Study of Higgs pair production in the 4 b quarks final state at 100 TeV for the FCC-hh

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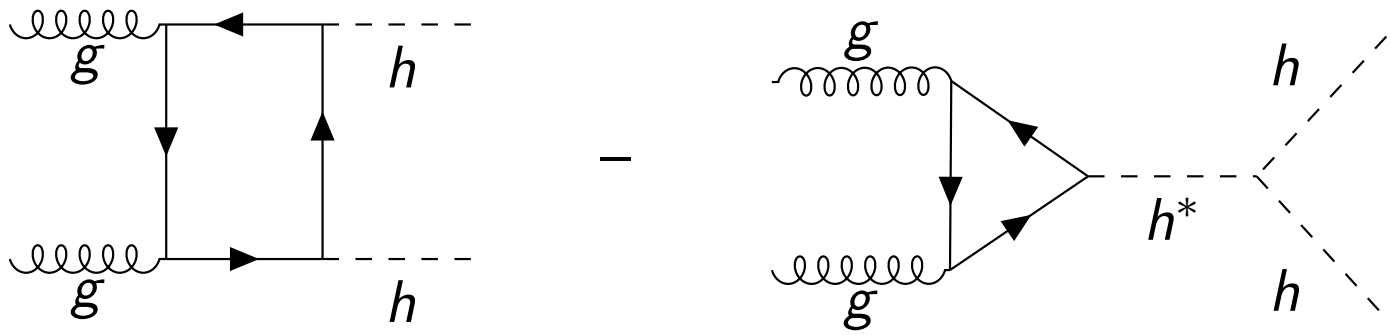
Overview I

Channel: $pp \to hh \to b\bar{b}b\bar{b}$



Goals:

- Evaluate the analysis sensitivity to SM Higgs pair production as well as to BSM scenarios (**2HDM** and **DM mediator**)
- Evaluate how the analysis sensitivity varies with the granularity of the HCAL
- Compare the performance of HCAL-only and particle flow jets

Overview II

Analysis strategy:

- Boosted category (Higgs candidates reconstructed as two fat jets)
- Cut-based analysis ("Cut and count")
- Standalone ROOT starting from FCC samples (produced new samples for BSM signals and increased stats for some backgrounds)

Monte Carlo samples: MG5+Pythia8+Delphes3 (FCC fast simulation)

Signal and backgrounds

FCC-hh samples

Sample	$\sigma \times BR$ [pb]	k-factor	$\sim$ no. events
$pp \to hh \to b\bar{b}b\bar{b}$ (**SM**)	0.827	1.09	5×10^6
$gg \to hh \to b\bar{b}b\bar{b}$ (**2HDM**)	0.466	1.0	5×10^6
$gg \to hh \to b\bar{b}b\bar{b}$ (**DM**)	0.218	1.0	5×10^6
4b+j (QCD, $200 < p_T^j < 500$)	756.4	2.0	10×10^6
4b+j (QCD, $p_T^j > 500$)	57.71	2.0	10×10^6
4b+j (QCD+EWK)	6.204	1.0	10×10^6
4b+j (EWK)	0.07206	1.0	5×10^6
jj+0/1/2 j ($500 < H_T < 1000$)	1.64×10^7	1.0	10×10^6
jj+0/1/2 j ($1000 < H_T < 2000$)	1.67×10^6	1.0	1×10^6
jj+0/1/2 j ($2000 < H_T < 4000$)	1.32×10^5	1.0	1×10^6
jj+0/1/2 j ($4000 < H_T < 7200$)	7.32×10^3	1.0	1×10^6
jj+0/1/2 j ($7200 < H_T < 15000$)	4.75×10^2	1.0	1×10^6
jj+0/1/2 j ($15000 < H_T < 25000$)	7.35	1.0	1×10^6
jj+0/1/2 j ($25000 < H_T < 35000$)	0.176	1.0	5×10^5
jj+0/1/2 j ($35000 < H_T < 100000$)	0.00765	1.0	3×10^5
$t\bar{t}$+0/1/2 j	4.31×10^4	1.74	5×10^6

NOTE: We do not include the multijet sample with $0 < H_T < 500$ because the cross section is huge ($\sim 10^9$) and we assume it can be completely rejected (backup).

