UNITARITY VIOLATION FROM NONSTANDARD HIGGS COUPLINGS

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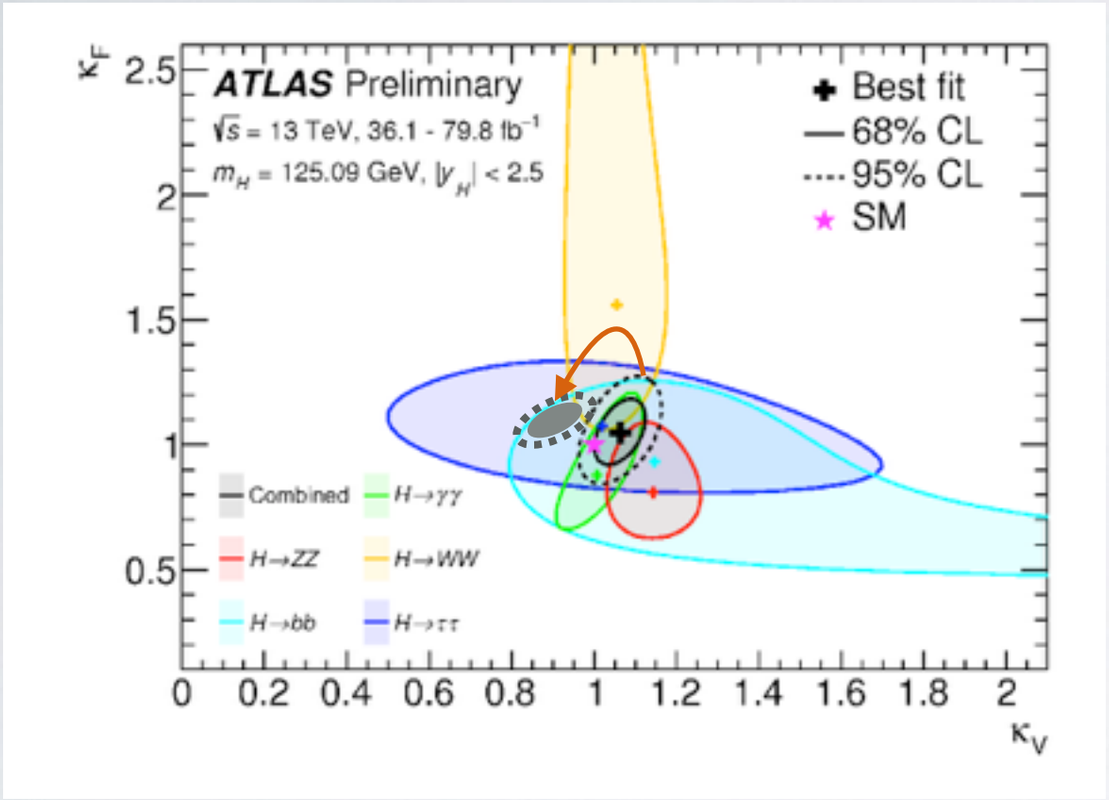
Spencer Chang (U. Oregon)
w/ Markus Luty 1902.05556+ongoing
also see Falkowski & Rattazzi 1902.05936
and earlier work by Belyaev et.al. 1212.3860

SNOWMASS EF02 6/26/20 Meeting

NEW PHYSICS SCALE BOUND FROM UNITARITY VIOLATION (W/ LUTY)



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 1812.09299)

GENERAL HIGGS POTENTIAL

$$V_{SM}(h) = \frac{m_h^2}{2}h^2 + \frac{m_h^2}{2v}h^3 + \frac{m_h^2}{8v^2}h^4$$

$$V_{gen}(h) = m_h^2 v^2 \left(\frac{h^2}{2v^2} + c_3 \frac{h^3}{3!v^3} + c_4 \frac{h^4}{4!v^4} + c_5 \frac{h^5}{5!v^5} \cdots \right)$$

$$= V_{SM} + m_h^2 v^2 \left(\delta_3 \, c_{3,SM} \frac{h^3}{3!v^3} + \delta_4 \, c_{4,SM} \frac{h^4}{4!v^4} + c_5 \frac{h^5}{5!v^5} \cdots \right)$$

