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The Branco Weiss Fellowship
Society in Science

Light quark yukawas in triboson final states

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Based on 2011.09551 A. Falkowski, S. Ganguly, P. Gras, J. No, K. Tobioka, N. Vignaroli, **TY**

Introduction

- No understanding of **arbitrary Higgs couplings** in the SM
- **Light yukawas** still unconstrained by orders of magnitude
- The Higgs sector of the Standard Model cries out for a **deeper explanation**
- It is therefore crucial to measure the Higgs **and related processes** as completely as possible
- Such processes **need not involve an on-shell Higgs** in the final state: *measuring Higgs couplings without the Higgs* 1812.09299 Henning et al
- Leads us to consider **triboson measurements** as probes of light quark yukawas

Higgs without Higgs

- Higgs couplings measured **on-shell** are related to **off-shell** processes

1812.09299 Henning et al

- e.g. the **Higgs-gluon-gluon** coupling

$$\mathcal{O}_{GG} = g_s^2 |H|^2 G^a_{\mu\nu} G^{a\,\mu\nu}$$

$$|H|^2 = \frac{1}{2}\left(v^2 + 2hv + h^2 + 2\phi^+\phi^- + (\phi^0)^2\right)$$

$$\sim \frac{E^2}{\Lambda^2}$$

- Benefits from **energy growth** in amplitude

Higgs without Higgs

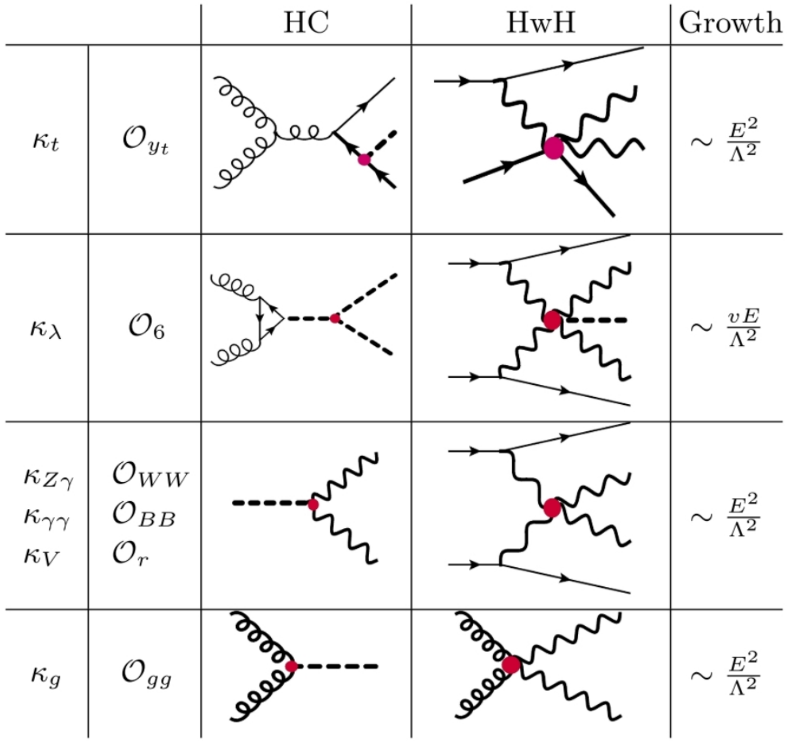
- Higgs couplings measured **on-shell** are related to **off-shell** processes

$$\mathcal{O}_{y_\psi} = Y_\psi |H|^2 \psi_L H \psi_R$$

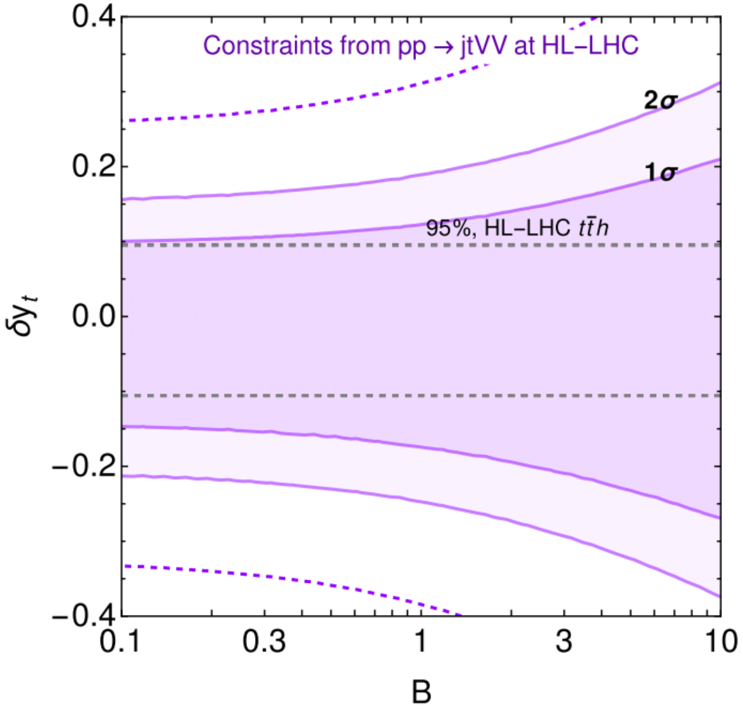
$$\mathcal{O}_6 = |H|^6$$

$$\mathcal{O}_{WW} = g^2 |H|^2 W^a_{\mu\nu} W^{a\,\mu\nu}$$

$$\mathcal{O}_{GG} = g_s^2 |H|^2 G^a_{\mu\nu} G^{a\,\mu\nu}$$



1812.09299 Henning et al

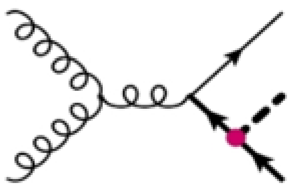
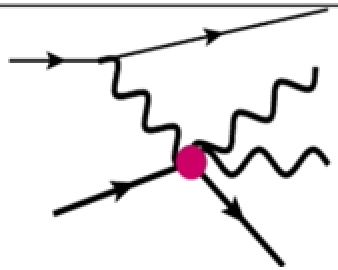


