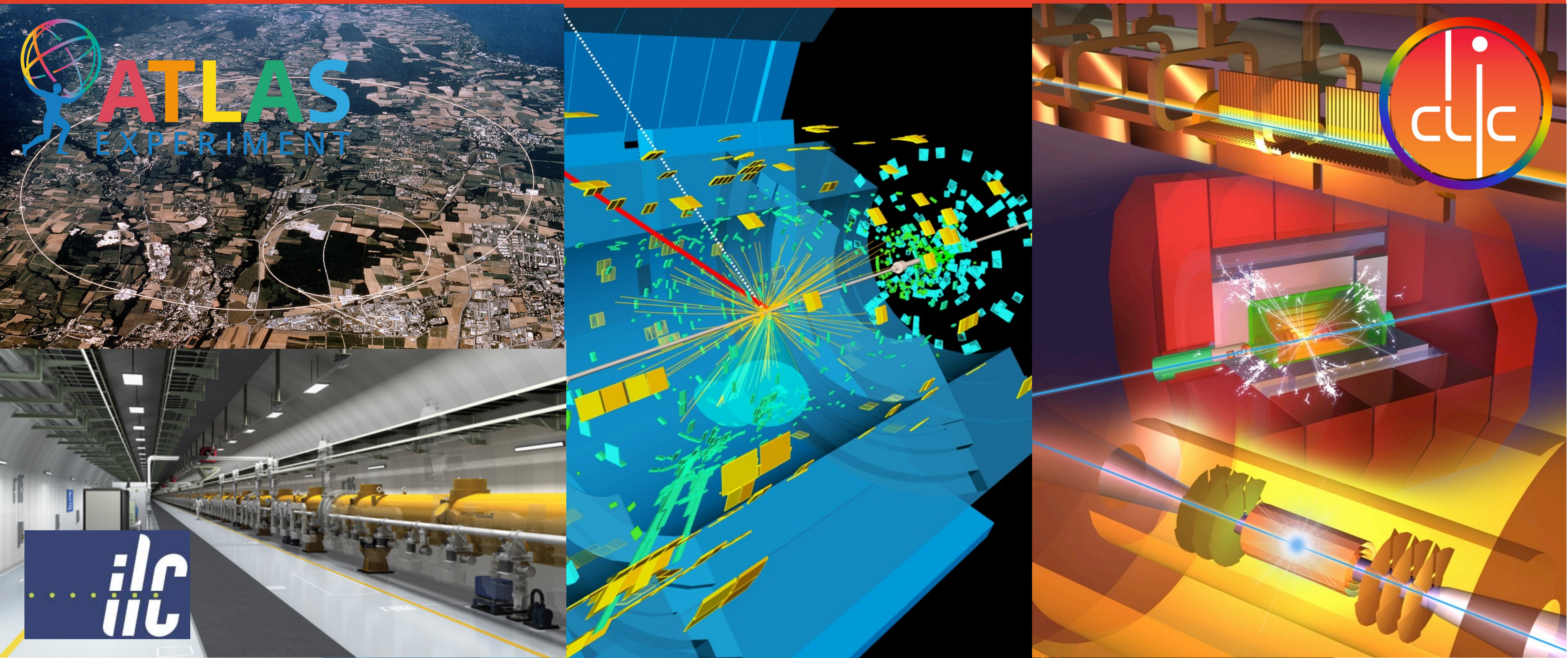
The Higgs boson: a new window on the universe



Flavourful Physics Workshop, Valencia, 3 February 2025

Aidan Robson, University of Glasgow

The problem, c. 1964…

$$\mathcal{L}_{\rm QED} = \overline{\psi}(i\gamma_\mu\partial^\mu - m_f)\psi + q\overline{\psi}\gamma_\mu A^\mu\psi - \tfrac{1}{4}F_{\mu\nu}F^{\mu\nu} \quad + \tfrac{1}{2}m_\gamma^2 A_\mu A^\mu$$

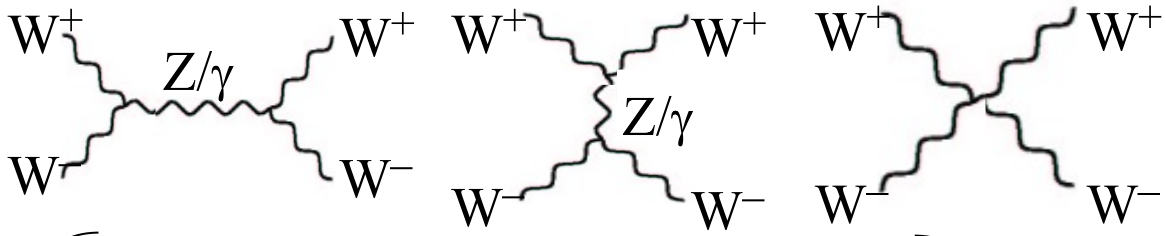
$$\mathcal{L}_{\rm EWK} = \overline{\psi}\gamma_\mu(i\partial^\mu + g\boldsymbol{\tau}\cdot\mathbf{W} + \tfrac{g'}{2}YB^\mu)\psi - \tfrac{1}{4}B_{\mu\nu}B^{\mu\nu} - \tfrac{1}{4}\mathbf{W}_{\mu\nu}\cdot\mathbf{W}^{\mu\nu}$$

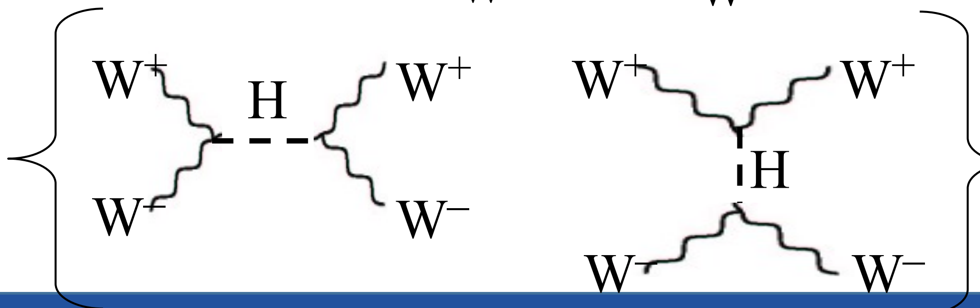
$$+\tfrac{1}{2}m_B^2 B_\mu B^\mu + \tfrac{1}{2}m_W^2 \mathbf{W}_\mu\cdot\mathbf{W}^\mu$$

$$+ \tfrac{1}{2}(\partial_\mu H\partial^\mu H + 2\mu^2 H^2) - \tfrac{\lambda}{4}(4vH^3 + H^4)$$

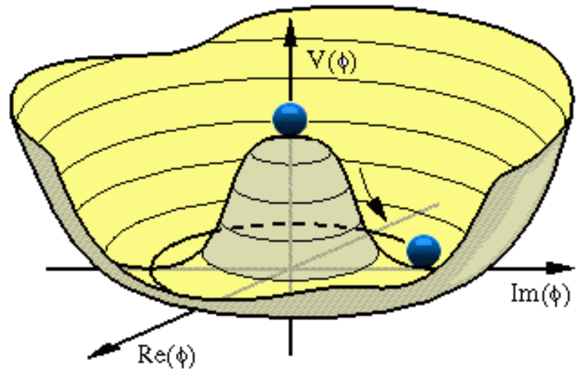
$$+ \tfrac{g^2}{4}(v^2 + 2vH + H^2)W_\mu^- W^{+\mu} + \tfrac{g^2+g'^2}{8}(v^2 + 2vH + H^2)Z_\mu Z^\mu$$

$$-\tfrac{g_e}{\sqrt{2}}(v + H)(\overline{\psi}_L\psi_R + \overline{\psi}_R\psi_L)$$



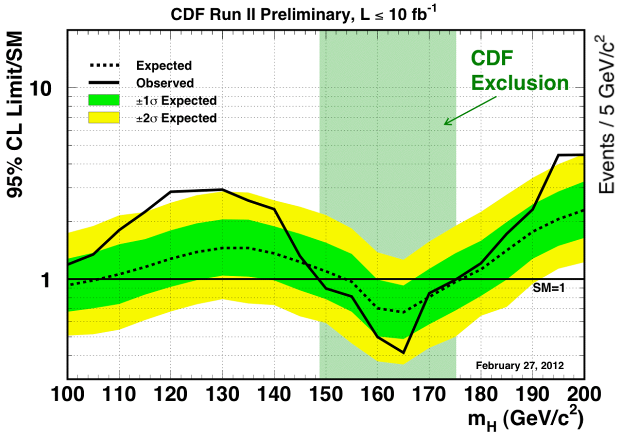


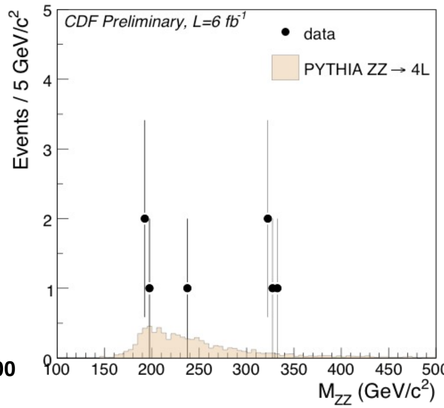
required to cancel high-energy behaviour



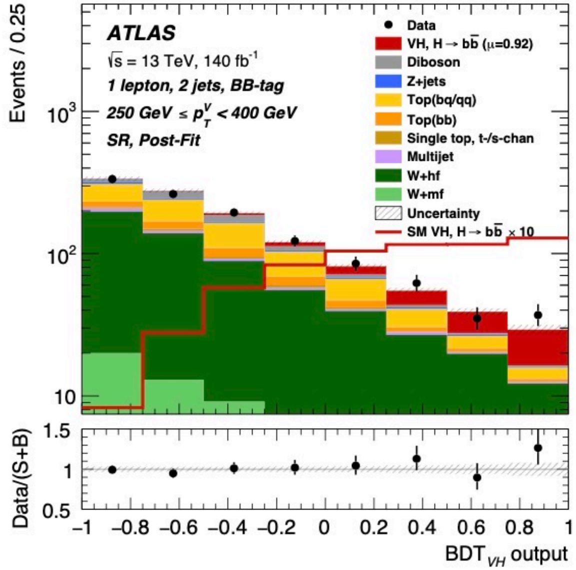
For me, 20 years…

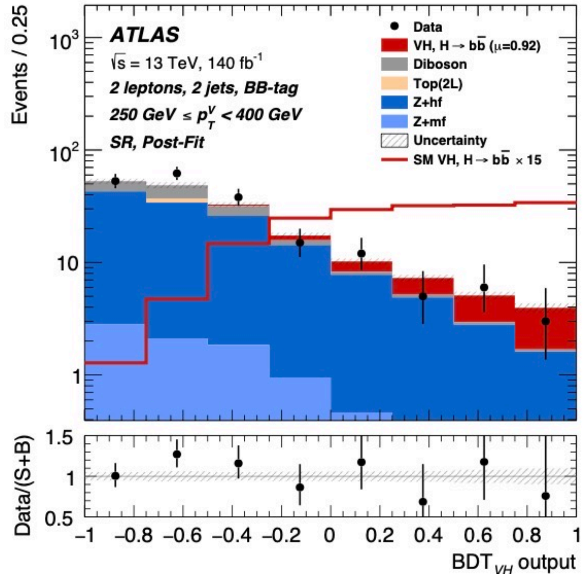
◆ 2005–2012: Searching for H–>WW, & ZZ resonances at CDF





◆ 2012–2024: VH, H–>bb at ATLAS

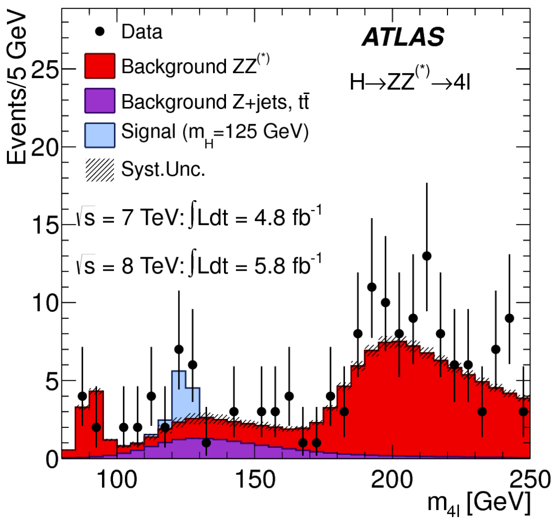




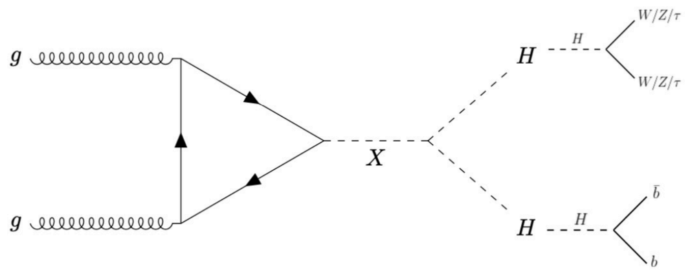
2018 H–>bb observation
2024 differential analyses…

◆ 2009–2013: ZZ at ATLAS

2012 H–>ZZ observation



◆ 2022–> HH at ATLAS



First a new resonance search…

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?

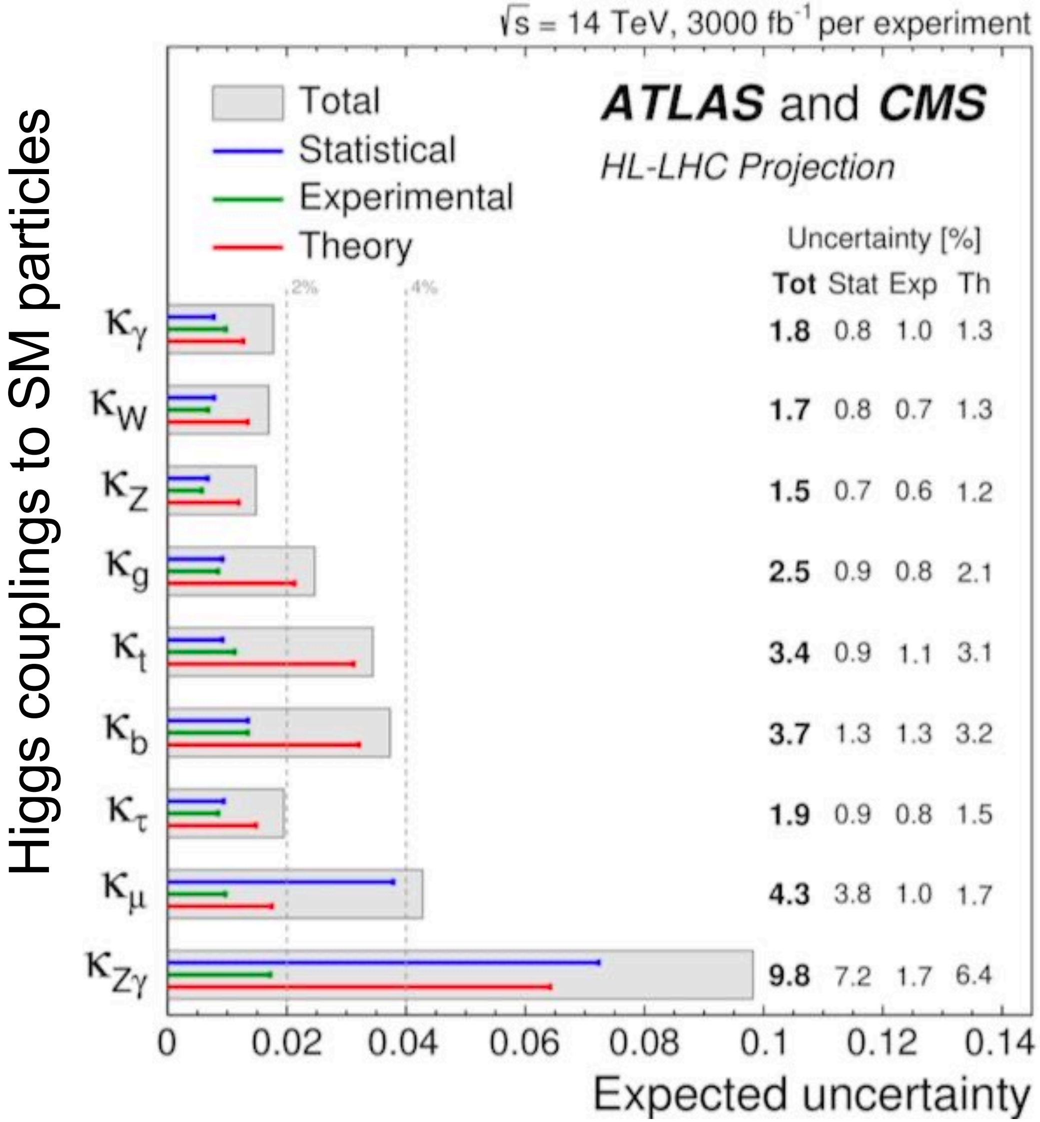
  => small contributions -> need precise measurements!