BSM samples

CP conserving type II 2HDM

- **Two CP-even scalars:** $m_h = 125$ GeV, $m_H = 900$ GeV
- **One CP-odd scalar:** $m_A = 850$ GeV
- **Two charged:** $m_{H^\pm} = 800$ GeV
- $\beta = \frac{v_1}{v_2} = \frac{\pi}{4}$, $\alpha = -0.75$

1 TeV scalar DM mediator

- Dark matter particles
- **Scalar mediator:** $m_X = 1$ TeV (couples DM particles to SM)

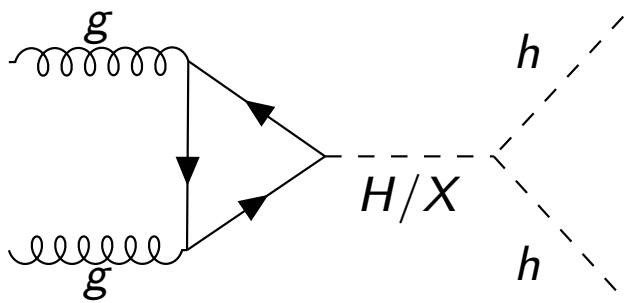


Figure: Additional (with respect to SM) Feynman diagram

HCAL granularity configurations

Table: Summary of the benchmark granularity configurations of the HCAL.

FCC detector simulation plus	$\Delta\eta \times \Delta\phi$	η range
1 (ATLAS HCAL)	0.1×0.1	$\lvert\eta\rvert < 2.5$
	0.2×0.2	$2.5 < \lvert\eta\rvert < 5.0$
2 (ATLAS HCAL $\eta \times 4$)	0.025×0.1	$\lvert\eta\rvert < 1.7$
	0.1×0.1	$1.7 < \lvert\eta\rvert < 2.5$
	0.2×0.2	$2.5 < \lvert\eta\rvert < 5.0$
3 (FCC HCAL $\phi/2$)	0.025×0.05	$\lvert\eta\rvert < 2.5$
	0.05×0.1	$2.5 < \lvert\eta\rvert < 6.0$
4 (FCC HCAL)	0.025×0.025	$\lvert\eta\rvert < 2.5$
	0.05×0.05	$2.5 < \lvert\eta\rvert < 6.0$
5 (FCC HCAL $\eta, \phi \times 2$)	0.0125×0.0125	$\lvert\eta\rvert < 2.5$
	0.025×0.025	$2.5 < \lvert\eta\rvert < 6.0$
ATLAS detector simulation plus	$\Delta\eta \times \Delta\phi$	η range
1 (ATLAS HCAL)	0.1×0.1	$\lvert\eta\rvert < 2.5$
	0.2×0.2	$2.5 < \lvert\eta\rvert < 5.0$

Event selection

Particle flow, anti-k_T, $R = 0.8$ jets

B-tagging:

- The soft-drop subjets are b-tagged by ΔR matching to truth level partons (b and c quarks)
- Efficiency and mistag rates are applied (from FCC-hh Delphes card)
- A jet is considered b-tagged if **both** subjets are b-tagged

Cuts (optimized selection):

- No. of b-tagged jets ≥ 2
- $p_T(j_1, j_2) > 200$ GeV
- $p_T(j1) > 300$ GeV
- $p_T(j1 + j2) > 100$ GeV
- $\tau_{21}(j_1, j_2) < 0.4$
- $|\Delta\eta(j_1, j_2)| < 1.5$
- $H_2(j_1) > 0.2$
- $100 < M_{SD}(j1, j2) < 135$ GeV

Analysis strategy and uncertainties

- Consider integrated luminosity of 30 ab^{-1}
- Use $S/\sqrt{B}$ and signal efficiency to optimize selection and compare detector benchmarks

Statistical unc.

- Events normalized to integrated luminosity scenario $\left(w = \frac{\mathcal{L} \times \sigma}{N}\right)$
- Propagate errors to $S/\sqrt{B}$

Systematic unc.

