HIGGS COUPLINGS MEASUREMENTS AND MODEL INDEPENDENT BOUNDS ON BSM

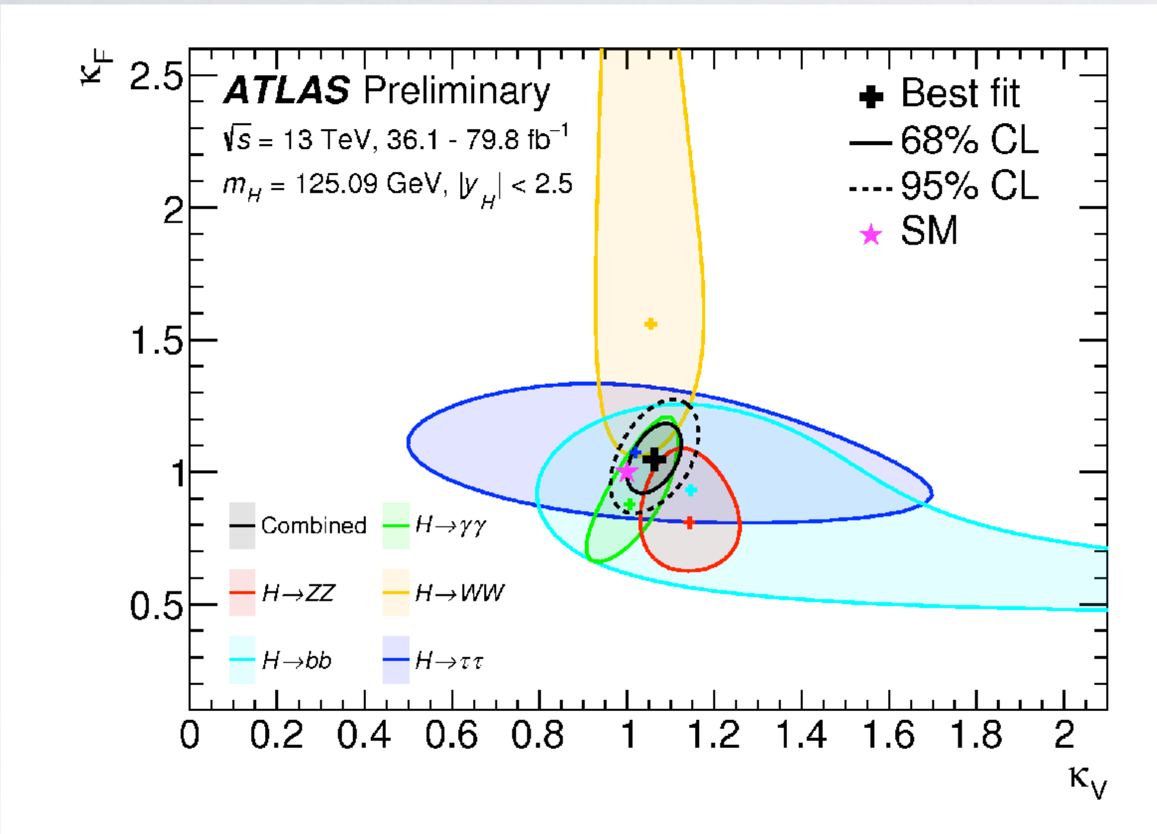
freepik.com

Spencer Chang (U. Oregon)
w/ F. Abu-Ajamieh, M. Chen, M. Luty

JHEP 2020, 140 (2020) and arXiv:2009.11293

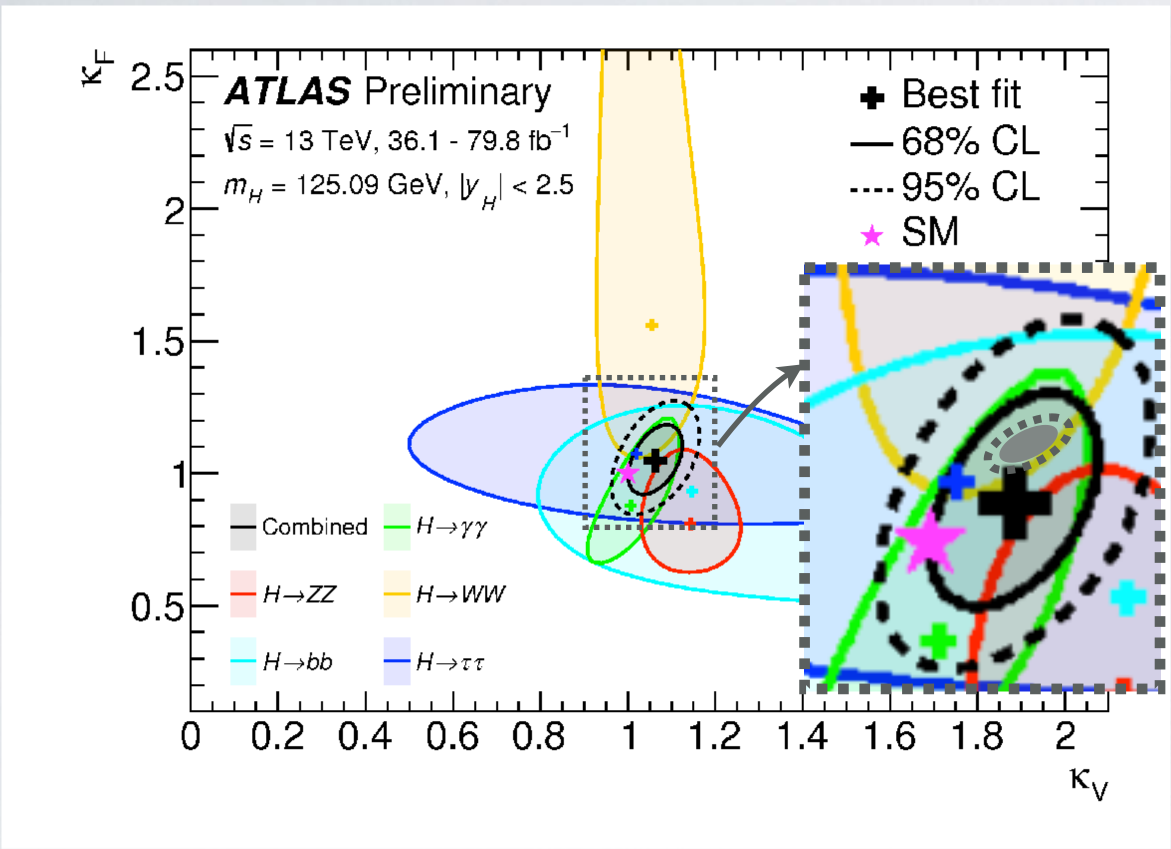
CEPC 10/26/20 Workshop

NEW PHYSICS SCALE BOUND FROM UNITARITY VIOLATION



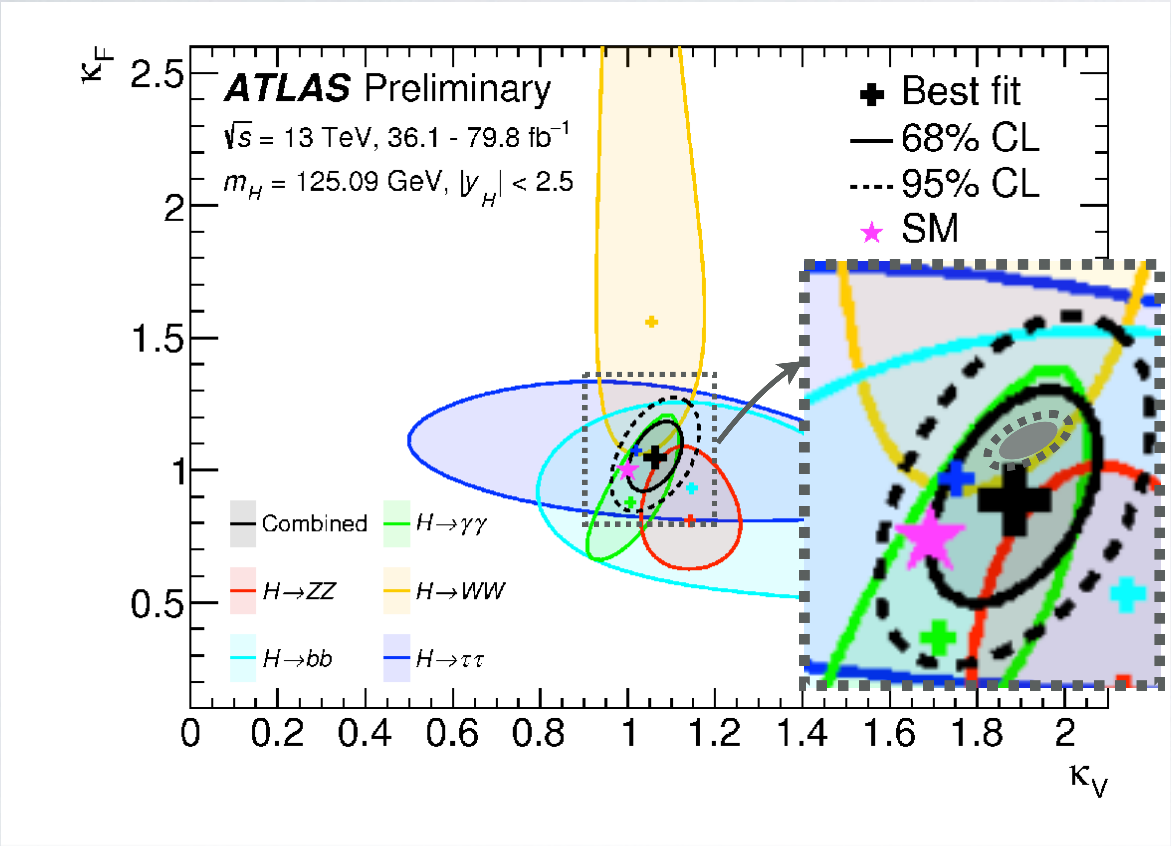
What are the new physics implications of a Higgs coupling deviation?