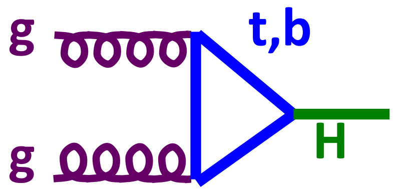
- What is the shape of the Higgs potential, and its evolution?
  - do Higgs bosons self-interact?
  - at which strength? => 1st or 2nd order phase transition?

  => discover and study di-Higgs production

The HL-LHC legacy

- HL-LHC will run ~2030–2042; very bright prospects for Higgs physics
- Projections being continuously updated; will be public in March 2025 for European Strategy





Principal LHC production mechanism

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

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

The 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 !**

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◆ The LHC is not enough!

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

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

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

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

In particular:

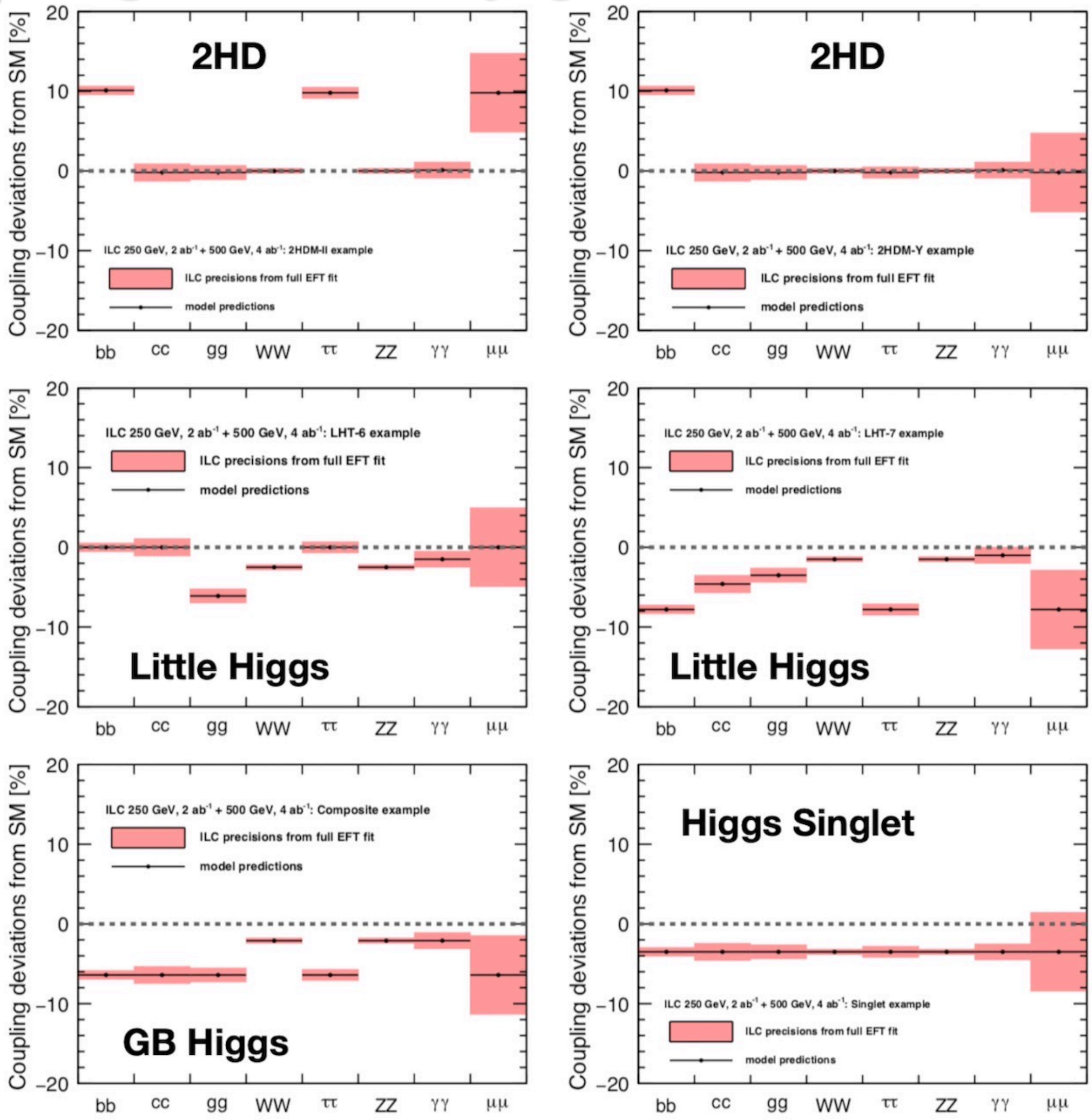
- low backgrounds
- clean events
- triggerless operation (LCs)

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.

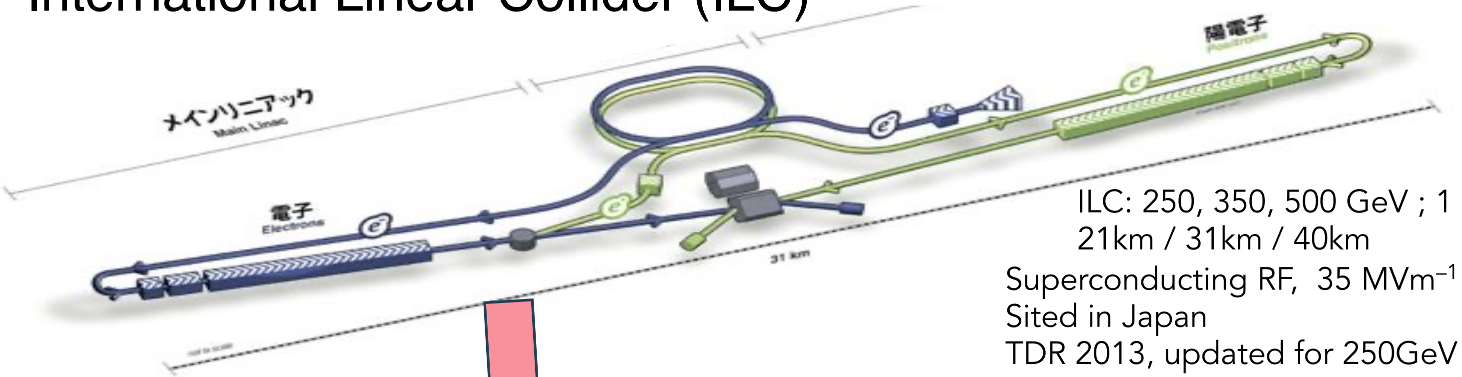


Barklow/Peskin 1708.08912

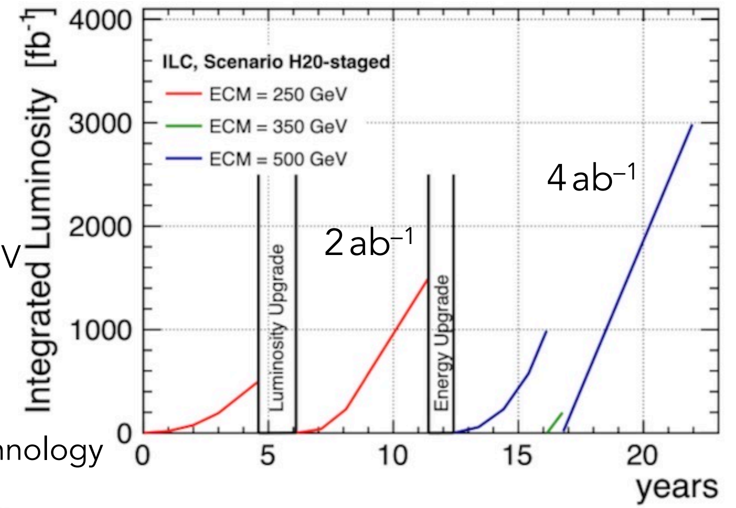
- Typical models give coupling deviations at 1% level; **this is the target (and e+e– factories can reach this sensitivity and beyond).** **More precise measurements give greater discovery potential**

Higgs factory contenders (1): Linear Colliders

International Linear Collider (ILC)



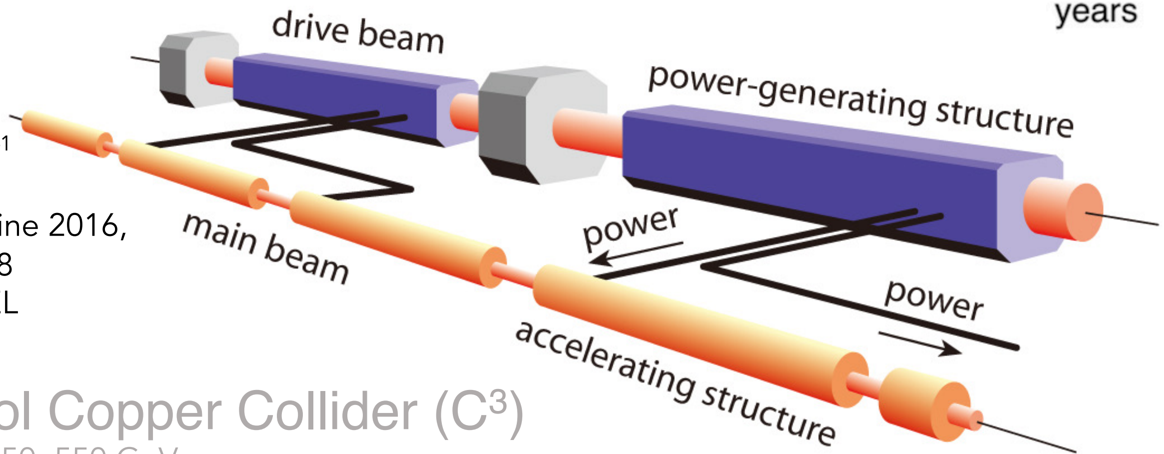
ILC: 250, 350, 500 GeV ; 1 TeV
21km / 31km / 40km
Superconducting RF, 35 MVm^{-1}
Sited in Japan
TDR 2013, updated for 250GeV
European XFEL demonstrates technology



Compact Linear Collider (CLIC)

Recently updated luminosities:
380 GeV : 2.2ab^{-1} at 50Hz
or 4.3ab^{-1} at 100Hz
1.5 TeV : 4ab^{-1}
3 TeV : 5ab^{-1}

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

Linear Collider Facility @CERN

Footprints of superconducting (ILC-like) and normal-conducting (CLIC-like) machines made to be the same –> either could be realised
Incorporates two interaction points (different from original ILC and CLIC proposals).

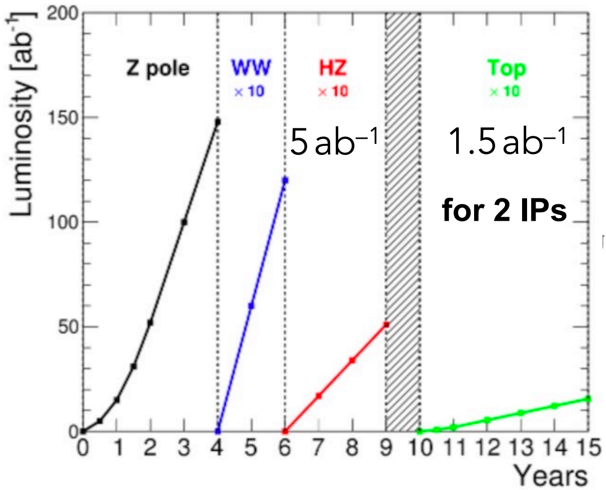
Hybrid Asymmetric Linear Higgs Factory (HALHF)

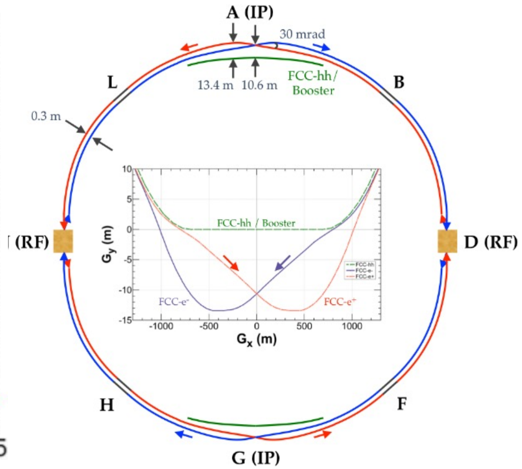
HALHF: 250 GeV (e^- 500GeV, e^+ 31GeV)
3.3km
25 MVm^{-1} conventional, 6.3GVm^{-1} plasma
Pre-CDR

Higgs factory contenders (2): Circular Colliders

Future Circular Collider (FCC-ee)

