Higgs self-coupling at the FCC-hh

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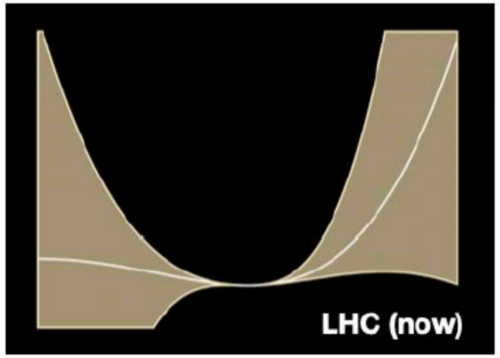
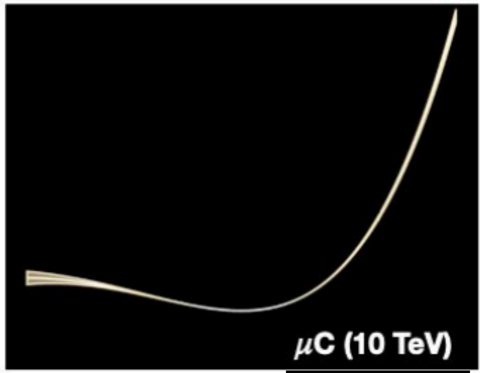
Grenoble, 9 April 2024



R. Petrossian-Byrne/N. Craig



or FCC-hh

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Higgs potential

In the SM, the coupling λ determines the Higgs potential shape

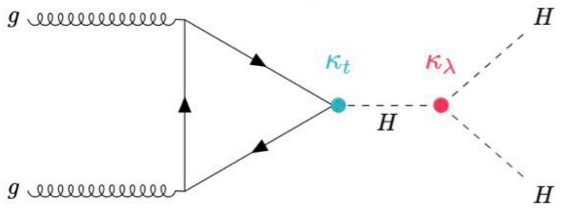
It is measured via Higgs self-coupling, e.g. directly via di-Higgs production

- It would be the first evidence of a particle interacting with itself

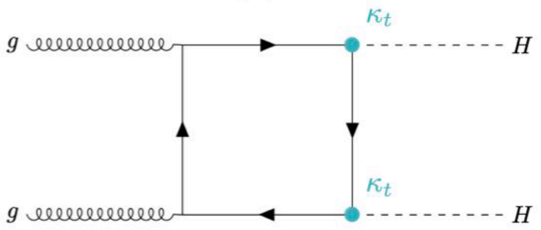
However the cross section is small due to the negative interference with the top-box diagram, so that

$$\sigma(ggHH) \simeq 1/1000\ \sigma(ggH)$$

"triangle"

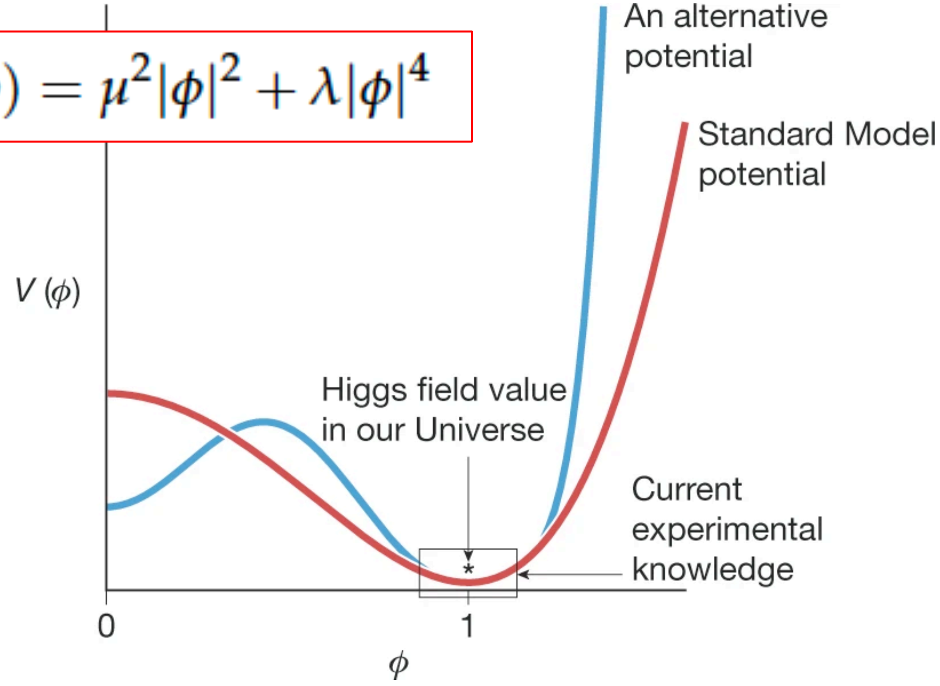


"box"