NEW PHYSICS SCALE BOUND FROM UNITARITY VIOLATION



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

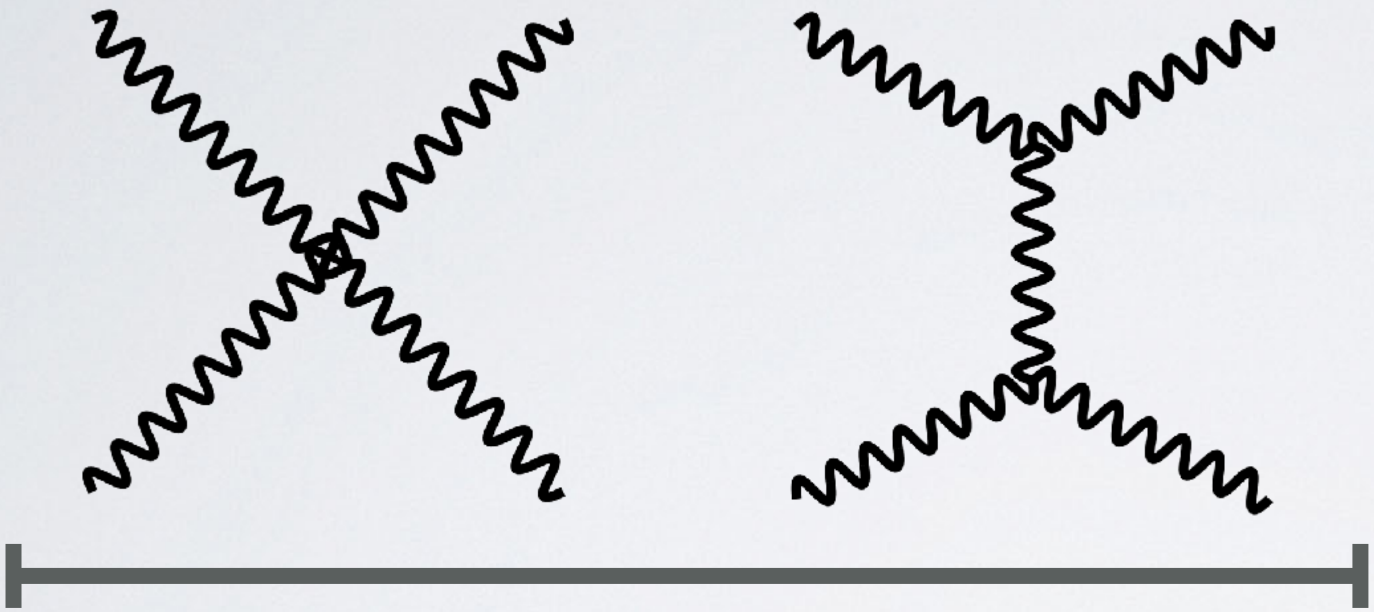
NEW PHYSICS SCALE BOUND FROM UNITARITY VIOLATION



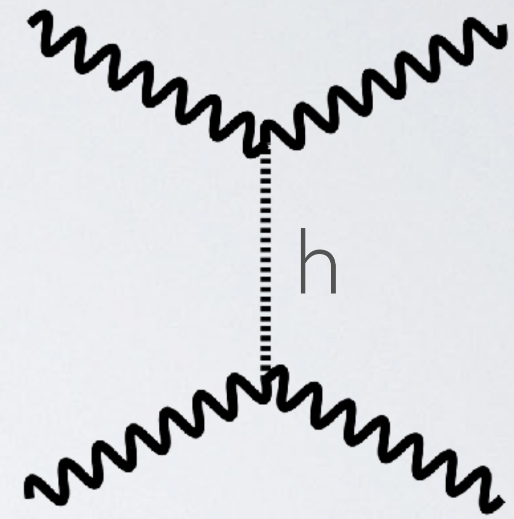
What are the new physics implications of a Higgs coupling deviation?

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 Henning et.al. 1812.09299 & Stolarski, Wu 2006.09374)

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

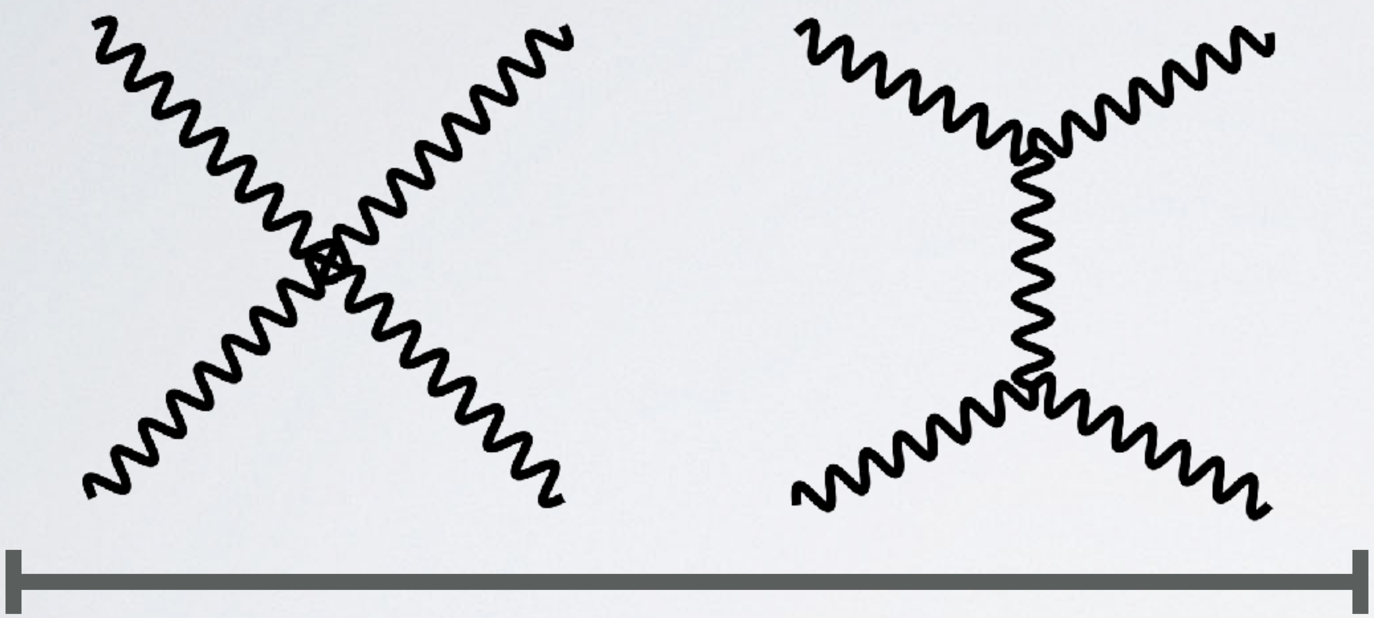


$M = c\ \text{Energy}^2 + \ldots$

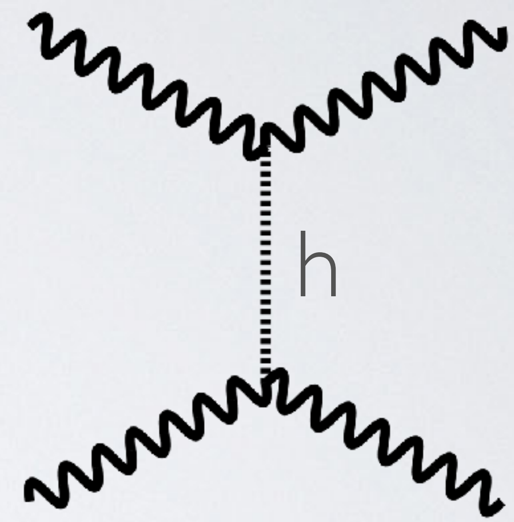


$M = -c\ \text{Energy}^2 + \ldots$

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

$$
\begin{aligned}
\mathcal{L} = \mathcal{L}_{\mathrm{SM}} &- \delta_3 \frac{m_h^2}{2v} h^3 - \delta_4 \frac{m_h^2}{8v^2} h^4 - \sum_{n=5}^{\infty} \frac{c_n}{n!} \frac{m_h^2}{v^{n-2}} h^n + \cdots \\
&+ \delta_{Z1} \frac{m_Z^2}{v} h Z^\mu Z_\mu + \delta_{W1} \frac{2m_W^2}{v} h W^{\mu+} W_\mu^- + \delta_{Z2} \frac{m_Z^2}{2v^2} h^2 Z^\mu Z_\mu + \delta_{W2} \frac{m_W^2}{v^2} h^2 W^{\mu+} W_\mu^- \\
&+ \sum_{n=3}^{\infty} \left[\frac{c_{Zn}}{n!} \frac{m_Z^2}{v^n} h^n Z^\mu Z_\mu + \frac{c_{Wn}}{n!} \frac{2m_W^2}{v^n} h^n W^{\mu+} W_\mu^- \right] + \cdots \\
&- \delta_{t1} \frac{m_t}{v} h \bar{t} t - \sum_{n=2}^{\infty} \frac{c_{tn}}{n!} \frac{m_t}{v^n} h^n \bar{t} t + \cdots
\end{aligned}
$$

