Off-shell probes of the Higgs Yukawa couplings

based on
Falkowski, Ganguly, Gras, No, Tobioka, NV, You,
JHEP 04 (2021) 023
NV, *Symmetry 14 (2022) 6, 1183*

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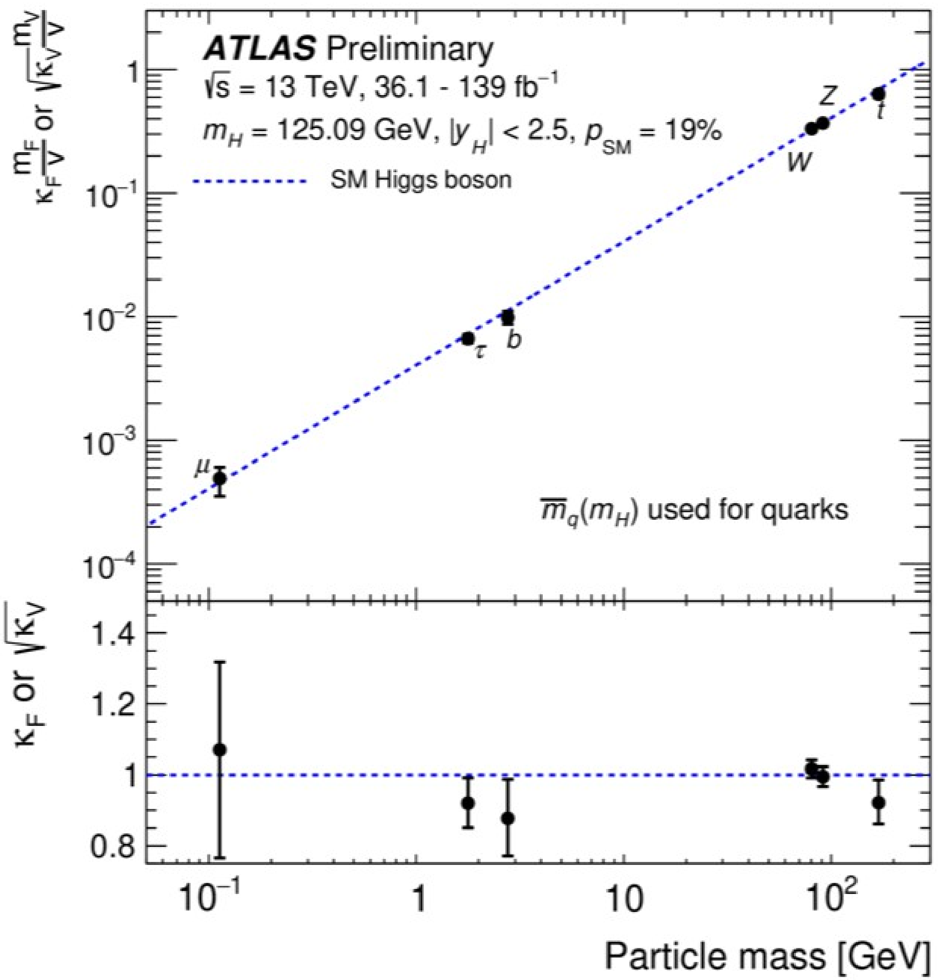
LFC 2022, ECT*

Higgs properties

Firm evidence of Higgs decays (within SM) to top, bottom, tau. $O(10\%)$ accuracy

JHEP 01 (2021) 148
Recent first evidence for Higgs decay to muons (leptonic second generation)

Crucial indication on the **Higgs role in mass generation of I and II generation** fermions would come from measurements of **Light quark Yukawas (difficult measurement)**



Light quark Yukawas, how to test possible BSM deviations?

