Future Circular Collider Physics prospects

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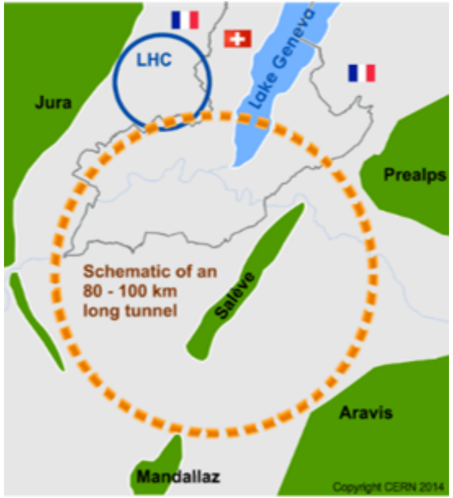
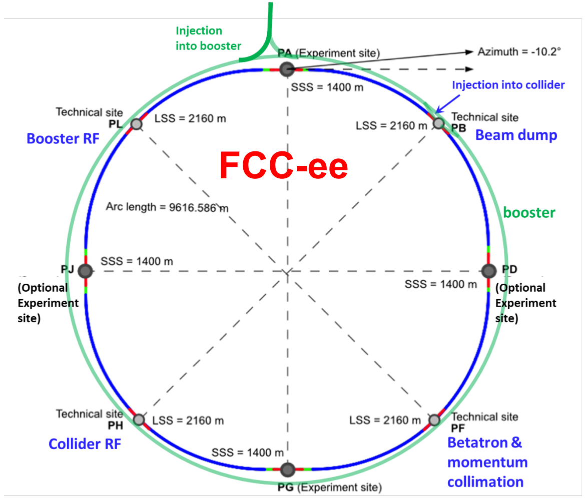
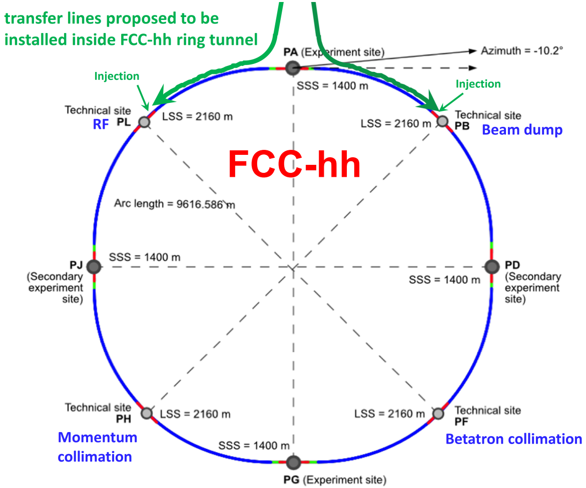
FCC integrated program

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

Slide from Micheal Benedikt

Main geometrical parameters

Main changes

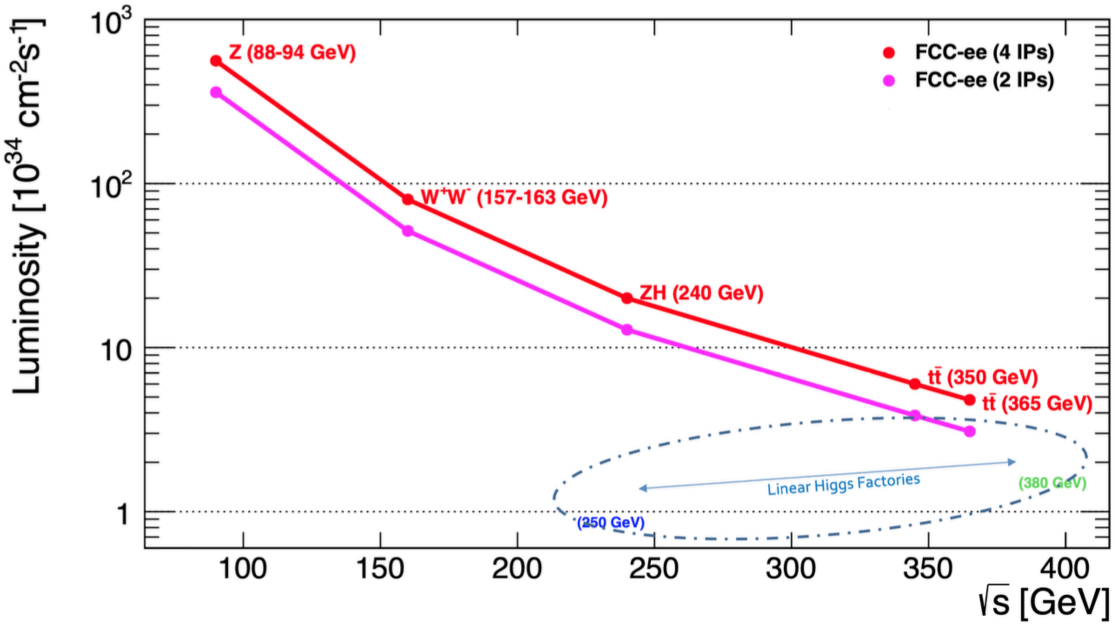
- **# access points** reduced from 12 to 8
- facilitating placement and reducing the overall surface area required
- **circumference has shrunk** from 97.75 km to 90.657 km
- new layout with **4-fold superperiodicity**, enabling FCC-ee operation with either **2 or 4 collision points**
- **hadron collider** 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 [illegible]

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

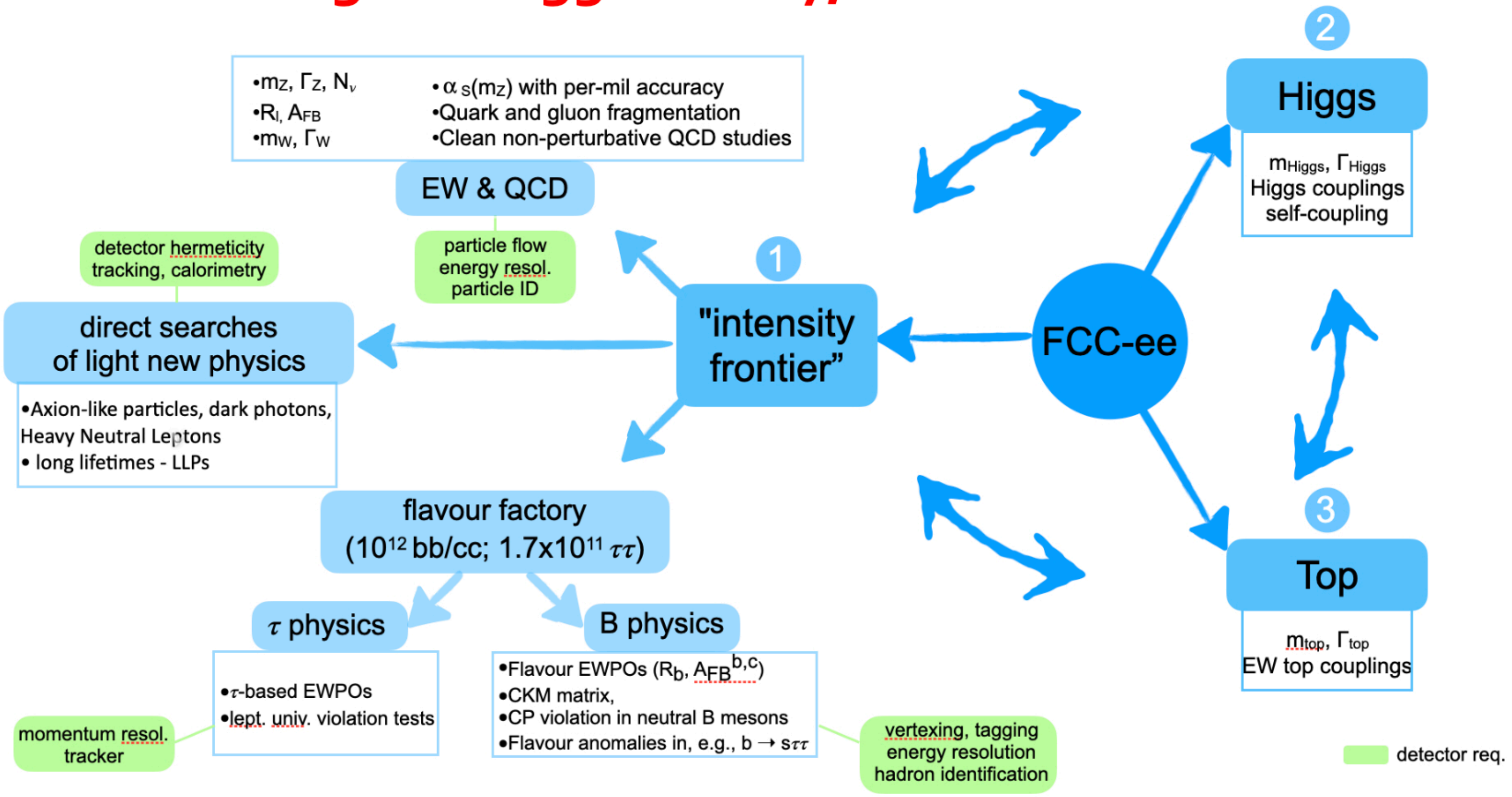
FCC-ee Energy range & luminosity

- 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	

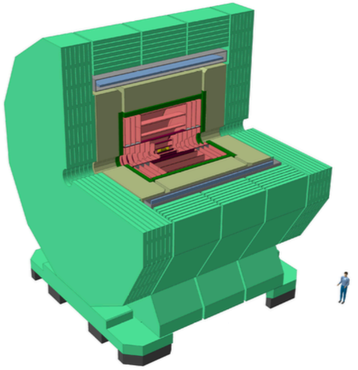
FCC-ee: a great Higgs factory, and so much more