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

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

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

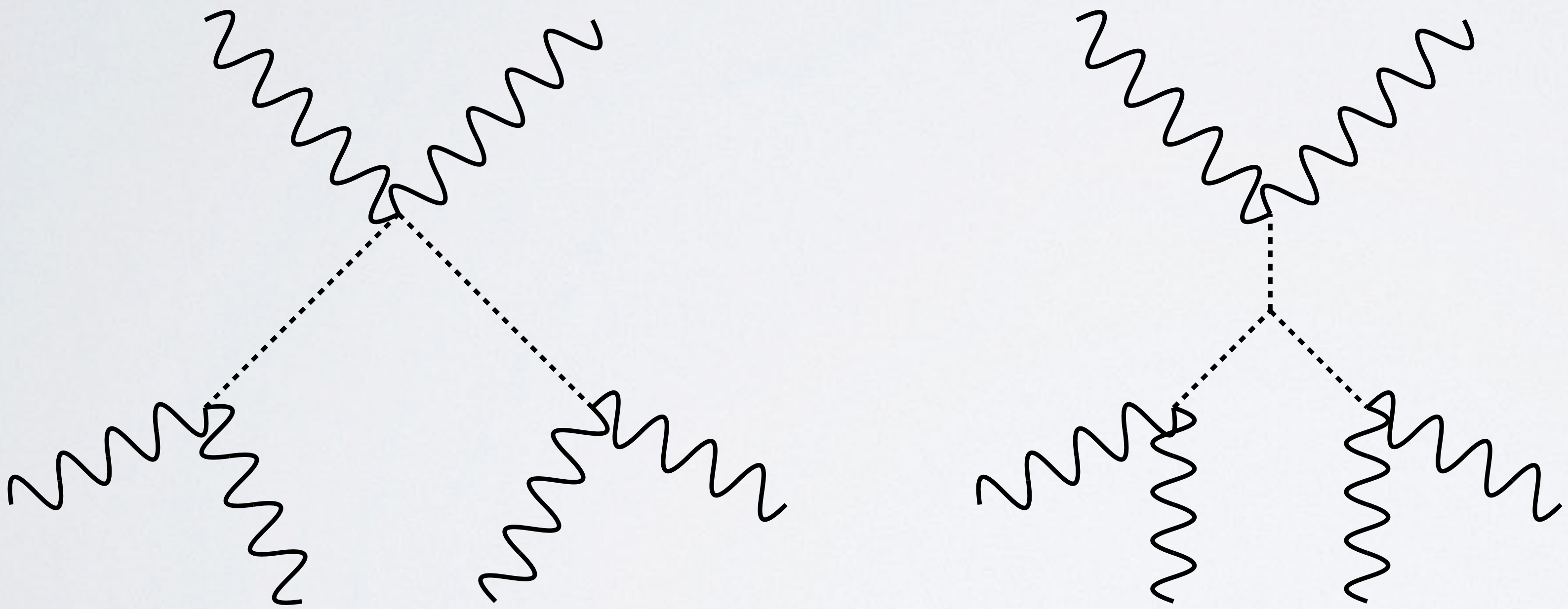
$$+ \sum_{n=3}^{\infty} \left[\frac{c_{Zn}}{n!} \frac{m_Z^2}{v^n} h^n Z^\mu Z_\mu + \frac{c_{Wn}}{n!} \frac{2m_W^2}{v^n} h^n W^{\mu +} W_\mu^- \right] + \cdots$$ W/Z Couplings

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

Any nonzero **δ** or ***c*** coupling is a sign of new physics, which leads to unitarity violation at high energies, giving an upper bound on this new physics

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 $M \sim 1/\mathrm{Energy}^2$ requires SM trilinear value!

BEST CHANNELS FOR HIGGS POTENTIAL

$$hW_L^+W_L^- \to W_L^+W_L^- \ : \ E_{max} = \frac{6.4 \ \mathrm{TeV}}{\left|\frac{\delta_3}{11}\right|}$$

$$W_L^+W_L^+W_L^- \to W_L^+W_L^+W_L^- \ : \ E_{max} = \frac{4.3 \ \mathrm{TeV}}{\sqrt{\left|\frac{\delta_3}{11}\right|}}$$

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

BEST CHANNELS FOR HIGGS POTENTIAL

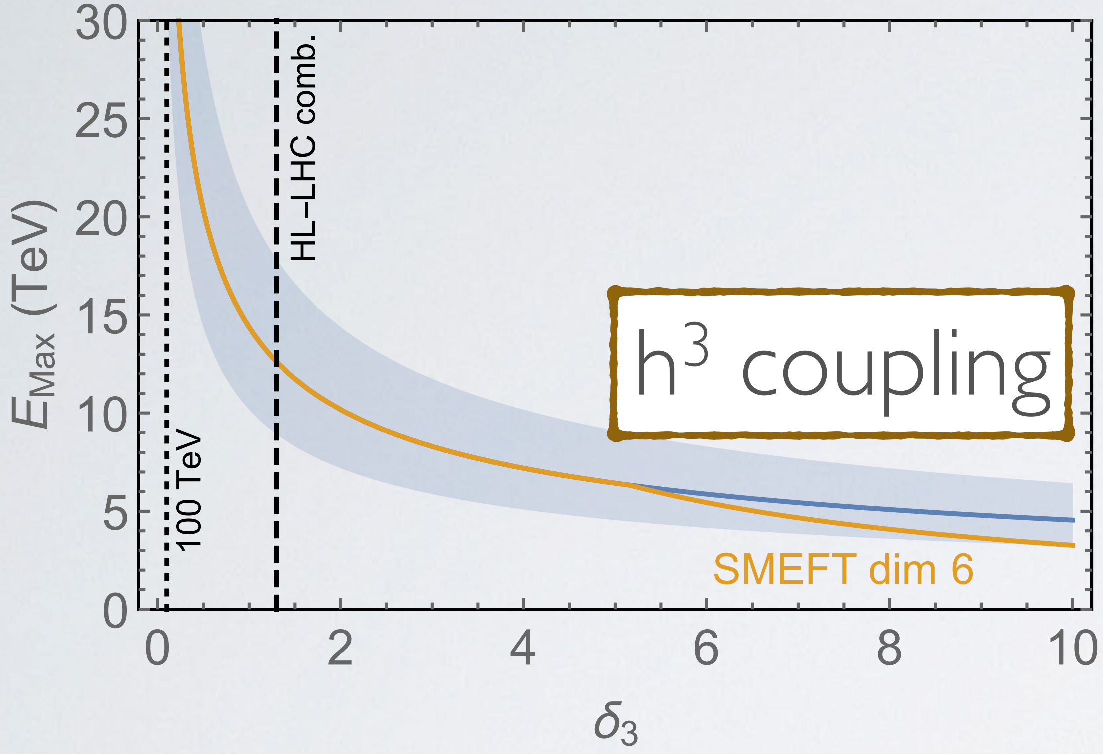
$$hW_L^+W_L^- \to W_L^+W_L^- \ : \ E_{max} = \frac{6.4 \text{ TeV}}{\left|\frac{\delta_3}{11}\right|}$$

$$W_L^+W_L^+W_L^- \to W_L^+W_L^+W_L^- \ : \ E_{max} = \frac{4.3 \text{ TeV}}{\sqrt{\left|\frac{\delta_3}{11}\right|}}$$

