Higgs at the FCC-ee

Higgs Couplings'17

Heidelberg, 10th Nov. 2017

David d'Enterria

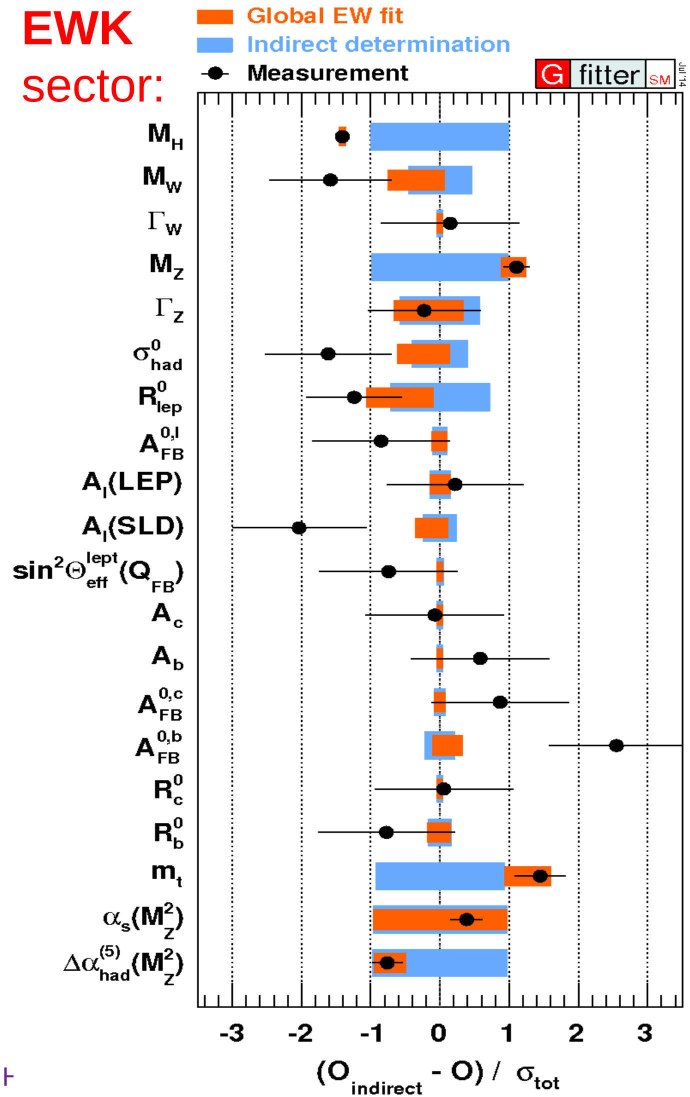
(on behalf of FCC-ee study group)

CERN

Standard Model of particles & interactions

- Renormalizable QFT of electroweak $SU(2)_L \times U(1)_Y$ & strong $SU(3)_c$ gauge interactions
  O(20) parameters: Couplings, H mass&vev, H-f Yukawa, CKM mix., CP phases.
  Experimentally confirmed to great precision for over 40(!) years:

EWK sector:



$$\mathcal{L} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{8}tr(\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}) - \frac{1}{2}tr(\mathbf{G}_{\mu\nu}\mathbf{G}^{\mu\nu})$$
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$$+(\bar{u}_L, \bar{d}_L)\,\tilde{\sigma}^\mu iD_\mu \begin{pmatrix}u_L\\ d_L\end{pmatrix} + \bar{u}_R\sigma^\mu iD_\mu u_R + \bar{d}_R\sigma^\mu iD_\mu d_R + (\text{h.c.})$$
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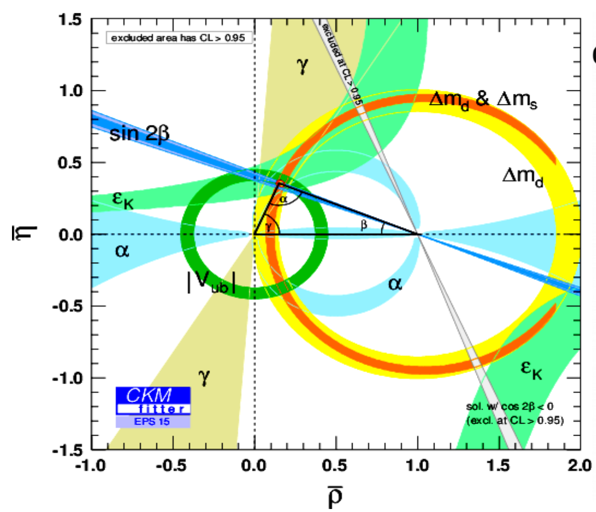
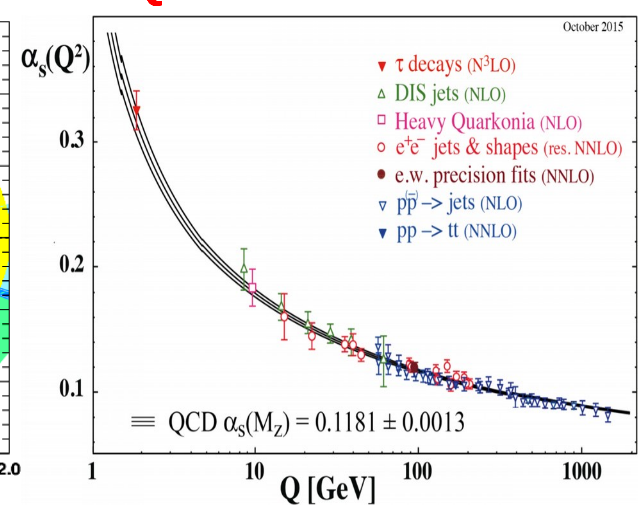
$$+\overline{(D_\mu\phi)}D^\mu\phi - m_h^2[\bar{\phi}\phi - v^2/2]^2/2v^2.$$

Flavour sector:



QCD sector:



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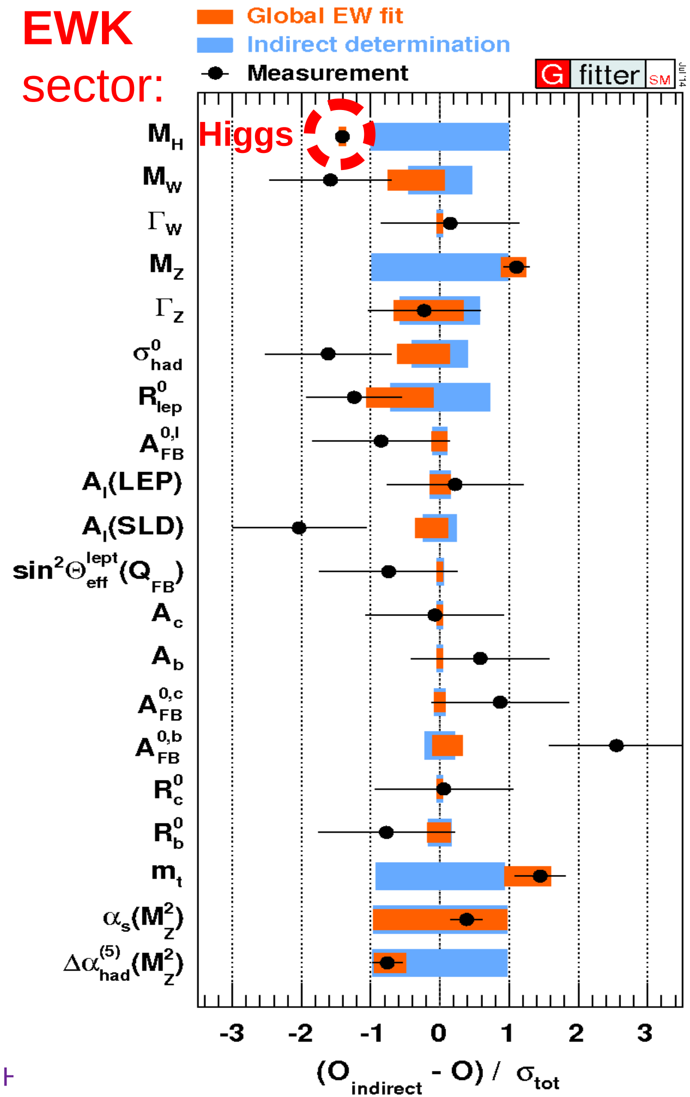

$$
\begin{aligned}
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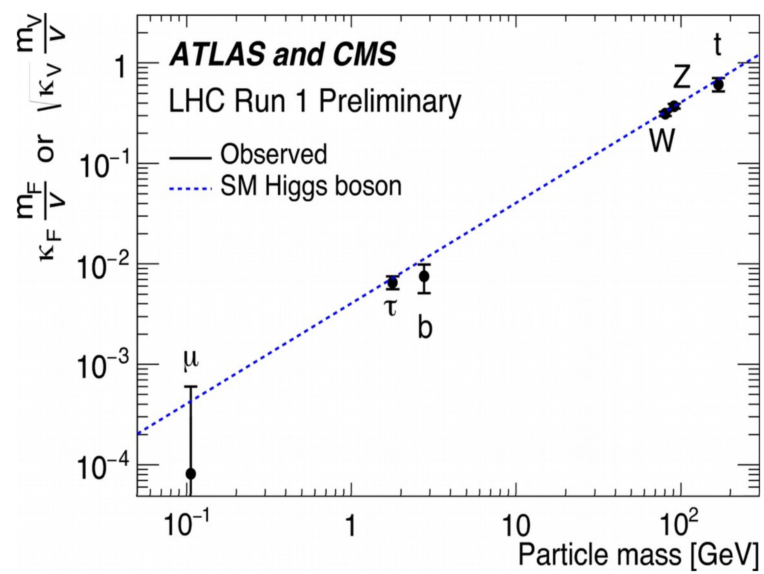
Higgs sector:



David d'Enterria (CERN)

Open questions in the SM (1)

$$\mathcal{L} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{8}tr(\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}) - \frac{1}{2}tr(\mathbf{G}_{\mu\nu}\mathbf{G}^{\mu\nu})$$ [Gauge interactions: $U(1)_Y$, $SU(2)_L$, $SU(3)_c$]

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$$-\frac{\sqrt{2}}{v}\left[(\bar{\nu}_L, \bar{e}_L)\,\phi M^e e_R + \bar{e}_R \bar{M}^e \bar{\phi}\begin{pmatrix} \nu_L \\ e_L \end{pmatrix}\right] - \frac{\sqrt{2}}{v}\left[(-\bar{e}_L, \bar{\nu}_L)\,\phi^* M^\nu \nu_R + \bar{\nu}_R \bar{M}^\nu \phi^T \begin{pmatrix} -e_L \\ \nu_L \end{pmatrix}\right]$$ [Lepton masses]

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✘ Light masses: Higgs mechanism for lightest fermions (u,d,s,e;ν's) to be proven

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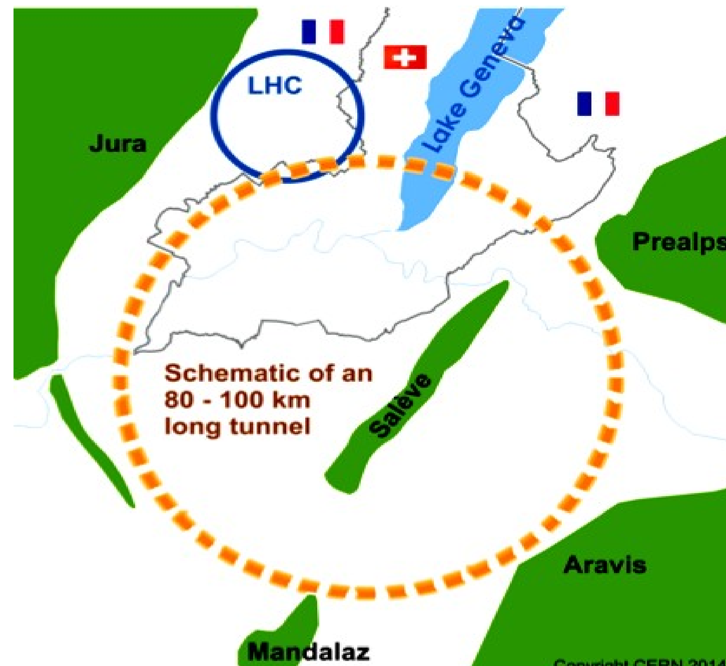
Some/Most(?) of these questions will not be fully answered at the LHC

CERN Future Circular Collider (FCC) project

- Solving those & others HEP open problems requires higher-energy collider:

- 100 km ring, Nb_3Sn 16 T magnets, LHC used as injector:
  - pp at $\sqrt{s}$=100 TeV, L~$2\mathrm{x}10^{35}$, L_{int}=2 ab^{-1}/yr (also pPb, PbPb at $\sqrt{s}$=39–63 TeV)
  - e^+e^- option (before pp) at $\sqrt{s}$=90–350 GeV L~10^{35}–$4\cdot10^{36}$, L_{int}=1–40 ab^{-1}/yr for H, Z
  - e-h collider option at $\sqrt{s}$=3.5 TeV, L~10^{34}



Why new e^+e^- colliders ?

- New physics (NP): Hiding well ? Beyond present reach ?
  At larger masses? At smaller couplings? Or both?
- Electron-positron colliders:
  - ➡ Direct model-indep. discovery of new particles coupling to Z*/γ* up to m~√s/2
  - ➡ Low, very-well understood backgrounds: Fill “blind spots” in p-p searches
  - ➡ Indirect NP constraints via virtual corrections. From generic EFT $L_{\rm eff} = \sum_n \frac{c_n}{\Lambda^2} O_n$

New scalar-coupled physics: $\Lambda \gtrsim (1\,\mathrm{TeV})/\sqrt{(\delta g_{\rm HXX}/g^{\rm SM}_{\rm HXX})/5\%}$

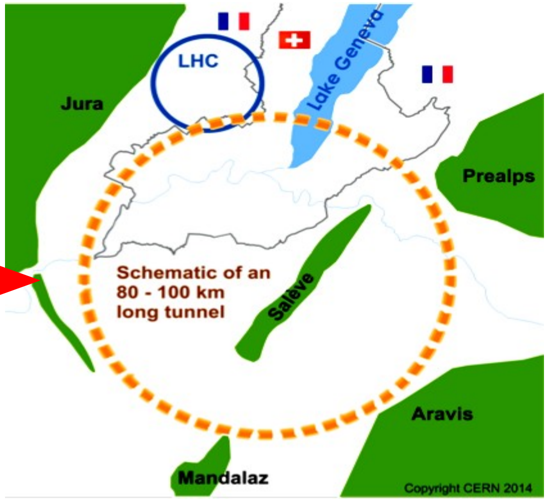
HL-LHC: ~5% deviations of Higgs couplings wrt. SM ⇒ Λ > 1 TeV

With 10^6 Higgs: ~0.1% Higgs couplings precision ⇒ Λ > 7 TeV

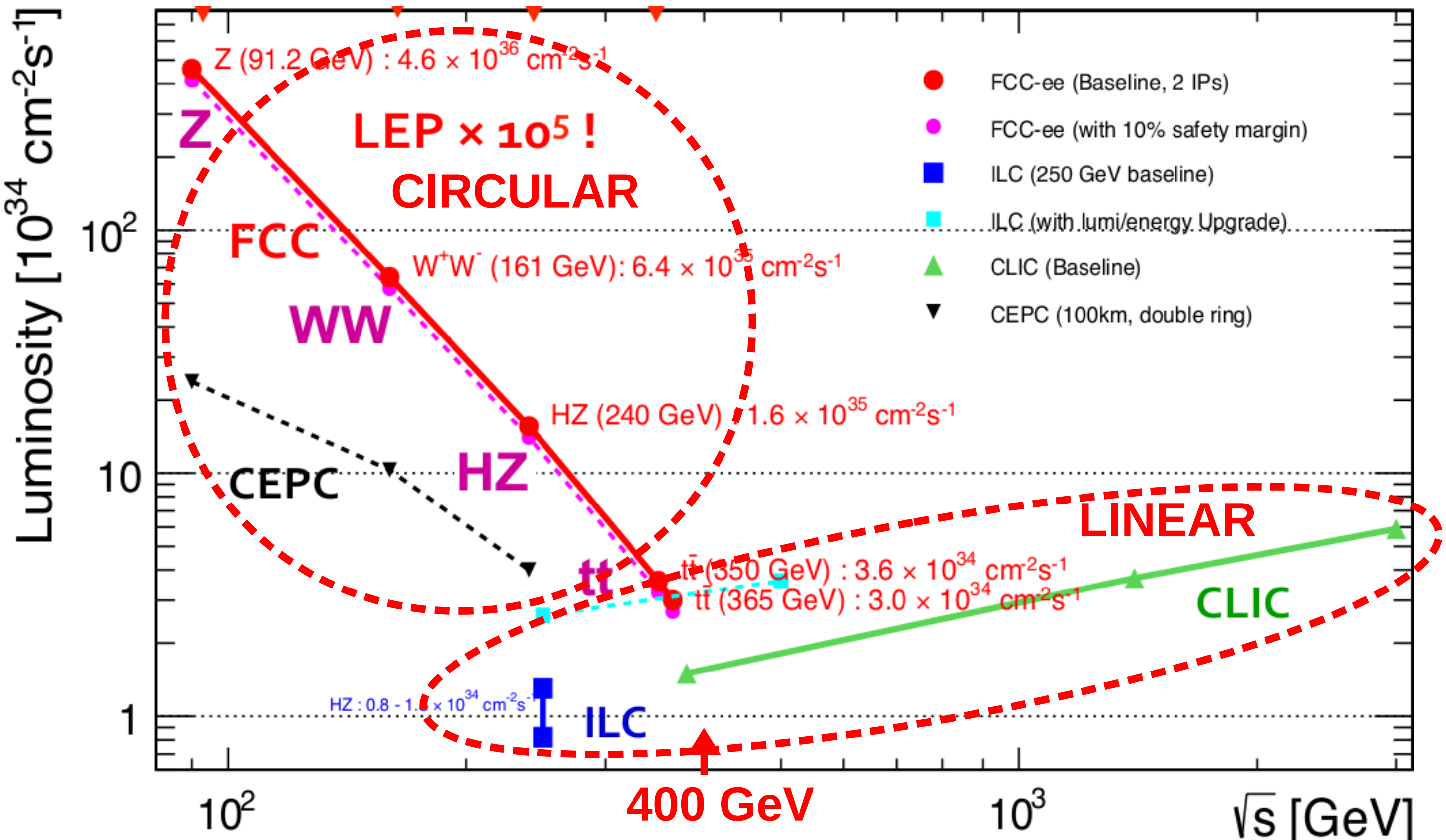
New electroweak-coupled physics: $\Lambda \propto (1\,\mathrm{TeV})/\sqrt{\delta X}$