Current best constraints from **fit to Higgs strength**

$$\mu = \frac{1}{1 + \sum_q (2\delta y_q + \delta y_q^2)\mathrm{Br}(h \to qq)_{\mathrm{SM}}}$$

Modification to Higgs production can be safely neglected for $\delta y_q < \mathcal{O}(1000)$

Using the most recent measurement from CMS[1] and ATLAS[2]:

$$\textbf{ATLAS}: \quad \delta y_d < 400, \quad \delta y_u < 820, \quad \delta y_s < 19,$$
$$\textbf{CMS}: \quad \delta y_d < 450, \quad \delta y_u < 930, \quad \delta y_s < 22$$

[1] CMS-PAS-HIG-19-005 $\mu = 1.02^{+0.07}_{-0.06}$ [2] ATLAS-CONF-2020-027 $\mu = 1.06 \pm 0.07$

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Considering that the HL-LHC is expected to measure the total Higgs signal strength with an error of order 2-3% *:

$$\delta y_d \lesssim 340, \quad \delta y_u \lesssim 700, \quad \delta y_s \lesssim 17 \quad \text{(HL-LHC)}$$

* *CERN Yellow Rep.Monogr. 7* (2019) 221-584

Alternative strategies (complementarity)

- Higgs kinematics (p_T, y)

Soreq, Zhu, Zupan,
JHEP 12 (2016) 045

$\delta y_d \lesssim 380 \quad \delta y_u \lesssim 640 \quad$ [HL-LHC]

- $W^{\pm}h$ charge asymmetry

Yu, JHEP 02 (2017) 083

$\delta y_d \lesssim 1300 \quad \delta y_u \lesssim 2900 \quad$ [HL-LHC]

- Double Higgs production

Alasfar, Lopez, Grober
JHEP 11 (2019) 088

$\delta y_d \lesssim 850 \quad \delta y_u \lesssim 1200 \quad$ [HL-LHC]

- Rare Higgs decays (h -> MV)

$\delta y_q \lesssim 10^6 \quad$ [HL-LHC]

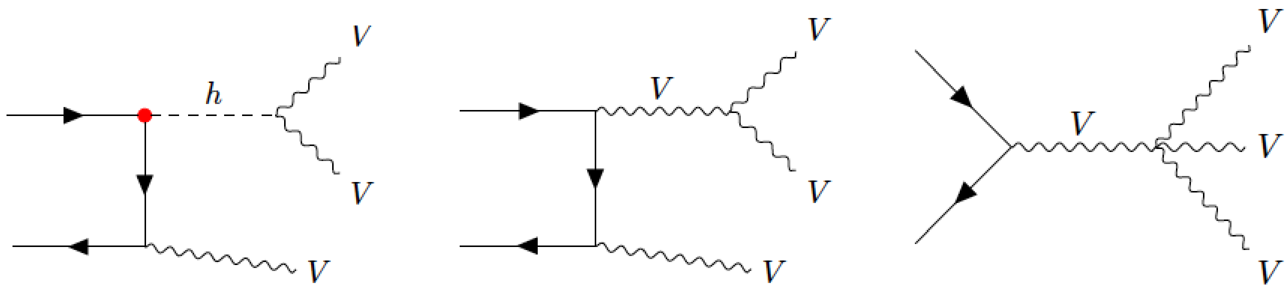
Kagan, Perez, Petriello, Soreq, Stoynev, Zupan
Phys.Rev.Lett. 114 (2015) 10, 101802

Our strategy: pp -> VVV (Higgs off-shell)

Follows the idea of *"measuring the Higgs without the Higgs"*

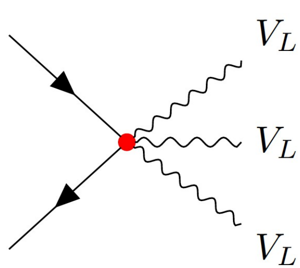
Henning, Lombardo, Riembau, Riva, Phys Rev Lett 123 (2019) 181801

Unitary gauge



Modifications to SM Higgs Yukawas affect the delicate cancellations which avoid violation of perturbative unitarity at high energy

non-unitary gauge



Energy-growing amplitudes

SMEFT description

We focus on the dimension-6 operators:

$$H = \frac{1}{\sqrt{2}} \begin{pmatrix} i\sqrt{2}G_+ \\ v + h + iG_z \end{pmatrix}$$

$$\mathcal{L}_{\rm SMEFT} \supset \frac{Y_u |H|^2}{v^2} \bar{u}_R Q_{1,L} H + \frac{Y_d |H|^2}{v^2} \bar{d}_R H^\dagger Q_{1,L} + \frac{Y_s |H|^2}{v^2} \bar{s}_R H^\dagger Q_{2,L} + \text{h.c.}$$

