Higgs Precision at FCC-hh

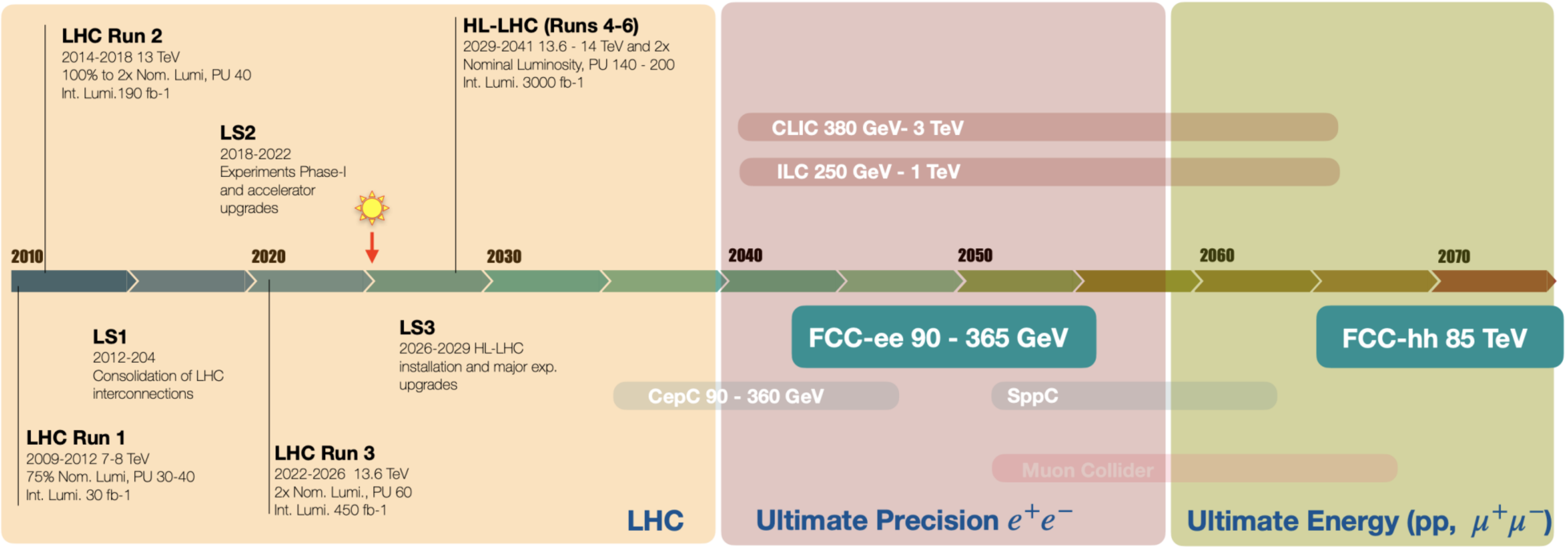
P. Mastrapasqua
UCLouvain, Belgium

11th July, EPS-HEP 2025

The FCC integrated program

- A coherent, long-term research infrastructure to address the most pressing questions in Particle Physics
- A ~50 years project: 15y of lepton collider stage (FCC-ee) + 10y transition + 25y of hadron collider (FCC-hh)

Advancing the Legacy of LHC and HL-LHC at CERN with the FCC program



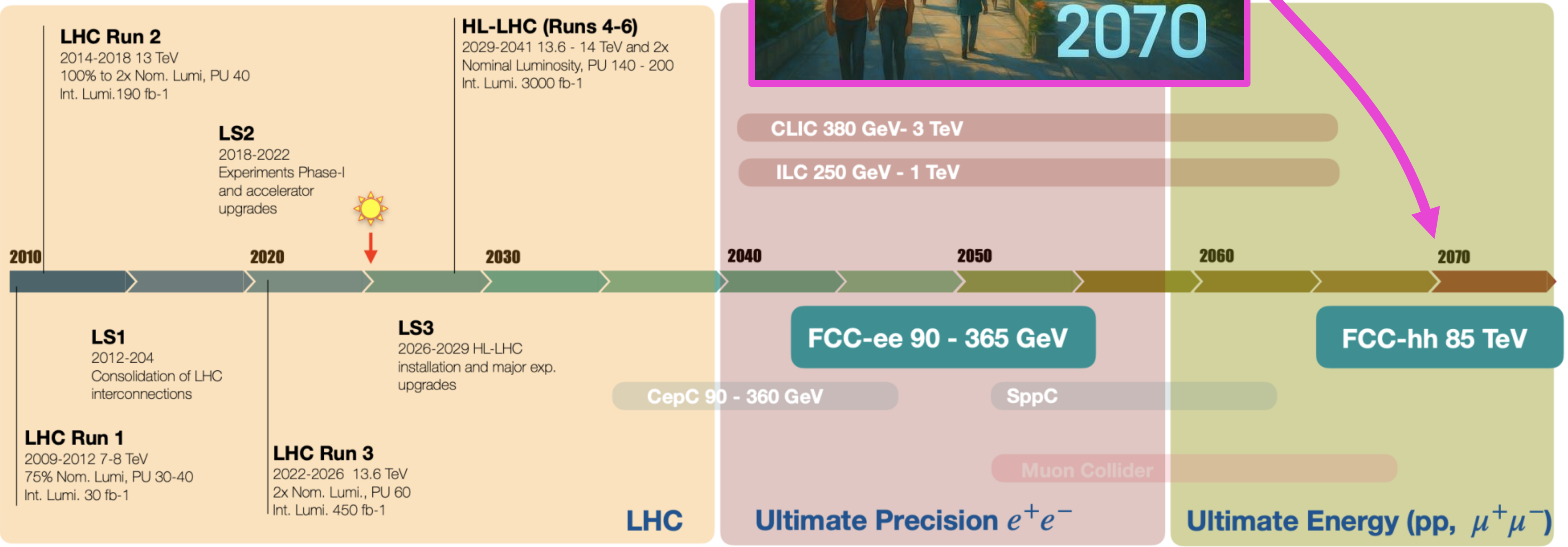
From M. Kado's Talk at FCC Week

The FCC integrated program

How physics program will look like in 50y from now?

TRIP TO THE FUTURE

Advancing the Legacy of LHC and HL-LHC at CERN with the FCC program



From M. Kado’s Talk at FCC Week

The FCC-hh stage: running scenarios

- FCC-hh CDR baseline plan was a total of **30 ab^{-1} of pp-collision data** @ 100 TeV
- Alternative FCC-hh running scenarios are considered given several potential limitations: dipole magnets, synchrotron radiation and extreme levels of pile-up
- The new baseline in the Feasibility Study is @ **84 TeV**, with the **same target luminosity**

ESPPU input #247

	F12*	F14	F17	F20	*HL-LHC*
CM energy (TeV)	72	84	102	120	*14*
Dipole field (T)	12	14	17	20	*8.3*
Init. pile-up	580 - 2820	590	732	141	*135*
Lumi/year (fb^{-1})	950 - 2000	920	920	370	*240*

**F12 includes 3 different scenarios for high, low lumi & PU*

FCC-hh projection study workflow

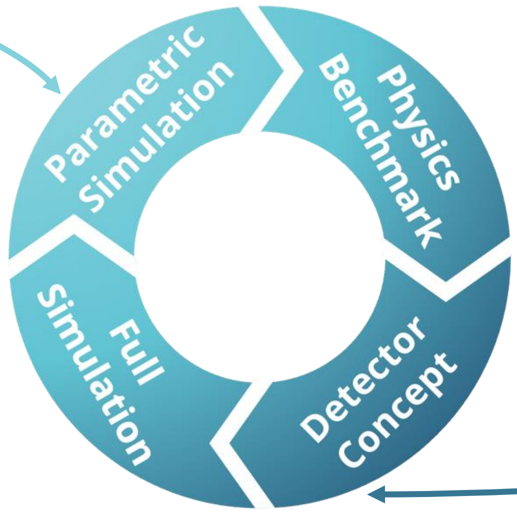
DELPHES fast simulation

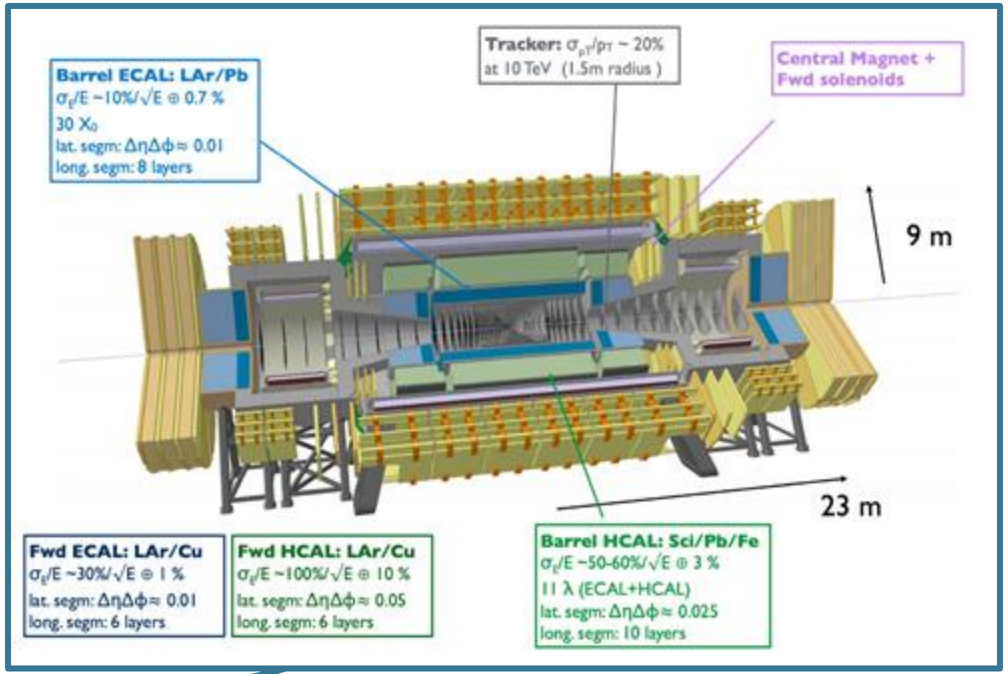
Efficiencies & resolutions as functions of p_T and η

