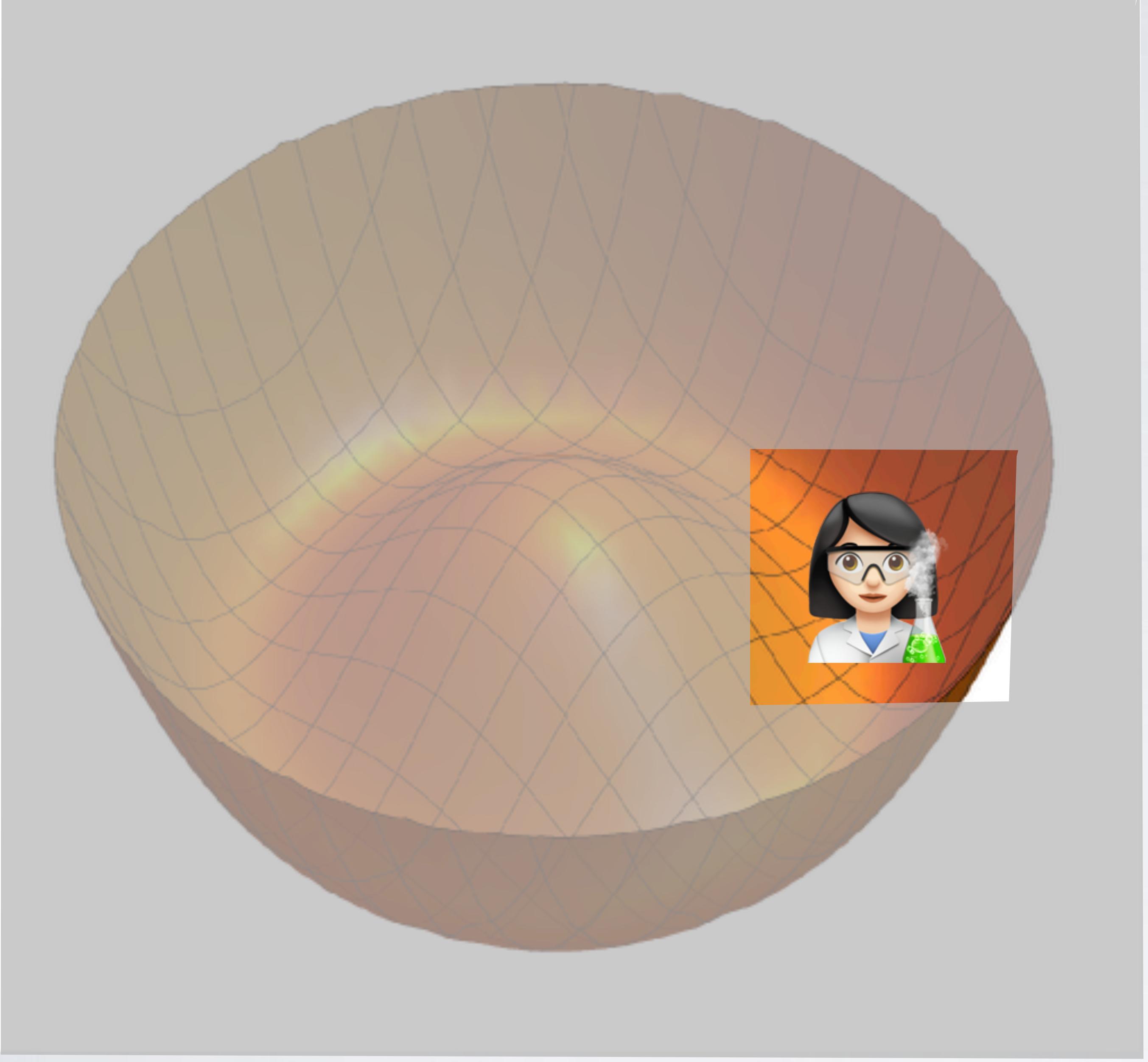
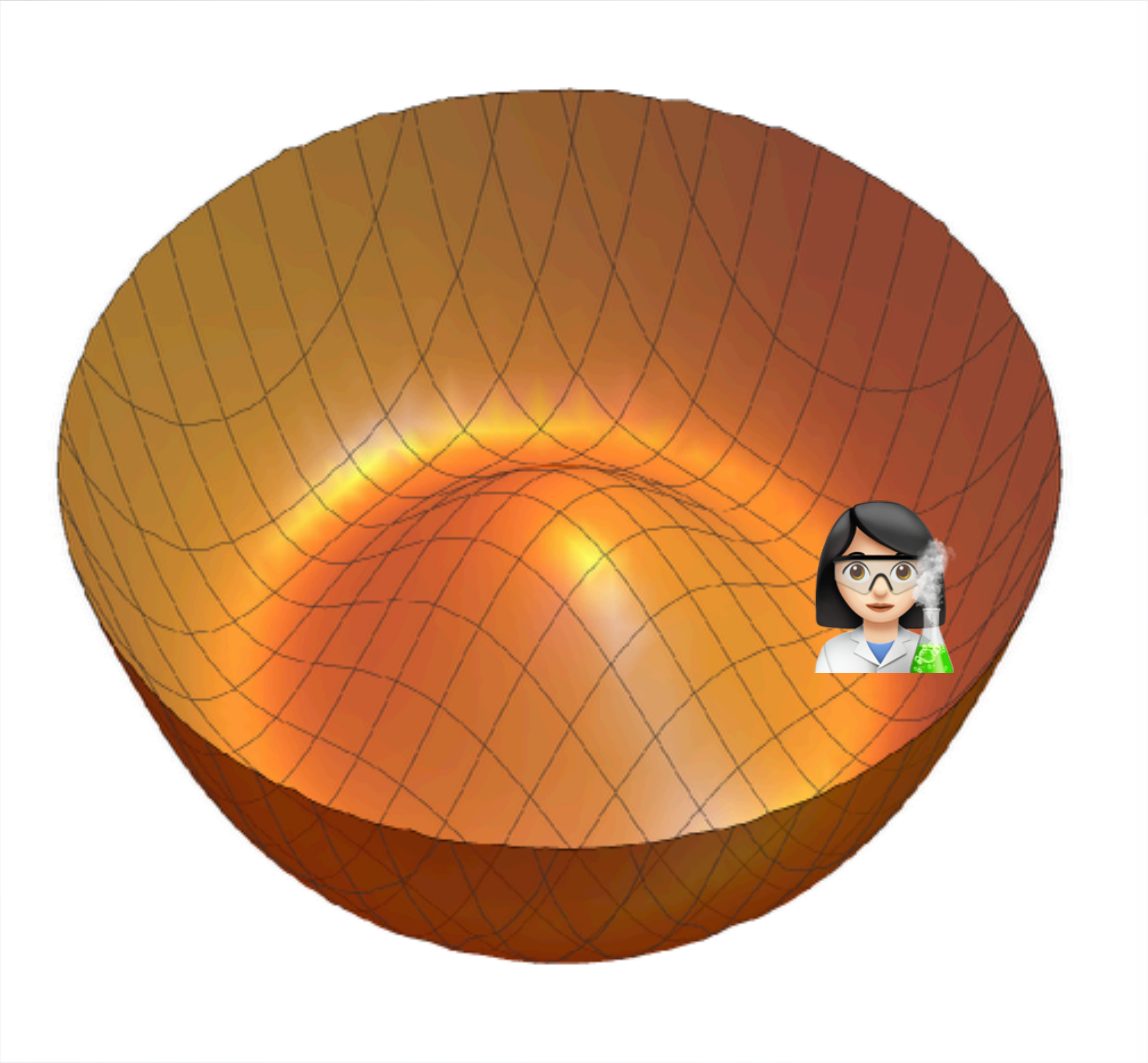


THE HIGGS TRILINEAR COUPLING AND THE SCALE OF NEW PHYSICS

Spencer Chang (U. Oregon/NTU)
w/ Markus Luty 1902.05556
also see Falkowski & Rattazzi 1902.05936
and earlier work by Belyaev et.al. 1212.3860
Kavli IPMU 3/20/19

ELECTROWEAK SYMMETRY BREAKING



The simplest interpretation of the LHC results is the Standard Model is nearly complete, with the Higgs being a Standard Model (SM) Higgs

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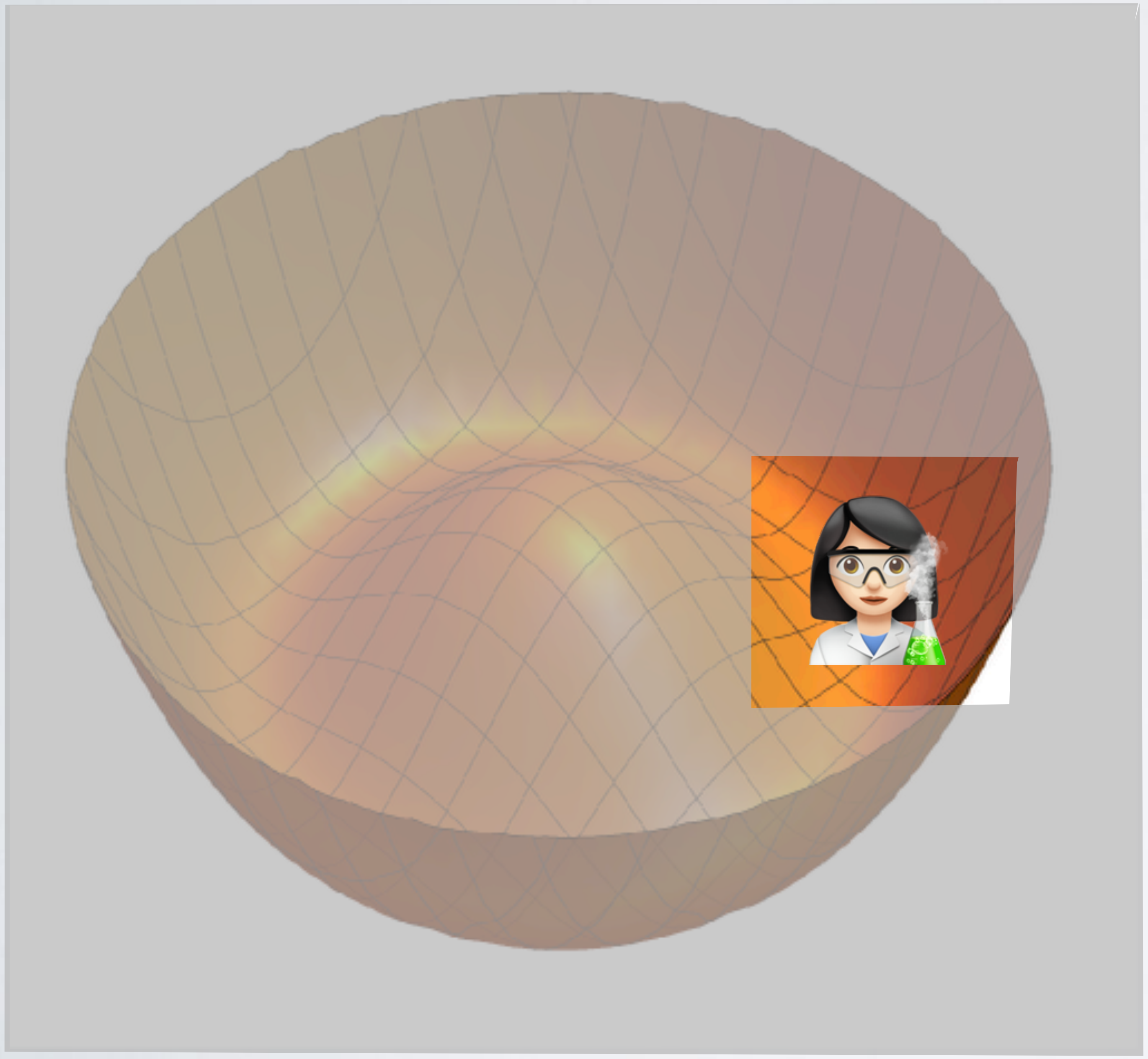

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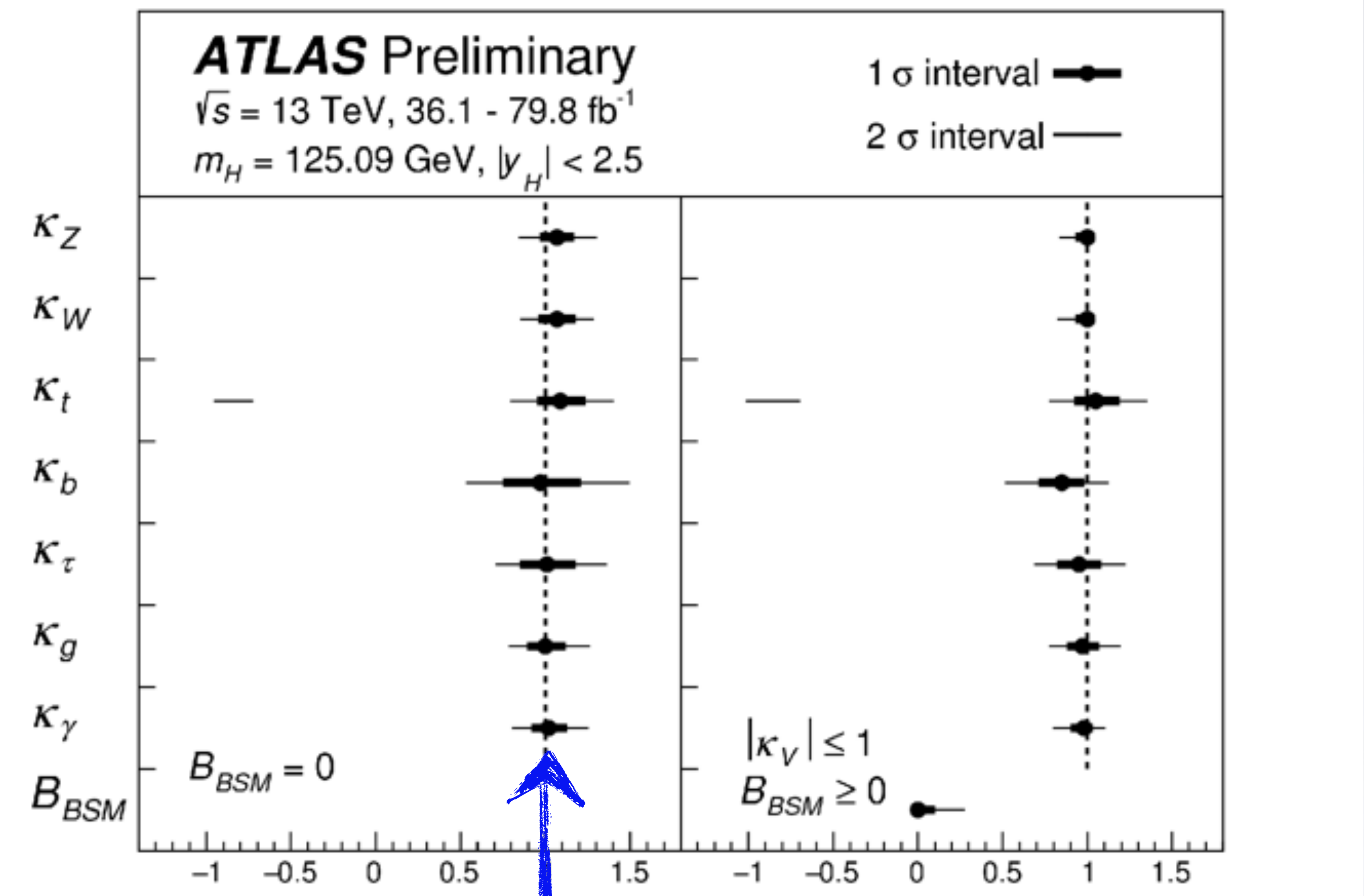
PRECISE HIGGS PROPERTIES

