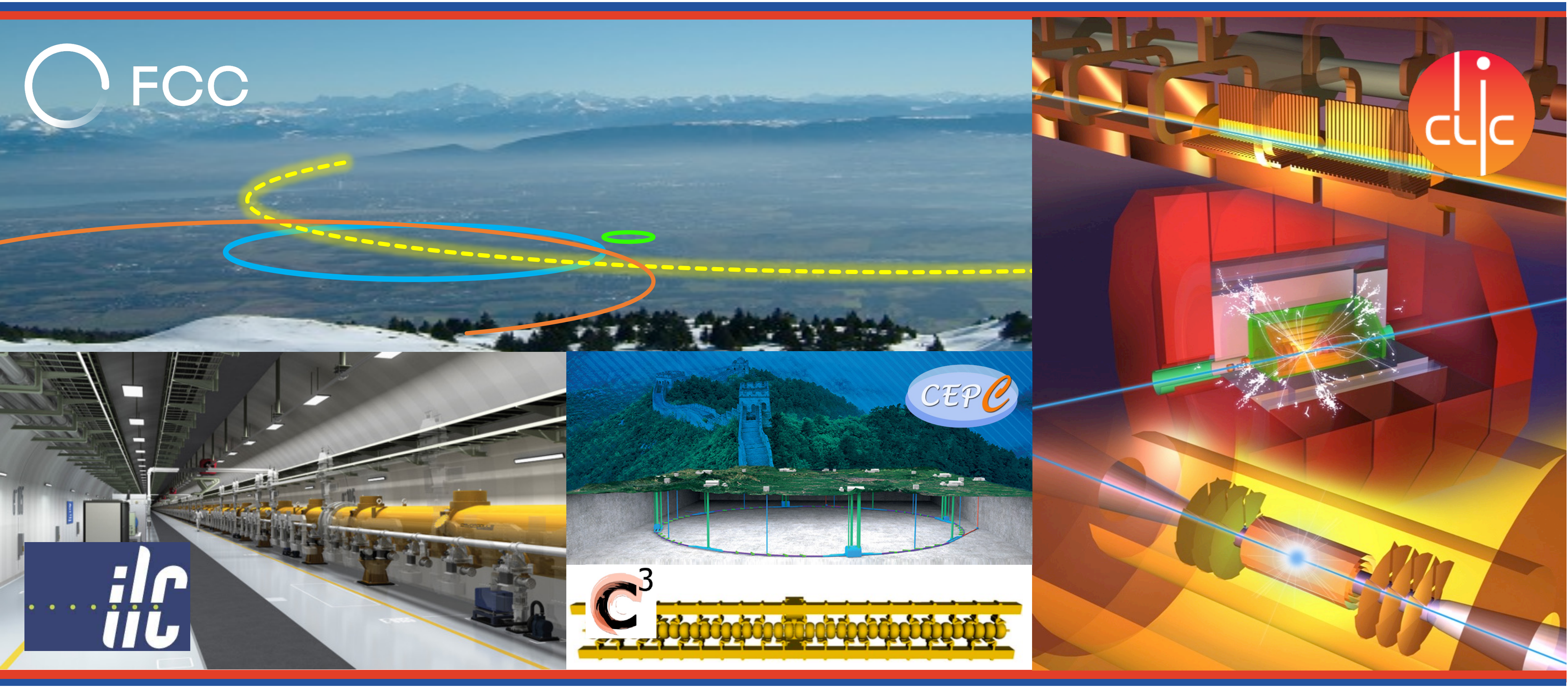
e^+e^- colliders: Higgs measurements

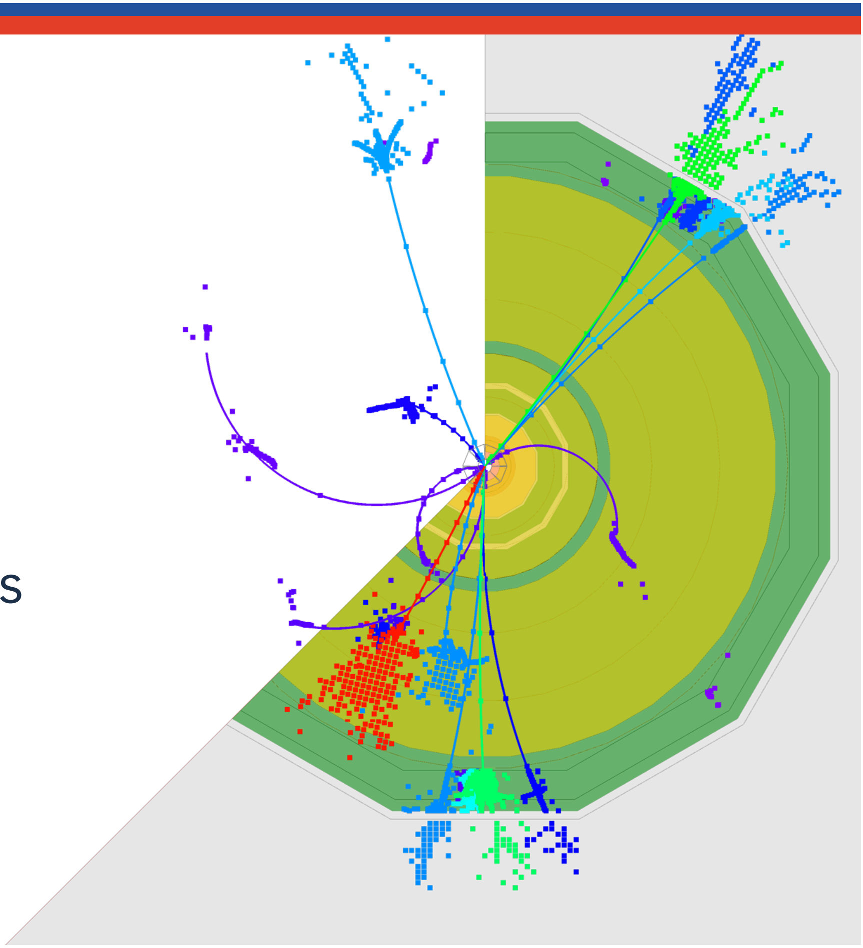


ECFA-UK Physics Workshop, 23 September 2024

Aidan Robson, University of Glasgow

Higgs Factories

- Why Higgs ?
- HL-LHC –> e+e–
- Initial stage Higgs Factory programme
  - – including recent highlights & UK activities
- Higher energies: HH and ttH
- Lower energies: electron Yukawa
- Conclusion



The Higgs Boson and the Universe

- What is Dark Matter made of?
- What drove cosmic inflation?
- What generates the mass pattern in quark and lepton sectors?
- What created the matter-antimatter asymmetry?
- What drove electroweak phase transition?
  – and could it play a role in baryogenesis?

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

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

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

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

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

  => small contributions -> need precise measurements!

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

  => discover and study di-Higgs production

The Higgs Factory mission

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

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

◆ To interpret these Higgs measurements, also need:

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

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

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

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

In particular:

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

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

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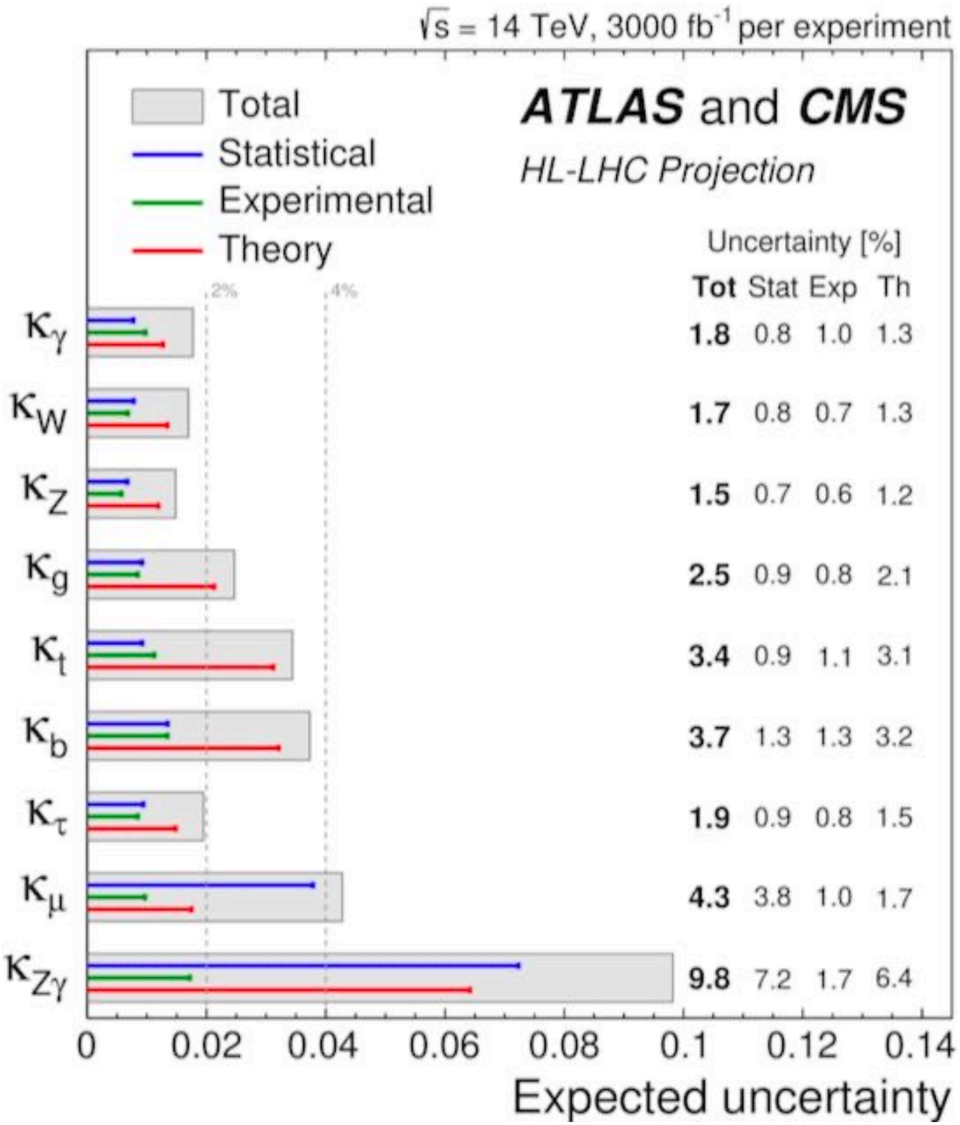
The HL-LHC legacy

- Very bright prospects for Higgs physics at the HL-LHC
- Projections being continuously updated; will be revised for ESPPU 2025/26



- Broad bottom line:
  couplings at 1–10% level

–> for details, updates, and current activities see LHC Higgs talk by Nicholas Wardle on Friday morning

ATLAS and CMS Collaborations.
Snowmass White Paper Contribution: Physics with the Phase-2 ATLAS and CMS Detectors.
ATL-PHYS-PUB-2022-018

