Measuring Higgs boson properties effectively at the LHC

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Due to absence of signs of new physics

HEP has 'Big Mac' blues,

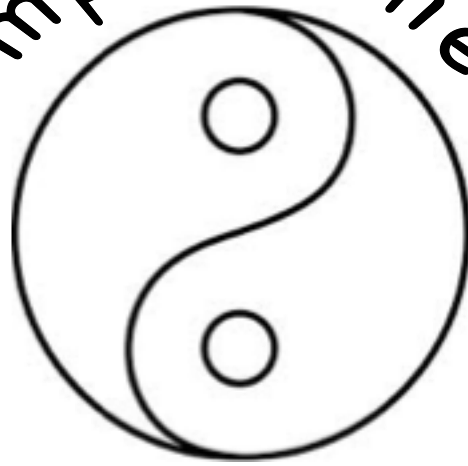
i.e. why nature not like (as natural as) advertised?

Commercial Reality

Sure, Higgs boson does the job, but...

The Higgs boson, a window to new physics

Compositeness



Effective Theory

$\mathcal{L}_{\text{eff}} = \sum C_i \mathcal{O}_i$

Symmetry

SUSY, CW, ...

Naturalness

fermionic top partners

simplified models

scalar top partners

simplified models

Leptons width Measurements Jets

mass MET boost Photons interference

Improved/Unified way of interpretation of measurements

- interpretation of any measurement model dependent
- interpretation requires communication between different scales as well as theorists and experimentalists

Connecting measurements with UV physics

Kappa Framework

- NP models simple rescaling of couplings $\sigma(g_p) \times \mathrm{BR}(g_d)$
- No new Lorentz -structures or kinematics

EFT

- SM degrees of freedom and symmetries
- New kinematics/ Lorentz structures

Simplified Models

- New low-energy degrees of freedom
- Subset of states of full models, reflective at scale of measurement

Full (UV) Model

- Very complex and often high-dimensional parameter space
- Allows to correlate high-scale and low-scale physics

Complexity/Flexibility

EFT fit is next step to tension theory with data

Agnostic operator basis highly complex:

2499 non-redundant parameters at dim-6

Flavor diagonal still complex:

59 operators

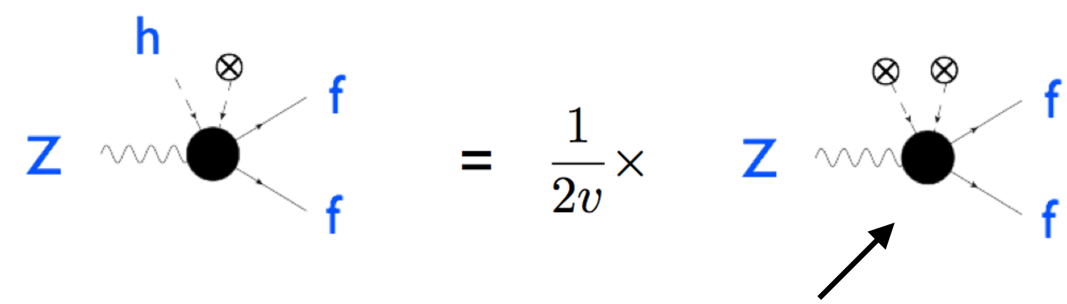
$$\mathcal{O}_H = \tfrac{1}{2}(\partial^\mu |H|^2)^2$$
$$\mathcal{O}_T = \tfrac{1}{2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$$
$$\mathcal{O}_6 = \lambda |H|^6$$

$$\mathcal{O}_W = \tfrac{ig}{2}\left(H^\dagger \sigma^a \overleftrightarrow{D}^\mu H\right) D^\nu W^a_{\mu\nu}$$
$$\mathcal{O}_B = \tfrac{ig'}{2}\left(H^\dagger \overleftrightarrow{D}^\mu H\right) \partial^\nu B_{\mu\nu}$$
$$\mathcal{O}_{2W} = -\tfrac{1}{2}(D^\mu W^a_{\mu\nu})^2$$
$$\mathcal{O}_{2B} = -\tfrac{1}{2}(\partial^\mu B_{\mu\nu})^2$$
$$\mathcal{O}_{2G} = -\tfrac{1}{2}(D^\mu G^A_{\mu\nu})^2$$

$$\mathcal{O}_{BB} = g'^2 |H|^2 B_{\mu\nu}B^{\mu\nu}$$
$$\mathcal{O}_{GG} = g_s^2 |H|^2 G^A_{\mu\nu}G^{A\mu\nu}$$
$$\mathcal{O}_{HW} = ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$$
$$\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$$
$$\mathcal{O}_{3W} = \tfrac{1}{3!} g \epsilon_{abc} W^{a\,\nu}_\mu W^b_{\nu\rho} W^{c\,\rho\mu}$$
$$\mathcal{O}_{3G} = \tfrac{1}{3!} g_s f_{ABC} G^{A\,\nu}_\mu G^B_{\nu\rho} G^{C\,\rho\mu}$$

$\mathcal{O}_{y_u} = y_u \lvert H\rvert^2 \bar{Q}_L \widetilde{H} u_R$	$\mathcal{O}_{y_d} = y_d \lvert H\rvert^2 \bar{Q}_L H d_R$	$\mathcal{O}_{y_e} = y_e \lvert H\rvert^2 \bar{L}_L H e_R$
$\mathcal{O}^u_R = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{u}_R\gamma^\mu u_R)$	$\mathcal{O}^d_R = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{d}_R\gamma^\mu d_R)$	$\mathcal{O}^e_R = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{e}_R\gamma^\mu e_R)$
$\mathcal{O}^q_L = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{Q}_L\gamma^\mu Q_L)$		$\mathcal{O}^l_L = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{L}_L\gamma^\mu L_L)$
$\mathcal{O}^{(3)\,q}_L = (iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H)(\bar{Q}_L\gamma^\mu \sigma^a Q_L)$		$\mathcal{O}^{(3)\,l}_L = (iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H)(\bar{L}_L\gamma^\mu \sigma^a L_L)$
$\mathcal{O}^u_{LR} = (\bar{Q}_L\gamma^\mu Q_L)(\bar{u}_R\gamma^\mu u_R)$	$\mathcal{O}^d_{LR} = (\bar{Q}_L\gamma^\mu Q_L)(\bar{d}_R\gamma^\mu d_R)$	$\mathcal{O}^e_{LR} = (\bar{L}_L\gamma^\mu L_L)(\bar{e}_R\gamma^\mu e_R)$
$\mathcal{O}^{(8)\,u}_{LR} = (\bar{Q}_L\gamma^\mu T^A Q_L)(\bar{u}_R\gamma^\mu T^A u_R)$	$\mathcal{O}^{(8)\,d}_{LR} = (\bar{Q}_L\gamma^\mu T^A Q_L)(\bar{d}_R\gamma^\mu T^A d_R)$	
$\mathcal{O}^u_{RR} = (\bar{u}_R\gamma^\mu u_R)(\bar{u}_R\gamma^\mu u_R)$	$\mathcal{O}^d_{RR} = (\bar{d}_R\gamma^\mu d_R)(\bar{d}_R\gamma^\mu d_R)$	$\mathcal{O}^e_{RR} = (\bar{e}_R\gamma^\mu e_R)(\bar{e}_R\gamma^\mu e_R)$
$\mathcal{O}^q_{LL} = (\bar{Q}_L\gamma^\mu Q_L)(\bar{Q}_L\gamma^\mu Q_L)$		$\mathcal{O}^l_{LL} = (\bar{L}_L\gamma^\mu L_L)(\bar{L}_L\gamma^\mu L_L)$
$\mathcal{O}^{(8)\,q}_{LL} = (\bar{Q}_L\gamma^\mu T^A Q_L)(\bar{Q}_L\gamma^\mu T^A Q_L)$		
$\mathcal{O}^{ql}_{LL} = (\bar{Q}_L\gamma^\mu Q_L)(\bar{L}_L\gamma^\mu L_L)$		
$\mathcal{O}^{(3)\,ql}_{LL} = (\bar{Q}_L\gamma^\mu \sigma^a Q_L)(\bar{L}_L\gamma^\mu \sigma^a L_L)$		
$\mathcal{O}^{qe}_{LR} = (\bar{Q}_L\gamma^\mu Q_L)(\bar{e}_R\gamma^\mu e_R)$		
$\mathcal{O}^{lu}_{LR} = (\bar{L}_L\gamma^\mu L_L)(\bar{u}_R\gamma^\mu u_R)$	$\mathcal{O}^{ld}_{LR} = (\bar{L}_L\gamma^\mu L_L)(\bar{d}_R\gamma^\mu d_R)$	
$\mathcal{O}^{ud}_{RR} = (\bar{u}_R\gamma^\mu u_R)(\bar{d}_R\gamma^\mu d_R)$		
$\mathcal{O}^{(8)\,ud}_{RR} = (\bar{u}_R\gamma^\mu T^A u_R)(\bar{d}_R\gamma^\mu T^A d_R)$		
$\mathcal{O}^{ue}_{RR} = (\bar{u}_R\gamma^\mu u_R)(\bar{e}_R\gamma^\mu e_R)$	$\mathcal{O}^{de}_{RR} = (\bar{d}_R\gamma^\mu d_R)(\bar{e}_R\gamma^\mu e_R)$	
$\mathcal{O}^{ud}_R = y_u^\dagger y_d (i\widetilde{H}^\dagger \overleftrightarrow{D}_\mu H)(\bar{u}_R\gamma^\mu d_R)$		
$\mathcal{O}_{y_u y_d} = y_u y_d (\bar{Q}^r_L u_R)\epsilon_{rs}(\bar{Q}^s_L d_R)$		
$\mathcal{O}^{(8)}_{y_u y_d} = y_u y_d (\bar{Q}^r_L T^A u_R)\epsilon_{rs}(\bar{Q}^s_L T^A d_R)$		
$\mathcal{O}_{y_u y_e} = y_u y_e (\bar{Q}^r_L u_R)\epsilon_{rs}(\bar{L}^s_L e_R)$		
$\mathcal{O}'_{y_u y_e} = y_u y_e (\bar{Q}^{r\,\alpha}_L e_R)\epsilon_{rs}(\bar{L}^s_L u^\alpha_R)$		
$\mathcal{O}_{y_e y_d} = y_e y_d^\dagger (\bar{L}_L e_R)(\bar{d}_R Q_L)$		
$\mathcal{O}^u_{DB} = y_u \bar{Q}_L \sigma^{\mu\nu} u_R \widetilde{H} g' B_{\mu\nu}$	$\mathcal{O}^d_{DB} = y_d \bar{Q}_L \sigma^{\mu\nu} d_R H g' B_{\mu\nu}$	$\mathcal{O}^e_{DB} = y_e \bar{L}_L \sigma^{\mu\nu} e_R H g' B_{\mu\nu}$
$\mathcal{O}^u_{DW} = y_u \bar{Q}_L \sigma^{\mu\nu} u_R \sigma^a \widetilde{H} g W^a_{\mu\nu}$	$\mathcal{O}^d_{DW} = y_d \bar{Q}_L \sigma^{\mu\nu} d_R \sigma^a H g W^a_{\mu\nu}$	$\mathcal{O}^e_{DW} = y_e \bar{L}_L \sigma^{\mu\nu} e_R \sigma^a H g W^a_{\mu\nu}$
$\mathcal{O}^u_{DG} = y_u \bar{Q}_L \sigma^{\mu\nu} T^A u_R \widetilde{H} g_s G^A_{\mu\nu}$	$\mathcal{O}^d_{DG} = y_d \bar{Q}_L \sigma^{\mu\nu} T^A d_R H g_s G^A_{\mu\nu}$	

- Focus on operators with Higgs involvement (new kid on the block)



constrained by LEP at permille level

- Focus on operators that are probed predominantly at LHC

Choose SILH basis:

$$\begin{aligned}
\mathcal{L}_{\rm SILH} =\; & \frac{\bar{c}_H}{2v^2}\partial^\mu\left(H^\dagger H\right)\partial_\mu\left(H^\dagger H\right) + \frac{\bar{c}_T}{2v^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) - \frac{\bar{c}_6\lambda}{v^2}\left(H^\dagger H\right)^3 \\
& + \left(\frac{\bar{c}_{u,i}y_{u,i}}{v^2} H^\dagger H \bar{u}^{(i)}_L H^c u^{(i)}_R + \text{h.c.}\right) + \left(\frac{\bar{c}_{d,i}y_{d,i}}{v^2} H^\dagger H \bar{d}^{(i)}_L H d^{(i)}_R + \text{h.c.}\right) \\
& + \frac{i\bar{c}_W g}{2m_W^2}\left(H^\dagger \sigma^i \overleftrightarrow{D^\mu} H\right)\left(D^\nu W_{\mu\nu}\right)^i + \frac{i\bar{c}_B g'}{2m_W^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(\partial^\nu B_{\mu\nu}\right) \\
& + \frac{i\bar{c}_{HW} g}{m_W^2}(D^\mu H)^\dagger \sigma^i (D^\nu H) W^i_{\mu\nu} + \frac{i\bar{c}_{HB} g'}{m_W^2}(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu} \\
& + \frac{\bar{c}_\gamma g'^2}{m_W^2} H^\dagger H B_{\mu\nu}B^{\mu\nu} + \frac{\bar{c}_g g_S^2}{m_W^2} H^\dagger H G^a_{\mu\nu}G^{a\mu\nu}\,.
\end{aligned}$$

