Energizing Higgs Phenomenology for the High-Luminosity Runs

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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

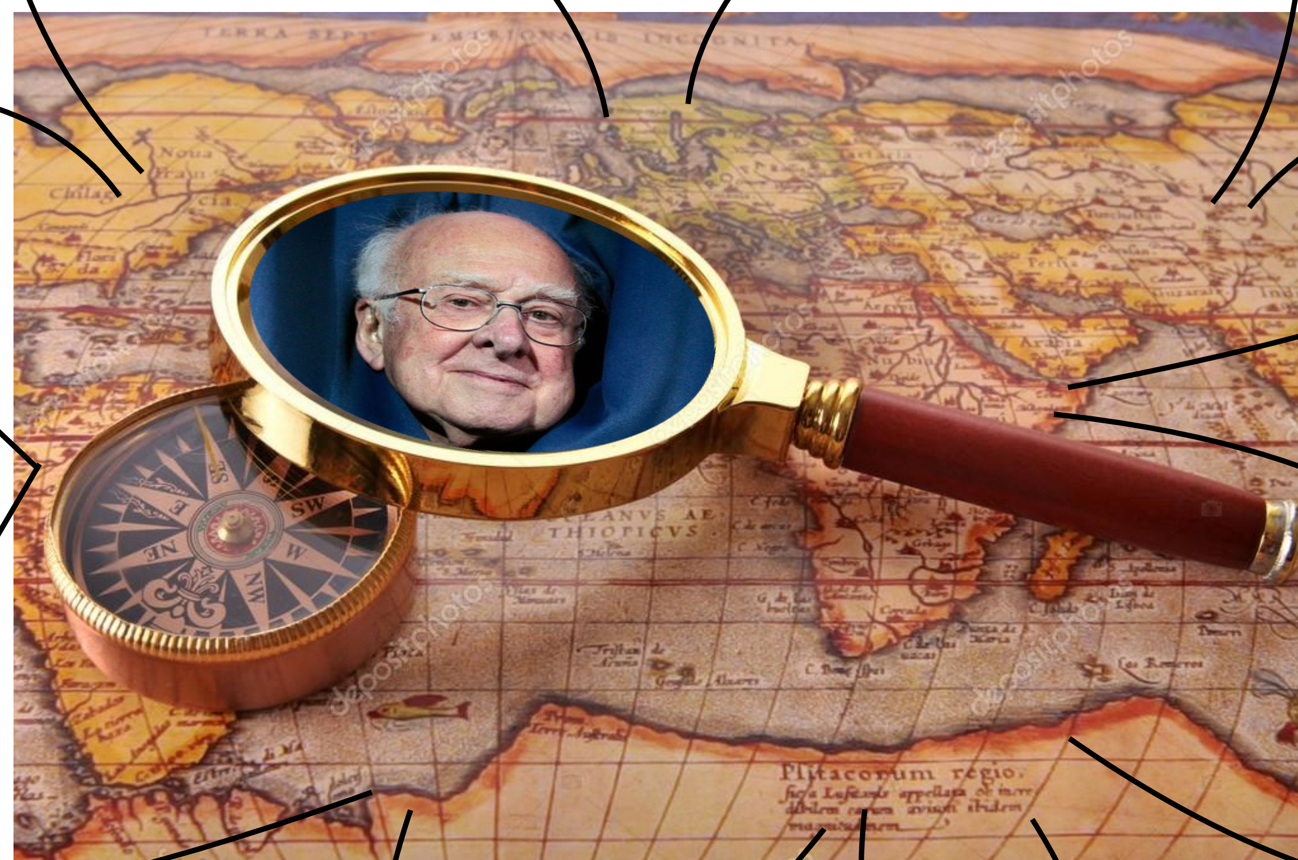
Sure, Higgs boson does the job, but...

hierarchy problem

non-pert. topological defects

elementary or composite

Matter/Antimatter asymmetry



Inflation and Reheating

Global structure of SSB potential

CP violation

Existence of light dof

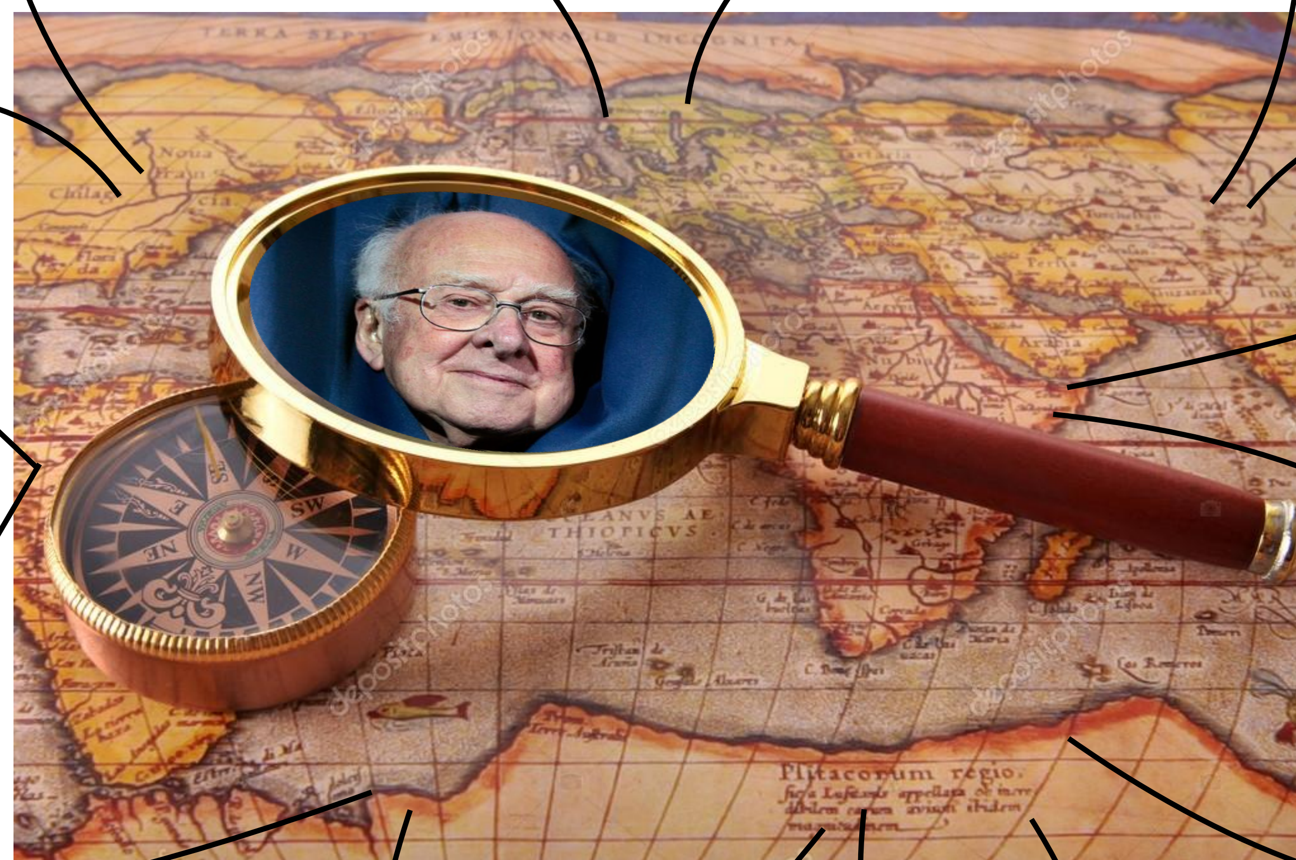
Talk by Shinya Matsuzaki

hierarchy problem

non-pert. topological defects

elementary or composite

Talk by Honghao Zhang



Talk by T. Yanagida

Talk by Yang Zhang

Matter/Antimatter asymmetry

Inflation and Reheating

Talk by Yi Wang

Talk by Cheng-Cheng Han

Talk by Li-Gong Bian

Talk by Jianghao Yu

Global structure of SSB potential

CP violation

Talk by Qinghong Cao

Existence of light dof

Talk by Zhongzhi Xianyu

Talk by Hong-jian He

Talk by Yan Wang

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

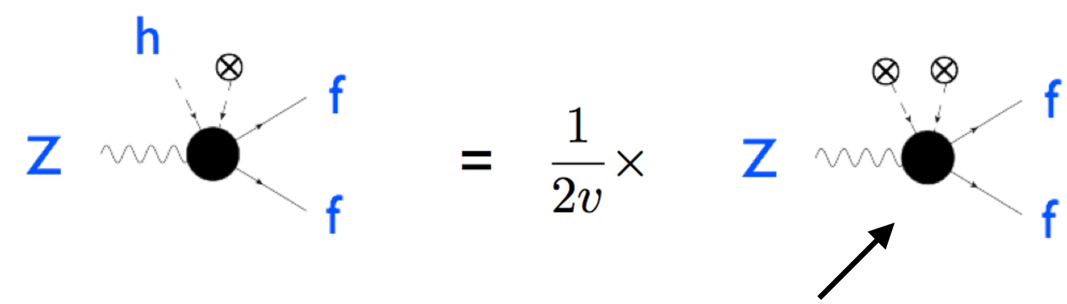
$$\mathcal{O}_H = \tfrac{1}{2}(\partial^\mu |H|^2)^2$$
$$\mathcal{O}_T = \tfrac{1}{2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$$
$$\mathcal{O}_6 = \lambda |H|^6$$

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

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

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

- 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:

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

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

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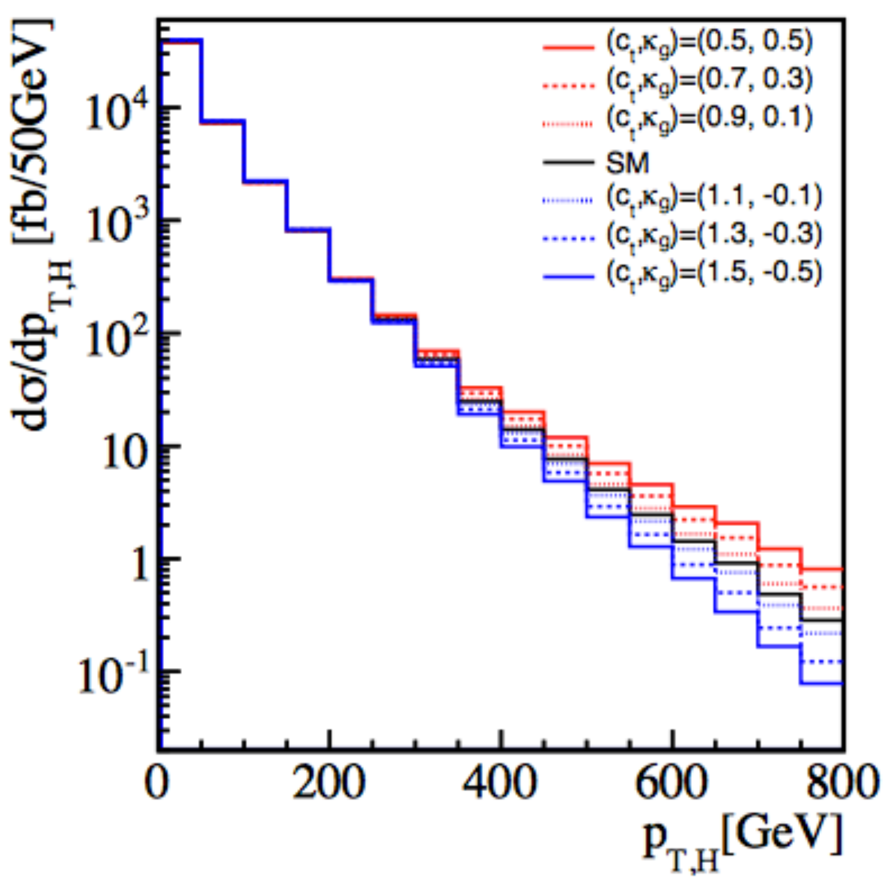
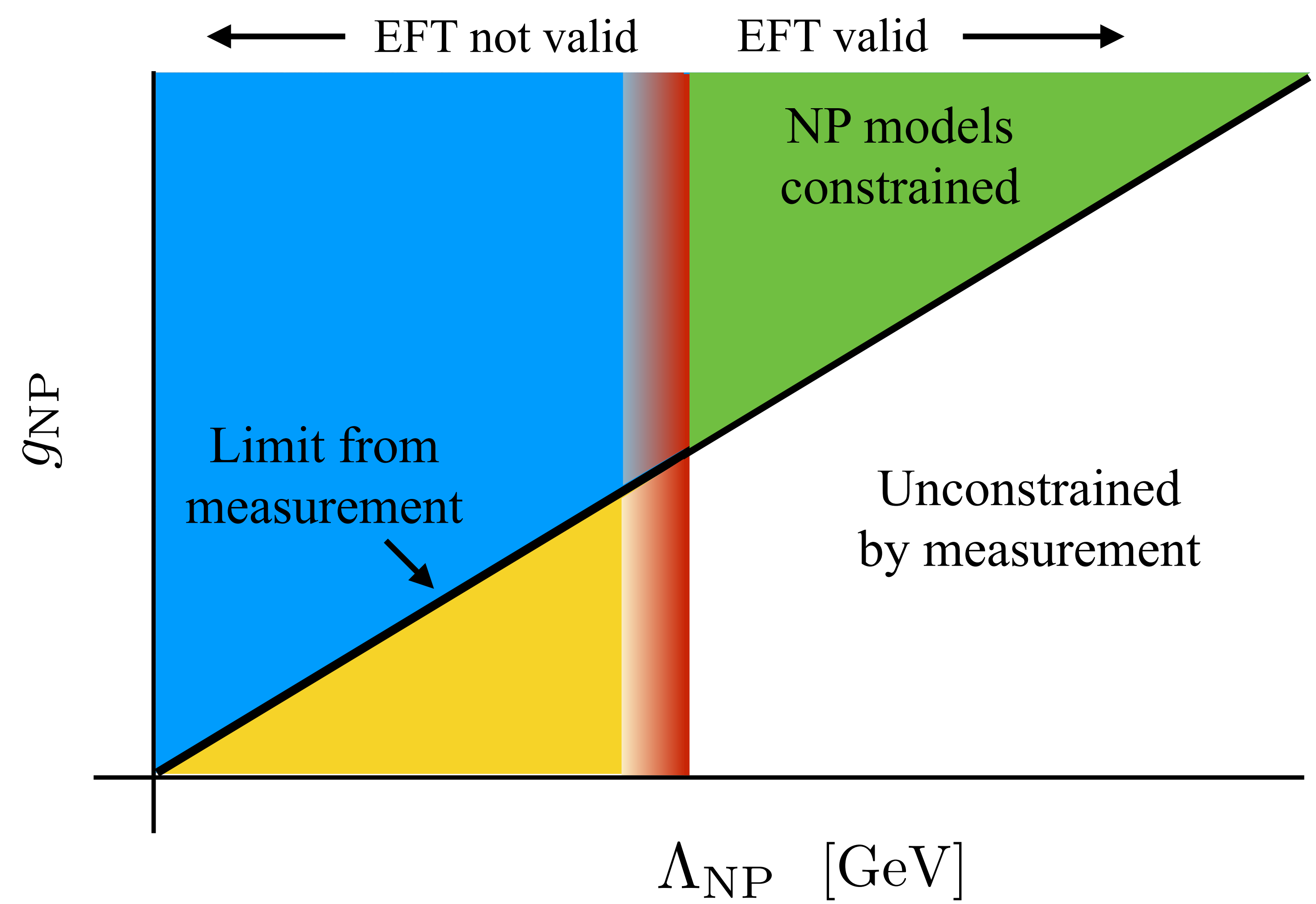
[Englert, MS '14]





