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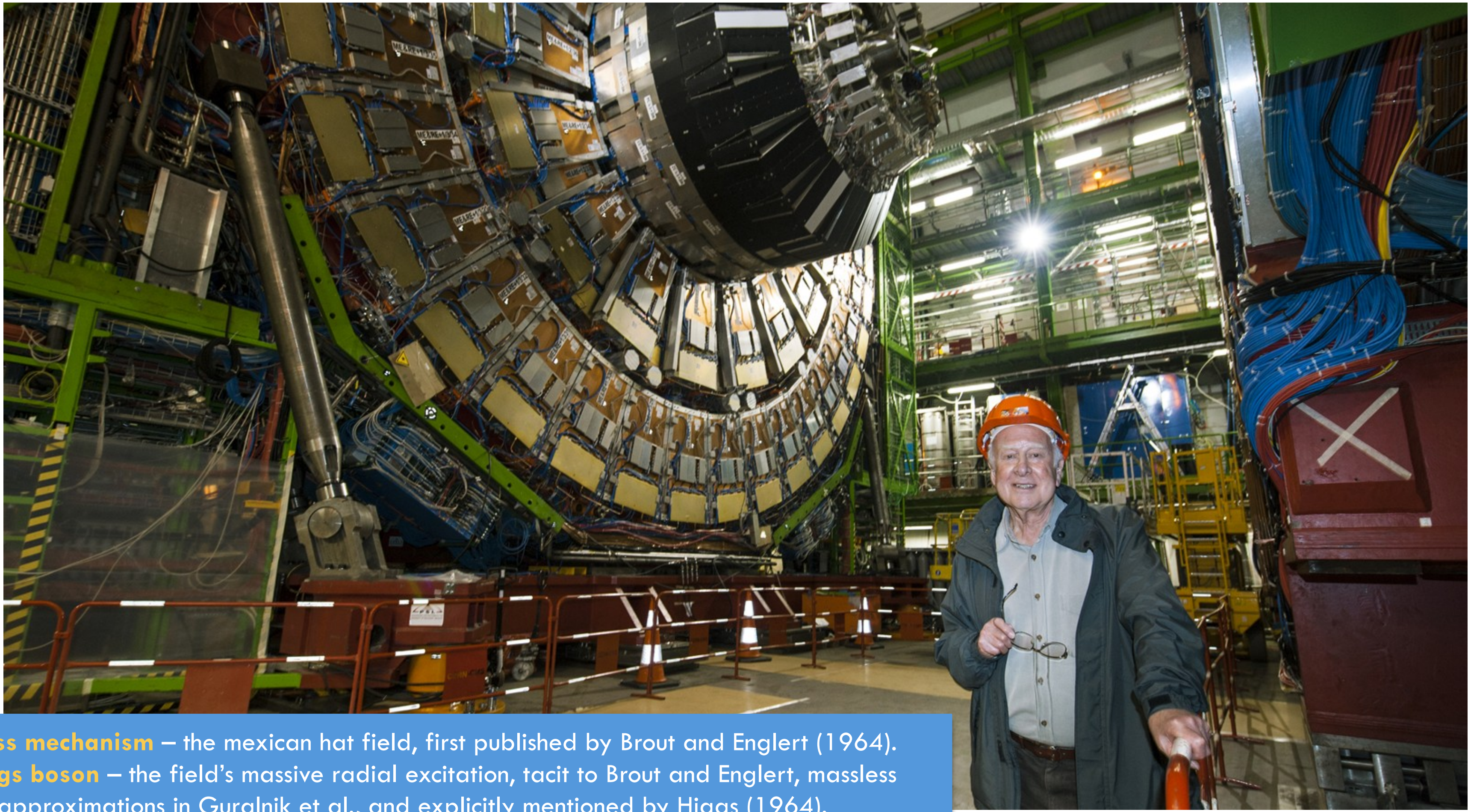
PROPERTIES OF THE HIGGS BOSON WE CANNOT "UNSEE"

LHC Physics 2013

André David (CERN)

Higgs in CMS – ca. 2008

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

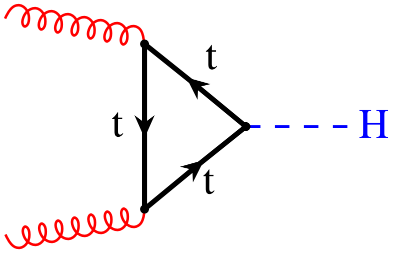


- **Mass mechanism** – the mexican hat field, first published by Brout and Englert (1964).
- **Higgs boson** – the field's massive radial excitation, tacit to Brout and Englert, massless via approximations in Guralnik et al., and explicitly mentioned by Higgs (1964).
- **Viability** – photons and massive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

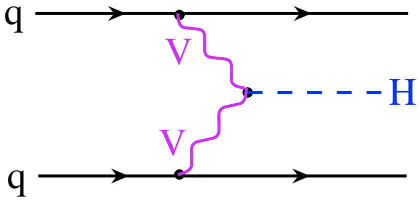
How SM Higgses are born

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

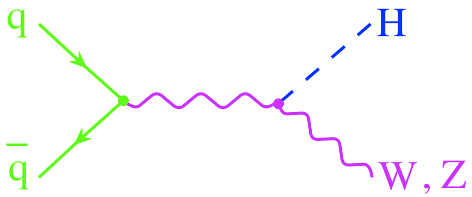
- **Gluon fusion**



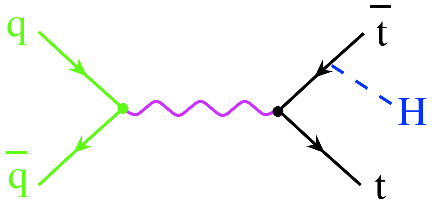
- **VBF**

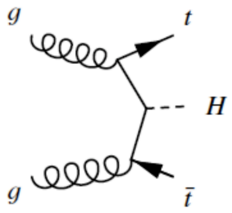


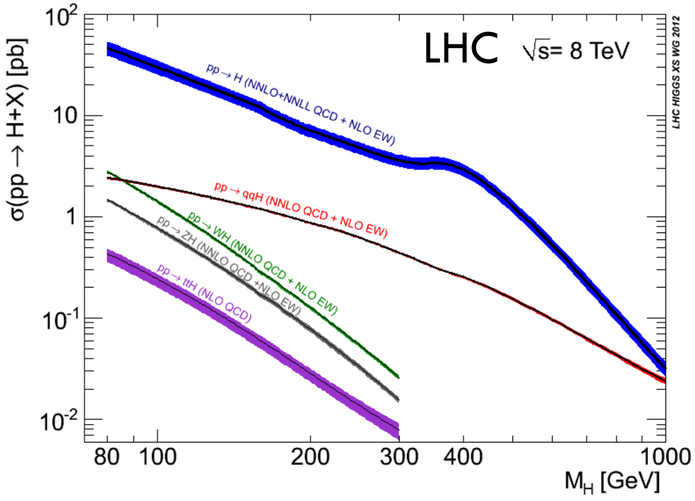
- **VH**

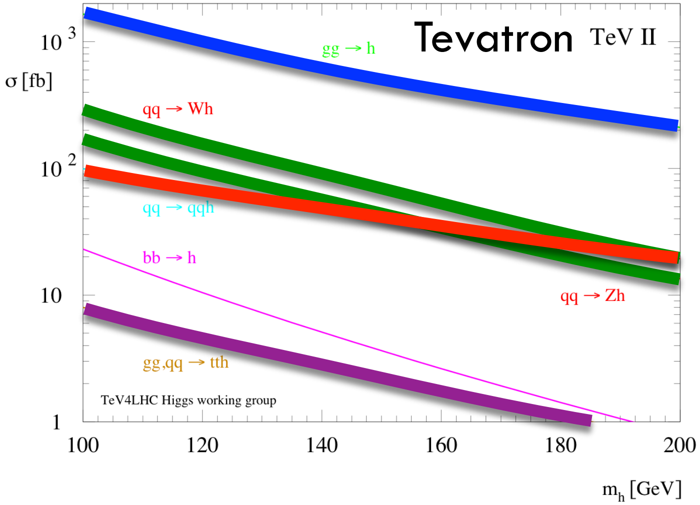


- **ttH**





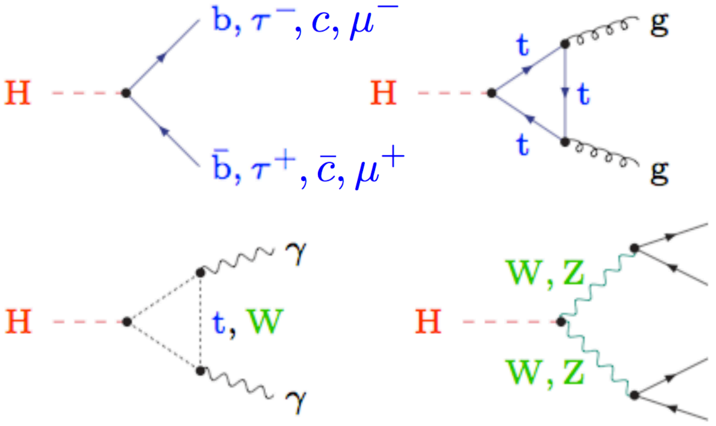




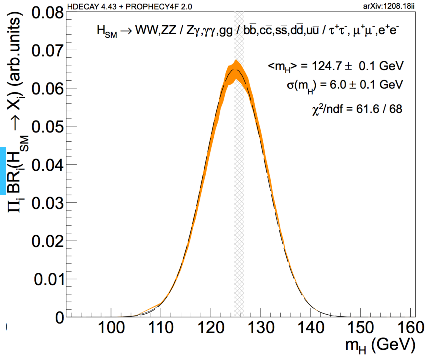
How SM Higgses die

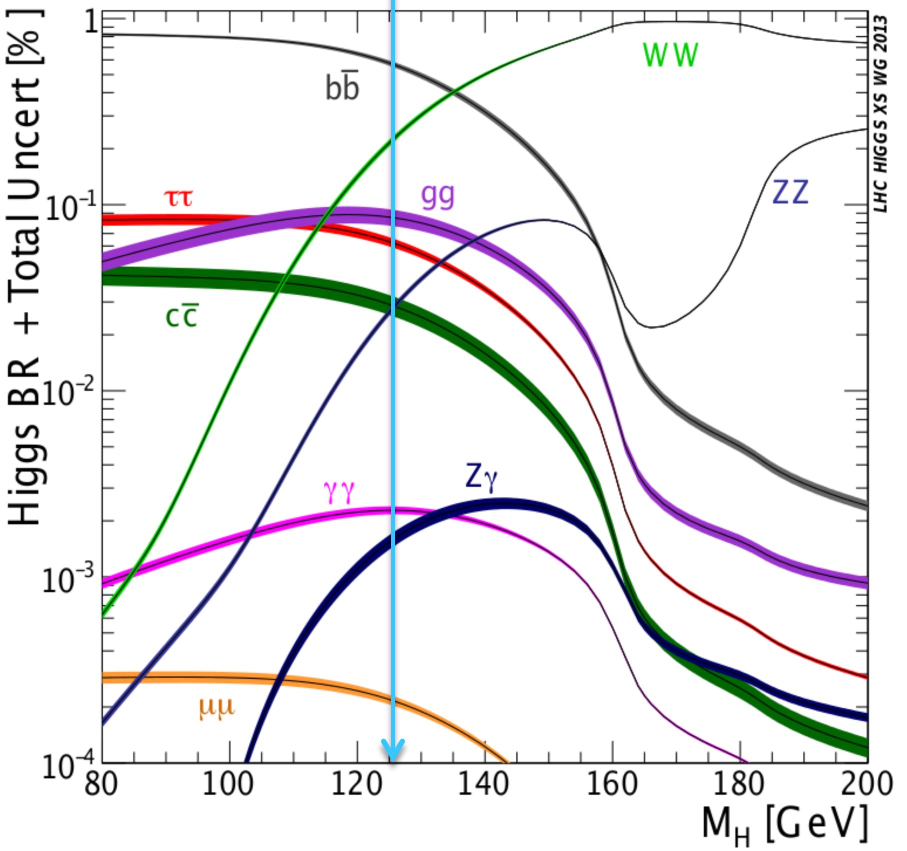
[http://cern.ch/go/qkh6] [arXiv:1208.1993]

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



Near to maximal ΠBR_i ⟶





Things you can’t “unsee”

[http://cern.ch/go/Dxh7]

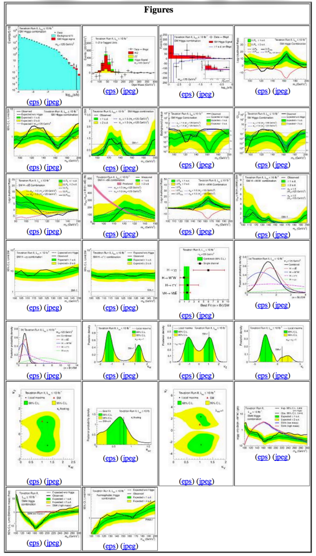
Things you can’t “unsee”

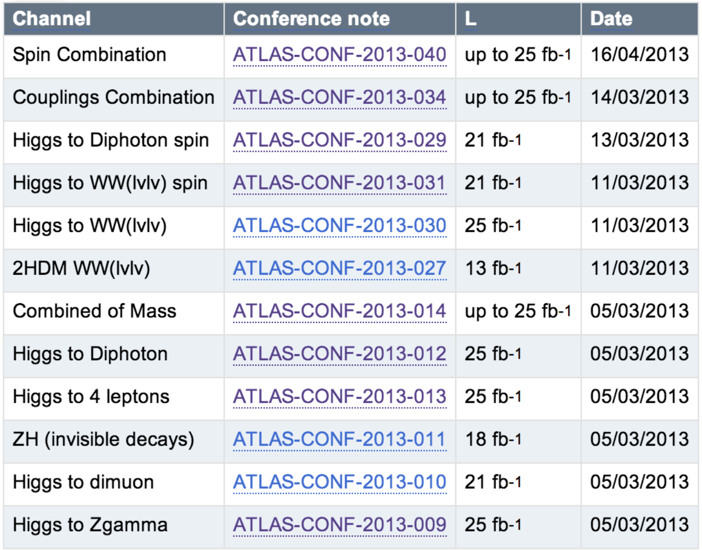
[http://cern.ch/go/Dxh7]

Things you can't "unsee"

[http://cern.ch/go/Dxh7]

(self-inflicted) Mission: impossible





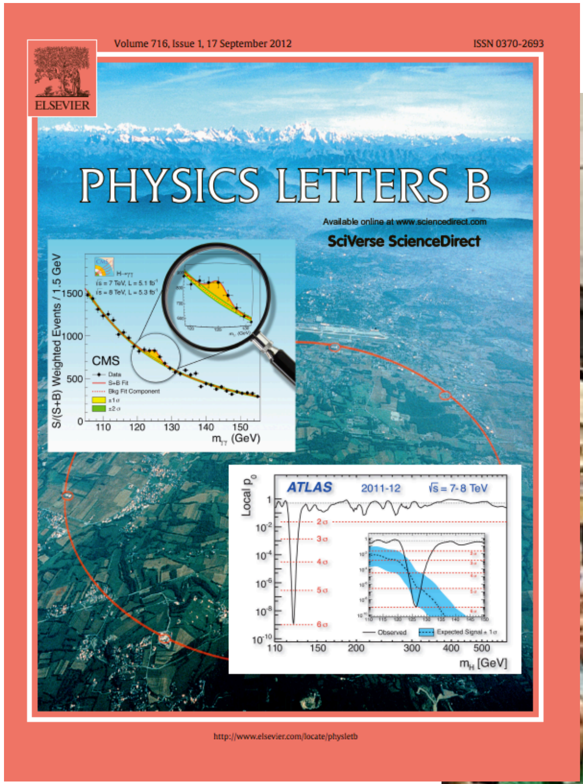
Channel	Conference note	L	Date
Spin Combination	ATLAS-CONF-2013-040	up to 25 fb-1	16/04/2013
Couplings Combination	ATLAS-CONF-2013-034	up to 25 fb-1	14/03/2013
Higgs to Diphoton spin	ATLAS-CONF-2013-029	21 fb-1	13/03/2013
Higgs to WW(lvlv) spin	ATLAS-CONF-2013-031	21 fb-1	11/03/2013
Higgs to WW(lvlv)	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

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 properties from the LHC and Tevatron experiments.
  - Any omission or mistake are the speaker’s fault.

Looking up to a new boson

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



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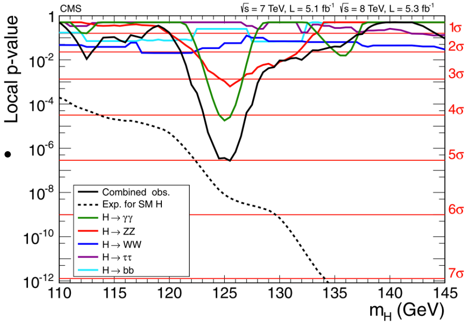
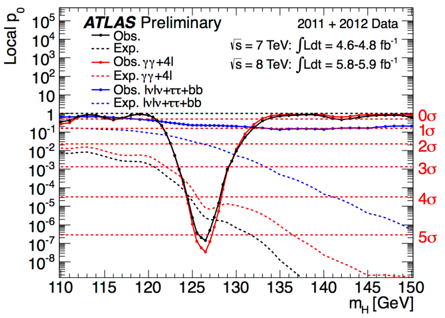
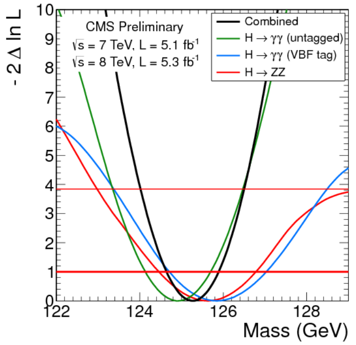
Higgsdependence day recap

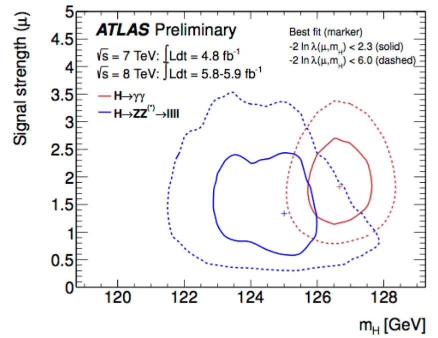
[http://cern.ch/go/q8jx]

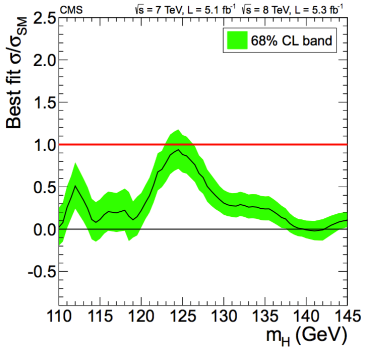
- **Both experiments at 5.0 σ.**
  - One above expectations… **$\sigma_{ATLAS}/\sigma_{SM}$ = 1.2 ±0.3** (at 126.5 GeV).
  - …the other one below. **σ_{CMS}/σ_{SM} = 0.80 ±0.20** (at 125 GeV).
- Mass
  - ATLAS: min. p-value at 126.5 GeV.
  - CMS: m_X = 125.3 ±0.6 GeV.
- "Proto-couplings" compatible with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

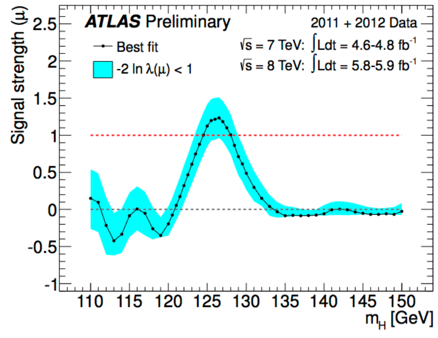


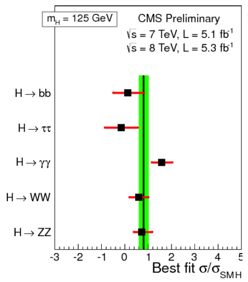


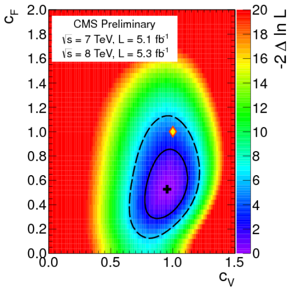


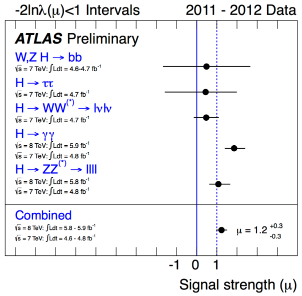






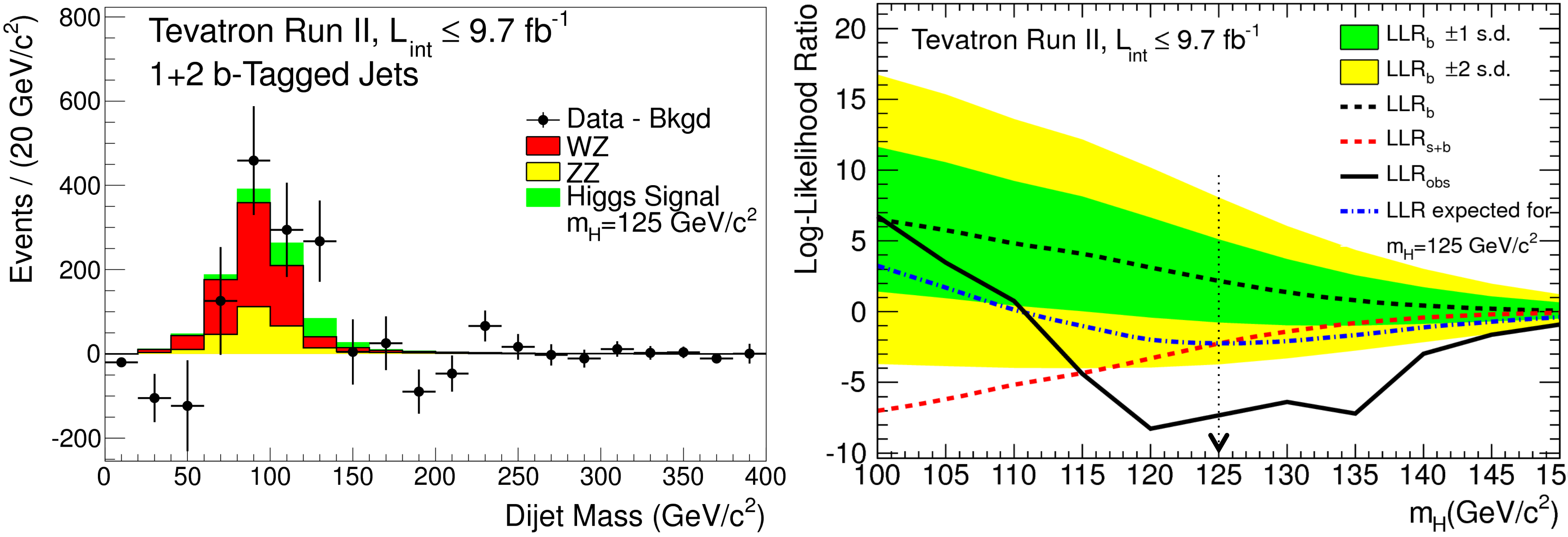






From the other side of the pond

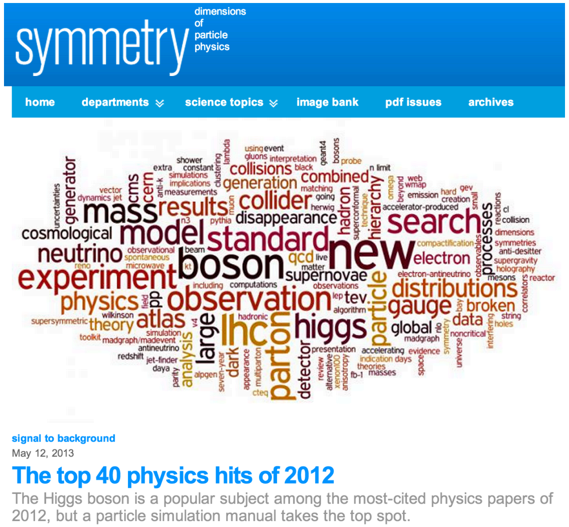
[arXiv:1207.6436]



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

A 2012 hit

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

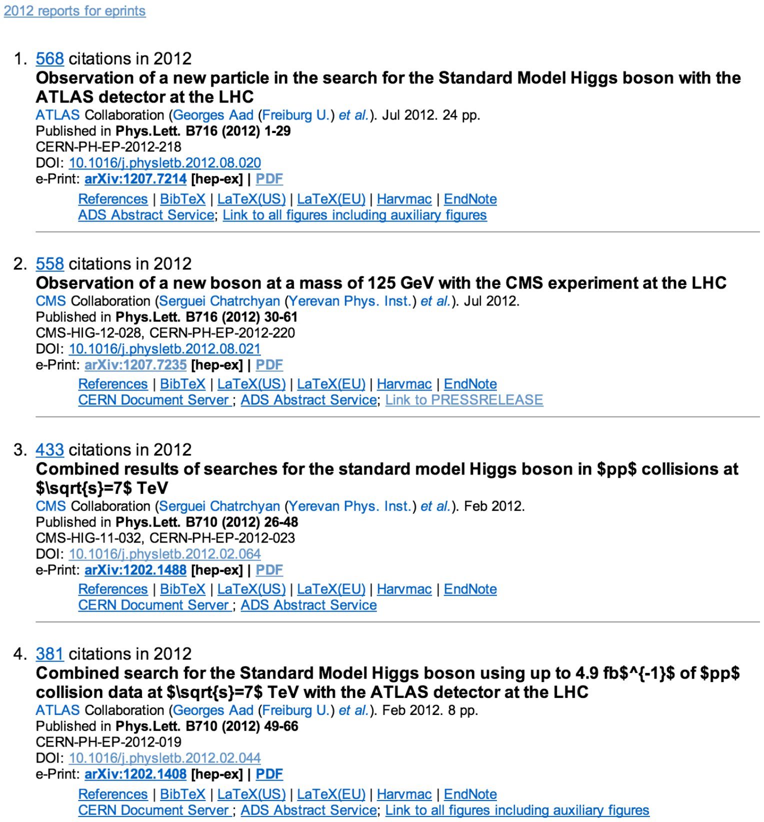


signal to background

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.



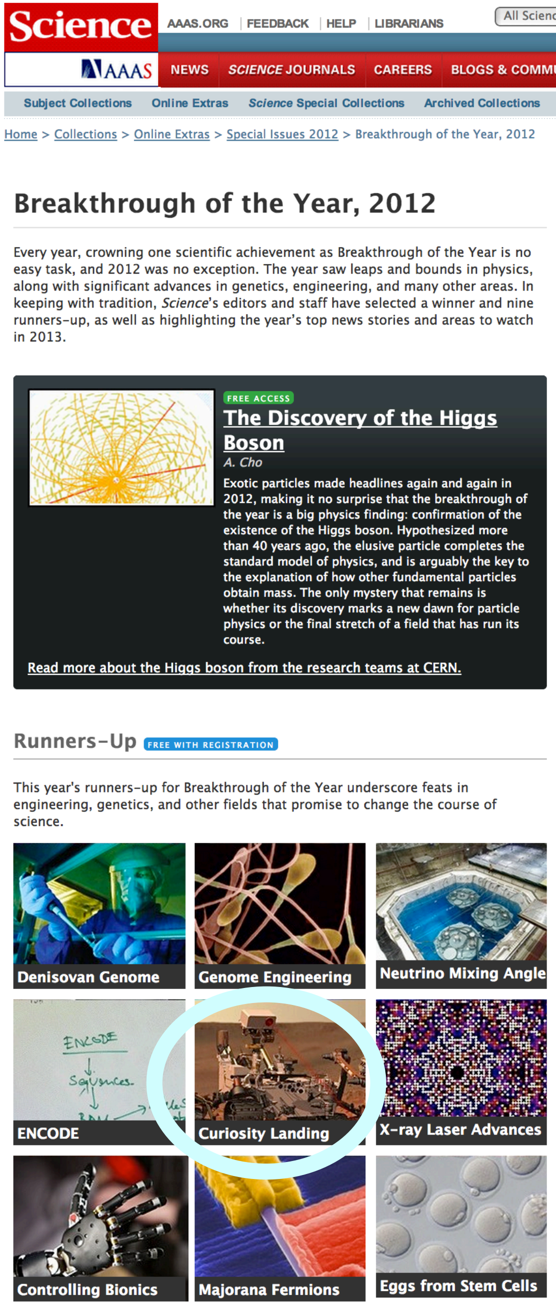
2012 reports for eprints

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



Home > Collections > Online Extras > Special Issues 2012 > Breakthrough of the Year, 2012

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

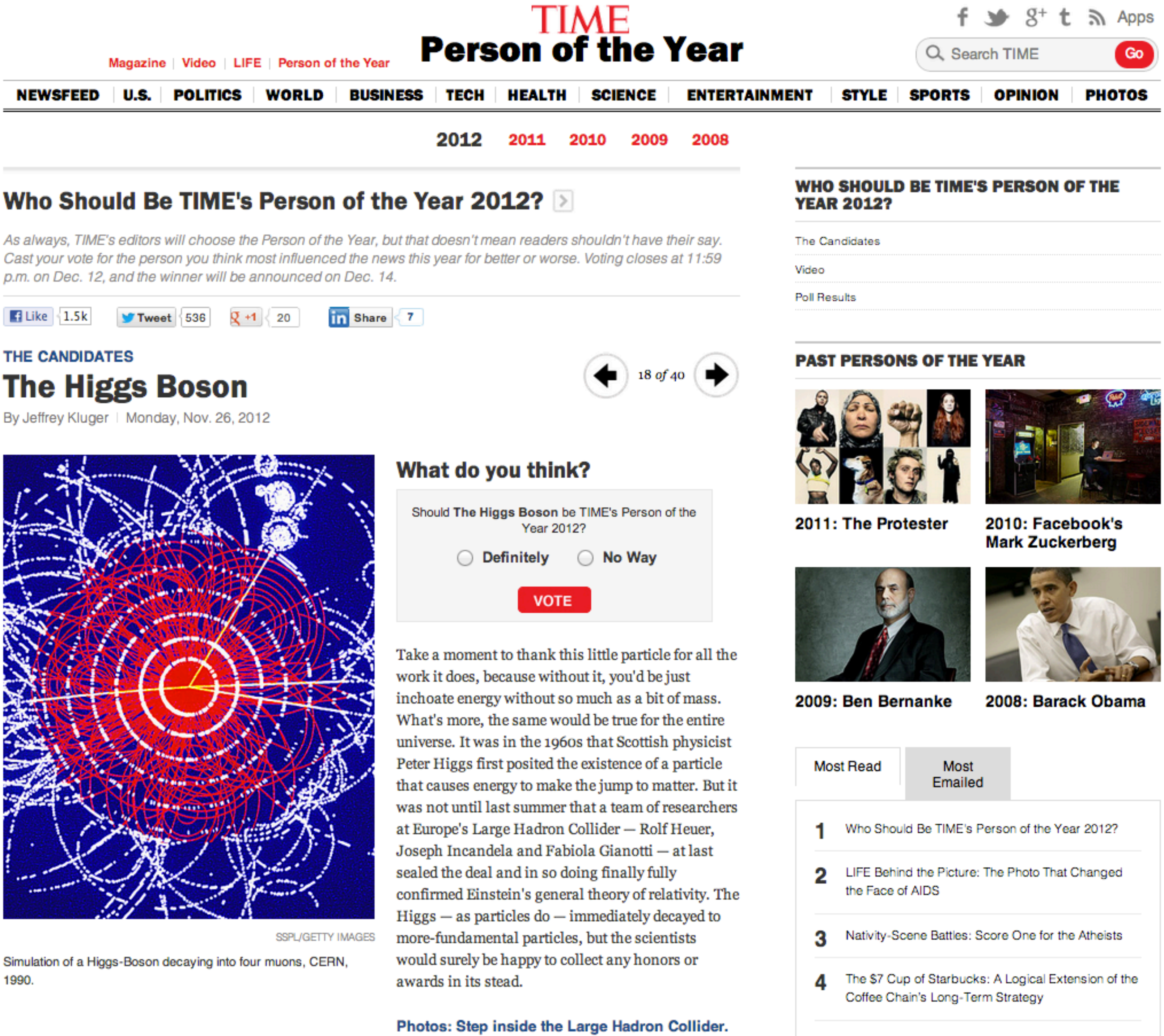
A. Cho

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.