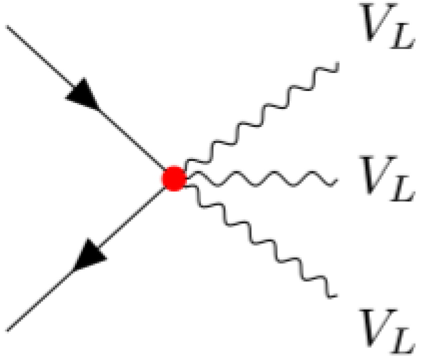
- e.g. **competitive constraints** on top Yukawa pp → jtVV

Triboson

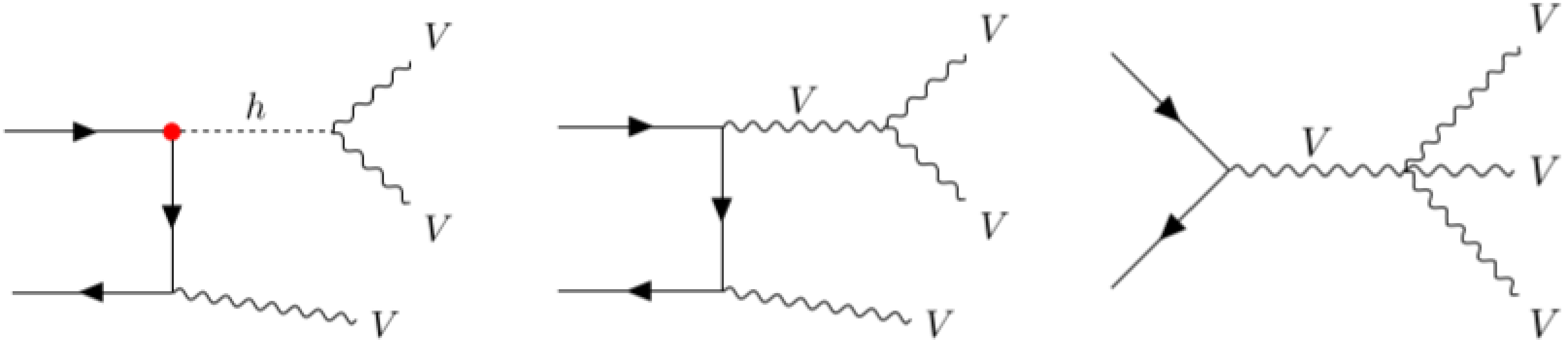
- **Triboson** final state for Yukawa couplings

$$\mathcal{O}_{y_\psi} = Y_\psi |H|^2 \psi_L H \psi_R$$

		HC	HwH	Growth
κ_t	$\mathcal{O}_{y_t}$			$\sim \frac{E^2}{\Lambda^2}$



- In **unitary gauge**:



- Modifying Yukawa couplings **breaks cancellations**

Theoretical framework: SMEFT

- Consider **up**, **down**, and **strange** Yukawas

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

- Relation to **modified Higgs coupling strength**:

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

- Estimate **parton-level** cross-sections using equivalence principle:

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

$$\begin{aligned}
\sigma(q\bar{q}\to G_zG_+G_-) &= (y_q^{\rm SM}\delta y_q)^2 I(\hat{s}), \qquad I(\hat{s}) \equiv \frac{\hat{s}}{6144\pi^3 v^4}. \\
\sigma(q\bar{q}\to 3G_z) &= \frac{3}{2}(y_q^{\rm SM}\delta y_q)^2 I(\hat{s}), \\
\sigma(u\bar{q}'\to G_+G_zG_z) + \sigma(q'\bar{u}\to G_-G_zG_z) &= \frac{1}{2}\left[(y_u^{\rm SM}\delta y_u)^2 + (y_{q'}^{\rm SM}\delta y_{q'})^2\right] I(\hat{s}), \\
\sigma(u\bar{q}'\to G_+G_+G_-) + \sigma(q'\bar{u}\to G_-G_-G_+) &= 2\left[(y_u^{\rm SM}\delta y_u)^2 + (y_{q'}^{\rm SM}\delta y_{q'})^2\right] I(\hat{s}), \qquad (2.6)
\end{aligned}$$

- Focus on **WWW** and **ZZZ**

Theoretical framework: SMEFT

- Consider **up**, **down**, and **strange** Yukawas

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

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

Table 2. Values of different triboson production cross sections for $\sqrt{s} = 14$ TeV LHC (upper table) and $\sqrt{s} = 100$ TeV FCC-hh (lower table) for the SM (computed at NLO in QCD [39, 40]) and with the addition of the dimension-6 operators from Eq. (2.1), with $Y_d = 1$ (with $Y_{\neq d} = 0$), $Y_u = 1$ (with $Y_{\neq u} = 0$) and $Y_s = 1$ (with $Y_{\neq s} = 0$), respectively. These latter cross sections are computed at LO.

