Surprises of Higgs and Top

Sunghoon Jung
Seoul National University

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1708.08912, 1708.09079, 1505.00291 and ongoing works with Junghwan Lee, M. E. Peskin, J. Tian, M. Vos, and Ke-Pan Xie

Surprises

1. Higgs kappa-fit is not enough. A d=6 EFT is one general approach.

2. Electroweak precision test is not precise enough; for Higgs measurements.

3. Tops can be probed without tops: @ 250 GeV e+e-.

4. Higgs is not always a resonance peak; becoming a generic phenomenon.

5. Broad resonances are also becoming generic. How can we discover/measure them?

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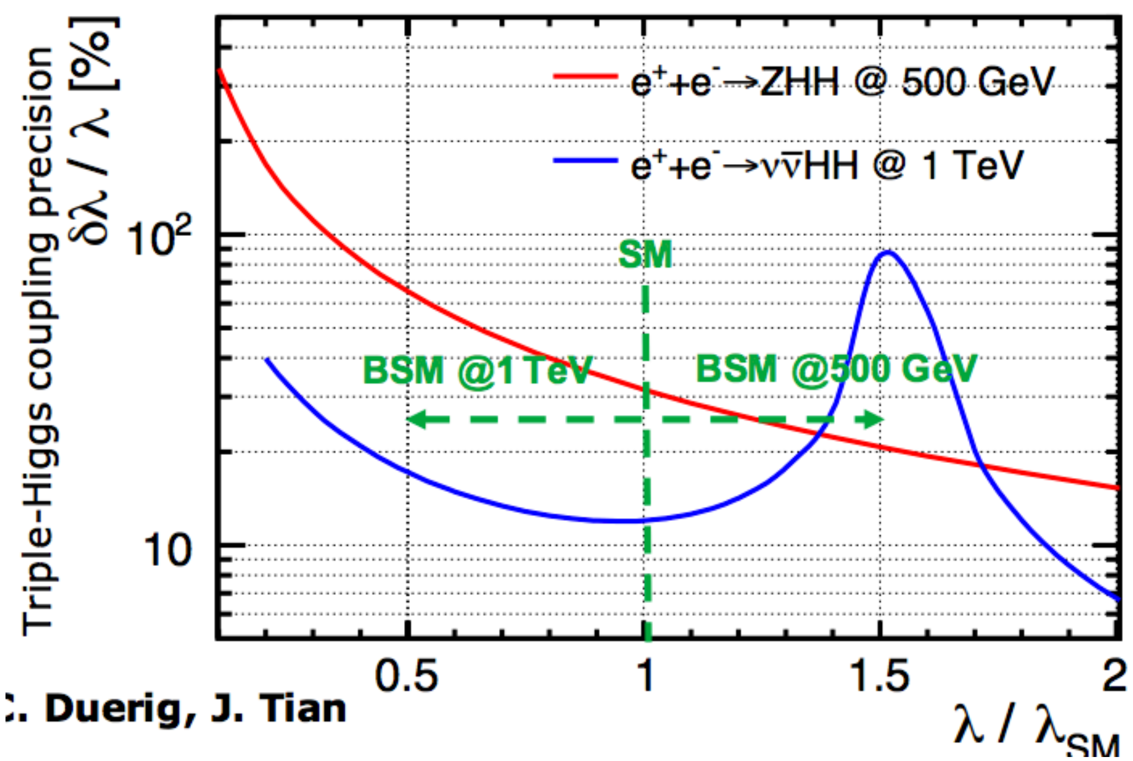
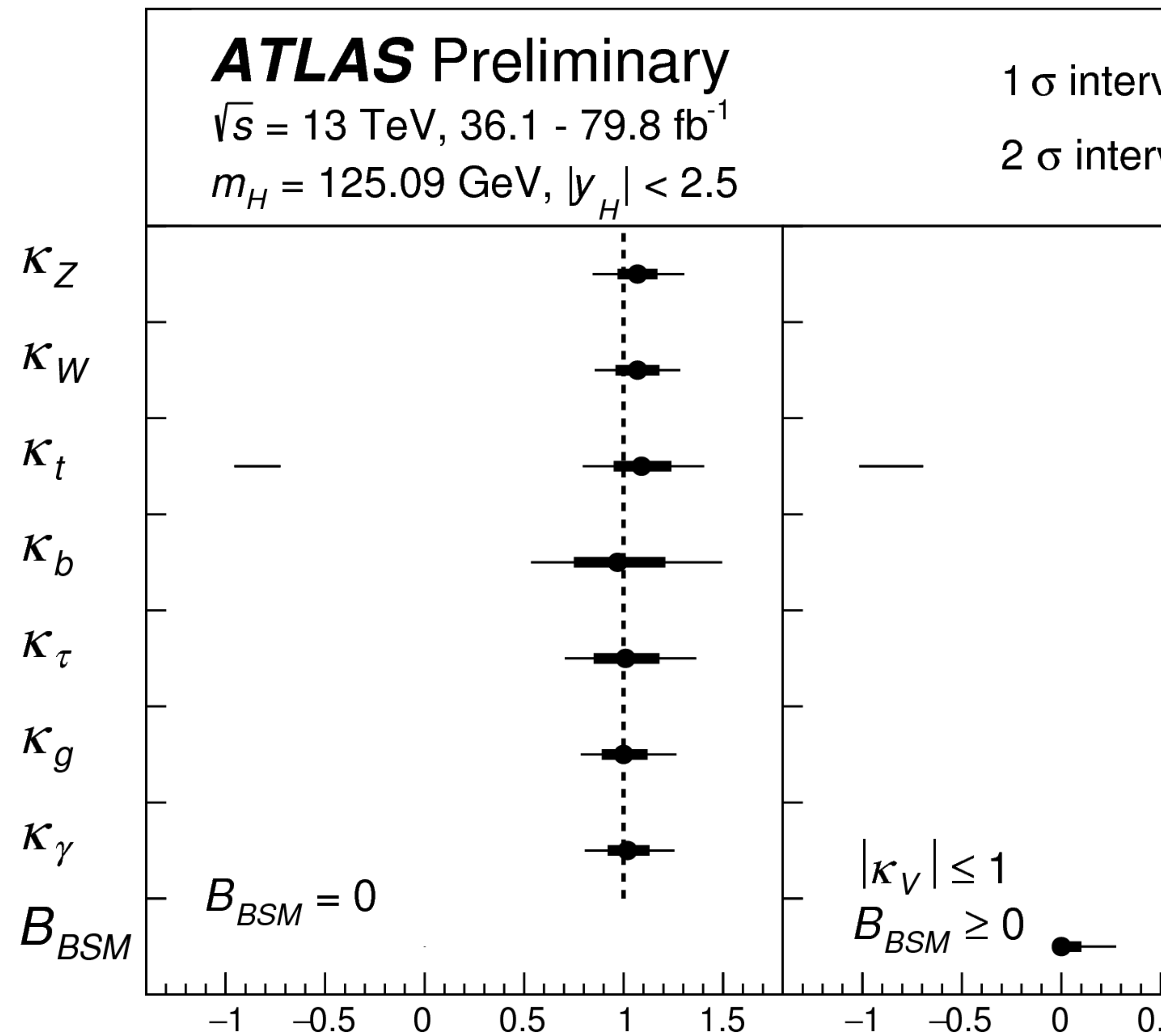
How we usually think about Higgs precision





Kappa is not enough

- For hWW and hZZ, in particular, kappa is clearly not enough.