Who Should Be TIME's Person of the Year 2012?

As always, TIME's editors will choose the Person of the Year, but that doesn't mean readers shouldn't have their say. Cast your vote for the person you think most influenced the news this year for better or worse. Voting closes at 11:59 p.m. on Dec. 12, and the winner will be announced on Dec. 14.

THE CANDIDATES

The Higgs Boson

By Jeffrey Kluger | Monday, Nov. 26, 2012

SSPL/GETTY IMAGES

Simulation of a Higgs-Boson decaying into four muons, CERN, 1990.

What do you think?

Should **The Higgs Boson** be TIME's Person of the Year 2012?

○ Definitely ○ No Way

Take a moment to thank this little particle for all the work it does, because without it, you'd be just inchoate energy without so much as a bit of mass. What's more, the same would be true for the entire universe. It was in the 1960s that Scottish physicist Peter Higgs first posited the existence of a particle that causes energy to make the jump to matter. But it was not until last summer that a team of researchers at Europe's Large Hadron Collider — Rolf Heuer, Joseph Incandela and Fabiola Gianotti — at last sealed the deal and in so doing finally fully confirmed Einstein's general theory of relativity. The Higgs — as particles do — immediately decayed to more-fundamental particles, but the scientists would surely be happy to collect any honors or awards in its stead.

Photos: Step inside the Large Hadron Collider.

WHO SHOULD BE TIME'S PERSON OF THE YEAR 2012?

PAST PERSONS OF THE YEAR

2011: The Protester

2010: Facebook's Mark Zuckerberg

2009: Ben Bernanke

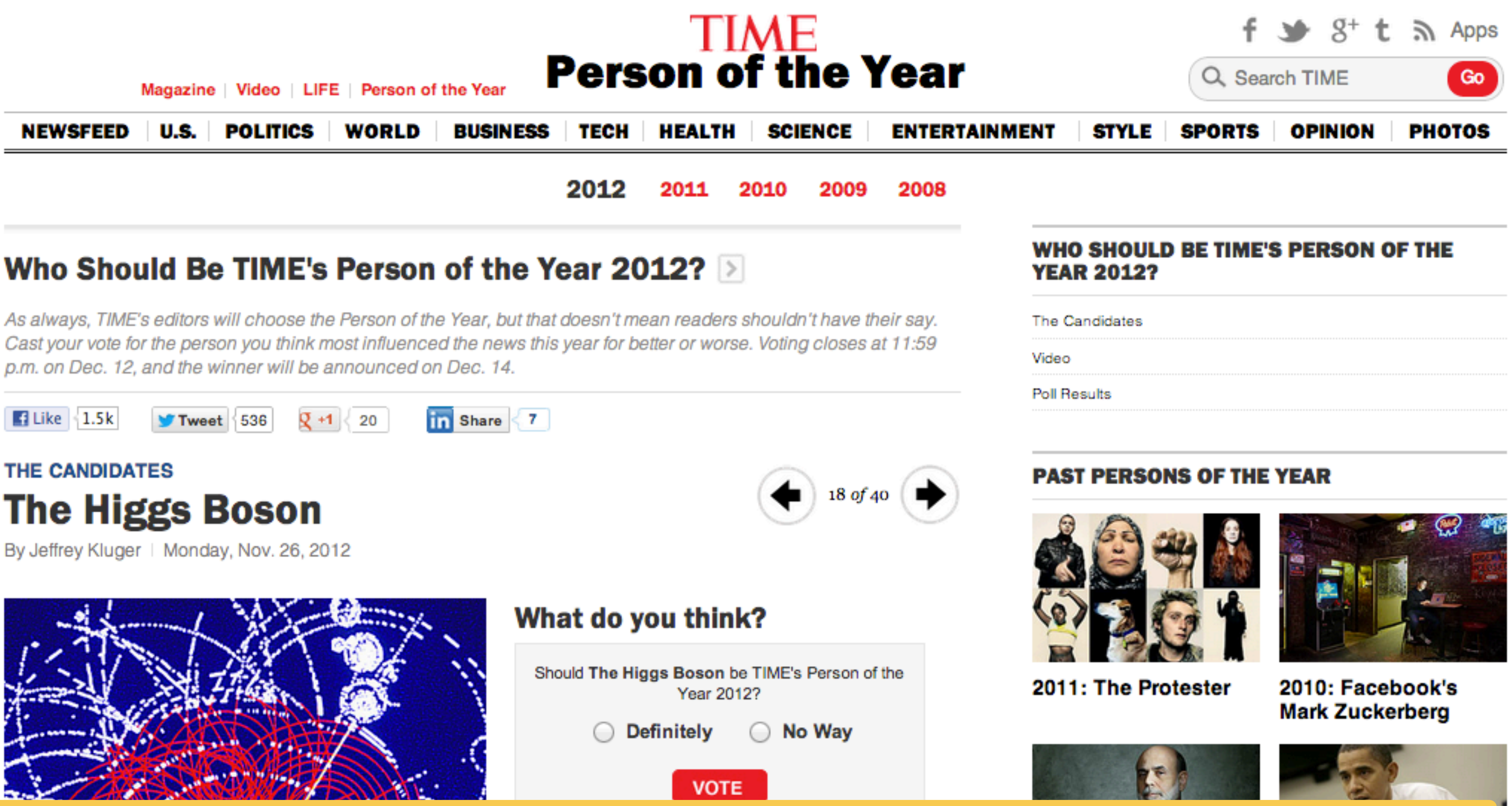
2008: Barack Obama

1 Who Should Be TIME's Person of the Year 2012?

2 LIFE Behind the Picture: The Photo That Changed the Face of AIDS

3 Nativity-Scene Battles: Score One for the Atheists

4 The $7 Cup of Starbucks: A Logical Extension of the Coffee Chain's Long-Term Strategy



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WHO SHOULD BE TIME'S PERSON OF THE YEAR 2012?

- The Candidates
- Video
- Poll Results

PAST PERSONS OF THE YEAR

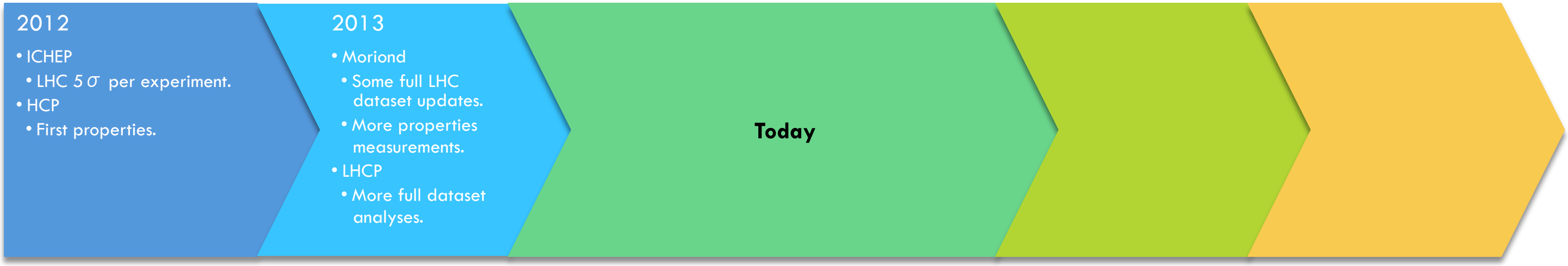
2011: The Protester

2010: Facebook's Mark Zuckerberg

last summer that a team of researchers at Europe's Large Hadron Collider — Rolf Heuer, Joseph Incandela and Fabiola Gianotti — at last sealed the deal and in so doing finally fully confirmed Einstein's general theory of relativity. The

Photos: Step inside the Large Hadron Collider.

Timeline of the results

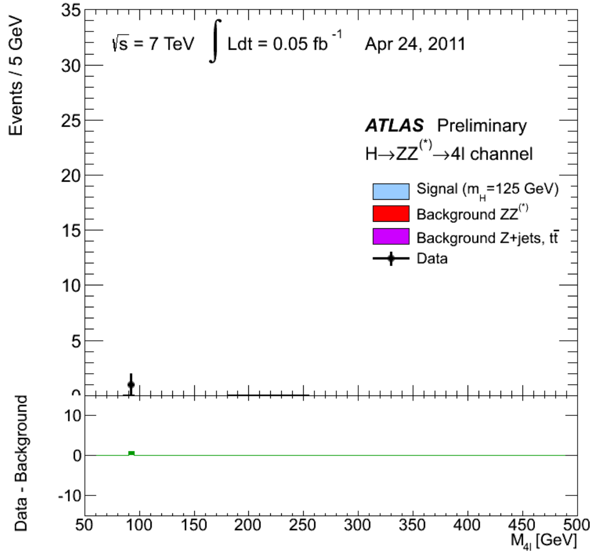


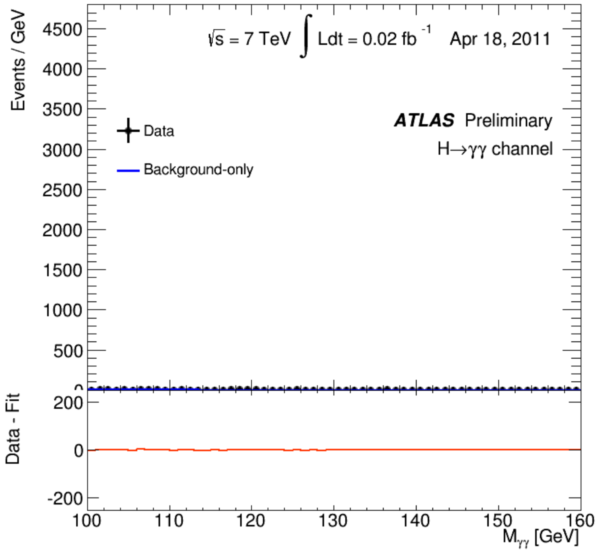
2012
- ICHEP
  - LHC 5 σ per experiment.
- HCP
  - First properties.

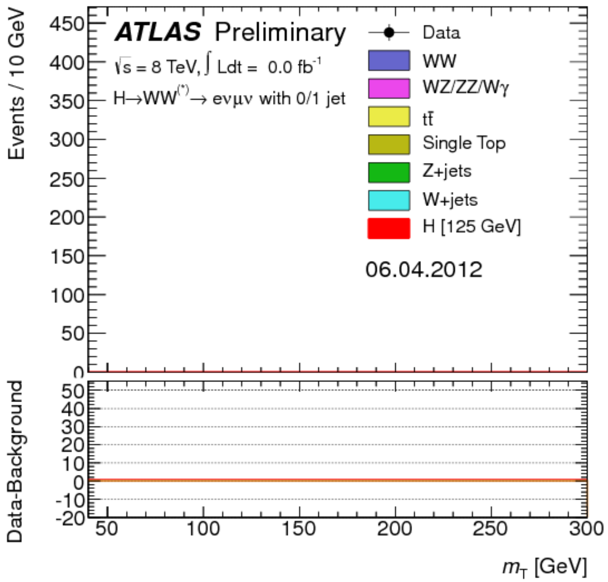
2013
- Moriond
  - Some full LHC dataset updates.
  - More properties measurements.
- LHCP
  - More full dataset analyses.

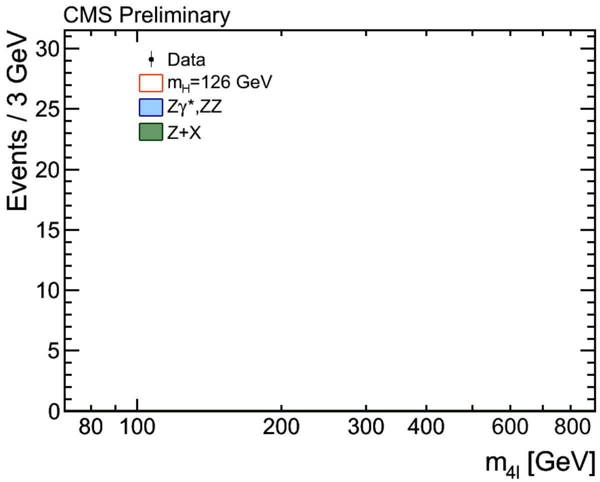
Today

The build up of a signal





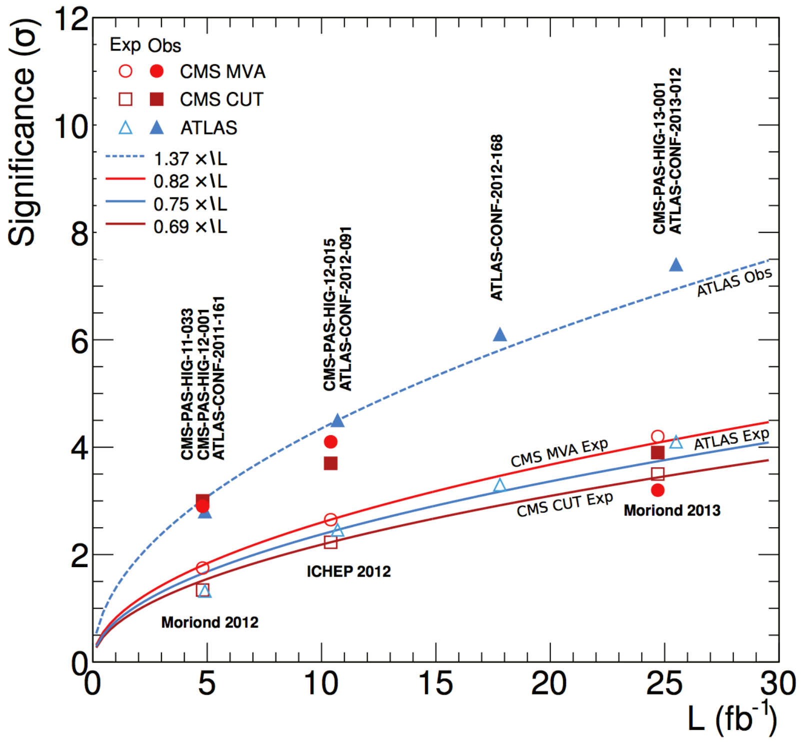


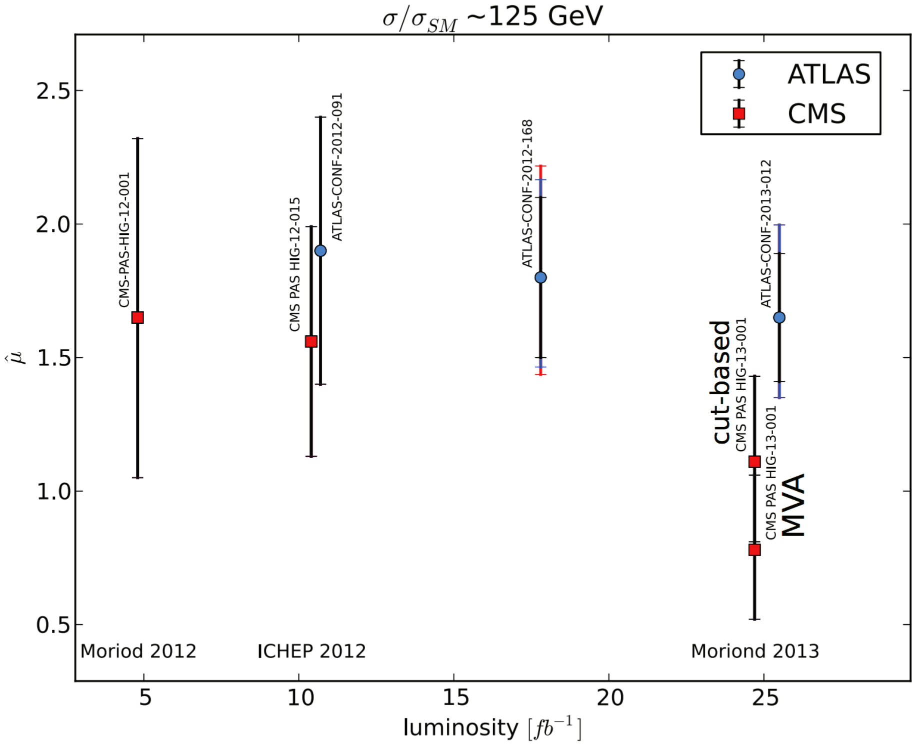


- Thanks to the excellent performance of the LHC !
  - >15 fb^{-1} delivered after July 2012.

Interesting H→ $\gamma\gamma$ comparisons

[http://cern.ch/go/lc9j]

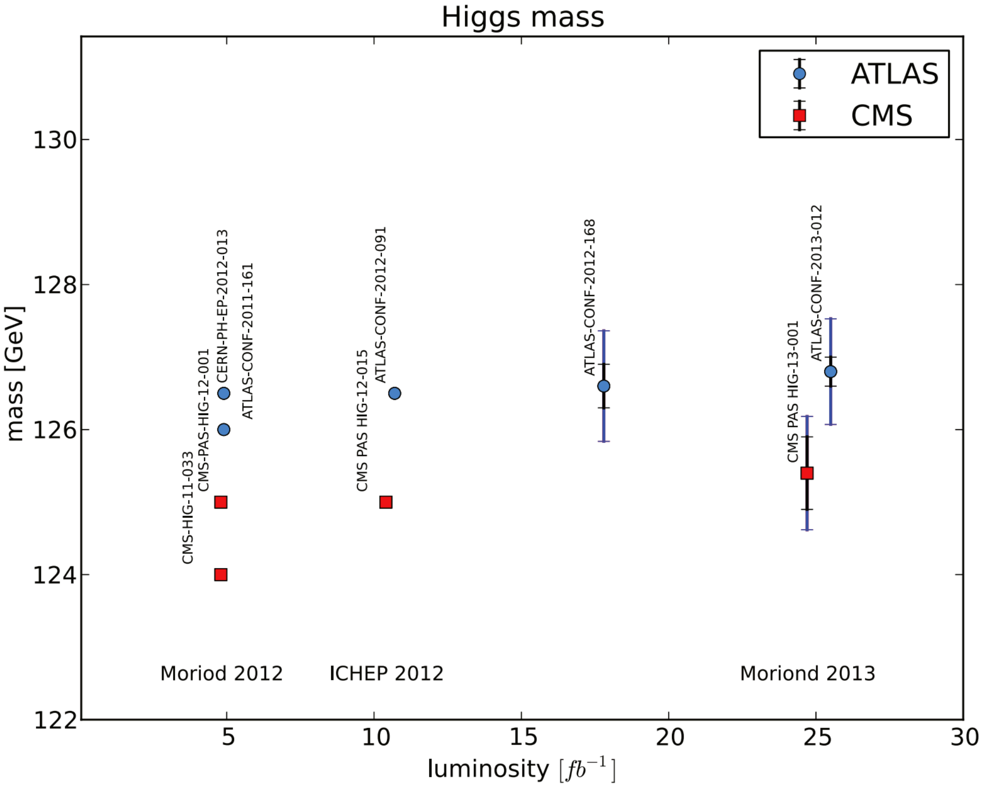




- VI Workshop Italiano sulla Fisica p-p a LHC

Interesting $H \rightarrow \gamma \gamma$ comparisons

[http://cern.ch/go/lc9j]



- ☐ VI Workshop Italiano sulla Fisica p-p a LHC

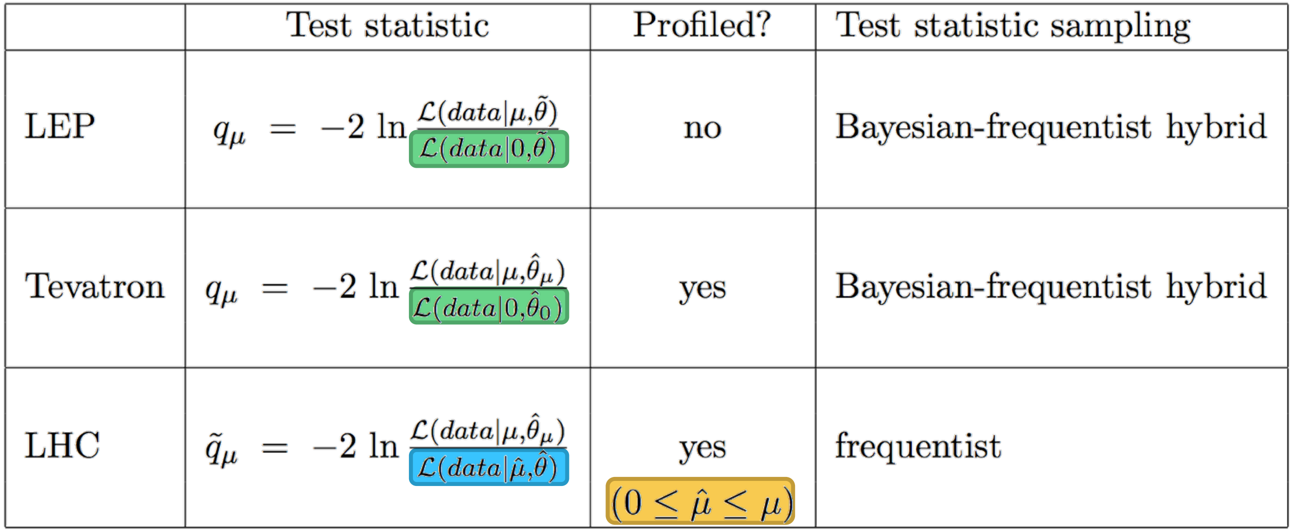
Where we stand today

Significance Obs. (pre-fit exp.)	$H \to ZZ$	$H \to \gamma\gamma$	$H \to WW$	$H \to b\bar{b}$	$H \to \tau\tau$
ATLAS	**6.6σ** (4.4σ)	**7.4σ** (4.1σ)	**2.5σ** (1.6σ)	-0.4σ (**1.0σ**)	1.1σ (**1.7σ**)
	124.3 GeV	*126.8 GeV*	*125 GeV*		
CMS	6.7σ (**7.1σ**)	3.9σ (**4.2σ**)	3.9σ (**5.6σ**)	2.0σ (**2.1σ**)	**2.8σ** (2.7σ)
	125.7 GeV				

- Combined p-values $<10^{-20}$ are telling us to make measurements…

Statistics interlude

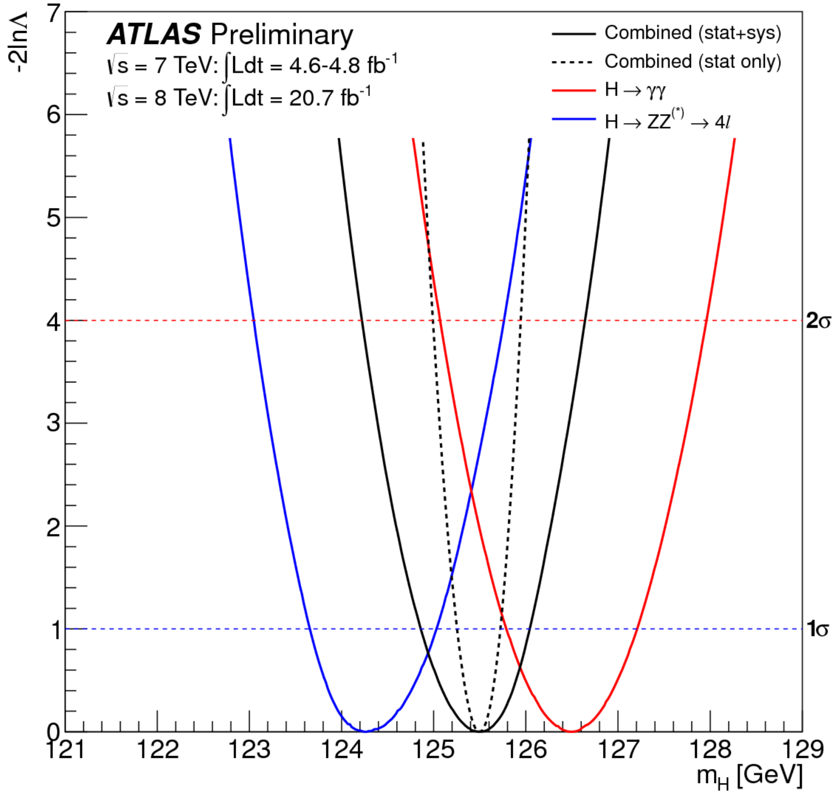
[ATL-PHYS-PUB-2011-11, CMS NOTE-2011/005]

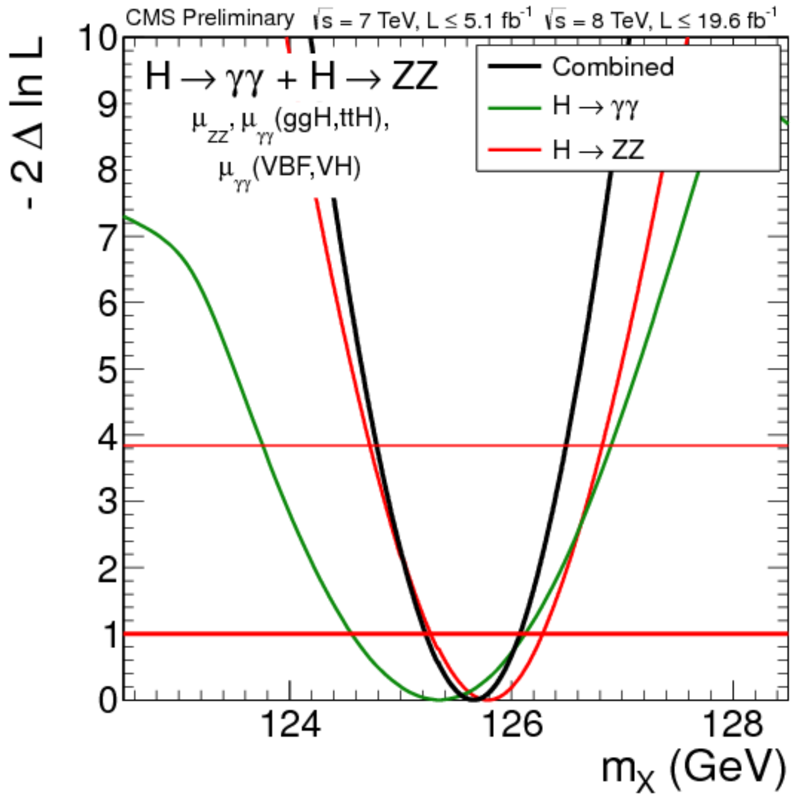


	Test statistic	Profiled?	Test statistic sampling
LEP	$q_\mu = -2\ln\frac{\mathcal{L}(data\|\mu,\tilde{\theta})}{\mathcal{L}(data\|0,\tilde{\theta})}$	no	Bayesian-frequentist hybrid
Tevatron	$q_\mu = -2\ln\frac{\mathcal{L}(data\|\mu,\hat{\theta}_\mu)}{\mathcal{L}(data\|0,\hat{\theta}_0)}$	yes	Bayesian-frequentist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

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

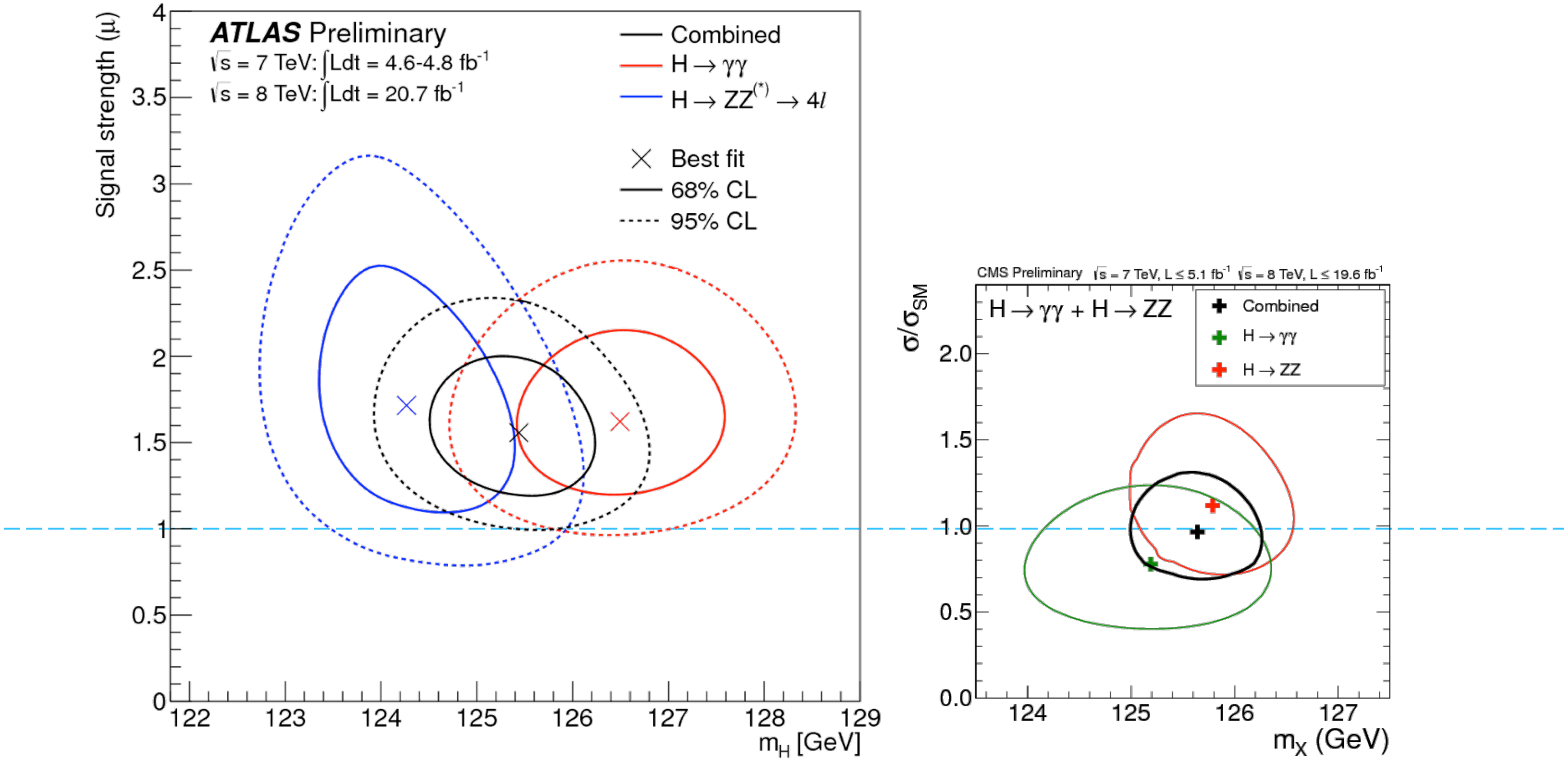
Measuring the mass





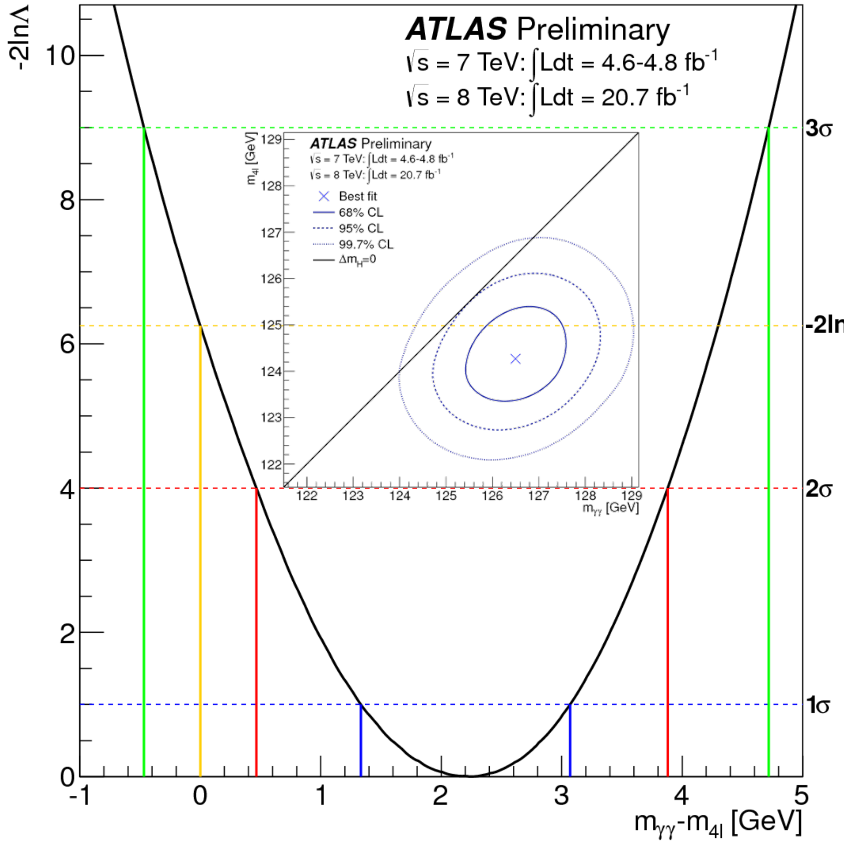
	ATLAS	**CMS**
m_X	125.5 ±0.2 (stat.) $^{+0.5}_{-0.6}$ (syst.) GeV	125.7 ±0.3 (stat.) ±0.3 (syst.) GeV
	Naïve average: 125.6 ±0.4 GeV	

Measuring the mass



- Combinations of the high-resolution channels.

