

A COMBINED FIT TO THE HIGGS BRANCHING RATIOS AT ILD

LCWS 2021

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OUTLINE



A combined fit to the Higgs Branching Ratios at ILD

Previously :

Following up on JC Brient's talk at LCWS2019.

Currently :

Still a work in progress.

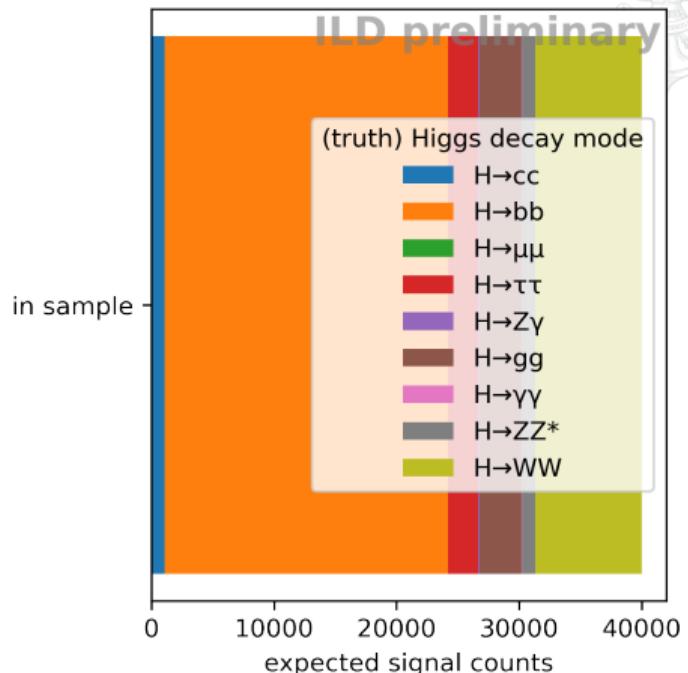
1. Introduction
2. Simplifications
3. Categories
4. Optimization
5. Conclusion



HIGGS-BRS ALL-IN-ONE

Trying to adapt a τ branching ratio [paper](#) from ALEPH to Higgs at ILD :

1. Build a sample with all Higgs decay modes (Higgsstrahlung, $Z \rightarrow (e^+e^-, \mu^+\mu^-, \nu\bar{\nu})$).
2. Construct categories to separate the decay modes (& background) as well as possible.
3. Fit the Higgs branching ratios to the observed category counts.

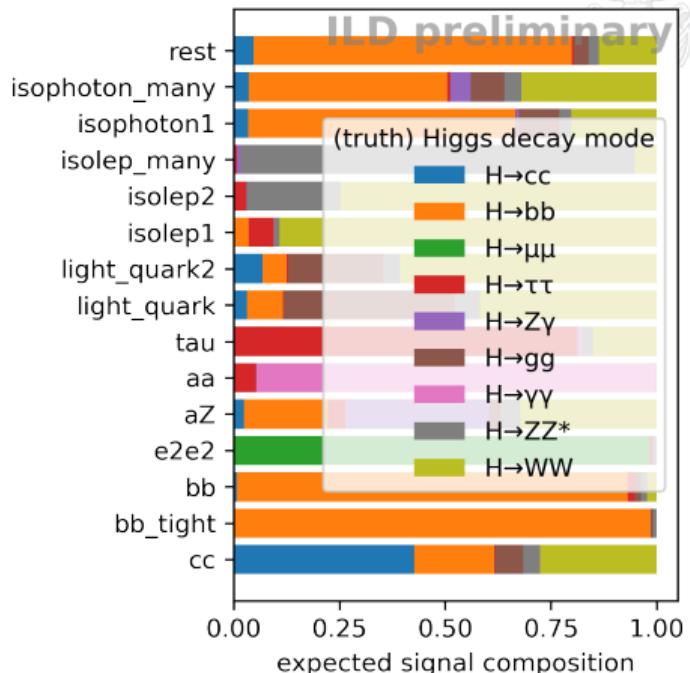




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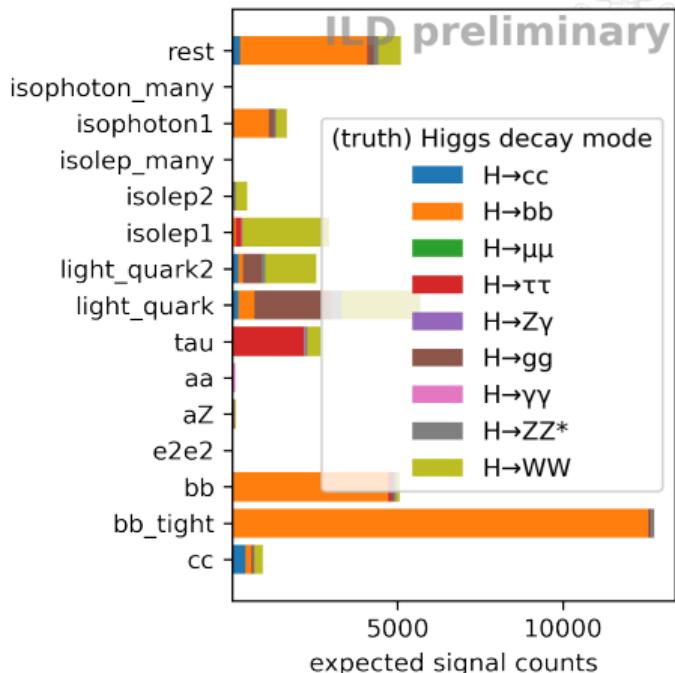




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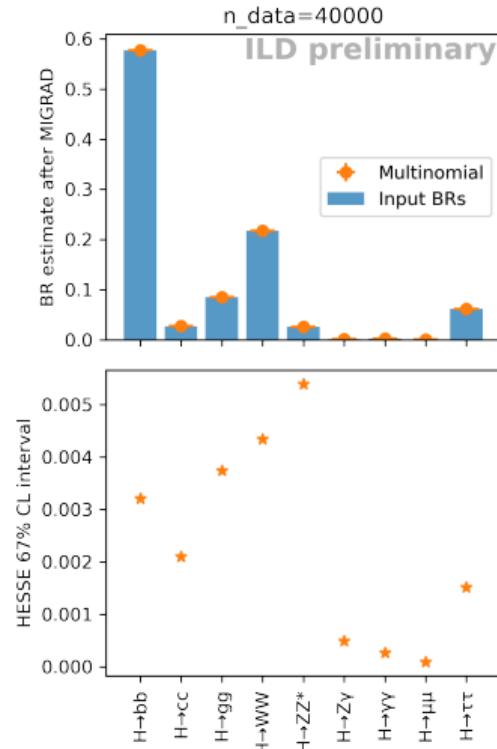




HIGGS-BRS ALL-IN-ONE

Trying to adapt a τ branching ratio [paper](#) from ALEPH to Higgs at ILD :

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Trying to adapt a τ branching ratio [paper](#) from ALEPH to Higgs at ILD :

Advantages

1. Build a sample with all Higgs decay modes (Higgsstrahlung, $Z \rightarrow (e^+e^-, \mu^+\mu^-, \nu\bar{\nu})$).
2. Construct categories to separate the decay modes (& background) as well as possible.
3. Fit the Higgs branching ratios to the observed category counts.