- Apply numbers from previous analyses/studies
- Signal b-tagging efficiency: 30%
  ATLAS search: CERN-EP-2018-029
- QCD background normalization: 50%
- $t\bar{t}$ background normalization: 20%
  FCC studies: Resonances at 100 TeV, C.Helsens, M.Selvaggi, D.Taiwan, FCC week, April 2018

Signal efficiency

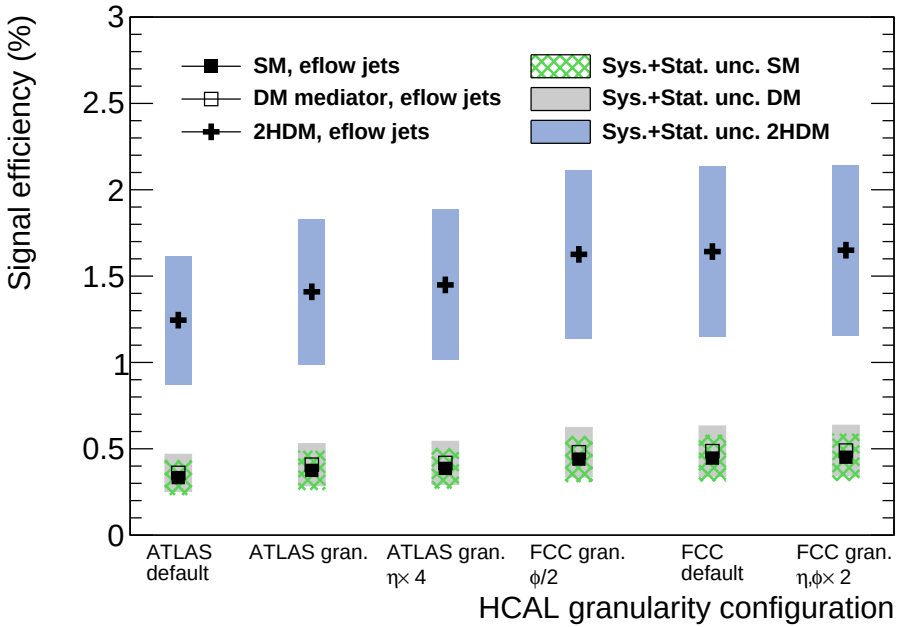


Figure: Particle flow jets

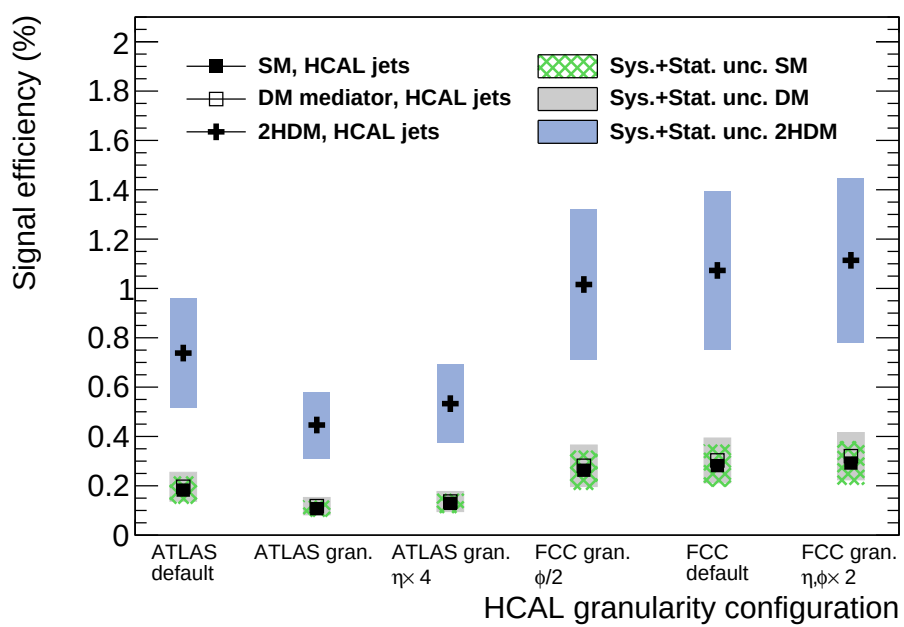


Figure: HCAL jets

- High efficiency of 2HDM is due to fully resonant production
- Signal efficiency increases with HCAL granularity (as expected)
- Stronger dependence for HCAL-only jets

Significance

Signal sample	FCC w/ ATLAS HCAL	FCC default
SM	7.5 ± 1.3 (stat.) $^{+3.5}_{-2.6}$ (sys.)	8.8 ± 1.6 (stat.) $^{+4.1}_{-3.1}$ (sys.)
DM mediator	2.0 ± 0.4 (stat.) $^{+0.9}_{-0.7}$ (sys.)	2.3 ± 0.4 (stat.) $^{+1.1}_{-0.8}$ (sys.)
2HDM type II	14.6 ± 2.7 (stat.) $^{+6-8}_{-5.0}$ (sys.)	16.7 ± 3.0 (stat.) $^{+7.8}_{-5.8}$ (sys.)

