What can we say about the Higgs self-coupling with the hadronic ZH process at FCC-ee?

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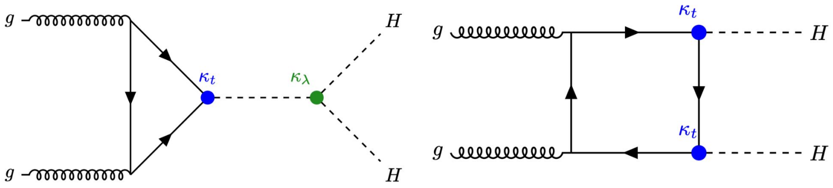
- Want a **precise** measurement
  - Fundamental test of **SM,** use to search for **BSM**
- Estimated precision at HL-LHC:
  ~50% (conservative) w/ **Higgs pair production**



- Estimated precision at FCC-hh: **~5%**

collider	single-H	HH	combined
HL-LHC	100-200%	50%	**50%**
$CEPC_{240}$	49%	–	49%
ILC_{250}	49%	–	49%
ILC_{500}	38%	27%	22%
ILC_{1000}	36%	10%	10%
$CLIC_{380}$	50%	–	50%
$CLIC_{1500}$	49%	36%	29%
$CLIC_{3000}$	49%	9%	9%
FCC-ee	33%	–	33%
FCC-ee (4 IPs)	24%	–	24%
HE-LHC	-	15%	15%
* FCC-hh	-	5%	**5%**

These values are combined with an independent determination of the self-coupling with uncertainty 50% from the HL-LHC.

Sally Dawson, Caterina Vernieri @ LHC Higgs Working Group, December 3, 2021

* arXiv:2004.03505 2.9-5.5% depending on the systematic assumptions

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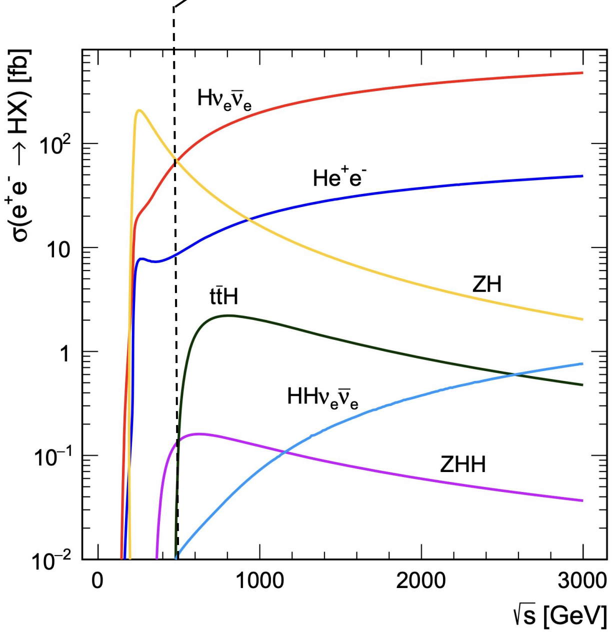
Self-coupling access at FCC-ee

- HH production turns on at e^+e^- collider:
  - $\sqrt{s}$ **~500 GeV** for **ZHH**
  - Even higher for **HH$\nu\nu$**

~ 500 GeV



σ vs. √s, including HH

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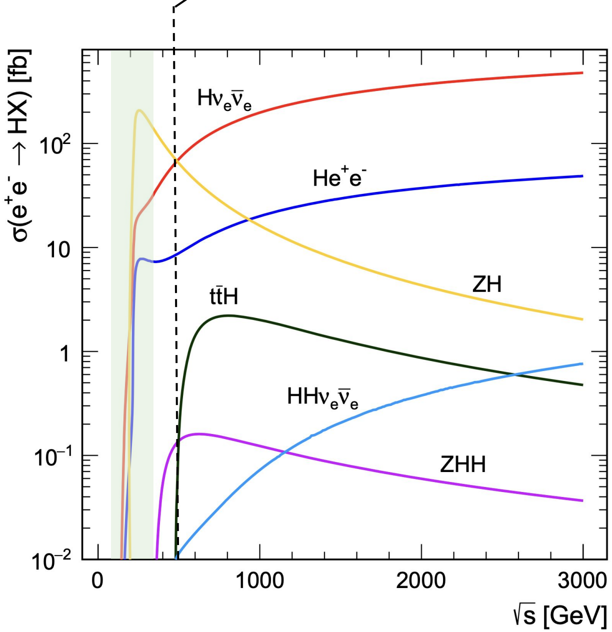

