BSM prospects at the Future Circular Collider

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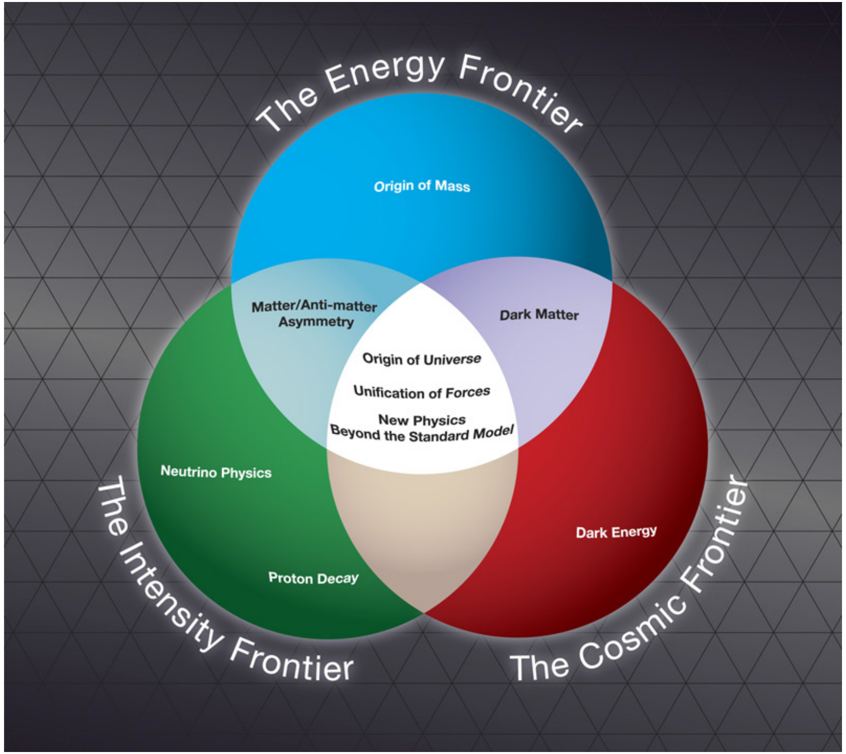
CATCH 2022+2
Dublin May 2nd 2024

What should come after the HL-LHC?

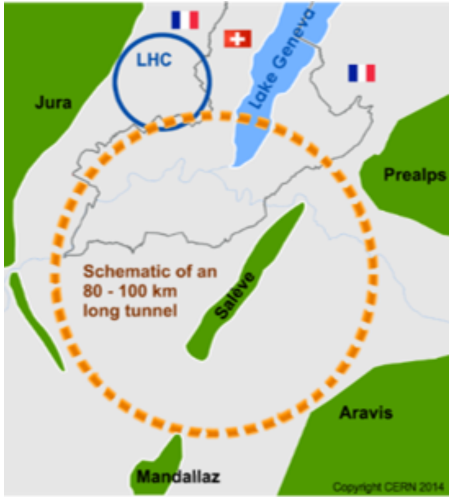


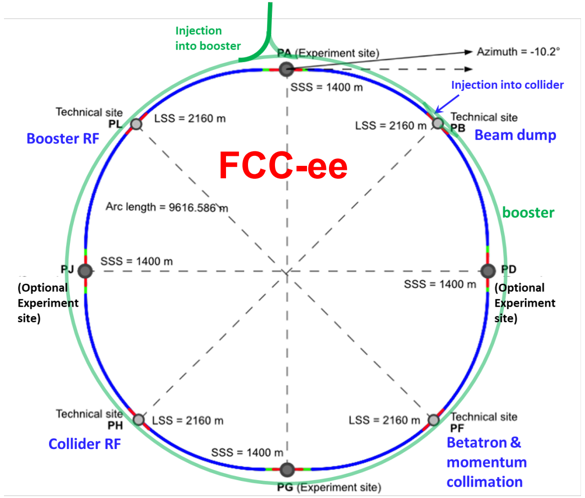
- **Energy & Intensity frontier are complementary in the search for new physics**
- With a high luminosity e^+e^- circular collider we could obtain:
  - **Indirect evidence** of new physics up to very high scales (~100TeV)
  - **Direct discovery** of low mass feebly interacting BSM particles
  - **Explore the interaction of the Higgs** with the 2nd and maybe first generation particles

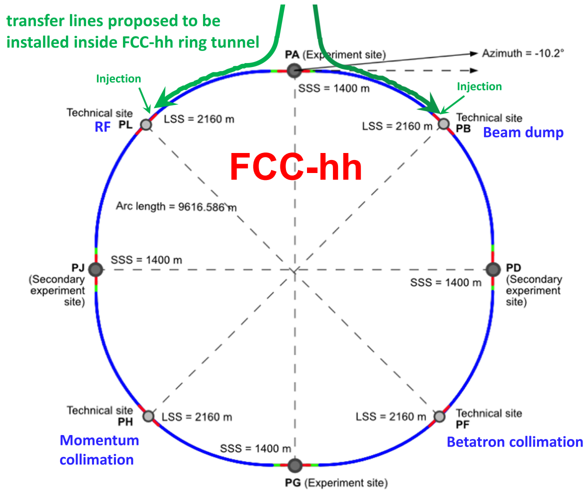
FCC integrated program

Comprehensive long-term program maximizes physics opportunities at both frontiers:

- **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**
- FCC integrated project allows the start of a new, major facility at CERN within a few years of the end of HL-LHC





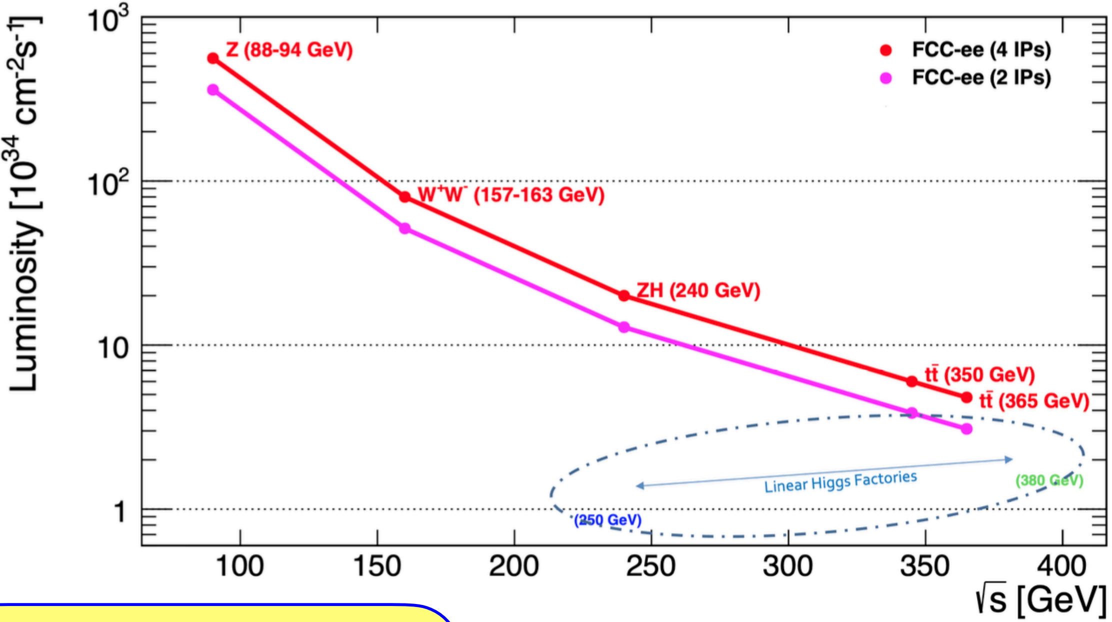


2020 - 2040 | 2045 - 2063 | 2070 - 2095

Slide from Michael Benedikt

FCC-ee Energy range & luminosity

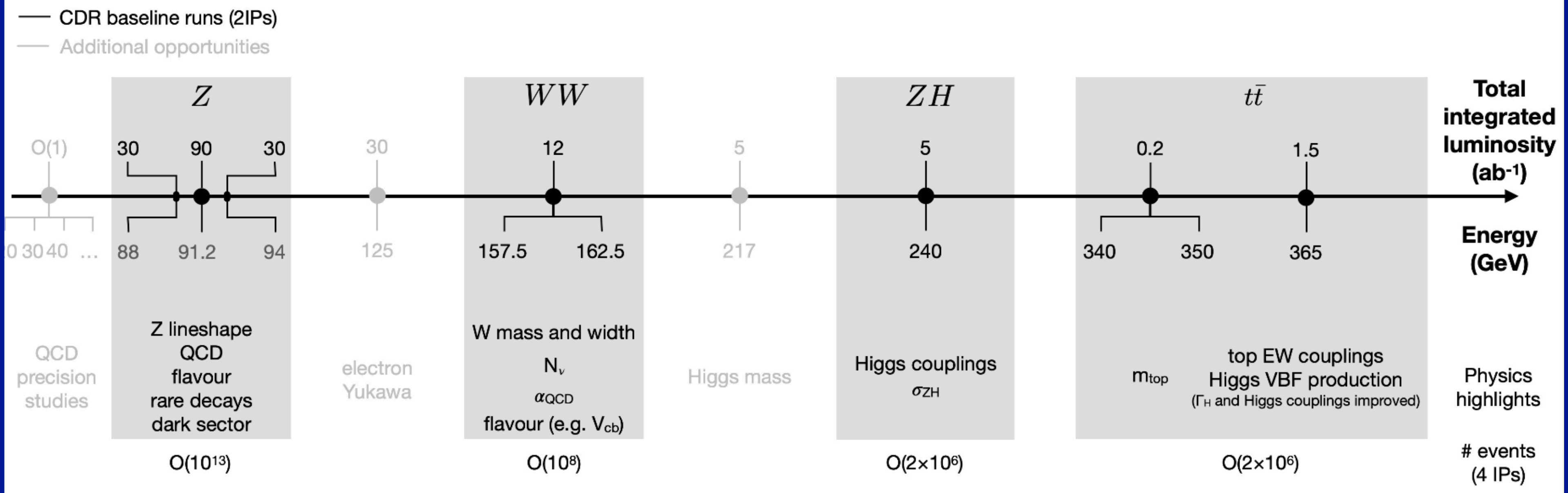
- e^+e^- first in the tunnel
- Producing in a clean environment all the heaviest SM particles
- Extending sensitivity to weakly coupled BSM models



