(Update on) Higgs self-coupling determination at the FCC-hh

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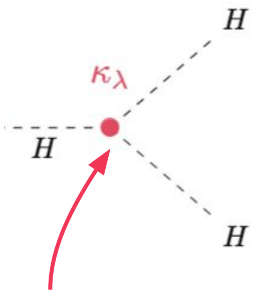
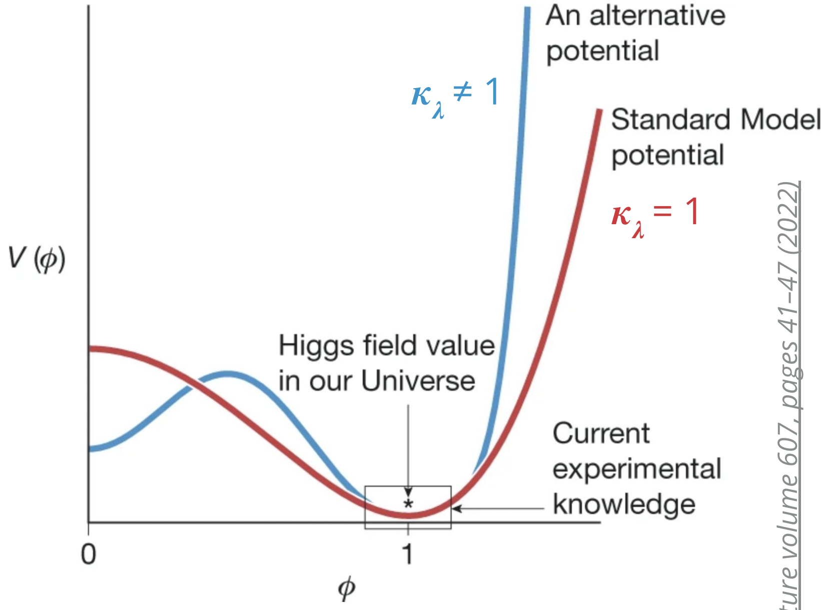
Why do we want to measure the Higgs self-coupling?



Higgs self-coupling modifier: $\kappa_\lambda = \lambda^{meas}/\lambda^{SM}$

- Measuring the Higgs self-coupling allows us to gain insight into the nature of the Higgs potential and electroweak symmetry breaking → of our universe
  - It would be the first evidence of a particle interacting with itself

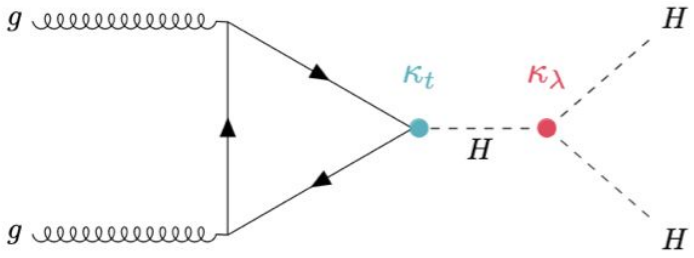


$$V(\Phi^+\Phi) = \mu^2\Phi^+\Phi + \lambda(\Phi^+\Phi)^2$$

Nature volume 607, pages 41–47 (2022)

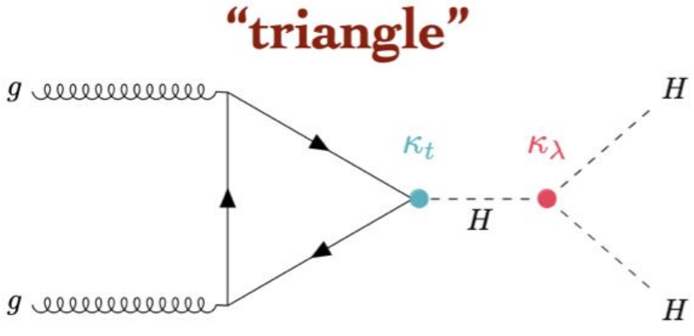
How can we measure the Higgs self-coupling (at FCC-hh)?

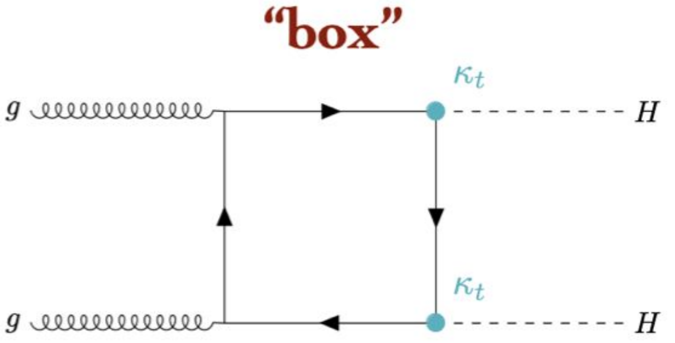
- Cross-section of Higgs pair production is proportional to $\boldsymbol{\kappa}_{\boldsymbol{\lambda}}$



How can we measure the Higgs self-coupling (at FCC-hh)?

- Cross-section of Higgs pair production is proportional to κ_λ





- But, there is destructive interference of triangle and box contributions
  - Tiny cross-section in the SM: $\sigma(ggHH) \sim O(1000)$ smaller than $\sigma(ggH)$
  - Experimentally very challenging !

Overview of Higgs self-coupling limits & prospects

- At LHC we set limits: $-0.4 < \kappa_\lambda < 6.3$ (*ATLAS-HDBS-2022-03*)