Salam, Wang, Zanderighi, "The Higgs boson turns ten", Nature 607 (2022) 41

$$V(\phi) = \mu^2|\phi|^2 + \lambda|\phi|^4$$

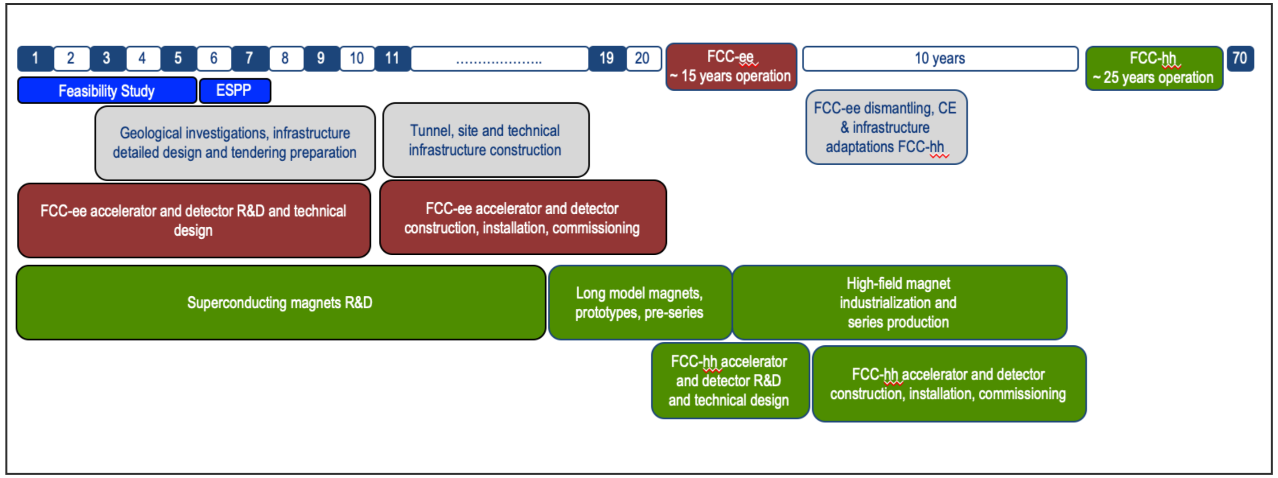


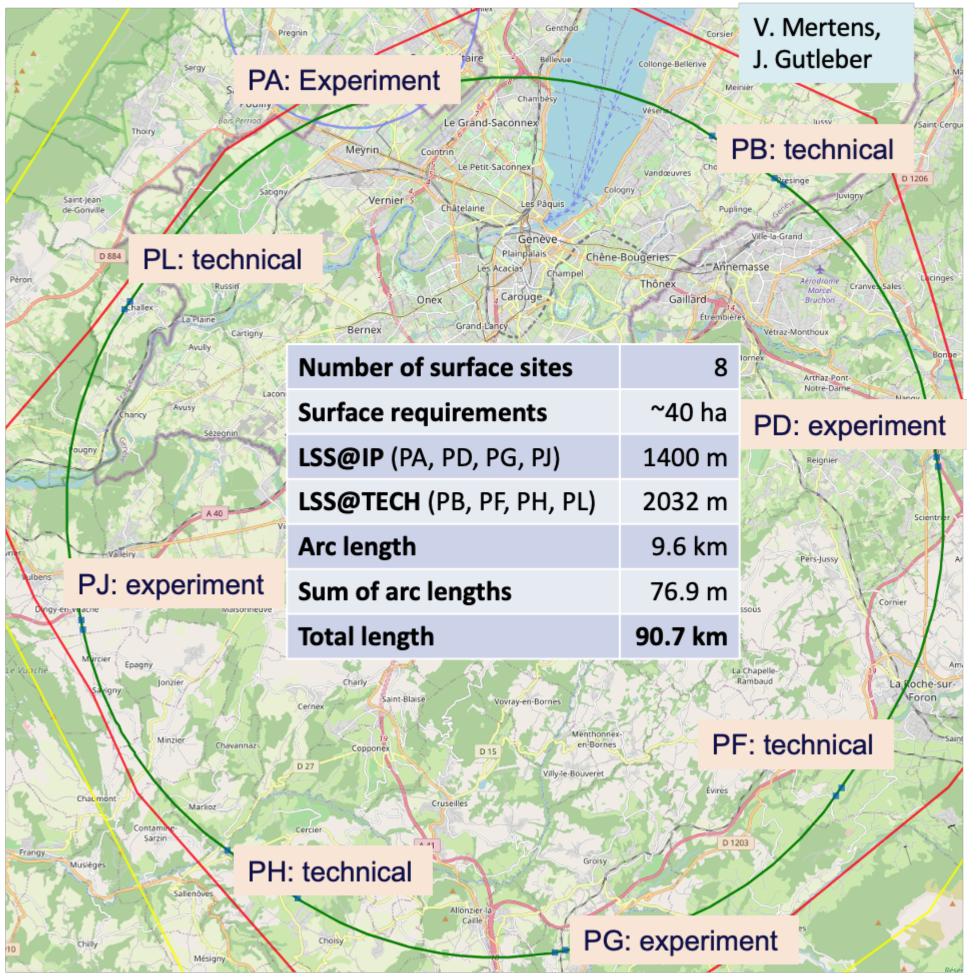
FCC-hh

Layout as presented in the Midterm report of the FCC feasibility study (February 2024) : 90.7 km ring, 8 surface points

1st stage: FCC-ee at different energies (Z/WW/ZH/tt)

2nd stage: FCC-hh, hadron-hadron collider at ~100 TeV, time-scale is driven by the high-field magnet development





Number of surface sites	8
Surface requirements	~40 ha
LSS@IP (PA, PD, PG, PJ)	1400 m
LSS@TECH (PB, PF, PH, PL)	2032 m
Arc length	9.6 km
Sum of arc lengths	76.9 m
Total length	**90.7 km**

FCC-hh

At the FCC-hh:

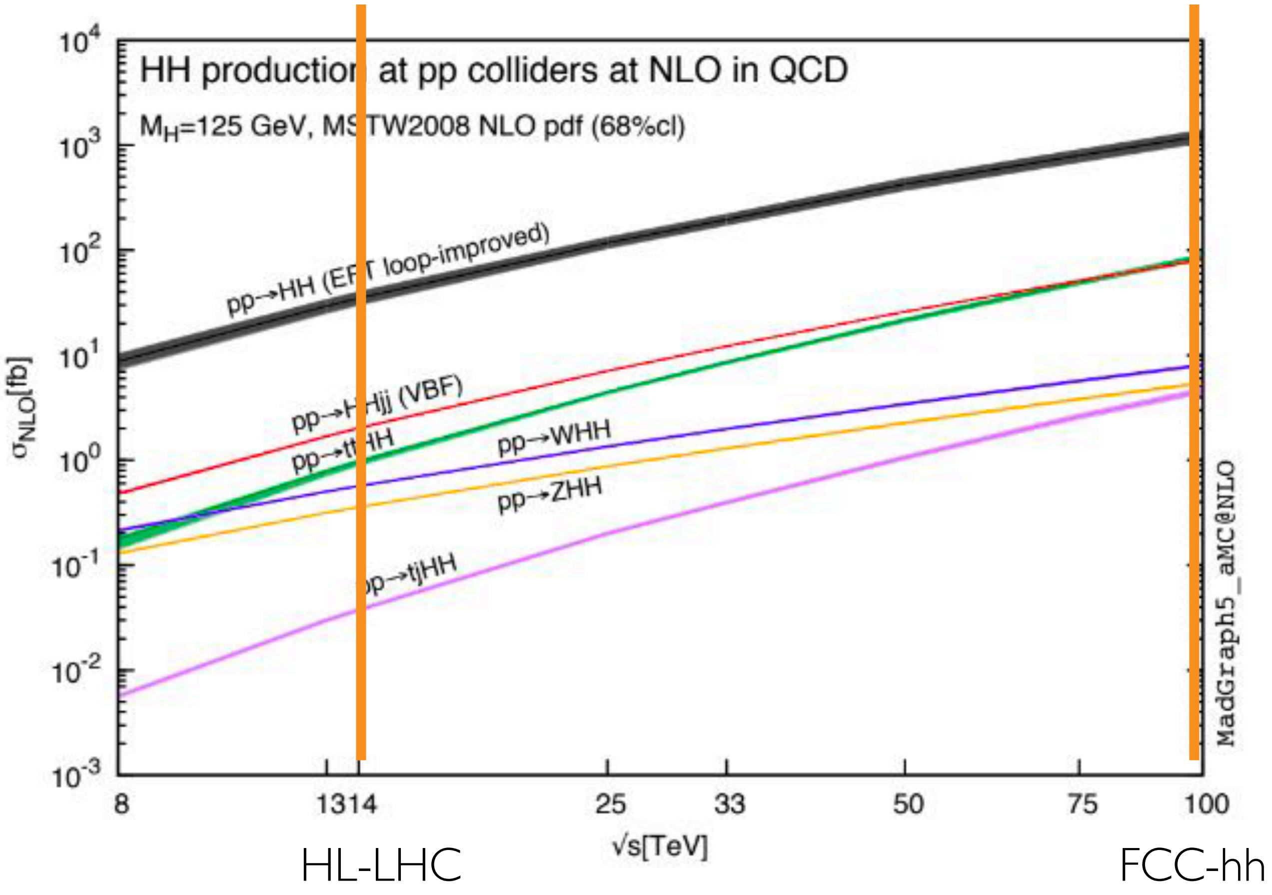
$30\ ab^{-1}$ of integrated luminosity, about 10X the one at the end of HL-LHC at a centre-of-mass energy of 100 TeV (2/fb per day initially and up to 8/fb day for nominal parameters)

It will allow for Higgs physics:

- To measure k_λ with percent precision
- To measure rare decays ($\mu\mu, Z\gamma, c\bar{c}$)..
- To go to higher p_T where backgrounds could be different

