Probing Higgs couplings to light SM quarks

($h+\gamma$ & more...)

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Higgs Yukawa couplings
to 2nd gen. & 1st gen. SM quarks
(very) weakly constrained

¿New strategies to constrain y_q @ LHC?

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❶ Higgs + photon production

Aguilar-Saavedra, Cano, No. 2008.12538

$$pp \to h\,\gamma$$

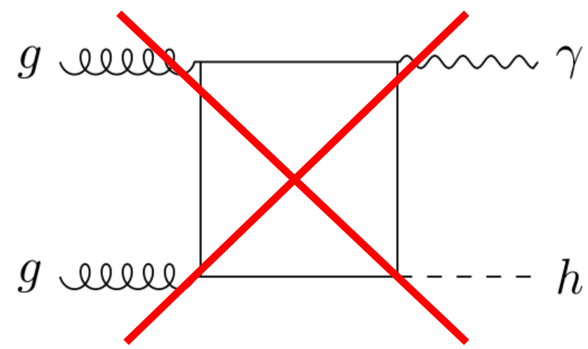
❷ Triple gauge boson production

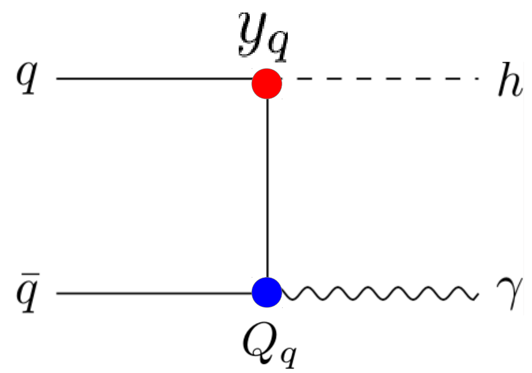
Falkowski, Ganguly, Gras, No, Tobioka, Vignaroli, Venturini, You. To Appear

$$pp \to V\,V\,V$$

Higgs + photon

Would-be leading contribution
vanishes (Furry Theorem)





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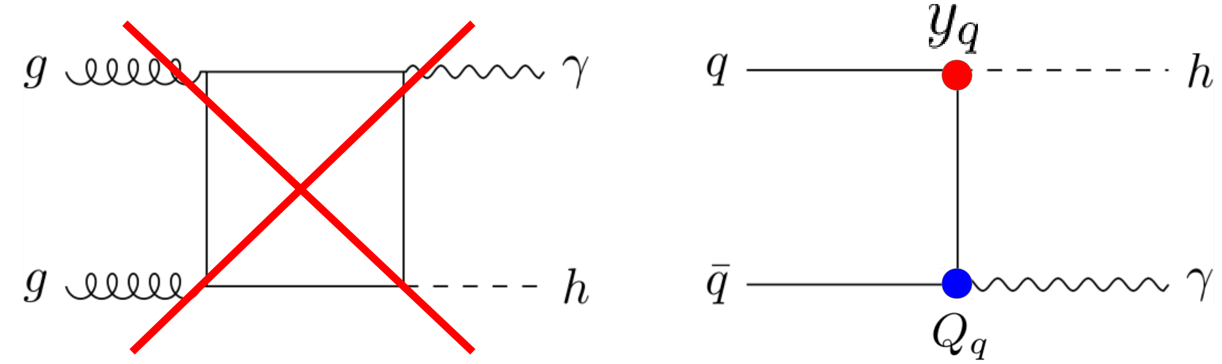

⇨ $(Q_u/Q_d)^2 = 4$, so focus on up-type quarks

⇨ SM cross section small, enhanced for BSM Higgs Yukawas: $\kappa_q > 1$

(e.g. $\sigma_{u\bar{u}} = 1.3$ fb for $y_u(m_h) \sim y_c^{\rm SM}(m_h)$)

$\kappa_q = y_q(m_h)/y_q^{\rm SM}(m_h)$

⇨ Most promising final state: $h \to WW^* \to \ell\nu\ell\nu$

(Clean + sufficient XS)

Higgs + photon

$$h \to WW^* \to \ell\nu\ell\nu$$

⇨ Dominant SM backgrounds:

$$pp \to \ell^+\nu\ell^-\bar{\nu}\gamma$$

$$pp \to Z\gamma,\ Z \to \tau^+\tau^-$$

$$pp \to t\bar{t}\gamma \quad \begin{array}{l} t \to b\ell^+\nu \\ \bar{t} \to \bar{b}\ell^-\bar{\nu} \end{array}$$

