Higgs pair production at the FCC-hh

Matt Sullivan

2^{nd} June 2022

Higgs pair workshop

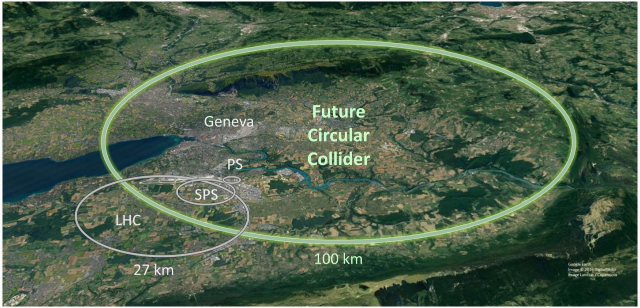
Overview

- Future Circular Collider:
  - FCC introduction & timeline
  - FCC detector design & simulation
  - FCCAnalyses framework
- HH at FCC-hh
  - Existing prospects studies
  - Work-in-progress $b\bar{b}\tau\tau$ study

FCC detector, simulation & analysis

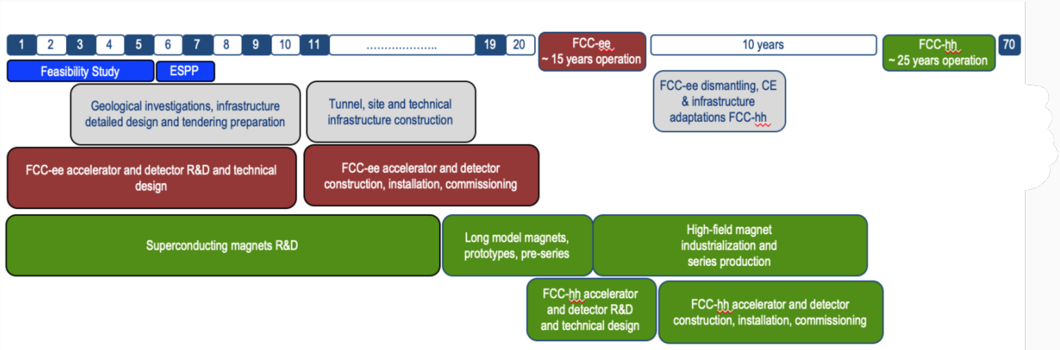
FCC introduction

- Future Circular Collider (FCC) is proposed ∼100 km successor to HL-LHC
- Three phases:
  - *ee* phase: $\sqrt{s} \sim$ 91-365 GeV, precision EW, Higgs physics
  - *eh* phase: $\sqrt{s} \sim$ 3.5 TeV, precision QCD, DIS
  - *hh* phase: $\sqrt{s} = 100$ TeV, unprecedented search reach
- Rich *HH* potential at the FCC-hh - focus of this talk!



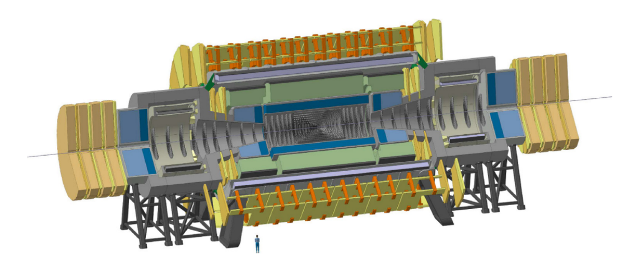
FCC introduction

- Update on FCC given by Fabiola on Monday at FCC week (now)
- Feasibility study underway, result expected to be published ∼2025
- Key dates:
  - Construction begins early 2030s
  - FCC-ee operation begins ∼2040
  - FCC-hh operation begins ∼2065