ggHH cross-section X40 times higher than at the HL-LHC

Discussion at 80 and 120 TeV also started

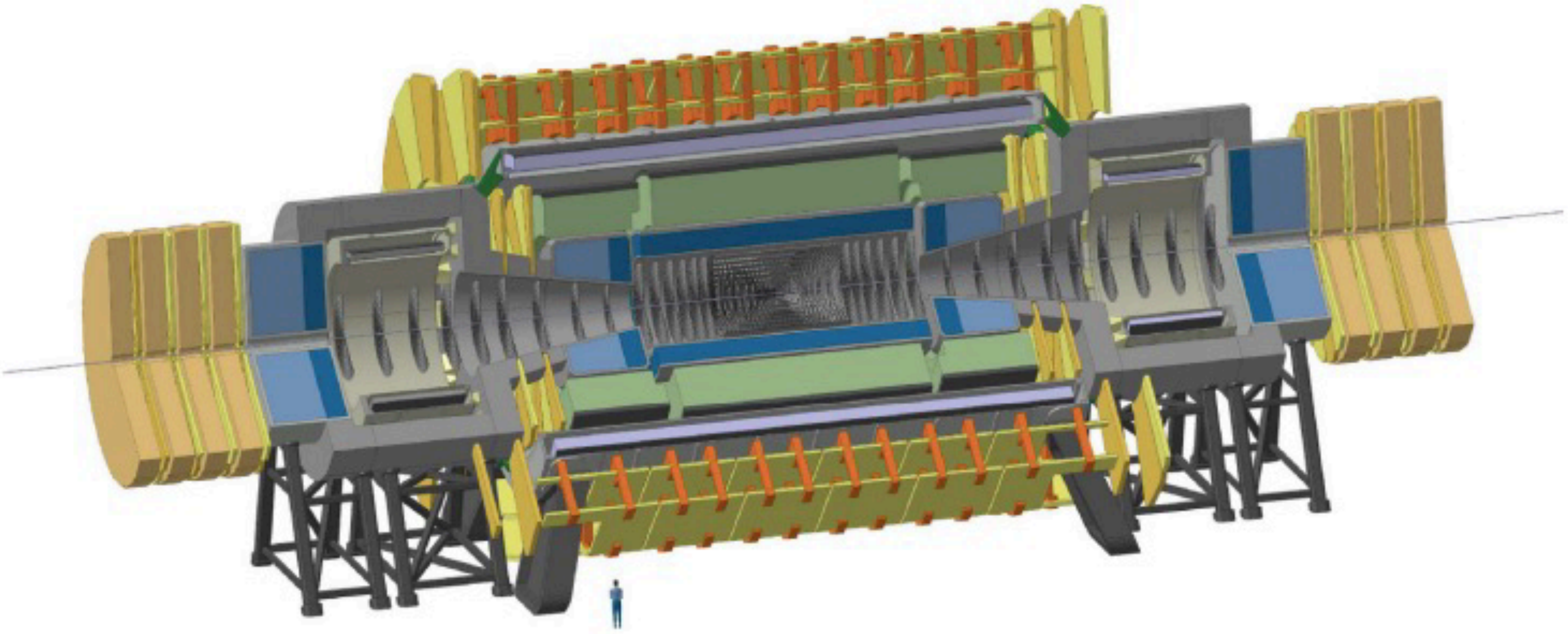


400X HH events at FCC-hh compared to HL-LHC, 20X precision in k_λ

Detector concept

Reference detector:

- Silicon tracking detector
- Electromagnetic with LAr and hadron calorimeter with Pb/steel and scintillating tiles
- Outer muon system with drift tubes



Pile-up of 1000 at these luminosities,
High granularity, timing detectors, etc. will be needed to have performances like for LHC now

Detector reference design: 50 m overall length, 20m diameter; central solenoid and 2 forward solenoids with 4 T field; coverage up to $|\eta| < 6$ (FCC-hh CDR)

Fast simulation at the FCC-hh

MC samples were generated and simulated with DELPHES, which uses a ParticleFlow algorithm with parametrized object resolutions and efficiencies in two Scenarios

It assumes a perfect detector a la LHC Run 2 (Scenario I) and a less optimistic scenario a la CDR (Scenario II)

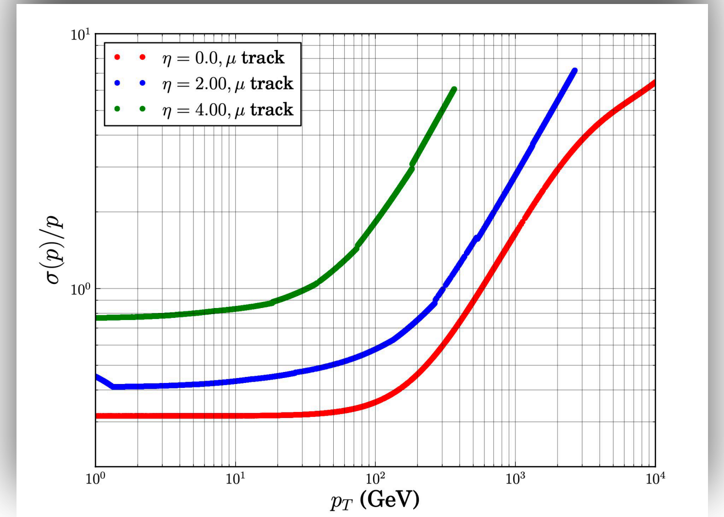
Use of the Key4HEP project: EDM4HEP format for the events, processed via the FCCanalyses framework.

	Relative momentum resolution		Efficiency	
Object	Scenario I	Scenario II	Scenario I	Scenario II
Electrons	0.4-1%	0.8-3.0%	76-95%	72-90%
Muons	0.5-3%	1.0-6.0%	90-99%	88-97%%
	Medium b-tagging		80-90%	76-86%

b-jets are reconstructed with the anti-KT algorithm with R=0.4 and their efficiency is parametrized as a function of the p_T

The effect of pile-up is in the parametrization of efficiencies and resolutions

Example of muon parametrization



Status of measurements and projections

$k_\lambda = \lambda_{measured}/\lambda_{SM}$

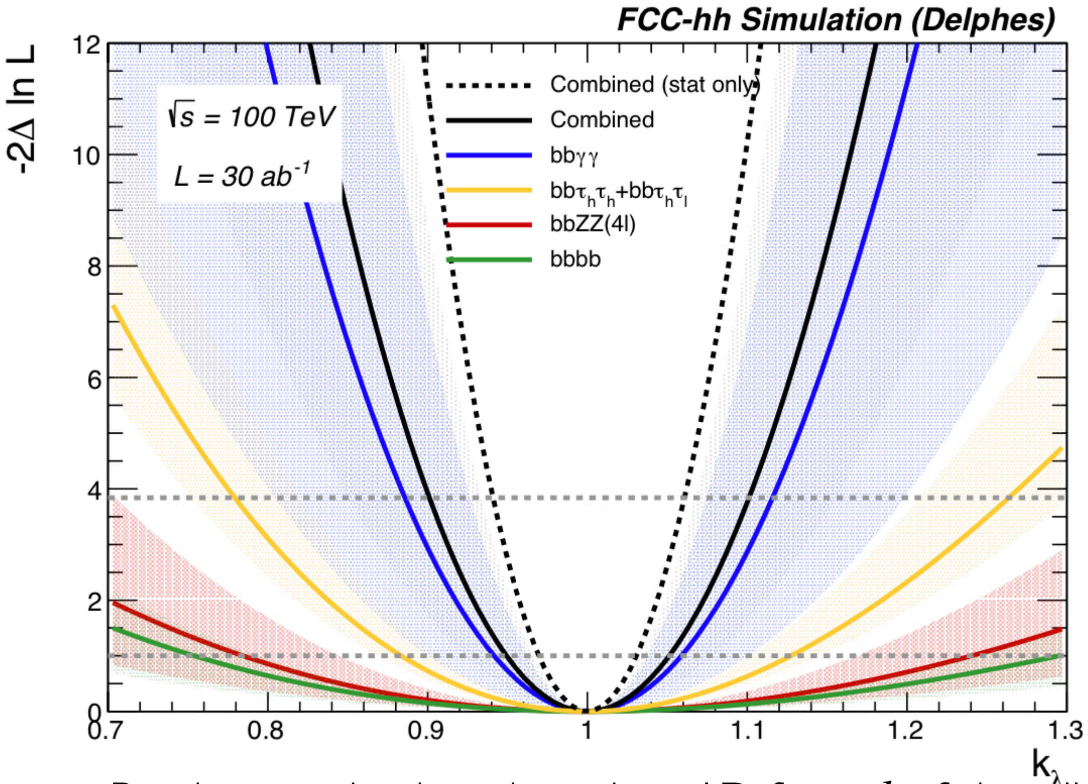
https://arxiv.org/abs/2004.03505

$-0.4 < k_\lambda < 6.3$ (ATLAS Run 2 H+HH in PLB 843 (2023) 137745)

$-1.2 < k_\lambda < 7.5$ (CMS Run 2 H+HH in CMS-PAS-HIG-23-006)