- [Official FCC-hh scenarios]
- Common software stack: [key4hep]

CDS note

10.17181/71pvXA5-tvf87





Reference detector design from CDR

CERN-ACC-2018-0058

Higgs Physics at FCC-hh

- Several **physics benchmarks** have been studied to extend and update previous results (with the new baseline)
- Goal: **reinforce the physics case for the FCC-hh**
- Results have been submitted for the **2026 European Strategy for Particle Physics Update** (ESPPU)

[Link]

Prospects for physics at FCC-hh

Editors:
M. Mangano [*1], M. Selvaggi [*2], B. Stapf [*2], A. Taliercio [*4], S. Williams [*5]

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Abstract

This submission reviews and updates the extensive work done over the years to explore and quantify the physics potential of FCC-hh, the hadron collider component of the integrated Future Circular Collider facility. The document introduces the context of these studies, as it has developed over the years, and offers an update of key targets of FCC-hh such as the precision Higgs studies and the discovery reach at the highest mass scales. New analyses added or improved with respect to the CDR, are introduced. A general assessment is also given of the impact of the new energy/luminosity baseline for the accelerator, and of alternative configurations, on the physics results.

April 10, 2025

Contribution to the European Strategy for Particle Physics Update 2025-2026

Higgs Physics at FCC-hh

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- Goal: **reinforce the physics case for the FCC-hh**
- Results have been submitted for the **2026 European Strategy for Particle Physics Update** (ESPPU)
- In this talk:
  1) Higgs self-coupling with Higgs pair production(HH)
     - $HH \rightarrow bb\gamma\gamma$ / $bb\tau\tau$
  2) Top Yukawa coupling
     - $ttH \rightarrow \gamma\gamma$
  3) Higgs rare decays
     - $H \rightarrow \mu\mu$

[Link]

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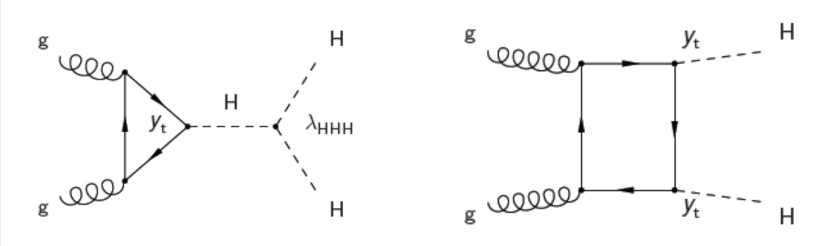
Higgs self-coupling with HH searches

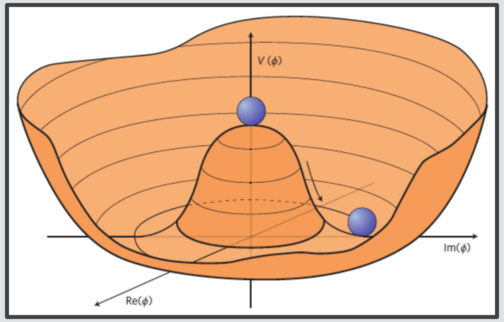
$HH \rightarrow bb\gamma\gamma \ / \ bb\tau\tau$

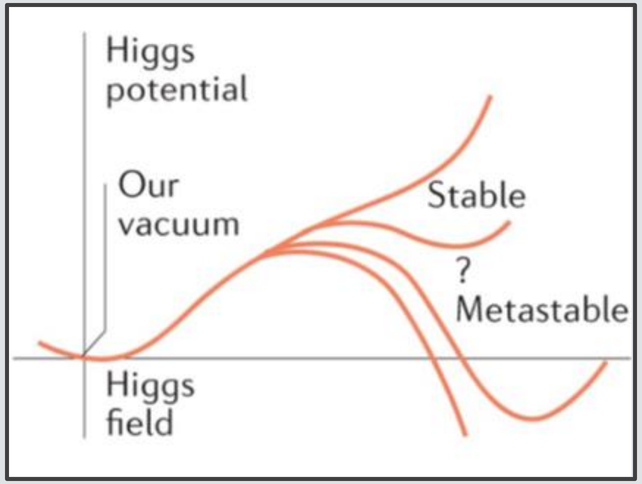
Motivation for HH searches

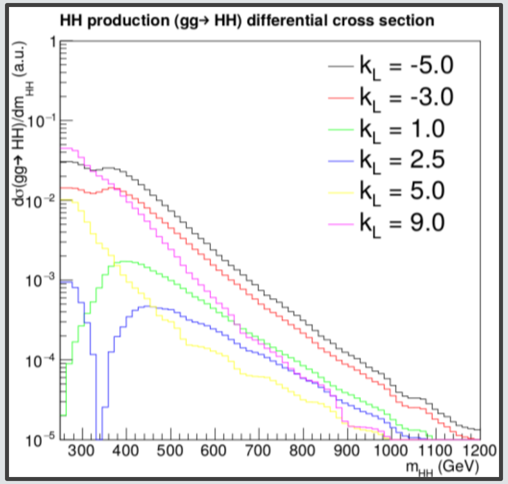
- HH production is sensitive to the Higgs trilinear coupling λ
  - Direct measure of the λ parameter
  - Test of the Electroweak Symmetry Breaking (EWSB) mechanism

LO SM Feynman diagrams









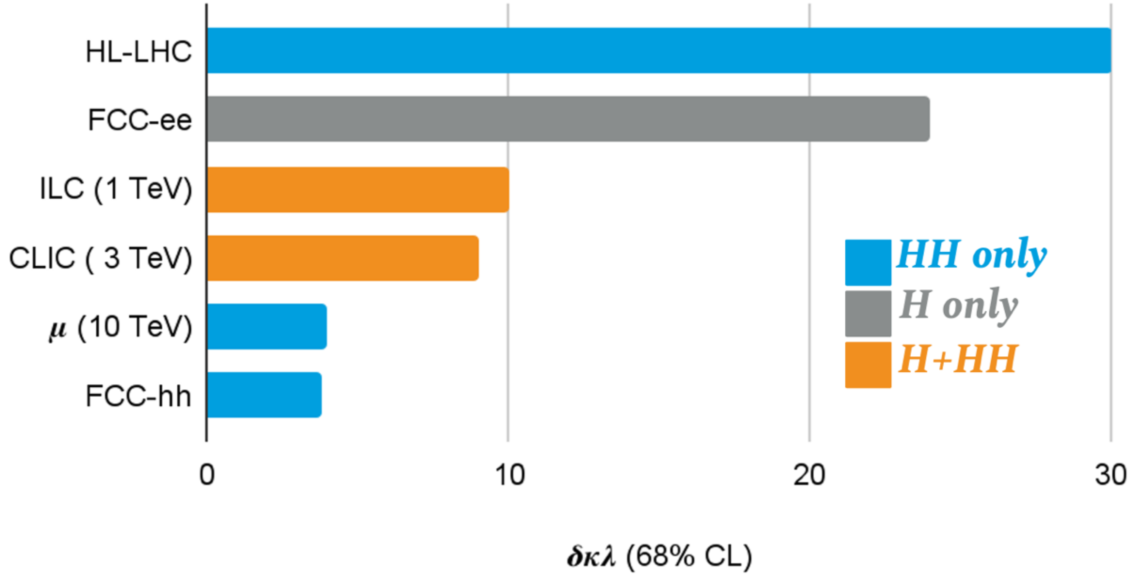
- HH production is also a probe for BSM theories as they predict sizeable effects on λ
  - Deviations parametrized in terms of $\kappa_\lambda = \lambda/\lambda_{SM}$

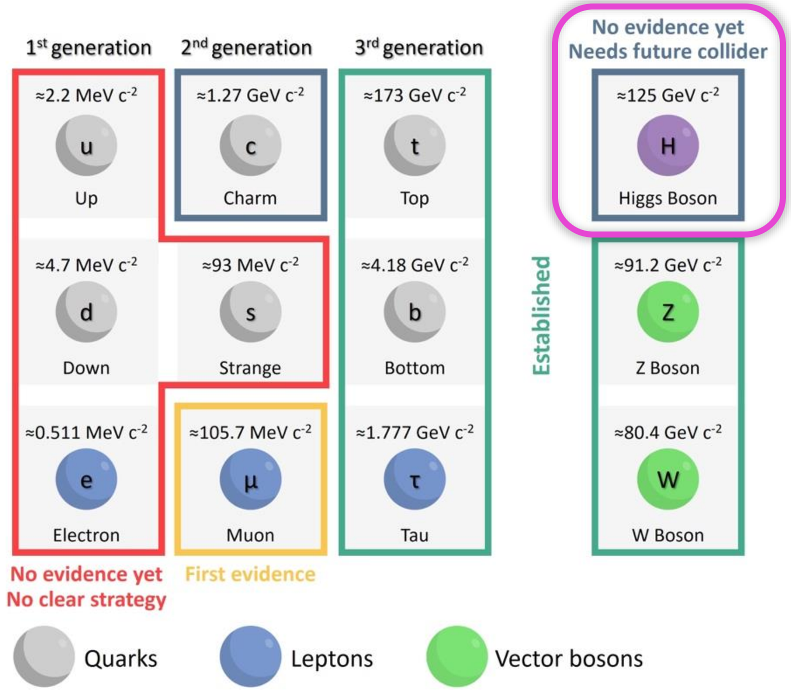
Deep fundamental questions

- What is the order of the EW phase transition?
- What is the fate of the Universe? Is it stable?