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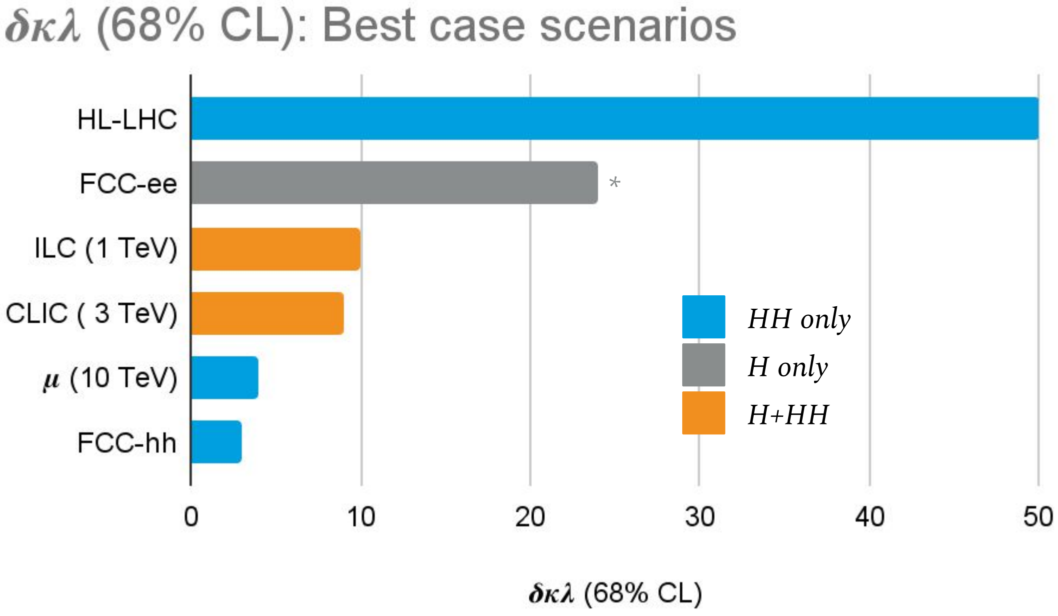
- Only at future colliders we will reach a precision measurement



Details & references in back-up

** For FCC-ee the Higgs self-coupling is measured indirectly via one loop-effect in the ZH process*

Overview of Higgs self-coupling limits & prospects

- At LHC we set limits: $-0.4 < \kappa_\lambda < 6.3$ (ATLAS-HDBS-2022-03)
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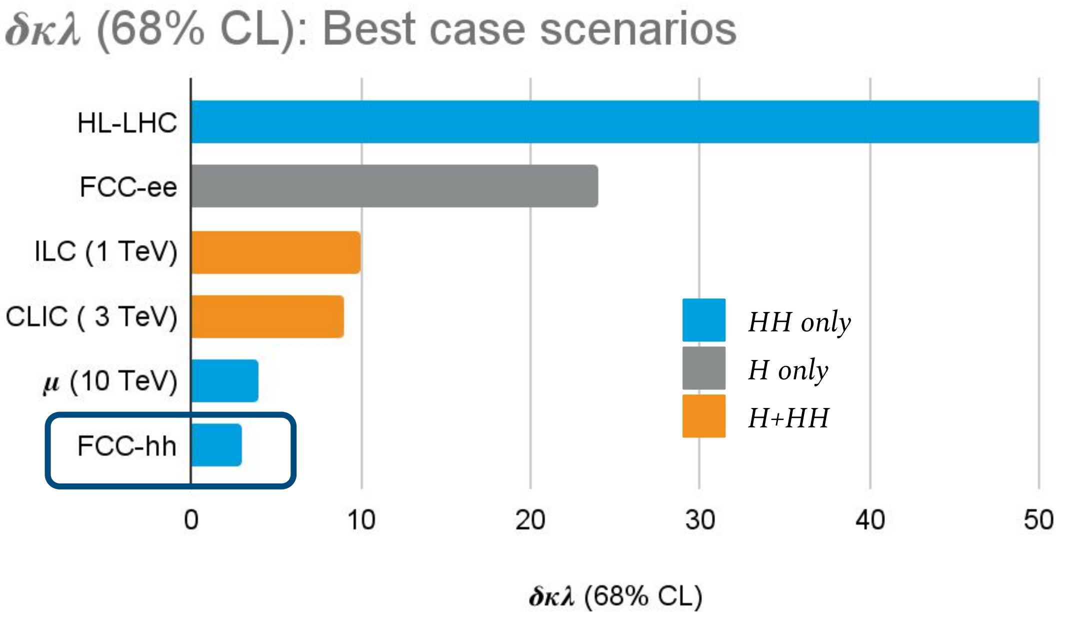
FCC-hh offers best prospects for %-level measurement from Higgs pair production



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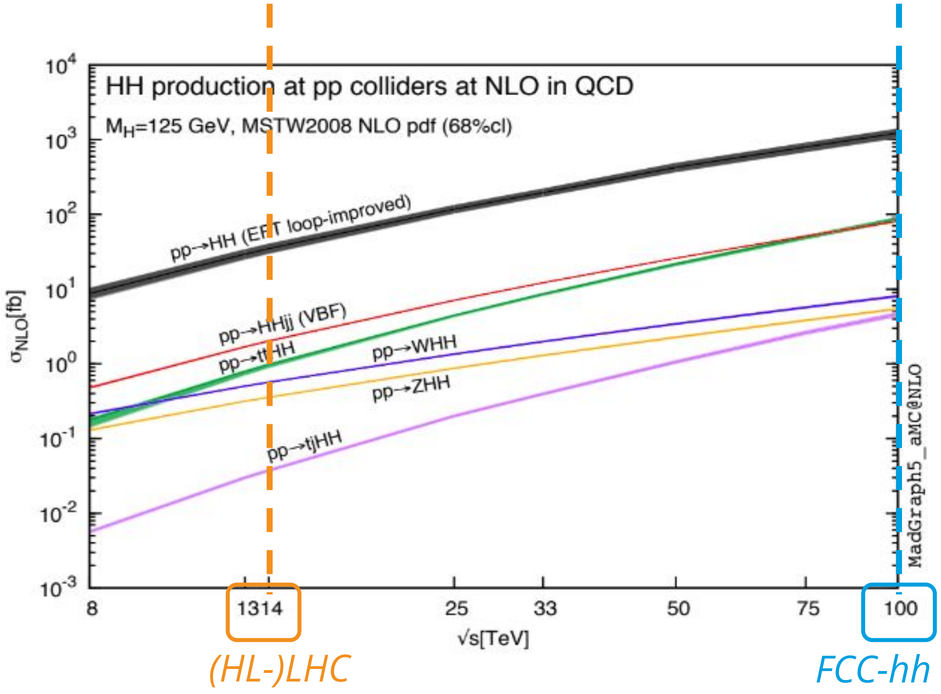
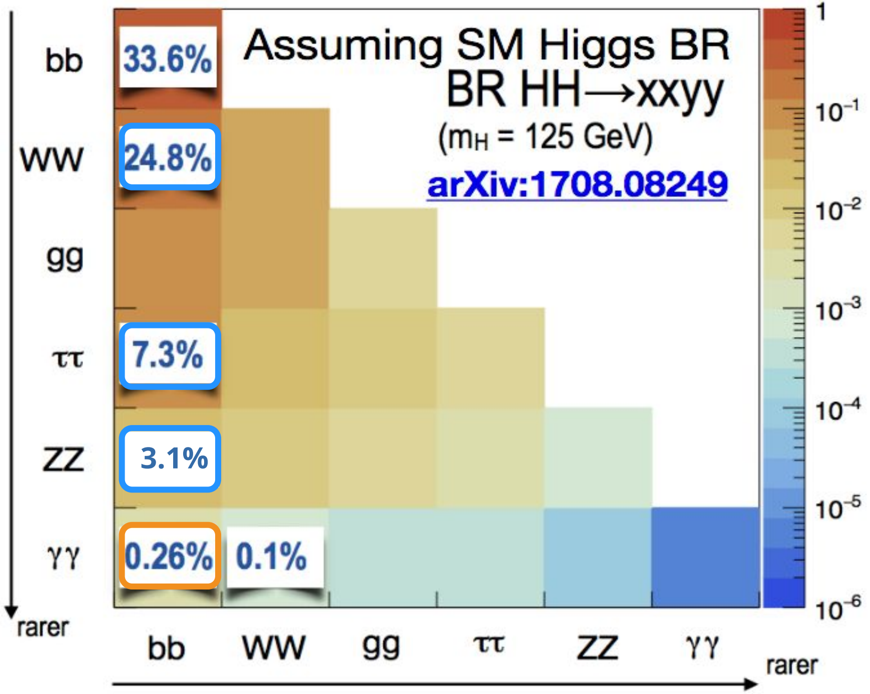
Precision Higgs self-coupling measurement at FCC-hh



