Laboratoire Leprince-Ringuet

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ÉCOLE POLYTECHNIQUE

IP PARIS

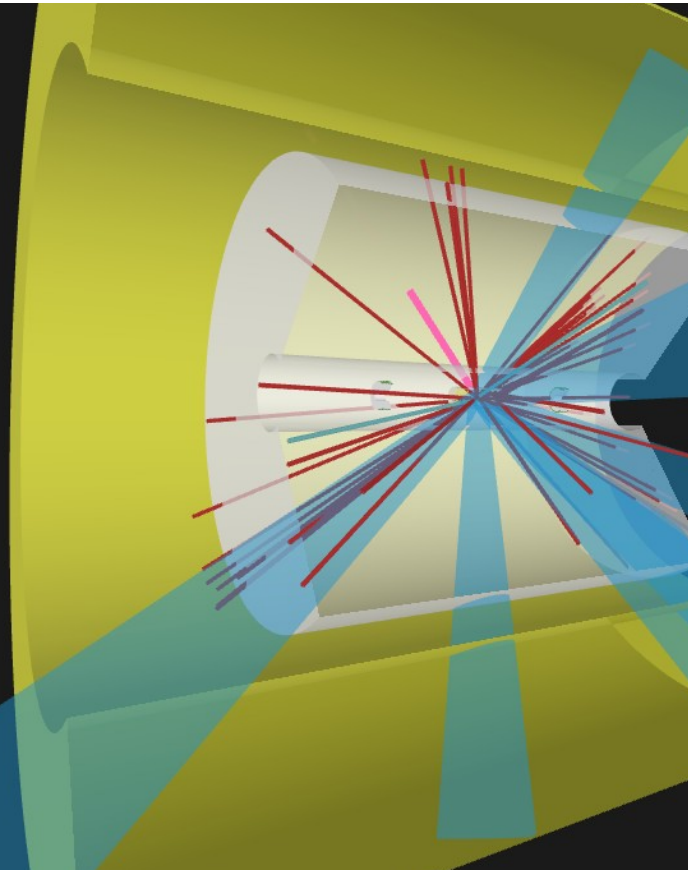
FUTURE CIRCULAR COLLIDER

Higgs self-coupling measurement at FCC-ee

Louis Portalès

Jamboree FCC / Future colliders - APC

07/07/2023



The Higgs boson self coupling

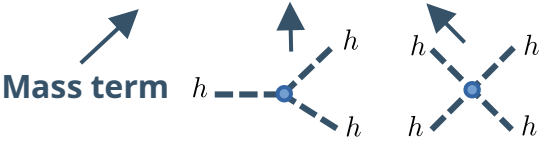
The Standard Model predicts self-interaction for the Higgs boson

→ ***Unique property of the Higgs boson!*** Other SM interactions change particle identities

→ ***Appears in the Higgs potential:***

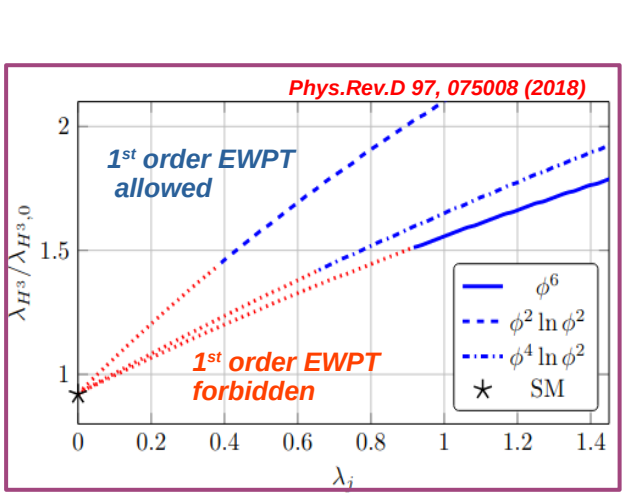
$$V(h) \sim -\frac{m_h^2}{2}h^2 - \lambda\nu h^3 - \frac{\lambda}{4}h^4$$