Few baseline detector concepts for FCC-ee

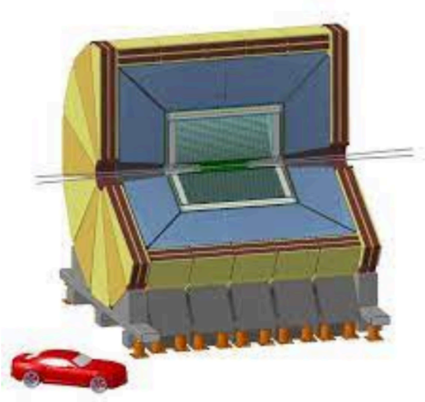
CLIC-like Detector (CLD)

- Full silicon vertex-detector + tracker
- 3D high-granularity calorimeter
- Solenoid outside calorimeter



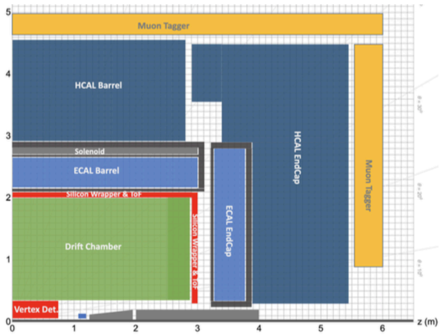
Innovative Detector for an Electron-Positron Accelerator (IDEA)

- Silicon vertex detector
- Short-drift chamber tracker
- Dual-readout calorimeter (solenoid inside)



Noble Liquid

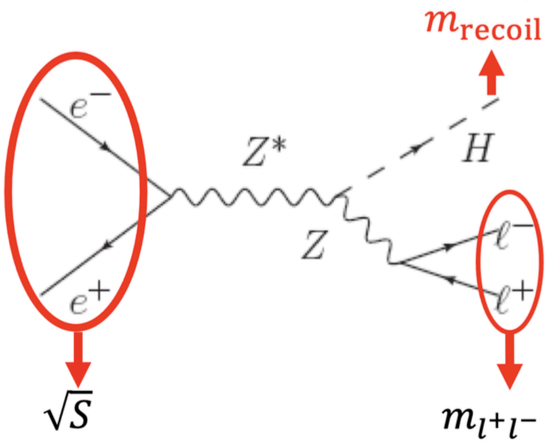
- High-granularity noble liquid calorimeter
- LAr or Lar + Lead or Tungsten absorber
- Newest proposal

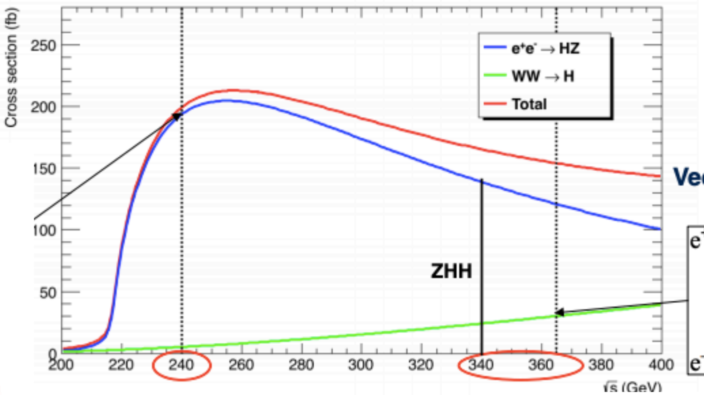


- In the process of extracting the requirement on the detector performance from the physics
  - With 4IP, opportunity to have detector optimised for specific processes
- Spoiler: “Higgs factory” requirements are not the most stringent

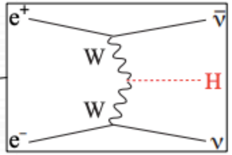
Higgs production at FCC-ee & the recoil method

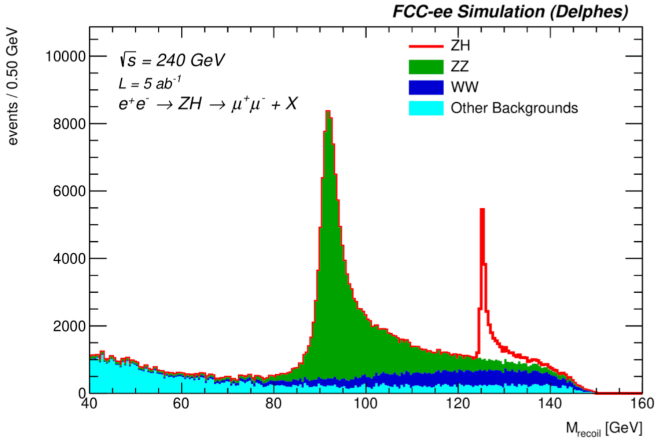
Higgs strahlung





Vector Boson Fusion





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

- Allows model independent determination of couplings

Higgs coupling precision expectations

			FCC-ee	FCC-Int
Collider	HL-LHC	+ 240 GeV	+ 240 +365 GeV	+ FCC-hh
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

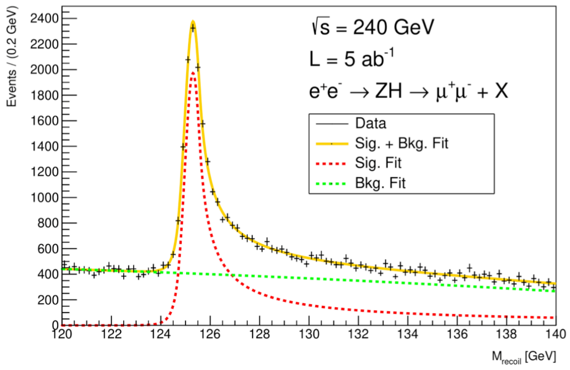
Table adapted from arxiv:1905.03764

- 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

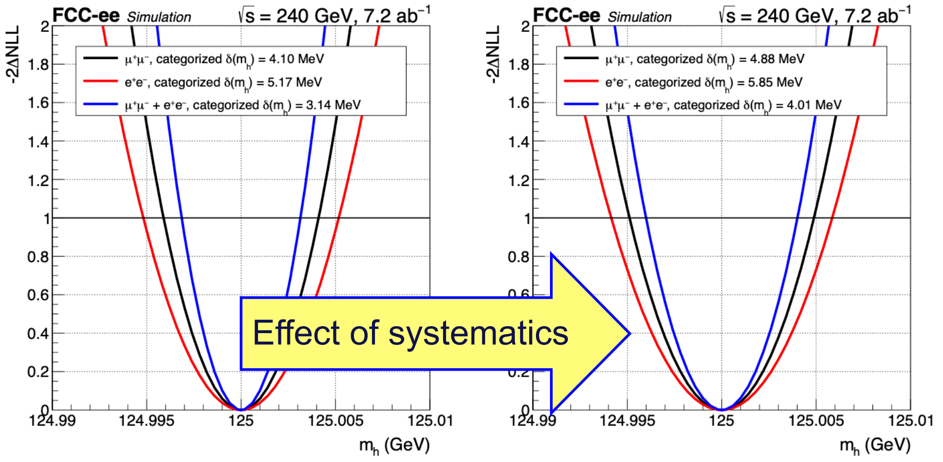
- FCC-hh produces over 10^{10} Higgs bosons, 10^8 ttH and 2×10^7 HH pairs:
  - Improving precision on g_{Htt}, g_{HHH}
    - with top EW couplings (and other BRs) measured at FCC-ee
  - Access to Rare Decays: $\mu\mu, \gamma\gamma, Z\gamma$

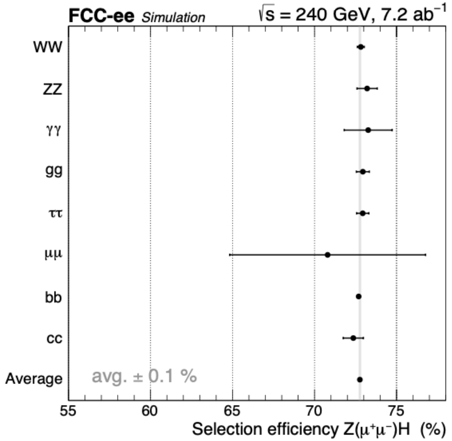
- **FCC-ee + FCC-hh is outstanding:**
  - All accessible couplings with per-mil precision
  - Self-coupling with per-cent precision

