Higgs couplings and New Physics

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Edinburgh
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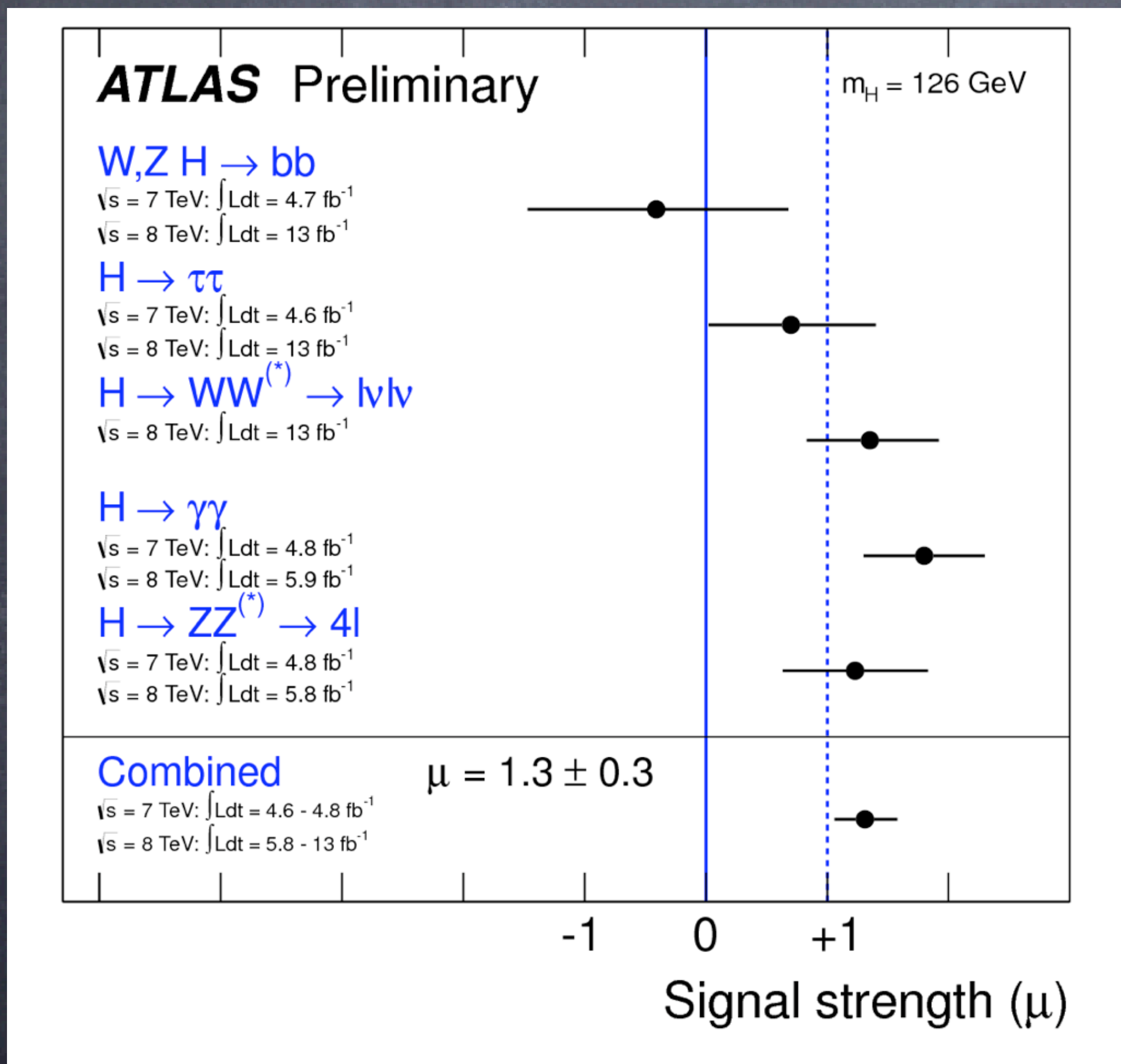
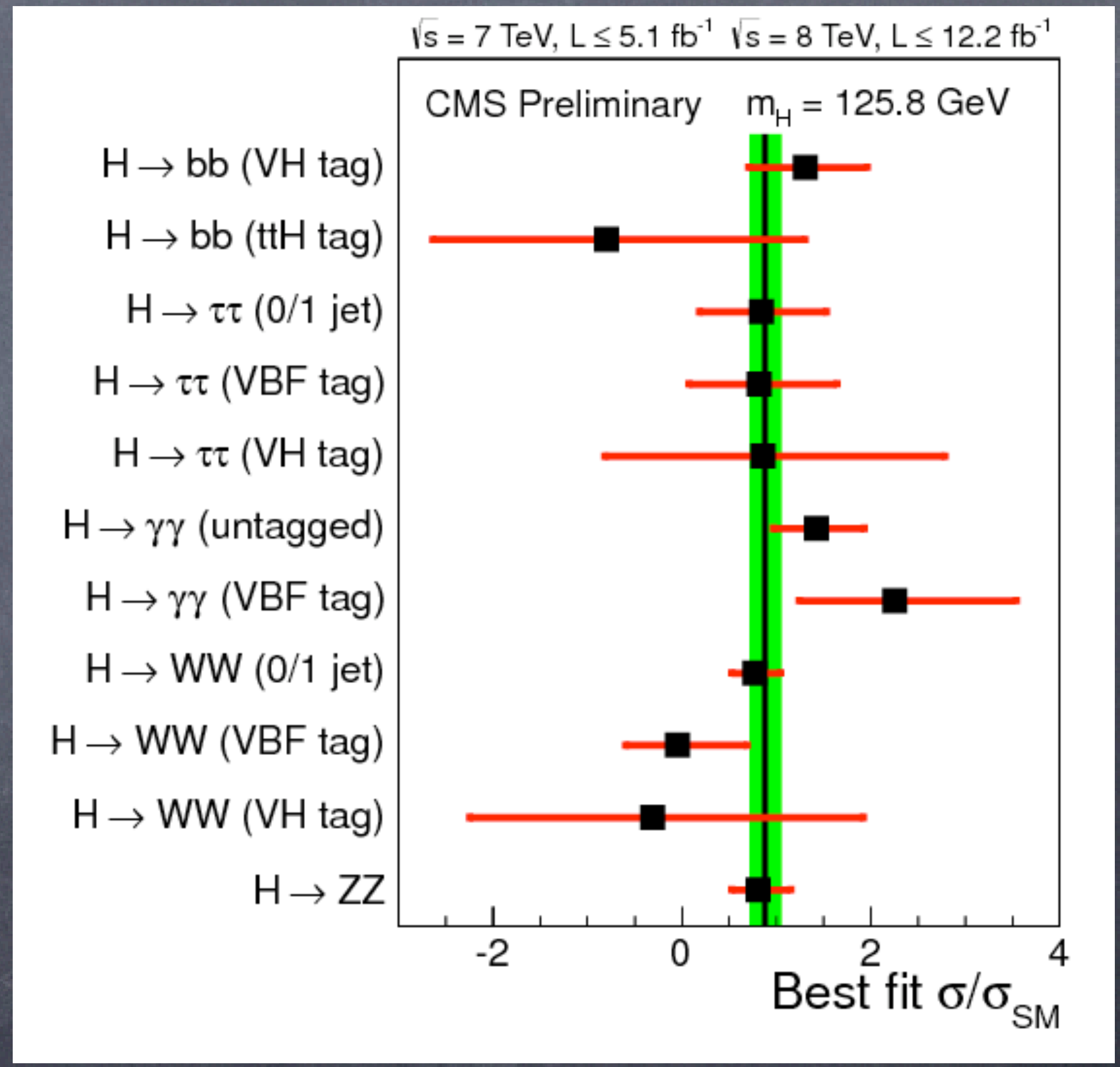
The Higgs has been discovered!

The Higgs has been discovered!
...has it?

