COUPLINGS FROM CMS

Higgs Couplings Workshop
1st - 3rd Oct 2014

A. David (CERN) *for the CMS Collaboration*

~~COUPLINGS~~ FROM CMS

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DEVIATIONS FROM CMS

Higgs Couplings Workshop
1^{st} - 3^{rd} Oct 2014

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CMS @HiggsCouplingst2014

[http://cern.ch/go/S6pm]

- **A. Massironi** – $H \to ZZ \to 4\ell$, $H \to \gamma\gamma$, $H \to WW$
- **R. Manzoni** – H and fermions
- **A. Martelli** – Mass measurement
- **R. Wolf & R. Castello** – BSM
- **C. Charlot** – Total width
- **M. Xiao** – Spin and parity

Oversimplified big picture

★ "seen" ☆ "tried"	H→bb̄	H→ττ	H→WW	H→ZZ	H→γγ	H→Z(*)γ	H→inv.	H→μμ	H→cc̄ H→HH
ggH		★	★	★	★	☆		☆	
VBF	☆	★	★	☆	★	☆	☆	☆	
VH	★	☆	☆	☆	☆		☆		
ttH	☆	☆	☆		☆				

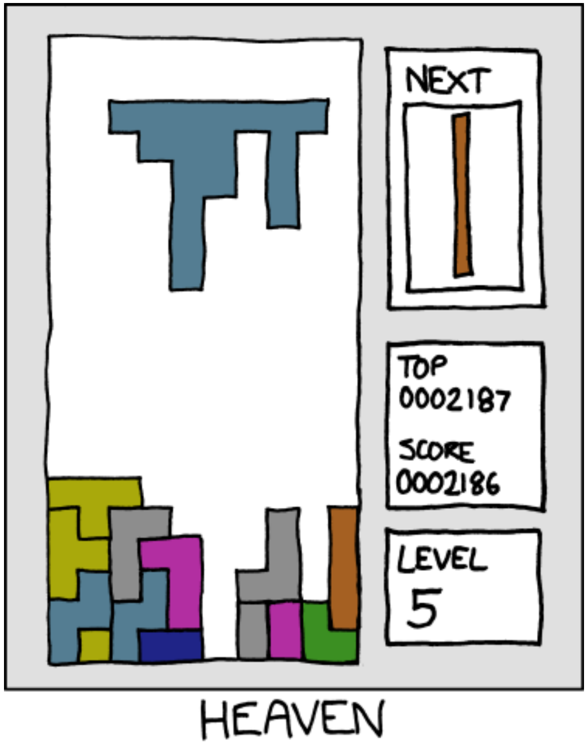
- **Still much to explore on the rarer ends.**

  (to the right and to the bottom) (and outside this picture)

Deviations of H(125)

[http://xkcd.com/888/]

- **Heavy New Physics**
  - LHC HXSWG WG2
  - Decoupling of heavy d.o.f.
  - Indirect effects, loops, dim-6 operators, etc.
- **Light New Physics**
  - LHC HXSWG WG3
  - Other states, degenerate states, etc.



Handles on deviations

- Mass
  - Exp. Uncertainties
  - SM consistency: (m_H, m_W, m_{top})
- Spin
  - Are we happy now?
- Charge
  - Zero. (That was easy.)
- Parity
  - Amplitude decomposition → EFT
- Scalar couplings
  - $\kappa \rightarrow \kappa(q) \rightarrow f(q) \rightarrow$ EFT

An actual measurement

- **Mass**
  - **Exp. Uncertainties**
  - **SM consistency: (m_H, m_W, m_{top})**
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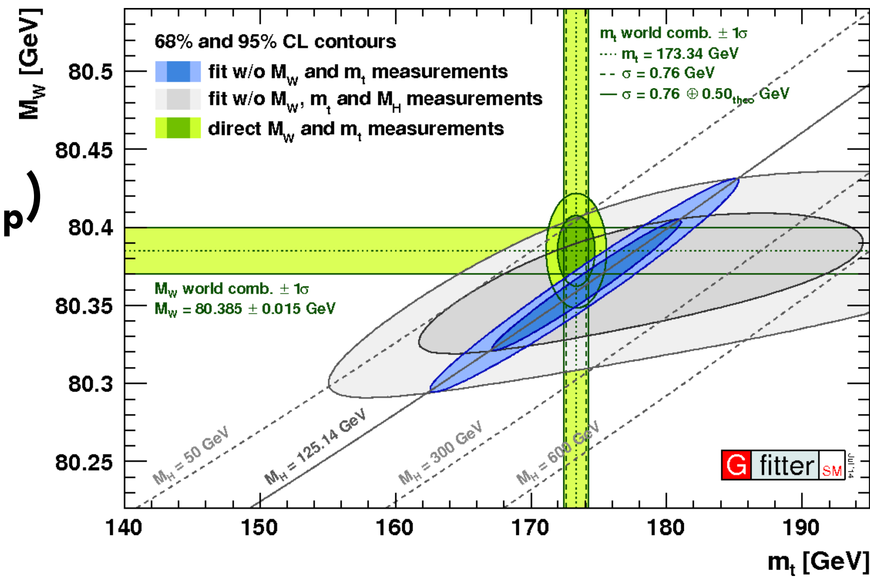

One model

One model


Fiat 124

Fiat 126

One model


Fiat 125
a very high-performance saloon
$2898
Willys Motors
STAND No. 8
(AUSTRALIA) PTY. LTD. 79 YARRABANK ROAD, SOUTH MELBOURNE. 69-7411
594 ELIZABETH STREET, MELBOURNE. Phone 34-1519


Fiat 124


CB 29070
Fiat 126

One model


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125 ±0.3
a very
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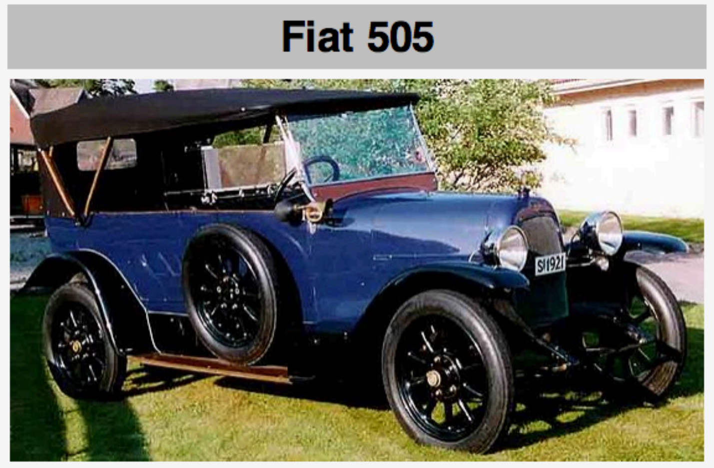
Other models?

[http://cern.ch/go/X6rC]

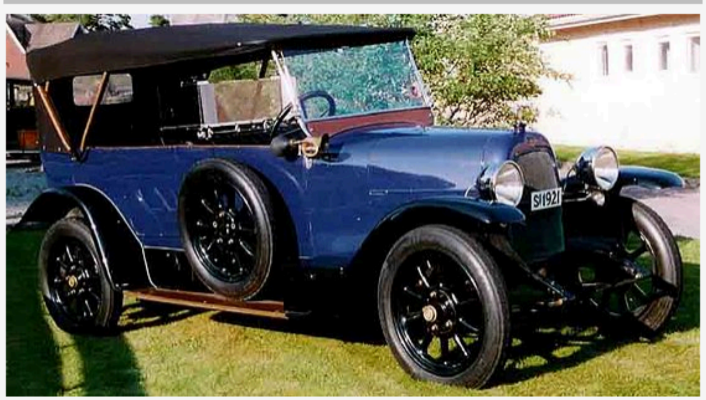


Other models?

[http://cern.ch/go/X6rC]

Fiat 1400/1900

Fiat 505



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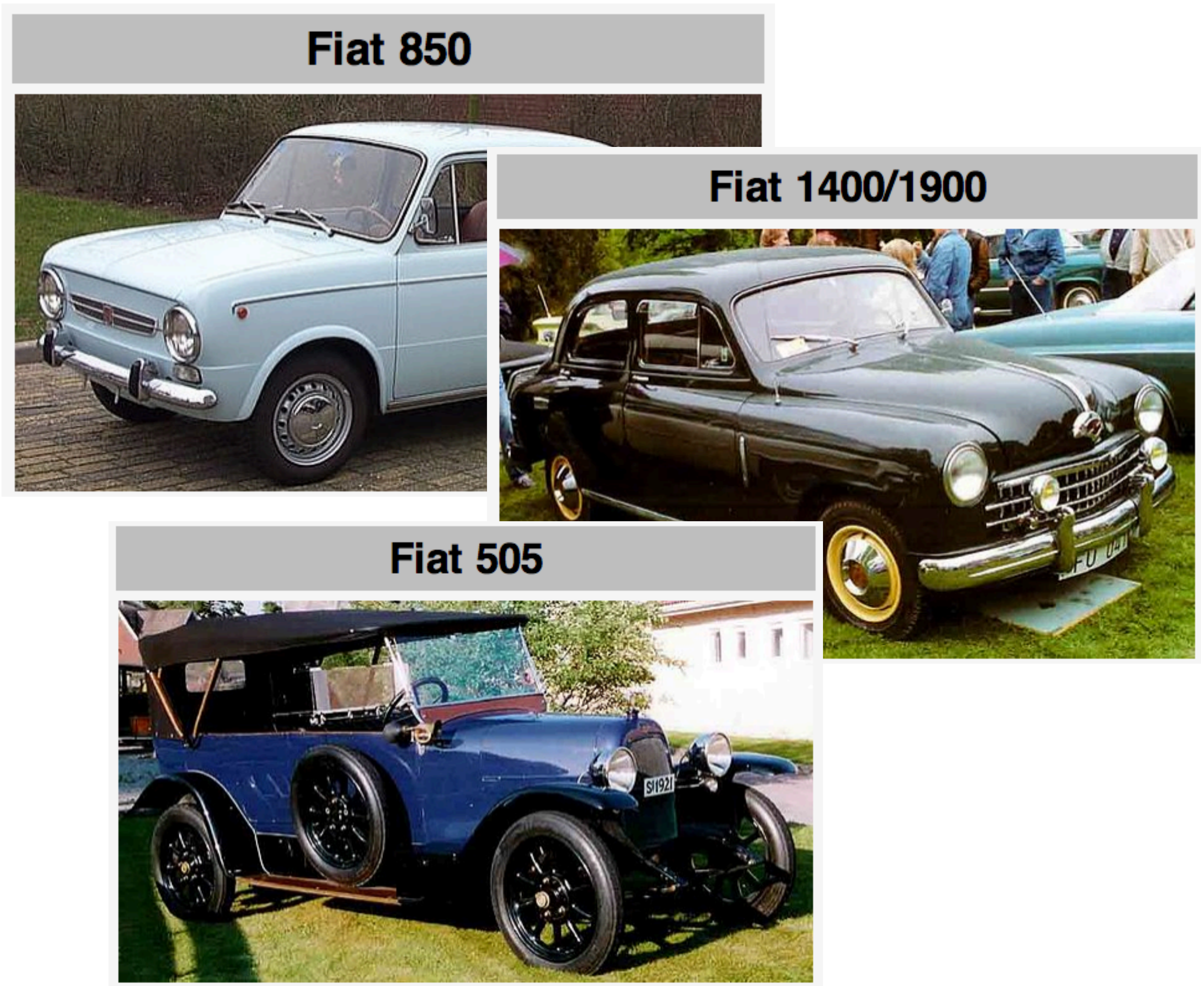


Other models?

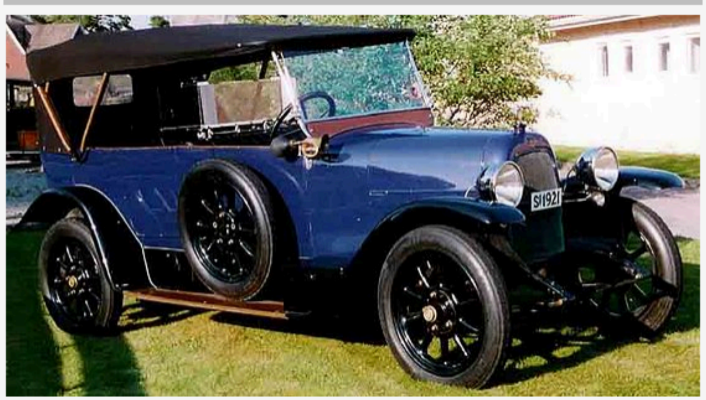
[http://cern.ch/go/X6rC]

Fiat 850

Fiat 1400/1900

Fiat 2300

Fiat 505



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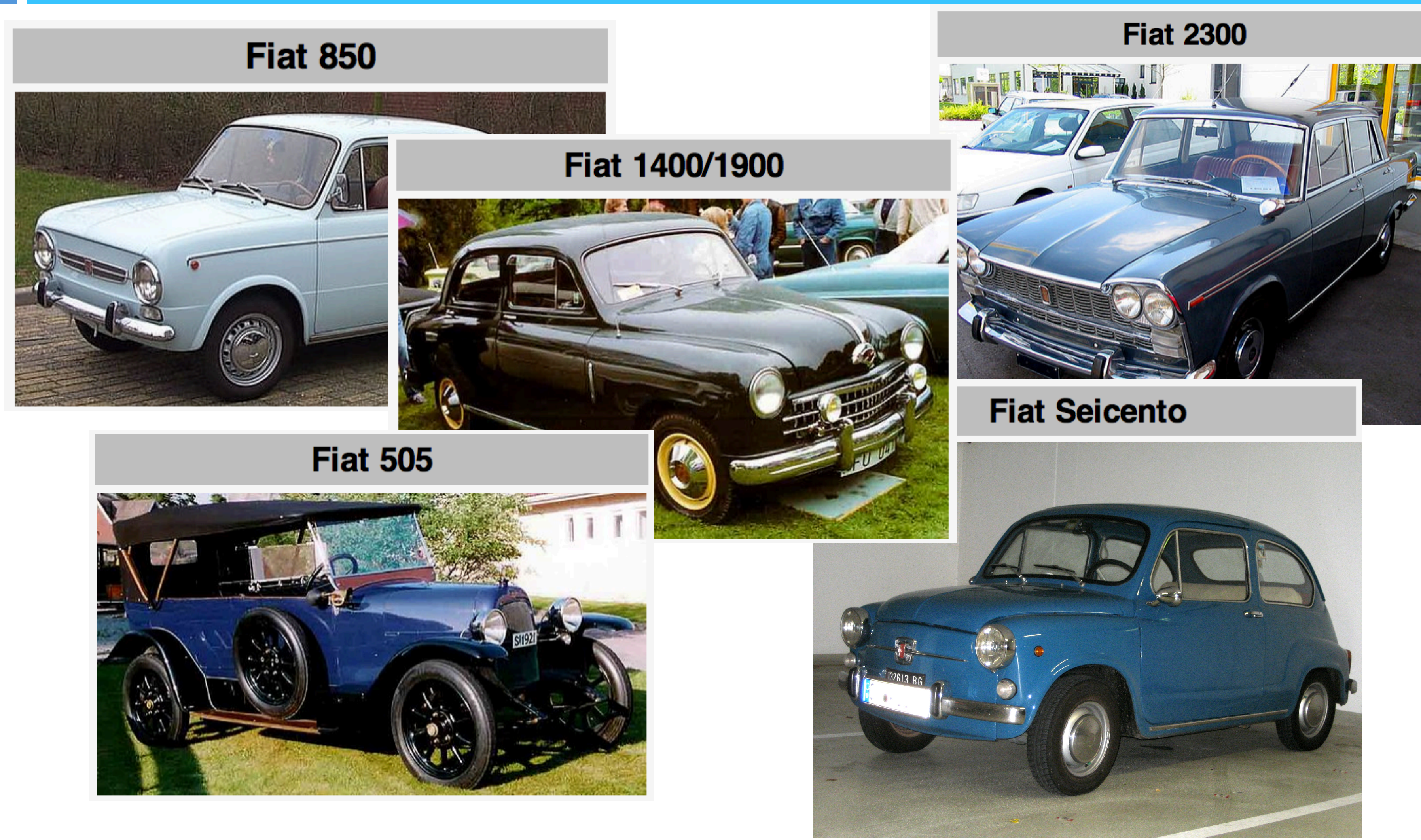

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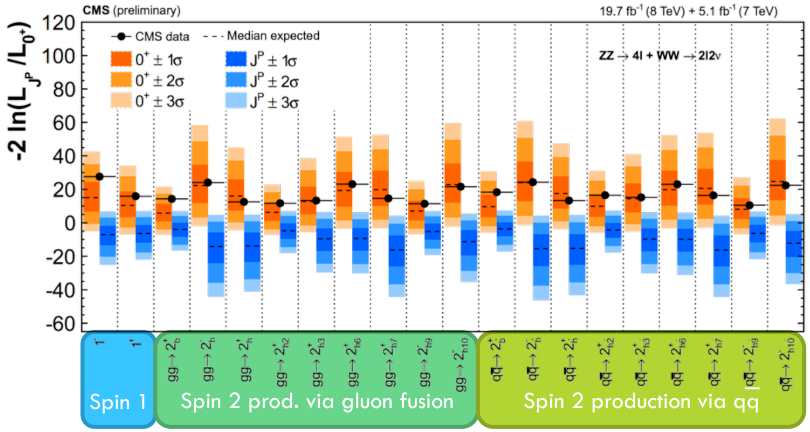

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0

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  - **Amplitude decomposition → EFT**
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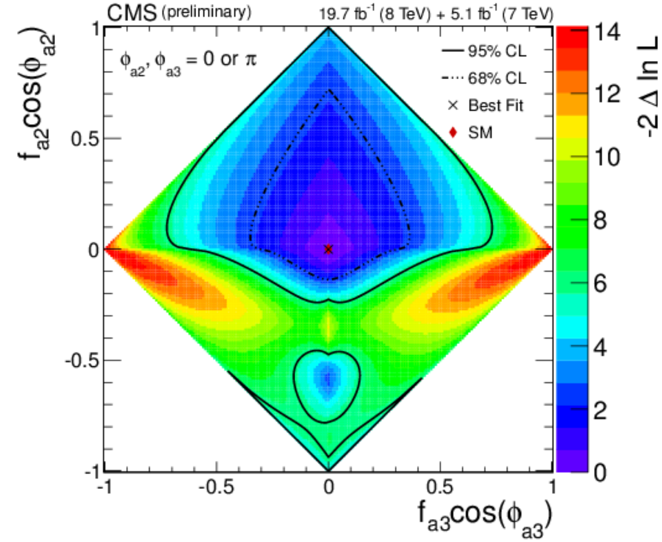
$$A(X_{J=0} \to V_1 V_2) \sim v^{-1}\Bigg(\left[a_1 - e^{i\phi_{\Lambda_1}}\frac{q_{Z_1}^2 + q_{Z_2}^2}{(\Lambda_1)^2}\right] m_Z^2 \epsilon^*_{Z_1}\epsilon^*_{Z_2} + a_2 f^{*(Z_1)}_{\mu\nu} f^{*(Z_2),\mu\nu} + a_3 f^{*(Z_1)}_{\mu\nu} \tilde{f}^{*(Z_2),\mu\nu} + a_2^{Z\gamma} f^{*(Z)}_{\mu\nu} f^{*(\gamma),\mu\nu} + a_3^{Z\gamma} f^{*(Z)}_{\mu\nu} \tilde{f}^{*(\gamma),\mu\nu} + a_2^{\gamma\gamma} f^{*(\gamma_1)}_{\mu\nu} f^{*(\gamma_2),\mu\nu} + a_3^{\gamma\gamma} f^{*(\gamma_1)}_{\mu\nu} \tilde{f}^{*(\gamma_2),\mu\nu}\Bigg)$$



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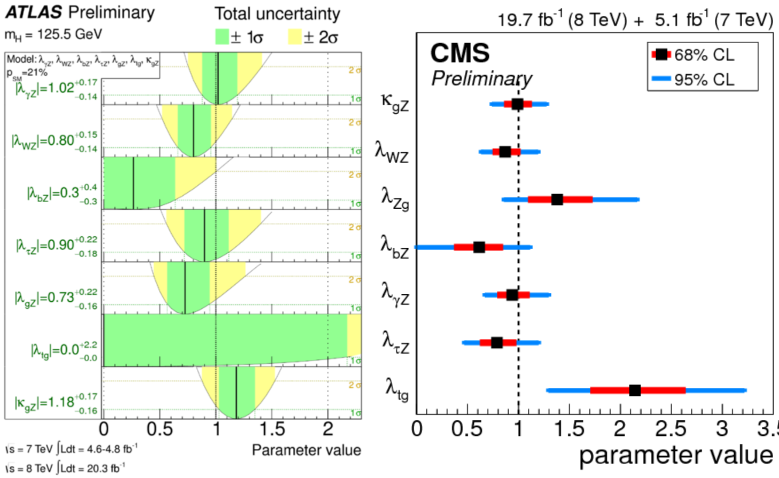
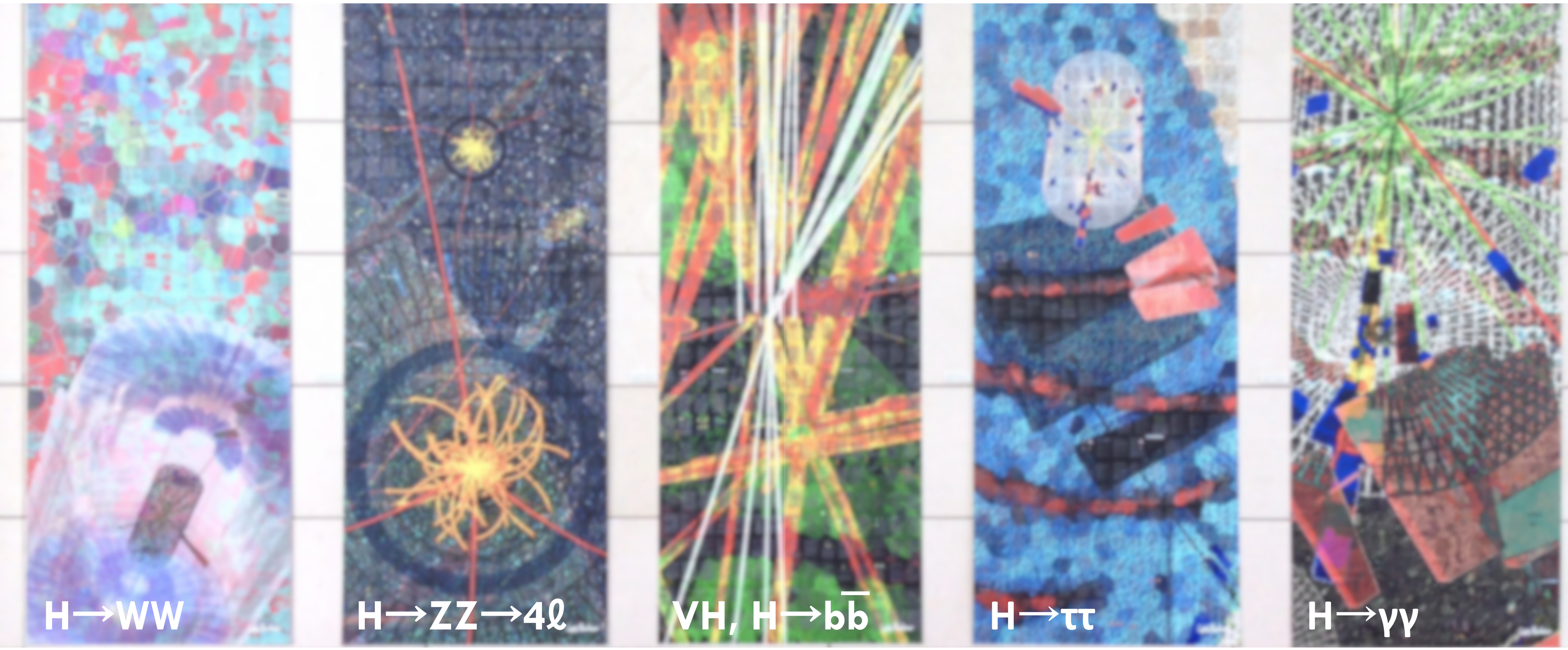


A combination of final results



JHEP 01(2014) 096 | PRD 89 (2014) 092007 | PRD 89 (2014) 012003 | JHEP 05 (2014) 104 | arXiv:1407.0558 (subm. to EPJC)

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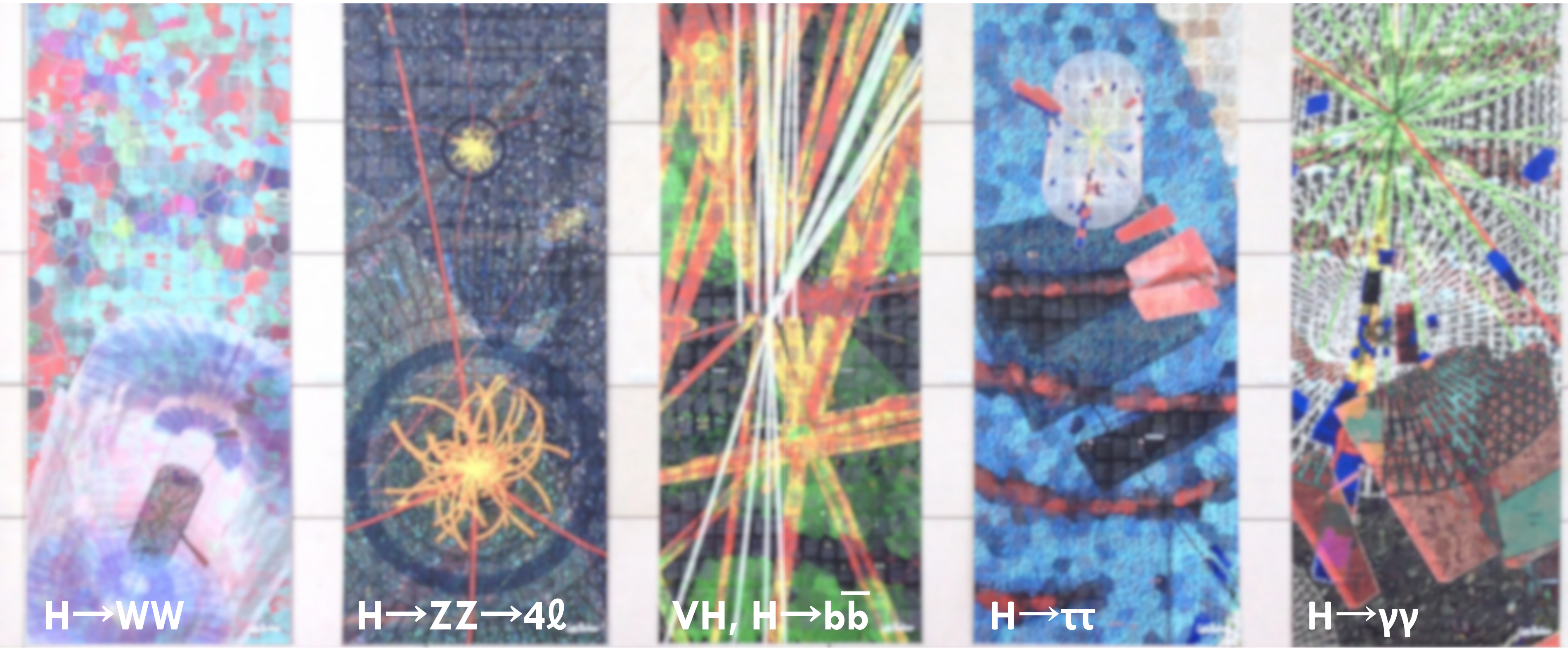

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Also include further ttH searches:

- JHEP 05(2013)145 – ttH, $H\to b\bar{b}$ (7 TeV).
- CMS-PAS-HIG-13-019 – ttH, $H\to b\bar{b}$ and $H\to\tau\tau$ (8 TeV).
- CMS-PAS-HIG-13-020 – ttH, with H decaying to multiple leptons.