Higgs mass & cross section



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



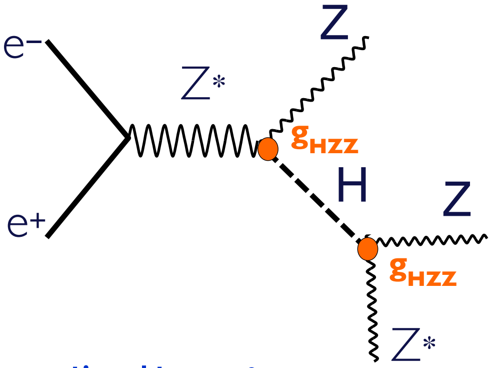


- Higgs mass, fit with analytic shape: $\sigma(m_H) = 3.1(4.0)$ **MeV stat(sys)**
  - Precise m(H) measurement is needed for a possible monochromatic run at $e^+e^- \rightarrow H$
- Model independent ZH cross-section crucial for Higgs couplings (and more)
  - Estimated sensitivity in CDR ~0.5%
  - Challenge to keep analysis as much as possible a decay-mode independent
- (Preliminary) **combined uncertainty 0.68(0.69 w/syst)%**
  - Systematics considered: BES, √s, lepton energy scale

Higgs width

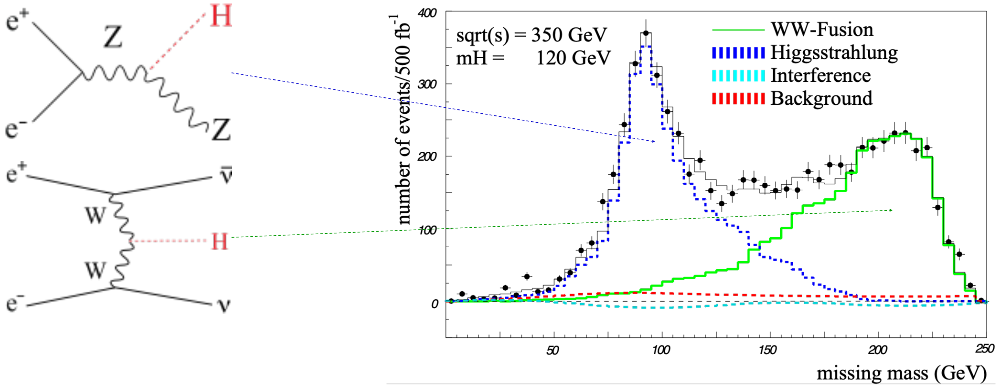
- **Model independent determination of the total Higgs decay width down to 1.3% with runs at √s=240 and √s=365 GeV**
- First analysis in progress on the $Z(\ell^+\ell^-)Z(jj)Z(\nu\bar{\nu})$ channel.

ee →HZ & H → ZZ at √s = 240 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**

WW → H νν→ bbνν at √s = 365 GeV



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

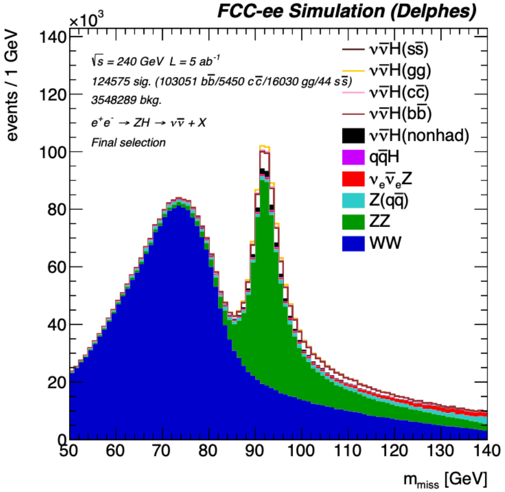
Higgs hadronic couplings

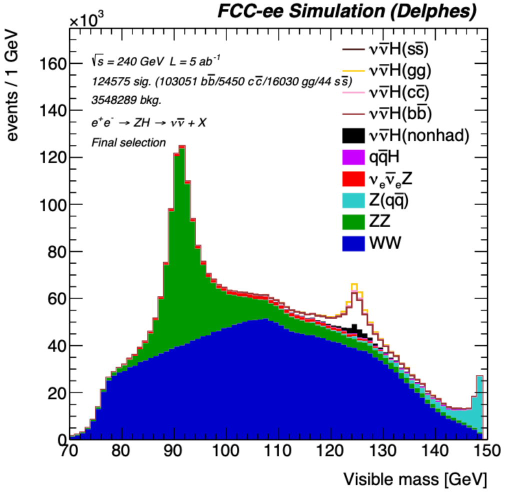
10.17181/9pr7y-3v657 Del Vecchio, Gouskos, Marchiori, Selvaggi

- 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.

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

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





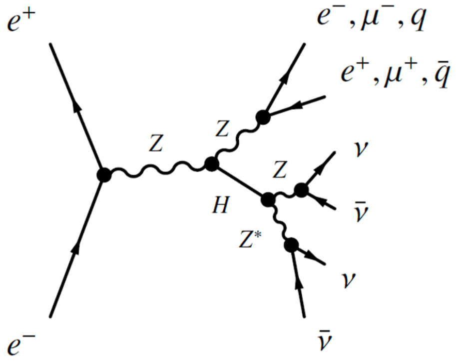
$Z \to \nu\bar{\nu}$ channel

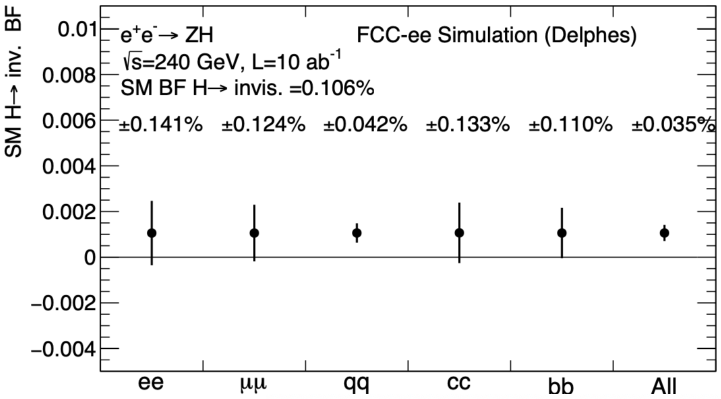
$H \to b\bar{b}$	$H \to c\bar{c}$	$H \to s\bar{s}$	$H \to gg$
0.4	2.9	140	1.2

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

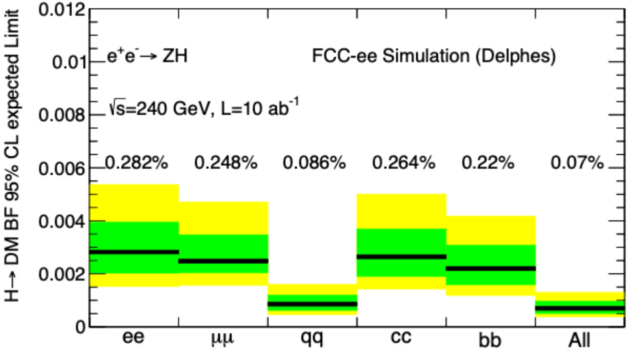
$L_{int} = 10\,ab^{-1}$

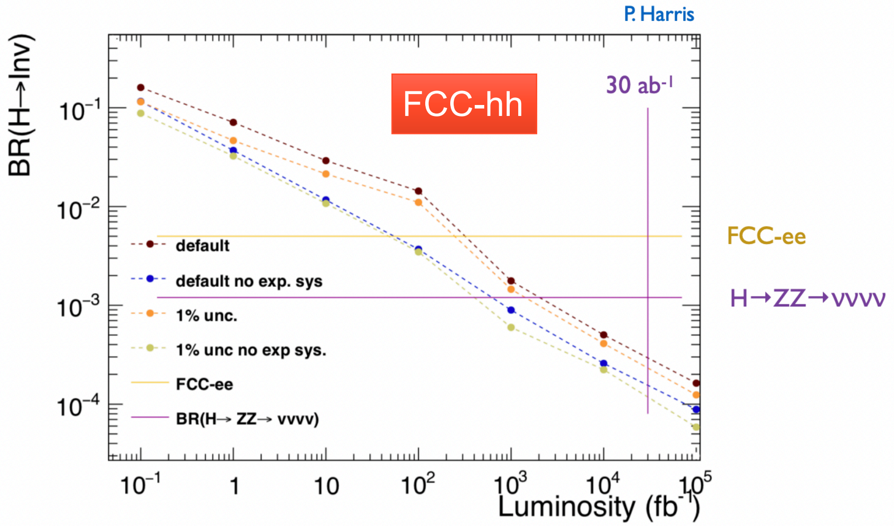
Higgs to invisible





BR(SM) with ~45% uncertainty



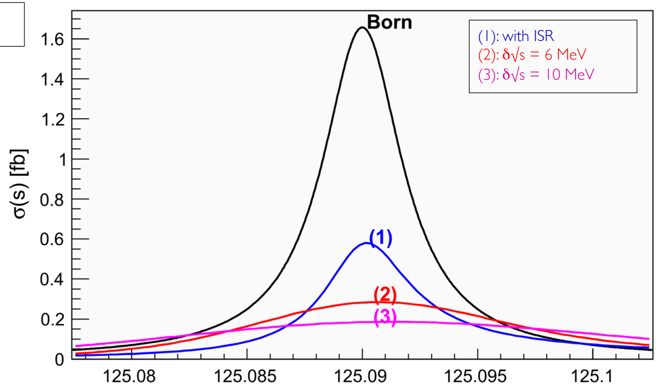


- If SM treated as background, sensitivity to EXO decays:
- **5σ for BR>0.18% and 95% exclusion if BR <0.07**

