PHYSICS AT TEV COLLIDERS LES HOUCHES 2013

HIGGS WORKING GROUP

Conveners:

Roberto Contino (theory)

Filip Moortgat (experiment)

A short intro

What data say on the new boson

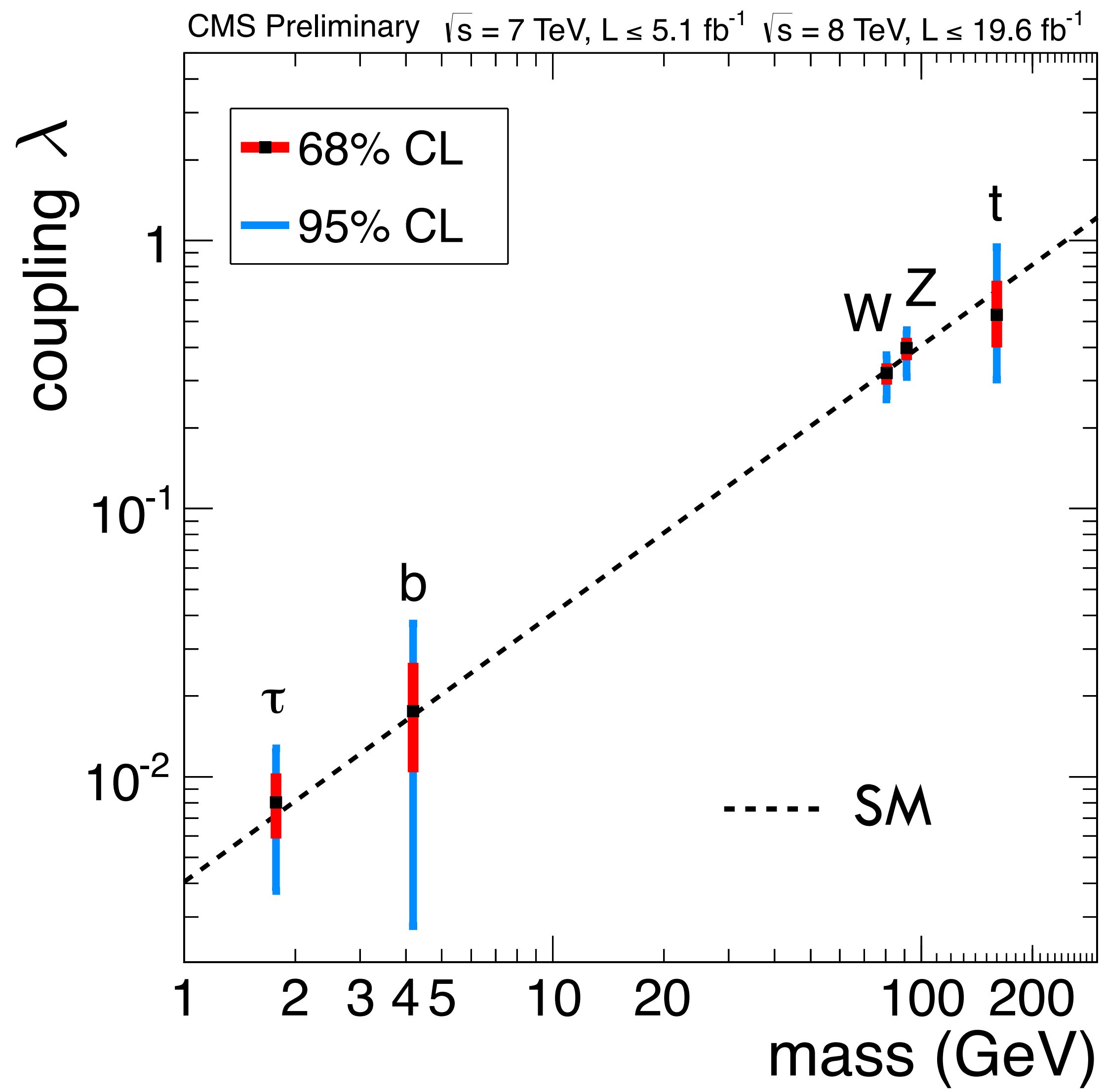
“It has to do with the EWSB”

Already first data gave evidence of:

$$\lambda_\psi \propto \frac{m_\psi}{v}\,, \qquad \lambda_V^2 \equiv \frac{g_{VVh}}{2v} \propto \frac{m_V^2}{v^2}$$

True in the SM:

$$\lambda_\psi = \frac{m_\psi}{v}\,, \qquad \lambda_V = \frac{m_V}{v}$$



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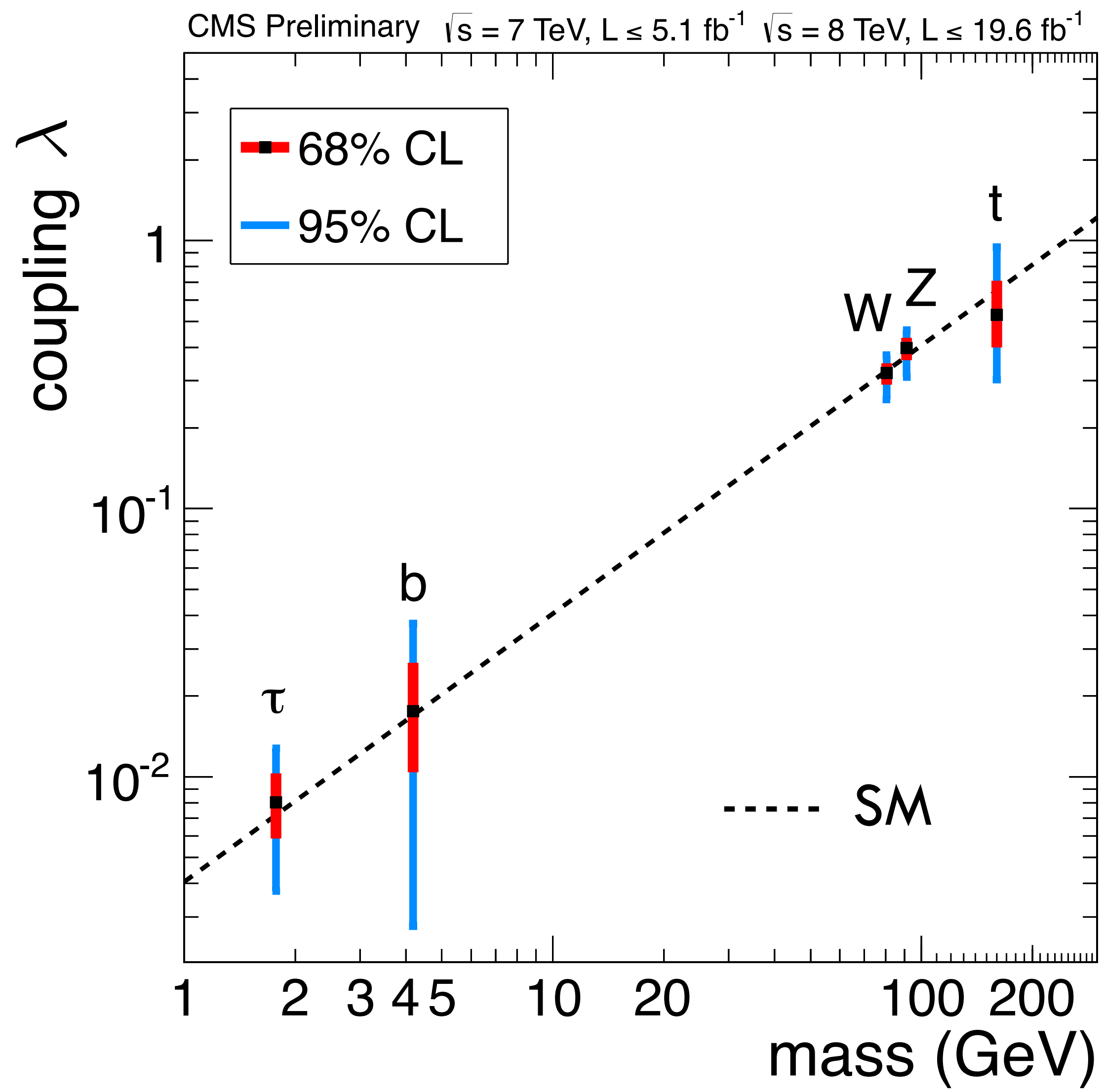
Scaling coupling $\propto$ mass follows naturally if the new boson is part of the sector that breaks the EW symmetry

It does *not* necessarily imply that the new boson is part of an $SU(2)_L$ doublet