Pre-Moriond





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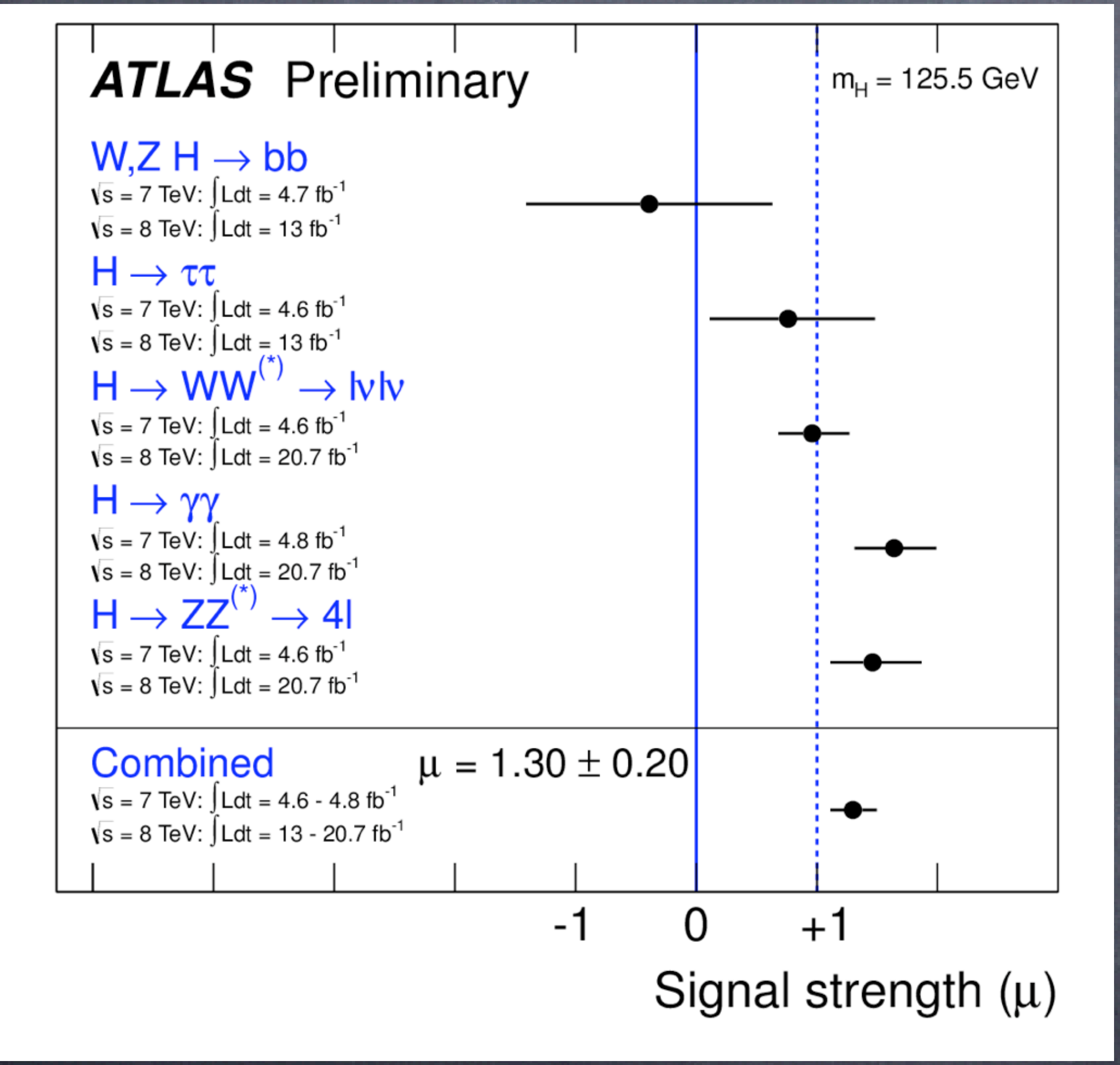
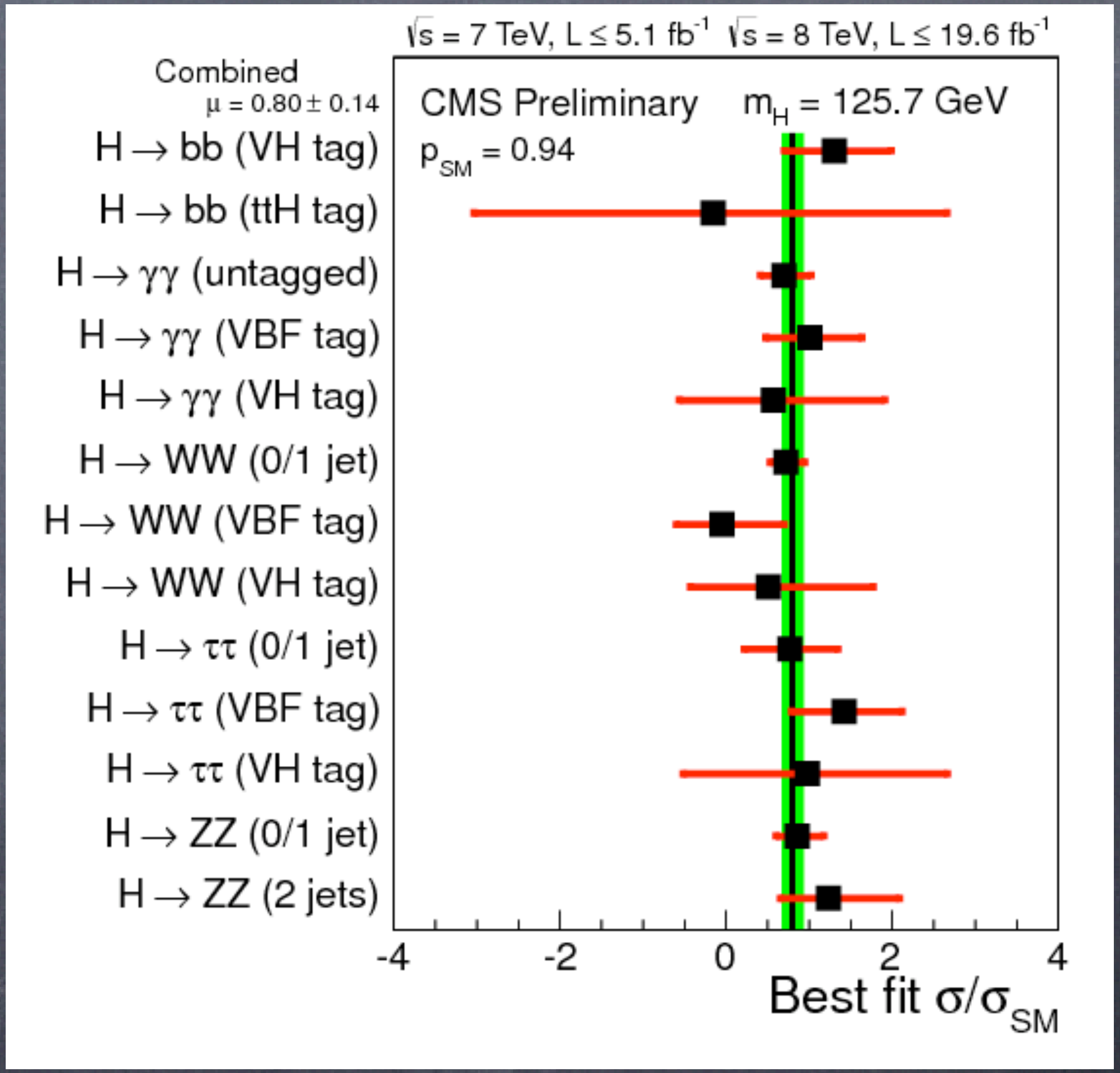
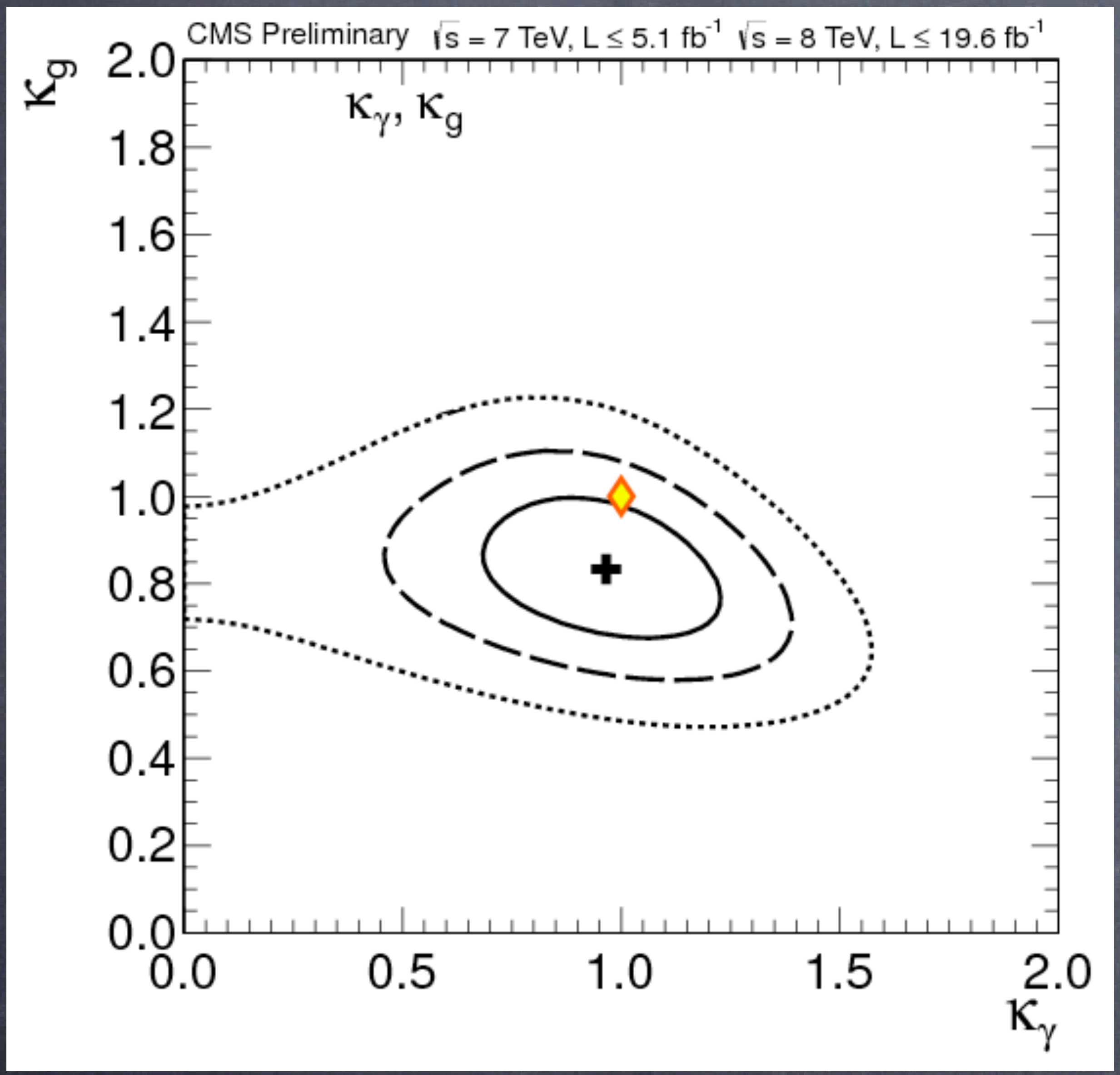
Moriond

