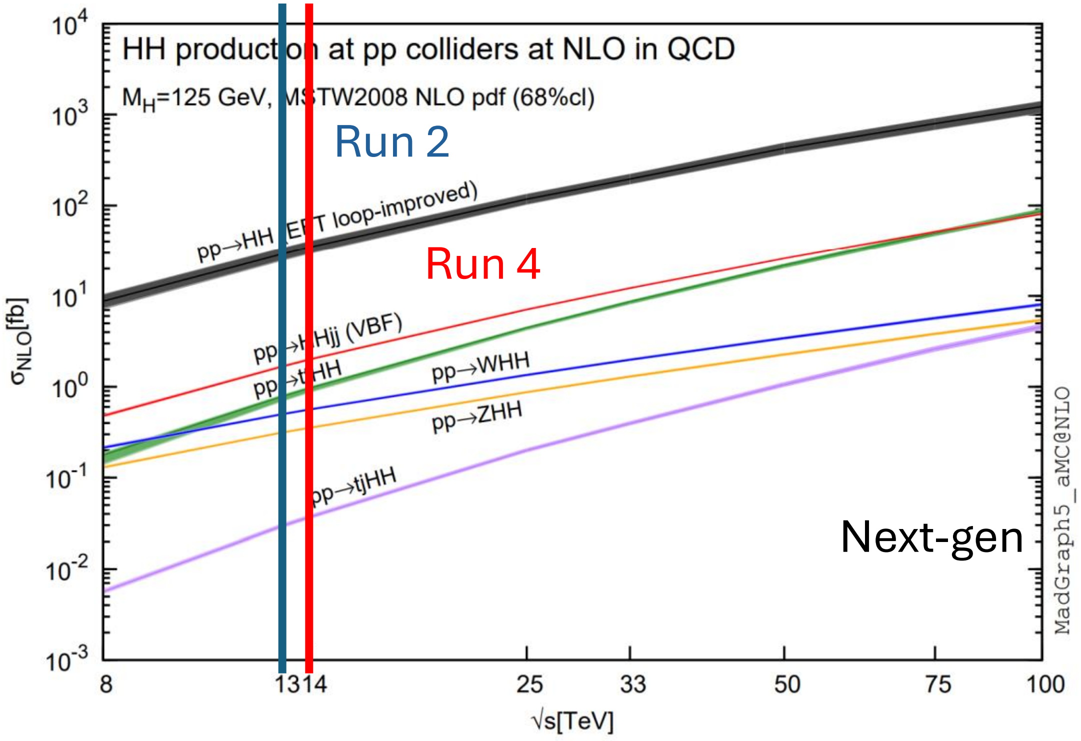
$ttHH$ proporsal via $bb\tau\tau$ decay mode

