Experimental prospects @Future Circular collider

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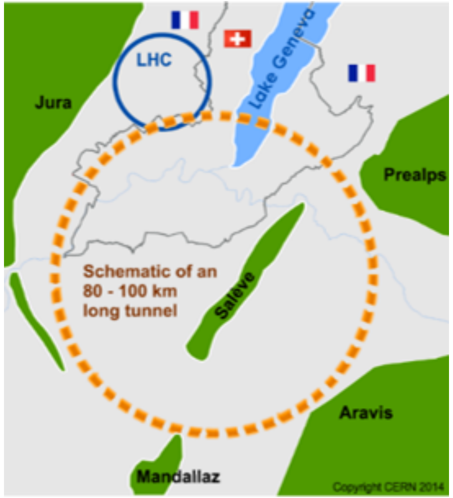
Higgs Hunting 2023
Paris, 11-13 September 2023

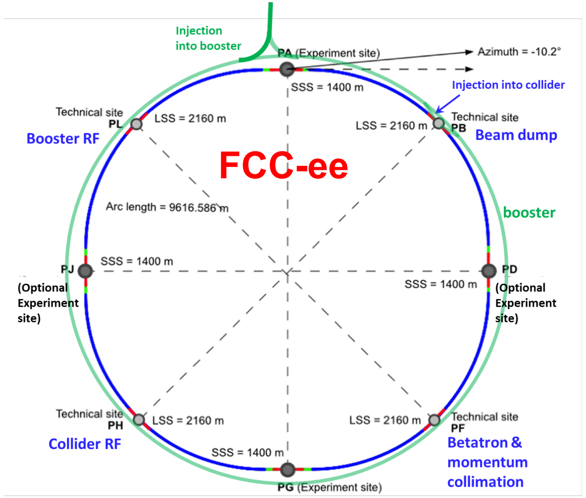
INFN PADOVA

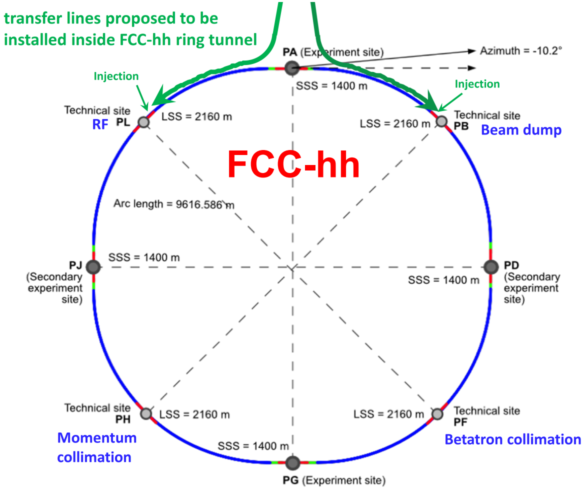
FCC integrated program

comprehensive long-term program maximizing physics opportunities

- **stage 1: FCC-ee (Z, W, H, $t\bar{t}$) as Higgs factory, electroweak & top factory at highest luminosities**
- **stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, pp & AA collisions; e-h option**
- highly synergetic and complementary programme boosting the physics reach of both colliders (e.g. model-independent measurements of the Higgs couplings at FCC-hh thanks to input from FCC-ee; and FCC-hh as “energy upgrade” of FCC-ee)
- common civil engineering and technical infrastructures, building on and reusing CERN’s existing infrastructure
- FCC integrated project allows the start of a new, major facility at CERN within a few years of the end of HL-LHC







2020 - 2040 | 2045 - 2063 | 2070 - 2095

Main geometrical parameters

Main changes

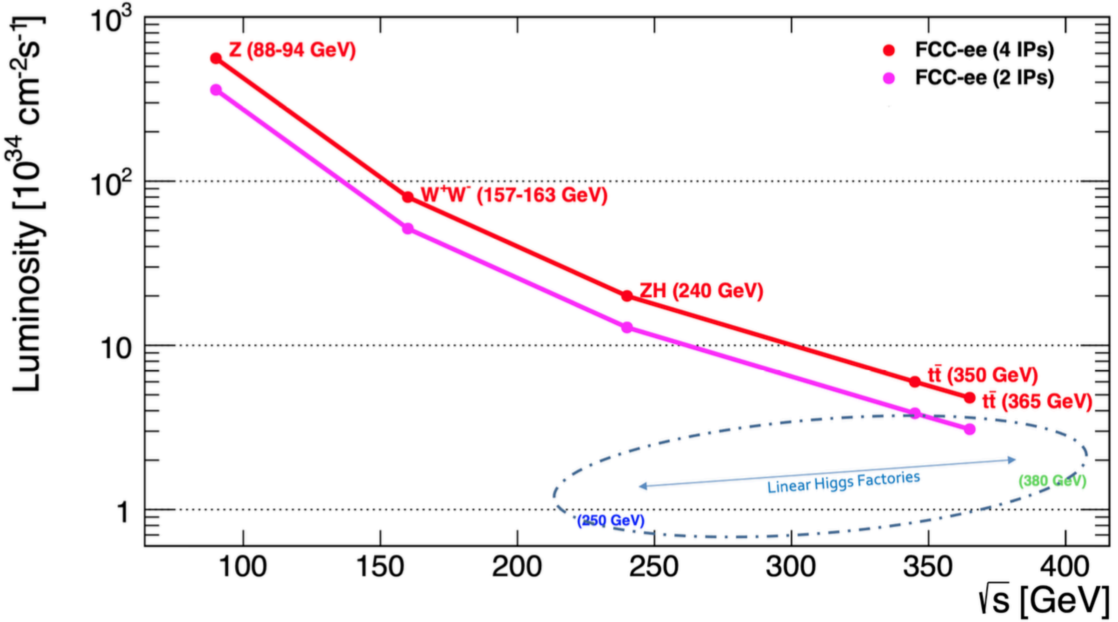
- **# access points** reduced from 12 to 8
- facilitating placement and reducing the overall surface area required
- **circumference has shrunk** from 97.75 km to 90.657 km
- new layout with **4-fold superperiodicity**, enabling FCC-ee operation with either **2 or 4 collision points**
- **hadron collider** RF system now **shares** a **klystron gallery tunnel with lepton collider**
- new circumference matched to both LHC and the SPS tunnels, corresponding to 400 MHz harmonic ratios of h_{FCC}/h_{LHC}=1010/297 & h_{FCC}/h_{SPS}=1010/77, **allowing for hadron beam injection from either the LHC or from a new superconducting SPS**, with bunch spacings of 2.5, 5.0, 7.5, 10, 12.5, 15, 20, and 25

Parameter	unit	2018 CDR [1]	2023 Optimised
Total circumference	km	97.75	90.657
Total arc length	km	83.75	76.93
Arc bending radius	km	13.33	12.24
Arc lengths (and number)	km	8.869 (8), 3.2 (4)	9.617 (8)
Number of surface sites	—	12	8
Number of straights	—	8	8
Length (and number) of straights	km	1.4 (6), 2.8 (2)	1.4 ([illegible]), 2.[illegible] (4)
superperiodicity	—	2	4