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

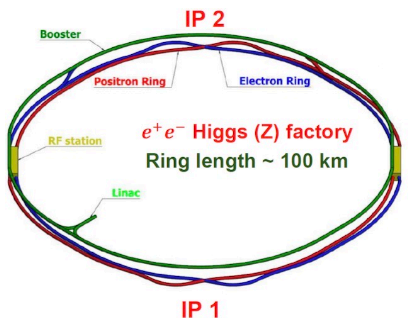




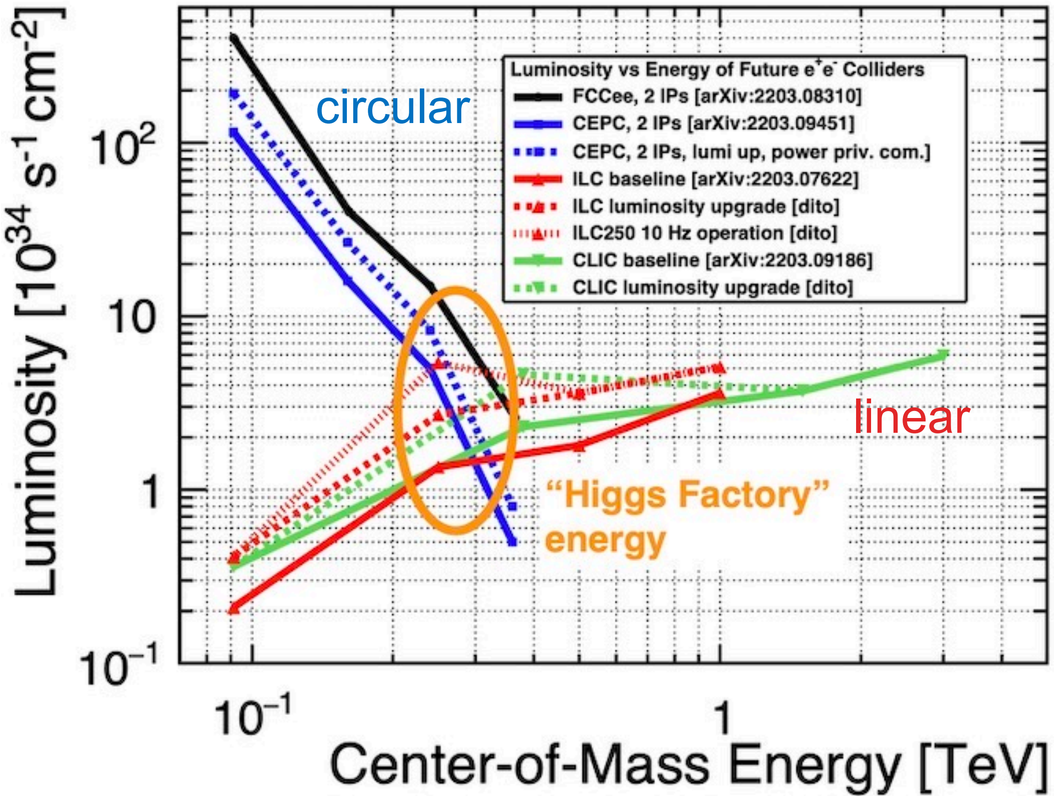
FCC: ~92km ring
FCCee CDR 2019
Accelerator technology mostly proven >50yr
Feasibility study has made significant progress on e.g. siting

Circular Electron Positron Collider (CEPC)

CEPC: 91, 160, 240 GeV
CEPC: ~100km ring
CEPC CDR 2018
3 years at Z/WW, 7 years at HZ,
5.6ab⁻¹ for 2 IPs



◆ Key difference linear/circular: luminosity performance with energy



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

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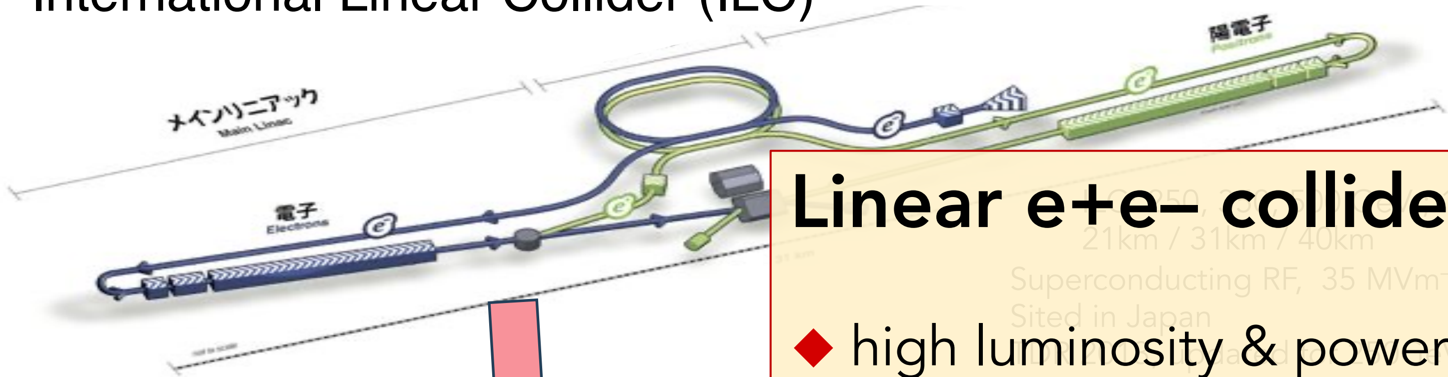

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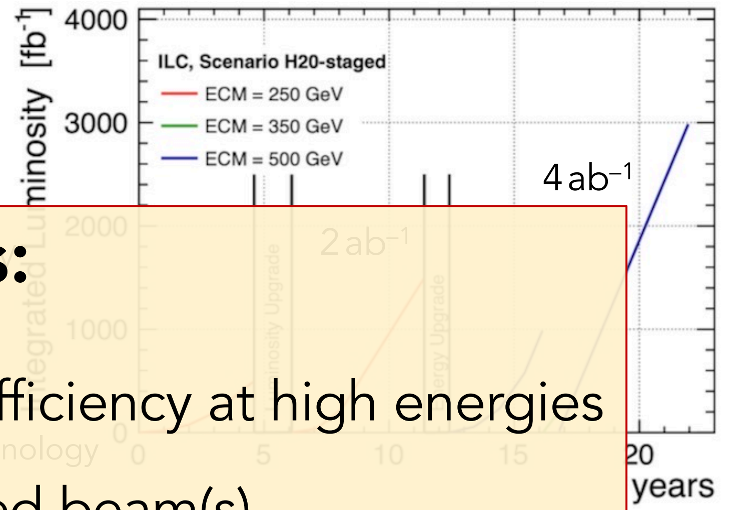

Linear e+e– colliders:

- high luminosity & power efficiency at high energies
- longitudinally spin-polarised beam(s)
- Long-term upgrades: energy extendability
  - same technology: by increasing length
  - or by replacing accelerating structures with advanced technologies
    - RF cavities with high gradient
    - plasma acceleration?

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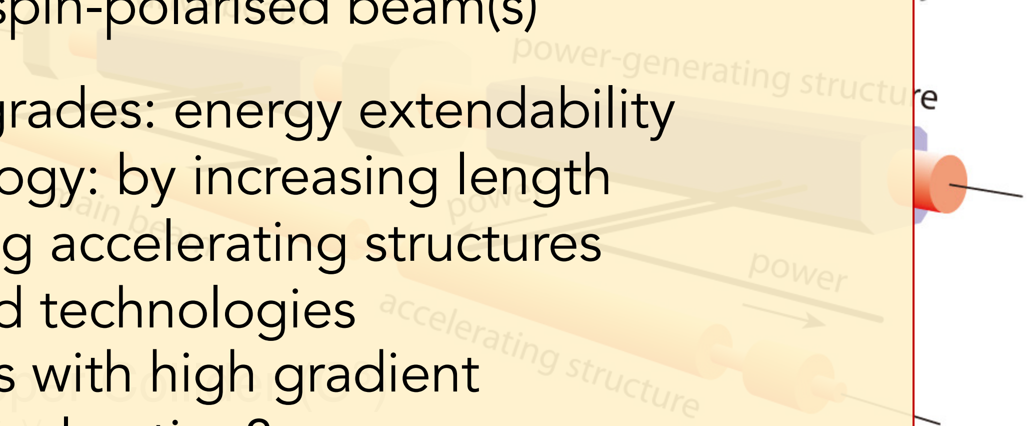

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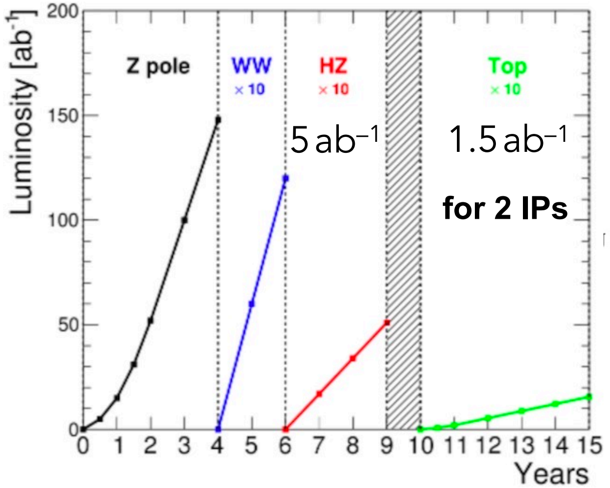

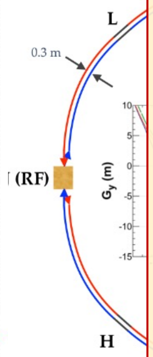

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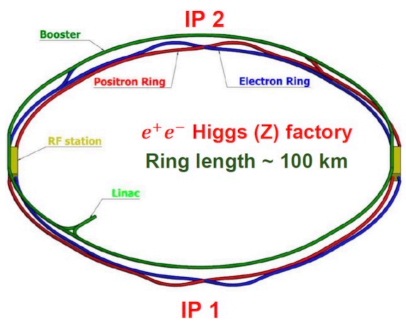

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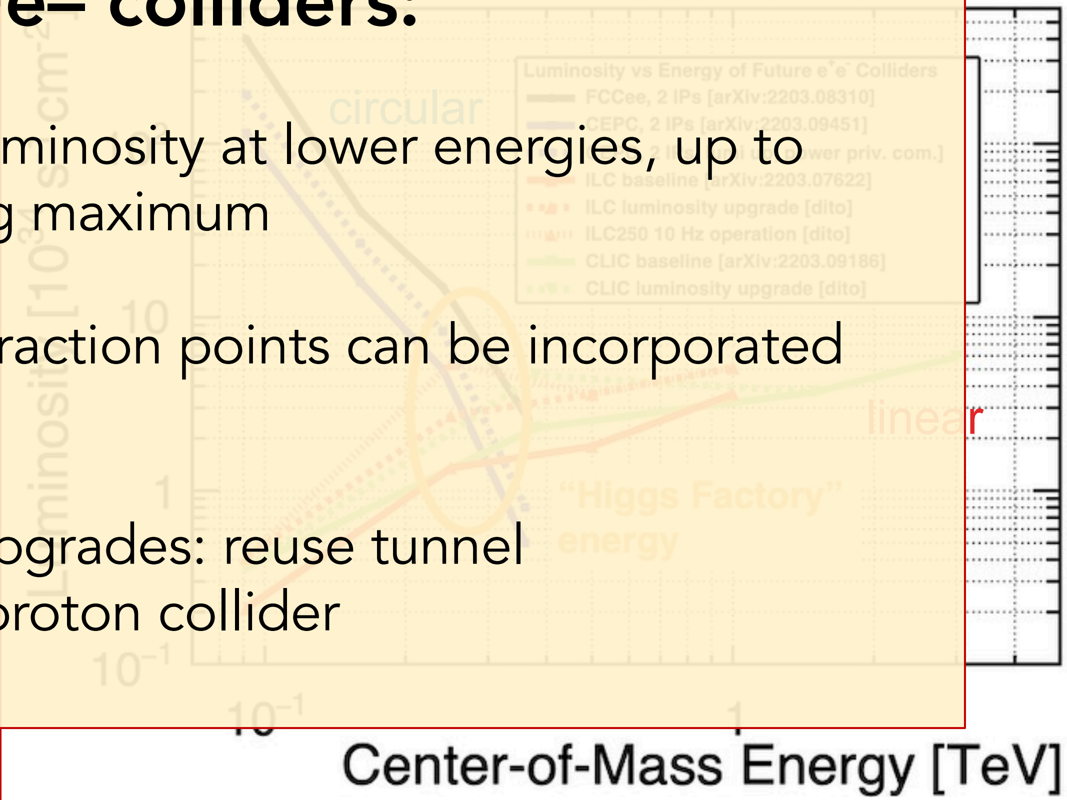

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Circular e+e– colliders:

◆ (very) high luminosity at lower energies, up to Higgs-strahlung maximum

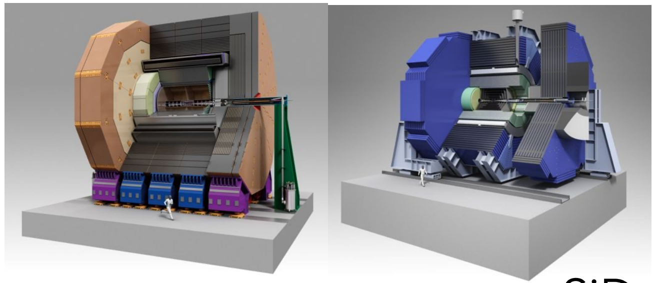
◆ multiple interaction points can be incorporated naturally

◆ Long-term upgrades: reuse tunnel
- e.g. proton-proton collider

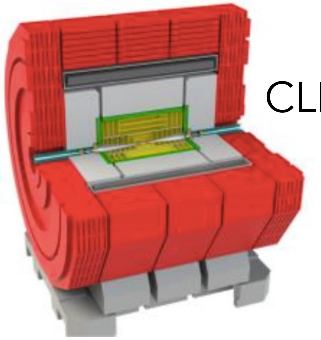
Detector requirements

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

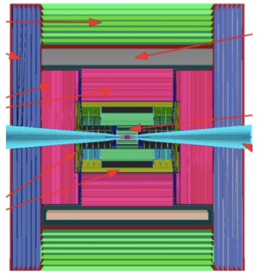
- Well-developed detector concepts extending from linear to circular projects



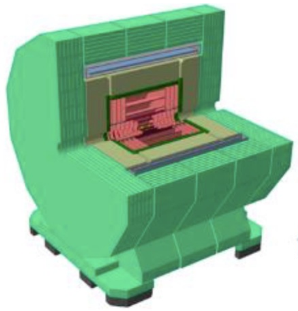
ILD SiD



CLICdet

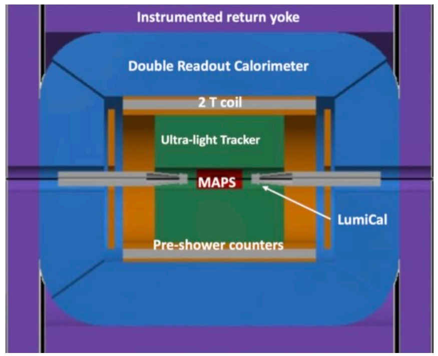


(CLICdet adapted for muon collider!)