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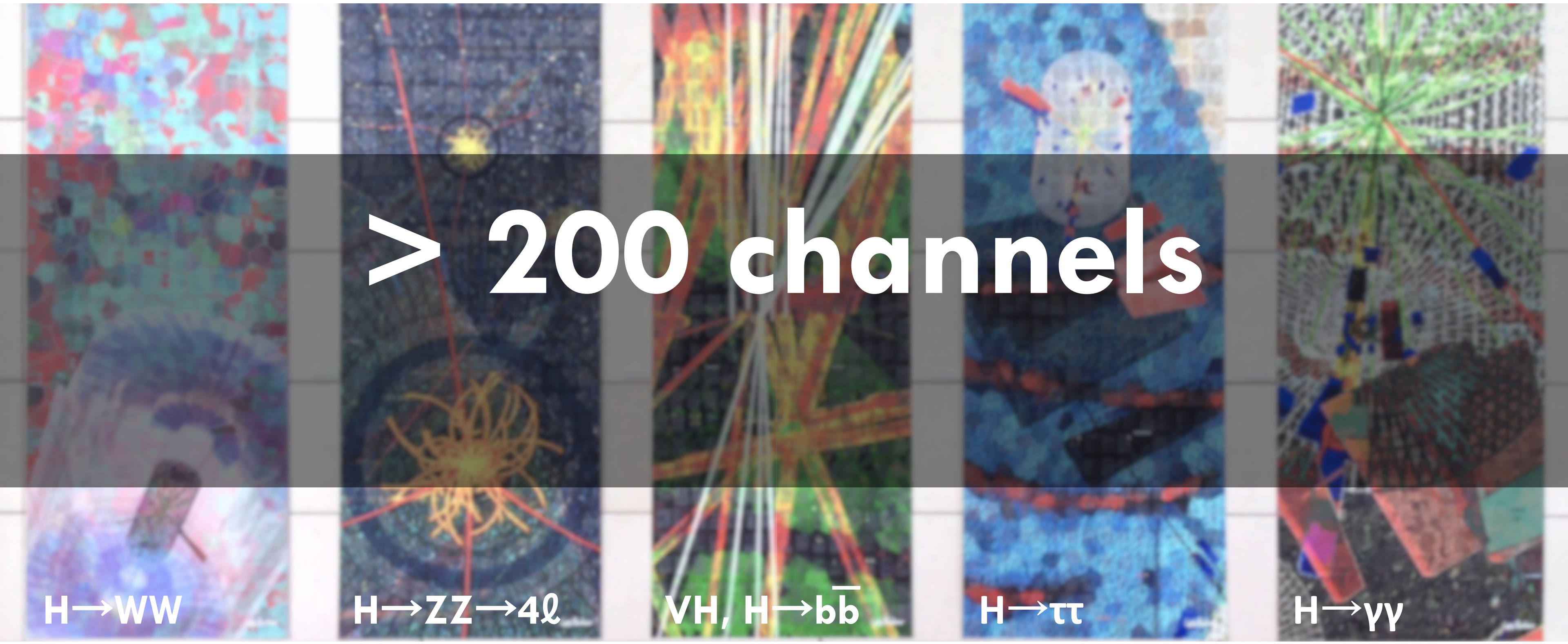

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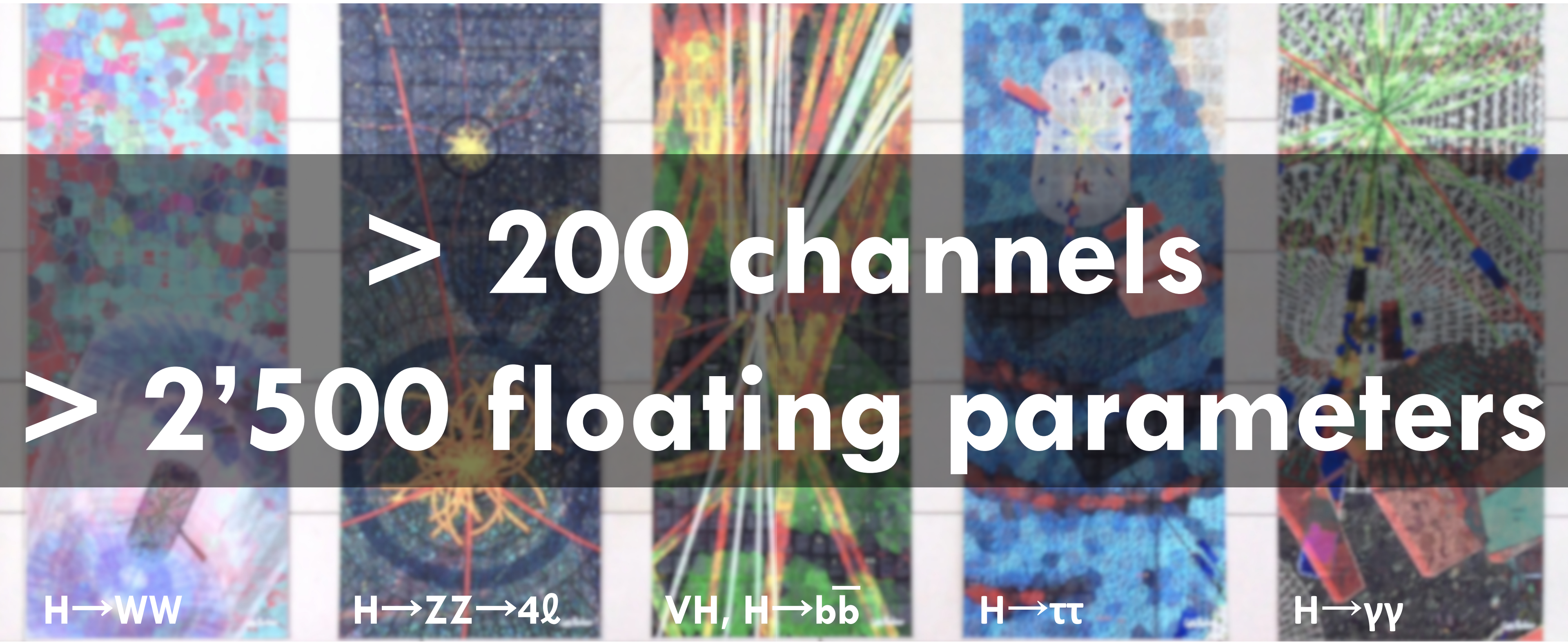

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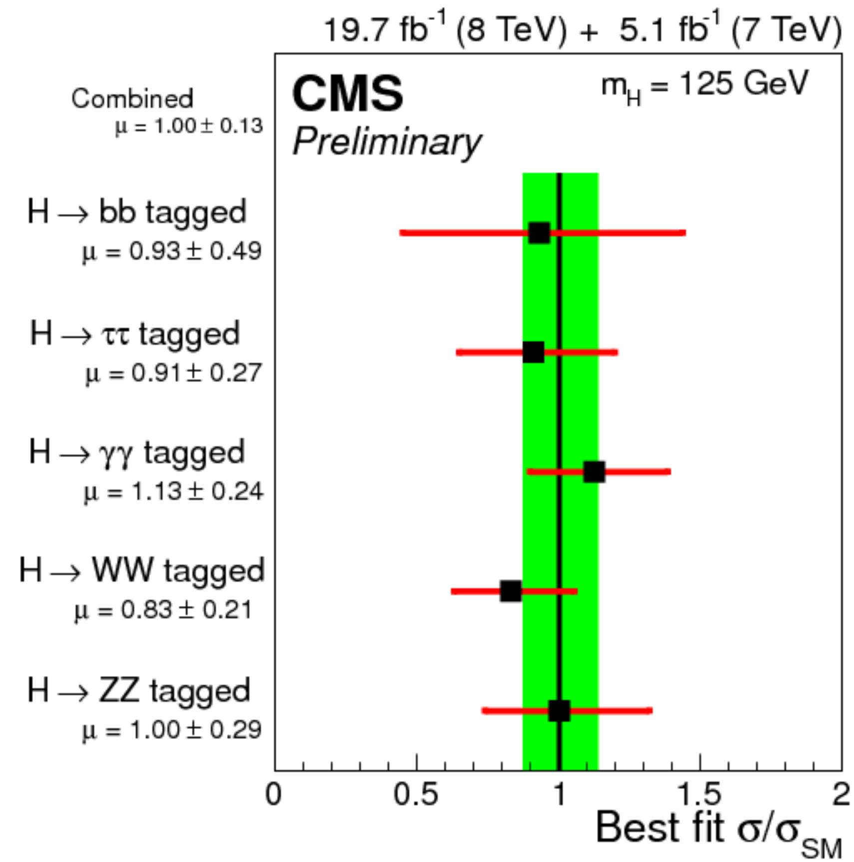
Signal strength

$$\sigma/\sigma_{\text{SM}} = 1.00 \pm 0.13 \left[\pm 0.09(\text{stat.})^{+0.08}_{-0.07}(\text{theo.}) \pm 0.07(\text{syst.})\right]$$

- Grouped by dominant decay:
  - χ^2/dof = 0.9/5
  - p-value = 0.97 (asymptotic)

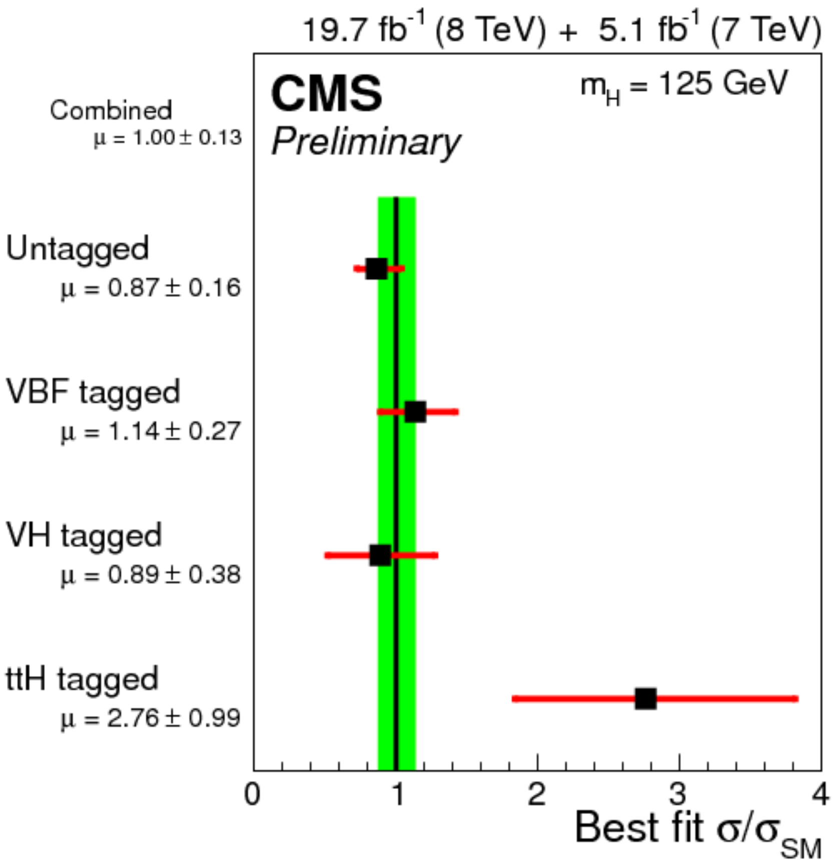


Signal strength

 [CMS-PAS-HIG-14-009]

$$\sigma/\sigma_{SM} = 1.00 \pm 0.13 \left[\pm 0.09(\text{stat.})^{+0.08}_{-0.07}(\text{theo.}) \pm 0.07(\text{syst.})\right]$$

- Grouped by production tag:
  - $\chi^2/\text{dof} = 5.3/4$
  - p-value = 0.26 (asymptotic)
- **ttH-tagged 2.0σ above SM.**

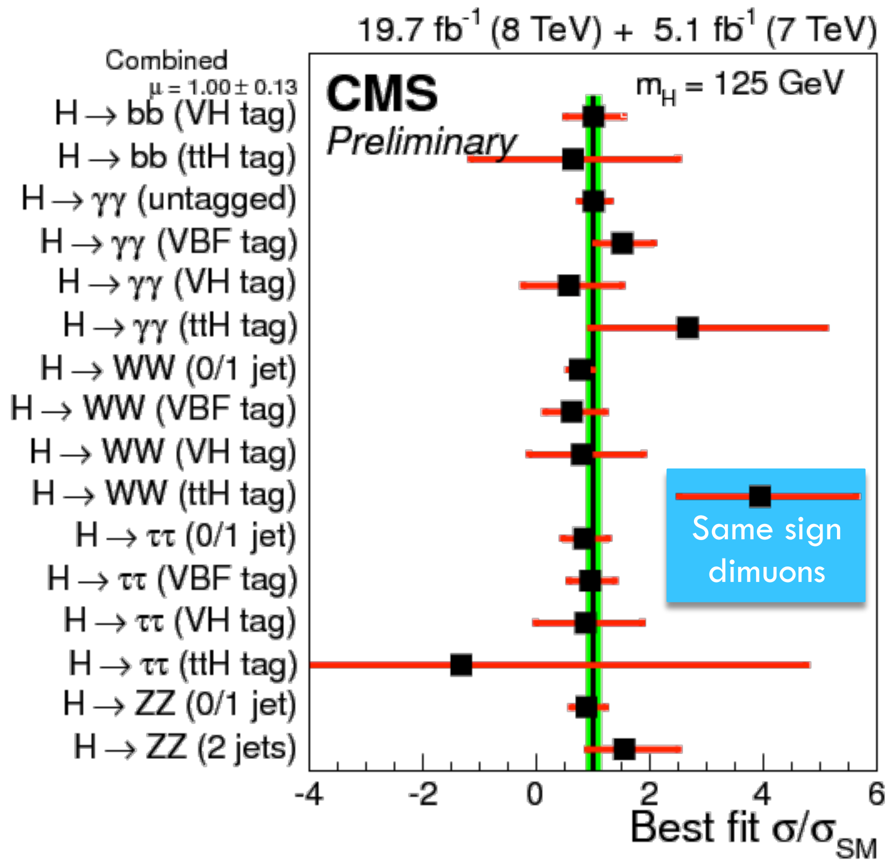


Signal strength

[CMS-PAS-HIG-14-009]

$$\sigma/\sigma_{\rm SM} = 1.00 \pm 0.13 \left[\pm 0.09({\rm stat.})^{+0.08}_{-0.07}({\rm theo.}) \pm 0.07({\rm syst.})\right]$$

- Grouped by production tag and dominant decay:
  - χ^2/dof = 10.5/16
  - p-value = 0.84 (asymptotic)
- ttH-tagged 2.0σ above SM.
  - **Driven by one channel.**

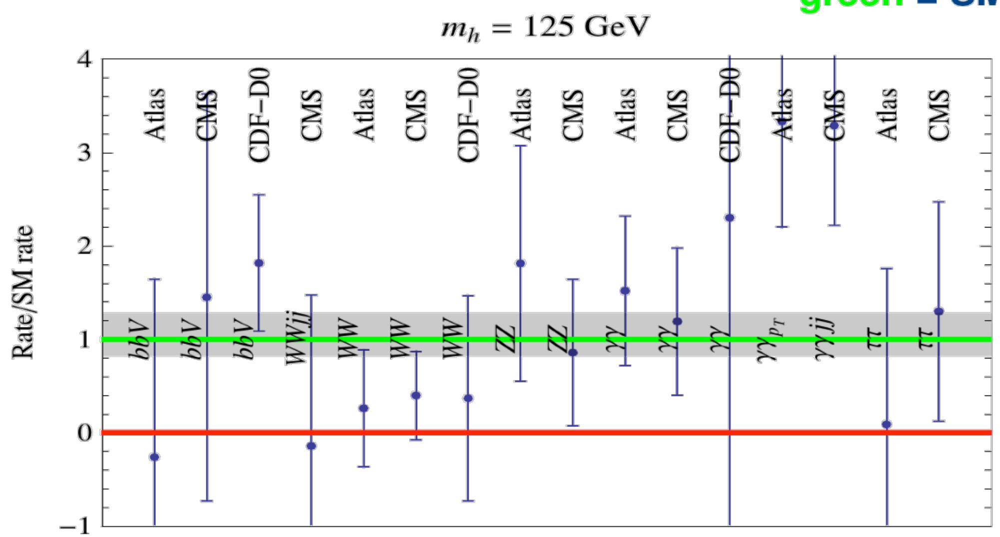


In 2012 some theorists speculated…

[http://goo.gl/CVm6s]

- After Moriond 2012, new fits disfavor the SM and motivate for New Physics

red = no Higgs boson
green = SM



P. Giardino, K. Kannike, M. Raidal, A. Strumia, 1203.4254

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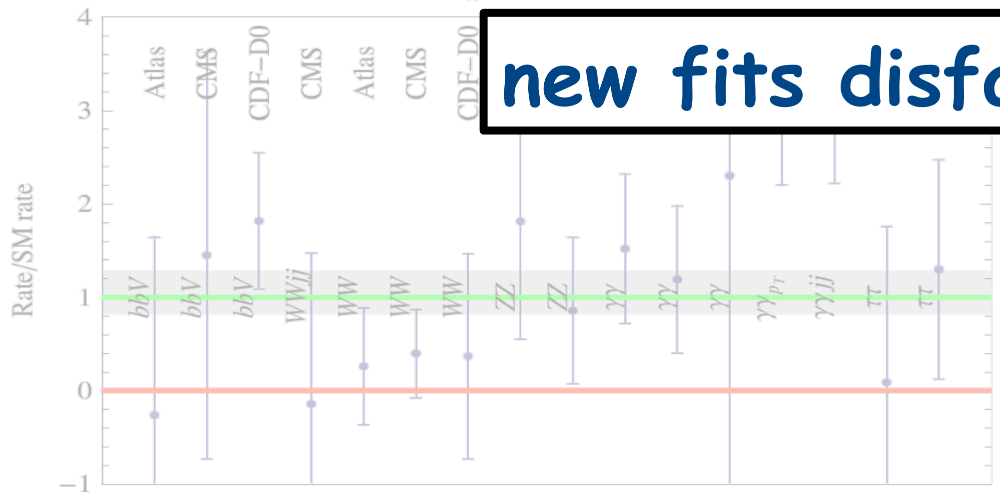
new fits disfavor the SM

new fits disfavor the SM

new fits disfavor the SM



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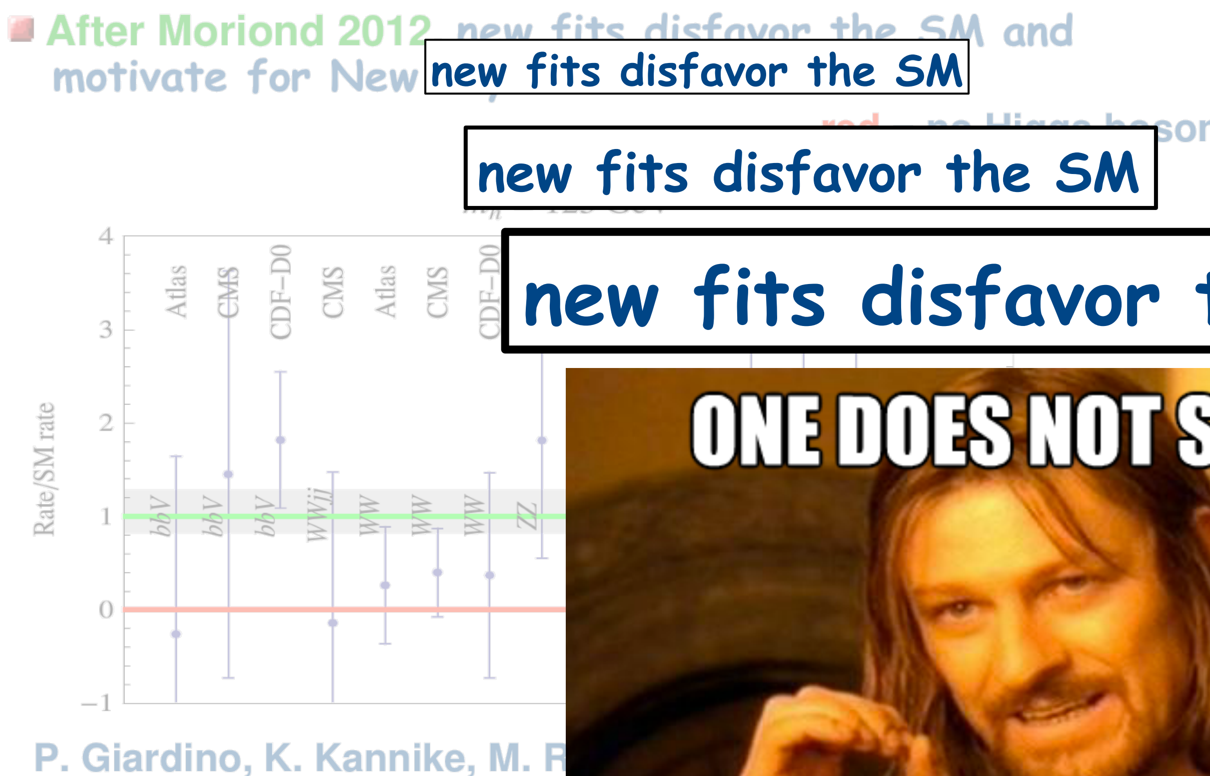

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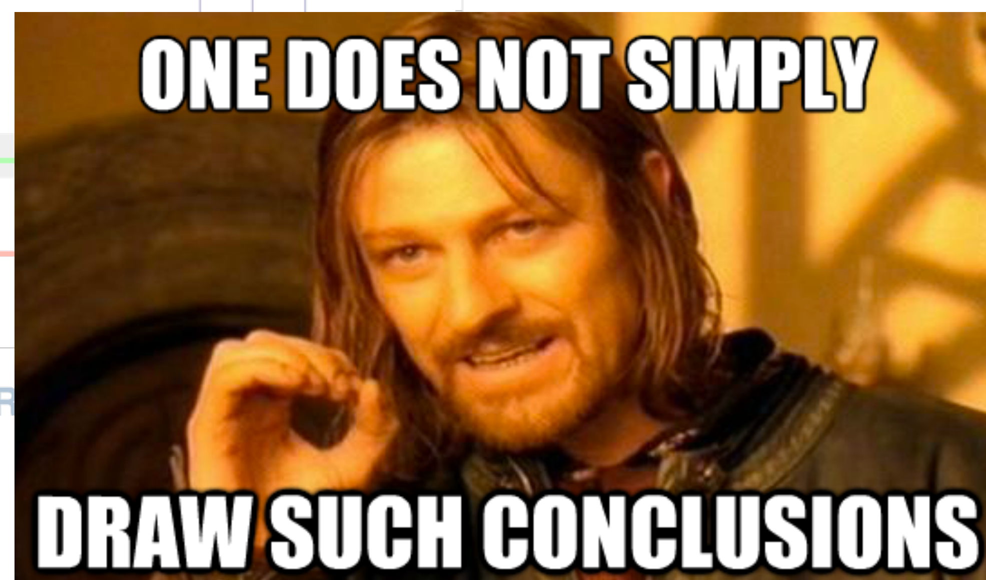
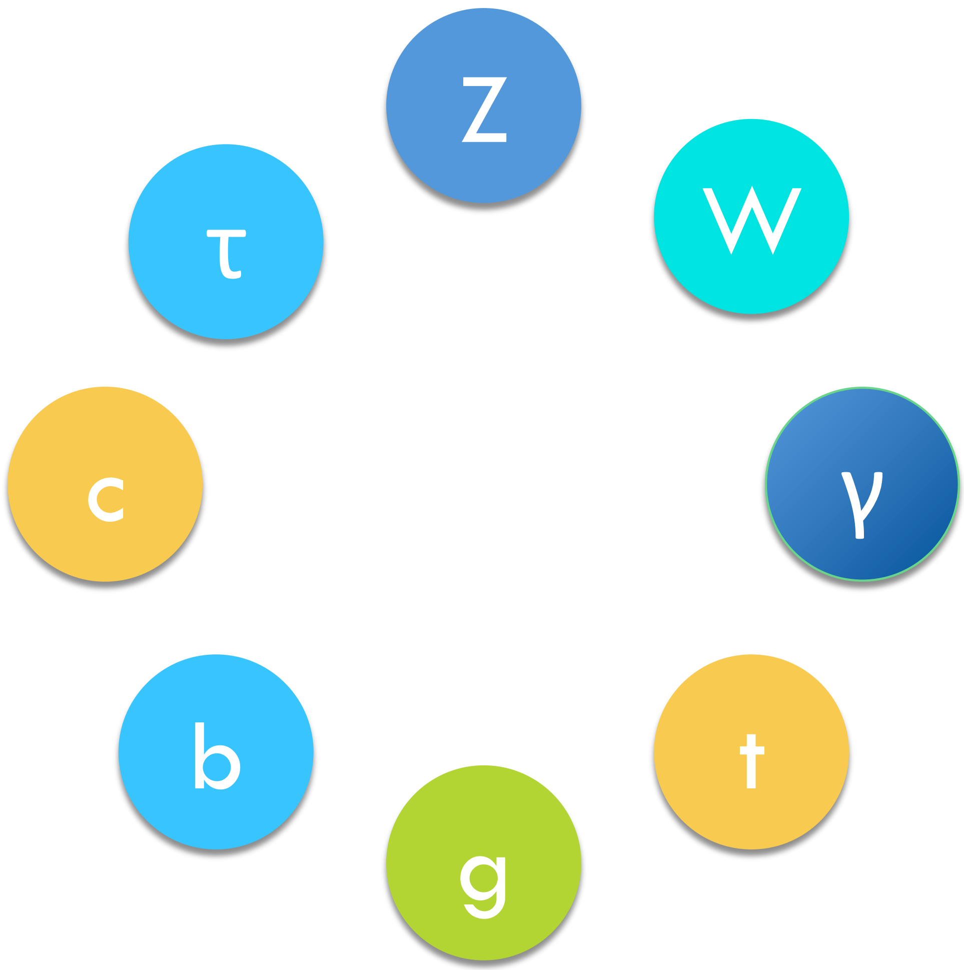


Scalar coupling structure



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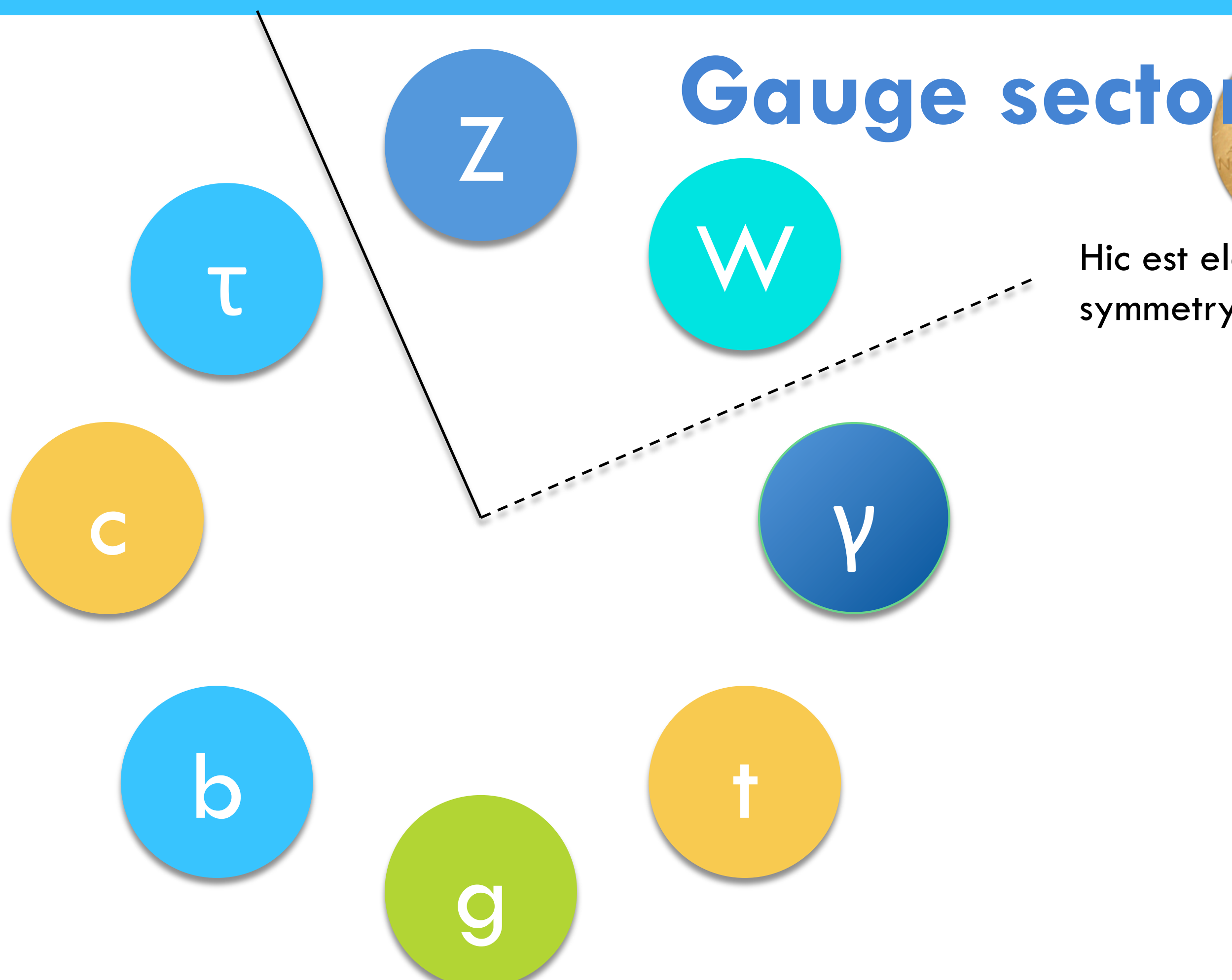

