Physics at Future colliders: overview & recent exp. developments

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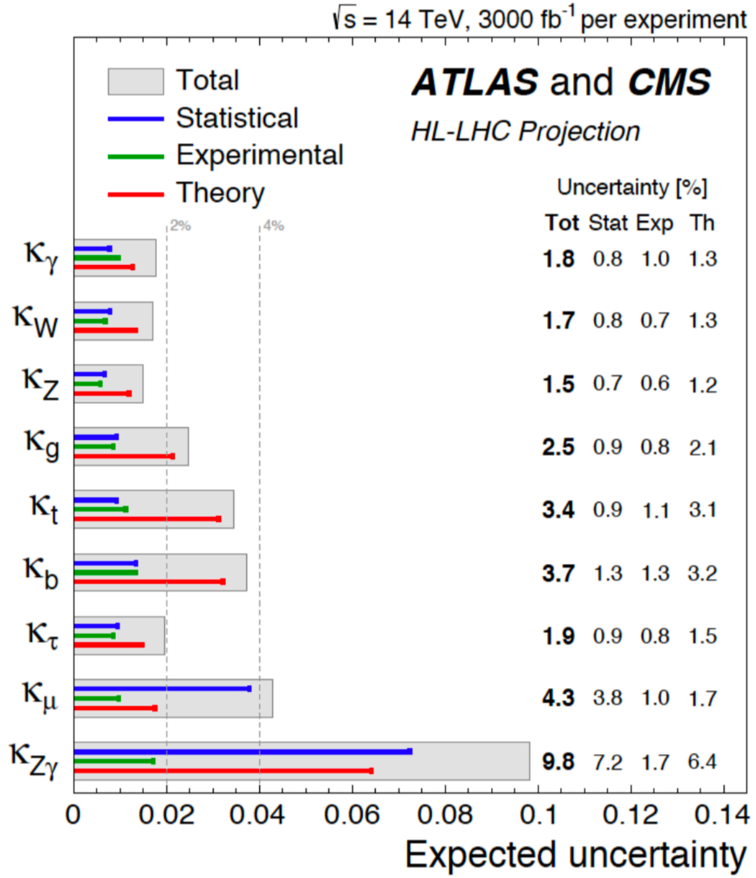
September 14, 2022

- Emphasis on future e^+e^- and pp colliders
- Strong emphasis on measurements pertaining to the Higgs sector

Physics goals of colliders after HL-LHC



- Explore in detail the Higgs properties
  understand the deep origin of EWSB

  Beyond HL-LHC measurements:
  - Couplings to fermions to %-level
  - to bosons to per-mil
  - self-coupling
  - Invisible decays
  - BSM Higgses

- Extend sensitivity to physics beyond the SM. Could have been missed at LHC because:
  - Weakly coupled or elusive signatures
    - More statistics, better sensitivity
  - Too heavy
    - Imprints of NP in high precision measurements
    - Direct: higher √s

Future Collider projects

Consensus in the community: post HL-LHC collider should be a “Higgs factory”.
Multi-TeV scale to be studied next.

- Linear e^+e^- collider
  - ILC / C3 [International Linear Collider / Cool Copper Collider]
    - Start explore the Higgs at 250 GeV, upgradable to 500 GeV (and 1 TeV)
  - CLIC [Compact Linear Collider]
    - Start explore the Higgs at 380 GeV, upgrades to 1.5 TeV and 3 TeV
  - Both may include runs at lower energy

- Circular e^+e^- collider
  - FCC-ee / CEPC [Future Circular Collider / Circular Electron Positron Collider]
    - Broad range of energies: from the Z peak to about 365 GeV
    - Explore the Higgs at O(250 GeV) and 350-365 GeV
    - Upgradable to O(100 TeV) pp collider in same tunnel

- e-p collider
  - LHeC at $\sqrt{s}$ ~ 1.6 TeV, or FCC-ep

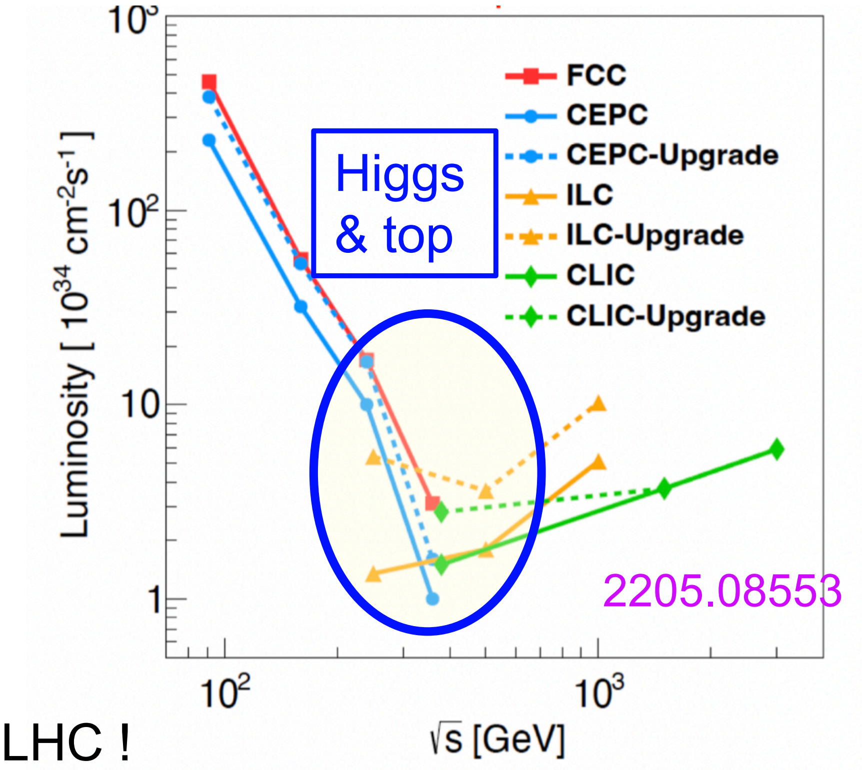
- Muon collider
  - $\sqrt{s}$ = 125 GeV or O(TeV). Upgradable to O(10 TeV).

- High-energy pp collider
  - FCC-hh, 100 TeV. second stage of the FCC project. Also CEPC → SppC

Zoom on future e^+e^- projects

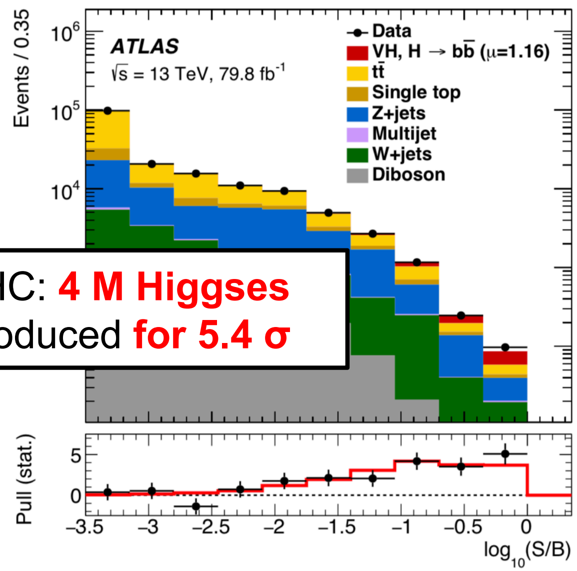
- Could start in 2035 – 2045
- 15 – 25 years depending on the projects
- Different running plans, but all projects plan integrated luminosities of a few ab^{-1} at each $\sqrt{s}$ point above ZH threshold

> - O(1 M) Higgs bosons produced
> - O(1 M) ttbar pairs

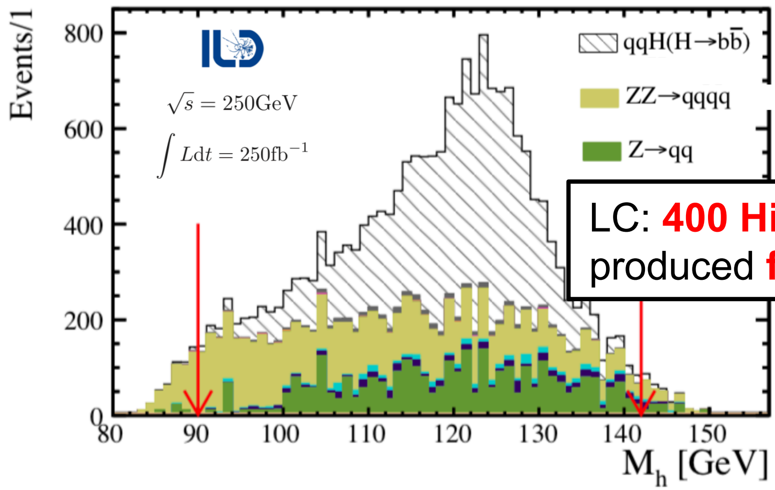


"Higgs factories" ?? > 100 M Higgses at HL-LHC !

