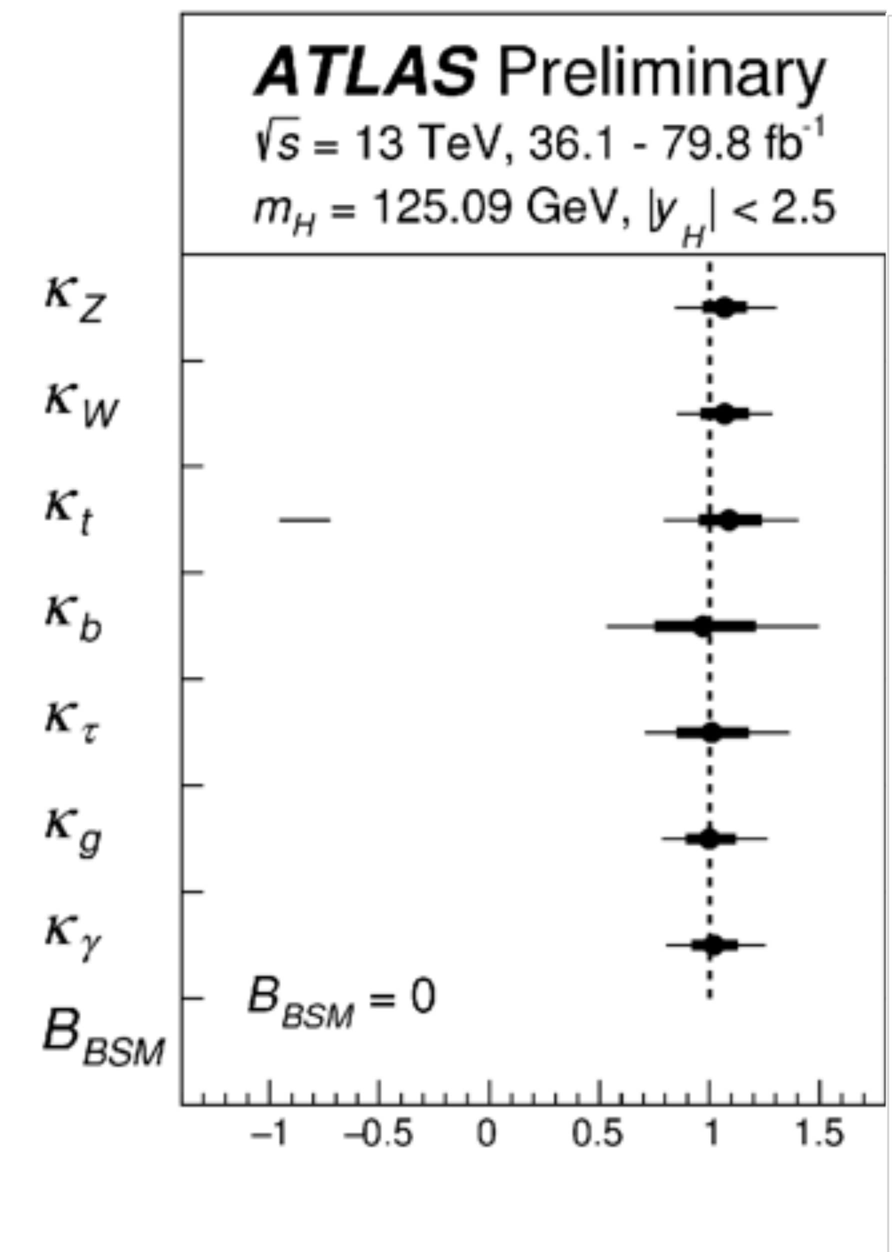
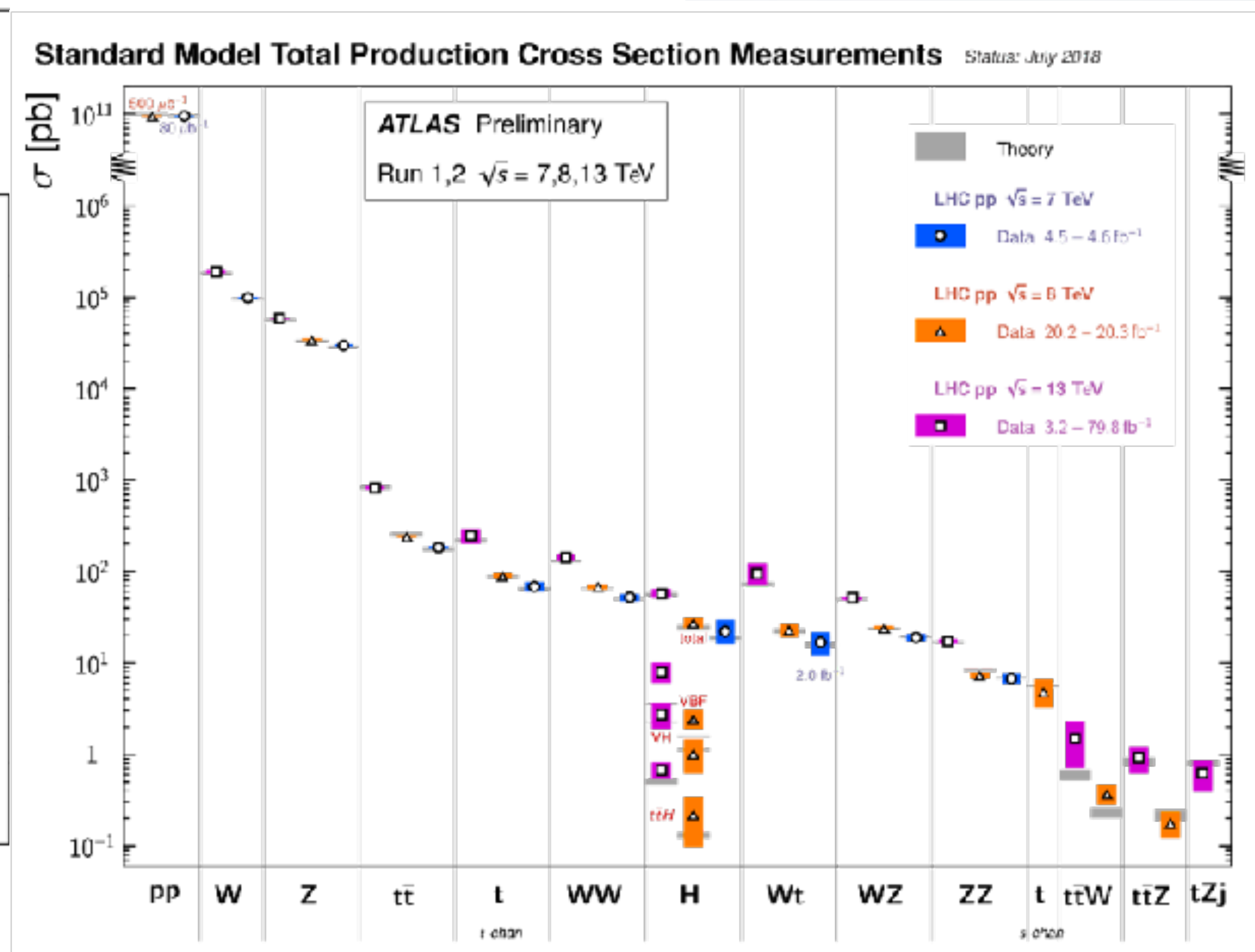
UNITARITY VIOLATION FROM NONSTANDARD HIGGS COUPLINGS





Spencer Chang (Oregon/NTU) w/ M. Luty 1902.05556

43rd Johns Hopkins Workshop KIPMU 6/6/19

FUTURE COLLIDER GOALS

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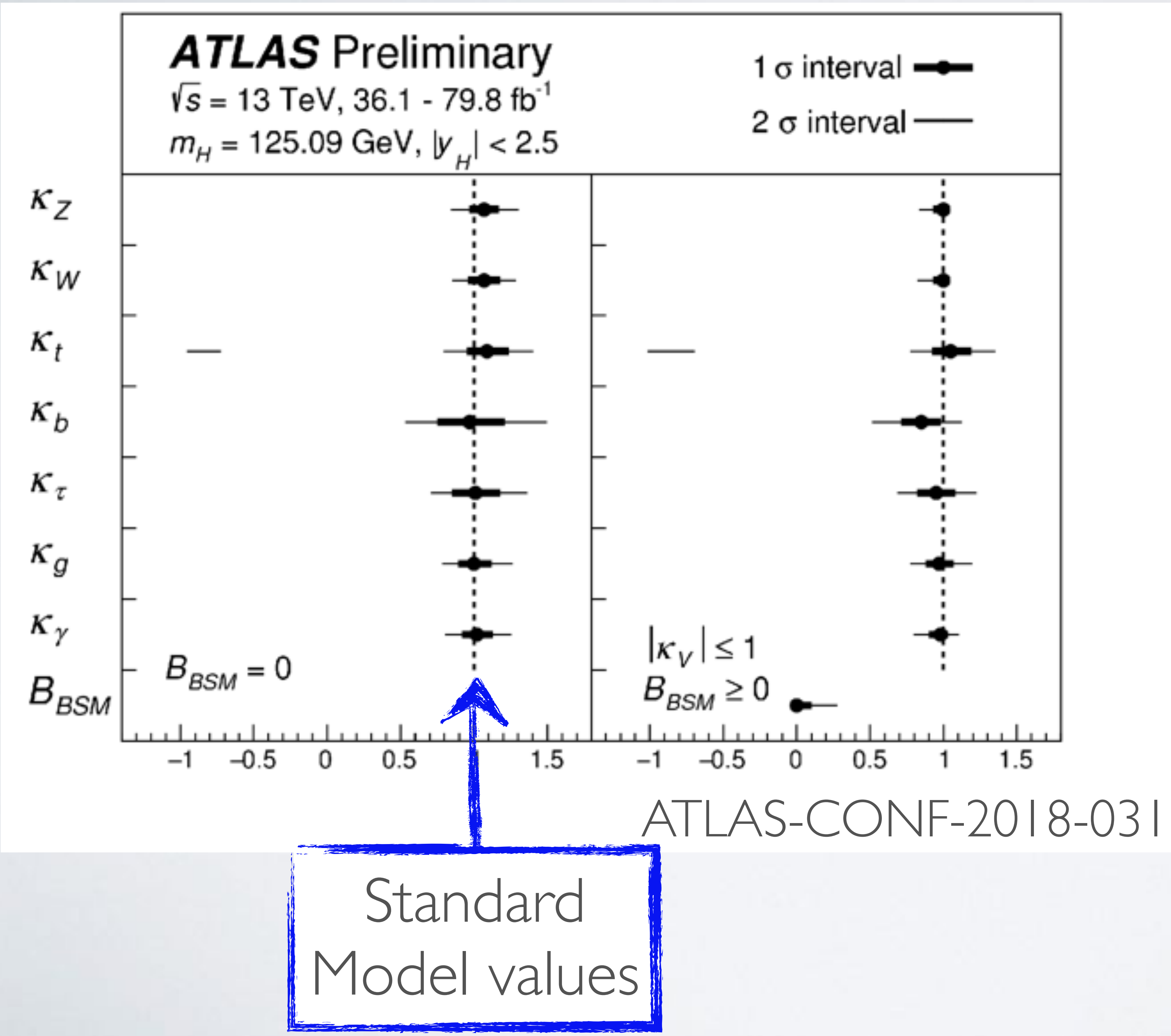
PINNING DOWN HIGGS COUPLINGS



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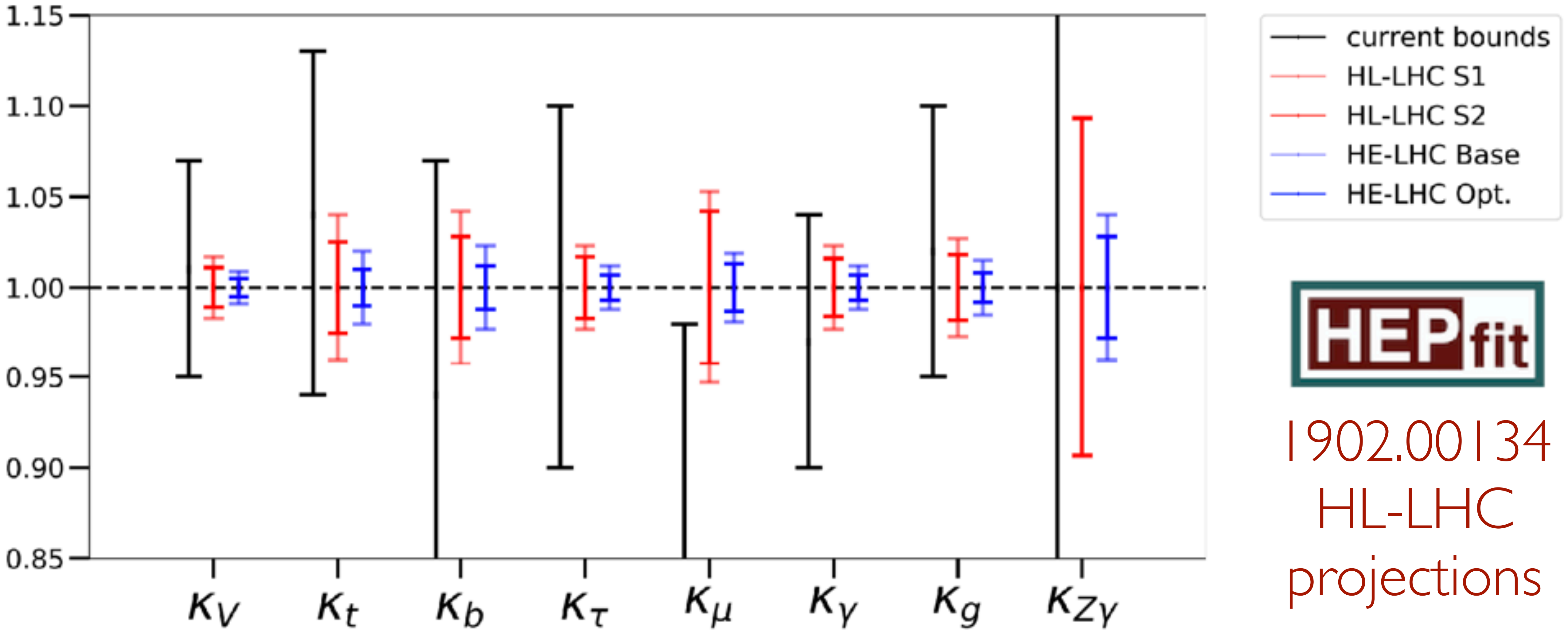
Fits for Higgs couplings Standard Model particles have 20-50% errors

One of the main motivation of HL-LHC and future colliders is measuring these better

PINNING DOWN HIGGS COUPLINGS



HEPfit

1902.00134
HL-LHC
projections

is measuring these
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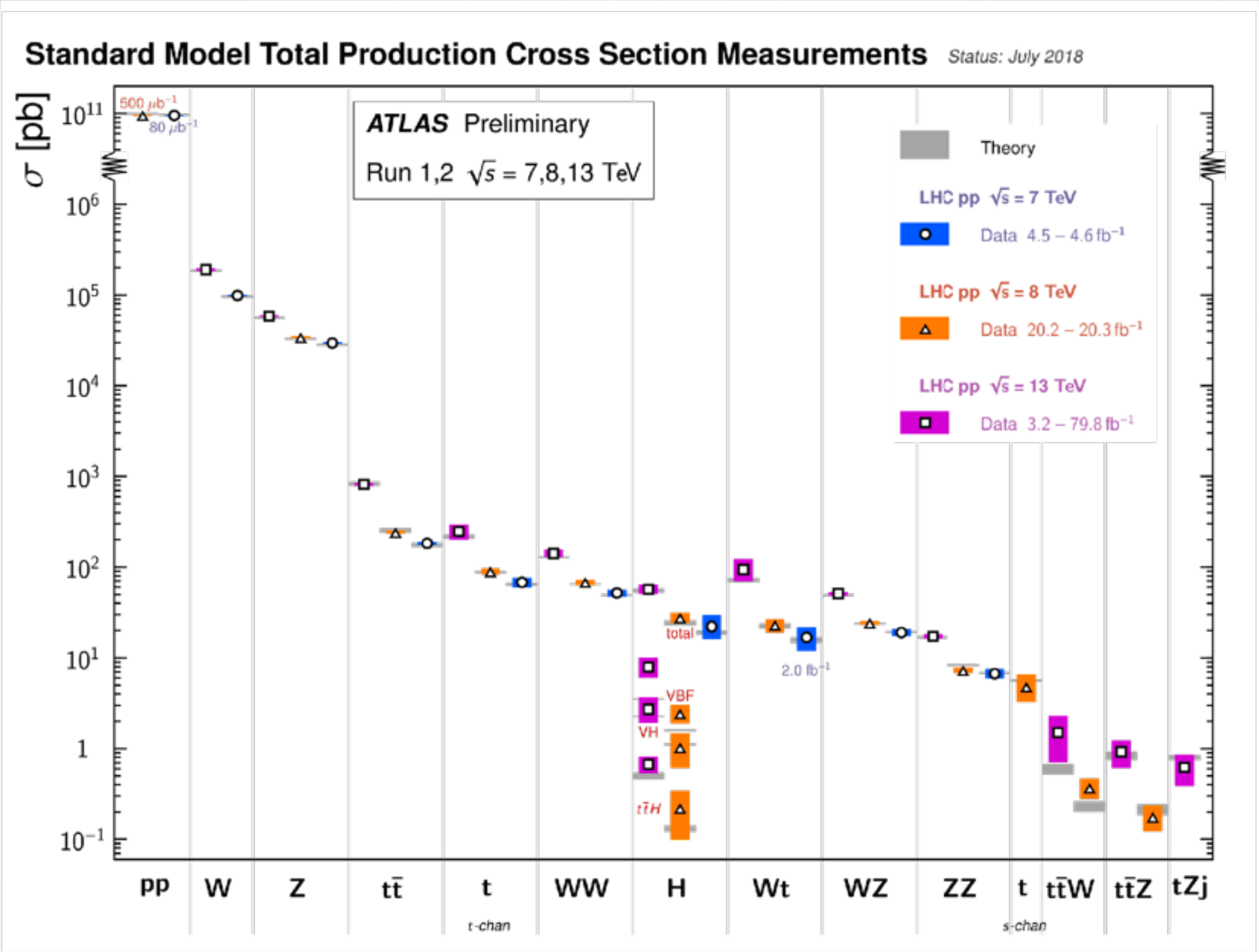
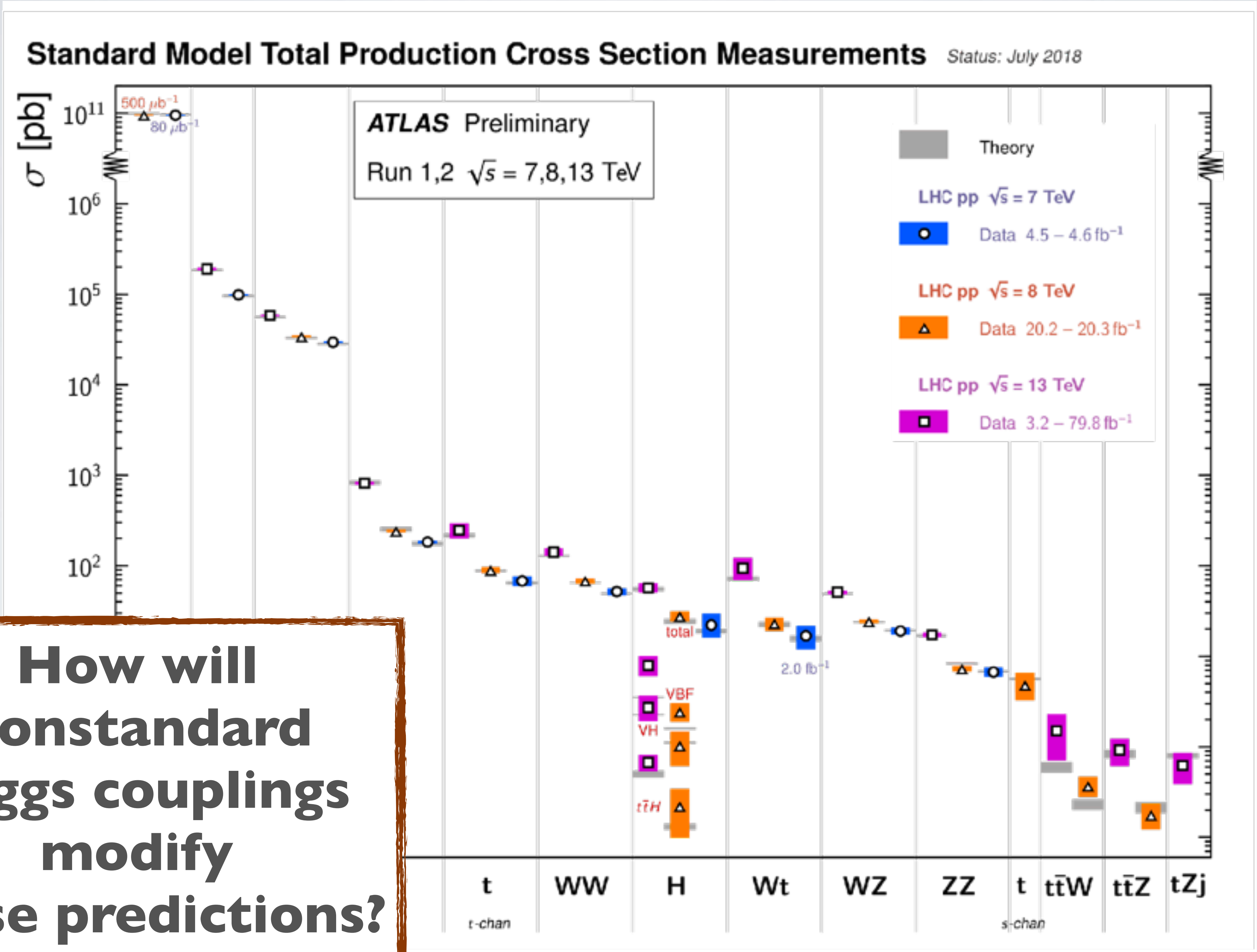
Standard
Model values

