(Prospects of) Higgs self-coupling measurements at the FCC-hh

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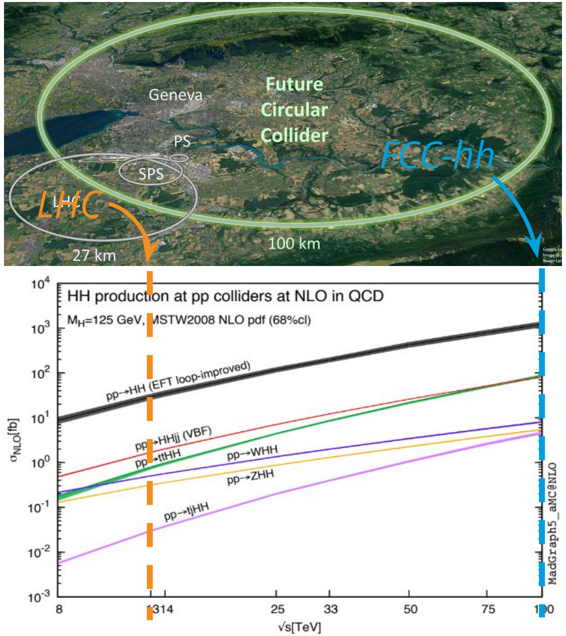
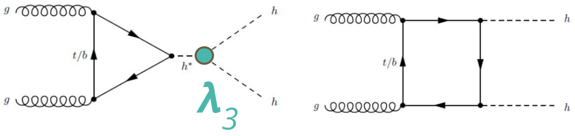
Higgs self-coupling @ FCC-hh: What & why?





- **FCC-hh**: *pp*-collisions at 100 TeV, 30 ab^{-1} in ~25 years
  - Energy and precision frontier!
- Measuring the **Higgs self-coupling via di-Higgs production** is key benchmark for FCC-hh
  - SM: $\sigma(ggHH) \sim O(1000)$ smaller than $\sigma(ggH)$
  - Large cross-section and data-set at FCC-hh
    - 20 x precision of HL-LHC
  - Access rarer, more difficult channels

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

Overview of Higgs self-coupling limits & prospects

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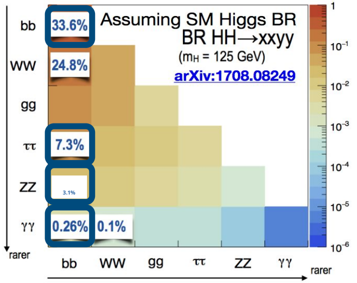
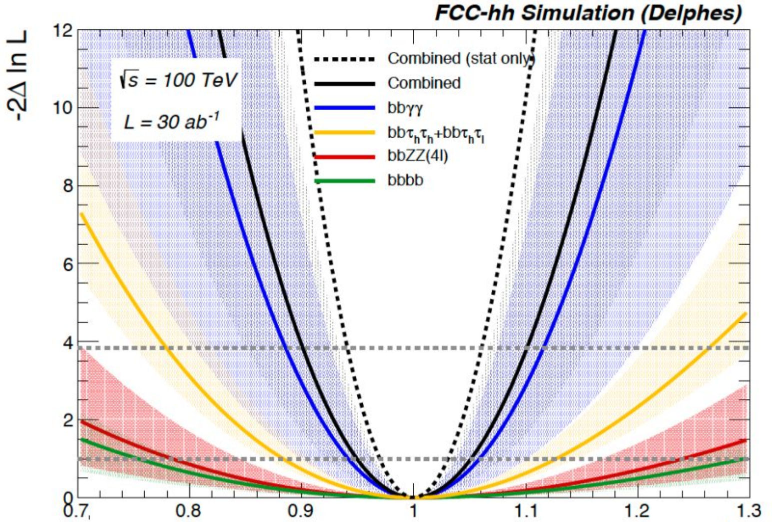
Best case scenarios for Future Colliders			
Experiment	$\delta\kappa_\lambda$ (68% CL)	Reference	
ILC (1 TeV)	10%	arXiv:2203.07622 v2	$H{+}HH$
CLIC (3 TeV)	9%	arXiv:1812.01644 v1	$H{+}HH$
FCC-ee	24%	JHEP01(2020)139	H only
μ (10 TeV)	4%	arXiv:2203.07261 v2	HH
FCC-hh	3%	*arXiv:2004.03505 v2*	HH

Higgs self-coupling projections for FCC-hh



M. Mangano, G. Ortona, M. Selvaggi



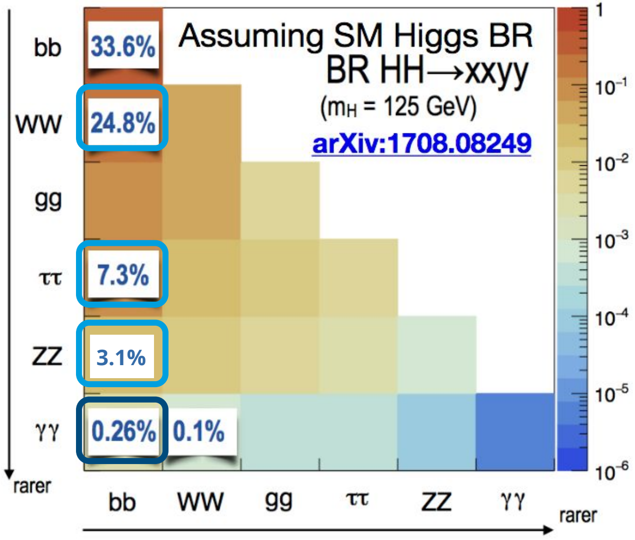
arXiv:2004.03505v2

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

- **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 TDR**

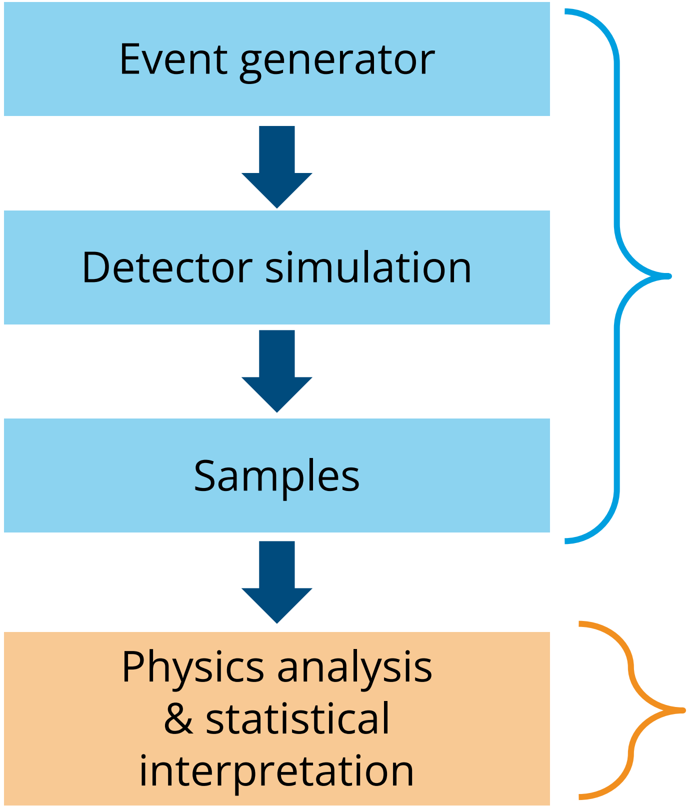
This talk: Update of $\bar{b}byy$ and adding $\bar{b}bll+E_T^{miss}$

- Studying only $ggF\ HH$ production mode (so far)



Final state	$BR(HH \rightarrow X)$	Description
$\bar{b}byy$	0.26%	• High precision, despite small BR: Clean signature with well reconstructed objects • DNN-based analysis
$\bar{b}bll+E_T^{miss}$	3.24%	• Summing contributions from $\bar{b}bWW(l\nu l\nu)+\bar{b}b\tau\tau(ll\nu l\nu)+\bar{b}bZZ(ll\nu\nu)$ • Larger BR, but more background contaminated, limited precision • Not studied at FCC-hh before • Cut-based analysis

Common software stack for future facilities



All part of key4hep project: Consistent software stack for all future projects - sustainable & future-proof approach, "turn-key software"