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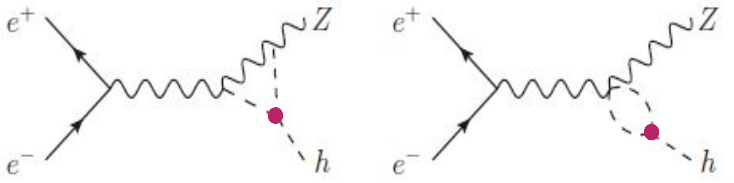
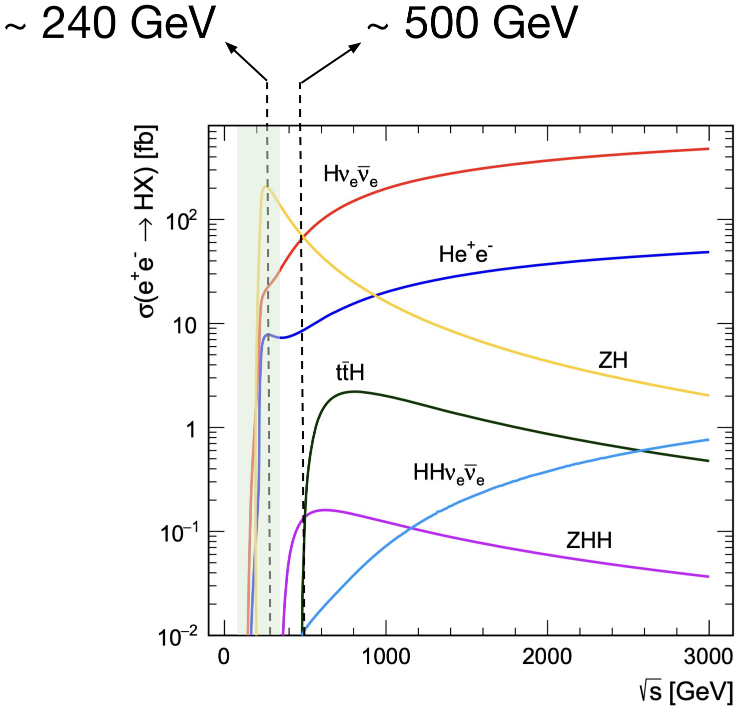
- Indirect sensitivity from **higher order** contributions to **ZH** (main production mode)





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    H(bb, cc, gg, ss, $\tau\tau$, WW, Zy, ZZ)
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- Background processes:
  - ZZ, WW, Zqq

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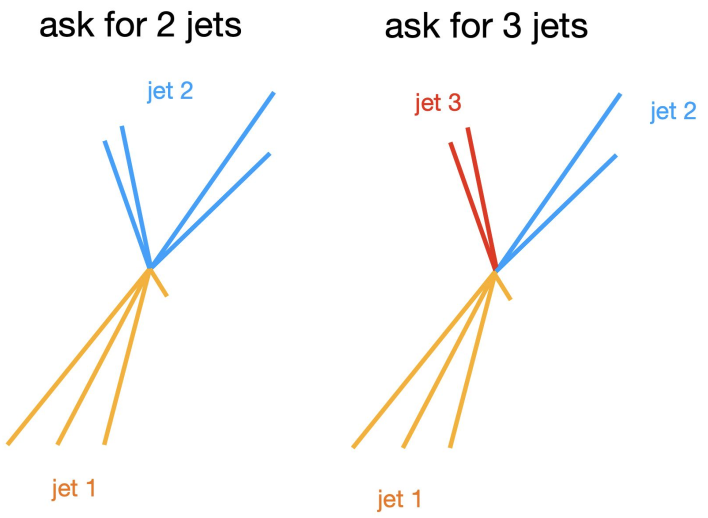
Durham kt algorithm, require **4 jets**



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Same event,
two interpretations!

