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.

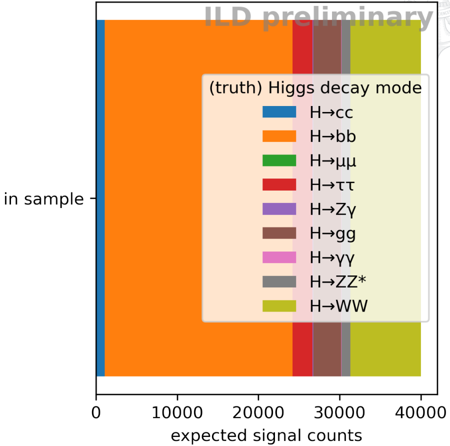
Currently :
Still a work in progress.

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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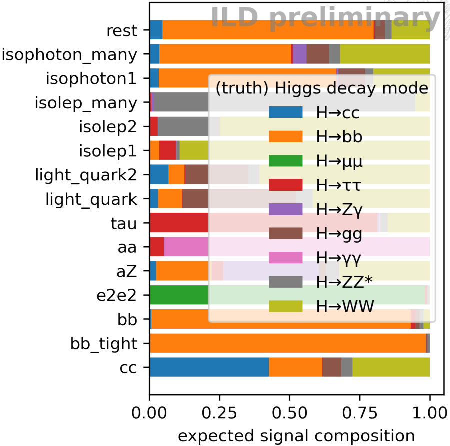

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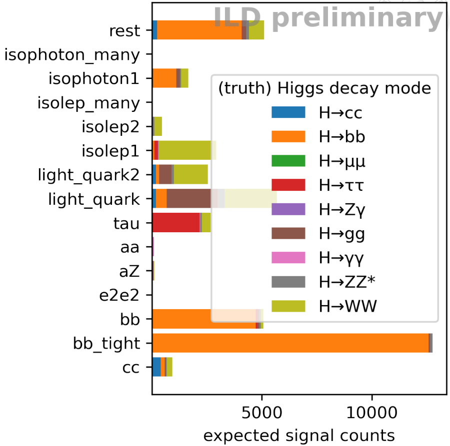

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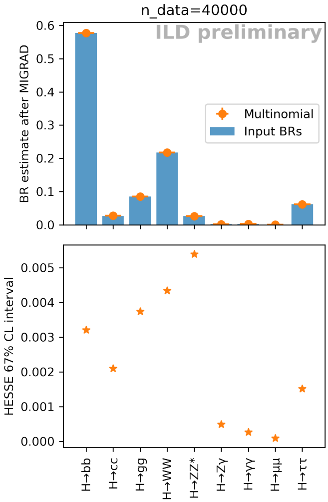

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Advantages

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

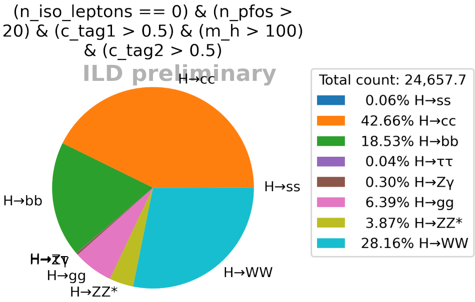
CURRENT SIMPLIFICATIONS

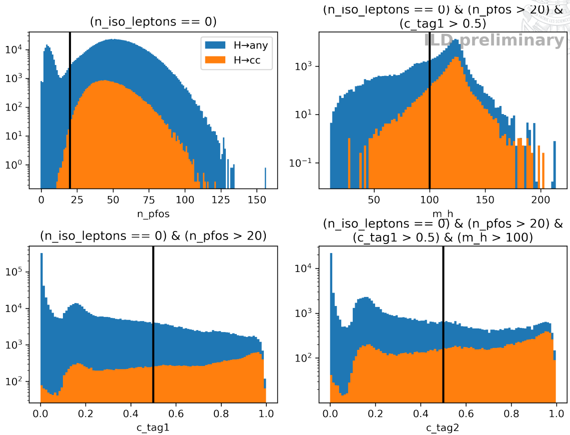
Reconstructed events from the new $\sqrt{s} = 250$ GeV SetA mass production (`ILD_l5_o1_v02`, `v02-02`).

