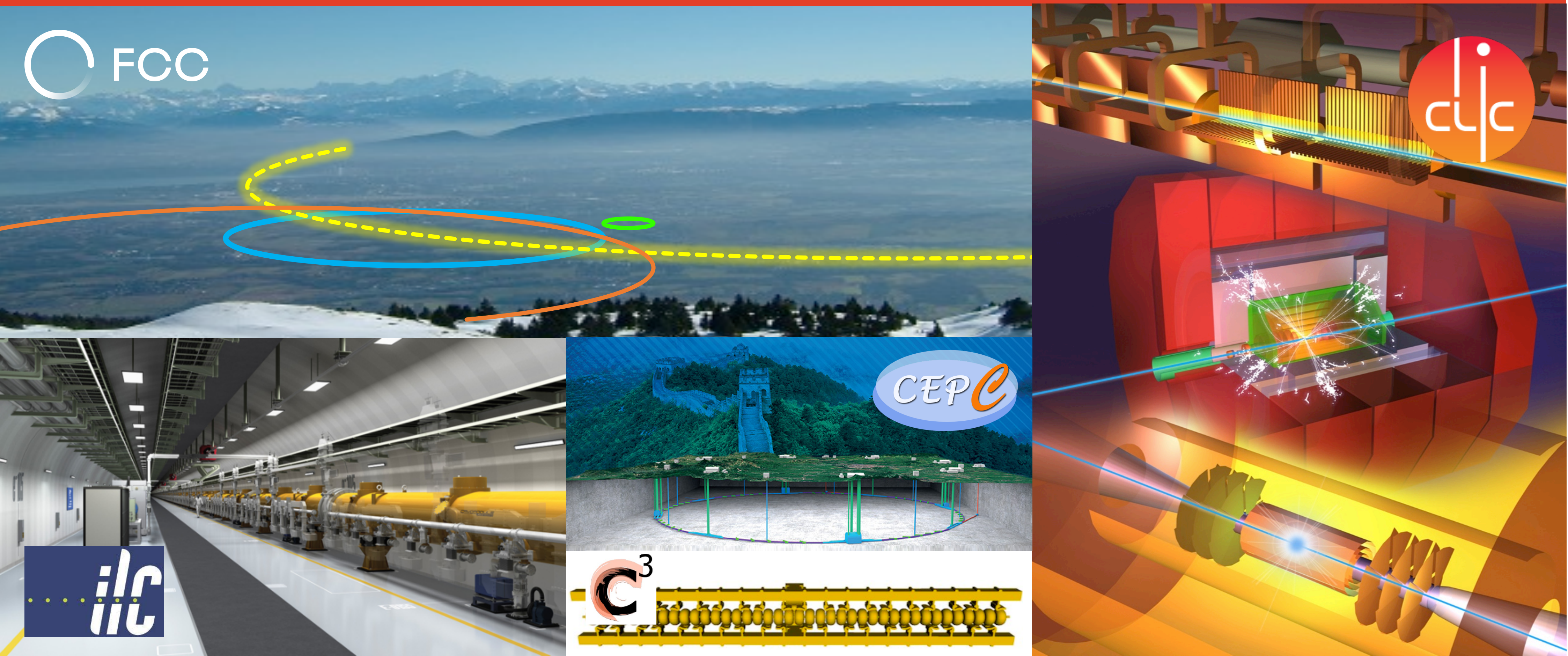
e^+e^- colliders

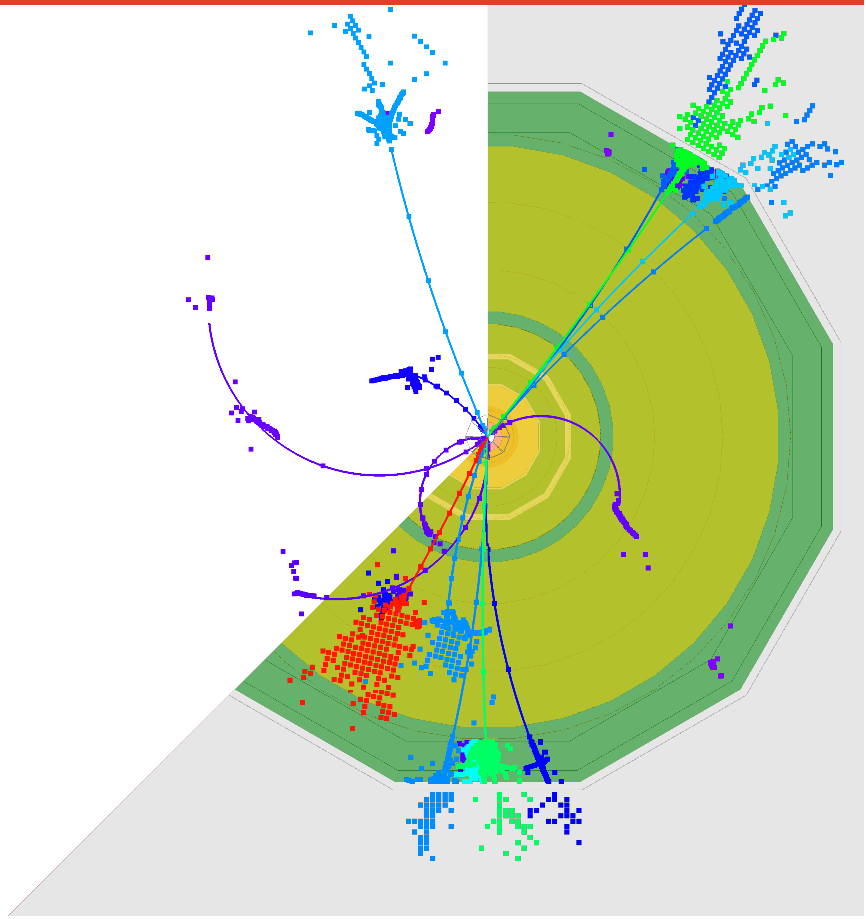


Higgs Pairs Workshop, 30 May – 3 June 2022, Dubrovnik

Aidan Robson, University of Glasgow

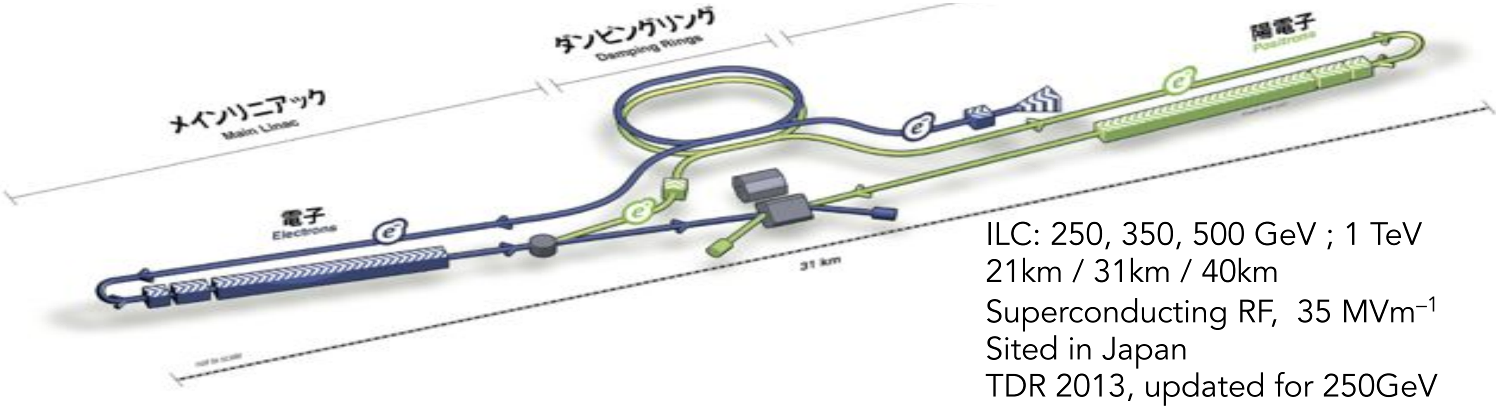
e^+e^- colliders

- Proposed colliders
- Higgs physics
- Higgs self-coupling – direct and indirect
- BSM physics in Higgs pairs
- Project outlooks

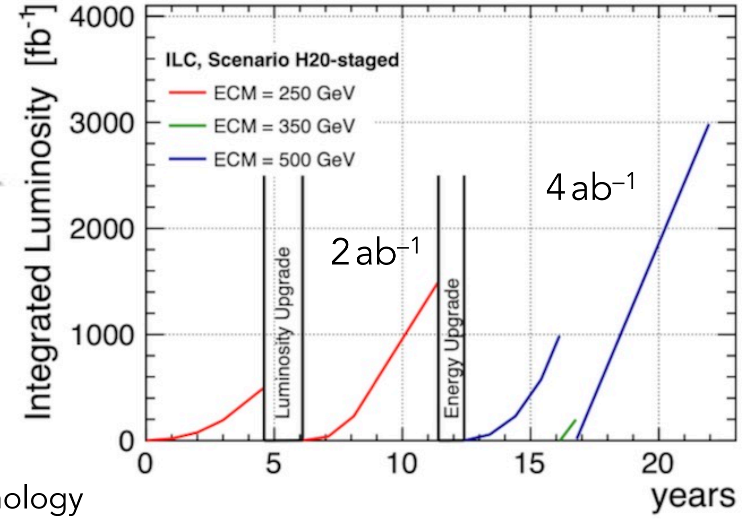


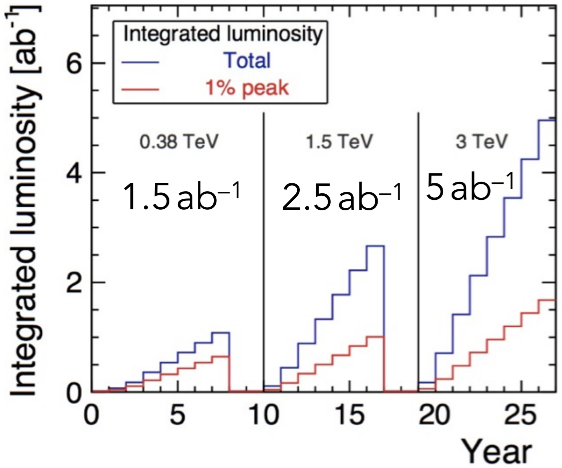
Linear Colliders

International Linear Collider (ILC)



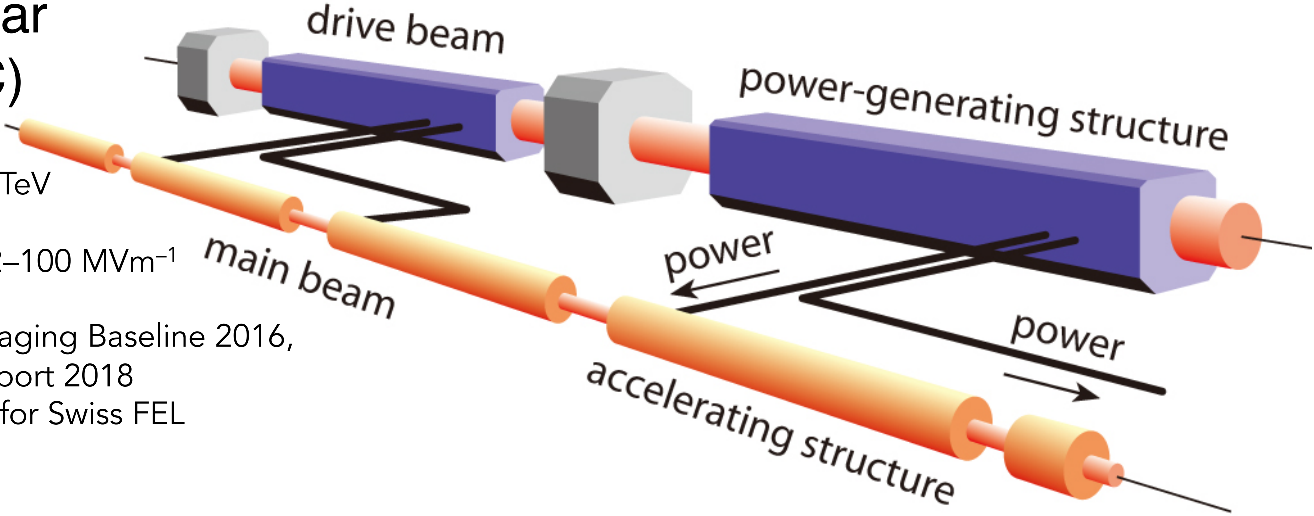
ILC: 250, 350, 500 GeV ; 1 TeV
21km / 31km / 40km
Superconducting RF, 35 MVm^{-1}
Sited in Japan
TDR 2013, updated for 250GeV
European XFEL demonstrates technology





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 Readiness Report 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

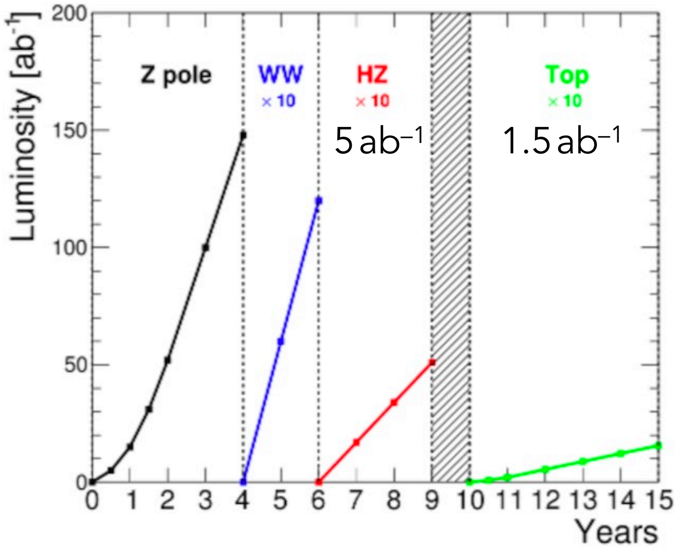
C^3 Beam delivery / IP identical to ILC
Damping rings / injector similar to CLIC
Physics output very similar to ILC