In each detector:
10^5 Z/sec, 10^4 W/hour, 1500 Higgs/day, 1500 top/day

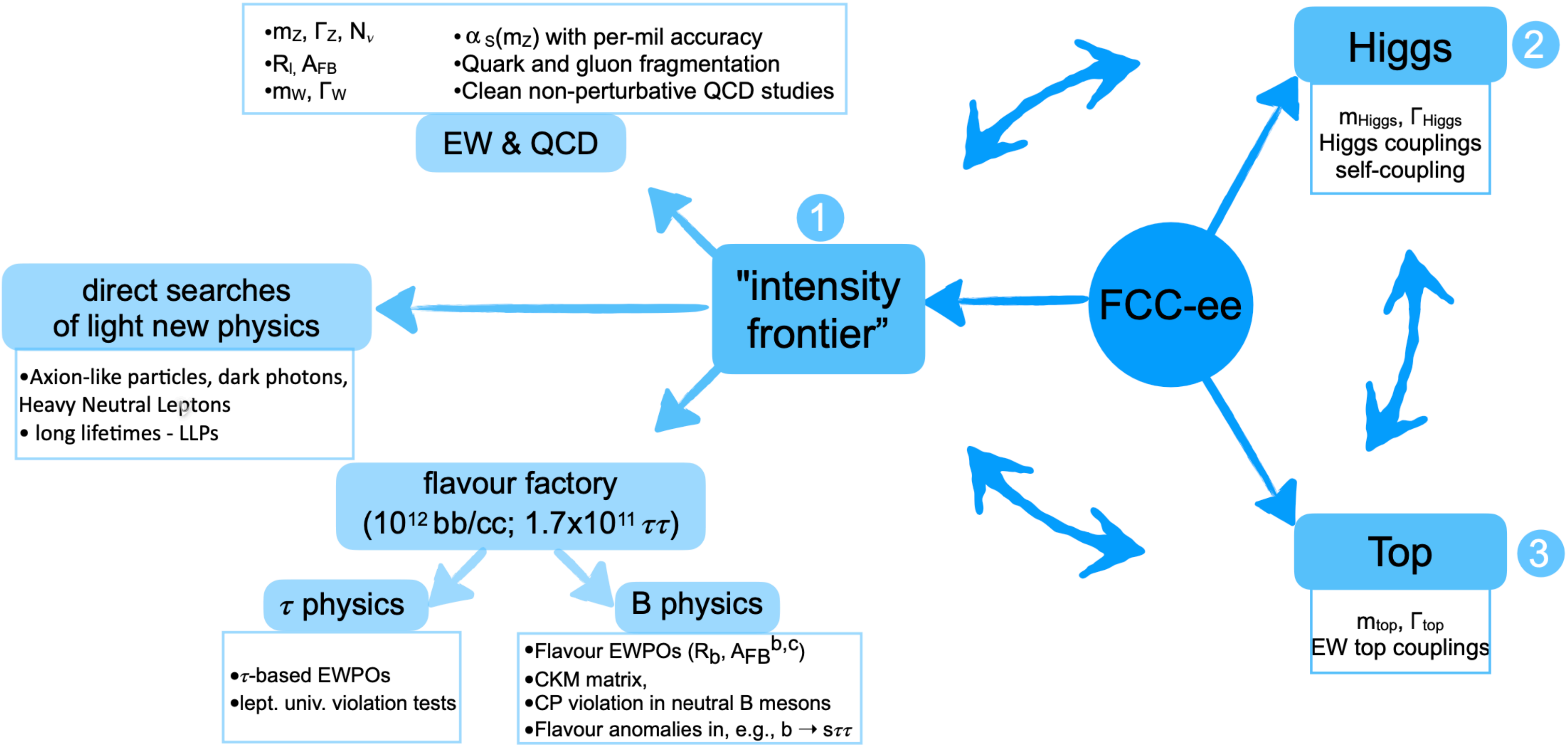
Working point	Z, years 1-2		...ater	ZH	$t\bar{t}$	
$\sqrt{s}$ (GeV)	88, 91			240	340–350	365
Lumi/IP (10^{34} cm^{-2}s^{-1})	70			5.0	0.75	1.20
Lumi/year (ab^{-1})	34			2.4	0.36	0.58
Run time (year)	2			3	1	4
Number of events	6×10^{12} Z		2.4×10^8 WW	1.45×10^6 ZH + 45k WW $\rightarrow$ H	1.9×10^6 $t\bar{t}$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

Flexible collider program



- **Opportunities** beyond the baseline plan (√s below Z, 125GeV, 217GeV; larger integrated lumi…)
- **Opportunities** to exploit FCC facility differently (to be studied more carefully):
  - using the electrons from the injectors for beam-dump experiments,
  - extracting electron beams from the booster,
  - reusing the synchrotron radiation photons.

A broad physics program



BSM & FCC-ee

- EXPLORE INDIRECTLY the 10-100 TeV energy scale with precision measurements
  - From the correlated properties of the Z , b, c, τ, W, Higgs, and top particles
  - Up to 20-50-fold improved precision on ALL electroweak observables (EWPO)
  - Up to 10 × more precise and model-independent Higgs couplings (width, mass) measurements
- DISCOVER that the Standard Model does not fit
- DISCOVER a violation of flavour conservation/universality
- DISCOVER dark matter, e.g., as invisible decays of Higgs or Z
- DISCOVER DIRECTLY elusive (aka feebly-coupled) particles
  - in the 5-100 GeV mass range, such as right-handed neutrino

Higgs coupling precision expectations

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
BR_{inv} [%]	1.9	0.22	0.19	0.024

Table adapted from arxiv:1905.03764

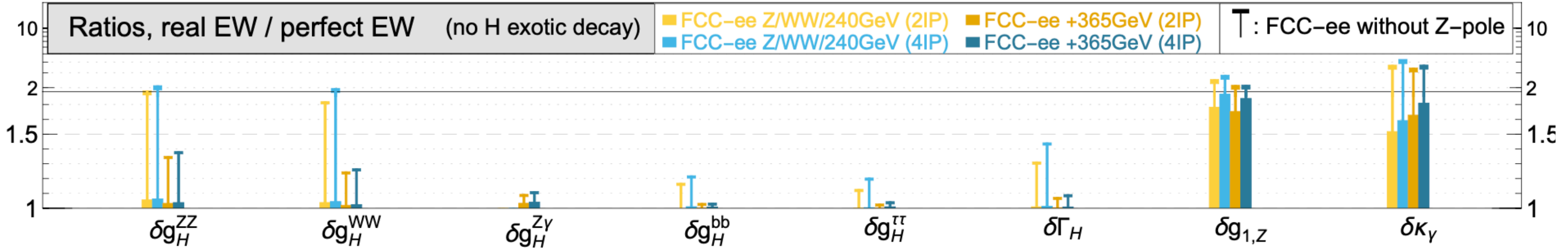
- FCC-ee measures g_{HZZ} to 0.2% (absolute, model-independent, standard candle) from $\sigma(ZH)$
  - $\Gamma(H)$, g_{Hbb}, g_{Hcc}, $g_{H\tau\tau}$, g_{HWW}, follow
  - Standard candle fixes all HL-LHC couplings
- FCC-hh produces over 10^{10} Higgs bosons, 10^8 ttH and 2×10^7 HH pairs:
  - Improving 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

Interplay of EWK measurement on Higgs precision

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!**



Higgs couplings

arXiv:2106.13885

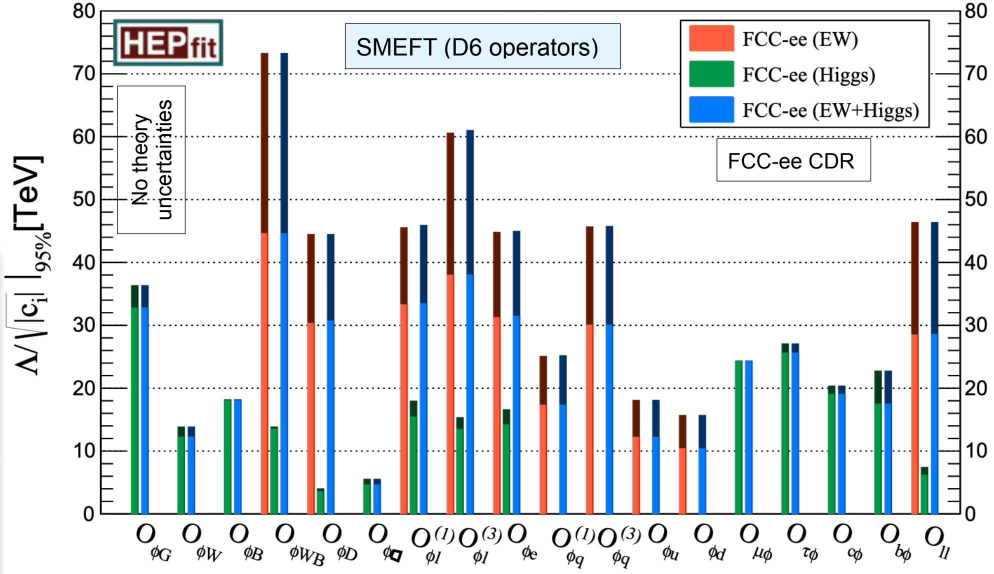
Indirect BSM sensitivity from EWPO

- **Target: reduce syst. uncertainties to the level of statistical**
- Exquisite √s precision (100keV@Z, 300keV@WW)
- ~50 times better precision than LEP/LSD on EW precision observables