We parametrize the Yukawa couplings as:

$$\mathcal{L} \supset -\frac{h}{v} \sum_{q=u,d,s} m_q \big(1 + \delta y_q\big) \bar{q} q$$

Then the shifts in the Yukawas are related to the parameters of the effective operators as:

$$\delta y_q = -\frac{Y_q}{y_q^{\rm SM}}$$

Energy-growing behaviour

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The effective operators lead to contact interactions between two quarks and three Goldstone bosons:

$$\mathcal{L} \supset \frac{1}{v^2} \left(G_+ G_- + \frac{1}{2} G_z^2 \right) \left\{ i y_u^{\text{SM}} \delta y_u \left(\sum_{q'=d,s} \bar{u}_R q'_L G_+ - \bar{u}_R u_L \frac{G_z}{\sqrt{2}} \right) \right.$$
$$\left. + i \sum_{q'=d,s} y_{q'}^{\text{SM}} \delta y_{q'} \left(\bar{q}'_R u_L G_- + \bar{q}'_R q'_L \frac{G_z}{\sqrt{2}} \right) + \text{h.c.} \right\}$$

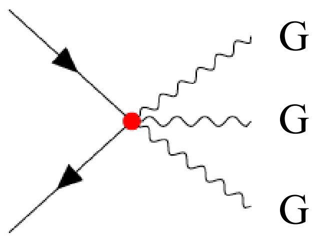
Energy-growing behaviour

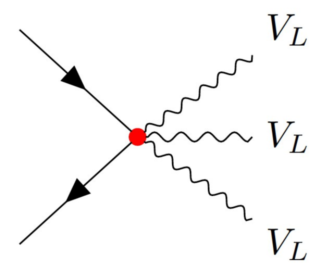
$$\mathcal{M}(q\bar{q} \to GGG) \sim \mathcal{O}(\delta y_q E/v^2)$$

$$\sqrt{\hat{s}} \gg m_Z$$

Equivalence theorem

$$\mathcal{M}(q\bar{q} \to V_L V_L V_L)$$





$$\sigma(q\bar{q} \to G_z G_+ G_-) = (y_q^{\rm SM}\delta y_q)^2 I(\hat{s}),$$

$$\sigma(q\bar{q} \to 3G_z) = \frac{3}{2}(y_q^{\rm SM}\delta y_q)^2 I(\hat{s}),$$

$$\sigma(u\bar{q}' \to G_+ G_z G_z) + \sigma(q'\bar{u} \to G_- G_z G_z) = \frac{1}{2}\left[(y_u^{\rm SM}\delta y_u)^2 + (y_{q'}^{\rm SM}\delta y_{q'})^2\right] I(\hat{s}),$$

$$\sigma(u\bar{q}' \to G_+ G_+ G_-) + \sigma(q'\bar{u} \to G_- G_- G_+) = 2\left[(y_u^{\rm SM}\delta y_u)^2 + (y_{q'}^{\rm SM}\delta y_{q'})^2\right] I(\hat{s})$$

$$I(\hat{s}) \equiv \frac{\hat{s}}{6144\pi^3 v^4}$$

$(\delta y_q)^2$ E^2 growing behaviour

pp -> VVV

Triboson recently observed for the first time by CMS

Sirunyan et al (CMS). PRL 125 (2020) 151802 [CMS-SMP-19-014]

$pp \to W^\pm W^\pm W^\mp \to \ell^\pm \ell^\pm \nu\nu jj$ SSD channel

Main CMS selection, designed to extract SM 3V signal, not optimized to test deviations in the Yukawas