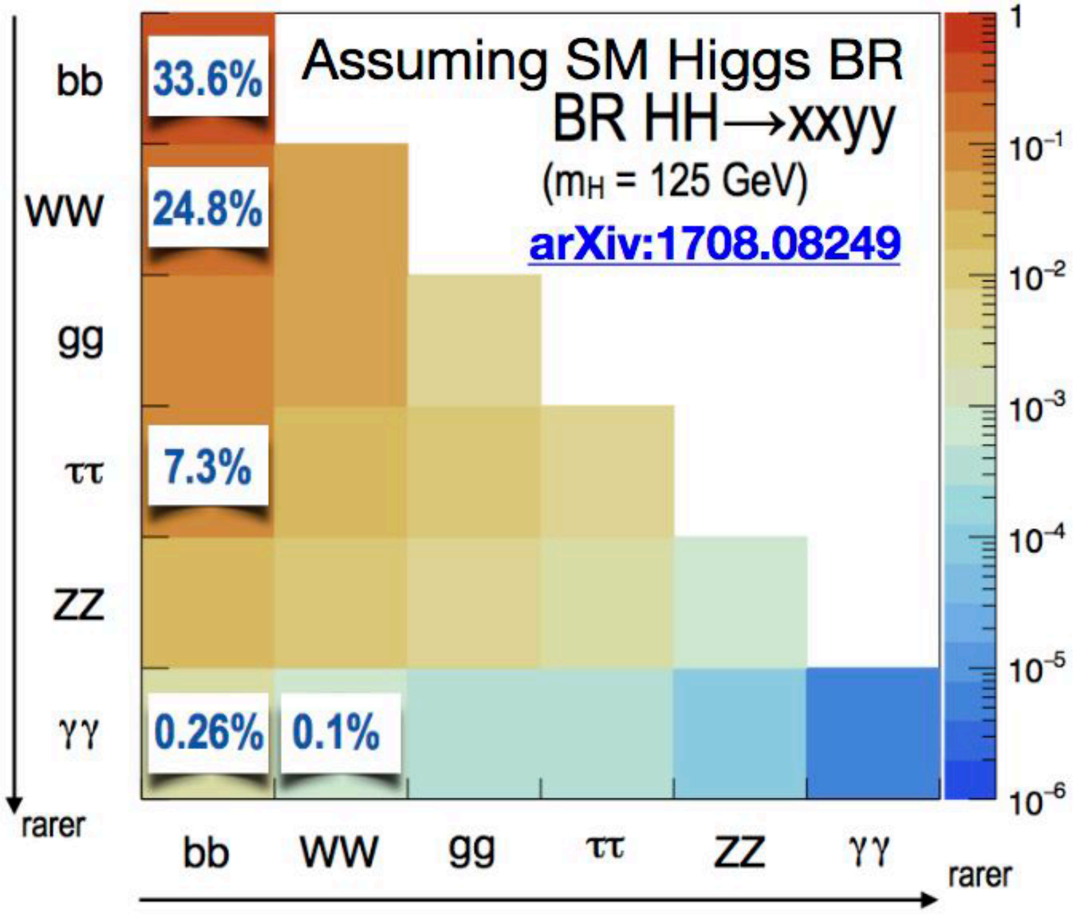
collider	Indirect-h	hh	combined
HL-LHC [78]	100-200%	50%	50%
ILC_{250}/C^3-250 [51, 52]	49%	–	49%
ILC_{500}/C^3-550 [51, 52]	38%	20%	20%
$CLIC_{380}$ [54]	50%	–	50%
$CLIC_{1500}$ [54]	49%	36%	29%
$CLIC_{3000}$ [54]	49%	9%	9%
FCC-ee [55]	33%	–	33%
FCC-ee (4 IPs) [55]	24%	–	24%
FCC-hh [79]	-	3.4-7.8%	3.4-7.8%
μ(3 TeV) [64]	-	15-30%	15-30%
μ(10 TeV) [64]	-	4%	4%

From Snowmass report arXiv:2209.07510



Previous projections, based on 1D fit on k_λ, fixing all other couplings at the SM value (safe assumption, due to their expected precision at FCC-hh).
In best systematic scenario (Scenario I, a la LHC Run 2), 3.4 % projected uncertainty on k_λ

Update of projections: $bb\gamma\gamma, bbll + E_T^{miss}$



ggHH **production only studied here, two decay channels:**

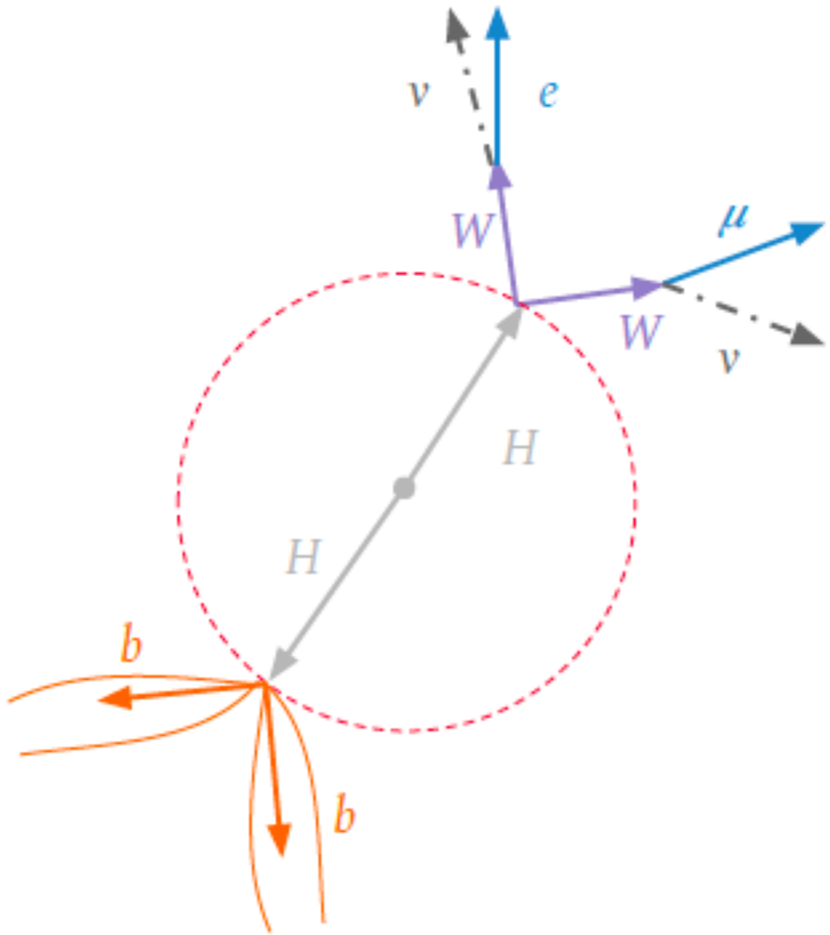
$bb\gamma\gamma$: traditional channel, one of the most sensitive due to the EM resolution, in spite of the low branching ratio (0.26%)

Signature: two b-jets, two photons at the H mass

$bb + ll + E_T^{miss}$: higher branching ratio (3.24%) but missing ET makes HH signal extraction more difficult. Interesting as sensitive to pile-up.

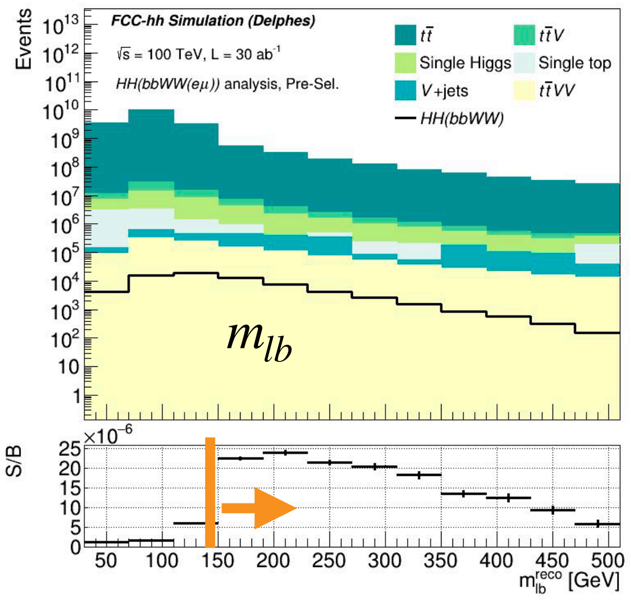
It includes:
$b\bar{b}WW(l\nu l\nu) + b\bar{b}\tau\bar{\tau}(l\nu l\nu) + bbZZ(ll\nu\nu)$
Signature: a pair of opposite-sign (OS) electrons or muons, same (SFOS) or different flavor (DFOS) flavor, two b-jets

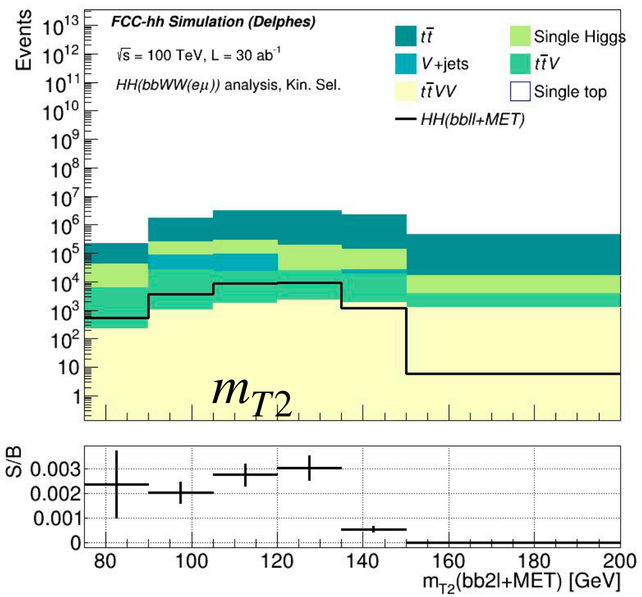
$bb + ll + E_T^{miss}$ channel



Cut-based analysis exploiting the topology

- two b-jets close in space and with m_{bb} around the Higgs mass
- Two leptons close in space and separated from the b-jets
- Large separation between the missing energy and the b-jets
- Top-pair is the main background, use m_{lb} for further suppression
- Use transverse mass m_{T2} for the statistical inference