Need TH results to fully exploit Tera-Z

Quantity	Current precision	FCC-ee stat. (syst.) precision	Required theory input	Available calc. in 2019	Needed theory improvement[†]
m_Z Γ_Z $\sin^2\theta^\ell_{\rm eff}$	2.1 MeV 2.3 MeV 1.6×10^{-4}	0.004 (0.1) MeV 0.004 (0.025) MeV $2(2.4)\times10^{-6}$	non-resonant $e^+e^-\to f\bar{f}$, initial-state radiation (ISR)	NLO, ISR logarithms up to 6th order	NNLO for $e^+e^-\to f\bar{f}$
m_W	12 MeV	0.25 (0.3) MeV	lineshape of $e^+e^-\to WW$ near threshold	NLO ($ee\to 4f$ or EFT framework)	NNLO for $ee\to WW$, $W\to f\bar{f}$ in EFT setup
HZZ coupling	—	0.2%	cross-sect. for $e^+e^-\to ZH$	NLO + NNLO QCD	NNLO electroweak
m_{top}	100 MeV	17 MeV	threshold scan $e^+e^-\to t\bar{t}$	N^{3}LO QCD, NNLO EW, resummations up to NNLL	Matching fixed orders with resummations, merging with MC, α_s (input)

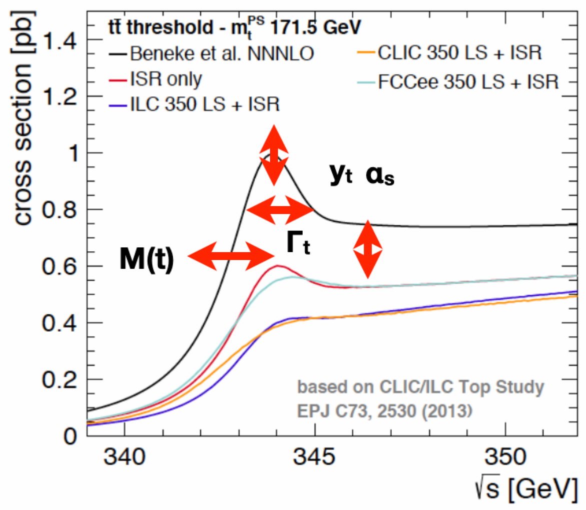
[†]The listed needed theory calculations constitute a minimum baseline; additional partial higher-order contributions may also be required.

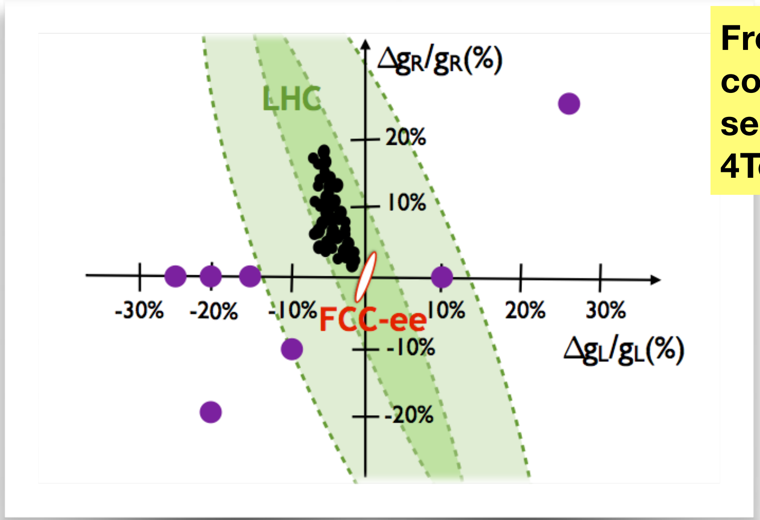


Indirect sensitivity to 70TeV-scale sector connected to EW/Higgs

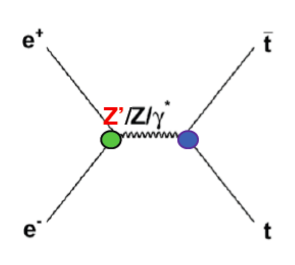
BSM in Top physics

- Threshold scan allows **most precise measurements of top mass** (<20MeV stat), width, and estimate of Yukawa coupling (10% with better α_s).
  - Best to combine with HL-LHC result of about 3.1%, removing the model dependence





From top EWK coupling precision sensitivity up to 4TeV Z' mass



Barducci, De Curtis,Moretti, Pruna 1311.3305

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

BSM in Flavour/Tau physics with the Tera-Z run

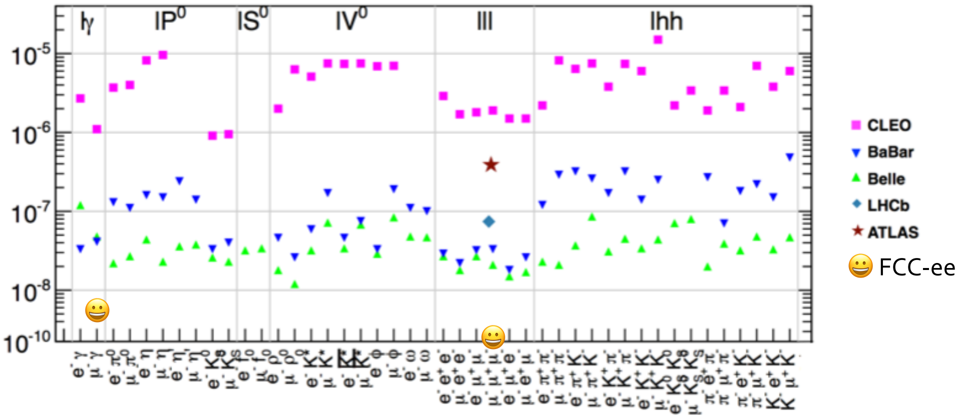
Particle production (10^9)	B^0	B^-	B^0_s	Λ_b	$c\bar{c}$	$\tau^-\tau^+$
Belle II	27.5	27.5	n/a	n/a	65	45
FCC-*ee*	400	400	100	100	600	170

~10 times Belle's stat

Boost at the Z!

- **Enormous statistics 10^{12} $b\bar{b}$, $c\bar{c}$, 2x10^{11} $\tau\tau$ events**
- Clean environment
- Favourable kinematics -> boost
- Excellent vertexing/tracking/PID

LFV tau decays



- Lots of BSM searches/signatures from: rare decays, LFV/LFU tests

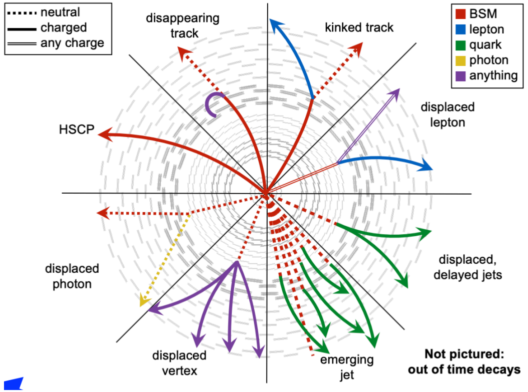
BSM from FIP direct searches

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

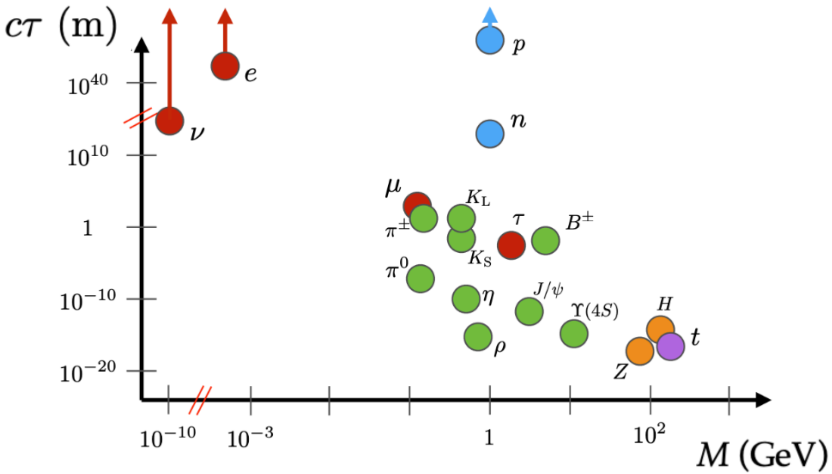
Detector Requirements

- 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)**

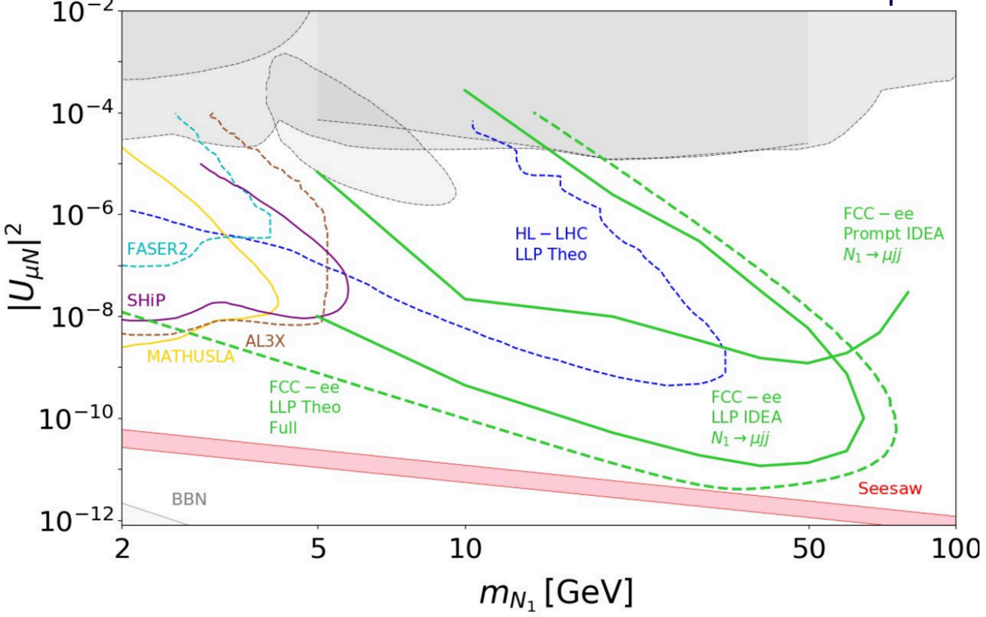


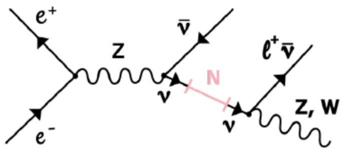
- **Wide variety** of:
  - Charges
  - Final states
  - Decay locations
  - Lifetimes
- Design **signature-driven** searches