- Samples in EDM4HEP format
- Details see e.g. T. Madlener @ ECFA workshop

Analysis with common framework FCCAnalyses

Common software stack for future facilities

Event generator

Detector simulation

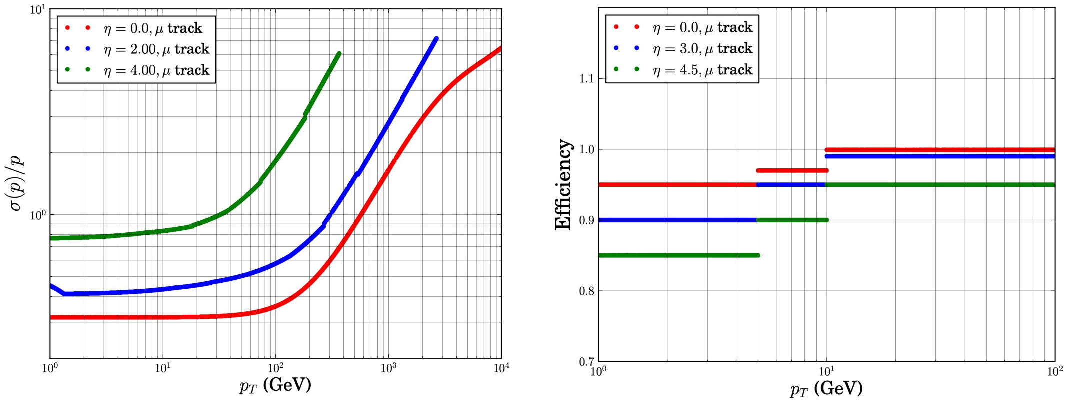
Samples

Physics analysis & statistical interpretation

Fast, parametrized detector simulation with Delphes with updated FCC-hh card

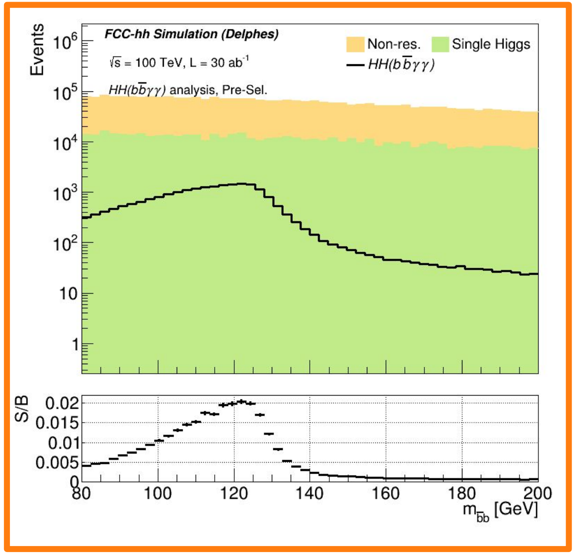
- Very optimistic “ideal” scenario, implement fixes & new features

Example parametrization for muons

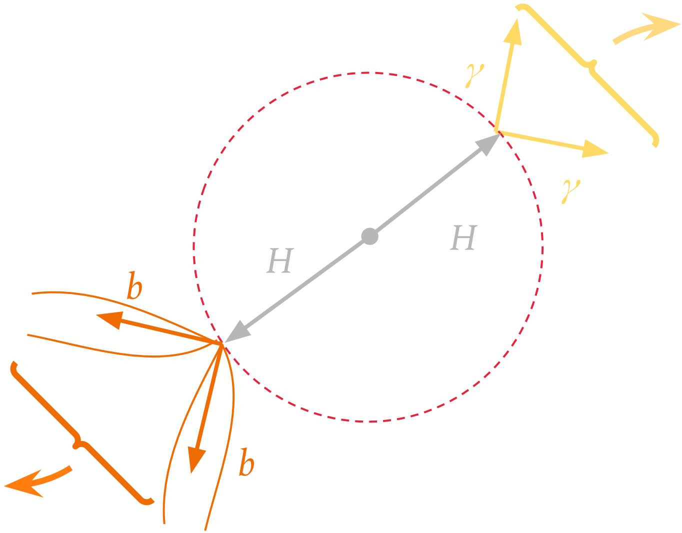


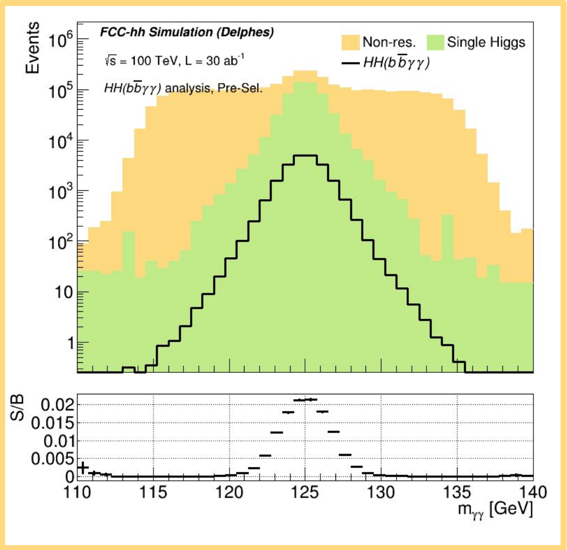
$\bar{b}b\gamma\gamma$ analysis: Strategy overview

Pre-selected events



Signal signature





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

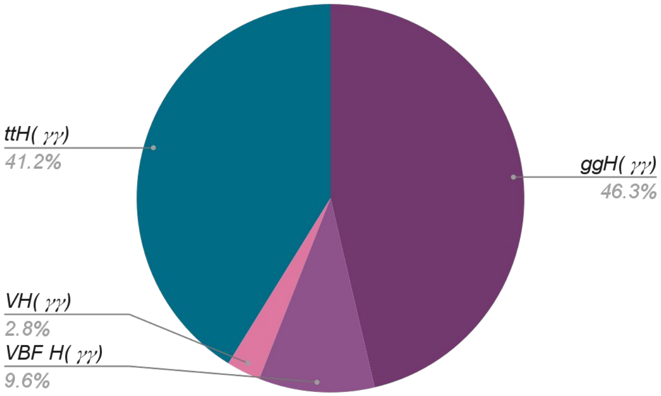
- Backgrounds:
  - Non-resonant QCD: $\gamma\gamma$+jets and γ+jets
  - Single Higgs production

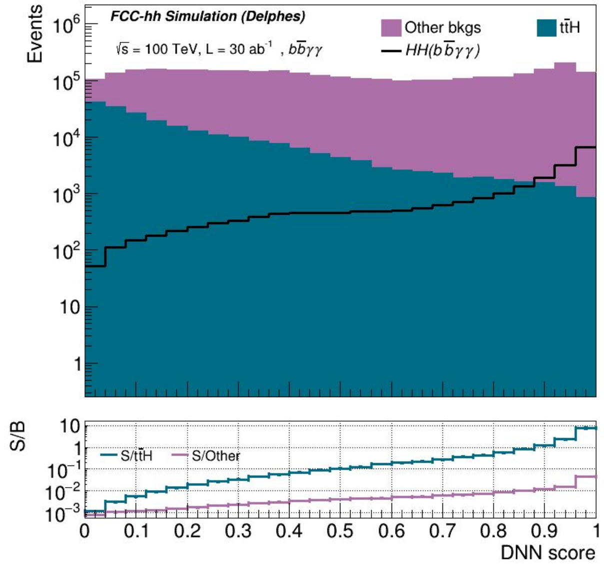
$\bar{b}b\gamma\gamma$ analysis: Strategy overview

Pre-selected events

DNN-based $t\bar{t}H$ tagger

Single Higgs bkg composition





- $t\bar{t}H$ enhanced - same final state as signal signature
  - $\boldsymbol{\sigma}(t\bar{t}H \to \boldsymbol{\gamma\gamma}) \sim 3\ \boldsymbol{\sigma}(ggHH \to bb\boldsymbol{\gamma\gamma})$
- Exploit expected differences in kinematics:
  - $t\bar{t}H$ more jets, but less energetic
  - $t\bar{t}H$ can contain high pT leptons
  - $\bar{b}b$- and $\boldsymbol{\gamma\gamma}$-pair back to back in signal

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

$$m_x = m_{\bar{b}b\gamma\gamma} - m_{\bar{b}b} - m_{\gamma\gamma} + 250\text{GeV}$$

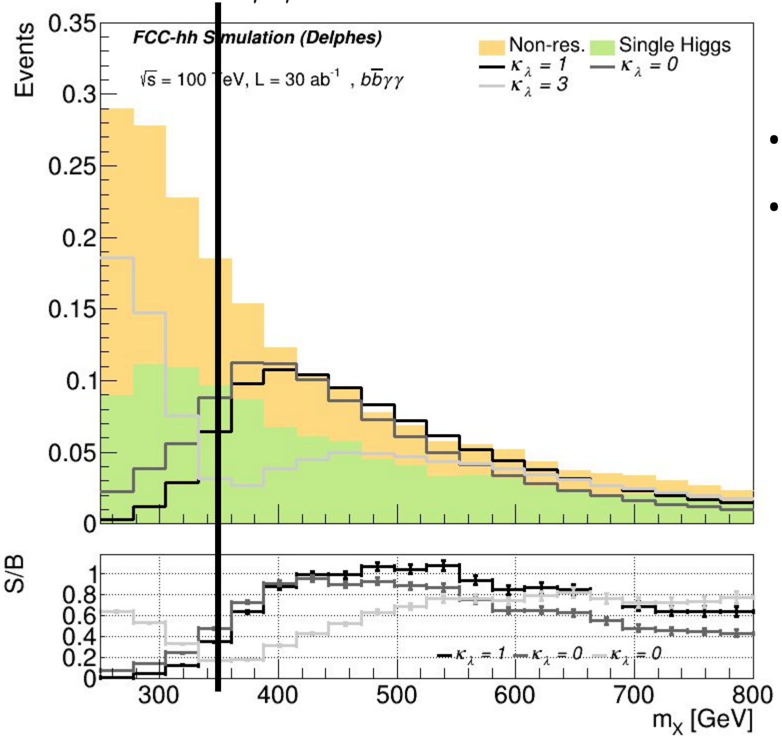
Pre-selected events

↓

DNN-based $\bar{t}tH$ tagger

↓

m_x < 350 GeV	*m_x > 350 GeV*



- Shape depends on $\boldsymbol{\kappa_\lambda}$
- Region m_x < 350 GeV has low S/B for $\boldsymbol{\kappa_\lambda}$=1 (SM) , but contributions from $\boldsymbol{\kappa_\lambda}$≠1 (BSM) signals

