UNITARITY VIOLATION FROM NONSTANDARD HIGGS COUPLINGS

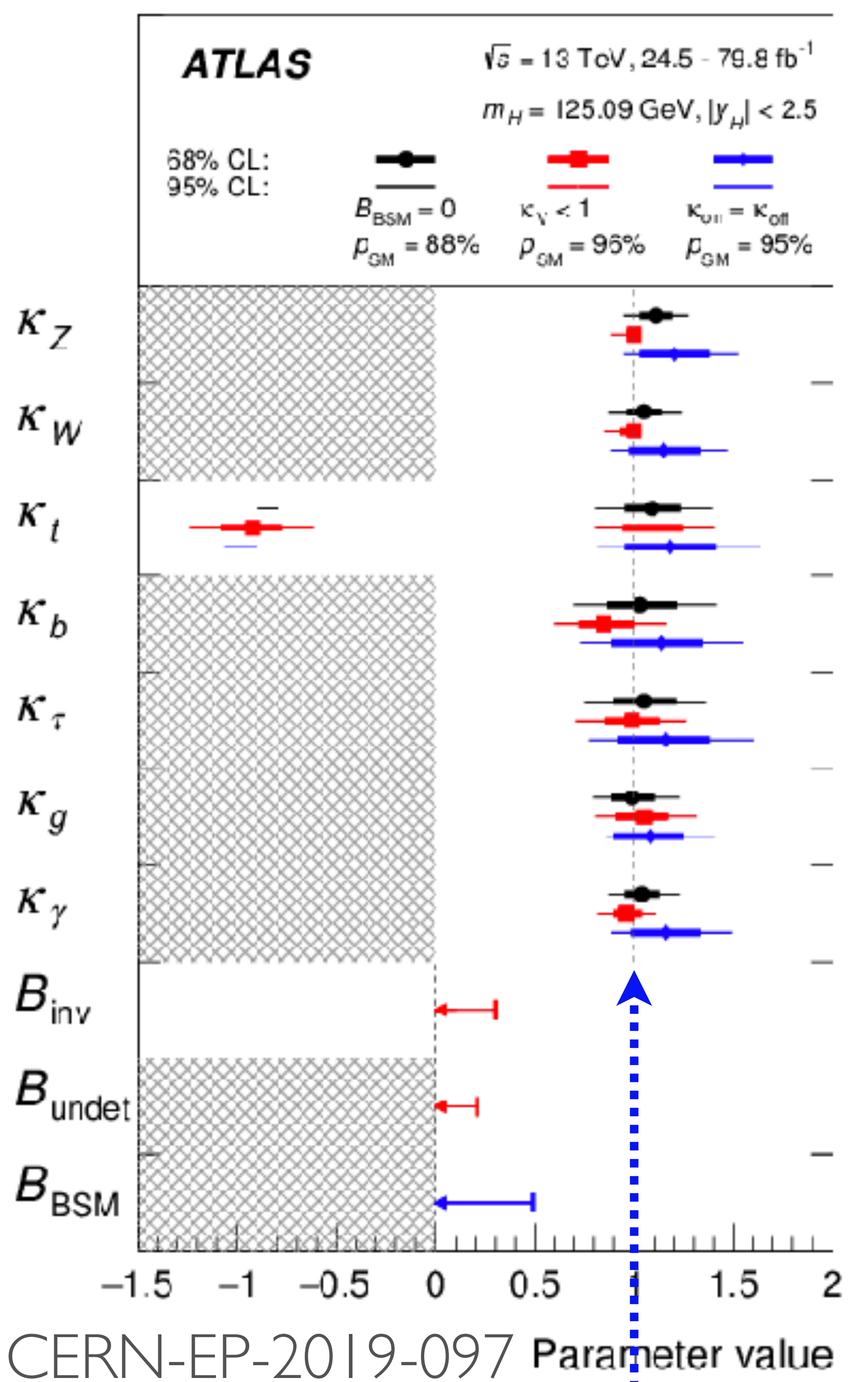
Spencer Chang (U. Oregon)
w/ Markus Luty 1902.05556+ongoing

also see Falkowski & Rattazzi 1902.05936
and earlier work by Belyaev et.al. 1212.3860

IBS CTPU Workshop 12/12/19

PINNING DOWN HIGGS PROPERTIES

Post-discovery, major goal of LHC and future colliders is measuring Higgs properties so we can test EWSB mechanism, mass generation, but also to 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$\star$	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)

HIGHER ORDER HIGGS COUPLINGS

HL-LHC and future colliders will be sensitive to higher order Higgs couplings, including self-interactions and quadratic couplings to W, top