[Giudice, Grojean, Pomarol, Rattazzi '07]

here $c_T \sim T$ and

$c_B + c_W \sim S$

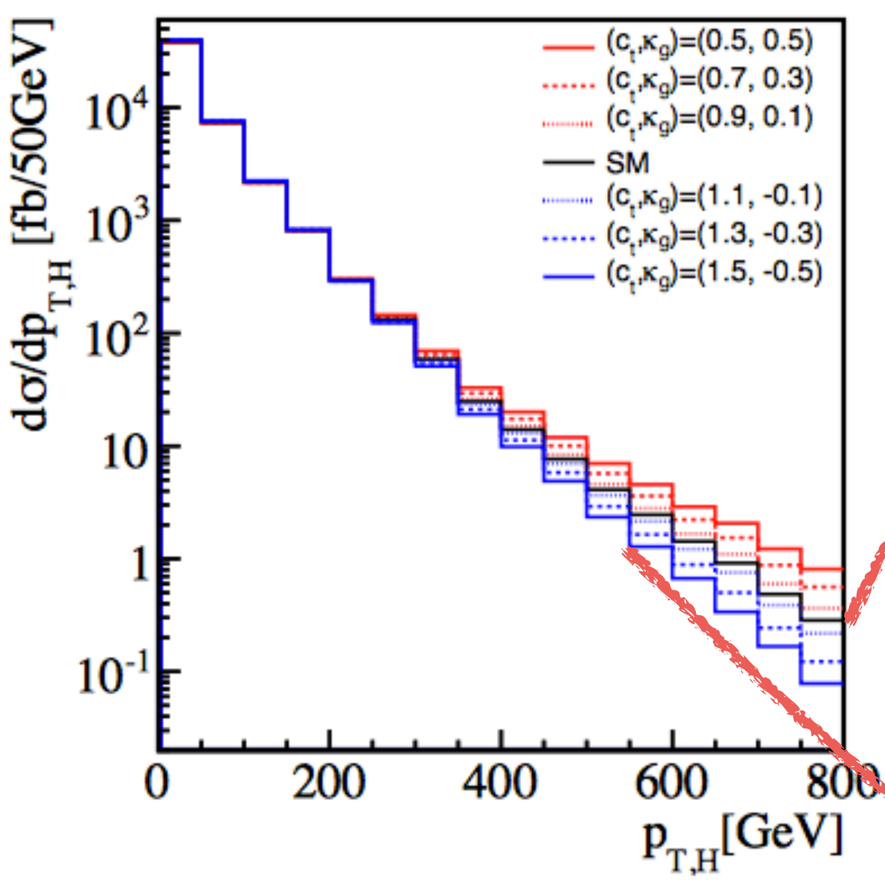
[Peskin, Takeuchi '91]

Validity and Relevance of EFT approach

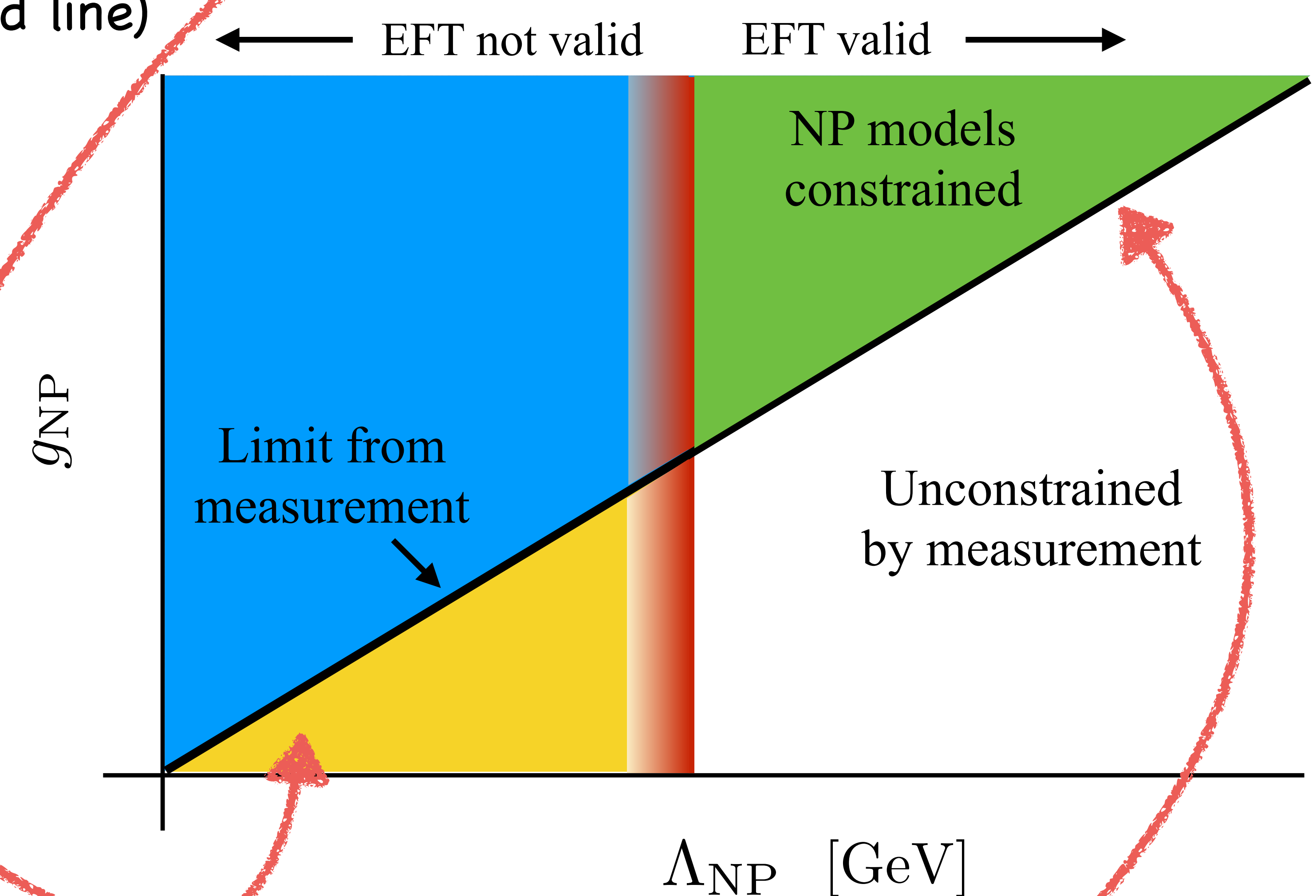
EFT used to set limits on UV models from non-observation of new physics

Lagrangian dim-6: $\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_i \frac{g_i^2}{\Lambda_{\rm NP}^2}\mathcal{O}_i$

Endpoint of kinematic distribution sets lower cut-off for NP (red line)



[Englert, MS '14]



shape sets limit on Wilson coefficient (black line)

Any UV (weakly coupled) models left?

Results for linearised LO EFT approach

[Englert, Kogler, Schulz, MS 1511.05170]

Focus on linear contribution of EFT for theory prediction:

$$\mathcal{M} = \mathcal{M}_{\rm SM} + \mathcal{M}_{d=6}$$

$$|\mathcal{M}|^2 = |\mathcal{M}_{\rm SM}|^2 + 2\,{\rm Re}\{\mathcal{M}_{\rm SM}\mathcal{M}^*_{d=6}\} + \mathcal{O}(1/\Lambda^4)$$

Number of predicted events:

$$N_{\rm th} = \sigma(H+X) \times {\rm BR}(H \to YY) \times \mathcal{L} \times {\rm BR}(X, Y \to \text{final state})$$

We assume that production and decay factorise to good approximation

Each channel has own prod. and decay efficiencies:

$$N_{\rm ev} = \epsilon_p \epsilon_d N_{\rm th}$$

Wilson coefficients can be (over) constraint in many decay and production processes:

Decays:	$H \to f\bar{f}$	$H \to \gamma\gamma$	$H \to \gamma Z$
	$H \to ZZ^*$	$H \to WW^*$	
Production:	$pp \to H$	$pp \to Hj$	$pp \to Hjj$
	$pp \to HV$	$pp \to ttH$	

→

signal strength:

36 indep. meas. (300 ifb)

46 indep. meas. (3000 ifb)

differential:

88 indep. meas. (300 ifb)

123 indep. meas. (3000 ifb)

To show benefit of differential distribution need observable

- Different observables can give different results for fit

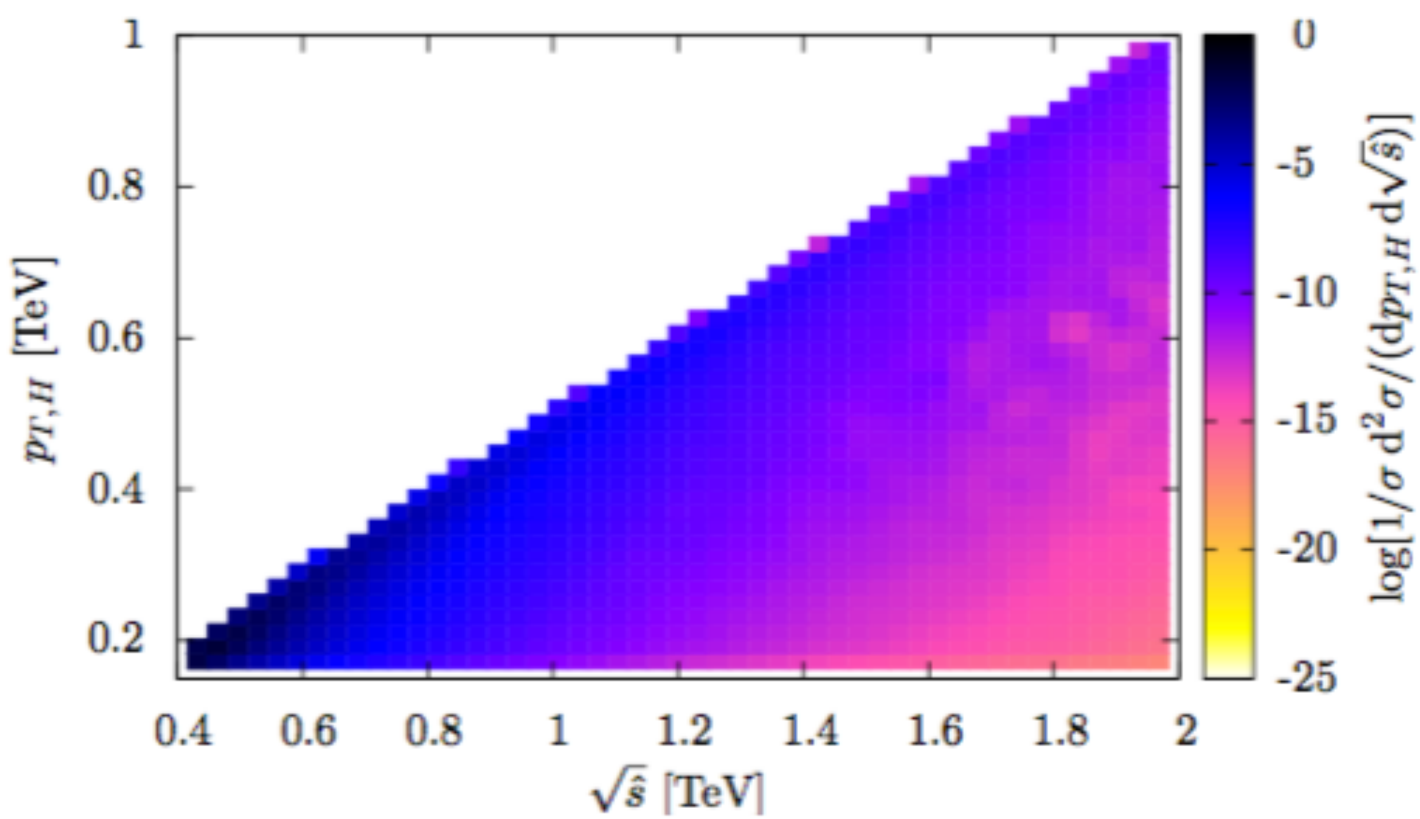
- 2->2 scattering leaves only 2 degrees of freedom,
  but 2->3 (tth, vbf) more complex

- However, exp. need to be able to provide unfolded distributions

  → most likely and practical **pT,H** unfolded

high correlation

$$\sqrt{\hat{s}} \sim m_H + p_{T,H}$$



Three sources of **uncertainties**

Theoretical uncertainties

(taken from exp. Run-1 papers)

Flat over pT,H range...

production process		decay process	
$pp \to H$	14.7	$H \to b\bar{b}$	6.1
$pp \to H + \mathrm{j}$	15	$H \to \gamma\gamma$	5.4
$pp \to H + 2\mathrm{j}$	15	$H \to \tau^+\tau^-$	2.8
$pp \to HZ$	5.1	$H \to 4l$	4.8
$pp \to HW$	3.7	$H \to 2l2\nu$	4.8
$pp \to t\bar{t}H$	12	$H \to \mu^+\mu^-$	2.8