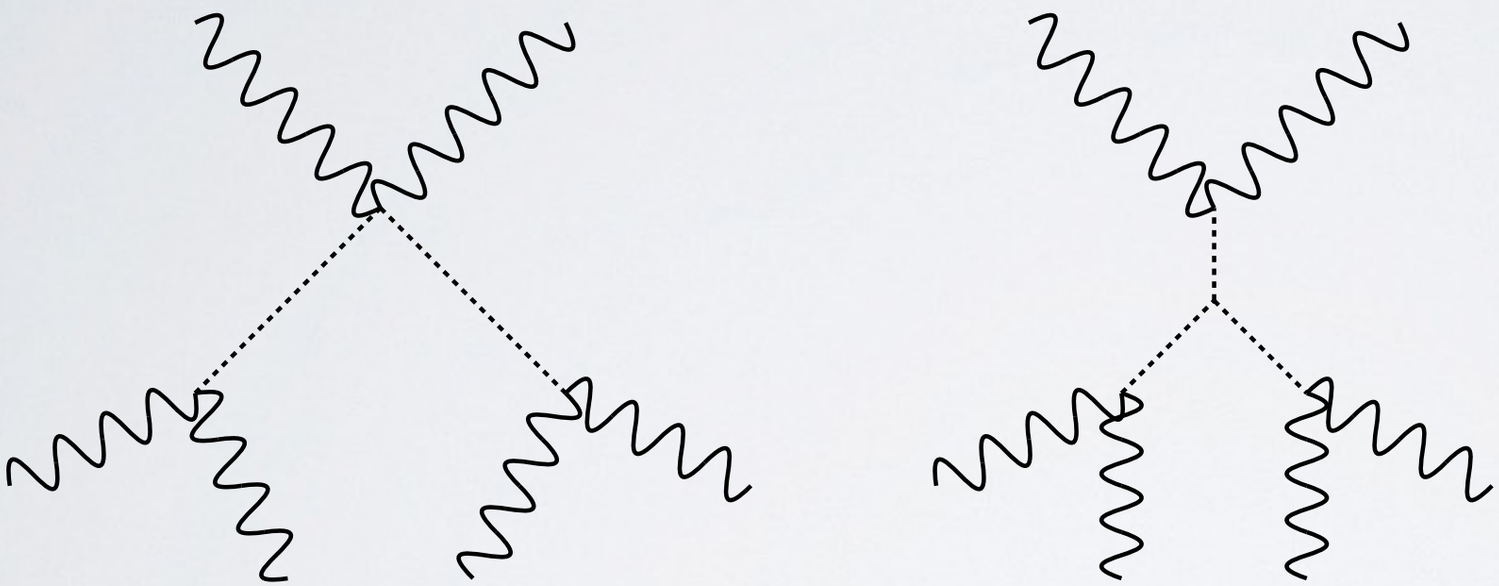
In some frameworks, like dimension 6 SMEFT op. $|H|^6$ predicts correlations of deviations,
e.g. $\boldsymbol{\delta}_4 = 6\boldsymbol{\delta}_3$, $c_5 = 45\boldsymbol{\delta}_3$, $c_6 = 45\boldsymbol{\delta}_3$

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!

Using equivalence theorem, can show at linear order in c_n, only V_L^6 and hV_L^4 amplitudes depend on just $\boldsymbol{\delta}_3$