NP excluded below Λ ~ 3 TeV by current EWK precision fit.

e^+e^- with R~80–100 km:
×10^4 more stats. (10^8 W's, 10^{11} Z's)
×10^2 precision w.r.t. LEP (10^4 W's, 10^7 Z's)
i.e. Λ >30 TeV



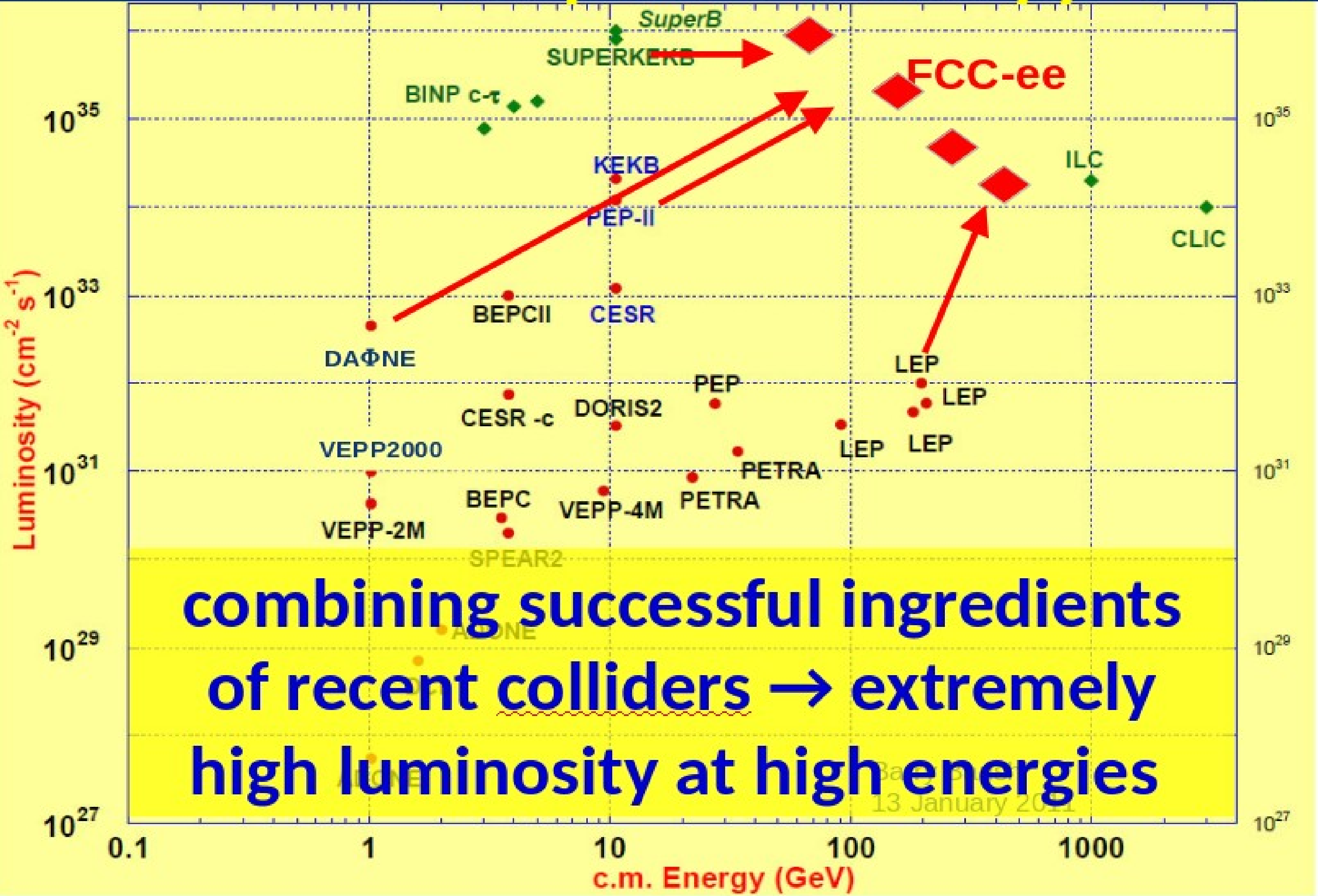
Circular vs. linear e^+e^- colliders



- $\sqrt{s}$ limited to ~400 GeV by SR~E^4/R
- Large # of circulating bunches:
  - → Much higher Lumi (better at low $\sqrt{s}$, lower SR)
  - → Top-up injection ring to compensate L burnoff
- Various Interaction Points possible
- Precise E_{beam} from resonant depolarization

- Larger $\sqrt{s}$ reach (TeV's)
- Low repetition rate
  - → Lumi from nm-size beams
  - → Large bremsstrahlung
  - → Large energy spread
- Longitudinal polarization easier

FCC-ee exploits lessons & recipes from past e^+e^- and *pp* colliders



LEP:
high energy
SR effects

B-factories:
KEKB & PEP-II:
high beam currents
top-up injection

DAFNE:
crab waist

Super B-factories
S-KEKB:
low β_y^*

KEKB:
e^+ source

HERA, LEP, RHIC:
spin gymnastics

FCC-ee technologies, time lines, analysis highlights
Frank Zimmermann
KET workshop, Munich, 2 May 2016

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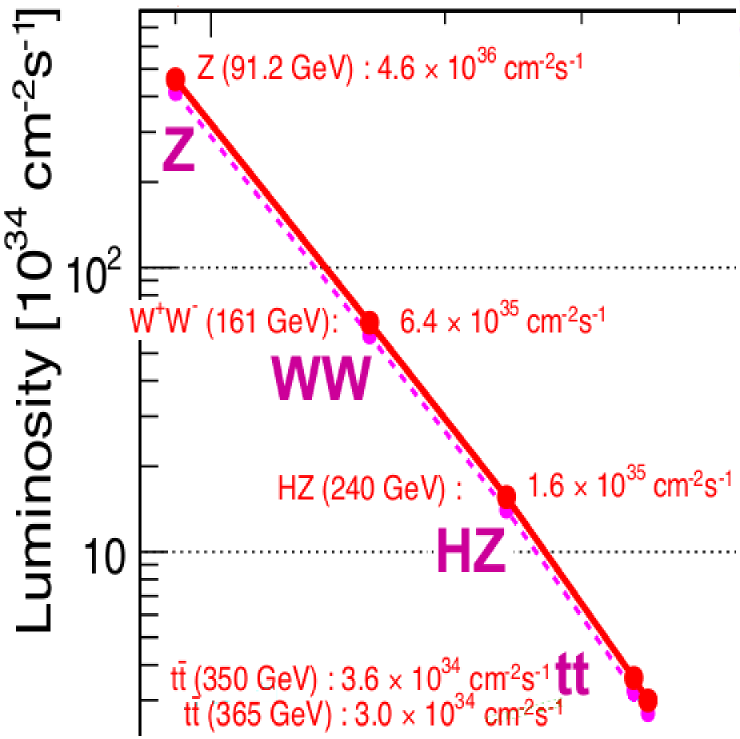
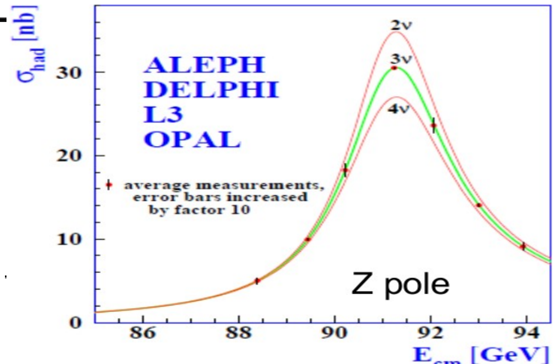
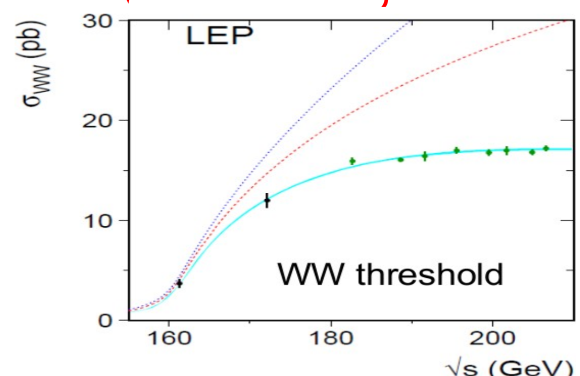
FCC-ee physics programme in a nutshell



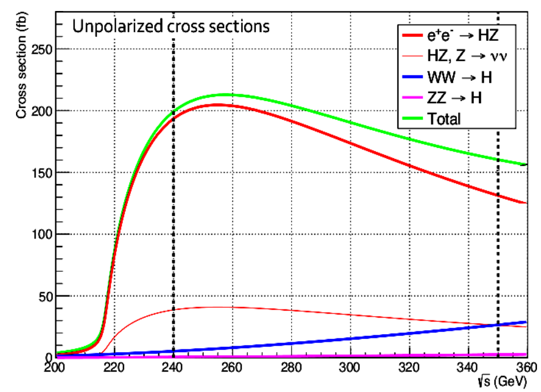
√s=91 GeV, 10^{12} Z's



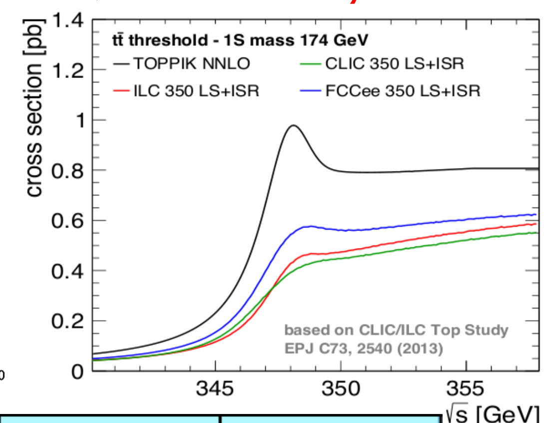
√s=161 GeV, 10^8 W's



√s=240 GeV, 10^6 H's



√s=350 GeV, 5·10^5 t's



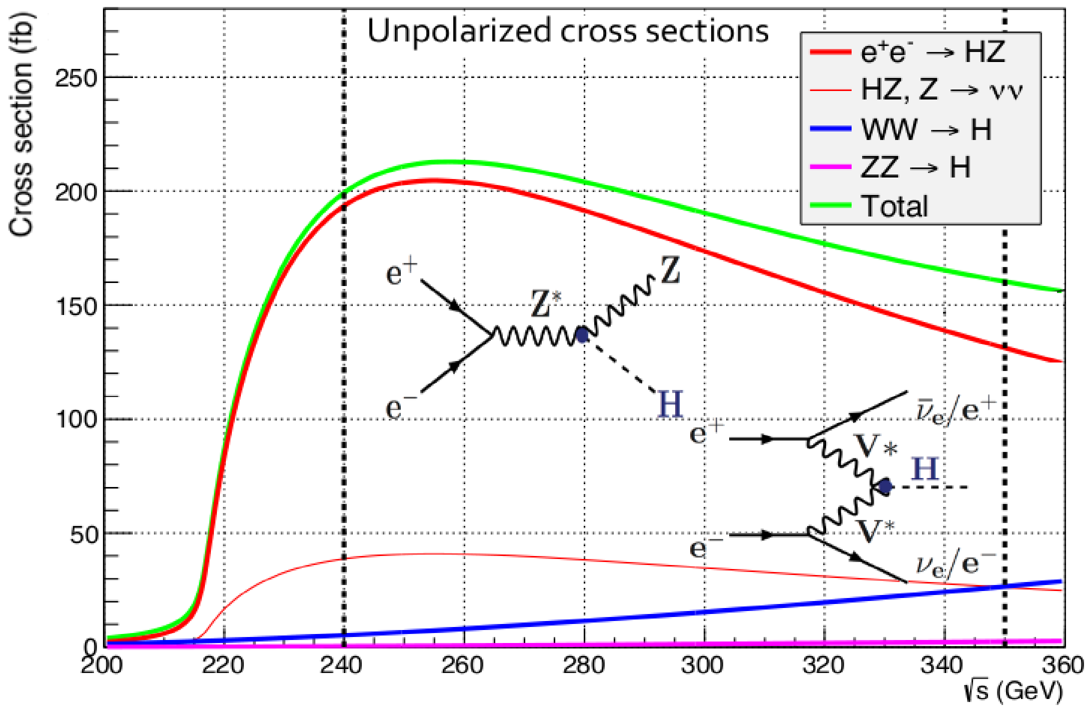
Working point	Z, years 1-2	Z, later	WW	HZ	$t\bar{t}$ threshold	365 GeV
Lumi/IP (10^{34} cm^{-2}s^{-1})	100	200	13	7	1.6	1.3
Lumi/year (2 IP)	26 ab^{-1}	52 ab^{-1}	7.8 ab^{-1}	1.8 ab^{-1}	0.4 ab^{-1}	0.35 ab^{-1}
Physics goal	150		10	5	0.2	1.5
Run time (year)	2	2	1	3	0.5	4

- FCC-ee core physics programme to be completed in 12–13 years

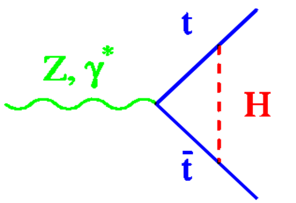
FCC-ee = Higgs boson factory

- Cross section: $\sigma(e^+e^- \rightarrow H+X) \approx 200 + 50$ fb
- Large number of Higgs produced: $\sim 2 \cdot 10^6$, with small & controlled backgrounds, plus no pileup:

Total Integrated Luminosity (ab^{-1})	**10**
Number of Higgs bosons from $e^+e^- \rightarrow HZ$	**2,000,000**
Number of Higgs bosons from boson fusion	**50,000**



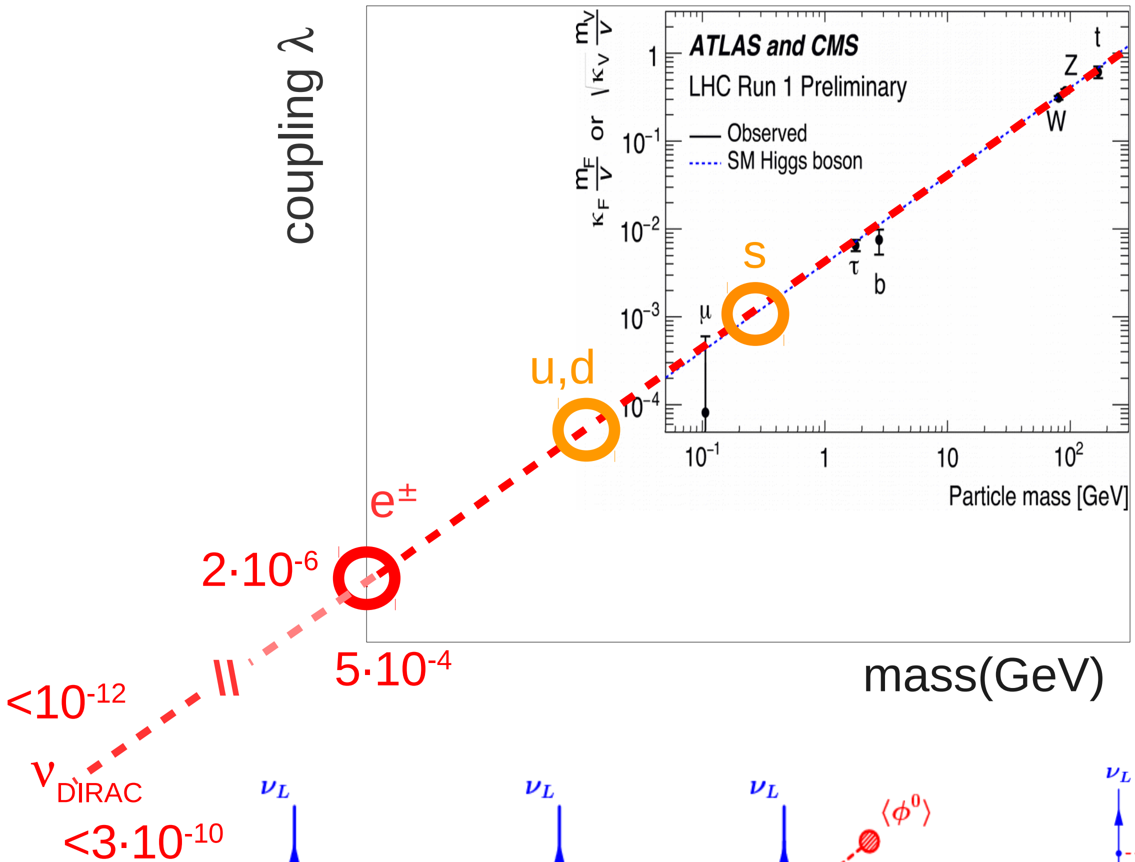
(also sensitivity to y_t)