Slide from Micheal Benedikt

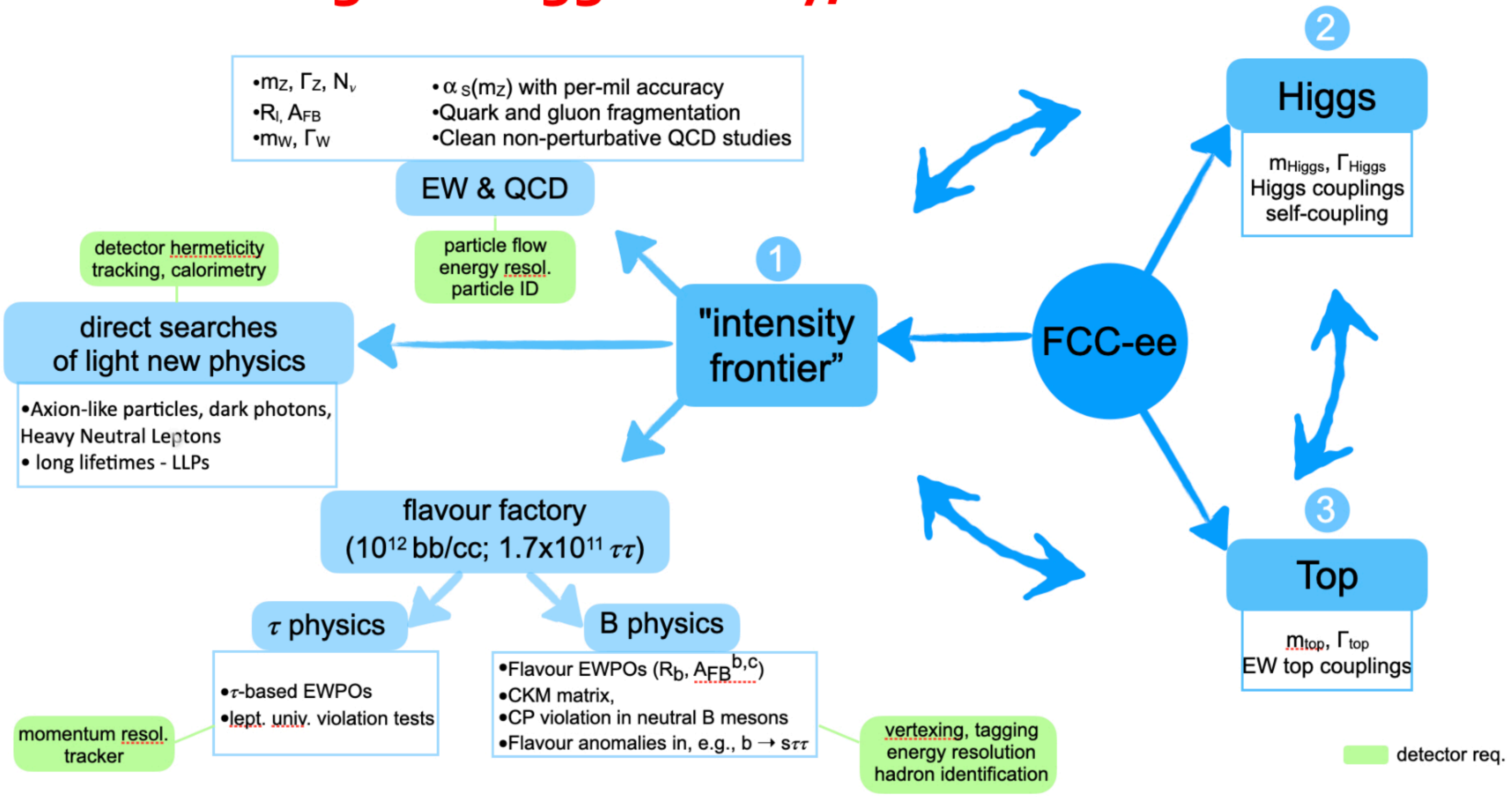
FCC-ee Energy range & luminosity

- e^+e^- first in the tunnel
- Producing in a clean environment all the heaviest SM particles
- Extending sensitivity to weakly coupled BSM models



Working point	Z, years 1-2	Z, later	WW, years 1-2	WW, later	ZH	$t\bar{t}$	
$\sqrt{s}$ (GeV)	88, 91, 94		157, 163		240	340–350	365
Lumi/IP (10^{34} cm^{-2}s^{-1})	70	140	10	20	5.0	0.75	1.20
Lumi/year (ab^{-1})	34	68	4.8	9.6	2.4	0.36	0.58
Run time (year)	2	2	2	0	3	1	4
Number of events	6×10^{12} Z		2.4×10^8 WW		1.45×10^6 ZH + 45k WW $\rightarrow$ H	1.9×10^6 $t\bar{t}$ +330k ZH +80k WW $\rightarrow$ H	

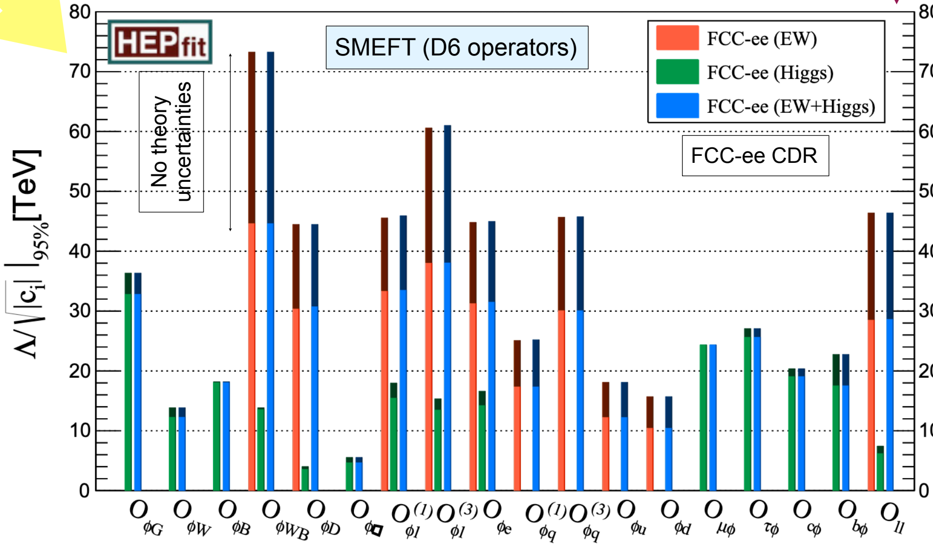
FCC-ee: a great Higgs factory, and so much more



Precision EW measurements

arXiv:2106.13885

- Many interconnected measurements
  - The whole FCC-ee run plan is essential (Z,W,top)
  - Complementary to Higgs for New Physics
  - Huge statistics → precision
    - Real chance of discovery
  - Most of the work is (will be) on systematics
    - Experimental and theoretical



Observable	present value ± error	FCC-ee Stat.	FCC-ee Syst.	Comment and leading exp. error	
m_Z (keV)	91186700 ± 2200	**4**	100	From Z line shape scan Beam energy calibration	
Γ_Z (keV)	2495200 ± 2300	**4**	25	From Z line shape scan Beam energy calibration	
$\sin^2\theta_W^{eff}(\times 10^6)$	231480 ± 160	**2**	2.4	from $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration	
$1/\alpha_{QED}(m_Z^2)(\times 10^3)$	128952 ± 14	**3**	small	from $A_{FB}^{\mu\mu}$ off peak QED&EW errors dominate	
R_ℓ^Z $(\times 10^3)$	20767 ± 25	**0.06**	0.2-1	ratio of hadrons to leptons **acceptance for leptons**	
$\alpha_s(m_Z^2)$ $(\times 10^4)$	1196 ± 30	**0.1**	0.4-1.6	from R_ℓ^Z above	Z
σ_{had}^0 $(\times 10^3)$ (nb)	41541 ± 37	**0.1**	4	peak hadronic cross section luminosity measurement	
$N_\nu(\times 10^3)$	2996 ± 7	**0.005**	1	Z peak cross sections Luminosity measurement	
R_b $(\times 10^6)$	216290 ± 660	**0.3**	< 60	ratio of $b\bar{b}$ to hadrons stat. extrapol. from SLD	
$A_{FB}^b, 0$ $(\times 10^4)$	992 ± 16	**0.02**	1-3	b-quark asymmetry at Z pole from jet charge	
$A_{FB}^{pol,\tau}$ $(\times 10^4)$	1498 ± 49	**0.15**	<2	τ polarization asymmetry τ decay physics	
τ lifetime (fs)	290.3 ± 0.5	**0.001**	0.04	radial alignment	
τ mass (MeV)	1776.86 ± 0.12	**0.004**	0.04	momentum scale	
τ leptonic $(\mu\nu_\mu\nu_\tau)$ B.R. (%)	17.38 ± 0.04	**0.0001**	0.003	e/μ/hadron separation	
m_W (MeV)	80350 ± 15	**0.25**	0.3	From WW threshold scan Beam energy calibration	W
Γ_W (MeV)	2085 ± 42	**1.2**	0.3	From WW threshold scan Beam energy calibration	
$\alpha_s(m_W^2)(\times 10^4)$	1170 ± 420	**3**	small	from R_ℓ^W	
$N_\nu(\times 10^3)$	2920 ± 50	**0.8**	small	ratio of invis. to leptonic in radiative Z returns	
m_{top} (MeV/c^2)	172740 ± 500	**17**	small	From $t\bar{t}$ threshold scan QCD errors dominate	top
Γ_{top} (MeV/c^2)	1410 ± 190	**45**	small	From $t\bar{t}$ threshold scan QCD errors dominate	
$\lambda_{top}/\lambda_{top}^{SM}$	1.2 ± 0.3	**0.10**	small	From $t\bar{t}$ threshold scan QCD errors dominate	
ttZ couplings	± 30%	**0.5 – 1.5 %**	small	From $\sqrt{s} = 365$ GeV run	

Flavor Factory opportunities

Particle production (10^9)	B^0	B^-	B_s^0	Λ_b	$c\bar{c}$	$\tau^-\tau^+$
Belle II	27.5	27.5	n/a	n/a	65	45
FCC-*ee*	400	400	100	100	600	170

~10 times Belle's stat

Boost at the Z!

- **Enormous statistics 10^{12} bb, cc, 2×10^{11} ττ events**
- **Clean environment**
- **Favourable kinematics -> boost**
- **Excellent vertexing (smaller beam pipe)**

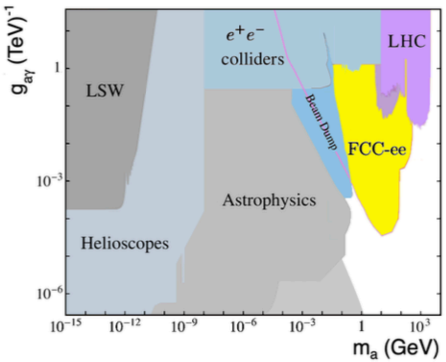
PROMISING OBSERVABLES

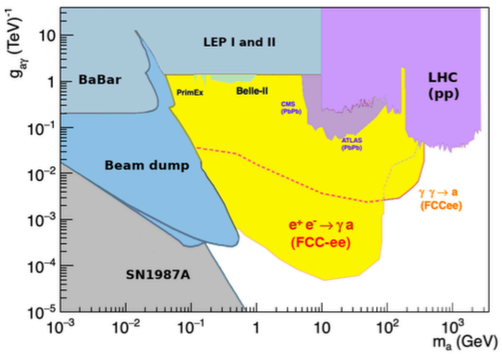
- Rare b-hadron decays with $\tau\tau^-$ pairs in the final state.
- Charged-current b-hadrons decays with a τν pair in the final state.
- Lepton flavour violating τ decays
- Lepton-universality tests in τ decays.

