Constraining Pesky Higgs Branching Ratios at the LHC and Beyond

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plan of the talk

- $H \to c\bar{c}$ @ LHC
- $H \to gg$ @ FCC$_{\rm ee}$
- summary

$H \to c\bar{c}$ @ LHC

setting the scene

- goal: check Yukawa couplings of 2$^{\rm nd}$ gen quarks
- problem: backgrounds, not least $H \to b\bar{b}$:

  BRs: $BR(H \to c\bar{c})/BR(H \to b\bar{b}) = 2.89\%/58.2\% \approx 0.05$

- current limits on signal strength (with ≈ 140 fb^{-1}):

$$\mu_{VH(c\bar{c})} \leq 31^{+12}_{-8} \;/\; 26 \text{ (ATLAS, expected/observed)}$$
$$\mu_{VH(c\bar{c})} \leq 7.6^{+3.4}_{-2.3} \;/\; 14 \text{ (CMS, expected/observed)}$$

- projected limits on signal strength (with ≈ 3000 fb^{-1}):

$$\mu_{VH(c\bar{c})} \leq 6.4 \text{ (ATLAS)} \;\&\; \mu_{VH(c\bar{c})} \leq 1.6 \text{ (CMS)}$$

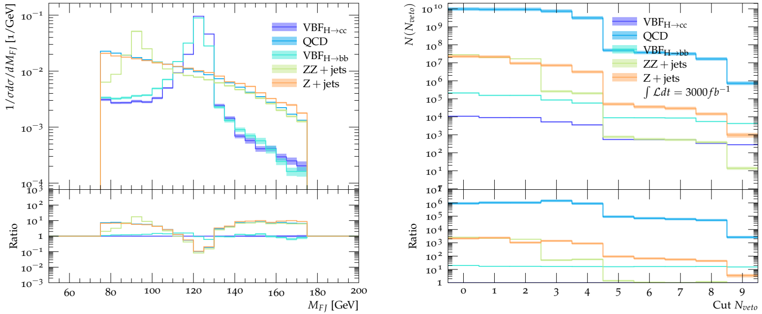
little pheno analysis: processes etc.

(Joe Walker & FK, 2202.13937)

- three categories with cuts on jets, leptons, MET etc.:
  - "0 leptons (0L)": WBF, $H+2$ jets
  - "1 leptons (1L)": WH
  - "2 leptons (2L)": ZH
- backgrounds:
  - V+jets, VV+jets, $t\bar{t}$+jets, QCD multijets, ...
- cuts:
  - MET from tracks with $p_T^{tr} > 100$ MeV & $|\eta^{tr}| < 4$
  - isolated leptons ($R^\ell = 0.2$, 5%, $p_T^\ell > 20$ GeV)
  - fat jet ($R^J = 1.0$, $p_T^J > 250$ GeV, 75 GeV $\leq m_J \leq$ 175 GeV): must contain 3 tracks, 2 subjets with $R = 0.4$, $p_T^j > 20$ GeV & 1 displ.vertex
  - additional cuts for 0L, 1L, 2L categories
- everything (including signals) with LO multijet merging,

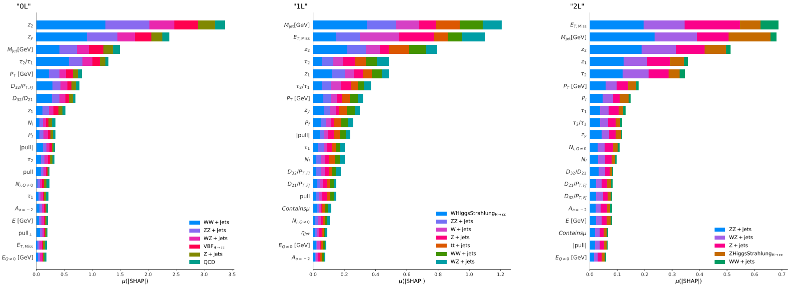
  (conservative: NLO corrections work in signal favour & reduce uncerts)
- uncerts from seven-point variation in $\mu_{F,R}$

impact of cuts: 0L



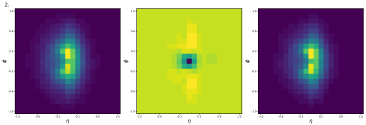
now ML the hell out of it (1)

