BSM Theory in The Tails: Dibosons, VBF, & VBS

Fady Bishara

VBSCan: BSM models in VBS
Lisbon, 4.12.19

Why is vector boson scattering – and di-(weak) boson processes in general – interesting?

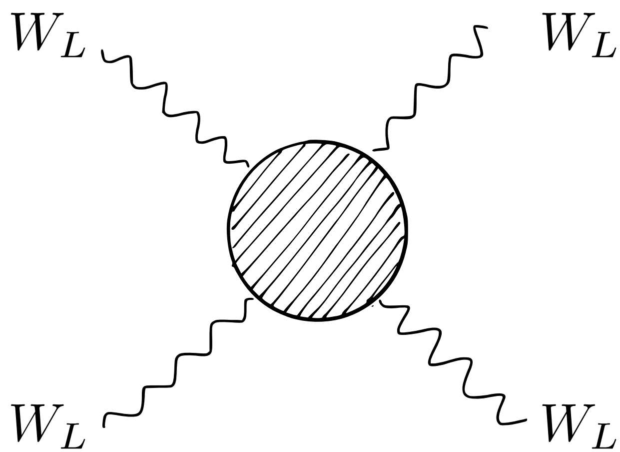
In the **SM**, the enregy dependence of these processes is well behaved. The **Higgs** unitarizes the scattering.

Without additional physics, any deviations in Higgs couplings, TGC, QGC, ... will lead to violation of unitarity at some scale.

Perturbative unitarity

$$g_{hVV} \equiv c_V \, g_{hVV}^{\text{SM}}, \qquad g_{hhVV} \equiv c_{2V} \, g_{hhVV}^{\text{SM}}$$

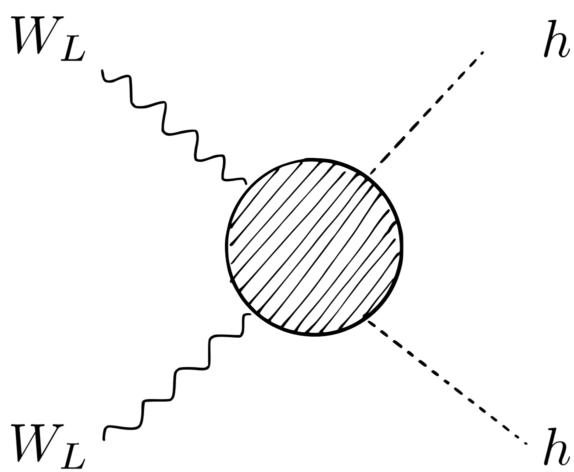
VBS



$$\propto \frac{\hat{s}}{v^2}\left(1 - c_V^2\right)$$

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

di-Higgs



$$\propto \frac{\hat{s}}{v^2}\left(c_{2V} - c_V^2\right)$$

Deviations = new physics at some scale

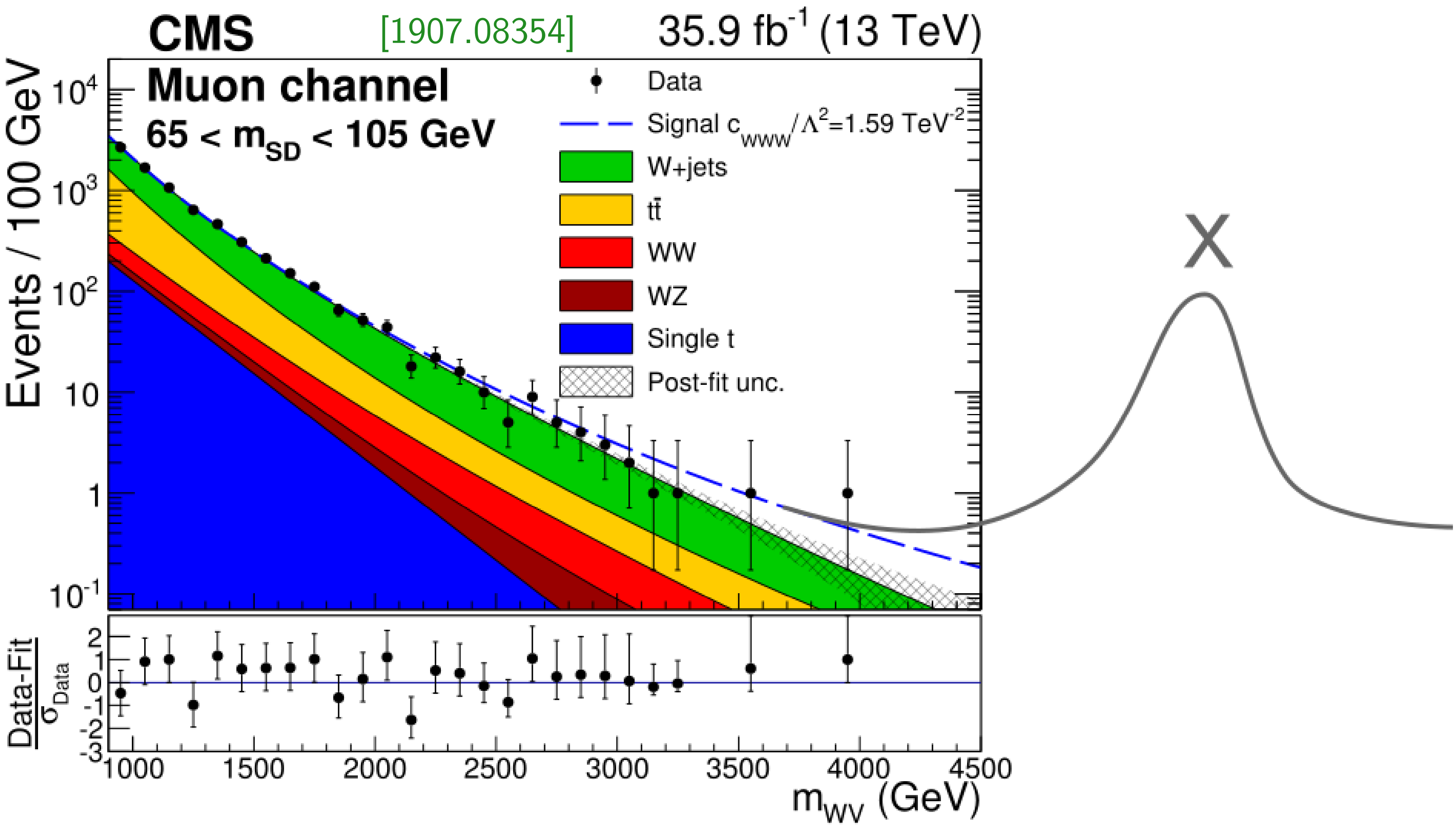
Motivation

- Habemus Higgs; are we done? Not even close! The SM does not say anything about, e.g., dark matter, the origin of neutrino masses, baryon asymmetry, ...