More on ATLAS mass



- Slight difference in ATLAS results:
  - $\Delta m = 2.3^{+0.6}_{-0.7}$(stat.) ±0.6(syst.) GeV
  - 2.4σ (p=1.5%)
- Using more conservative energy scale uncertainties: **1.8σ (p=8%).**

Where we stand today – with cookery

Significance Obs. (pre-fit exp.)	**$H \longrightarrow ZZ$**	**$H \longrightarrow \gamma\gamma$**	**$H \longrightarrow WW$**	**$H \longrightarrow b\bar{b}$**	**$H \longrightarrow \tau\tau$**
ATLAS	$\mu = 1.5 \pm 0.4$ **~3.8 σ** (~2.5 σ)	$\mu = 1.6 \pm 0.3$ **~5.3 σ** (~3.3 σ)	**2.5 σ** (1.6 σ)	-0.4 σ (**1.0 σ**)	1.1 σ (**1.7 σ**)
	125.5 GeV		*125 GeV*		
CMS	6.7 σ (**7.1 σ**)	3.9 σ (**4.2 σ**)	3.9 σ (**5.6 σ**)	2.0 σ (**2.1 σ**)	**2.8 σ** (2.7 σ)
			125.7 GeV		

- Combined p-values $<10^{-20}$ are telling us to make measurements…

Spin is so much more than a number

[arXiv:1208.4018]

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

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

Spin is so much more than a number

[arXiv:1208.4018]

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

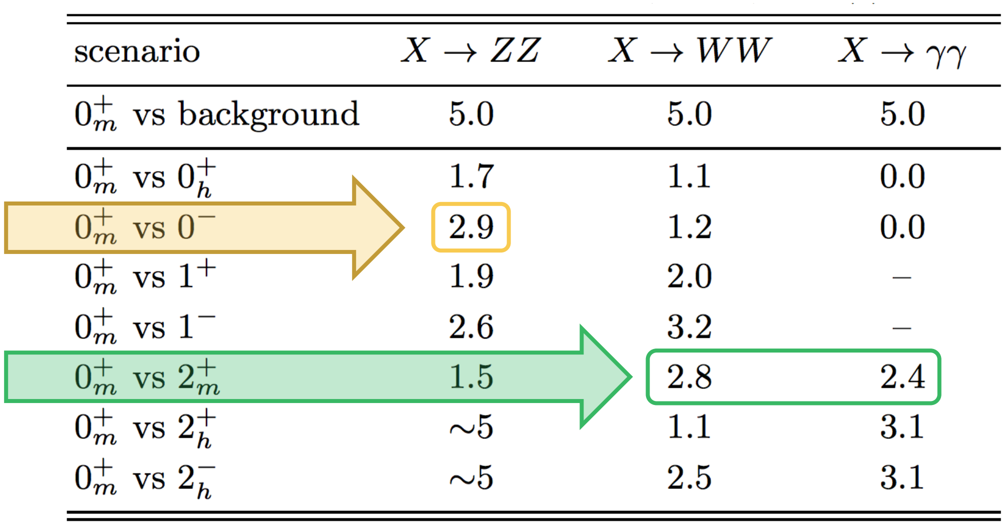
$$\begin{aligned}A(X \to V_1 V_2) = \Lambda^{-1} \Big[& 2g_1^{(2)} t_{\mu\nu} f^{*(1)\mu\alpha} f^{*(2)\nu\alpha} + \xcancel{2g_2^{(2)} t_{\mu\nu} \frac{q_\alpha q_\beta}{\Lambda^2} f^{*(1)\mu\alpha} f^{*(2)\nu\beta}} + \xcancel{g_3^{(2)} \frac{\tilde{q}^\beta \tilde{q}^\alpha}{\Lambda^2} t_{\mu\nu}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

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

J^P: a simplified picture

[arXiv:1208.4018]

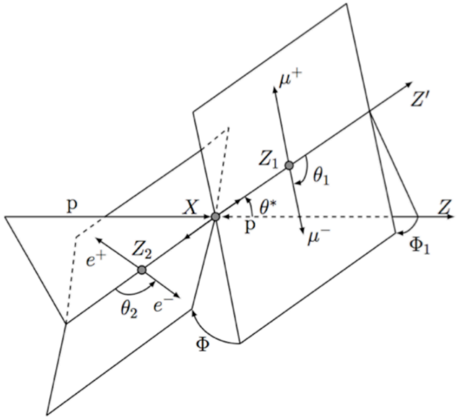
- **Until there is enough data, perform pairwise hypothesis tests against SMH (0^+).**
- Select models using simplifying assumptions on amplitudes:
  - 0^- (parity) "from" ZZ.
  - 2^+_m (graviton-like minimal couplings) also "from" WW and $\gamma\gamma$.

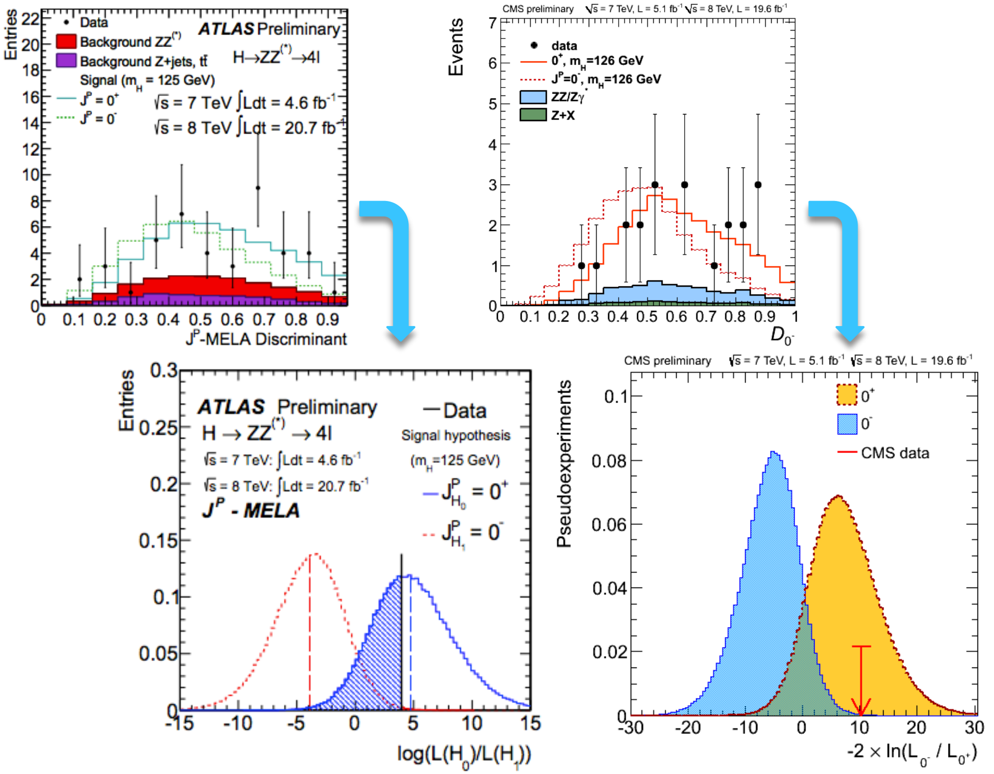


scenario	$X \to ZZ$	$X \to WW$	$X \to \gamma\gamma$
0^+_m vs background	5.0	5.0	5.0
0^+_m vs 0^+_h	1.7	1.1	0.0
0^+_m vs 0^-	2.9	1.2	0.0
0^+_m vs 1^+	1.9	2.0	–
0^+_m vs 1^-	2.6	3.2	–
0^+_m vs 2^+_m	1.5	2.8	2.4
0^+_m vs 2^+_h	∼5	1.1	3.1
0^+_m vs 2^-_h	∼5	2.5	3.1

Parity: $H \rightarrow ZZ \rightarrow 4\ell$

[ATLAS-CONF-2013-013] [CMS-PAS-HIG-13-003]



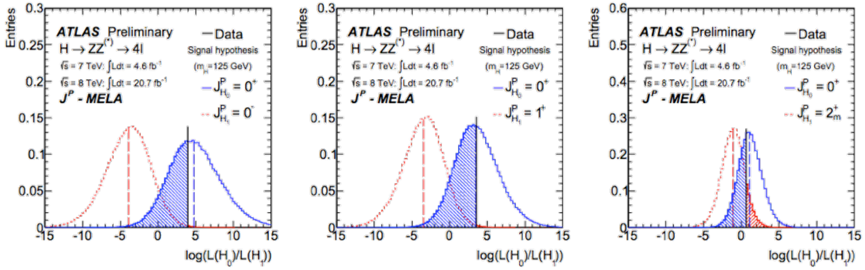


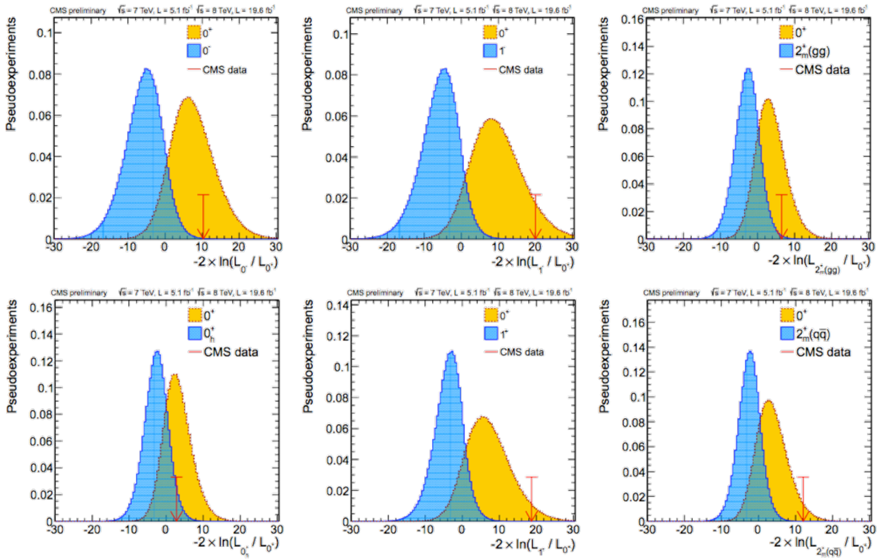
- Discriminants built from decay angles and invariant masses.
- Profiled likelihood ratio test statistic.
  - CL_S criterion protects against fluctuations from null hypothesis.

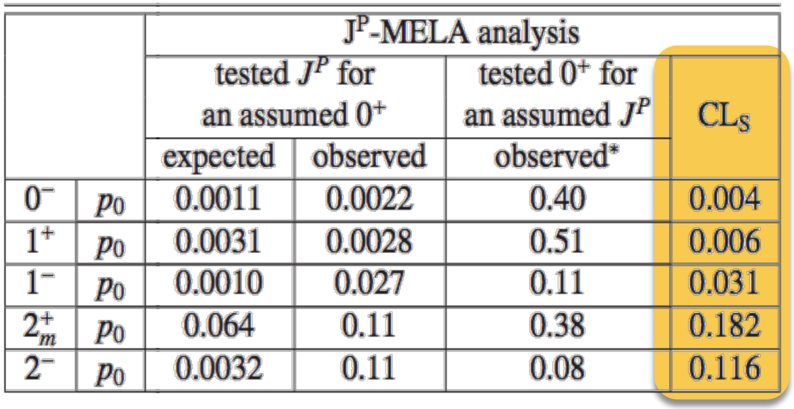
	ATLAS	CMS
CL_S	**0.37%**	**0.16%**
P(obs.|0^+)	0.40	-0.5 σ
P(obs.|0^-)	0.0022	3.3 σ

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

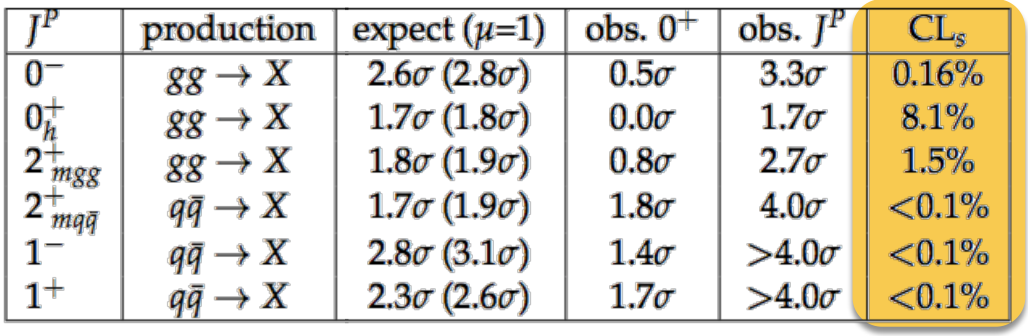
[ATLAS-CONF-2013-013] [CMS-PAS-HIG-13-003]







		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

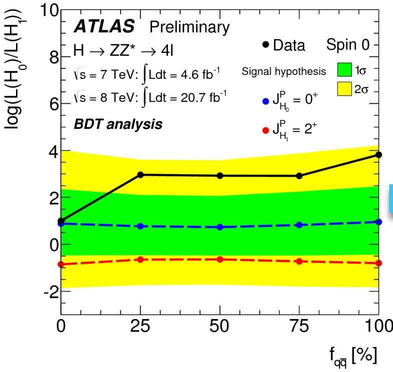


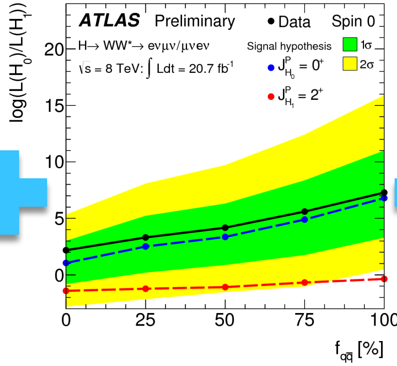
J^P	production	expect (μ=1)	obs. 0^+	obs. J^P	CL_s
0^-	$gg \to X$	2.6σ (2.8σ)	0.5σ	3.3σ	0.16%
0^+_h	$gg \to X$	1.7σ (1.8σ)	0.0σ	1.7σ	8.1%
2^+_{mgg}	$gg \to X$	1.8σ (1.9σ)	0.8σ	2.7σ	1.5%
$2^+_{mq\bar{q}}$	$q\bar{q} \to X$	1.7σ (1.9σ)	1.8σ	4.0σ	<0.1%
1^-	$q\bar{q} \to X$	2.8σ (3.1σ)	1.4σ	$>4.0\sigma$	<0.1%
1^+	$q\bar{q} \to X$	2.3σ (2.6σ)	1.7σ	$>4.0\sigma$	<0.1%

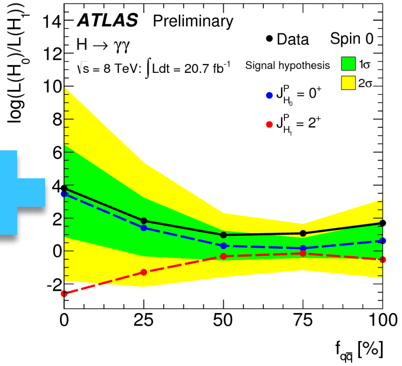
	ATLAS	**CMS**
CL_s for J≠0	**< 18.2%**	**< 1.5%**

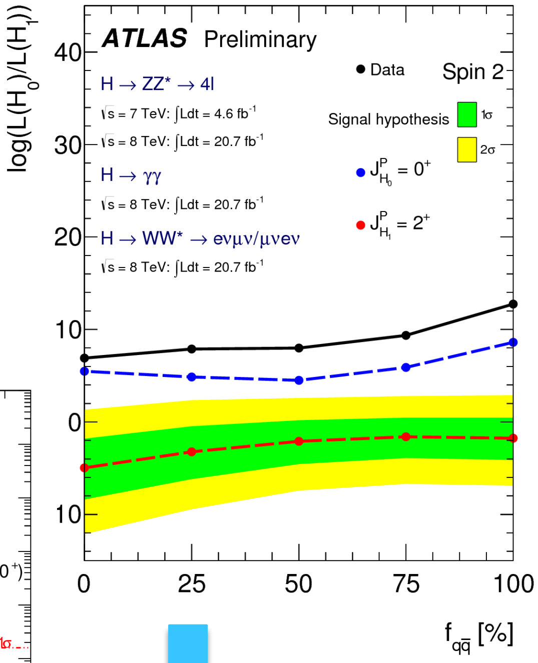
ATLAS: focus on 2^+_m

[ATLAS-CONF-2013-040]

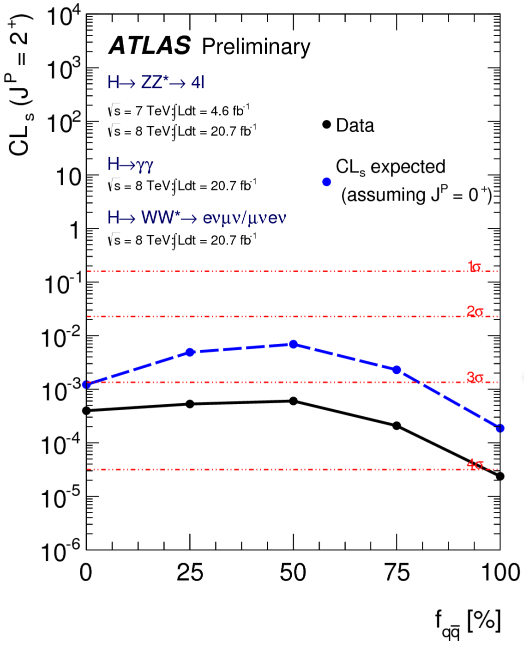








- Combined H⟶ZZ, WW, and $\gamma\gamma$.
- Scan for fraction of $(gg/q\bar{q})\longrightarrow 2^+_m$:
  - **$CL_s < 0.06\%\ \forall\ f_{q\bar{q}}$.**



Oversimplified big picture

T – Tevatron; A – ATLAS; C – CMS; recent results in red.

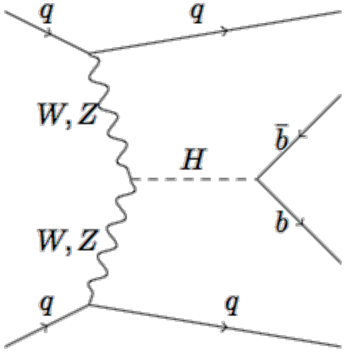
★ "seen" ☆ "tried" - "impossible"	$H\to b\bar{b}$			$H\to\tau\tau$			$H\to WW$			$H\to ZZ$			$H\to\gamma\gamma$			$H\to Z\gamma$			$H\to$inv.			$H\to\mu\mu$			$H\to c\bar{c}$ $H\to HH$		
	T	A	C	T	A	C	T	A	C	T	A	C	T	A	C	T	A	C	T	A	C	T	A	C	T	A	C
ggH	-	-	-	☆	☆	★	☆	★	★	☆	★	★	☆	★	★	-	☆	☆				-	☆		-		
VBF			☆	☆	☆	★		★	★		★	☆		★	☆	-						-			-		
VH	★	☆	★	☆		☆	☆		☆		☆			☆	☆	-				☆		-			-		
ttH		☆	☆	☆			☆								☆	-						-			-		

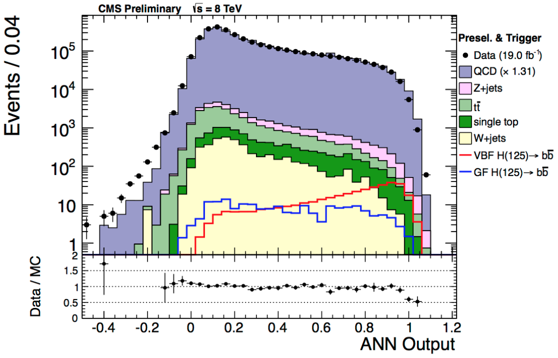
- **Still much to explore on the rarer ends.**

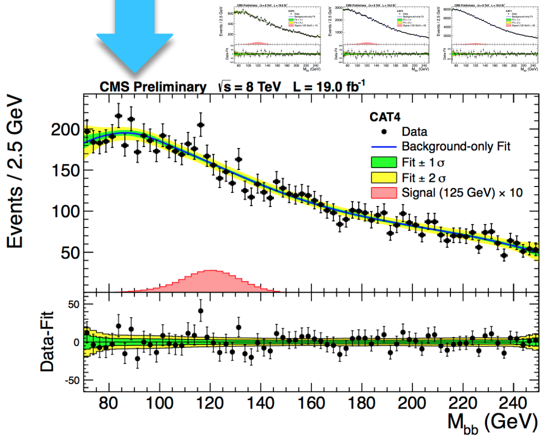
(to the right and to the bottom)

☆ VBF, H⟶$b\bar{b}$

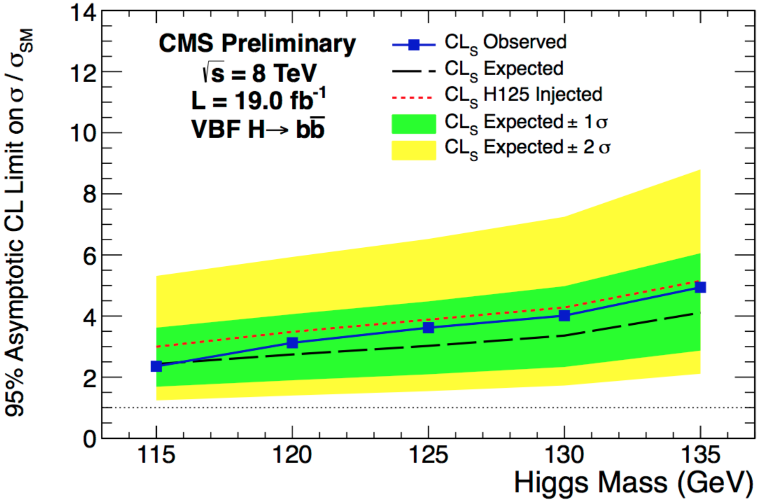
[CMS-PAS-HIG-13-011]







- ☐ Neural network event classifier.
- ☐ Simultaneous $m_{b\bar{b}}$ fits to 4 ANN categories.
- ☐ At m_H=125 GeV, μ **< 3.6 (3.0)** (95%CL), obs.(exp.) or μ **= 0.7 ±1.4.**

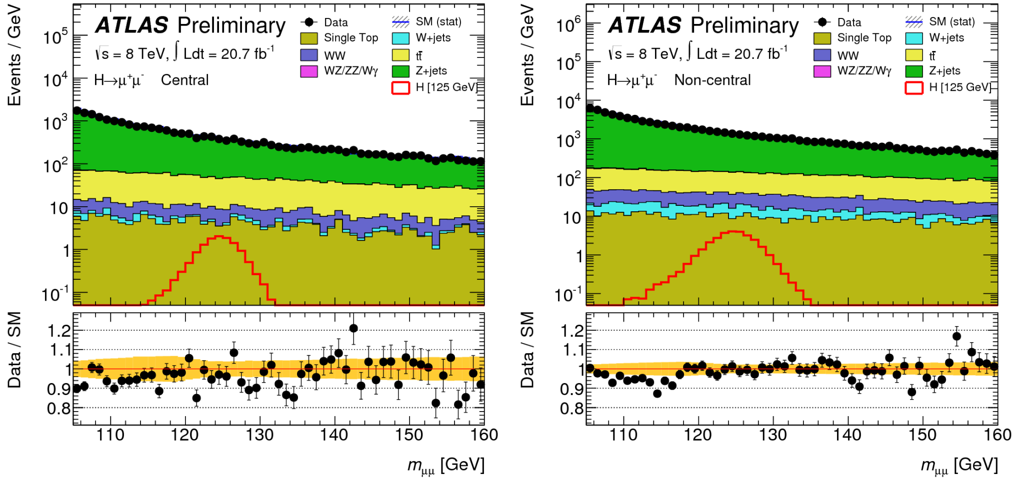


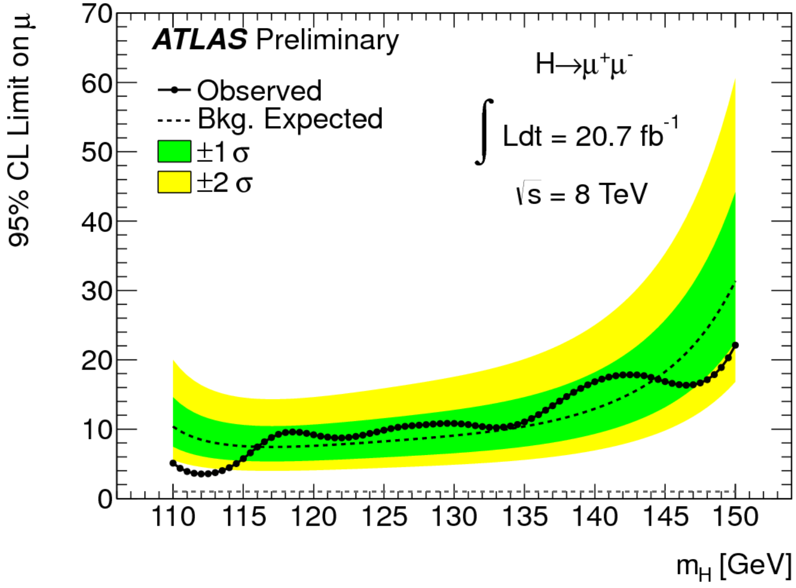
☆ $H \longrightarrow \mu\ \mu$

[ATLAS-CONF-2013-010]

- Probe coupling to second-generation fermions.
- Clean final state.
- BR < 10^{-4} in the search range.

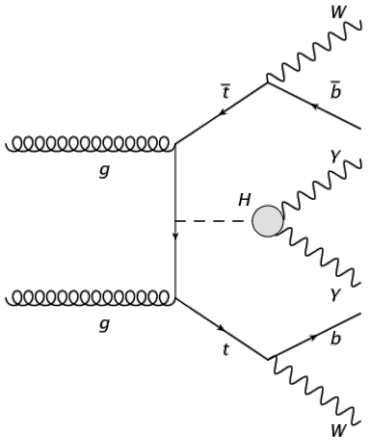
- **At m_H=125 GeV, $\mu < 9.8$ (8.2)** (95%CL), obs.(exp.).