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

Pre-selected events

↓

DNN-based $t\bar{t}H$ tagger

↓

$m_x < 350$ GeV	$m_x > 350$ GeV

→

DNN to suppress non-$t\bar{t}H$ backgrounds

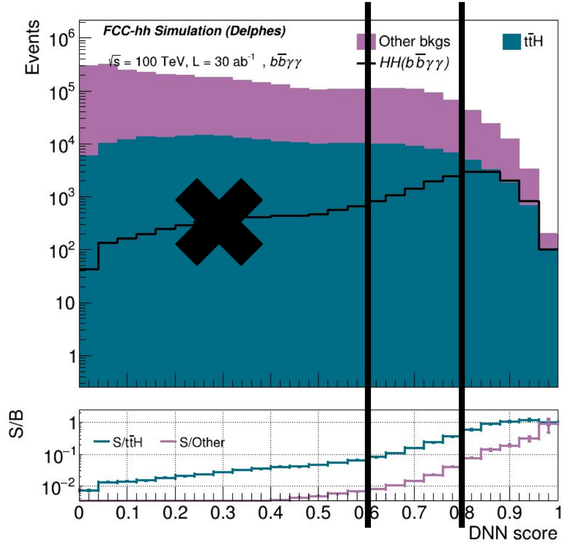
↑

Optimization of DNN score cuts

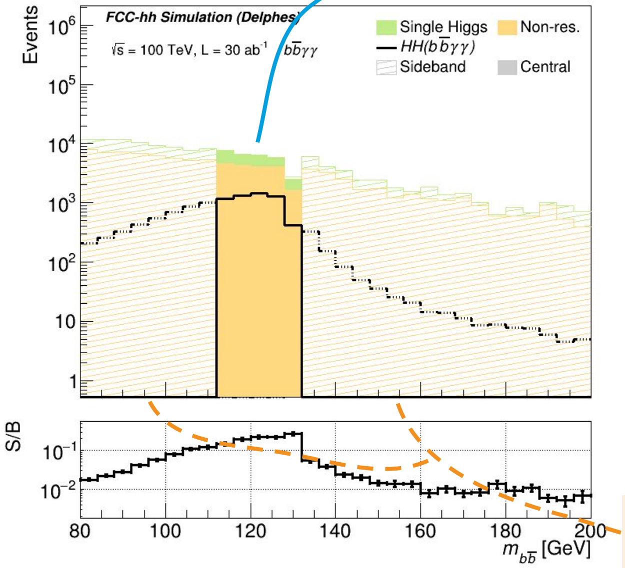
↑

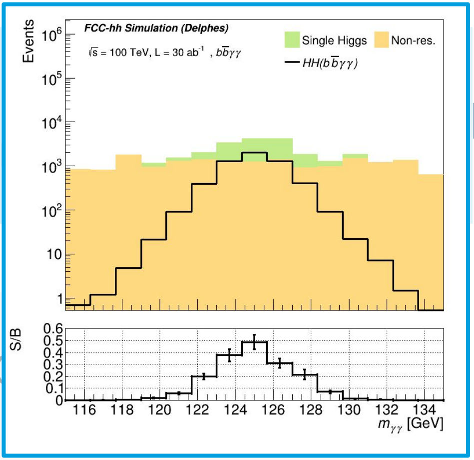
Medium purity	*High purity*

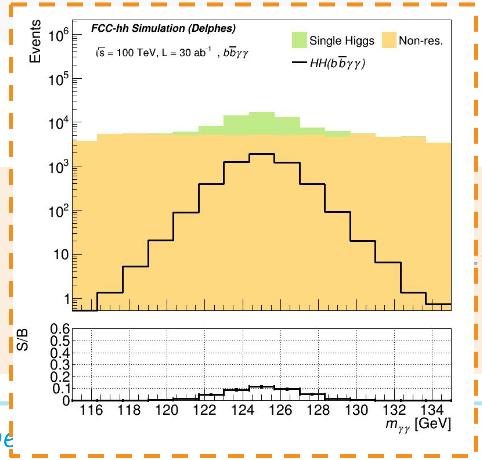
- Separate DNNs for suppressing non-background, using same input variables as $t\bar{t}H$ tagger
- Optimization of cuts based on significance



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







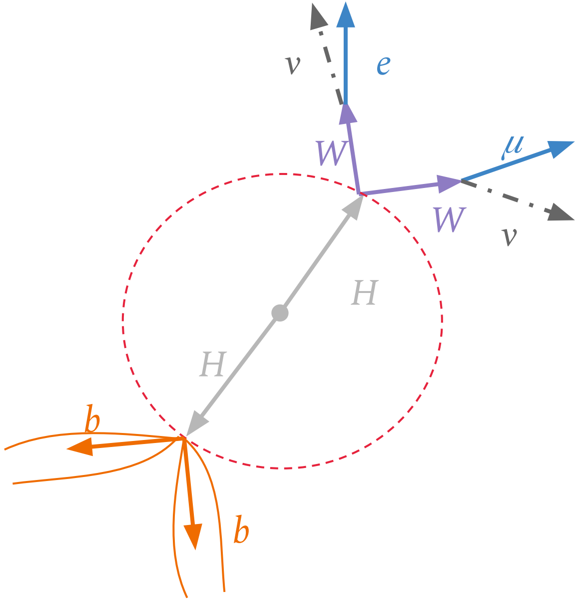
Categorize based on $m_{\bar{b}b}$

Sideband | *Central region*

Fit $m_{\gamma\gamma}$ in 8 categories

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

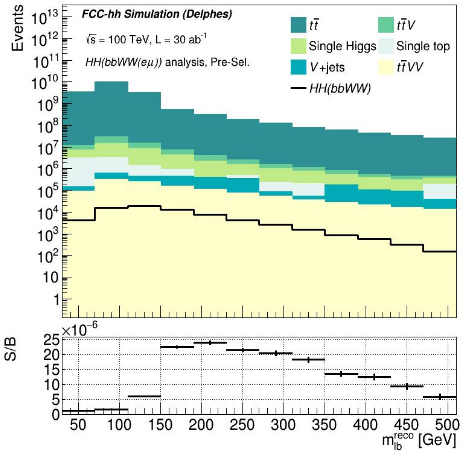
Signal signature

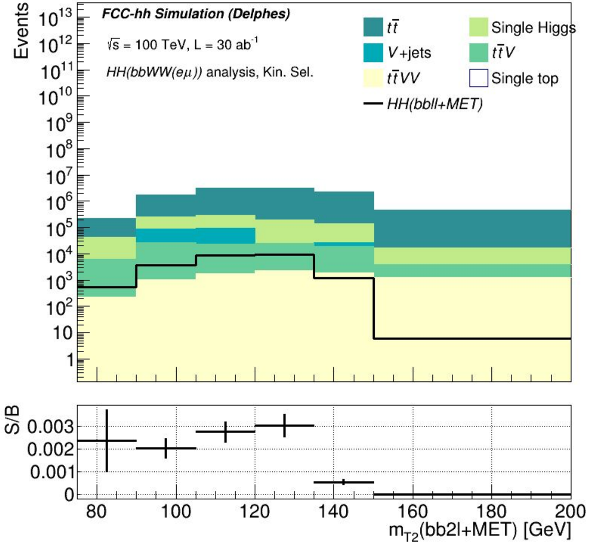


- Lepton pair + E_T^{Miss} + 2 b-jets
  - Leptons isolated from b-jets

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

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





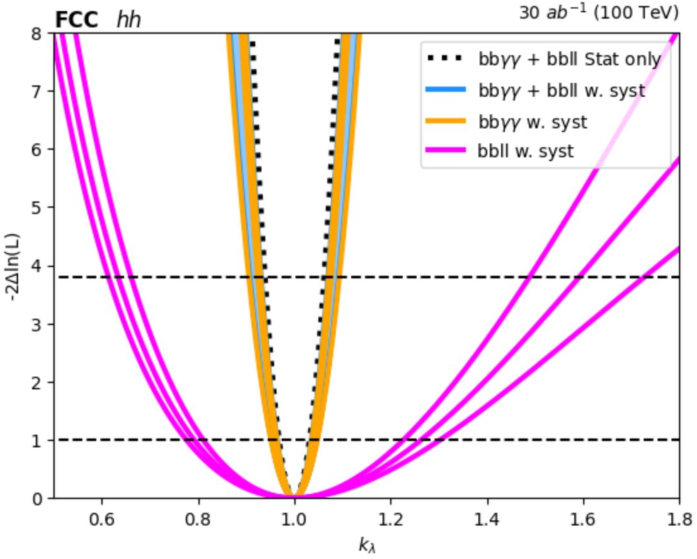
- <u>Stransverse mass</u> m_{T2} predicts invisible mass contribution
  - Capture the full HH decay
  - Fit to m_{T2} distribution in 5 categories depending on lepton flavours and if $Z(ll)$ decay