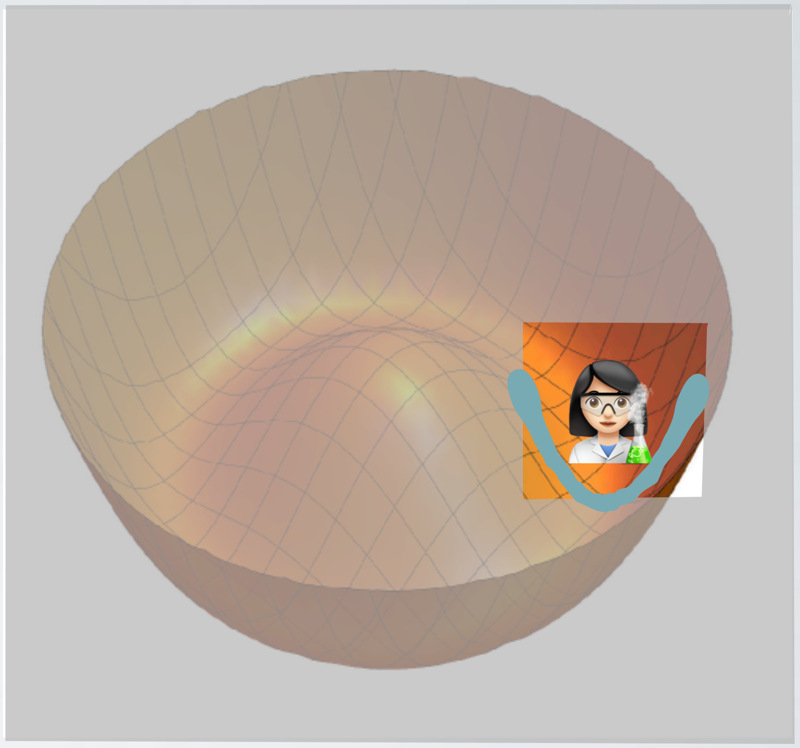


ATLAS-CONF-2018-031

Fits for Higgs couplings
Standard Model
particles have
20-50% errors
and currently
agree with SM value

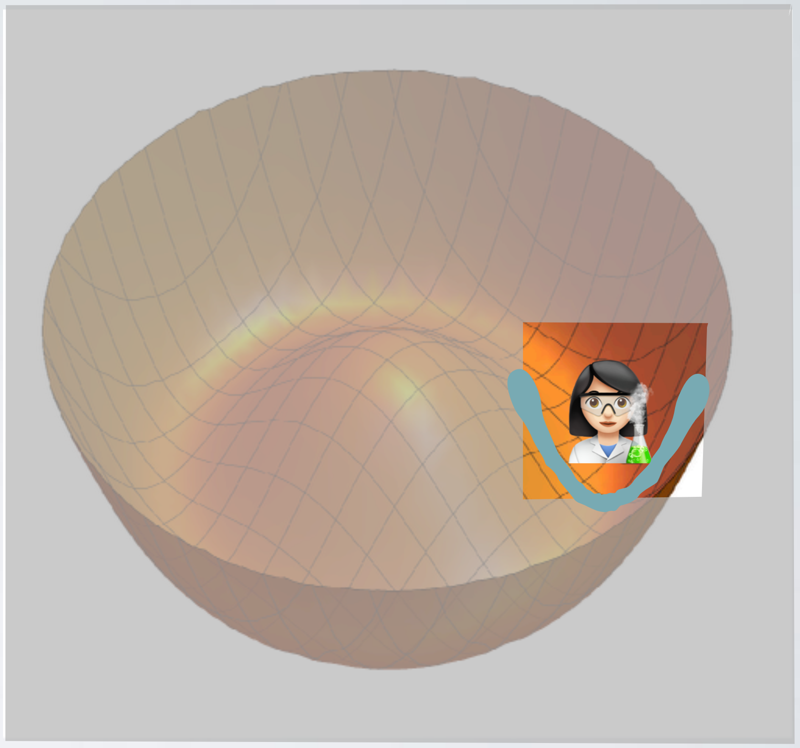
Standard
Model values

HIGGS POTENTIAL WE ONLY KNOW THE MASS



HIGGS POTENTIAL WE ONLY KNOW THE MASS

Standard EWSB



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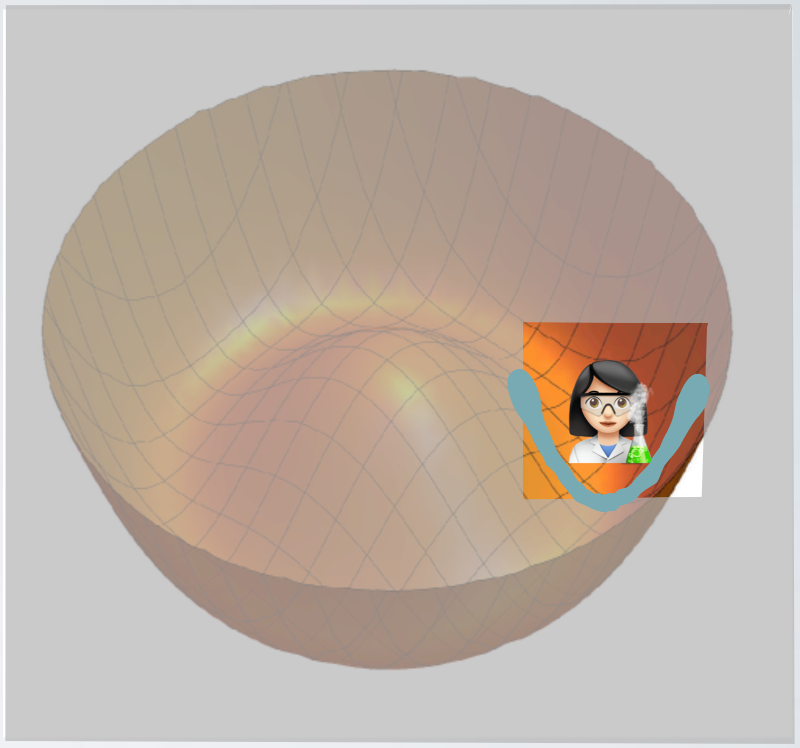
Standard EWSB

Tilted Hat



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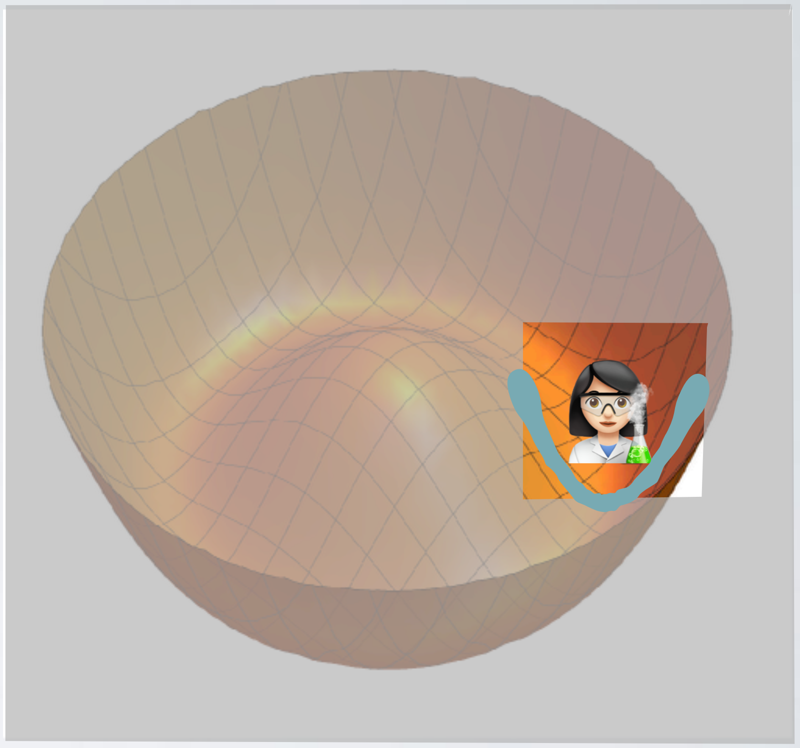
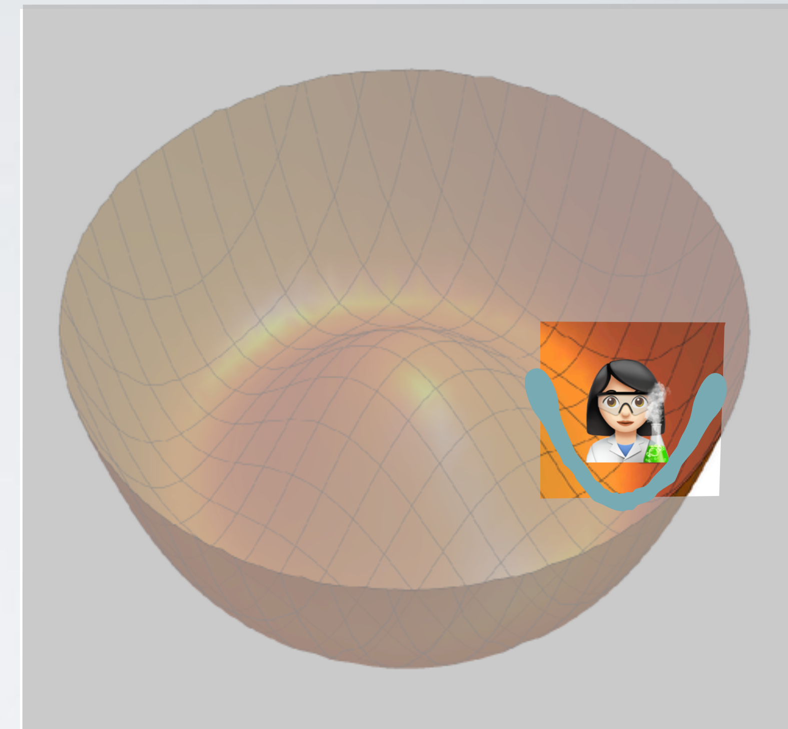


Tilted Bowl

HIGGS POTENTIAL WE ONLY KNOW THE MASS

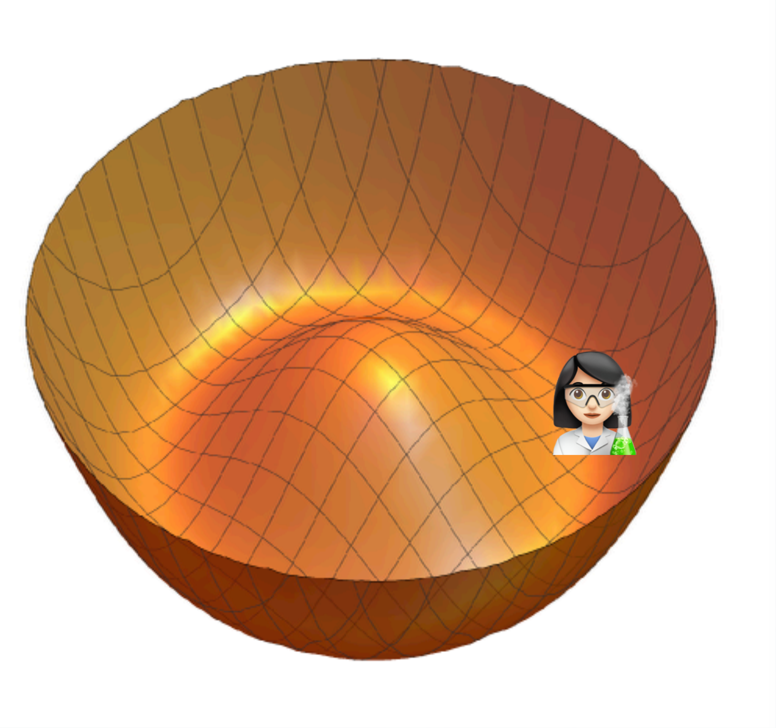
Standard EWSB

Tilted Hat



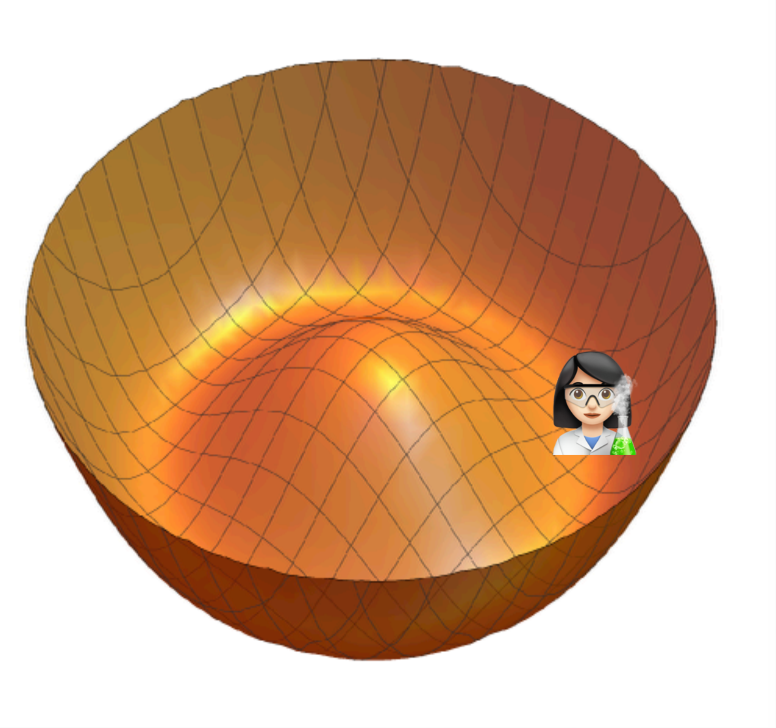
Tilted Bowl

Nonstandard Potentials occur in many scenarios w/ new EWSB source e.g. 2HDM, induced EWSB



HIGGS TRILINEAR AND QUARTIC

$$\lambda\left(|H|^2 - \frac{v^2}{2}\right)^2 = \lambda v^2 h^2 + \lambda v h^3 + \frac{\lambda}{4} h^4$$



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$$m_h^2 = 2\lambda v^2$$

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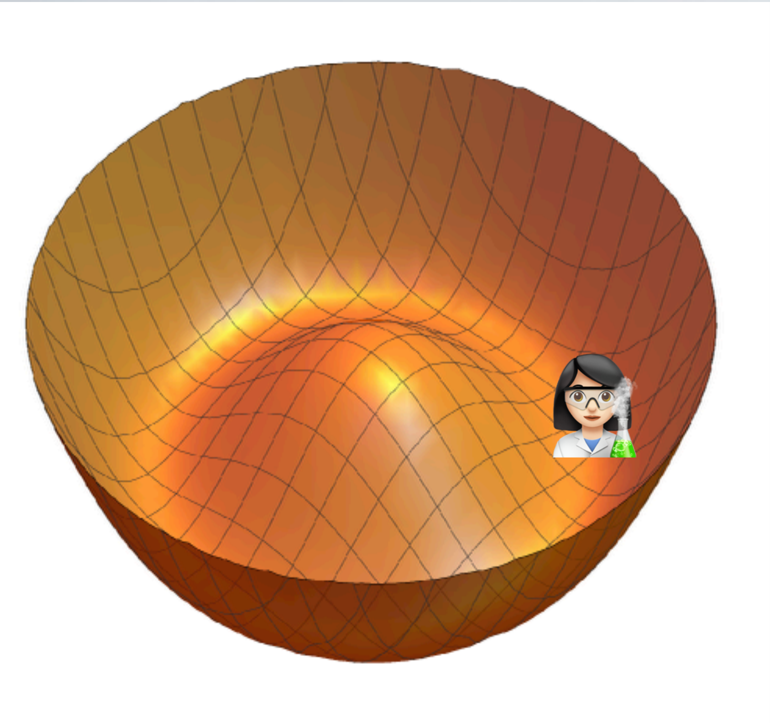

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sometimes referred to as **κ_λ**