- A model independent extraction of all branching ratios (at once).
- Independent of any Higgs production cross section measurement.
- Gaussian errors \rightarrow multinomial errors, as everything is in the same sample.
 - Promising e.g. for $H \rightarrow b\bar{b}$. See [19](#) in backup.

CURRENT SIMPLIFICATIONS



Reconstructed events from the new $\sqrt{s} = 250$ GeV SetA mass production (ILD_15_o1_v02, v02-02).

- So far, only using the signal (Higgsstrahlung).
 - $\geq 400k$ simulated events/decay mode.
- $ZH \rightarrow \nu\bar{\nu}H$, so no confusion between Z and H at this stage.
- MC-Veto on overlay particles (and LCFIPlus re-vertexing on remaining PFOS).
 - Not necessary, but should redo some category boundaries. See 17, 18 in backup.

Assumption for the fit (later) : $\sigma_{ZH}^{\text{unpol.}} \approx 200 \text{ fb}, 2000 \text{ fb}^{-1}$ H-20 scenario,
catch 10 % of the signal $\rightarrow O(40,000)$ Higgs events.

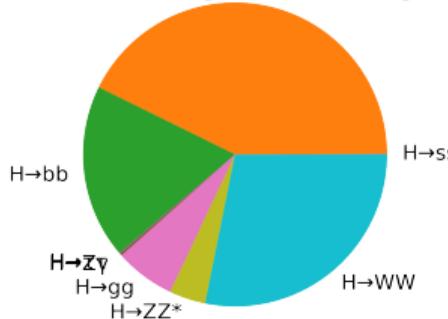
CATEGORY BUILDING EXAMPLE : CC

CATEGORIES

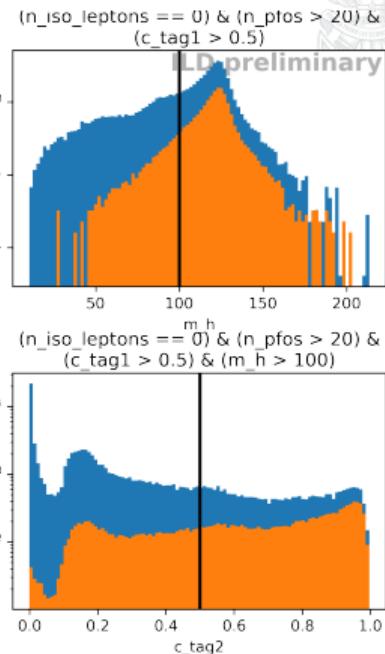
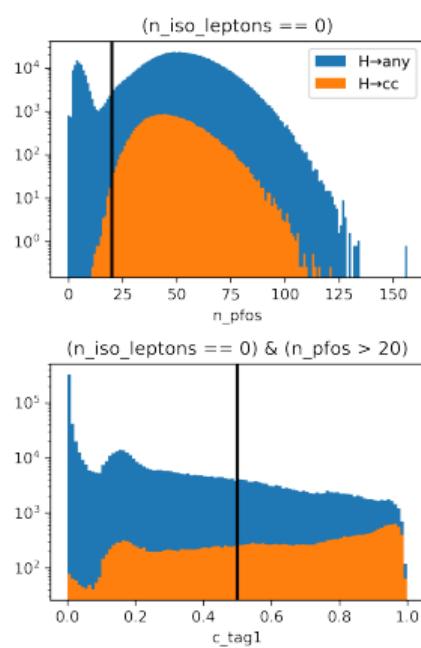


$(n_{iso_leptons} == 0) \& (n_{pfos} > 20) \& (c_{tag1} > 0.5) \& (m_h > 100) \& (c_{tag2} > 0.5)$

ILD preliminary



Total count: 24,657.7
0.06% $H \rightarrow ss$
42.66% $H \rightarrow cc$
18.53% $H \rightarrow bb$
0.04% $H \rightarrow \tau\tau$
0.30% $H \rightarrow Z\gamma$
6.39% $H \rightarrow gg$
3.87% $H \rightarrow ZZ^*$
28.16% $H \rightarrow WW$



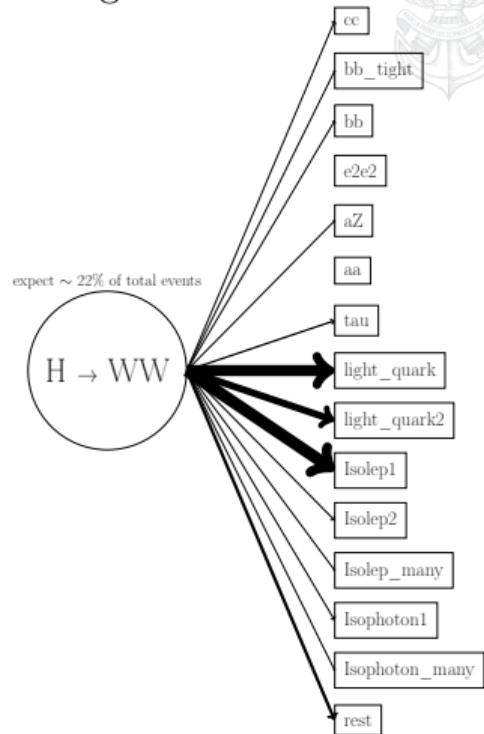
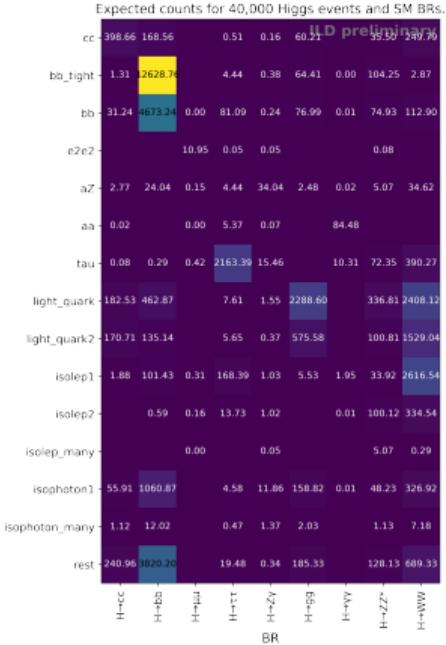
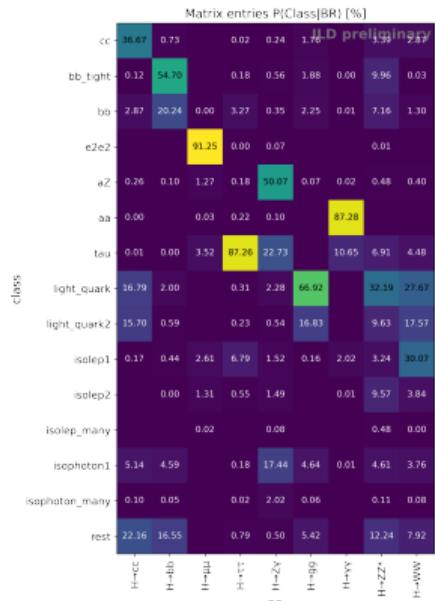