Selections

- Use selections from ZH analysis designed for **Higgs hadronic coupling measurements**: Haider Abidi, George Iakovidis, Iza Veliscek [Annecy talk], [MIT talk]:

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- N_{jets} == 4, <= 2 leptons → **Select expected final state particles**
- Selections on clustering distance parameter: →
- For each **jet**, **tag** flavor based on highest **ParticleNet** flavor score among **{b, c, s, d, u, g, τ}**
    - Ignore events with 4 different flavor tagged jets (small percentage)

Parameter [GeV]^2	min	max
d_{12}	15000	58000
d_{23}	400	18000
d_{34}	100	6000

$$\sqrt{(m_{Z_{jj}} - m_W)^2 + (m_{H_{jj}} - m_W)^2} > 10, \sqrt{(m_{Z_{jj}} - m_Z)^2 + (m_{H_{jj}} - m_Z)^2} > 10$$

Remove WW **Remove ZZ**

- 50 < m_{Zjj} < 125 GeV, m_{Hjj} > 91 GeV → Minimize H/Z faking Z/H

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Categorization

- Categorize events by **pair flavor scores** with different purity categories

	bb, cc, gg	ss
Low	< 1.1	< 0.8
Medium	[1.1, 1.8]	[0.8, 1.4]
High	> 1.8	> 1.4

Categorization

- Categorize events by **pair flavor scores** with different purity categories
- Example: H_{bb} process reco Higgs mass vs. reco Z mass
- Aim to maximize signal over background near Higgs, Z mass peaks

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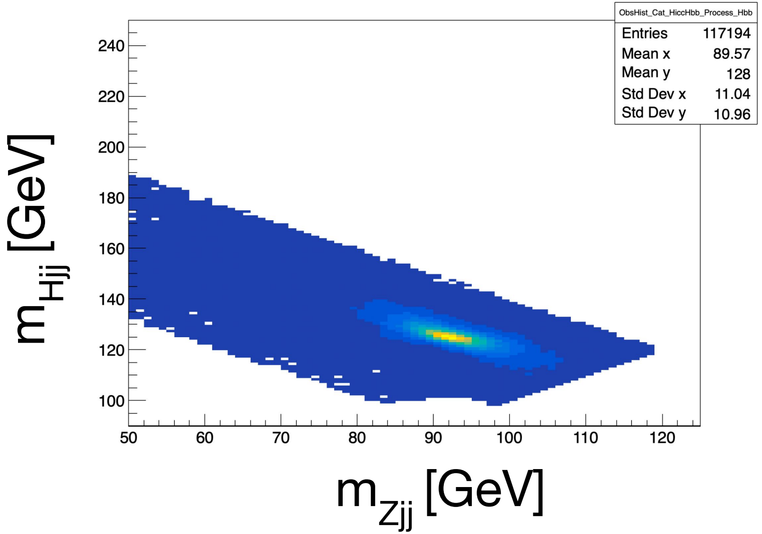
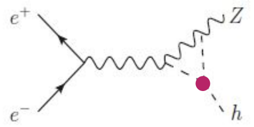