- However, the LHC hasn't discovered any new states so far. What if NP is too heavy? Even for FCC? Can still learn something from EFTs.

- Some NP amplitudes grow with energy, good handle at high invariant mass.

To illustrate the point...



Effects in the tail (⇒ EFT), well below the resonance

⚠ EFT validity ↔ $E, p_T \ll M_X$

Getting a bound on the Wilson coefs

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_i \frac{\mathcal{C}_i^{(6)}}{\Lambda^2} Q_i^{(6)} + \sum_i \frac{\mathcal{C}_i^{(8)}}{\Lambda^4} Q_i^{(8)} + \cdots$$

$$\sigma_{\rm BSM} = \sigma_{\rm SM} + \delta\sigma$$

$$\chi^2 \sim \left(\frac{\delta\sigma}{\sigma_{\rm SM}}\right)^2 \cdot \frac{1}{\Delta^2}$$

$$C \lesssim \Delta \left(\frac{\Lambda}{\sqrt{\hat{s}}}\right)^{2\alpha}$$

$$\Delta^2 = \left(\frac{1}{\sqrt{N}}\right)^2 + \sum_i \epsilon_i^2$$

STAT + SYST

For same bound on $\mathcal{C}$ at LHC vs. LEP

$$\Delta_{\rm LHC} \sim \Delta_{\rm LEP} \left(\frac{\sqrt{\hat{s}}}{m_W}\right)^{2\alpha} \sim \mathcal{O}(10\%)$$

The form of the BSM cross-section

These terms are well behaved by definition $\because \Lambda \gg M_W$

$$f = a_1\,\mathcal{C}\,\frac{M_W^2}{\Lambda^2} + a_2\,\mathcal{C}^2\,\frac{M_W^4}{\Lambda^4} + \text{dim. } 8 + \cdots +$$

$$b_1\,\mathcal{C}\,\frac{E^2}{\Lambda^2} + b_2\,\mathcal{C}^2\,\frac{E^4}{\Lambda^4} + \ldots$$

Linear terms arise from Interference with the SM amplitudes

⚠ Must ensure EFT validity with these terms, i.e., enforce $E < \Lambda$

Interference and growth

① Interference but no growth with energy

$$\delta\sigma = \Delta\,\sigma_{\rm SM} \Rightarrow \mathcal{C}\frac{M_W^2}{\Lambda^2} = 0.1 \times \mathcal{O}(1) \Rightarrow \mathcal{C} = 0.1 \times \frac{\Lambda^2}{M_W^2}$$

C.I. on $|\mathcal{C}| = 250$ ✗

② Interference but with growth with enregy

$$\mathcal{C} = 0.1 \times \frac{\Lambda^2}{E^2}$$

C.I. on $|\mathcal{C}| = 0.3$ ✓

Where we have chosen $\Lambda = 5$ TeV and $E = 3$ TeV; $\mathcal{C} \sim g_*^2$

aTGC in dibosons

- NP amplitudes grow $\propto \hat{s}$ ✔
- NP amplitdues interfere with SM ✔

Diboson production and aTGCs

$$\mathcal{L}_{\rm TGC} = ie\left(W^+_{\mu\nu}W^-_{\mu} - W^-_{\mu\nu}W^+_{\mu}\right)A_\nu + ie\left[(1+\delta\kappa_\gamma)\,A_{\mu\nu}W^+_\mu W^-_\nu\right]$$

$$+\,igc_W\Big[(1+\delta g_{1,z})\left(W^+_{\mu\nu}W^-_{\mu} - W^-_{\mu\nu}W^+_{\mu}\right)Z_\nu$$

$$+\,(1+\delta\kappa_z)\,Z_{\mu\nu}W^+_\mu W^-_\nu\Big]$$

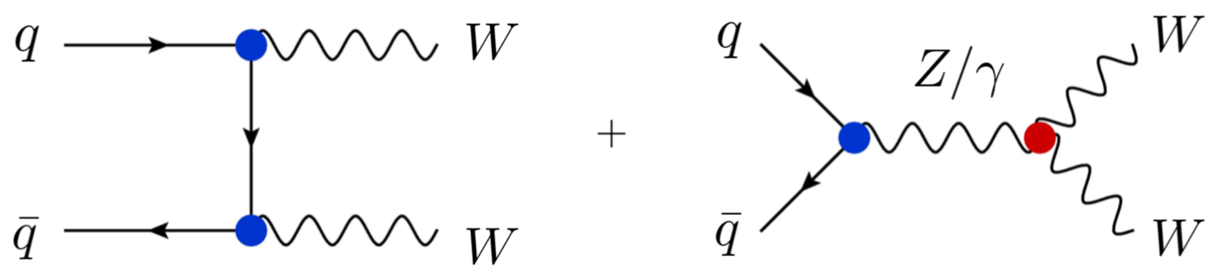
$$+\,i\frac{e}{m_W^2}\lambda_\gamma W^+_{\mu\nu}W^-_{\nu\rho}A_{\rho\mu} + i\frac{gc_W}{m_W^2}\lambda_z W^+_{\mu\nu}W^-_{\nu\rho}Z_{\rho\mu}$$

In most BSM models, these are generated at 1-loop

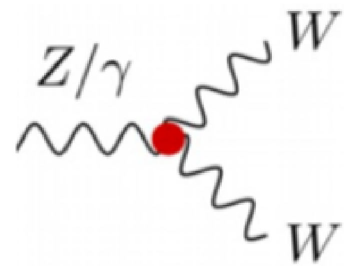
At dim. 6, $\lambda_z = \lambda_\gamma$

WW production

[Butter et al.: 1604.03105]
[Azatov et al.: 1707.08060]
[Grojean et al.: 1810.05149]
[+ more]



Improving LEP-2 bounds on
anomalous Triple Gauge Couplings



Bounds on aTGC

Butter et al 1604.03105

	LHC Run I				LEP			
	68 % CL	Correlations			68 % CL	Correlations		
Δg_1^Z	0.010 ± 0.008	1.00	0.19	−0.06	$0.051^{+0.031}_{-0.032}$	1.00	0.23	−0.30
$\Delta\kappa_\gamma$	0.017 ± 0.028	0.19	1.00	−0.01	$-0.067^{+0.061}_{-0.057}$	0.23	1.00	−0.27
λ	0.0029 ± 0.0057	−0.06	−0.01	1.00	$-0.067^{+0.036}_{-0.038}$	−0.30	0.27	1.00

Per mille at LHC !!