- So far, only using the signal (Higgsstrahlung).
  - $\geq$ 400k simulated events/decay mode.
- $ZH \to \nu\bar{\nu}H$, 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) : $\sigma_{ZH}^{\text{unpol.}} \approx 200$ fb, 2000 fb^{-1} H-20 scenario, catch 10 % of the signal $\to O(40,000)$ Higgs events.

CATEGORY BUILDING EXAMPLE : CC



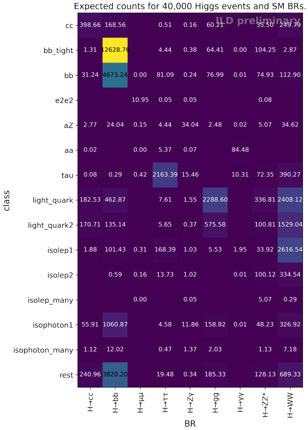


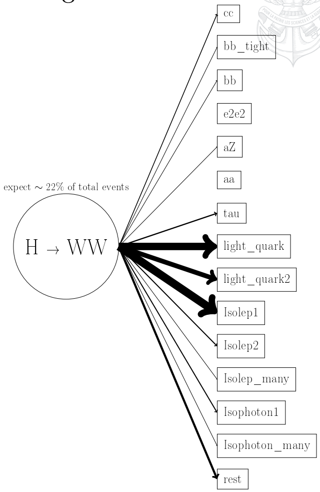
CATEGORIES

- Reuse common tools :
  - `LCFIPlus` 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

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





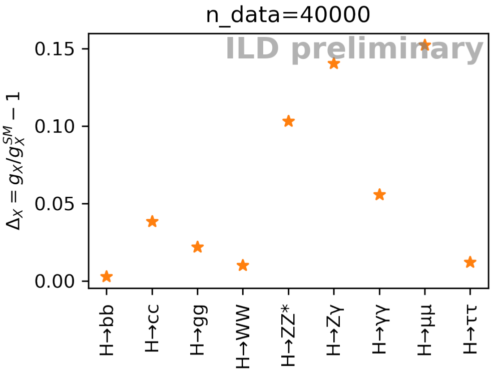
OPTIMIZATION - SETUP

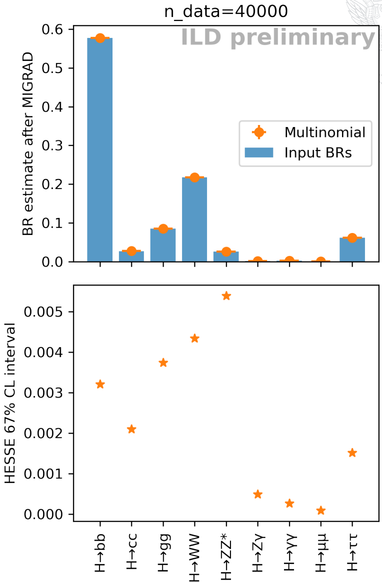
BRs from minimization through `MINUIT`/iminuit.

- $\vec{S} = M \cdot \vec{B} = \vec{f}(\vec{B})$, 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.
  - $-\ln\mathcal{L} = -N_{\text{data}} \sum_i S_i \ln\left(\sum_j M_{ij} B_j\right)$.
  - $B_{H\to ZZ^*} = 1 - \sum_{i \neq H\to ZZ^*} B_i$.
  - Each BR constrained to $[0, 1]$.

OPTIMIZATION - RESULTS

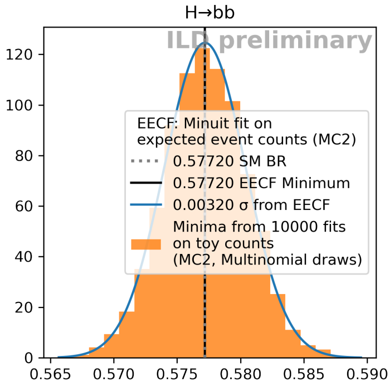
The fitted $\mathrm{BR}^{\mathrm{min}}$ reproduces $\mathrm{BR}^{\mathrm{true}}$ within its uncertainties. $\sigma_{B_{H\to ZZ^*}}$ through uncertainty propagation. See 21 in backup.