CLD for FCC-ee

+ IDEA for FCC-ee



- Key requirements from Higgs physics

p_T resolution (total ZH cross-section)
$\sigma(1/p_T) = 2\times10^{-5}\ \mathrm{GeV}^{-1} \oplus 1\times10^{-3}/(p_T \sin^{1/2}\theta)$ ~ CMS/40

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

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

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

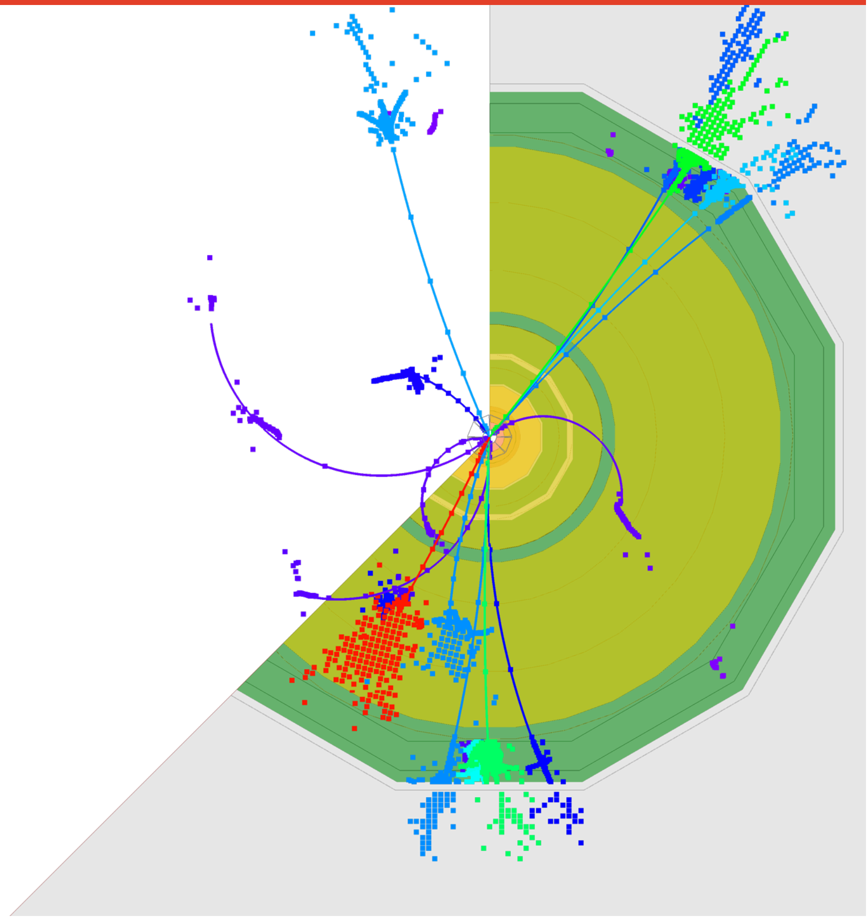
Very challenging!

–> Determine the key features of the detector:

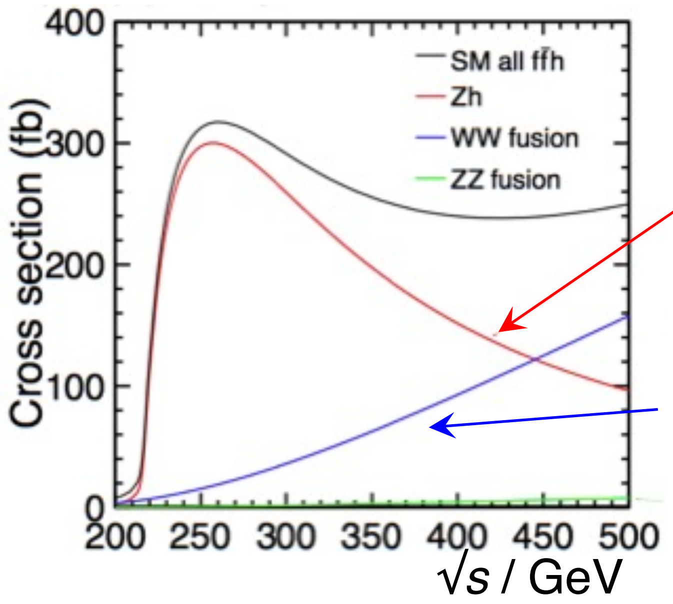
- Low-mass tracker (e.g. VTX: 0.15% rad. length / layer)
- Calorimeters
  highly granular, optimised for particle flow
  or dual readout, LAr, …

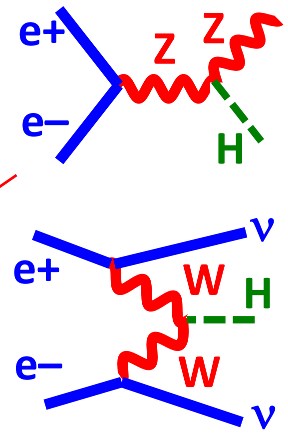
Enables the precision Higgs programme

Higgs in e^+e^-



Higgs production in e^+e^-

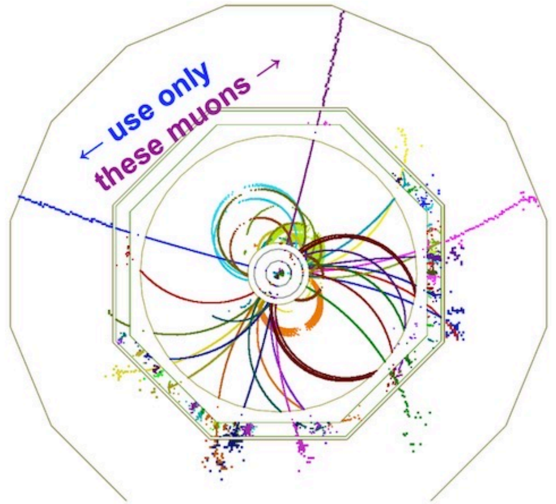




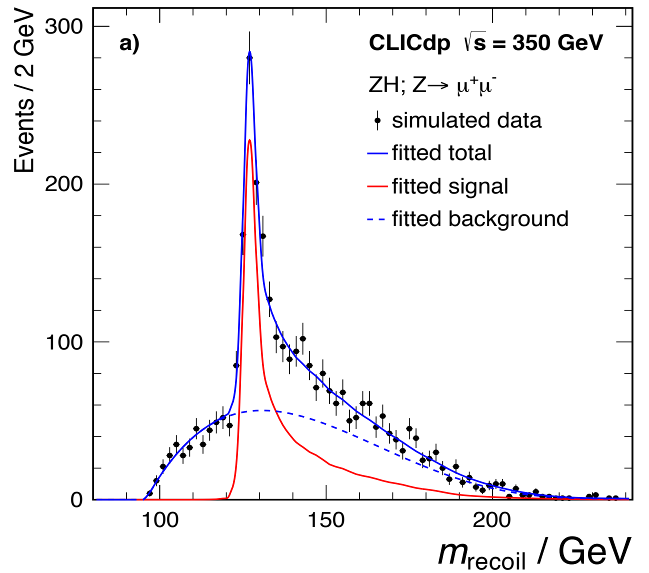
- ZH process allows reconstruction of H by looking exclusively at recoil of Z –> model-independent extraction of g_{HZZ} coupling

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

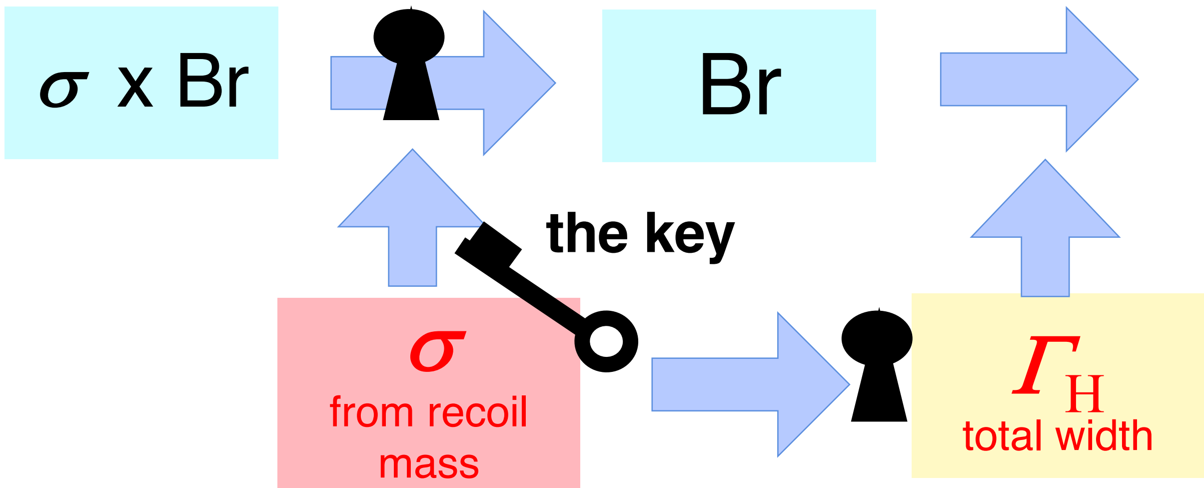
$$\frac{\sigma_{ZH} .Br(H\text{->}bb)}{\sigma_{\nu\nu H} .Br(H\text{->}bb)} \propto \frac{g^2_{HZZ}}{g^2_{HWW}}$$



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



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

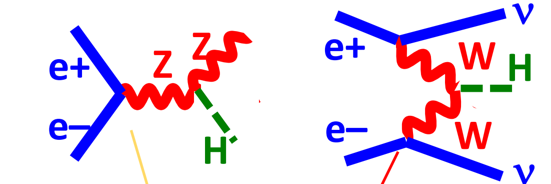


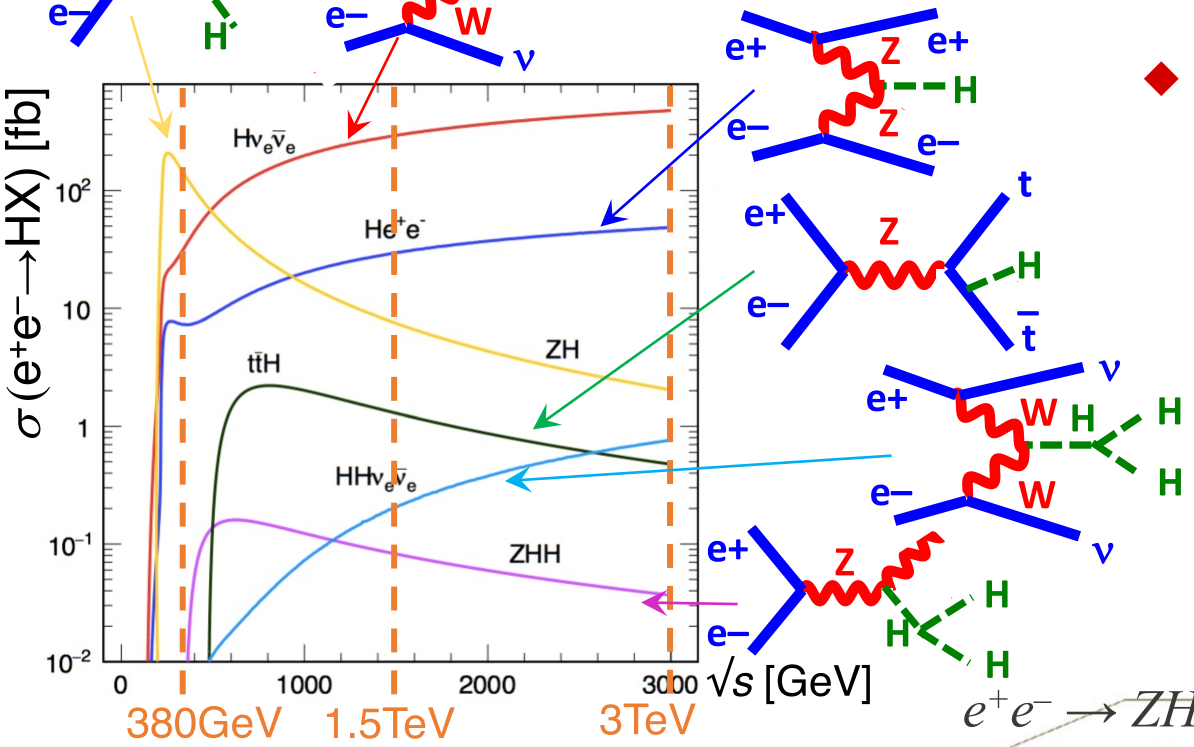
(WW fusion helps with precision total width at higher $\sqrt{s}$)

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

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

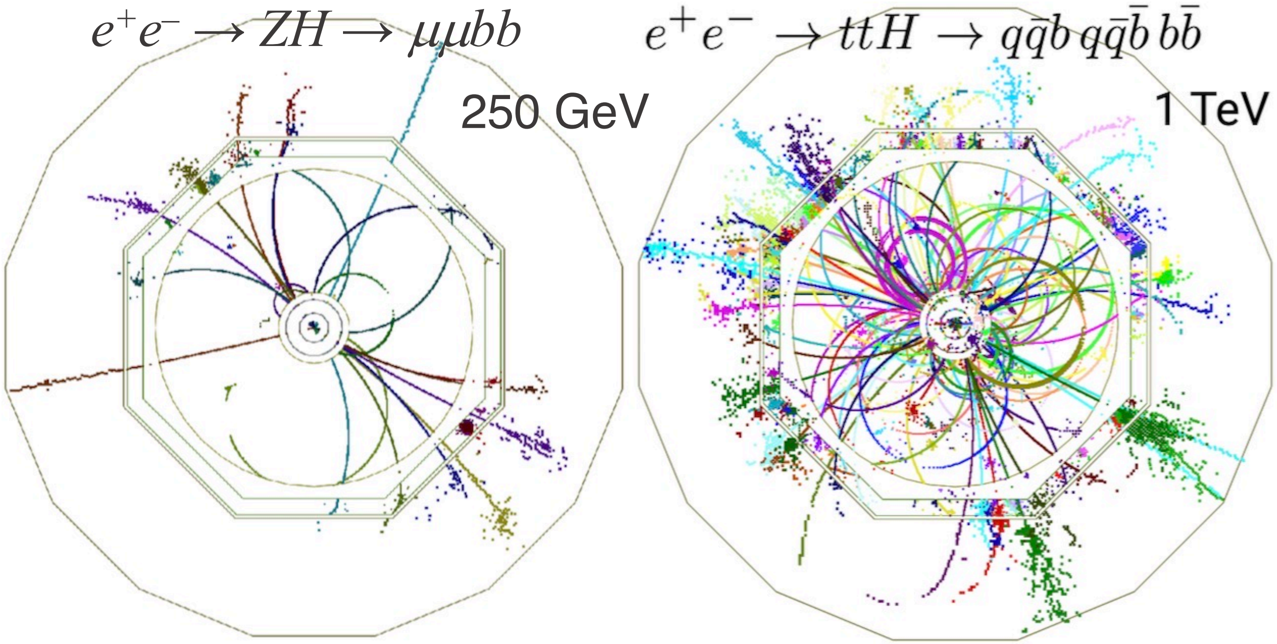
Higgs production in e^+e^-





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

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

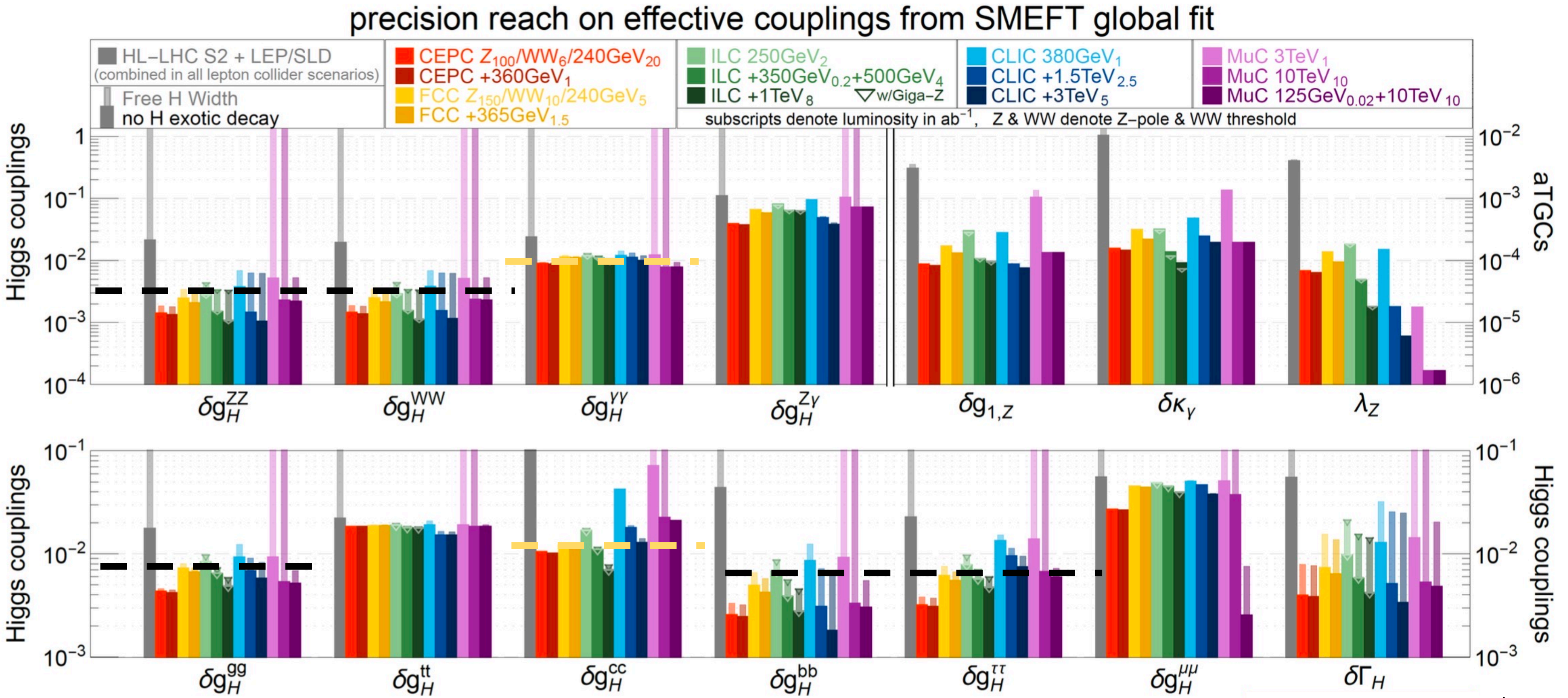


Higgs couplings sensitivity

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

Standard Model
Dim-6 operators
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