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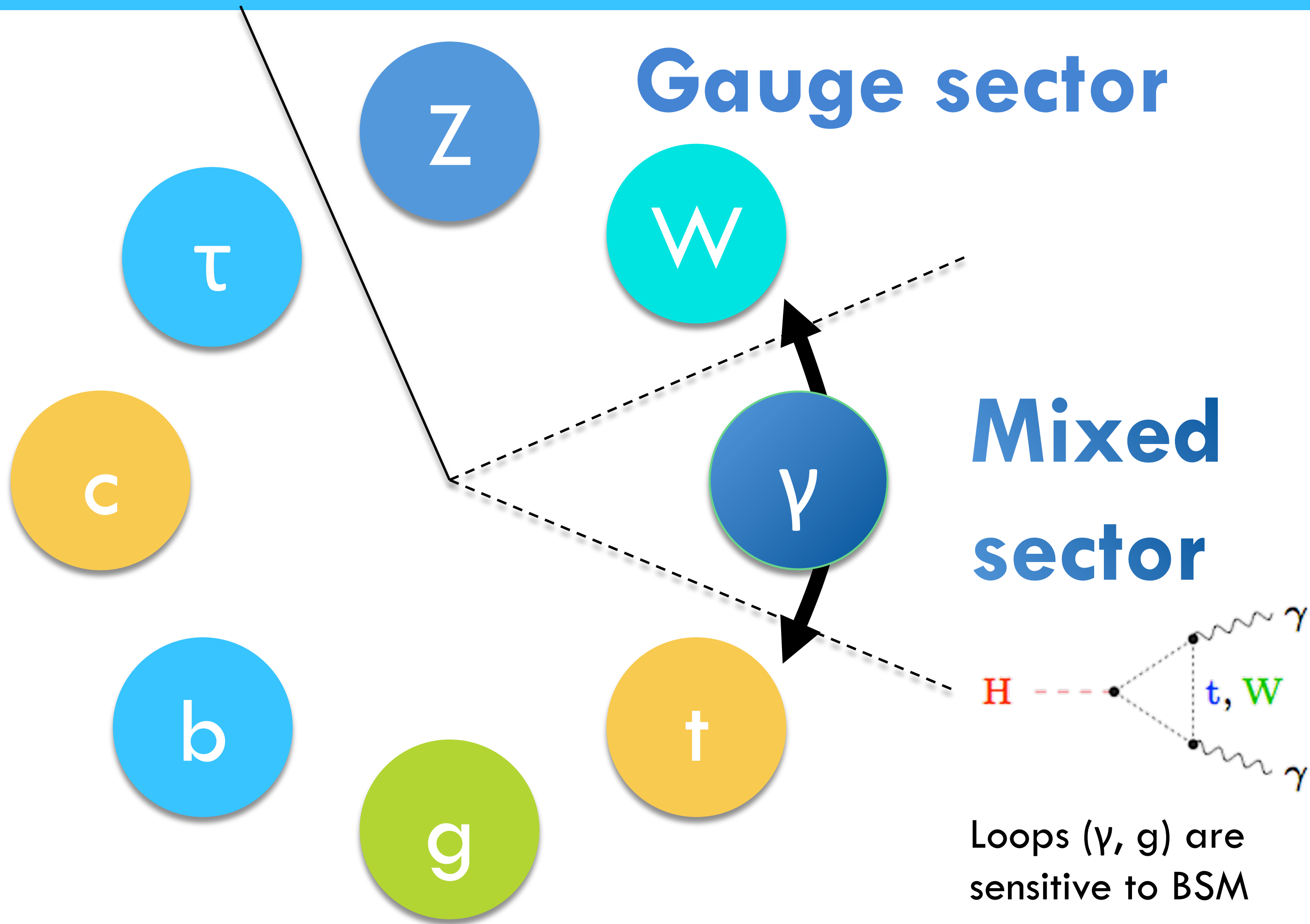


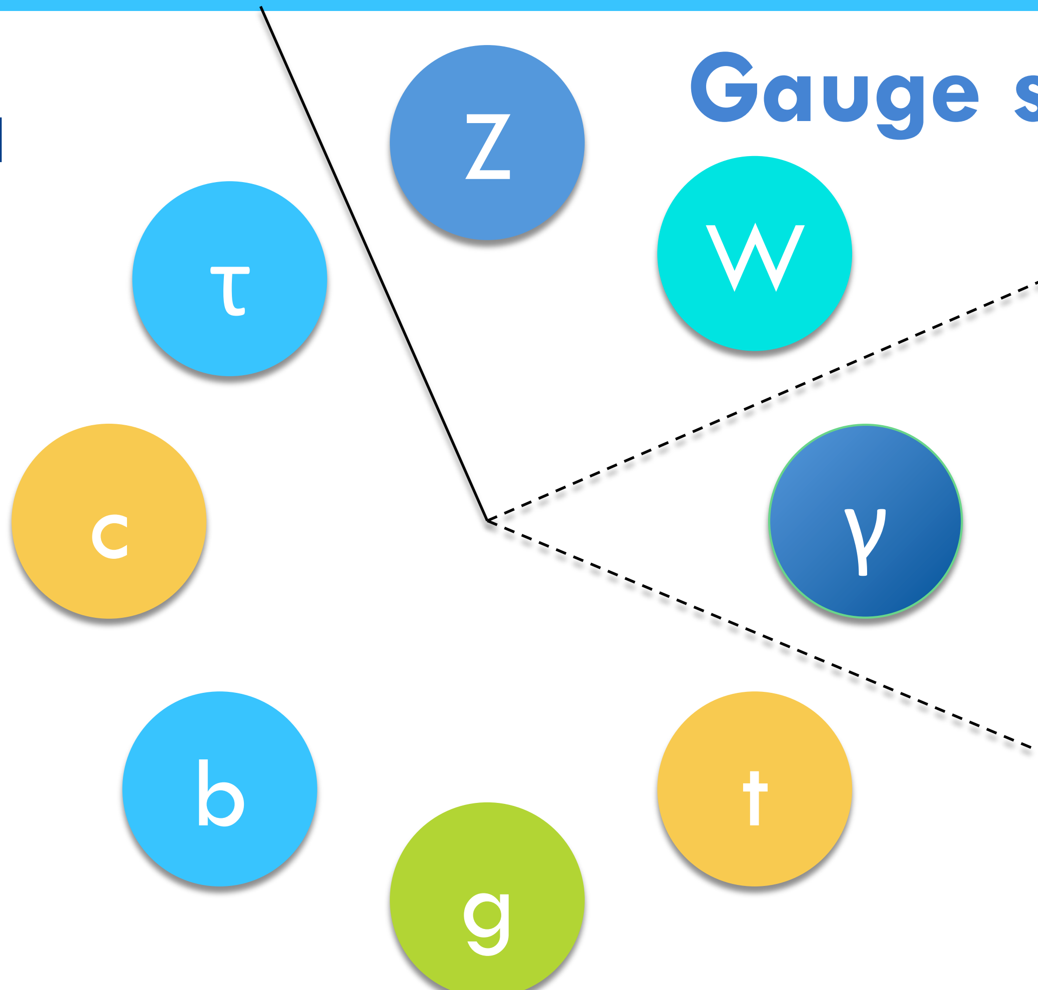
Loops (γ, g) are sensitive to BSM contributions.

Scalar coupling structure

Yukawa sector

Gauge sector

Mixed sector



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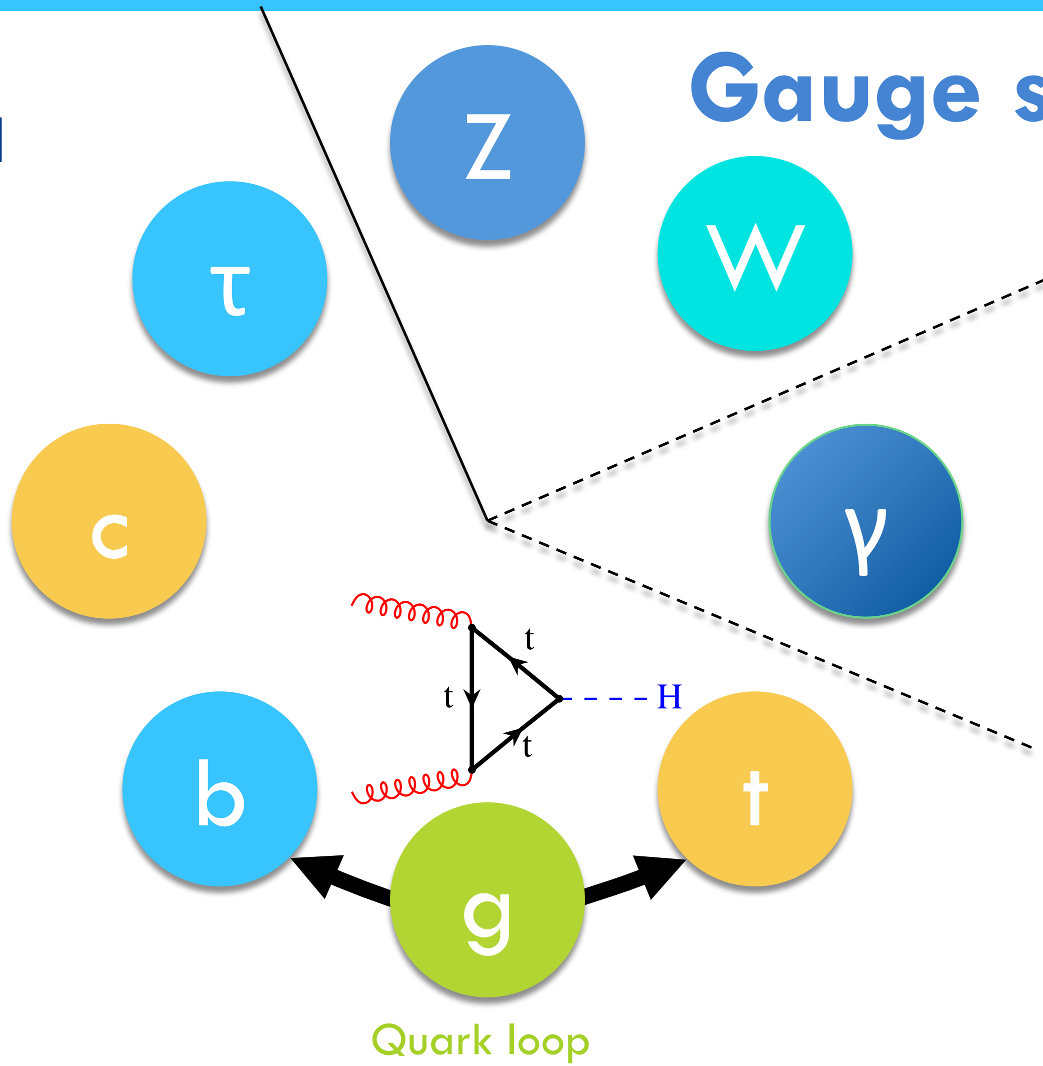

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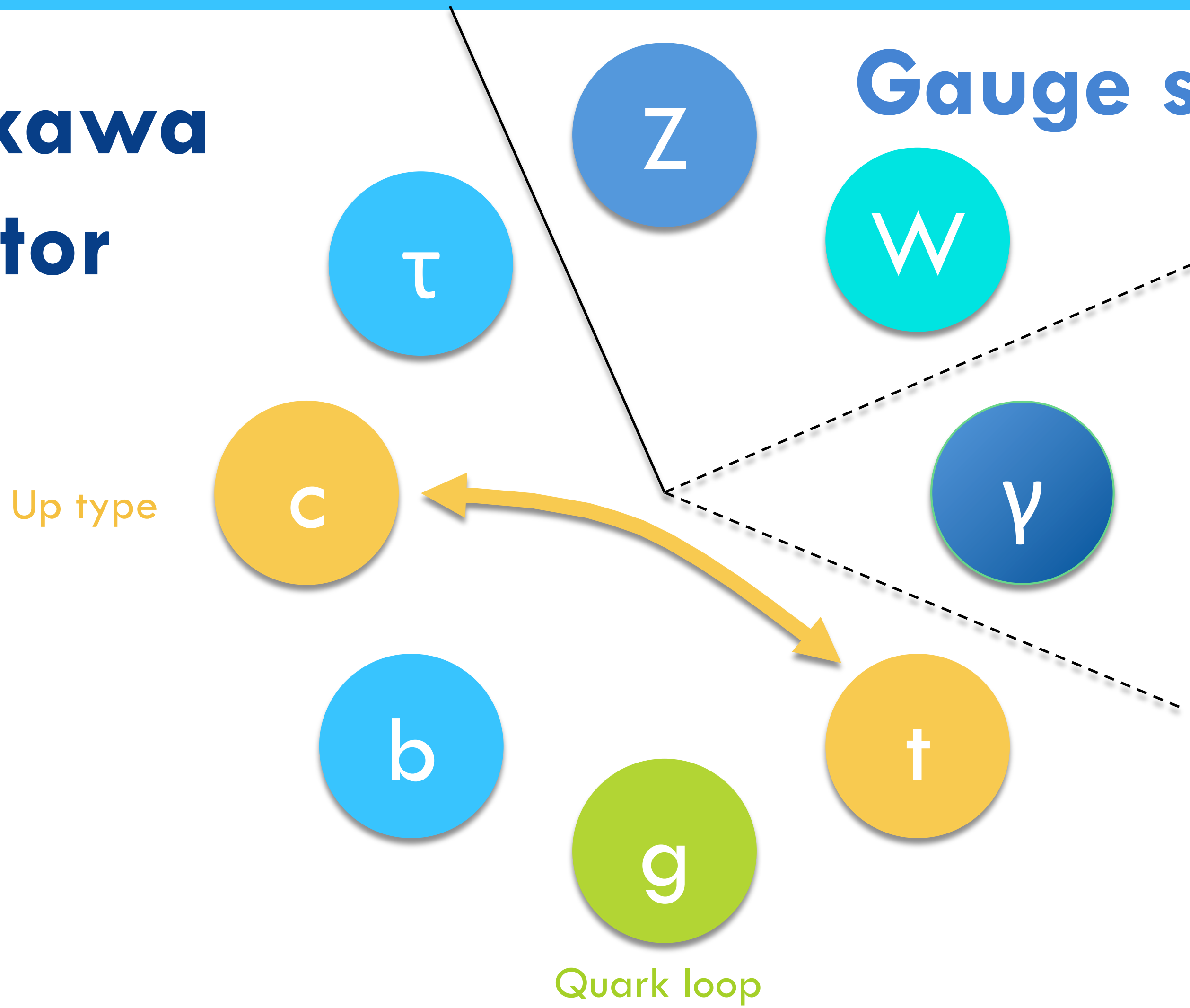

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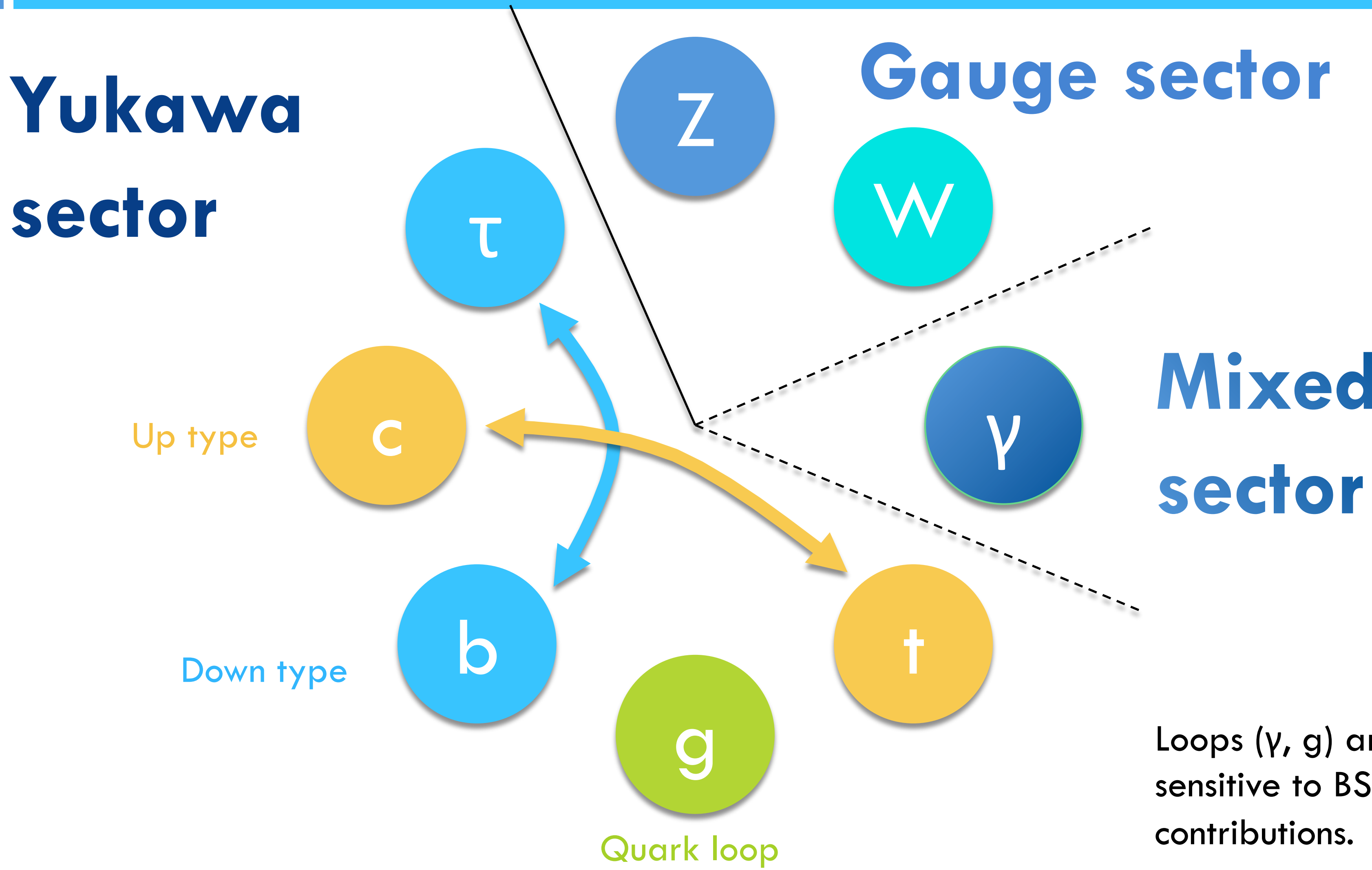

Loops (γ, g) are sensitive to BSM contributions.

Scalar coupling deviations framework

[arXiv:1307.1347]

Production modes

$$\frac{\sigma_{ggH}}{\sigma^{SM}_{ggH}} = \begin{cases} \kappa^2_g(\kappa_b, \kappa_t, m_H) \\ \kappa^2_g \end{cases}$$

$$\frac{\sigma_{VBF}}{\sigma^{SM}_{VBF}} = \kappa^2_{VBF}(\kappa_W, \kappa_Z, m_H)$$

$$\frac{\sigma_{WH}}{\sigma^{SM}_{WH}} = \kappa^2_W$$

$$\frac{\sigma_{ZH}}{\sigma^{SM}_{ZH}} = \kappa^2_Z$$

$$\frac{\sigma_{t\bar{t}H}}{\sigma^{SM}_{t\bar{t}H}} = \kappa^2_t$$

Detectable decay modes

$$\frac{\Gamma_{WW^{(*)}}}{\Gamma^{SM}_{WW^{(*)}}} = \kappa^2_W$$

$$\frac{\Gamma_{ZZ^{(*)}}}{\Gamma^{SM}_{ZZ^{(*)}}} = \kappa^2_Z$$

$$\frac{\Gamma_{b\bar{b}}}{\Gamma^{SM}_{b\bar{b}}} = \kappa^2_b$$

$$\frac{\Gamma_{\tau^-\tau^+}}{\Gamma^{SM}_{\tau^-\tau^+}} = \kappa^2_\tau$$

$$\frac{\Gamma_{\gamma\gamma}}{\Gamma^{SM}_{\gamma\gamma}} = \begin{cases} \kappa^2_\gamma(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W, m_H) \\ \kappa^2_\gamma \end{cases}$$

$$\frac{\Gamma_{Z\gamma}}{\Gamma^{SM}_{Z\gamma}} = \begin{cases} \kappa^2_{(Z\gamma)}(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W, m_H) \\ \kappa^2_{(Z\gamma)} \end{cases}$$

Currently undetectable decay modes

$$\frac{\Gamma_{t\bar{t}}}{\Gamma^{SM}_{t\bar{t}}} = \kappa^2_t$$

$$\frac{\Gamma_{gg}}{\Gamma^{SM}_{gg}} : \text{see Section 3.1.2}$$

$$\frac{\Gamma_{c\bar{c}}}{\Gamma^{SM}_{c\bar{c}}} = \kappa^2_t$$

$$\frac{\Gamma_{s\bar{s}}}{\Gamma^{SM}_{s\bar{s}}} = \kappa^2_b$$

$$\frac{\Gamma_{\mu^-\mu^+}}{\Gamma^{SM}_{\mu^-\mu^+}} = \kappa^2_\tau$$

Total width

$$\frac{\Gamma_H}{\Gamma^{SM}_H} = \begin{cases} \kappa^2_H(\kappa_i, m_H) \\ \kappa^2_H \end{cases}$$

- Single state, spin 0, and CP-even.
- Narrow-width approximation: $(\sigma\times BR) = \sigma \cdot \Gamma/\Gamma_H$

Scalar coupling deviations framework

[arXiv:1307.1347]

Production modes

$$\frac{\sigma_{\mathrm{ggH}}}{\sigma^{\mathrm{SM}}_{\mathrm{ggH}}} = \begin{cases} \kappa_g^2(\kappa_b,\kappa_t,m_H) \\ \kappa_g^2 \end{cases}$$

$$\frac{\sigma_{\mathrm{VBF}}}{\sigma^{\mathrm{SM}}_{\mathrm{VBF}}} = \kappa^2_{\mathrm{VBF}}(\kappa_W,\kappa_Z,m_H)$$

$$\frac{\sigma_{\mathrm{WH}}}{\sigma^{\mathrm{SM}}_{\mathrm{WH}}} = \kappa_W^2$$

$$\frac{\sigma_{\mathrm{ZH}}}{\sigma^{\mathrm{SM}}_{\mathrm{ZH}}} = \kappa_Z^2$$

$$\frac{\sigma_{t\bar{t}H}}{\sigma^{\mathrm{SM}}_{t\bar{t}H}} = \kappa_t^2$$

Detectable decay modes

$$\frac{\Gamma_{WW^{(*)}}}{\Gamma^{\mathrm{SM}}_{WW^{(*)}}} = \kappa_W^2$$

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$$\frac{\Gamma_{b\bar{b}}}{\Gamma^{\mathrm{SM}}_{b\bar{b}}} = \kappa_b^2$$

$$\frac{\Gamma_{\tau^-\tau^+}}{\Gamma^{\mathrm{SM}}_{\tau^-\tau^+}} = \kappa_\tau^2$$

$$\frac{\Gamma_{\gamma\gamma}}{\Gamma^{\mathrm{SM}}_{\gamma\gamma}} = \begin{cases} \kappa_\gamma^2(\kappa_b,\kappa_t,\kappa_\tau,\kappa_W,m_H) \\ \kappa_\gamma^2 \end{cases}$$

$$\frac{\Gamma_{Z\gamma}}{\Gamma^{\mathrm{SM}}_{Z\gamma}} = \begin{cases} \kappa_{(Z\gamma)}^2(\kappa_b,\kappa_t,\kappa_\tau,\kappa_W,m_H) \\ \kappa_{(Z\gamma)}^2 \end{cases}$$

Currently undetectable decay modes

$$\frac{\Gamma_{t\bar{t}}}{\Gamma^{\mathrm{SM}}_{t\bar{t}}} = \kappa_t^2$$

$$\frac{\Gamma_{gg}}{\Gamma^{\mathrm{SM}}_{gg}} \; : \; \text{see Section 3.1.2}$$

$$\frac{\Gamma_{c\bar{c}}}{\Gamma^{\mathrm{SM}}_{c\bar{c}}} = \kappa_t^2$$

$$\frac{\Gamma_{s\bar{s}}}{\Gamma^{\mathrm{SM}}_{s\bar{s}}} = \kappa_b^2$$

$$\frac{\Gamma_{\mu^-\mu^+}}{\Gamma^{\mathrm{SM}}_{\mu^-\mu^+}} = \kappa_\tau^2$$

Total width

$$\frac{\Gamma_H}{\Gamma^{\mathrm{SM}}_H} = \begin{cases} \kappa_H^2(\kappa_i,m_H) \\ \kappa_H^2 \end{cases}$$

- Loops resolved at NLO QCD and LO EWK accuracy.
- Peg the as-of-yet unmeasured to “closest of kin”.