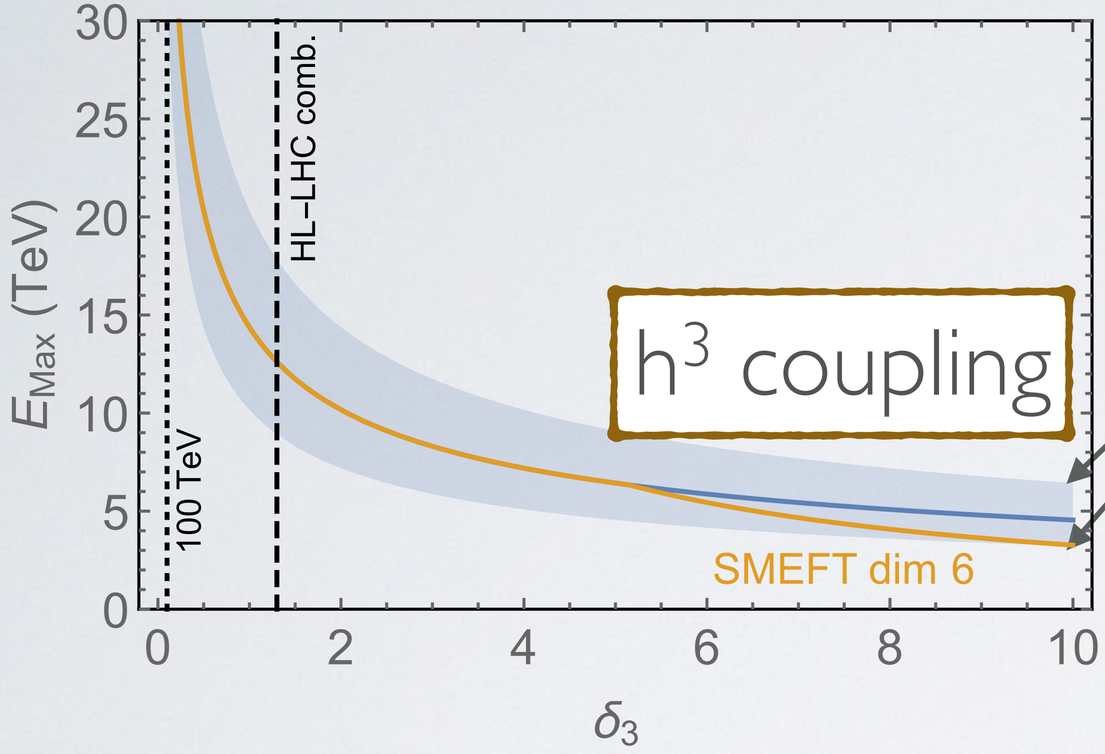
(Normalized to largest deviation consistent with ATLAS and CMS di-Higgs 95%CL constraints)

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

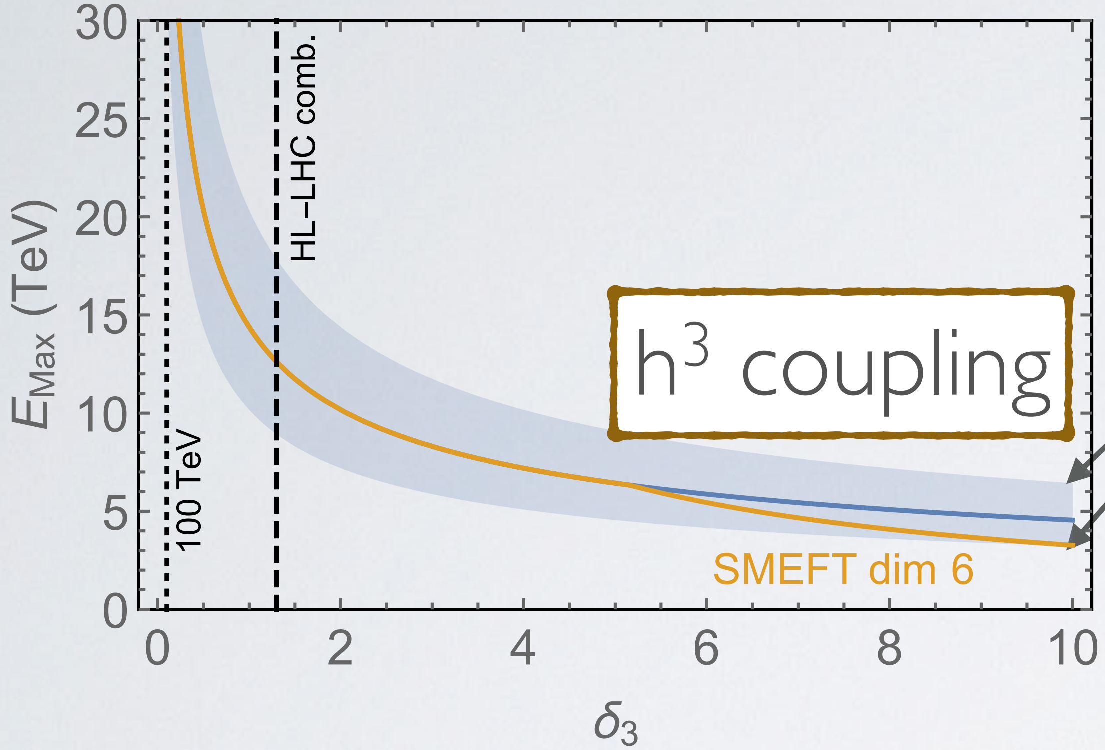


HIGGS TRILINEAR COUPLING DEVIATION



Estimated
Theoretical uncertainty of
Unitarity violating scale

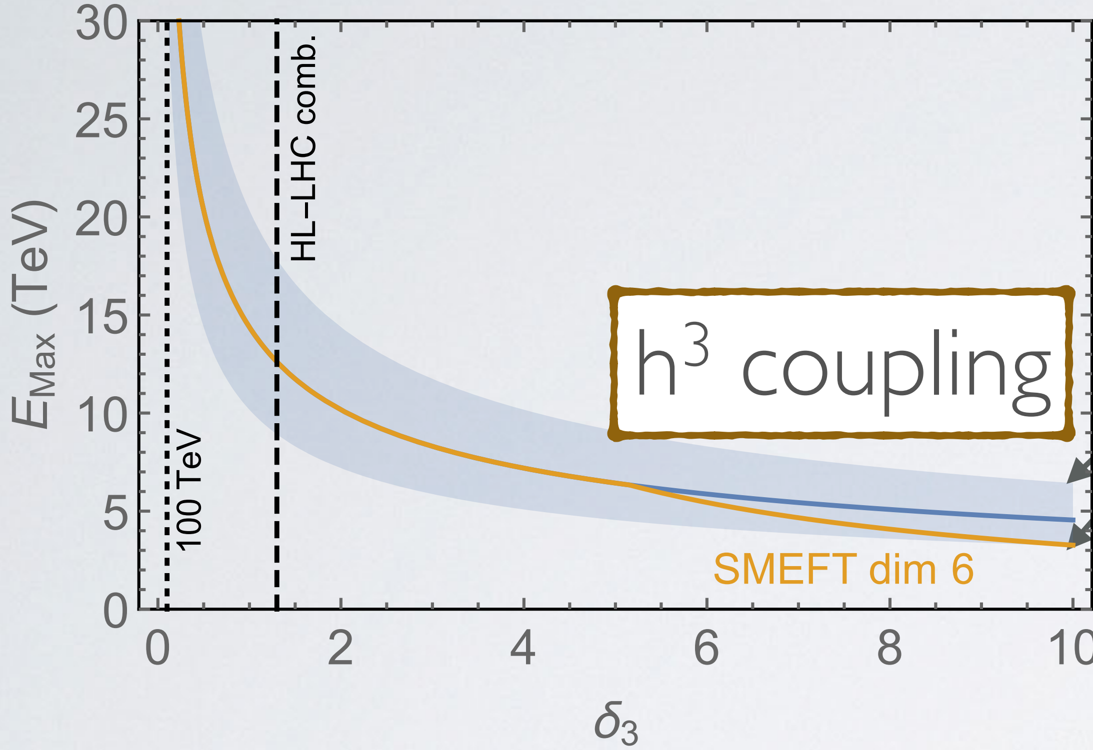
HIGGS TRILINEAR COUPLING DEVIATION



Estimated
Theoretical uncertainty of
Unitarity violating scale

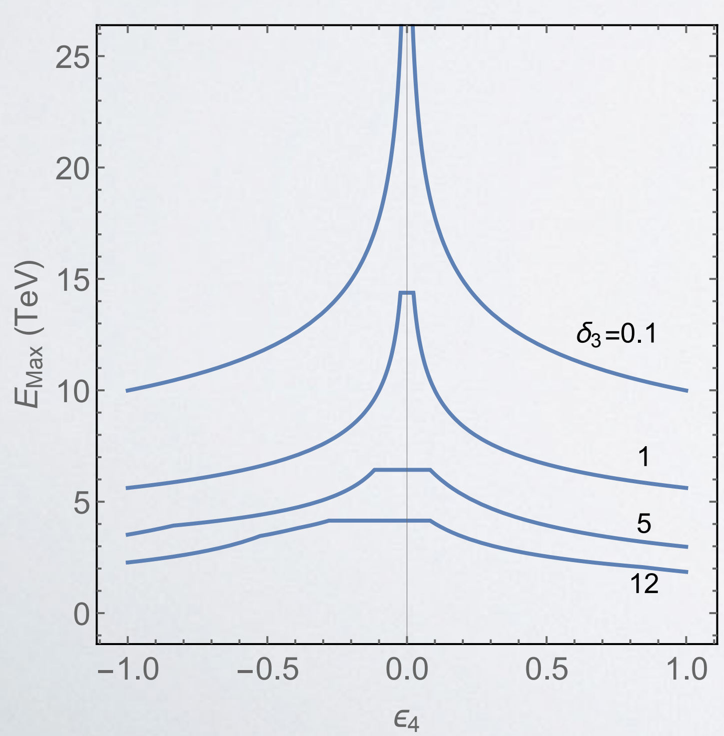
Current bound allows new physics below ~ 4 TeV