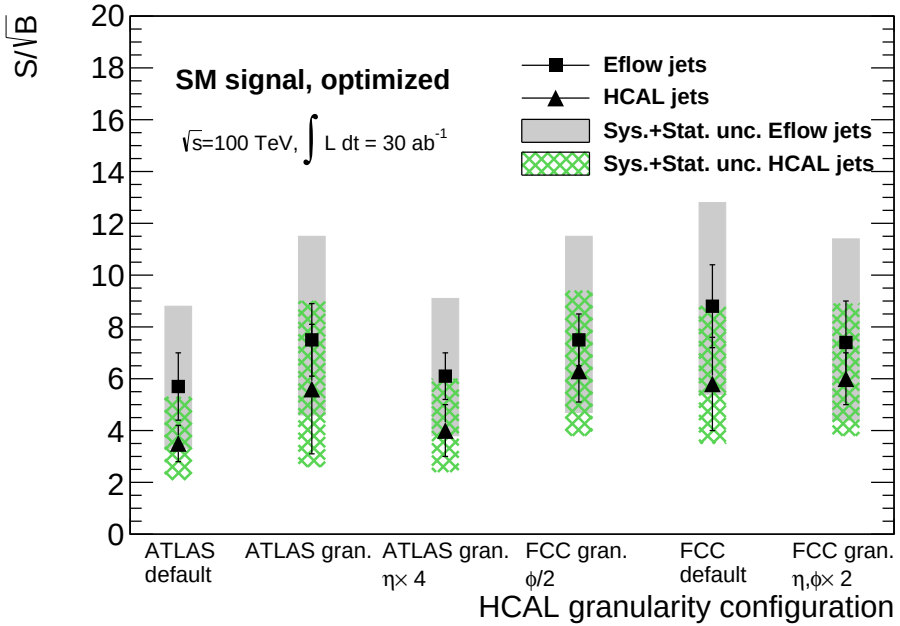


Figure: SM signal

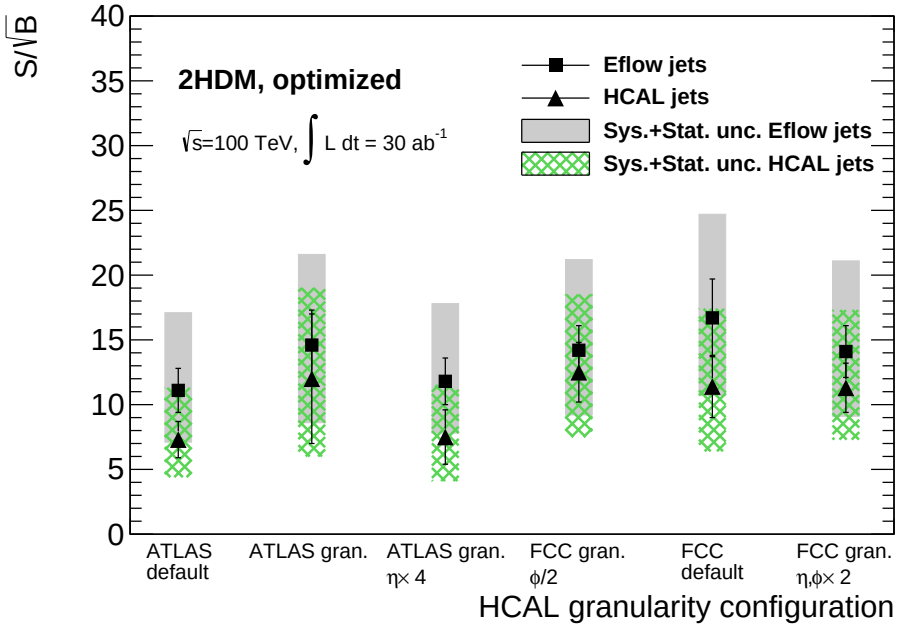


Figure: 2HDM signal

Significance

Comments

Table

- $S/\sqrt{B}$ above 5σ for SM and 2HDM (exciting!)
- **SM:** $\sim 17\%$ increase going from ATLAS HCAL to FCC HCAL
- Observation/Exclusion of this DM mediator model is probably unachievable