$$\delta\mathcal{L} = (1+\eta_Z)\frac{m_Z^2}{v} h Z_\mu Z^\mu + \zeta_Z \frac{h}{2v} Z_{\mu\nu} Z^{\mu\nu}$$

$$\sigma(e^+e^- \to Zh) = (SM)\cdot(1+2\eta_Z+(5.7)\zeta_Z)$$

$$\Gamma(h \to ZZ^*) = (SM)\cdot(1+2\eta_Z-(0.50)\zeta_Z)$$

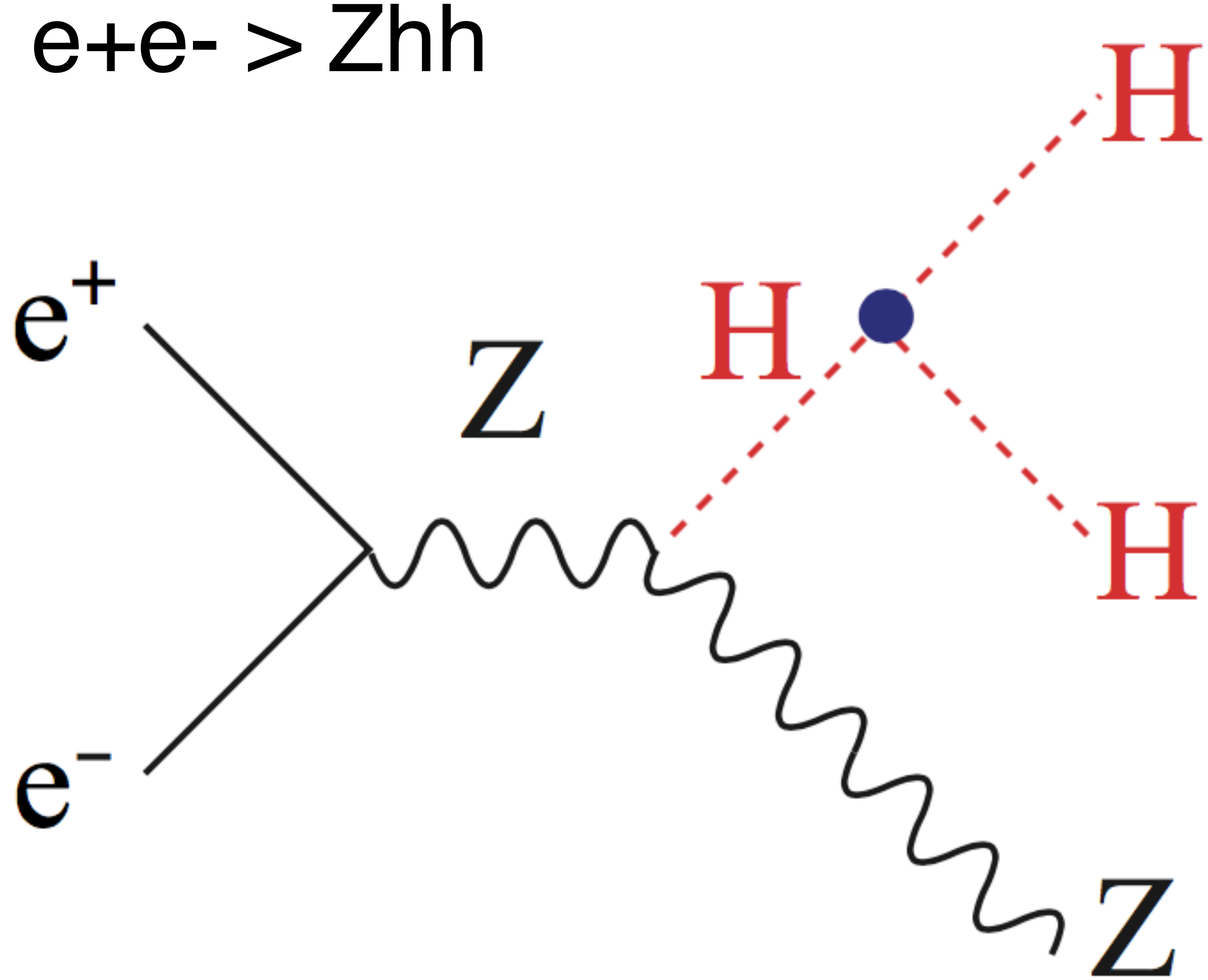
- Two different couplings give different contributions and energy dependences, that single kappa cannot.

Deviation means new physics

- These results of Delta lambda and kappa might be good enough if the only question is to test the SM.
- If there's a deviation, there's a new physics! Not only lambda, but many others will be non-SM.
- To interpret Higgs-potential deviation from the SM, we need to separate deviations in the Higgs potential from possible deviations of other SM parameters.

How shall we do?

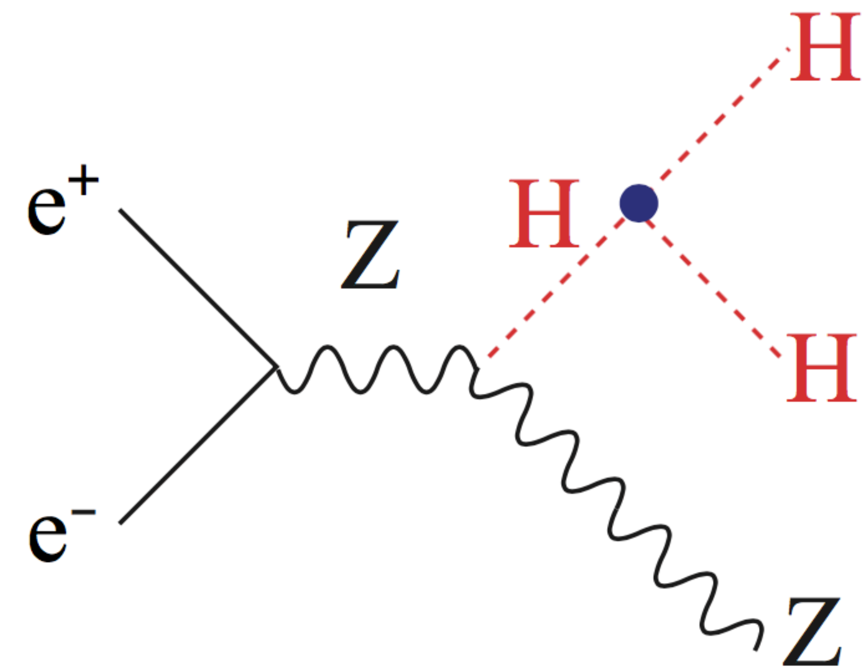
Focusing on e+e- > Zhh



EFT as a model-independent framework

- The deviation of the Higgs potential (triple Higgs coupling, in particular) is associated with

$$\Delta\mathcal{L} = -\frac{c_6\lambda}{v^2}|\Phi^\dagger\Phi|^3$$



10 relevant d=6 operators

(1) at least one Higgs or EW gauge,
(2) only Higgs, EW gauge and electrons

$$\begin{aligned}\Delta\mathcal{L} = &\frac{c_H}{2v^2}\partial^\mu(\Phi^\dagger\Phi)\partial_\mu(\Phi^\dagger\Phi) + \frac{c_T}{2v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)(\Phi^\dagger \overleftrightarrow{D}_\mu \Phi) - \frac{c_6\lambda}{v^2}(\Phi^\dagger\Phi)^3 \\ &+\frac{g^2 c_{WW}}{m_W^2}\Phi^\dagger\Phi W^a_{\mu\nu}W^{a\mu\nu} + \frac{4gg' c_{WB}}{m_W^2}\Phi^\dagger t^a\Phi W^a_{\mu\nu}B^{\mu\nu} \\ &+\frac{g'^2 c_{BB}}{m_W^2}\Phi^\dagger\Phi B_{\mu\nu}B^{\mu\nu} + \frac{g^3 c_{3W}}{m_W^2}\epsilon_{abc}W^a_{\mu\nu}W^{b\nu}{}_\rho W^{c\rho\mu} \\ &+i\frac{c_{HL}}{v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)(\overline{L}\gamma_\mu L) + +4i\frac{c'_{HL}}{v^2}(\Phi^\dagger t^a \overleftrightarrow{D}^\mu\Phi)(\overline{L}\gamma_\mu t^a L) \\ &+i\frac{c_{HE}}{v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)(\overline{e}\gamma_\mu e)\ .\end{aligned}$$

All 10 ops contribute to Zhh!