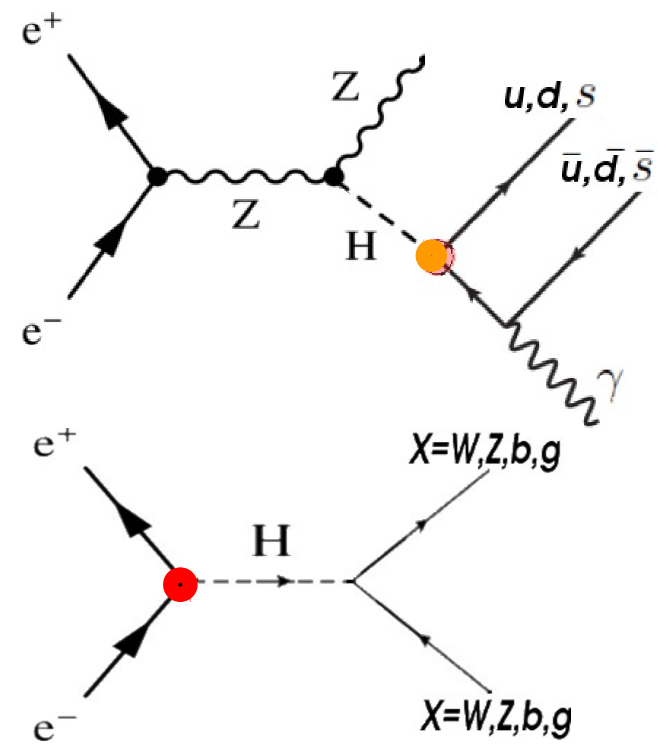


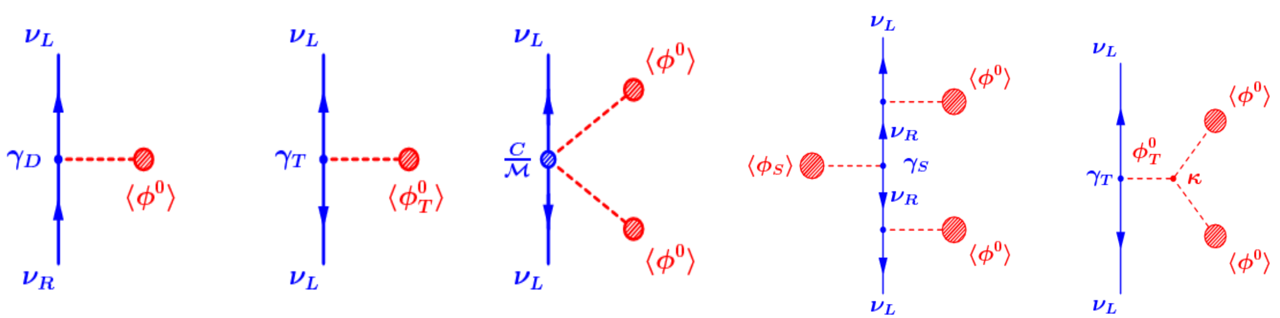
- Access to precision (<<1%) Higgs couplings, and rare & BSM decays

Open SM issue (1): Generation of lightest fermion (u,d,s, ν's) masses

- LHC can only access 3rd (plus few 2nd)-gen.Yukawas. What about the rest?

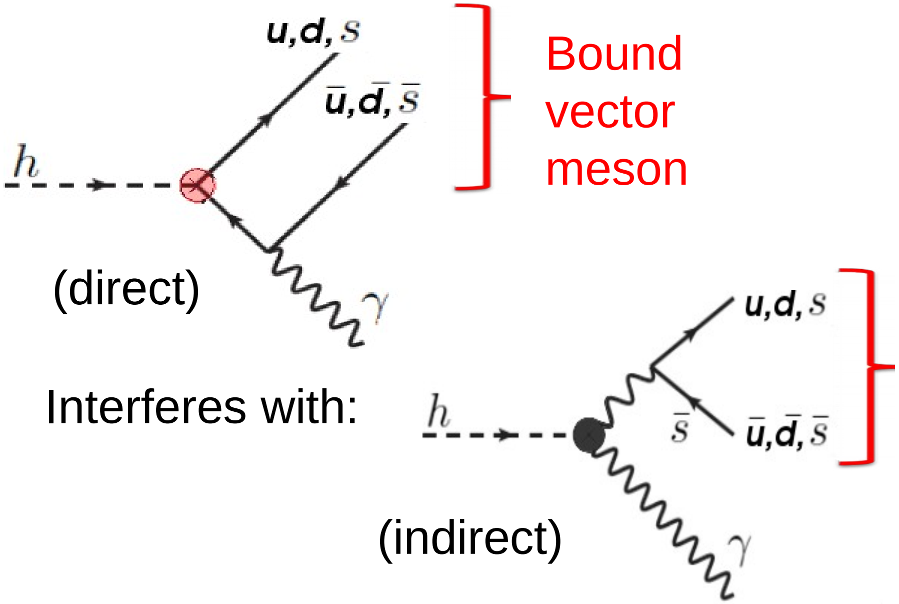






1^{st}-generation quark Yukawa couplings

- 1^{st} & 2^{nd} gen. quark Yukawa accessible via exclusive $H\to V\gamma$, $V=\rho,\omega,\phi$



[G. Perez et al, arXiv:1505.06689]

Mode / Method	Branching Fraction [10^{-6}] LCDA LO [170]	LCDA NLO [173]
$\mathrm{Br}(H\to\rho^0\gamma)$	19.0 ± 1.5	16.8 ± 0.8
$\mathrm{Br}(H\to\omega\gamma)$	1.60 ± 0.17	1.48 ± 0.08
$\mathrm{Br}(H\to\phi\gamma)$	3.00 ± 0.13	2.31 ± 0.11

- $H\to\rho(\pi\pi)\gamma$ channel most promising: N~40 counts expected, low backgds
- Sensitivity to u/d quark Yukawa couplings:

$$\frac{\mathrm{BR}_{h\to\rho\gamma}}{\mathrm{BR}_{h\to b\bar{b}}}=\frac{\kappa_\gamma\left[(1.9\pm0.15)\kappa_\gamma-0.24\bar{\kappa}_u-0.12\bar{\kappa}_d\right]}{0.57\bar{\kappa}_b^2}\times10^{-5}$$

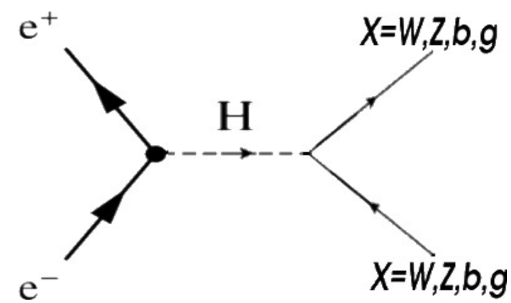
($k_q=y_q/y_b$)

- All channels also accessible with higher stats at FCC-pp, but much worse backgrounds (QCD and pileup).

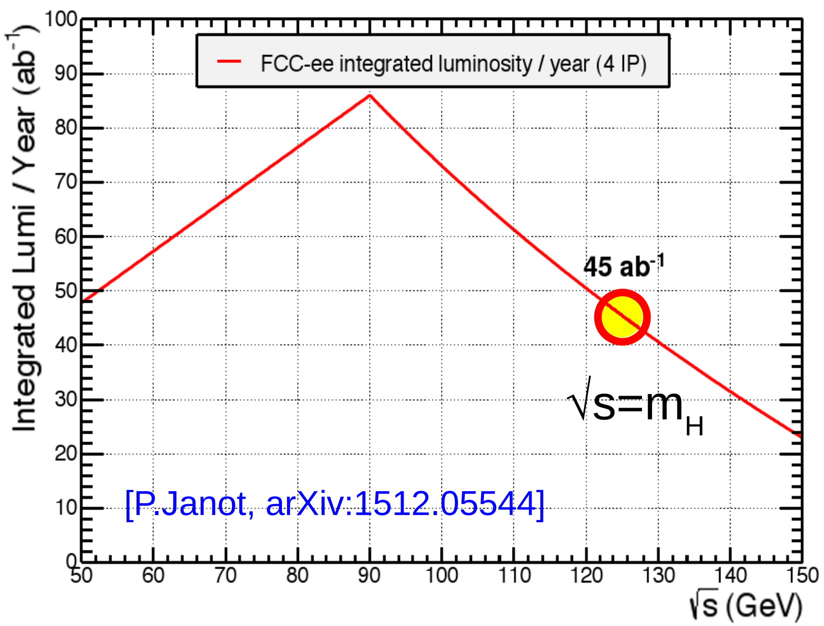
e Yukawa via s-channel $e^+e^- \to H$ production

- Higgs decay to e+e- is unobservable: BR($H\to e^+e^-$) ≈ $5\cdot 10^{-9}$
- Resonant Higgs production considered so far only for muon collider:
  $\sigma(\mu\mu\to H) \approx 70$ pb. Tiny g_{eH} Yukawa coupling ⇒ Tiny $\sigma(ee\to H)$:

$$\sigma(e^+e^-\to H) = \frac{4\pi\Gamma_H^2 Br(H\to e^+e^-)}{(\hat{s}-M_H^2)^2+\Gamma_H^2 M_H^2} = 1.64 \text{ fb } (m_H=125 \text{ GeV}, \Gamma_H=4.2 \text{ MeV})$$



- Huge luminosities available at FCC-ee:



In theory, FCC-ee running at H pole-mass $L_{int} \approx 45$ ab^{-1}/yr would produce O(75.000) H's

IFF we can handle: (i) beam-energy spread, (ii) ISR, and (iii) huge backgrounds, then:

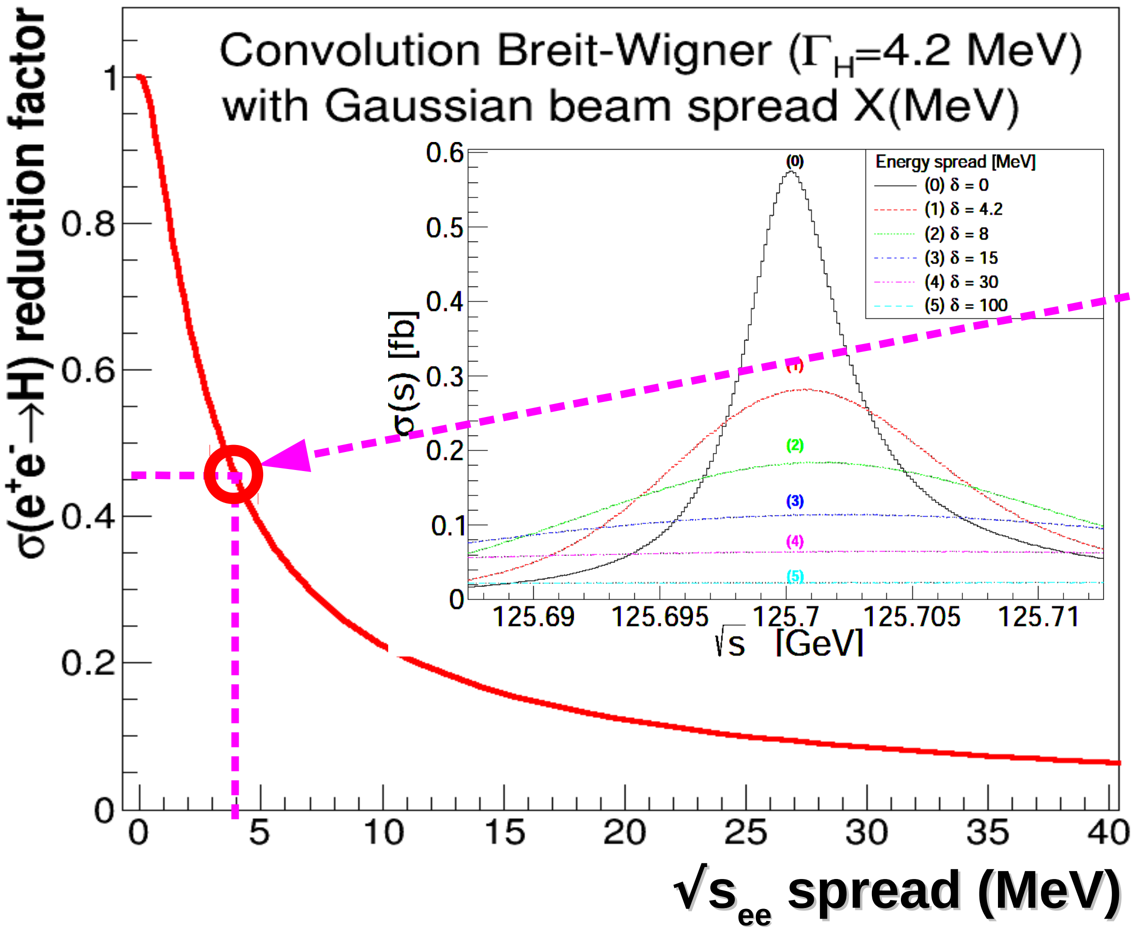
→ Electron Yukawa coupling measurable?

→ Higgs width measurable (threshold scan)?