HIGGS TRILINEAR COUPLING DEVIATION



Estimated
Theoretical uncertainty of
Unitarity violating scale

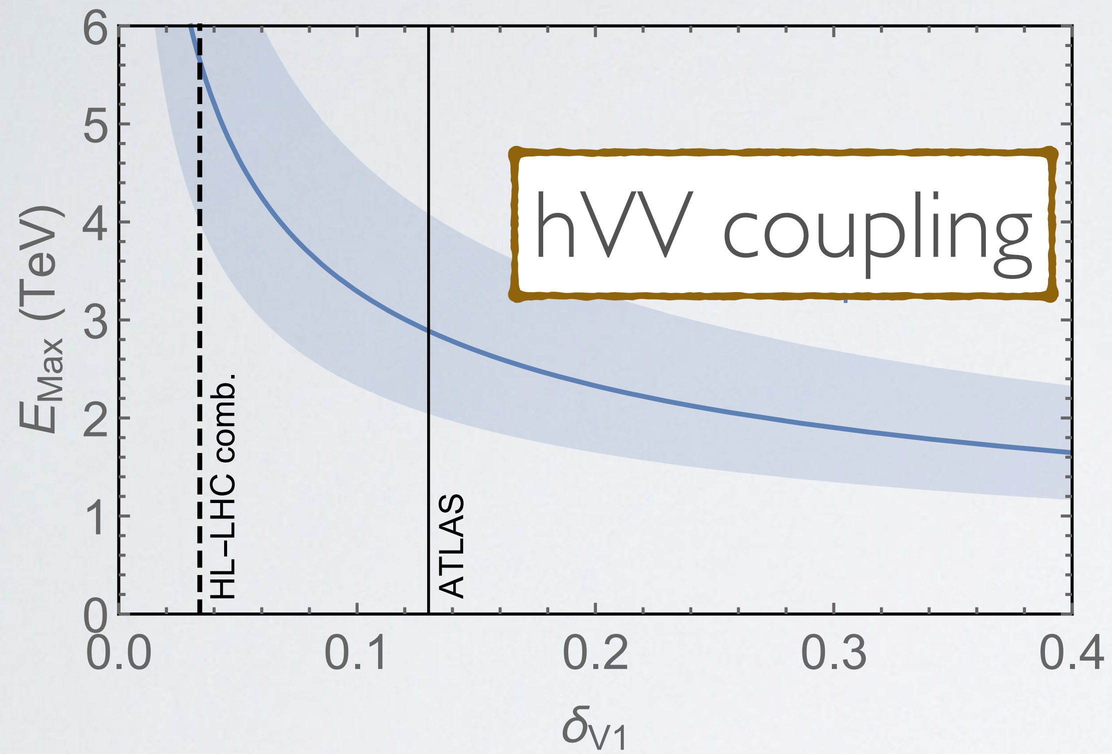
Current bound allows new physics below ~ 4 TeV

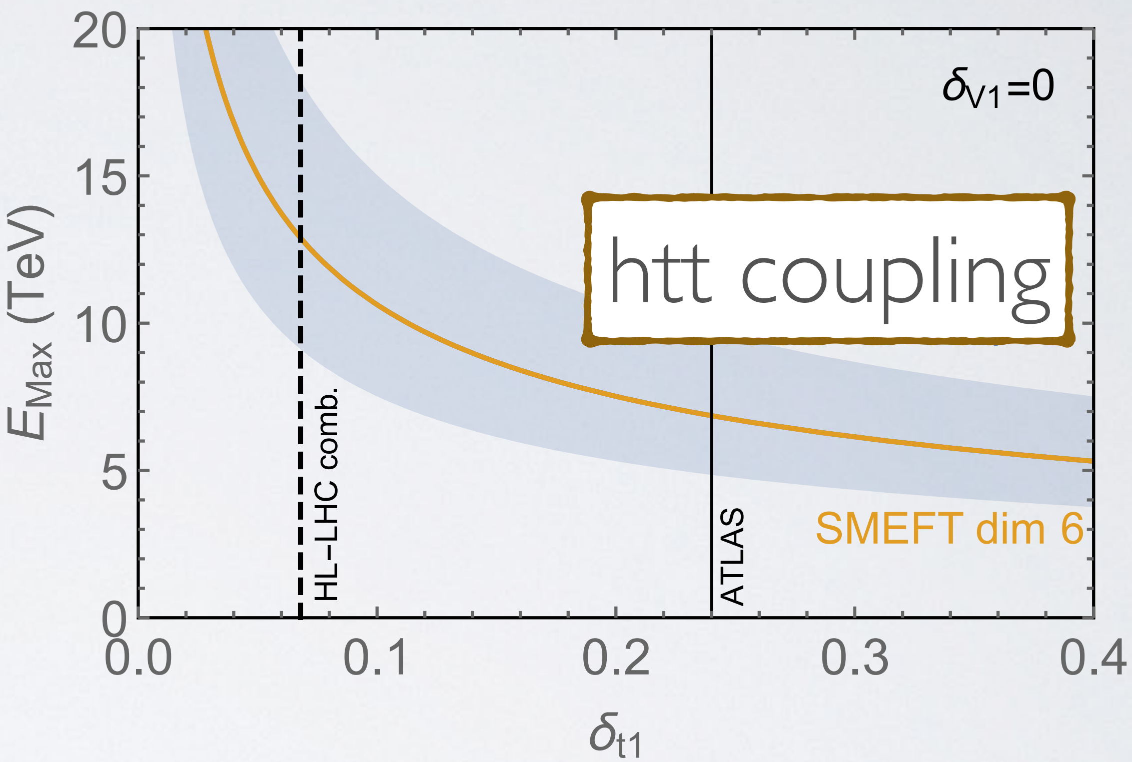


Unitarity requires higher order couplings to be correlated

Quartic deviation must satisfy SMEFT-like relation, $\delta_4=6\delta_3(1+\epsilon_4)$, to keep new physics above 10 TeV

VECTOR AND TOP COUPLINGS





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!

PRECISION HIGGS

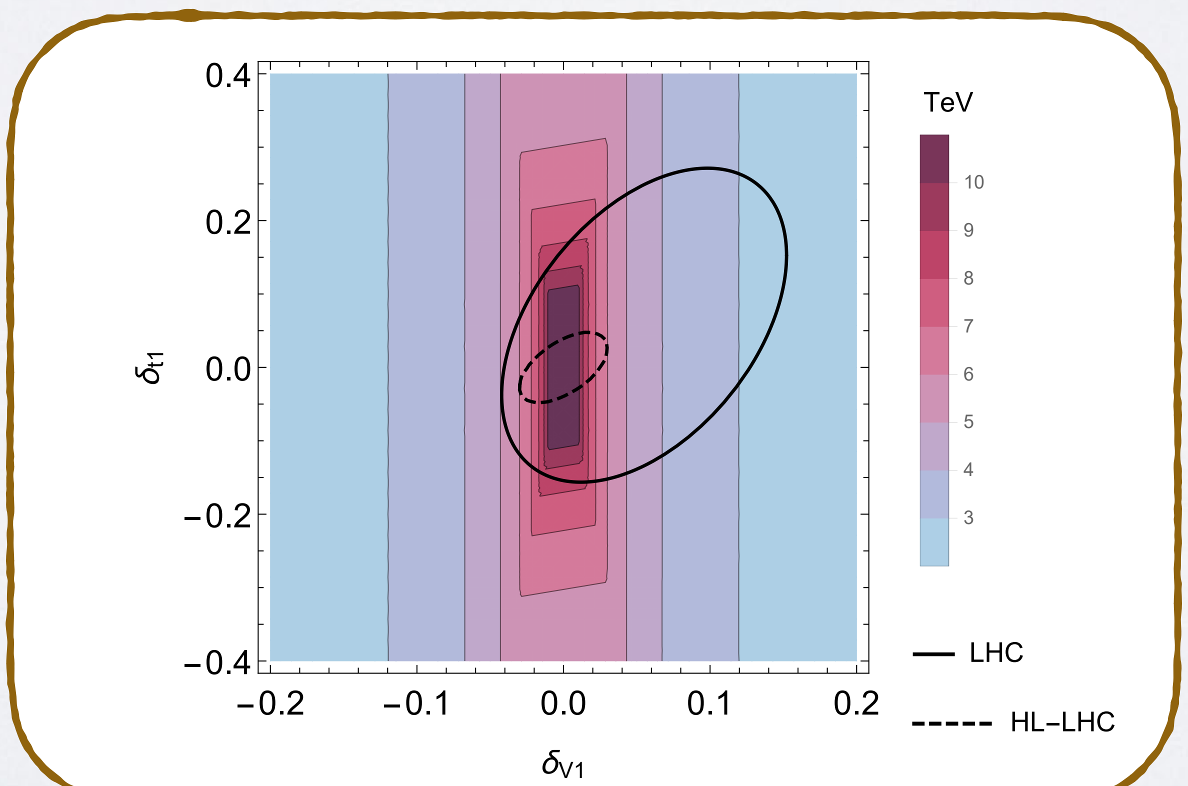
kappa-0	HL-LHC	LHeC	HE-LHC		ILC			CLIC			CEPC	FCC-ee		FCC-ee/eh/hh
			S2	S2′	250	500	1000	380	15000	3000		240	365	
κ_W [%]	1.7	0.75	1.4	0.98	1.8	0.29	0.24	0.86	0.16	0.11	1.3	1.3	0.43	0.14
κ_Z [%]	1.5	1.2	1.3	0.9	0.29	0.23	0.22	0.5	0.26	0.23	0.14	0.20	0.17	0.12
κ_g [%]	2.3	3.6	1.9	1.2	2.3	0.97	0.66	2.5	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

