Search for Higgs-like scalar particles in the $bb\gamma\gamma$ final state with the ATLAS experiment

Enlightening the beauty of the Higgs

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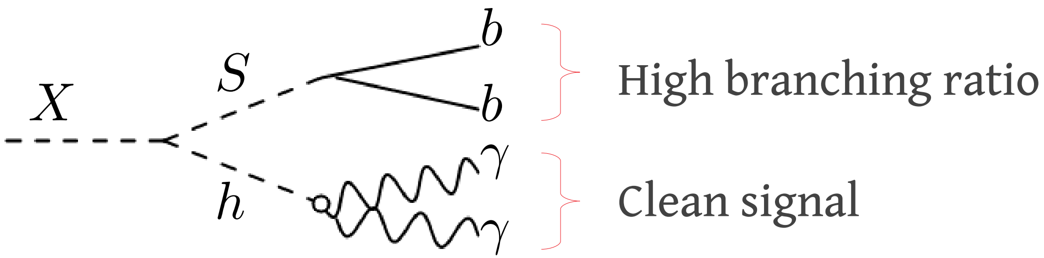
Introduction

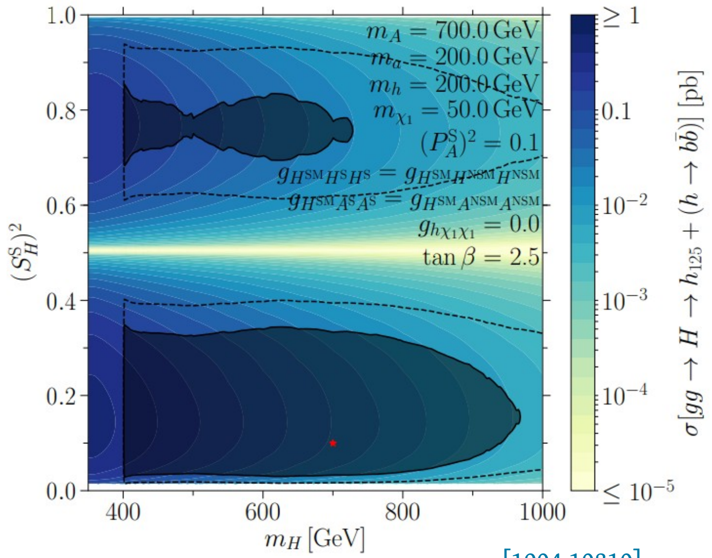
- Baryon-antibaryon asymmetry can be achieved by extensions of the Higgs sector.
- Baryogenesis via *Strong First Order Electroweak Phase Transition* which also generates primordial gravitational wave, testable by space-based gravitational wave detector.
  - See talk by G. Dorsch in LHCP2022!
- Most experimental efforts so far have been focused on CP-conserving models which do not allow for this signature.

- We will focus on Higgs sector extension models which contain X (heavier), S (lighter) scalar particles.

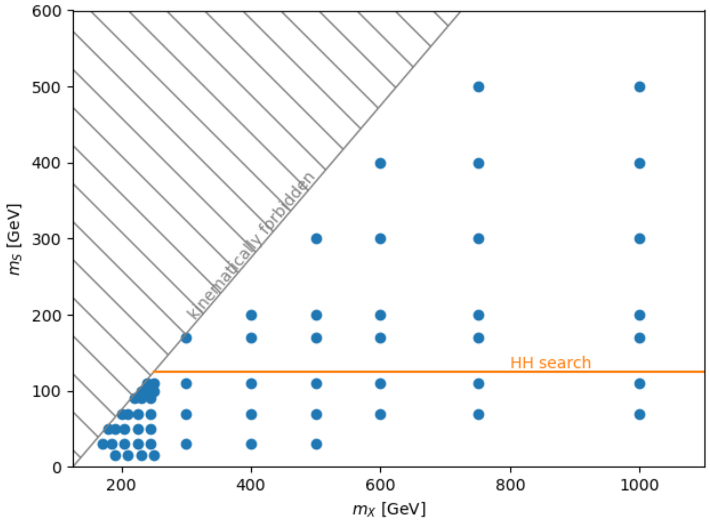


Signal parameter space

- Learning from 2HDM+S projection [1904.10810]:
  - ATLAS could be sensitive to the dark shaded regions with 300 fb^{-1} using *bbbb* and *bbγγ* final states.
  - Probably not worth it to go search beyond 1000 GeV m_X.



[1904.10810]



- Our signal grid:
  - mX = [170, 1000] GeV
  - mS = [15, 500] GeV
- Beyond m_X = 250 GeV, we start to share the search space with resonant HH search.
- We will do the search using 139 fb^{-1} data of Run-2 to provide model-independent limit.
- This will serve as a stepping stone for Run-3.

Signal parameter space

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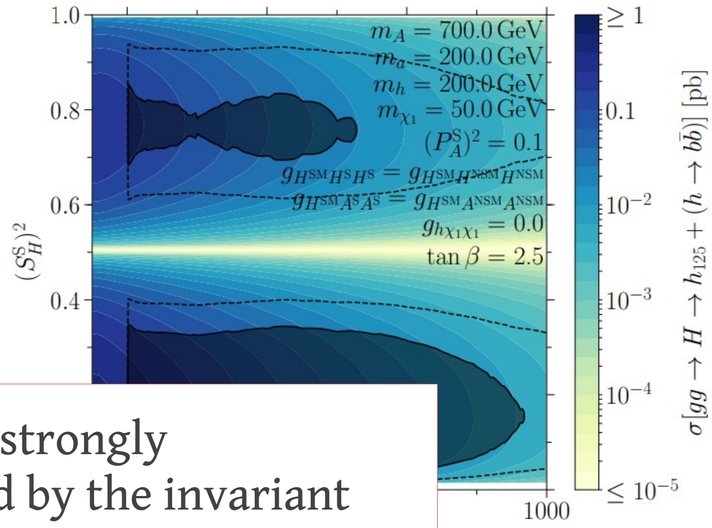
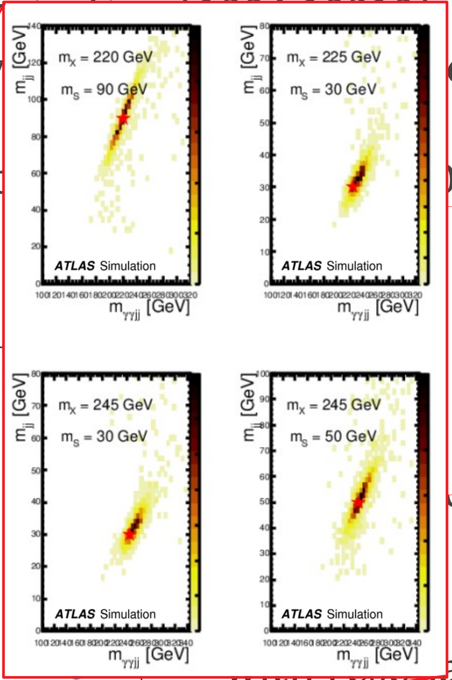
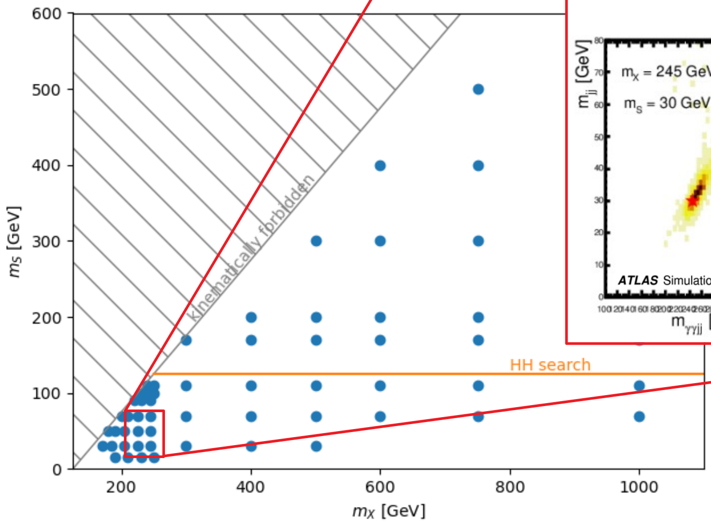


[1904.10810]

The signal is strongly characterized by the invariant masses of the final state particles m_{bbyy} & m_{bb}.





