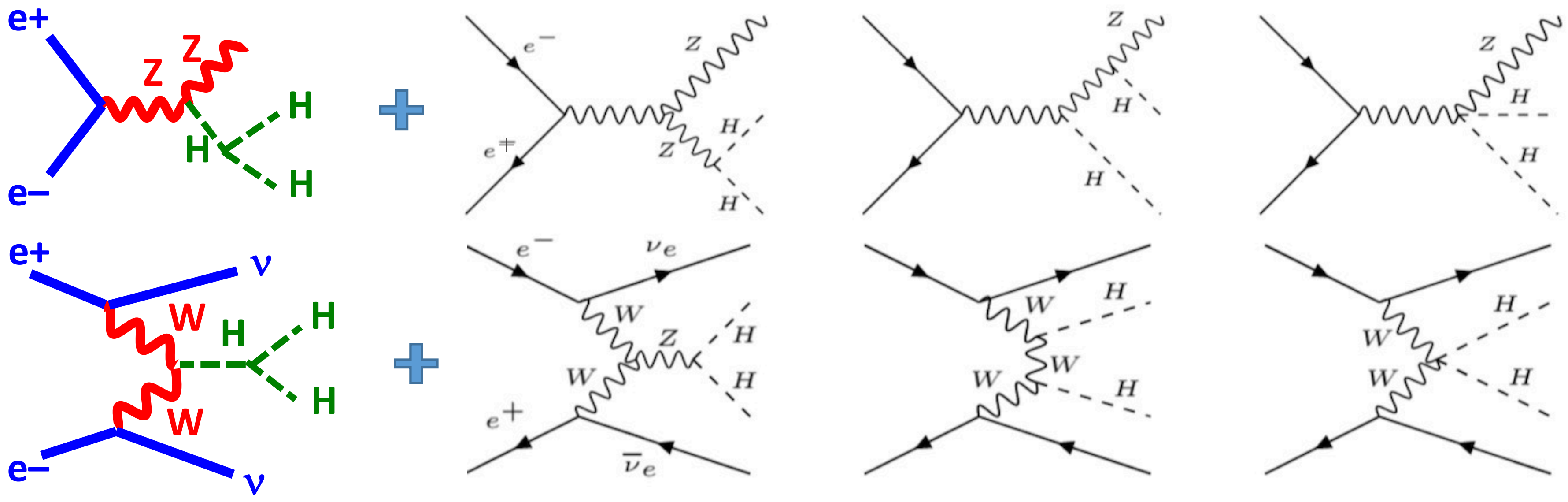
rate-only analysis

differential analysis

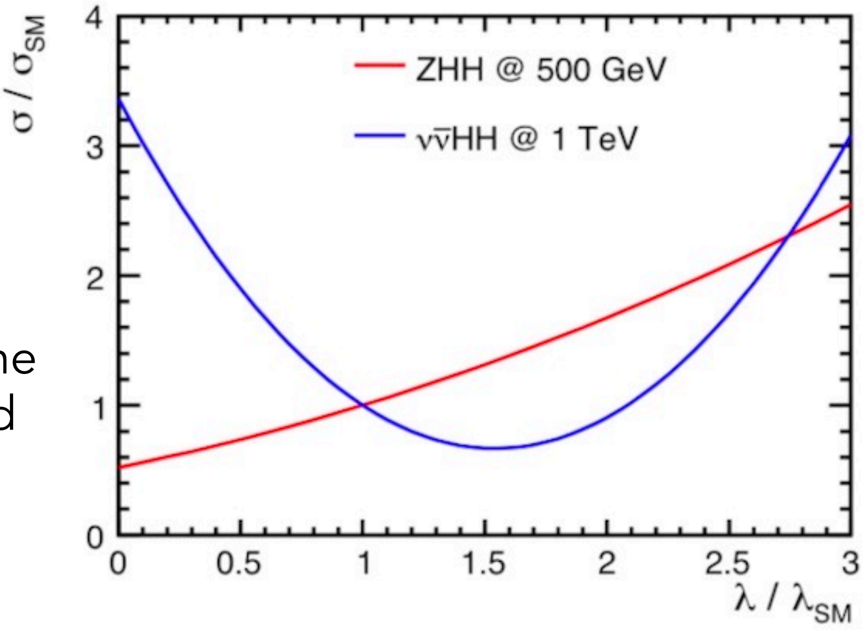
Eur. Phys. J. C 80, 1010 (2020)