FCC-hh: Detector design

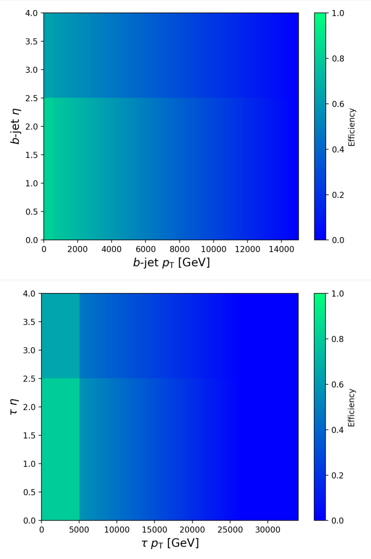
- FCC CDRs: FCC-ee, FCC-hh
- Key parameters for FCC-hh:
  - $\mathcal{L} = 3 \times 10^{35}$ cm^{-2} s^{-1}
  - Upto $< \mu > = 1000$
- Baseline detector design aims for both precision and discovery:
  - Tracking upto $|\eta| \sim 4$
  - Calorimetery upto $|\eta| \sim 6$
  - Efficient jet/τ-tagging
  - Excellent track measurement across large p_{T} range



Baseline FCC-hh detector design

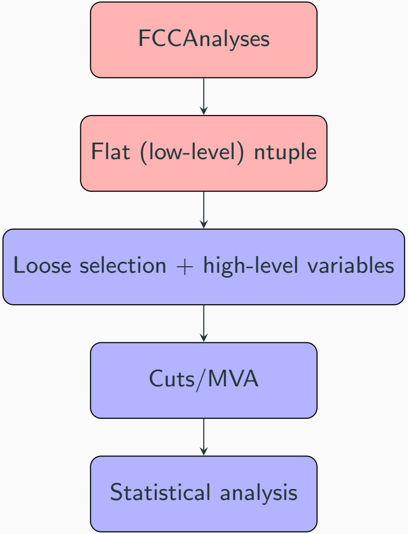
FCC-hh: Detector simulation

- Baseline FCC-hh detector response simulated using Delphes parameterisation
- Lepton (e, μ) and photon reconstruction employs parameterised reco/ID efficency & resolution effects
- Jet reconstruction uses Anti-k_T algorithm with $R = 0.4$
- Object isolation calculated using cone of $R = 0.3$
- b-tagging, c-tagging and τ-tagging efficiency parameterised in p_{T}, η



FCC-hh: FCCAnalyses framework (1/2)

- Common RDataFrame analysis framework developed for FCC physics studies: FCCAnalyses
- Common C++ analysers, analysis-specific Python config & analysis:
  - See C. Helsens talk for example workflow
  - FCC analysis starterkit
- Inputs to analyses are produced in EDM4HEP format:
  - All available MC listed here
- Efficient analysis possible with handful of scripts



FCC-hh: FCCAnalyses framework (2/2)

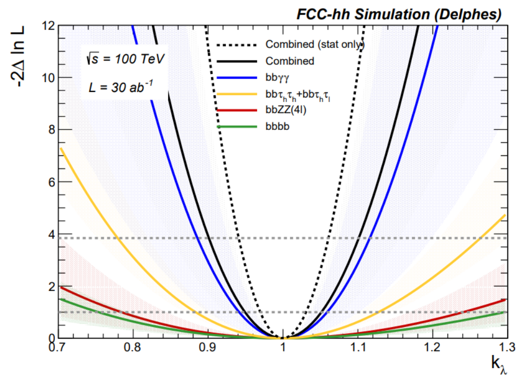
- Example FCC-hh analysis skeleton developed at Liverpool: fcchh-liverpool
- Columnar setup enables rapid prototyping of analysis and easy interface to python ML libraries
- Code to create generic ntuple containing only low-level (p_T, η, ϕ, m, E) information of light jets, b-jets, c-jets, τ, e/γ, μ and E_T^{miss}
- Scripts to add composite variables & apply selections, make plots etc
- **Everything** one needs to start their own FCC analysis!