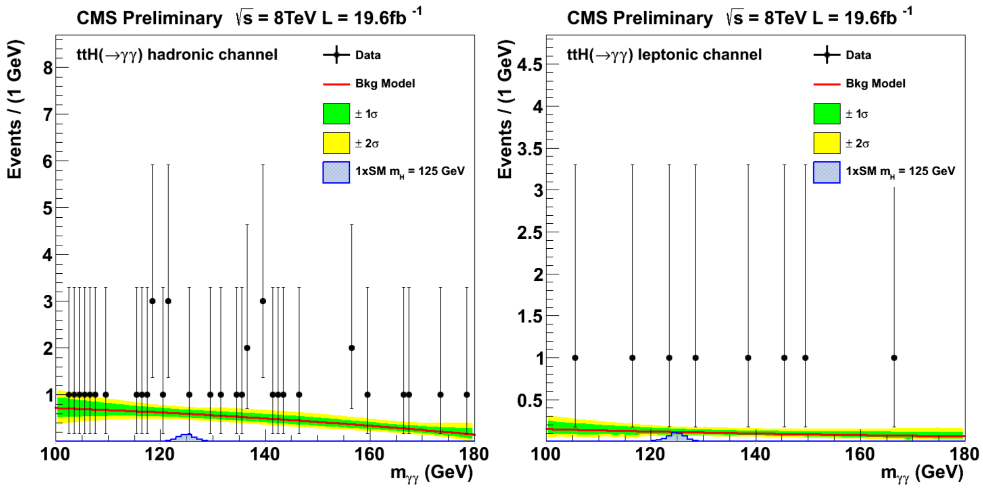


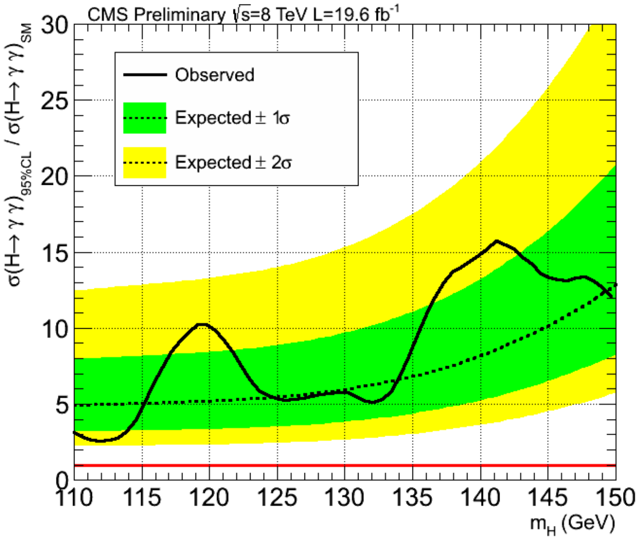


☆ ttH, H⟶$\gamma\gamma$

[CMS-PAS-HIG-13-015]



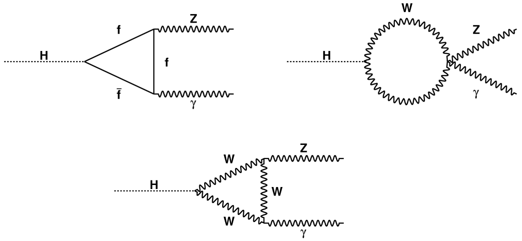




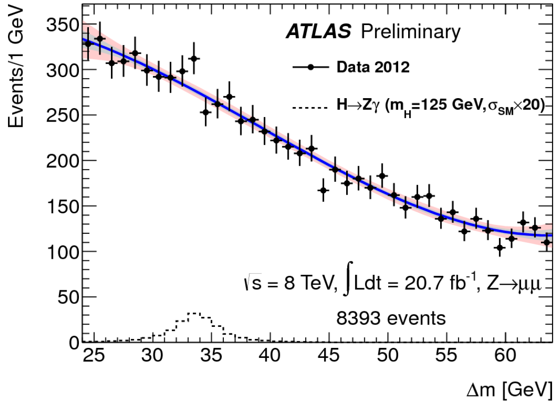
- ☐ Tagging of leptonic and hadronic W decays from top (anti-)quarks.
- ☐ **At m_H=125 GeV, μ < 5.4 (5.3)** (95%CL), obs.(exp.).

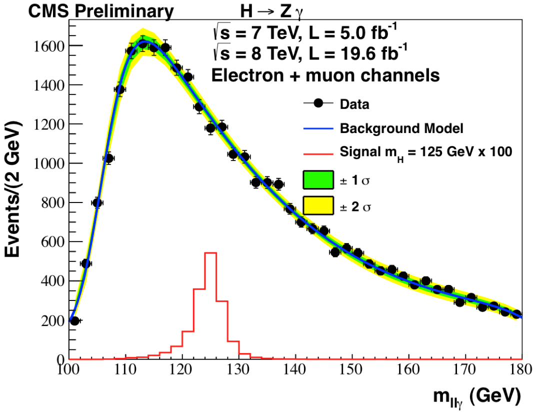
☆ $H \longrightarrow Z\gamma \longrightarrow \ell\ell\gamma$

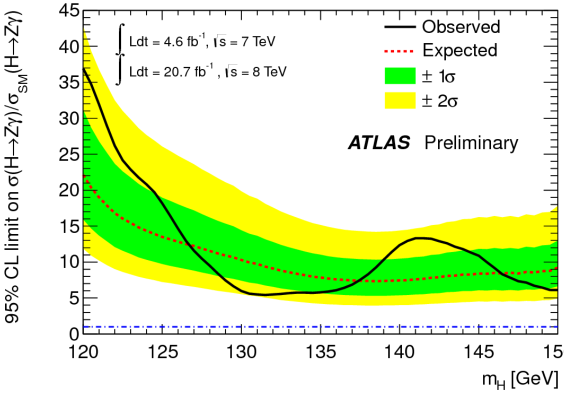
[ATLAS-CONF-2013-009] [CMS-PAS-HIG-13-006]

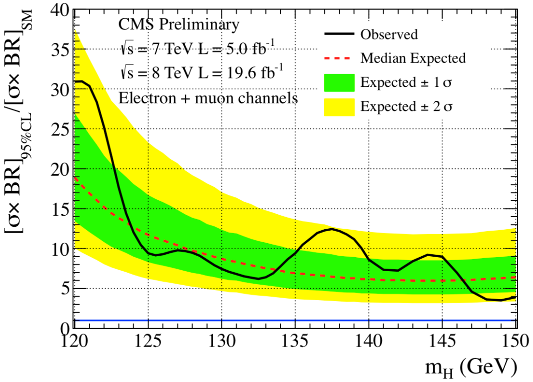


- ☐ Loop-mediated decay: sensitive to BSM.
- ☐ Both analyses on full 7 and 8 TeV data sets.









Obs. (exp.)	**ATLAS**	**CMS**
μ at 125 GeV (95% CL)	**< 18.2 (13.5)**	**< 9 (12)**

Oversimplified big picture

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

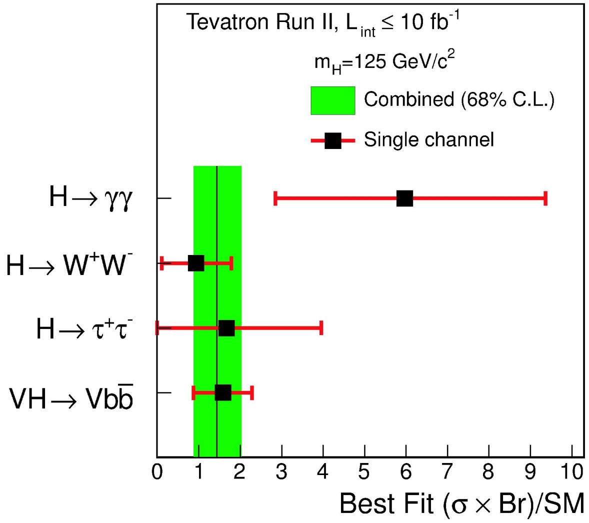
★ "seen" ☆ "tried" - "impossible"	$H \to b\bar{b}$			$H \to \tau\tau$			$H \to WW$			$H \to ZZ$			$H \to \gamma\gamma$			$H \to Z\gamma$			$H \to$ inv.			$H \to \mu\mu$			$H \to c\bar{c}$ $H \to HH$		
	T	A	C	T	A	C	T	A	C	T	A	C	T	A	C	T	A	C	T	A	C	T	A	C	T	A	C
ggH	-	-	-	☆	☆	★	☆	★	★	☆	★	★	☆	★	★	-	☆	☆				-	☆		-		
VBF			☆	☆	☆	★		★	★		★	☆		★	☆	-						-			-		
VH	★	☆	★	☆		☆	☆		☆		☆			☆	☆	-				☆		-			-		
ttH		☆	☆	☆			☆								☆	-						-			-		

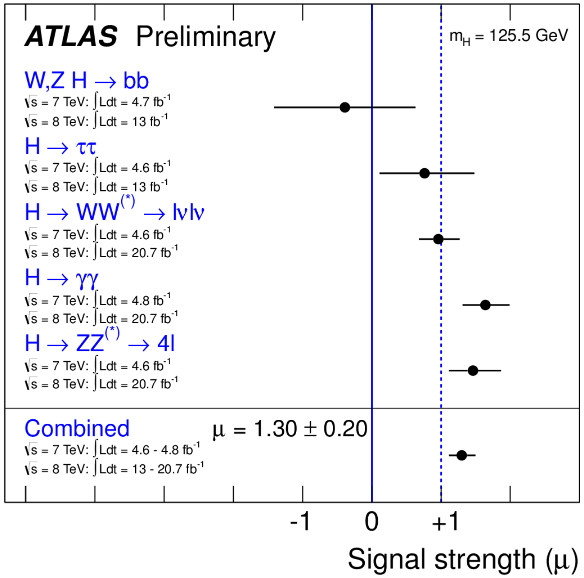
- ☐ **Still much to explore on the rarer ends.**

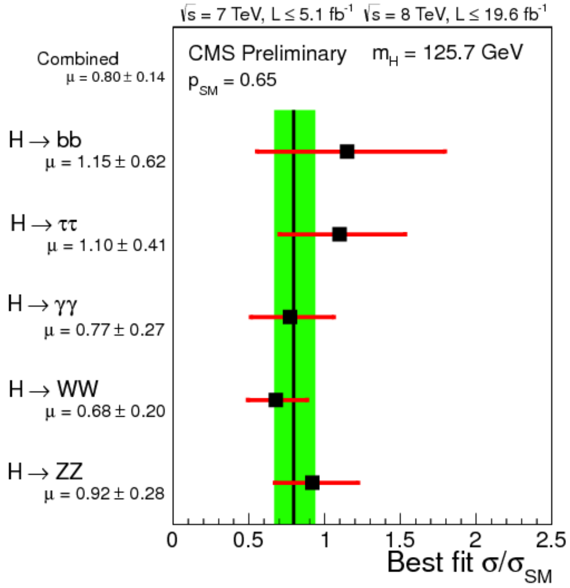
  (to the right and to the bottom)

Relative signal strengths

[arXiv:1303.6346] [ATLAS-CONF-2013-034] [CMS-PAS-HIG-13-005]



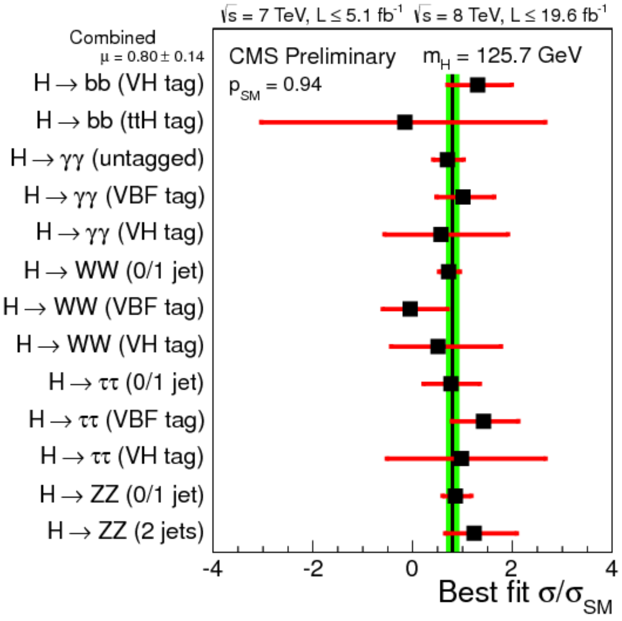


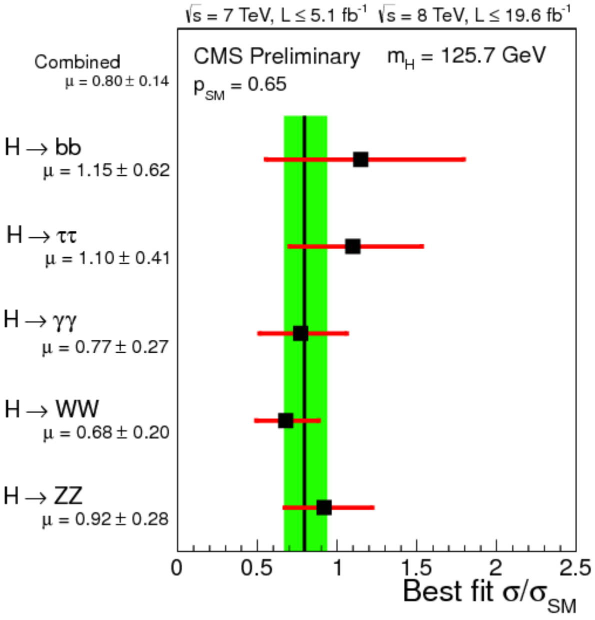


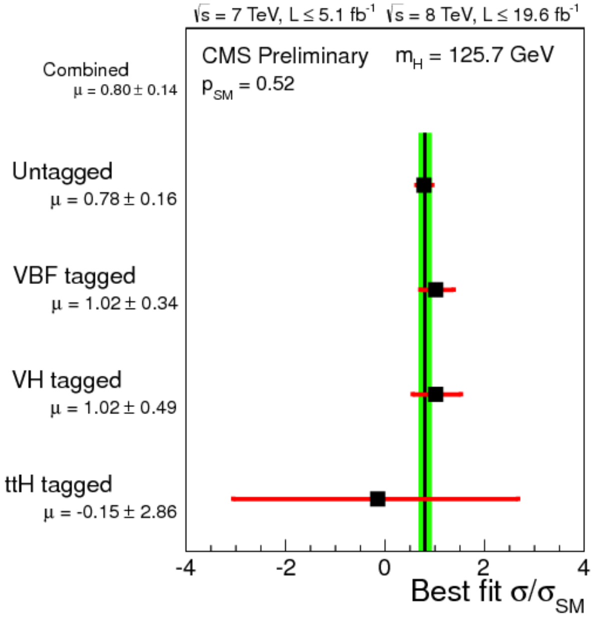
	Tevatron	ATLAS	CMS
m_H	125 GeV	125.5 GeV	125.7 GeV
$\mu = \sigma/\sigma_{SM}$	$1.44^{+0.59}_{-0.56}$	1.30 ±0.20	0.80 ±0.14

Naïve average: 0.98 ±0.11

CMS: channel compatibility

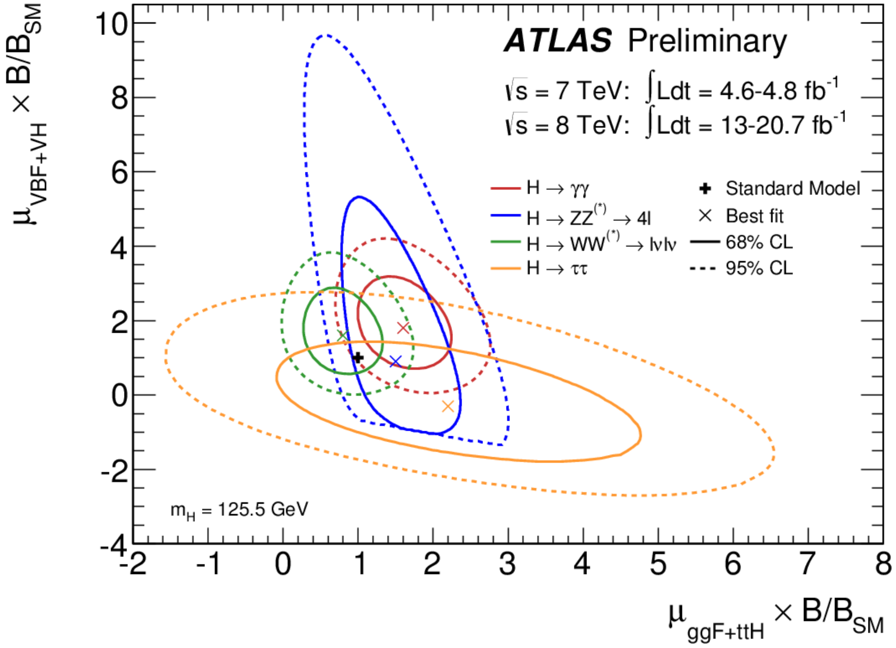


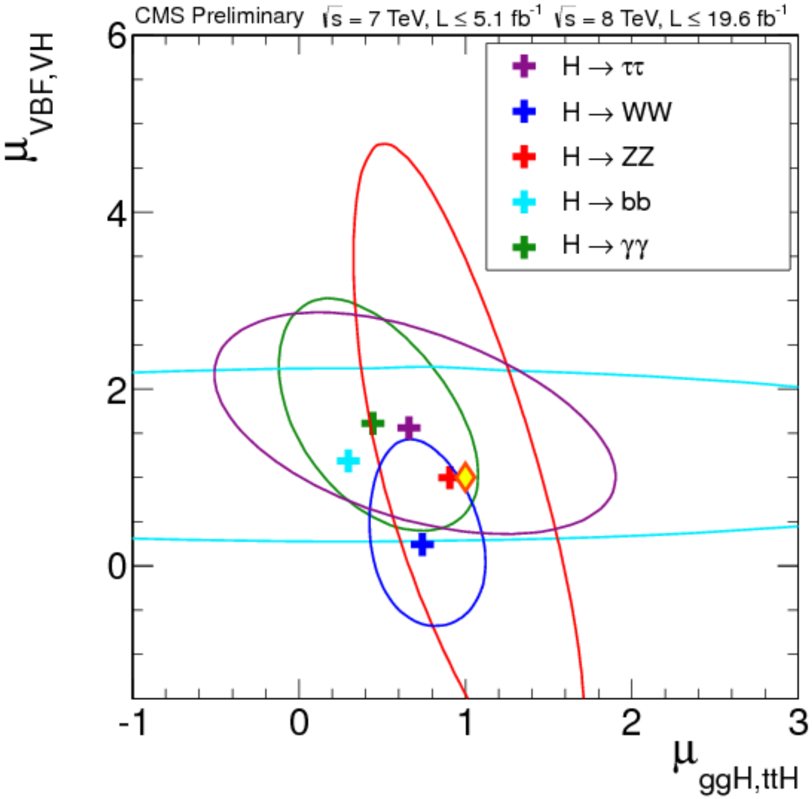




Production mechanisms

[ATLAS-CONF-2013-034] [CMS-PAS-HIG-13-005]

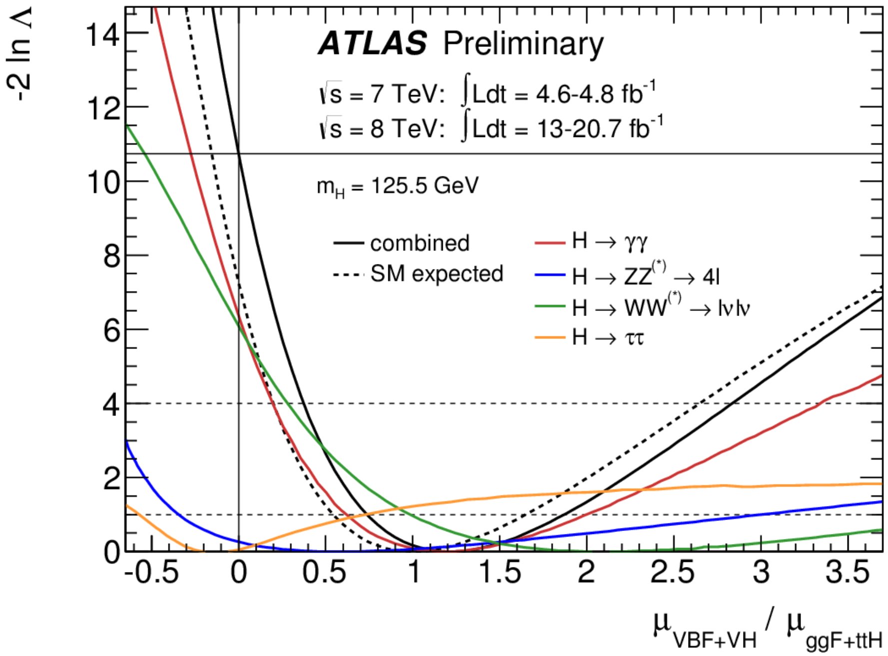


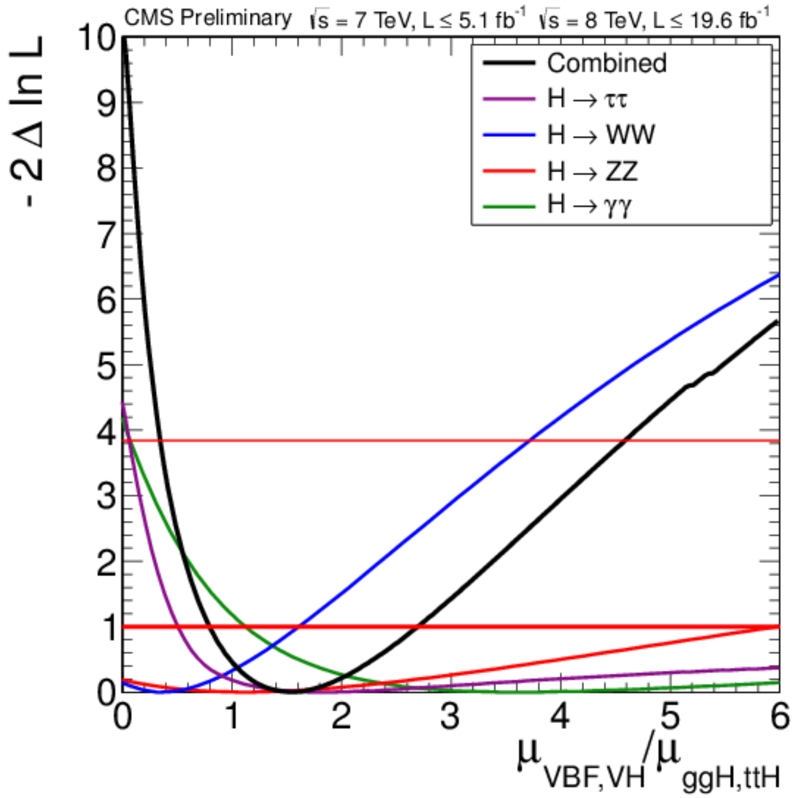


- Scale fermion-mediated (ggH & ttH) and vector-boson-mediated (VBF & VH) together.

Production mechanisms

[ATLAS-CONF-2013-034] [CMS-PAS-HIG-13-005]





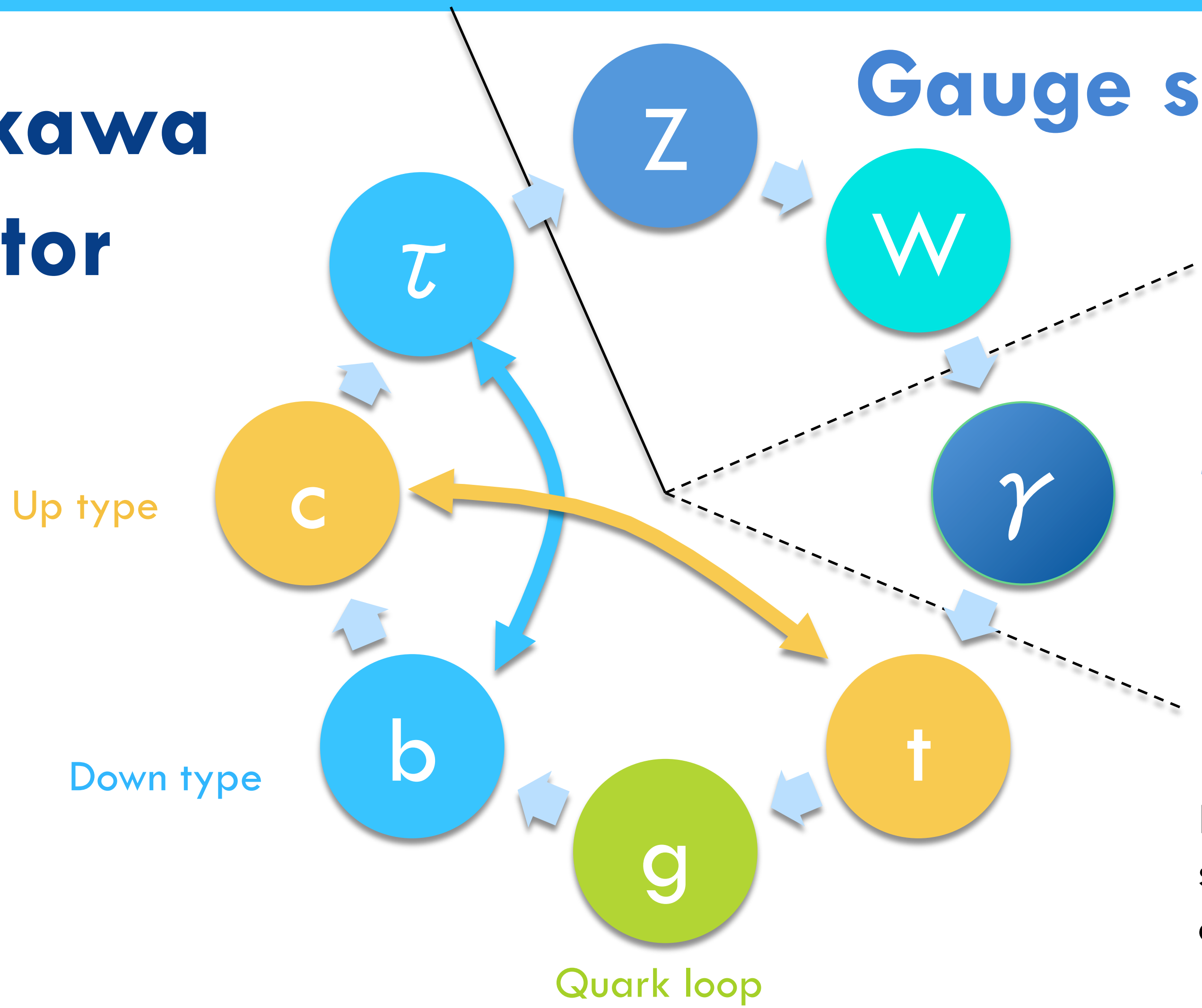
- Ratio of production scaling factors does not depend on decay mode.
  - **Combined > 3σ evidence for $\mu_{\mathrm{VBF,VH}} / \mu_{\mathrm{ggH,ttH}} > 0$.**