- Focus on **WWW (largest xsec**) and **ZZZ (largest ratio to SM**)

WWW: same-sign di-lepton final state

- **Process**: $pp \to W^\pm W^\pm W^\mp \to \ell^\pm \ell^\pm \nu\nu jj$ **cross-section**: $\sigma(Y_d) = 7.5\,\text{fb} + Y_d^2 \times 210\,\text{fb}$
- Place limit from **CMS** *13 TeV 137 /fb* **analysis** 2006.11191 CMS
- Most **sensitive final states**: $\mu^\pm\mu^\pm$, $e^\pm\mu^\pm$ in "mjj-in" 2lss category
- **Cuts**:

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

Efficiency:

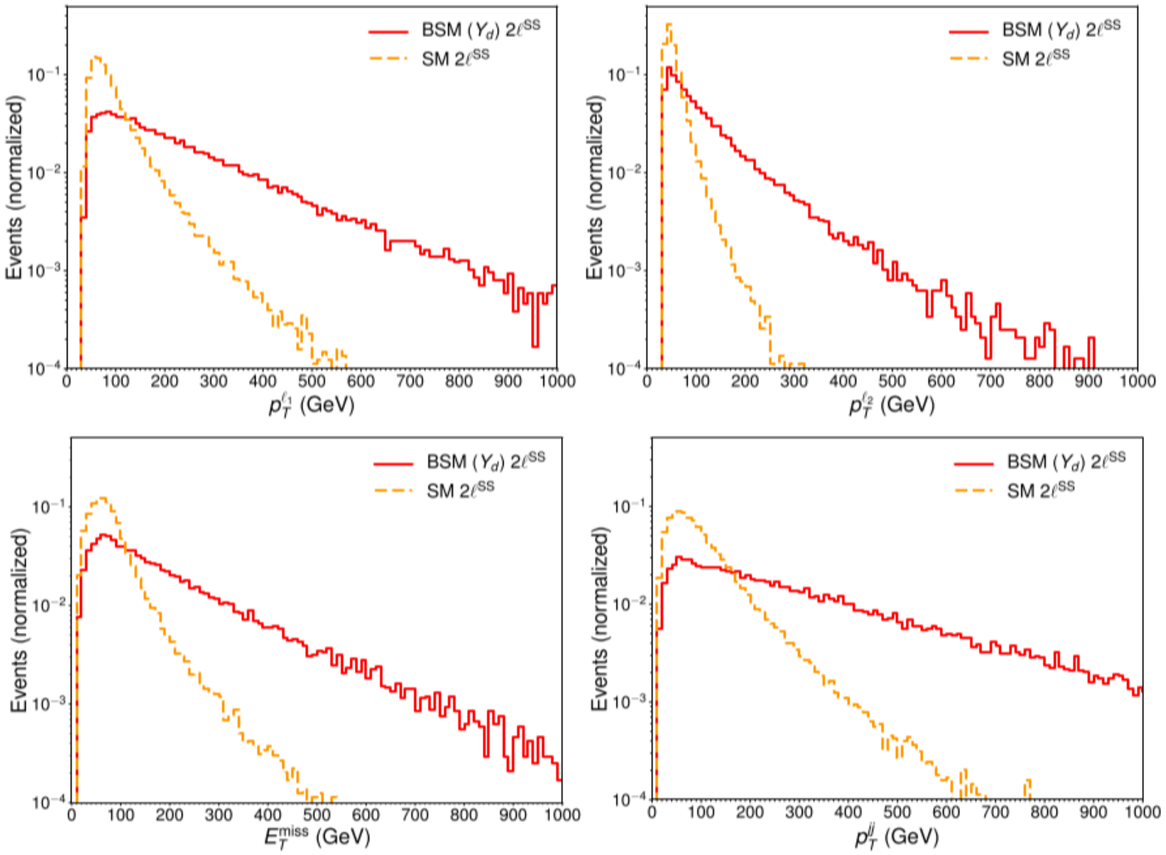
$$\epsilon_S = 0.45 \quad , \quad \epsilon_B = 0.27$$

- SM backgrounds taken from CMS analysis

- **2σ** bound: $\delta y_d \lesssim 6800$ (LHC CMS analysis [27])

WWW: same-sign di-lepton final state

- **Process**: $pp \to W^{\pm}W^{\pm}W^{\mp} \to \ell^{\pm}\ell^{\pm}\nu\nu jj$ **cross-section**: $\sigma(Y_d) = 7.5\,\text{fb} + Y_d^2 \times 210\,\text{fb}$
- Improve **HL-LHC** sensitivity by **more stringent** cuts



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

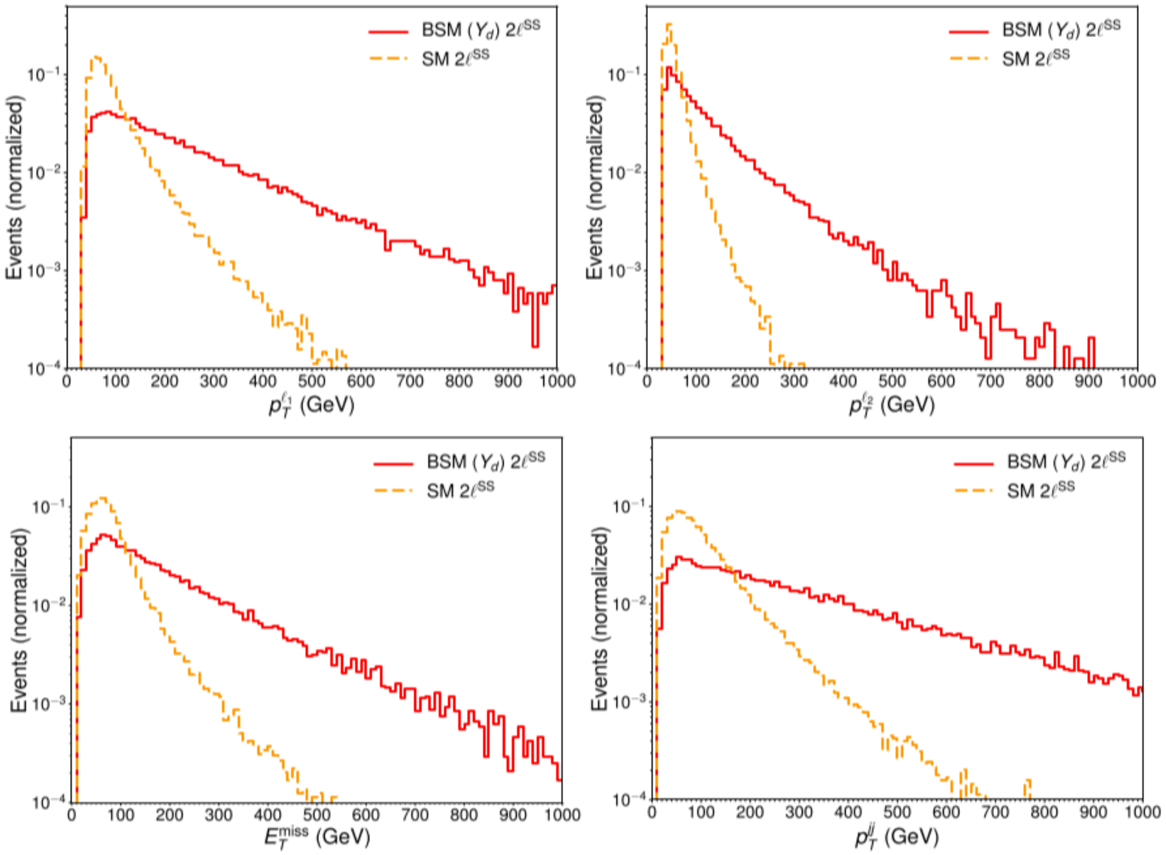
$$\epsilon_S = 0.61 \text{ (HL-LHC)}$$
$$\epsilon_B = 0.015 \text{ (HL-LHC)}$$