Plots

- Particle flow jets always give larger $S/\sqrt{B}$ (for the same detector configuration)
- Despite the **large error bars**, $S/\sqrt{B}$ seems to increase with granularity (as expected)

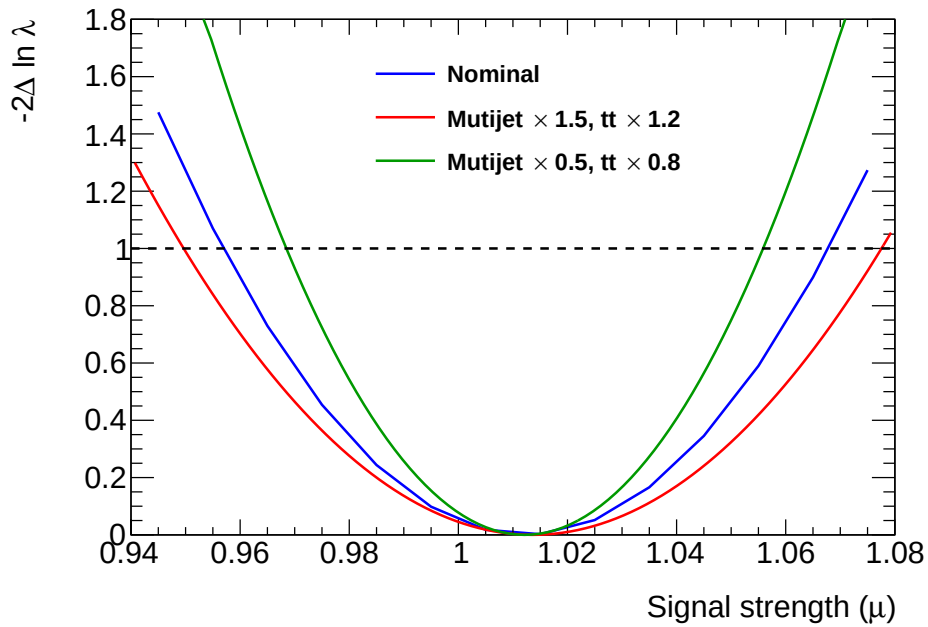
Uncertainty on signal strength

- Negative log likelihood fit to $m(hh)$ distribution to extract signal strength (after all cuts)
- **Likelihood function:**

$$-2\ln\lambda(\mu) = -2\ln\frac{\mathcal{L}(\mu)}{\mathcal{L}(\hat{\mu})} = 2\sum_{i=1}^{N_{\text{bins}}}\left[(k_i) - n_i + n_i\ln\left(\frac{n_i}{k_i}\right)\right]$$

with $k_i = \mu\, s_i + b_i$ and $\hat{\mu}$ defined by $\sum_i n_i = \hat{\mu}\sum_i s_i + \sum_i b_i$

- **Result:** $\mu = 1.01 \pm 0.06$
- Statistical uncertainty: 6%
- Impact of simplified systematics: $\sim 10\%$



Uncertainty on Higgs triple coupling

On going work

- Took samples with $k_\lambda = 0.5, 0.9, 1.1, 1.5$
- Computed likelihood using different expected distributions