For a non-doublet one naively expects: $$\frac{\lambda - \lambda^{SM}}{\lambda^{SM}} = O(1)$$

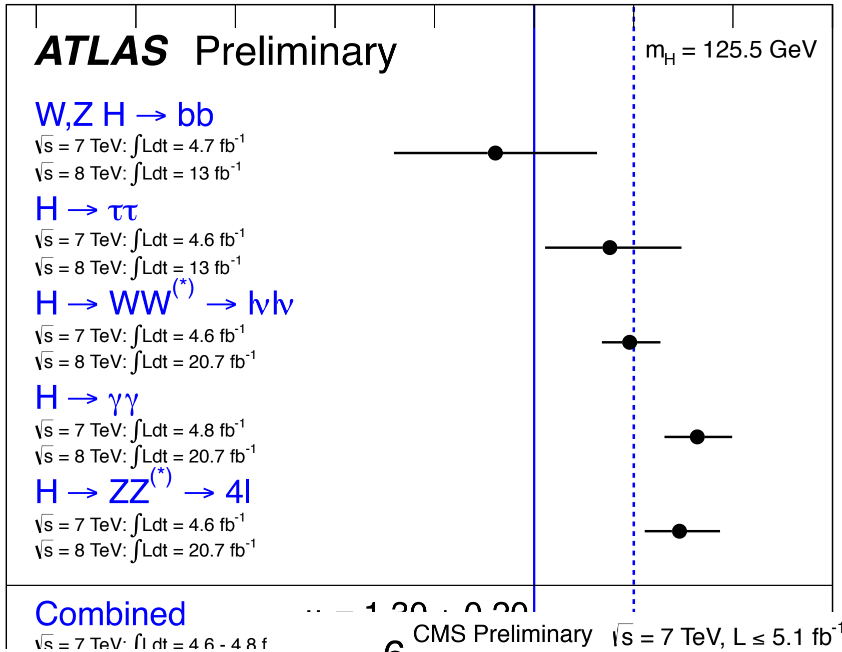


Ex: composite NG boson in TC

"It looks like a doublet"

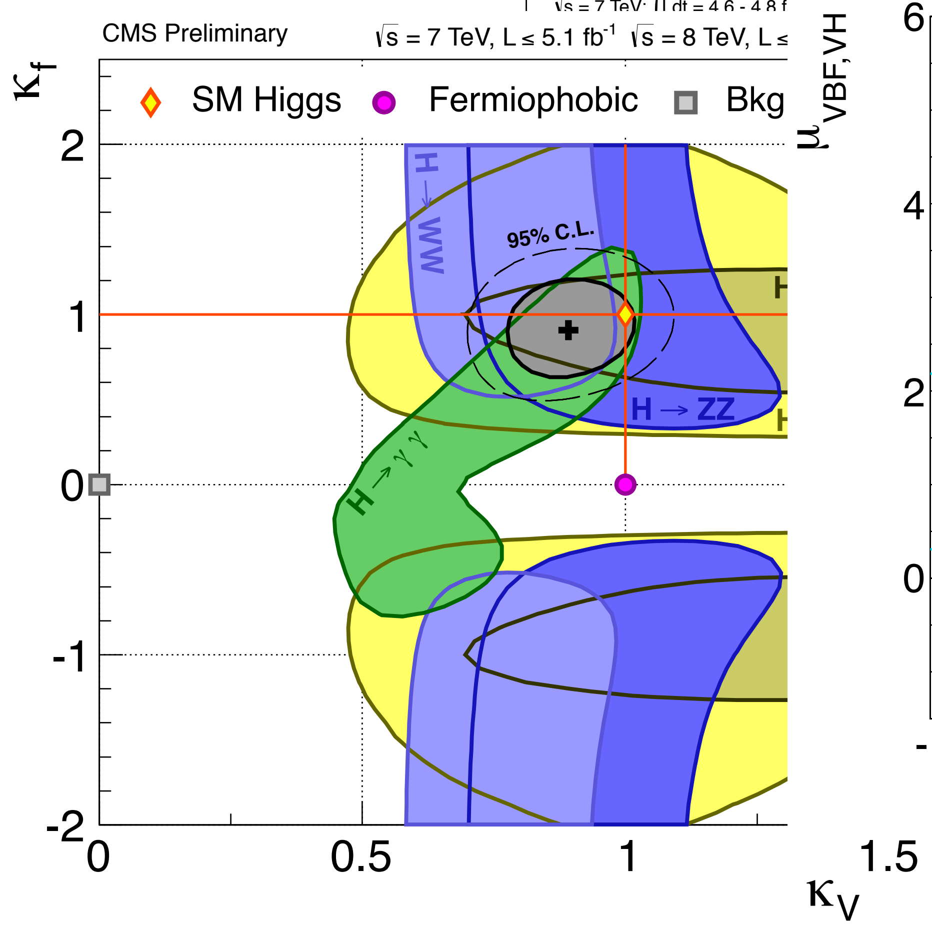
New data show an agreement with the SM prediction within ~20%-30%:

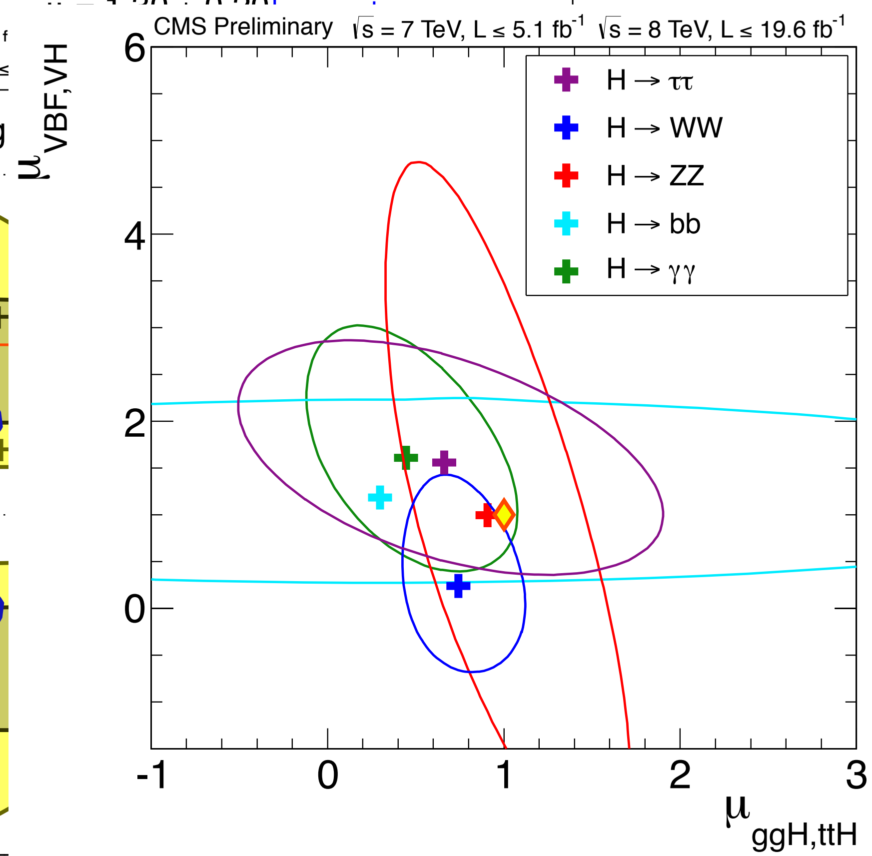
The new boson does not look an impostor at all, it closely resembles the SM Higgs



Experimental evidence based on many detailed analyses:

- Overall compatibility with SM
- Decay rates
- Production rates
- Global fit on couplings