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

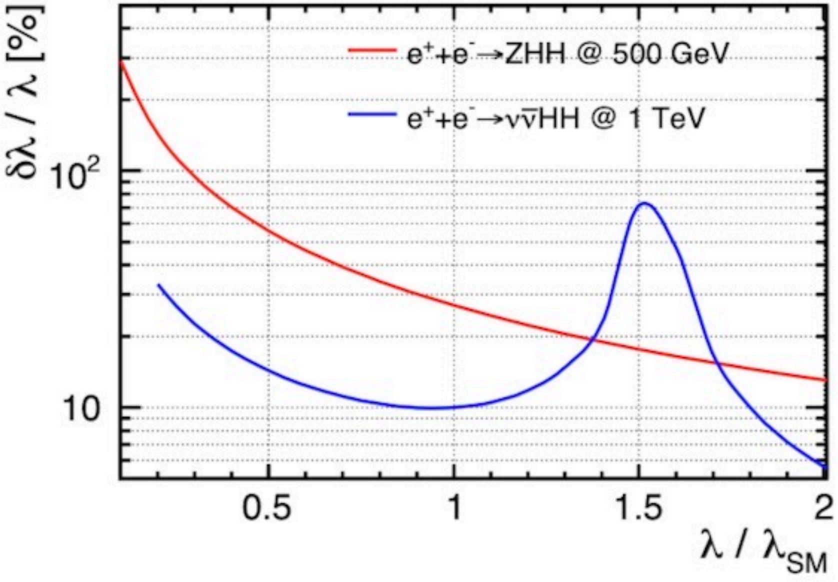


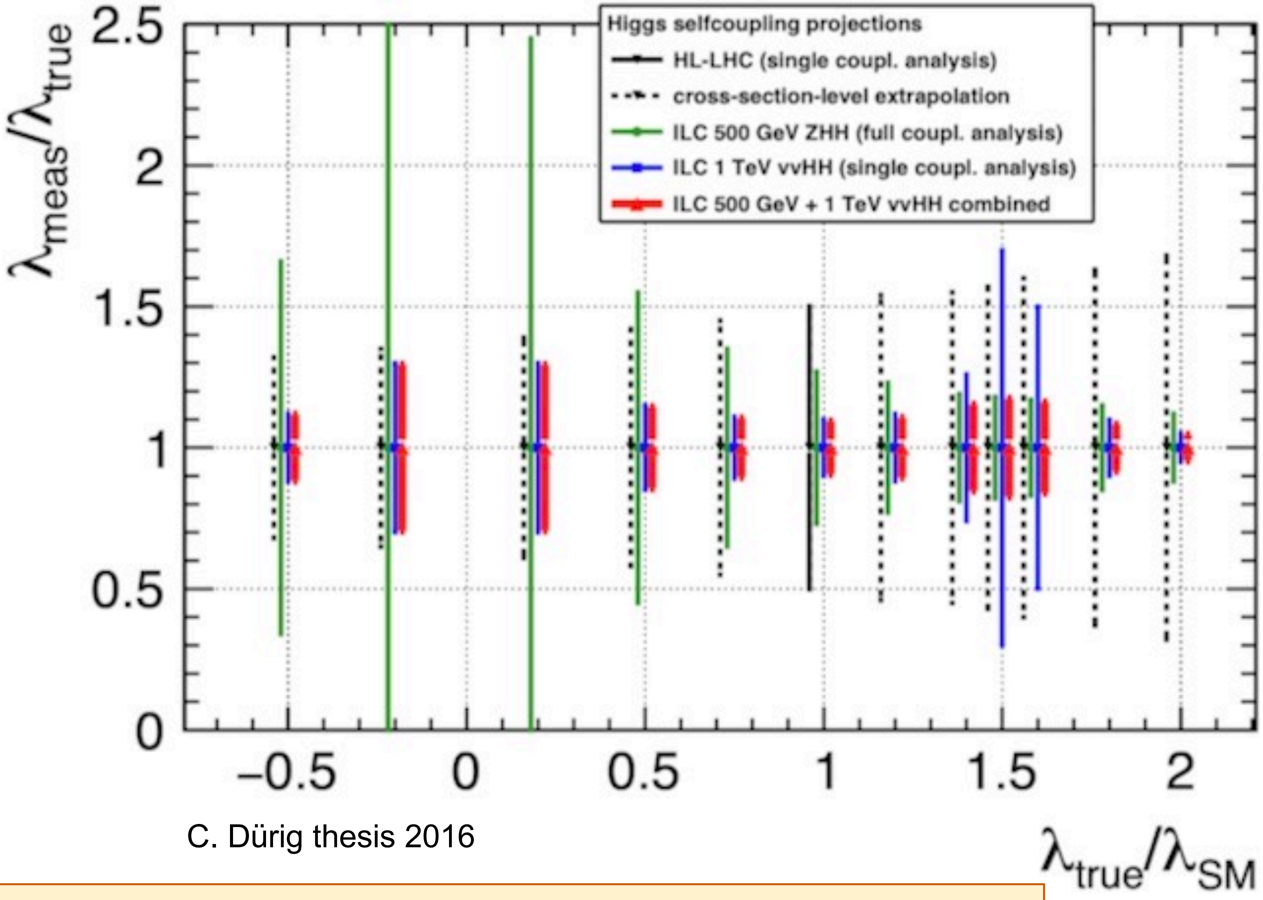
- Self-coupling diagram interferes constructively in ZHH and destructively in ννHH – whatever the sign of the deviation of κ_λ from 1, one of the processes will have an increased cross-section (and increased statistical sensitivity)