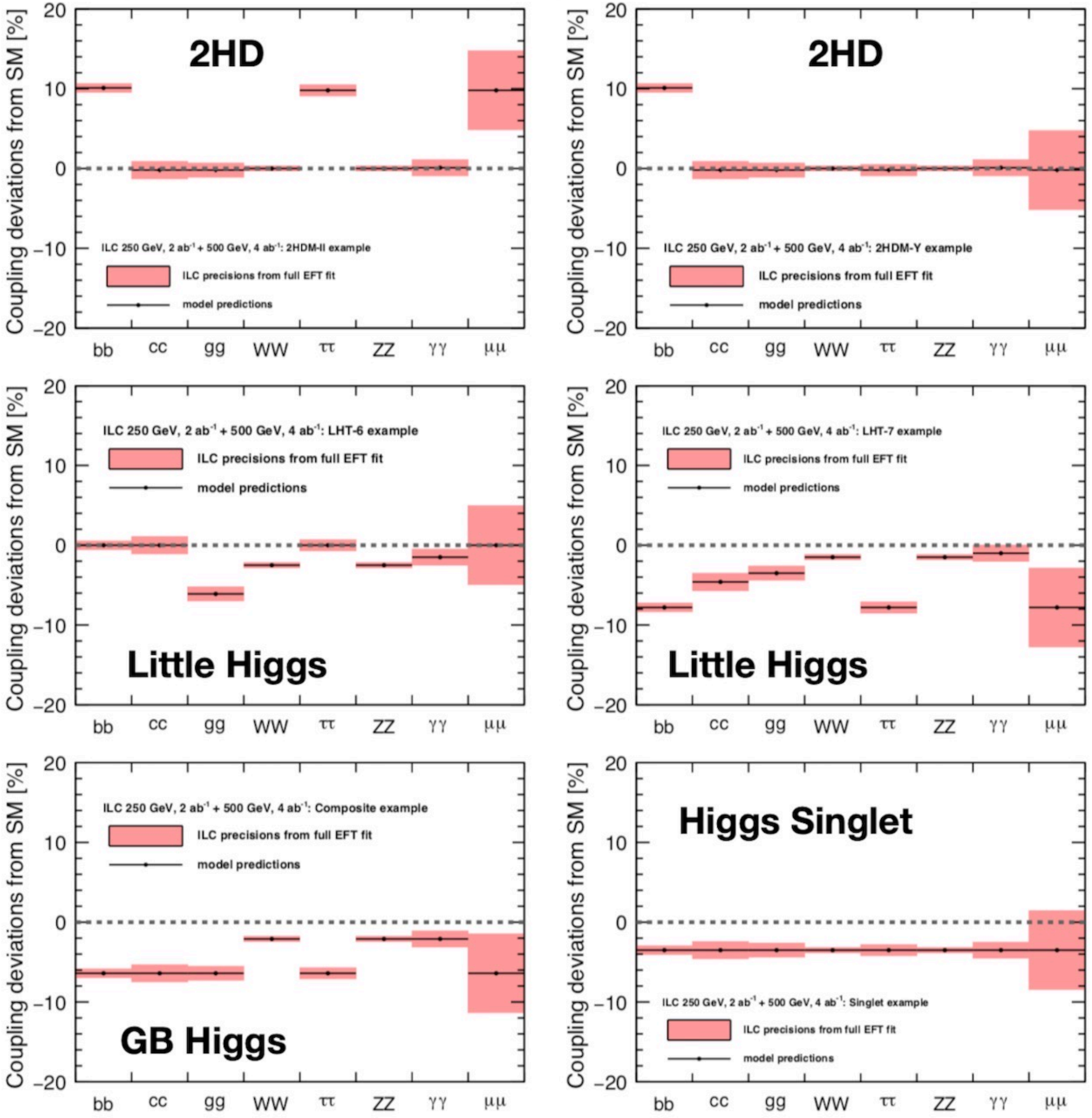
Higgs couplings sensitivity goals

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

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

- A pattern of well-established deviations can point to a common origin. Size of deviations determined by NP energy scale.

- Typical models give coupling deviations at 1% level; **this is the target (and e+e– factories can reach this sensitivity and beyond).** More precise measurements give greater discovery potential

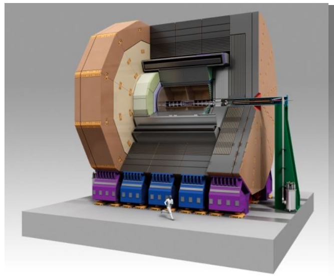


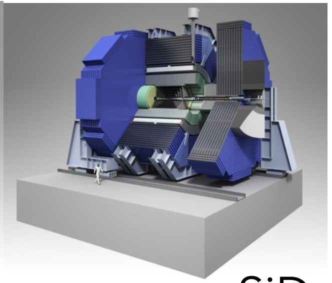
Barklow/Peskin 1708.08912

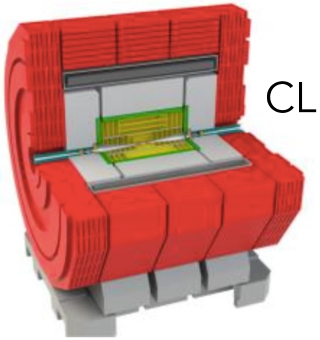
Detector requirements

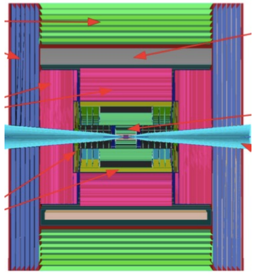
Detector requirements for all projects are set by the core Higgs programme

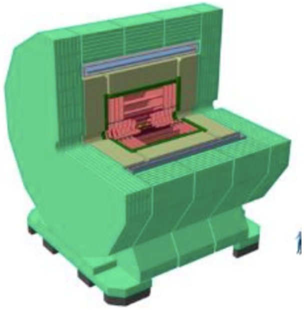
◆ Well-developed detector concepts extending from linear to circular projects


ILD

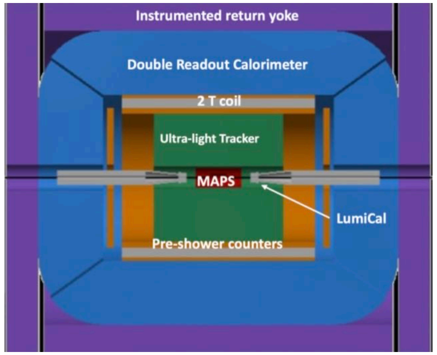

SiD


CLICdet


(CLICdet adapted for muon collider!)


CLD for FCC-ee

+ IDEA for FCC-ee



◆ Key requirements from Higgs physics

p_T resolution (total ZH cross-section)
$\sigma(1/p_T) = 2\text{x}10^{-5}\ \text{GeV}^{-1} \oplus 1\text{x}10^{-3}/(p_T \sin^{1/2}\theta)$ ~ CMS/40

Vertexing (H->bb/cc/ττ)
$\sigma(d_0) < 5 \oplus 10 / (p\,[\text{GeV}]\, \sin^{3/2}\theta)\ \mu\text{m}$ ~ CMS/4

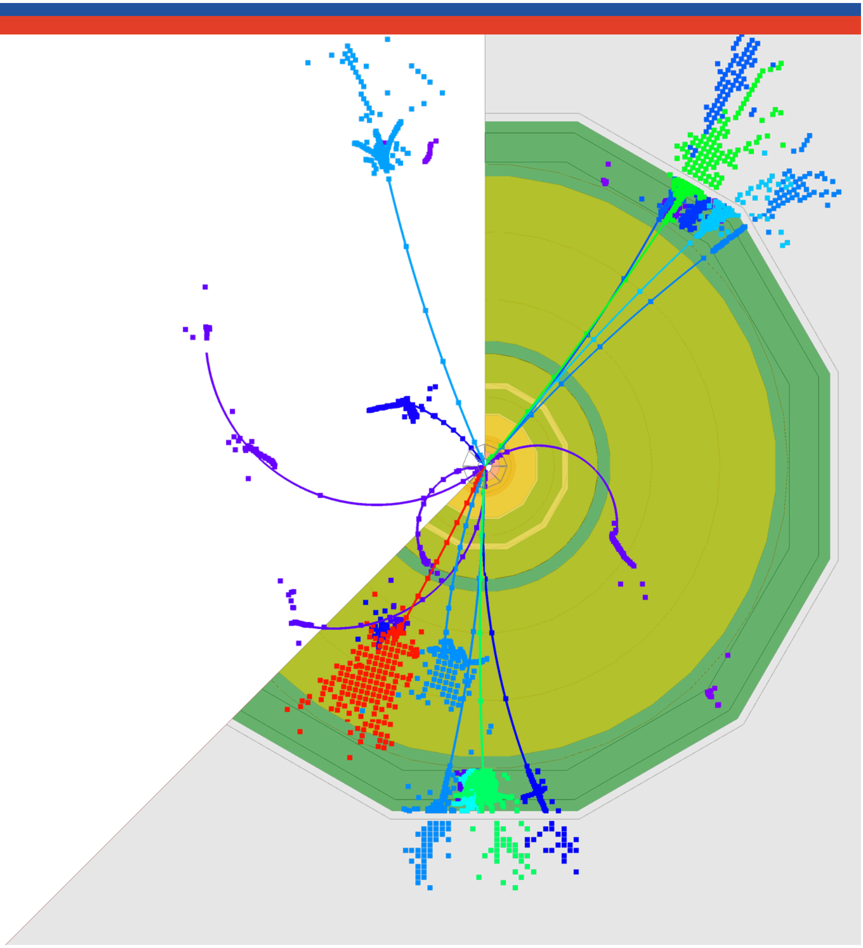
Jet energy resolution (H->invisible) 3–4% ~ ATLAS/2

Hermeticity (H->invisible, BSM) θ_{min} = 5 mrad ~ ATLAS/3
(FCCee: ~50mrad)

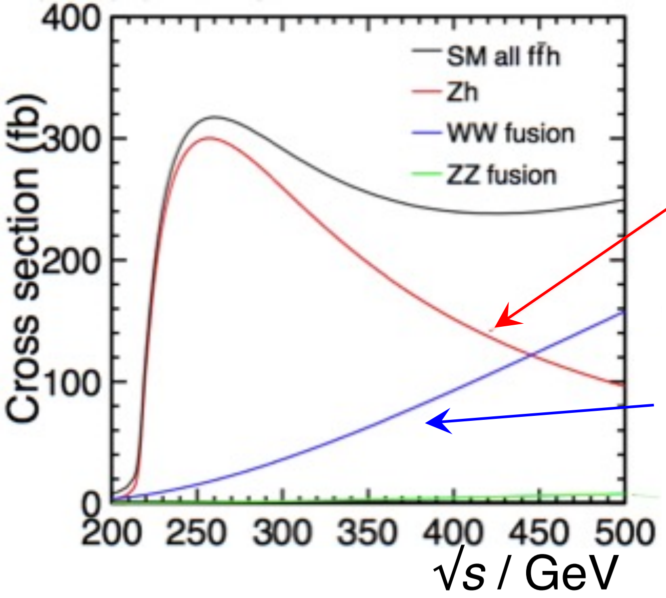
–> Determine the key features of the detector:
- Low-mass tracker (e.g. VTX: 0.15% rad. length / layer)
- Calorimeters
  highly granular, optimised for particle flow
  or dual readout, LAr, …

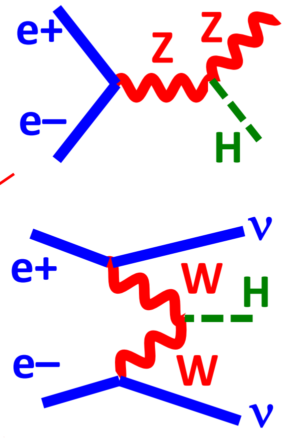
Enables the precision Higgs programme

Higgs in e^+e^-



Higgs production in e^+e^-



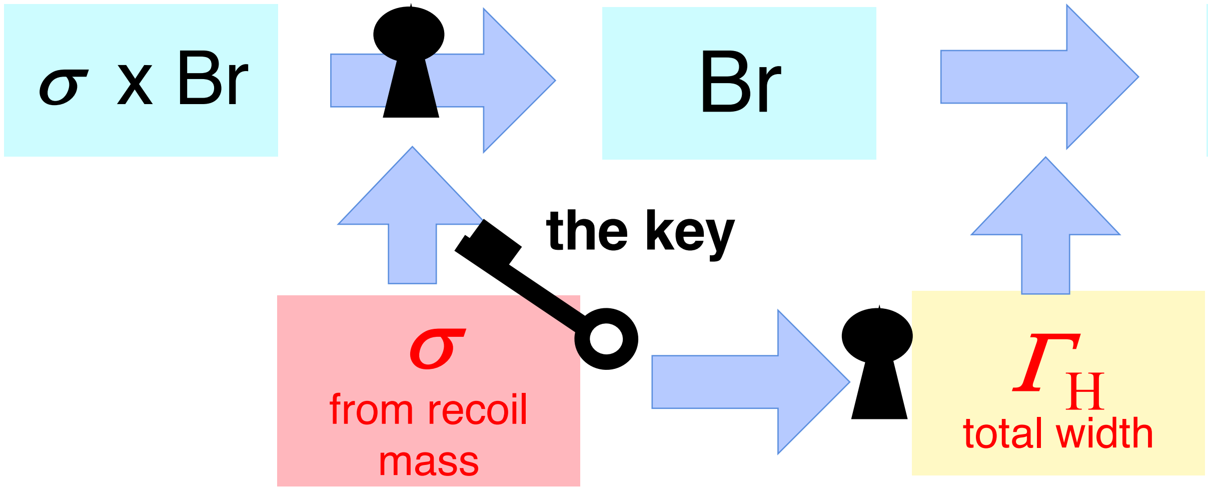


◆ ZH process allows reconstruction of H by looking exclusively at recoil of Z –> model-independent extraction of g_{HZZ} coupling