BEST CHANNELS

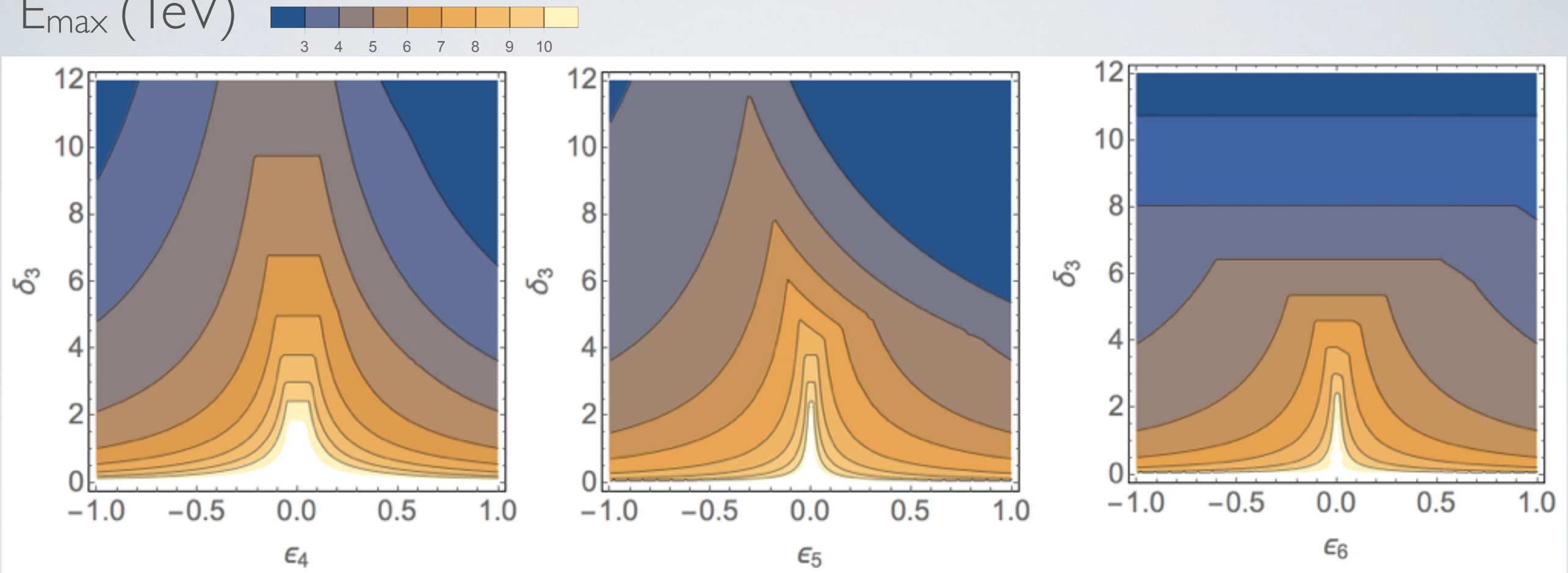
$$hW_L^+W_L^- \to W_L^+W_L^- \ : \ E_{max} = \frac{6.4 \text{ TeV}}{\left|\frac{\delta_3}{11}\right|}$$

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

(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

UNITARITY IMPLICATIONS ON H^4, H^5, H^6 COUPLINGS



h^4 frac. deviation from SMEFT dim 6 prediction

h^5

h^6

Takeaway: If cubic is nonstandard and predicts a unitarity scale ≫ TeV, higher couplings have to satisfy SMEFT prediction to keep unitarity scale high

CONCLUSIONS

- Precision Higgs couplings could discover a deviation from SM, suggesting new physics at some energy scale, unitarity puts upper bound on this

