$HH \to b\bar{b}\tau^+\tau^-$ at the FCC-hh

Prof Monica D'Onofrio, Dr Carl Gwilliam, Dr Cristiano Sebastiano, Dr Matt Sullivan

7^{th} February 2022

FCC Physics Workshop

Overview

- Preliminary sensitivity study @ FCC-hh:
  - Study outline
  - Software & MC
  - Selection & MVA
  - Sensitivity estimate
- BSM Higgs @ FCC-hh
- Outlook

$HH \to b\bar{b}\tau\tau$ at the FCC-hh

$HH \to b\bar{b}\tau\tau$ @ FCC-hh: Study outline

- Existing $HH \to b\bar{b}\tau\tau$ studies at FCC-hh:
  - HH production, $\delta_{\kappa_\lambda} = 9.8 - 13.8\%$ (arXiv 2004:03505)
  - HHj production, $\delta_{\kappa_\lambda} \sim 8\%$ (arXiv:1802.01607)
- Setup and validate software framework & cross-check with existing results
  - Use same framework for BSM Higgs studies
- Aim to improve upon existing HH studies:
  - Use modern multivariate packages (Tensorflow, XGBoost)
  - Improve training techniques using k-folding, including more backgrounds
  - Optimise MVA specifically for challenging $b\bar{b}\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$ final state
  - Study additional systematic assumptions

$HH \to b\bar{b}\tau\tau$ @ FCC-hh: Software framework

- Adapt RDataFrame skeleton code to produce all analysis ntuples:
  - FCCAnalyses (GitHub)
  - Liverpool code (GitLab)
  - Thanks to Clement Helsens for the help while developing our framework!
- For cut-based studies, use existing FCC analysis & plotting code
- For ML analysis, use common Python packages:
  - Uproot: Load/process dataframes
  - ML: Keras (Tensorflow), XGBoost
  - Also use Numpy, Matplotlib & Pandas

$HH \to b\bar{b}\tau\tau$ @ FCC-hh: MC samples

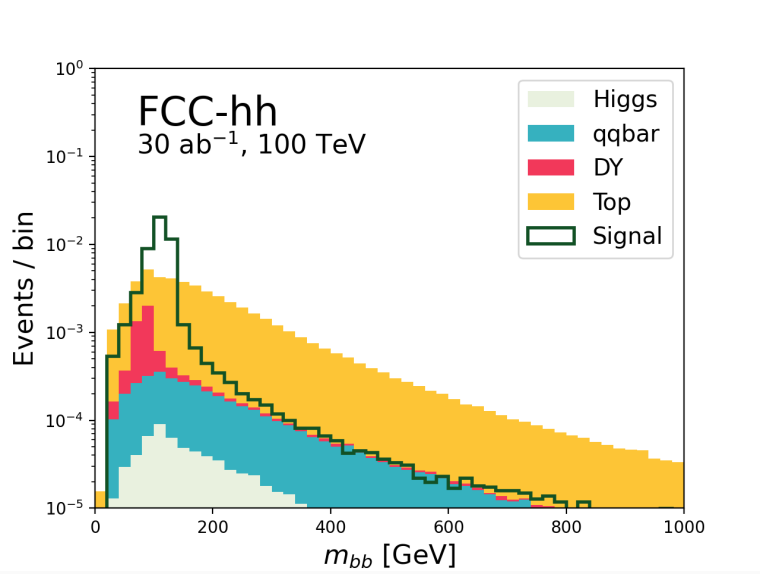
- Use Delphes EDM4Hep MC samples (v0.4): Samples list