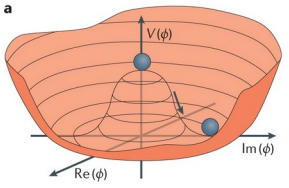
Mass term

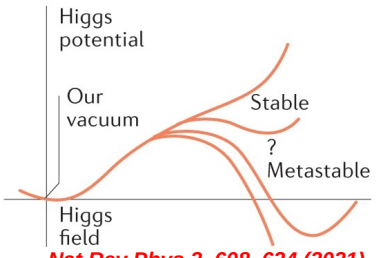


→ ***Critical to the understanding of the past and future of our universe***

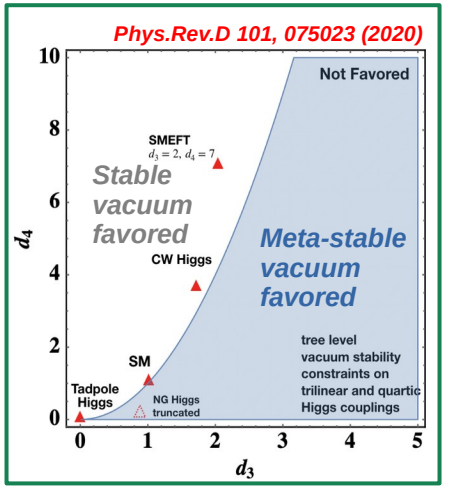
- SM: $\lambda = \frac{m_h^2}{2\nu^2}$, with already strong experimental constraints on m_h
- Deviations from the SM value required for a ***first-order electroweak phase transition***
  - → Would provide an explanation for matter/anti-matter asymmetry !
  - → Requires high precision (~10%) on λ
- BSM values of λ could also ***insure stability of the vacuum***
  - → SM at the edge of stable/meta-stable !





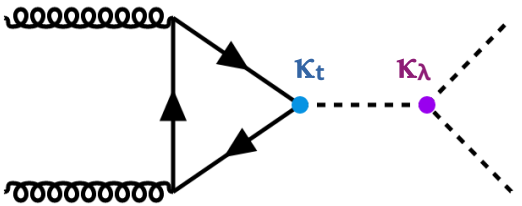


Nat Rev Phys 3, 608–624 (2021)



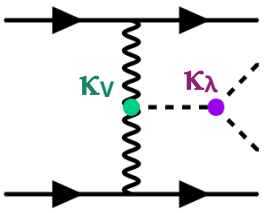
Measuring λ at the (HL-)LHC

Direct access to self-coupling through di-Higgs production



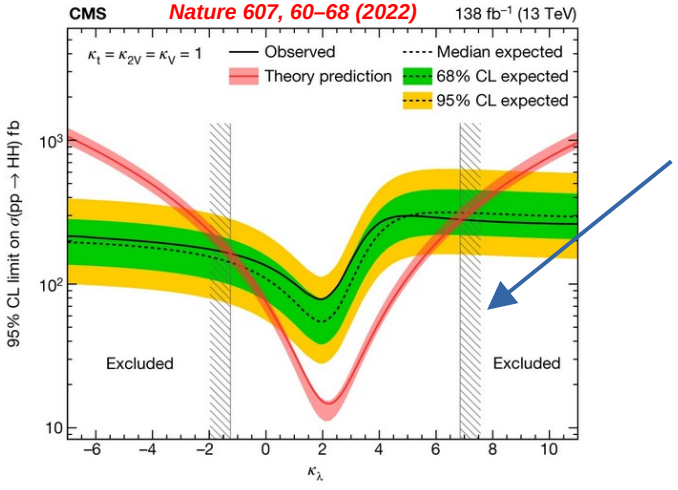
→ ***Rare process:***

- $\sqrt{s} = 13\ \text{TeV}: \begin{cases} \sigma_{\text{SM}}^{\text{NNLO}}(\text{ggF-HH}) = 31.1\ \text{fb} \\ \sigma_{\text{SM}}^{\text{N}^3\text{LO}}(\text{VBF-HH}) = 1.73\ \text{fb} \end{cases}$