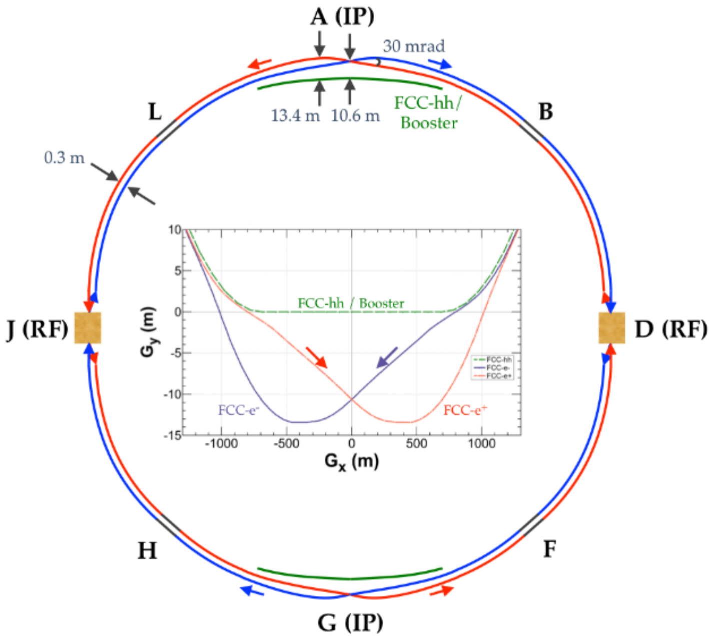
Circular Colliders

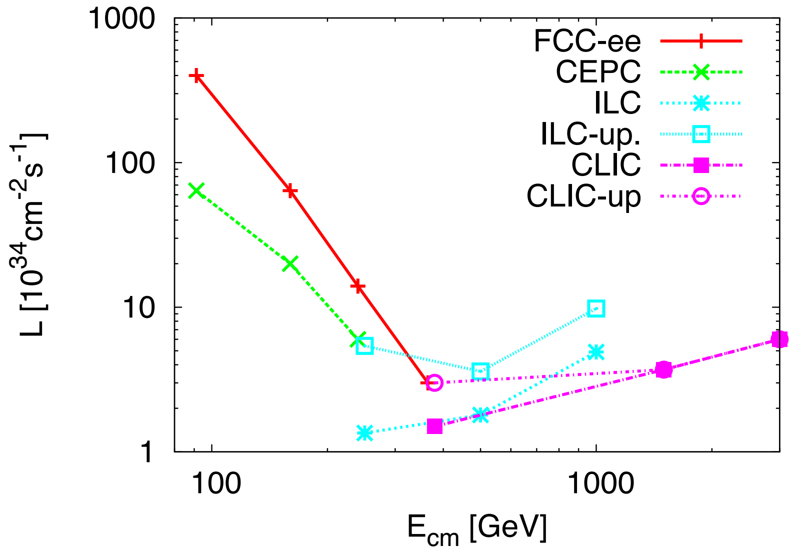
Future Circular Collider (FCC-ee)

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

for 2 IPs



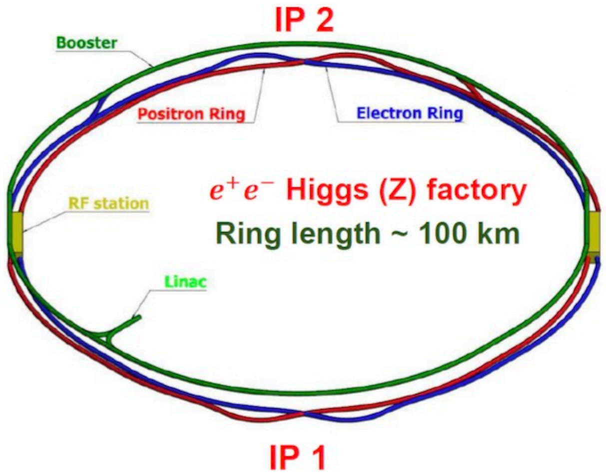




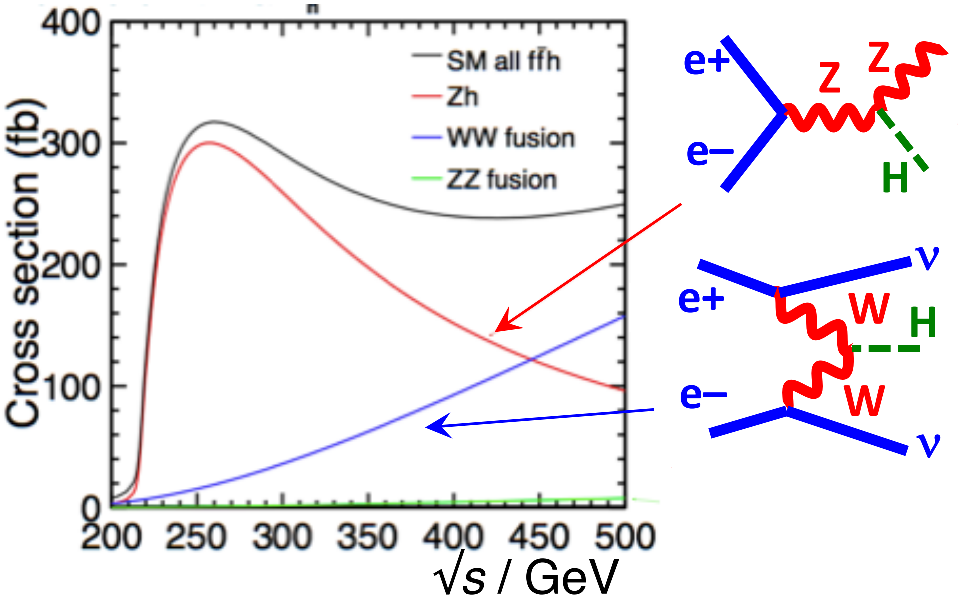
FCC: ~92k, ring; CEPC: ~100km ring
FCCee CDR 2019; CEPC CDR 2018
Accelerator technology mostly proven >50yr

Circular Electron Positron Collider (CEPC)

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



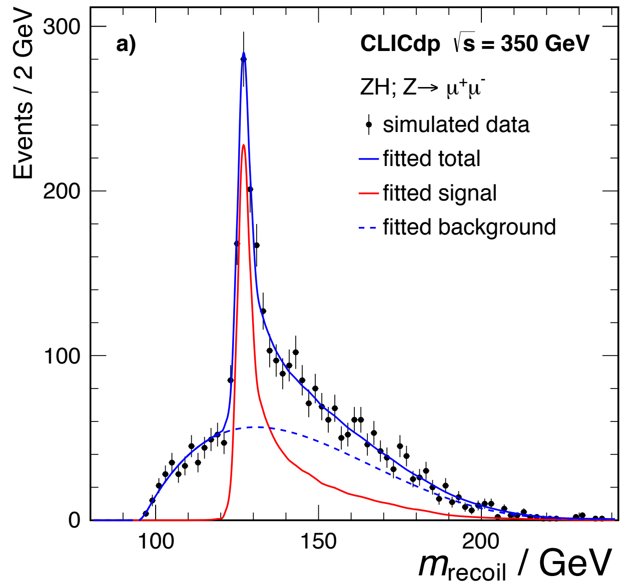
Higgs production in e⁺e⁻



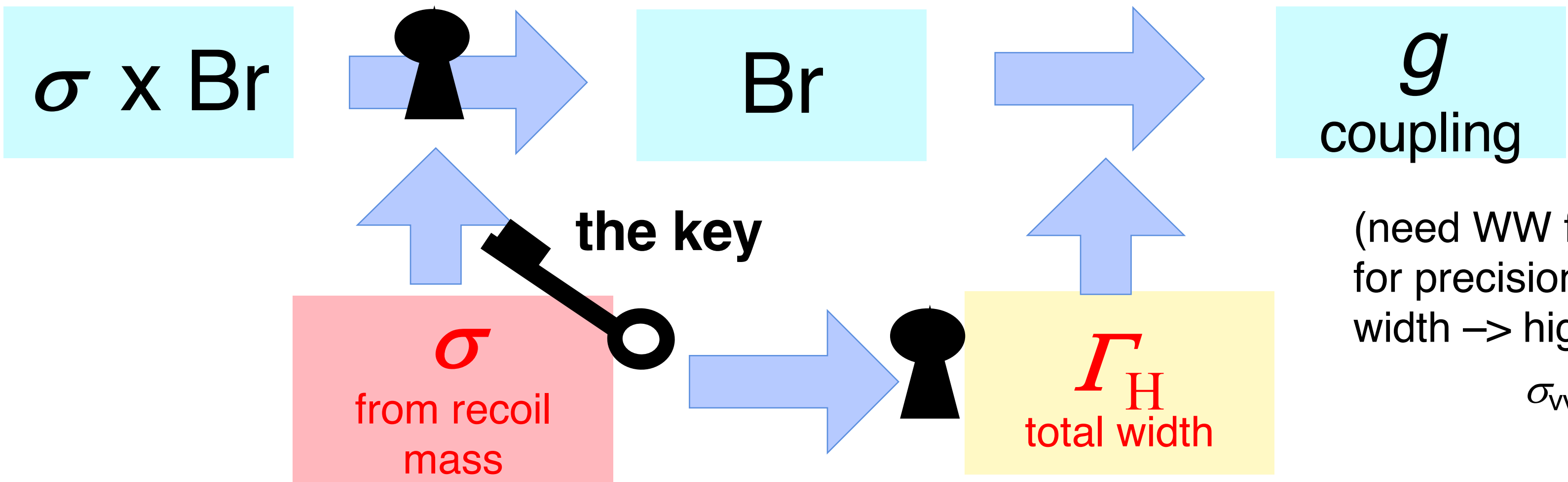
- ZH process allows reconstruction of H by looking exclusively at recoil of Z –> model-independent extraction of g_{HZZ} coupling

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

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



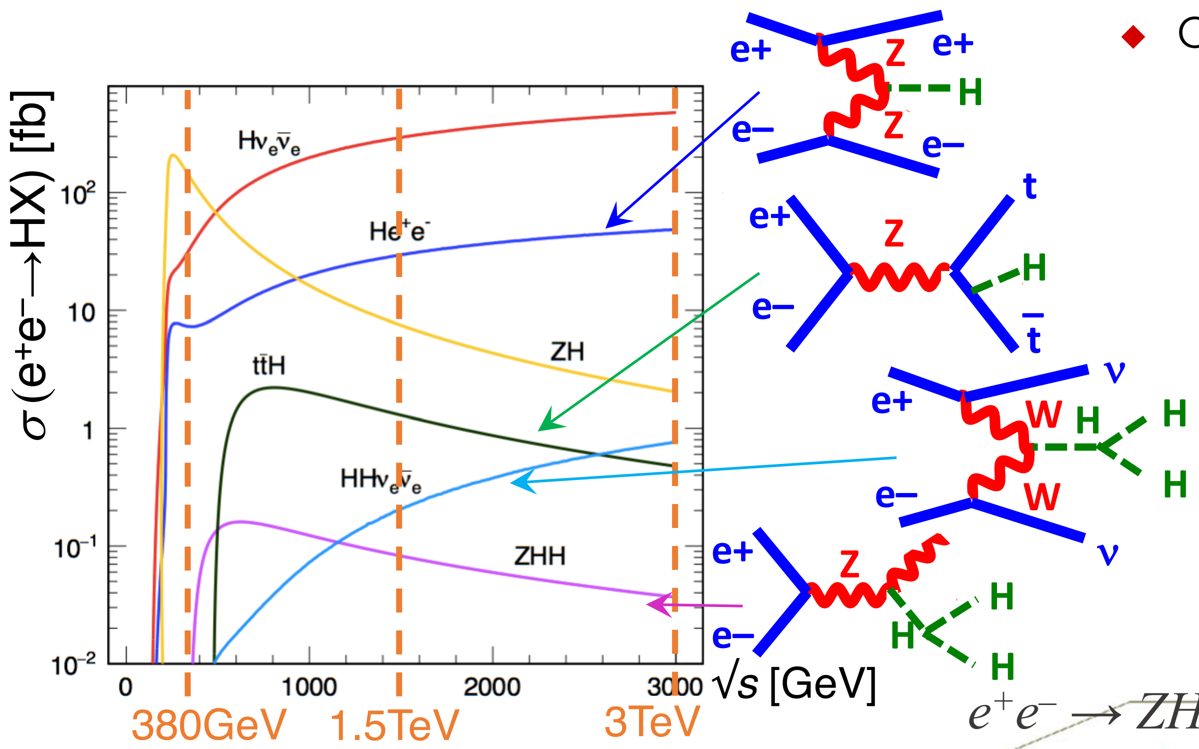
$$g^2_{HAA} \propto \Gamma(H \to AA) = \Gamma_H \cdot BR(H \to AA)$$



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

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

Higgs production in e^+e^-



- Other processes turn on at higher energies

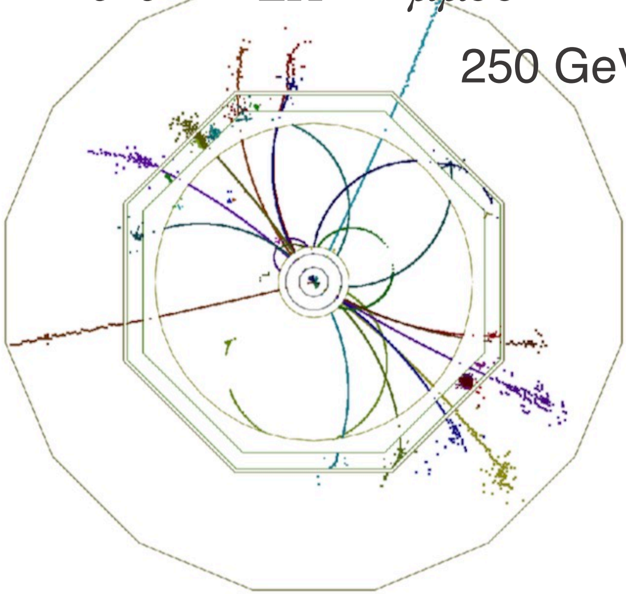
Channel	Measurement	Observable
ZH	Recoil mass distribution	m_H
ZH	$\sigma(ZH) \times BR(H \to \text{invisible})$	Γ_{inv}
ZH	$\sigma(ZH) \times BR(Z \to l^+l^-)$	g^2_{HZZ}
ZH	$\sigma(ZH) \times BR(Z \to q\bar{q})$	g^2_{HZZ}
ZH	$\sigma(ZH) \times BR(H \to b\bar{b})$	$g^2_{HZZ}g^2_{Hbb}/\Gamma_H$
ZH	$\sigma(ZH)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