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

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

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



σ x Br

Br

g
coupling

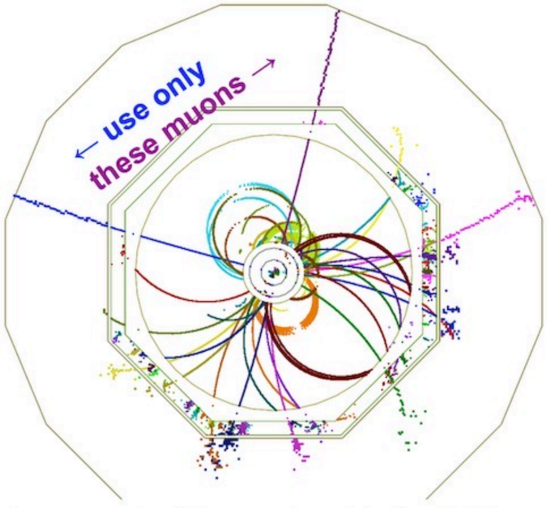
the key

σ
from recoil mass

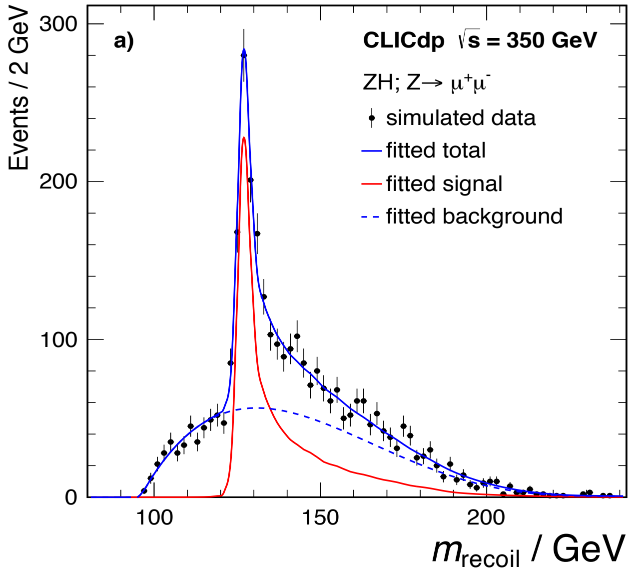
Γ_H
total width

(WW fusion helps with precision total width at higher √*s*)

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

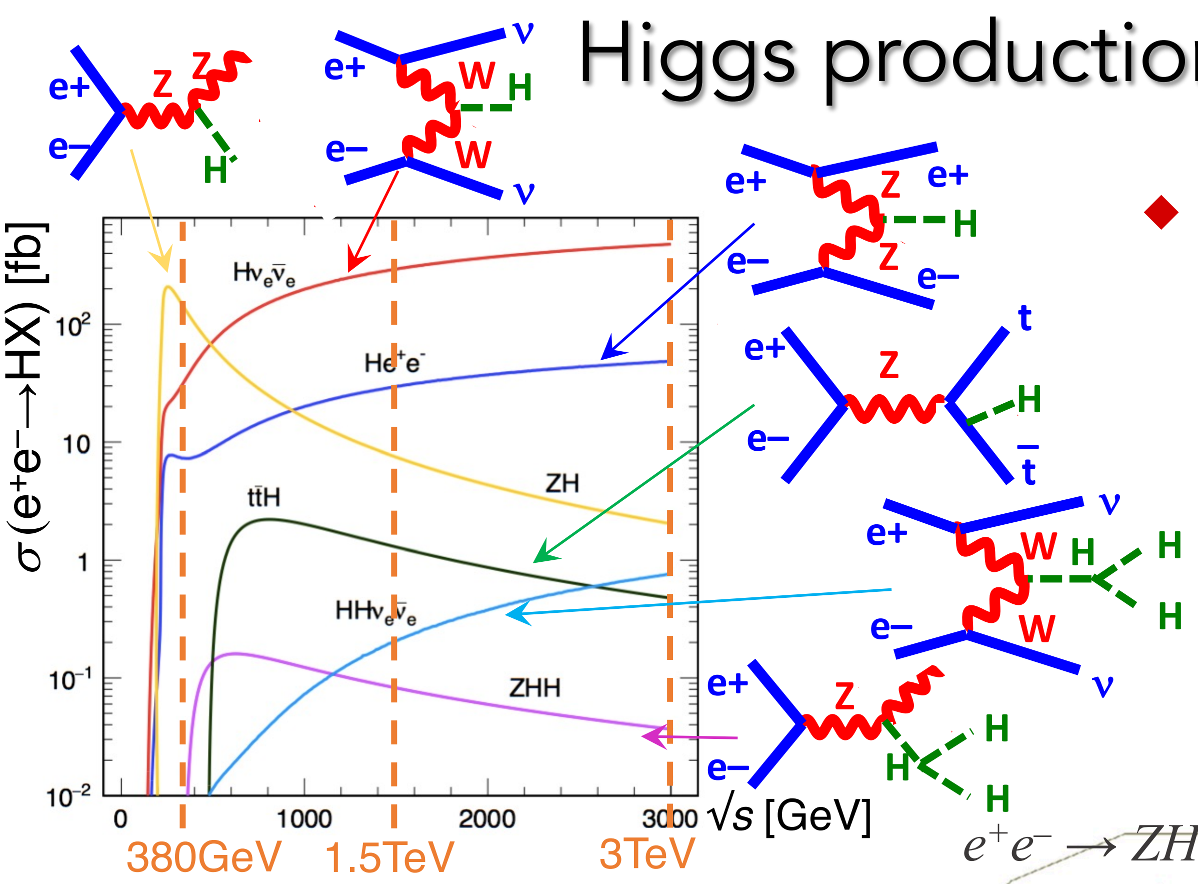


$e^+e^- \to \mu^+\mu^-H \to \mu^+\mu^-$ bb in ILD



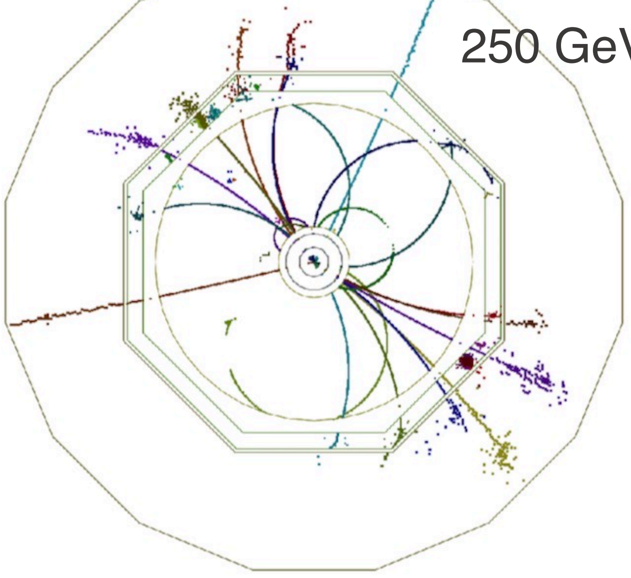
Yields model-independent absolute couplings – not possible at LHC!

Higgs production in e^+e^-

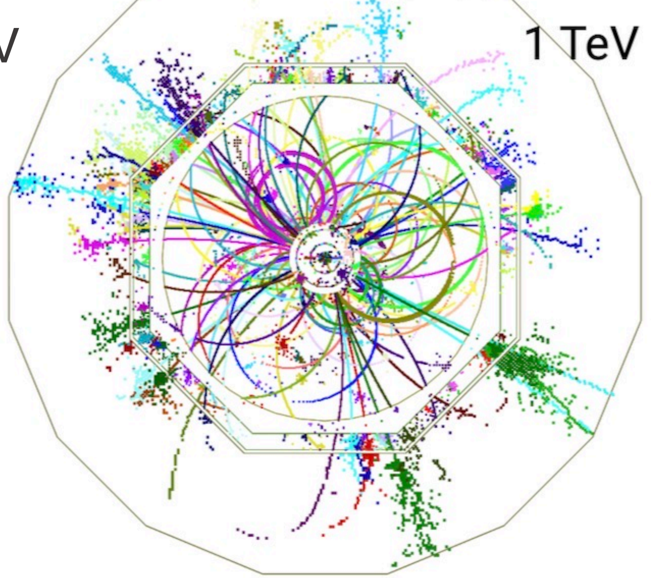


- Common to all projects: ZH threshold at 250 / 380 GeV
  - Other processes turn on at higher energies

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



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



- Clean experimental environment
- Imaging calorimetry approach allows e.g. H->bb/cc/gg separation