But O(each) Higgs produced in e+e- is useful. Example: observation of Hbb



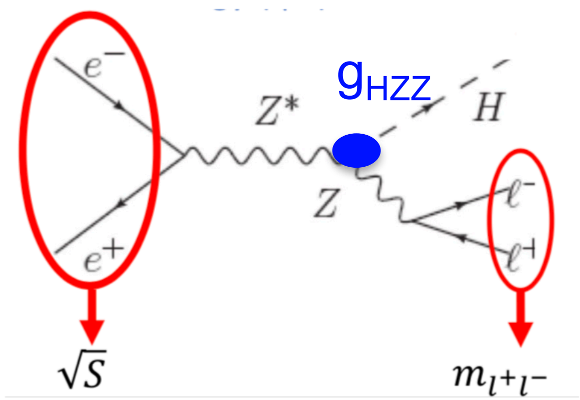
LHC: **4 M Higgses** produced **for 5.4 σ**



LC: **400 Higgses** produced **for 5.2 σ**

[J Tiang, LCWS 2018]

Key process in e^+e^- Higgs factories: Higgsstrahlung



$\sigma(ZH) \propto g^2_{HZZ}$

Max. σ at √s = 250 GeV : σ ≈ 200 fb

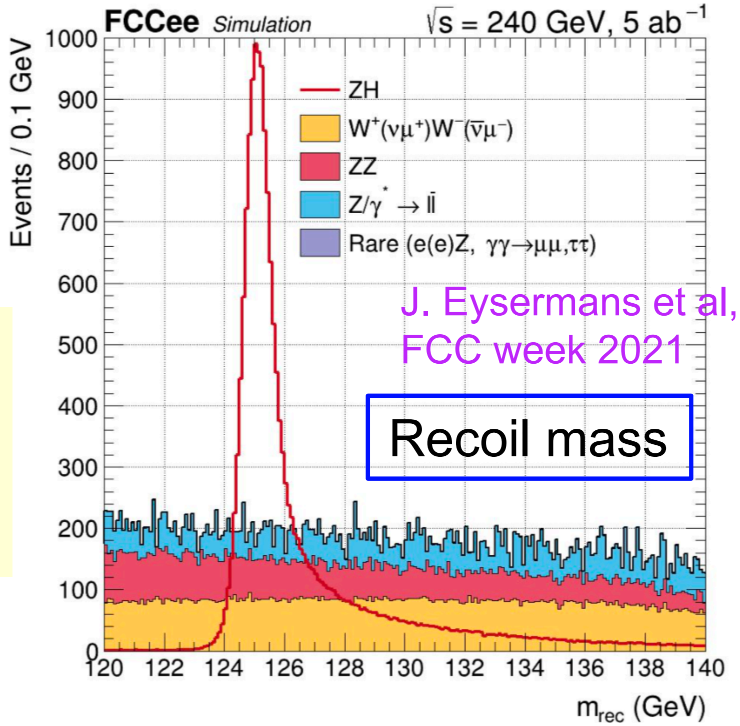
ZH events tagged by the Z, without reconstructing the Higgs decay. Unique to lepton colliders.

e.g. when Z → leptons :

$$m^2_{\text{recoil}} = s + m^2_{\ell\ell} - 2\sqrt{s}(E_{\ell^+} + E_{\ell^-})$$

A fit to the recoil mass distribution allows:

- ❑ A measurement of σ(ZH) independent of the Higgs decay mode. Hence an absolute deterrmination on g_{HZZ}
- ❑ A precise measurement of the Higgs mass



- Easiest case: Z → lep.
- Z → had: careful design of the analysis needed to ensure that the measured σ(ZH) is independent from BR(Higgs → jets).

Model-independent determination of Higgs couplings

- Once g_{HZZ} is known: measure σ x BR for specific Higgs decays

$$\sigma_{\mathrm{ZH}} \times \mathcal{B}(\mathrm{H} \rightarrow \mathrm{X\overline{X}}) \propto \frac{g^2_{\mathrm{HZZ}} \times g^2_{\mathrm{HXX}}}{\Gamma_{\mathrm{H}}}$$

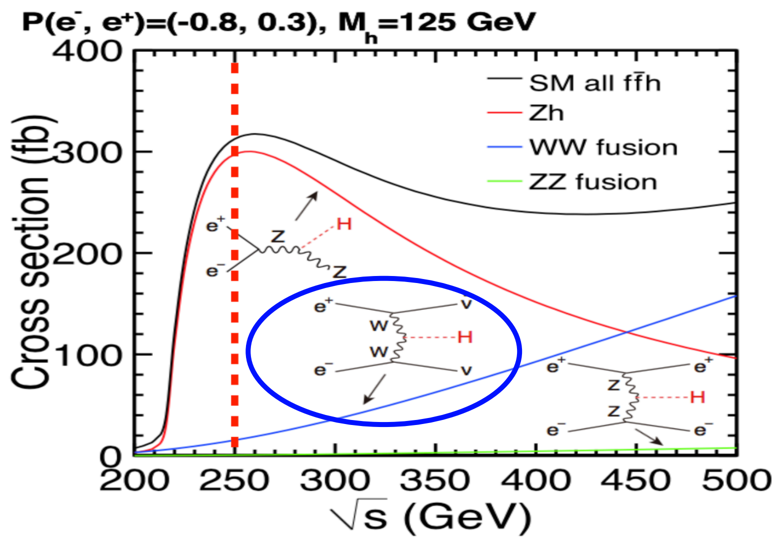
- H → ZZ* provides Γ_H
- H → XX provides g_{HXX}

Hence a model-indep determination of Higgs couplings.

NB: ZH with recoil against "nothing" gives Γ(H → inv)
recoil against "funny" gives Γ(H → exo)

- Data at higher energy bring important additional observables:

$$\sigma_{\mathrm{H}\nu_e\bar{\nu}_e} \times \mathcal{B}(\mathrm{H} \rightarrow \mathrm{X\overline{X}}) \propto \frac{g^2_{\mathrm{HWW}} \times g^2_{\mathrm{HXX}}}{\Gamma_{\mathrm{H}}}$$



- In practice: Higgs couplings and Γ_H extracted from a global fit to all σ x BR measts
  - Kappa framework
  - SMEFT framework
    - The fit includes electroweak measurements in that case (more later)

Higgs couplings at other future colliders

- ep collisions : with 2 ab^{-1}, LHeC (FCC-eh) produces 0.5 M (2 M) Higgs bosons via VBF
  - Much cleaner than pp, e.g. can access Hcc
  - Good determination of g_{HWW}
  - drawback : no model-independent determination of the couplings & the width

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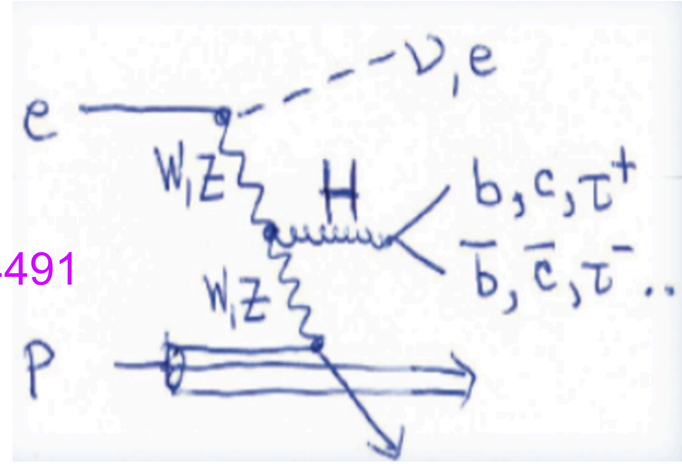


- Muon collider:
  - No point in √s = 250 GeV (far too less lumi w.r.t. e^+e^-)
  - High energy μCol (e.g. √s = 3 TeV, 10 TeV):
    - Higgs produced via VBF – mostly WW
    - E.g. 10M Higgses at 10 TeV, 10 ab^{-1}
    - No model-independent determination of the couplings and width
  - Run at the Higgs pole : √s = 125 GeV
    - μμ → H : lineshape scan could determine Γ_H to % level
      - From O(10^5) Higgs events with a few fb^{-1}
      - Hence absolute determination of couplings when combined with HL-LHC - or with high stat. measurements at high √s μCol
    - Provided the machine can deliver a very small beam energy spread !
      - $\Delta E / E \sim \Gamma_H / E \sim 3\ 10^{-5}$ challenging…

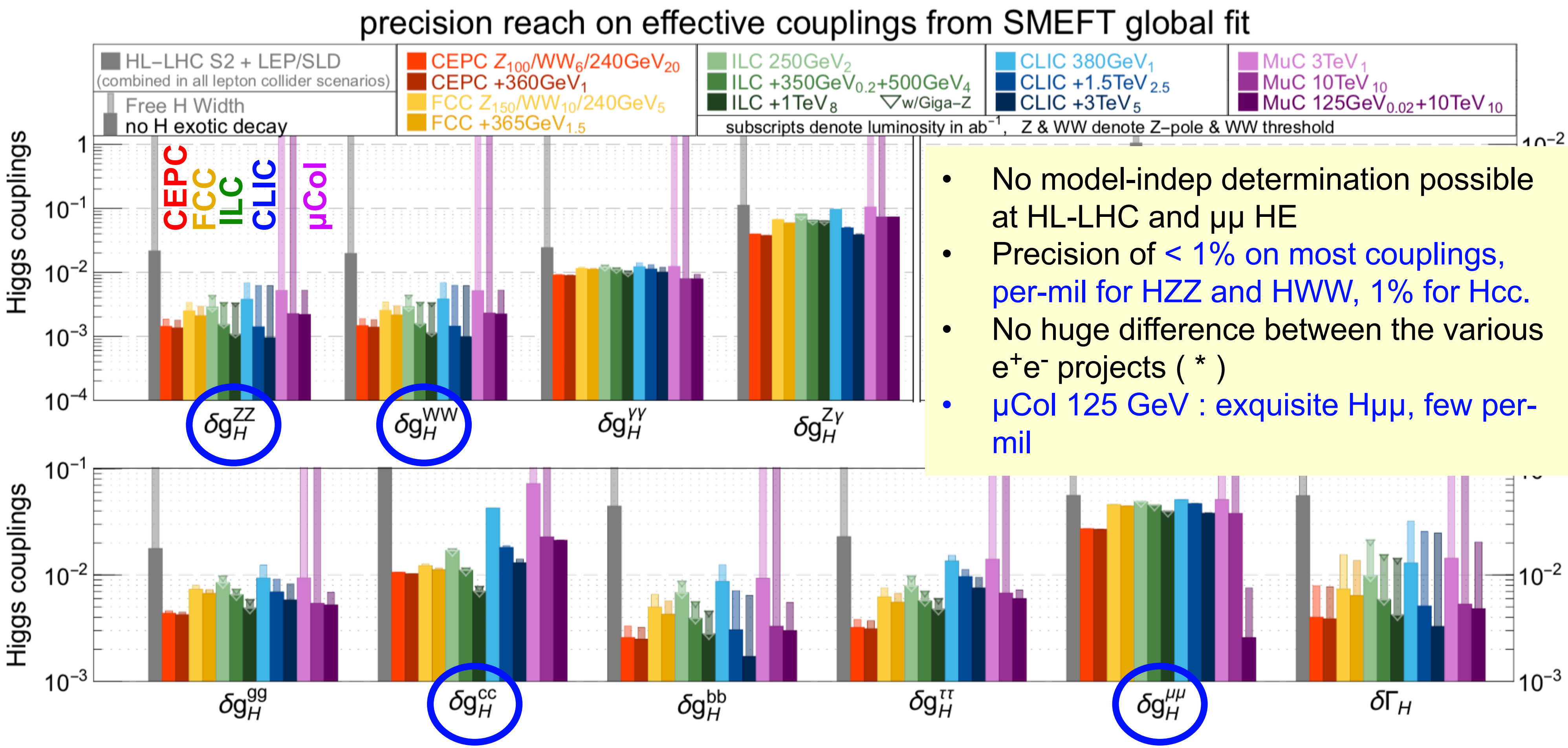
2203.07256

Higgs couplings from global fits

Example fit from arXiv:2206.08326, SMEFT framework

- Thin (thick) bars: Free (constrained) Γ_H
- Future colliders combined with HL-LHC

Input Higgs measurements: main difference w.r.t. ESU is the updated CEPC running scenario (20 ab-1 instead of 5 ab-1)



- No model-indep determination possible at HL-LHC and μμ HE
- Precision of < 1% on most couplings, per-mil for HZZ and HWW, 1% for Hcc.
- No huge difference between the various e^+e^- projects (*)
- μCol 125 GeV : exquisite Hμμ, few per-mil

(*) Some projects need less years than others to reach this precision.