STANDARD MODEL PROCESSES



STANDARD MODEL PROCESSES

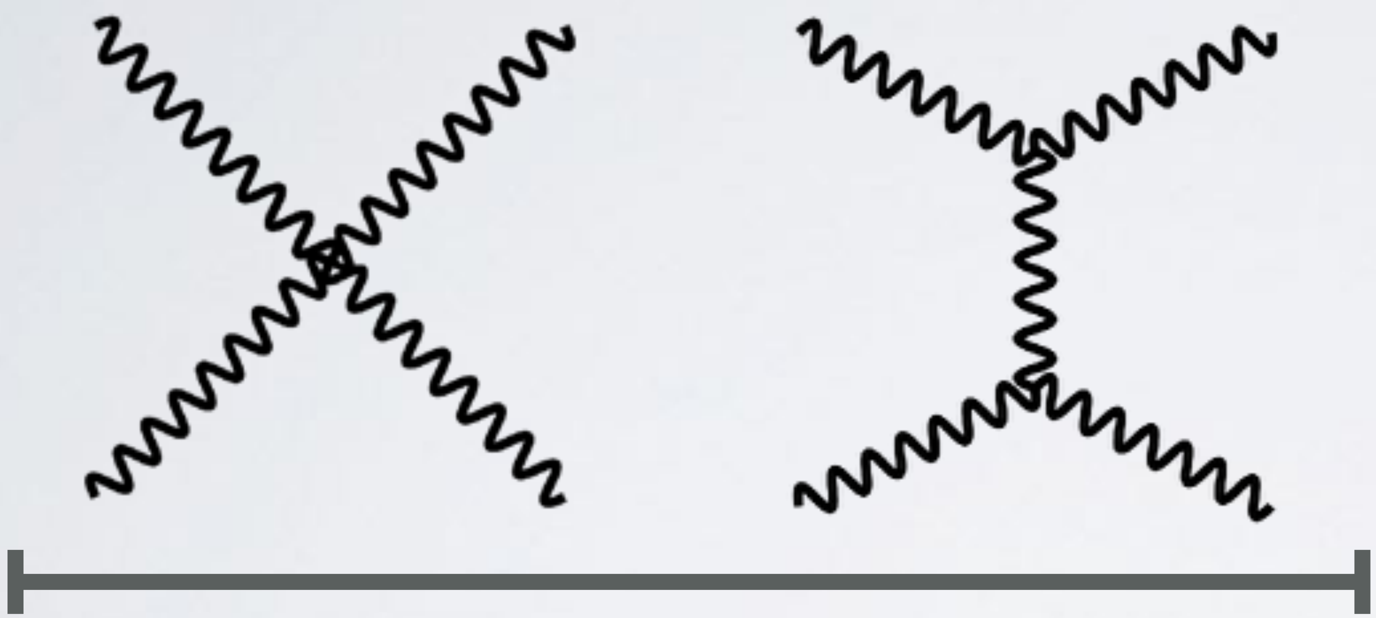


How will nonstandard Higgs couplings modify these predictions?

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 ⇔ W^+_L W^-_L



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

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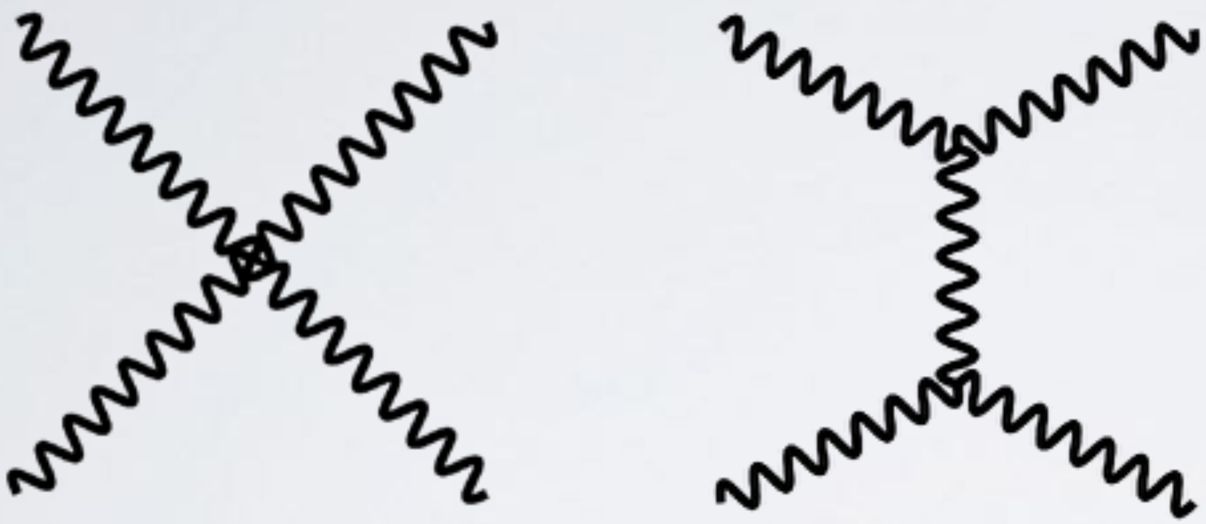

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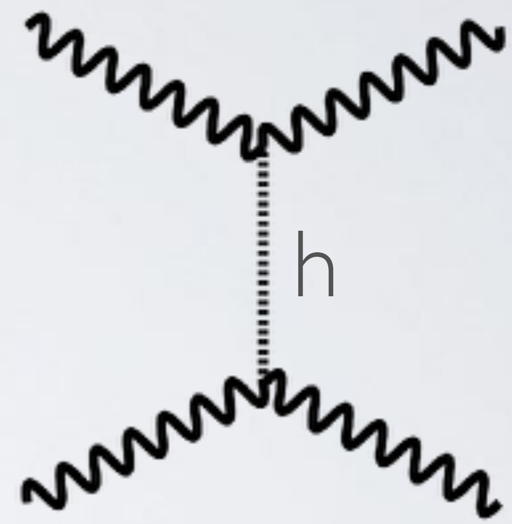

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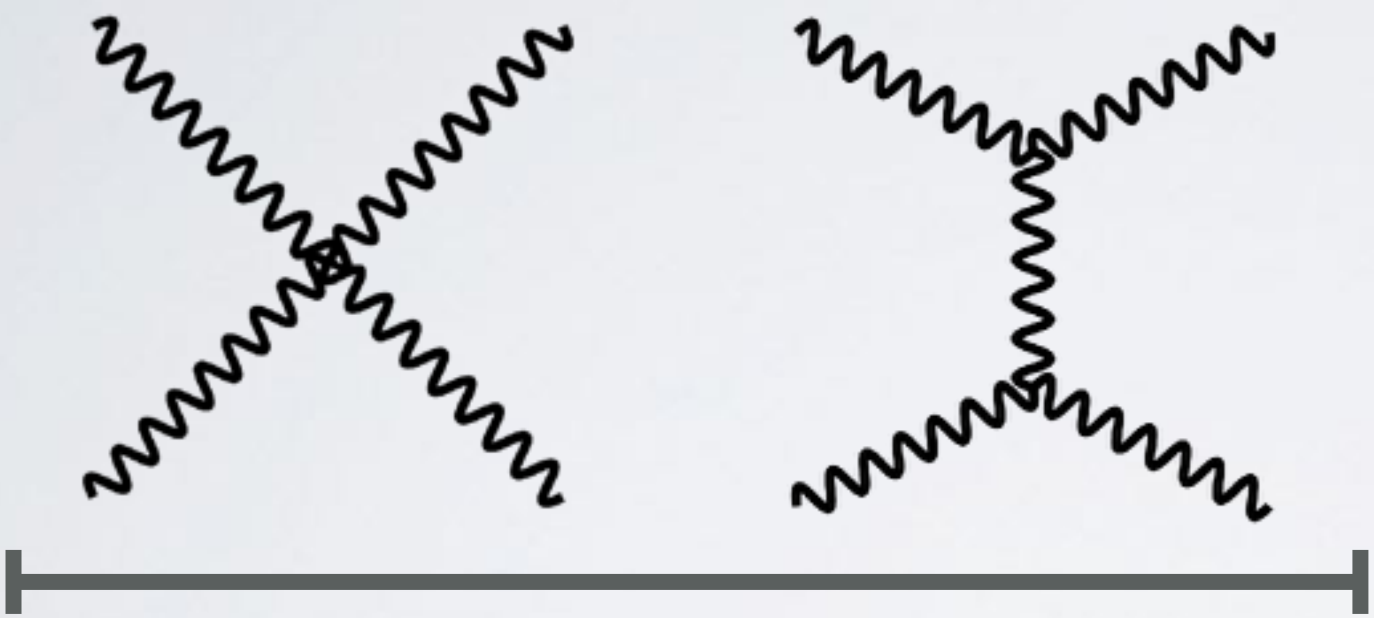

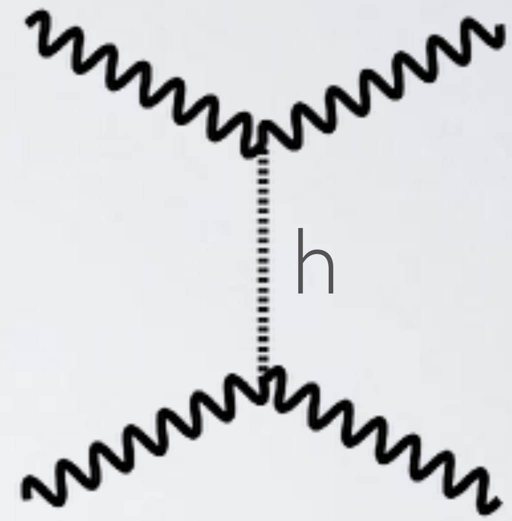

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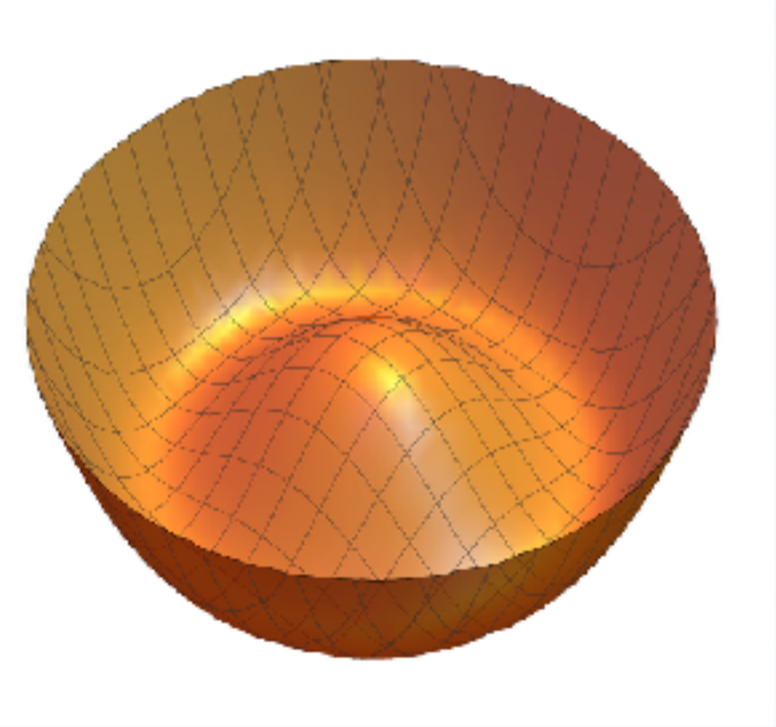
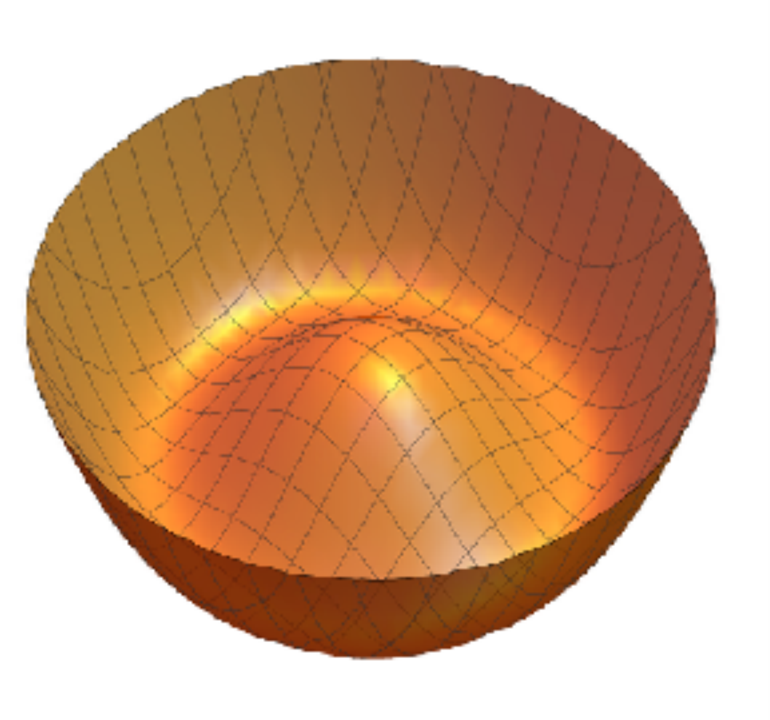
Higgs exchange cancels high energy growth if its couplings are SM-like, matrix element is Unitary if $m_H \lesssim 1\,\text{TeV}$ (Lee, Quigg, Thacker)



HIGGS POTENTIAL UNITARITY

(SC, LUTY, ALSO FALKOWSKI, RATTAZZI)

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



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Higgs self-couplings probe its potential and test mechanism of electroweak symmetry breaking

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

$$\delta_3 = \frac{\lambda_{hhh}}{m_h^2/(2v)} - 1$$

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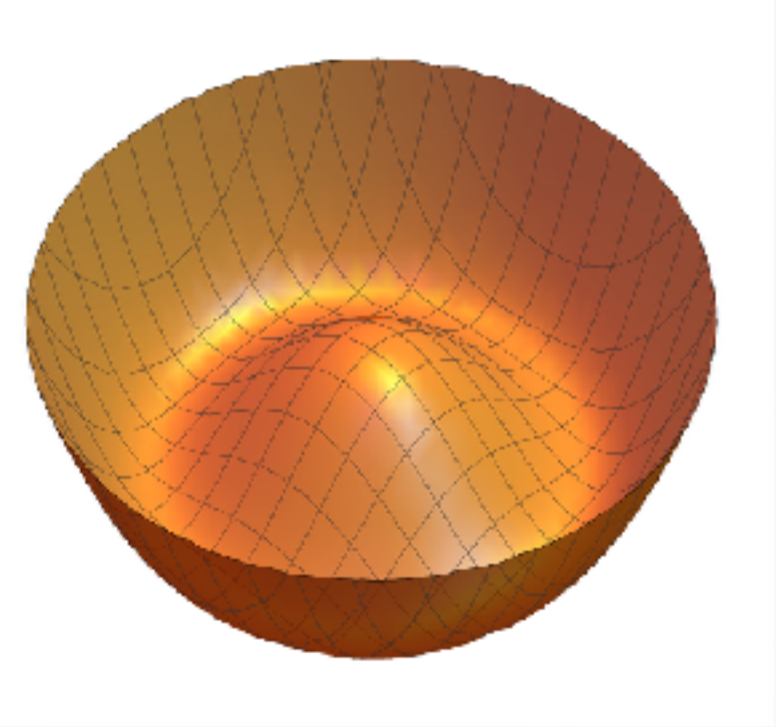

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also referred to as κ_λ

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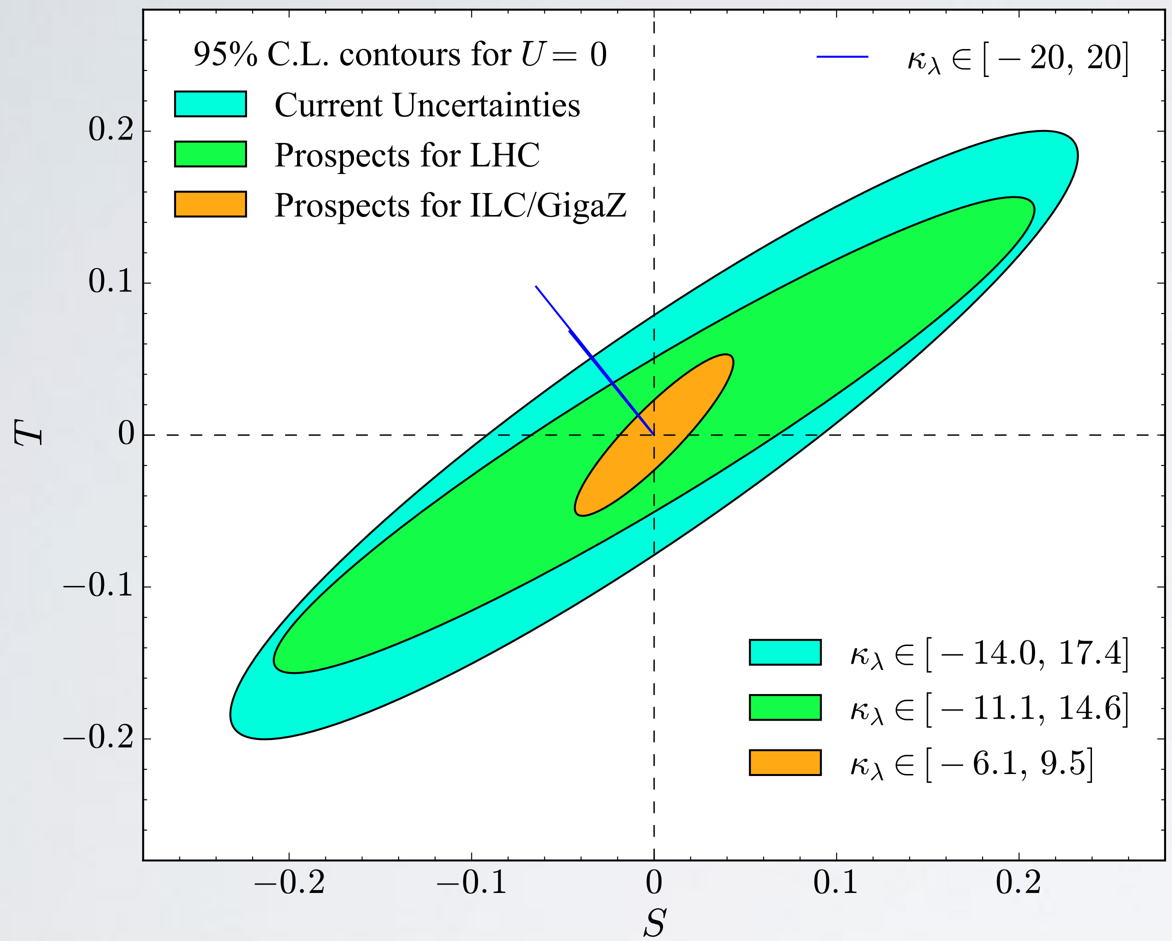
EXISTING INDIRECT TRILINEAR CONSTRAINTS