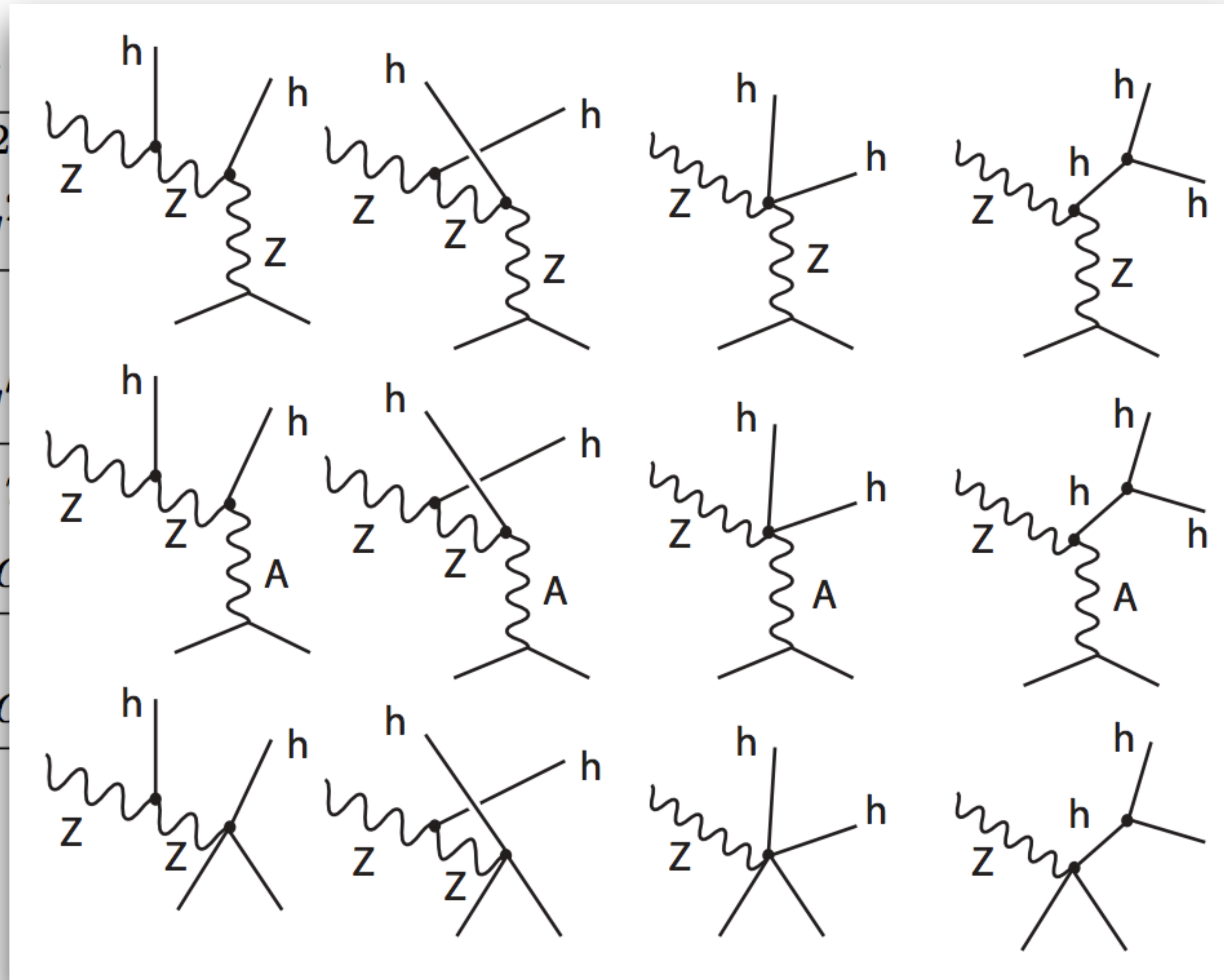
$$\Delta\mathcal{L} = \frac{c_H}{2v^2} \cdots \frac{c_6\lambda}{v^2}(\Phi^\dagger\Phi)^3$$

$$+\frac{g}{\cdots}$$

$$+\frac{g'}{\cdots}$$

$$+i\frac{c}{\cdots} \cdots \bar{L}\gamma_\mu t^a L)$$

$$+i\frac{c}{\cdots}$$



(2) only Higgs, EW gauge and electrons

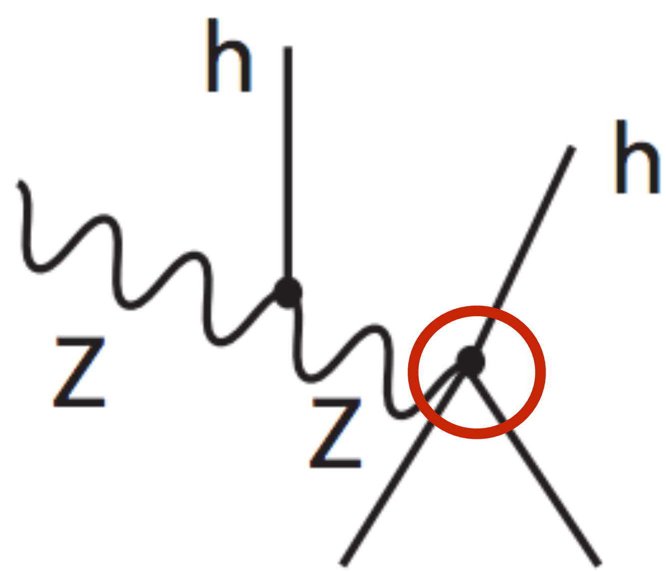
Finally, e+e- > Zhh

$$\frac{\sigma(e^+e^- \to Zhh)}{SM} = 1 + \boxed{0.056 c_6} - 4.15 c_H + 15.1 (8 c_{WW}) + \cdots$$
$$+62.1 (c_{HL} + c'_{HL}) - 53.5 c_{HE}$$

Surprisingly,
there are several noisy contributions with large coefficients!

Why so large?
Will those ops be well constrained by then?

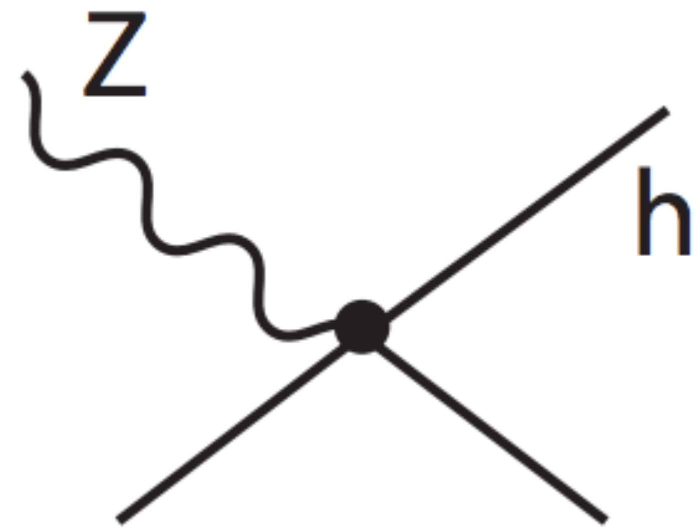
Challenge: s/mZ^2 enhancement of contact ops



Contact-interaction contributions are enhanced by
s/mz^2 (~ 50 at 500 GeV).

To measure c6 at 1% level, these ops shall be measured at 1/50%~0.01% level.

Challenge: s/mZ^2 enhancement of contact ops



Similarly, e+e- > Zh is plagued by the same kind of enhancements.

LEP precision leads to a poor constraint on the Higgs field strength ~1%, not 0.01% needed for Higgs potential measurement.

Finally, e+e- > Zhh

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After all, only c6 ~ 28% is possible (mostly stat only)
(e.g. ILC 500 2/ab).