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

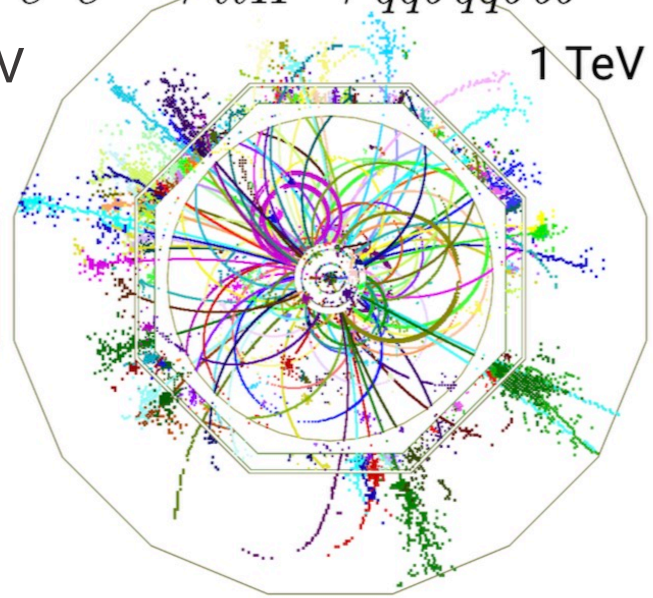
All projects have studied many channels

- Experimental environment relatively 'clean' (consider VBF production, where Higgs decay is the only visible product)
- Imaging calorimetry approach allows e.g. H->bb/cc/gg separation
- Target Higgs coupling sensitivity at 1% level for significant improvement on HL-LHC and sensitivity to typical BSM scenarios

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

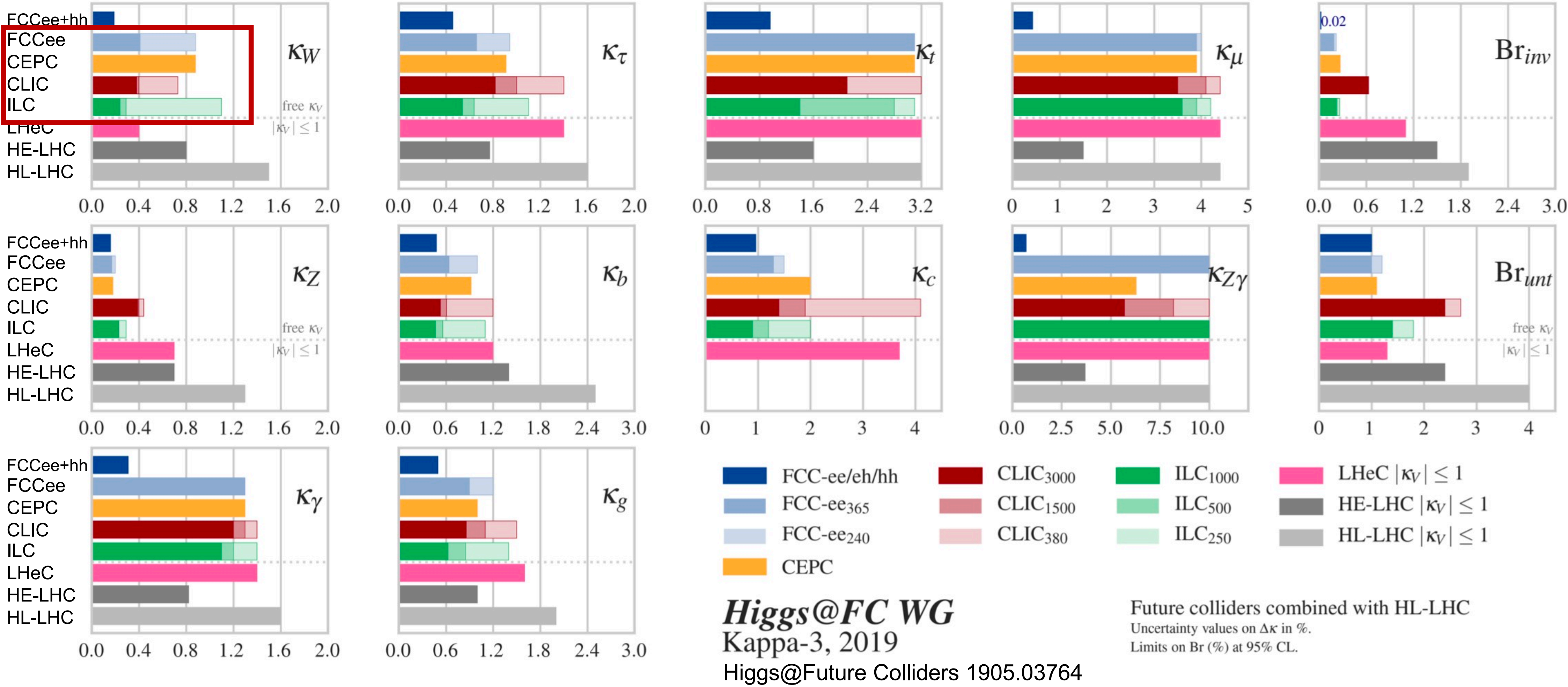


$e^+e^- \to ttH \to q\bar{q}b\,q\bar{q}\bar{b}\,b\bar{b}$



Higgs couplings sensitivity

- Illustrative comparison of sensitivities (combined with HL-LHC) – κ is deviation of coupling from SM value
- Individual inputs also used as input for EFT fits and interpreted as Higgs couplings
  –> preferable and leads to similar overall conclusions



- Note FCChh sensitivities could alternatively be added in with CEPC, ILC, or CLIC
- Different projects are optimised in different ways but result in largely similar sensitivities

Flexibility in run scenarios

- All proposals have chosen some baseline running plan, but have flexibility to adapt (e.g. to external constraints)

- Just one example, from CLIC: possibility of doubling bunch train repetition rate at initial stage from 50Hz to 100 Hz and increasing initial stage from 8 to 13 years CERN-ACC-2019-0051
–> modest increase in cost (~5%) and power (from 170MW to 220MW)
–> Integrated luminosity at 380GeV increases from $1ab^{-1}$ to $4ab^{-1}$

– baseline 1st + 2nd stage, or longer 1st stage, give competitive results

	Benchmark	HL-LHC	HL-LHC + CLIC 380 ($4\,ab^{-1}$)	HL-LHC + CLIC 380 ($1\,ab^{-1}$) + 1500 ($2.5\,ab^{-1}$)	HL-LHC + FCC-ee 240	HL-LHC + FCC-ee 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 first stage

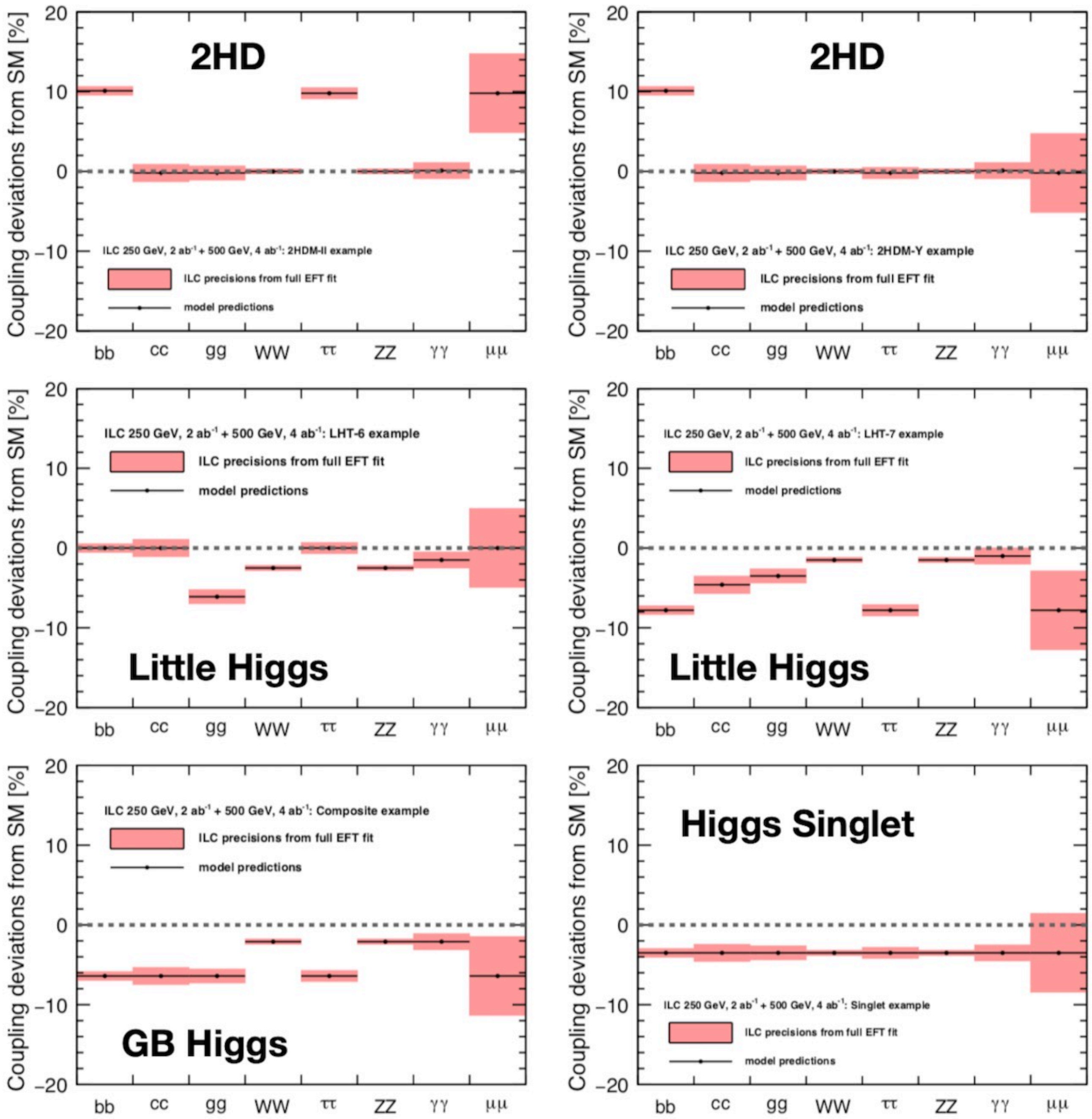
CLIC baseline

From arXiv: 2001.05278

From European Strategy Briefing Book

- Proposed e^+e^- colliders give similar Higgs performance at the initial stage "Higgs Factory"

Higgs couplings sensitivity



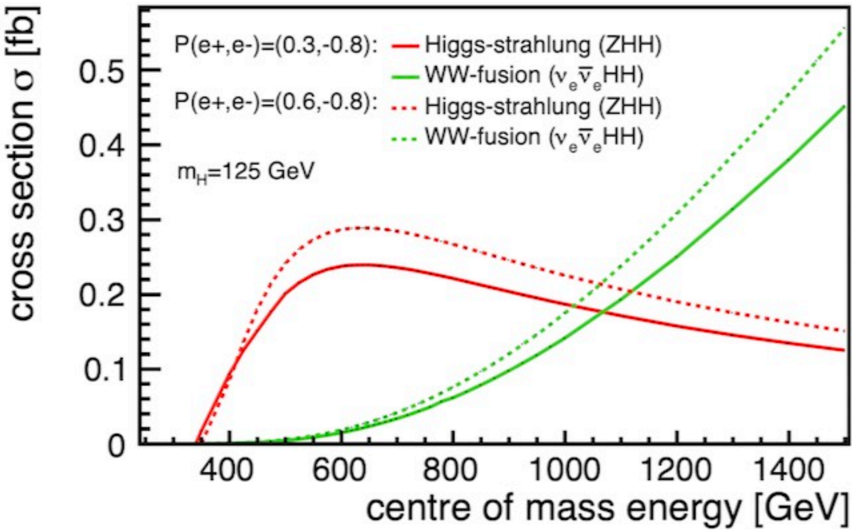
- Aim of precision Higgs measurements is to ***discover violation of the SM***
- Complementary to direct searches at LHC – these are examples with large coupling deviations due to new particles that are out of reach of HL-LHC, shown with projected ILC precisions at 500GeV

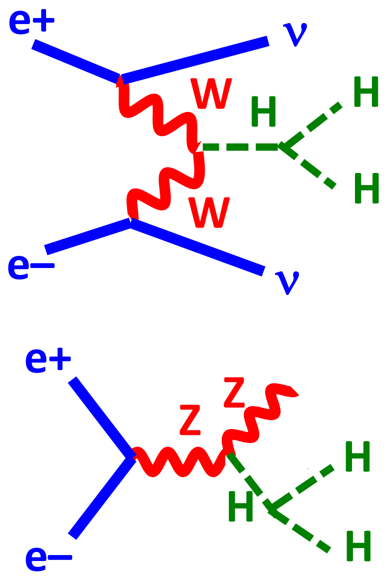
(Barklow et al. 1708.08912)