Scalar coupling structure

Yukawa sector

Gauge sector

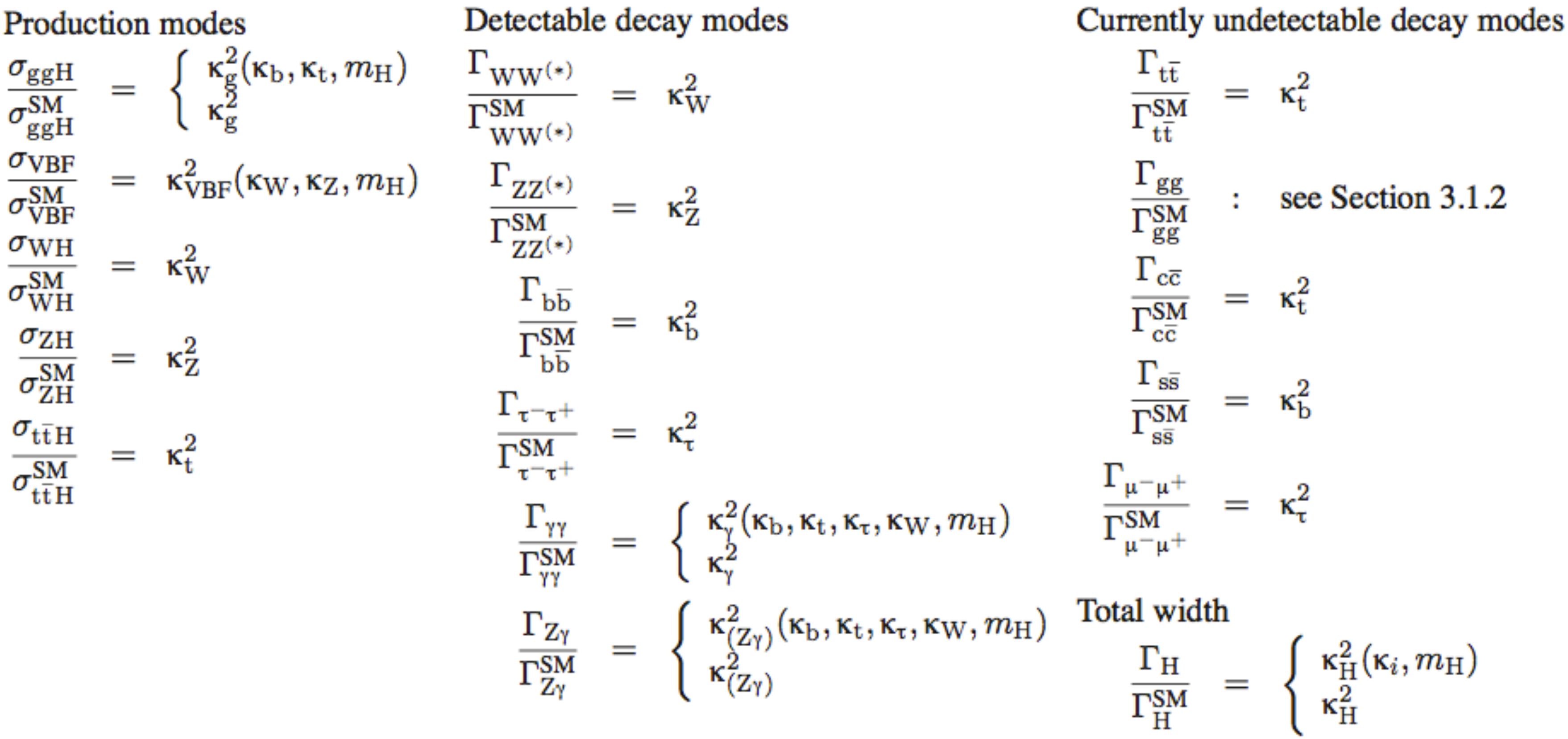
Mixed sector



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

Interim scalar coupling deviations framework

[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

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

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

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

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

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

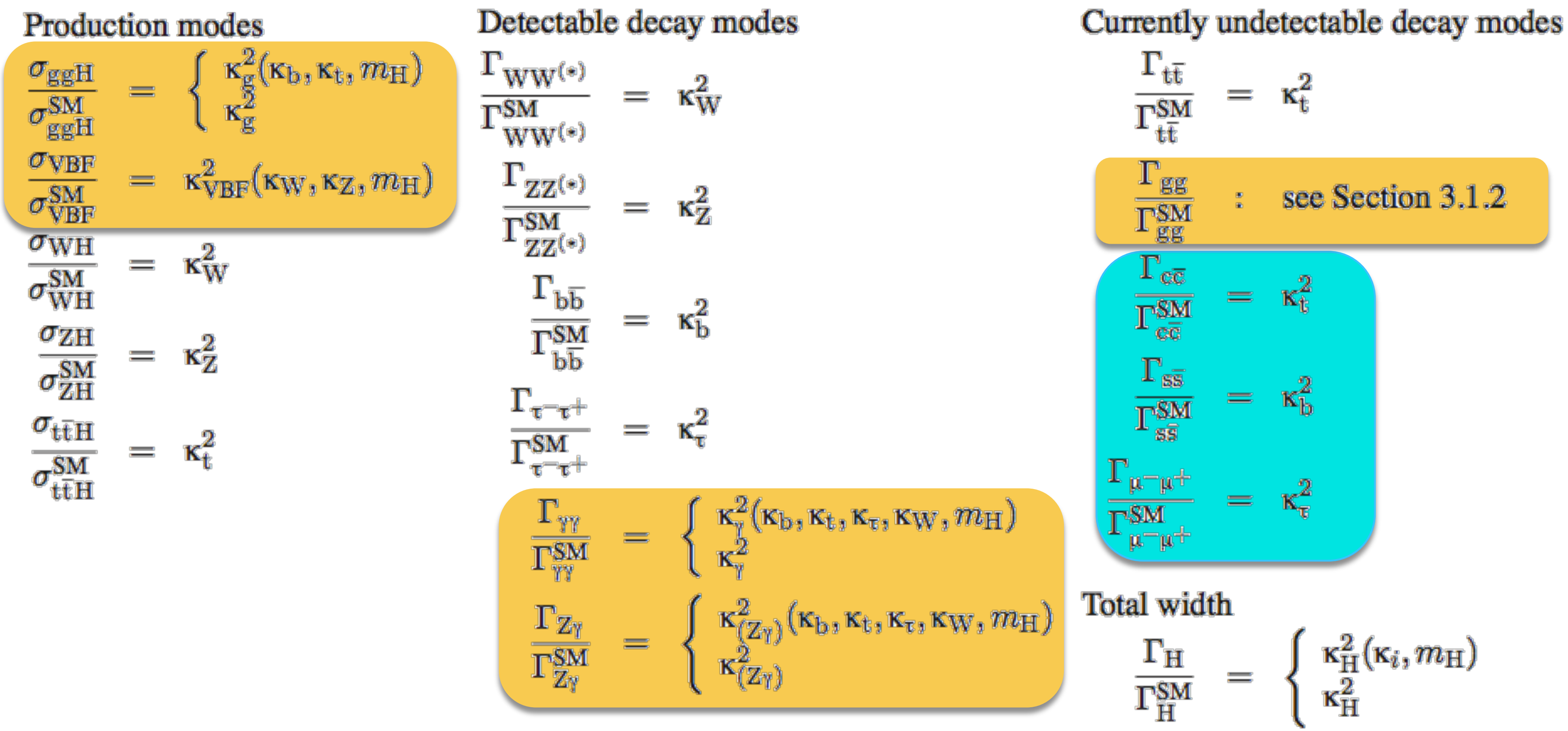
Total width

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

- Narrow-width approximation: $(\sigma \times BR) = \sigma \cdot \Gamma / \Gamma_H$

Interim scalar coupling deviations framework

[arXiv:1209.0040]



Production modes

$$\frac{\sigma_{\mathrm{ggH}}}{\sigma^{\mathrm{SM}}_{\mathrm{ggH}}} = \begin{cases} \kappa_{\mathrm{g}}^2(\kappa_{\mathrm{b}},\kappa_{\mathrm{t}},m_{\mathrm{H}}) \\ \kappa_{\mathrm{g}}^2 \end{cases}$$

$$\frac{\sigma_{\mathrm{VBF}}}{\sigma^{\mathrm{SM}}_{\mathrm{VBF}}} = \kappa_{\mathrm{VBF}}^2(\kappa_{\mathrm{W}},\kappa_{\mathrm{Z}},m_{\mathrm{H}})$$

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

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

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

Detectable decay modes

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

$$\frac{\Gamma_{\mathrm{ZZ}^{(*)}}}{\Gamma^{\mathrm{SM}}_{\mathrm{ZZ}^{(*)}}} = \kappa_{\mathrm{Z}}^2$$

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

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

$$\frac{\Gamma_{\gamma\gamma}}{\Gamma^{\mathrm{SM}}_{\gamma\gamma}} = \begin{cases} \kappa_{\gamma}^2(\kappa_{\mathrm{b}},\kappa_{\mathrm{t}},\kappa_{\tau},\kappa_{\mathrm{W}},m_{\mathrm{H}}) \\ \kappa_{\gamma}^2 \end{cases}$$

$$\frac{\Gamma_{\mathrm{Z}\gamma}}{\Gamma^{\mathrm{SM}}_{\mathrm{Z}\gamma}} = \begin{cases} \kappa_{(\mathrm{Z}\gamma)}^2(\kappa_{\mathrm{b}},\kappa_{\mathrm{t}},\kappa_{\tau},\kappa_{\mathrm{W}},m_{\mathrm{H}}) \\ \kappa_{(\mathrm{Z}\gamma)}^2 \end{cases}$$

Currently undetectable decay modes

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

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

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

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

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

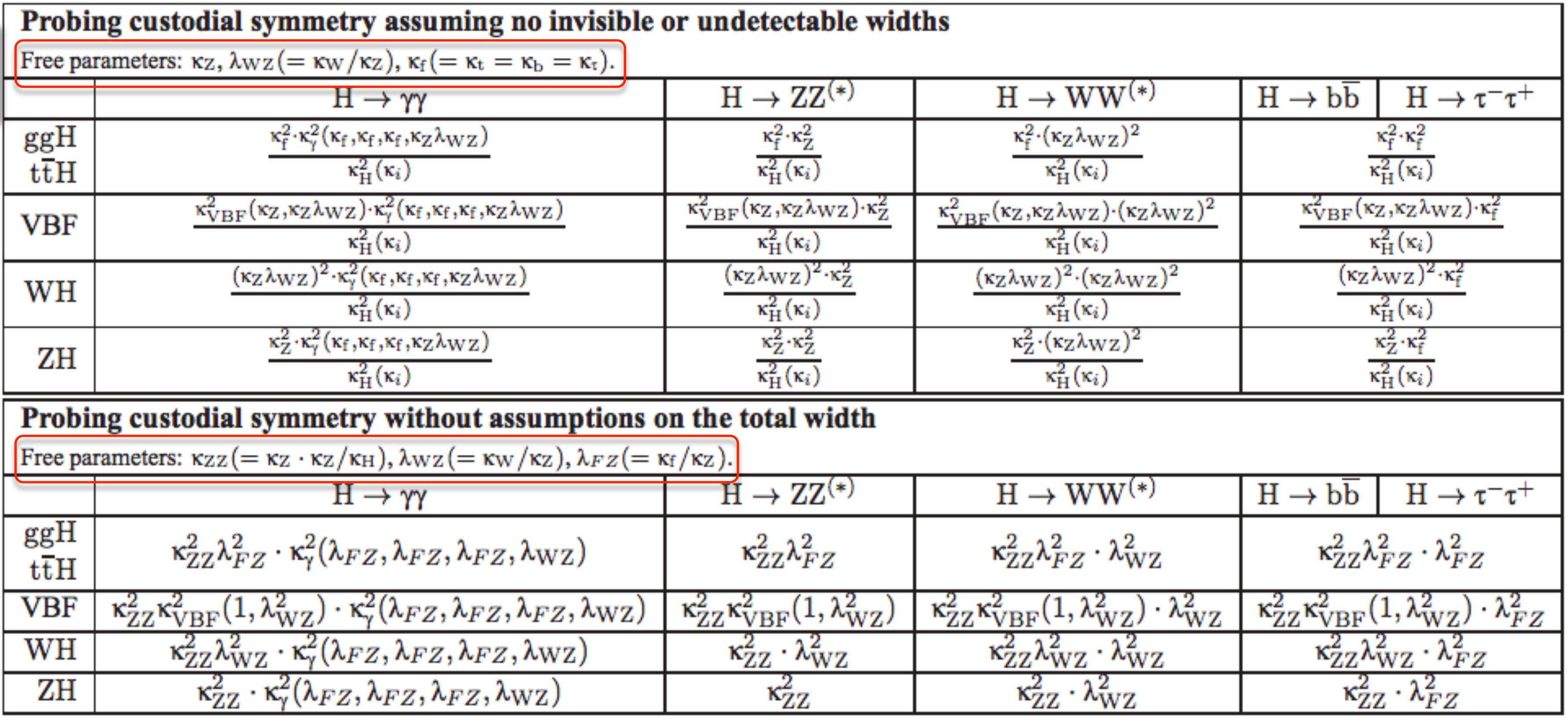
Total width

$$\frac{\Gamma_{\mathrm{H}}}{\Gamma^{\mathrm{SM}}_{\mathrm{H}}} = \begin{cases} \kappa_{\mathrm{H}}^2(\kappa_i,m_{\mathrm{H}}) \\ \kappa_{\mathrm{H}}^2 \end{cases}$$

- Contributions resolved at NLO QCD and LO EWK.
- Peg the unmeasured to “closest of kin”.

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	$\frac{\kappa_Z^2\cdot\kappa_\gamma^2(\kappa_f,\kappa_f,\kappa_f,\kappa_Z\lambda_{WZ})}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_Z^2\cdot\kappa_Z^2}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_Z^2\cdot(\kappa_Z\lambda_{WZ})^2}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_Z^2\cdot\kappa_f^2}{\kappa_H^2(\kappa_i)}$	

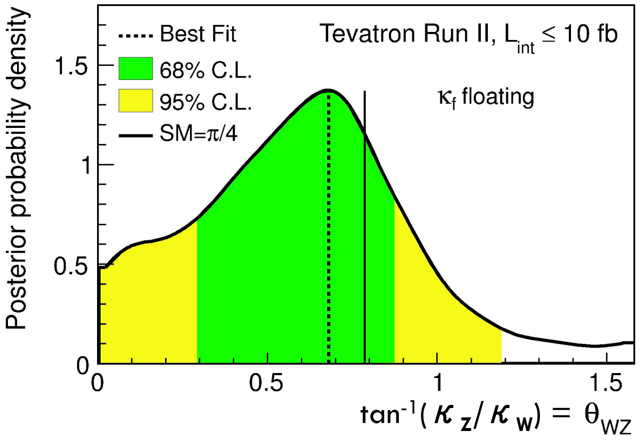
Probing custodial symmetry without assumptions on the total width

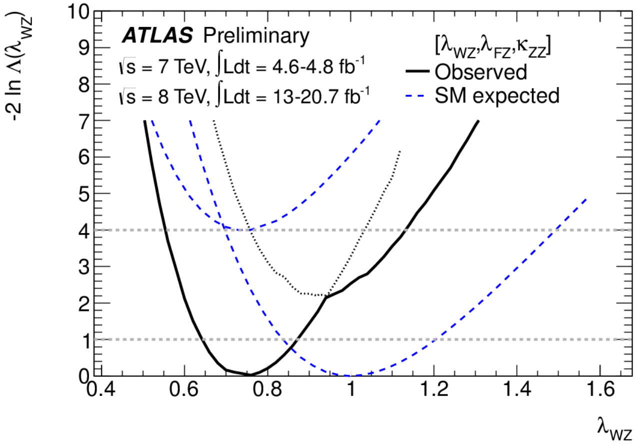
Free parameters: $\kappa_{ZZ}(=\kappa_Z\cdot\kappa_Z/\kappa_H)$, $\lambda_{WZ}(=\kappa_W/\kappa_Z)$, $\lambda_{FZ}(=\kappa_f/\kappa_Z)$.

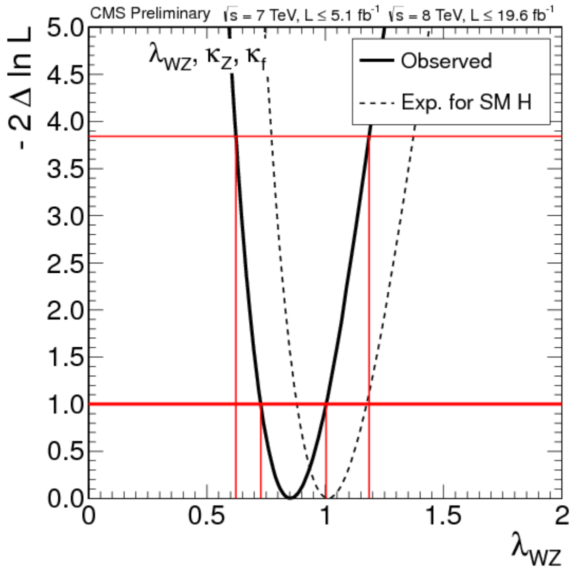
	$H\to\gamma\gamma$	$H\to ZZ^{(*)}$	$H\to WW^{(*)}$	$H\to b\bar{b}$	$H\to\tau^-\tau^+$
ggH $t\bar{t}H$	$\kappa_{ZZ}^2\lambda_{FZ}^2\cdot\kappa_\gamma^2(\lambda_{FZ},\lambda_{FZ},\lambda_{FZ},\lambda_{WZ})$	$\kappa_{ZZ}^2\lambda_{FZ}^2$	$\kappa_{ZZ}^2\lambda_{FZ}^2\cdot\lambda_{WZ}^2$	$\kappa_{ZZ}^2\lambda_{FZ}^2\cdot\lambda_{FZ}^2$	
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-2013-034] [CMS-PAS-HIG-13-005]



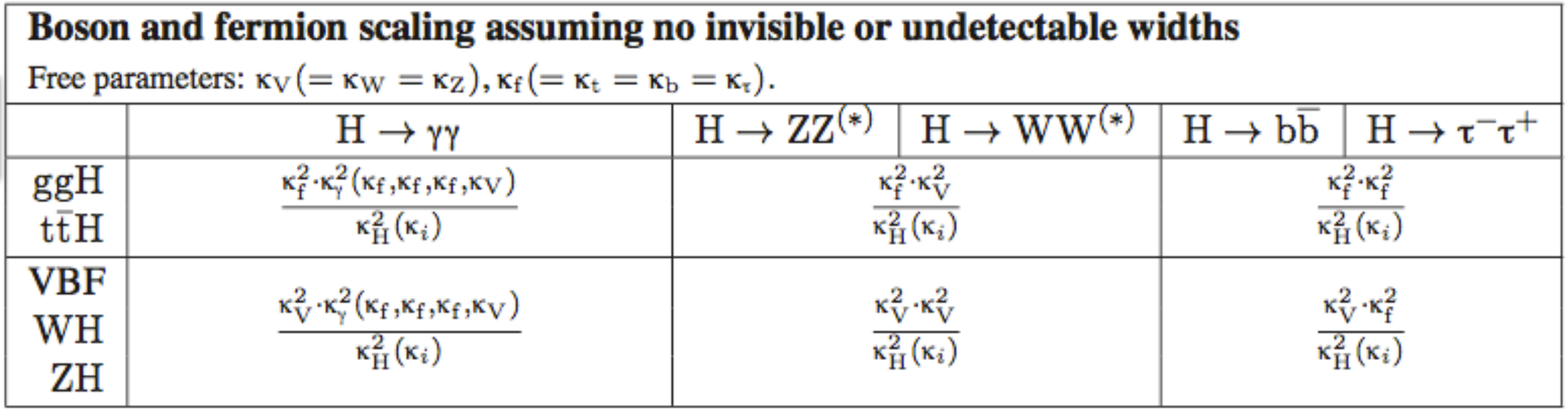




	Tevatron $[\kappa_W, \kappa_Z, \kappa_f]$	**ATLAS** $[\lambda_{WZ}, \lambda_{FZ}, \kappa_{ZZ}]$	**CMS** $[\lambda_{WZ}, \kappa_Z, \kappa_f]$
λ_{WZ}	$\mathbf{1.24^{+2.34}_{-0.42}}$	**[0.64, 0.87]**	**0.86 ±0.13**

Weak bosons and fermions

[arXiv:1209.0040]



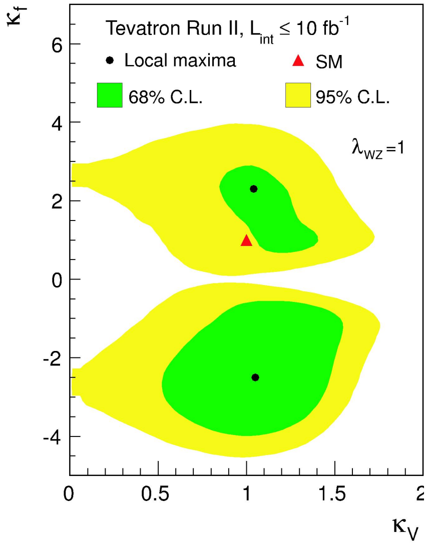
Boson and fermion scaling assuming no invisible or undetectable widths

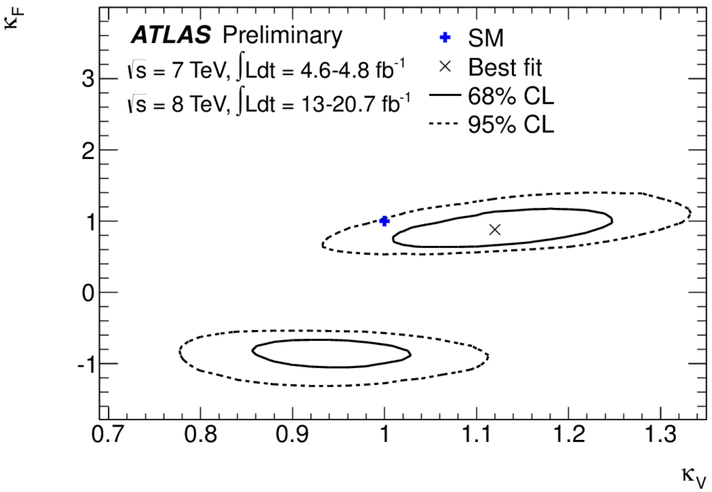
Free parameters: $\kappa_V (= \kappa_W = \kappa_Z)$, $\kappa_f (= \kappa_t = \kappa_b = \kappa_\tau)$.

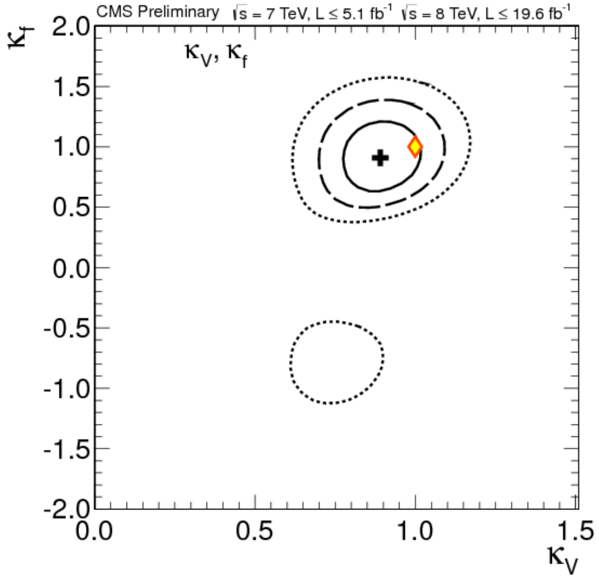
	$H \rightarrow \gamma\gamma$	$H \rightarrow ZZ^{(*)}$	$H \rightarrow WW^{(*)}$	$H \rightarrow b\bar{b}$	$H \rightarrow \tau^-\tau^+$
ggH $t\bar{t}H$	$\frac{\kappa_f^2 \cdot \kappa_\gamma^2(\kappa_f, \kappa_f, \kappa_f, \kappa_V)}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_f^2 \cdot \kappa_V^2}{\kappa_H^2(\kappa_i)}$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

Weak bosons and fermions

[arXiv:1303.6346] [ATLAS-CONF-2013-034] [CMS-PAS-HIG-13-005]



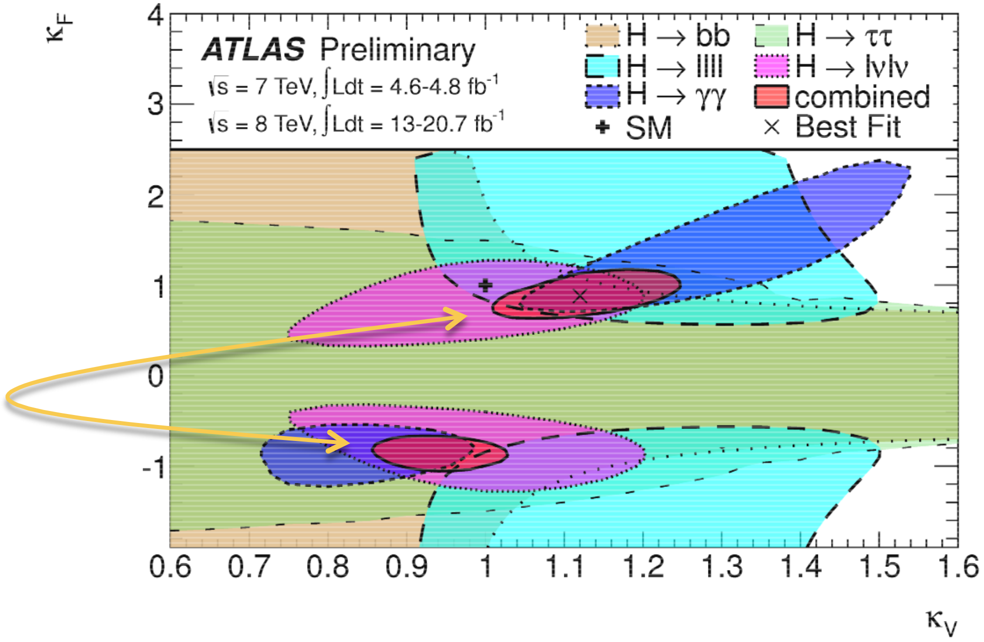


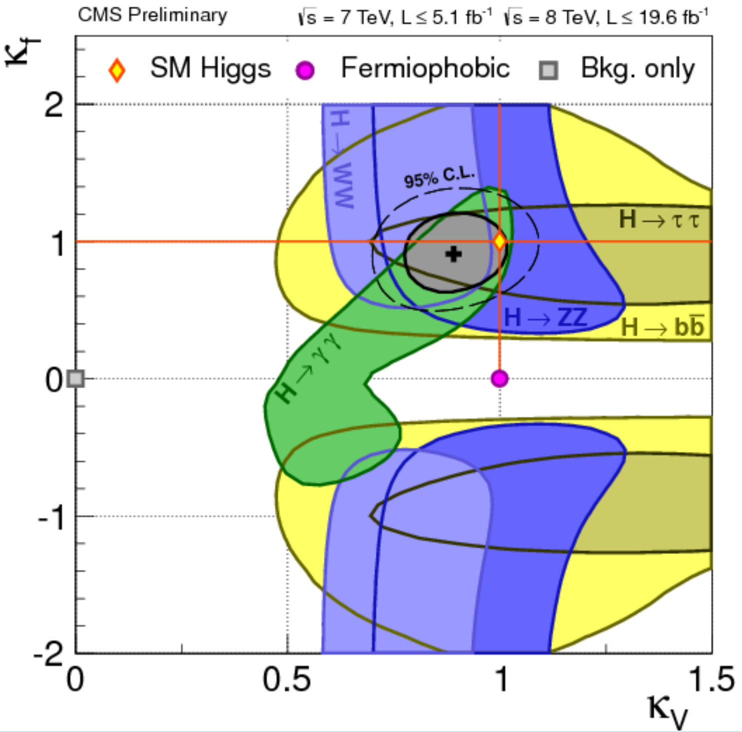


	Tevatron	ATLAS	CMS
P(SM)	-	8%	< 1 σ

Weak bosons and fermions

[ATLAS-CONF-2013-034] [CMS-PAS-HIG-13-005]

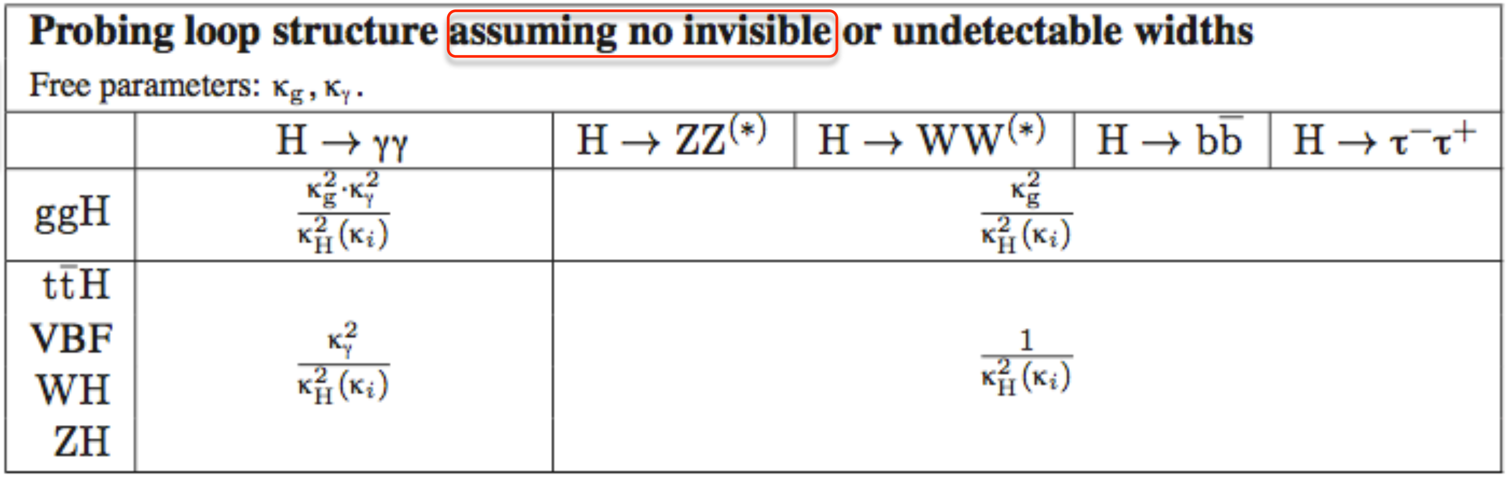




	ATLAS	CMS
P(SM)	**8%**	**< 1 σ**

Looking for new particles

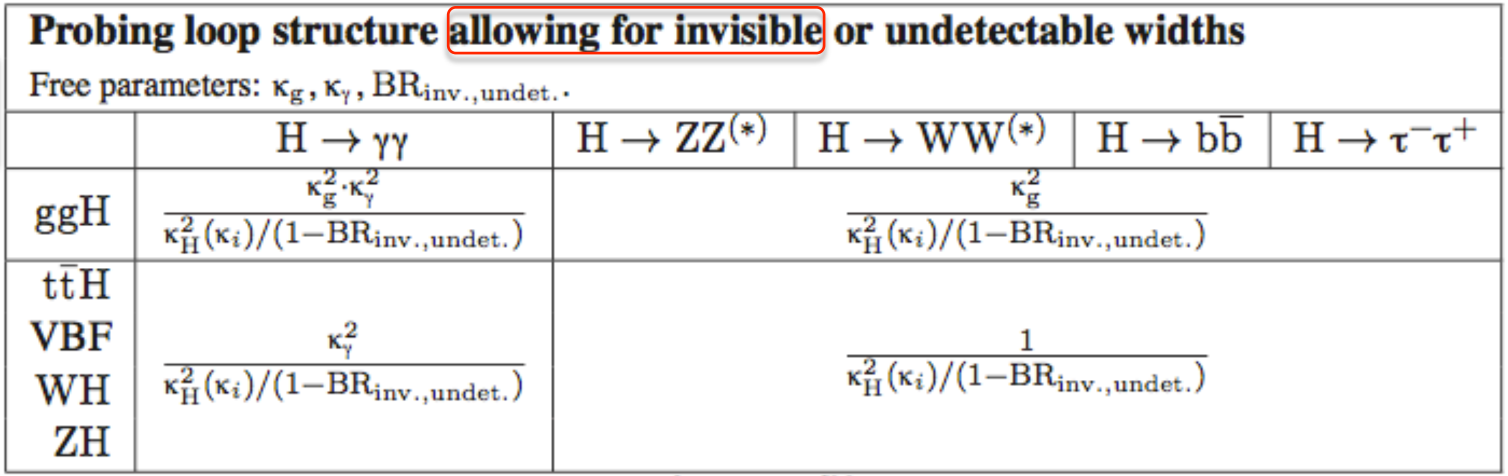
[arXiv:1209.0040]



Probing loop structure assuming no invisible or undetectable widths

Free parameters: κ_g, κ_γ.