Higgs + photon

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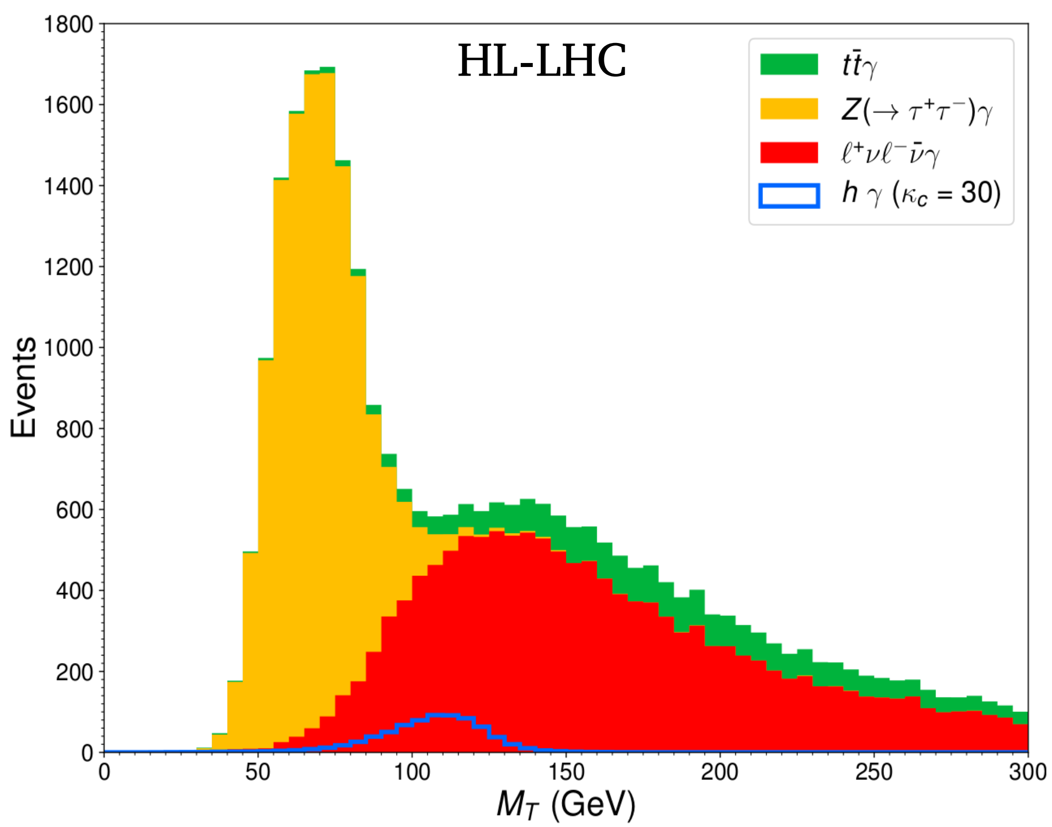
Initial selection

$$p_T^\gamma > 25 \text{ GeV}$$

$$p_T^{\ell_1} > 18 \text{ GeV}, p_T^{\ell_2} > 15 \text{ GeV} \ || \ p_T^{\ell_1} > 23 \text{ GeV}, p_T^{\ell_2} > 9 \text{ GeV}$$

$$\not{E}_T > 35 \text{ GeV}$$



$$M_T^2 = \left(\sqrt{M_{\ell\ell}^2 + |\vec{p}_T^{\,\ell\ell}|^2} + \not{E}_T\right)^2 + \left|\vec{p}_T^{\,\ell\ell} + \vec{\not{E}}_T\right|^2$$