Higgs self-coupling at Future Colliders

- Extremely small cross section: σ(ggHH) ~ 1/1000 σ(ggH)
- We will reach a precision measurement of the Higgs self-coupling only with Future Colliders
- FCC-hh offers the best prospects for **%-level measurement from HH searches**





$HH \rightarrow bb\gamma\gamma$: analysis strategy

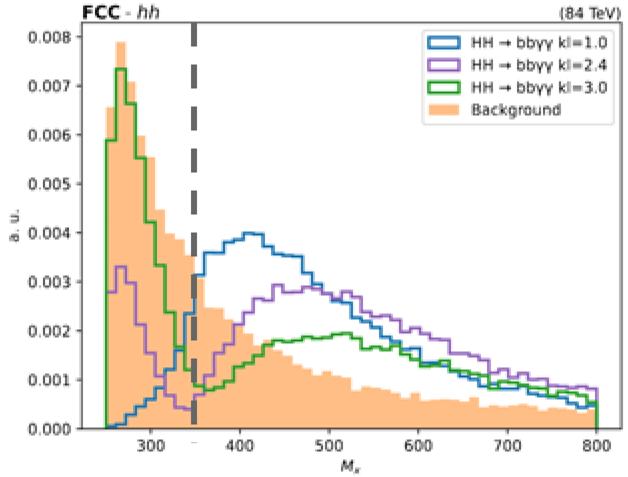
CDS note
[10.17181/w6928-gr929](https://doi.org/10.17181/w6928-gr929)

Pre-selected events

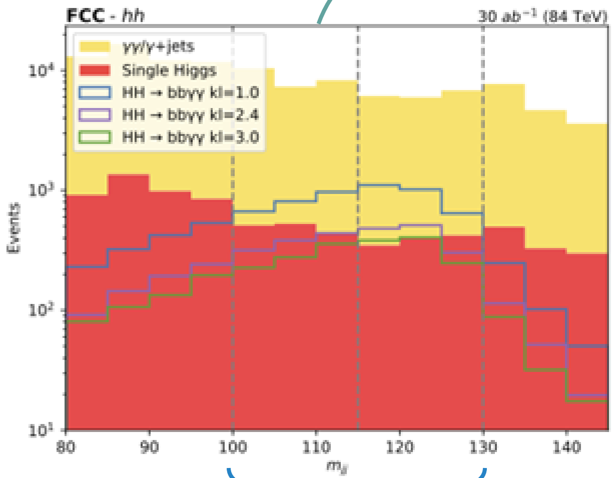
↓

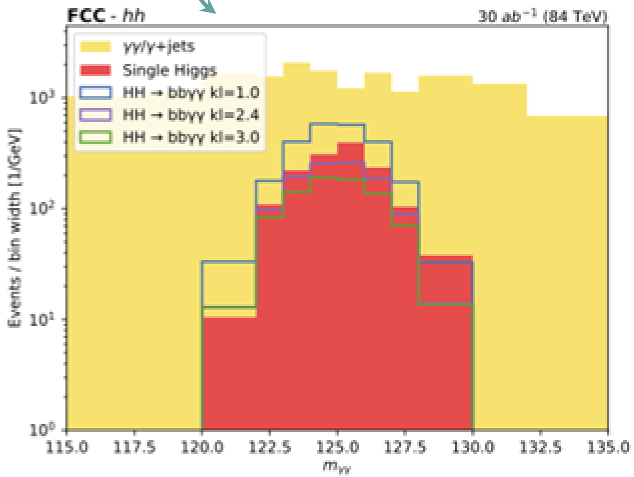
Categorize in m_x

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



Example bin





Most sensitive bins

DNN to suppress backgrounds → Bins in m_{bb} → Fit $m_{\gamma\gamma}$

$HH \rightarrow bb\gamma\gamma$: results

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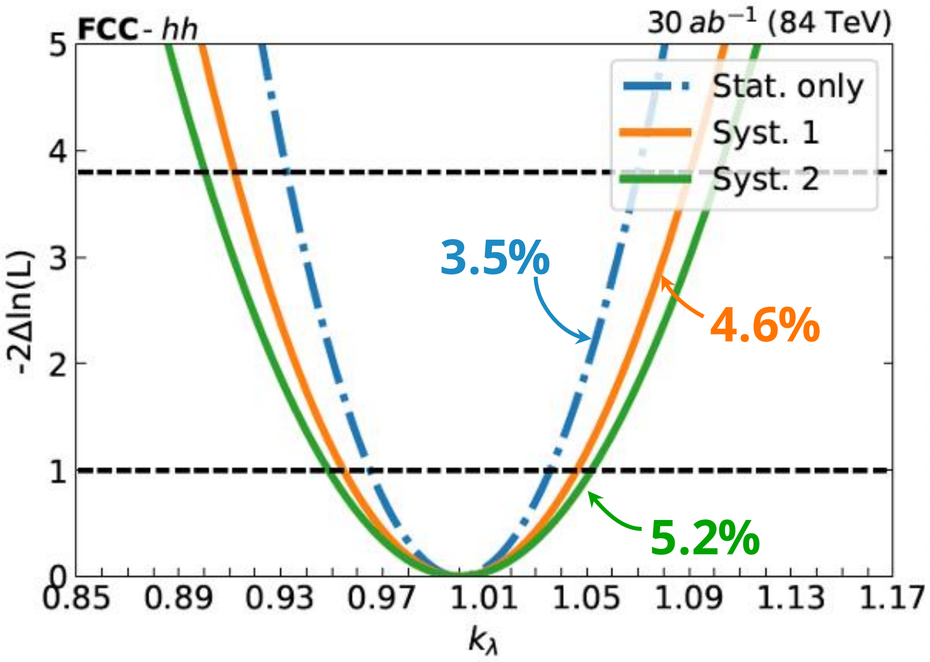
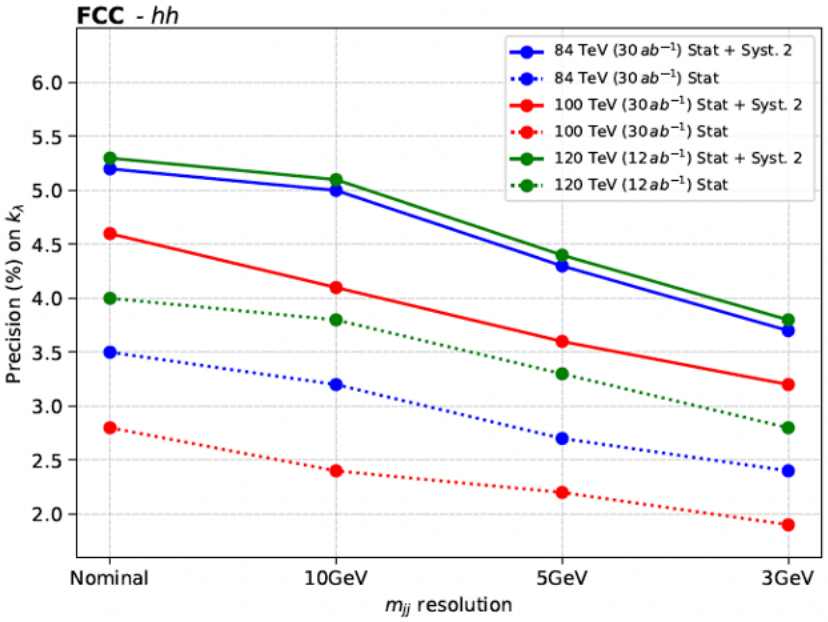
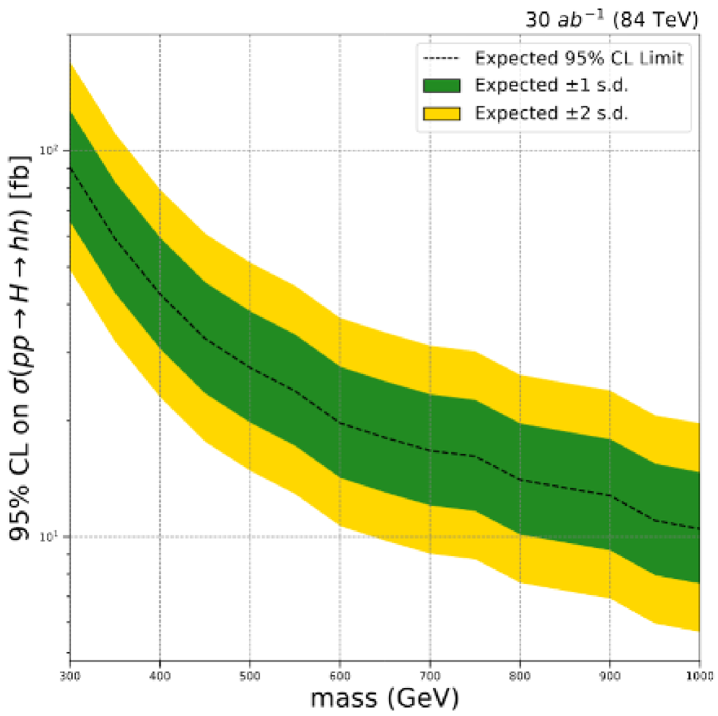




