HIGGS COUPLINGS : AN EXPERIMENTAL VIEW

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The flavor of Higgs

23-26 June 2014

Weizmann Institute of Science

Europe/Zurich timezone

The distinctive taste [of this Higgs]

flavor | ˈflāvər | (Brit.**flavour**)

noun

1 the distinctive taste of a food or drink: *the yogurt comes in eight fruit flavors | adding sun-dried tomatoes gives the sauce extra flavor.*

• the general quality of taste in a food: *no other cracker adds so much flavor to the cheese.*

• a substance used to alter or enhance the taste of food or drink; a flavoring: *we use vanilla and almond flavors.*

2 [in sing.] an indication of the essential character of something: *the extracts give* ***a flavor of*** *the content and tone of the conversation.*

• [in sing.] a distinctive quality or atmosphere: *whitewashed walls and red pantiles gave the resort a Mediterranean flavor.*

3 a kind, variety, or sort: *various flavors of firewall are evolving.*

4 Physics a quantized property of quarks that differentiates them into at least six varieties (up, down, charmed, strange, top, bottom). Compare with COLOR.

degustation

The ~~flavor~~ of Higgs

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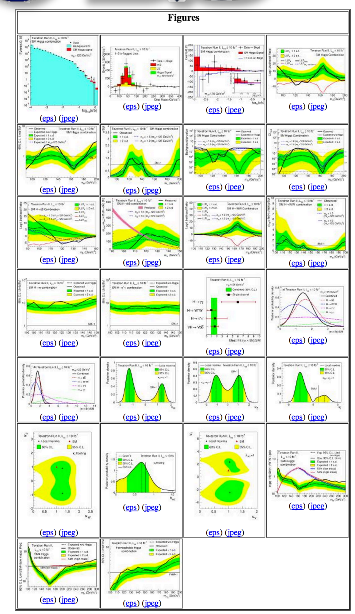
(self-inflicted) Mission: impossible

CDF DØ



ATLAS

Channel	Conference note	L	Date
Charged Higgs tau nu + jets	ATLAS-CONF-2013-090	20 fb-1	27/09/2013
High Mass WW(lvlv)	ATLAS-CONF-2013-067	21 fb-1	18/07/2013
Higgs to Diphoton differential cross sections	ATLAS-CONF-2013-072	21 fb-1	18/07/2013
Higgs in VH(WW)	ATLAS-CONF-2013-075	25 fb-1	18/07/2013
Higgs in VH(bb)	ATLAS-CONF-2013-079	25 fb-1	18/07/2013
ttH (diphoton)	ATLAS-CONF-2013-080	20 fb-1	25/07/2013
FCNC top to Higgs (diphoton) Charm	ATLAS-CONF-2013-081	25 fb-1	25/07/2013

Channel	Conference note	L	Date
Spin Combination	ATLAS-CONF-2013-040	up to 25 fb-1	[illegible]
Couplings Combination	ATLAS-CONF-2013-034	[illegible]	[illegible]
Higgs to Diphoton spin	ATLAS-CONF-2013-029	[illegible]	[illegible]
Higgs to WW(lvlv) spin	ATLAS-CONF-2013-031	2[illegible]	11/03/2013
Higgs to WW(lvlv)	ATLAS-CONF-2013-030	25 fb-1	11/03/2013
2HDM WW(lvlv)	ATLAS-CONF-2013-027	13 fb-1	11/03/2013
Combined of Mass	ATLAS-CONF-2013-014	up to 25 fb-1	05/03/2013
Higgs to Diphoton	ATLAS-CONF-2013-012	25 fb-1	05/03/2013
Higgs to 4 leptons	ATLAS-CONF-2013-013	25 fb-1	05/03/2013
ZH (invisible decays)	ATLAS-CONF-2013-011	18 fb-1	05/03/2013
Higgs to dimuon	ATLAS-CONF-2013-010	21 fb-1	05/03/2013
Higgs to Zgamma	ATLAS-CONF-2013-009	25 fb-1	05/03/2013

CMS

Oct-2013	Z(bb)H, H -> invisible	TWiki, PAS
Oct-2013	SM H -> mumu	TWiki, PAS
Oct-2013	ttH Combination	TWiki
Sep-2013	Full 8 TeV dataset: ttH, H -> multi-leptons	TWiki, PAS
Aug-2013	Full 8 TeV dataset: VBF H -> invisible	TWiki, PAS
Aug-2013	Full 7+8 TeV dataset: VBF H -> WW	TWiki, PAS
Jul-2013	Full 8 TeV dataset: ttH, H -> bb or tautau	TWiki, PAS
Jul-2013	Fu[illegible] dataset: H -> ZZ -> 2l2j	TWiki, PAS
Jul-20[illegible]	[illegible]ataset: h -> 2a + X -> 4mu + X	TWiki, PAS
[illegible]	[illegible]dataset: VH, H -> invisible	TWiki, PAS
[illegible]	[illegible]eV dataset: VH, H -> WW(2l2nu) + V -> jj	TWiki, PAS
[illegible]	[illegible]ull 7+8 TeV dataset: Higgs properties from H -> gamma gamma	TWiki, PAS

+ recent updates

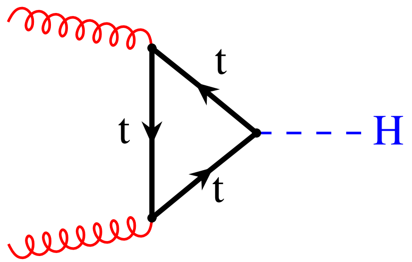
May-2013	Full 8 TeV dataset: VBF H, H -> bb	TWiki, PAS
May-2013	Full 8 TeV dataset: ttH, H -> gamma gamma	TWiki, PAS
May-2013	Full 7+8 TeV dataset: VH, H -> bb	TWiki, PAS
May-2013	Full 8 TeV dataset: H -> WW -> lnuJ	TWiki, PAS
May-2013	Full 7+8 TeV dataset: H -> ZZ -> 2l2nu	TWiki, PAS
Apr-2013	Moriond Higgs Combination	TWiki, PAS
Mar-2013	Full 7+8 TeV dataset: H -> gamma gamma	TWiki, PAS
Mar-2013	Full 7+8 TeV dataset: H -> ZZ -> 4l	TWiki, PAS
Mar-2013	Full 7+8 TeV dataset: H -> WW -> 2l2nu	TWiki, PAS
Mar-2013	Full 7+8 TeV dataset: H -> tau tau	TWiki, PAS
Mar-2013	Full 7+8 TeV dataset: H -> Z gamma	TWiki, PAS
Mar-2013	Full 7+8 TeV dataset: H -> WWW -> 3l3nu	TWiki, PAS
Mar-2013	Full 7+8 TeV dataset: VH -> tau tau	TWiki, PAS

- Present a coherent view of present-day results of Higgs couplings from the LHC and Tevatron experiments.
  - Any omission or mistake are the speaker's fault (send email).

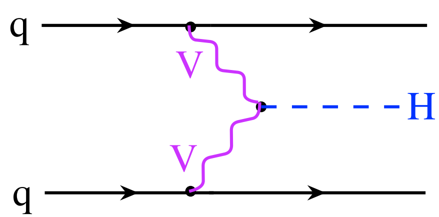
How SM Higgses are born

[http://cern.ch/go/cWH8] [http://cern.ch/go/SnJ8]

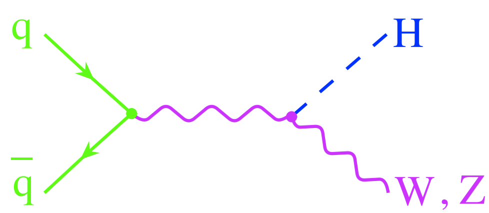
- **Gluon fusion**



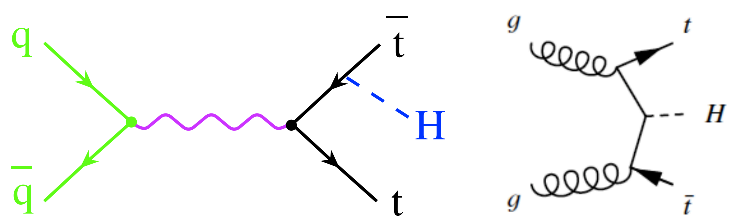
- **VBF**

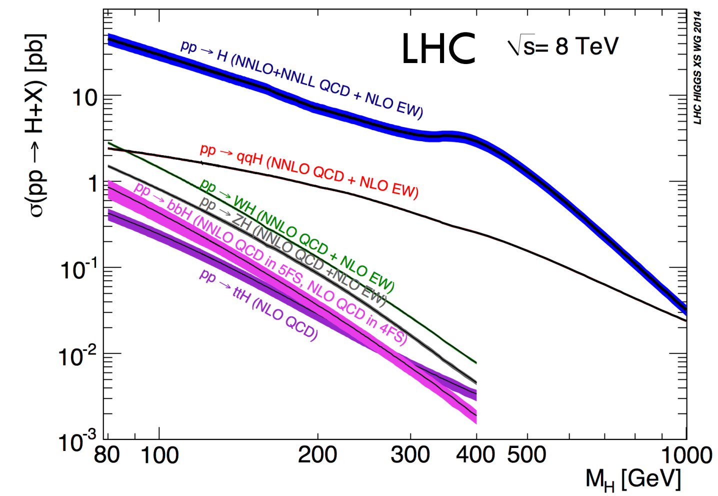


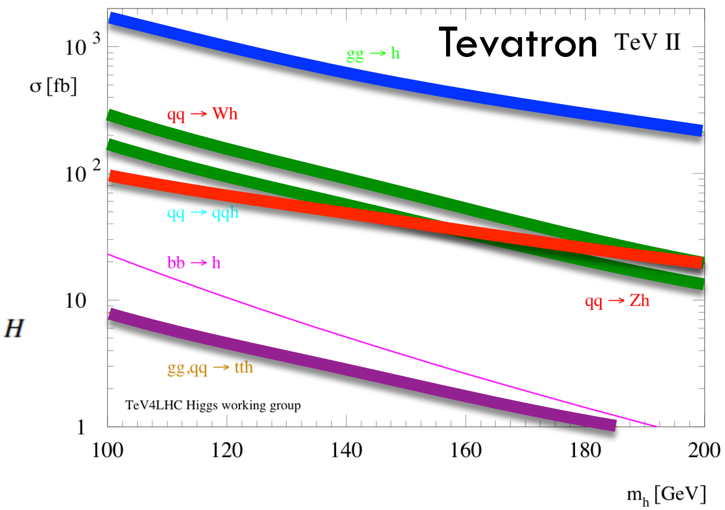
- **WH, ZH**



- **bbH, ttH**



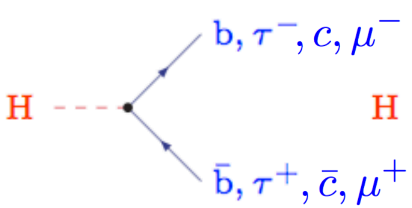


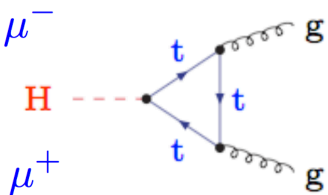


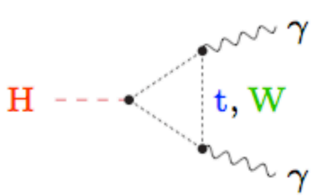
How SM Higgses die

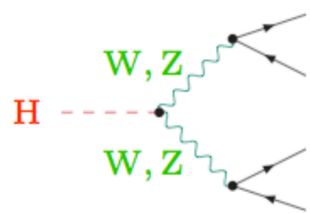
[http://cern.ch/go/qkh6] [arXiv:1208.1993]

- Couplings and kinematics drive BR ($b\bar{b}$, WW, $\tau\ \tau$, ZZ).
  - Decays with photons ($\gamma\ \gamma$, $Z\gamma$) through loops.

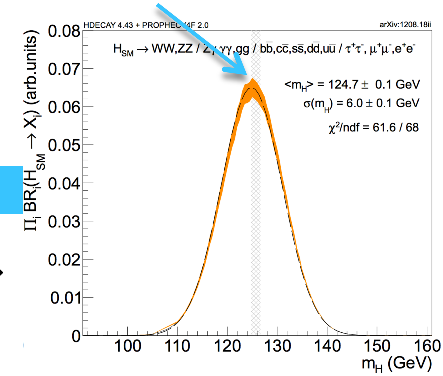


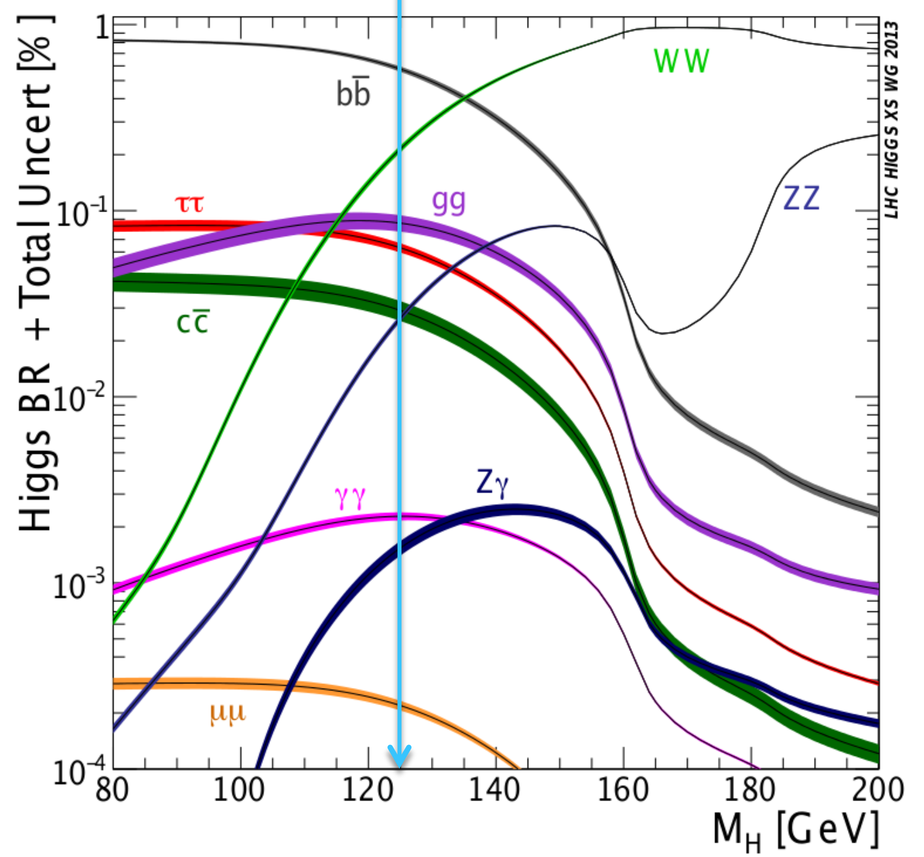






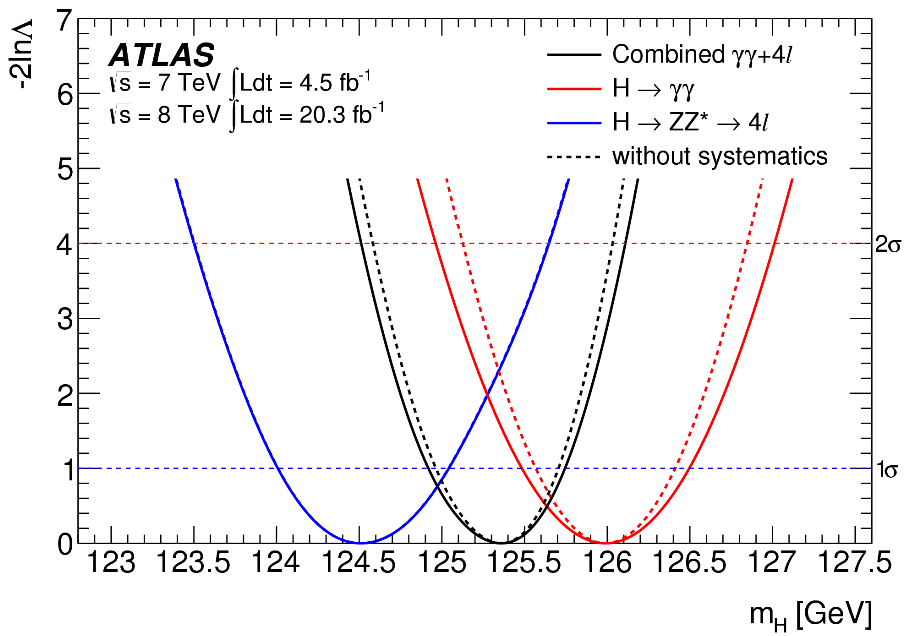
Near to maximal ΠBR_i $\longrightarrow$

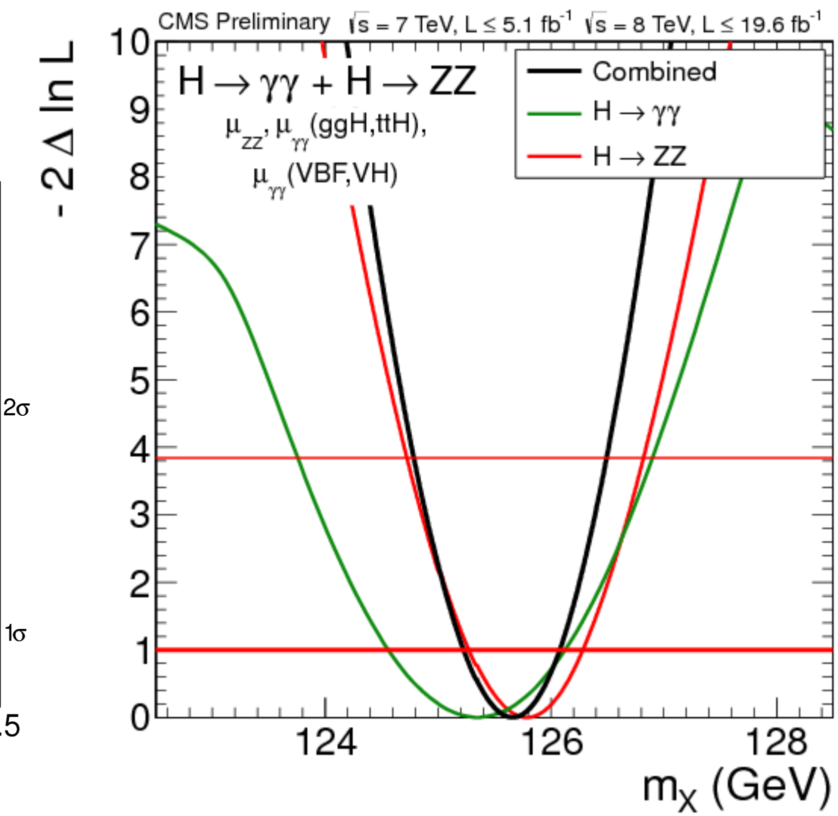




First things first: the mass

[arXiv:1406.3827] [CMS-PAS-HIG-13-005]

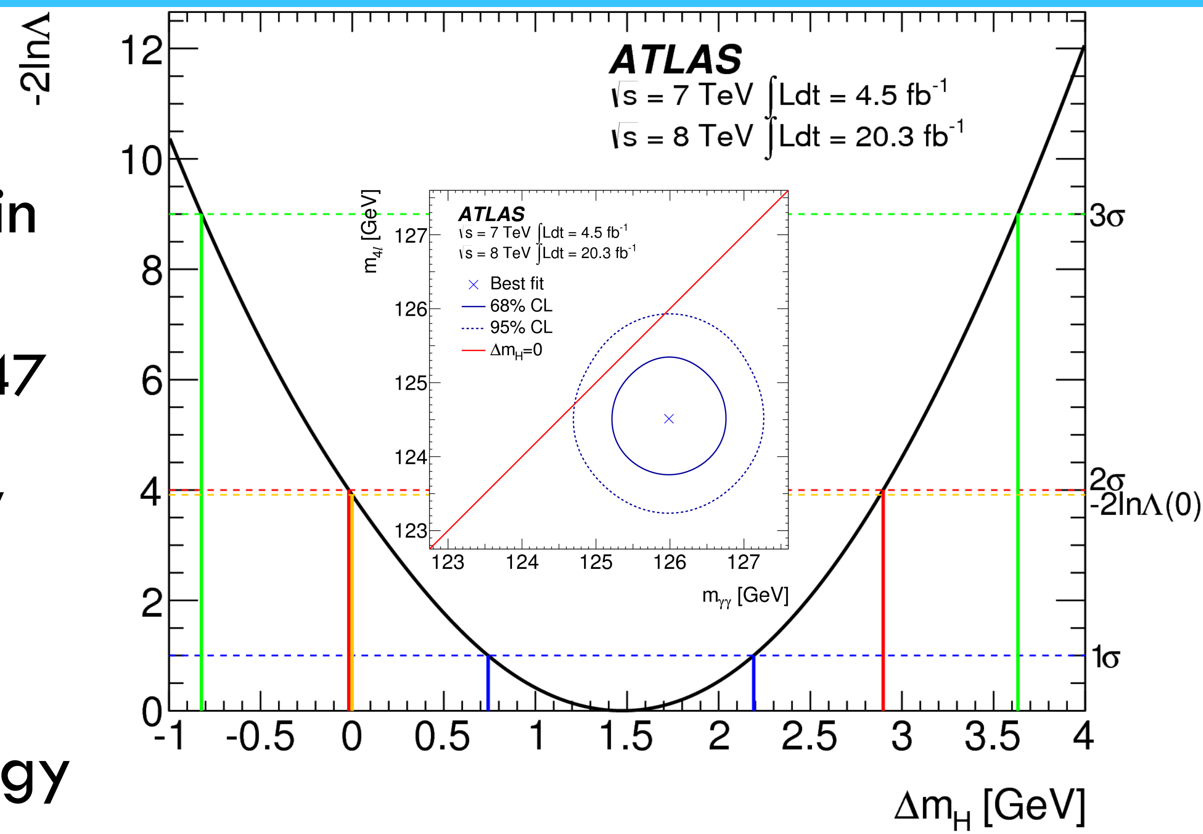




	ATLAS	CMS
m_X	125.36 ±0.37(stat.) ±0.18(syst.) GeV	125.7 ±0.3 (stat.) ±0.3 (syst.) GeV
Naïve average: 125.5 ±0.3 GeV		

More on ATLAS mass

- Slight difference in ATLAS results:
  - $m_H^{\gamma\gamma} - m_H^{ZZ} = 1.47 \pm 0.67(\text{stat.}) \pm 0.28(\text{syst.})$ GeV
  - 1.97σ (p=4.9%).
- Using more conservative energy scale uncertainties: **1.8σ (p=7.5%).**



Oversimplified big picture

T – Tevatron; A – ATLAS; C – CMS; combination drivers in red.

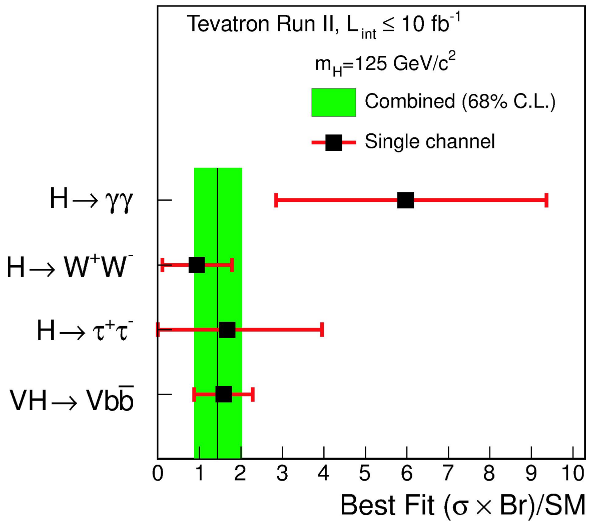
★ "seen" ☆ "tried" - "impossible"	H→bb̄			H→ττ			H→WW			H→ZZ			H→γγ			H→Zγ			H→inv.			H→μμ			H→cc̄ H→HH		
	T	A	C	T	A	C	T	A	C	T	A	C	T	A	C	T	A	C	T	A	C	T	A	C	T	A	C
ggH	-	-	-	☆	★	★	☆	★	★	☆	★	★	☆	★	★	-	☆	☆				-	☆	☆	-		
VBF			☆	☆	★	★		★	★		★	☆		★	☆	-		☆			☆	-		☆	-		
VH	★	☆	★	☆		☆	☆	☆	☆		☆	☆		☆	☆	-				☆	☆	-			-		
tt̄H		☆	☆	☆		☆	☆							☆	☆	-						-			-		

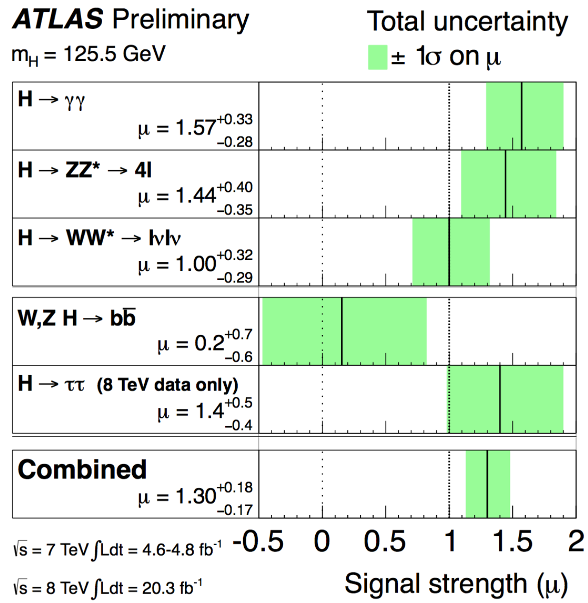
- **Still much to explore on the rarer ends.**

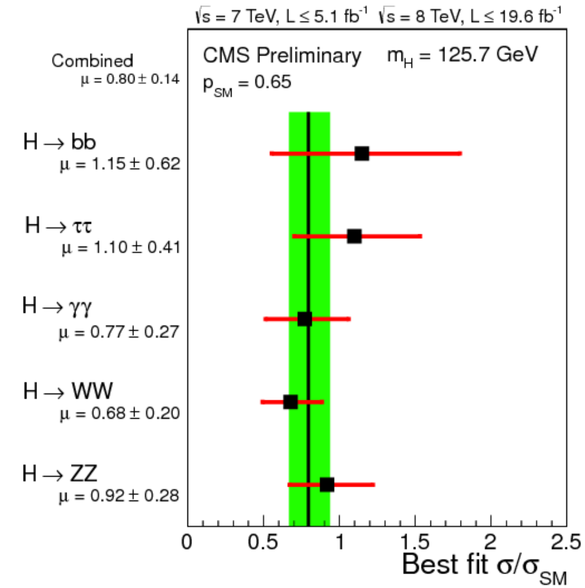
  (to the right and to the bottom) (and outside this picture)

Relative signal strengths

[arXiv:1303.6346] [ATLAS-CONF-2014-009] [CMS-PAS-HIG-13-005]



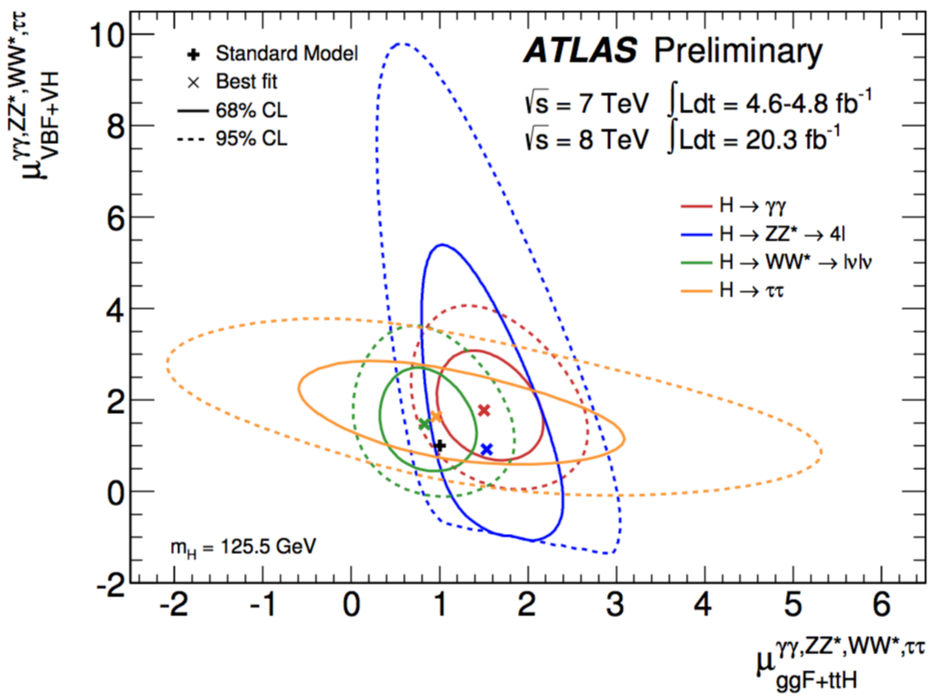


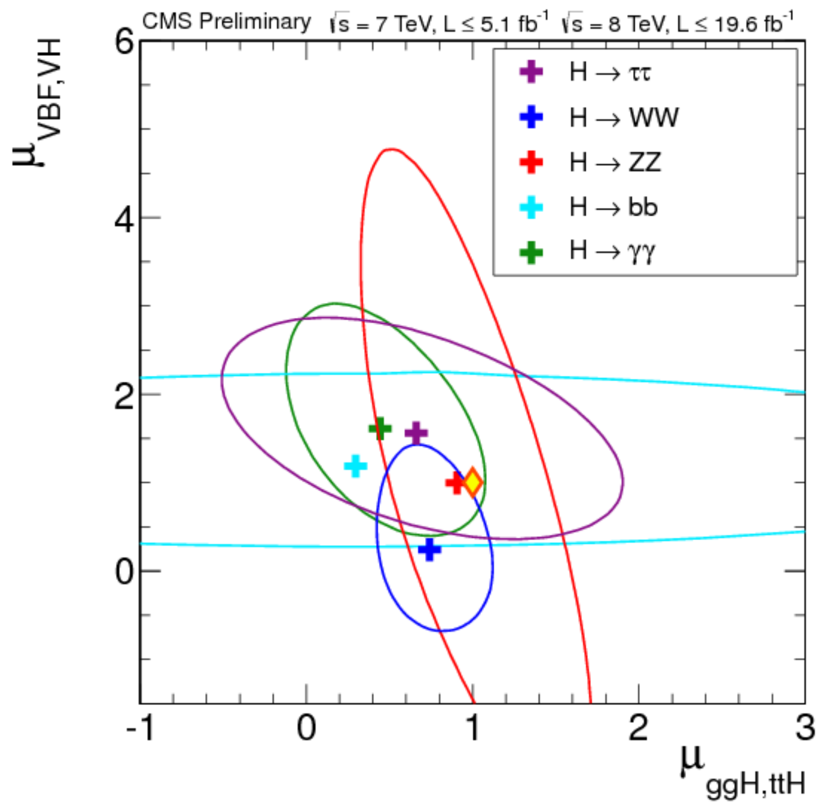


	Tevatron	ATLAS	CMS
m_H	125 GeV	125.5 GeV	125.7 GeV
$\mu = \sigma/\sigma_{SM}$	$1.44^{+0.59}_{-0.56}$	1.30 ±0.18	0.80 ±0.14
Naïve average: 0.98 ±0.11			

Production mechanisms

[ATLAS-CONF-2014-009] [CMS-PAS-HIG-13-005]

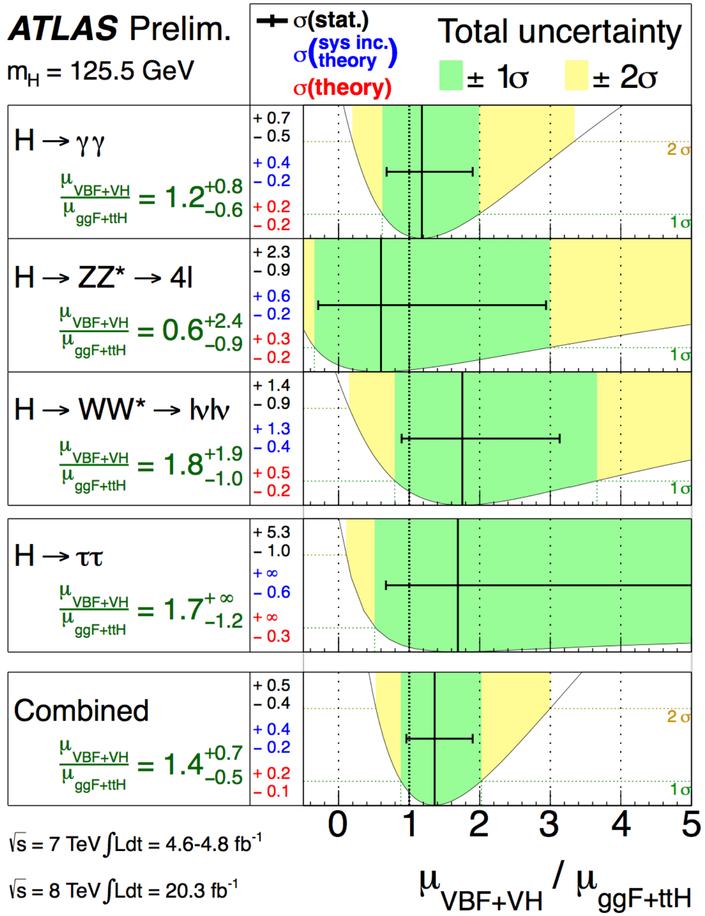


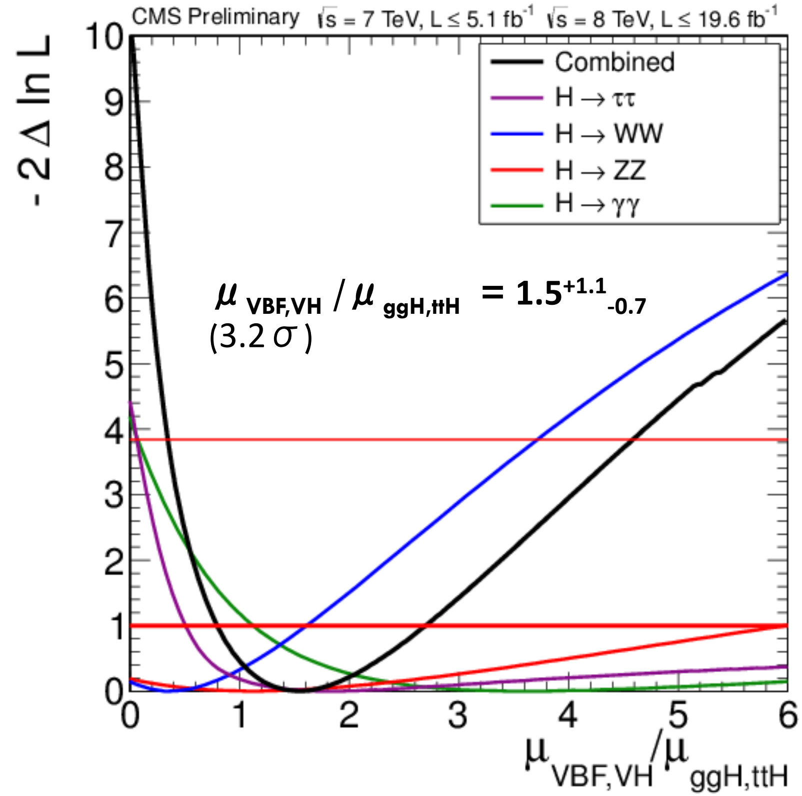


- Scale fermion-mediated (ggH & ttH) and vector-boson-mediated (VBF & VH) together.