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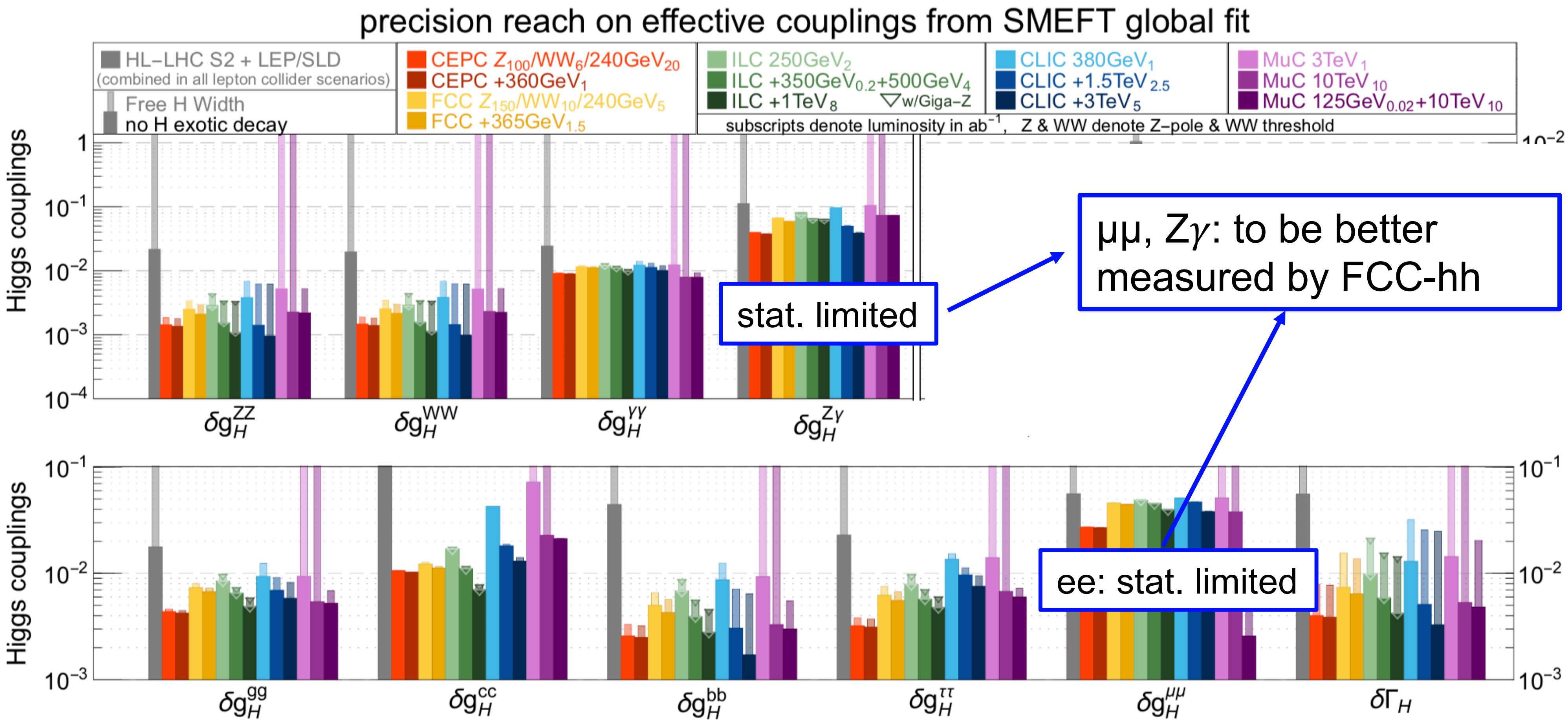


Stat. limited couplings: further improvements from FCC-hh

pp, $\sqrt{s}$ ~ 100 TeV, integrate 30 ab^{-1} : - 2 10^{10} Higgs bosons, 200x HL-LHC
- 1 M Higgses at p_T > 1 TeV (higher S/B, smaller systs)

pp does not measure $\Gamma(H \to X)$ but σ_{prod} x BR(X). But model-independent determination of the couplings through ratios of BRs :

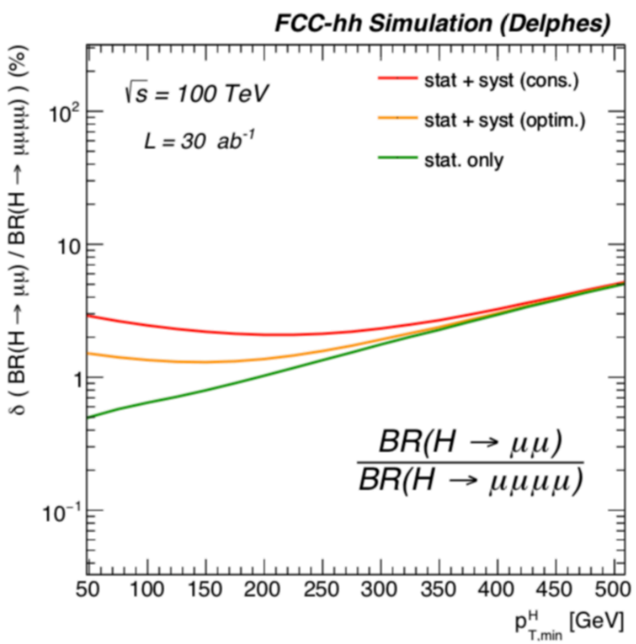
$$BR(H \to X) / BR(H \to ZZ^*) \approx g^2_X / g^2_{HZZ}$$

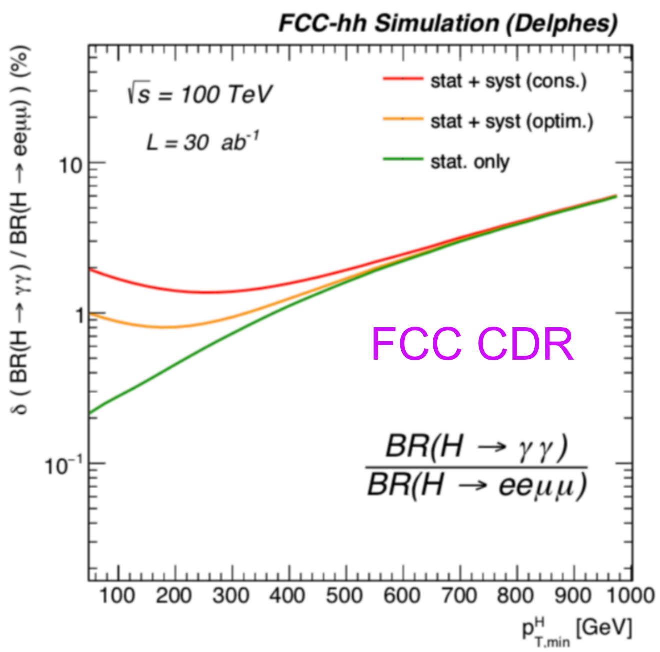
Complementarity (FCC-)ee & FCC-hh

where g_{HZZ} is known to << 1% thanks to ee measurements !

Cancelation of correlated systematic uncertainties (lumi, σ_{prod}, etc)

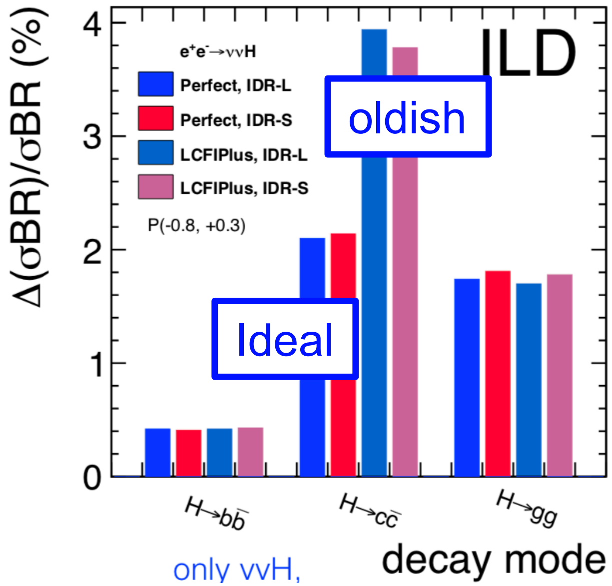
Leads to < 1 % precision on μμ, γγ, Zγ from this combination of FCC-hh and e+e-