Self-coupling scan

- For each κ_λ (λ / λ_{SM}) value:
  - Scale ZH signal strength
  - Compute **likelihood**

$$\kappa_\lambda = \lambda / \lambda_{SM}$$



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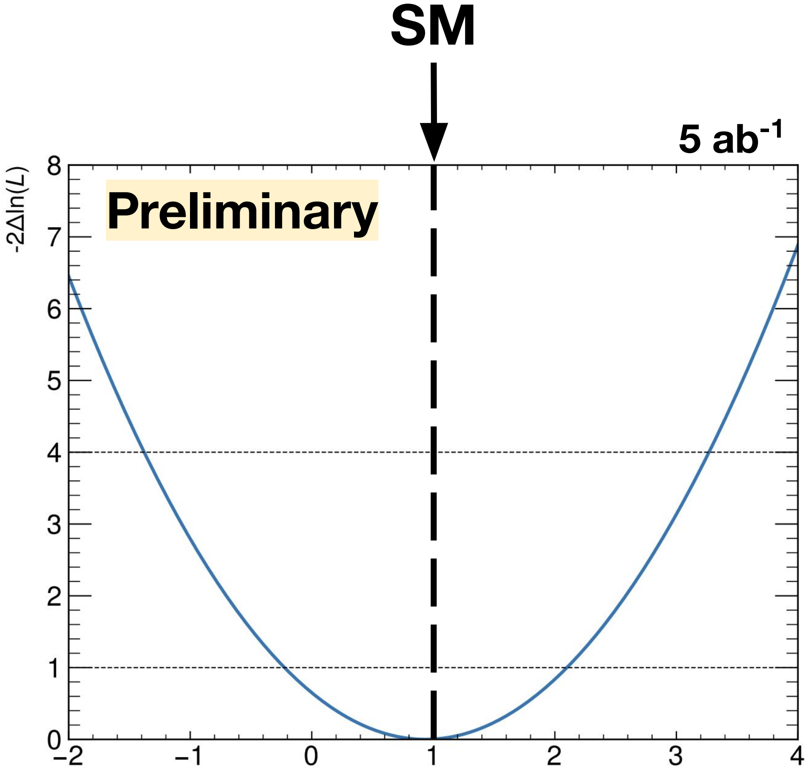
- Evaluate **1σ constraint** on self-coupling as **intersect points at 1**

- **Initial** result: $\kappa_\lambda \in [0.2, 2.1]$ at 1σ



κ_λ

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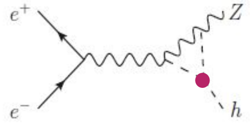

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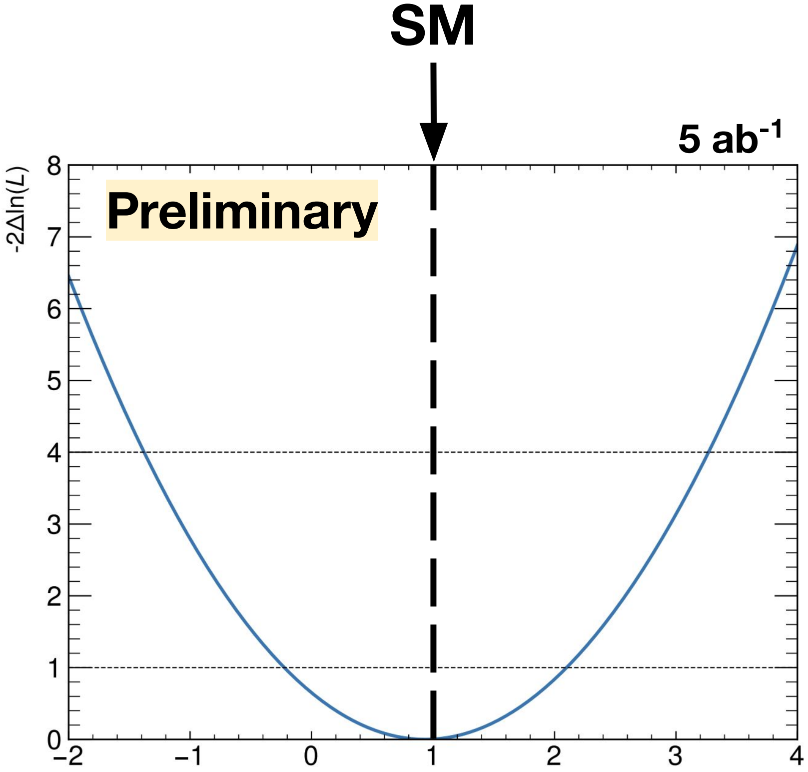
- Expect to improve with additional selections, can use as **benchmark for detector optimization**