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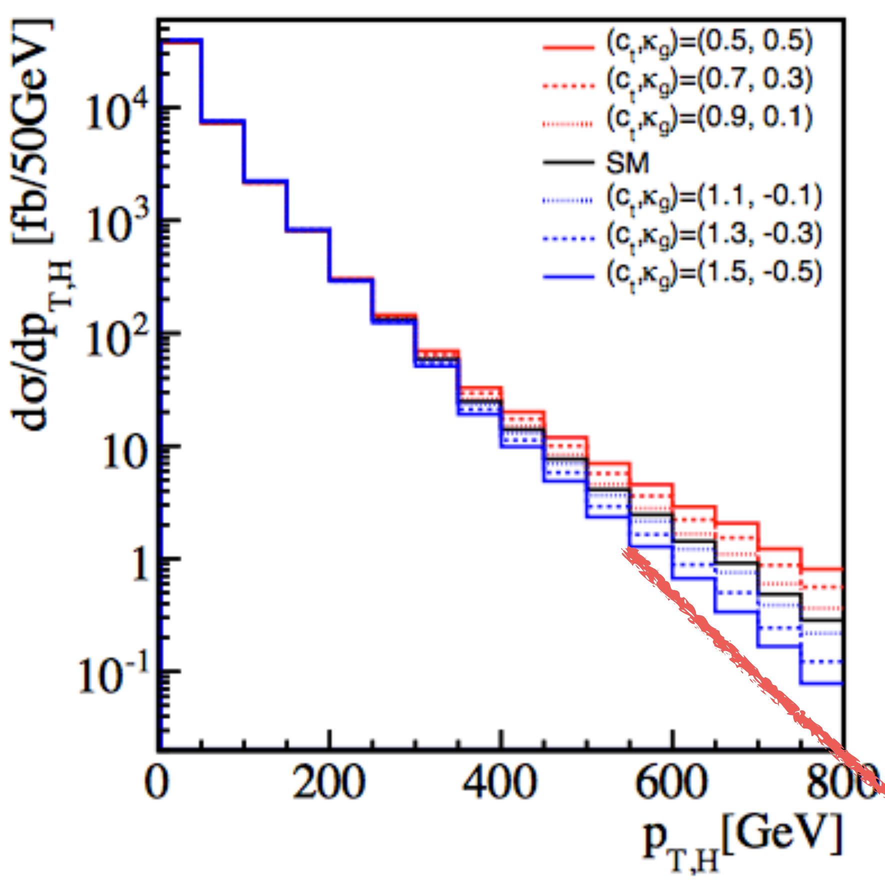
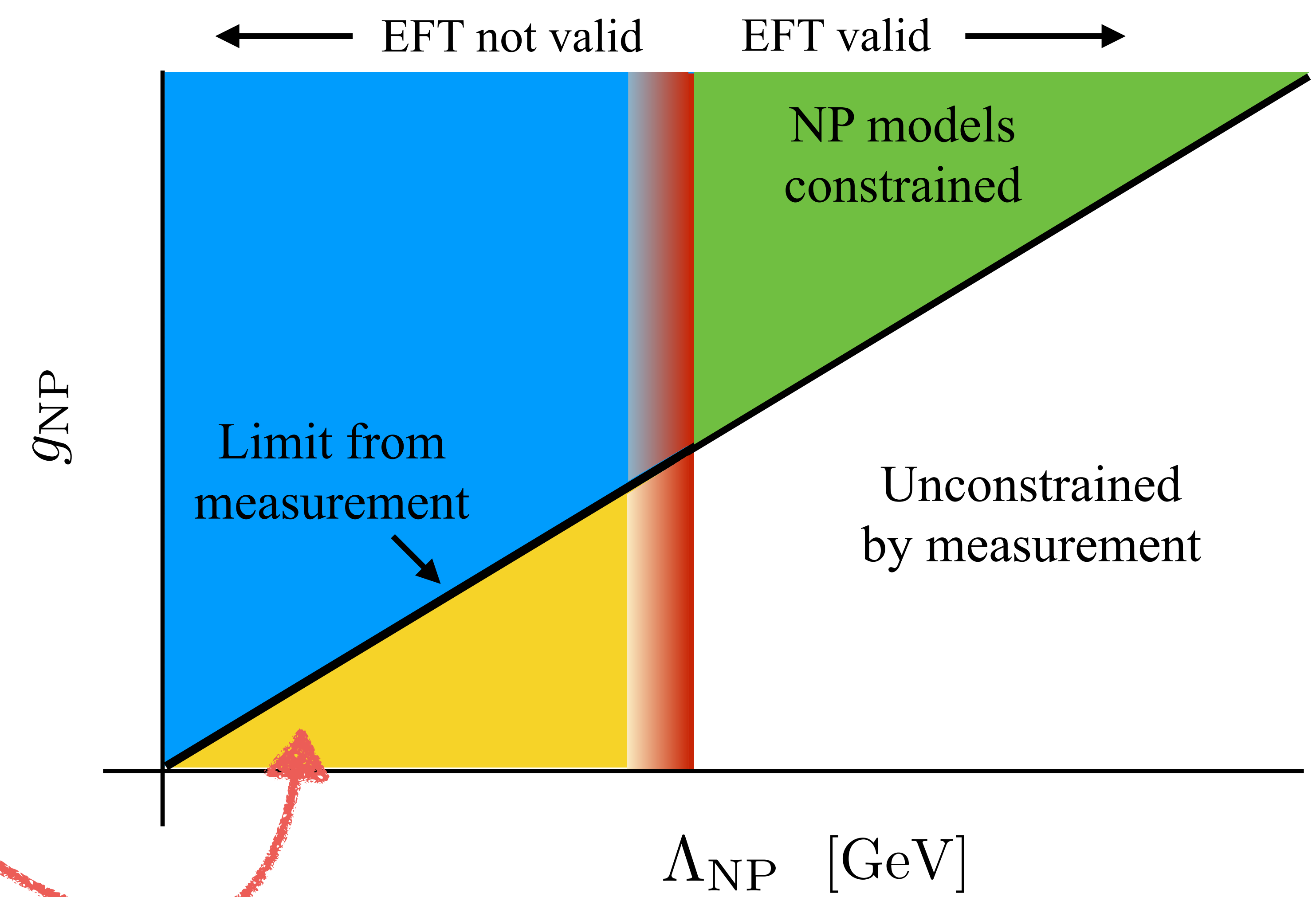


shape sets limit on Wilson coefficient (black line)



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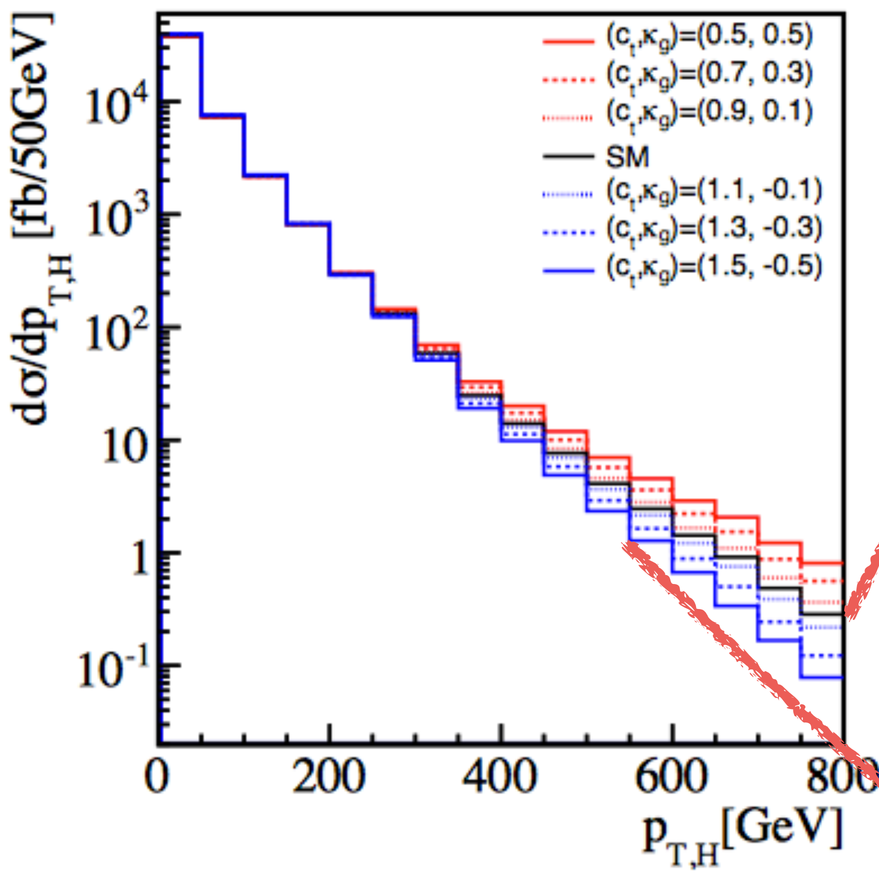
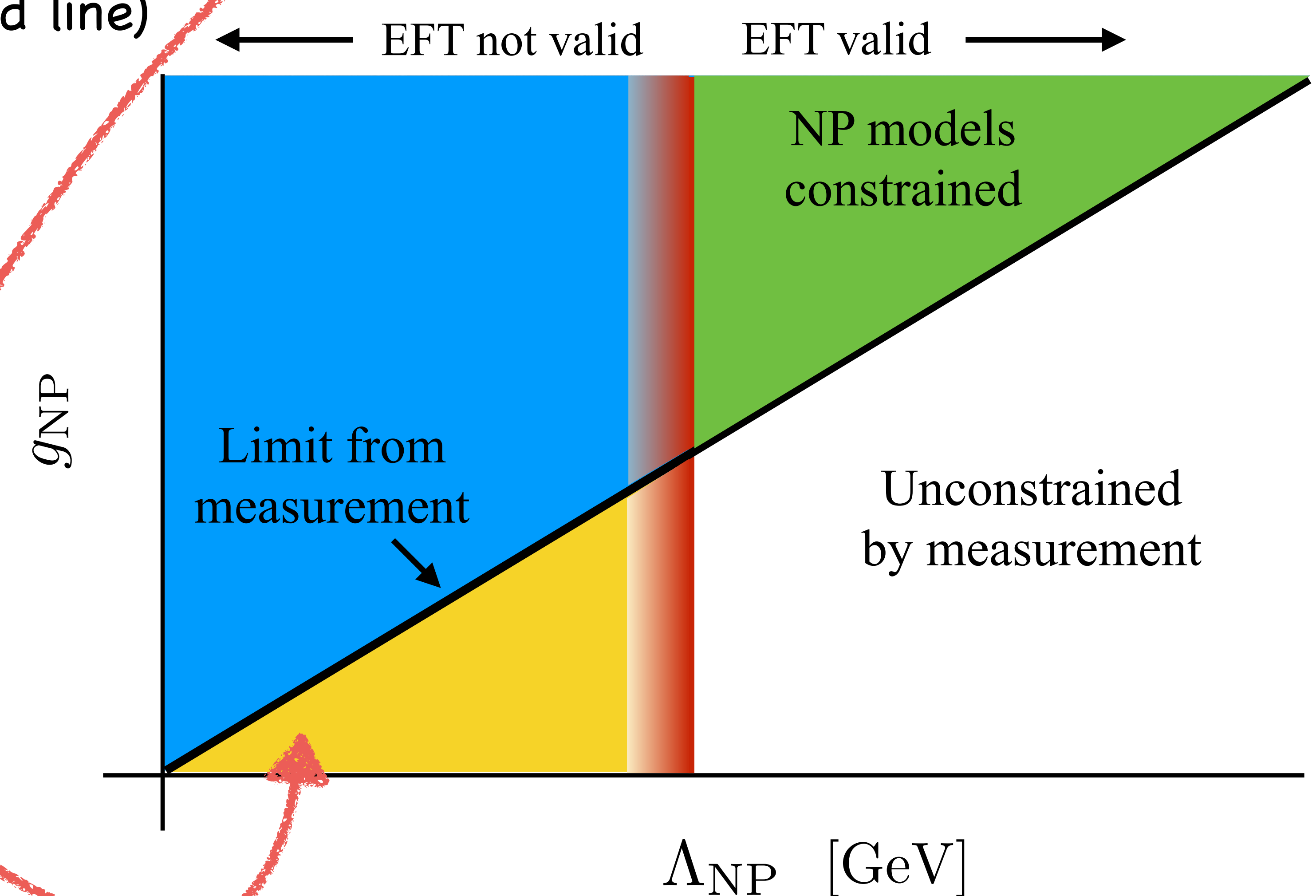
Endpoint of kinematic distribution sets lower cut-off for NP (red line)



[Englert, MS '14]