Percent at LEP

Slide from Marc Montull

Diboson channels: WW, WZ, Wh, Zh

Franceschini, Panico, Pomarol, Riva, Wulzer: [1810.05149]

Amplitude	High-energy primaries	Low-energy primaries
$\bar{u}_L d_L \to W_L Z_L, W_L h$	$\sqrt{2} a_q^{(3)}$	$\sqrt{2}\frac{g^2}{m_W^2}\left[c_{\theta_W}(\delta g^Z_{uL} - \delta g^Z_{dL})/g - c^2_{\theta_W}\delta g_1^Z\right]$
$\bar{u}_L u_L \to W_L W_L$ $\bar{d}_L d_L \to Z_L h$	$a_q^{(1)} + a_q^{(3)}$	$-\frac{2g^2}{m_W^2}\left[Y_L t^2_{\theta_W}\delta\kappa_\gamma + T_Z^{u_L}\delta g_1^Z + c_{\theta_W}\delta g^Z_{dL}/g\right]$
$\bar{d}_L d_L \to W_L W_L$ $\bar{u}_L u_L \to Z_L h$	$a_q^{(1)} - a_q^{(3)}$	$-\frac{2g^2}{m_W^2}\left[Y_L t^2_{\theta_W}\delta\kappa_\gamma + T_Z^{d_L}\delta g_1^Z + c_{\theta_W}\delta g^Z_{uL}/g\right]$
$\bar{f}_R f_R \to W_L W_L, Z_L h$	a_f	$-\frac{2g^2}{m_W^2}\left[Y_{f_R} t^2_{\theta_W}\delta\kappa_\gamma + T_Z^{f_R}\delta g_1^Z + c_{\theta_W}\delta g^Z_{fR}/g\right]$

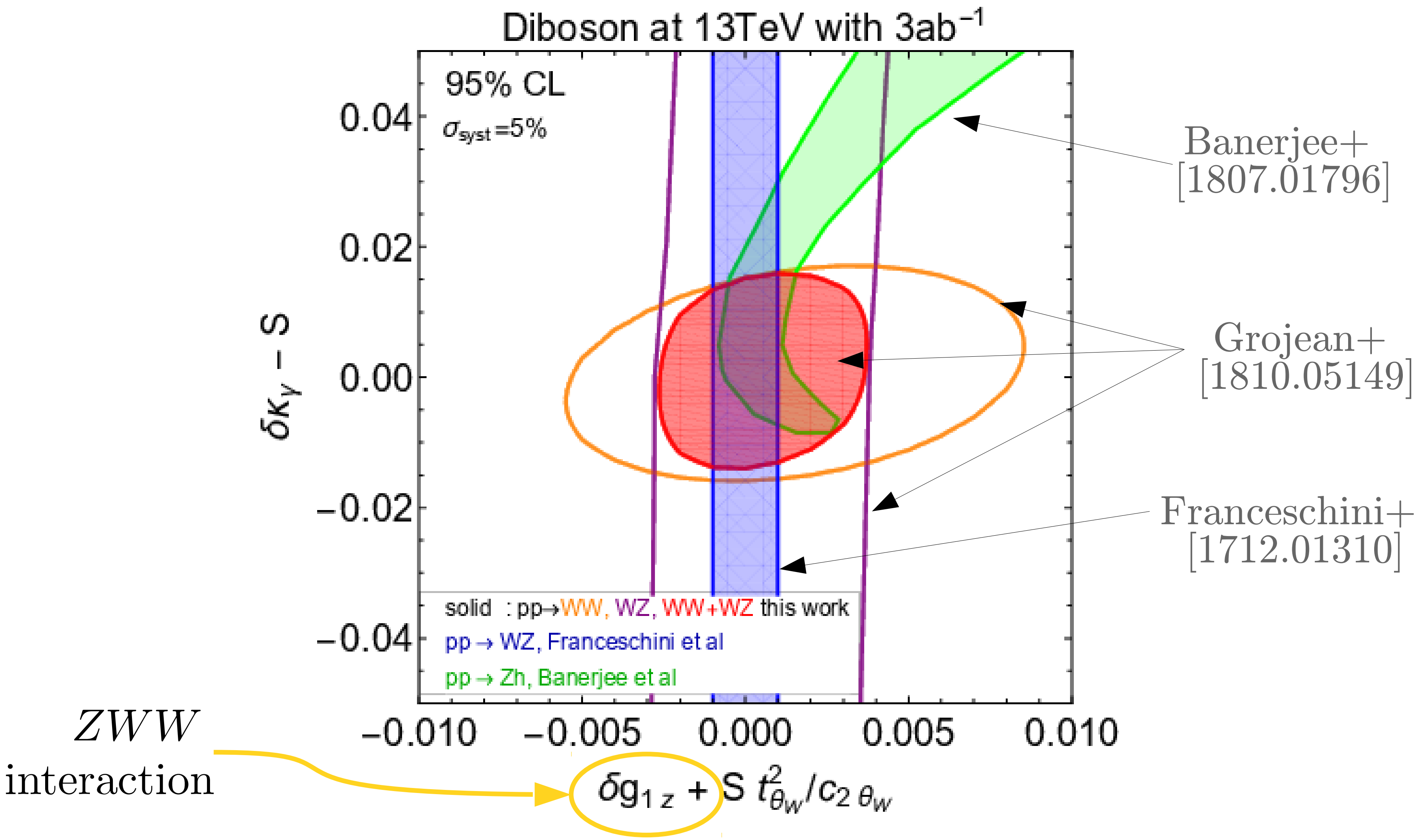
In the limit $E \gg M_W$ 💡, probe 4 directions in the SMEFT

$$a_q^{(3)}\,(\bar{q}_L\sigma^a\gamma^\mu q_L)\left(iH^\dagger\sigma^a \overleftrightarrow{D}_\mu H\right), \qquad a_u\,(\bar{u}_R\gamma^\mu u_R)\left(iH^\dagger \overleftrightarrow{D}_\mu H\right),$$
$$a_q^{(1)}\,(\bar{q}_L\gamma^\mu q_L)\left(iH^\dagger \overleftrightarrow{D}_\mu H\right), \qquad a_d\,(\bar{d}_R\gamma^\mu d_R)\left(iH^\dagger \overleftrightarrow{D}_\mu H\right).$$