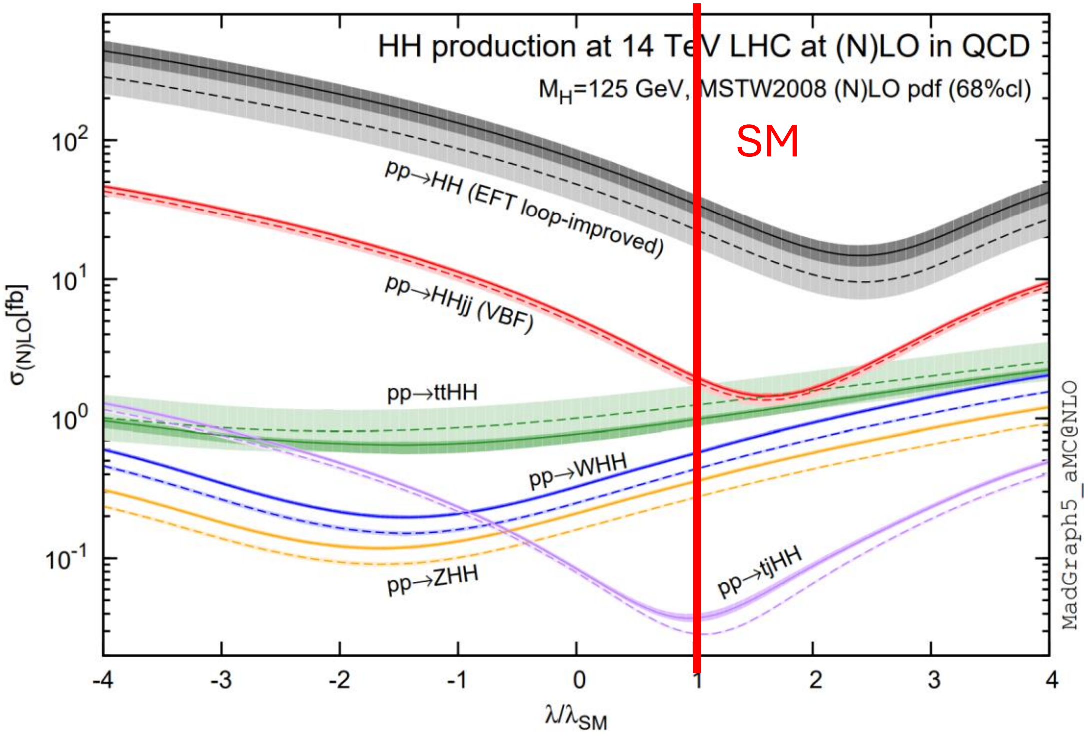
Yang Tianyi

Why ttHH

Cross-section w.r.t CME



Cross-section w.r.t HHH strength



- $ttHH$ is the **third leading** process of HH production, becoming the second leading in FCC-hh or SPPC.
- $ttHH$ has **low interference**; ggF and VBF have destructive interference.

Phys. Lett. B732 (2014) 142

Ongoing CMS $ttHH$ groups

- HIG-24-016
  - Notes: AN -2022/122
  - Channel: $ttHH \ + \ HH \rightarrow b\bar{b}b\bar{b}$
  - Contact person: aurore.savoy.navarro@cern.ch (SACLAY, France)

- HIG-23-004
  - Notes: AN-2022/104
  - Channel: $ttHH \ + \ H \rightarrow \gamma\gamma \ + \ H \rightarrow b\bar{b}/WW/\tau\tau,$
  - Contact person: angelo.giacomo.zecchinelli@cern.ch (Boston, US)

All possible Higgs decay modes

- The 125 GeV Higgs BR theoretical computation*:
  - $H \to b\bar{b}$: 58.24%
  - $H \to \gamma\gamma$: 0.227%
  - $H \to WW$: 21.37%
  - $H \to ZZ$: 2.619%
  - $H \to \tau\tau$: 6.272%
- The possible channel to consider would be:
  - $HH \to b\bar{b}b\bar{b}$
  - $HH \to b\bar{b} + \gamma\gamma/WW/ZZ/\tau\tau$
- $t\bar{t}$ could decay hadronically, single lepton (SL) and double leptons (DL).

* CERNYellowReportPageBR twiki by LHCHXSWG

Branching ratios

Branching Ratio (BR)	0L	SL	DL	
$HH \rightarrow b\bar{b}b\bar{b}$	15.41%	9.76%	1.54%	France Group
$HH \rightarrow b\bar{b} + \tau\tau$, 1p+lep	1.096%	0.694%	0.110%	
$HH \rightarrow b\bar{b} + \tau\tau$, 1p+1p	0.730%	0.462%	0.073%	
$HH \rightarrow b\bar{b} + WW$, leplep	0.515%	0.326%	0.052%	
$HH \rightarrow b\bar{b} + WW$, lephad	3.254%	2.060%	0.326%	Sungbeom's study
$HH \rightarrow b\bar{b} + ZZ$, qqll	0.130%	0.083%	0.013%	
$HH \rightarrow b\bar{b} + ZZ$, 4l	0.00628%	0.00397%	0.00063%	
$HH \rightarrow b\bar{b} + \gamma\gamma$	0.120%	0.076%	0.012%	Boston Group

XS	Run2	Run3	HL-LHC
$\sqrt{s}$ / TeV	13	13.6	14
fb	0.764	0.87	0.947

- Assuming 300 fb^{-1}, 260 ttHH events expected without acceptance in Run3.
- <0.38% gets less than one yield expected.
- ZZ multilepton final state is too small.
- $\boldsymbol{WW}$ and $\boldsymbol{\tau\tau}$ are possible choices with acceptable BR remaining.

