HIGGS COUPLINGS MEASUREMENTS AND THE SCALE OF NEW PHYSICS

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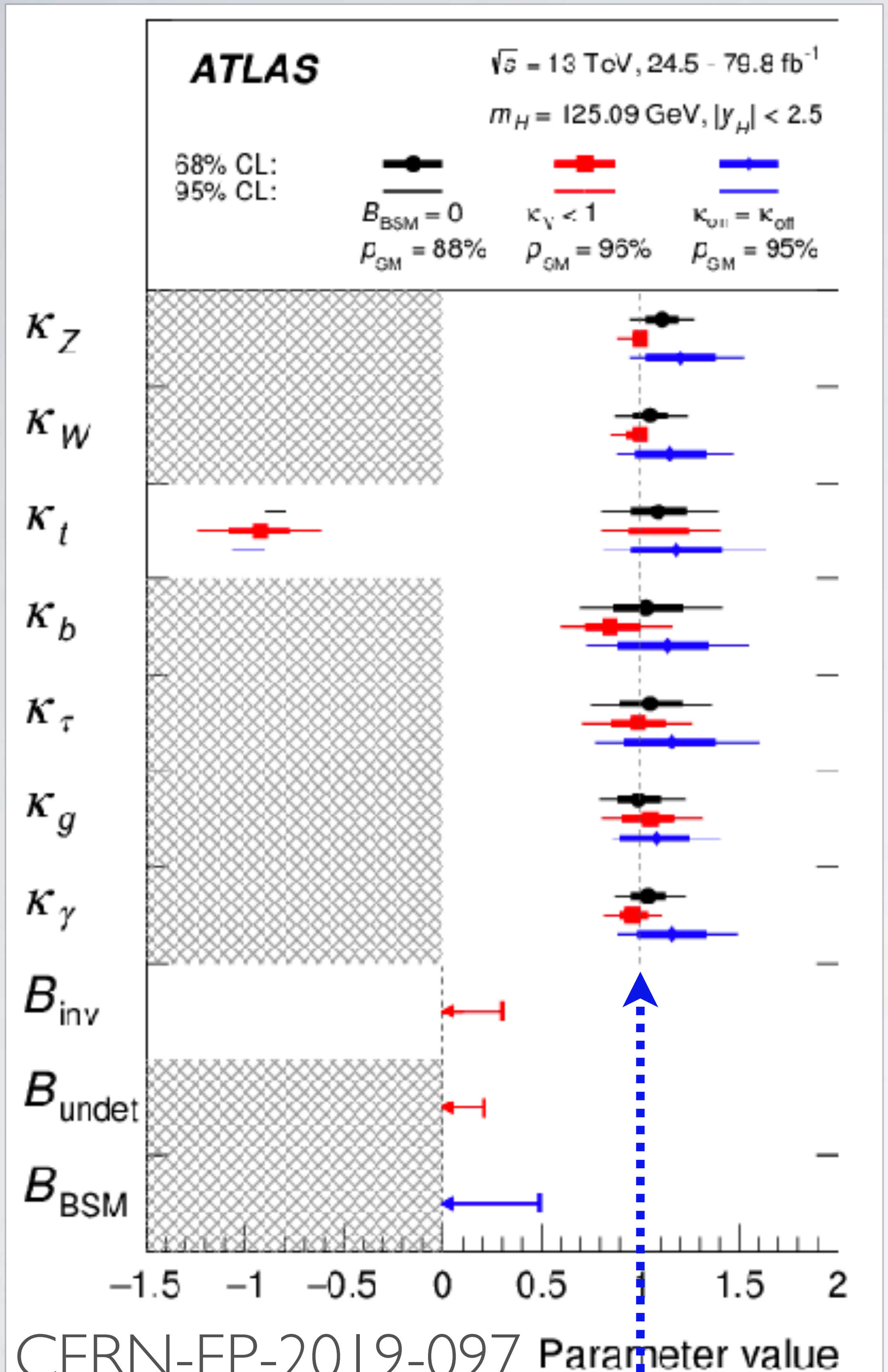
Oklahoma State 2/18/21 Seminar

PINNING DOWN HIGGS PROPERTIES

Post-discovery, goal of LHC and future colliders to measure Higgs properties to test EWSB mechanism, mass generation, and
look for new physics beyond the Standard Model



CERN-EP-2019-097

Standard Model values

HIGGS COUPLINGS MEASUREMENTS

Fits to
σ x Branching Ratios,
for Higgs couplings
have **10-25%**
errors and currently
agree with SM value

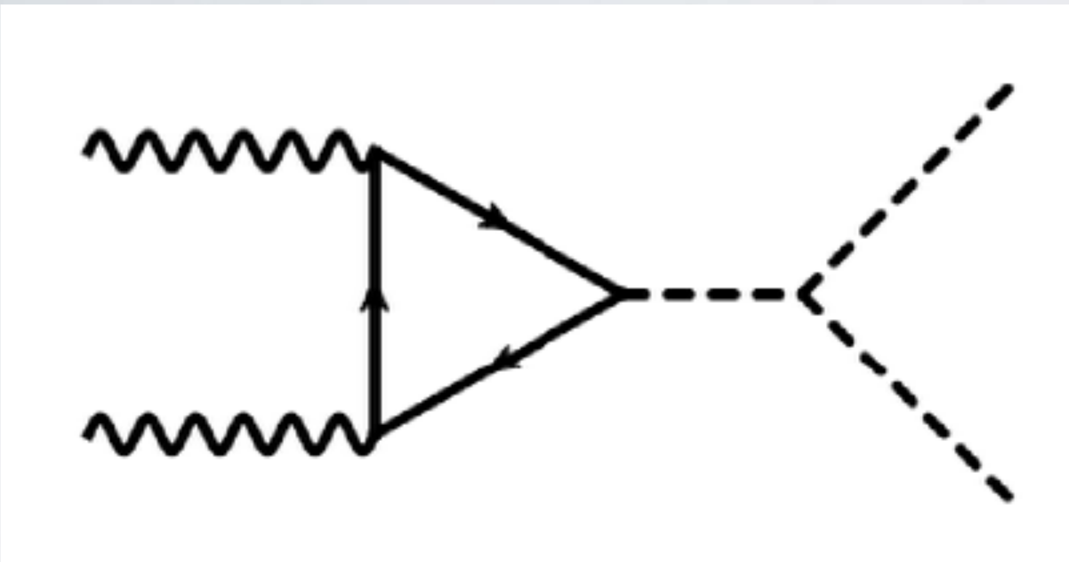
HIGGS COUPLINGS IN FUTURE

kappa-0	HL-LHC	LHeC	HE-LHC		ILC			CLIC			CEPC	FCC-ee		FCC-ee/eh/hh
			S2	S2′	250	500	1000	380	15000	3000		240	365	
κ_W [%]	1.7	0.75	1.4	0.98	1.8	0.29	0.24	0.86	0.16	0.11	1.3	1.3	0.43	0.14
κ_Z [%]	1.5	1.2	1.3	0.9	0.29	0.23	0.22	0.5	0.26	0.23	0.14	0.20	0.17	0.12
κ_g [%]	2.3	3.6	1.9	1.2	2.3	0.97	0.66	2.5	1.3	0.9	1.5	1.7	1.0	0.49
κ_γ [%]	1.9	7.6	1.6	1.2	6.7	3.4	1.9	98⋆	5.0	2.2	3.7	4.7	3.9	0.29
$\kappa_{Z\gamma}$ [%]	10.	–	5.7	3.8	99⋆	86⋆	85⋆	120⋆	15	6.9	8.2	81⋆	75⋆	0.69
κ_c [%]	–	4.1	–	–	2.5	1.3	0.9	4.3	1.8	1.4	2.2	1.8	1.3	0.95
κ_t [%]	3.3	–	2.8	1.7	–	6.9	1.6	–	–	2.7	–	–	–	1.0
κ_b [%]	3.6	2.1	3.2	2.3	1.8	0.58	0.48	1.9	0.46	0.37	1.2	1.3	0.67	0.43
κ_μ [%]	4.6	–	2.5	1.7	15	9.4	6.2	320⋆	13	5.8	8.9	10	8.9	0.41
κ_τ [%]	1.9	3.3	1.5	1.1	1.9	0.70	0.57	3.0	1.3	0.88	1.3	1.4	0.73	0.44

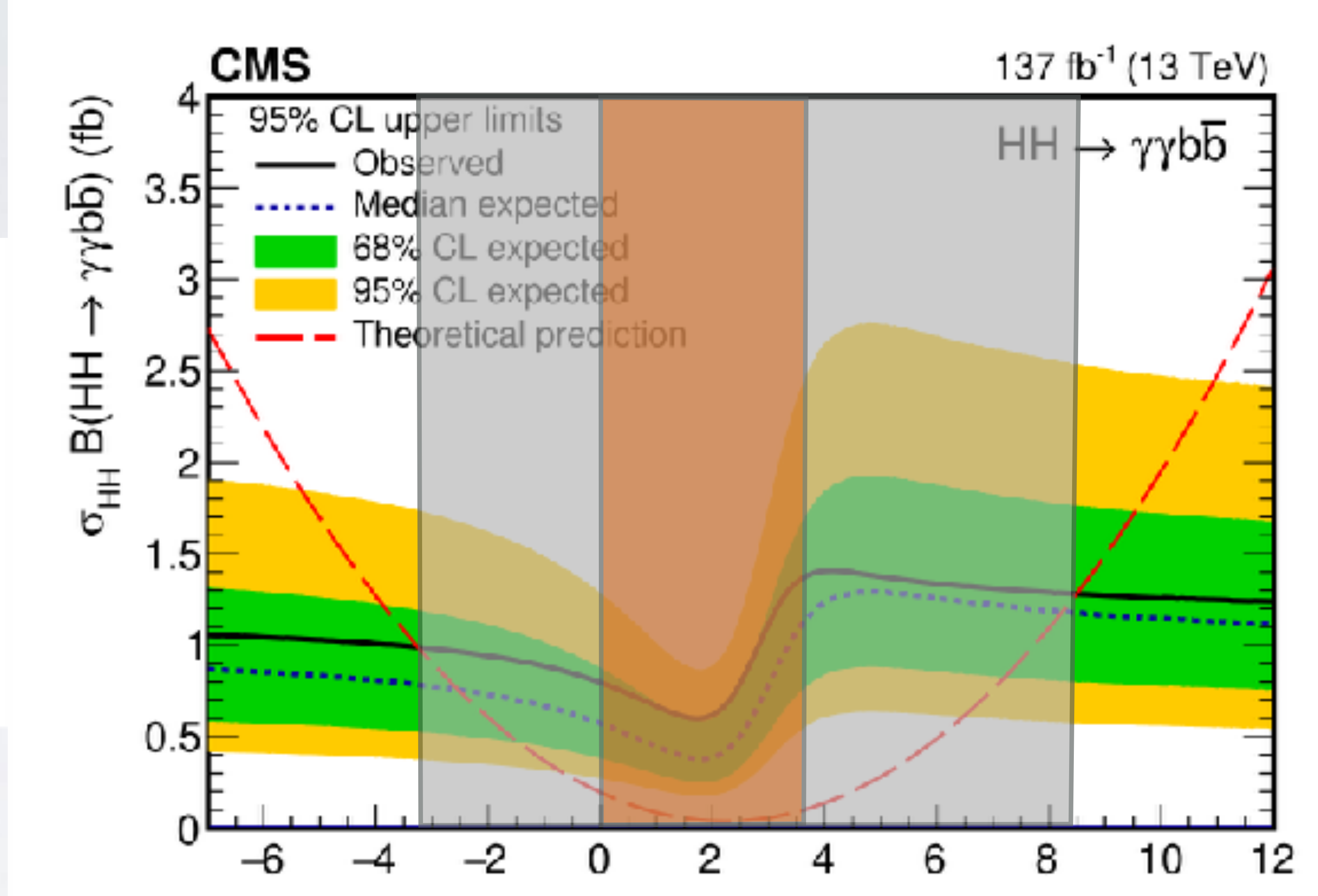
Higgs@FutureColliders report (1905.03764)