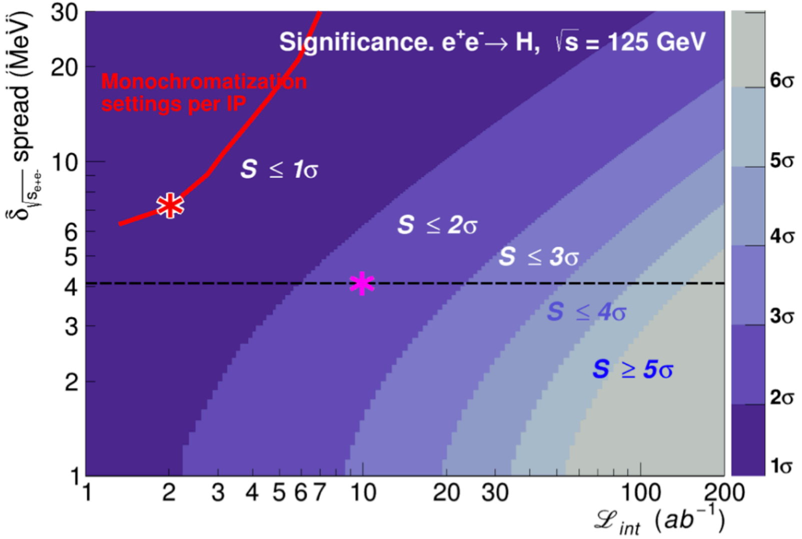
Electron Yukawa coupling *(unique!)*

arXiv:2107.02686

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



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



- 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 √s
  - Different e+ and e- energies (to avoid integer spin tune)
  - Extremely sensitive event selection against SM backgrounds

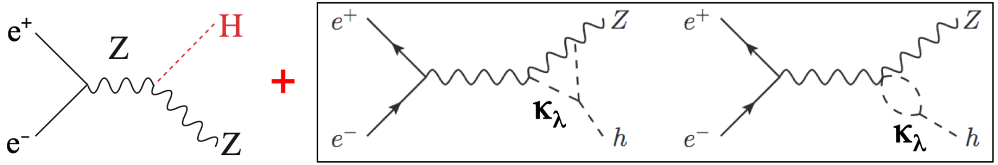
5y run @optimal monochromatization could achieve 1.7σ with 4IPs

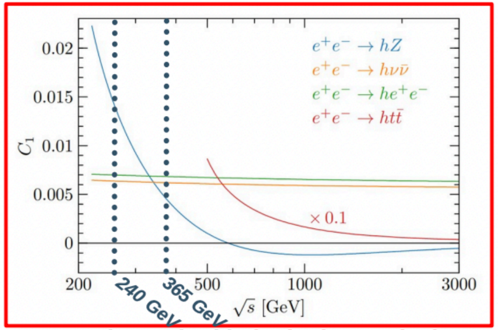
Higgs self-coupling with single Higgs

C. Grojean et al. arXiv:1711.03978

M. McCullough arXiv:1312.3322

σ_{HZ}

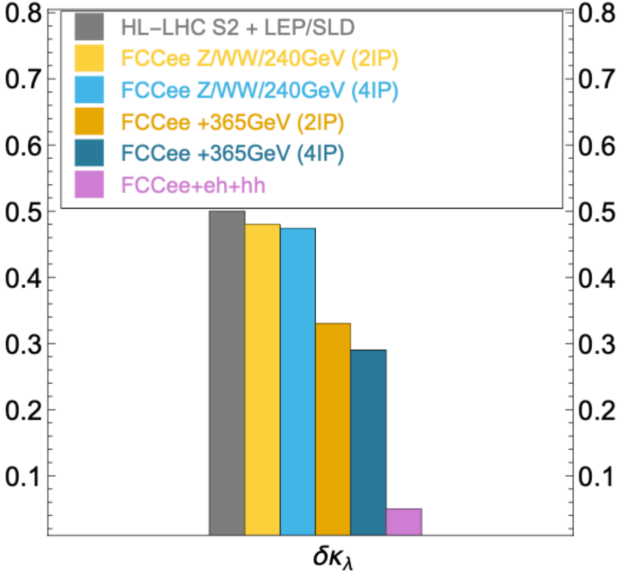




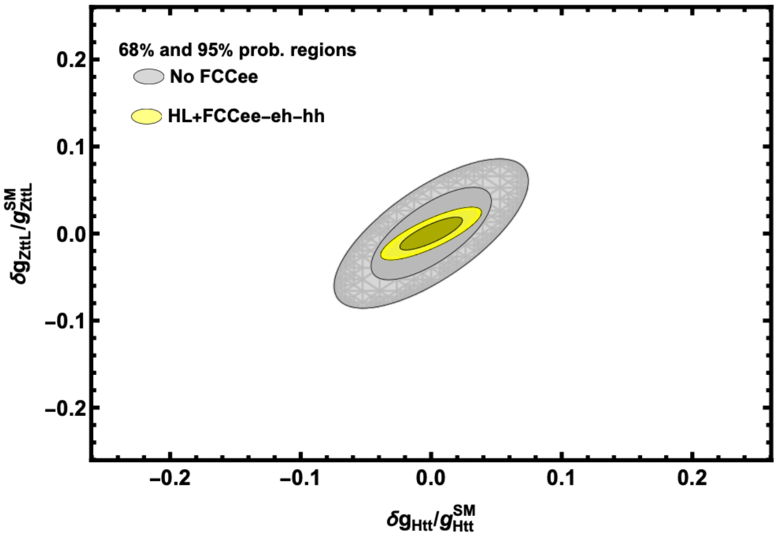
$$\Sigma_{\rm NLO} = Z_H \Sigma_{\rm LO}(1 + \kappa_\lambda C_1) \qquad \kappa_\lambda \equiv \frac{\lambda_3}{\lambda_3^{\rm SM}}$$

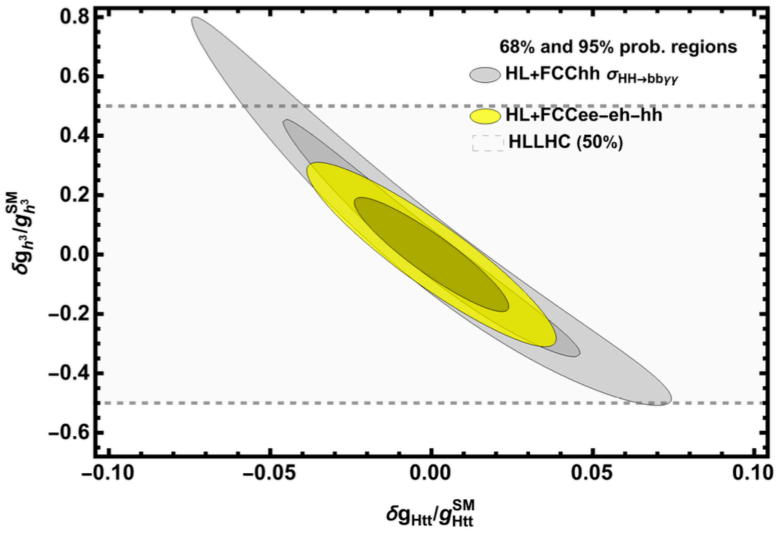
- The precision of FCC-ee on the ZH cross section measurement (0.1%) allows to exploit the higher order effects from the Higgs self-coupling and have an estimate of $\delta k_\lambda \approx 30\,\%$ with 4IPs

- Measurements at different √s (365GeV) needed to lift degeneracy between processes



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

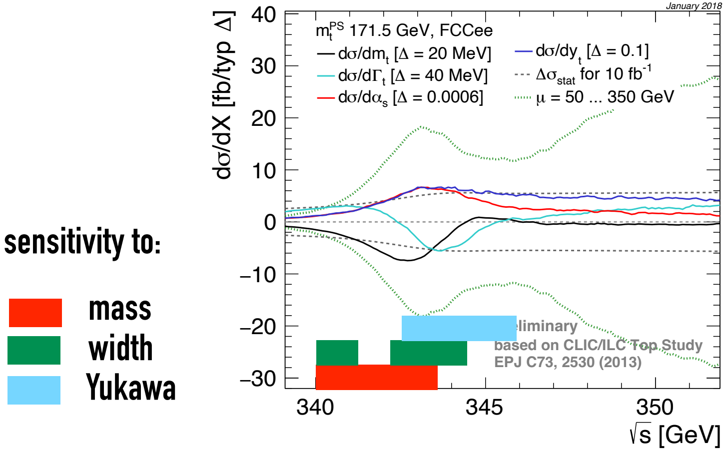


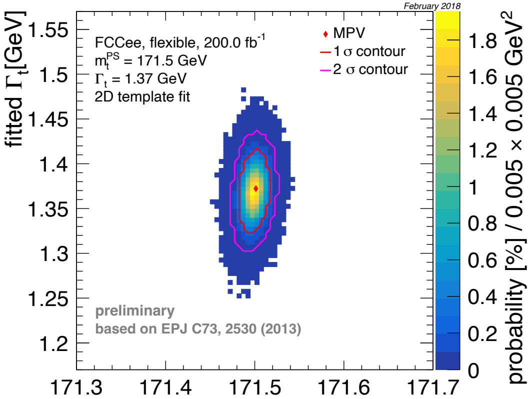


- The determination of the Ztt couplings from $e^+e^- \to t\bar{t}$ during the 365GeV run of the FCC-ee, in conjunction with the ttH/ttZ FCC-hh would help to **reduce the few per-cent uncertainty on δg_{tt} from the HL-LHC to ~1%.**
- Current estimates combining the $bb\gamma\gamma$, $bb\tau\tau$, $bbZZ$, $bbbb$ 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