Precision Electroweak

$|\kappa_\lambda| \lesssim 14$

Kribs et.al. 1702.07678

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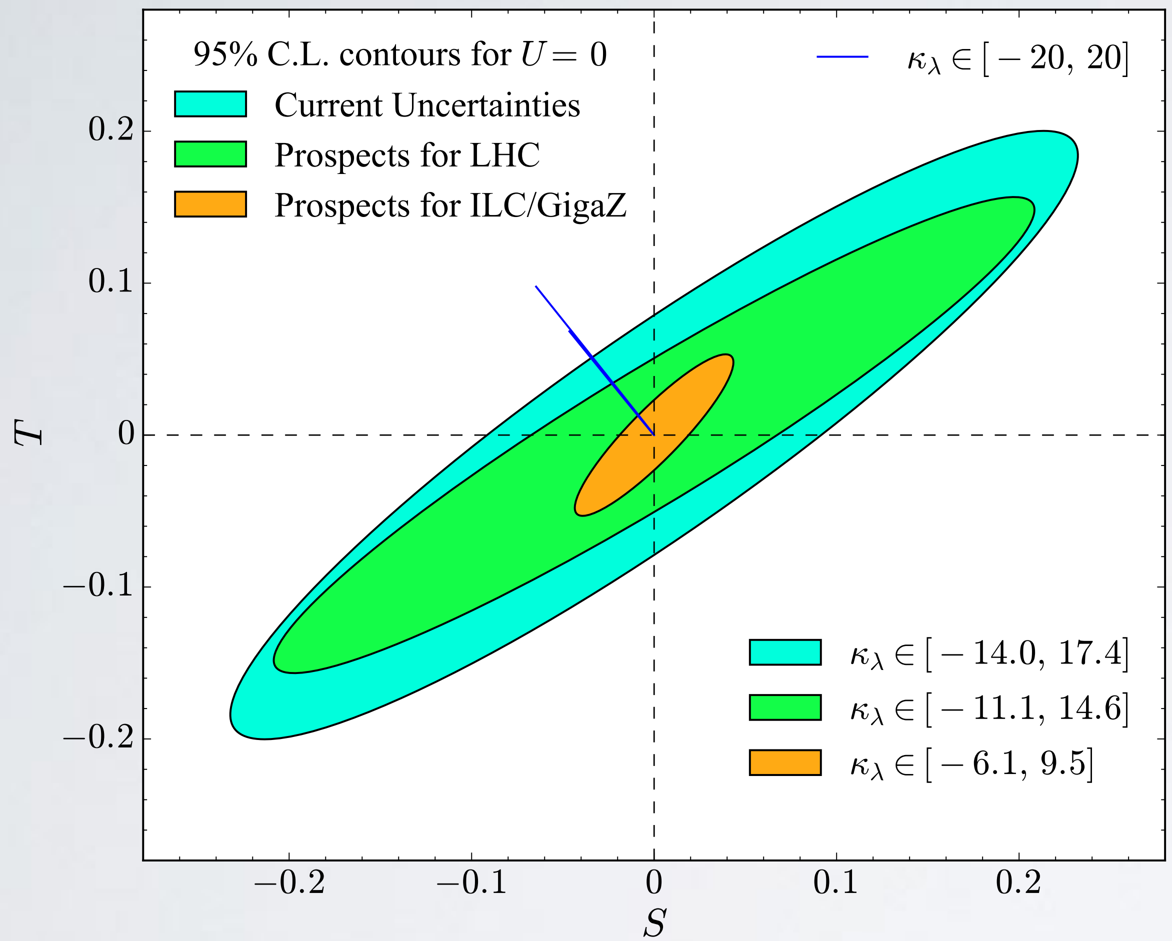

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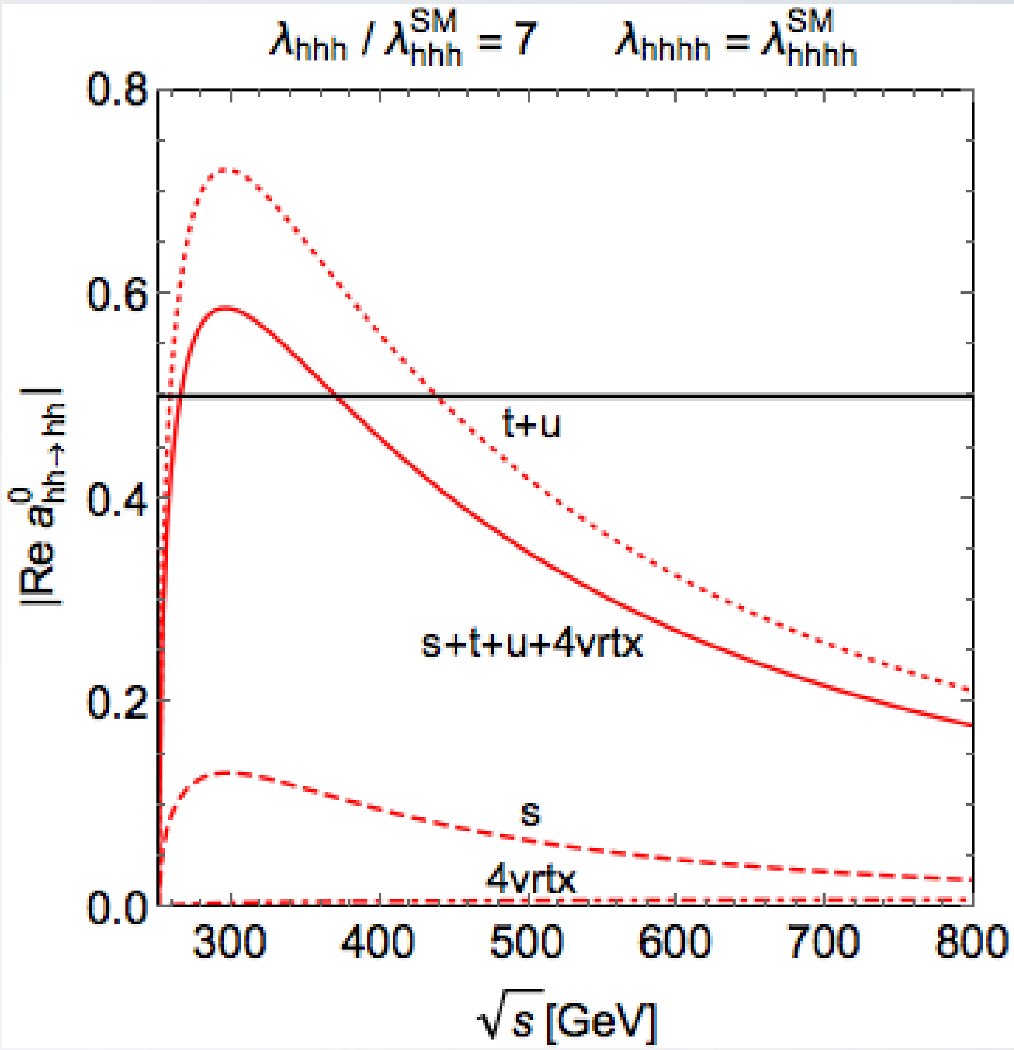
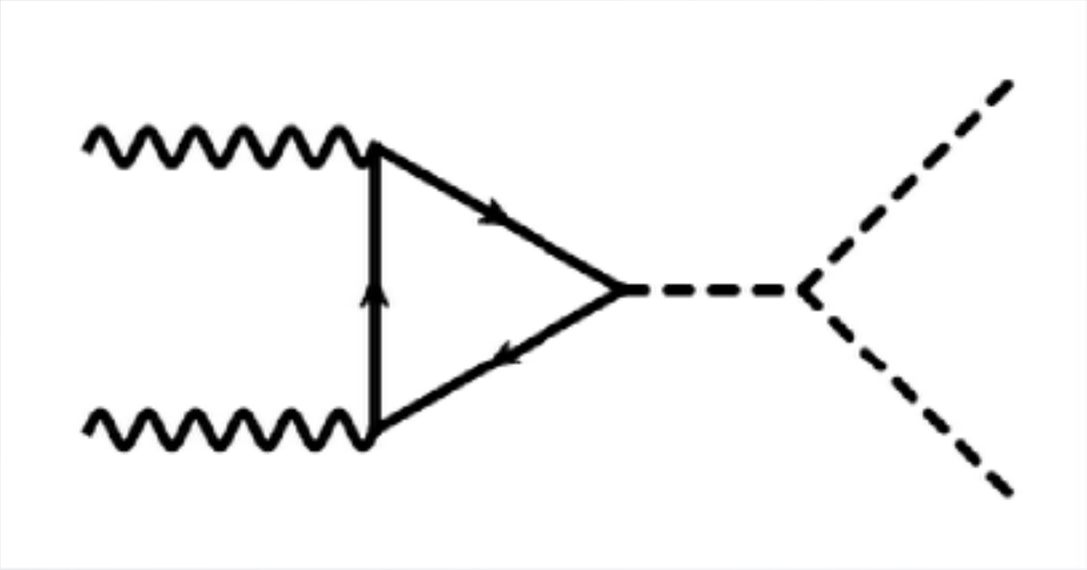


Low Energy Unitarity hh → hh

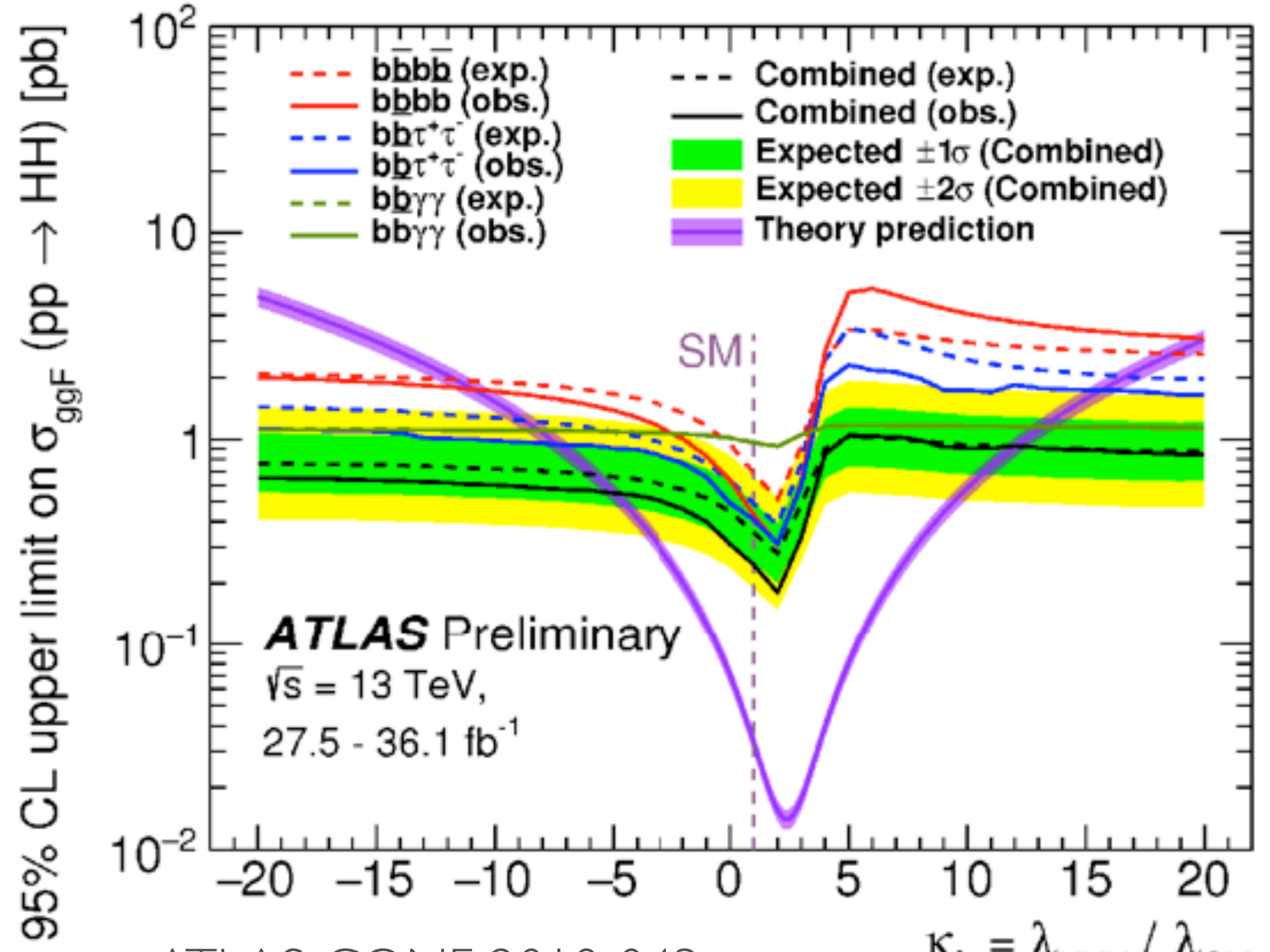
$|\kappa_\lambda| \lesssim 7$

Di Luzio et.al. 1704.02311

HIGGS TRILINEAR



Trilinear probed by search for Double Higgs production



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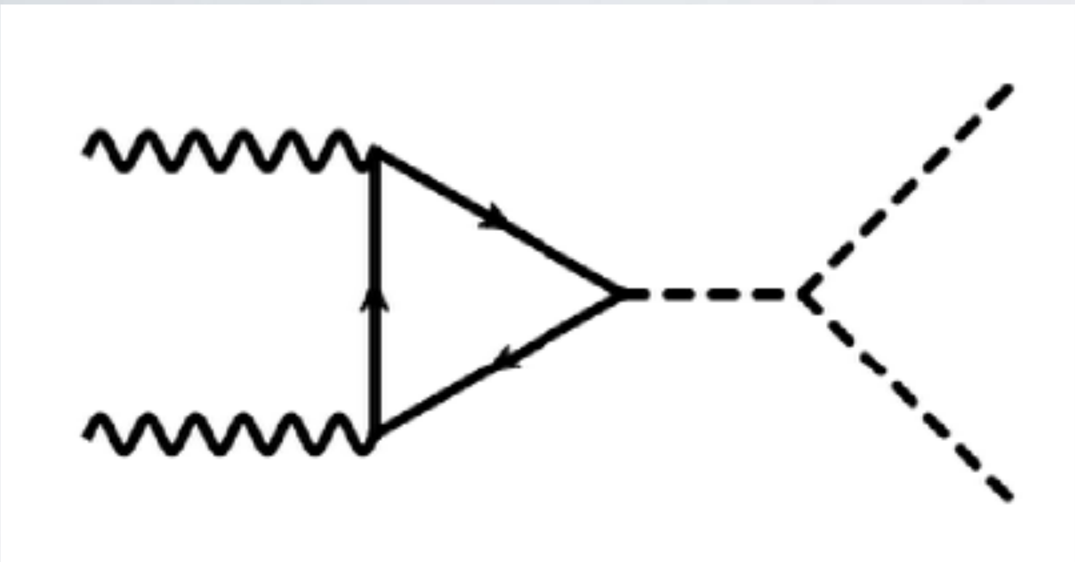

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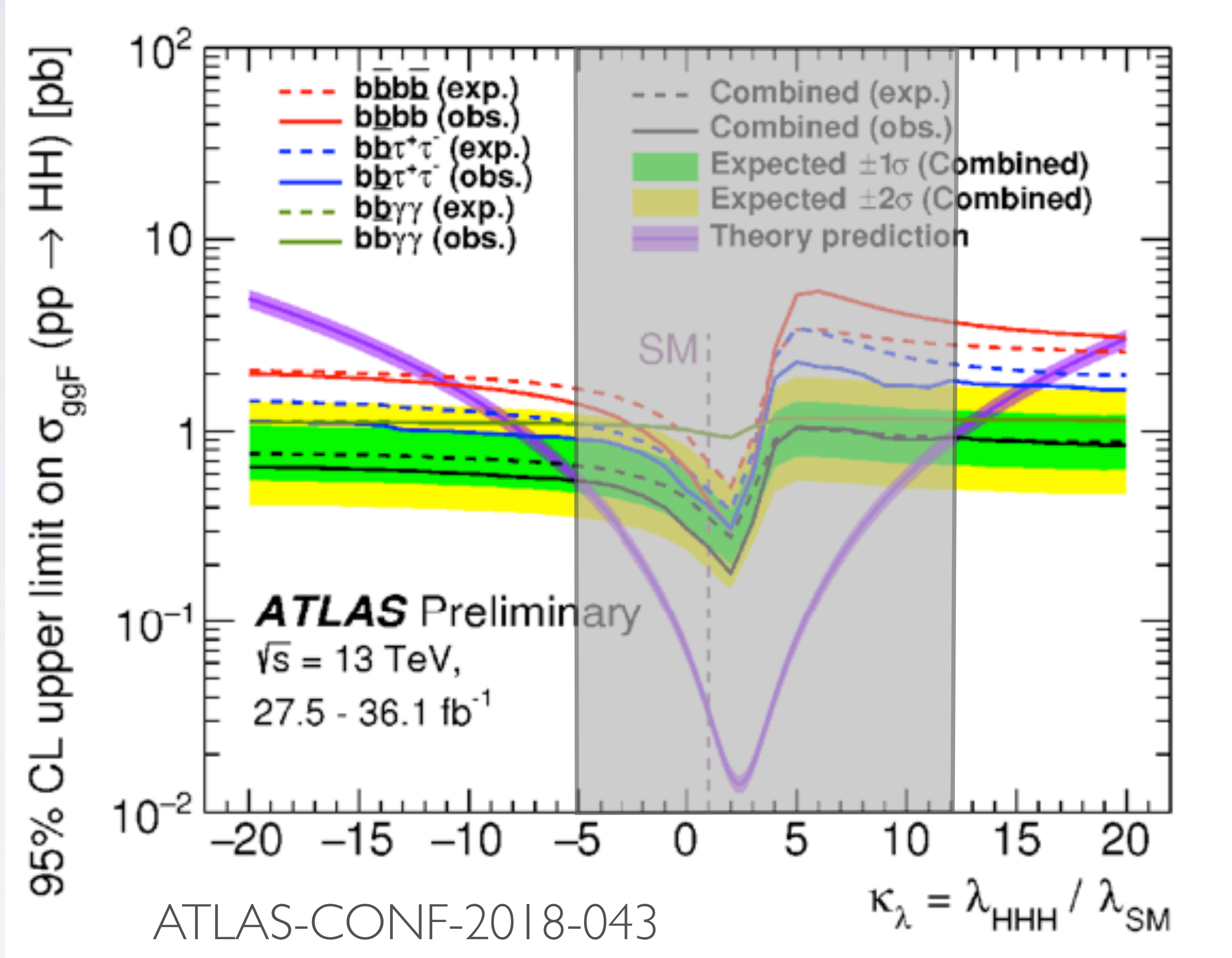

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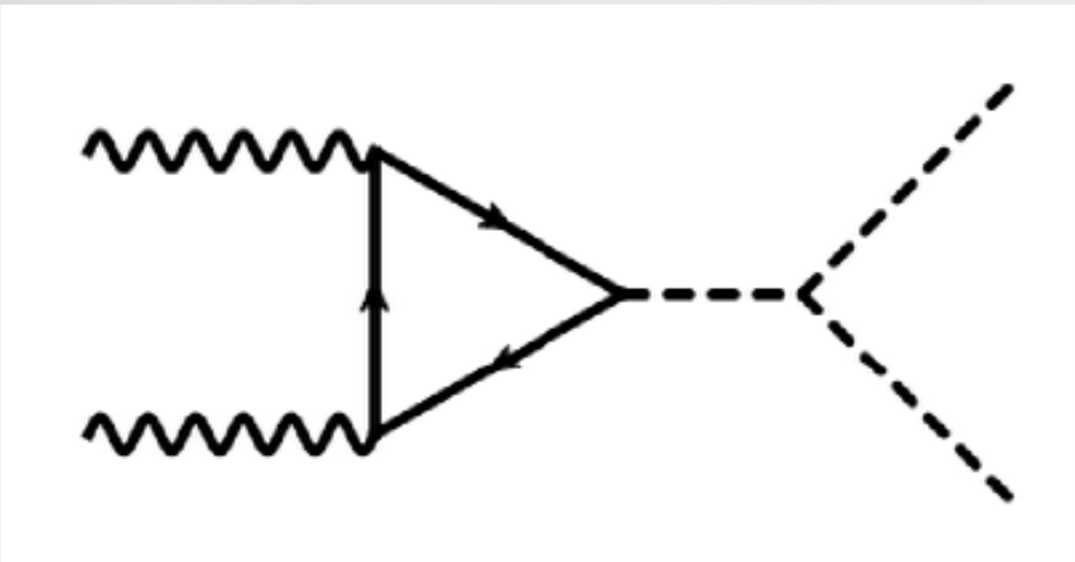