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

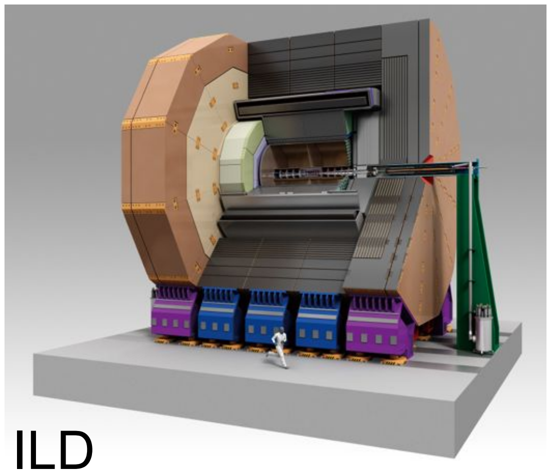
Barklow/Peskin

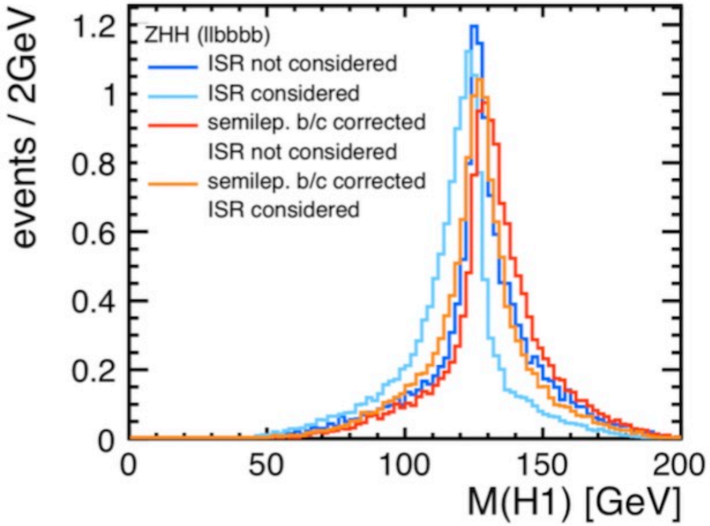
Higgs self-coupling – direct (0.5–1TeV)

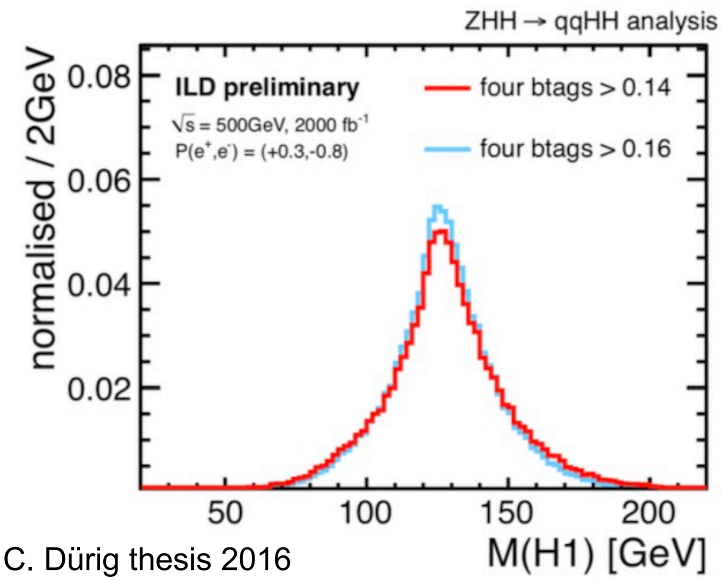




- Two contributing direct production mechanisms: ZHH and ννHH
- ZHH becomes available at ILC 500 – studied in full sim with ILD detector Z->ll / Z->qq, HH->bbbb /HH->bbWW*
- If self-coupling λ is at SM value then double-Higgs process observable at 8σ, with 27% precision on λ
- Adding ννHH at 1TeV brings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





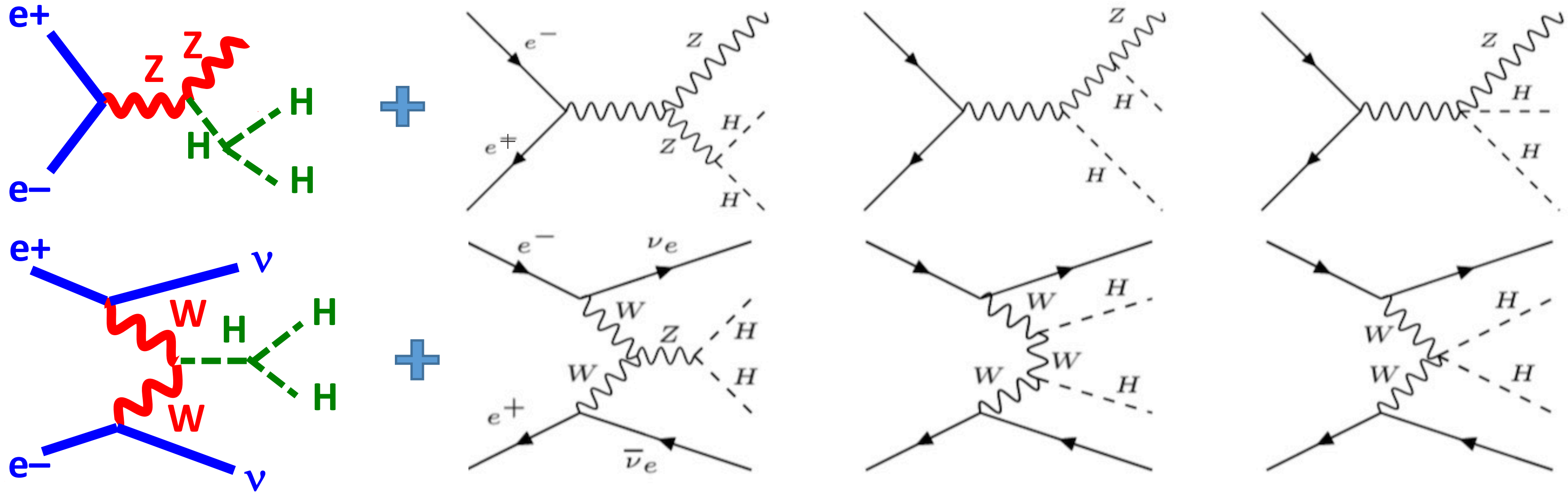


C. Dürig thesis 2016

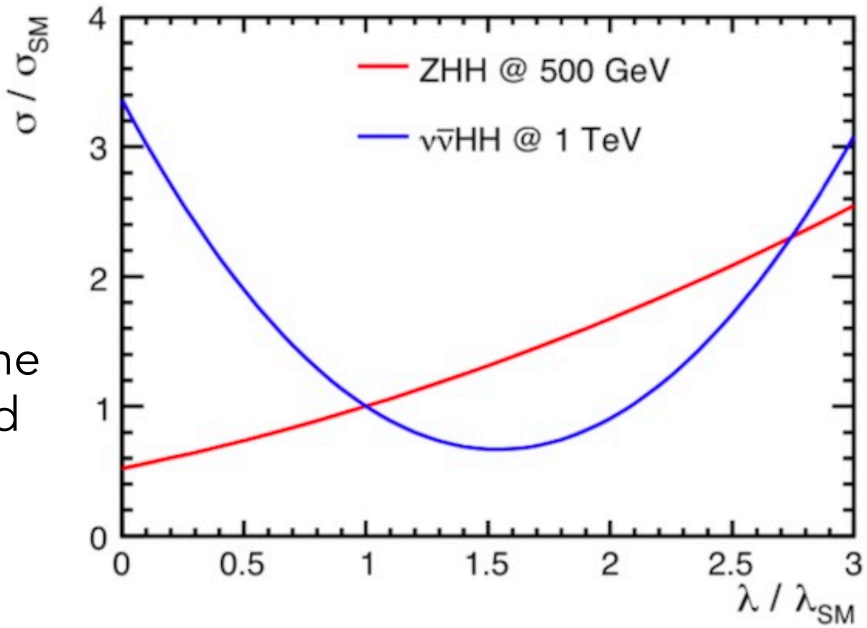
- used state-of-the-art reconstruction at the time, but sensitivity very dependent on b-tagging performance, dijet mass resolution ➡ see Julie Torndal's talk this afternoon for recent developments

Higgs self-coupling – direct (0.5–1TeV)

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

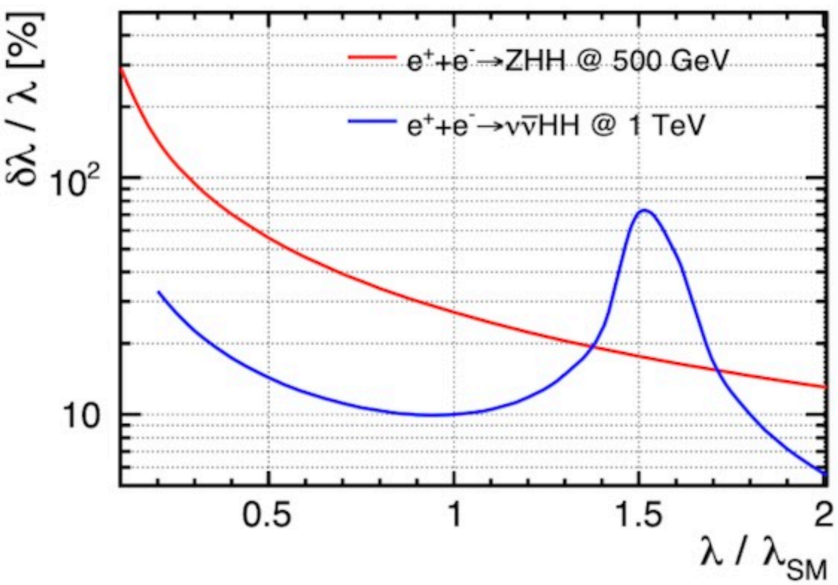


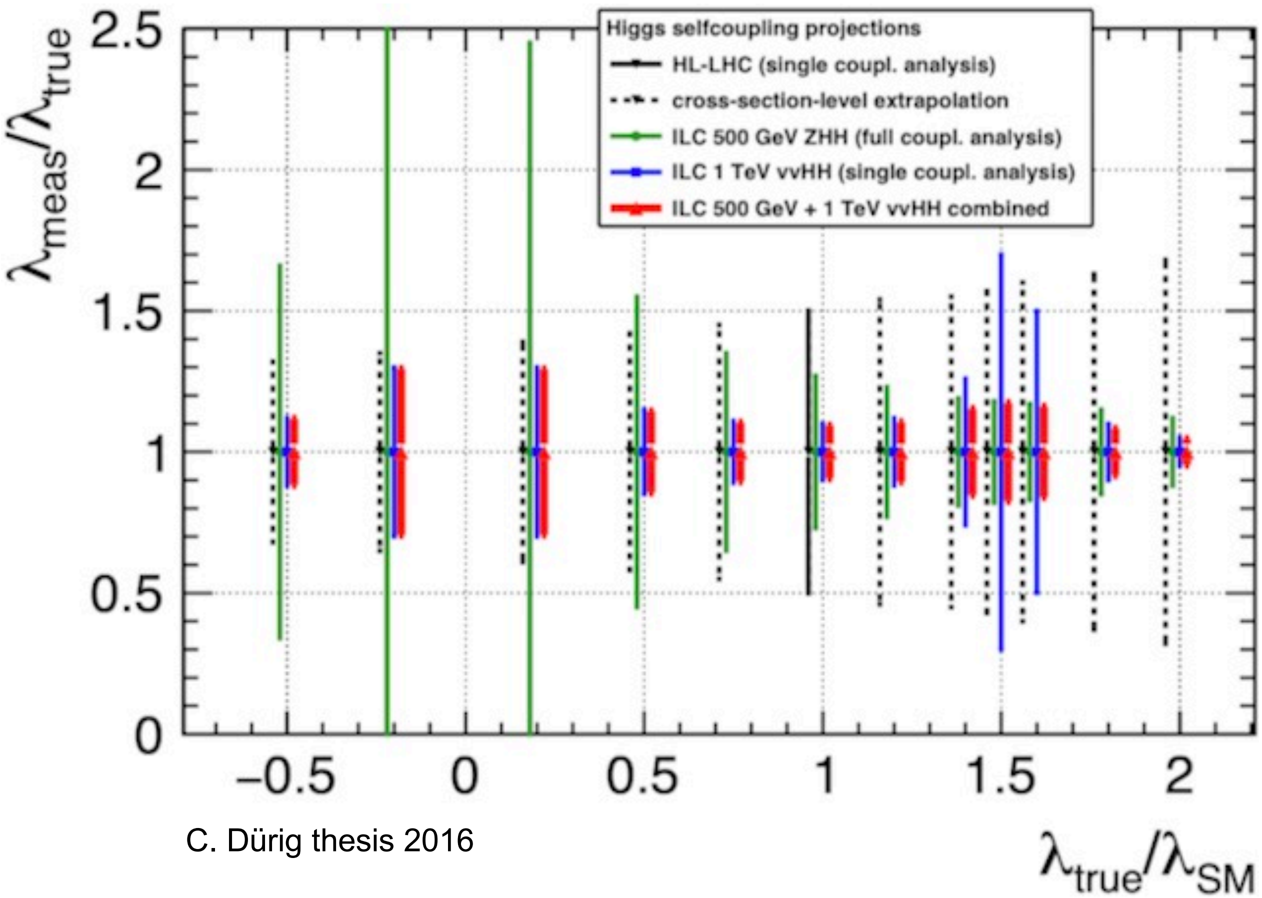
- Self-coupling diagram interferes constructively in ZHH and destructively in ννHH – whatever the sign of the deviation of κ_λ from 1, one of the processes will have an increased cross-section (and increased statistical sensitivity)



Higgs self-coupling – direct (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