→ Separation of possible nearly-degen. H's?

s-channel $e^+e^- \to H$ visible cross section

- $\sigma(e^+e^- \to H) = 1.64$ fb for Breit-Wigner with $\Gamma_H = 4.2$ MeV width. Higgs production greatly suppressed off resonant peak.
- Convolution of Gaussian energy spread of each $e^\pm$ beam with Higgs B.-W. results on a (Voigtian) effective cross-section decrease:



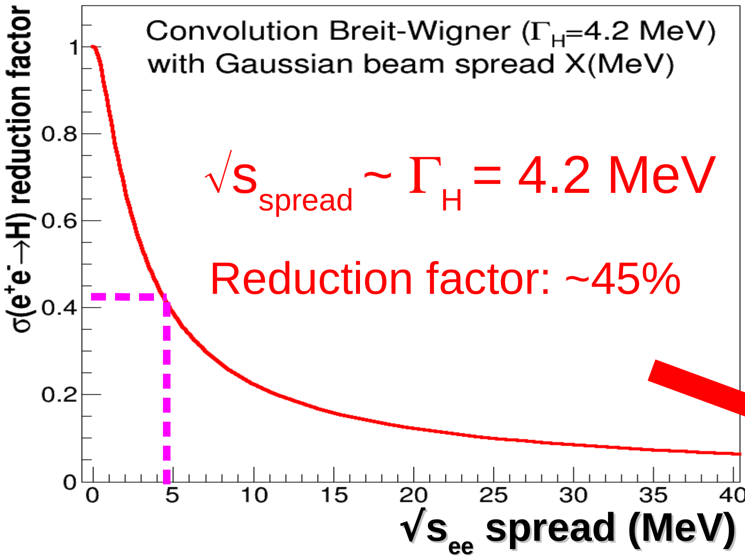
$\sqrt{s}_{spread} = \Gamma_H = 4.2$ MeV

Monochromatization(*):

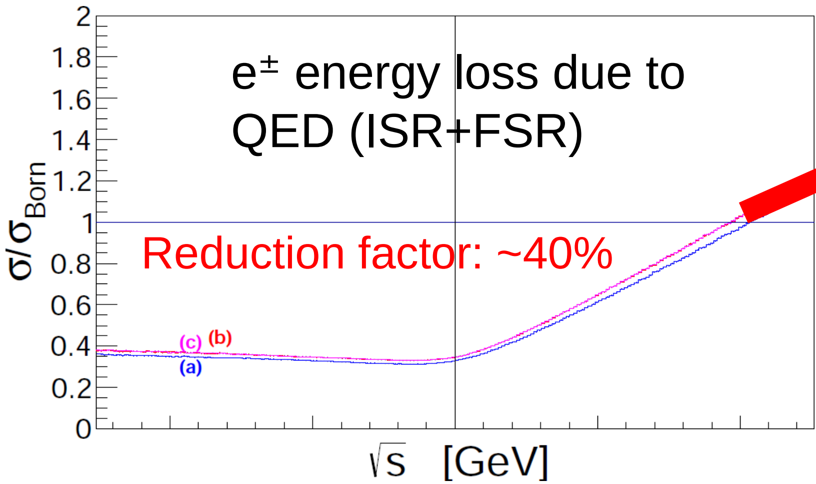
~45% reduction factor

(*)[F.Zimmermann, M.Valdivia-García JACoW-IPAC2017-WEPIK015]

s-channel $e^+e^- \rightarrow H$ visible cross section

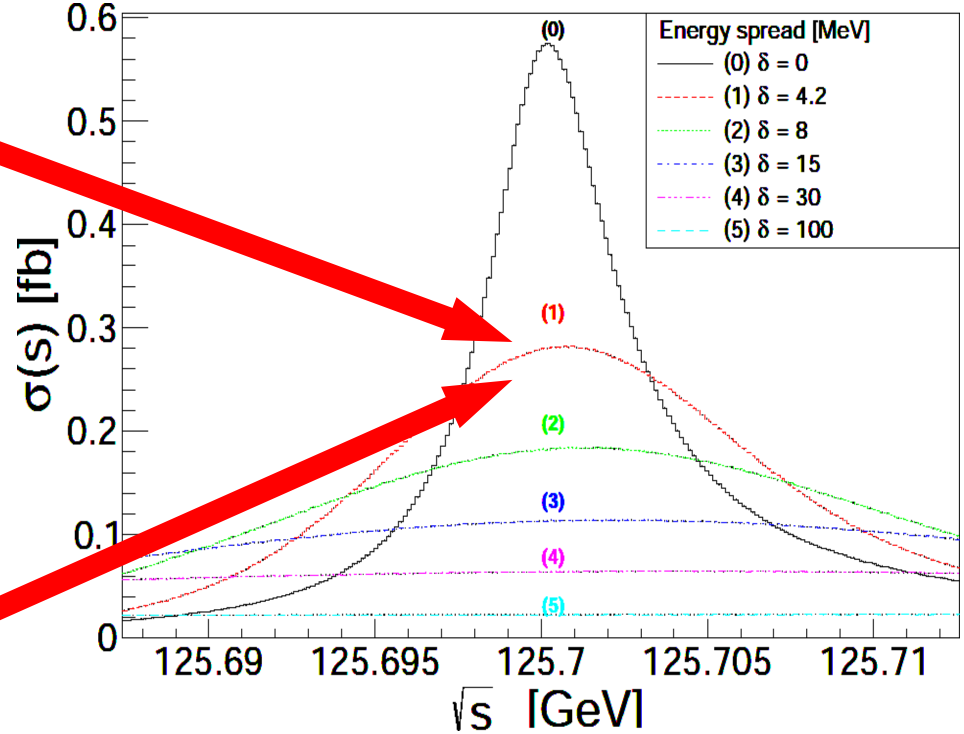


- Extra ~40% reduction due to QED radiation:



- Full convolution of both effects:

[S.Jadach et. al. arXiv:1509.02406]

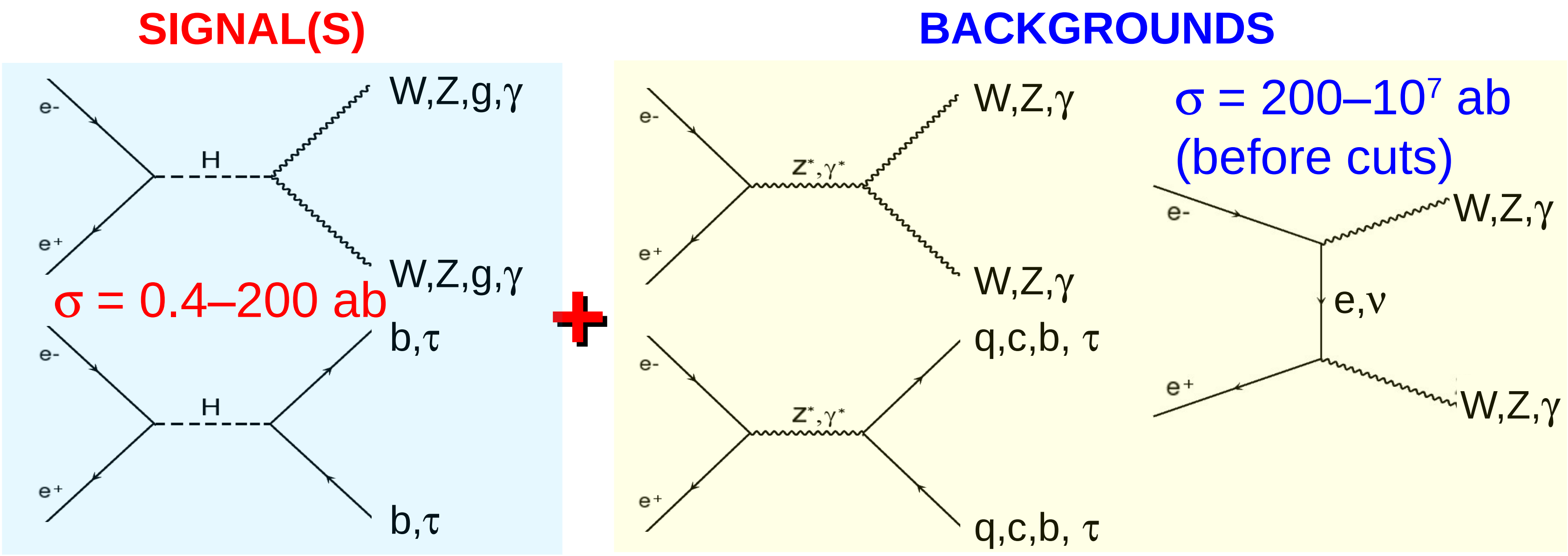


For $\sqrt{\sigma}_{spread} \approx \Gamma_H = 4.2$ MeV

$\sigma_{spread+ISR}(e^+e^- \rightarrow H) = 0.17 \times \sigma(e^+e^- \rightarrow H) = 290$ ab

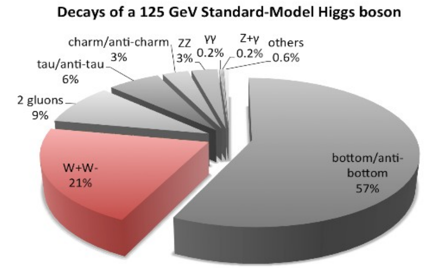
s-channel $e^+e^- \to H$ measurement at FCC(125 GeV)

- PYTHIA8 e^+e^- at $\sqrt{s} = m_H = 125$ GeV to generate 10 final-states for Higgs signal plus backgrounds ($e^+e^- \to WW^*$, ZZ^*, $\gamma\gamma$, gg, $\tau\tau$, bb, cc, qq):



- Exclusive e^+e^- (2,4) k_T jet algorithm. Realistic b,c,q,τ (mis)reco efficiencies
- Reducible backgrounds:
  – Cuts on single & pair jets, leptons kin.vars: $p_{T,i}$, η_i, ϕ_i, mass$_i$, charge, Δr_{isol}, $p_{T,max}$, $p_{T,min}$, η_{max}, η_{min}, ϕ_{max}, ϕ_{min}, m_{inv}, $\cos(\theta_{ij})$, $\Delta\eta_i$, $\Delta\phi_i$, H_T
  – Global evt variables: E_{tot}, (ME, m_{ME}), sphericity, aplanarity, thrust min,max…
- Irreducible continuum background: MVA BTD

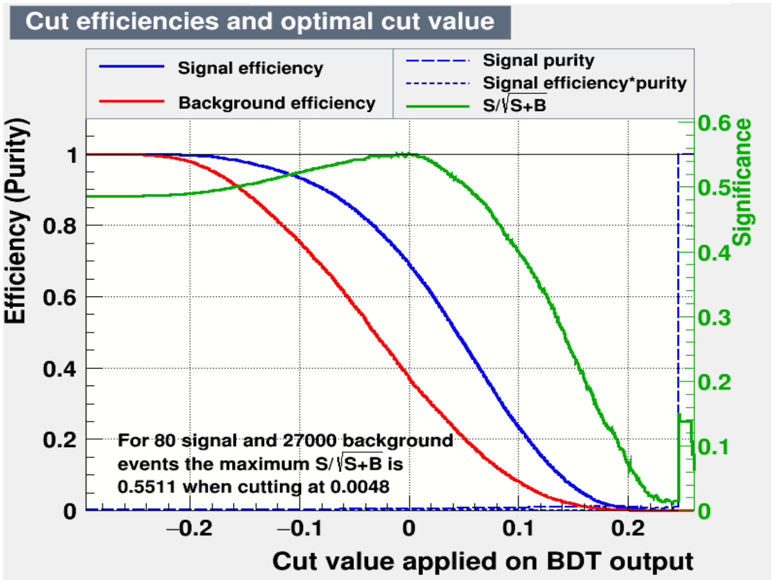
Most significant channel: $e^+e^- \to H(WW^*) \to l\nu jj$



- Final state (retains 80% of σ(WW*(lνjj)) = 28 ab):
  1 isolated e,μ,τ(e),τ(μ) + ME>2 GeV + 2 jets (excl.)

- Analysis cuts:

✓ $E_{j1,j2}$ < 52,45 GeV ¬ Kills $e^+e^- \to q\bar{q}$
✓ $m_{w(l\nu)}$ > 12 GeV/c^2 ¬ Kills $e^+e^- \to q\bar{q}$
✓ E_{lepton} > 10 GeV ¬ Kills $e^+e^- \to q\bar{q}$
✓ ME > 20 GeV ¬ Kills $e^+e^- \to q\bar{q}$
✓ m_{ME} < 3 GeV/c^2 ¬ Kills $e^+e^- \to \tau\tau$
✓ BDT MVA ¬ Kills $e^+e^- \to WW^*$ continuum
(exploits opposite $W^\pm$ polarizations in H decay)



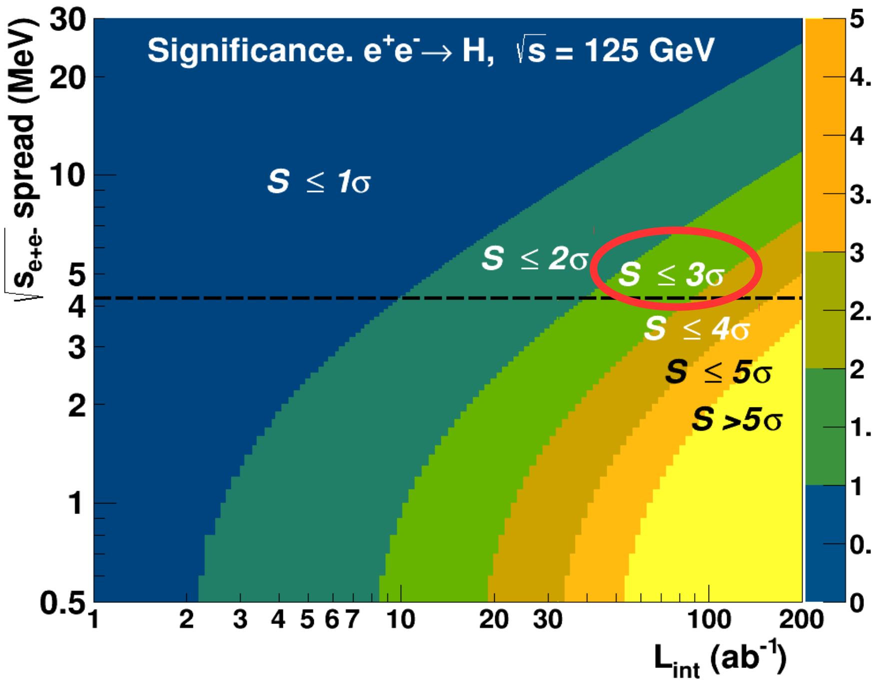
- Signal & backgrounds before/after cuts:

$q\bar{q}$:	σ = 22 pb ⇒	σ(after) = 4 ab
τ τ:	σ = 1 pb ⇒	σ(after) = 2.6 ab
WW*:	σ = 16.3 fb ⇒	σ(after) = 2.7 fb
H(WW*):	σ = 23 ab ⇒	σ(after) = 8 ab

For L_{int}=10 ab^{-1}
S/√B = 80/√27.e3 ≈ 0.5
Significance ≈ 0.5

$e^{\pm}$ Yukawa coupling at FCC-ee(125)

- Counting experiment combining signal+backgd in 10 Higgs decay channels:

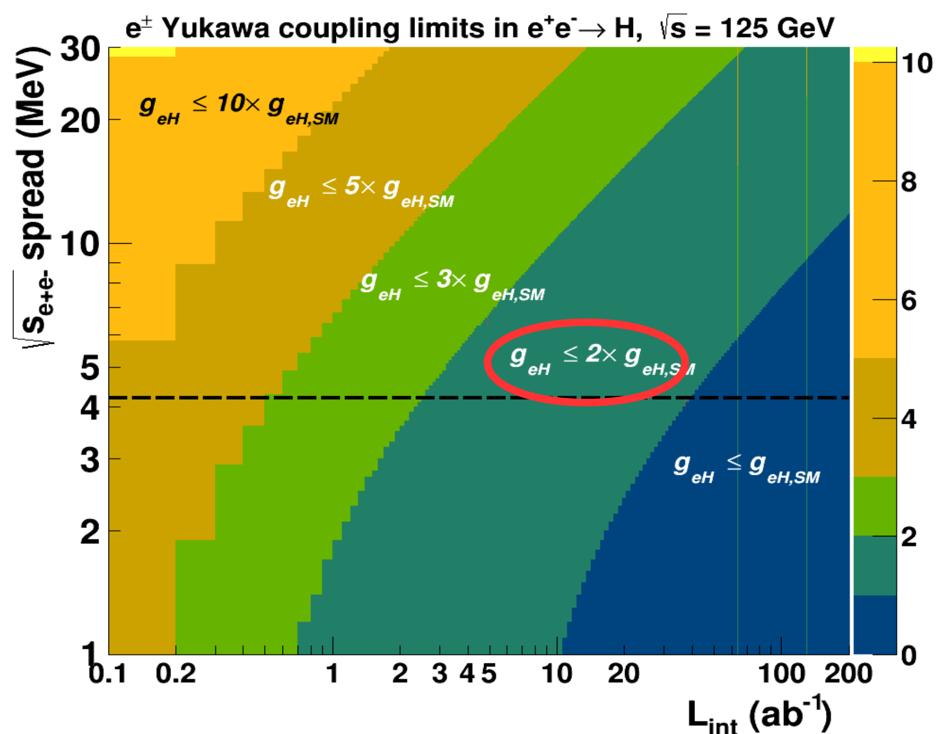


- Significance on e-Yukawa coupling:

3σ evidence requires L_{int} = 90 ab^{-1}

- Limits on BR&Yukawa for 10 ab^{-1}: (reachable w/ monochromatization)

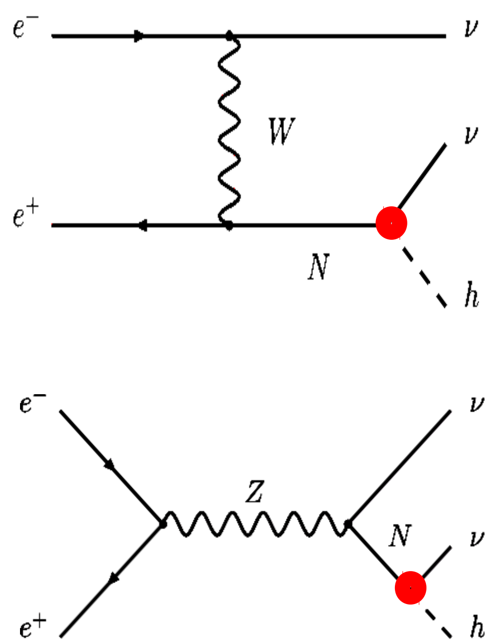
Significance~0.7
BR(Hee) **< 2.8**×BR_{SM} (95% CL)
g_{eH} **< 1.7**×$g_{eH,SM}$ (95% CL)