Hcc and recent progress on jet flavour tagging

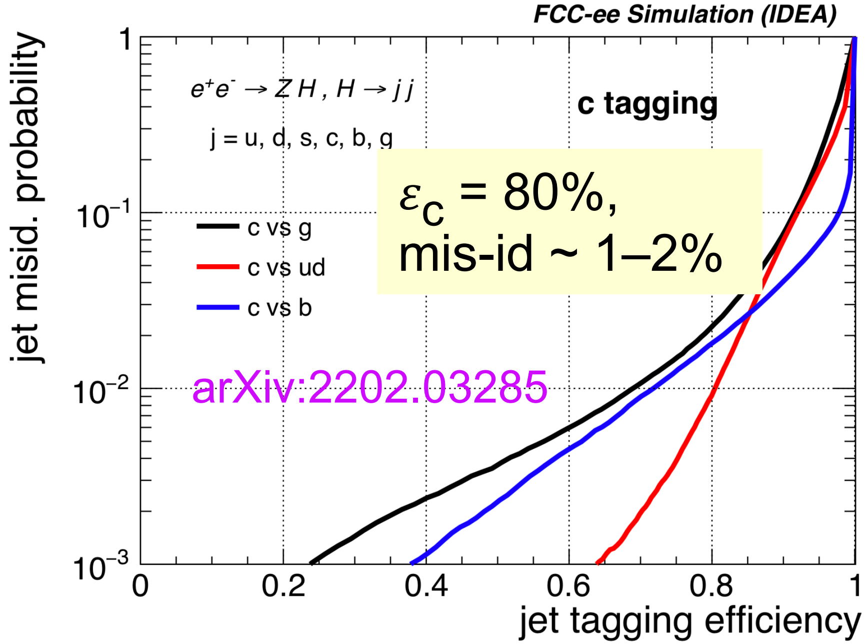
- Tagging of b, c and g jets: key to the measurements of hadronic Higgs BRs
  - e^+e^- projections shown earlier rely on tagging performance from old-ish algorithms
  - Large room for improvement for σ x BR(cc)



- State-of-the-art flavour-tagging algorithm developed recently in the context of FCC-ee. Exploits experience gained at the LHC.
  - Advanced machine learning (Dynamic Graph Convolutional Neural Network).

- Very promising performance
  - Mis-id efficiency lower by O(10) compared to traditional approaches

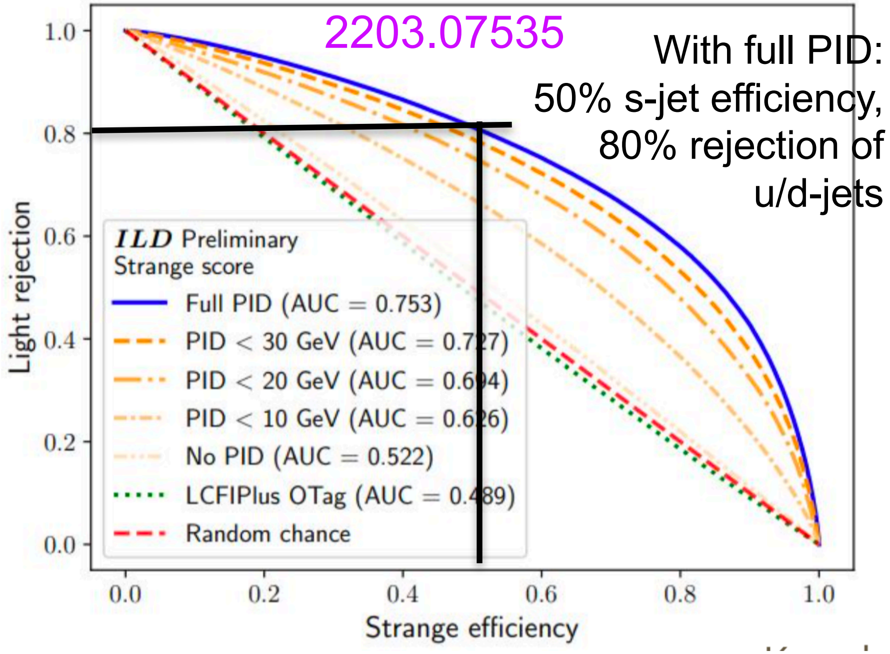
- At FCC / CEPC : optimisations ongoing
  - E.g. smaller beam-pipe compared to CDR designs, further improves c-tagging performance.



Strange tagging and Higgs to s ?

Recent analysis efforts, using advanced NNs.
Handles:

- often a K^+ in a s jet with a relatively large fraction of the jet momentum
  → PID (K / π separation) crucial
  → up to large momentum !
- K^0_s and Λ's reconstruction also helps

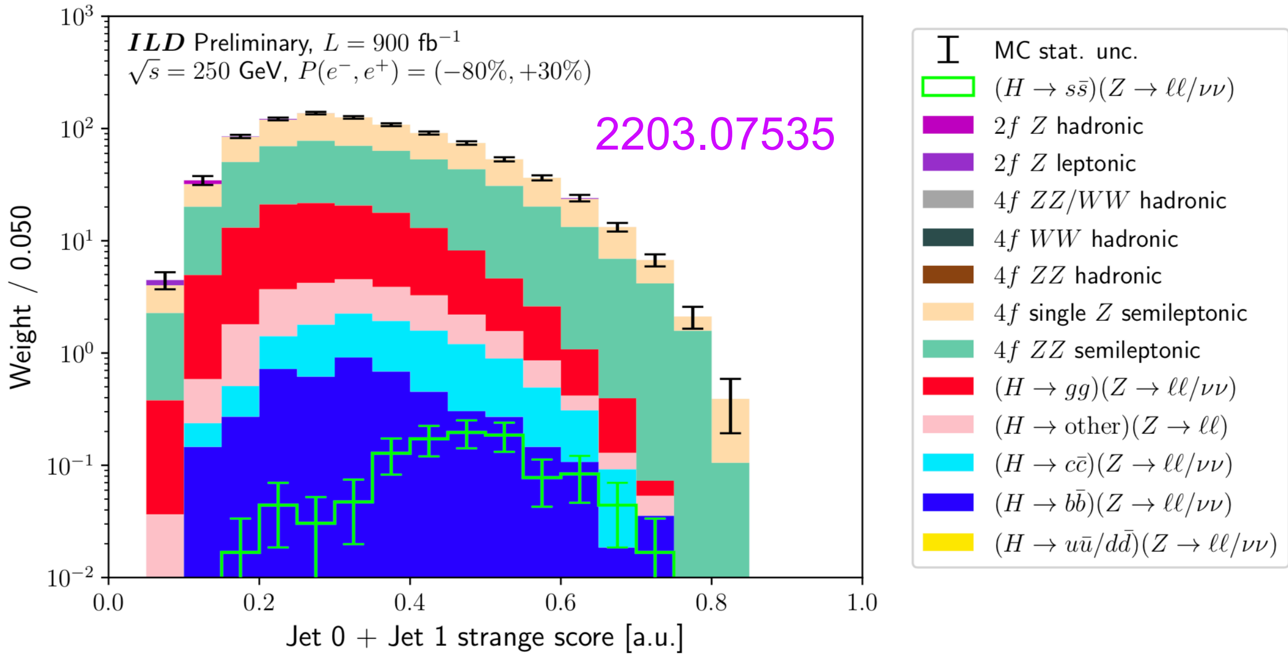


Higgs coupling to ss

SM: expect O(100) Hss decays at e^+e^- 250 GeV. Analysis (ILC) made in Z(vv)H and Z(ll)H.

Observation unlikely with SM rates, but

- y_s < O (7x SM)
- BSM enhancements ?
- Or H+ → cs



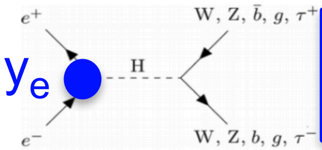
(b) $Z \to \ell\bar{\ell}$ channel

The electron Yukawa coupling ?

arXiv:2107.02686

Run at the Higgs pole to measure ee → H, hence y_e ? Under study for FCC (not in baseline). Stat. limited, hence only relevant for a circular collider.

- Resonant s-channel Higgs production at FCC-ee ($\sqrt{s}$ = 125.00 GeV):



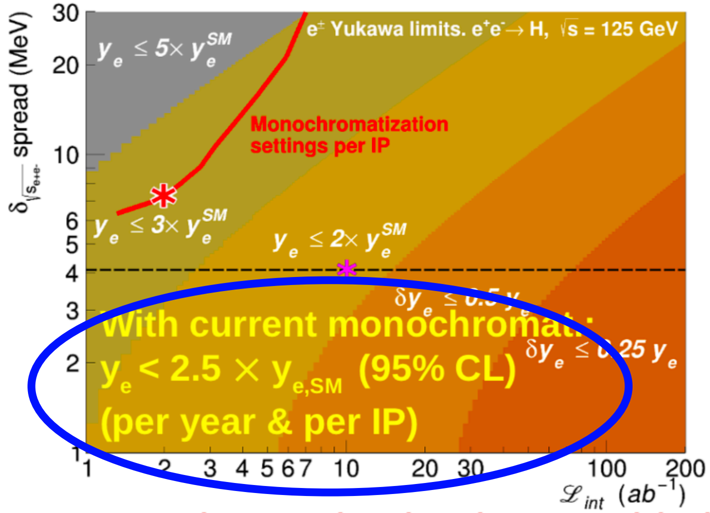
$\sigma(e^+e^- \to H)_{B\text{-}W}$ = 1.64 fb

$\sigma(e^+e^- \to H)_{spread}$ = 280 ab (ISR + $\sqrt{s}_{spread} = \Gamma_H$ = 4.2 MeV)

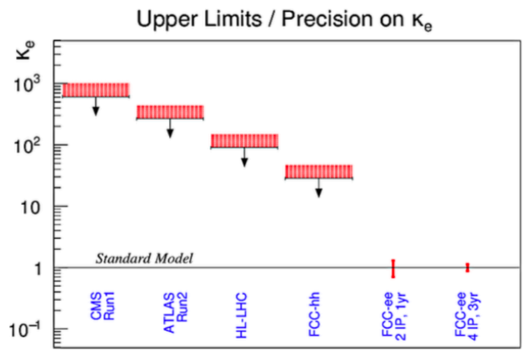
At best O(10^3) of events…

- Prerequisite: Higgs mass extraction δm_H = O(3 MeV) via HZ @ 240,217 GeV
- Generator-level study for signal + backgrounds for 10 decay channels:

  Most significant channels: H→gg (for light-q mistag ~1%), H→WW*→l+jets



For 10 ab^{-1} & $\sqrt{s}_{spread} = \Gamma_H$: Signif ≈ 1.3σ

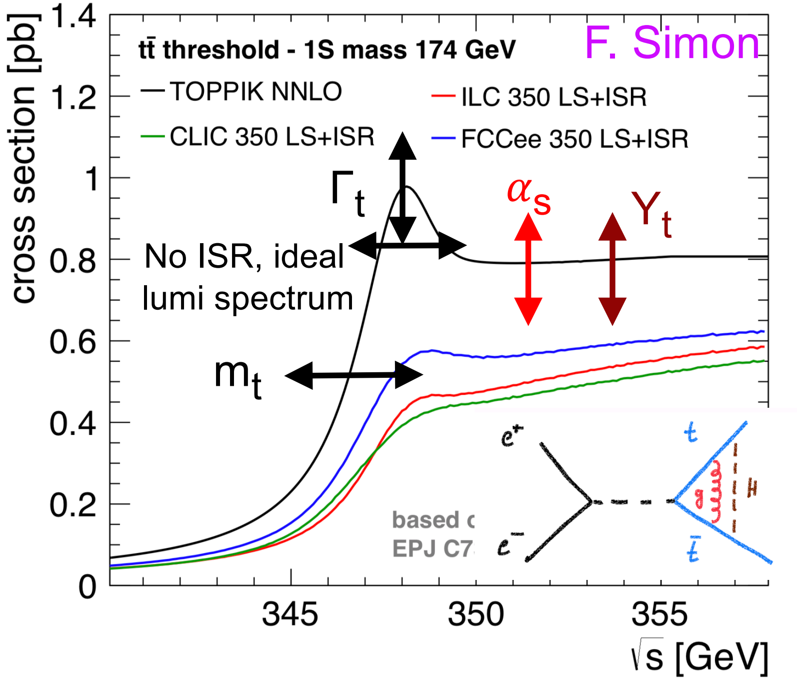


- Monochromatization improvable beyond ($\sqrt{s}_{spread}$, $\mathcal{L}_{int}$)≈(7 MeV, 2 ab^{-1})?
- Fundamental unique physics accessible:
  - → Electron Yukawa coupling: Limits ×100 (×30) better than HL-LHC (FCC-hh)
  - → BSM scale affecting e± Yukawa pushed up to Λ_{BSM} > 110 TeV

E.Perez

Top Yukawa coupling: threshold scan in e^+e^- collisions

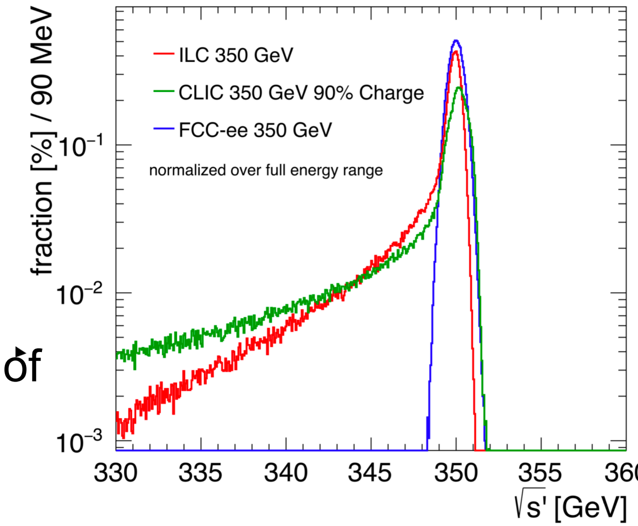
All e^+e^- projects propose a short scan at the tt threshold. Determines m_{top} in a theoretically clean way, Γ_{top}, and the Yukawa coupling of the top.



Threshold shape affected by ISR & lumi spectrum (= main difference between the colliders).

Measure σ at a few points around $2m_{top}$, e.g. 200 fb^{-1}

Recent re-optimisation of the scan (CLIC)



- M_{top} determined with a stat uncertainty of 15-20 MeV, syst ~ 40 MeV

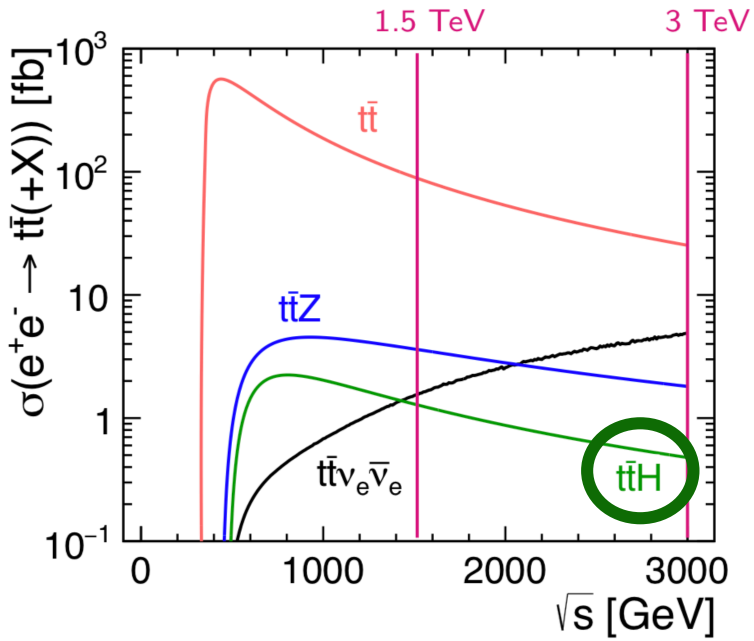
- y_{top} only to about 10% - 20%
  - NB: improved determination of α_s (e.g. from the "Tera-Z" run at FCC-ee / CEPC) important to separate Higgs exchange from QCD effects and reach this 10%

Top Yukawa coupling: ttH production (√s ≥ 500 GeV)

❑ ttH production in e+e- : limited statistics…

- ILC : ~ 5% with 4 ab^{-1} at 500 GeV (quickly improves with higher √s)
- CLIC: ~ 3% with 2.5 ab^{-1} at 1.5 TeV – not better at 3 TeV

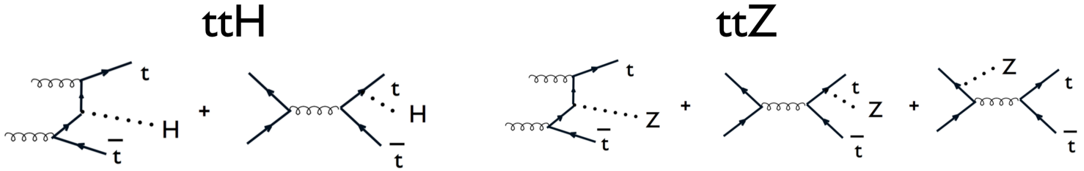
i.e. barely improves w.r.t. HL-LHC (3.4 %)



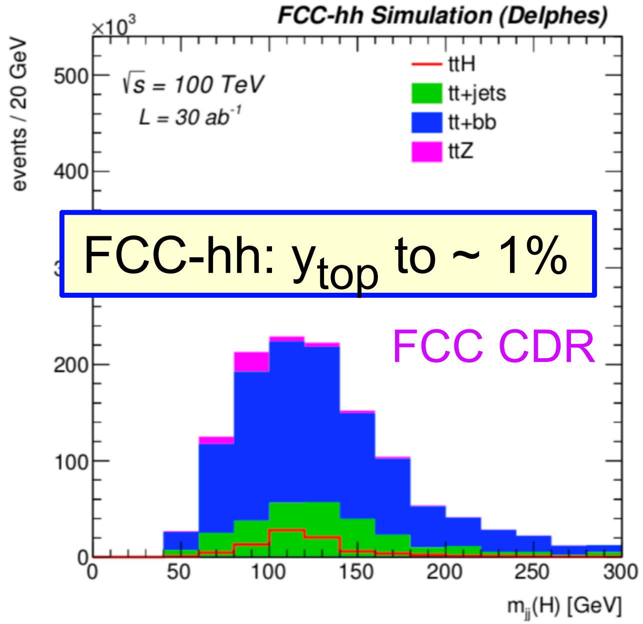
❑ pp collisions, 100 TeV

~ 1B ttH events in 30 ab^{-1}, HL-LHC x 250

ttH = Leading Higgs prod. channel at p_T(H) > TeV



Measure σ(tt H) / σ(tt Z) with H & Z → bb in the boosted regime: fit the fat-jet mass spectrum with templates. Many syst. cancel in the ratio.



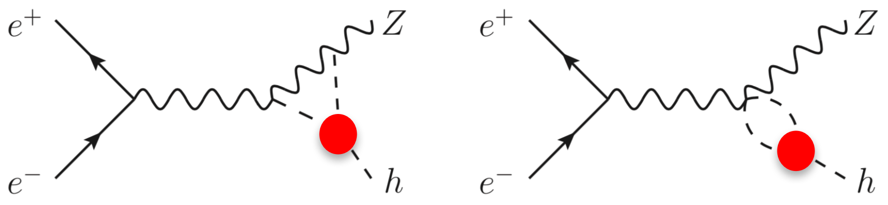
Ratio ~ $y^2_b \, y^2_t / g^2_{ttZ}$

Hbb and ttZ known to < 1% from e^+e^-

Higgs self-coupling at √s < 500 GeV – i.e. ZH & tt thresholds

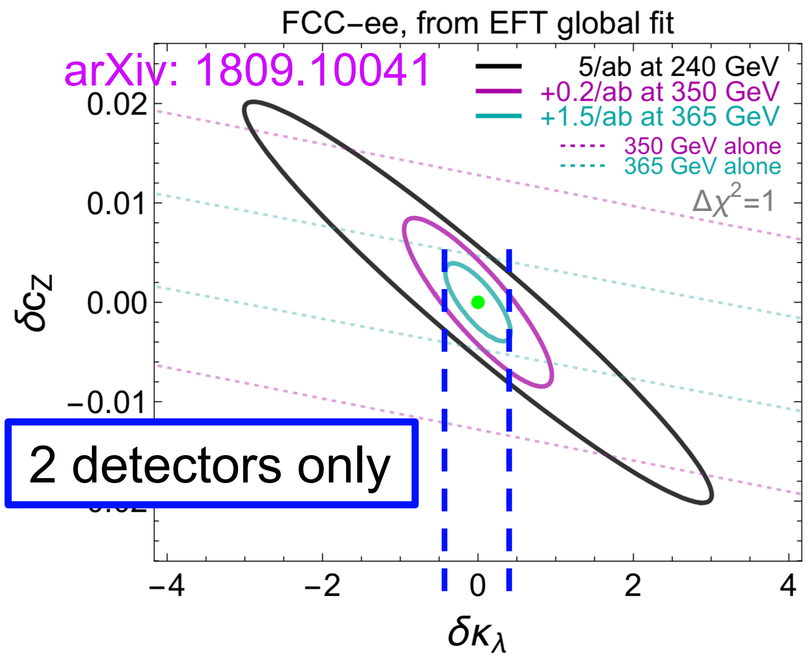
(NB: 365 GeV > ZHH threshold, but too low ZHH x-section)

g_{HHH} affects single-Higgs prod at NLO



e.g. 100% variation on g_{HHH} modifies σ(ZH) by ~ 2% at 240 and ~ 0.5% at 365 GeV. Larger than / comparable with the exp. precision on σ(ZH).