→ Conservative for inclusive rate, aggressive for distributions

Systematic uncertainties

obtained for 7/8 TeV are scaled to 14 TeV with 300 and 3000 ifb respectively by $\sqrt{\mathcal{L}_8/\mathcal{L}_{14}}$

statistical uncertainties

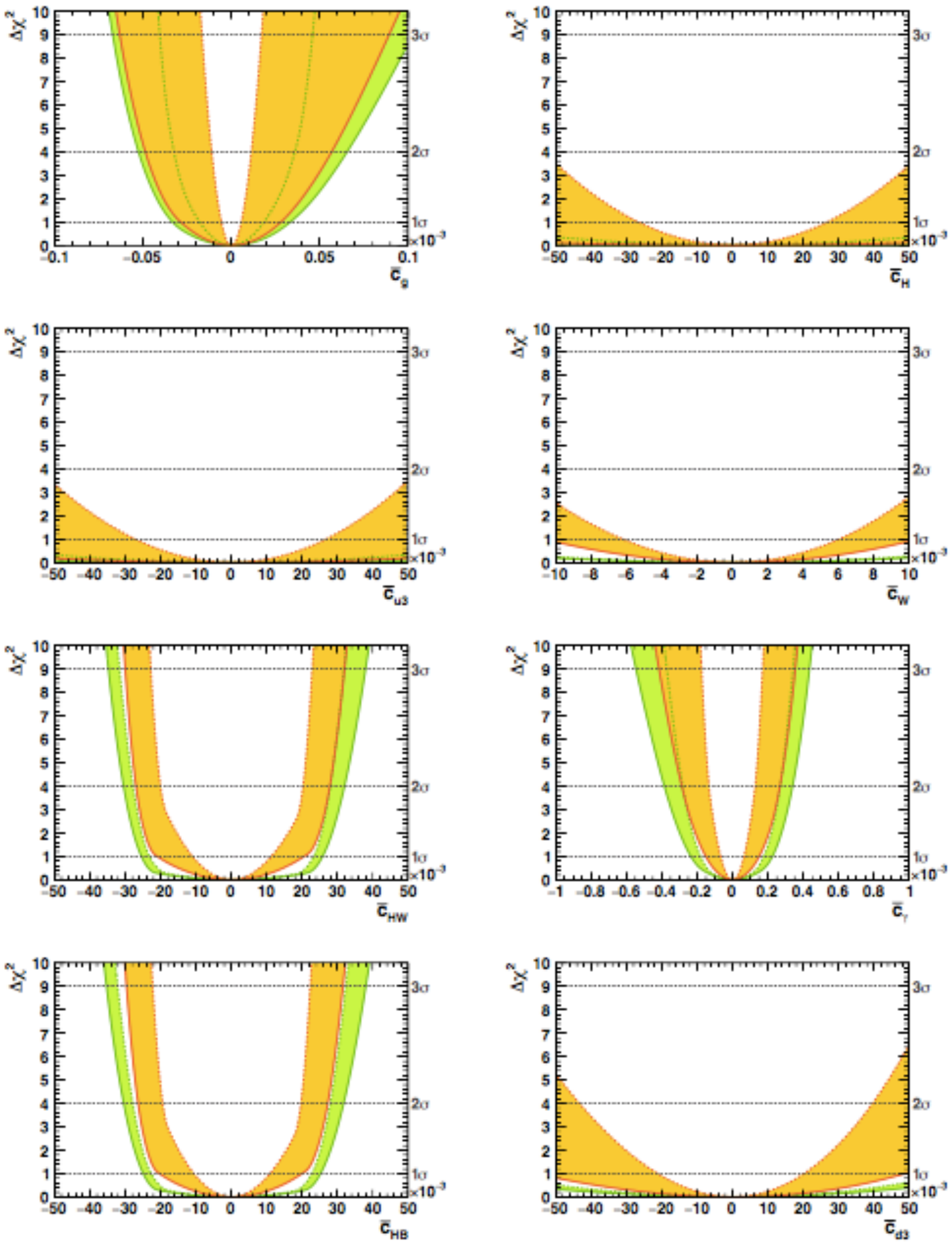
part of fit and we require **5** events to consider a channel

production process		decay process	
$pp \to H$	10	$H \to b\bar{b}$	25
$pp \to H + \mathrm{j}$	30	$H \to \gamma\gamma$	20
$pp \to H + 2\mathrm{j}$	100	$H \to \tau^+\tau^-$	15
$pp \to HZ$	10	$H \to 4l$	20
$pp \to HW$	50	$H \to 2l2\nu$	15
$pp \to t\bar{t}H$	30	$H \to Z\gamma$	150
		$H \to \mu^+\mu^-$	150

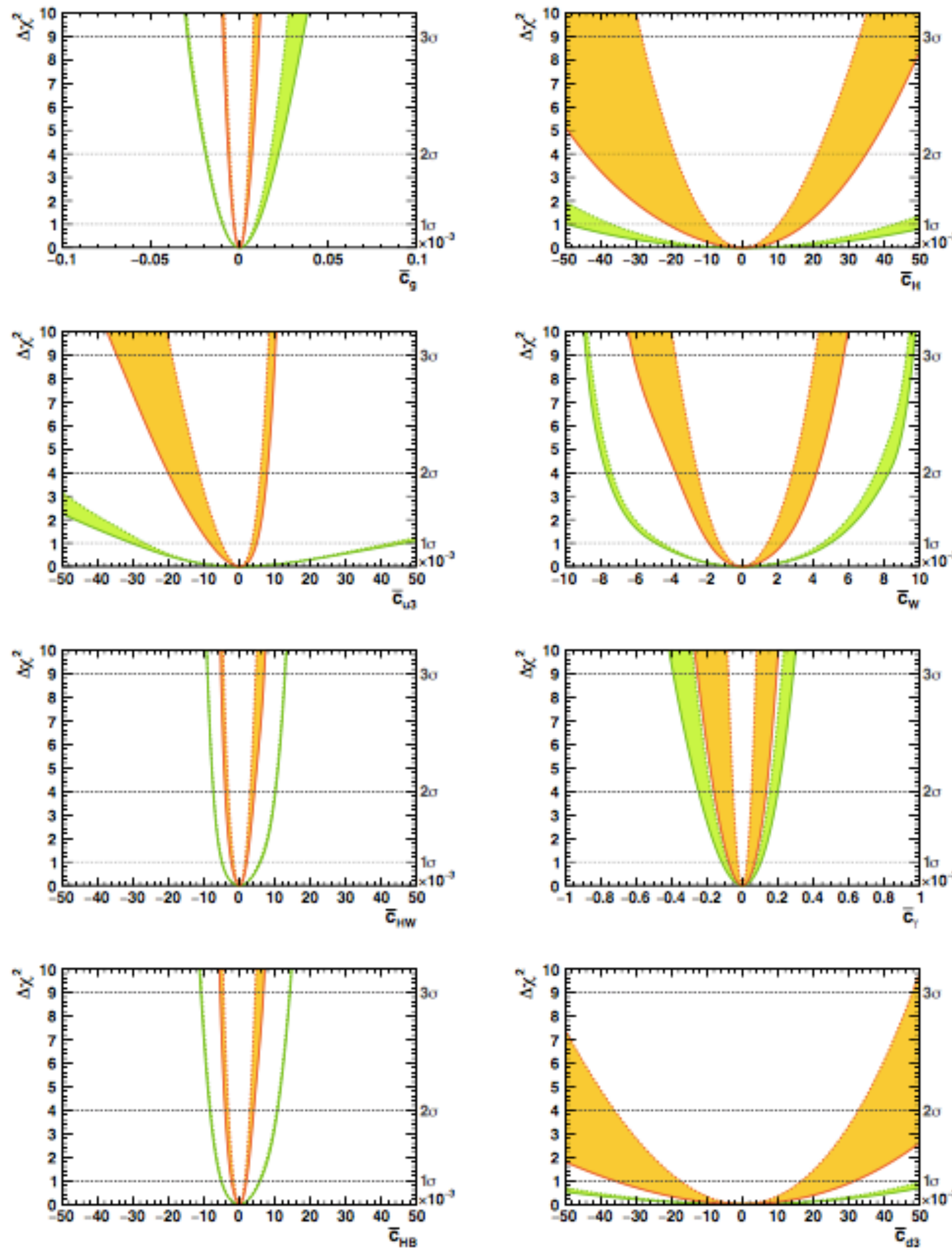
	$t\bar{t}H$	HZ	HW	H incl.	$H+\mathrm{j}$	$H+2\mathrm{j}$
$H \to b\bar{b}$	80	25	40	100	100	150
$H \to \gamma\gamma$	60	70	30	10	10	20
$H \to \tau^+\tau^-$	100	75	75	80	80	30
$H \to 4l$	70	30	30	20	20	30
$H \to 2l2\nu$	70	100	100	20	20	30
$H \to Z\gamma$	100	100	100	100	100	100
$H \to \mu^+\mu^-$	100	100	100	100	100	100