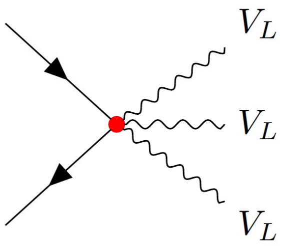
$$p_T^{\ell_{1,2}} > 25\,\mathrm{GeV}\,, \quad m_{\ell\ell} > 20\,\mathrm{GeV}\,, \quad m_{jj} \in [65, 95]\,\mathrm{GeV}\,(\text{“}m_{jj}\text{ in”})\,,$$
$$E_T^{\mathrm{miss}} > 45\,\mathrm{GeV}\,, \; m_T^{\mathrm{max}}(\ell) > 90\,\mathrm{GeV}$$

$$\sigma(Y_d) = 7.5\,\mathrm{fb} + Y_d^2 \times 210\,\mathrm{fb}$$

$\delta y_d \lesssim 6800$ CMS [LHC 13 TeV]

Light quark Yukawas in pp ->VVV

We will test deviations in the up, down, strange Yukawa couplings*



Main features to exploit:

- Cross section energy enhancement ($\delta y_q^2 E^2$)
- Peculiar kinematics (hard spectrum, peculiar angular distributions)

Ideal case for FCC

* charm Yukawa better tested (with an analogous strategy) in pp -> WWcj final state

Light quark Yukawas in pp -> VVV

HL-LHC	SM	BSM ($Y_d = 1$)	BSM ($Y_u = 1$)	BSM ($Y_s = 1$)
$W^+W^-W^+$	152 fb	3.6 pb	3.6 pb	110 fb
$W^+W^-W^-$	87 fb	1.5 pb	1.5 pb	110 fb
ZZW^+	40 fb	1.0 pb	1.0 pb	31 fb
ZZW^-	23 fb	0.43 pb	0.43 pb	31 fb
ZW^+W^-	191 fb	1.5 pb	2.4 pb	120 fb
ZZZ	16 fb	0.99 pb	1.7 pb	66 fb

$$\delta y_q = -\frac{Y_q}{y_q^{\mathrm{SM}}}$$

SM: NLO in QCD

BSM: LO (UFO model)

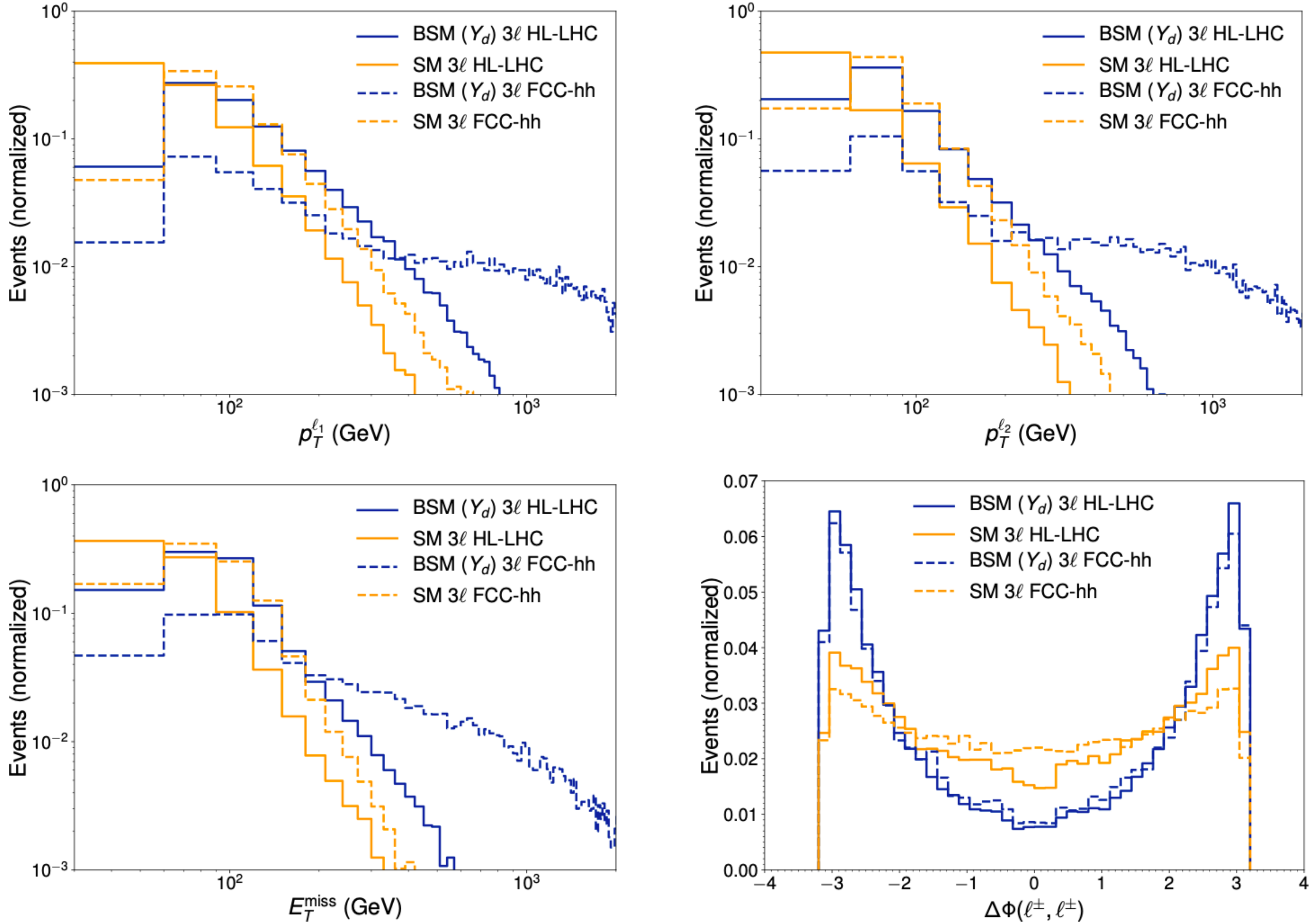
Available at: https://feynrules.irmp.ucl.ac.be/wiki/YqHEFT