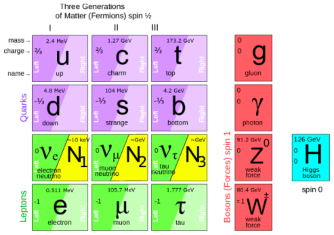
- Opportunities from the clean environment of the FCC-ee
- Few concrete examples: **HNL, ALPS, Dark photons**

Direct search: Heavy Neutral Leptons

From mid-term report







$$L \sim \frac{3\,[cm]}{|U|^2 .\,(m_N[GeV]\,)^6}$$

arXiv:2203.05502

L~1m for m^N=50GeV and $|U|^2=10^{-12}$

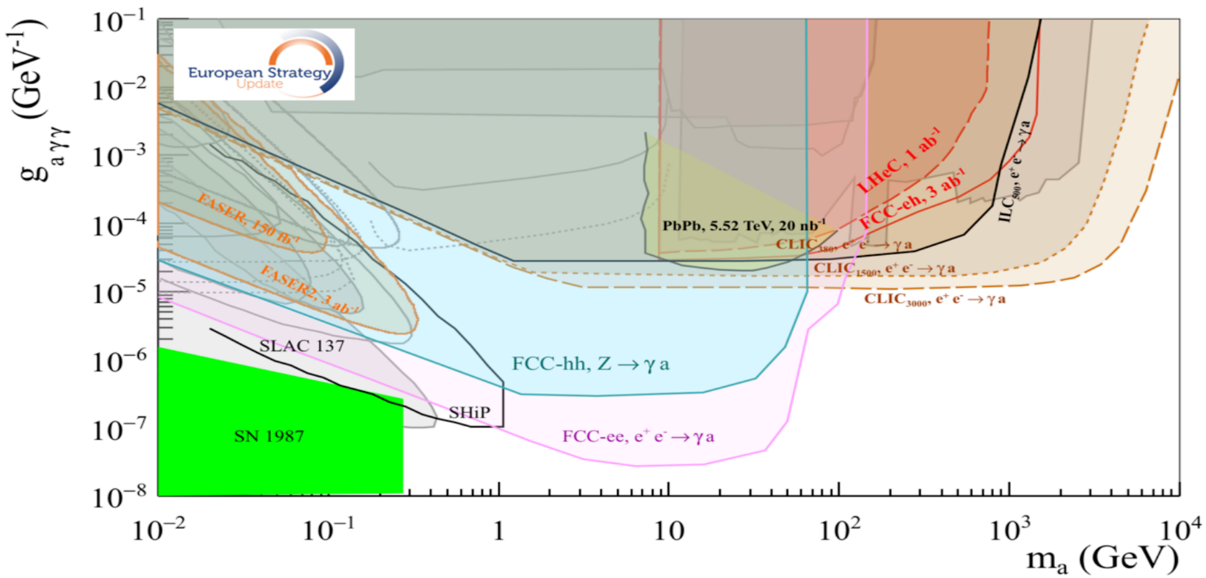
- Dirac or Majorana sterile neutrinos with very small mixing with active neutrinos could provide answers to Neutrino masses, Baryon asymmetry, Dark matter
- **Can be long lived!!!**

- **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

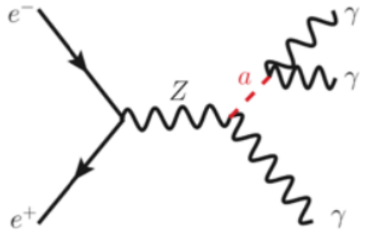
Direct search - ALPS

arXiv:1808.10323, arXiv:2108.08949

- 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



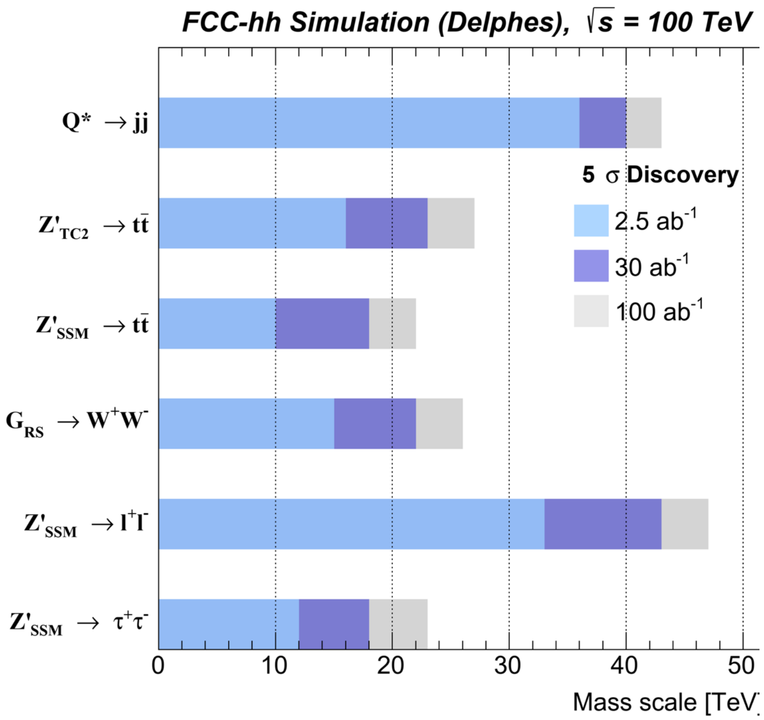
$$e^+e^- \to \gamma a, ha$$



- 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

Conclusions

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

Multiple access to rare and BSM processes at all energies.

Extensive sensitivity to FIP in a unique parameter space

Possibility to design an optimised detector for FIP

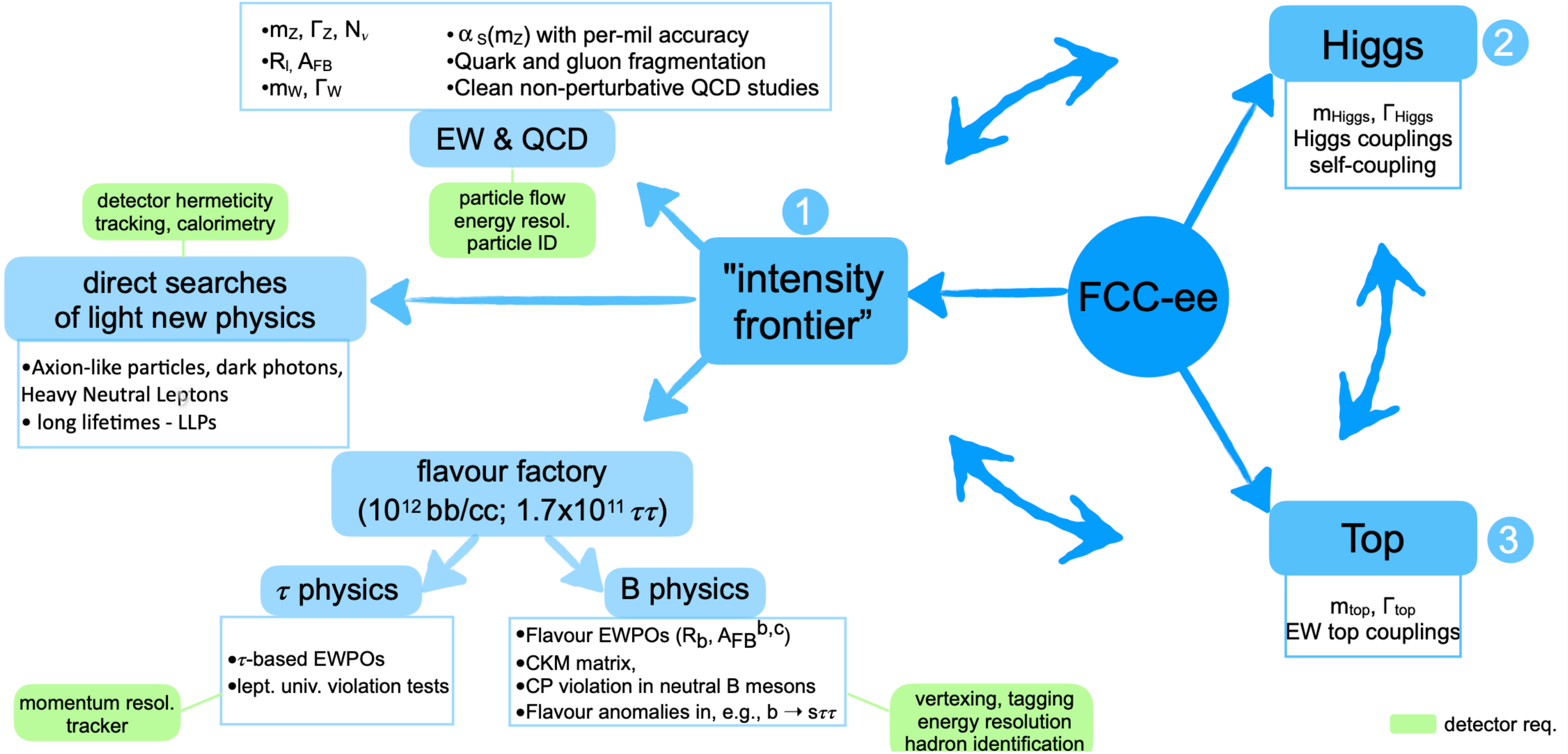
Best way to prepare the way for high energy exploration with FCC-hh

The FCC project offers unprecedented opportunities on many different fronts. No LHC/SSC-like **no-lose theorem** but a **promise** of making significant steps forward in our understanding of the fundamental laws of Nature.