$$(1+\delta_3)\frac{m_h^2}{2v}h^3 + (1+\delta_4)\frac{m_h^2}{8v^2}h^4$$

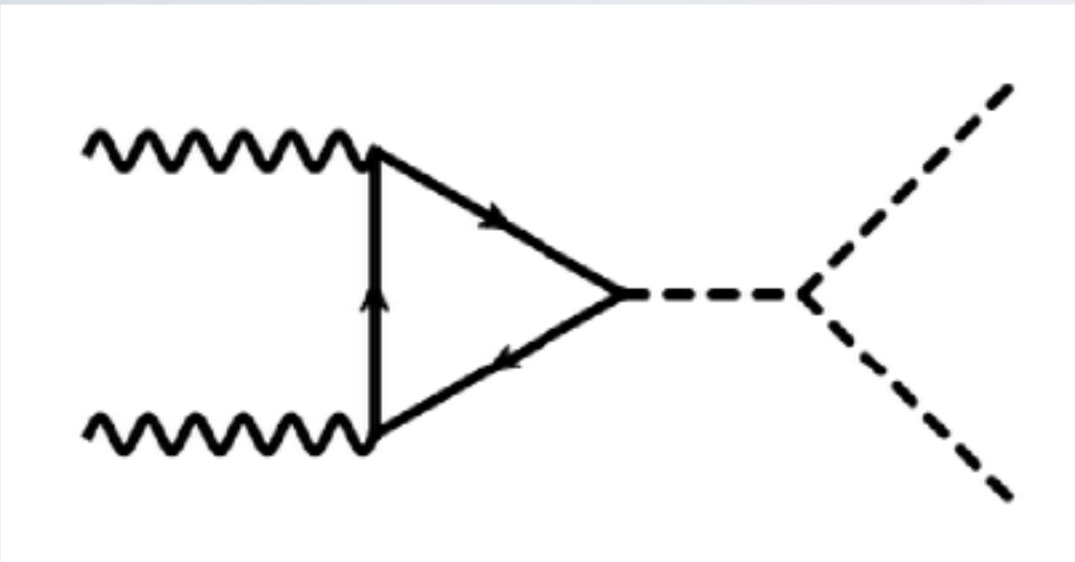
$$\dots$$

$$(\frac{1}{2}m_Z^2 Z^2 + m_W^2 W^2)(1+\delta_{hhVV})\frac{h^2}{v^2}$$

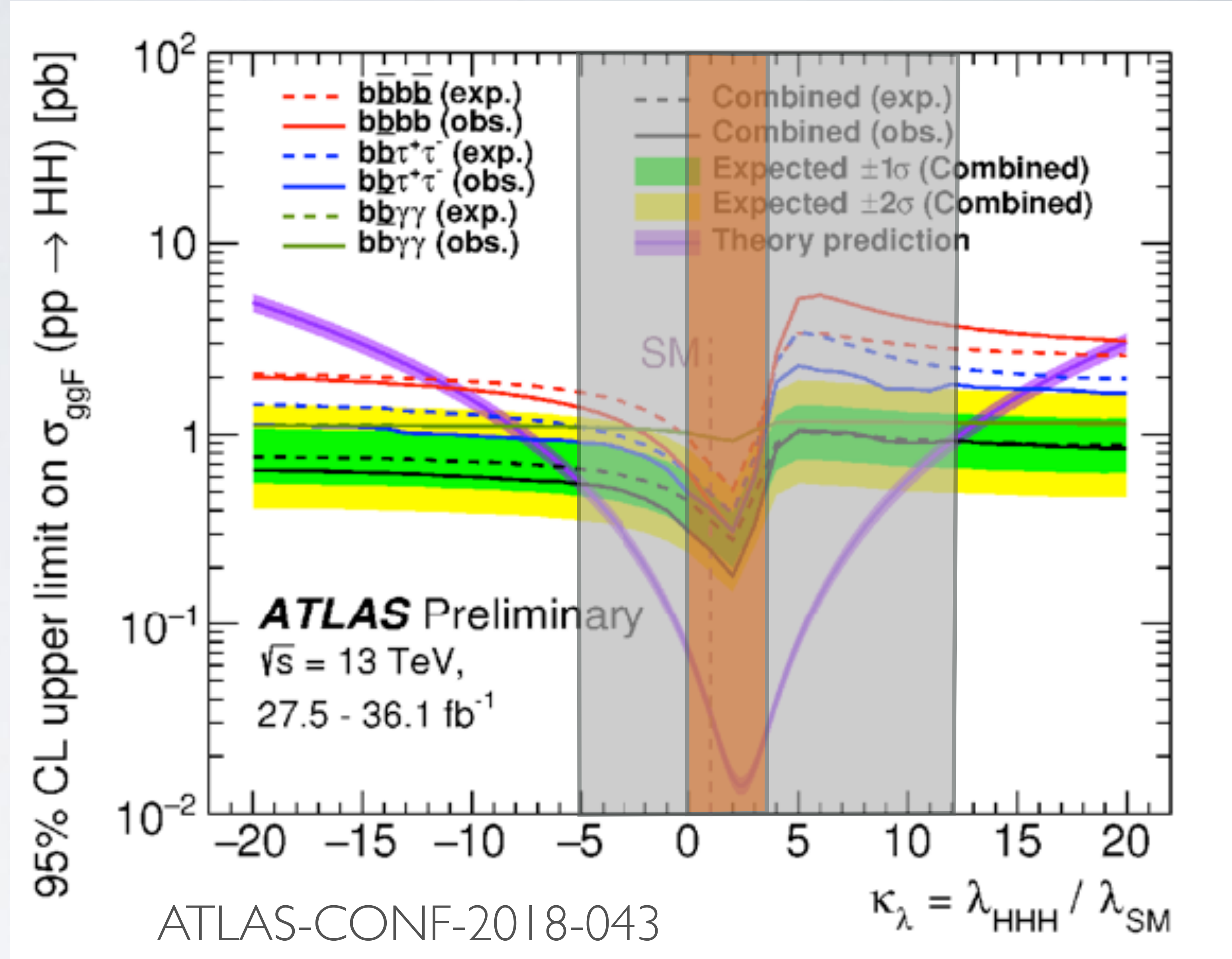
$$\dots$$

$$-\frac{m_t}{2v^2}c_2 h^2 \bar{T}T$$

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

TRIPLE HIGGS PROCESS

Papaefstathiou and Sakurai
See also Chien et.al.

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

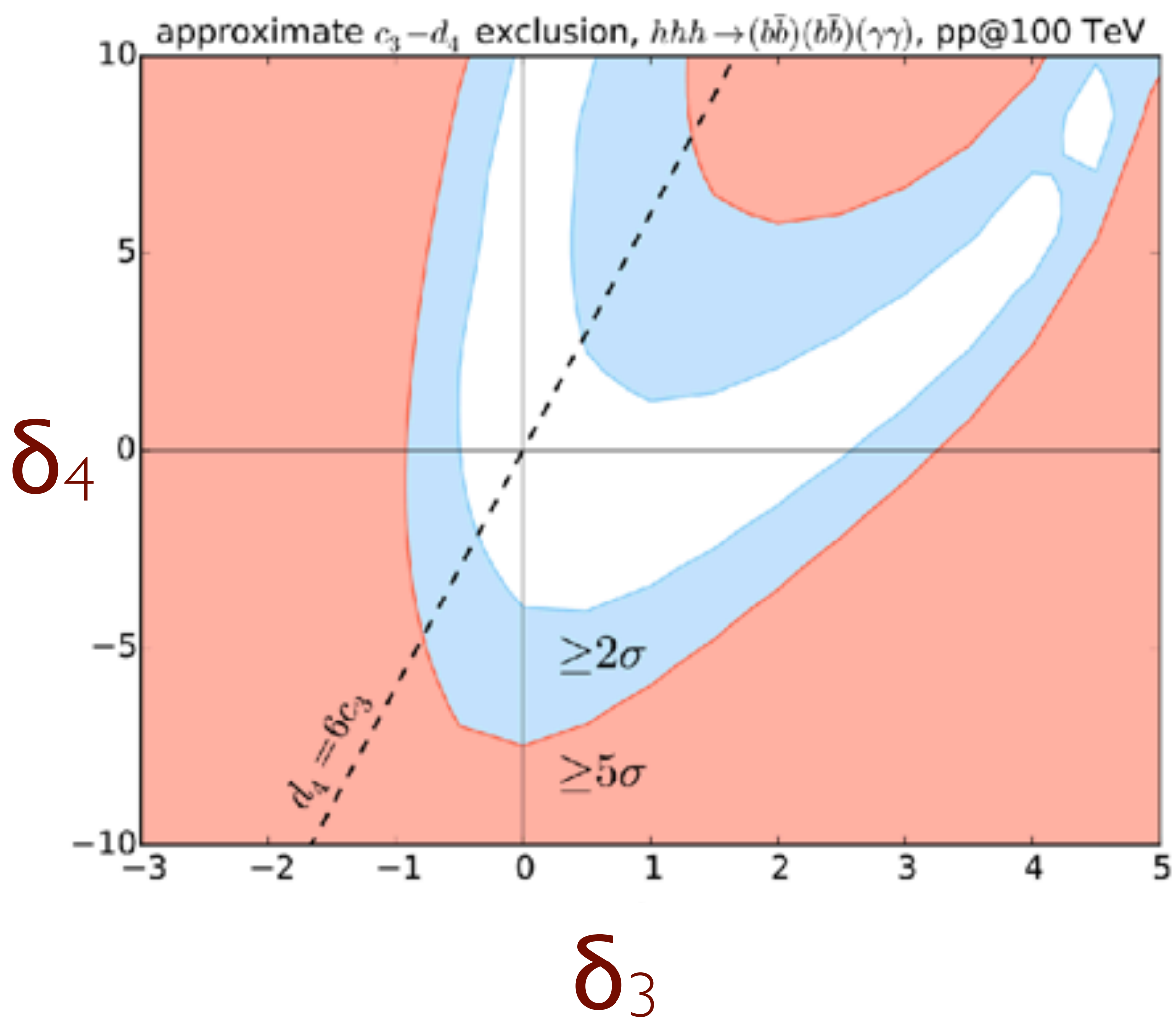
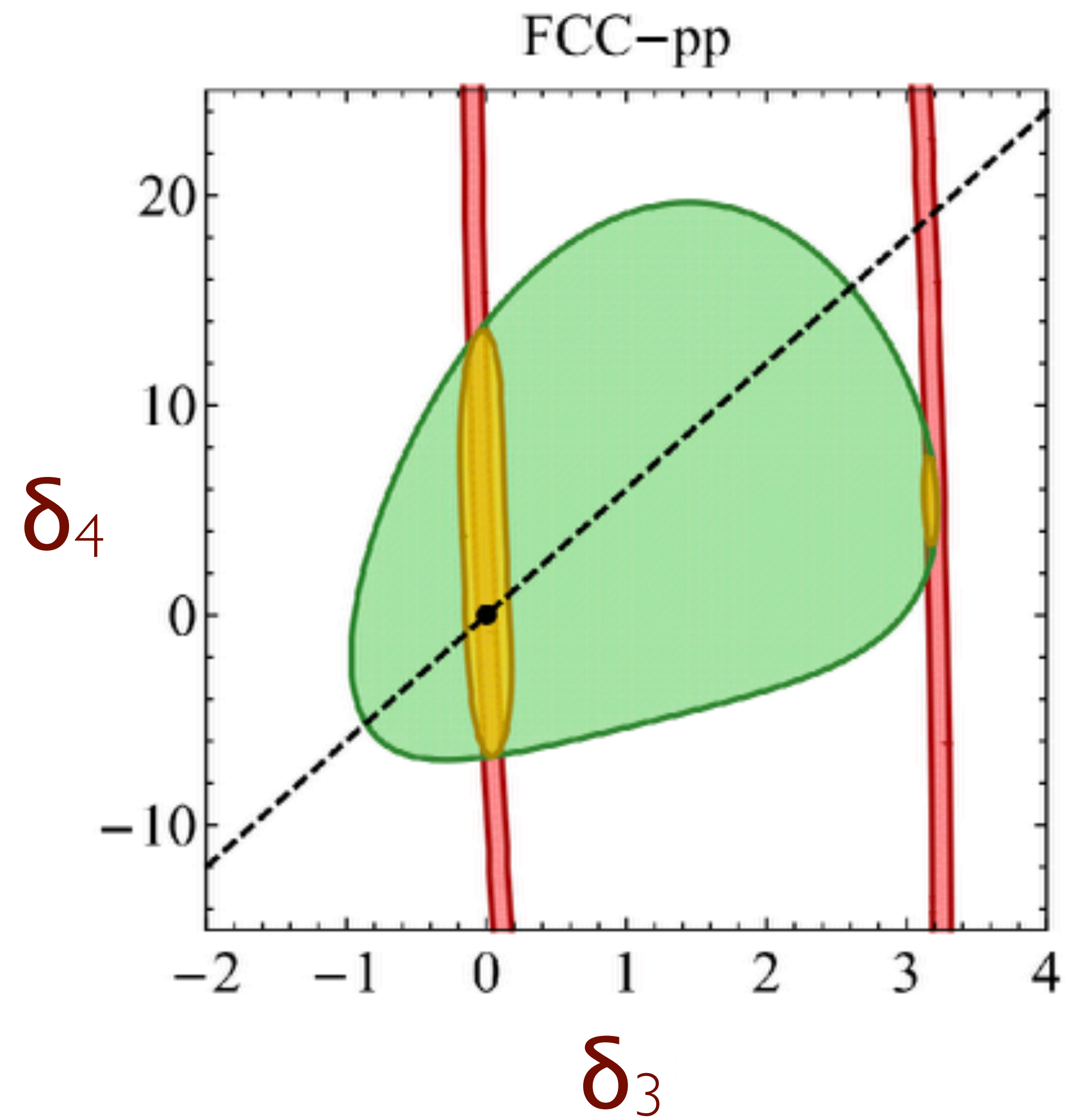


FIG. 6: The approximate expected 2σ (blue) and 5σ (red) exclusion regions on the c_3-d_4 plane after 30 ab^{-1} of integrated luminosity, derived assuming a constant signal efficiency, calculated along the $d_4 = 6c_3$ line in $c_3 \in [-3.0, 4.0]$.