	$H \to \gamma\gamma$	$H \to ZZ^{(*)}$	$H \to WW^{(*)}$	$H \to b\bar{b}$	$H \to \tau^-\tau^+$
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

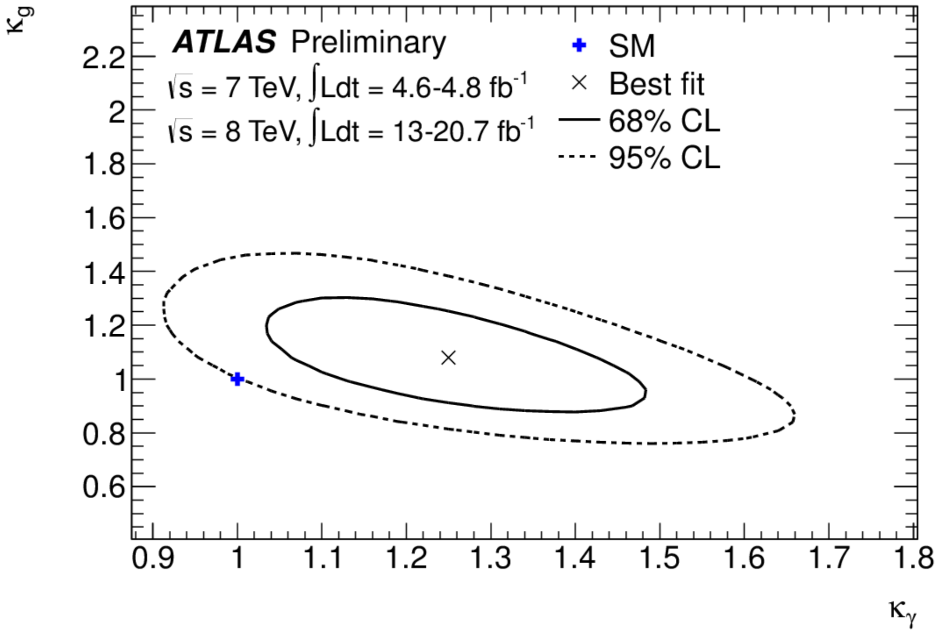
Free parameters: $\kappa_g, \kappa_\gamma, \mathrm{BR}_{\mathrm{inv.,undet.}}$.

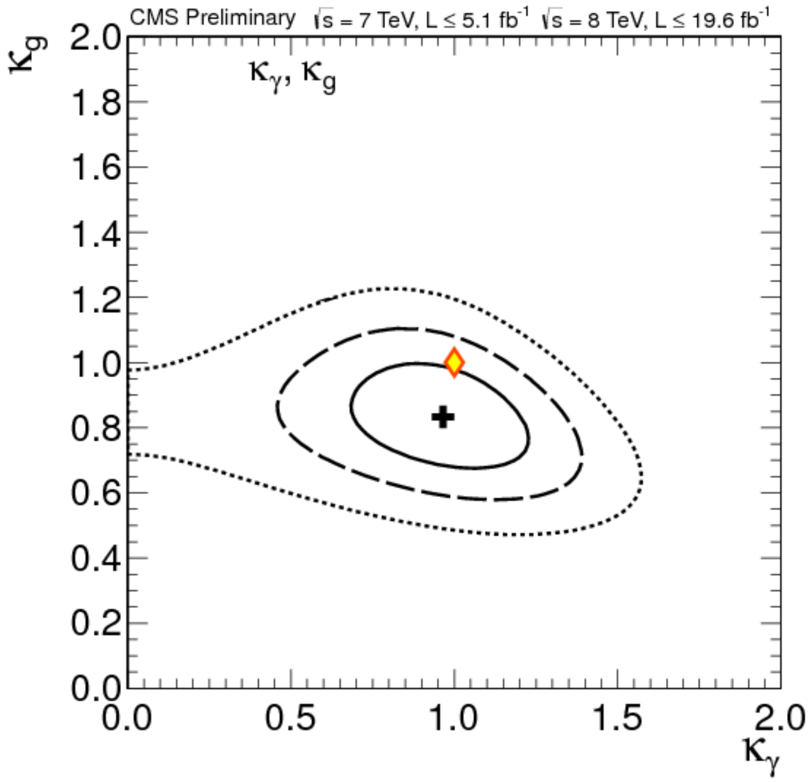
	$H \to \gamma\gamma$	$H \to ZZ^{(*)}$	$H \to WW^{(*)}$	$H \to b\bar{b}$	$H \to \tau^-\tau^+$
ggH	$\frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2(\kappa_i)/(1-\mathrm{BR}_{\mathrm{inv.,undet.}})}$	$\frac{\kappa_g^2}{\kappa_H^2(\kappa_i)/(1-\mathrm{BR}_{\mathrm{inv.,undet.}})}$			
$t\bar{t}H$ VBF WH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

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

Looking for new particles in loops

[ATLAS-CONF-2013-034] [CMS-PAS-HIG-13-005]

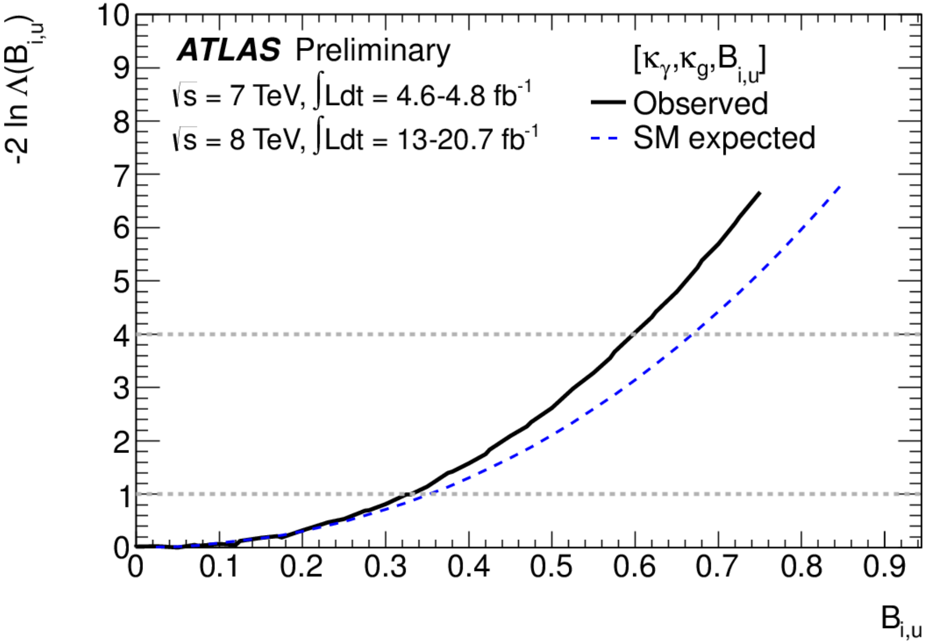


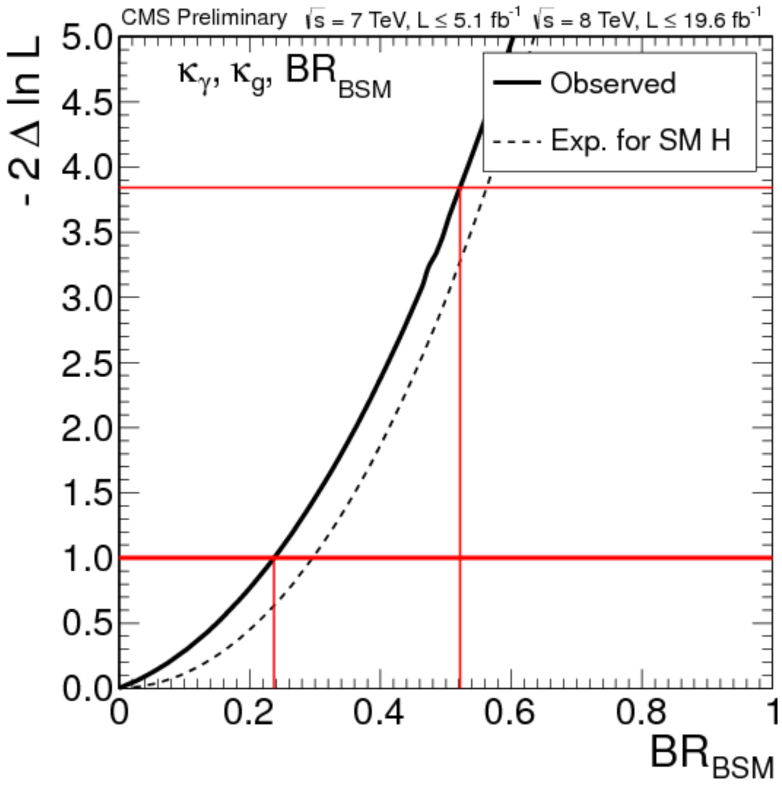


	ATLAS	**CMS**
κ_γ	**$1.23^{+0.16}_{-0.13}$**	**0.97 ±0.18**
κ_g	**1.08 ±0.14**	**0.83 ±0.11**

Looking for new particles

[ATLAS-CONF-2013-034] [CMS-PAS-HIG-13-005]

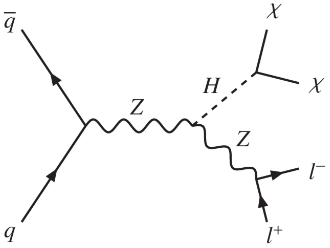




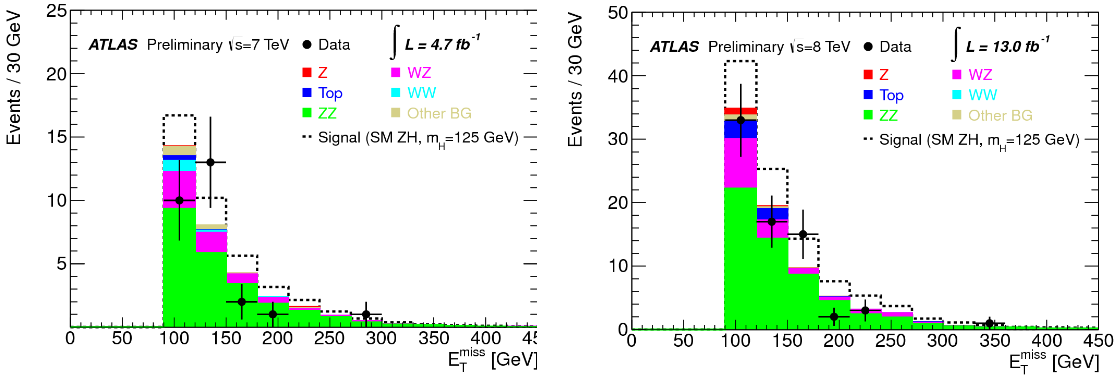
	ATLAS	CMS
BR_{BSM}	< 0.6 (95% CL)	< 0.52 (95% CL)

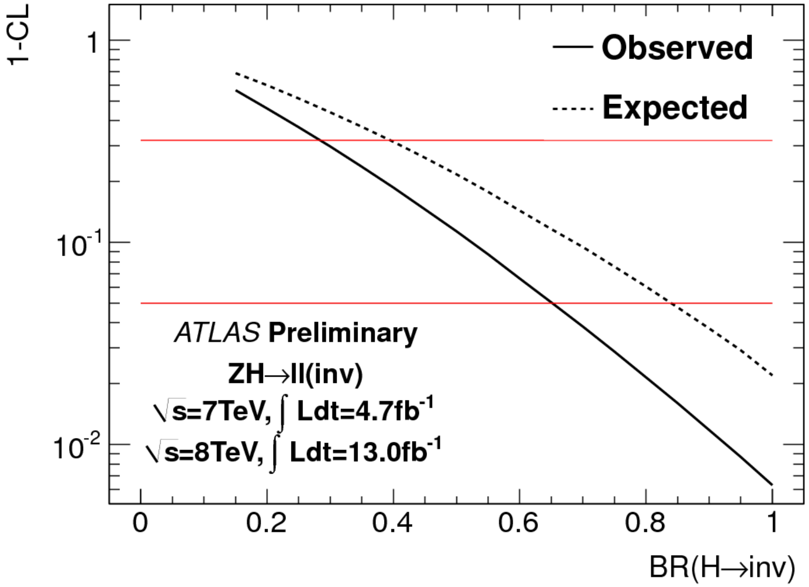
ZH⟶ℓℓ+invisible

[ATLAS-CONF-2013-011]



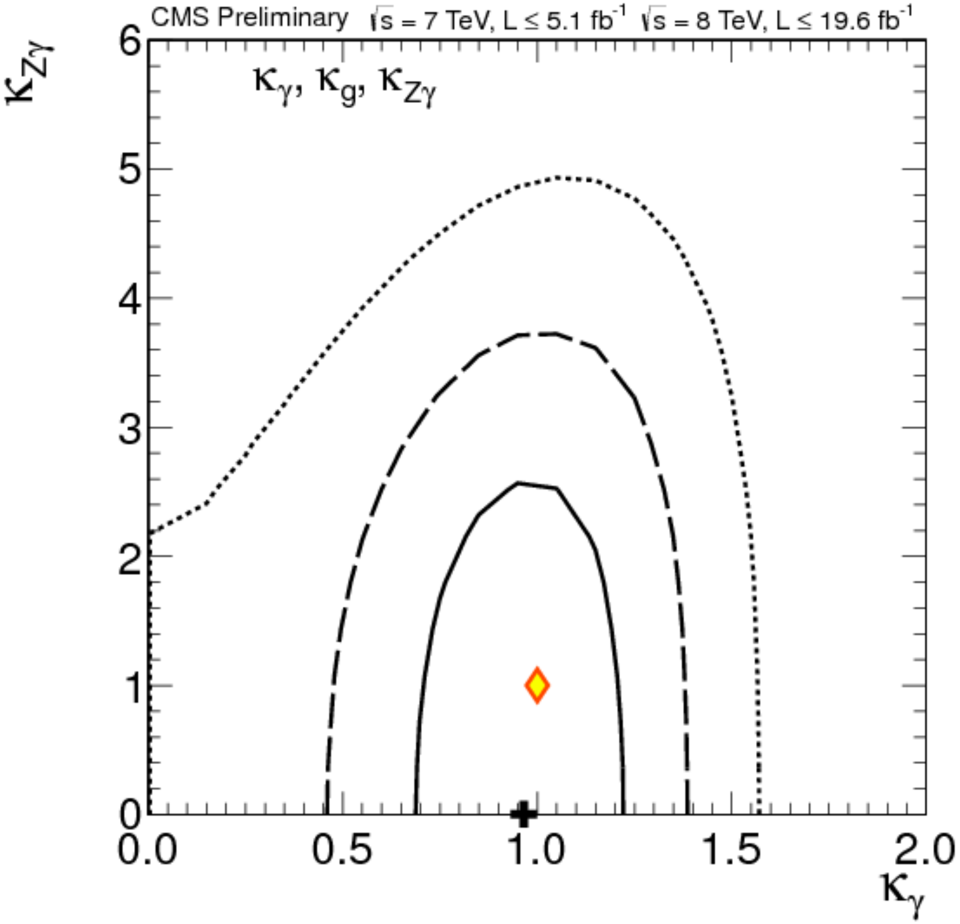
- MET > 90 GeV.
- 2D sideband on:
  - $|\mathrm{MET}-p_T^{\ell\ell}|/p_T^{\ell\ell}$
  - $\Delta\phi(\mathrm{MET}, \vec{p}_T^{\,\mathrm{miss.}})$
- Not yet sensitive to standard candle: ZH⟶ZZZ⟶2ℓ4ν
- **At m_H=125 GeV, $BR_{inv.}$ < 0.65 (0.84)** (95%CL), obs.(exp.).





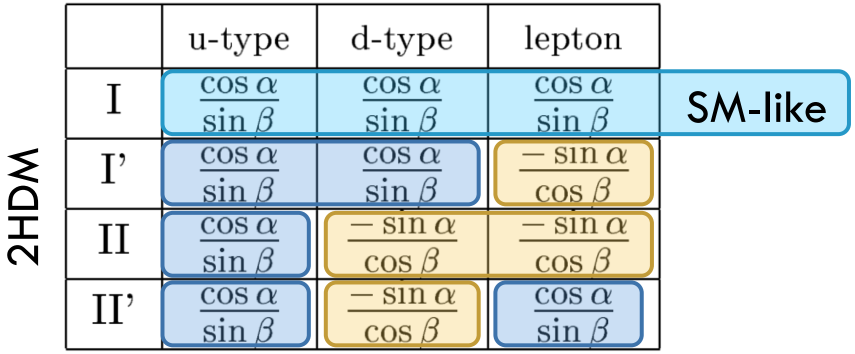
A further take on loops

- Resolve the H⟶γγ, H⟶Zγ, and ggH loops.



Probing the fermion sector

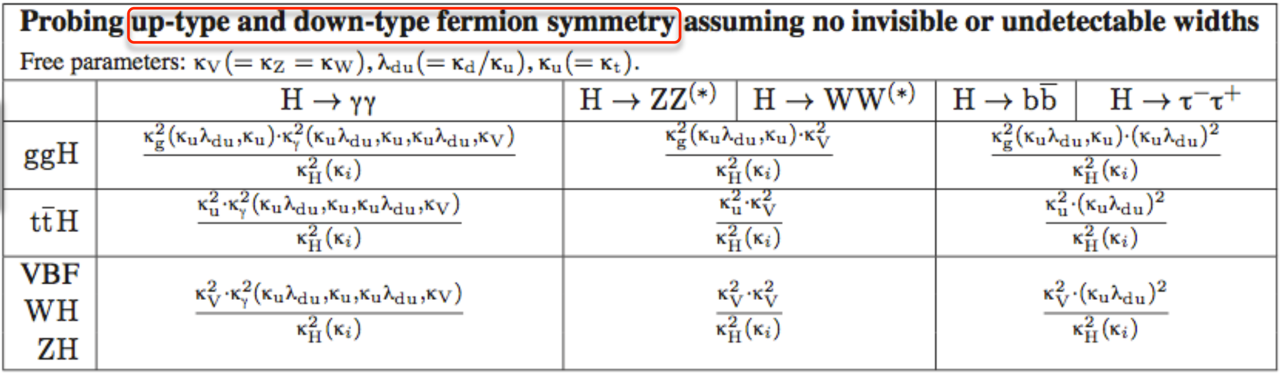
[arXiv:1209.0040]



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'	$\frac{\cos\alpha}{\sin\beta}$	$\frac{-\sin\alpha}{\cos\beta}$	$\frac{\cos\alpha}{\sin\beta}$

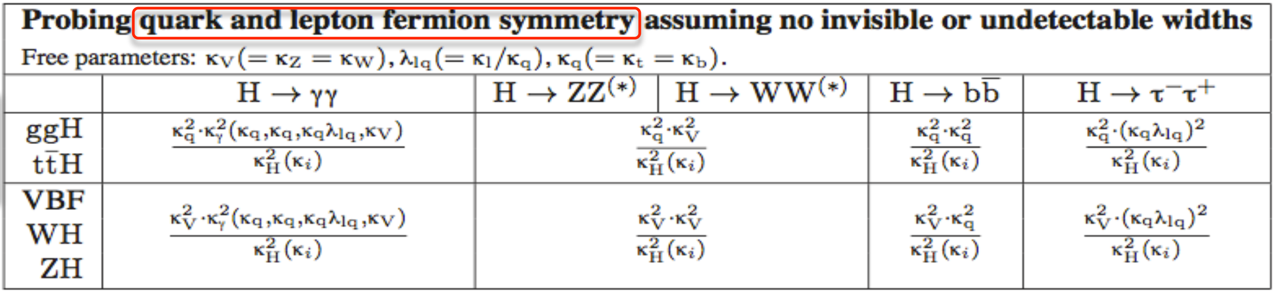
SM-like



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

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

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



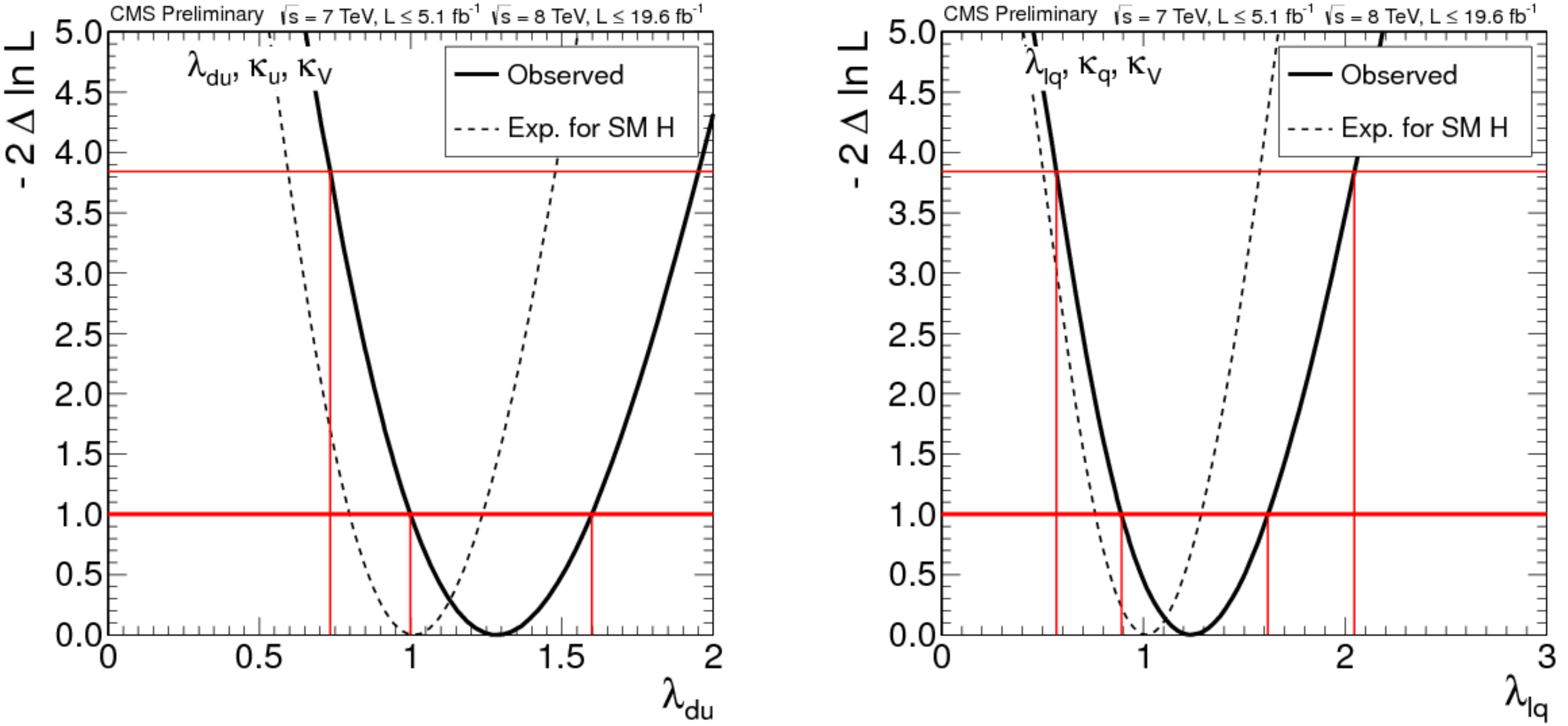
Probing quark and lepton fermion symmetry assuming no invisible or undetectable widths

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

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

Probing the fermion sector

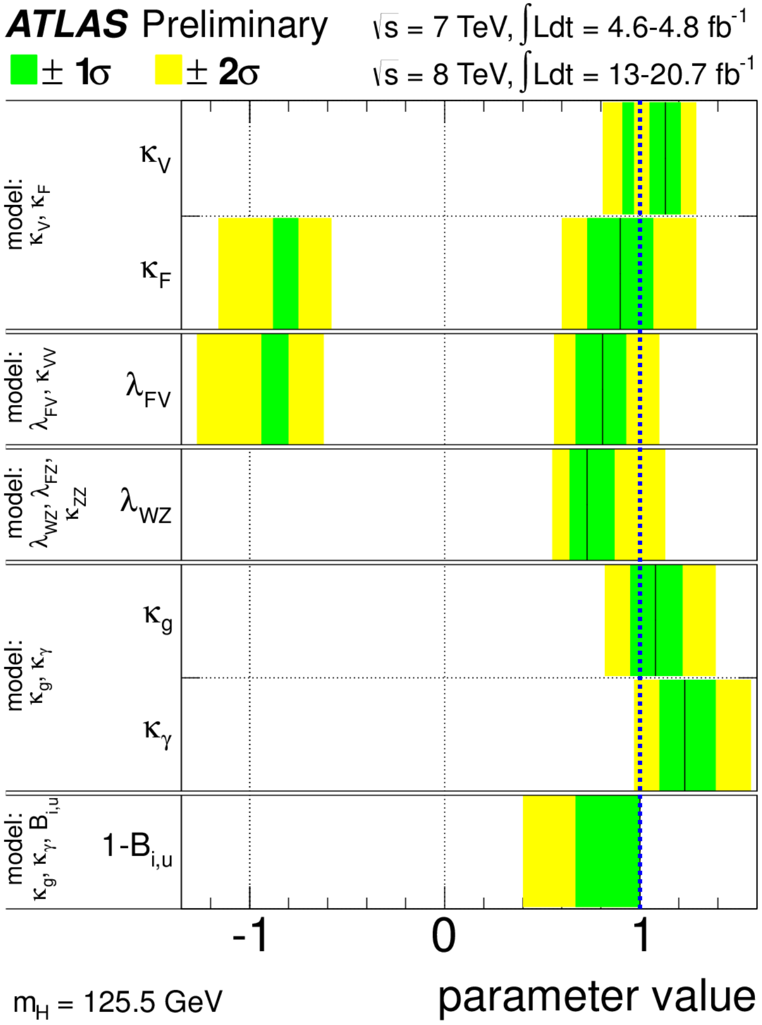
[CMS-PAS-HIG-13-005]

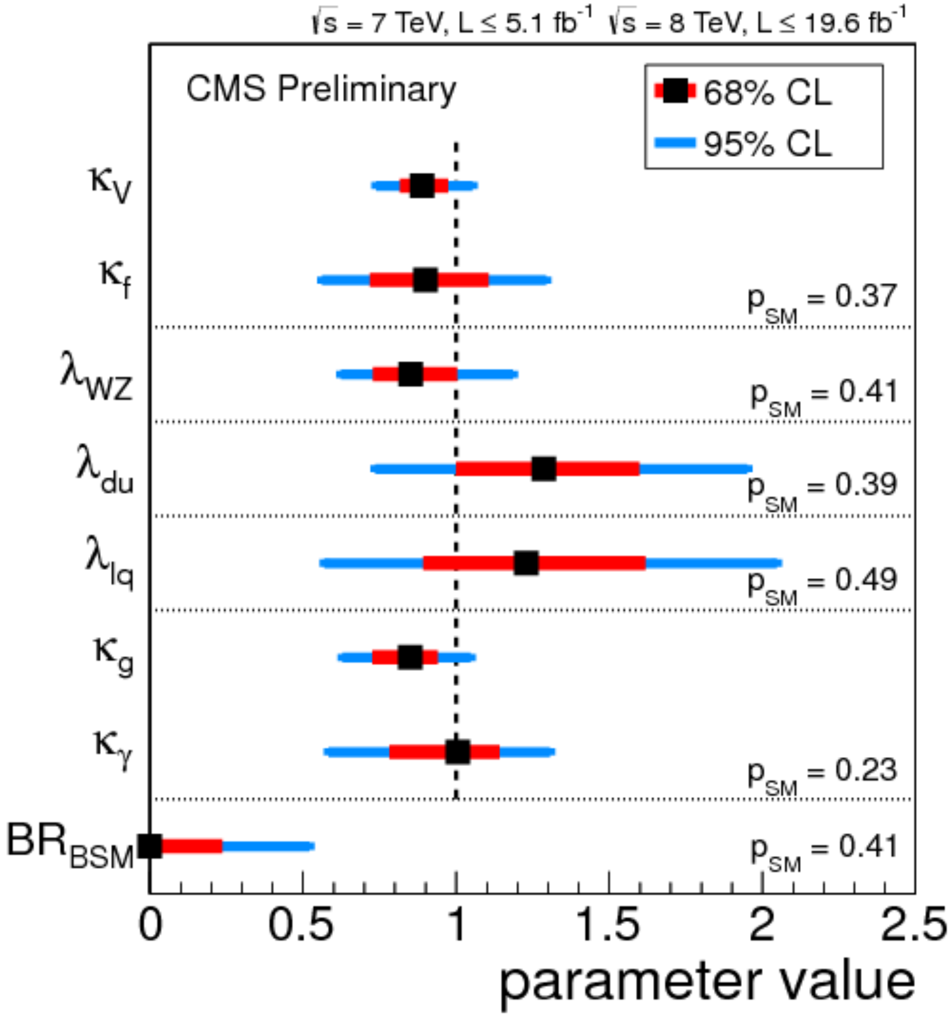


	λ_{du}	λ_{lq}
CMS	**[0.74, 1.95] (95% CL)**	**[0.57, 2.05] (95% CL)**

Summary of scalar couplings tests

[ATLAS-CONF-2013-034] [CMS-PAS-HIG-13-005]





“C6” vs “resolved C6”

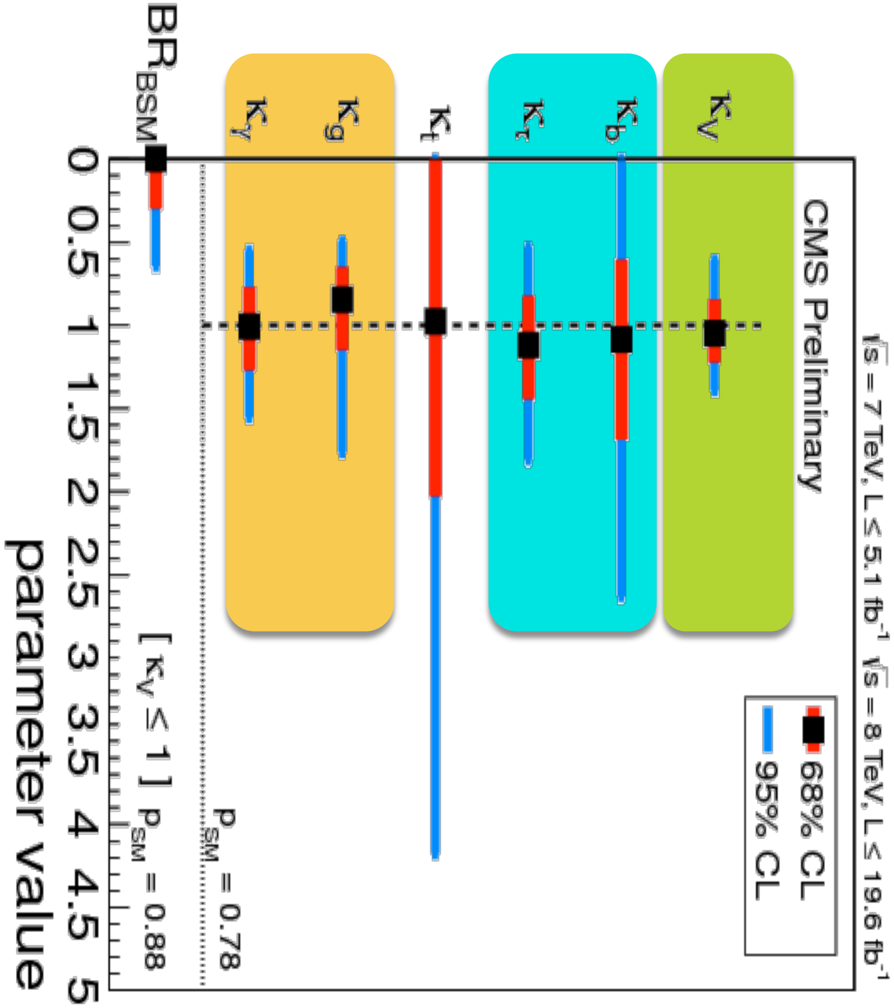
Generic coupling fit

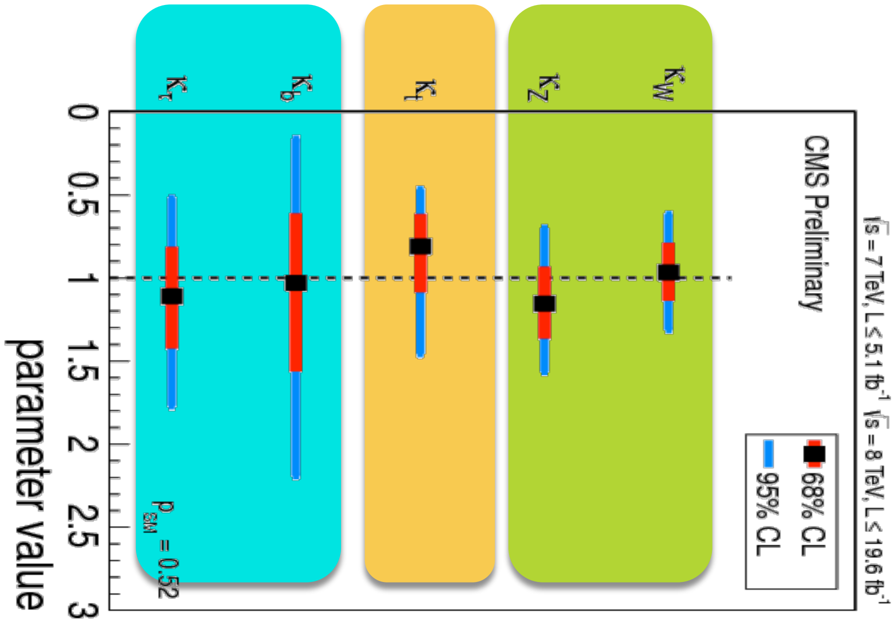
- Assume custodial symmetry ($\kappa_V = \kappa_W = \kappa_Z$).
- Loops treated effectively (κ_γ, κ_g).
- Option to allow BSM decays, forcing $\kappa_V \leq 1$.