Sensitivity for weakly coupled objects (BSM)

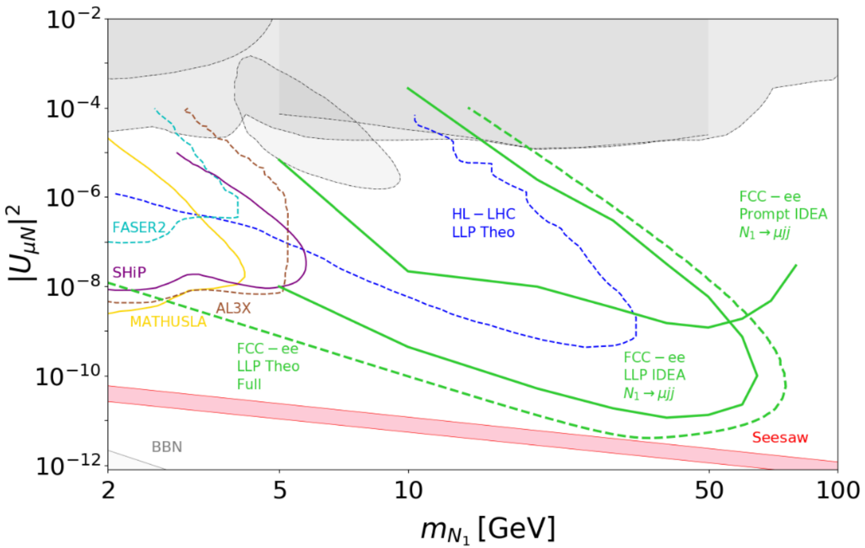
- Dark photons: $e^+e^- \to A'\gamma,\ e^+e^- \to A'H$ or $Z'H$
- ALPS: $e^+e^- \to a\gamma,\ \gamma\gamma \to a$
- LLPs from H/Z exotic decays
- Heavy Neutral Leptons

New analyses in progress that can help define detector requirements



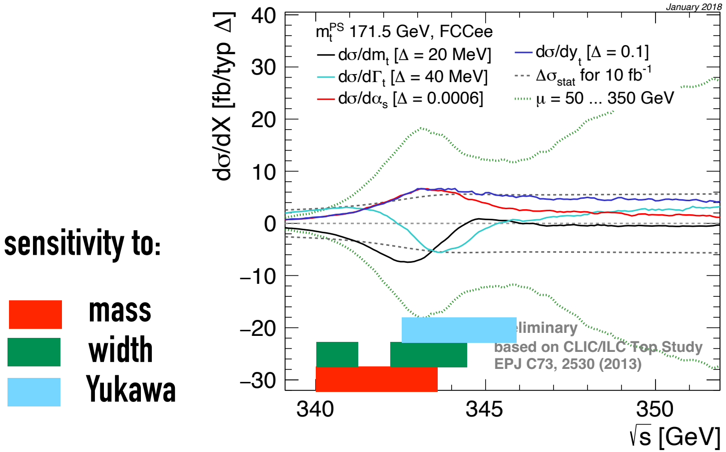


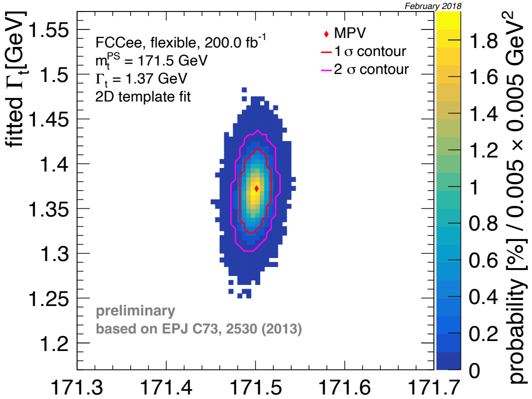
Sensitivity to photon couplings down to < 10^{-4}–4 TeV^{-1}
(3 orders of magnitude improvement)



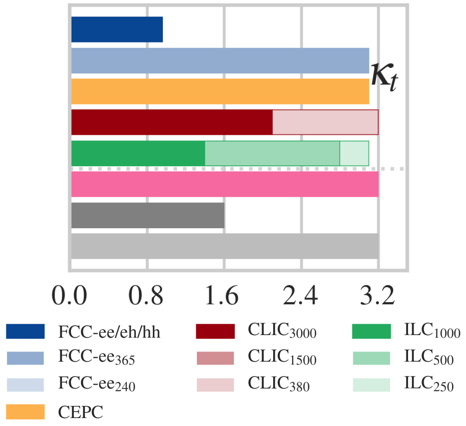
Top physics

- Threshold region allows most precise measurements of top mass, width, and estimate of Yukawa coupling.
  - Precision on top Yukawa coupling from the measurements at thresholds ~10% precision (profiting of the better α_s).
  - But, HL-LHC result of about 3.1% already better (with FCC-ee Higgs measurements removing the model dependence)



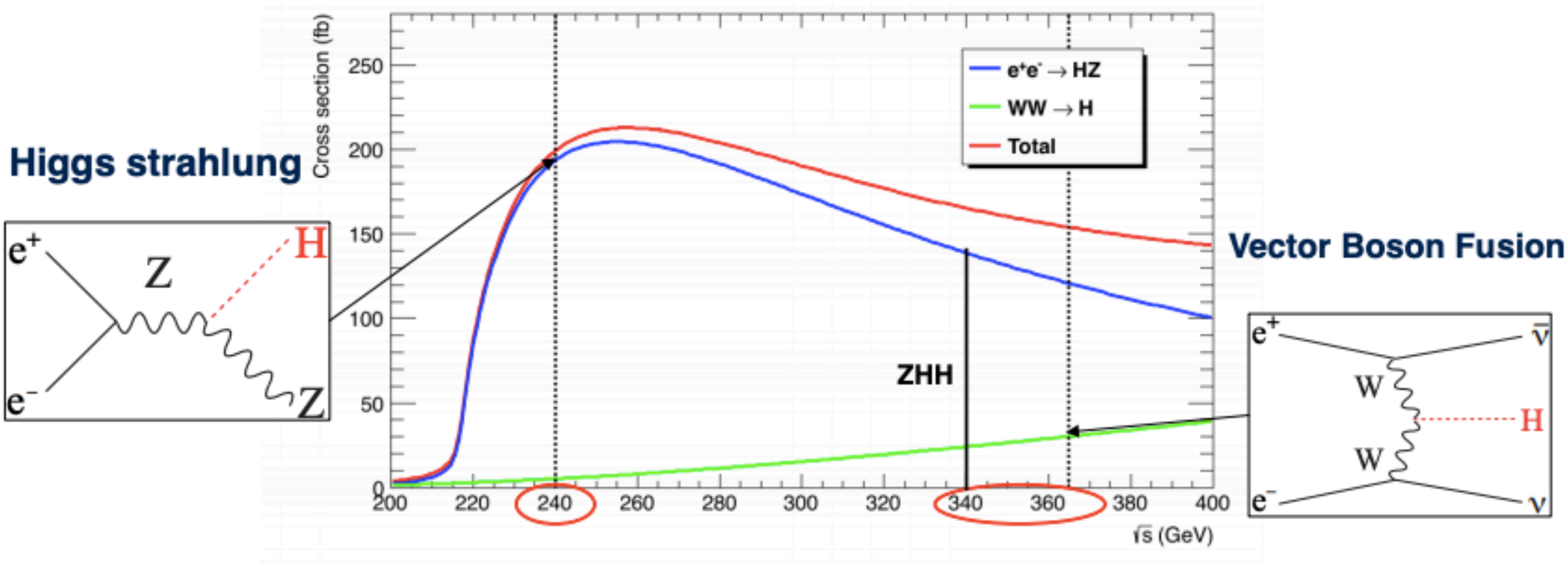


Mass only: 8.8 MeV (stat), 5.4 MeV (α_s [2 x 10-4]), 44 MeV (theo)



➢ **Run at 365 GeV used also for measurements of top EWK couplings (at the level of 10^{-2}-10^{-3}) and FCNC in the top sector.**

Higgs production at FCC-ee



- Optional run at 125 GeV $e^+e^- \to H$ direct probe of electron-Yukawa coupling.