- Reuse common tools :
 - LCFIPplus for jet construction and flavor tagging.
 - IsolatedLeptonTaggingProcessor, IsolatedPhotonTaggingProcessor.
- Custom variables motivated by specific channels :
 - $M_{\mu^+\mu^-}$, $M_{\gamma\gamma}$.
 - Recoil of the leading (Isolated) Photon against ($E = M_H, \vec{p} = 0$) at rest ($\approx 60 - 100$ GeV for $H \rightarrow Z\gamma$).
 - ...
- Only use so-far not categorized events in classes further down in the list.

CATEGORY MATRIX

CATEGORIES

This shows how events from a given BR distribute among categories. E.g. $H \rightarrow W^+W^-$.





OPTIMIZATION - SETUP

BRs from minimization through MINUIT/iminuit.

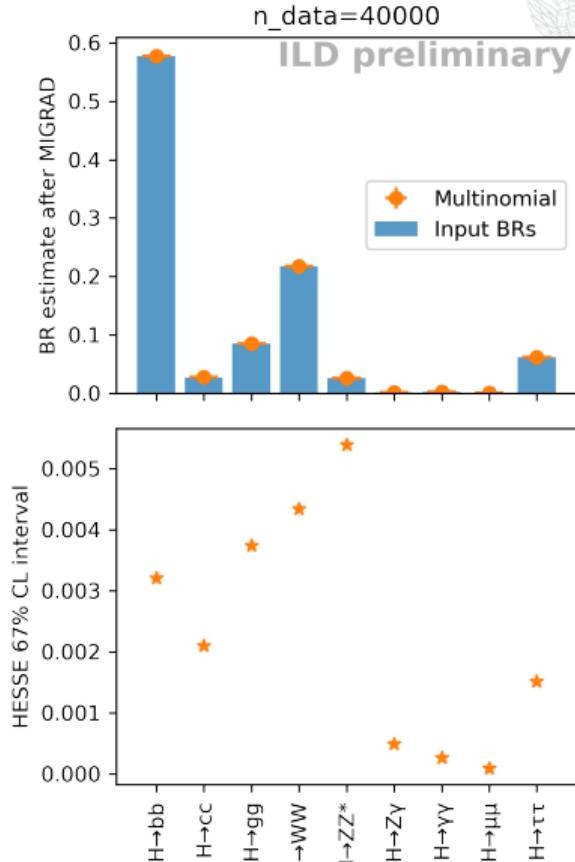
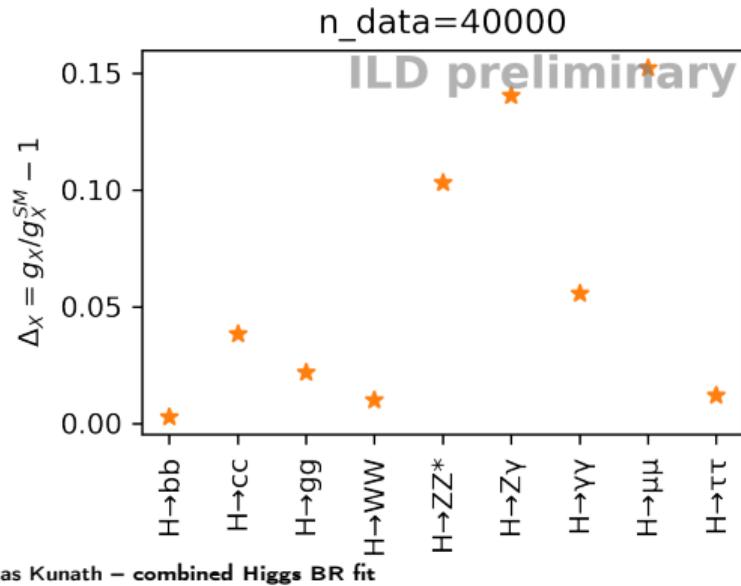
- $\vec{S} = M \cdot \vec{B} = \vec{f}(\vec{B})$, with
 - \vec{S} : The signal counts per category ($S = data - bkg$). MC2.
 - M : The matrix built from simulated events, as outlined above. MC1.
 - \vec{B} : The target. Use e.g. the Standard Model BRs as fit starting values.
- MC2 : Events that are (statistically) independent from MC1. Will be replaced by the detector data.
- The cost function : Multinomial log-likelihood.
 - $-\ln\mathcal{L} = -N_{\text{data}} \sum_i S_i \ln \left(\sum_j M_{ij} B_j \right)$.
 - $B_{H \rightarrow ZZ^*} = 1 - \sum_{i \neq H \rightarrow ZZ^*} B_i$.
 - Each BR constrained to $[0, 1]$.