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

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



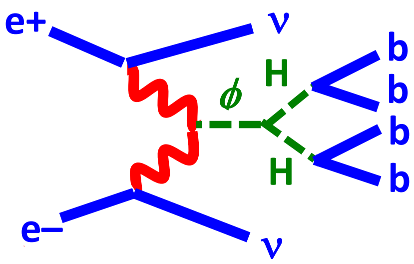


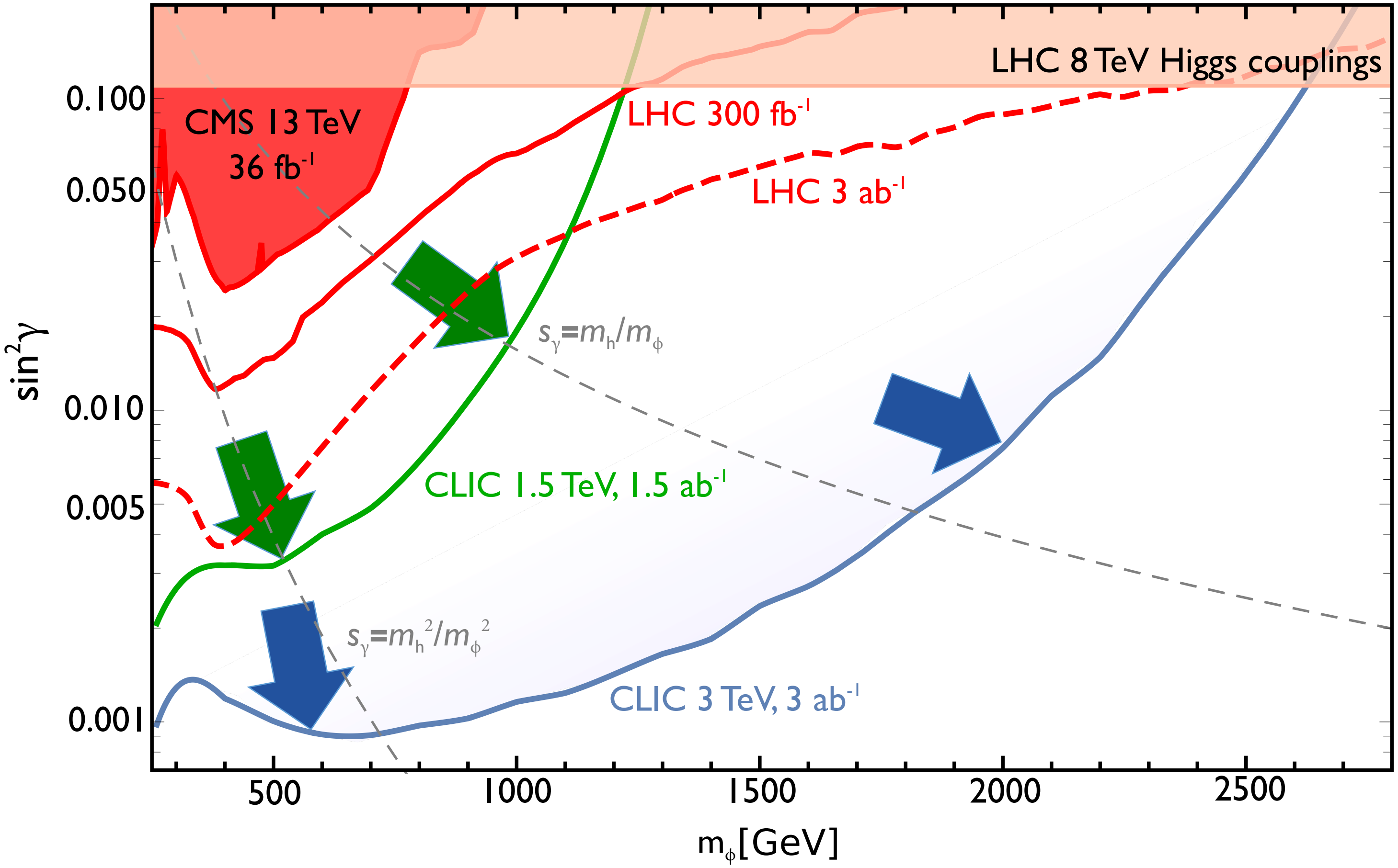
C. Dürig thesis 2016

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

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

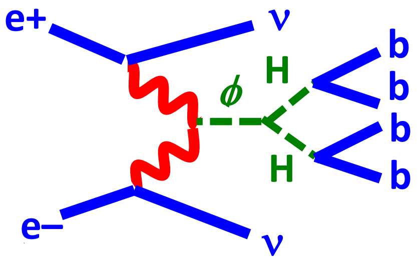
$$h = h_0 \cos\gamma + S \sin\gamma$$

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

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:



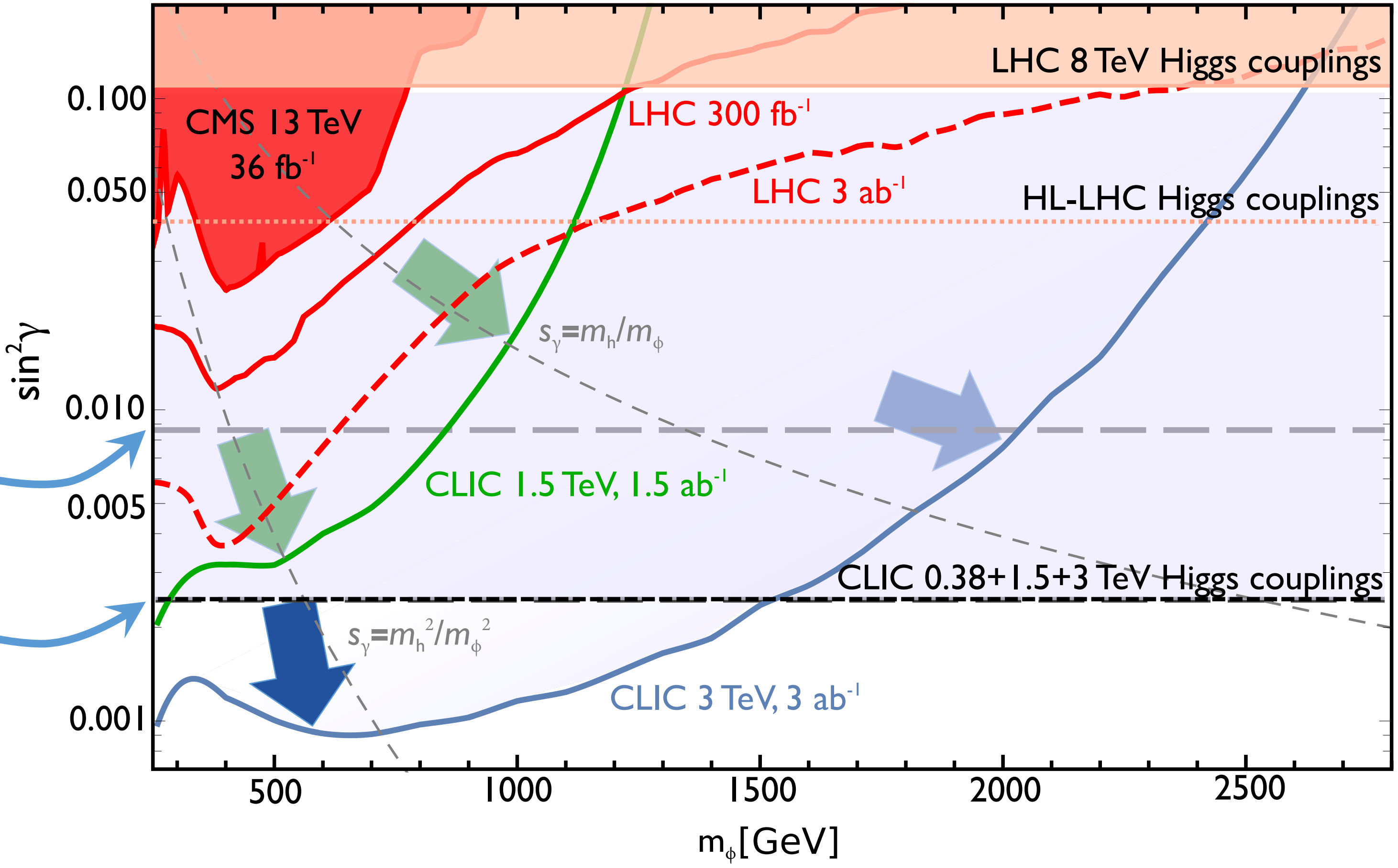
Complementary:

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)



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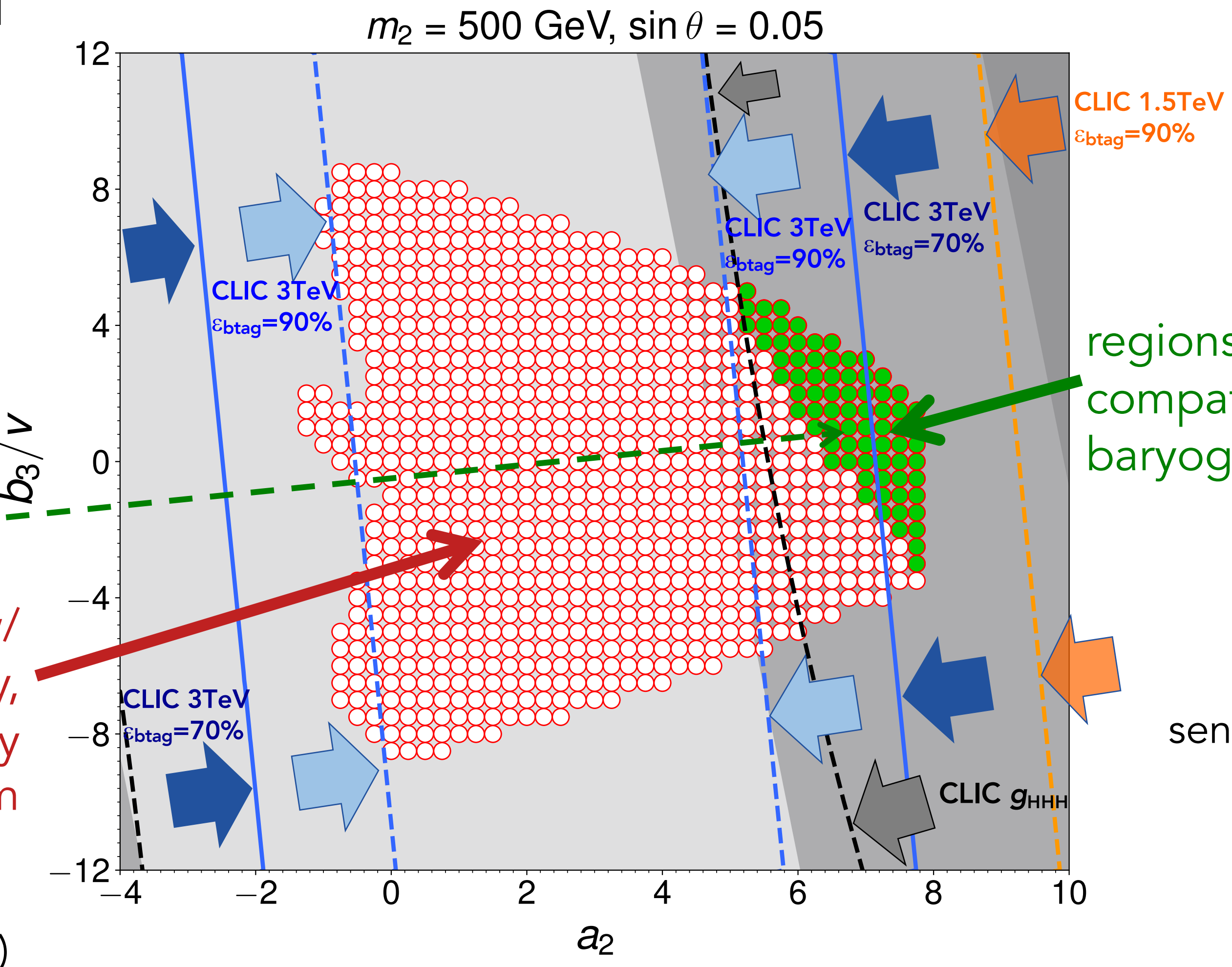
γ is mixing angle of SM-like Higgs (m_h=125GeV), and singlet-like state ϕ

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



regions compatible w/ unitarity, perturbativity, and absolute stability of the EW vacuum

regions also compatible with baryogenesis

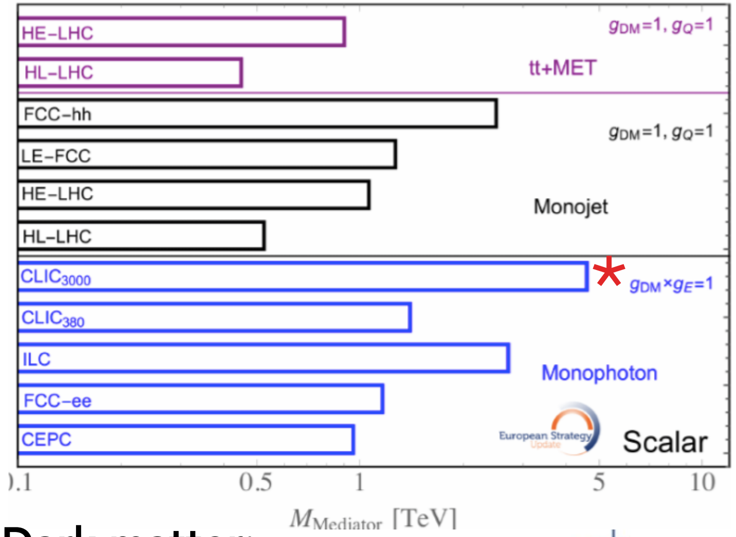
HL-LHC not sensitive at this low mixing sin θ=0.05