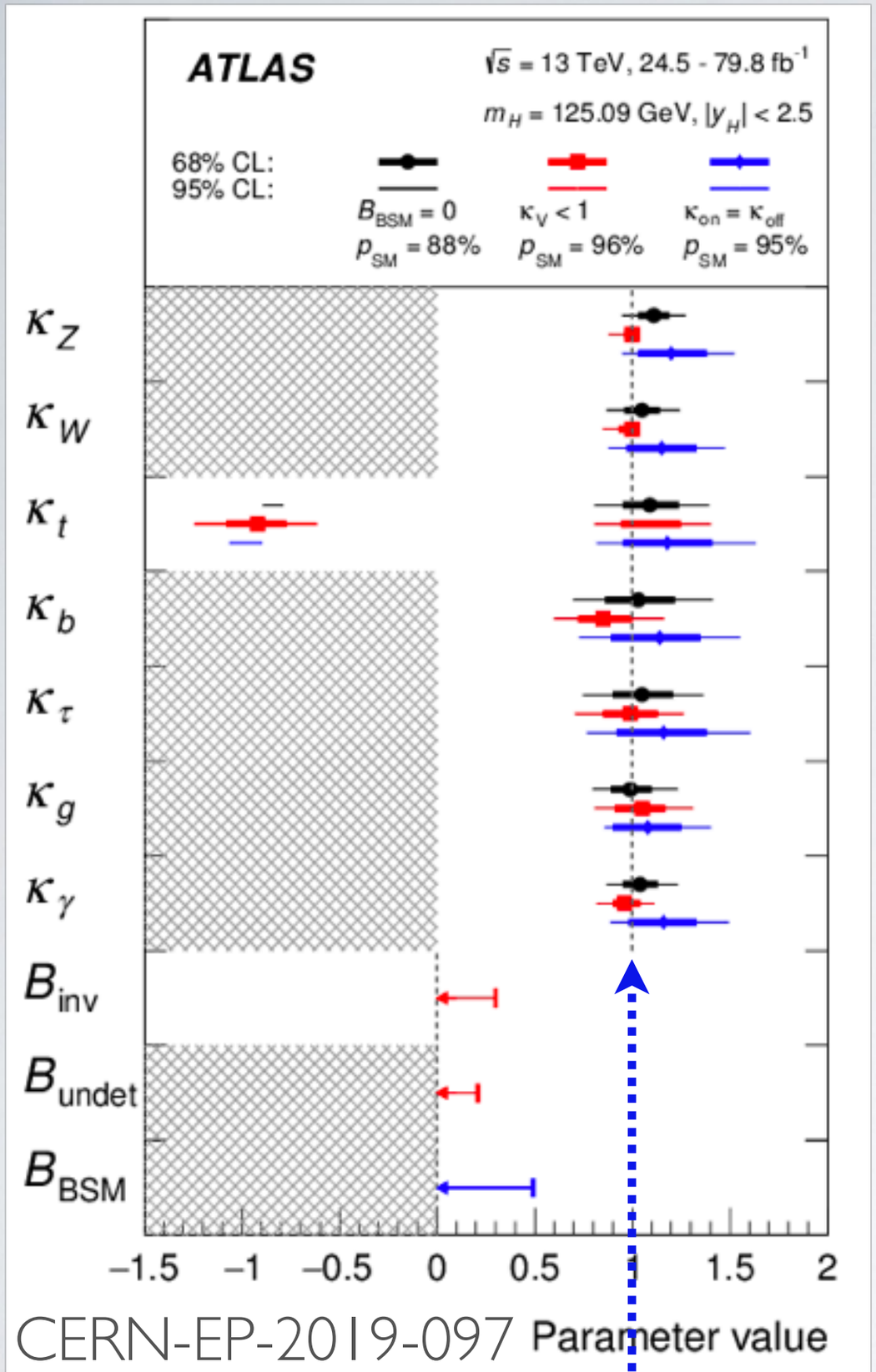
- Higgs self-couplings (and also tt, VV) can be analyzed, current bounds allow new physics at LHC energies (We're interested in working w/ those thinking about coupling projections)

- Possible to predict additional couplings are SMEFT-like if new physics scale is kept 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

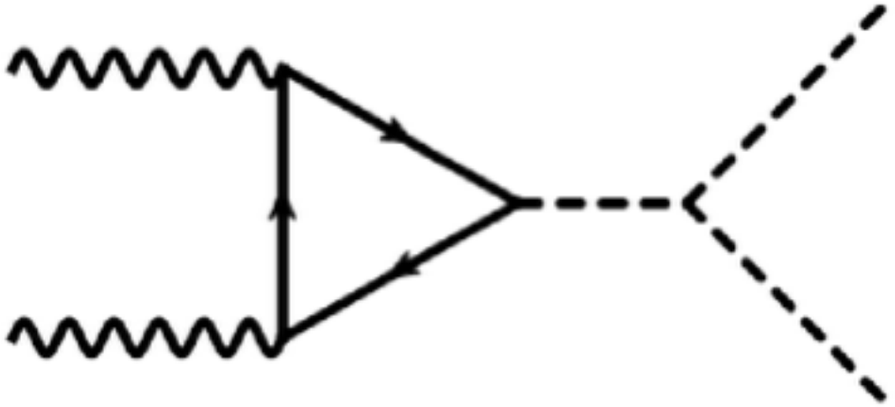
Fits to
σ x Branching Ratios,
for Higgs couplings
have 10-25%
errors and currently
agree with SM value