Combination: 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.	✗
$b\bar{b}\ell\ell + E_T^{miss}$ 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

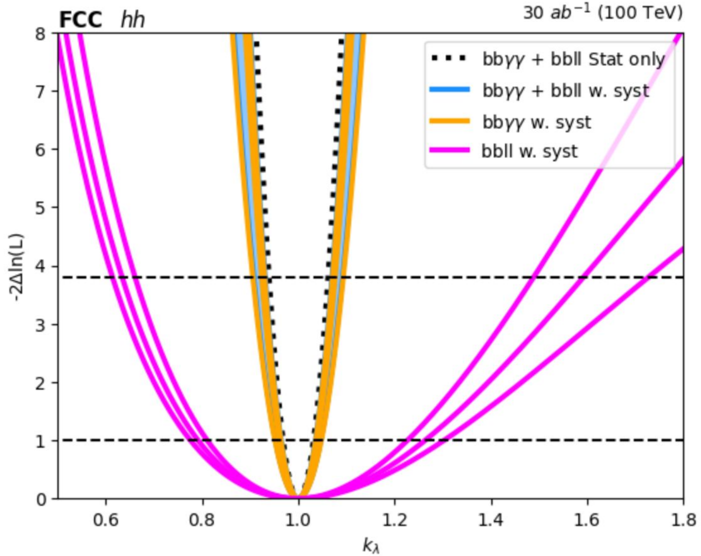
Combination: Self-coupling precision



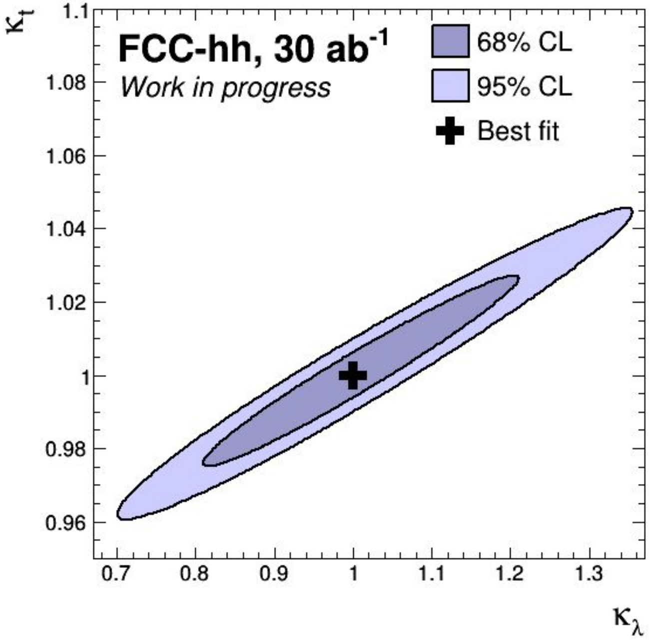
- Higgs self-coupling modifier κ_λ interpretation
  - Parametrized dependence of $\sigma(ggHH)$ on κ_λ
    - Inputs: κ_λ =1.0, 2.4, 3.0
  - All other couplings fixed to SM
  - NLO cross-sections at 100 TeV, with k-factor independent of κ_λ
  - No Higgs BR dependance on κ_λ and uncertainties or other additional theory uncertainties

	Stat. only	Syst. 1	Syst. 2	Syst. 3
$\delta\kappa_\lambda$ (68% CL)	3.2%	3.6%	3.9%	5.7%

Combination: Self-coupling precision



Combined, stat. only



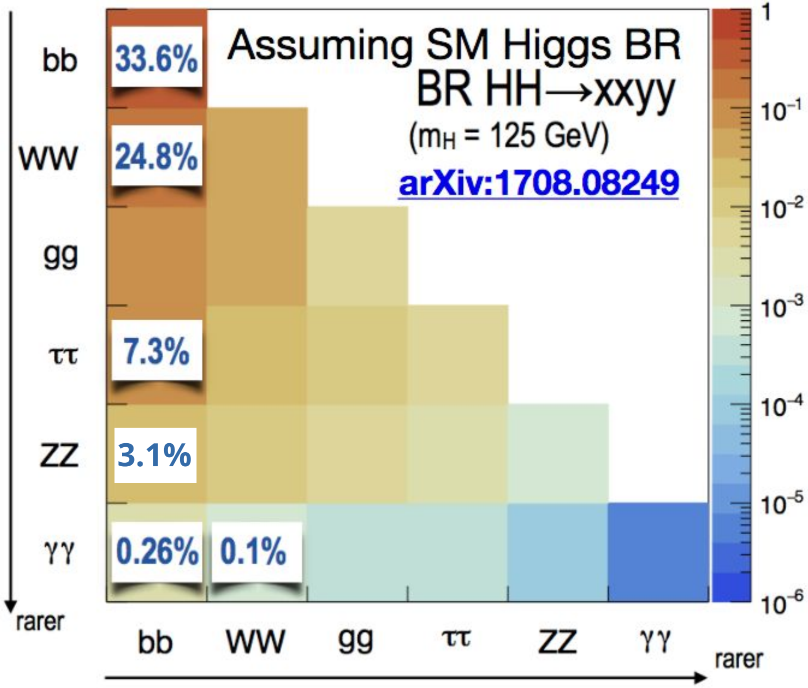
	Stat. only	Syst. 1	Syst. 2	Syst. 3
$\delta\kappa_\lambda$ (68% CL)	3.2%	3.6%	3.9%	5.7%

Summary

- Explored $\bar{b}b\gamma\gamma$ and $\bar{b}bll{+}E_T^{Miss}$ final states for di-Higgs measurements @ FCC-hh
    - Using updated (optimistic) Delphes scenario
    - $\bar{b}b\gamma\gamma$ analysis using multiple DNN
        - Dedicated $\bar{t}tH$ tagger + DNN against non-resonant & rest single Higgs
    - $\bar{b}bll{+}E_T^{Miss}$ new addition, fully cut-based
        - Sensitivity limited by large $\bar{t}t$ background
- Combination reaches 3-5% κ_λ precision, depending on syst. uncertainties
    - Driven by $bb\gamma\gamma$, $bbll{+}E_T^{Miss}$ reaches ~20% precision only
    - Preliminary results from restarting FCC-hh di-Higgs effort

