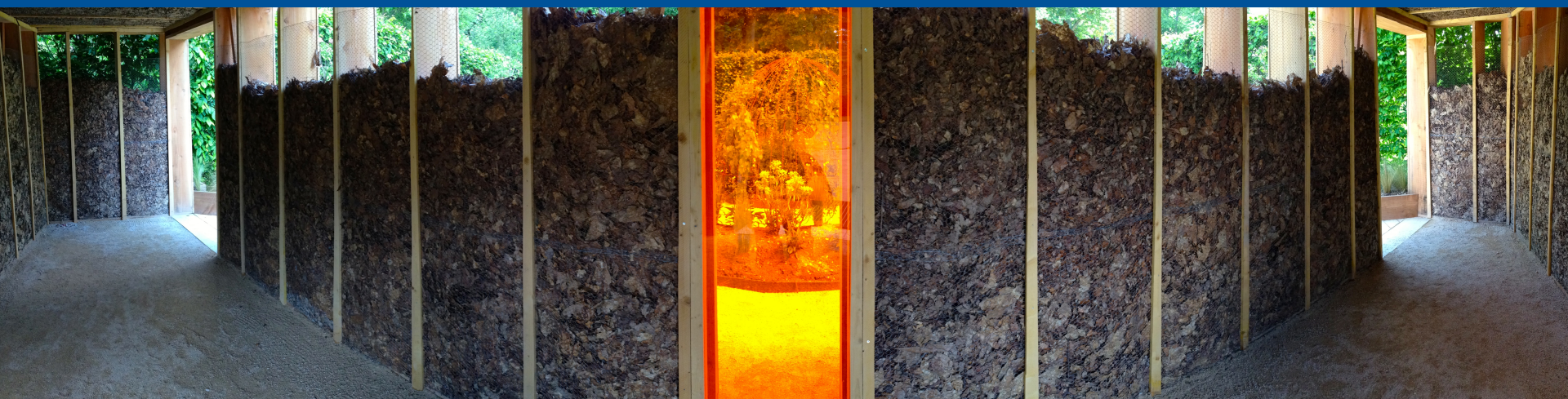




# PROPERTIES OF THE HIGGS BOSON WE CANNOT “UNSEE”

André David (CERN)



2

# Things you can't "unsee"

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







3

# Things you can't "unsee"

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





4

# Things you can't "unsee"

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





# 2011: nothing else in the horizon

- We first saw that we could not exclude a narrow range.