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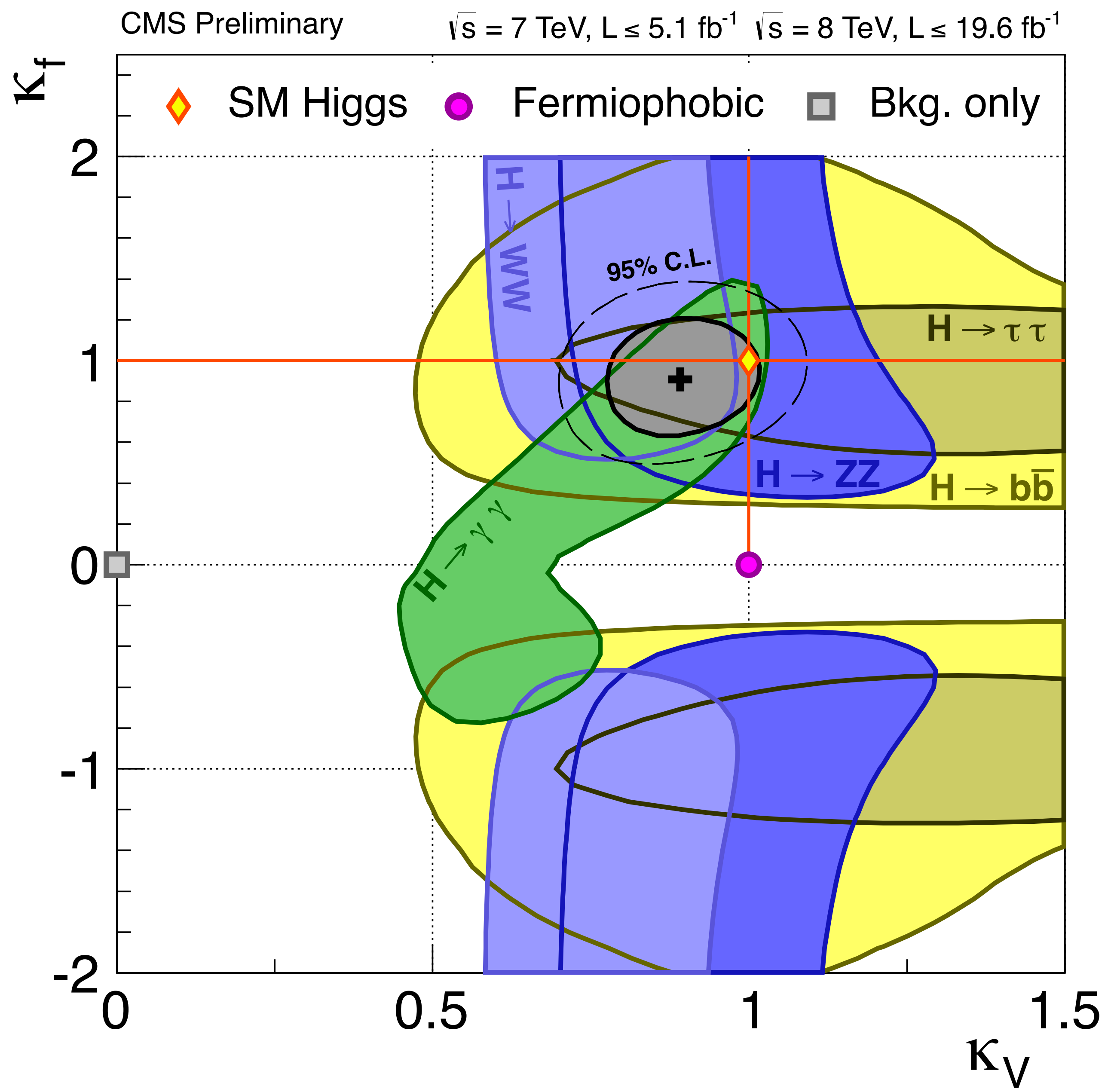
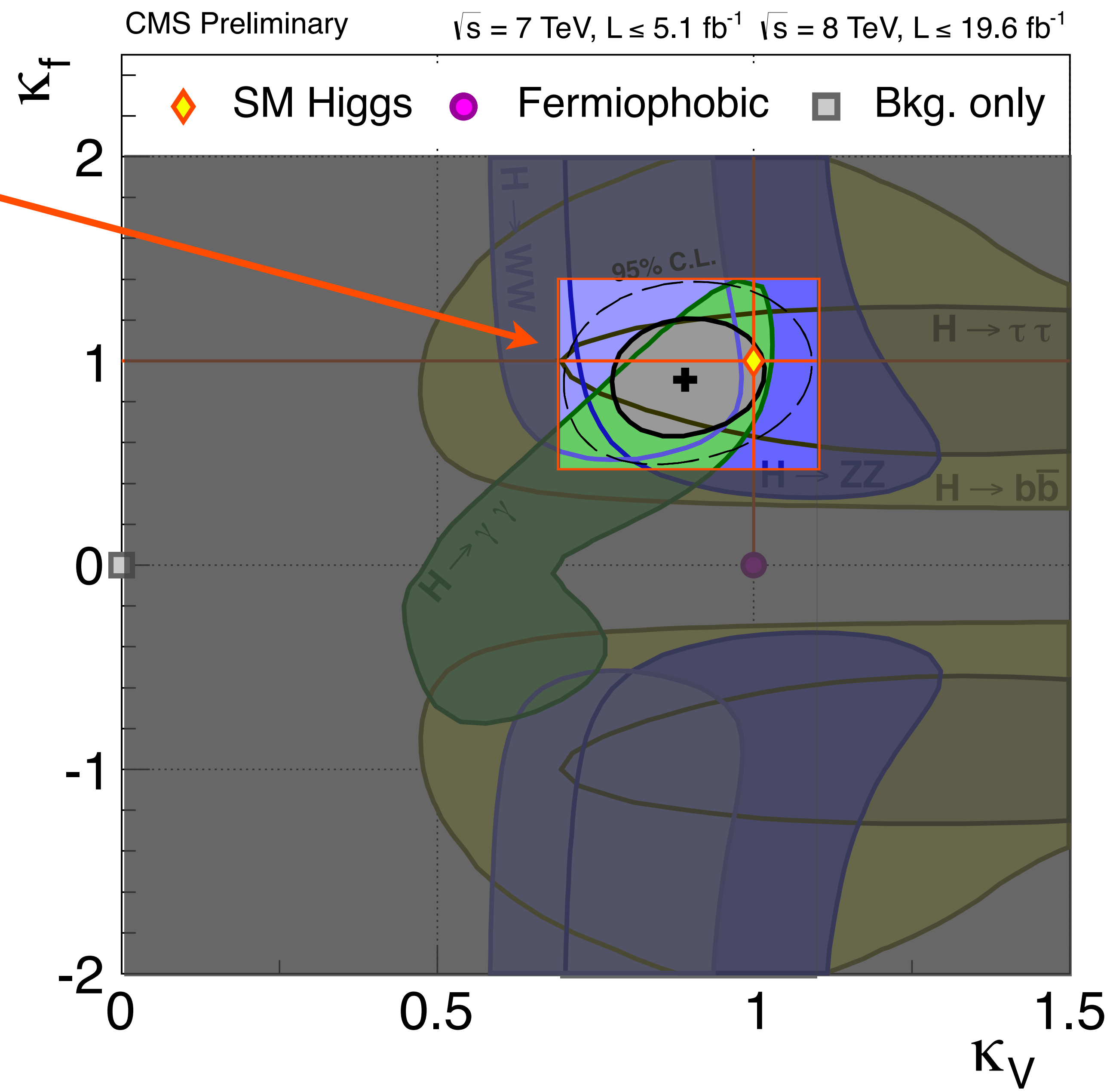


“It looks like a doublet”