HIGGS COUPLINGS IN FUTURE

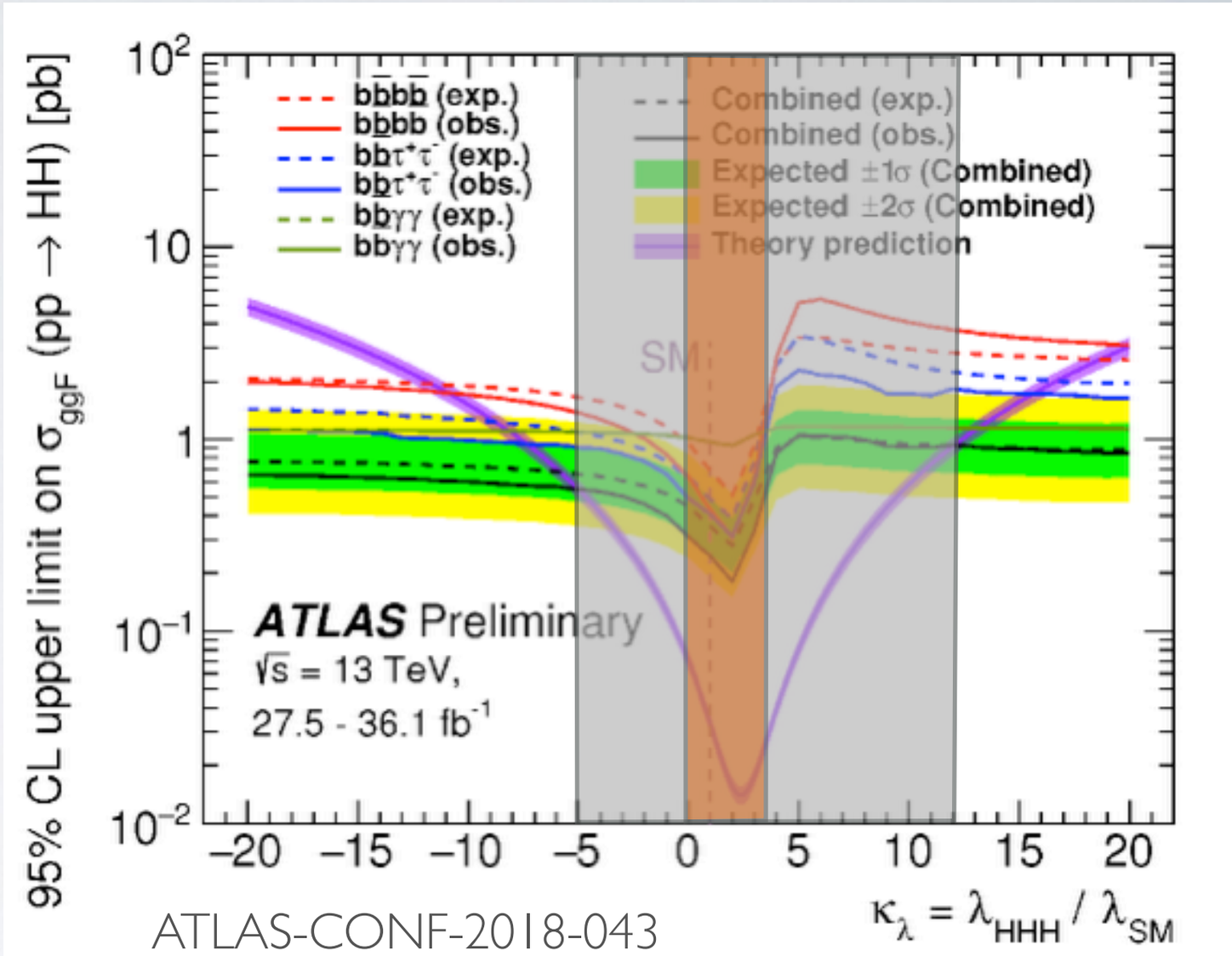
kappa-0	HL-LHC	LHeC	HE-LHC		ILC			CLIC			CEPC	FCC-ee		FCC-ee/eh/hh
			S2	S2′	250	500	1000	380	15000	3000		240	365	
κ_W [%]	1.7	0.75	1.4	0.98	1.8	0.29	0.24	0.86	0.16	0.11	1.3	1.3	0.43	0.14
κ_Z [%]	1.5	1.2	1.3	0.9	0.29	0.23	0.22	0.5	0.26	0.23	0.14	0.20	0.17	0.12
κ_g [%]	2.3	3.6	1.9	1.2	2.3	0.97	0.66	2.5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

Taken from Higgs@FutureColliders report (1905.03764)