(Assuming **negligible reducible background**)

$$\delta y_d \lesssim 550 \text{ (HL-LHC)}$$
$$\delta y_u \lesssim 1100 \text{ (HL-LHC)}$$
$$\delta y_s \lesssim 150 \text{ (HL-LHC)}$$

WWW: same-sign di-lepton final state

- **Process**: $pp \to W^\pm W^\pm W^\mp \to \ell^\pm \ell^\pm \nu\nu jj$ **cross-section**: $\sigma(Y_d) = 7.5\,\text{fb} + Y_d^2 \times 210\,\text{fb}$
- Improve **HL-LHC** sensitivity by **more stringent** cuts



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

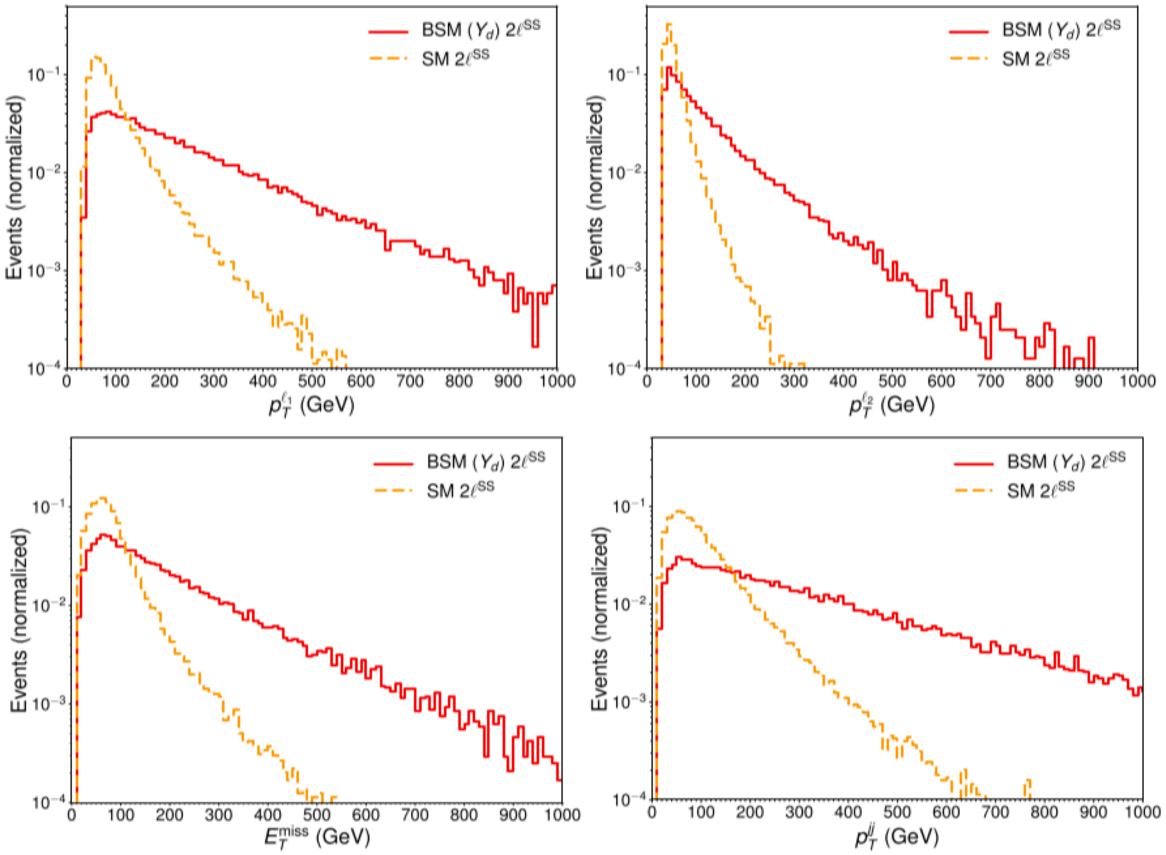
$$\epsilon_S = 0.61 \text{ (HL-LHC)}$$
$$\epsilon_B = 0.015 \text{ (HL-LHC)}$$

(With **top reducible background** estimate)

$$\delta y_d \lesssim 570 \text{ (HL-LHC)}$$
$$\delta y_u \lesssim 1200 \text{ (HL-LHC)}$$
$$\delta y_s \lesssim 160 \text{ (HL-LHC)}$$

WWW: same-sign di-lepton final state

- **Process**: $pp \to W^{\pm}W^{\pm}W^{\mp} \to \ell^{\pm}\ell^{\pm}\nu\nu jj$ **cross-section**: $\sigma(Y_d) = 7.5\,\mathrm{fb} + Y_d^2 \times 210\,\mathrm{fb}$
- Improve **HL-LHC** sensitivity by **more stringent** cuts