Precise measurement of σ(ZH) constrains a combination of g_{HHH} and g_{HZZ}. Measurements at two values of √s needed to determine separately g_{HHH} and g_{HZZ}.



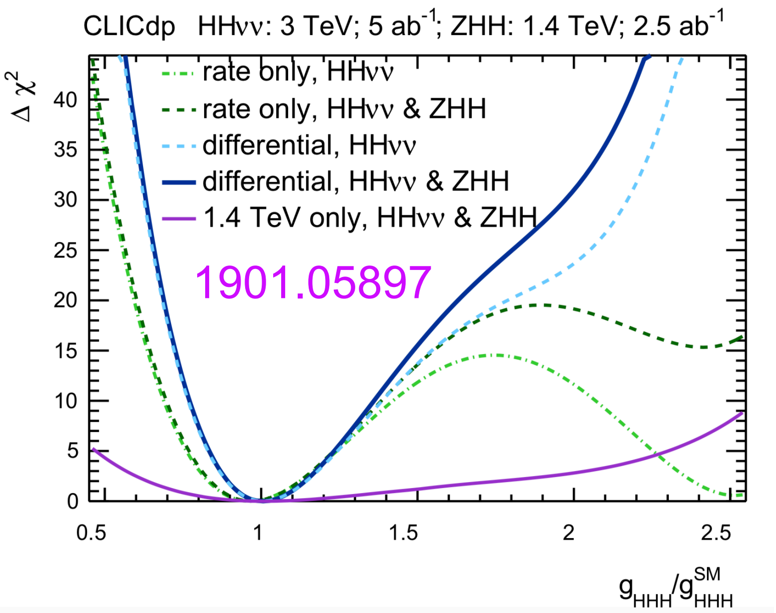
FCC-ee baseline (2 IPs): 40% on g_{HHH} (33% when combined with HL-LHC).
Recent: 4 IPs possible. More than x2 stat: need less time to complete the EW programme (see later), hence can spend more time at 240 and 365 GeV → 24% (21% with HL-LHC)

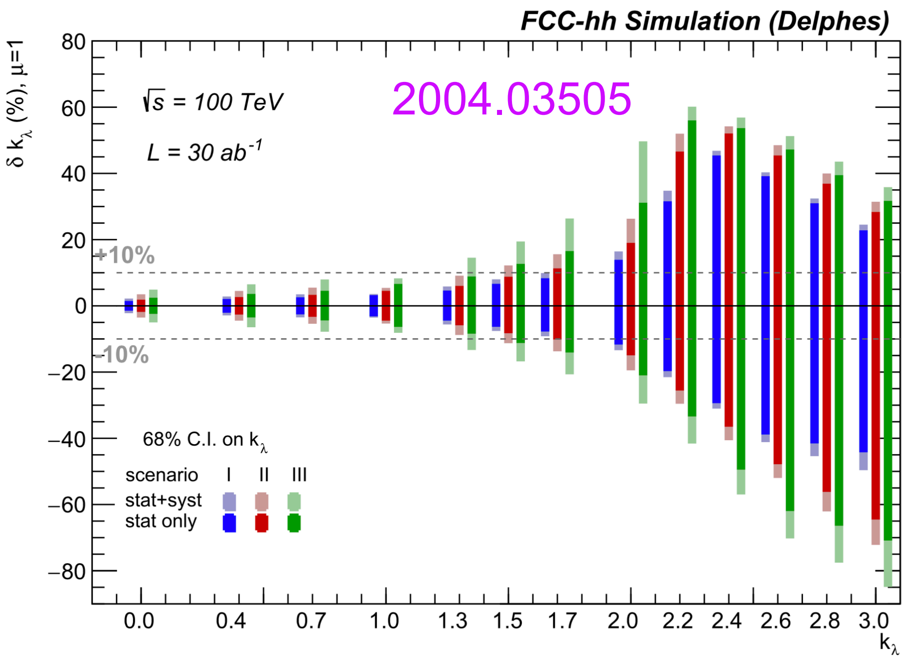
With 4 IPs: 5σ observation of g_{HHH} within reach with 15 years of operation at FCC-ee.

Higgs self-coupling at higher energy: HH production (I)

- e^+e^-: σ(ZHH) and σ(ννHH), from 0.1 fb (250 GeV) to O(1 fb) at 3 TeV.
  Best sensitivity: HH → 4b.
- μCol: VBF, vvHH
- pp 100 TeV : σ = LHC x40
  Best channel is bbγγ. Sensitivity studied for several assumptions on detector performance.

From σ to g_{HHH}: Some diagrams do not involve HHH. ambiguities, can be resolved by combining measurements or by meas. differential in M(HH).



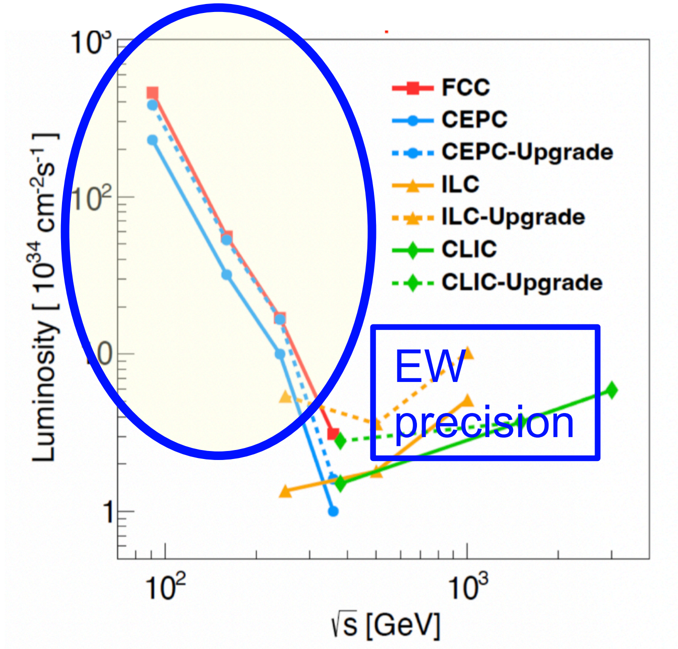


Going below the 10% level requires highest energies. Not for the "first stages".

(SM case)

e+e-	ILC 500 GeV 4 ab-1	27% (oldish ..)
	ILC + 1 TeV 8 ab-1	10%
	CLIC 3 TeV, 5 ab-1	-8% / +11%
μCol	3 TeV 0.9 ab-1	~ 25%
	10 TeV 10 ab-1	4 %
pp	100 TeV 30 ab-1	3 – 8%

e^+e^- : also "Electroweak factories"



FCC CDR

- Circular colliders: huge statistics :
  - at the Z peak: 150 ab^{-1}, 5 10^{12} Z's, "Tera Z"
    - LEP x 2.5 10^5 !
  - at the WW threshold: 10^8 W's
    - and large stat of ee → WW at higher $\sqrt{s}$ too (e.g. for aTGCs)

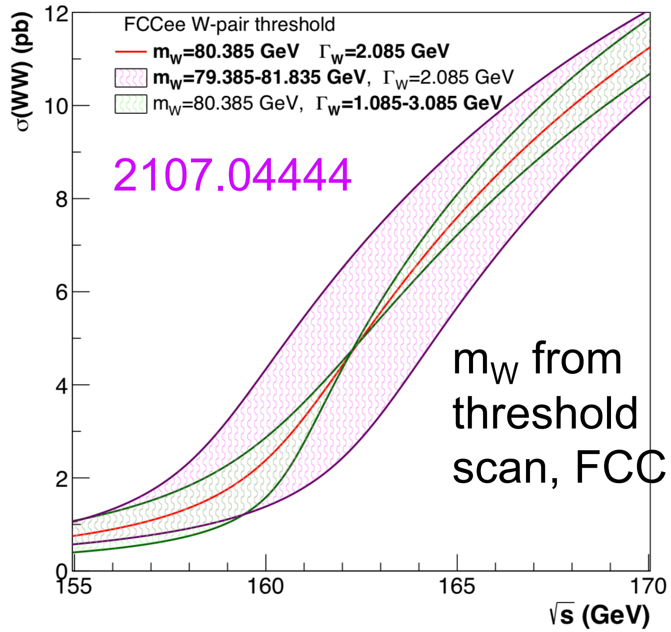
arXiv:1908.11299

- Linear colliders:
  - In "Higgs / top" baseline runs at 250 GeV or at ttbar :
    - measurements at e.g. 250 GeV from ee → WW
      - E.g. 2 ab^{-1} @ 250 GeV (ILC): 10 M W's
    - Measurements of Z properties from radiative return events, ee → $Z\gamma$
      - E.g. 2 ab^{-1} @ 250 GeV : ~ 100 M Z's
  - Additional dedicated runs possible (not in the baseline)
    - "Giga-Z" : 100 fb^{-1} at the Z peak, i.e. 4 10^9 Z's (costs 1-3 years)
    - Scan of the WW threshold , a few 100's fb^{-1}

Huge (some) reduction of uncertainties on electroweak measurements are at hand at circular (linear) ee colliders.