The focus now is on a region of the parameter space around the SM point



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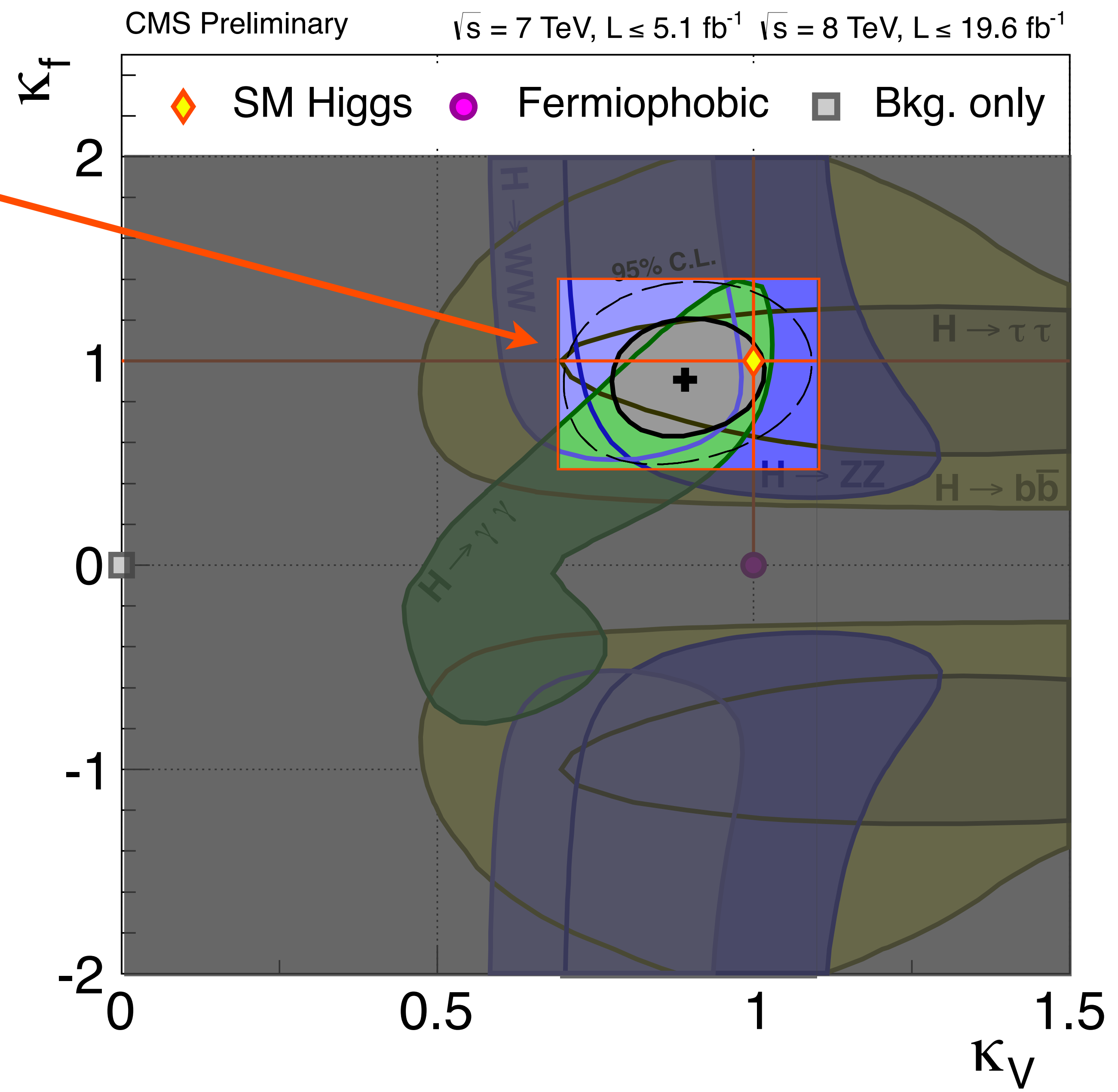

This is a *natural* region to live if:

1. The new boson is part of an $SU(2)_L$ doublet
2. There is a gap between the NP scale and m_H

$$\frac{\delta c}{c_{SM}} \sim \frac{g_H^2 v^2}{M^2}$$

g_H = Higgs coupling strength

$$\frac{\delta c}{c_{SM}} \lesssim 0.2 \quad \Rightarrow \quad M \gtrsim g_H \times 550\,\mathrm{GeV}$$

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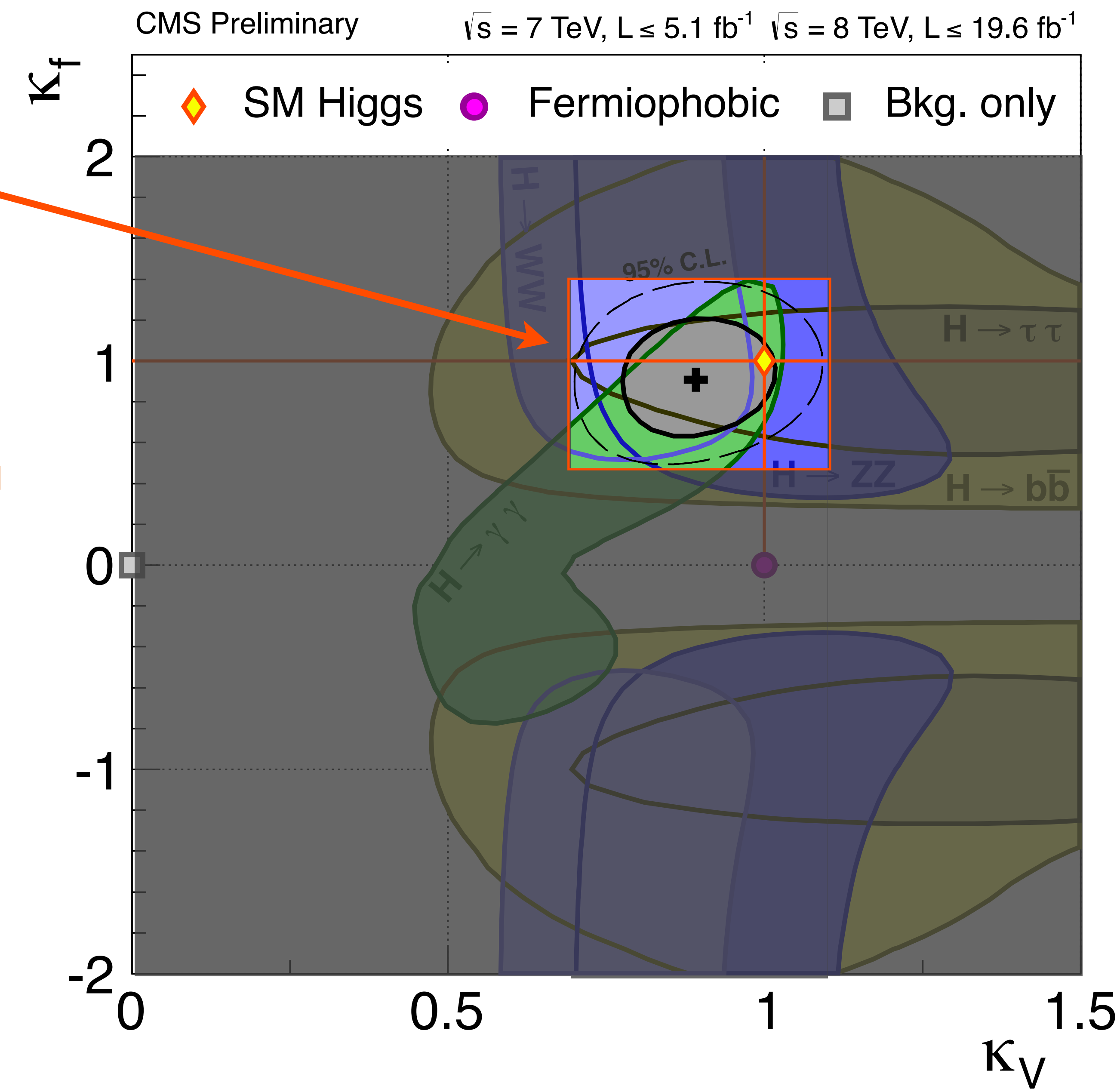

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Notice: the SM point is the only one in which the low-energy theory is *renormalizable and weakly coupled up to high energies*

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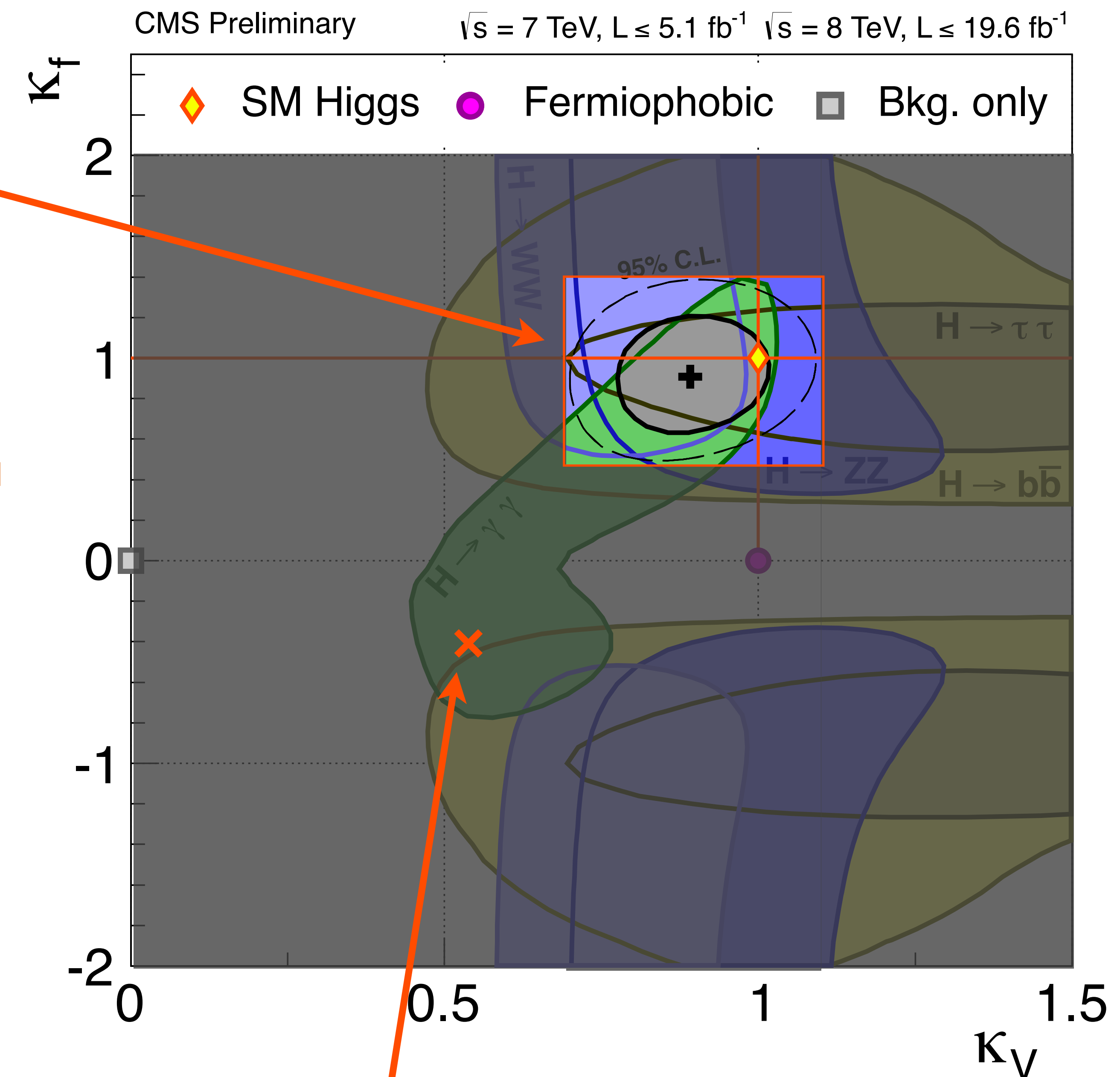