Scalar coupling deviations framework

[arXiv:1307.1347]

Production modes

$$\frac{\sigma_{ggH}}{\sigma_{ggH}^{SM}} = \begin{cases} \kappa_g^2(\kappa_b, \kappa_t, m_H) \\ \kappa_g^2 \end{cases}$$

$$\frac{\sigma_{VBF}}{\sigma_{VBF}^{SM}} = \kappa_{VBF}^2(\kappa_W, \kappa_Z, m_H)$$

$$\frac{\sigma_{WH}}{\sigma_{WH}^{SM}} = \kappa_W^2$$

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$$\frac{\sigma_{t\bar{t}H}}{\sigma_{t\bar{t}H}^{SM}} = \kappa_t^2$$

Detectable decay modes

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$$\frac{\Gamma_{c\bar{c}}}{\Gamma_{c\bar{c}}^{SM}} = \kappa_t^2$$

$$\frac{\Gamma_{s\bar{s}}}{\Gamma_{s\bar{s}}^{SM}} = \kappa_b^2$$

$$\frac{\Gamma_{\mu^-\mu^+}}{\Gamma_{\mu^-\mu^+}^{SM}} = \kappa_\tau^2$$

Total width

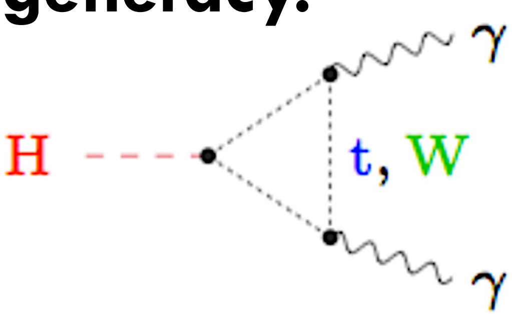
$$\frac{\Gamma_H}{\Gamma_H^{SM}} = \begin{cases} \kappa_H^2(\kappa_i, m_H) \\ \kappa_H^2 \end{cases}$$

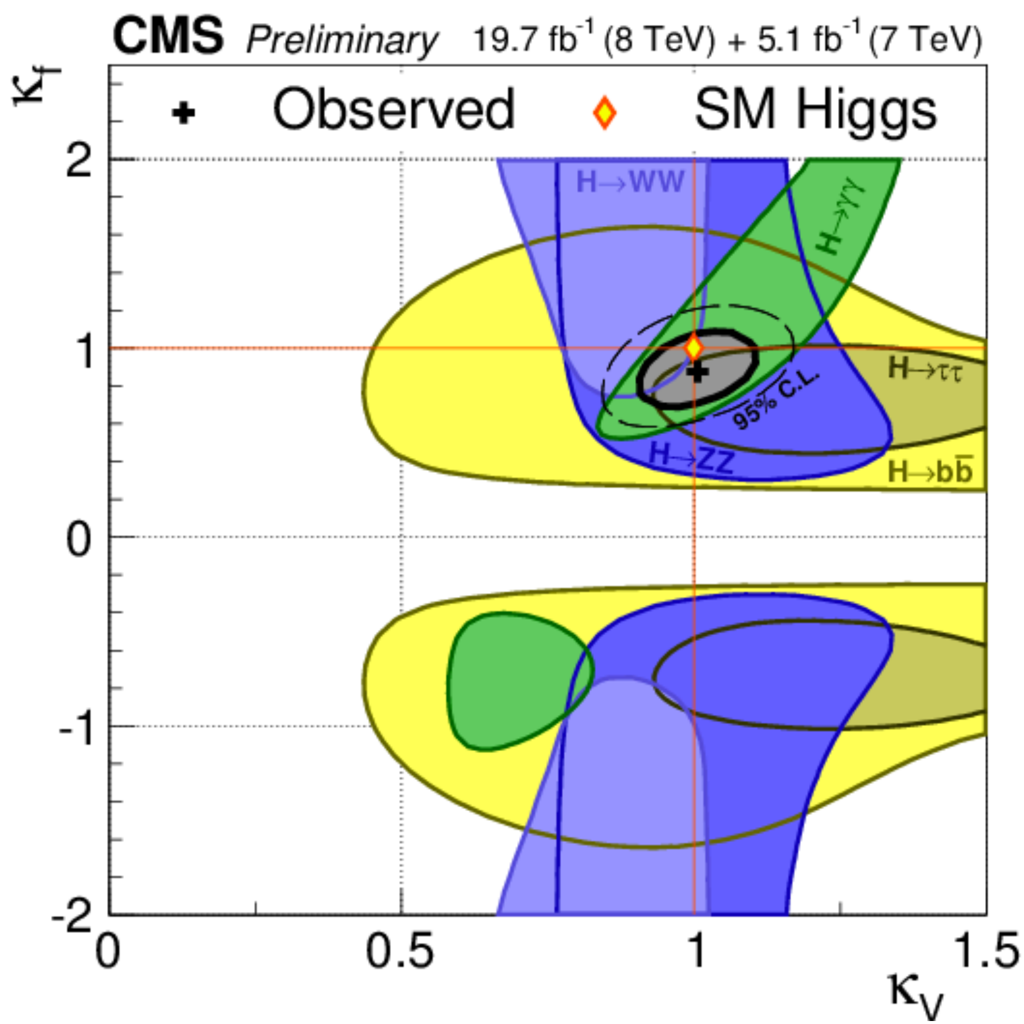
- Total width as dependent function of all κ_i.
- Total width scaled as free parameter: κ_H.

Coupling deviations

[CMS-PAS-HIG-14-009] [arXiv:1307.1347]

- Scaling the couplings to fermions (κ_f) and vector bosons (κ_V).
- **Destructive interference in H⟶ γγ decay loop breaks degeneracy.**

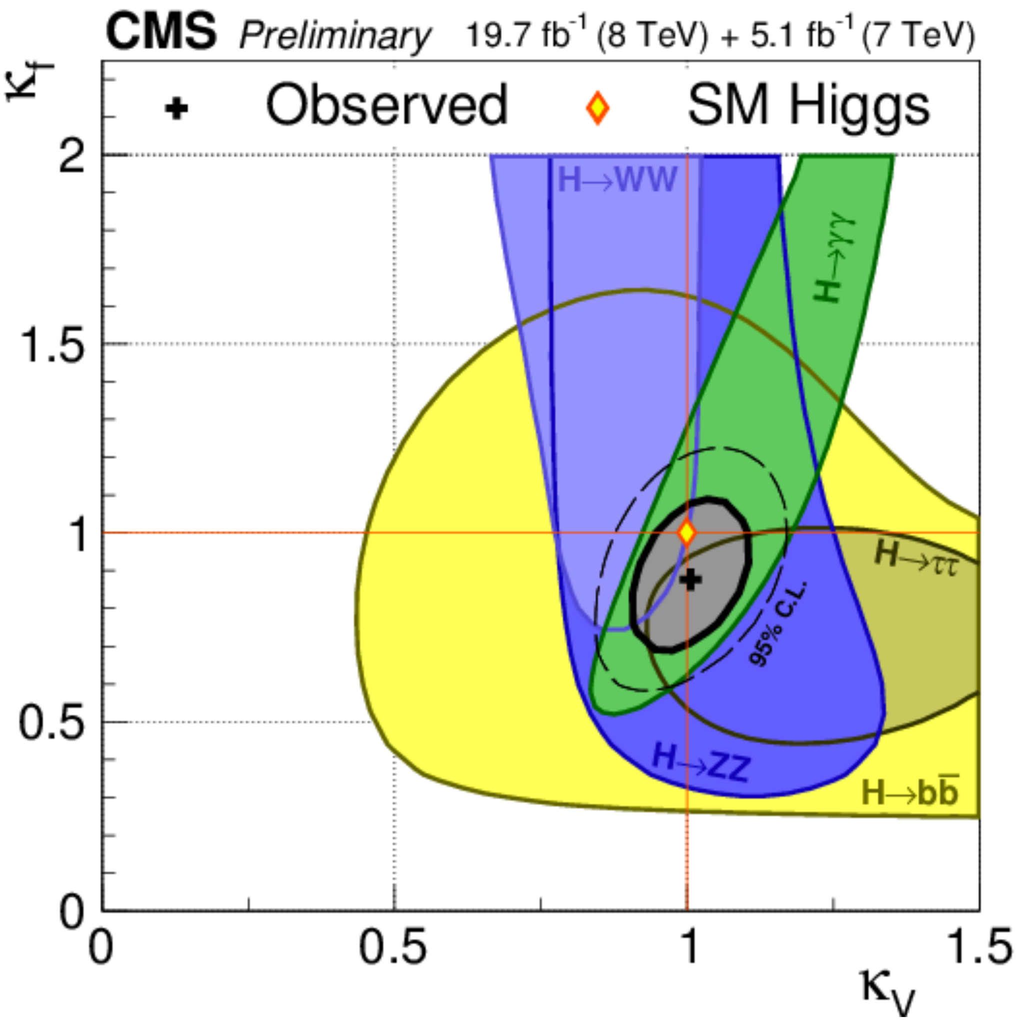




Coupling deviations

[CMS-PAS-HIG-14-009] [arXiv:1307.1347]

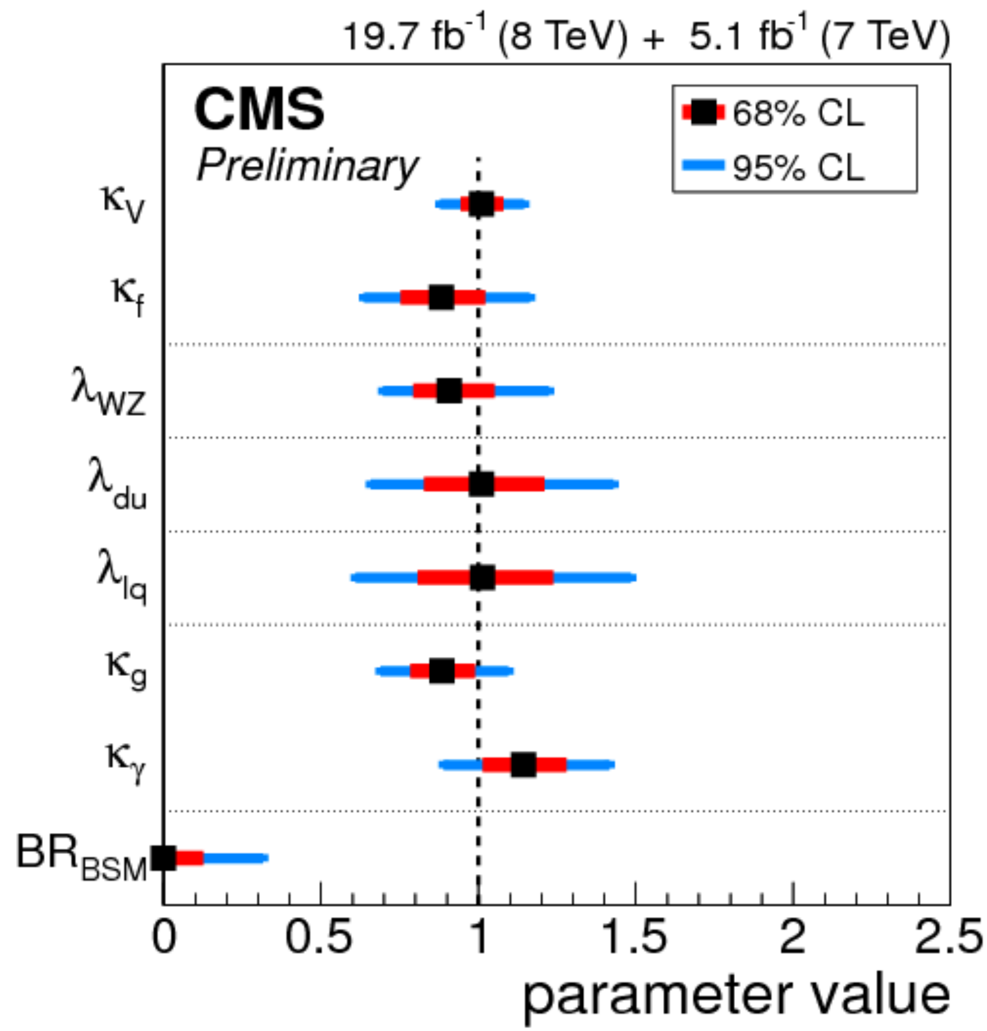
- Scaling the couplings to fermions (κ_f) and vector bosons (κ_V).
- **All decay channels converging around SM expectation.**



Coupling deviations summaries

[CMS-PAS-HIG-14-009] [arXiv:1307.1347]

- Summary of the fits of **six benchmarks models** probing:
  - Fermions and vector bosons.
  - Custodial symmetry.
  - Up/down fermion coupling ratio.
  - Lepton/quark coupling ratio.
  - BSM in loops: gluons and photons.
  - Extra width: BR_{BSM}.
- **No significance deviations from SM.**

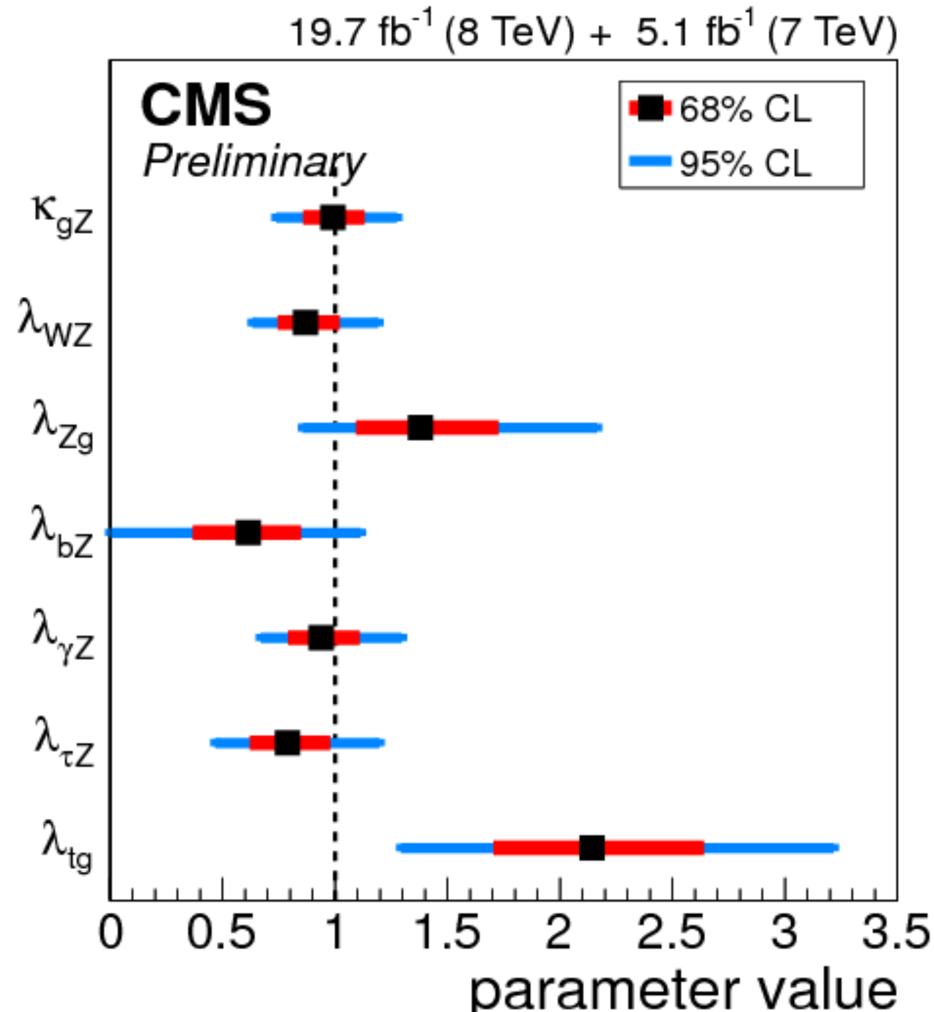


$\lambda_{xy} = \kappa_x/\kappa_y$

Coupling deviations summaries

[CMS-PAS-HIG-14-009] [arXiv:1307.1347]

- Most general benchmark floating the total width.
  - Same ttH-related excess in $\lambda_{tg} = \kappa_{top}/\kappa_{gluon}$.

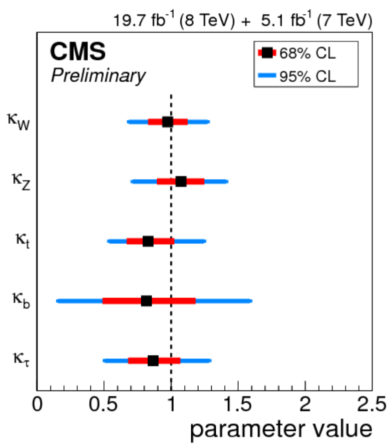


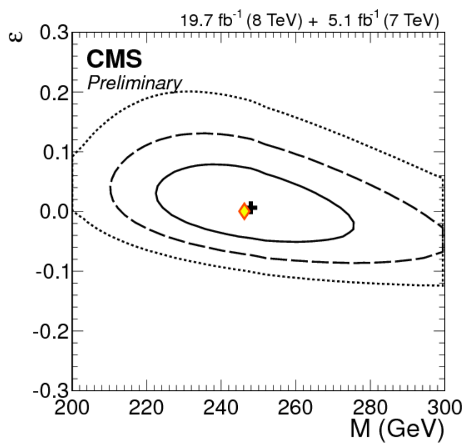
$\lambda_{xy} = \kappa_x/\kappa_y$; $\kappa_{xy} = \kappa_x\kappa_y/\kappa_H$

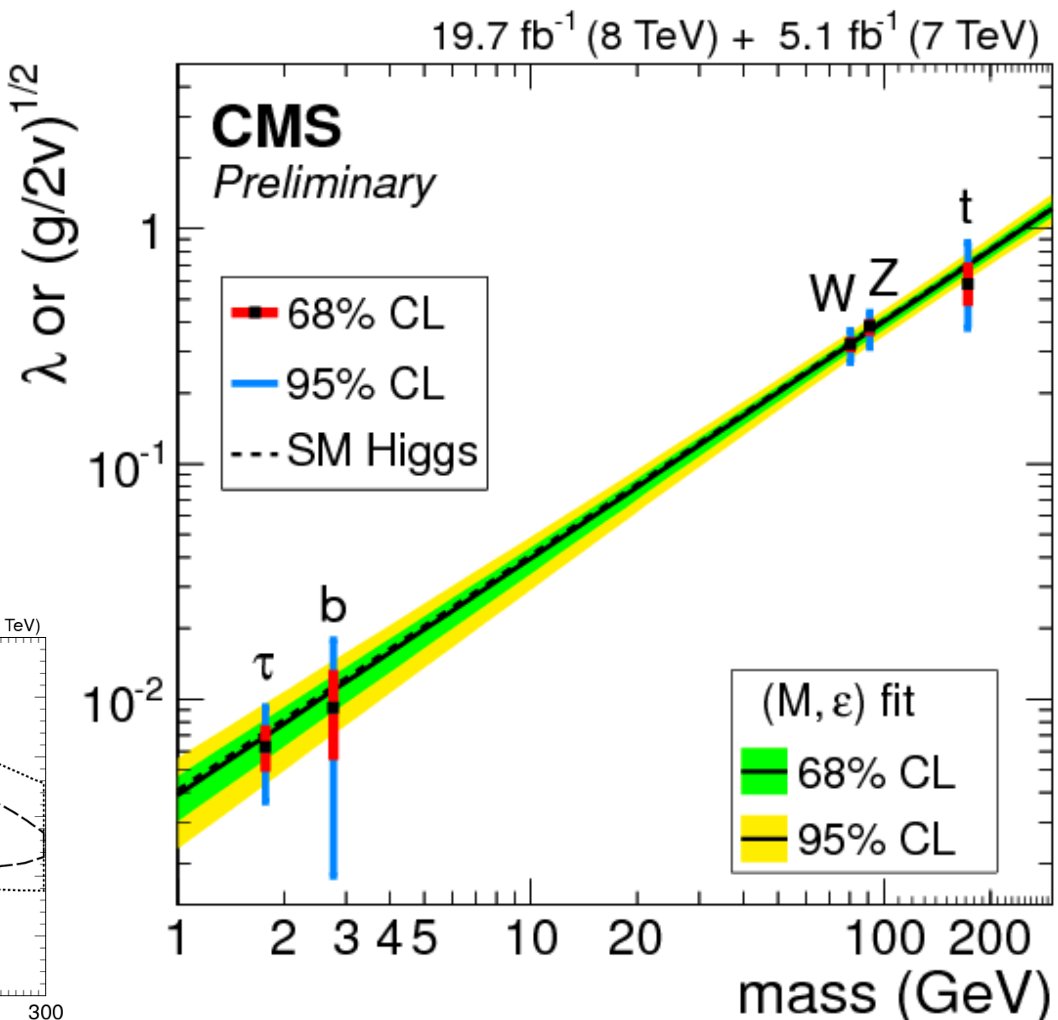
Coupling deviations summaries

[CMS-PAS-HIG-14-009] [arxiv:1207.1693] [arxiv:1303.3570]

- Assuming no BSM particles.







SOME PERSONAL THOUGHTS ON THE IMMEDIATE FUTURE

André David (CERN)

Deviations are on a diet

[arXiv:1306.6352]

- SUSY ($\tan\beta = 5$): $$\frac{g_{hbb}}{g_{h_{\rm SM}bb}} = \frac{g_{h\tau\tau}}{g_{h_{\rm SM}\tau\tau}} \simeq 1 + 1.7\% \left(\frac{1\ \mathrm{TeV}}{m_A}\right)^2$$
- Composite Higgs: $$\frac{g_{hff}}{g_{h_{\rm SM}ff}} \simeq \frac{g_{hVV}}{g_{h_{\rm SM}VV}} \simeq 1 - 3\% \left(\frac{1\ \mathrm{TeV}}{f}\right)^2$$
- Top partners: $$\frac{g_{hgg}}{g_{h_{\rm SM}gg}} \simeq 1 + 2.9\% \left(\frac{1\ \mathrm{TeV}}{m_T}\right)^2, \qquad \frac{g_{h\gamma\gamma}}{g_{h_{\rm SM}\gamma\gamma}} \simeq 1 - 0.8\% \left(\frac{1\ \mathrm{TeV}}{m_T}\right)^2$$

Anatomy of deviations

$$\mu = \frac{(\sigma \cdot \mathrm{BR})_{\mathrm{observed}}}{(\sigma \cdot \mathrm{BR})_{\mathrm{expected}}}$$

- Deviations are searched relative to SM expectation.
- *Conclusions are only as good as the accuracy and precision of the numerator and denominator.*

Anatomy of deviations

$$\mu = \frac{(\sigma \cdot \mathrm{BR})_{\mathrm{observed}}}{(\sigma \cdot \mathrm{BR})_{\mathrm{expected}}}$$

Data

- **Deviations** are searched relative to SM expectation.
- *Conclusions are only as good as the accuracy and precision of the numerator and denominator.*

Anatomy of deviations

$$\mu = \frac{(\sigma \cdot \mathrm{BR})_{\mathrm{observed}}}{(\sigma \cdot \mathrm{BR})_{\mathrm{expected}}}$$

Data

Standard Model

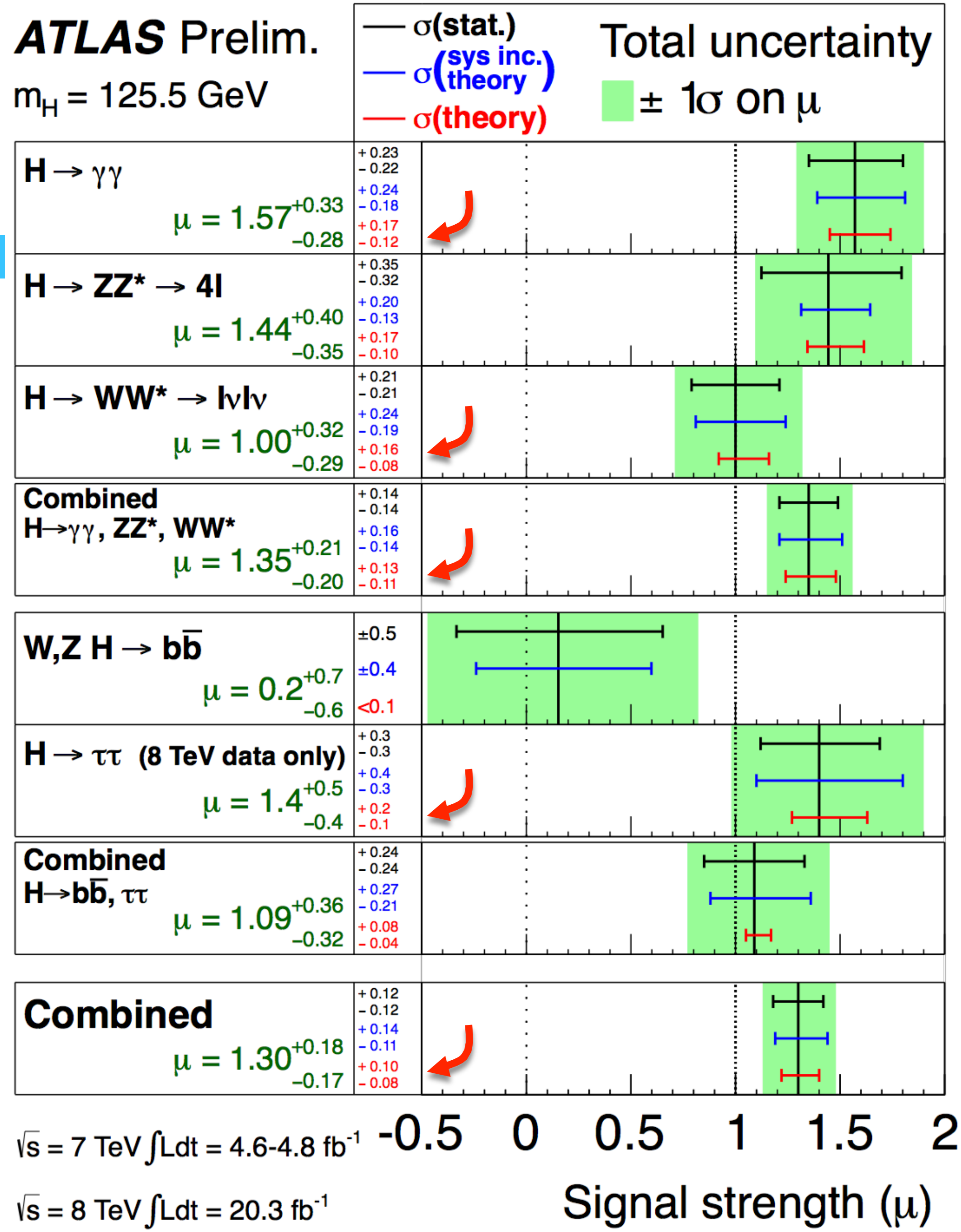
- **Deviations** are searched **relative to SM expectation.**
- *Conclusions are only as good as the **accuracy and precision** of the **numerator and denominator.***

Theory uncertainties

[ATLAS-CONF-2014-009]

- PDFs not dominating on μ .
  - ggH vs VBF+VH.
  - PDF4LHC prescription too conservative?
    - **Changing soon!**
  - PDG $\sigma(\alpha_s)$ too aggressive?

- NNLO+NNLL not enough to tame large QCD corrections in gluon-fusion?



Theory uncertainties: MHOU

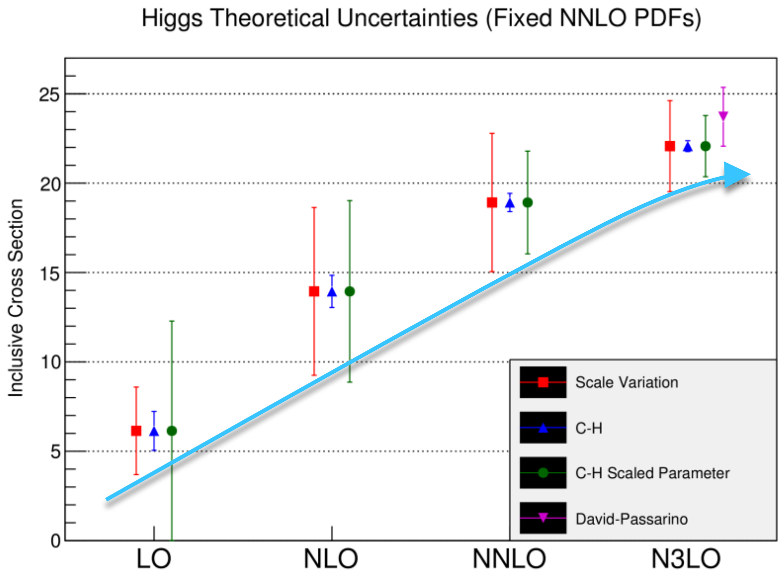
[arXiv:1307.1843] [http://cern.ch/go/V8xJ]

- Scale variations are not theory uncertainties.
- **The uncertainty is due to missing higher orders.**

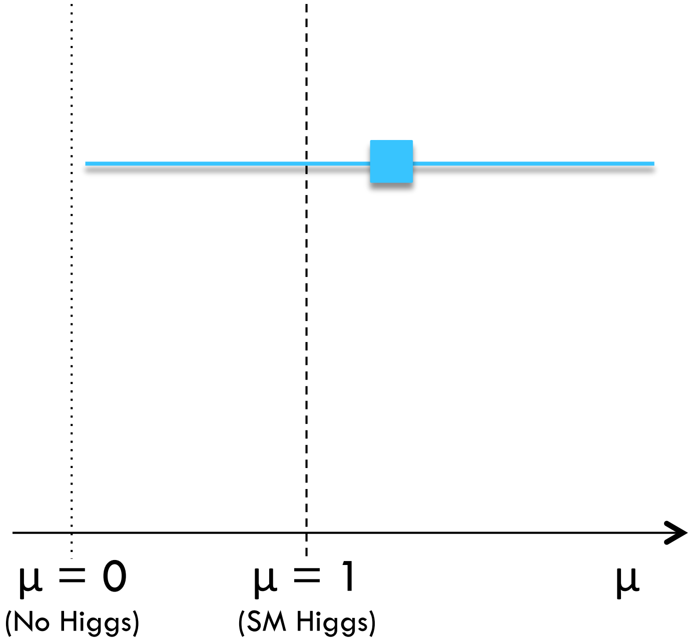
$$\frac{\sigma_{gg}(\sqrt{s}, M_H)}{\sigma_{gg}^{\mathrm{LO}}(\sqrt{s}, M_H)} = 1 + \sum_{n=1}^{\infty} \alpha_s^n(\mu_R)\, K_{gg}^n(\sqrt{s}, \mu = M_H)$$

8 TeV	$\mu = M_H/2$	$\mu = M_H$	$\mu = 2M_H$
K_{gg}^1		11.879	
K_{gg}^2		72.254	
K_{gg}^3	168.98 ± 30.87	377.20 ± 30.78	681.72 ± 29.93

- Take gluon-gluon fusion:
  - All series terms are positive.
  - We can try and complete the series instead of **always** being off.