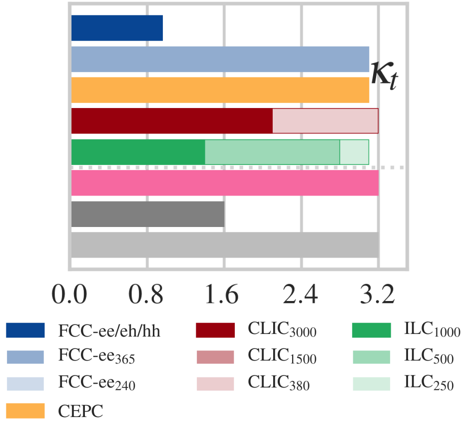
Top physics

- 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 (αs [2 x 10-4]), 44 MeV (theo)

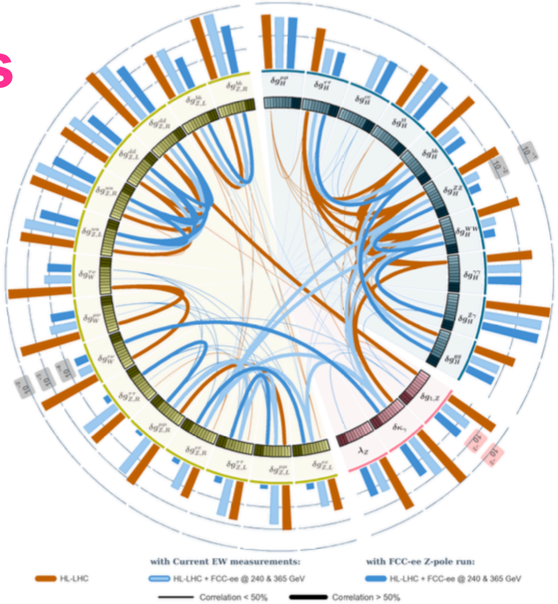


➤ **Run at 365 GeV used also for measurements of top EWK couplings (at the level of 10^{-2}-10^{-3}) and FCNC in the top sector.**

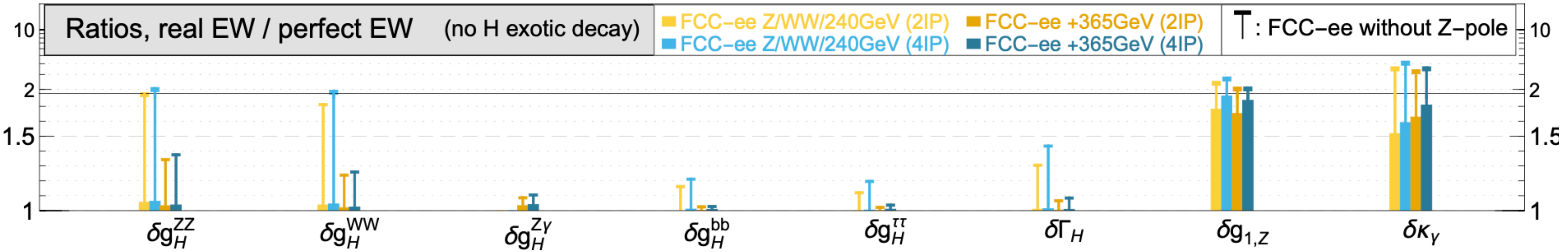
Interplay of EWK measurement on Higgs

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!



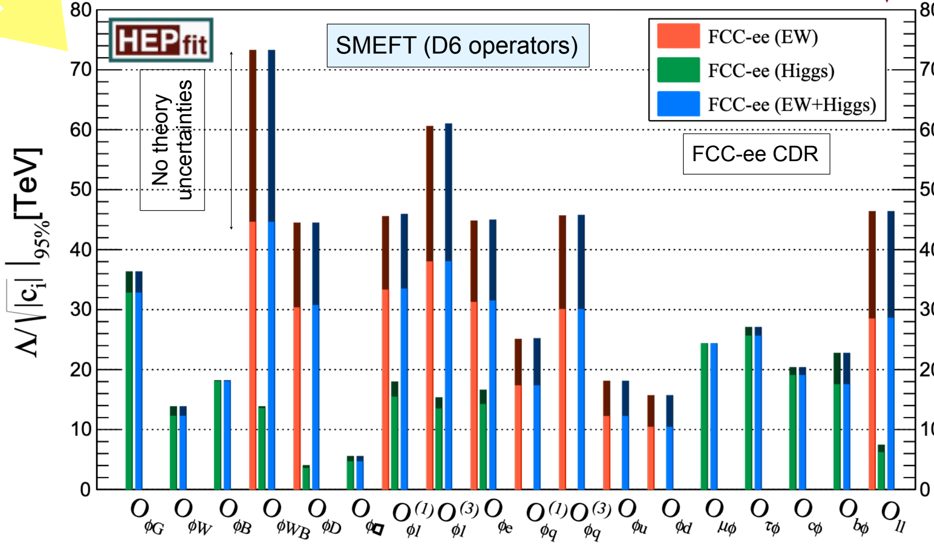
Dark blue= withTeraZ



arXiv:2106.13885

Indirect BSM sensitivity

- 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
$\sin^2\theta_W^{eff}(\times10^6)$	231480 ± 160	**2**	2.4	from $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{QED}(m_Z^2)(\times10^3)$	128952 ± 14	**3**	small	from $A_{FB}^{\mu\mu}$ off peak QED&EW errors dominate
$R_\ell^Z\ (\times10^3)$	20767 ± 25	**0.06**	0.2-1	ratio of hadrons to leptons **acceptance for leptons**
$\alpha_s(m_Z^2)\ (\times10^4)$	1196 ± 30	**0.1**	0.4-1.6	from R_ℓ^Z above
$\sigma^0_{had}\ (\times10^3)$ (nb)	41541 ± 37	**0.1**	4	peak hadronic cross section luminosity measurement
$N_\nu(\times10^3)$	2996 ± 7	**0.005**	1	Z peak cross sections Luminosity measurement
$R_b\ (\times10^6)$	216290 ± 660	**0.3**	< 60	ratio of $b\bar{b}$ to hadrons stat. extrapol. from SLD
$A_{FB}^{b},0\ (\times10^4)$	992 ± 16	**0.02**	1-3	b-quark asymmetry at Z pole from jet charge
$A_{FB}^{pol,\tau}\ (\times10^4)$	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
Γ_W (MeV)	2085 ± 42	**1.2**	0.3	From WW threshold scan Beam energy calibration
$\alpha_s(m_W^2)(\times10^4)$	1170 ± 420	**3**	small	from R_ℓ^W
$N_\nu(\times10^3)$	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
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

Z

W

top

Flavor Factory opportunities with the Tera-Z run

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, 2x10^{11} ττ events**
- **Clean environment**
- **Favourable kinematics -> boost**
- **Excellent vertexing (smaller beam pipe)**

PROMISING OBSERVABLES

- Rare b-hadron decays with $\tau\bar{\tau}$ 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.

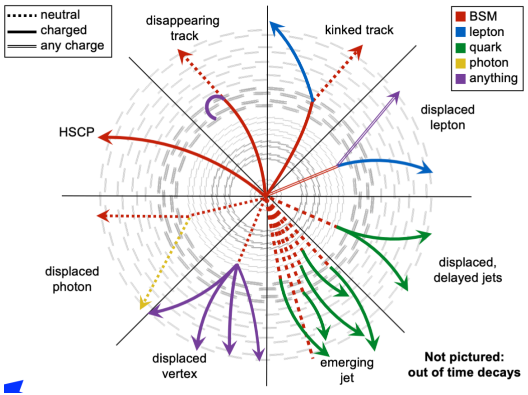
Discovery opportunity: BSM Rare processes FIP

- Intensity frontier at Tera-Z offers the opportunity to directly observe new feebly interacting particles in a very clean environment

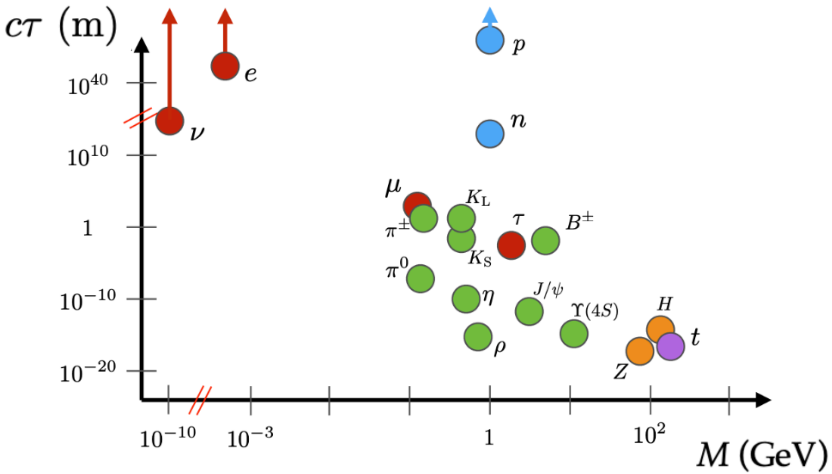
Detector Requirements

- Invisible final states ⇒ Detector hermeticity
- Sensitivity to far-detached vertices (mm → m)
  - Tracking: more layers, continuous tracking
  - Calorimetry: granularity, tracking capability
  - Muon detectors: standalone tracking capability
- Timing
- Larger decay lengths ⇒ extended detector volume (external detectors?)
- *Unusual final states ⇒ ad-hoc reconstruction*