Hints from ggF study (Run 2 published)

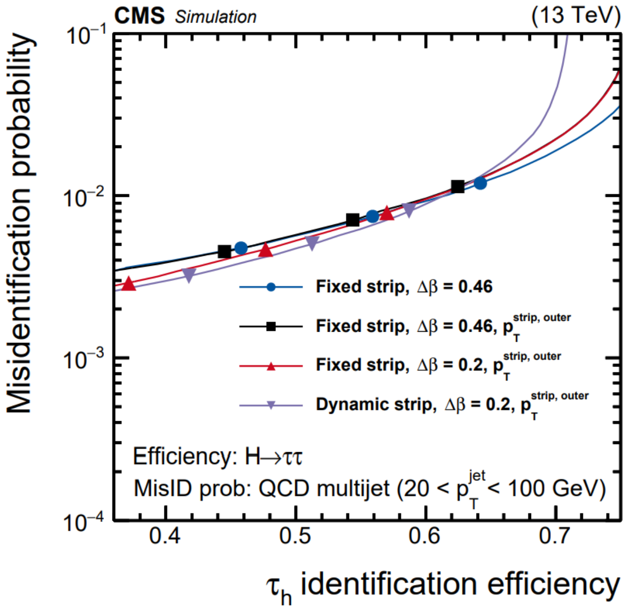
- $HH \rightarrow b\bar{b}\gamma\gamma$, ggF+VBF, **HIG-19-018**
  - Excluding **7.7** times SM prediction ggF+VBF XS+BR (5.2 expected).
  - *JHEP03(2021)257*
- $HH \rightarrow b\bar{b}ZZ(4l)$, ggF, **HIG-20-004**
  - Excluding **32.4** times SM prediction ggF signal strength (39.6 expected).
  - *JHEP06(2023)130*
- $HH \rightarrow b\bar{b}b\bar{b}$, ggF+VBF, **HIG-20-005**
  - Excluding **3.9** times SM prediction ggF+VBF XS (7.8 expected).
  - *PhysRevLett.129.081802*
- $HH \rightarrow b\bar{b}\tau\tau$, ggF+VBF, **HIG-20-010**
  - Excluding **3.3** times SM prediction ggF+VBF XS (5.2 expected).
  - *Physics Letters B 842 (2023) 137531*
- $HH \rightarrow WWWW/WW\tau\tau/\tau\tau\tau\tau$, multi-leptons, ggF+VBF, **HIG-21-002**
  - Excluding **21.3** times SM prediction ggF+VBF XS (19.4 expectedd)
  - JHEP07(2023)095
- $HH \rightarrow b\bar{b}WW$, >1 lep, ggF+VBF, **HIG-21-005**
  - Excluding **14** times SM prediction of ggF+VBF XS (18 expected)
  - JHEP07(2024)293

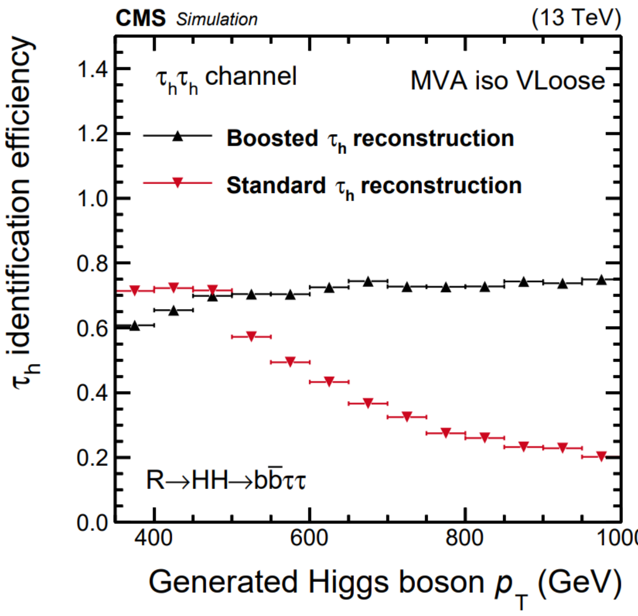
Is $bb\tau\tau$ a good channel?