Sensitivity to Higgs quartic is poor even in optimistic cases

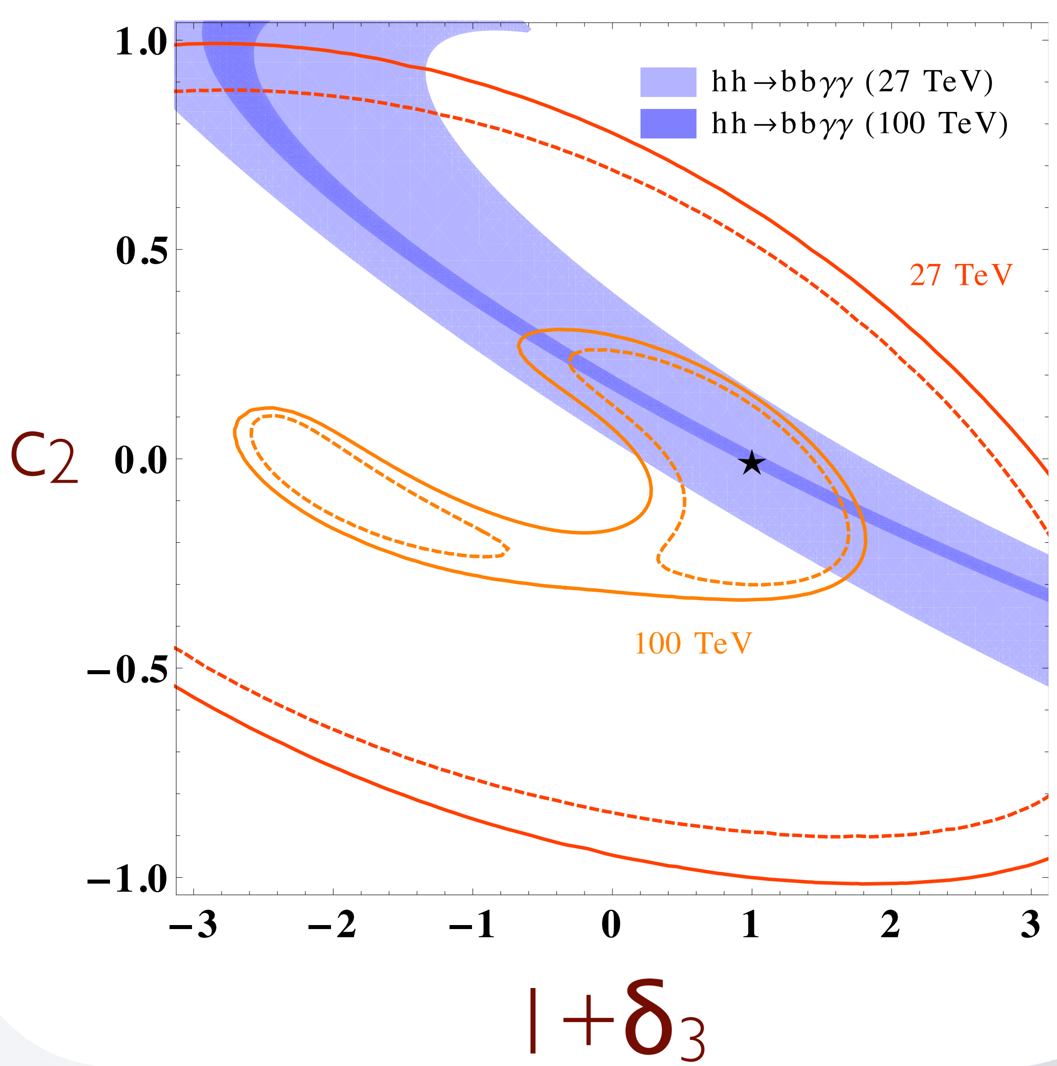
W/Z AND TOP COUPLINGS TO HH

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

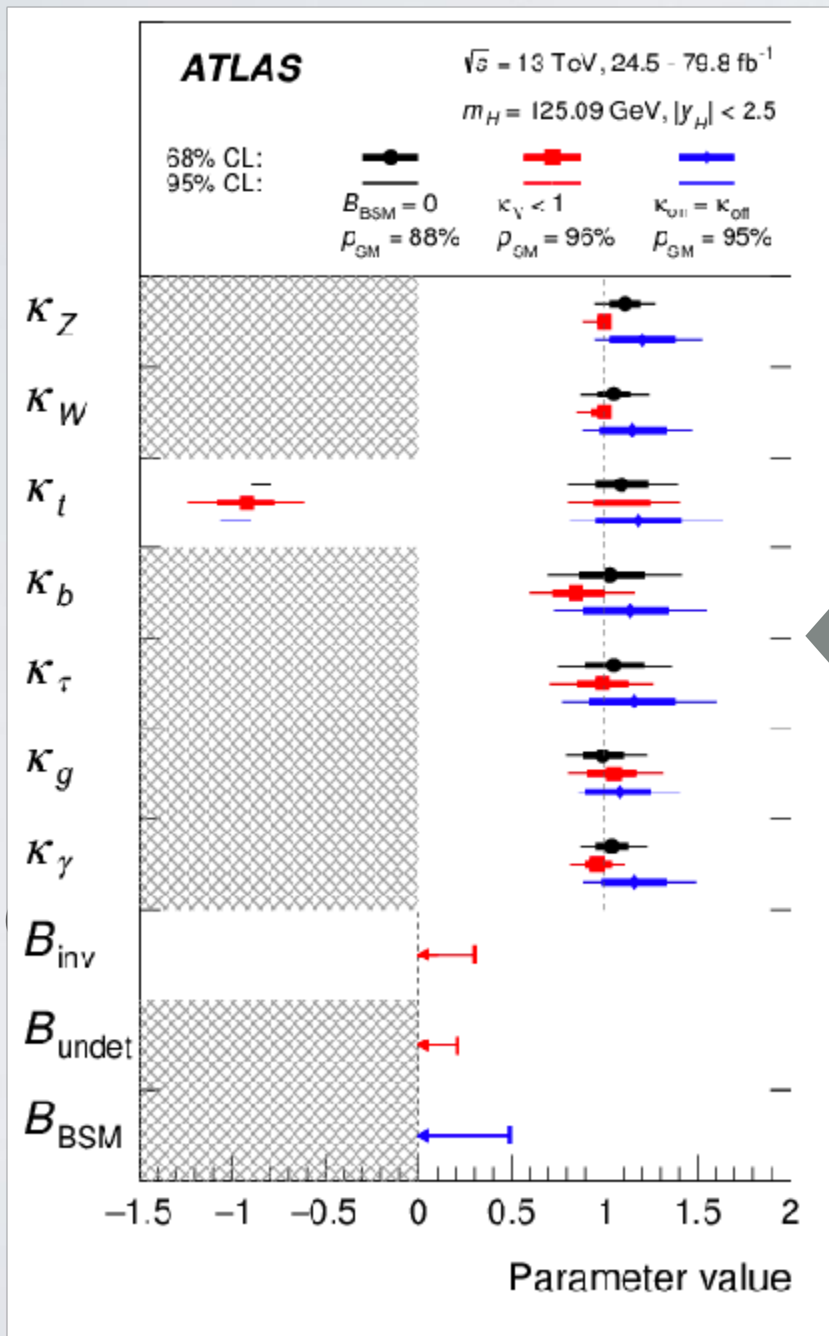
tthh coupling
probed by tthh
production
Li et.al. (1905.03772)



SUMMARY OF HIGGS COUPLING PROSPECTS

- Currently many Higgs linear couplings constrained to 10-25% level, improved to few % in future
- Higher order couplings: VVhh more promising by almost order of magnitude than h^3, tthh. O(1) at HL-LHC, O(10%) at future colliders