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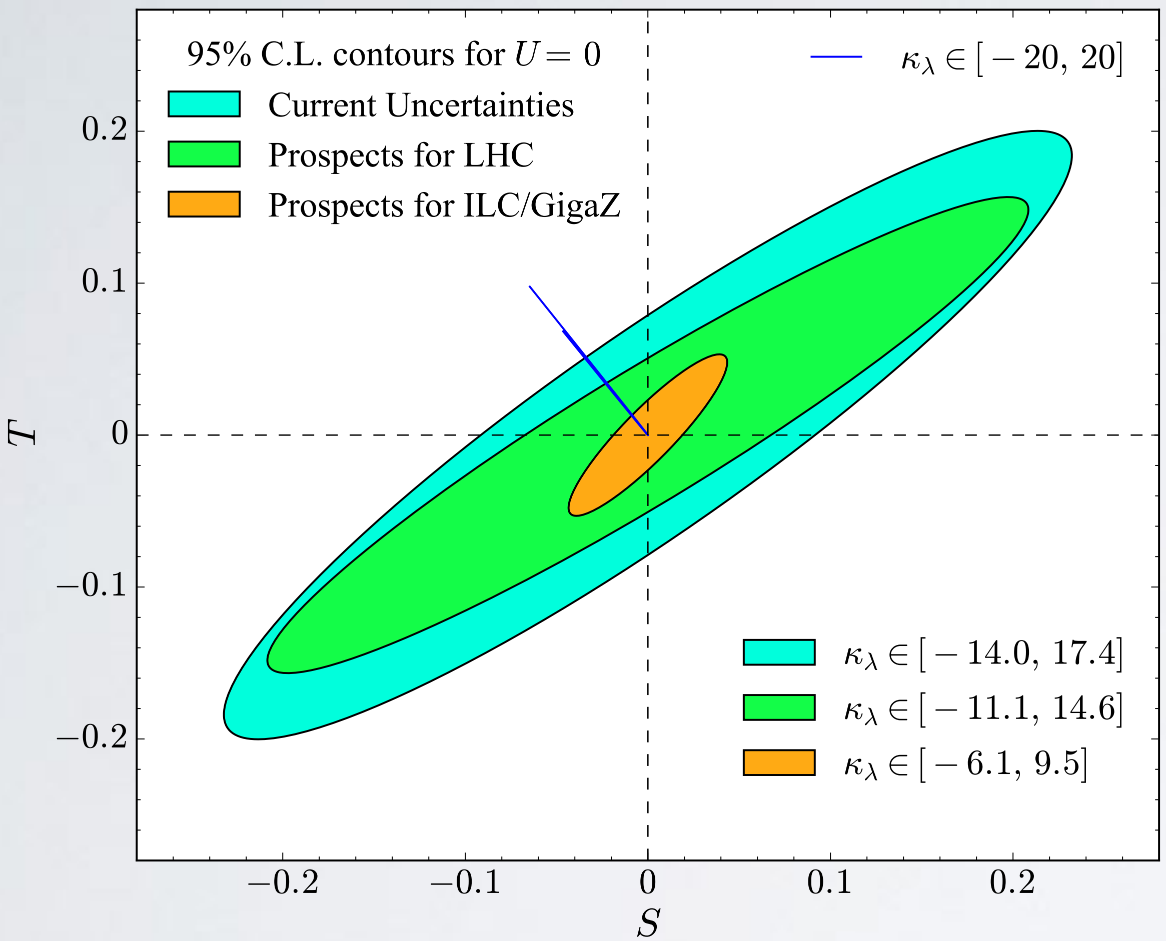
EXISTING INDIRECT TRILINEAR CONSTRAINTS



Precision Electroweak

$|\kappa_\lambda| \lesssim 14$

Kribs et.al. 1702.07678

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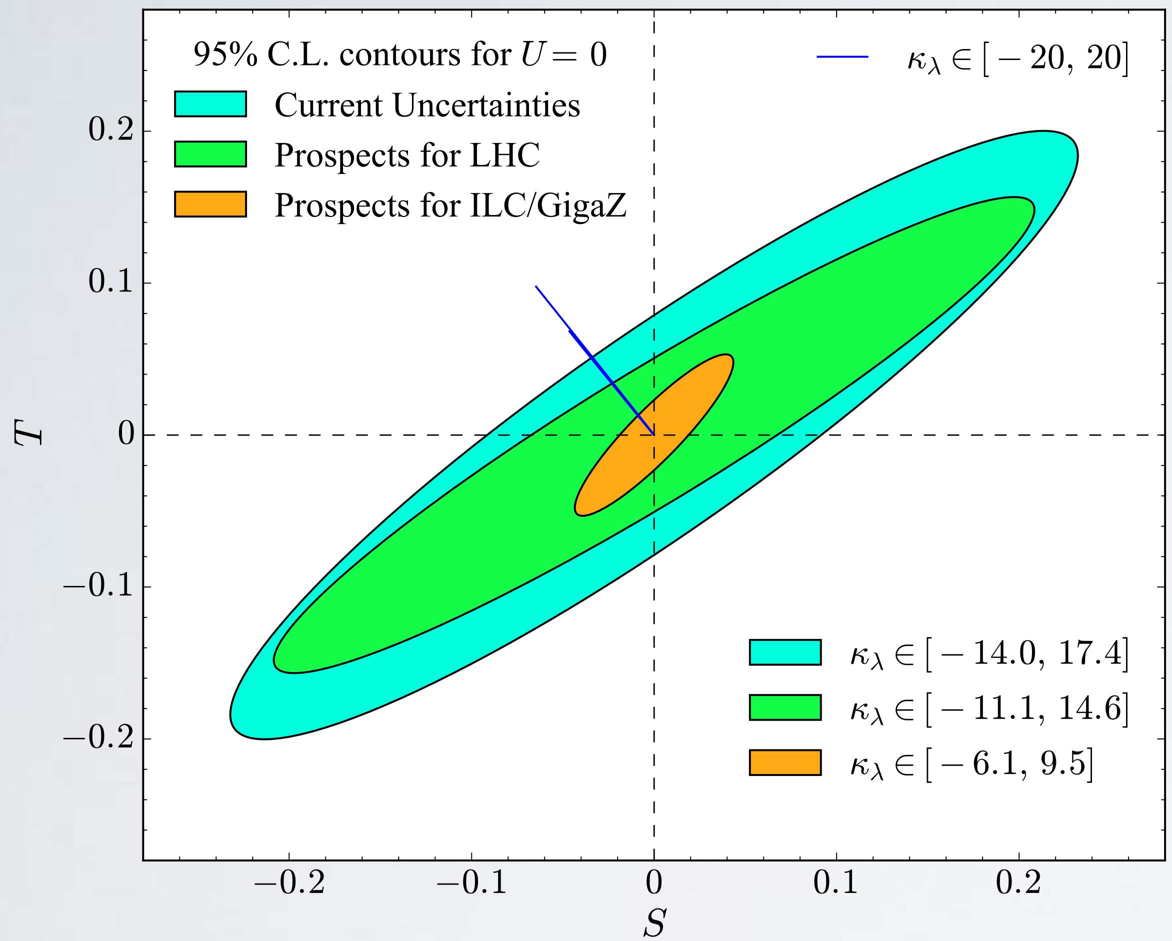
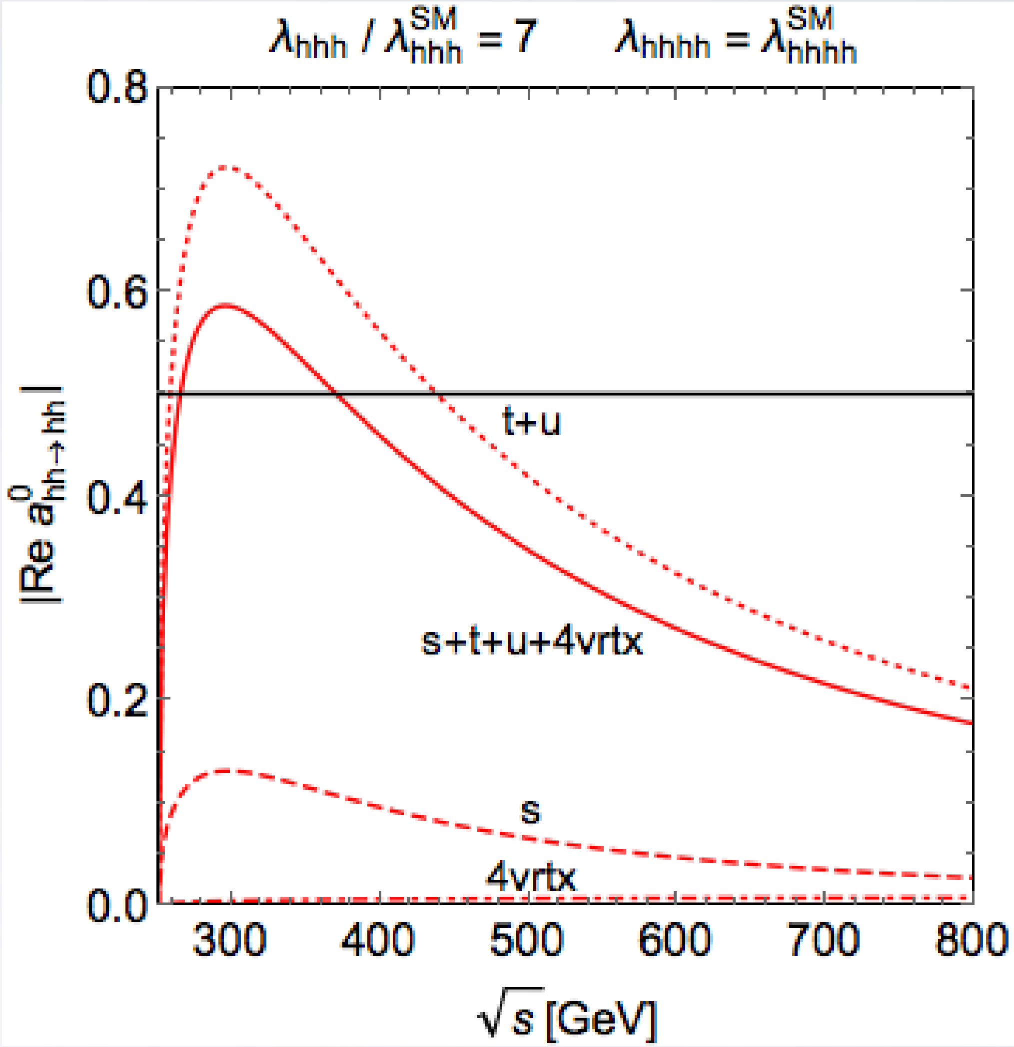