Production mechanisms

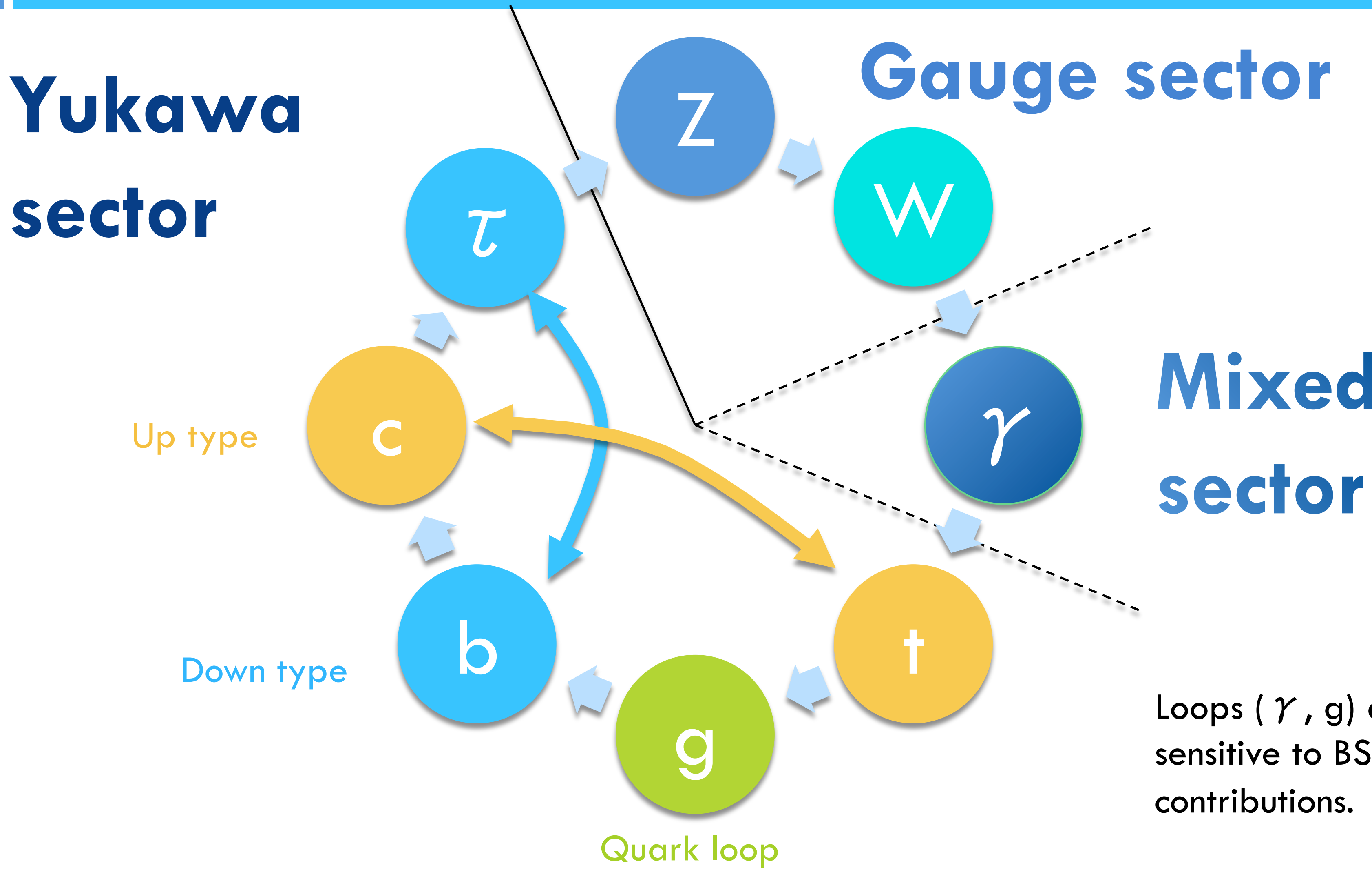
[ATLAS-CONF-2014-009] [CMS-PAS-HIG-13-005]





- Ratio of production scaling factors does not depend on decay mode.
  - **> 3σ evidence for $\mu_{VBF,VH} / \mu_{ggH,ttH}$ > 0 in both experiments.**

Scalar coupling structure



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

Couplings deviations

[arXiv:1209.0040]

Production modes

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

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

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

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

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

Detectable decay modes

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

$$\frac{\Gamma_{ZZ^{(*)}}}{\Gamma_{ZZ^{(*)}}^{SM}} = \kappa_Z^2$$

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

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

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

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

Currently undetectable decay modes

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

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

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

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

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

Total width

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

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

Couplings deviations

[arXiv:1209.0040]

Production modes

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

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

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

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

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

Detectable decay modes

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

$$\frac{\Gamma_{ZZ^{(*)}}}{\Gamma_{ZZ^{(*)}}^{SM}} = \kappa_Z^2$$

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

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

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

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

Currently undetectable decay modes

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

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

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

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

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

Total width

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

- Contributions resolved at NLO QCD and LO EWK.
- Peg the as-of-yet unmeasured to "closest of kin".

Couplings deviations

[arXiv:1209.0040]

Production modes

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

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

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

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

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

Detectable decay modes

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

$$\frac{\Gamma_{ZZ^{(*)}}}{\Gamma_{ZZ^{(*)}}^{SM}} = \kappa_Z^2$$

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

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

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

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

Currently undetectable decay modes

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

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

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

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

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

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 other κ .
- Total width scaled as free parameter.

Probing custodial symmetry

[arXiv:1209.0040]

Probing custodial symmetry assuming no invisible or undetectable widths

Free parameters: κ_Z, $\lambda_{WZ}(=\kappa_W/\kappa_Z)$, $\kappa_f(=\kappa_t=\kappa_b=\kappa_\tau)$.

	$H\to\gamma\gamma$	$H\to ZZ^{(*)}$	$H\to WW^{(*)}$	$H\to b\bar{b}$	$H\to\tau^-\tau^+$
ggH $t\bar{t}H$	$\frac{\kappa_f^2\cdot\kappa_\gamma^2(\kappa_f,\kappa_f,\kappa_f,\kappa_Z\lambda_{WZ})}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_f^2\cdot\kappa_Z^2}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_f^2\cdot(\kappa_Z\lambda_{WZ})^2}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_f^2\cdot\kappa_f^2}{\kappa_H^2(\kappa_i)}$	
VBF	$\frac{\kappa_{VBF}^2(\kappa_Z,\kappa_Z\lambda_{WZ})\cdot\kappa_\gamma^2(\kappa_f,\kappa_f,\kappa_f,\kappa_Z\lambda_{WZ})}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_{VBF}^2(\kappa_Z,\kappa_Z\lambda_{WZ})\cdot\kappa_Z^2}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_{VBF}^2(\kappa_Z,\kappa_Z\lambda_{WZ})\cdot(\kappa_Z\lambda_{WZ})^2}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_{VBF}^2(\kappa_Z,\kappa_Z\lambda_{WZ})\cdot\kappa_f^2}{\kappa_H^2(\kappa_i)}$	
WH	$\frac{(\kappa_Z\lambda_{WZ})^2\cdot\kappa_\gamma^2(\kappa_f,\kappa_f,\kappa_f,\kappa_Z\lambda_{WZ})}{\kappa_H^2(\kappa_i)}$	$\frac{(\kappa_Z\lambda_{WZ})^2\cdot\kappa_Z^2}{\kappa_H^2(\kappa_i)}$	$\frac{(\kappa_Z\lambda_{WZ})^2\cdot(\kappa_Z\lambda_{WZ})^2}{\kappa_H^2(\kappa_i)}$	$\frac{(\kappa_Z\lambda_{WZ})^2\cdot\kappa_f^2}{\kappa_H^2(\kappa_i)}$	
ZH	$\frac{\kappa_Z^2\cdot\kappa_\gamma^2(\kappa_f,\kappa_f,\kappa_f,\kappa_Z\lambda_{WZ})}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_Z^2\cdot\kappa_Z^2}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_Z^2\cdot(\kappa_Z\lambda_{WZ})^2}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_Z^2\cdot\kappa_f^2}{\kappa_H^2(\kappa_i)}$	

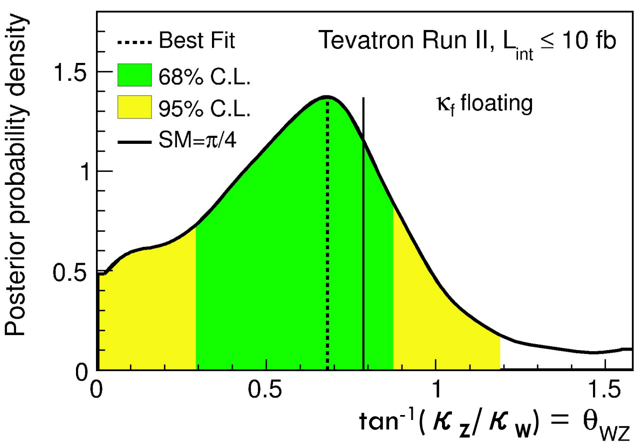
Probing custodial symmetry without assumptions on the total width

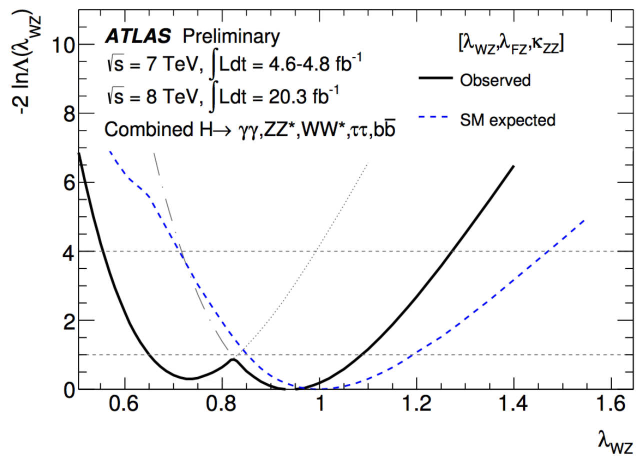
Free parameters: $\kappa_{ZZ}(=\kappa_Z\cdot\kappa_Z/\kappa_H)$, $\lambda_{WZ}(=\kappa_W/\kappa_Z)$, $\lambda_{FZ}(=\kappa_f/\kappa_Z)$.

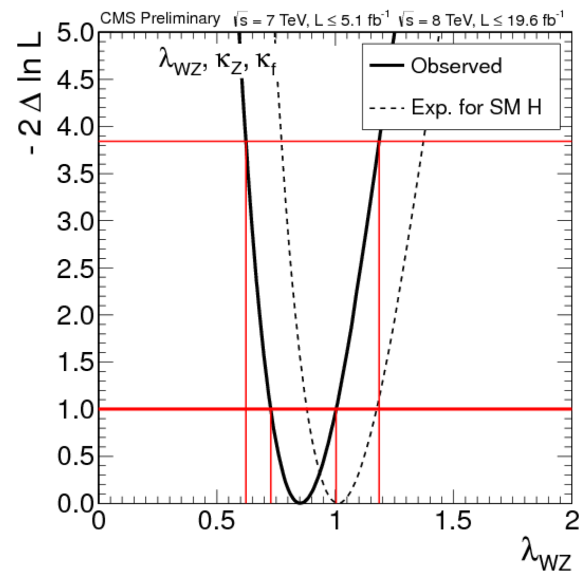
	$H\to\gamma\gamma$	$H\to ZZ^{(*)}$	$H\to WW^{(*)}$	$H\to b\bar{b}$	$H\to\tau^-\tau^+$
ggH $t\bar{t}H$	$\kappa_{ZZ}^2\lambda_{FZ}^2\cdot\kappa_\gamma^2(\lambda_{FZ},\lambda_{FZ},\lambda_{FZ},\lambda_{WZ})$	$\kappa_{ZZ}^2\lambda_{FZ}^2$	$\kappa_{ZZ}^2\lambda_{FZ}^2\cdot\lambda_{WZ}^2$	$\kappa_{ZZ}^2\lambda_{FZ}^2\cdot\lambda_{FZ}^2$	
VBF	$\kappa_{ZZ}^2\kappa_{VBF}^2(1,\lambda_{WZ}^2)\cdot\kappa_\gamma^2(\lambda_{FZ},\lambda_{FZ},\lambda_{FZ},\lambda_{WZ})$	$\kappa_{ZZ}^2\kappa_{VBF}^2(1,\lambda_{WZ}^2)$	$\kappa_{ZZ}^2\kappa_{VBF}^2(1,\lambda_{WZ}^2)\cdot\lambda_{WZ}^2$	$\kappa_{ZZ}^2\kappa_{VBF}^2(1,\lambda_{WZ}^2)\cdot\lambda_{FZ}^2$	
WH	$\kappa_{ZZ}^2\lambda_{WZ}^2\cdot\kappa_\gamma^2(\lambda_{FZ},\lambda_{FZ},\lambda_{FZ},\lambda_{WZ})$	$\kappa_{ZZ}^2\cdot\lambda_{WZ}^2$	$\kappa_{ZZ}^2\lambda_{WZ}^2\cdot\lambda_{WZ}^2$	$\kappa_{ZZ}^2\lambda_{WZ}^2\cdot\lambda_{FZ}^2$	
ZH	$\kappa_{ZZ}^2\cdot\kappa_\gamma^2(\lambda_{FZ},\lambda_{FZ},\lambda_{FZ},\lambda_{WZ})$	κ_{ZZ}^2	$\kappa_{ZZ}^2\cdot\lambda_{WZ}^2$	$\kappa_{ZZ}^2\cdot\lambda_{FZ}^2$	

Probing custodial symmetry

[arXiv:1303.6346] [ATLAS-CONF-2014-009] [CMS-PAS-HIG-13-005]







	Tevatron $[\kappa_W, \kappa_Z, \kappa_f]$	ATLAS $[\lambda_{WZ}, \lambda_{FZ}, \kappa_{ZZ}]$	CMS $[\lambda_{WZ}, \kappa_Z, \kappa_f]$
λ_{WZ}	**$1.24^{+2.34}_{-0.42}$**	**$0.94^{+0.14}_{-0.29}$**	**0.86 ± 0.13**

Weak bosons and fermions

[arXiv:1209.0040]

Boson and fermion scaling assuming no invisible or undetectable widths

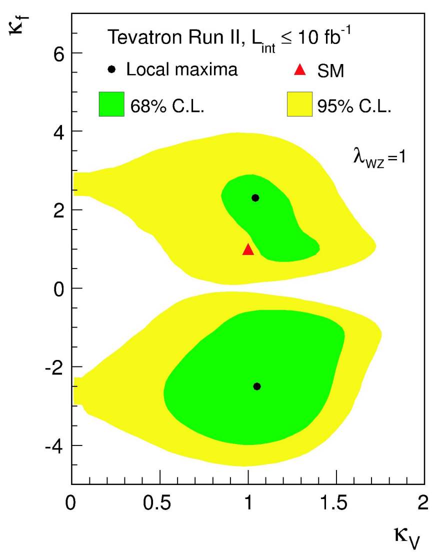
Free parameters: $\kappa_V (= \kappa_W = \kappa_Z), \kappa_f (= \kappa_t = \kappa_b = \kappa_\tau)$.

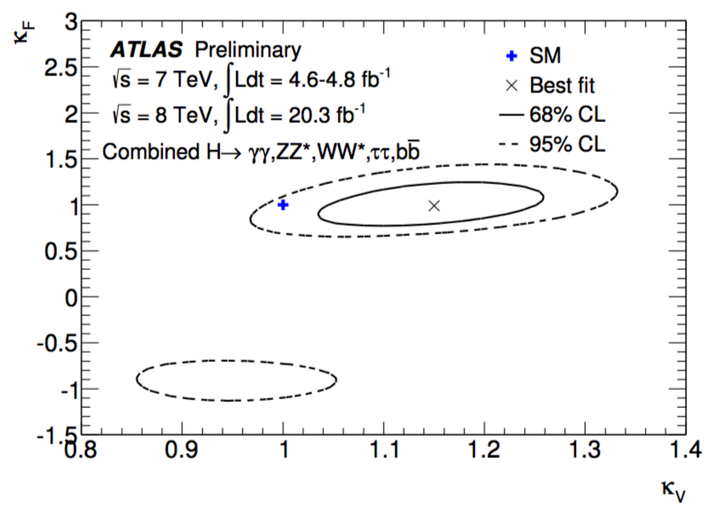
	$H \to \gamma\gamma$	$H \to ZZ^{(*)}$ / $H \to WW^{(*)}$	$H \to b\bar{b}$ / $H \to \tau^-\tau^+$
ggH $t\bar{t}H$	$\frac{\kappa_f^2 \cdot \kappa_\gamma^2(\kappa_f, \kappa_f, \kappa_f, \kappa_V)}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_f^2 \cdot \kappa_V^2}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_f^2 \cdot \kappa_f^2}{\kappa_H^2(\kappa_i)}$
VBF WH ZH	$\frac{\kappa_V^2 \cdot \kappa_\gamma^2(\kappa_f, \kappa_f, \kappa_f, \kappa_V)}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_V^2 \cdot \kappa_V^2}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_V^2 \cdot \kappa_f^2}{\kappa_H^2(\kappa_i)}$

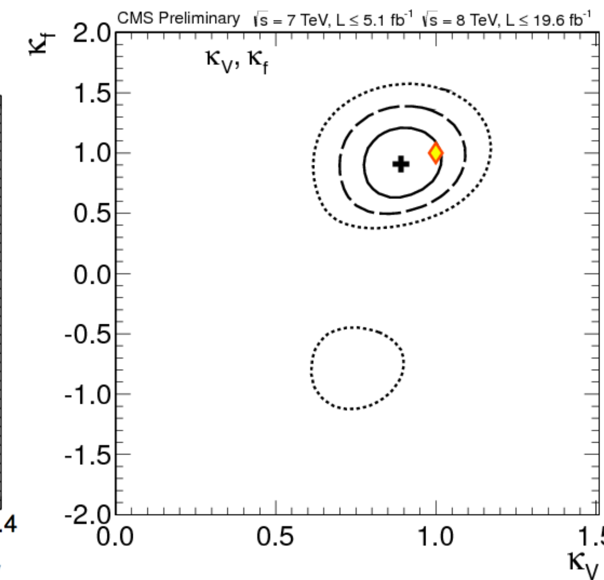
$H \to \gamma\gamma$ resolved into top-loop, b-loop, τ-loop, and W-loop.

Weak bosons and fermions

[arXiv:1303.6346] [ATLAS-CONF-2014-009] [CMS-PAS-HIG-13-005]



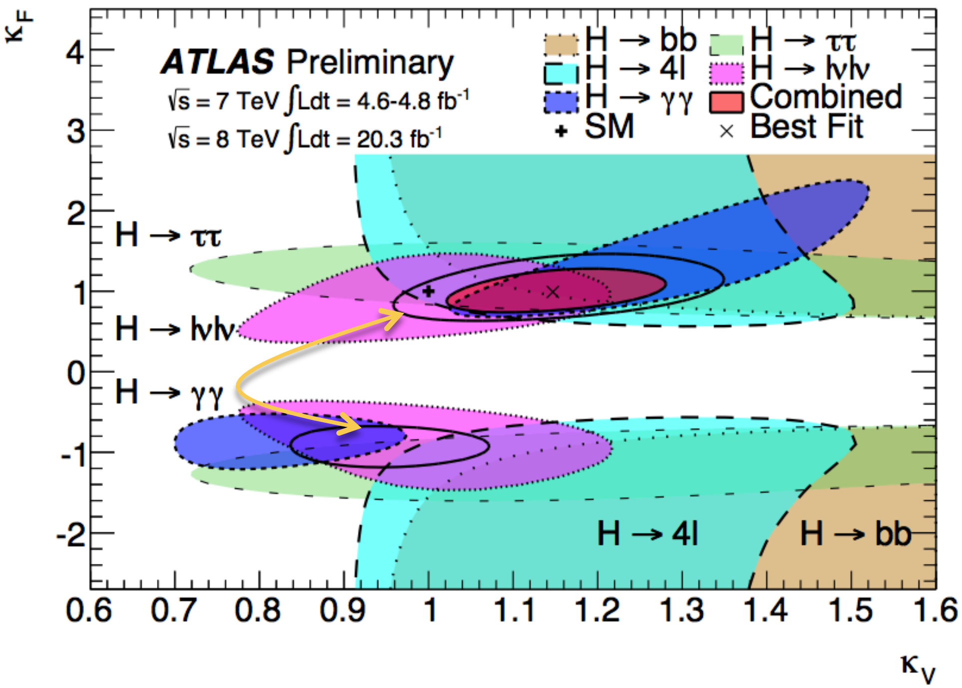


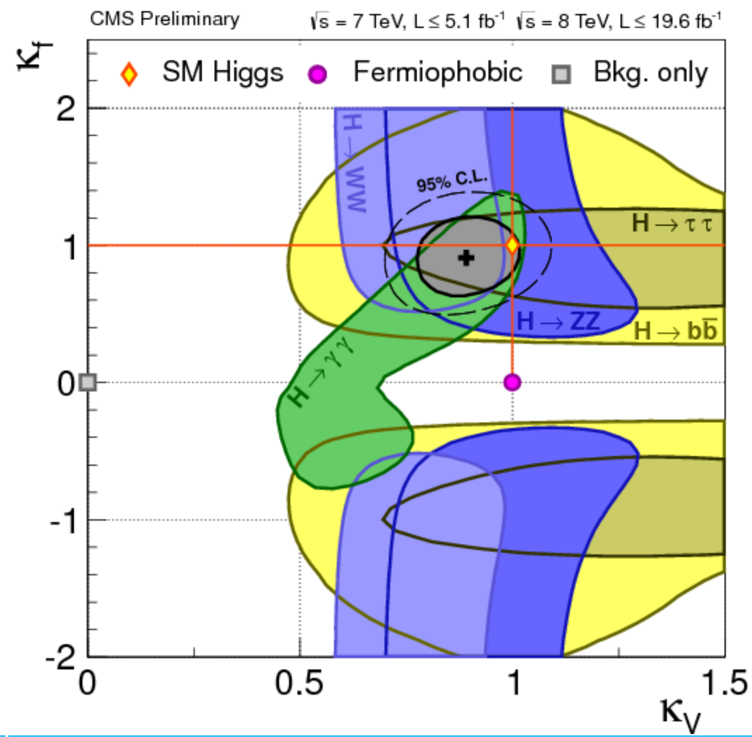


	Tevatron	ATLAS	CMS
p(SM)	-	10%	< 1 σ

Weak bosons and fermions

[ATLAS-CONF-2014-009] [CMS-PAS-HIG-13-005]





	ATLAS	CMS
P(SM)	**10%**	**< 1 σ**

Composite (R.Contino)

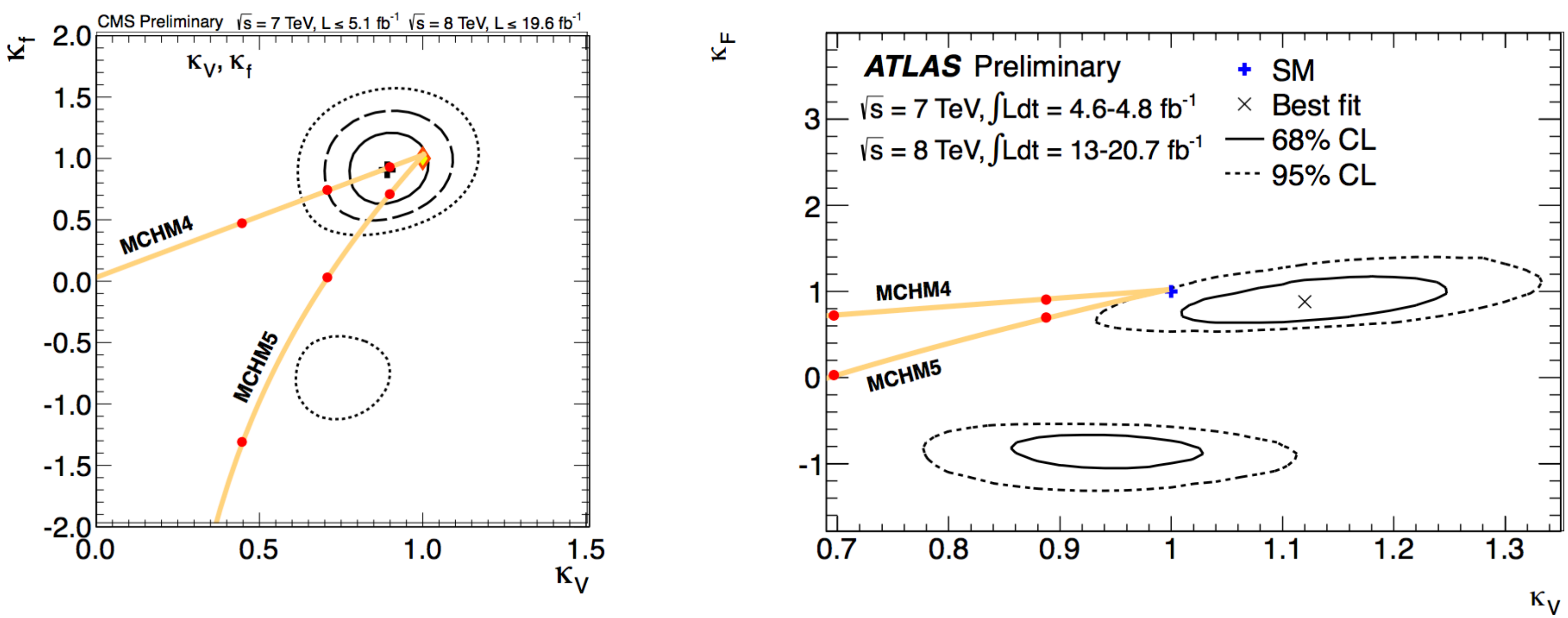
[http://cern.ch/go/W96V]

- Leading effects in tree-level couplings and Zγ rate

$$c_V, c_u, c_d = 1 + O\left(\frac{v^2}{f^2}\right) \qquad \frac{\Gamma(h \to Z\gamma)}{\Gamma_{SM}} = 1 + O\left(\frac{v^2}{f^2}\right)$$

f = Higgs decay constant

$$m_{\text{new}} = g_* f \lesssim 4\pi f$$



Red points at $(v/f)^2 = 0.2,\ 0.5,\ 0.8$

Looking for new particles

[arXiv:1209.0040]

Probing loop structure assuming no invisible or undetectable widths

Free parameters: κ_g, κ_γ.

	$H \rightarrow \gamma\gamma$	$H \rightarrow ZZ^{(*)}$	$H \rightarrow WW^{(*)}$	$H \rightarrow b\bar{b}$	$H \rightarrow \tau^-\tau^+$
ggH	$\frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_g^2}{\kappa_H^2(\kappa_i)}$			
$t\bar{t}H$ VBF WH ZH	$\frac{\kappa_\gamma^2}{\kappa_H^2(\kappa_i)}$	$\frac{1}{\kappa_H^2(\kappa_i)}$			

Probing loop structure allowing for invisible or undetectable widths

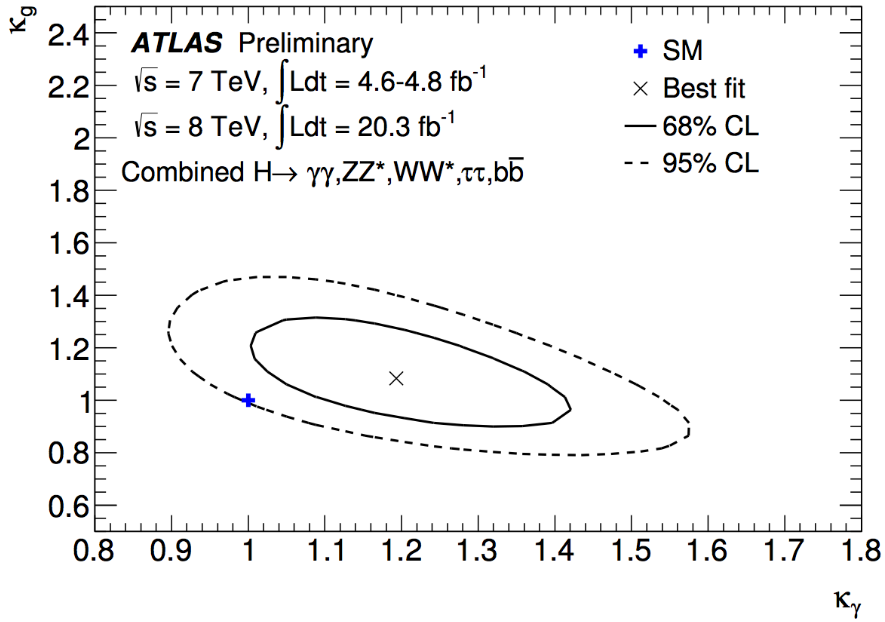
Free parameters: $\kappa_g, \kappa_\gamma, BR_{inv.,undet.}$.

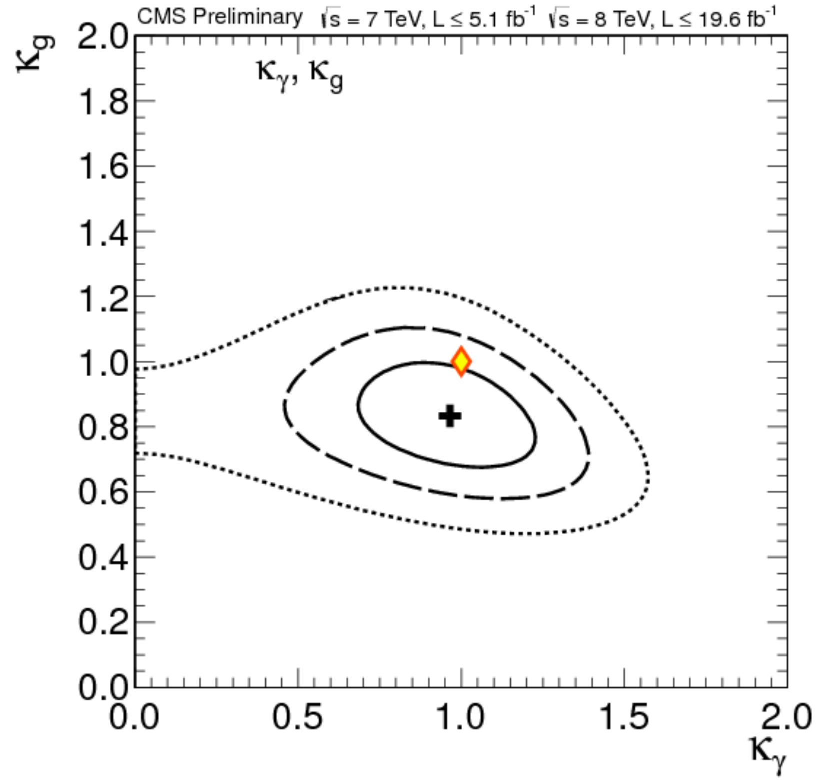
	$H \rightarrow \gamma\gamma$	$H \rightarrow ZZ^{(*)}$	$H \rightarrow WW^{(*)}$	$H \rightarrow b\bar{b}$	$H \rightarrow \tau^-\tau^+$
ggH	$\frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2(\kappa_i)/(1-BR_{inv.,undet.})}$	$\frac{\kappa_g^2}{\kappa_H^2(\kappa_i)/(1-BR_{inv.,undet.})}$			
$t\bar{t}H$ VBF WH ZH	$\frac{\kappa_\gamma^2}{\kappa_H^2(\kappa_i)/(1-BR_{inv.,undet.})}$	$\frac{1}{\kappa_H^2(\kappa_i)/(1-BR_{inv.,undet.})}$			

$$\kappa_i^2 = \Gamma_{ii}/\Gamma_{ii}^{SM}$$

Looking for new particles in loops

[ATLAS-CONF-2014-009] [CMS-PAS-HIG-13-005]





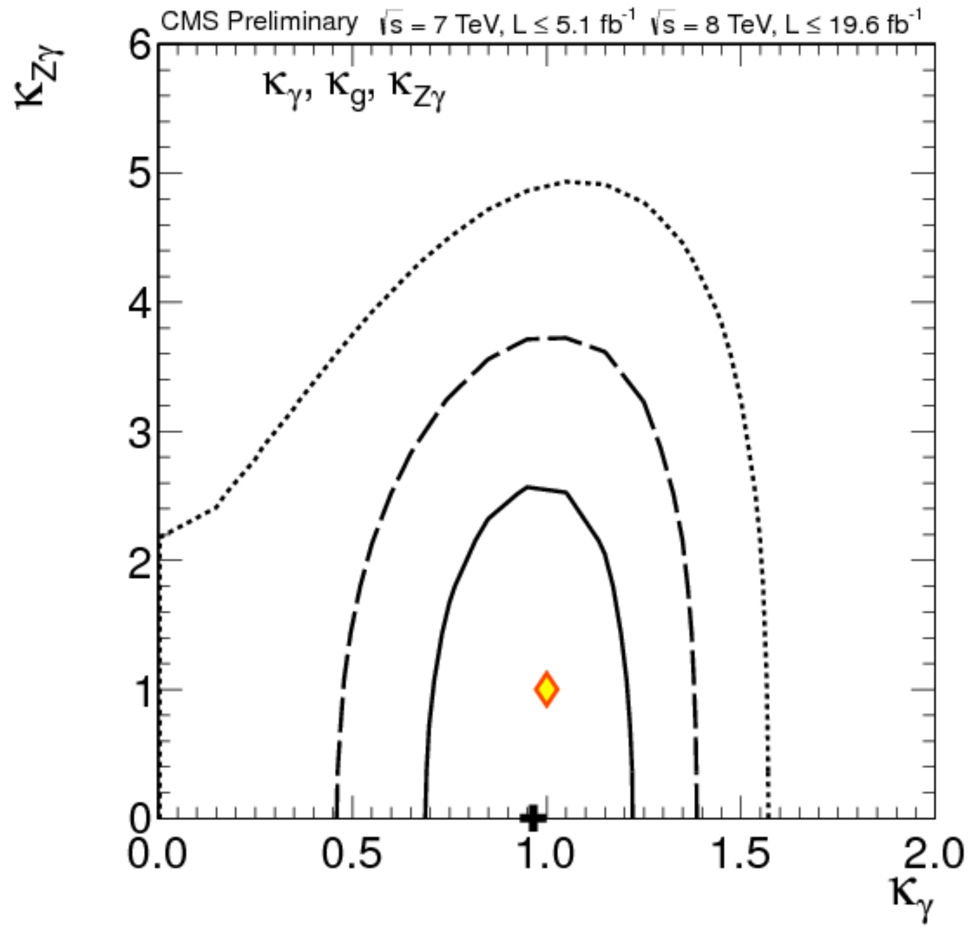
	ATLAS	CMS
κ_γ	$1.19^{+0.15}_{-0.12}$	0.97 ± 0.18
κ_g	1.08 ± 0.14	0.83 ± 0.11

A further take on loops

[CMS-PAS-HIG-13-005]

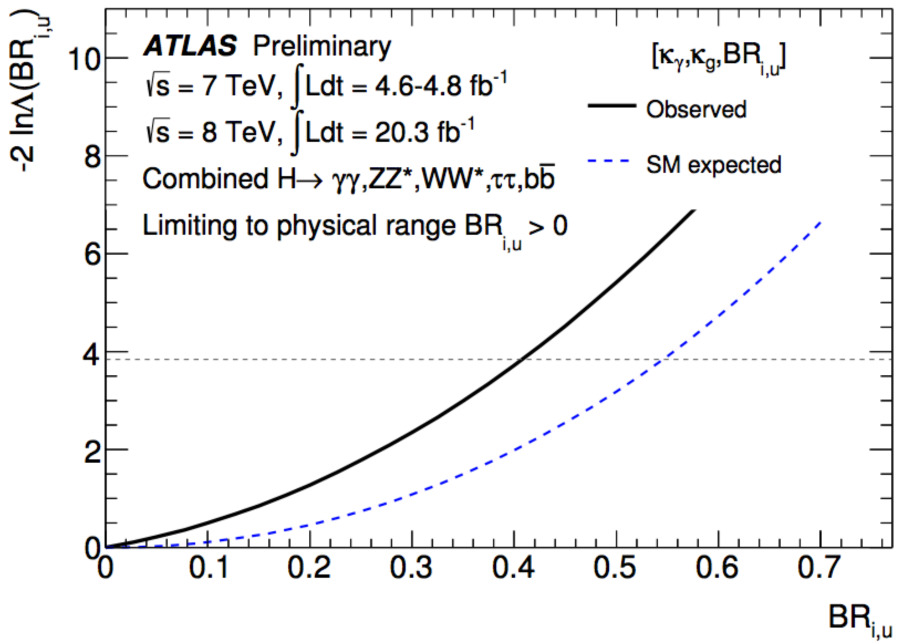
Effective H⟶$\gamma\gamma$, H⟶Zγ, and ggH loops.