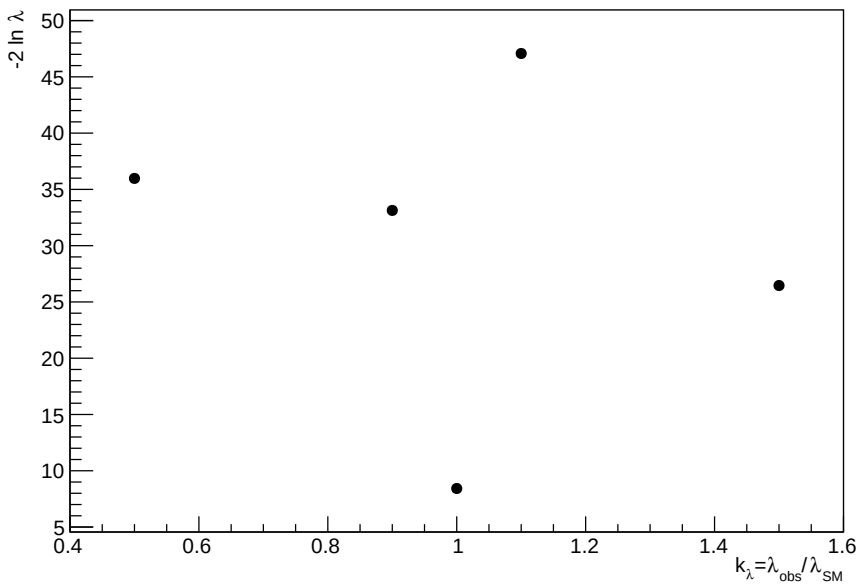


Figure: Likelihood

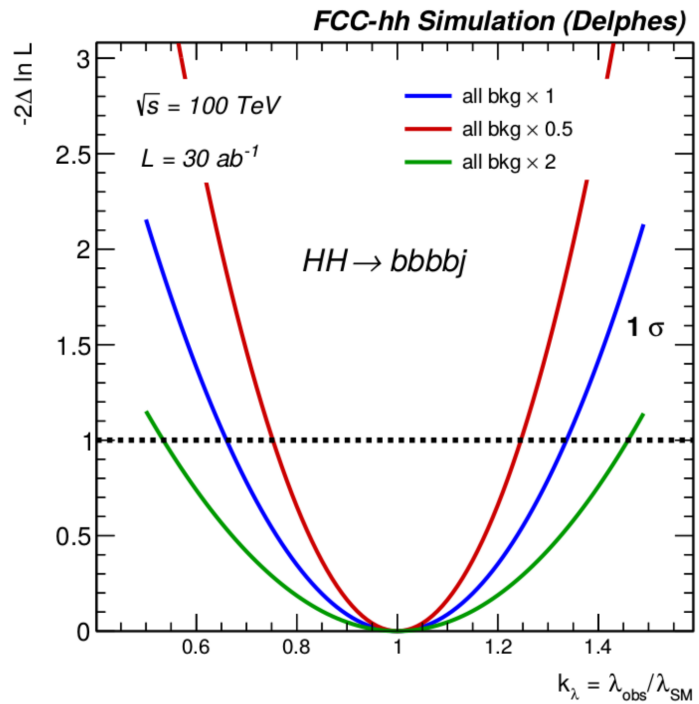


Figure: Previous study of $hh \to bbbj$ from CDR

Summary

Analysis sensitivity (significance):

- $S/\sqrt{B}$ (**SM**) $= 8.8 \pm 1.6$ (stat.) $^{+4.1}_{-3.1}$ (sys.)
- $S/\sqrt{B}$ (**2HDM**) $= 16.7 \pm 3.0$ (stat.) $^{+7.8}_{-5.8}$ (sys.)
- Both number above 5σ

Signal strength:

- μ (**SM**) $= 1.01 \pm 0.06$
- Impact of simplified systematics: $\sim 10\%$

Higgs triple coupling:

- On going work
- Expect to get final results in the next couple of weeks

Backup

Multijet samples

Additional contributions (not included)

- $jj + 0/1/2j$, $0 < H_T < 500$
  - $\sigma \sim 10^9$ pb
  - Considering $\epsilon \sim 1/10^9 \rightarrow <10\%$ effect on $S/\sqrt{B}$
  - Considering $\epsilon \sim 1/10^8 \rightarrow \sim 40\%$ effect on $S/\sqrt{B}$ (nominal value still above 5σ)
  - **Might require further studies**

- $4b + j$, $(30 < p_T < 200)$ GeV
  - $\sigma = 7450$ pb
  - $\epsilon(\%) < 9 \times 10^{-4}$
  - Decrease in $S/\sqrt{B}$ of $\sim 0.22\%$
  - **Safe to neglect**

Additional backgrounds

Processes involving Higgs bosons

Table: Effective cross section ($\sigma \times$ BR $\times$ k-factor), efficiency and expected number of events for $\mathcal{L} = 30$ ab^{-1} for the $t\bar{t}h + 0/1\ j$ ($h \to b\bar{b}$) and $h + 0/1/2\ j$ ($h \to b\bar{b}$) backgrounds.