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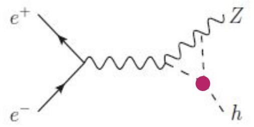

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Summary

- **The Higgs self-coupling can be measured indirectly at the FCC-ee, hopefully with higher precision than at the HL-LHC**
  - This measurement depends on defining a high sensitivity phase space, using data from runs at several center-of-mass energies

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- **The Higgs self-coupling can be measured indirectly at the FCC-ee, hopefully with higher precision than at the HL-LHC**
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- Use **Fully-Hadronic ZH** process, **flavor tagging** [ref.],obtains expected self-coupling constraint
  - $\kappa_\lambda \in [0.2, 2.1]$ → To be improved with further selections
  - **Will use as benchmark for detector optimization studies**
  - Can combine with Z(ℓℓ)H final states for more sensitive result
  - Also investigating optimal **jet reclustering method** → See Phil's talk

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Backup

Exclusive Durham k_t algorithm

M. Cacciari, G. Salam G. Soyez

- Combine low energy particles with neighbors
- Reiterate until you reach d_{cut} or n_{jets}

Simplest all-round decent e^+e^- algorithm

the "exclusive" Durham k_t algorithm

- determine $d_{ij} = 2\min(E_i^2, E_j^2)(1 - \cos\theta_{ij})$ between each pair of particles i, j
- recombine i, j pair with smallest d_{ij}, and update all distances
- stop when:

  n_{jets} mode. you have reached a predetermined number of jets (e.g. $n = 4$ for $ZH \to q\bar{q}b\bar{b}$)

  d_{cut} mode. all remaining $d_{ij} >$ some threshold (called d_{cut})

In "n_{jets} mode", you often want to look at what the next d_{ij} *would* have been and discard the event if it is below some threshold. **Simple and effective.**

In "d_{cut} mode", you usually make sure you have at least n jets for your process (e.g. 4 for $ZH \to q\bar{q}b\bar{b}$), otherwise discard the event. If you have more than n jets, decide whether to keep the event, and if so which jets to use.

Cacciari, Salam, Soyez Basic Jets Guidance for FCC-ee, June 2022 6

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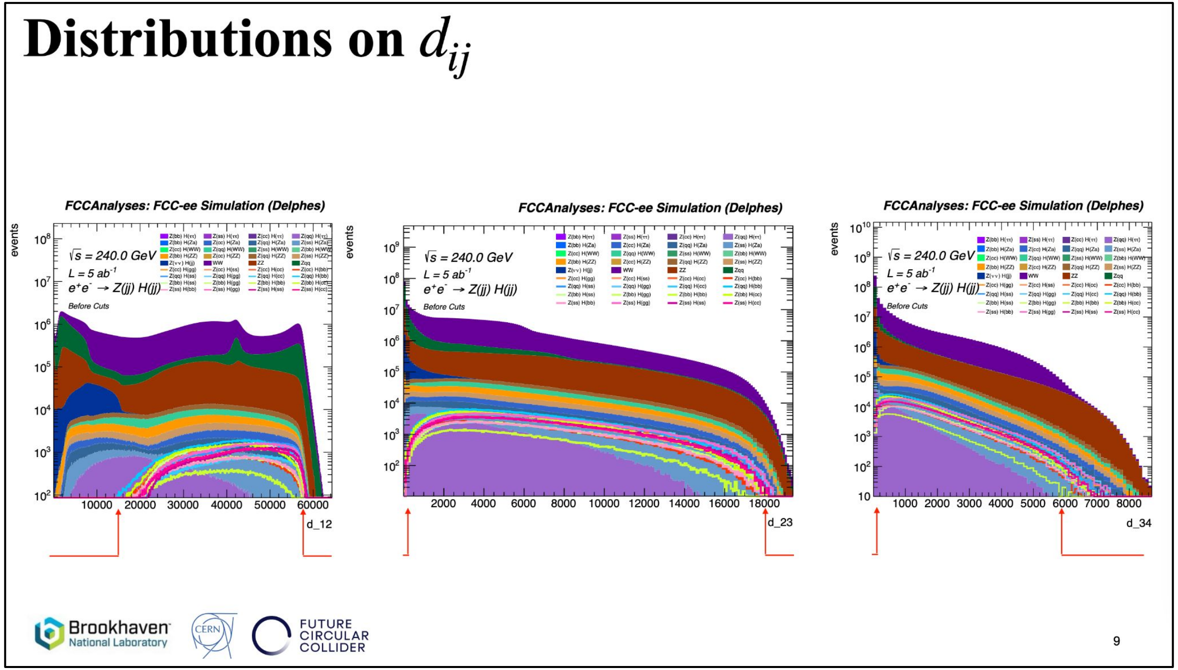
d_{ij} distributions from similar analysis