Higgs coupling precision expectation

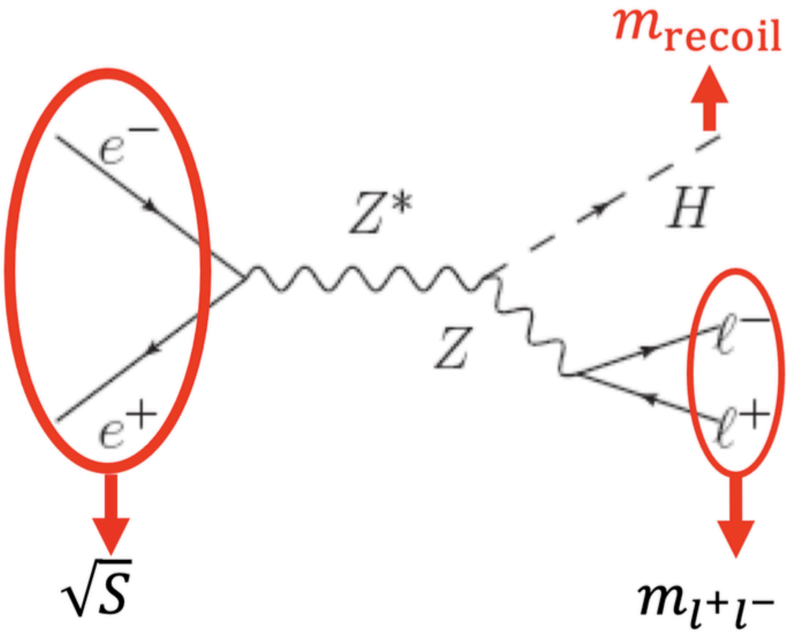
Collider	HL-LHC	+ 240 GeV	+ 240 +365 GeV (FCC-ee)	+ FCC-hh (FCC-Int)
g_{HWW} [%]	0.99	0.88	0.41	0.19
g_{HZZ} [%]	0.99	0.20	0.17	0.16
g_{Hgg} [%]	2.00	1.20	0.90	0.5
$g_{H\gamma\gamma}$ [%]	1.60	1.3	1.3	0.31 ★
$g_{HZ\gamma}$ [%]	10.0	10.0	10.0	0.7 ★
g_{Hcc} [%]	*Coming…*	1.50	1.30	0.96
g_{Htt} [%]	3.20	3.10	3.10	0.96
g_{Hbb} [%]	2.50	1.00	0.64	0.48
$g_{H\mu\mu}$ [%]	4.40	4.00	3.90	0.43 ★
$g_{H\tau\tau}$ [%]	1.60	0.94	0.66	0.46
$\mathrm{BR}_{\mathrm{inv}}$ [%]	1.9	0.22	0.19	0.024

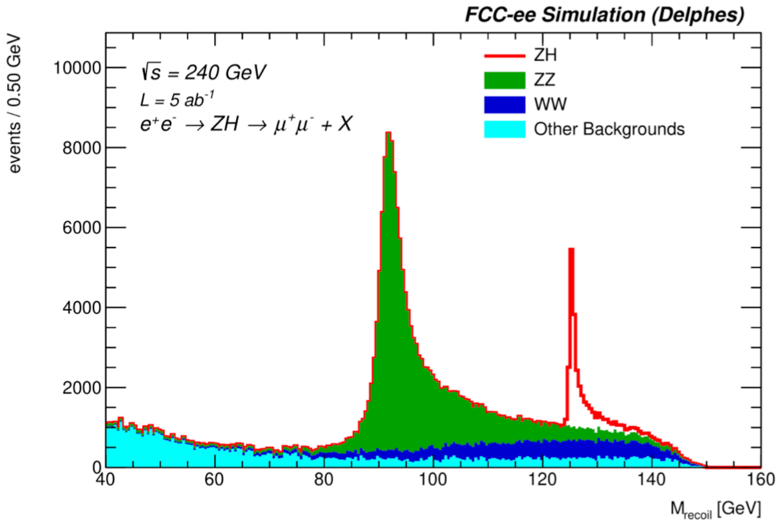
Table adapted from arxiv:1905.03764

- FCC-ee measures g_{HZZ} to 0.2% (absolute, model-independent, standard candle) from $\sigma(ZH)$
  - $\Gamma(H)$, g_{Hbb} , g_{Hcc} , $g_{H\tau\tau}$, g_{HWW} , follow
  - Standard candle fixes all HL-LHC couplings
- FCC-hh produces over 10^{10} Higgs bosons, 10^8 ttH and $2\mathrm{x}10^7$ HH pairs:
  - Improving precision on g_{Htt}, g_{HHH}
    - with top EW couplings (and other BRs) measured at FCC-ee
  - Access to Rare Decays: $\mu\mu, \gamma\gamma, Z\gamma$
- **FCC-ee + FCC-hh is outstanding:**
  - All accessible couplings with per-mil precision
  - Self-coupling with per-cent precision

Recoil method

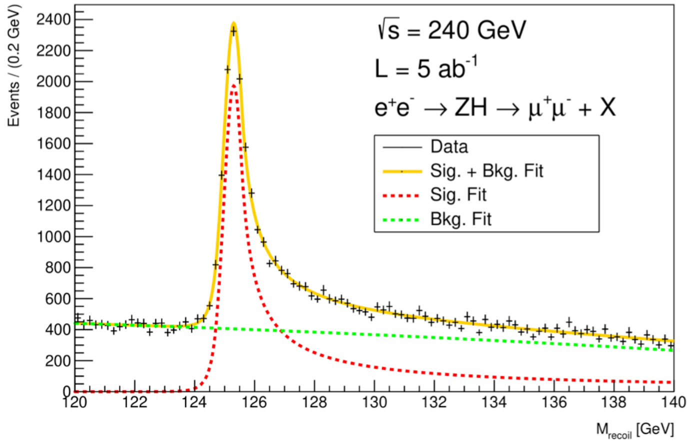
$$m_{\text{recoil}}^2 = (\sqrt{s} - E_{l\bar{l}})^2 - p_{l\bar{l}}^2 = s - 2E_{l\bar{l}}\sqrt{s} + m_{l\bar{l}}^2$$

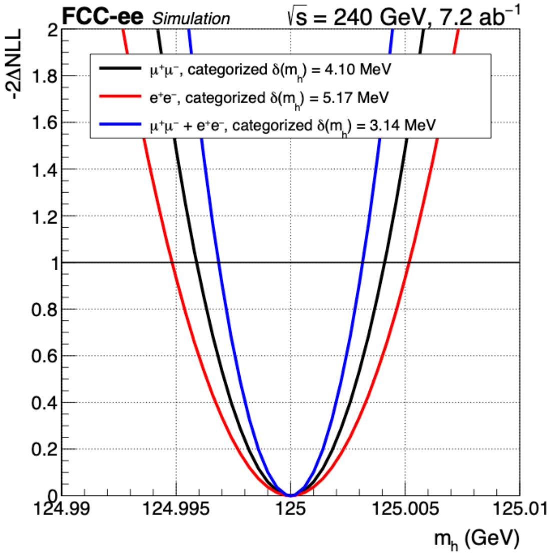


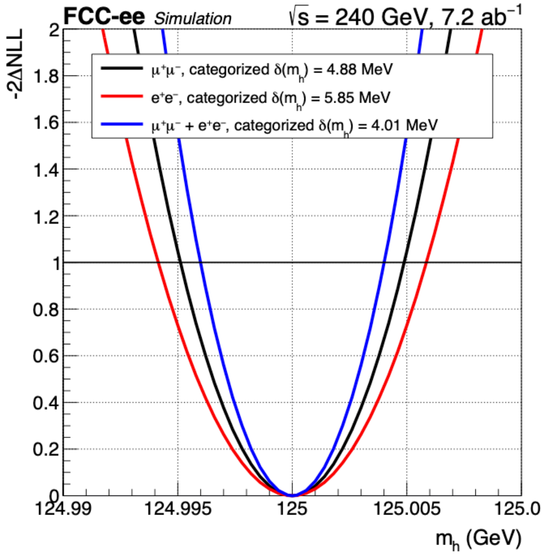


Higgs mass

$L_{int} = 7.2\, ab^{-1}$







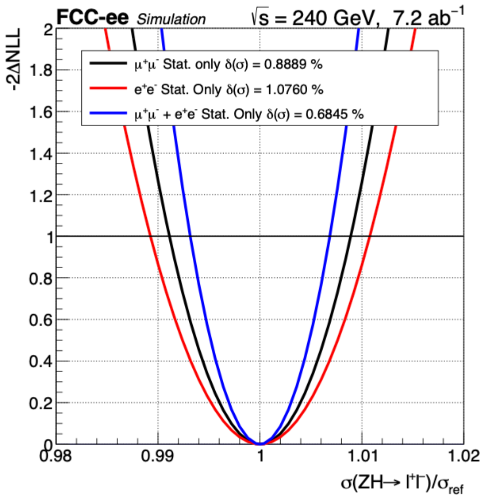
- Higgs mass, fit with analytic shape: $\sigma(m_H) = 3.1(4.0)$ **MeV stat(sys)**

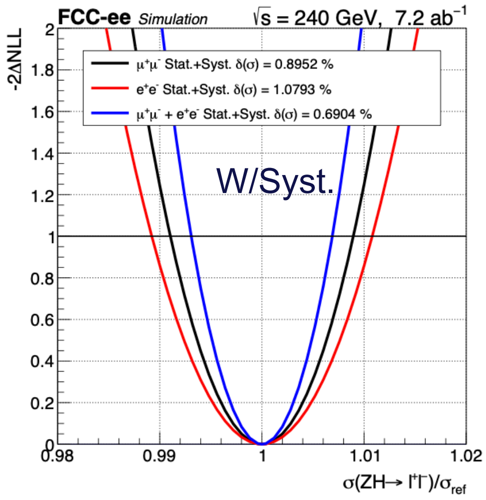
- Precise m(H) measurement is needed for a possible monochromatic run at $e^+e^- \to H$
- Several effects investigated to extract detector requirements