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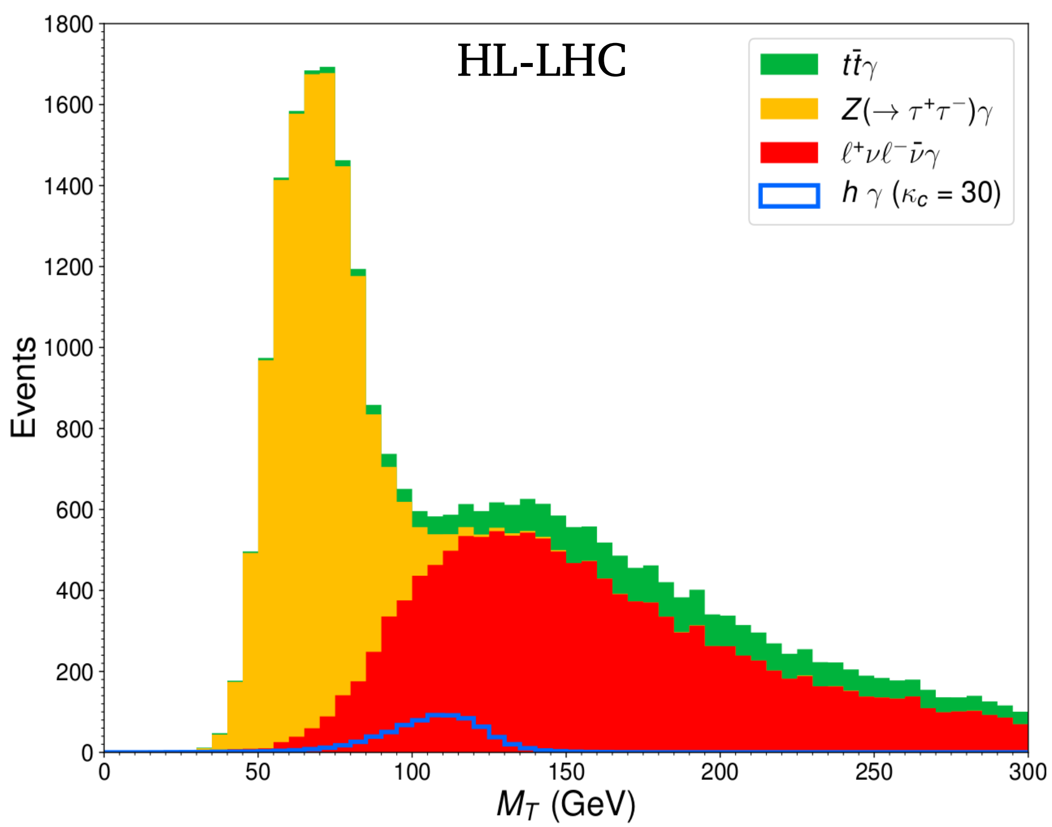

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Kinematically rich final state

Multivariate analysis can significantly increase cut-&-count sensitivity

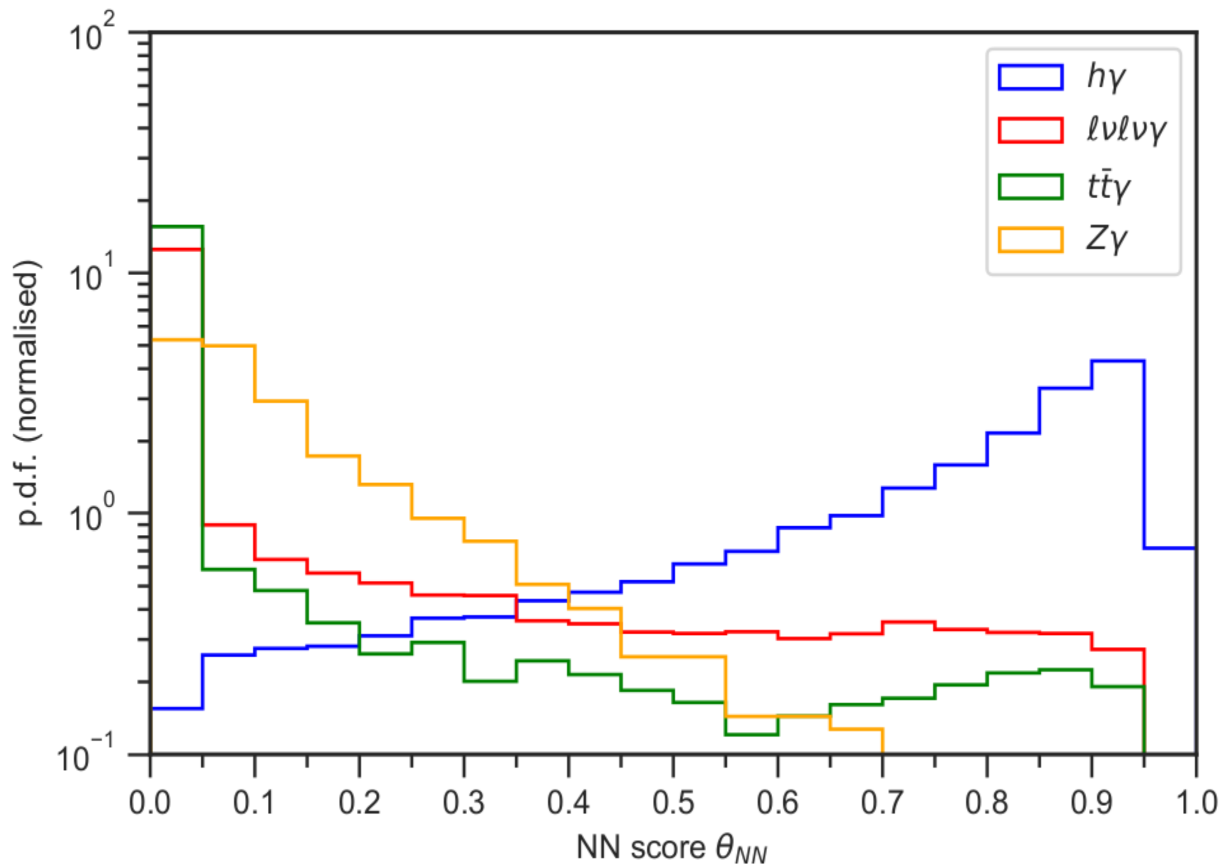
$$M_T\,,\, M_{\ell\ell}\,,\, M_{\ell\ell\gamma}\,,\, \vec{p}_T^{\,\ell_1}\,,\, \vec{p}_T^{\,\ell_2}\,,\, \vec{p}_T^{\,\gamma}\,,\, \not{E}_T\,,$$