Coupling sensitivities playing a role in next collider discussion

TRILINEAR SEARCH



Trilinear probed by search for Double Higgs production



CMS-HIG-19-018

Currently only sensitive to O(10) variations, but projections estimate trilinear sensitivity to ~ [-0.2,3.6] at HL-LHC w/ 3 ab^{-1} and 20-30% at future colliders

TRIPLE HIGGS PROCESS

Papaefstathiou and Sakurai
See also Chien et.al.

hh and hhh at one loop
e.g. Bizon et.al.

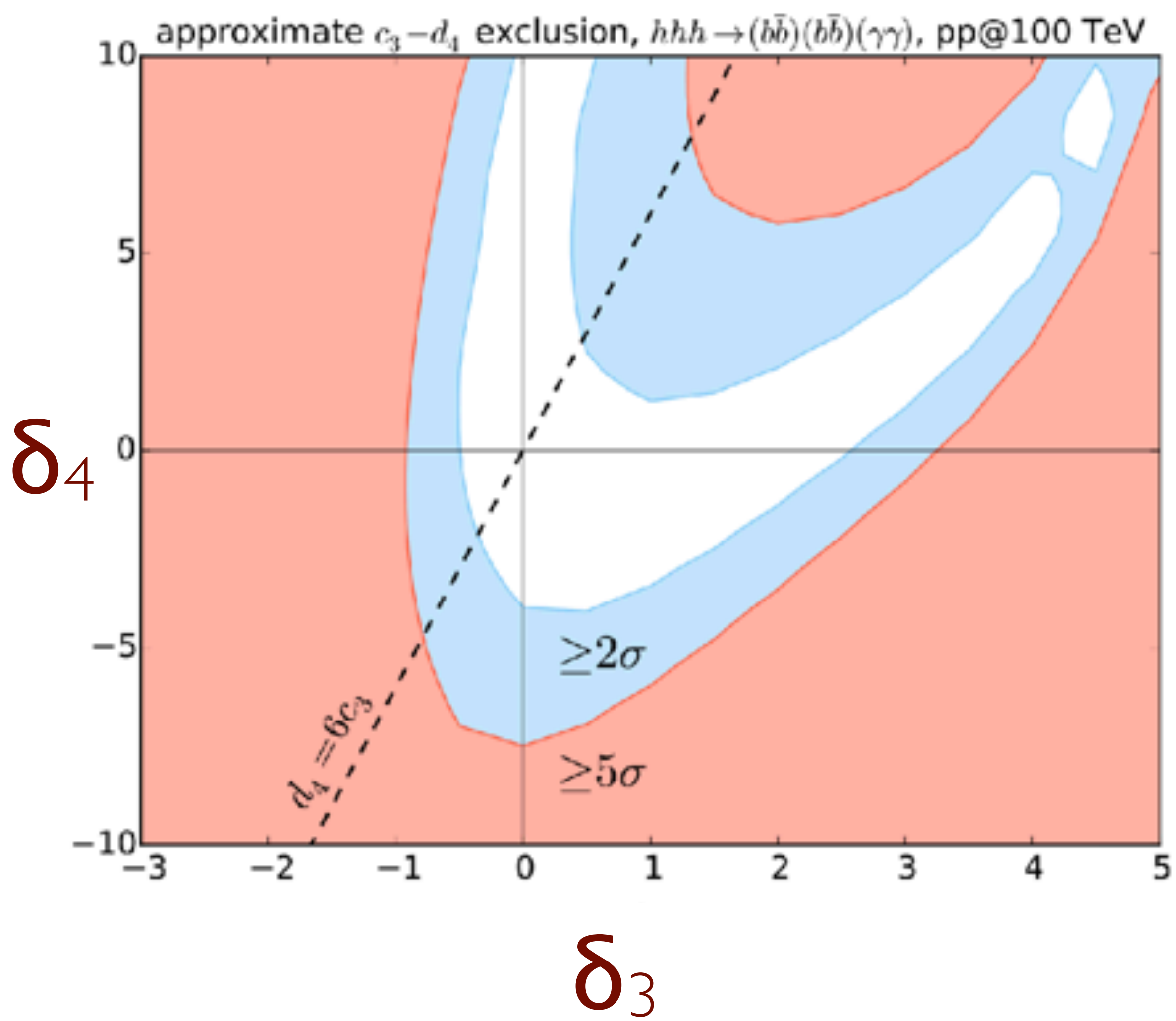
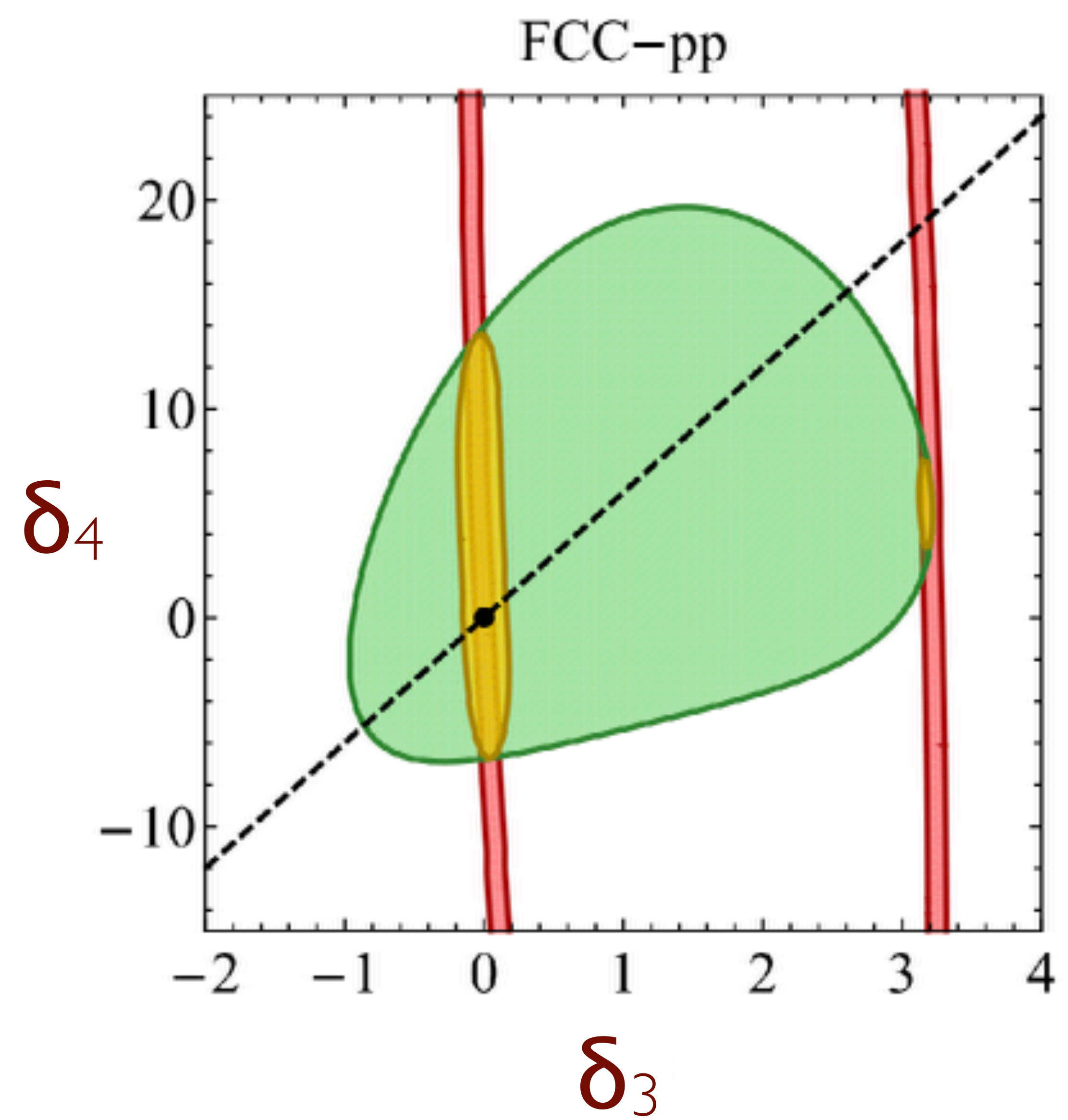


FIG. 6: The approximate expected 2σ (blue) and 5σ (red) exclusion regions on the $c_3 - d_4$ plane after 30 ab^{-1} of integrated luminosity, derived assuming a constant signal efficiency, calculated along the $d_4 = 6c_3$ line in $c_3 \in [-3.0, 4.0]$.