class	Matrix entries $P(\text{Class} \text{BR}) [\%]$								
	H \rightarrow CC	H \rightarrow bb	H \rightarrow ll	H \rightarrow tt	H \rightarrow ZZ	H \rightarrow gg	H \rightarrow NN	H \rightarrow ZZ	H \rightarrow WW
cc	36.67	0.73	0.02	0.24	1.76	3.39	2.87		
bb_tight	0.12	54.70	0.18	0.56	1.88	0.00	9.96	0.03	
bb	2.87	20.24	0.00	3.27	0.35	2.25	0.01	7.16	1.30
c2e2			91.25	0.00	0.07				0.01
aZ	0.26	0.10	1.27	0.18	50.07	0.07	0.02	0.48	0.40
aa	0.00		0.03	0.22	0.10		87.28		
tau	0.01	0.00	3.52	87.26	22.73		10.65	6.91	4.48
light_quark	16.79	2.00		0.31	2.28	66.92		32.19	27.67
light_quark2	15.70	0.59		0.23	0.54	16.83		9.63	17.57
isolep1	0.17	0.44	2.61	6.79	1.52	0.16	2.02	3.24	30.07
isolep2		0.00	1.31	0.55	1.49		0.01	9.57	3.84
isolep_many			0.02		0.08			0.48	0.00
isophoton1	5.14	4.59		0.18	17.44	4.64	0.01	4.61	3.76
isophoton_many	0.10	0.05		0.02	2.02	0.06		0.11	0.08
rest	22.16	16.55		0.79	0.50	5.42		12.24	7.92
	H \rightarrow CC	H \rightarrow bb	H \rightarrow ll	H \rightarrow tt	H \rightarrow ZZ	H \rightarrow gg	H \rightarrow NN	H \rightarrow ZZ	H \rightarrow WW
	BR								

OPTIMIZATION - RESULTS



The fitted BR^{\min} reproduces BR^{true} within its uncertainties. $\sigma_{B_{H \rightarrow ZZ^*}}$ through uncertainty propagation. See 21 in backup.

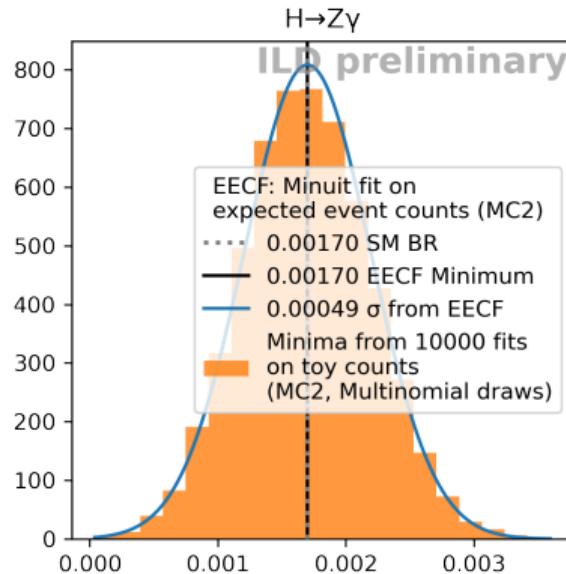
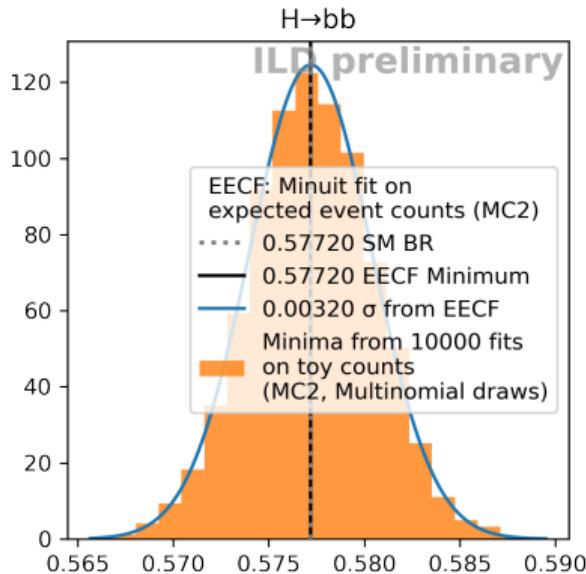


OPTIMIZATION - VALIDITY CHECK



Toy study : Draw from multinomial (N_{data} fixed).

Shown : 2 of the toy fit distributions for multinomial $\ln \mathcal{L}$ with $[0, 1]$ boundaries.

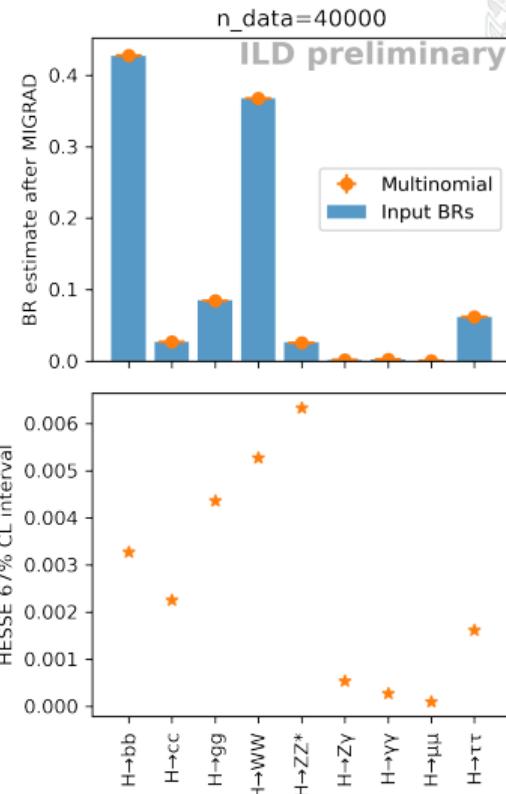
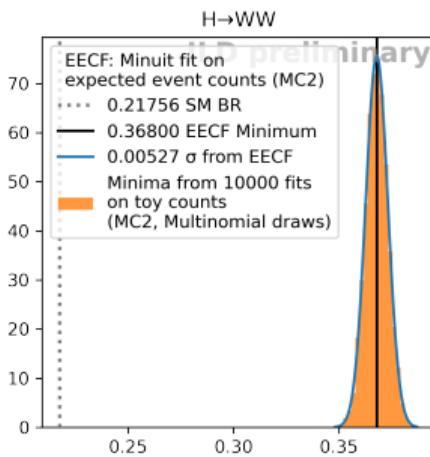
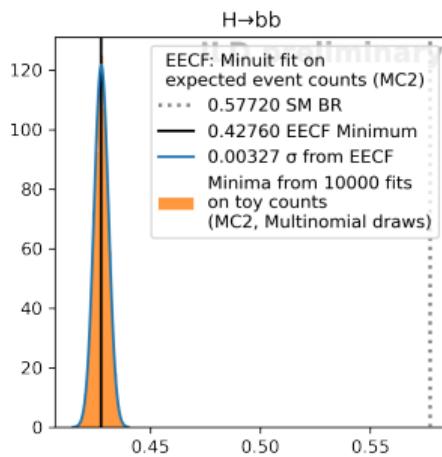


For this slide only, we used $MC1 = MC2$. $MC1 \neq MC2$ shown in 22 (backup).

FIT IN A NON-SM SCENARIO



Assume $57.7\% \rightarrow 42.7\% \ BR(H \rightarrow b\bar{b})$, $21.8\% \rightarrow 36.8\% \ BR(H \rightarrow W^+W^-)$.