Precision Electroweak

$|\kappa_\lambda| \lesssim 14$

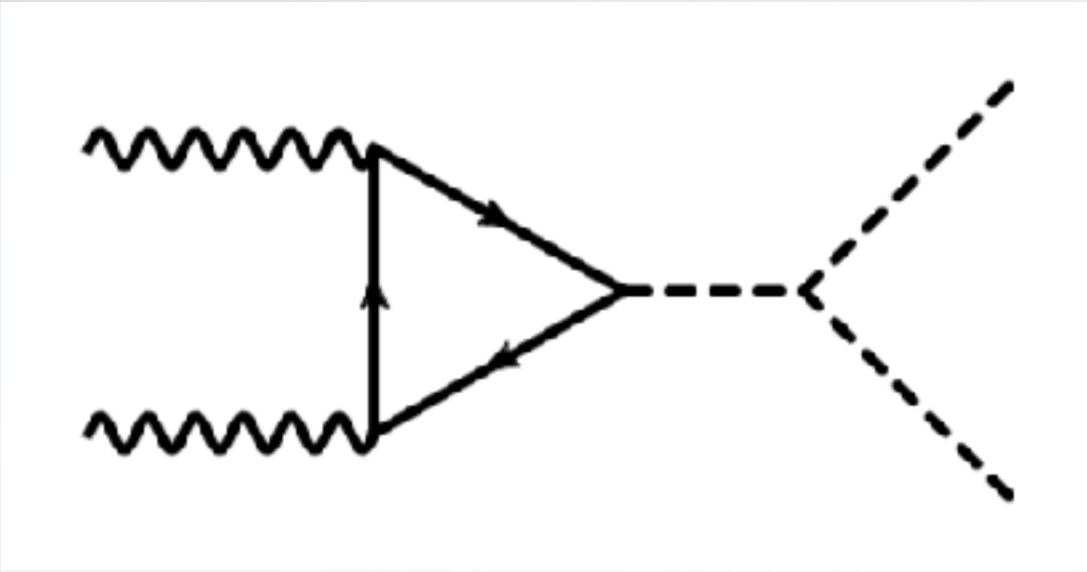
Kribs et.al. 1702.07678

Low Energy Unitarity hh → hh

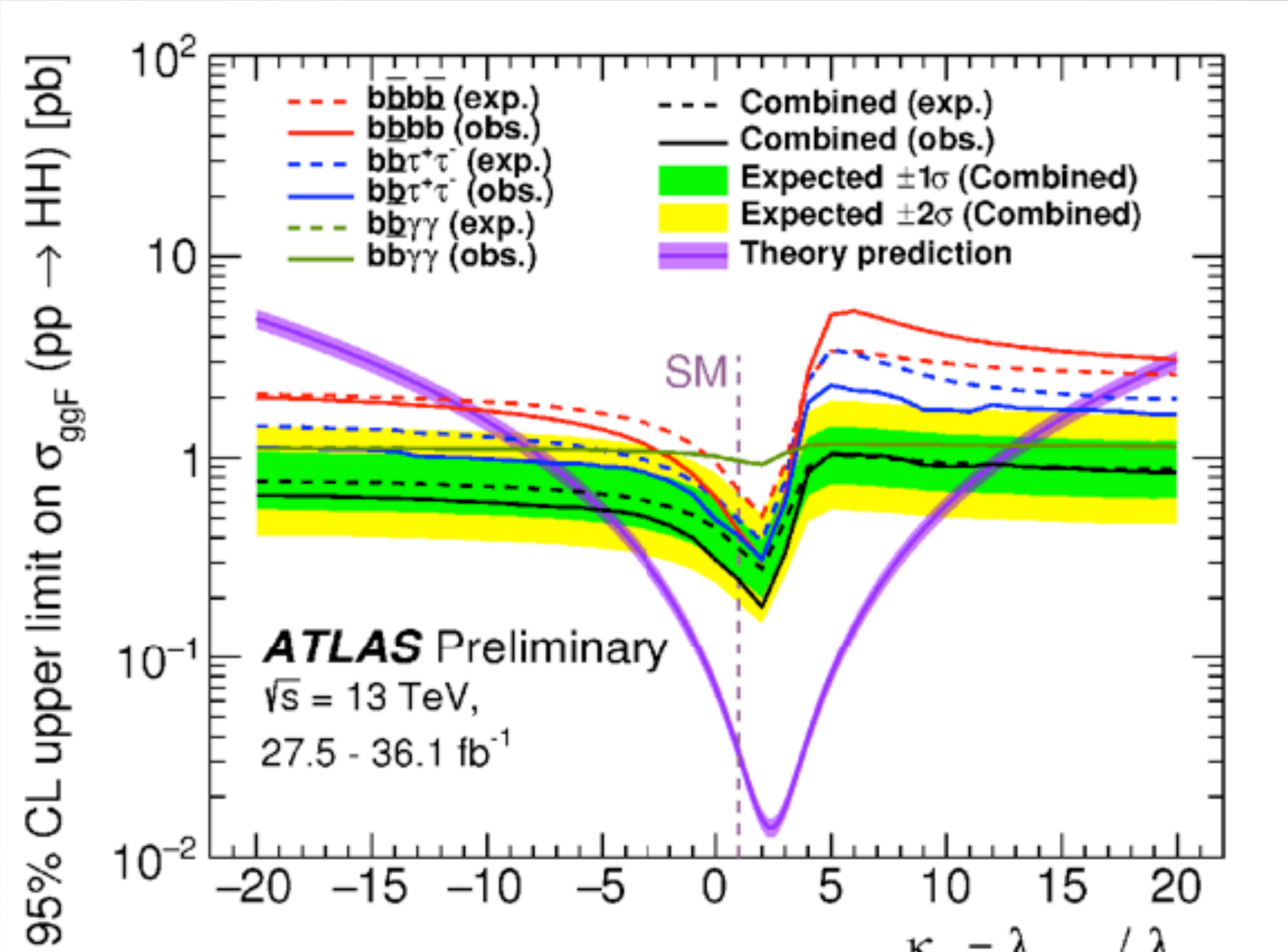
$|\kappa_\lambda| \lesssim 7$

Di Luzio et.al. 1704.02311

DIRECT SEARCH

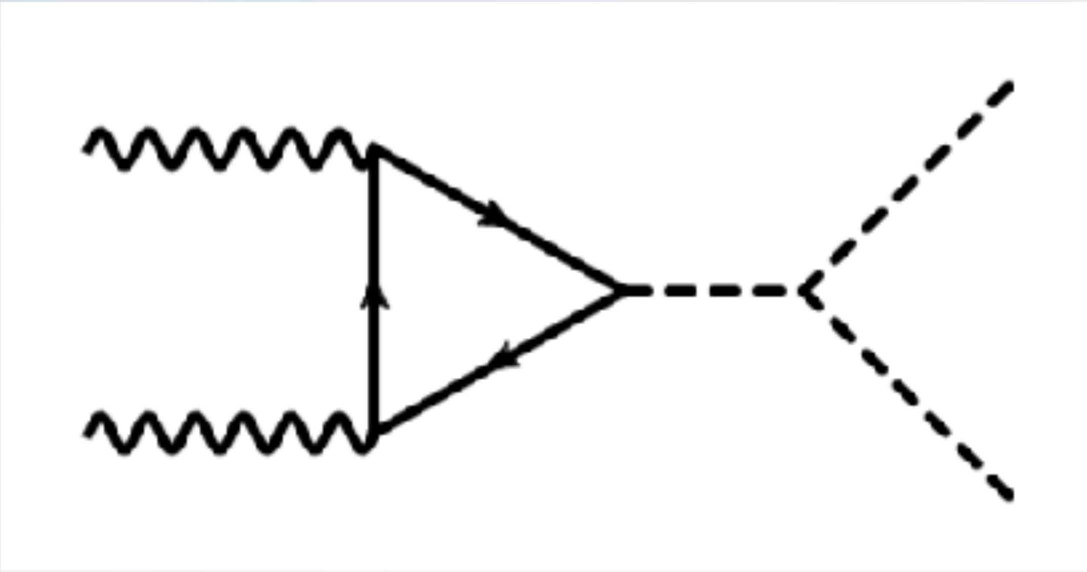


Trilinear probed by search for Double Higgs production



ATLAS-CONF-2018-043

DIRECT SEARCH



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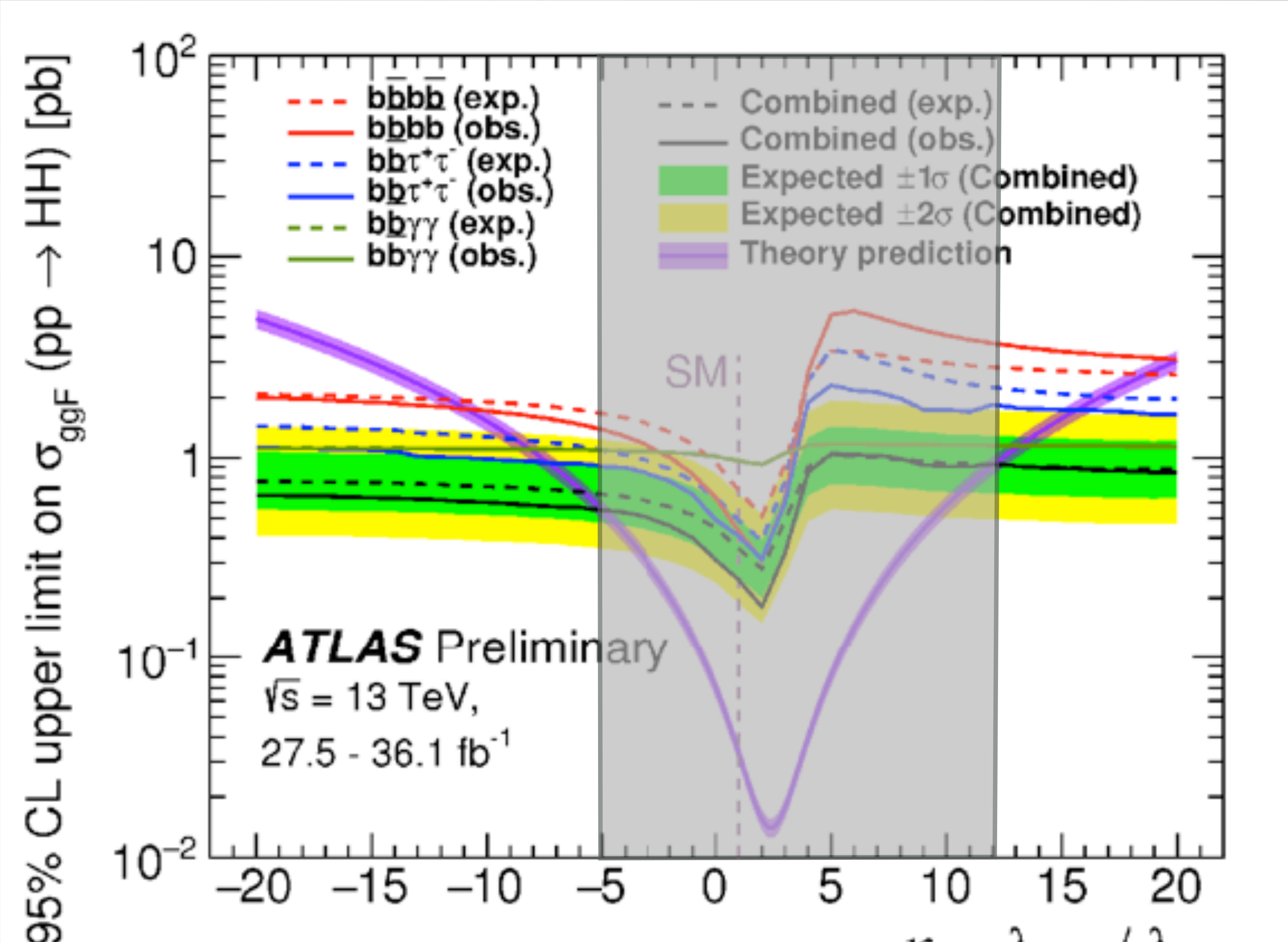
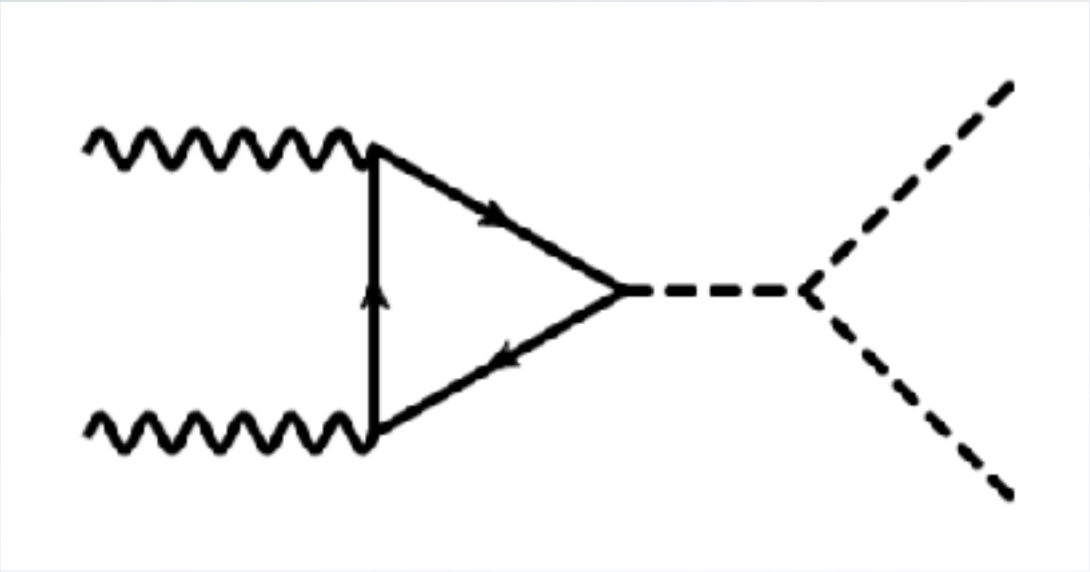


ATLAS-CONF-2018-043

DIRECT SEARCH



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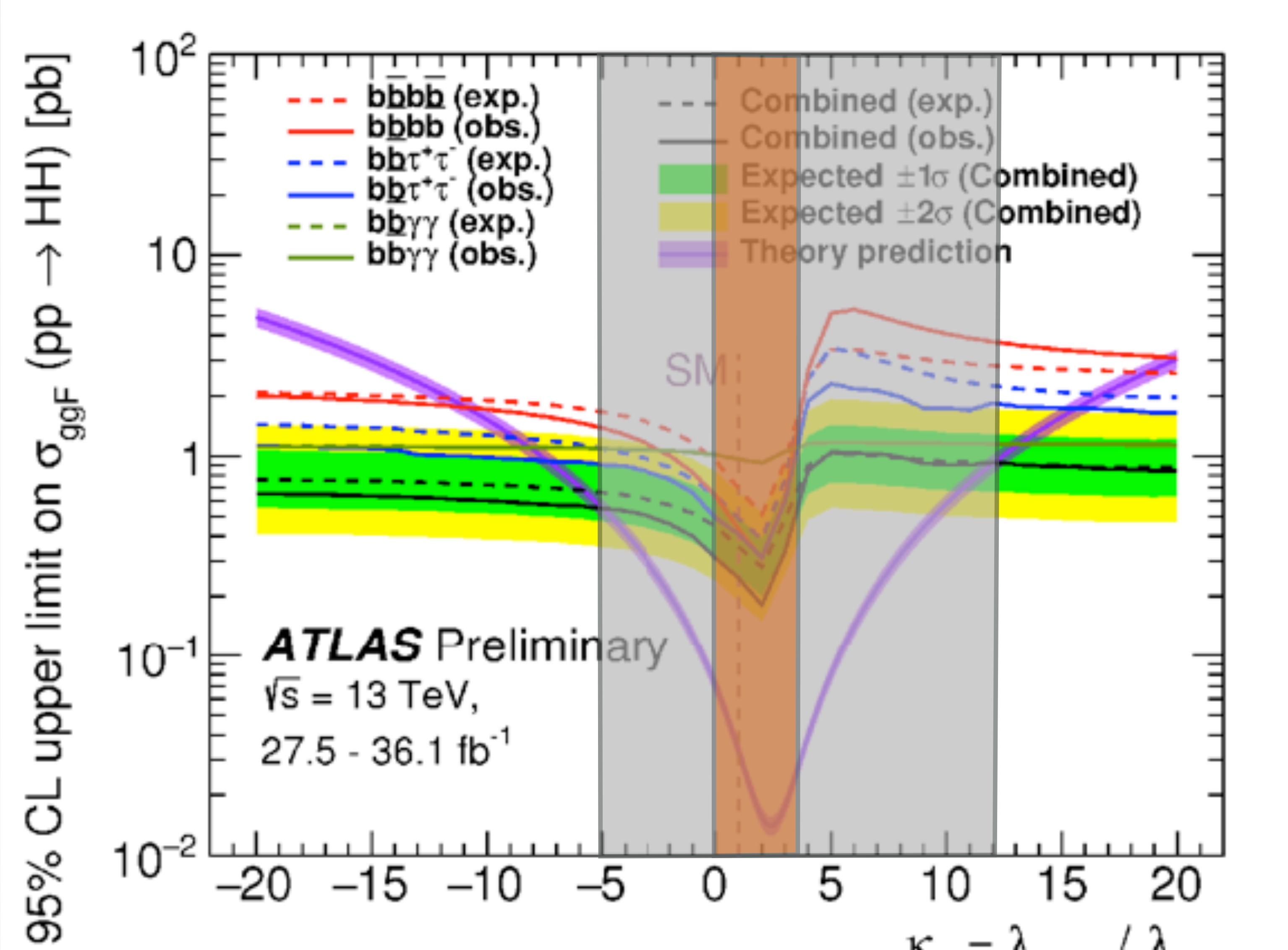
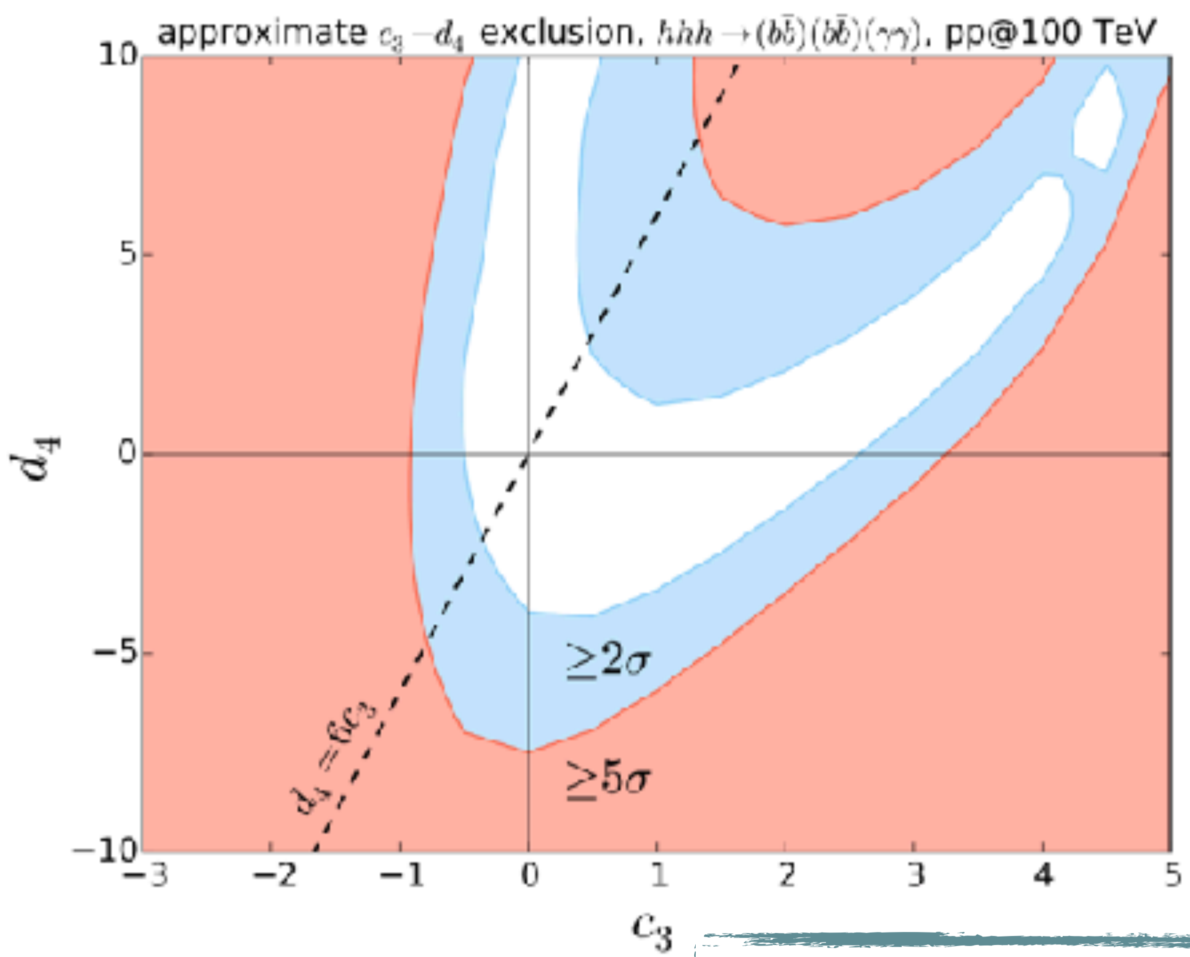


ATLAS-CONF-2018-043

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

TRIPLE HIGGS PROCESS

Papaefstathiou and Sakurai
See also Chien et.al.



(a)

$c_3 = \delta_3$, $d_4 = \delta_4$

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 $c_3 \in [-3.0, 4.0]$.