- Working full steam toward completion of the Feasibility Study by Spring 2025 to build the **strongest case for the FCC project for the next European Strategy**

BACKUP

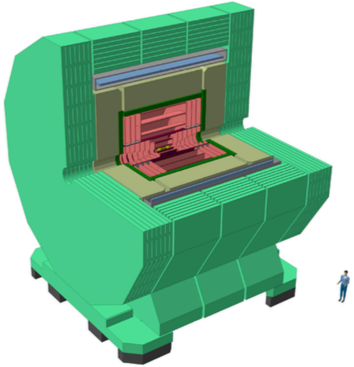
Setting strong detector requirements



Some preliminary detector concepts for FCC-ee

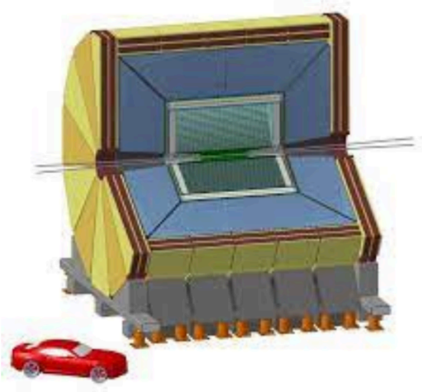
CLIC-like Detector (CLD)

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



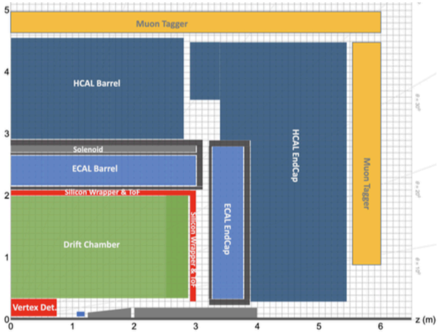
Innovative Detector for an Electron-Positron Accelerator (IDEA)

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



Noble Liquid

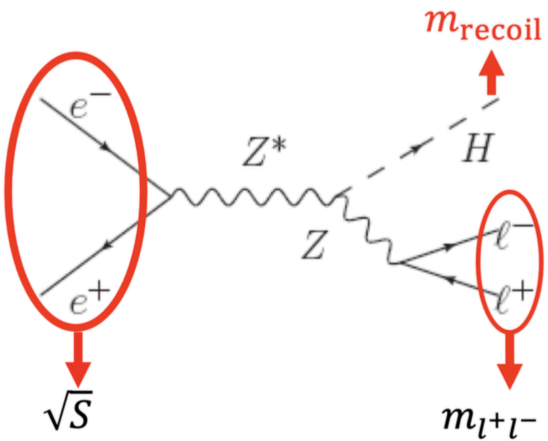
- High-granularity noble liquid calorimeter
- LAr or Lar + Lead or Tungsten absorber
- Newest proposal

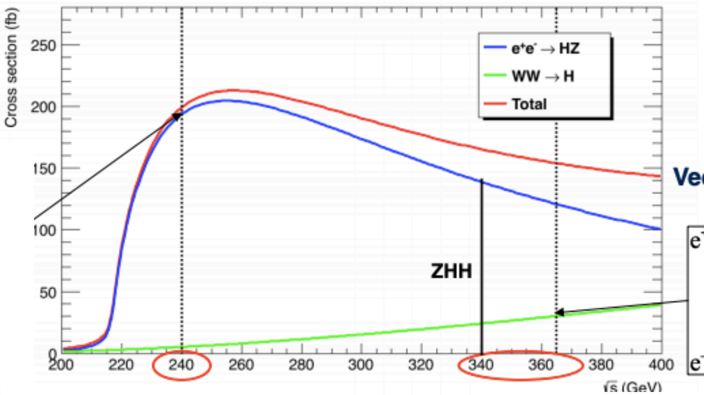


- In the process of extracting the requirement on the detector performance from the physics
  - With 4IP, opportunity to have detector optimised for specific processes
- Spoiler: “Higgs factory” requirements are not the most stringent

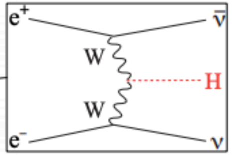
Higgs production at FCC-ee & the recoil method

Higgs strahlung

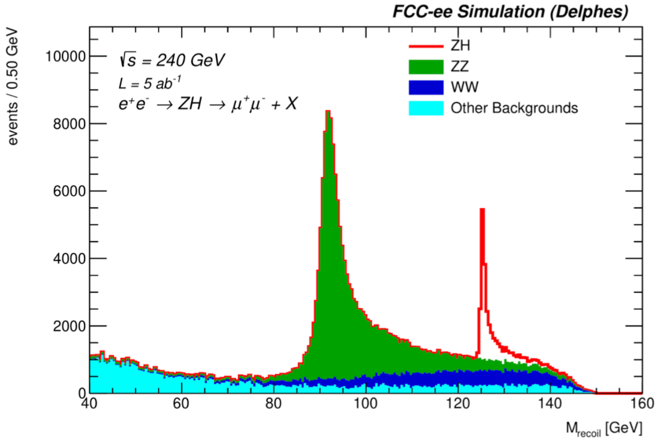




Vector Boson Fusion

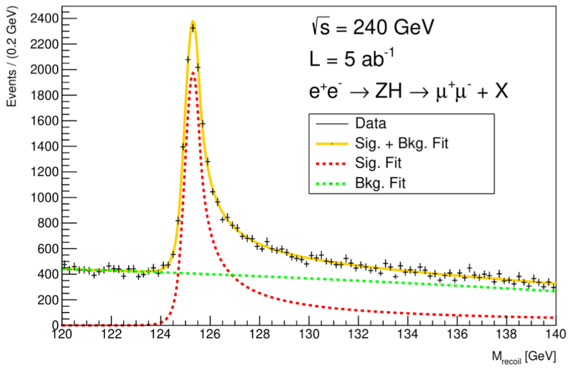


$$m_{\text{recoil}}^2 = (\sqrt{s} - E_{l\bar{l}})^2 - p_{l\bar{l}}^2 = s - 2E_{l\bar{l}}\sqrt{s} + m_{l\bar{l}}^2$$

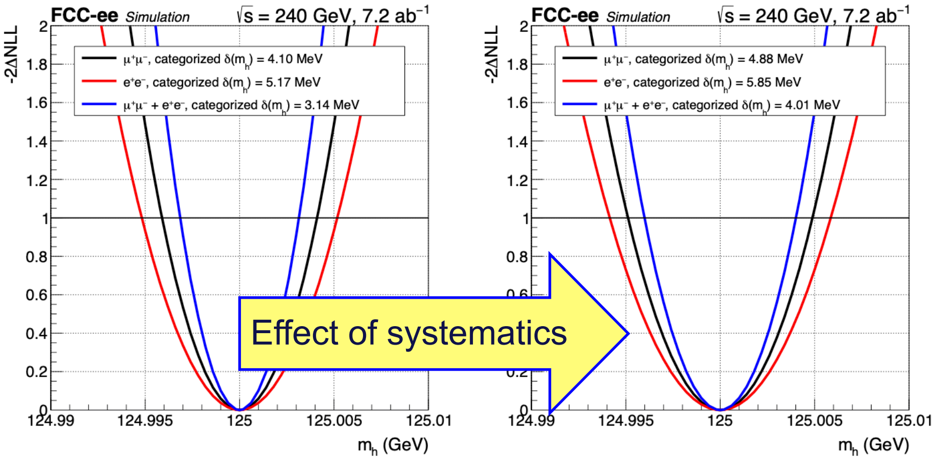


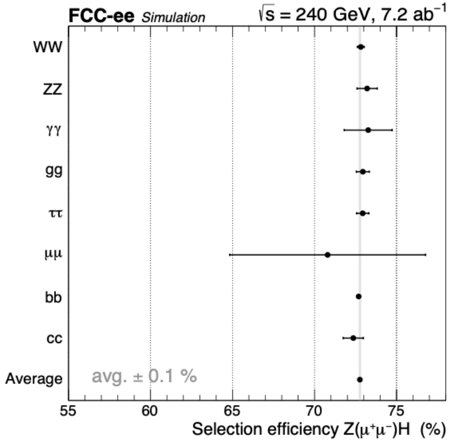
- Allows model independent determination of couplings

Higgs mass & cross section



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



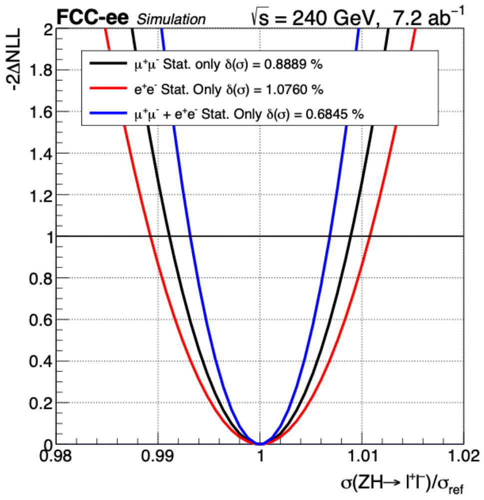


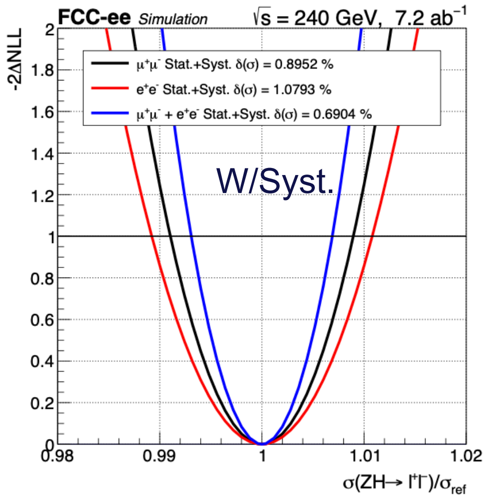
- Higgs mass, fit with analytic shape: $\sigma(m_H) = 3.1(4.0)$ **MeV stat(sys)**
  - Precise m(H) measurement is needed for a possible monochromatic run at $e^+e^- \rightarrow H$
- Model independent ZH cross-section crucial for Higgs couplings (and more)
  - Estimated sensitivity in CDR ~0.5%
  - Challenge 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