$$\Delta\phi^{\ell\ell}\,,\, \Delta\phi^{\ell_1\gamma}\,,\, \Delta\phi^{\ell_2\gamma}\,,\, \Delta\eta^{\ell\ell}\,,\, \eta^{\ell_1}\,,\, \eta^{\ell_2}\,,\, \eta^{\gamma}$$

Higgs + photon

$h \to WW^* \to \ell\nu\ell\nu$

Neural Network (NN) multivariate analysis



➔ Optimal cut

$$\theta_{\rm NN} > 0.78$$

HL-LHC sensitivity (3 ab^{-1}):

$$|\kappa_c| < 11.8$$
$$|\kappa_u| < 1930$$
(95% C.L.)

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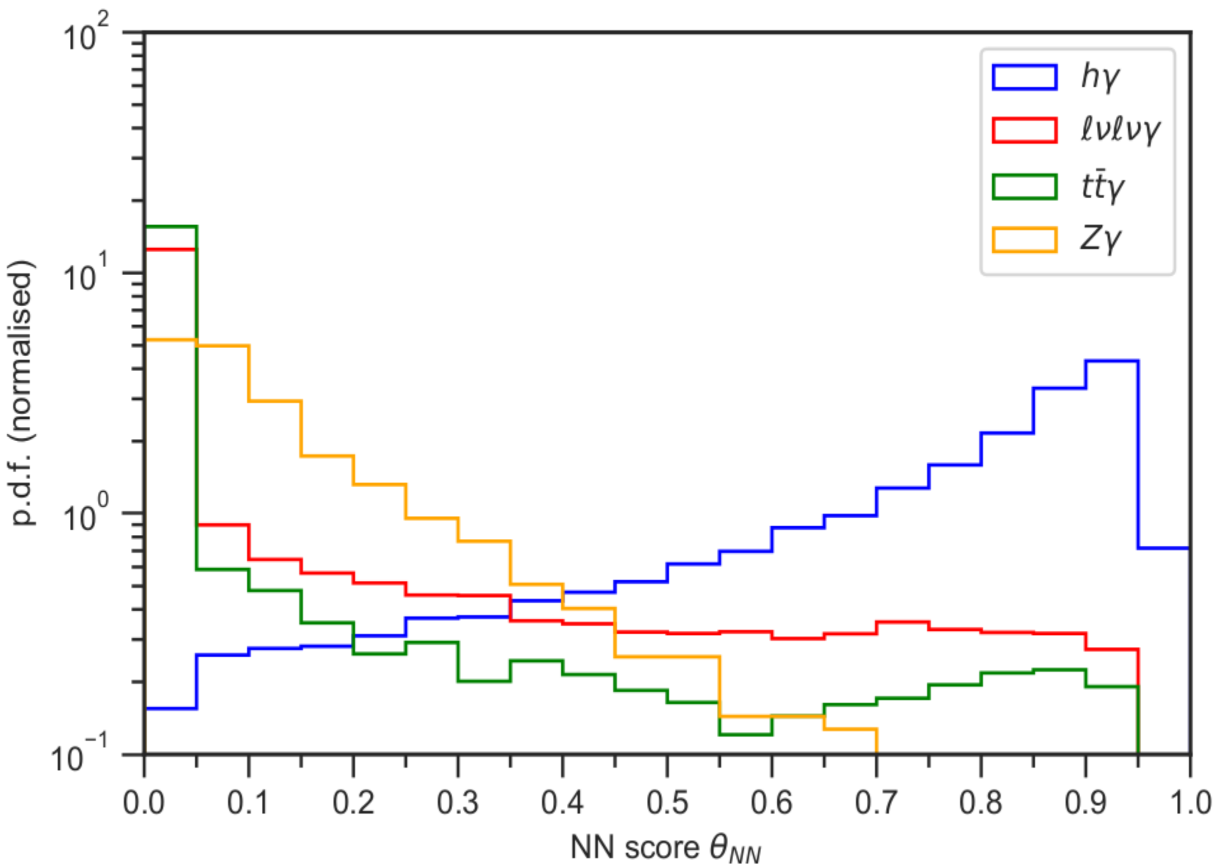