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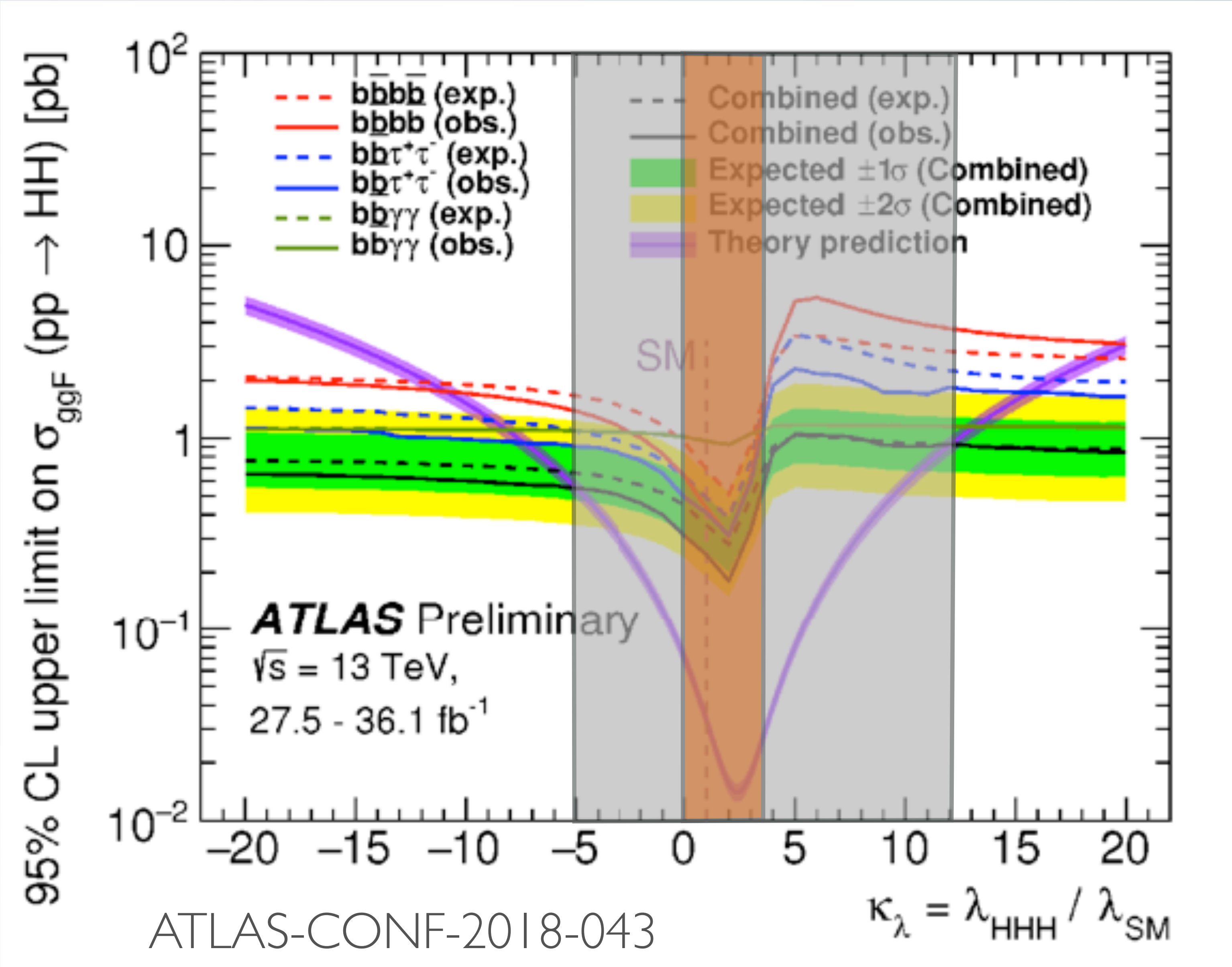
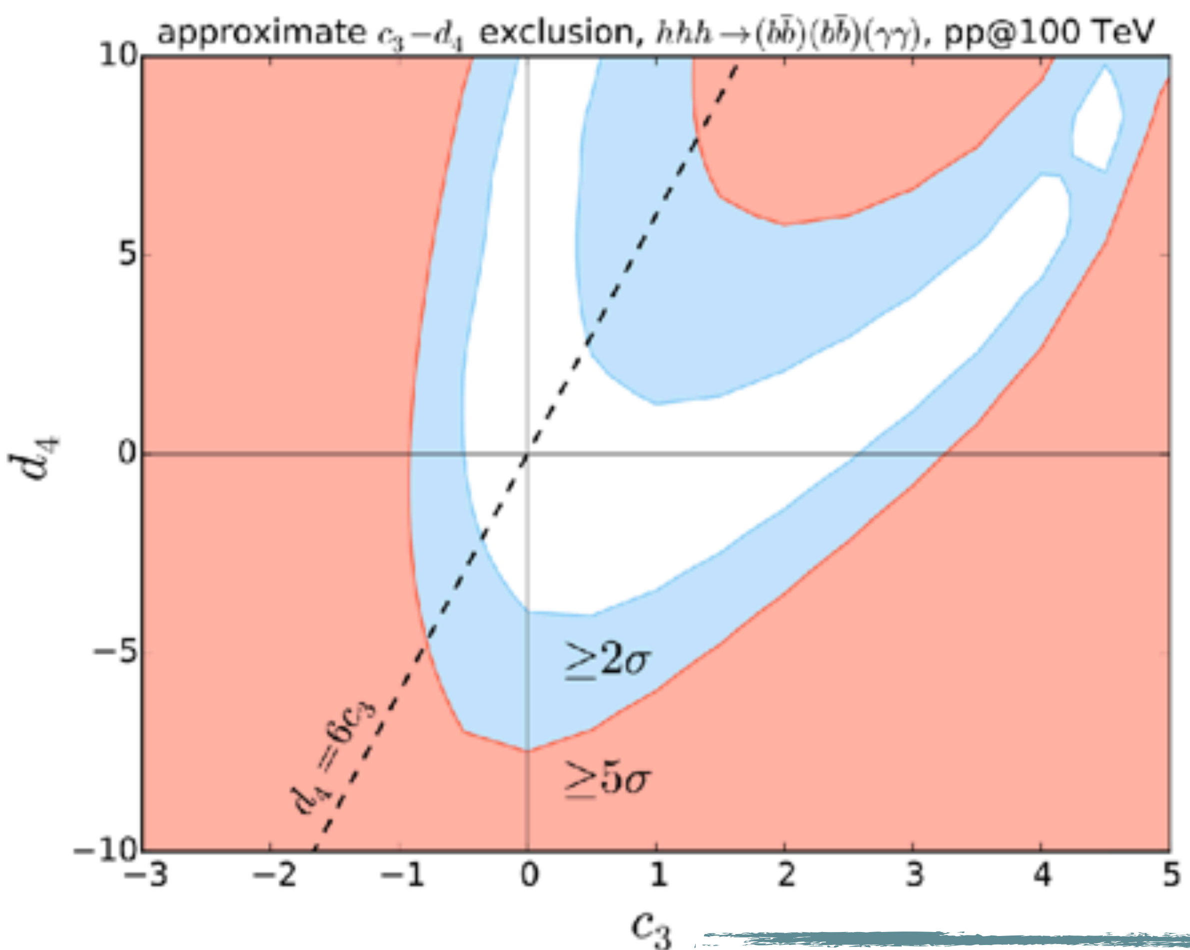


Currently only sensitive to O(10) variations, but projections estimate trilinear sensitivity to ~ [-0.2,3.6] at LHC w/ 3 ab^{-1} and 20-30% at future colliders

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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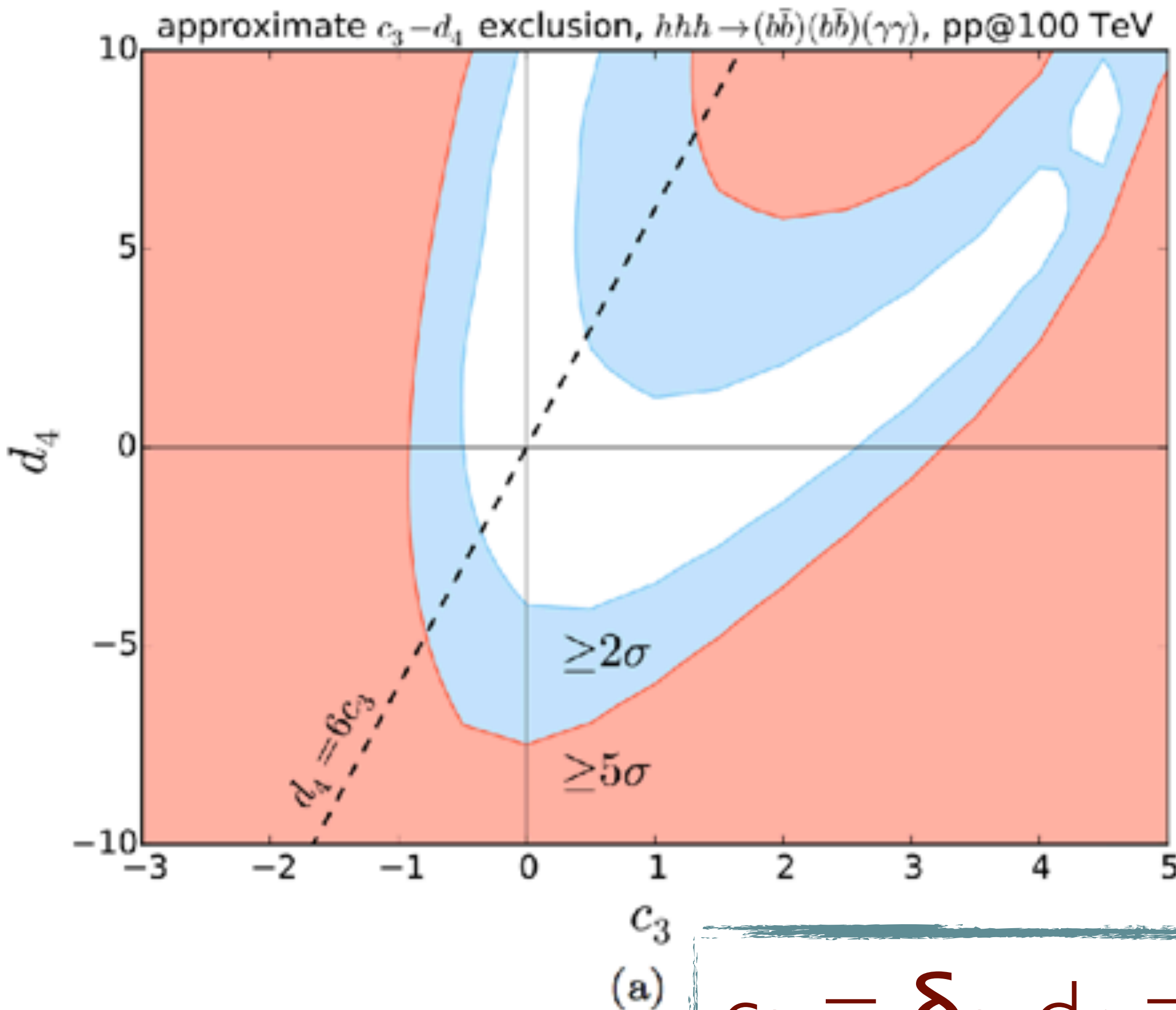
e.g. Bizon, et.al. (also Liu et.al.)



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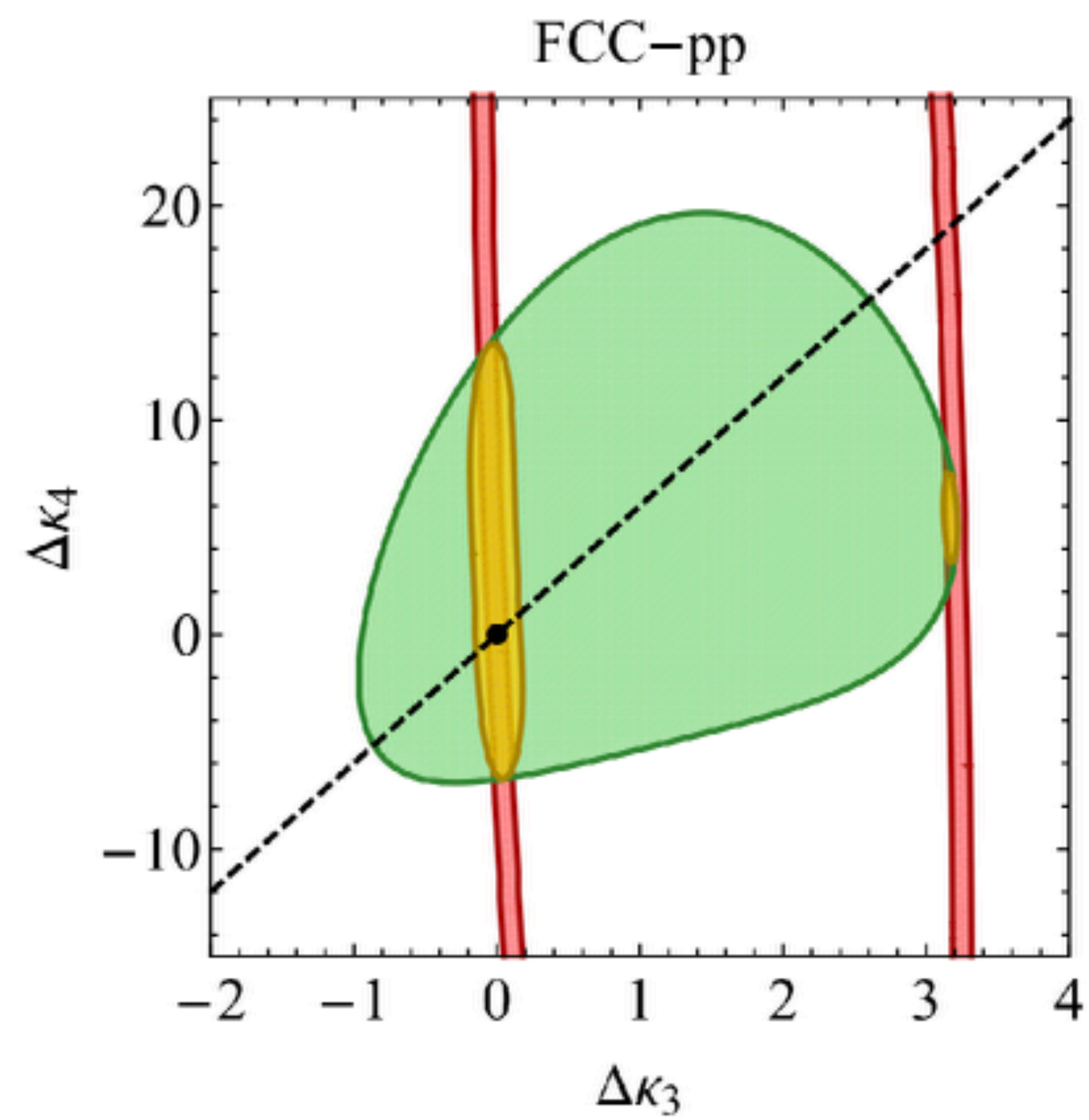

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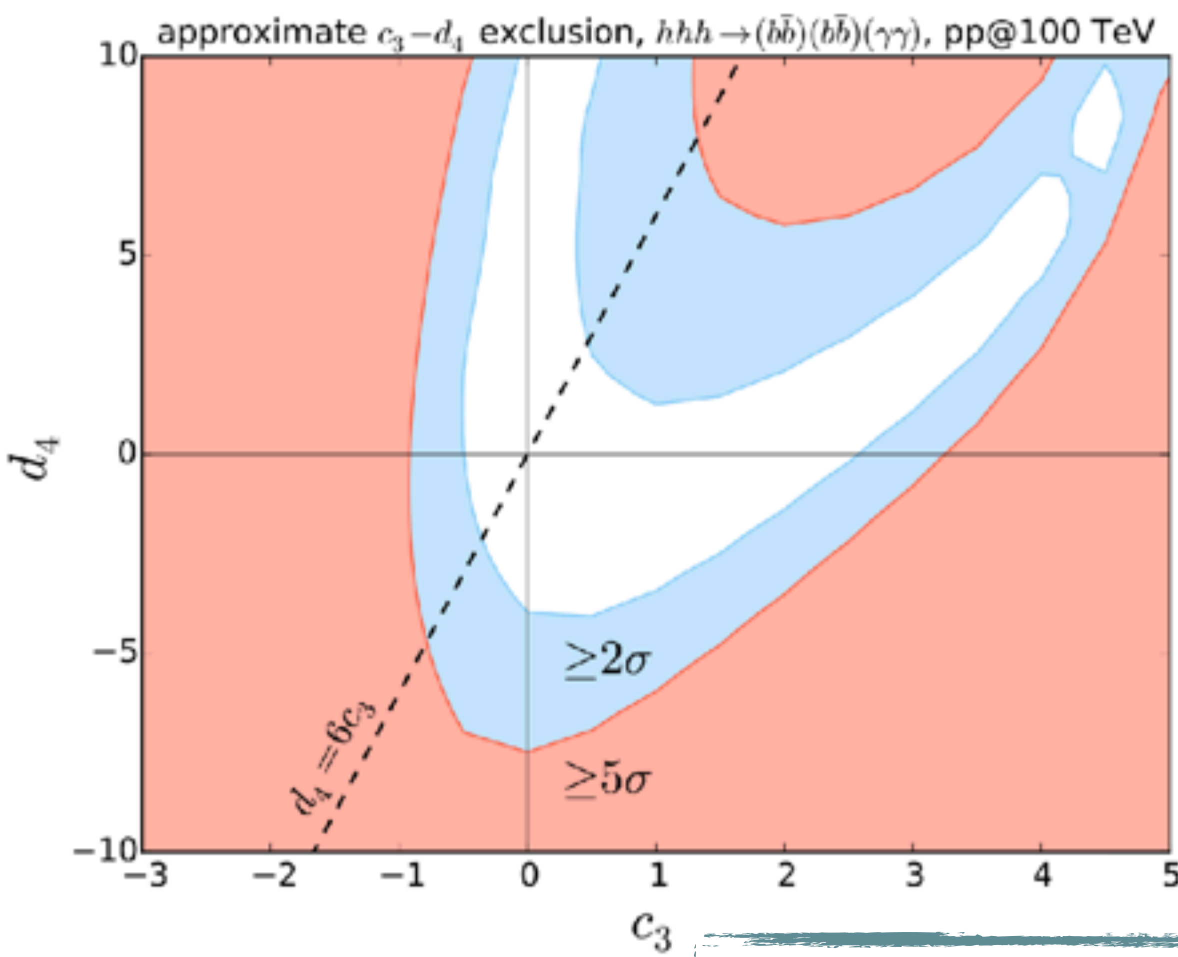

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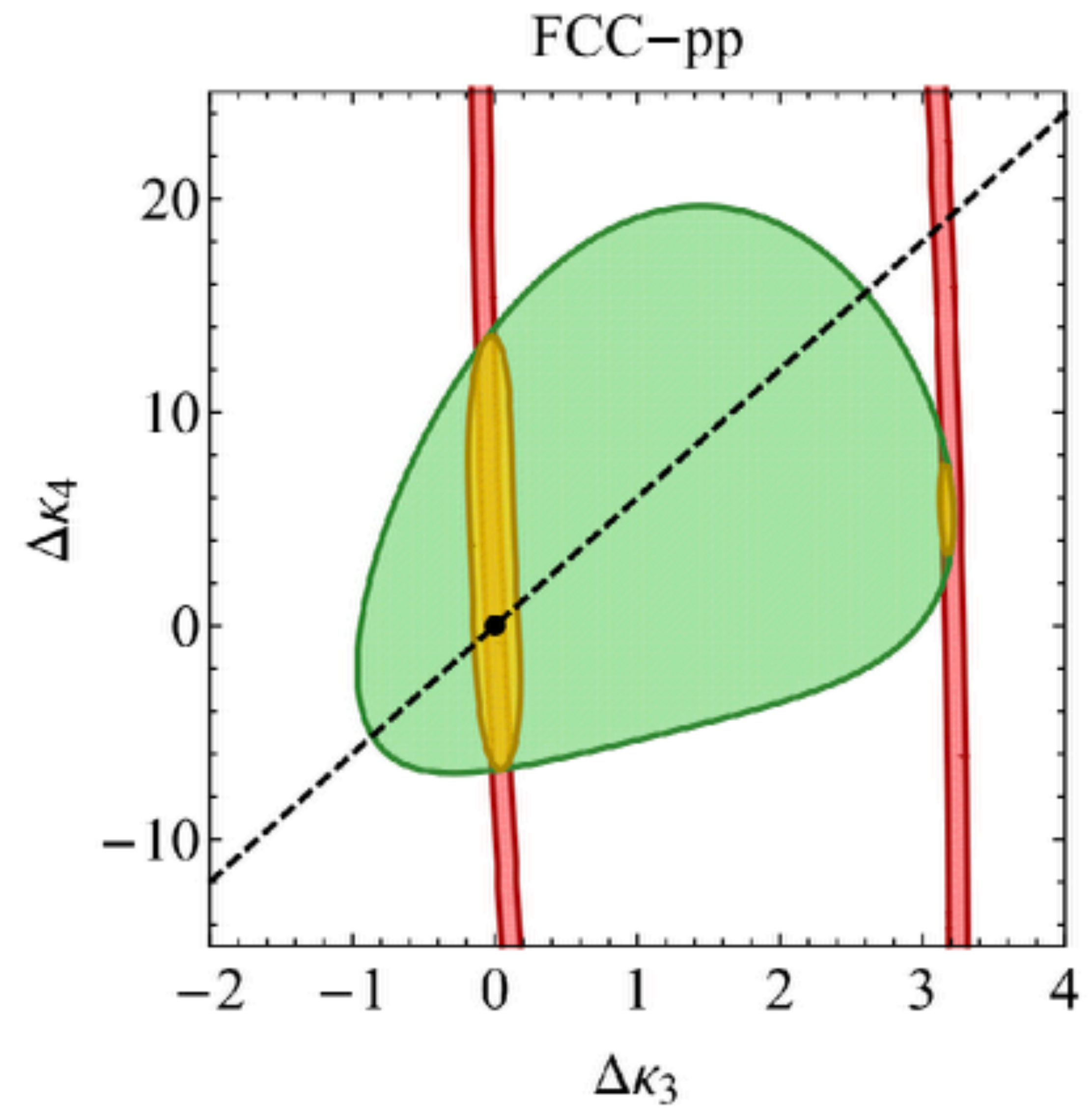