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



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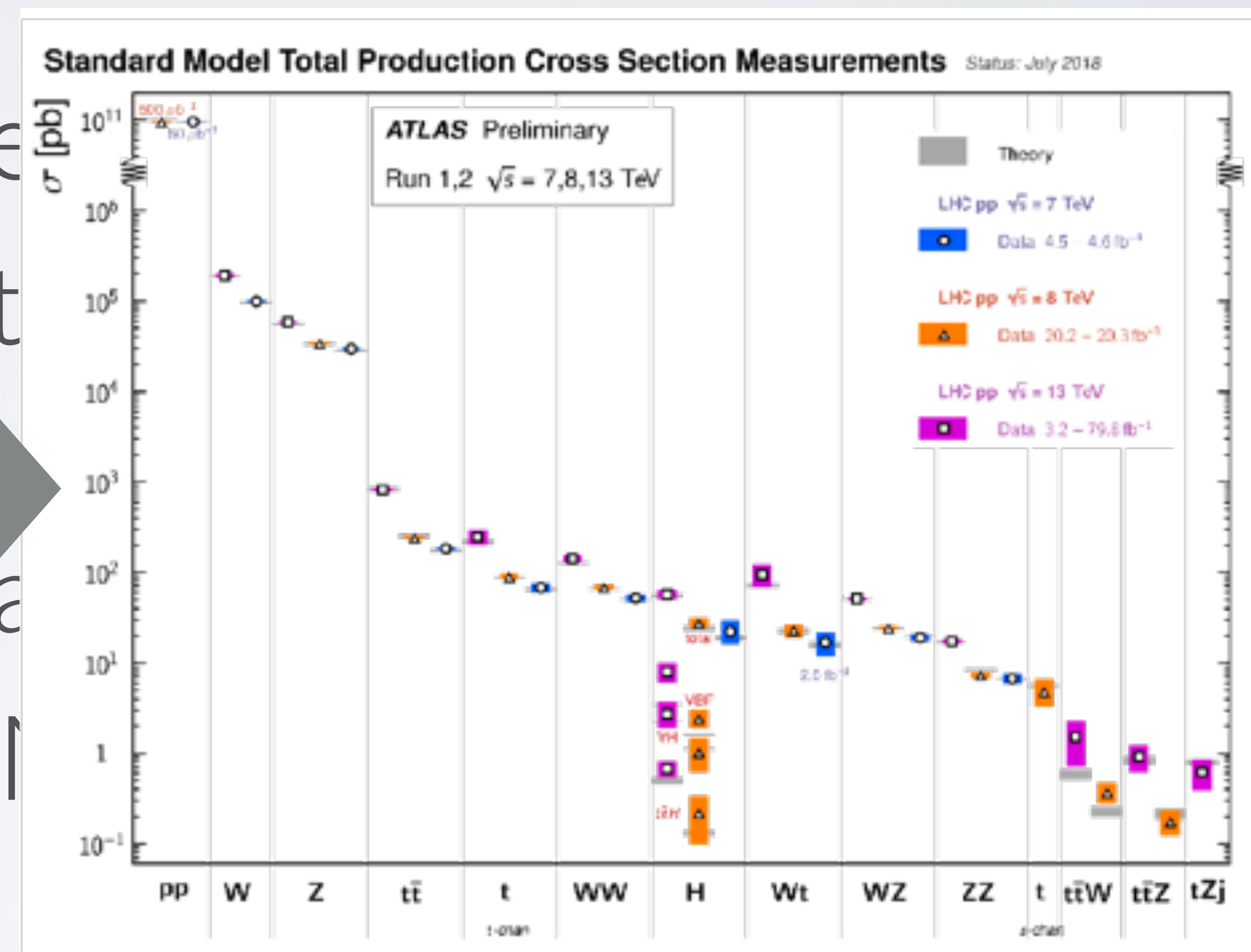
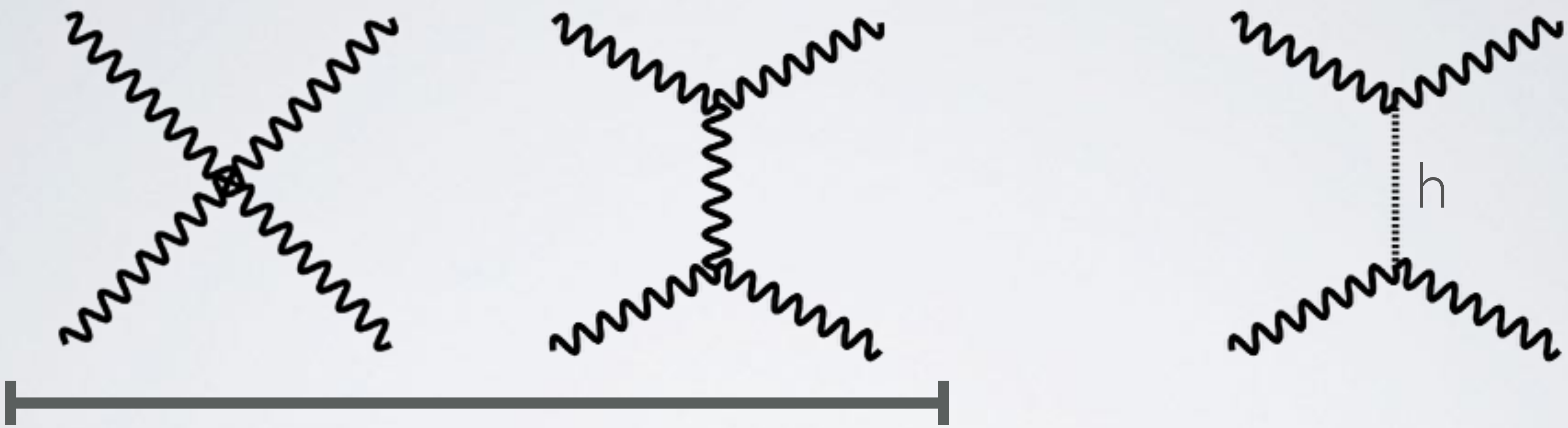


NEW PHYSICS SCALE BOUND FROM UNITARITY VIOLATION (W/ LUTY)

The Standard Model
is a precise deck of cards,
modifications (due to
higher dimensional operators)
lead to problems at high
energies.

Unitarity violating processes
give interesting
processes to measure and
put bound on new physics
scale

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



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

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

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)

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

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

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

V AND TOP COUPLINGS

Use a nonanalytic Higgs doublet

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

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

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

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

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

OUR GENERAL UNITARITY VIOLATION APPROACH

$$|P, \alpha\rangle$$

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

Properly normalized

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

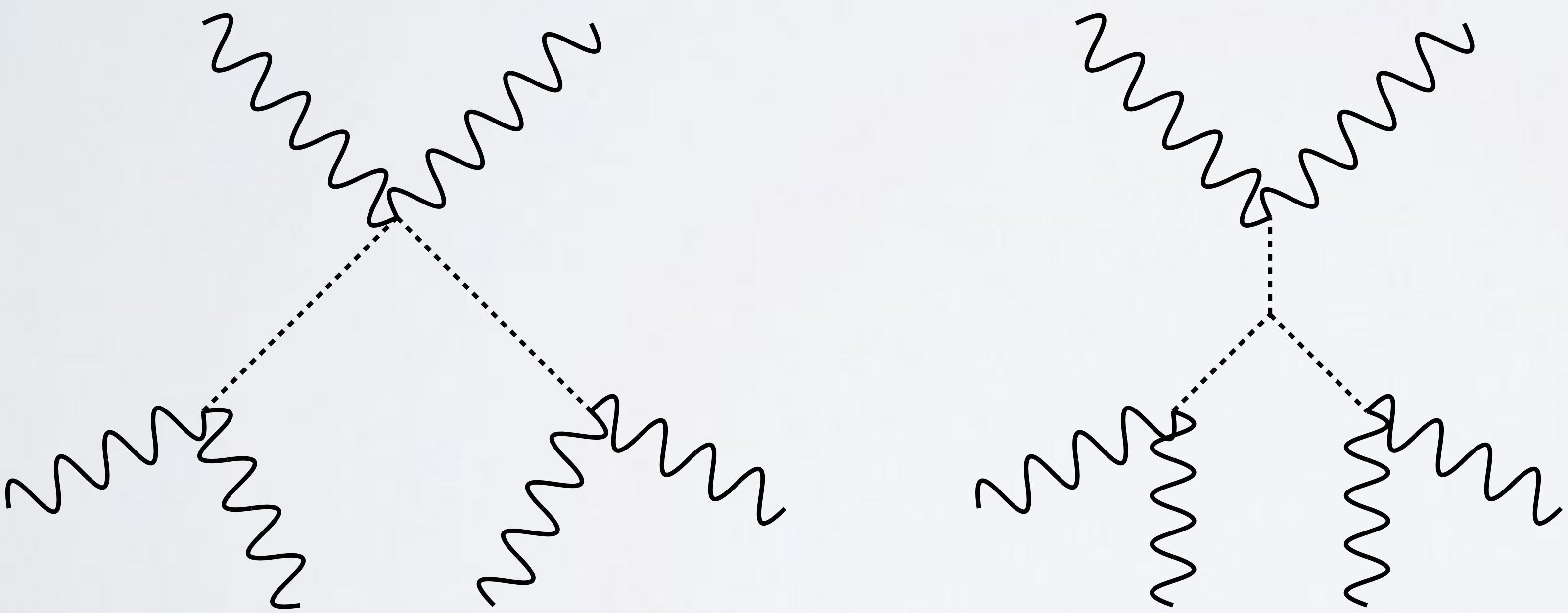
Leads to bounds $|T_{\alpha\alpha'}| \leq 1$

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

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

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!