Bonus

Di-Higgs final states



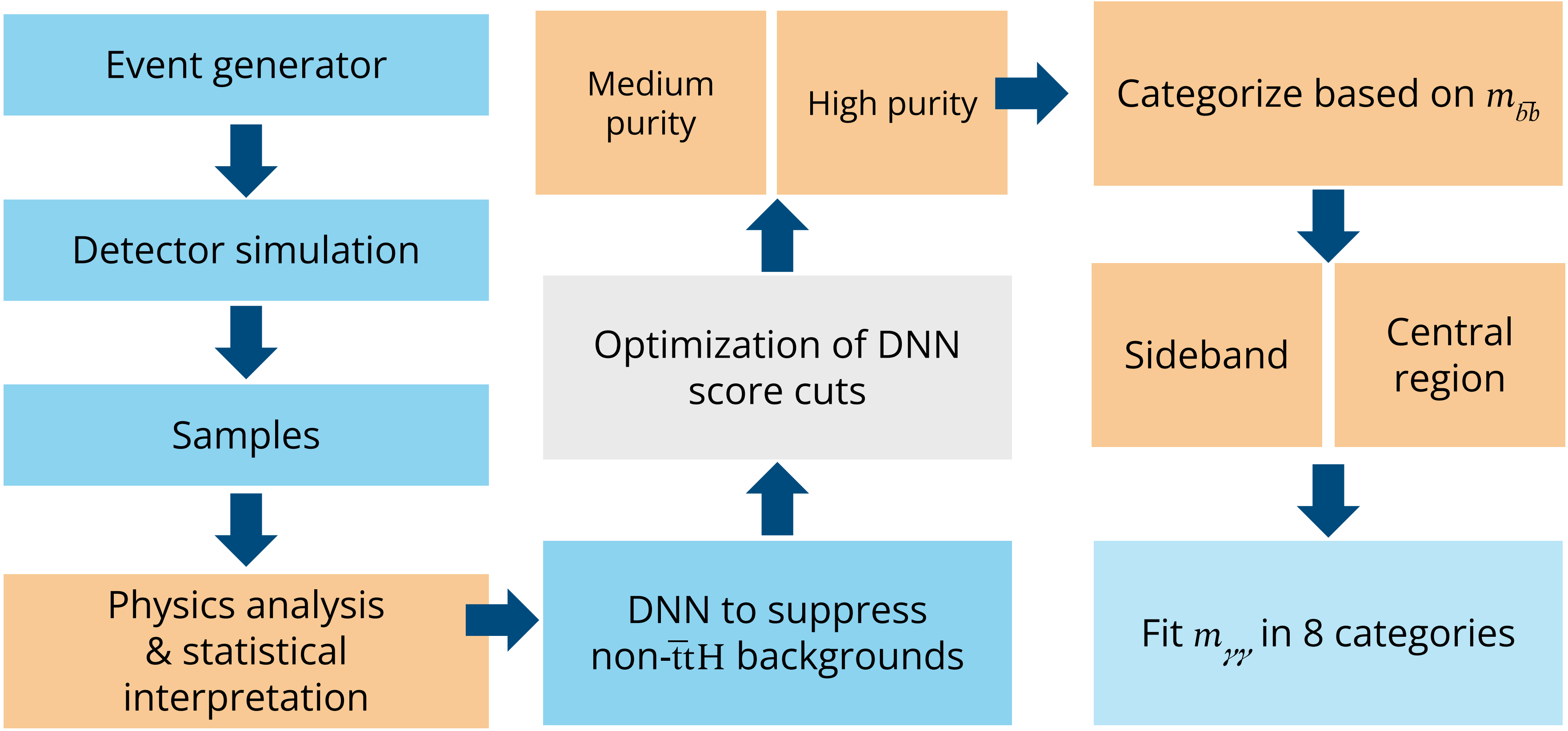
Parametrization of detector performance with Delphes

- Relevant efficiencies & resolutions for $\bar{b}b\gamma\gamma$ and $\bar{b}bll$+E_T^{miss}

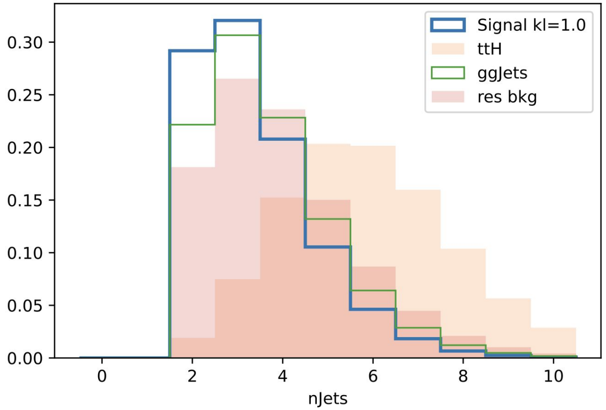
	Relative p resolution	Efficiency
Electrons	0.4-1%	80-99%
Muons	0.05-0.4%	94-99%
Photons	0.4-0.1%	80-95%

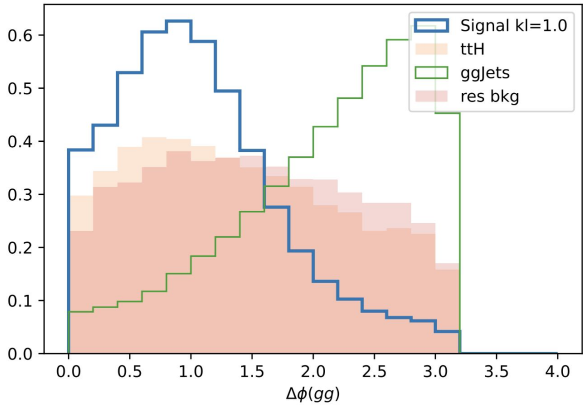
b-tagging efficiency: 80-90% *("medium" working point)*

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



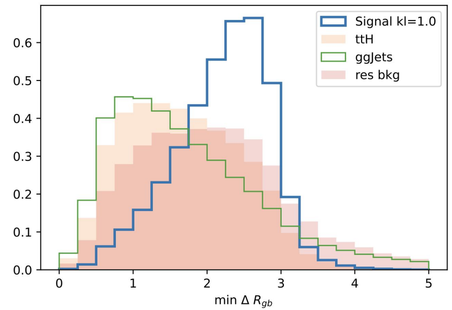
$\bar{b}b\gamma\gamma$ analysis: DNN input variables

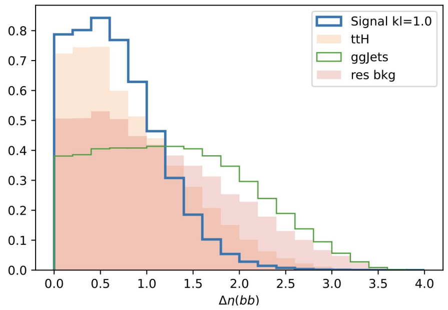


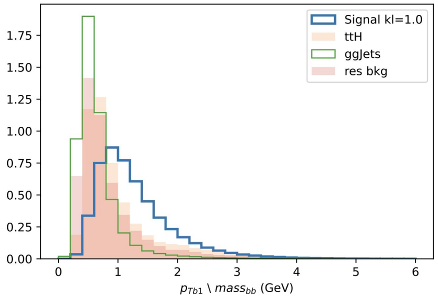


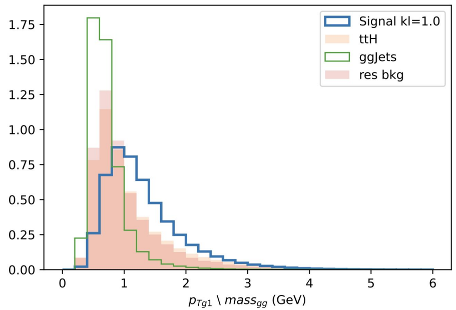
$\bar{b}b\gamma\gamma$ analysis: DNN input variables

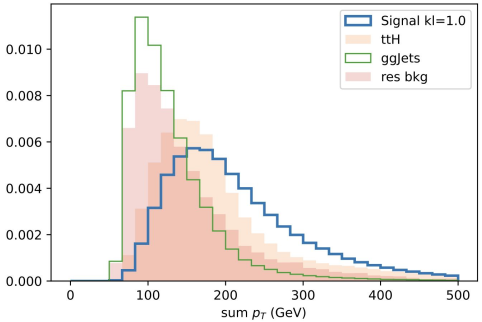
- The number of jets (with no b tag requirement)
- The b tag of the leading and subleading jet;
- $p_T(j)/m(jj)$ of the leading and subleading jet.
- $p_T(jj)/m(jj)$ of the dijet object;
- $p_T(\gamma)/m(\gamma\gamma)$ of the leading and subleading photon;
- $p_T(\gamma\gamma)/m(\gamma\gamma)$ of the diphoton object;
- The scalar sum of the jet p_T;
- The ΔR between the closest photon-jet pair;
- The ΔR between the other photon-jet pair;
- The $\Delta\phi$ and $\Delta\eta$ between the leading and subleading photon;
- The $\Delta\phi$ and $\Delta\eta$ between the leading and subleading jet;
- The $\Delta\phi$ and $\Delta\eta$ between the diphoton and the dijet object,
- The angle between the diphoton object and the beam axis in the dijet rest frame;
- The angle between the leading jet and the beam axis in the dijet rest frame;
- The angle between the leading photon and the beam axis in the diphoton rest frame;
- Number of leptons, i.e. muons and electrons
- p_T of muons and electrons