- ..., 1000] GeV
- ... 500] GeV
- ... = 250 GeV, we start to share the search space with resonant HH search.
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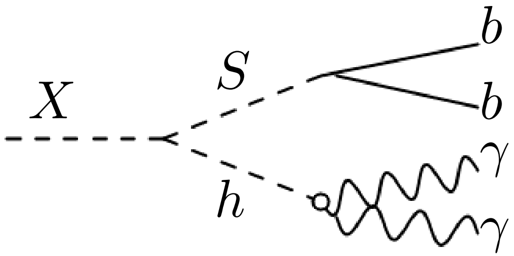
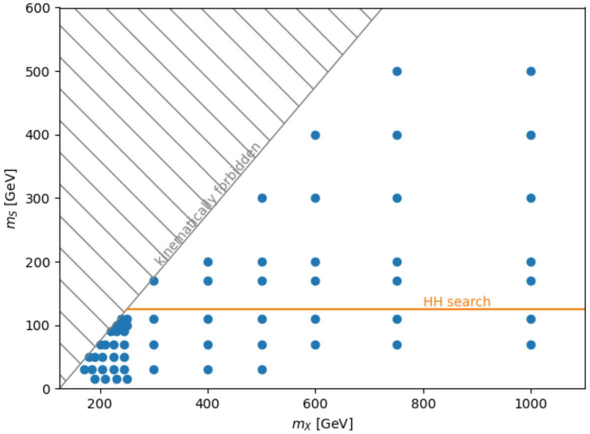
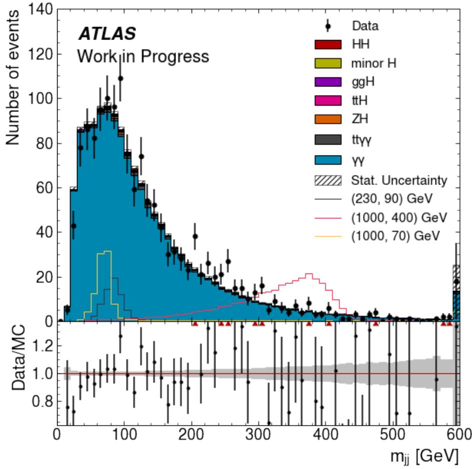
Signal characteristics

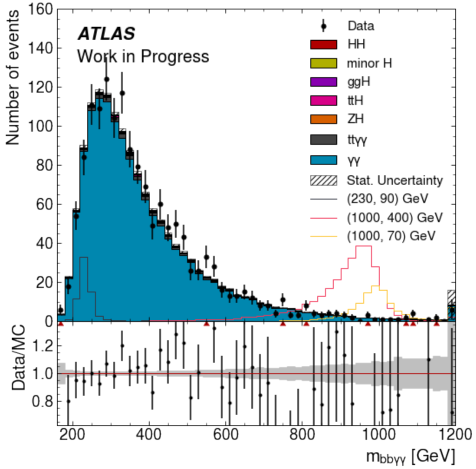
Data in higgs mass peakband is blinded!



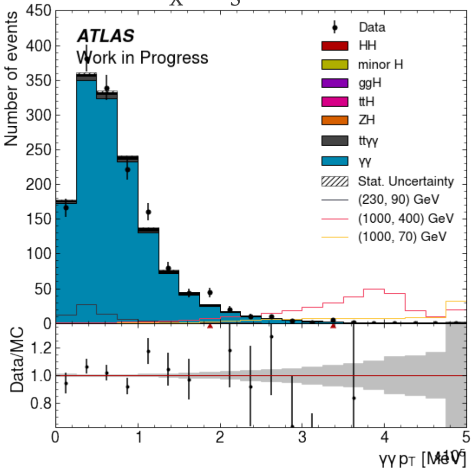


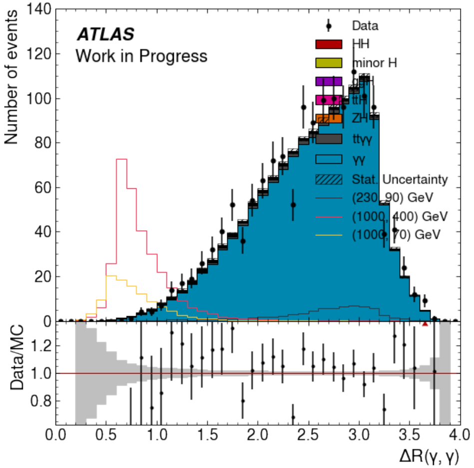
High dependency on invariant masses.





yy system dependent on $\Delta m = m_X - m_S$

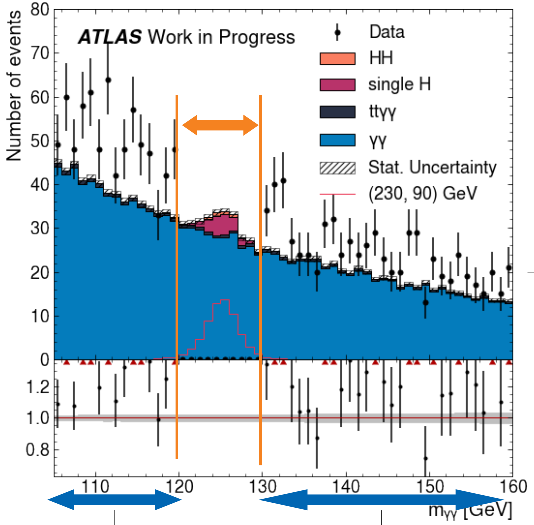




Analysis Strategy

Preselection

- 2 b-tagged jets @ 77% WP
- 2 photons
- No lepton
- $N_{central\ jets} \in [2, 5]$