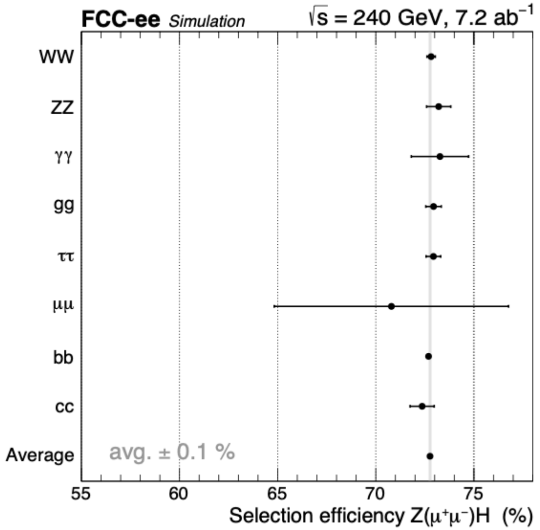
Total ZH production cross section

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

- 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

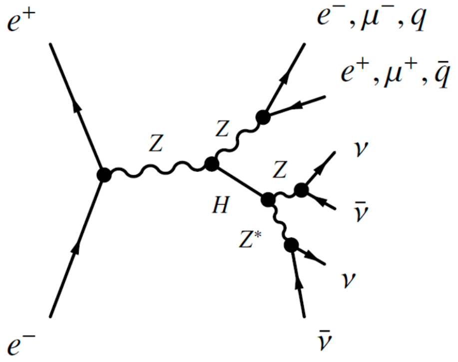


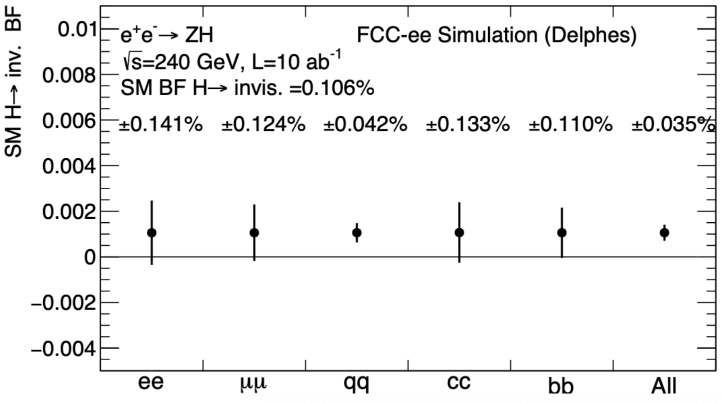




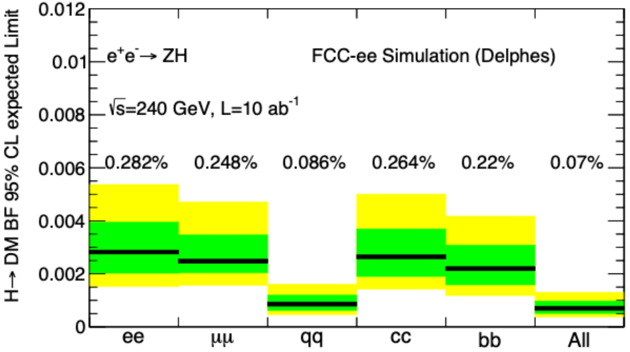
$L_{int} = 10\,ab^{-1}$

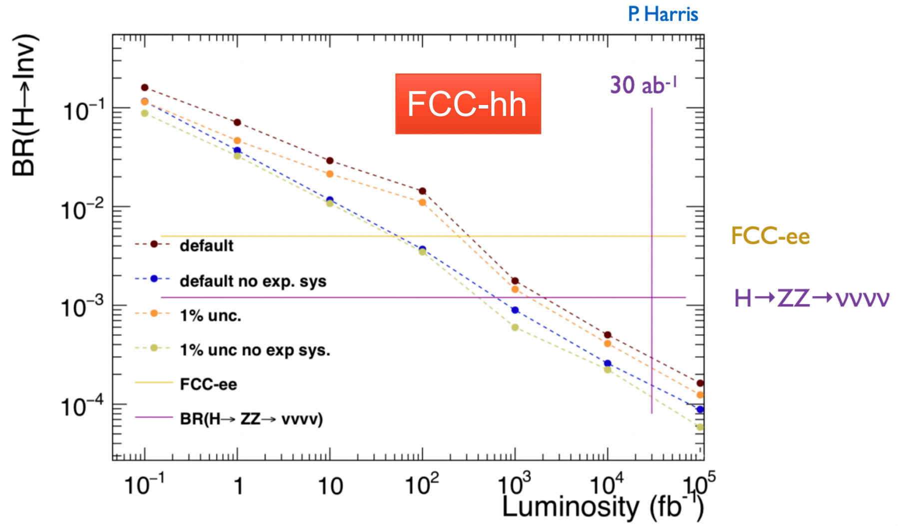
Higgs to invisible





BR(SM) with ~45% uncertainty





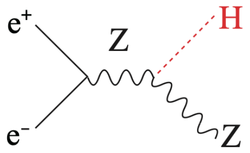
- If SM treated as background, sensitivity to EXO decays:
- **5σ for BR>0.18% and 95% exclusion if BR <0.07**

Higgs self-coupling with single Higgs

C. Grojean et al. arXiv:1711.03978

M. McCullough arXiv:1312.3322

σ_{HZ}



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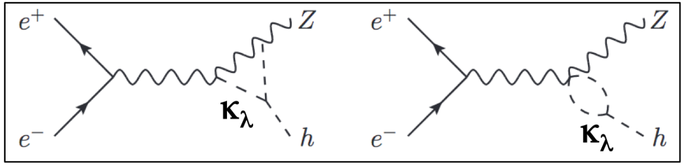
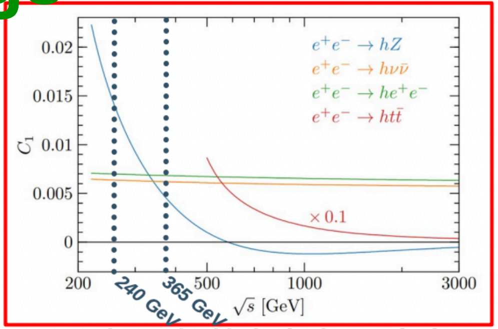
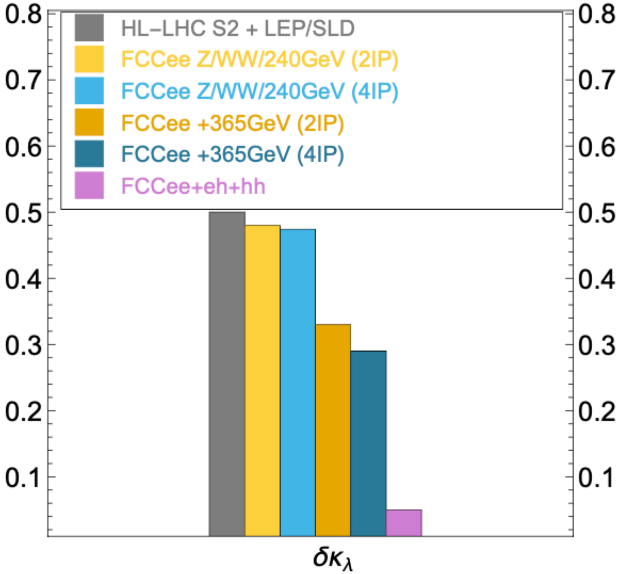


$$\Sigma_{\rm NLO} = Z_H \Sigma_{\rm LO}(1 + \kappa_\lambda C_1) \qquad \kappa_\lambda \equiv \frac{\lambda_3}{\lambda_3^{\rm SM}}$$



- 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

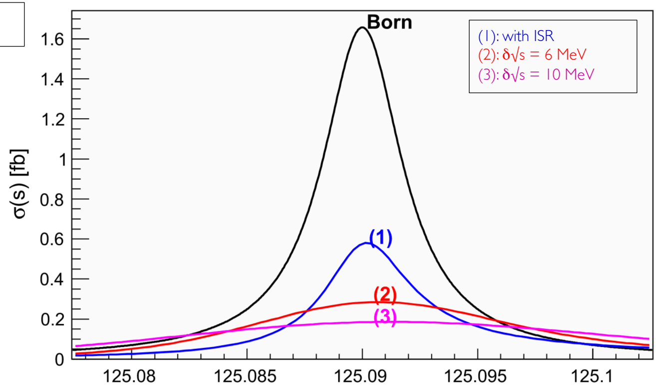
- Measurements at different √s (365GeV) needed to lift degeneracy between processes



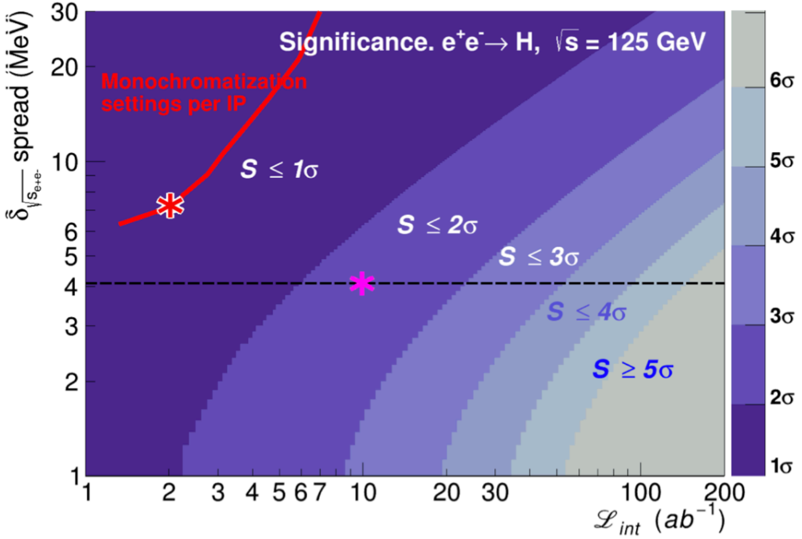
Electron Yukawa coupling *(unique!)*

arXiv:2107.02686

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



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



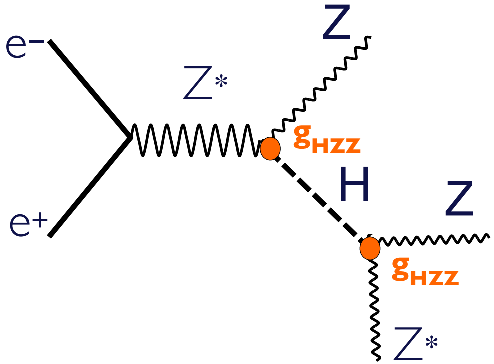
- Something unique: electron Yukawa coupling from $e^+e^- \to H$
- One of the toughest challenges, which requires:
  - Higgs boson mass prior knowledge to a couple MeV
  - Huge luminosity (i.e., several years with possibly 4 IPs)
  - (Mono)chromatisation: Γ_H (4.2 MeV) « $\delta_{\sqrt{s}}$ (100 MeV)
  - 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 width