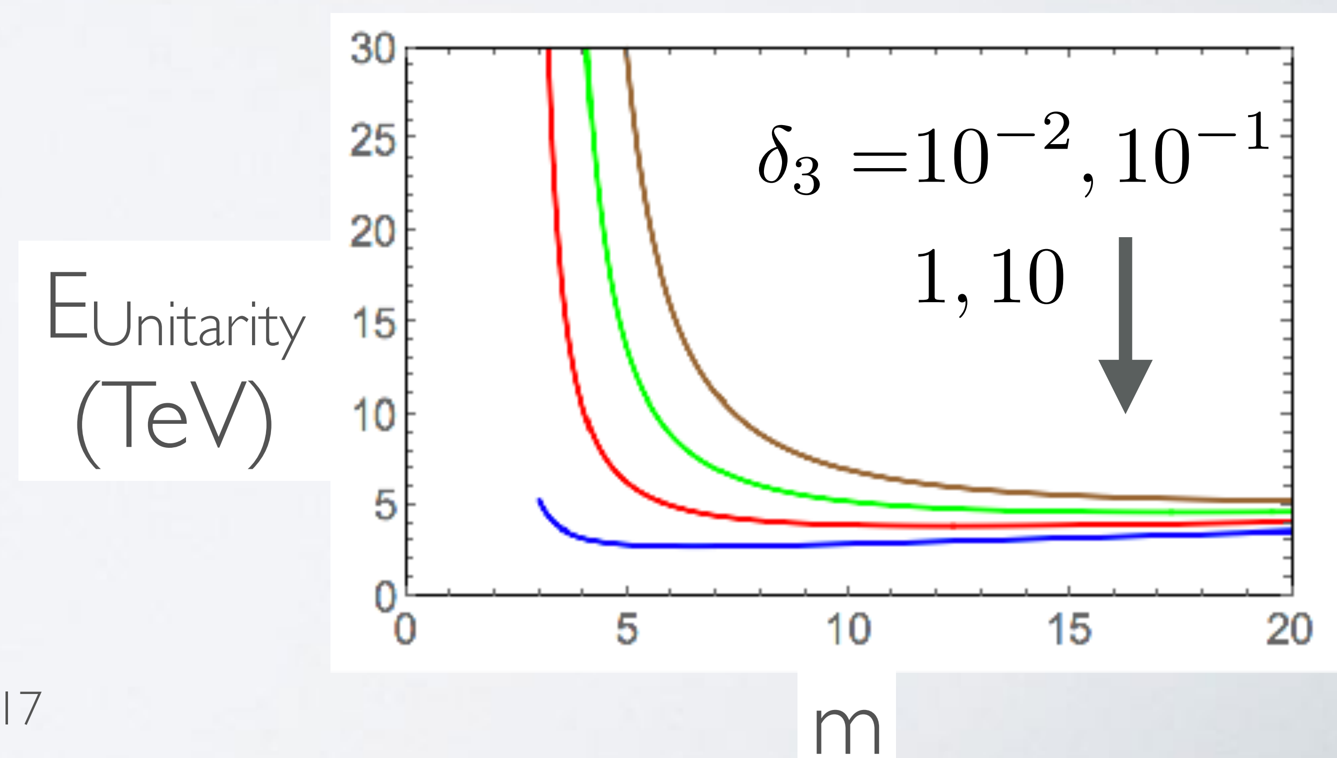
HIGGS TRILINEAR MODIFICATION

$$\frac{m_h^2}{2v}\delta_3 X^3 = \frac{m_h^2}{2v}\delta_3\left(\sqrt{(v+h)^2+\vec{G}^2}-v\right)^3$$

$$\supset \sum_m \delta_3(-1)^m \frac{3m_h^2}{4v^m}\vec{G}^2 h^m$$

Goldstone Equivalence Theorem says Goldstone scattering gives high energy longitudinal W,Z scattering

Unitarity violating scale for
$Z_L\, h^{m/2} \Leftrightarrow Z_L\, h^{m/2}$
is ~5 TeV for m ~ 10-15
(nondecoupling effect)



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!

STANDARD MODEL EFT (SMEFT)

Nonanalytic nature of HEFT around v = 0 reflects a nonlocal EFT for Higgs doublet in ultraviolet

SMEFT instead looks at the most general EW gauge invariant analytic EFT for H

$$Y \equiv |H|^2 - \frac{v^2}{2} = vh + \frac{1}{2}\left(h^2 + \vec{G}^2\right)$$

$$V(Y) = \lambda_{SM} Y^2 + c_3 Y^3 + c_4 Y^4 + \cdots$$

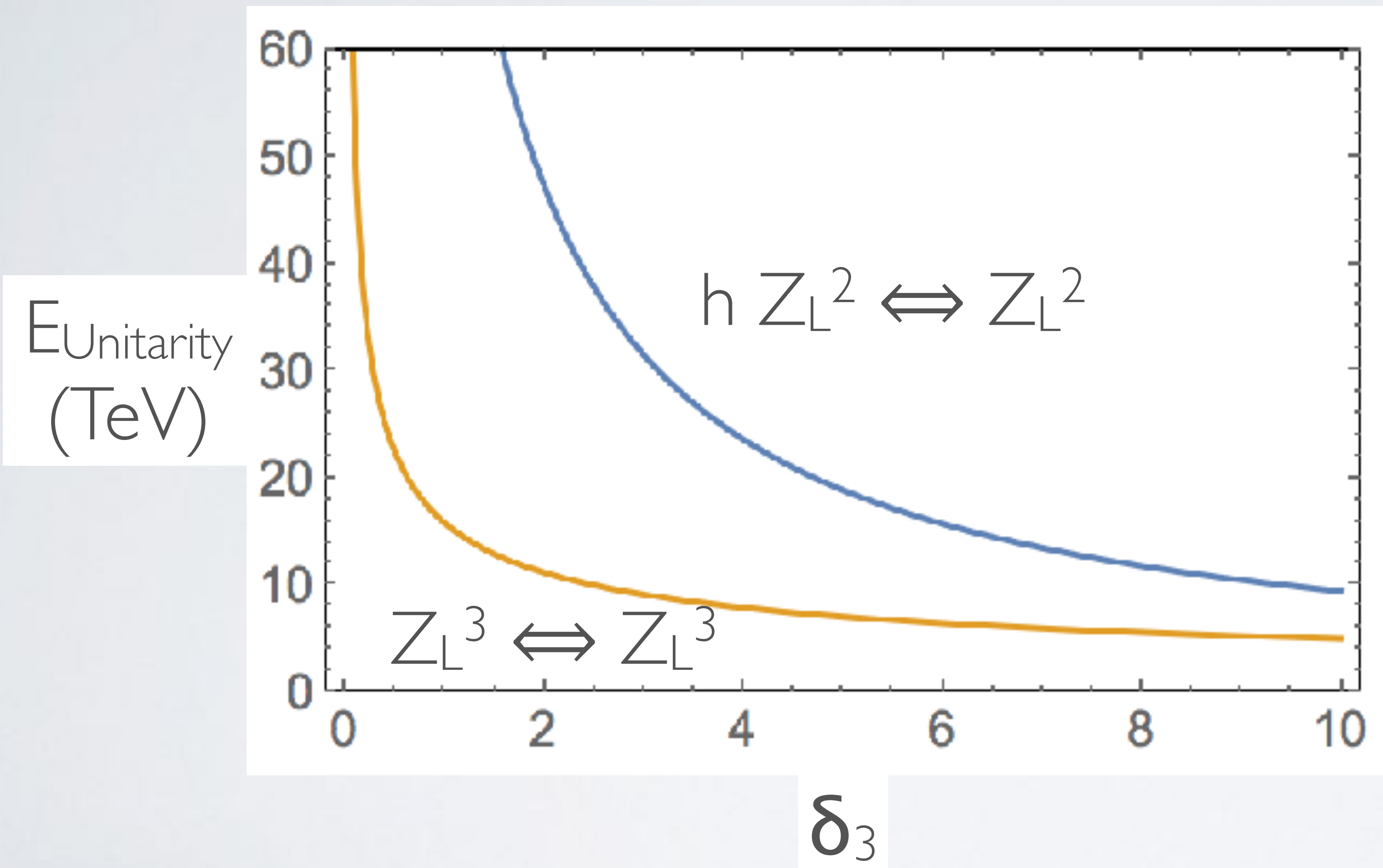
SMEFT TRILINEAR

$$V = V_{SM} + \frac{m_h^2}{2v^4}\delta_3\, Y^3 + \cdots$$
$$= V_{SM} + \frac{m_h^2}{2v}\delta_3\, h^3 + \frac{3m_h^2}{4v^2}\delta_3\, h^4 + \frac{3m_h^2}{8v^3}\delta_3\, h^5 + \frac{m_h^2}{16v^4}\delta_3\, h^6 \cdots$$

This operator only leads to contact interactions up to 6-body, so it proves that high multiplicities can be cancelled by choosing correlated h^4,h^5,h^6 couplings

These potential cancellations suggest one should focus on processes that only depend on trilinear (i.e. G^6, hG^5)

MODEL INDEPENDENT VIOLATION



These couplings only depend on trilinear modifications and give much higher bounds than ~5 TeV, but also decouple as coupling vanishes, giving a conservative bound

Coupled channel analysis leads to improved bound $13\ \text{TeV}/\sqrt{\delta_3}$

W/Z COUPLINGS (IN PROGRESS)

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

tells us that only up to 4-body processes are dependent solely on δ_{hVV}

e.g. WW → ZZ, gives E< 4.7 TeV/$\sqrt{(\delta_{hVV}/0.05)}$

However, if only hhVV is modified, then need a higher dimensional operator, which says now 6-body processes are interesting

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

e.g. WWZ → WWZ, gives E< 2.6 TeV/$\delta^{1/4}_{hhVV}$

TOP COUPLINGS (IN PROGRESS)

$$Y\bar{T}_R H \epsilon Q_L$$

tells us that only up to 5-body processes are dependent solely on δ_{htt}

e.g. $t_R \bar{b}_R \to W^+ W^+ W^-$ gives E< 33 TeV/√(δ_{htt}/0.05)