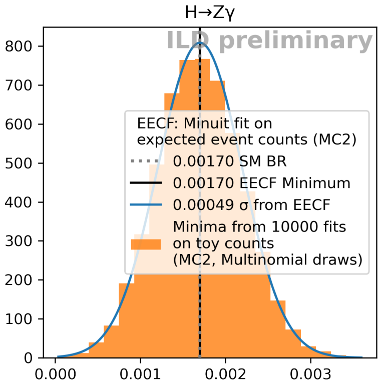




OPTIMIZATION - VALIDITY CHECK

Toy study : Draw from multinomial (N_{data} fixed).
Shown : 2 of the toy fit distributions for multinomial $\ln\mathcal{L}$ with $[0, 1]$ boundaries.

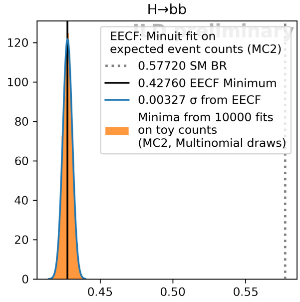


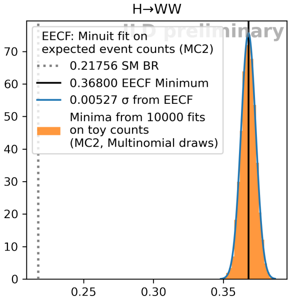


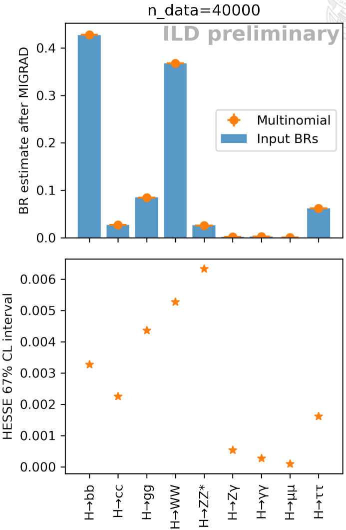
For this slide only, we used `MC1` $=$ `MC2`. `MC1` $\neq$ `MC2` *shown in 22 (backup).*

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

+ An extraction of all major branching ratios.
+ Independent of σ_{ZH} and $\sigma_{\text{WW-fusion}}$.
+ 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 $ZH, Z \to (e^+e^-, \mu^+\mu^-, \nu\bar{\nu})$?

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

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

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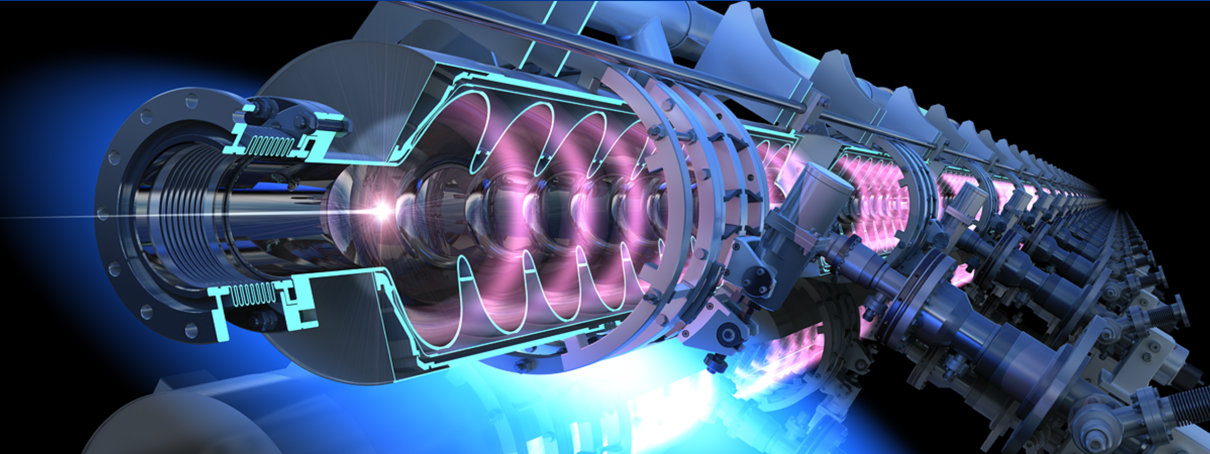
BACK-UP