FCC-hh	SM	BSM ($Y_d = 1$)	BSM ($Y_u = 1$)	BSM ($Y_s = 1$)
$W^+W^-W^+$	2.35 pb	290 pb	290 pb	16 pb
$W^+W^-W^-$	1.76 pb	140 pb	140 pb	16 pb
ZZW^+	756 fb	74 pb	74 pb	4.4 pb
ZZW^-	579 fb	36 pb	36 pb	4.4 pb
ZW^+W^-	3.93 pb	94 pb	150 pb	12 pb
ZZZ	231 fb	110 pb	180 pb	11 pb

We consider the most efficient channels:
WWW (SSD and 3 lep)
ZZZ (4 lep)

It would be interestig to combine analyses in different final states:
Neutral channels (as ZZZ) would allow to break Y_u and Y_d degeneracies

WWW: three-lepton final state



WWW: three-lepton final state

LHC:

$$p_T^{\ell_1} > 70\,\mathrm{GeV}\,,\ p_T^{\ell_2} > 50\,\mathrm{GeV}\,,\ p_T^{\ell_3} > 30\,\mathrm{GeV}\,,\ E_T^{\mathrm{miss}} > 80\,\mathrm{GeV}\,,\ |\Delta\Phi(\ell^\pm,\ell^\pm)| > 2$$

FCC-hh:

$$p_T^{\ell_1} > 150\,\mathrm{GeV}\,,\ p_T^{\ell_2} > 80\,\mathrm{GeV}\,,\ p_T^{\ell_3} > 50\,\mathrm{GeV}\,,\ E_T^{\mathrm{miss}} > 120\,\mathrm{GeV}\,,\ |\Delta\Phi(\ell^\pm,\ell^\pm)| > 1.5$$

Selection:

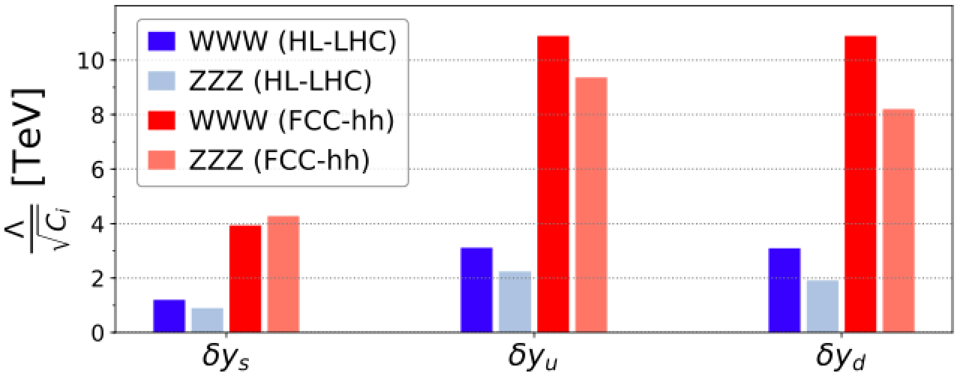
Main cuts above + shape analysis (for simplicity we just focus on the leading lepton p_T)