- **FCC-hh**: *pp*-collisions at 100 TeV, 30 ab^{-1} in ~25 years
  - Energy ***and*** precision frontier
  - Large cross-section ***and*** large data-set
    - 20 x precision of HL-LHC

Our work: Update of $\bar{b}b\gamma\gamma$ and adding $\bar{b}bll+E_T^{miss}$

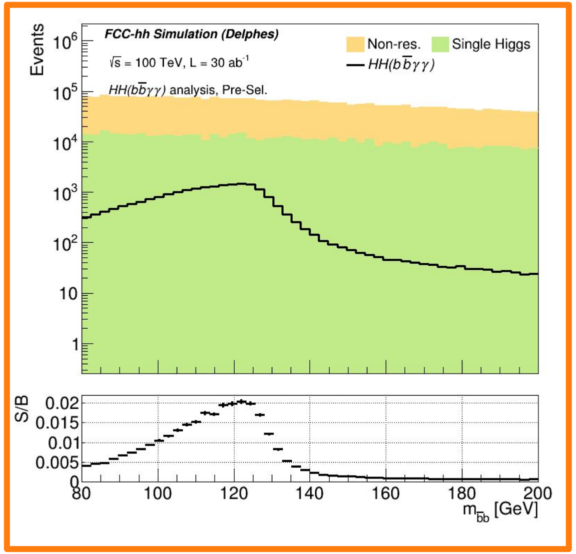


Final state	Description
$\bar{b}b\gamma\gamma$	• High precision, despite small BR: Clean signature with well reconstructed objects
$\bar{b}bll+E_T^{miss}$	• Summing contributions from $\bar{b}bWW(l\nu l\nu)+\bar{b}b\tau\tau(l\nu l\nu)+\bar{b}bZZ(ll\nu\nu)$ • Larger BR, but more background contaminated, limited precision

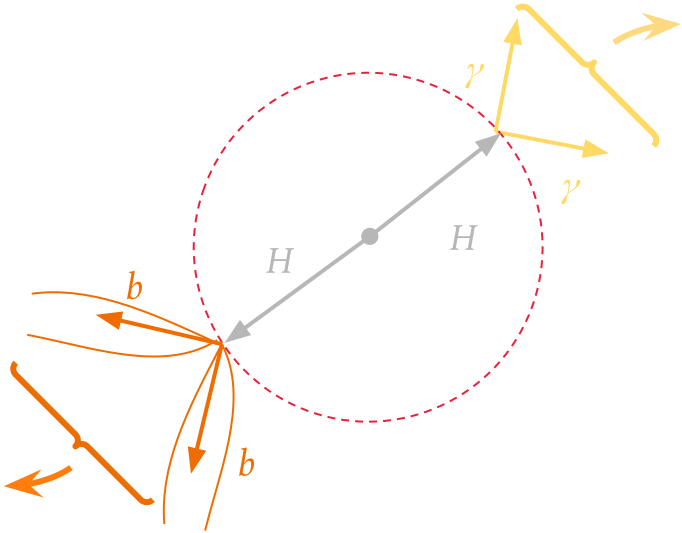
Analyses performed within key4hep, on Delphes fast simulation with an optimistic detector scenario

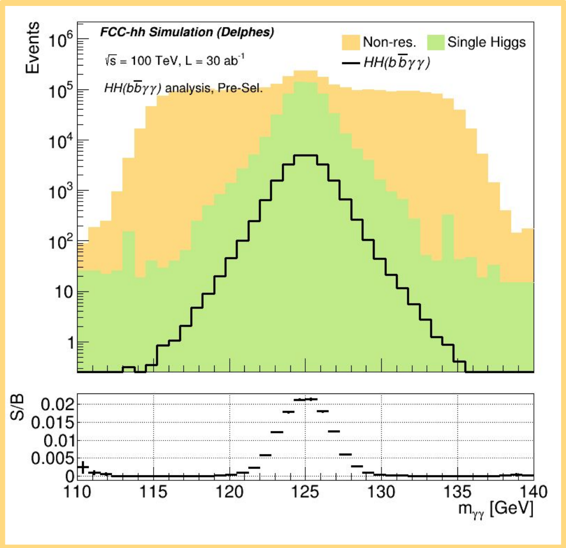
$b\bar{b}\gamma\gamma$ analysis: Strategy overview

