Novel probes of Higgs couplings to light SM quarks

Jose Miguel No
IFT-UAM/CSIC, Madrid

Based on 2008.12538 (w. Aguilar-Saavedra & Cano)
2011.09551 (w. Falkowski, Ganguly, Gras, Tobioka, Vignaroli, You)

UNIVERSIDAD AUTONOMA DE MADRID
Instituto de Física Teórica UAM-CSIC

Why?

Higgs Yukawa couplings to light SM fermions

- Establish role of Higgs in mass generation of 1st & 2nd generation SM fermions

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- Establish role of Higgs in mass generation of 1st & 2nd generation SM fermions

[source: nobelprize.org]

“Higgs flavour”

Leptons:

- Recent ATLAS & CMS evidence of Higgs coupling to muons

CMS-HIG-19-006

CERN-EP-2020-164
2020/09/10

Evidence for Higgs boson decay to a pair of muons

The CMS Collaboration*

2009.04363

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

Phys. Lett. B 812 (2021) 135980
DOI: 10.1016/j.physletb.2020.135980

CERN-EP-2020-117
16th December 2020

A search for the dimuon decay of the Standard Model Higgs boson with the ATLAS detector

The ATLAS Collaboration

2007.07830

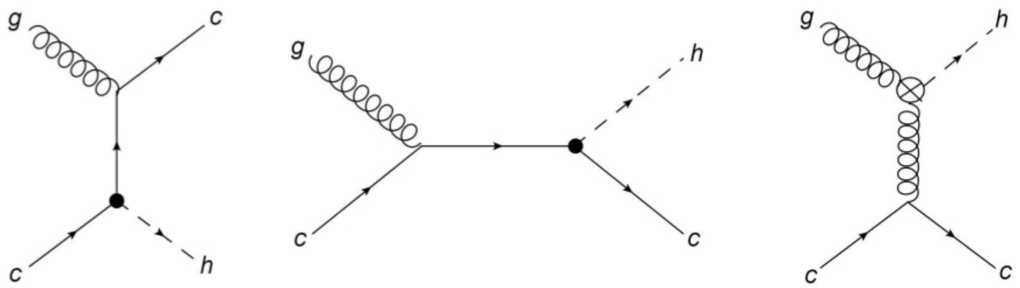
Quarks: (more complicated...)

- Strategies *(non-exhaustive!)* to probe light quark Yukawas @ LHC

▸ Higgs + charm production

Brivio, Isidori, Goertz. PRL 115, 211801 (1507.02916)

(requires charm-jet tagging)



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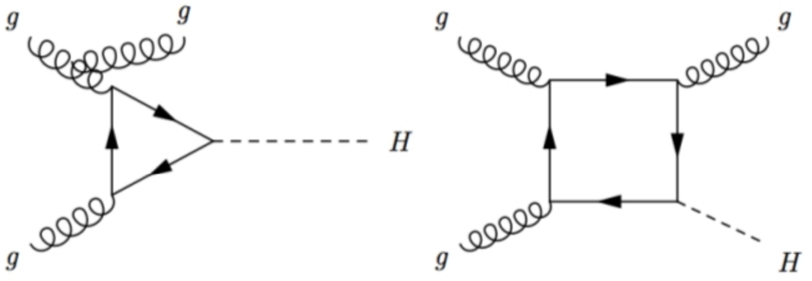

[source: 1410.5806]

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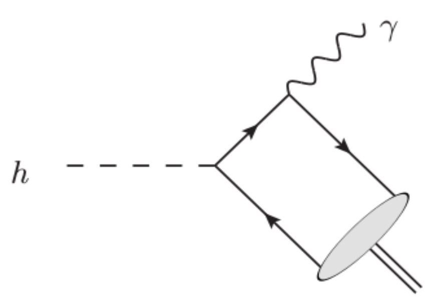

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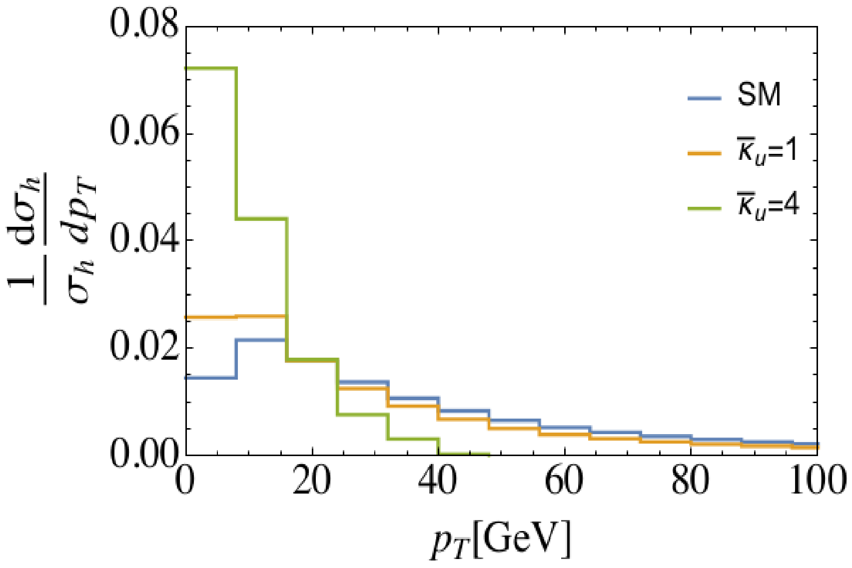

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- Double Higgs production
  Alasfar, Corral Lopez, Grober. JHEP 11 (2019) 088 (1909.05279)
  Egana-Ugrinovic, Hollimer, Meade. 2101.04119

Quarks:

- Strategies to probe light quark Yukawas @ LHC

  - Higgs + charm production
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Are all these needed?

Why look for new strategies?

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Are all these needed?

Why look for new strategies?

Complementarity

"Different probes are sensitive to different sets of couplings / EFT operators"

New strategies to constrain Higgs Yukawas @ LHC

❶ Higgs + photon production

Aguilar-Saavedra, Cano, No. 2008.12538

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

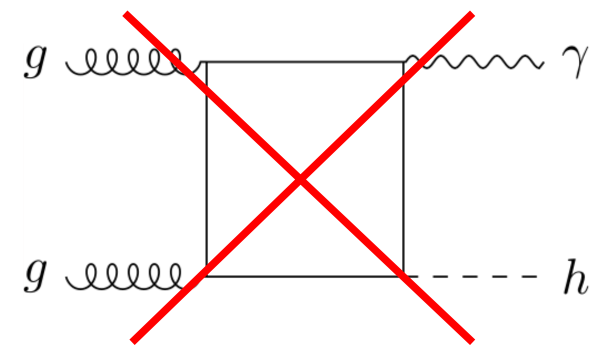
❷ Triple gauge boson production

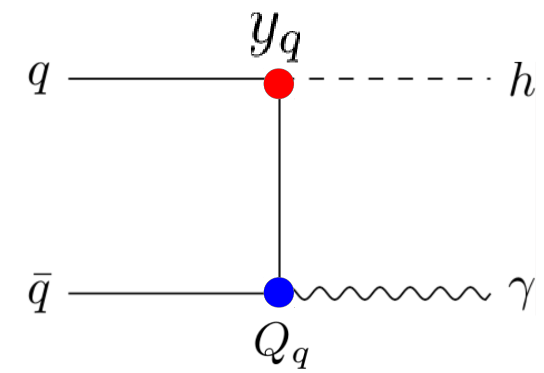
Falkowski, Ganguly, Gras, No, Tobioka, Vignaroli, You. 2011.09551

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

Higgs + photon

Would-be leading contribution
vanishes (Furry Theorem)





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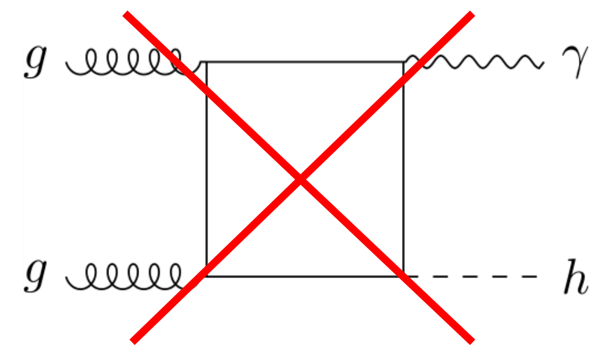

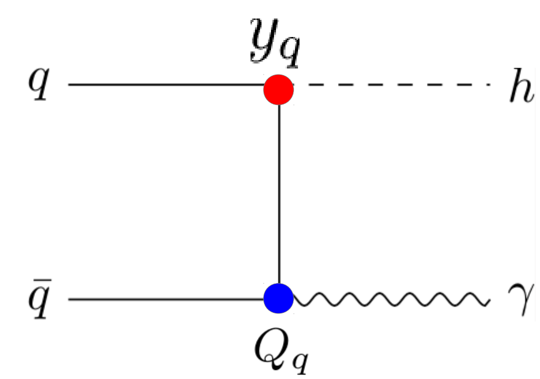

⇨ $(Q_u/Q_d)^2 = 4$ ➔ more sensitive to up-type quark Yukawa deviations

⇨ 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:

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

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

$$pp \to t\bar{t}\gamma$$

$$t \to b\ell^+\nu$$
$$\bar{t} \to \bar{b}\ell^-\bar{\nu}$$

Higgs + photon

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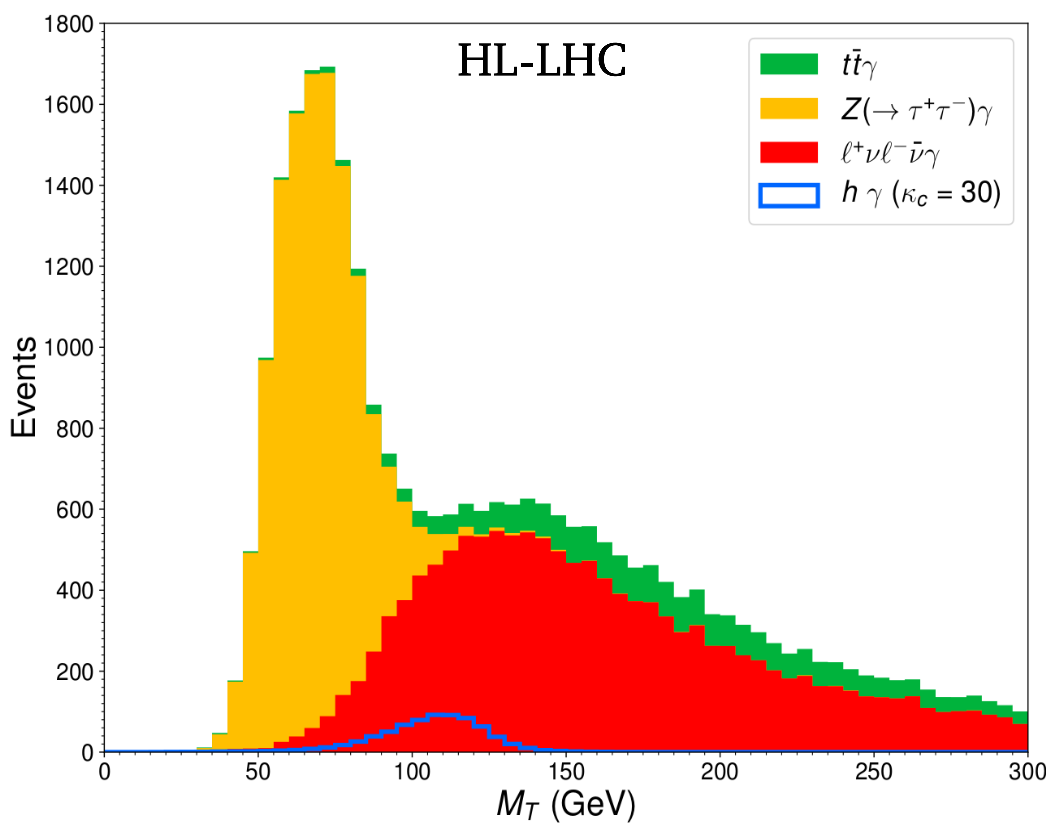
$$pp \to t\bar{t}\gamma \quad t \to b\ell^+\nu,\; \bar{t} \to \bar{b}\ell^-\bar{\nu}$$

Initial selection

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

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

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



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

Higgs + photon

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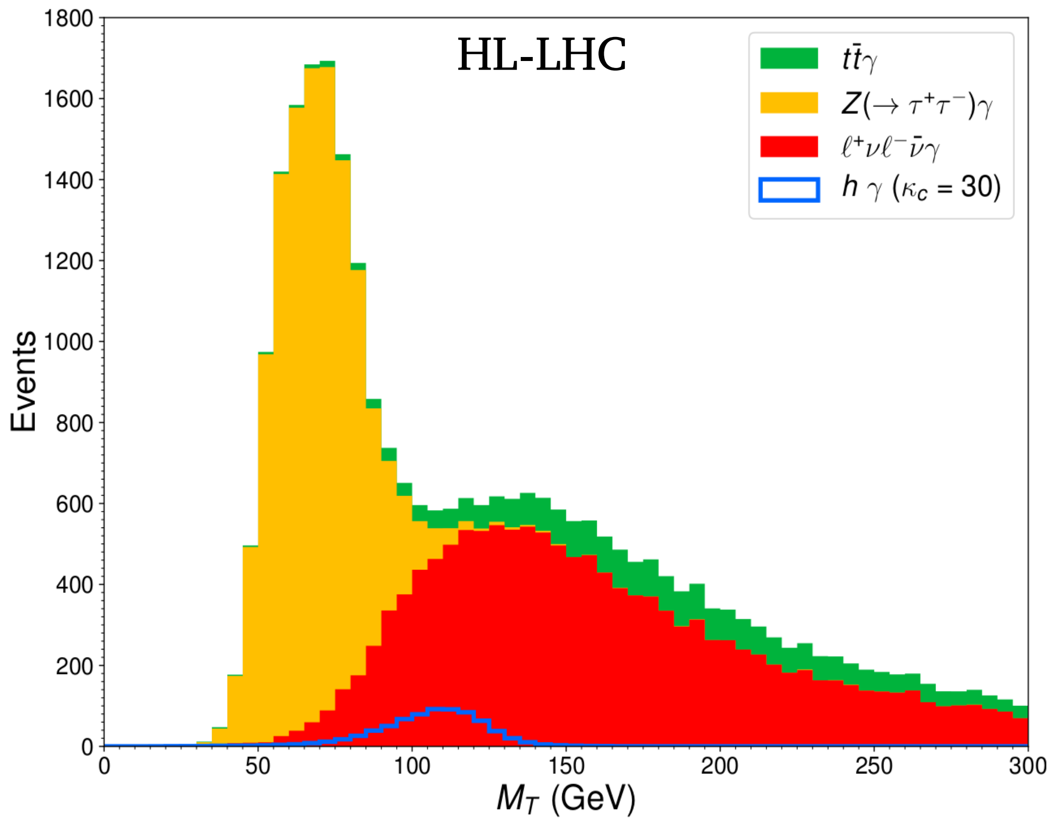

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Kinematically rich final state

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

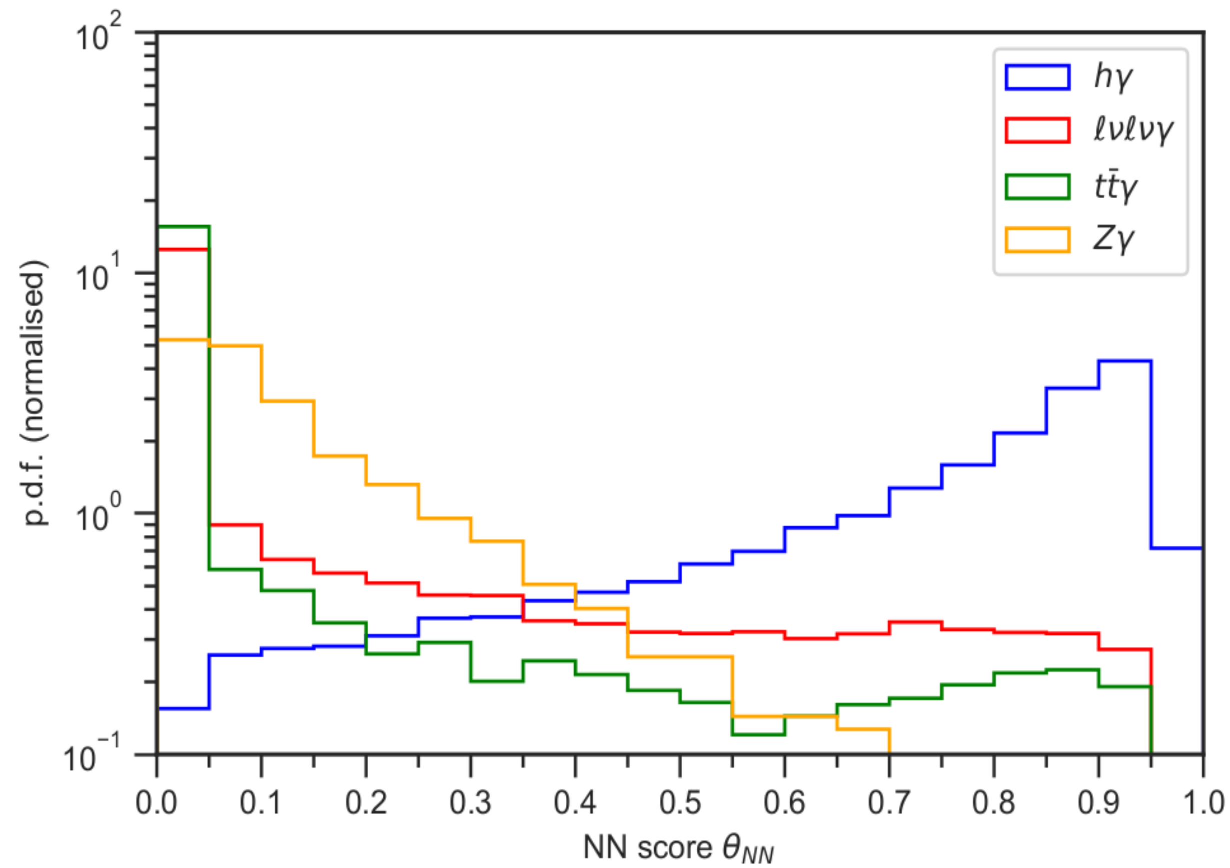
Strong correlations among variables

Multivariate analysis significantly increases cut-&-count sensitivity

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.)