💡 If $E \sim M_W$, the subleading contributions are of the same size and should be considered, but …

Diboson results

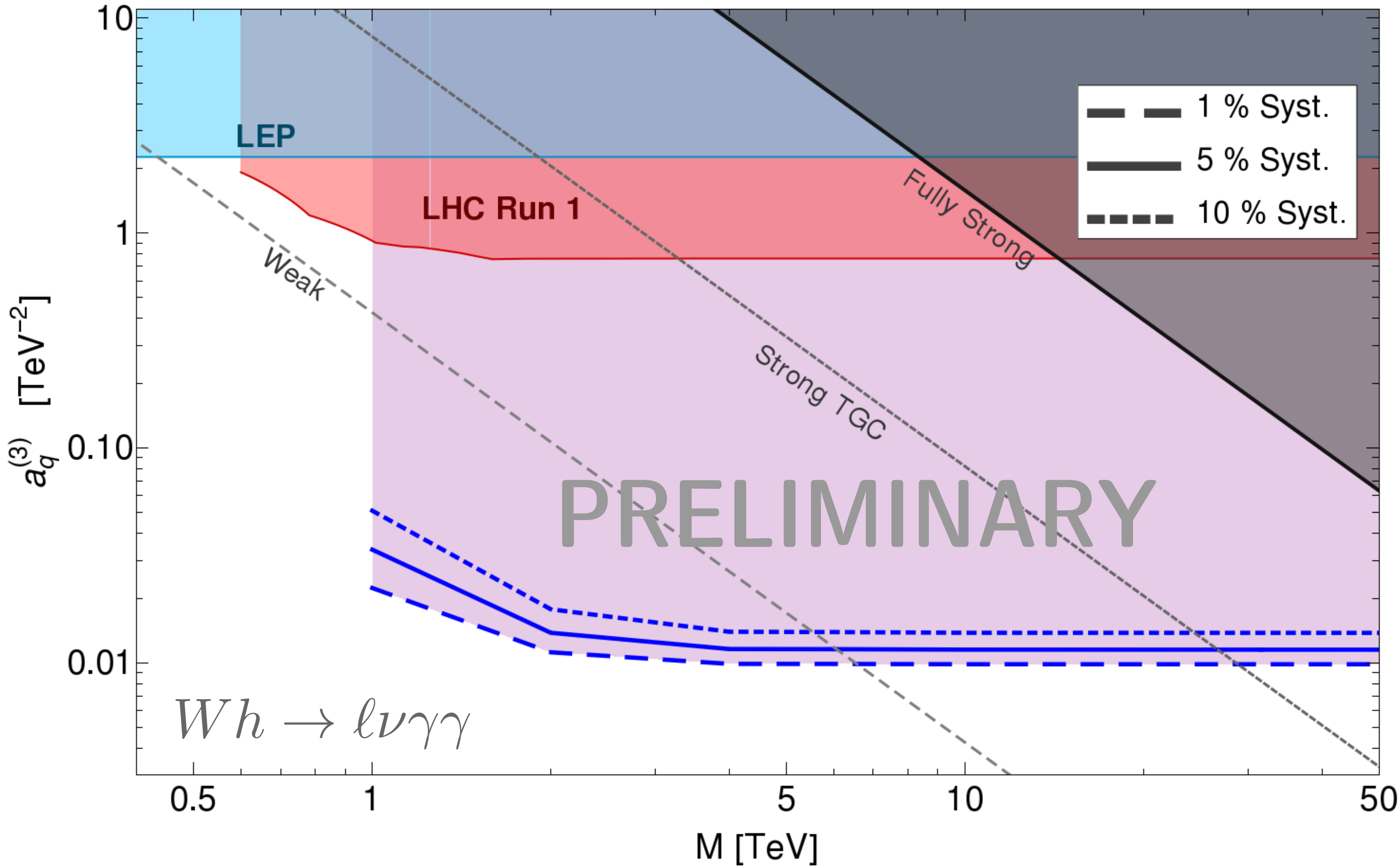
Grojean, Montull, Riembau: [1810.05149]



– Bound from LEP fills the plot area!
– Wh is ongoing and shows competitive sensitivty (preliminary)

Wh preliminary results

FB, Englert, Grojean, Montull, Panico, Rossia [WIP – to appear soon]