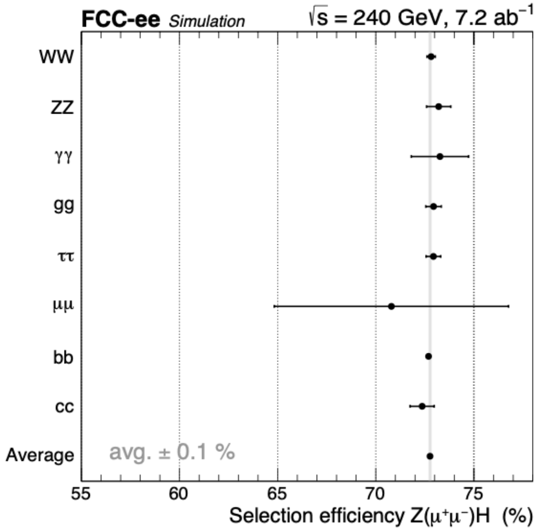
Total ZH production cross section

$L_{int} = 7.2\, ab^{-1}$

- Measuring the ZH cross-section in a model independent way is possible at electron-positron colliders.
  - Essential piece for "model independent" Higgs couplings determination (and more)
  - Estimated sensitivity (CDR) ~0.5%
- Challenge to keep analysis as much as possible a decay-mode independent
- Preliminary estimate from Delphes analysis: **combined uncertainty 0.68(0.69 w/syst)%**
  - Systematics considered: BES, √s, lepton energy scale





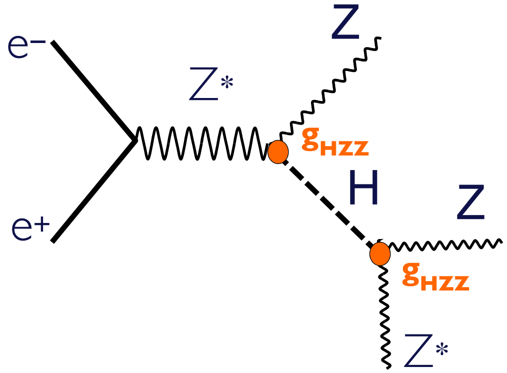


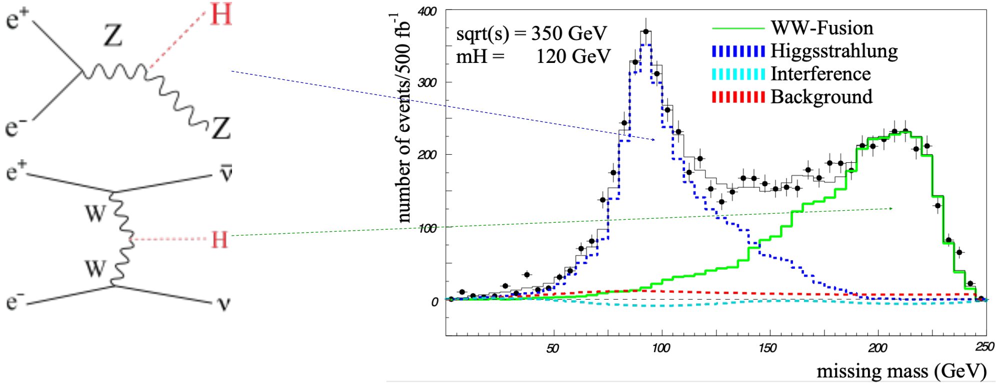
Higgs width (from 2019 CDR)

- Model independent determination of the total Higgs decay width down to 1.3% with runs at √s=240 and √s=365 GeV

ee →HZ & H → ZZ at √s = 240 GeV

WW → H νν→ bbνν at √s = 365 GeV





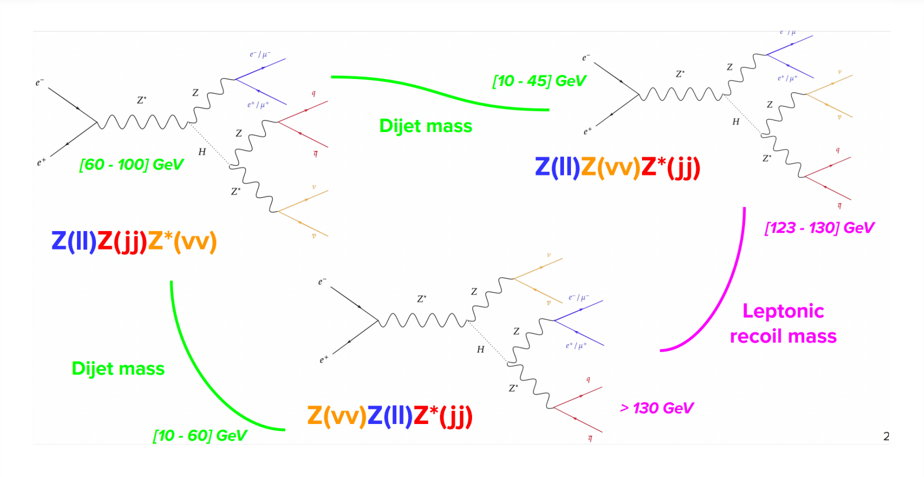
- σ_{HZ} is proportional to g_{HZZ}^2
- BR(H → ZZ) = Γ(H → ZZ) / Γ_H is proportional to g_{HZZ}^2 / Γ_H
  - σ_{HZ} × BR(H → ZZ) is proportional to g_{HZZ}^4 / Γ_H
- Infer the total width Γ_H

$$\Gamma_H \propto \frac{\sigma_{WW\to H}}{BR(H\to WW)} = \frac{\sigma_{WW\to H\to b\bar{b}}}{BR(H\to WW)\times BR(H\to b\bar{b})}$$

First analysis of the Higgs width

$L_{int} = 7.2\, ab^{-1}$

- First study at 240GeV $H \to ZZ^*$ (Delphes):
  - $Z(\ell^+\ell^-)Z(jj)Z(\nu\bar{\nu})$, one off-shell from Higgs decay
  - Orthogonal selection of the final states
  - Fit the BDT score
  - Determine the uncertainty on the Higgs width from the cross-section



$$\Gamma_H \propto \frac{\sigma^2_{ZH}}{\sigma_{ZH(ZZ^*)}}$$

$$\frac{\delta\Gamma_H}{\Gamma_H} \sim \frac{\delta\sigma(e^+e^- \to ZH, H \to ZZ)}{\sigma(e^+e^- \to ZH, H \to ZZ)} \sim 3.8\%$$

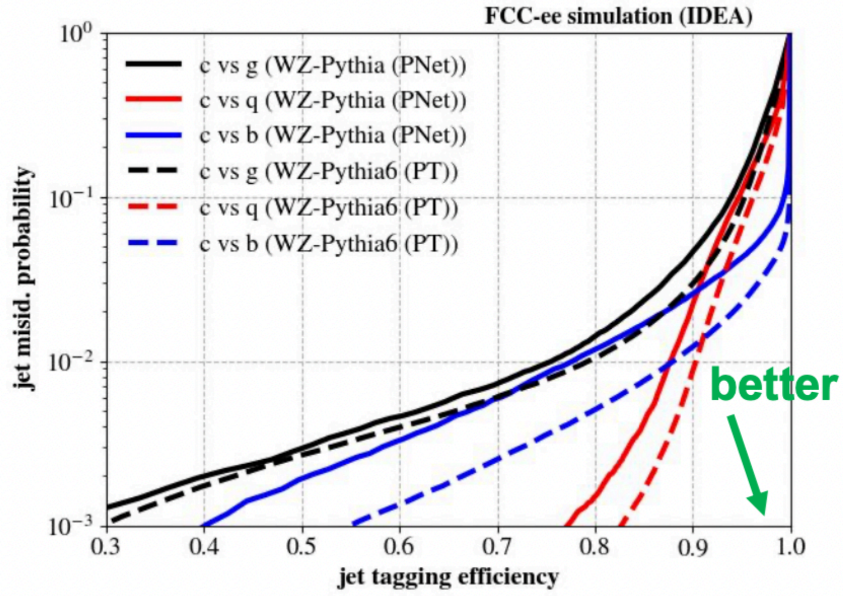
Other decay channels work in progress

ParticleNet 2202.03285 Gouskos, Selvaggi et al.
Delphes

A new tagger from CMS to FCC-ee: ParticleNet

- A must for any Higgs factory
  - Precise measurement of all Higgs couplings to ff, VV
  - H(cc), H(gg) won't be measured at HL-LHC
- Flavour tagging is the key
  - Algorithm based on state-of-the-art advanced Neural Networks
  - Evolving to include u,d and taus…

Relevant at all energies: Z, WW, Higgs & top



- Requirements on detector can be obtained:
  - Position of innermost layer of vertex as close as possible to the beam pipe.
    - Also smaller beam pipe
  - Particle ID capabilities (timing?)