Focus on long lived particles searches



Standard model particles span a **wide range of lifetimes (τ)**

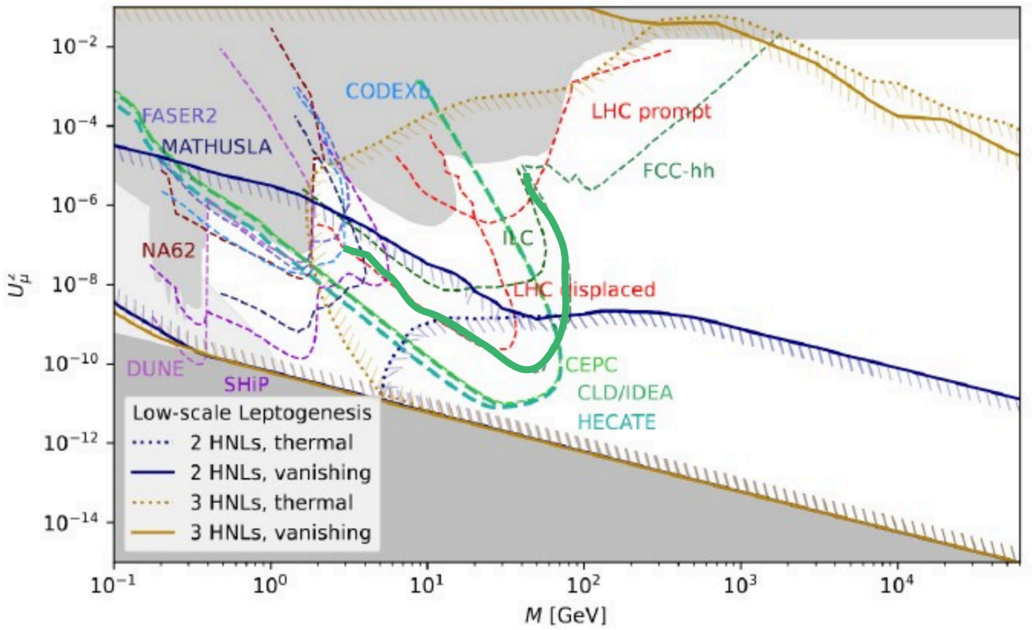


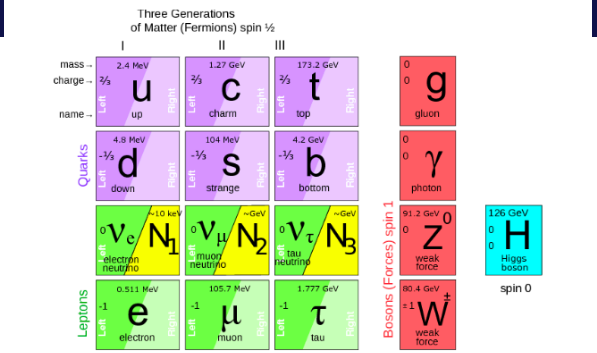
- **Wide variety** of:
  - Charges
  - Final states
  - Decay locations
  - Lifetimes
- Design **signature-driven** searches

- Opportunities from the clean environment of the FCC-ee
- Few concrete examples: **HNL, ALPS, Dark photons**

Heavy Neutral Leptons

Assume for FCC-ee 5x1012 Z produced





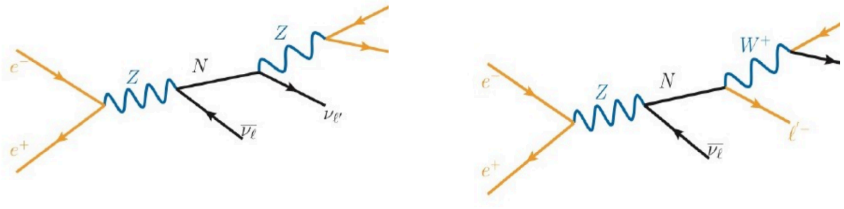
arXiv:2203.05502

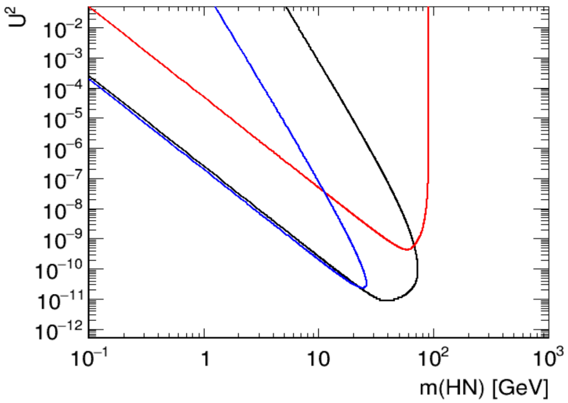
- Dirac or Majorana sterile neutrinos with very small mixing with active neutrinos
  - Could provide answers to some open questions of the SM: Neutrino masses, Baryon asymmetry, Dark matter

- FCC will probe space not constrained by astrophysics or cosmology, complementary to fixed target, neutrino, and 0vbb prospects
  - Possible to test Type-I SeeSaw models and Leptogenesis

G. Polesello, N. Valle

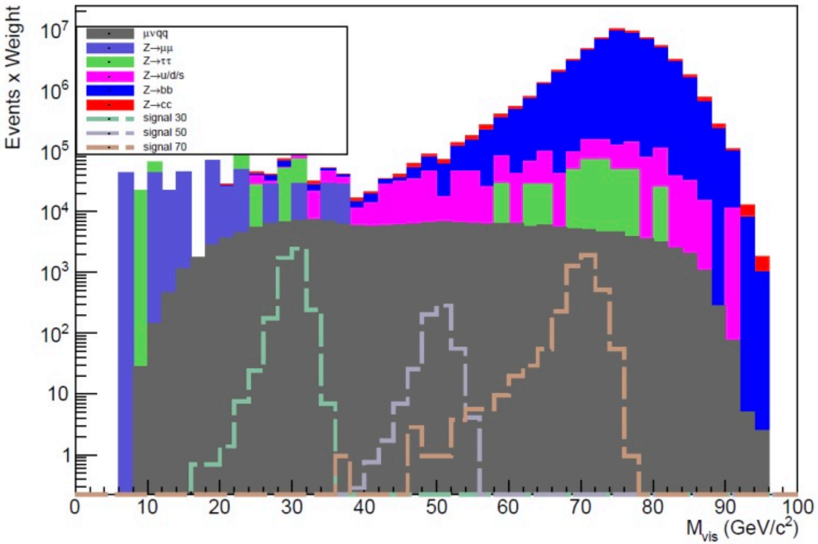
HNL: $N \to \mu jj$





Assume 1 flavour active
5×10^{12}Z at Z peak
Require 100 events for prompt decay and
4 events for long-lived

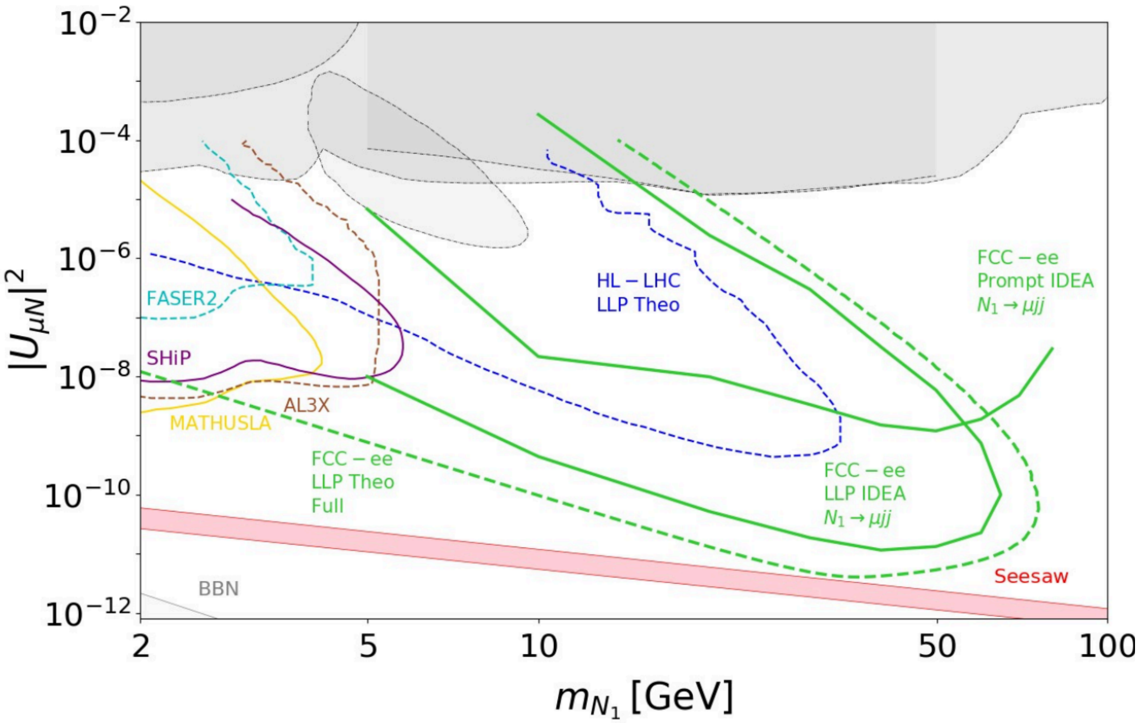
Red: Prompt:
0< λ < 1mm
Black:ID decay
0.04<λ< 150 cm
Blue: Calo decay
200<λ< 450 cm