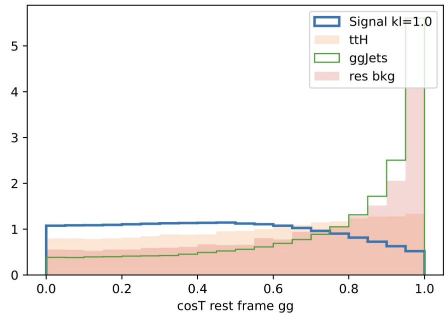




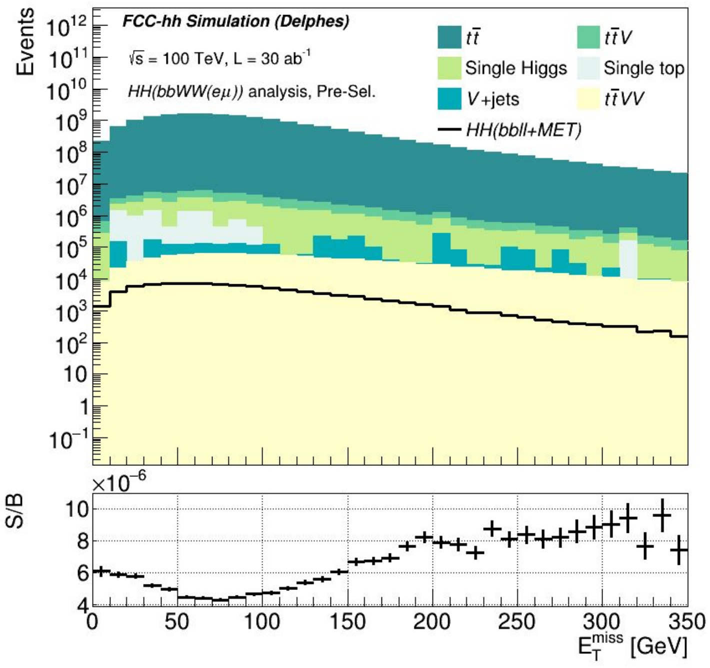








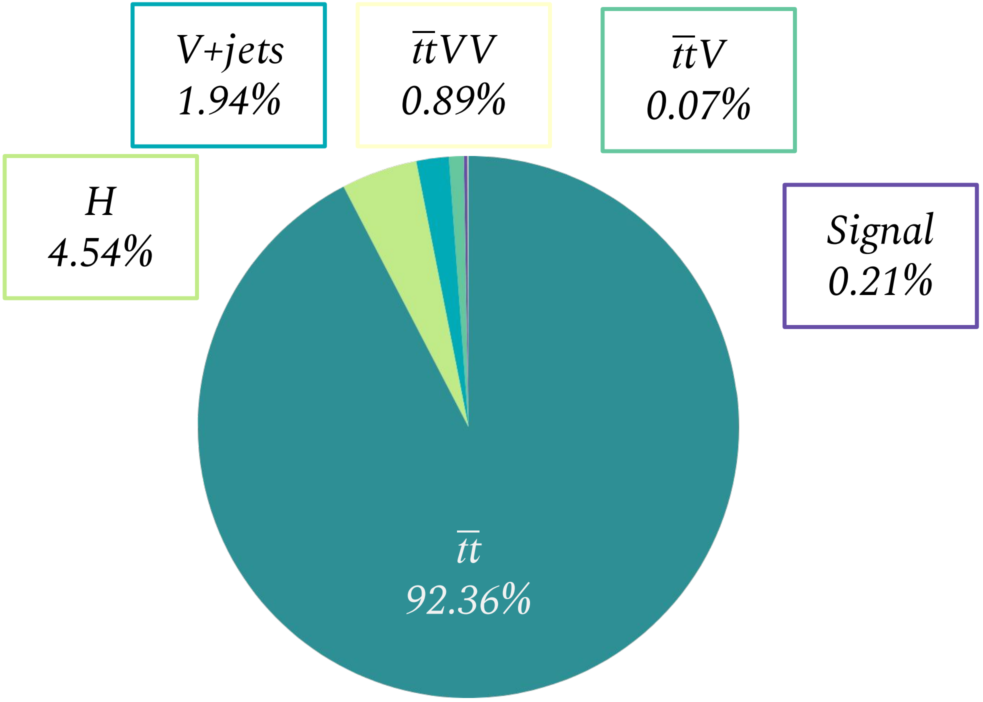
$b\bar{b}ll+E_T^{miss}$: Analysis strategy



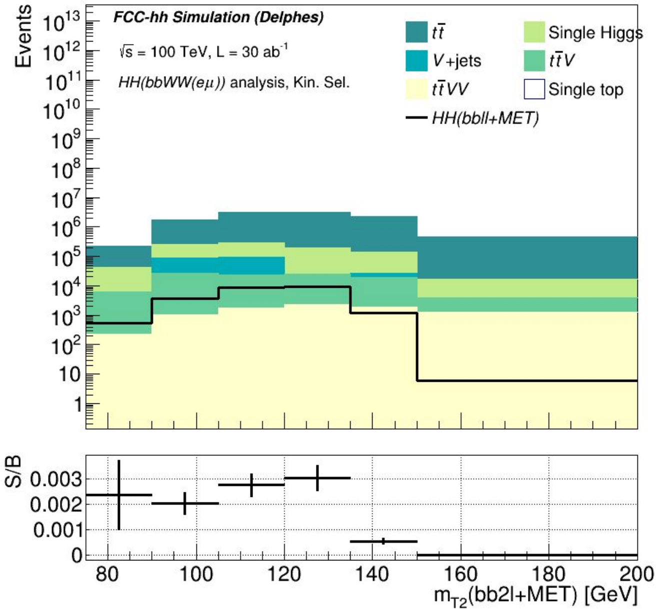
$e\mu$-category

- Signal signature: Lepton pair + E_T^{Miss} + 2 b-jets
  - Leptons isolated from b-jets (ΔR > 0.4)
- Backgrounds from:
  - $\bar{t}t$ and single top
  - $\bar{t}tV$
  - Single Higgs (ggF, VBF, $\bar{t}tH$, VH)
  - V+jets
  - $\bar{t}tVV$
- Categorization of events based on lepton flavours and whether (on-shell) Z(ll) decay is present

$b\bar{b}ll+E_T^{miss}$: Fit inputs



$S/\sqrt{B} \sim 7$



- <u>Stransverse mass</u> m_{T2} predicts invisible mass contribution
  - Capture the full HH decay

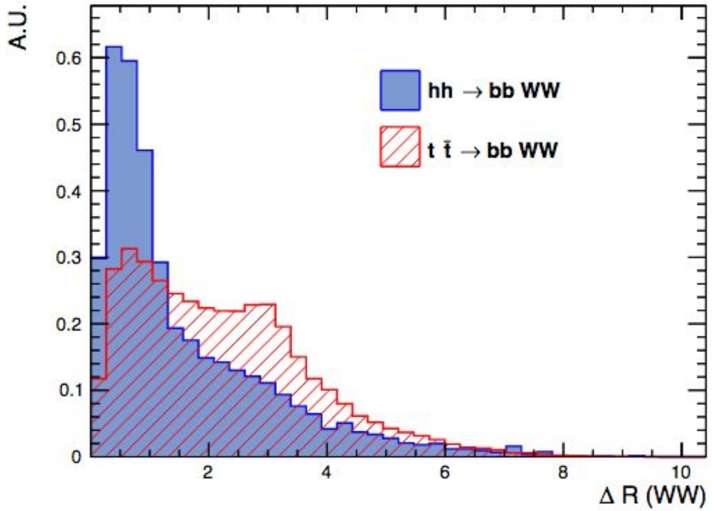
$b\bar{b}ll+E_T^{miss}$: Event selection & categorization

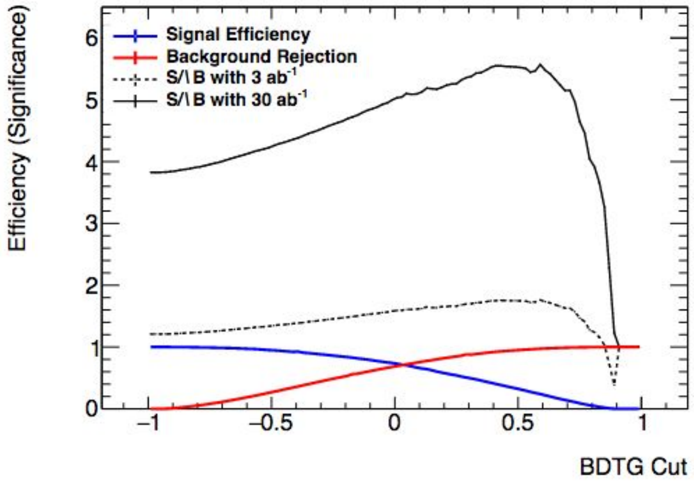
	Analysis category		
	DFOS	SFOS, no Z-peak	SFOS, on Z-peak
Main signals	$b\bar{b}WW^*$, $b\bar{b}\tau\tau$	$b\bar{b}WW^*$, $b\bar{b}\tau\tau$	$b\bar{b}ZZ^*$, $b\bar{b}\tau\tau$
Selection variable		Criterion	
Lepton pair	$e\mu$	ee or $\mu\mu$	ee or $\mu\mu$
Number of b-jets		≥ 2	
m_{bb}		85 - 105 GeV	
ΔR_{bb}		< 2	
$\Delta R_{\ell\ell}$		< 1.8	
H_{T2}^{ratio}		> 0.8	
m_{lb}^{reco}		> 150 GeV	
$\Delta\phi(\ell\ell, E_T^{\text{miss}})$	< 2		< 1.2
$m_{\ell\ell}$	10 - 80 GeV		81 - 101 GeV
$\Delta\phi(\ell\ell, E_T^{\text{miss}})$-categories	< 1.2 ("low") and $1.2 - 2.0$ ("high")		-

Table 3.25.: Overview of the harmonized event selection and categorization.