Pre-selected events



Signal signature

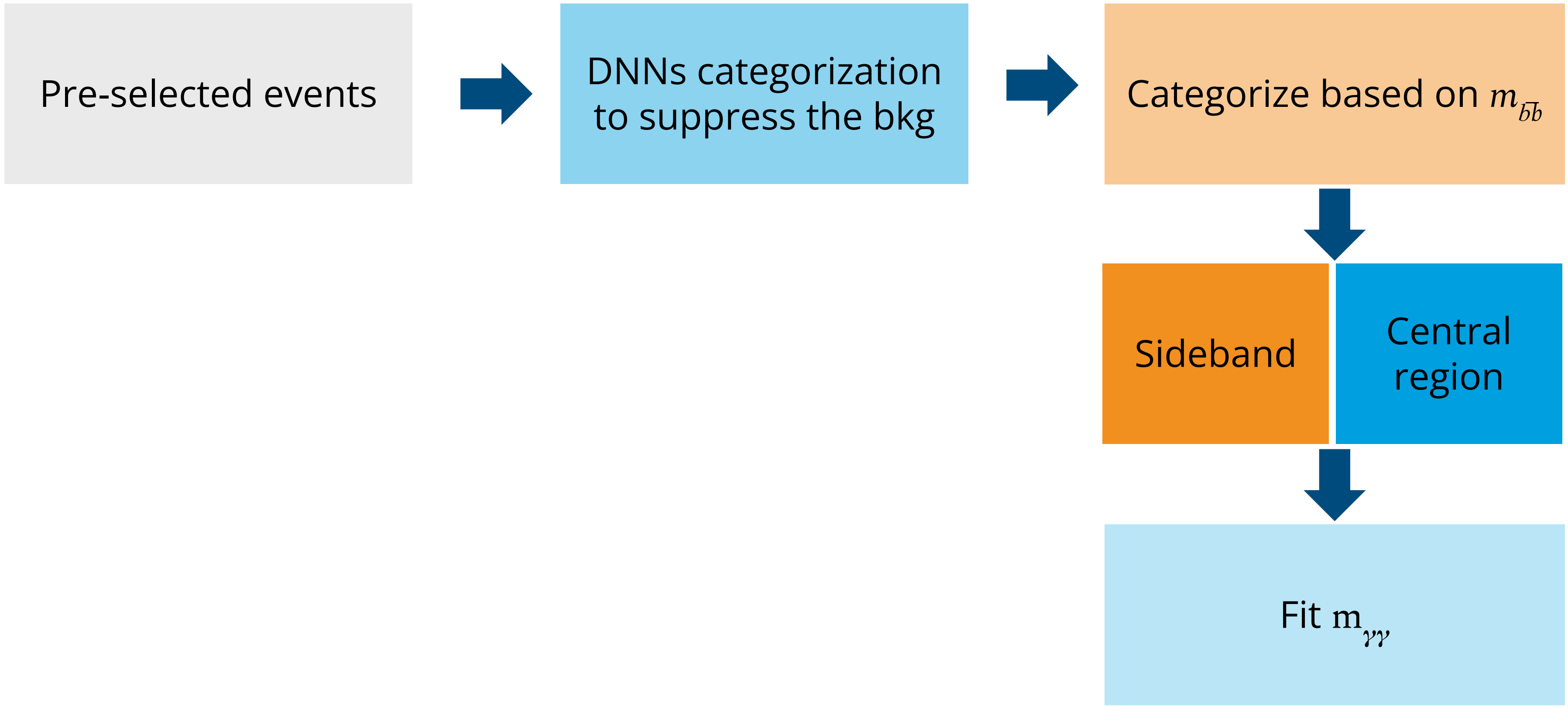




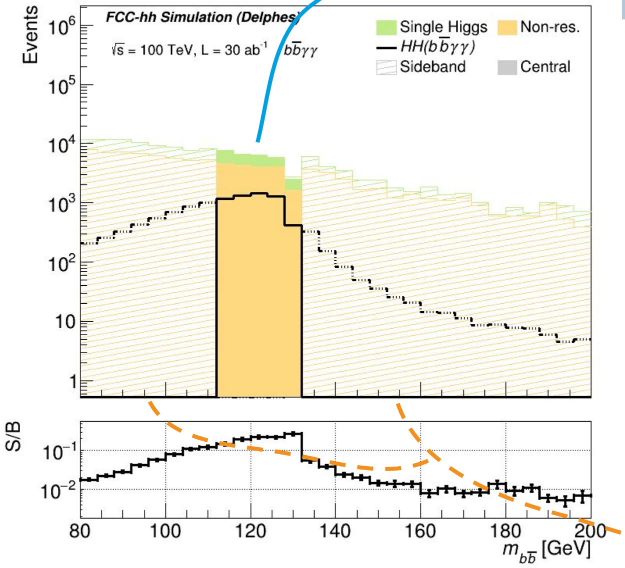
- 2 b-jets & 2 photons with invariant masses near m_H

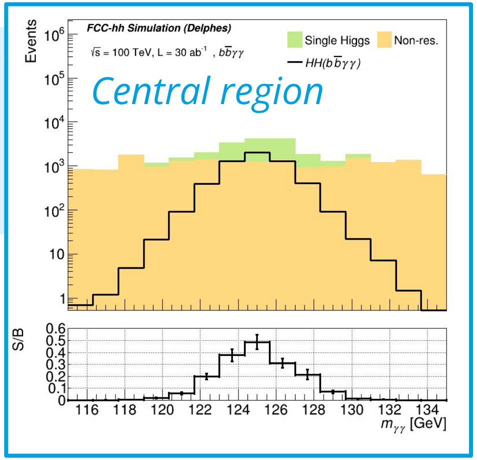
- Backgrounds:
  - Non-resonant QCD: $\gamma\gamma$+jets and γ+jets
  - Single Higgs production

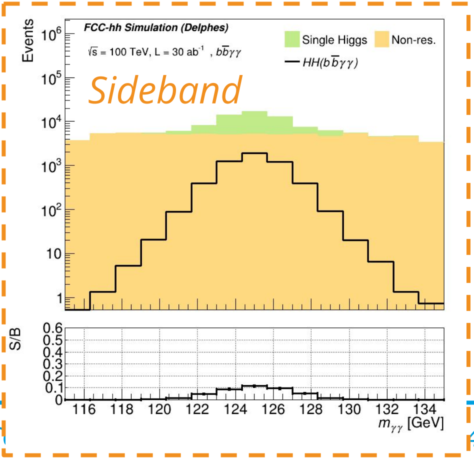
$\bar{b}byy$ analysis: Strategy overview