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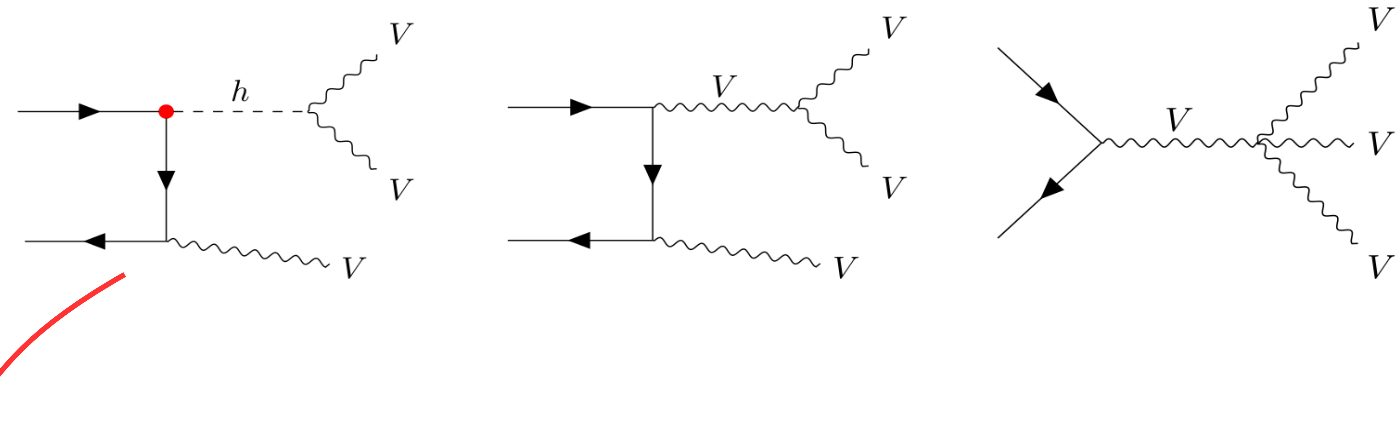
Possible to look for $h + \gamma$ in other final states?

Besides its sensitivity to y_q, $h + \gamma$ interesting in its own right:

Unobserved Higgs production mode!

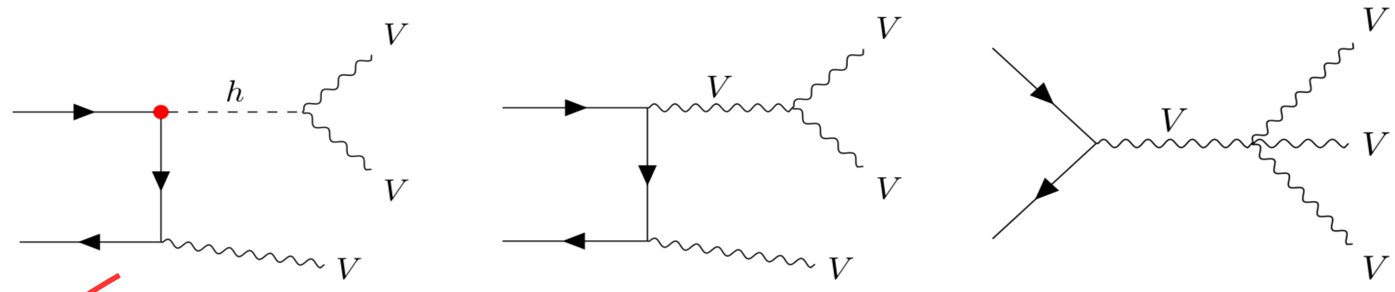
Tri-boson



Key in controlling high-energy behaviour of VVV amplitude

(deviation in $h\bar{q}q$ coupling from SM leads to quadratic growth with c.o.m energy for $q\bar{q} \to VVV$ XS)