Sensitivity to Higgs quartic is poor even in optimistic cases

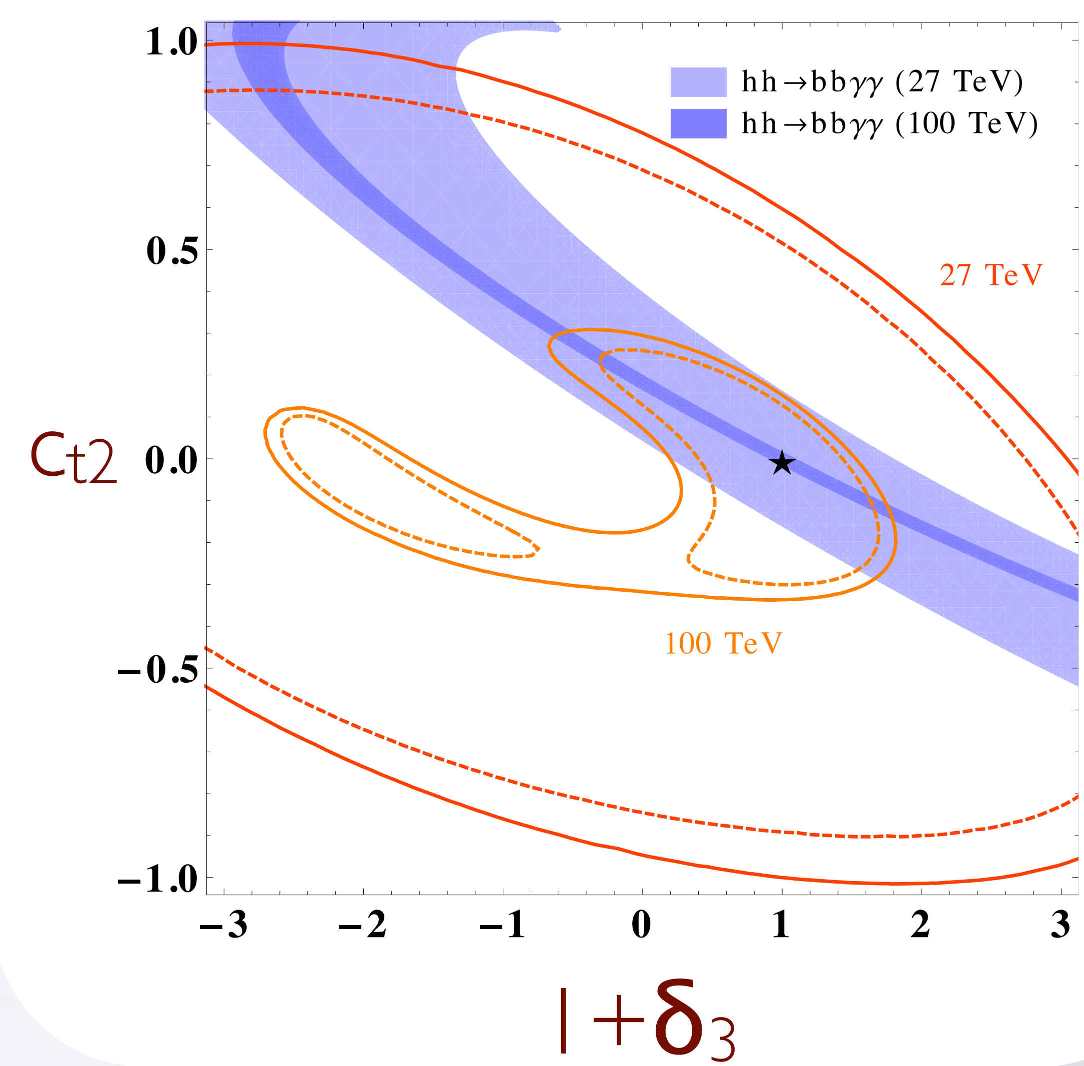
W/Z AND TOP COUPLINGS TO HH

VVhh measured in
VBF DiHiggs to 4b's
Bishara et.al. (1611.03860)

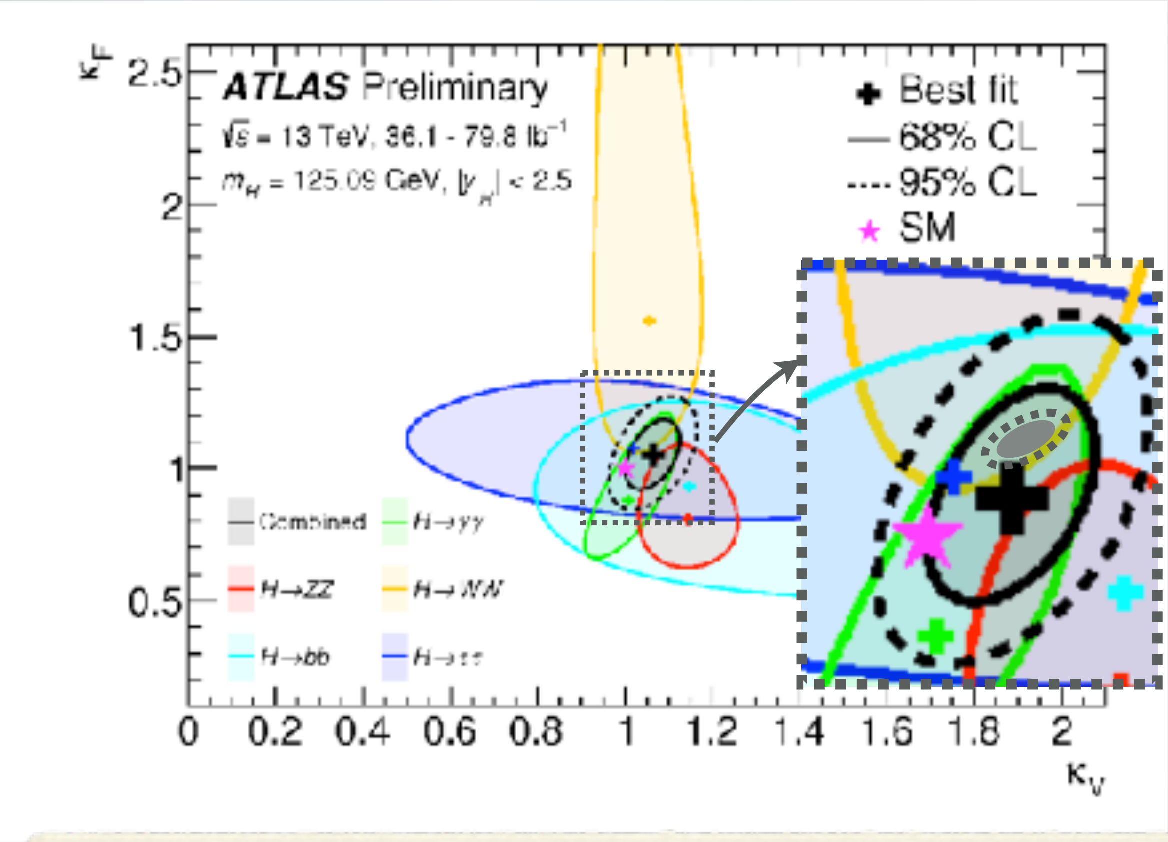
	68% probability interval on δ_{hhVV}	
	$1 \times \sigma_{bkg}$	$3 \times \sigma_{bkg}$
LHC_{14}	$[-0.37, 0.45]$	$[-0.43, 0.48]$
HL-LHC	$[-0.15, 0.19]$	$[-0.18, 0.20]$
FCC_{100}	$[0, 0.01]$	$[-0.01, 0.01]$

Sensitivity to O(.1-1) for quadratic Higgs couplings

tthh coupling
probed by tthh
production
Li et.al. (1905.03772)



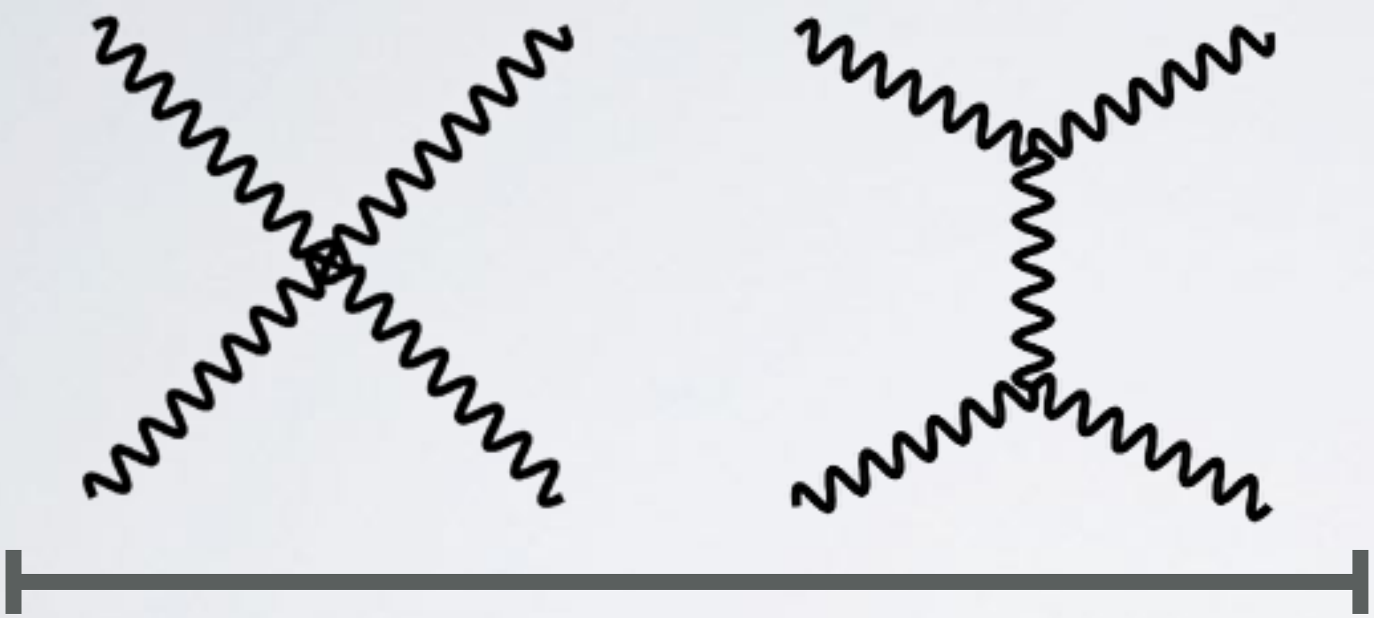
NEW PHYSICS SCALE BOUND FROM UNITARITY VIOLATION



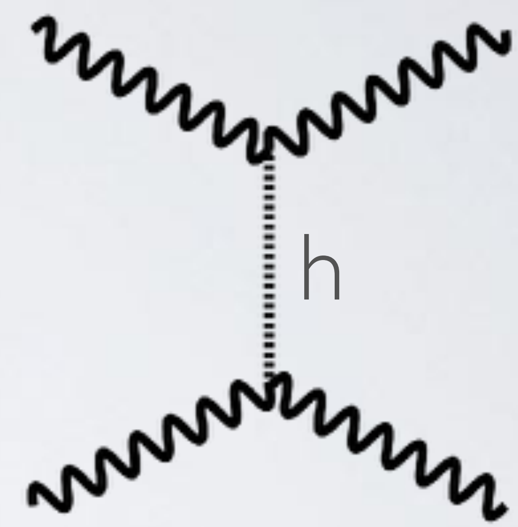
What are the new physics implications of a Higgs coupling deviation?