rel. syst. uncertainty in %

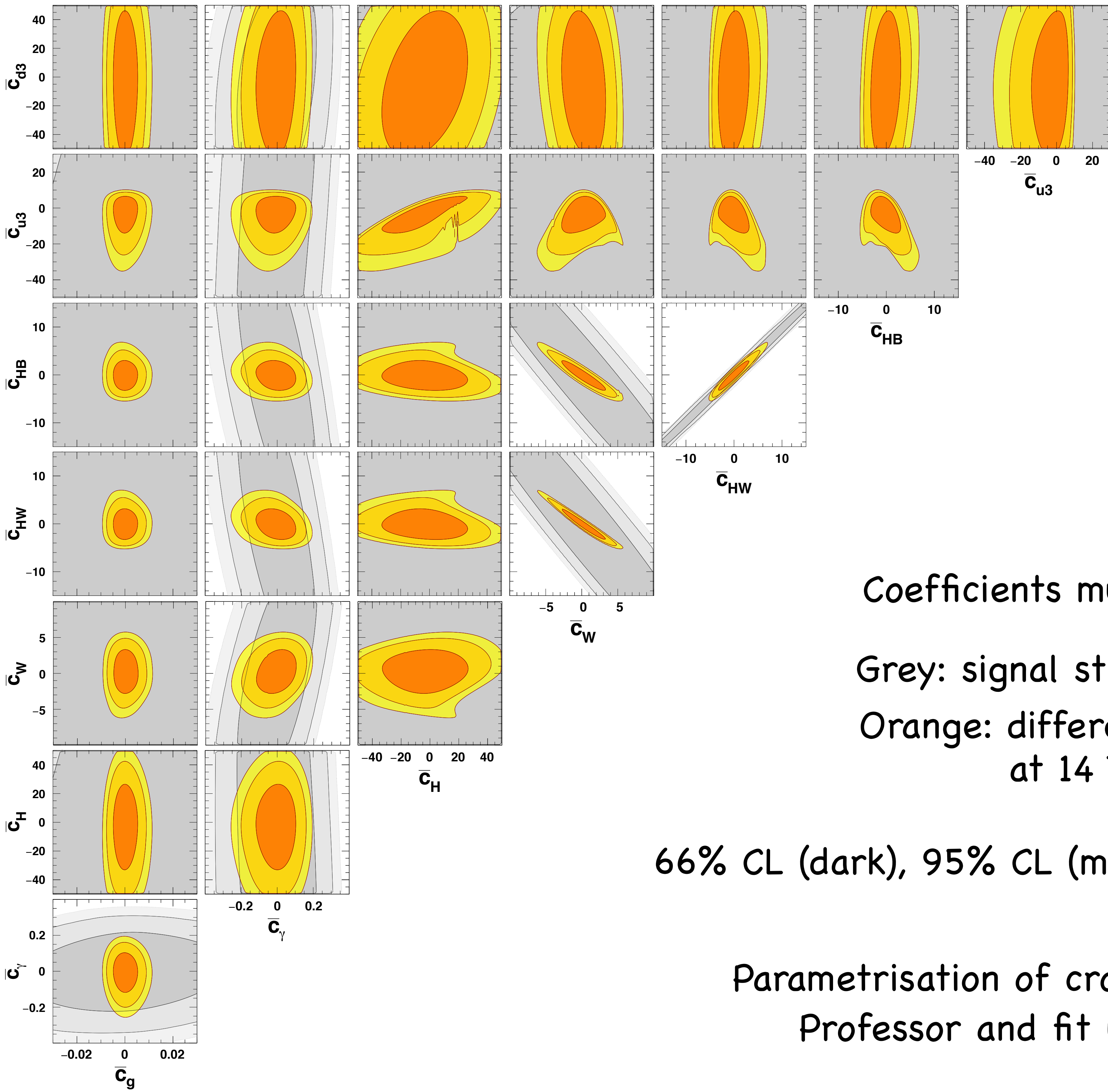
signal strength measurement



differential measurement



green = 300 ifb   orange = 3000 ifb



Coefficients multiplied by 10^3

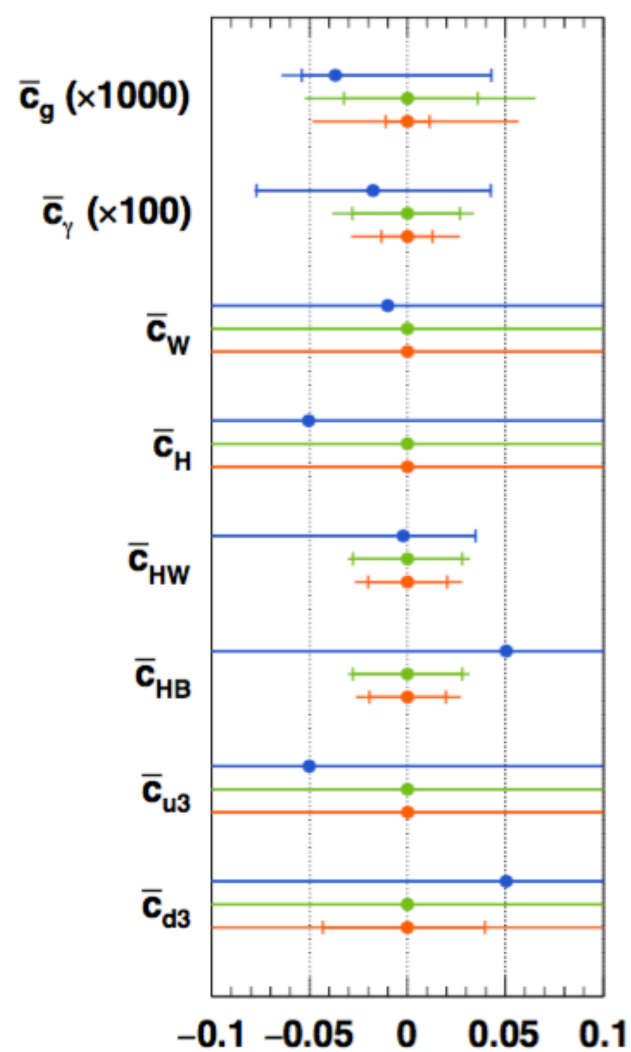
Grey: signal strength only

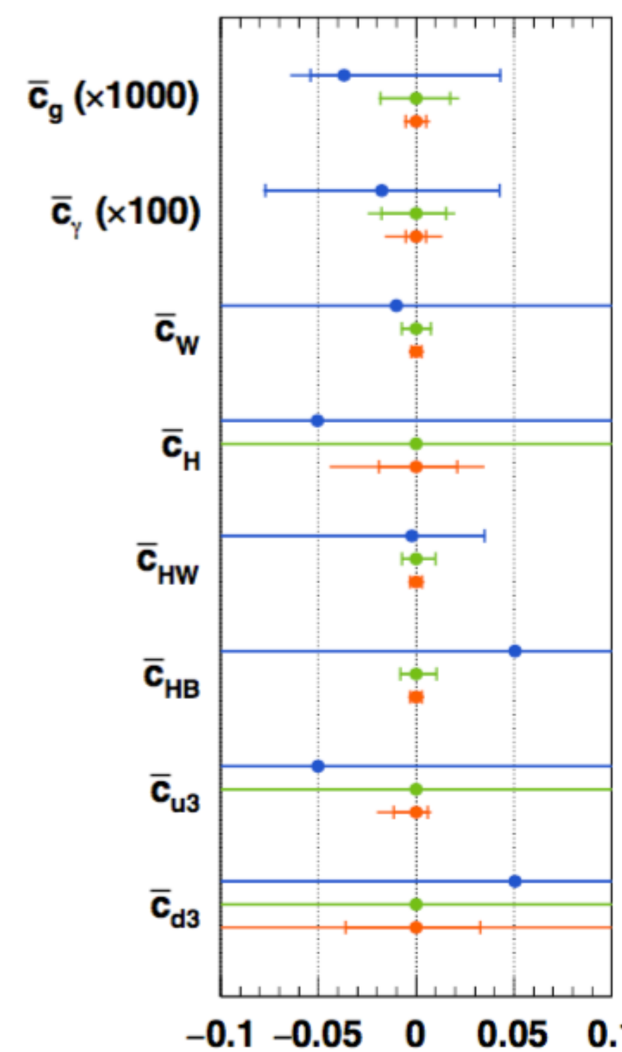
Orange: differential distributions at 14 TeV and 3000 ifb

66% CL (dark), 95% CL (middle), 99% CL (light)

Parametrisation of cross sections with Professor and fit using Gfitter

Signal strength only differential distributions





7/8 TeV (blue)

14 TeV, 300 ifb (green)

14 TeV, 3000 ifb (orange)

Setup allows to address most fundamental question for high-energy physics:

- Which theory calculations most important?
- Which systematic uncertainties most limiting?
- Where can we improve knowledge most?

[Englert, Kogler, Schulz, MS '17]

Interpretation of results

Composite (SILH) Higgs:

One expects $\bar{c}_g \sim \frac{m_W^2}{16\pi^2}\frac{y_t^2}{\Lambda^2}$ with comp. scale $\Lambda \sim g_\rho f$

with $|\bar{c}_g| \lesssim 5 \times 10^{-6}$ we get $\Lambda \gtrsim 2.8$ TeV

indirect probe of new physics scenario using Higgs observables only

MSSM:

$$\bar{c}_g = \frac{m_W^2}{(4\pi)^2}\frac{1}{24}\left(\frac{h_t^2 - g_1^2 c_{2\beta}/6}{m_{\tilde{Q}}^2} + \frac{h_t^2 + g_1^2 c_{2\beta}/3}{m_{\tilde{t}_R}^2} - \frac{h_t^2 X_t^2}{m_{\tilde{Q}}^2 m_{\tilde{t}_R}^2}\right)$$

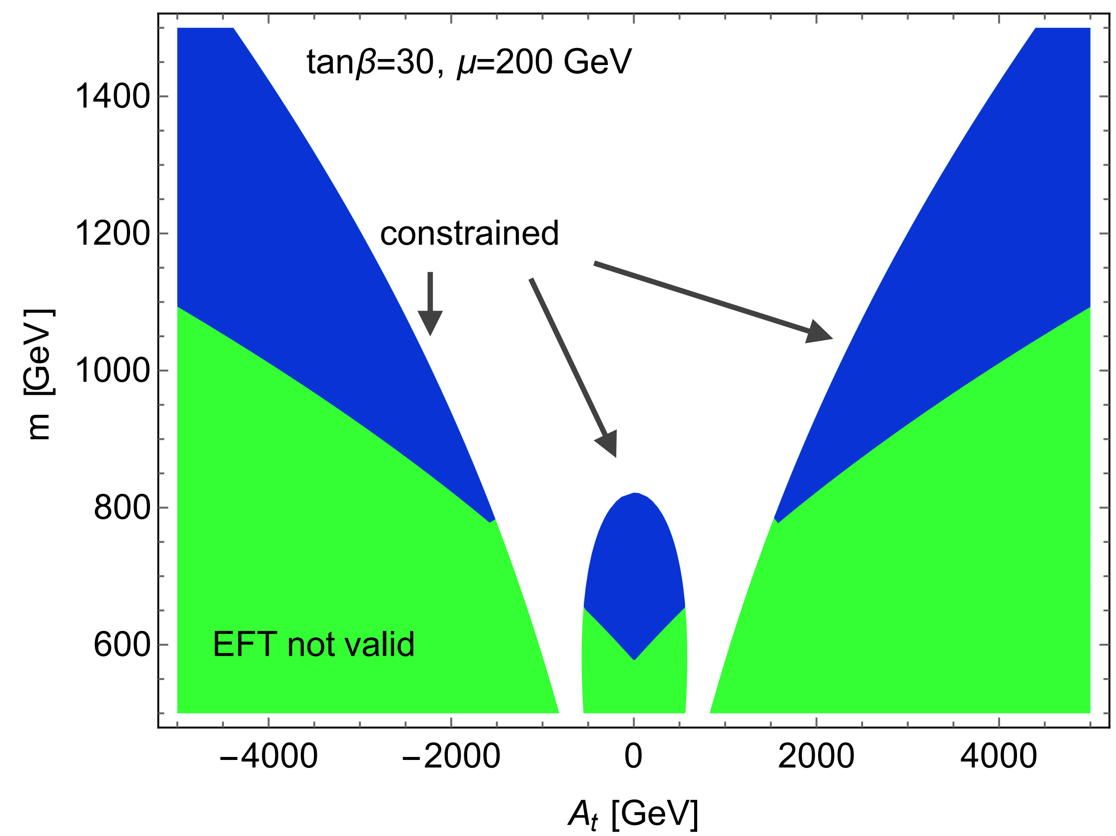
$m_{\tilde{Q}} = m_{\tilde{t}} = m$

$\tan\beta = 30$

$\mu = 200$ GeV

$h_t \equiv y_t s_\beta$

large At can be constrained



Three Higgs properties are of particular interest

Total width of Higgs (invisible decays)

Decay into spec. channel

Production

$$\sigma \cdot BR \propto g_p^2 \frac{g_d^2}{\Gamma_H}$$

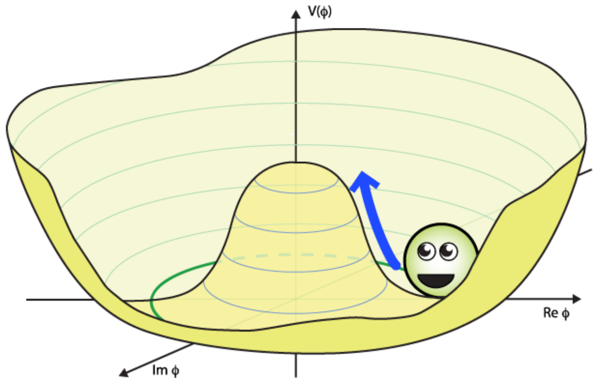
Sum of all possible decays

- Width affects all decay channels
- Indicative of new couplings (i.e. invisible or novel particles)

Higgs self-coupling

$$V(\phi) = -\mu^2 H^\dagger H + \lambda (H^\dagger H)^2$$

$$H = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h \end{pmatrix}$$



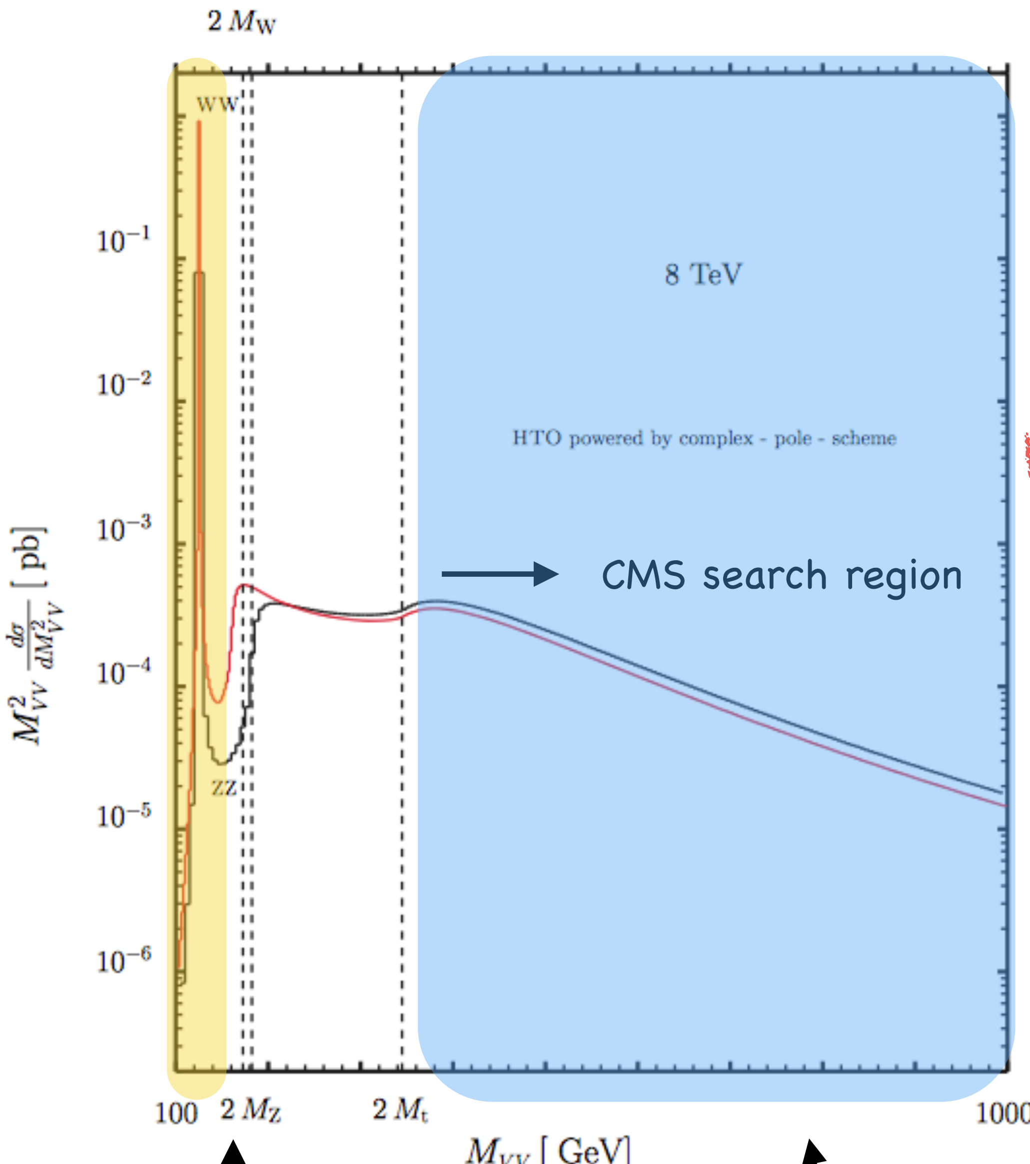
$$V(H) = \underbrace{\frac{1}{2} m_h^2}_{\mu^2} h^2 + \frac{1}{3!} \lambda_{hhh} h^3 + \frac{1}{4!} \lambda_{hhhh} h^4$$