CERN-ACC-2018-0045

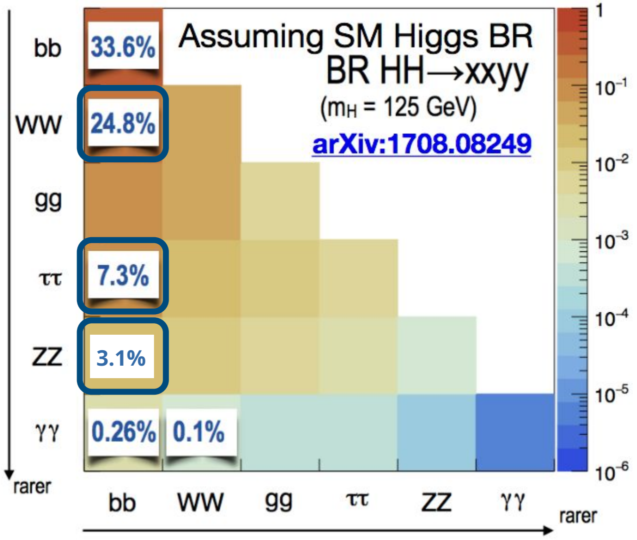
Previous projections for $\bar{b}bWW$ @ FCC-hh





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

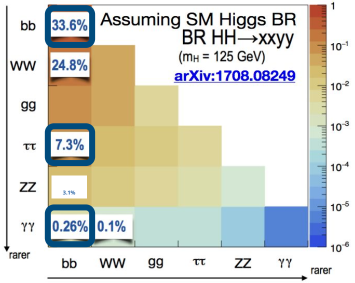
$\bar{b}bll + E_T^{miss}$: signals



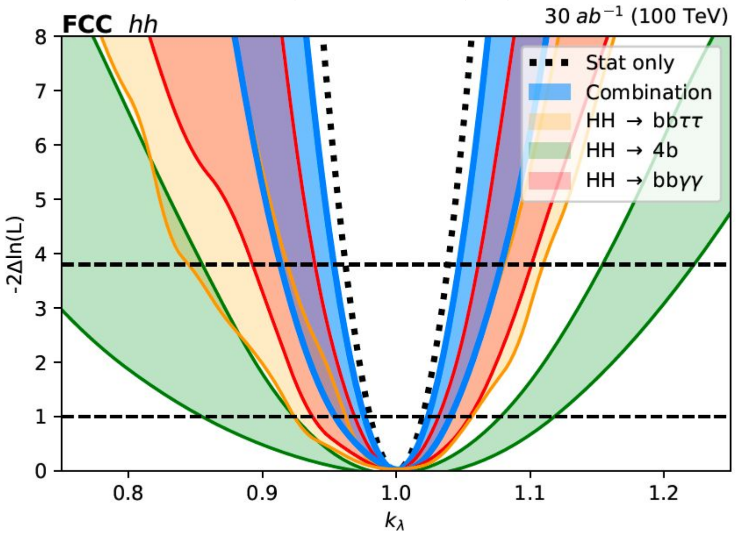
Signal	***BR(HH→X)***	**Advantage**
$bbWW(l\nu l\nu)$	2.24%	Largest BR in $bbll+E_T^{Miss}$ final state Established for HH-studies @ LHC
$bb\tau\tau(l\nu\nu l\nu\nu)$	0.88%	$e\mu$ channel established for single Higgs studies @ LHC
$bbZZ(ll\nu\nu)$	0.12%	Reconstruct $Z(ll)$ decay

- Sum the contribution from all decay modes
  - Do not consider Higgs BR uncertainties
  - Three categories depending on lepton flavours, and if there is a $Z(ll)$ resonance

Higgs self-coupling projections for FCC-hh



A. Taliercio et. al.

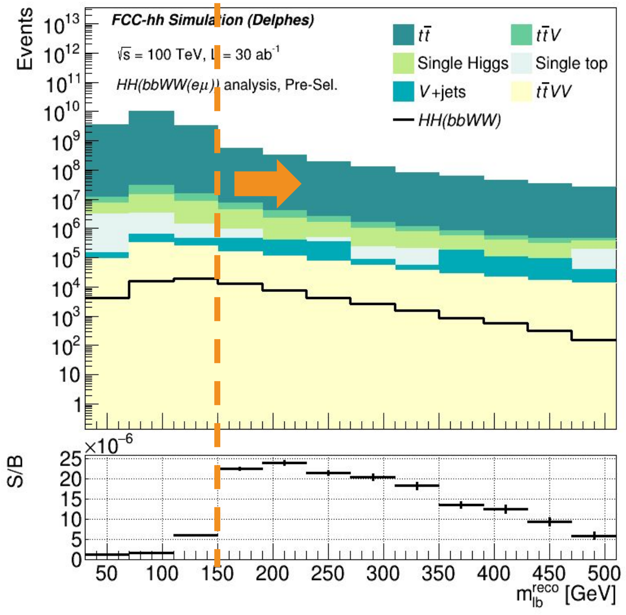


arXiv:2203.08042

	Stat. only
$\delta\kappa_\lambda$ (68% CL)	2.0%

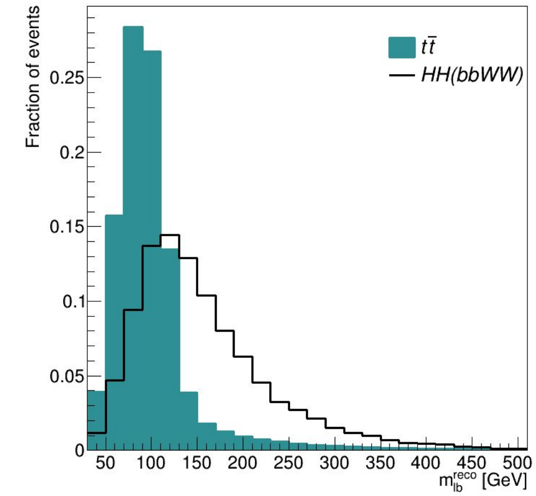
- Recently published update on *bbyy*, *bbττ*(*hh+lh*), *4b* and their combination
- Analysis improvements from using Deep Neural Networks
- Simplified (more optimistic) Delphes and systematics scenarios, with explicit pile-up overlay

$b\bar{b}ll+E_T^{miss}$: Event kinematics & selection



M_{lb}^{reco} specifically targeted to reduce $\overline{t}t$

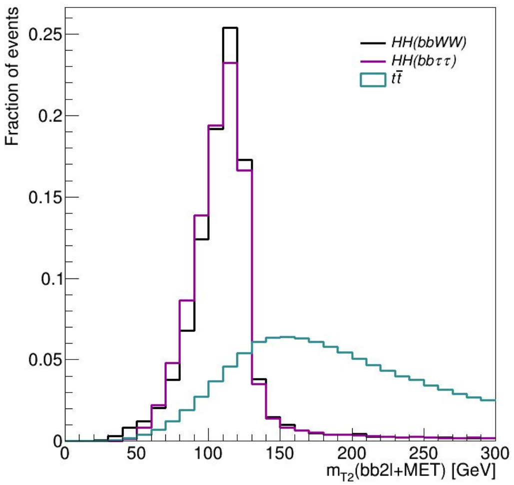
- Defined for top-quark mass measurements in dileptonic channel



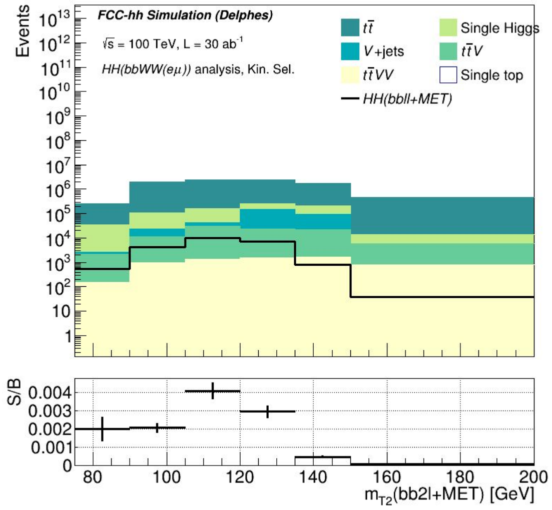
$$m_{lb}^{\mathrm{reco}} = \min\left(\frac{m_{l_1b_1}+m_{l_2b_2}}{2}, \frac{m_{l_2b_1}+m_{l_1b_2}}{2}\right)$$