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

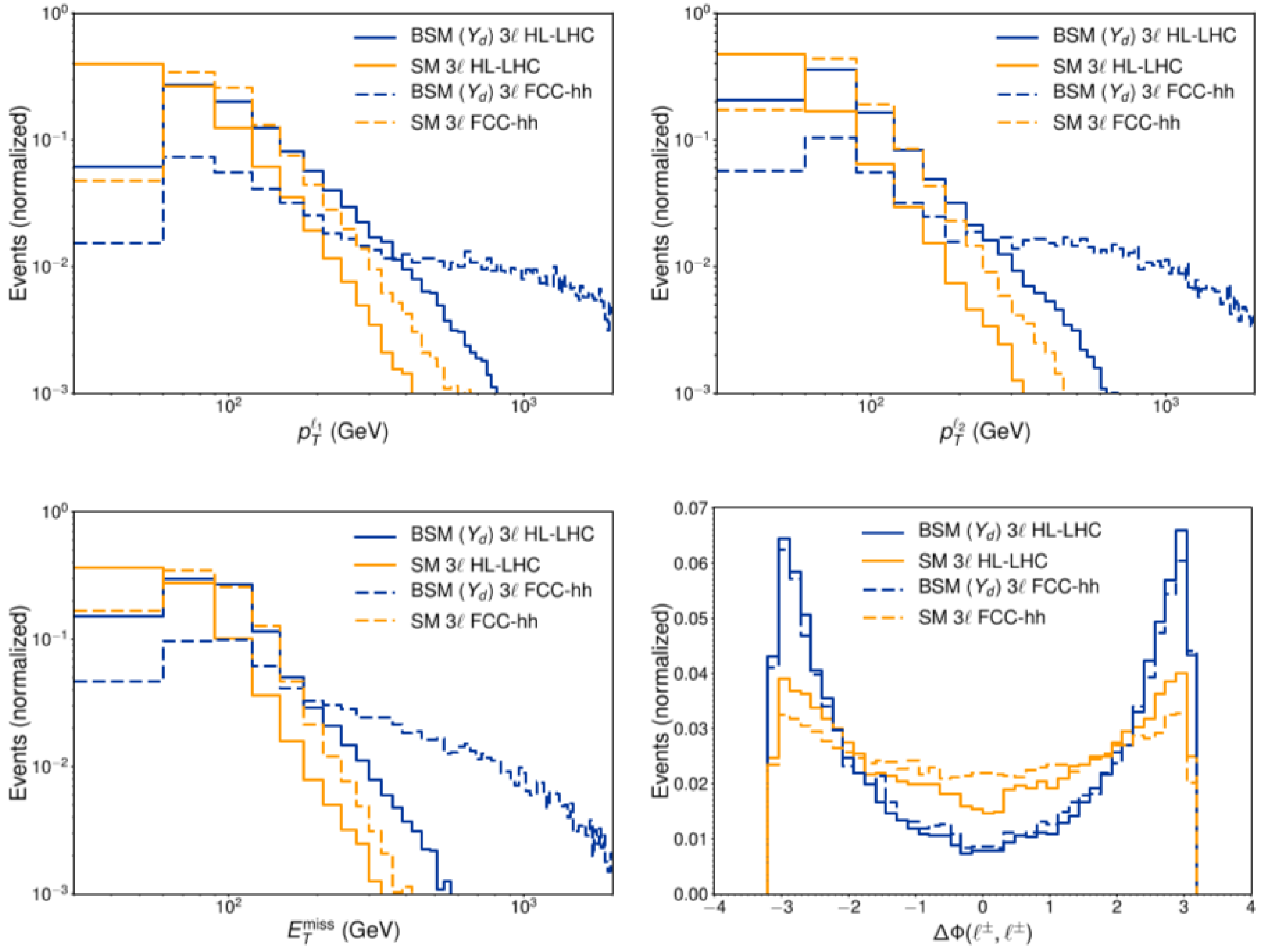
$$\epsilon_S = 0.61\ (\mathrm{HL\text{-}LHC})$$
$$\epsilon_B = 0.015\ (\mathrm{HL\text{-}LHC})$$

(With **pTll differential distribution** shape)

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

WWW: tri-lepton final state

- **Process** $pp \to W^{\pm}W^{\pm}W^{\mp} \to \ell^{\pm}\ell^{\pm}\ell^{\mp}\nu\nu\nu$



HL-LHC:

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

FCC-hh:

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

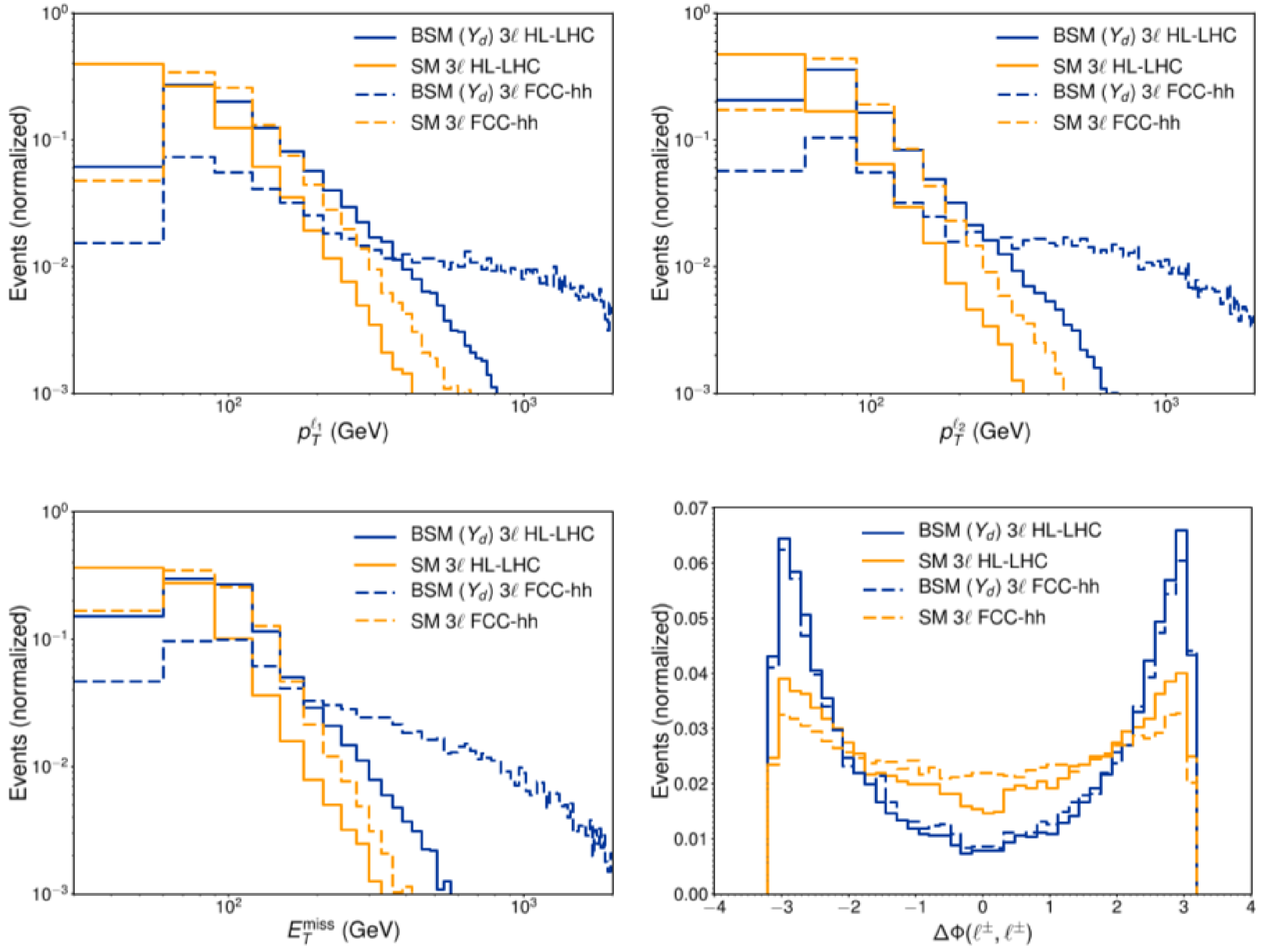
$$\epsilon_S = 0.62\ (\text{HL-LHC}) \quad , \quad \epsilon_S = 0.50\ (\text{FCC-hh})\,,$$
$$\epsilon_B = 0.037\ (\text{HL-LHC}) \quad , \quad \epsilon_B = 0.014\ (\text{FCC-hh})\,.$$

(Reducible background **negligible**)

$$\delta y_d \lesssim 900\ (\text{HL-LHC}) \quad , \quad \lesssim 120\ (\text{FCC-hh})\,,$$
$$\delta y_u \lesssim 1900\ (\text{HL-LHC}) \quad , \quad \lesssim 240\ (\text{FCC-hh})\,,$$
$$\delta y_s \lesssim 230\ (\text{HL-LHC}) \quad , \quad \lesssim 40\ (\text{FCC-hh})\,.$$

WWW: tri-lepton final state

- **Process** $pp \to W^{\pm}W^{\pm}W^{\mp} \to \ell^{\pm}\ell^{\pm}\ell^{\mp}\nu\nu\nu$



HL-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:

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

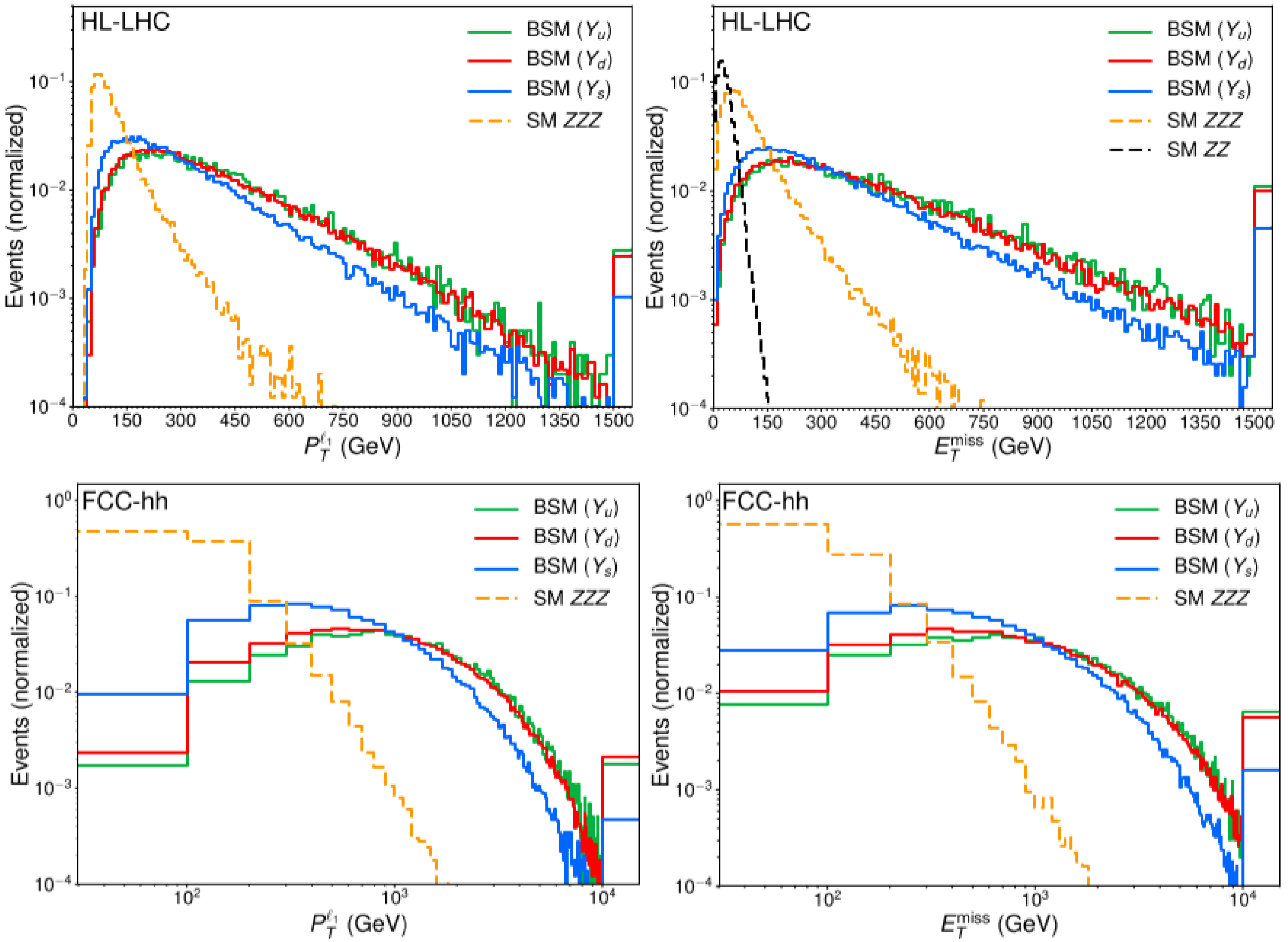
$$\epsilon_S = 0.62\ (\text{HL-LHC}) \quad , \quad \epsilon_S = 0.50\ (\text{FCC-hh})\,,$$
$$\epsilon_B = 0.037\ (\text{HL-LHC}) \quad , \quad \epsilon_B = 0.014\ (\text{FCC-hh})\,.$$