Higgs couplings sensitivity

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

Standard Model

Dim-6 operators

Scale of new decoupled physics

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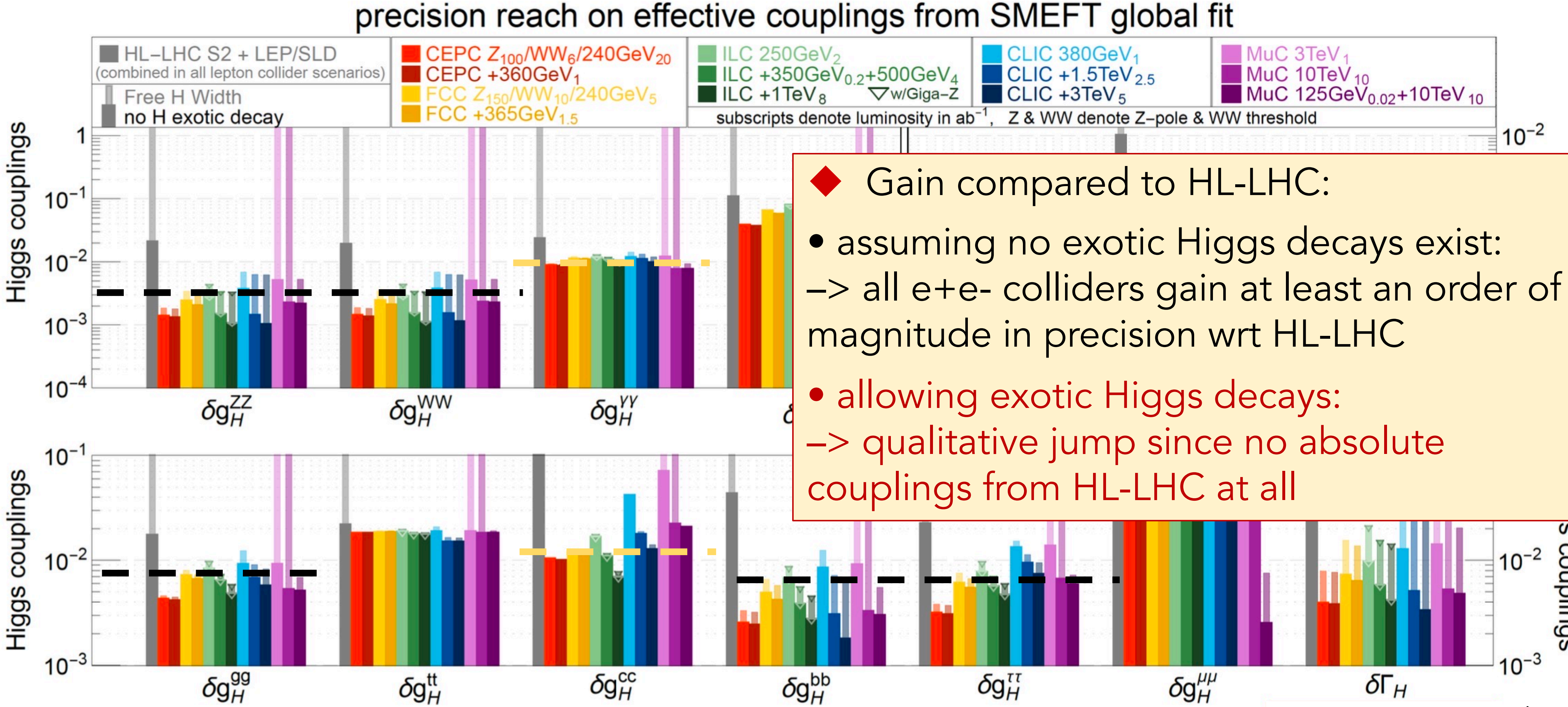

- Gain compared to HL-LHC:
  - assuming no exotic Higgs decays exist: –> all e+e- colliders gain at least an order of magnitude in precision wrt HL-LHC
  - allowing exotic Higgs decays: –> qualitative jump since no absolute couplings from HL-LHC at all

Snowmass EFT couplings arxiv: 2206.08326

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  - several couplings at few-0.1% level: Z, W, g, b, τ
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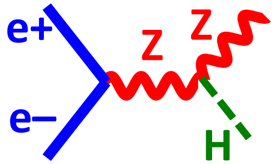
Aside on datasets / integrated luminosities / polarization

◆ **Projects propose different integrated luminosities.**

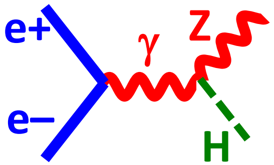
Assumptions in previous slide:
FCC-ee: 5 ab^{-1} for 2 IPs
CEPC: 5.6 ab^{-1} for 2 IPs
ILC: 2 ab^{-1} at 250 GeV
CLIC: 1 ab^{-1} at 380GeV

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

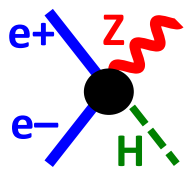
◆ Example: A_{LR} of Higgsstrahlung lifts degeneracy between operators and helps to disentangle different SMEFT contributions



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



~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 –> baseline already increased through improved modelling of beam emittances; further, could double rep rate to 100Hz
ILC –> could double bunches per pulse & rep rate

Every option has an associated cost – care should be taken when comparing sensitivities.

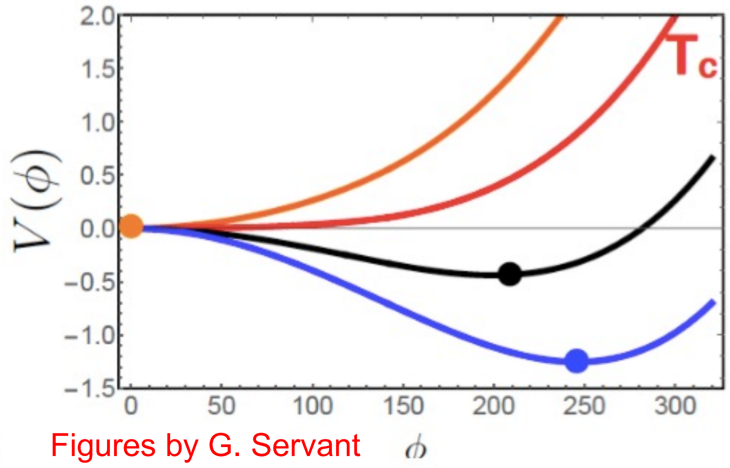
Also, run plans would be adapted according to funding (e.g. if only the first stage of CLIC were built, it would be run for longer)

e.g. arXiv:2001.05278

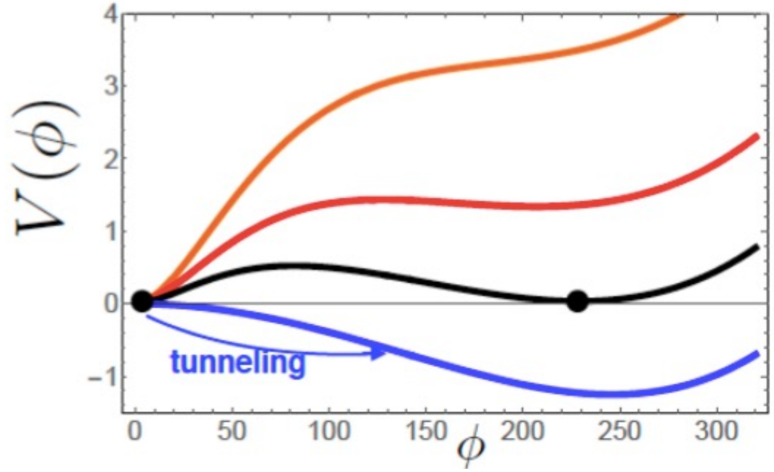
Higgs self-coupling

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

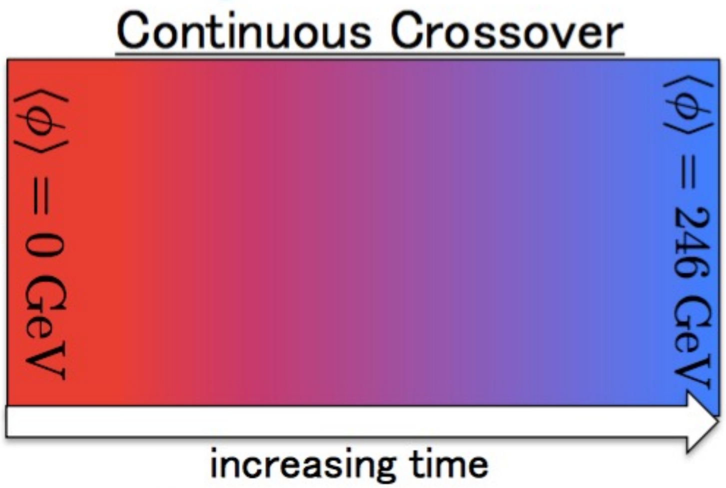
Standard Model:

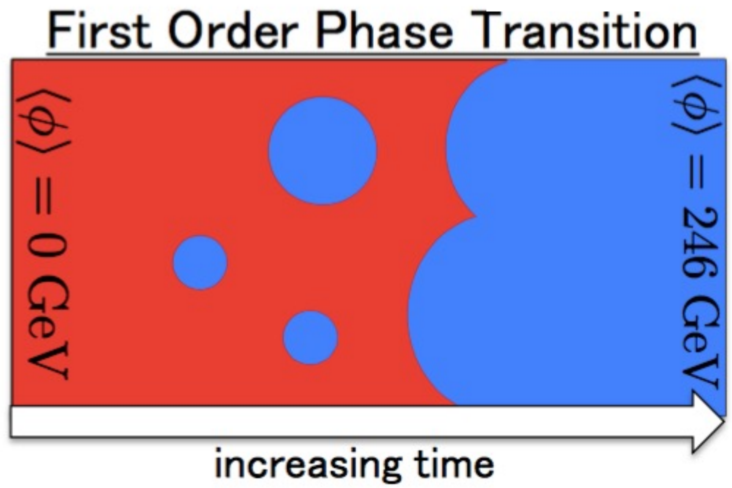


Possible alternative:



In this case, two phases can coexist:





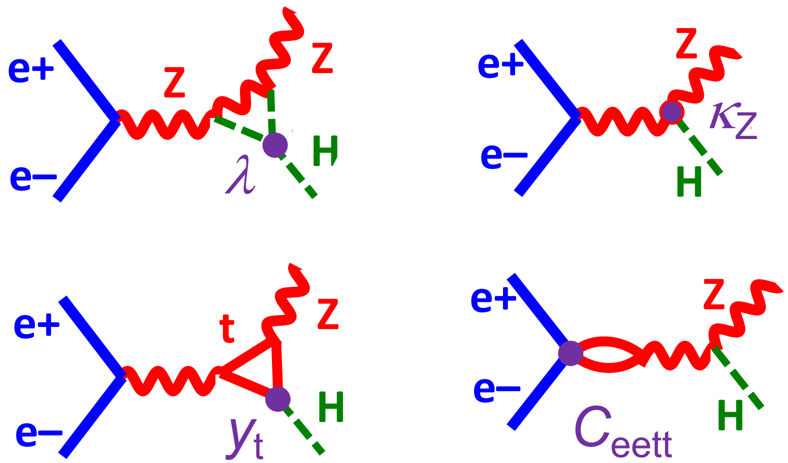
–> electroweak baryogenesis possible

Higgs self-coupling: indirect access at lower energies

◆ Important question: how well can the Higgs self-coupling λ be constrained from measurements of single Higgs bosons? – that's all that's available below ~500 GeV.