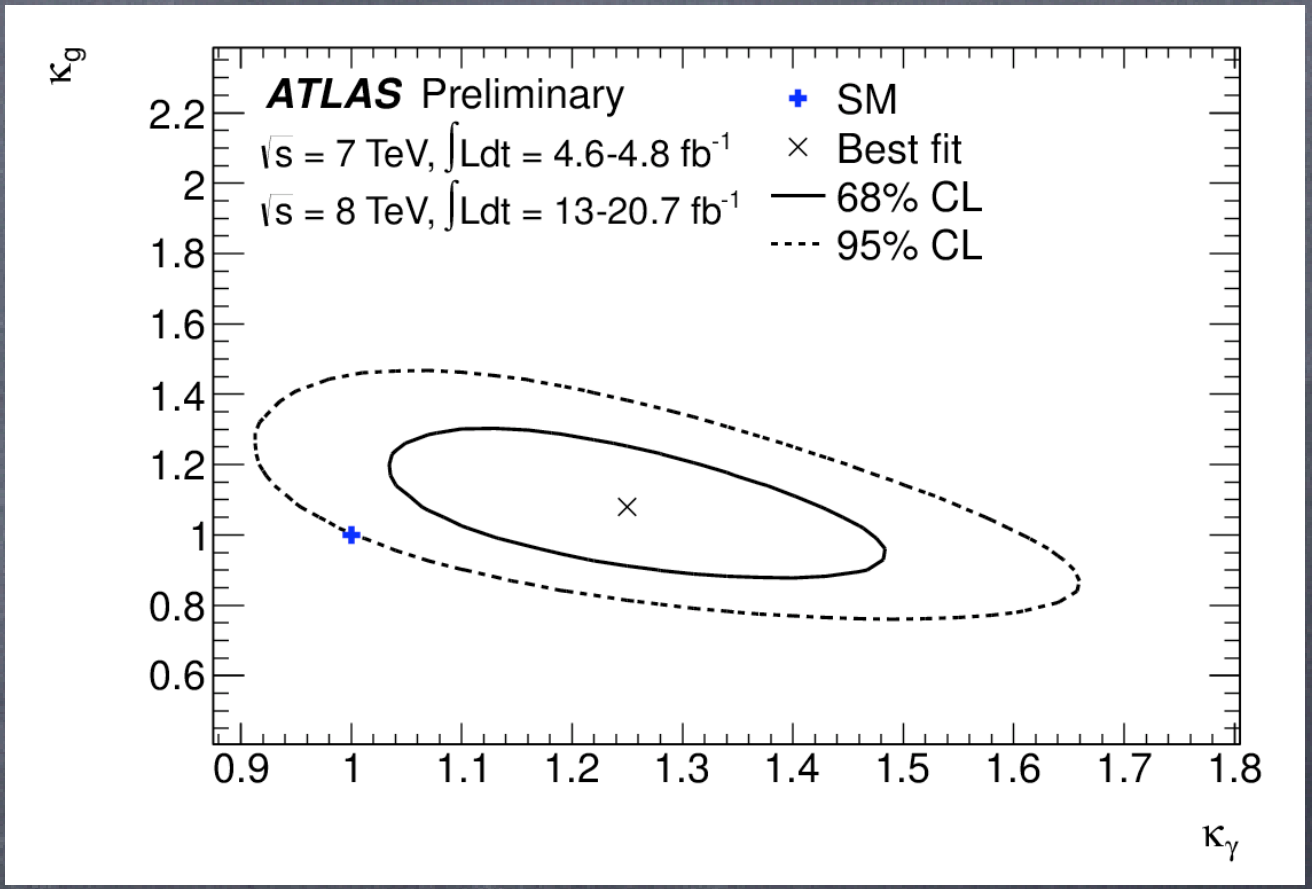




ATLAS and CMS fits

ATLAS sees enhancement in ZZ and γγ
CMS sees slight deficit

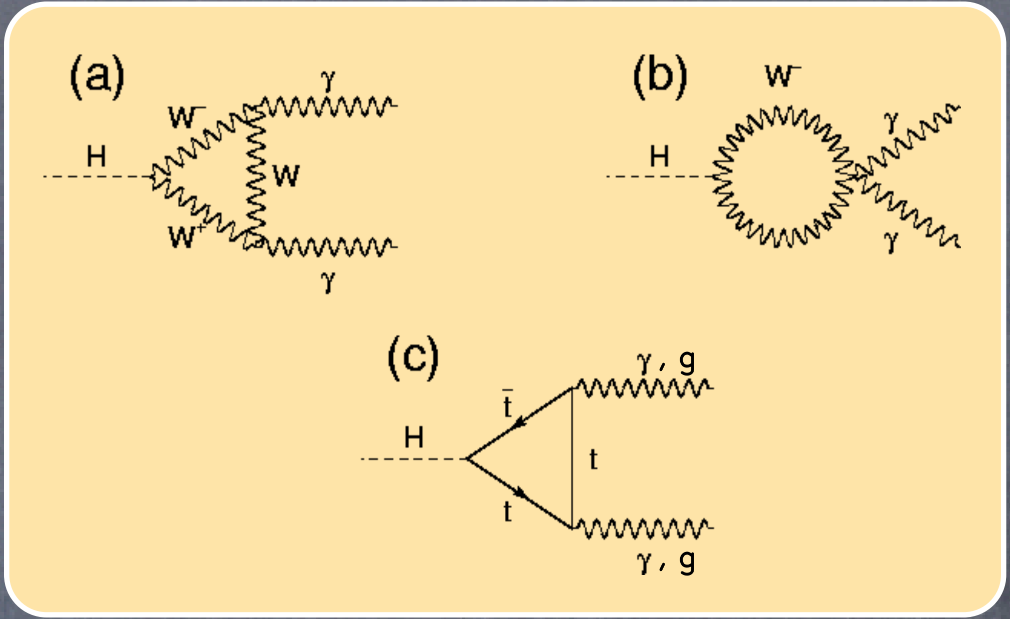




Not so much new information in these fits !!!