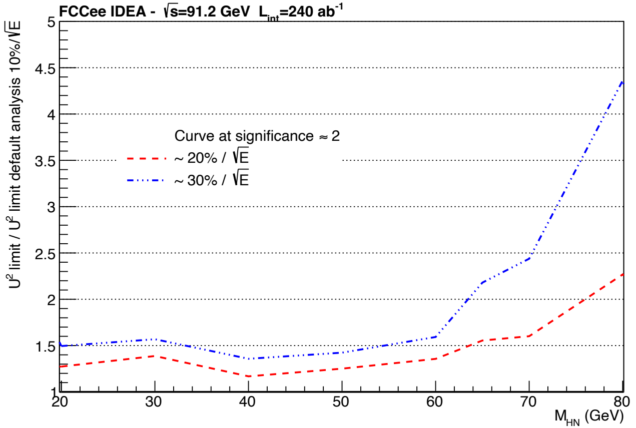


- Final state in μjj BR~50%
- Splitting analysis strategy in prompt and long-lived case
  - Mass dependent selection
  - Backgrounds considered

G. Polesello, N. Valle

HNL: $N \rightarrow \mu jj$ results

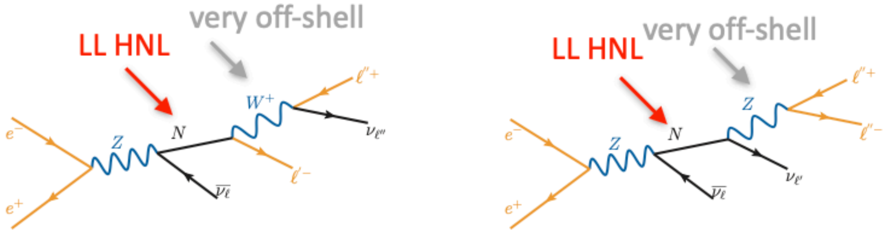




- **Effect of hadronic resolution on the result:** showing the ratio of the U^2 limit obtained with 20% and 30% resolutions with respect to the nominal resolution as a function of M_{HN}
- Result is more affected when the S/B gets worse (close to the Z)

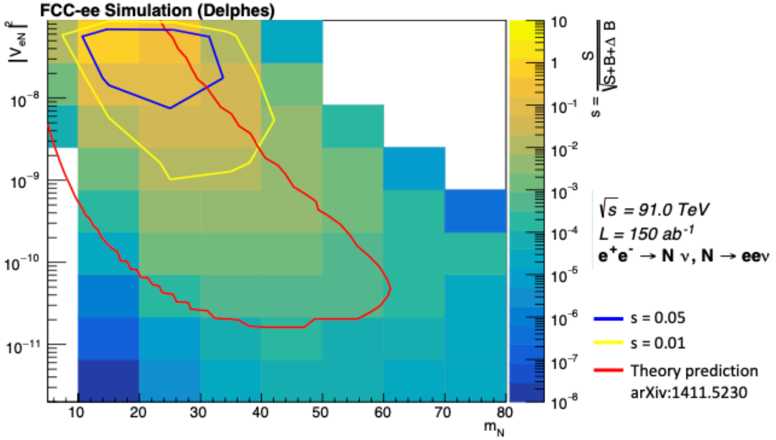
Lovisa Rygaard thesis

HNL: $N \rightarrow ee\nu_e$



- Preliminary sensitivity shown with $\frac{S}{\sqrt{S+B+\Delta B}}$
- **This analysis:** $N \rightarrow ee\nu$
  - Contours show where FOM = 0.01 and 0.05
- Theory prediction from arXiv:1411.5230
  - Includes all HNL decay modes, not only electrons

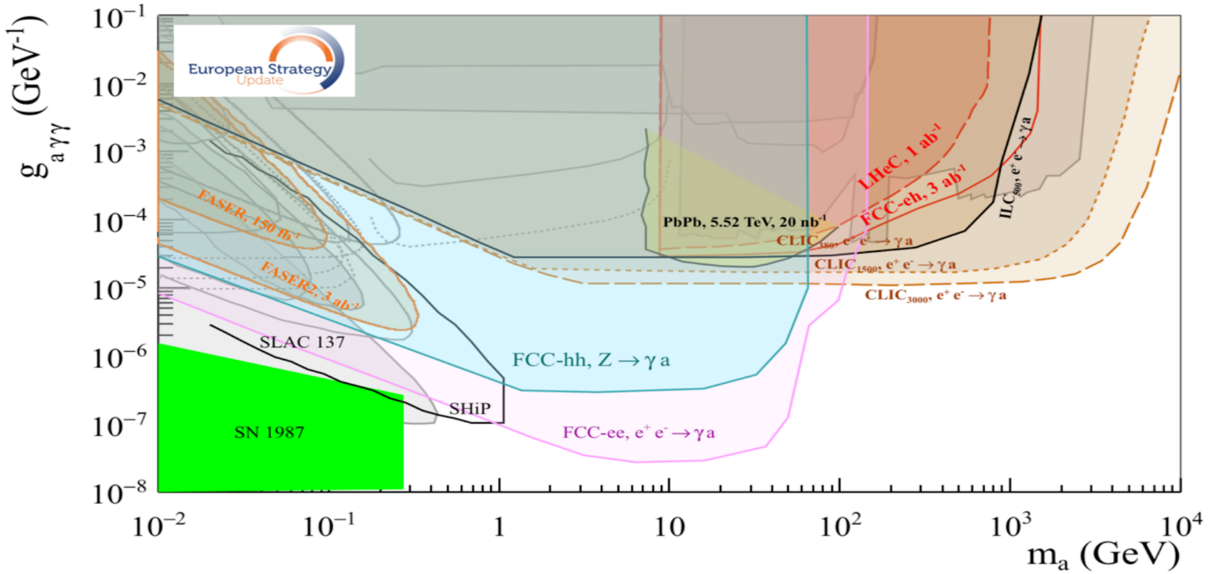
- **Main selections:**
  - Exactly 2 electrons, veto on additional photons, muons, and jets
  - Missing energy > 10 GeV (reduce Z->ee background with fake missing momentum)
  - Electron |d0| > 0.5 mm (remove most of the rest of SM background)

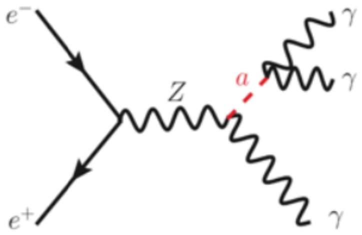


- *Preliminary study done with fast simulation: to be updated with the full simulation in the near future* arXiv:1808.10323, arXiv:2108.08949

BSM Direct searches - ALPS

- Axion-like Particles (ALPs) are pseudo-scalars in models with spontaneously broken global symmetries. Very weakly coupled to the dark sector
- At the FCC-ee predominantly produced in association with a photon, Z or Higgs boson.
  - Search possible at the different √s, complementarity with high-energy lepton colliders

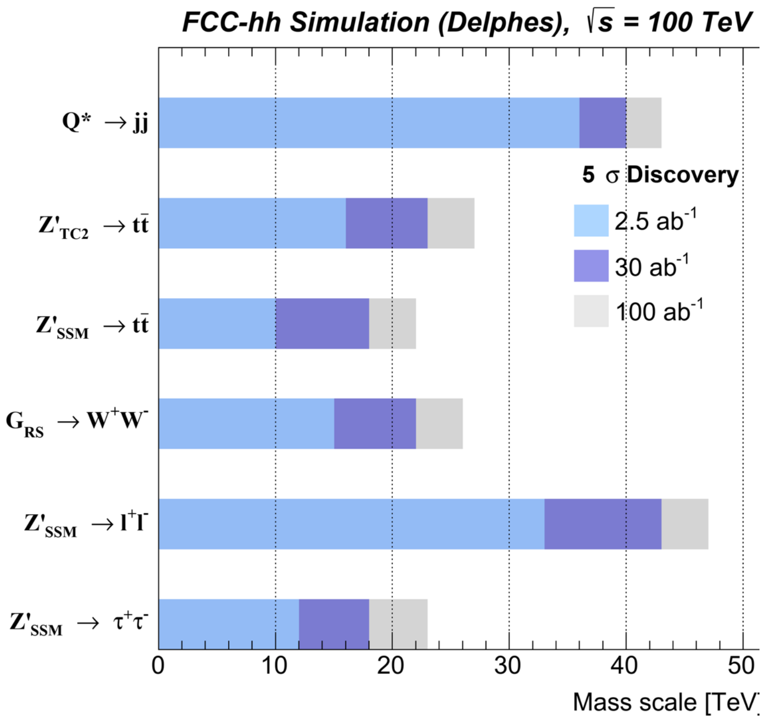




- ALPS might be long-lived when couplings and mass are small
  - Final states with at least 1 photon(or more) can set requirements on the electromagnetic calorimeter energy resolution and granularity