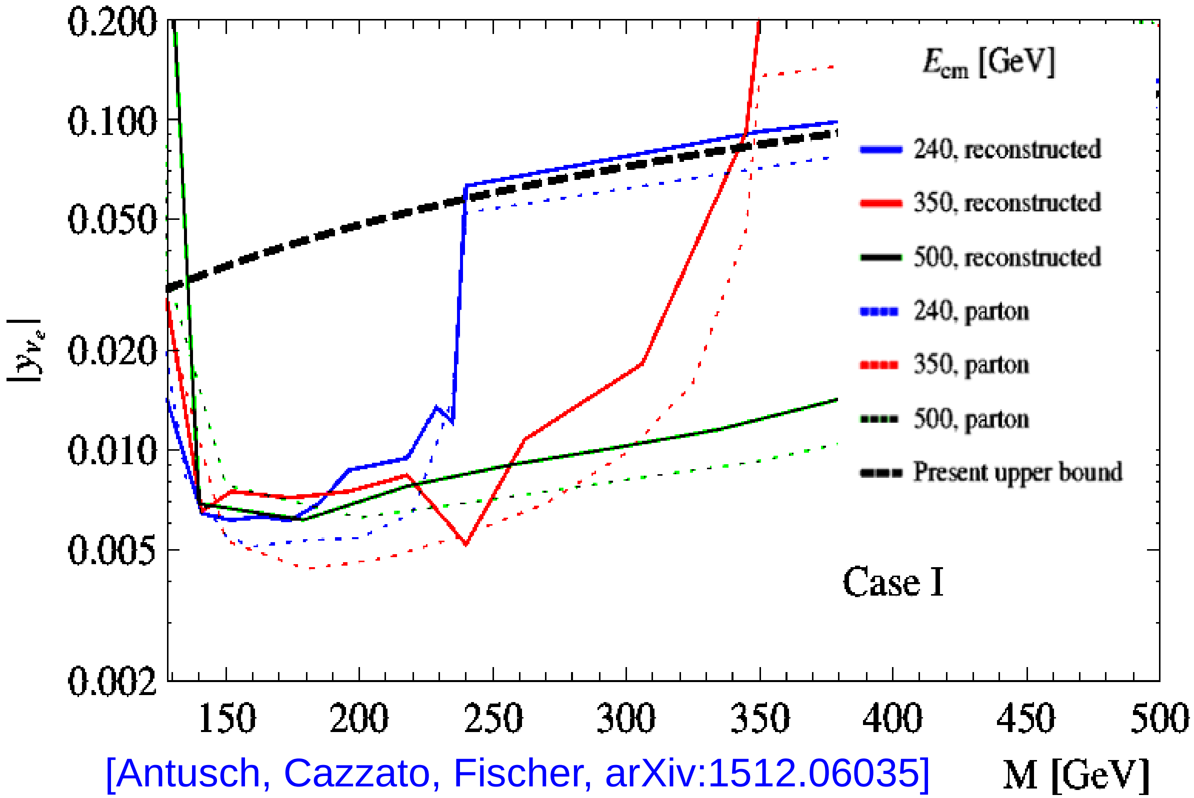


[D.d'E., Wojcik, Aleksan, arXiv:1701.02663]

Higgs couplings to heavy-neutrinos

- (Symmetry-protected) low-mass seesaw scenario with 2 sterile ν (N_i): large neutrino Yukawa couplings & masses: $y_\nu \approx 10^{-3}$, $m_N \approx 10^2$ GeV
- N_i decay to Higgs+ν. Signature: mono-Higgs(jj) plus missing energy



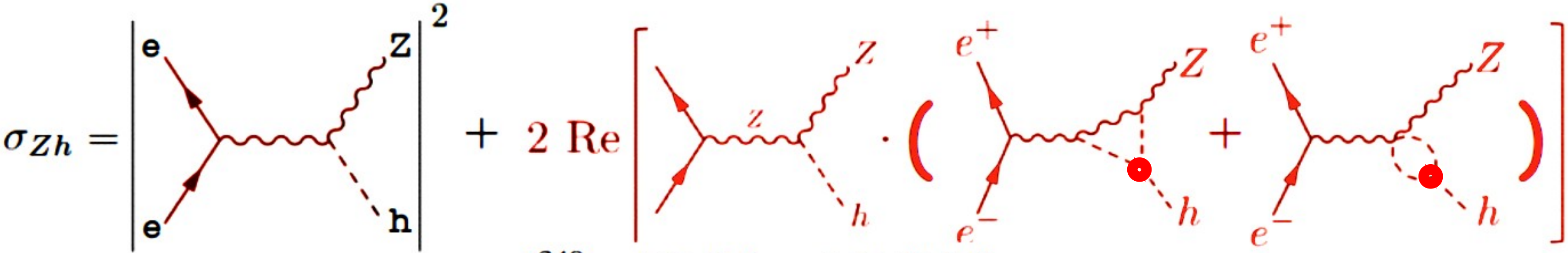


[Antusch, Cazzato, Fischer, arXiv:1512.06035]

- FCC-ee sensitivity down to $|y_{\nu e}|\sim5\times10^{-3}$ for unexplored $m_N\sim100$–300 GeV

Open SM issue (2): Higgs self-coupling

- Higgs trilinear indirectly constrained through loop corrections to σ(H+Z):



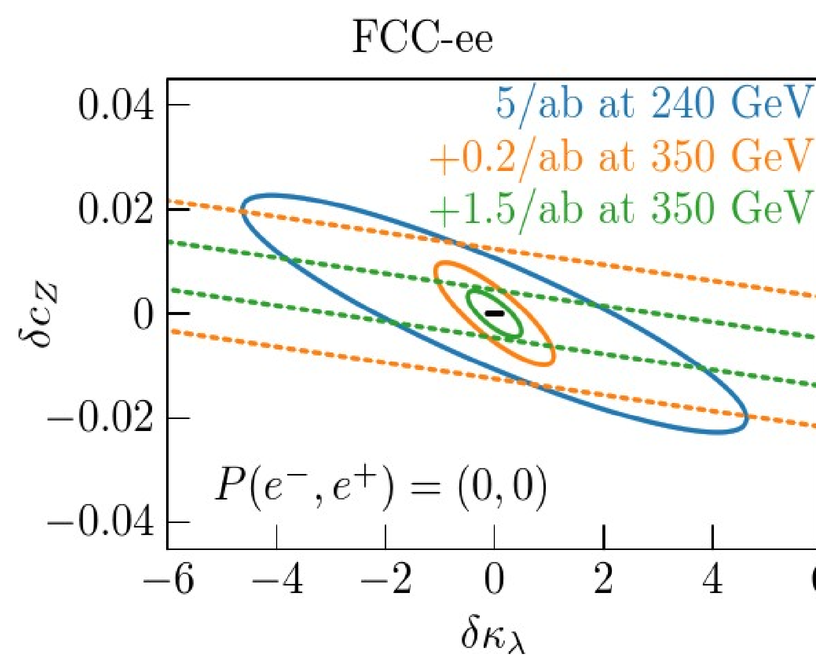
[M. McCullough, 2014]

$$\delta_\sigma^{240} = 100\,(2\delta_Z + 0.014\delta_h)\,\%$$

Self-coupling correction δ_h: energy-dependent

δ_Z: energy-independent (distinguishable).

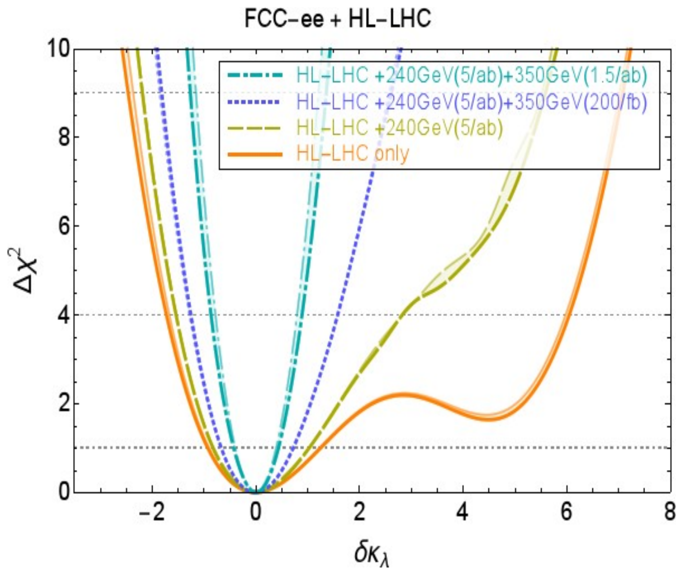
[G. Durieux, Wed. session]



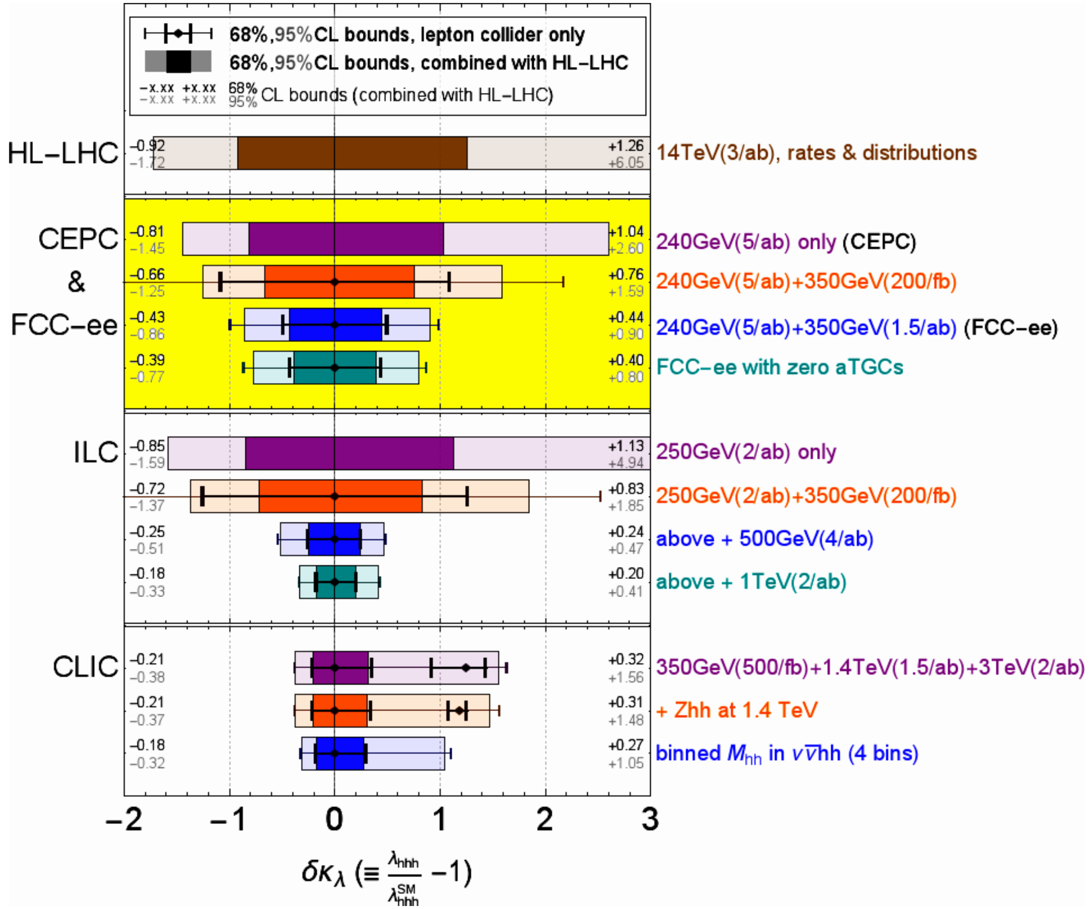
- Tiny effect, but visible thanks to extreme (0.4%) precision on σ_{ZH} coupling reachable at FCC-ee.

- Indirect limits on trilinear λ coupling at ~40% level combining 240+350GeV

Higgs self-coupling through σ(H+Z)



- Addition of FCC-ee 240+350GeV Higgs cross section solves 2nd minimum on λ from HL-LHC data alone.



- Higgs self-coupling constrained to within ~40%. Higher-energy e^+e^- collisions required to reduce it to ~20%

[G. Durieux, Wed. session]

Open issue in the SM (3): Hierarchy/Naturalness (BSM scalar-coupled physics)

- Solved via many BSM realizations: SUSY, composite-H, little-H,...
- Parametrize (B)SM as an Effective Theory:

$$\mathcal{L}_{\rm Eff} = \sum_{d=4}^{\infty} \frac{1}{\Lambda^{d-4}} \mathcal{L}_d = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \cdots$$

$$\mathcal{L}_d = \sum_i C_i^d \mathcal{O}_i \qquad\qquad [\mathcal{O}_i] = d$$

- Indirect (loop) constraints on new physics coupled to Higgs:

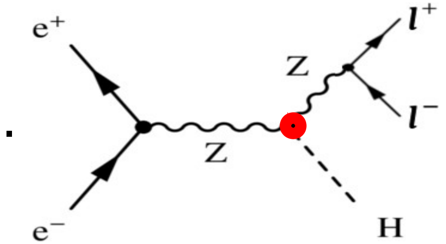
$$\Lambda \gtrsim (1\,{\rm TeV})/\sqrt{(\delta g_{\rm HXX}/g^{\rm SM}_{\rm HXX})/5\%}$$

~5% deviations of Higgs couplings wrt. SM: Λ >1 TeV

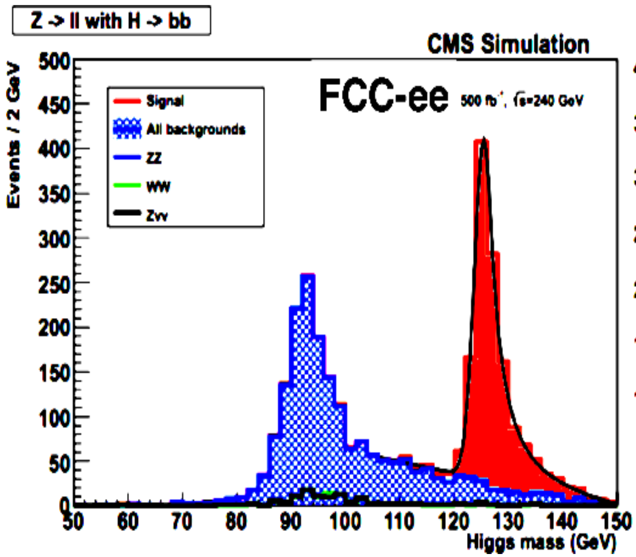
~0.1% Higgs couplings precision (~10^6 Higgs) ⇒ Λ>7 TeV

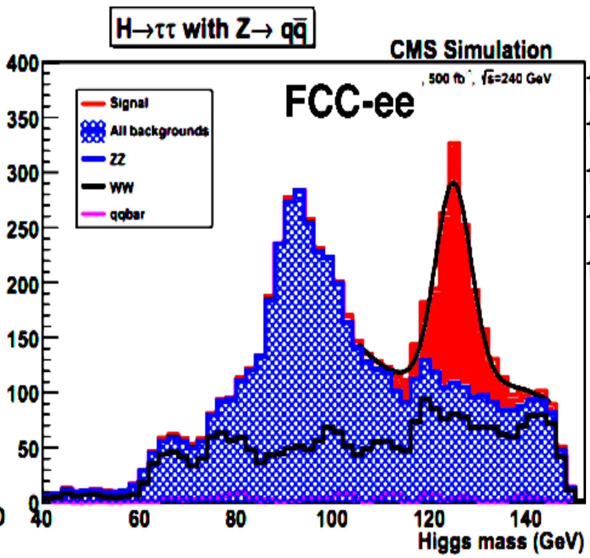
Precision H couplings, width, mass at FCC-ee

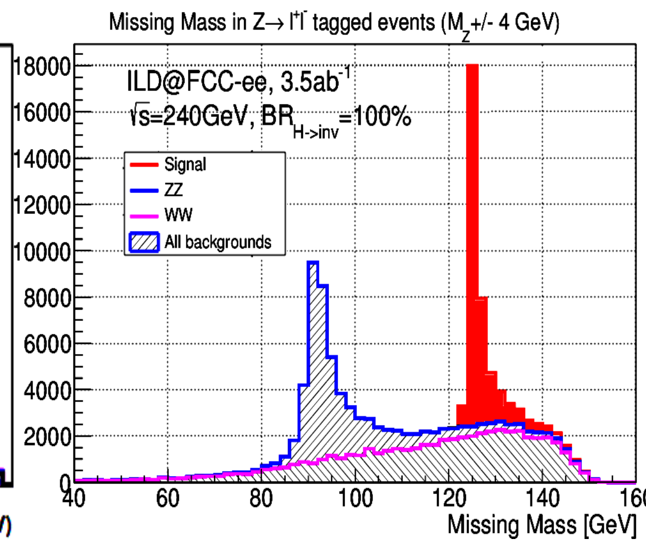
- Recoil method in H-Z(ll) unique to lepton collider: reconstruct H 4-mom. independent of H decay mode.
- High-precision (0.4%) σ_{ZH} provides model-indep. g_Z coupling $\sigma(ee \to ZH) \propto g_Z^2$, with ±0.2% uncert.



$$m^2_{\mathrm{recoil}} = (\sqrt{s} - E_{f\bar{f}})^2 - p^2_{f\bar{f}}$$







- Total width (Γ_H) with ~1% precision from combination of measurements $\sigma(ee \to ZH)$, $\sigma(ee \to ZH \to ZZ^*)$, $\Gamma_{H \to ZZ}$: $\sigma(e^+e^- \to HZ \to ZZZ) = \sigma(e^+e^- \to HZ) \times \frac{\Gamma(H \to ZZ)}{\Gamma_H}$
- Limits in BR to invisible from missing mass: <0.5% (95% CL)
- Higgs mass (m_H) from recoil mass in $Z \to \mu\mu$,ee