Higgs physics 101: the couplings

The Higgs couples to massless particles at loop level



$$g_{h\gamma\gamma} \sim \frac{e^2}{16\pi^2 v^2}\left(A_W(\tau_W) + 3\left(\frac{2}{3}\right)^2 A_f(\tau_t) + 3\left(\frac{1}{3}\right)^2 A_f(\tau_b) + A_f(\tau_\tau) + \dots\right)$$

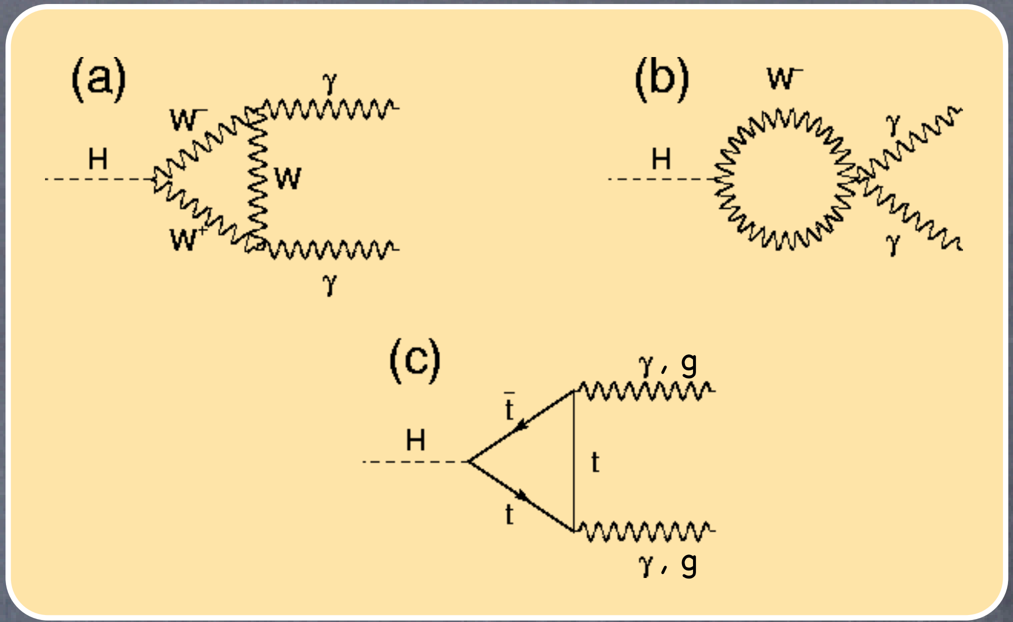
$$g_{hgg} \sim \frac{g_s^2}{16\pi^2 v^2}\left(A_f(\tau_t) + A_f(\tau_b) + \dots\right)$$

$A_f(\tau_f) \sim \tau_f = \dfrac{4m_f^2}{m_h^2}$ for $m_h \gg m_f \;\; (\tau_f \ll 1)$

$A_f(\tau_f) \sim \dfrac{4}{3}$ for $m_h \ll m_f \;\; (\tau_f \gg 1)$ Non-decoupling limit!

Higgs physics 101: the couplings

The Higgs couples to massless particles at loop level



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$$g_{hgg} \sim \frac{g_s^2}{16\pi^2 v^2}\left(A_f(\tau_t) + A_f(\tau_b) + \ldots\right)$$

Result independent on top Yukawa coupling!

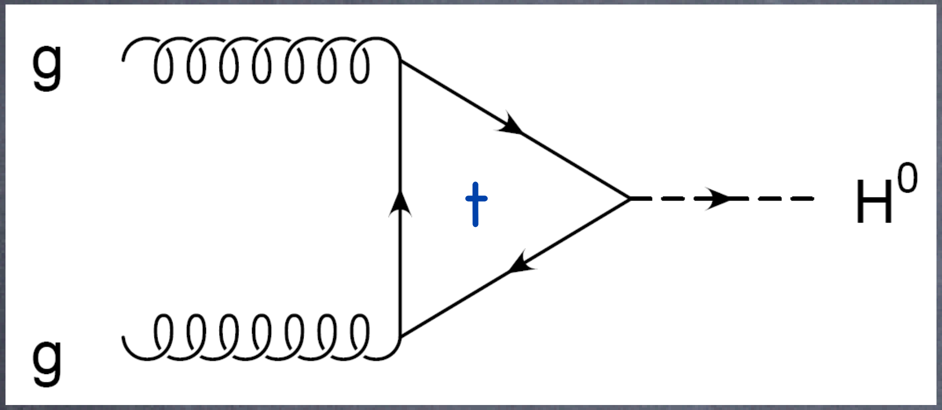
$$A_f(\tau_f) \sim \tau_f = \frac{4m_f^2}{m_h^2} \quad \text{for} \quad m_h \gg m_f \ \ (\tau_f \ll 1)$$

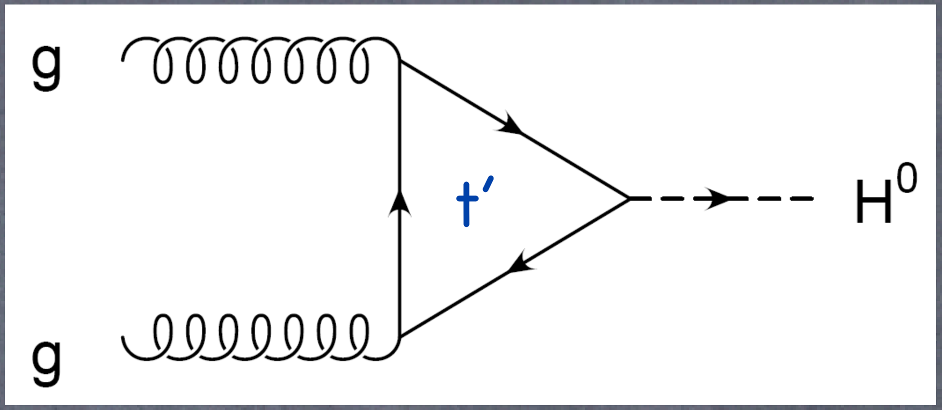
$$A_f(\tau_f) \sim \frac{4}{3} \quad \text{for} \quad m_h \ll m_f \ \ (\tau_f \gg 1)$$

Non-decoupling limit!

Where can New Physics appear?
Loops:

Loop induced couplings are very sensitive to new states that couple to the Higgs!





Where can New Physics appear?
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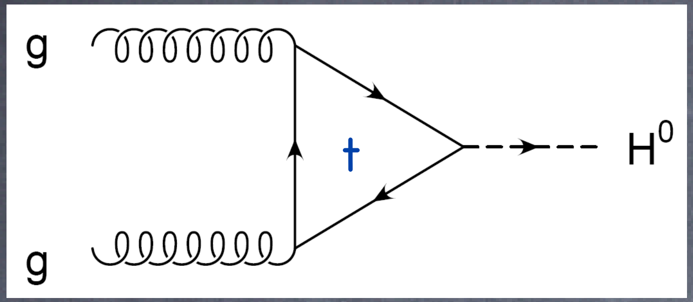
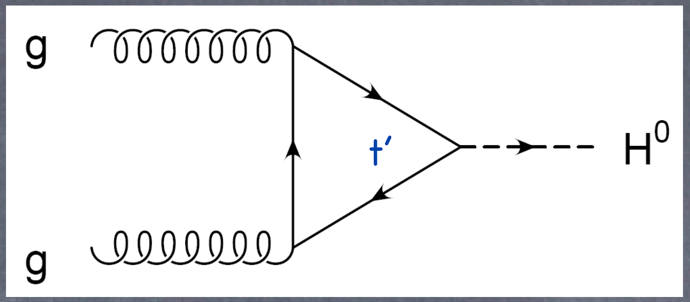




Large effects?
However, cancellations may lure...

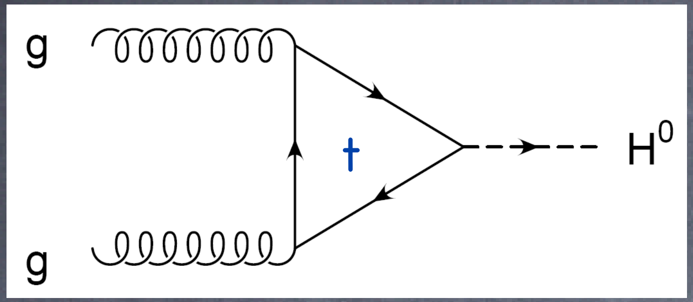
Model of a single Vector-like quark:

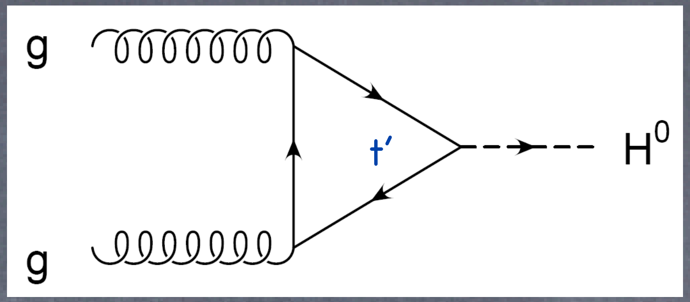
$$\mathcal{L}_{Yukawa} = -y\bar{Q}\phi_H t_R - \lambda\bar{Q}\phi_H T_R - M\bar{T}_L T_R + h.c.$$

$$\mathcal{M} = \begin{pmatrix} \frac{yv}{\sqrt{2}} & \frac{\lambda v}{\sqrt{2}} \\ 0 & M \end{pmatrix} \Rightarrow m_t,\ m_{t'}$$

Mass eigenstates:
both depend on M and v.
m_t = top mass

Where can New Physics appear? Loops:





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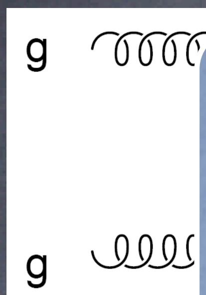
$$\mathcal{L}_{Yukawa} = -y\bar{Q}\phi_H t_R - \lambda\bar{Q}\phi_H T_R - M\bar{T}_L T_R + h.c.$$

$$\mathcal{M} = \begin{pmatrix} \frac{yv}{\sqrt{2}} & \frac{\lambda v}{\sqrt{2}} \\ 0 & M \end{pmatrix} \Rightarrow m_t,\ m_{t'} \qquad \frac{v}{m_t}\frac{\partial m_t}{\partial v} + \frac{v}{m_{t'}}\frac{\partial m_{t'}}{\partial v} = 1$$

$$g_{hgg} \sim \frac{v}{m_t}\frac{\partial m_t}{\partial v} A_f(\tau_t) + \frac{v}{m_{t'}}\frac{\partial m_{t'}}{\partial v} A_f(\tau_{t'}) \sim A_f$$

Cancellation between change in top loop and t′ loop.