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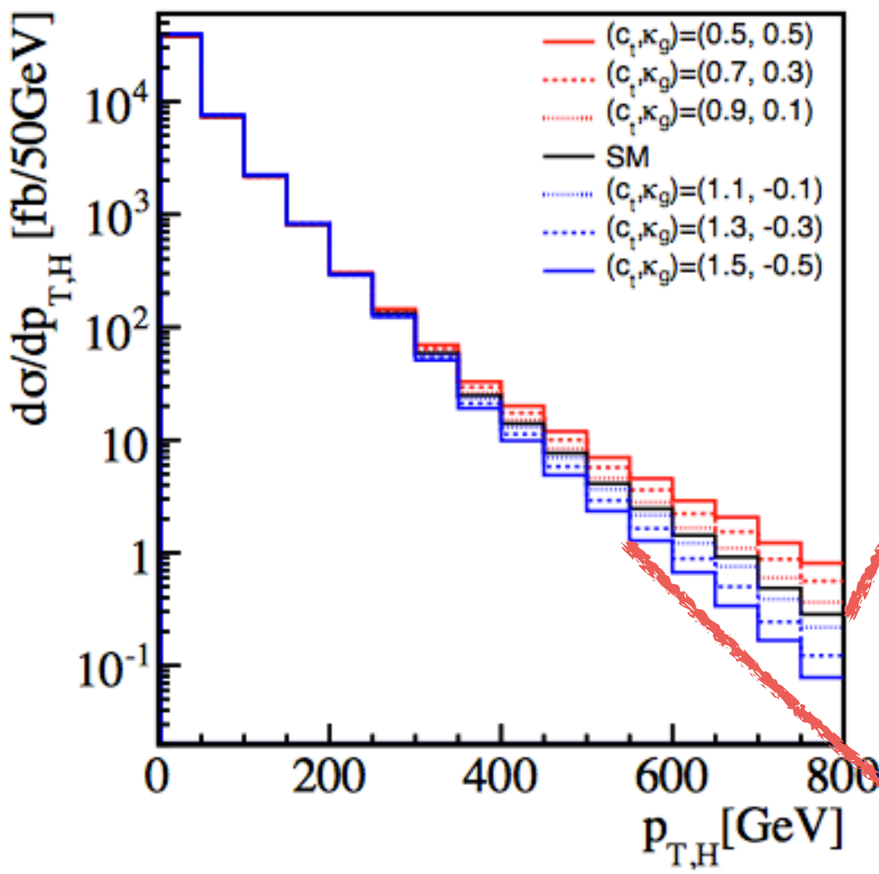
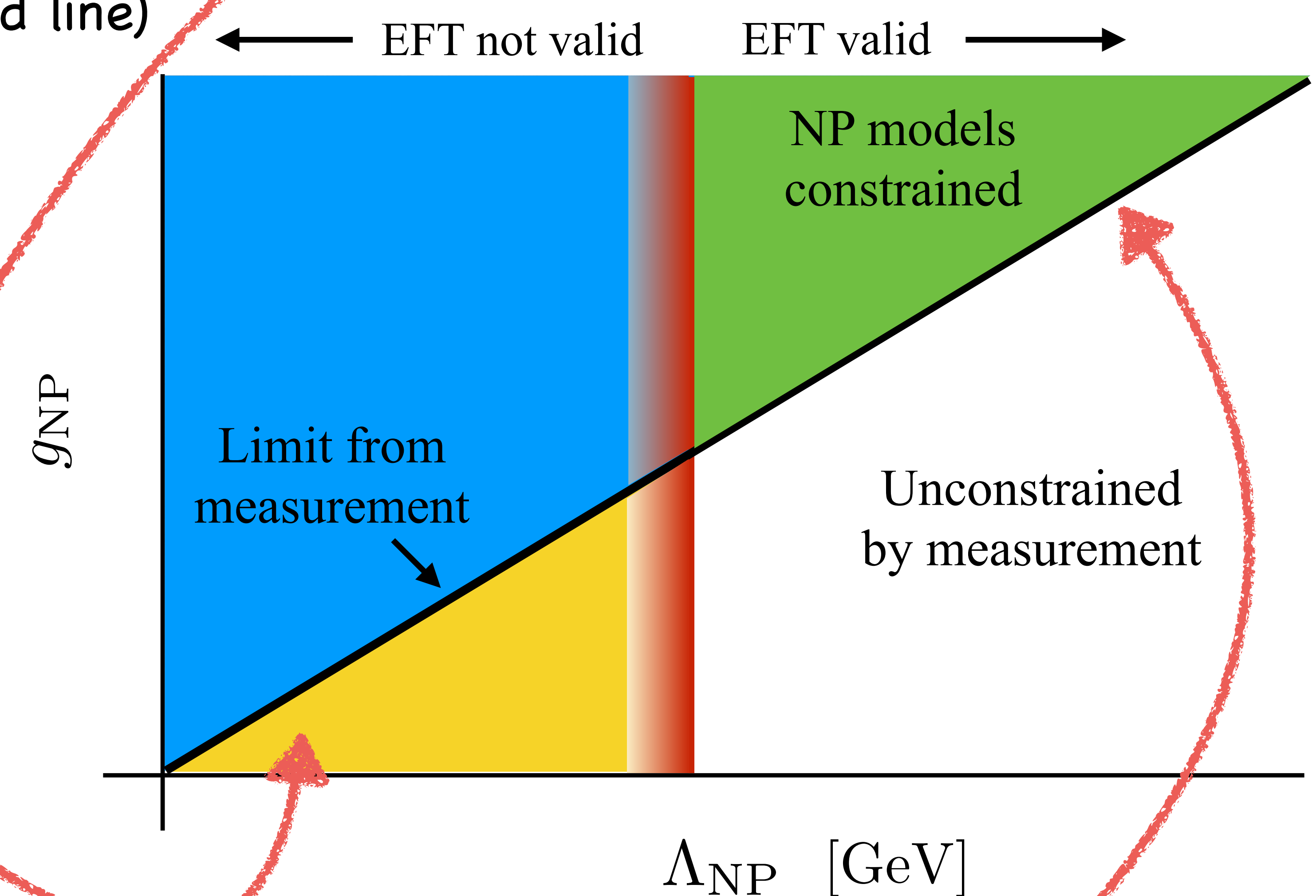




shape sets limit on Wilson coefficient (black line)

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:

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

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

Number of predicted events:

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

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)

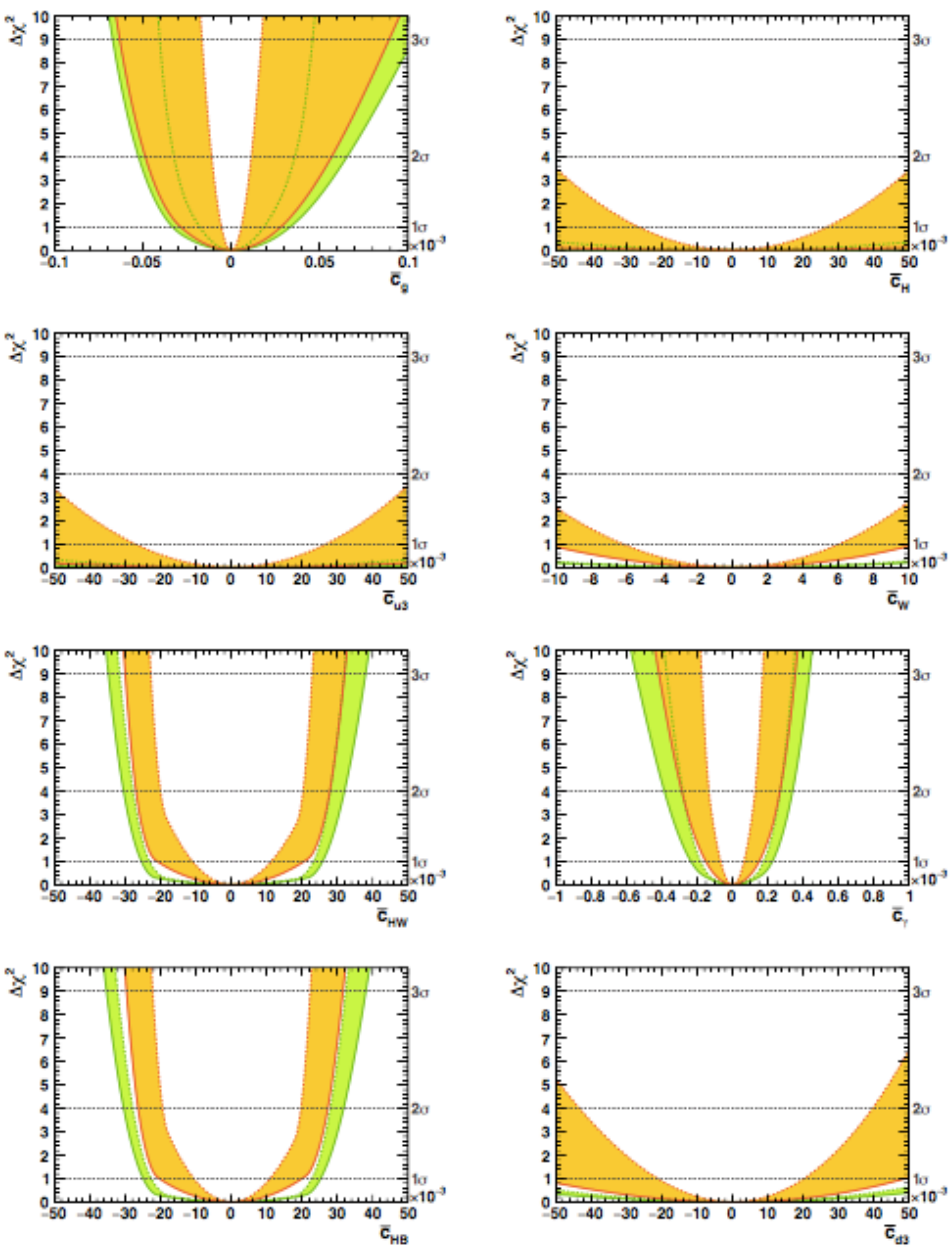
46 indep. meas. (3000 ifb)

differential:

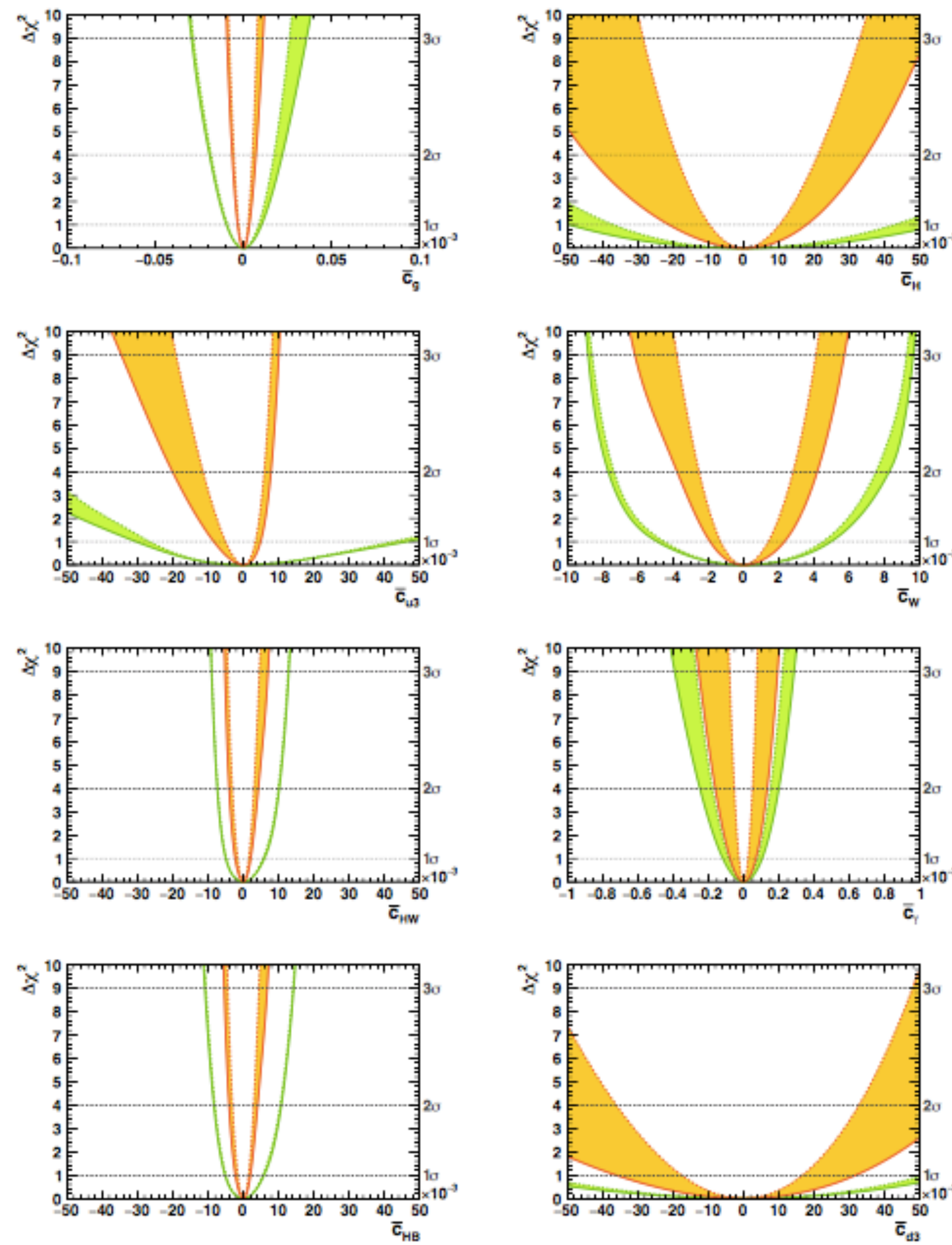
88 indep. meas. (300 ifb)

123 indep. meas. (3000 ifb)