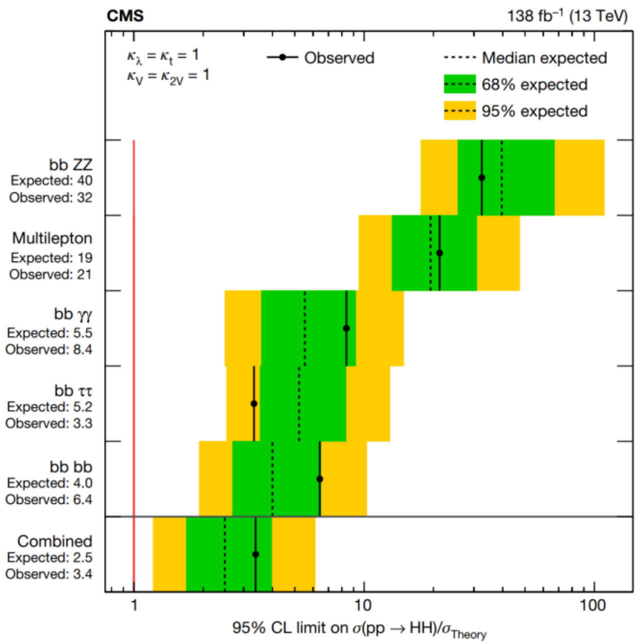
- Though $ttHH$ is different from ggF, we still get $H \to VV$ has low excluding power.
- The $bb\tau\tau$ channel in ggF looks promising.
- $\tau\tau$ decay channel limits:
  - lep-lep decay: only possible with different flavour ($e\mu$), with heavy $t\bar{t}$ background (not suitable with $ttHH$), with low acceptance and too many ν (≥ 4).
  - 3-prong: difficulty in a_1 reconstruction, its variables may have low sensitivity.
  - May need to start with hadhad and lephad with 1-prong.

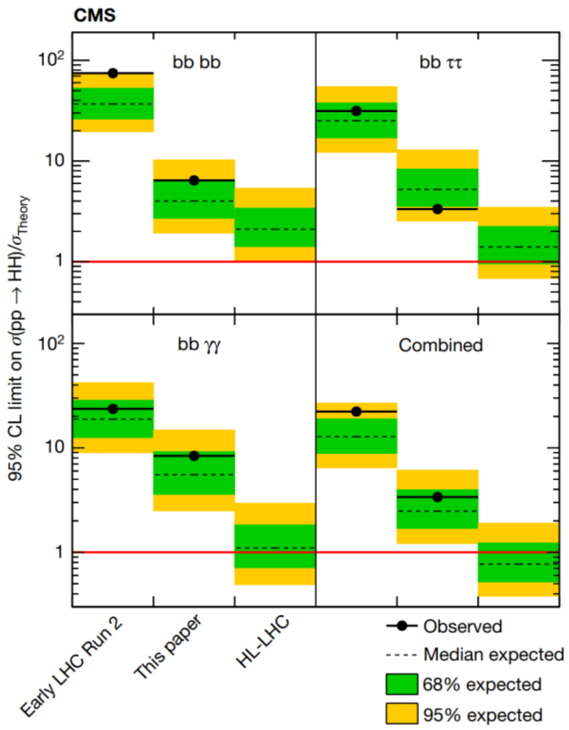
Is $bb\tau\tau$ a good channel?

- Advantage of $bb\tau\tau$:
  - τ_{had} has light flavour final states. In principle separatable from other final state particles, i.e. $t\bar{t}$ and $H \to b\bar{b}$?
  - Though difficult to contribute to multi-lepton, it is fine with 1 lepton final-state.
  - Relatively large BR with confidence from ggF study.