CONCLUSION

CONCLUSION



- + An extraction of all major branching ratios.
- + Independent of σ_{ZH} and $\sigma_{WW\text{-fusion}}$.
- + Can automatically adapt to BR scenarios drastically different from SM.
- + Uncertainties look promising. See 24 in backup.

More work needed :

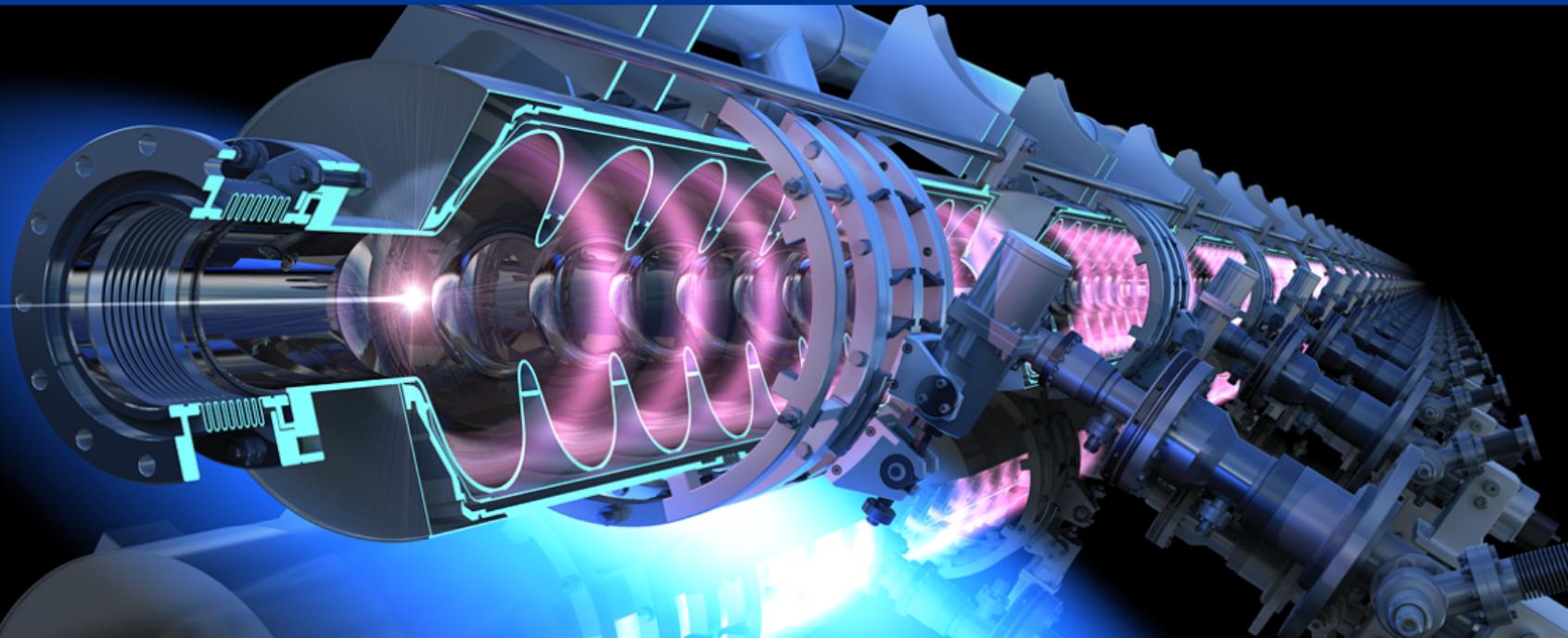
- Signal selection/background rejection omitted so far.
- Overlap with dedicated analyses on $ZH, Z \rightarrow (e^+e^-, \mu^+\mu^-, \nu\bar{\nu})$?

Table – Results of a MINUIT fit on the expected event counts. In %. ILD preliminary.

	SM BR	minimum	σ
$H \rightarrow cc$	2.718	2.733	0.210
$H \rightarrow bb$	57.720	57.743	0.321
$H \rightarrow \mu\mu$	0.030	0.030	0.009
$H \rightarrow \tau\tau$	6.198	6.207	0.152
$H \rightarrow Z\gamma$	0.170	0.176	0.050
$H \rightarrow gg$	8.550	8.499	0.374
$H \rightarrow \gamma\gamma$	0.242	0.243	0.027
$H \rightarrow WW$	21.756	21.761	0.434
$H \rightarrow ZZ^*$	2.616	2.608	0.539

5

BACK-UP



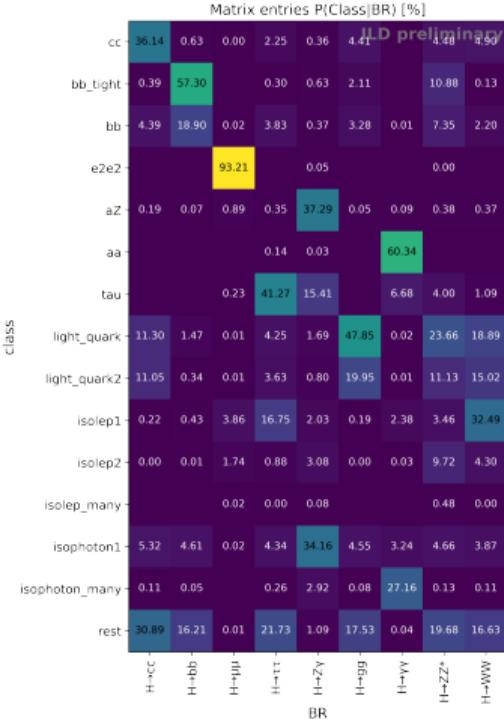


EXPECTED COUNTS PER (CATEGORY, BR) PAIR

Removed ILC overlay particles.



With overlay, categories not adapted yet.