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

◆ e.g. (κ_λ–1)=1 increases σ(e^+e^-->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

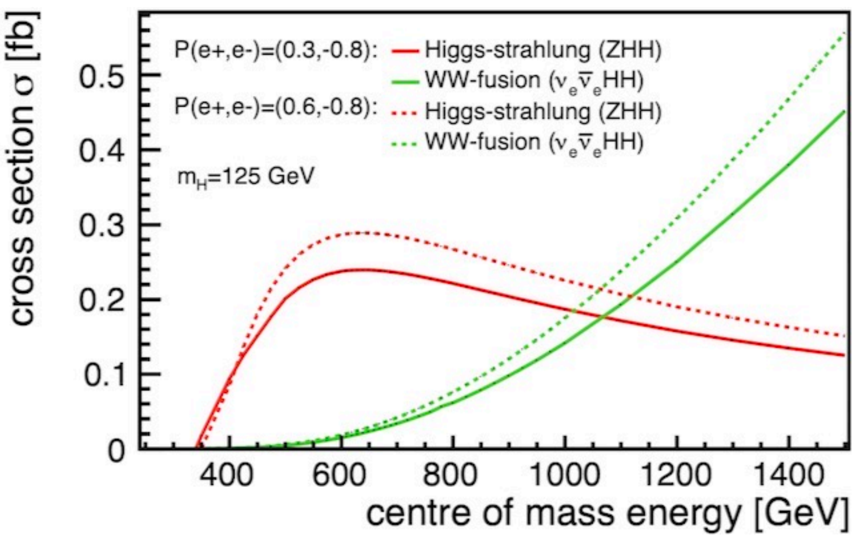
◆ ECFA Higgs@Future Colliders WG fitted single Higgs measurements, first to 1-parameter fit (SM modified only to shift of parameter κ_λ) – driven by ZH statistics

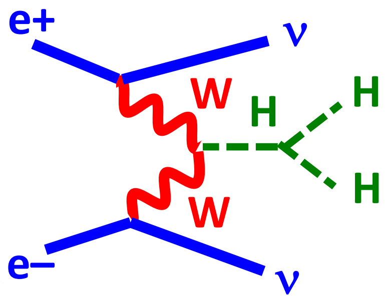
collider	1-parameter	full SMEFT
CEPC 240	18%	-
FCC-ee 240	21%	-
FCC-ee 240/365	21%	44%
FCC-ee (4IP)	15%	27%
ILC 250	36%	-
ILC 250/500	32%	58%
ILC 250/500/1000	29%	52%
CLIC 380	117%	-
CLIC 380/1500	72%	-
CLIC 380/1500/3000	49%	-

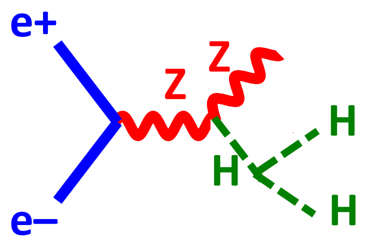
Higgs@Future Colliders 1905.03764 "-" means fit does not close

◆ 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 at ILC 500, with ~15% precision on λ,
- Adding ννHH at 1TeV brings further precision on λ

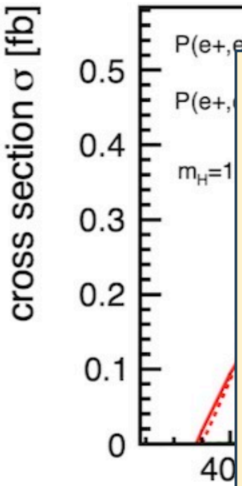
  sensitivity very dependent on b-tagging performance, dijet mass resolution etc –> *update is ongoing*

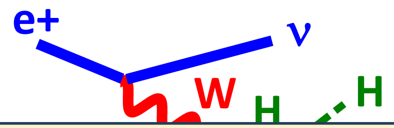
- At 1.4TeV CLIC rate-only analysis gives relative uncertainties –29% and +67% around SM value of g_{HHH}
- 3TeV differential measurement gives –8% and +11% assuming SM g_{HHWW}
- simultaneous measurement of triple and quartic couplings gives constraints below 4% in g_{HHWW} and below 20% in g_{HHH}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

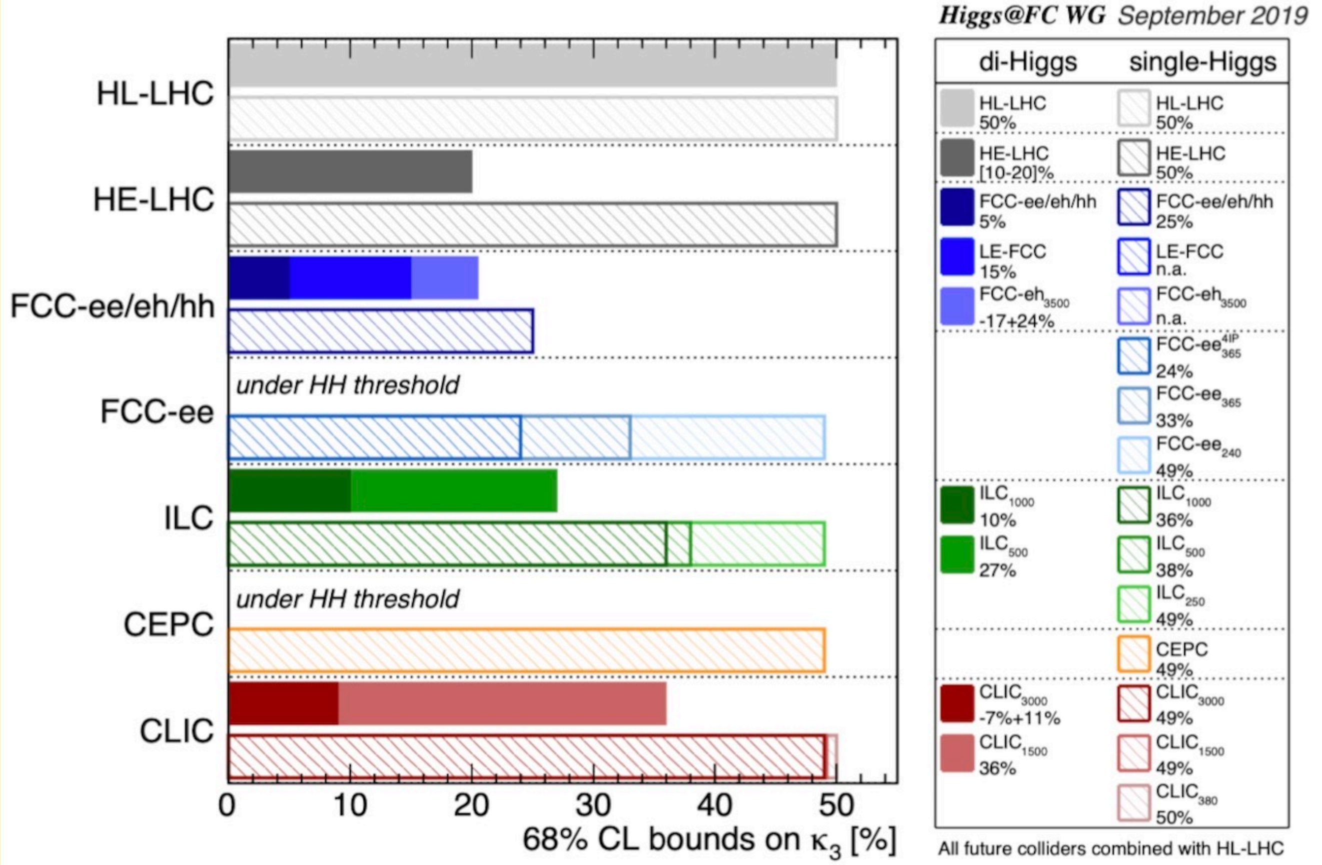
Higgs self-coupling: direct double-Higgs production





◆ Two contributing direct production mechanisms: ZHH and ννHH

–> these are the entries in the summary plot on λ from the 2019 European Strategy Briefing Book   arxiv:1910.11775



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

en
at
ner
gging
etc

◆ At 1.4 … relative u… SM value
◆ 3TeV … –8% and
◆ simult… quartic c… in g_{HHWW} and below 20% in g_{HHH} for large modifications of g_{HHWW}

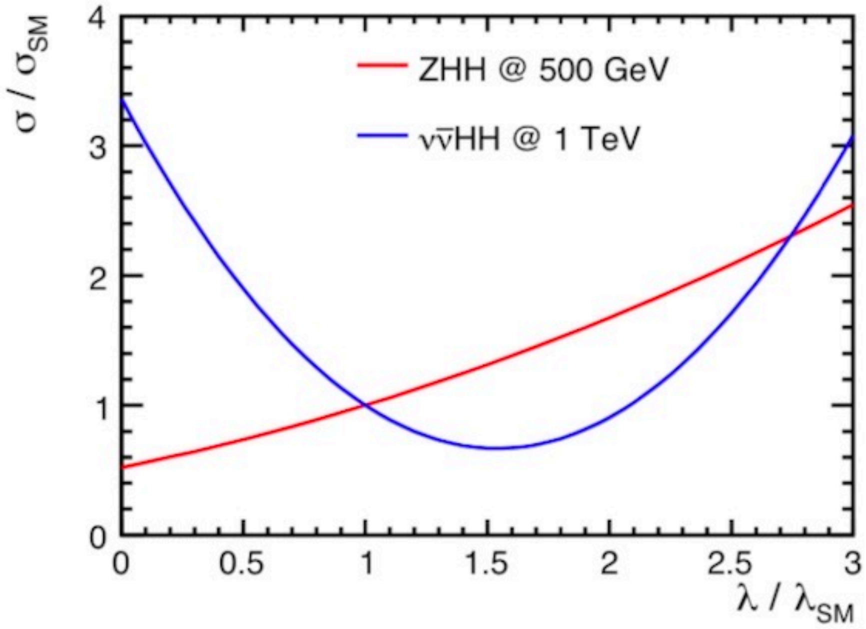
	ON	
	rate-only analysis	differential analysis

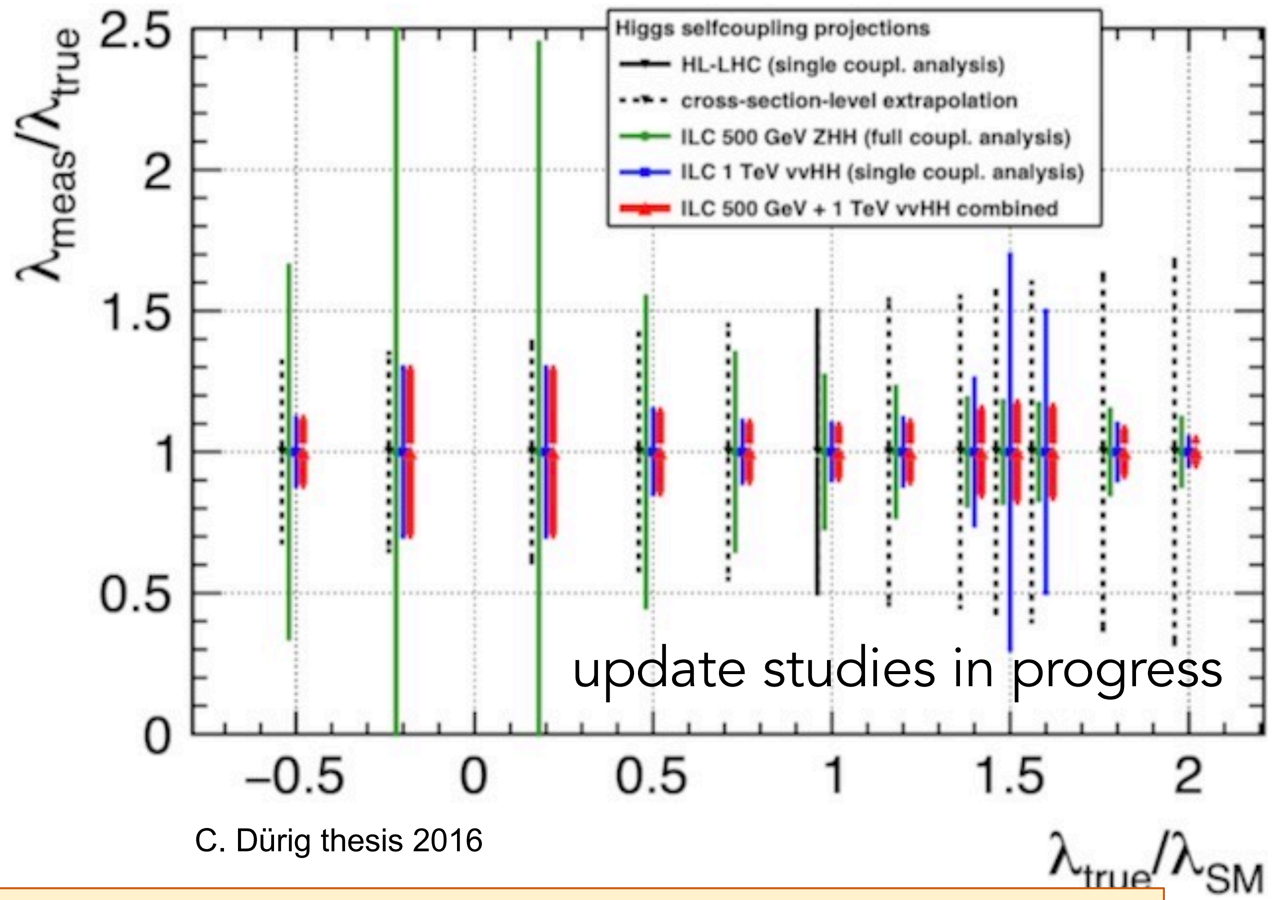
Eur. Phys. J. C 80, 1010 (2020)

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





C. Dürig thesis 2016

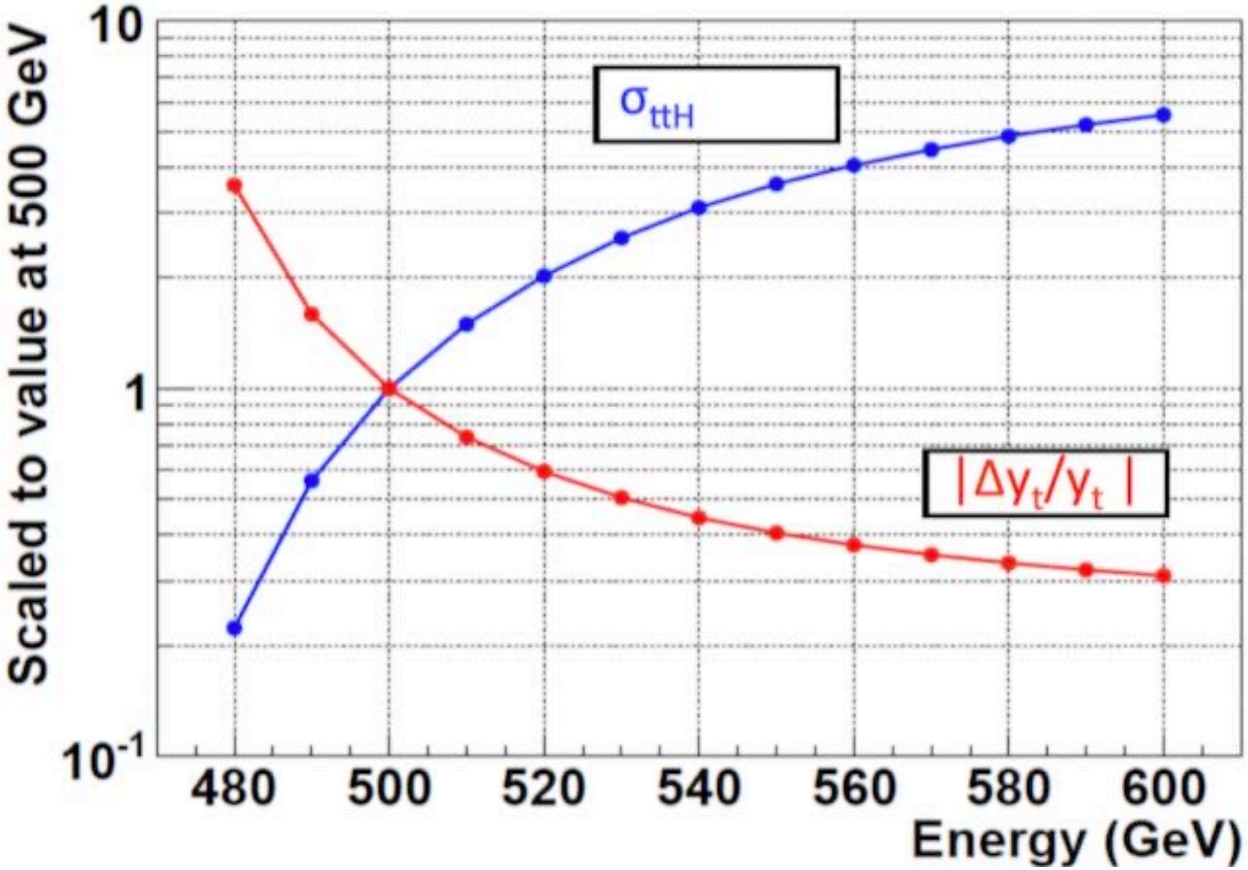
- Owing to their different behaviours, combining ZHH and ννHH gives a measurement of λ at the level of 10–15% *for any value of λ* – **strong benefit of reaching higher energies**

- 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

- Higgs is not the only physics programme at a high-energy e+e– collider; also top-quark physics, standard model electroweak, searches, …

- 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
      –> further study needed



PRD 84 (2011) 014033
arXiv:1506.07830

- full coupling structure of ttH vertex including CP can be explored using polarised beams

Future visions

Broad agreement across collider community on the physics we want to do with a next collider – everyone involved would be delighted for ***any*** Higgs factory to be realised…

However, there can be different routes to the physics:

◆ Linear Collider

– a Higgs factory as soon as possible, upgradable

– R&D for the machine beyond in parallel; no constraints imposed by the LC

– a strong diversified programme using the LC complex

Initial Linear Collider can be followed (if funding permits) by energy increases and/or independent muon and/or hadron machines with radius and magnets to be determined – can also overlap in time with hadron/muon machines

In the longer future: the civil infrastructure can be used with novel acceleration techniques e.g. plasma

◆ Circular Collider

– an integrated programme of e^+e^- and pp

– R&D for FCC-hh magnets in parallel, but large-scale civil infrastructure secured at the first stage

– larger experimental community with up to 4 interaction points (IPs)

Initial Higgs Factory civil infrastructure reused (if funding permits) for hadron machine with radius fixed; magnets to be determined. Sequential progression.