TAU-16-003; HIG-20-011

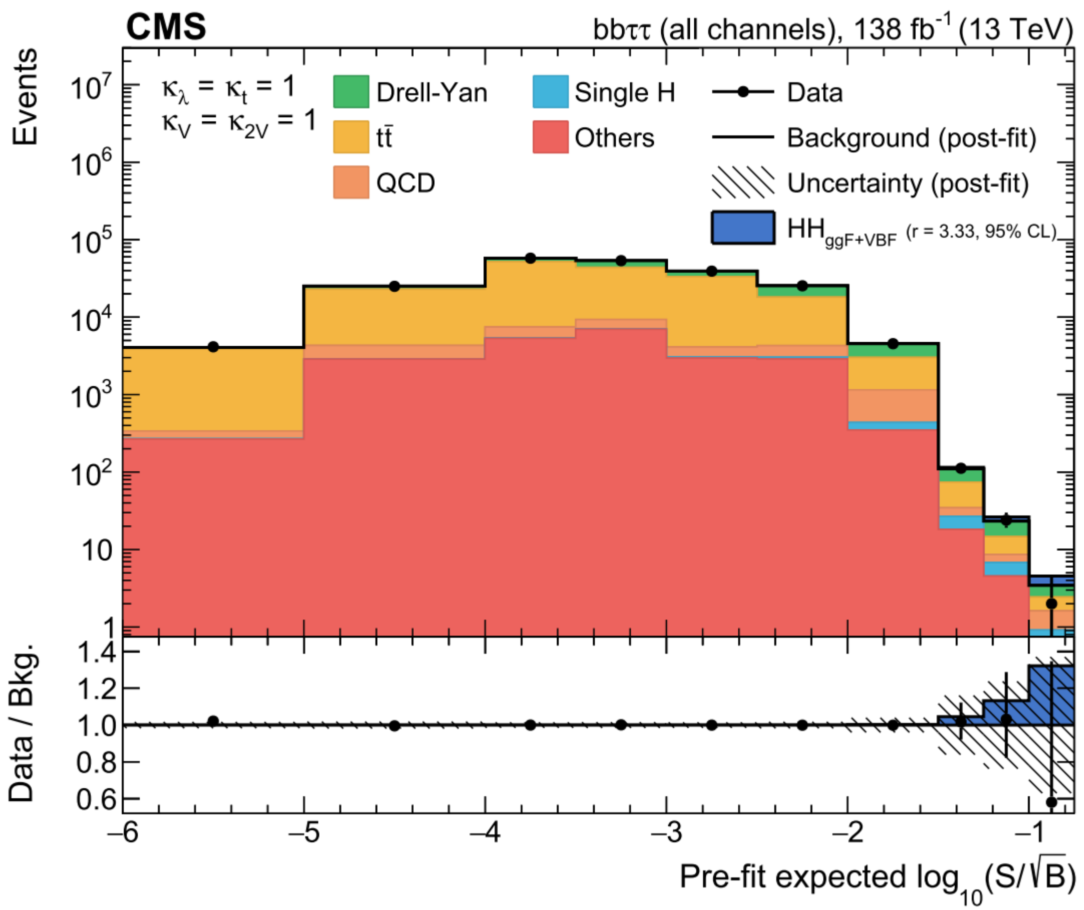
Backgrounds for $HH \to bb\tau\tau$

- Decay mode: lep-had + had-had
- Signal:
  - ggF HH @NLO using POWHEG v2.0
  - VBF HH @LO using MG5_aMC@NLO
- Backgrounds:
  - $Z/\gamma^* \to ll$ + jets; W + jets, dominant for had-had
  - $t, H, t\bar{t}$ + jets, dominant for lep-had
  - Diboson & triboson
  - $t\bar{t}V, t\bar{t}VV$

Event categorization for $HH \rightarrow bb\tau\tau$

- VBF-tagged:
  - $m_{jj} > 500$ GeV & $\Delta\eta_{jj} > 3$
  - Signal subclasses: classVBF, classGGF,
  - Backgrounds subclasses: classttH, classTT, classDY
- Boosted:
  - Not VBF-tagged & $\Delta R(b, b) < 0.8$
  - Two AK4 jets merged to AK8 jet, $m_{AK8} > 30$ GeV, $\Delta R(b, b) < 0.4$ passing loose b-tagging
- Resolved:
  - Not meet boosted.
  - B-tag multiplicity classification: res1b, res2b
- In each of the region, DNN algorithm is used for discriminant between HH signal and background.
- $ttHH$ study would not need VBF-tagging, but need more b-tagging.