Higgs couplings sensitivity

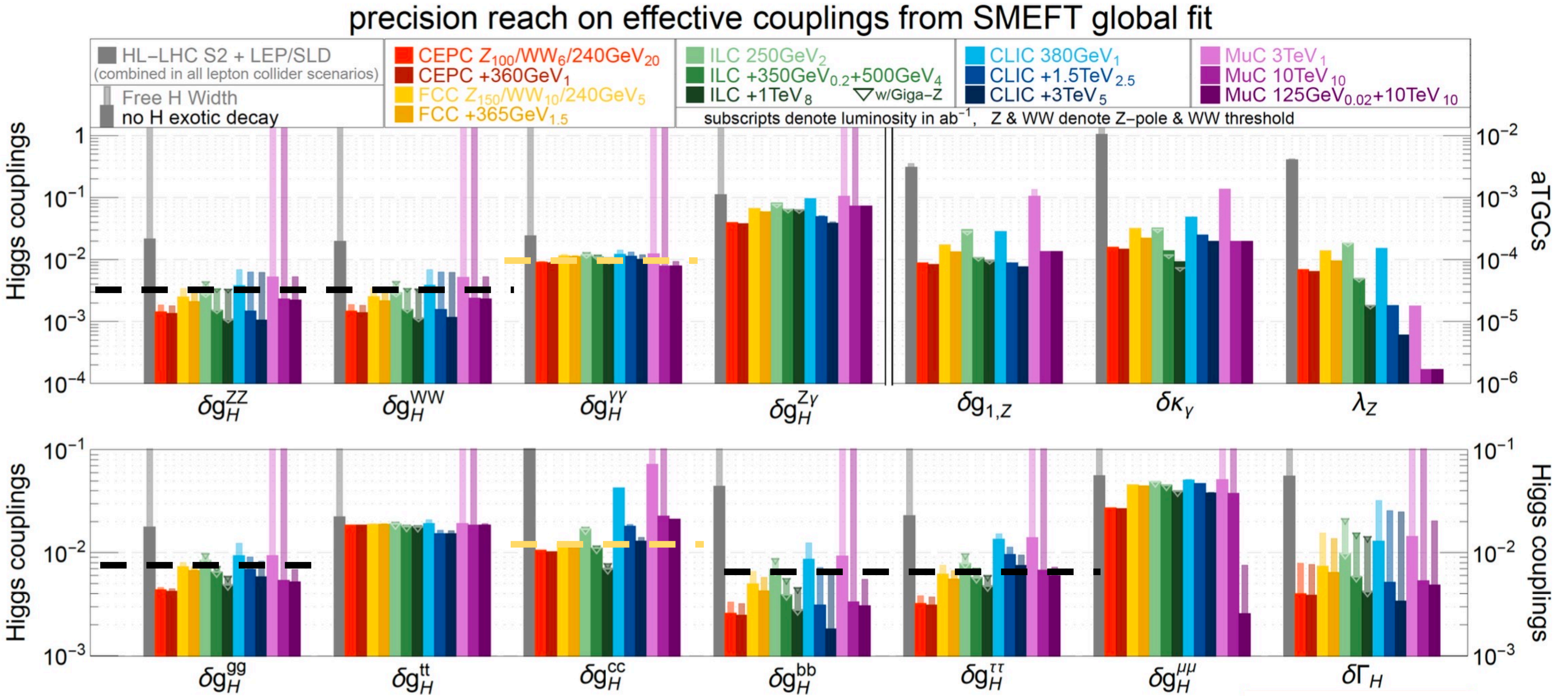
Standard Model

Dim-6 operators

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

Scale of new decoupled physics

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



Snowmass EFT couplings
arxiv: 2206.08326

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

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

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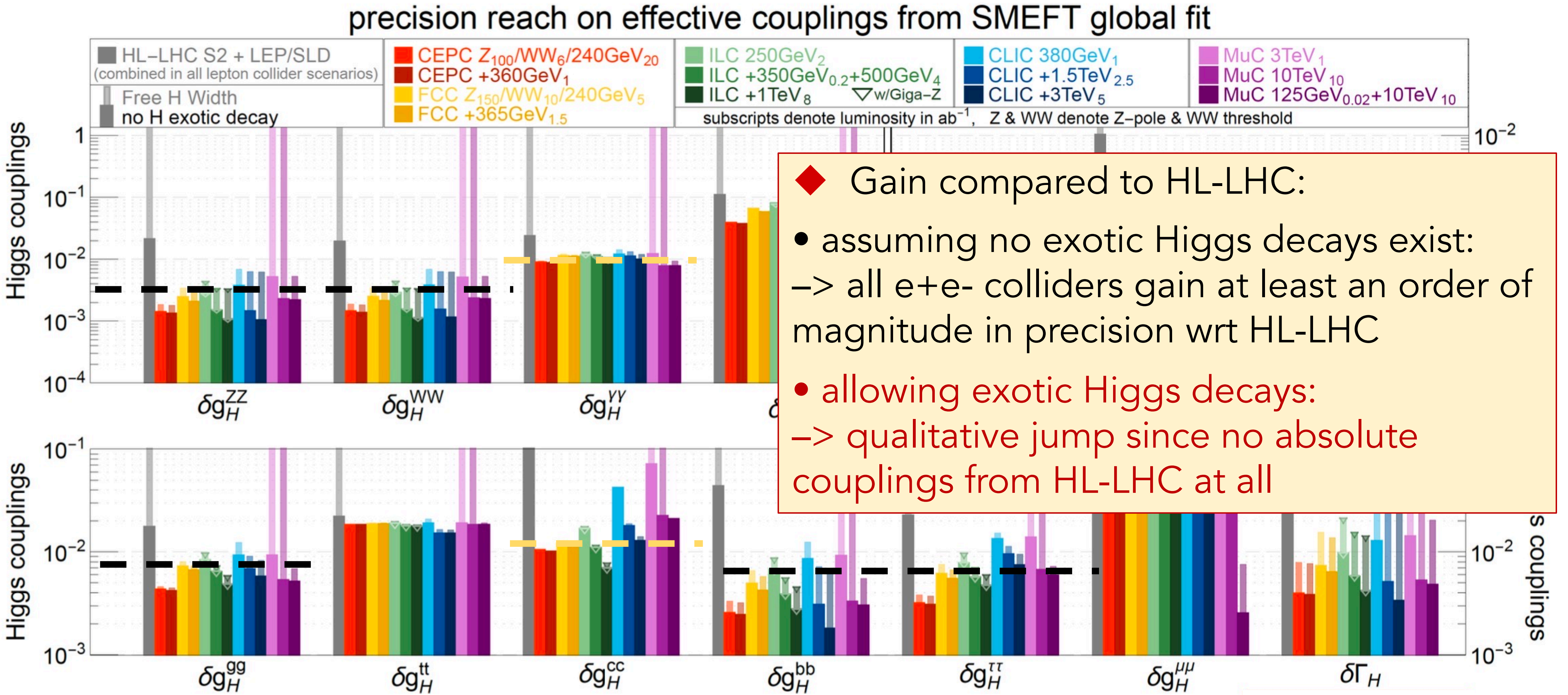

- Gain compared to HL-LHC:
  - assuming no exotic Higgs decays exist:
–> all e+e- colliders gain at least an order of magnitude in precision wrt HL-LHC
  - allowing exotic Higgs decays:
–> qualitative jump since no absolute couplings from HL-LHC at all

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  - several couplings at few-0.1% level: Z, W, g, b, τ
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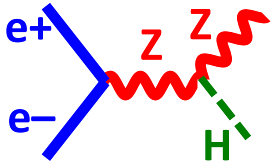
Note on datasets

- **Projects propose different integrated luminosities.**

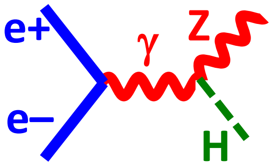
Assumptions in previous slide:
FCC-ee: 5 ab^{-1} for 2 IPs
CEPC: 5.6 ab^{-1} for 2 IPs
ILC: 2 ab^{-1} at 250 GeV
CLIC: 1 ab^{-1} at 380GeV

Projected Higgs sensitivities are very similar – beam polarisation at linear colliders compensates for smaller dataset

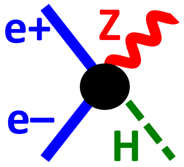
- Example: A_{LR} of Higgsstrahlung lifts degeneracy between operators and helps to disentangle different SMEFT contributions



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

Overall, **2 ab^{-1} polarised** ≈ **5 ab^{-1} unpolarised**
See e.g. arXiv:1903.01629

Core Higgs programme sensitivities tend to be statistics limited; all projects have ways of increasing the dataset size:

FCC-ee –> recently changed baseline to 4 IPs
CLIC –> could double rep rate to 100Hz
ILC –> could double bunches per pulse & rep rate

All have associated cost – care should be taken when comparing sensitivities.

Also, run plans would be adapted according to funding (e.g. if only the first stage of CLIC were built, it would be run for longer) e.g. arXiv:2001.05278

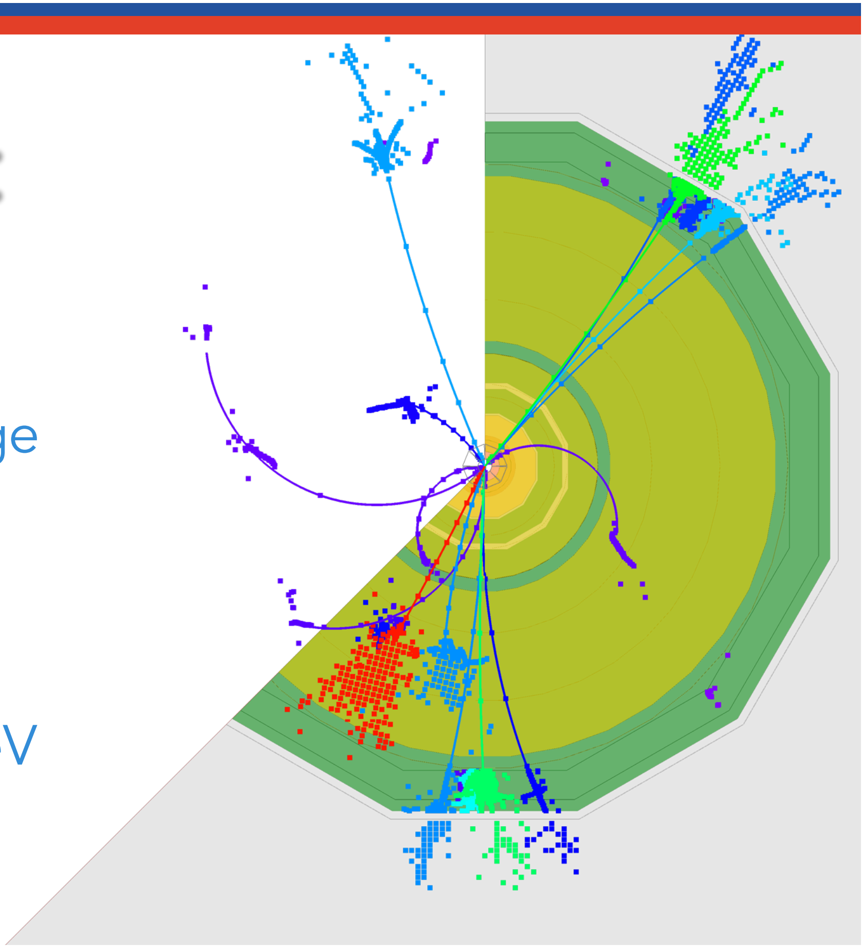
Snapshot of ongoing work:

- H–>ss
- H–>invisible UK 🇬🇧
- H–>μμ UK 🇬🇧
- Higgs CP UK 🇬🇧
- Higgs self coupling – indirect
- Higgs self coupling – direct
- ttH
- electron Yukawa

initial stage energy

$\sqrt{s} \gtrsim 550$ GeV

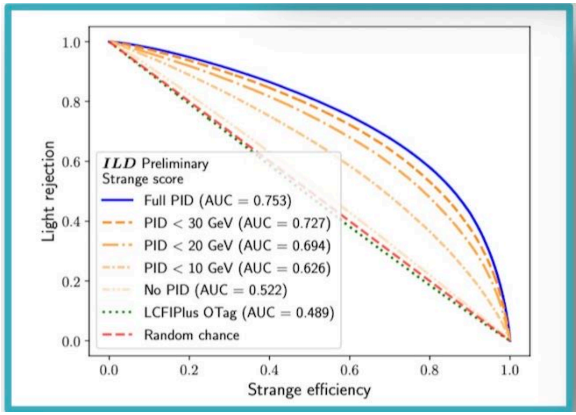
$\sqrt{s} = m_H$

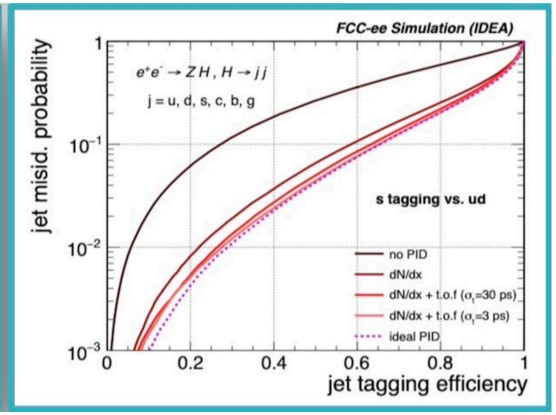


Highlight: H–>ss

- Nearly impossible to probe directly at HL-LHC; very challenging in e+e– Topic has been gathering increasing interest and crosses all aspects of physics sensitivity, algorithm development, & detector design optimisation

For Snowmass, ~only ILD-based studies were complete from RICH to PID to analysis; now studies at FCC and CEPC evolved from tagger-only to include analysis and RICH





Example active points:

❖ fragmentation models – changing at generation level in Pythia 8 to assess sensitivity

❖ PID reco: compare d*N*/dx and RICH performance –> update ILD studies with reconstructed PID

❖ RICH: detector designs are evolving into full Geant 4 simulation now, and first H->ss events are being run through –> analyse how this impacts Particle Flow performance

– for detector design options considering tradeoff of cooling and material
–> important study as it motivates addition of new detector systems

Clear strong benefit from cross-project collaboration.
Not all studies will be complete by ESPPU, but some important updates for report