However, if only hhtt is modified, then 7-body processes are interesting

$$Y^2 \bar{T}_R H \epsilon Q_L$$

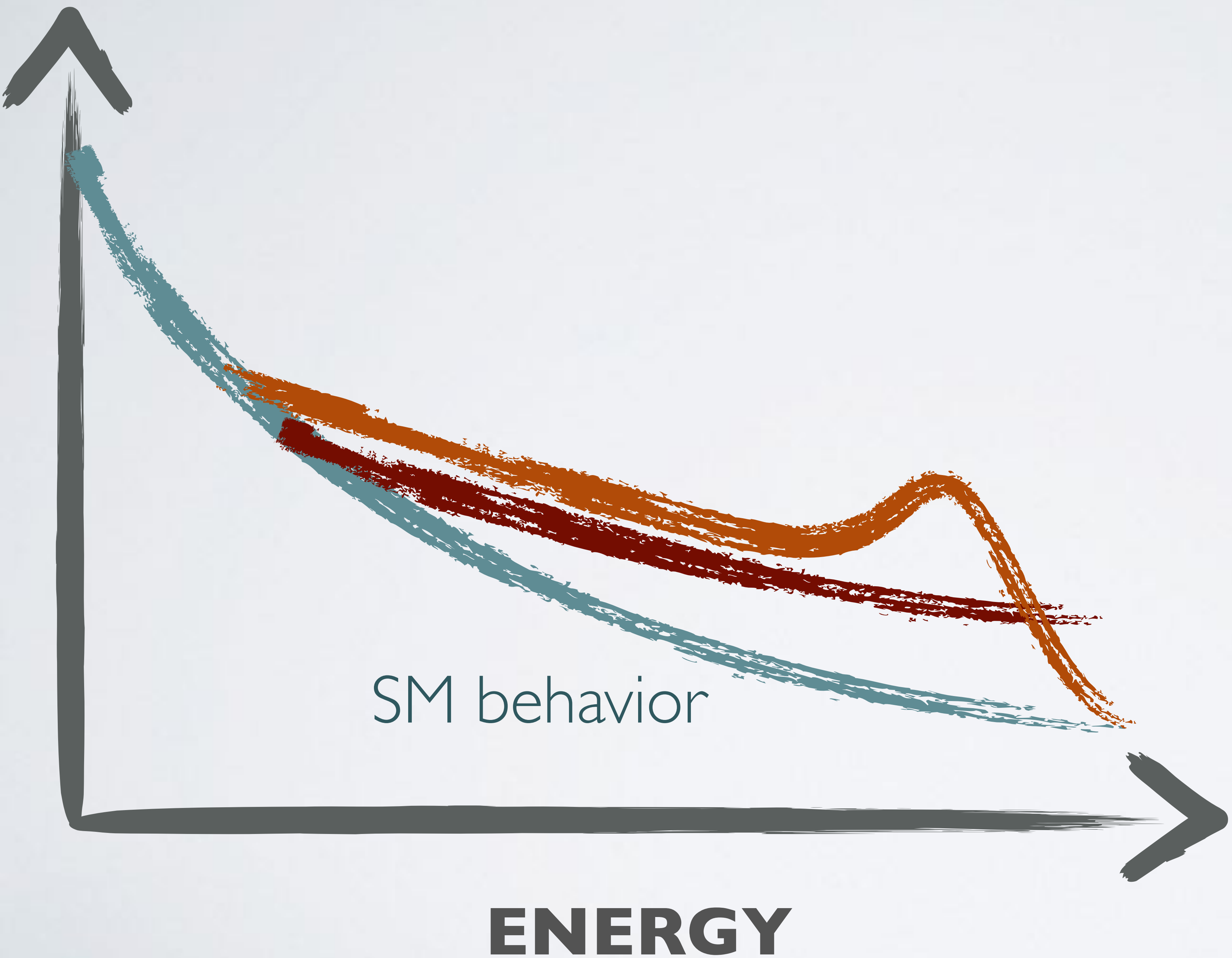
e.g. $t_R \bar{b}_R W^- \to W^4$ gives E< 4 TeV/$c_2^{1/4}$

UNITARITY BOUND SUMMARY

Higgs Trilinear	hVV hhVV	htt hhtt
$13\ \mathrm{TeV}/\sqrt{\delta_3}$	$0.7\ \mathrm{TeV}/\sqrt{(\delta_{hVV}/0.05)}$ $2.6\ \mathrm{TeV}/\delta^{1/4}_{hhVV}$	$33\ \mathrm{TeV}/\sqrt{(\delta_{htt}/0.05)}$ $4\ \mathrm{TeV}/c_2^{1/4}$

These suggest, nontrivial V or top couplings is kinematically accessible at 14-27 TeV hadron collider, while trilinear requires 100 TeV. (For HEFT, bounds would be few TeV.)

COLLIDER PROBES

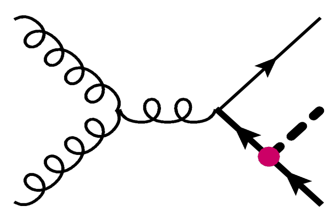
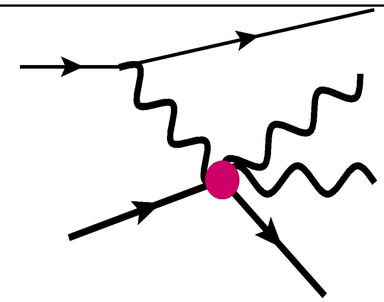
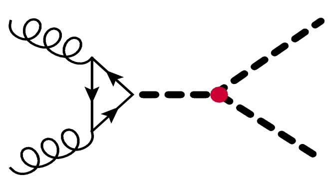
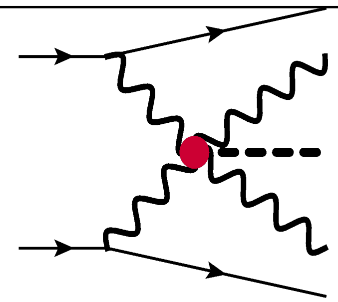


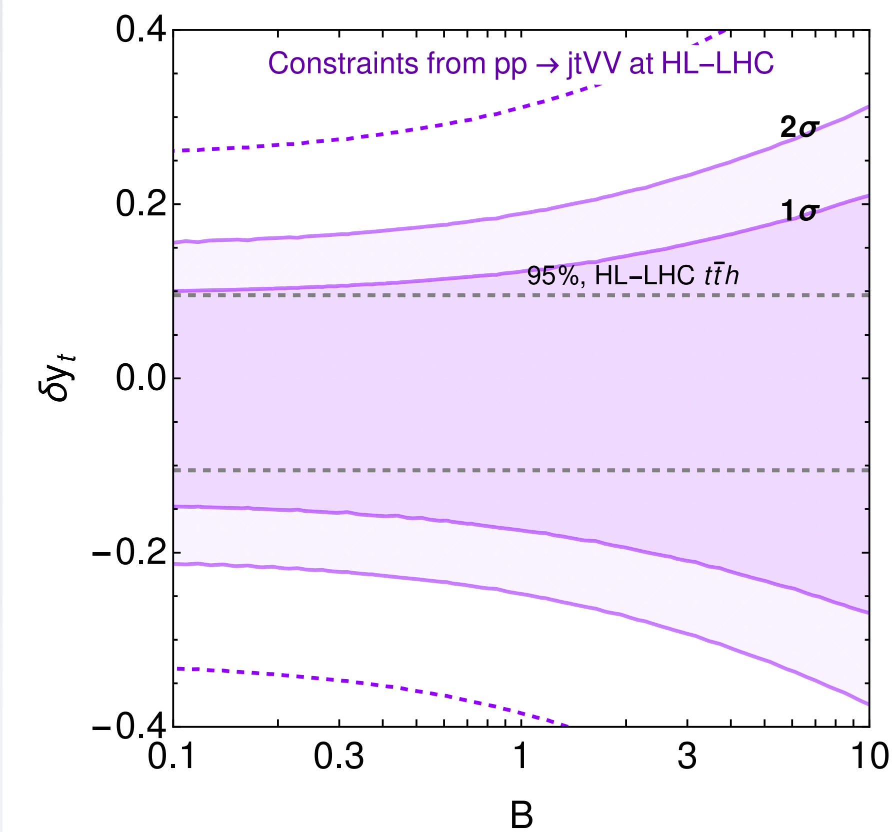
Probing high energy processes can test energy growth, complementary sensitivity to Higgs couplings

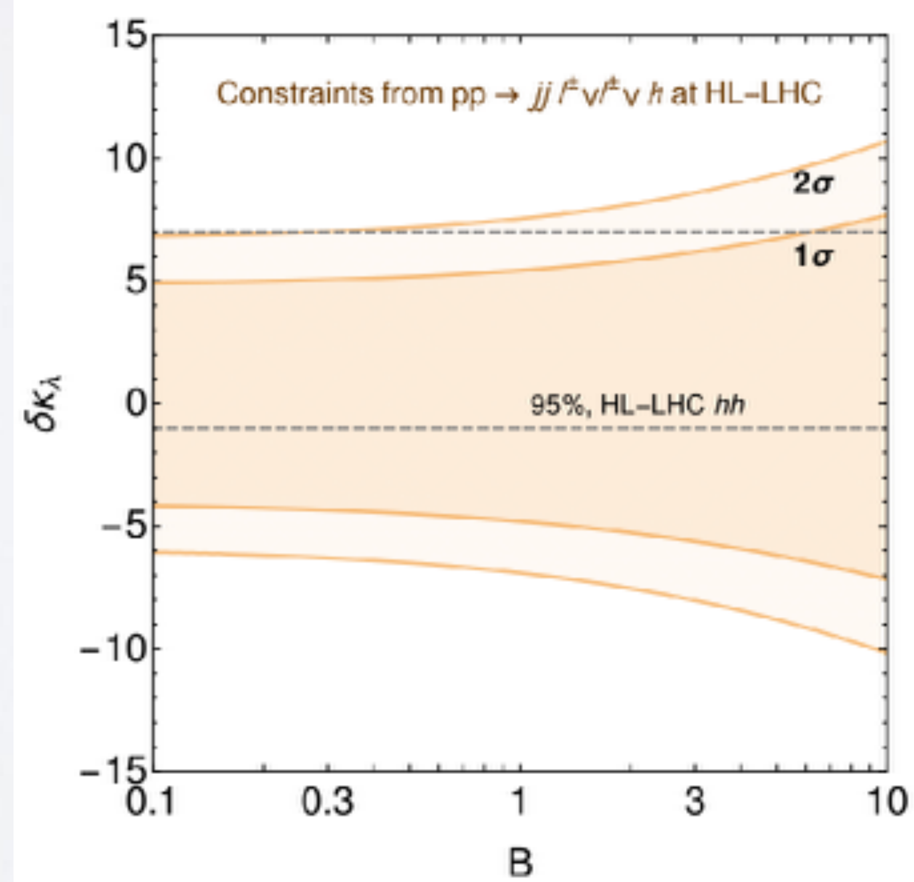
New resonances possible, but not guaranteed.
E.g. Higgs not discovered in VB scattering

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?

