Light quark Yukawas in triboson final states

based on
Falkowski, Ganguly, Gras, No, Tobioka, NV, You,
JHEP 04 (2021) 023

Natascia Vignaroli Pisa University

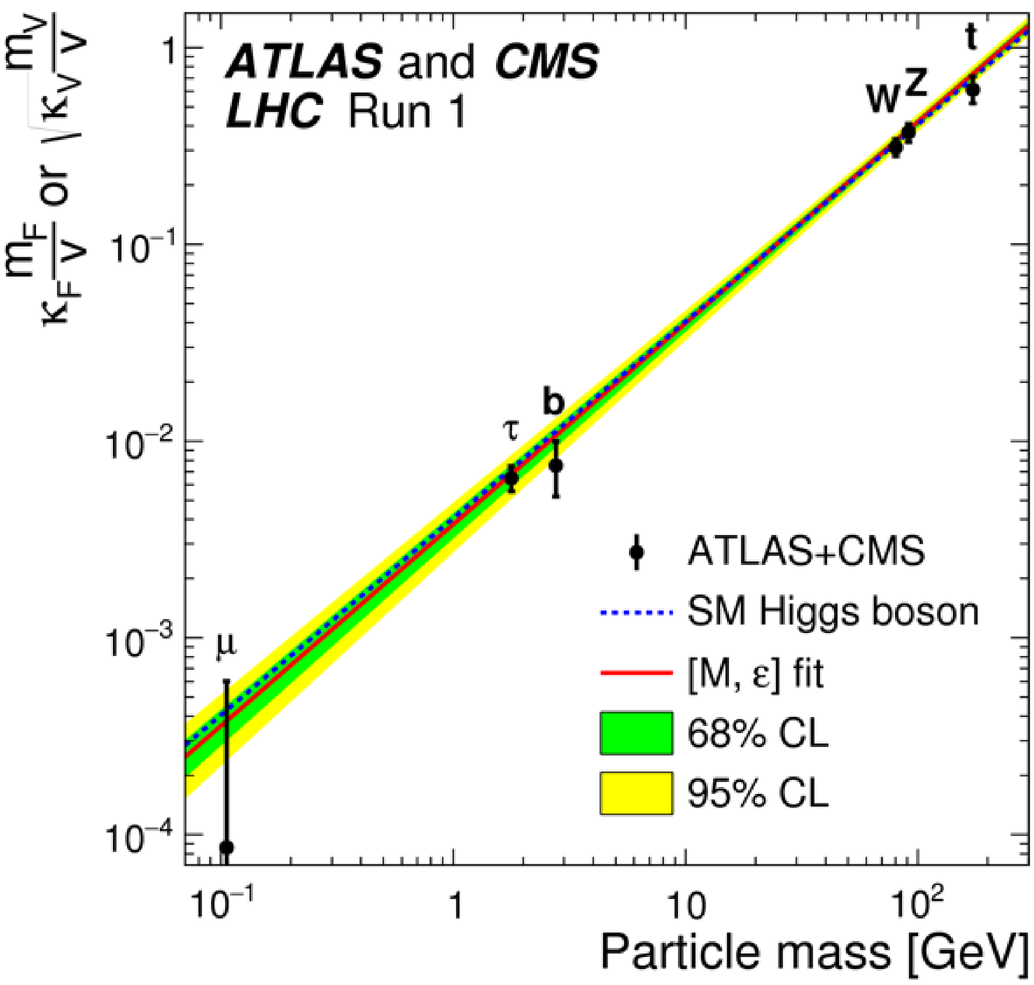
HEFT 2021

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]:

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

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

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 $\delta y_q < \mathcal{O}(1000)$

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]