FCC-hh Direct discovery potential

- Higher parton centre-of-mass energy ➡ high mass reach:
  - Strongly coupled new particles, new gauge bosons (Z', W'), excited quarks: up to 40 TeV!
  - Extra Higgs bosons: up to 5-20 TeV
  - High sensitivity to high energy phenomena, e.g., WW scattering, DY up to 15 TeV



about x6 LHC mass reach at high mass, well matched to reveal the origin of deviations indirectly detected at the FCC-ee

Summary & next steps

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

Extensive sensitivity to FIP in a unique parameter space

Possibility to design an optimised detector for FIP

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

- **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 considered on Higgs mass measurement

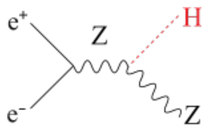
Some extended studies performed regarding detector effects

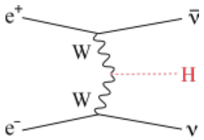
- Looking at impact on m_H resolution
  → to be compared to **stat-only (syst.), Nominal**
- ~ Going from crystal calorimeter to Dual readout (tight artificial smearing applied to electrons)
- Nominal 2 T field → 3 T (stronger field → better tracking)
- IDEA drift chamber → CLD silicon tracker
- Important 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

√s = 240 GeV





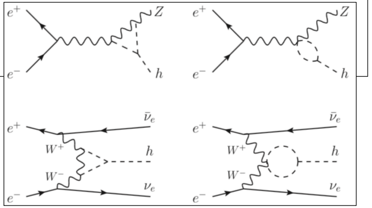
√s = 365 GeV

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%

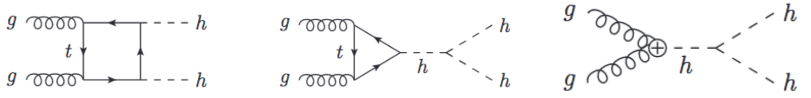
- → **Fixed « candle » for all other measurements**
  including those made at HL-LHC or FCC-hh
- → **Measure couplings to WW, bb, ττ, cc, gg, …**
  Even possibly the Hee coupling!
- → **First sensitivity to g_{HHH} to ~30% with 4IPs**

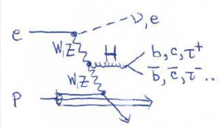


FCC-hh provides 3×10^{10} Higgs bosons

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





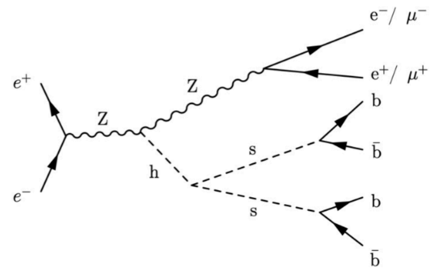
FCC-eh provides 2.5 10^6 Higgs bosons

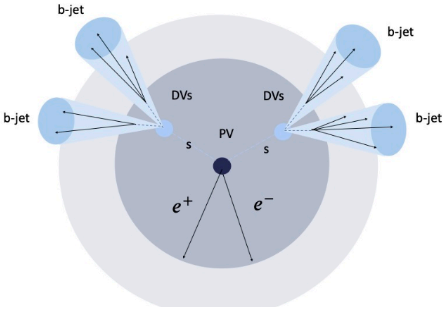
With the FCC-ee candle, further improves on several measurements (e.g., g_{HWW})

Case study: Exotic Higgs decays

Magdalena Van der Voorde, Giulia Ripellino

- Higgs bosons could undergo exotic decays (see Higgs invisible width) to e.g. scalars that could be long-lived
- New scalar could be a portal between the SM and a dark sector (arXiv:1312.4992, arXiv:1412.0018)
  - Higgs boson (h) and the scalar (s) mix with a mixing angle sin θ
  - • For sufficiently small mixing, the scalar can be long-lived
  - cτ~meters if $\theta \leq 1e^{-6}$
- WIP: Probe h→ss→bbbb in events with 2 displaced vertices and Z boson in $ee, \mu\mu$ pair





Selection:

Type	Parameter	Value
Track Selection	Min p_T	1 GeV
	Min $\|d_0\|$	2 mm
Vertex Reconstruction	V^0 rejection	True
	Max χ^2	9
	Max M_{inv}	40 GeV
	Max χ^2 added track	5
	Vertex merging	False
Vertex Selection	Min r_{DV-PV}	4 mm
	Max r_{DV-PV}	2000 mm
	Min $M_{charged}$	1 GeV

	Selection
Pre-selection	$\geq$ 2 oppositely charged electrons or muons
Z boson tag	$70 < m_{ll} < 110$ GeV
Multiplicity of DVs	n_DVs ≥ 2

Sensitivity:

- Backgrounds:

	Before selection	Pre-selection	$70 < m_{ll} < 110$ GeV	n_DVs ≥ 2
WW	8.22e+07 ± 7.45e+06	2.11e+06 ± 4.16e+04	4.68e+05 ± 1.96e+04	0 ($\leq$ 1.96e+04)
ZZ	6.79e+06 ± 1.77e+05	8.91e+05 ± 7.78e+03	5.85e+05 ± 6.31e+03	0 ($\leq$ 6.31e+03)
ZH	1.01e+06 ± 1.01e+04	5.97e+04 ± 7.76e+02	4.75e+04 ± 6.93e+02	0 ($\leq$ 6.93e+02)

- Signals:

m_s, sin θ	Before selection	Pre-selection	$70 < m_{ll} < 110$ GeV	n_DVs ≥ 2
20 GeV, 1e-5	44.3 ± 0.0295	29.8 ± 0.363	28.9 ± 0.358	3.55 ± 0.125
20 GeV, 1e-6	44.3 ± 0.0295	30.4 ± 0.367	29.7 ± 0.363	22.4 ± 0.315
20 GeV, 1e-7	44.3 ± 0.0295	36.3 ± 0.401	35.6 ± 0.397	0.531 ± 0.0485
60 GeV, 1e-5	13.1 ± 0.00474	8.38 ± 0.105	8.12 ± 0.103	0 ($\leq$ 0.103)
60 GeV, 1e-6	13.1 ± 0.00474	8.34 ± 0.104	8.09 ± 0.103	6.43 ± 0.0917
60 GeV, 1e-7	13.1 ± 0.00474	9.69 ± 0.113	9.45 ± 0.111	4.10 ± 0.0732

All but 2 signal points could be excluded at 95% CL

Tanishq Sharma thesis

HNL Case study: $N \rightarrow ee\nu_e$ Dirac vs Majorana

Dirac (LNC) and Majorana (LNC+LNV) HNLs produce different kinematic distributions: arXiv:2105.06576

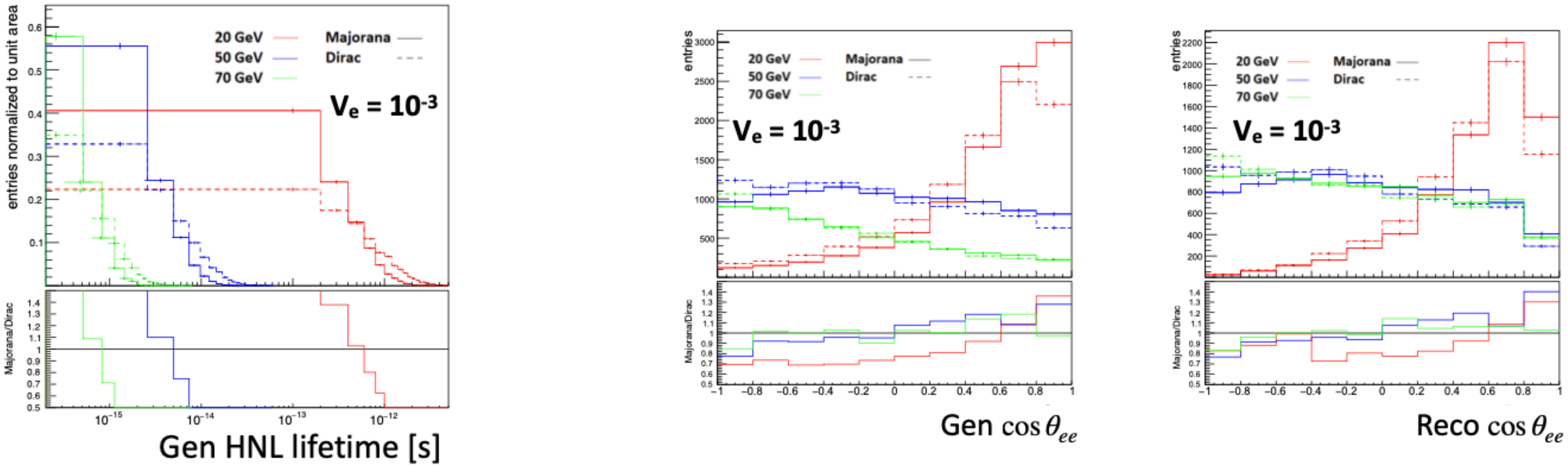
Variables that can distinguish between Majorana and Dirac HNLs:

HNL Lifetime

(model-dependent)

$\cos\theta_{ee}$

(opening angle between final state electron/positron)



- *Preliminary studies done with fast simulation: to be updated with the full simulation in the near future*