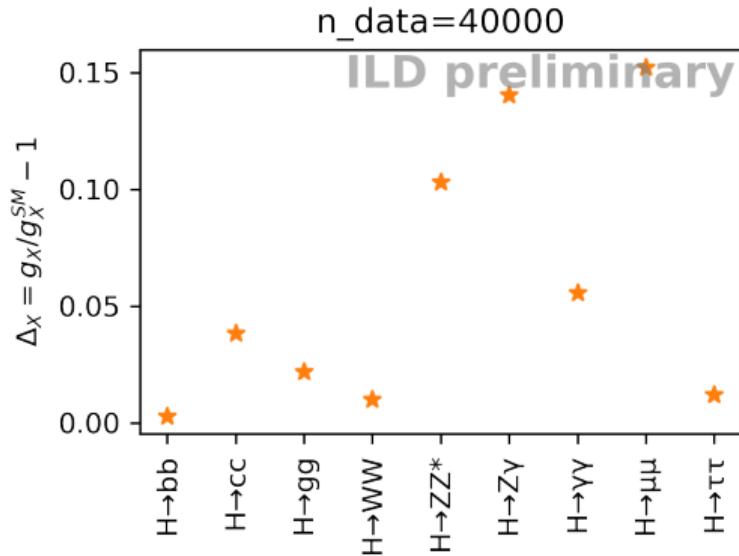




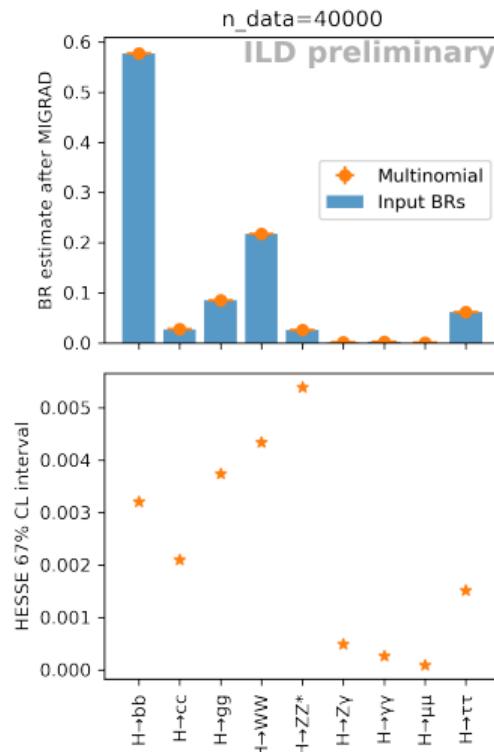
EFFECT OF OVERLAY PARTICLES ON THE FIT

All fits on Higgsstrahlung events without additional background events.

Category definitions are **not** adapted to the scenario with overlay events.



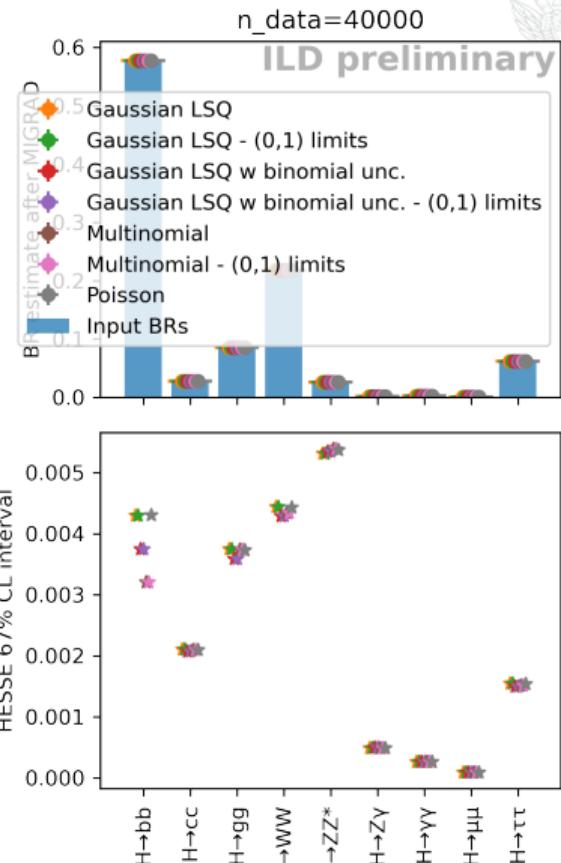
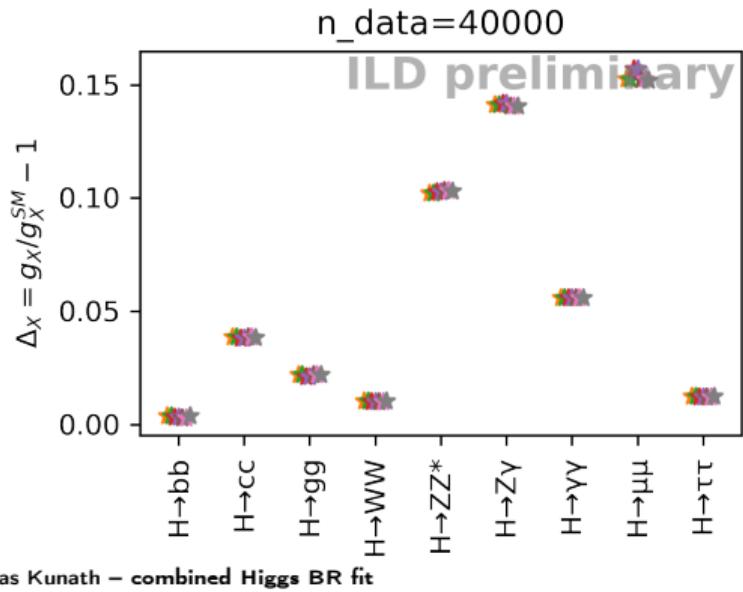
Jonas Kunath – combined Higgs BR fit



OPTIMIZATION - LIKELIHOOD FUNCTION

BACK-UP

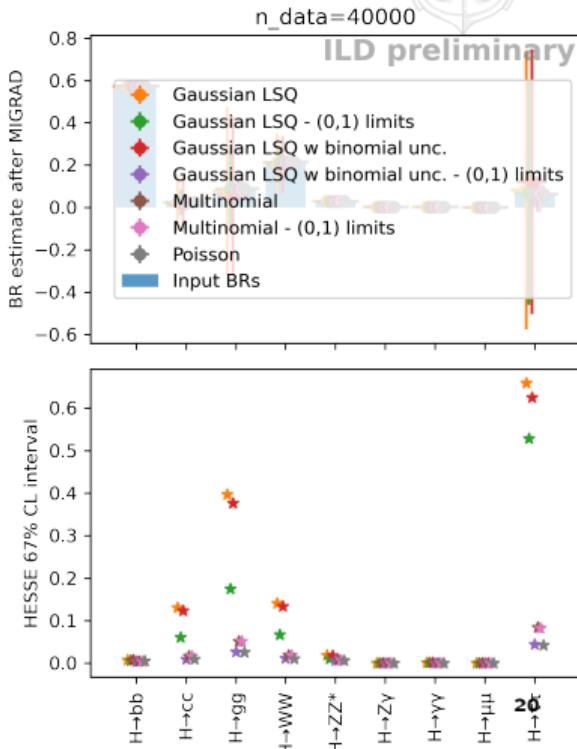
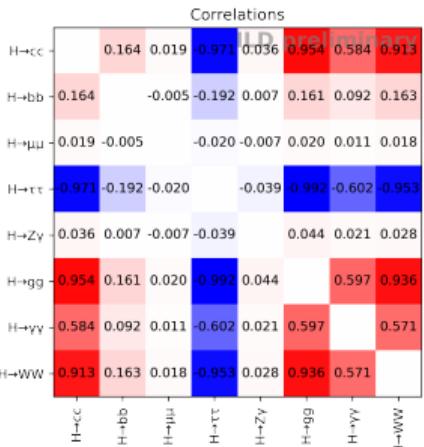
Effect of the likelihood fct definition on the uncertainties.
The highest BR, $H \rightarrow b\bar{b}$, benefits most from the multinomial description.