Higgs + photon

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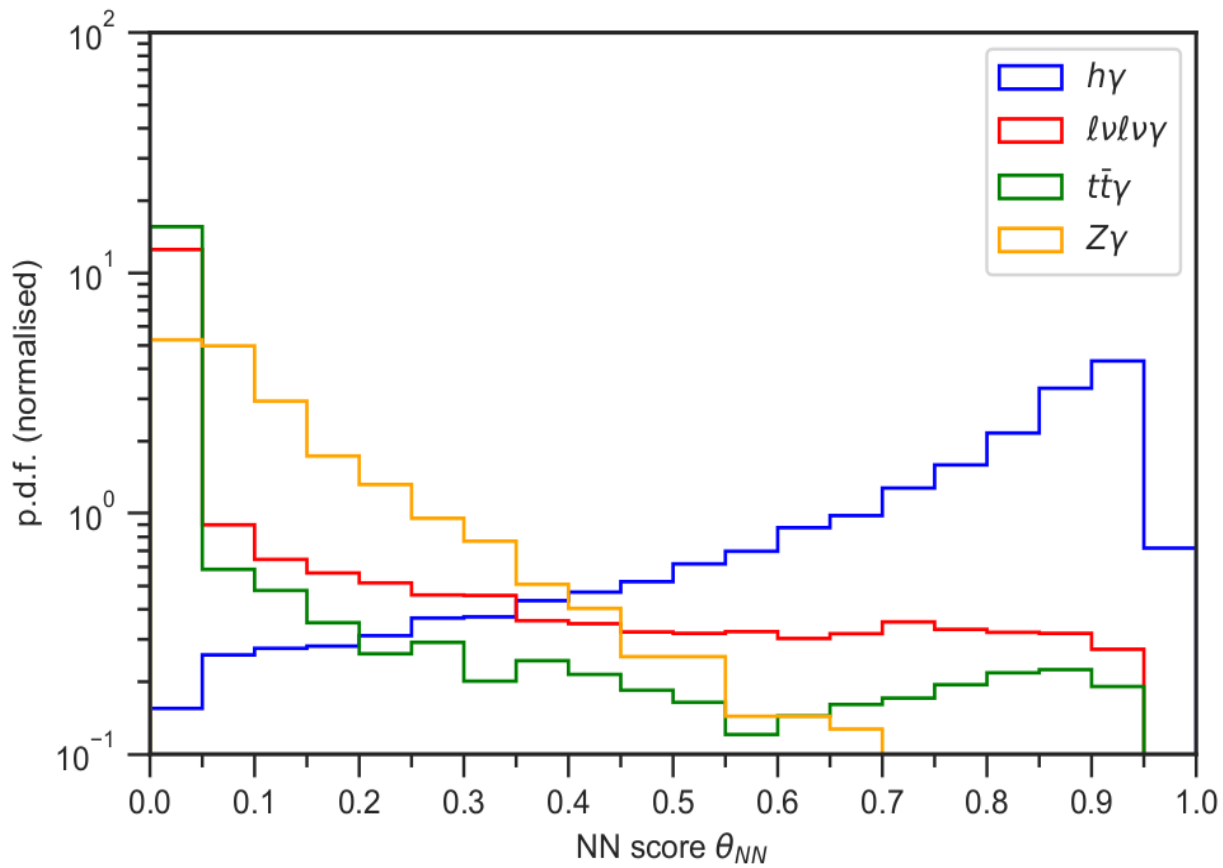

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Possible to look for $h + \gamma$ in other final states?

Besides its Yukawa sensitivity, $h + \gamma$ interesting in its own right: Unobserved Higgs production mode!

Tri-boson

Triple massive gauge boson production
recently observed for the first time @ LHC!


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Observation of the Production of Three Massive Gauge Bosons at $\sqrt{s} = 13$ TeV

A. M. Sirunyan *et al.* (CMS Collaboration)
Phys. Rev. Lett. **125**, 151802 – Published 5 October 2020

Physics See synopsis: Hat Trick Observation for Bosons


PHYS.ORG

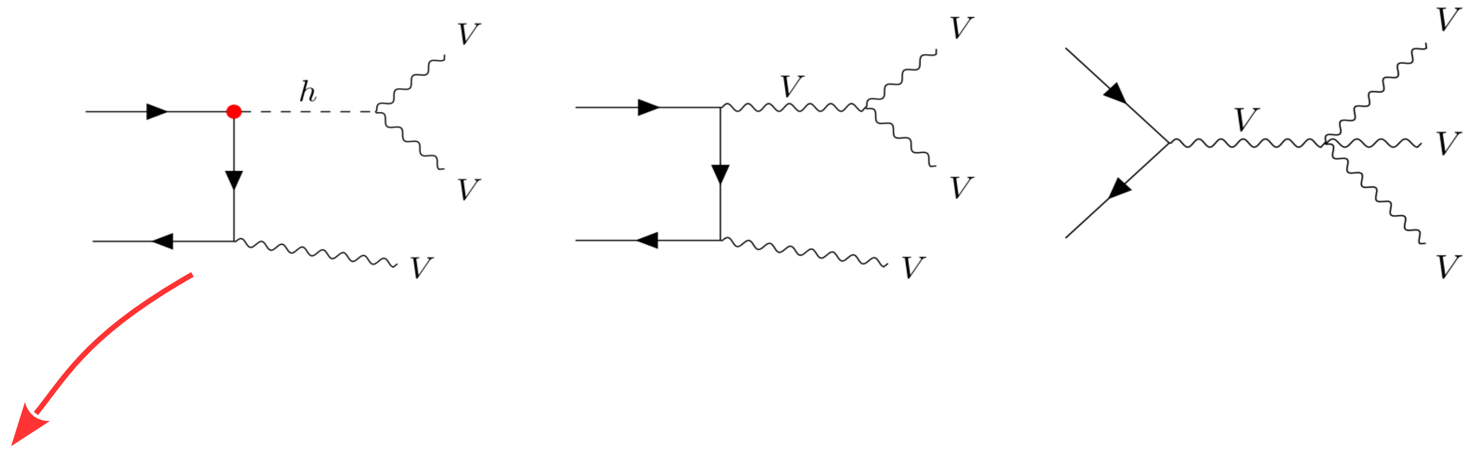
Topics

DECEMBER 7, 2020 FEATURE

Triple threat: The first observation of three massive gauge bosons produced in proton-proton collisions

by Ingrid Fadelli , Phys.org

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)

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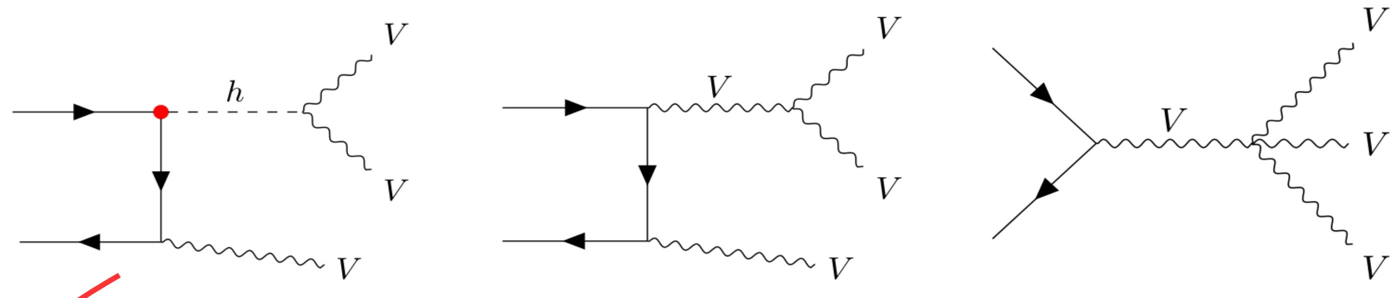

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VVV can be used to constrain Higgs Yukawa couplings

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

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

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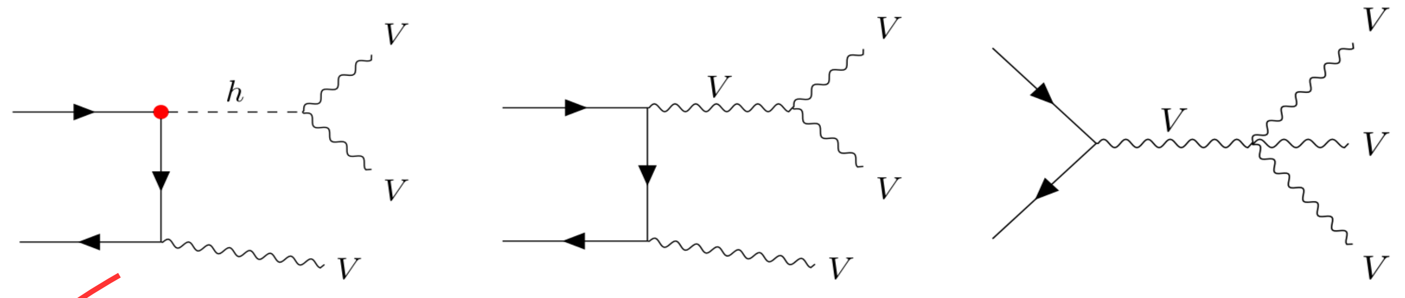

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Deviations of Higgs Yukawas from SM: EFT description