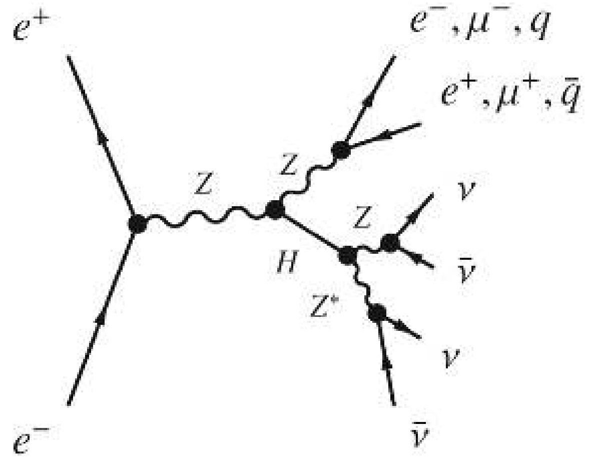
UK Highlight: H–>invisible at FCC-ee

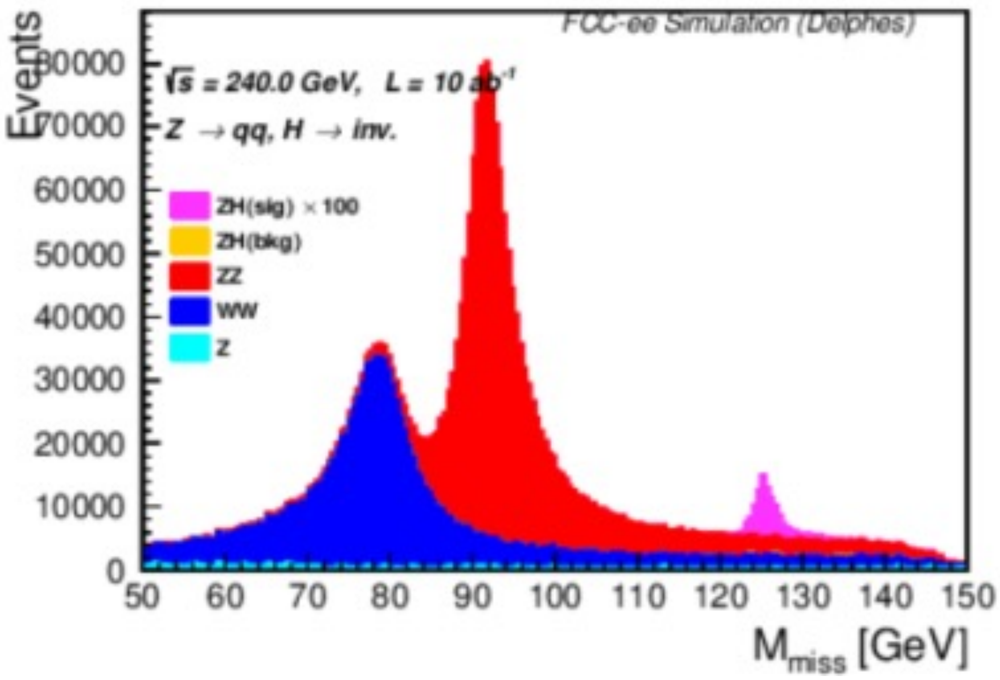
Liverpool: Andy Mehta & Nikos Rompotis

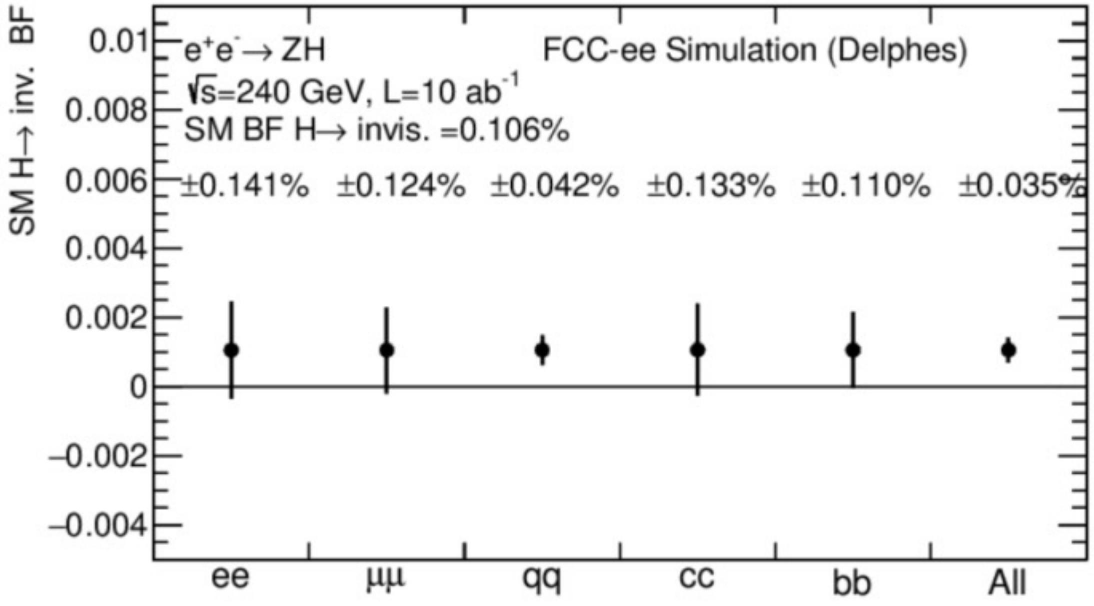
- Use e+e–>ZH process
- select a visible final state (qq, ee, μμ) compatible with a Z decay
- recoiling against “nothing”
- if signal observed: discovery! of Dark Matter?

This analysis:

- use both leptonic and hadronic Z decays
- fully reconstruct Higgs mass using missing mass
- Z–>qq best channel
- measure SM with 35% precision for 10 fb^{-1} of data





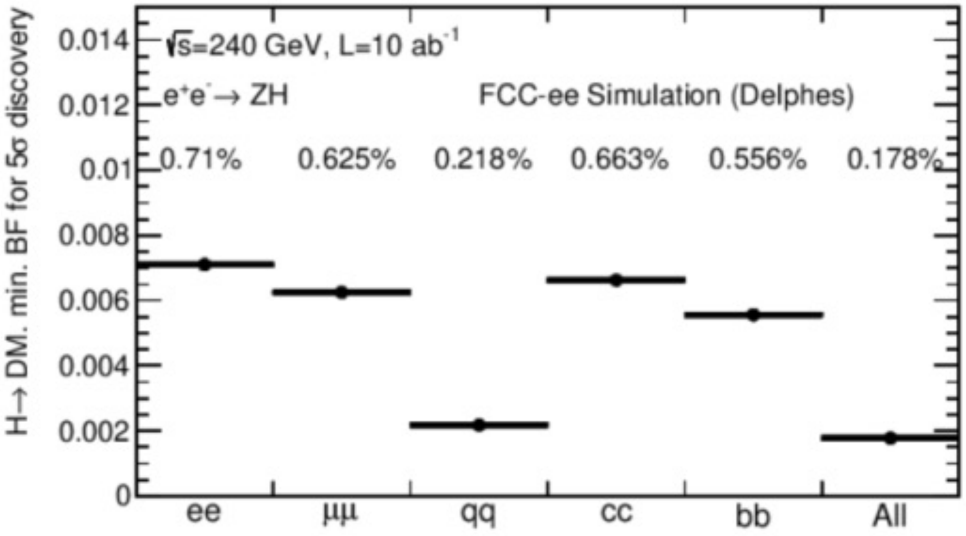


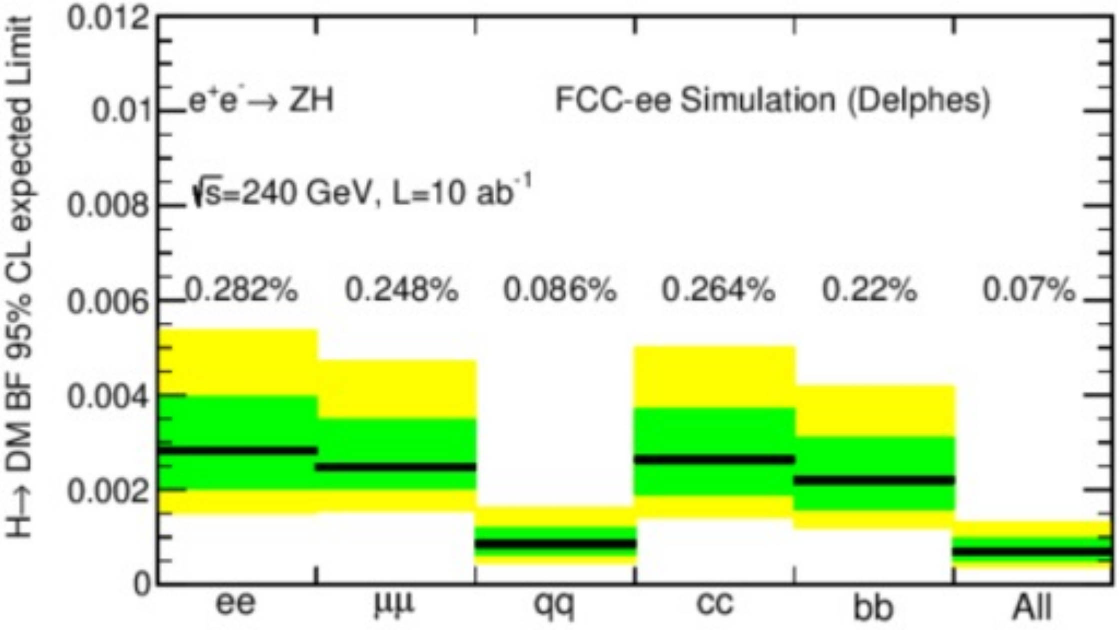
UK Highlight: H–>invisible at FCC-ee

Liverpool: Andy Mehta & Nikos Rompotis

- Treat SM Higgs –> invisible as background and look for new physics
- Discover new physics at 5σ if BF>0.18%
- Exclude new physics for BF>0.07% at 95% CLS

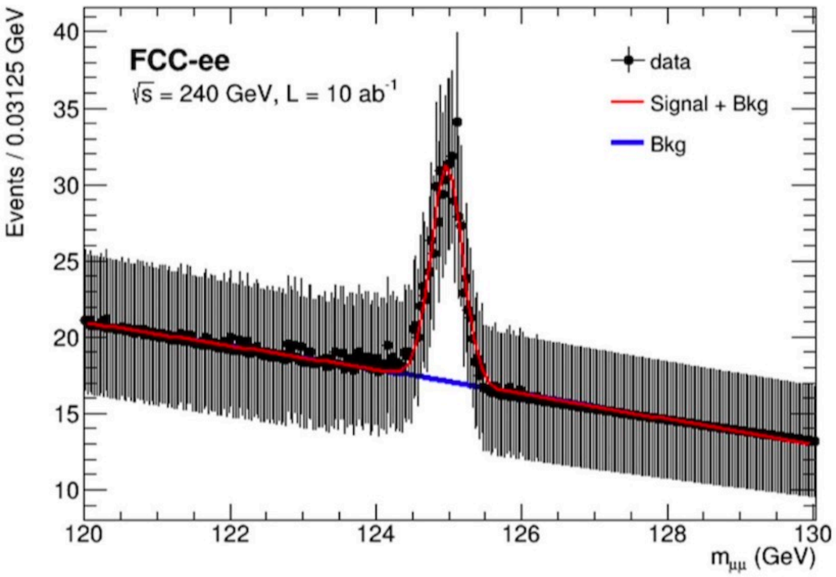
  (HL-LHC expected sensitivity: 2.5%)





UK Highlight: H–>μμ

Liverpool: Andy Mehta & Stephen Randles (UG)



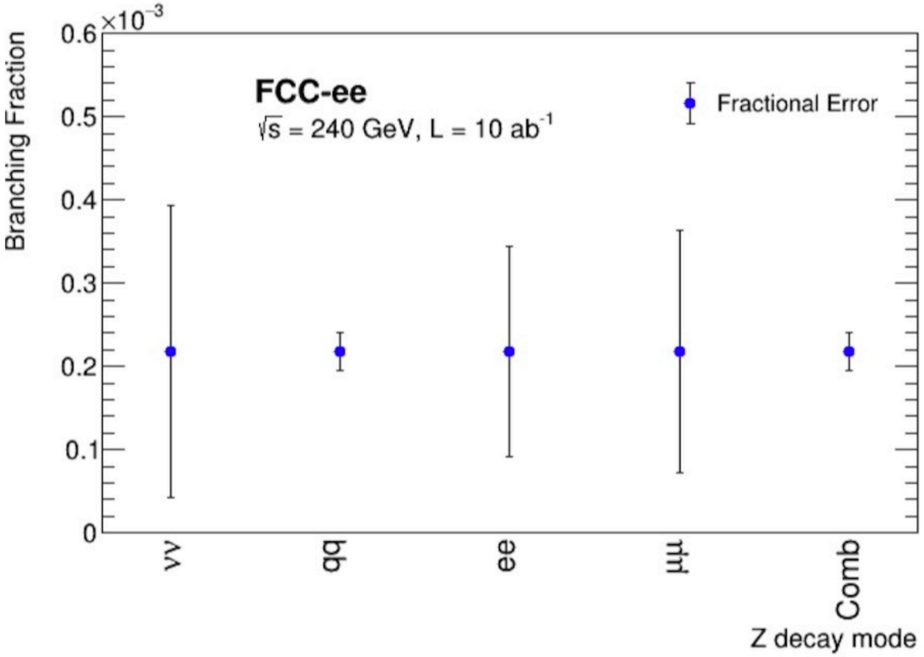
◆ FCC-ee Delphes study using IDEA samples