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

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

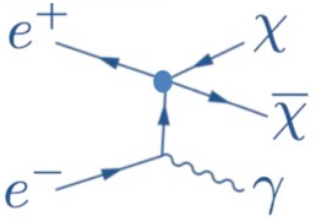
BSM direct searches

◆ Examples



- **Dark matter:**

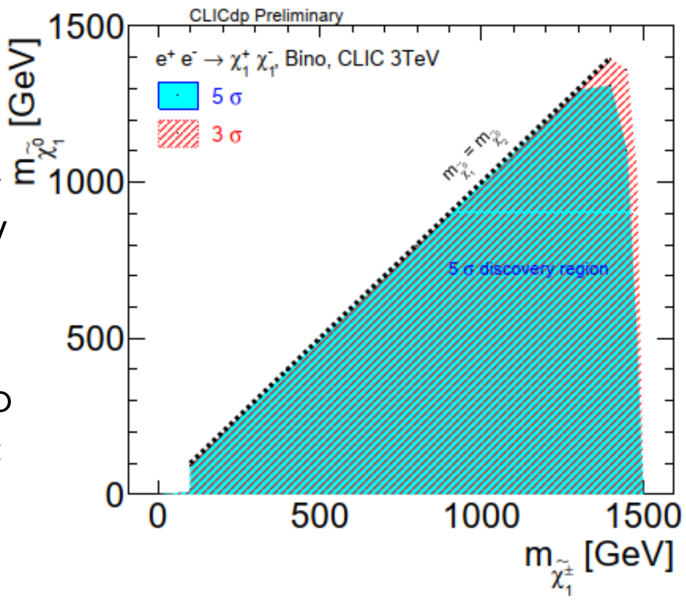
Searching for simplified model dark matter scalar mediator using mono-photon signature –> higher mass reach



- **SUSY signatures:**

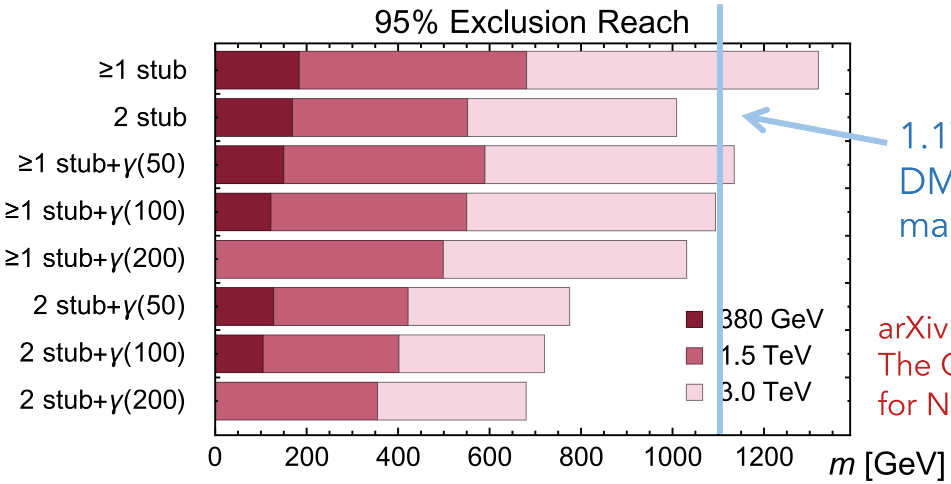
$e^+e^- \to \chi_1^+ \chi_1^-$
with $\chi_1^\pm \to \chi_1^0 W^\pm$
and $W^+W^- \to qqqq$
or $W^+W^- \to e^-\mu^+\nu\nu$
or $e^+\mu^-\nu\ \nu$

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



- **Higgsino:**

With other superpartners decoupled:
$\chi^\pm$ slightly heavier than χ^0 ; $\chi^\pm \to \pi^\pm \chi^0$
leaving 'disappearing track' signature



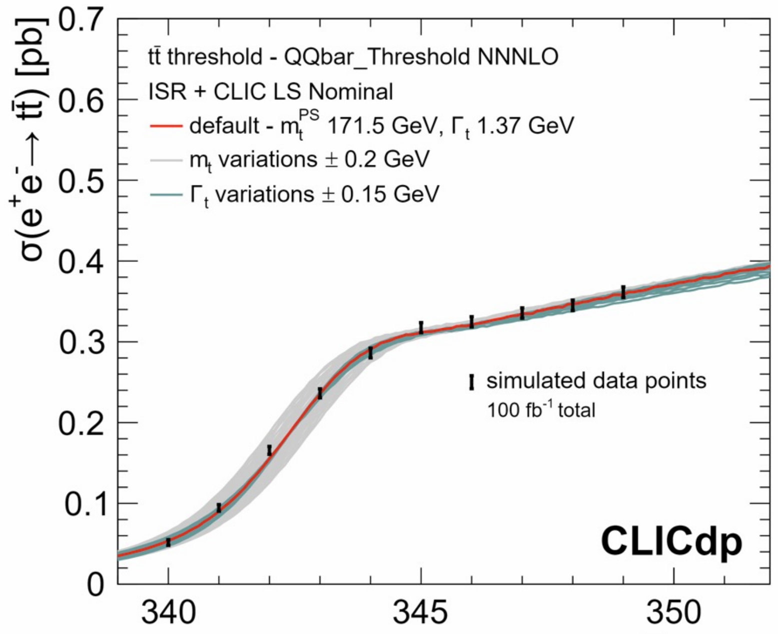
1.1TeV for DM relic mass density

arXiv:1812.02093
The CLIC Potential for New Physics

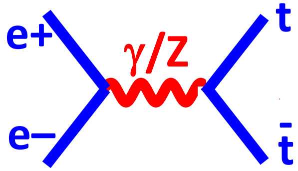
Top-quark physics

- **CLIC is unique among e+e– colliders by accessing top-quark physics from the initial energy stage**

◆ Threshold scan:



sensitive to top mass (Δm_t~50MeV), width, couplings



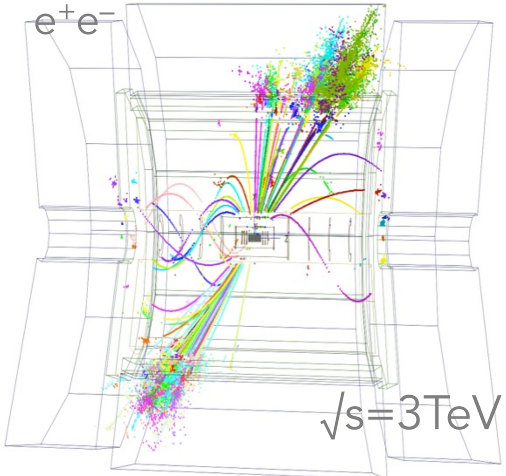
Electron beam polarisation provides new observables