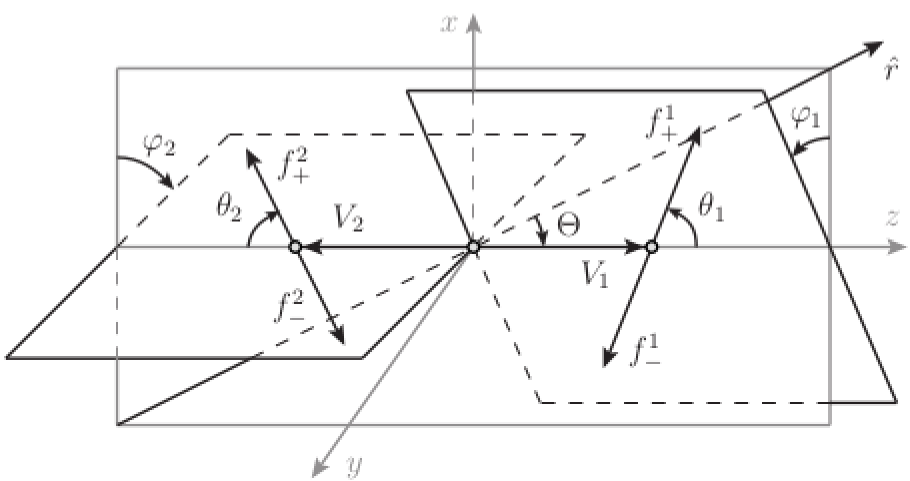
Transverse polarizations

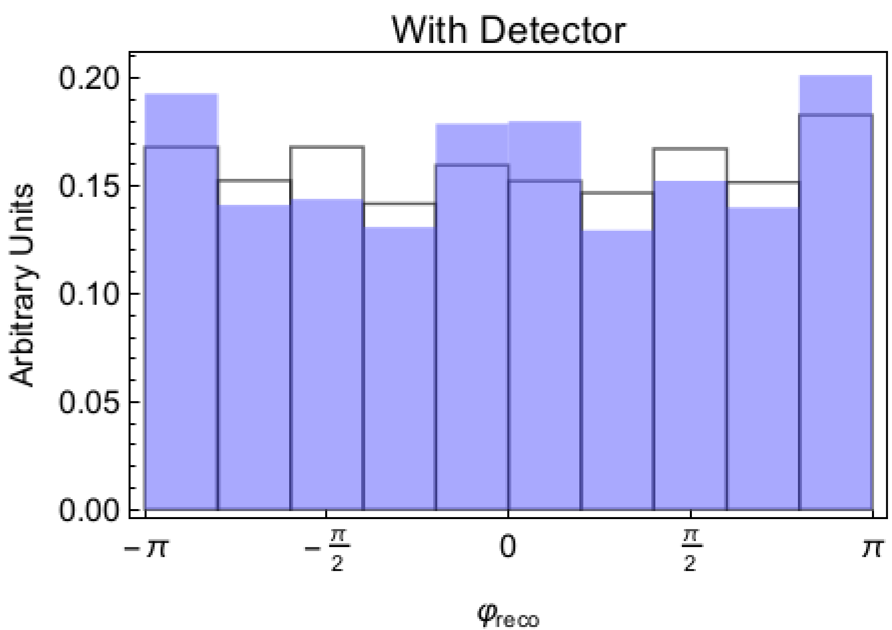
Panico, Riva, Wulzer [1708.07823]

$$\mathcal{O}_{3W} = \epsilon^{ijk} W_\mu^{i\nu} W_\nu^{j\rho} W_\rho^{k\mu}$$
$$\lambda_\gamma = 6 C_{3W} m_W^2 / g$$

- Involves transverse polarization
- But Interference between T and L via exclusive lepton azimuthal angle gives sensitivity

	SM	BSM
$q_{L,R}\bar{q}_{L,R} \to V_L V_L(h)$	~ 1	$\sim E^2/M^2$
$q_{L,R}\bar{q}_{L,R} \to V_\pm V_L(h)$	$\sim m_W/E$	$\sim m_W E/M^2$
$q_{L,R}\bar{q}_{L,R} \to V_\pm V_\pm$	$\sim m_W^2/E^2$	$\sim E^2/M^2$
$q_{L,R}\bar{q}_{L,R} \to V_\pm V_\mp$	~ 1	~ 1



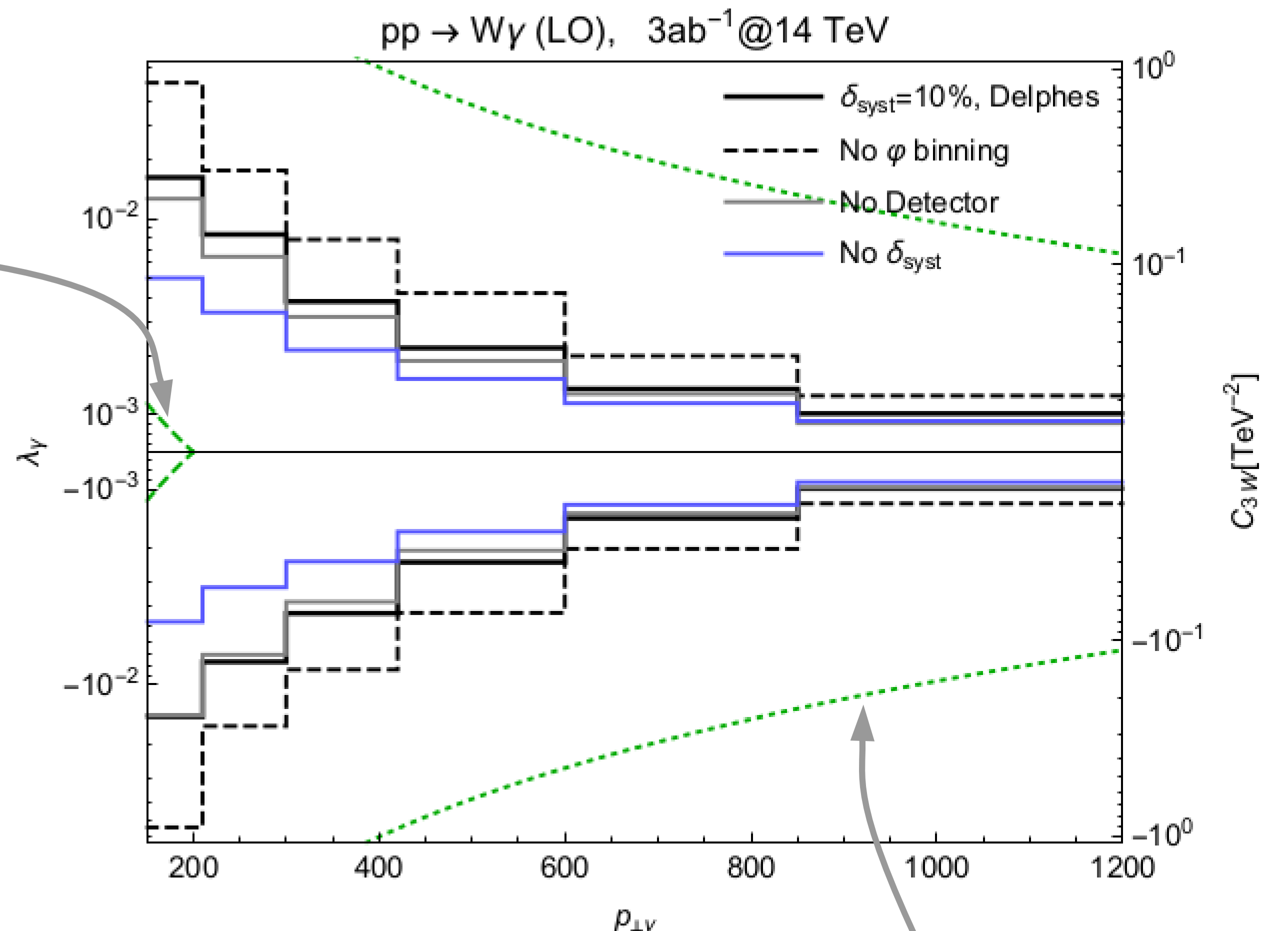


Transverse polarizations: results

Panico, Riva, Wulzer [1708.07823]

Tree generated

$$\lambda_\gamma \sim \frac{6g^3 m_W^2}{(16\pi^2 M^2)}$$



Bound at HL-LHC

$|\lambda_\gamma| < 1.0 \times 10^{-3}$ with int.