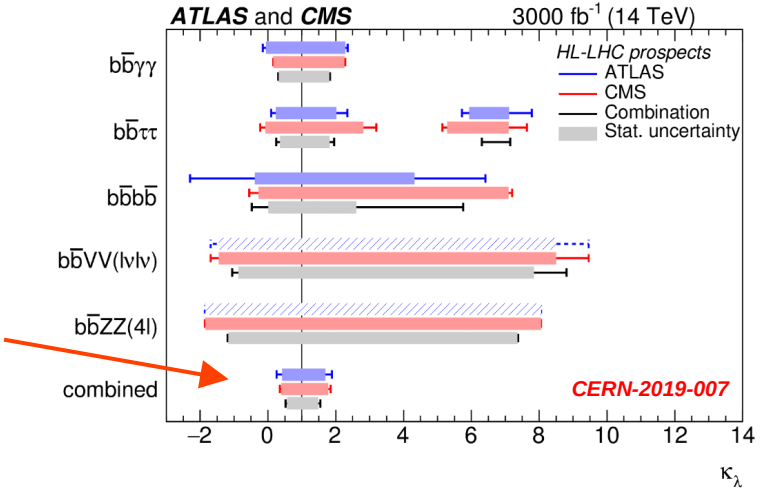
→ ***Experimentally challenging***

- Complex final state topologies to identify in busy collision environment



Constrained to [−1.24, 6.49] with Run 2 (CMS only, Similar results with ATLAS)

~50% precision threshold expected with HL-LHC (ATLAS+CMS)



Phys. Rev. D 92, 039903 (2015)
J. High Energ. Phys. 2016, 80 (2016)
J. High Energ. Phys. 2018, 178 (2018)

Measuring λ at FCC-ee

At FCC-ee, things will look much different

→ ***Two relevant datasets***

- "ZH" run @ 240 GeV: ~2 million ZH events, ~40k VBF-H events w/ 4IP (10 ab^{-1})
- "ttbar" run @ 365 GeV: ~500k ZH events, ~100k VBF-H events w/ 4 IP(3 ab^{-1})

→ ***Below the requirement for HHZ production***

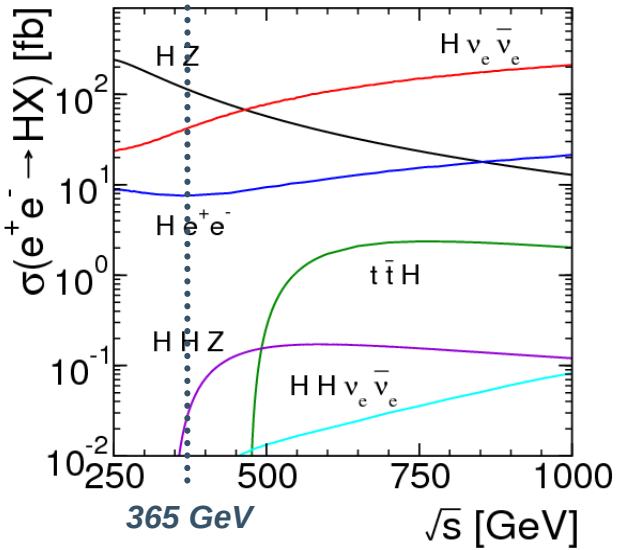
- No direct access to λ

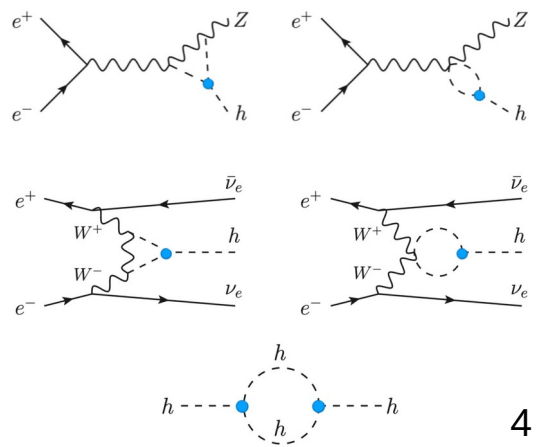
→ ***BUT large ZH (@240 GeV) and VBF-H (@365 GeV) cross-sections***