Programme fixed to ~2090s or beyond.

Needs careful thought about how best to achieve Higgs Factory and beyond
– trade-offs / risks

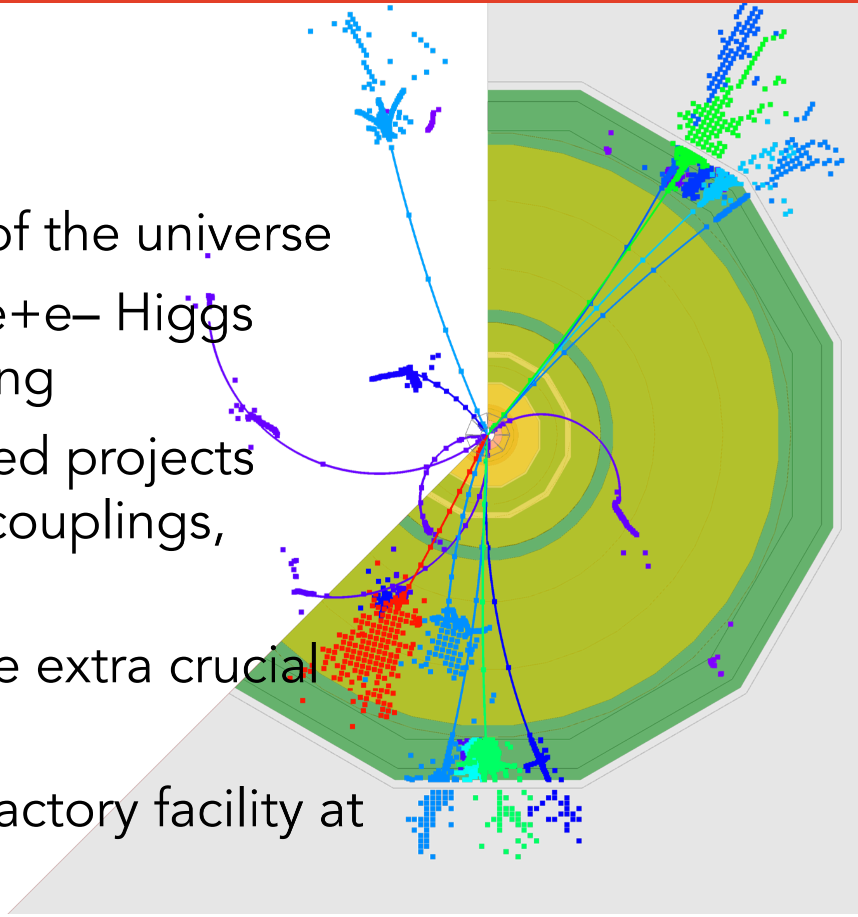
My personal view…

- We are not ready to take a decision on the next-to-next collider with O(10TeV) in parton centre-of-mass (e.g. the magnets for FCC-hh are not currently realisable and their cost is unknown; equally, technologies for different options e.g. a muon collider are immature)
- A Higgs factory should be realised as quickly as possible (following directly from HL-LHC) and given the uncertainty on the next-to-next collider, it should be as flexible as possible, after each stage giving the choice of upgrading to higher-energy e+e– collisions or moving to the next-to-next collider.
- A Linear Collider Facility at CERN fits this bill and matches the CERN budget (updated costings to be made public in March).
- A superconducting machine could be realised quickest and has the benefit of building on the wide experience that European (and other) industry has in SCRF.
- A warm machine would take several years longer preparation, but has other advantages if the timeline fits.

- A Linear Collider Facility at CERN provides a very attractive option for particle physics!

Summary

- The Higgs boson provides a completely new probe of the universe
- We will continue to learn a lot from HL-LHC, but an e+e– Higgs factory would give a qualitative step in our understanding
- Core Higgs programme common to all e+e– proposed projects provides ~order of magnitude improvement on Higgs couplings, motivated by sensitivity to new physics
- Higher energies unlock further processes and provide extra crucial physics programmes (e.g. top-quark).
- There is a chance to realise a Linear Collider Higgs Factory facility at CERN during our career-lifetimes!



Flavourful Physics and Equity, Diversity, and Inclusion

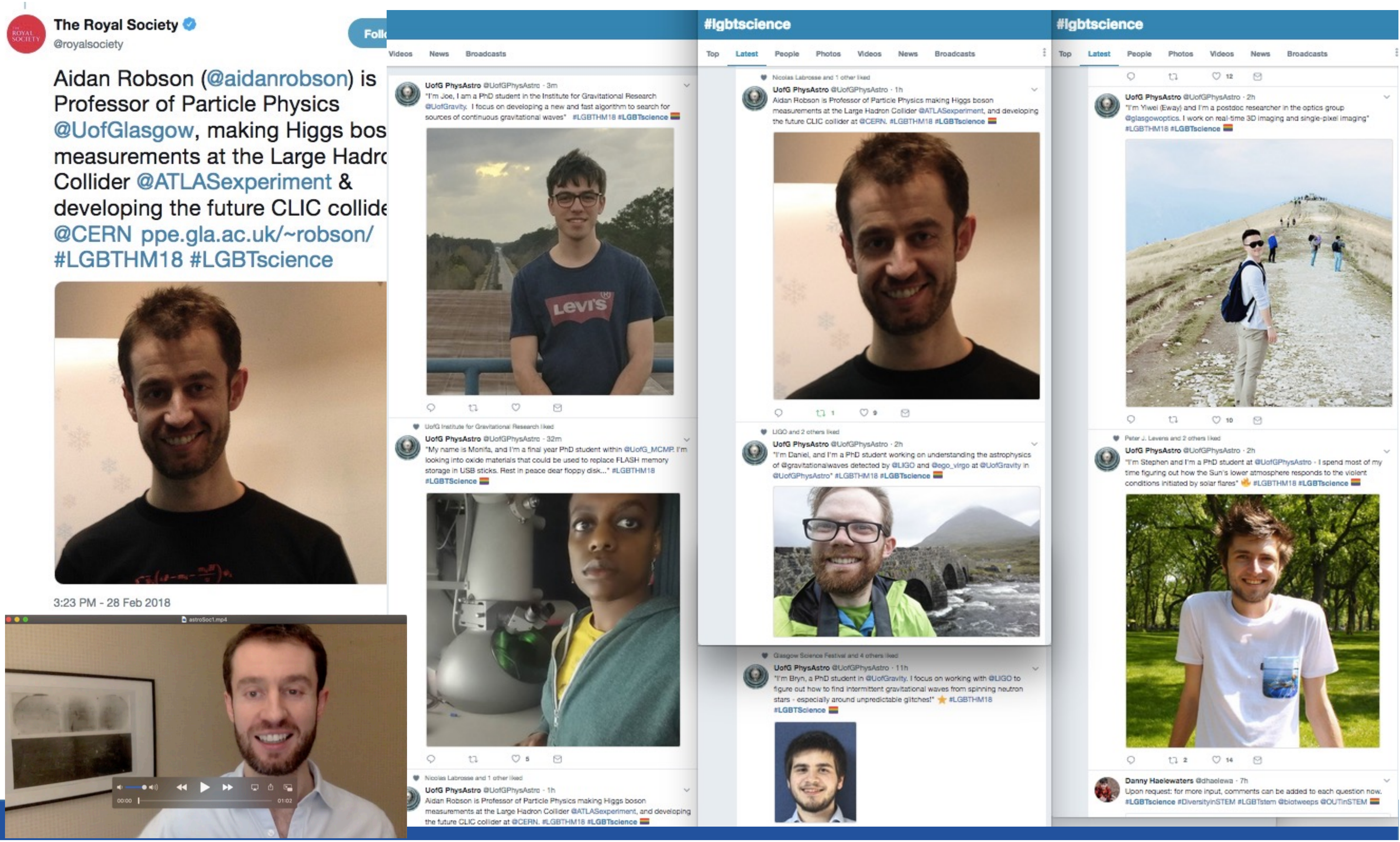
STAFF LGBT+ ROLE MODELS

The University believes individuals can inspire and empower others to change the world. Our staff Role Models share their experiences of being LGBT+ in their workplaces at the University and aim to show that being yourself should never be a barrier to success.

+ Professor Dee Heddon
+ Dr Andrew Struan
+ Mx Nicole Kipar
+ Professor Aidan Robson
+ Dr Amanda Sykes

LGBT History Month @ UofG Physics & Astronomy

UofG Physics & Astronomy 'LGBT faces' (NB, not my initiative!)



Around University of Glasgow Physics and beyond

This Office Supports Diversity in Physics

oSTEM
@ University of Glasgow

Glasgow JEDI in Physics
Justice * Equity * Diversity * Inclusion

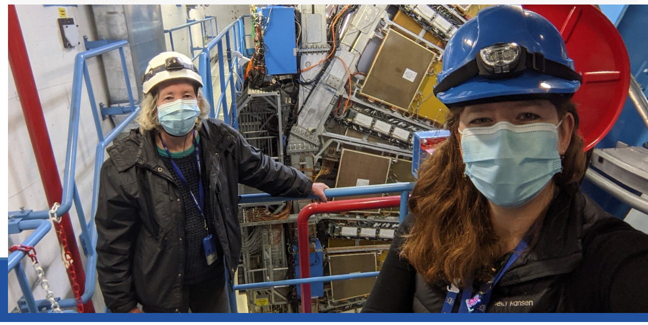
Home / University events / LGBT History Month

LGBT HISTORY MONTH

Large Hadron Collider visit with the School of Physics & Astronomy and LGBTQ CERN

Date: Wednesday 17 February 2021
Time: 13:00 - 14:00
Categories: Public lectures, Social events, Student events, Alumni events
Venue: Online
Speaker: Dr Clara Nellist, Prof Aidan Robson

Live link-up with the ATLAS Experiment at the Large Hadron Collider, for LGBT History Month



Rainbow frames around the department

Most of these are not my initiatives, but show what can happen in an inclusive environment

More widely in fundamental physics

CMS Experiment at CERN
5 July 2018
Rainbow colours today also for CMS!
Happy International #LGBTSTEMDay!

ATLAS Experiment @ATLASexperiment · May 17, 2016
On #IDAHOT, the ATLAS collaboration has a message for all LGBTQ scientists: You are welcome here! #IDAHOT2016

ATLAS EXPERIMENT
"YOU ARE WELCOME HERE!"

CLIC
@CLIC_study
The CLIC collaborations at @CERN support #LGBTSTEMDay!

CMS · LHCb · ALICE · MINERvA · ISOLDE · Medicis · µBooNE · DES · DUNE · LIGO · Belle II · IceCube South Pole Neutrino Observatory · LArIAT

CERN
4 890 Tweets

Abonné

CERN
@CERN
#CERN, the European Organization for Nuclear Research, is the world's largest particle physics lab, home of the #LHC.
French: @CERN_FR
Traduire la biographie
Geneva · home.cern · A rejoint Twitter en juin 2008
439 abonnements · 2,5 M abonnés
Suivi par Harriet Watson, Andrea Knue et 372 autres personnes que vous suivez

Tweets | Tweets et réponses | Médias | J'aime

Tweet épinglé
CERN @CERN · 2h
Today for #LGBTSTEMDay/#LGBTQSTEMday, we join friends around the world to celebrate the presence and important contributions of LGBTQ+ people across all STEM disciplines!

Find out more: prideinstem.org/lgbtstemday/


Living D
Everyday
10 KM
CAROUGE
UMASS
80
CERN Relay Race 2019


FREE
CUPCAKES


LGBTQ
CERN
plus de couleurs,
plus de saveurs
LGBTQ
CERN
la refraction
en action
LGBTQ
CERN
Without colors,
there's no
strong interaction.
LGBTQ
CERN
Nous sommes
chromodynamiques.
LGBTQ
CERN
We're
Chromodynamic

But things can also go backwards…

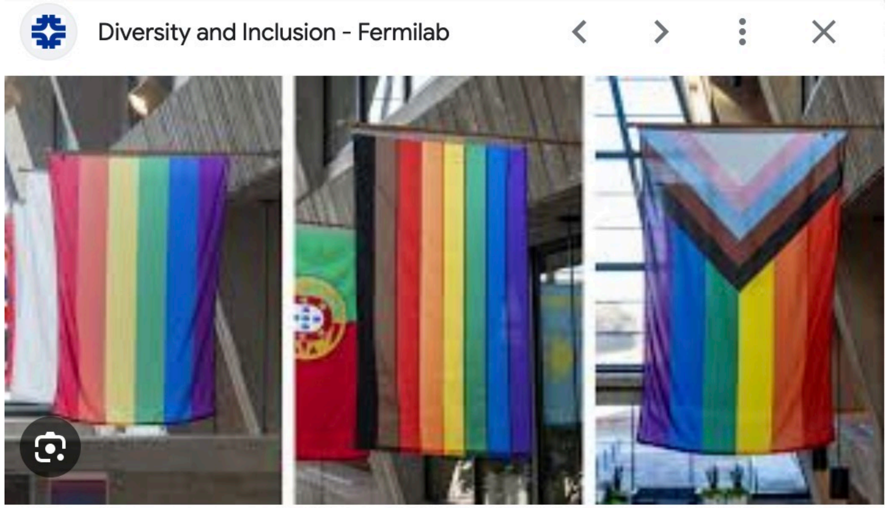
Fermilab
@Fermilab

Happy #PrideMonth!

Did you know that the #pride flag is displayed year-round in Fermilab's Wilson Hall?
Traduire le post

8:20 PM · 8 juin 2021

In the past



https://diversity.fnal.gov/edia-recognition-awards/ Search

For the last
2 weeks

Hmm. We're having trouble finding that site.

We can't connect to the server at diversity.fnal.gov.