Add D = 6 operators to SM:

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

⇨ We 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)

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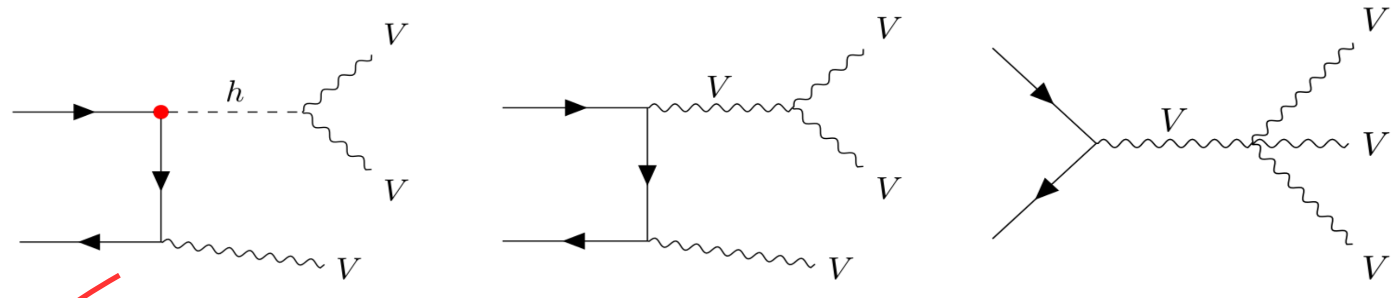

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Relation between mass and Yukawa after EWSB:

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

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

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

By **Equivalence Theorem**:

$$\mathcal{M}(q\bar{q} \to V_L V_L V_L) \xleftrightarrow{\sqrt{s} \gg m_Z} \mathcal{M}(q\bar{q} \to GGG)$$

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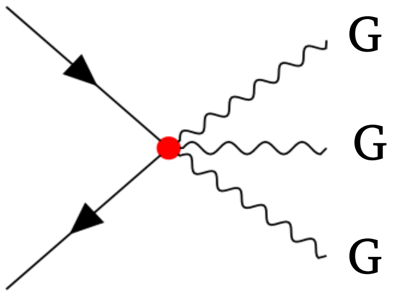
Contact interaction (2 quarks + 3 Goldstone bosons)

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



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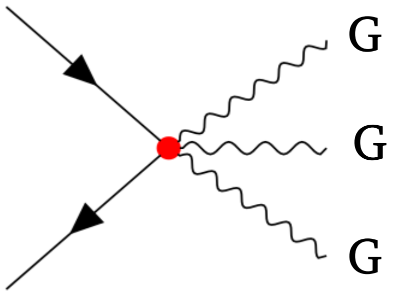

Leading contribution

(other tree-level diagrams more suppressed from extra internal propagators)

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

By **Equivalence Theorem**:

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

$$\mathcal{M}(q\bar{q} \to V_L V_L V_L) \xleftrightarrow{\sqrt{\hat{s}} \gg m_Z} \mathcal{M}(q\bar{q} \to GGG)$$

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

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

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

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

$$\left(\begin{array}{l} q = u, d, s \\ q' = d, s \end{array} \right)$$

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

→ c.o.m. energy of partonic collision ($\sqrt{\hat{s}}$)

$\mathbf{E}^2$ growth of partonic cross section

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

$$\left(\begin{array}{l} q = u, d, s \\ q' = d, s \end{array} \right)$$

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

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

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

- For **charged** (± 1) final states ($W^\pm W^\pm W^\mp$, $W^\pm ZZ$)
  same cross section enhancement for δy_u and δy_d

- For **neutral** final states (ZW^+W^-, ZZZ)
  different cross section enhancement for δy_u and δy_d

By **Equivalence Theorem**:

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

$$\mathcal{M}(q\bar{q} \to V_L V_L V_L) \xleftrightarrow{\sqrt{\hat{s}} \gg m_Z} \mathcal{M}(q\bar{q} \to GGG)$$

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

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

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

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

$$\left(\begin{array}{l} q = u, d, s \\ q' = d, s \end{array} \right)$$

- For **charged** (± 1) final states ($W^\pm W^\pm W^\mp$, $W^\pm ZZ$)
  same cross section enhancement for δy_u and δy_d

- For **neutral** final states (ZW^+W^-, ZZZ)
  different cross section enhancement for δy_u and δy_d

Break degeneracies combining several tri-boson channels

Cross sections

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
$W^+W^-W^-$	87 fb	1.5 pb	1.5 pb	109 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	115 fb
ZZZ	16 fb	0.99 pb	1.7 pb	66 fb

(SM: NLO with MadGraph)

(BSM: LO with MadGraph)

Cross sections

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
$W^+W^-W^-$	87 fb	1.5 pb	1.5 pb	109 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	115 fb
ZZZ	16 fb	0.99 pb	1.7 pb	66 fb

(SM: NLO with MadGraph)

(BSM: LO with MadGraph)

$W^{\pm}W^{\pm}W^{\mp}$ Largest cross section (+ BR into leptons larger for W than for Z)

ZZZ Largest cross section enhancement w.r.t. SM

Cross sections

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
$W^+W^-W^-$	87 fb	1.5 pb	1.5 pb	109 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	115 fb
ZZZ	16 fb	0.99 pb	1.7 pb	66 fb

(SM: NLO with MadGraph)

(BSM: LO with MadGraph)

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

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

Large BSM cross section enhancement

Cross sections

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
$W^+W^-W^-$	87 fb	1.5 pb	1.5 pb	109 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	115 fb
ZZZ	16 fb	0.99 pb	1.7 pb	66 fb

(SM: NLO with MadGraph)

(BSM: LO with MadGraph)

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

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

Large BSM cross section enhancement

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:

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

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

$\Downarrow$

$$\delta y_d \lesssim 6800$$

Cross sections

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
$W^+W^-W^-$	87 fb	1.5 pb	1.5 pb	109 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	115 fb
ZZZ	16 fb	0.99 pb	1.7 pb	66 fb

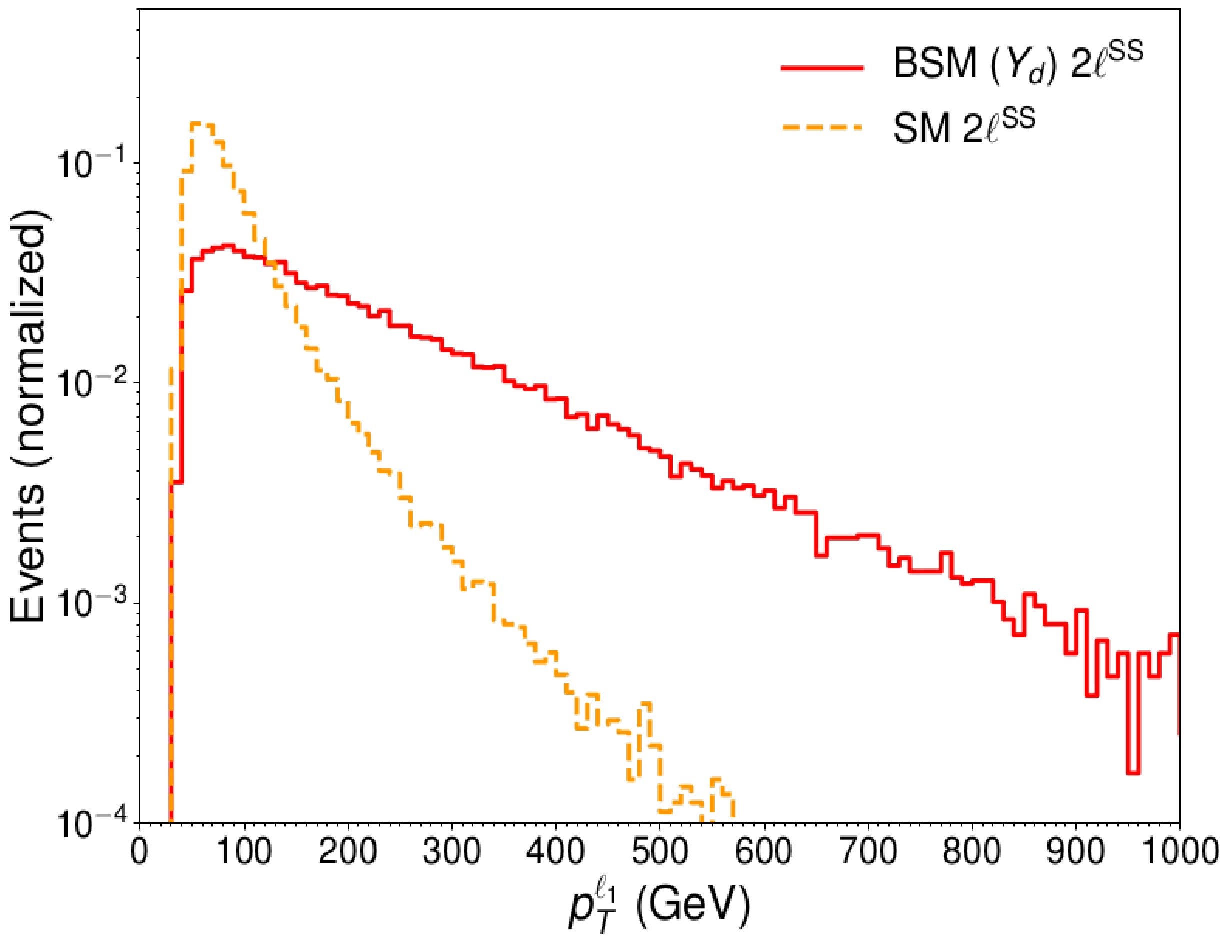
(SM: NLO with MadGraph)

(BSM: LO with MadGraph)

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

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

Large BSM cross section enhancement



Selection cuts:

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

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

These cuts are not optimized for BSM!