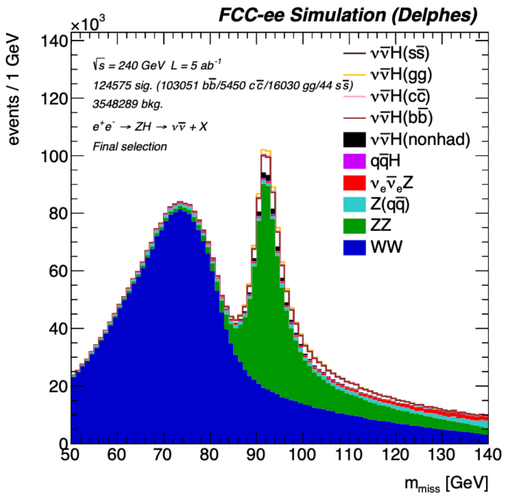
Few microns resolution needed on $\sigma(d_0)$
Requirements from tagging charm and more (s or tau) stricter than bottom

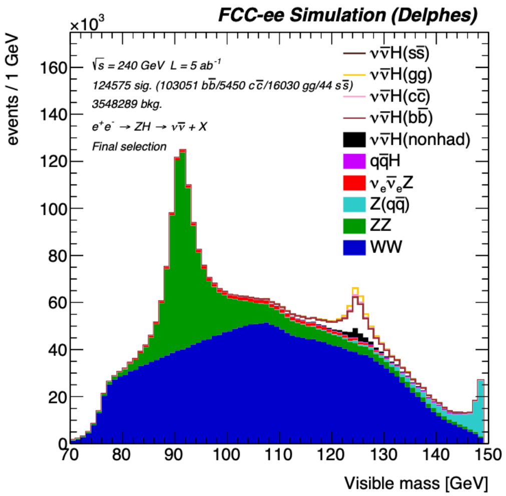
Higgs hadronic couplings

$L_{int} = 5.0\, ab^{-1}$

- Considering ZH process with $H \to b\bar{b}, c\bar{c}, s\bar{s}, gg$ (and other) and various Z final states:
  - $Z \to \ell^+\ell^-$: clean but smaller BR, fit to the Recoil Mass
  - $Z \to \nu\bar{\nu}$: Good efficiency and reasonable purity. 2D fit with the Visible Mass and the Missing Mass
  - $Z \to q\bar{q}$: will add significant statistical power. Work in progress.

Signal strength $Z \to \ell^+\ell^-$	Unc.%
$b\bar{b}$	0.81
$c\bar{c}$	4.93
gg	2.73
other	2.19
$s\bar{s}$	410



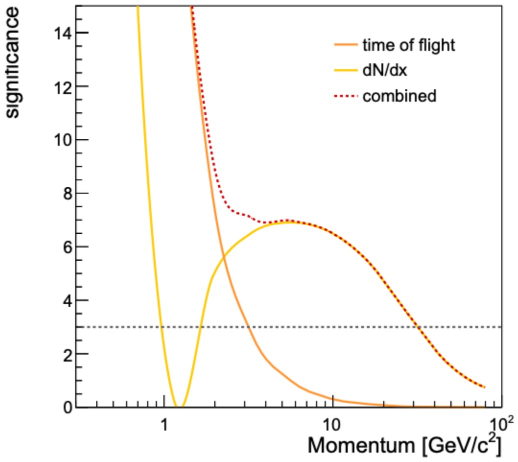


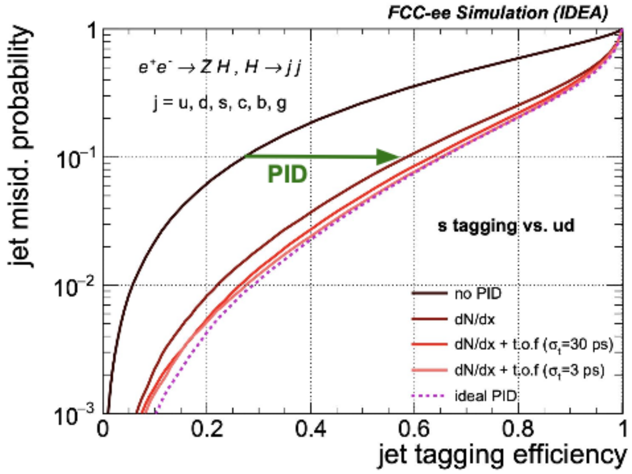
$Z \to \nu\bar{\nu}$ channel

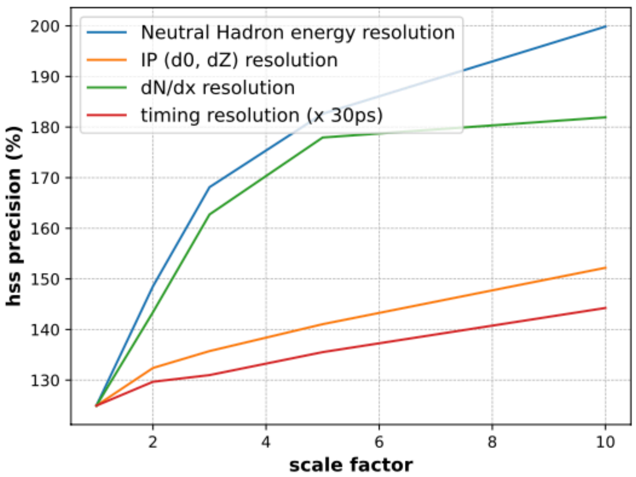
H→ bb̄	H→ cc̄	H→ ss̄	H→ gg
0.4	2.9	140	1.2

when scaled to $10\, ab^{-1}$
$\delta\mu(H \to s\bar{s}) \approx 100\,\%$ … intriguing

New opportunities: strange tagging







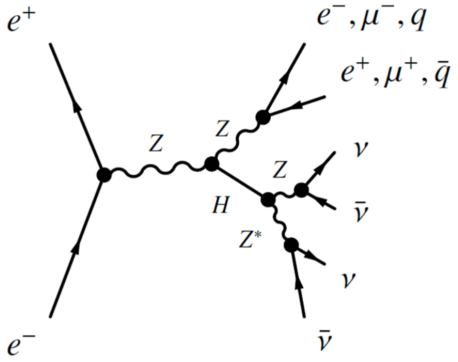
Adding in the Delphes simulation particle ID capabilities (dN/dx, dE/ dx) and time of flight measurement (30ps resolution for this plot)

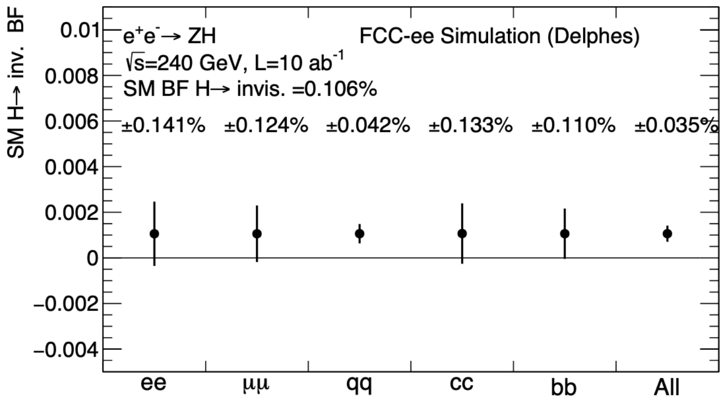
Training the ParticleNet with the additional information and comparing to ideal strange identification

Interesting to study the dependence on the uncertainties on the degradation of the detector performance

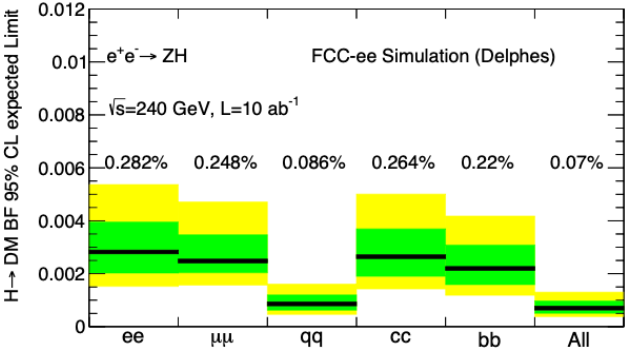
Higgs to invisible

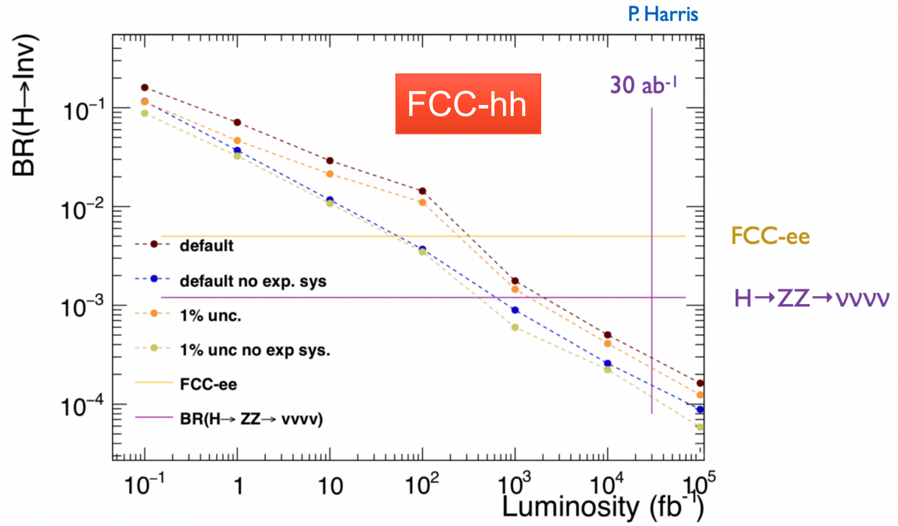
$L_{int} = 10\, ab^{-1}$





BR(SM) with ~45% uncertainty

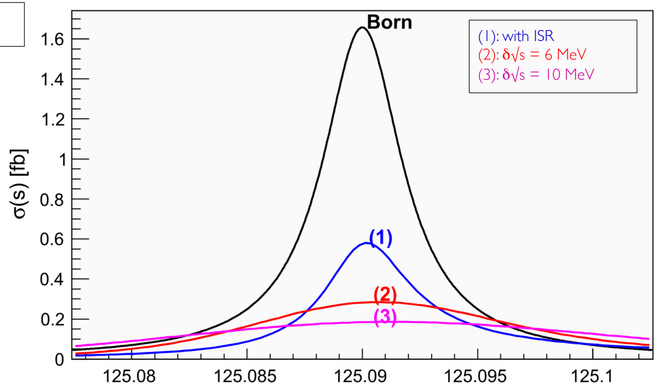




- If SM treated as background, sensitivity to EXO decays:
- **5σ for BR>0.18% and 95% exclusion if BR <0.07**