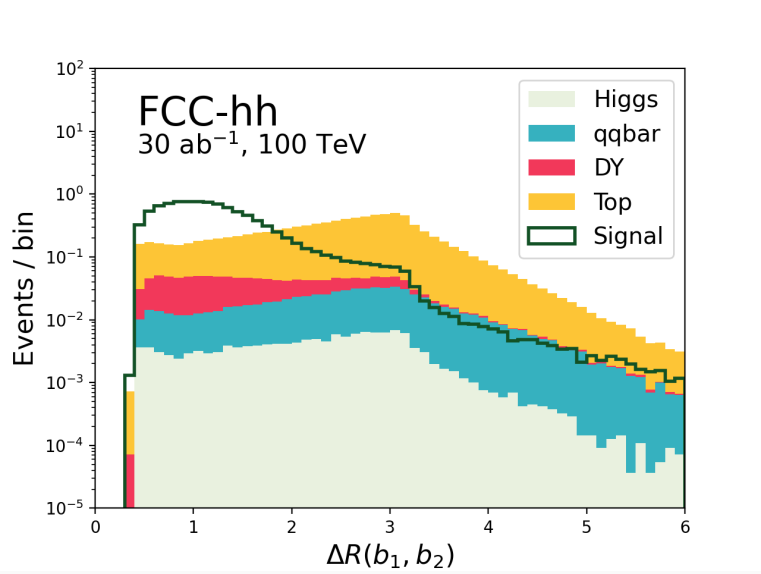
Process	MC cross-section [pb]	MC stats.
$HH \to b\bar{b}\tau\tau$	0.089	5M
$t\bar{t}$	35030.3	80M
Single top ($s-$, $t-$channel)	16251.8	3M
ggF Higgs	2209.0	7M
VBF Higgs	361.9	7M
QCD+EW	75.6	5M
$t\bar{t}Z$	63.9	1M
$t\bar{t}H$	54.7	1M
VH	49.4	2M
$t\bar{t}W$	16.4	2M
$t\bar{t}WW$	1.1	2M
EW	0.6	5M
$t\bar{t}WZ$	0.2	2M
$t\bar{t}ZZ$	0.2	1M

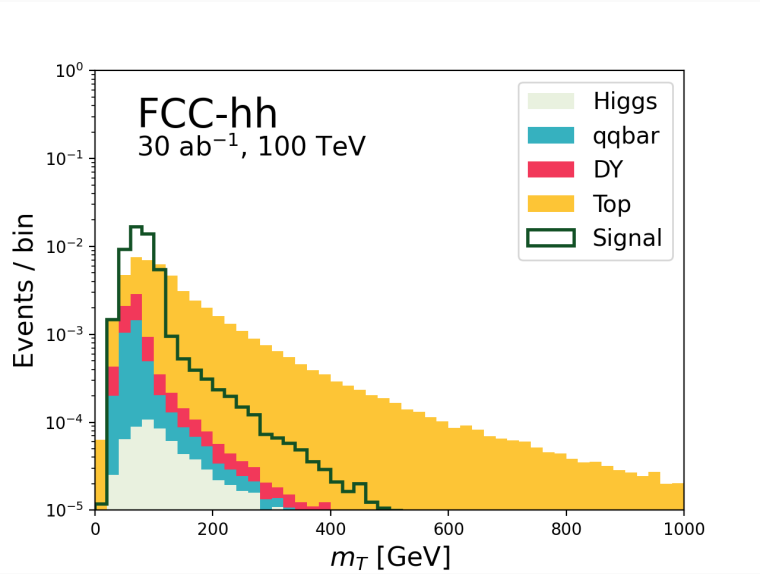
$HH \to b\bar{b}\tau\tau$ at FCC-hh: Preliminary selection & features