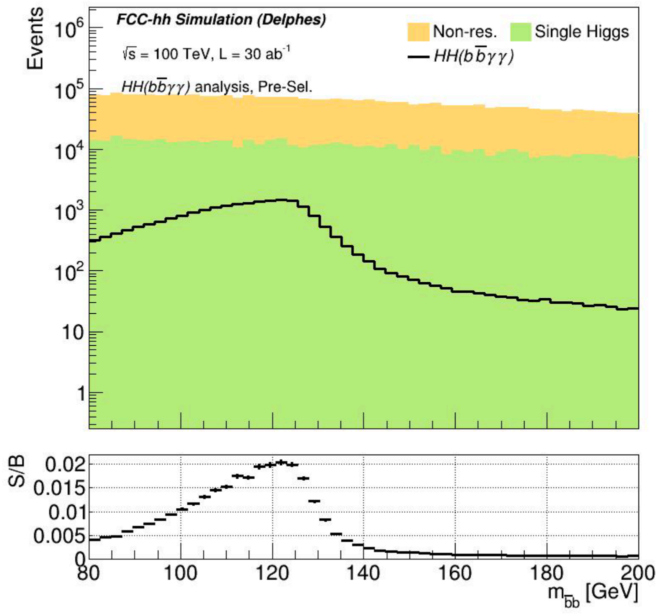


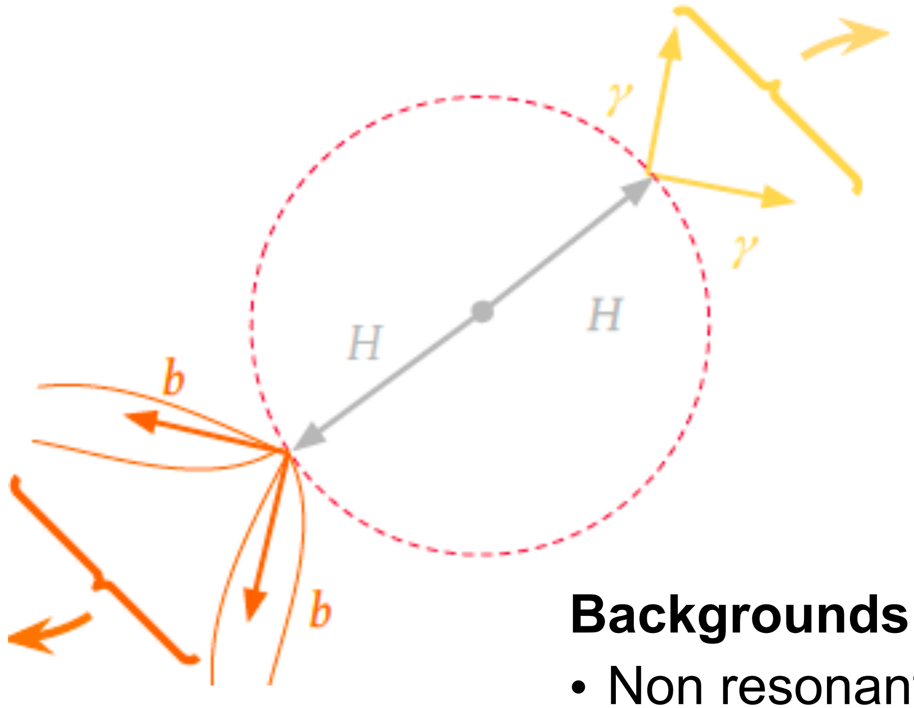


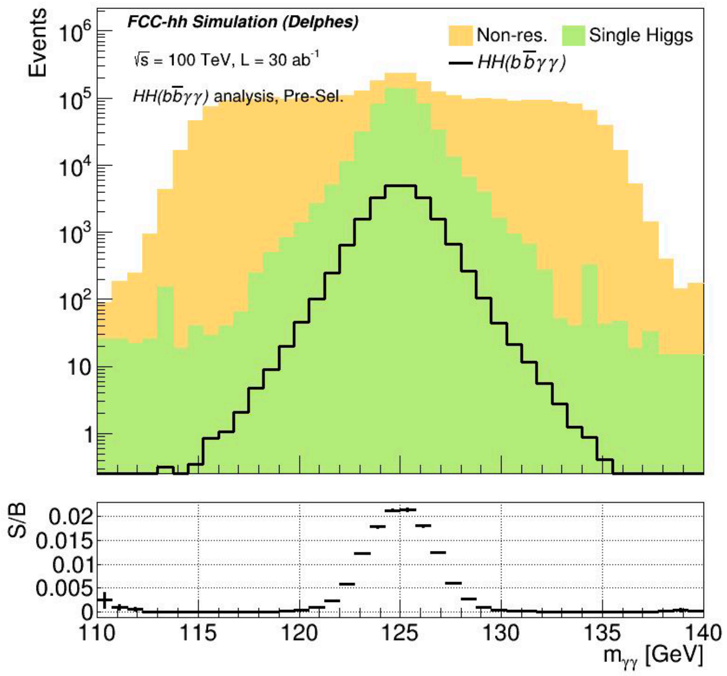
$$m_{lb}^{\rm reco} = \min\left(\frac{m_{l_1b_1} + m_{l_2b_2}}{2}, \frac{m_{l_2b_1} + m_{l_1b_2}}{2}\right)$$

$bb + \gamma\gamma$

Topology: two photons and 2 b-jets peaking at the H mass







Backgrounds:

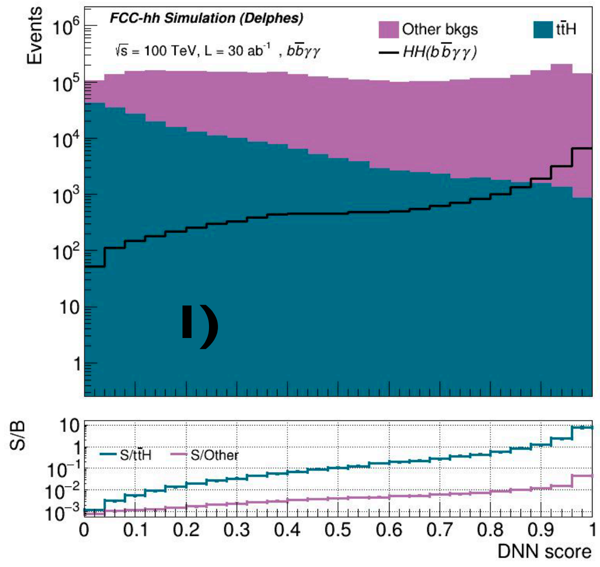
- Non resonant, QCD $\gamma\gamma + jet, \gamma + jets$
- Resonant: single Higgs production
- 3 DNNs to suppress the various backgrounds
- A la Run 2 CMS analysis