$b\bar{b}\gamma\gamma$ analysis: Strategy overview







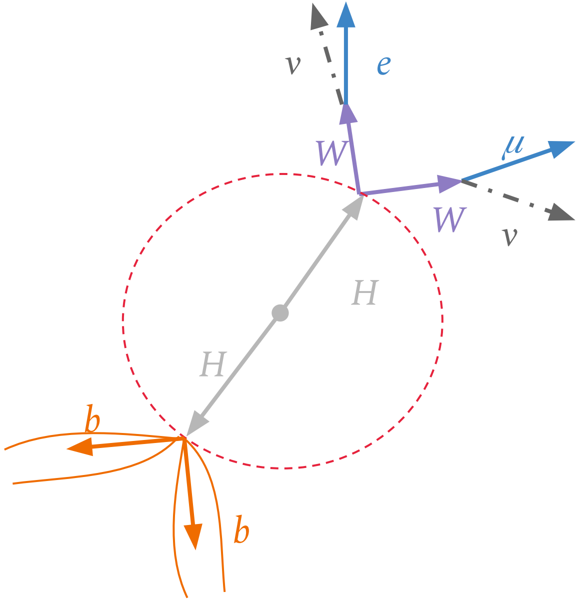
Categorize based on $m_{b\bar{b}}$

Sideband | Central region

Fit $m_{\gamma\gamma}$

$\bar{b}bll+E_T^{miss}$: Strategy overview

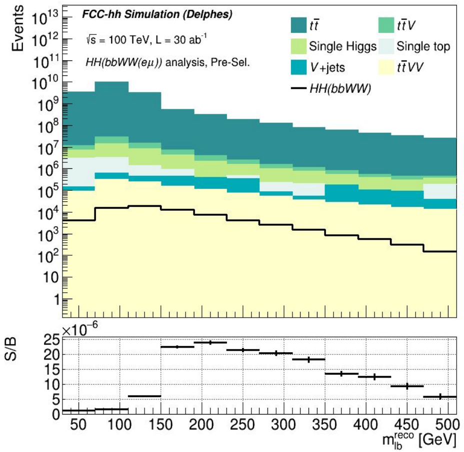
Signal signature

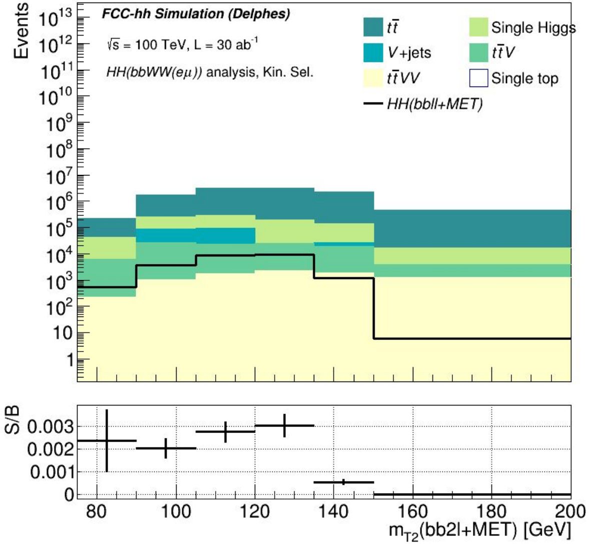


- Lepton pair + E_T^{Miss} + 2 b-jets
  - Leptons isolated from b-jets

- Cut-based event selection exploiting signal kinematics
  - Targeted suppression of $t\bar{t}$ background using

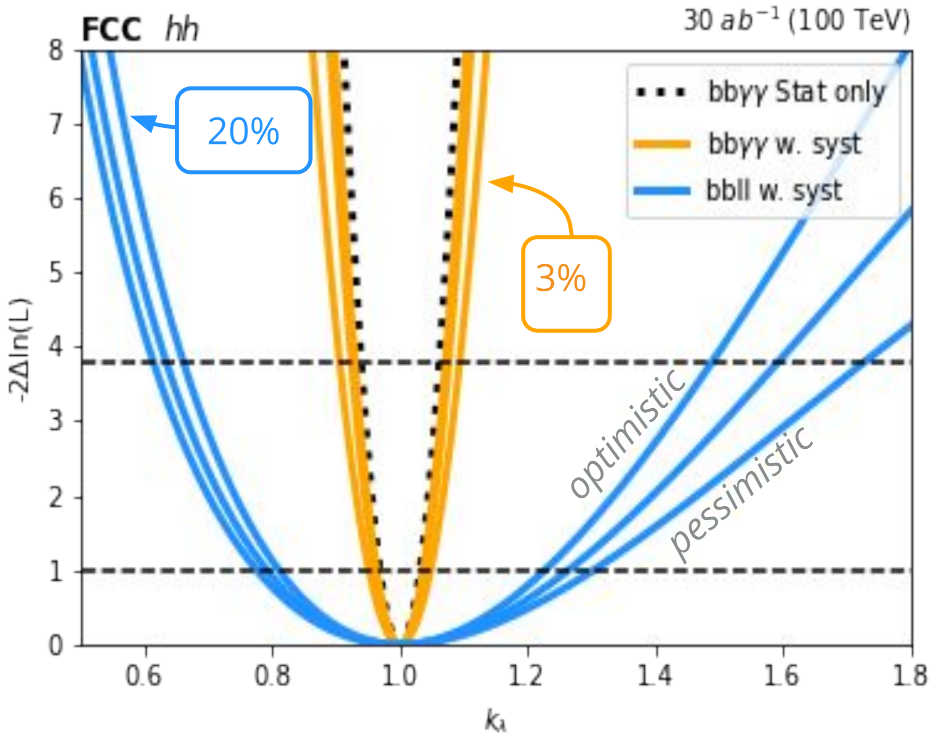
$$m_{lb}^{\text{reco}} = \min\left(\frac{m_{l_1b_1}+m_{l_2b_2}}{2}, \frac{m_{l_2b_1}+m_{l_1b_2}}{2}\right)$$





- <u>Stransverse mass</u> m_{T2} predicts invisible mass contribution
  - Capture the full HH decay
  - Fit to m_{T2} distribution in 5 categories depending on lepton flavours and if $Z(ll)$ decay

Results



- Extracting Higgs self-coupling modifier $\boldsymbol{\kappa_\lambda}$
  - Parametrized dependence of $\boldsymbol{\sigma}(ggHH)$ on $\boldsymbol{\kappa_\lambda}$
  - 3 different assumptions on systematic uncertainties going from optimistic to more pessimistic *(details in backup)*

Baseline analysis for $\bar{b}b\gamma\gamma$
→ Higher precision possible!