Finally, e+e- > Zhh

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After all, only c6 ~ 28% is possible (mostly stat only)
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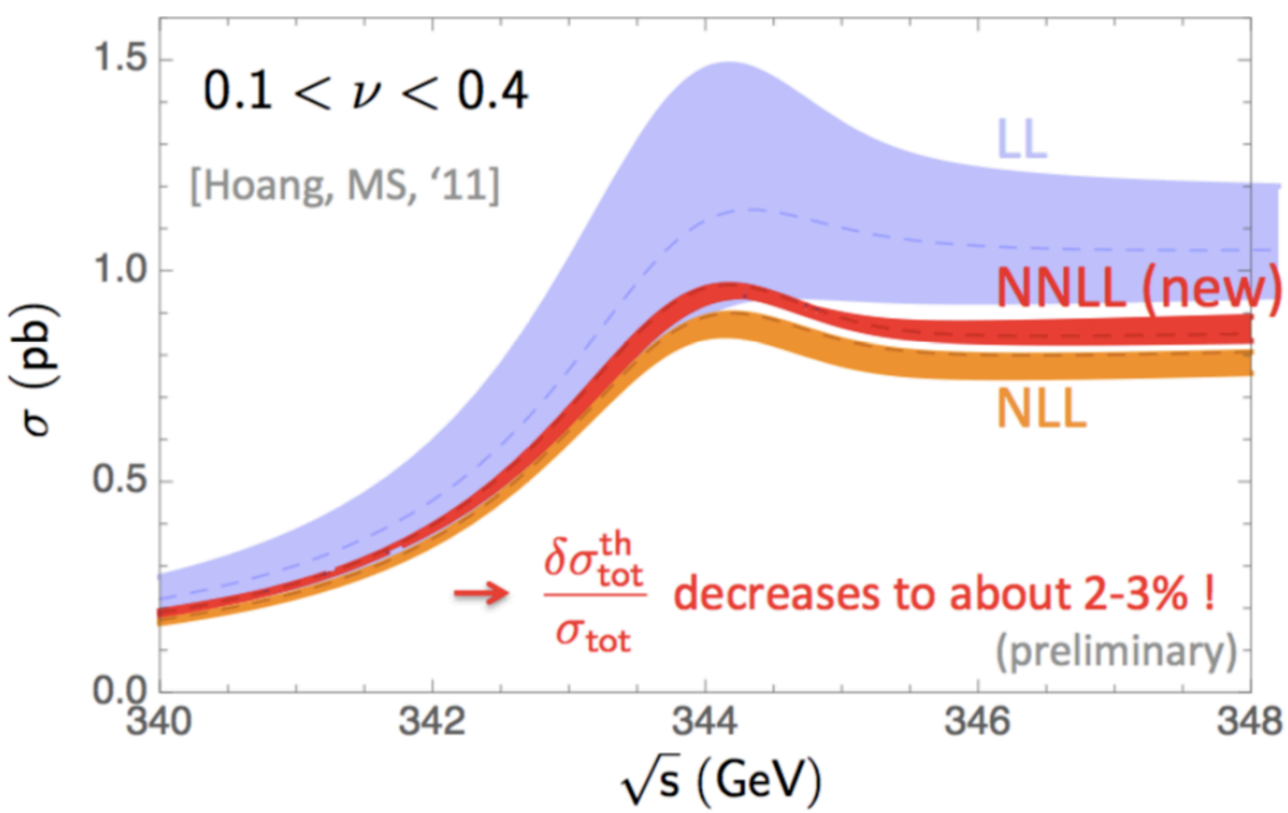
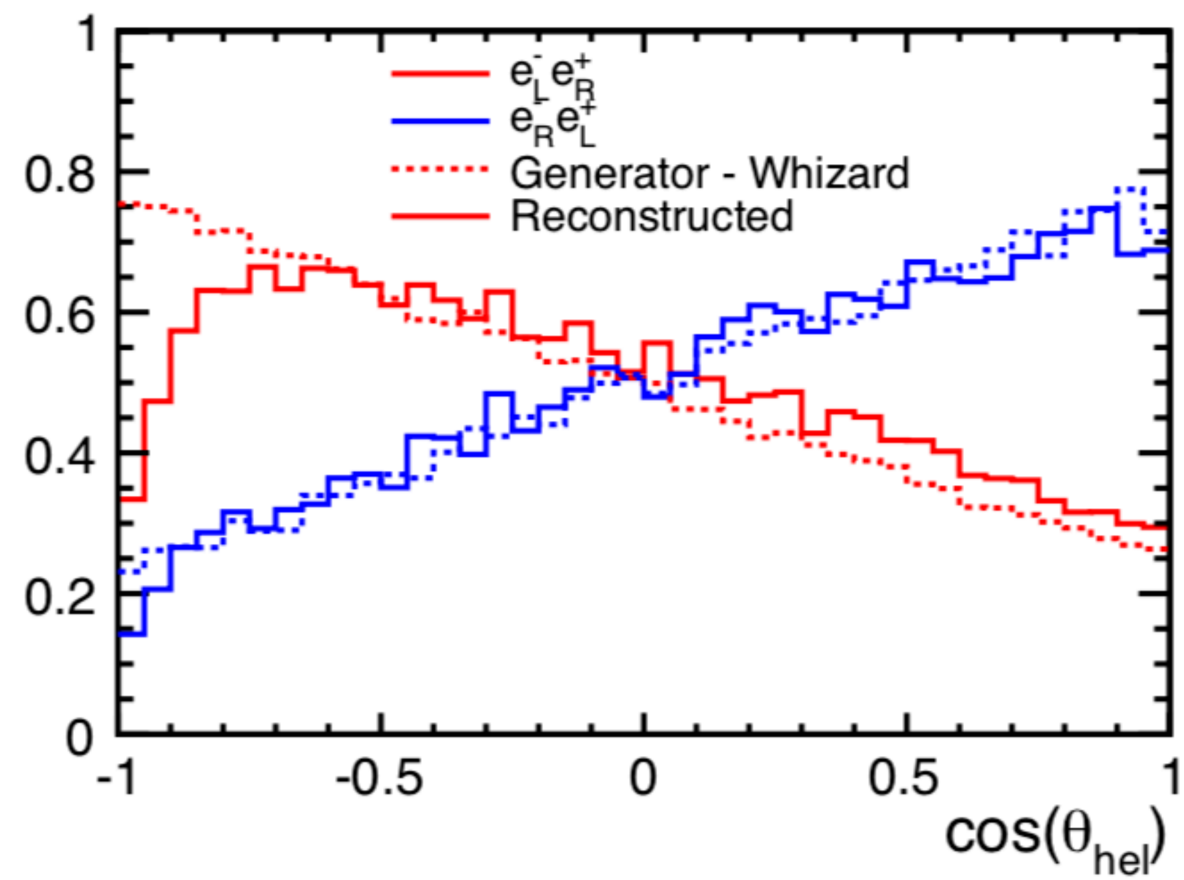
Only after improving EWPT & contact ops with ILC 250+500,
c6 ~ 5% (stat) is *model-independently* possible.