Top-quark physics at CLIC: JHEP11 (2019) 003

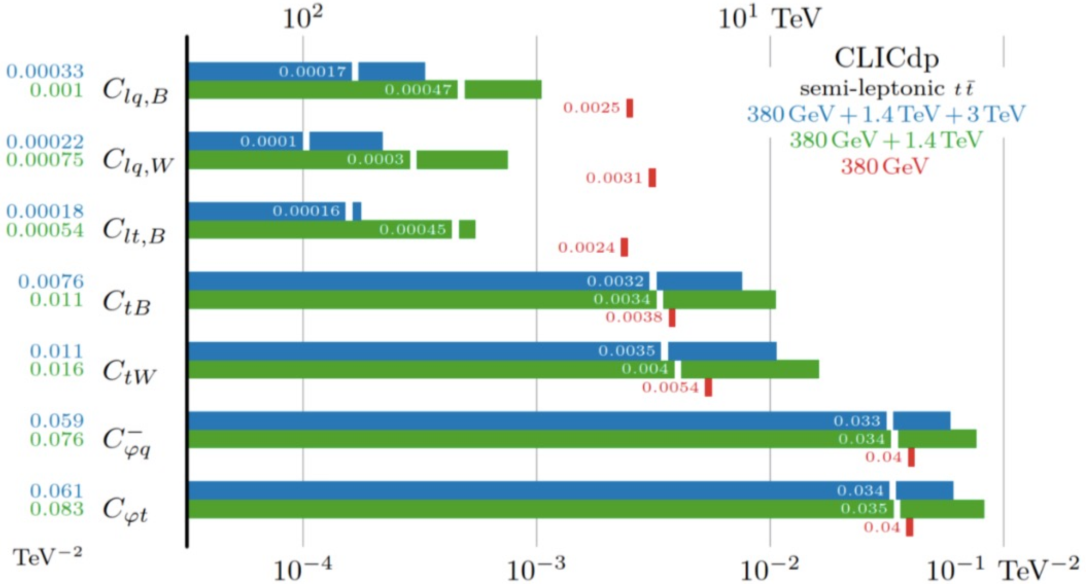
◆ Pair production:

- Top cross-sections, both polarisations ~1%
- Top forward-backward asymmetries ~3–4%
- Statistically optimal observables for top EWK couplings; more than one energy stage allows global fit