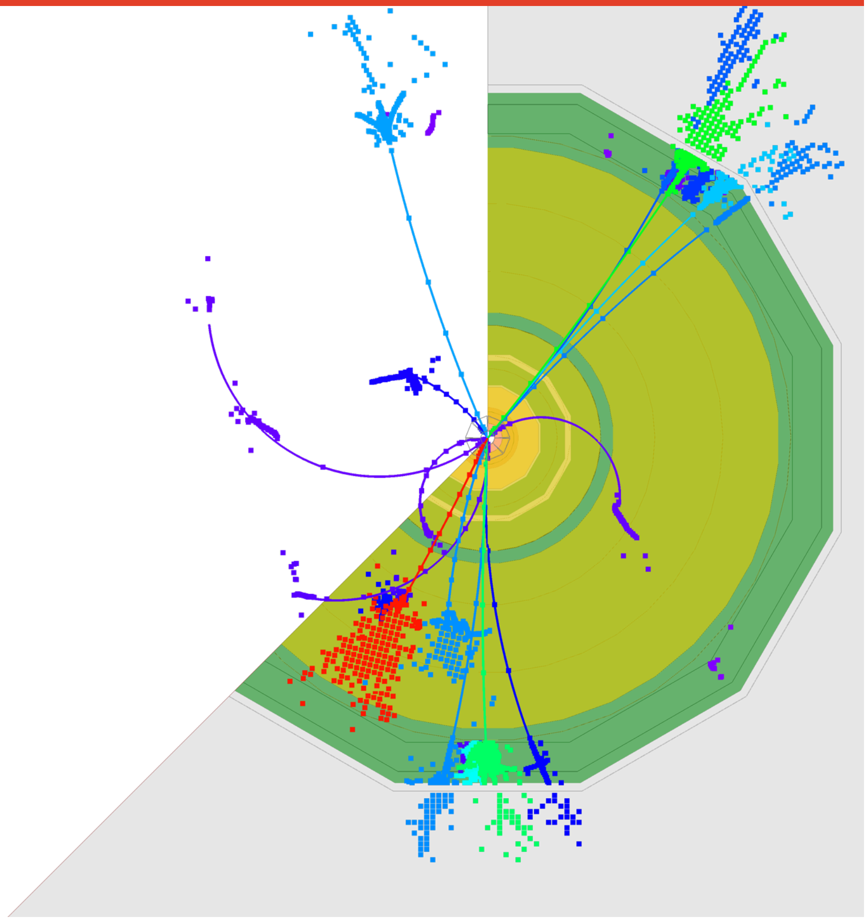
If you entered the right address, you can:

- Try again later
- Check your network connection
- Check that Firefox has permission to access the web (you might be connected but behind a firewall)

Try Again

=> let's keep on embedding EDI, for everybody's benefit!


Thank you!



Menu of physics to be covered?

- 91 GeV –> precision EW
- 250 GeV –> precision Higgs mass and Higgs branching fractions
- 350 GeV –> precision top quark mass (threshold scan)
- 550–600 GeV –> double Higgs-strahlung
  -> ZHH, top electroweak couplings, precision WW –> H fusion
- 800–1000 GeV –> double Higgs from WW fusion
  -> ννHH, precision top Yukawa and CP
- beyond: pure exploration

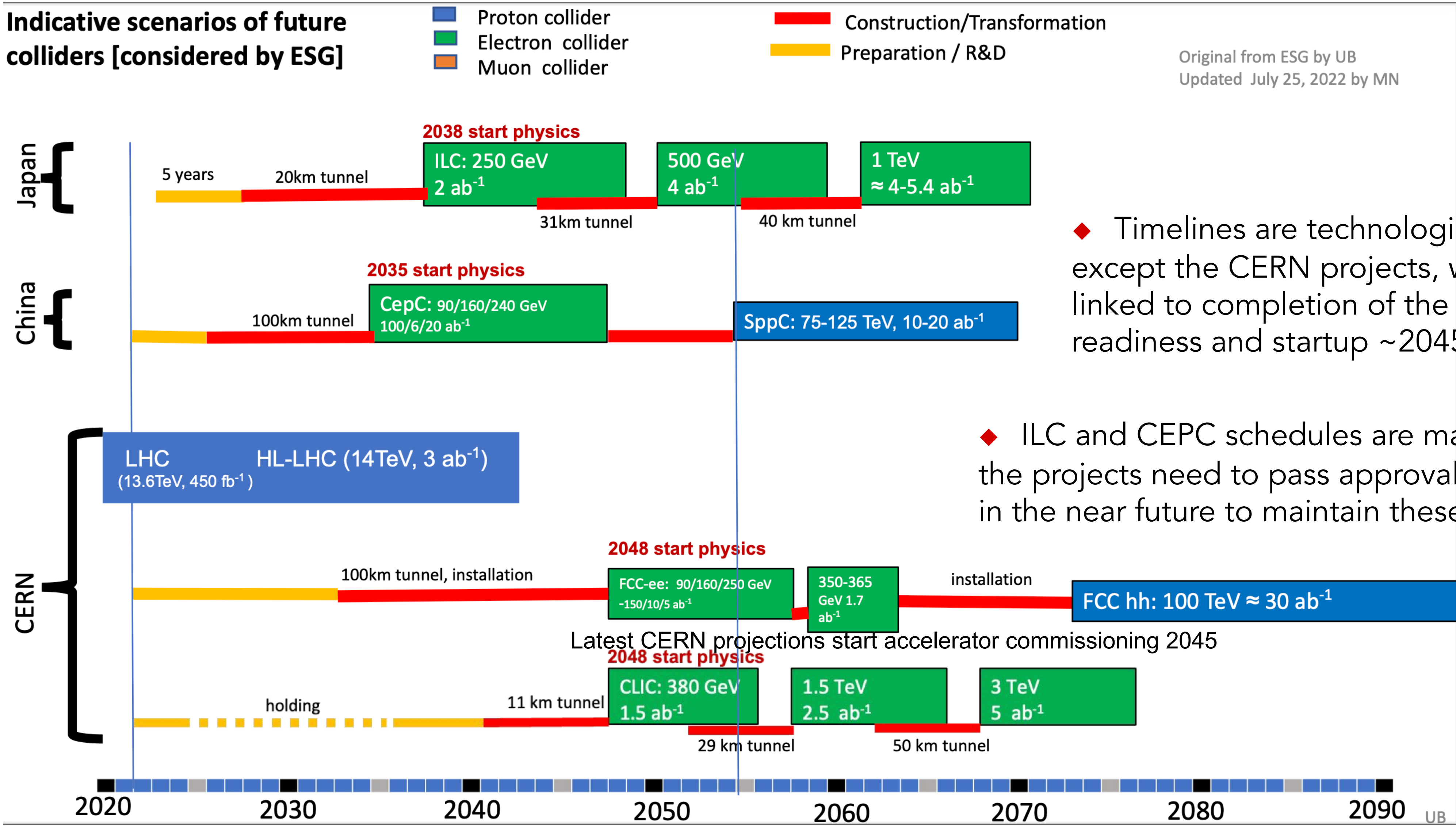
Broad agreement that we want to do all of this physics

Different proposals take different approaches:
ILC/C^3 proposal runs at each energy;
CLIC proposal consolidates Higgs & top to 380GeV then >1TeV;
FCC puts some parts with hh.

- **Strategic question 1:**
  – how much of the programme should be done with the next machine (e^+e^-) ?
  – or are we prepared to wait for the next-to-next (hh or μμ) ?

Timelines?

◆ **Strategic question 2:**
– how long are we prepared to wait for aspects of the physics programme?



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

◆ ILC and CEPC schedules are mature, but the projects need to pass approval processes in the near future to maintain these schedules

Sustainability?

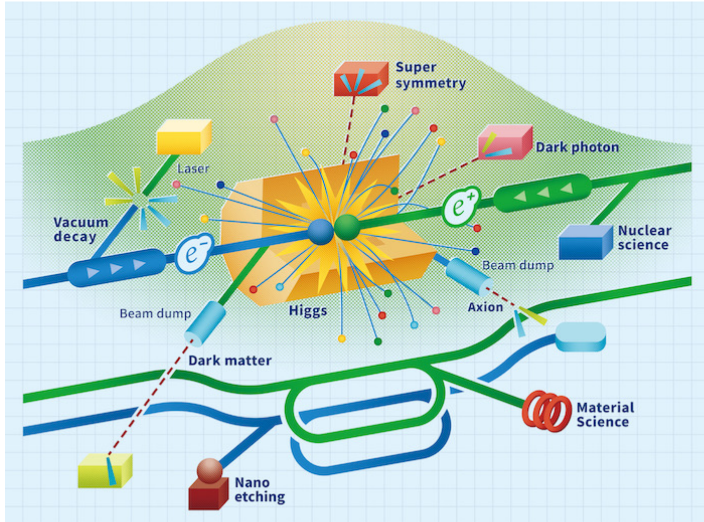
◆ **Strategic question 3:**
– when/how to fold in environmental considerations?

Power:
Projects working on improving power efficiency

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

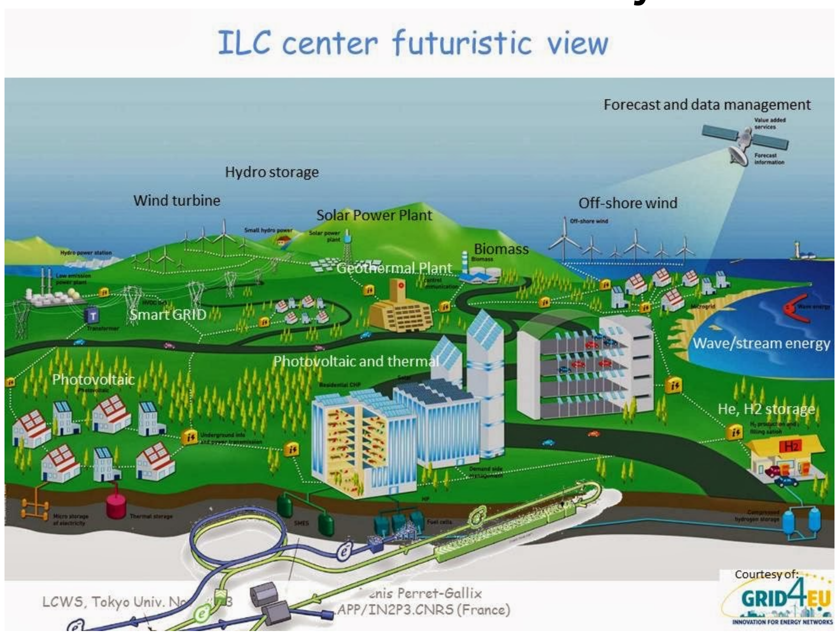
– what should be the metric?

Proposal Name	Power Consumption (MW)
FCC-ee (0.24 TeV)	290
CEPC (0.24 TeV)	340
ILC (0.25 TeV)	140 *
CLIC (0.38 TeV)	110
ILC (3 TeV)	~400
CLIC (3 TeV)	~550



Full use of infrastructures – all projects
FCCee considering:
– electrons from injector to beam-dump
– extracting electrons from booster
– use of synchrotron photons

Towards 'Green ILC': similarly @ CERN



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

Assesses Global Warming Potential of underground civil engineering – raw materials, transport, construction activities

CLIC 380GeV:
127kton CO_2-eq (two-beam option)
290kton CO_2-eq (klystron option)

ILC 250GeV:
266kton CO_2-eq

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

Now commissioning extended study to account for accelerator components & detectors

Flexibility?

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

- Looking ahead to the next-to-next machine:
  – are we ready to make the decision now on the next-to-next machine?
  – is FCC-hh definitely realisable at an achievable cost? (magnets?)
  – what is the timescale for currently-developing technologies to mature? and should we leave space for them to enter?
  (muon collider? plasma wakefield acceleration?)

Flexibility?

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

- Looking ahead to the next-to-next machine:
  – are we ready to make the decision now on the next-to-next machine?
  – is FCC-hh definitely realisable at an achievable cost? (magnets?)
  – what is the timescale for currently-developing technologies to mature?
  and should we leave space for them to enter?
  (muon collider? plasma wakefield acceleration?)

- Linear machines are intrinsically flexibile in their run scenarios
  –> allows to adapt to external factors (physics landscape / budgetary)
  and postpone decision on next-to-next machine

- NB, linear options studied in detail are 'just' benchmarks;
  CLIC could be built with initial stage at 250, or a stage at 500;
  (or ILC could be built at 380)
  –> these are physics choices to be made
  And e.g. ILC could be built in Europe

Staging optimisation example:
CLIC baseline run plan is optimised to move to TeV energies quickly, but core Higgs coupling sensitivities can be achieved with CLIC just running longer at first stage

	Benchmark	HL-LHC	HL-LHC + CLIC		HL-LHC + FCC-ee	
			380 ($4\,ab^{-1}$)	380 ($1\,ab^{-1}$) + 1500 ($2.5\,ab^{-1}$)	240	365
$g^{eff}_{HZZ}[\%]$	$SMEFT_{ND}$	3.6	0.3	0.2	0.5	0.3
$g^{eff}_{HWW}[\%]$	$SMEFT_{ND}$	3.2	0.3	0.2	0.5	0.3
$g^{eff}_{H\gamma\gamma}[\%]$	$SMEFT_{ND}$	3.6	1.3	1.3	1.3	1.2
$g^{eff}_{HZ\gamma}[\%]$	$SMEFT_{ND}$	11.	9.3	4.6	9.8	9.3
$g^{eff}_{Hgg}[\%]$	$SMEFT_{ND}$	2.3	0.9	1.0	1.0	0.8
$g^{eff}_{Htt}[\%]$	$SMEFT_{ND}$	3.5	3.1	2.2	3.1	3.1
$g^{eff}_{Hcc}[\%]$	$SMEFT_{ND}$	–	2.1	1.8	1.4	1.2
$g^{eff}_{Hbb}[\%]$	$SMEFT_{ND}$	5.3	0.6	0.4	0.7	0.6
$g^{eff}_{H\tau\tau}[\%]$	$SMEFT_{ND}$	3.4	1.0	0.9	0.7	0.6
$g^{eff}_{H\mu\mu}[\%]$	$SMEFT_{ND}$	5.5	4.3	4.1	4.	3.8
$\delta g_{1Z}[\times 10^2]$	$SMEFT_{ND}$	0.66	0.027	0.013	0.085	0.036
$\delta\kappa_\gamma[\times 10^2]$	$SMEFT_{ND}$	3.2	0.032	0.044	0.086	0.049
$\lambda_Z[\times 10^2]$	$SMEFT_{ND}$	3.2	0.022	0.005	0.1	0.051

CLIC longer ($4ab^{-1}$) first stage
CLIC baseline: $1ab^{-1}$+1.5TeV

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Cost, community, and scenarios?

- **Strategic question 5:**
  - when/how to fold in cost considerations?
    - how to consider 'loss of opportunity' if money spent on one thing not others?

Cost

ILC 250: ~5 BCHF

CLIC:
380GeV: 5.9 BCHF
to 1.5 TeV: add 5.1 BCHF
to 3 TeV: add 7.3 BCHF

Cost

FCC-ee (to $\sqrt{s}$=365): ~11.6 BCHF

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

NB these are the costings presented at the last European Strategy; they are all being updated. This is a set of costings that can be compared

- **Strategic question 6:**
  - how to we wish to see the (collider) particle physics community evolving?
    - concentrated in one large project or allowing room for more, smaller experiments?
      - FCC-ee up to 4 IPs; LCs up to 2 expts via (ILC) push-pull or (CLIC) 2 IPs

- **Strategic question 7:**
  - what should Europe do in the case that CEPC goes ahead?
    - extent to which it would be possible to participate?
    - or enter into a 'race' for a circular machine?
    - or do something complementary e.g. higher $\sqrt{s}$ e+e– ?