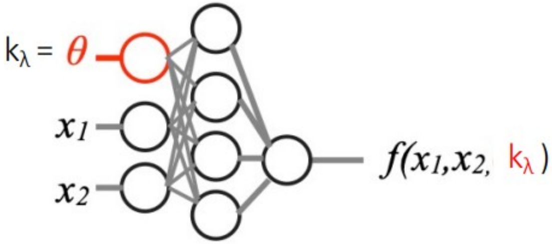
NN cut

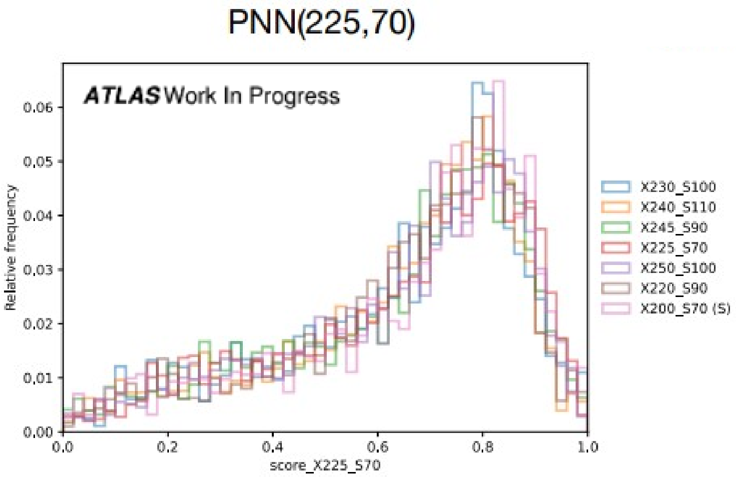
2D fit on $m_{bbyy} - m_{bb}$

Use the m_{yy} sideband to normalize diphoton background

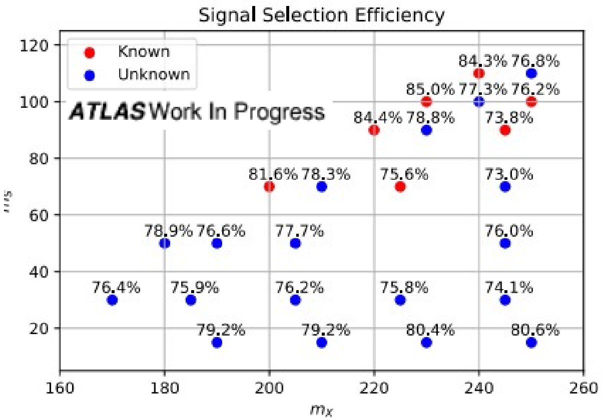
Parameterized NN development

- We are developing PNN with m_X and m_S as parameters.
- Signal efficiency and background rejection seems to be good, for both known and unknown points.
- The PNN seems to learned to generalize the signals, but then struggle to distinguish between them.





- Now we plan to try with DNN (without parameterization)
- Test training with and without m_{bb} and $m_{bb\gamma\gamma}$ to see if it harms the 2D fit by creating sensitivity holes in-between signal grid.

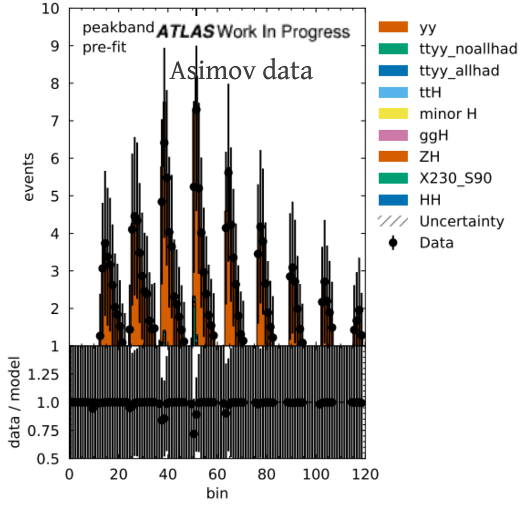


Study by Laura S.

Fit strategy

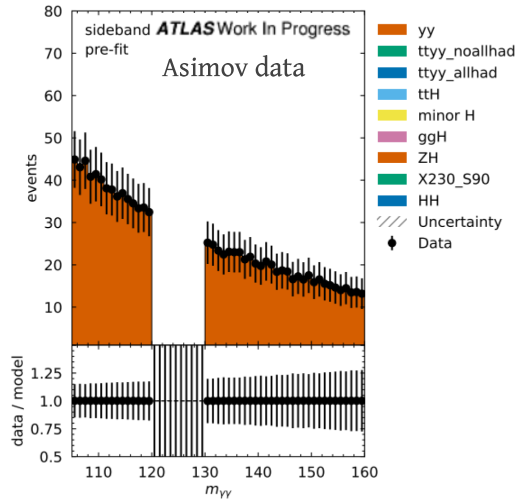
- We will use binned likelihood fit powered by pyhf.

$$L\left(\boldsymbol{n},\boldsymbol{\theta}^0 \mid \mu_{\text{sig}},\boldsymbol{\mu}_p,\boldsymbol{\theta}\right) = \mathcal{P}_{\text{SR}} \times \mathcal{P}_{\text{CR}} \times \mathcal{C}_{\text{syst}}$$
$$= \prod_{i\in\text{SR}} P\left(n_i \mid \lambda_i\left(\mu_{\text{sig}},\boldsymbol{\mu}_p,\boldsymbol{\theta}\right)\right)$$
$$\times \prod_{i\in\text{CR}} P\left(n_i \mid \lambda_i\left(\mu_{\text{sig}},\boldsymbol{\mu}_p,\boldsymbol{\theta}\right)\right)$$
$$\times\, C_{\text{syst}}\left(\boldsymbol{\theta}^0,\boldsymbol{\theta}\right)$$



Peakband

- Acts as a signal region.
- 120 bins in total from a 2D distribution:
  - $m_{bbyy} \in [160, 400]$ GeV, bin width 20 GeV
  - $m_{bb} \in [0, 200]$ GeV, bin width 20 GeV



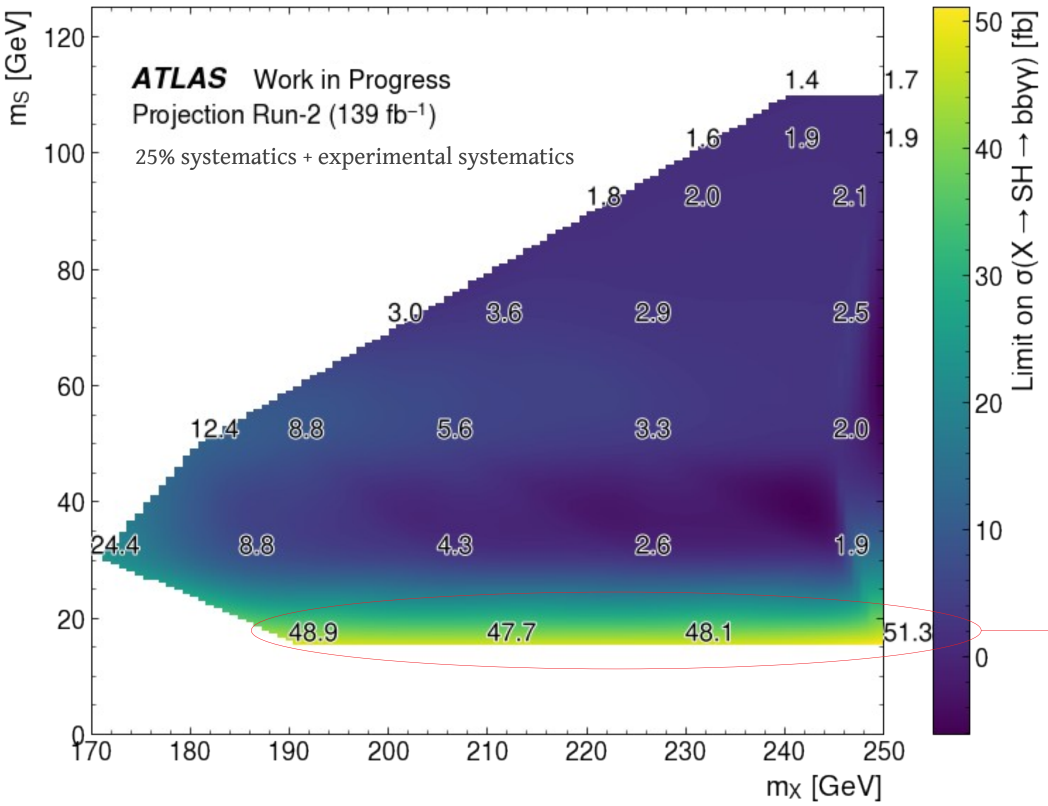
Sideband

- To normalize the dominant yy continuum background.
- $m_{yy} \in [105, 120] \mid [130, 160]$ GeV, bin width 1 GeV.