- Reach **3.5% *(5.2%)* stat. *(stat.+syst.)* precision on $\boldsymbol{\kappa_\lambda}$** with $bb\gamma\gamma$ channel alone (only ggHH)!
- Conservative assumptions on non-resonant background
- Improvements of detector & reconstruction techniques such as e.g. $m_{b\bar{b}}$ regression have potential to increase precision significantly

$HH \rightarrow bb\gamma\gamma$ bonus: resonant version

Preliminary



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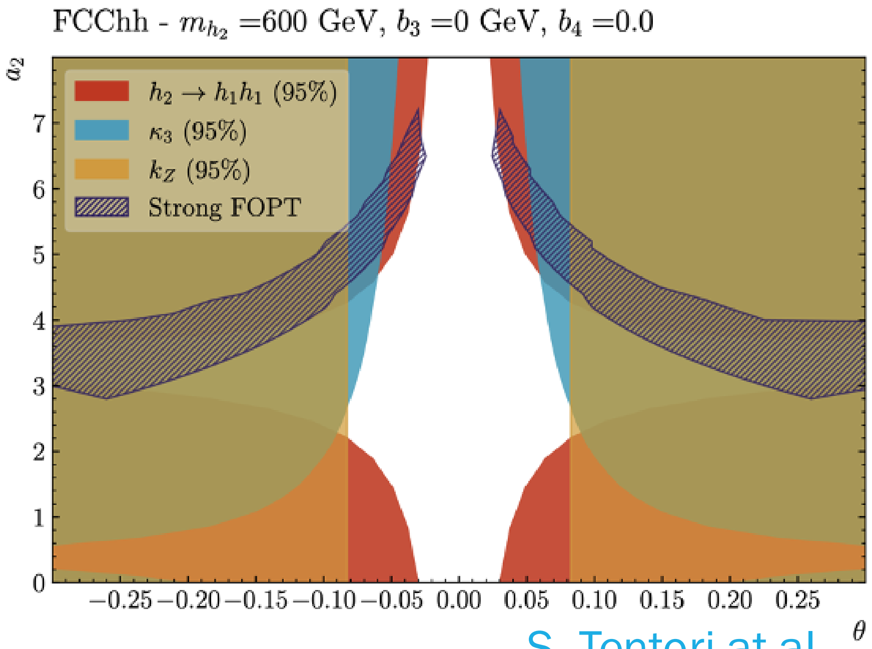
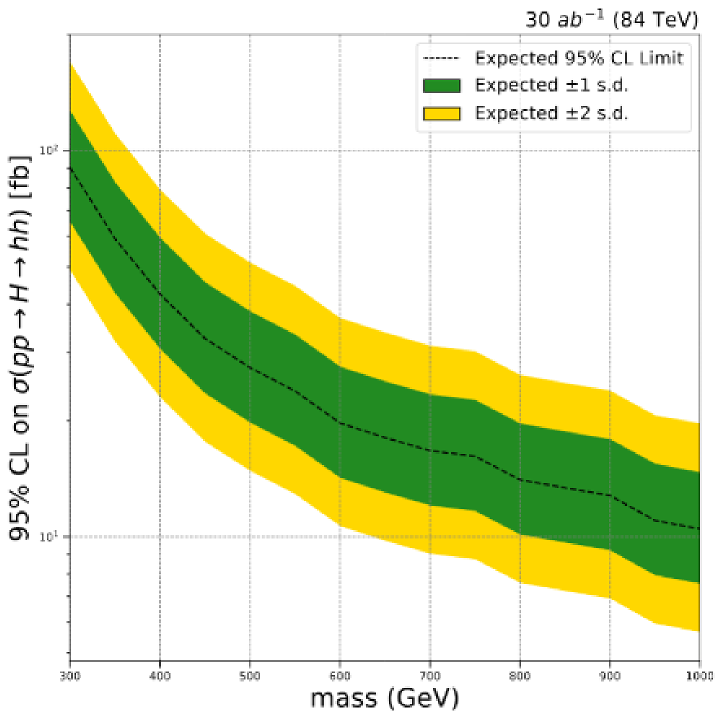


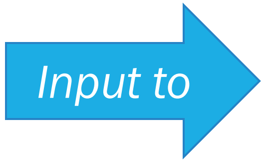
S. Tentori at al.

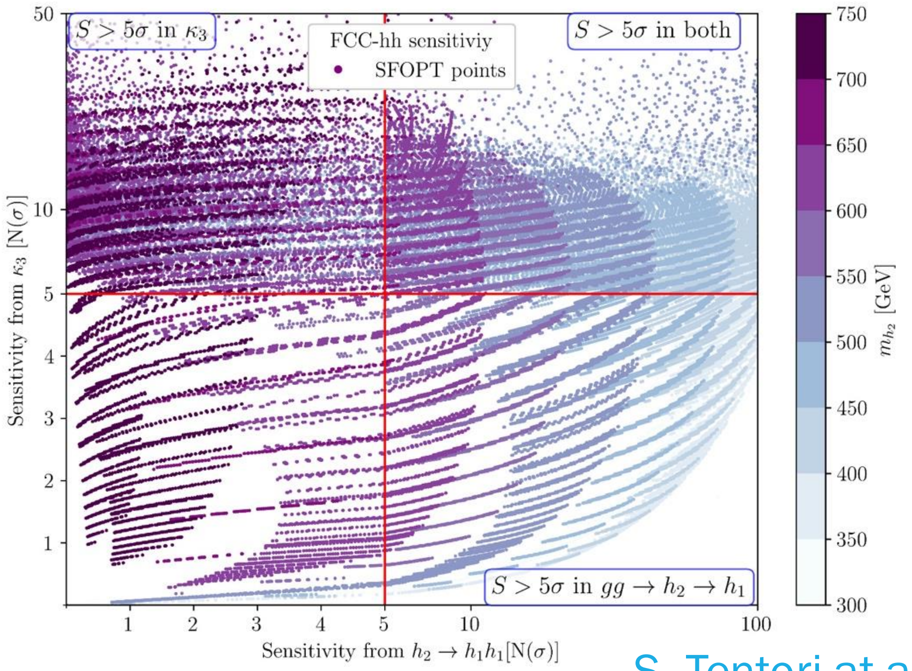
- Use same strategy as non-resonant analysis to deliver limits on a new resonance decaying to HH
- Results can be directly compared to HL-LHC ones
- Singlet model interpretation shows FCC-hh exclusion (or discovery!) power

$HH \to bb\gamma\gamma$ bonus: resonant version

Preliminary







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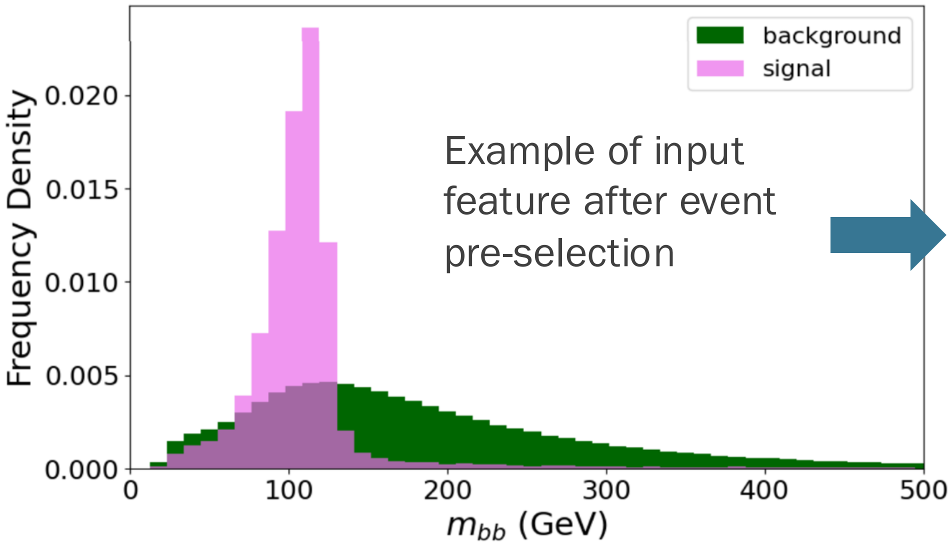
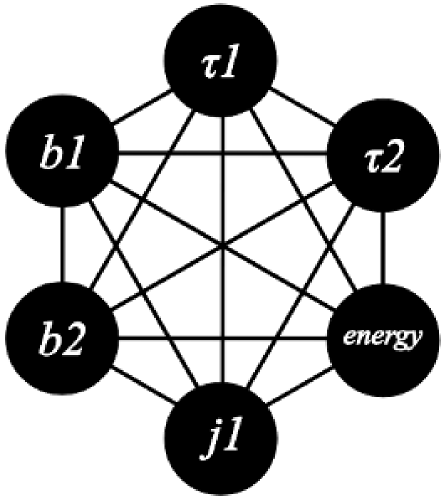
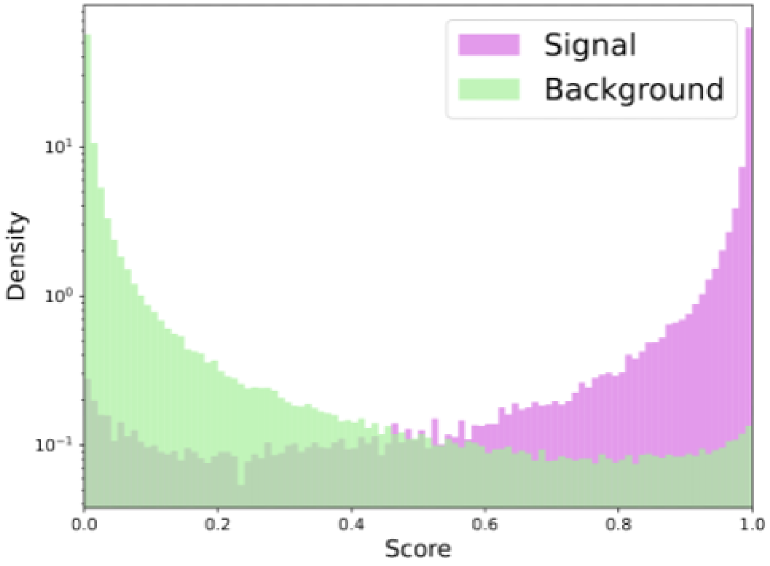
$HH \rightarrow bb\tau\tau$: analysis strategy