TRILINEAR SEARCH



Trilinear probed by search for Double Higgs production

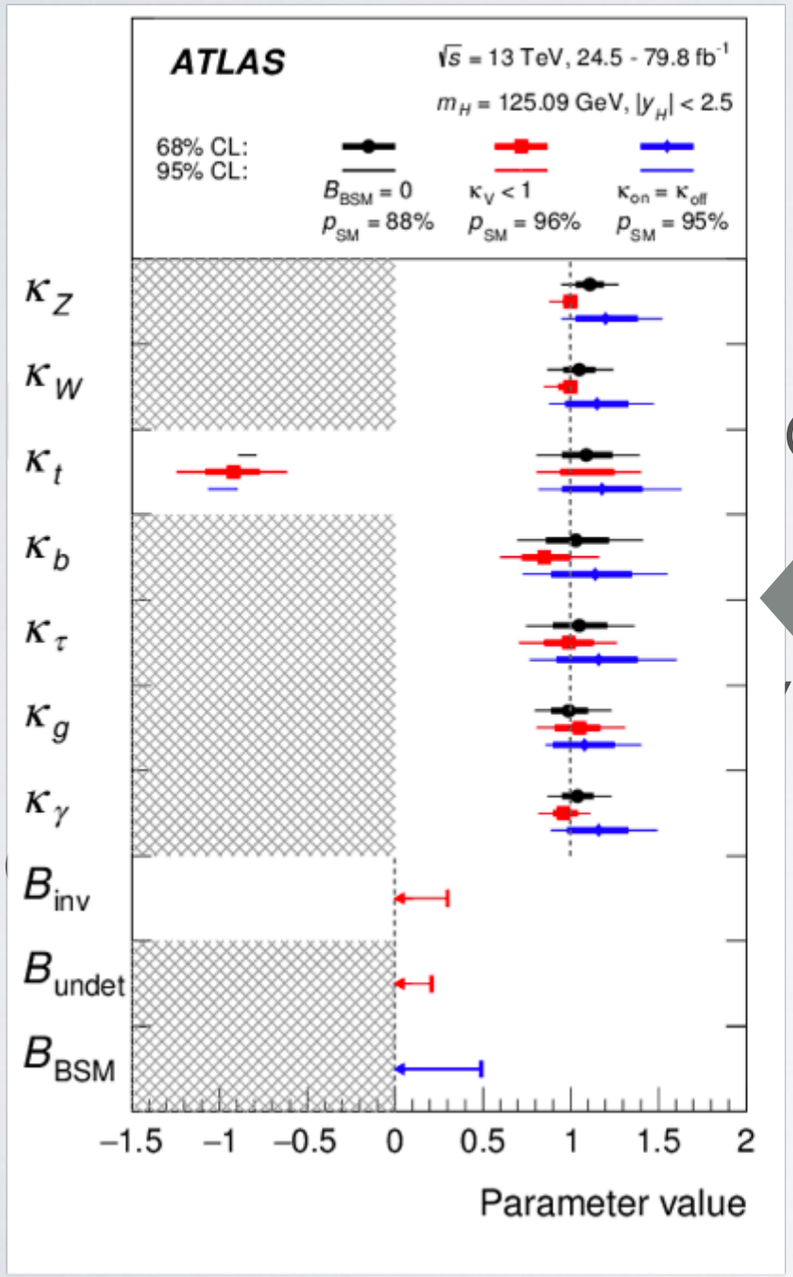


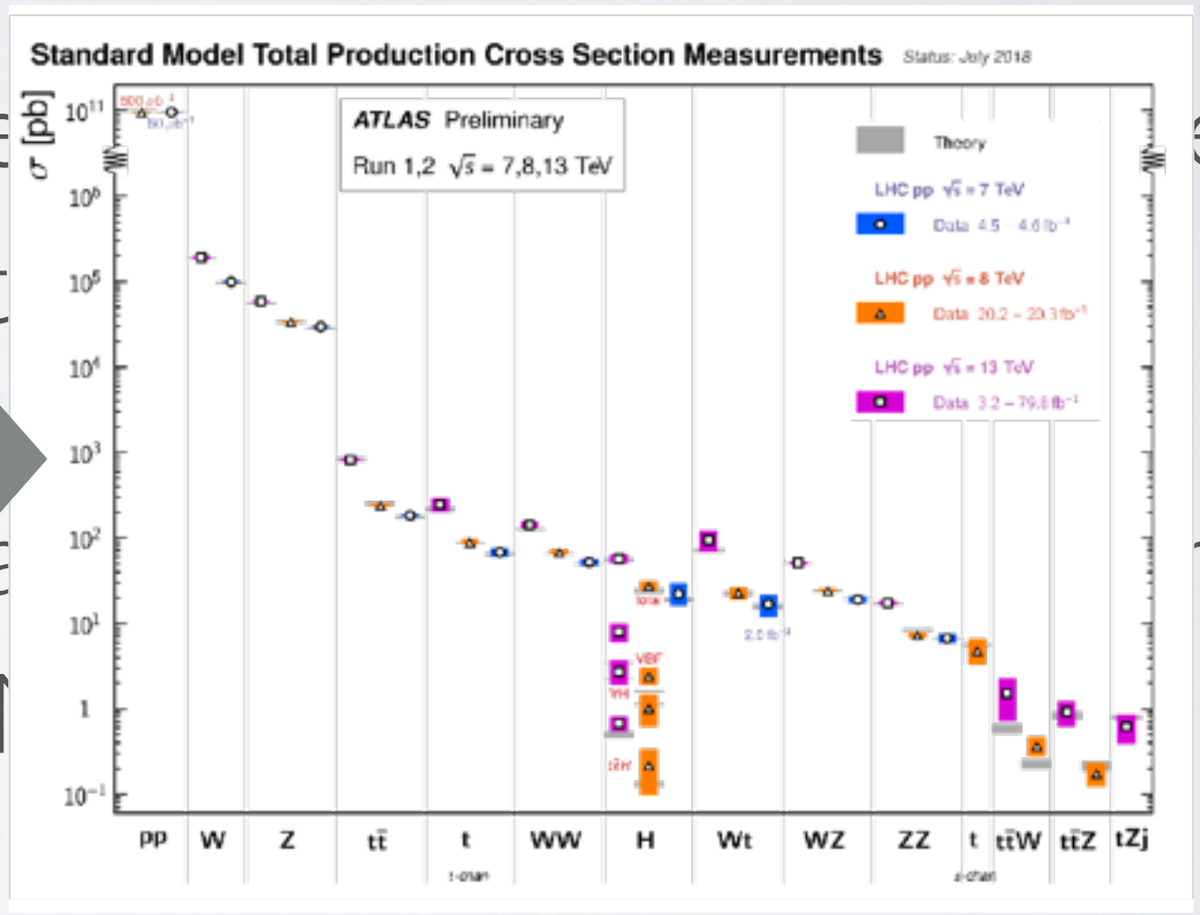
ATLAS-CONF-2018-043

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?

- acce el
- ociat
- be a
- in SI





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

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