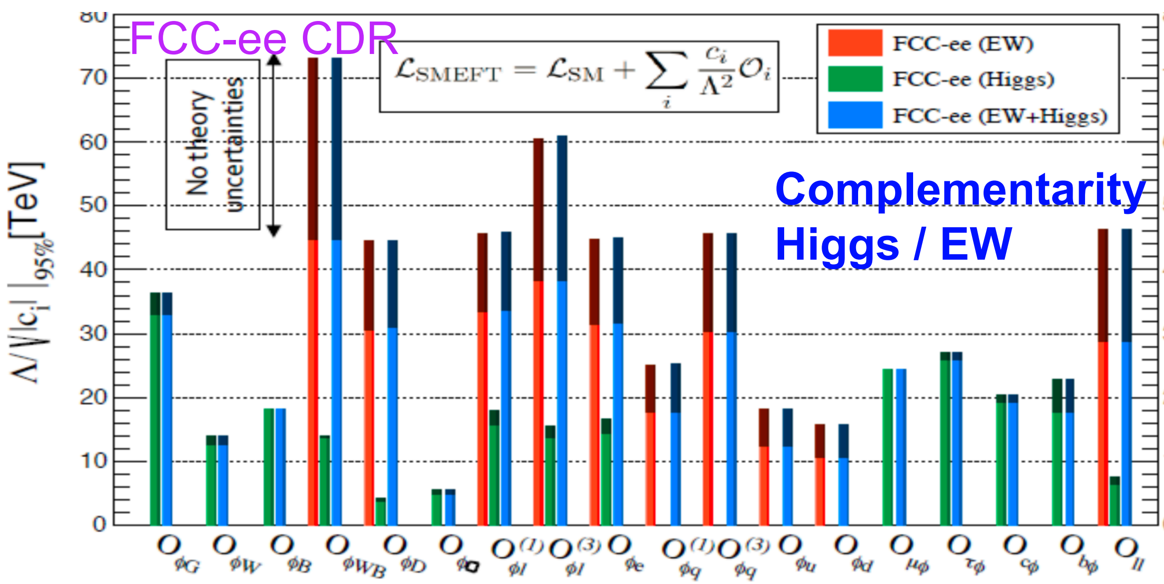
EW precision measurements: examples

	FCC	ILC	improvement
M_W	500 keV	1.5 - 2 MeV	8 - 30
M_Z	100 keV	< 1 MeV	> 2 - 20
Γ_Z	25 keV	< 1 MeV	> 2 - 100
$\sin^2\theta_{eff}$ (A_{LR})		$1 – 2\ 10^{-5}$	10 - 20
$\sin^2\theta_{eff}$ (τ pol)	$3\ 10^{-6}$		60
$\alpha_{QED}(m^2_Z)$	$3\ 10^{-5}$		4 (stat. lim. !)
Rb	$2\ 10^{-5}$	$1.4 - 2\ \ 10^{-4}$	3 - 30
…			



Key experimental handles:

- knowledge of √s (exquisite at circular collider with resonant depolarisation method)
- Linear : longitudinal polarisation



In terms of weakly-coupled new physics: FCC-ee precision corresponds to sensitivity on Λ_{NP} up to 70 TeV, anticipating what FCC-pp would focus on.

also significant impact of EW measurements in the determination of Higgs couplings in SMEFT fits shown earlier.

Some aspects that I did not touch upon

- Tera-Z : “intensity frontier”, very rich program beyond EW precision measurements:
  - 10^{12} b’s and c’s: B and D physics, CP violation, etc
  - 2 10^{11} taus : tests Lepton Flavour Universality in charged current to 10^{-5} via τ lifetime and $BR_{lep}(\tau)$
  - Lepton Flavour Universality tests in NC via Z decays, same sensitivity
  - Lepton Flavor Violation in Z or tau decays
  - QCD studies (e.g. α_s)
  - Direct searches for light, weakly coupled new particles
    - Right-handed neutrinos, dark photons, axions, LLPs, etc

- High energy
  - Direct searches for new particles too heavy for LHC
    - Resonances, pair production, DM searches
  - EW measurements at highest scales (DY, ee → ff or VV)

Conclusions

- Very rich programme of Higgs & top measurements at all proposed future colliders

  e+e- : has been studied for two decades or more. But new experimental developments still coming in:

  - progress on detector R&D, reconstruction algorithms, ML revolution, allow to contemplate more ambitious goals

- Very rich programme of EW precision measurements at e+e- colliders

  Very high statistics calls for careful studies of systematic uncertainties, and of corresponding detector requirements: exp. developments ongoing.

- Very rich programme of flavour physics and searches (LLPs etc) at circular e+e- coll.

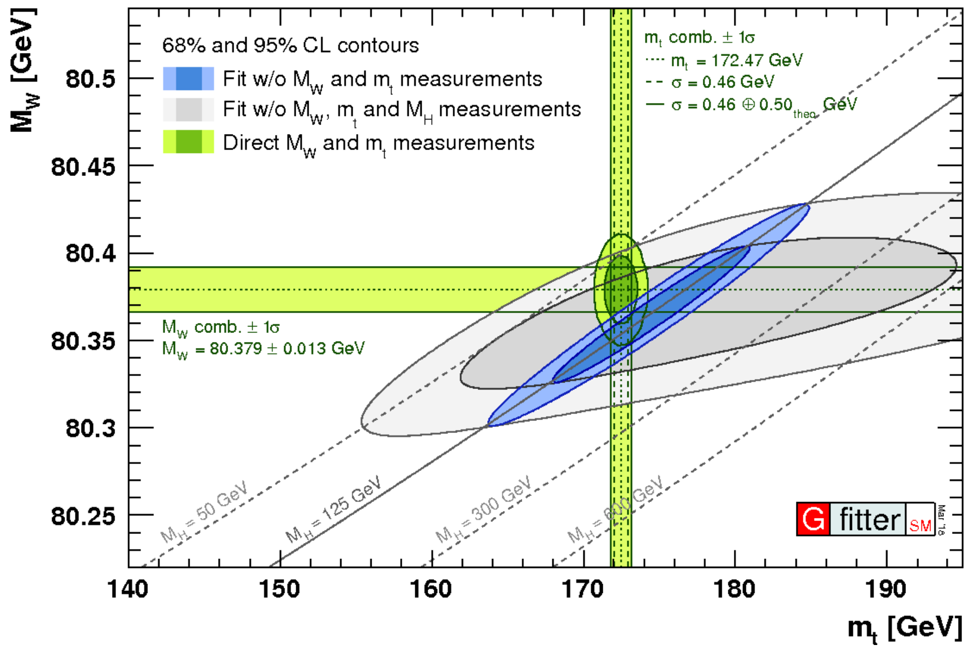
  May call for dedicated detectors. Defining detector concepts is one of the exp. priorities for the next 2-3 years.

Lots of opportunities for experimental physicists to contribute to shaping the future of the field !

Backup

The case for precision Electroweak measurements in e+e-

With m_{top}, m_W and m_H fixed by measurements: the SM has nowhere to go !



Will (e.g.) this plot show first hints of physics beyond the SM ?

- Improve the direct determination of MW and Mtop
  - PDG 2020: MW to 12 MeV
- And the SM fit prediction for these quantities, e.g. :

$$m_W = 80.3584 \pm 0.0055_{m_{top}} \pm 0.0025_{m_Z} \pm 0.0018_{\alpha_{QED}} \pm 0.0020_{\alpha_S} \pm 0.0001_{m_H} \pm 0.0040_{\text{theory}} \text{ GeV} = 80.358 \pm 0.008_{\text{total}} \text{ GeV},$$

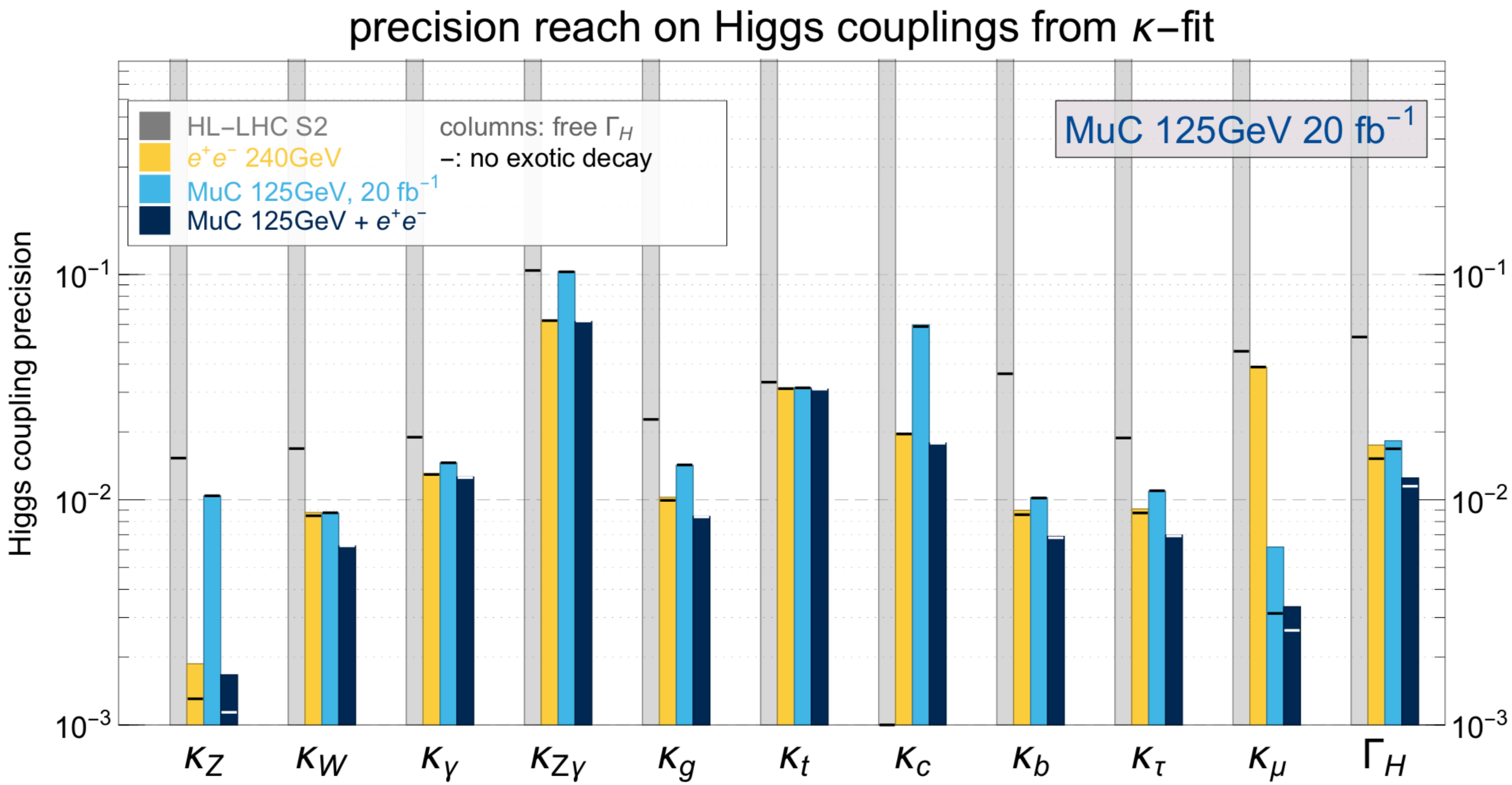
Estimates from S.