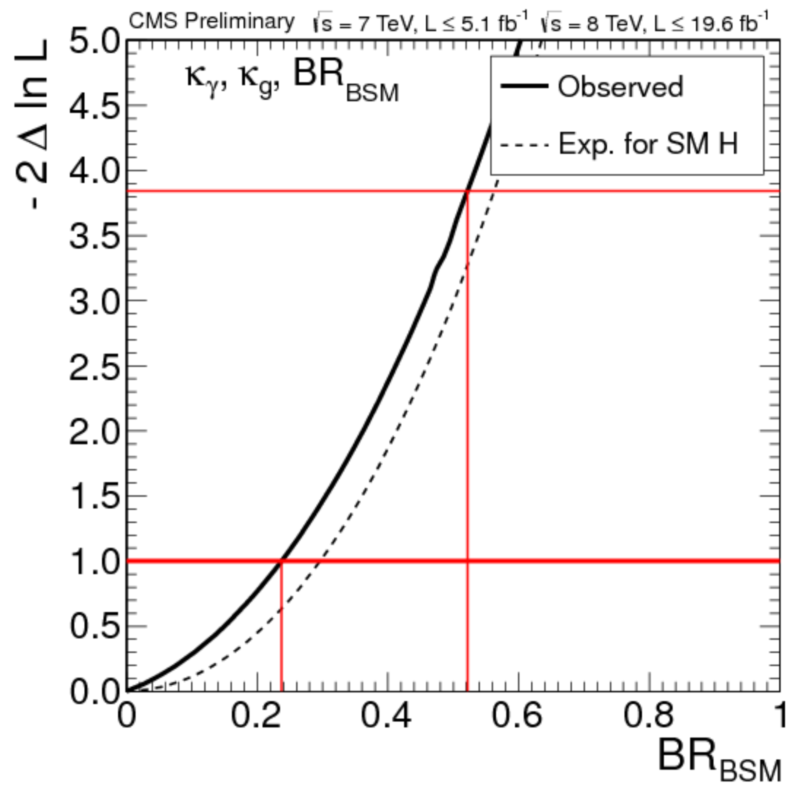
- Waiting for more data.



Looking for new particles

[ATLAS-CONF-2014-009] [CMS-PAS-HIG-13-005]





	ATLAS	CMS
BR_{BSM}	< 0.41 (95% CL)	< 0.52 (95% CL)

Probing the fermion sector

[arXiv:1209.0040]

2HDM

	u-type	d-type	lepton
I	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$
I'	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$-\frac{\sin\alpha}{\cos\beta}$
II	$\frac{\cos\alpha}{\sin\beta}$	$-\frac{\sin\alpha}{\cos\beta}$	$-\frac{\sin\alpha}{\cos\beta}$
II'	$\frac{\cos\alpha}{\sin\beta}$	$-\frac{\sin\alpha}{\cos\beta}$	$\frac{\cos\alpha}{\sin\beta}$

SM-like

Probing up-type and down-type fermion symmetry assuming no invisible or undetectable widths

Free parameters: $\kappa_V(=\kappa_Z=\kappa_W), \lambda_{du}(=\kappa_d/\kappa_u), \kappa_u(=\kappa_t)$.

Probing up-type and down-type fermion symmetry without assumptions on the total width

Free parameters: $\kappa_{uu}(=\kappa_u\cdot\kappa_u/\kappa_H), \lambda_{du}(=\kappa_d/\kappa_u), \lambda_{Vu}(=\kappa_V/\kappa_u)$.

	$H\to\gamma\gamma$	$H\to ZZ^{(*)}$	$H\to WW^{(*)}$	$H\to b\bar{b}$	$H\to\tau^-\tau^+$
ggH	$\kappa_{uu}^2\kappa_g^2(\lambda_{du},1)\cdot\kappa_\gamma^2(\lambda_{du},1,\lambda_{du},\lambda_{Vu})$	$\kappa_{uu}^2\kappa_g^2(\lambda_{du},1)\cdot\lambda_{Vu}^2$		$\kappa_{uu}^2\kappa_g^2(\lambda_{du},1)\cdot\lambda_{du}^2$	
ttH	$\kappa_{uu}^2\cdot\kappa_\gamma^2(\lambda_{du},1,\lambda_{du},\lambda_{Vu})$	$\kappa_{uu}^2\cdot\lambda_{Vu}^2$		$\kappa_{uu}^2\cdot\lambda_{du}^2$	
VBF WH ZH	$\kappa_{uu}^2\lambda_{Vu}^2\cdot\kappa_\gamma^2(\lambda_{du},1,\lambda_{du},\lambda_{Vu})$	$\kappa_{uu}^2\lambda_{Vu}^2\cdot\lambda_{Vu}^2$		$\kappa_{uu}^2\lambda_{Vu}^2\cdot\lambda_{du}^2$	

Probing quark and lepton fermion symmetry assuming no invisible or undetectable widths

Free parameters: $\kappa_V(=\kappa_Z=\kappa_W), \lambda_{lq}(=\kappa_l/\kappa_q), \kappa_q(=\kappa_t=\kappa_b)$.

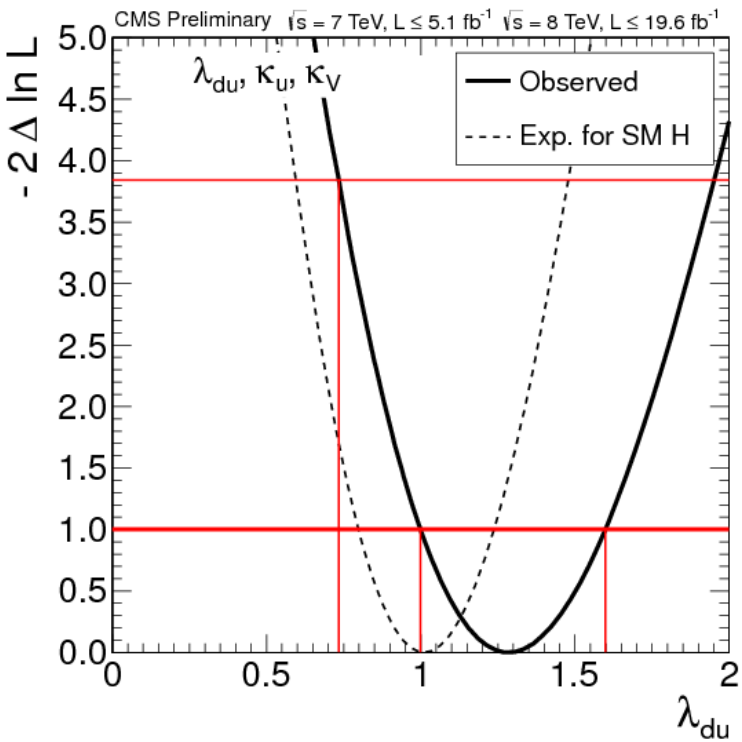
Probing quark and lepton fermion symmetry without assumptions on the total width

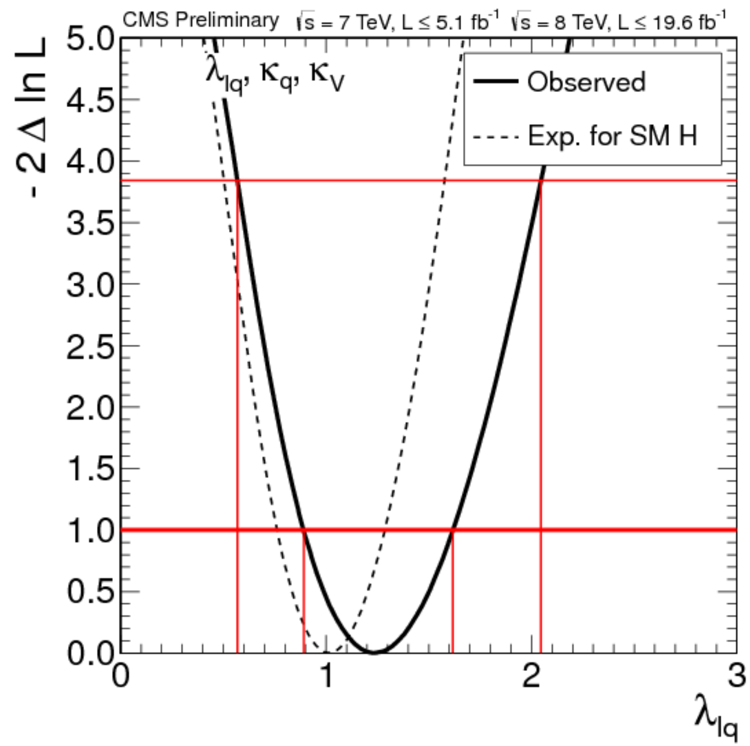
Free parameters: $\kappa_{qq}(=\kappa_q\cdot\kappa_q/\kappa_H), \lambda_{lq}(=\kappa_l/\kappa_q), \lambda_{Vq}(=\kappa_V/\kappa_q)$.

	$H\to\gamma\gamma$	$H\to ZZ^{(*)}$	$H\to WW^{(*)}$	$H\to b\bar{b}$	$H\to\tau^-\tau^+$
ggH ttH	$\kappa_{qq}^2\cdot\kappa_\gamma^2(1,1,\lambda_{lq},\lambda_{Vq})$	$\kappa_{qq}^2\cdot\lambda_{Vq}^2$		κ_{qq}^2	$\kappa_{qq}^2\cdot\lambda_{lq}^2$
VBF WH ZH	$\kappa_{qq}^2\lambda_{Vq}^2\cdot\kappa_\gamma^2(1,1,\lambda_{lq},\lambda_{Vq})$	$\kappa_{qq}^2\lambda_{Vq}^2\cdot\lambda_{Vq}^2$		$\kappa_{qq}^2\cdot\lambda_{Vq}^2$	$\kappa_{qq}^2\lambda_{Vq}^2\cdot\lambda_{lq}^2$

Probing the fermion sector

[CMS-PAS-HIG-13-005]



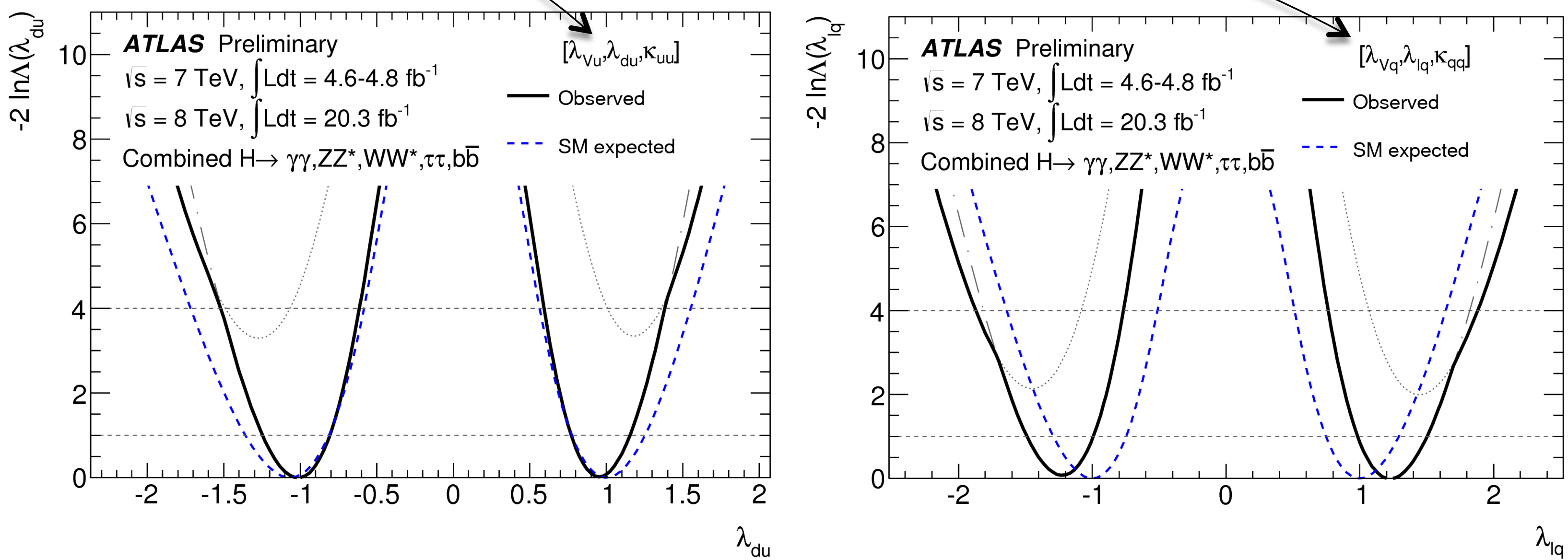


	λ_{du}	λ_{lq}
CMS	**[1.00, 1.60] (68% CL)**	**[0.89, 1.63] (68% CL)**

Probing the fermion sector

[ATLAS-CONF-NOTE-2014-009]

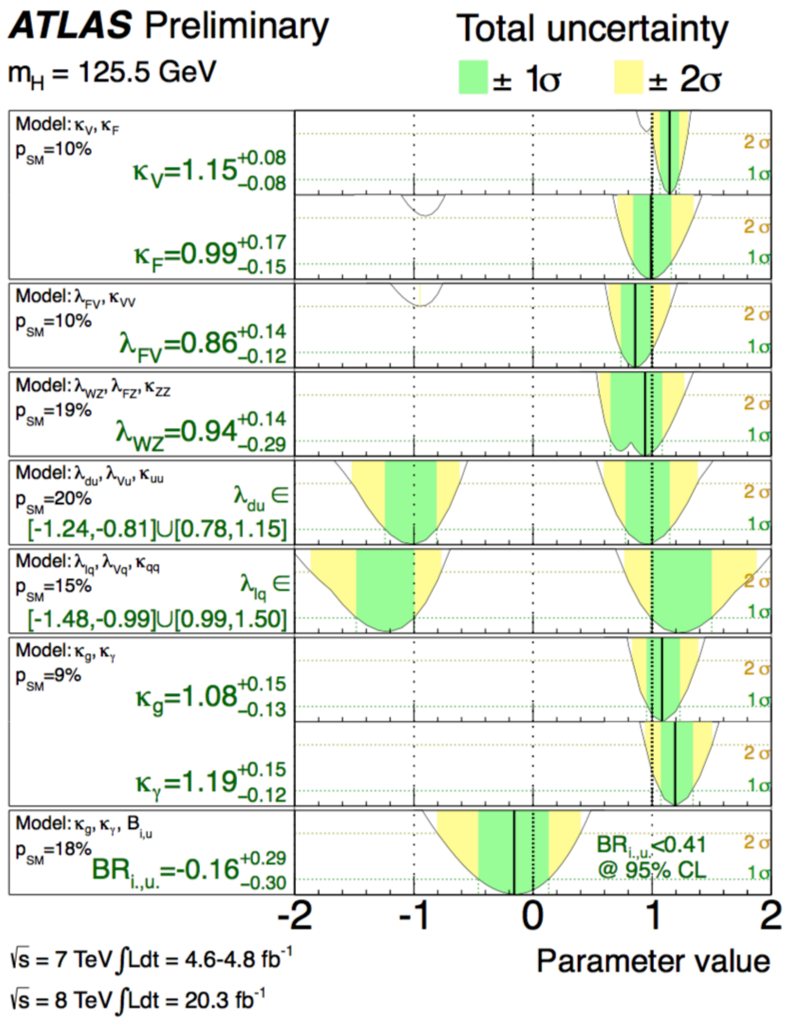
Floating total width

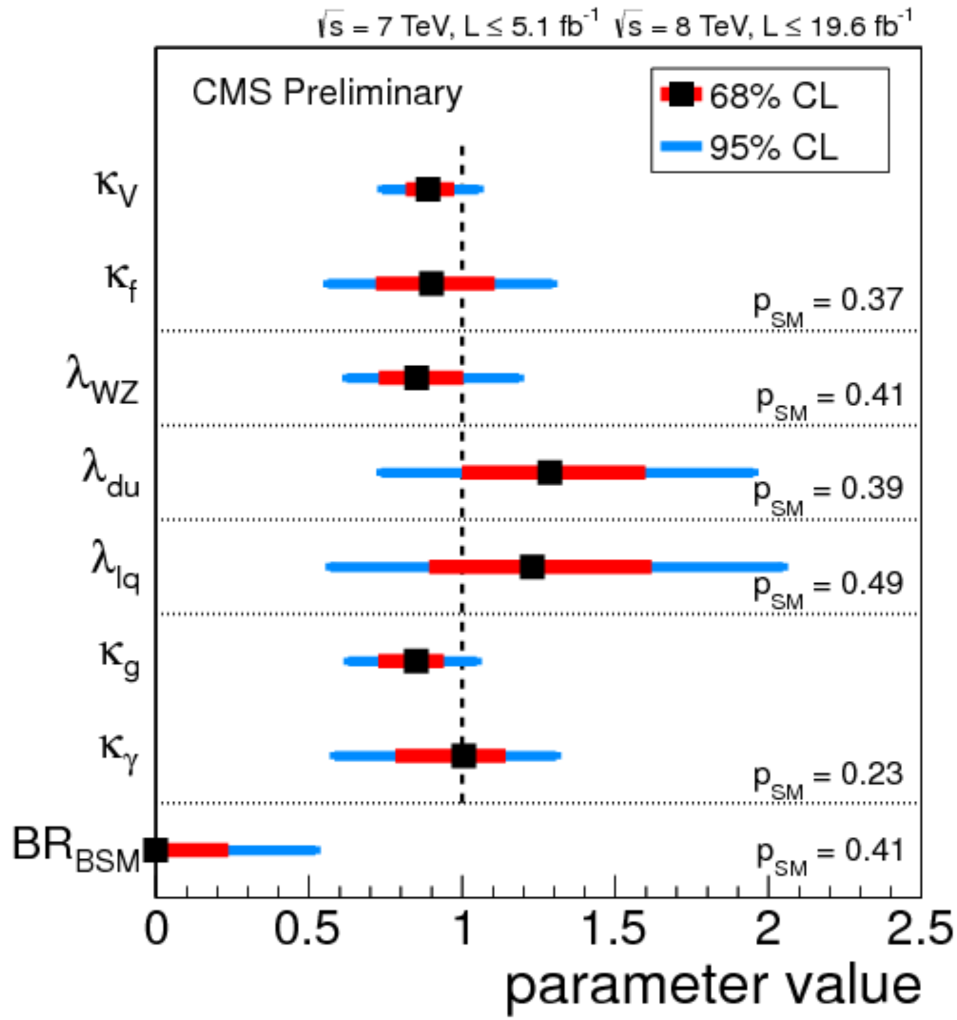


	λ_{du}	λ_{lq}
ATLAS	**[−1.24, −0.81] ∪ [0.78, 1.15] (68% CL)**	**[−1.48, −0.99] ∪ [0.99, 1.50] (68% CL)**

The deviations that we do not (yet) see

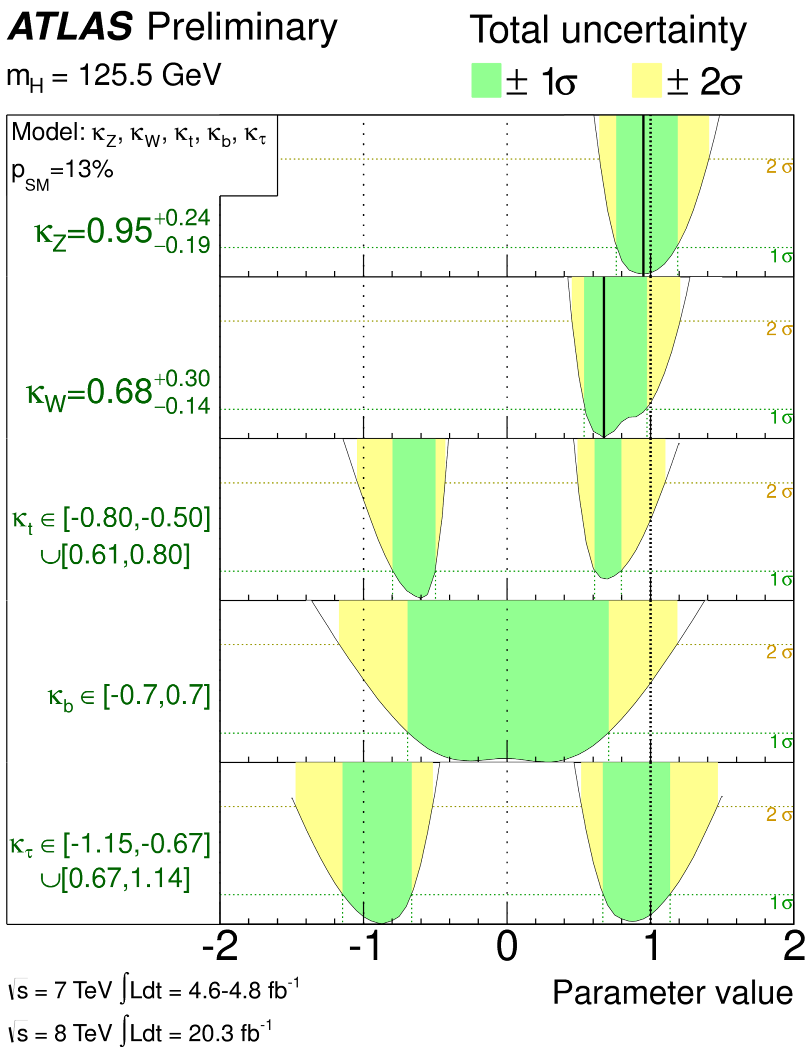
[ATLAS-CONF-2014-009] [CMS-PAS-HIG-13-005]

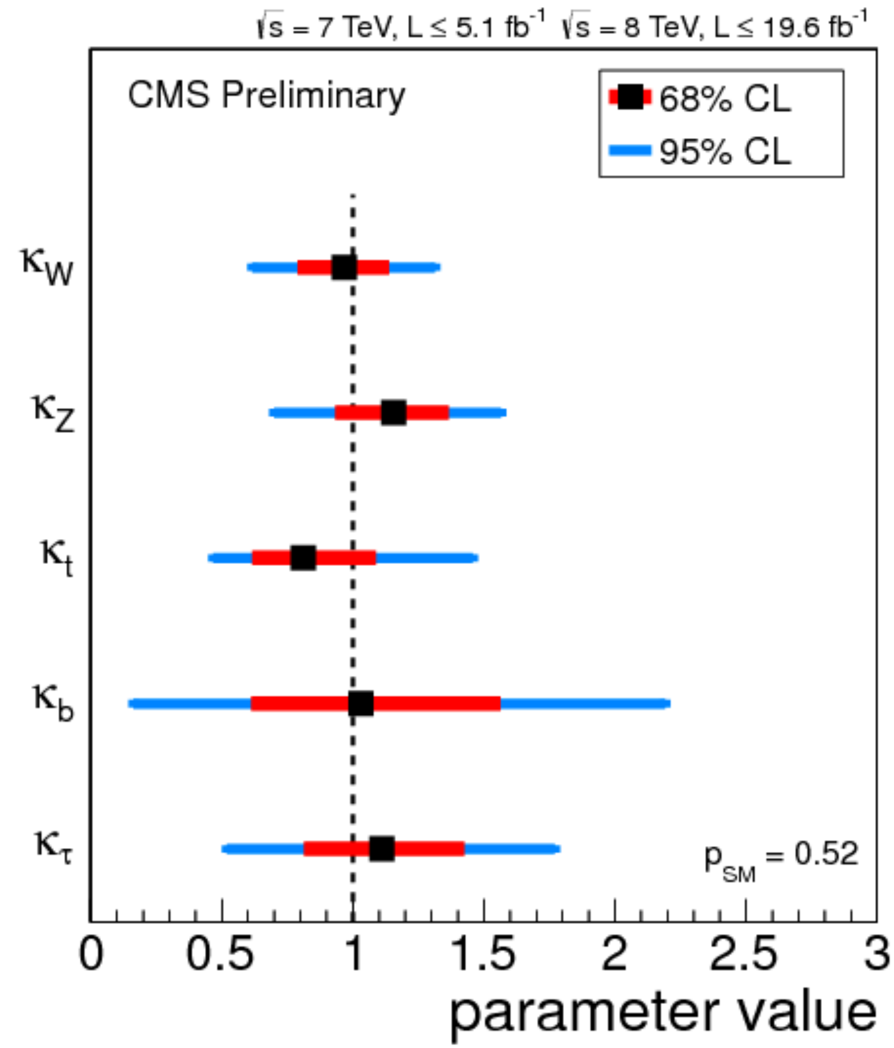




Resolving SM contributions

[ATLAS-CONF-2014-009] [CMS-PAS-HIG-13-005]

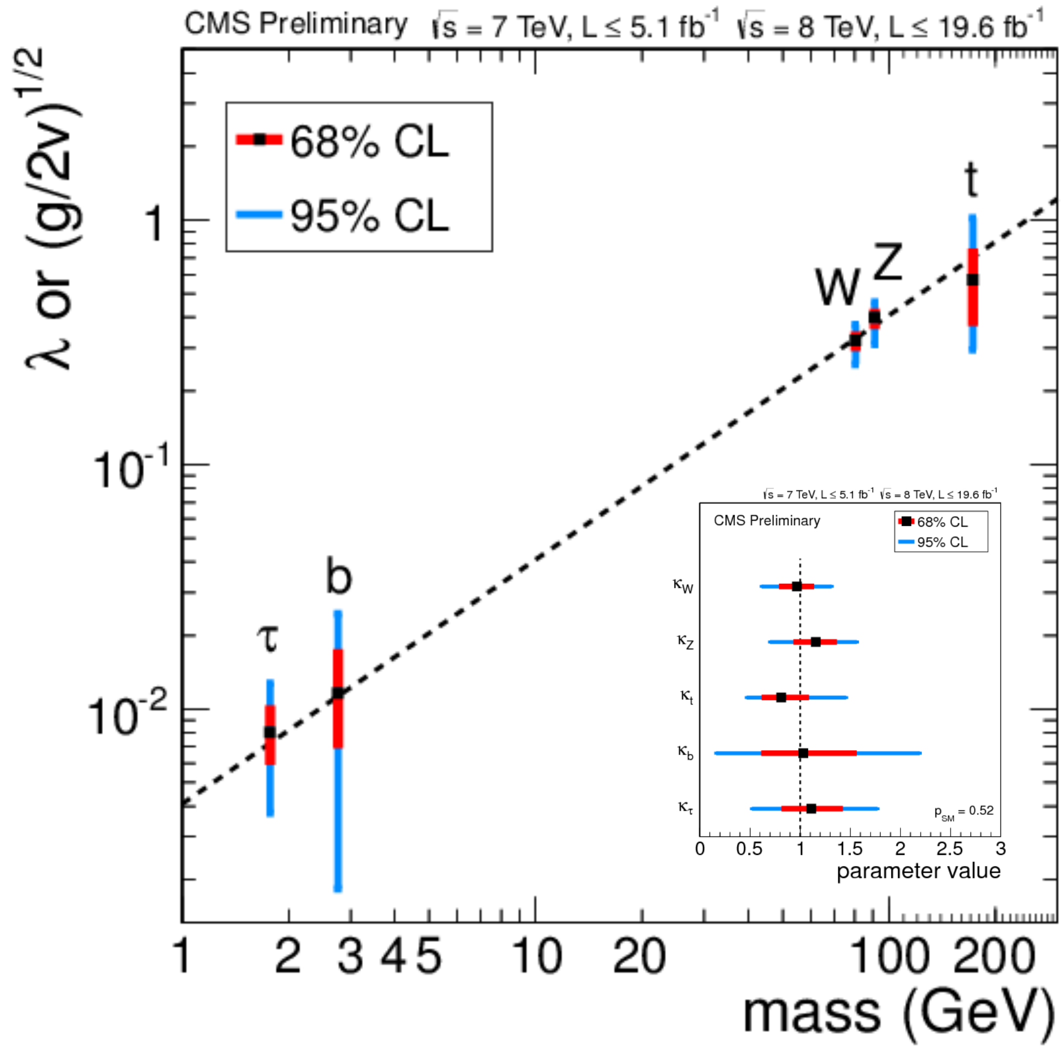




Resolving SM contributions

[CMS-PAS-HIG-13-005]

- Individual coupling scaling factors:
  - $\kappa_W, \kappa_Z, \kappa_b, \kappa_t, \kappa_\tau$.
  - All loops resolved:
    - $\kappa_\gamma(\kappa_W, \kappa_t)$
    - $\kappa_g(\kappa_t, \kappa_b)$
  - SMH width scaled.
- **P(SM)=0.52.**
- "Reduced" couplings as function of "mass":
  - $\lambda_f = \kappa_f\,(m_f/vev)$
  - $(g_V/2vev)^{1/2} = \kappa_V^{1/2}\,(m_V/vev)$



Spin is so much more than a number

[arXiv:1208.4018]

- The spin-2 amplitude has many (higher-order) terms:

$$
\begin{aligned}
A(X \to V_1 V_2) = \Lambda^{-1} \Bigg[& 2g_1^{(2)} t_{\mu\nu} f^{*(1)\mu\alpha} f^{*(2)\nu\alpha} + 2g_2^{(2)} t_{\mu\nu} \frac{q_\alpha q_\beta}{\Lambda^2} f^{*(1)\mu\alpha} f^{*(2)\nu\beta} + g_3^{(2)} \frac{\tilde{q}^\beta \tilde{q}^\alpha}{\Lambda^2} t_{\beta\nu} \left(f^{*(1)\mu\nu} f^{*(2)}_{\mu\alpha} + f^{*(2)\mu\nu} f^{*(1)}_{\mu\alpha} \right) \\
& + g_4^{(2)} \frac{\tilde{q}^\nu \tilde{q}^\mu}{\Lambda^2} t_{\mu\nu} f^{*(1)\alpha\beta} f^{*(2)}_{\alpha\beta} + m_V^2 \left(2g_5^{(2)} t_{\mu\nu} \epsilon_1^{*\mu} \epsilon_2^{*\nu} + 2g_6^{(2)} \frac{\tilde{q}^\mu q_\alpha}{\Lambda^2} t_{\mu\nu} \left(\epsilon_1^{*\nu} \epsilon_2^{*\alpha} - \epsilon_1^{*\alpha} \epsilon_2^{*\nu} \right) + g_7^{(2)} \frac{\tilde{q}^\mu \tilde{q}^\nu}{\Lambda^2} t_{\mu\nu} \epsilon_1^* \epsilon_2^* \right) \\
& + g_8^{(2)} \frac{\tilde{q}_\mu \tilde{q}_\nu}{\Lambda^2} t_{\mu\nu} f^{*(1)\alpha\beta} \tilde{f}^{*(2)}_{\alpha\beta} + m_V^2 \left(g_9^{(2)} \frac{t_{\mu\alpha} \tilde{q}^\alpha}{\Lambda^2} \epsilon_{\mu\nu\rho\sigma} \epsilon_1^{*\nu} \epsilon_2^{*\rho} q^\sigma + \frac{g_{10}^{(2)} t_{\mu\alpha} \tilde{q}^\alpha}{\Lambda^4} \epsilon_{\mu\nu\rho\sigma} q^\rho \tilde{q}^\sigma \left(\epsilon_1^{*\nu} (q\epsilon_2^*) + \epsilon_2^{*\nu} (q\epsilon_1^*) \right) \right) \Bigg], \qquad (18)
\end{aligned}
$$

Spin is so much more than a number

[arXiv:1208.4018]

- The spin-2 amplitude has many (higher-order) terms:

$$
\begin{aligned}
A(X \to V_1 V_2) = \Lambda^{-1} \Big[& 2g_1^{(2)} t_{\mu\nu} f^{*(1)\mu\alpha} f^{*(2)\nu\alpha} + \cancel{2g_2^{(2)} t_{\mu\nu} \frac{q_\alpha q_\beta}{\Lambda^2} f^{*(1)\mu\alpha} f^{*(2)\nu\beta}} + \cancel{g_3^{(2)} \frac{\tilde{q}^\beta \tilde{q}^\alpha}{\Lambda^2} t_{\beta\nu} \left(f^{*(1)\mu\nu} f^{*(2)}_{\mu\alpha} + f^{*(2)\mu\nu} f^{*(1)}_{\mu\alpha} \right)} \\
& + \cancel{g_4^{(2)} \frac{\tilde{q}^\nu \tilde{q}^\mu}{\Lambda^2} t_{\mu\nu} f^{*(1)\alpha\beta} f^{*(2)}_{\alpha\beta}} + m_V^2 \left(2g_5^{(2)} t_{\mu\nu} \epsilon_1^{*\mu} \epsilon_2^{*\nu} + \cancel{2g_6^{(2)} \frac{\tilde{q}^\mu q_\alpha}{\Lambda^2} t_{\mu\nu} \left(\epsilon_1^{*\nu} \epsilon_2^{*\alpha} - \epsilon_1^{*\alpha} \epsilon_2^{*\nu} \right)} + \cancel{g_7^{(2)} \frac{\tilde{q}^\mu \tilde{q}^\nu}{\Lambda^2} t_{\mu\nu} \epsilon_1^* \epsilon_2^*} \right) \\
& + \cancel{g_8^{(2)} \frac{\tilde{q}_\mu \tilde{q}_\nu}{\Lambda^2} t_{\mu\nu} f^{*(1)\alpha\beta} \tilde{f}^{*(2)}_{\alpha\beta}} + \cancel{m_V^2 \left(g_9^{(2)} \frac{t_{\mu\alpha} \tilde{q}^\alpha}{\Lambda^2} \epsilon_{\mu\nu\rho\sigma} \epsilon_1^{*\nu} \epsilon_2^{*\rho} q^\sigma\right.} + \cancel{\left.\frac{g_{10}^{(2)} t_{\mu\alpha} \tilde{q}^\alpha}{\Lambda^4} \epsilon_{\mu\nu\rho\sigma} q^\rho \tilde{q}^\sigma \left(\epsilon_1^{*\nu} (q\epsilon_2^*) + \epsilon_2^{*\nu} (q\epsilon_1^*) \right)\right)} \Big],
\end{aligned}
\tag{18}
$$

- Keep only dim-4 terms ($g_1 = g_5 \neq 0$):
  - Graviton-like "couplings" (2^+_m).