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

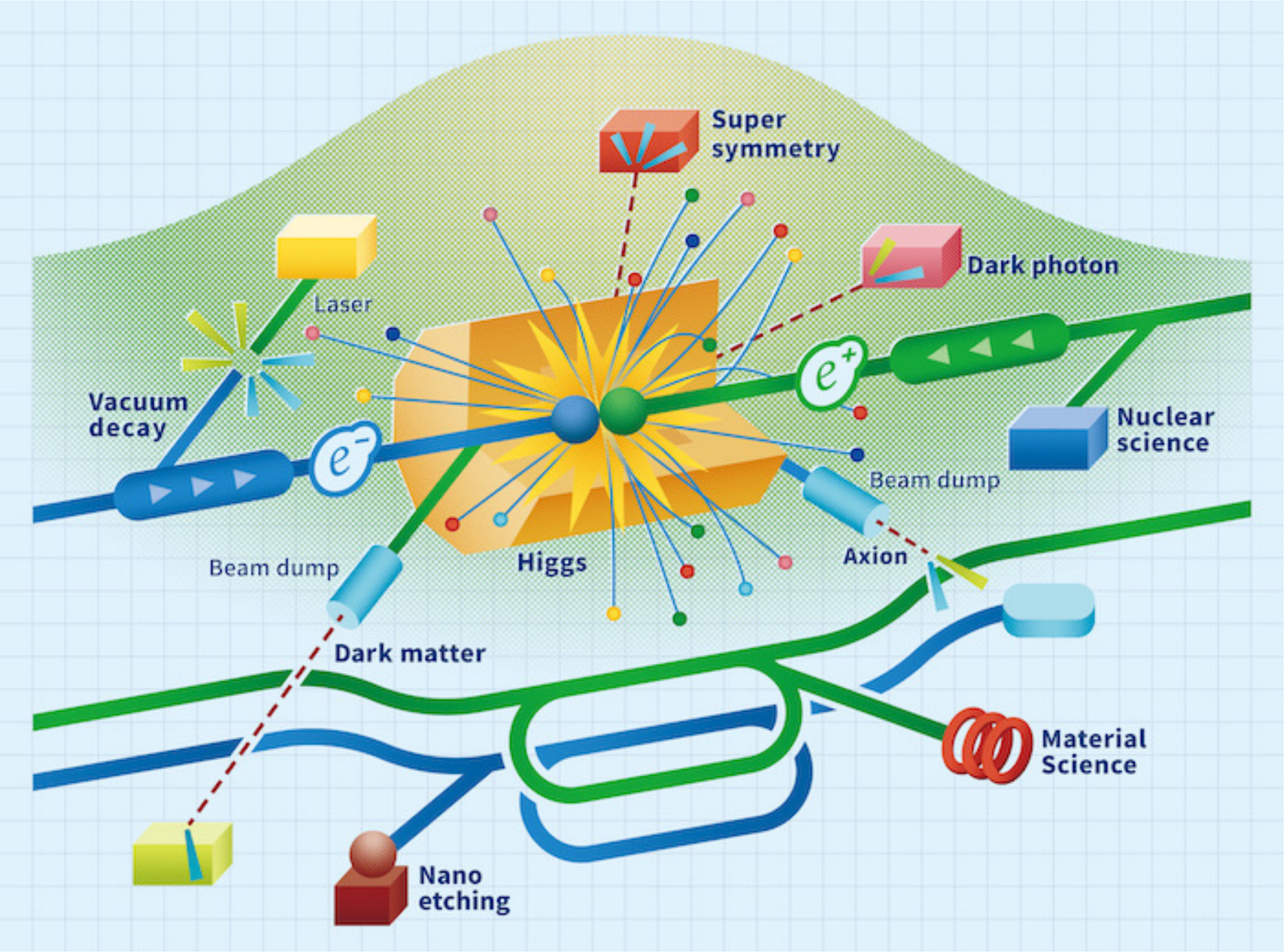


$e^+e^- \to t\bar{t} \to q\bar{q}q\bar{q}b\bar{b}$

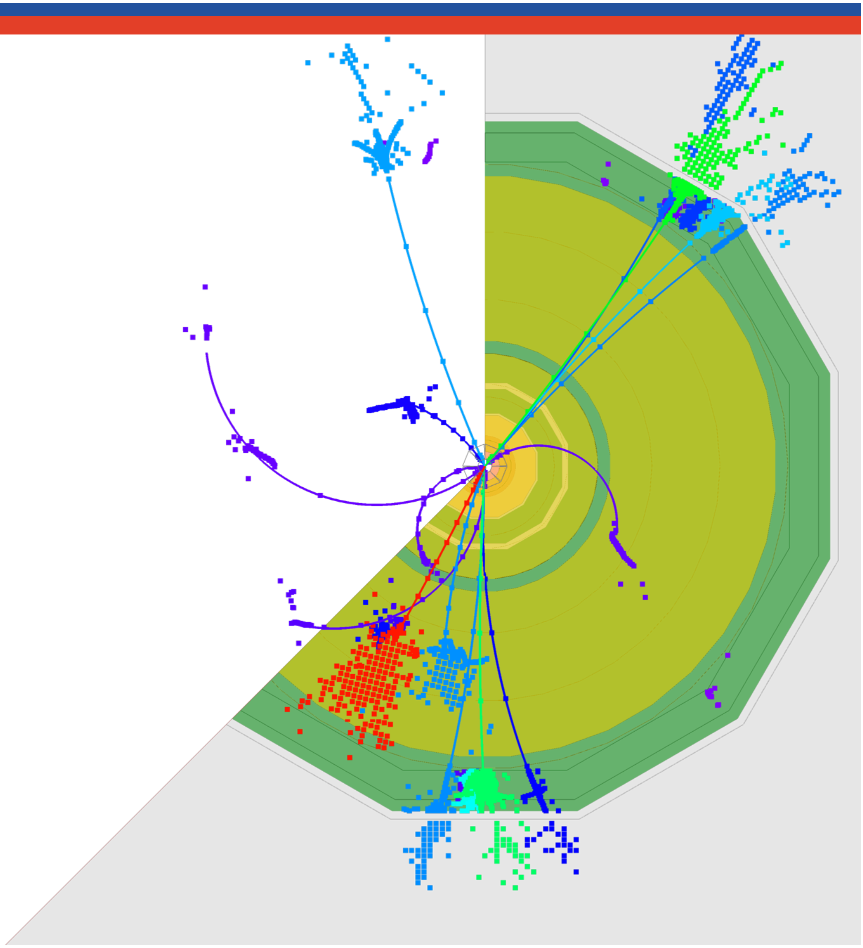


Beyond Collider Physics

- Considering full use of the infrastructure associated with a linear collider complex



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

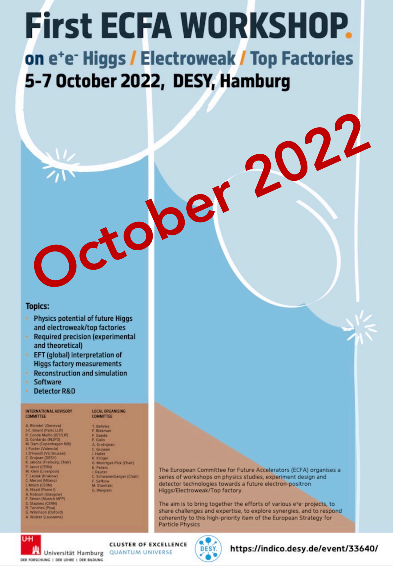
–> Build on previous coherent efforts e.g. Higgs@FutureColliders working group for last European Strategy Update

◆ Structure of the study:

Activities organised via three Working Groups

Two major workshops so far

ECFA Report as input to next European Strategy



First ECFA WORKSHOP.

on e^+e^- Higgs / Electroweak / Top Factories

5-7 October 2022, DESY, Hamburg

October 2022

Topics:

- Physics potential of future Higgs and electroweak/top factories
- Required precision (experimental and theoretical)
- EFT (global) interpretation of Higgs factory measurements
- Reconstruction and simulation
- Software
- Detector R&D

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The European Committee for Future Accelerators (ECFA) organises a series of workshops on physics studies, experiment design and detector technologies towards a future electron-positron Higgs/Electroweak/Top factory.

The aim is to bring together the efforts of various e^+e^- projects, to share challenges and expertise, to explore synergies, and to respond coherently to this high-priority item of the European Strategy for Particle Physics

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https://indico.desy.de/event/33640/

SECOND • ECFA • WORKSHOP

on e^+e^- Higgs / Electroweak / Top Factories

11-13 October 2023
Paestum / Salerno / Italy

October 2023

Topics:

- Physics potential of future Higgs and electroweak/top factories
- Required precision (experimental and theoretical)
- EFT (global) interpretation of Higgs factory measurements
- Reconstruction and simulation
- Software
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ECFA Study on Higgs/top/electroweak factories