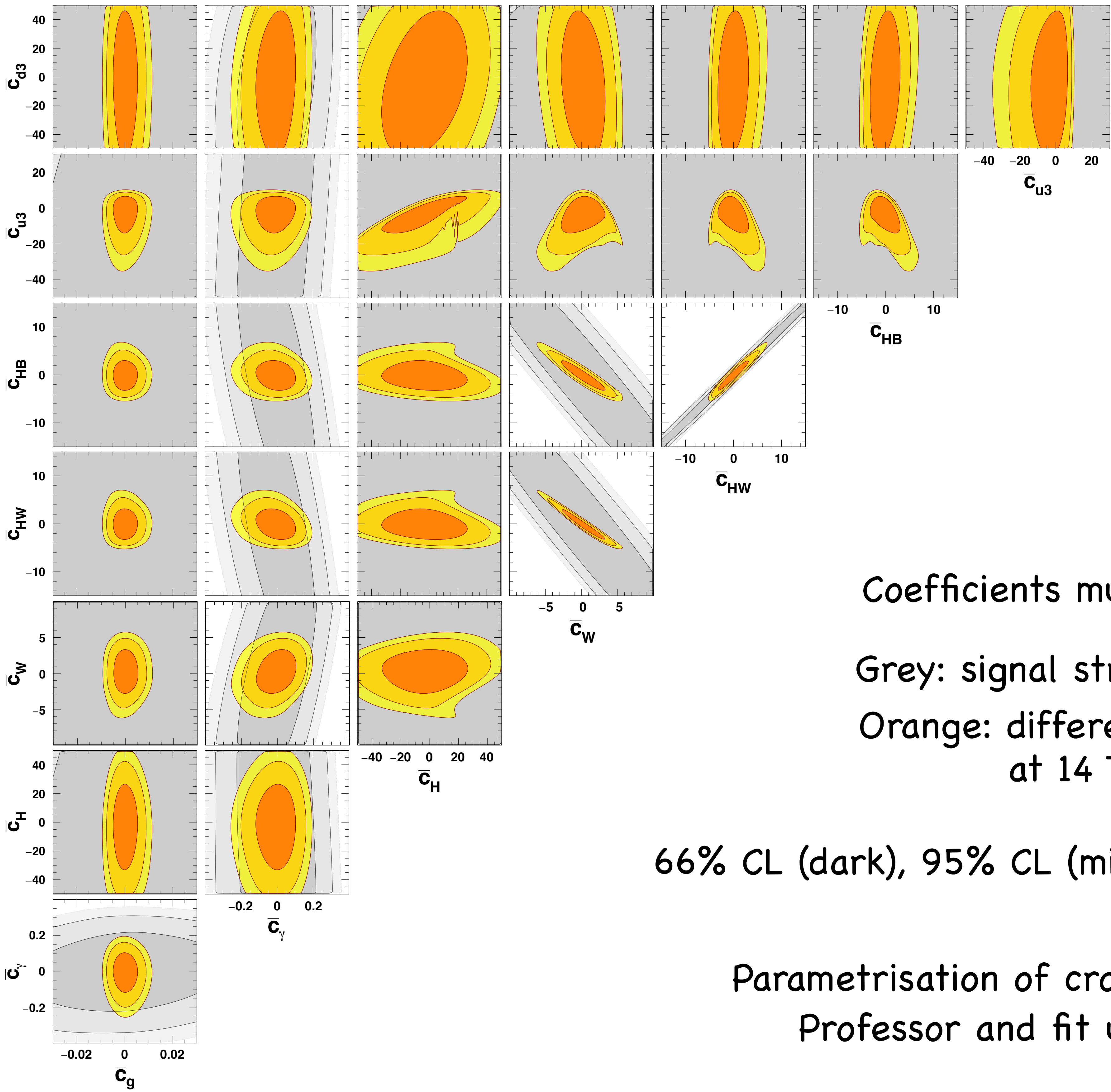
signal strength measurement



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

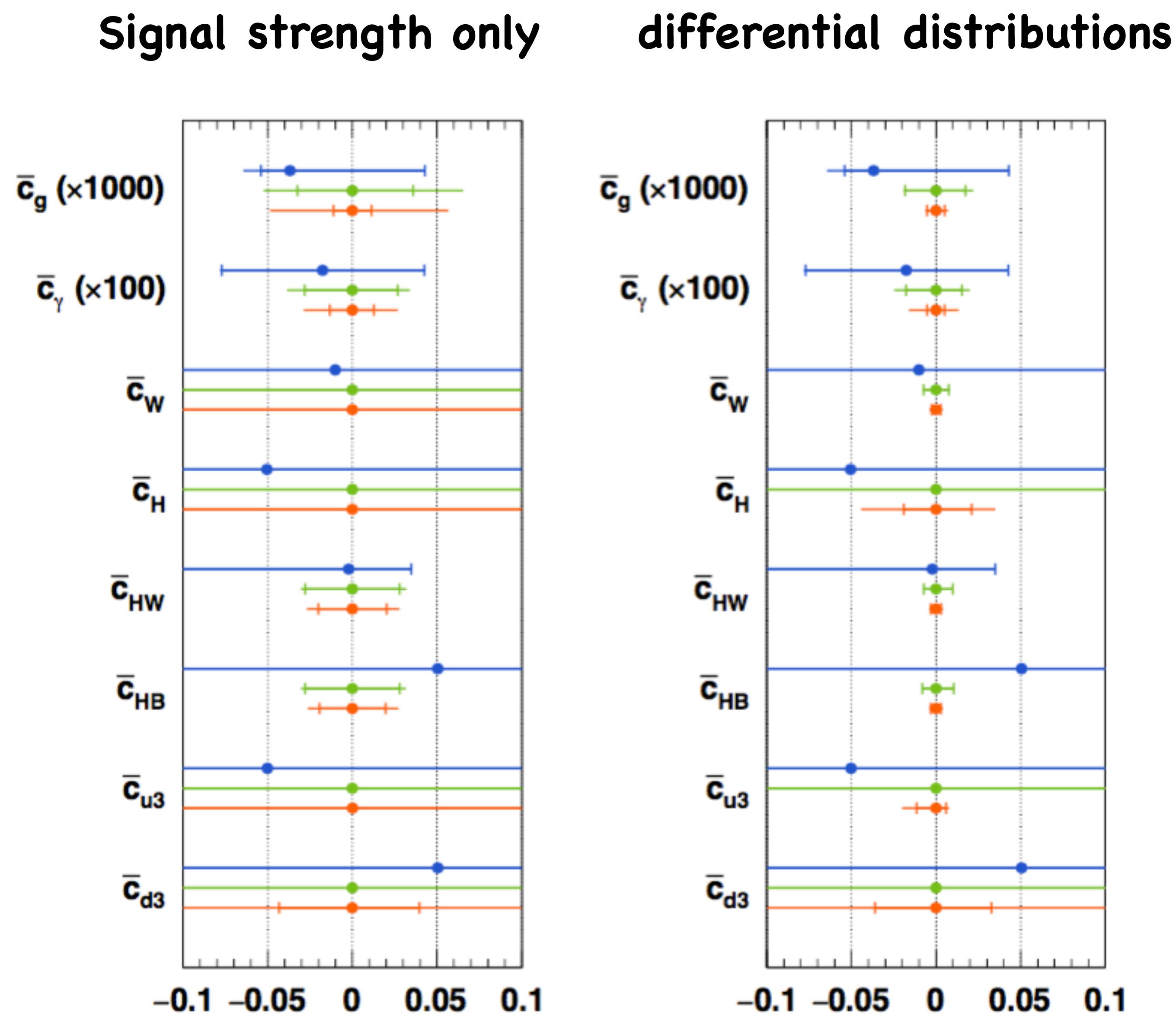
66% CL (dark), 95% CL (middle), 99% CL (light)

Parametrisation of cross sections with Professor and fit using Gfitter

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:

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

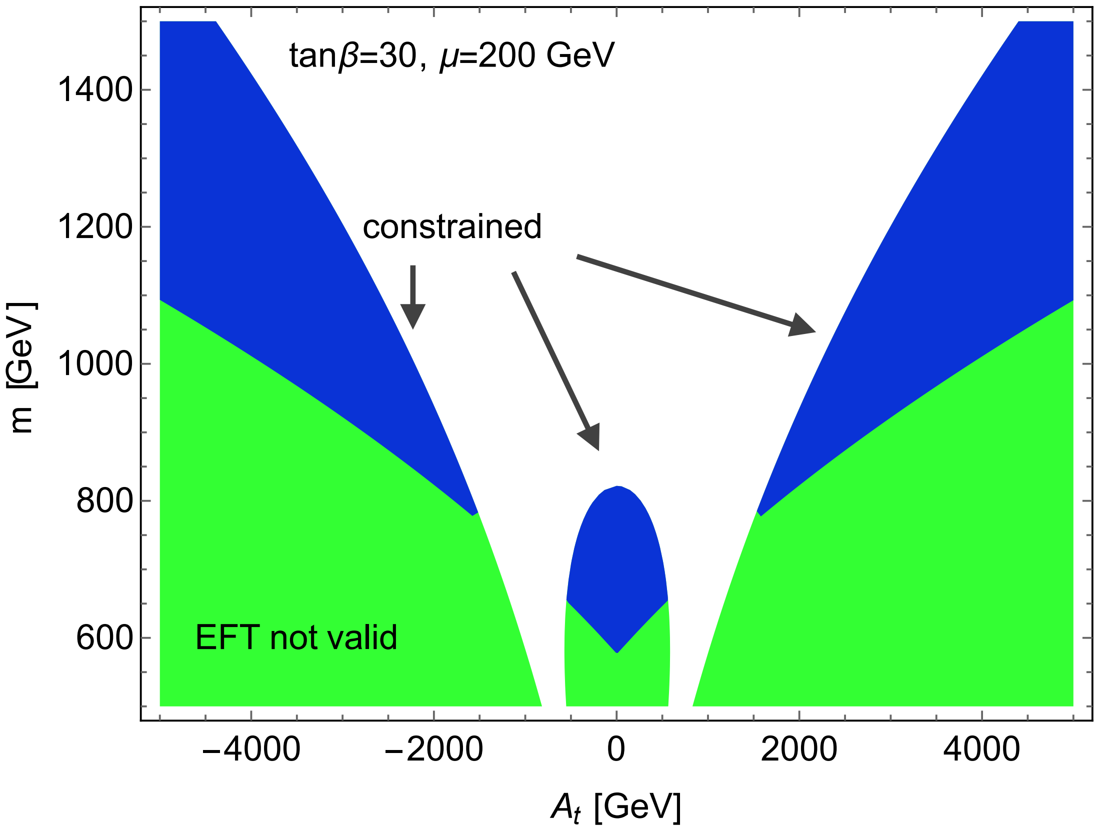
$m_{\tilde{Q}} = m_{\tilde{t}} = m$

$\tan\beta = 30$

$\mu = 200$ GeV

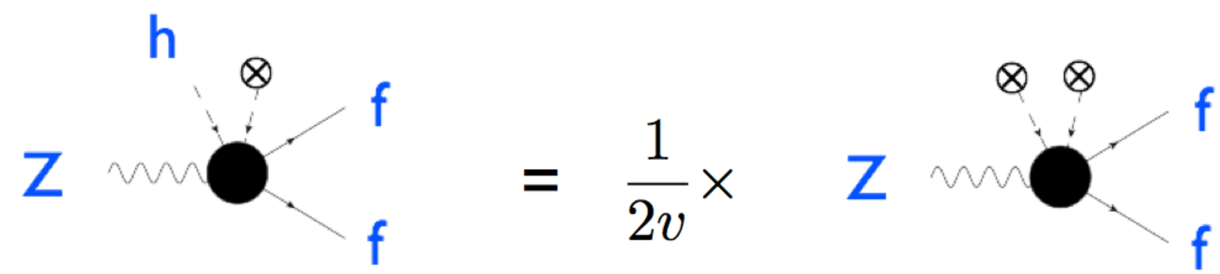
$h_t \equiv y_t s_\beta$

→ large At can be constrained



However, how about operators that have been tested at LEP via Z and W pole measurements?

Can energy enhancement in EFT framework combined with direct Higgs measurement overcome precision of linear e+e- collider? E.g. for

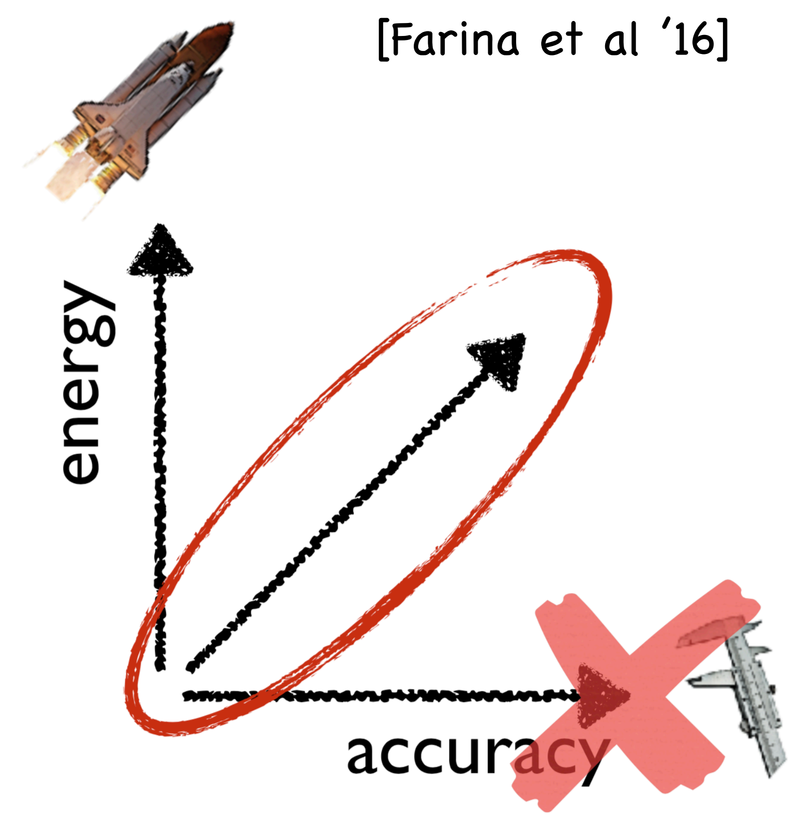


Can we perform electroweak precision measurements at the LHC?

[Farina et al '16]

Yes, `cause energy helps accuracy within an EFT framework:

$$\frac{\mathcal{A}_{\rm SM+BSM}}{\mathcal{A}_{\rm SM}} \sim 1 + \# \frac{E^2}{\Lambda^2}$$



LHC can match LEP accuracy in high E regime

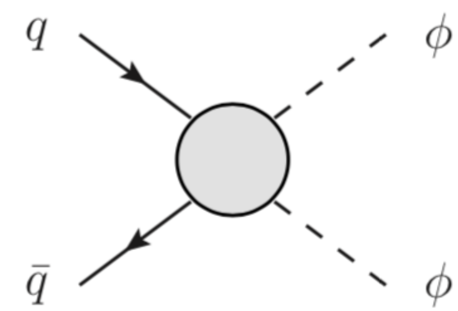
$$0.1\ \%\quad \text{at}\quad 100\ \text{GeV} \longrightarrow 10\ \%\quad \text{at}\quad 1\ \text{TeV}$$

LEP energy *LHC energy*

Higgs dynamics at high energies

- at high goldstone equivalence allows to test Higgs dynamics

- diboson production at high energies



- Interference between the SM and new-physics (at dim-6 level) only at longitudinal

→ growth at high energy

- 4 high-energy Primaries with leading-order interference and energy growth

Amplitude	High-energy primaries	Low-energy primaries
$\bar{u}_L d_L \to W_L Z_L, W_L h$	$\sqrt{2} a_q^{(3)}$	$\sqrt{2}\frac{g^2}{m_W^2}\left[c_{\theta_W}(\delta g_{uL}^Z - \delta g_{dL}^Z)/g - c_{\theta_W}^2 \delta g_1^Z\right]$
$\bar{u}_L u_L \to W_L W_L$ $\bar{d}_L d_L \to Z_L h$	$a_q^{(1)} + a_q^{(3)}$	$-\frac{2g^2}{m_W^2}\left[Y_L t_{\theta_W}^2 \delta\kappa_\gamma + T_Z^{u_L}\delta g_1^Z + c_{\theta_W}\delta g_{dL}^Z/g\right]$
$\bar{d}_L d_L \to W_L W_L$ $\bar{u}_L u_L \to Z_L h$	$a_q^{(1)} - a_q^{(3)}$	$-\frac{2g^2}{m_W^2}\left[Y_L t_{\theta_W}^2 \delta\kappa_\gamma + T_Z^{d_L}\delta g_1^Z + c_{\theta_W}\delta g_{uL}^Z/g\right]$
$\bar{f}_R f_R \to W_L W_L, Z_L h$	a_f	$-\frac{2g^2}{m_W^2}\left[Y_{f_R} t_{\theta_W}^2 \delta\kappa_\gamma + T_Z^{f_R}\delta g_1^Z + c_{\theta_W}\delta g_{fR}^Z/g\right]$