Tri-boson



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VVV can be used to constrain Higgs Yukawa couplings

… following idea of *"measuring Higgs couplings without Higgs bosons"*

Henning, Lombardo, Riembau, Riva. PRL 123 (2019) 181801

Deviations of Higgs Yukawas from SM: EFT description

Add D = 6 operators to SM:

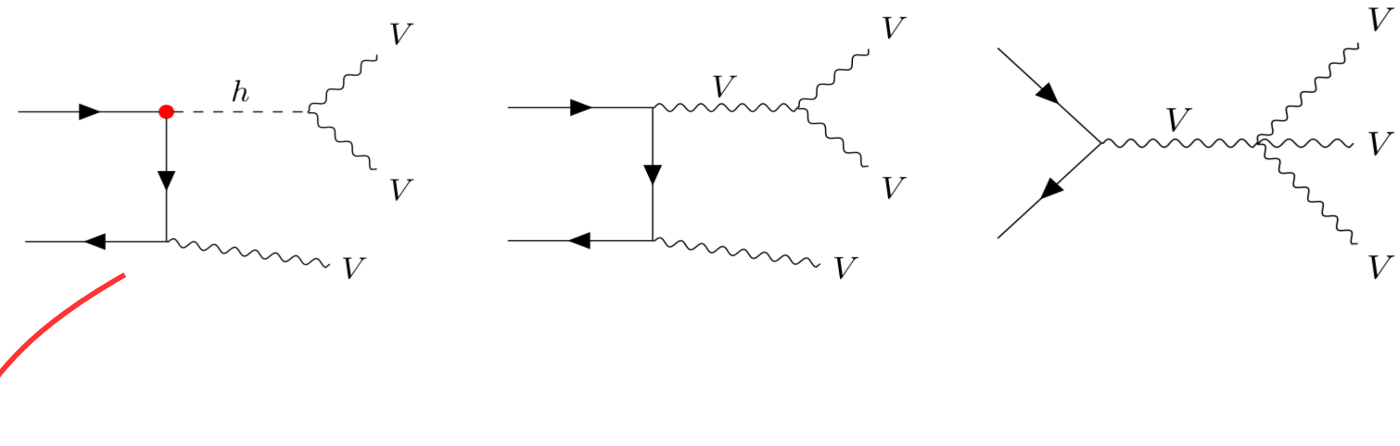
$$\mathcal{L}_{\mathrm{SMEFT}} \supset \frac{Y_u|H|^2}{v^2}\bar{u}_R Q_{1,L} H + \frac{Y_d|H|^2}{v^2}\bar{d}_R H^\dagger Q_{1,L} + \frac{Y_s|H|^2}{v^2}\bar{s}_R H^\dagger Q_{2,L} + \text{h.c.}$$

⇨ We focus on u, d, s

⇨ For q = c, t, $pp \to WWqj$ more sensitive

Brooijmans, Buckley, Caron, Falkowski, Fuks, Gilbert, Murray, Nardecchia, No, Torre, You, Zevi della Porta. PhysTeV 2019.
New Physics WG, 2002.12220 (Contribution 12)

Tri-boson



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Relation between mass and Yukawa after EWSB:

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

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

Tri-boson

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	109 fb
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ZZW^+	40 fb	1.0 pb	1.0 pb	31 fb
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(SM: NLO with MadGraph)

(BSM: LO with MadGraph)

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

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(studied also 3-lepton [WWW] and 4-lepton [ZZZ] channels)

Falkowski, Ganguly, Gras, No, Tobioka, Vignaroli, Venturini, You. To Appear

STAY TUNED

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$$\sigma(Y_d) = 7.5\,\text{fb} + Y_d^2 \times 205\,\text{fb}$$

Large BSM cross section enhancement

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Can readily use CMS observation of SM tri-boson production to constrain δy_q