Slide from [George Iakovidis]:



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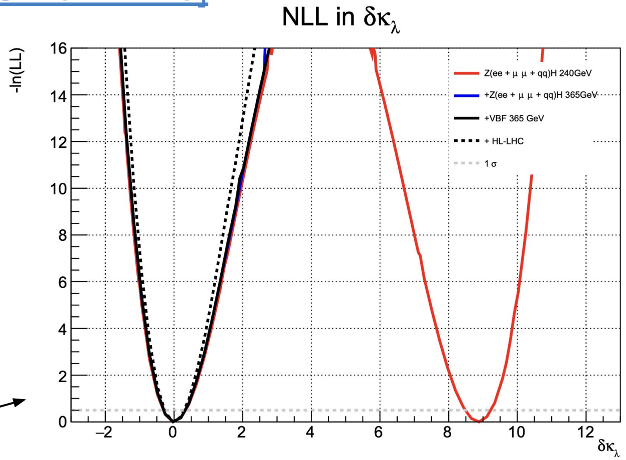
Existing hadronic ZH analysis

- **Extensive** ZH analysis performed **(240 and 365 GeV)**:
  - FCC physics performance meeting: [17 October 2022 - Nico Häringer]
  - Documented as masters thesis: [CERN-THESIS-2022-143]

- Targets **leptonic** and **hadronic** Z decays, inclusive Higgs decays, VBF-H

- **Cut based** and **BDT based** analysis (depending on production mode / final state)

- Projected FCC-ee results include:
  - Higgs **mass** measurement
  - ZH, VBFH production **cross-section** measurements
  - **Self-coupling constraint**



	FCC-ee (This work)	+ HL-LHC
$\delta\kappa_\lambda$ (68% CL interval)	[-0.36, 0.40]	[-0.29, 0.31]

κ_λ constraint - including **240** and **365 GeV** categories (other parameters **fixed** to SM values)

Cross section parameterization

- Cross section parameterization as a function of kl

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

$$Z_H = \frac{1}{1 - \kappa_\lambda^2 \delta Z_H},$$

$$\delta Z_H = -\frac{9}{16} \frac{G_F m_H^2}{\sqrt{2}\pi^2} \left(\frac{2\pi}{3\sqrt{3}} - 1 \right) \approx -0.00154.$$

Equations from Nico Härringer's masters thesis: [CERN-THESIS-2022-143]