Any Higgs coupling deviation from SM prediction leads to unitarity violation at high energies, placing an upper bound on new physics. Also, leads to interesting processes to measure (see Kilian et.al. 1808.05534, Henning et.al. 1812.09299 & Stolarski, Wu 2006.09374)

CLASSIC EXAMPLE SCATTERING $Z_L\ Z_L \Leftrightarrow W^+_L\ W^-_L$



$M = c\ \text{Energy}^2 + \ldots$



$M = -c\ \text{Energy}^2 + \ldots$

Higgs exchange cancels high energy growth if its couplings are SM-like, matrix element is unitary if $m_H \lesssim 1$ TeV (Lee, Quigg, Thacker), motivating LHC design

GENERAL HIGGS COUPLINGS

$$\mathcal{L} = \mathcal{L}_{\rm SM} - \delta_3 \frac{m_h^2}{2v} h^3 - \delta_4 \frac{m_h^2}{8v^2} h^4 - \sum_{n=5}^{\infty} \frac{c_n}{n!} \frac{m_h^2}{v^{n-2}} h^n + \cdots$$ Higgs Potential Couplings

$$+ \delta_{Z1} \frac{m_Z^2}{v} h Z^\mu Z_\mu + \delta_{W1} \frac{2m_W^2}{v} h W^{\mu +} W_\mu^- + \delta_{Z2} \frac{m_Z^2}{2v^2} h^2 Z^\mu Z_\mu + \delta_{W2} \frac{m_W^2}{v^2} h^2 W^{\mu +} W_\mu^-$$

$$+ \sum_{n=3}^{\infty} \left[\frac{c_{Zn}}{n!} \frac{m_Z^2}{v^n} h^n Z^\mu Z_\mu + \frac{c_{Wn}}{n!} \frac{2m_W^2}{v^n} h^n W^{\mu +} W_\mu^- \right] + \cdots$$ W/Z Couplings

$$- \delta_{t1} \frac{m_t}{v} h \bar{t} t - \sum_{n=2}^{\infty} \frac{c_{tn}}{n!} \frac{m_t}{v^n} h^n \bar{t} t + \cdots$$ top Couplings

Any nonzero **δ** or ***c*** coupling is a sign of new physics, which leads to unitarity violation at high energies (higher dim. operators), placing an upper bound on this new physics

ASIDE: TECHNIQUE DETAILS

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OUR GENERAL UNITARITY VIOLATION APPROACH

$$|P, \alpha\rangle$$

Define states of total momentum P w/ other properties **α** (e.g. # Higgses)

Properly normalized

$$\langle P', \alpha' | P, \alpha\rangle = (2\pi)^4 \delta(P - P') \delta_{\alpha\alpha'}$$

Leads to unitarity bounds $|T_{\alpha\alpha'}| \leq 1$

$$\langle P', \alpha' | T | P, \alpha\rangle = (2\pi)^4 \delta(P - P') T_{\alpha\alpha'}$$

Allows us to go beyond 2 to 2 processes and set better bounds

EXAMPLE STATES

Only Scalars

$$|P, k_1, \ldots, k_r\rangle = C_{k_1 \cdots k_r} \int d^4x \, e^{-iP\cdot x} \prod_{i=1}^{r} \left[\phi_i^{(-)}(x)\right]^{k_i} |0\rangle$$

$$\frac{1}{|C_{k_1\cdots k_r}|^2} = \frac{\Pi_i k_i!}{8\pi(\sum_i k_i - 1)!(\sum_i k_i - 2)!} \left(\frac{E}{4\pi}\right)^{2\sum_i k_i - 4}$$

Two Fermions

$$|P; k_1, \ldots, k_r, L/R\rangle \equiv C''_k \int d^4x \, e^{-iP\cdot x} \, \phi_1^{(-)}(x)^{k_1} \cdots \phi_r^{(-)}(x)^{k_r} \overline{\psi}^{a(-)}_{R/L}(x) \psi^{a(-)}_{L/R}(x)|0\rangle$$

$$\frac{1}{|C''_k|^2} = \frac{2N_c E^2 \, \Pi_i k_i!}{8\pi(\sum_i k_i + 1)!(\sum_i k_i)!} \left(\frac{E}{4\pi}\right)^{2\sum_i k_i}$$

EQUIVALENCE THEOREM

For general h couplings, restore SU(2)xU(1) invariance, by introducing Goldstone bosons to use equivalence theorem for W_L, Z_L amplitudes

Higgs self-interactions

$$X \equiv \sqrt{2|H|^2} - v = \sqrt{(v+h)^2 + \vec{G}^2} - v$$

$$= h + \frac{1}{2v}\vec{G}^2 - \frac{1}{2v^2}h\vec{G}^2 + \cdots$$

For W/Z and top interactions

$$P = \frac{H}{\sqrt{|H|^2}} = \begin{pmatrix} 0 \\ 1 \end{pmatrix} + \begin{pmatrix} \sqrt{2}G^+/v \\ iG^0/v \end{pmatrix} + \cdots$$

END ASIDE

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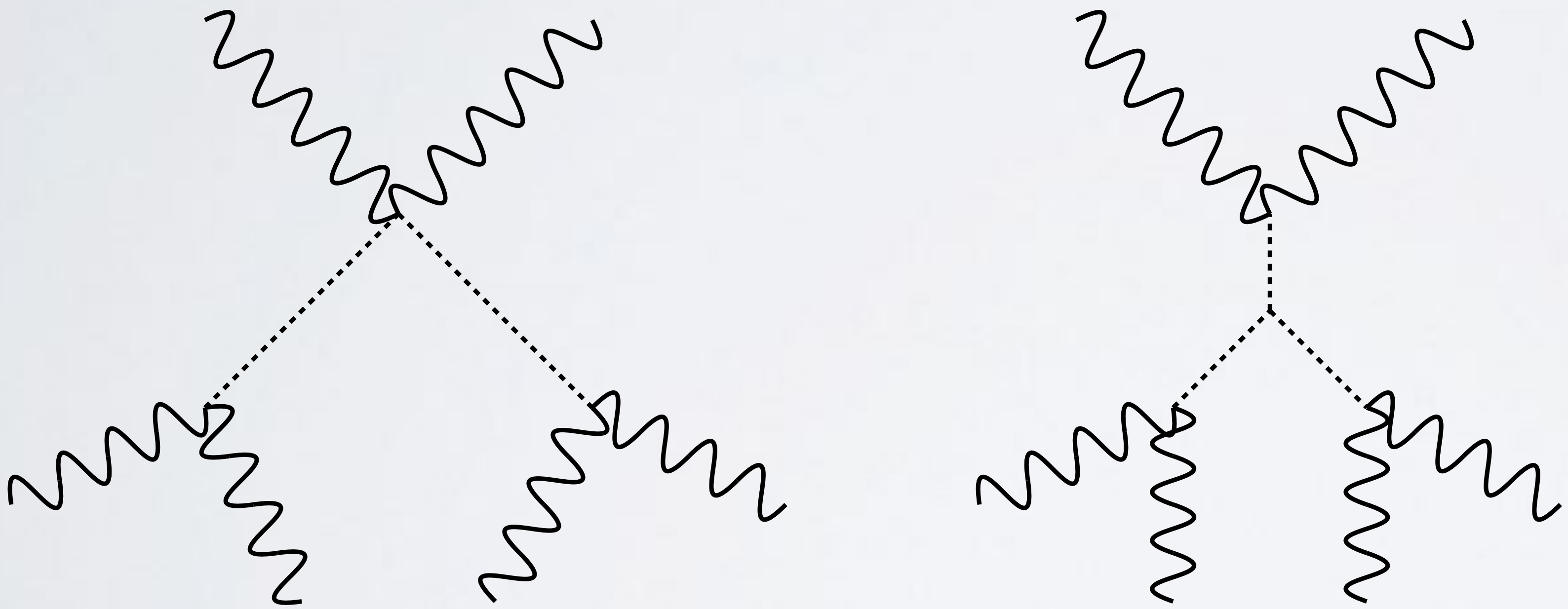
EXAMPLE: TRILINEAR UNITARITY VIOLATION

Modifying trilinear from SM value automatically leads to Unitarity violation at high energies



Example:

$Z_L\ Z_L\ Z_L \Leftrightarrow Z_L\ Z_L\ Z_L$

Cancellation to get $M \sim 1/\text{Energy}^2$ requires SM trilinear value!

MODEL DEPENDENCE OF INTERACTIONS

$$X^3 \sim h^3 + \vec{G}^2(h^2 + h^3 + \cdots) + \vec{G}^4(h + h^2 + \cdots) + \vec{G}^6(1 + h + \cdots)$$
$$+ \vec{G}^8(1 + h + \cdots) + \vec{G}^{10}(1 + h + \cdots) + \cdots ,$$
$$X^4 \sim h^4 + \vec{G}^2(h^3 + h^4 + \cdots) + \vec{G}^4(h^2 + h^3 + \cdots) + \vec{G}^6(h + h^2 + \cdots)$$
$$+ \vec{G}^8(1 + h + \cdots) + \vec{G}^{10}(1 + h + \cdots) + \cdots ,$$
$$X^5 \sim h^5 + \vec{G}^2(h^4 + h^5 + \cdots) + \vec{G}^4(h^3 + h^4 + \cdots) + \vec{G}^6(h^2 + h + \cdots)$$
$$+ \vec{G}^8(h + h^2 + \cdots) + \vec{G}^{10}(1 + h + \cdots) + \cdots ,$$

(Schematic without coefficients, but we know cancellations can occur due to SMEFT description)

Terms circled can only come from trilinear!