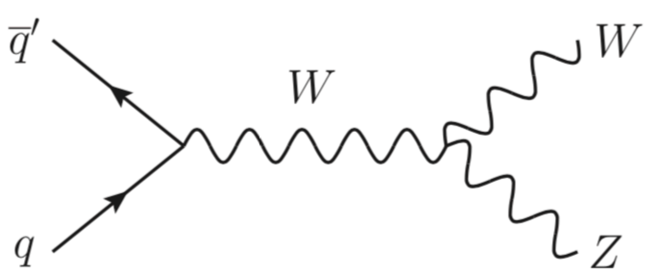
Warsaw

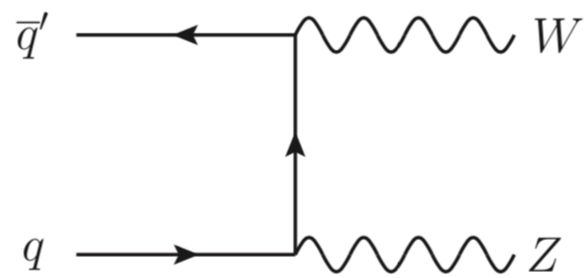
$$\mathcal{O}_L^3 = (\bar{q}_L \sigma^a \gamma^\mu q_L)(iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H)$$
$$\mathcal{O}_L = (\bar{q}_L \gamma^\mu q_L)(iH^\dagger \overleftrightarrow{D}_\mu H)$$
$$\mathcal{O}_R^u = (\bar{u}_R \gamma^\mu u_R)(iH^\dagger \overleftrightarrow{D}_\mu H)$$
$$\mathcal{O}_R^d = (\bar{d}_R \gamma^\mu d_R)(iH^\dagger \overleftrightarrow{D}_\mu H)$$

Rel to SILH: $a_q^{(3)} = \frac{g^2}{M^2}(c_W + c_{HW} - c_{2W})$ and $a_q^{(1)} = \frac{g'^2}{3M^2}(c_B + c_{HB} - c_{2B})$

WZ production

[Franceschini, Panico, Pomarol, Riva, Wulzer '17]

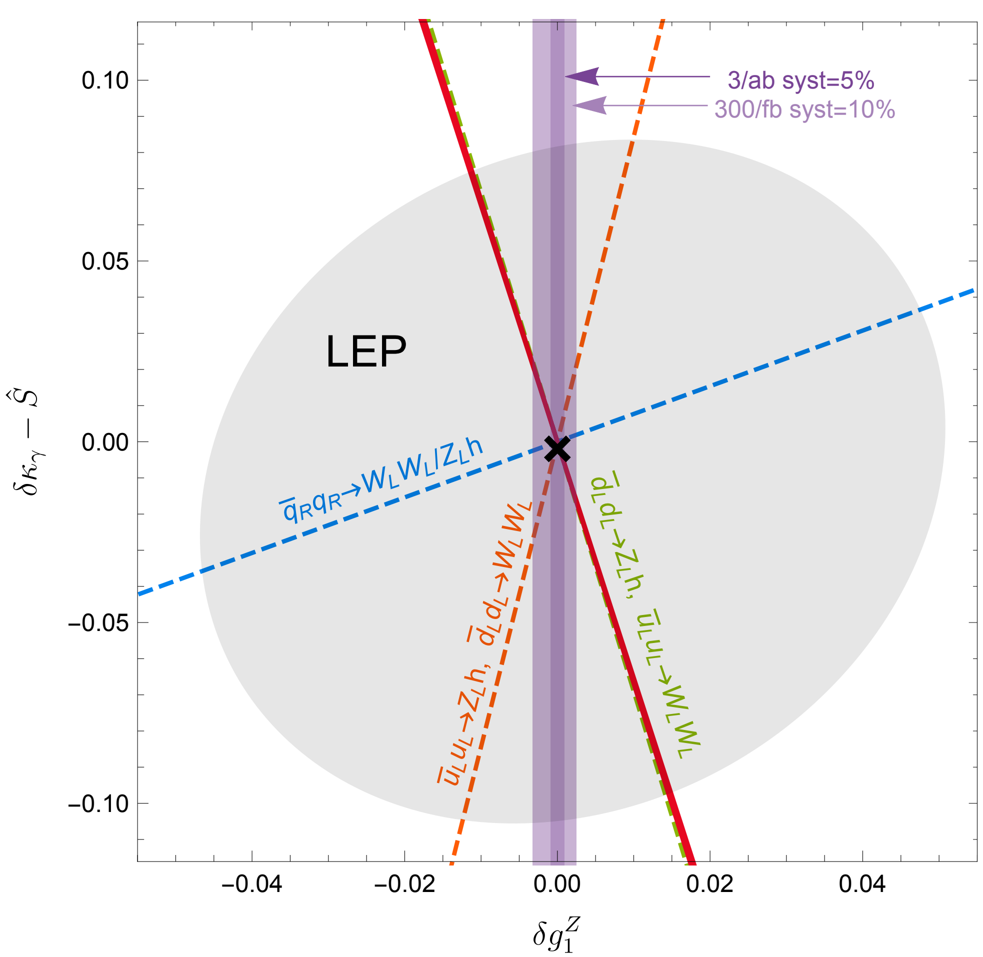




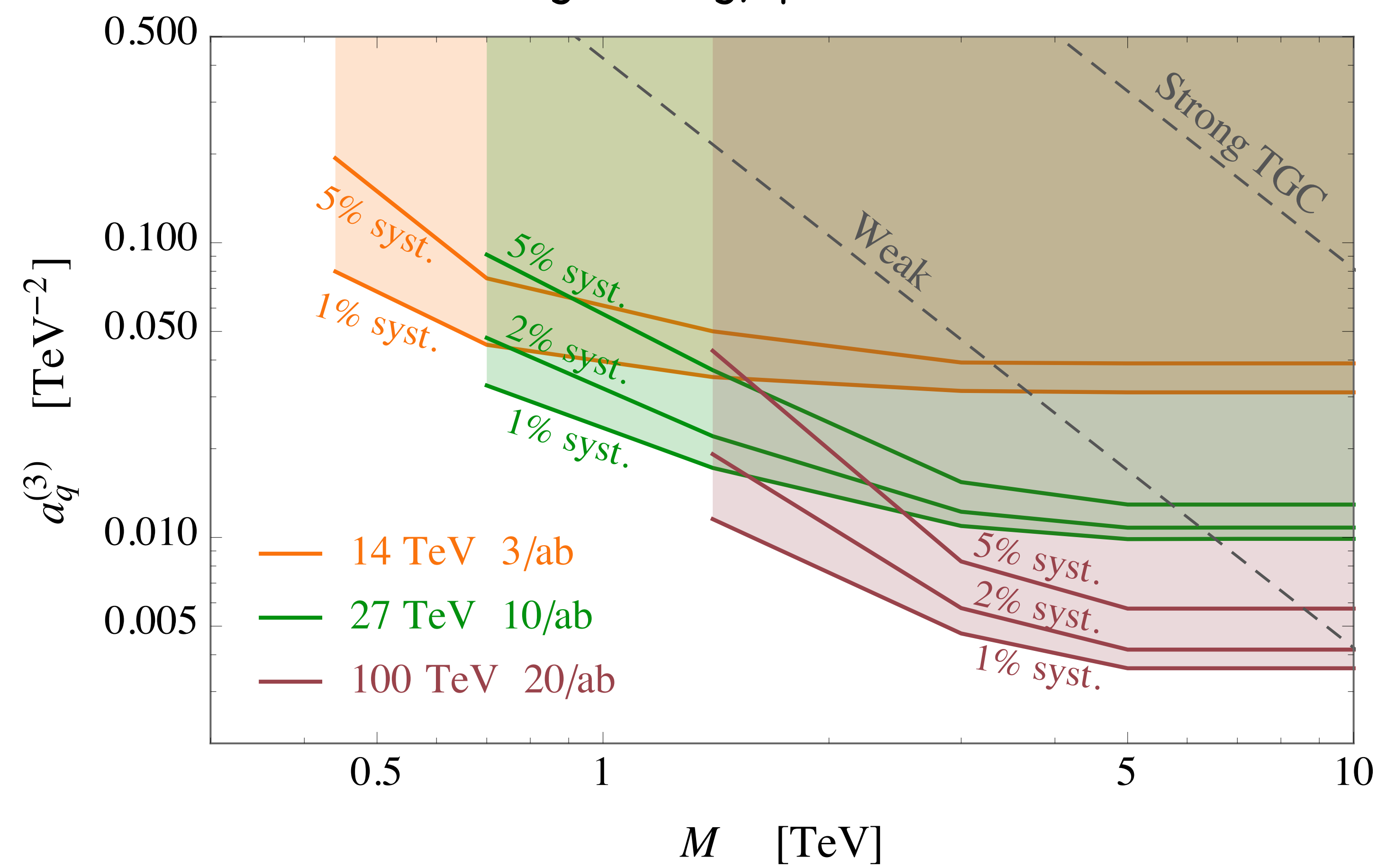
$$\frac{\mathcal{A}_{LL}^{\text{SM + BSM}}(q\bar{q} \to WZ)}{\mathcal{A}_{LL}^{\text{SM}}(q\bar{q} \to WZ)} \sim 1 + a_q^{(3)} E^2$$

- transverse modes minimal for central scattering though longitudinal maximal

Low-energy primaries



high-energy primaries



HZ / HW production

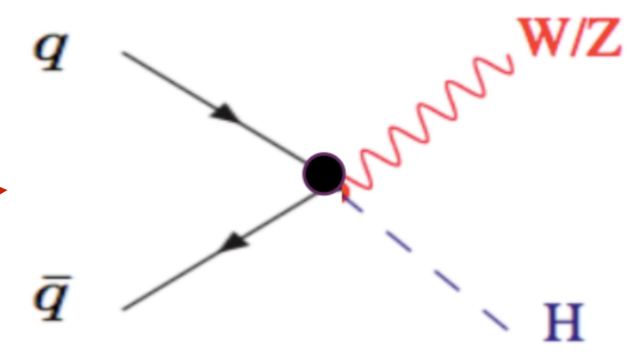
[Banerjee, Englert, Gupta, MS '18]

$$\Delta\mathcal{L}_6 \supset \sum_f \delta g_f^Z Z_\mu \bar{f}\gamma^\mu f + \delta g_{ud}^W (W_\mu^+ \bar{u}_L \gamma^\mu d_L + h.c.)$$

$$g_{VV}^h\, h \left[W^{+\,\mu} W_\mu^- + \frac{1}{2c_{\theta_W}^2} Z^\mu Z_\mu\right] + \delta g_{ZZ}^h\, h \frac{Z^\mu Z_\mu}{2c_{\theta_W}^2}$$

$$\sum_f g_{Zf}^h \frac{h}{v} Z_\mu \bar{f}\gamma^\mu f + g_{Wud}^h \frac{h}{v}(W_\mu^+ \bar{u}_L \gamma^\mu d_L + h.c.)$$

$$+\kappa_{Z\gamma}\frac{h}{v}A^{\mu\nu}Z_{\mu\nu} + \kappa_{WW}\frac{h}{v}W^{+\,\mu\nu}W_{\mu\nu}^- + \kappa_{ZZ}\frac{h}{2v}Z^{\mu\nu}Z_{\mu\nu}\,.$$



this leads to four matrix elements contributing to the process

$$\mathcal{M}(ff \to Z_L h) =$$

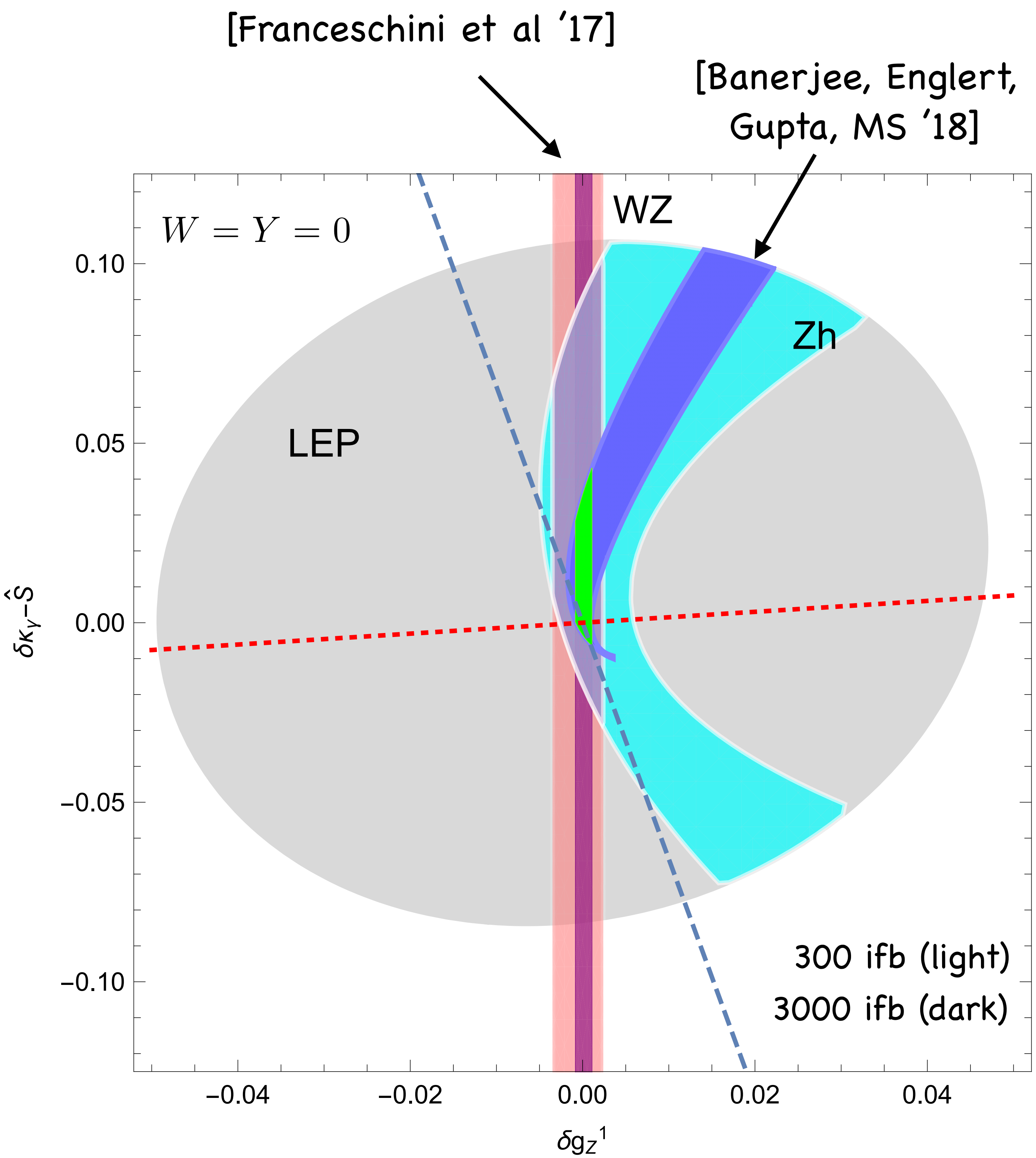
$$g_f^Z \frac{q\cdot J_f}{v}\frac{2m_Z}{\hat{s}}\left[1 + \frac{g_{Zff}^h}{g_f^Z}\frac{\hat{s}}{2m_Z^2}\right]$$

$$g_{Zu_Lu_L}^h = -\frac{g}{c_{\theta_W}}\left((c_{\theta_W}^2 + \frac{s_{\theta_W}^2}{3})\delta g_1^Z + W + \frac{t_{\theta_W}^2}{3}(\hat{S} - \delta\kappa_\gamma - Y)\right)$$

$$g_{Zd_Ld_L}^h = \frac{g}{c_{\theta_W}}\left((c_{\theta_W}^2 - \frac{s_{\theta_W}^2}{3})\delta g_1^Z + W - \frac{t_{\theta_W}^2}{3}(\hat{S} - \delta\kappa_\gamma - Y)\right)$$

$$g_{Zu_Ru_R}^h = -\frac{4gs_{\theta_W}^2}{3c_{\theta_W}^3}(\hat{S} - \delta\kappa_\gamma + c_{\theta_W}^2\delta g_1^Z - Y)$$

$$g_{Zd_Rd_R}^h = \frac{2gs_{\theta_W}^2}{3c_{\theta_W}^3}(\hat{S} - \delta\kappa_\gamma + c_{\theta_W}^2\delta g_1^Z - Y)$$