living in any other point requires either light NP or strong dynamics

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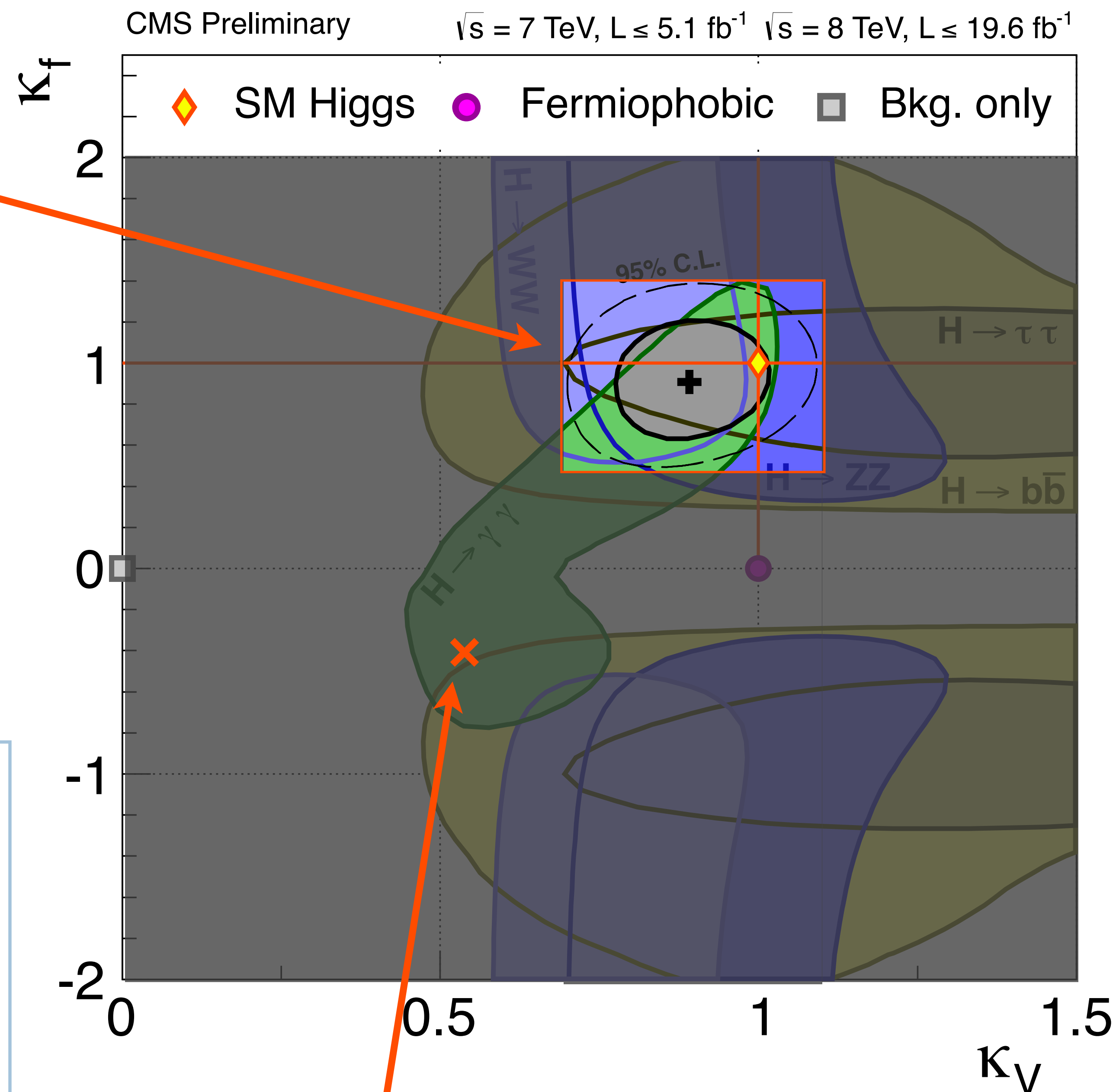
Conclusion:

Theories w/o a Higgs boson or with strong dynamics at low scale are now excluded

Ex: TC and CH with $M \approx 4\pi v$



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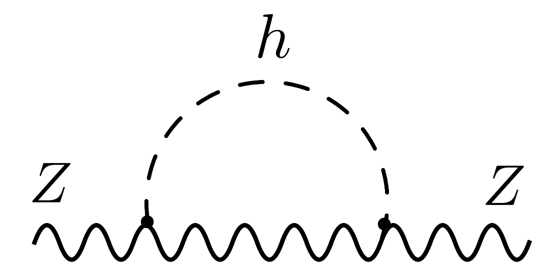
"Didn't we know already from LEP ?"

Not quite so:

1. evidence was indirect (through loops)
2. only hVV coupling and m_H constrained



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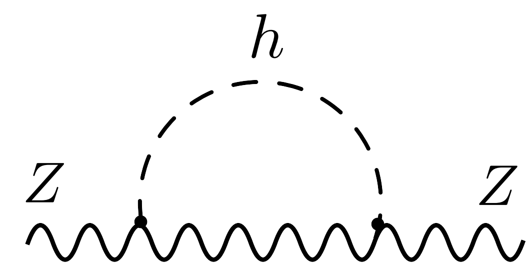


In fact:

Most recent EW fits much more stringent than before due to:

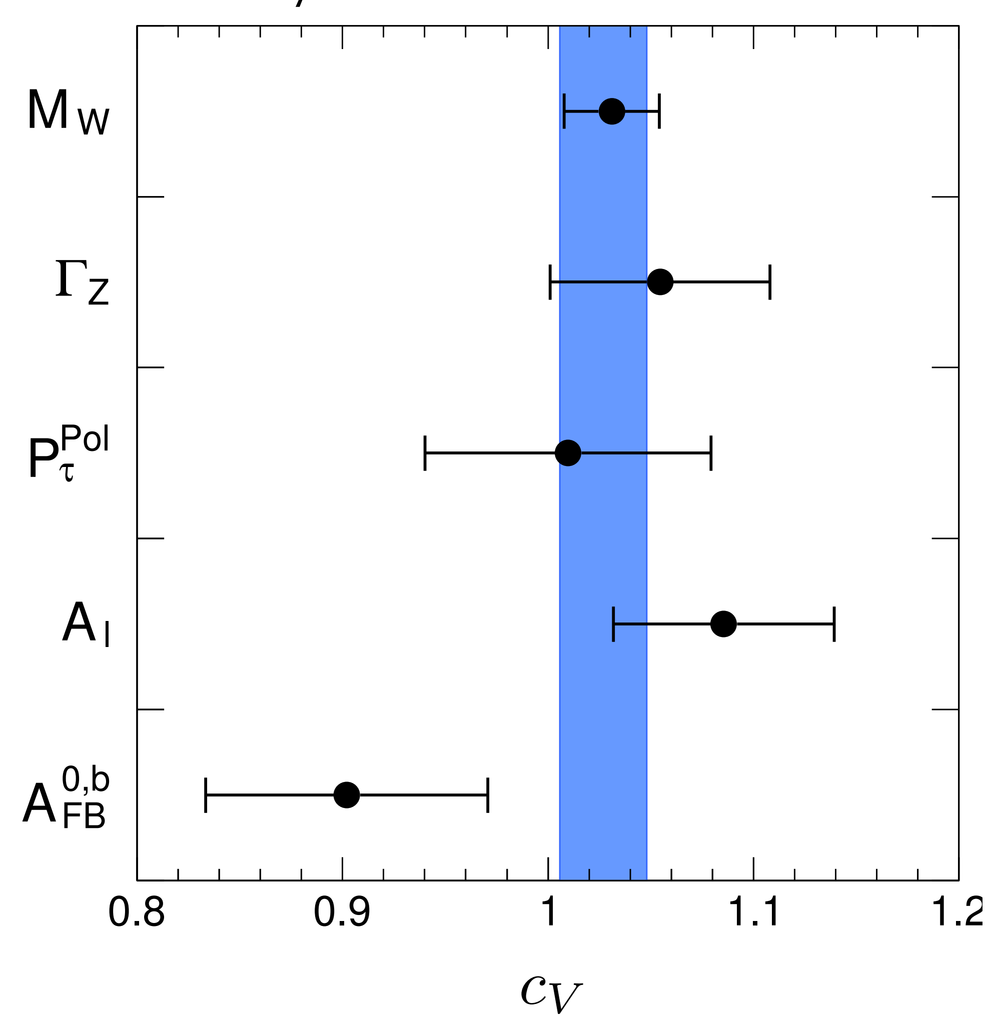
– mH now precisely known

– new m_W from Tevatron

Precision on c_V at the level of ~5% !

[Assuming no extra contribution to EWPO from new particles]

courtesy of S. Mishima



M. Ciuchini, E. Franco, L. Silvestrini, S. Mishima, to appear

If one assumes that

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2. There is a gap between the NP scale and m_H

then it must follow:

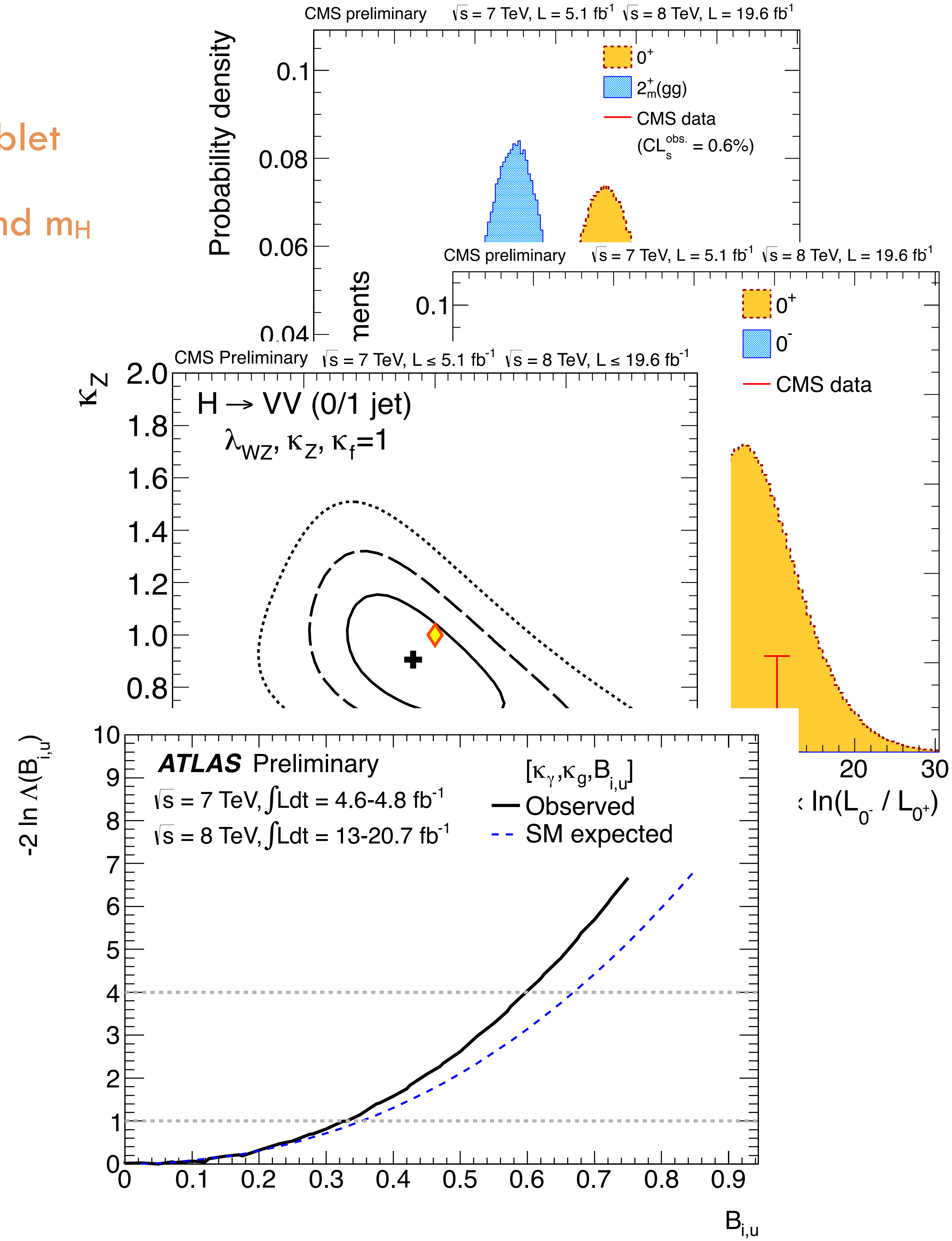
- h has spin 0 ✓
- h is (mostly) CP=+ ✓
- There exists a correlation among processes with 0,1,2 Higgs bosons

  Ex: custodial symmetry ✓

$$\frac{m_W}{m_Z \cos\theta_W} = 1 \;\Rightarrow\; \lambda_{WZ} = \frac{c_W}{c_Z} = 1$$

- There are no new light states to which the Higgs boson can decay

  Ex: Invisible width=0 ✓



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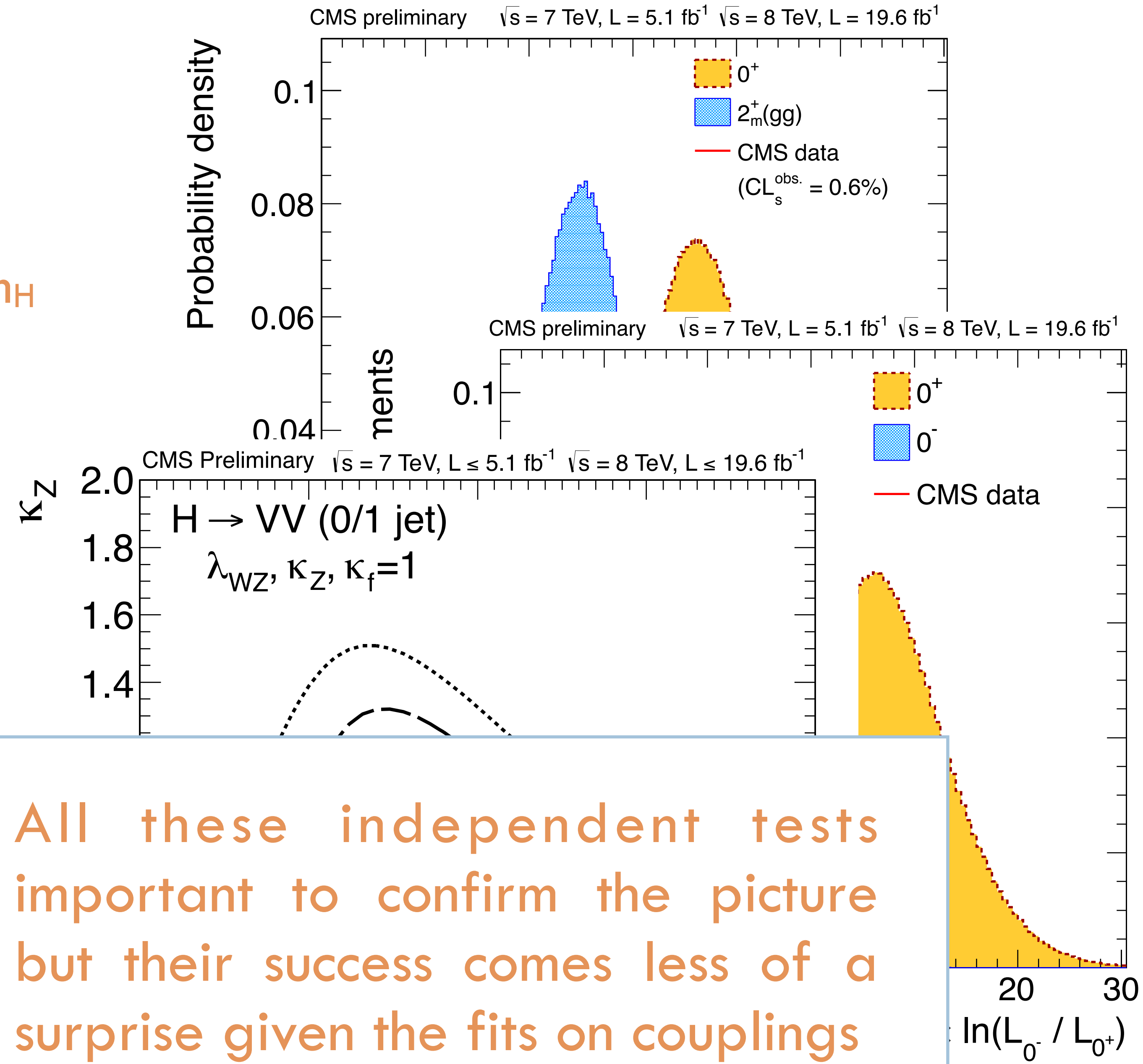