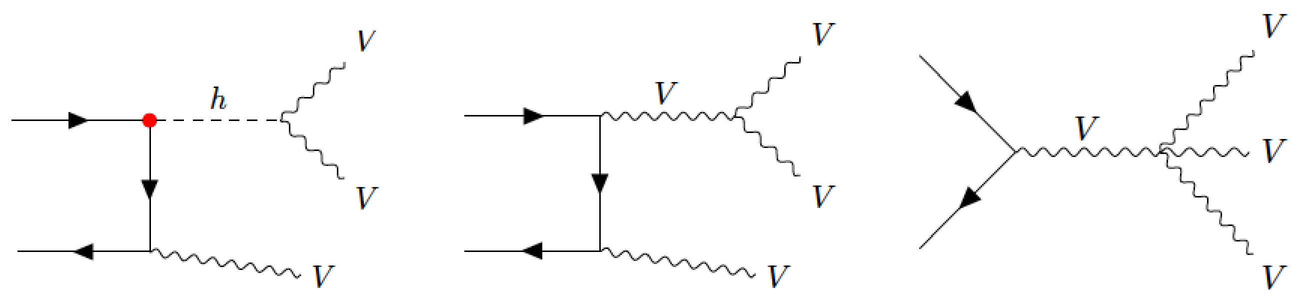
Kagan, Perez, Petriello, Soreq, Stoynev, Zupan
Phys.Rev.Lett. 114 (2015) 10, 101802

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

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

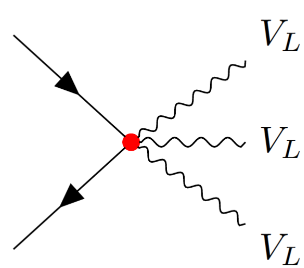
Henning, Lombardo, Riembau, Riva, Phys Rev Lett 123 (2019) 181801

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:

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

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

We focus on the dimension-6 operators:

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

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

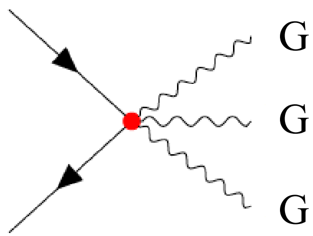
The effective operators lead to contact interactions between two quarks and three Goldstone bosons:

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

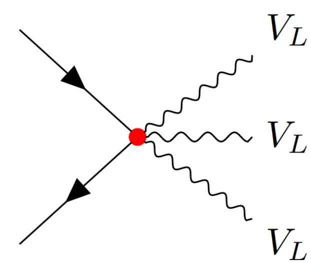
Energy-growing behaviour

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

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



Equivalence theorem



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

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

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

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

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

$(\delta y_q)^2$ 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

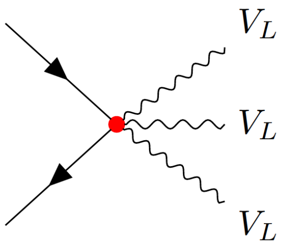
$$p_T^{\ell_{1,2}} > 25\,\text{GeV}\,,\quad m_{\ell\ell} > 20\,\text{GeV}\,,\quad m_{jj} \in [65, 95]\,\text{GeV}\;(\text{“}m_{jj}\text{ in”})\,,$$
$$E_T^{\text{miss}} > 45\,\text{GeV}\,,\; m_T^{\text{max}}(\ell) > 90\,\text{GeV}$$

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

$\delta y_d \lesssim 6800$ 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)

* charm Yukawa better tested (with an analogous strategy) in pp -> WWqj final state
Brooijmans et al. PhysTeV 2019. New Physics WG, 2002.12220 (Contribution 12)