Cross sections

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
$W^+W^-W^-$	87 fb	1.5 pb	1.5 pb	109 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	115 fb
ZZZ	16 fb	0.99 pb	1.7 pb	66 fb

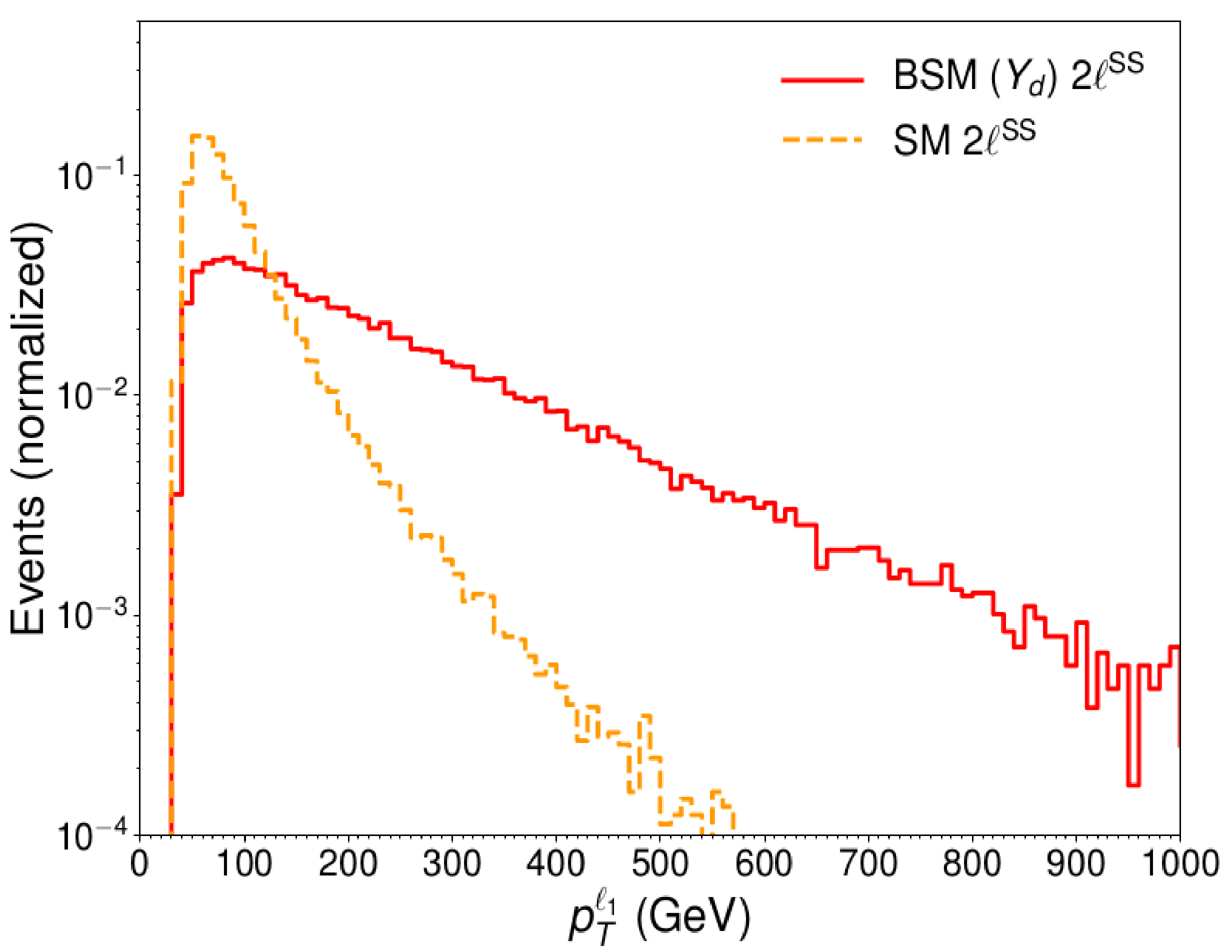
(SM: NLO with MadGraph)

(BSM: LO with MadGraph)

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

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

Large BSM cross section enhancement



BSM much harder kinematics than SM

Improved selection cuts:

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

+ binned likelihood analysis:

$$\delta y_d \lesssim 430 \text{ (HL-LHC)}$$
$$\delta y_u \lesssim 850 \text{ (HL-LHC)}$$
$$\delta y_s \lesssim 150 \text{ (HL-LHC)}$$

Cross sections

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
$W^+W^-W^-$	87 fb	1.5 pb	1.5 pb	109 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	115 fb
ZZZ	16 fb	0.99 pb	1.7 pb	66 fb

(SM: NLO with MadGraph)

(BSM: LO with MadGraph)

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

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

Large BSM cross section enhancement

These projected limits get very little affected by reducible SM backgrounds:

We simulate

$t\bar{t}W^\pm$, $t\bar{t}Z$ (NLO in QCD)

$W^\pm Z\,jj$ (LO)

Together they yield (after cuts!) ~ 20% of SM tri-boson (LHC)

$$\delta y_d \lesssim 430 \text{ (HL-LHC)}$$
$$\delta y_u \lesssim 850 \text{ (HL-LHC)}$$
$$\delta y_s \lesssim 150 \text{ (HL-LHC)}$$

Cross sections

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
$W^+W^-W^-$	87 fb	1.5 pb	1.5 pb	109 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	115 fb
ZZZ	16 fb	0.99 pb	1.7 pb	66 fb

(SM: NLO with MadGraph)

(BSM: LO with MadGraph)

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

Analysis for FCC-hh (stronger set of cuts)

$$p_T^{\ell_{1,2}} > 100\,\text{GeV}\,, \quad E_T^{\text{miss}} > 150\,\text{GeV}\,, \quad p_T^{jj} > 150\,\text{GeV}\,, \quad |\Delta\eta(\ell_1, \ell_2)| < 2$$

$$\delta y_d \lesssim 36 \text{ (FCC-hh)}$$
$$\delta y_u \lesssim 71 \text{ (FCC-hh)}$$
$$\delta y_s \lesssim 13 \text{ (FCC-hh)}$$

Cross sections

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
$W^+W^-W^-$	87 fb	1.5 pb	1.5 pb	109 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	115 fb
ZZZ	16 fb	0.99 pb	1.7 pb	66 fb

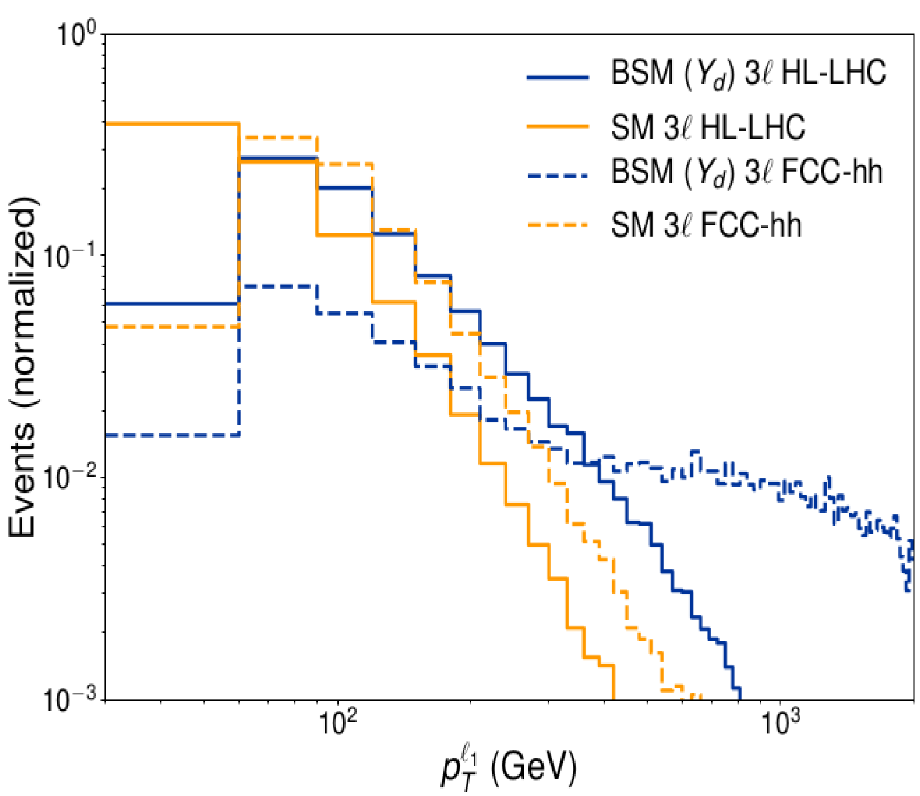
(SM: NLO with MadGraph)