- With intervention of λ at loop-level:

$$\sigma_{i,\mathrm{NLO}} = Z_{\mathrm{H}}\,\sigma_{i,\mathrm{LO}}\,(1 + \kappa_\lambda C_{1,i})$$

Universal wave function renormalization — *LO cross-section* — *Process & energy dependent coeff. From loop-tree interference*



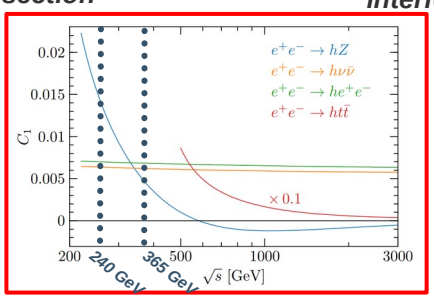


Decay Modes

C_1^Γ[%]	$\gamma\gamma$	ZZ	WW	$f\bar{f}$	gg
on-shell H	0.49	0.83	0.73	0	0.66

$C_1^{\Gamma_{\mathrm{tot}}} \equiv \sum_j \mathrm{BR}^{\mathrm{SM}}(j) C_1^\Gamma(j)$ ~2.3x10^{-3}

Can be probed in exclusive analyses targeting the specific Higgs decays



Can be probed in inclusive analysis (@ 2 CoM energies)

Inclusive λ measurement

Clean e^+e^- collision environment allows for fully inclusive study of ZH production

→ ***Recoil technique:*** Higgs boson mass can be inferred from Z boson kinematics and CoM energy

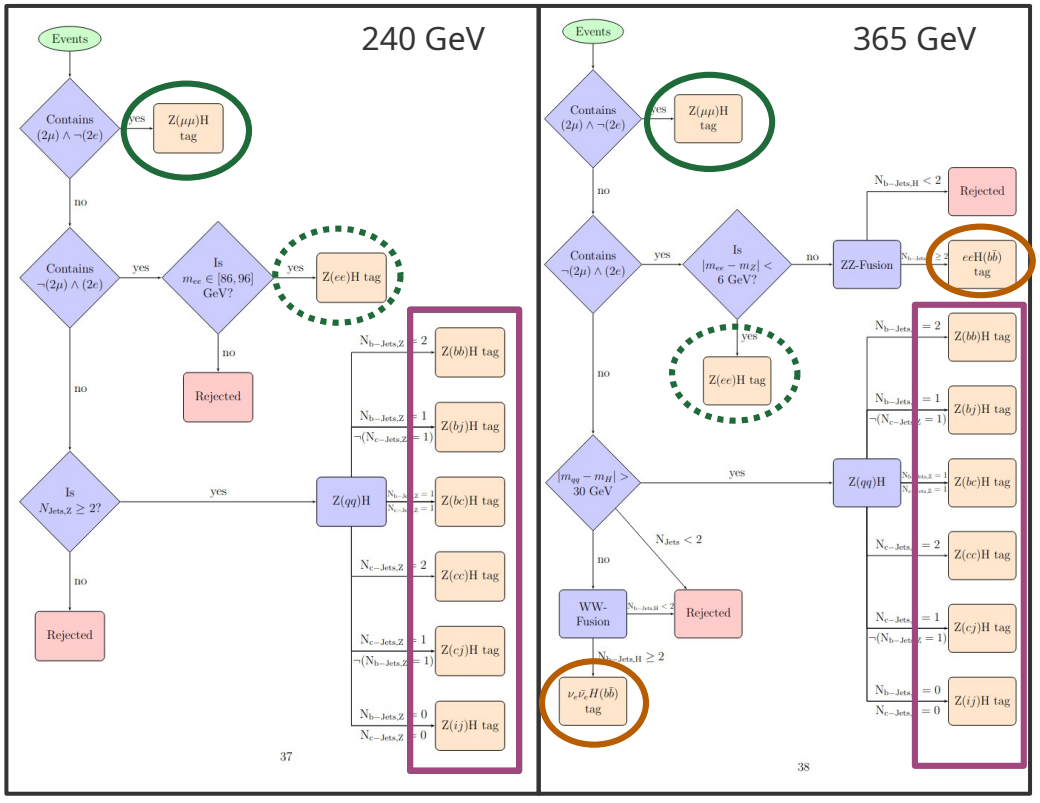
- $M^2_{\text{rec.}} = s - 2E_Z\sqrt{s} + M^2_Z$
- Probed in different Z boson decay channels: $\mu^+\mu^-$, e^+e^-, $q\bar{q}$