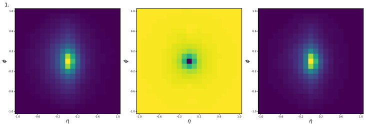
- MVA networks (TensorFlow, 10k events each) on bunch of obs'bles: m_J, MET, $\sum_{i\in J} p_\perp^{(i)}$, subjet $z_{1,2}$, 2-subjettiness τ_2, planar flow P_F, ...
- Shapely distributions to elucidate relative importance



now ML the hell out of it (2)

- fully connected CNN on rotated RGB jet images:
  - $R = -\sum_{i\in J} \log(E^{(i)}/E_J)$
  - $G = -\sum_{i\in J} \log(p_\perp^{(i)})$
  - $B = -\sum_{i\in J} |Q^{(i)}|$
- average images in 0L:





- fully connected RNN on particle features

now ML the hell out of it (3)

- produced our own charm vs. botton vs. light MVA-NN discriminator based on structure of primary/secondary vertices

(not as good as exp.ones: MV2, DL1, . . .)

- efficiencies after comparison with JetFitterCharm:

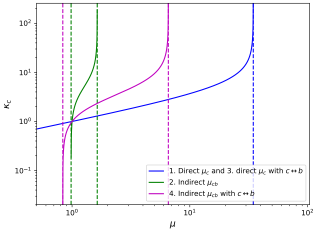
	ϵ_c	$1/\epsilon_b$	$1/\epsilon_l$
“Loose”	0.95	1.65	1.03
“Medium”	0.21	13.2	149

results (1)

- signal strength (naive):

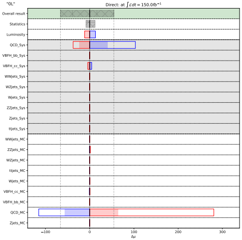
$$\mu_c = \frac{\kappa_c^2}{1 + BR^{\rm SM}(H \to c\bar{c}) \cdot (1 - \kappa_c^2)}$$

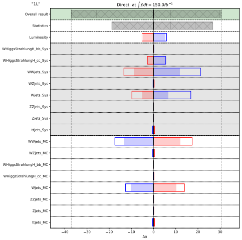
- similar if one adds efficiencies, and combines $c + b$ final states
- results @ 95% CL obtained including uncerts due to stats, lumi, scales, MC stats
- direct/combined measurements with and w/o b/c identification

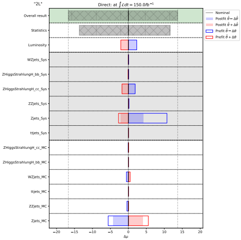


results (2)

- uncerts.budget to 95% CL is using M_J







results (3)

- limits on signal strengths and best obs combination

Search	μ w/ $\mathcal{H}_{M_J}$	μ w/ $\mathcal{H}_{\rm best}$	$\mathcal{H}_{\rm best}$
$\int \mathcal{L}dt = 150 fb^{-1}$			
Direct, μ_c	$53.7^{+22.7}_{-15.9}$	$42.7^{+17.4}_{-12.4}$	$\mathcal{H}(M_J, P_f)$
Indirect, μ_{cb}	$4.0^{+1.3}_{-0.9}$	$3.1^{+1.0}_{-0.7}$	$\mathcal{H}(M_J, \theta_p)$
Direct, μ_c with $b \leftrightarrow c$ discrimination	$48.1^{+19.2}_{-13.8}$	$8.0^{+3.6}_{-2.3}$	$\mathcal{H}(Z_1, P_f)$
Indirect, μ_{cb} with $b \leftrightarrow c$ discrimination	$4.7^{+1.6}_{-1.1}$	$2.0^{+0.6}_{-0.4}$	$\mathcal{H}(Z_1, P_f)$
$\int \mathcal{L}dt = 3000 fb^{-1}$			
Direct, μ_c	$35.5^{+14.0}_{-10.3}$	$12.1^{+5.1}_{-3.4}$	$\mathcal{H}(M_J, P_f)$
Indirect, μ_{cb}	$3.0^{+0.8}_{-0.6}$	$1.5^{+0.2}_{-0.2}$	$\mathcal{H}(M_J, \theta_p)$
Direct, μ_c with $b \leftrightarrow c$ discrimination	$33.9^{+13.2}_{-8.9}$	$2.1^{+0.6}_{-0.4}$	$\mathcal{H}(Z_1, P_f)$
Indirect, μ_{cb} with $b \leftrightarrow c$ discrimination	$4.0^{+1.2}_{-0.8}$	$1.1^{+0.1}_{-0.1}$	$\mathcal{H}(Z_1, P_f)$