J^P: a simplified picture

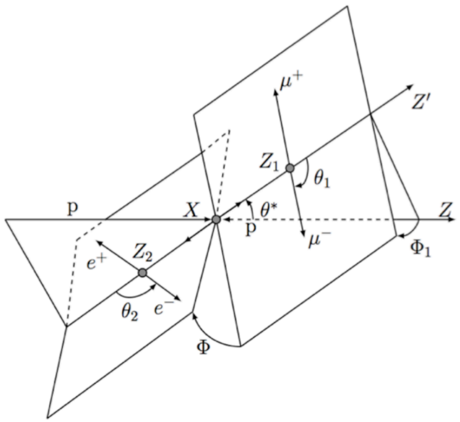
[arXiv:1208.4018]

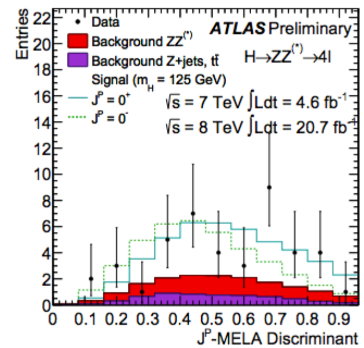
- **Until there is enough data, perform pairwise hypothesis tests against SMH (0^+).**
- Select models using simplifying assumptions on amplitudes:
  - 0^- (parity) “from” ZZ.
  - 2^+_m (graviton-like minimal couplings) also “from” WW and $\gamma\gamma$.

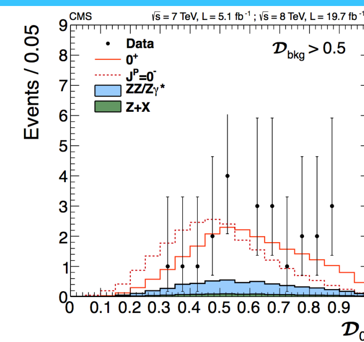
scenario	$X \to ZZ$	$X \to WW$	$X \to \gamma\gamma$
0^+_m vs background	5.0	5.0	5.0
0^+_m vs 0^+_h	1.7	1.1	0.0
0^+_m vs 0^-	$\boxed{2.9}$	1.2	0.0
0^+_m vs 1^+	1.9	2.0	–
0^+_m vs 1^-	2.6	3.2	–
0^+_m vs 2^+_m	1.5	$\boxed{2.8}$	$\boxed{2.4}$
0^+_m vs 2^+_h	∼5	1.1	3.1
0^+_m vs 2^-_h	∼5	2.5	3.1

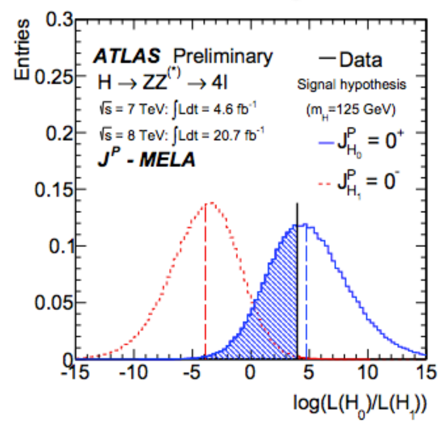
Parity: H⟶ZZ⟶4ℓ

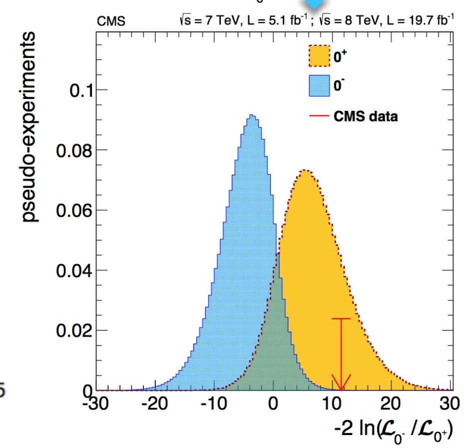
[ATLAS-CONF-2013-013] [arXiv:1312.5353]









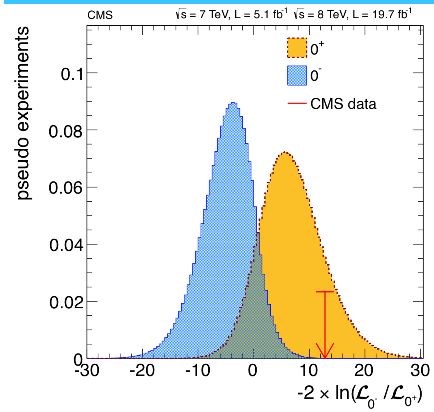


- Discriminants built from decay angles and invariant masses.
- Profiled likelihood ratio test statistic.
  - CL_S criterion protects against fluctuations from null hypothesis.

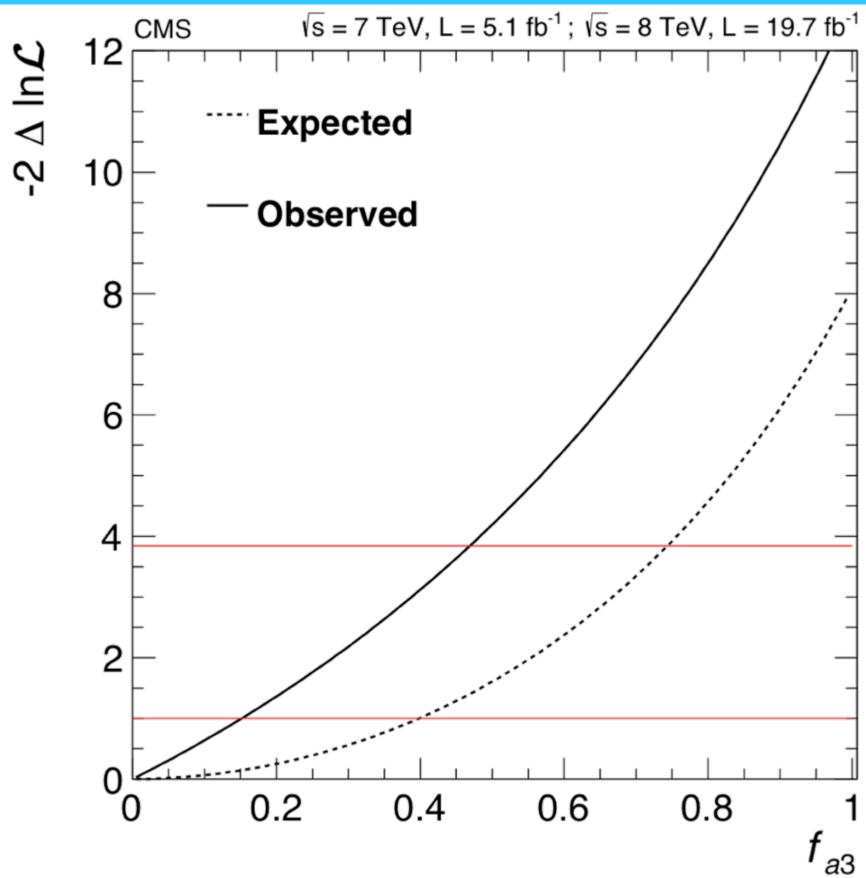
	ATLAS	CMS
CL_S	**0.37%**	**0.09%**
P(obs.|0^+)	0.2 σ	-0.9 σ
P(obs.|0^-)	2.8σ	3.6 σ

Even-odd mix?

[arXiv:1312.5353]



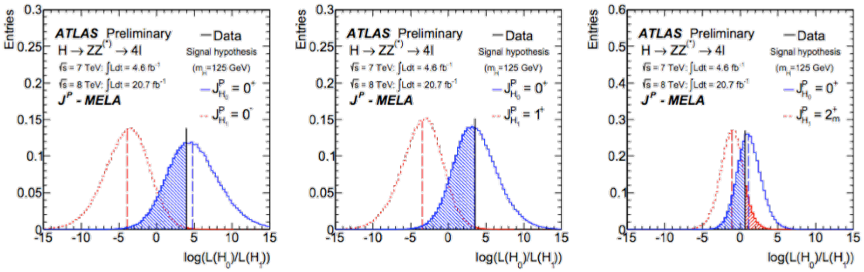
$$f_{a3} = \frac{|a_3|^2\sigma_3}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3}$$

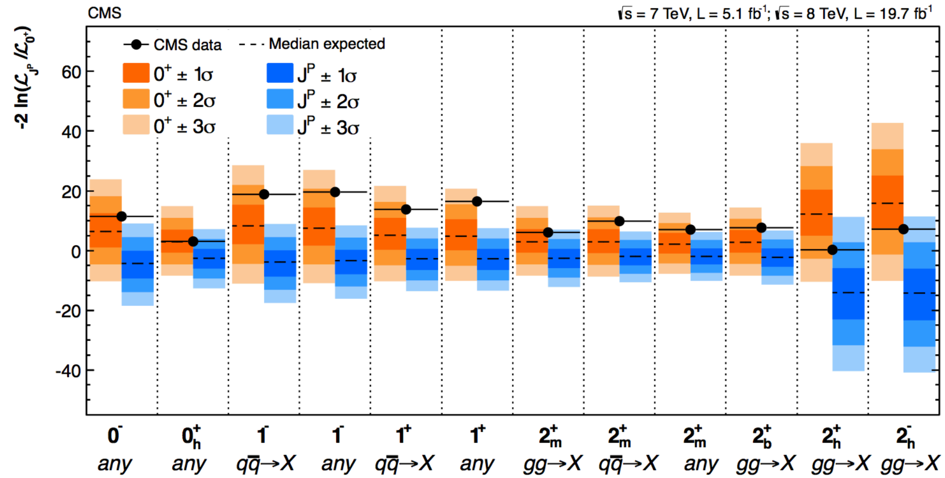


	CMS
f_{a3} (ϕ_{a3}=0,π)	< 0.47 (95% CL)

Other J^P in $H \longrightarrow ZZ \longrightarrow 4\ell$

[ATLAS-CONF-2013-013] [arXiv:1312.5353]





		J^P-MELA analysis			
		tested J^P for an assumed 0^+		tested 0^+ for an assumed J^P	CL_S
		expected	observed	observed*	
0^-	p_0	0.0011	0.0022	0.40	0.004
1^+	p_0	0.0031	0.0028	0.51	0.006
1^-	p_0	0.0010	0.027	0.11	0.031
2^+_m	p_0	0.064	0.11	0.38	0.182
2^-	p_0	0.0032	0.11	0.08	0.116

J^P model	J^P production	Expected ($\mu = 1$)	Obs. 0^+	Obs. J^P	CL_s
0^-	any	2.4σ (2.7σ)	-0.9σ	$+3.6\sigma$	0.09%
0^+_h	any	1.7σ (1.9σ)	-0.0σ	$+1.8\sigma$	7.1%
1^-	$q\bar{q} \to X$	2.6σ (2.7σ)	-1.4σ	$+4.8\sigma$	0.001%
1^-	any	2.6σ (2.6σ)	-1.7σ	$+4.9\sigma$	0.001%
1^+	$q\bar{q} \to X$	2.1σ (2.3σ)	-1.5σ	$+4.1\sigma$	0.03%
1^+	any	2.0σ (2.1σ)	-1.9σ	$+4.5\sigma$	0.01%
2^+_m	$gg \to X$	1.7σ (1.8σ)	-0.8σ	$+2.6\sigma$	1.9%
2^+_m	$q\bar{q} \to X$	1.6σ (1.7σ)	-1.6σ	$+3.6\sigma$	0.03%
2^+_m	any	1.5σ (1.5σ)	-1.3σ	$+3.0\sigma$	1.4%
2^+_b	$gg \to X$	1.6σ (1.8σ)	-1.2σ	$+3.1\sigma$	0.9%
2^+_h	$gg \to X$	3.7σ (4.0σ)	$+1.8\sigma$	$+1.9\sigma$	3.1%
2^-_h	$gg \to X$	4.0σ (4.5σ)	$+1.0\sigma$	$+3.0\sigma$	1.7%

	ATLAS	CMS
Worse CL_s for $J \neq 0$	< 18.2%	< 3.1%

Nobel prizes…

The Nobel Prize in Physics 2013
François Englert, Peter Higgs

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The Nobel Prize in Physics 2013

Photo: A. Mahmoud
François Englert
Prize share: 1/2

Photo: A. Mahmoud
Peter W. Higgs
Prize share: 1/2

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"*

…and knighthoods.

Eminent physicists receive royal honours

by Deborah Evanson, Colin Smith, Gail Wilson
16 June 2014

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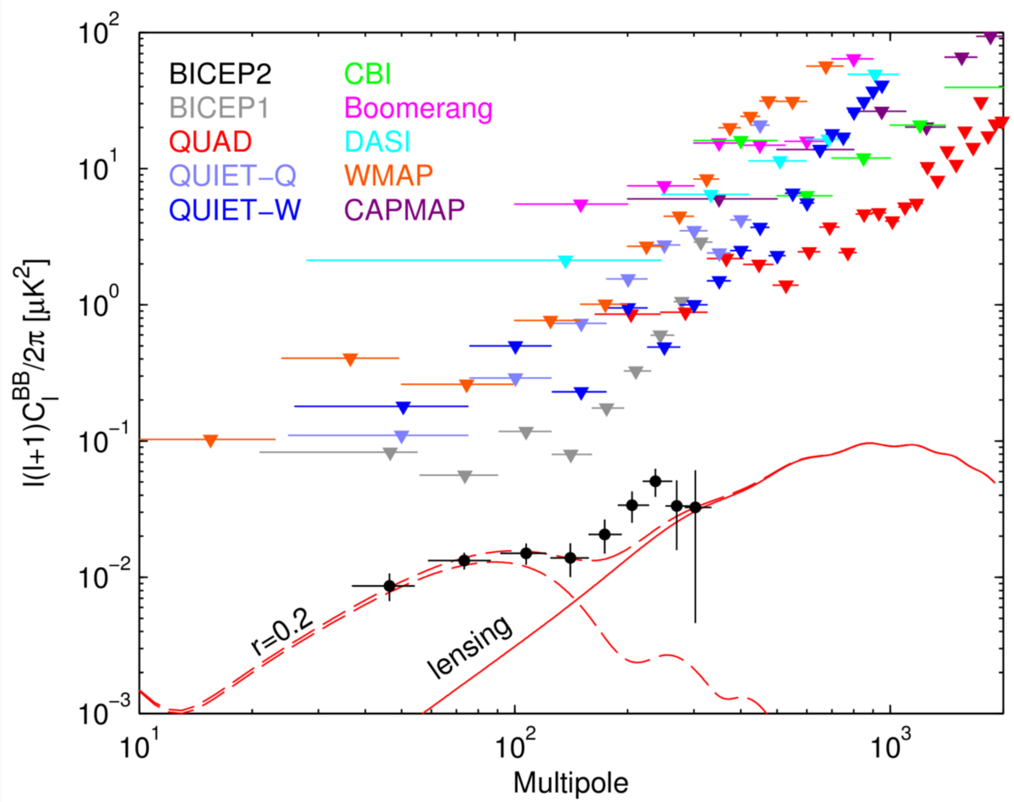
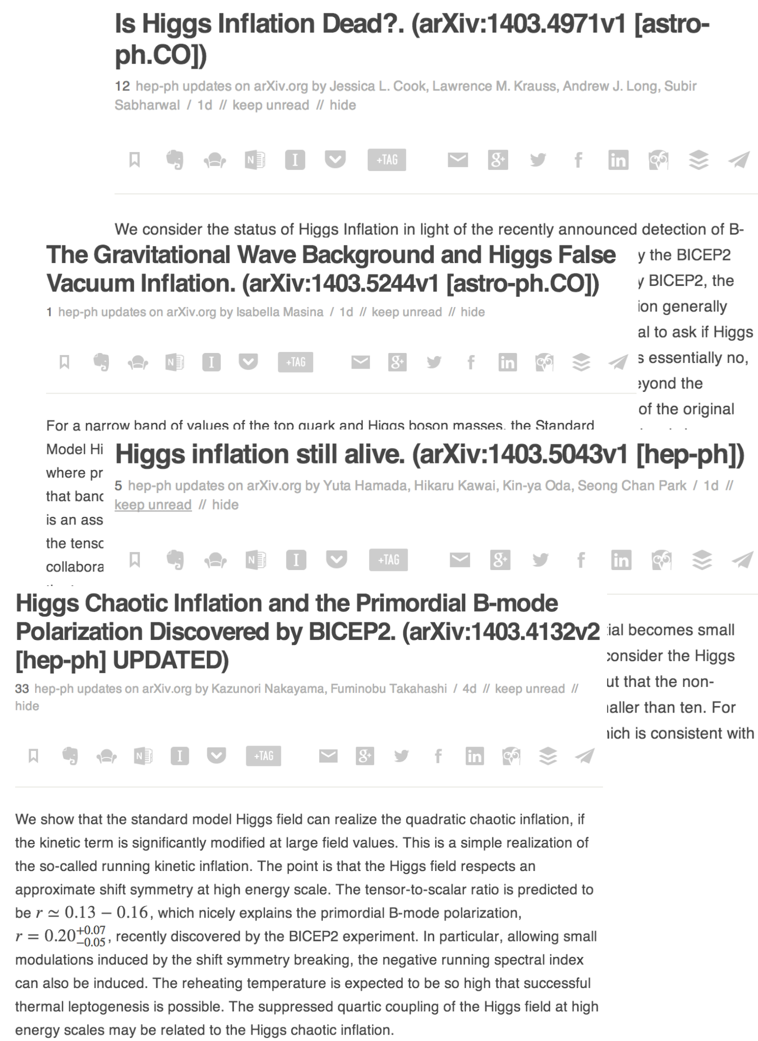
Two of Imperial's physicists, best known for predicting and finding the Higgs boson, have been knighted in this year's Queen's Birthday honours list.

Flexing your BICEP2 muscles

[arXiv:1403.3985]





Is Higgs Inflation Dead?. (arXiv:1403.4971v1 [astro-ph.CO])

12 hep-ph updates on arXiv.org by Jessica L. Cook, Lawrence M. Krauss, Andrew J. Long, Subir Sabharwal / 1d // keep unread // hide

We consider the status of Higgs Inflation in light of the recently announced detection of B-
... y the BICEP2
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The Gravitational Wave Background and Higgs False Vacuum Inflation. (arXiv:1403.5244v1 [astro-ph.CO])

1 hep-ph updates on arXiv.org by Isabella Masina / 1d // keep unread // hide

For a narrow band of values of the top quark and Higgs boson masses, the Standard
Model Hi...
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Higgs inflation still alive. (arXiv:1403.5043v1 [hep-ph])

5 hep-ph updates on arXiv.org by Yuta Hamada, Hikaru Kawai, Kin-ya Oda, Seong Chan Park / 1d // keep unread // hide

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Higgs Chaotic Inflation and the Primordial B-mode Polarization Discovered by BICEP2. (arXiv:1403.4132v2 [hep-ph] UPDATED)

33 hep-ph updates on arXiv.org by Kazunori Nakayama, Fuminobu Takahashi / 4d // keep unread // hide

We show that the standard model Higgs field can realize the quadratic chaotic inflation, if the kinetic term is significantly modified at large field values. This is a simple realization of the so-called running kinetic inflation. The point is that the Higgs field respects an approximate shift symmetry at high energy scale. The tensor-to-scalar ratio is predicted to be $r \simeq 0.13 - 0.16$, which nicely explains the primordial B-mode polarization, $r = 0.20^{+0.07}_{-0.05}$, recently discovered by the BICEP2 experiment. In particular, allowing small modulations induced by the shift symmetry breaking, the negative running spectral index can also be induced. The reheating temperature is expected to be so high that successful thermal leptogenesis is possible. The suppressed quartic coupling of the Higgs field at high energy scales may be related to the Higgs chaotic inflation.

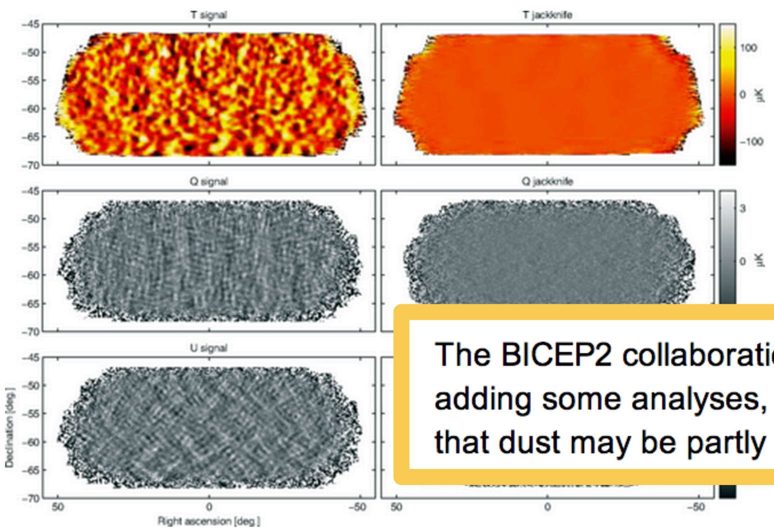
- Who knows ?

Published in PRL but…

[http://cern.ch/go/nr66]

BICEP2 researchers publish nuanced account of stunning patterns in the microwave sky

2 hours ago



BICEP2 T, Q, U maps. The left column shows the basic signal maps with 0.25° pixelization as output by the reduction pipeline. The right column shows difference (jackknife) maps made with the first and second halves of the data set. No … more

Following a thorough peer-review process, the researchers who previously announced the detection of B-mode polarization in a patch of the microwave sky have published their findings today in the journal *Physical Review Letters.*

The BICEP2 collaboration addresses these claims directly, changing, removing and adding some analyses, but they acknowledge that they cannot rule out the possibility that dust may be partly or entirely responsible for the gravitational-wave-like signals.

Published in PRL but…

[http://cern.ch/go/8HwP]

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Big Bang breakthrough team back-pedals on major result

› 18:56 19 June 2014 by Jacob Aron , Lisa Grossman and Stuart Clark

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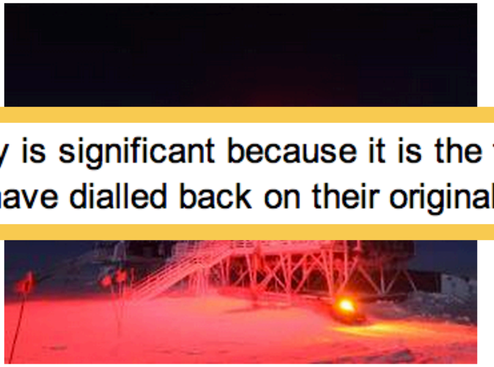
It was hailed as the discovery of the century. But now the researchers who earlier this year reported the first detection of primordial gravitational waves – ripples in space time hailing from the early universe – say they are not so sure after all.

"Has my confidence gone down? Yes," says Clement Pryke of the University of Minnesota, co-leader of the team that reported the original result.

In March, the team, which uses a te
South Pole, announced their discov
Astrophysics in Cambridge, Massac
online.

The paper published today is significant because it is the first time the researchers themselves have dialled back on their original claims.

Today, the first peer-reviewed version of their results appears in the journal *Physical Review Letters* – and it backtracks on the certainty of the original announcement.



BICEP2: dust in its eyes? *(Image: Steffen Richter/Bicep2)*

Star dust

A very long way to go…

Decay Modes

Γ_i	Mode	Fraction (Γ_i / Γ)	Scale Factor/ Confidence Level	P (MeV/c)
Γ_1	$H^0 \to WW^*$	seen		
Γ_2	$H^0 \to ZZ^*$	seen		
Γ_3	$H^0 \to \gamma\gamma$	seen		
Γ_4	$H^0 \to b\bar{b}$	possibly seen		
Γ_5	$H^0 \to \tau^+\tau^-$	possibly seen		

H^0 SIGNAL STRENGTHS IN DIFFERENT CHANNELS

Combined Final States	1.07 ± 0.26	(S = 1.4)
WW^* Final State	0.88 ± 0.33	(S = 1.1)
ZZ^* Final State	$0.89\ ^{+0.30}_{-0.25}$	
$\gamma\gamma$ Final State	1.65 ± 0.33	
$b\bar{b}$ Final State	$0.5\ ^{+0.8}_{-0.7}$	
$\tau^+\tau^-$ Final State	0.1 ± 0.7	

Decay Modes

Γ_i	Mode	Fraction (Γ_i / Γ)	Scale Factor/ Confidence Level	P (MeV/c)
Γ_1	$Z \to e^+e^-$	3.363 ± 0.004 %		45594
Γ_2	$Z \to \mu^+\mu^-$	3.366 ± 0.007 %		45594
Γ_3	$Z \to \tau^+\tau^-$	3.370 ± 0.008 %		45559
Γ_4	$Z \to \ell^+\ell^-$	3.3658 ± 0.0023 %		
Γ_5	$Z \to \ell^+\ell^-\ell^+\ell^-$	$(4.2\ ^{+0.9}_{-0.8}) \times 10^{-6}$		45594
Γ_6	$Z \to$ invisible	$(2.000 \pm .006) \times 10^{-1}$		
Γ_7	$Z \to$ hadrons	$(6.991 \pm .006) \times 10^{-1}$		
Γ_8	$Z \to (u\bar{u} + c\bar{c})/2$	$.116 \pm .006$		
Γ_9	$Z \to (d\bar{d} + s\bar{s} + b\bar{b})/3$	$.156 \pm .004$		
Γ_{10}	$Z \to c\bar{c}$	$(1.203 \pm .021) \times 10^{-1}$		
Γ_{11}	$Z \to b\bar{b}$	$(1.512 \pm .005) \times 10^{-1}$		
Γ_{12}	$Z \to b\bar{b}b\bar{b}$	$(3.6 \pm 1.3) \times 10^{-4}$		

About the future

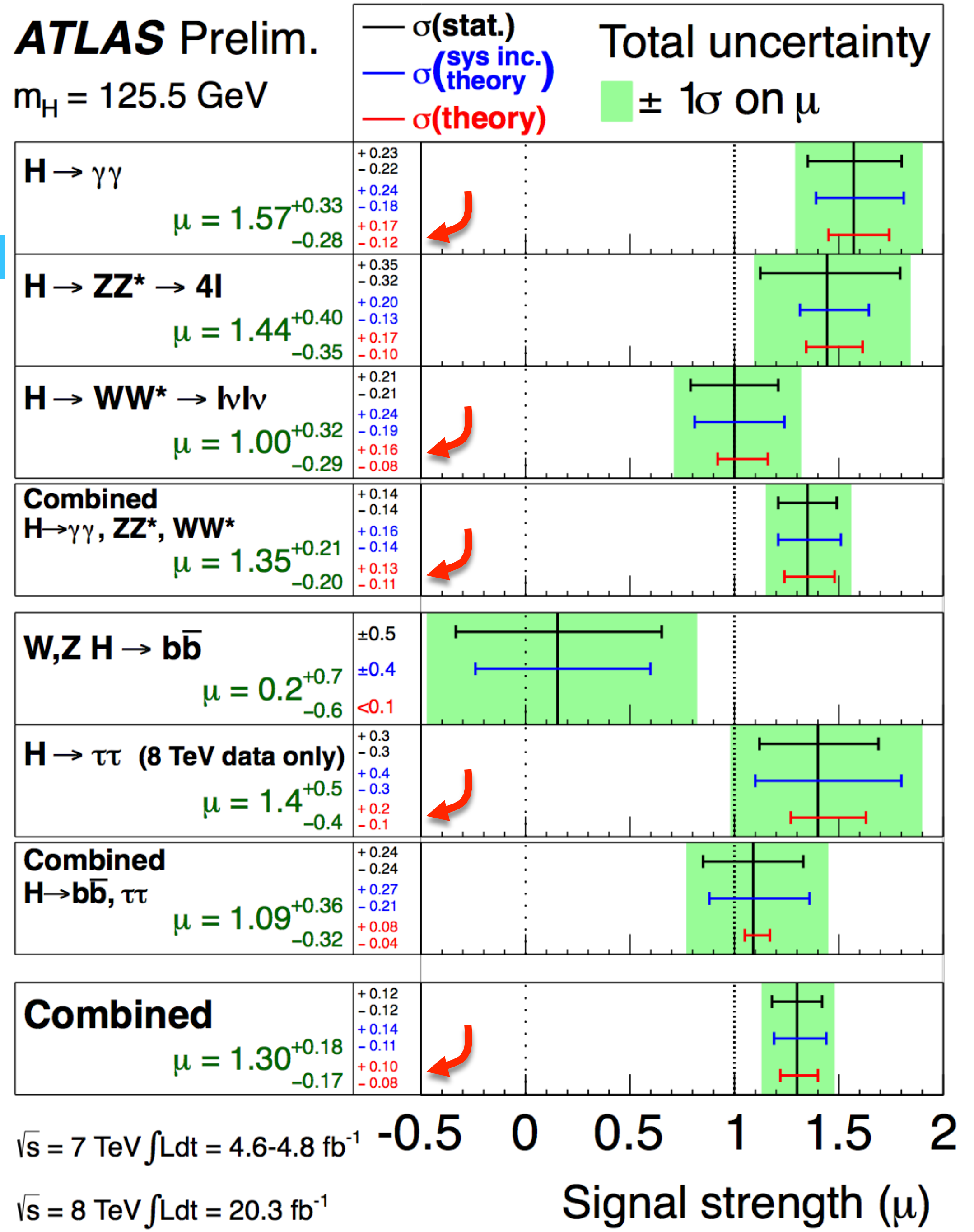
- Boson "solo gigs":
  - Theory uncertainties and ratios.
  - The adventure of unfolding: going differential.
  - Statistics-limited: ttH, tH, invisible.
  - Loops and rare decays: $Z\gamma$, $\gamma\gamma$, full Dalitz, $\mu\mu$.
  - Weird decays: vector mesons, $t \rightarrow cH$ FCNC, etc.
- Boson & friends:
  - Small deviations: from the κ-framework to Wilson coefficients.
  - Global electroweak picture: EWPD, Higgs, and aTGCs.

- **Caveats**:
  - Not directly discussing beyond-one-doublet alternatives: extra singlet, MSSM, 2HDM, nMSSM, triplet and double charged, etc.
    - **They need searching as well !**
  - Not discussing parity, which is a definitely not a closed case.

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

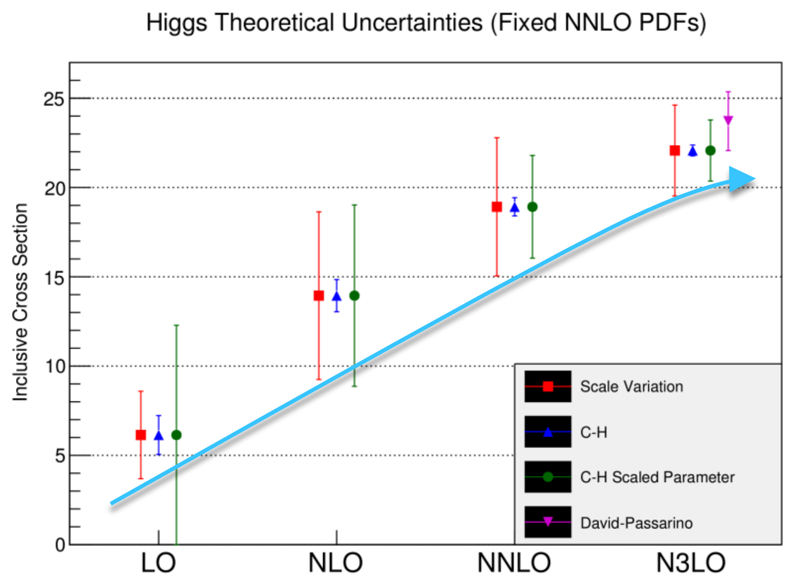
[arXiv:1307.1843] [http://cern.ch/go/V8xJ]

- 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

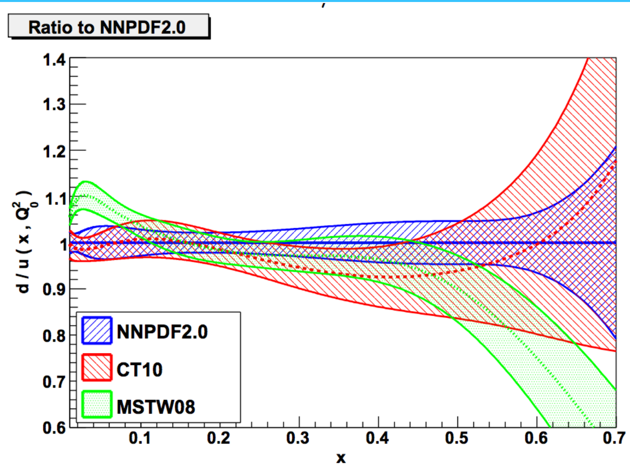
- Take gluon-gluon fusion:
  - All series terms are positive.
  - We can try and complete the series instead of **always** being off.