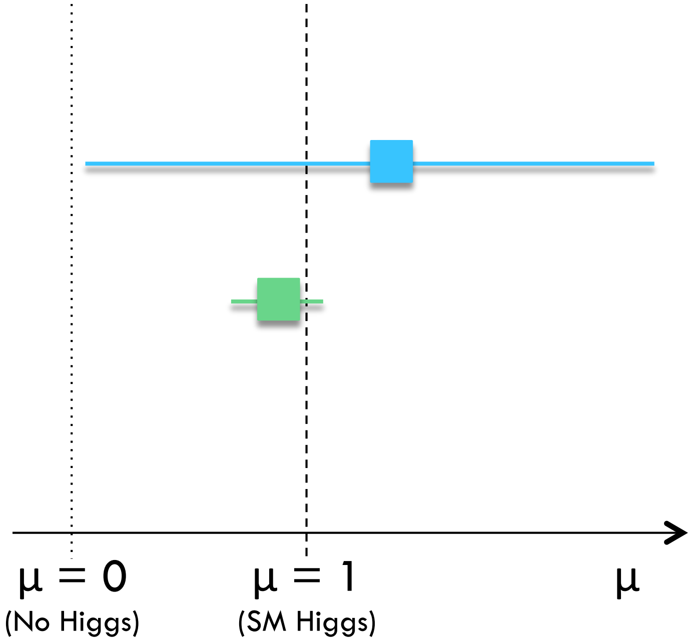
The anatomy of deviations



Imprecise measurement compatible with anything.
Inconclusive, “more data needed”.

- $\mu = 1$ means that the data match the SM.
  - Uncertainty on μ quantifies the compatibility with the SM:
    - **$\mu = 1.3 \pm 1.2$ is inconclusive and “more data is needed”**, but
    - $\mu = 2.0 \pm 0.2$ could mean New Physics (or a systematic effect).

The anatomy of deviations

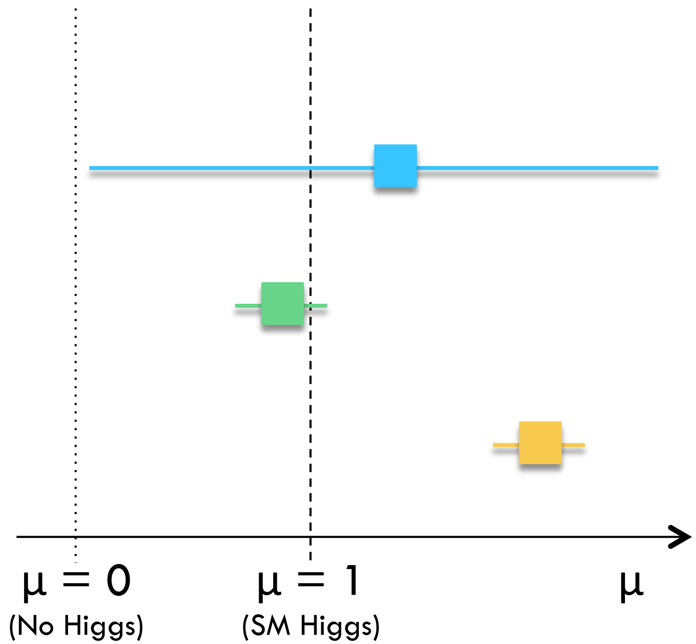


Imprecise measurement compatible with anything.
Inconclusive, "more data needed".

Precise measurement **compatible** with the SM.
Large deviations excluded!

- **$\mu = 1$ means that the data match the SM.**
  - Uncertainty on μ quantifies the compatibility with the SM:
    - $\mu = 1.3 \pm 1.2$ usually means "more data needed", but
    - $\mu = 2.0 \pm 0.2$ could mean New Physics (or systematic effect).

The anatomy of deviations



Imprecise measurement compatible with anything.
Inconclusive, "more data needed".

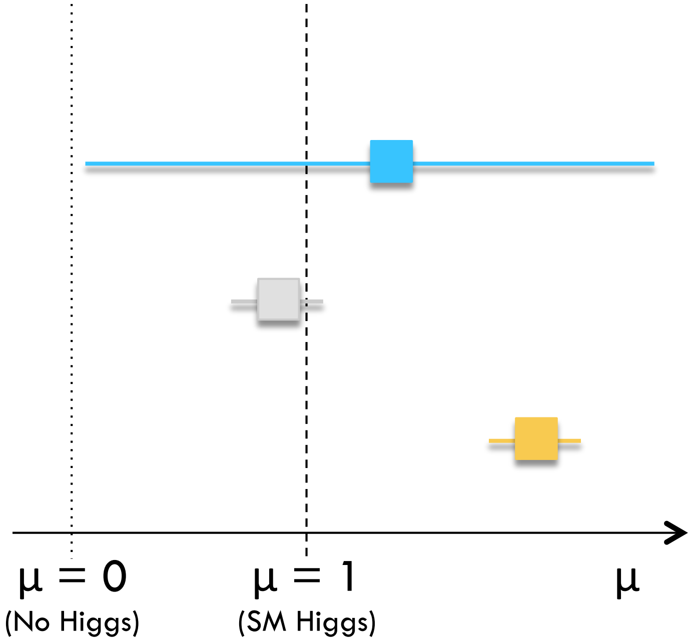
Precise measurement **compatible** with the SM.
Large deviations excluded!

Precise measurement **incompatible** with the SM!
Evidence of a deviation.

"New Physics ⇒ Deviation" but "Deviation ⇏ New Physics"
See, e.g., http://cern.ch/go/W8wW

- $\mu = 1$ means that the data match the SM.
  - Uncertainty on μ quantifies the compatibility with the SM:
    - $\mu = 3 \pm 5$ usually means "more data needed", but
    - **$\mu = 2.0 \pm 0.2$ could mean New Physics (or systematic effect).**

The anatomy of deviations



Imprecise measurement compatible with anything.
Inconclusive, "more data **or better theory** needed".

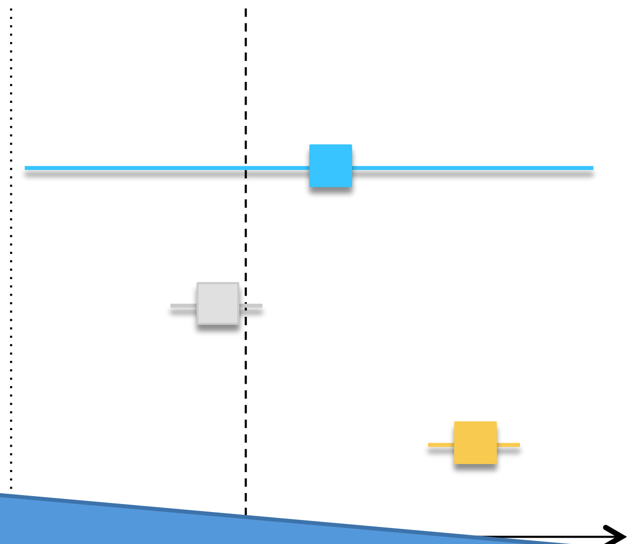
Precise measurement **compatible** with the SM.
Large deviations excluded!

Precise measurement **incompatible** with the SM!
Evidence of a deviation **or exp./theory bias.**

"New Physics ⇒ Deviation" but "Deviation ⇏ New Physics"
See, e.g., http://cern.ch/go/W8wW

- $\mu = 1$ means that the data match the SM.
  - Uncertainty on μ quantifies the compatibility with the SM:
    - $\mu = 3 \pm 5$ usually means "more data needed", but
    - **$\mu = 2.0 \pm 0.2$ could mean New Physics (or systematic effect).**

The anatomy of deviations



Imprecise measurement compatible with anything.
Inconclusive, "more data **or better theory** needed".

Precise measurement **compatible** with the SM.
Large deviations excluded!

Precise measurement **incompatible** with the SM!
Evidence of a deviation **or exp./theory bias.**

"New Physics $\Rightarrow$ Deviation" but "Deviation $\not\Rightarrow$ New Physics"
See, e.g., http://cern.ch/go/W8wW

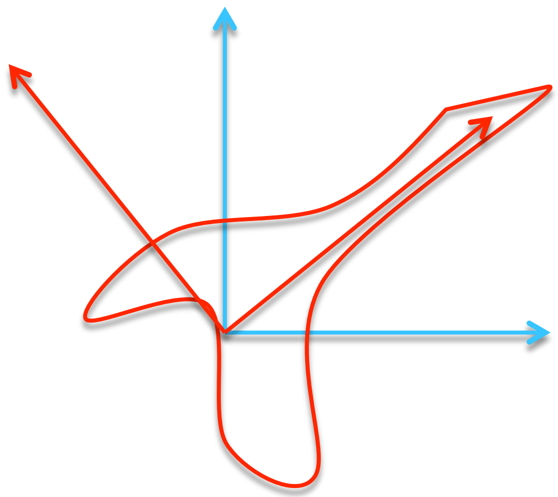
SM theorists contribute as much to the conclusions as experimentalists !

- μ = 2.0 ±0.2 could mean

Effective field theory (EFT): the idea

[NPB 268 (1986) 621]

- Instead of an experimentally-driven basis of parameters use a basis of QFT operators that may be more aligned with the BSM physics.



- **EFT allows to perform accurate calculations**
  - NLO EWK effects, etc.
  - More sensitive interpretation.
- 59 dim-6 operators already mapped out in 1986.
  - **Which operators to keep?**
  - **What about dim-8?**
  - **What about loop processes?**

First steps in YR3

[arXiv:1307.1347]

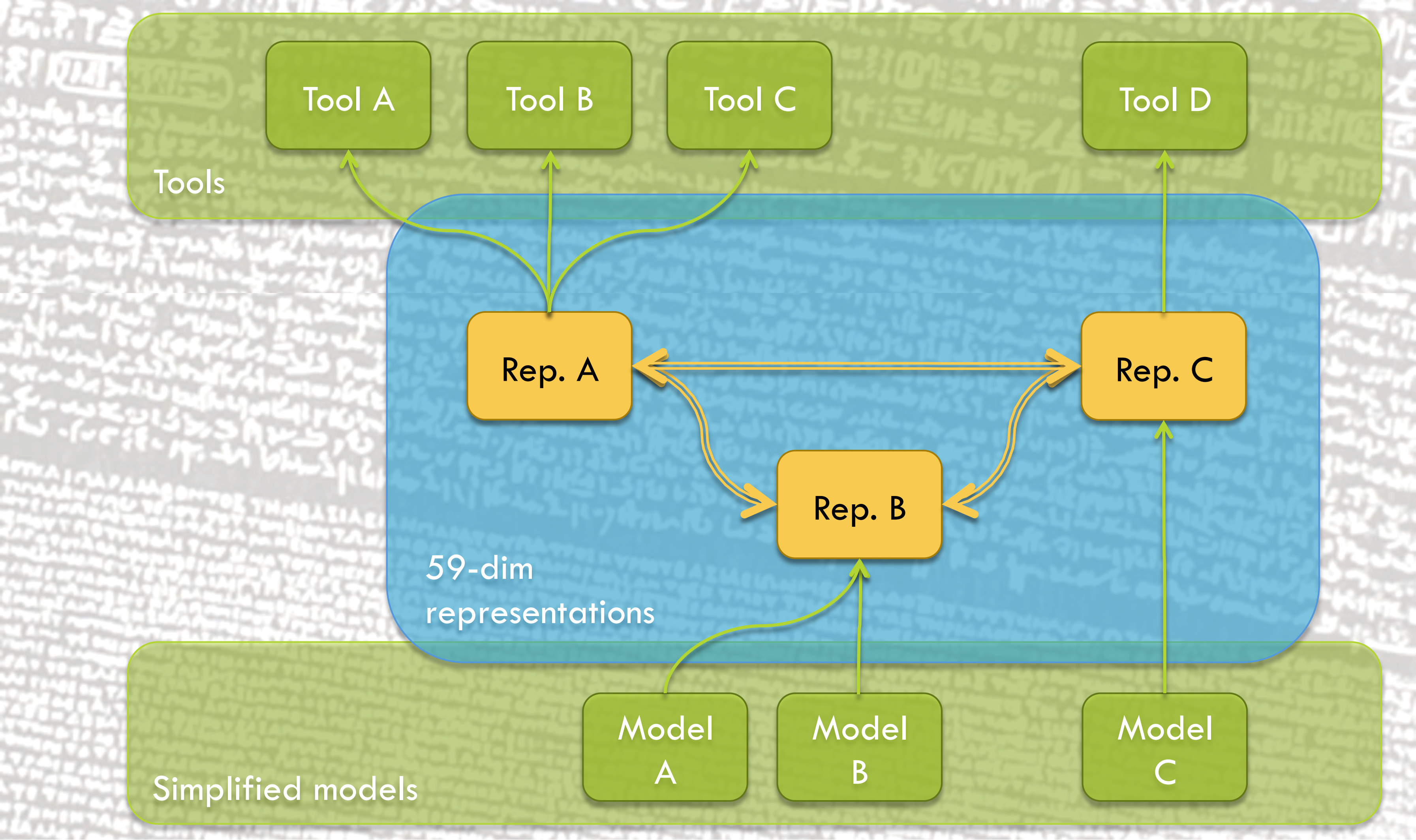
Table 52: Dimension-6 operators involving Higgs doublet fields or gauge-boson fields. For all $\psi^2\Phi^3$, $\psi^2\mathrm{X}\Phi$ operators and for $\mathcal{O}_{\Phi\mathrm{ud}}$ the hermitian conjugates must be included as well.

Φ^6 and $\Phi^4 D^2$	$\psi^2\Phi^3$	X^3
$\mathcal{O}_{\Phi} = (\Phi^\dagger\Phi)^3$	$\mathcal{O}_{\mathrm{e}\Phi} = (\Phi^\dagger\Phi)(\bar{\mathrm{l}}\,\Gamma_{\mathrm{e}}\mathrm{e}\Phi)$	$\mathcal{O}_{G} = f^{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$
$\mathcal{O}_{\Phi\square} = (\Phi^\dagger\Phi)\square(\Phi^\dagger\Phi)$	$\mathcal{O}_{\mathrm{u}\Phi} = (\Phi^\dagger\Phi)(\bar{\mathrm{q}}\,\Gamma_{\mathrm{u}}\mathrm{u}\widetilde{\Phi})$	$\mathcal{O}_{\widetilde{G}} = f^{ABC}\widetilde{G}_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$
$\mathcal{O}_{\Phi D} = (\Phi^\dagger D^\mu\Phi)^*(\Phi^\dagger D_\mu\Phi)$	$\mathcal{O}_{\mathrm{d}\Phi} = (\Phi^\dagger\Phi)(\bar{\mathrm{q}}\,\Gamma_{\mathrm{d}}\mathrm{d}\Phi)$	$\mathcal{O}_{\mathrm{W}} = \varepsilon^{IJK}\mathrm{W}_\mu^{I\nu}\mathrm{W}_\nu^{J\rho}\mathrm{W}_\rho^{K\mu}$
		$\mathcal{O}_{\widetilde{\mathrm{W}}} = \varepsilon^{IJK}\widetilde{\mathrm{W}}_\mu^{I\nu}\mathrm{W}_\nu^{J\rho}\mathrm{W}_\rho^{K\mu}$
$\mathrm{X}^2\Phi^2$	$\psi^2\mathrm{X}\Phi$	$\psi^2\Phi^2 D$
$\mathcal{O}_{\Phi G} = (\Phi^\dagger\Phi)G_{\mu\nu}^A G^{A\mu\nu}$	$\mathcal{O}_{\mathrm{u}G} = (\bar{\mathrm{q}}\sigma^{\mu\nu}\frac{\lambda^A}{2}\Gamma_{\mathrm{u}}\mathrm{u}\widetilde{\Phi})G_{\mu\nu}^A$	$\mathcal{O}_{\Phi\mathrm{l}}^{(1)} = (\Phi^\dagger \mathrm{i}\overleftrightarrow{D}_\mu\Phi)(\bar{\mathrm{l}}\gamma^\mu\mathrm{l})$
$\mathcal{O}_{\Phi\widetilde{G}} = (\Phi^\dagger\Phi)\widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$	$\mathcal{O}_{\mathrm{d}G} = (\bar{\mathrm{q}}\sigma^{\mu\nu}\frac{\lambda^A}{2}\Gamma_{\mathrm{d}}\mathrm{d}\Phi)G_{\mu\nu}^A$	$\mathcal{O}_{\Phi\mathrm{l}}^{(3)} = (\Phi^\dagger \mathrm{i}\overleftrightarrow{D}_\mu^I\Phi)(\bar{\mathrm{l}}\gamma^\mu\tau^I\mathrm{l})$
$\mathcal{O}_{\Phi\mathrm{W}} = (\Phi^\dagger\Phi)\mathrm{W}_{\mu\nu}^I\mathrm{W}^{I\mu\nu}$	$\mathcal{O}_{\mathrm{eW}} = (\bar{\mathrm{l}}\sigma^{\mu\nu}\Gamma_{\mathrm{e}}\mathrm{e}\tau^I\Phi)\mathrm{W}_{\mu\nu}^I$	$\mathcal{O}_{\Phi\mathrm{e}} = (\Phi^\dagger \mathrm{i}\overleftrightarrow{D}_\mu\Phi)(\bar{\mathrm{e}}\gamma^\mu\mathrm{e})$
$\mathcal{O}_{\Phi\widetilde{\mathrm{W}}} = (\Phi^\dagger\Phi)\widetilde{\mathrm{W}}_{\mu\nu}^I\mathrm{W}^{I\mu\nu}$	$\mathcal{O}_{\mathrm{uW}} = (\bar{\mathrm{q}}\sigma^{\mu\nu}\Gamma_{\mathrm{u}}\mathrm{u}\tau^I\widetilde{\Phi})\mathrm{W}_{\mu\nu}^I$	$\mathcal{O}_{\Phi\mathrm{q}}^{(1)} = (\Phi^\dagger \mathrm{i}\overleftrightarrow{D}_\mu\Phi)(\bar{\mathrm{q}}\gamma^\mu\mathrm{q})$
$\mathcal{O}_{\Phi\mathrm{B}} = (\Phi^\dagger\Phi)\mathrm{B}_{\mu\nu}\mathrm{B}^{\mu\nu}$	$\mathcal{O}_{\mathrm{dW}} = (\bar{\mathrm{q}}\sigma^{\mu\nu}\Gamma_{\mathrm{d}}\mathrm{d}\tau^I\Phi)\mathrm{W}_{\mu\nu}^I$	$\mathcal{O}_{\Phi\mathrm{q}}^{(3)} = (\Phi^\dagger \mathrm{i}\overleftrightarrow{D}_\mu^I\Phi)(\bar{\mathrm{q}}\gamma^\mu\tau^I\mathrm{q})$
$\mathcal{O}_{\Phi\widetilde{\mathrm{B}}} = (\Phi^\dagger\Phi)\widetilde{\mathrm{B}}_{\mu\nu}\mathrm{B}^{\mu\nu}$	$\mathcal{O}_{\mathrm{eB}} = (\bar{\mathrm{l}}\sigma^{\mu\nu}\Gamma_{\mathrm{e}}\mathrm{e}\Phi)\mathrm{B}_{\mu\nu}$	$\mathcal{O}_{\Phi\mathrm{u}} = (\Phi^\dagger \mathrm{i}\overleftrightarrow{D}_\mu\Phi)(\bar{\mathrm{u}}\gamma^\mu\mathrm{u})$
$\mathcal{O}_{\Phi\mathrm{WB}} = (\Phi^\dagger\tau^I\Phi)\mathrm{W}_{\mu\nu}^I\mathrm{B}^{\mu\nu}$	$\mathcal{O}_{\mathrm{uB}} = (\bar{\mathrm{q}}\sigma^{\mu\nu}\Gamma_{\mathrm{u}}\mathrm{u}\widetilde{\Phi})\mathrm{B}_{\mu\nu}$	$\mathcal{O}_{\Phi\mathrm{d}} = (\Phi^\dagger \mathrm{i}\overleftrightarrow{D}_\mu\Phi)(\bar{\mathrm{d}}\gamma^\mu\mathrm{d})$
$\mathcal{O}_{\Phi\widetilde{\mathrm{W}}\mathrm{B}} = (\Phi^\dagger\tau^I\Phi)\widetilde{\mathrm{W}}_{\mu\nu}^I\mathrm{B}^{\mu\nu}$	$\mathcal{O}_{\mathrm{dB}} = (\bar{\mathrm{q}}\sigma^{\mu\nu}\Gamma_{\mathrm{d}}\mathrm{d}\Phi)\mathrm{B}_{\mu\nu}$	$\mathcal{O}_{\Phi\mathrm{ud}} = \mathrm{i}(\widetilde{\Phi}^\dagger D_\mu\Phi)(\bar{\mathrm{u}}\gamma^\mu\Gamma_{\mathrm{ud}}\mathrm{d})$

Table 53: Alternative basis of dimension-6 operators involving Higgs doublet fields or gauge-boson fields.

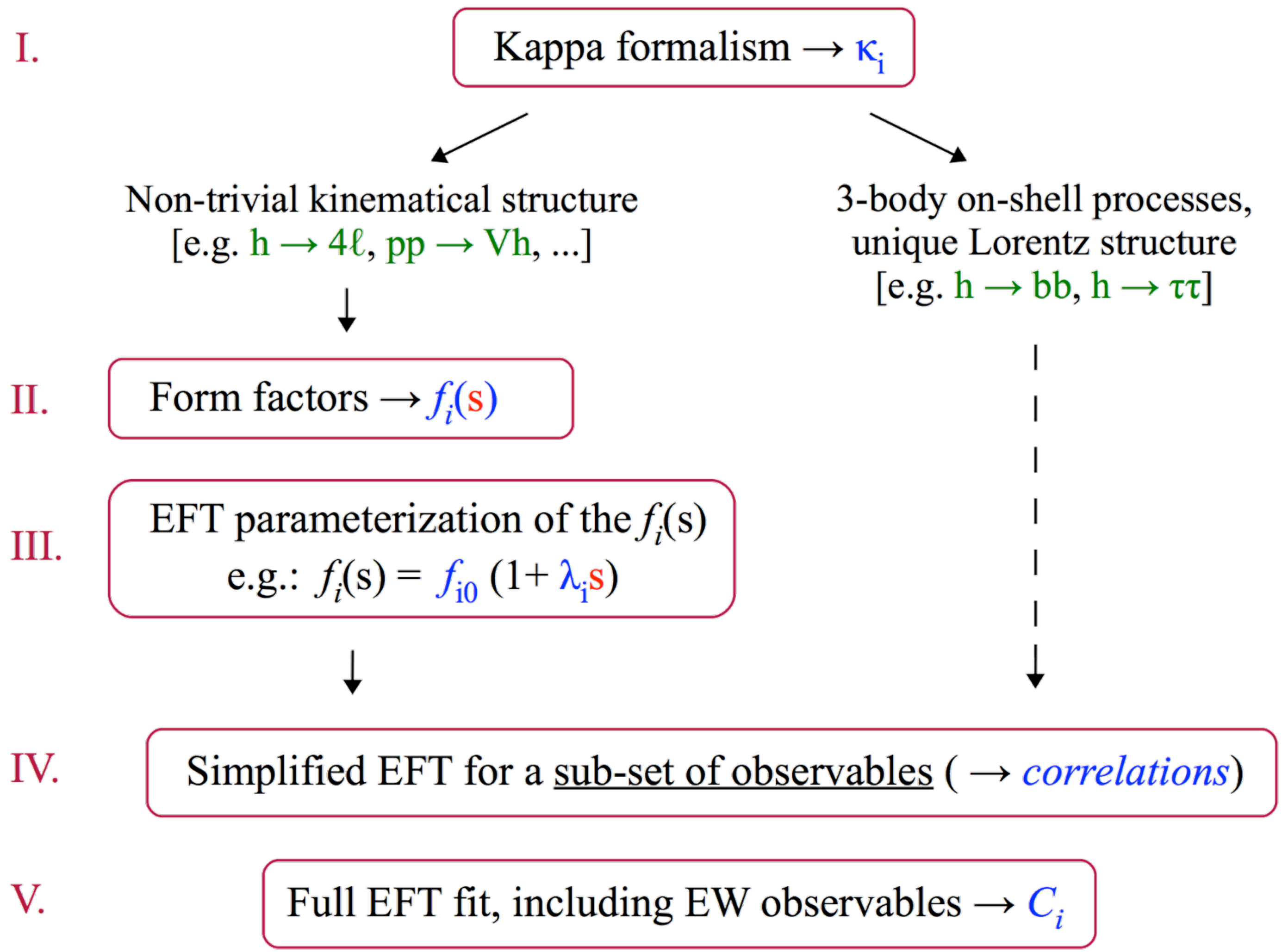
Φ^6 and $\Phi^4 D^2$	$\psi^2\Phi^3$	X^3
$\mathcal{O}'_6 = (\Phi^\dagger\Phi)^3$	$\mathcal{O}'_{\mathrm{e}\Phi} = (\Phi^\dagger\Phi)(\bar{\mathrm{l}}\,\Gamma_{\mathrm{e}}\mathrm{e}\Phi)$	$\mathcal{O}'_{G} = f^{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$
$\mathcal{O}'_{\Phi} = \partial_\mu(\Phi^\dagger\Phi)\partial^\mu(\Phi^\dagger\Phi)$	$\mathcal{O}'_{\mathrm{u}\Phi} = (\Phi^\dagger\Phi)(\bar{\mathrm{q}}\,\Gamma_{\mathrm{u}}\mathrm{u}\widetilde{\Phi})$	$\mathcal{O}'_{\widetilde{G}} = f^{ABC}\widetilde{G}_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$
$\mathcal{O}'_{\mathrm{T}} = (\Phi^\dagger\overleftrightarrow{D}_\mu\Phi)(\Phi^\dagger\overleftrightarrow{D}^\mu\Phi)$	$\mathcal{O}'_{\mathrm{d}\Phi} = (\Phi^\dagger\Phi)(\bar{\mathrm{q}}\,\Gamma_{d}d\Phi)$	$\mathcal{O}'_{\mathrm{W}} = \varepsilon^{IJK}\mathrm{W}_\mu^{I\nu}\mathrm{W}_\nu^{J\rho}\mathrm{W}_\rho^{K\mu}$
		$\mathcal{O}'_{\widetilde{\mathrm{W}}} = \varepsilon^{IJK}\widetilde{\mathrm{W}}_\mu^{I\nu}\mathrm{W}_\nu^{J\rho}\mathrm{W}_\rho^{K\mu}$
$\mathrm{X}^2\Phi^2$	$\psi^2\mathrm{X}\Phi$	$\psi^2\Phi^2 D$
$\mathcal{O}'_{\mathrm{D}W} = \left(\Phi^\dagger\tau^I\mathrm{i}\overleftrightarrow{D^\mu}\Phi\right)(D^\nu\mathrm{W}_{\mu\nu})^I$	$\mathcal{O}'_{\mathrm{u}G} = (\bar{\mathrm{q}}\sigma^{\mu\nu}\frac{\lambda^A}{2}\Gamma_{\mathrm{u}}\mathrm{u}\widetilde{\Phi})G_{\mu\nu}^A$	$\mathcal{O}'^{(1)}_{\Phi\mathrm{l}} = (\Phi^\dagger \mathrm{i}\overleftrightarrow{D}_\mu\Phi)(\bar{\mathrm{l}}\gamma^\mu\mathrm{l})$
$\mathcal{O}'_{D\mathrm{B}} = \left(\Phi^\dagger\mathrm{i}\overleftrightarrow{D^\mu}\Phi\right)(\partial^\nu\mathrm{B}_{\mu\nu})$	$\mathcal{O}'_{\mathrm{d}G} = (\bar{\mathrm{q}}\sigma^{\mu\nu}\frac{\lambda^A}{2}\Gamma_{\mathrm{d}}\mathrm{d}\Phi)G_{\mu\nu}^A$	$\mathcal{O}'^{(3)}_{\Phi\mathrm{l}} = (\Phi^\dagger \mathrm{i}\overleftrightarrow{D}_\mu^I\Phi)(\bar{\mathrm{l}}\gamma^\mu\tau^I\mathrm{l})$
$\mathcal{O}'_{D\Phi\mathrm{W}} = \mathrm{i}(D^\mu\Phi)^\dagger\tau^I(D^\nu\Phi)\mathrm{W}_{\mu\nu}^I$	$\mathcal{O}'_{\mathrm{eW}} = (\bar{\mathrm{l}}\sigma^{\mu\nu}\Gamma_{\mathrm{e}}\mathrm{e}\tau^I\Phi)\mathrm{W}_{\mu\nu}^I$	$\mathcal{O}'_{\Phi\mathrm{e}} = (\Phi^\dagger \mathrm{i}\overleftrightarrow{D}_\mu\Phi)(\bar{\mathrm{e}}\gamma^\mu\mathrm{e})$
$\mathcal{O}'_{D\Phi\widetilde{\mathrm{W}}} = \mathrm{i}(D^\mu\Phi)^\dagger\tau^I(D^\nu\Phi)\widetilde{\mathrm{W}}_{\mu\nu}^I$	$\mathcal{O}'_{\mathrm{uW}} = (\bar{\mathrm{q}}\sigma^{\mu\nu}\Gamma_{\mathrm{u}}\mathrm{u}\tau^I\widetilde{\Phi})\mathrm{W}_{\mu\nu}^I$	$\mathcal{O}'^{(1)}_{\Phi\mathrm{q}} = (\Phi^\dagger \mathrm{i}\overleftrightarrow{D}_\mu\Phi)(\bar{\mathrm{q}}\gamma^\mu\mathrm{q})$
$\mathcal{O}'_{D\Phi\mathrm{B}} = \mathrm{i}(D^\mu\Phi)^\dagger(D^\nu\Phi)\mathrm{B}_{\mu\nu}$	$\mathcal{O}'_{\mathrm{dW}} = (\bar{\mathrm{q}}\sigma^{\mu\nu}\Gamma_{\mathrm{d}}\mathrm{d}\tau^I\Phi)\mathrm{W}_{\mu\nu}^I$	$\mathcal{O}'^{(3)}_{\Phi\mathrm{q}} = (\Phi^\dagger \mathrm{i}\overleftrightarrow{D}_\mu^I\Phi)(\bar{\mathrm{q}}\gamma^\mu\tau^I\mathrm{q})$
$\mathcal{O}'_{D\Phi\widetilde{\mathrm{B}}} = \mathrm{i}(D^\mu\Phi)^\dagger(D^\nu\Phi)\widetilde{\mathrm{B}}_{\mu\nu}$	$\mathcal{O}'_{\mathrm{eB}} = (\bar{l}\sigma^{\mu\nu}\Gamma_{\mathrm{e}}\mathrm{e}\Phi)B_{\mu\nu}$	$\mathcal{O}'_{\Phi\mathrm{u}} = (\Phi^\dagger \mathrm{i}\overleftrightarrow{D}_\mu\Phi)(\bar{\mathrm{u}}\gamma^\mu\mathrm{u})$
$\mathcal{O}'_{\Phi\mathrm{B}} = (\Phi^\dagger\Phi)B_{\mu\nu}\mathrm{B}^{\mu\nu}$	$\mathcal{O}'_{\mathrm{uB}} = (\bar{\mathrm{q}}\sigma^{\mu\nu}\Gamma_{\mathrm{u}}\mathrm{u}\widetilde{\Phi})\mathrm{B}_{\mu\nu}$	$\mathcal{O}'_{\Phi\mathrm{d}} = (\Phi^\dagger \mathrm{i}\overleftrightarrow{D}_\mu\Phi)(\bar{\mathrm{d}}\gamma^\mu\mathrm{d})$
$\mathcal{O}'_{\Phi\widetilde{\mathrm{B}}} = (\Phi^\dagger\Phi)\mathrm{B}_{\mu\nu}\widetilde{\mathrm{B}}^{\mu\nu}$	$\mathcal{O}'_{\mathrm{dB}} = (\bar{\mathrm{q}}\sigma^{\mu\nu}\Gamma_{\mathrm{d}}\mathrm{d}\Phi)\mathrm{B}_{\mu\nu}$	$\mathcal{O}'_{\Phi\mathrm{ud}} = \mathrm{i}(\widetilde{\Phi}^\dagger D_\mu\Phi)(\bar{\mathrm{u}}\gamma^\mu\Gamma_{\mathrm{ud}}\mathrm{d})$
$\mathcal{O}'_{\Phi G} = \Phi^\dagger\Phi G_{\mu\nu}^A G^{A\mu\nu}$		
$\mathcal{O}'_{\Phi\widetilde{G}} = \Phi^\dagger\Phi G_{\mu\nu}^A\widetilde{G}^{A\mu\nu}$		