Summary & outlook

- We restarted the effort of FCC-hh Higgs self-coupling studies:
  - Using the common software tools, working on integration of our developments into the main repositories
- $\bar{b}b\gamma\gamma$
  - Ultimate goal is to achieve 1% precision on the Higgs self-coupling
- $\bar{b}bll+E_T^{miss}$
  - No previous study of this channel

More details on both analyses in the parallel session

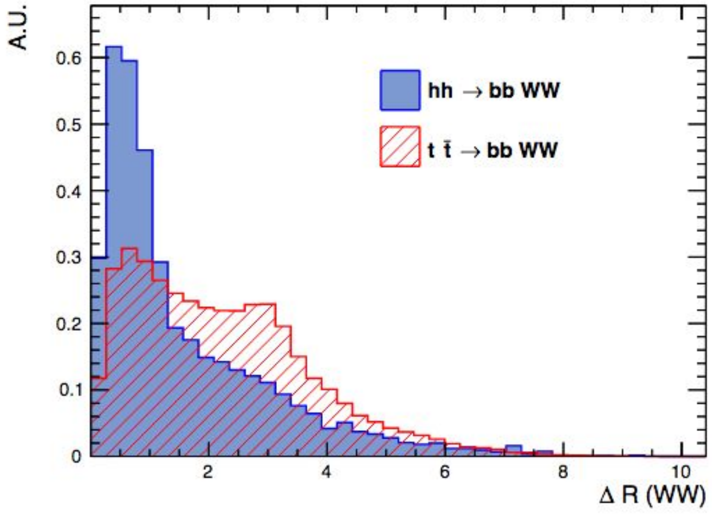
Bonus

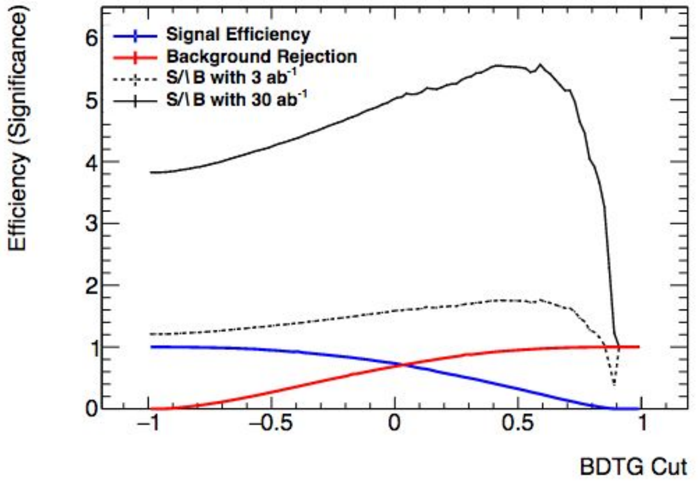
Systematic uncertainties

Source of uncertainty	Syst. 1	Syst. 2	Syst. 3	Applies to	Correlated
Common systematics					
b-jet ID / b-jet	0.5%	1%	2%	Signals, MC bkgs.	✓
Luminosity	0.5%	1%	2%	Signals, MC bkgs.	✓
Signal cross-section	0.5%	1%	1.5%	Signals, MC bkgs.	✓
$b\bar{b}\gamma\gamma$ systematics					
γ ID / γ	0.5%	1%	2%	Signals, MC bkgs.	✗
$b\bar{b}\ell\ell + E_{\mathrm{T}}^{\mathrm{miss}}$ systematics					
Lepton ID / lepton	0.5%	1%	2%	Signals, MC bkgs.	✗
Data-driven bkg. est.	-	1%	1%	$V+$jets	✗
Data-driven bkg. est.	-	-	1%	$t\bar{t}$	✗

- Following previous di-Higgs studies@FCC-hh
- Applied as rate systematics only, no shape effect

Previous projections for $\bar{b}bWW$ @ FCC-hh





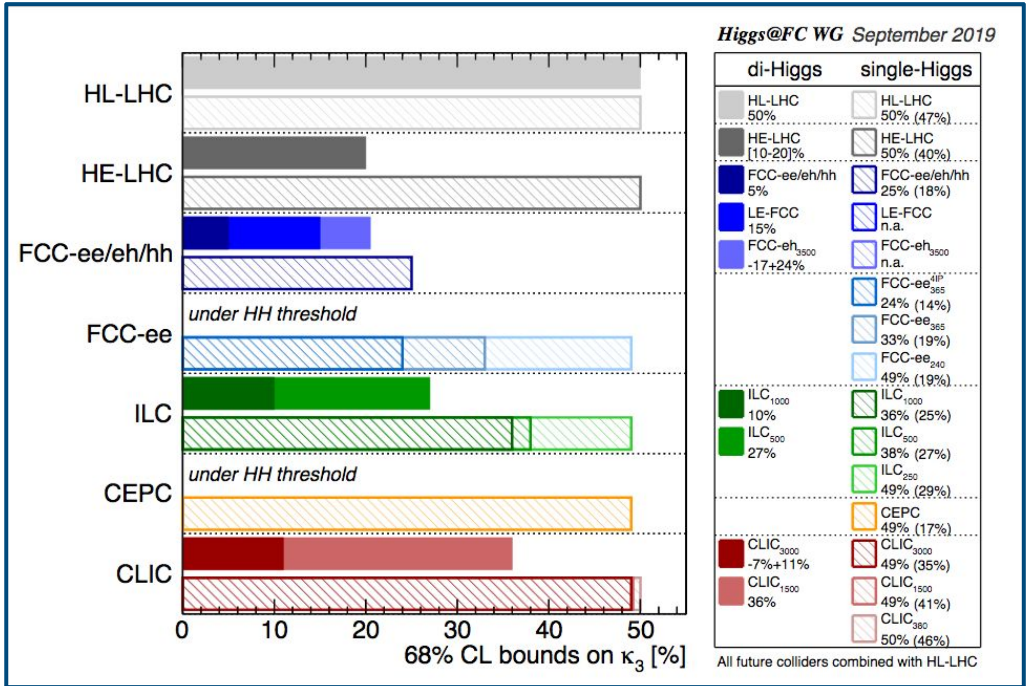
- $bbWW(2jl\nu)$ studied using BDT, with similar input variables as used here
- Achieved 40% precision (@68% CL) on κ

Overview of Higgs self-coupling limits & prospects

Experiment	95% CL limit	Reference
ATLAS - *HH* - *H+HH*	$-0.6 < \kappa_\lambda < 6.6$ $-0.4 < \kappa_\lambda < 6.3$	ATLAS-HDBS-2022-03
CMS - *HH*	$-1.2 < \kappa_\lambda < 6.5$	Nature 607 (2022) 60
	$\delta\kappa_\lambda$ (68% CL)	
HL-LHC	~50%	e.g. ATL-PHYS-PUB-2022-005

Best case scenarios for Future Colliders			
Experiment	$\delta\kappa_\lambda$ (68% CL)	Reference	
ILC (1 TeV)	10%	arXiv:2203.07622 v2	*H+HH*
CLIC (3 TeV)	9%	arXiv:1812.01644 v1	*H+HH*
FCC-ee	24%	JHEP01(2020)139	*H only*
μ (10 TeV)	4%	arXiv:2203.07261 v2	*HH*
FCC-hh	3%	*arXiv:2004.03505 v2*	*HH*

Why di-Higgs at FCC-hh?