How we usually think about top measurements

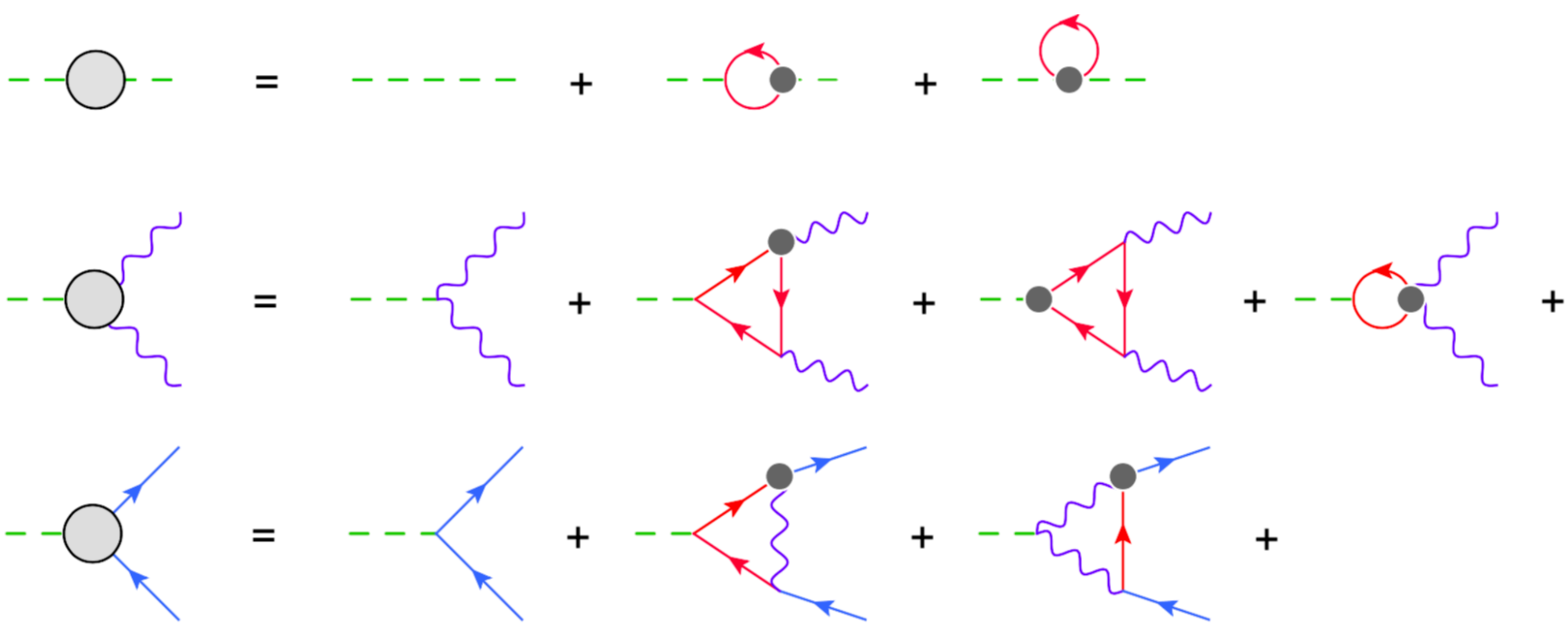




Top-loop effects in Higgs+EWPT @ 250 GeV

There are new physics info contained in the top sector that can be measured without tops, i.e., @ 250 GeV e+e-.

with non-SM top interactions



RG operator mixings

Equivalently, Top ops can mix with Higgs + EWPT ops.

$$\mathcal{O}_{tH} = (\Phi^\dagger \Phi)(\bar{Q} t \tilde{\Phi})$$

$$\mathcal{O}_{HQ(1)} = (\Phi^\dagger i \overleftrightarrow{D}_\mu \Phi)(\bar{Q}\gamma^\mu Q)$$

$$\mathcal{O}_{HQ(3)} = (\Phi^\dagger i \overleftrightarrow{D}^a_\mu \Phi)(\bar{Q}\gamma^\mu \tau^a Q)$$

$$\mathcal{O}_{Ht} = (\Phi^\dagger i \overleftrightarrow{D}_\mu \Phi)(\bar{t}\gamma^\mu t)$$

$$\mathcal{O}_{Htb} = i(\tilde{\Phi}^\dagger D_\mu \Phi)(\bar{t}\gamma^\mu b)$$

$$\mathcal{O}_{tW} = (\bar{Q}\sigma^{\mu\nu} t)\tau^a \tilde{\Phi} W^a_{\mu\nu}$$

$$\mathcal{O}_{tB} = (\bar{Q}\sigma^{\mu\nu} t)\tilde{\Phi} B_{\mu\nu}$$

Example RGE

$$\dot{c}_H = (12 y_t^2 N_c - 4 g^2 N_c) c^{(3)}_{Hq} - 12 y_t y_b N_c c_{Htb}$$

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$$\mathcal{O}_{HQ(3)} = (\Phi^\dagger i \overleftrightarrow{D}^a_\mu \Phi)(\bar{Q}\gamma^\mu \tau^a Q) \qquad \mathcal{O}_{Ht} = (\Phi^\dagger i \overleftrightarrow{D}_\mu \Phi)(\bar{t}\gamma^\mu t)$$

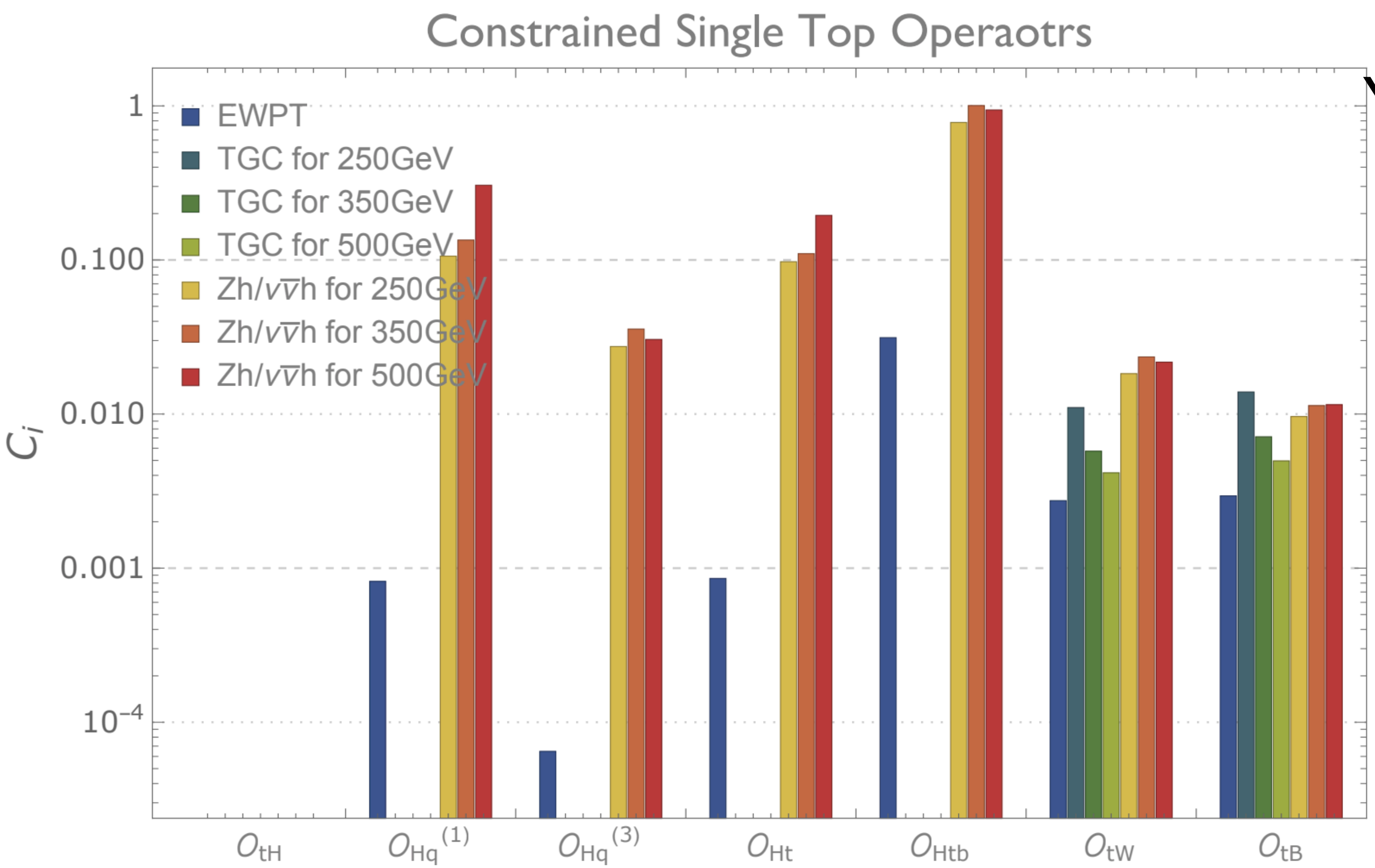
$\mathcal{O}$

$\mathcal{O}_t$

But aren't these loop effects subdominant?