COLLIDER PROBES QUESTIONS

Have we exhausted interesting processes? Unitarity violation only suggests sensitivity for very high energies, so is there another way to identify processes?

Also, if new physics is at accessible scale, need to systematically explore UV completions
(e.g. Historical lesson, W/Z and Higgs weren't discovered by looking at unitarity violating processes, appeared at much lower energy than then needed to)

CONCLUSIONS

- Precision Higgs couplings could discover a deviation from SM, suggesting new physics at some energy scale
- Unitarity violation places a bound on this energy scale and identifies interesting correlated processes to measure
- Higgs trilinear modifications lead to Unitarity violation at high energies (~ 5 - 13 TeV for $\delta_3 \sim 1$ depending on assumptions)
- VVhh, tthh is of interest at HL-LHC and future colliders, Unitarity bound is ~3-5 TeV for O(1) coupling

Thanks for your attention!

EXTRA SLIDES

DISCUSSION QUESTIONS

- Possible to systematically model build UV completions of these coupling modifications? If so, what are the correlated signals?
- Other technique besides Equivalence theorem that identifies interesting processes that are modified by nonstandard couplings?

UNITARITY CONSTRAINTS ON NON-DERIVATIVE COUPLINGS

$$\frac{\lambda}{n_1! \cdots n_r!} \phi_1^{n_1} \cdots \phi_r^{n_r}$$

Consider s-wave scattering

$$\phi_1^{k_1} \cdots \phi_r^{k_r} \leftrightarrow \phi_1^{n_1-k_1} \cdots \phi_r^{n_r-k_r}$$

If we properly normalize these states, then unitarity bounds are easy (see paper for more details)

Unitarity constraints from this amplitude requires

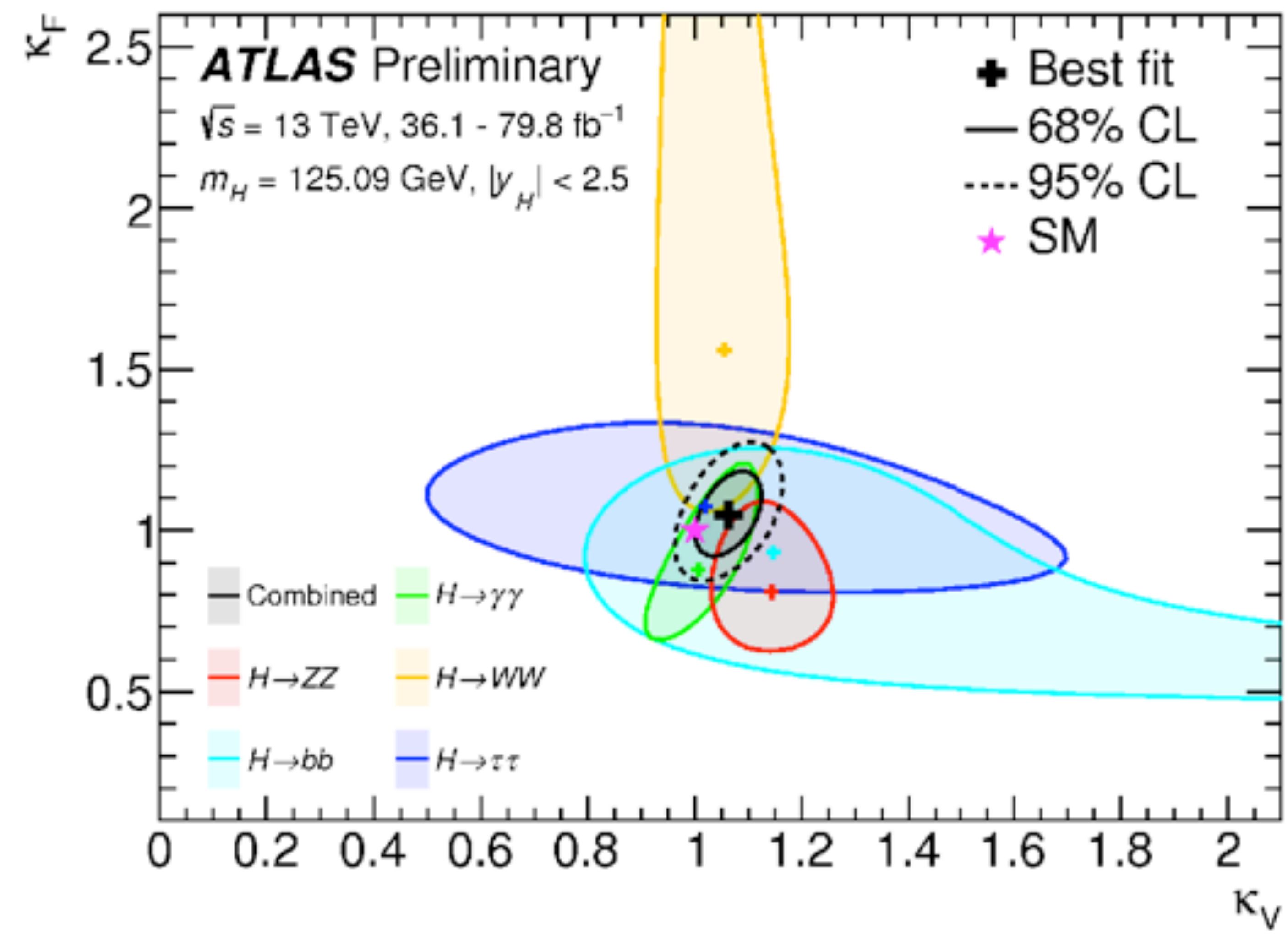
$$E \leq 4\pi \left[\frac{64\pi^2}{\lambda^2} \left(k_1! \cdots k_r! \, (k-1)! \, (k-2)!\right) \left((n_1-k_1)! \cdots (n_r-k_r)! \, (n-k-1)! \, (n-k-2)!\right) \right]^{\frac{1}{2n-8}}$$

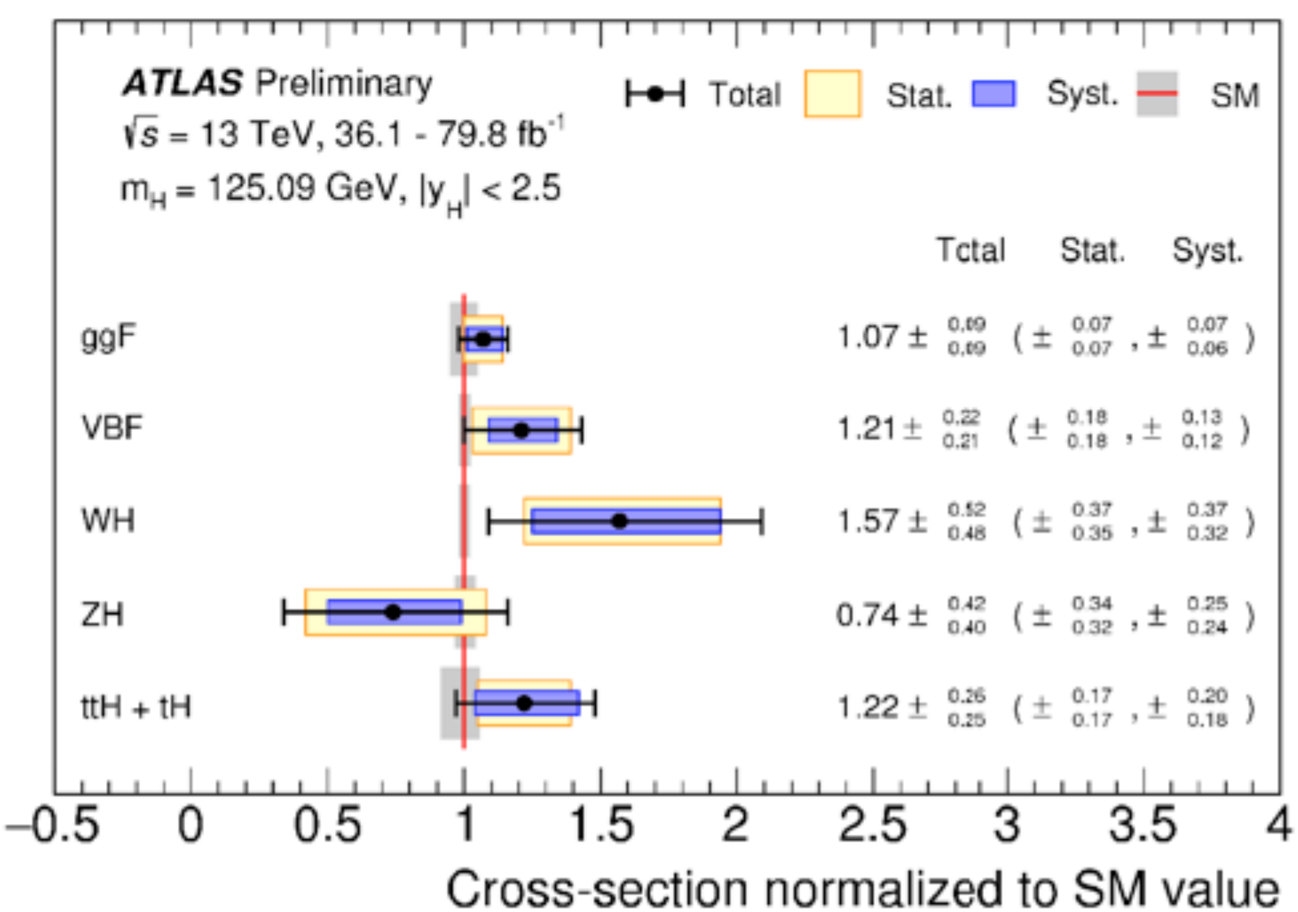
where $n \equiv n_1 + \cdots + n_r, k \equiv k_1 + \cdots + k_r$