CDS note
[10.17181/8cdq9-dj340](https://doi.org/10.17181/8cdq9-dj340)







- Focus on channels with at least on hadronic τ decay (fully leptonic included in $bb\ell\ell + E_T^{miss}$)
- Graph Neural Network (GNN) trained in the two channels: $\tau_{lep}\tau_{had}$ and $\tau_{had}\tau_{had}$
- Working on extracting precision with fit on GNN score in bins of HH invariant mass
- ~3% precision on signal strength → Competitive with $bb\gamma\gamma$ channel – combination planned

CDS note
[10.17181/ebp10-yeg26](https://doi.org/10.17181/ebp10-yeg26)

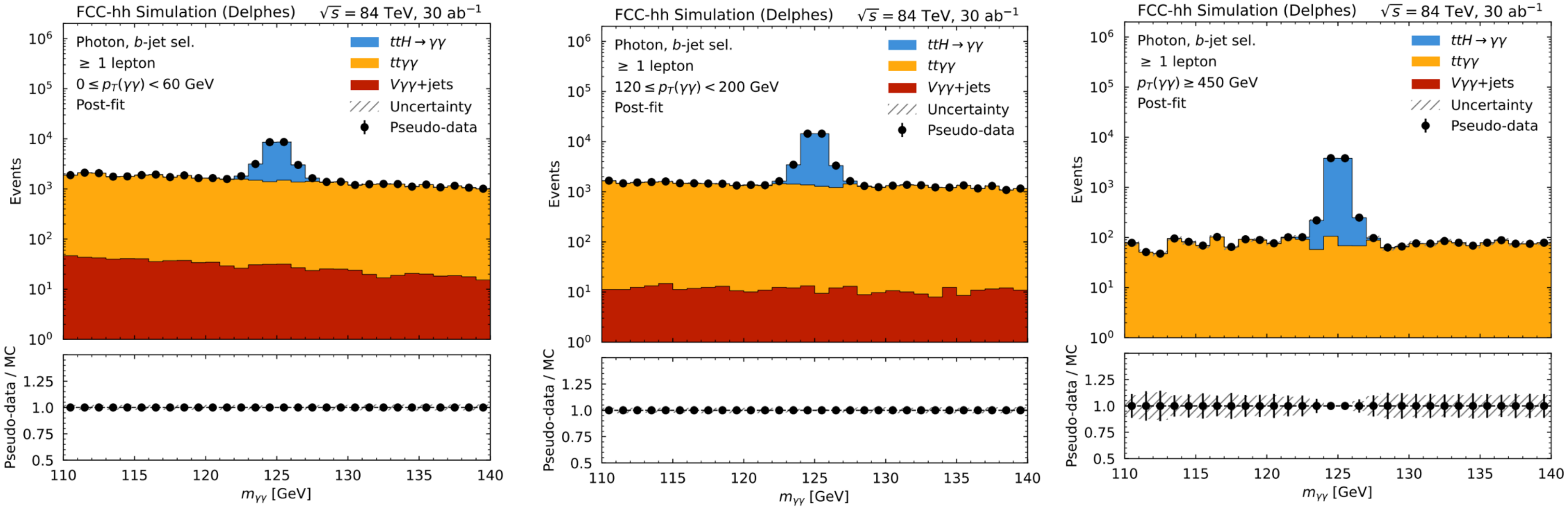
Top Yukawa coupling

$ttH \rightarrow \gamma\gamma$

$ttH \rightarrow \gamma\gamma$: analysis strategy

CDS note
10.17181/tr6k7-bm770

- Focus on ttH where at least one top-quark decays leptonically
- $H \rightarrow \gamma\gamma$: clear experimental signature and excellent photon energy resolution
- Measurement is performed in bins of $p_T^{\gamma\gamma}$ fitting the di-photon mass



$0 \leq p_T^{\gamma\gamma} < 60$ GeV

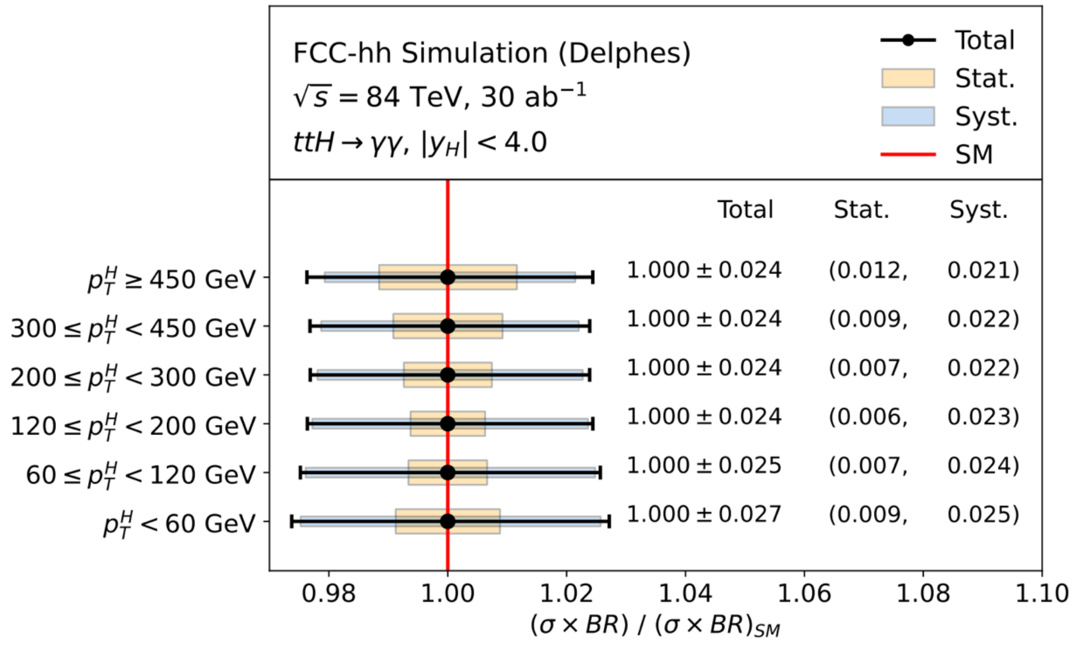
$120 \leq p_T^{\gamma\gamma} < 200$ GeV

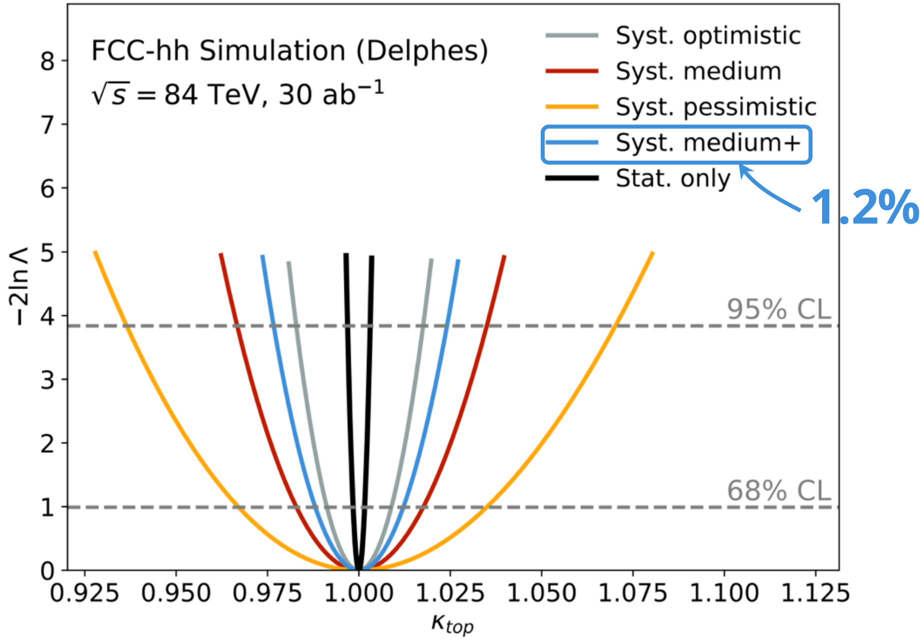
$p_T^{\gamma\gamma} > 450$ GeV

$ttH \to \gamma\gamma$: results

CDS note
10.17181/tr6k7-bm770

- Target measurement of top Yukawa coupling
  - For comparison: currently precision ~11% at LHC[arXiv:2207.00043, 2207.00092], exp. 3.4% at HL-LHC [arXiv:1902.00134]
- Working on incorporating ratio ttH/ttZ to exploit systematic unc. cancellation (see previous study)