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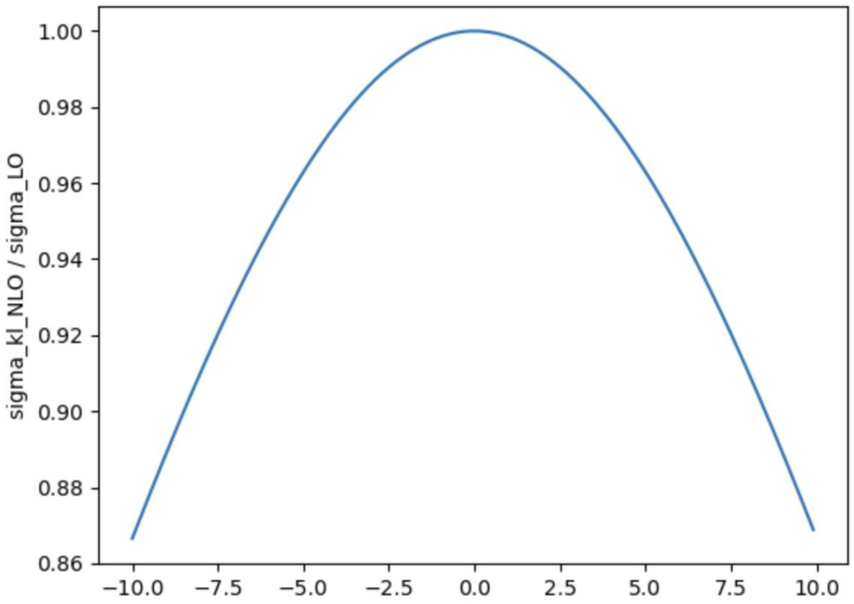
σ_{kl}

- ZH(bb) NLO/LO cross-section as a function of δ(kappa lambda)

- Cross-section falls off, leads to changing likelihood.



$\delta(\kappa_\lambda) = 1 - \kappa_\lambda$ (SM = 0)

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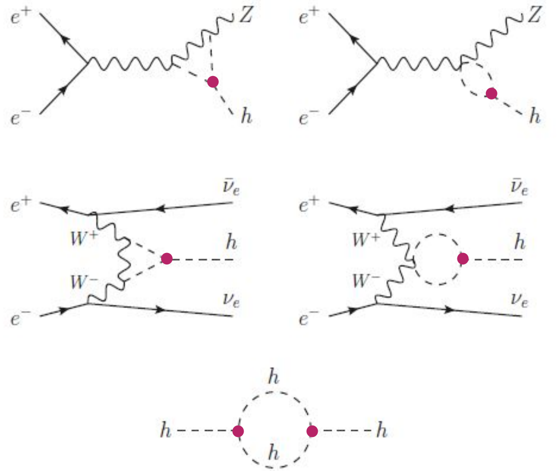
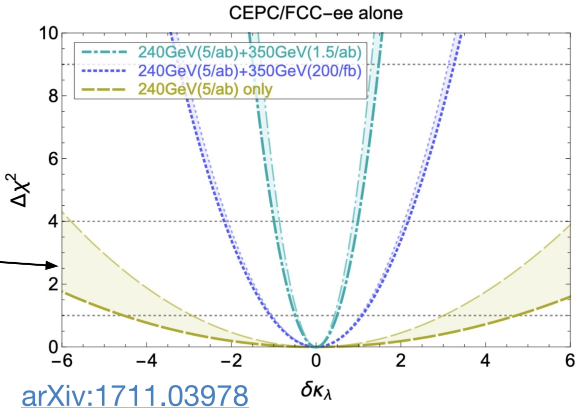
How to measure the Higgs self-coupling at the FCC-ee?

- The self-coupling measurement depends on measurements of Higgs production cross sections and decays to other particles.
- The κ analysis is expected to reach **~20%** accuracy [arXiv:1905.03764], while the global effective field theory fit will reach **~30%** [arXiv:1711.03978] (in combination with HL-LHC projections!)
- **The ZH cross section (240 GeV run) is most sensitive to changes in the self-coupling**
  - 365 GeV run is crucial for reducing uncertainties!





arXiv:1711.03978