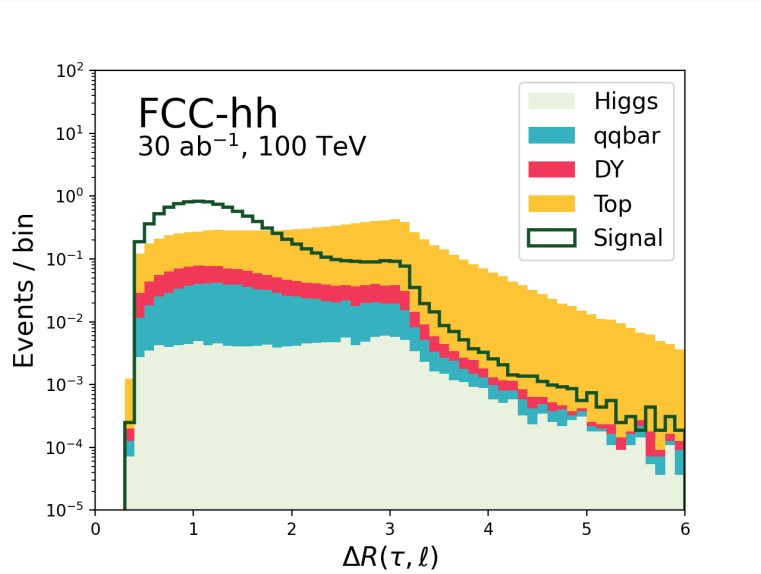
- This study follows the general strategy of the ATLAS Run-2 analysis (Preliminary result: ATLAS-CONF-2021-030)
- Topological selection:
  - Exactly 2 b-tagged jets ($p_{\mathrm{T}} > 30$ GeV)
  - Exactly one electron or muon ($p_{\mathrm{T}} > 30$ GeV)
  - Exactly one τ_{had} ($p_{\mathrm{T}} > 30$ GeV)
  - Lepton and τ are opposite charge
- Input features for both cut-based & ML analyses:
  - $H(b\bar{b})$: $m_{b\bar{b}}$, $\Delta R(b_1, b_2)$, $p_{\mathrm{T}}^{b_1,b_2}$
  - $H(\tau\tau)$: $m_{\mathrm{T}}(\ell, E_{\mathrm{T}}^{\mathrm{miss}})$, $\Delta R(\tau, \ell)$
  - Event: $E_{\mathrm{T}}^{\mathrm{miss}}$, $E_{\mathrm{T}}^{\mathrm{miss}}$ centrality, m_{HH}, $\Delta\phi(H_1, H_2)$