Where can New Physics appear?
Loops:



...cts?
...llations
...

$\mathcal{M} =$

Ignoring the mass,
the Higgs couples
to a single fermion!

$$\mathcal{L}_{Yukawa} = -\bar{Q}\phi_H(yt_R + \lambda T_R) = -\tilde{y}\,\bar{Q}\phi_H\tilde{t}_R$$

g_{hgg} ... $m_t\,\partial v$ ... $m_{t'}\,\partial v$

...etween
... loop
and t' loop.

Where can New Physics appear?
An impostor:

Dilatons couple to the breaking of scaling invariance:
masses of SM particles!

$$\mathcal{L}_{dilaton} = -e^{\varphi/f} m_W^2 W^\mu W_\mu \sim \frac{m_W^2}{f} \varphi W^\mu W_\mu + \ldots$$

$$g_{\varphi pp} \sim \frac{v}{f} g_{hpp} < g_{hpp}$$

Generic reduction of couplings to
massive SM particles

$$g_{\varphi\gamma\gamma}\,, \quad g_{\varphi gg}$$

Loop induced couplings receive
extra contributions from New Physics

3 parameters enough to characterise a dilaton!

Where can New Physics appear?
An impostor:

Dilatons couple to the breaking of scaling invariance:
masses of SM particles!

$\mathcal{L}_{dilat}$ ... $V_\mu + \ldots$

Can a dilaton
fit the Higgs data?

(Technicolour, Higgsless...)

$g_{\varphi pp}$ ... plings to ... es

$g_{\varphi\gamma\gamma}$, ... receive ... ew Physics

3 parameters enough to characterise a dilaton!

Higgs couplings: general analysis

Two possible strategies:

- Operator analysis: chiral lagrangian!

Theoretically consistent. Model independent?

- Parameterisation: effective couplings!

Experimentally driven. Truly model independent.

Chiral lagrangian

Assumptions:

- SU(2)xU(1) gauge symmetry at high energies
- The Higgs h is a CP even scalar field
- Approximate custodial symmetry in the EWSB sector
- Power counting:

Derivative -> $1/\Lambda$ probes New Physics scale
Higgs -> $g^*/\Lambda = 1/f$ probes Higgs couplings

Chiral lagrangian

$$
\begin{aligned}
\Delta\mathcal{L}_B = {} & \frac{\bar{c}_H}{2v^2}\,\partial^\mu\left(H^\dagger H\right)\partial_\mu\left(H^\dagger H\right) + \frac{\bar{c}_T}{2v^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) - \frac{\bar{c}_6\lambda}{v^2}\left(H^\dagger H\right)^3 \\
& + \frac{\bar{c}_u}{v^2}\,y_u\,H^\dagger H\,\bar{q}_L H^c u_R + \frac{\bar{c}_d}{v^2}\,y_d\,H^\dagger H\,\bar{q}_L H d_R + \frac{\bar{c}_l}{v^2}\,y_l\,H^\dagger H\,\bar{L}_L H l_R + h.c. \\
& + \frac{i\bar{c}_W g}{2m_W^2}\left(H^\dagger \sigma^i \overleftrightarrow{D^\mu} H\right)\left(D^\nu W_{\mu\nu}\right)^i + \frac{i\bar{c}_B g'}{2m_W^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(\partial^\nu B_{\mu\nu}\right) \\
& + \frac{i\bar{c}_{HW} g}{m_W^2}\left(D^\mu H\right)^\dagger \sigma^i \left(D^\nu H\right) W_{\mu\nu}^i + \frac{i\bar{c}_{HB} g'}{m_W^2}\left(D^\mu H\right)^\dagger \left(D^\nu H\right) B_{\mu\nu} \\
& + \frac{\bar{c}_\gamma {g'}^2}{m_W^2}\,H^\dagger H B_{\mu\nu} B^{\mu\nu} + \frac{\bar{c}_g g_S^2}{m_W^2}\,H^\dagger H G_{\mu\nu}^a G^{a\mu\nu}\,,
\end{aligned}
$$

Chiral lagrangian

Forbidden by custodial symmetry

$$\Delta\mathcal{L}_B = \frac{\bar{c}_H}{2v^2}\,\partial^\mu(H^\dagger H)\,\partial_\mu(H^\dagger H) + \frac{\bar{c}_T}{2v^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) - \frac{\bar{c}_6\lambda}{v^2}\left(H^\dagger H\right)^3$$

Probe Higgs couplings

$$+ \frac{\bar{c}_u}{v^2}\,y_u\,H^\dagger H\,\bar{q}_L H^c u_R + \frac{\bar{c}_d}{v^2}\,y_d\,H^\dagger H\,\bar{q}_L H d_R + \frac{\bar{c}_l}{v^2}\,y_l\,H^\dagger H\,\bar{L}_L H l_R + h.c.$$

Probe NPh scale

$$+ \frac{i\bar{c}_W g}{2m_W^2}\left(H^\dagger\sigma^i\overleftrightarrow{D^\mu}H\right)(D^\nu W_{\mu\nu})^i + \frac{i\bar{c}_B g'}{2m_W^2}\left(H^\dagger\overleftrightarrow{D^\mu}H\right)(\partial^\nu B_{\mu\nu})$$

$$+ \frac{i\bar{c}_{HW} g}{m_W^2}(D^\mu H)^\dagger\sigma^i(D^\nu H)W^i_{\mu\nu} + \frac{i\bar{c}_{HB} g'}{m_W^2}(D^\mu H)^\dagger(D^\nu H)B_{\mu\nu}$$

$$+ \frac{\bar{c}_\gamma g'^2}{m_W^2}H^\dagger H B_{\mu\nu}B^{\mu\nu} + \frac{\bar{c}_g g_S^2}{m_W^2}H^\dagger H G^a_{\mu\nu}G^{a\mu\nu}\,,$$

Chiral lagrangian

Forbidden by custodial symmetry

$$\Delta\mathcal{L}_B = \frac{\bar{c}_H}{2v^2}\,\partial^\mu\left(H^\dagger H\right)\partial_\mu\left(H^\dagger H\right) + \frac{\bar{c}_T}{2v^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) - \frac{\bar{c}_6\lambda}{v^2}\left(H^\dagger H\right)^3$$

Probe Higgs couplings

$$+\frac{\bar{c}_u}{v^2}\,y_u\,H^\dagger H\,\bar{q}_L H^c u_R + \frac{\bar{c}_d}{v^2}\,y_d\,H^\dagger H\,\bar{q}_L H d_R + \frac{\bar{c}_l}{v^2}\,y_l\,H^\dagger H\,\bar{L}_L H l_R + h.c.$$

These operators modify the tree level couplings of the Higgs boson:

$$\frac{g_{hVV}}{g^{SM}_{hVV}} = \kappa_V = 1 - \frac{\bar{c}_H}{2} \qquad \frac{g_{hf\bar{f}}}{g^{SM}_{hf\bar{f}}} = \kappa_f = 1 - \frac{\bar{c}_H}{2} - \bar{c}_f$$

$$\frac{g_{hhh}}{g^{SM}_{hhh}} = 1 - \frac{3\bar{c}_H}{2} + \bar{c}_6$$

Chiral lagrangian

$$\Delta\mathcal{L}_B = +\frac{i\bar{c}_{HW}g}{m_W^2}(D^\mu H)^\dagger\sigma^i(D^\nu H)W^i_{\mu\nu} + \frac{i\bar{c}_{HB}g'}{m_W^2}(D^\mu H)^\dagger(D^\nu H)B_{\mu\nu}$$
$$+\frac{\bar{c}_\gamma g'^2}{m_W^2}H^\dagger H B_{\mu\nu}B^{\mu\nu} + \frac{\bar{c}_g g_S^2}{m_W^2}H^\dagger H G^a_{\mu\nu}G^{a\mu\nu}\,,$$

These operators modify the couplings to gauge bosons:

$$\frac{\bar{c}_i}{m_W^2} \sim \frac{1}{\Lambda^2}\times\frac{g_*^2}{16\pi^2} \sim \frac{1}{16\pi^2 f^2}$$

Operators of this sort can only be generated at loop level in “minimal” models

Chiral lagrangian

Pros:

- Theoretically consistent framework!
- Constraints on the parameters can be imposed.
- New state scan be easily added.