→ ***Analysis setup***:

- **Spring 2021 samples** (older baseline w/ IDEA detector)
  → to be updated!

→ ***Categorization tuned for the two energy points (240, 365 GeV)***

- 18 orthogonal categories
  → 2x2 Z(ee/μμ)H categories – ***similar to mass & xsec analysis***
  → 2x6 Z(qq)H categories – ***per qq flavor***
  → Additional eeH(→bb) & ννH(bb) categories @ 365 GeV



Inclusive λ measurement – ZH selection

→ ***Similar selection as inclusive mH/xsec analysis for Z→ee/μμ***

- SF-OS lepton pair
- $86<m_{2lep}<96$ GeV
- $20<p_T^{2lep}<70$ GeV (>70GeV @365GeV)
- $|\cos(\theta_{miss})|<0.98$

→ ***Tuned selection for Z→qq***

- ***6 flavor categories (bb,cc,ll,bc,bl,cl)***

  → Assuming ad-hoc tagging efficiencies:

	b jet	c jet	l jet	g jet
b tag	0.80	0.08	0.01	0.01
c tag	0.10	0.60	0.01	0.03
l tag	-	-	0.80	-

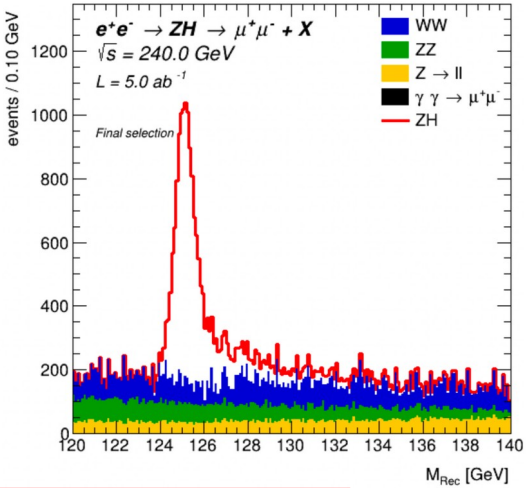
  → Dedicated Z→cc optimisation ongoing (@BNL)

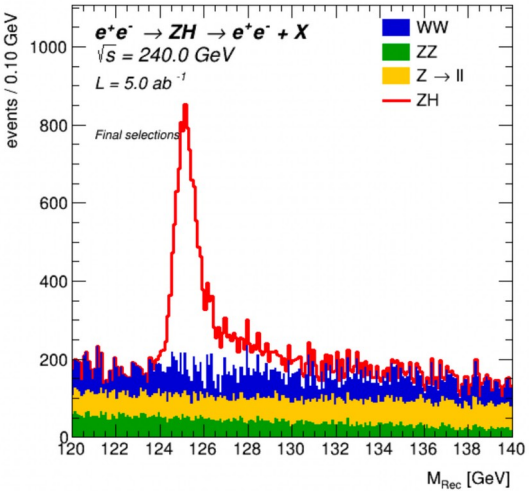
- $86 < m_{qq} < 96$ GeV, $120 < M_{rec} < 140$ GeV
- $|\cos(\theta_{miss})|< 0.90$