H couplings, width, mass: FCC-ee vs. others

- e^+e^- colliders provide factor > 50 (10) improvement in precision w.r.t. model-dependent! LHC (HL-LHC) expectations:

[DdE, arXiv:1701.02663]

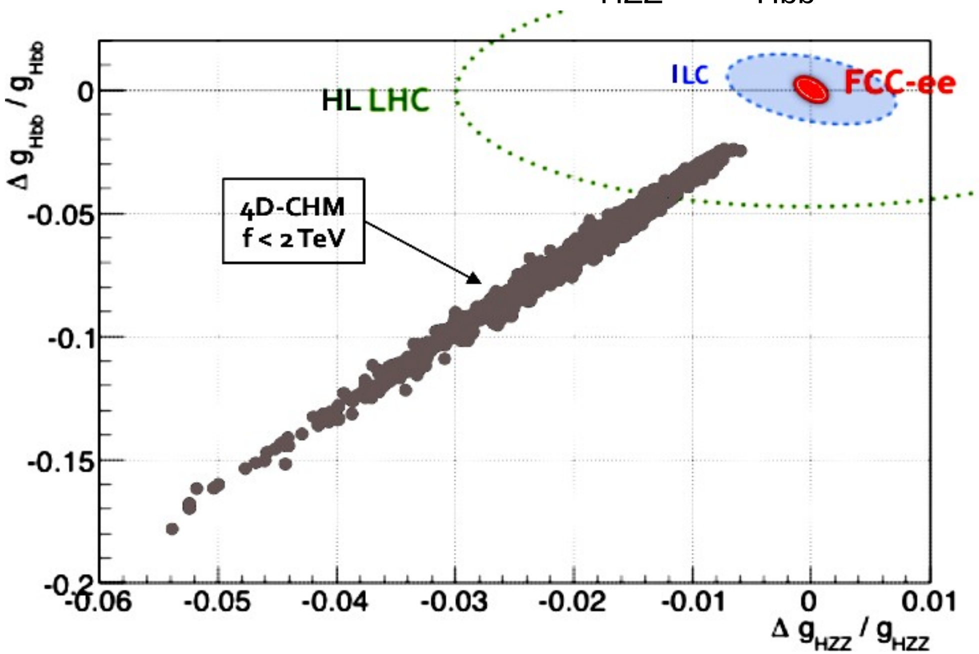
Parameter	Current* 7+8+13 TeV $\mathcal{O}$(70 fb^{-1})	HL-LHC* 14 TeV (3 ab^{-1})	FCC-ee Baseline (10 yrs)	ILC Lumi upgrade (20 yrs)	CEPC Baseline (10 yrs)	CLIC Baseline (15 yrs)
σ(HZ)	–	–	0.4%	0.7%	0.5%	1.6%
g_{ZZ}	10%	2–4%	0.15%	0.3%	0.25%	0.8%
g_{WW}	11%	2–5%	0.2%	0.4%	1.6%	0.9%
g_{bb}	24%	5–7%	0.4%	0.7%	0.6%	0.9%
g_{cc}	–	–	0.7%	1.2%	2.3%	1.9%
$g_{\tau\tau}$	15%	5–8%	0.5%	0.9%	1.4%	1.4%
$g_{t\bar{t}}$	16%	6–9%	13%	6.3%	–	4.4%
$g_{\mu\mu}$	–	8%	6.2%	9.2%	17%	7.8%
$g_{e^+e^-}$	–	–	<100%	–	–	–
g_{gg}	–	3–5%	0.8%	1.0%	1.7%	1.4%
$g_{\gamma\gamma}$	10%	2–5%	1.5%	3.4%	4.7%	3.2%
$g_{Z\gamma}$	–	10–12%		(to be determined)		9.1%
Δm_H	200 MeV	50 MeV	11 MeV	15 MeV	5.9 MeV	32 MeV
Γ_H	<26 MeV	5–8%	1.0%	1.8%	2.8%	3.6%
Γ_{inv}	<24%	<6–8%	<0.45%	<0.29%	<0.28%	<0.97%

- Most precise g_{ZZ} ~0.15% coupling sets limit on new scalar-coupled physics at: $\Lambda \gtrsim (1\,\mathrm{TeV})/\sqrt{(\delta g_{HXX}/g^{SM}_{HXX})/5\%}$ > 6 TeV

Precision H properties: Concrete BSM bounds

- FCC-ee precision measurements greatly improve scalar-coupled BSM limits.
- 4D-Composite Higgs models:

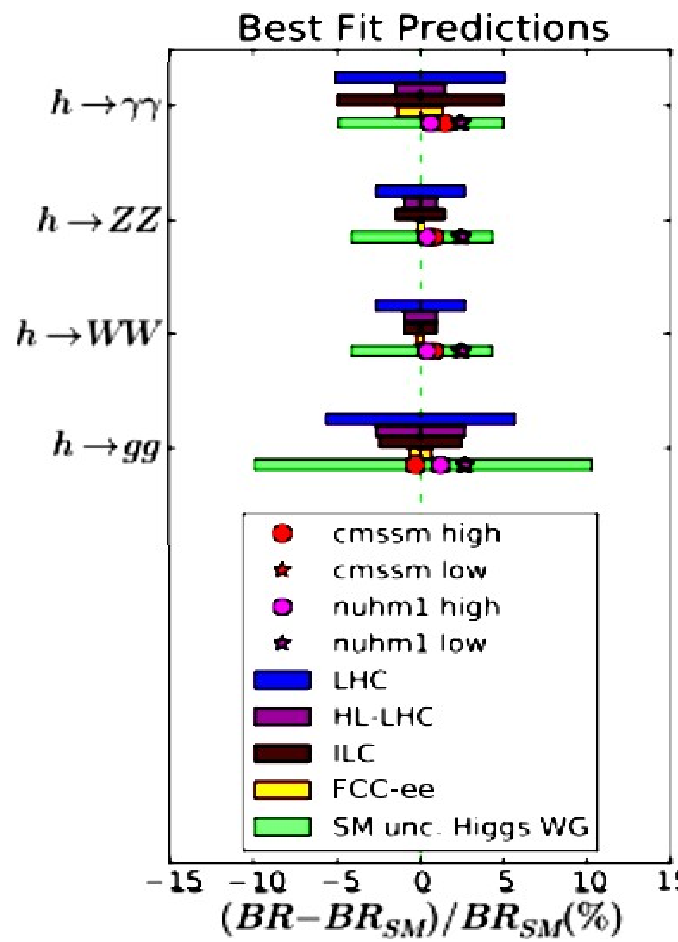
Correlated effect on g_{HZZ} & g_{Hbb}



(All other couplings affected in a similar manner)

FCC-ee sensitivity on composite-scale parameter: f > 4–5 TeV

- Benchmark SUSY models (CMSSM, NUHM1)

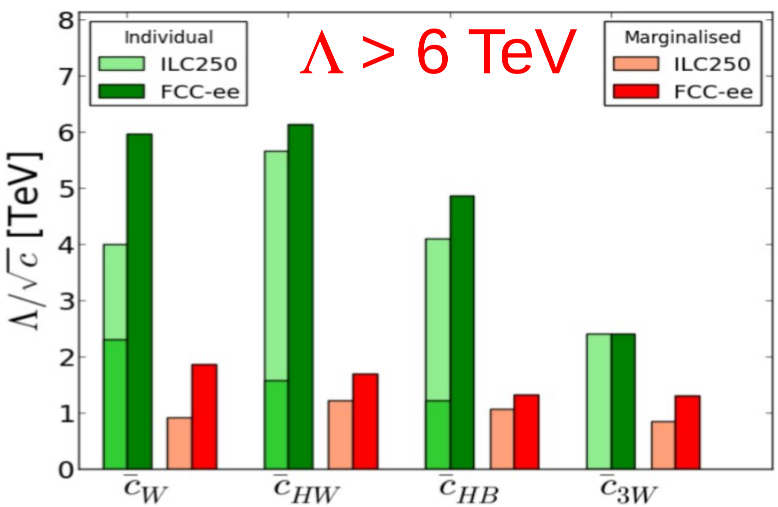


[arXiv:1308.6176]

Precision H properties: Generic BSM bounds

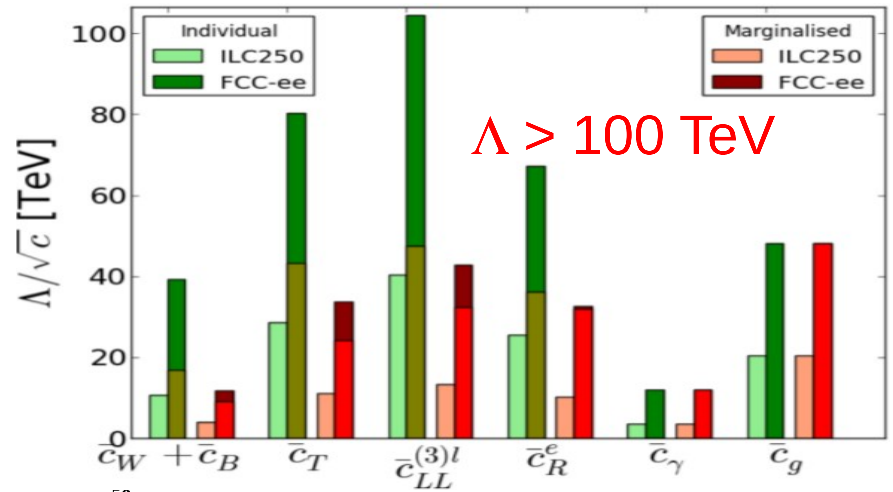
- FCC-ee precision measurements greatly improve scalar-coupled BSM limits.

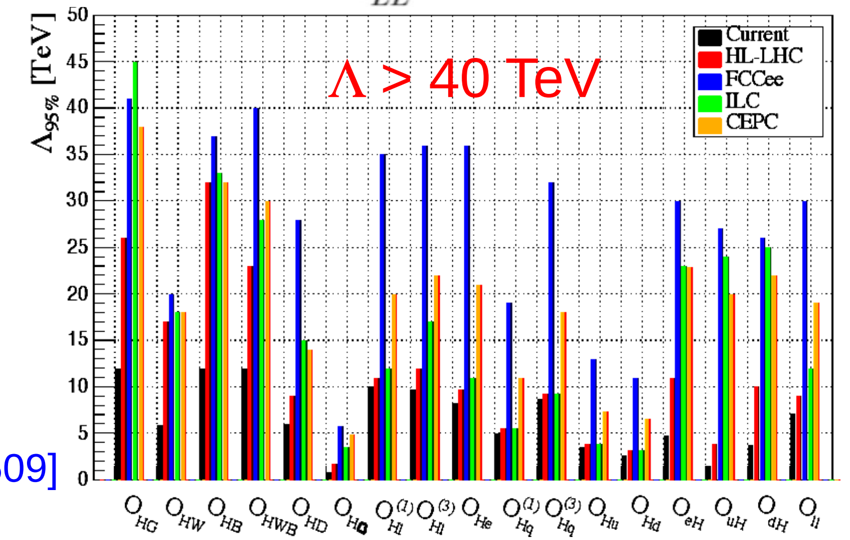
- NP bounds from FCC-ee Higgs:



[J.Ellis and T.You, arXiv:1510:04561]

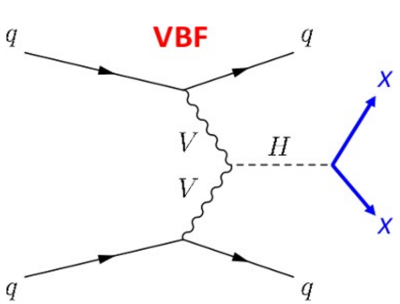
- From H+EWPO combined:

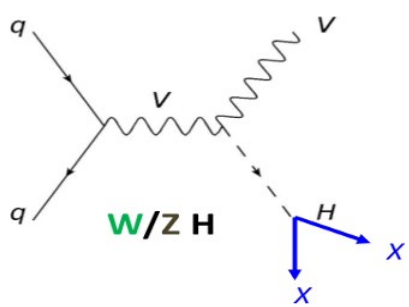


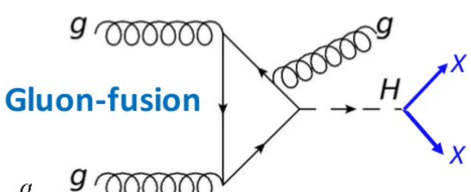


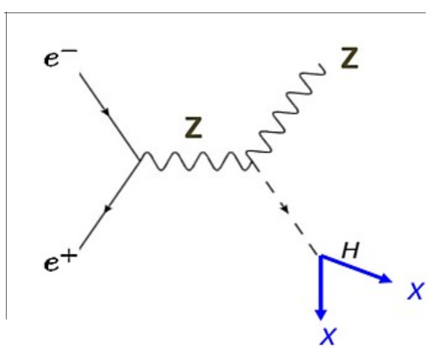
[DeBlas et al. arXiv:1608.01509]

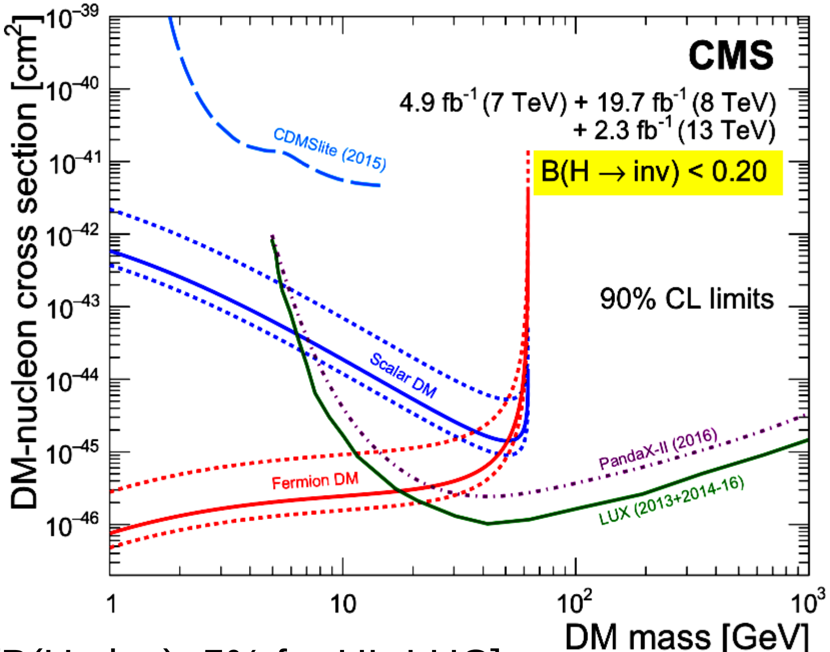
Open issue in the SM (4): Dark matter (Higgs-portal)







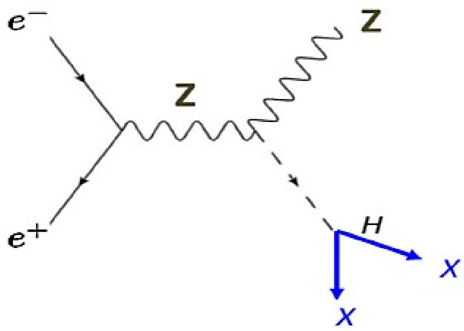


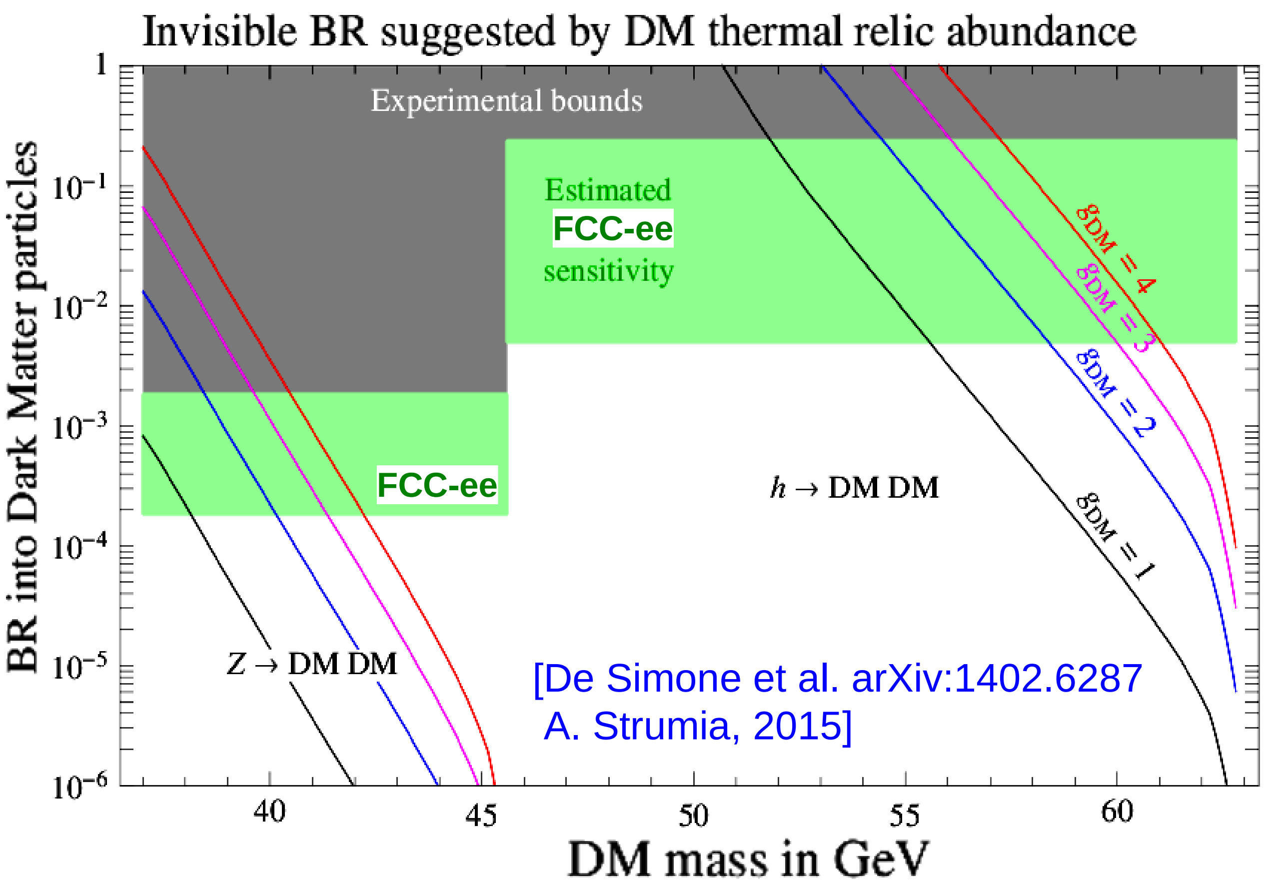


[B(H→inv)>5% for HL-LHC]

Dark Matter (m_{DM}<$m_H/2$) via H decays

- DM freeze-out fixes $\sigma v \approx 3\ 10^{-26} cm^3/s$. If m_{DM} is just below $m_{Z,H}/2$, DM freeze-out dominated by resonant Z,H exchange, fixing $\Gamma_{Z,H}$.