BEST CHANNELS FOR HIGGS TRILINEAR

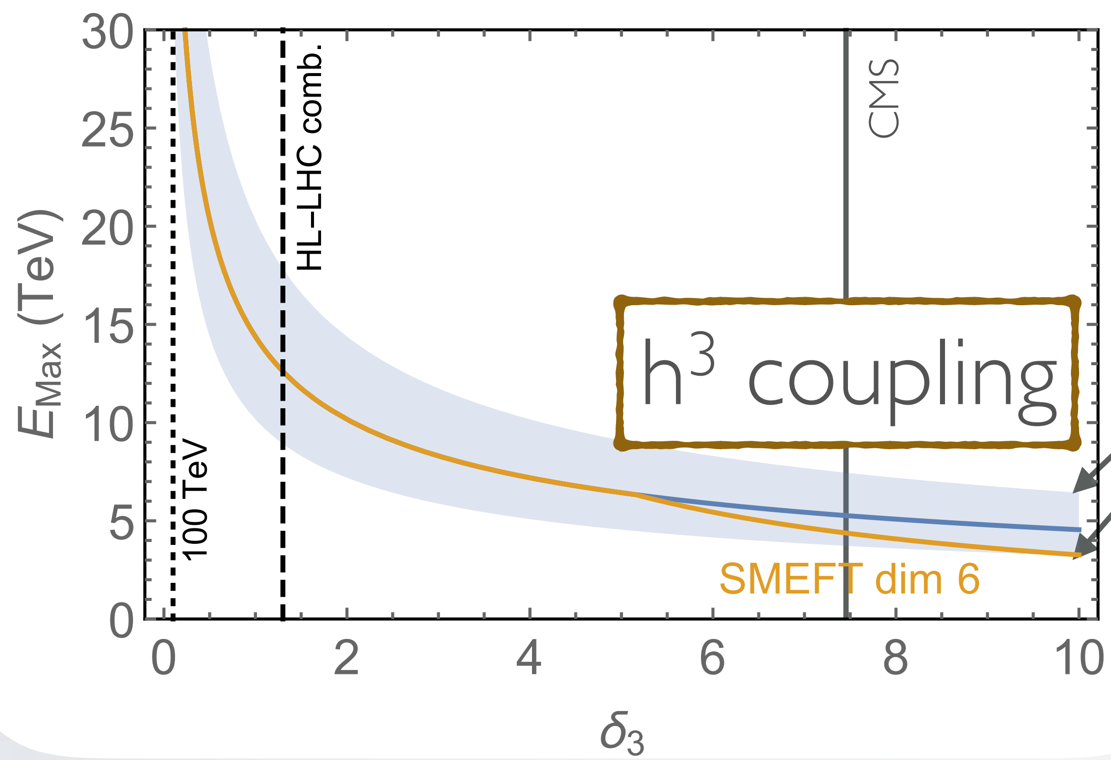
$$hW_L^+W_L^- \to W_L^+W_L^- \ : E_{max} = \frac{9.4 \text{ TeV}}{|\frac{\delta_3}{7.5}|}$$

$$W_L^+W_L^+W_L^- \to W_L^+W_L^+W_L^- \ : E_{max} = \frac{5.2 \text{ TeV}}{\sqrt{|\frac{\delta_3}{7.5}|}}$$

(Normalized to largest deviation consistent with ATLAS and CMS di-Higgs 95%CL constraints)

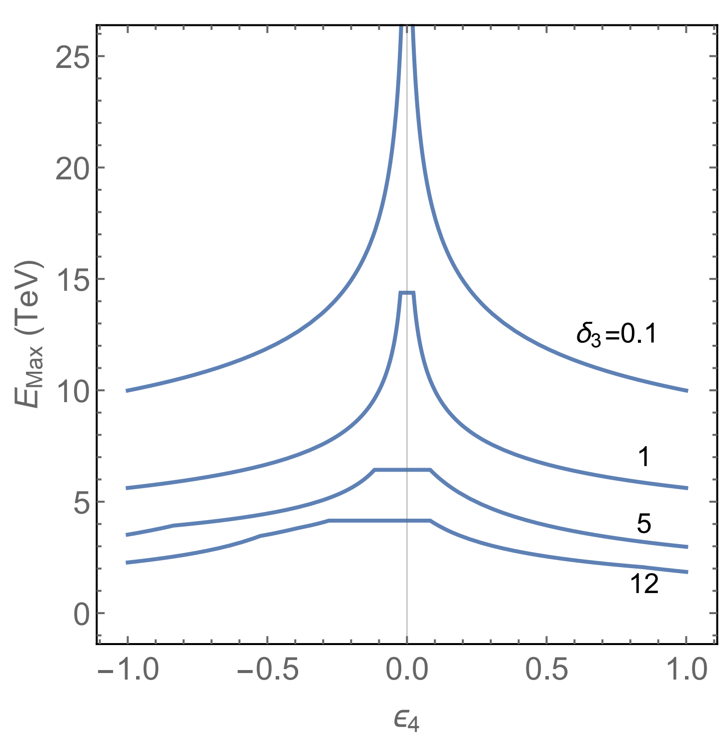
Takeaway: Current constraints still allow low unitarity bound w/ nearby new physics, a measured coupling deviation from SM places an upper bound on new physics

HIGGS TRILINEAR COUPLING DEVIATION



Estimated
Theoretical uncertainty of
Unitarity violating scale

Current bound allows new physics below ~ 5 TeV



Unitarity requires higher order couplings to be correlated

Quartic deviation must satisfy SMEFT-like relation, $\delta_4 = 6\delta_3(1+\varepsilon_4)$ as predicted by $|H|^6$, to keep new physics above 10 TeV

W/Z, TOP COUPLINGS

Processes that only depend on hWW, hZZ couplings

$$W_L^+W_L^+ \to W_L^+W_L^+ : E_{\max} \simeq \frac{1.2\ \text{TeV}}{|\delta_{W1}|^{1/2}},$$

$$Z_L Z_L \to W_L^+W_L^- : E_{\max} \simeq \frac{1.5\ \text{TeV}}{|\delta_{Z1}+\delta_{W1}|^{1/2}},$$

$$W_L^+ h \to W_L^+ Z_L : E_{\max} \simeq \frac{1.0\ \text{TeV}}{|\delta_{Z1}-\delta_{W1}|^{1/2}},$$

$$W_L^+W_L^+W_L^- \to W_L^+ Z_L : E_{\max} \simeq \frac{1.5\ \text{TeV}}{|\delta_{Z1}-\delta_{W1}|^{1/3}}.$$

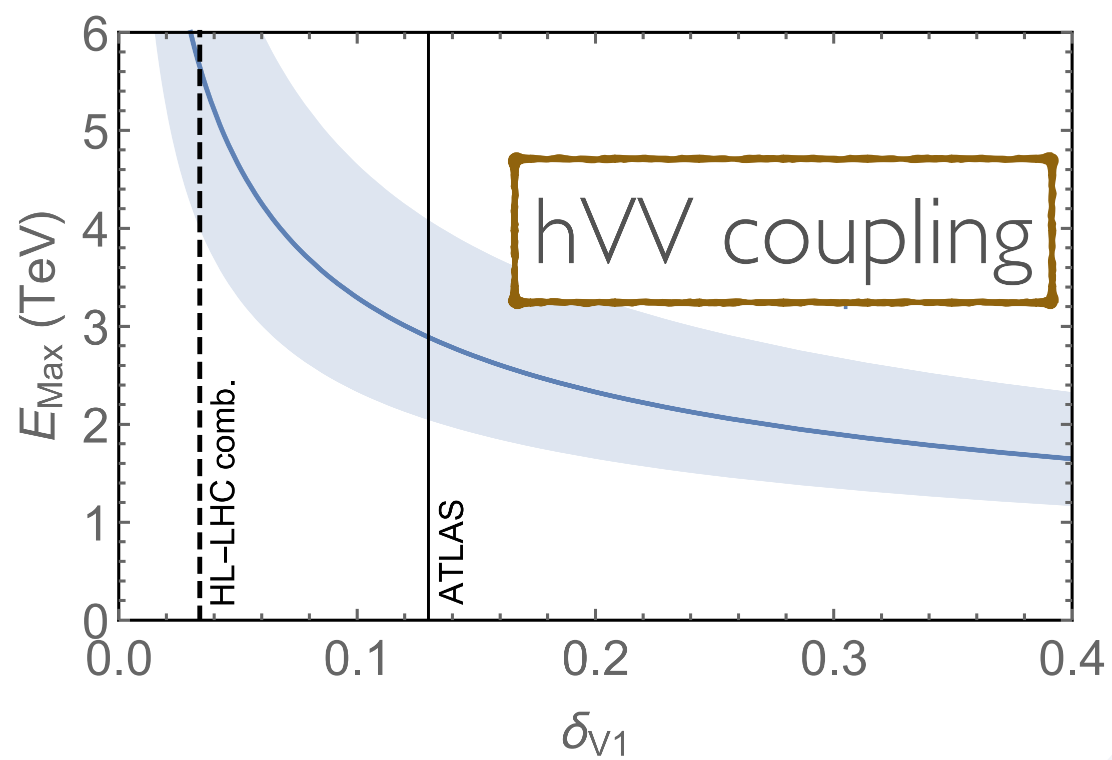
Processes that only depend on htt (and hVV) coupling