$$\Lambda(\delta y_q) = -2\sum_i^{\mathrm{bins}} \log \frac{L(S_i + B_i, B_i)}{L(B_i, B_i)}$$

Final Results for HL-LHC and (FCC-hh)

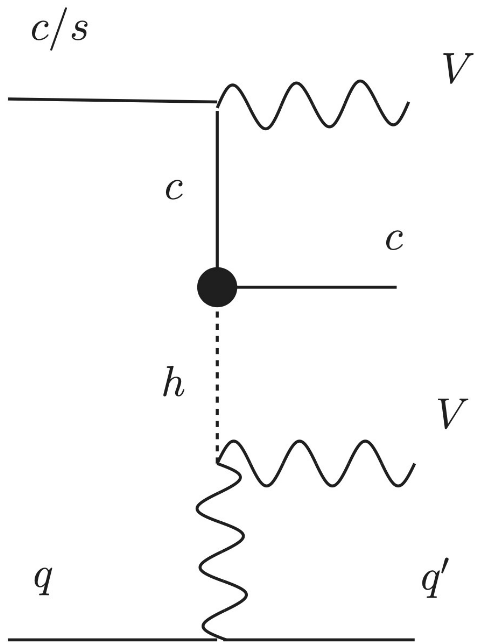
	WWW			ZZZ		
	$\ell^\pm\ell^\pm + 2\nu + 2j$	$\ell^\pm\ell^\pm\ell^\mp + 3\nu$	Comb.	$4\ell + 2\nu$	$4\ell + 2j$	Comb.
δy_d	430 (36)	840 (54)	420 (34)	1500 (65)	1300 (93)	1100 (60)
δy_u	850 (71)	1700 (110)	830 (68)	2300 (100)	1800 (140)	1600 (92)
δy_s	150 (13)	230 (33)	140 (13)	300 (12)	290 (16)	250 (11)

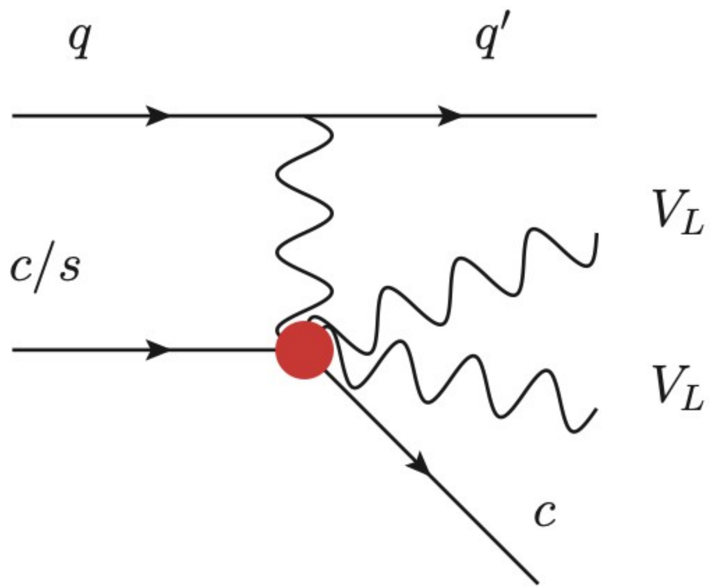
$Y_i = C_i\, v^2/\Lambda^2$



- Results competitive and complemetary to contraints from global fits and other on-shell probes at the HL-LHC
- Large improvement (by one order of magnitude) expected at the FCC-hh