- Isolating couplings to u- vs d-quark and L vs R is difficult at LHC

eff. L/R couplings:

$$g^Z_{\mathbf{u}} = g^h_{Zu_L} + \frac{g^Z_{u_R}}{g^Z_{u_L}} g^h_{Zu_R}$$

$$g^Z_{\mathbf{d}} = g^h_{Zd_L} + \frac{g^Z_{d_R}}{g^Z_{d_L}} g^h_{Zd_R}$$

eff. up/down couplings:

$$g^Z_{\mathbf{p}} = g^Z_{\mathbf{u}} + \frac{\mathcal{L}_d(\hat{s})}{\mathcal{L}_u(\hat{s})} g^Z_{\mathbf{d}}$$

eff proton coupling:

$$g^Z_{\mathbf{p}} = g^h_{Zu_L} - 0.76\ g^h_{Zd_L} - 0.45\ g^h_{Zu_R} + 0.14\ g^h_{Zd_R}$$

- Boosted Higgs (H->bb)Z analysis

Projected sensitivity

$$g^h_{Z\mathbf{p}} \in [-0.003, 0.003] \quad (300\ \text{fb}^{-1})$$
$$g^h_{Z\mathbf{p}} \in [-0.001, 0.001] \quad (3000\ \text{fb}^{-1})$$

	Our Projection	LEP Bound
$\delta g^Z_{u_L}$	$\pm 0.002\ (\pm 0.0007)$	-0.0026 ± 0.0016
$\delta g^Z_{d_L}$	$\pm 0.002\ (\pm 0.0005)$	0.0023 ± 0.001
$\delta g^Z_{u_R}$	$\pm 0.003\ (\pm 0.001)$	-0.0036 ± 0.0035
$\delta g^Z_{d_R}$	$\pm 0.011\ (\pm 0.004)$	0.0016 ± 0.0052
δg^Z_1	$\pm 0.003\ (\pm 0.001)$	$0.009^{+0.043}_{-0.042}$
$\delta \kappa_\gamma$	$\pm 0.020\ (\pm 0.008)$	$0.016^{+0.085}_{-0.096}$
S	$\pm 0.020\ (\pm 0.008)$	0.0004 ± 0.0007
W	$\pm 0.002\ (\pm 0.0008)$	0.0000 ± 0.0006
Y	$\pm 0.020\ (\pm 0.008)$	0.0003 ± 0.0006

- ee and pp colliders provide complementary view. One design not sufficient to rule them all (EFT operators).

- ee even more advantageous for leptonic operators

Two Higgs properties are of particular interest

Total width of Higgs (invisible decays)

Production

Decay into spec. channel

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

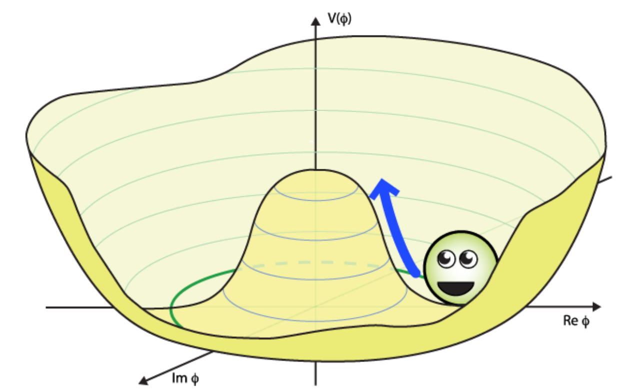
Sum of all possible decays

- Width affects all decay channels
- Indicative of new couplings (i.e. invisible or novel particles)
- Indicative of large coupling modifications, e.g. to second generation

Higgs self-coupling

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

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

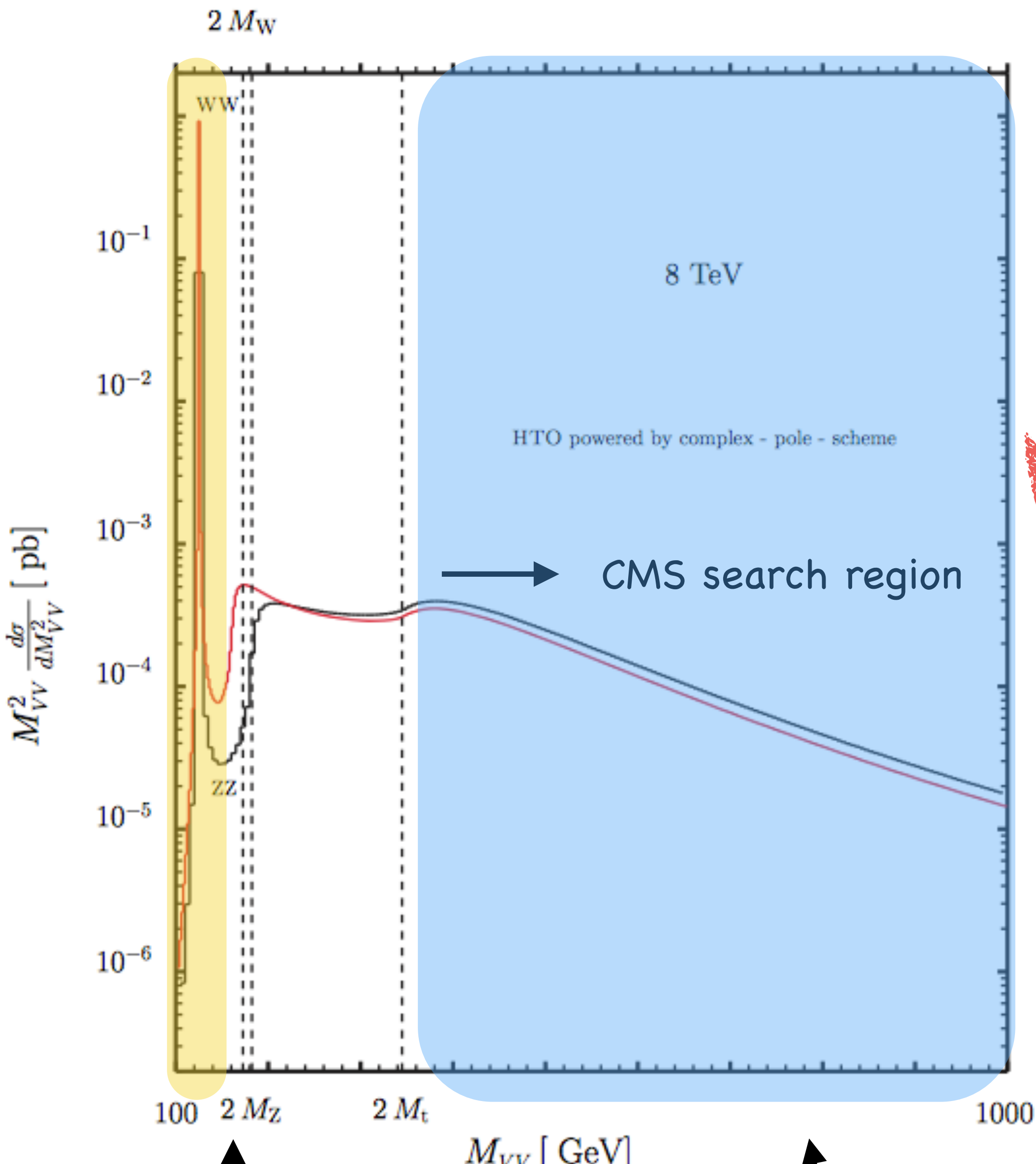


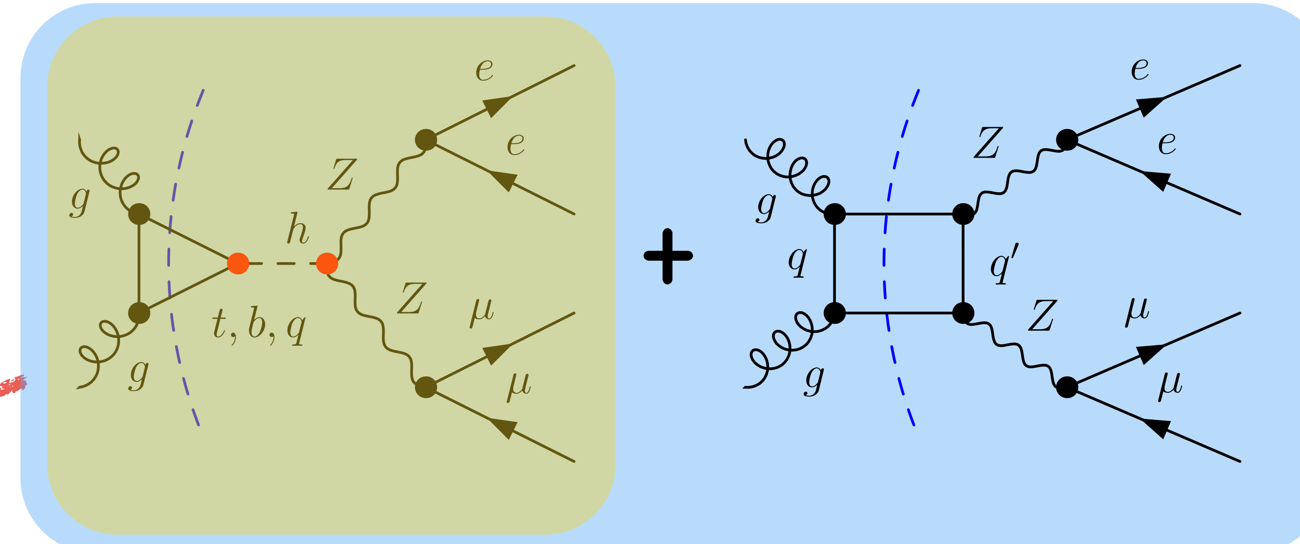
$$V(H) = \underbrace{\frac{1}{2} m_h^2}_{\mu^2} h^2 + \frac{1}{3!} \lambda_{hhh} h^3 + \frac{1}{4!} \lambda_{hhhh} h^4$$

- Indicative of ew sym. breaking potential
- Matter/Anti-matter asymmetry

CMS ‘width’ Measurement

See talk by Mingshui Chen





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

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

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

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

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

See talk by
Zhuoni Qian

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Kappa Framework

EFT

Simplified Models

Full (UV) Model

See talk by Zhuoni Qian

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Kappa Framework

- Assuming global coupling rescaling

EFT

Simplified Models

Full (UV) Model

See talk by Zhuoni Qian

Example 'width-measurement'

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

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

Kappa Framework ✓

- Assuming global coupling rescaling

EFT ✓

- Assuming valid and no flat directions

Simplified Models

Full (UV) Model

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Kappa Framework

- Assuming global coupling rescaling

EFT

- Assuming valid and no flat directions

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

See talk by Zhuoni Qian

Example 'width-measurement'

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

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Kappa Framework ✓

- Assuming global coupling rescaling

EFT ✓

- Assuming valid and no flat directions

Simplified Models ⚡

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Full (UV) Model ⚡

- Uninteresting width not a free parameter of the theory

  width derived and fully determined

See talk by Zhuoni Qian

Example 'width-measurement'