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

Selection cuts:

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

$$E_T^{\text{miss}} > 45\,\text{GeV}\,, m_T^{\text{max}}(\ell) > 90\,\text{GeV}$$

$\Downarrow$

$$\delta y_d \lesssim 6800$$

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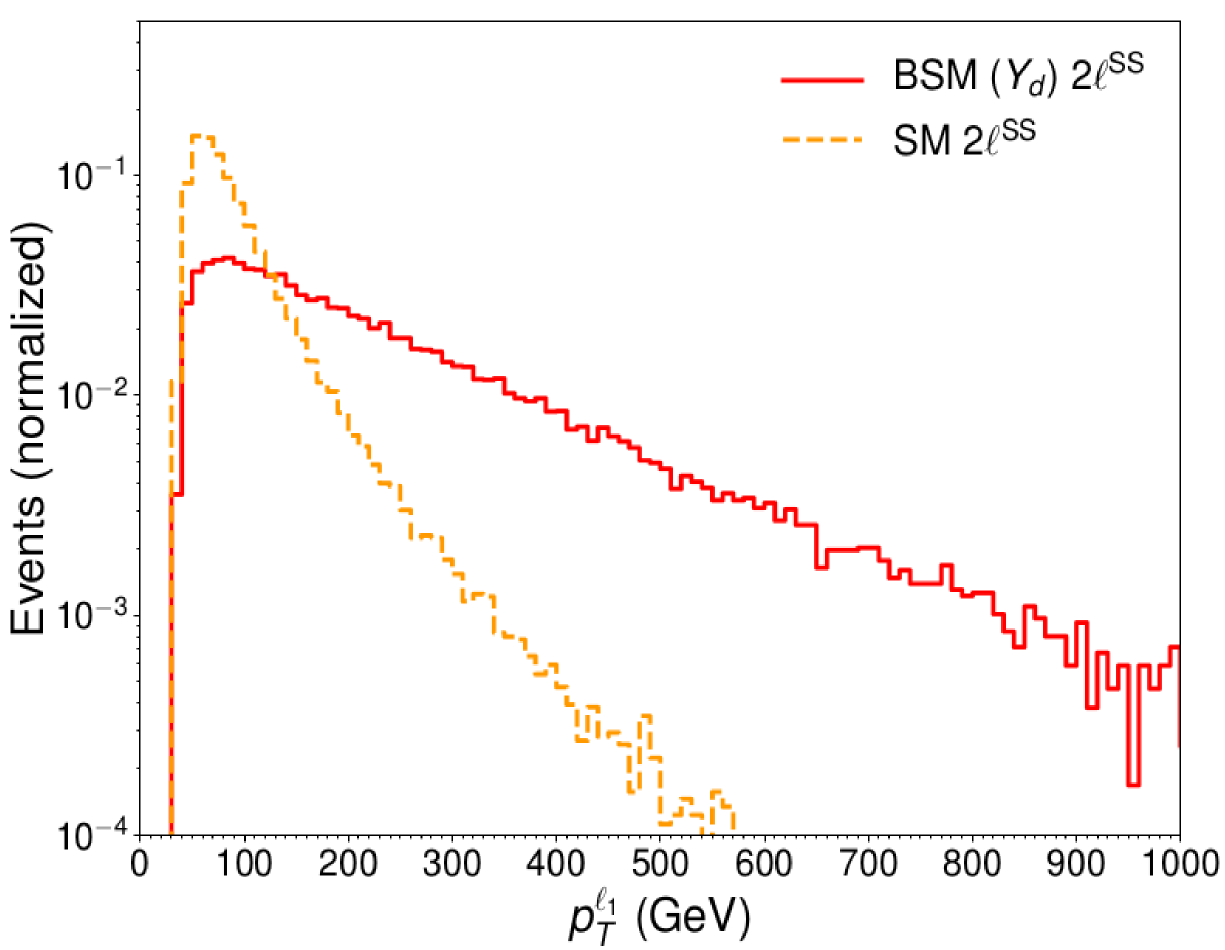

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These cuts are not optimized for BSM!