$HH \to b\bar{b}\tau\tau$ at FCC-hh: $H(b\bar{b})$, $H(\tau\tau)$

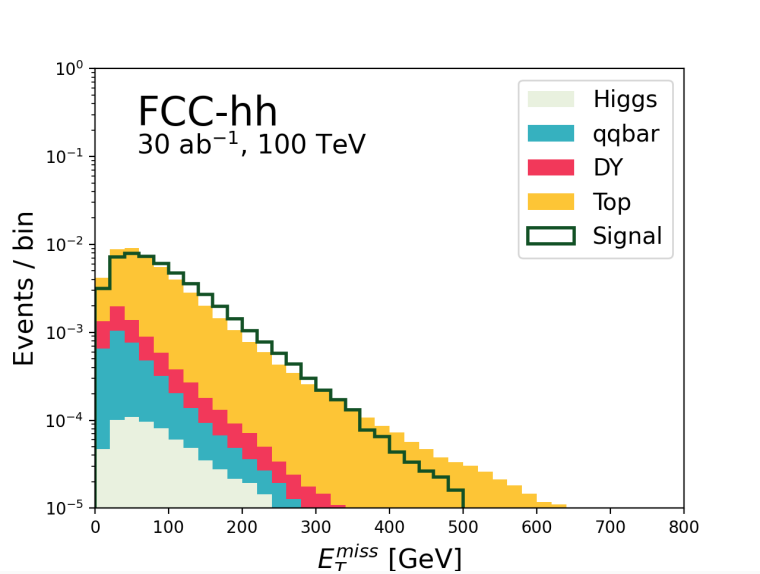


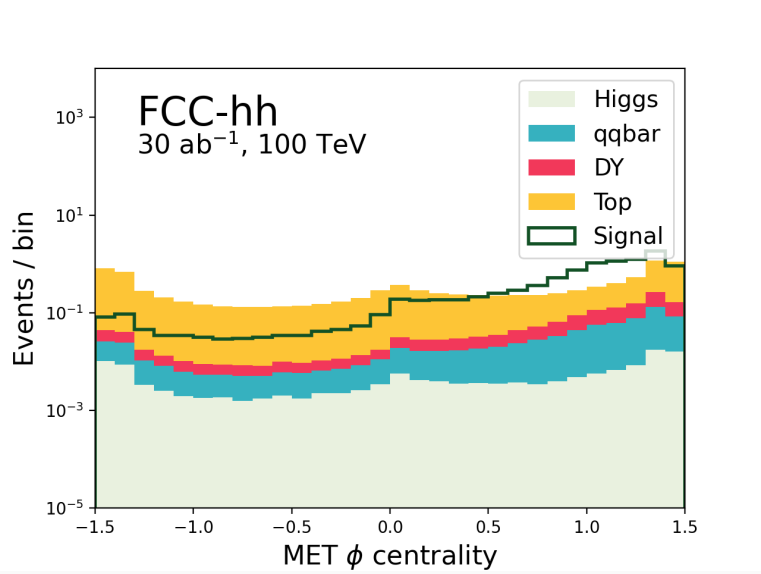


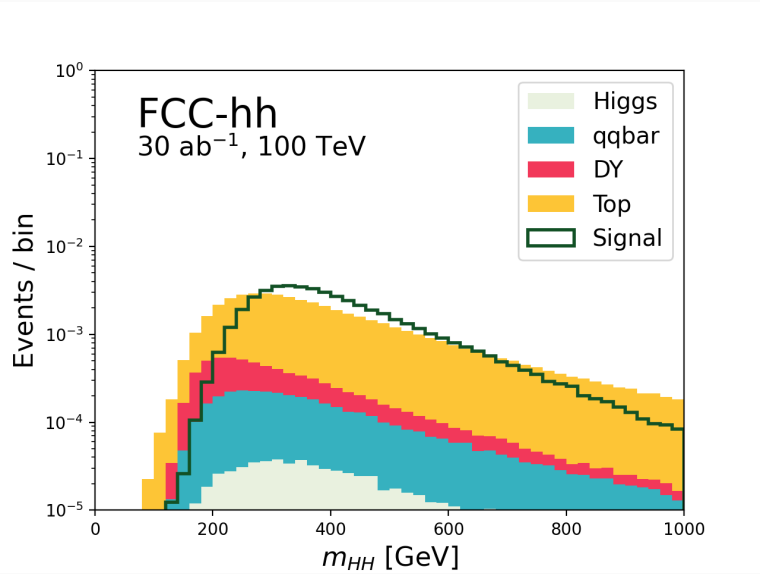


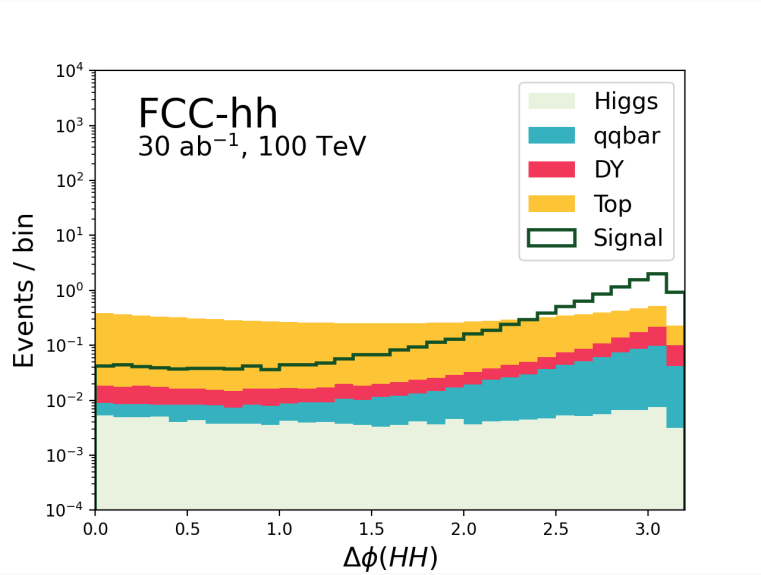


$HH \to b\bar{b}\tau\tau$ at FCC-hh: HH system



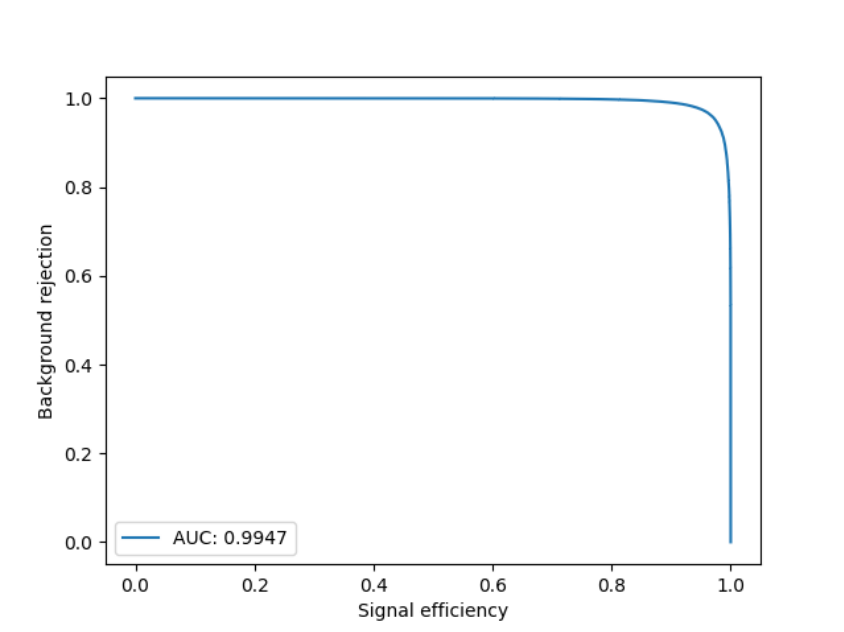


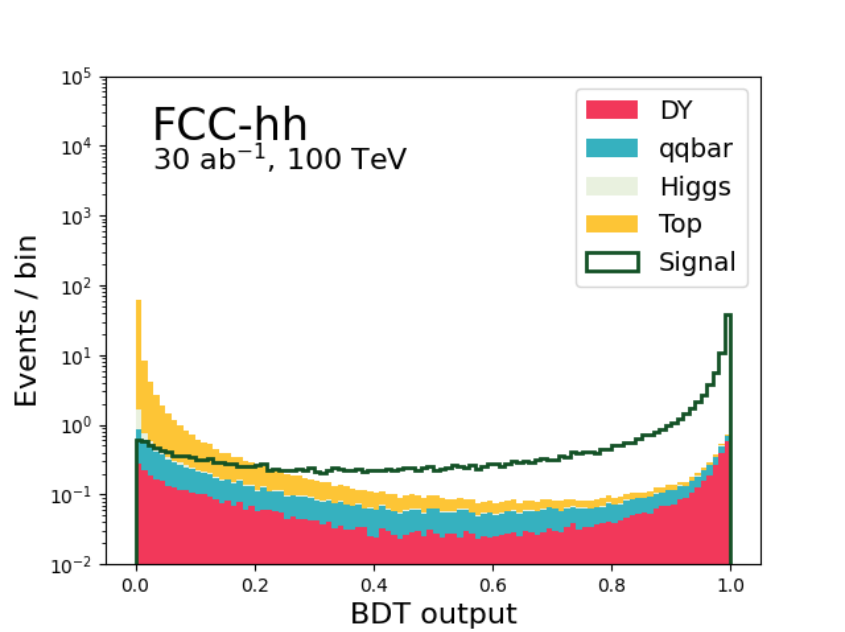




$HH \to b\bar{b}\tau\tau$ at FCC-hh: Multivariate analysis

- Use XGBoost BDT to perform binary classification