Taken from Higgs@FutureColliders report (1905.03764)

PRECISION HIGGS

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$\star$	5.0	2.2	3.7	4.7	3.9	0.29
$\kappa_{Z\gamma}$ [%]	10.	–	5.7	3.8	99$\star$	86$\star$	85$\star$	120$\star$	15	6.9	8.2	81$\star$	75$\star$	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$\star$	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

Taken from Higgs@FutureColliders report (1905.03764)



CONCLUSIONS

CONCLUSIONS

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

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)

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

CONCLUSIONS

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

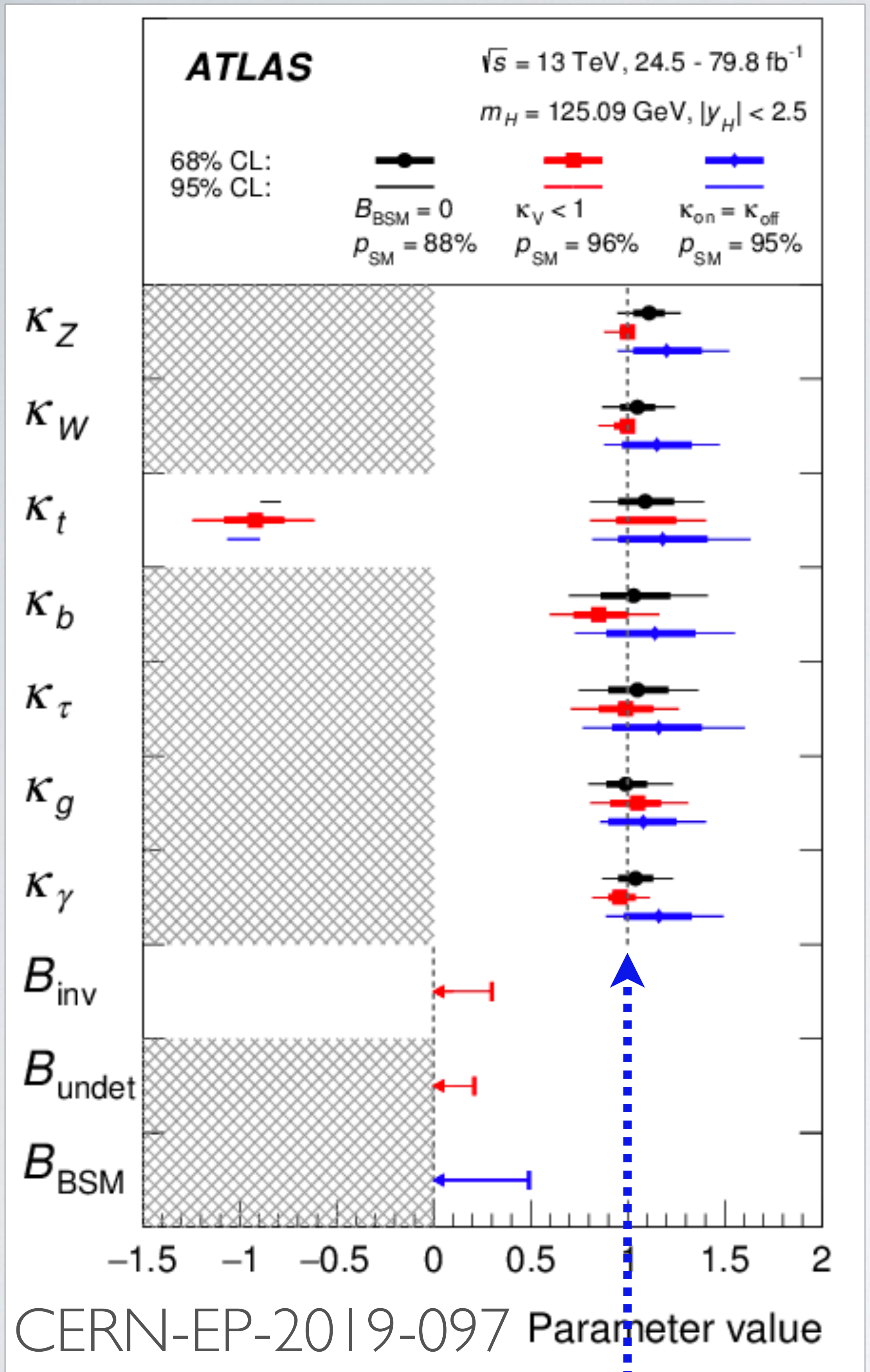
- Higgs self-couplings, hVV, htt current bounds allow new physics at LHC energies and future sensitivities can still place bounds below 10 TeV (with different sensitivities)

- Higher order couplings (e.g. hhhh, hhVV, hhtt) are SMEFT-like if new physics scale is well above TeV scale

- Alternatively, if no new physics is found other than coupling deviation, indirect evidence for SMEFT-like structure