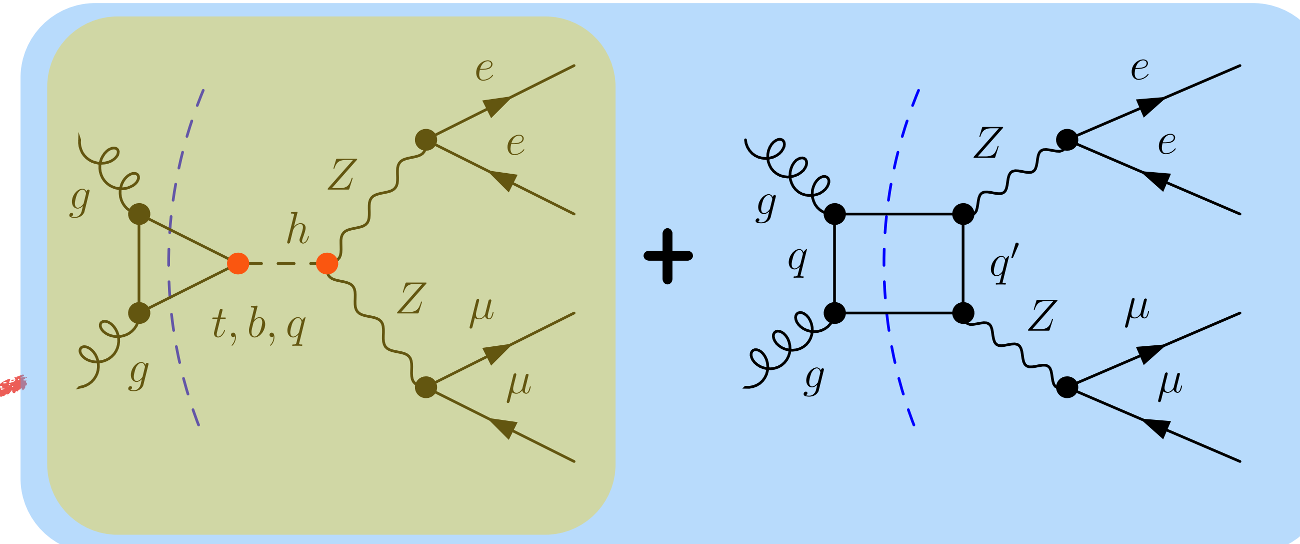
- Indicative of ew sym. breaking potential

CP properties of Higgs interactions

- Matter/Anti-matter asymmetry (Baryogenesis)

CMS 'width' Measurement





I. Count events in on-shell region

→ fix signal strength $\mu_{i,j} = \sigma_{H,i} \times BR_j \sim \frac{g_{ggH} g_{HZZ}}{\Gamma_H}$

II. measure $g^2_{ggH} g^2_{HZZ}$ in off-shell region

using angular correlations of 4l decay products

III. insert off-shell coupling measurement in

on-shell signal strength to bound width

$$\sigma^{\text{on-peak}}_{gg \to H \to ZZ} \sim \frac{g^2_{ggH} g^2_{HZZ}}{\Gamma_H}$$

$$\sigma^{\text{off-peak}}_{gg \to H \to ZZ} \sim g^2_{ggH} g^2_{HZZ}$$

Obs.(exp.) @95% C.L:

Γ_H< 4.2(8.5) Γ_H^{SM}

Γ_H< 17.4 (35.3) MeV

[Kauer, Passarino 2011]

[Caola, Melnikov 2013]

Example 'width-measurement'

Measure coupling off-shell -> limit denominator on-shell

$$\sigma_{gg\to H\to ZZ}^{\mathrm{on-peak}} \sim \frac{g_{ggH}^2 g_{HZZ}^2}{\Gamma_H} \longleftrightarrow \sigma_{gg\to H\to ZZ}^{\mathrm{off-peak}} \sim g_{ggH}^2 g_{HZZ}^2$$

Kappa Framework ✓

- Assuming global coupling rescaling

EFT ✓

- Assuming valid and no flat directions

↓

Coupling assumptions strong
LEP limits stronger than LHC

$$0.73\ \Gamma_{SM} \lesssim \Gamma_h \lesssim 1.87\ \Gamma_{SM}$$

[Englert, McCullough, MS '15]

Simplified Models ⚡

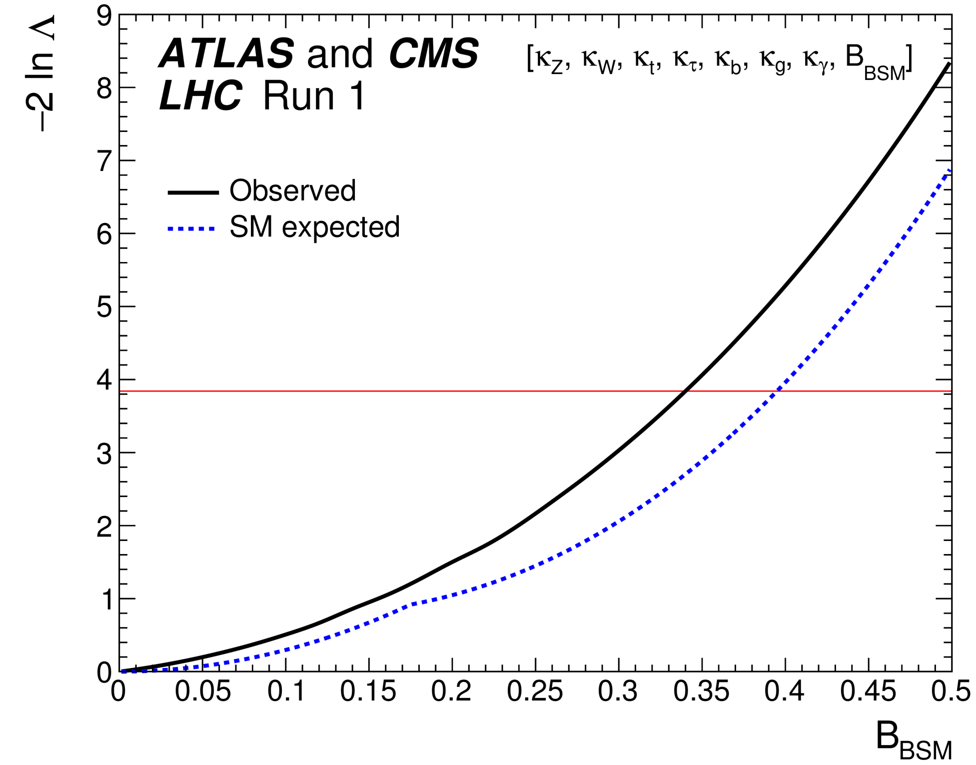
- Eg. **Higgs portal**, NP can contribute on-shell but not off-shell
  [Englert, MS '14]
- Eg. **Higgs triplet**, new scalar below measurement range cancels on-shell enhancement
  [Logan '15]

Full (UV) Model ⚡

- Uninteresting width not a free parameter of the theory

  width derived and fully determined

Limit on invisible branching ratio from global Higgs fit



- In Kappa framework for Run 1: BR < 0.34 at 95% CL (assumed kV < 1)

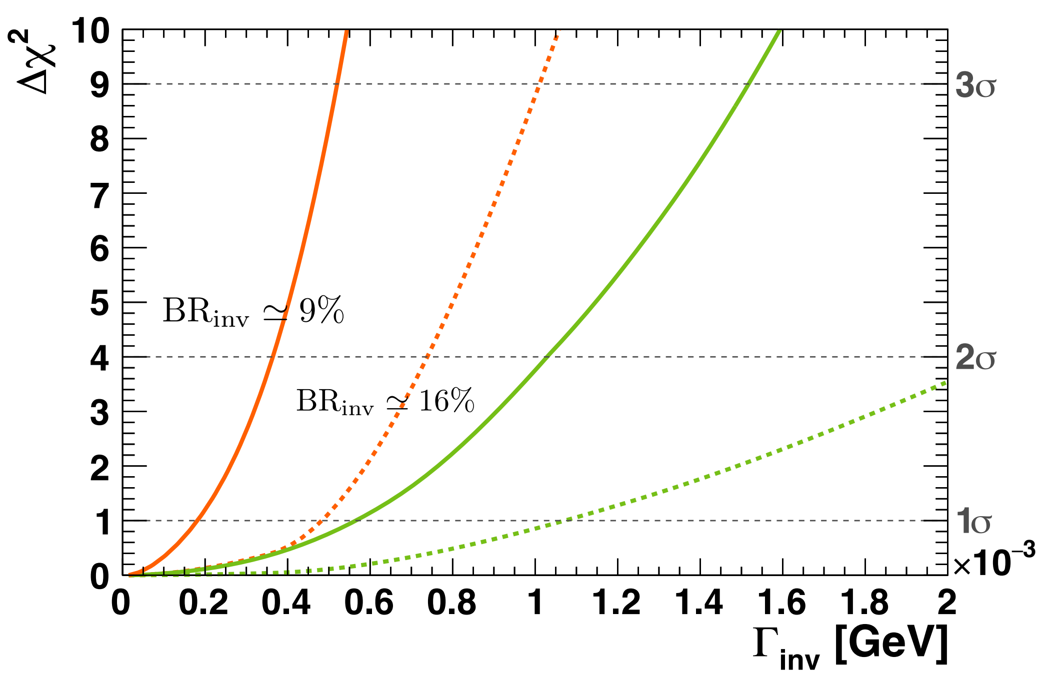
- Extend SM EFT by light degree of freedom, e.g. fermionic DM candidate

$$\mathrm{BR_{inv}} = \frac{\Gamma_{\mathrm{inv}}}{\Gamma_{\mathrm{SM}} + \Gamma_{\mathrm{inv}}}$$

Flat reduction of event count in all channels

All/many operators need to conspire to compensate for loss in total rate

Most operators mom. dependent. Rate compensated by large increase in tail



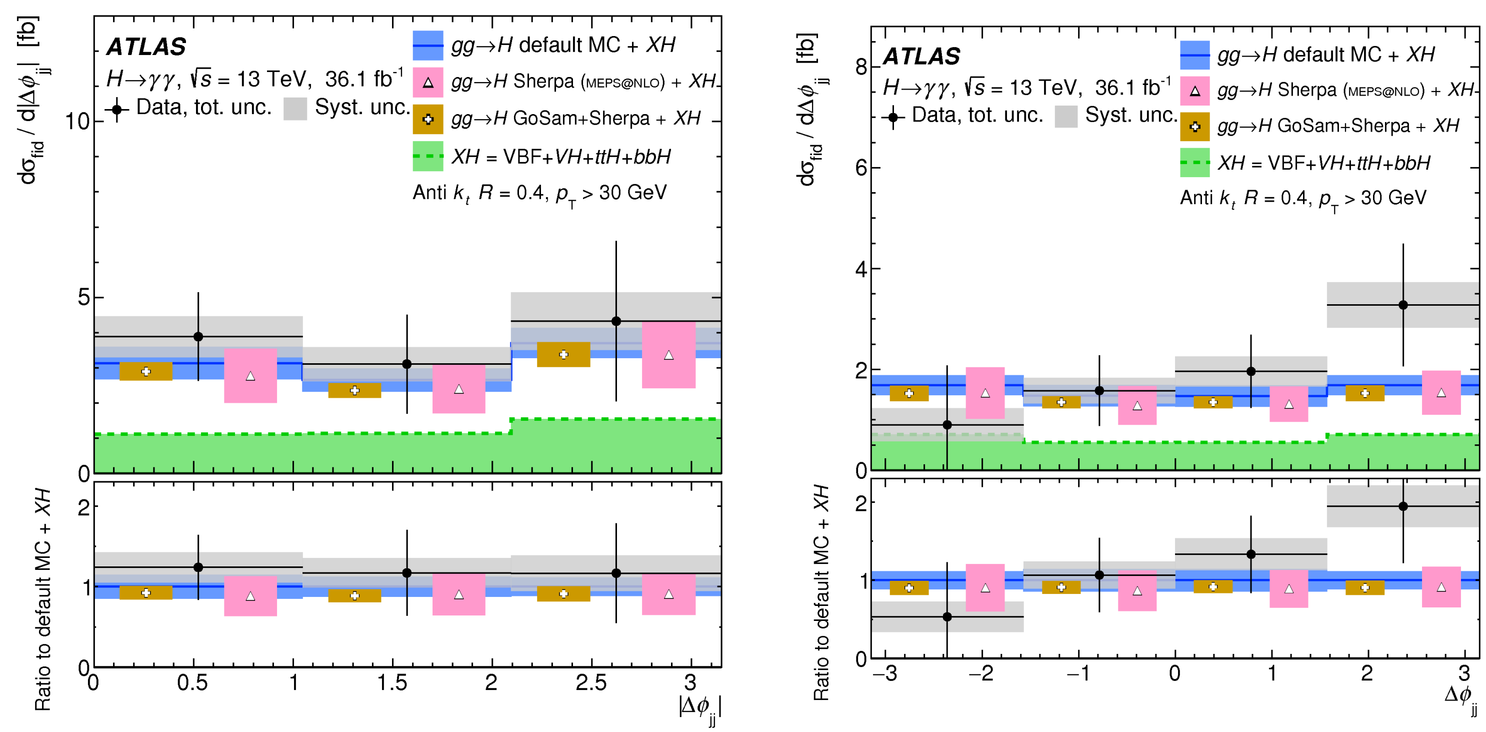
orange/green = 3k/300 ifb   sig. str. (dashed), pT (solid)