Process	$\sigma \times$ BR $\times$ k-factor [pb]	Efficiency [%]	Expected no. events
$t\bar{t}h + 0/1\ j(h \to b\bar{b})$	31.86	0.089	8.5×10^5
$h + 0/1/2\ j(h \to b\bar{b})$	1286.52	0.0041	1.6×10^6

- Decrease in $S/\sqrt{B}$ of $\sim 0.26\%$
- **Safe to neglect**

Comparing with other studies

Extrapolation to the HL-LHC

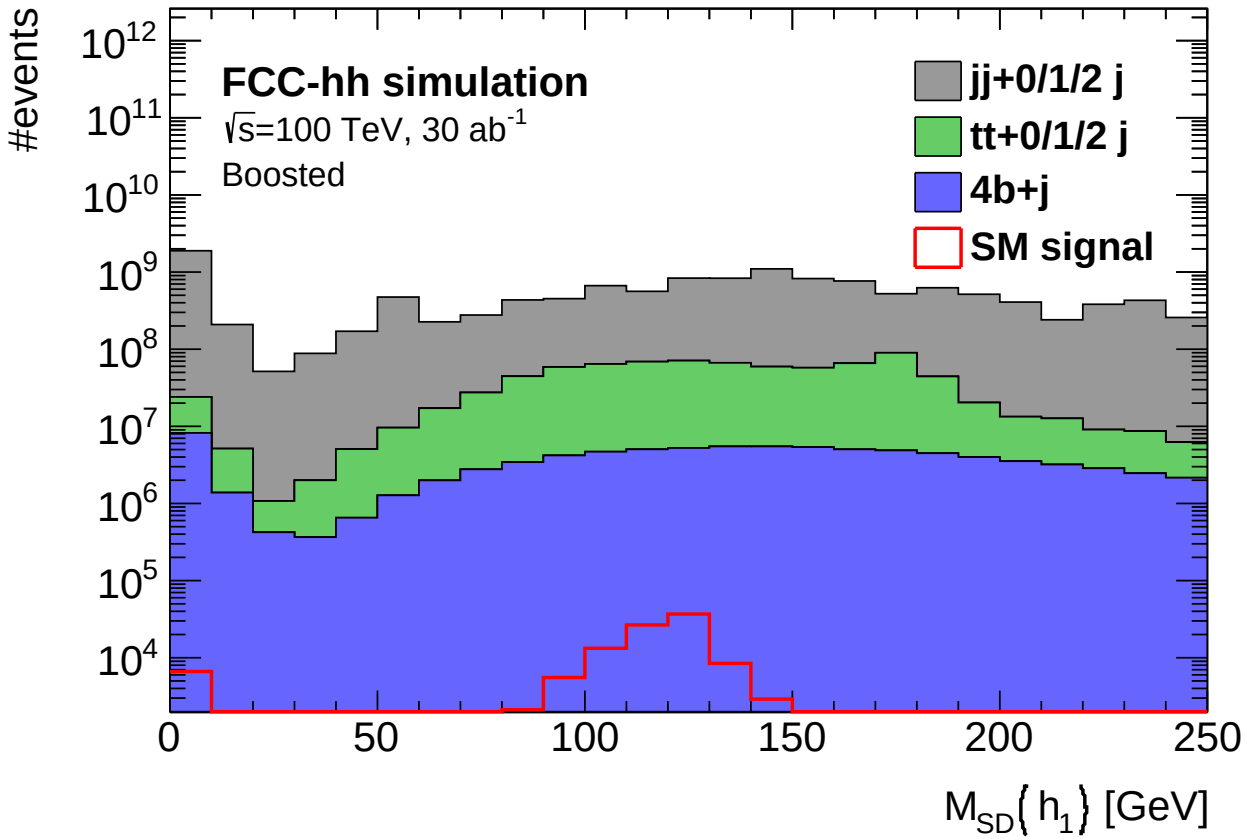
Parameters: $\sqrt{s} = 14$ TeV, $\mathcal{L} = 3$ ab^{-1}

Signal sample	ATLAS default
SM	$1.4^{+0.8}_{-0.6}$
2HDM type II	$5.4^{+2.8}_{-2.1}$

CMS projection: $Z_{\text{value}} = 4.4$ (resolved analysis)

Distributions

Before mass cuts



Jet mass resolution