Name	Last commit
..	
CMakeLists.txt	Committing to Liverpool Gitlab
add_variables.py	Committing to Liverpool Gitlab
analysis.cc	Committing to Liverpool Gitlab
analysis.py	Committing to Liverpool Gitlab
finalSel.py	Committing to Liverpool Gitlab
plots.py	Committing to Liverpool Gitlab
preSel.py	Committing to Liverpool Gitlab

HH physics at FCC-hh

HH studies for FCC-hh (1/2)

- Numerous existing studies on *HH* at FCC-hh:
  - *HH* production ($b\bar{b}b\bar{b}$, $b\bar{b}\tau\tau$, $b\bar{b}\gamma\gamma$)
  - *HH* + jet production (boosted $b\bar{b}b\bar{b}$, $b\bar{b}\tau\tau$, resolved $b\bar{b}\tau\tau$)
- Combination of resolved channels has expected δ_μ of 2.4-5.1%, δ_{κ_λ} of 3.4-7.8%
- Boosted $b\bar{b}\tau\tau$ can constrain κ_λ to within 8% alone!
- What can be improved upon?



arXiv 2004.03505

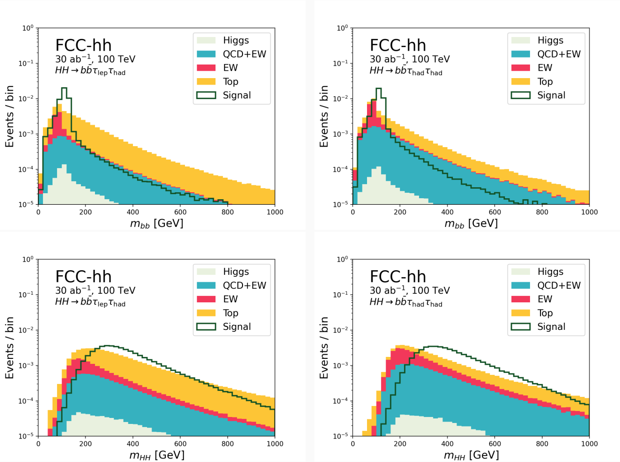
- Focus on $HH \to b\bar{b}\tau\tau$ channel
- Use more modern MVA tools to improve S/B:
  - XGBoost, DNNs
- Use latest & greatest FCC-hh simulated samples with more complete background estimation:
  - Top backgrounds: $t\bar{t}$, single top (s-, $t-$channel), $t\bar{t}V$, $t\bar{t}VV$
  - Single Higgs backgrounds: ggF, VBF, $t\bar{t}H$, VH
  - Continuum backgrounds: QCD+EW (e.g. $pp \to b\bar{b}Z/\gamma^*$), EW (e.g. $pp \to HZ/\gamma^*$)

	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

Process	σ [pb]
ggF HH	1.224 (NNLO$_{FT}$)
Inclusive $t\bar{t}$	35000 (NNLO)

$HH \to b\bar{b}\tau\tau$: Preliminary selection

- Apply loose topological and kinematic cuts:
  - $b\bar{b}\tau_\ell\tau_h$: 2 b-jets, exactly 1 e/μ and exactly 1 hadronic τ (OS)
  - $b\bar{b}\tau_h\tau_h$: 2 b-jets, exactly 2 hadronic τ (OS), lepton veto
- Example distributions with loose selection applied for $b\bar{b}\tau_\ell\tau_h$ (left) and $b\bar{b}\tau_h\tau_h$ (right)