- Train classifier to distinguish signal vs dominant $t\bar{t}$ background
- ROC curve & BDT predictions show promising discrimination performance





$HH \to b\bar{b}\tau\tau$ at FCC-hh: Sensitivity estimate

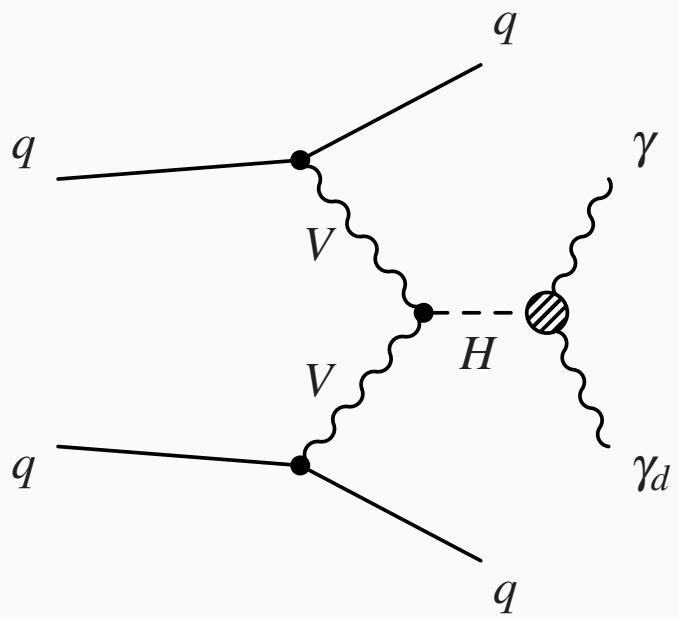
- Calculate sensitivity estimate with binned BDT output distribution
  - 10 bins from 0.99-1.00
- Significance: $\frac{s}{\sqrt{b+(\sigma_b b)^2}}$
- High S/B obtained, with significant dependence on systematic scenario
- 'Envelope' existing HHj study, known differences in samples used