Higgs rare decays

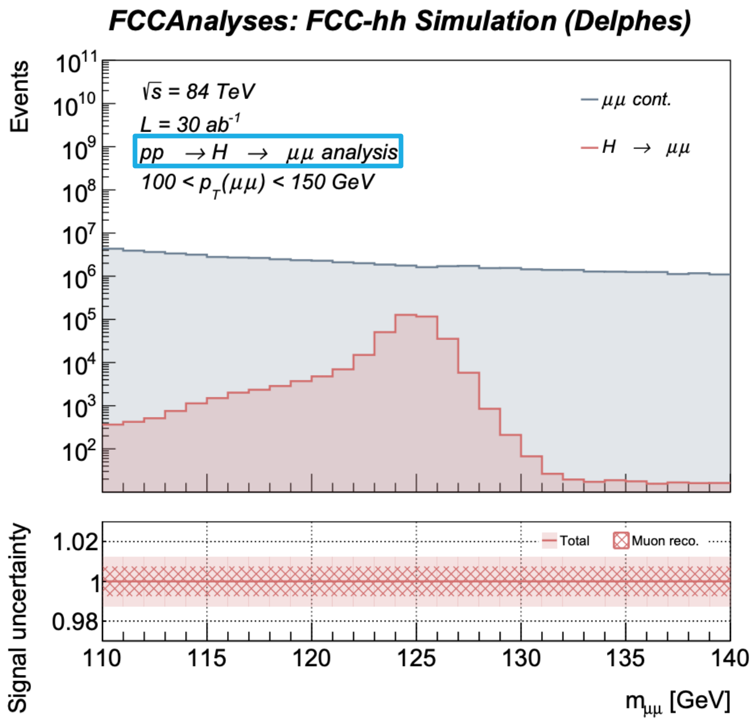
$H \rightarrow \mu\mu$

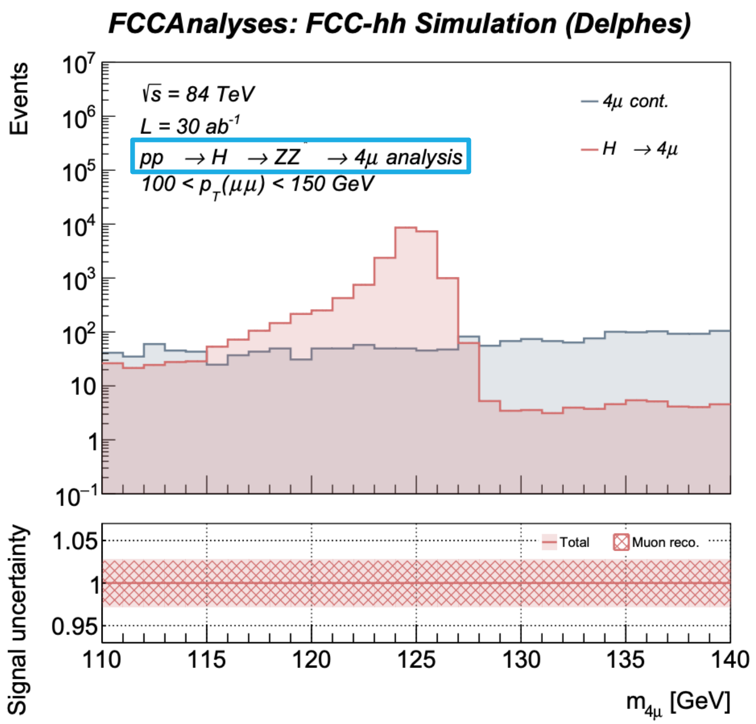
$H \to \mu\mu$: analysis strategy

CDS note

10.17181/sxreb-8h751

- Benefit from larger FCC-hh dataset: explore high $p_T^{\mu\mu}$ region where exp. uncertainties are usually smaller
- Measure ratio of signal strength $H \to \mu\mu$ / $H \to ZZ \to 4\mu$ to:
  - Cancel out theory uncertainty
  - Take advantage of FCC-ee permille precision on $H \to ZZ$
- Fit of $m_{\mu\mu}(m_{4\mu})$ invariant mass in $p_T^{\mu\mu}$ ($p_T^{4\mu}$) bins