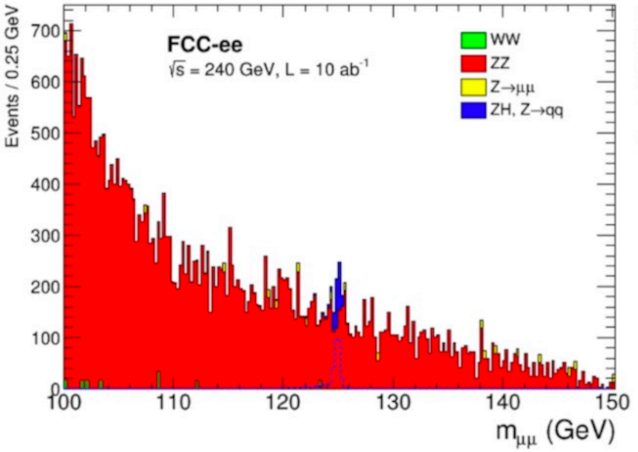
◆ Z–>qq most powerful channel: increased statistics compared with Z–>ee and Z–>μμ; and lower backgrounds than Z–>νν

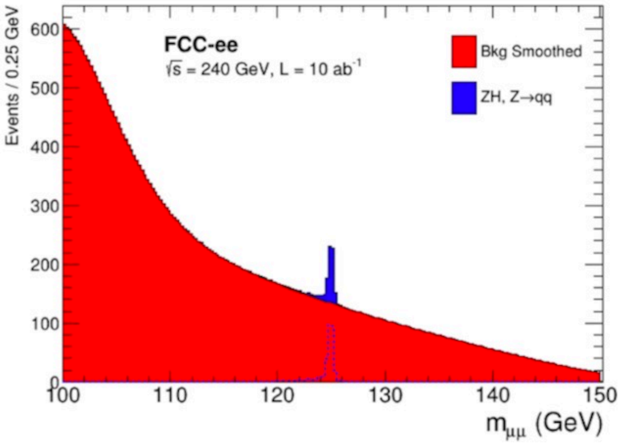
◆ Results:

H –>μμ branching fraction can be measured to ~10% – better than HL-LHC projections

m_H can be measured with a precision of ~30 MeV.

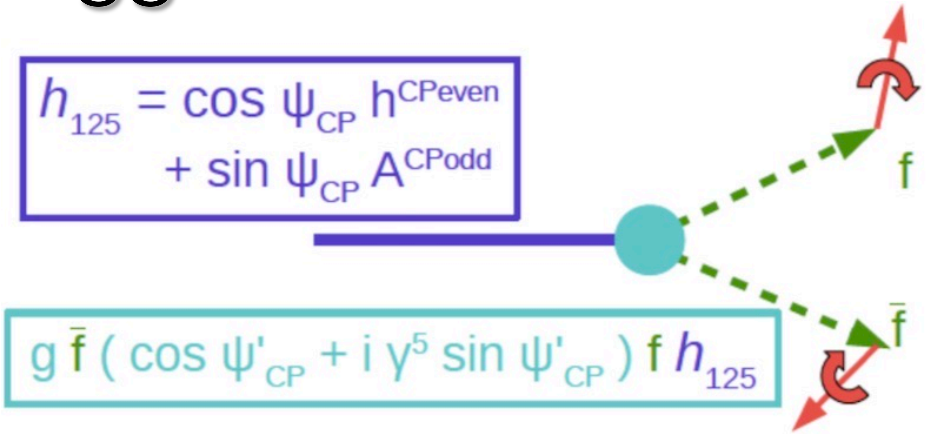






UK Highlight: Higgs CP

Manchester, Cambridge, Edinburgh, Glasgow
A. Atwal, J. Burridge, A. Costa, C. Englert, S. Farrington,
J. Nesbitt, L. Pereira, A. Pilkington, A. Robson, J. Silva,
S. Williams, Y. Zhang



$$h_{125} = \cos\psi_{CP}\, h^{CPeven} + \sin\psi_{CP}\, A^{CPodd}$$

$$g\,\bar{f}\,(\cos\psi'_{CP} + i\,\gamma^5 \sin\psi'_{CP})\, f\, h_{125}$$

h is a spin-0 state

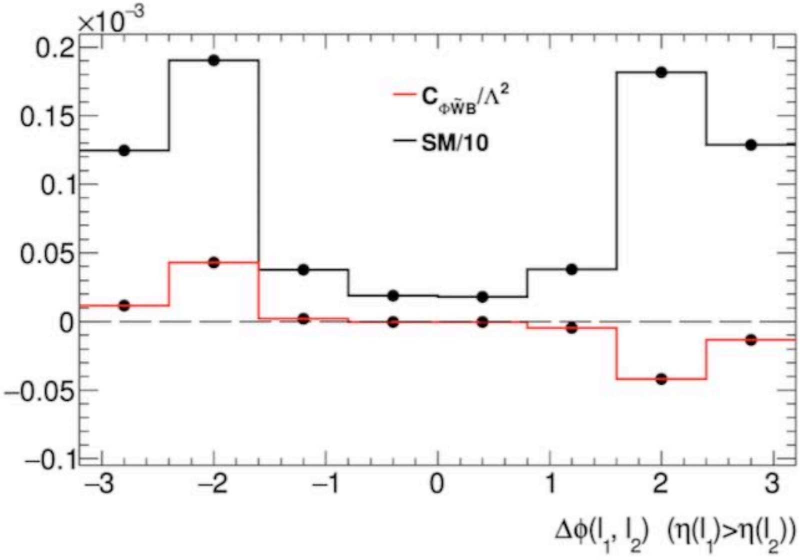
$$|f\bar{f}\rangle = |\uparrow\downarrow\rangle + e^{2i\psi}|\downarrow\uparrow\rangle \qquad \psi = \begin{cases} 0 & \text{CP even} \\ \pi/2 & \text{CP odd} \end{cases}$$

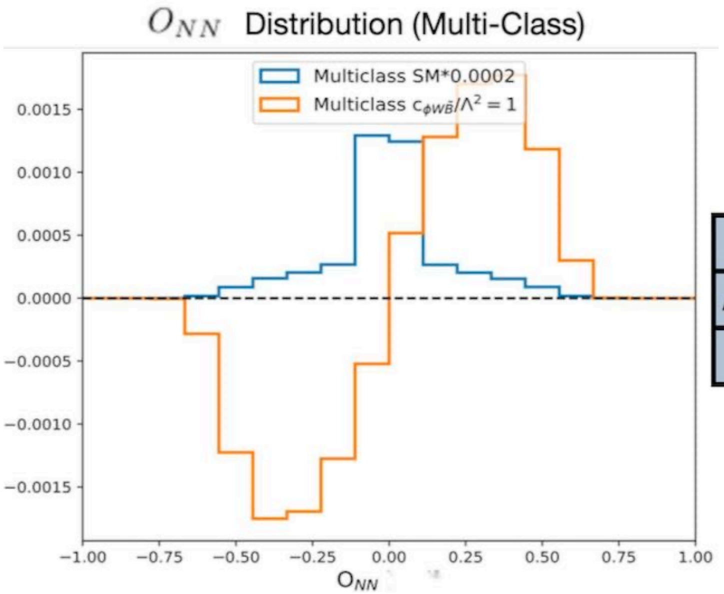
◆ Explore CP structure of HZZ vertex using e+e– –> ZH [and associated studies in pp]

◆ Interference between SM and CP-odd operators produces asymmetries in CP-odd variables

$$\tilde{\mathcal{O}}_{\Phi\tilde{B}} = \Phi^\dagger\Phi B^{\mu\nu}\tilde{B}_{\mu\nu} \qquad \tilde{\mathcal{O}}_{\Phi\tilde{W}} = \Phi^\dagger\Phi W^{i\mu\nu}\tilde{W}^{i}_{\mu\nu} \qquad \tilde{\mathcal{O}}_{\Phi\tilde{W}B} = \Phi^\dagger\sigma^i\tilde{W}^{i\mu\nu}B_{\mu\nu}$$

◆ NN trained on interference contribution; variable constructed from NN classification





◆ Limits set on EFT operators [work in progress]

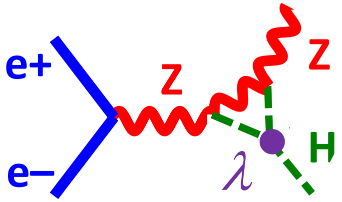
	cHWtil	cHBtil	cHWBtil
$\Delta\phi_{ll}$	[-0.41,0.41]	[-0.60,0.60]	[-1.2,1,2]
$\Delta\phi_{ll}$ vs m_{12}	[-0.35,0.35]	[-0.30,0.30]	[-0.5,1,2]
O_{NN}	[-0.35,0.35]	[-0.22,0.22]	[-0.4,0,4]

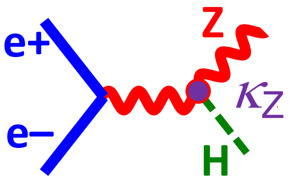
–> see also poster by Julia Silva!

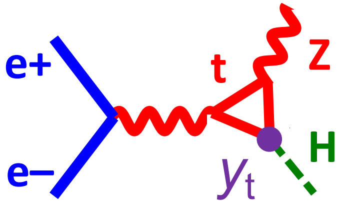
Higgs self-coupling: indirect access

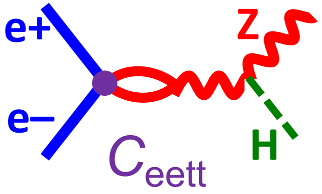
◆ If λ deviates from SM, loop diagrams will modify single-Higgs production Higgs decays

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









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

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

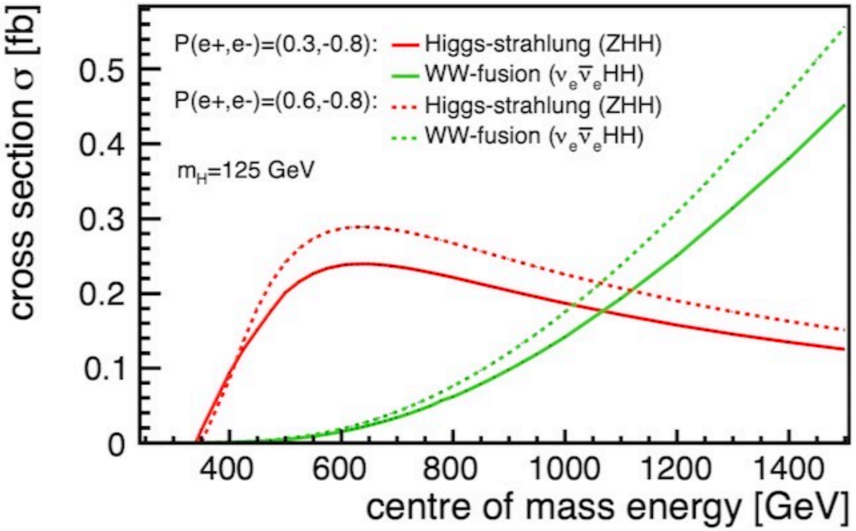
collider	1-parameter	full SMEFT
CEPC 240	18%	-
FCC-ee 240	21%	-
FCC-ee 240/365	21%	44%
FCC-ee (4IP)	15%	27%
ILC 250	36%	-
ILC 250/500	32%	58%
ILC 250/500/1000	29%	52%
CLIC 380	117%	-
CLIC 380/1500	72%	-
CLIC 380/1500/3000	49%	-