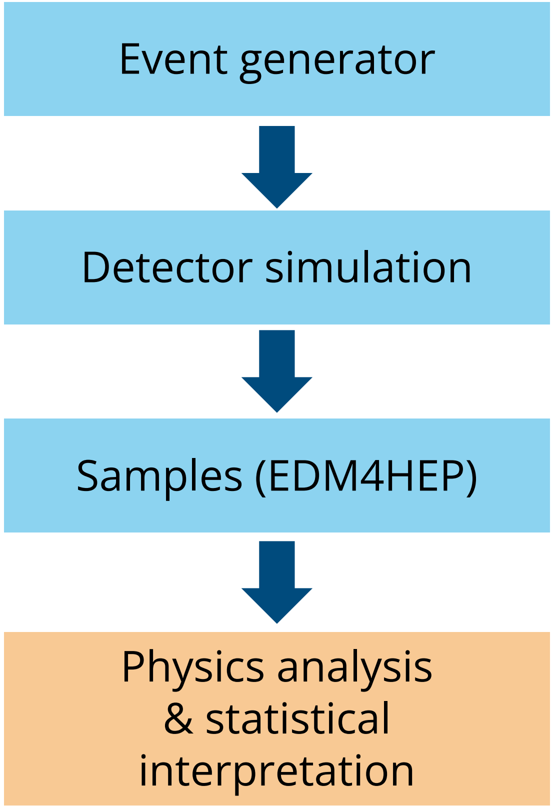
[arXiv:1905.03764v2]

FCC-hh is the only perspective for a Higgs self-coupling precision measurement

↔

Higgs self-coupling measurement is a clear benchmark channel for the FCC-hh

Common software stack for future facilities



All part of key4hep project: Consistent software stack for all future projects

- Fast, parametrized simulation in Delphes
- Using EventProducer framework (fork)
- Samples in EDM4HEP format

Analysis with common framework FCCAnalyses

- Currently on fork with some new additions
  - E.g. getting tagged jets from Delphes
- Plan to integrate into main repo

Common software stack for future facilities

Event generator

↓

Detector simulation

↓

Samples

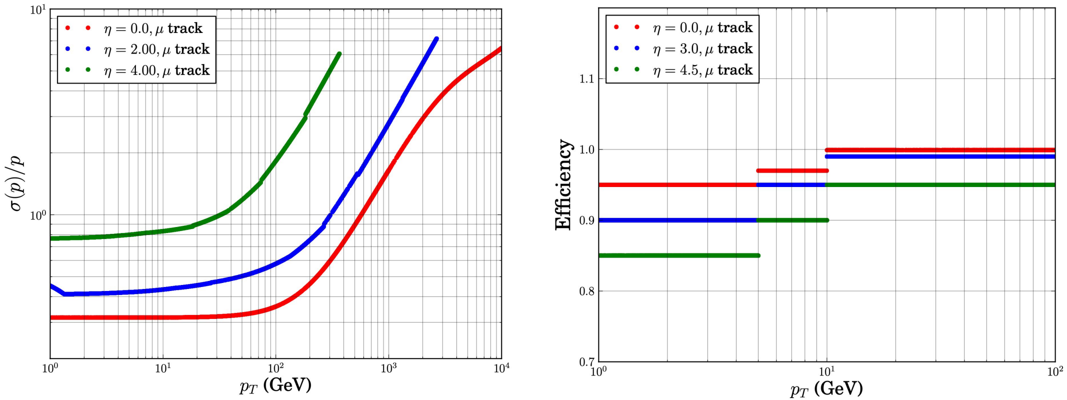
↓

Physics analysis & statistical interpretation

Fast, parametrized detector simulation with <u>Delphes</u> with <u>updated FCC-hh card</u>

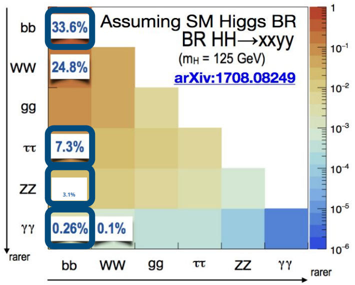
- Very optimistic “ideal” scenario, implement fixes & new features