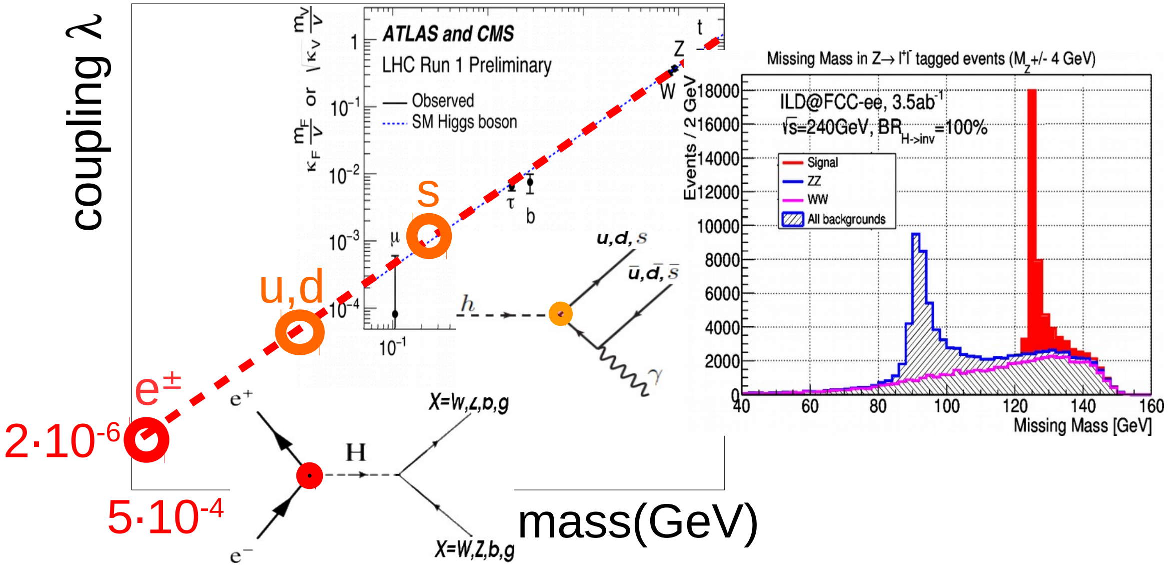




- Precision (<10^{-3} and <10^{-1}) measurements of invisible Z & H widths are best collider option to test any m_{DM}<$m_{Z,H}/2$ that couples via SM mediators.

Summary

- FCC provides unparalleled luminosities (up to 20 ab^{-1}) in e^+e^- at c.m. energy 125–350 GeV for high-precision Higgs studies (down to ~0.15% uncert.): Testing SM ($g_{1st\text{-}gen}$, λ_3), constraining scalar-coupled BSM up to multi-TeV:



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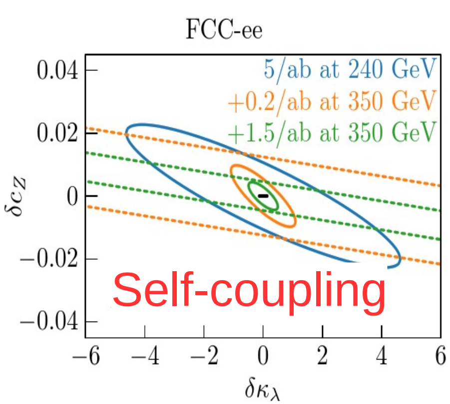
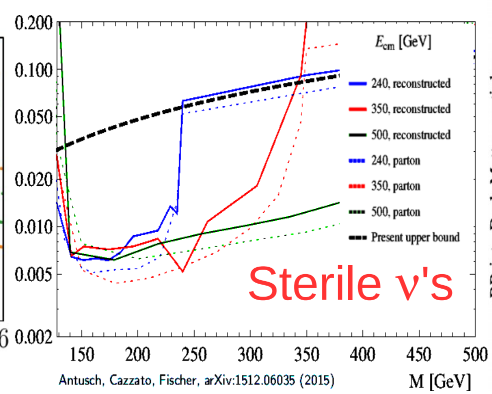
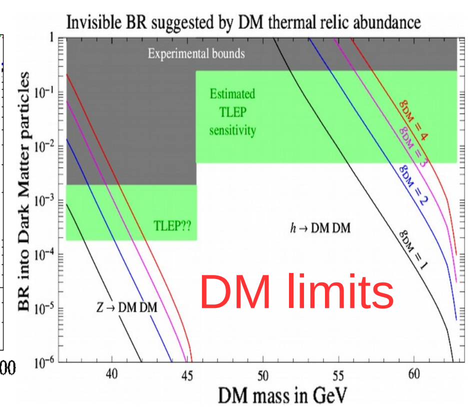
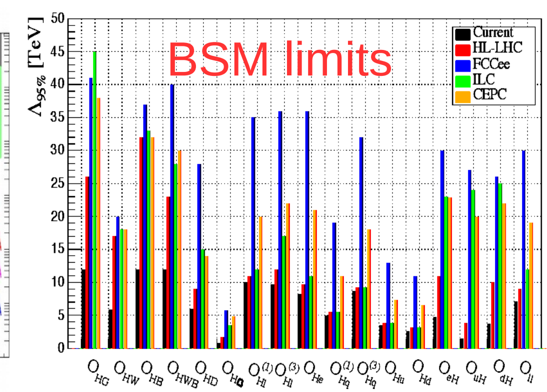
g_{WW}	11%	2–5%	0.2%	0.4%	1.6%	0.9%
g_{bb}	24%	5–7%	0.4%	0.7%	0.6%	0.9%
g_{cc}	–	–	0.7%	1.2%	2.3%	1.9%
$g_{\tau\tau}$	15%	5–8%	0.5%	0.9%	1.4%	1.4%
$g_{t\bar{t}}$	16%	6–9%	13%	6.3%	–	4.4%
$g_{\mu\mu}$	–	8%	6.2%	9.2%	17%	7.8%
g_{ee}	–	–	<100%	–	–	–
g_{gg}	–	3–5%	0.8%	1.0%	1.7%	1.4%
$g_{\gamma\gamma}$	10%	2–5%	1.5%	3.4%	4.7%	3.2%
$g_{Z\gamma}$	–	10–12%	(to be determined)			9.1%
Δm_H	200 MeV	50 MeV	11 MeV	15 MeV	5.9 MeV	32 MeV
Γ_H	<26 MeV	5–8%	1.0%	1.8%	2.8%	3.6%
Γ_{inv}	<24%	<6–8%	<0.45%	<0.29%	<0.28%	<0.97%

Table 2: Summary of the best statistical precision attainable for Higgs observables at future e^+e^- colliders (FCC-ee [5], ILC [18], CEPC [19], CLIC [20]) compared to (model-dependent*) current LHC [21] and expected HL-LHC [14] pp results.









Backup slides

BSM reach at e^+e^- colliders

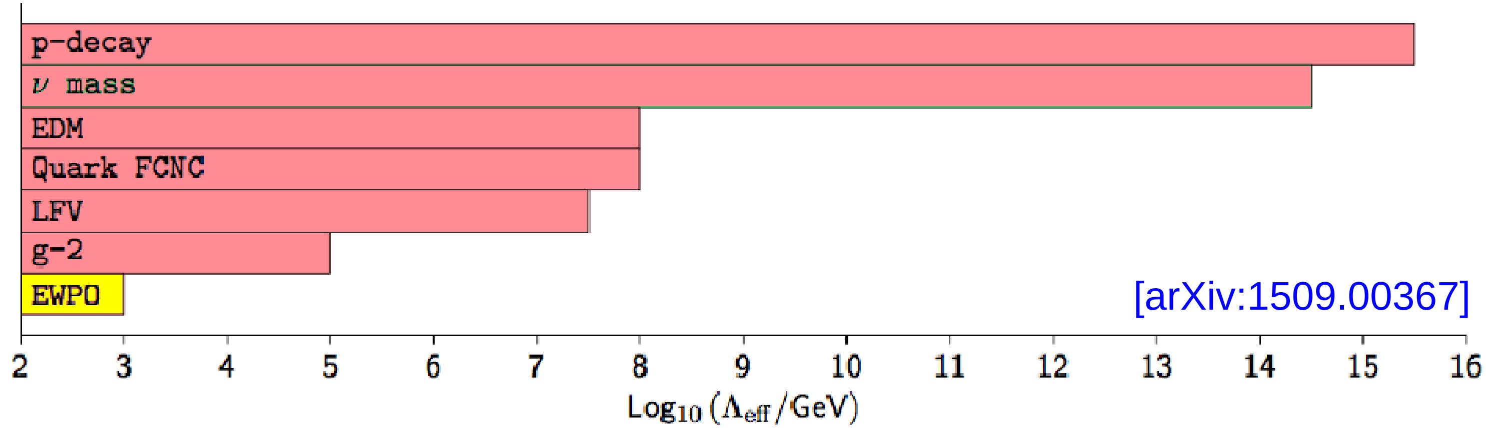
- Indirect searches through loops in high-stats W, Z, H, top precision studies (<<1% accuracy) in very high-luminosity e^+e^- collisions.
- Indirect constraints on new physics from generic EFT: $L_{\text{eff}} = \sum_n \frac{c_n}{\Lambda^2} O_n$

New scalar-coupled physics: $\Lambda \gtrsim (1\,\text{TeV})/\sqrt{(\delta g_{\text{HXX}}/g^{\text{SM}}_{\text{HXX}})/5\%}$

HL-LHC: ~5% deviations of Higgs couplings wrt. SM ⇒ Λ > 1 TeV
With 10^6 Higgs: ~0.1% Higgs couplings precision ⇒ Λ > 7 TeV

New electroweak-coupled physics: $\Lambda \propto (1\,\text{TeV})/\sqrt{\delta X}$

NP excluded below Λ ~ 3 TeV by current EWK precision fit:



[arXiv:1509.00367]

BSM reach at e^+e^- colliders

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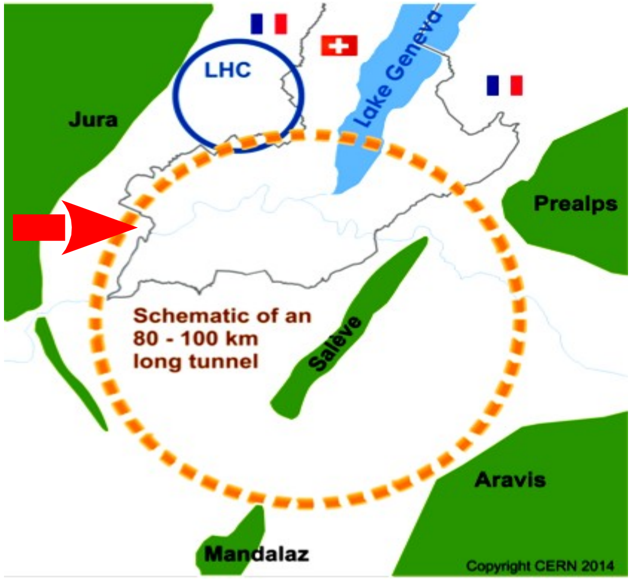
New <u>electroweak-coupled</u> physics: $\Lambda \propto (1\,\text{TeV})/\sqrt{\delta X}$

NP excluded below Λ_{NP} ~ 3 TeV by current EWK precision fit:

e^+e^- circular collider with R~80–100 km:
×10^4 more stats. (10^8 W's, 10^{11} Z's)
×10^2 precision w.r.t. LEP (10^4 W's, 10^7 Z's)
i.e. Λ ~30 TeV



High-precision W, Z, top: FCC-ee uncertainties

[D.d'E., arXiv:1602.05043]

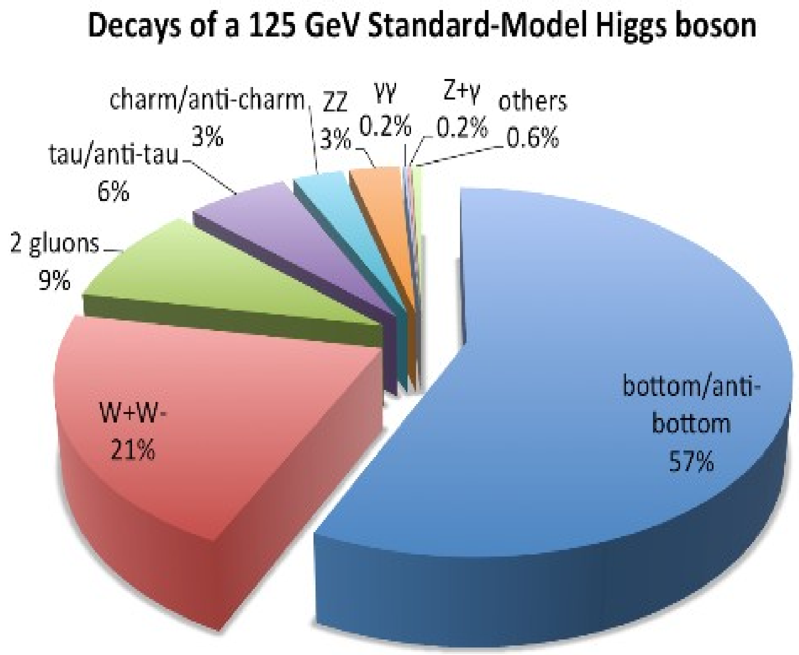
- Exp. uncertainties (stat. uncert. ~negligible) improved by factors ×3–100:

Observable	Measurement	Current precision	FCC-ee stat.	Possible syst.	Challenge
m_Z (MeV)	Z lineshape	91187.5 ± 2.1	0.005	< 0.1	QED corr.
Γ_Z (MeV)	Z lineshape	2495.2 ± 2.3	0.008	< 0.1	QED corr.
R_ℓ	Z peak	20.767 ± 0.025	0.0001	< 0.001	QED corr.
R_b	Z peak	0.21629 ± 0.00066	0.000003	< 0.00006	$g \to b\bar{b}$
N_ν	Z peak	2.984 ± 0.008	0.00004	0.004	Lumi meas.
N_ν	$e^+e^- \to \gamma Z(\text{inv.})$	2.92 ± 0.05	0.0008	< 0.001	–
$A_{FB}^{\mu\mu}$	Z peak	0.0171 ± 0.0010	0.000004	< 0.00001	E_{beam} meas.
$\alpha_s(m_Z)$	$R_\ell, \sigma_{\text{had}}, \Gamma_Z$	0.1190 ± 0.0025	0.000001	0.00015	New physics
$1/\alpha_{\text{QED}}(m_Z)$	$A_{FB}^{\mu\mu}$ around Z peak	128.952 ± 0.014	0.004	0.002	EW corr.
m_W (MeV)	WW threshold scan	80385 ± 15	0.3	< 1	QED corr.
$\alpha_s(m_W)$	$\Gamma_W, B_{\text{had}}^W$	$B_{\text{had}}^W = 67.41 \pm 0.27$	0.00018	0.00015	CKM matrix
m_t (MeV)	$t\bar{t}$ threshold scan	173200 ± 900	10	10	QCD
Γ_t (MeV)	$t\bar{t}$ threshold scan	1410^{+290}_{-150}	12	?	$\alpha_s(m_Z)$
y_t	$t\bar{t}$ threshold scan	$\mu = 2.5 \pm 1.05$	13%	?	$\alpha_s(m_Z)$
$F_{1V,2V,1A}^{\gamma t, Z t}$	$d\sigma^{t\bar{t}}/dx\, d\cos(\theta)$	4%–20% (LHC-14 TeV)	(0.1–2.2)%	(0.01–100)%	–