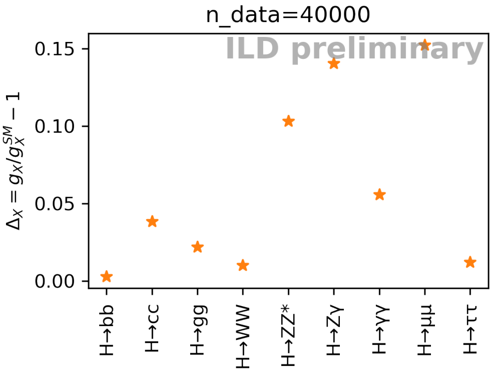
EXPECTED COUNTS PER (CATEGORY, BR) PAIR

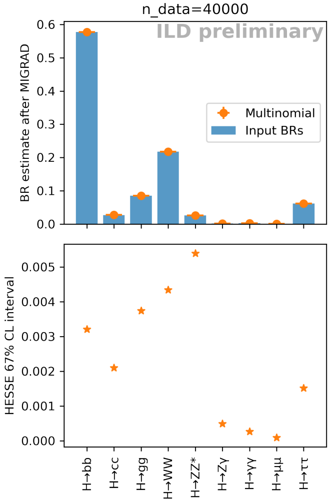
Removed ILC overlay particles.

With overlay, categories not adapted yet.

EFFECT OF OVERLAY PARTICLES ON THE FIT

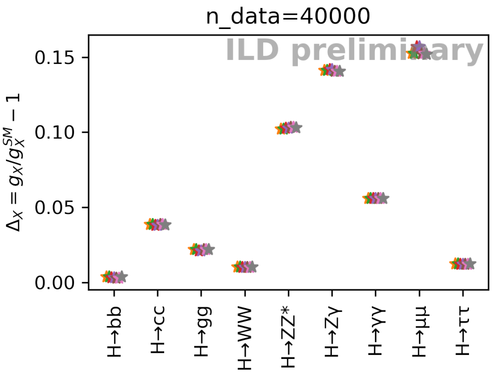
All fits on Higgsstrahlung events without additional background events.
Category definitions are **not** adapted to the scenario with overlay events.

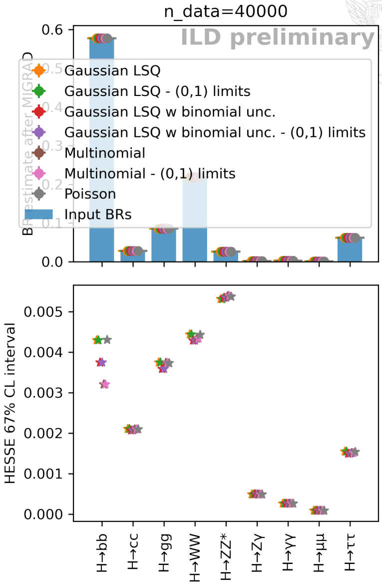




OPTIMIZATION - LIKELIHOOD FUNCTION

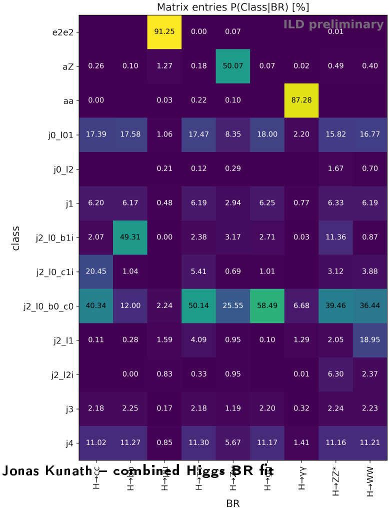
Effect of the likelihood fct definition on the uncertainties. The highest BR, $H \to b\bar{b}$, benefits most from the multinomial description.