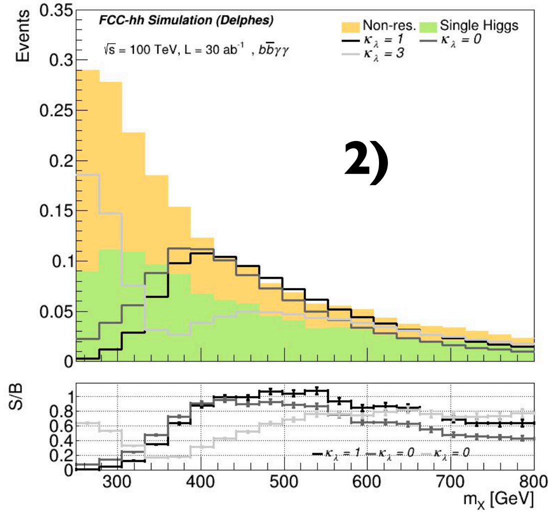
Selection steps for $bb\gamma\gamma$

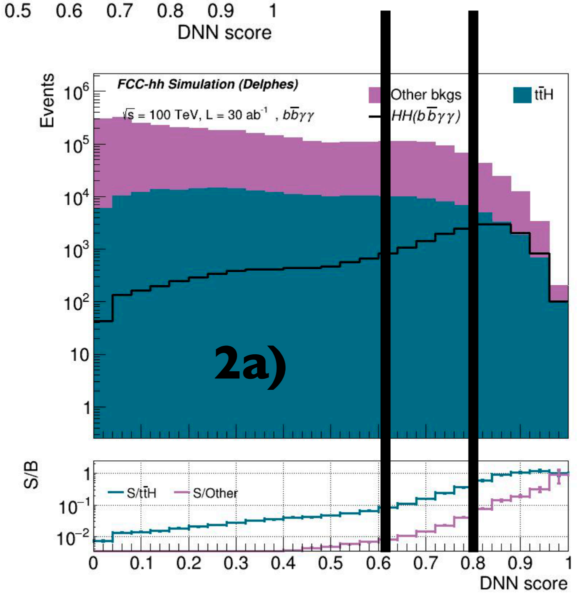
1) DNN-based tagger to suppress tth, which is the main background
$(\sigma(t\bar{t}H \to \gamma\gamma) \simeq 3 \times \sigma(ggHH \to bb\gamma\gamma)\ )$

2) Split events in two categories and train 2 DNNs in the two regions:
$m_X < 350\ GeV, m_X > 350\ GeV, m_x = m_{bb\gamma\gamma} - m_{bb} - m_{\gamma\gamma} + 250$
The shape of m_X depends on k_λ

2a) Define a medium and high category based on the DNN score, exclude the region with DNN score <0.6



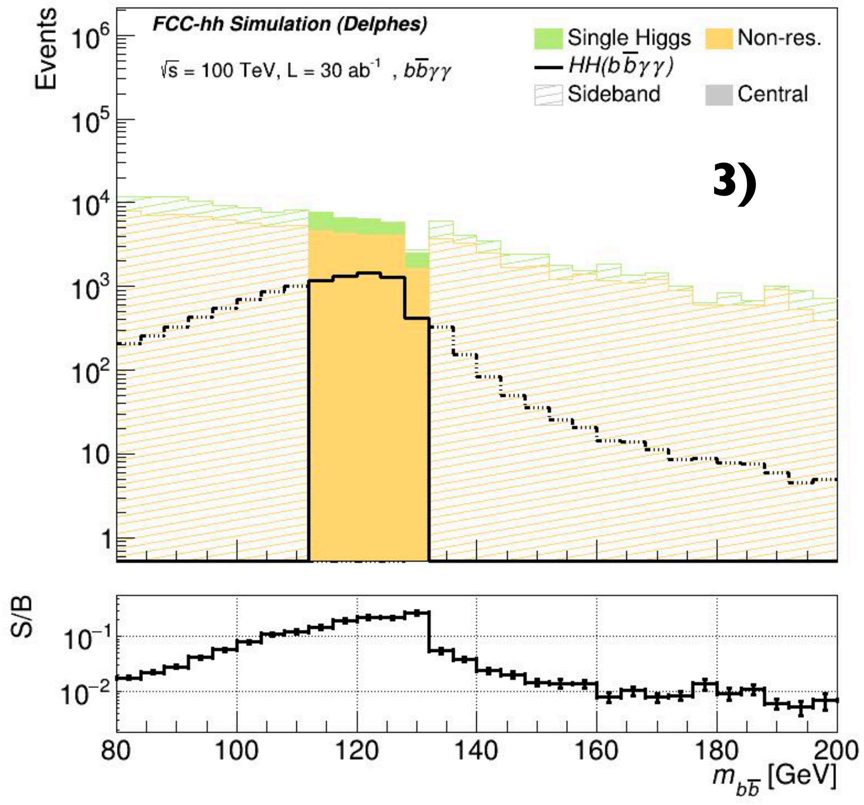


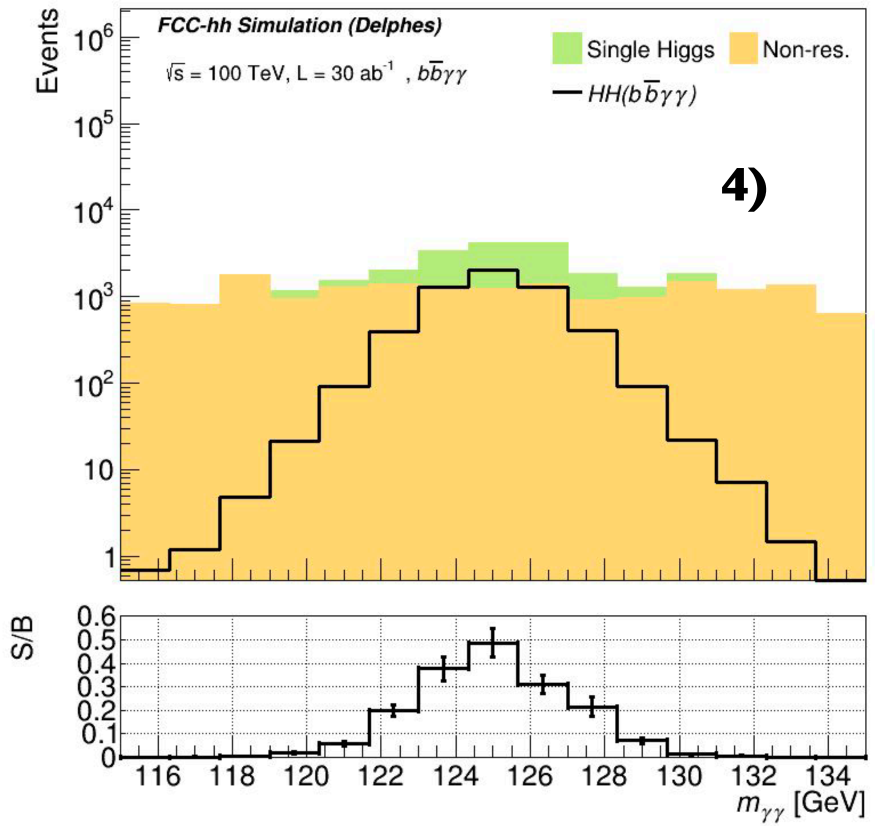


Selection steps for $bb\gamma\gamma$

3) Split events in addition in m_{bb} bins, central + sidebands

4) Use $m_{\gamma\gamma}$ in the statistical inference to extract the signal in the eight resulting categories