- Theoretical developments needed to match expected experimental uncertainties

s-channel $e^+e^- \to H$ measurement at FCC(125 GeV)

- Counting experiment over 10 decay channels:



- *Other 2-jet final-state (cc) swamped by $e^+e^- \to Z^*, \gamma^* \to cc$ (20 pb)*
- *Other 4-jet final-state (ZZ*) swamped by $e^+e^- \to Z^*, \gamma^* \to qq$ (100 pb), $e^+e^- \to WW^*, ZZ^*$ (20 fb)*
- *Rarer decays (4ℓ) have ~0 counts.*

1) **bb (2 b-jets)**: σ = 156 ab
   Dominant bckgd (ee→ bb): σ=20 pb (S/B~10^{-5})
2) **WW* (4j)**: σ = 28 ab
   Dominant bckgd (ee→4j): σ=16 fb (S/B~10^{-3})
3) **WW* (2jlν)**: σ = 27 ab
   Dom. bckgd (ee→WW*): σ=20 fb (S/B~10^{-3})
4) **WW* (2l2ν)**: σ = 6.7 ab
   Dom. bckgd (ee→WW*): σ=5 fb (S/B~10^{-3})
5) **gg (2 jets)**: σ = 24 ab
   Dom. bckgd (ee→"gg"): σ=0.9 pb (S/B~10^{-4})
6) **ττ (2 τ-jets)**: σ = 7.5 ab
   Dom. bckgd (ee→ττ): σ=10 pb (S/B~10^{-7})
7) **ZZ* (2j2ν)**: σ = 2.3 ab
   Dom. bckgd (ee→ZZ*): σ=213 ab (S/B~10^{-2})
8) **ZZ* (2l2j)**: σ = 1.14 ab
   Dominant bckgd (ee→ZZ*):σ=114 ab (S/B~10^{-2})
9) **ZZ* (2l2ν)**: σ = 0.34 ab
   Dominant bckgd (ee→ττ):σ=10 pb (S/B~10^{-8})
10) **γγ (2 isolated γ)**: σ = 0.65 ab
   Dominant bckgd (ee→γγ): σ=36 pb (S/B~10^{-8})

ee→H significance: Multi-Channel Combination

- Channels combination using Roostats-based tool for LHC Higgs analyses: Profile likelihood & hybrid significances all give ~identical results (very close to naive S/√B expectation, negligible background uncertainty).

Channel	Significance (1 ab^{-1})	Significance (10 ab^{-1})
WW→lν2j,2l2ν,4j	0.15⊕0.09⊕0.03	0.50⊕0.30⊕0.08
ZZ→2j2ν,2l2j,2l2ν	0.07⊕0.05⊕0.01	0.21⊕0.16⊕0.03
bb	0.03	0.10
gg	0.03	0.09
ττ	–	0.02
γγ	–	0.01
Combined	0.2	0.7

- For 10 ab^{-1}: Significance ≈ 0.7 (preliminary, optimizations under study)
  Limit (95% CL) for branching ratio: $BR(H\to ee) < 2.8\times BR_{SM}(H\to ee)$
  Limit (95% CL) for SM Yukawa: $g_{eH} < 1.7\times g_{eH,SM}$

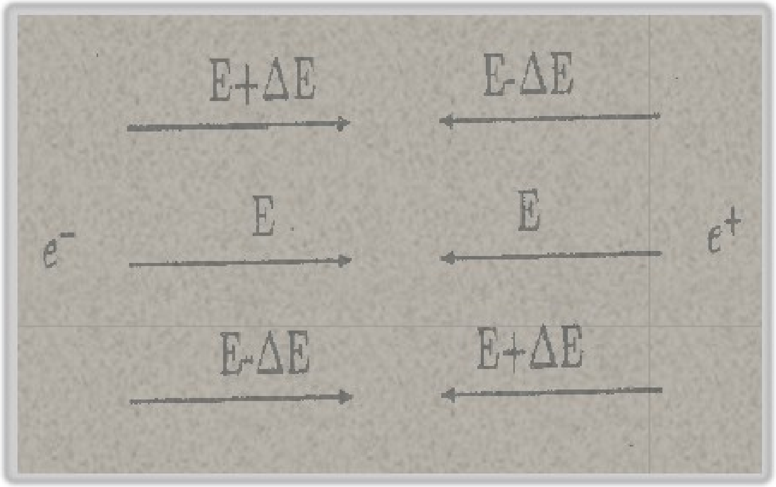
mono-chromatization at 2x63 GeV?

direct *s* channel Higgs production $e^+e^- \rightarrow H$

rms beam energy spread at 63 GeV ~30 MeV
total width of SM Higgs Γ ~ 4 MeV

effective collision energy spread is decreased by introducing opposite-sign IP dispersion

$$\frac{\sigma_W}{W} = \sqrt{\frac{2\varepsilon_x}{\left(\frac{{D^*_x}^2}{\beta^*_x} + \frac{\varepsilon_x}{{\sigma_\epsilon}^2}\right)}}$$



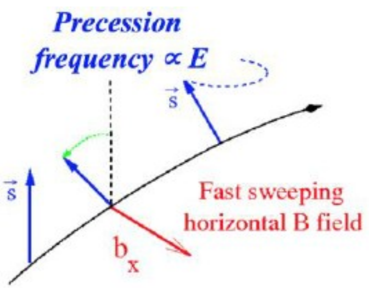
first proposed by A. Renieri (1975); historical studies for VEPP4, SPEAR, LEP, τ-c factory;never tested experimentally

reducing cm energy spread x1/10 w/o loss of luminosity?!
implementation for crab-waist scheme?

Beam energy spread via resonant depolarization

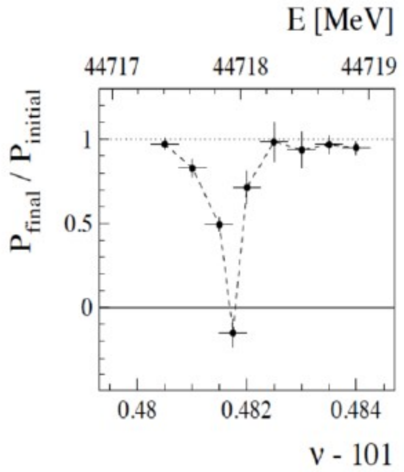
Resonant depolarization

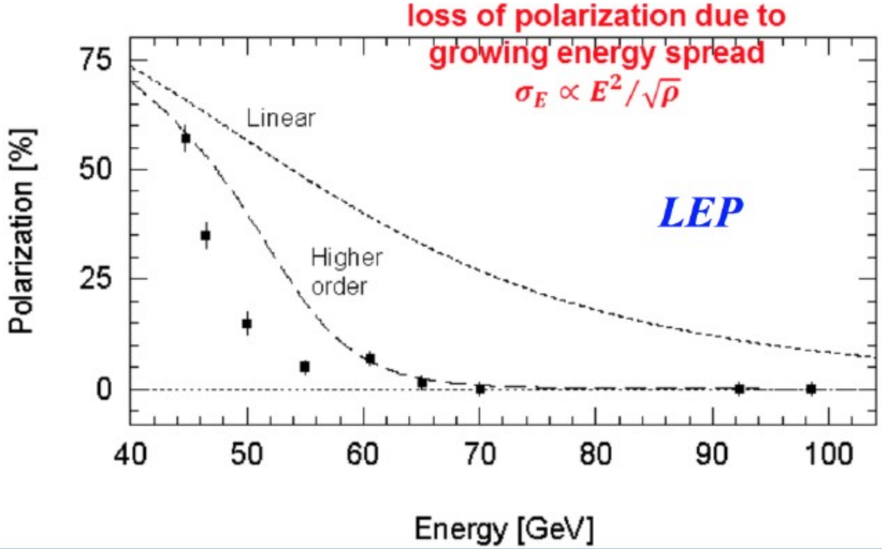
- use naturally occuring transverse beam polarization
- add fast oscillating horizontal B field to depolarize at Thomas precession frequency



Experience from LEP: Depolarization resonance very narrow: ~100 keV precision for each measurement

- However, final systematic uncertainty was 1.5 MeV due to transport from dedicated polarization runs
- At FCC-ee, continuous calibration with dedicated bunches: no transport uncertainty



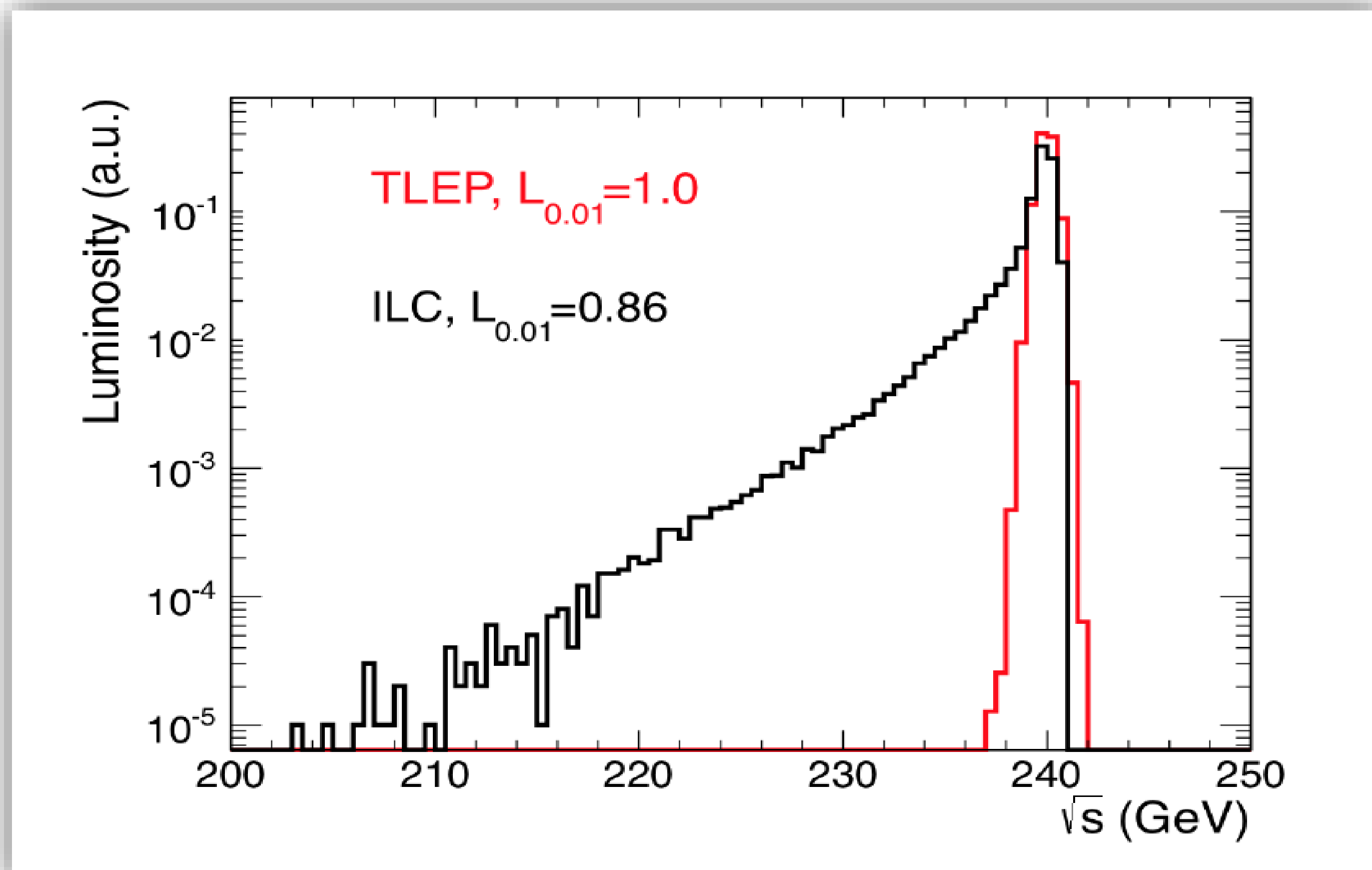


Scaling from LEP experience:

- Polarization expected up to the WW threshold

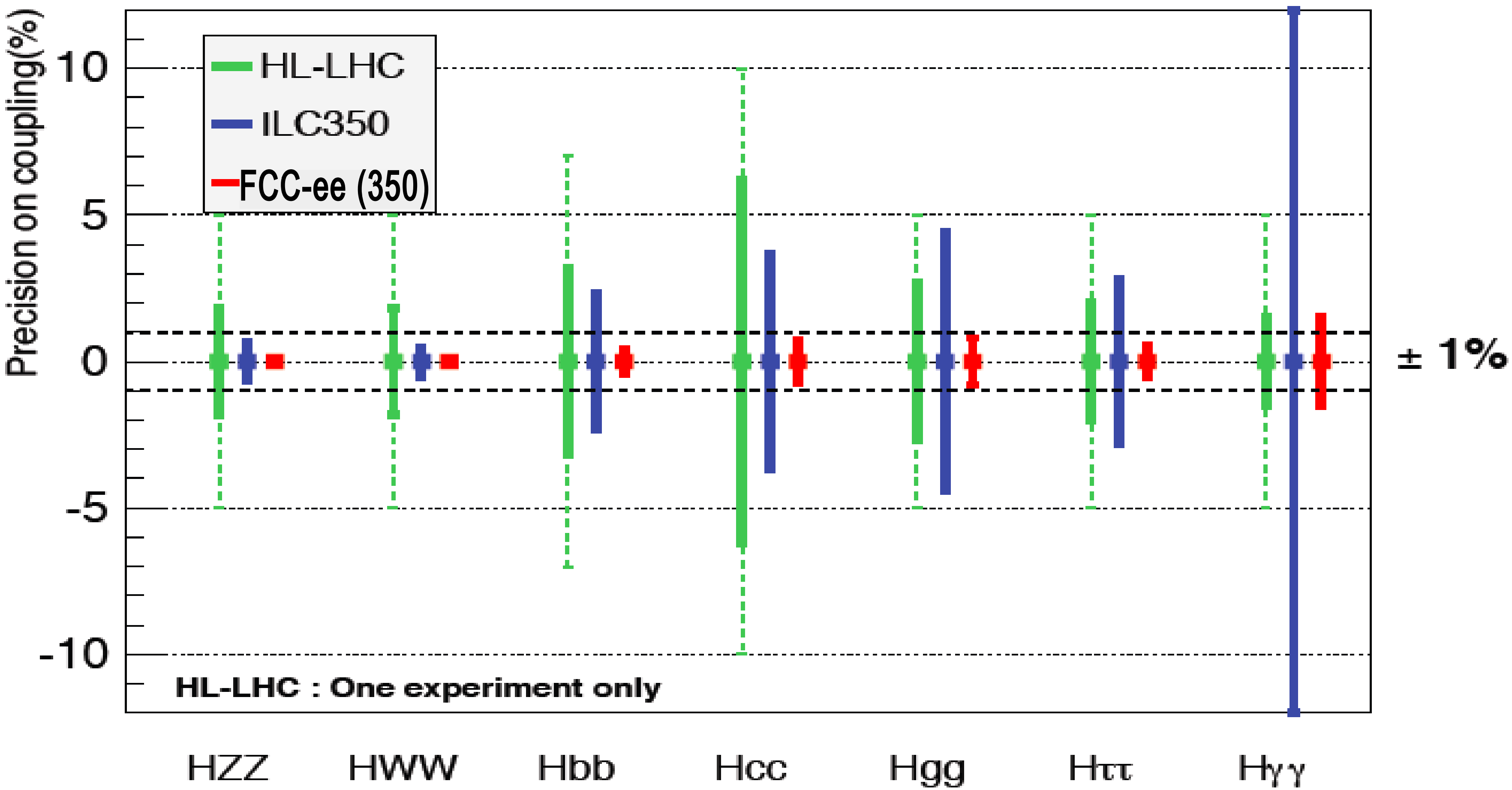
< 100 keV beam energy calibration at Z peak and at WW threshold

FCC-ee beam energy spread



Non-destructive focusing and collision of beams:
- Center-of-mass energy spread by construction modest

Precision Higgs couplings: FCC-ee vs. ILC



- Most precise (g_{HZZ}) ~0.1% coupling sets limit on new scalar-coupled physics at: $\Lambda \gtrsim (1\,\mathrm{TeV})/\sqrt{(\delta g_{HXX}/g^{SM}_{HXX})/5\%}$ >7 TeV