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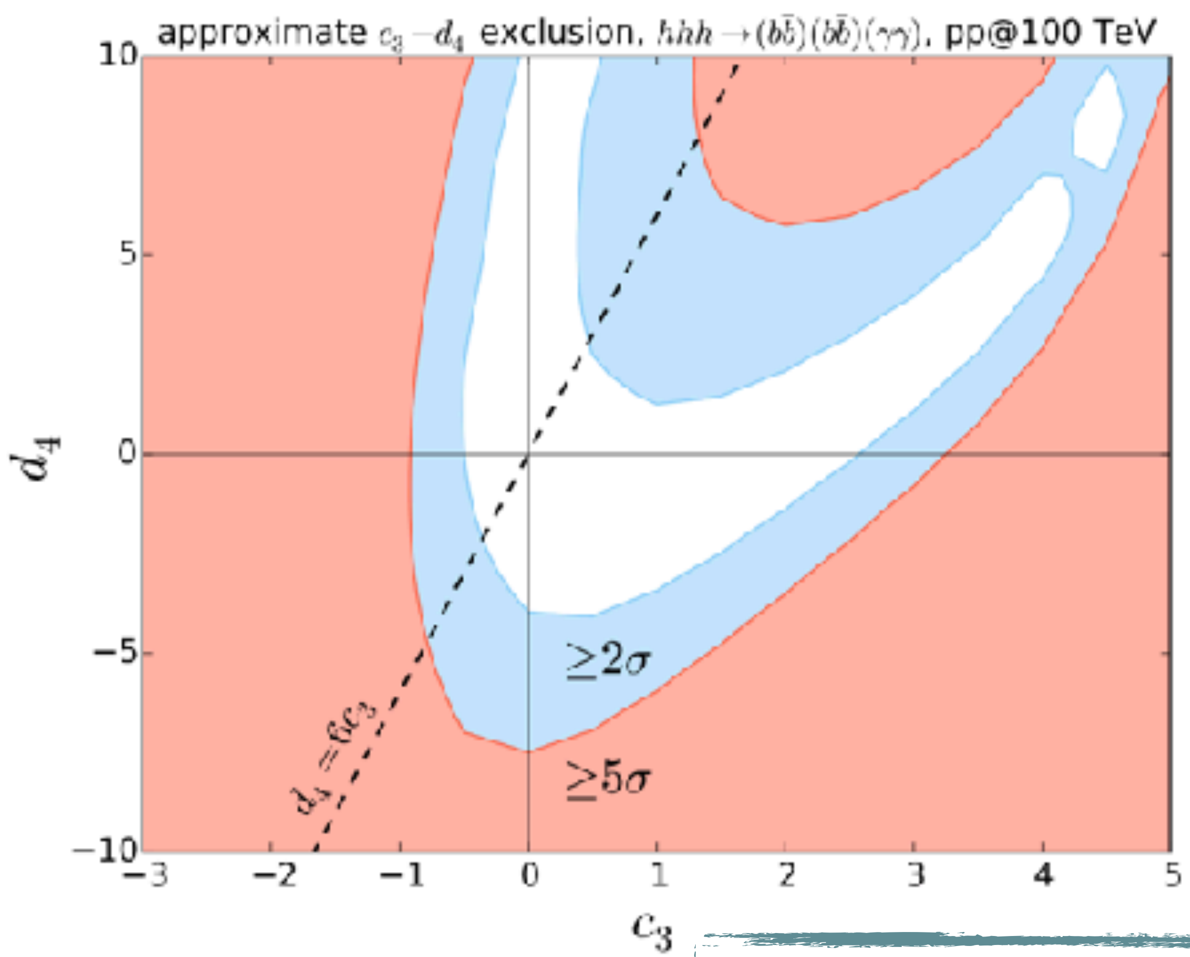

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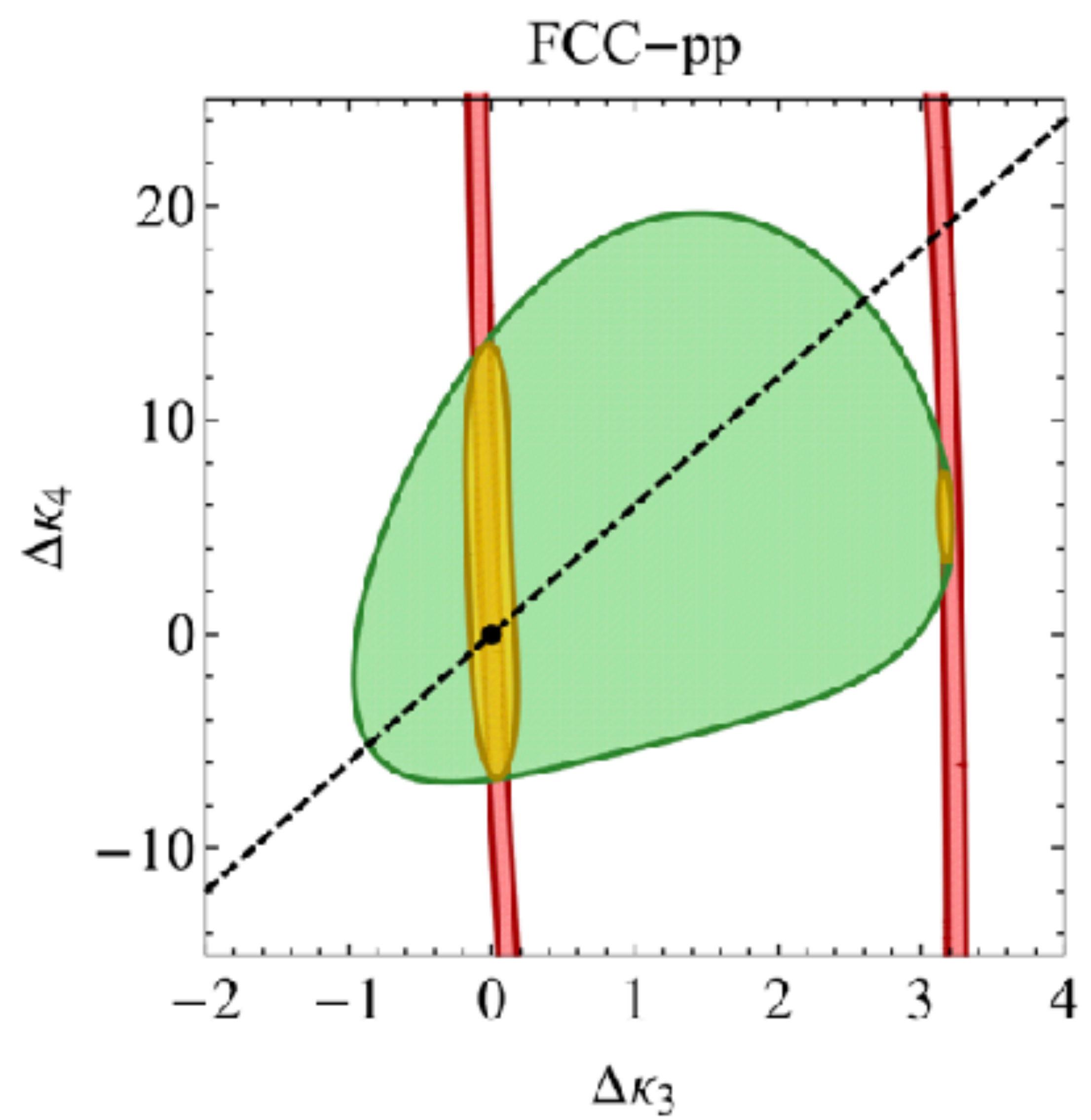

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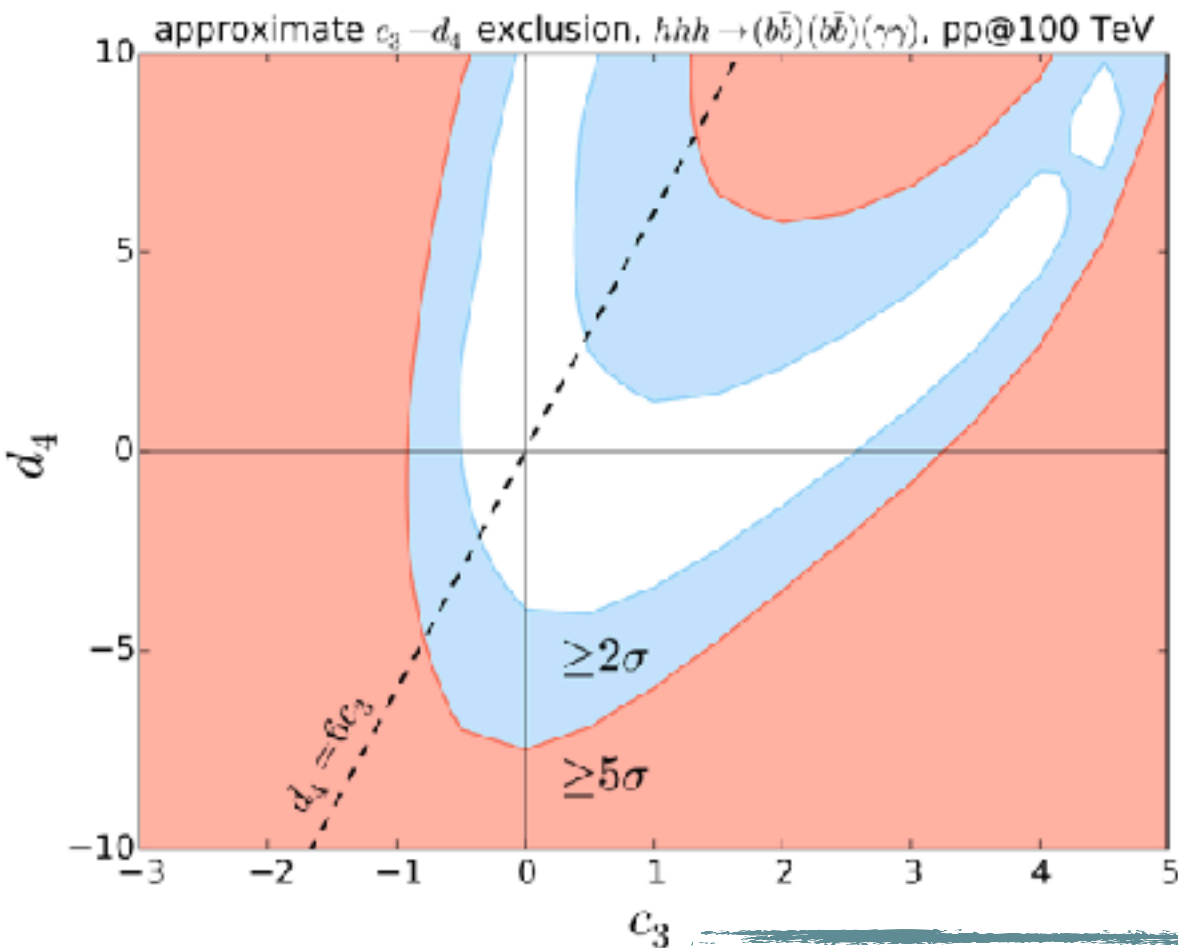

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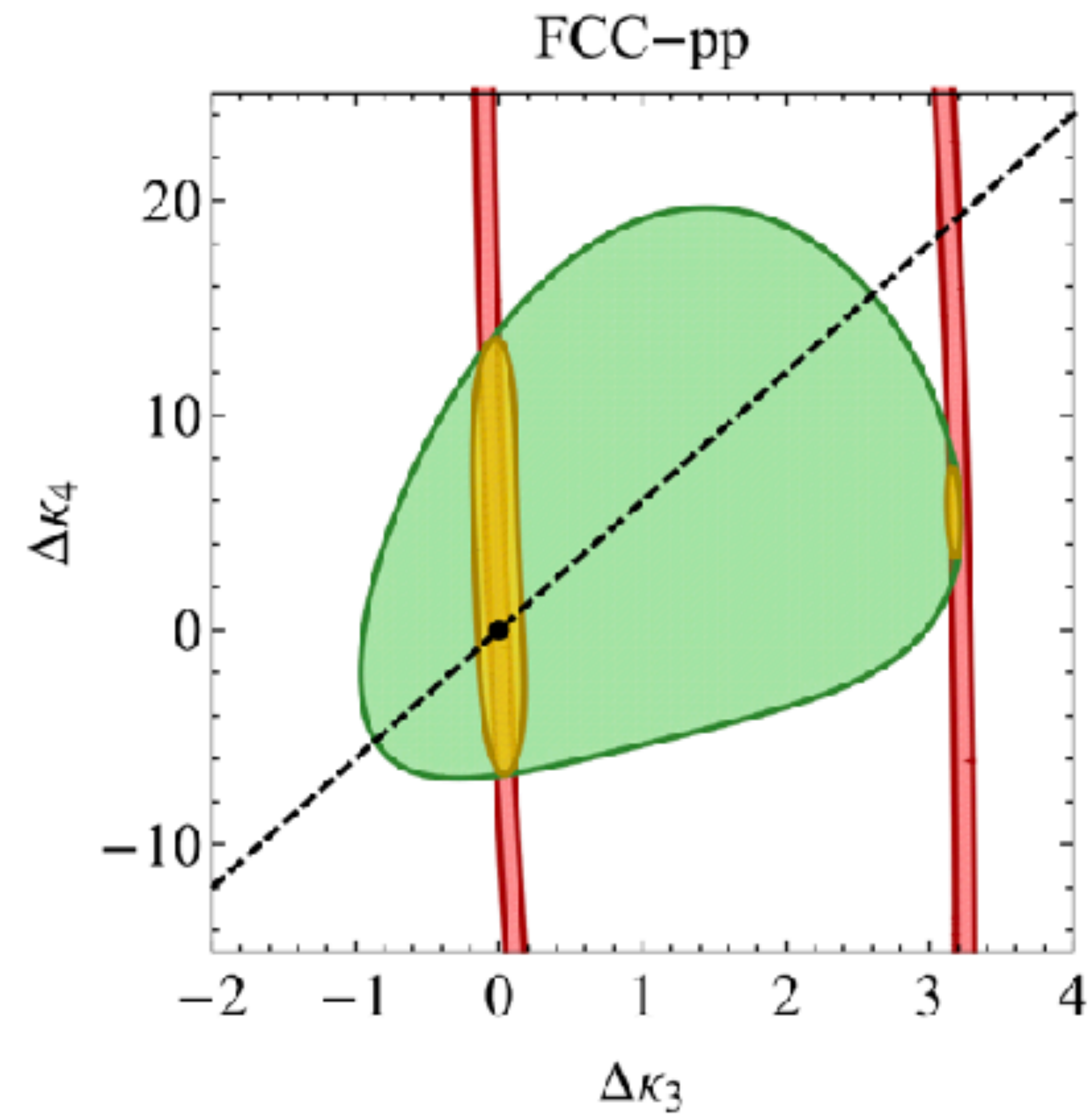

Sensitivity to Higgs quartic is poor even in optimistic cases

NONSTANDARD POTENTIAL MYSTERY

What if a nonstandard trilinear is observed in the future? What would be the consequence?

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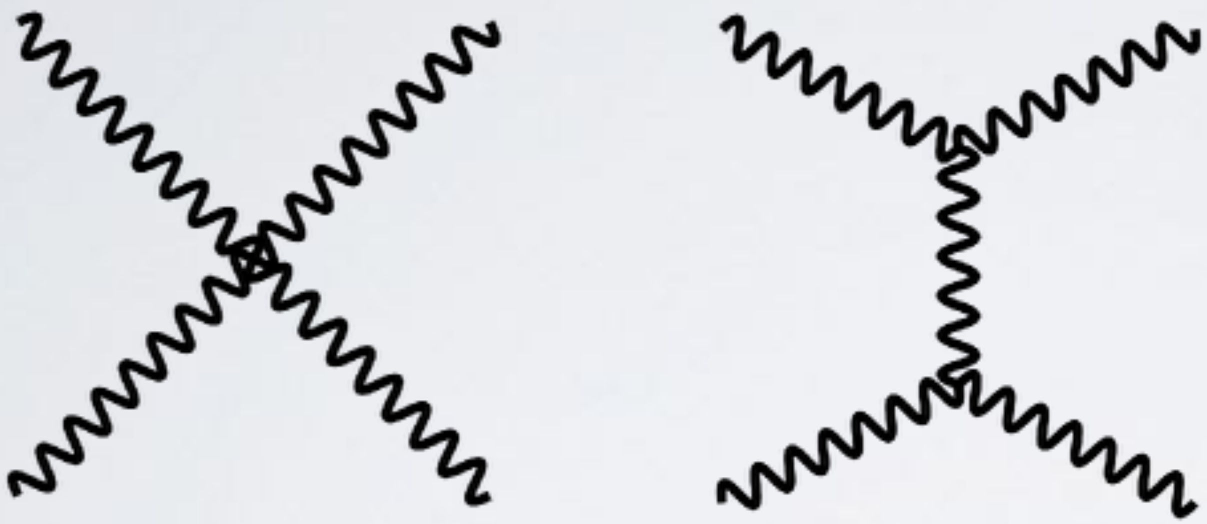
What if a nonstandard trilinear is observed in the future? What would be the consequence?