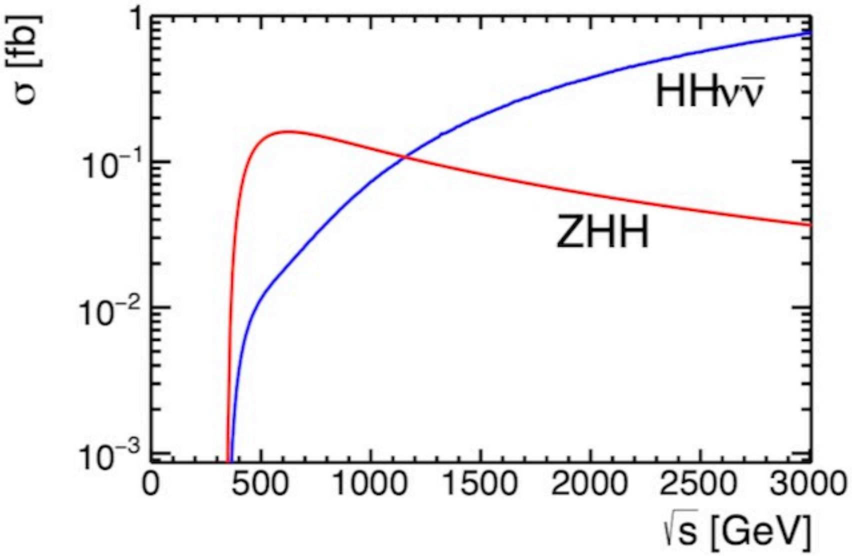




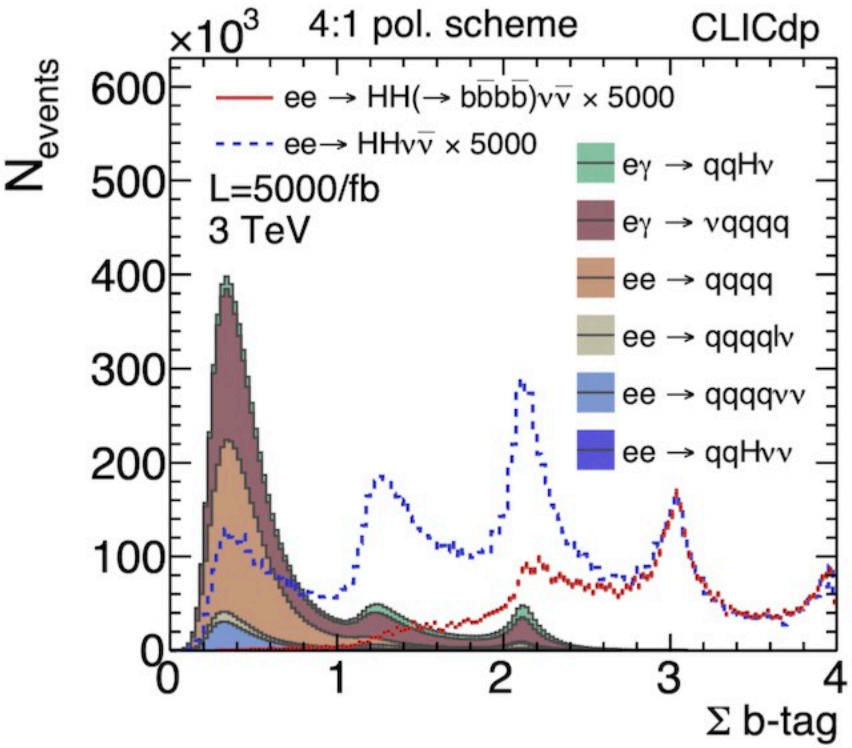
C. Dürig thesis 2016

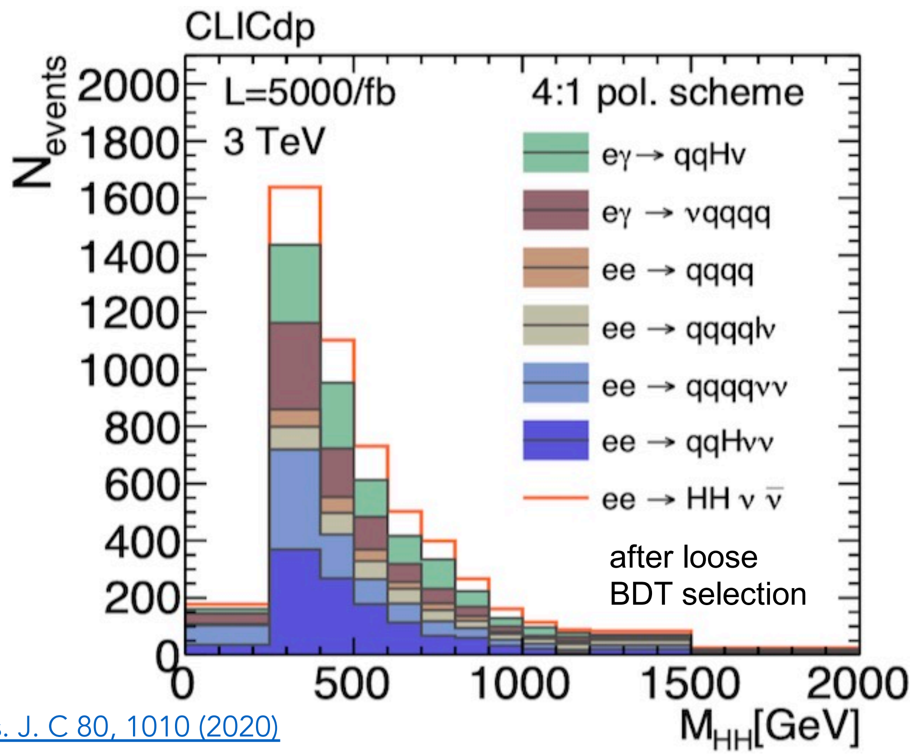
- Owing to their different behaviours, combining ZHH and ννHH gives a measurement of λ of at least 30% *for any value of λ*
- e.g. 2HDM models where fermions couple to only one Higgs doublet allow $0.5 \lesssim \lambda/\lambda_{SM} \lesssim 1.5$, while EWK baryogenesis typically requires $1.5 \lesssim \lambda/\lambda_{SM} \lesssim 2.5$

Higgs self-coupling – direct (>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 $700fb^{-1}$)

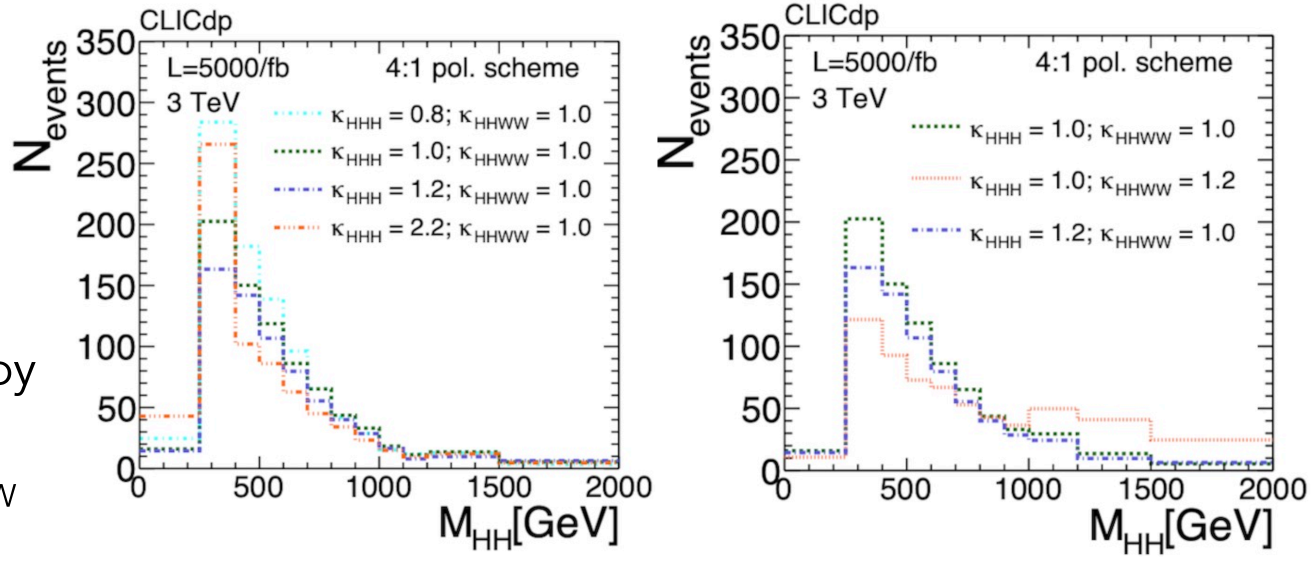


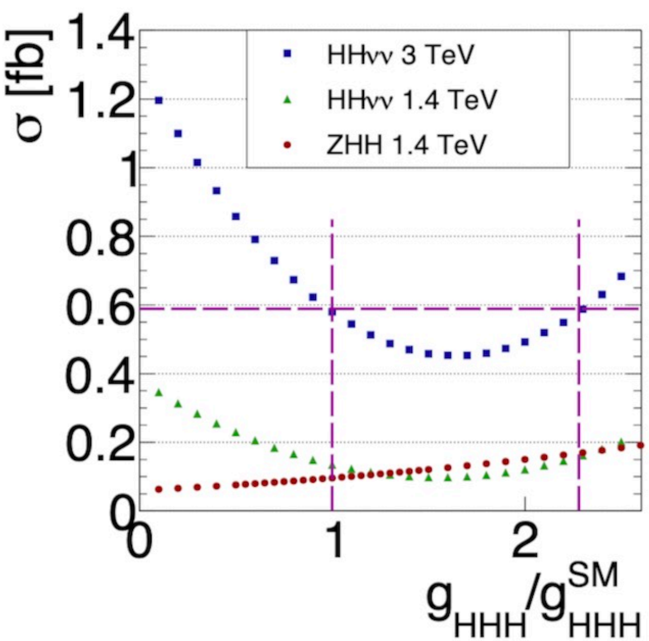


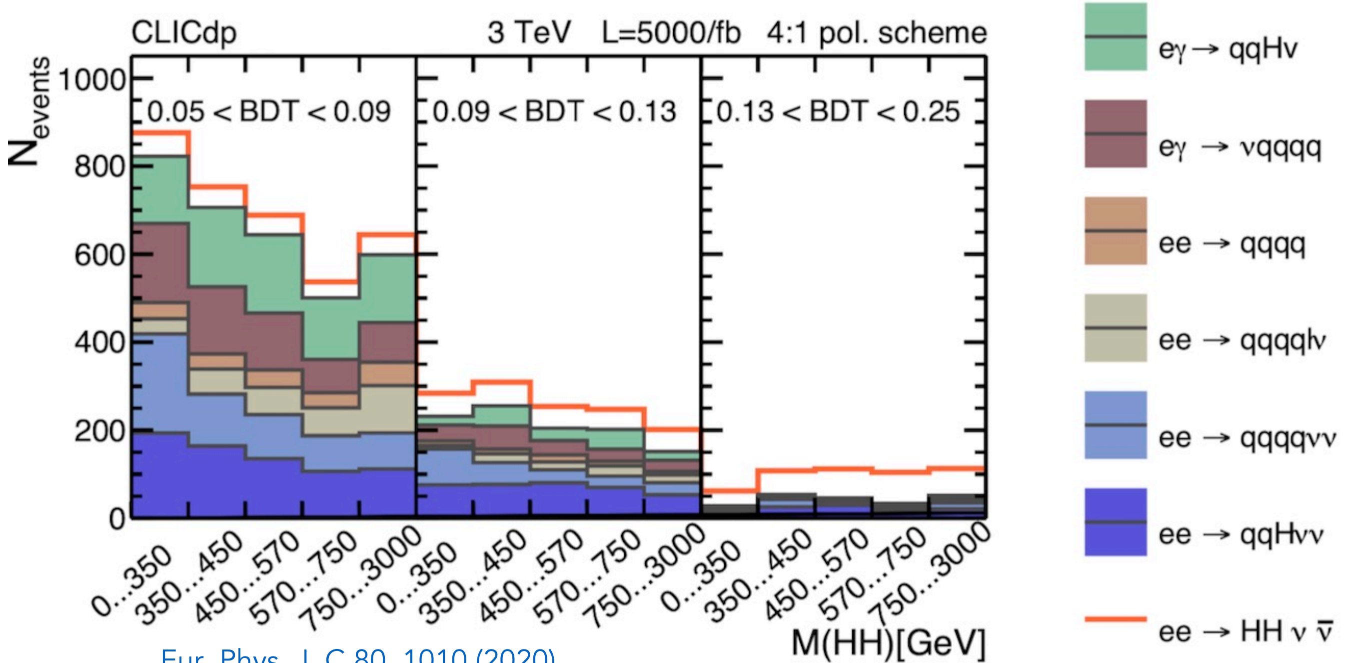
Eur. Phys. J. C 80, 1010 (2020)

Higgs self-coupling – direct (>1TeV)

- information beyond cross-sections required to disambiguate effect of self-coupling diagram
-> look differentially in M_{HH}
- λ/λ_{SM} extracted from template fit to binned M_{HH} in bins of BDT response
- Disambiguation can also be achieved by adding ZHH σ measurement from 1.4TeV
- Note M_{HH} also resolves g_{HHH} and g_{HHWW} effects; g_{HHWW} affects higher M_{HH}