$\bar{b}bll{+}E_T^{miss}$: Stransverse mass

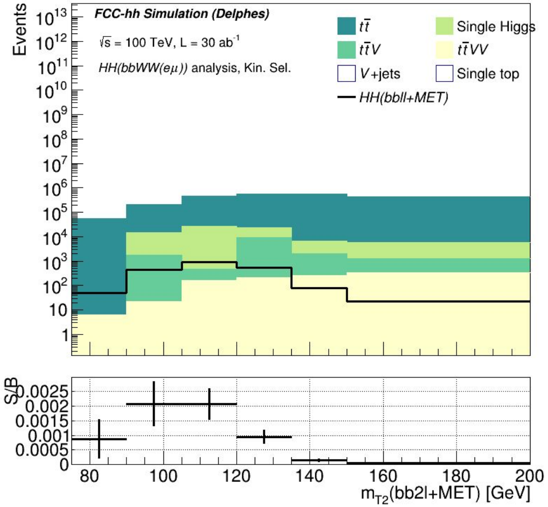
DFOS, pre-selection



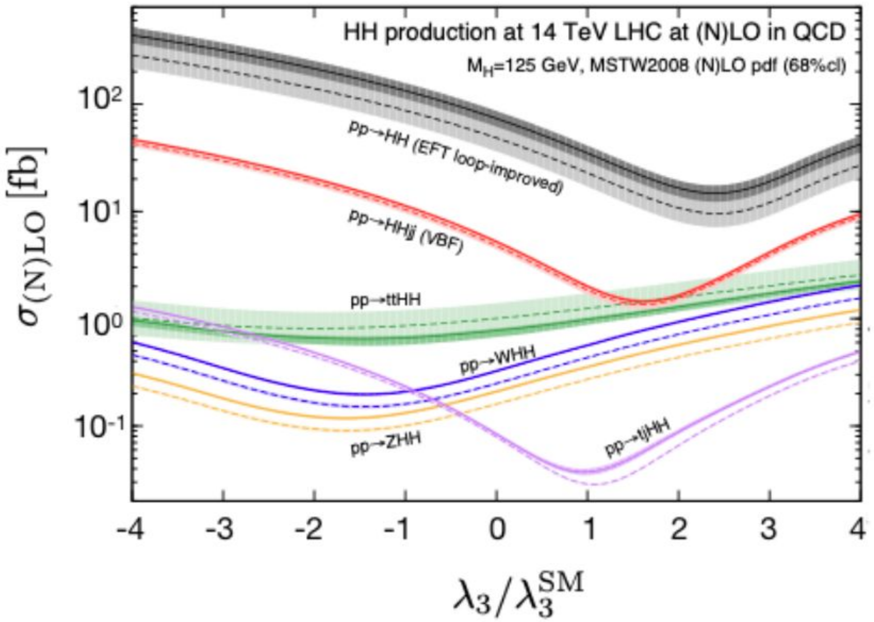
DFOS, low dPhi

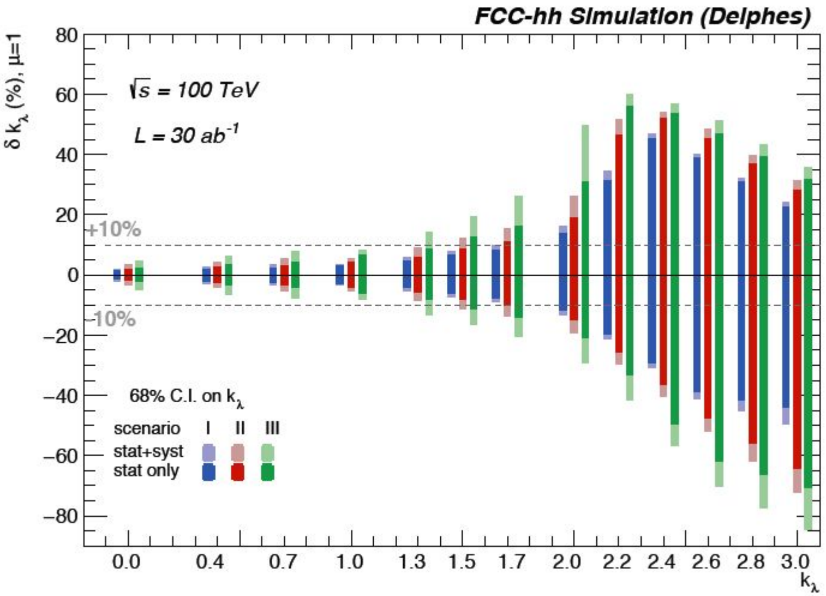


DFOS, high dPhi



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

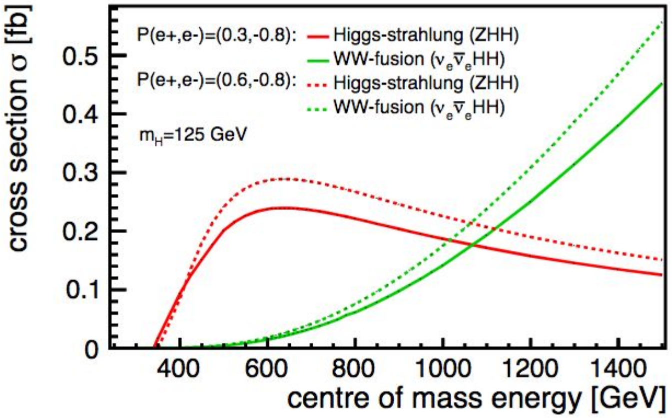


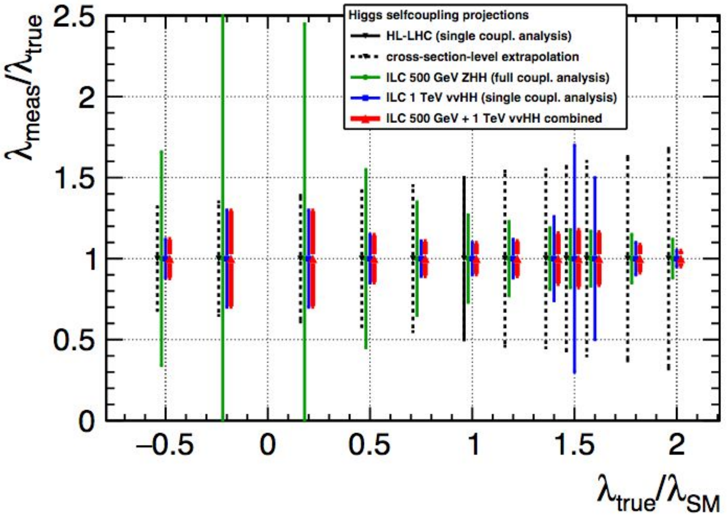


arXiv:2004.03505v2

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

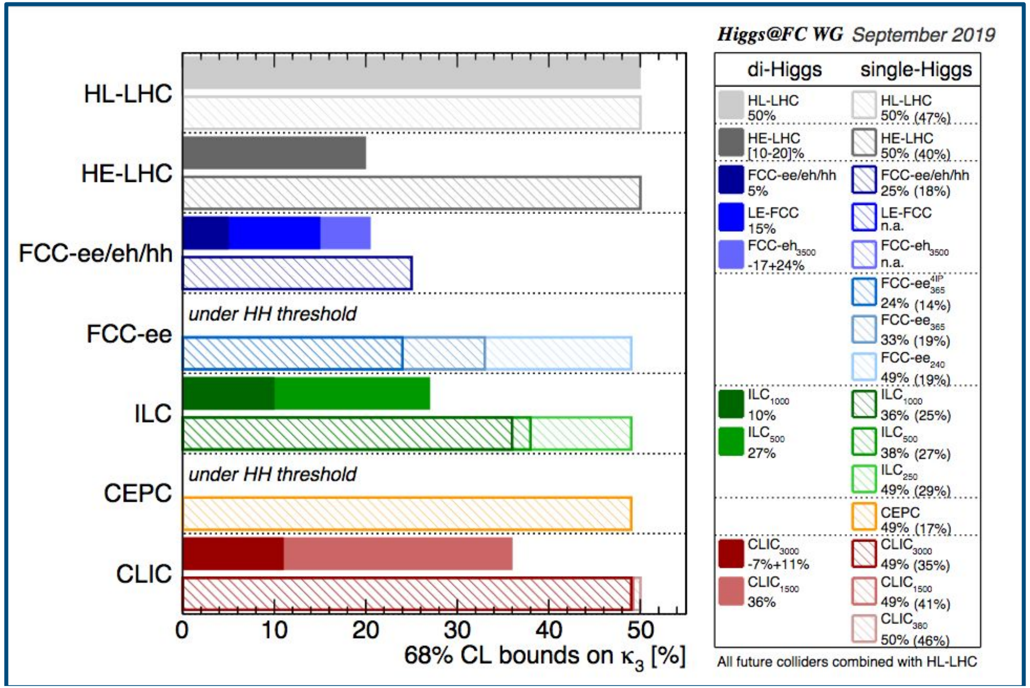
- Studied dominant channels $4b$ and $bbWW$
- Advantage of ee-collider: ZHH cross-section increases with κ_λ, hence better constraints at values $\kappa_\lambda > 1$ than pp-colliders

Higgs self-coupling @ muon collider

- Only $4b$

	3 TeV μ-coll. L≈ 1 ab^{-1}	10 TeV μ-coll. L= 10 ab^{-1}	14 TeV μ-coll. L≈ 20 ab^{-1}	30 TeV μ-coll. L= 90 ab^{-1}
		68% prob. interval		
$\delta\kappa_\lambda$	[-0.27,0.35] ∪ [0.85,0.94] →[-0.15,0.16] (2× L)	[-0.035, 0.037]	[-0.024, 0.025]	[-0.011, 0.012]

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