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

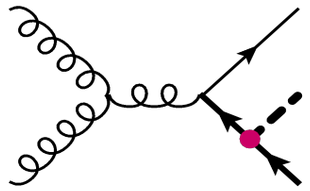
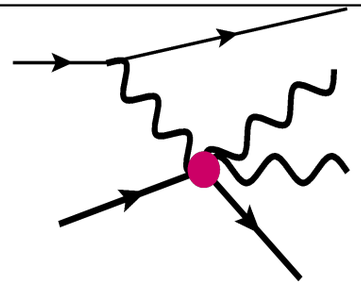
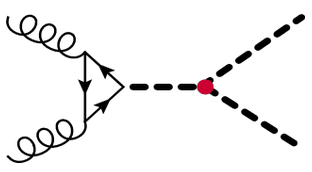
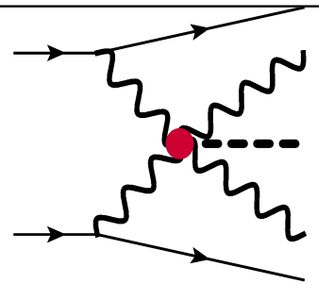
$$X^5 \sim h^5 + \vec{G}^2(h^4 + h^5 + \cdots) + \vec{G}^4(h^3 + h^4 + \cdots) + \vec{G}^6(h^2 + h + \cdots) + \vec{G}^8(h + h^2 + \cdots) + \vec{G}^{10}(1 + h + \cdots) + \cdots,$$