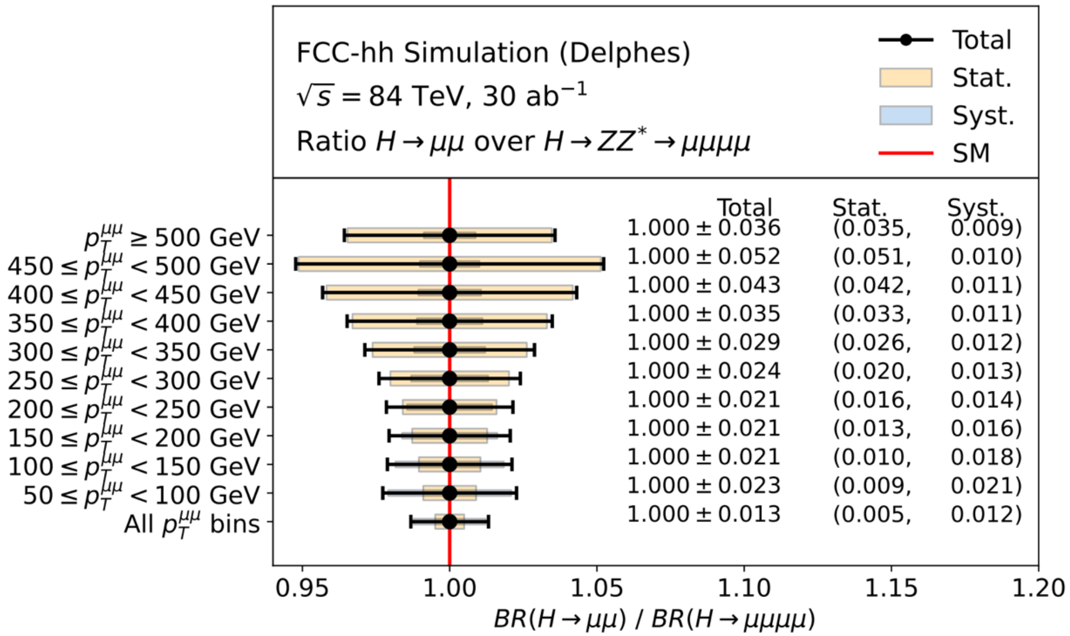


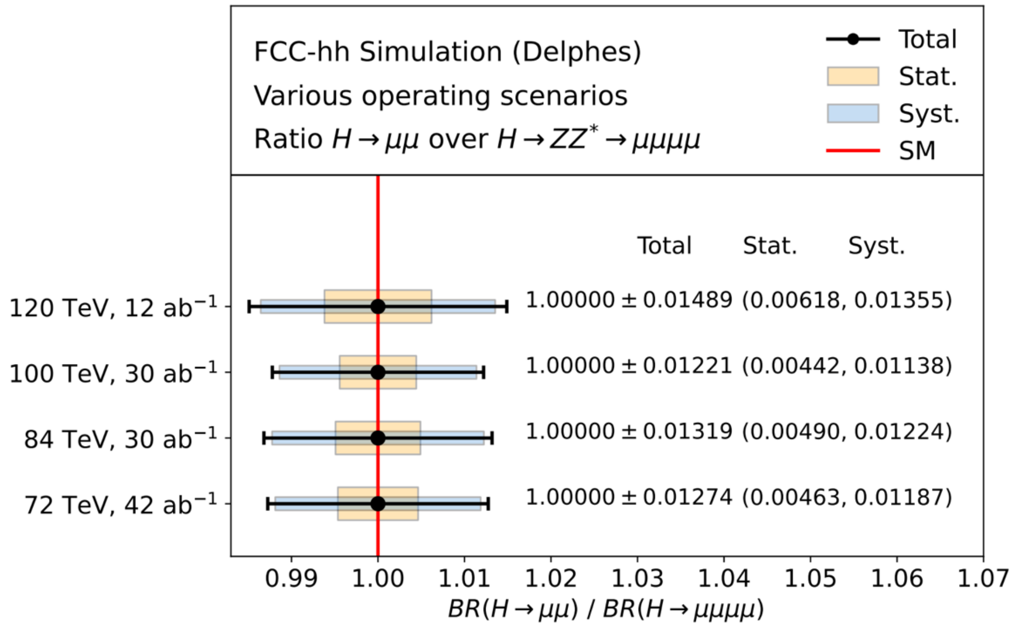


$H \to \mu\mu$: results

CDS note
10.17181/sxreb-8h751

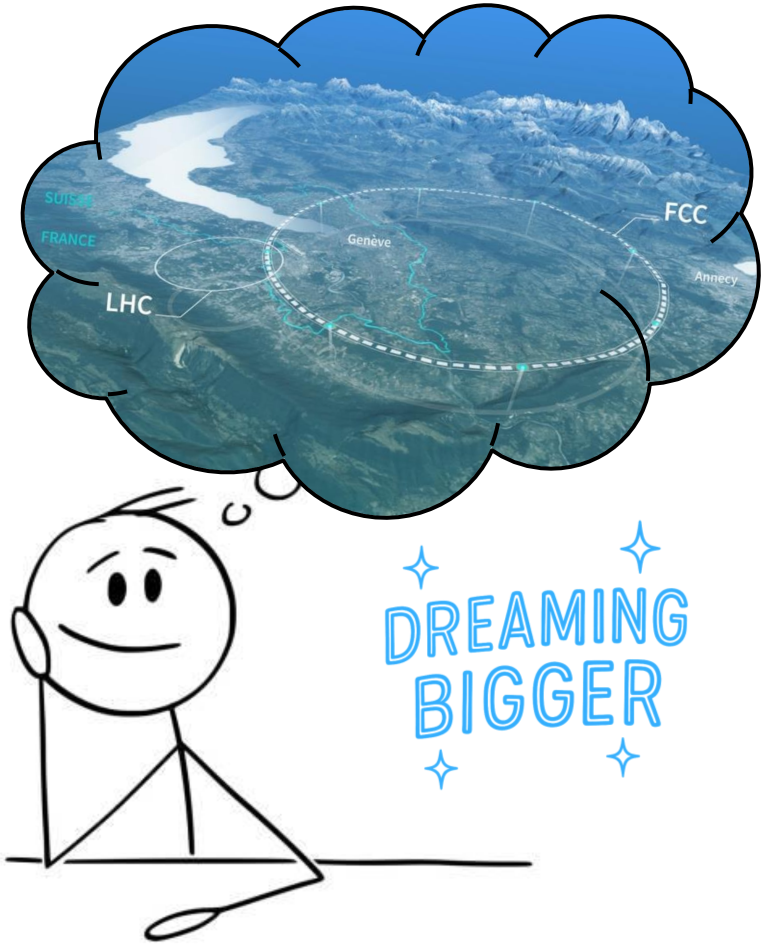
- A precision on the ratio of signal strength of 1.32% can be achieved in the nominal scenario
- **Precision on the absolute coupling of Higgs to muons of 0.66%** (compared to ~4% for FCC-ee)
- Similar studies can be done on $H \to \gamma\gamma$ and $H \to Z\gamma$, which are also statistically limited at FCC-ee





Summary & Outlook

- Key Higgs benchmark studies updated for new baseline operating scenario at 84 TeV (and alternatives)
- Overall picture does not change from 100 TeV CDR case
  - **FCC-hh remains the ultimate test for Higgs self-coupling**
  - **FCC-hh can access rare Higgs decay mode, complementing FCC-ee**
- Addition of new studies and more advanced analysis techniques may boost the FCC-hh physics case even further
- Several ongoing studies & further updates to be completed
  - [FCC-hh P&P working group documentation page]



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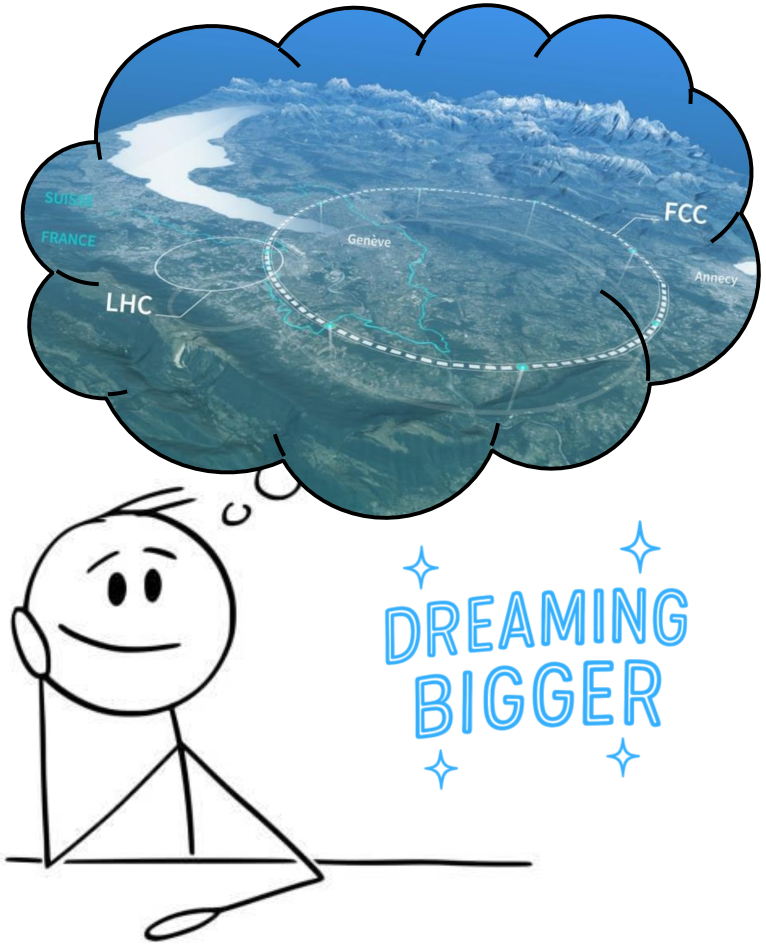
BACK TO THE PRESENT

Now it's the time to decide how the future will look like!



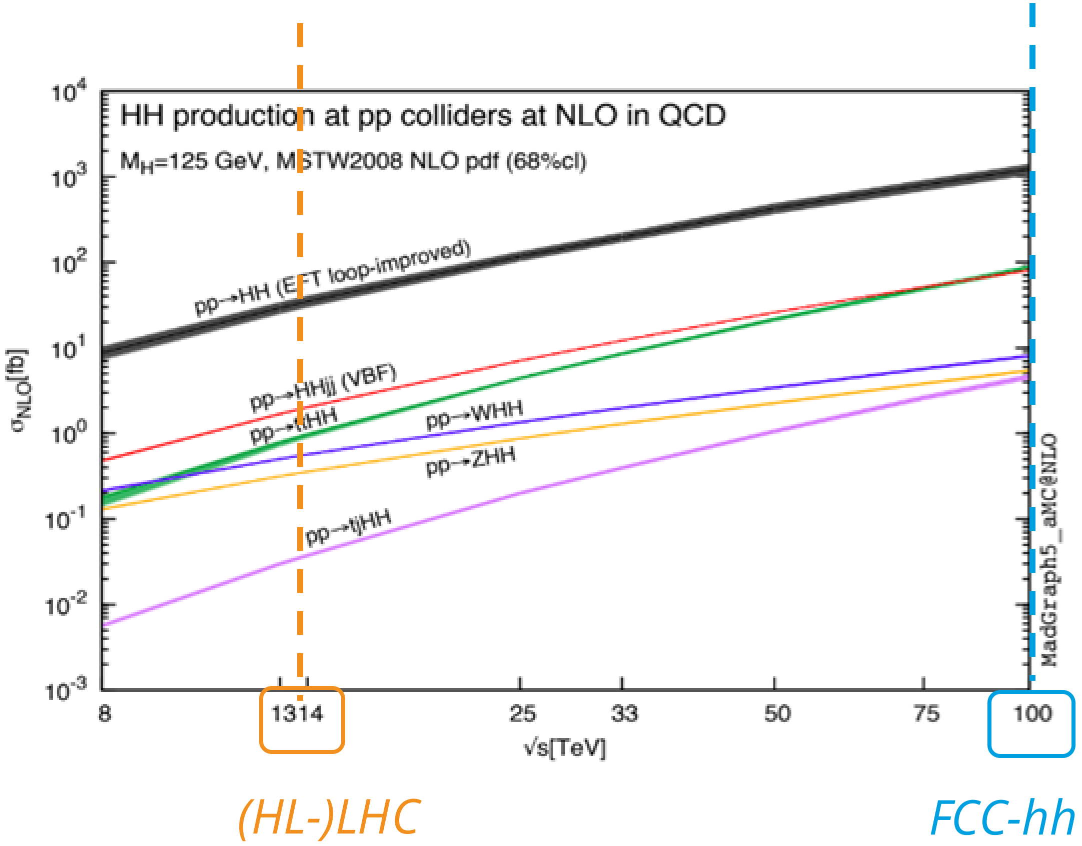
Backup

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	~30%	ESPPU #170

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

Setting the scene: self-coupling at FCC-hh



FCC-hh offers excellent prospects for a precision measurement of Higgs self-coupling

- Higgs pair production cross-section increases by factor ~40 compared to (HL)-LHC
- Recent HL-LHC projections exceeding initial expectations and reaching ~30% precision on κ_λ
- Previous studies @ FCC-hh proved percent level precision on κ_λ combining several channels

FCC-hh timelines

[ESPPU input #247]