Sensitivity to Higgs quartic is poor even in optimistic cases

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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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

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

TRILINEAR UNITARITY VIOLATION

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

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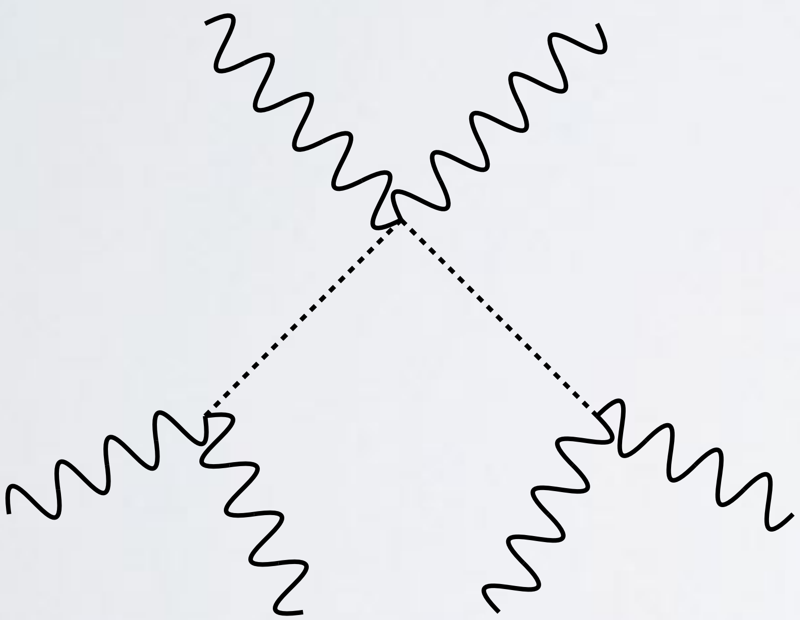

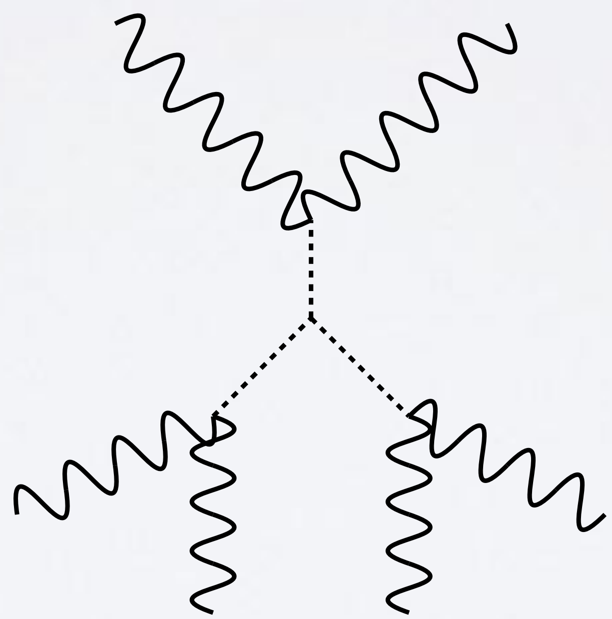

Example:

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

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

HIGGS TRILINEAR MODIFICATION

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

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

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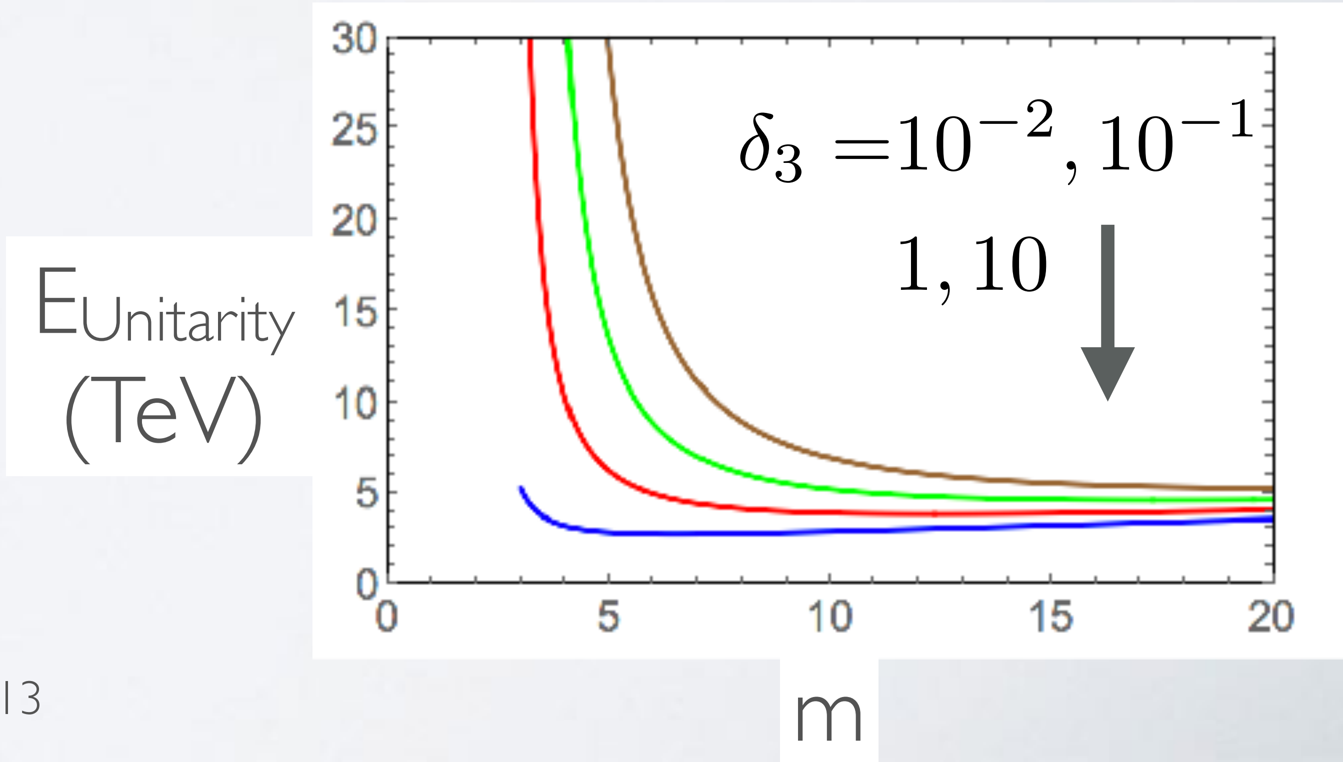
Unitarity violating scale for $Z_L\, h^{m/2} \Leftrightarrow Z_L\, h^{m/2}$ is ~5 TeV for m ~ 10-15



MODEL DEPENDENCE OF INTERACTIONS

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

(Schematic without coefficients)

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(Schematic without coefficients)

Terms circled can only come from trilinear!

HIGHER POINT CANCELLATIONS

SMEFT

$|H|^6$

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$|H|^6$

$$\delta_3 \lambda v \left(\frac{2|H|^2 - v^2}{2v}\right)^3 = \delta_3 \lambda v \left(h + \frac{h^2 + \vec{G}^2}{2v}\right)^3$$

$$= \delta_3 \lambda v \left(h^3 + \frac{3}{2v} h^4 + \frac{3}{4v^2} h^5 + \frac{1}{8v^3} h^6 + O(G^6)\right)$$

HIGHER POINT CANCELLATIONS

SMEFT
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Contact interactions with multiplicity greater than 7 particles are dependent on couplings that will never be directly measured

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$$hG^2 \leftrightarrow G^2$$

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

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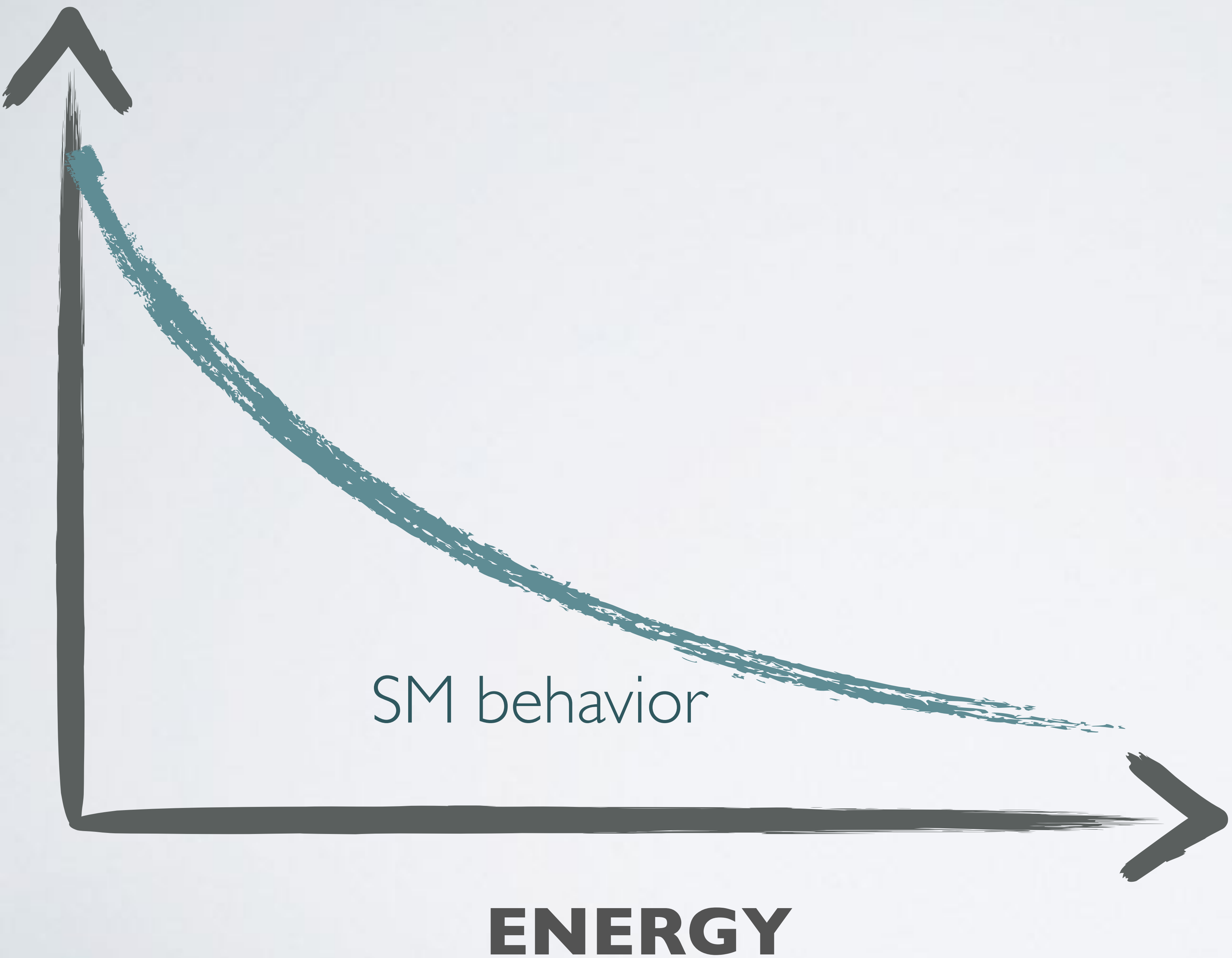
Identifies VBF production of hh, hVV and VVVV as interesting processes and motivates

100 TeV pp collider can test new physics of trilinear

COLLIDER PROBES



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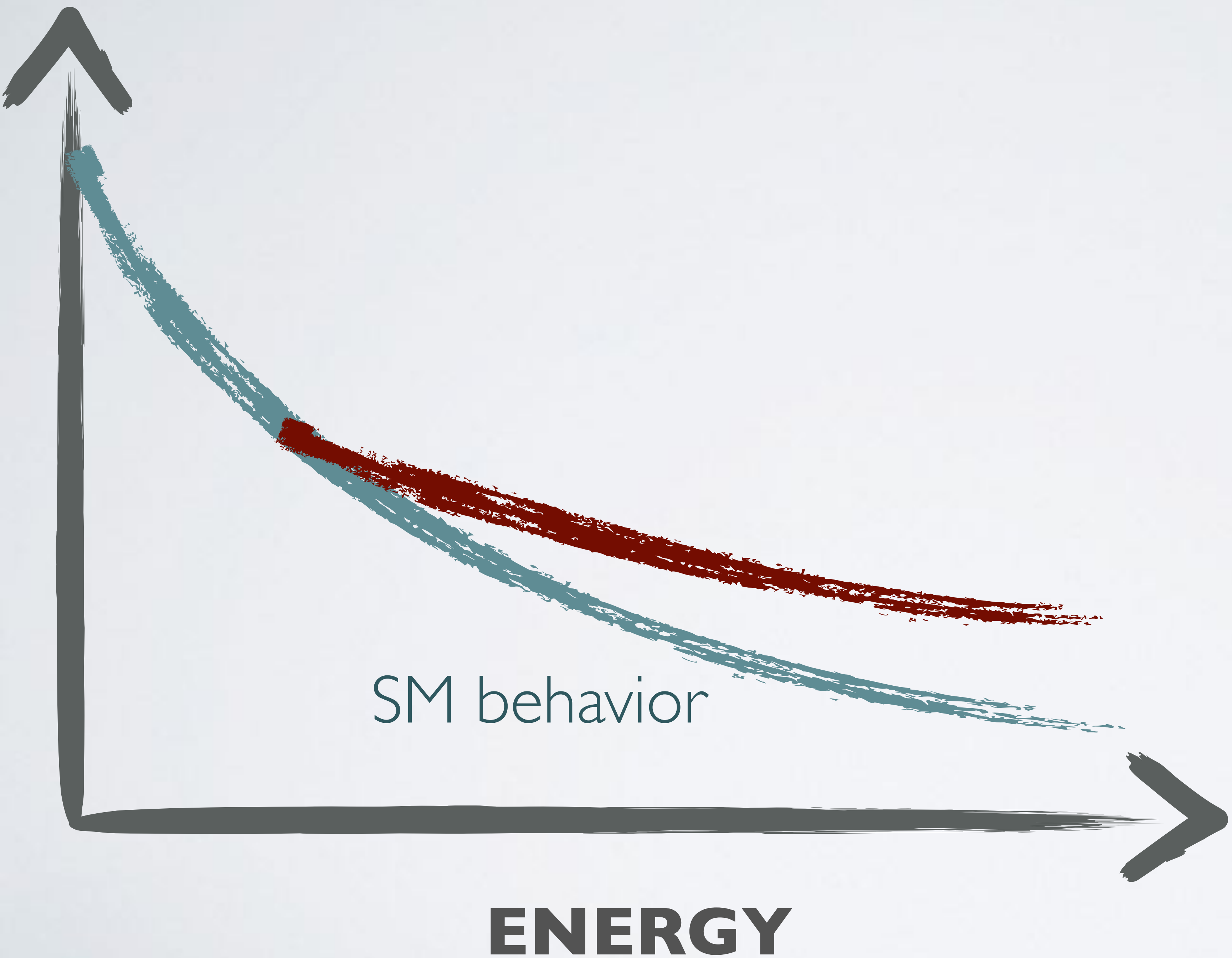

Probing high energy processes can test energy growth, complementary sensitivity to Higgs couplings

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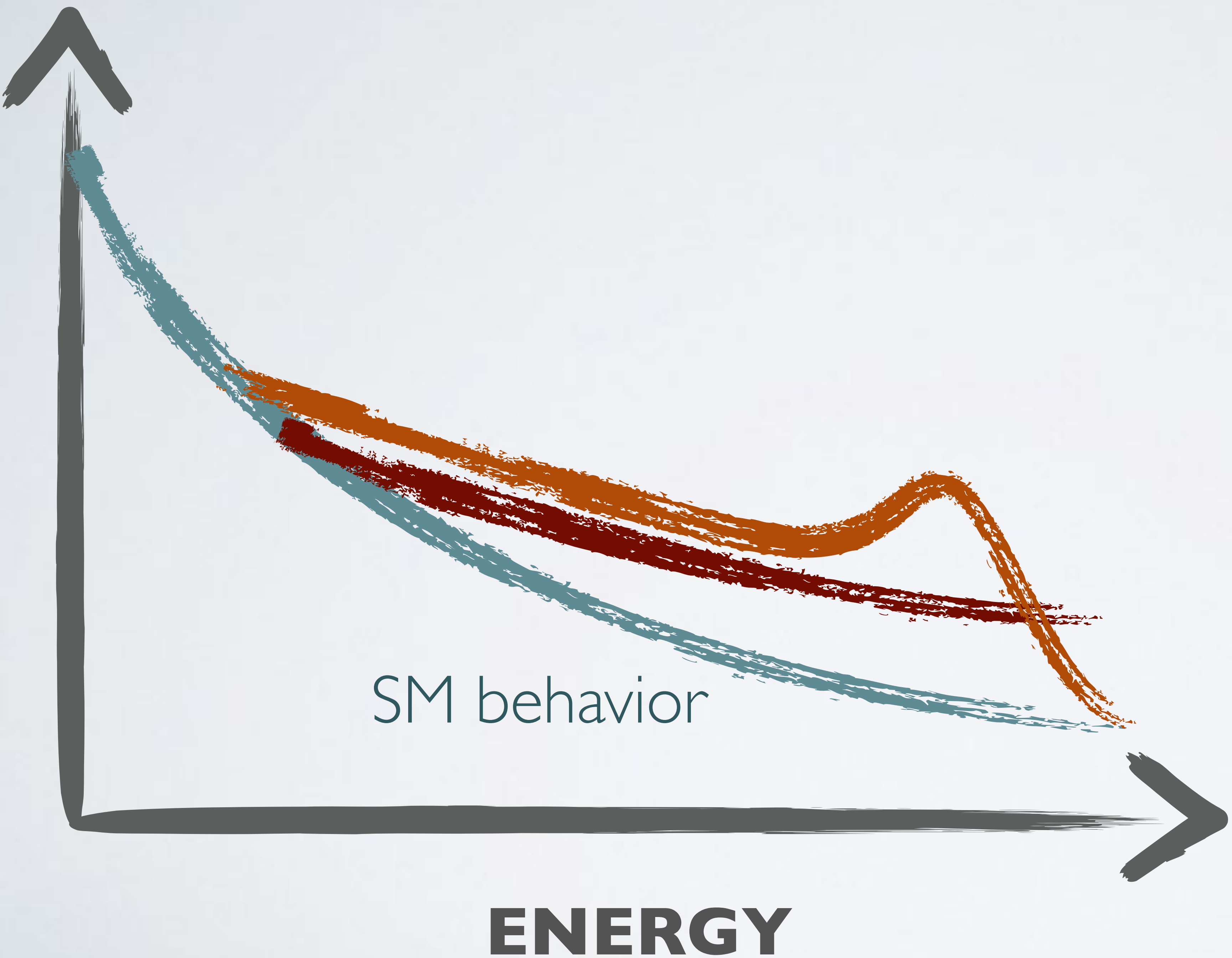
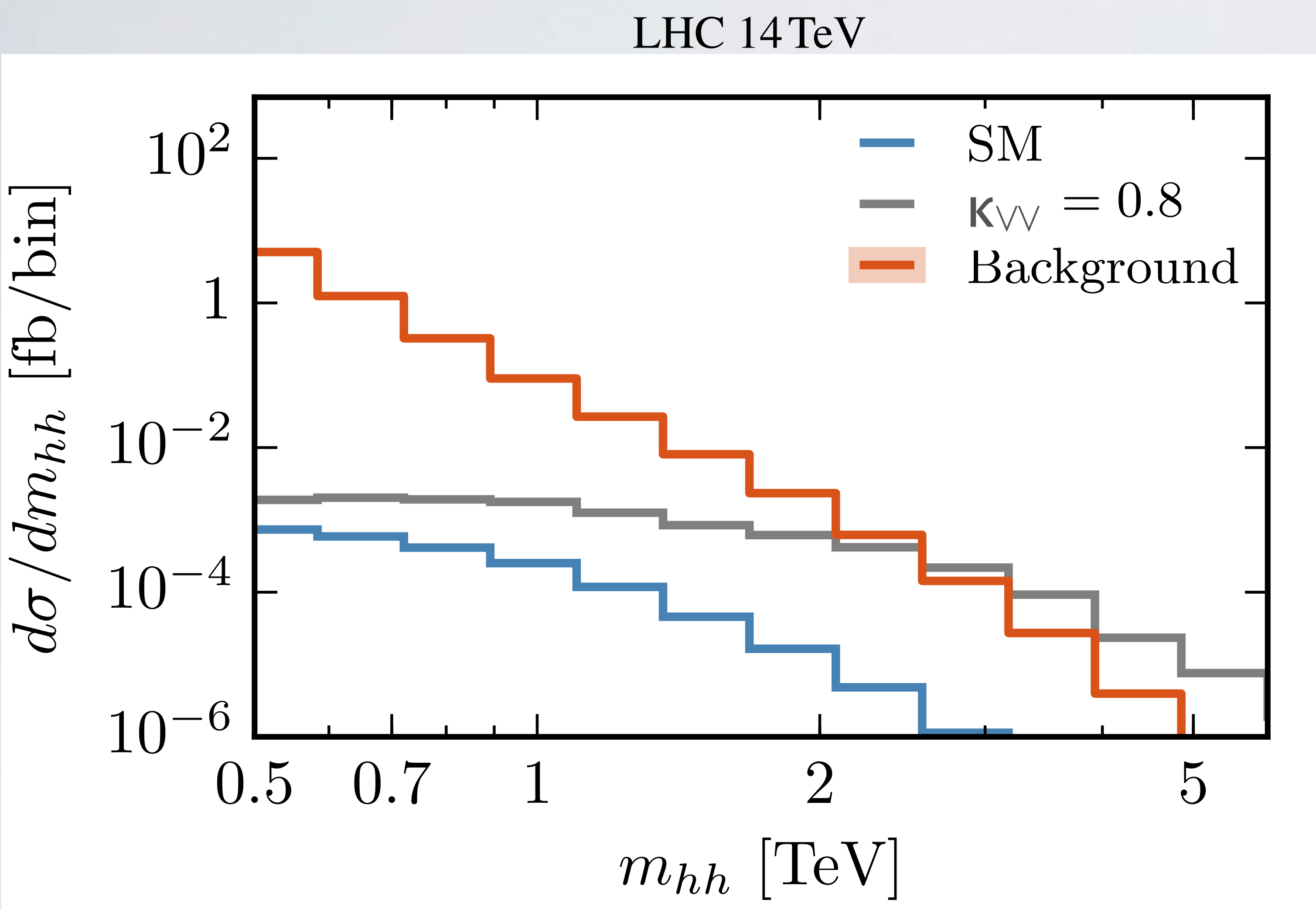