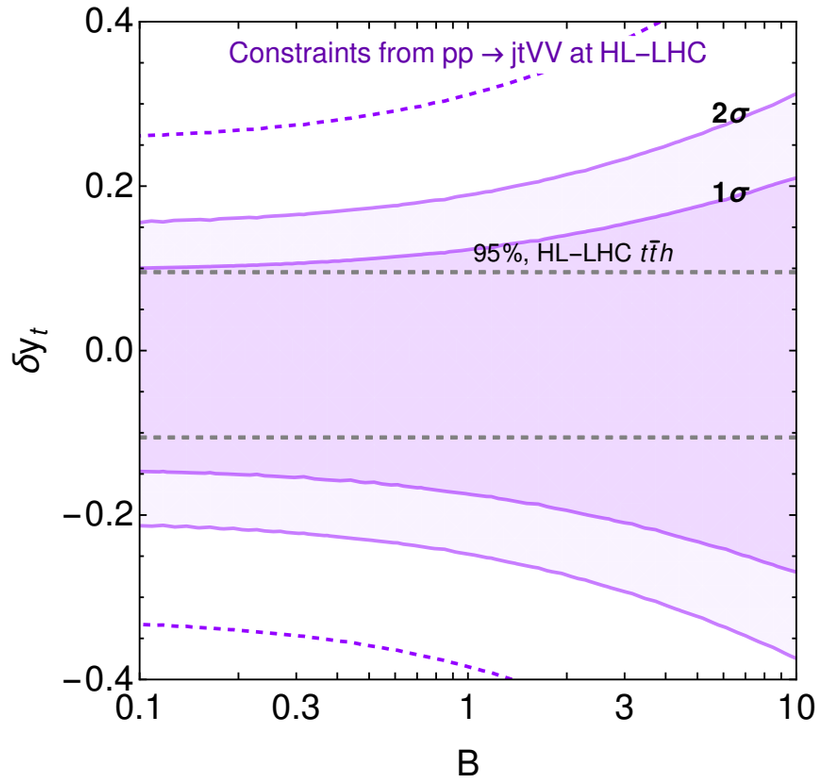
(Schematic without coefficients, but we know cancellations can occur due to SMEFT description)

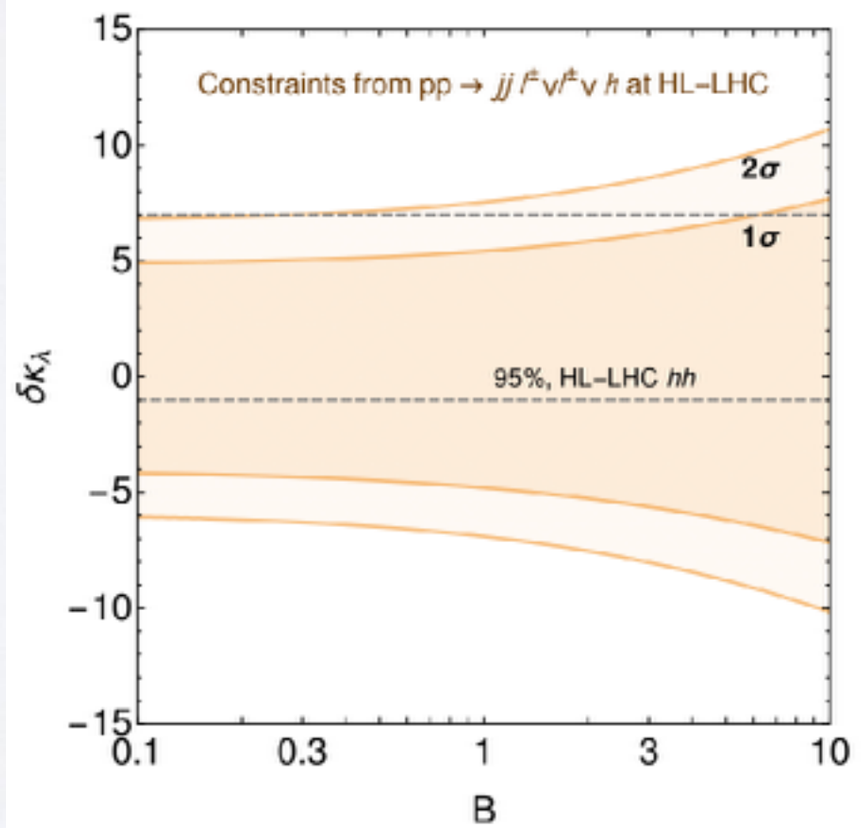
Terms circled can only come from trilinear!

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?