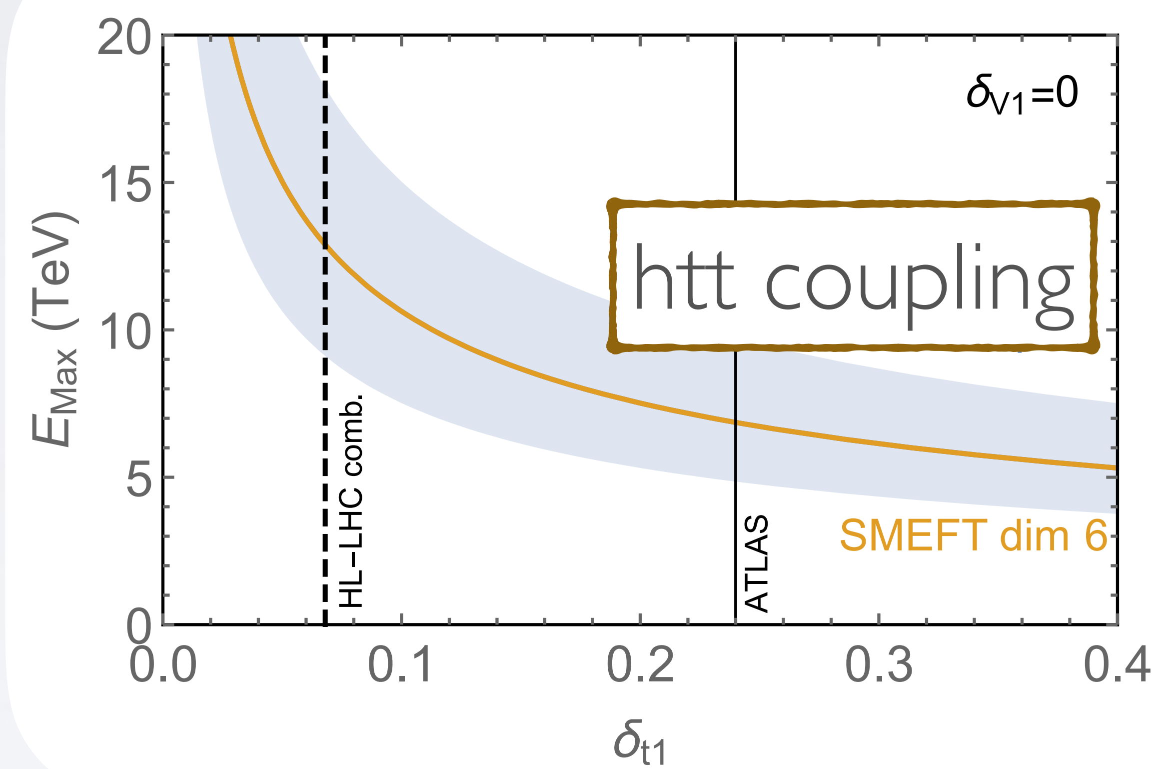
$$t_R\bar{t}_R \to W_L^+W_L^- : E_{\max} \simeq \frac{5.1\ \text{TeV}}{|\delta_{t1}+\delta_{V1}|},$$

$$t_R\bar{b}_R \to W_L^+ h : E_{\max} \simeq \frac{3.6\ \text{TeV}}{|\delta_{t1}-\delta_{V1}|}$$

$$t_R\bar{b}_R \to W_L^+W_L^+W_L^- : E_{\max} \simeq \frac{3.3\ \text{TeV}}{\sqrt{|\delta_{t1}-\frac{1}{3}\delta_{V1}|}},$$

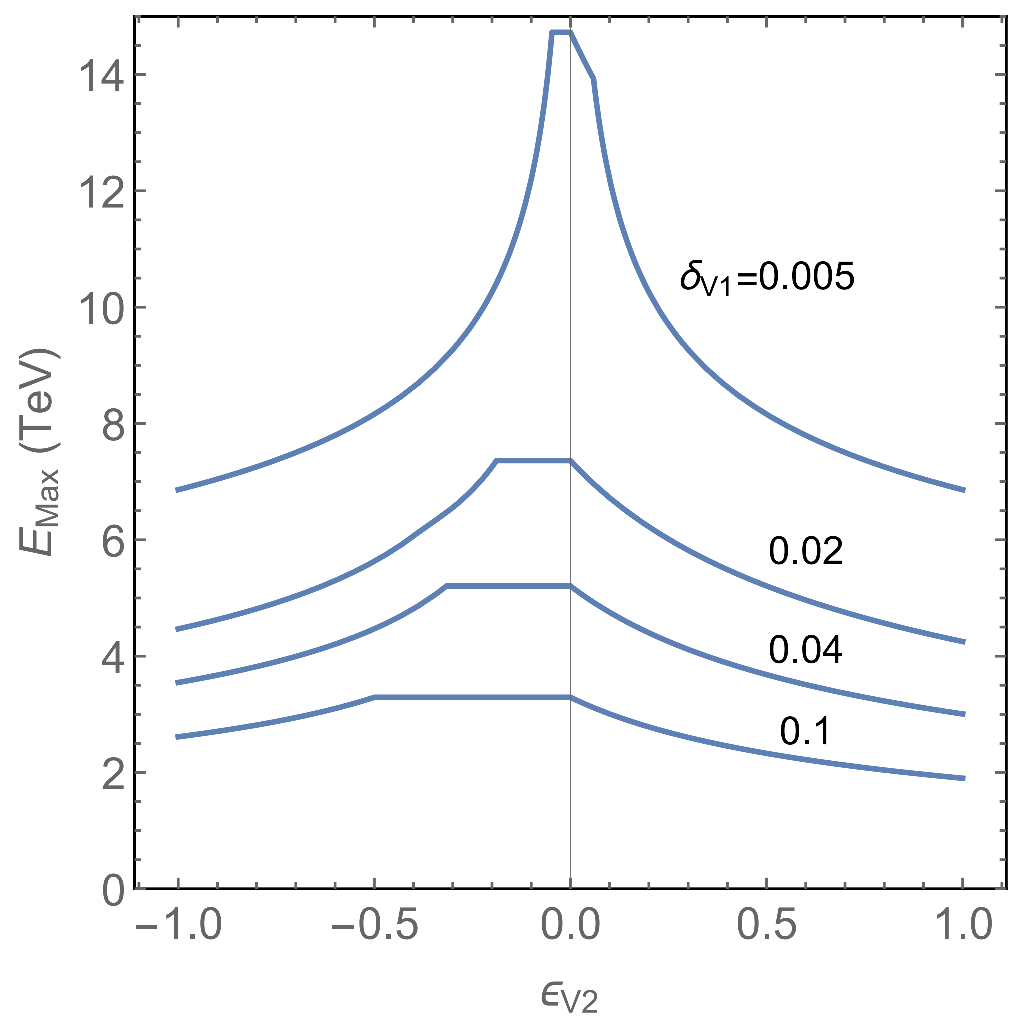
W/Z AND TOP BOUNDS

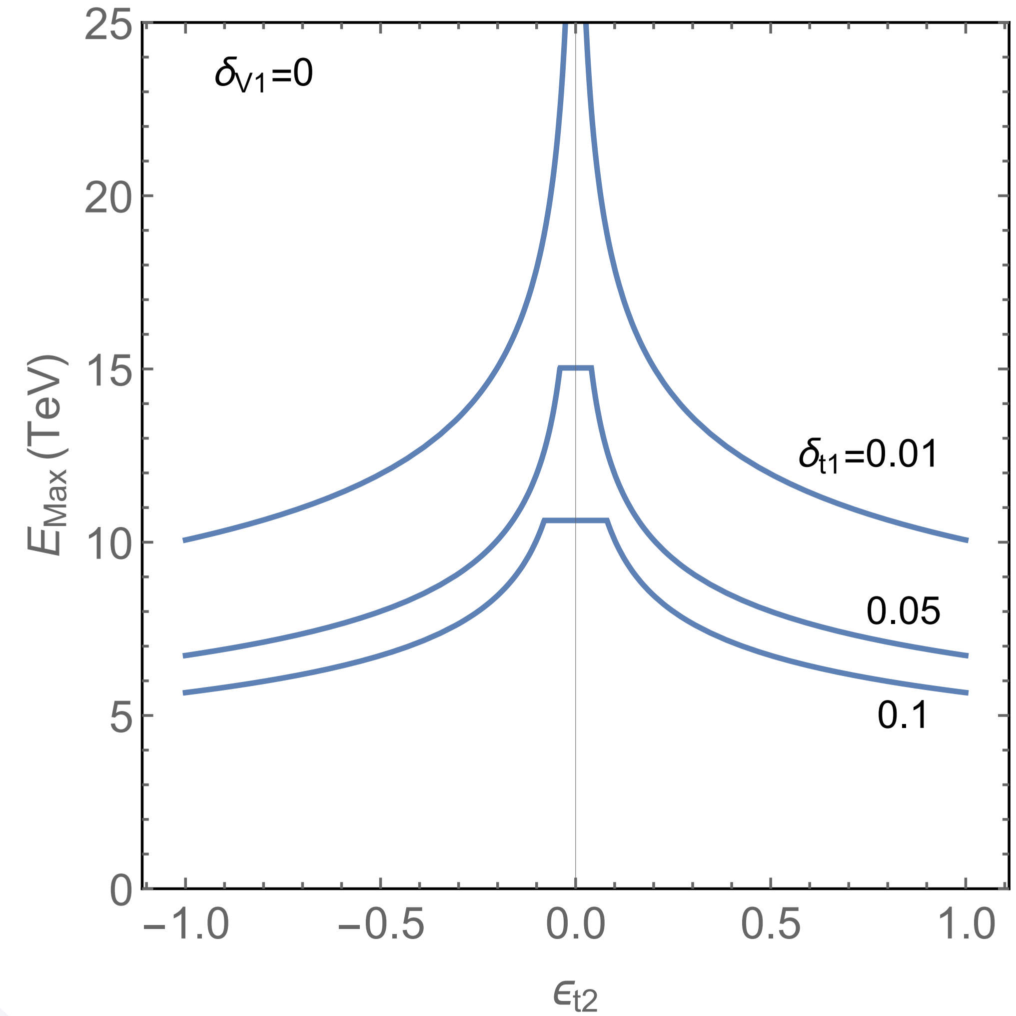




Existing strong bounds on these couplings still allow future deviations where new physics has to appear below ~ 3-8 TeV. In fact, hVV is more powerful than h^3!