Probing high energy processes can test energy growth, complementary sensitivity to Higgs couplings

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

VECTOR BOSON FUSION OF HH

(BISHARA ET.AL. 1611.03860)



More promising than vector boson scattering (sensitive to hVV, hhVV, hhh couplings)

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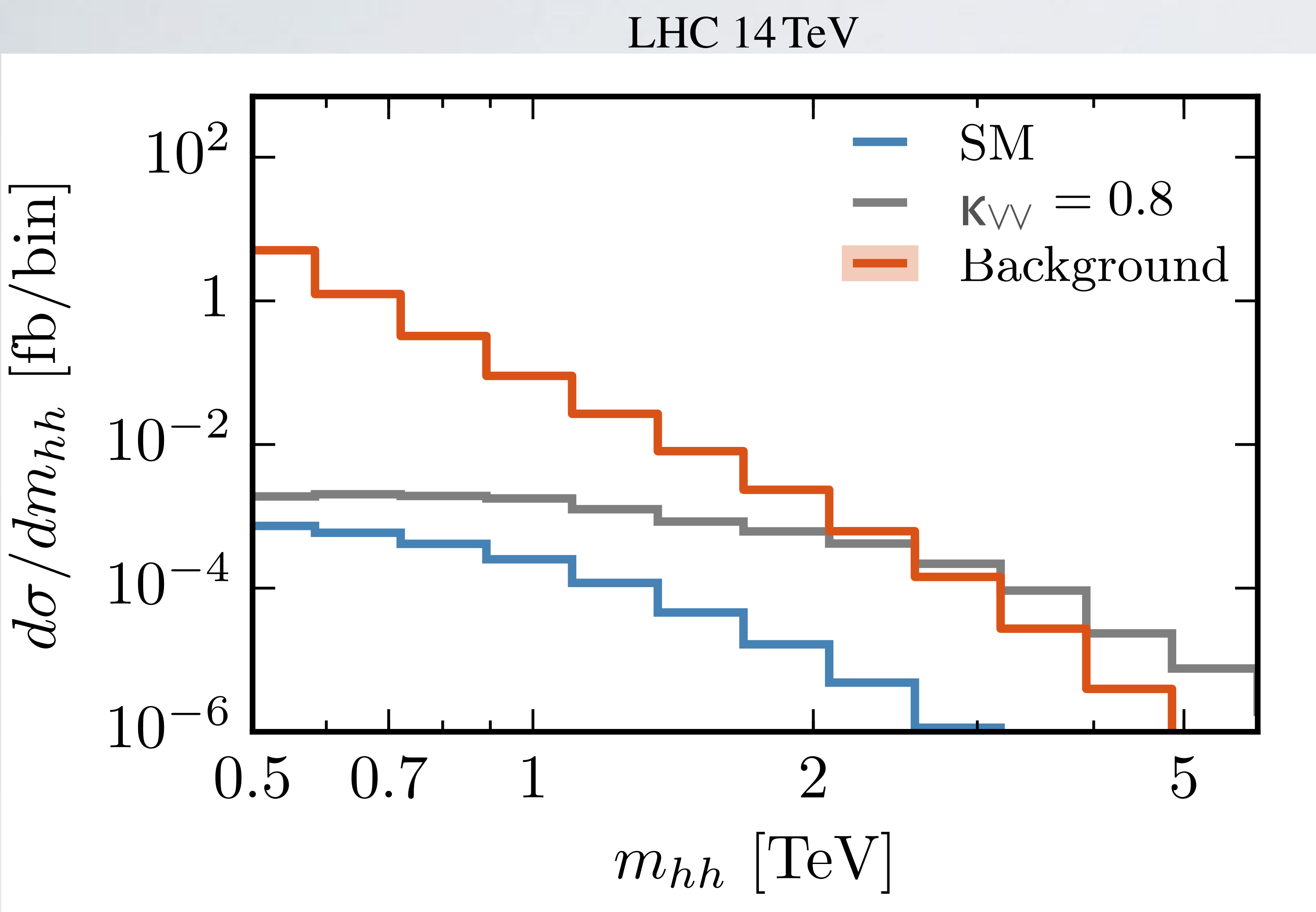
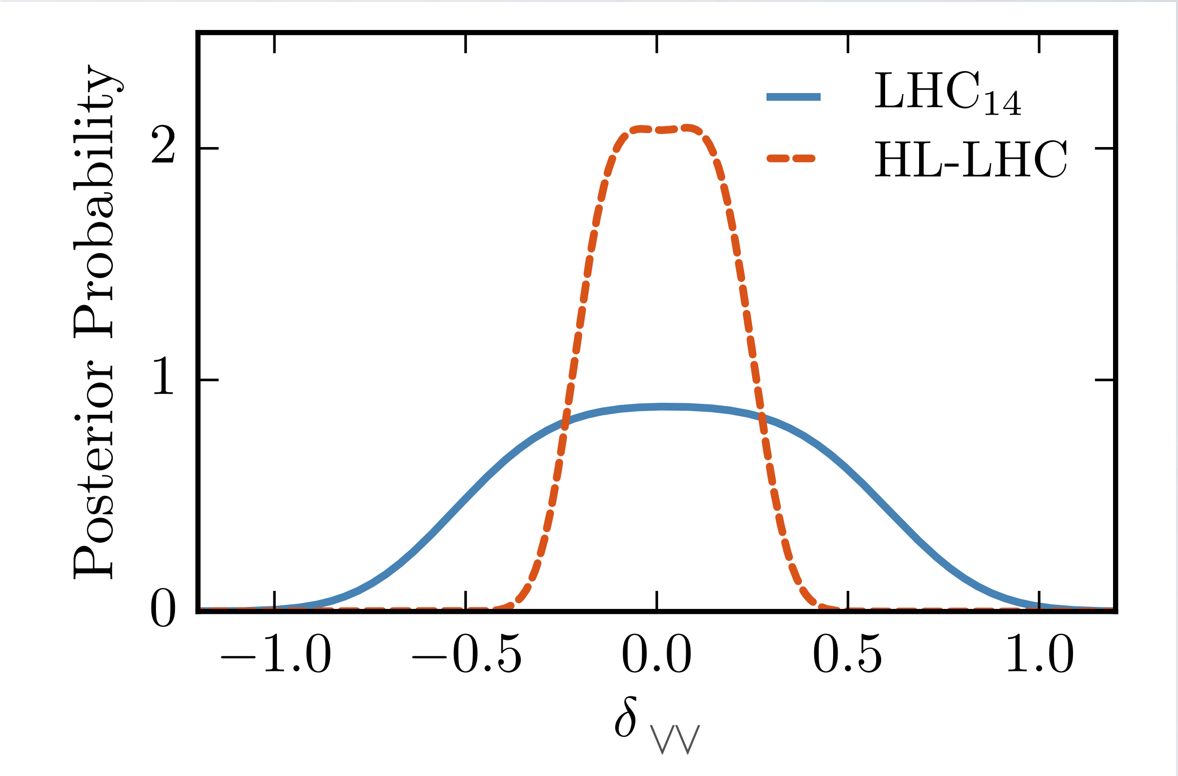


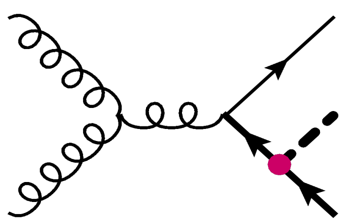
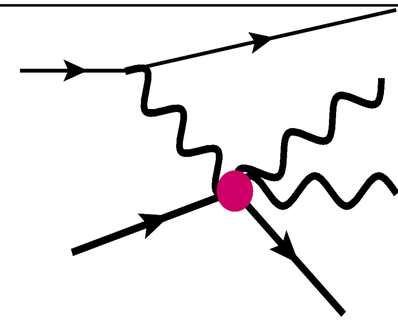
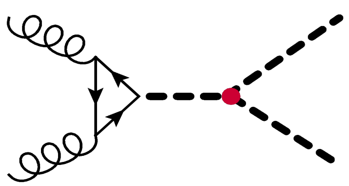
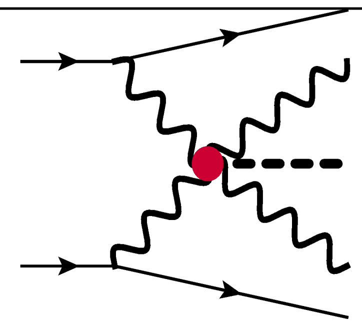
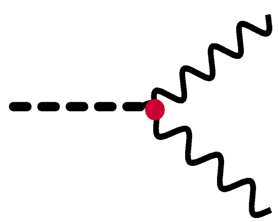
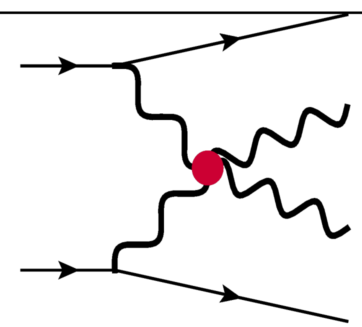
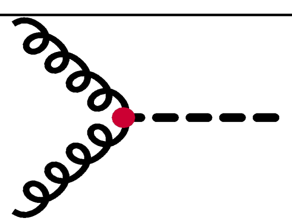
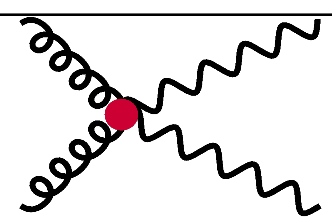


More promising than vector boson scattering (sensitive to hVV, hhVV, hhh couplings)

Search for jjbbbb is sensitive to hhVV coupling of 30% (1%) at HL-LHC (100 TeV)

"HIGGS W/O HIGGS"

Henning et.al. 1812.09299

		HC	HwH	Growth
κ_t	$\mathcal{O}_{y_t}$			$\sim \frac{E^2}{\Lambda^2}$
κ_λ	$\mathcal{O}_6$			$\sim \frac{vE}{\Lambda^2}$
$\kappa_{Z\gamma}$ $\kappa_{\gamma\gamma}$ κ_V	$\mathcal{O}_{WW}$ $\mathcal{O}_{BB}$ $\mathcal{O}_r$			$\sim \frac{E^2}{\Lambda^2}$
κ_g	$\mathcal{O}_{gg}$			$\sim \frac{E^2}{\Lambda^2}$

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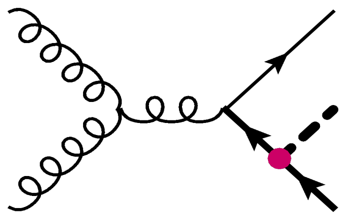
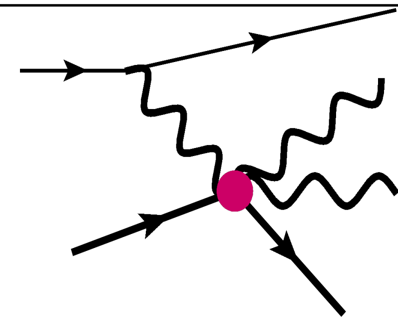
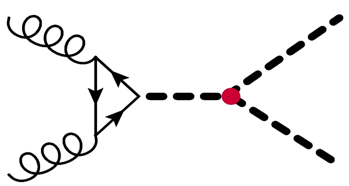
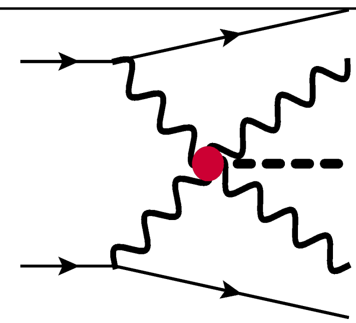
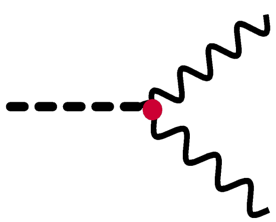
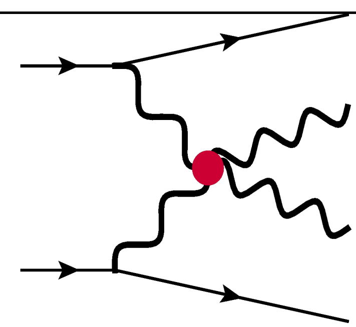
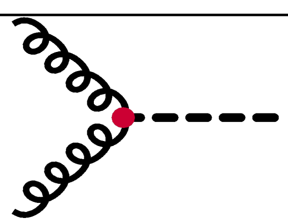
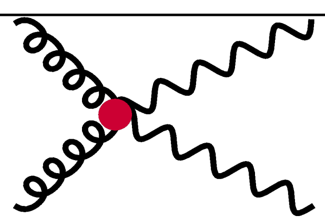
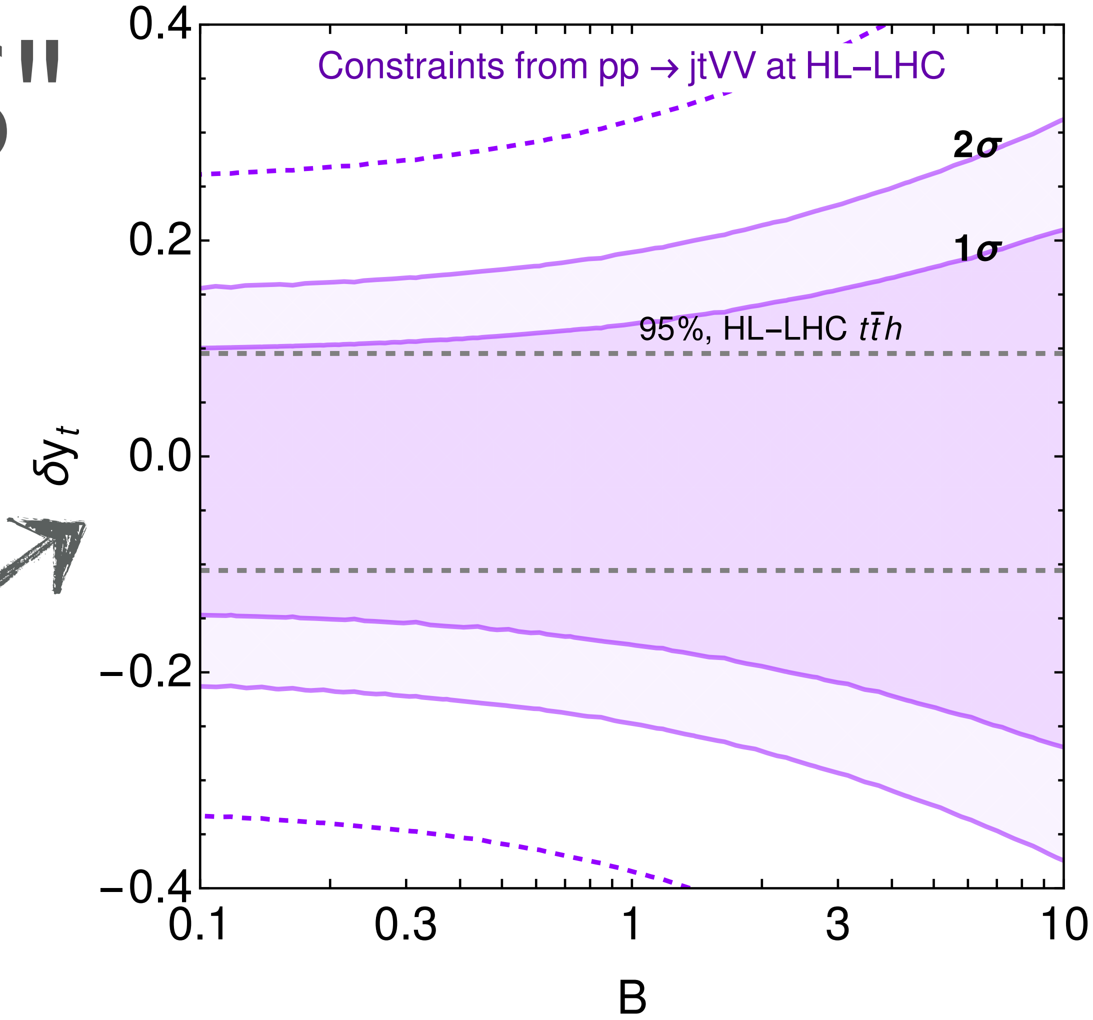
κ_t	$\mathcal{O}_{y_t}$			$\sim \frac{E^2}{\Lambda^2}$
κ_λ	$\mathcal{O}_6$			$\sim \frac{vE}{\Lambda^2}$
$\kappa_{Z\gamma}$ $\kappa_{\gamma\gamma}$ κ_V	$\mathcal{O}_{WW}$ $\mathcal{O}_{BB}$ $\mathcal{O}_r$			$\sim \frac{E^2}{\Lambda^2}$
κ_g	$\mathcal{O}_{gg}$			$\sim \frac{E^2}{\Lambda^2}$