CP violating interactions of the Higgs boson

[Bernlocher et al '18]

$$O_{H\tilde{G}} = H^\dagger H G^{a\mu\nu}\tilde{G}^a_{\mu\nu}\,,$$
$$O_{H\tilde{W}} = H^\dagger H W^{a\mu\nu}\tilde{W}^a_{\mu\nu}\,,$$
$$O_{H\tilde{B}} = H^\dagger H B^{\mu\nu}\tilde{B}_{\mu\nu}\,,$$
$$O_{H\tilde{W}B} = H^\dagger \tau^a H B_{\mu\nu}\tilde{W}^{a\mu\nu}\,,$$

cp-violating tth interactions degenerate with $O_{H\tilde{G}}$ for our observables (blind direction)



Use recent ATLAS measurements in $h \to \gamma\gamma$ and $h \to ZZ^* \to 4\ell$

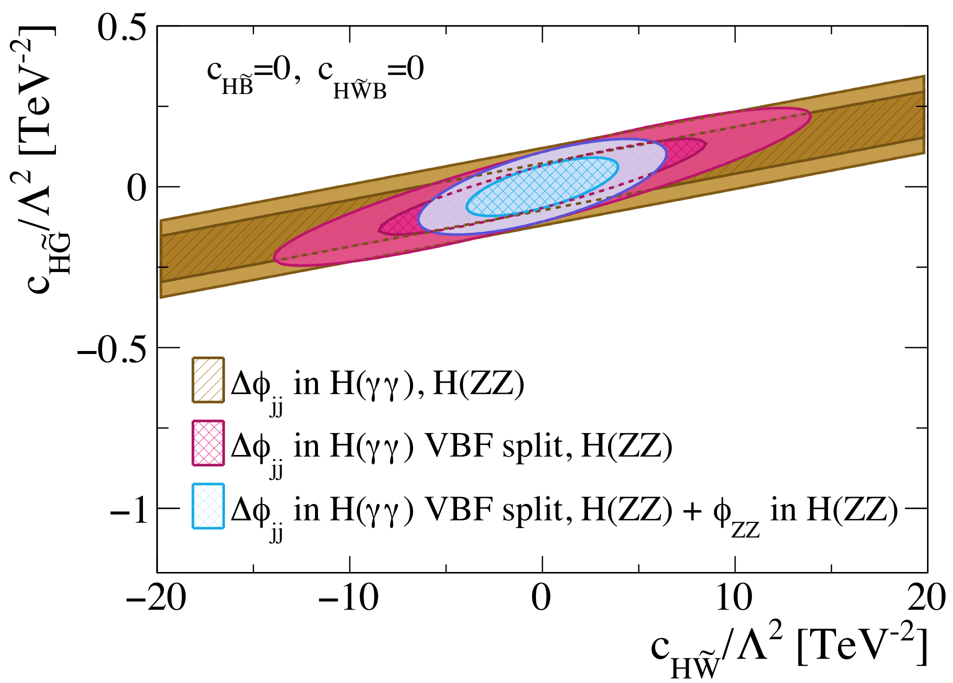
Need to construct CP sensitive observables in linearised framework $|\mathcal{M}|^2 = |\mathcal{M}_{\rm SM}|^2 + 2{\rm Re}\,(\mathcal{M}^\star_{\rm SM}\mathcal{M}_{\rm d6}) + \mathcal{O}(\Lambda^{-4})$.

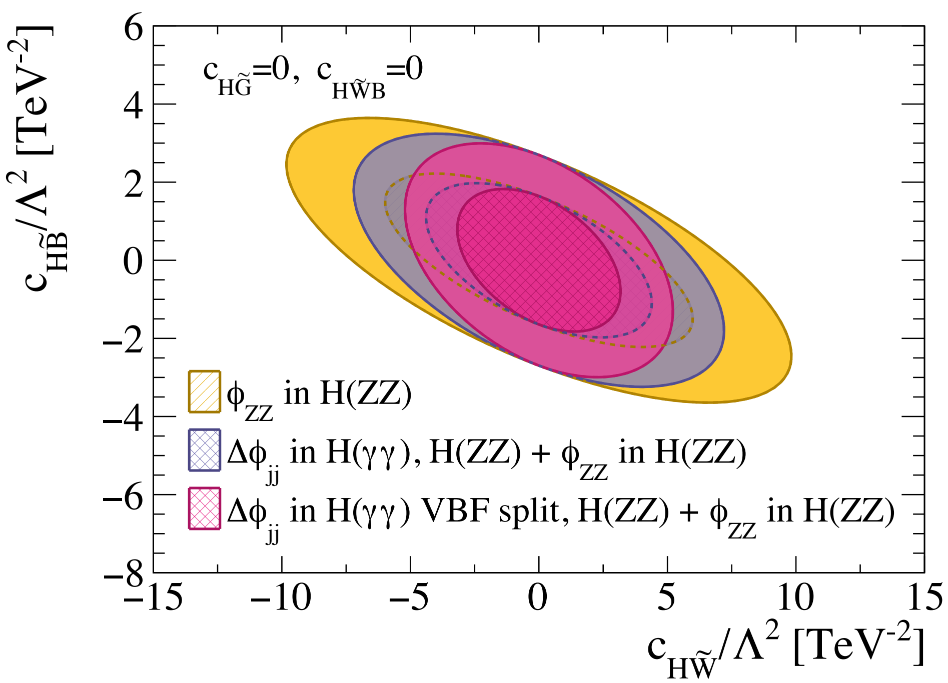
for example: $\Delta\phi_{jj} = \phi_1 - \phi_2,$ in Hjj $\quad A = \dfrac{\sigma(0<\Delta\phi_{jj}<\pi) - \sigma(-\pi<\Delta\phi_{jj}<0)}{\sigma(0<\Delta\phi_{jj}<\pi) + \sigma(-\pi<\Delta\phi_{jj}<0)}$

with ATLAS data one finds $\quad A = \; 0.3 \pm 0.2$

Future sensitivity can be improved by separating enriched regions of GF and WBF and by studying H->4l decay angles, e.g.

$$\cos\Phi = \left.\frac{(\mathbf{p}_{l^-} \times \mathbf{p}_{l^+}) \cdot (\mathbf{p}_{l'^-} \times \mathbf{p}_{l'^+})}{\sqrt{(\mathbf{p}_{l^-} \times \mathbf{p}_{l^+})^2 \, (\mathbf{p}_{l'^-} \times \mathbf{p}_{l'^+})^2}}\right|_h$$





Coefficient [TeV^{-2}]	36.1 fb^{-1}	300 fb^{-1}	3000 fb^{-1}
$c_{H\tilde{G}}/\Lambda^2$	$[-0.19, 0.19]$	$[-0.067, 0.067]$	$[-0.021, 0.021]$
$c_{H\tilde{W}}/\Lambda^2$	$[-11, 11]$	$[-3.8, 3.8]$	$[-1.2, 1.2]$
$c_{H\tilde{B}}/\Lambda^2$	$[-5.9, 5.9]$	$[-2.1, 2.1]$	$[-0.65, 0.65]$
$c_{H\tilde{W}B}/\Lambda^2$	$[-14, 14]$	$[-4.9, 4.9]$	$[-1.5, 1.5]$

Marginalised over other coefficients

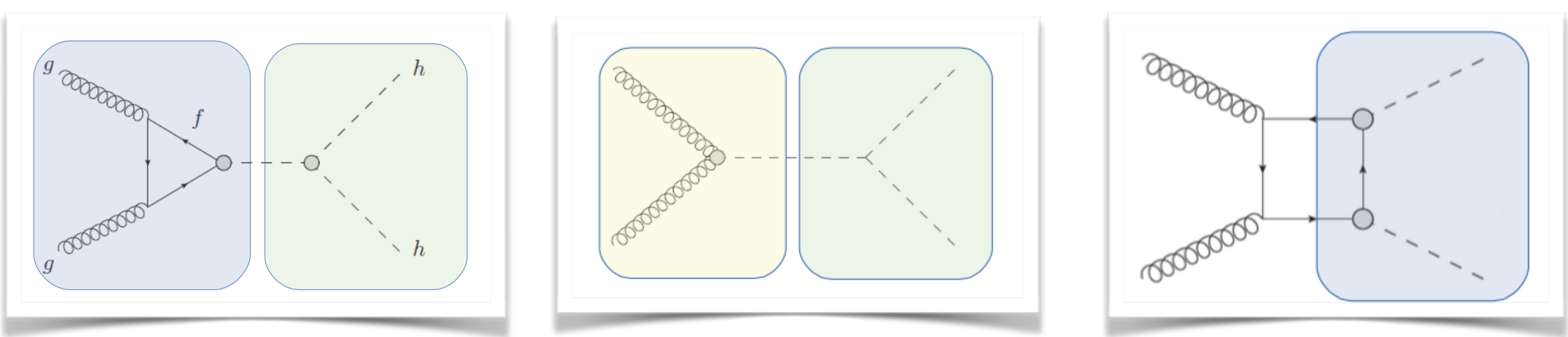
Measure modification of self-coupling

[Contino, et al '12]
[Goertz, et al '14]

- If new physics heavy can parametrise effect using EFT

$$\mathcal{L}_{\mathrm{Dim6}} \supset c_H \partial^\mu (\Phi^\dagger \Phi) \partial_\mu (\Phi^\dagger \Phi) - c_6 (\Phi^\dagger \Phi)^3$$
$$+ (c_y \Phi^\dagger \Phi \bar{Q}_L \Phi q_R + h.c.) + c_g \Phi^\dagger \Phi G^a_{\mu\nu} G^{a\mu\nu}$$

- Non-resonant loop-induced HH production affected



- c6 can only be constrained in global fit, after over-constraining the system

Measurement prospects at future colliders

[Tian, Fujii 1311.6528]

- e+e- collider WBF most sensitive channel for large energies > 500 GeV
- Decay via H->bb
- Unless 1 TeV ILC precision low

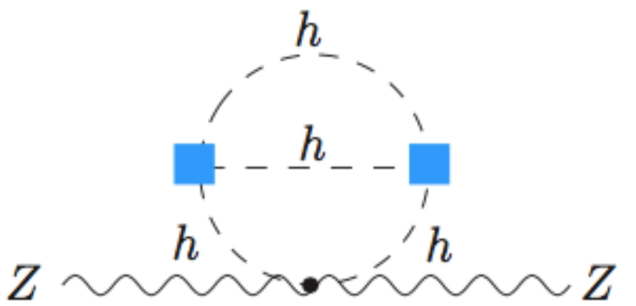
$\Delta g/g$	Baseline			LumiUP		
	250 GeV	+ 500 GeV	+ 1 TeV	250 GeV	+ 500 GeV	+ 1 TeV
g_{HZZ}	1.3%	1.0%	1.0%	0.61%	0.51%	0.51%
g_{HWW}	4.8%	1.2%	1.1%	2.3%	0.58%	0.56%
g_{Hbb}	5.3%	1.6%	1.3%	2.5%	0.83%	0.66%
g_{Hcc}	6.8%	2.8%	1.8%	3.2%	1.5%	1.0%
g_{Hgg}	6.4%	2.3%	1.6%	3.0%	1.2%	0.87%
$g_{H\tau\tau}$	5.7%	2.3%	1.7%	2.7%	1.2%	0.93%
$g_{H\gamma\gamma}$	18%	8.4%	4.0%	8.2%	4.5%	2.4%
$g_{H\mu\mu}$	-	-	16%	-	-	10%
g_{Htt}	-	14%	3.1%	-	7.8%	1.9%
Γ_H	11%	5.0%	4.6%	5.4%	2.5%	2.3%
λ_{HHH}	-	83%	21%	-	46%	13%

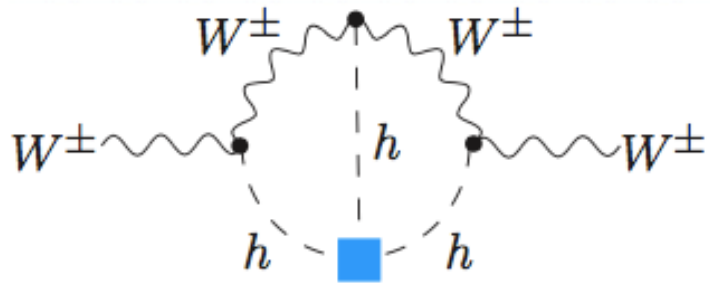
- Promising predictions at FCC-hh 100 TeV: O(5)% accuracy

  [Barr, Dolan, Englert, Ferreira, MS '14] [Azatov, Contino, Panico, Son '15] [Yao '15] [Papaefstathiou, Sakurai '15] [Papaefstathiou '15] [Banerjee, Englert, Mangano, Selvaggi, MS '18]

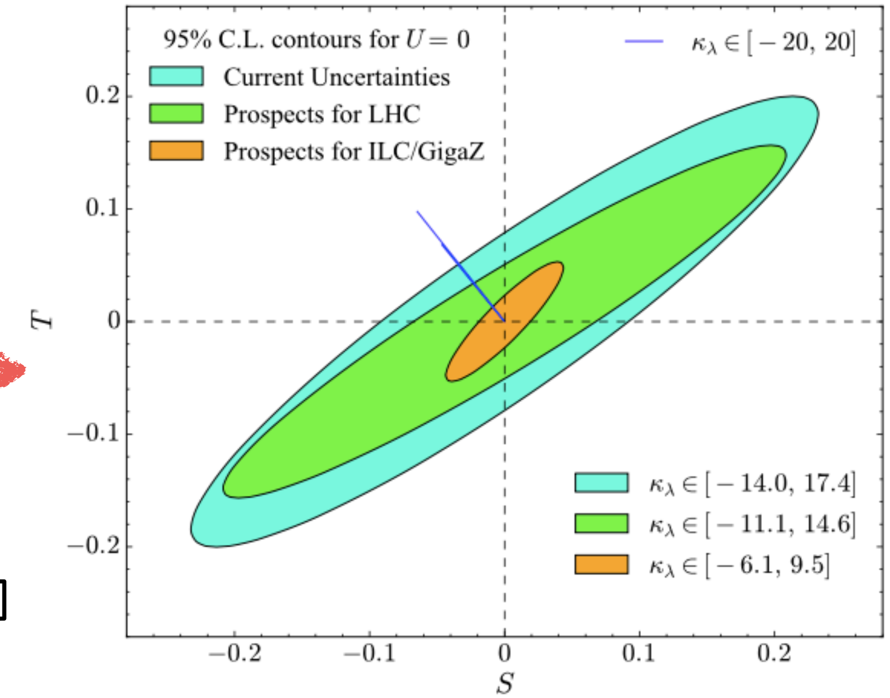
- For long time to come, HL-LHC is best chance to measure self-coupling, but is it good enough?