SMEFT CONSTRAINTS





$$|H|^2|D_\mu H|^2$$

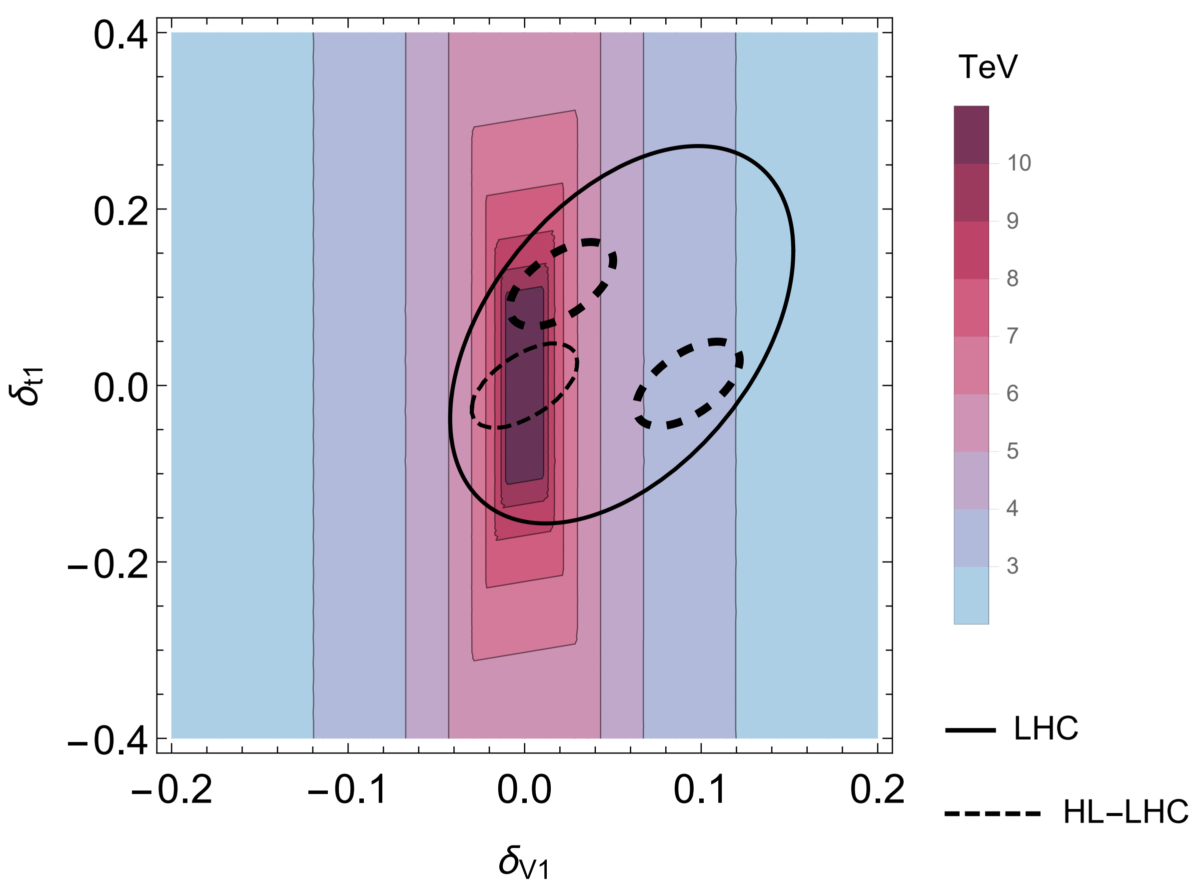
$$|H|^2\bar{Q}HP_LQ + h.c.$$

Again, for new physics to be much higher than a TeV, need a SMEFT-like structure

WHAT DOES PRECISION BUY?

kappa-0	HL-LHC	LHeC	HE-LHC		ILC			CLIC			CEPC	FCC-ee		FCC-ee/eh/hh
			S2	S2′	250	500	1000	380	15000	3000		240	365	
κ_W [%]	1.7	0.75	1.4	0.98	1.8	0.29	0.24	0.86	0.16	0.11	1.3	1.3	0.43	0.14
κ_Z [%]	1.5	1.2	1.3	0.9	0.29	0.23	0.22	0.5	0.26	0.23	0.14	0.20	0.17	0.12
κ_g [%]	2.3	3.6	1.9	1.2	2.3	0.97	0.66	2.5	1.3	0.9	1.5	1.7	1.0	0.49
κ_γ [%]	1.9	7.6	1.6	1.2	6.7	3.4	1.9	98⋆	5.0	2.2	3.7	4.7	3.9	0.29
$\kappa_{Z\gamma}$ [%]	10.	–	5.7	3.8	99⋆	86⋆	85⋆	120⋆	15	6.9	8.2	81⋆	75⋆	0.69
κ_c [%]	–	4.1	–	–	2.5	1.3	0.9	4.3	1.8	1.4	2.2	1.8	1.3	0.95
κ_t [%]	3.3	–	2.8	1.7	–	6.9	1.6	–	–	2.7	–	–	–	1.0
κ_b [%]	3.6	2.1	3.2	2.3	1.8	0.58	0.48	1.9	0.46	0.37	1.2	1.3	0.67	0.43
κ_μ [%]	4.6	–	2.5	1.7	15	9.4	6.2	320⋆	13	5.8	8.9	10	8.9	0.41
κ_τ [%]	1.9	3.3	1.5	1.1	1.9	0.70	0.57	3.0	1.3	0.88	1.3	1.4	0.73	0.44

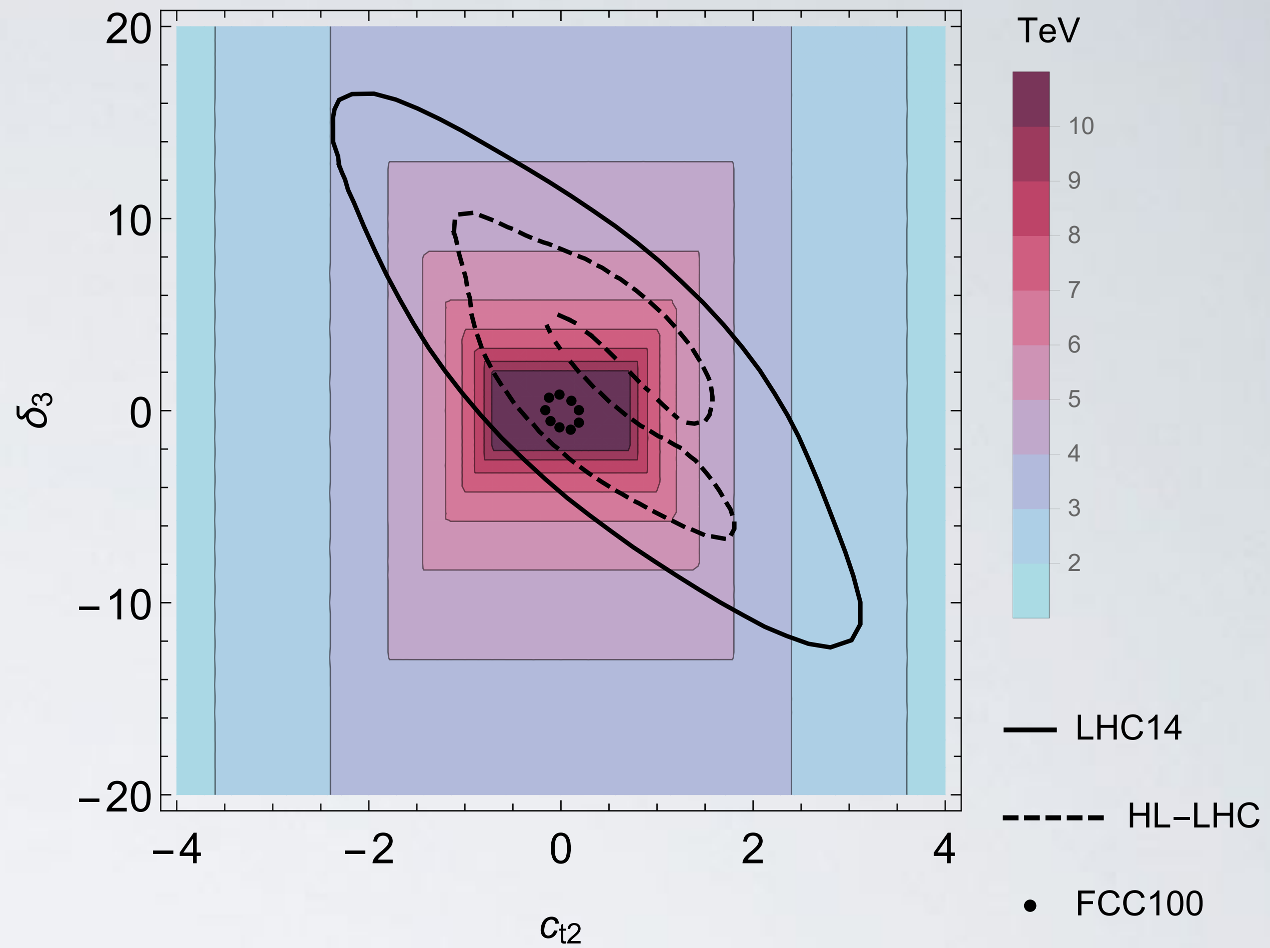
Higgs@FutureColliders report (1905.03764)

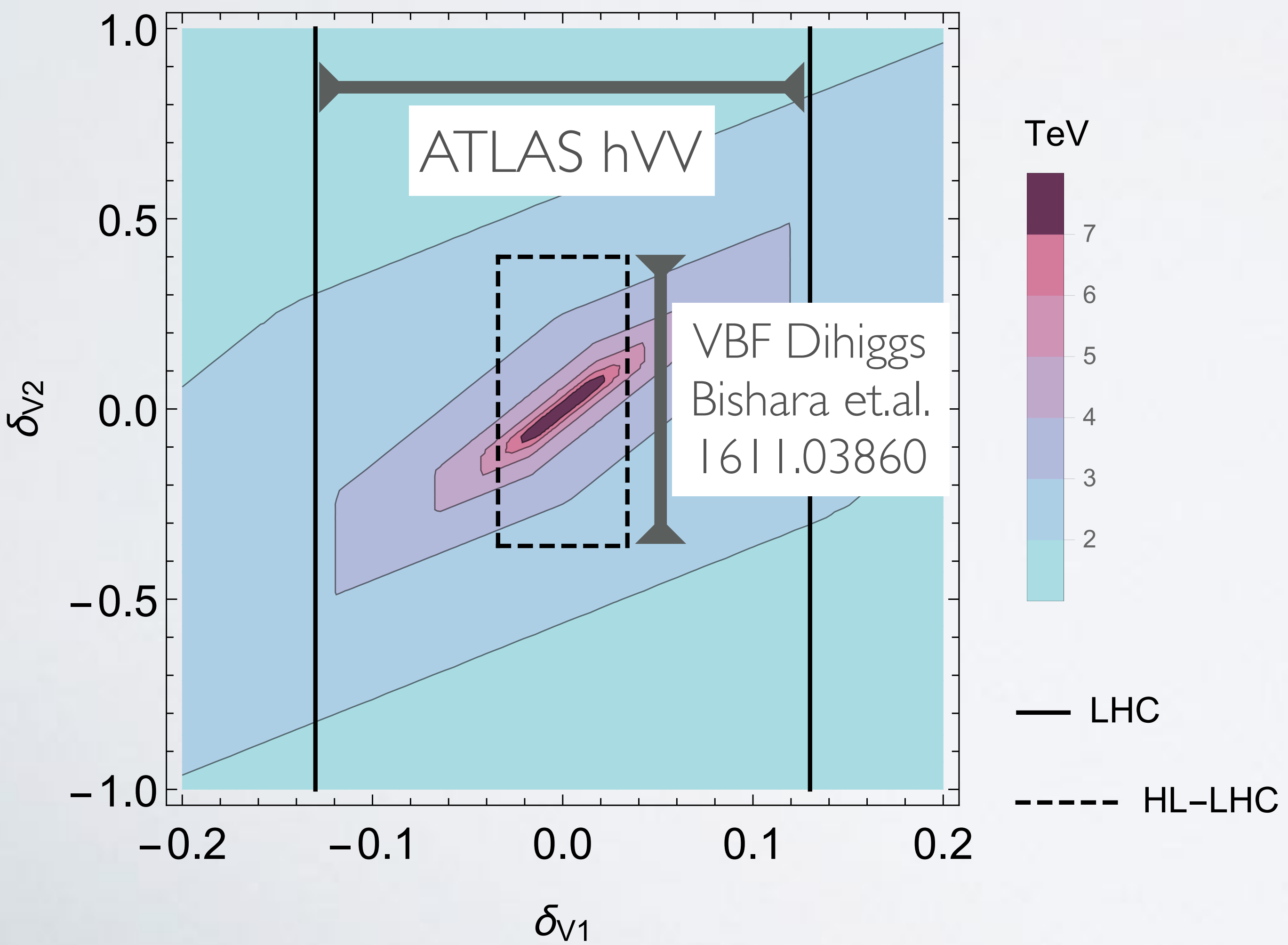


Unitarity bounds gives a quantitative reason to improve precision outside of better precision