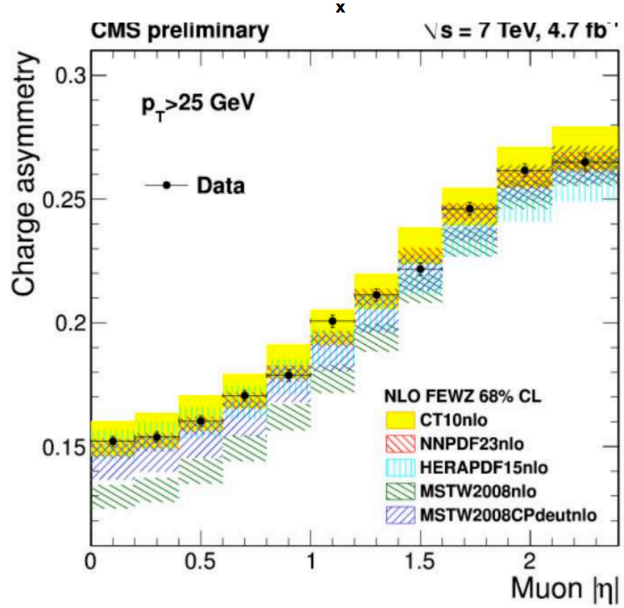


Theory uncertainties: a tale of PDFs

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

- Long-standing difference in d/u ratio between MSTW and others.
- Neatly resolved by CMS W asymmetry measurements.
- MSWT made parameterization more flexible: case closed.





Theory uncertainties

- Bottom-line for Run2:
  - Consider measurements that constrain PDF fits.
  - For higher orders, more than precision, also a matter of accuracy.
    - Need to work with theorists to get these right, also differentially.

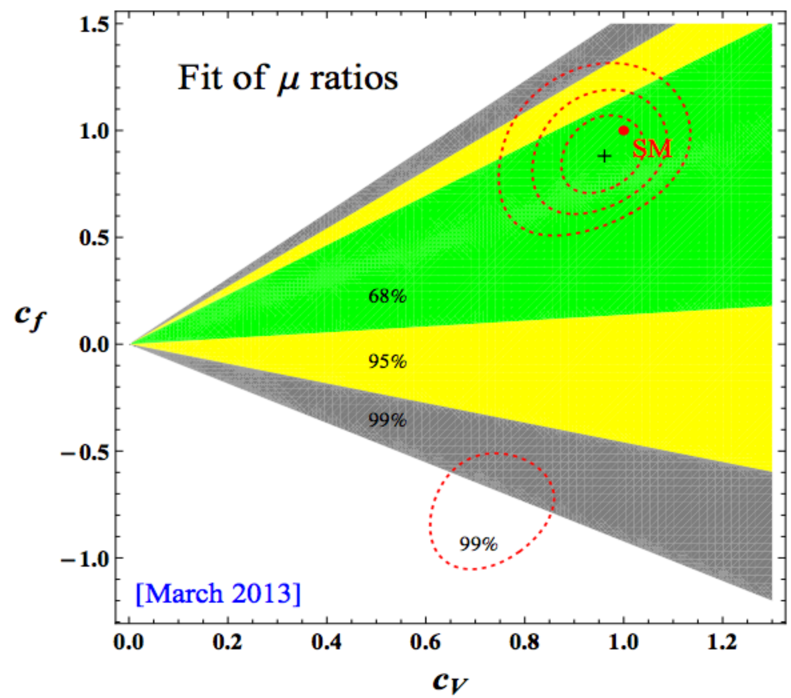
- Or you can try to dodge them with ratios…

Ratios to the rescue?

[arXiv:1303.6591] [http://cern.ch/go/gLP9]

- Total width not accessible at the LHC
  - More on that later.
- Idea: take ratios and cancel out the TH uncertainties.
- But this is naïve:
  THU only cancel if the phase-space probed is exactly the same.
- **More statistics allows for exactly matched kinematics.**

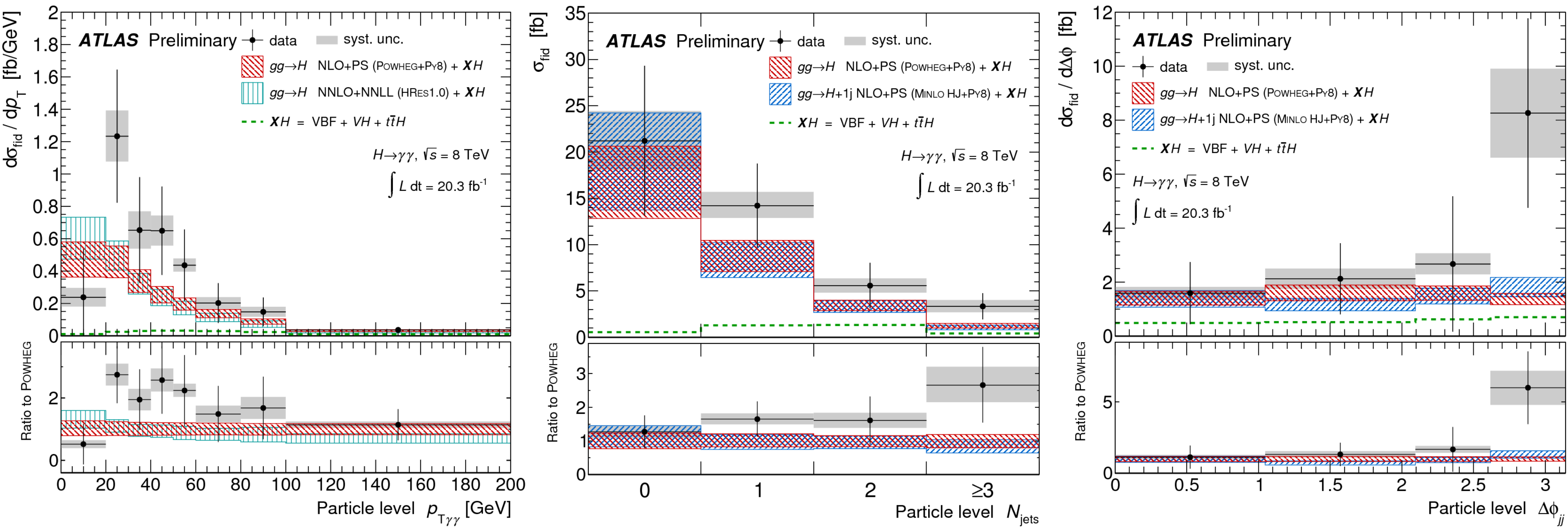
$$D_{XX} \hat{=} \frac{\mu_{XX}}{\mu_{VV}} \simeq \frac{\frac{\sigma(pp\to H)\times \mathrm{BR}(H\to XX)}{\sigma(pp\to H)|_{\mathrm{SM}}\times \mathrm{BR}(H\to XX)|_{\mathrm{SM}}}}{\frac{\sigma(pp\to H)\times \mathrm{BR}(H\to VV)}{\sigma(pp\to H)|_{\mathrm{SM}}\times \mathrm{BR}(H\to VV)|_{\mathrm{SM}}}} = \frac{\frac{\mathrm{BR}(H\to XX)}{\mathrm{BR}(H\to XX)|_{\mathrm{SM}}}}{\frac{\mathrm{BR}(H\to VV)}{\mathrm{BR}(H\to VV)|_{\mathrm{SM}}}} = \frac{\frac{\Gamma(H\to XX)}{\Gamma(H\to XX)|_{\mathrm{SM}}}}{\frac{\Gamma(H\to VV)}{\Gamma(H\to VV)|_{\mathrm{SM}}}} = \frac{|c_X|^2}{|c_V|^2}$$



Differential distributions

[ATLAS-CONF-2013-072]

- Differential picture directly touches fundamental aspects:
  - The loop structure where new particles may be running (p_T shape).
  - The QCD structure of the calculations (N_{jets}).
- ATLAS $H\rightarrow\gamma\gamma$ result and the adventure of unfolding.
  - Illustrates the power of having more statistics (signal-like excess).



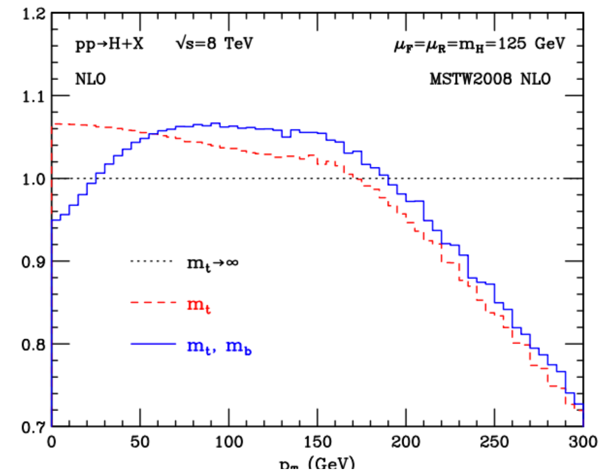
Boosted Higgs + Ratios

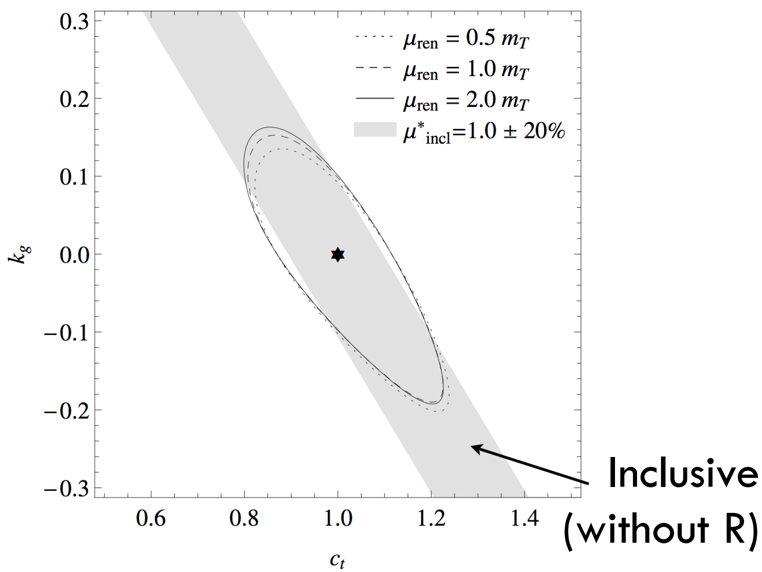
[arXiv:1306.4581] [http://cern.ch/go/lqB8]

- $p_T(H)$ sensitive to the loop particle masses.
  - m_b intrinsically ill-defined.
- Idea: check $p_T(H)$ in H+j and use THU "cancelling":

$$\mathcal{R}(c_t, k_g) = \frac{\sigma_{650\,\mathrm{GeV}}}{\sigma_{150\,\mathrm{GeV}}}(c_t, k_g)\frac{K_{650}}{K_{150}}$$

  - But it's a 3000/fb venture.



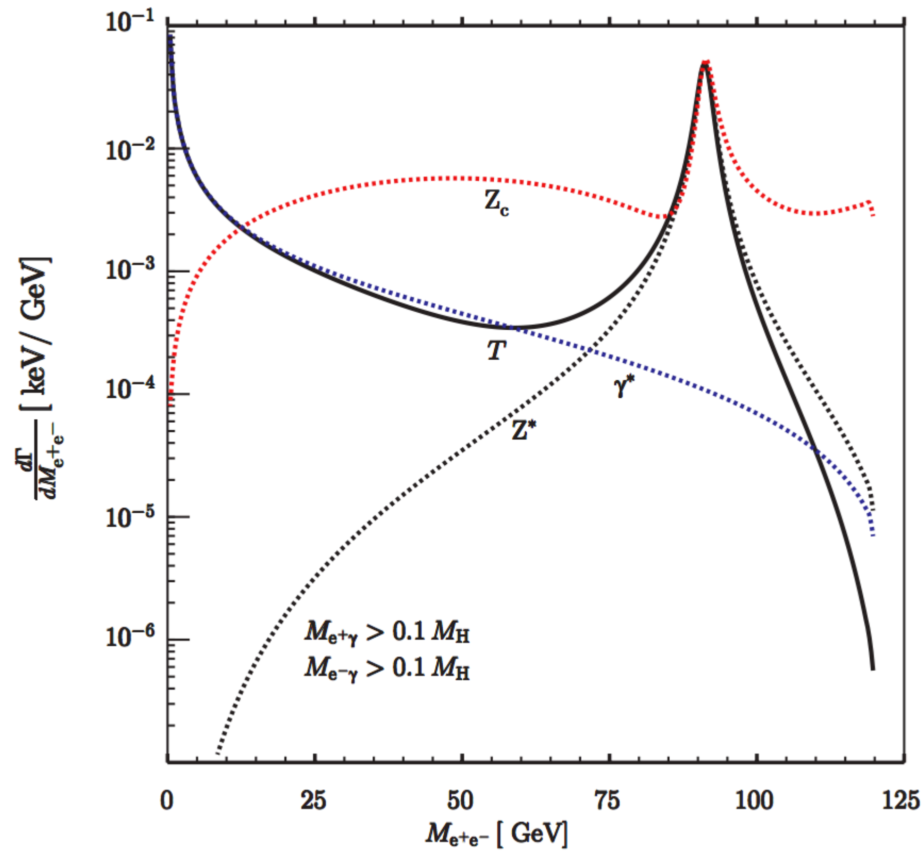


Rare decays: full Dalitz analysis

[arXiv:1308.0422]

- $\gamma\gamma$ and $Z\gamma$ loops sensitive to different physics because of V-A structure for Z.

- More information from full $m_{\ell\ell}$ spectrum.
  - Need to clearly define the phase-space used in analysis.

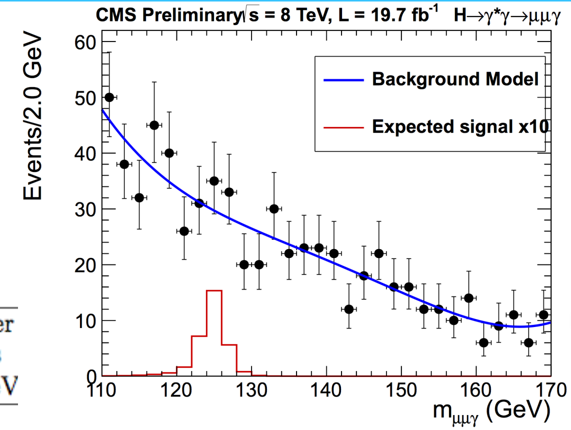


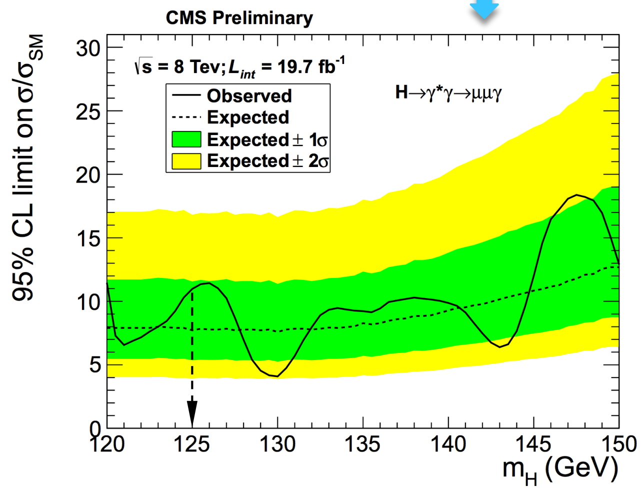
$H \to \gamma^* \gamma \to \ell\ell\gamma$

[CMS-PAS-HIG-14-003]

- $m_{\mu\mu} < 20$ GeV.
- Veto J/ψ and Υ.

Requirement	Observed event yield	Expected number of signal events for $m_H = 125$ GeV
Trigger, photon selection, $p_T^{\gamma} > 25$ GeV	0.6M	6.2
Muon selection, $p_T^{\mu 1} > 23$ GeV and $p_T^{\mu 2} > 4$ GeV	55836	4.7
110 GeV $< m_{\mu\mu\gamma} <$ 170 GeV	7800	4.7
$m_{\mu\mu} < 20$ GeV	1142	3.9
$\Delta R(\gamma, \mu) > 1$	1138	3.9
Removal of resonances	1020	3.7
$p_T^{\gamma}/m_{\mu\mu\gamma} > 0.3$ and $p_T^{\mu\mu}/m_{\mu\mu\gamma} > 0.3$	665	3.3
122 GeV $< m_{\mu\mu\gamma} <$ 128 GeV	99	2.9





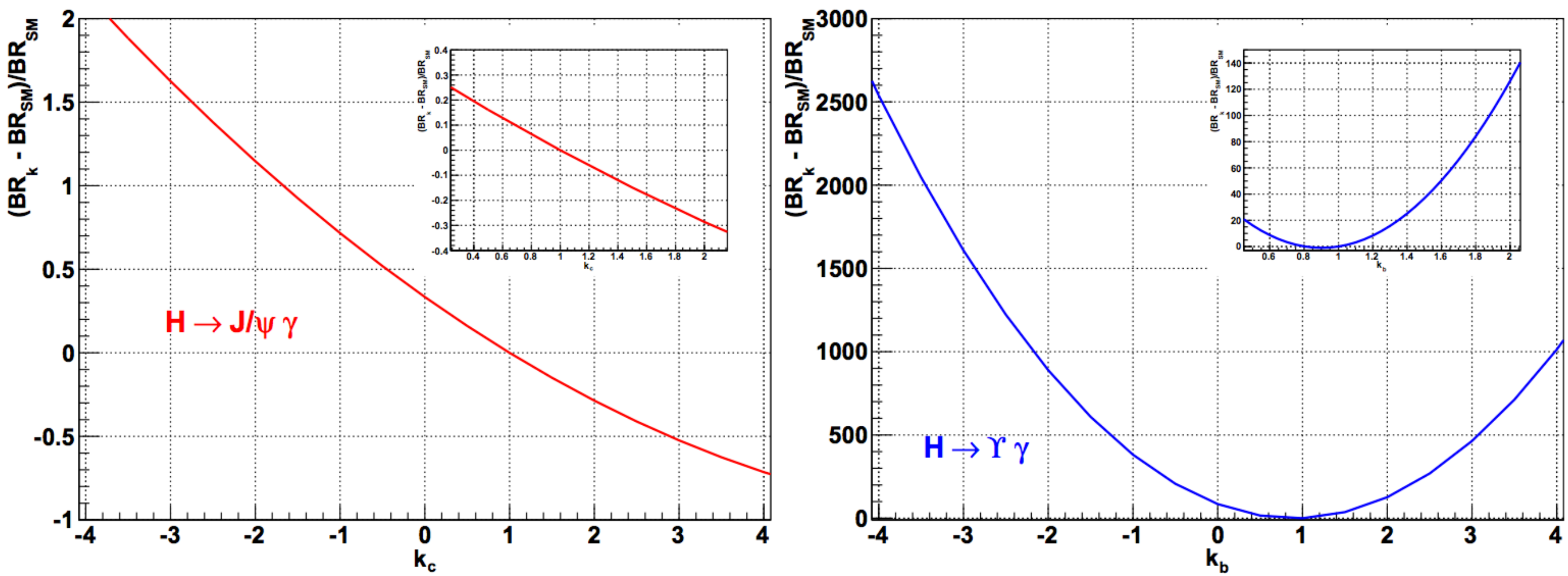
Obs. (exp.)	CMS
μ at 125 GeV (95% CL)	< 11 (8)

Weird decays: $H \rightarrow Q\bar{Q} + \gamma$

[arXiv:1306.5770]

- Complementary way to get to the bottom.
- A way to get to charm?

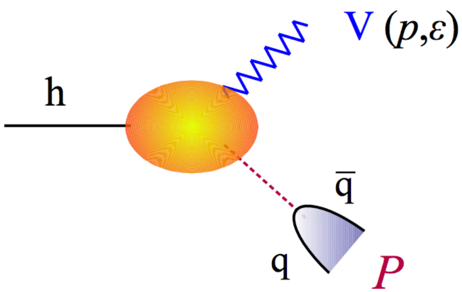
$$BR_{SM}(H \to J/\psi\,\gamma) = (2.46^{+0.26}_{-0.25}) \times 10^{-6}$$
$$BR_{SM}(H \to \Upsilon(1S)\,\gamma) = (1.41^{+2.03}_{-1.14}) \times 10^{-8}$$



Weird decays: H⟶VP

[http://cern.ch/go/8gXr]

- Accessible due to small m_H.
- Relatively clean.
- Can bear O(1) BSM changes.



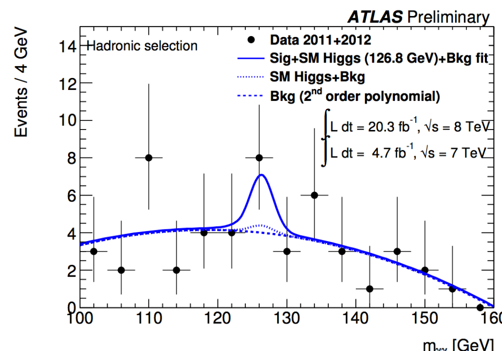
VP mode	$\mathcal{B}^{SM}$	VP^* mode	$\mathcal{B}^{SM}$
$W^-\pi^+$	0.6×10^{-5}	$W^-\rho^+$	0.8×10^{-5}
W^-K^+	0.4×10^{-6}	$Z^0\phi$	0.4×10^{-5}
$Z^0\pi^0$	0.3×10^{-5}	$Z^0\rho^0$	0.4×10^{-5}
$W^-D_s^+$	2.1×10^{-5}	$W^-D_s^{*+}$	3.5×10^{-5}
W^-D^+	0.7×10^{-6}	W^-D^{*+}	1.2×10^{-6}
$Z^0\eta_c$	1.4×10^{-5}	Z^0J/ψ	1.4×10^{-5}

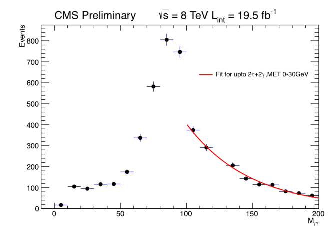
Weird decays: t⟶cH FCNC

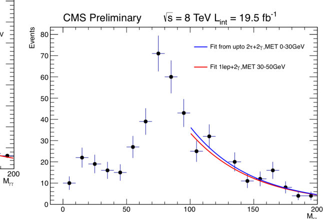
[ATLAS-CONF-2013-081] [CMS-PAS-HIG-13-034]

Process	SM	QS	2HDM-III	FC-2HDM	MSSM
$t \to u\gamma$	$3.7 \cdot 10^{-16}$	$7.5 \cdot 10^{-9}$	—	—	$2 \cdot 10^{-6}$
$t \to uZ$	$8 \cdot 10^{-17}$	$1.1 \cdot 10^{-4}$	—	—	$2 \cdot 10^{-6}$
$t \to uH$	$2 \cdot 10^{-17}$	$4.1 \cdot 10^{-5}$	$5.5 \cdot 10^{-6}$	—	10^{-5}
$t \to c\gamma$	$4.6 \cdot 10^{-14}$	$7.5 \cdot 10^{-9}$	$\sim 10^{-6}$	$\sim 10^{-9}$	$2 \cdot 10^{-6}$
$t \to cZ$	$1 \cdot 10^{-14}$	$1.1 \cdot 10^{-4}$	$\sim 10^{-7}$	$\sim 10^{-10}$	$2 \cdot 10^{-6}$
$t \to cH$	$3 \cdot 10^{-15}$	$4.1 \cdot 10^{-5}$	$1.5 \cdot 10^{-3}$	$\sim 10^{-5}$	10^{-5}

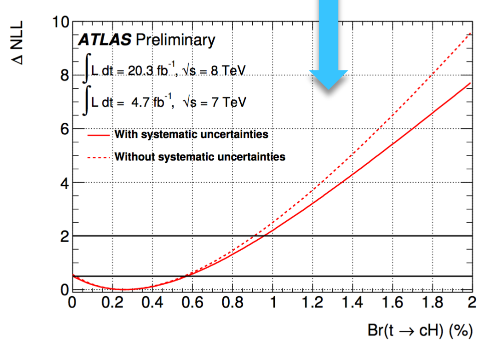
- Tree-level in BSM.
- SMH now a background:
  - ATLAS H⟶$\gamma\gamma$.
  - CMS H⟶$\gamma\gamma$ & multileptons.







OSSF pair	$N_{\tau_{had}}$	E_T^{miss} [GeV]	H_T [GeV]	$N_{b\text{-jets}}$	data	background	signal	efficiency [10^{-5}]
below Z	0	50–100	0–200	≥ 1	48	48 ± 23	9.5 ± 2.3	10.3 ± 2.5
n/a	0	50–100	0–200	≥ 1	29	26 ± 13	5.9 ± 1.3	6.4 ± 1.4
below Z	0	0–50	0–200	≥ 1	34	42 ± 11	5.9 ± 1.2	6.4 ± 1.3
n/a	0	0–50	0–200	≥ 1	29	23 ± 10	4.3 ± 1.1	4.7 ± 1.2
below Z	0	50–100	> 200	≥ 1	10	9.9 ± 3.7	3.0 ± 1.1	3.3 ± 1.2
below Z	0	0–50	> 200	≥ 1	5	10 ± 2.5	2.8 ± 0.8	3.1 ± 0.9
below Z	0	50–100	0–200	0	142	125 ± 27	9.7 ± 2.1	10.6 ± 2.3
n/a	1	0–50	0–200	≥ 1	237	240 ± 113	13.1 ± 2.6	14.3 ± 2.8
n/a	0	50–100	0–200	0	35	38 ± 15	4.3 ± 1.1	4.7 ± 1.2
above Z	0	0–50	0–200	≥ 1	17	18 ± 6.7	2.8 ± 0.8	3.1 ± 0.9



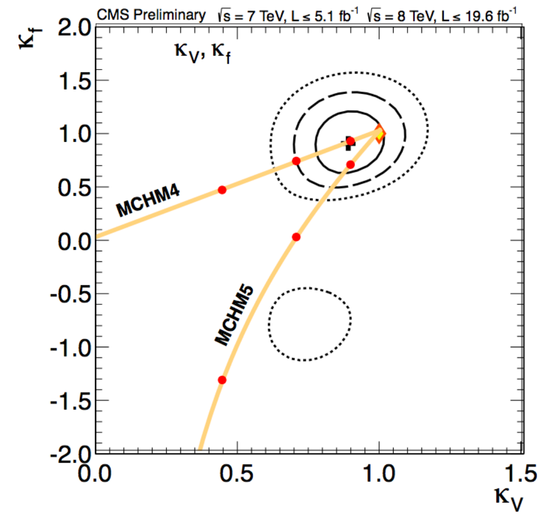
Higgs Decay Mode		observed	expected	1σ range
$H \to WW^*$	$(\mathcal{B} = 23.1\,\%)$	1.58 %	1.57 %	(1.02–2.22) %
$H \to \tau\tau$	$(\mathcal{B} = 6.15\,\%)$	7.01 %	4.99 %	(3.53–7.74) %
$H \to ZZ^*$	$(\mathcal{B} = 2.89\,\%)$	5.31 %	4.11 %	(2.85–6.45) %
combined multileptons (WW^*, $\tau\tau$, ZZ^*)		1.28 %	1.17 %	(0.85–1.73) %
$H \to \gamma\gamma$	$(\mathcal{B} = 0.23\,\%)$	0.69 %	0.81 %	(0.60–1.17) %
combined multileptons + diphotons		0.56 %	0.65 %	(0.46–0.94) %

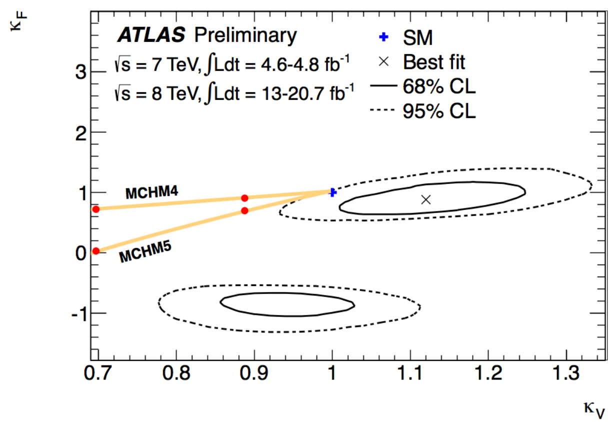
Obs. (exp.)	ATLAS	CMS
BR(t⟶cH) (95% CL)	**< 0.83% (0.53%)**	**< 0.56% (0.65%)**

From deviations to EFTs

[http://cern.ch/go/W96V]

- Today we talk about deviations from the SMH.
  - arXiv:1209.0040 or equivalent.
  - **Draw/exclude your own theory. ➔**
- **One (single) nice feature: $\kappa=1$ recovers best SMH calculations.**
  - But that's it: we can find deviations, but only roughly fathom their meaning.





And 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: $$\frac{g_{hgg}}{g_{h_{\rm SM}gg}} \simeq 1 + 2.9\% \left(\frac{1\ \mathrm{TeV}}{m_T}\right)^2, \qquad \frac{g_{h\gamma\gamma}}{g_{h_{\rm SM}\gamma\gamma}} \simeq 1 - 0.8\% \left(\frac{1\ \mathrm{TeV}}{m_T}\right)^2$$

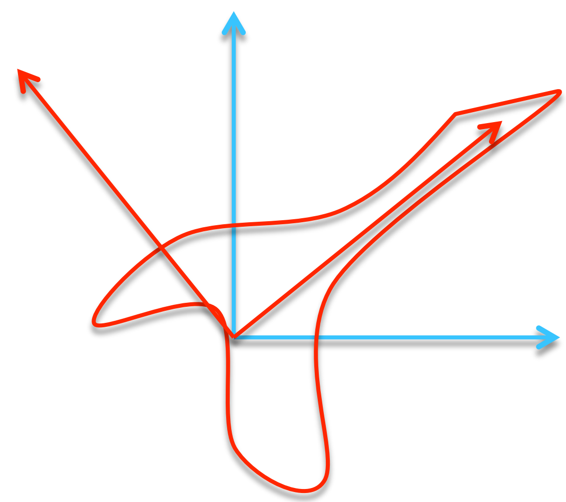
Effective field theory (EFT): the idea

[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]

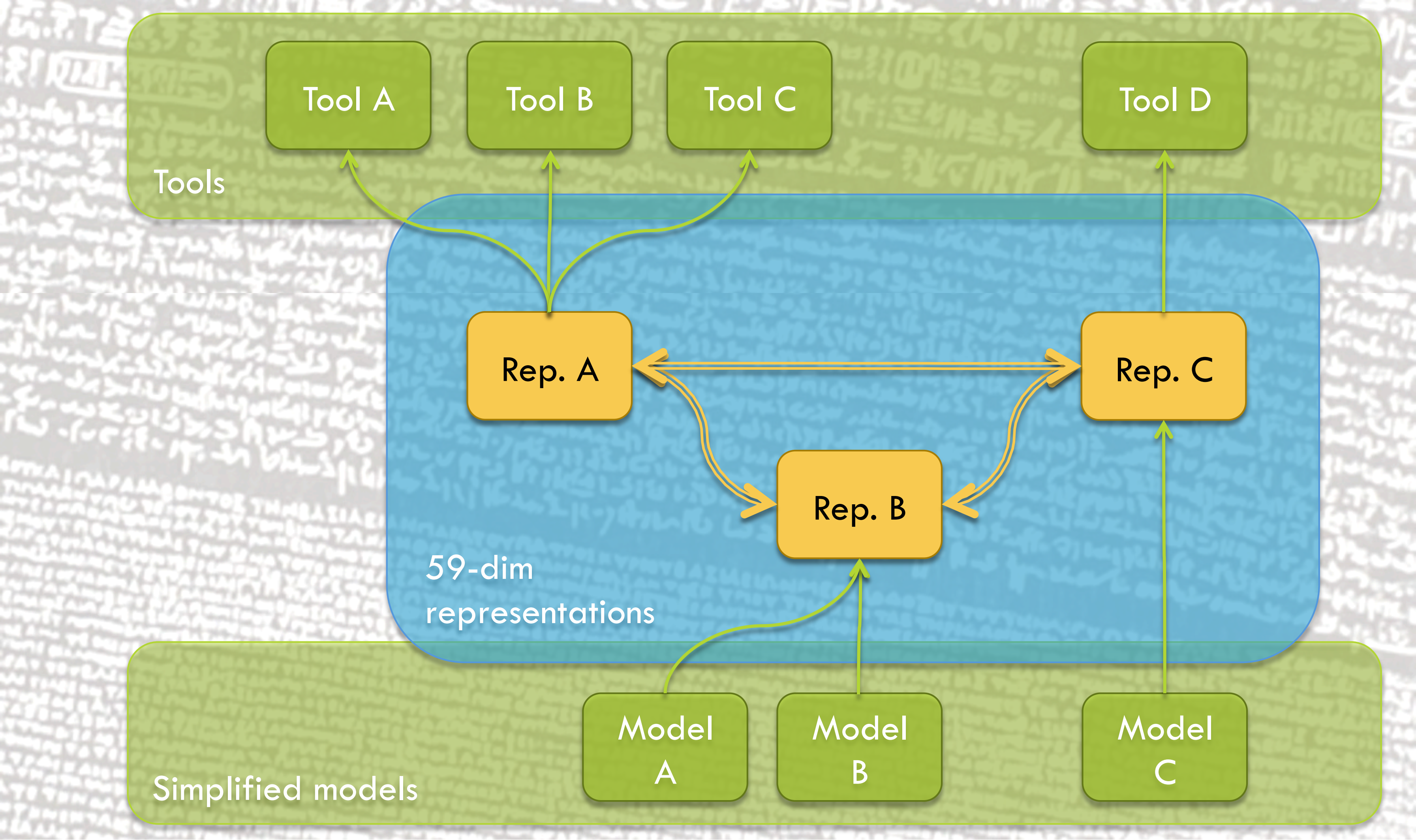
Table 52: Dimension-6 operators involving Higgs doublet fields or gauge-boson fields. For all $\psi^2\Phi^3$, $\psi^2\mathrm{X}\Phi$ operators and for $\mathcal{O}_{\Phi\mathrm{ud}}$ the hermitian conjugates must be included as well.

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

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



EFT: one model

[http://cern.ch/go/lgT8]

- Multiple sectors affected:
  - **Electroweak precision data.**
  - **Anomalous triple gauge couplings.**
  - **Higgs only.**
- Global EWK fit should be possible.