Cons:

- Predictions can change in the presence of light new states!
- Theoretical considerations (bias) necessary to reduce number of parameters.

Effective couplings

Cross sections and partial decay widths can be rescaled:

$$\sigma_{Wh} = \kappa_W^2 \sigma_{Wh}^{\rm SM} \qquad \sigma_{Zh} = \kappa_Z^2 \sigma_{Zh}^{\rm SM} \qquad \sigma_{t\bar{t}h} = \kappa_t^2 \sigma_{t\bar{t}h}^{\rm SM} \qquad \sigma_{VBF} = \kappa_W^2 \sigma_{WWh}^{\rm SM} + \kappa_Z^2 \sigma_{ZZh}^{\rm SM}$$

$$\Gamma_{b\bar{b}} = \kappa_b^2 \Gamma_{b\bar{b}}^{\rm SM} \quad \Gamma_{WW} = \kappa_W^2 \Gamma_{WW}^{\rm SM} \quad \Gamma_{ZZ} = \kappa_Z^2 \Gamma_{ZZ}^{\rm SM} \quad \Gamma_{\tau^+\tau^-} = \kappa_\tau^2 \Gamma_{\tau^+\tau^-}^{\rm SM} \ldots$$

Similarly, for the loop induced couplings:

$$\sigma_{ggh} = \kappa_g^2 \sigma_{ggh}^{\rm SM} \qquad \Gamma_{gg} = \kappa_g^2 \Gamma_{gg}^{\rm SM} \qquad \Gamma_{\gamma\gamma} = \kappa_\gamma^2 \Gamma_{\gamma\gamma}^{\rm SM}$$

Problem: correlations!

Effective couplings

$$\sigma_{ggh} = \kappa_g^2 \sigma_{ggh}^{\rm SM} \qquad \Gamma_{gg} = \kappa_g^2 \Gamma_{gg}^{\rm SM} \qquad \Gamma_{\gamma\gamma} = \kappa_\gamma^2 \Gamma_{\gamma\gamma}^{\rm SM}$$

These quantities depend on tree level couplings:

$$\Gamma_{\gamma\gamma} = \frac{G_F \alpha^2 m_H^2}{128\sqrt{2}\pi^3} \left| \kappa_W A_W + C_t^\gamma 3 \left(\frac{2}{3}\right)^2 \kappa_t A_t + \ldots \right|^2$$

$$\Gamma_{gg} = \frac{G_F \alpha_s^2 m_H^2}{16\sqrt{2}\pi^3} \left| C_t^g \frac{1}{2} \kappa_t A_t + \ldots \right|^2$$

$$\sigma_{gg} \propto \Gamma_{gg}$$

$A_W = -8.32 \quad A_t = 1.37 \qquad C_t^\gamma \, , \, C_t^g$ are QCD corrections.

Problem: correlations!

Effective couplings

Our proposal: parameterise the NPh loop contributions independently from the tree level couplings!

$$\Gamma_{\gamma\gamma} = \frac{G_F \alpha^2 m_H^2}{128\sqrt{2}\pi^3} \left| \kappa_W A_W + C_t^\gamma 3 \left(\frac{2}{3}\right)^2 (\kappa_t + \kappa_{\gamma\gamma}) A_t + \ldots \right|^2$$

$$\Gamma_{gg} = \frac{G_F \alpha_s^2 m_H^2}{16\sqrt{2}\pi^3} \left| C_t^g \frac{1}{2} (\kappa_t + \kappa_{gg}) A_t + \ldots \right|^2$$

$$\sigma_{gg} \propto \Gamma_{gg}$$

All parameters are truly independent!

Flexible and easy to compute!

Effective couplings

$$\Gamma_{\gamma\gamma} = \frac{G_F \alpha^2 m_H^2}{128\sqrt{2}\pi^3} \left| \kappa_W A_W + C_t^\gamma 3 \left(\frac{2}{3}\right)^2 (\kappa_t + \kappa_{\gamma\gamma}) A_t + \ldots \right|^2$$

$$\Gamma_{gg} = \frac{G_F \alpha_s^2 m_H^2}{16\sqrt{2}\pi^3} \left| C_t^g \frac{1}{2} (\kappa_t + \kappa_{gg}) A_t + \ldots \right|^2$$

$$\sigma_{gg} \propto \Gamma_{gg}$$

Easily computable in models of New Physics:
for instance, in the Simplest Little Higgs

$$\kappa_W = 1 - \frac{1}{3}\frac{m_W^2}{m_{W'}^2}, \qquad \kappa_t = 1 + \frac{m_t^2}{m_{t'}^2} - \frac{4}{3}\frac{m_W^2}{m_{W'}^2},$$

$$\kappa_{\gamma\gamma} = -\frac{m_t^2}{m_{t'}^2} + \frac{63}{16}\frac{m_W^2}{m_{W'}^2}, \qquad \kappa_{gg} = -\frac{m_t^2}{m_{t'}^2}.$$

Deviations scale like 1/M^2!!

Effective couplings

$$\Gamma_{\gamma\gamma} = \frac{G_F \alpha^2 m_H^2}{128\sqrt{2}\pi^3} \left| \kappa_W A_W + C_t^\gamma 3 \left(\frac{2}{3}\right)^2 (\kappa_t + \kappa_{\gamma\gamma}) A_t + \ldots \right|^2$$

$$\Gamma_{gg} = \frac{G_F \alpha_s^2 m_H^2}{16\sqrt{2}\pi^3} \left| C_t^g \frac{1}{2} (\kappa_t + \kappa_{gg}) A_t + \ldots \right|^2$$

$$\sigma_{gg} \propto \Gamma_{gg}$$

Flexible: un-measurable parameters can be reabsorbed.
For instance, the top couplings:

$$\kappa'_{\gamma\gamma} = \kappa_{\gamma\gamma} + \kappa_t - 1 = \frac{125}{48} \frac{m_W^2}{m_{W'}^2}, \qquad \kappa'_{gg} = \kappa_{gg} + \kappa_t - 1 = -\frac{4}{3} \frac{m_W^2}{m_{W'}^2}.$$

Parameters only depend on W' mass!

Effective couplings

$$\Gamma_{\gamma\gamma} = \frac{G_F \alpha^2 m_H^2}{128\sqrt{2}\pi^3} \left| \kappa_W A_W + C_t^\gamma 3 \left(\frac{2}{3}\right)^2 (\kappa_t + \kappa_{\gamma\gamma}) A_t + \ldots \right|^2$$

$$\Gamma_{gg} = \frac{G_F \alpha_s^2 m_H^2}{16\sqrt{2}\pi^3} \left| C_t^g \frac{1}{2} (\kappa_t + \kappa_{gg}) A_t + \ldots \right|^2$$

$$\sigma_{gg} \propto \Gamma_{gg}$$

In specific models, correlations can be easily explored:

$$\kappa_{\gamma\gamma} = \sum_{NP} \frac{C_{NP}^\gamma}{C_t^\gamma} \frac{3}{4} N_{c,NP} Q_{NP}^2 \, g_{hNP} \, \epsilon_{NP} \,,$$

$$\kappa_{gg} = \sum_{NP} \frac{C_{NP}^g}{C_t^g} 2C(r_{NP}) \, g_{hNP} \, \epsilon_{NP} \,,$$

$$\epsilon_{NP} = 1 \quad \text{for fermions;}$$

$$\epsilon_{NP} = -21/4 \quad \text{for vectors;}$$

$$\epsilon_{NP} = 1/4 \quad \text{for scalars.}$$

In models with a single new state in the loop:

$$\frac{\kappa_{\gamma\gamma}}{\kappa_{gg}} = \frac{3N_{c,NP} Q_{NP}^2}{C(r_{NP})} = 1$$

For a top partner!