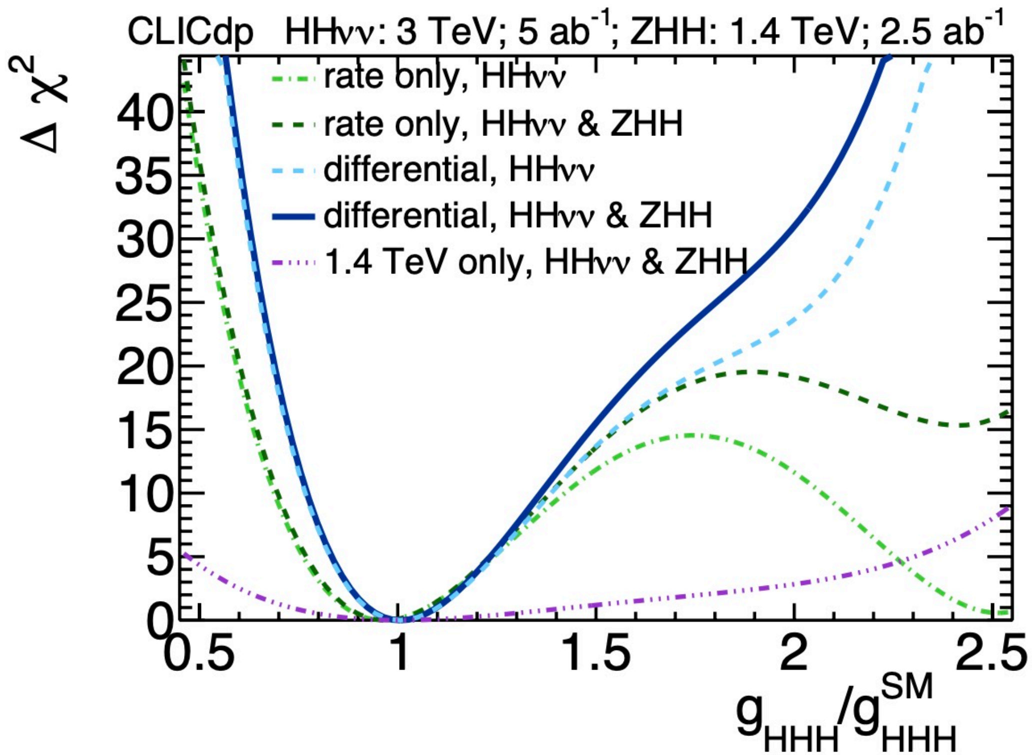


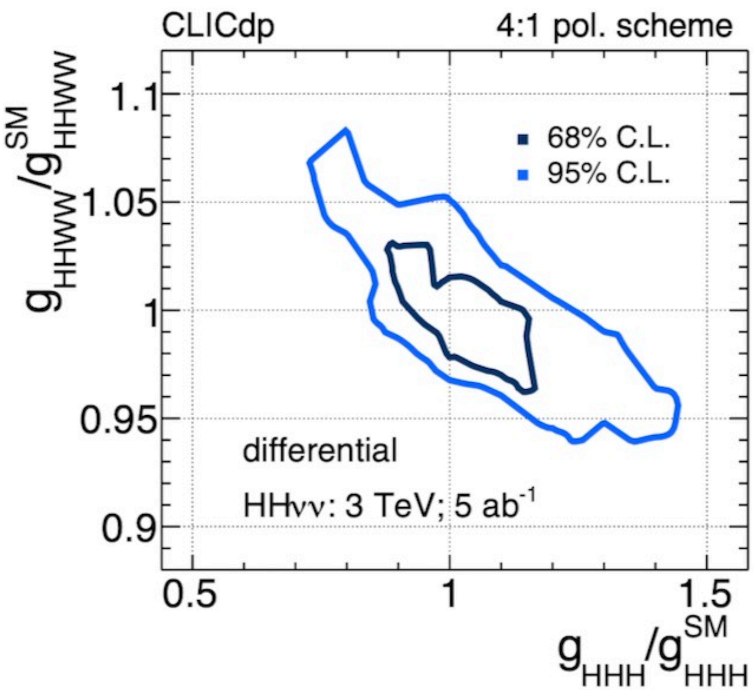




Eur. Phys. J. C 80, 1010 (2020)

Higgs self-coupling – direct (>1TeV)





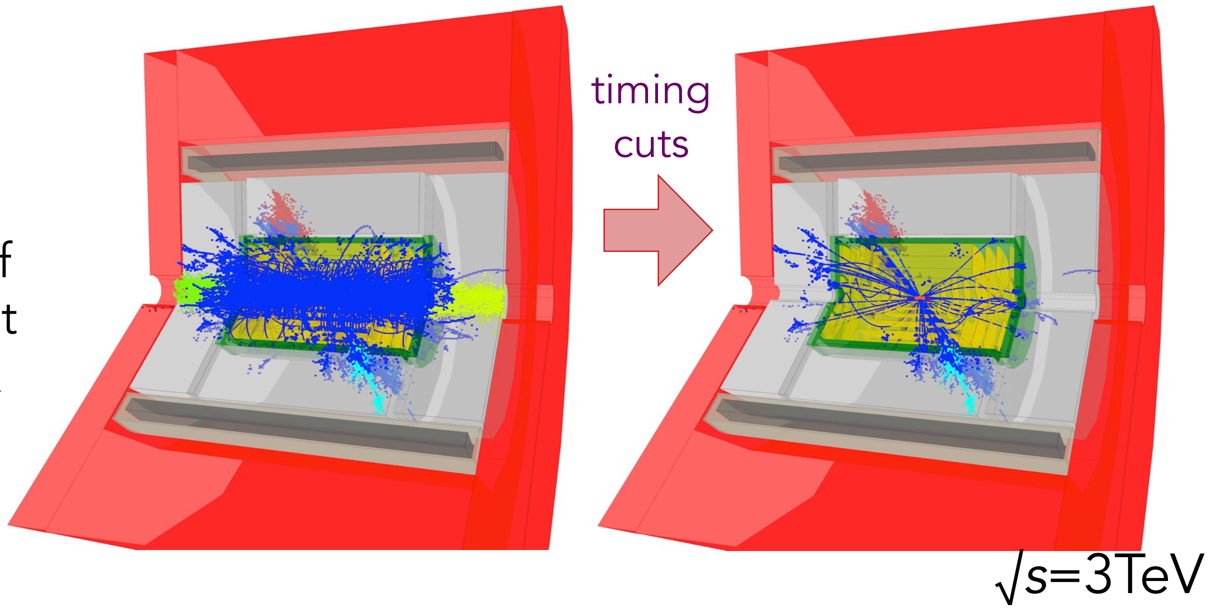
- at 1.4TeV rate-only analysis gives relative uncertainties –29% and +67% around SM value of g_{HHH}
- 3TeV differential measurement gives –8% and +11% assuming SM g_{HHWW}
- simultaneous measurement of triple and quartic couplings gives constraints below 4% in g_{HHWW} and below 20% in g_{HHH} for large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

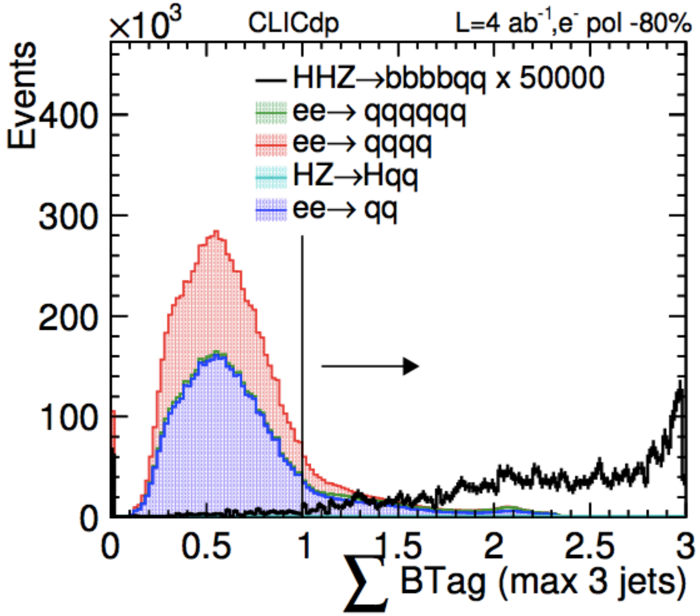
	1.4TeV	3TeV
$\sigma(HH\nu_e\bar{\nu}_e)$	≥3σ EVIDENCE $\frac{\Delta\sigma}{\sigma}$ = 28%	≥5σ OBSERVATION $\frac{\Delta\sigma}{\sigma}$ = 7.3%
$\sigma(ZHH)$	3.3σ EVIDENCE	2.4σ EVIDENCE
g_{HHH}/g_{HHH}^{SM}	1.4TeV: –29%, +67% rate-only analysis	1.4 + 3TeV: **–8%, +11%** differential analysis

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

Higgs self-coupling – direct (>1TeV)

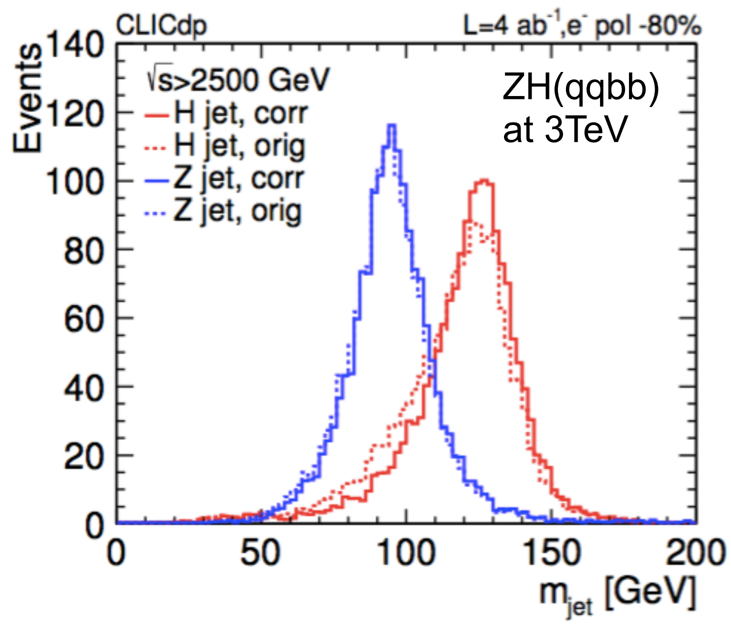
- high energies dominated by ννHH; influence of ZHH had been estimated using assumptions from full-simulation studies
- recently confirmed using full simulation of ZHH and ZH(qqbb) at 3TeV as one of the first uses of the new optimized CLICdet model & reconstruction software chain





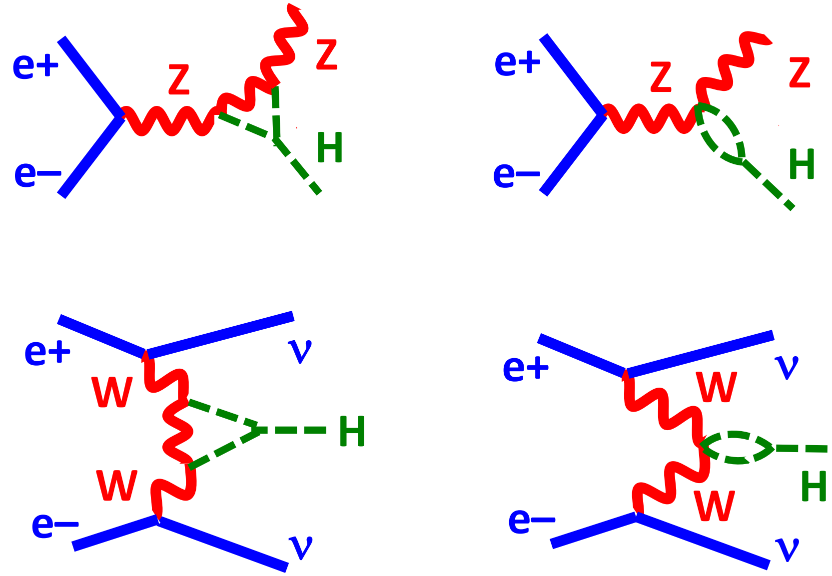
all-hadronic ZHH https://arxiv.org/abs/2008.05198

- Strict timing cuts imposed to reject large beam-induced γγ->hadron backgrounds
- Different jet-clustering approaches investigated (6 VLC jets showed better performance than 3 fat jets)
- >2σ significance for ZHH at 3TeV confirmed



Higgs self-coupling – indirect

- If λ deviates from SM, loop diagrams will give corrections to single-Higgs production and to Higgs decays
- e.g. (κ_λ–1)=1 increases σ(e^+e^-->ZH) by around 1.5% at $\sqrt{s}$=240GeV
- 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



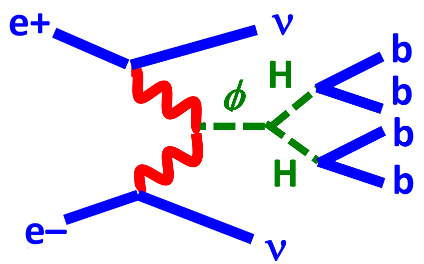
collider	1-parameter	full SMEFT
CEPC 240	18%	-
FCC-ee 240	21%	-
FCC-ee 240/365	21%	44%
FCC-ee (4IP)	15%	27%
ILC 250	36%	-
ILC 250/500	32%	58%
ILC 250/500/1000	29%	52%
CLIC 380	117%	-
CLIC 380/1500	72%	-
CLIC 380/1500/3000	49%	-