NO HIGGS OBSERVABLES: ELWP (NNLO)



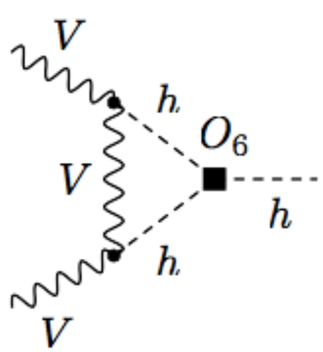


[Degrassi, Fedele, Giardino '17] [Kribs, Maier, Rzehak, MS, Waite '17]

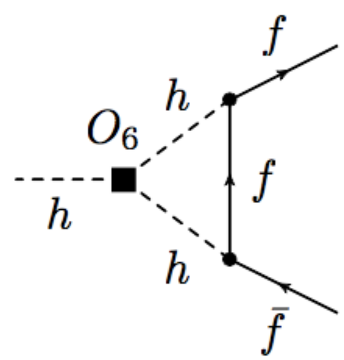


SINGLE-HIGGS OBSERVABLES: Higgs couplings (NLO)

production



decay

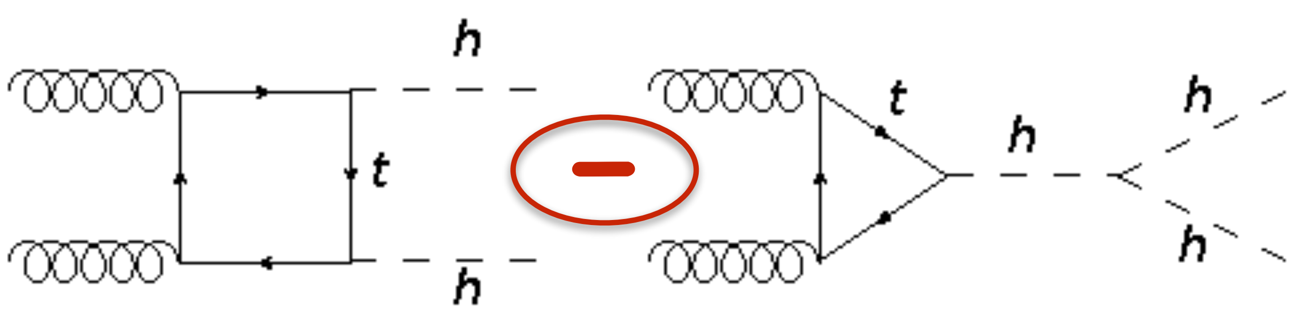


combination of different production and decay modes $-9.4 < \kappa_\lambda^{2\sigma} < 17$

[Bizon, Gorbahn, Haisch, Zanderighi '16] [Maltoni, Pagani, Shivaji, Zhao '17]

[Degrassi, Giardino, Maltoni, Pagani '16]

DOUBLE-HIGGS OBSERVABLES: Direct production (LO)



Di-Higgs production with various subsequent decay channels. Assumed CS accuracy 50%

$$-0.8 < \kappa_\lambda^{2\sigma} < 8.5$$

[Di Vita, Grojean, Panico, Riembau, Vantalon '17]

Can Higgs-selfcoupling be bounded by theoretical considerations?

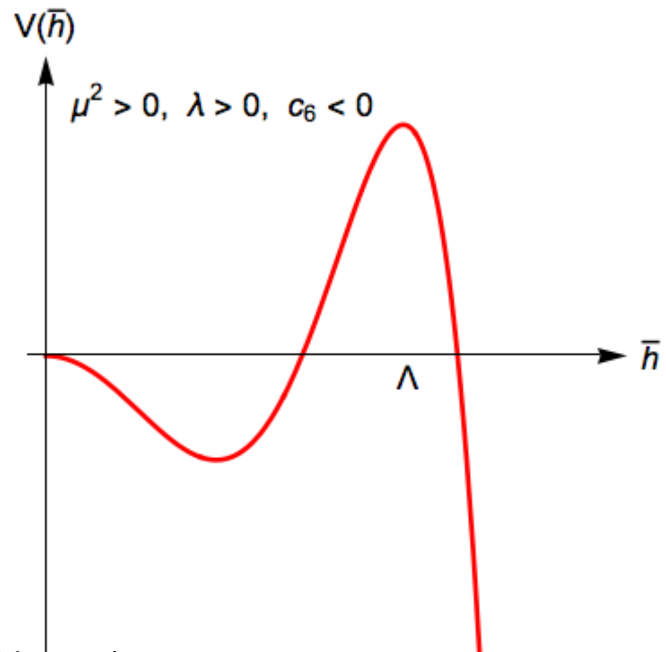
- Vacuum stability

  Introducing new c6 contribution results in two possible instabilities for potential

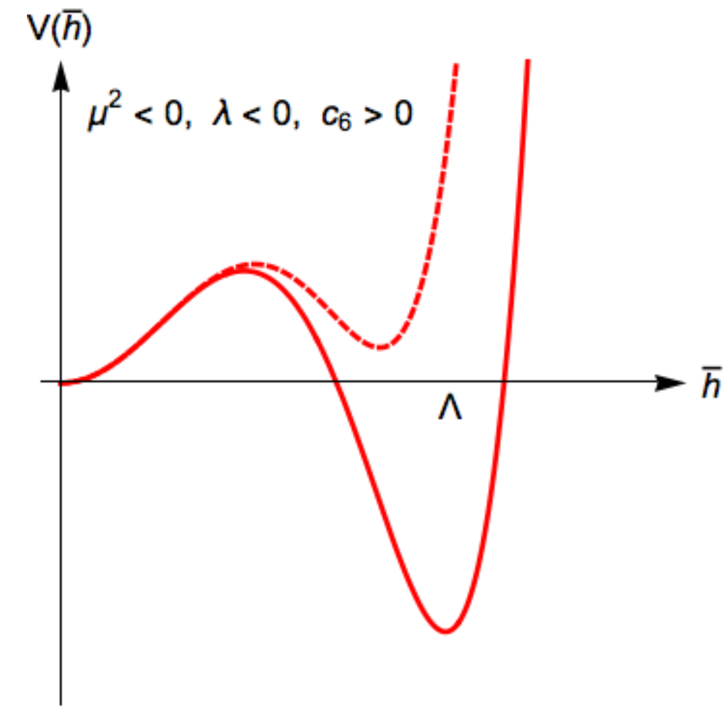
  → (lfi) requires resummation of large field contributions

  → (sfi) requires too small cut-off scale for EFT approach

large field instability (lfi)



small field instability (sfi)



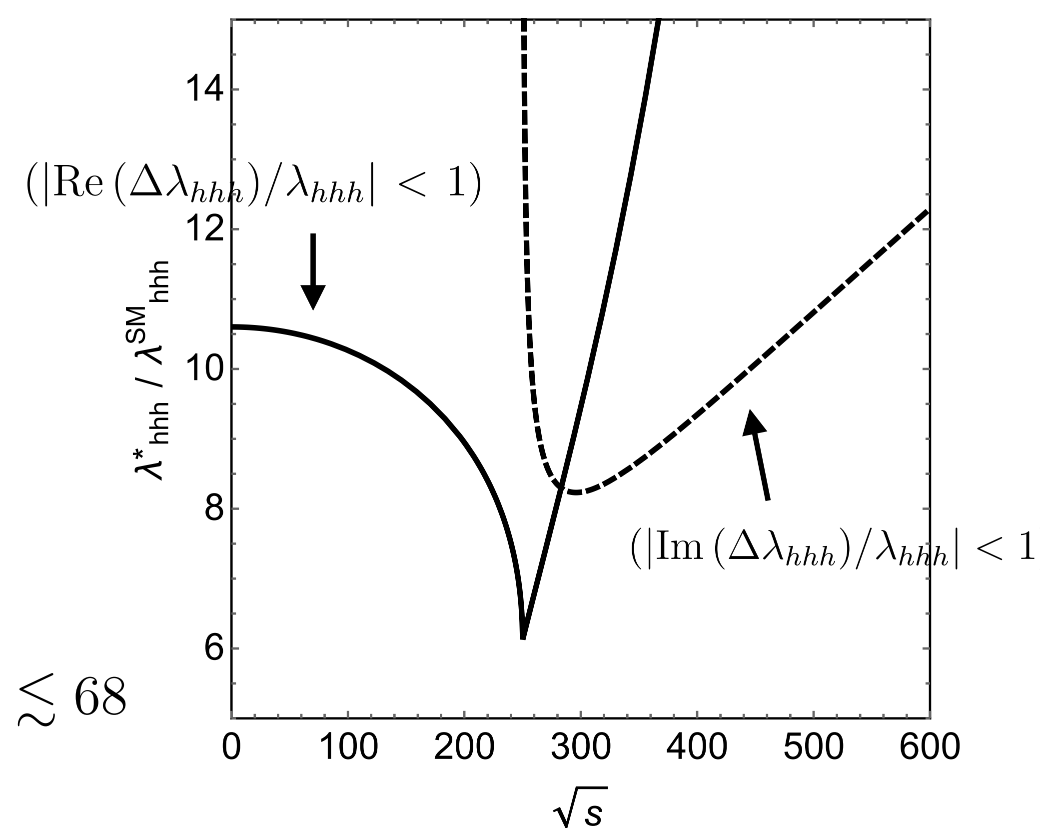
→ cannot connect vac. instabilities to bound on c6 within EFT

- Perturbativity

  require loop corrections to be smaller than tree-level vertex

$$\Delta\lambda_{hhh}(\sqrt{s}, m_h) = -\frac{1}{16\pi^2}\lambda_{hhh}^3 C_0(m_h^2, m_h^2, s; m_h, m_h, m_h)$$

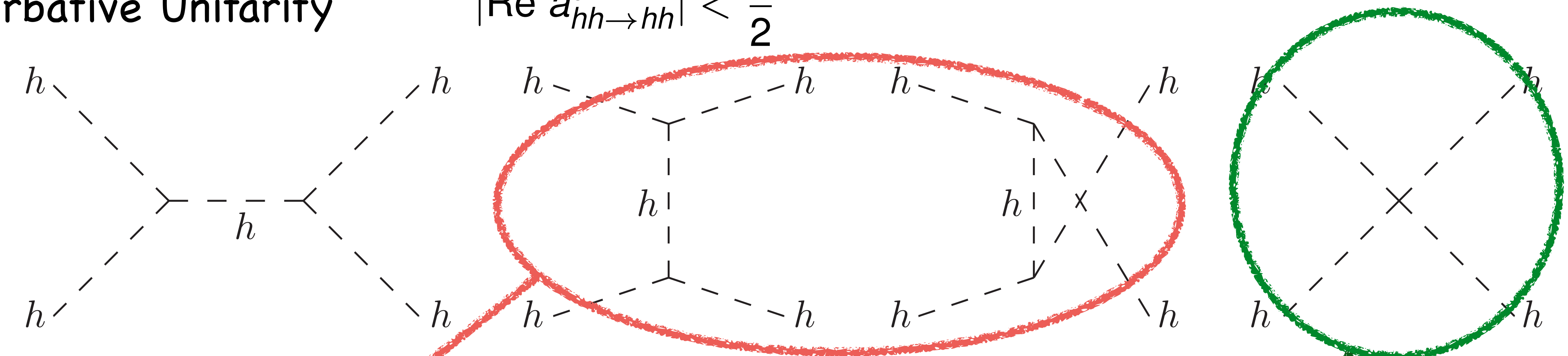
→ $|\lambda_{hhh}/\lambda_{hhh}^{SM}| \lesssim 6$