Our fits

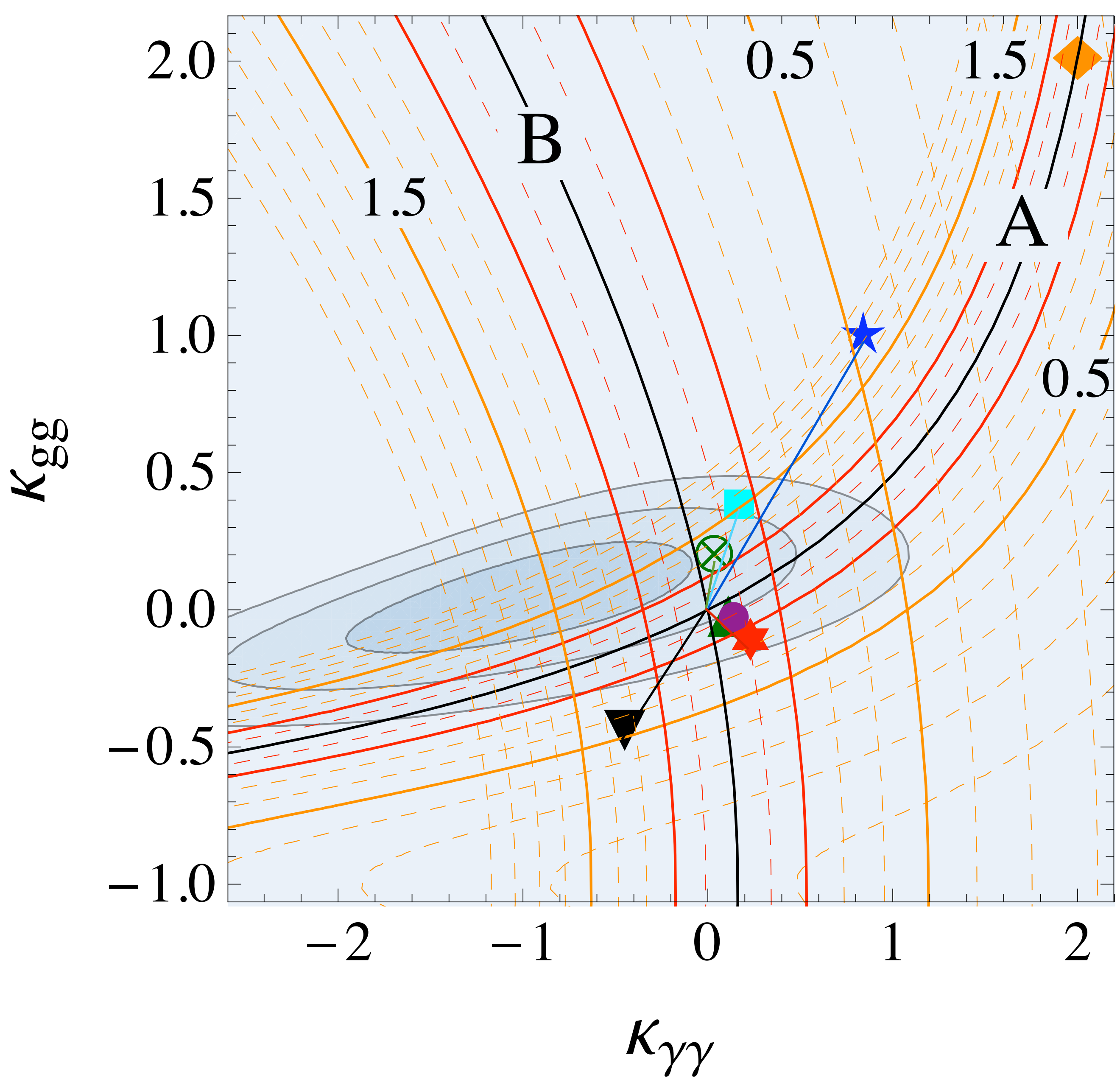
- We computed the parameters in various models of New Physics:

Model	parameter(s)	$\kappa_W - 1$	$\kappa'_{gg}(\kappa_t)$	$\kappa'_{\gamma\gamma}(\kappa_t)$	$\kappa'_{\gamma\gamma}(\kappa_t, \kappa_W)$
4^{th} generation	-	0	2	2	2
Simplest Little Higgs	$m_{W'} = 500$ GeV	-0.009	-0.034	0.067	0.11
Littlest Higgs	$f = 700$ GeV $m_{W'} = 500$ GeV, $x = 0$	-0.05	-0.11	-0.014	0.23
colour octet	$m_S = 750$ GeV $\lambda_1 = 4$, $\lambda_2 = 1$	0	0.37	0.17	0.17
5D UED	$m_{KK} = 500$ GeV	0	0.20	0.034	0.034
6D UED (RP^2)	$m_{KK} = 600$ GeV ($R_5 = 1.5\ R_4$)	0	1.00	0.84	0.84
composite Higgs	$1/R' = 1$ TeV	-0.04	-0.04	-0.03	0.14
flat brane Higgs	$m_{W'} = 2$ TeV	-0.005	-0.45	-0.47	-0.45
warped brane Higgs	$1/R' = 1$ TeV	-0.11	-0.65	-1.08	-0.57