(Using **pTll differential distribution** shape)

$$\delta y_d \lesssim 840\ (\text{HL-LHC}) \quad , \quad \lesssim 54\ (\text{FCC-hh})\,,$$
$$\delta y_u \lesssim 1700\ (\text{HL-LHC}) \quad , \quad \lesssim 110\ (\text{FCC-hh})\,,$$
$$\delta y_s \lesssim 230\ (\text{HL-LHC}) \quad , \quad \lesssim 33\ (\text{FCC-hh})\,.$$

ZZZ: four-lepton final state

- **Process** $pp \to ZZZ \to 4\ell + 2\nu$ **cross-section:** $\sigma(Y_d) = 0.013\,\text{fb} + Y_d^2 \times 1.8\,\text{fb}\,,$



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

HL-LHC:

$$E_T^{\text{miss}} > 200\ \text{GeV}.$$

FCC-hh:

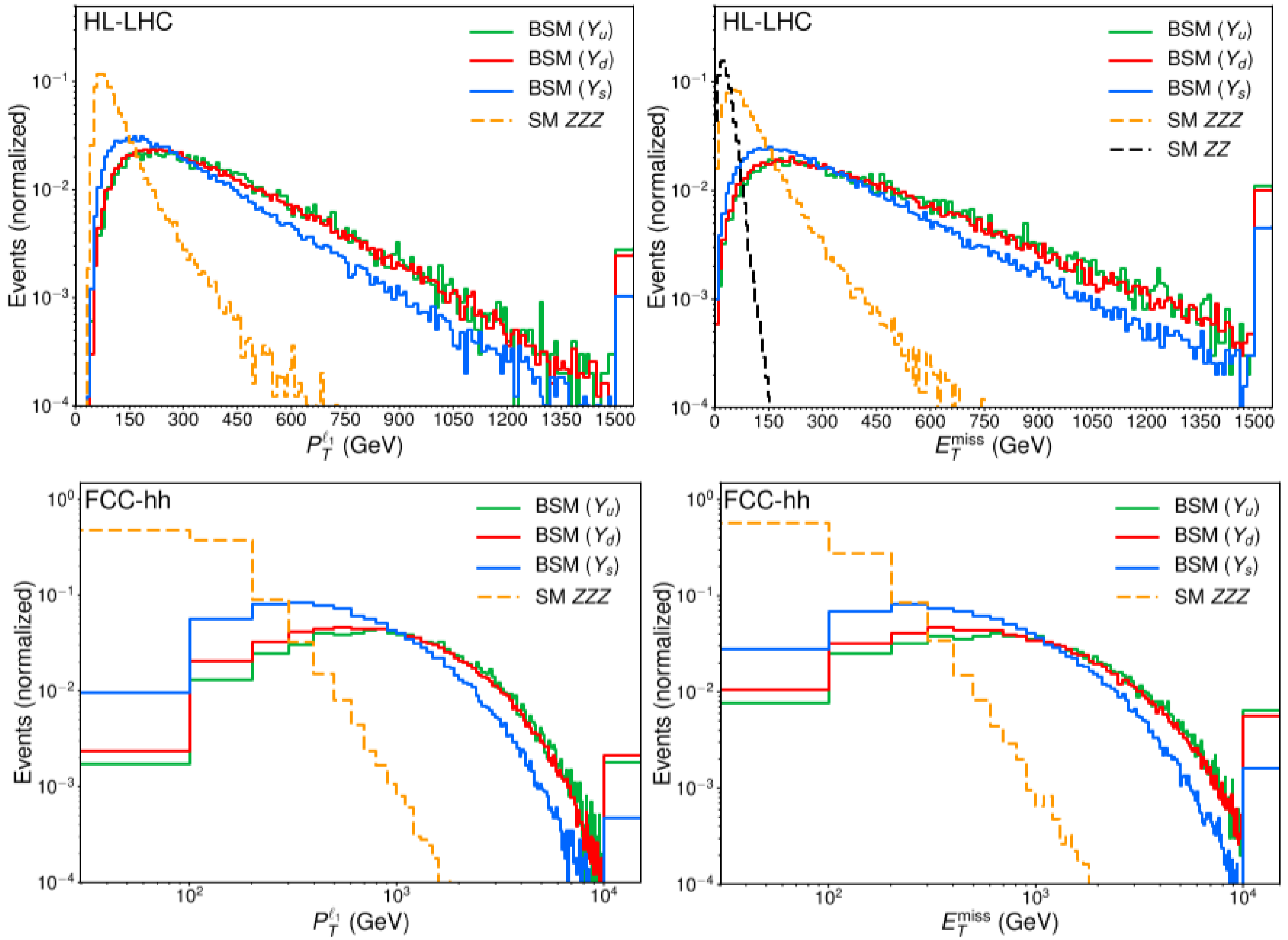
$$\Delta R_{\ell\ell} > 0.01 \qquad E_T^{\text{miss}} > 500\ \text{GeV}$$