$$\dot{c}_H = (12 y_t^2 N_c - 4 g^2 N_c) c_{Hq}^{(3)} - 12 y_t y_b N_c c_{Htb}$$

Constraints on top ops from Higgs+EWPT

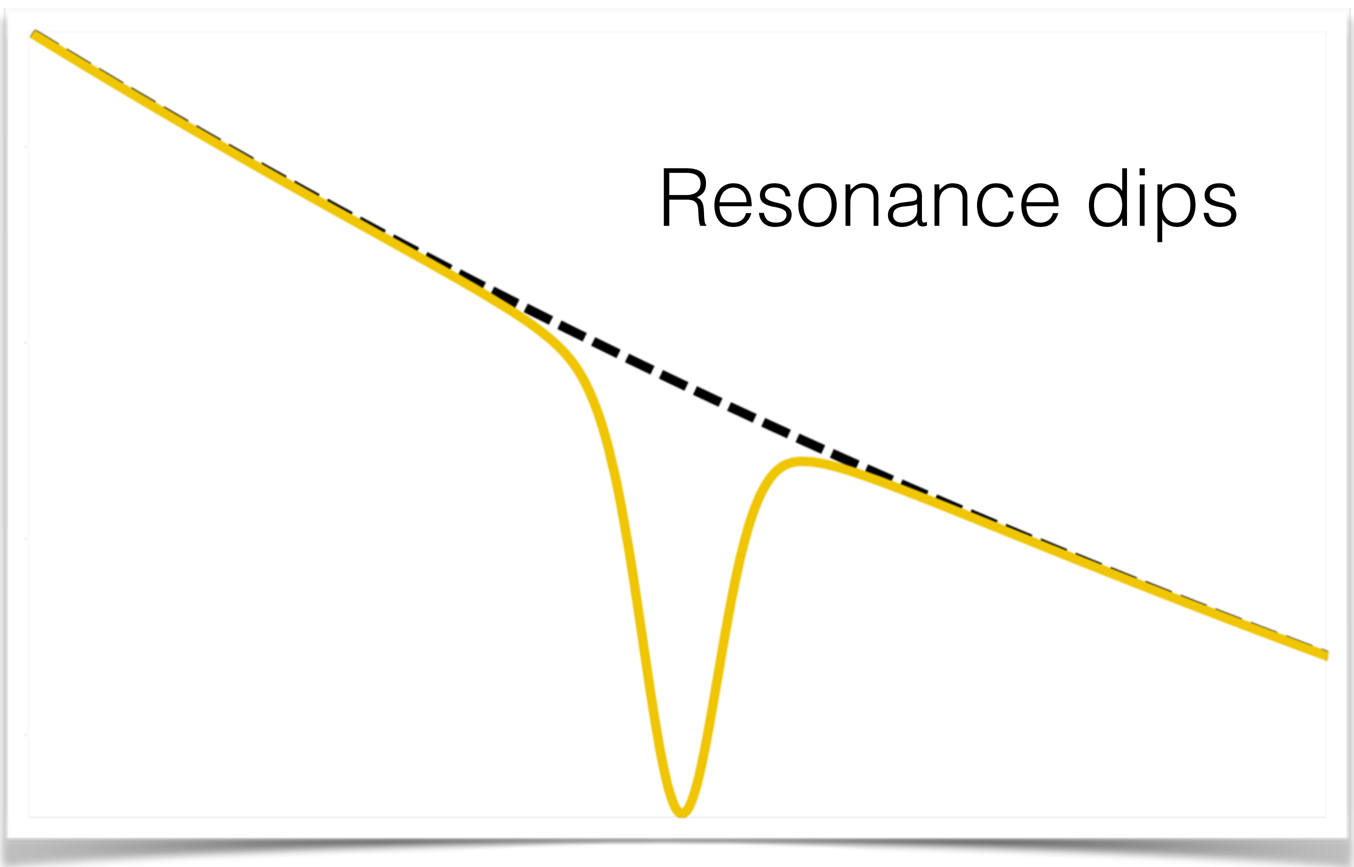


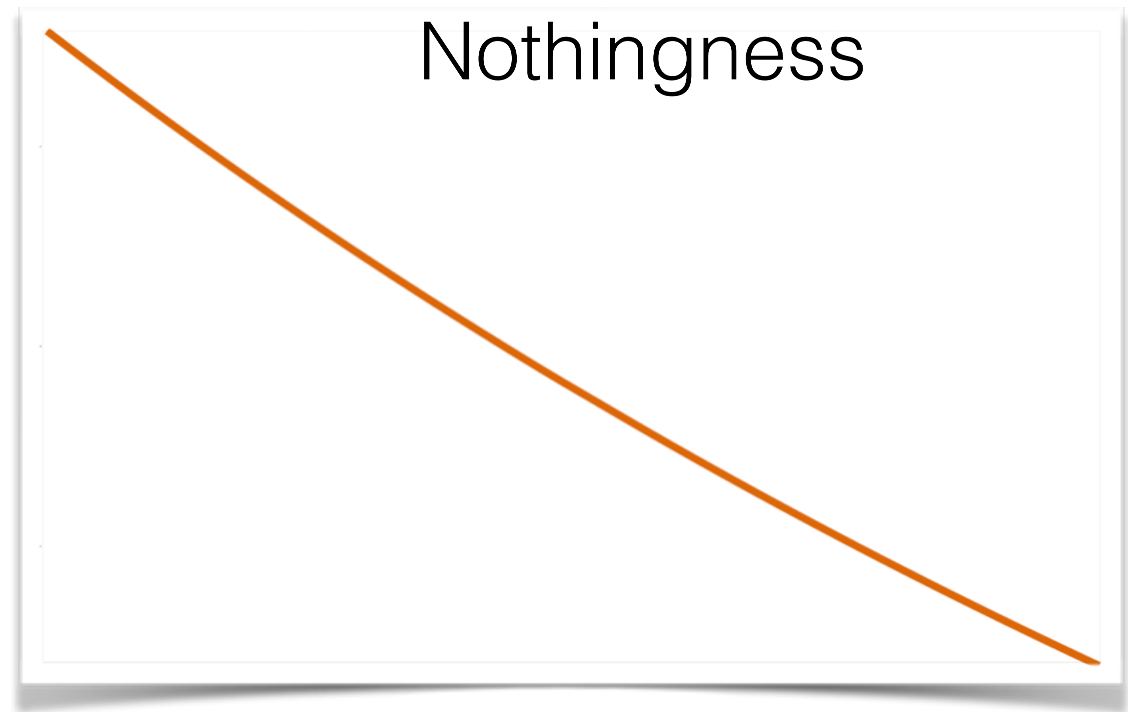
Yes, but still indeed, meaningful constraints.

This also implies that top ops cannot be ignored in Higgs precision.

Preliminary with Junghwan Lee, J. Tian, M. Vos

Higgs has more surprises: dip or nothingness





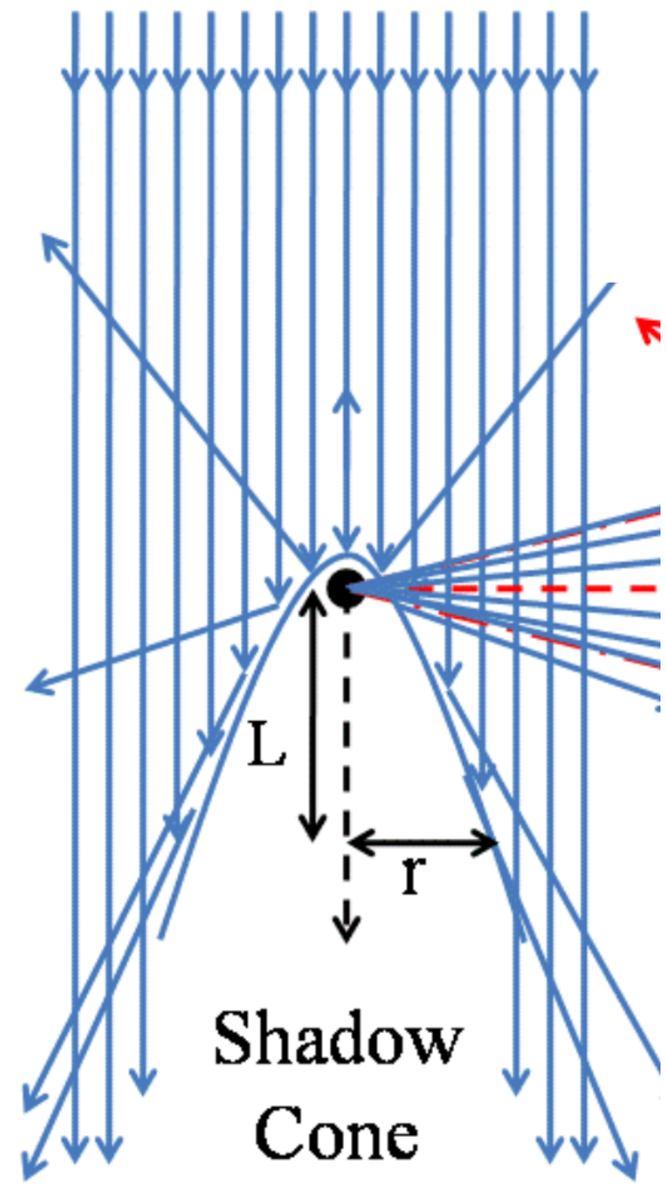
Higgs “particle” is not always a resonance “peak”, in a large part of SUSY parameter space.