DI-HIGGS INTERPLAY

Projected contours from Azatov et.al. 1502.00539 on di-Higgs from gluon fusion

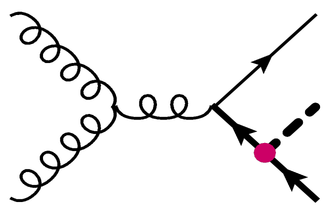
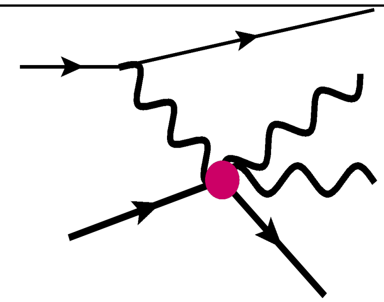
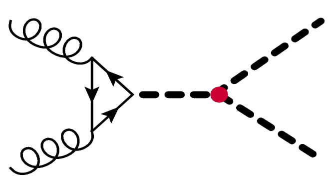
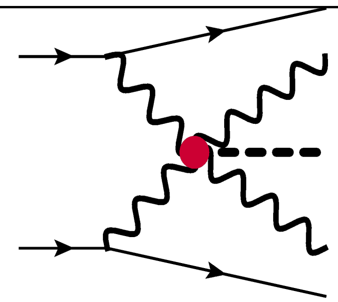


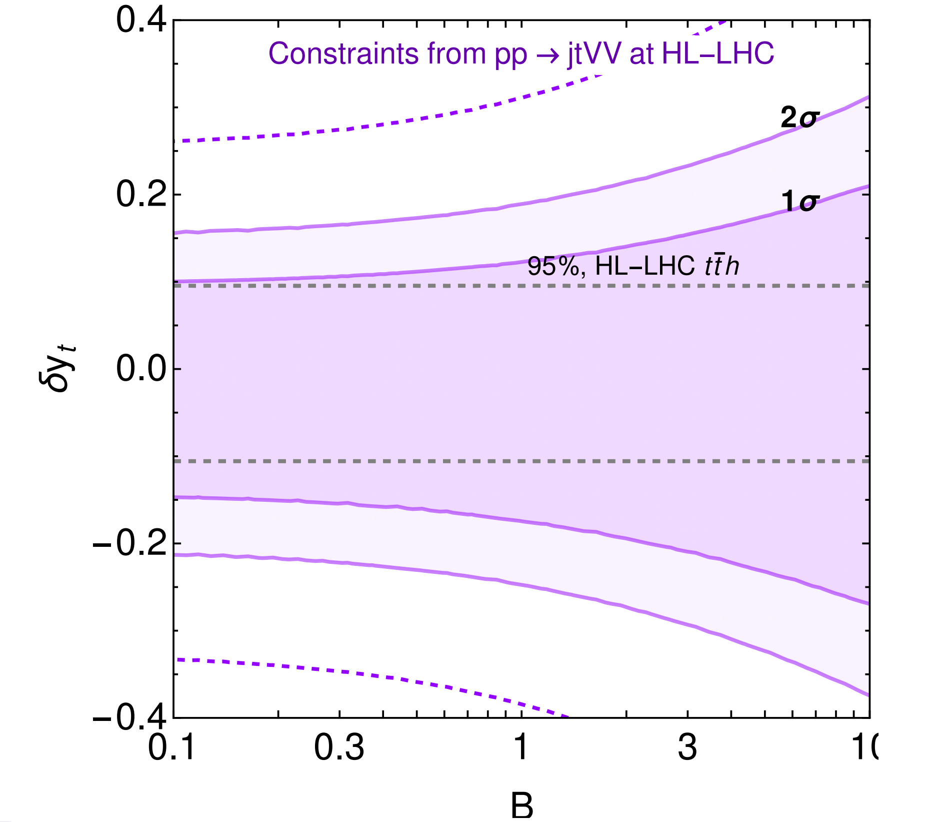


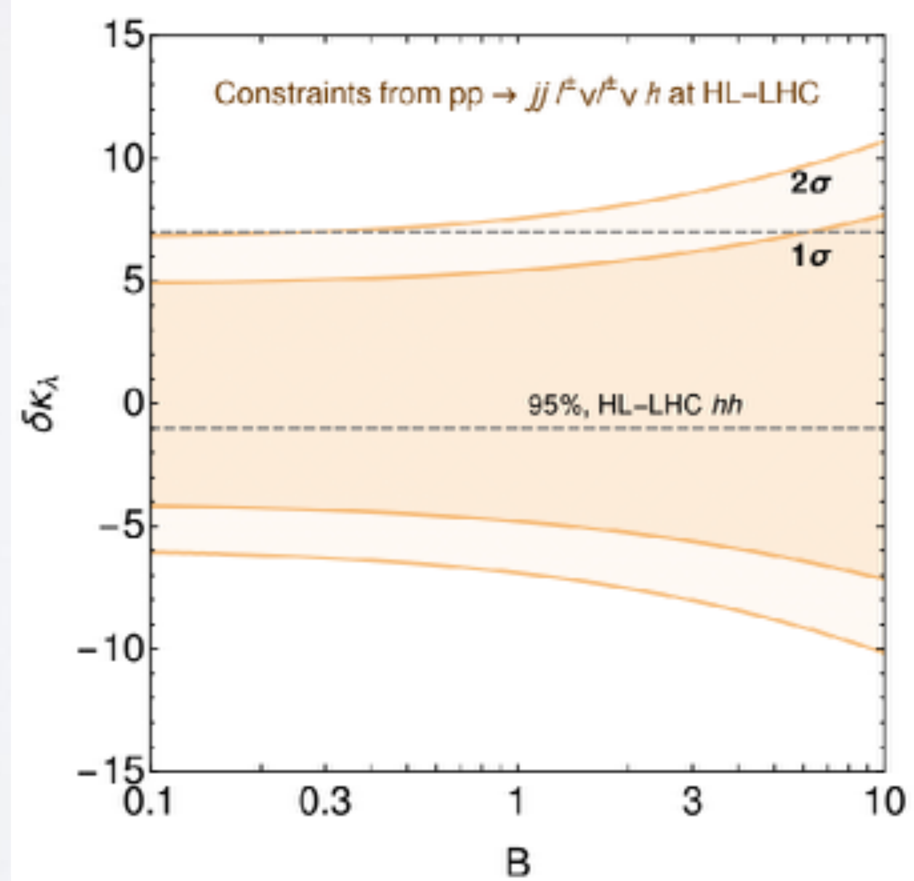
Vector boson di-Higgs production constrains hhVV

COLLIDER TESTS OF UNITARITY VIOLATION

Henning et.al.1812.09299
See also Kilian et.al.1808.05534, & Stolarski, Wu 2006.09374

κ_t	$\mathcal{O}_{y_t}$			$\sim \frac{E^2}{\Lambda^2}$
κ_λ	$\mathcal{O}_6$			$\sim \frac{vE}{\Lambda^2}$





Searching for Unitarity violating processes (solid) has similar sensitivities to coupling measurement (dashed) for tth, hhh

Extension to tthh and VVhh?

CONCLUSIONS

- Precision Higgs couplings can discover a SM deviation; unitarity violation gives quantitative connection btw coupling deviations and bound on new physics

- Higgs self-couplings, hVV, htt current bounds allow new physics at LHC energies and future sensitivities can still place bounds below 10 TeV (with different sensitivities)

- Higher order couplings (e.g. hhhh, hhVV, hhtt) are SMEFT-like if new physics scale is well above TeV scale. If no new physics accompanies coupling deviation, evidence for SMEFT-like structure

CONCLUSIONS (CONT.)

- Di-Higgs searches test hhh, hhVV, hhtt couplings, with interesting interplay for new physics bounds
- Future direction 1: Can we develop no lose theorems for the new physics accompanying a coupling deviations?
- Future direction 2: Are these amplitudes useful beyond unitarity violation? Are there better/stronger unitarity amplitudes?

THANK YOU

EXTRA SLIDES

V AND TOP COUPLINGS

Use a nonanalytic Higgs doublet

$$P = \frac{H}{\sqrt{|H|^2}} = \begin{pmatrix} 0 \\ 1 \end{pmatrix} + \begin{pmatrix} \sqrt{2}G^+/v \\ iG^0/v \end{pmatrix} + \cdots$$

$$(m_W^2 W^2 + \frac{1}{2} m_Z^2 Z^2) \left(1 + 2(1+\delta_{hVV})\frac{h}{v} + (1+\delta_{hhVV})\frac{h^2}{v^2} + c_3 \frac{h^3}{v^3}\right)$$

$$\to |DP|^2 \left(\delta_{hVV} v X + \frac{1}{2}\delta_{hhVV} X^2 + \frac{c_3}{2v} X^3\right)$$

$$-m_t \overline{T} T \left[1 + (1+\delta\kappa_t)\frac{h}{v} + \frac{1}{2} c_2 \left(\frac{h}{v}\right)^2 + \frac{1}{6} c_3 \left(\frac{h}{v}\right)^3\right]$$

$$\to -m_t \overline{T}_R P \epsilon \begin{pmatrix} T_L \\ B_L \end{pmatrix} \left[\delta\kappa_t \frac{X}{v} + \frac{1}{2} c_2 \left(\frac{X}{v}\right)^2 + \frac{1}{6} c_3 \left(\frac{X}{v}\right)^3 + \cdots\right] + h.c.$$