Systematics

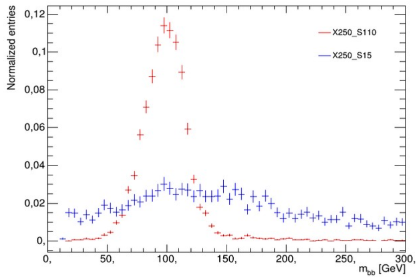
- Theory & experimental uncertainties

Limit projection

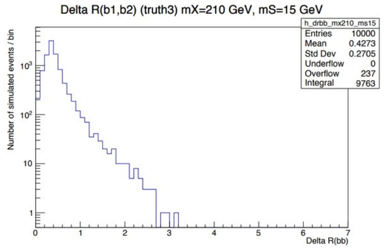


- Here is the projected expected cross section limit at 139 fb^{-1}.
- Evaluated at preselection.
- With the help of better signal/background discrimination by NN we hope to improve upon this.

b-jet merging issue here:



- Low mS causing the S(bb) system to be boosted.
  - 2 b's in 1 jet.
  - No m_{bb} peak



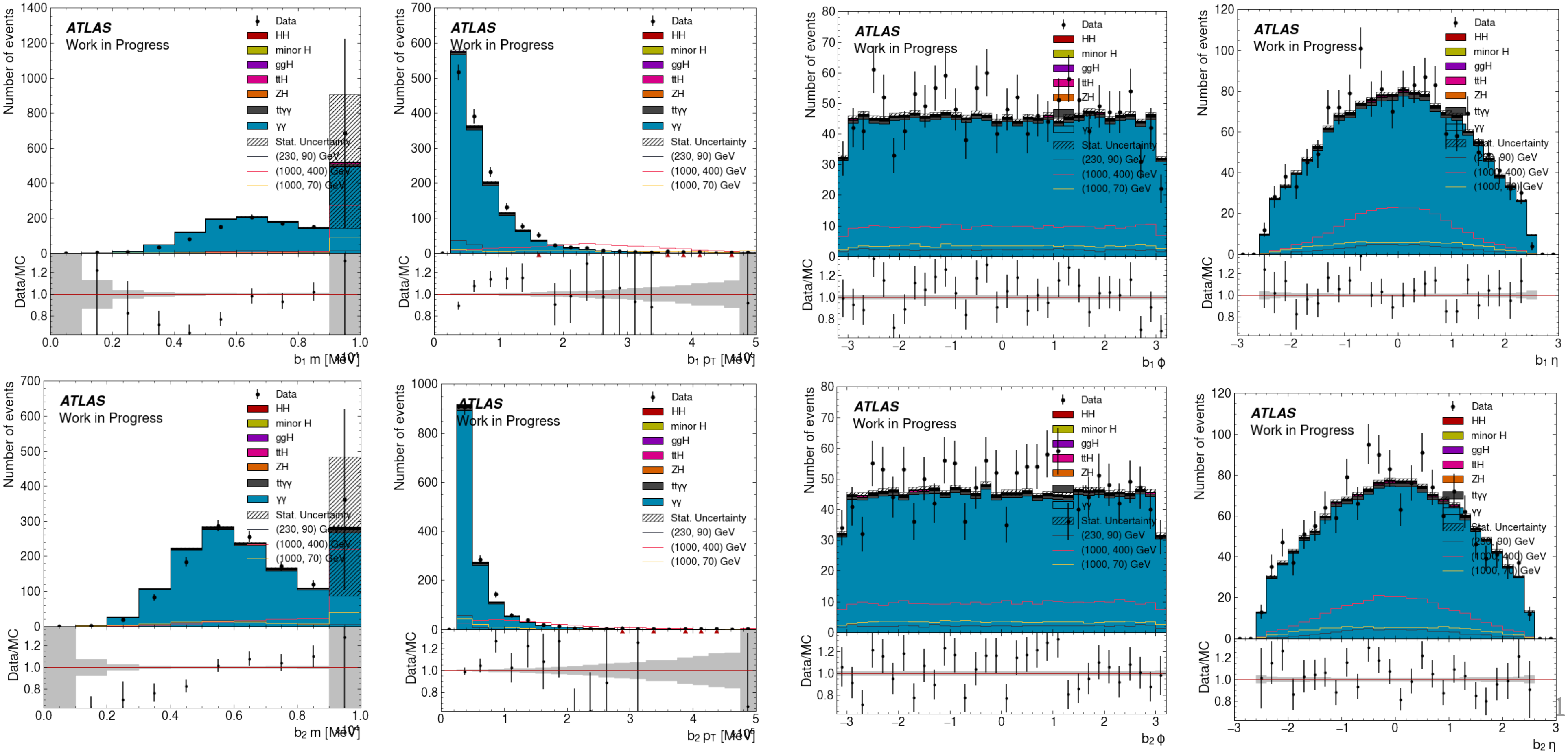
Summary

- New X→SH search on bbyy final states is being developed.
- Using 2 dimensional parameter space
- 2D fitting framework is used to put limit on 2D parameter space: m_{bbyy}-m_{bb}.
- (P)NN for optimized selection is under-development.
- Preliminary cross-section limit projected with Run-2 integrated luminosity is shown.