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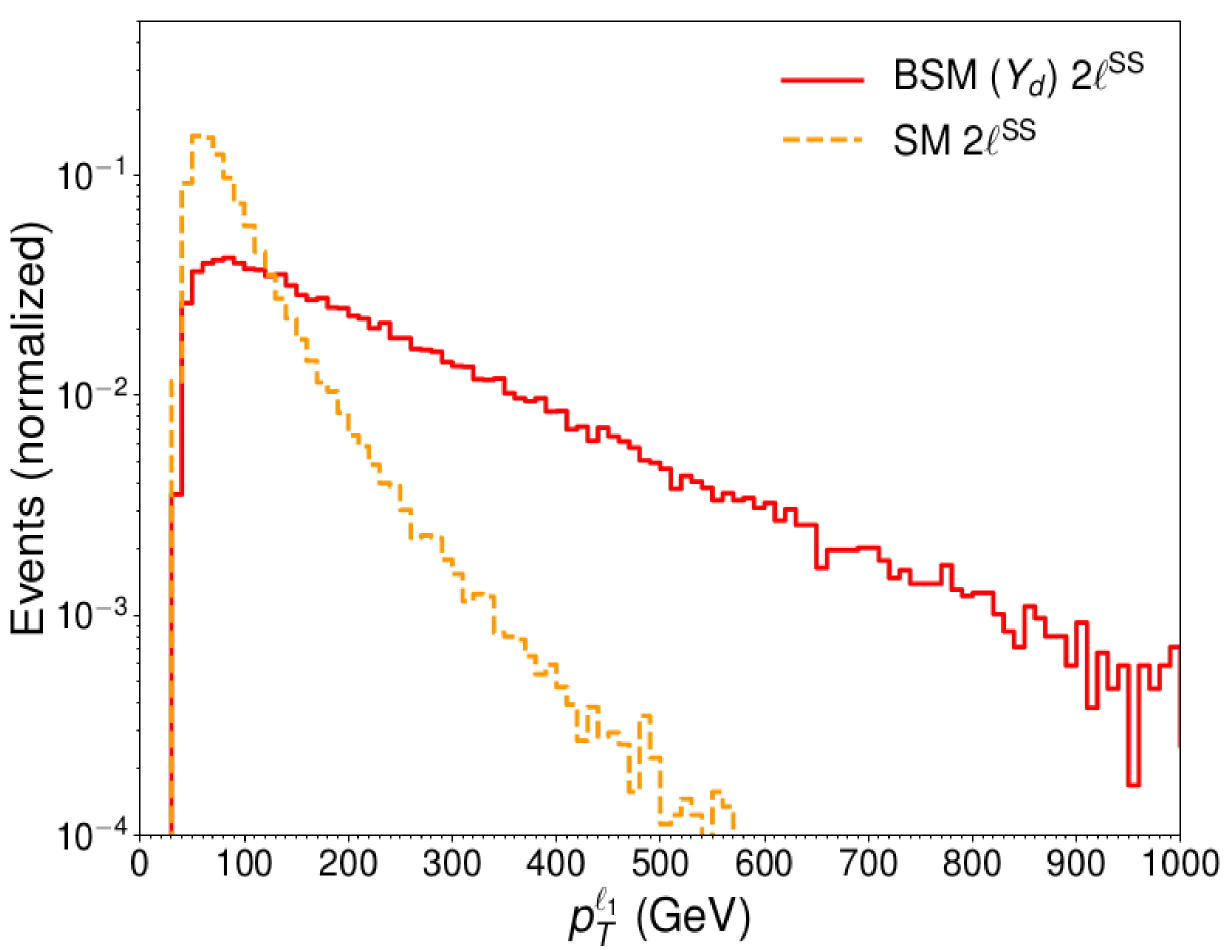

Improved selection cuts:

$$p_T^{\ell_{1,2}} > 60\,\text{GeV}\,, \quad E_T^{\text{miss}} > 120\,\text{GeV}\,, \quad p_T^{jj} > 120\,\text{GeV}\,, \quad |\Delta\eta(\ell_1, \ell_2)| < 2$$

Efficiencies:

$\epsilon_S = 0.61$ (HL-LHC)

$\epsilon_B = 0.015$ (HL-LHC)

$\delta y_d \lesssim 430$ (HL-LHC)

$\delta y_u \lesssim 850$ (HL-LHC)

$\delta y_s \lesssim 150$ (HL-LHC)

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Other EFT operators can also impact VVV signatures (e.g. anomalous TGCs) [Global Fit]

Very sensitive probe of y_q

$\delta y_d \lesssim 430$ (HL-LHC)

$\delta y_u \lesssim 850$ (HL-LHC)

$\delta y_s \lesssim 150$ (HL-LHC)

Thank you!