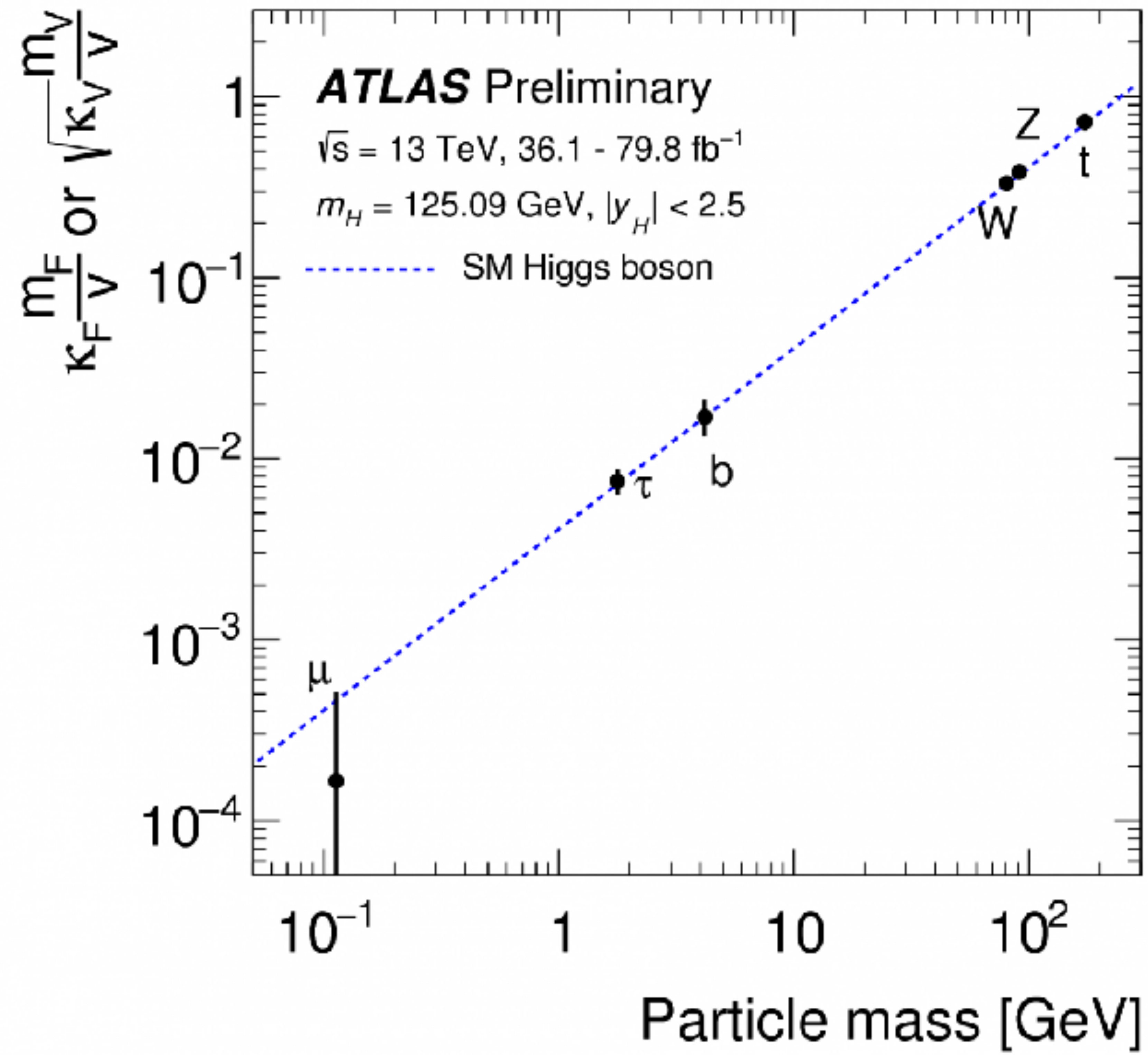
SCALAR STATES

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

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


ATLAS Preliminary
√s = 13 TeV, 36.1 - 79.8 fb⁻¹
m_H = 125.09 GeV, |y_H| < 2.5
Best fit
68% CL
95% CL
SM
Combined
H→γγ
H→ZZ
H→WW
H→bb
H→ττ
κ_F
κ_V


ATLAS Preliminary
√s = 13 TeV, 36.1 - 79.8 fb⁻¹
m_H = 125.09 GeV, |y_H| < 2.5
Total
Stat.
Syst.
SM
Tctal Stat. Syst.
ggF 1.07 ± 0.09 0.09 (± 0.07 0.07 , ± 0.07 0.06)
VBF 1.21 ± 0.22 0.21 (± 0.18 0.18 , ± 0.13 0.12)
WH 1.57 ± 0.52 0.48 (± 0.37 0.35 , ± 0.37 0.32)
ZH 0.74 ± 0.42 0.40 (± 0.34 0.32 , ± 0.25 0.24)
ttH + tH 1.22 ± 0.26 0.25 (± 0.17 0.17 , ± 0.20 0.18)
Cross-section normalized to SM value


ATLAS Preliminary
√s = 13 TeV, 36.1 - 79.8 fb⁻¹
m_H = 125.09 GeV, |y_H| < 2.5
SM Higgs boson
Z
t
W
b
τ
μ
1
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻¹
1
10
10²
Particle mass [GeV]
κ_F m_F/v or √κ_V m_V/v

INCLUDING QUARTIC

$$V \supset \frac{m_h^2}{8v^2}(1+\delta_4)\, h^4 + \frac{m_h^2}{4v^3}(\delta_4 - 3\delta_3)\, h^3 \vec{G}^2 + \frac{3m_h^2}{16v^4}(\delta_4 - 5\delta_3)\, h^2 \vec{G}^4$$
$$+ \frac{m_h^2}{16v^5}(\delta_4 - 6\delta_3)\, h\vec{G}^6 + \frac{m_h^2}{128v^6}(\delta_4 - 6\delta_3)\, \vec{G}^8.$$

Process	Unitarity Violating Scale
$h^2 Z_L \leftrightarrow hZ_L$	$66.7\ \text{TeV}/\lvert\delta_3 - \frac{1}{3}\delta_4\rvert$
$hZ_L^2 \leftrightarrow Z_L^2$	$94.2\ \text{TeV}/\lvert\delta_3\rvert$
$hW_L Z_L \leftrightarrow W_L Z_L$	$141\ \text{TeV}/\lvert\delta_3\rvert$
$hZ_L^2 \leftrightarrow hZ_L^2$	$9.1\ \text{TeV}/\sqrt{\lvert\delta_3 - \frac{1}{5}\delta_4\rvert}$
$hW_L Z_L \leftrightarrow hW_L Z_L$	$11.1\ \text{TeV}/\sqrt{\lvert\delta_3 - \frac{1}{5}\delta_4\rvert}$
$Z_L^3 \leftrightarrow Z_L^3$	$15.7\ \text{TeV}/\sqrt{\lvert\delta_3\rvert}$
$Z_L^2 W_L \leftrightarrow Z_L^2 W_L$	$20.4\ \text{TeV}/\sqrt{\lvert\delta_3\rvert}$
$hZ_L^3 \leftrightarrow Z_L^3$	$6.8\ \text{TeV}/\lvert\delta_3 - \frac{1}{6}\delta_4\rvert^{\frac{1}{3}}$
$hZ_L^2 W_L \leftrightarrow Z_L^2 W_L$	$8.0\ \text{TeV}/\lvert\delta_3 - \frac{1}{6}\delta_4\rvert^{\frac{1}{3}}$
$Z_L^4 \leftrightarrow Z_L^4$	$6.1\ \text{TeV}/\lvert\delta_3 - \frac{1}{6}\delta_4\rvert^{\frac{1}{4}}$