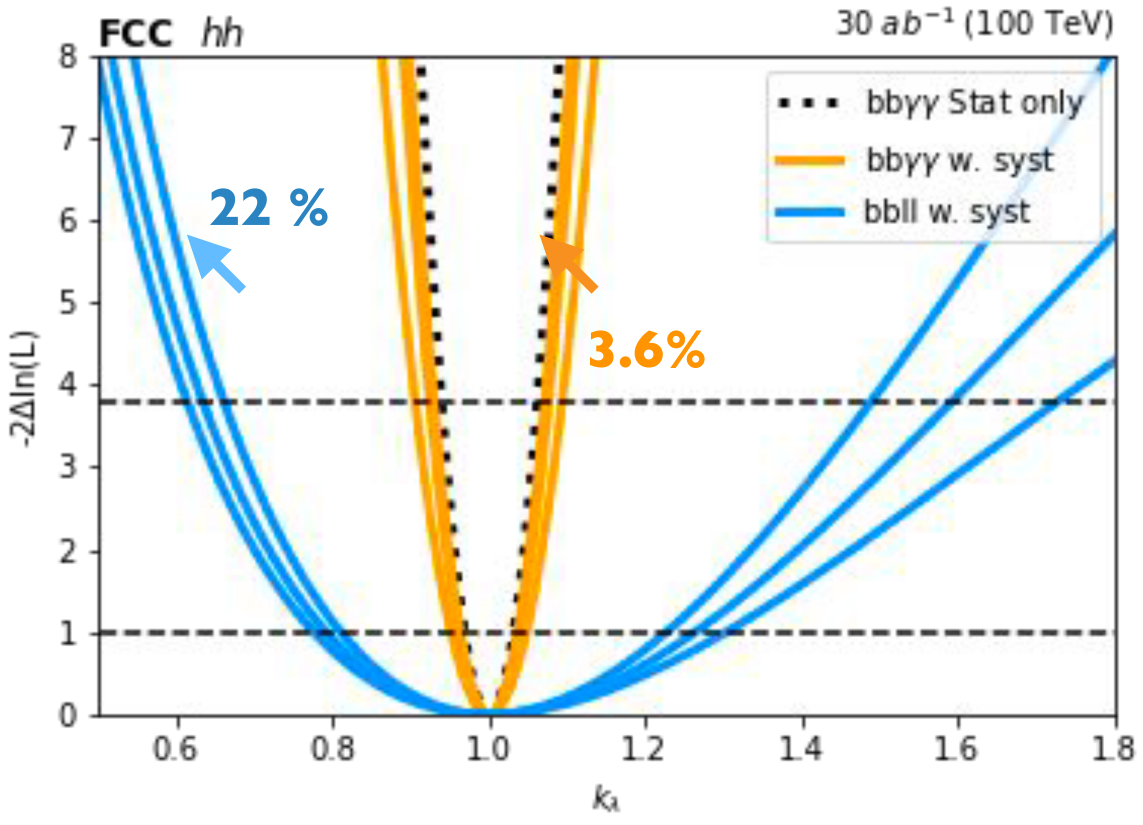


Systematics

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%	$t\bar{t}$	✗

Applied as log-normal uncertainty

Results



Fit from a parametrized dependence of the ggHH cross-section vs the trilinear coupling, 1-dimensional fit with all other couplings fixed to their SM value (Scenario I, lines are Syst1/Syst2/Syst3)

$bbll + E_T^{miss}$: Scenario I + Syst 1

$k_\lambda = 1.00^{+0.23}_{-0.22}$

$bb\gamma\gamma$: Scenario I

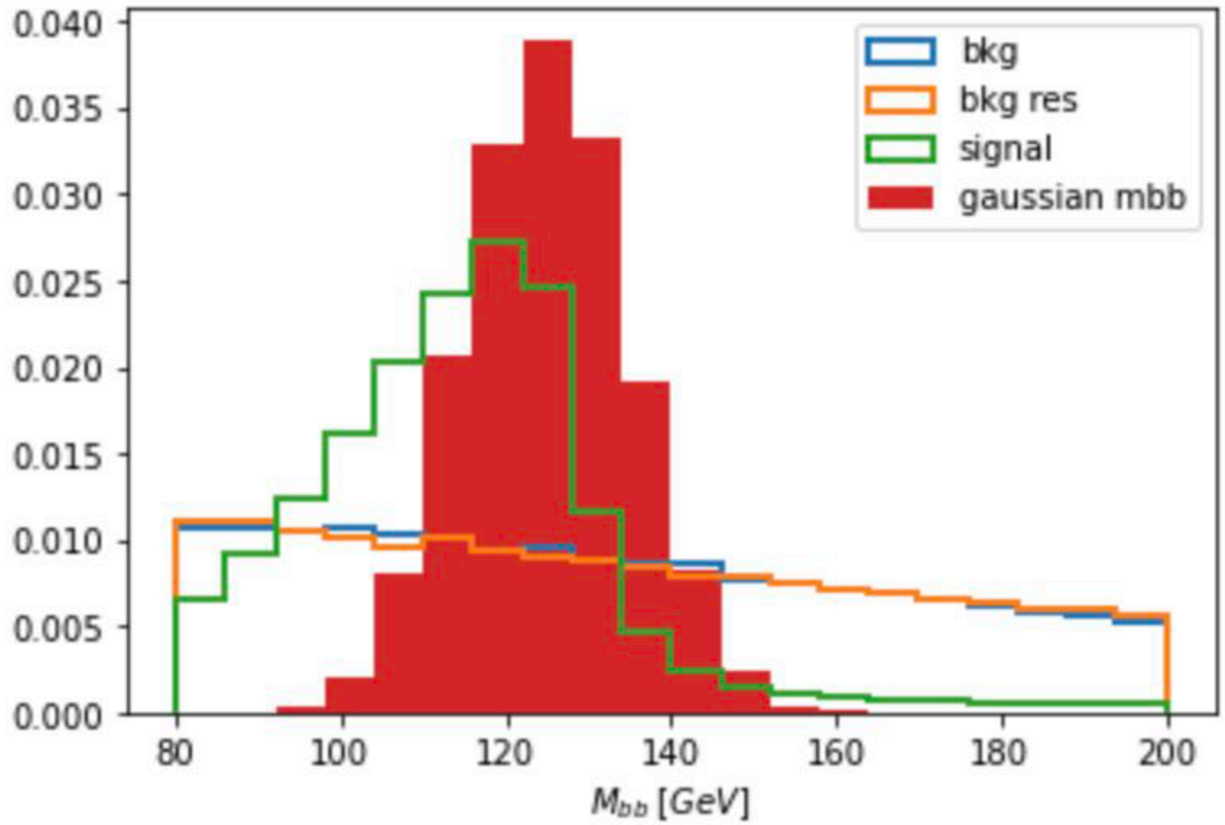
- Stat. only 3.2% uncertainty on k_λ
- Stat + Syst 1 3.6% uncertainty on k_λ

The uncertainty is driven by the resolution of the m_{bb} distribution

Can we reach 1% on k_λ ?

We could ask the inverse question, how well we should reconstruct our objects to decrease the uncertainty

Parametrize the resolution on the invariant mass of the two b-jets and see how it should be improved with an optimal calorimeter



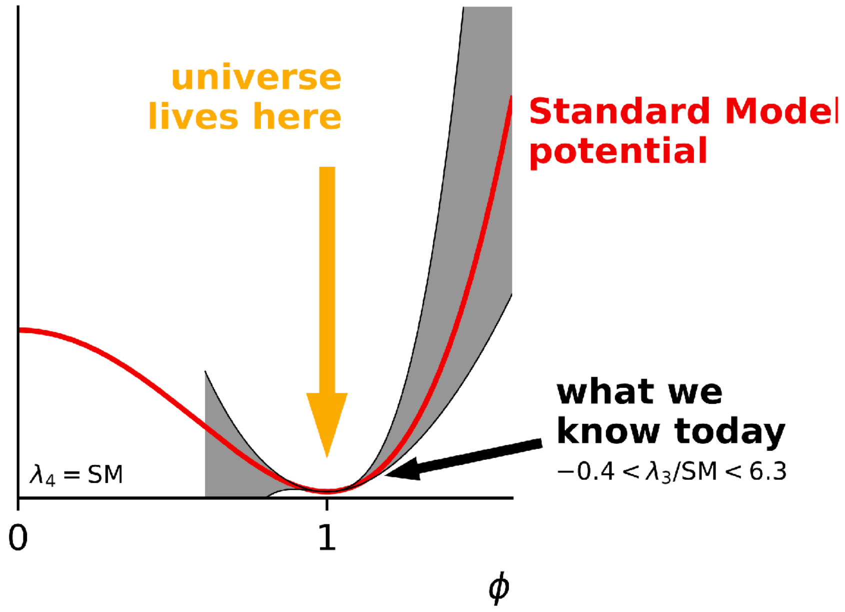
Precision on k_λ

m(bb) resolution at M(H)	Stat only Scenario I	Syst I
No assumption	3.2%	3.6%
10 GeV	2.5%	2.7%
5 GeV	2.0%	2.3%
3 GeV	1.8%	2.0%