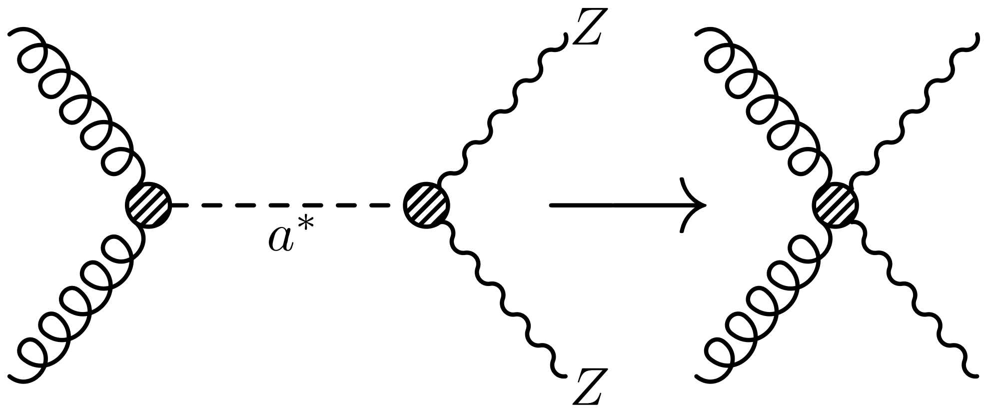
$|\lambda_\gamma| < 1.3 \times 10^{-3}$ w/o int.

Tree generated

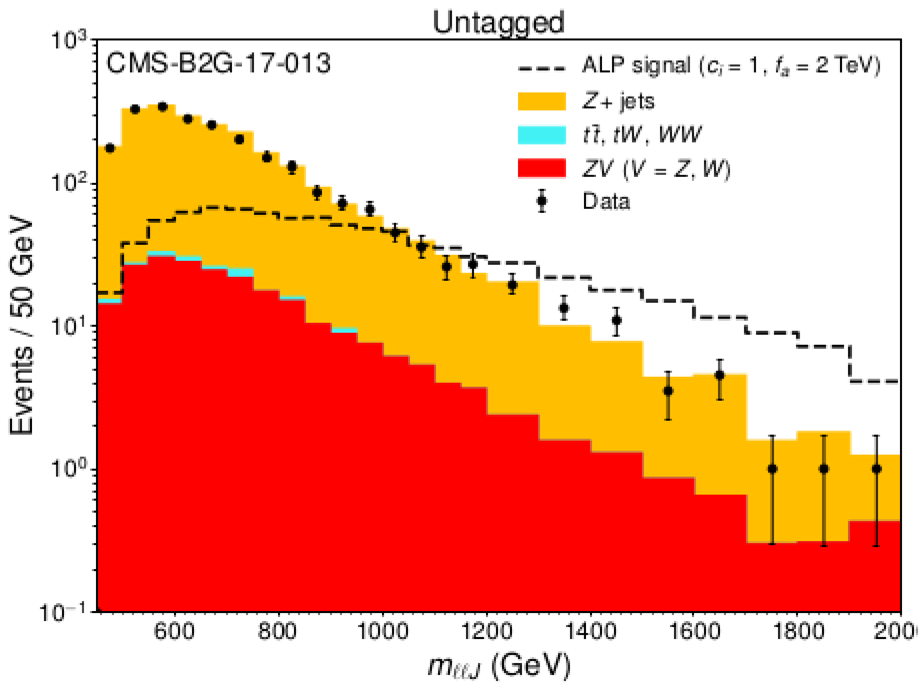
$$\lambda_\gamma \sim \frac{6gm_W^2}{\Lambda^2}$$

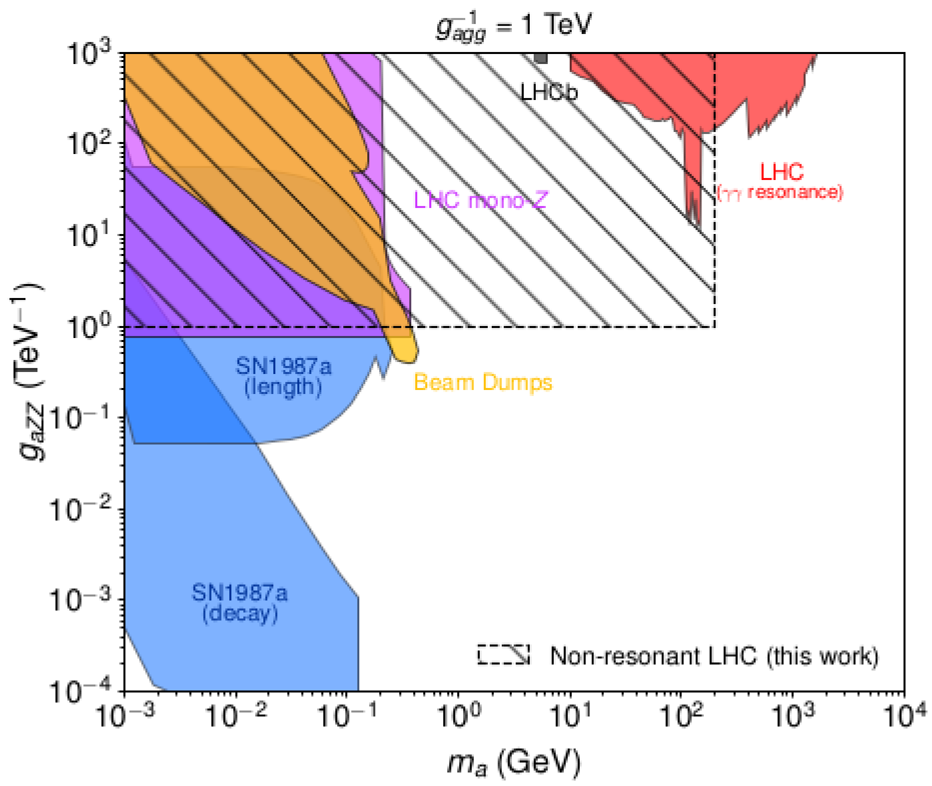
Non-resonant ALPs: anomalous ggZZ

Gavela, No, Sanz, Troconiz: [1905.12953]