A model independent approach to constraining this new physics is (perturbative) unitarity violation

UNITARITY VIOLATION

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

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



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

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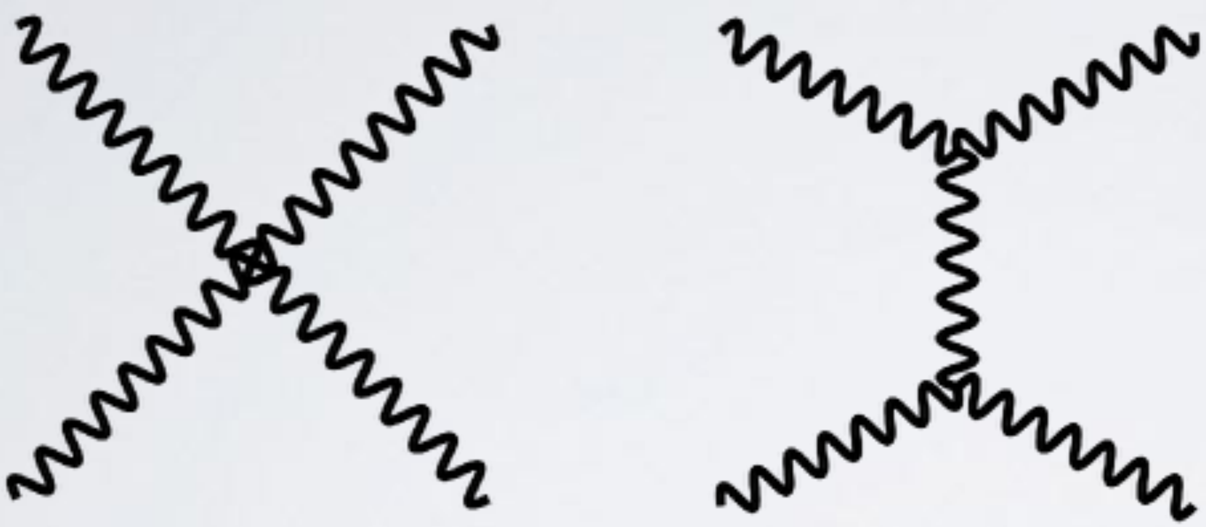

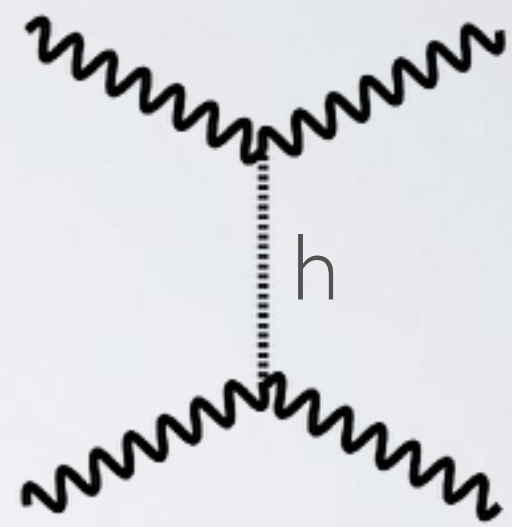

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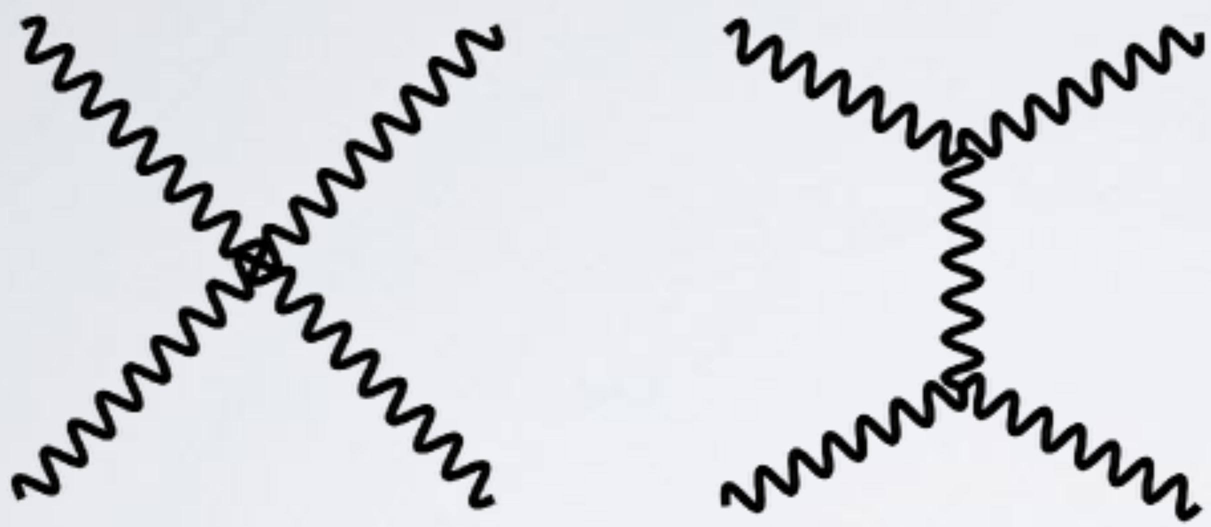

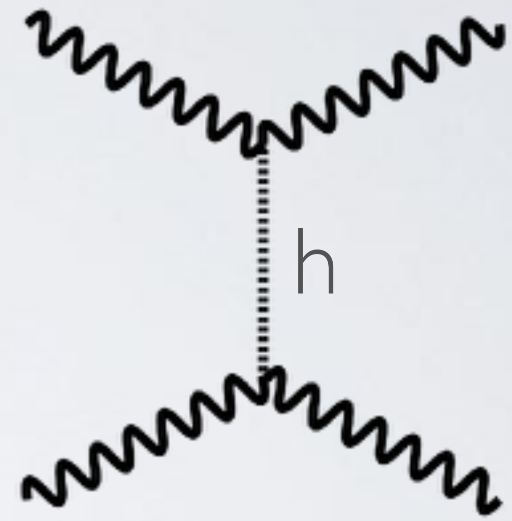

$M = c\ \text{Energy}^2 + \ldots$

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Higgs exchange cancels high energy growth if its couplings are SM-like, matrix element is Unitary if $m_H \lesssim 1\,\text{TeV}$ (Lee, Quigg, Thacker)

GENERAL HIGGS POTENTIAL

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

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

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

Phenomenological and agnostic about origin of Higgs boson
Not SU(2) x U(1) invariant, but can be lifted to EW gauge invariant theory via

$$X \equiv \sqrt{2|H|^2} - v = \sqrt{(v+h)^2 + \vec{G}^2} - v$$
$$= h + \frac{1}{2v}\vec{G}^2 - \frac{1}{2v^2} h\vec{G}^2 + \cdots$$

STANDARD MODEL EFT (SMEFT)

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

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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

$$Y \equiv |H|^2 - \frac{v^2}{2}$$

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

NONSTANDARD HIGGS TRILINEAR

HEFT

$$V = V_{SM} + \frac{m_h^2}{2v}\delta_3\; X^3 + \cdots$$
$$= V_{SM} + \frac{m_h^2}{2v}\delta_3\; h^3 + \cdots$$

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SMEFT

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

NONSTANDARD HIGGS TRILINEAR

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SMEFT correlations

TRILINEAR UNITARITY VIOLATION

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

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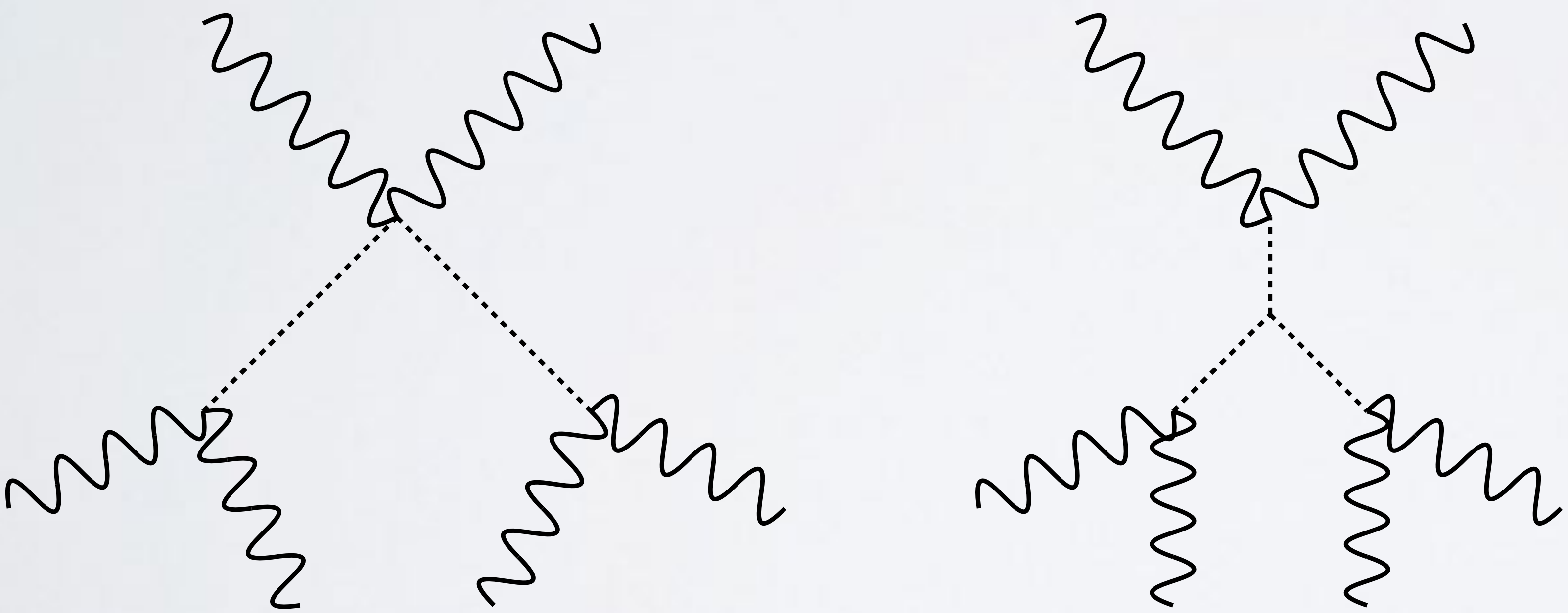

Example:

$Z_L Z_L Z_L \Leftrightarrow Z_L Z_L Z_L$

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

UNITARITY CONSTRAINTS ON NON-DERIVATIVE COUPLINGS

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

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Consider s-wave scattering

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

ONE PARTICLE EXAMPLE

$$\frac{\lambda}{n!}\phi^n$$

Optimal bound is when k = n/2

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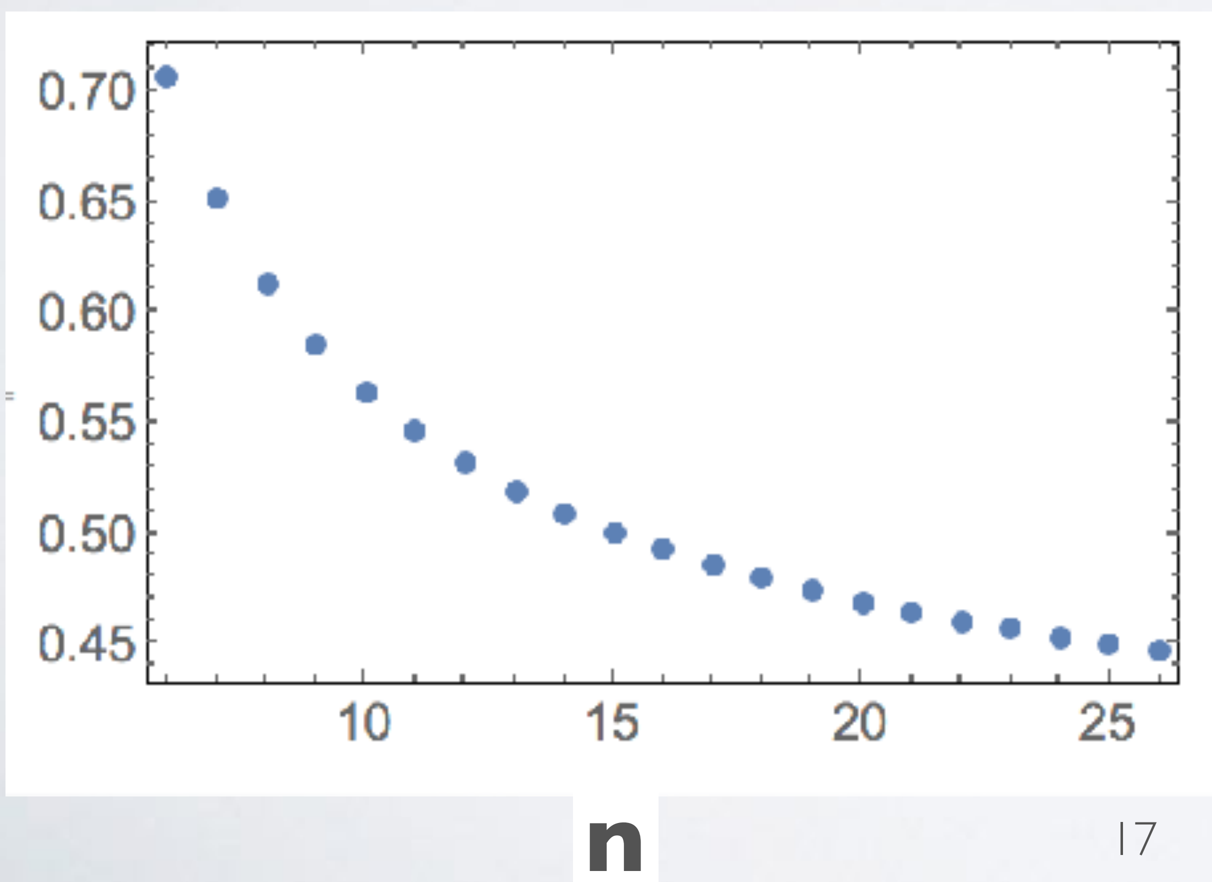
Optimal bound is when k = n/2

$$\frac{E_{k=n/2}}{E_{k=2}} = \left[\frac{\{(n/2)!(n/2-1)!(n/2-2)!\}^2}{2!1!0!(n-2)!(n-3)!(n-4)!}\right]^{1/(2n-8)}$$



n/2 ⟺ n/2 channel improves Unitarity bound by up to factor of two compared to standard 2 ⟺ n-2

HEFT TRILINEAR
(ALSO SEE FALKOWSKI, RATTAZZI)

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

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

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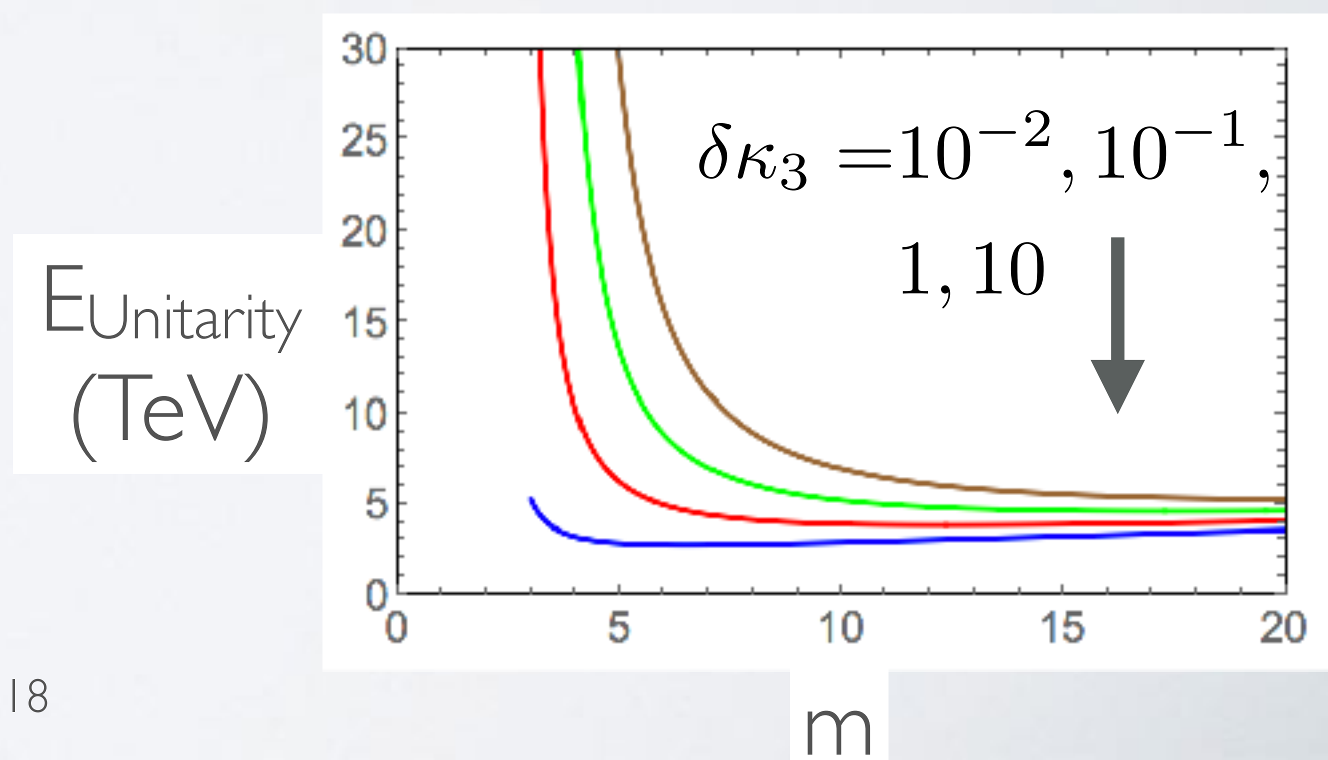
Unitarity violating scale for $Z_L\, h^{m/2} \Leftrightarrow Z_L\, h^{m/2}$ is ~5 TeV for m ~ 10-15



SMEFT VS HEFT

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cuts off at 6-pt interactions
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has infinite tower of interactions
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Thus, these higher order terms are model dependent and are due to assumptions about Higgs potential modifications (e.g. existence of h^4, h^5, h^6 corrections)