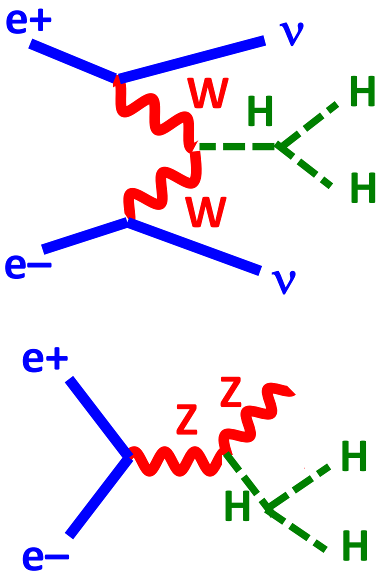
Higgs@Future Colliders 1905.03764

"-" means fit does not close

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

Higgs self-coupling: direct double-Higgs production





- ◆ Two contributing direct production mechanisms: ZHH and ννHH
- ◆ If self-coupling λ is at SM value then double-Higgs process observable at 8σ, with 27% precision on λ, at ILC 500
- ◆ Adding ννHH at 1TeV brings precision on λ to 10%

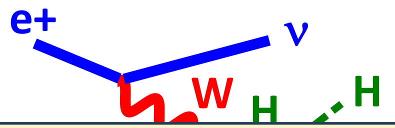
- ◆ ILC analysis used state-of-the-art reconstruction at the time (2016), but sensitivity very dependent on b-tagging performance, dijet mass resolution –> *update is ongoing*

- ◆ At 1.4TeV CLIC 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)

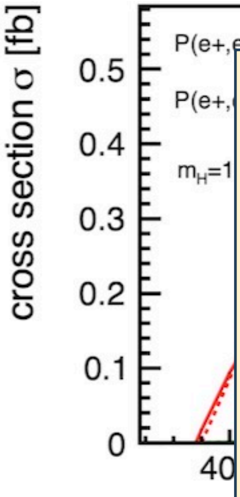
Higgs self-coupling: direct double-Higgs production



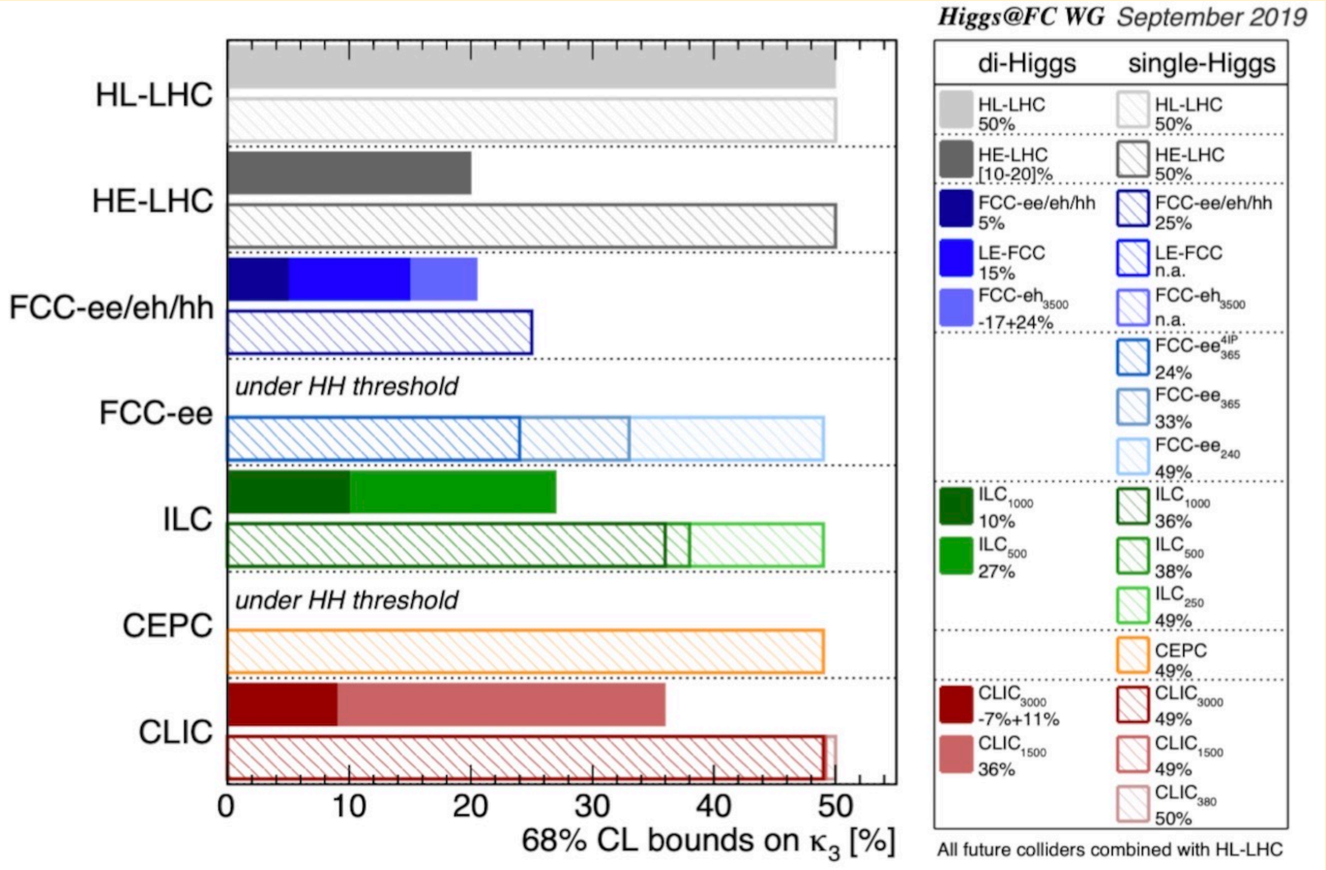
◆ Two contributing direct production mechanisms: ZHH and ννHH

en

8σ,



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



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

◆ d

◆ At 1.4
relative u
SM value

◆ 3TeV c
–8% and

◆ simult
quartic c
in g_{HHWW} and below 20% in g_{HHH} for large modifications of g_{HHWW}

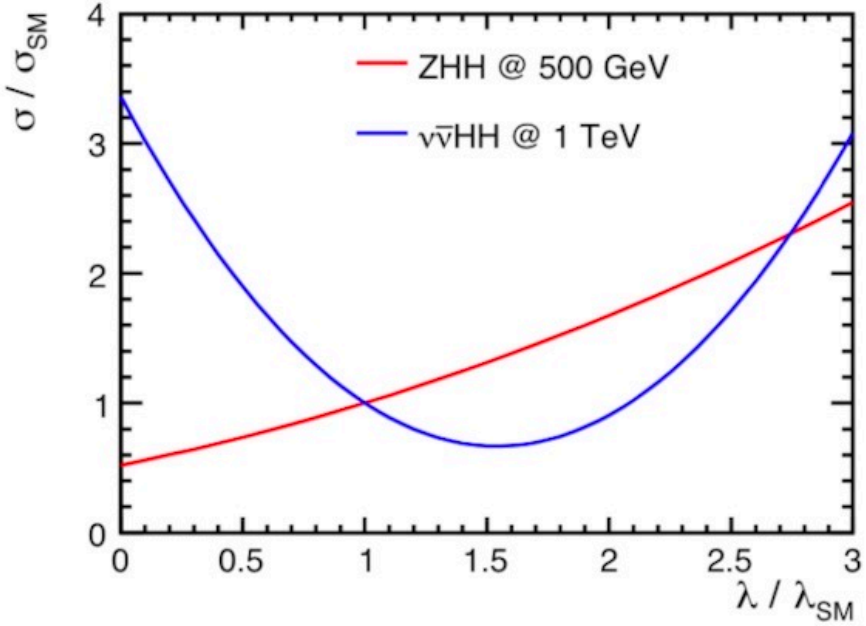
		ON
	rate-only analysis	differential analysis

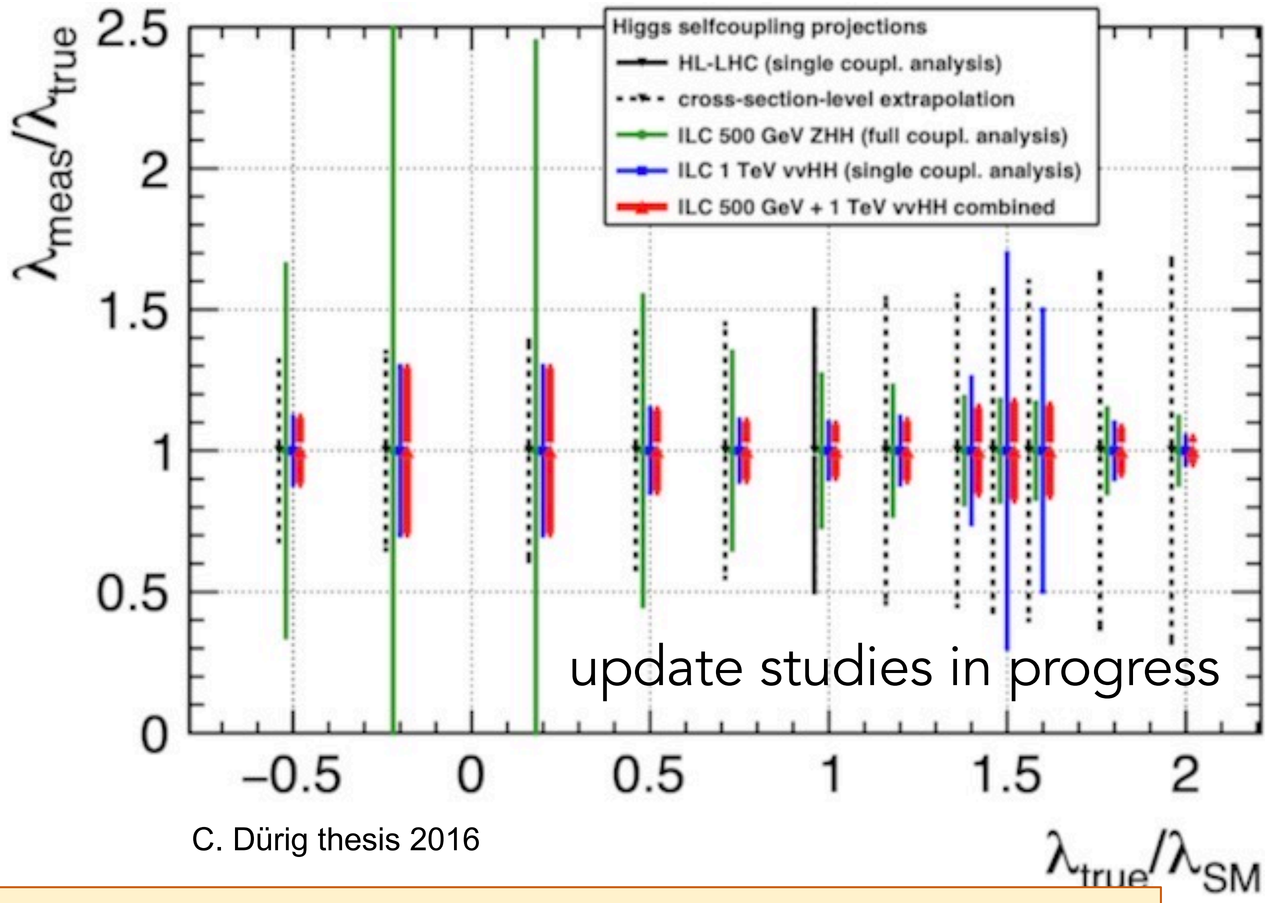
Eur. Phys. J. C 80, 1010 (2020)