$H \to gg$ @ FCC$_{\rm ee}$

setting the scene

- also try to measure/constrain Higgs boson couplings to light QCD:

$$BR(H \to gg) \approx 9\%, \quad \sum_{q\in\{u,d,s\}} BR(H \to q\bar{q}) \approx 0.01\%$$

- probably hopeless @ LHC: try at lepton collider
- projection for FCC$_{ee}$ @ 5 ab^{-1} / 68% CL: $|\Delta\kappa_{H\to gg}| < 1.6\%$

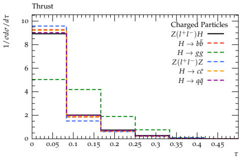
(Eur.Phys.J.ST 228 (2019) 2, 261-623)

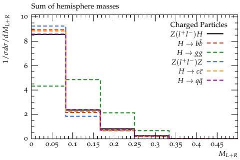
- so far: analysis strategy based on heavy-quark vetoes

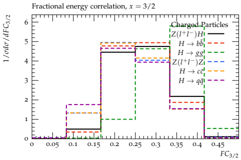
(i.e. implicitly adding $H \to q\bar{q}$ to $H \to gg$)

maybe a QCD problem?

- diffences in QCD radiation pattern
  - quarks vs. gluons (C_F vs. C_A)
  - heavy vs/ light quarks ("death cone" = collinear suppression)
- capture in event shapes - less sensitive to non-pert. stuff
- example normalised shapes







maybe a QCD problem?

- diffences in QCD radiation pattern
  - quarks vs. gluons (C_F vs. C_A)
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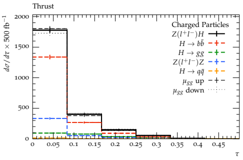
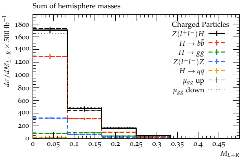
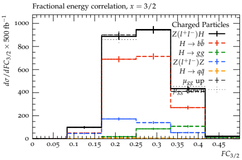
- capture in event shapes - less sensitive to non-pert. stuff
- example differential cross sections







(very preliminary) results

- a first peek (no fixed-order corrections, no scale variations): systematics from {CSSHOWER, DIRE } ⊗ {AHADIC, LUND }
- single-variable limits on signal strength:

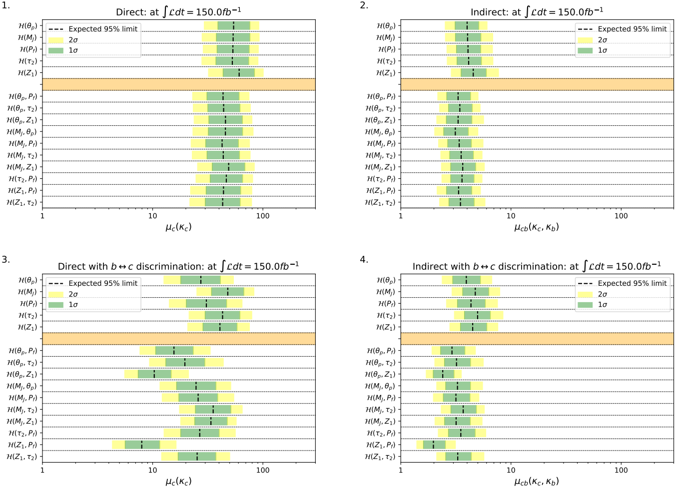
Obs.	μ_g limits	κ_g limits
$FC_{3/2}$	(0.91, 1.09)	4.5%
FC_1	(0.89, 1.11)	5.4%
$FC_{1/2}$	(0.88, 1.12)	5.8%
hemisphere mass	(0.87, 1.13)	6.3%
hemisphere broadening	(0.88, 1.12)	5.8%
thrust	(0.86, 1.14)	6.8%
thrust minor	(0.83, 1.17)	8.2%
thrust major	(0.89, 1.11)	5.4%

summary

- played a bit with ML technology for $H \to c\bar{c}$
  - lesson 1: not a magic bullet if applied without insights
  - lesson 2: QCD intuition helps for QCD final states
  - results are conservative & more or less competitive
- first stab at $H \to gg$ & $H \to q\bar{q}$ $(q \in \{u, d, s\})$
  - results are not (yet) competitive: will need to MVA etc.
  - better simulation of signals & backgrounds
  - better syst.uncerts. from profiling of non-pert. params
  - plan is to disentangle $H \to gg$ and $H \to q\bar{q}$ and constrain both

bonus tracks (1)

- LL distributions for different obs @ 150 fb^{-1}



bonus tracks (2)

- LL distributions for different obs @ 3000 fb^{-1}