with J.Song, Y.W.Yoon 1505.00291, 1510.03450, 1601.00006

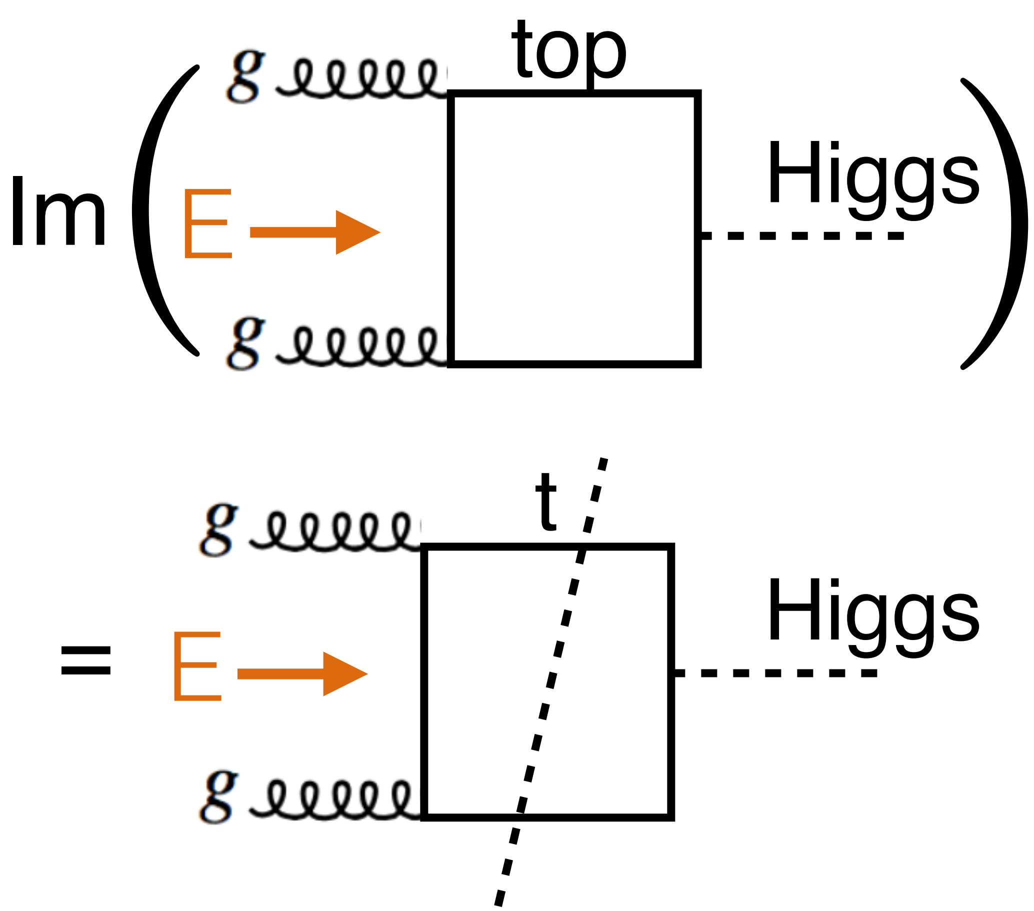
Shadow scattering from complex interference

Attenuation of forward-going wave (shadow)
= Imaginary part of forward-scatt. amplitude
= Total scattering cross-section

Optical theorem



Complex phase from Cutkosky cut



$$E = m_{\rm Higgs} > 2m_{\rm top}$$

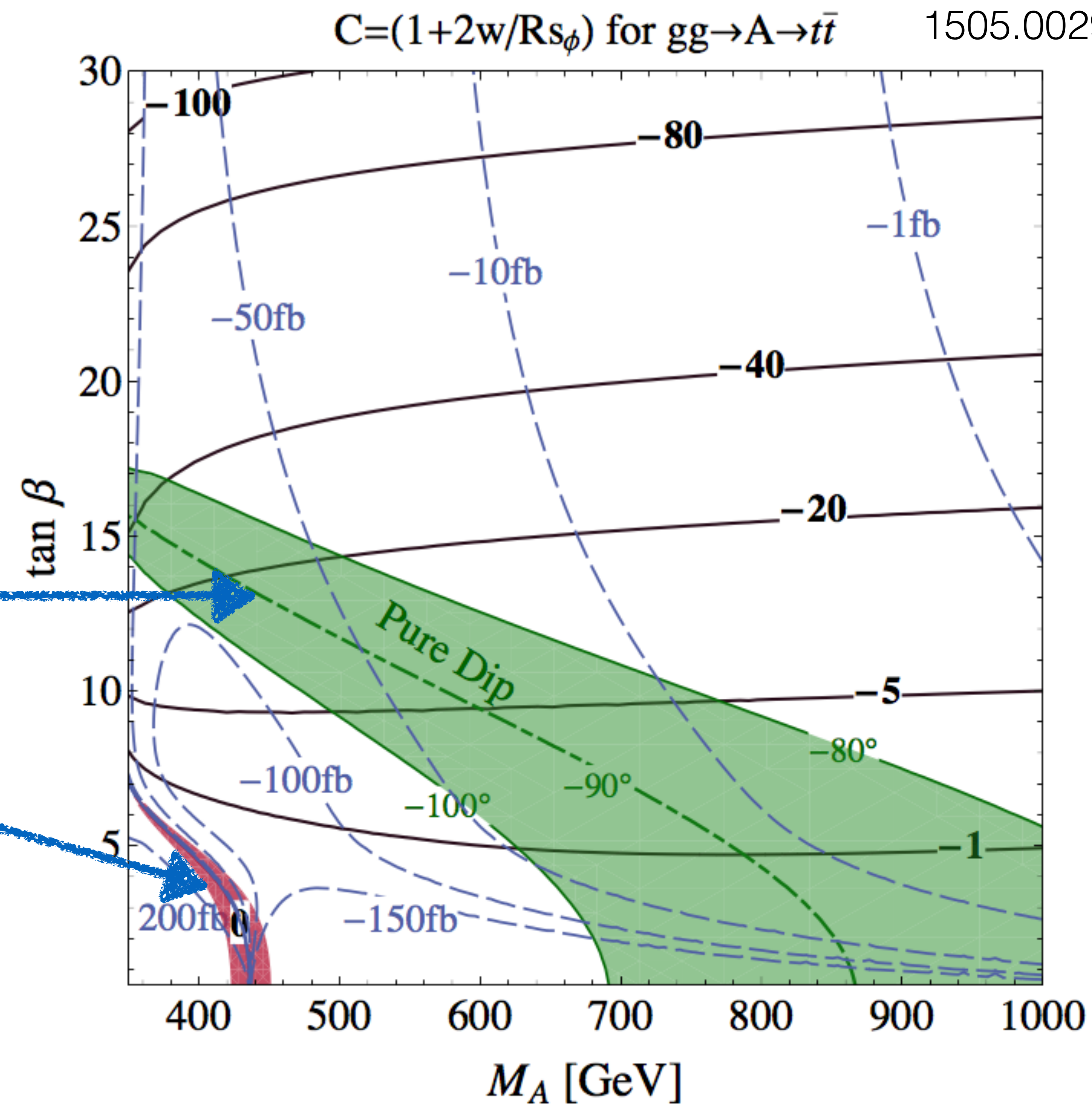
Shadow interference is proportional to the width

$$\frac{d\hat{\sigma}}{dz} = \frac{1}{32\pi\hat{s}} \sum \left| A_{\rm bg} e^{i\phi_{\rm bg}} + \frac{M^2}{\hat{s} - M^2 + iM\Gamma} \cdot A_{\rm res} e^{i\phi_{\rm res}} \right|^2$$

ttbar resonance shapes in the MSSM

with J.Song and Y.W.Yoon 1505.00291,

- No pure peak anywhere!
- Pure dip and nothingness regions.