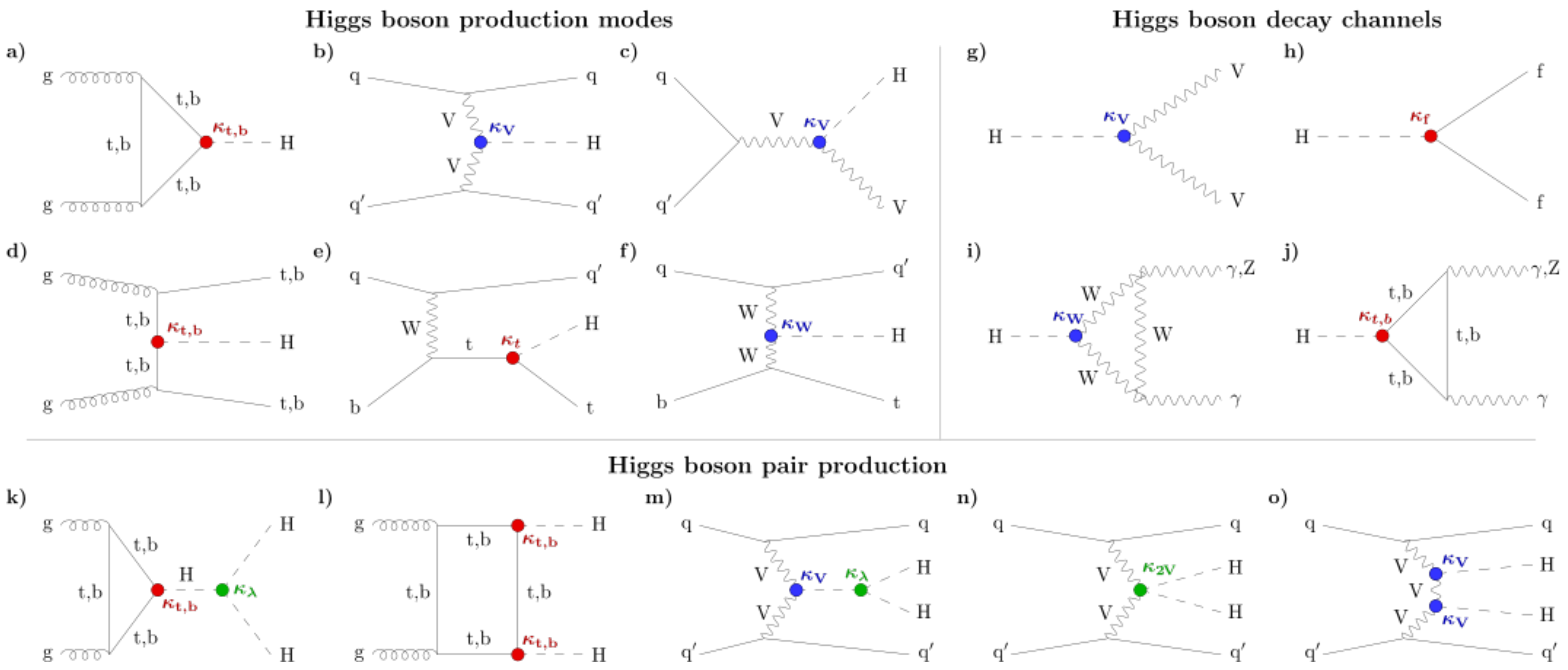
A precision of <~2 % could be reached with a m(bb) resolution of 3 GeV at the Higgs mass

Summary

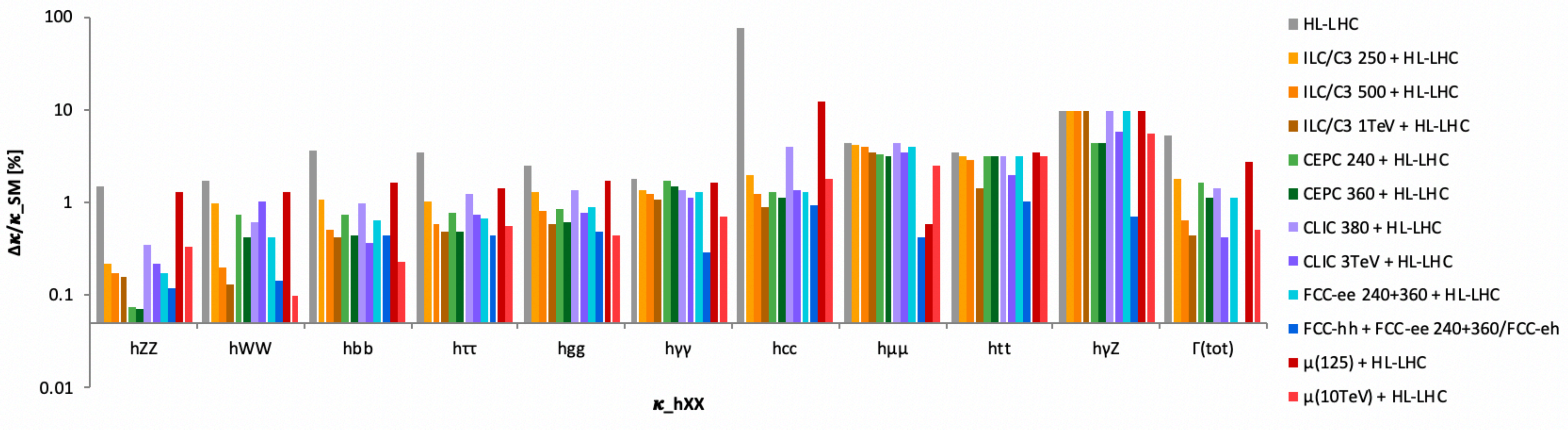
- We have restarted studies on Higgs physics at the FCC-hh
- We are looking especially at double Higgs production as benchmark channel
- Two channels studied for now, a re-optimized study of $bb\gamma\gamma$ and a new channel $bbll + E_T^{miss}$
- As expected $bb\gamma\gamma$ would drive the final precision. The present projection is around 3.6%, but a precision on the trilinear coupling of below 2% could be achieved with an optimal calorimeter and more refined analysis



Backup


Higgs boson production modes
Higgs boson decay channels
Higgs boson pair production
a)
b)
c)
d)
e)
f)
g)
h)
i)
j)
k)
l)
m)
n)
o)

Backup



Fron Snowmass report arXiv:2209.07510

Backup

Parameter	FCC-hh		HL-LHC	LHC
collision energy cms [TeV]	80-116		14	14
dipole field [T]	14 (Nb_3Sn) – 20 (HTS/Hybrid)		8.33	8.33
circumference [km]	90.7		26.7	26.7
beam current [A]	0.5		1.1	0.58
bunch intensity [10^{11}]	1	1	2.2	1.15
bunch spacing [ns]	25	25	25	25
synchr. rad. power / ring [kW]	1020-4250		7.3	3.6
SR power / length [W/m/ap.]	13-54		0.33	0.17
long. emit. damping time [h]	0.77-0.26		12.9	12.9
beta* [m]	1.1	0.3	0.15 (min.)	0.55
normalized emittance [μm]	2.2		2.5	3.75
peak luminosity [10^{34} $cm^{-2}s^{-1}$]	5	30	5 (lev.)	1
events/bunch crossing	170	1000	132	27
stored energy/beam [GJ]	6.1-8.9		0.7	0.36
integrated luminosity [fb^{-1}]	20000		3000	300

From Fabiola Gianotti, FCC Week London 2023

Backup

	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	
$H_{\mathrm{T2}}^{\mathrm{ratio}}$		> 0.8	
$m_{\ell b}^{\mathrm{reco}}$		> 150 GeV	
$\Delta\phi(\ell\ell, E_T^{\mathrm{miss}})$	< 2		< 1.2
$m_{\ell\ell}$	10 - 80 GeV		81 - 101 GeV
$\Delta\phi(\ell\ell, E_T^{\mathrm{miss}})$-categories	< 1.2 ("low") and $1.2 - 2.0$ ("high")		-

Table 3: Summary of the event selection and categorization.

Present CMS Run 2 results

https://cds.cern.ch/record/2882424/files/HIG-23-006-pas.pdf

Hypothesis	Best fit $\pm 1\sigma$ Expected	Observed	95% CL interval Expected	Observed
Other couplings fixed to SM	$1.0^{+4.6}_{-1.7}$	$3.1^{+3.0}_{-3.0}$	$[-2.0, +7.7]$	$[-1.2, +7.5]$
Floating $(\kappa_V, \kappa_{2V}, \kappa_f)$	$1.0^{+4.7}_{-1.8}$	$4.5^{+1.8}_{-4.7}$	$[-2.2, +7.8]$	$[-1.7, +7.7]$
Floating $(\kappa_V, \kappa_t, \kappa_b, \kappa_\tau)$	$1.0^{+4.8}_{-1.8}$	$4.7^{+1.7}_{-4.1}$	$[-2.3, +7.7]$	$[-1.4, +7.8]$
Floating $(\kappa_V, \kappa_{2V}, \kappa_t, \kappa_b, \kappa_\tau, \kappa_\mu)$	$1.0^{+4.8}_{-1.8}$	$4.7^{+1.7}_{-4.2}$	$[-2.3, +7.8]$	$[-1.4, +7.8]$