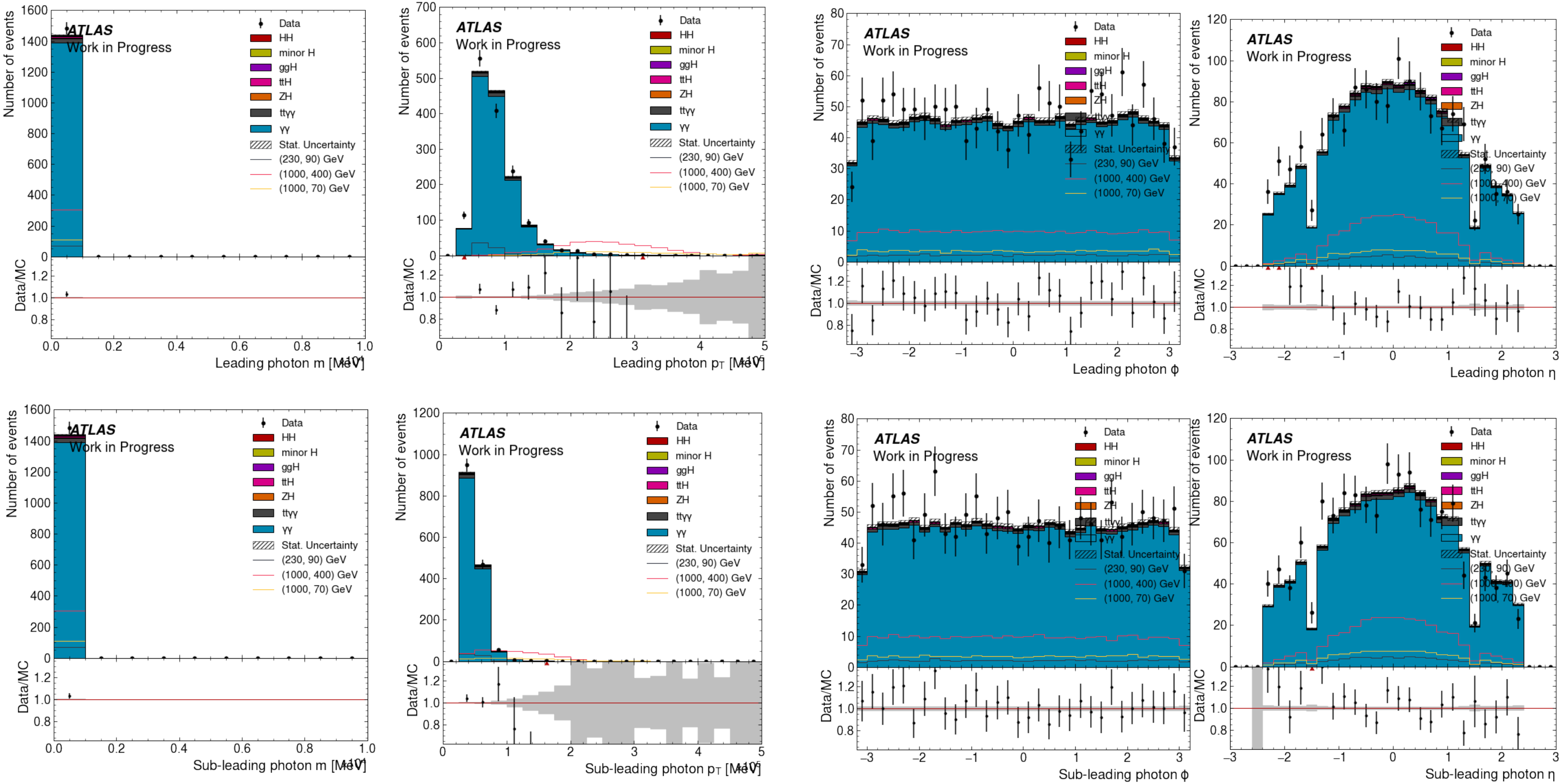
- Stay tune for more results!

BACKUP

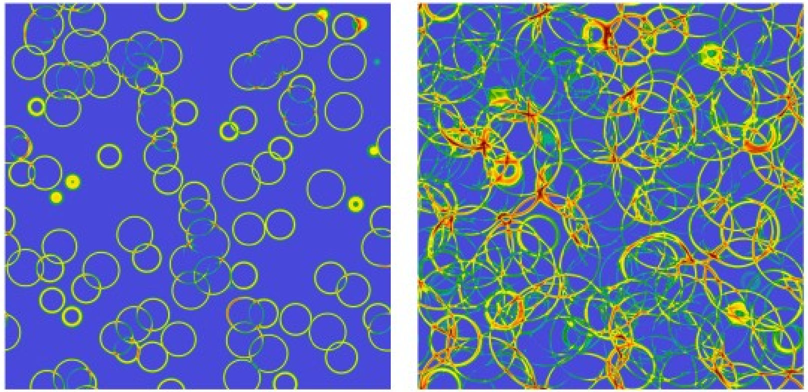
B kinematics



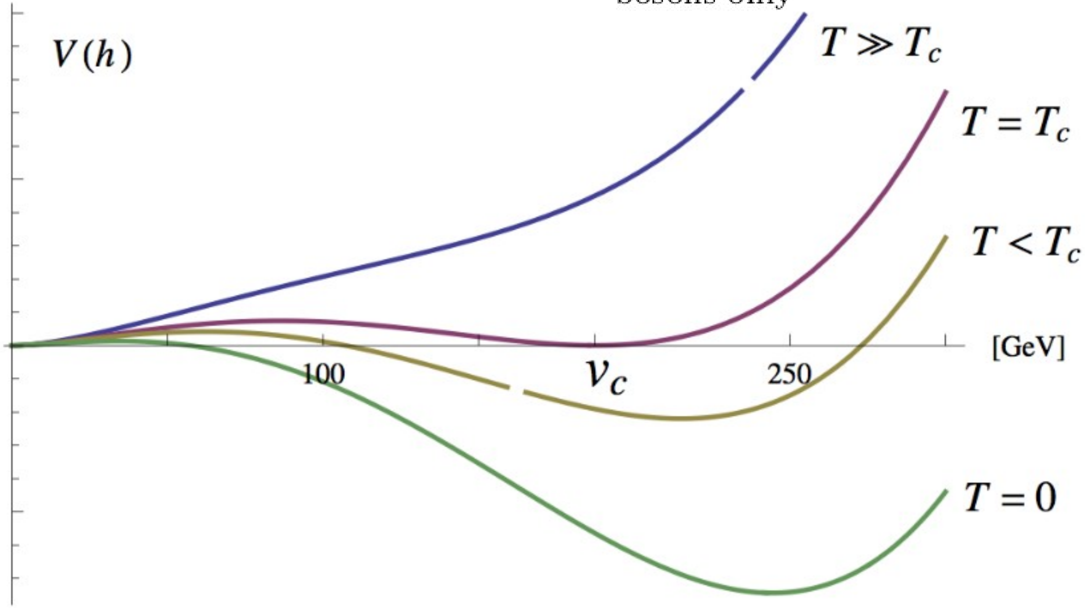
y kinematics



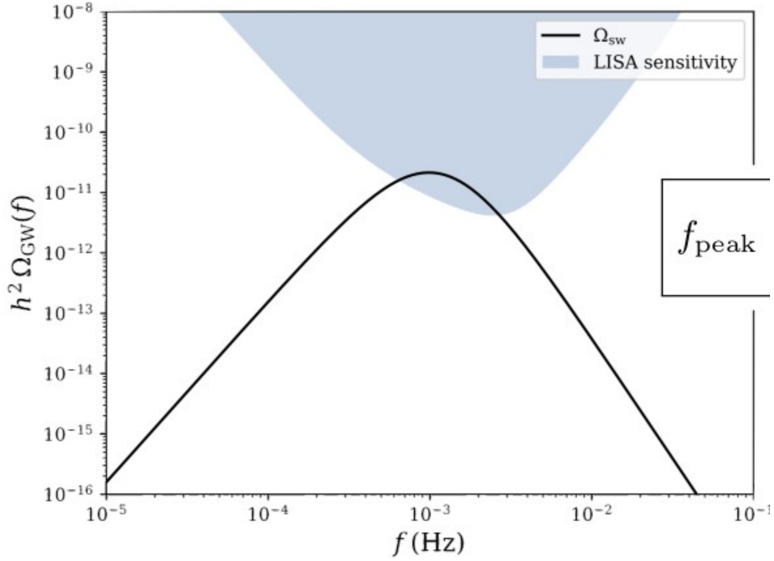
Higgs sector and GW



$$V_{\rm eff} \overset{\text{high T}}{\approx} V_0 + \sum_i g_i \frac{T^2}{24} m_i^2 \underbrace{- \frac{T}{12\pi} m_i^3}_{\text{bosons only}} + \dots$$