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”

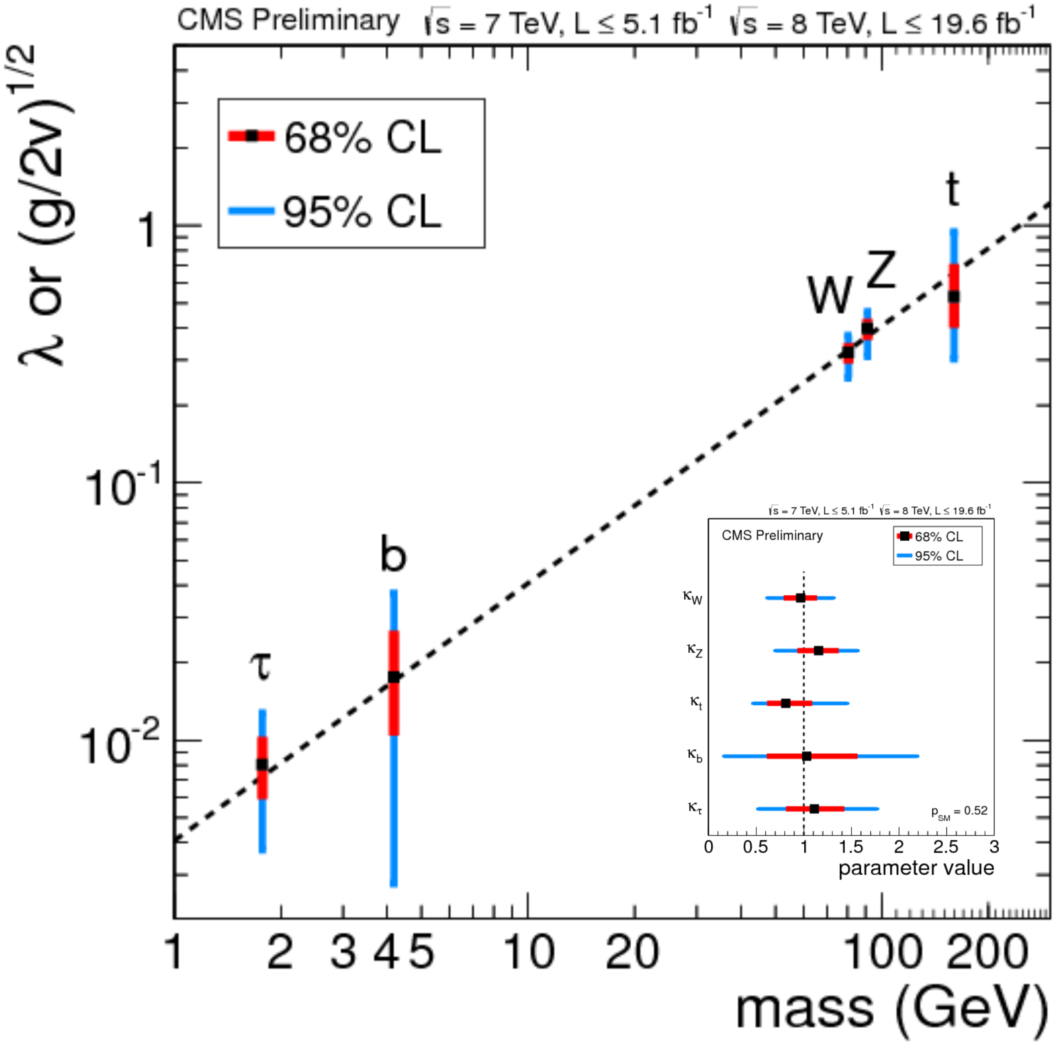




Resolving SM contributions

[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”:
  - $\lambda_f = \kappa_f\,(m_f/vev)$
  - $(g_V/2vev)^{1/2} = \kappa_V^{1/2}\,(m_V/vev)$



MSSM (R.Contino)

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

- Shifts to tree-level couplings due to mixing with heavier Higgs

$$c_V = \sin(\beta - \alpha) \qquad c_t = \frac{\cos\alpha}{\sin\beta} \qquad c_b = -\frac{\sin\alpha}{\cos\beta}$$

c_V always reduced

if $c_t > 1$ then $c_b < 1$
and viceversa

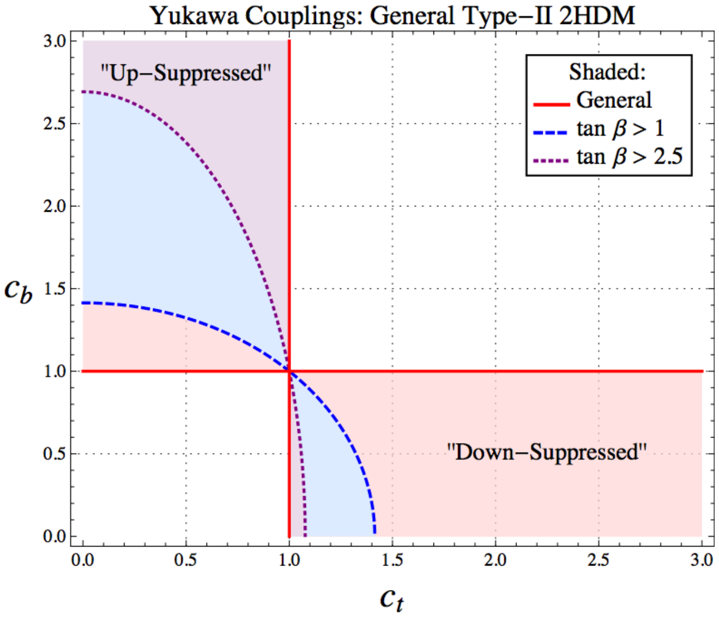
$$\begin{pmatrix} h^0 \\ H^0 \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \mathrm{Re}\, H_u^0 \\ \mathrm{Re}\, H_d^0 \end{pmatrix}$$

$$\tan\beta = \frac{v_u}{v_d}$$

Only two regions in the (c_t, c_b) plane accessible in a *generic* Type-II 2HDM

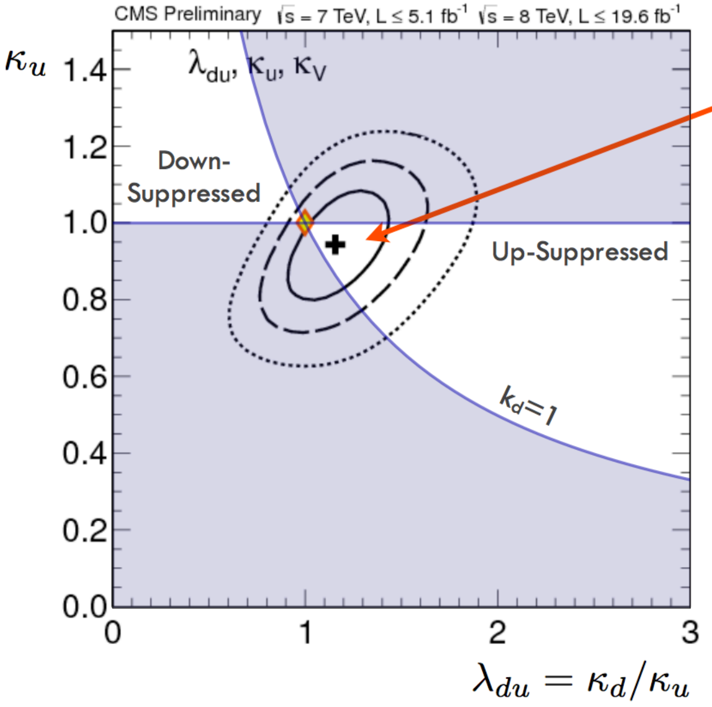
Down-Suppressed region almost *not accessible* in the MSSM for $\tan\beta > 1$

see: Azatov, Chang, Craig, Galloway PRD 86 (2012) 075033



MSSM (R.Contino)

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



the current fit by CMS seems to favor the MSSM region, though errors are large

It would be nice to see the same plot by ATLAS and even nicer to see plot in the plane (κ_u, κ_d)

For the impatient ones here is a theorist's combination of ATLAS+CMS+Tevatron:

from: Azatov, Galloway Int. J. Mod. Phys. A28 (2013) 1330004

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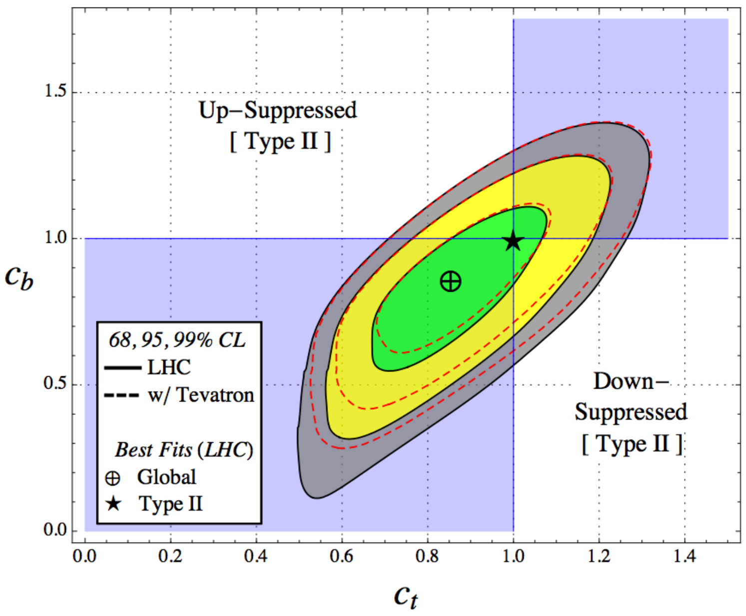


MSSM (R.Contino)

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

- Implications on the masses of the heavier Higgses

In the decoupling limit: $\boxed{\alpha \to \beta - \pi/2}$

$$c_V = 1 - \Delta^2 \frac{1}{\tan^2\beta} + O(\Delta^3)$$

starts at $O(m_H^{-4})$

$$c_t = 1 - \Delta \frac{1}{\tan^2\beta} + O(\Delta^2)$$

$$\Delta = O\left(\frac{m_Z^2}{m_H^2}\right)$$

$$c_b = 1 + \Delta + O(\Delta^2)$$

c_b most sensitive probe of spectrum of Heavy Higgses

$$\frac{\delta c_b}{c_b} > 0.1 \Rightarrow m_H > 300 - 400\,\mathrm{GeV}$$

Notice:

masses of Heavy Higgses are *not* linked to naturalness of m_h anyway

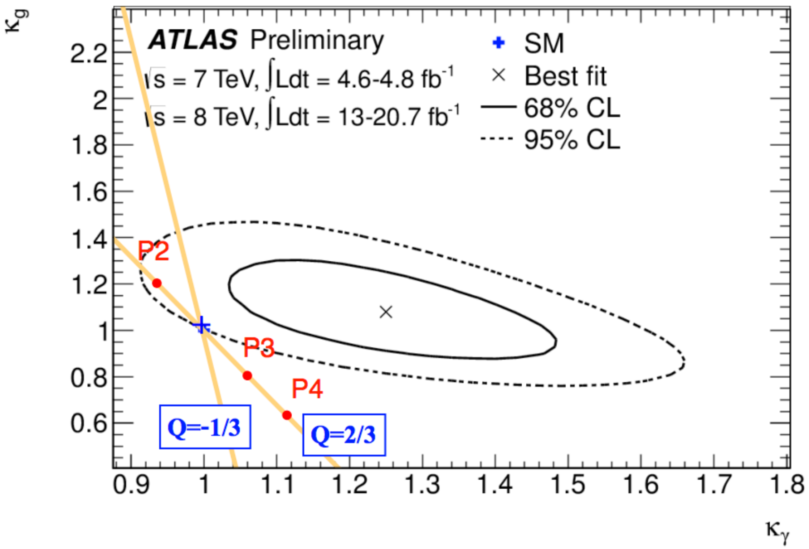
Lighter masses (up to m_H ~200 GeV) however simple to obtain in explicit models (ex: NMSSM) with mild tuning of Δ

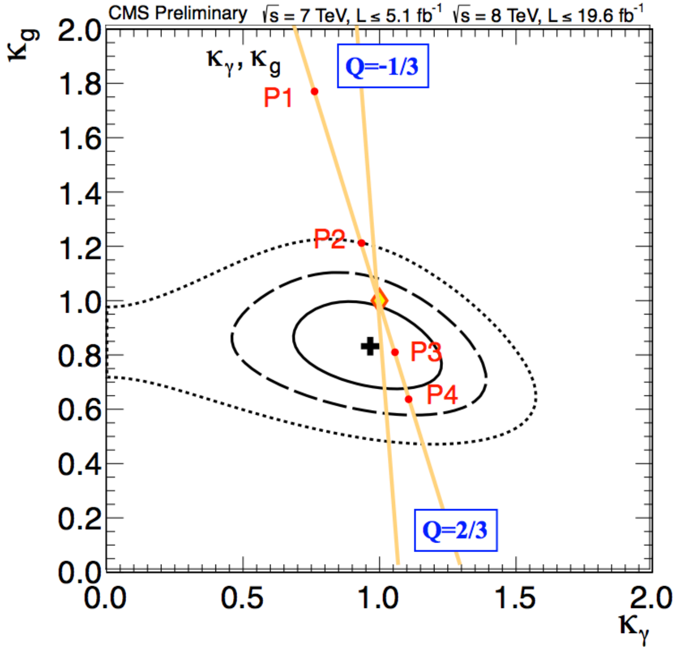
see for example: Barbieri et al. arXiv:1304.3670

MSSM (R.Contino)

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

- Shifts to loop-induced couplings due to squarks





Small mixing: ➡ $\Gamma(gg \to h)$ enhanced

$\Gamma(h \to \gamma\gamma)$ suppressed

Large mixing: ➡ $\Gamma(gg \to h)$ suppressed

$\Gamma(h \to \gamma\gamma)$ enhanced

P1: $m_{\tilde{t}_1} = 100\,\mathrm{GeV},\ m_{\tilde{t}_2} = 300\,\mathrm{GeV},\ \theta_t = 0$

P2: $m_{\tilde{t}_1} = 200\,\mathrm{GeV},\ m_{\tilde{t}_2} = 500\,\mathrm{GeV},\ \theta_t = 0$

P3: $m_{\tilde{t}_1} = 400\,\mathrm{GeV},\ m_{\tilde{t}_2} = 1000\,\mathrm{GeV},\ \theta_t = \pi/4$

P4: $m_{\tilde{t}_1} = 500\,\mathrm{GeV},\ m_{\tilde{t}_2} = 1500\,\mathrm{GeV},\ \theta_t = \pi/4$

Composite (R.Contino)

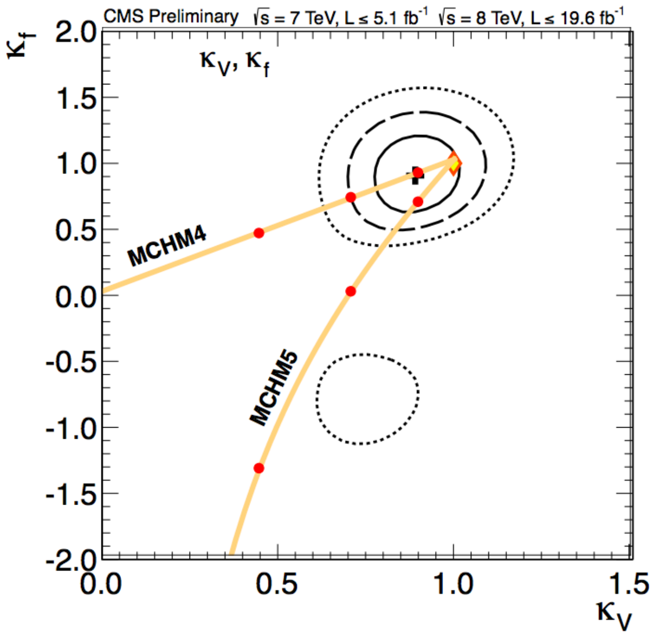
[http://cern.ch/go/W96V]

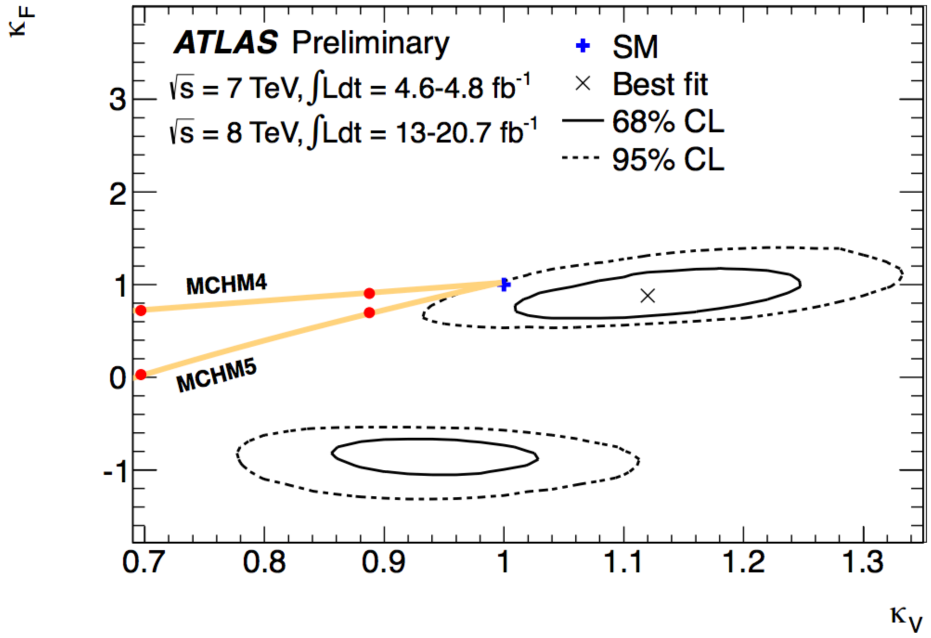
- Leading effects in tree-level couplings and Zγ rate

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

f = Higgs decay constant

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





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

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The case for the SMH (R.Contino)

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

If one assumes that

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

then it must follow:

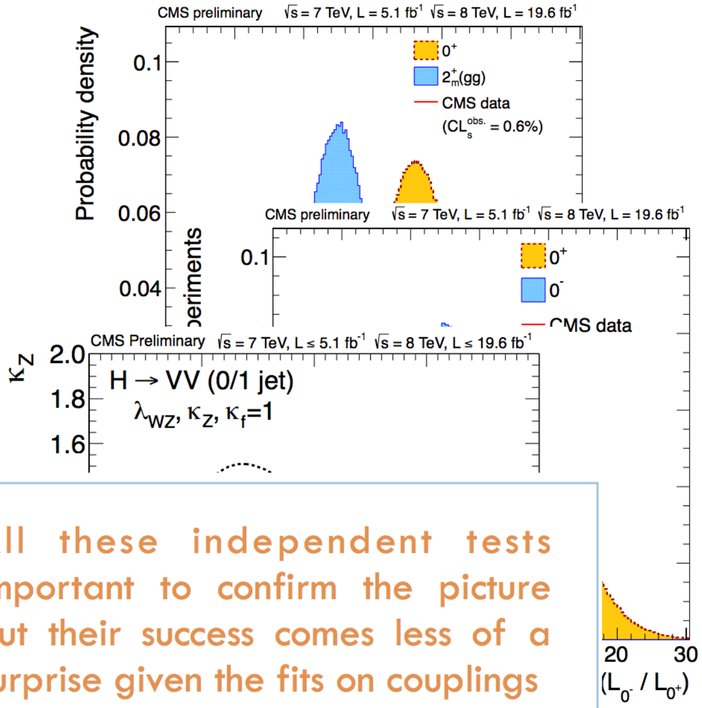
- h has spin 0 ✓
- h is (mostly) CP=+ ✓
- There exists a correlation among processes with 0,1,2 Higgs bosons

  Ex: custodial symmetry ✓

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

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

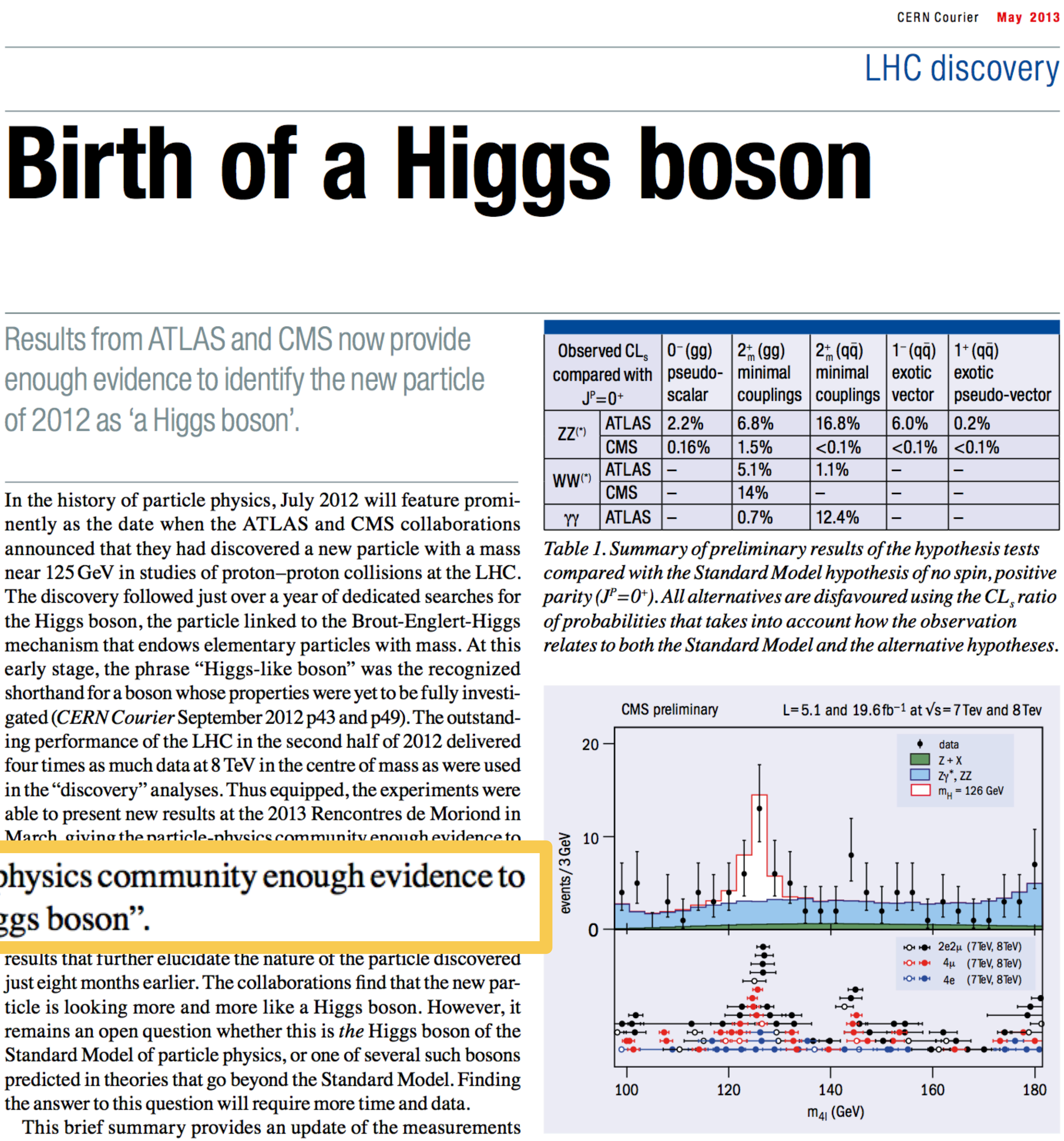
  Ex: Invisible width=0 ✓



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

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

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



Birth of a Higgs boson

Results from ATLAS and CMS now provide enough evidence to identify the new particle of 2012 as 'a Higgs boson'.

In the history of particle physics, July 2012 will feature prominently as the date when the ATLAS and CMS collaborations announced that they had discovered a new particle with a mass near 125 GeV in studies of proton–proton collisions at the LHC. The discovery followed just over a year of dedicated searches for the Higgs boson, the particle linked to the Brout-Englert-Higgs mechanism that endows elementary particles with mass. At this early stage, the phrase "Higgs-like boson" was the recognized shorthand for a boson whose properties were yet to be fully investigated (*CERN Courier* September 2012 p43 and p49). The outstanding performance of the LHC in the second half of 2012 delivered four times as much data at 8 TeV in the centre of mass as were used in the "discovery" analyses. Thus equipped, the experiments were able to present new results at the 2013 Rencontres de Moriond in March, giving the particle-physics community enough evidence to

March, giving the particle-physics community enough evidence to name this new boson "a Higgs boson".

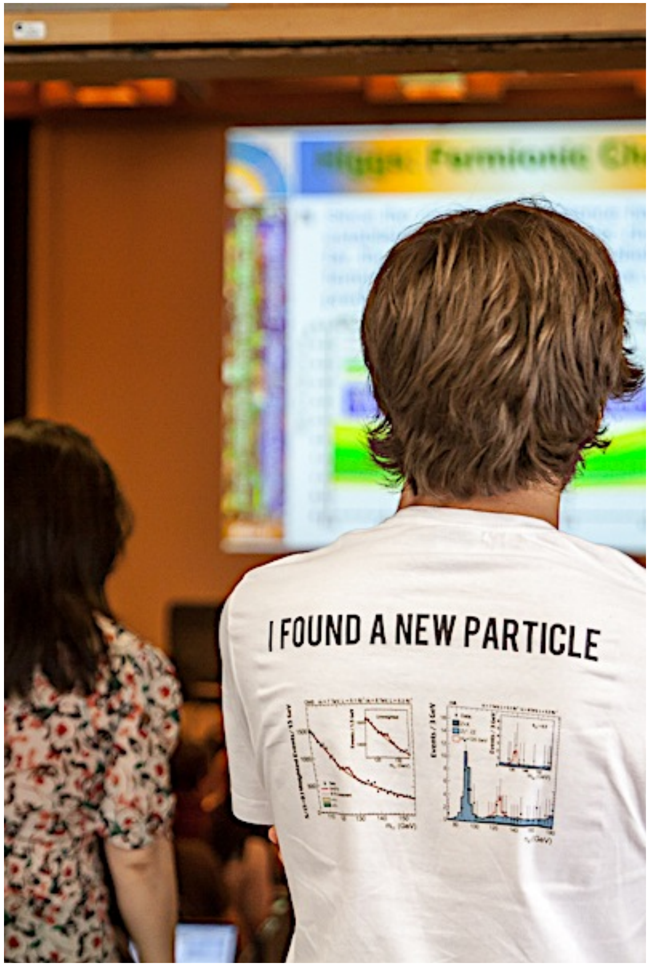
results that further elucidate the nature of the particle discovered just eight months earlier. The collaborations find that the new particle is looking more and more like a Higgs boson. However, it remains an open question whether this is *the* Higgs boson of the Standard Model of particle physics, or one of several such bosons predicted in theories that go beyond the Standard Model. Finding the answer to this question will require more time and data.

This brief summary provides an update of the measurements

Observed CL_s compared with $J^P=0^+$		0^- (gg) pseudo-scalar	2^+_m (gg) minimal couplings	2^+_m ($q\bar{q}$) minimal couplings	1^- ($q\bar{q}$) exotic vector	1^+ ($q\bar{q}$) exotic pseudo-vector
$ZZ^{(*)}$	ATLAS	2.2%	6.8%	16.8%	6.0%	0.2%
	CMS	0.16%	1.5%	<0.1%	<0.1%	<0.1%
$WW^{(*)}$	ATLAS	–	5.1%	1.1%	–	–
	CMS	–	14%	–	–	–
$\gamma\gamma$	ATLAS	–	0.7%	12.4%	–	–

Table 1. Summary of preliminary results of the hypothesis tests compared with the Standard Model hypothesis of no spin, positive parity ($J^P=0^+$). All alternatives are disfavoured using the CL_s ratio of probabilities that takes into account how the observation relates to both the Standard Model and the alternative hypotheses.