Signal and background for $HH \to bb\tau\tau$



- DNN used for binned fit.
- Combining bins with similar sensitivity in DNN bins in each category, year, and τ decay mode.
- The upper limit of signal strength result is shown as follows:

Expected limit	2016	2017	2018	Combined
$\sigma_{ggF+VBF}(pp \to HH)/\sigma^{SM}_{ggF+VBF}$	10.6	11.7	8.2	5.2
$\sigma_{ggF+VBF}(pp \to HH)$ [fb]	324	356	249	159
$\sigma_{ggF+VBF}(pp \to HH \to bb\tau\tau)$ [fb]	23.6	26.0	18.2	11.6
Observed limit	**2016**	**2017**	**2018**	**Combined**
$\sigma_{ggF+VBF}(pp \to HH)/\sigma^{SM}_{ggF+VBF}$	8.9	9.5	5.5	3.3
$\sigma_{ggF+VBF}(pp \to HH)$ [fb]	272	291	169	102
$\sigma_{ggF+VBF}(pp \to HH \to bb\tau\tau)$ [fb]	19.6	21.2	12.4	7.5

Dominant background in ttH

Process	$1\ell + 1\tau_h$	$0\ell + 2\tau_h$
$t\bar{t}H$	183 ± 41	24.4 ± 6.0
tH	65 ± 46	16 ± 12
$t\bar{t}Z + t\bar{t}\gamma^*$	203 ± 24	27.1 ± 3.8
$t\bar{t}W + t\bar{t}WW$	254 ± 34	3.8 ± 0.5
WZ	198 ± 37	42.5 ± 8.7
ZZ	98 ± 13	34.2 ± 4.8
DY	4480 ± 460	1430.0 ± 220
$t\bar{t}$+jets	41900 ± 1900	861 ± 98
Misidentified leptons	25300 ± 1900	3790 ± 220
Rare backgrounds	1930 ± 420	60 ± 14
Conversion	–	–
$ggH + qqH + VH + t\bar{t}VH$	38.5 ± 3.6	26.7 ± 3.6
Total expected background	73550 ± 610	6290 ± 130
Data	73736	6310

- Full Run 2 ttH with multilepton (and τ_h) decay study.
- In ttH channel with $t\bar{t}$, also the $Z \to ll$ and $t\bar{t}$+jets are dominant backgrounds.
- $\tau_h\tau_h$ channel might suppress the $t\bar{t}$ background, in comparison to $HH \to b\bar{b}b\bar{b}$ channel.

HIG-19-008

$ttHH$ pre-study

- We may have some feasibility pre-study for $ttHH$ channel.
- If we may try $ttHH + bb\tau\tau$, we can have:
  - Generate some samples for $ttHH + bb\tau\tau$ and Drill-Yan with jets, $t\bar{t}$ samples might be shared between multi-lepton decay study and $bb\tau\tau$ study.
  - Have some discussion on the pre-selection and event categorization for this channel based on the first observation of samples.
  - Test the reconstruction and identification of $\tau_h\tau_h$ performance with the presence of additional $t\bar{t}$.
  - Valid the dominant backgrounds and consider discriminant for $\tau_{e/\mu}\tau_h$ and $\tau_h\tau_h$ seperately.

Possibility to collaborate with France group

- On Wednesday, I had a discussion with Sungbeom about the possibility to collaborate with the France group.

- Though $ttHH$ might not have strong boosted topology, the jet merging does exist, maybe also between jets from Higgs and top.
- Sungbeom noticed that in their nanoAOD code, the fat jet was turned off. We might turn on the fat jet to see if there is anything interesting.
- This operation might also be applied to different decay modes.