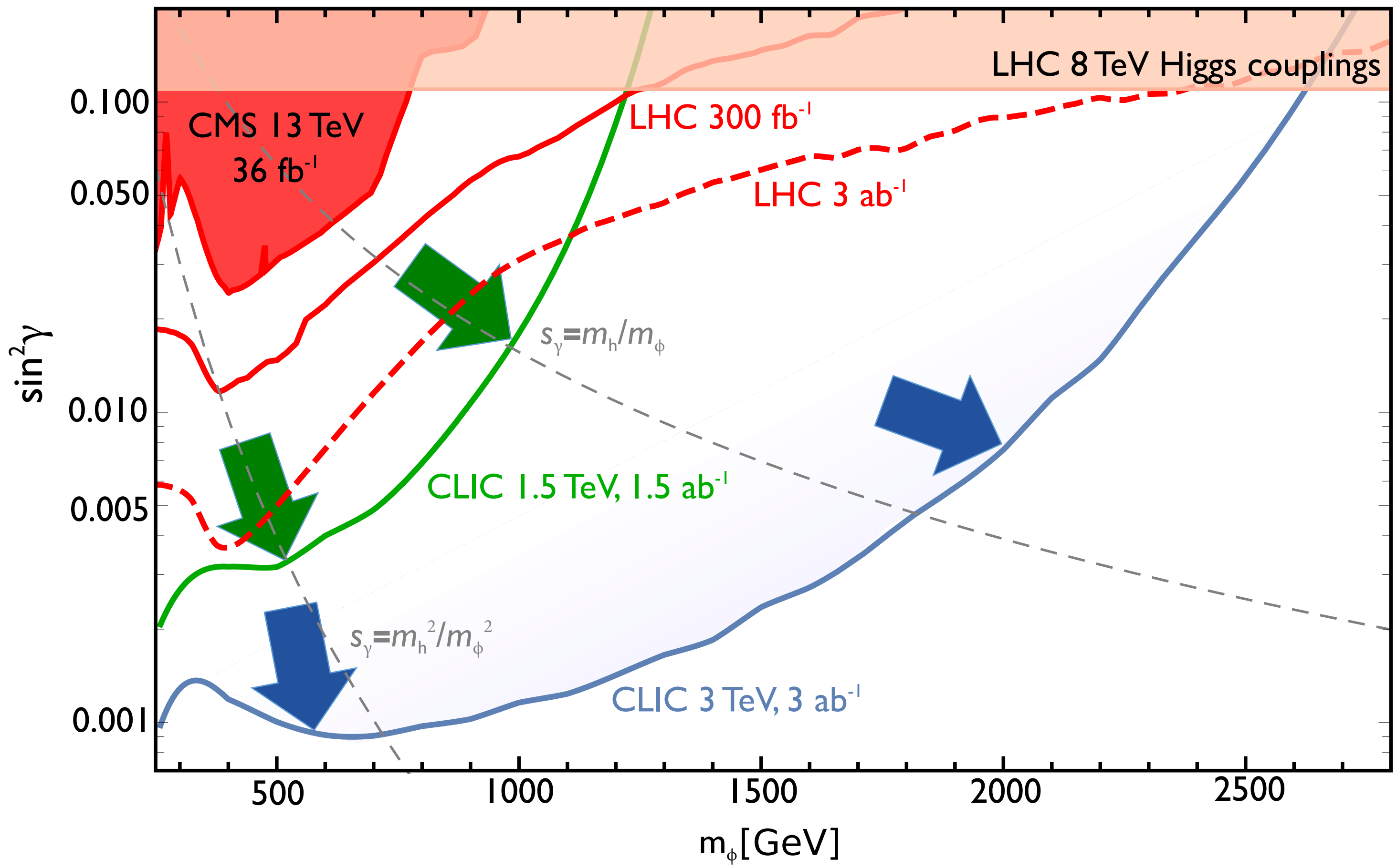
Higgs@Future Colliders 1905.03764 "-" means fit does not close

- 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

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

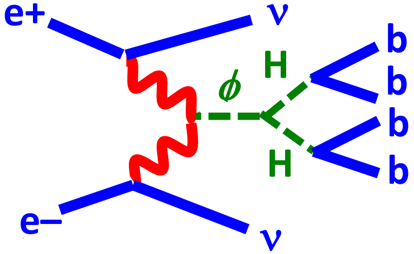
$$h = h_0 \cos\gamma + S \sin\gamma$$

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

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:



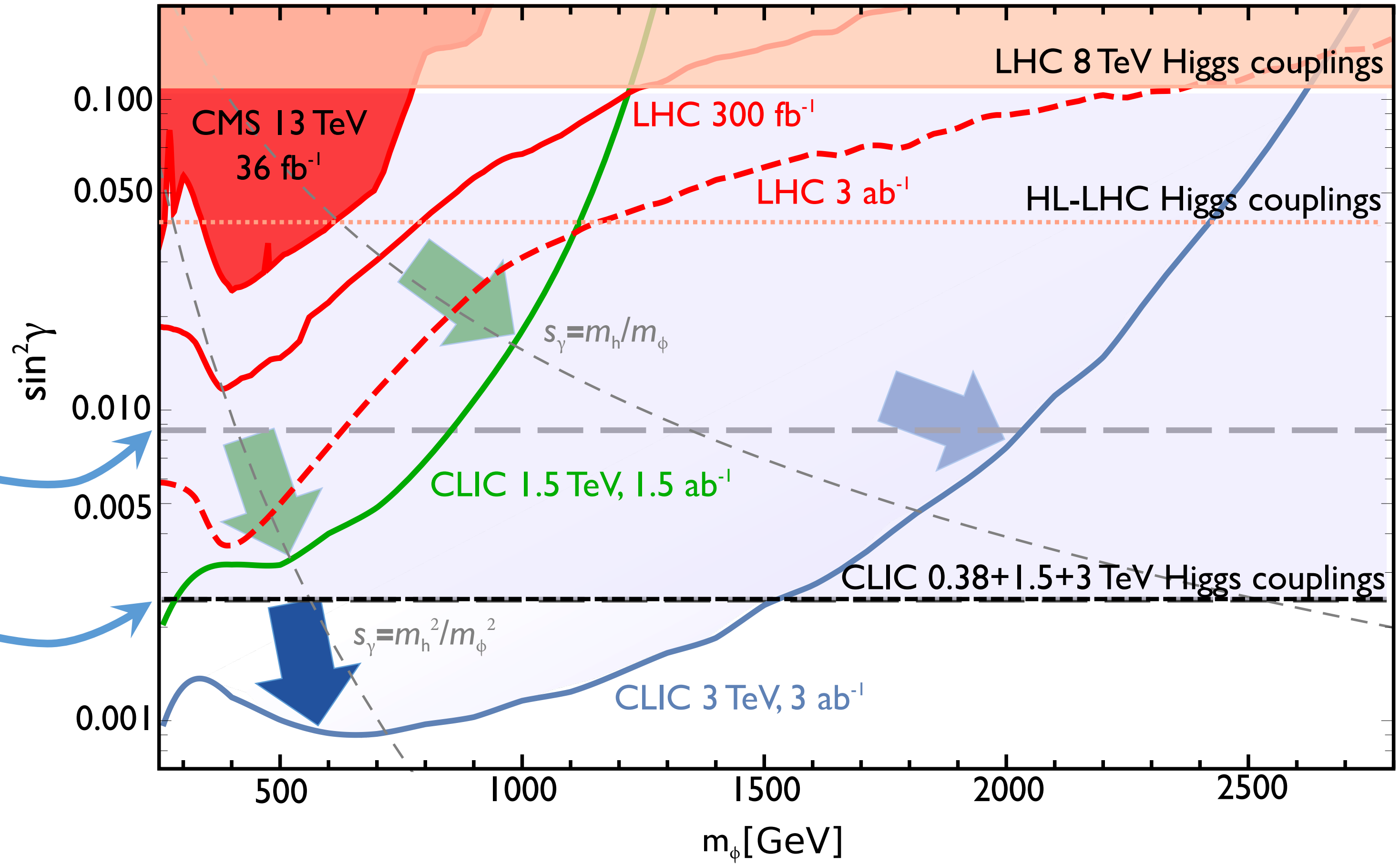
Complementary:

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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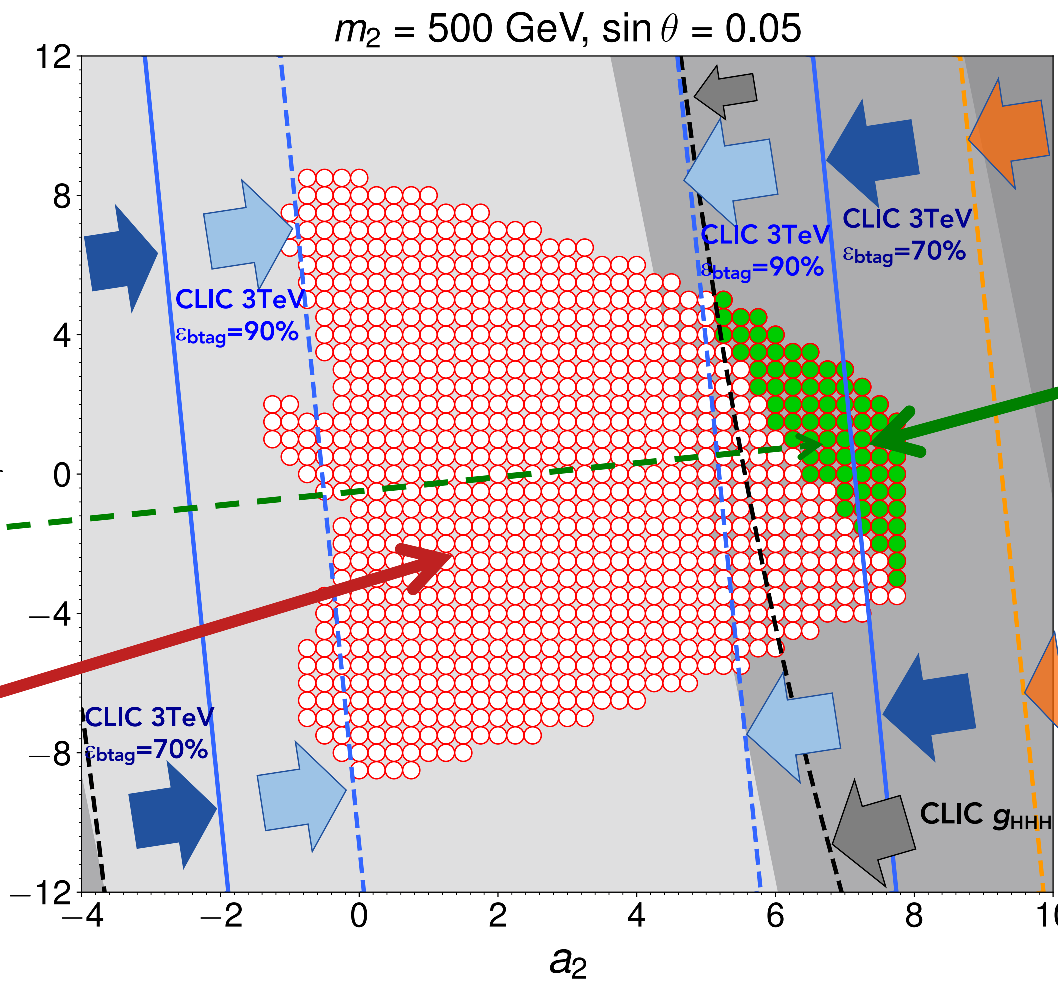
BSM Models: Baryogenesis

- 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

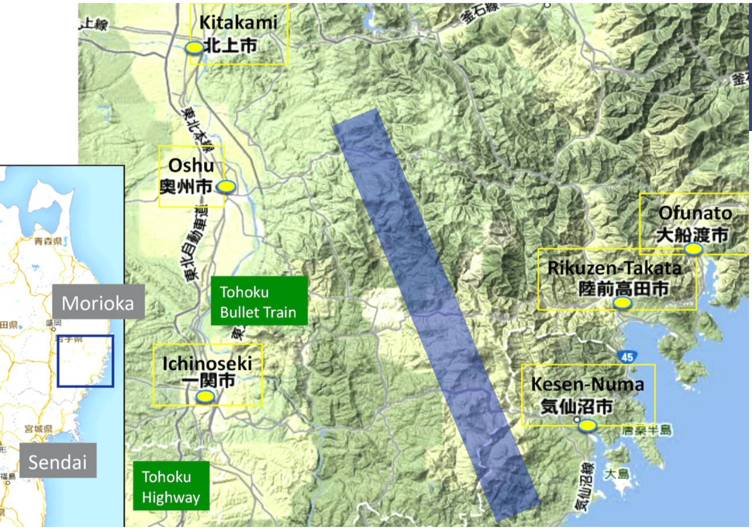
HL-LHC not sensitive at this low mixing sinθ=0.05

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

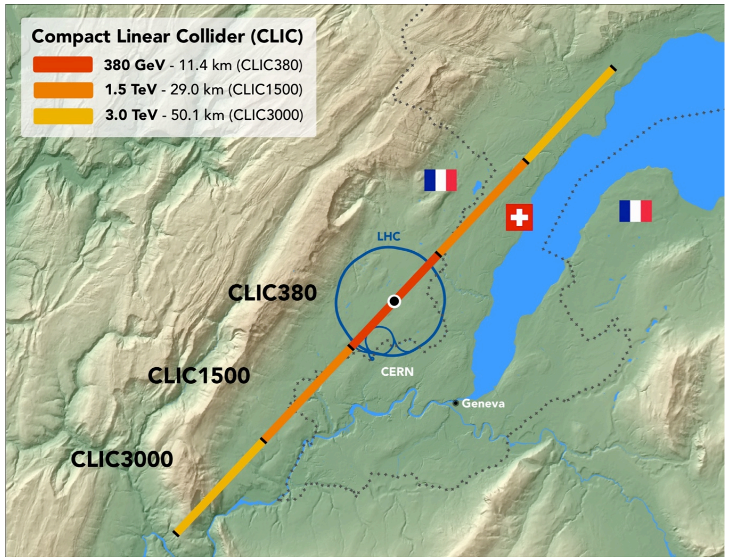
See Fran Arco's talk this afternoon for more examples of BSM scenarios

Project outlooks

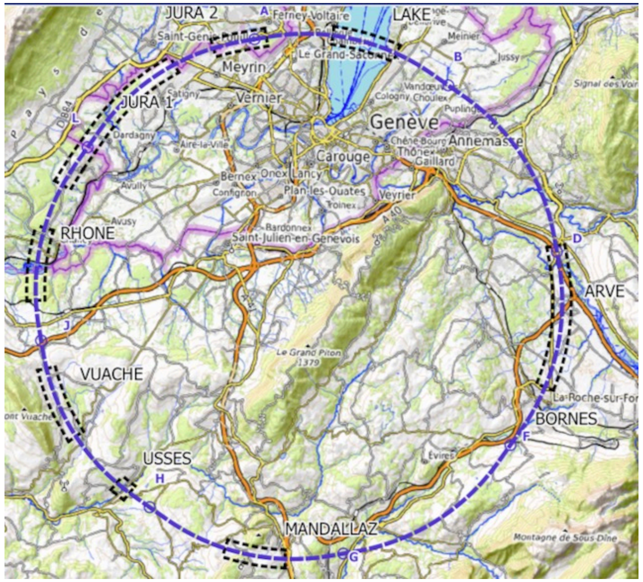


- The International Development Team (IDT) was set up in 2020 to prepare the ILC Pre-lab
- IDT includes active detector & physics working groups with regular open topical meetings and mini-workshops (all welcome)
- Pre-lab envisaged to complete engineering designs for machine and civil construction; support intergovernmental negotiation of organisation, governance, cost-sharing
- Japanese ministry was not ready to receive Pre-lab funding bid in 2021. IDT/KEK currently preparing bid for summer/autumn 22 towards high-priority accelerator development starting in 2023