	$s/\sqrt{b}$ $(\sigma_b = 0)$	$\sigma_b = 10\%$	$\sigma_b = 20\%$
	HH production		
Cuts	19.11	0.22	0.11
XGBoost	57.84	2.41	1.20
	Boosted HHj production		
arXiv 1802.01607	24.97	1.47	0.73
Cuts	10.14	0.15	0.08
XGBoost	43.33	1.84	0.92

Bonus study - BSM Higgs

BSM Higgs at FCC-hh: Summary

- Exploit VBF + $E_{\mathrm{T}}^{\mathrm{miss}}$ + γ final state to study dark sector models: $H \to \gamma\gamma_d$
- Current limits from LHC + FCC-hh prospects:
  - ATLAS: BR($H \to \gamma\gamma_d$) $< 1.8\%$
  - CMS: BR($H \to \gamma\gamma_d$) $< 2.9\%$
  - FCC-hh: BR($H \to \gamma\gamma_d$) $< 0.1\%$?
- Signal MC generated and preliminary event selection based on ATLAS Run-2 paper in progress
- Background $V\gamma$+jets not centrally available - local production in progress



Summary

Summary

HH physics:

- *HH* production provides experimental handle on λ
- LHC/HL-LHC provides constraints on $\kappa_\lambda = \lambda/\lambda_{\mathrm{SM}}$
- FCC-hh needed to measure observe & measure *HH* production

Preliminary sensitivity study @ FCC-hh:

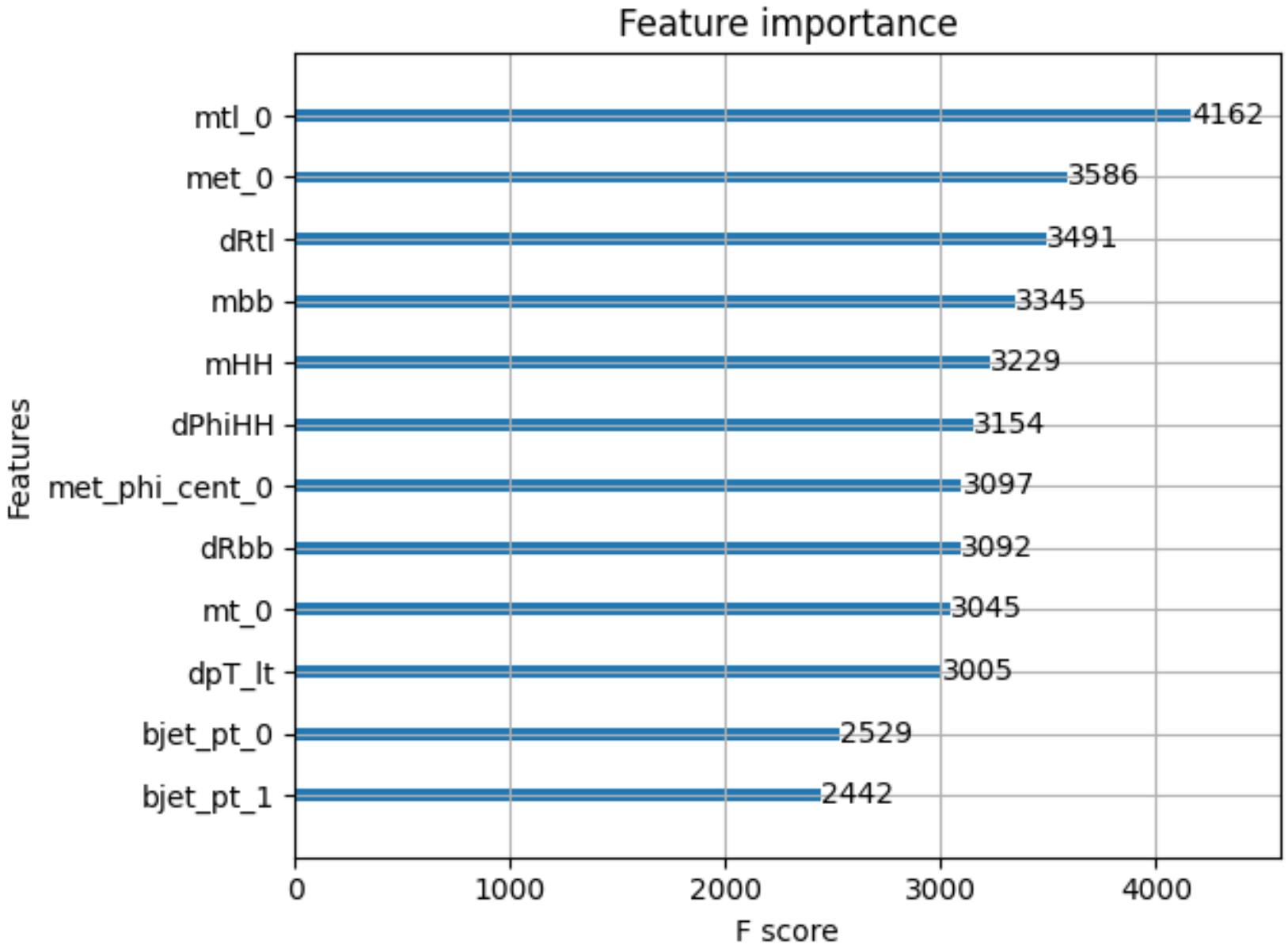
- Study *HH* production in $b\bar{b}\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$
- Sensitivity projected for FCC-hh strongly dependent on systematics scenario
- To-do: Improve BDT training: train on all backgrounds, *k*-fold training
- To-do: Detailed systematics study

Backup

Cut-based analysis

Cut	$HH \to b\bar{b}\tau\tau$ yield	Efficiency (%)	$t\bar{t}$ yield	Efficiency (%)
Initial	2633387.9	100.0	1050909714000.0	100.0000
$N_{b-\mathrm{jets}} = 2$	1047155.6	39.8	408903238094.7	38.9095
$N_{\mathrm{lepton}} = 1$	184812.2	7.0	74468020822.6	7.0861
$N_{\tau_{\mathrm{had}}} = 1$	89448.1	3.4	9192058348.3	0.8747
Opposite charge	85861.0	3.3	5984355086.3	0.5694
$m_{b\bar{b}}$ [95, 140] GeV	60186.0	2.3	1147438366.7	0.1092
$m_{\tau\ell}$ [40, 100] GeV	48037.0	1.8	410331642.2	0.0390
$\Delta R(b_1, b_2) < 1.4$	33106.3	1.3	44361613.4	0.0042
$\Delta R(\tau, \ell) < 1.6$	30371.9	1.2	27759213.2	0.0026
$m_{(T)} < 30$ GeV	22082.6	0.8	6149529.0	0.0006
MET centrality ¿ 0.8	18272.5	0.7	3705655.7	0.0004
$\Delta\phi(HH)$	16674.5	0.6	557840.6	0.0001

BDT feature importance



$E_{\mathrm{T}}^{\mathrm{miss}}$ centrality

$$A = \frac{\sin\left(\phi_{\mathrm{MET}} - \phi_{\tau}\right)}{\sin\left(\phi_{\ell} - \phi_{\tau}\right)} \tag{1}$$

$$B = \frac{\sin\left(\phi_{\ell} - \phi_{\mathrm{MET}}\right)}{\sin\left(\phi_{\ell} - \phi_{\tau}\right)} \tag{2}$$

$$\mathrm{MET\ centrality} = \frac{A + B}{\sqrt{A^2 + B^2}} \tag{3}$$