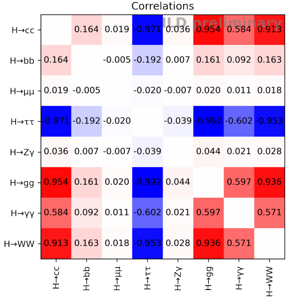


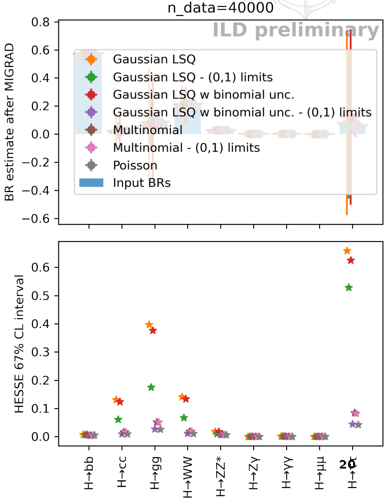


A FIT WITH CATEGORIES THAT ARE TOO CORRELATED

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



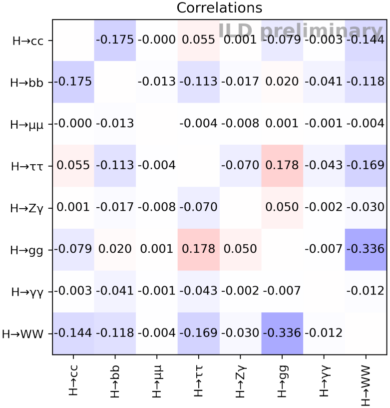


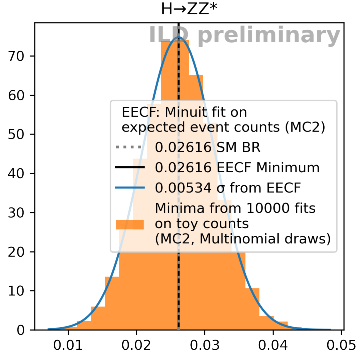


BR CORRELATIONS WITH THE CURRENT CATEGORIES

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

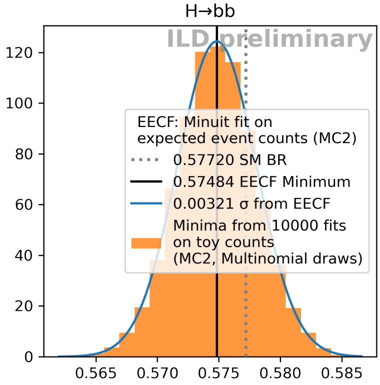
$$B_{ZZ^*} = 1 - \sum_{i \neq ZZ^*} B_i \Rightarrow \sigma^2_{ZZ^*} = \sum_{i \neq ZZ^*} \sum_{j \neq ZZ^*} \rho_{ij} \sigma_i \sigma_j$$





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).



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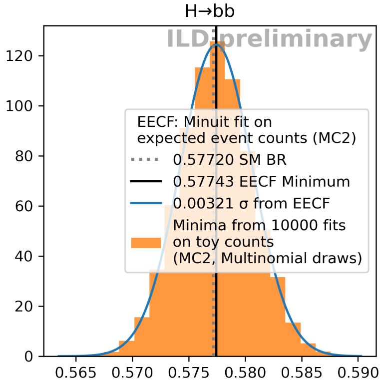

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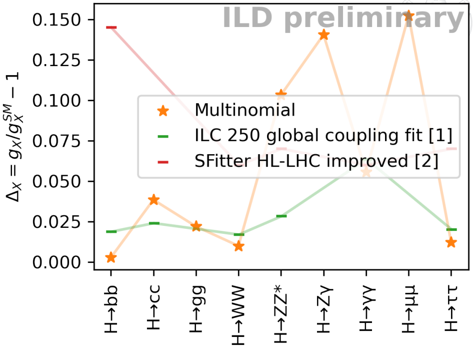
COMPARISON WITH GLOBAL COUPLING FITS

- [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

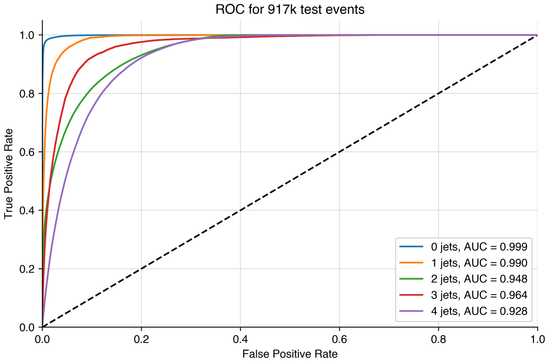

```python
no_iso = '(n_iso_leptons == 0) & (n_iso_photons == 0) & '
categories = dict(
    cc=no_iso+'(n_pfos > 20) & (b_tag2 < 0.7) & (m_h > 100) & (c_tag1 > 0.5) & (c_tag2 > 0.5)',
    bb_tight=no_iso+'(b_tag1 > .8) & (b_tag2 > .8)',
    bb=no_iso+'(b_tag1 > .8)',
    e2e2='(e2e2_mass > 100) & (e2e2_mass < 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

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



- 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.