THANK YOU

EXTRA SLIDES



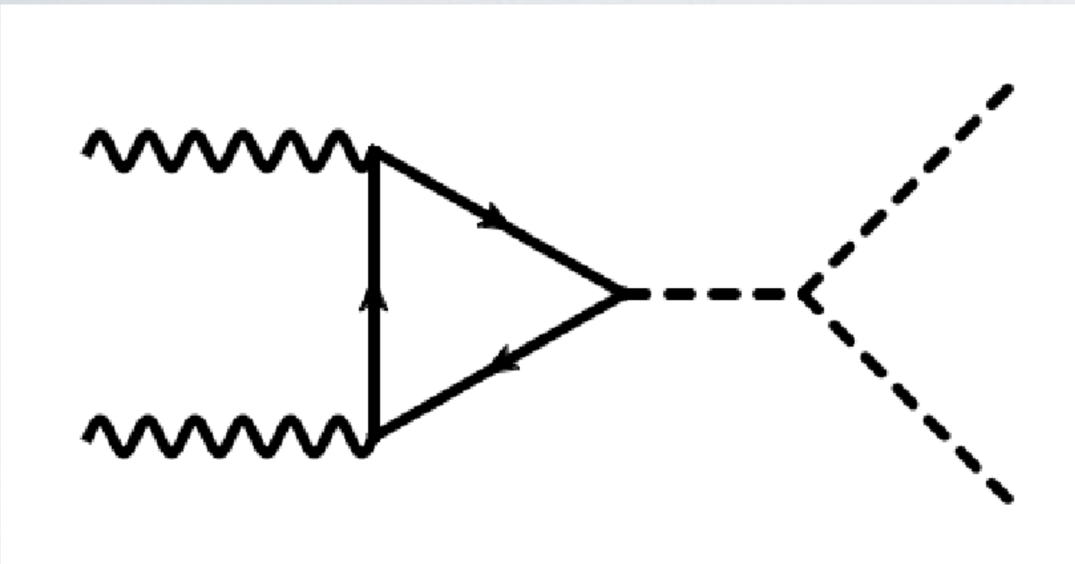
CERN-EP-2019-097

Standard Model values

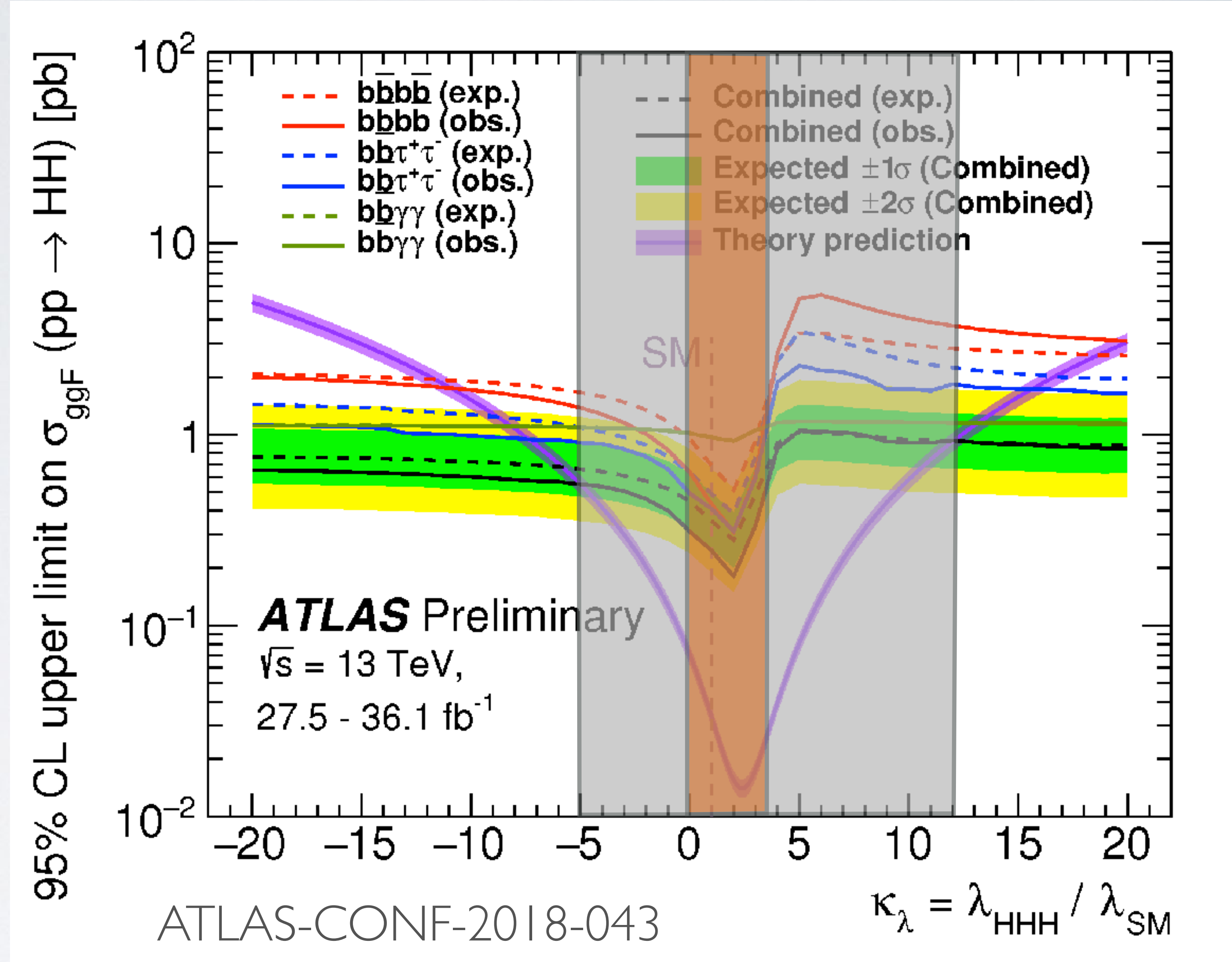
HIGGS COUPLINGS MEASUREMENTS

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

TRILINEAR SEARCH



Trilinear probed by search for Double Higgs production



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

What do we do if we find a significant deviation from the SM prediction?

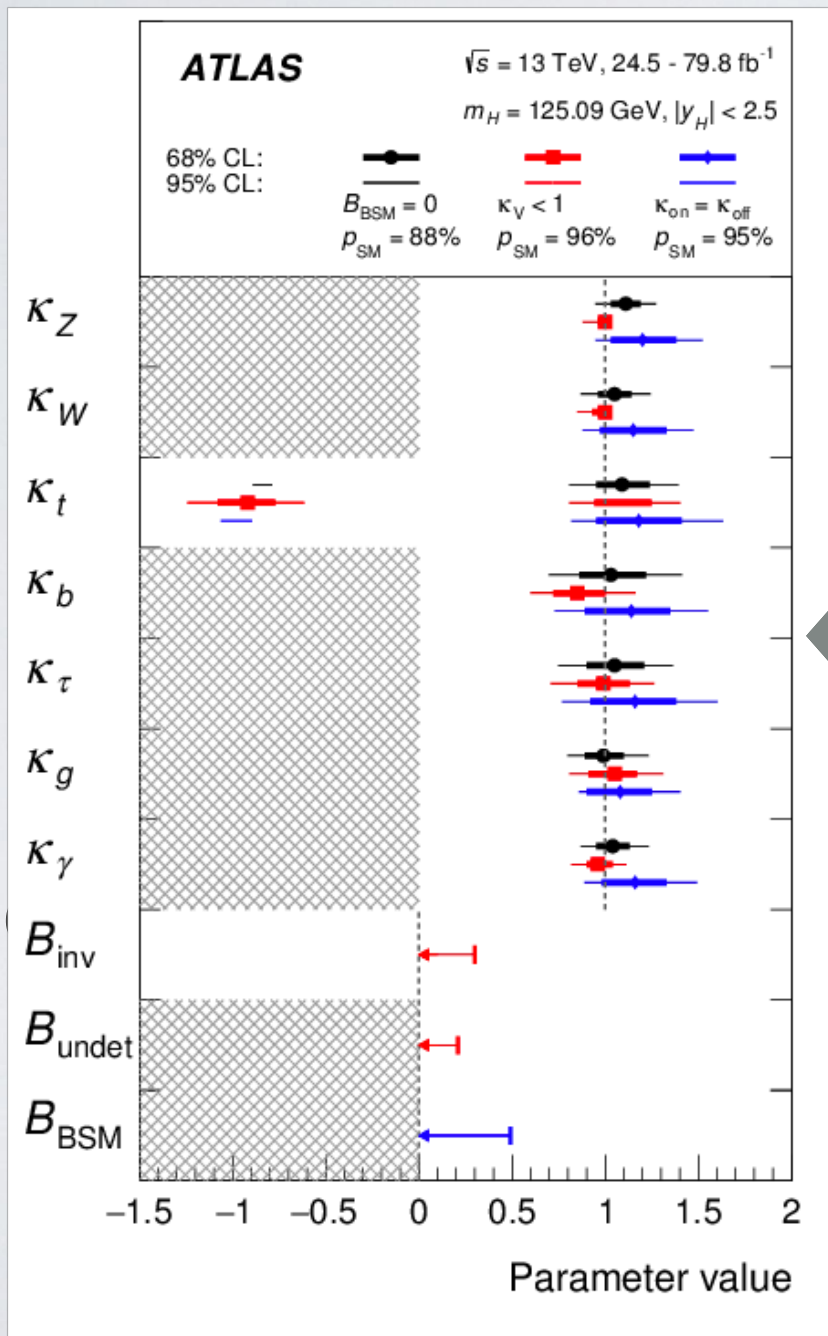
What do we do if we find a significant deviation from the SM prediction?

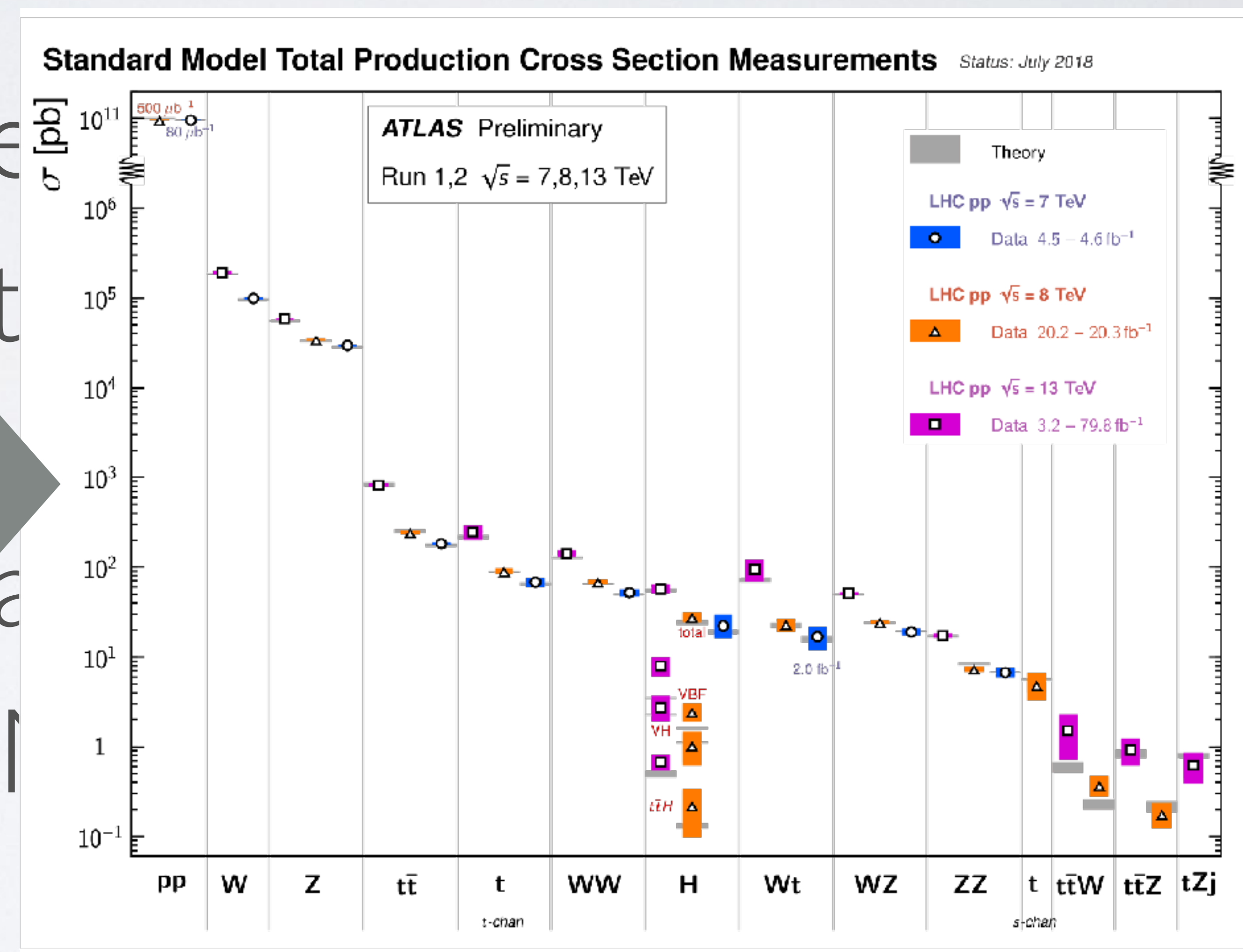
- New physics is at accessible energy scales: Model build and find associated particles/dynamics

What do we do if we find a significant deviation from the SM prediction?