$HH \to b\bar{b}\tau\tau$: ML analysis

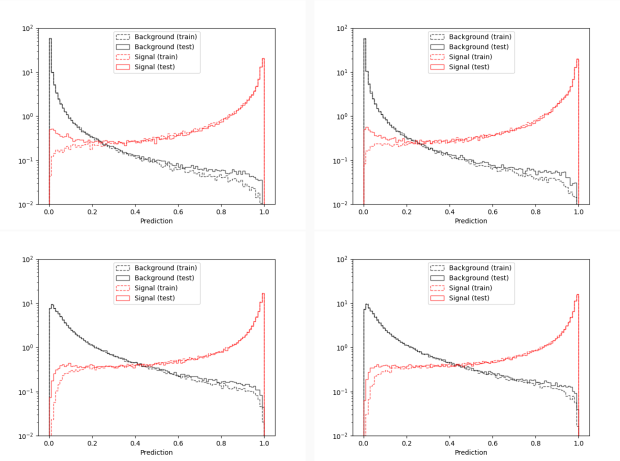
- Use XGBoost classifier to separate signal from background constructed with $t\bar{t}$, QCD+EW and EW processes
- Randomly split signal and background into two folds:
  - Train on one half, apply to other half
- Use same strategy for both $\tau_\ell\tau_h$ and $\tau_h\tau_h$

$b\bar{b}\tau_\ell\tau_h$	$b\bar{b}\tau_h\tau_h$
m_{bb}	
$p_{\mathrm{T}}(b_{1,2})$	
$\Delta R(b_1, b_2)$	
$m_{\tau\ell}$	$m_{\tau\tau}$
$\Delta R(\tau, \ell)$	$\Delta R(\tau, \tau)$
$\Delta p_{\mathrm{T}}(\tau, \ell)$	$\Delta p_{\mathrm{T}}(\tau, \tau)$
$m_{\mathrm{T}}(\ell)$	-
m_{HH}	
$\Delta\phi(H, H)$	
$E_{\mathrm{T}}^{\mathrm{miss}}$ centrality	

$HH \to b\bar{b}\tau\tau$: ML analysis

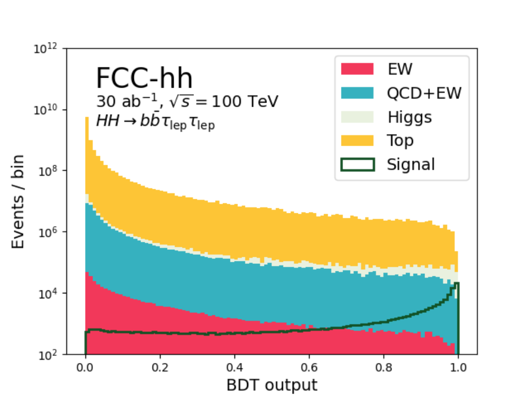
(2/3)

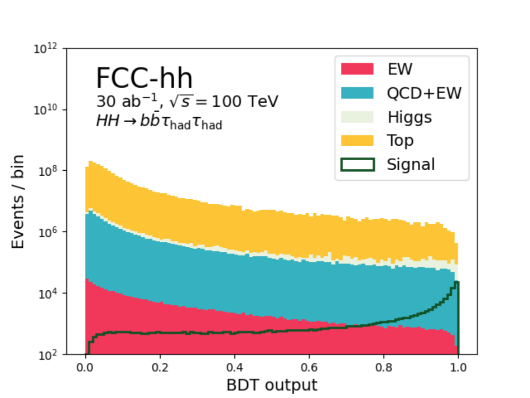
- BDT output distributions for $b\bar{b}\tau_\ell\tau_h$ (top) and $b\bar{b}\tau_h\tau_h$ (bottom) with fold 0 (left) and fold 1 (right)
- Similar performance between folds
- Some overtraining present
  - Impact mitigated by k-folding



$HH \to b\bar{b}\tau\tau$: ML analysis

- Apply each BDT to respective folds for $t\bar{t}$, QCD+EW and EW backgrounds, apply BDT_0 on minor backgrounds





$HH \to b\bar{b}\tau\tau$: Results

- Use BDT distribution as final discriminant
  - Binning driven by low MC stats at high BDT output
  - Low MC stats can be seen in yields table
- How does this compare to previous studies?