2 parameter fits

Update of 1210.8102
to appear soon on arXiv

ATLAS data



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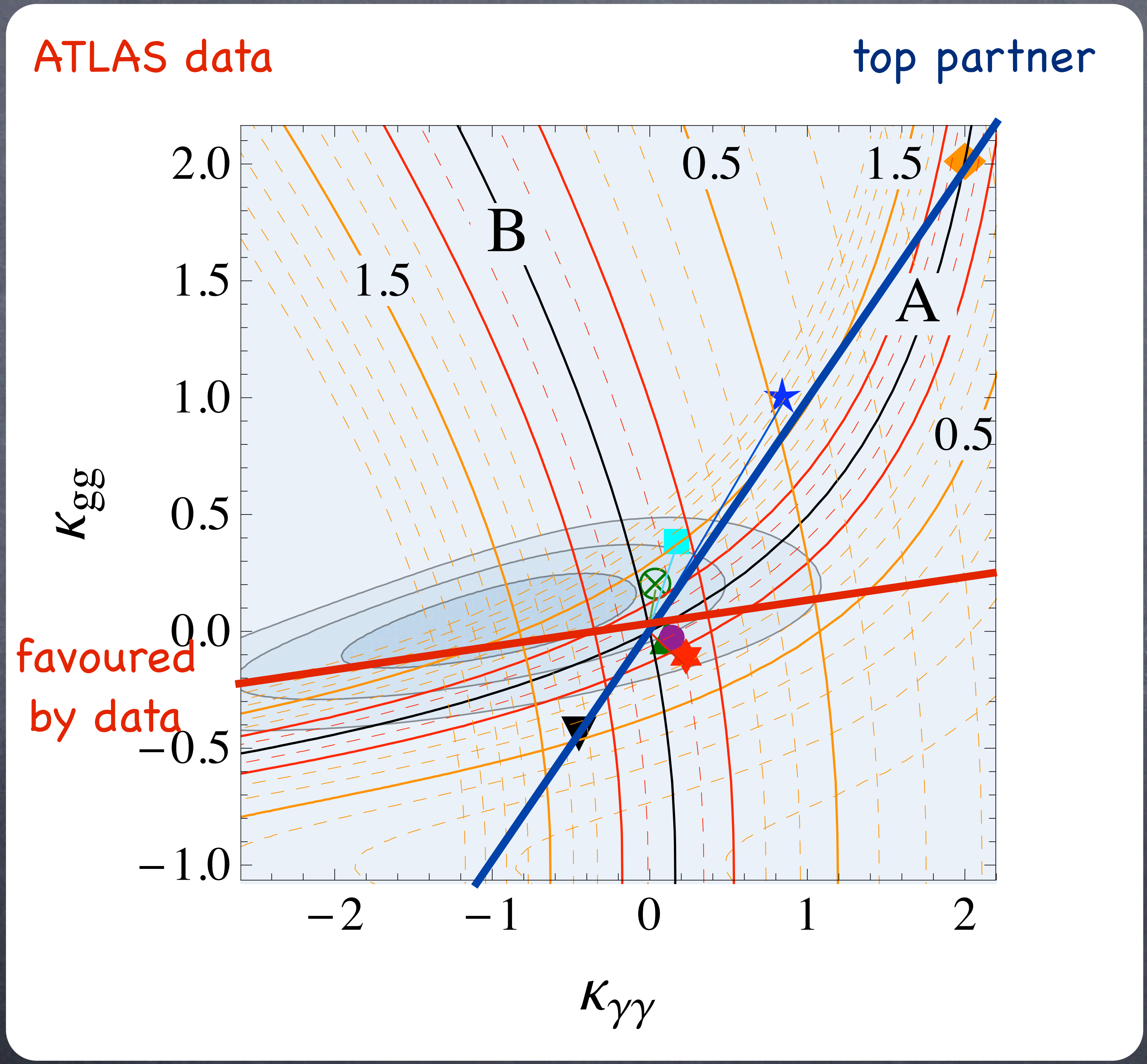
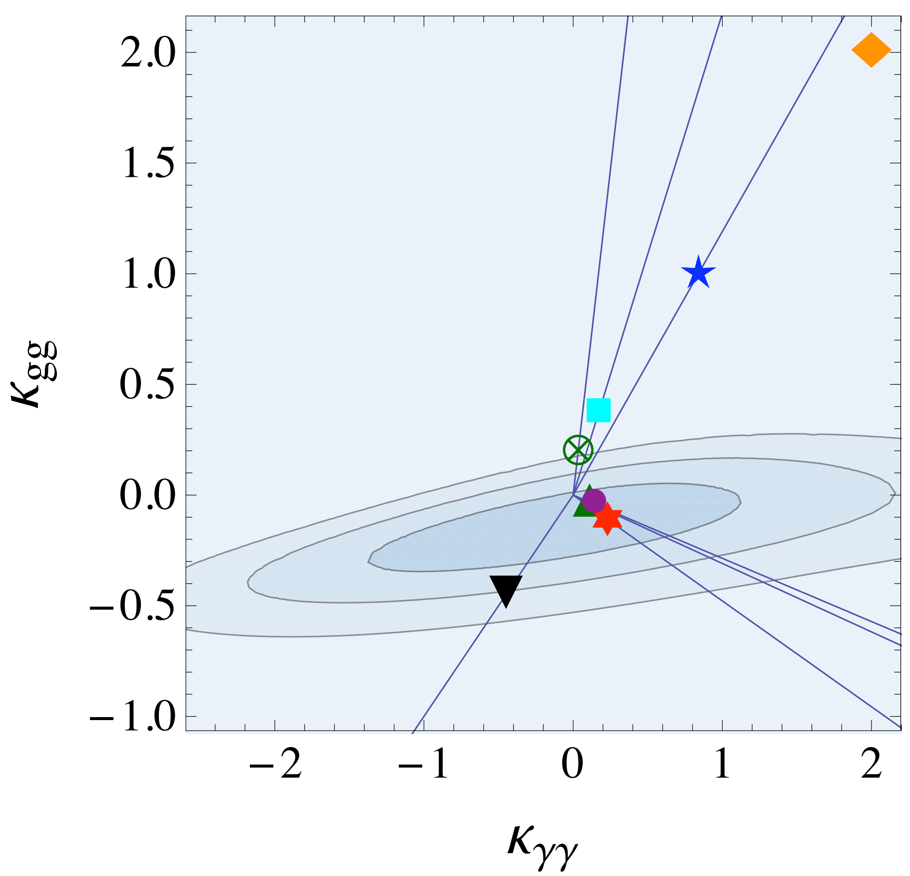
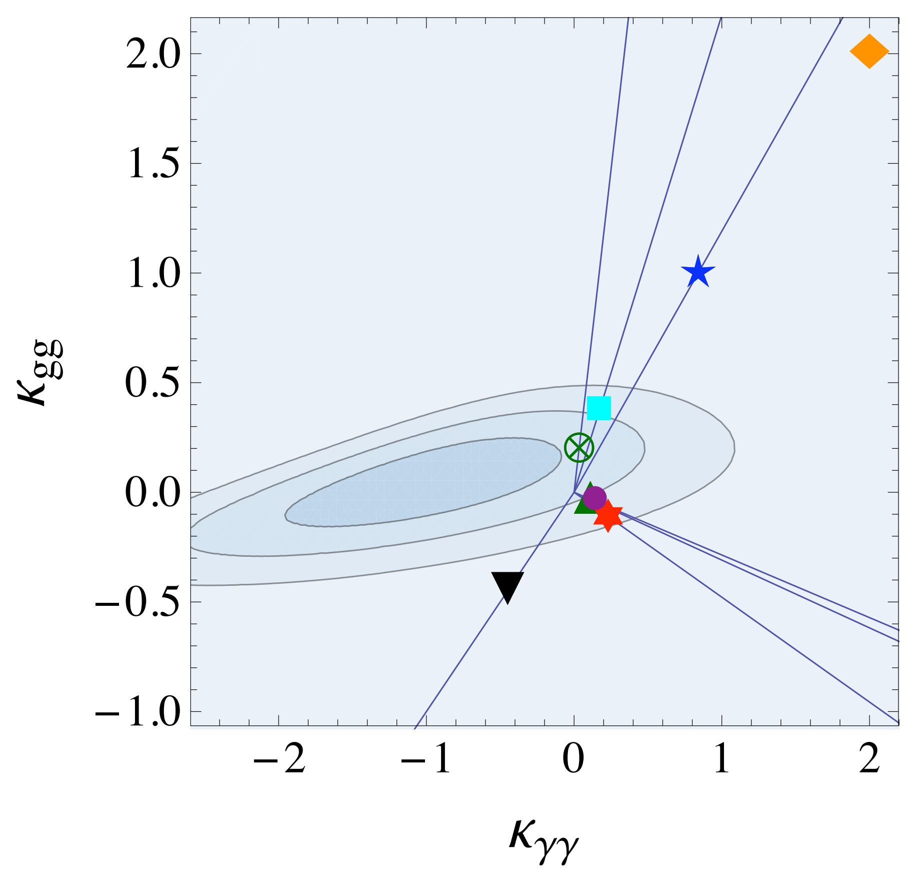


ATLAS vs. CMS

CMS data



ATLAS data



Dilaton fits

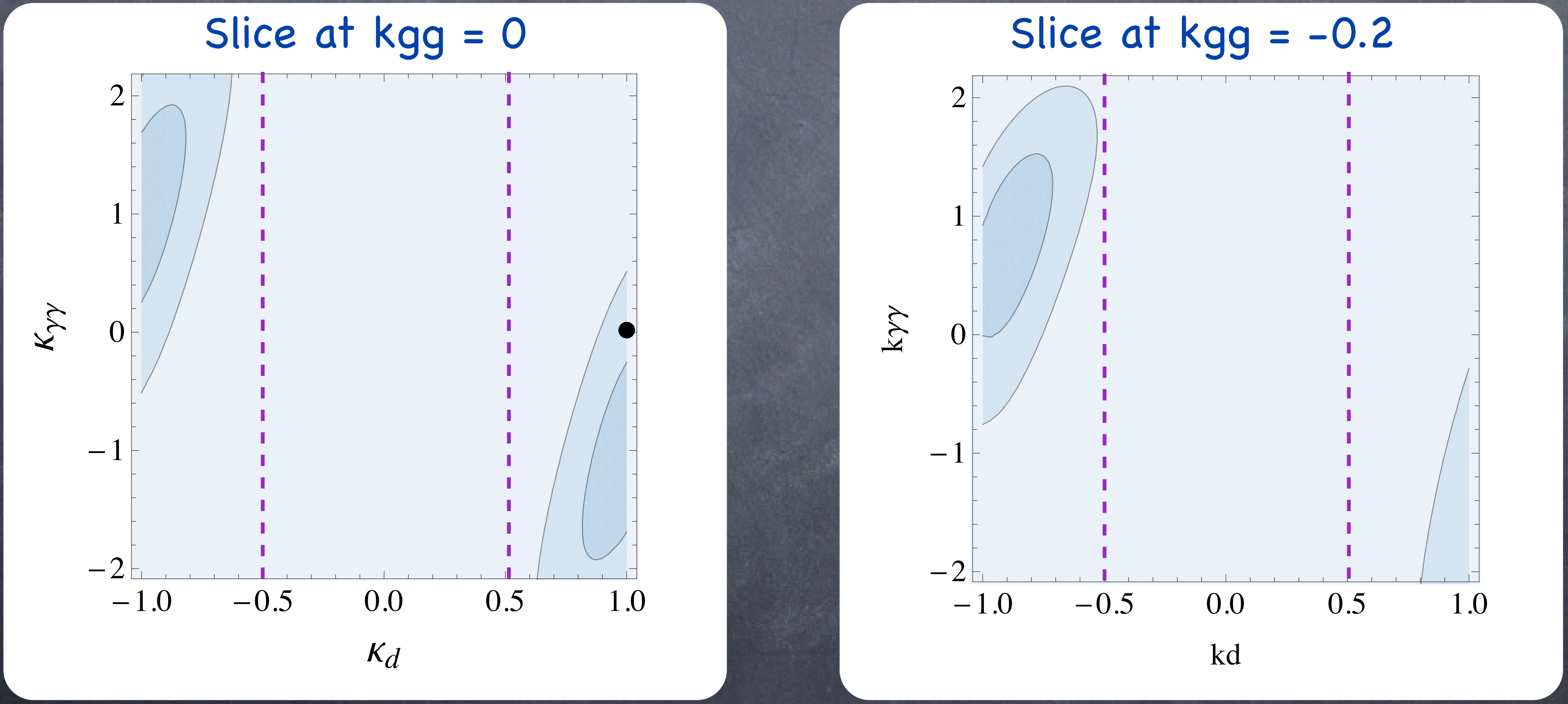
Update of 1210.8102
to appear soon on arXiv

Rescale all tree level couplings:

$$\kappa_W = \kappa_Z = \kappa_f = \kappa_d$$

3 parameter fit

|kd| < 0.5 disfavoured!



Conclusions

- Measuring the couplings of the new resonance crucial to determine if it is the Higgs!
- Simple and flexible parameterisations of the couplings can help extract information and connect to models of New Physics!
- Complementary approach to a Chiral Lagrangian/operator expansion!