A FIT WITH CATEGORIES THAT ARE TOO CORRELATED

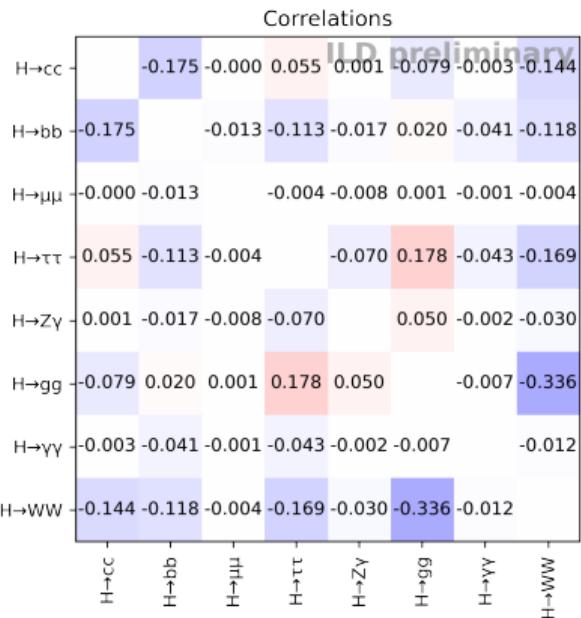
With a highly correlated category definition/fit, the uncertainties of the MINUIT fit are huge, and details in the likelihood function definition matter.





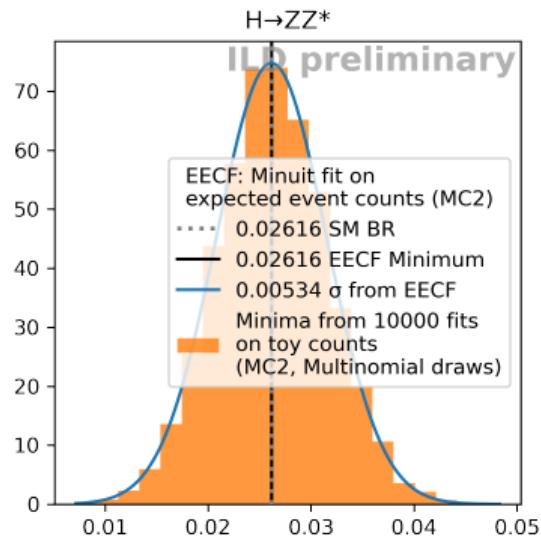
BR CORRELATIONS WITH THE CURRENT CATEGORIES

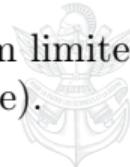
Higher correlations motivate improvements in the category definition. Needed to include the results in a global fit. Also needed for the last BR :



Jonas Kunath – combined Higgs BR fit

$$B_{ZZ^*} = 1 - \sum_{i \neq ZZ^*} B_i \Rightarrow \sigma_{ZZ^*}^2 = \sum_{i \neq ZZ^*} \sum_{j \neq ZZ^*} \rho_{ij} \sigma_i \sigma_j$$





BIAS FROM MC SAMPLE SIZE

Originally, we only used 50k events per branching ratio for each MC1, MC2. The bias from limited MC samples is visible (SM BR \neq EECF minimum). Larger MC samples help (next slide).

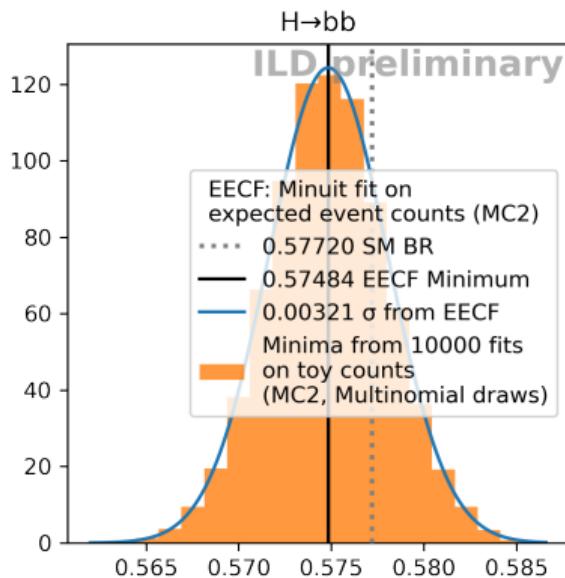


Table – Results of a MINUIT fit on the expected event counts. In %. ILD preliminary.

	SM BR	minimum	σ
$H \rightarrow cc$	2.718	2.984	0.212
$H \rightarrow bb$	57.720	57.483	0.321
$H \rightarrow \mu\mu$	0.030	0.030	0.009
$H \rightarrow \tau\tau$	6.198	6.211	0.152
$H \rightarrow Z\gamma$	0.170	0.160	0.052
$H \rightarrow gg$	8.550	8.411	0.378
$H \rightarrow \gamma\gamma$	0.242	0.240	0.027
$H \rightarrow WW$	21.756	21.683	0.433
$H \rightarrow ZZ^*$	2.616	2.797	0.542