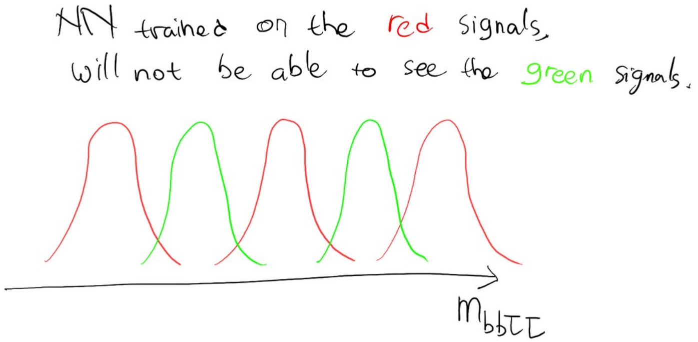
$$\frac{d\Omega_{\rm GW}}{d\ln k} = \frac{1}{12H^2}\frac{k^3}{2\pi^2}P_{\dot h}(\mathbf{k},t)$$

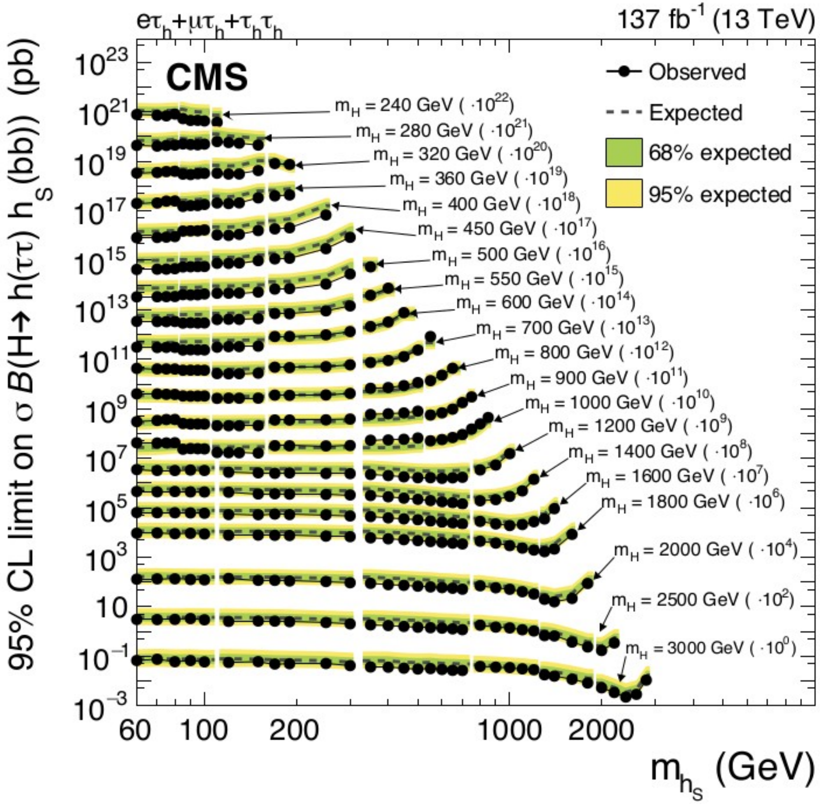


Source: G. Dorsch in LHCP2022

Sensitivity gap problem

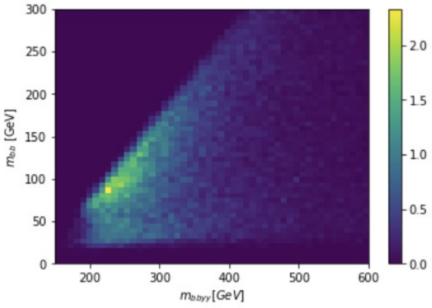
- Study case: CMS SH→bbττ (arXiv:2106.10361)
- CMS did 1D fit for each mH value, scanning the mS.
- They utilized many NNs trained on $m_{bb\tau\tau}$
  - May leave sensitivity gaps between trained $m_{bb\tau\tau}$!
  - The limit on the spacing of the signal grid cannot be interpolated from the result!





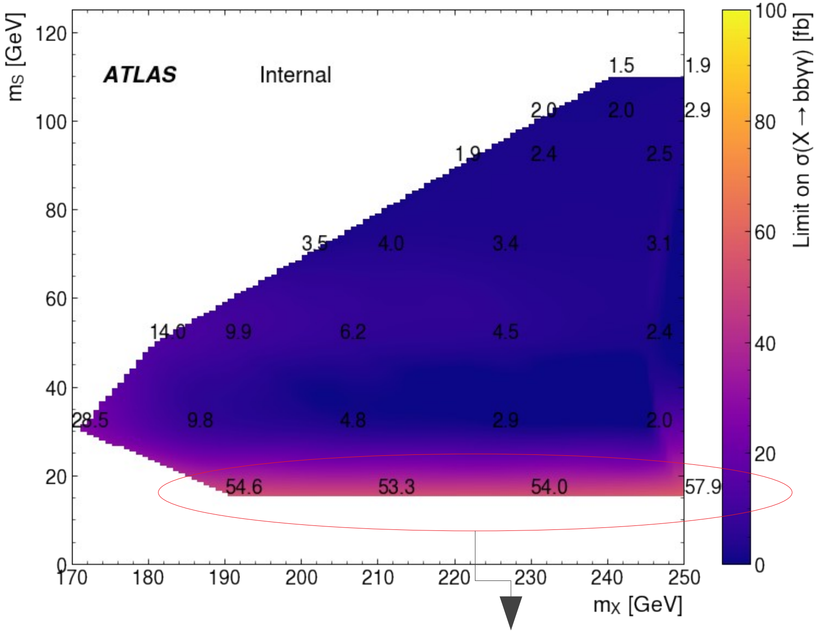
2D fit framework

- A fitting framework to handle fit on 2D distributions: m_{bbyy}-m_{bb} is being developed.
- Fitting utilities imported from pyhf.
- Full python environment and dedicated only for binned data analysis.



Preliminary limit:

- Only preselection
- Flat systematics = 25%



B-jet merging issue here

Motivation for binned data analysis:

- Correlation between m_{bbyy} – m_{bb}
  - Difficult to come up with analytical function that can handle this correlation.
- Binned fit is able to reproduce the unbinned fit result (see backup).