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All these independent tests important to confirm the picture but their success comes less of a surprise given the fits on couplings

Ex: there's no reason why a $J^P=0^-$ boson should have SM coupling strength

$$|D_\mu H|^2 \quad \text{vs} \quad \frac{\tilde{c}_{WW}}{M^2} W_{\mu\nu}\tilde{W}^{\mu\nu} H^\dagger H$$

MORAL:

Era of Higgs precision physics is about to start.
In absence of new particles use an Effective Lagrangian
to make predictions and parametrize new effects

- The explicit form of the Lagrangian depends on the assumptions one makes

Reasonable assumptions:

1) $SU(2)_L x U(1)_Y$ is linearly realized at high energies

2) h is a scalar (mostly CP even) part of an $SU(2)_L$ doublet H

3) The EWSB dynamics has an (approximate) custodial symmetry

   global symmetry includes: $SU(2)_L x SU(2)_R \rightarrow SU(2)_V$

Effective Lagrangian for a Higgs doublet

see recent review: RC, Ghezzi, Grojean, Muehlleitner, Spira arXiv:1303.3876

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \bar{c}_i O_i \equiv \mathcal{L}_{SM} + \Delta\mathcal{L}_{SILH} + \Delta\mathcal{L}_{F_1} + \Delta\mathcal{L}_{F_2}$$

dimension-6 operators
(only those relevant for Higgs physics)

$\vdots$

The list of dim=6 operators of the effective Lagrangian has been known in the literature since long time

Buchmuller and Wyler
NPB 268 (1986) 621

Minimal and complete list first appeared in:

Grzadkowski et al.
JHEP 1010 (2010) 085

Most useful parametrization from:

Giudice, Grojean, Pomarol, Rattazzi
JHEP 0706 (2007) 045

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

- Basis introduced by Giudice et al. (SILH basis)
- Absence of FCNC from tree-level exchange of the Higgs requires flavor alignment
- 12 operators in $\Delta\mathcal{L}_{SILH}$ + 5 made only of gauge fields (not shown)

only this operator formally breaks custodial symmetry

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

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

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

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$$\Delta\mathcal{L}_{F_1} = \frac{i\bar{c}_{Hq}}{v^2}\left(\bar{q}_L\gamma^\mu q_L\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) + \frac{i\bar{c}'_{Hq}}{v^2}\left(\bar{q}_L\gamma^\mu\sigma^i q_L\right)\left(H^\dagger\sigma^i \overleftrightarrow{D}_\mu H\right)$$
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$$+ \frac{i\bar{c}_{HL}}{v^2}\left(\bar{L}_L\gamma^\mu L_L\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) + \frac{i\bar{c}'_{HL}}{v^2}\left(\bar{L}_L\gamma^\mu\sigma^i L_L\right)\left(H^\dagger\sigma^i \overleftrightarrow{D}_\mu H\right)$$
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- 8 ($\Delta\mathcal{L}_{F_1}$) + 8 ($\Delta\mathcal{L}_{F_2}$) operators + 22 four-fermion operators (not shown)

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dipole operators

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POWER COUNTING: [Giudice et al. JHEP 0706 (2007) 045]

- each extra derivative costs a factor $1/M$
- each extra power of H(x) costs a factor $g_*/M \equiv 1/f$

For a strongly-interacting light Higgs (SILH): $\frac{1}{f} \gg \frac{1}{M}$

Naive estimate at the scale M:

$$\bar{c}_H, \bar{c}_T, \bar{c}_6, \bar{c}_\psi \sim O\left(\frac{v^2}{f^2}\right), \quad \bar{c}_W, \bar{c}_B \sim O\left(\frac{m_W^2}{M^2}\right), \quad \bar{c}_{HW}, \bar{c}_{HB}, \bar{c}_\gamma, \bar{c}_g \sim O\left(\frac{m_W^2}{16\pi^2 f^2}\right)$$

$$\bar{c}_{H\psi}, \bar{c}'_{H\psi} \sim O\left(\frac{\lambda_\psi^2}{g_*^2}\frac{v^2}{f^2}\right), \quad \bar{c}_{Hud} \sim O\left(\frac{\lambda_u \lambda_d}{g_*^2}\frac{v^2}{f^2}\right), \quad \bar{c}_{\psi W}, \bar{c}_{\psi B}, \bar{c}_{\psi G} \sim O\left(\frac{m_W^2}{16\pi^2 f^2}\right)$$

Specific symmetry protections might be at work in the UV theory

- Ex: in the MSSM $g_* \sim g$

R-parity ➡ $\bar{c}_W, \bar{c}_B \sim \frac{m_W^2}{M^2} \times \frac{g^2}{16\pi^2}$

- Ex: if the Higgs is a pNGB

Goldstone symmetry ➡ $\bar{c}_\gamma, \bar{c}_g \sim \frac{m_W^2}{16\pi^2 f^2} \times \frac{g_{\not{G}}^2}{g_*^2}$

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Muon and electron (g-2), EDM

Outlook

A short list of possible topics for Les Houches

Higgs Effective Lagrangian (HEL)

- Full implementation of HEL in MC generators

Production - $gg \to h$ (POWHEG ?)

Decay - $h \to 4f$ (tools exist ?)

- eHDECAY for BRs and partial widths

Implementing the Effective Lagrangian: eHDECAY

[from: RC, Ghezzi, Grojean, Muehlleitner, Spira arXiv:1303.3876]

- eHDECAY fully implements the SILH and non-linear Lagrangians (plus two benchmark CH models) for the calculation of Higgs decay rates and BRs

- Software based on HDECAY v5.10; Freely available at the web page:

  http://www-itp.particle.uni-karlsruhe.de/~maggie/eHDECAY

- Perturbative expansion in the parameters $\alpha_{SM}/4\pi,\ (E/M)^2,\ (v/f)^2$ performed consistently