(Reducible background **negligible**)

$$\delta y_d \lesssim 1700 \quad (\text{HL-LHC}) \quad , \quad \lesssim 120 \quad (\text{FCC-hh})\,,$$
$$\delta y_u \lesssim 2600 \quad (\text{HL-LHC}) \quad , \quad \lesssim 190 \quad (\text{FCC-hh})\,,$$
$$\delta y_s \lesssim 340 \quad (\text{HL-LHC}) \quad , \quad \lesssim 19 \quad (\text{FCC-hh})\,.$$

ZZZ: four-lepton final state

- **Process** $pp \to ZZZ \to 4\ell + 2\nu$ **cross-section:** $\sigma(Y_d) = 0.013\,\text{fb} + Y_d^2 \times 1.8\,\text{fb}\,,$



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

HL-LHC:

$$E_T^{\text{miss}} > 200 \text{ GeV}$$

FCC-hh:

$$\Delta R_{\ell\ell} > 0.01 \qquad E_T^{\text{miss}} > 500 \text{ GeV}$$

(Using **ETmiss differential distribution** shape)

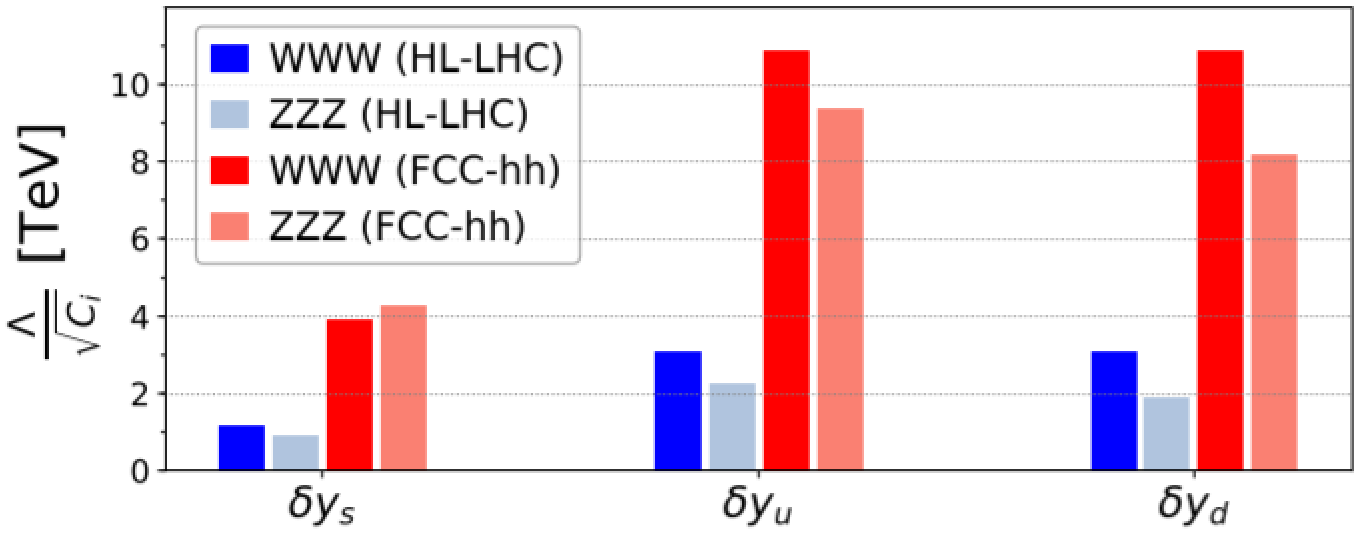
$$\delta y_d \lesssim 1500 \quad (\text{HL-LHC}) \quad , \quad \lesssim 65 \quad (\text{FCC-hh})\,,$$
$$\delta y_u \lesssim 2300 \quad (\text{HL-LHC}) \quad , \quad \lesssim 100 \quad (\text{FCC-hh})\,,$$
$$\delta y_s \lesssim 300 \quad (\text{HL-LHC}) \quad , \quad \lesssim 12 \quad (\text{FCC-hh})\,.$$

Summary

- **2σ sensitivity** estimates $\mathcal{L} \supset -\frac{h}{v} \sum_{q=u,d,s} m_q(1+\delta y_q)\bar{q}q$

	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)

- **Dimension-6 operator** scale $\mathcal{L}_{\text{SMEFT}} \supset \frac{Y_u|H|^2}{v^2}\bar{u}_R Q_{1,L} H + \frac{Y_d|H|^2}{v^2}\bar{d}_R H^\dagger Q_{1,L} + \frac{Y_s|H|^2}{v^2}\bar{s}_R H^\dagger Q_{2,L} + \text{h.c.}$



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

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

Conclusion

- **Multi-boson interactions** are *essential* for probing fundamental processes
- **Complementary** to on-shell Higgs measurements
- Contribute to closing **flat directions** in global fits
- **Maximise sensitivity**: dedicated analyses and channel combinations
- **Future colliders** open up further measurements