Ideal case for FCC

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

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

SM: NLO in QCD

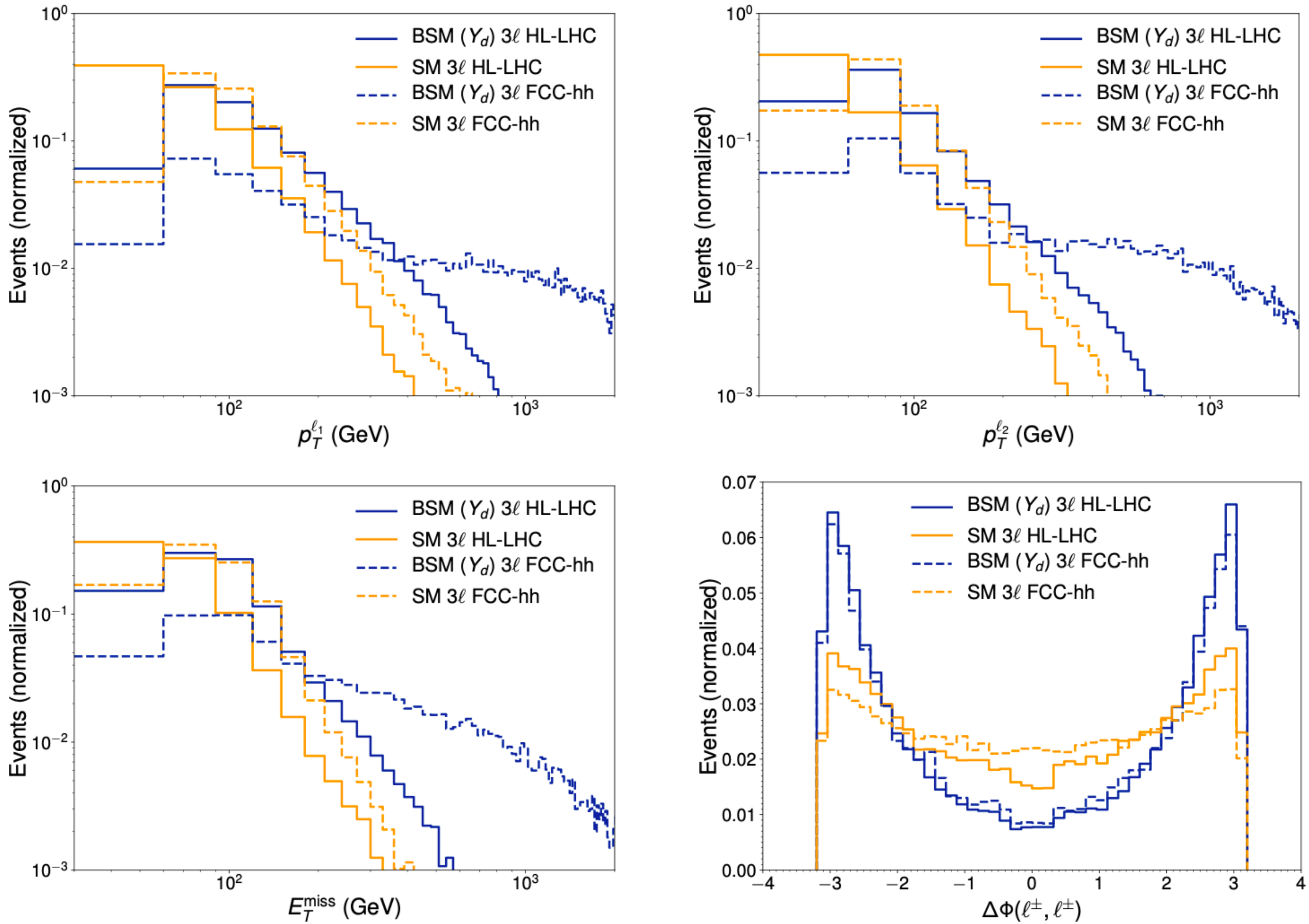
BSM: LO (UFO model)

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:

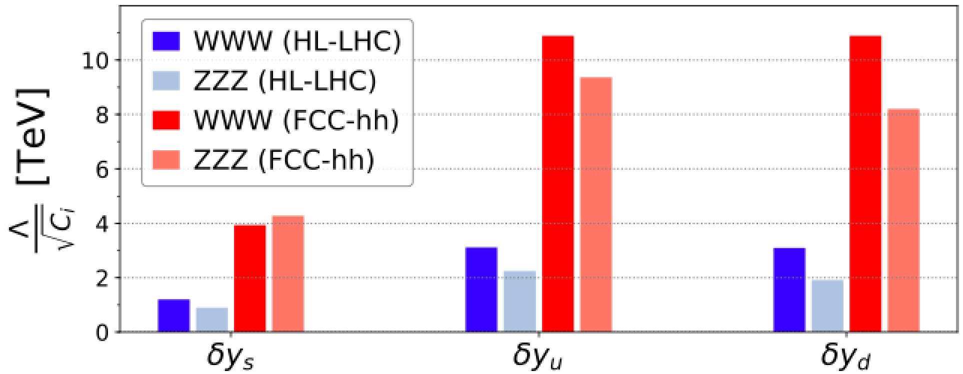
Main cuts above + shape analysis (for simplicity we just focus on the leading lepton p_T)

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

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