Electron Yukawa coupling

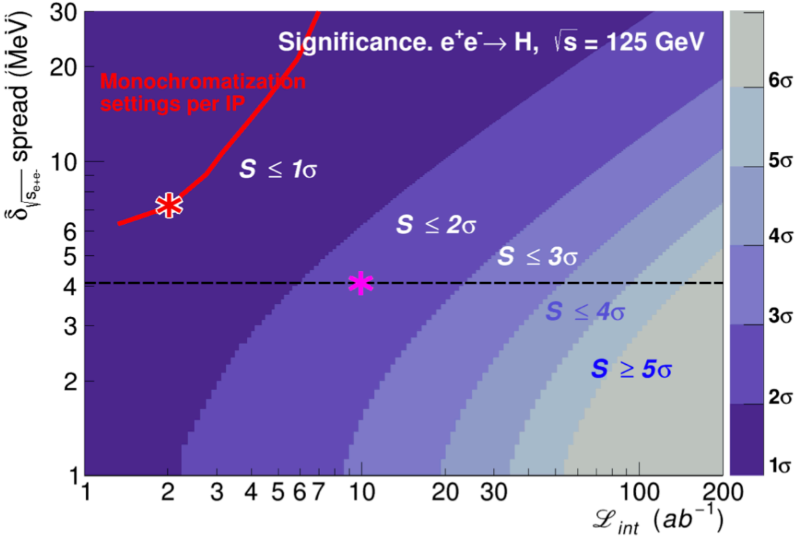
S. Jadach, R.A. Kycia
arXiv:1509.02406



- Something unique: electron Yukawa coupling from $e^+e^- \to H$
- One of the toughest challenges, which requires:
  - Higgs boson mass prior knowledge to a couple MeV
  - Huge luminosity (i.e., several years with possibly 4 IPs)
  - (Mono)chromatisation: Γ_H (4.2 MeV) ≪ $\delta_{\sqrt{s}}$ (100 MeV)
  - Continuous monitoring and adjustment of $\sqrt{s}$
  - Different e+ and e- energies (to avoid integer spin tune)
  - Extremely sensitive event selection against SM backgrounds

arXiv:2107.02686

$$\sigma_{ee\to H} = \frac{4\pi \Gamma_H \Gamma(H \to e^+e^-)}{(s - m_H^2)^2 + m_H^2 \Gamma_H^2},$$



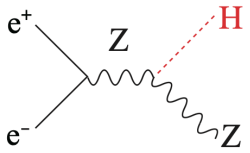
5y run @optimal monochromatization could achieve 1.7σ with 4IPs

Higgs self-coupling with single Higgs

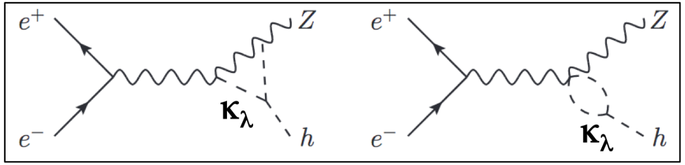
C. Grojean et al. arXiv:1711.03978

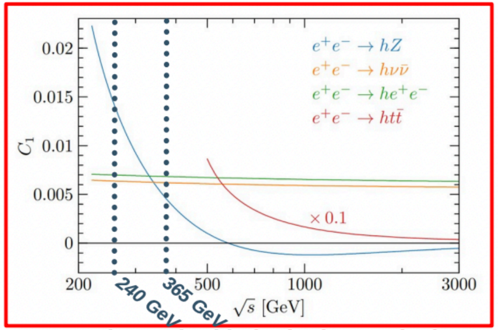
M. McCullough arXiv:1312.3322

σ_{HZ}



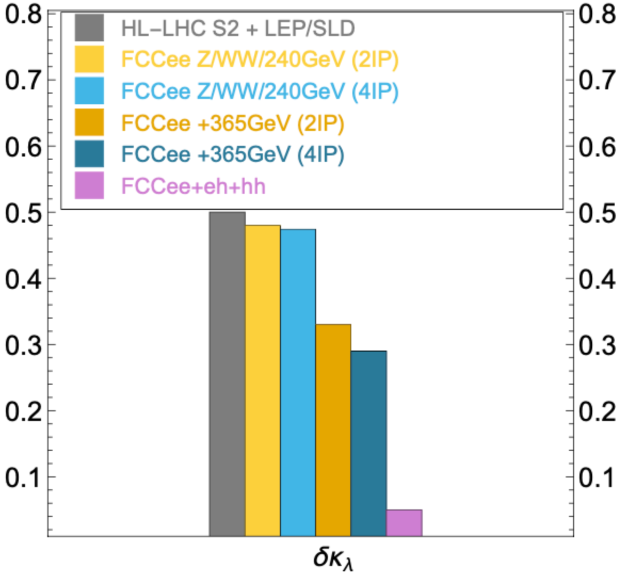
+



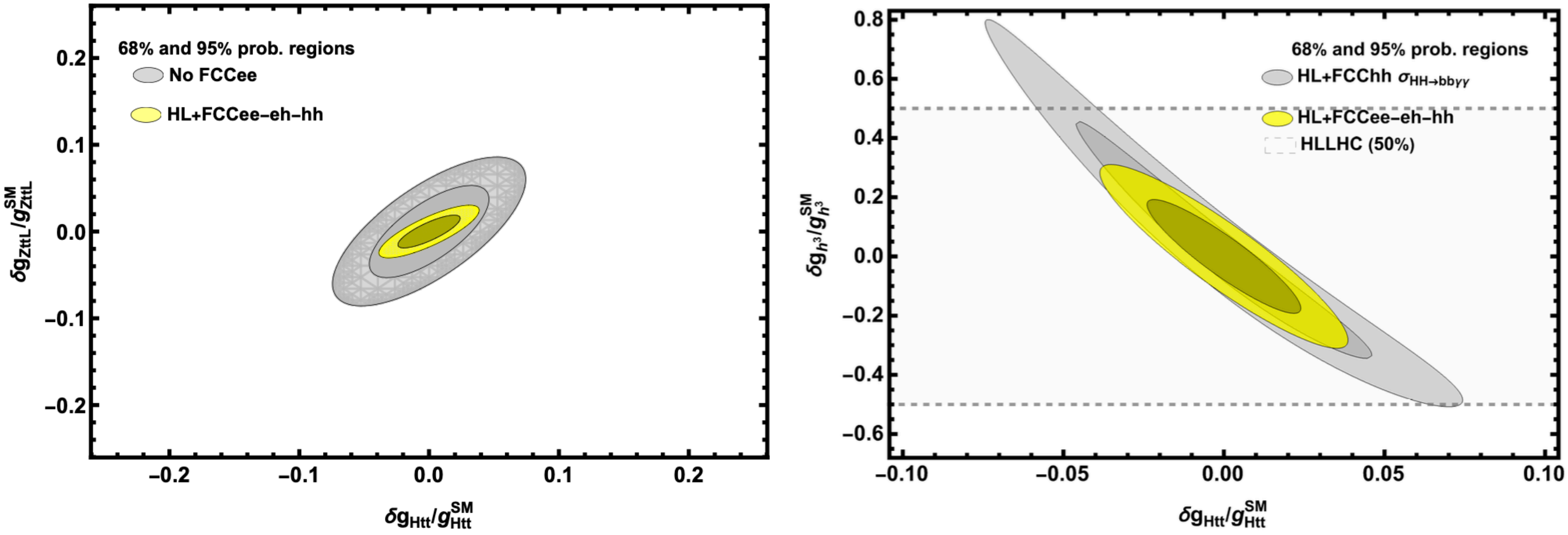


$$\Sigma_{\mathrm{NLO}} = Z_H \Sigma_{\mathrm{LO}}(1 + \kappa_\lambda C_1) \qquad \kappa_\lambda \equiv \frac{\lambda_3}{\lambda_3^{\mathrm{SM}}}$$

- The precision of FCC-ee on the ZH cross section measurement (0.1%) allows to exploit the higher order effects from the Higgs self-coupling and have an estimate of $\delta k_\lambda \approx 30\,\%$ with 4IPs
- Measurements at different √s (365GeV) needed to lift degeneracy between processes