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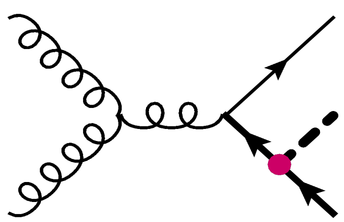
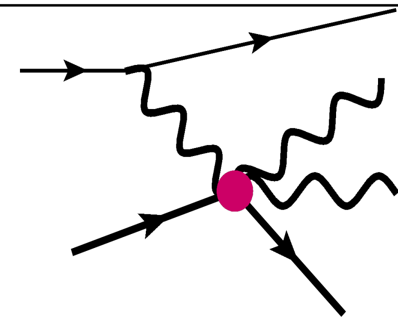
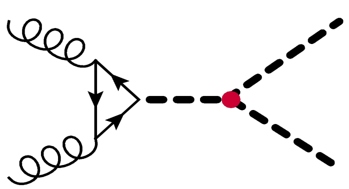
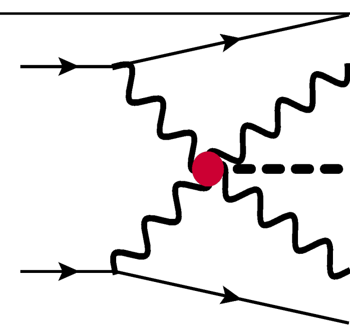
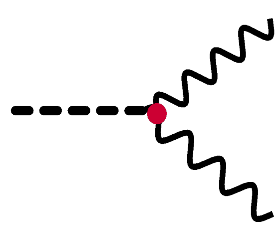
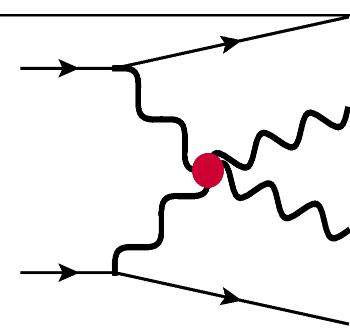
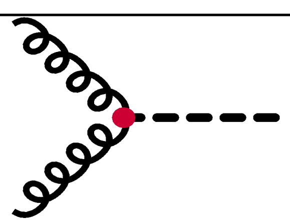
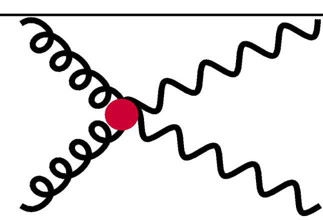
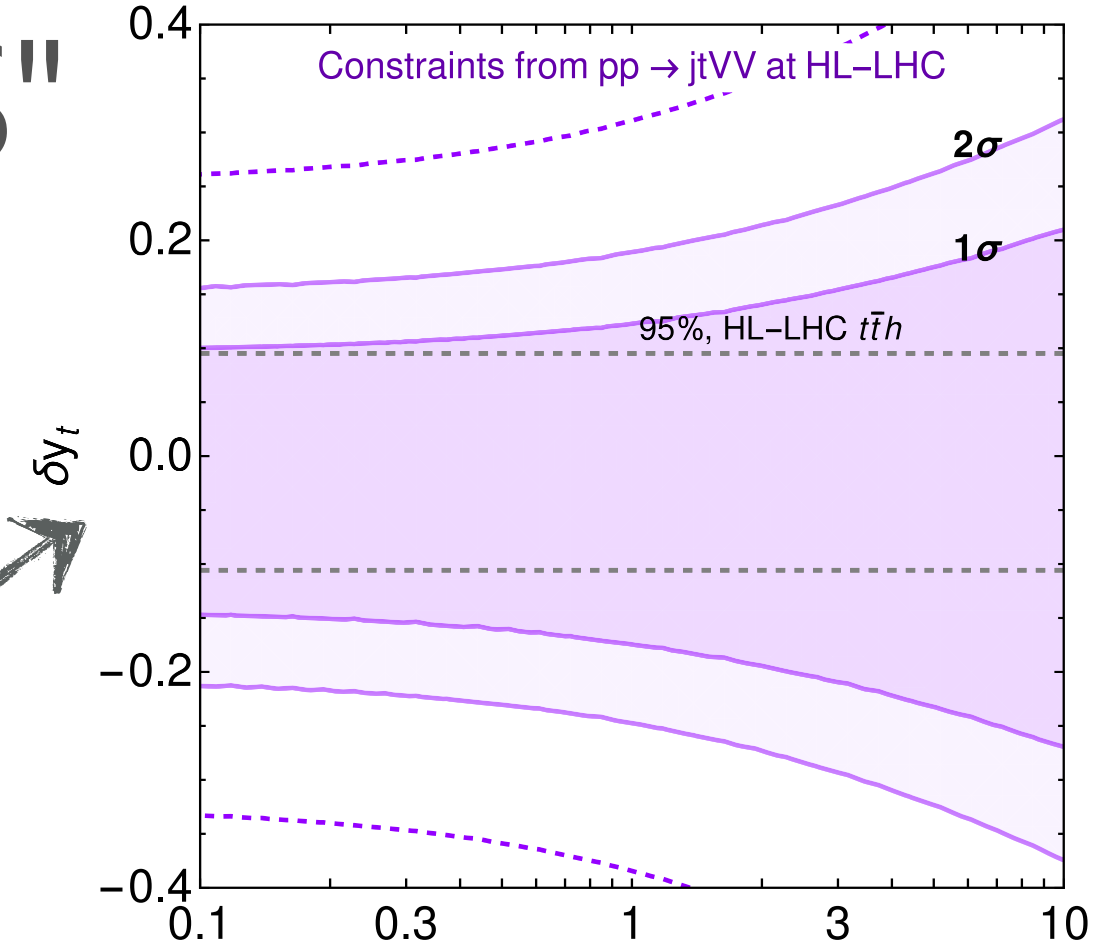
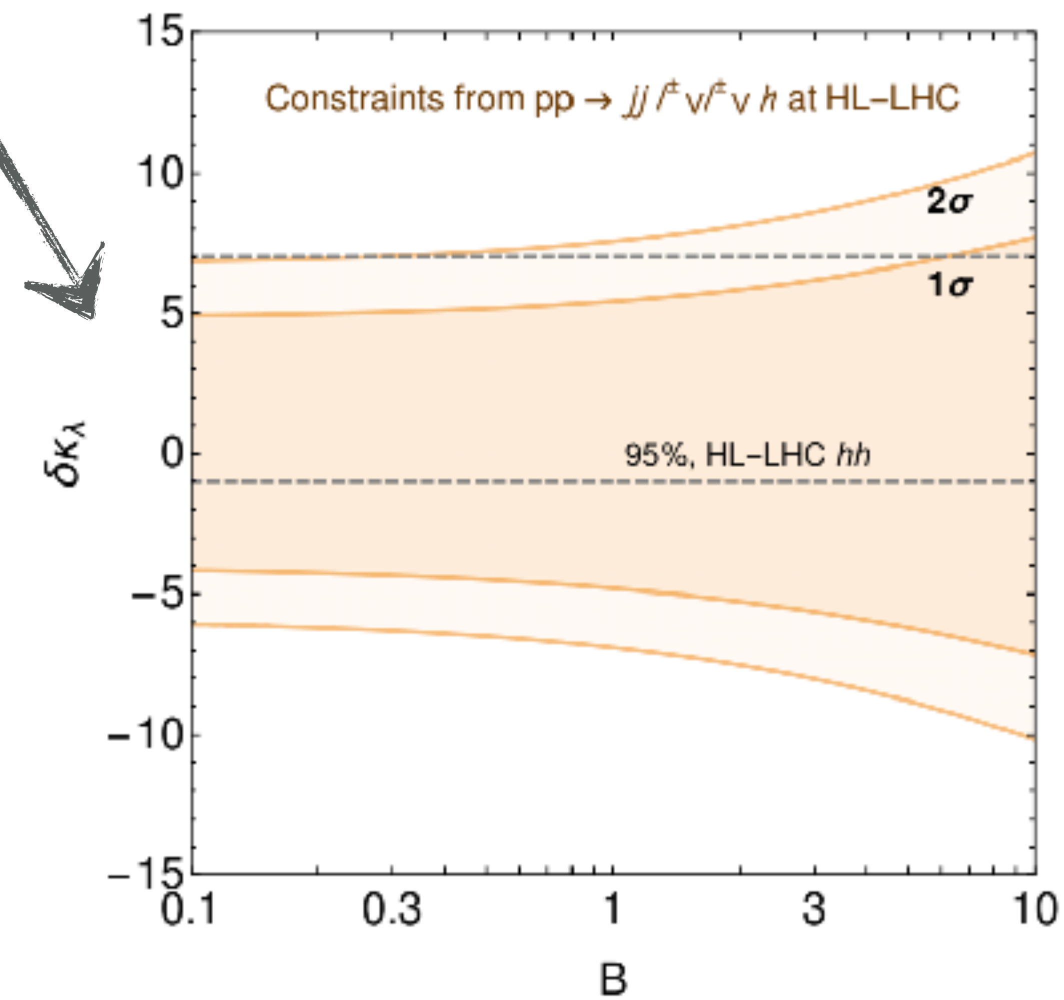
κ_t	$\mathcal{O}_{y_t}$			$\sim \frac{E^2}{\Lambda^2}$
κ_λ	$\mathcal{O}_6$			$\sim \frac{vE}{\Lambda^2}$
$\kappa_{Z\gamma}$ $\kappa_{\gamma\gamma}$ κ_V	$\mathcal{O}_{WW}$ $\mathcal{O}_{BB}$ $\mathcal{O}_r$			$\sim \frac{E^2}{\Lambda^2}$
κ_g	$\mathcal{O}_{gg}$			$\sim \frac{E^2}{\Lambda^2}$





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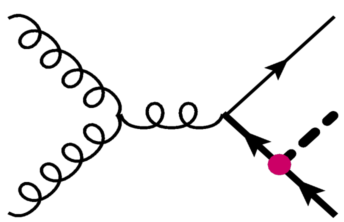
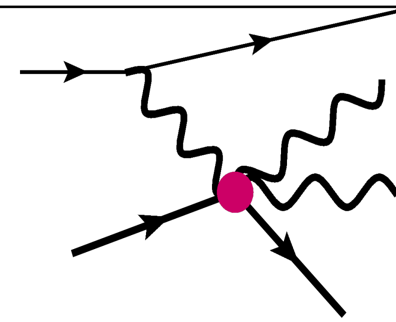
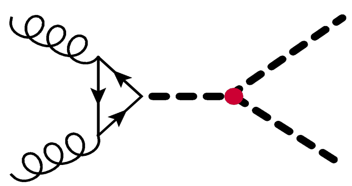
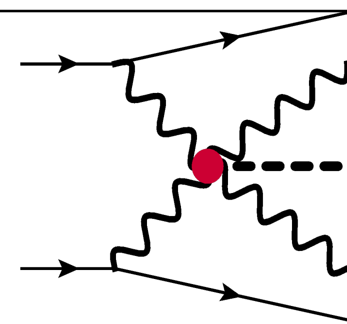
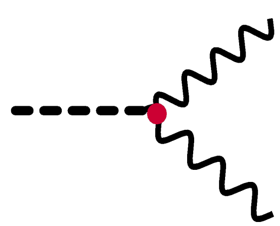
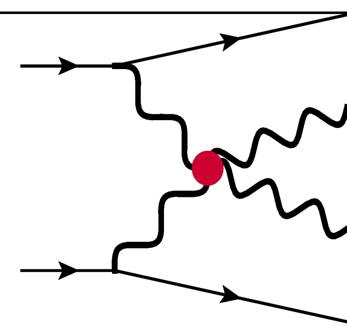
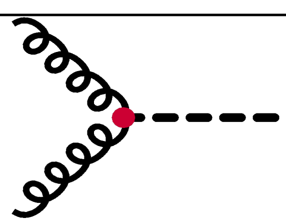
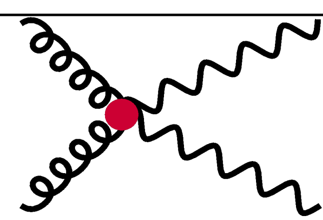
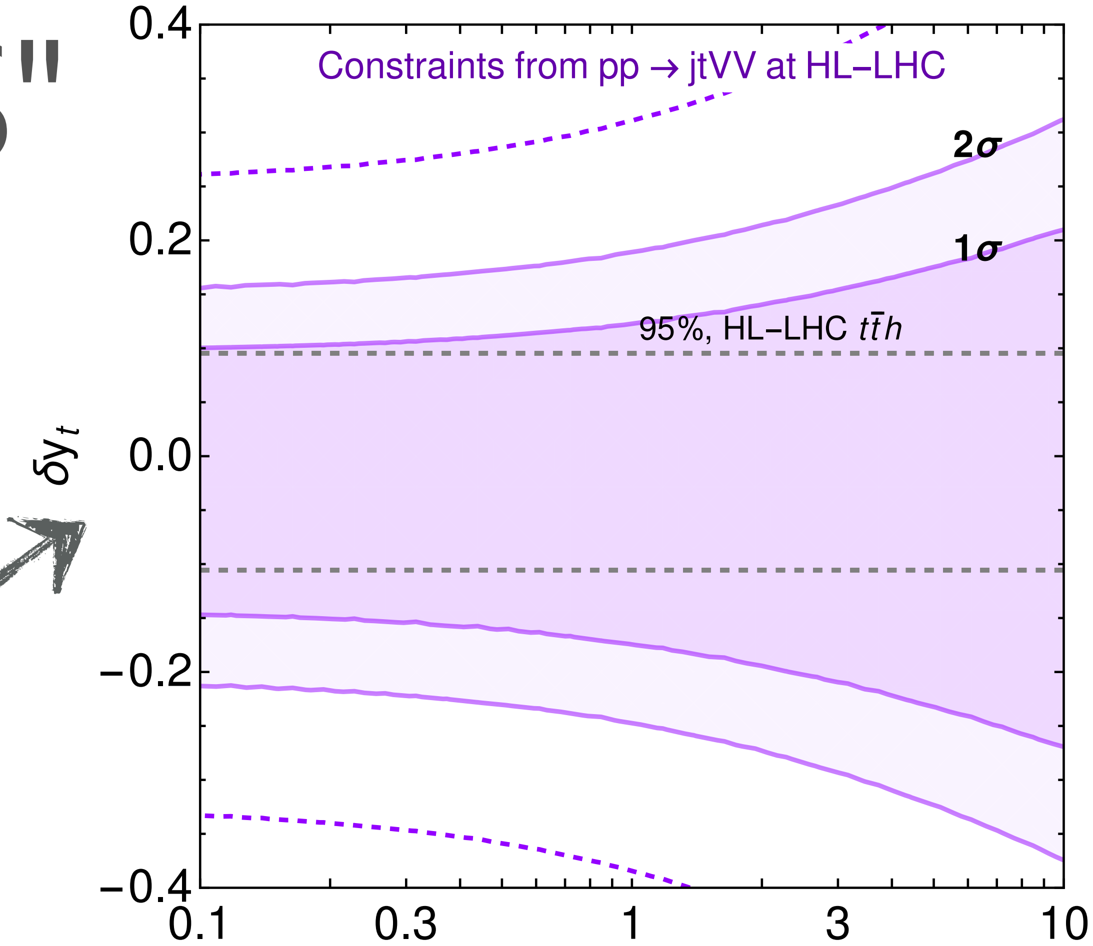
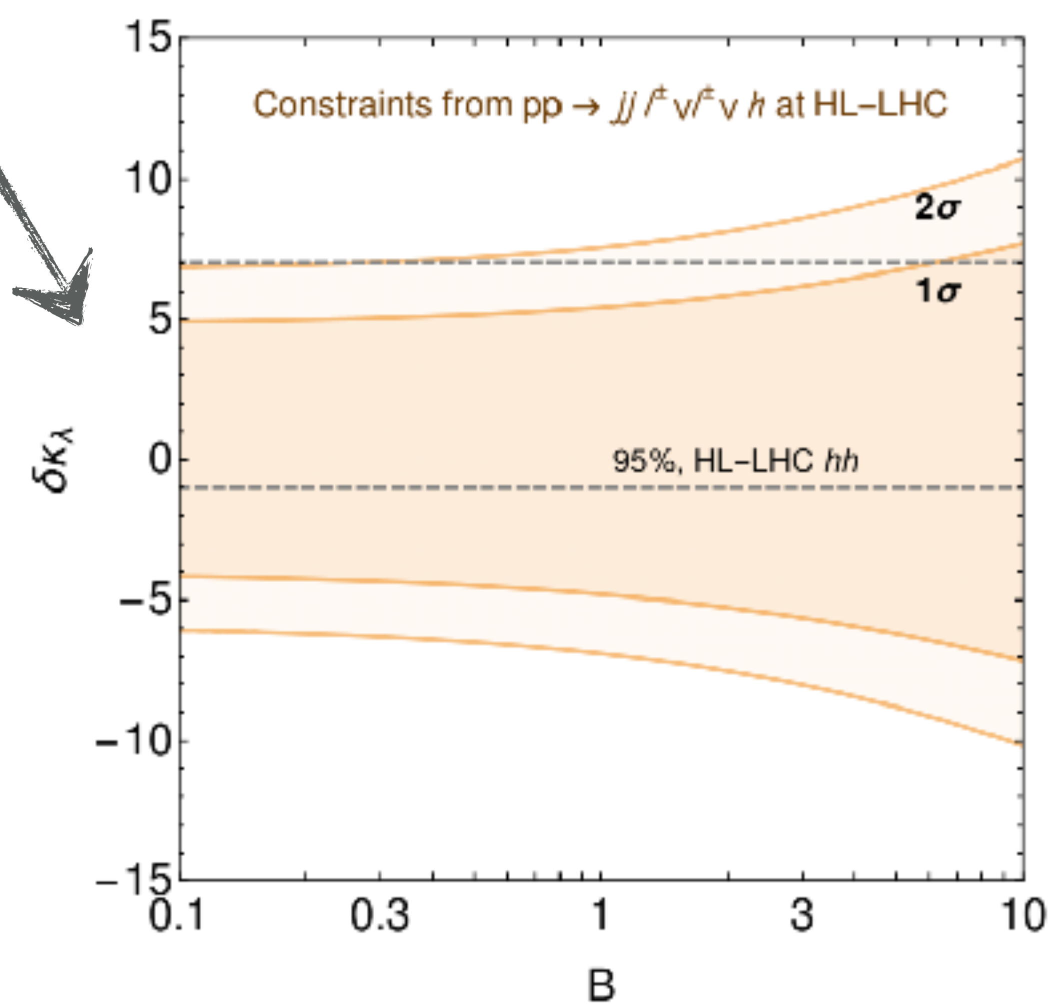
κ_t	$\mathcal{O}_{y_t}$			$\sim \frac{E^2}{\Lambda^2}$
κ_λ	$\mathcal{O}_6$			$\sim \frac{vE}{\Lambda^2}$
$\kappa_{Z\gamma}$ $\kappa_{\gamma\gamma}$ κ_V	$\mathcal{O}_{WW}$ $\mathcal{O}_{BB}$ $\mathcal{O}_r$			$\sim \frac{E^2}{\Lambda^2}$
κ_g	$\mathcal{O}_{gg}$			$\sim \frac{E^2}{\Lambda^2}$





tthh (see Y-Y Li talk), ZZhh, ...

CONCLUSIONS

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- Higgs coupling measurements and searches for deviations in SM processes are correlated

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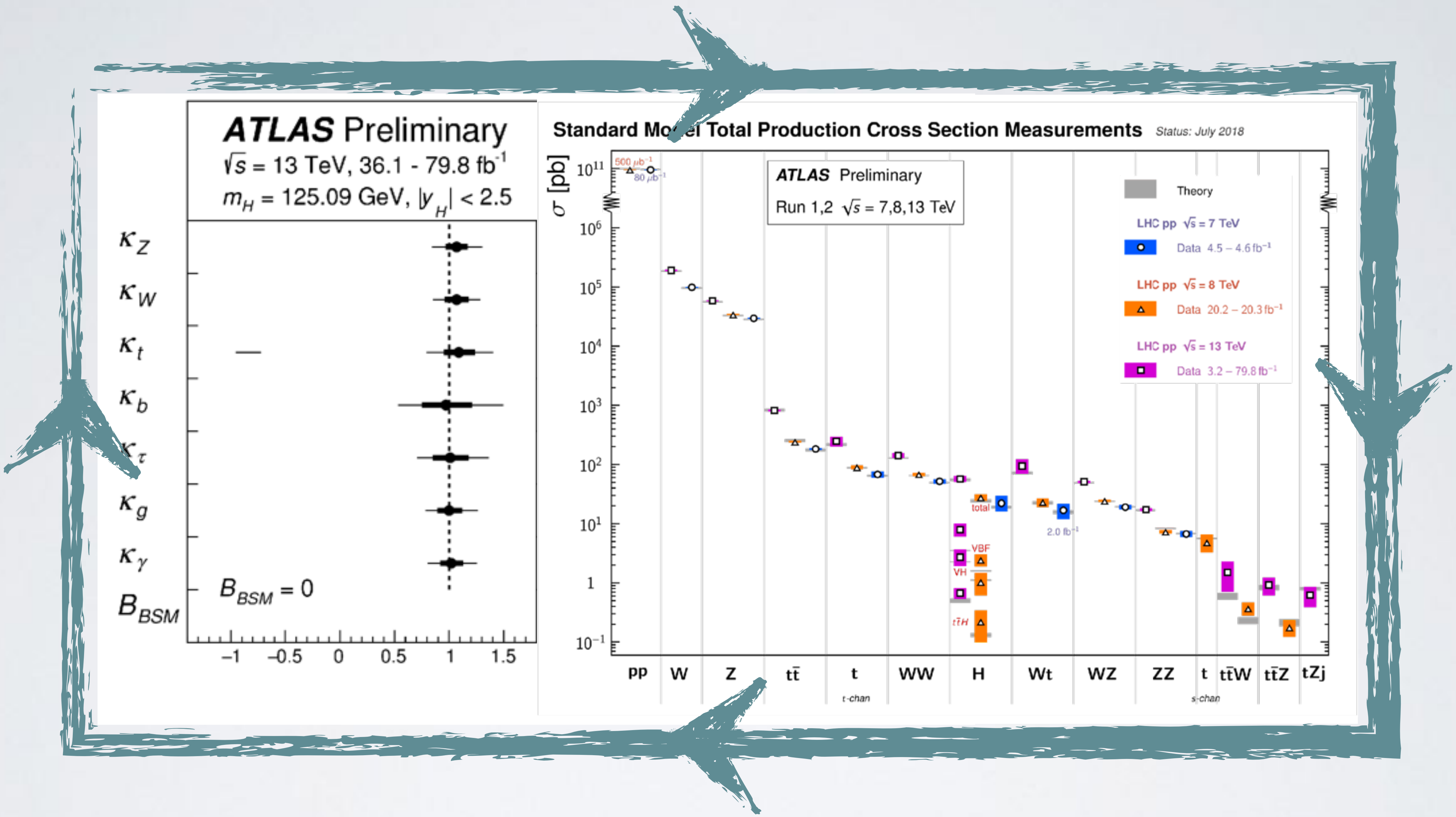
- Trilinear Higgs modifications lead to Unitarity violation at high energies (~ 5 - 13 TeV for $\delta_3 \sim 1$ depending on assumptions)
- Work in progress systematically investigating Unitarity violating channels

THANKS FOR YOUR TIME!