MODEL DEPENDENCE OF TERMS

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

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

MODEL DEPENDENCE OF TERMS

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

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

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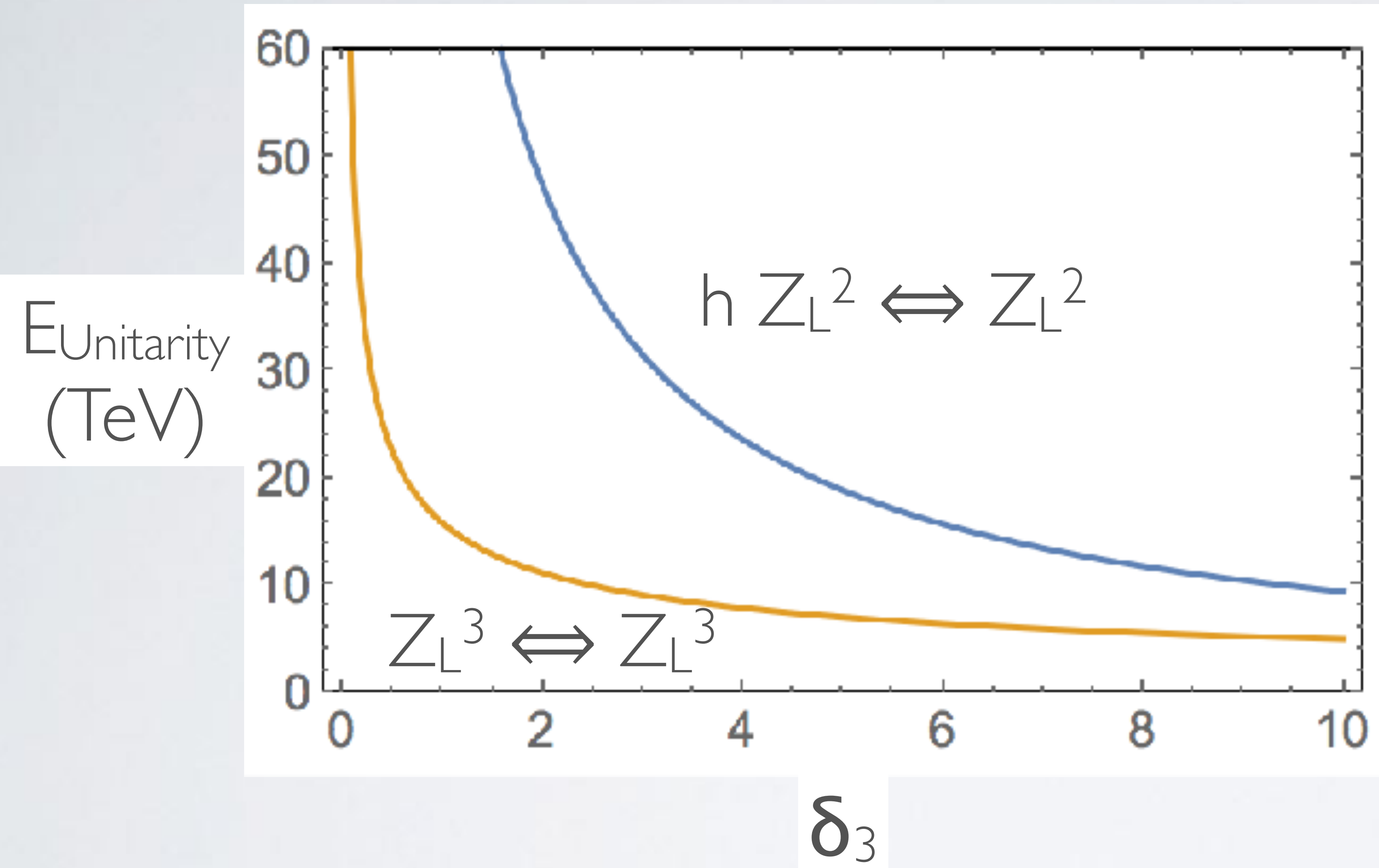
Terms circled can only come from trilinear!

MODEL INDEPENDENT VIOLATION



These couplings only depend on trilinear modifications and give much weaker bounds (15 TeV for $\delta_3 = 1$)

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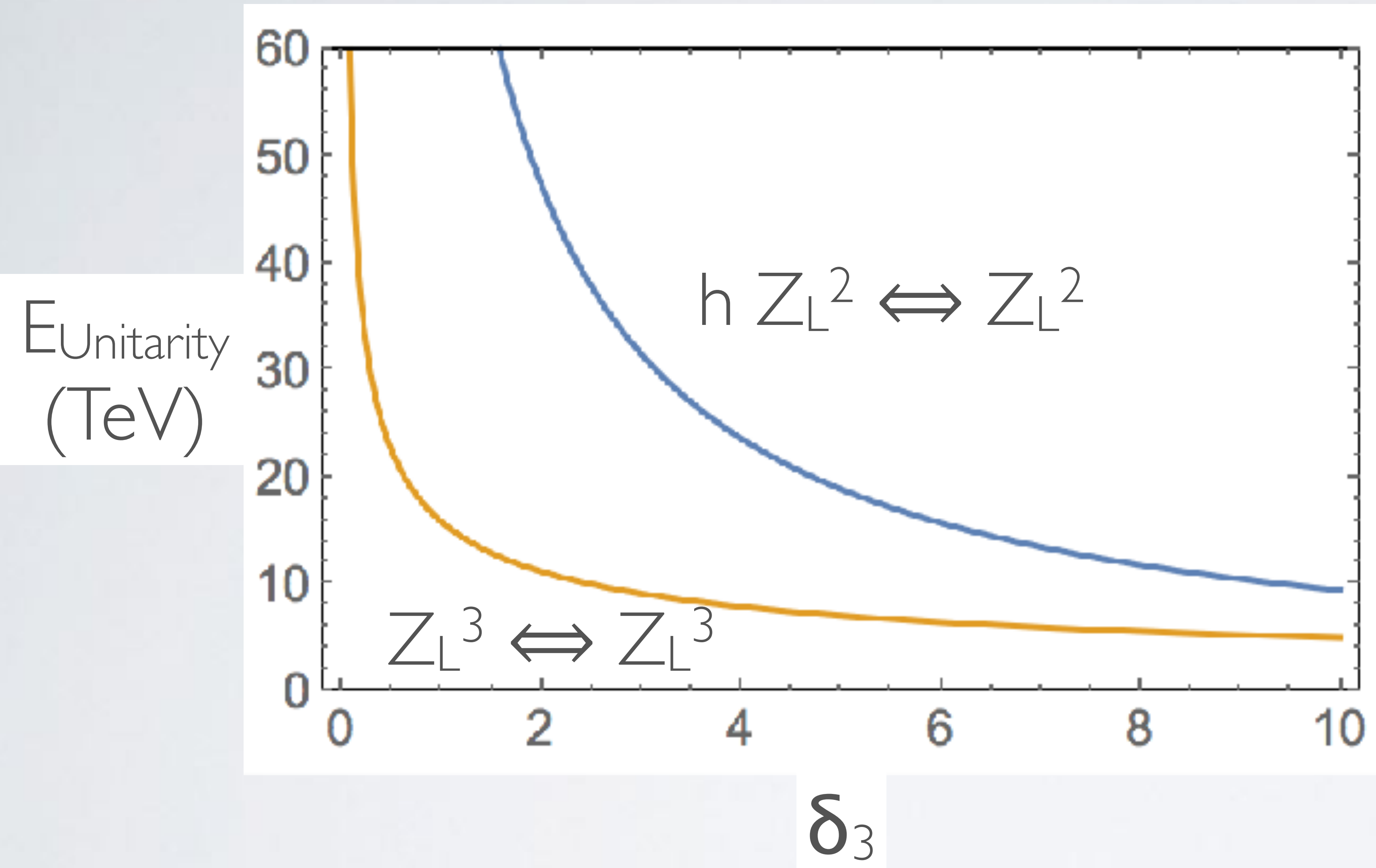

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In SMEFT with correlated trilinear to hexilinear couplings bound does not get better until much larger δ_3 (w/o large multiplicity disaster)

ISOSPIN ANALYSIS

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Weak Isospin = 1, 3 channels
triplet channel gives best bound of
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Weak Isospin = 0, 1, 2 channels
singlet channel gives best bound of
57.4 TeV/δ_3

SMEFT VS HEFT SUMMARY

Effective Theory	SMEFT	HEFT
Advantages	Better High Energy Behavior	Parameters are closer to extracted Higgs couplings
Disadvantages	Larger correlations assumed amongst Higgs modifications	Breaks down at a low energy scale unless couplings are tuned towards SMEFT

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O(1) deviation in trilinear suggests new physics must appear below 5 TeV for generic Higgs couplings, 13 TeV assuming UV structure (Aside: trilinear interactions from derivatives, have even lower Unitarity bounds)

EMBEDDINGS INTO UV COMPLETION

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However, in realistic models, we expect new physics to be lower, much like the Higgs was below the 1 TeV Unitarity bound

EFT POWER COUNTING

Our scenario has large modifications for the Higgs potential, but not in non-derivative couplings

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$$\delta\mathcal{L} = \frac{M^4}{g_*^2} F\left(\frac{g_* H}{M}, \frac{\partial}{M}, \cdots\right)$$

Non-Nambu-Goldstone SILH power counting would realize for strong coupling $g_* >> 1$

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Generic scaling for a UV completion with one mass scale M and one coupling strength g_*

SCENARIOS REALIZING MODEL-INDPT BOUND

In these scenarios the new physics can appear at $M = 13.4\ \mathrm{TeV}/\delta_3^{1/2}$ and fitting the trilinear requires $g_* = 7$

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However, Higgs mass and quartic have to be tuned since they should be of order M and g_*^2 respectively!

GENERIC HIGGS BOUND

$$X^3 = (\sqrt{v^2 + 2Y} - v)^3 = \frac{Y^3}{v^3} - \frac{3Y^4}{2v^5} + \frac{9Y^5}{4v^7} - \frac{7Y^6}{2v^9} + \cdots$$

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Strong coupling is larger than nonperturbative and $f \sim M/g_* = v$, so all Higgs coupling deviations should be order one, not 10-20%!
(also see Falkowski & Rattazzi for alternative argument)

POWER COUNTING LESSON

It is possible to push the new physics to the model-independent Unitarity bound, but not the generic bound

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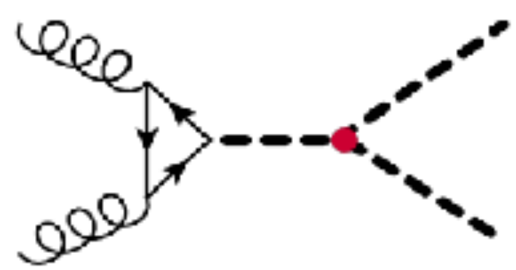
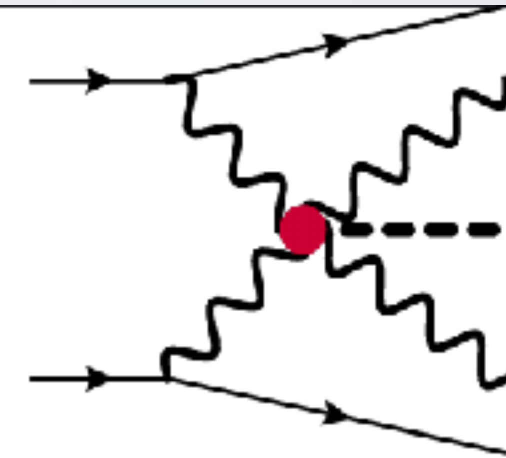
It is possible to push the new physics to the model-independent Unitarity bound, but not the generic bound

Weakly coupled, non-tuned models will have new physics at lower energies just like the Higgs turned out

COLLIDER PROBES

Henning et.al.1812.09299

Some work towards observing Unitarity violating processes

κ_λ	$\mathcal{O}_6$			$\sim \frac{vE}{\Lambda^2}$

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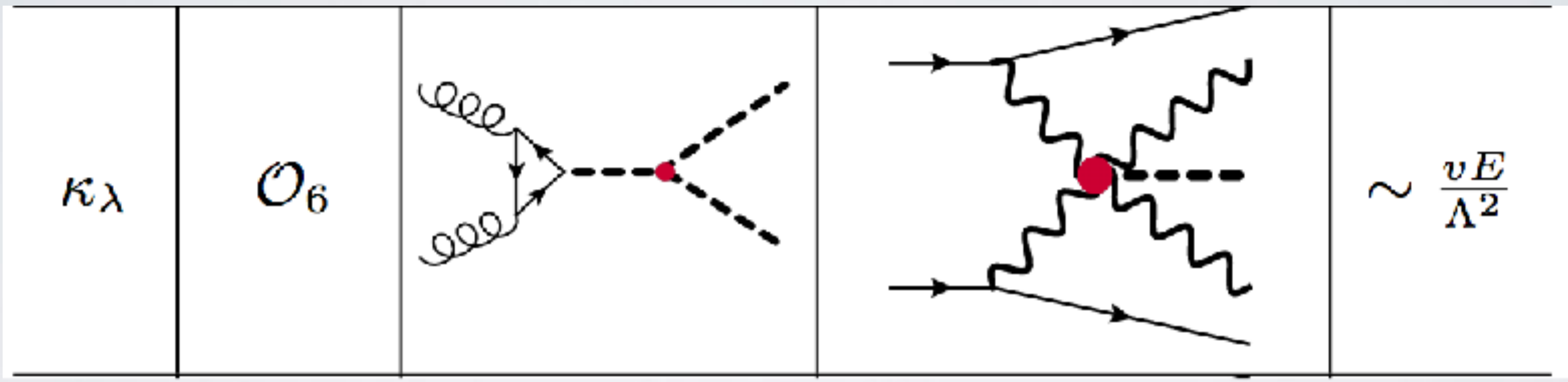

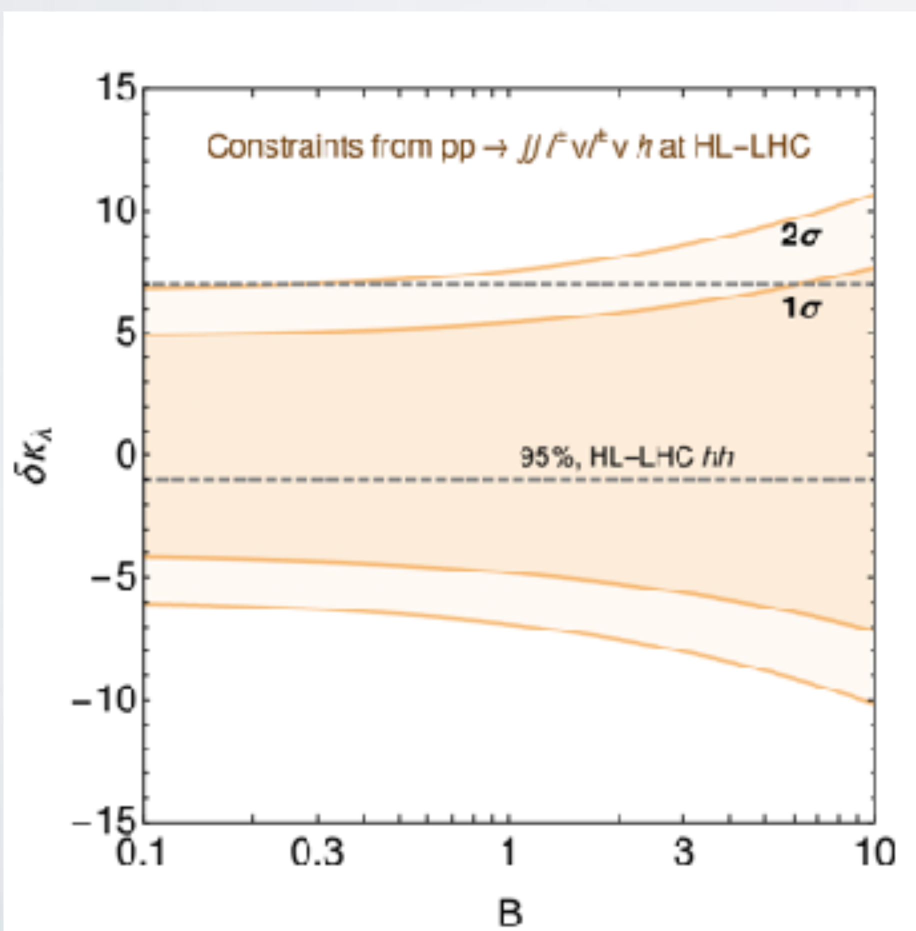

Searching for Unitarity violating process has similar sensitivity as double Higgs production

But Higgs wasn't discovered by vector boson scattering, so need to continue to explore model dependent signals

CONCLUSIONS

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- Nonstandard EWSB is possible and measuring trilinear is a major goal of high luminosity LHC and future colliders