19= 8+3+8

change Higgs kin. term: VV→h

$\mathcal{O}_H = \frac{1}{2}(\partial^\mu |H|^2)^2$

$\mathcal{O}_T = \frac{1}{2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$

$\mathcal{O}_6 = \lambda |H|^6$

Affects h^3: It can be measured in the far future by GG→hh

$\mathcal{O}_W = \frac{ig}{2}\left(H^\dagger \sigma^a \overleftrightarrow{D}^\mu H\right) D^\nu W^a_{\mu\nu}$

$\mathcal{O}_B = \frac{ig'}{2}\left(H^\dagger \overleftrightarrow{D}^\mu H\right) \partial^\nu B_{\mu\nu}$

$\mathcal{O}_{HW} = ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$

$\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$

KHW-KHB → h→Zγ

h→γγ ← $\mathcal{O}_{BB} = g'^2 |H|^2 B_{\mu\nu} B^{\mu\nu}$

GG→h ← $\mathcal{O}_{GG} = g_s^2 |H|^2 G^A_{\mu\nu} G^{A\mu\nu}$

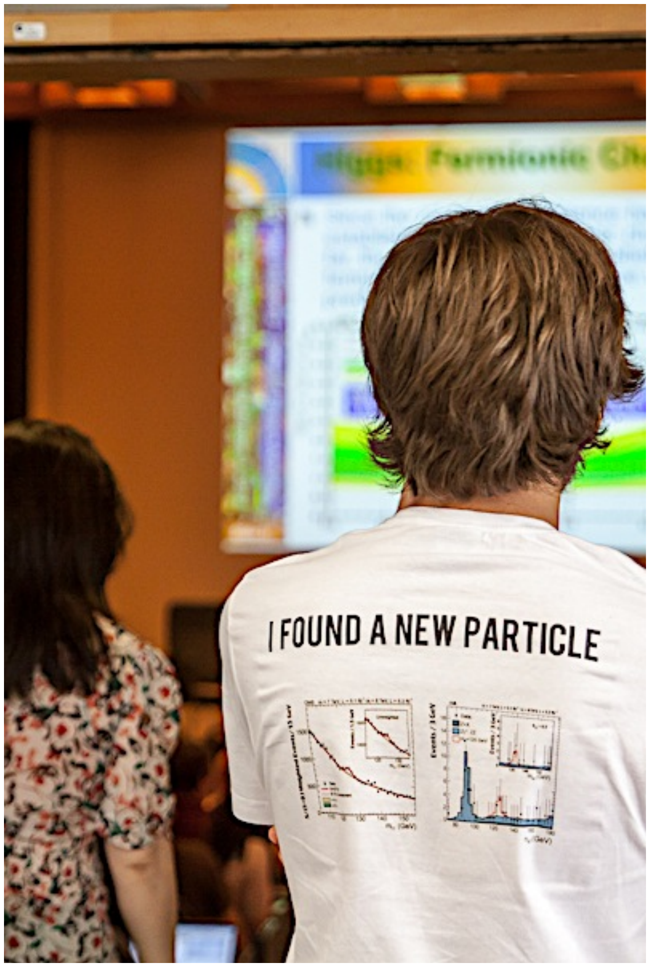
$\mathcal{O}_{3W} = \frac{1}{3!} g \epsilon_{abc} W^{a\,\nu}_{\mu} W^b_{\nu\rho} W^{c\,\rho\mu}$

h→ff

$\mathcal{O}_{y_u} = y_u \lvert H\rvert^2 \bar{Q}_L \widetilde{H} u_R$	$\mathcal{O}_{y_d} = y_d \lvert H\rvert^2 \bar{Q}_L H d_R$	$\mathcal{O}_{y_e} = y_e \lvert H\rvert^2 \bar{L}_L H e_R$
$\mathcal{O}_R^u = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{u}_R \gamma^\mu u_R)$ $\mathcal{O}_L^q = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{Q}_L \gamma^\mu Q_L)$ $\mathcal{O}_L^{(3)\,q} = (iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H)(\bar{Q}_L \sigma^a \gamma^\mu Q_L)$	$\mathcal{O}_R^d = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{d}_R \gamma^\mu d_R)$	$\mathcal{O}_R^e = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{e}_R \gamma^\mu e_R)$
		$\mathcal{O}_{LL}^{(3)\,l} = (\bar{L}_L \sigma^a \gamma^\mu L_L)(\bar{L}_L \sigma^a \gamma_\mu L_L)$

CP-even: **8 (precision test) + 3 (TGC) + 8 (Higgs physics)**
CP-odd: **+ 2 (TGC) + 3 (Higgs physics)**

Summary

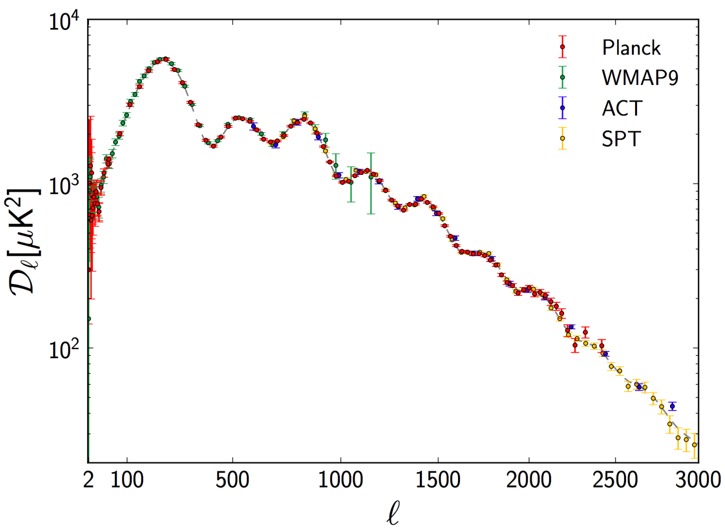


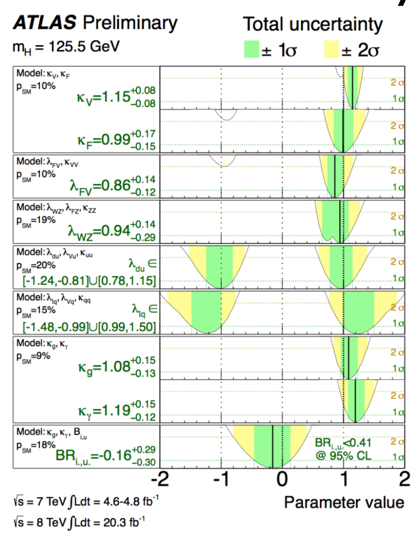
- **LHC13: last chance before a "BSM desert".**
  - Tevatron: Run I → top discovery, Run II → SM precision.
  - LHC 2010: early SUSY and EXO exclusions.
- **Higgs, one way out of the "SM oasis":**
  - From O(10%) to differential.
  - From "seen" to O(%) measurements.
  - From limits on rare things to observations.
  - From conjectures on weird things, to putting limits on them.
  - From ad-hoc κ fits to global EWK EFT fits.
- **We have a long way to go.**
  All it takes is one deviation.

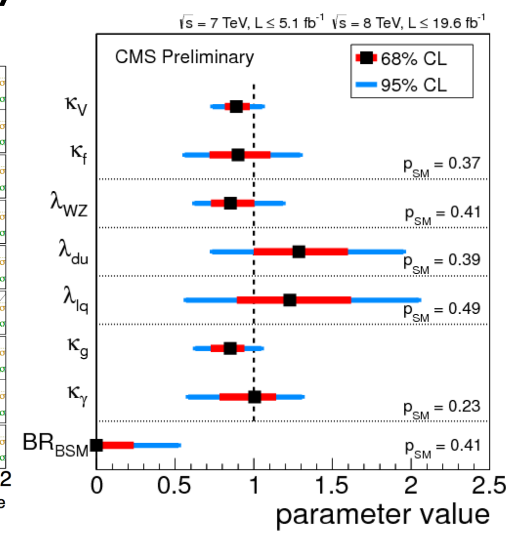
The ~~beautiful~~ ~~boring~~ 2014 Universe

[arXiv:1303.5062]

- **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, …

KEEP
CALM
AND
DISCUSS

References

"…and references therein."

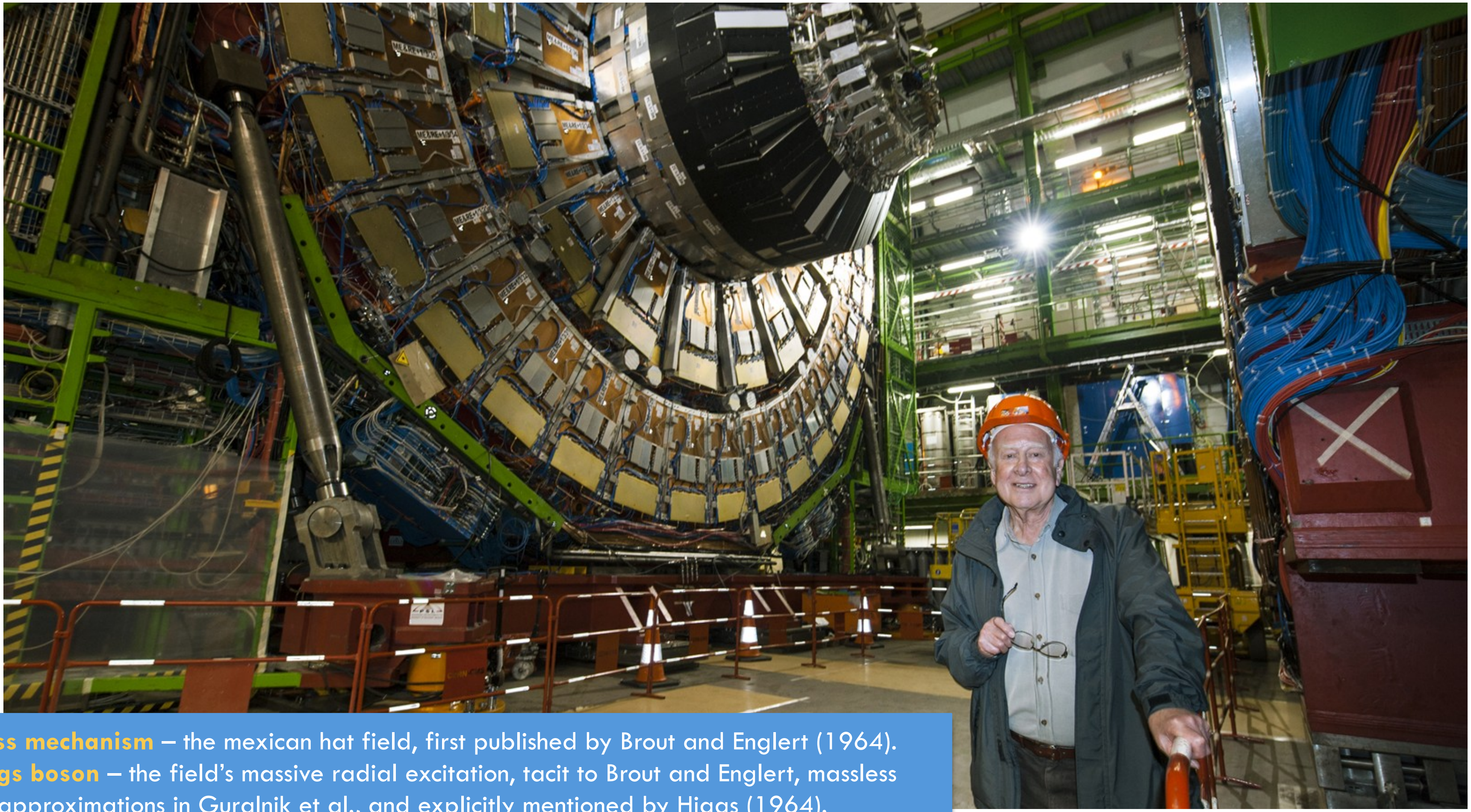
- ATLAS: http://cern.ch/go/7IDT
- CMS: http://cern.ch/go/6qmZ
- Tevatron: http://cern.ch/go/h9jX
  - CDF: http://cern.ch/go/q8NV
  - D0: http://cern.ch/go/9Djq

- 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

For discussion

Higgs in CMS – ca. 2008

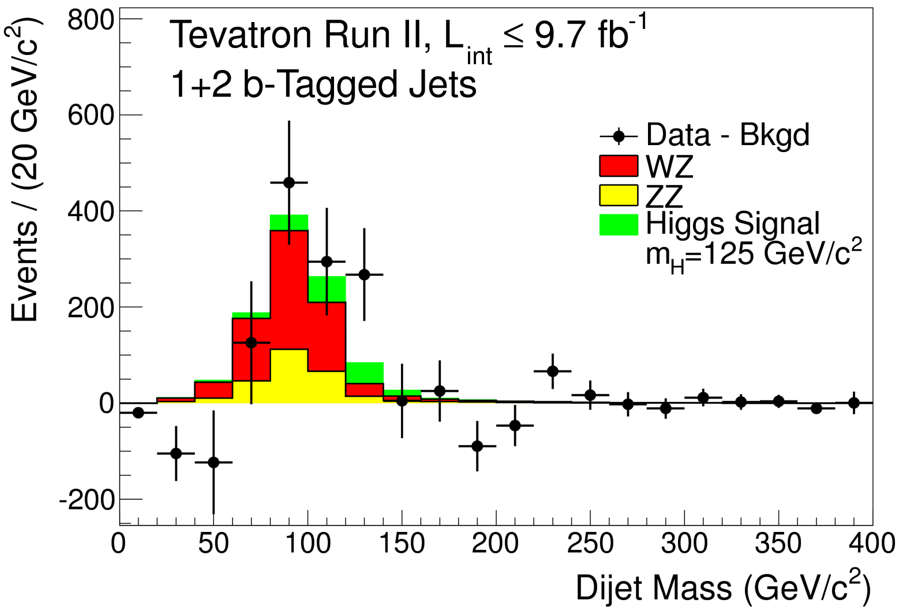
[http://cern.ch/go/dJf7] [http://cern.ch/go/Sx8m]

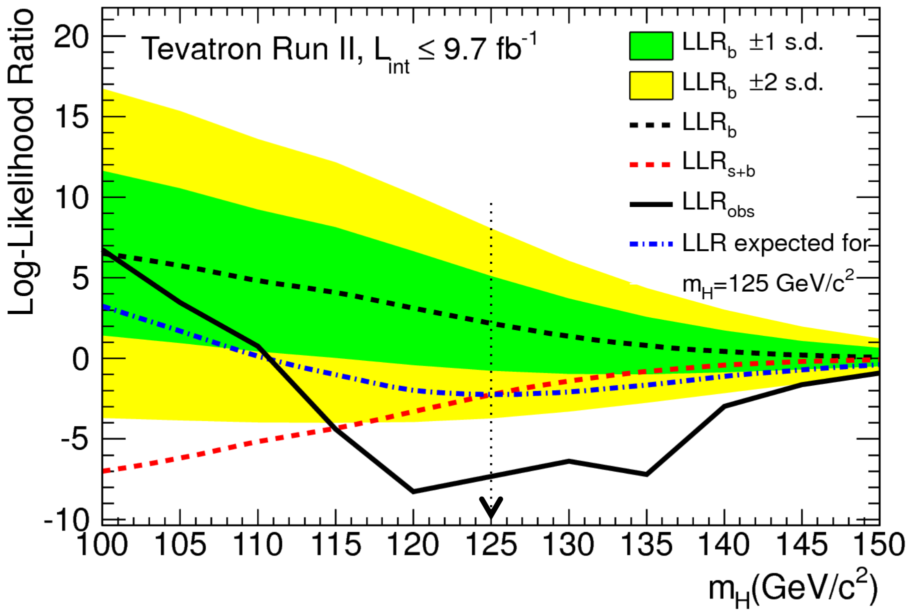


- **Mass mechanism** – the mexican hat field, first published by Brout and Englert (1964).
- **Higgs boson** – the field's massive radial excitation, tacit to Brout and Englert, massless via approximations in Guralnik et al., and explicitly mentioned by Higgs (1964).
- **Viability** – photons and massive weak bosons can coexist was shown by Kibble (1967).

From the other side of the pond

[arXiv:1207.6436]

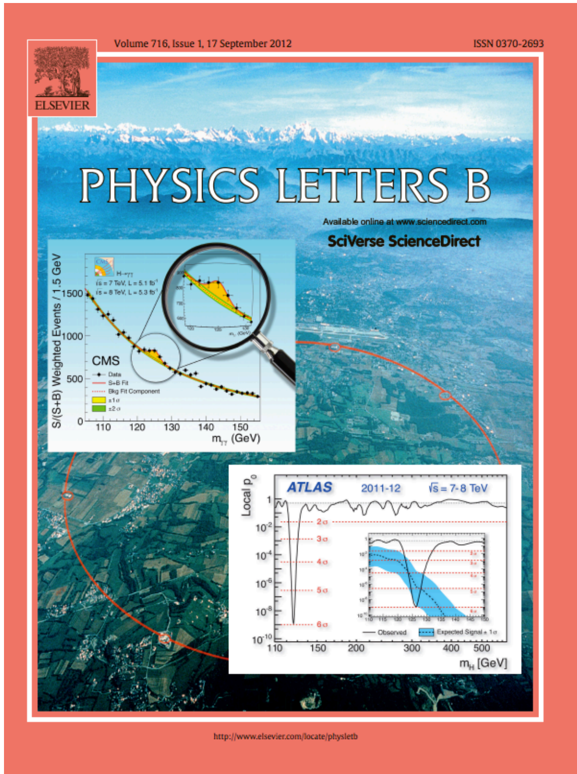




- Combination of Tevatron $VH \longrightarrow b\bar{b}$ searches, in July 2012:
  - **2.8 σ local significance at m_H=125 GeV.**

Looking up to a new boson

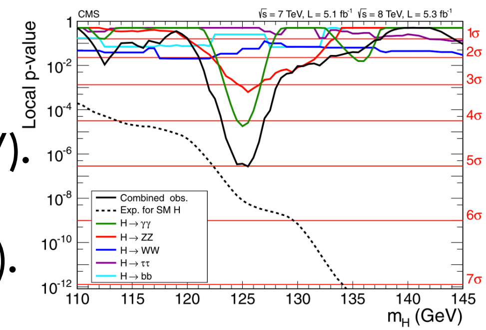
[http://cern.ch/go/q8jx]

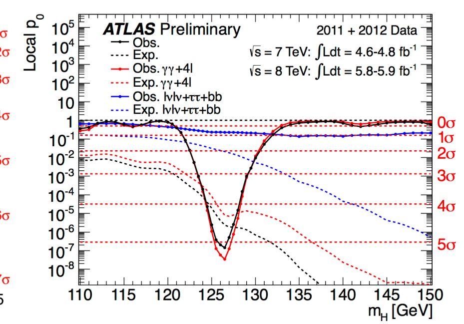


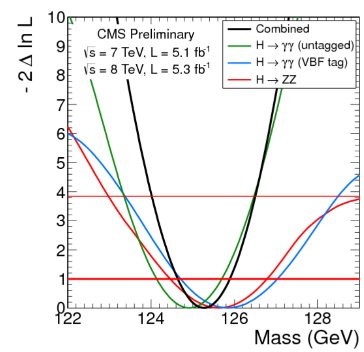
Higgsdependence day recap

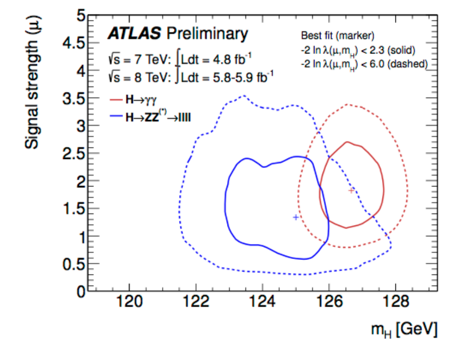
[http://cern.ch/go/q8jx]

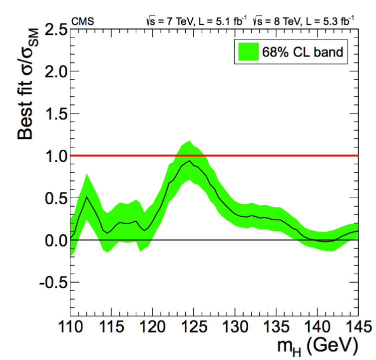
- **Both experiments at 5.0σ.**
  - One above expectations… **$\sigma_{ATLAS}/\sigma_{SM}$ = 1.2 ±0.3** (at 126.5 GeV).
  - …the other one below. **σ_{CMS}/σ_{SM} = 0.80 ±0.20** (at 125 GeV).
- Mass
  - ATLAS: min. p-value at 126.5 GeV.
  - CMS: m_X = 125.3 ±0.6 GeV.
- "Proto-couplings" compatible with SM.
- ***"More data needed…"***

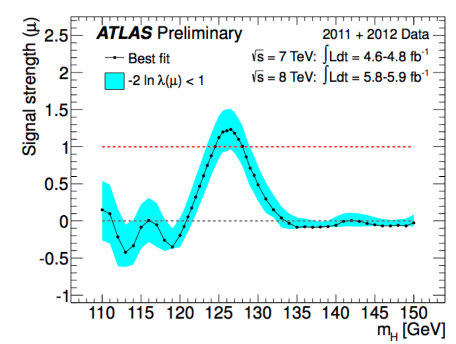


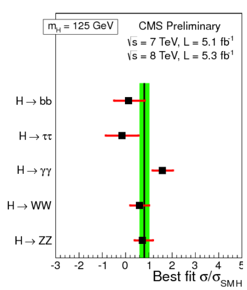


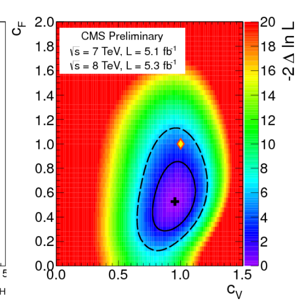


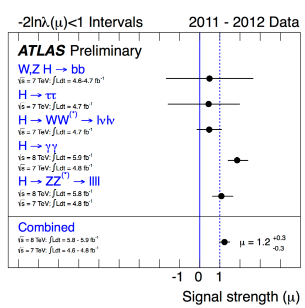












A 2012 hit

[http://goo.gl/49c0c] [http://goo.gl/suJzZ] [http://goo.gl/ShJJG]

symmetry dimensions of particle physics

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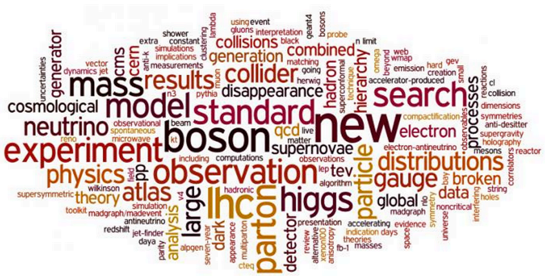

signal to background

May 12, 2013

The top 40 physics hits of 2012

The Higgs boson is a popular subject among the most-cited physics papers of 2012, but a particle simulation manual takes the top spot.

2012 reports for eprints

1. 568 citations in 2012
Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC
ATLAS Collaboration (Georges Aad (Freiburg U.) *et al.*). Jul 2012. 24 pp.
Published in **Phys.Lett. B716 (2012) 1-29**
CERN-PH-EP-2012-218
DOI: 10.1016/j.physletb.2012.08.020
e-Print: **arXiv:1207.7214 [hep-ex]** | PDF
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service; Link to all figures including auxiliary figures

2. 558 citations in 2012
Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC
CMS Collaboration (Serguei Chatrchyan (Yerevan Phys. Inst.) *et al.*). Jul 2012.
Published in **Phys.Lett. B716 (2012) 30-61**
CMS-HIG-12-028, CERN-PH-EP-2012-220
DOI: 10.1016/j.physletb.2012.08.021
e-Print: **arXiv:1207.7235 [hep-ex]** | PDF
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
CERN Document Server ; ADS Abstract Service; Link to PRESSRELEASE

3. 433 citations in 2012
Combined results of searches for the standard model Higgs boson in pp collisions at $\sqrt{s}=7$ TeV
CMS Collaboration (Serguei Chatrchyan (Yerevan Phys. Inst.) *et al.*). Feb 2012.
Published in **Phys.Lett. B710 (2012) 26-48**
CMS-HIG-11-032, CERN-PH-EP-2012-023
DOI: 10.1016/j.physletb.2012.02.064
e-Print: **arXiv:1202.1488 [hep-ex]** | PDF
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
CERN Document Server ; ADS Abstract Service

4. 381 citations in 2012
Combined search for the Standard Model Higgs boson using up to 4.9 fb^{-1} of pp collision data at $\sqrt{s}=7$ TeV with the ATLAS detector at the LHC
ATLAS Collaboration (Georges Aad (Freiburg U.) *et al.*). Feb 2012. 8 pp.
Published in **Phys.Lett. B710 (2012) 49-66**
CERN-PH-EP-2012-019
DOI: 10.1016/j.physletb.2012.02.044
e-Print: **arXiv:1202.1408 [hep-ex]** | PDF
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
CERN Document Server ; ADS Abstract Service; Link to all figures including auxiliary figures

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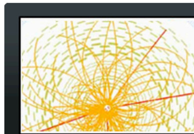
Breakthrough of the Year, 2012

Every year, crowning one scientific achievement as Breakthrough of the Year is no easy task, and 2012 was no exception. The year saw leaps and bounds in physics, along with significant advances in genetics, engineering, and many other areas. In keeping with tradition, *Science*'s editors and staff have selected a winner and nine runners-up, as well as highlighting the year's top news stories and areas to watch in 2013.



FREE ACCESS

The Discovery of the Higgs Boson

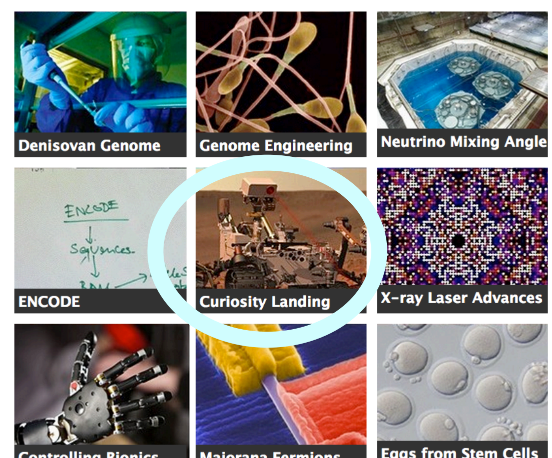
A. Cho

Exotic particles made headlines again and again in 2012, making it no surprise that the breakthrough of the year is a big physics finding: confirmation of the existence of the Higgs boson. Hypothesized more than 40 years ago, the elusive particle completes the standard model of physics, and is arguably the key to the explanation of how other fundamental particles obtain mass. The only mystery that remains is whether its discovery marks a new dawn for particle physics or the final stretch of a field that has run its course.

Read more about the Higgs boson from the research teams at CERN.

Runners-Up FREE WITH REGISTRATION

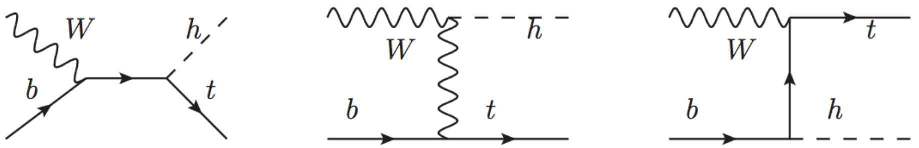
This year's runners-up for Breakthrough of the Year underscore feats in engineering, genetics, and other fields that promise to change the course of science.



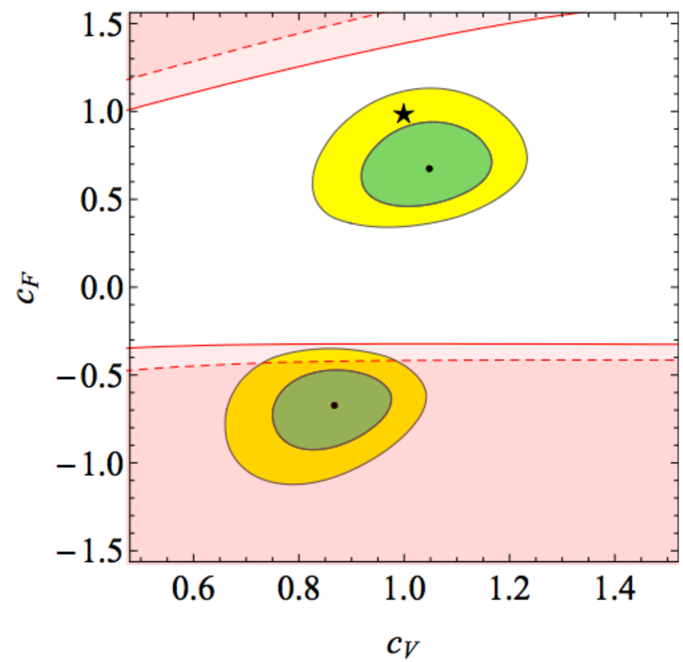
Statistics-limited: tH

[arXiv:1211.3736]

- Interesting added value to the couplings fit.
  - Esp. in the presence of a diphoton excess.

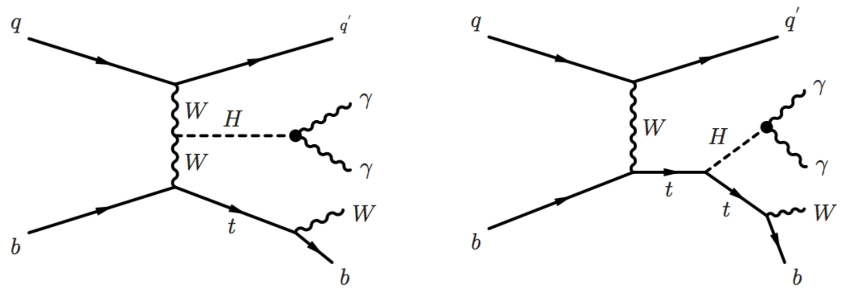


- At the top-Higgs border.
  - TH projection for 14 TeV and 50/fb looks promising.

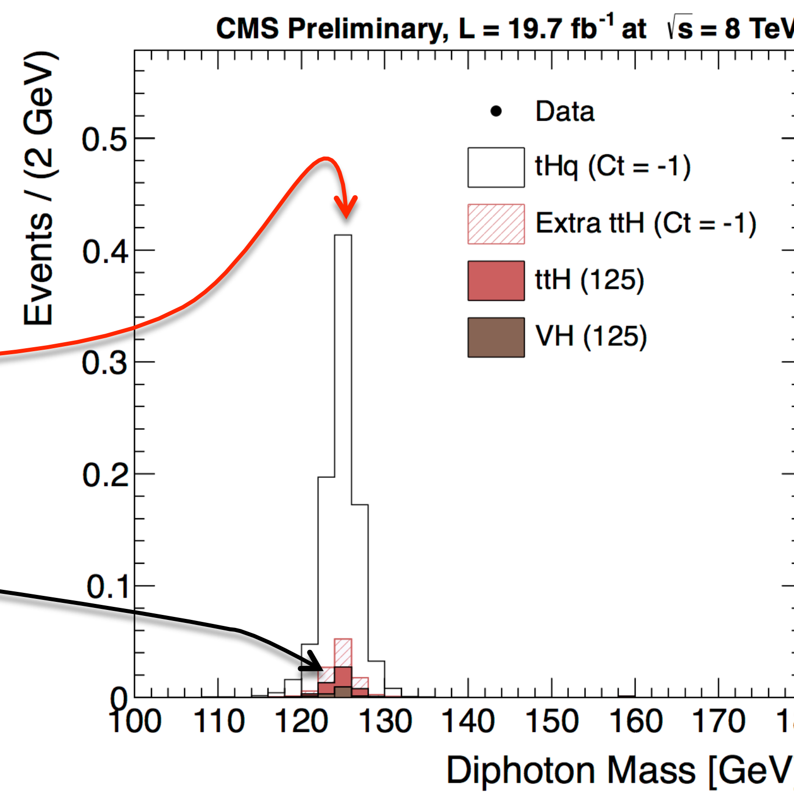


tHq and flipped couplings

[CMS-PAS-HIG-14-001]



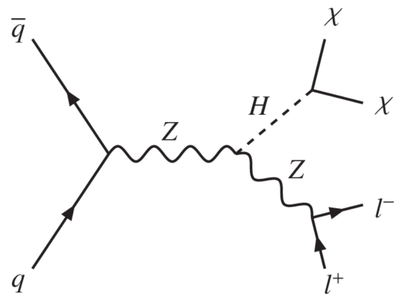
- Interference gives sensitivity to sign of $\kappa_t \kappa_W$:
  - In tHq production: **15x SM if flipped**.
  - In $H \longrightarrow \gamma\gamma$ decay: **2x SM if flipped**.
- **SMH now a background !**
- Tight selection against ttH.
  - **No data survives selection.**



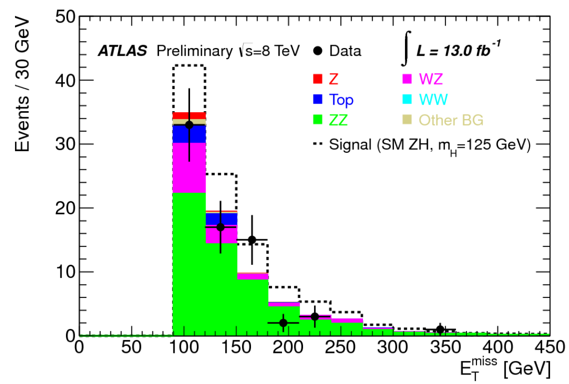
Obs. (exp.)	CMS
$\mu(\kappa_t = -1)$ at 125 GeV (95% CL)	< 4.1 (4.1)

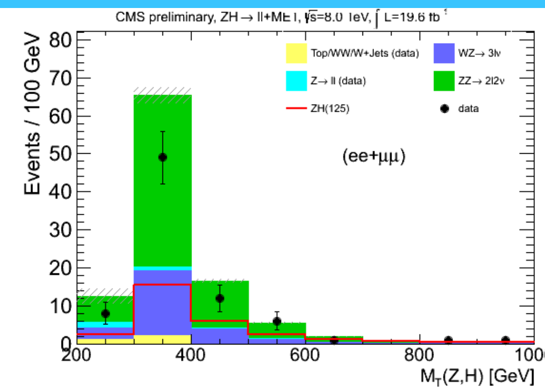
☆ ZH⟶ℓℓ+invisible

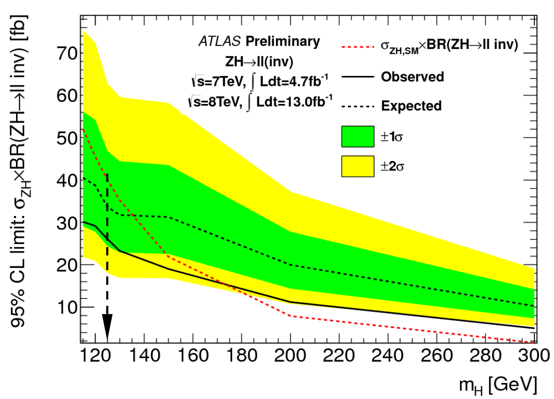
[ATLAS-CONF-2013-011] [CMS-PAS-HIG-13-018]

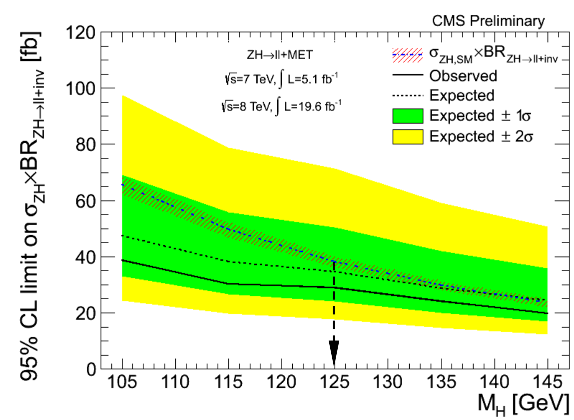


- What if?
- Disentangles *invisible* from *undetectable*.
- Cosmic connection via limits on Dark Matter.
- Also VBF and $Z \to b\bar{b}$ in CMS.