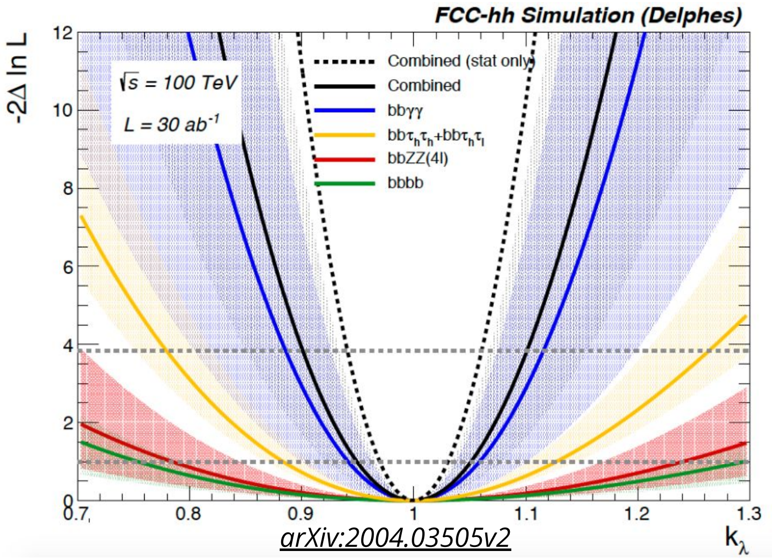
Example parametrization for muons



Higgs self-coupling projections for FCC-hh

M. Mangano, G. Ortona, M. Selvaggi

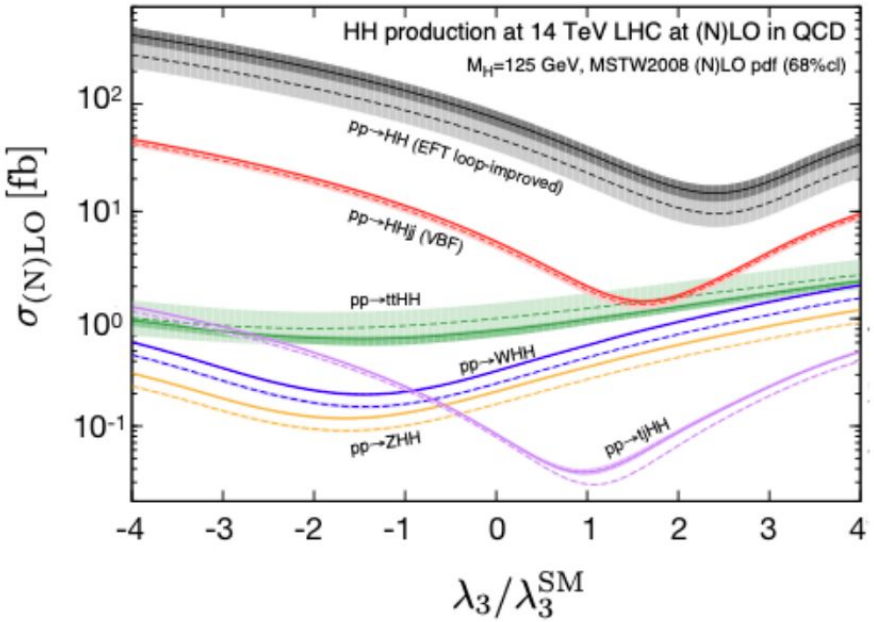


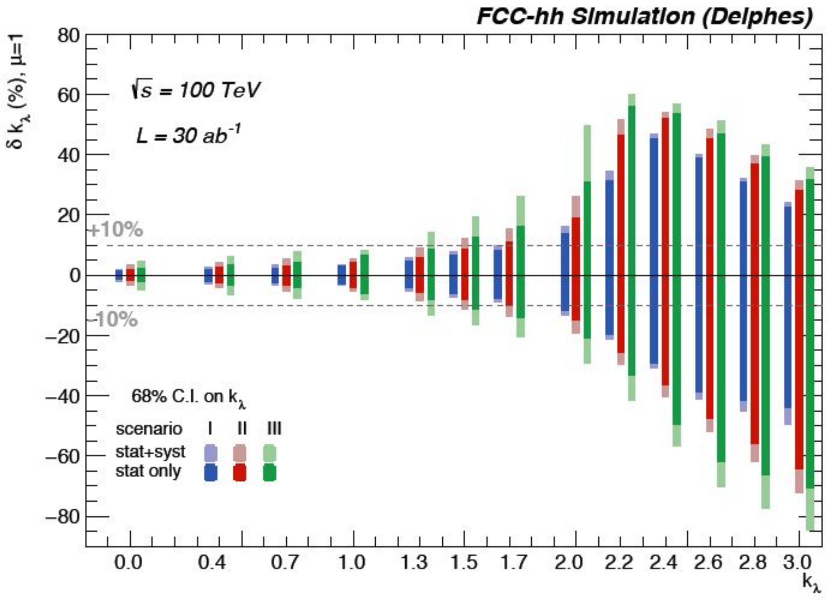


- **FCC-hh potential well established** in several channels
- Previously published combination included ***bbyy*, *bbττ(hh+lh)*, *4b* and *bbZZ(4l)***
- Considered three **different scenarios for detector performance** and systematic uncertainties by reweighting from main detector scenario **based on LHC performance & FCC-hh CDR**

	Combined precision
$\delta\kappa_\lambda$ (68% CL)	3.0% - 7.8%

Di-Higgs cross-section dependance on κ_λ in pp-collisions

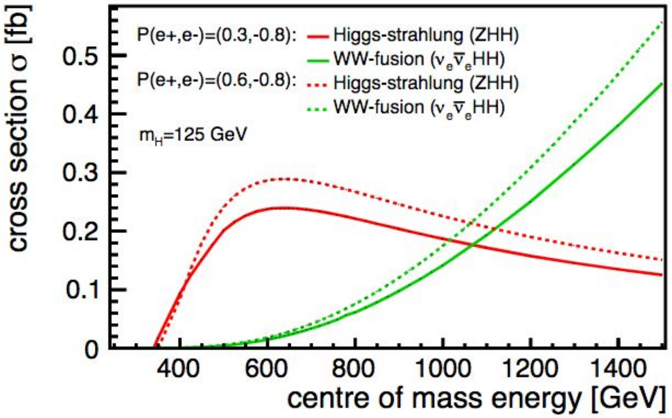


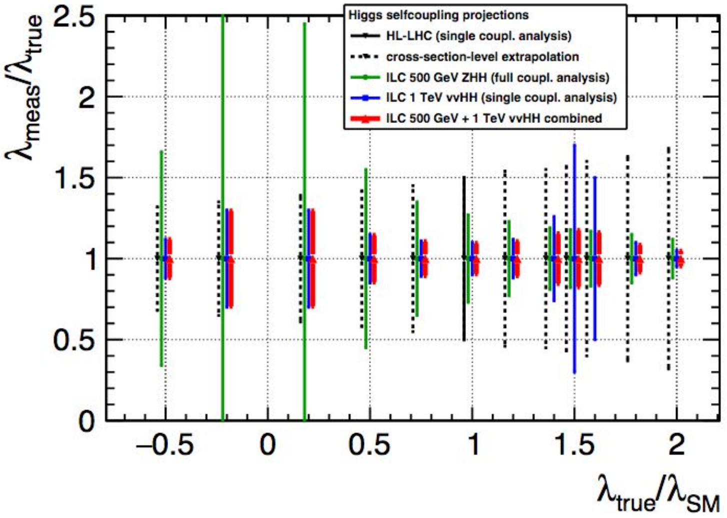


arXiv:2004.03505v2

arXiv:2203.07622v2

Higgs self-coupling @ ILC





- Two production modes:
  - Higgsstrahlung, peaks ~500 GeV
  - WW-fusion, above ~1 TeV
  - → need runs at both energies for maximum κ_λ precision

- Studied dominant channels $4b$ and $bbWW$
- Advantage of ee-collider: ZHH cross-section increases with κ_λ, hence better constraints at values $\kappa_\lambda > 1$ than pp-colliders