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

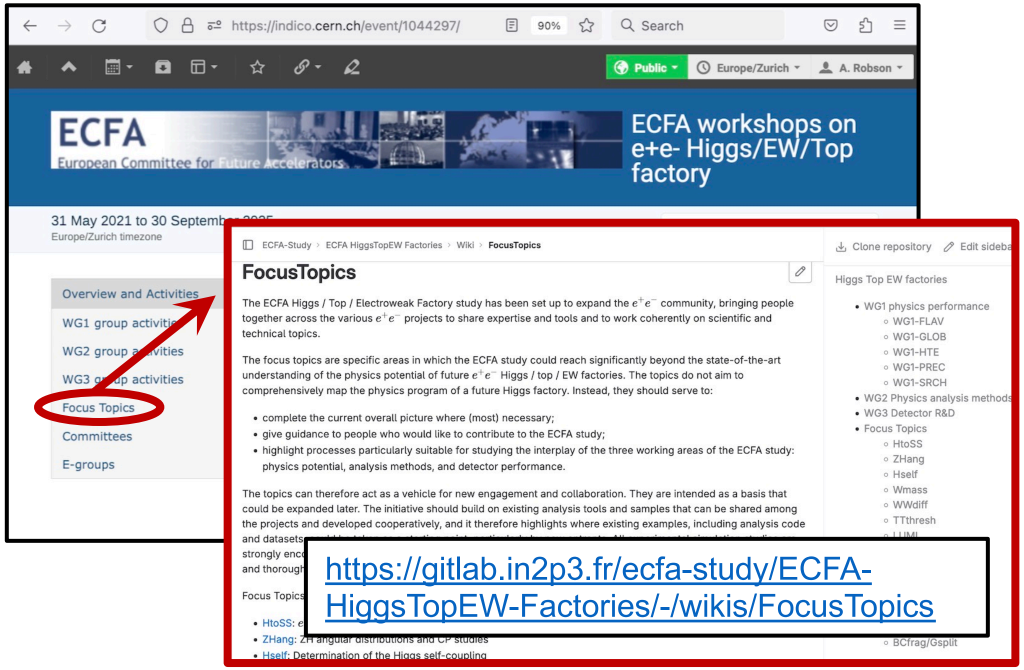
Focus topics are intended to encompass a wide range of activities spanning theory & experiment, analysis & algorithm development, and detector requirements & optimisation

◆ Overall aim: accumulate critical mass working on each topic, reaching publications on timescale of ECFA study
–> trying to attract newcomers to work on e+e– physics & detectors

◆ Focus topics definition/discussion document will appear on arXiv in around 1 week.

- 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

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



FocusTopics

The ECFA Higgs / Top / Electroweak Factory study has been set up to expand the e^+e^- community, bringing people together across the various e^+e^- projects to share expertise and tools and to work coherently on scientific and technical topics.

The focus topics are specific areas in which the ECFA study could reach significantly beyond the state-of-the-art understanding of the physics potential of future e^+e^- Higgs / top / EW factories. The topics do not aim to comprehensively map the physics program of a future Higgs factory. Instead, they should serve to:

- complete the current overall picture where (most) necessary;
- give guidance to people who would like to contribute to the ECFA study;
- highlight processes particularly suitable for studying the interplay of the three working areas of the ECFA study: physics potential, analysis methods, and detector performance.

The topics can therefore act as a vehicle for new engagement and collaboration. They are intended as a basis that could be expanded later. The initiative should build on existing analysis tools and samples that can be shared among the projects and developed cooperatively, and it therefore highlights where existing examples, including analysis code and datasets

strongly enc

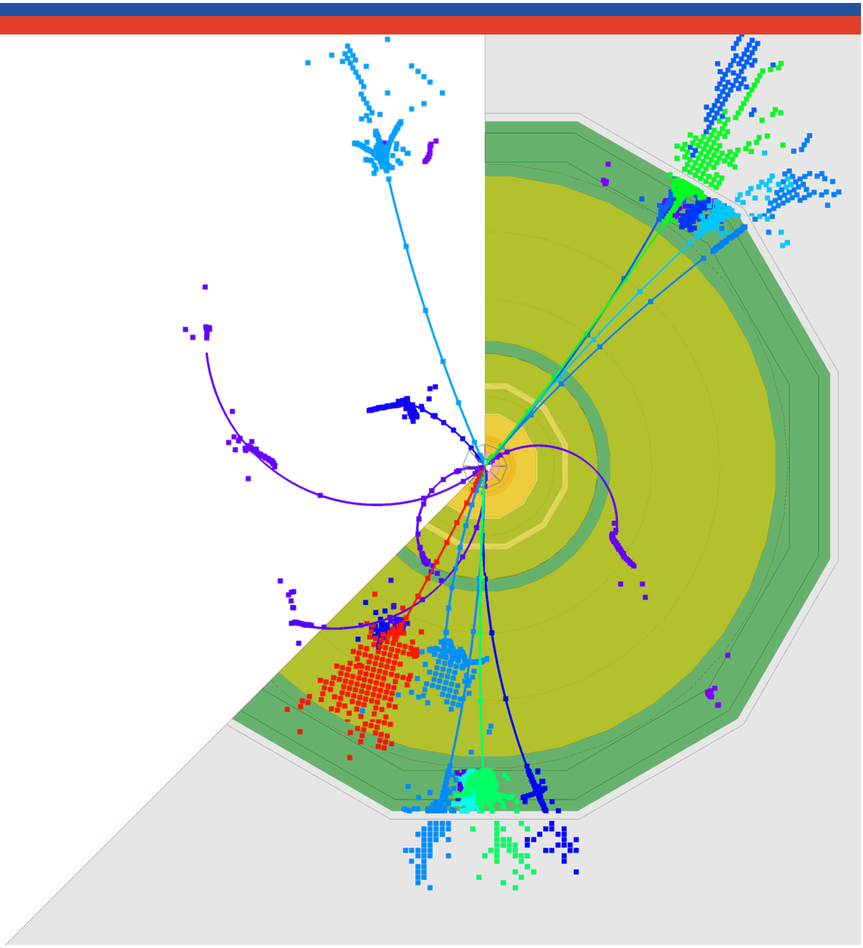
and thorough

Focus Topics

- HtoSS: e
- ZHang: ZH angular distributions and CP studies
- Hself: Determination of the Higgs self-coupling

https://gitlab.in2p3.fr/ecfa-study/ECFA-HiggsTopEW-Factories/-/wikis/FocusTopics

Summary



Linear Colliders vision

- ILC and CLIC are mature options for a Higgs factory; C^3 and HALHF could be interesting alternatives
- Initial stage Higgs factory; upgradable to TeV-energies – Beam polarization; direct double-Higgs production for Higgs self-coupling; interesting access to BSM signatures
- Global programme 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

    "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
- complementary to and succeeding HL-LHC

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