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

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

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





update studies in progress

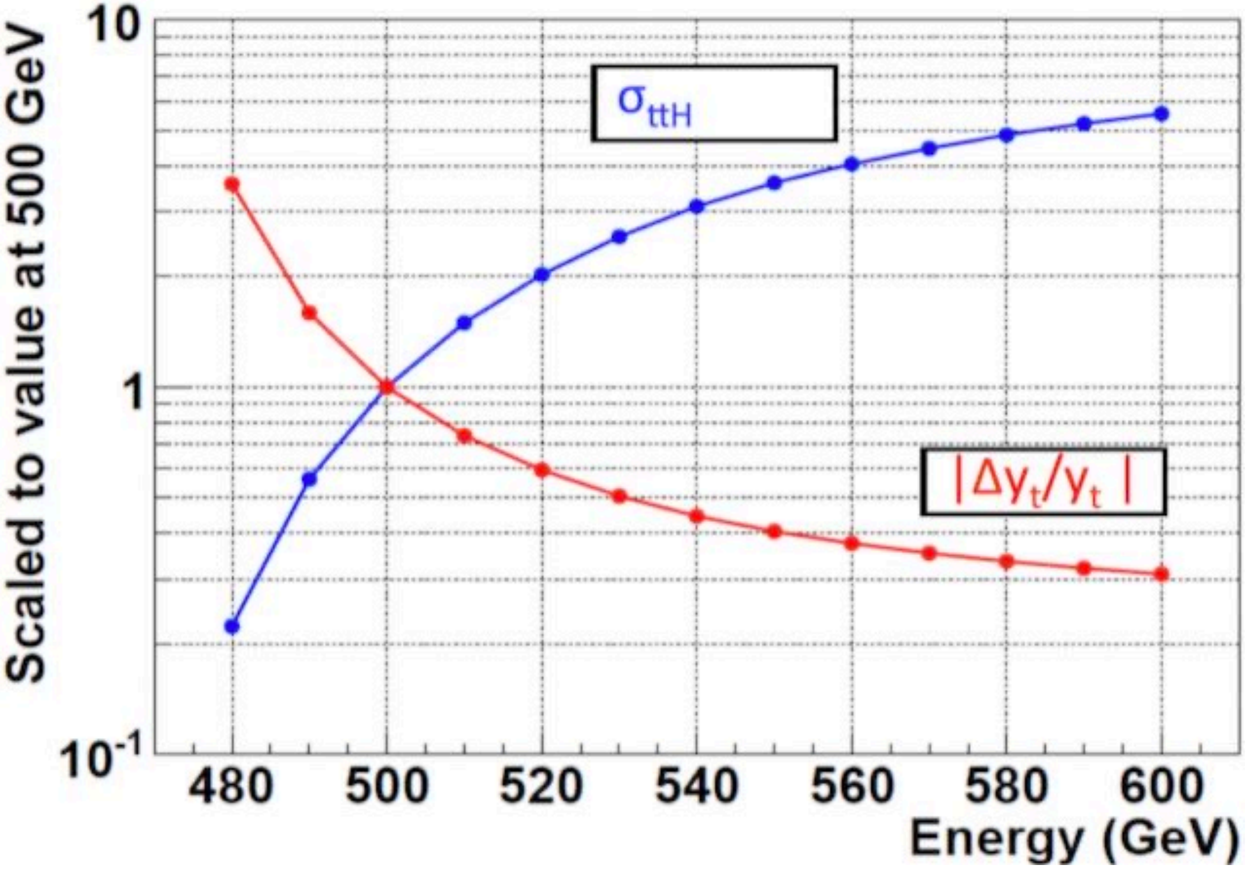
C. Dürig thesis 2016

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

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

Higher energies: ttH

- absolute value of $|y_t|$:
  - HL-LHC:
    $\delta\kappa_t$=3.2% with $|\kappa_V| \leq 1$
    or 3.4% in SMEFTND
  - e+e– LC:
    current full simulation
    achieved 6.3% at 500 GeV
    BUT strong dependence on
    exact choice of $\sqrt{s}$;
    e.g. 2% at 600 GeV
    - not included:
      - experimental improvement with higher energy (boost!)
      - channels other than H->bb
- full coupling structure of ttH vertex including CP can be explored using polarised beams

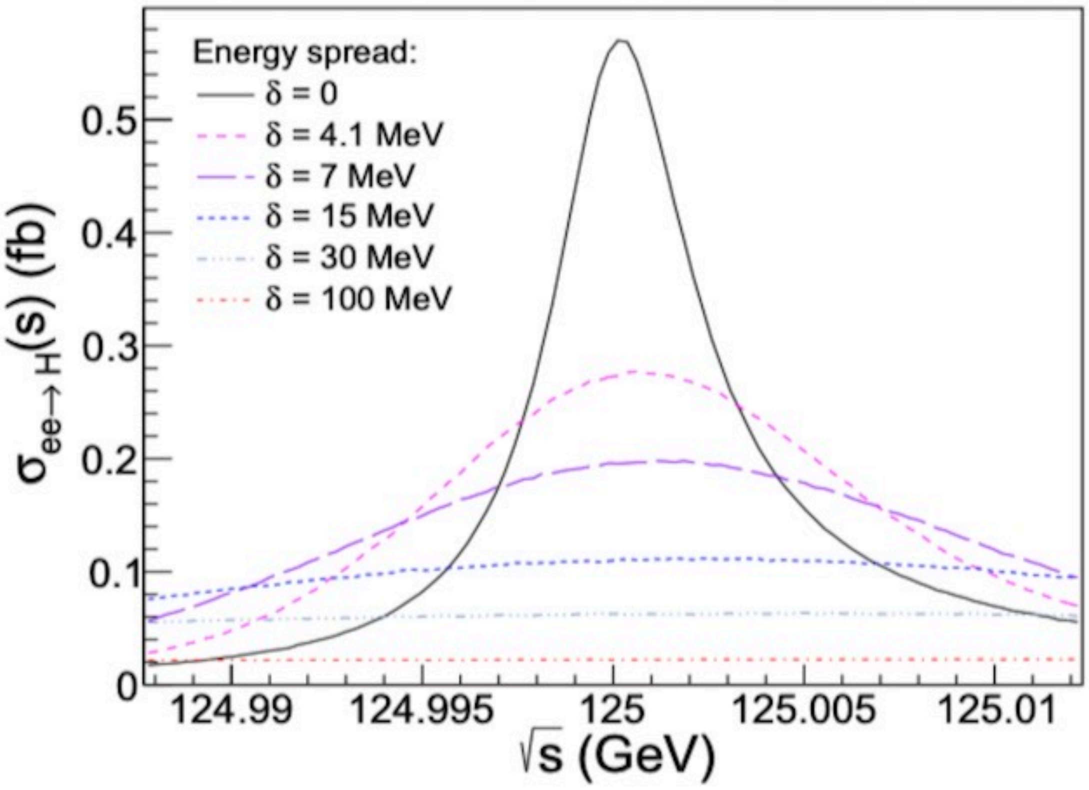


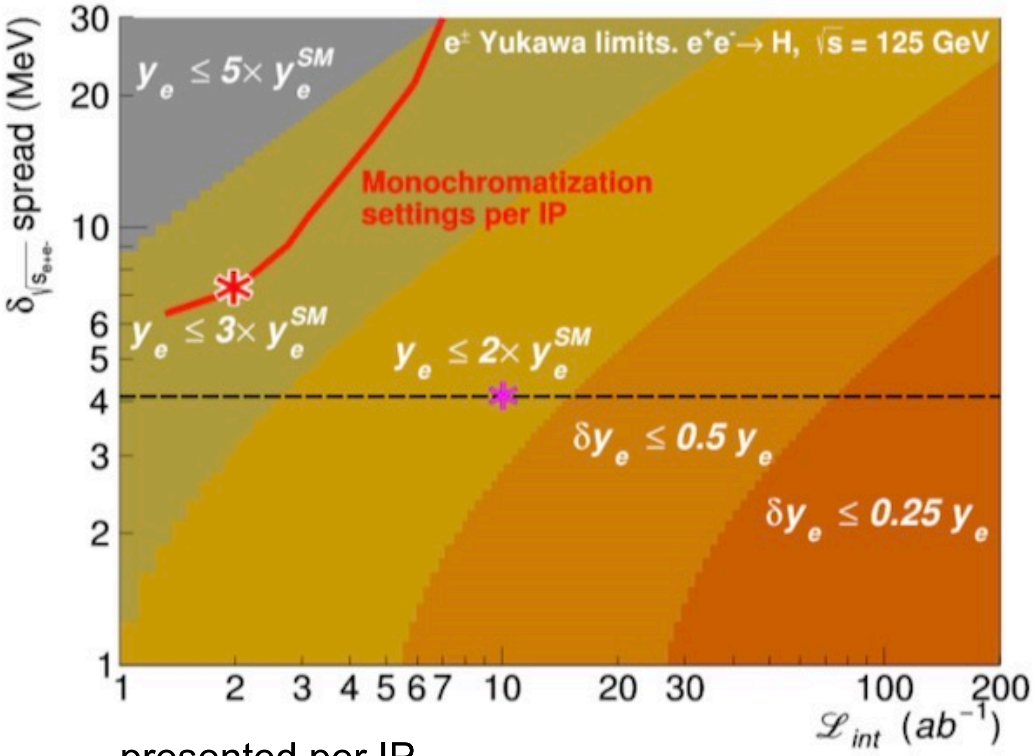
PRD 84 (2011) 014033
arXiv:1506.07830

- *needed*: full simulation study at 600 GeV

Lower energy: electron Yukawa

- Possibility of running FCC-ee at the Higgs pole
- Sensitivity to y_e depends strongly on beam energy spread achieved



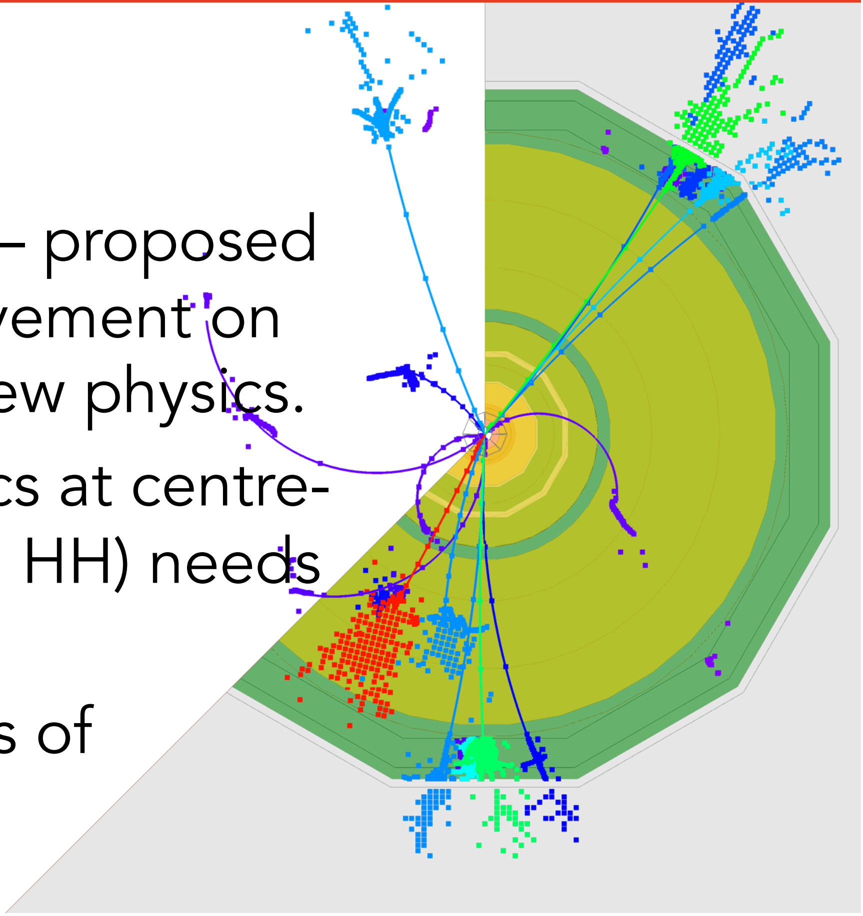


presented per IP
red curve is currently achieved in beam simulations

arxiv:2107.02686

- Dedicated 4-year run could reach $\kappa_e < 1.6$ at 95% CL

Summary



- Core Higgs programme common to all e+e– proposed projects provides ~order of magnitude improvement on Higgs couplings, motivated by sensitivity to new physics.
- Relative importance / prioritization of physics at centre-of-mass energies away from 250/380GeV (e.g. HH) needs to be discussed in the community.
- Ongoing studies are continuing to find ways of enriching the potential physics programme.

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

https://indico.in2p3.fr/event/32629/overview

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

9–11 October 2024

9–11 Oct 2024

Campus des Cordeliers, Paris, Metro Odeon

Europe/Paris timezone

REGISTRATION CLOSES TOMORROW, 24/9