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

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

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 ⚡

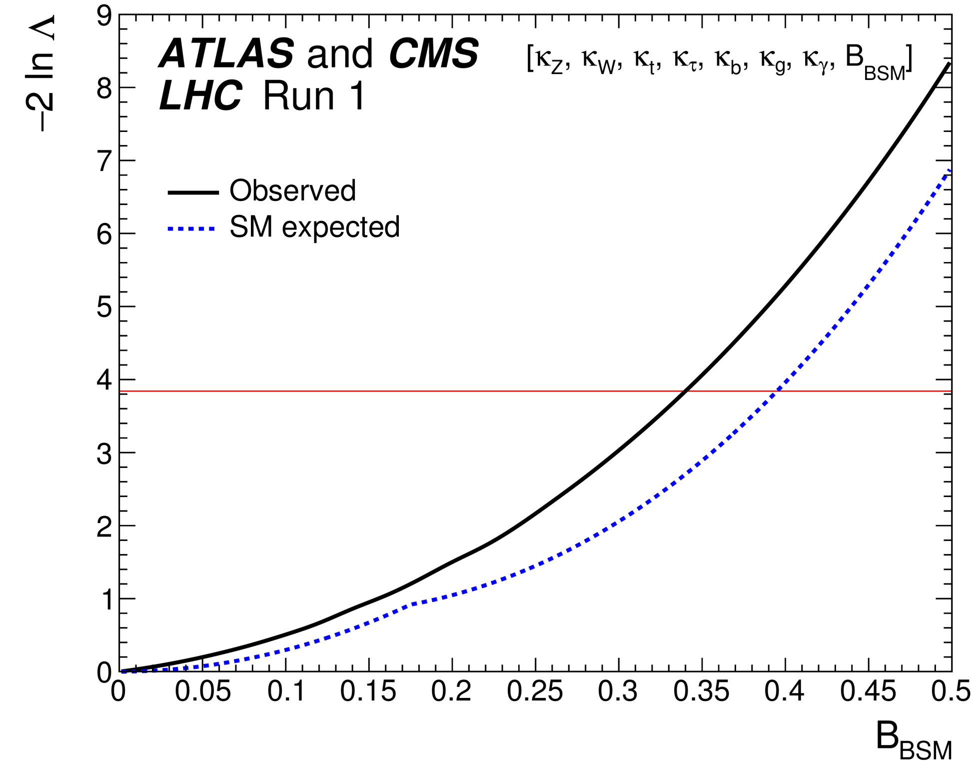
- Uninteresting width not a free parameter of the theory

  width derived and fully determined

See talk by Zhuoni Qian

Limit on invisible branching ratio from global Higgs fit

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



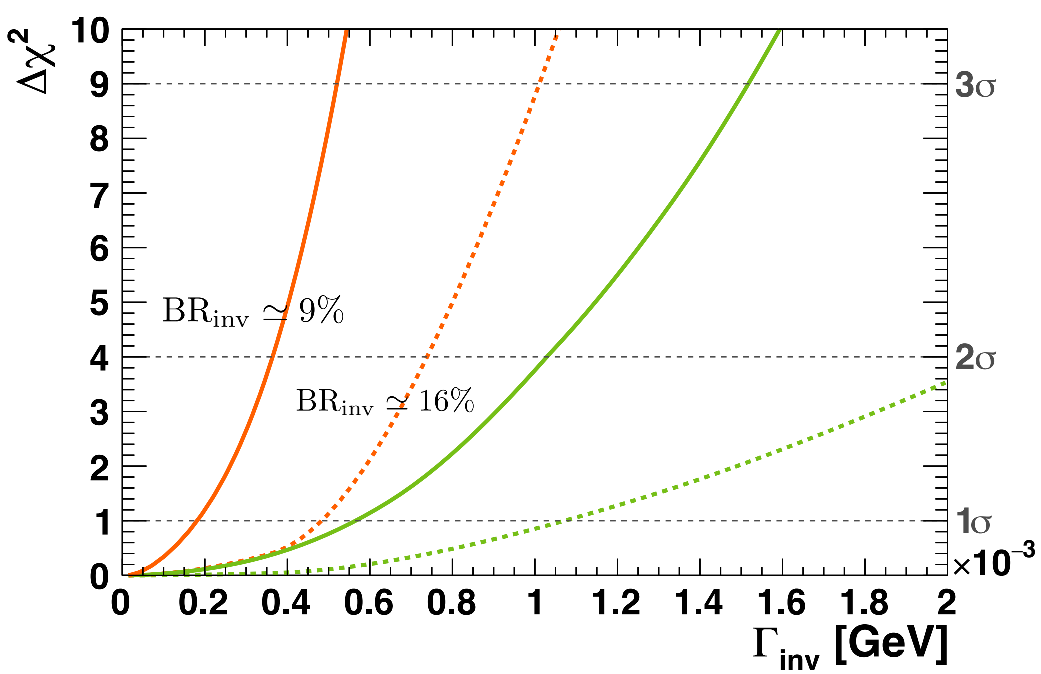
- Extend SM EFT by light degree of freedom, e.g. fermionic DM candidate

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

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)

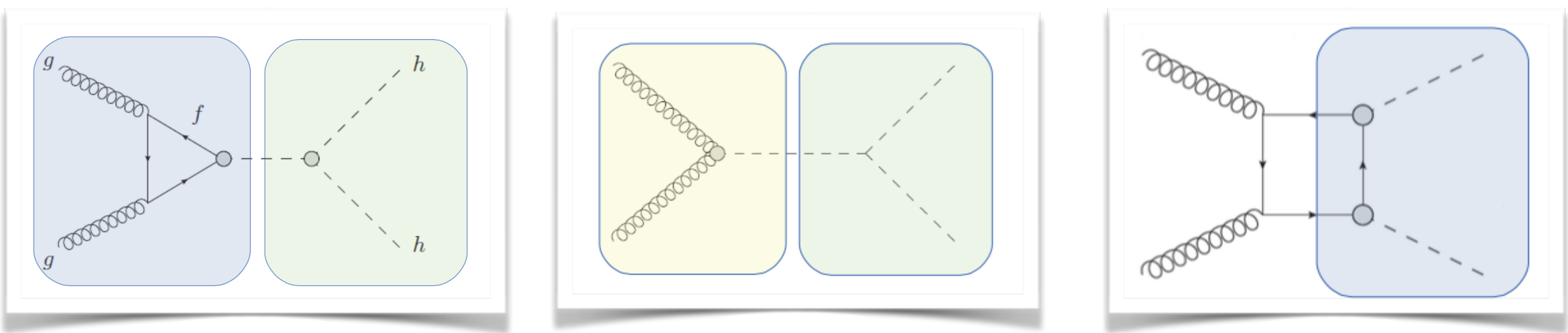
Measure modification of self-coupling

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

- If new physics heavy can parametrise effect using EFT

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

- 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%

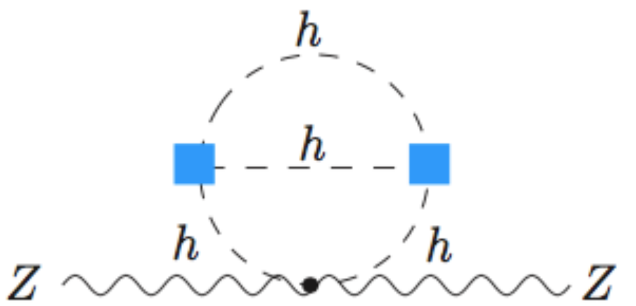
- Promising predictions at FCC-hh 100 TeV: O(5)% accuracy

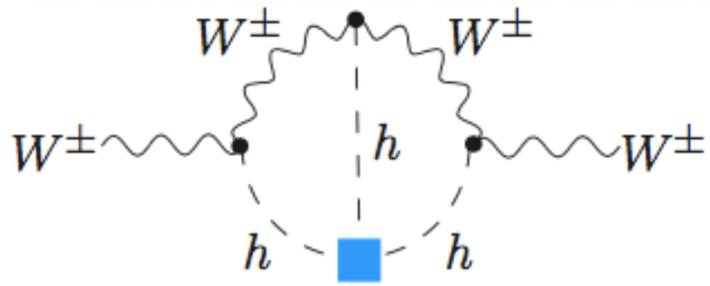
  [Barr, Dolan, Englert, Ferreira, MS '14] [Azatov, Contino, Panico, Son '15] [Yao '15]

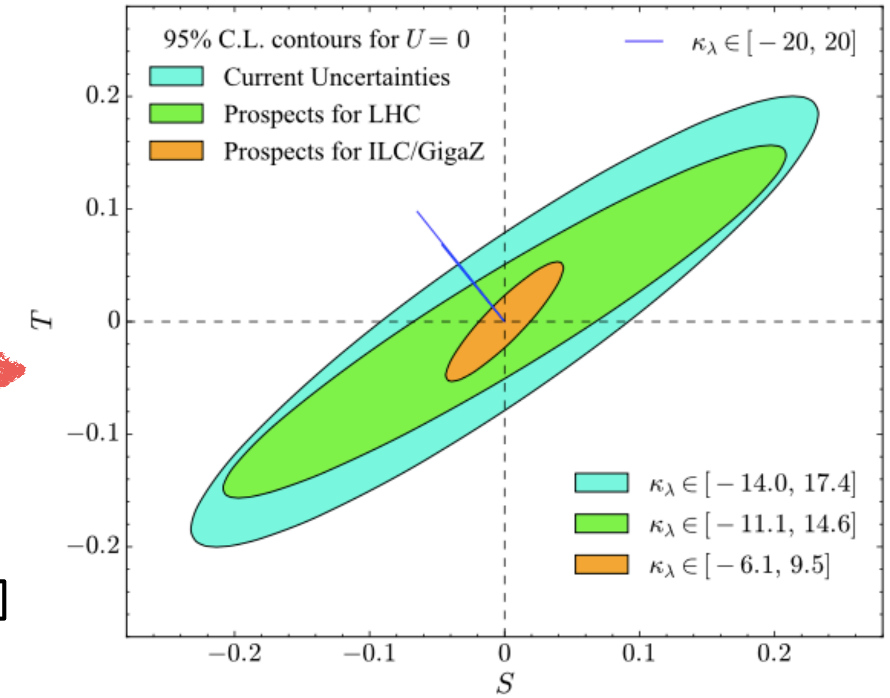
  [Papaefstathiou, Sakurai '15] [Papaefstathiou '15] [Banerjee, Englert, Mangano, Selvaggi, MS '18]

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

NO HIGGS OBSERVABLES: ELWP (NNLO)



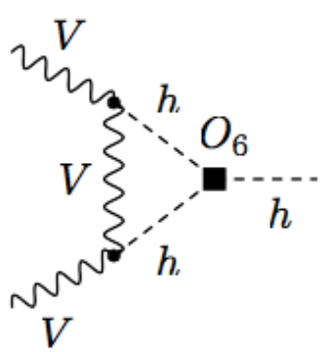




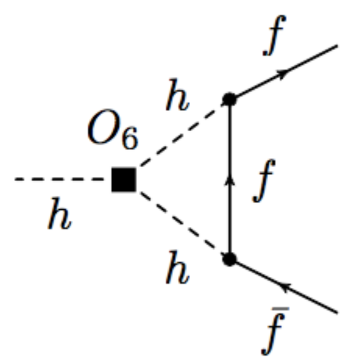
[Degrassi, Fedele, Giardino '17] [Kribs, Maier, Rzehak, MS, Waite '17]

SINGLE-HIGGS OBSERVABLES: Higgs couplings (NLO)

production



decay

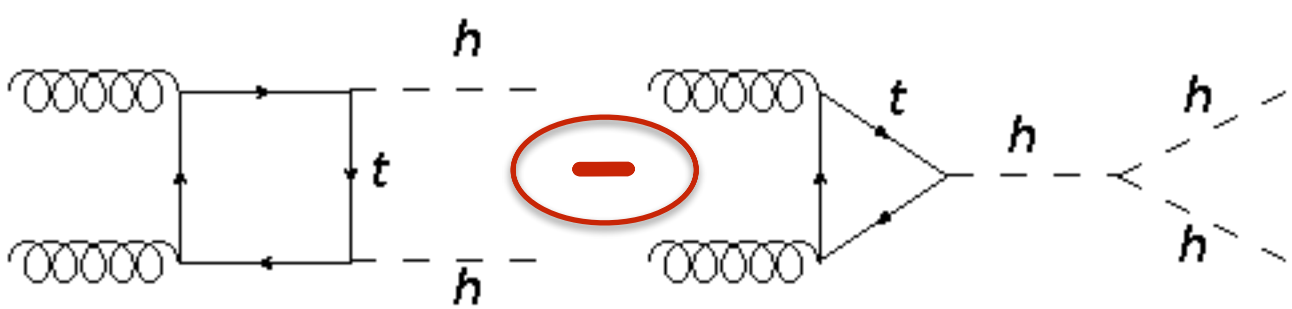


combination of different production and decay modes $-9.4 < \kappa_\lambda^{2\sigma} < 17$

[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?

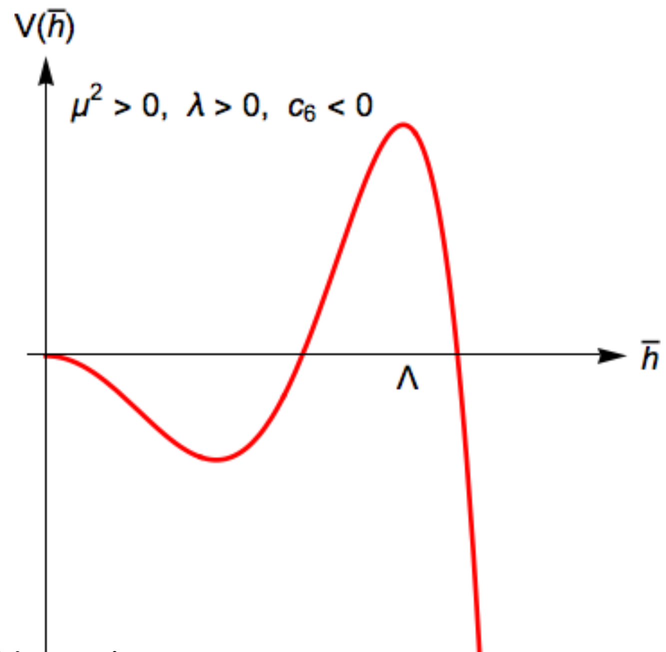
- Vacuum stability

  Introducing new c6 contribution results in two possible instabilities for potential

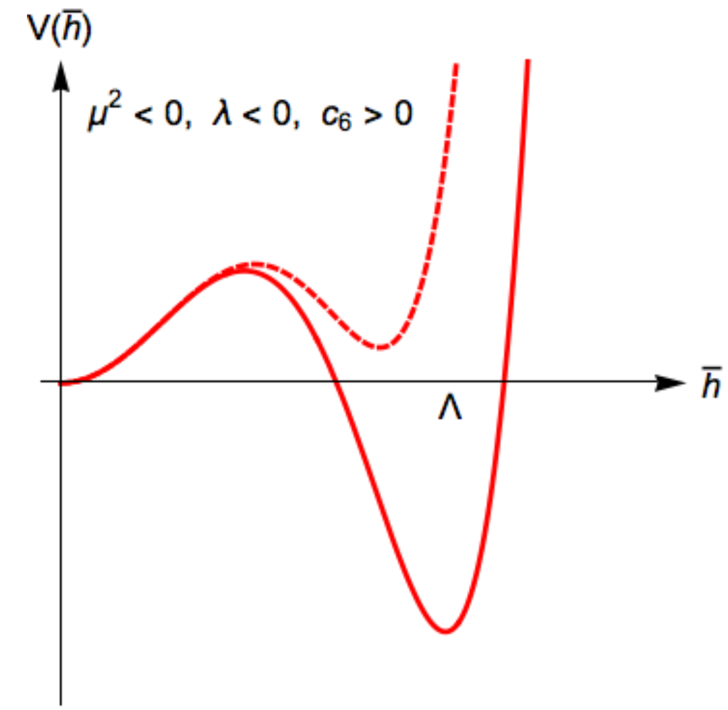
  ⟶ (lfi) requires resummation of large field contributions

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

large field instability (lfi)



small field instability (sfi)