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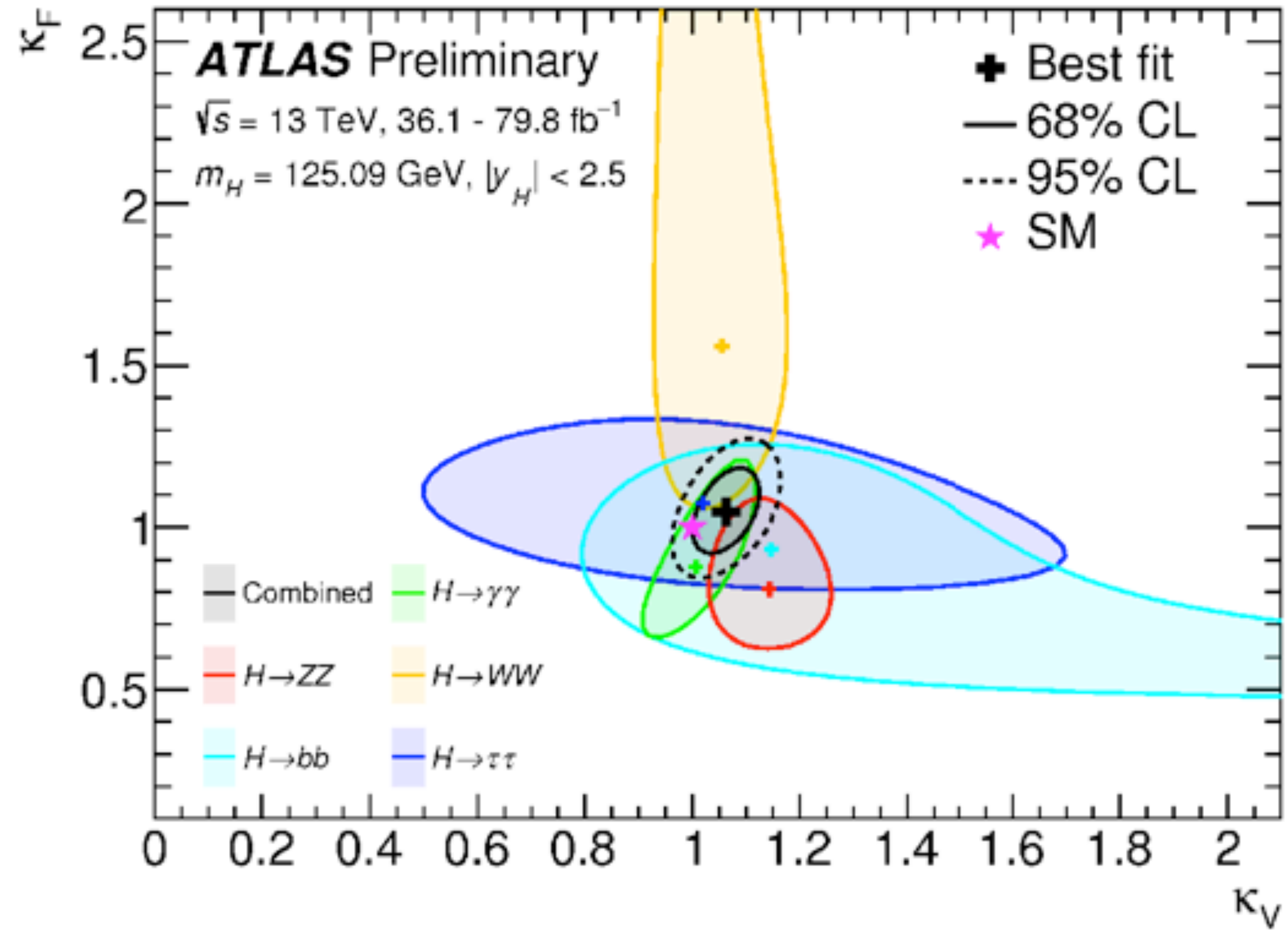
- Nonstandard EWSB is possible and measuring trilinear is a major goal of high luminosity LHC and future colliders

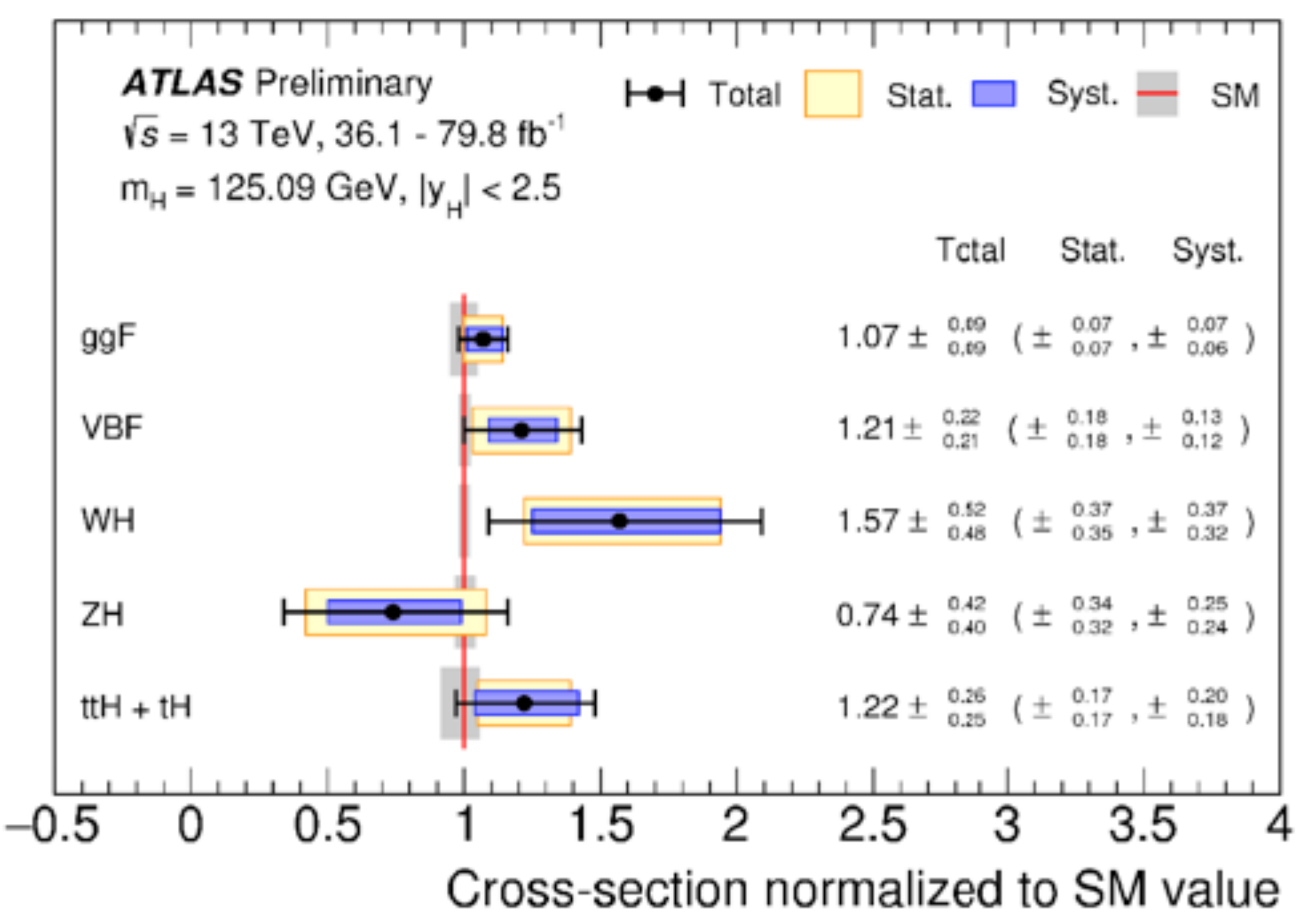
- Trilinear modifications lead to Unitarity violation at high energies (~ 5 - 13 TeV for δ_3 ~ 1 depending on assumptions)

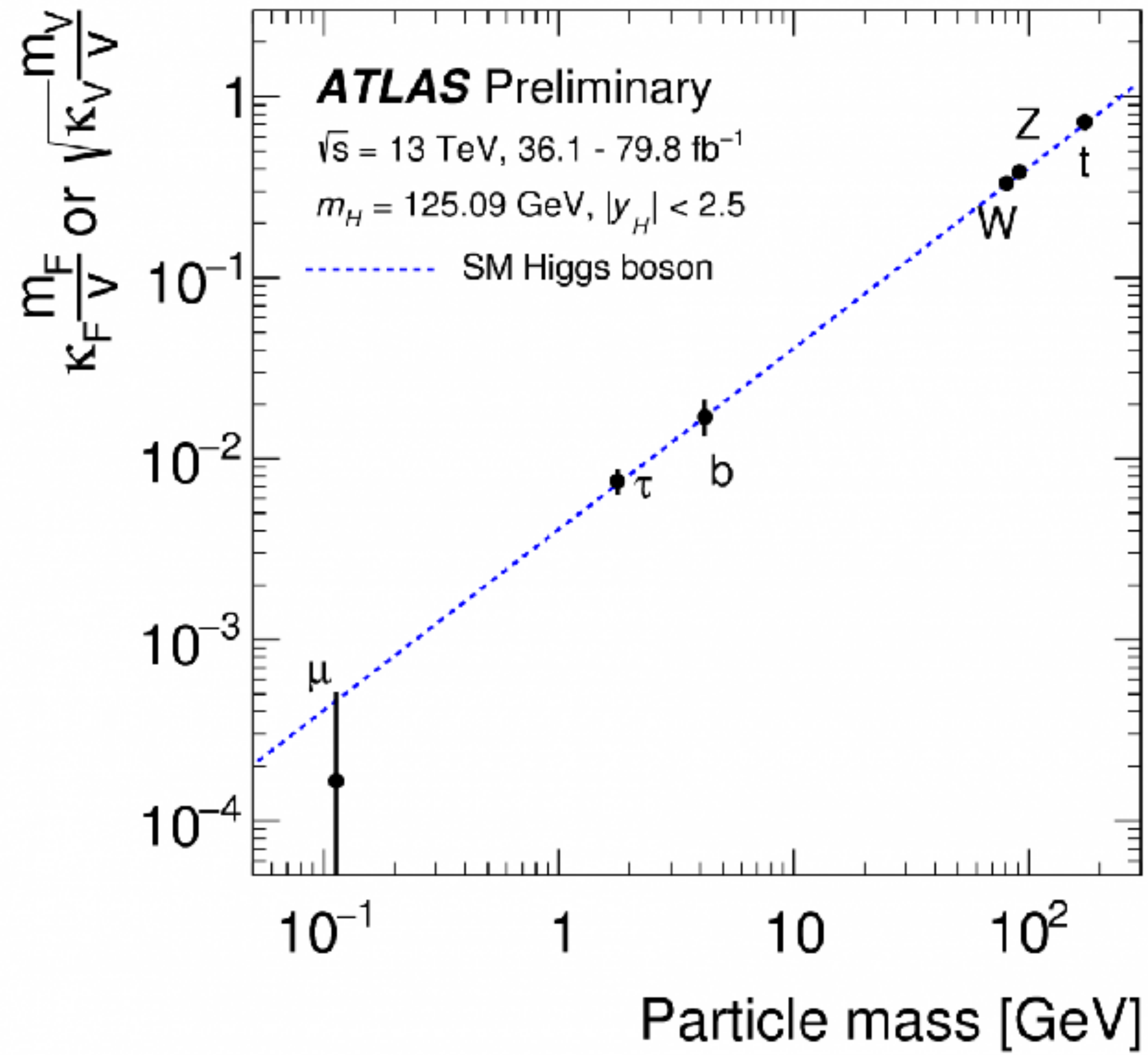
- Possible to push new physics to 13 TeV and have O(1) trilinear, but natural models will have it much lower

Thanks for your attention!

EXTRA SLIDES


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
Total 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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√s = 13 TeV, 36.1 - 79.8 fb⁻¹
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SM Higgs boson
$\kappa_F \frac{m_F}{v}$ or $\sqrt{\kappa_V}\frac{m_V}{v}$
Particle mass [GeV]
μ
τ
b
W
Z
t
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10
10^{2}

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

FALKOWSKI & RATTAZZI

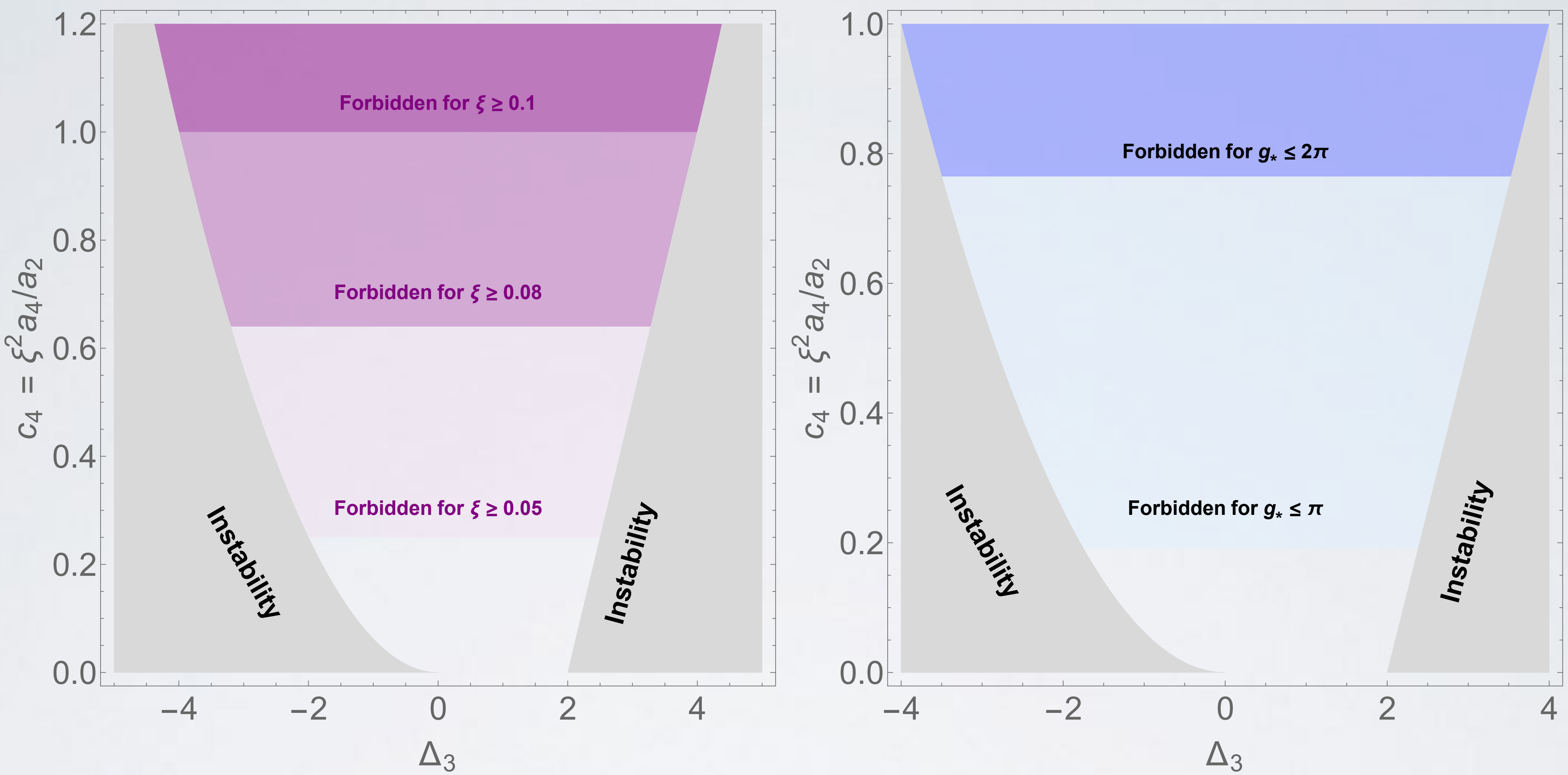

Figure 1: Parameter space for the cubic Higgs self-coupling deformation Δ_3 relative to the SM value. The allowed region depends on the value $c_4 = \xi a_4/a_2$, which encodes effects of dimension-8 SMEFT operators in the Higgs potential. The gray area is excluded by stability considerations, as the potential contains a deeper minimum that the EW vacuum at $\langle H^\dagger H \rangle = v^2/2$. Left: the purple areas are excluded for $a_4 = 1$ and $a_2 = 0.01$ under different hypotheses about the parameter $\xi = v^2/f^2$, which characterizes the size of the corrections to the single Higgs boson couplings to matter. Right: the blue areas are excluded for $a_4 = 1$ and $\xi = 0.1$ under different hypotheses about the coupling strength g_* of the BSM theory underlying the SM.