Off-shell probe of the charm Yukawa





$$\mathcal{L}_{\text{SMEFT}} \supset -\frac{Y_c|H|^2}{v^2}\bar{c}_R Q_{1,L} H + \text{h.c.} \qquad \delta y_c = \frac{Y_c}{y_c^{\text{SM}}}$$

Off-shell probe of the charm Yukawa

$$\sigma \approx \sigma^{\rm SM}(Y_c = 0) + Y_c\,\sigma^{\rm INT}(Y_c = 1) + Y_c^2\,\sigma^{\rm BSM}(Y_c = 1)$$

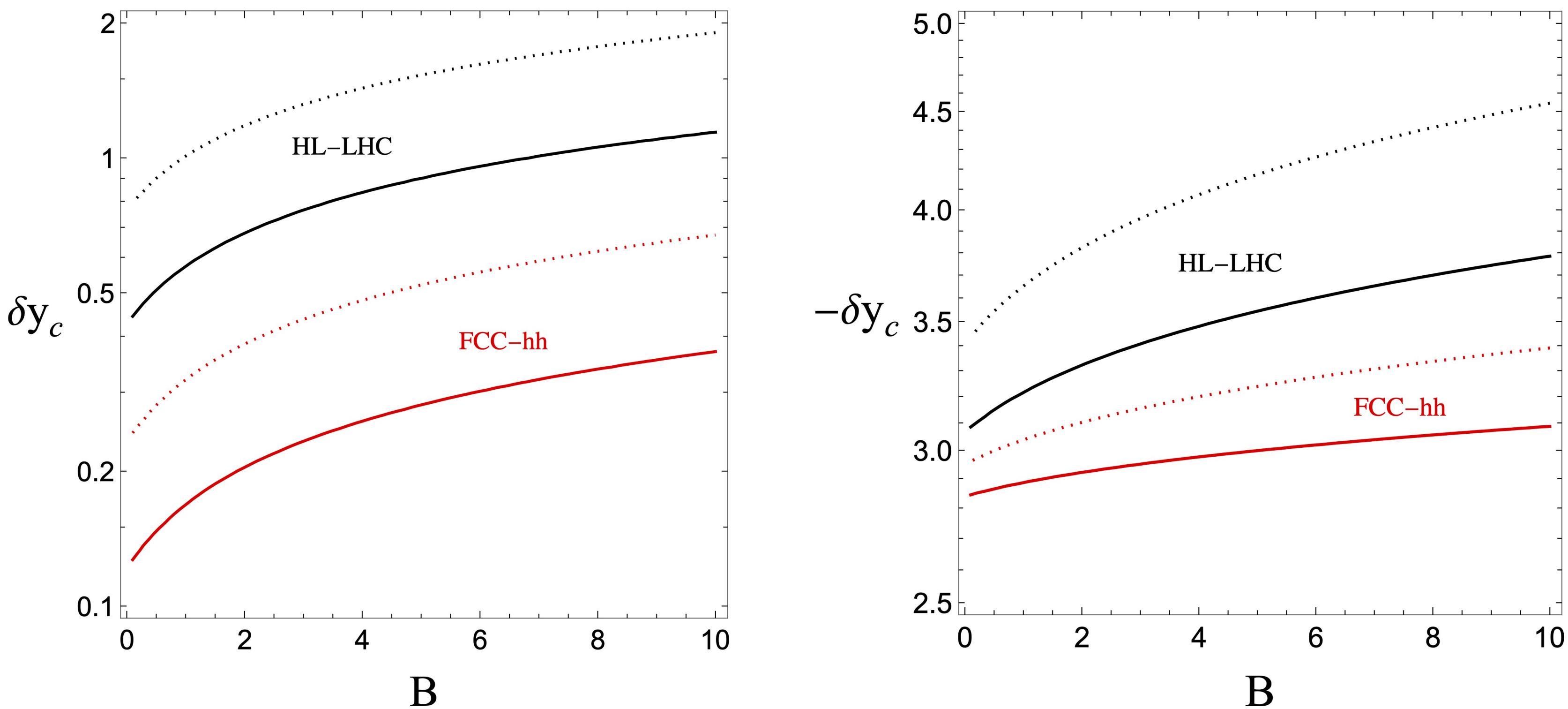
HL-LHC	SM ($Y_c = 0$)	INT ($Y_c = 1$)	BSM ($Y_c = 1$)
W^+W^-cj	2.3 pb	0.58 pb	63 pb
W^+Zcj	0.86 pb	0.17 pb	17 pb
W^-Zcj	0.79 pb	0.09 pb	9.1 pb
$ZZcj$	0.19 pb	0.14 pb	15 pb
W^+W^+cj	29 fb	0.42 fb	94 fb
W^-W^-cj	23 fb	0.31 fb	90 fb