FCC-ee & FCC-hh complementarity - k_t and k_λ

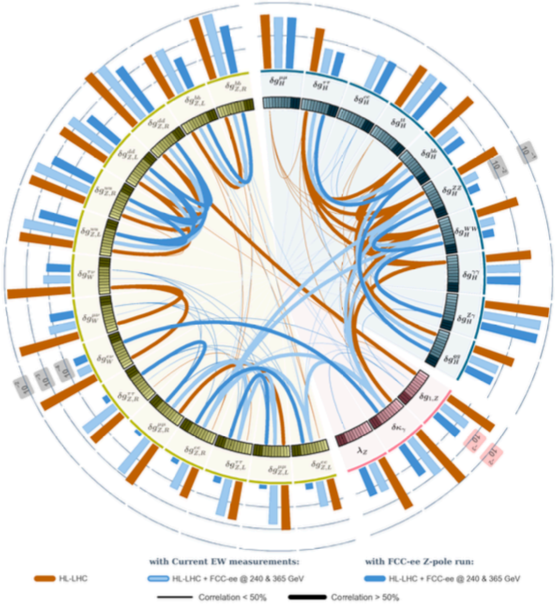


- The determination of the Ztt couplings from $e^+e^- \to t\bar{t}$ during the 365GeV run of the FCC-ee, in conjunction with the ttH/ttZ FCC-hh would help to **reduce the few per-cent uncertainty on δg_{tt} from the HL-LHC to ~1%.**
- Current estimates combining the $bb\gamma\gamma, bb\tau\tau, bbZZ, bbbb$ decay channels suggest that a precise determination of the self-coupling with an uncertainty of 3.4 − 7.8% would be within the reach of the 100 TeV pp collider

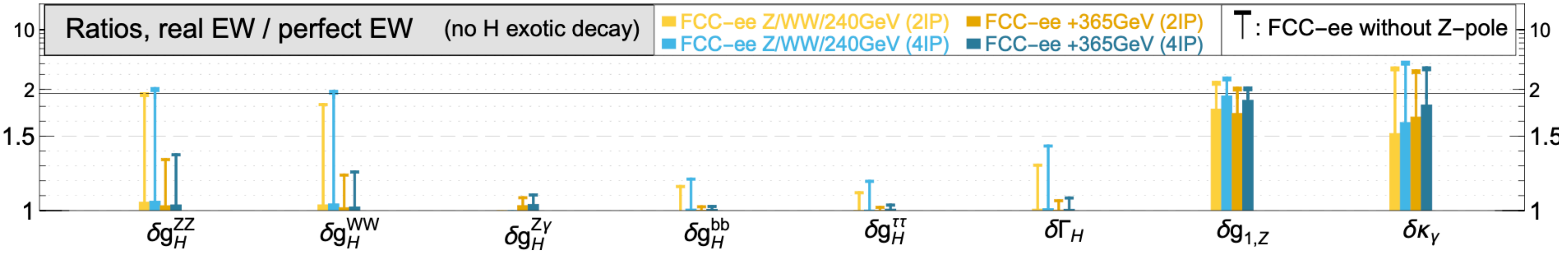
Interplay of EWK measurement on Higgs

https://doi.org/10.1140/epjp/s13360-021-01847-5
J. de Blas et al. in Snowmass 2021 (2022)

- Fit to new physics effects parameterised by dimension 6 SMEFT operators
    - Model independent result only for global fit
- The Z-pole run is essential to isolate Higgs measurements and ensure that uncertainties from EW coupling do not affect Higgs couplings
- The precision measurements of the Z pole run affect significantly Higgs operators: almost ideal if present, and a factor 2 worse if absent!



Dark blue= withTeraZ



Summary & next steps

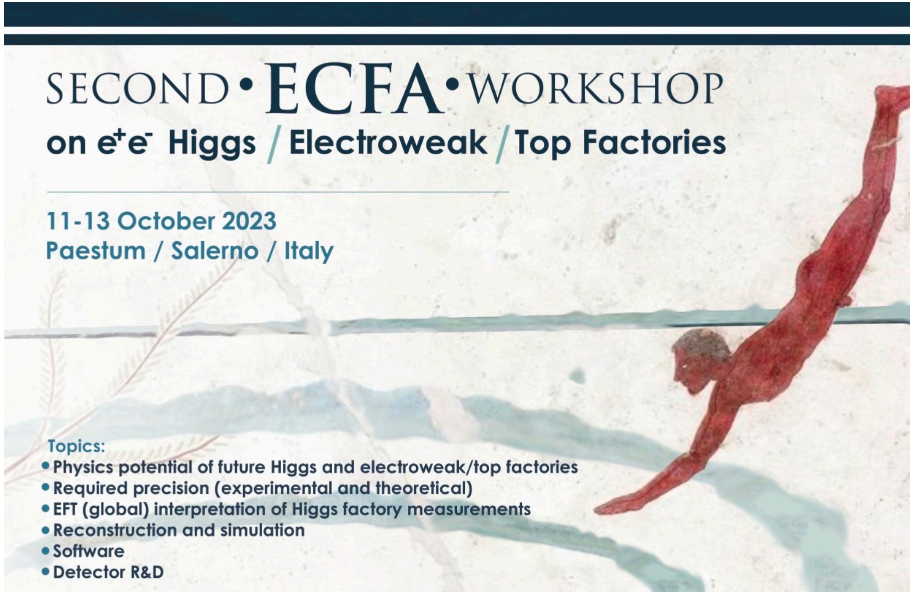
FCC-ee is the amazing Higgs factory HEP needs, and it brings so much more.

Lots of physics to be done by 4 experiments with different detectors

Best way to prepare the way for high energy exploration with FCC-hh

https://agenda.infn.it/event/34841/

- FCC Feasibility study ongoing: "mid-term" report coming out soon!
- Working full steam toward completion of the Feasibility study by 2025 to build the strongest case for the FCC project for the next European Strategy
- ECFA Workshop building a collaboration amongst all proposed Higgs Factories to share the knowledge across projects and educate the new generations



BACKUP

Detector effects

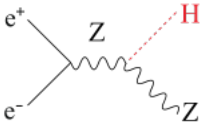
Some extended studies performed regarding detector effects

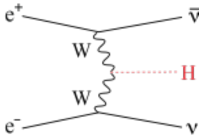
- Looking at impact on m_H resolution → to be compared to **stat-only (syst.), Nominal**
- ~ Going from crystal calorimeter to Dual readout (tight artificial smearing applied to electrons)
- Nominal 2 T field → 3 T (stronger field → better tracking)
- IDEA drift chamber → CLD silicon tracker
- Important impact of BES uncertainties
- Assuming "perfect" (== gen-level) momentum resolution → Not so far from the nominal

Fit configuration	$\mu^+\mu^-$ channel	e^+e^- channel	combination
Nominal	4.10 (4.88)	5.17 (5.85)	3.14 (4.01)
Inclusive	4.84 (5.53)	6.16 (6.73)	3.75 (4.50)
Degradation electron resolution (*)	4.10 (4.88)	5.98 (6.49)	3.32 (4.11)
Magnetic field 3T	3.38 (4.28)	4.30 (5.00)	2.60 (3.54)
CLD 2T (silicon tracker)	5.51 (6.07)	6.20 (6.70)	4.01 (4.66)
BES 6% uncertainty	4.10 (5.01)	5.17 (6.10)	3.14 (4.09)
Disable BES	2.27 (3.42)	3.11 (4.04)	1.80 (2.99)
Ideal resolution	2.89 (3.95)	3.89 (4.56)	2.39 (3.33)
Freeze backgrounds	4.10 (4.88)	5.17 (5.85)	3.14 (4.00)
Remove backgrounds	3.37 (4.34)	3.85 (4.80)	2.49 (3.56)

FCC Synergies: The Higgs boson

$\sqrt{s}$ = 240 GeV





$\sqrt{s}$ = 365 GeV

FCC-ee provides 10^6 HZ + 10^5 WW → H events

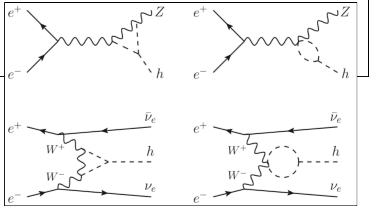
Absolute determination of g_{HZZ} to ±0.17%

Model-independent determination of Γ_H to ±1%

→ Fixed « candle » for all other measurements
including those made at HL-LHC or FCC-hh

→ Measure couplings to WW, bb, ττ, cc, gg, …
Even possibly the Hee coupling!

→ First sensitivity to g_{HHH} to ~30% with 4IPs



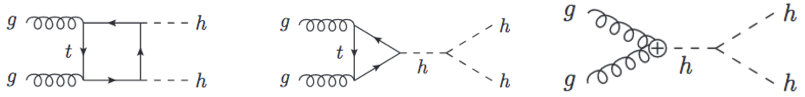
FCC-hh provides 3×10^{10} Higgs bosons

With this huge sample and using the FCC-ee candle

→ Model-independent ttH coupling to < 1%
(HL-LHC and FCC-ee give ±2.6%)
Use ±1% ttZ measurement at FCC-ee

→ Rare decays: couplings to μμ, γγ, Zγ …

→ Higgs self coupling g_{HHH} to ±3%
With double-Higgs production



FCC-eh provides 2.5 10^6 Higgs bosons

With the FCC-ee candle, further improves on several measurements (e.g., g_{HWW})