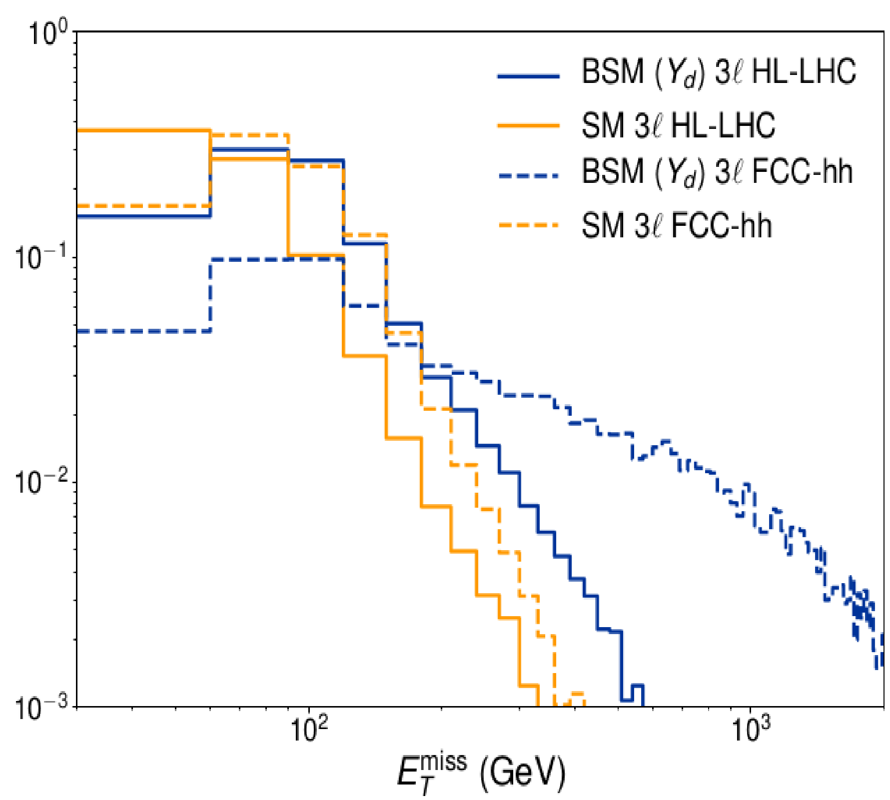
(BSM: LO with MadGraph)

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

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





$\delta y_d \lesssim 840$ (HL-LHC) , $\lesssim 54$ (FCC-hh)

$\delta y_u \lesssim 1700$ (HL-LHC) , $\lesssim 110$ (FCC-hh)

$\delta y_s \lesssim 230$ (HL-LHC) , $\lesssim 33$ (FCC-hh)

Cross sections

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
$W^+W^-W^-$	87 fb	1.5 pb	1.5 pb	109 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	115 fb
ZZZ	16 fb	0.99 pb	1.7 pb	66 fb

(SM: NLO with MadGraph)

(BSM: LO with MadGraph)

$$pp \to ZZZ \to 4\ell + 2\nu$$

$$p_T^{\ell_{1,2}} > 25 \text{ GeV}, \; p_T^{\ell_{3,4}} > 10 \text{ GeV}, \; |\eta_\ell| < 2.5, \; \Delta R_{\ell\ell} > 0.1, \; |m_Z - m_{\ell\ell}| < 10 \text{ GeV} \;, \; E_T^{\text{miss}} > 200 \text{ GeV}$$

($\Delta R_{\ell\ell} > 0.01$ FCC-hh) ($E_T^{\text{miss}} > 500$ GeV FCC-hh)

Cross sections

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
$W^+W^-W^-$	87 fb	1.5 pb	1.5 pb	109 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	115 fb
ZZZ	16 fb	0.99 pb	1.7 pb	66 fb

(SM: NLO with MadGraph)

(BSM: LO with MadGraph)

$$pp \to ZZZ \to 4\ell + 2\nu$$

$$p_T^{\ell_{1,2}} > 25 \text{ GeV}\,,\; p_T^{\ell_{3,4}} > 10 \text{ GeV}\,,\; |\eta_\ell| < 2.5\,,\; \Delta R_{\ell\ell} > 0.1\,,\; |m_Z - m_{\ell\ell}| < 10 \text{ GeV} \;\;,\;\; E_T^{\text{miss}} > 200 \text{ GeV}$$

($\Delta R_{\ell\ell} > 0.01$ FCC-hh) ($E_T^{\text{miss}} > 500$ GeV FCC-hh)

LHC:

$$\sigma(Y_u) = 0.013\,\text{fb} + Y_u^2 \times 3.0\,\text{fb}$$
$$\sigma(Y_d) = 0.013\,\text{fb} + Y_d^2 \times 1.8\,\text{fb}$$
$$\sigma(Y_s) = 0.013\,\text{fb} + Y_s^2 \times 0.14\,\text{fb}$$

FCC-hh:

$$\sigma(Y_u) = 0.11\,\text{fb} + Y_u^2 \times 340\,\text{fb}$$
$$\sigma(Y_d) = 0.11\,\text{fb} + Y_d^2 \times 220\,\text{fb}$$
$$\sigma(Y_s) = 0.11\,\text{fb} + Y_s^2 \times 26\,\text{fb}$$

Cross sections

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
$W^+W^-W^-$	87 fb	1.5 pb	1.5 pb	109 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	115 fb
ZZZ	16 fb	0.99 pb	1.7 pb	66 fb

(SM: NLO with MadGraph)

(BSM: LO with MadGraph)

$$pp \to ZZZ \to 4\ell + 2\nu$$

$$p_T^{\ell_{1,2}} > 25\text{ GeV}\,,\ p_T^{\ell_{3,4}} > 10\text{ GeV}\,,\ |\eta_\ell| < 2.5\,,\ \Delta R_{\ell\ell} > 0.1\,,\ |m_Z - m_{\ell\ell}| < 10\text{ GeV} \quad,\quad E_T^{\text{miss}} > 200\text{ GeV}$$

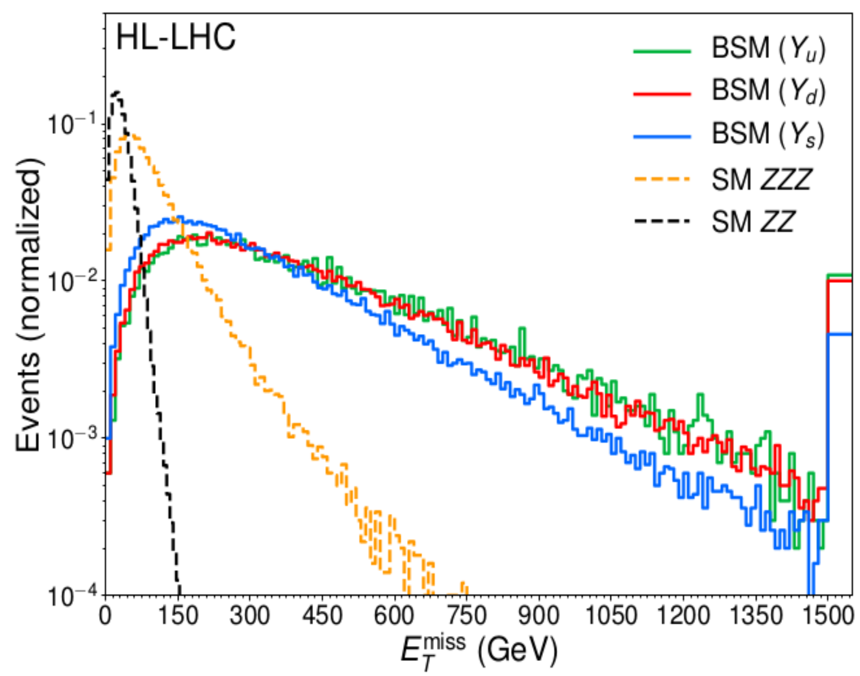
$(\Delta R_{\ell\ell} > 0.01$ FCC-hh) $(E_T^{\text{miss}} > 500$ GeV FCC-hh)

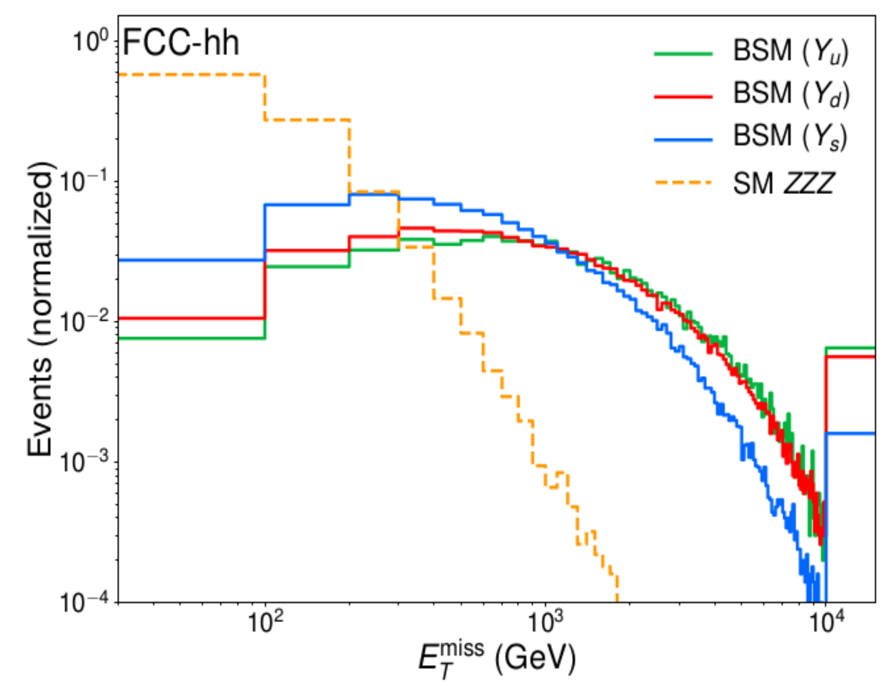
LHC:

$$\sigma(Y_u) = 0.013\,\text{fb} + Y_u^2 \times 3.0\,\text{fb}$$
$$\sigma(Y_d) = 0.013\,\text{fb} + Y_d^2 \times 1.8\,\text{fb}$$
$$\sigma(Y_s) = 0.013\,\text{fb} + Y_s^2 \times 0.14\,\text{fb}$$