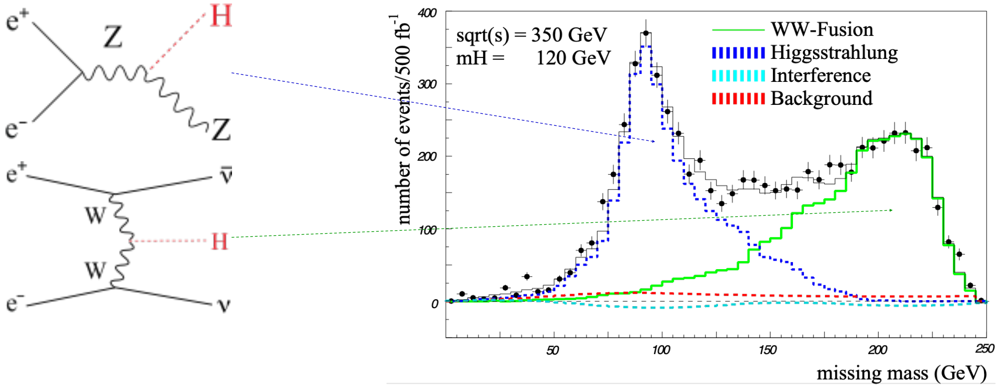
- **Model independent determination of the total Higgs decay width down to 1.3% with runs at √s=240 and √s=365 GeV**
- First analysis in progress on the $Z(\ell^+\ell^-)Z(jj)Z(\nu\bar{\nu})$ channel.

ee →HZ & H → ZZ at √s = 240 GeV



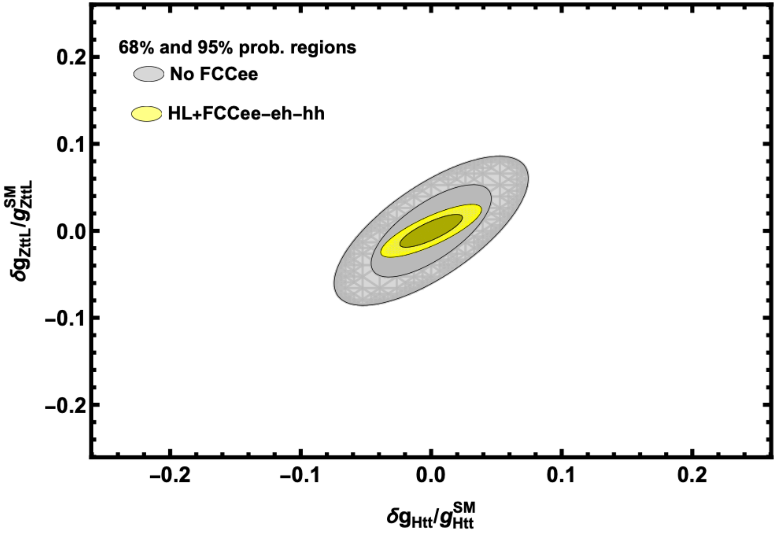
- σ_{HZ} **is proportional to** g_{HZZ}^2
- **BR(H → ZZ) =** $\Gamma(H \to ZZ) / \Gamma_H$ **is proportional to** g_{HZZ}^2 / Γ_H
  - $\sigma_{HZ} \times$ **BR(H → ZZ) is proportional to** g_{HZZ}^4 / Γ_H
- **Infer the total width** Γ_H

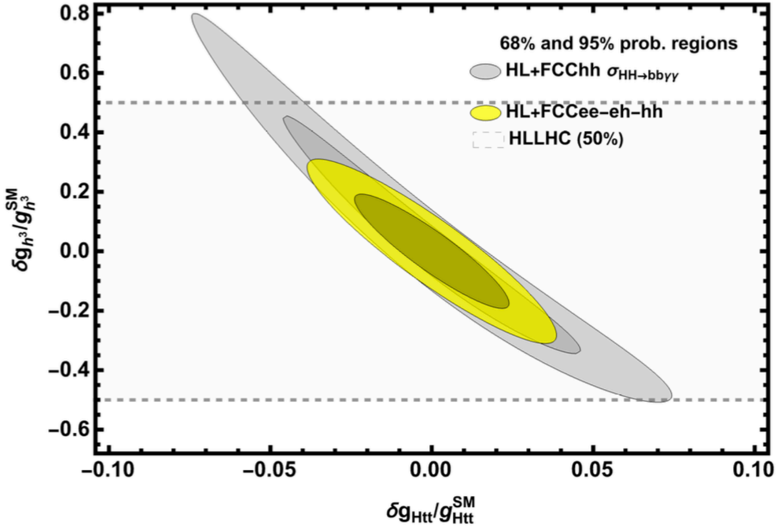
WW → H νν→ bbνν at √s = 365 GeV



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

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





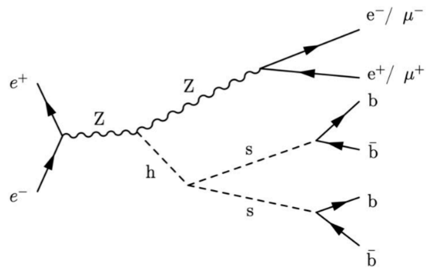
- The determination of the Ztt couplings from $e^+e^- \rightarrow t\bar{t}$ during the 365GeV run of the FCC-ee, in conjunction with the ttH/ttZ FCC-hh would help to **reduce the few per-cent uncertainty on δg_{tt} from the HL-LHC to ~1%.**
- Current estimates combining the $bb\gamma\gamma, bb\tau\tau,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

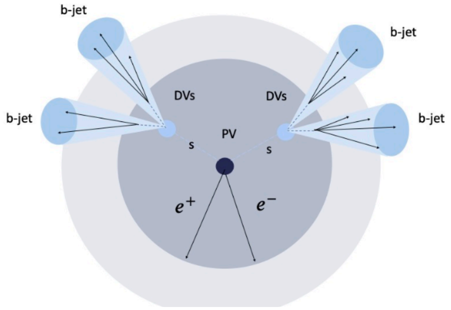
Magdalena Van der Voorde, Giulia Ripellino

Case study: Exotic Higgs decays

- 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	≥ 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 (≤ 1.96e+04)
ZZ	6.79e+06 ± 1.77e+05	8.91e+05 ± 7.78e+03	5.85e+05 ± 6.31e+03	0 (≤ 6.31e+03)
ZH	1.01e+06 ± 1.01e+04	5.97e+04 ± 7.76e+02	4.75e+04 ± 6.93e+02	0 (≤ 6.93e+02)

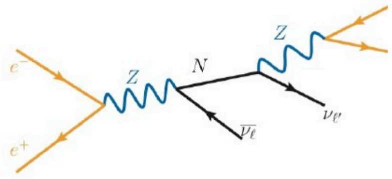
- Signals:

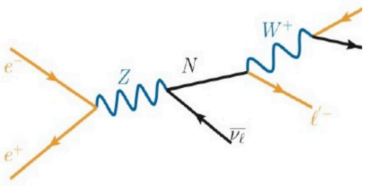
m_s, sin θ	Before selection	Pre-selection	$70 < m_{ll} < 110$ GeV	n_DVs ≥ 2
20 GeV, 1e-5	44.3 ± 0.0295	29.8 ± 0.363	28.9 ± 0.358	3.55 ± 0.125
20 GeV, 1e-6	44.3 ± 0.0295	30.4 ± 0.367	29.7 ± 0.363	22.4 ± 0.315
20 GeV, 1e-7	44.3 ± 0.0295	36.3 ± 0.401	35.6 ± 0.397	0.531 ± 0.0485
60 GeV, 1e-5	13.1 ± 0.00474	8.38 ± 0.105	8.12 ± 0.103	0 (≤ 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

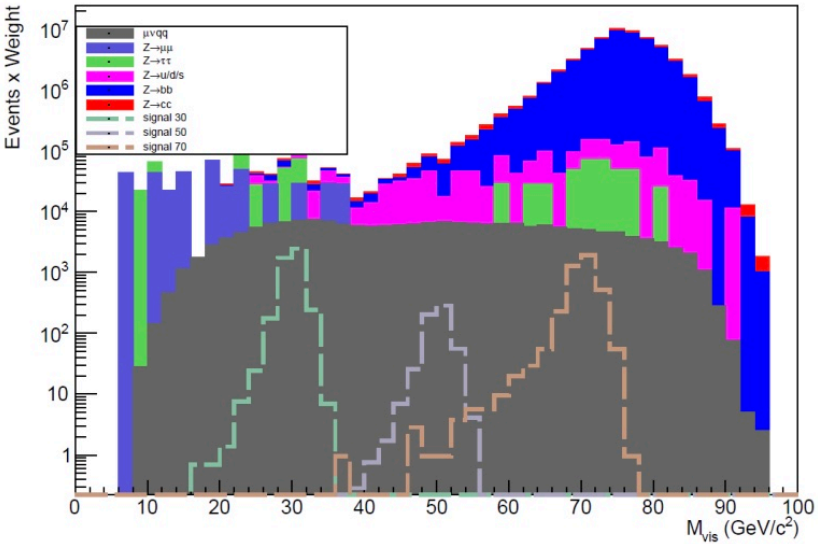
All but 2 signal points could be excluded at 95% CL