BIAS FROM MC SAMPLE SIZE

BACK-UP

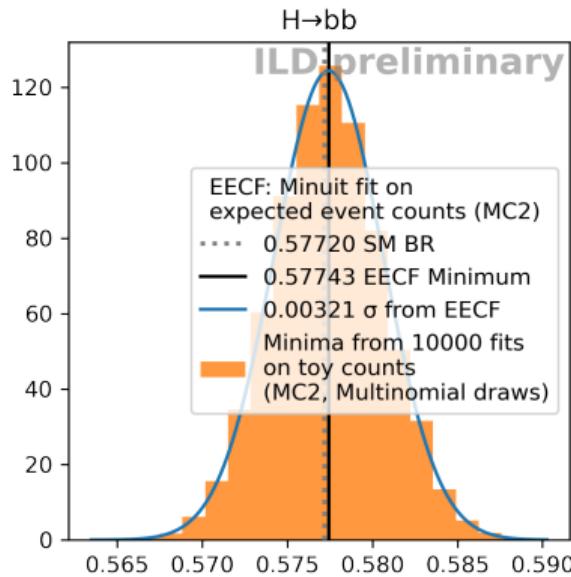


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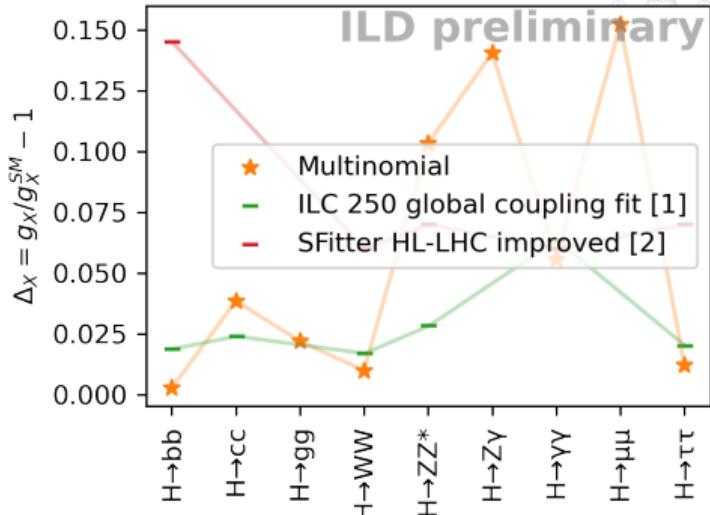
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COMPARISON WITH GLOBAL COUPLING FITS

BACK-UP



- [1], [2] use existing analyses and combine them to extract a combined sensitivity for the Higgs boson couplings.
 - [1] scaled to the H-20 ILC250 scenario.
 - *Multinomial* is our approach.
 - A single analysis directly fitting the branching ratios to data.
 - Expressed as couplings for comparison.
 - Remember : So far signal-only.
- Not a legitimate comparison. But gives hope that the results stay competitive even without the simplifications.



- [1] J Tian, K Fujii *Measurement of Higgs boson couplings at the International Linear Collider*.
[2] SFitter *Measuring Higgs Couplings at a Linear Collider*.

CATEGORY DEFINITIONS

BACK-UP



```
no_iso = '(n_iso_leptons == 0) & (n_iso_photons == 0) & '
categories = dict(
    cc=no_iso+'(n_pfos > 20) & (b_tag2 < 0.7) & (m_h > 100) & (c_tag1 > 0.5) & (c_tag2 > 0.5)',
    bb_tight=no_iso+'(b_tag1 > .8) & (b_tag2 > .8)',
    bb=no_iso+'(b_tag1 > .8)',
    e2e2='(e2e2_mass > 100) & (e2e2_mass < 130)',
    aZ='(aZ_a_energy > 20) & (aZ_a_energy < 50) & (aZ_other_mass > 75) & (aZ_other_mass < 100) &
        (abs(aZ_a_cos_theta) < 0.9)',
    aa='(n_iso_photons > 0) & (e_h > 125) & (n_pfos < 15) & (n_iso_leptons == 0) & (abs(aZ_a_cos_theta) < 0.9) &
        (aZ_a_energy > 35)',
    tau='(n_pfos < 15) & (n_iso_leptons == 0)',
    # tau='(y_45 < 1e-5) & (n_iso_leptons == 0)',
    light_quark=no_iso+'(b_tag1 + c_tag1 < .5)',
    light_quark2=no_iso+'(b_tag2 + c_tag2 < .5)',

    # Isolepton collector.
    isolep1='(n_iso_leptons == 1)',
    isolep2='(n_iso_leptons == 2)',
    isolep_many='(n_iso_leptons > 2)',
    isophoton1='(n_iso_photons == 1)',
    isophoton_many='(n_iso_photons > 1)',

    rest='(hDecay > 0)', # Cannot have empty expression -> Always true.
)
```

BUILDING NUMBER OF JETS LABEL

BACK-UP



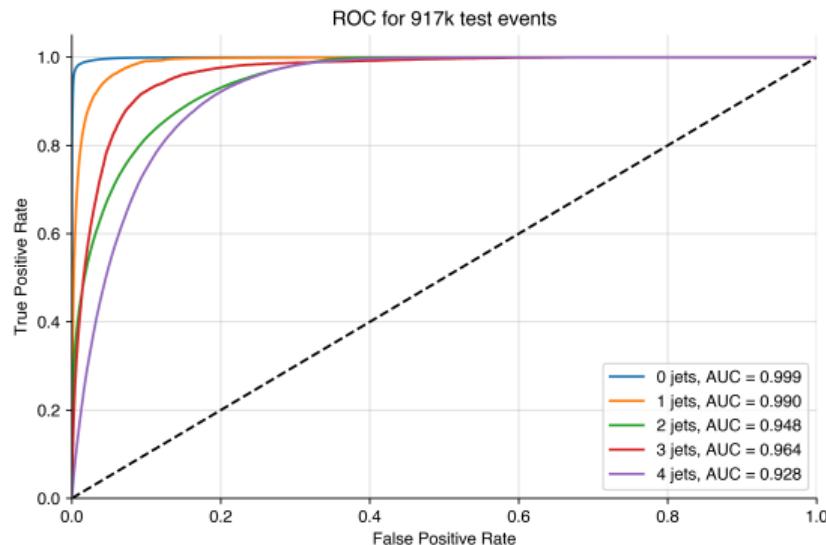
Not currently in use, but we investigate if it could help.

Trained a BDT for labeling events by the number of jets using the y and m variables.

- We use 20 input variables :
 - The masses of individual and combined (up to 4) jets, m .
 - The y_{ij} values from the jet clustering algorithm.
- The target used for training is the true number of hadronic jets.
- Trained the BDT using 100k events from the signal sample.
- Performed a randomized search on the following hyper parameters (**best**) :
 - `eta` : [0.05, 0.10, **0.20**, 0.30, 0.35] ,
 - `max_depth` : [2, 3, 4, **5**, 6],
 - `gamma` : [3, 1, **0.5**, 1e-01, 1e-02],
 - `colsample_bytree` : [0.5, **0.6**, 0.7].

BUILDING NUMBER OF JETS LABEL

BACK-UP



- Multiclass ROC using one-versus-rest strategy.
- Studies in progress to understand how well this classifier performs, particularly when tested in subsets of data (i.e. categories).
- Having a # jets predicted can help us build optimal categories for Higgs BR measurements.