A Rosetta stone for Higgs EFT



Isidori's 5 steps for 4ℓ ~~addicts~~ aficionados

[http://cern.ch/go/9GxP]



A possible roadmap

κ
- NWA
- 0^+
- Single state
- 1 d.o.f./SM particle

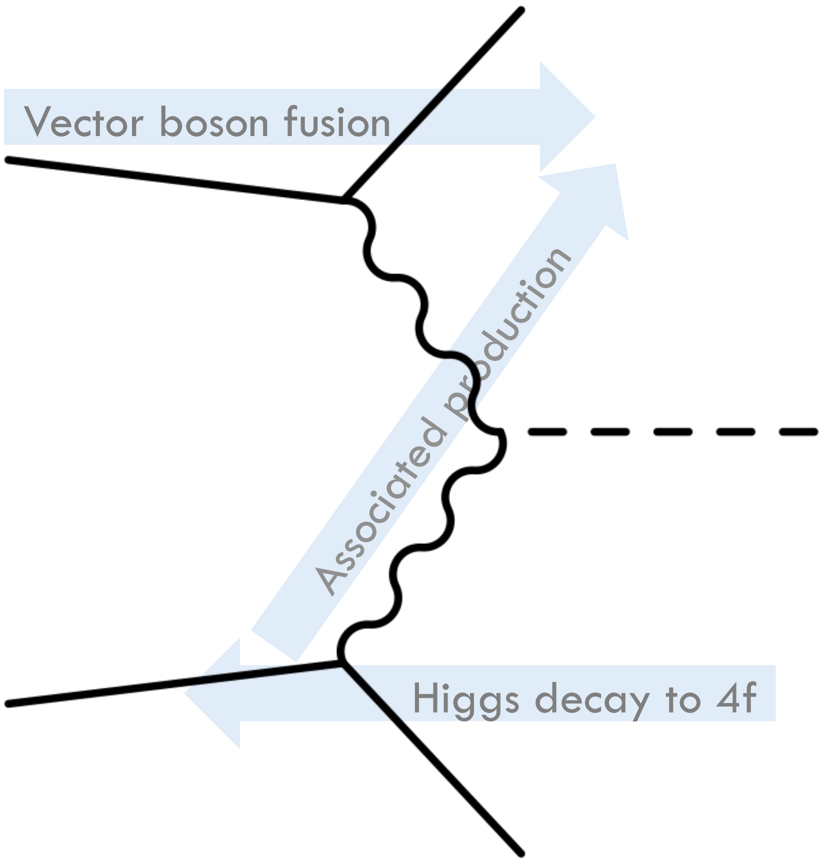
κ_∞
- Short-distance contribution to loops.
- Appears in at least $p_T(H)$ and m_{VV}.
- Just one more d.o.f.

κ (q)
- q = $p_T(H)$, m_{34}, m_{VV}, m_{ZH}, …
- "differential μ"
- 1 d.o.f./bin

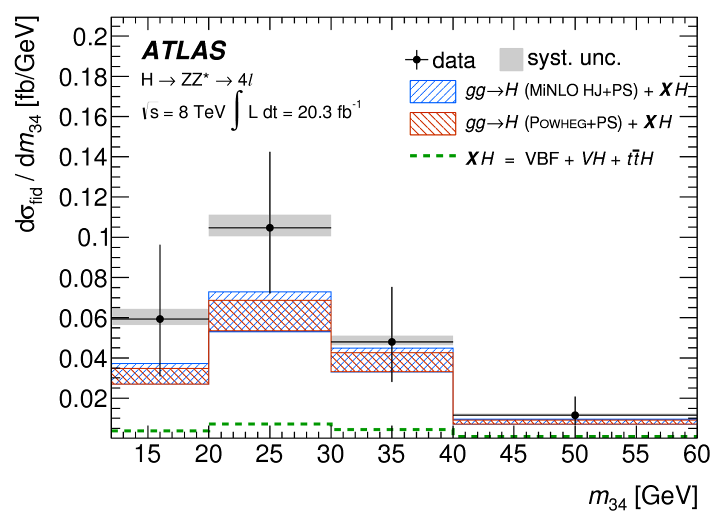
f(q) × Lorentz structures
- $f = f_0 + \lambda q$
- As done in flavour physics?
- 2 d.o.f./ observable

Full EFT
- Wilson coefficients c_i.
- Which ones?
- Which sets?
- Which assumptions?

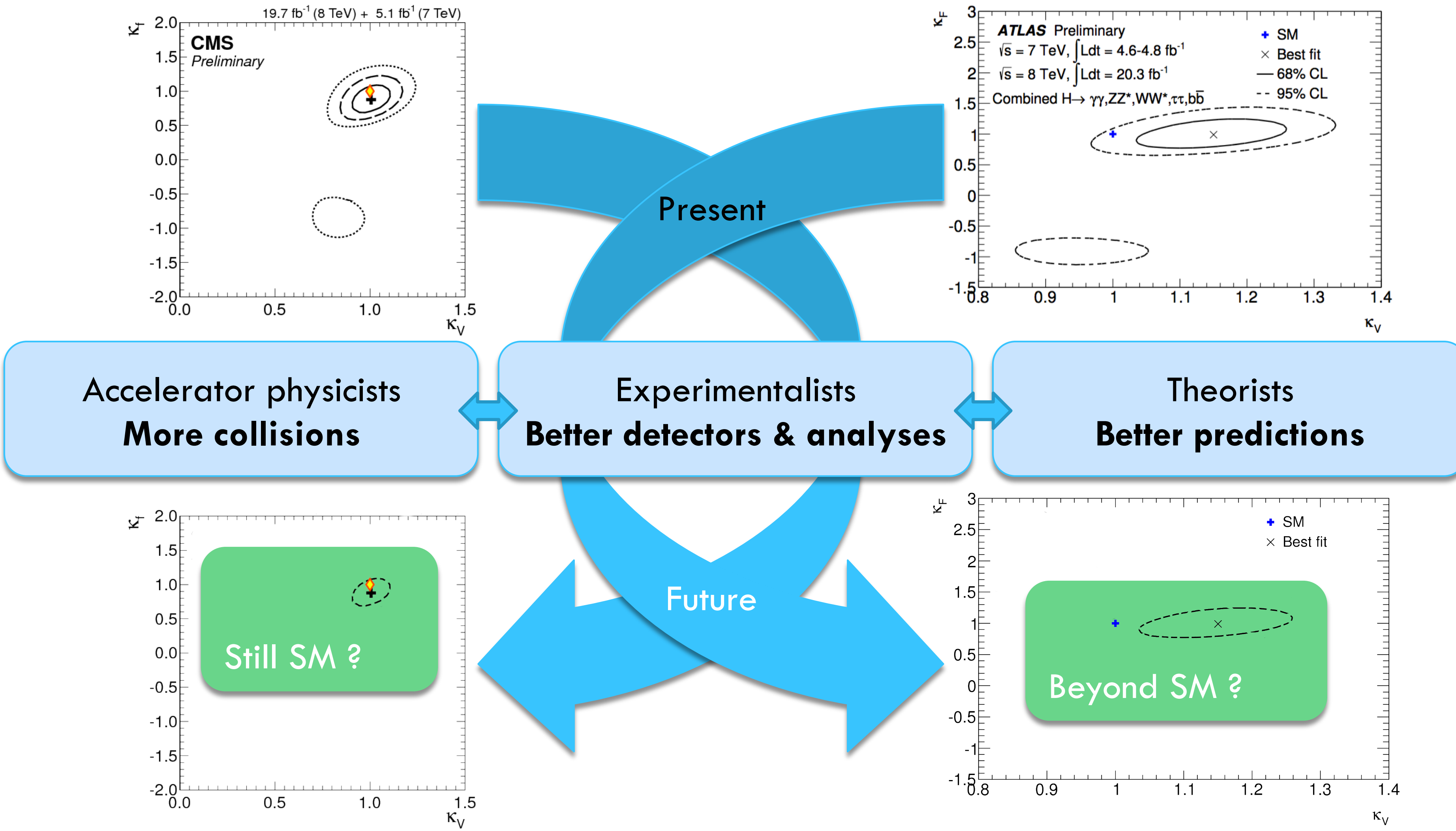
HVV systematization



Decay	γ	γ*/Z*	Z
γ	✓	✓	✓
γ*/Z*		? (VBF)	✓ (VH)
Z			✓ (H*)

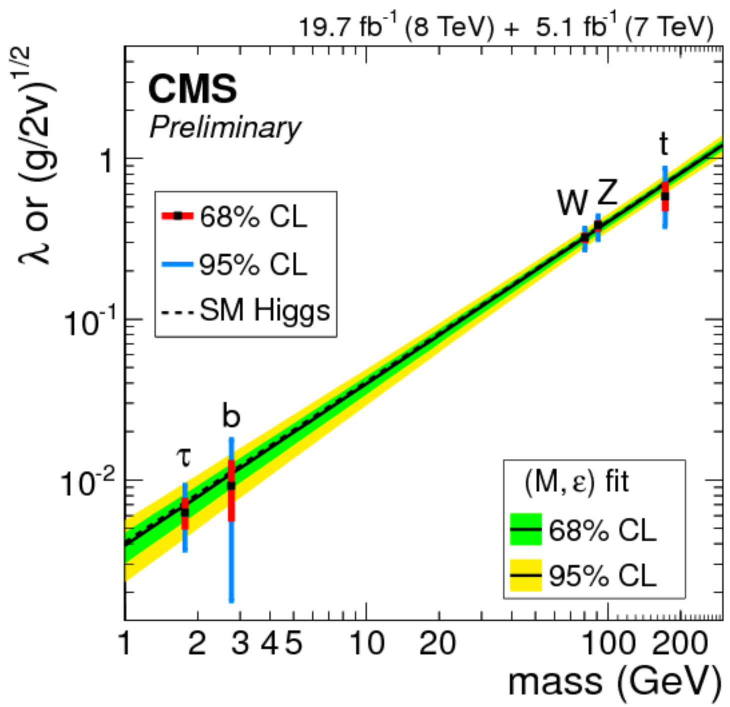


The future is in precision and accuracy



Conclusion

$m_H = 125.03 \pm 0.30 \left[^{+0.26}_{-0.27}(\text{stat.})^{+0.13}_{-0.15}(\text{syst.})\right]$ GeV



- **We've just started and there's a long and exciting way to go:**
  - Go from O(10%) measurements to differential.
  - Go from "seen" to O(%) measurements.
  - Go from limits on rare things to observations.
  - Reduce theory uncertainties.
  - Explore the full potential of the LHC and its upgrades.
- **All it takes is one deviation to point us on the right way beyond the SM.**

Conclusion

- We've just started and there's a long and exciting way to go:
  - Go from O(10%) measurements to differential.
  - Go from "seen" to O(%) measurements.
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- **All it takes is one deviation to point us on the right way beyond the SM.**

Need topics for discussion?

- Deviations: **precision** (uncertainties) vs. **accuracy** (higher orders) of SM expectation.
- "Lumi doubling": ATLAS+CMS vs. **uniform** & **comprehensive** (theory) uncertainties.
- Tools: **calculators** vs. **generators**.

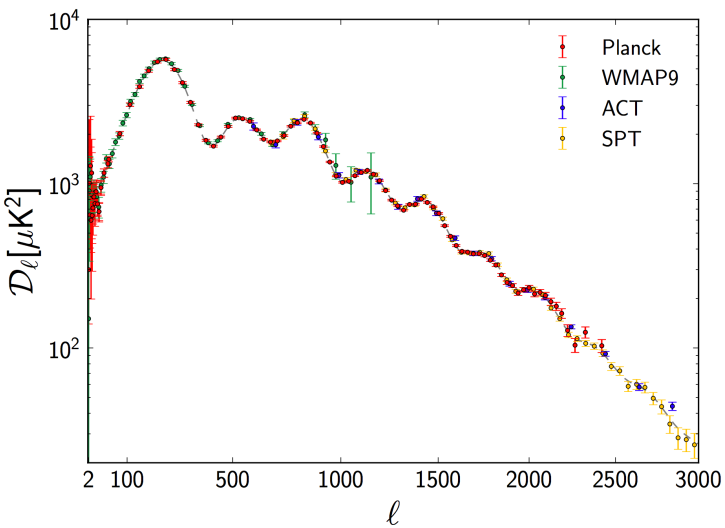
- **LHC Run 2**: more exclusive, more differential, more off-shell, more HVV, more Yukawas (discover VHbb, ttH).
- Towards **EFT**:
  - Consistency and validity: every complexity-reducing assumption must come with (in)validation experimental tests.
  - Consistency: observables vs. "inferables". Global fit of EWPD, a{T,Q}GC, and Higgs.
  - Consistency: EFT effects in background processes.
  - Accuracy: $|\text{dim-4} + \text{dim-6} + \text{dim-8} + \ldots|^2 = \mathbf{d4^2} + \text{d4}\times\text{d6}$ $(+\ \text{d6}^2 + \text{d4}\times\text{d8})$ $(+\ \text{d8}^2 + \text{d6}\times\text{d8}) + \ldots$
  - Validity: dim-8 in high-q^2 tails and/or where there is no tree-level dim-6.
- The many sides of the **HVV hexahedron**:
  - $H \rightarrow \{\gamma\gamma, \gamma\gamma^*, Z\gamma^*, ZZ\}$, plus VH and VBF (and how can the W fit in this picture?).
- Experiment-Theory **information interchange** interface.

KEEP CALM AND ASK QUESTIONS

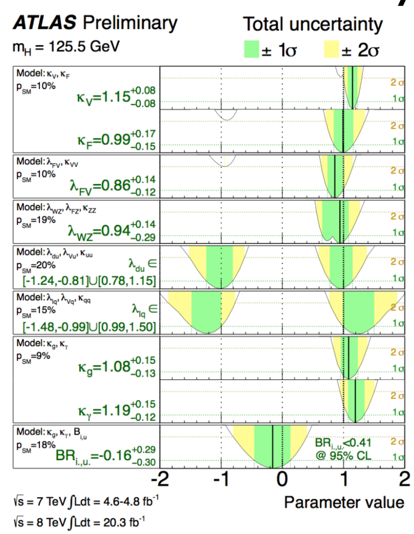
The ~~beautiful~~ ~~boring~~ 2014 Universe

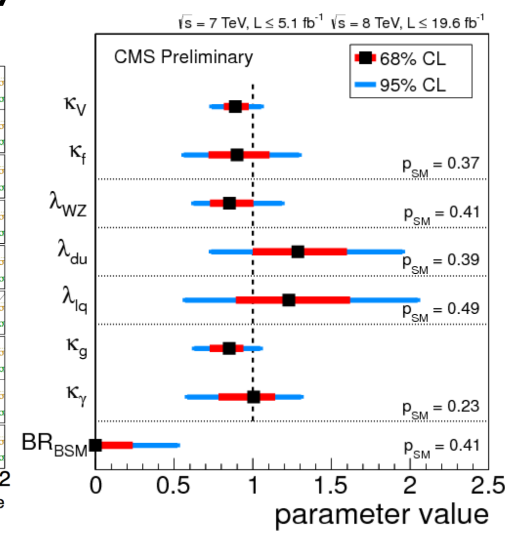
[arXiv:1303.5062] [ATLAS-CONF-NOTE-2014-009] [CMS-PAS-HIG-14-009]

- **Up above:** “Simple six-parameter ΛCDM”.



- **Down below:** (Not-as-simple) ~20-parameter Standard Model of Particle Physics.





Looking forward to LHC combination and surprises at higher energy: PeV neutrinos, LHC 13 TeV, …

References

"…and references therein."

- Experiments' pages on Higgs results:
  - ATLAS: http://cern.ch/go/7IDT
  - CMS: http://cern.ch/go/6qmZ
  - Tevatron: http://cern.ch/go/h9jX
    - CDF: http://cern.ch/go/q8NV
    - D0: http://cern.ch/go/9Djq
- Partial list of conferences and workshops:
  - Higgs Days 2013: http://cern.ch/go/6zBp
  - ECFA HL-LHC workshop: http://cern.ch/go/SFW6
  - Higgs EFT 2013: http://cern.ch/go/bR7w
  - Higgs Couplings 2013: http://cern.ch/go/THp9
  - Moriond 2014: http://cern.ch/go/k8FP
  - Bernasque 2014: http://cern.ch/go/Pz7I
  - ICHEP 2014: http://cern.ch/go/8Btf
  - Rencontres du Vietnam 2014: http://cern.ch/go/9ZJJ
  - Zuoz Summer School 2014: http://cern.ch/go/9SHw

KEEP
CALM
AND
DISCUSS

More on the combination

The challenge of combining

[CMS-PAS-HIG-14-009]

- Include **five main decays** and searches for **ttH production.**
- **207 channels.**
- **2519 parameters.**
  - 219 H→γγ background parameters.

Decay tag	Production tag	Expected signal composition	σ_{m_H}/m_H	Luminosity (fb^{-1}) / No. of categories: 7 TeV	8 TeV
$H \to \gamma\gamma$ [20], Section 2.1				*5.1*	*19.7*
$\gamma\gamma$	Untagged	76–93% ggH	0.8–2.1%	4	5
	2-jet VBF	50–80% VBF	1.0–1.3%	2	3
	Leptonic VH	≈95% VH (WH/ZH ≈ 5)	1.3%	2	2
	E_T^{miss} VH	70–80% VH (WH/ZH ≈ 1)	1.3%	1	1
	2-jet VH	≈65% VH (WH/ZH ≈ 5)	1.0–1.3%	1	1
	Leptonic $t\bar{t}H$	≈95% $t\bar{t}H$	1.1%	$1^{\dagger}$	1
	Multijet $t\bar{t}H$	>90% $t\bar{t}H$	1.1%		1
$H \to ZZ^{(*)} \to 4\ell$ [18], Section 2.2				*5.1*	*19.7*
4μ, $2e2\mu$, $4e$	2-jet	42% VBF + VH	1.3, 1.8, 2.2%‡	3	3
	Other	≈90% ggH		3	3
$H \to WW^{(*)} \to \ell\nu\ell\nu$ [17], Section 2.3				*4.9*	*19.4*
$ee + \mu\mu$, $e\mu$	0-jet	96–98% ggH	$e\mu$: 16%‡	2	2
	1-jet	82–84% ggH	$e\mu$: 17%‡	2	2
	2-jet VBF	78–86% VBF		2	2
	2-jet VH	31–40% VH		2	2
$3\ell 3\nu$ WH	SF-SS, SF-OS	≈100% WH, up to 20% $\tau\tau$		2	2
$\ell\ell + \ell'\nu jj$ ZH	eee, $ee\mu$, $\mu\mu\mu$, $\mu\mu e$	≈100% ZH		4	4
$H \to \tau\tau$ [19], Section 2.4				*4.9*	*19.7*
$e\tau_h$, $\mu\tau_h$	0-jet	≈98% ggH	11–14%	4	4
	1-jet	70–80% ggH	12–16%	5	5
	2-jet VBF	75–83% VBF	13–16%	2	4
$\tau_h\tau_h$	1-jet	67–70% ggH	10–12%	-	2
	2-jet VBF	80% VBF	11%	-	1
$e\mu$	0-jet	≈98% ggH, 23–30% WW	16–20%	2	2
	1-jet	75–80% ggH, 31–38% WW	18–19%	2	2
	2-jet VBF	79–94% VBF, 37–45% WW	14–19%	1	2
ee, $\mu\mu$	0-jet	88–98% ggH		4	4
	1-jet	74–78% ggH, ≈17% WW *		4	4
	2-jet CJV	≈50% VBF, ≈45% ggH, 17–24% WW *		2	2
$\ell\ell + LL'$ ZH	$LL' = \tau_h\tau_h, \ell\tau_h, e\mu$	≈15% (70%) WW for $LL' = \ell\tau_h$ ($e\mu$)		8	8
$\ell + \tau_h\tau_h$ WH		≈96% VH, ZH/WH ≈ 0.1		2	2
$\ell + \ell'\tau_h$ WH		ZH/WH ≈ 5%, 9–11% WW		2	4
VH with $H \to bb$ [16], Section 2.5				*5.1*	*18.9*
$W(\ell\nu)bb$	$p_T(V)$ bins	≈100% VH, 96–98% WH	≈10%	4	6
$W(\tau_h\nu)bb$		93% WH		-	1
$Z(\ell\ell)bb$	$p_T(V)$ bins	≈100% ZH		4	4
$Z(\nu\nu)bb$	$p_T(V)$ bins	≈100% VH, 62–76% ZH		2	3
$t\bar{t}H$ with $H \to$ hadrons [14, 28], Section 2.6				*5.0*	*19.3*
$H \to bb$	$t\bar{t}$ lepton+jets	≈90% bb but ≈24% WW in ≥6j + 2b		7	7
	$t\bar{t}$ dilepton	45–85% bb, 8–35% WW, 4–14% $\tau\tau$		2	3
$H \to \tau_h\tau_h$	$t\bar{t}$ lepton+jets	68–80% $\tau\tau$, 13–22% WW, 5–13% bb		-	6
$t\bar{t}H$ with $H \to$ leptons [29], Section 2.6				*-*	*19.6*
2ℓ-SS		$WW/\tau\tau \approx 3$		-	6
3ℓ		$WW/\tau\tau \approx 3$		-	2
4ℓ		$WW : \tau\tau : ZZ \approx 3:2:1$		-	1

H→VV results in combination

[JHEP 01 (2014) 096] [PRD 89 (2014) 092007] [CMS-PAS-HIG-14-009]

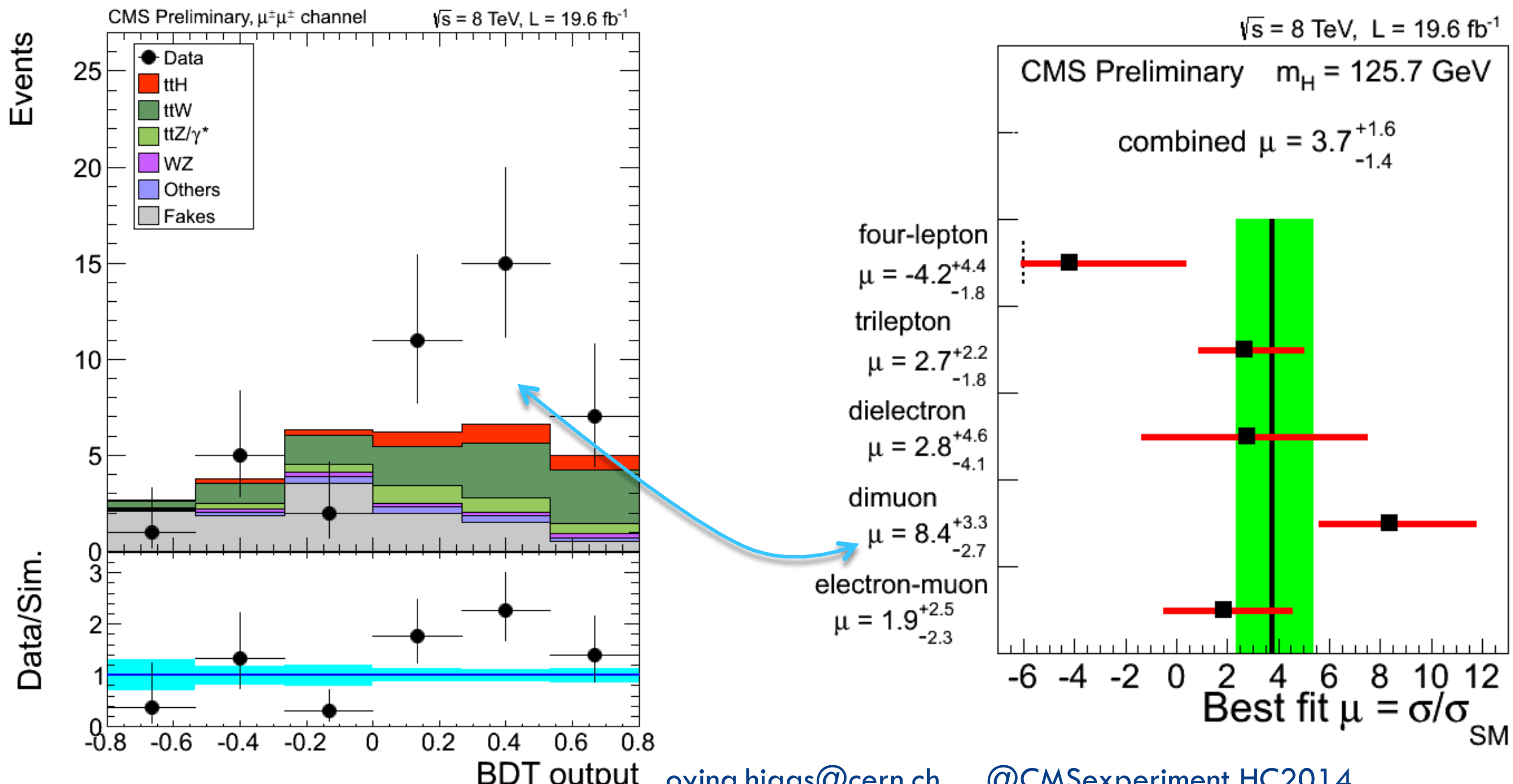
- What changed?
  - **BR(H→VV) changes by 4 – 5%.**
    - H→WW and H→ZZ paper results evaluated at H→ZZ m_H result: **m_H = 125.6 GeV.**
    - Combined mass slightly lower: **m_H = 125.0 GeV.**
  - In the combination **H→WW includes the ttH, H decaying to multi-lepton result:** $\sigma/\sigma_{SM} = 3.7 \pm 1.5$.