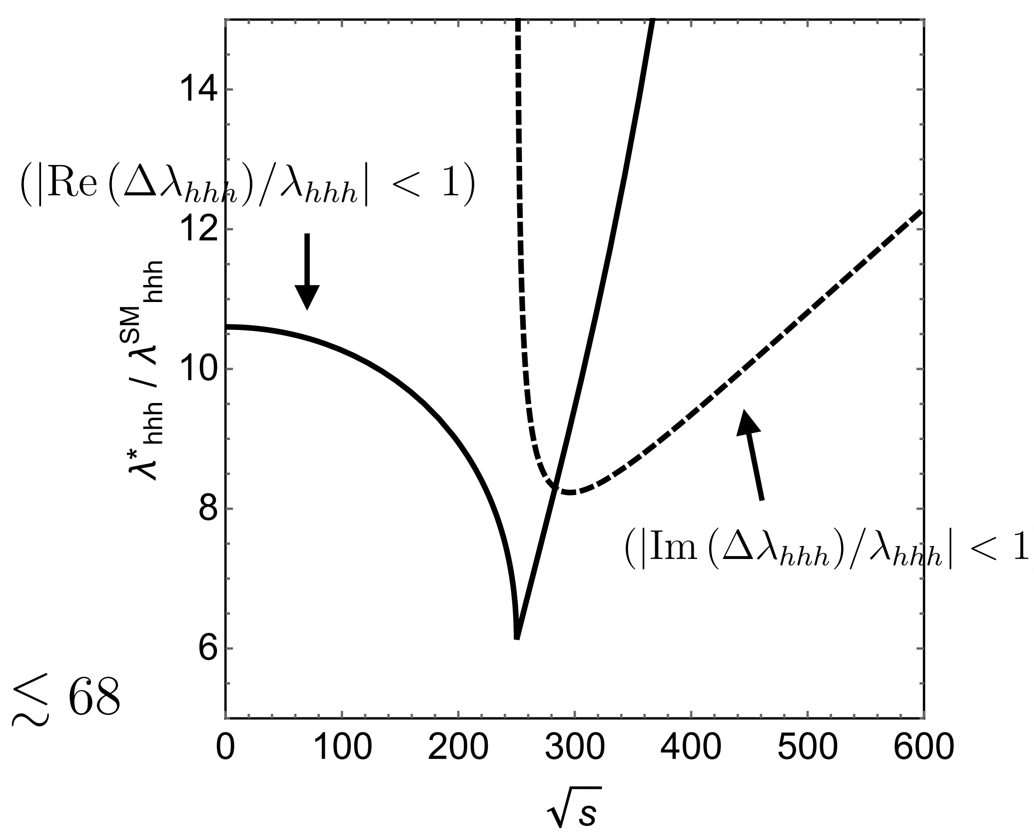
➔ cannot connect vac. instabilities to bound on c6 within EFT

- Perturbativity

  require loop corrections to be smaller than tree-level vertex

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

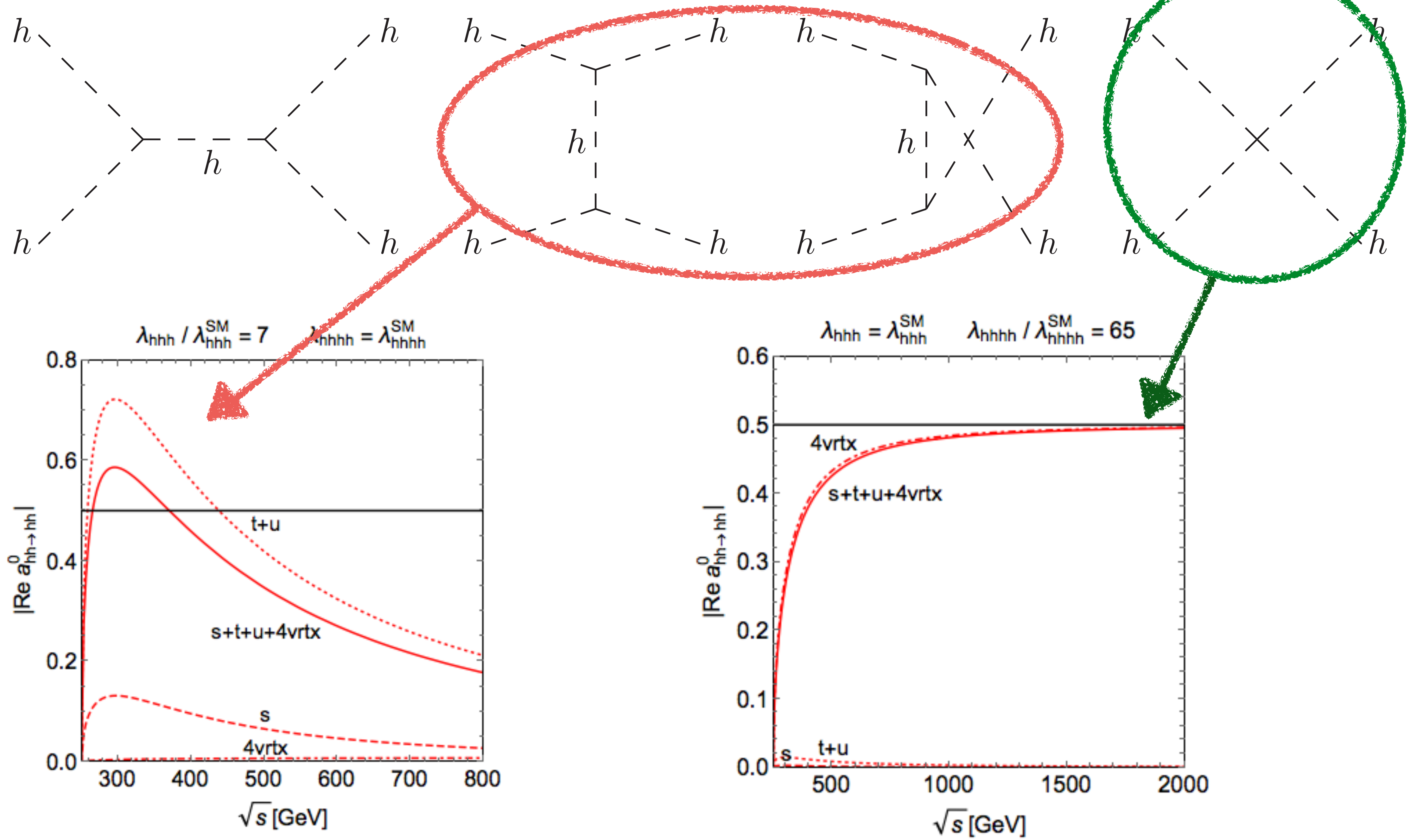
➔ $\left|\lambda_{hhh}/\lambda_{hhh}^{\rm SM}\right| \lesssim 6$



for quartic: $\left|\beta_{\lambda_{hhhh}}/\lambda_{hhhh}\right| < 1$ ➔ $\left|\lambda_{hhhh}/\lambda_{hhhh}^{\rm SM}\right| \lesssim 68$

Can Higgs-selfcoupling be bounded by theoretical considerations?

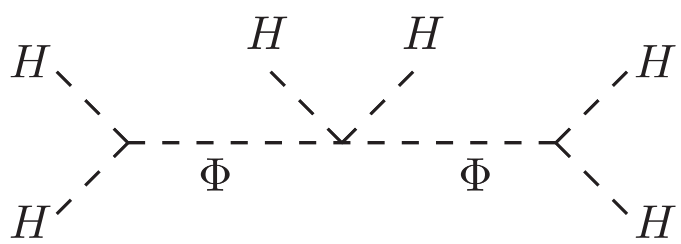
- Perturbative Unitarity $\qquad |\text{Re}\, a^0_{hh\to hh}| < \frac{1}{2}$



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

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

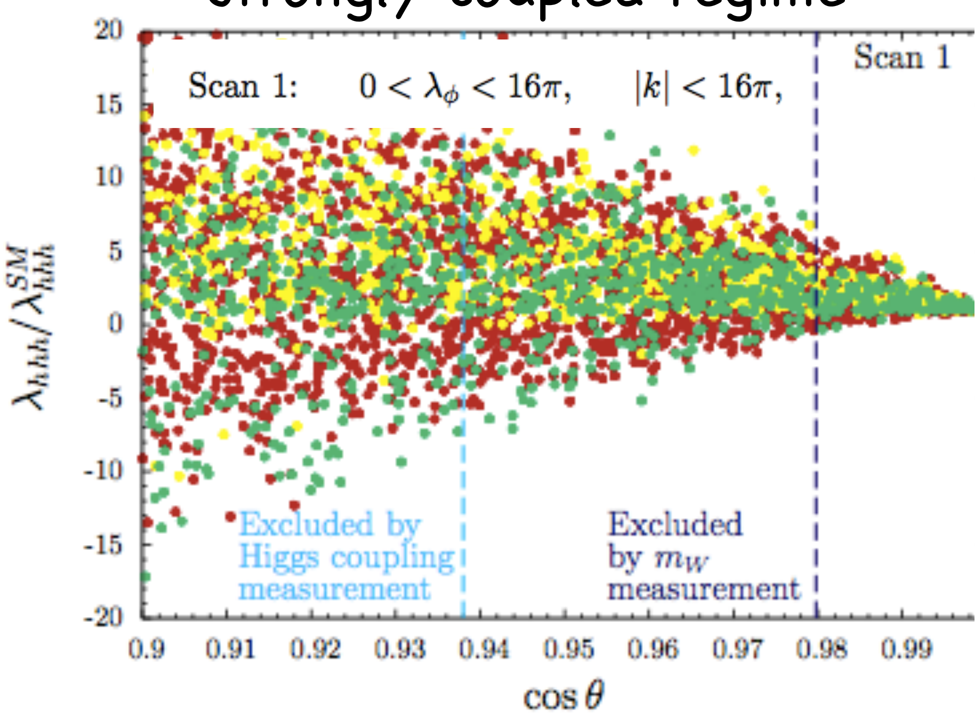


Φ	$\mathcal{O}_\Phi$
$(1,1,0)$	$\Phi H H^\dagger$
$(1,2,\frac{1}{2})$	$\Phi H H^\dagger H^\dagger$
$(1,3,0)$	$\Phi H H^\dagger$
$(1,3,1)$	$\Phi H^\dagger H^\dagger$
$(1,4,\frac{1}{2})$	$\Phi H H^\dagger H^\dagger$
$(1,4,\frac{3}{2})$	$\Phi H^\dagger H^\dagger H^\dagger$

Tree-level enhanced models

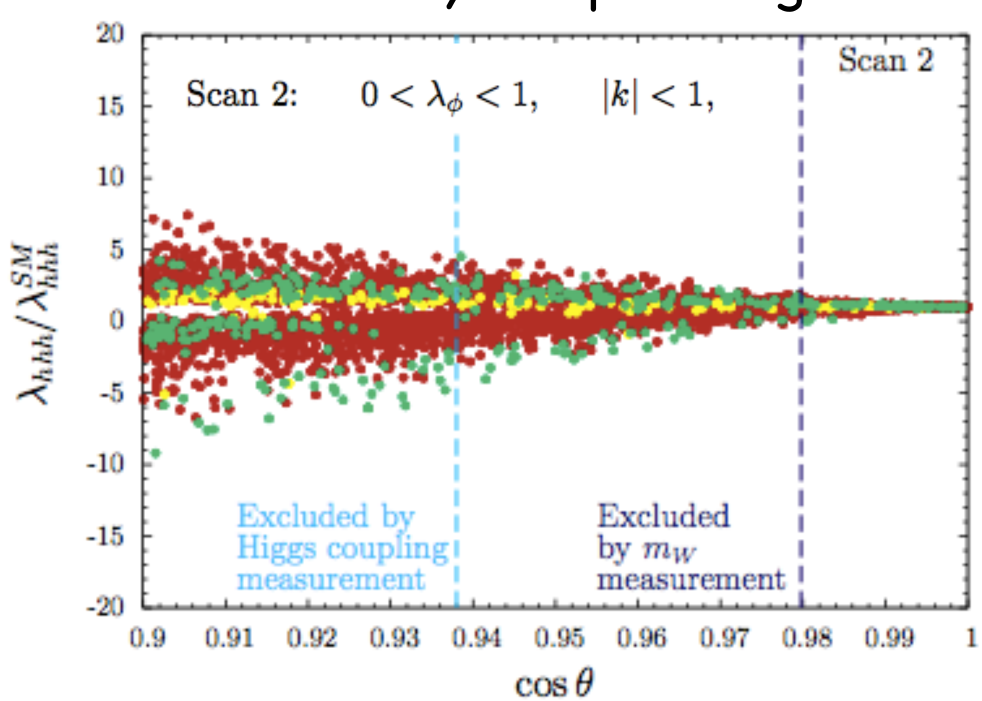
[Di Luzio, Groeber, MS '17]

strongly-coupled regime



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

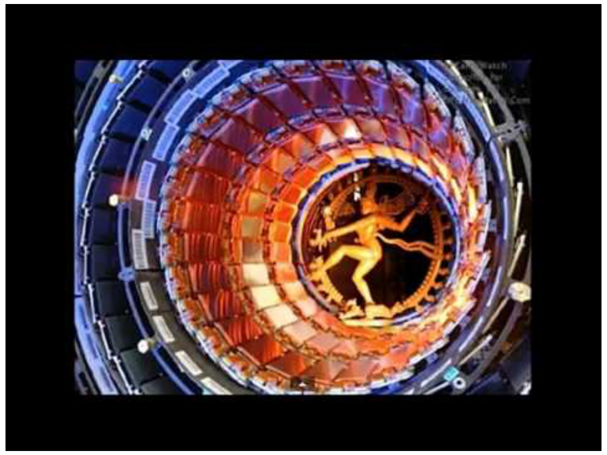
weakly-coupled regime



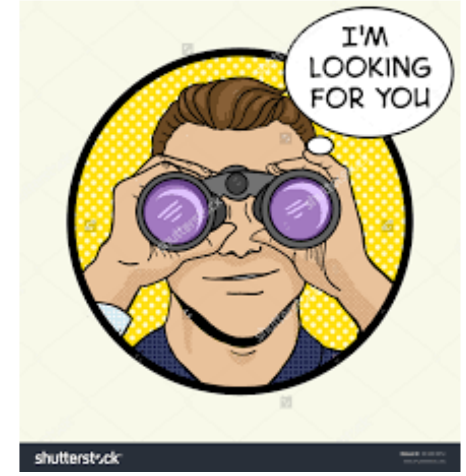
$-0.3 < \lambda_{hhh}/\lambda_{hhh}^{\rm SM} < 2.0$

- Higgs signal strength
- Perturbativity
- Vacuum stability
  stable, meta, unstable
- Electroweak precision

See talk by Jianghao Yu



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