  Ex: 1-loop EW corrections included only for the SILH Lagrangian

- Numerical approximate formulas for the decay rates are given in the paper

$$\frac{\Gamma(\bar{\psi}\psi)}{\Gamma(\bar{\psi}\psi)_{SM}} \simeq 1 - \bar{c}_H - 2\,\bar{c}_\psi \,,$$

$$\frac{\Gamma(h \to W^{(*)}W^*)}{\Gamma(h \to W^{(*)}W^*)_{SM}} \simeq 1 - \bar{c}_H + 2.2\,\bar{c}_W + 3.7\,\bar{c}_{HW} \,,$$

$$\frac{\Gamma(h \to Z^{(*)}Z^*)}{\Gamma(h \to Z^{(*)}Z^*)_{SM}} \simeq 1 - \bar{c}_H + 2.0\,\left(\bar{c}_W + \tan^2\theta_W\,\bar{c}_B\right) + 3.0\,\left(\bar{c}_{HW} + \tan^2\theta_W\,\bar{c}_{HB}\right) - 0.26\,\bar{c}_\gamma \,,$$

$$\frac{\Gamma(h \to Z\gamma)}{\Gamma(h \to Z\gamma)_{SM}} \simeq 1 - \bar{c}_H + 0.12\,\bar{c}_t - 5\cdot 10^{-4}\,\bar{c}_c - 0.003\,\bar{c}_b - 9\cdot 10^{-5}\,\bar{c}_\tau + 4.2\,\bar{c}_W + 0.19\left(\bar{c}_{HW} - \bar{c}_{HB} + 8\,\bar{c}_\gamma\sin^2\theta_W\right)\frac{4\pi}{\sqrt{\alpha_2\alpha_{em}}} \,,$$

$$\frac{\Gamma(h \to \gamma\gamma)}{\Gamma(h \to \gamma\gamma)_{SM}} \simeq 1 - \bar{c}_H + 0.54\,\bar{c}_t - 0.003\,\bar{c}_c - 0.007\,\bar{c}_b - 0.007\,\bar{c}_\tau + 5.04\,\bar{c}_W - 0.54\,\bar{c}_\gamma\,\frac{4\pi}{\alpha_{em}} \,,$$

$$\frac{\Gamma(h \to gg)}{\Gamma(h \to gg)_{SM}} \simeq 1 - \bar{c}_H - 2.12\,\bar{c}_t + 0.024\,\bar{c}_c + 0.1\,\bar{c}_b + 22.2\,\bar{c}_g\,\frac{4\pi}{\alpha_2} \,.$$

$$\alpha_2 \equiv \frac{\sqrt{2}\,G_F m_W^2}{\pi} \qquad\qquad \alpha_{em} \equiv \alpha_{em}(q^2 = 0)$$

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  Production: *- $gg \to h$ (POWHEG ?)*

  Decay: *- $h \to 4f$ (tools exist ?)*

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- EW corrections for Higgs precision physics:
  - *full RG evolution of Wilson coefficients (partial calculations exist)*
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  Make wishlist of NLO EW calculations within the HEL approach

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- Updated and complete analysis of constraints from Higgs, flavor and precision data on the coefficients of HEL

Example: put limits on hVV derivative couplings

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

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← LEP bounds

$$(\bar{c}_W + \bar{c}_B) \lesssim \text{a few} \times 10^{-3}$$

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

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

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

← LEP bounds

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$$\frac{\delta(d\Gamma/d\Omega)}{(d\Gamma/d\Omega)_{SM}} \lesssim O\left(\frac{m_W^2}{M^2} \times \frac{16\pi^2}{g^2}\right)$$

Take advantage of different angular distributions of final fermions

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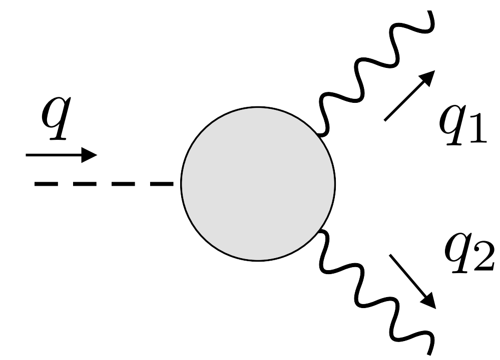
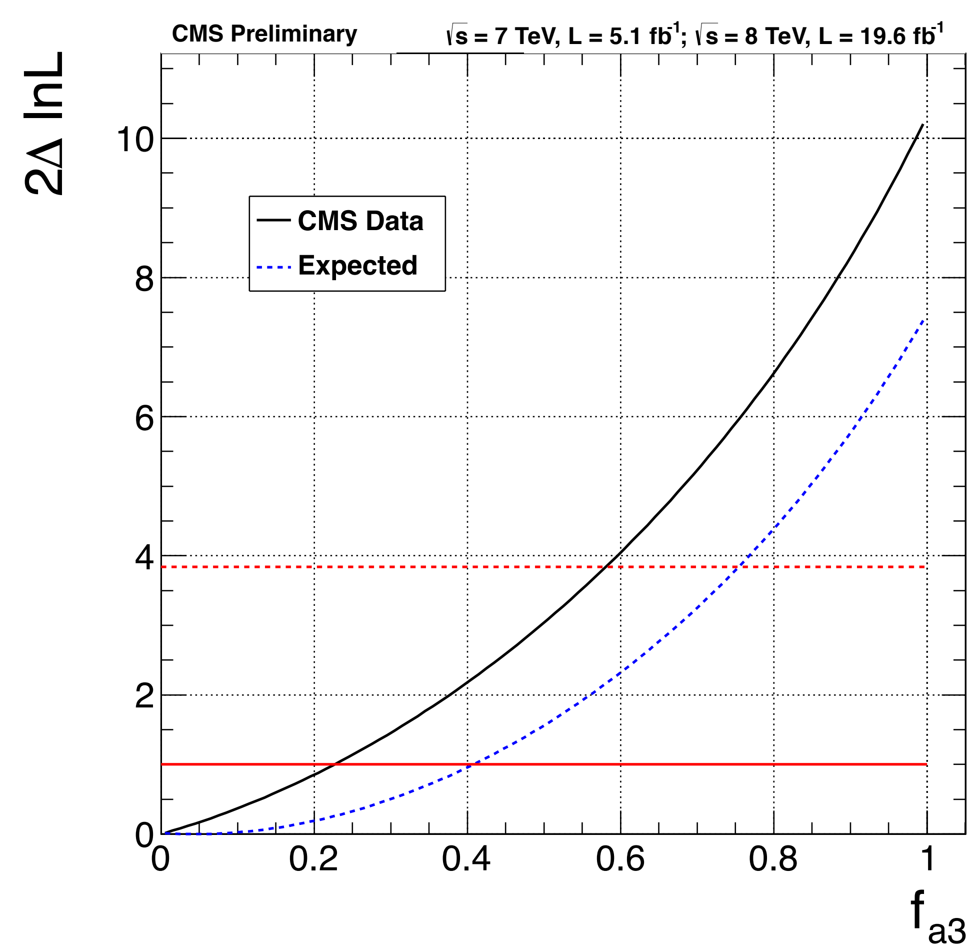


$$A(h \to ZZ) = v^{-1}\epsilon_1^\mu\epsilon_2^\nu\left(a_1 m_H^2\,\eta_{\mu\nu} + a_2\, q_\mu q_\nu + a_3\,\epsilon_{\mu\nu\rho\sigma}q_1^\rho q_2^\sigma\right)$$

$$a_1 = \frac{m_Z^2}{m_h^2} + (\bar{c}_W + \bar{c}_{HW}) + (\bar{c}_B + \bar{c}_{HB})\tan^2\theta_W$$
$$- \frac{2(q_1\cdot q_2)}{m_h^2}(\bar{c}_W + \bar{c}_B\tan^2\theta_W)$$

$$a_2 = 2\left(\bar{c}_{HW} + \bar{c}_{HB}\tan^2\theta_W\right)$$

$$a_3 = 2\left(\tilde{c}_{HW} + \tilde{c}_{HB}\tan^2\theta_W\right)$$



Higgs Effective Lagrangian (HEL)

- Full implementation of HEL in MC generators

Production: - $gg \rightarrow h$ (POWHEG ?)

Decay: - $h \rightarrow 4f$ (tools exist ?)

- eHDECAY for BRs and partial widths

- EW corrections for Higgs precision physics:
  - *full RG evolution of Wilson coefficients (partial calculations exist)*
  - *finite terms (long distance contributions)*

  Make wishlist of NLO EW calculations within the HEL approach

- Updated and complete analysis of constraints from Higgs, flavor and precision data on the coefficients of HEL

- Estimate of future sensitivity of the LHC on the coefficients of HEL

Q: “ *Given the current constraints and limits, what are the observables which are most promising to discover NP ?* ”

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- *fit of Wilson coefficients to get actual bounds*
- *see allowed parameter space and find ways to further constrain it at the LHC*

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From the point of view of models

- *natural SUSY*
- *Composite Higgs*

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Q: “ *How do searches at 14 TeV compare to those at 8 TeV ?* ”

- *new strategies (e.g. boosted techniques)*
- *new channels can become accessible*

- Study of model-specific processes

Ex: for composite Higgs

- *top partners decaying to Higgs*

  $(g^* \to) Tt \to tth$, $Bb \to bbh$, ...

- *spin1/spin0 resonances decaying to Higgs*

  $\rho \to Zh, Wh$ ...

- *double Higgs production*

  $VV \to hh$, $gg \to hh$

Ex: for DM models

- *Higgs portal models, Higgs→invisible, Higgs + invisible associated production*

EXTRA SLIDES

Fit in the plane (k_V,k_F) by ATLAS and CMS