Relative difference to nominal. Evaluated in the peakband. Error is statistical

Systematics	ttH	ggH	ZH
NOM	$0.0\% \pm 0.0\%$	$0.0\% \pm 0.0\%$	$0.0\% \pm 0.0\%$
EG_RESOLUTION_ALL__1down	$0.3\% \pm 0.0\%$	$2.3\% \pm 0.0\%$	$0.3\% \pm 0.0\%$
EG_RESOLUTION_ALL__1up	$-0.5\% \pm -0.0\%$	$1.4\% \pm 0.0\%$	$-0.5\% \pm -0.0\%$
EG_SCALE_ALL__1down	$-0.2\% \pm -0.0\%$	$1.4\% \pm 0.0\%$	$-0.2\% \pm -0.0\%$
EG_SCALE_ALL__1up	$-0.5\% \pm -0.0\%$	$1.5\% \pm 0.0\%$	$-0.5\% \pm -0.0\%$
FT_EFF_Eigen_B_0__1down	$1.7\% \pm 0.0\%$	$3.0\% \pm 0.1\%$	$2.8\% \pm 0.0\%$
FT_EFF_Eigen_B_0__1up	$-1.7\% \pm -0.0\%$	$-3.0\% \pm -0.1\%$	$-2.8\% \pm -0.0\%$
FT_EFF_Eigen_B_1__1down	$1.1\% \pm 0.0\%$	$0.6\% \pm 0.0\%$	$1.0\% \pm 0.0\%$
FT_EFF_Eigen_B_1__1up	$-1.1\% \pm -0.0\%$	$-0.6\% \pm -0.0\%$	$-1.0\% \pm -0.0\%$
FT_EFF_Eigen_B_2__1down	$-0.1\% \pm -0.0\%$	$-0.2\% \pm -0.0\%$	$-0.2\% \pm -0.0\%$
FT_EFF_Eigen_B_2__1up	$0.1\% \pm 0.0\%$	$0.2\% \pm 0.0\%$	$0.2\% \pm 0.0\%$
FT_EFF_Eigen_C_0__1down	$0.4\% \pm 0.0\%$	$1.7\% \pm 0.0\%$	$0.7\% \pm 0.0\%$
FT_EFF_Eigen_C_0__1up	$-0.4\% \pm -0.0\%$	$-1.6\% \pm -0.0\%$	$-0.7\% \pm -0.0\%$
FT_EFF_Eigen_C_1__1down	$-0.1\% \pm -0.0\%$	$-0.3\% \pm -0.0\%$	$-0.1\% \pm -0.0\%$
FT_EFF_Eigen_C_1__1up	$0.1\% \pm 0.0\%$	$0.3\% \pm 0.0\%$	$0.1\% \pm 0.0\%$
FT_EFF_Eigen_C_2__1down	$-0.0\% \pm -0.0\%$	$0.0\% \pm 0.0\%$	$-0.0\% \pm -0.0\%$
FT_EFF_Eigen_C_2__1up	$0.0\% \pm 0.0\%$	$-0.0\% \pm -0.0\%$	$0.0\% \pm 0.0\%$
FT_EFF_Eigen_Light_0__1down	$0.8\% \pm 0.0\%$	$2.9\% \pm 0.1\%$	$0.4\% \pm 0.0\%$
FT_EFF_Eigen_Light_0__1up	$-0.8\% \pm -0.0\%$	$-2.6\% \pm -0.0\%$	$-0.4\% \pm -0.0\%$
FT_EFF_Eigen_Light_1__1down	$0.1\% \pm 0.0\%$	$-0.5\% \pm -0.0\%$	$0.0\% \pm 0.0\%$
FT_EFF_Eigen_Light_1__1up	$-0.1\% \pm -0.0\%$	$0.6\% \pm 0.0\%$	$-0.0\% \pm -0.0\%$
FT_EFF_Eigen_Light_3__1down	$0.0\% \pm 0.0\%$	$-0.0\% \pm -0.0\%$	$0.0\% \pm 0.0\%$
FT_EFF_Eigen_Light_3__1up	$-0.0\% \pm -0.0\%$	$0.0\% \pm 0.0\%$	$-0.0\% \pm -0.0\%$
FT_EFF_Eigen_Light_4__1down	$-0.1\% \pm -0.0\%$	$-0.1\% \pm -0.0\%$	$-0.0\% \pm -0.0\%$
FT_EFF_Eigen_Light_4__1up	$0.1\% \pm 0.0\%$	$0.1\% \pm 0.0\%$	$0.0\% \pm 0.0\%$
JET_EffectiveNP_Detector1__1down	$0.0\% \pm 0.0\%$	$-0.1\% \pm -0.0\%$	$-0.0\% \pm -0.0\%$
JET_EffectiveNP_Detector1__1up	$-0.0\% \pm -0.0\%$	$-0.0\% \pm -0.0\%$	$0.0\% \pm 0.0\%$
JET_EffectiveNP_Detector2__1down	$0.0\% \pm 0.0\%$	$-0.0\% \pm -0.0\%$	$-0.0\% \pm -0.0\%$
JET_EffectiveNP_Detector2__1up	$-0.0\% \pm -0.0\%$	$-0.0\% \pm -0.0\%$	$0.0\% \pm 0.0\%$
JET_EffectiveNP_Mixed1__1down	$0.0\% \pm 0.0\%$	$-0.0\% \pm -0.0\%$	$-0.0\% \pm -0.0\%$
JET_EffectiveNP_Mixed1__1up	$-0.0\% \pm -0.0\%$	$-0.0\% \pm -0.0\%$	$0.0\% \pm 0.0\%$
JET_EffectiveNP_Mixed2__1down	$-0.0\% \pm -0.0\%$	$0.0\% \pm 0.0\%$	$0.1\% \pm 0.0\%$
JET_EffectiveNP_Mixed2__1up	$0.0\% \pm 0.0\%$	$-0.1\% \pm -0.0\%$	$-0.0\% \pm -0.0\%$
JET_EffectiveNP_Mixed3__1down	$0.0\% \pm 0.0\%$	$-0.1\% \pm -0.0\%$	$-0.0\% \pm -0.0\%$
JET_EffectiveNP_Mixed3__1up	$-0.0\% \pm -0.0\%$	$-0.0\% \pm -0.0\%$	$0.0\% \pm 0.0\%$
JET_EffectiveNP_Modelling1__1down	$0.7\% \pm 0.0\%$	$-1.7\% \pm -0.0\%$	$-0.9\% \pm -0.0\%$
JET_EffectiveNP_Modelling1__1up	$-0.8\% \pm -0.0\%$	$1.4\% \pm 0.0\%$	$0.9\% \pm 0.0\%$
JET_EffectiveNP_Modelling2__1down	$-0.0\% \pm -0.0\%$	$0.0\% \pm 0.0\%$	$0.1\% \pm 0.0\%$
JET_EffectiveNP_Modelling2__1up	$0.0\% \pm 0.0\%$	$-0.1\% \pm -0.0\%$	$-0.0\% \pm -0.0\%$
JET_EffectiveNP_Modelling3__1down	$0.0\% \pm 0.0\%$	$-0.1\% \pm -0.0\%$	$-0.0\% \pm -0.0\%$
JET_EffectiveNP_Modelling3__1up	$-0.0\% \pm -0.0\%$	$0.0\% \pm 0.0\%$	$0.0\% \pm 0.0\%$
JET_EffectiveNP_Modelling4__1down	$0.0\% \pm 0.0\%$	$-0.0\% \pm -0.0\%$	$-0.0\% \pm -0.0\%$
JET_EffectiveNP_Modelling4__1up	$-0.0\% \pm -0.0\%$	$-0.0\% \pm -0.0\%$	$0.0\% \pm 0.0\%$
JET_EffectiveNP_Statistical2__1up	$0.1\% \pm 0.0\%$	$-0.2\% \pm -0.0\%$	$-0.1\% \pm -0.0\%$
JET_EffectiveNP_Statistical3__1down	$0.0\% \pm 0.0\%$	$-0.0\% \pm -0.0\%$	$-0.0\% \pm -0.0\%$
JET_EffectiveNP_Statistical3__1up	$-0.0\% \pm -0.0\%$	$-0.0\% \pm -0.0\%$	$0.0\% \pm 0.0\%$