- Following the European Strategy Update, CLIC is maintained as CERN's "Plan B"
- 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



Project outlooks



FCC

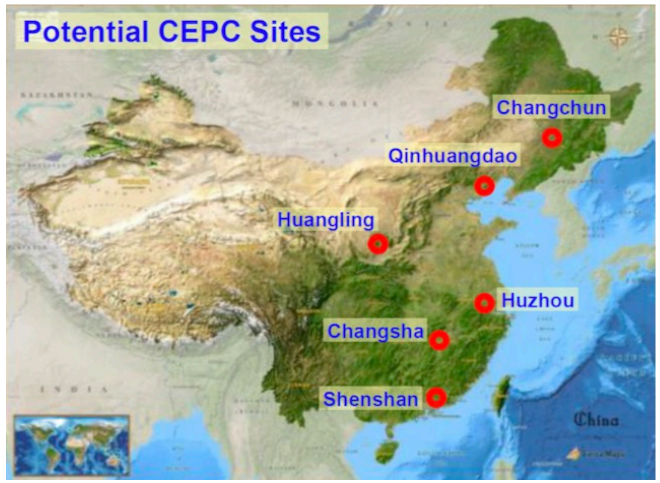
- Following ESPP Update, FCC is CERN's "Plan A".
- Feasibility study 2021-25 concentrates on:

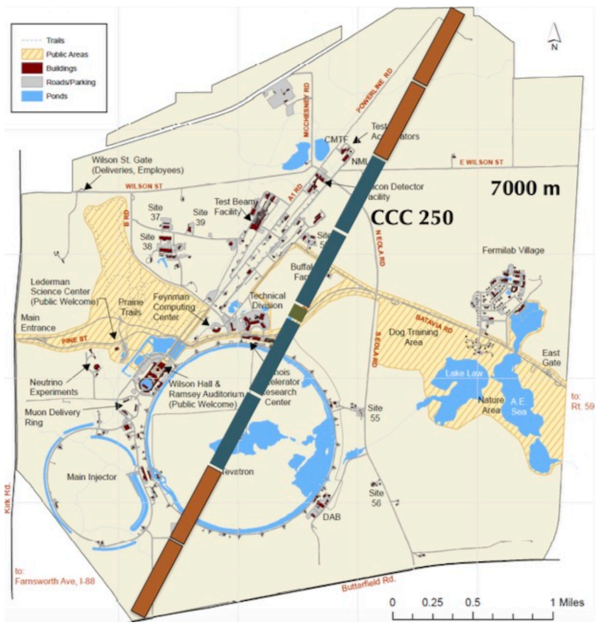
– technical & administrative feasibility of tunnel & surface areas
– optimisation of collider designs
– elaboration of a sustainable operational model
– development of a consolidated cost estimate
– identification of substantial resources from outside CERN's budget for the implementation of the first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

- Large working-group structure in place
- Feasibility Study Report to be prepared for end 2025

CEPC

- CEPC pursuing key technology R&D from CDR to TDR, site selection, international collaboration in period to 2025
- Ideally seeking approval in the 15th 5-Year Plan (runs 2026–30)



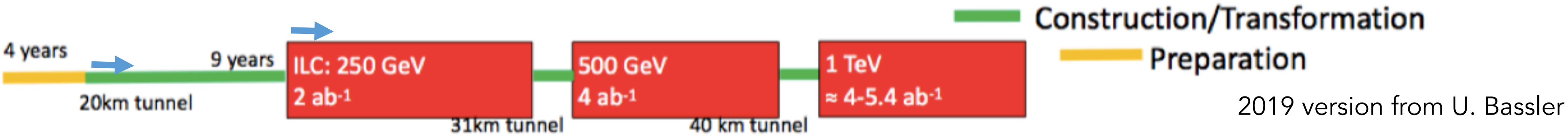


C3

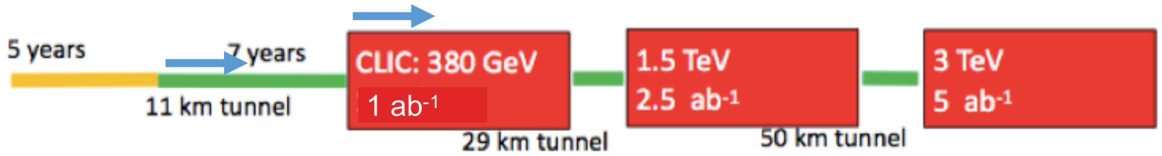
- C3 looking for endorsement in US Snowmass planning exercise and subsequent P5 funding
- Technology R&D and CDR/TDR development would follow

Possible timelines with respect to European Strategy 2019 inputs

"Updates" are only my personal observations.
Schedules are technical schedules but projects are funding-limited

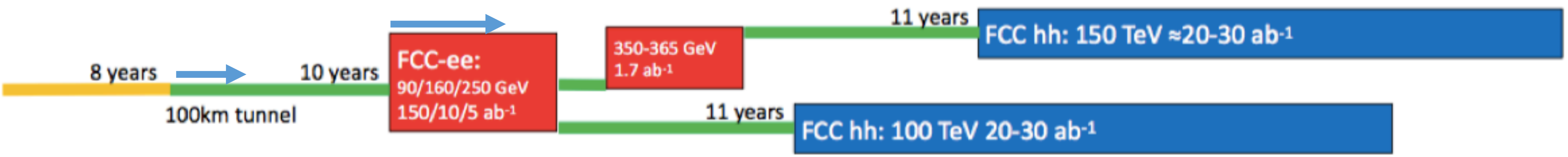


Update: ILC currently around 2 years behind envisaged plan for ILC Laboratory

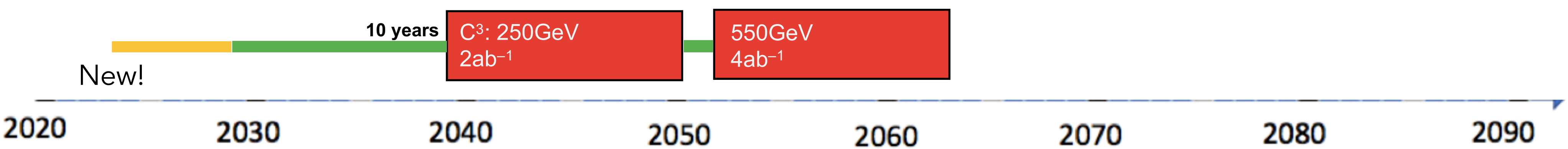


Update: If CLIC project approved 2028 after next ESPP, then construction could start ~2030

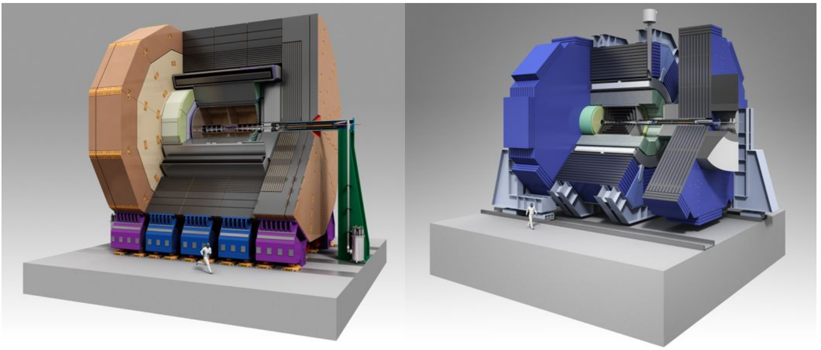
Update: Next opportunity for CEPC approval is the 15th 5-year plan; if so then construction could start 2025



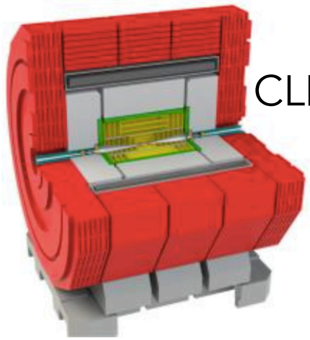
Update: If FCC project approved before end of decade, then construction could start early 2030s, operation ~2045



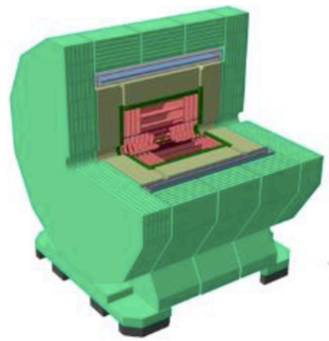
Detector & Physics: exploiting synergies



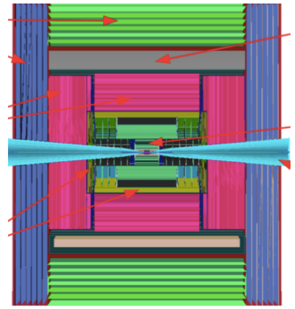
ILD SiD



CLICdet

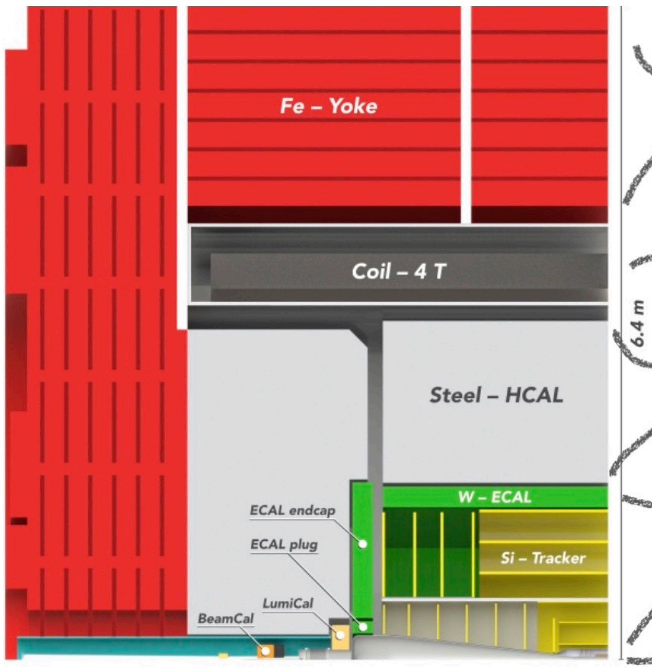


CLICdet adapted for FCC-ee



CLICdet adapted for muon collider

Priority: focusing on project synergies
– detector concepts and software tools
–> all moving to common framework



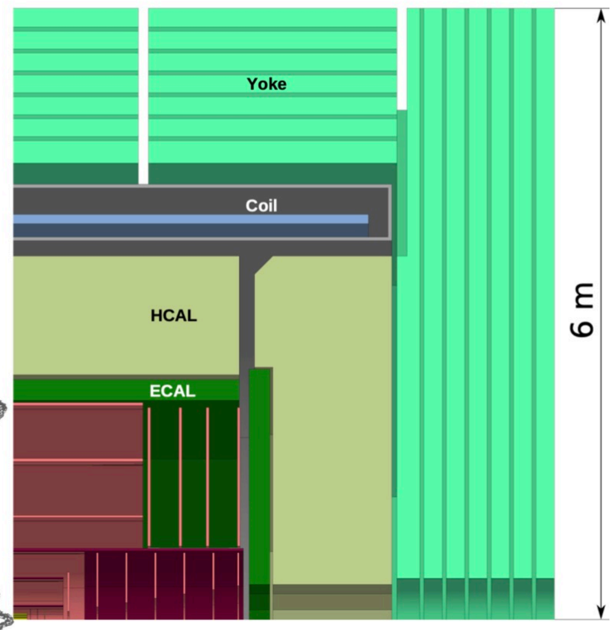
less steel: lower field allows reduced yoke thickness

lower field: enable high luminosity in circular collider

reduced HCAL thickness: enabled by lower energy

increase in tracker radius: retain p resolution

smaller VTX radius: profit from lower backgrounds, compensate material



From Frank SImon

Unified efforts

- European Strategy puts electron-positron Higgs factory as the highest-priority next collider
- To respond coherently, ECFA started a Higgs/EWK/top factories initiative, aiming to share challenges and expertise and explore synergies across efforts
- Intention: to bring the entire e+e- Higgs factory effort together and foster cooperation across various projects; collaborative research programmes are to emerge

- WG1: Physics programme
  – 5 physics themes with coordinators; mini-workshops and seminars underway
- WG2: Physics analysis methods
  – workshops already held on each of generators, simulation, reconstruction
- WG3: Detector technologies
  – starting soon in light of ECFA Detector R&D roadmap

–> all invited to participate

Registration open for First Workshop 5–7 Oct at DESY; abstract deadline 30 June
https://indico.desy.de/event/33640/

Summary

- An e+e– Higgs factory coupled with LHC results can reach percent-level precisions on most Higgs couplings
- At 250+365 GeV, a global fit can give indirect sensitivity to Higgs self-coupling – at the level of 27% for FCCee (4IP)
- TeV-scale linear colliders are needed for direct sensitivity to Higgs self-coupling through Higgs pair production; ILC@1TeV and CLIC@3TeV can reach 10% precision on SM value
- Access to two production mechanisms with different behaviour under non-SM Higgs self-coupling gives robust sensitivity under all new physics scenarios