Dips,, why now?

SM light particles do not easily satisfy shadow scattering conditions:

(1) no lighter loops giving complex phases
(2) width is small

But now, heavier new physics resonances can do easily:

(1) many sources of complex phase from light SM loops
(2) generically broad, proportional to the mass

Broad resonance discovery

Broad resonances will be everywhere soon.

Without beautiful and powerful resonance peaks,
how can we discover a broad resonance?

Maybe no clear and easy separation from human eyes.

Maybe a good example to apply machine learning.

Broad resonance ML

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We found so far that a machine has learned:
- pT
- boosted tagging !

preliminary with Ke-Pan Xie

Thank you

First of all, c6 is our main parameter for triple Higgs coupling

$$\begin{aligned}\Delta\mathcal{L} = &\frac{c_H}{2v^2}\partial^\mu(\Phi^\dagger\Phi)\partial_\mu(\Phi^\dagger\Phi) + \frac{c_T}{2v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu \Phi)(\Phi^\dagger \overleftrightarrow{D}_\mu \Phi) - \boxed{\frac{c_6\lambda}{v^2}(\Phi^\dagger\Phi)^3} \\ &+\frac{g^2 c_{WW}}{m_W^2}\Phi^\dagger\Phi W^a_{\mu\nu}W^{a\mu\nu} + \frac{4gg' c_{WB}}{m_W^2}\Phi^\dagger t^a \Phi W^a_{\mu\nu}B^{\mu\nu} \\ &+\frac{g'^2 c_{BB}}{m_W^2}\Phi^\dagger\Phi B_{\mu\nu}B^{\mu\nu} + \frac{g^3 c_{3W}}{m_W^2}\epsilon_{abc}W^a_{\mu\nu}W^{b\nu}{}_\rho W^{c\rho\mu} \\ &+i\frac{c_{HL}}{v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu \Phi)(\overline{L}\gamma_\mu L) + +4i\frac{c'_{HL}}{v^2}(\Phi^\dagger t^a \overleftrightarrow{D}^\mu \Phi)(\overline{L}\gamma_\mu t^a L) \\ &+i\frac{c_{HE}}{v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu \Phi)(\overline{e}\gamma_\mu e)\ .\end{aligned}$$

EWPT (LEP) + mh

	measured	σ	PDG SM fit
$\alpha^{-1}(m_Z)$	128.9220	(78)	same
G_F	1.1663787	(6)	same
m_Z	91.1876	(21)	91.1880
m_W	80.385	(15)	80.361
m_h	125.09	(24)	same
A_ℓ	0.1470	(13)	0.1480
$\Gamma(Z \to \ell^+\ell^-)$	83.385	(15)	83.995

Using these inputs, we can obtain a covariance matrix for 7 of our coefficients

$$\frac{\delta g}{g}\ ,\ \frac{\delta g'}{g'}\ ,\ \frac{\delta v}{v}\ ,\ \frac{\delta \lambda}{\lambda}\ ,\ c_T\ ,\ c_{HL}\ ,\ c_{HE}$$

with errors on single parameters at the 10^{-3} level.

e+e- > WW (TGC)

$$\Delta\mathcal{L}_{TGC} = ig_V\Big\{g_{1V}V^\mu(\hat{W}^-_{\mu\nu}W^{+\nu} - \hat{W}^+_{\mu\nu}W^{-\nu}) + \kappa_V W^+_\mu W^-_\nu \hat{V}^{\mu\nu} + \frac{\lambda_V}{m_W^2}\hat{W}^{-\rho}_\mu \hat{W}^+_{\rho\nu}\hat{V}^{\mu\nu}\Big\},$$

e+e- > WW physics is described by 3 independent coeffs, constraining 3 additional HEFT ops (cWB,cHL',c3W).

$$g_{1Z} = 1 + \frac{1}{c_0^2 - s_0^2}\left(-8\frac{s_0^2}{c_0^2}c_{WB} + \frac{1}{2}c_T - c'_{HL}\right),$$

$$\kappa_Z = g_{1Z} - 8\frac{s_0^2}{c_0^2}c_{WB}, \qquad \kappa_A = g_{1A}$$

$$\lambda_Z = xc_{3W}, \qquad \lambda_A = xc_{3W}$$

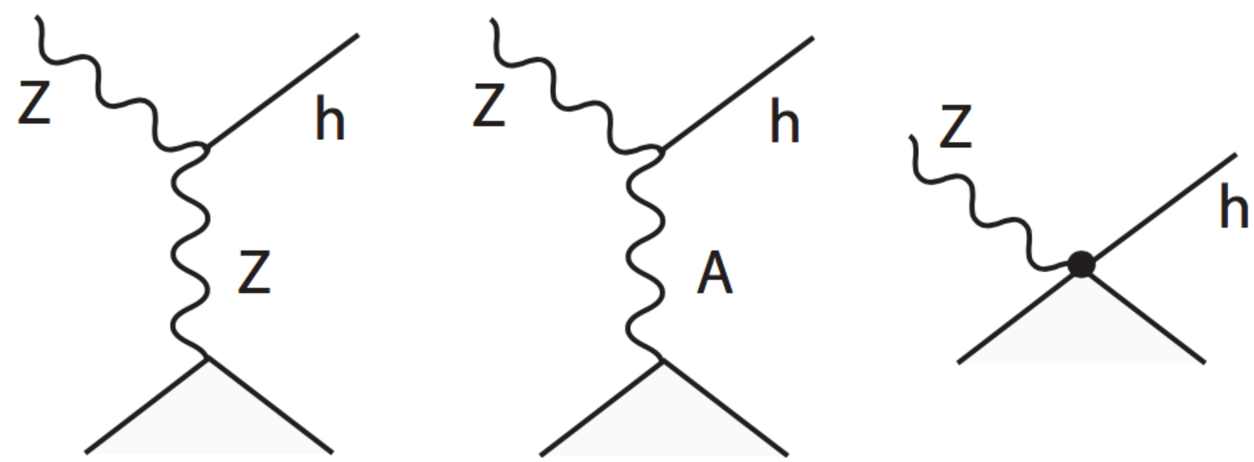
$$\begin{pmatrix} 7.7 & 5.6 & 3.0 \\ 5.6 & 7.6 & 2.8 \\ 3.0 & 2.8 & 15.6 \end{pmatrix} \times 10^{-4}$$

2/ab 250 GeV
Marchesini 2011

Single Higgs (LHC & Zh)

$$\Gamma(h \to \gamma\gamma) = \Gamma(h \to \gamma\gamma)_0 (1 + 528 s_w^2 (8c_{WW} - 2(8c_{WB}) + 8c_{BB}) + \cdots)$$

$$\Gamma(h \to \gamma Z) = \Gamma(h \to \gamma Z)_0 (1 + 290 s_w c_w (8c_{WW} - (1 - t_w^2)(8c_{WB}) - t_w^2 8c_{BB}) + \cdots)$$



$$\mathcal{L} \ni \frac{m_Z^2}{v_0^2} \eta_Z h Z_\mu Z^\mu, \; \frac{\zeta_Z}{2} \frac{h}{v_0} Z_{\mu\nu} Z^{\mu\nu}, \; g_{eZh} (\bar{e}\gamma_\mu e) Z^\mu \frac{h}{v_0}$$

Three additional coefficients can be constrained to O(0.1%)

except for cH ~ O(1) % (see later)