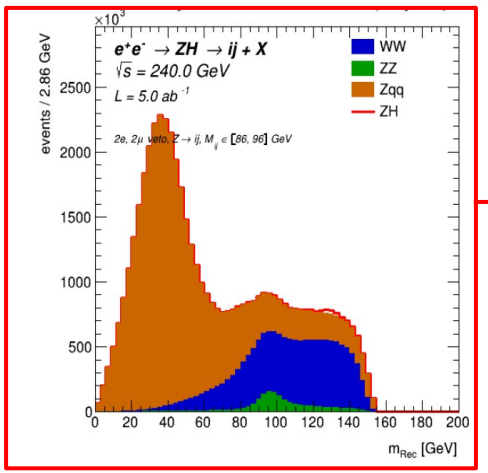
→ ***BDT used for selection***

- One per flavor category

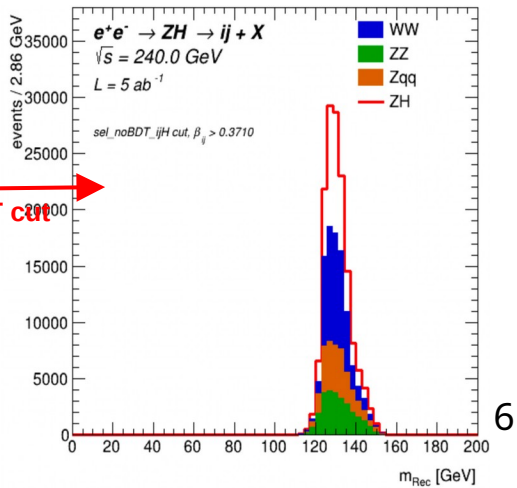
  → Using only Z→qq kinematics







BDT cut



Inclusive λ measurement– VBF selection

→ ***Recoil mass not sufficient to properly isolate a Higgs peak in VBF***

- Instead, looked at VBF H→bb

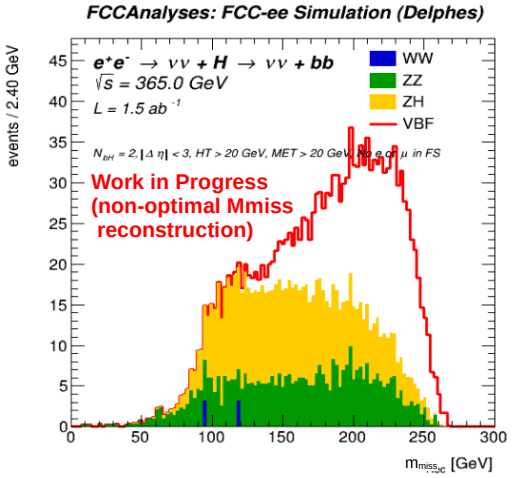
  → Exclusive measurement, some model-dependance introduced

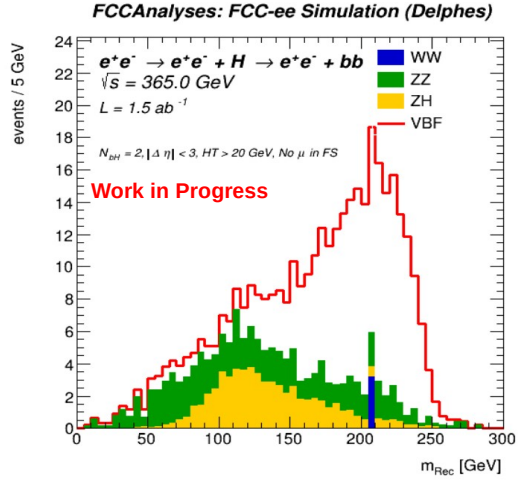
→ ***Defining selection adapted to VBF***

- No μμ pair reconstructed (ννH: no ee pair either)
- 2 b-tagged jets
- H_T > 20 GeV, $|\Delta\eta_{bb}|$<3 (ννH: + MET>20 GeV)
- $|M_{ee} - M_Z|$>=6 GeV (eeH)
- $|M_{qq} - M_H|$<= 30 GeV (ννH)

→ ***Still using Mrec as template variable for the fit***

- Cutting on BDT discriminants, using (b-)jet kinematics and multiplicity as inputs