- New physics is at accessible energy scales: Model build and find associated particles/dynamics
- New physics may be at higher scales: Find other correlated signals in SM processes

What do we do if we find a significant deviation from the SM prediction?





GENERAL HIGGS COUPLINGS

Higgs Effective Field Theory (HEFT) parameterizes most general Higgs couplings phenomenologically

$$V = \frac{1}{2} m_h^2 h^2 + \lambda_{hhh} h^3 + \lambda_{hhhh} h^4 + \lambda_{hhhhh} h^5 + \cdots$$

$$V \to \frac{1}{2} m_h^2 X^2 + \lambda_{hhh} X^3 + \lambda_{hhhh} X^4 + \lambda_{hhhhh} X^5 + \cdots$$

SU(2) x U(1) invariant form uses an nonanalytic field

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

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

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 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

MODEL DEPENDENCE OF TERMS

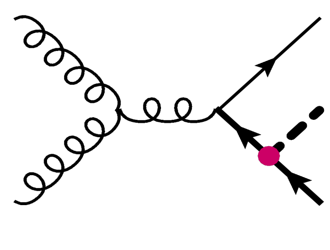
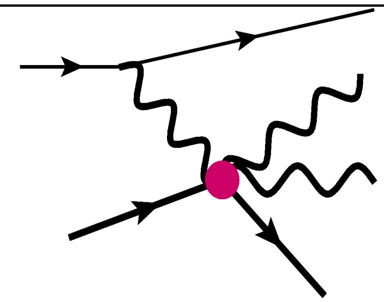
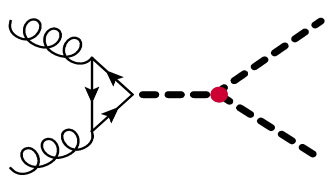
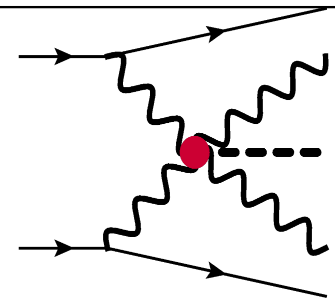
$$
\begin{aligned}
X^3 &\sim h^3 + \vec{G}^2(h^2 + h^3 + \cdots) + \vec{G}^4(h + h^2 + \cdots) + \vec{G}^6(1 + h + \cdots) \\
&\quad + \vec{G}^8(1 + h + \cdots) + \vec{G}^{10}(1 + h + \cdots) + \cdots\,, \\
X^4 &\sim h^4 + \vec{G}^2(h^3 + h^4 + \cdots) + \vec{G}^4(h^2 + h^3 + \cdots) + \vec{G}^6(h +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

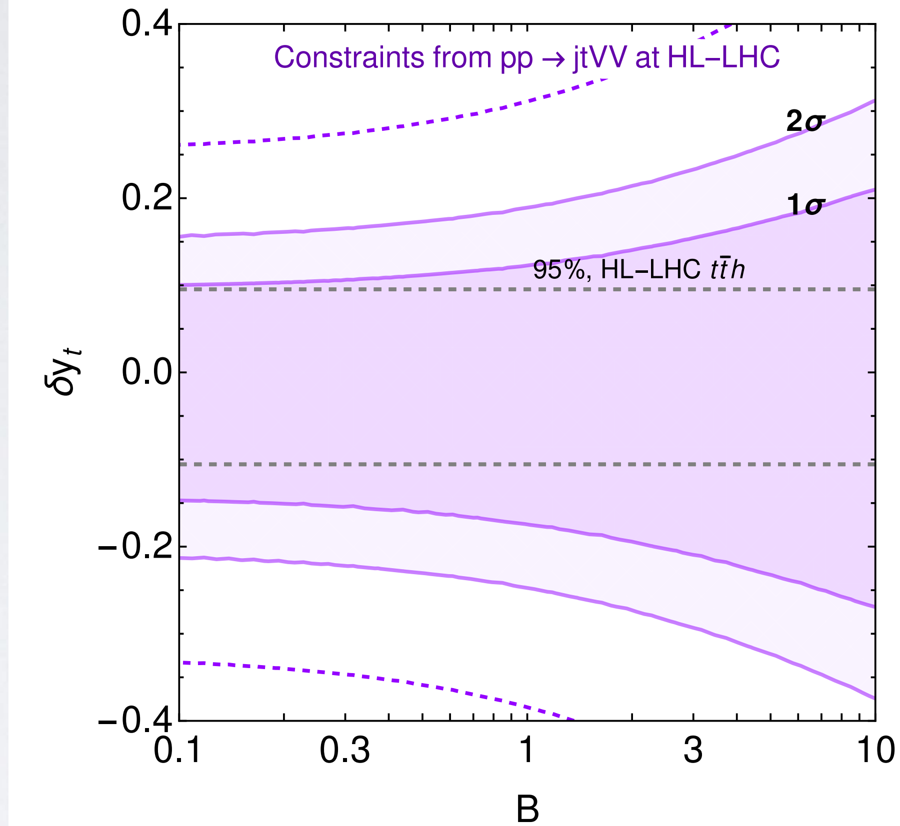
(Schematic without coefficients, but we know cancellations can occur due to SMEFT description)

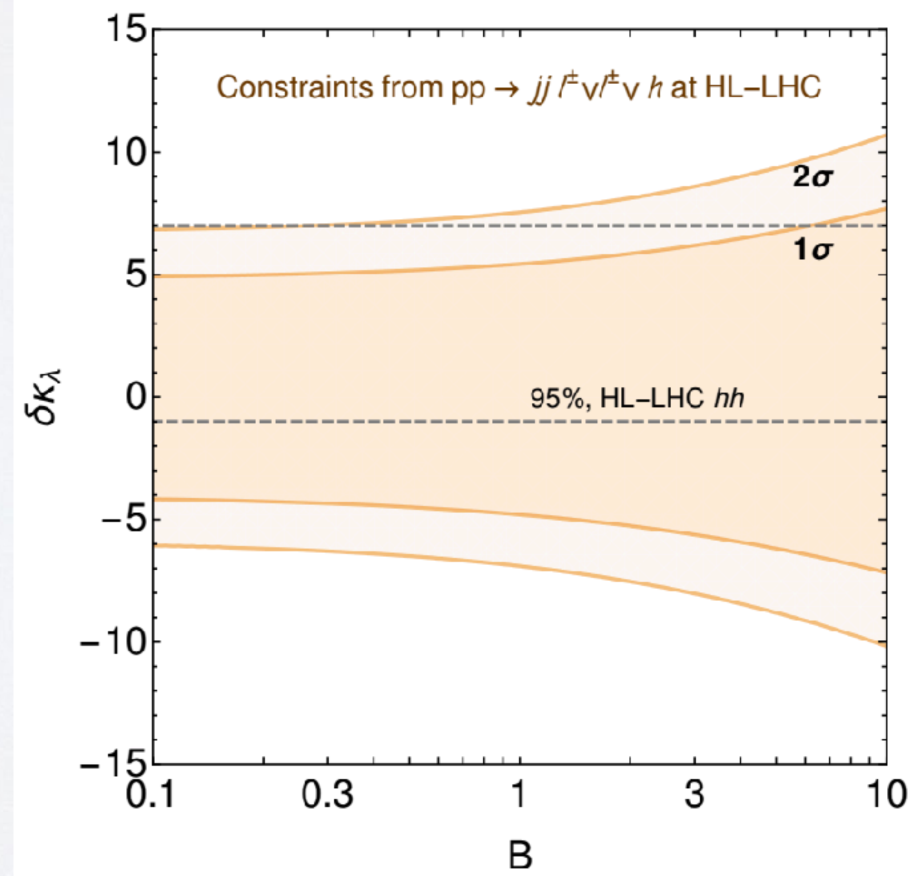
Terms circled can only come from trilinear!

COLLIDER TESTS OF UNITARITY VIOLATION

Henning et.al.1812.09299

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?