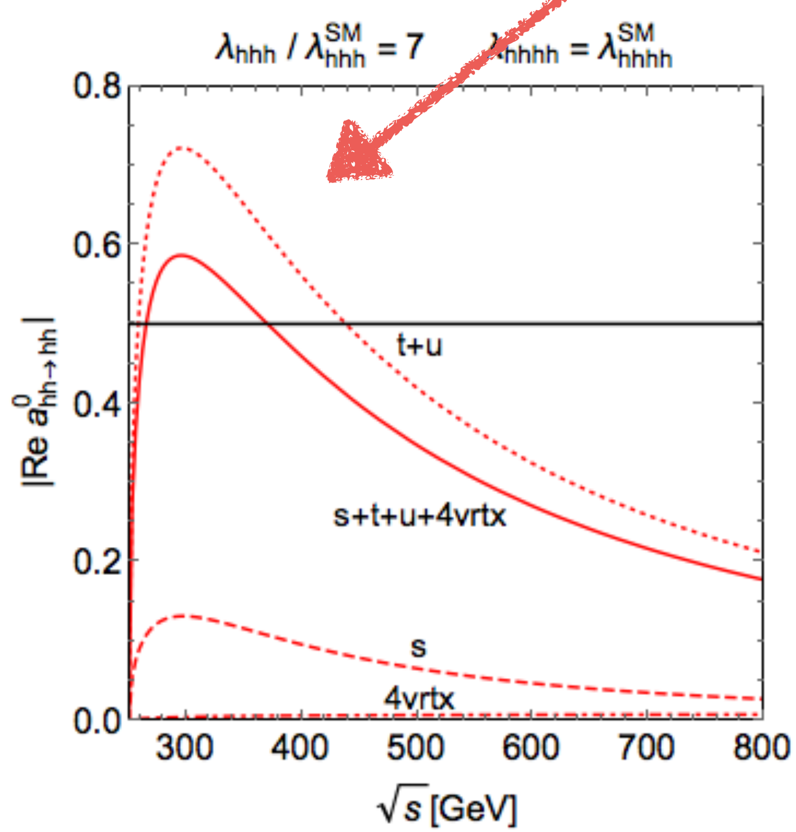


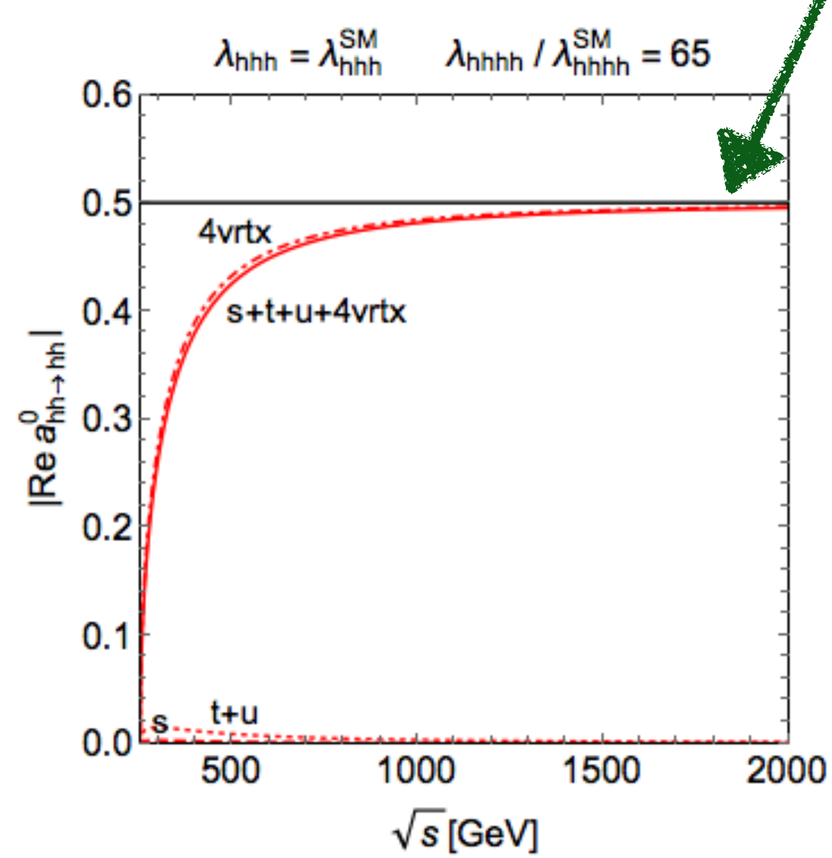
for quartic: $|\beta_{\lambda_{hhhh}}/\lambda_{hhhh}| < 1$ → $|\lambda_{hhhh}/\lambda_{hhhh}^{SM}| \lesssim 68$

Can Higgs-selfcoupling be bounded by theoretical considerations?

- Perturbative Unitarity $\quad |\mathrm{Re}\, a^0_{hh\to hh}| < \frac{1}{2}$



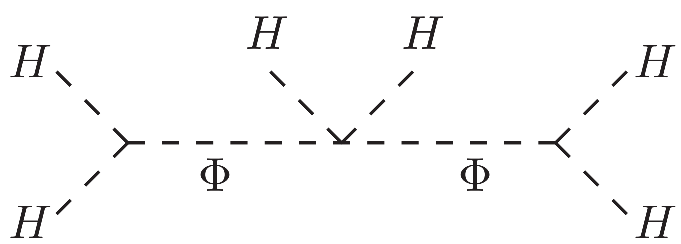




$\rightarrow \quad |\lambda_{hhh}/\lambda^{\mathrm{SM}}_{hhh}| \lesssim 6.5$ and $|\lambda_{hhhh}/\lambda^{\mathrm{SM}}_{hhhh}| \lesssim 65$

Largest shift in trilinear self-coupling $\mathcal{L}_6 = \frac{c_6}{\Lambda^2}|H|^6$ from tree-level contributions

Such scalar extensions can be classified by

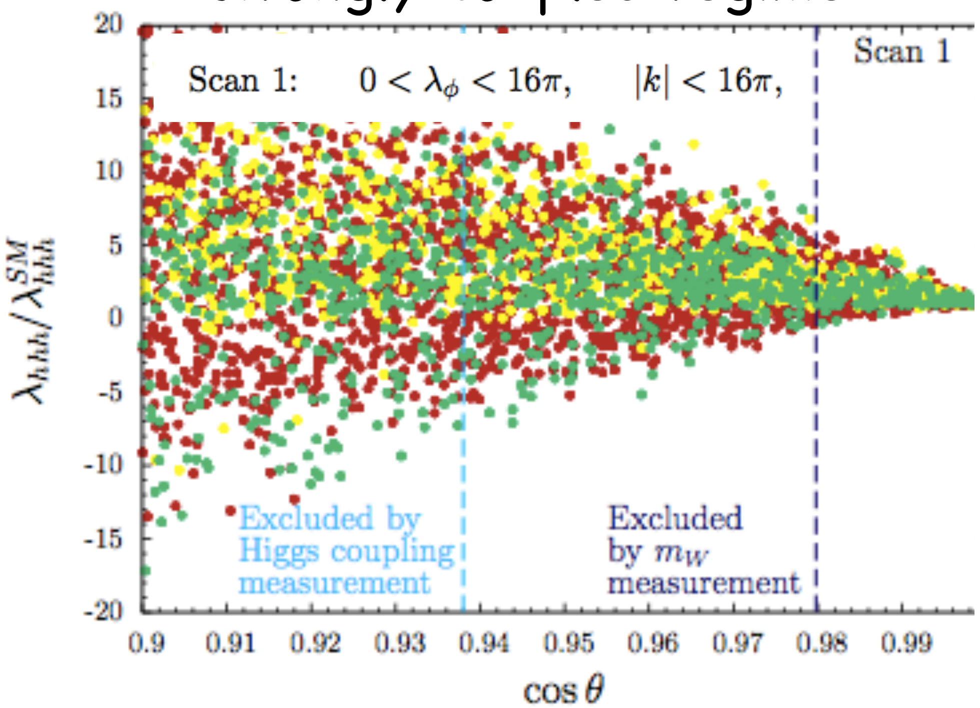


Φ	$\mathcal{O}_\Phi$
$(1,1,0)$	$\Phi H H^\dagger$
$(1,2,\frac{1}{2})$	$\Phi H H^\dagger H^\dagger$
$(1,3,0)$	$\Phi H H^\dagger$
$(1,3,1)$	$\Phi H^\dagger H^\dagger$
$(1,4,\frac{1}{2})$	$\Phi H H^\dagger H^\dagger$
$(1,4,\frac{3}{2})$	$\Phi H^\dagger H^\dagger H^\dagger$

Tree-level enhanced models

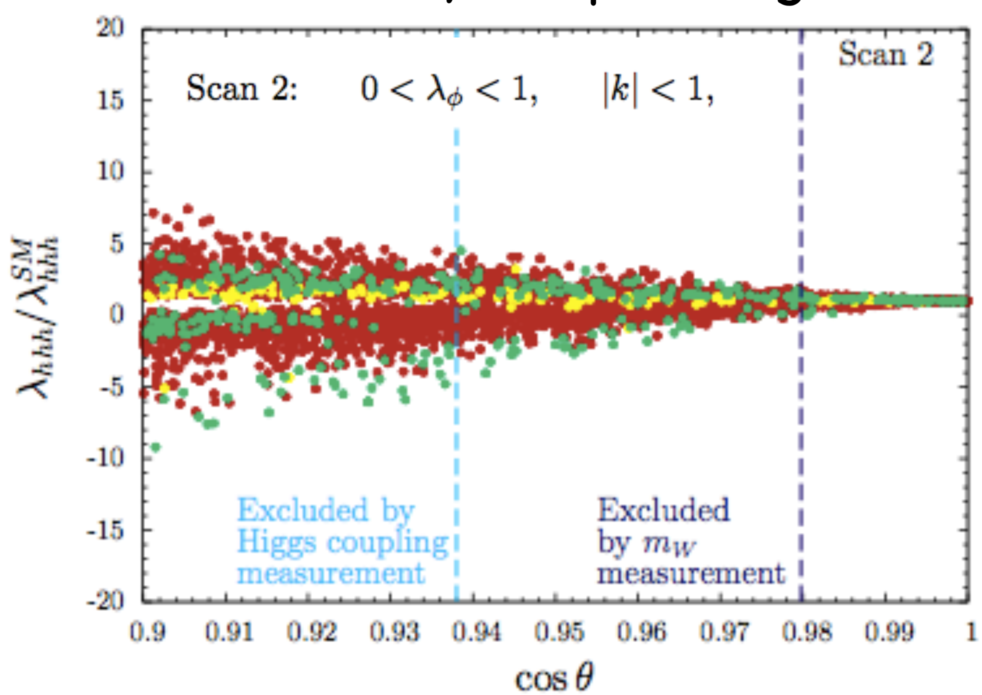
[Di Luzio, Groeber, MS '17]

strongly-coupled regime



$-1.5 < \lambda_{hhh}/\lambda_{hhh}^{\mathrm{SM}} < 8.7$

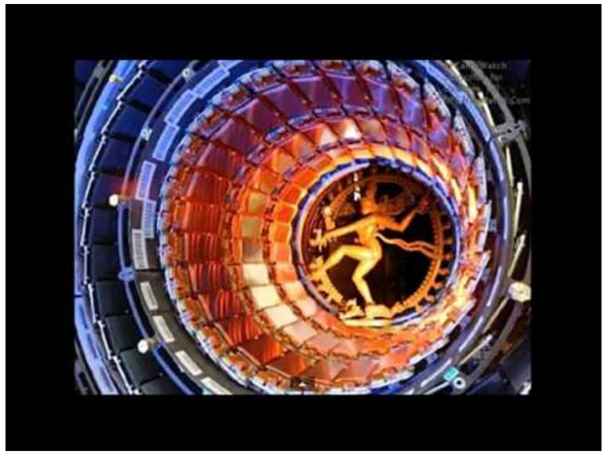
weakly-coupled regime



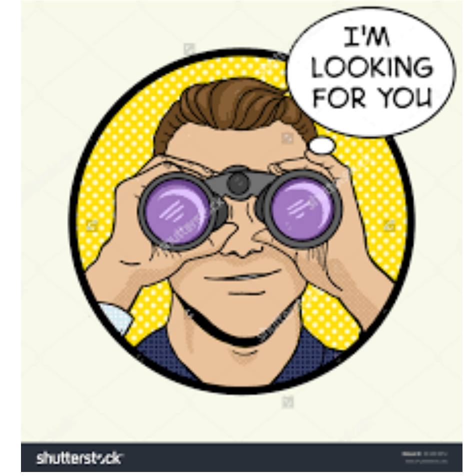
$-0.3 < \lambda_{hhh}/\lambda_{hhh}^{\mathrm{SM}} < 2.0$

- Higgs signal strength
- Perturbativity
- Vacuum stability

  stable, meta, unstable
- Electroweak precision



Summary



Optimising data analysis/interpretation is primary goal at LHC

➡ always trade-off between generality and precision (model dependence)

➡ EFT fits provide well-defined framework to extract information on UV physics from Higgs boson measurements

➡ Existing data and analysis strategies not sensitive enough to set strong constraints on Higgs width or Higgs selfcoupling

→ When sensitive, Higgs might cure us from Big Mac Blues