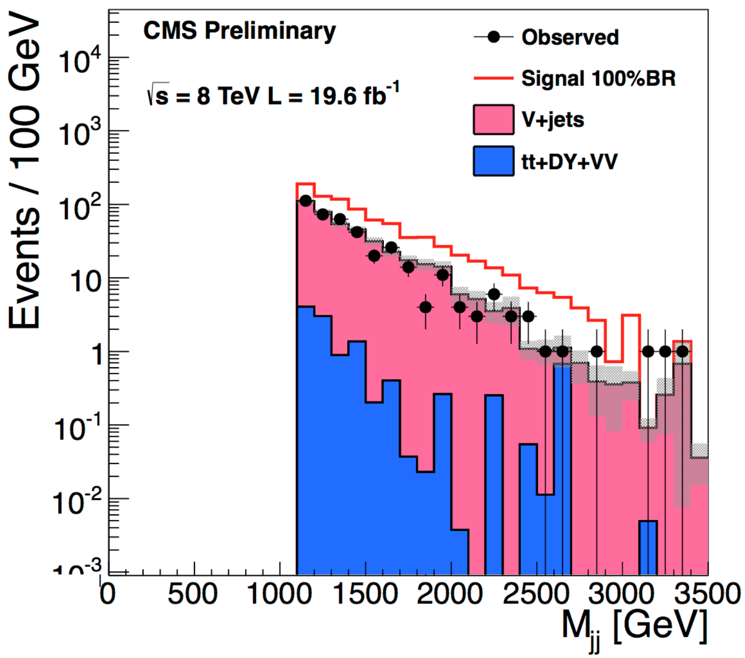


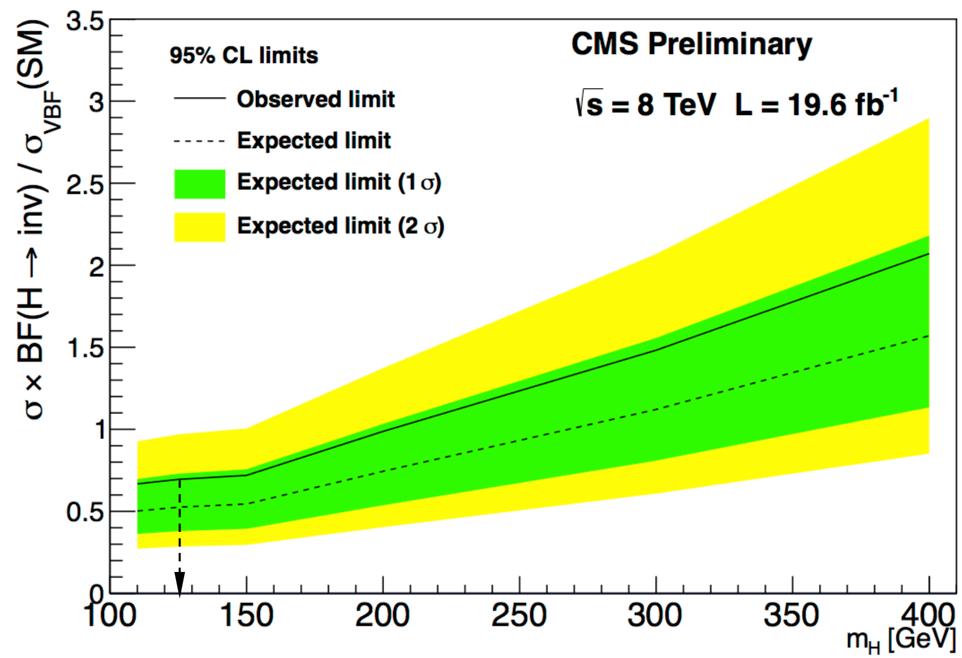


Obs. (exp.)	ATLAS	CMS
$BR_{inv.}$ at 125 GeV (95% CL)	**< 0.65 (0.84)**	**< 0.75 (0.91)**

☆ VBF, H⟶invisible

[CMS-PAS-HIG-13-013]



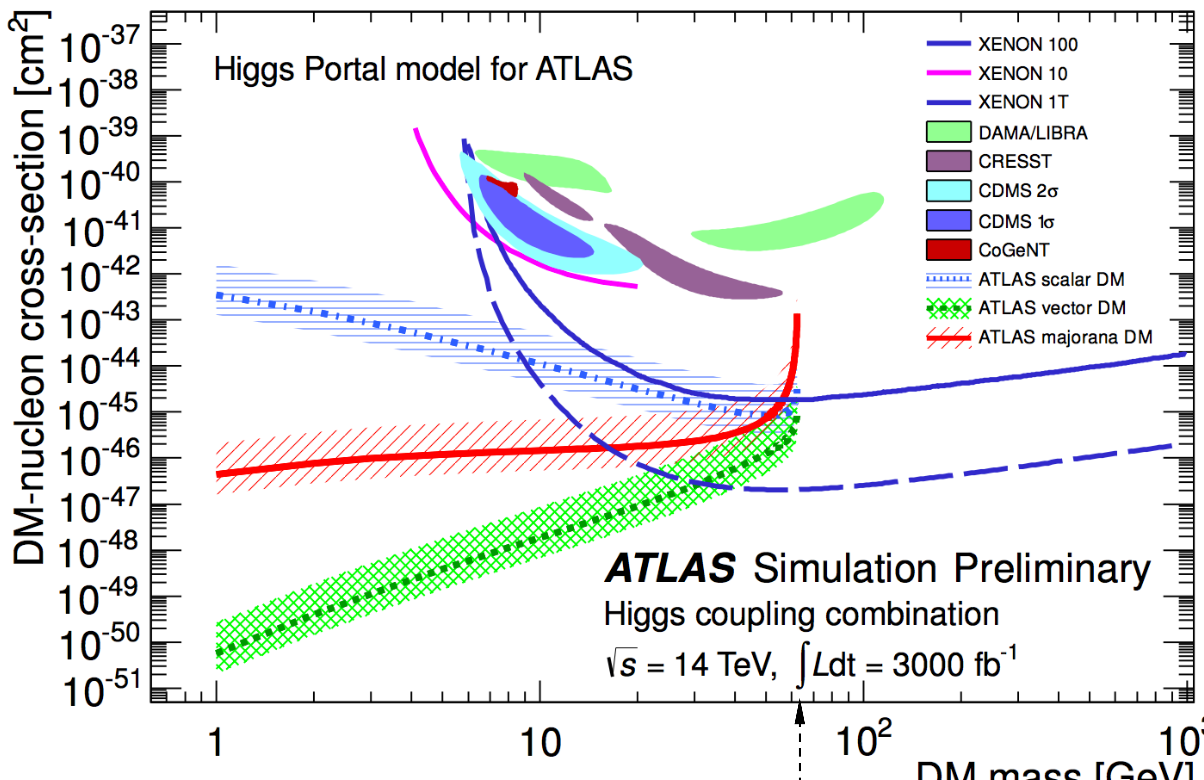


- At m_H=125 GeV,
  $BR_{inv.}$ < 0.69 (0.53) (95%CL), obs.(exp.).

Statistics-limited: invisible

[ATL-PHYS-PUB-2013-015]

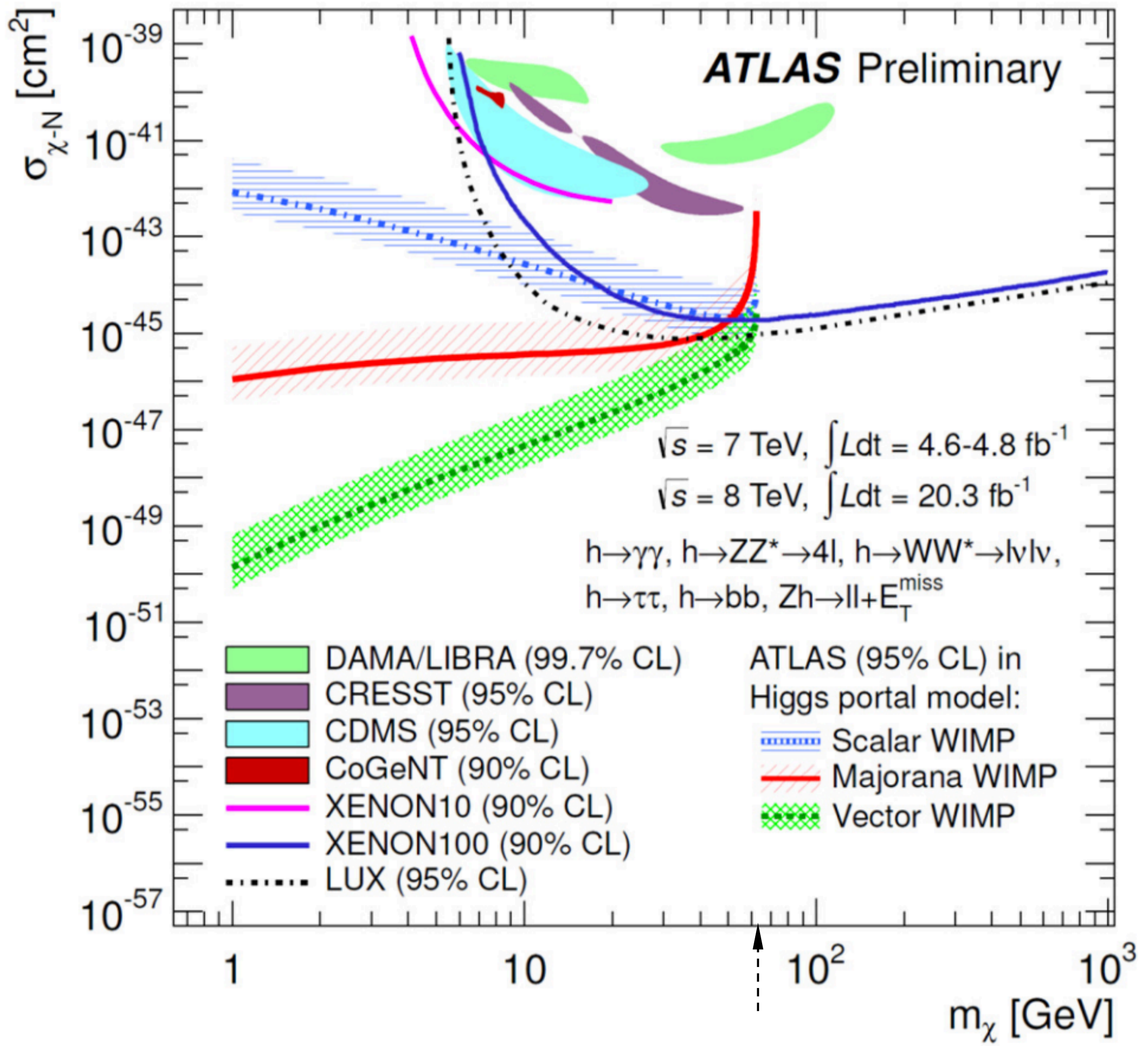
- Cosmic connection at the HL-LHC.
  - Direct bounds for massive dark particles with $m_\chi < m_H/2$.



Direct and indirect combined

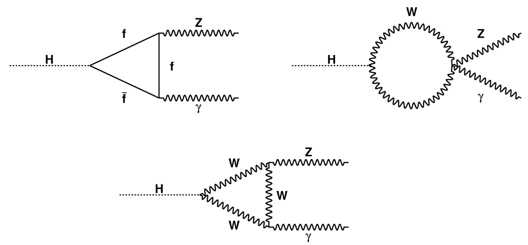
[ATLAS-CONF-2014-010] [http://cern.ch/go/bL8M]

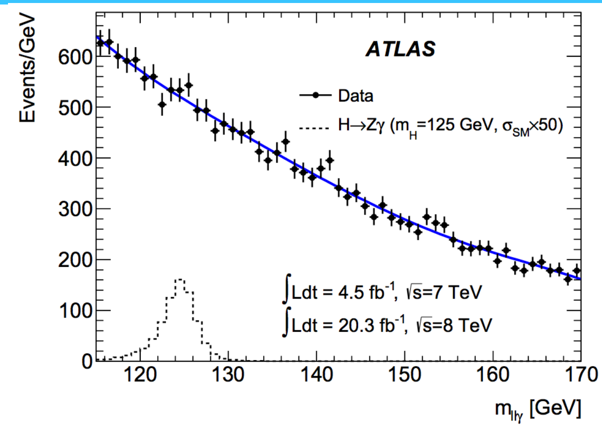
- Shown by ATLAS at Moriond 2014.
- Combination
  - **BR_{inv} < 0.37 (0.39) (95% CL), obs.(exp.)**
  - Dominated by constraints from the visible decays.

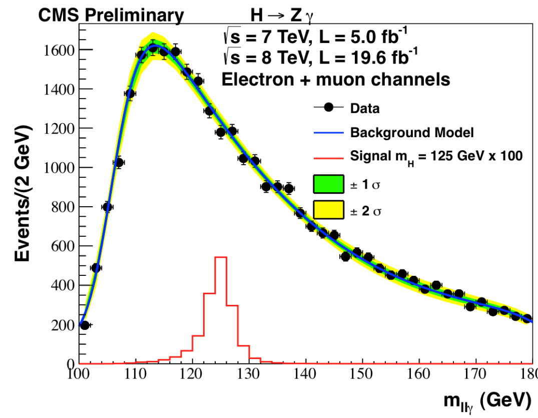


☆ $H \rightarrow Z\gamma \rightarrow \ell\ell\gamma$

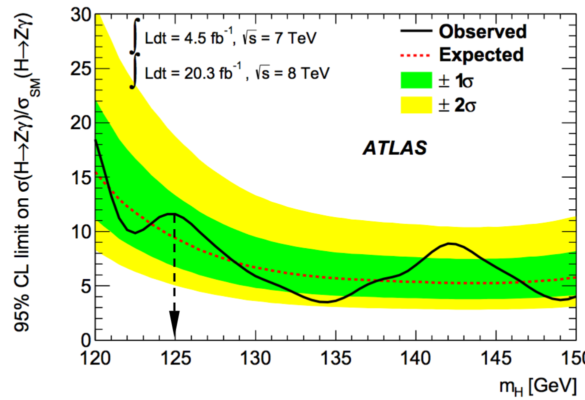
[arXiv:1402.3051] [CMS-PAS-HIG-13-006]

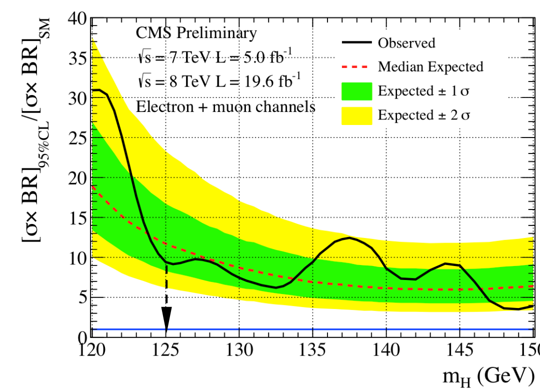






- Loop-mediated decay: sensitive to BSM.
- Both analyses on full 7 and 8 TeV data sets.



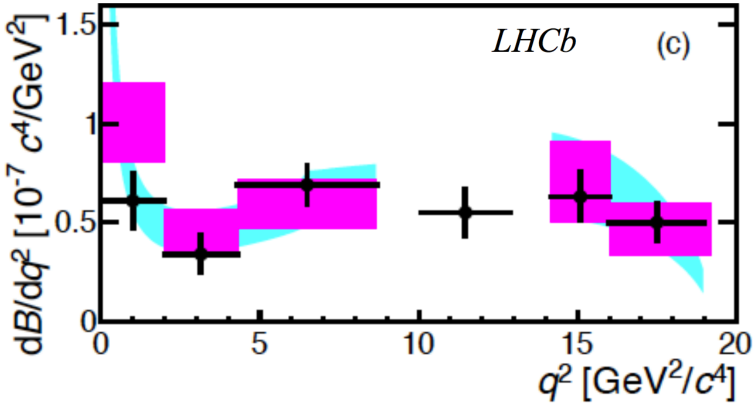


Obs. (exp.)	ATLAS	CMS
μ at 125 GeV (95% CL)	< 11 (9)	< 9 (12)

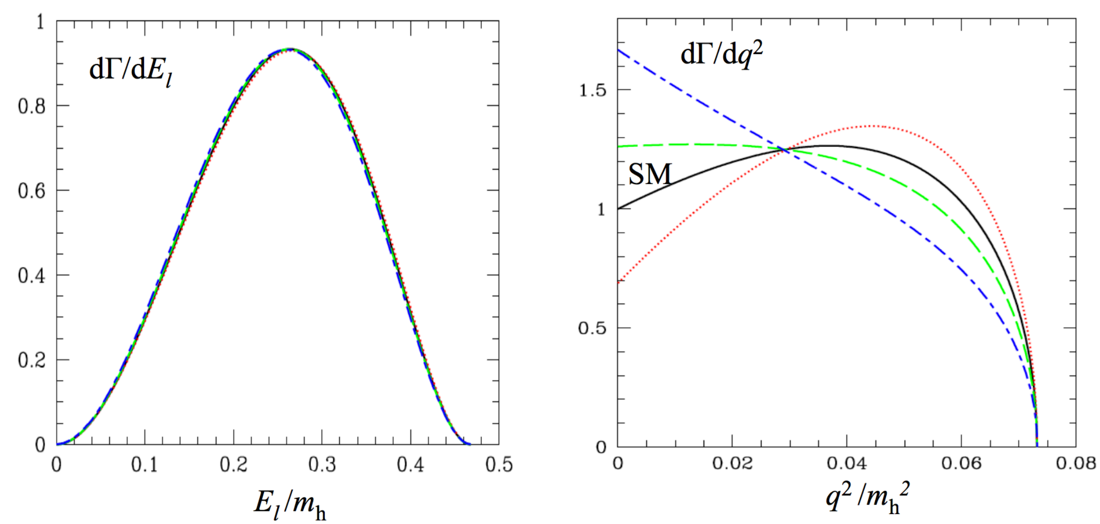
Weird form factors: H→Zℓℓ

[http://cern.ch/go/8gXr]

- Analogous to the LHCb analysis of B→K*ℓℓ.



- Can be done in the 4ℓ channel.
- Complementary to spin-CP analyses.

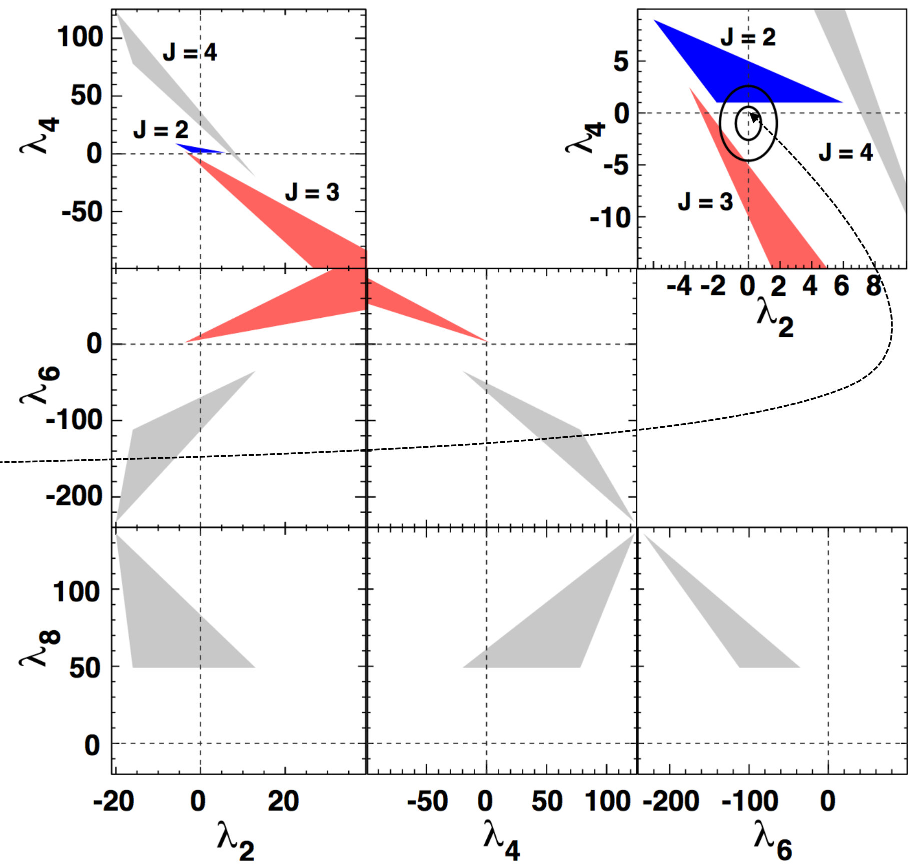


A way out the spin quandary?

[arXiv:1307.7121]

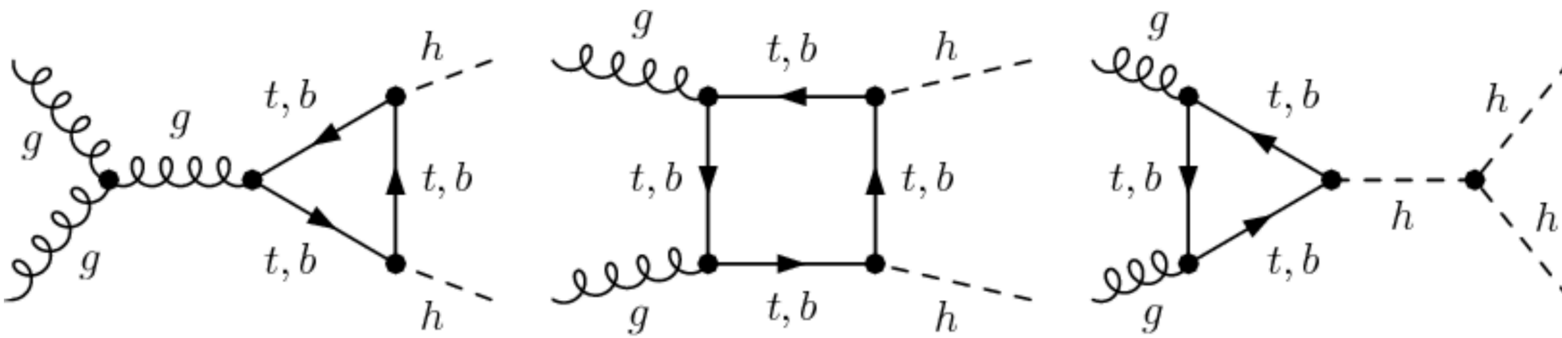
- It's not easy to kill all possible non-spin-0 alternatives.
- gg→H→ γ γ holds promise:
  - J≠0 allowed areas do not contain **J=0 point.**
  - But gluons and photons must be real…

$$w(\cos\vartheta \mid \vec{\lambda}) = \frac{1}{2} \frac{1+\sum_{i=1}^{2J} \lambda_i (\cos\vartheta)^i}{1+\sum_{j=1}^{J} \frac{\lambda_{2j}}{2j+1}}$$



Statistics-limited: HH and self-coupling

[http://cern.ch/go/7smd]



- Among main objectives for HL-LHC.
  - Tiny cross-section.
  - Diagrams interfere destructively…
  - Problematic even in e^+e^-.
- Experimental projections not finalized.

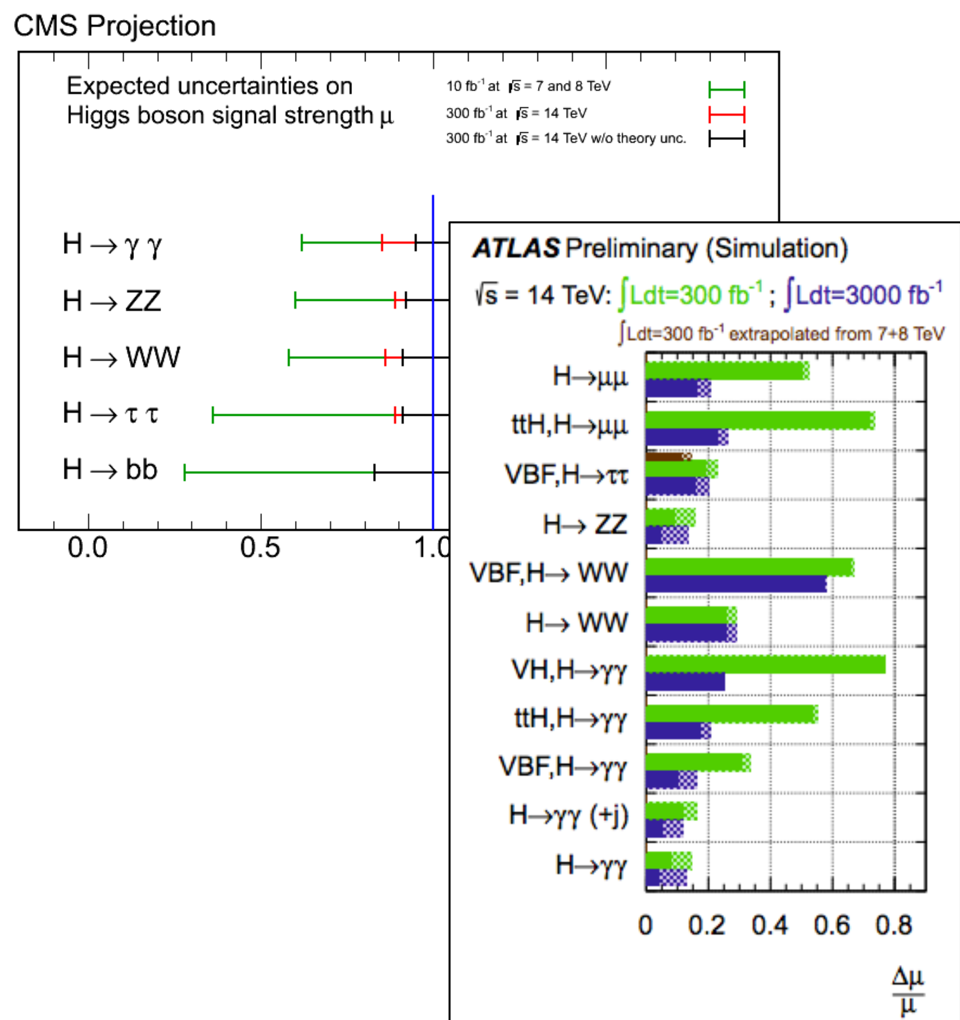
Estimated yields for 3000/fb	
$b\bar{b}WW$	30'000
$b\bar{b}\tau\tau$	9'000
WWWW	6'000
$\gamma\gamma b\bar{b}$	320
$\gamma\gamma\gamma\gamma$	1

The Future

Looking well ahead

[http://cern.ch/go/P8Tn] [http://cern.ch/go/I7RZ]

- 300/fb at 14 TeV:
  - Vast improvement over present datasets.
  - **Room for theory improvements.**
- For (HL-LHC) 3 ab^{-1}:
  - self-coupling seems feasible with $\lambda_{HH} \sim 3\sigma$/expt.



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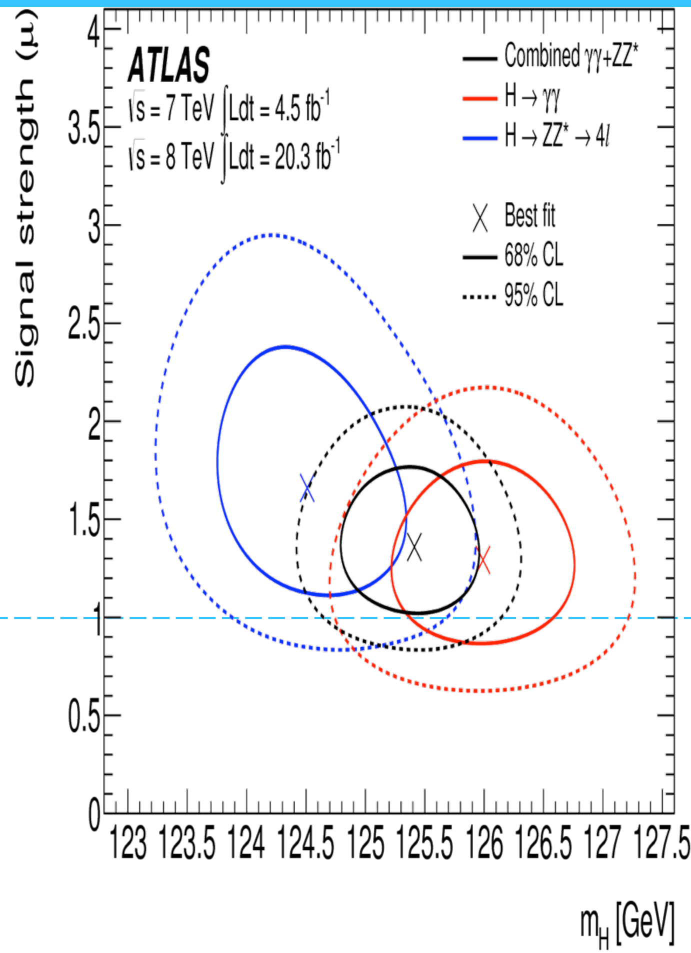
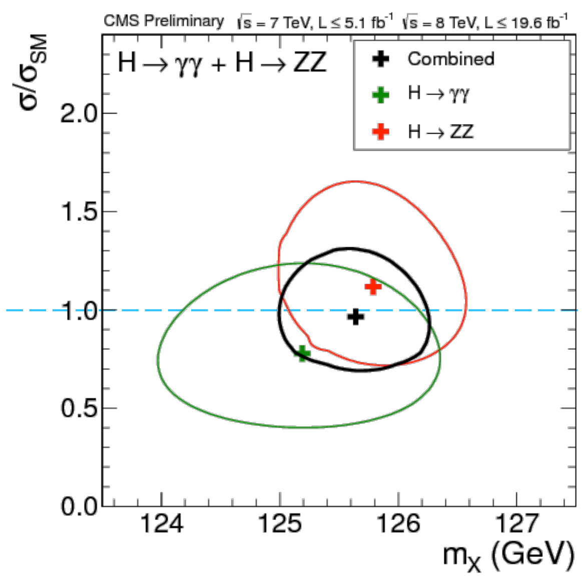
More on mass

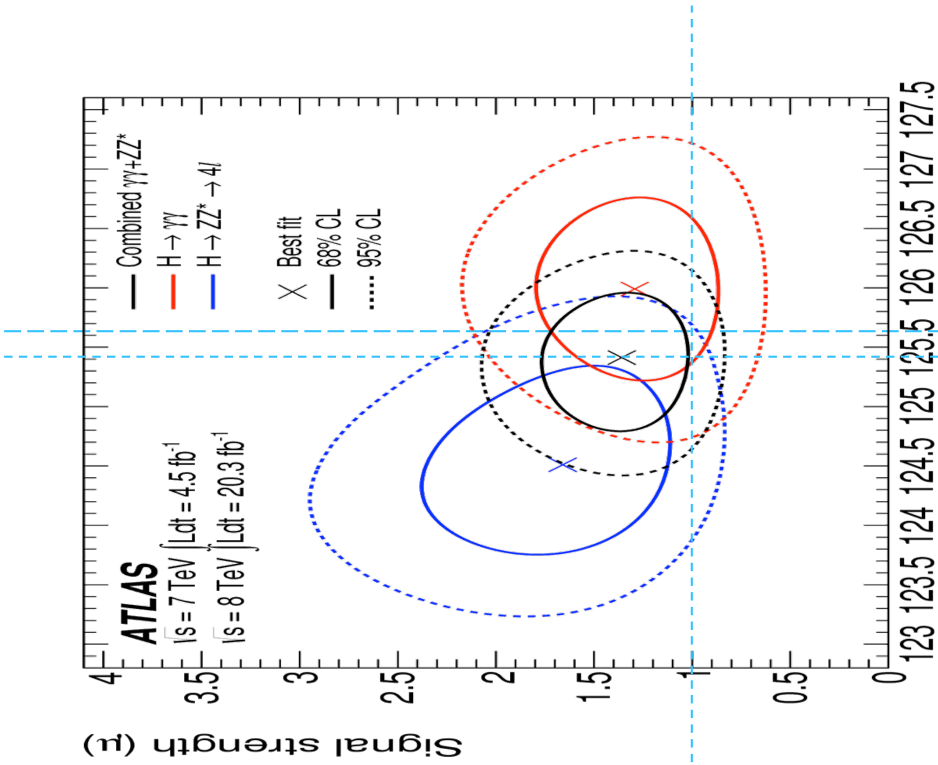
First things first: the mass

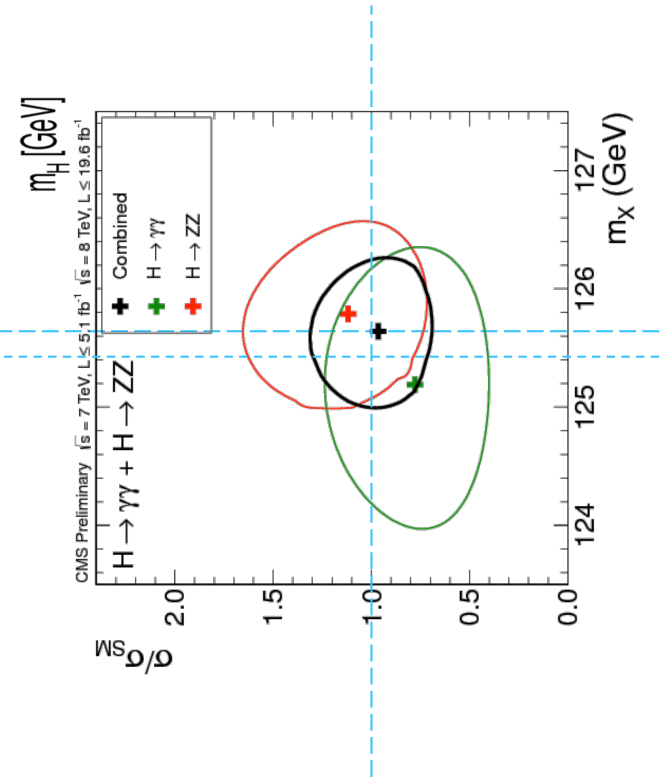




- Combinations of the high-resolution channels.