FCC-hh:

$$\sigma(Y_u) = 0.11\,\text{fb} + Y_u^2 \times 340\,\text{fb}$$
$$\sigma(Y_d) = 0.11\,\text{fb} + Y_d^2 \times 220\,\text{fb}$$
$$\sigma(Y_s) = 0.11\,\text{fb} + Y_s^2 \times 26\,\text{fb}$$





Cross sections

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
$W^+W^-W^-$	87 fb	1.5 pb	1.5 pb	109 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	115 fb
ZZZ	16 fb	0.99 pb	1.7 pb	66 fb

(SM: NLO with MadGraph)

(BSM: LO with MadGraph)

$$pp \to ZZZ \to 4\ell + 2\nu$$

$$p_T^{\ell_{1,2}} > 25 \text{ GeV}\,,\; p_T^{\ell_{3,4}} > 10 \text{ GeV}\,,\; |\eta_\ell| < 2.5\,,\; \Delta R_{\ell\ell} > 0.1\,,\; |m_Z - m_{\ell\ell}| < 10 \text{ GeV} \quad , \quad E_T^{\text{miss}} > 200 \text{ GeV}$$

$(\Delta R_{\ell\ell} > 0.01$ FCC-hh$)$ $\qquad (E_T^{\text{miss}} > 500$ GeV FCC-hh$)$

LHC:

$$\sigma(Y_u) = 0.013\,\text{fb} + Y_u^2 \times 3.0\,\text{fb}$$
$$\sigma(Y_d) = 0.013\,\text{fb} + Y_d^2 \times 1.8\,\text{fb}$$
$$\sigma(Y_s) = 0.013\,\text{fb} + Y_s^2 \times 0.14\,\text{fb}$$

FCC-hh:

$$\sigma(Y_u) = 0.11\,\text{fb} + Y_u^2 \times 340\,\text{fb}$$
$$\sigma(Y_d) = 0.11\,\text{fb} + Y_d^2 \times 220\,\text{fb}$$
$$\sigma(Y_s) = 0.11\,\text{fb} + Y_s^2 \times 26\,\text{fb}$$

$$\delta y_d \lesssim 1500 \quad (\text{HL-LHC}) \quad , \quad \lesssim 65 \quad (\text{FCC-hh})$$
$$\delta y_u \lesssim 2300 \quad (\text{HL-LHC}) \quad , \quad \lesssim 100 \quad (\text{FCC-hh})$$
$$\delta y_s \lesssim 300 \quad (\text{HL-LHC}) \quad , \quad \lesssim 12 \quad (\text{FCC-hh})$$

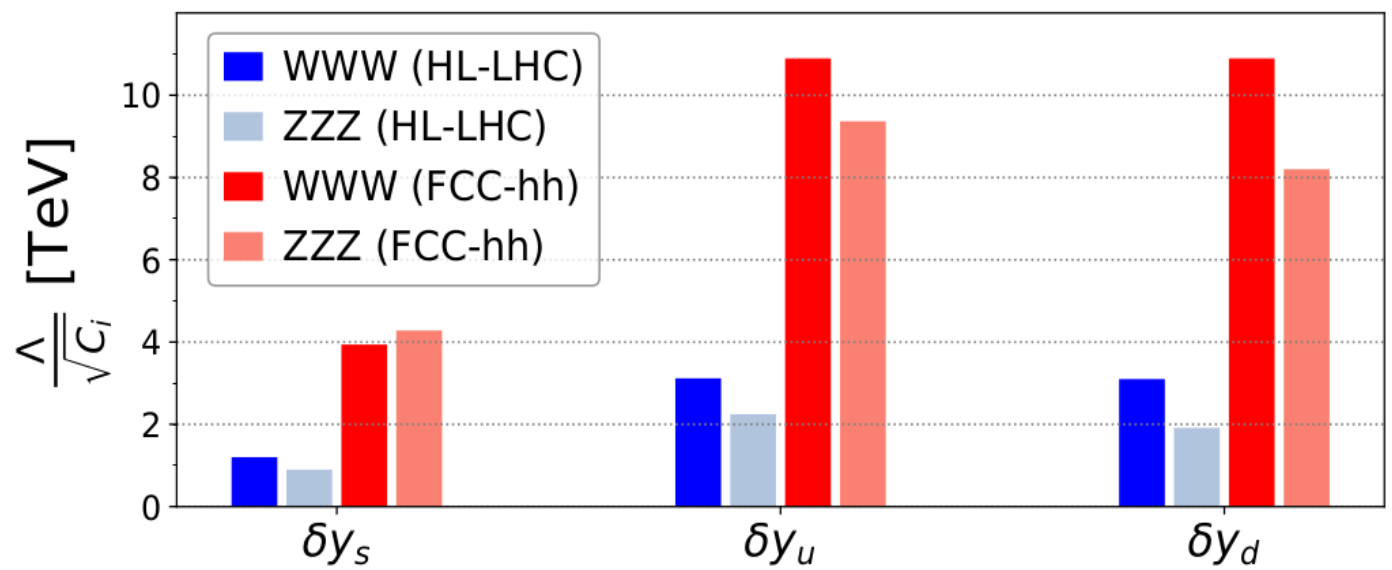
Sensitivity Summary HL-LHC (FCC-hh)

	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)

Sensitivity Summary HL-LHC (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)

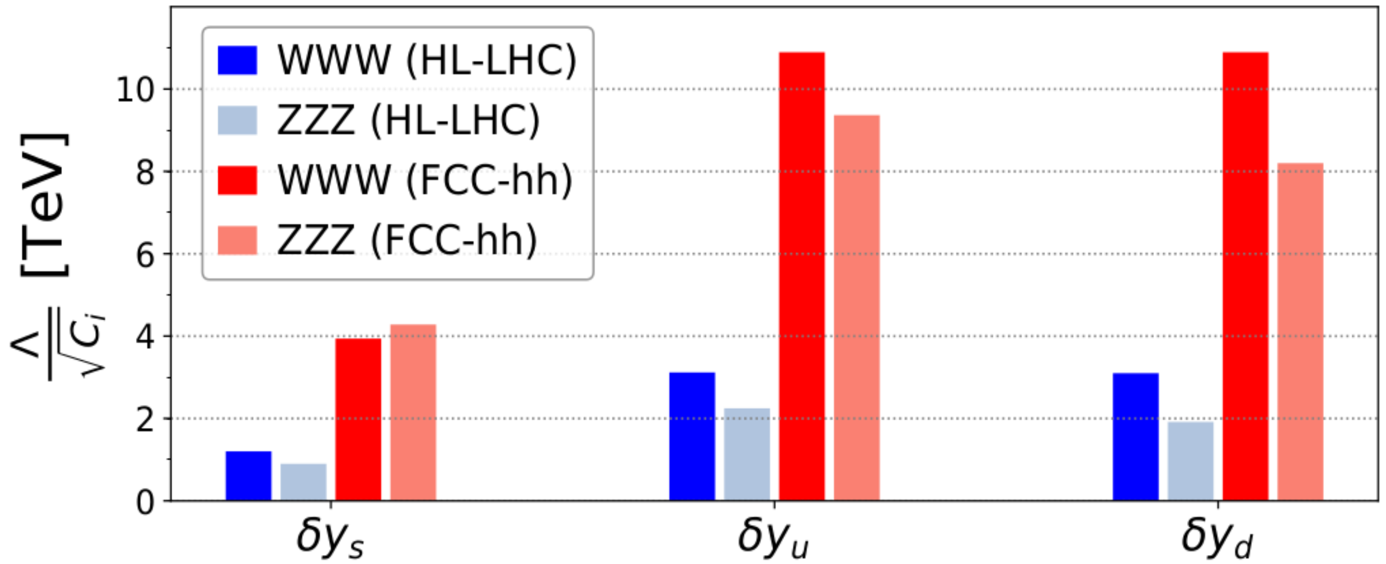
$$Y_i = C_i\, v^2/\Lambda^2$$



Sensitivity Summary HL-LHC (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)