Requires improved measurements of m_{top}, m_Z, $\alpha_{QED}(m^2_Z)$, α_S… and more generally all usual EWPO included in the EW fits.

Note: also significant impact of EW measurements in the determination of Higgs couplings in SMEFT fits shown earlier. And precision measurements are needed to fully capitalize on the experimental measurements in the Higgs sector (reduce parametric uncertainties in th. calc).

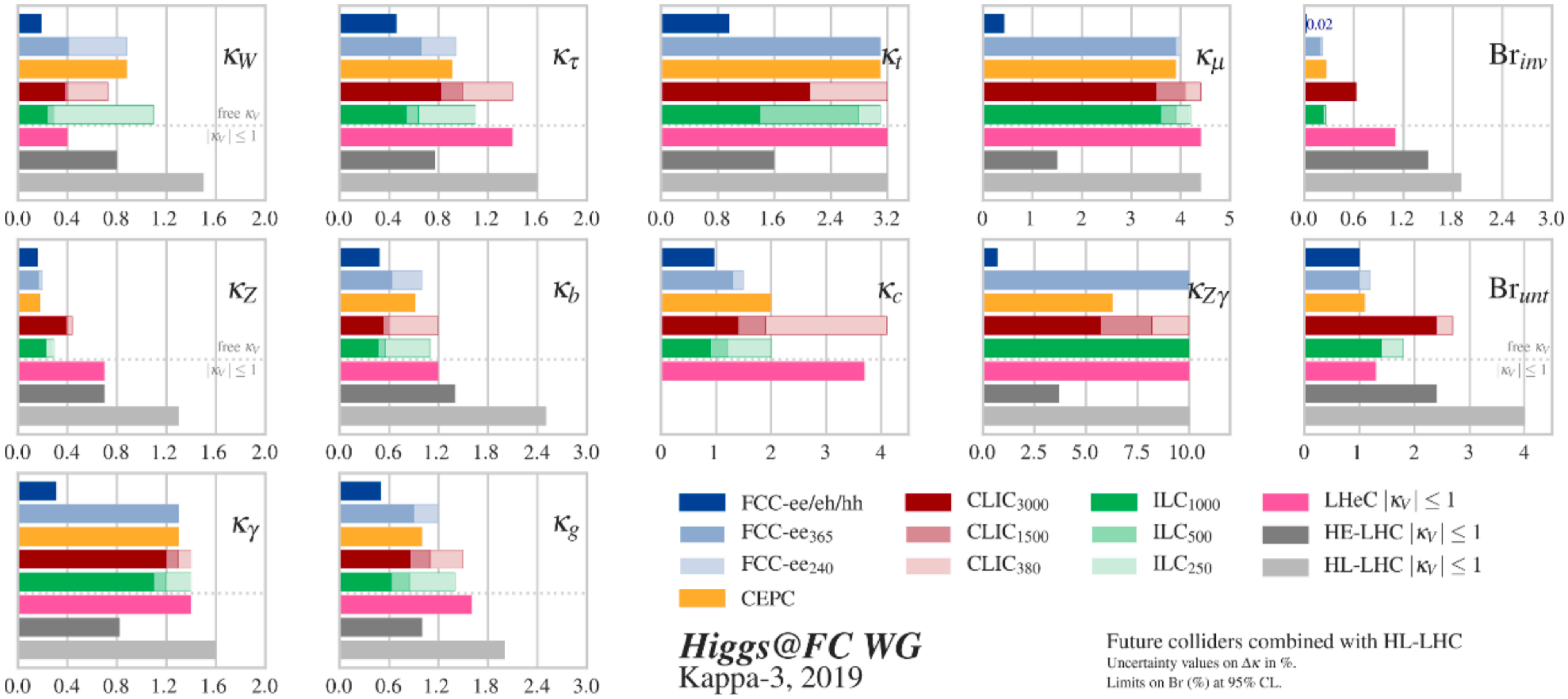
Higgs couplings from MuCol125 alone (combined with HL-LHC)

From arXiv:2203.04324



Improves significantly over HL-LHC only.
Muon Yukawa measured very precisely. Other couplings better measured with ee, although the precision of μ125 is quite good taking into account the much lower Higgs statistics. With 5 fb-1 though, μ125 significantly worse than ee.

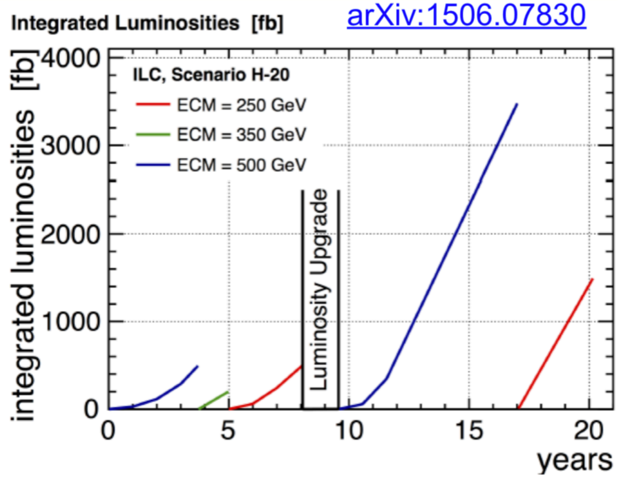
Higgs couplings, kappa framework, ESU



Current Running scenarios

ILC

arXiv:1506.07830

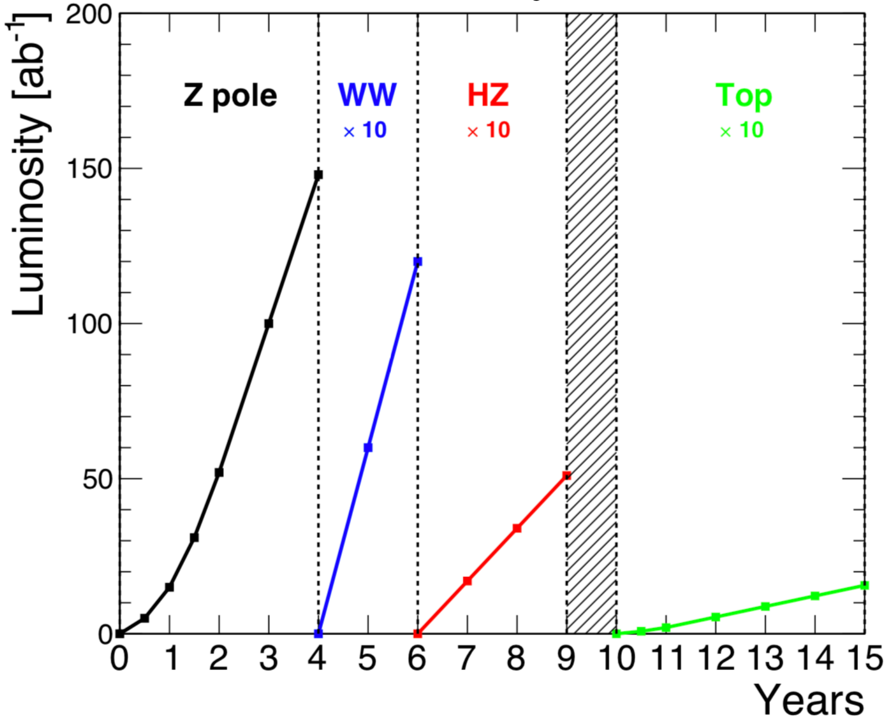


Lumi upgrade: x2 #bunches (requires addit 'al klystrons and possibly a 2nd e+ damping ring)

Total: 250 GeV: 2 ab-1
350 GeV : 0.2 ab-1
500 GeV : 4 ab-1

Overall ~ 20 years.

FCC – order may differ



CEPC :

Operation mode	Z factory	WW threshold	Higgs factory	$t\bar{t}$
$\sqrt{s}$ (GeV)	91.2	160	240	360
Run time (year)	2	1	10	5
Instantaneous luminosity ($10^{34} cm^{-2}s^{-1}$, per IP)	191.7	26.6	8.3	0.83
Integrated luminosity (ab^{-1}, 2 IPs)	100	6	20	1
Event yields	3×10^{12}	1×10^{8}	4×10^{6}	5×10^{5}

TABLE I. Nominal CEPC operation scheme, and the physics yield, of four different modes.

CLIC: overall 25-30 years

Stage	$\sqrt{s}$ [TeV]	$\mathscr{L}_{int}$
1	0.38 (and 0.35)	1
2	1.5	2
3	3.0	5