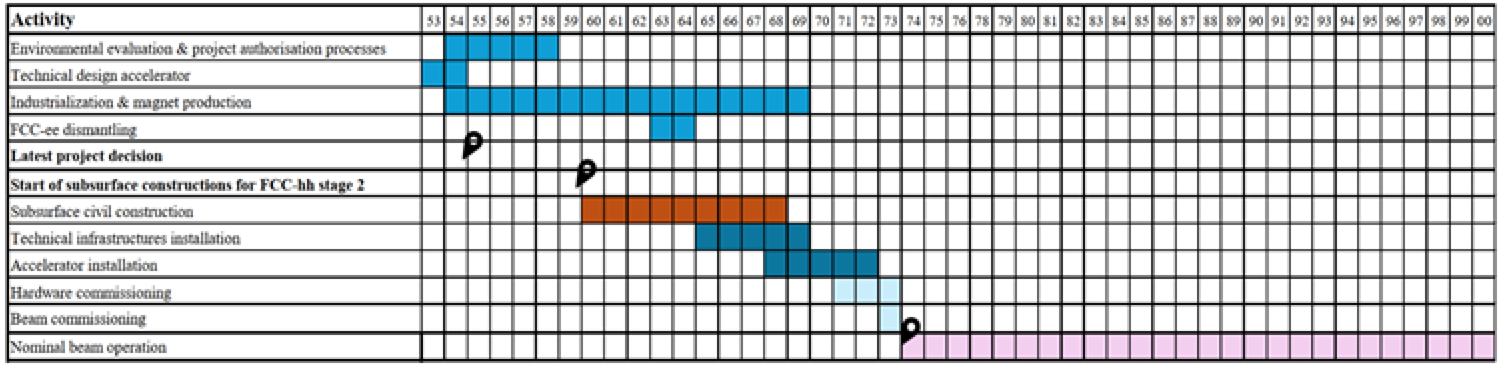


Fig. 9: Timeline of FCC-hh as second stage after FCC-ee from preparatory phase to the end of operation.

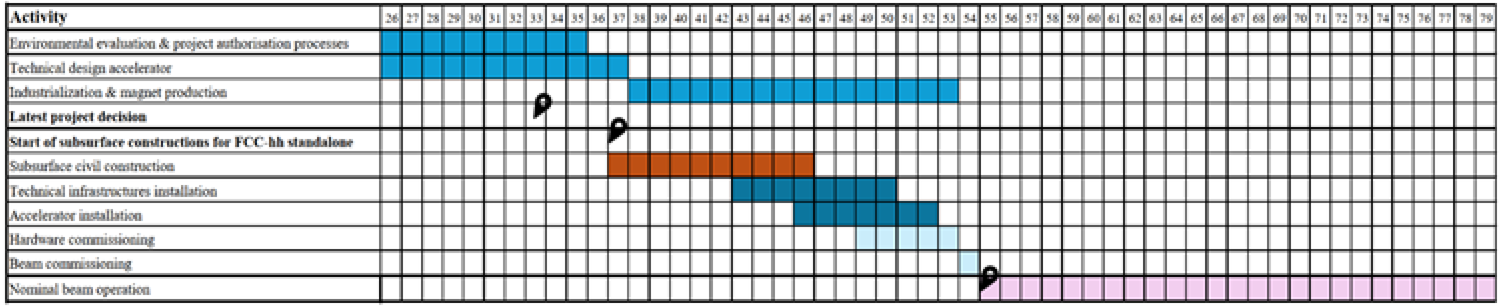


Fig. 10: Timeline of FCC-hh as stand-alone project from preparatory phase to the end of operation.

Efficiency parametrization in Delphes

Object	Relative momentum resolution	Efficiency
Photons	0.2-3.0%	72-90%
Electrons	0.8-3.0%	72-90%
Muons	1.0-6.0%	88-97%%
	Medium b-tagging	76-86%
	Mistag rates c-jets	10-20%

Table 1: Ranges of the relative momentum resolutions as well as efficiencies (including reconstruction and identification efficiency) of the relevant objects for the analysis, as parameterized in the DELPHES scenario studied [15].

$HH \rightarrow bb\gamma\gamma$ systematic uncertainty scenarios

Source of uncertainty	Value		Type	Applied to
	Syst. 1	Syst. 2		
Luminosity	0.50%	1.00%	lnN	Signals - Single Higgs
b-tagging eff. / b-jet	0.50%	1.00%	lnN	Signals - Single Higgs
Photon ID eff. / photon	0.50%	1.00%	lnN	Signals - Single Higgs
Single Higgs bkg normalisation	1.00%	1.00%	lnN	Single Higgs
Non-resonant bkg normalisation	5.00%	5.00%	lnU	Non-resonant QCD

Consider different scenarios for systematic uncertainties

- Reconstruction uncertainties apply to signal and single Higgs background, assuming it is determined from MC + additional 1% normalisation uncertainty on each single Higgs process
- Assume non-resonant background estimation data-driven from side-bands with 5% uncertainty (conservative - post-fit constrained to 2%)
- Explicitly no signal theory cross-section uncertainty included

$ttH \to \gamma\gamma$ systematic uncertainty scenarios

Uncertainty source	Uncertainty scenario			
	Optimistic	Medium	Medium+	Pessimistic
Photon ID	0.5%	1%	1.2% to 0.5% (p_T-dep.)	2%
Electron ID	0.5%	1%	2.0% to 0.5% (p_T-dep.)	2%
Muon ID	0.5%	1%	0.7% to 0.2% (p_T-dep.)	2%
Flavor Tagging	0.5%	1%	1.4% to 0.5% (p_T-dep.)	2%

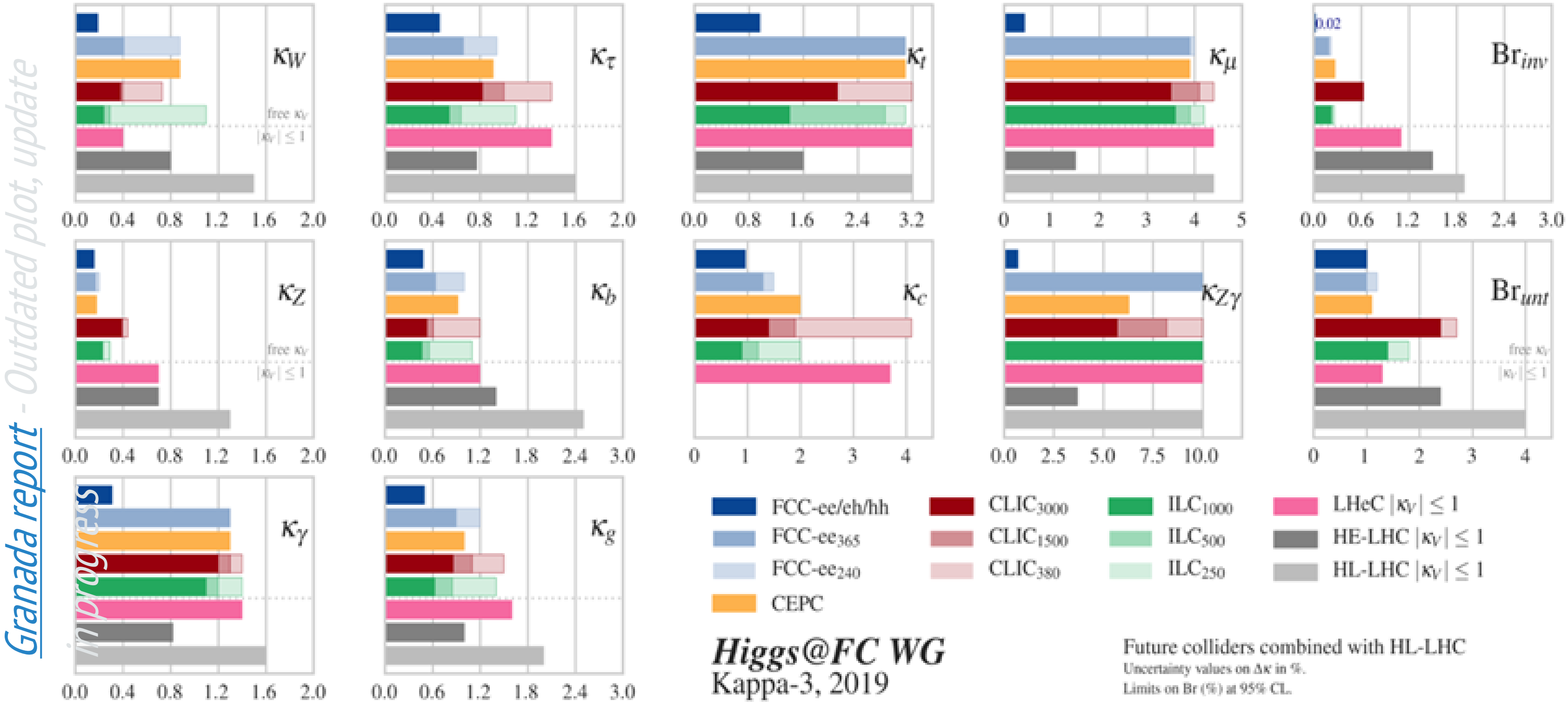
Table 3: Per-object uncertainty values under different scenarios.

Uncertainty source	Uncertainty scenario			
	Optimistic	Medium	Medium+	Pessimistic
Luminosity	0.5%	1%	1%	2%
$t\bar{t}H$ cross-section	0.5%	1%	1%	1.5%

Table 4: Per-event uncertainty values under different scenarios.

- In the medium+ scenario, the uncertainties on the object identification efficiency were determined using a pT-dependent parameterization

Higgs couplings: motivation



Significant precision improvements in couplings measurements in rare decay modes that remain (statistically) limited at FCC-ee/HL-LHC, or are not directly accessible at FCC-ee