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

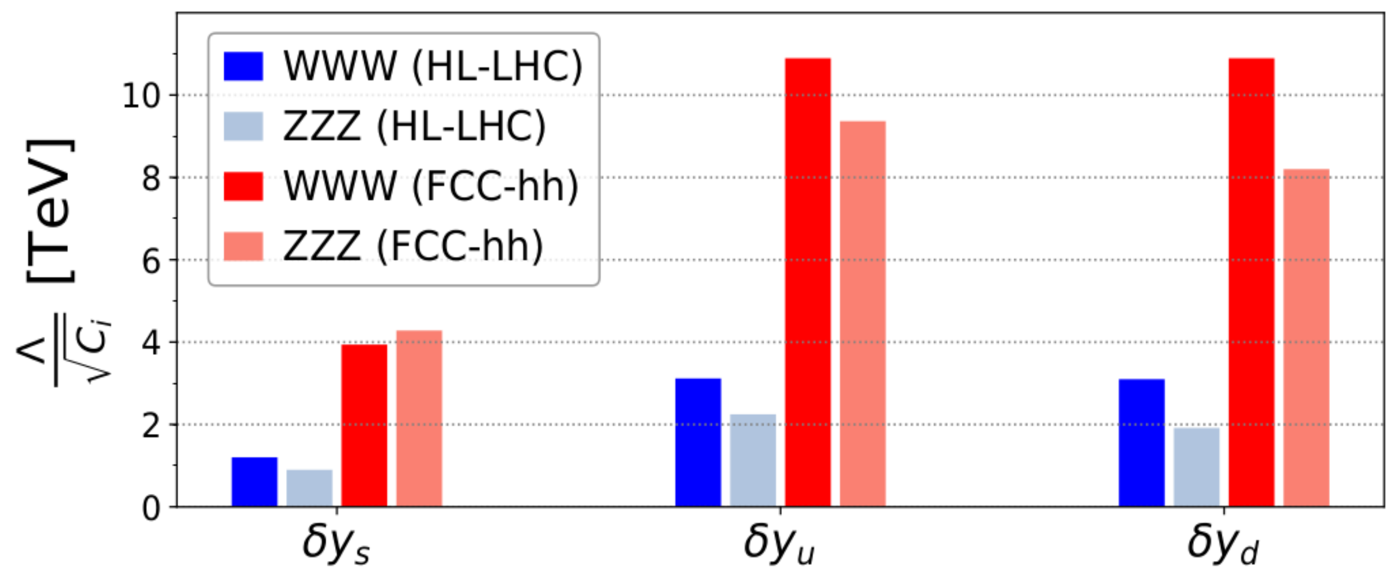


(Of course!) **other EFT operators may also impact VVV signatures** (e.g. anomalous TGCs)

Sensitivity Summary HL-LHC (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)

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



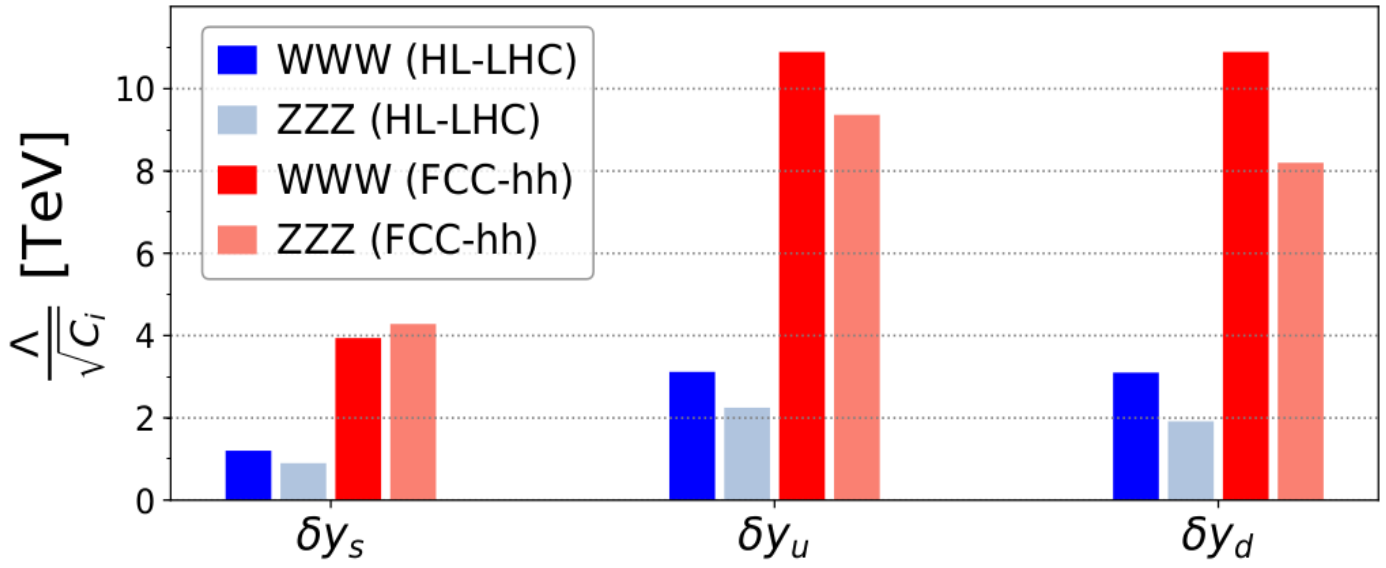
(Of course!) other EFT operators may also impact VVV signatures (e.g. anomalous TGCs)

[Global Fit]

Sensitivity Summary HL-LHC (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)

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



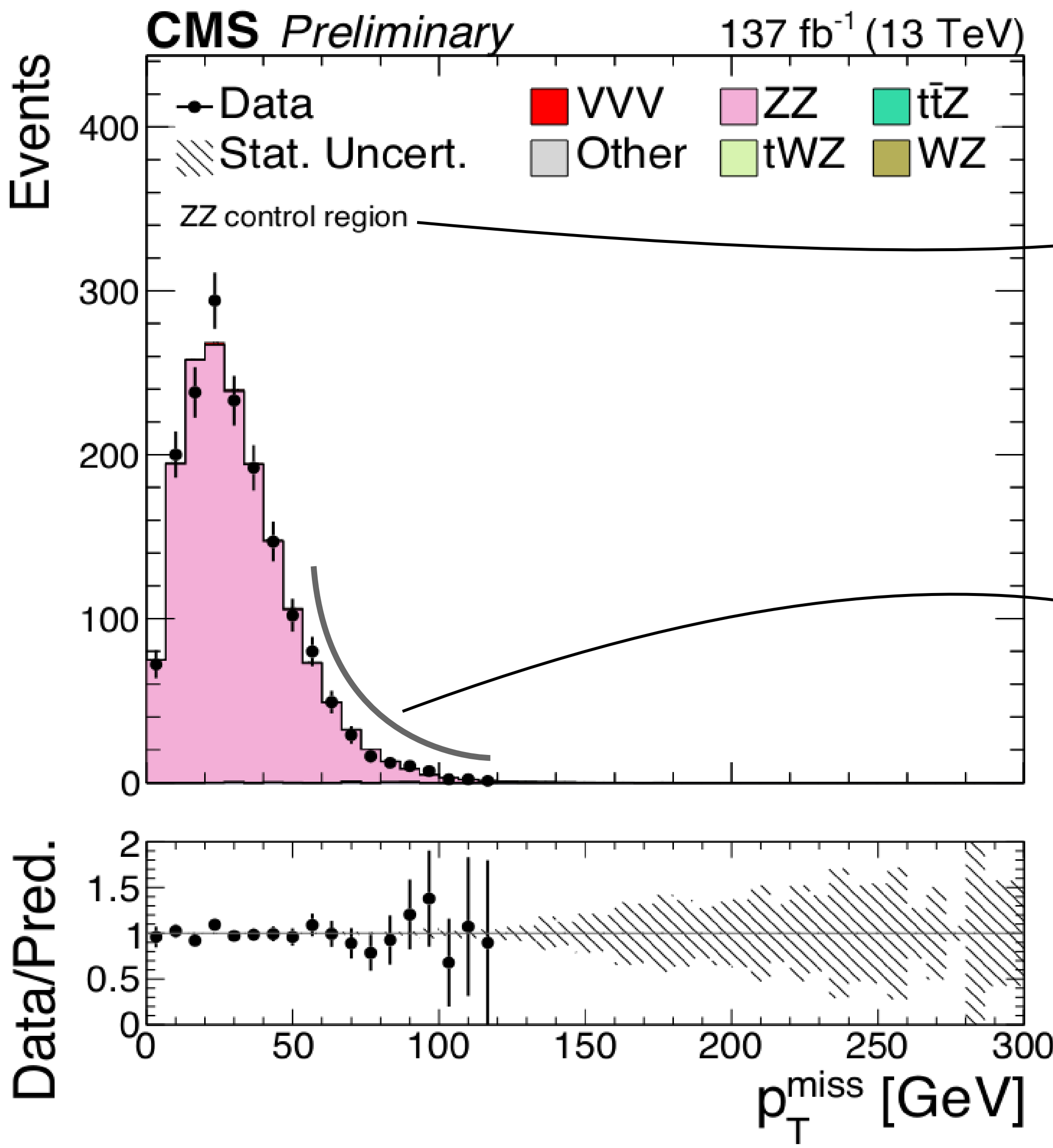
(Of course!) other EFT operators may also impact VVV signatures (e.g. anomalous TGCs)
[Global Fit]

Complementarity among various probes

$[h\,\gamma]$, $[VVV]$, $[h{+}j]\,(ggf)$, $[h\,h]$, $[h \to J/\psi{+}\gamma]$ ...

Thank you!

ZZ reducible background MET fit for $pp \to ZZZ \to 4\ell + 2\nu$



Control region (2 on-shell Z bosons) in "4 lepton" category of tri-boson search targeting WWZ

Exponential fit to the distribution tail

Auxiliary material of:

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