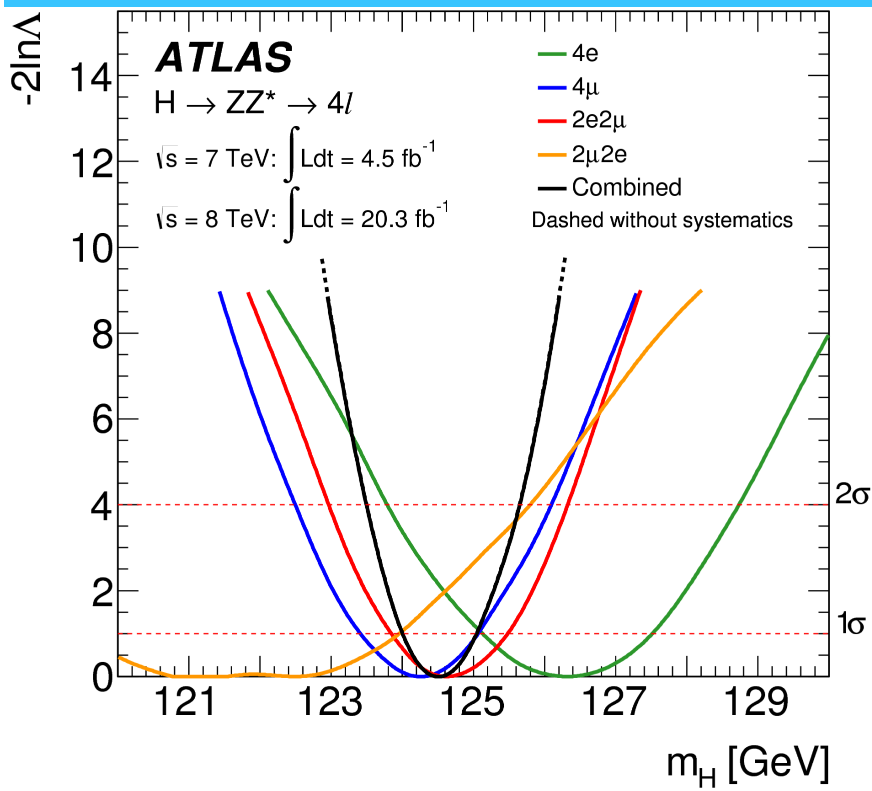
First things first: the mass

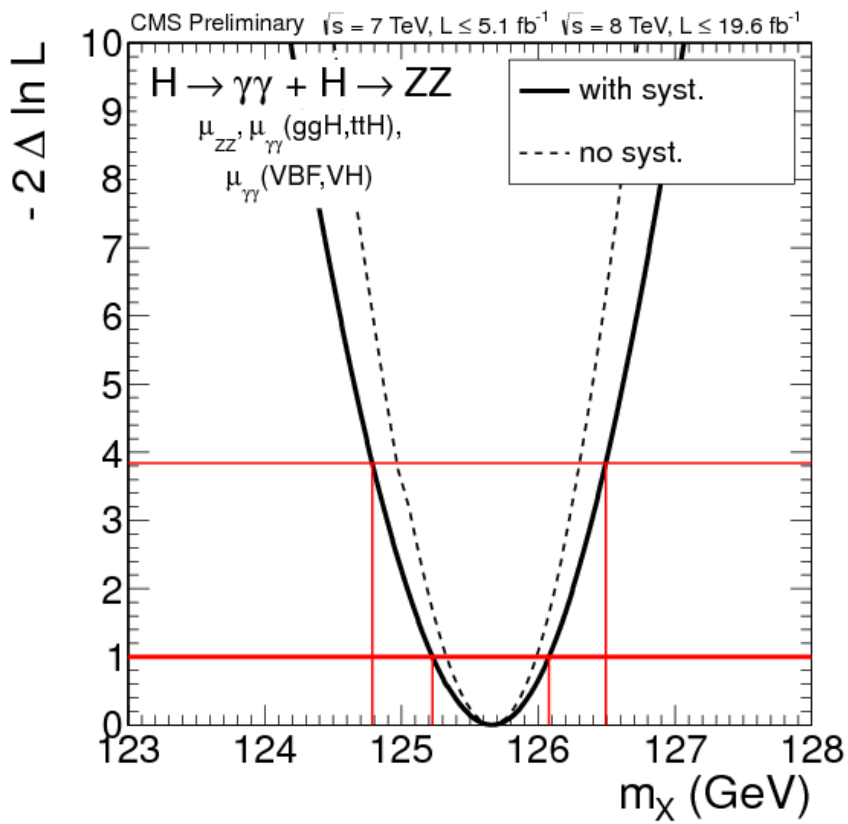




- Combinations of the high-resolution channels.

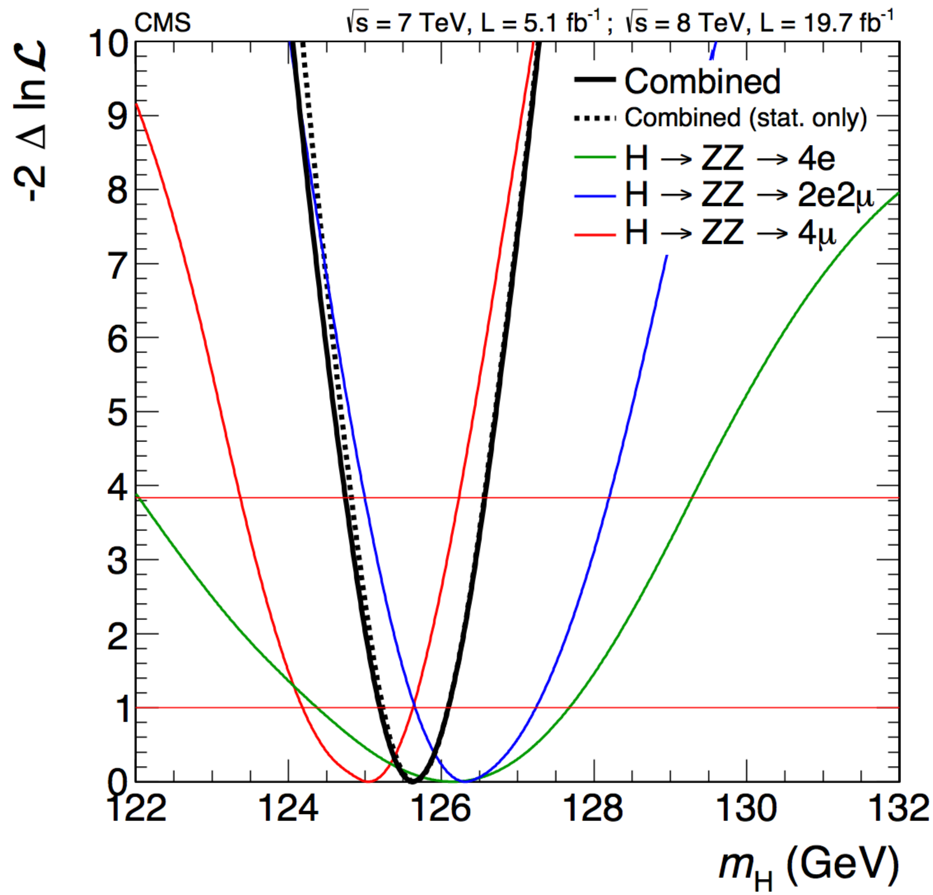
More on mass

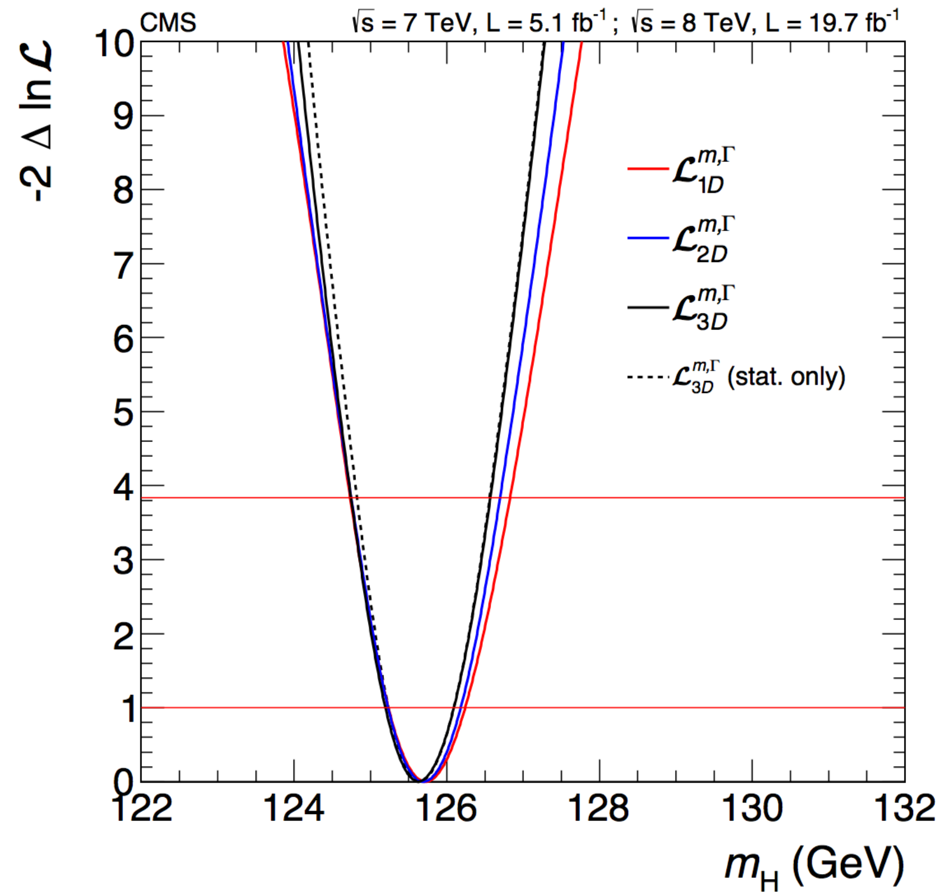

ATLAS
H → ZZ* → 4l
√s = 7 TeV: ∫Ldt = 4.5 fb-1
√s = 8 TeV: ∫Ldt = 20.3 fb-1
4e
4μ
2e2μ
2μ2e
Combined
Dashed without systematics
-2lnΛ
2σ
1σ
mH [GeV]


CMS Preliminary √s = 7 TeV, L ≤ 5.1 fb-1 √s = 8 TeV, L ≤ 19.6 fb-1
H → γγ + H → ZZ
μZZ, μγγ(ggH,ttH),
μγγ(VBF,VH)
with syst.
no syst.
- 2 Δ ln L
mX (GeV)

More on mass

[arXiv:1312.5353]





Miscellaneous

Statistics interlude

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

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

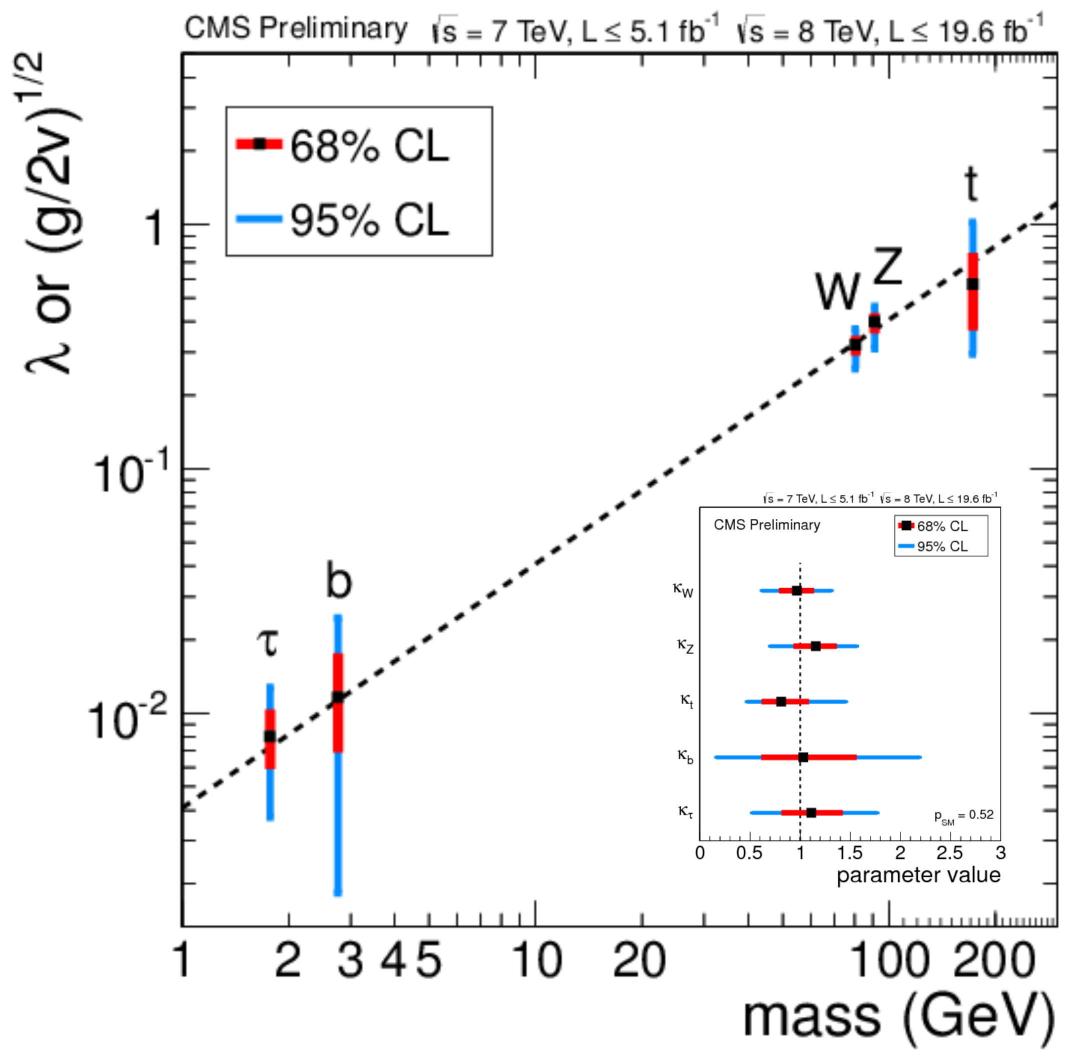
- **LEP**: nuisances parameters (θ) kept at nominal values (~).
- **Tevatron**: maximise likelihood against nuisances (^).
  - Denominator considers **background-only hypothesis** (μ =0).
- **LHC**: frequentist profiled likelihood.
  - Denominator considers **global best-fit likelihood** with **floating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

As a function of masses

Resolving SM contributions

[CMS-PAS-HIG-13-005]

- 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.
- **P(SM)=0.52.**
- "Reduced" couplings as function of "mass":
  - $\lambda_f = \kappa_f\,(m_f/vev)$
  - $(g_V/2vev)^{1/2} = \kappa_V^{1/2}\,(m_V/vev)$



"C6" vs "resolved C6"

Generic coupling fit	**Resolved coupling fit**

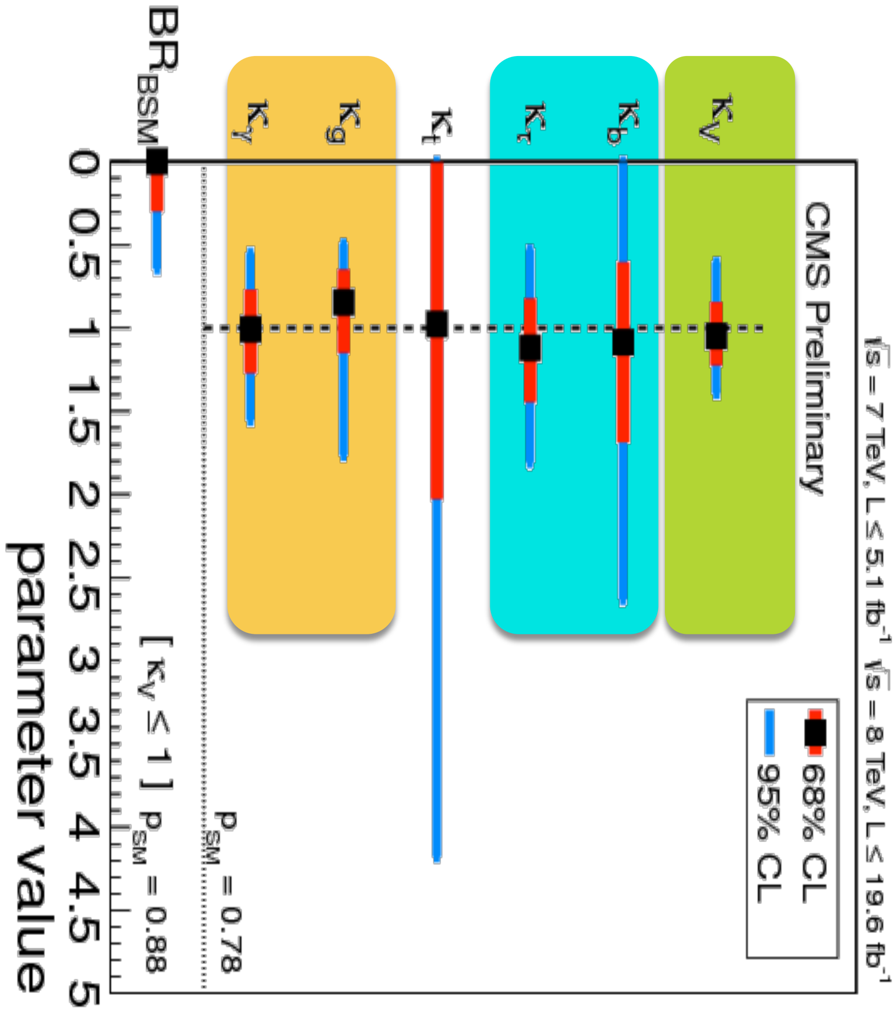
Generic coupling fit

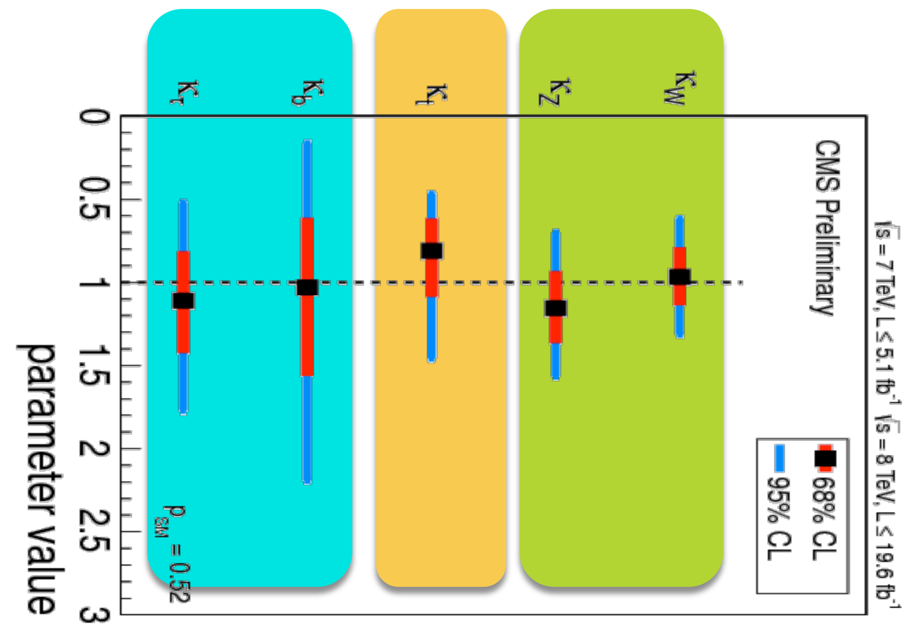
- Assume custodial symmetry ($\kappa_V = \kappa_W = \kappa_Z$).
- Loops treated effectively (κ_γ, κ_g).
- Option to allow BSM decays, forcing $\kappa_V \leq 1$.

Resolved coupling fit

- Keep W and Z separate.
- Loops assuming SM structure:
  - κ_g (κ_b, κ_t).
  - κ_γ (κ_W, κ_b, κ_t, κ_τ).
- Only SM-like decays.

“C6” vs “resolved C6”

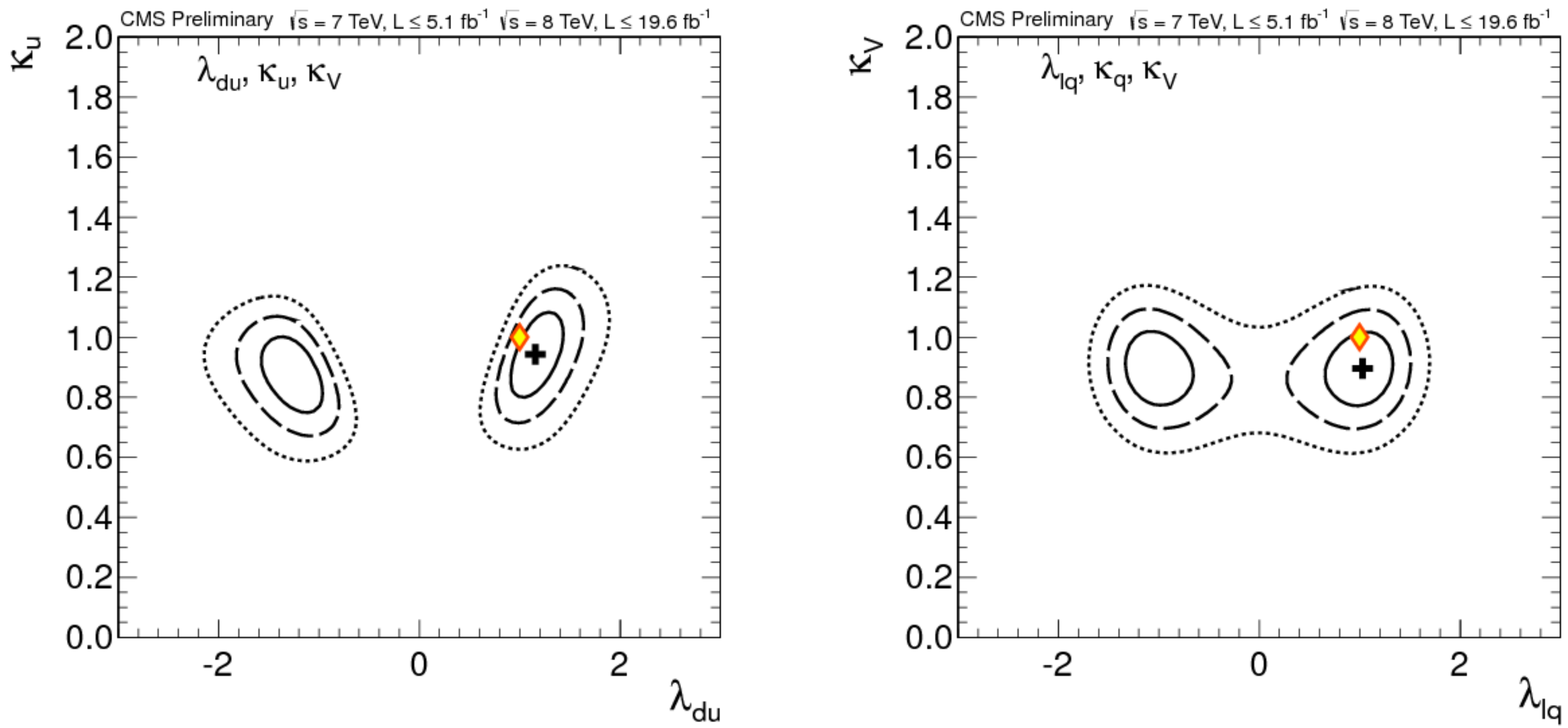




More on scalar couplings

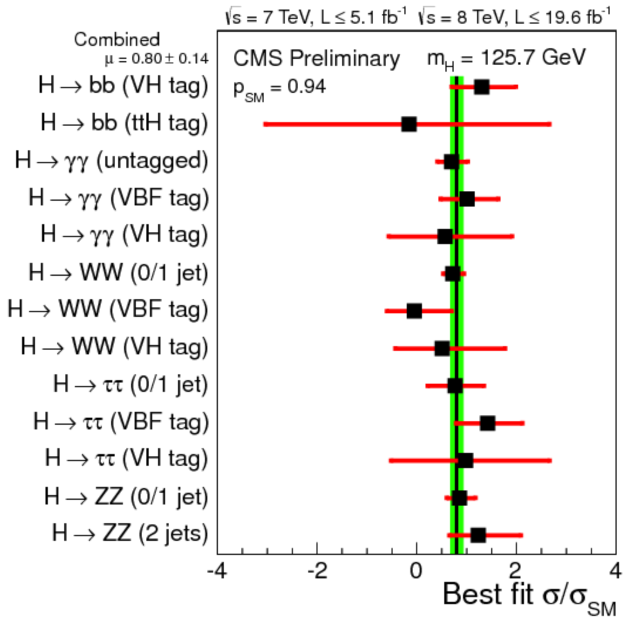
Probing possible 2HDM

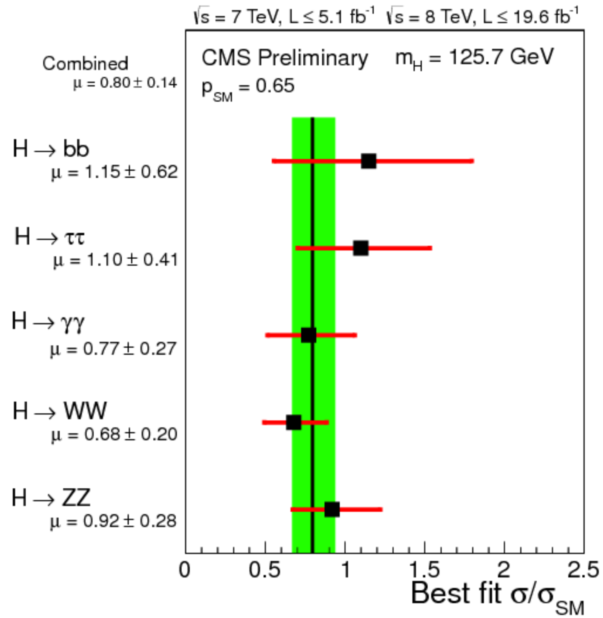
[CMS-PAS-HIG-13-005]

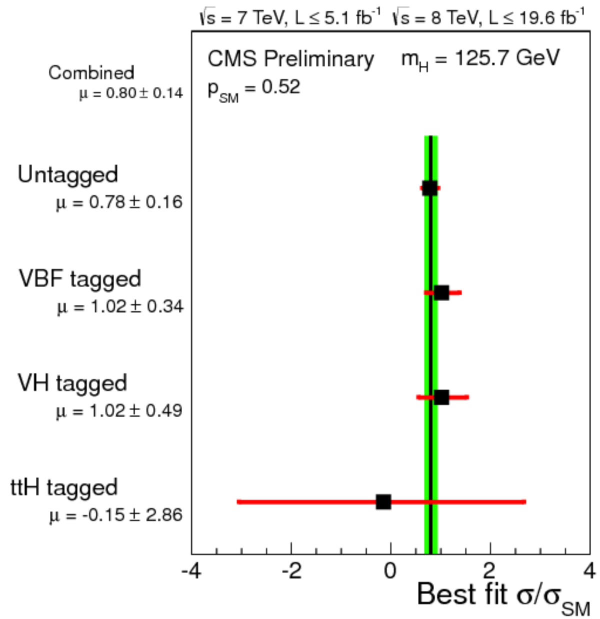


	λ_{du}	λ_{lq}
CMS	**[0.74, 1.95] (95% CL)**	**[0.57, 2.05] (95% CL)**

CMS: channel compatibility

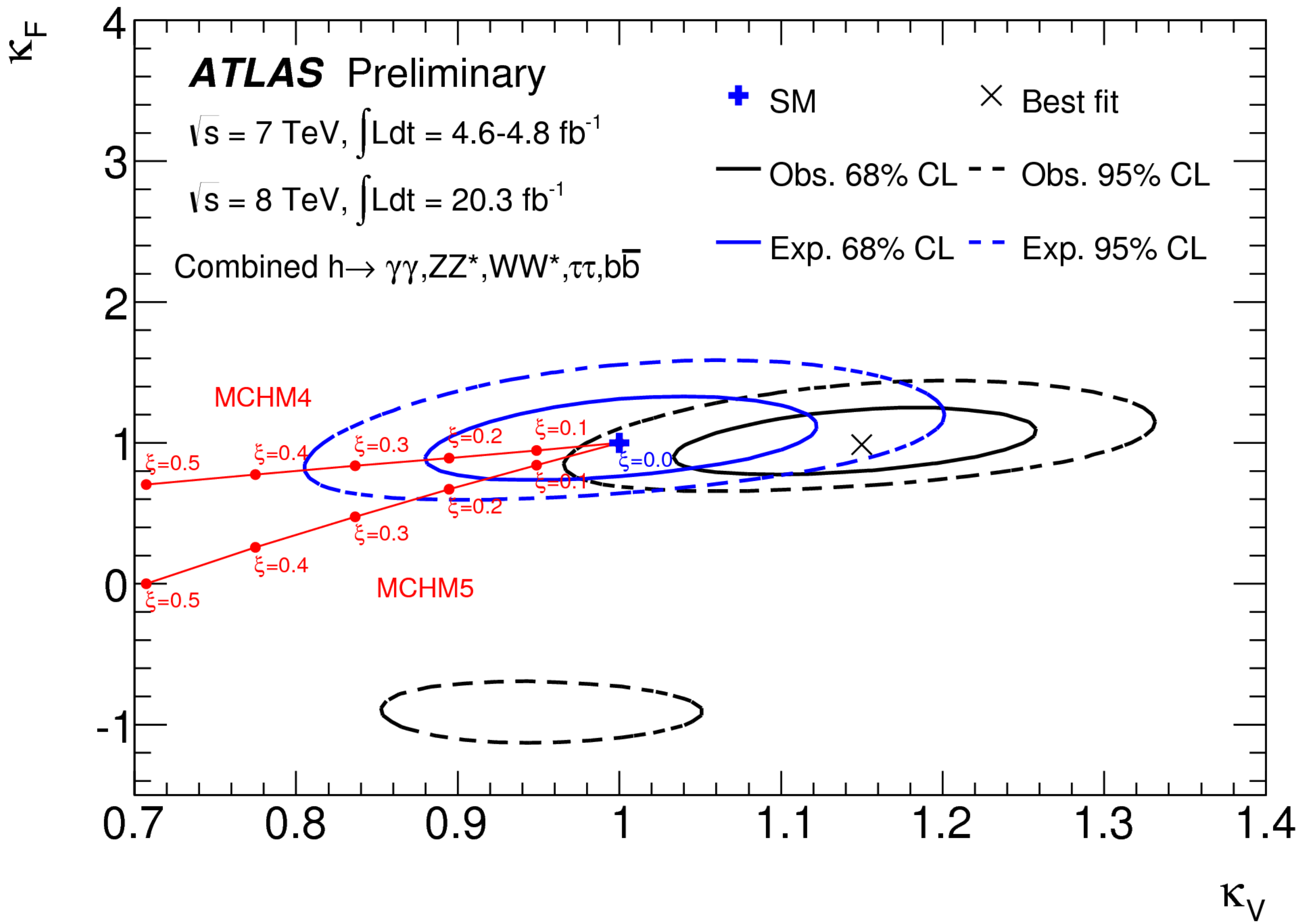






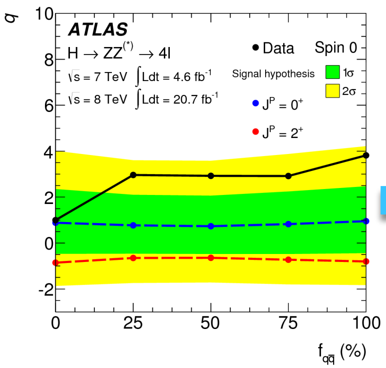
…and ATLAS obliged

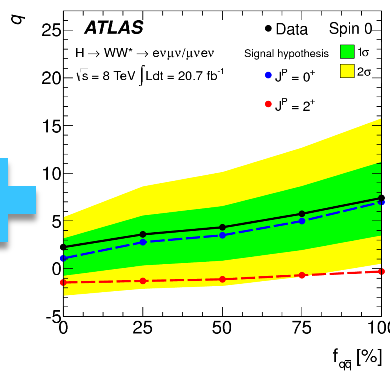
[ATLAS-CONF-NOTE-2014-010]

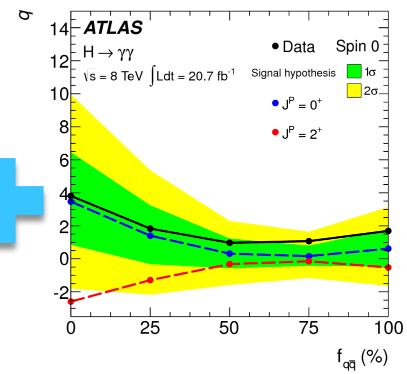


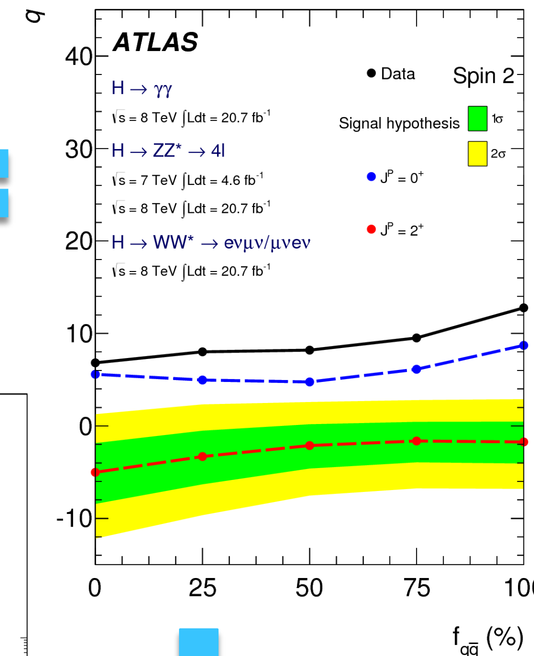
ATLAS: combination 0^+ vs. 2^+_m

[arXiv:1307.1432]

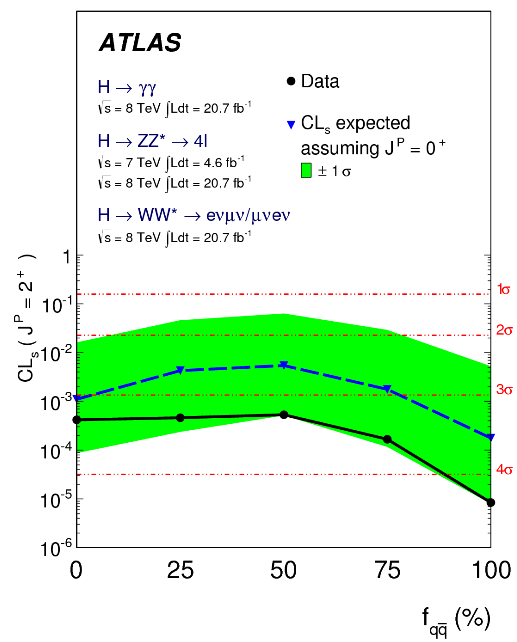








- Combined $H \longrightarrow ZZ$, WW, and $\gamma\gamma$.
- Scan for fraction of $(gg/q\bar{q}) \longrightarrow 2^+_m$:
  - **$CL_s < 0.06\%$ $\forall$ $f_{q\bar{q}}$.**



Delayed unitarization: until when?

[http://cern.ch/go/q8Gq]

- Assume that WW scattering is $\delta^{-1/2}$ that of SM.
- Things can look like the SM for a long time.
  - **Time ~ Energy.**