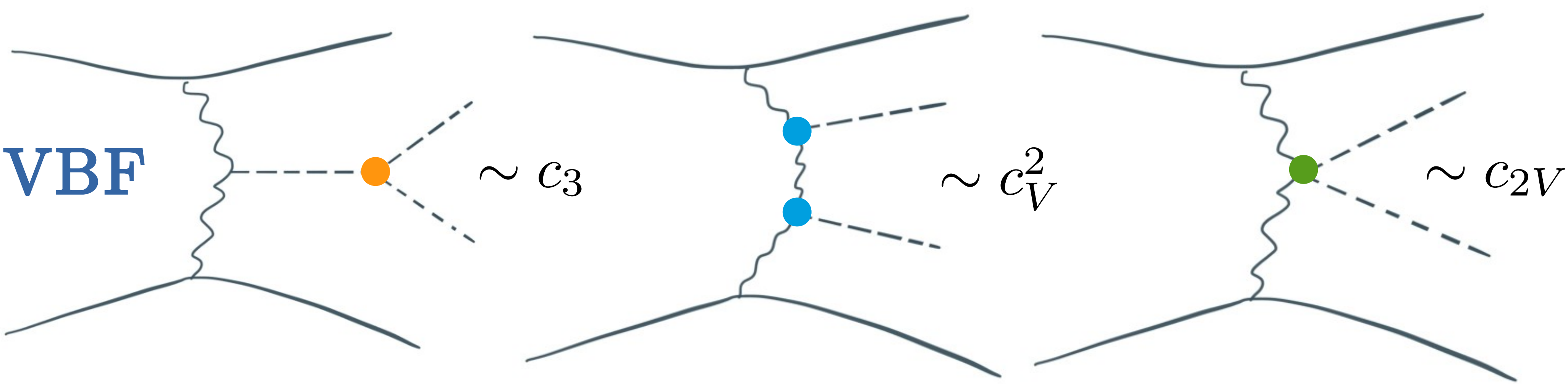
$$\sigma_{V_1 V_2} \propto g_{agg}^2 g_{aV_1V_2}^2 \hat{s} \sim \frac{\hat{s}}{f_a^4}$$





Double Higgs production

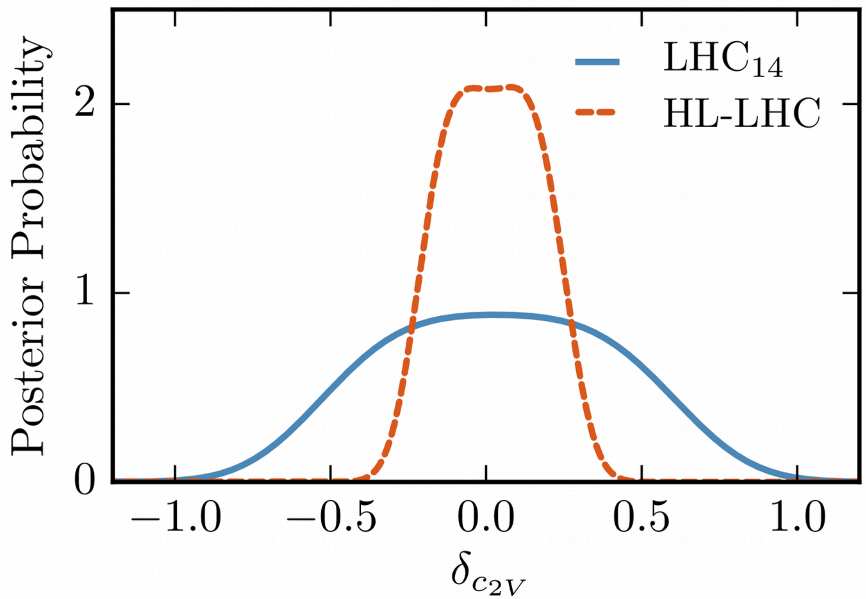
$$g_{hVV} \equiv c_V\, g_{hVV}^{\mathrm{SM}}, \qquad g_{hhVV} \equiv c_{2V}\, g_{hhVV}^{\mathrm{SM}}$$

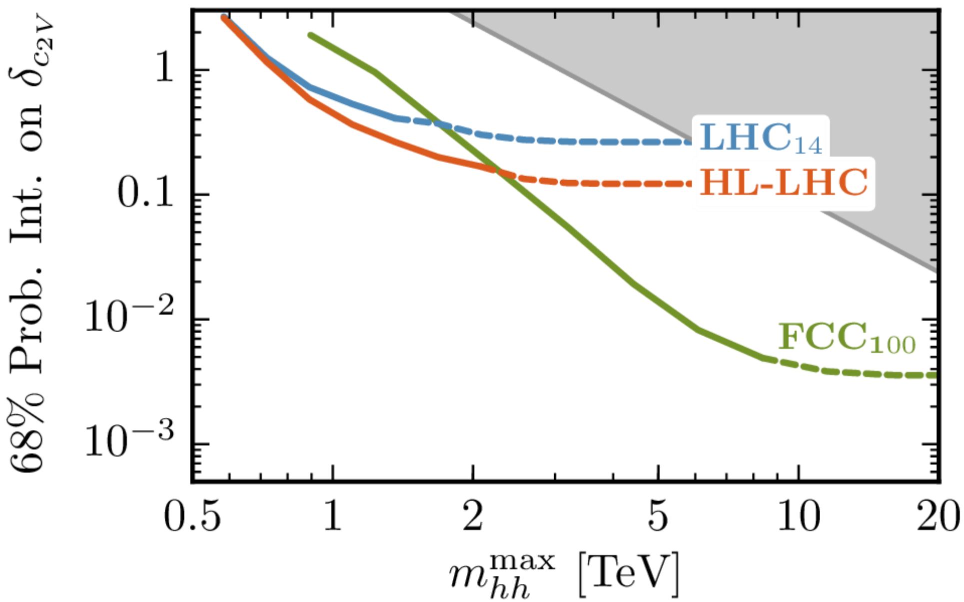


Results

FB, Contino, Rojo [1611.03860]