JET_EffectiveNP_Statistical4__1down	$-0.0\% \pm -0.0\%$	$-0.0\% \pm -0.0\%$	$0.0\% \pm 0.0\%$
JET_EffectiveNP_Statistical4__1up	$0.0\% \pm 0.0\%$	$-0.0\% \pm -0.0\%$	$-0.0\% \pm -0.0\%$
JET_EffectiveNP_Statistical5__1down	$0.0\% \pm 0.0\%$	$-0.0\% \pm -0.0\%$	$-0.0\% \pm -0.0\%$
JET_EffectiveNP_Statistical5__1up	$-0.0\% \pm -0.0\%$	$-0.0\% \pm -0.0\%$	$0.0\% \pm 0.0\%$
JET_EffectiveNP_Statistical6__1down	$0.0\% \pm 0.0\%$	$-0.0\% \pm -0.0\%$	$-0.0\% \pm -0.0\%$
JET_EffectiveNP_Statistical6__1up	$-0.0\% \pm -0.0\%$	$-0.0\% \pm -0.0\%$	$0.0\% \pm 0.0\%$
JET_EtaIntercalibration_Modelling__1down	$0.6\% \pm 0.0\%$	$-1.5\% \pm -0.0\%$	$-0.6\% \pm -0.0\%$
JET_EtaIntercalibration_Modelling__1up	$-0.6\% \pm -0.0\%$	$1.2\% \pm 0.0\%$	$0.7\% \pm 0.0\%$
JET_EtaIntercalibration_NonClosure_2018data__1down	$0.1\% \pm 0.0\%$	$-0.3\% \pm -0.0\%$	$-0.1\% \pm -0.0\%$
JET_EtaIntercalibration_NonClosure_2018data__1up	$-0.1\% \pm -0.0\%$	$0.2\% \pm 0.0\%$	$0.1\% \pm 0.0\%$
JET_JER_EffectiveNP_10__1down	$-0.2\% \pm -0.0\%$	$0.4\% \pm 0.0\%$	$-0.1\% \pm -0.0\%$
JET_JER_EffectiveNP_10__1up	$-0.0\% \pm -0.0\%$	$-0.4\% \pm -0.0\%$	$0.0\% \pm 0.0\%$
JET_JER_EffectiveNP_11__1down	$-0.0\% \pm -0.0\%$	$-0.5\% \pm -0.0\%$	$-0.0\% \pm -0.0\%$
JET_JER_EffectiveNP_11__1up	$-0.1\% \pm -0.0\%$	$0.3\% \pm 0.0\%$	$-0.1\% \pm -0.0\%$
JET_JER_EffectiveNP_1__1down	$-0.0\% \pm -0.0\%$	$-0.3\% \pm -0.0\%$	$-0.0\% \pm -0.0\%$
JET_JER_EffectiveNP_1__1up	$-0.3\% \pm -0.0\%$	$0.1\% \pm 0.0\%$	$-0.2\% \pm -0.0\%$
JET_JER_EffectiveNP_2__1down	$0.0\% \pm 0.0\%$	$-0.3\% \pm -0.0\%$	$0.0\% \pm 0.0\%$
JET_JER_EffectiveNP_2__1up	$-0.5\% \pm -0.0\%$	$0.8\% \pm 0.0\%$	$-0.4\% \pm -0.0\%$
JET_JER_EffectiveNP_3__1down	$-0.4\% \pm -0.0\%$	$0.3\% \pm 0.0\%$	$-0.2\% \pm -0.0\%$
JET_JER_EffectiveNP_3__1up	$0.0\% \pm 0.0\%$	$-0.3\% \pm -0.0\%$	$0.0\% \pm 0.0\%$
JET_JER_EffectiveNP_4__1down	$-0.5\% \pm -0.0\%$	$0.9\% \pm 0.0\%$	$-0.1\% \pm -0.0\%$
JET_JER_EffectiveNP_4__1up	$-0.0\% \pm -0.0\%$	$-0.3\% \pm -0.0\%$	$-0.0\% \pm -0.0\%$
JET_JER_EffectiveNP_5__1down	$-0.1\% \pm -0.0\%$	$0.1\% \pm 0.0\%$	$-0.1\% \pm -0.0\%$
JET_JER_EffectiveNP_5__1up	$-0.1\% \pm -0.0\%$	$-0.4\% \pm -0.0\%$	$0.0\% \pm 0.0\%$
JET_JER_EffectiveNP_6__1down	$-0.1\% \pm -0.0\%$	$0.1\% \pm 0.0\%$	$-0.2\% \pm -0.0\%$
JET_JER_EffectiveNP_6__1up	$-0.1\% \pm -0.0\%$	$-0.4\% \pm -0.0\%$	$0.1\% \pm 0.0\%$
JET_JER_EffectiveNP_7__1down	$-0.0\% \pm -0.0\%$	$-0.3\% \pm -0.0\%$	$0.0\% \pm 0.0\%$
JET_JER_EffectiveNP_7__1up	$-0.1\% \pm -0.0\%$	$0.1\% \pm 0.0\%$	$-0.1\% \pm -0.0\%$
JET_JER_EffectiveNP_8__1down	$-0.1\% \pm -0.0\%$	$-0.4\% \pm -0.0\%$	$0.1\% \pm 0.0\%$
JET_JER_EffectiveNP_8__1up	$-0.1\% \pm -0.0\%$	$-0.2\% \pm -0.0\%$	$-0.0\% \pm -0.0\%$
JET_JER_EffectiveNP_9__1down	$0.0\% \pm 0.0\%$	$-0.4\% \pm -0.0\%$	$0.0\% \pm 0.0\%$
JET_JER_EffectiveNP_9__1up	$-0.1\% \pm -0.0\%$	$0.2\% \pm 0.0\%$	$-0.1\% \pm -0.0\%$
JET_JvtEfficiency__1down	$0.0\% \pm 0.0\%$	$-0.0\% \pm -0.0\%$	$-0.0\% \pm -0.0\%$
JET_JvtEfficiency__1up	$0.0\% \pm 0.0\%$	$-0.0\% \pm -0.0\%$	$-0.0\% \pm -0.0\%$
JET_Pileup_OffsetMu__1down	$0.3\% \pm 0.0\%$	$-0.6\% \pm -0.0\%$	$-0.3\% \pm -0.0\%$
JET_Pileup_OffsetMu__1up	$-0.3\% \pm -0.0\%$	$0.6\% \pm 0.0\%$	$0.3\% \pm 0.0\%$
JET_Pileup_PtTerm__1down	$-0.0\% \pm -0.0\%$	$-0.0\% \pm -0.0\%$	$-0.0\% \pm -0.0\%$
JET_Pileup_PtTerm__1up	$0.0\% \pm 0.0\%$	$-0.1\% \pm -0.0\%$	$0.0\% \pm 0.0\%$
PH_EFF_ID_Uncertainty__1down	$-1.6\% \pm -0.0\%$	$-1.6\% \pm -0.0\%$	$-1.6\% \pm -0.0\%$
PH_EFF_ID_Uncertainty__1up	$1.6\% \pm 0.0\%$	$1.6\% \pm 0.0\%$	$1.6\% \pm 0.0\%$
PH_EFF_ISO_Uncertainty__1down	$-1.5\% \pm -0.0\%$	$-1.6\% \pm -0.0\%$	$-1.5\% \pm -0.0\%$
PH_EFF_ISO_Uncertainty__1up	$1.5\% \pm 0.0\%$	$1.5\% \pm 0.0\%$	$1.5\% \pm 0.0\%$
PH_EFF_TRIGGER_Uncertainty__1down	$-1.0\% \pm -0.0\%$	$-1.0\% \pm -0.0\%$	$-1.0\% \pm -0.0\%$
PH_EFF_TRIGGER_Uncertainty__1up	$1.0\% \pm 0.0\%$	$0.9\% \pm 0.0\%$	$1.0\% \pm 0.0\%$
PRW_DATASF__1down	$1.7\% \pm 0.0\%$	$1.9\% \pm 0.0\%$	$1.5\% \pm 0.0\%$
PRW_DATASF__1up	$-2.1\% \pm -0.0\%$	$1.9\% \pm 0.0\%$	$-1.7\% \pm -0.0\%$