FCC-hh	SM ($Y_c = 0$)	INT ($Y_c = 1$)	BSM ($Y_c = 1$)
W^+W^-cj	92 pb	6.4 pb	660 pb
W^+Zcj	36 pb	1.8 pb	190 pb
W^-Zcj	35 pb	1.3 pb	130 pb
$ZZcj$	6.8 pb	1.6 pb	180 pb
W^+W^+cj	0.76 pb	2.8 fb	3.0 pb
W^-W^-cj	0.68 pb	3.2 fb	3.0 pb

Off-shell probe of the charm Yukawa

We focus on the semileptonic final state and consider a naive rescaling of the (reducible) background:

$$\sigma = \frac{N_{SM+BSM} - N_{SM}}{\sqrt{N_{SM} + B \times N_{SM}}}$$



Off-shell probe of the charm Yukawa

In the limit of a negligible reducible background (compared to the SM irreducible):

$$\left\{\begin{array}{lll} \delta y_c \lesssim & 0.43\,(1\sigma)\; - \;0.77\,(2\sigma) & (\text{HL-LHC, } 2{\times}3\ \text{ab}^{-1}) \\ \delta y_c \lesssim & 0.12\,(1\sigma)\; - \;0.23\,(2\sigma) & (\text{FCC-hh, } 30\ \text{ab}^{-1}) \end{array}\right.$$

$$\left\{\begin{array}{lll} -\delta y_c \lesssim & 3.1\,(1\sigma)\; - \;3.4\,(2\sigma) & (\text{HL-LHC, } 2{\times}3\ \text{ab}^{-1}) \\ -\delta y_c \lesssim & 2.8\,(1\sigma)\; - \;2.9\,(2\sigma) & (\text{FCC-hh, } 30\ \text{ab}^{-1}) \end{array}\right.$$

Encouraging results (more refined analysis needed), competitive and complementary to other charm Yukawa probes:

$$|\delta y_c| \lesssim 2.1 \quad (\text{Higgs precision measurements})$$

Coyle, Wagner, Wei, *PRD* 100 (2019) 7, 073013

$$|\delta y_c| \lesssim 2.6 \quad (\text{Higgs plus charm})$$

Brivio, Goertz, Isidori, PRL 115 (2015) 21, 211801

Conclusions

The investigation of the Higgs properties, including *Yukawa couplings* to SM fermions, is of primary importance for the understanding of high energy physics. Crucial indication on the Higgs role in the mass generation of 1st and 2nd families would come from the measurement of the light quark Yukawas.

A novel technique to improve this challenging test is based on the study of the *triboson channel*, where the *Higgs is off-shell*. In this approach, the Yukawa couplings are determined indirectly, by their contributions via virtual Higgs exchange to the triboson process. This method relies on the fact that modifications of the Higgs Yukawas disturb the structure of the SM and leads to the violation of perturbative unitarity at high energy.
The study of the triboson channel gives results competitive and complementary to other on-shell Higgs probes and very promising for the FCC-hh.

We have then considered an *off-shell Higgs probe of the charm Yukawa.* In this case, we focus on the channel *VVcj*. First estimates of the HL-LHC and FCC-hh sensitivities indicate encouraging results and offer a useful starting point for more refined analyses at the LHC.
Our first naive estimates indicate sensitivities on δy_c in the diboson channel which could be realistically below order 1 at the HL-LHC, thus competitive and complementary to other charm Yukawa probes, and of the order of 20% at the FCC-hh. Interestingly, there is also the possibility to test the sign of the shift in the charm Yukawa.