EXTRA SLIDES

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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Consider s-wave scattering

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

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

ONE PARTICLE EXAMPLE

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

Optimal bound is when k = n/2

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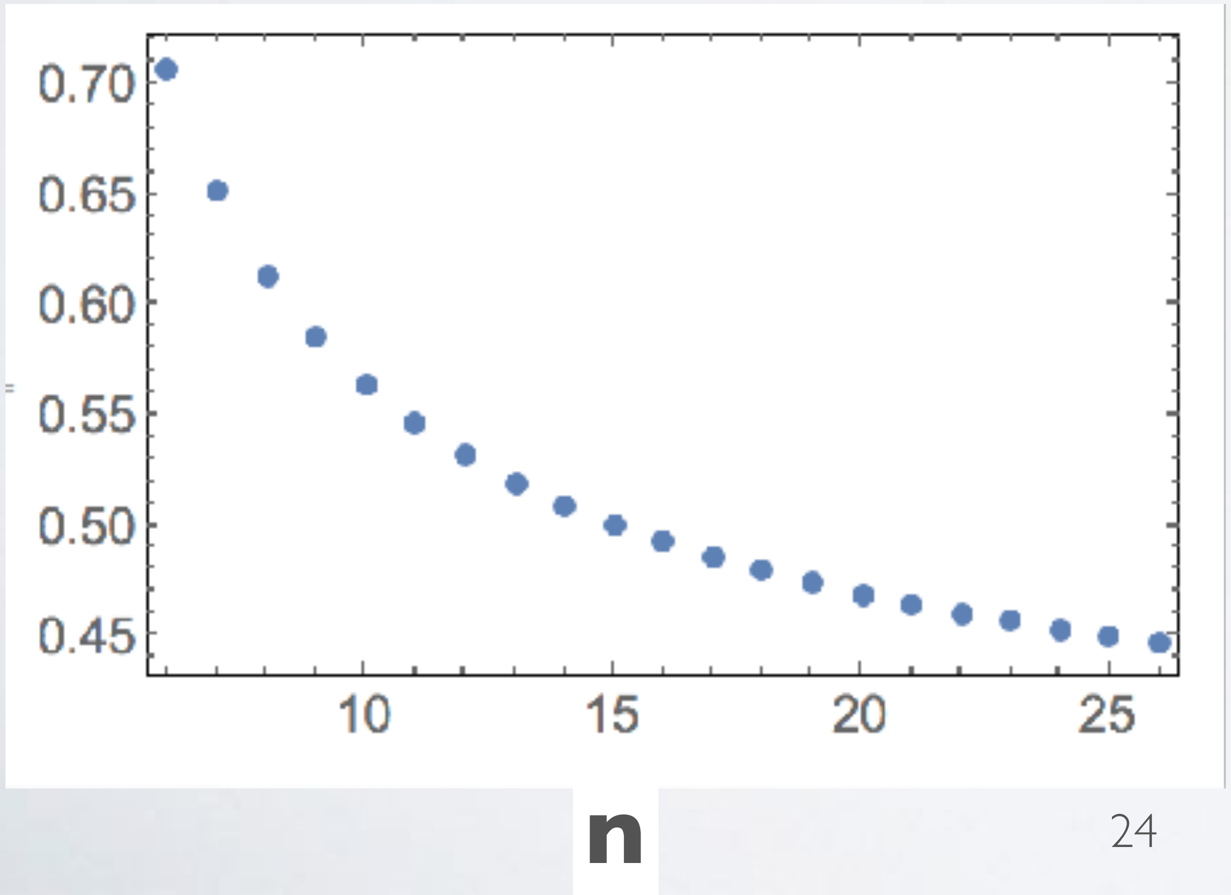
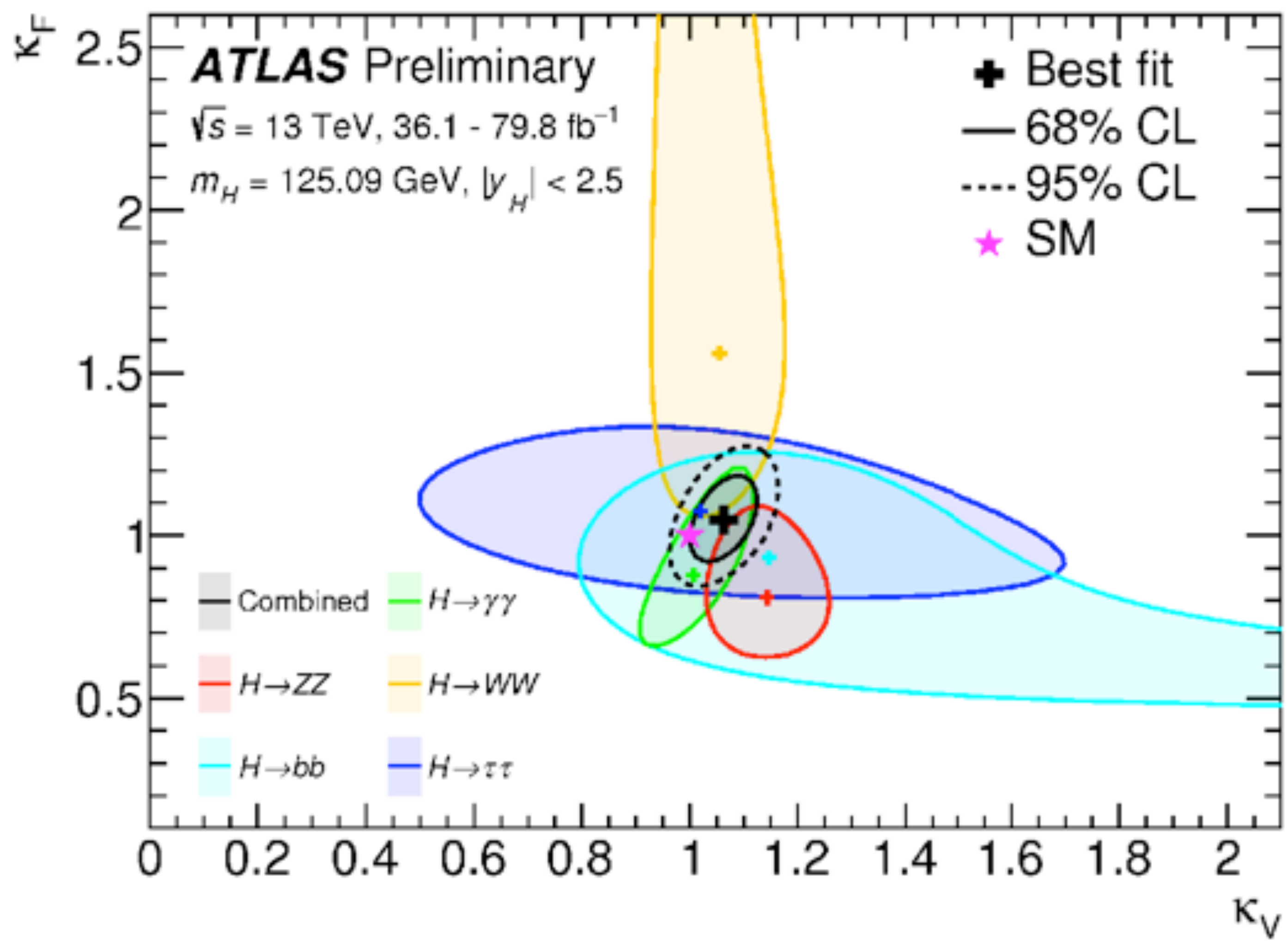
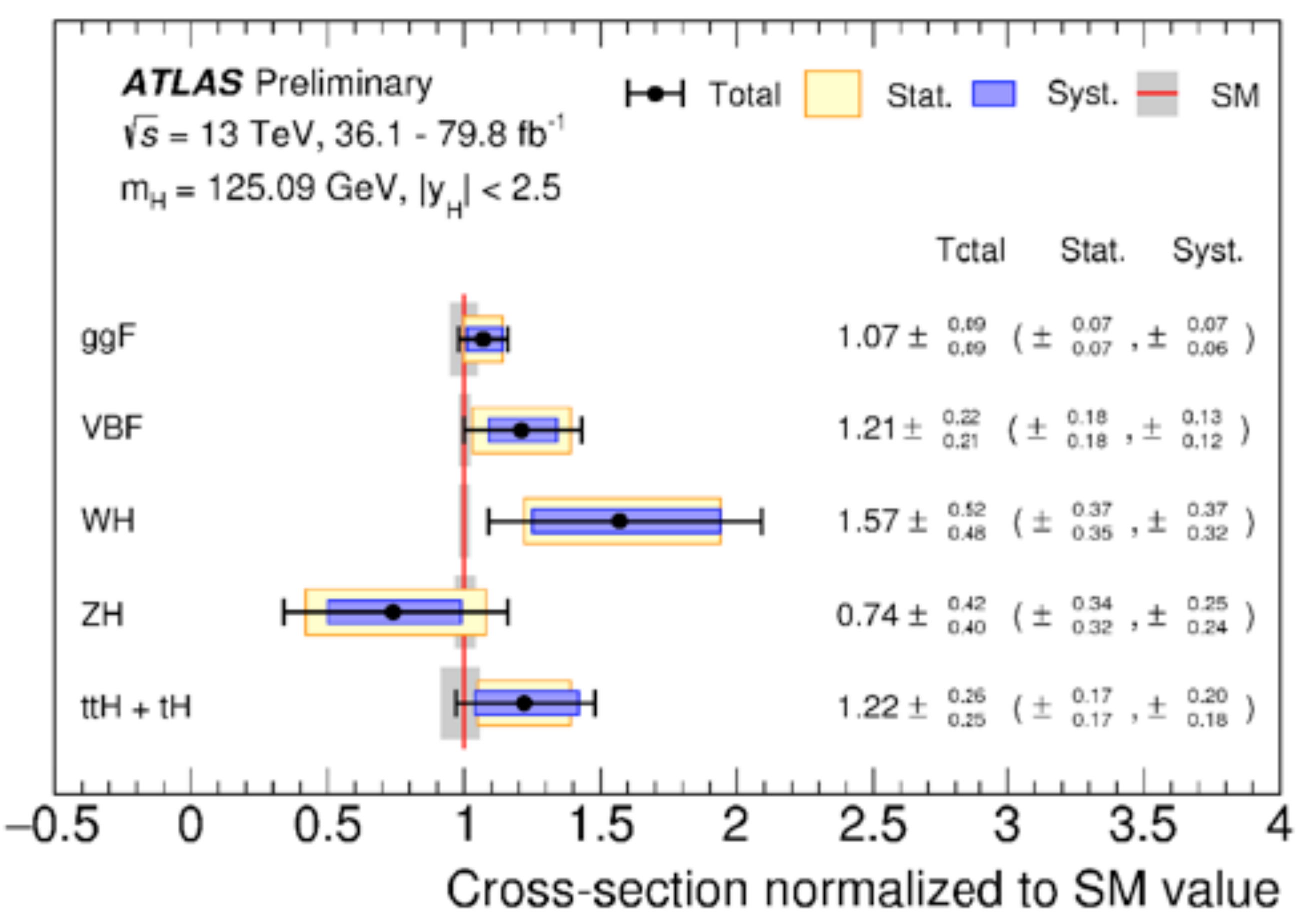
Optimal bound is when k = n/2

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



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


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
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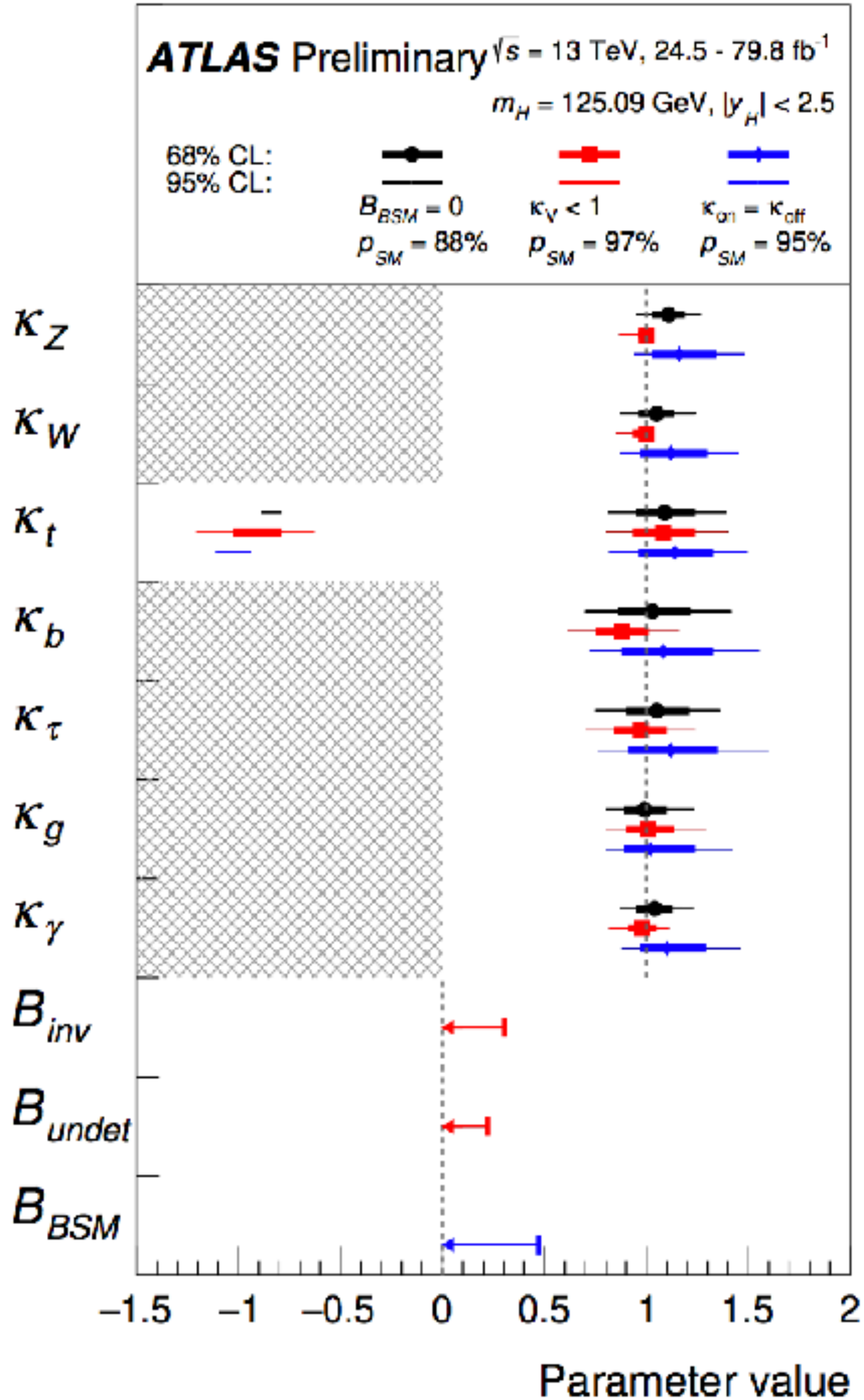
Total
Stat.
Syst.
SM
Total Stat. Syst.
ggF 1.07 ± 0.09 0.09 (± 0.07 0.07 , ± 0.07 0.06)
VBF 1.21 ± 0.22 0.21 (± 0.18 0.18 , ± 0.13 0.12)
WH 1.57 ± 0.52 0.48 (± 0.37 0.35 , ± 0.37 0.32)
ZH 0.74 ± 0.42 0.40 (± 0.34 0.32 , ± 0.25 0.24)
ttH + tH 1.22 ± 0.26 0.25 (± 0.17 0.17 , ± 0.20 0.18)
Cross-section normalized to SM value



ATLAS Preliminary √s = 13 TeV, 24.5 - 79.8 fb-1
mH = 125.09 GeV, |yH| < 2.5
68% CL:
95% CL:
BBSM = 0
pSM = 88%
κV < 1
pSM = 97%
κon = κoff
pSM = 95%
κZ
κW
κt
κb
κτ
κg
κγ
Binv
Bundet
BBSM
−1.5
−1
−0.5
0
0.5
1
1.5
2
Parameter value

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

FALKOWSKI & RATTAZZI

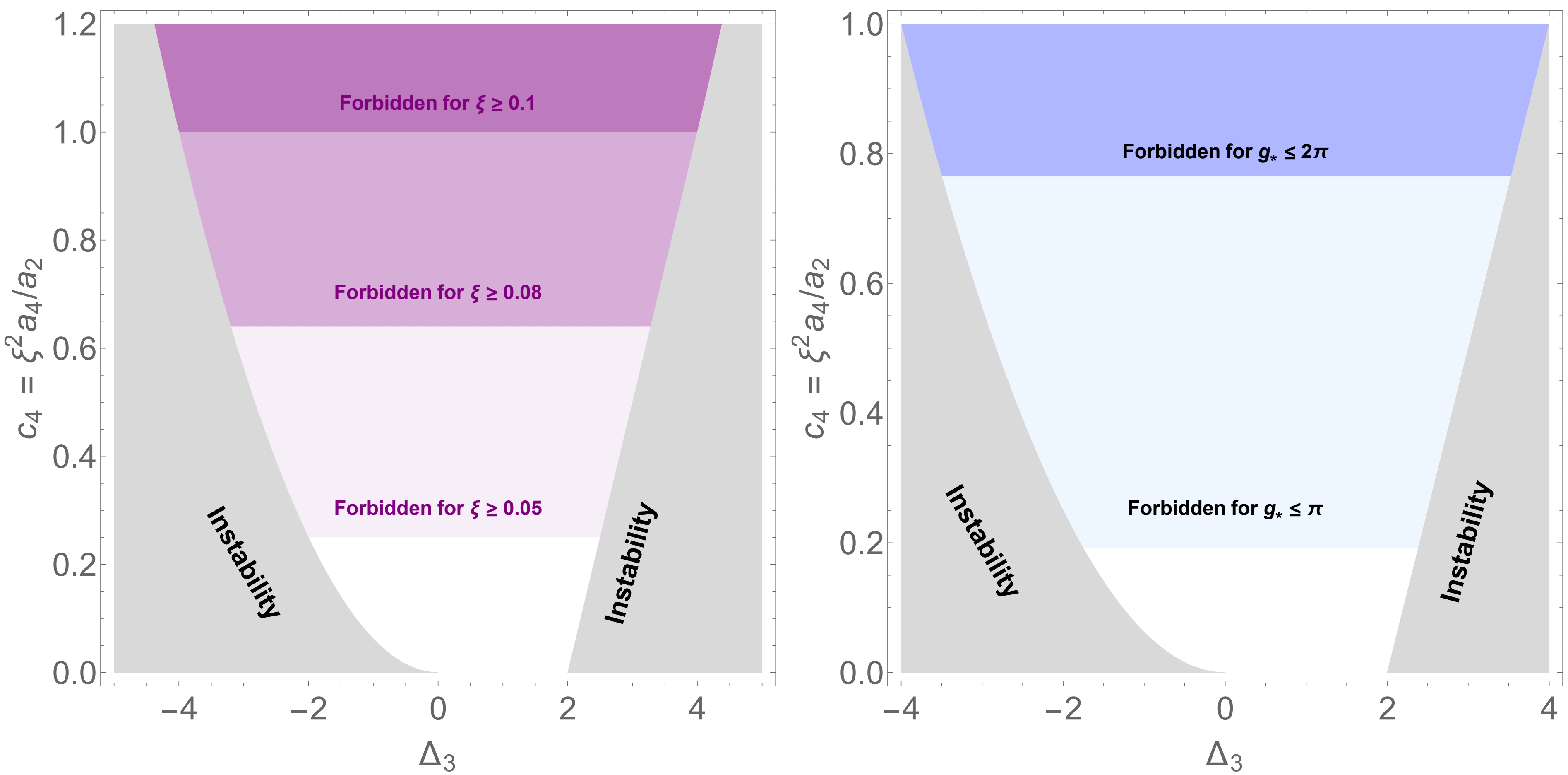


Figure 1: Parameter space for the cubic Higgs self-coupling deformation Δ_3 relative to the SM value. The allowed region depends on the value $c_4 = \xi a_4/a_2$, which encodes effects of dimension-8 SMEFT operators in the Higgs potential. The gray area is excluded by stability considerations, as the 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.