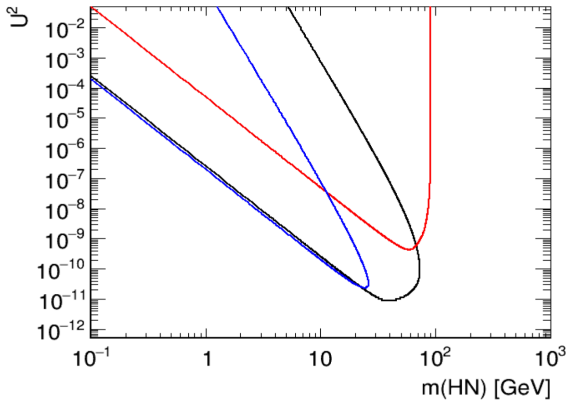
G. Polesello, N. Valle

HNL: $N \rightarrow \mu jj$









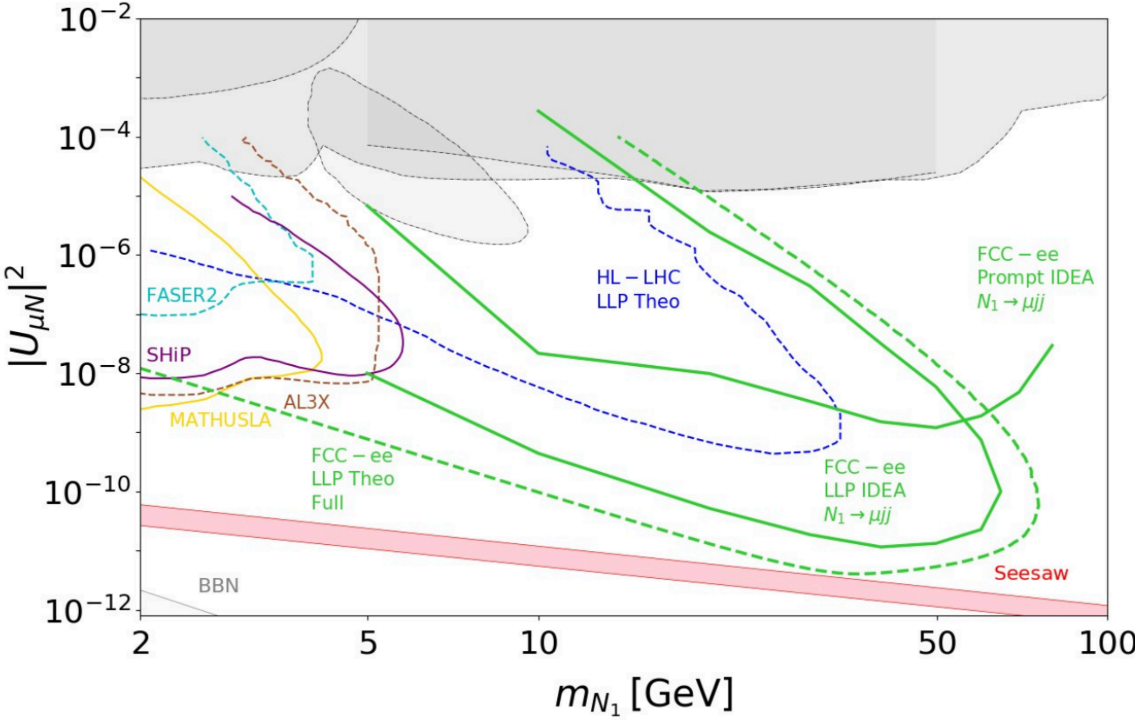
Assume 1 flavour active
5×10^{12}Z at Z peak
Require 100 events for prompt decay and
4 events for long-lived

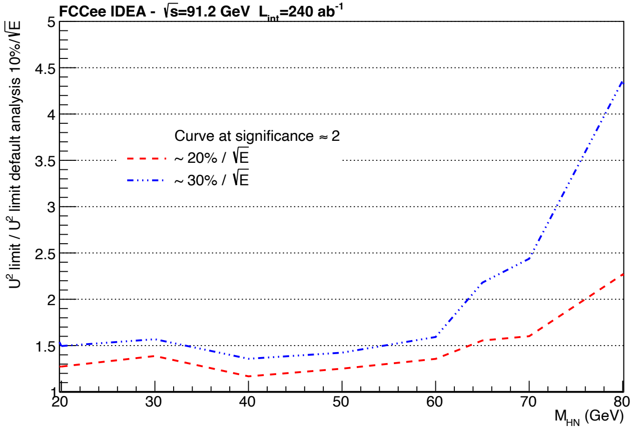
Red: Prompt:
0< λ < 1mm
Black:ID decay
0.04<λ< 150 cm
Blue: Calo decay
200<λ< 450 cm

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

HNL: $N \to \mu jj$ results

G. Polesello, N. Valle

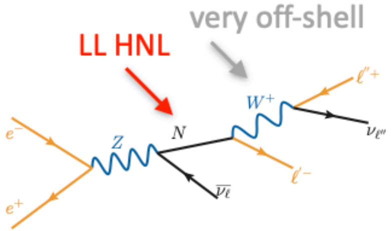


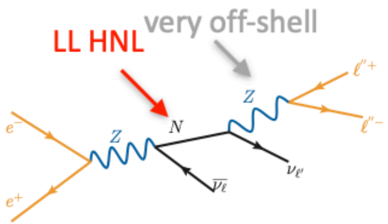


- **Effect of hadronic resolution on the result:** showing the ratio of the U^2 limit obtained with 20% and 30% resolutions with respect to the nominal resolution as a function of M_{HN}
- Result is more affected when the S/B gets worse (close to the Z)

HNL: $N \rightarrow ee\nu_e$

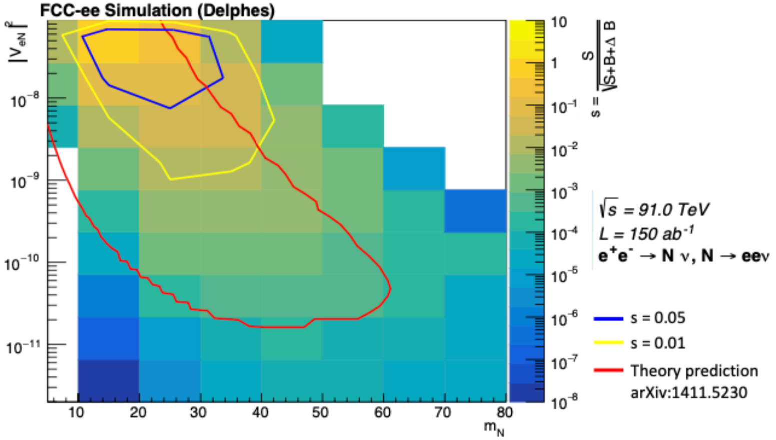
Lovisa Rygaard thesis





- 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

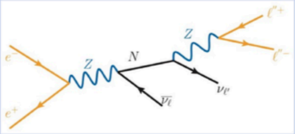
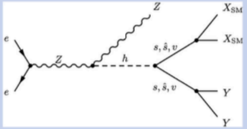
- **Main selections:**
  - Exactly 2 electrons, veto on additional photons, muons, and jets
  - Missing energy > 10 GeV (reduce Z->ee background with fake missing momentum)
  - Electron $|d_0|$ > 0.5 mm (remove most of the rest of SM background)



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

Ongoing FCC-ee LLP studies

Note: this table will soon be updated following the mid-term review!

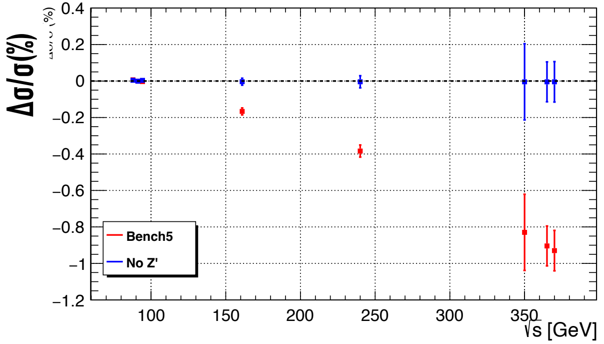
Physics scenario	FCC-ee signature	Studies for snowmass	Ongoing work
Heavy neutral leptons (HNLs)	Displaced vertices 	Generator validation and detector-level selection studies for $ee\nu\nu$. First look at Dirac vs Majorana	• Update $ee\nu\nu$ studies for winter23 samples. • First look at $\mu\mu\nu\nu$ channel (prompt +LLP) • First look at $\mu\nu$jj (prompt+LLP) • First look at $e\nu$jj including Dirac vs majorana (prompt)
Axion-like particles (ALPs)	Displaced photon/lepton pair	Generator-level validation for a→γγ at Z-pole run.	*No studies ongoing* ***-> Opportunities to get involved :)***
Exotic Higgs decays	e.g. 	Theoretical discussion and motivation for studies at ZH-pole	• Reco-level studies (inc. vertexing) for h→ss→bbbb

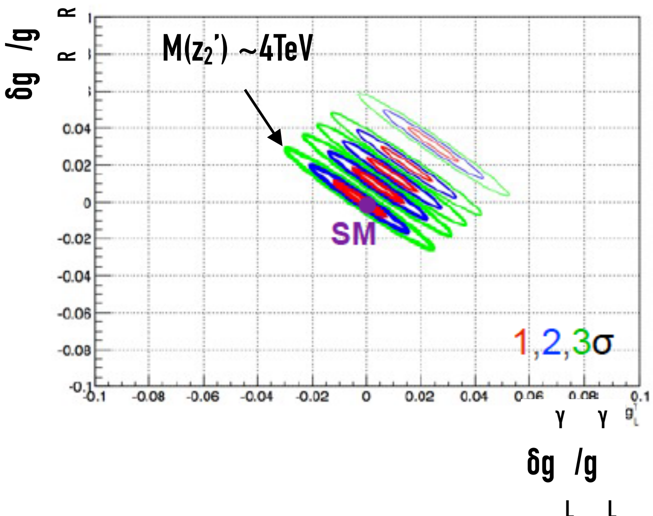
One Composite Higgs Model(CHM) example

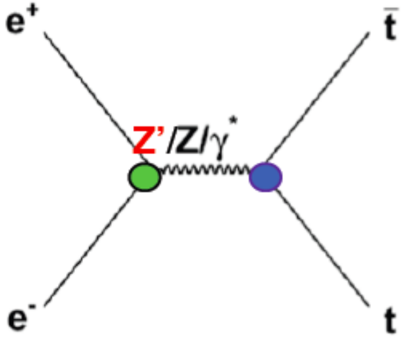
Barducci, De Curtis,Moretti, Pruna 1311.3305

- The CHM modification of the process arises via 3 effects:
  - modification of the Zee coupling (negligible)
  - modification of the Ztt coupling from mixing between top and extra fermions, mixing between Z and Z's
  - s-channel exchange of the Z's (interference)

$$e^+e^- \to \gamma, Z, Z' \to \mu^+\mu^-$$







One more step!
By combining muon cross-sections and A_{FB} with the top optimal observables **the model can be fully characterized @FCCee**

With FCC-ee precision sensitivity up to 4TeV Z' mass