$$\delta_{c_{2V}} \equiv c_{2V} - 1$$





	68% probability interval on $\delta_{c_{2V}}$	
	$1 \times \sigma_{\rm bkg}$	$3 \times \sigma_{\rm bkg}$
LHC_{14}	$[-0.37, 0.45]$	$[-0.43, 0.48]$
HL-LHC	$[-0.15, 0.19]$	$[-0.18, 0.20]$
FCC_{100}	~ $[0, 0.01]$	~ $[-0.01, 0.01]$

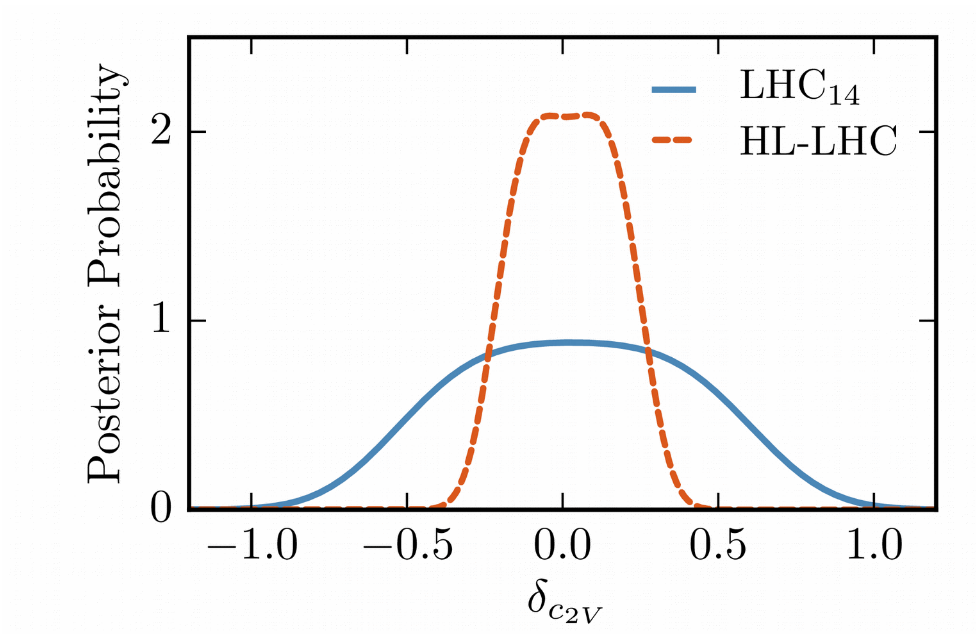
	95% probability upper limit on μ	
	$1 \times \sigma_{\rm bkg}$	$3 \times \sigma_{\rm bkg}$
LHC_{14}	109	210
HL-LHC	49	108
FCC_{100}	12	23

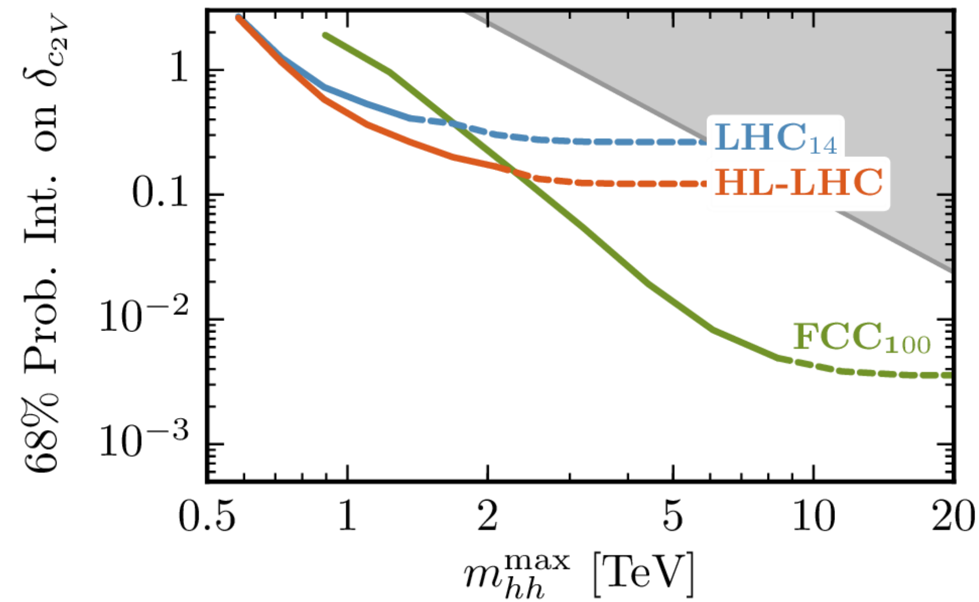
Deviations ~20% at HL-LHC and O(few %) at FCC achievable!

Results

FB, Contino, Rojo [1611.03860]

$$\delta_{c_{2V}} \equiv c_{2V} - 1$$





ATLAS EXPERIMENT

ATLAS-CONF-2019-030

$$95\%\ \text{CL:}\ -2.09 > \delta c_{2V} > 1.8\ \text{with}\ \mathcal{L} = 126\ \text{fb}^{-1}$$

Deviations ~20% at HL-LHC and O(few %) at FCC achievable!

Summary

- Hadron colliders can be competitive with LEP in constraining precision EW observables
- Diboson (and DY) channels are the most promising due to growth with energy and low systematics (e.g., in leptonic or semi-leptonic) final states
- More differential distribution, e.g., in azimuthal angle, additionally, can be used to constrain more operators
- Important to get theoretical uncertainties under control. E.g. higher order corrections QCD/EW/mixed.
- BSM models $\rightarrow$ talks by Franzosi, Cacciapaglia, and Salvioni on composite and twin Higgs.

Thank you!

The VHH channels