Inclusive λ measurement – combined fit

→ ***Measuring cross-section & coupling modifier***

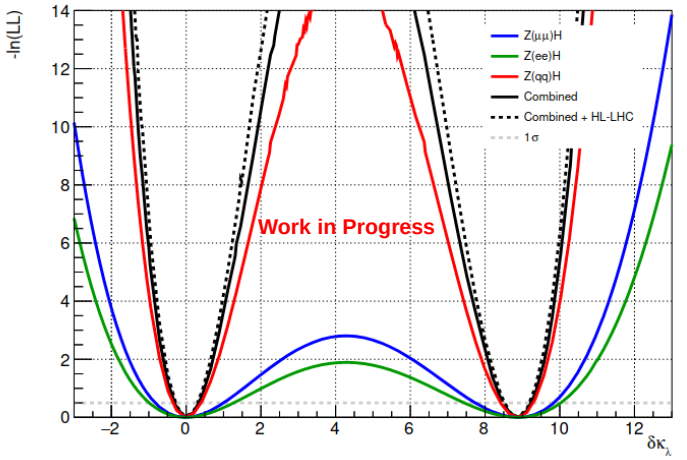
- Parametrised cross-section as a function of κ_λ
- Fitting all categories (ZH + VBF) together

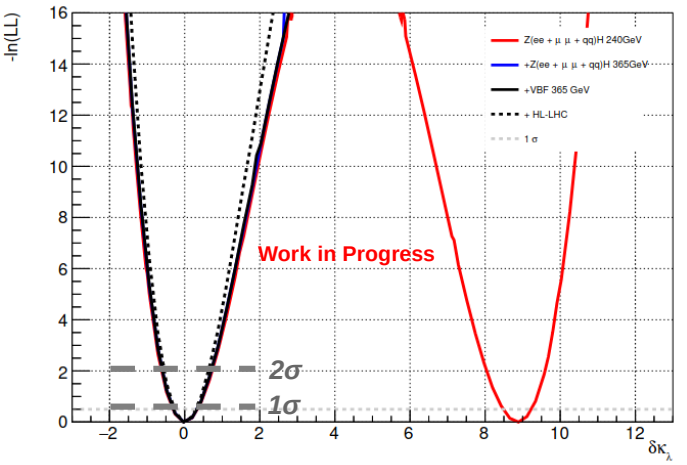
→ ***Assuming:***

- 0.1% luminosity uncertainty
- 1% selection efficiency uncertainty
- 2.8 MeV uncertainty on CoM energy
- m_h = 125.38 +/- 0.14 GeV (latest CMS result)
- Higgs decay BRs (H→bb) fixed to SM values

→ **Reaching $\delta\kappa_\lambda$ ~ 30% (~20% with 10 ab^{-1})**

- Combining with HL-LHC expected constraints
- Sensivity driven by Z(qq)H categories
- Adding ZH@365GeV resolves degerated minima
- Negligible impact from VBF-H (maybe due to Mrec issue)





Conclusion & final comments

Prospective sensitivity study to Higgs self coupling @ FCCee

→ **Combined analysis of ZH and VBF-H** production @ 240 GeV & 365 GeV

→ Reaching up to **~20% precision on coupling measurement** with little assumptions on Higgs boson properties

Study is preliminary, with room for improvement and refined understanding

→ **Analysis setup needs retuning**

- Esp. to be refreshed with state-of-the art tools (e.g. ParticleNet) & latest performance estimates/samples
- Ad-hoc flavour-tagging performance (particle-net to be investigated)

→ **Detector requirements to be studied**

- Similar trends as for mH/xsec analysis to be expected in Zee/Zμμ channels
- BUT sensitivity driven by Zqq categories → **Good physics usecase to compare calorimeter designs**

Not ultimate sensitivity?

→ **Self-coupling constraints from model-dependent (combined) EFT fit could yield further improvement**

- ~ 14% (~24%) precision floating only λ (full EFT fit) from 2019 ECFA studies
- Larger scale & more complex study, assuming ultimate precision already reached on m_H & g_Z

Back up