Summary

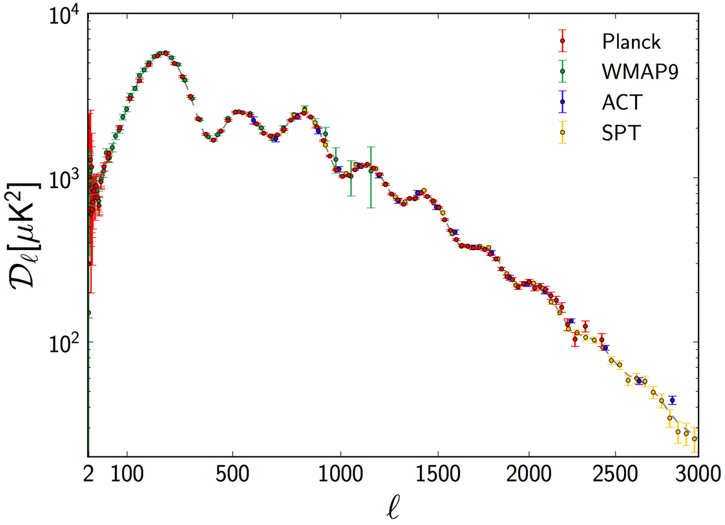


- **Went from "a new particle" to "a Higgs Boson".**
  - $m_X \sim 125.6 \pm 0.4$ GeV.
- **Big picture unfailingly consistent with SMH:**
  - Per channel, per final state, and per production mode.
  - No significant deviations of scalar couplings.
  - Parity hypothesis tests disfavor 0^-.
  - Other J^P hypothesis tests disfavor $J \neq 0$.
- **Working hard to leave no stone unturned.**
  - Look for the Higgs parallel session on Wednesday.
  - **Theoretical progress still needed (ggH).**
  - Many channels in the works: ttH, $\mu\mu$, invisible.
- **For when a LHC combination?**

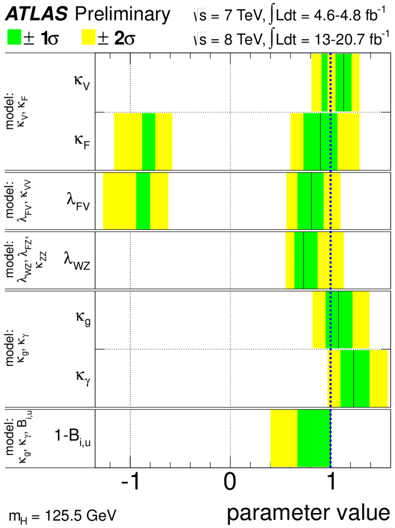
The ~~beautiful~~ ~~boring~~ 2013 Universe

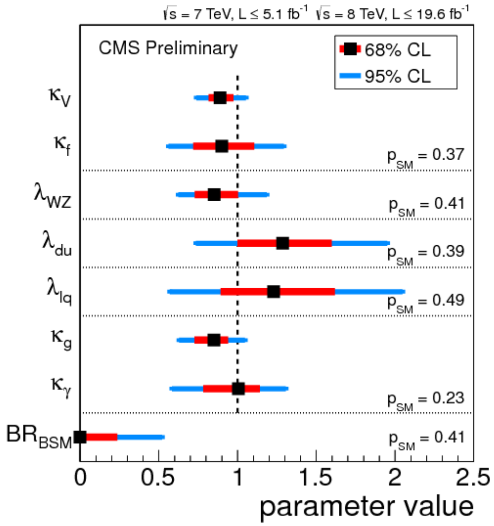
[arXiv:1303.5062]

- **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, …

References

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“…and references therein.”

- ATLAS
  https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults
- CMS
  https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG
- Tevatron
  http://tevnphwg.fnal.gov/
  - CDF
    http://www-cdf.fnal.gov/physics/new/hdg/Results.html
  - D0
    http://www-d0.fnal.gov/d0_publications/d0_pubs_list_bytopic.html#higgs

For discussion

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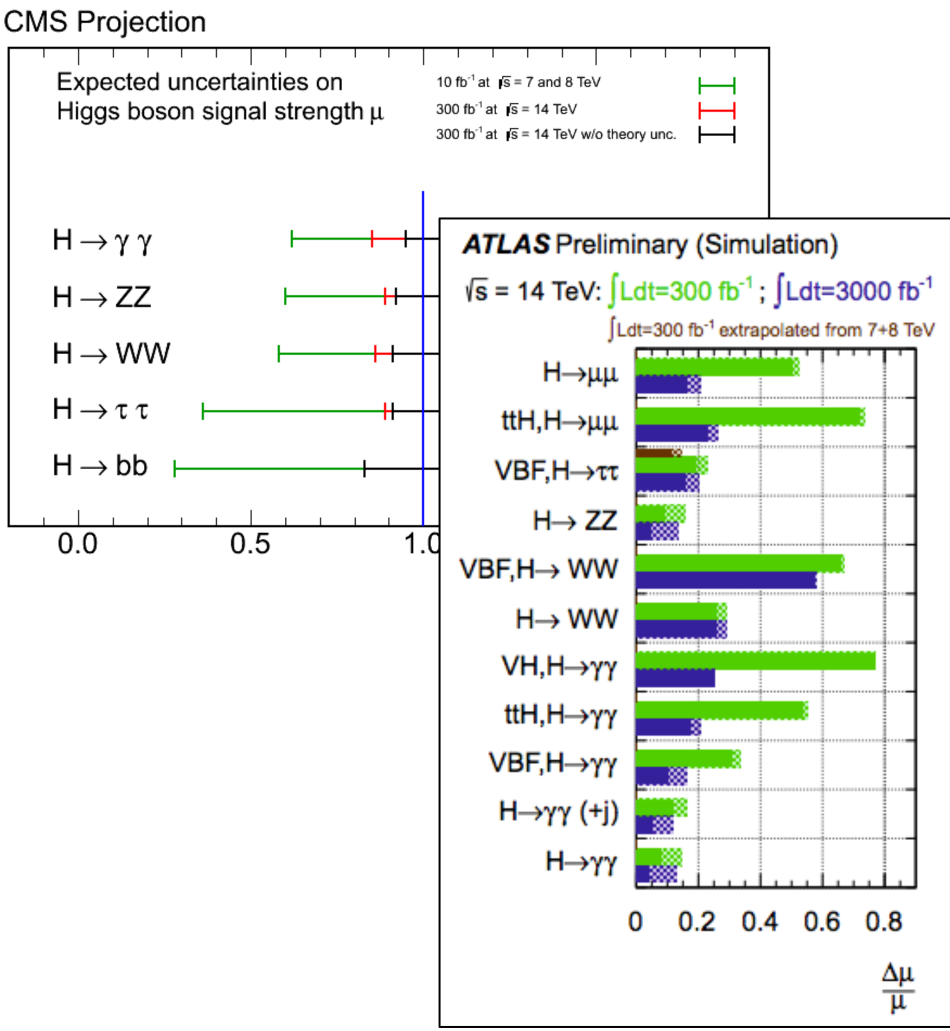
The Future

Looking well ahead

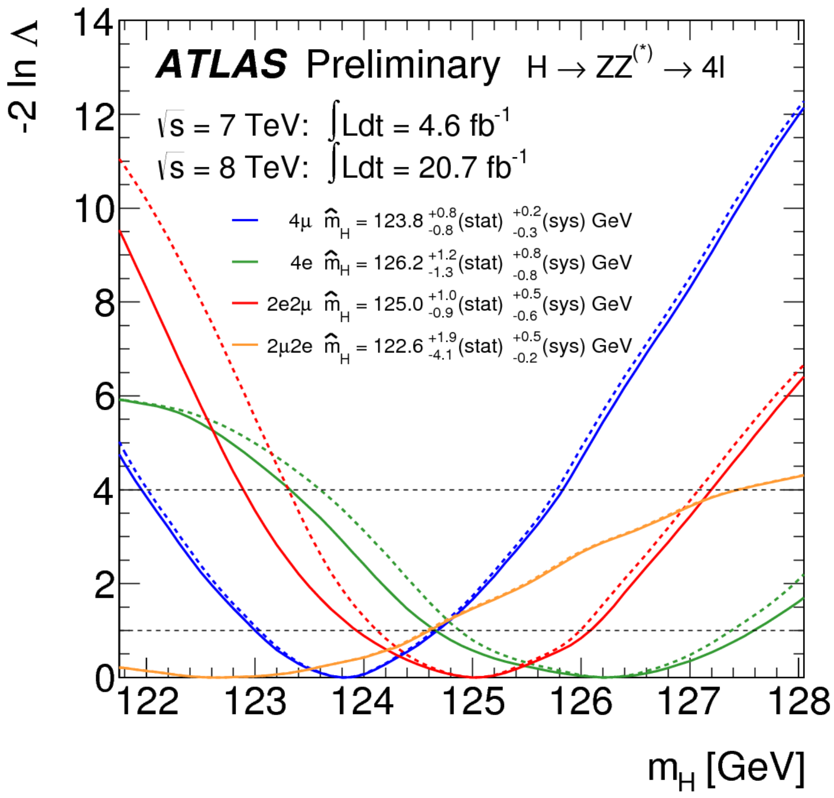
[http://cern.ch/go/P8Tn] [http://cern.ch/go/l7RZ]

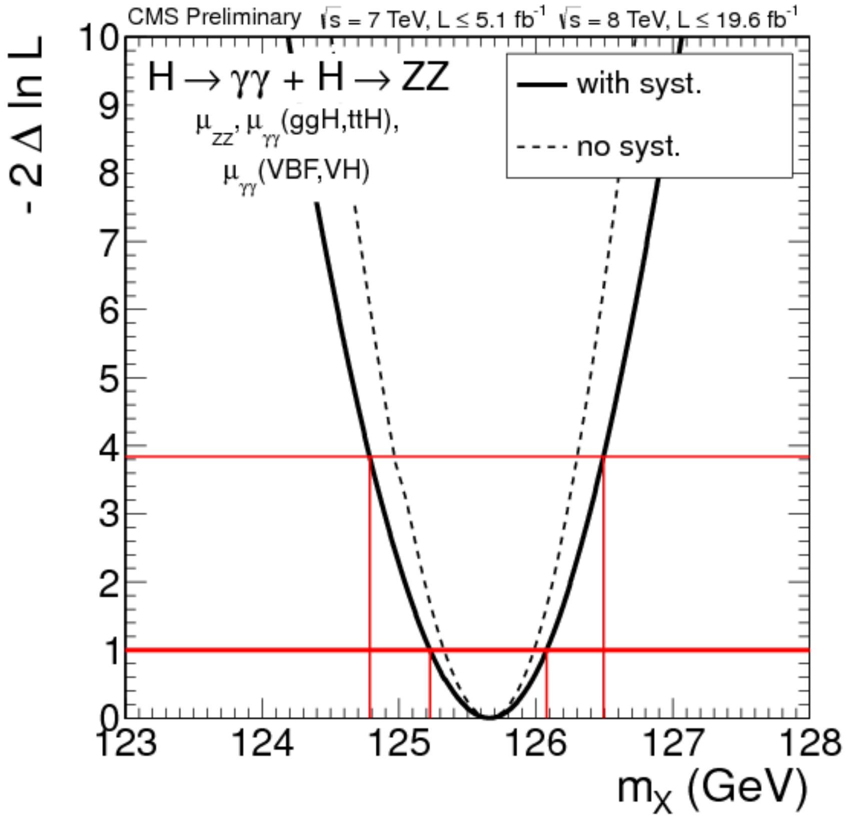
- 300/fb at 14 TeV:
  - Vast improvement over present datasets.
  - **Room for theory improvements.**
- For (HL-LHC) 3 ab^{-1}:
  - self-coupling seems feasible with $\lambda_{HH} \sim 3\sigma$ **/expt.**



More on mass

More on mass

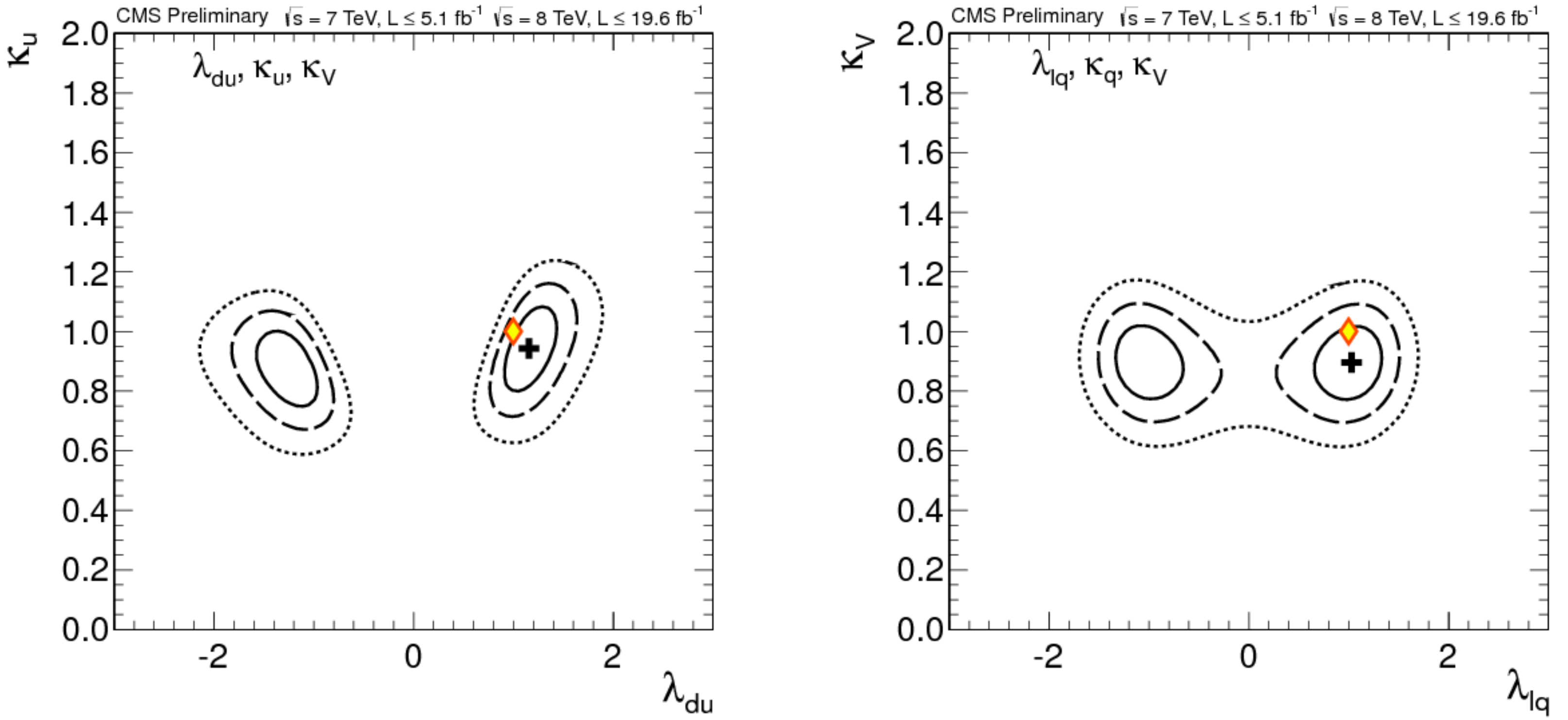

ATLAS Preliminary $H \rightarrow ZZ^{(*)} \rightarrow 4l$
$\sqrt{s}$ = 7 TeV: $\int Ldt$ = 4.6 fb^{-1}
$\sqrt{s}$ = 8 TeV: $\int Ldt$ = 20.7 fb^{-1}
4μ $\hat{m}_H = 123.8^{+0.8}_{-0.8}$(stat) $^{+0.2}_{-0.3}$(sys) GeV
4e $\hat{m}_H = 126.2^{+1.2}_{-1.3}$(stat) $^{+0.8}_{-0.8}$(sys) GeV
2e2μ $\hat{m}_H = 125.0^{+1.0}_{-0.9}$(stat) $^{+0.5}_{-0.6}$(sys) GeV
2μ2e $\hat{m}_H = 122.6^{+1.9}_{-4.1}$(stat) $^{+0.5}_{-0.2}$(sys) GeV
-2 ln Λ
0
2
4
6
8
10
12
14
122
123
124
125
126
127
128
m_H [GeV]


CMS Preliminary $\sqrt{s}$ = 7 TeV, L ≤ 5.1 fb^{-1} $\sqrt{s}$ = 8 TeV, L ≤ 19.6 fb^{-1}
$H \rightarrow \gamma\gamma + H \rightarrow ZZ$
μ_{ZZ}, $\mu_{\gamma\gamma}$(ggH,ttH),
$\mu_{\gamma\gamma}$(VBF,VH)
with syst.
no syst.
- 2 Δ ln L
0
1
2
3
4
5
6
7
8
9
10
123
124
125
126
127
128
m_X (GeV)

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)**

More on spin 2

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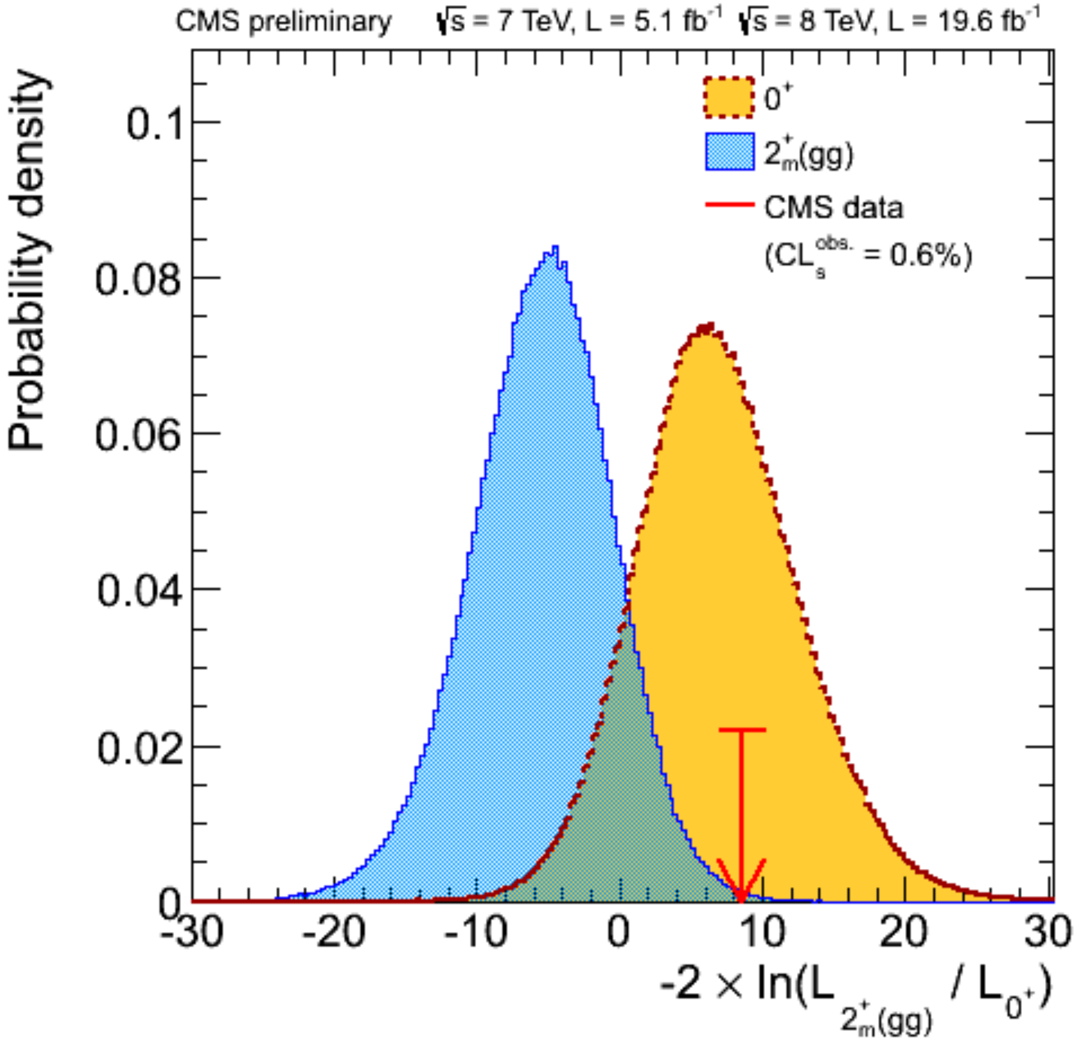
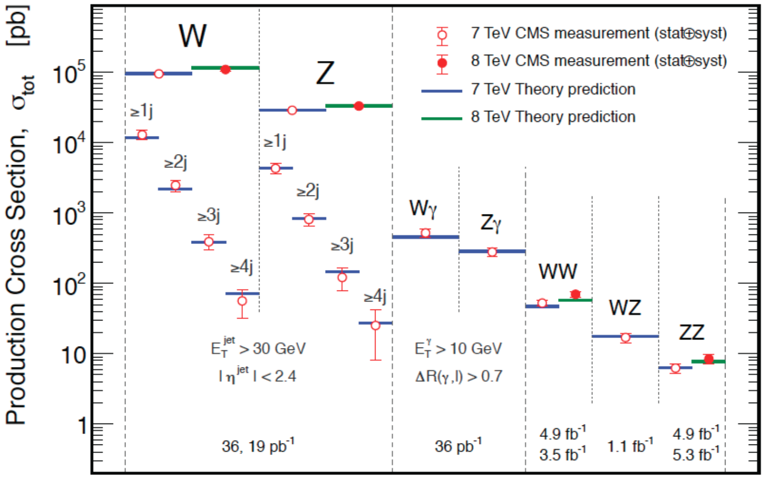
CMS: 2^+_m combination

- Combination of H⟶ZZ, WW:
  - p(obs.|0^+) = -0.34 σ
  - p(obs.|2^+_m(gg)) = 2.84 σ
  - **CL_s = 0.6%**



Higgs: production and decay

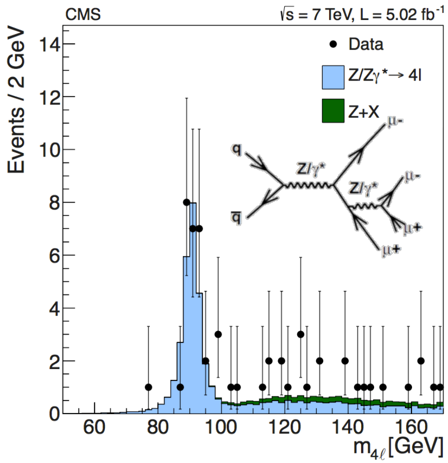
A tribute to those doing SM calculations

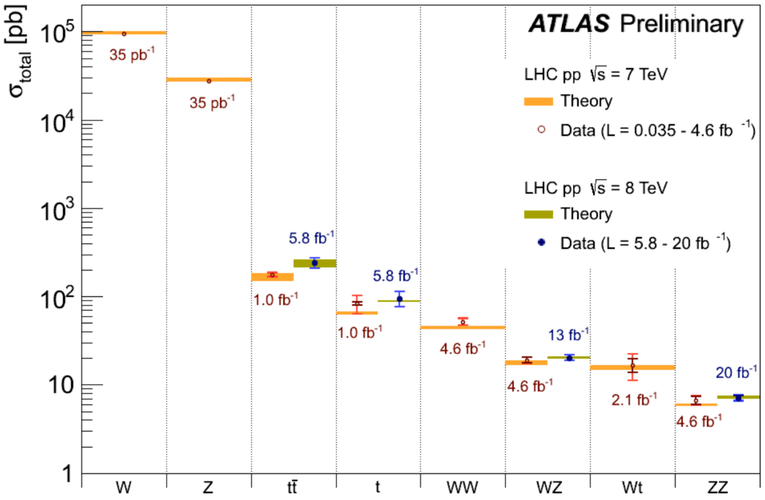


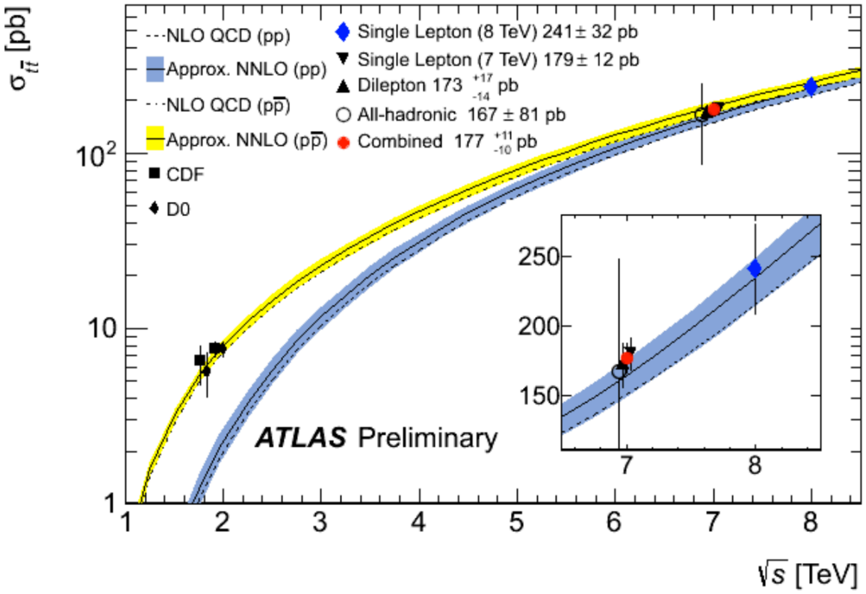
JHEP10(2011)132
JHEP01(2012)010
CMS-PAS-SMP-12-011 (W/Z 8 TeV)

PLB701(2011)535

CMS-PAS-EWK-11-010 (WZ)
CMS-PAS-SMP-12-005,
007, 013, 014 (WW ZZ)

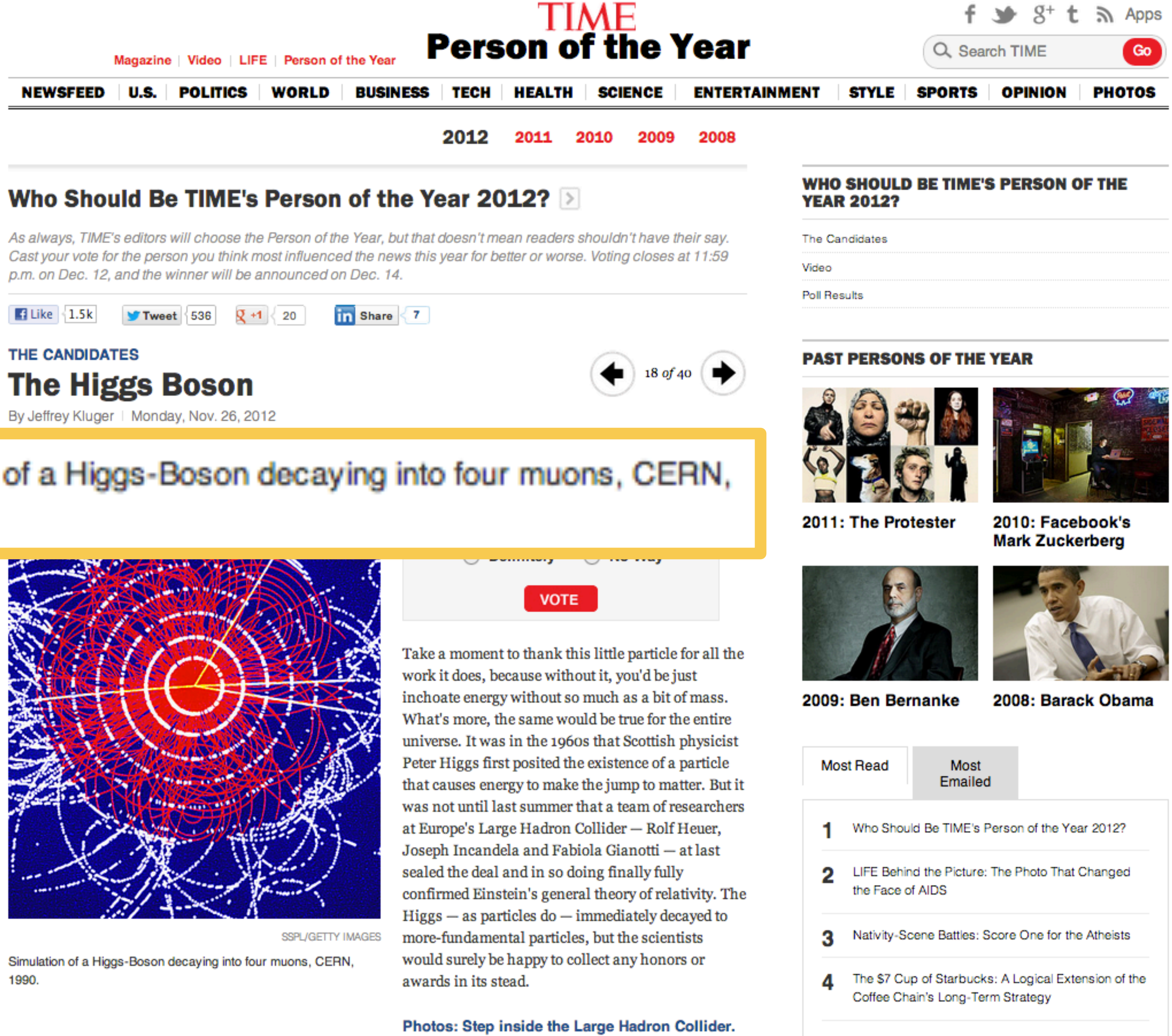






Miscellaneous

Simulation of a Higgs-Boson decaying into four muons, CERN, 1990.



Who Should Be TIME's Person of the Year 2012?

As always, TIME's editors will choose the Person of the Year, but that doesn't mean readers shouldn't have their say. Cast your vote for the person you think most influenced the news this year for better or worse. Voting closes at 11:59 p.m. on Dec. 12, and the winner will be announced on Dec. 14.

THE CANDIDATES

The Higgs Boson

By Jeffrey Kluger | Monday, Nov. 26, 2012

SSPL/GETTY IMAGES

Simulation of a Higgs-Boson decaying into four muons, CERN, 1990.

Take a moment to thank this little particle for all the work it does, because without it, you'd be just inchoate energy without so much as a bit of mass. What's more, the same would be true for the entire universe. It was in the 1960s that Scottish physicist Peter Higgs first posited the existence of a particle that causes energy to make the jump to matter. But it was not until last summer that a team of researchers at Europe's Large Hadron Collider — Rolf Heuer, Joseph Incandela and Fabiola Gianotti — at last sealed the deal and in so doing finally fully confirmed Einstein's general theory of relativity. The Higgs — as particles do — immediately decayed to more-fundamental particles, but the scientists would surely be happy to collect any honors or awards in its stead.

Photos: Step inside the Large Hadron Collider.

WHO SHOULD BE TIME'S PERSON OF THE YEAR 2012?

The Candidates

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PAST PERSONS OF THE YEAR

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2009: Ben Bernanke

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