Process	Signal region yield $b\bar{b}\tau_\ell\tau_\mathrm{h}$	$b\bar{b}\tau_\mathrm{h}\tau_\mathrm{h}$
$t\bar{t}$	1142245	332048
$t\bar{t}H$	24540	18405
$t\bar{t}Z$	3486	3486
$t\bar{t}ZZ$	30	30
QCD+EW	25561	25661
EW	323	185
$t\bar{t}W$	306	-
$t\bar{t}WW$	61	-
Single top	-	-
H (ggF)	70286	30122
H (VBF)	3290	3290
VH	9263	7411
Total background	1279491	420638
Signal	36564	22208

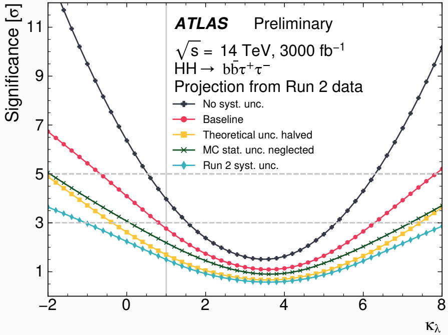
$HH \to b\bar{b}\tau\tau$: Results

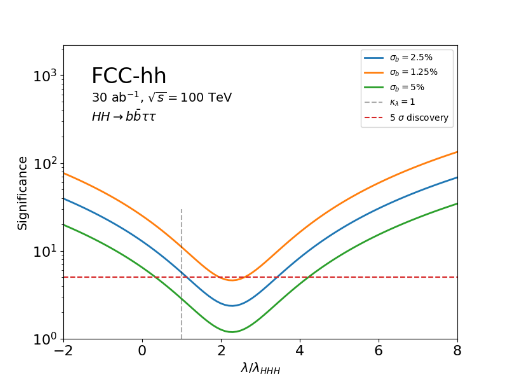
- Compare with HH+jet study
- Simplistic $S/\sqrt{B}$ gives similar sensitivity
  - No resolved $b\bar{b}\tau_h\tau_h$ result in HH+jet study
- Use binned BDT distribution to calculate final sensitivity
  - Calculate signal significance in BDT bins: $Z = N_s/\sqrt{N_b + (N_b\sigma_b)^2}$
  - Add per-bin significance in quadrature to get final estimate

	HH+jet study	WIP study
	Yield [fb^{-1}]	
Signal	0.14	1.22
Background	0.96	38.94
	$S/\sqrt{B}$	
$\tau_\ell\tau_h$	24.97	32.32

$b\bar{b}\tau_\ell\tau_h$ comparison

- Significance Z $= 5.7\sigma$ for $\kappa_\lambda = 1$: (2.9σ $b\bar{b}\tau_\ell\tau_h$, 4.9σ $b\bar{b}\tau_h\tau_h$)
- Sensitivity $\geq 5\sigma$ for large range of κ_λ values under various systematic assumptions
  - Below: comparison with recent ATLAS HL-LHC projection (ATL-PHYS-PUB-2021-044)
  - Caveat: signal rescaling only!





Summary

Summary

- Future Circular Collider
  - FCC promises a long programme of precision physics with unprecedented discovery potential
  - The 2/3 phases of FCC will take us to the end of the century
  - Constraining κ_λ is one of the primary goals of the FCC
- *HH* at the FCC-hh
  - Previous *HH* studies at FCC-hh show κ_λ constraints could be down to 5%
  - WIP updated $HH \to b\bar{b}\tau\tau$ study has promising results so far (some caveats!)

Thanks for listening!

Additional content

$HH \to b\bar{b}\tau\tau$: Preliminary selection

$\tau_\ell\tau_\mathrm{h}$		$\tau_h\tau_\mathrm{h}$	
Selection	Efficiency	Selection	Efficiency
$N(b\text{-jets}) = 2$	0.45	-	-
$b\text{-jet } p_\mathrm{T} > 30$	0.40	-	-
$N(e, \mu) = 1$	0.07	$N(e, \mu) = 0$	0.19
$N(\tau_h) = 1$	0.03	$N(\tau_h) = 2$	0.06
$\tau_\ell\tau_h$ OS	0.03	$\tau_h\tau_h$ OS	0.05

Efficiency under study!