σ/σ_{SM}	Individual publication	Combination
H→ZZ	0.93	1.00
H→WW	0.72	0.83

ttH multi-leptons

[CMS-PAS-HIG-13-020] [http://cern.ch/go/FKr9]

- Very extensive cross-checks performed: http://cern.ch/go/Xv8S



Significance of excesses

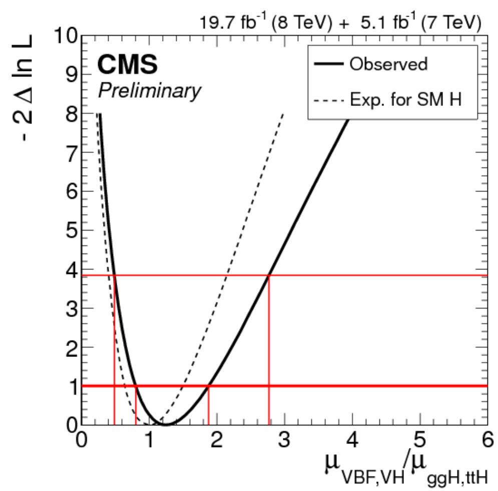
[CMS-PAS-HIG-14-009]

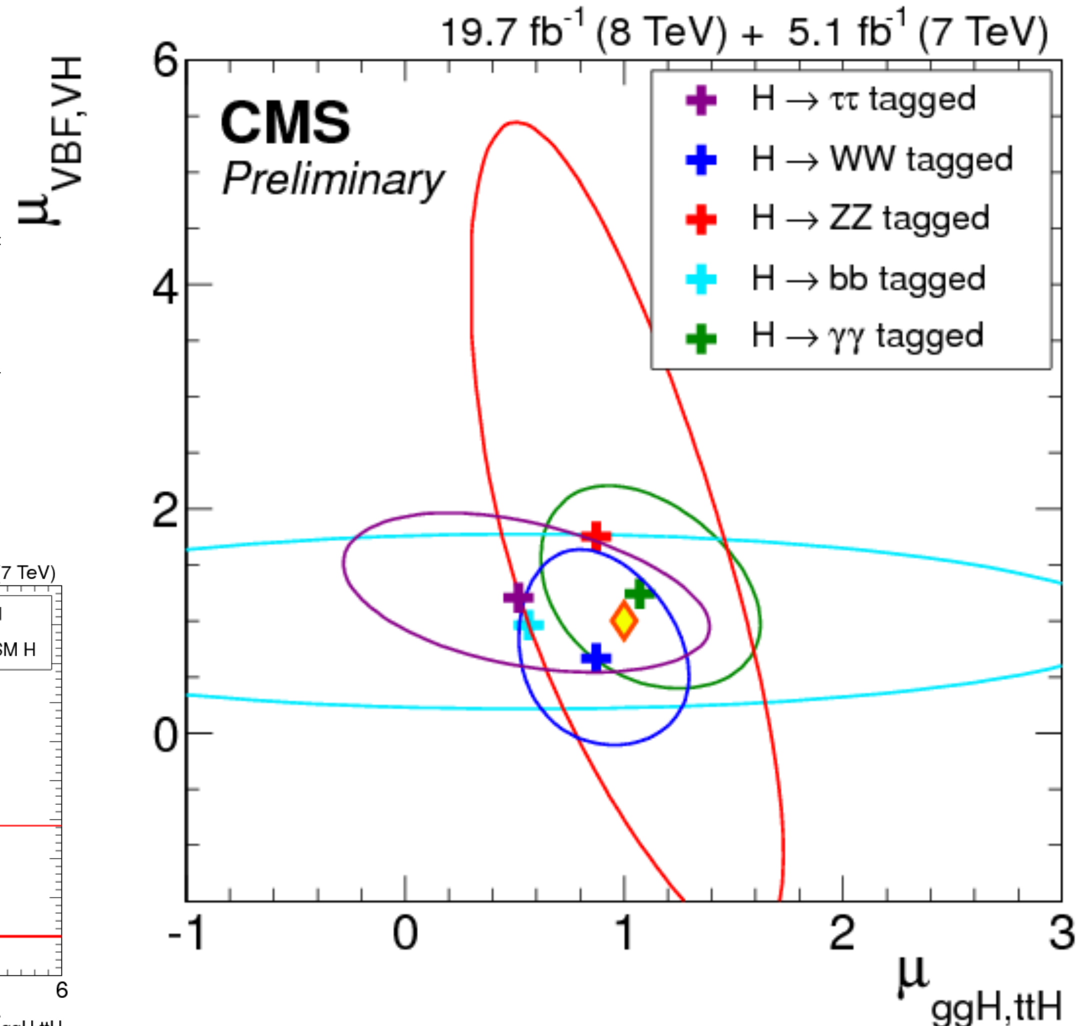
Channel grouping	Significance (σ) Observed	Significance (σ) Expected
$H \rightarrow ZZ$ tagged	6.5	6.3
$H \rightarrow \gamma\gamma$ tagged	5.6	5.3
$H \rightarrow WW$ tagged	4.7	5.4
Grouped as in Ref. [17]	4.3	5.4
$H \rightarrow \tau\tau$ tagged	3.8	3.9
Grouped as in Ref. [19]	3.9	3.9
$H \rightarrow bb$ tagged	2.0	2.3
Grouped as in Ref. [16]	2.1	2.3

Combined production measurement

[CMS-PAS-HIG-14-009]

Channel grouping	Best fit $(\mu_{ggH,t\bar{t}H}, \mu_{VBF,VH})$
$H \to ZZ$ tagged	$(0.88, 1.75)$
$H \to \gamma\gamma$ tagged	$(1.07, 1.24)$
$H \to WW$ tagged	$(0.87, 0.66)$
$H \to \tau\tau$ tagged	$(0.52, 1.21)$
$H \to bb$ tagged	$(0.57, 0.96)$
Combined best fit $\mu_{VBF,VH}/\mu_{ggH,t\bar{t}H}$	
	Observed (expected)
	$1.25^{+0.63}_{-0.45}$ $(1.00^{+0.49}_{-0.35})$



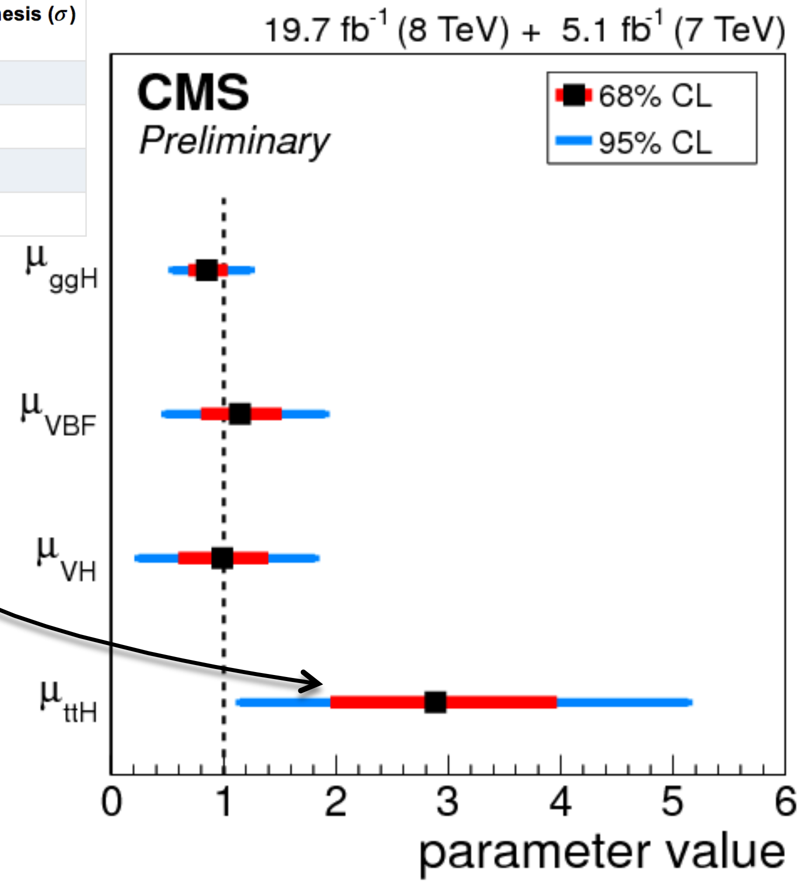


Production mode scaling assuming SM BR structure

[CMS-PAS-HIG-14-009]

- $\mu_{ggH} = 0.85 \,^{+0.11}_{-0.09}\,(\text{stat.})\,^{+0.11}_{-0.08}\,(\text{theo.})\,^{+0.10}_{-0.09}\,(\text{syst.})$

Parameter	Best fit result (68% CL) for full combination	Observed significance (σ)	Expected sensitivity (σ)	Pull to SM hypothesis (σ)
μ_{ggH}	$0.85^{+0.19}_{-0.17}$	6.5	7.5	-0.8
μ_{VBF}	$1.15^{+0.37}_{-0.35}$	3.6	3.3	0.4
μ_{VH}	$1.00^{+0.40}_{-0.40}$	2.7	2.7	0.0
μ_{ttH}	$2.93^{+1.04}_{-0.97}$	3.5	1.2	2.1

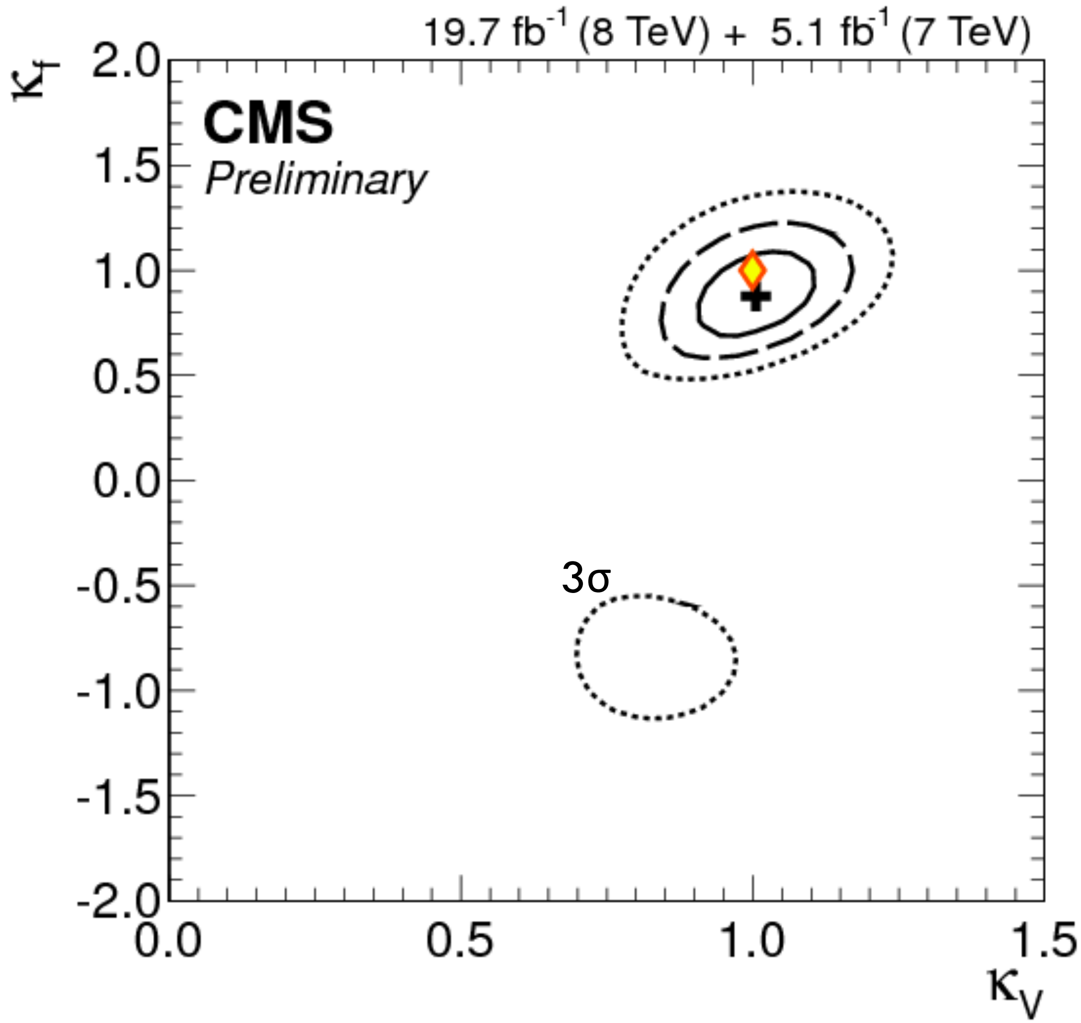


Parameter	Best fit result (68% CL) for 7 TeV data	Best fit result (68% CL) for 8 TeV data
μ_{ggH}	$1.00^{+0.36}_{-0.32}$	$0.80^{+0.19}_{-0.17}$
μ_{VBF}	$1.78^{+0.97}_{-0.91}$	$1.02^{+0.39}_{-0.36}$
μ_{VH}	$0.69^{+0.98}_{-0.66}$	$1.06^{+0.45}_{-0.43}$
μ_{ttH}	$0.00^{+2.13}_{-0.00}$	$3.22^{+1.14}_{-1.00}$

Coupling deviations

[CMS-PAS-HIG-14-009] [arXiv:1307.1347]

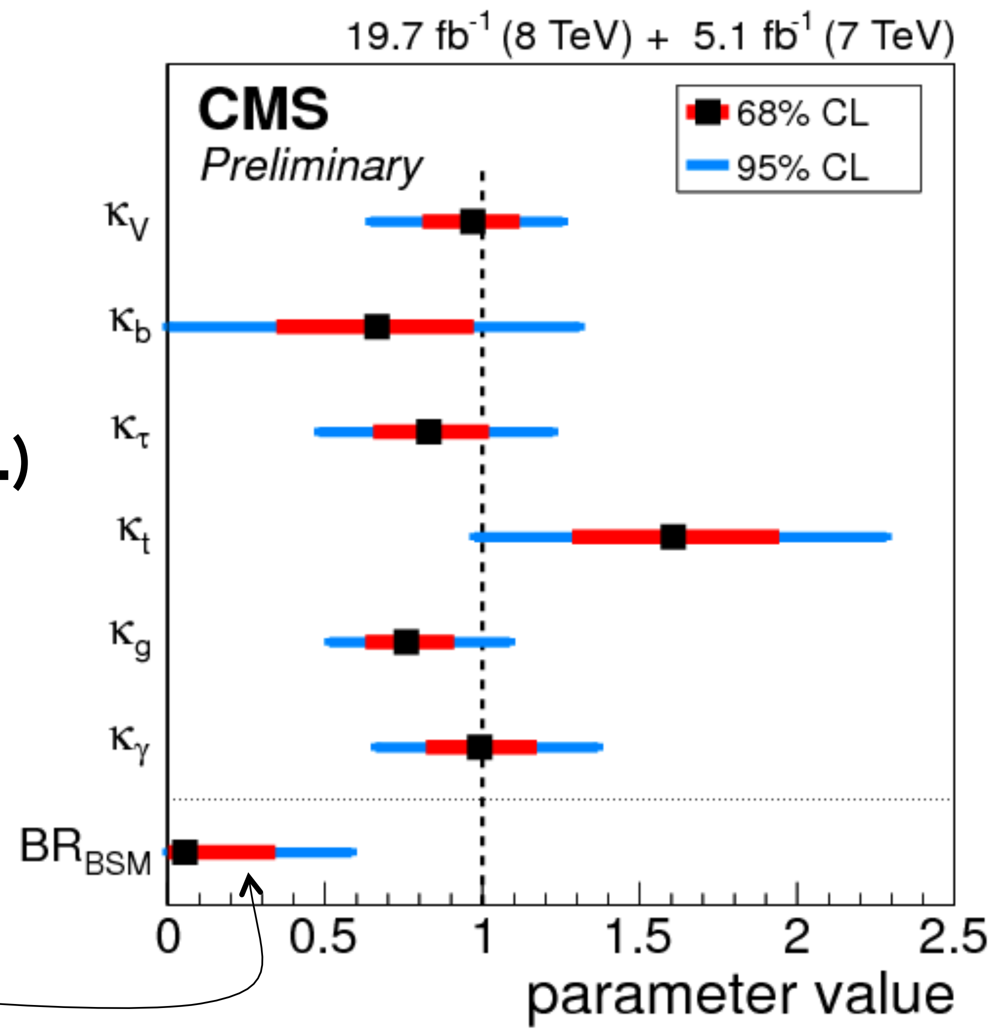
- Scaling the couplings to fermions (κ_f) and vector bosons (κ_V).
- **Interference in $H \rightarrow \gamma\gamma$ decay resolves degeneracy.**

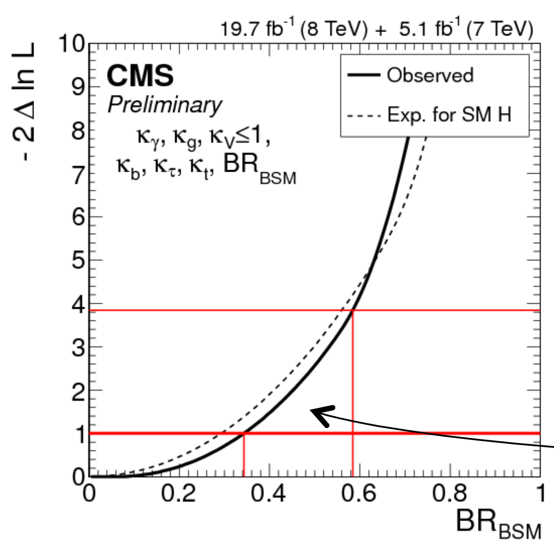


Coupling deviations summaries

[CMS-PAS-HIG-14-009] [arXiv:1307.1347]

- 6 or 7 parameter fits with effective loops.
- BR_{BSM} measured assuming $\kappa_V \leq 1$:
  - **$BR_{BSM} < 0.34$ (95% CL)**





Coupling deviations

[CMS-PAS-HIG-14-009] [arXiv:1307.1347]

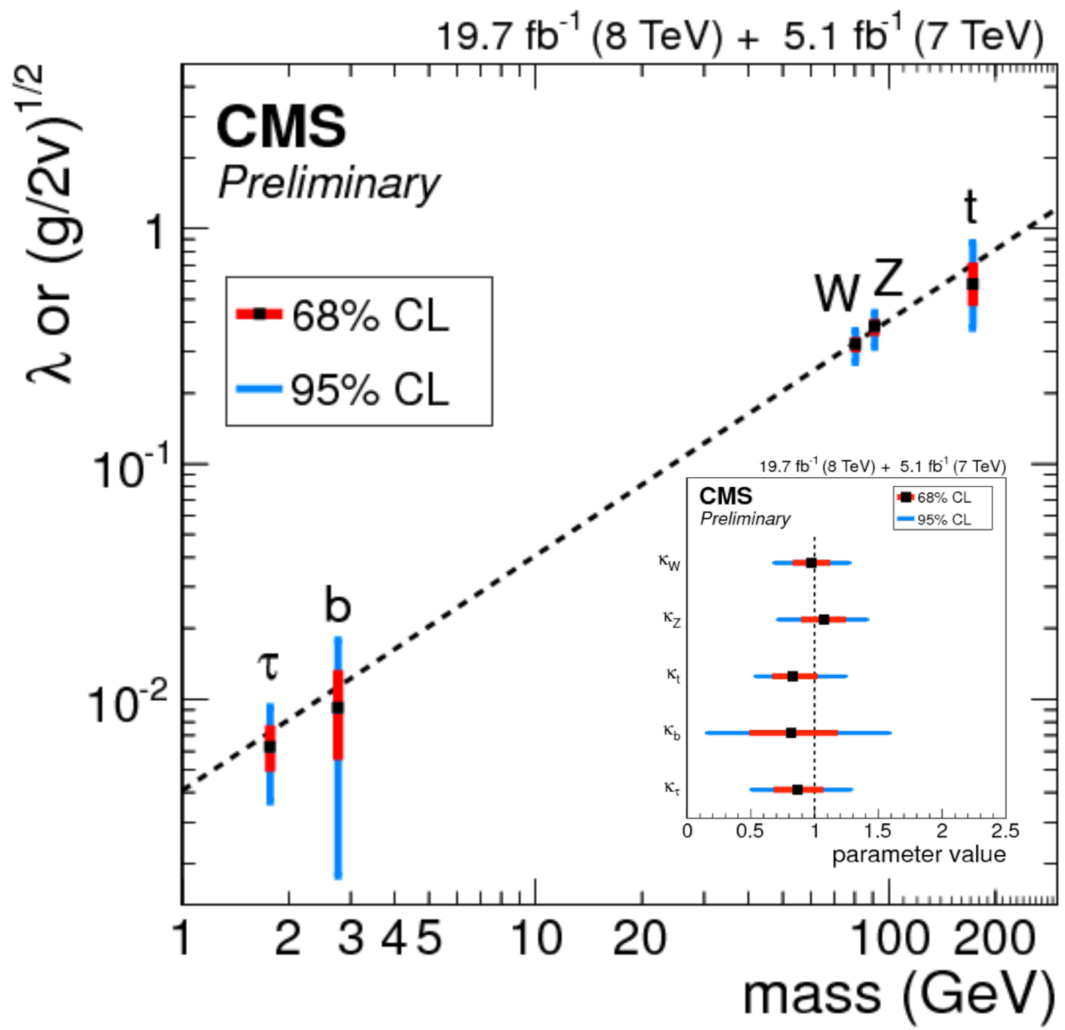
Model: Parameters	Model: Table in Ref. [27]	Best-fit result: Parameter	Best-fit result: 68% CL	Best-fit result: 95% CL	Comment
κ_Z, λ_{WZ} (κ_f =1)	-	λ_{WZ}	$0.94^{+0.22}_{-0.18}$	[0.61,1.45]	$\lambda_{WZ} = \kappa_W/\kappa_Z$ using ZZ and 0/1-jet WW channels.
κ_Z, λ_{WZ}, κ_f	44 (top)	λ_{WZ}	$0.91^{+0.14}_{-0.12}$	[0.70,1.22]	$\lambda_{WZ} = \kappa_W/\kappa_Z$ from full combination.
κ_V, κ_f	43 (top)	κ_V	$1.01^{+0.07}_{-0.07}$	[0.88,1.15]	κ_V scales couplings to W and Z bosons.
		κ_f	$0.89^{+0.14}_{-0.13}$	[0.64,1.16]	κ_f scales couplings to all fermions.
κ_g, κ_γ	48 (top)	κ_g	$0.89^{+0.10}_{-0.10}$	[0.69,1.10]	Effective couplings to gluons (g) and photons (γ).
		κ_γ	$1.15^{+0.13}_{-0.13}$	[0.89,1.42]	
κ_g, κ_γ, BR_{BSM}	48 (middle)	BR_{BSM}	≤ 0.13	[0.00,0.32]	Branching fraction for BSM decays.
κ_V, λ_{du}, κ_u	46 (top)	λ_{du}	$1.01^{+0.20}_{-0.19}$	[0.66,1.43]	$\lambda_{du} = \kappa_u/\kappa_d$, relating up-type and down-type fermions.
κ_V, $\lambda_{\ell q}$, κ_q	47 (top)	$\lambda_{\ell q}$	$1.02^{+0.22}_{-0.21}$	[0.61,1.49]	$\lambda_{\ell q} = \kappa_\ell/\kappa_q$, relating leptons and quarks.
κ_g, κ_γ, κ_V, κ_b, κ_τ, κ_t	Similar to 50 (top)	κ_g	$0.76^{+0.15}_{-0.13}$	[0.51,1.09]	
		κ_γ	$0.99^{+0.18}_{-0.17}$	[0.66,1.37]	
		κ_V	$0.97^{+0.15}_{-0.16}$	[0.64,1.26]	
		κ_b	$0.67^{+0.31}_{-0.32}$	[0.00,1.31]	Down-type quarks (via b).
		κ_τ	$0.83^{+0.19}_{-0.18}$	[0.48,1.22]	Charged leptons (via τ).
		κ_t	$1.61^{+0.33}_{-0.32}$	[0.97,2.28]	Up-type quarks (via t).
as above plus BR_{BSM} and $\kappa_V \leq 1$	-	BR_{BSM}	≤ 0.34	[0.00,0.58]	

Resolving SM contributions

[CMS-PAS-HIG-14-009] [arxiv:1303.3570]

- Individual coupling scaling factors:
  - κ_W, κ_Z, κ_b, κ_t, κ_τ.
  - All loops resolved:
    - $\kappa_\gamma(\kappa_W, \kappa_t)$
    - $\kappa_g(\kappa_t, \kappa_b)$
  - SMH width scaled.

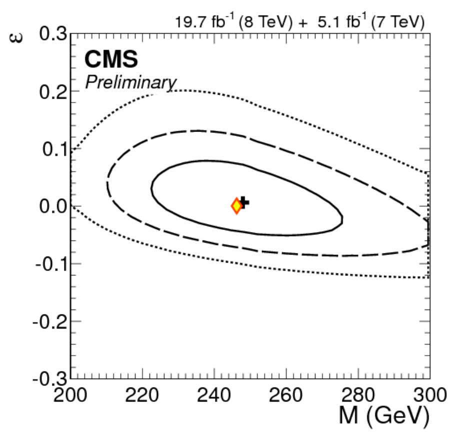
- "Reduced" couplings as function of "mass":
  - $\lambda_f = \kappa_f\,(m_f/vev)$
  - $(g_V/2vev)^{1/2} = \kappa_V^{1/2}\,(m_V/vev)$

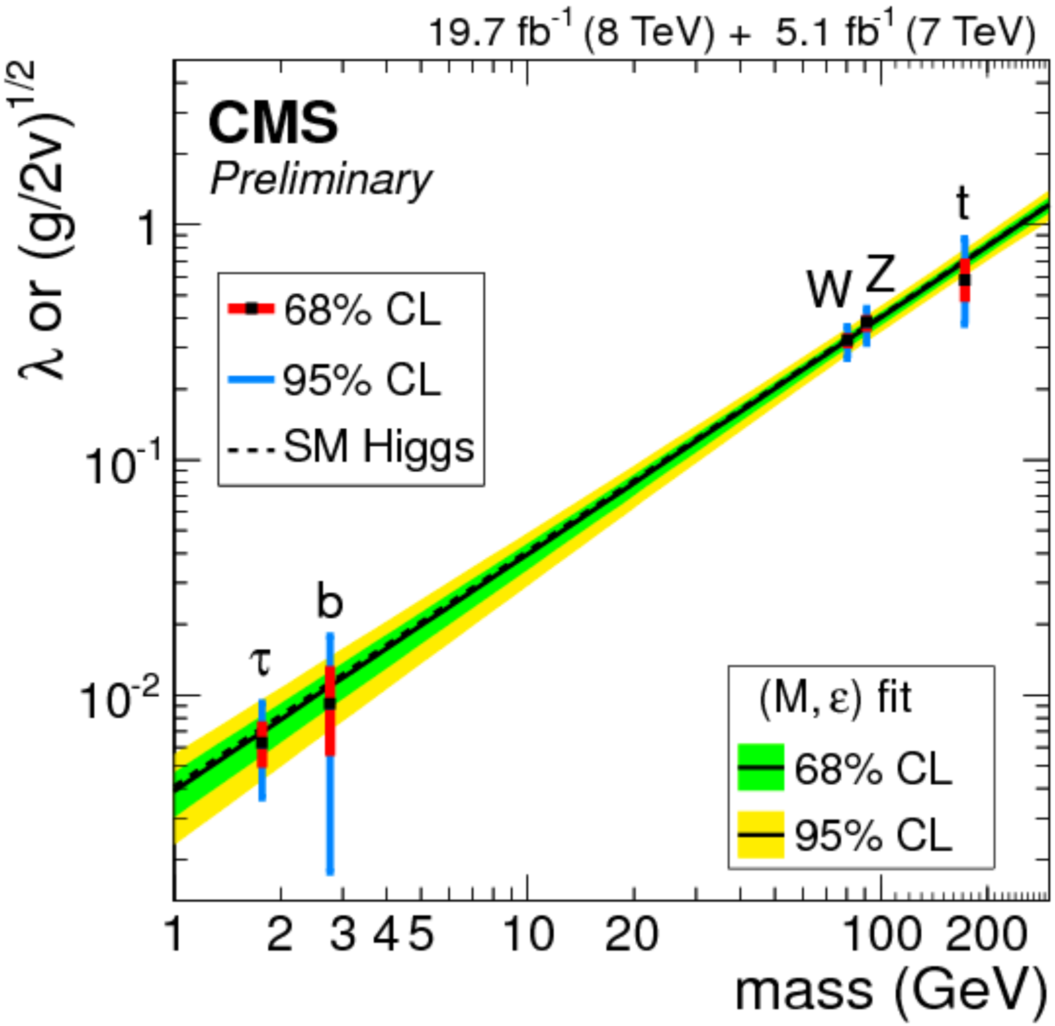


Mass power parametrization

[CMS-PAS-HIG-14-009] [arxiv:1207.1693]

- *Vev* modifier and power of coupling to mass:
  - Gauge bosons: $\kappa_V = vev \times m_V^{2\varepsilon} / M^{1+2\varepsilon}$
  - Fermions: $\kappa_f = vev \times m_f^{\varepsilon} / M^{1+\varepsilon}$
- For SMH, M = vev = 246.22 GeV and ε = 0.





Statistics

Statistics interlude

[ATL-PHYS-PUB-2011-11, CMS NOTE-2011/005]

	Test statistic	Profiled?	Test statistic sampling
LEP	$q_\mu = -2\ln\frac{\mathcal{L}(data\mid\mu,\tilde{\theta})}{\mathcal{L}(data\mid 0,\tilde{\theta})}$	no	Bayesian-frequentist hybrid
Tevatron	$q_\mu = -2\ln\frac{\mathcal{L}(data\mid\mu,\hat{\theta}_\mu)}{\mathcal{L}(data\mid 0,\hat{\theta}_0)}$	yes	Bayesian-frequentist hybrid
LHC	$\tilde{q}_\mu = -2\ln\frac{\mathcal{L}(data\mid\mu,\hat{\theta}_\mu)}{\mathcal{L}(data\mid\hat{\mu},\hat{\theta})}$	yes $(0 \leq \hat{\mu} \leq \mu)$	frequentist

- **LEP**: nuisances parameters (θ) kept at nominal values (~).
- **Tevatron**: maximise likelihood against nuisances (^).
  - Denominator considers **background-only hypothesis** (μ=0).
- **LHC**: frequentist profiled likelihood.
  - Denominator considers **global best-fit likelihood** with **floating signal strength**.
  - **Nice asymptotic properties, savings in computational power.**

Breaking down uncertainties

- Nuisances grouped into **stat, theo, other.**
  - **stat** includes $H \to \gamma\gamma$ background parameters.
  - **theo** includes QCD scales, PDF+α_s, UEPS, and BR.
  - **syst** = **theo** $\cup$ **other.**
- Procedures:
  - For (**stat**)+(**syst**):
    - σ_{all} from scan floating all nuisances.
    - σ_{stat} from scan floating **stat** group only.
    - $\sigma_{syst} = \sigma_{all} \ominus \sigma_{stat}$.
  - For (**stat**)+(**theo**)+(**other**)
    - σ_{all} from scan floating all nuisances.
    - σ_{stat} from scan floating **stat** group only.
    - $\sigma_{stat+other}$ from scan floating **stat** and **other.**
    - $\sigma_{theo} = \sigma_{all} \ominus \sigma_{stat+other}$.
    - $\sigma_{other} = \sigma_{all} \ominus \sigma_{stat} \ominus \sigma_{theo}$.

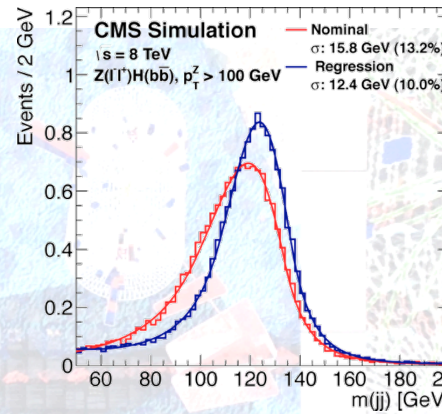
Analyses vignettes

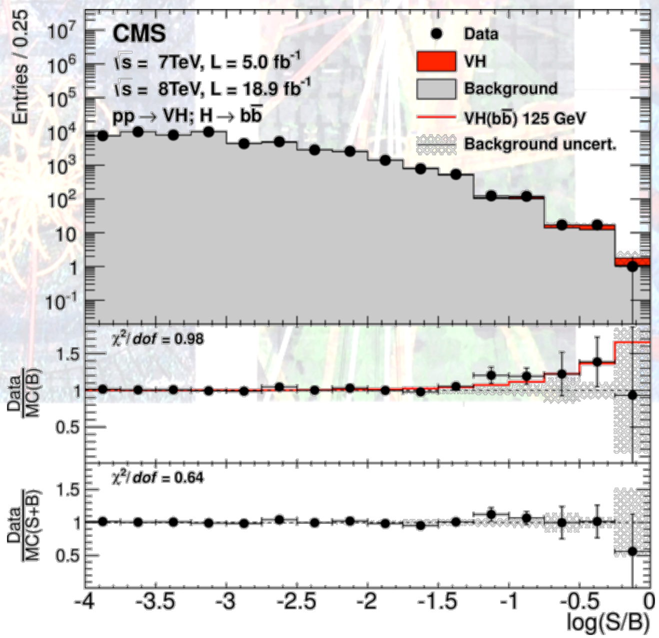
VH, H→b$\bar{b}$ vignettes

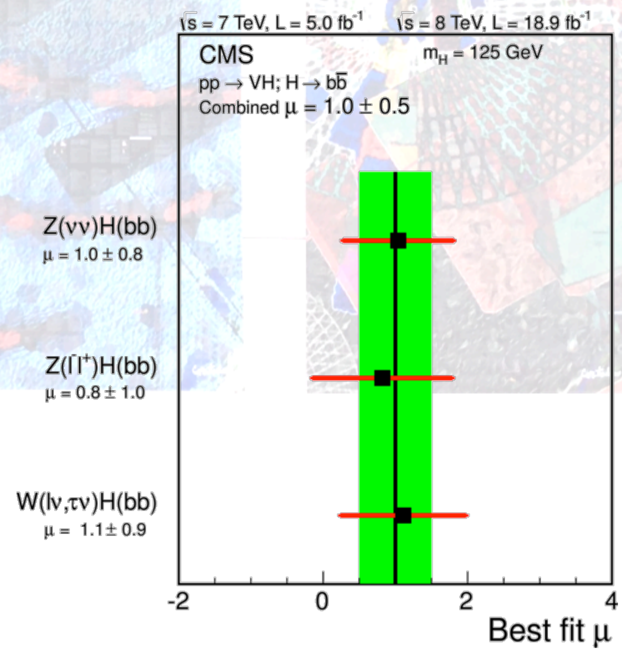
 [PRD 89 (2014) 012003]

- 2.1σ (2.3σ exp.)
- σ/σ_{SM} = 1.0 ±0.5

PRD 89 (2014) 012003

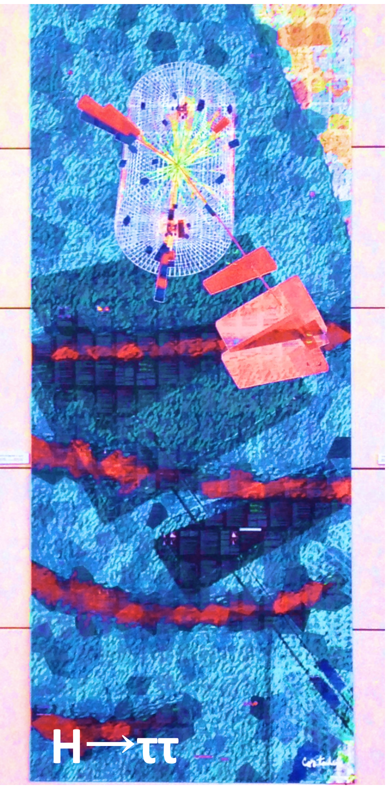






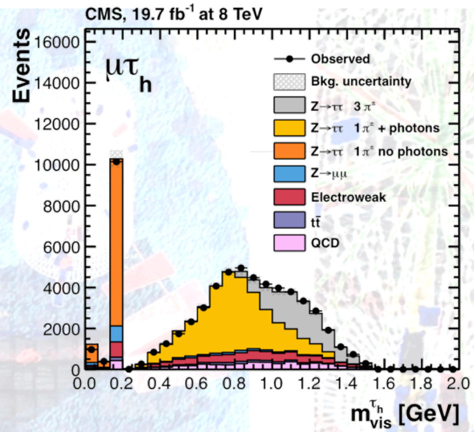
H→ττ vignettes

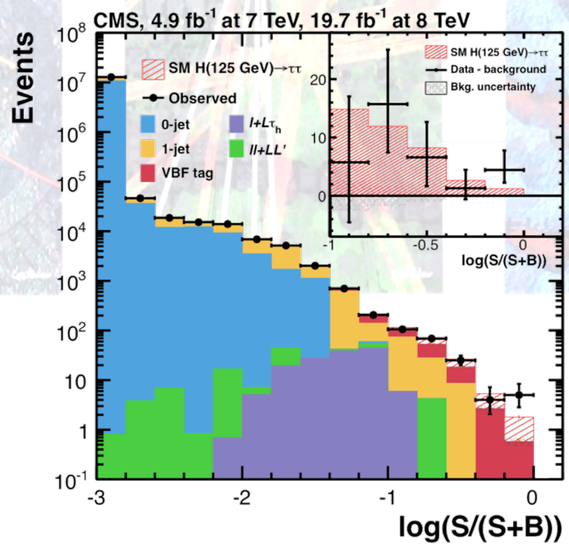
[JHEP 05 (2014) 104]

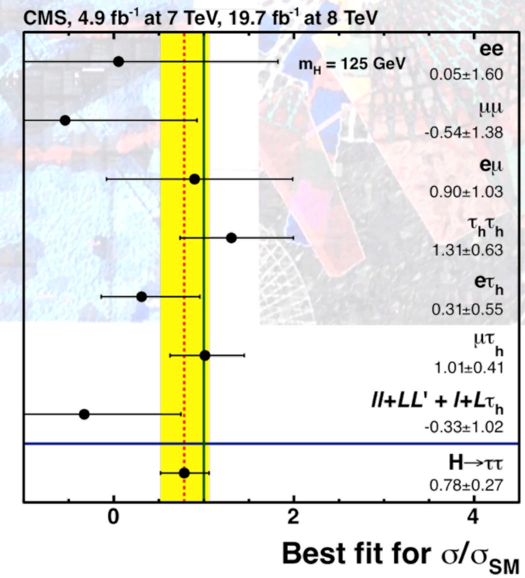


JHEP 05 (2014) 104

- 3.2σ (3.7σ exp.)
- $\sigma/\sigma_{SM} = 0.78 \pm 0.27$

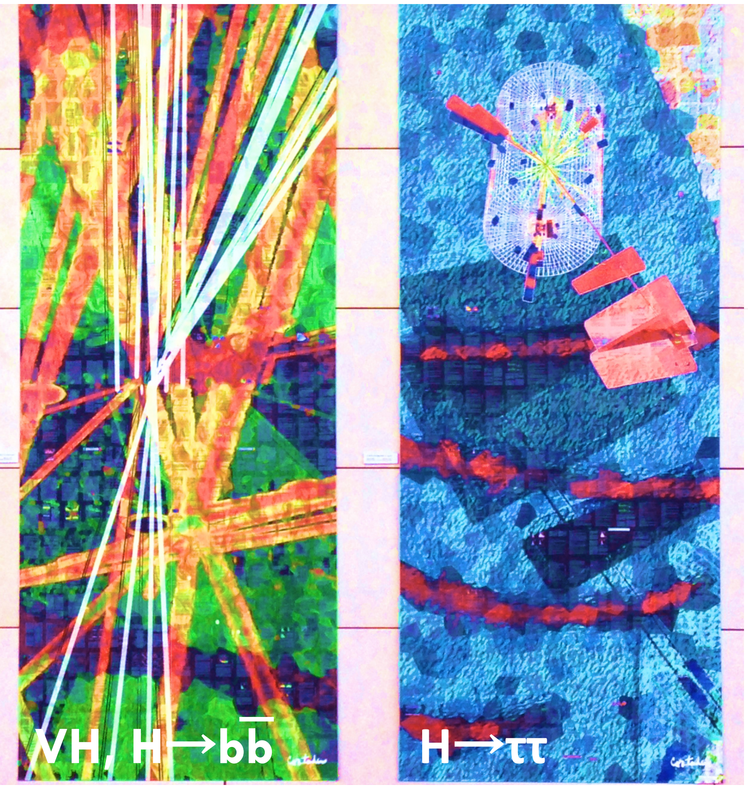






Fermion decay combination vignette

[Nature Physics, doi:10/1038/nphys3005]



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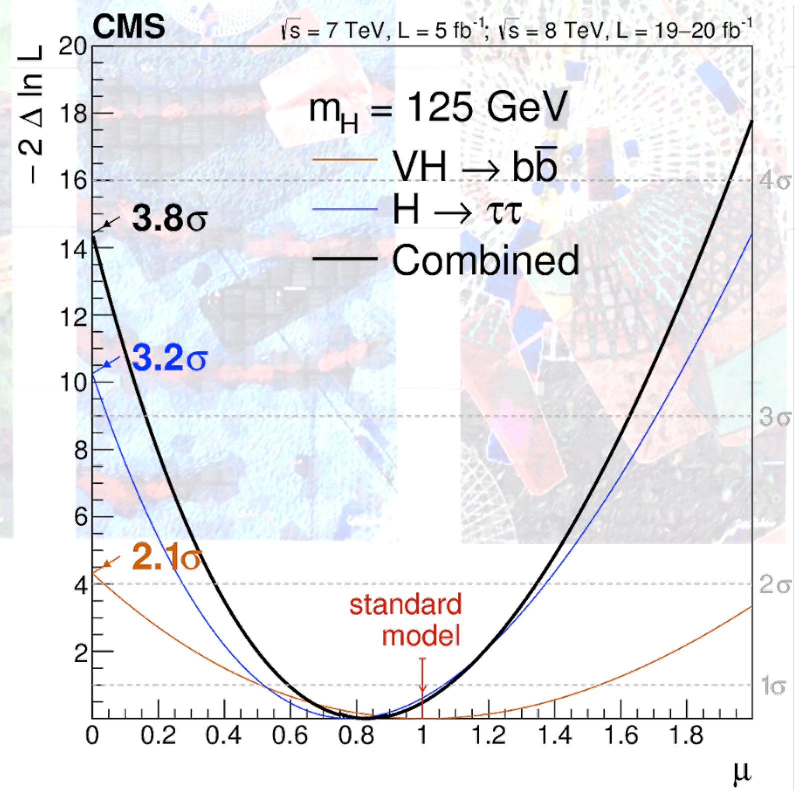
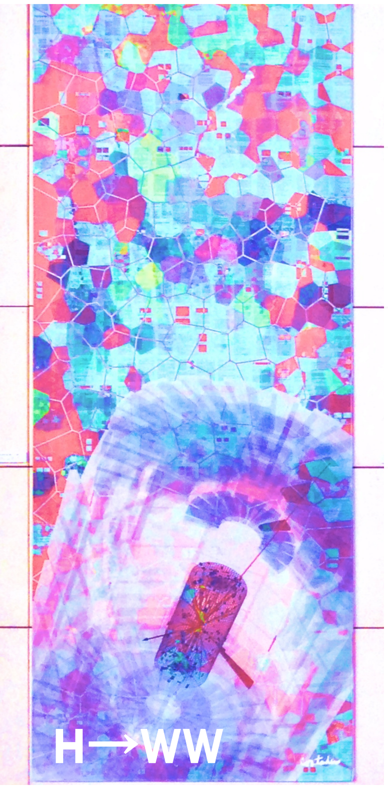
- 3.8σ (4.4σ exp.)
- $\sigma/\sigma_{SM} = 0.83 \pm 0.24$



Fermion decay combination
Nature Physics, doi:10.1038/nphys3005

H→WW vignettes

[JHEP 01 (2014) 096]



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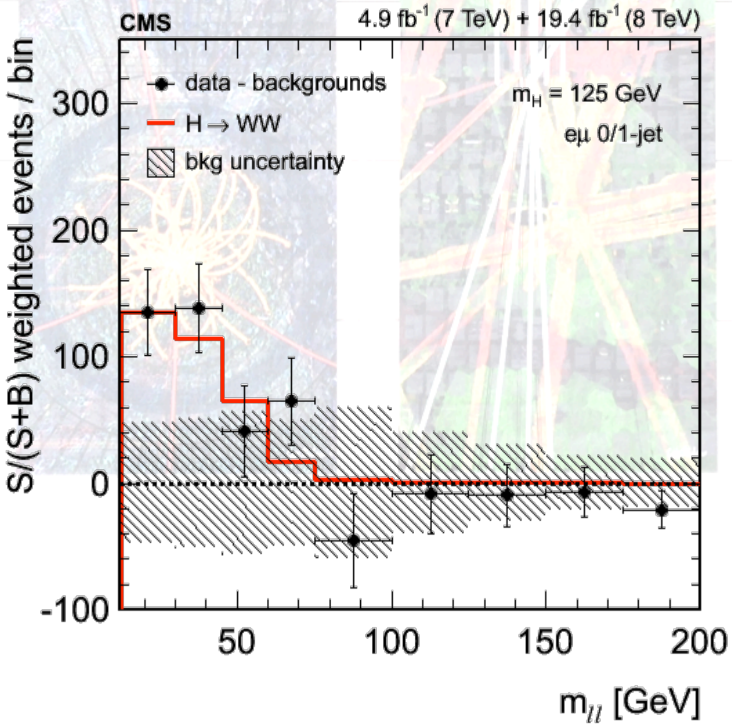
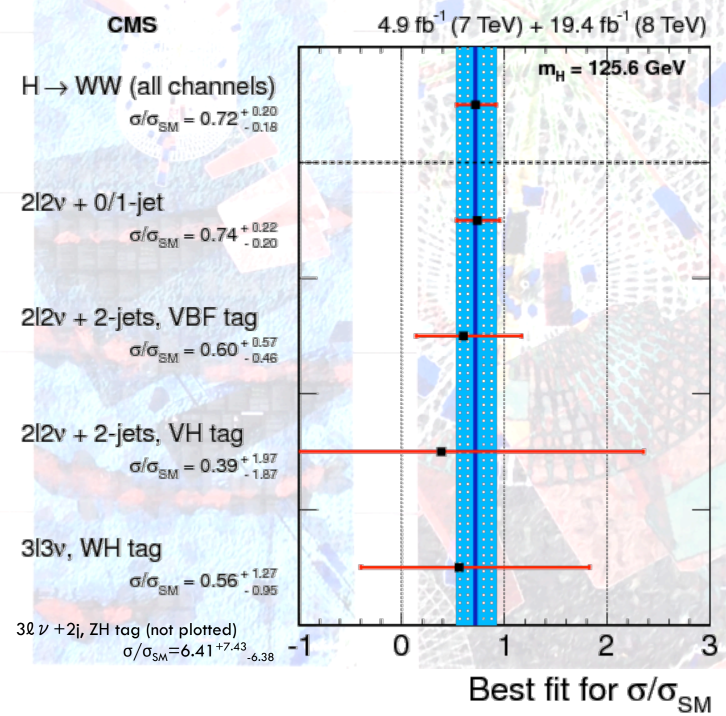
- 4.3σ (5.8σ exp.)
- $\sigma/\sigma_{SM} = 0.72 \pm 0.19$

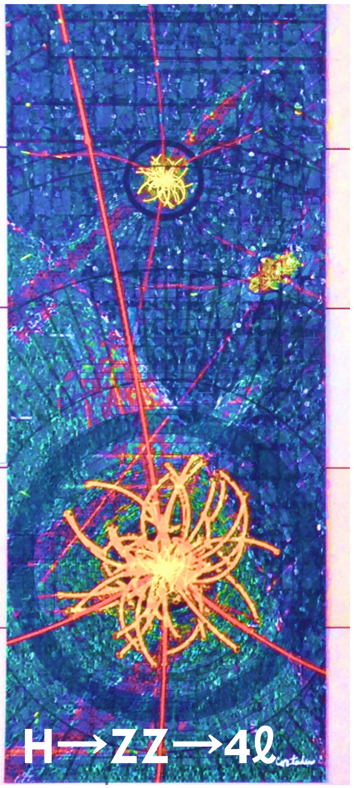




H→ZZ→4ℓ vignettes

 [PRD 89 (2014) 092007]

- 6.8σ (6.7σ exp.)
- m_H= 125.6 ± 0.4 (stat.) ± 0.2 (syst.) GeV
- σ/σ_{SM} = 0.93 ±0.25 (stat.) ±0.13 (syst.)



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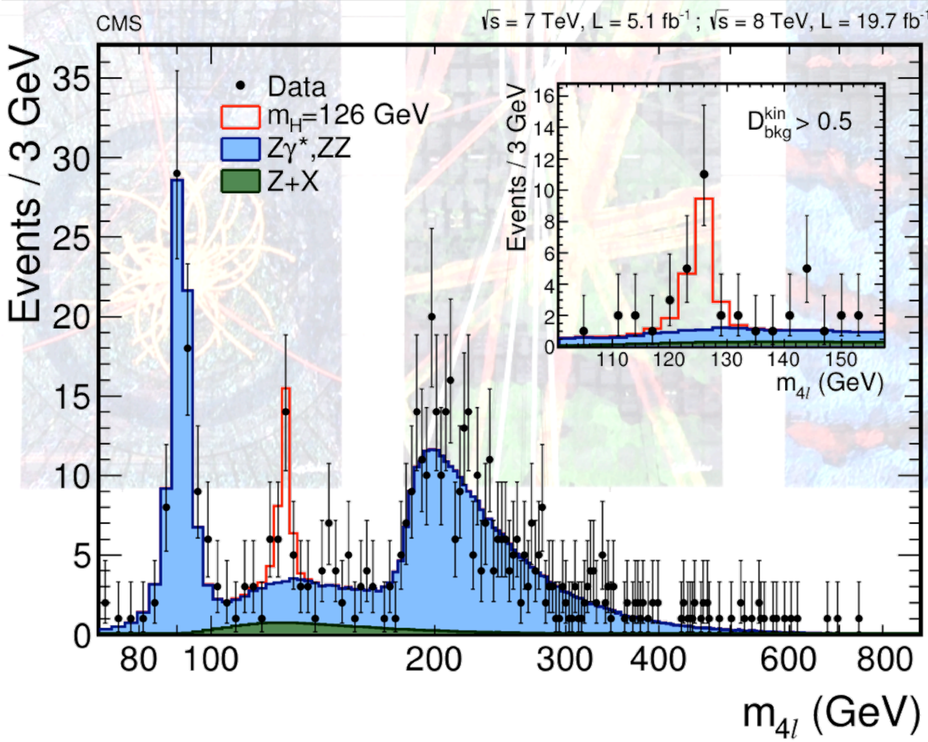

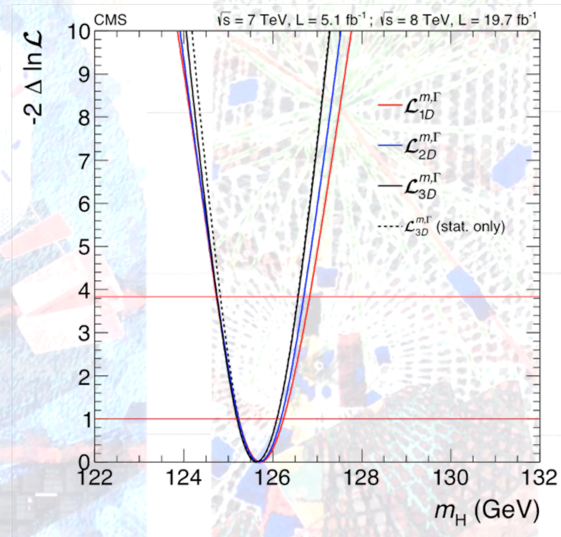

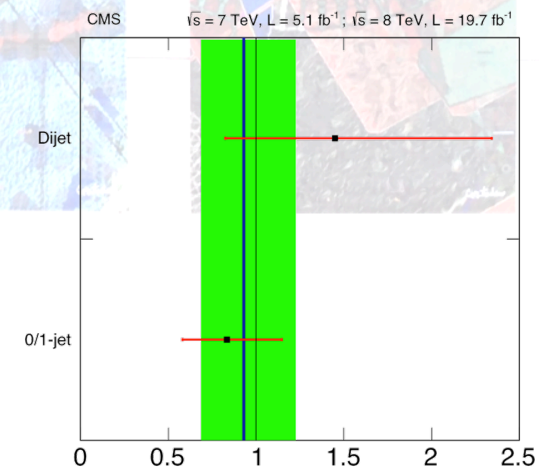

EFT questions

EFT questions

- $|\text{dim-4} + \text{dim-6} + \text{dim-8} + \ldots|^2 =$
  $= \mathbf{d4^2} + \text{d4}\times\text{d6}$ $(+\ \text{d6}^2 + \text{d4}\times\text{d8})$ $(+\ \text{d8}^2 + \text{d6}\times\text{d8}) + \ldots$
  - Weeding of the negligible, keeping of the sizable.
- Delicate choices because of:
  - Tails of large q values where dim-8 may not be so small.
  - Where there is no dim-6 tree contribution, dim-8 is leading.
- And let's not forget interferences.
  - Backgrounds are also physics processes.

EFT questions

- From 2499 dim-6 operators to 59/76 operators.
  - Symmetries guide culling:
    - Flavour, ~custodial, CP
    - Each assumption must come with **test** measurements/ observables.

- But down from ~60 should be guided by experimental sensitivity and consistently:
  - include LEP, Tevatron, etc experimental constraints.
  - bridge with aTGC/aQGC searches.