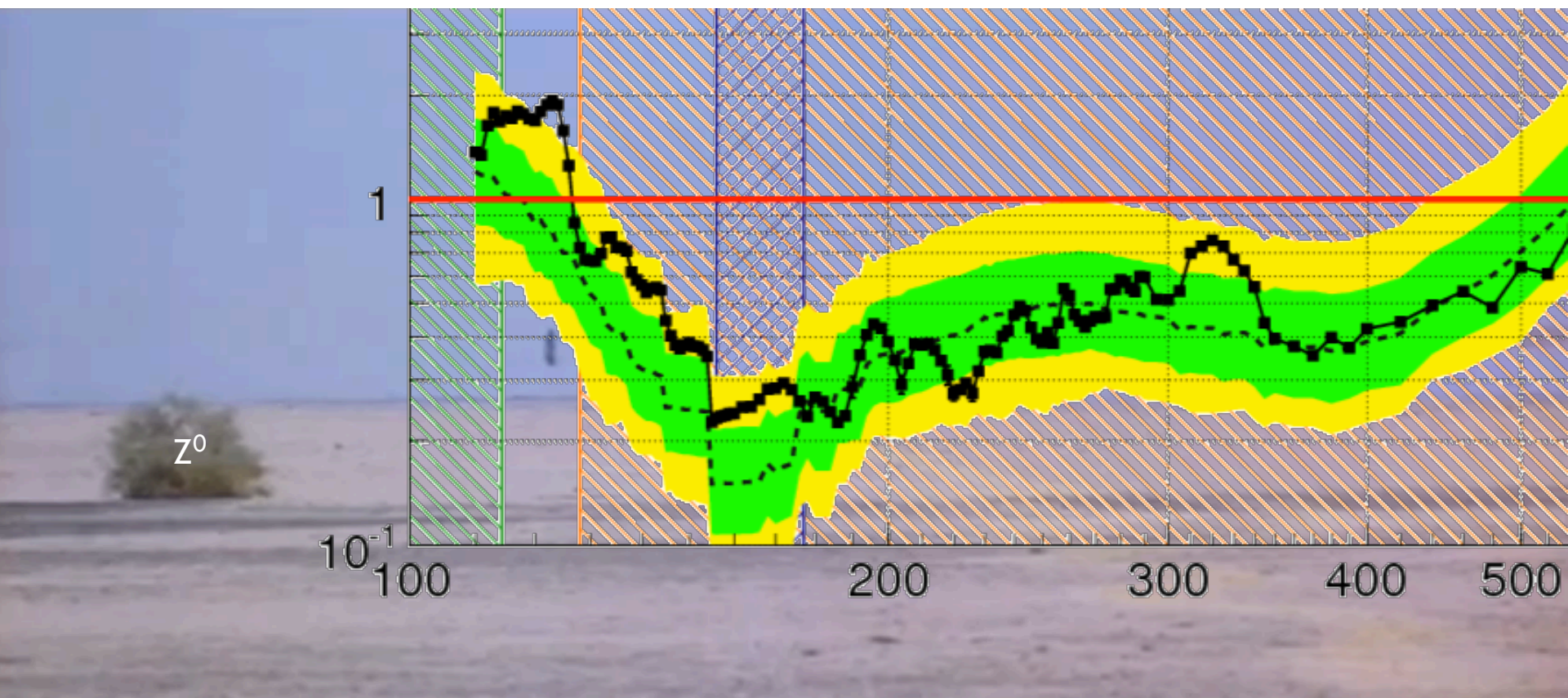




# 2011: nothing else in the horizon

["Lawrence of Arabia" idea from C. Grojean]

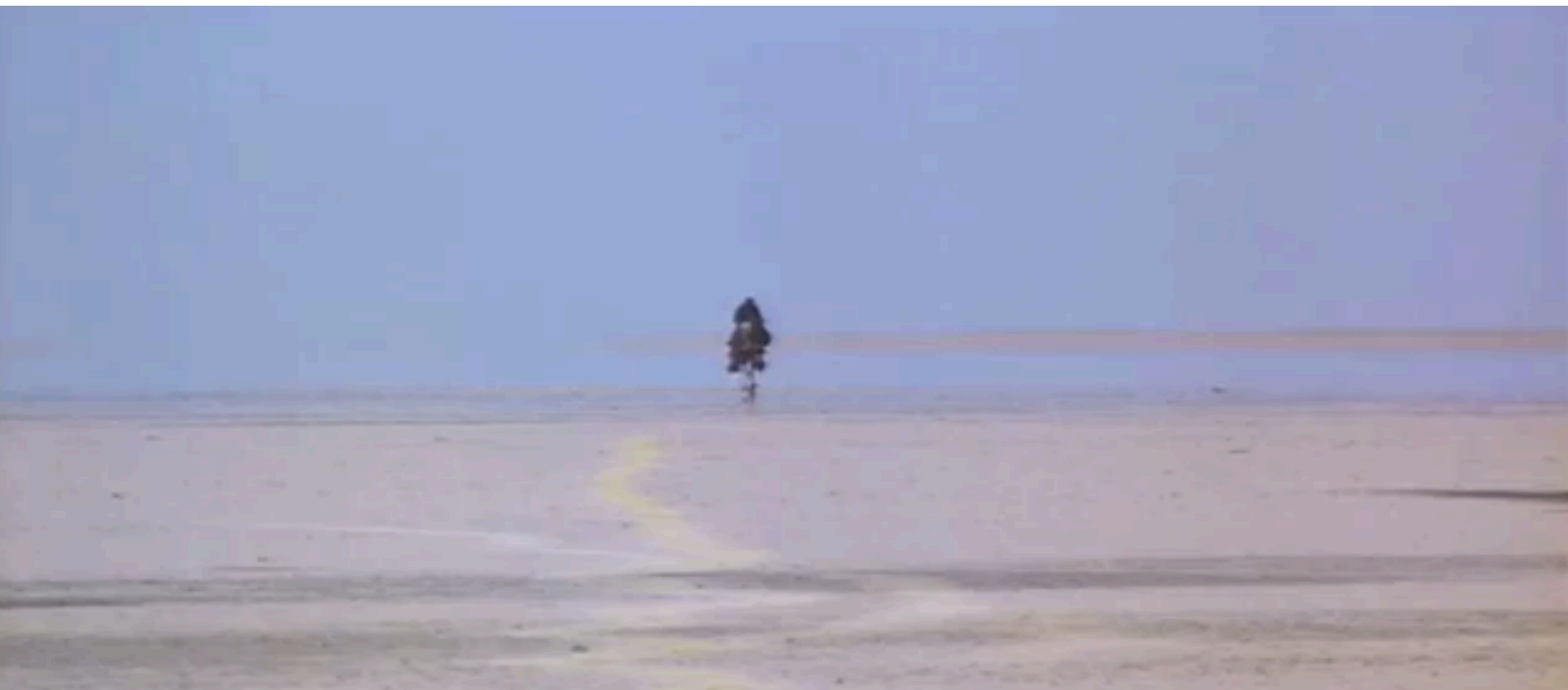
- We first saw that we could not exclude a narrow range.



# 2012: a rider!

["Lawrence of Arabia" idea from C. Grojean]

- We discovered a peak rising from the background.



2012 2011 2010 2009 2008

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

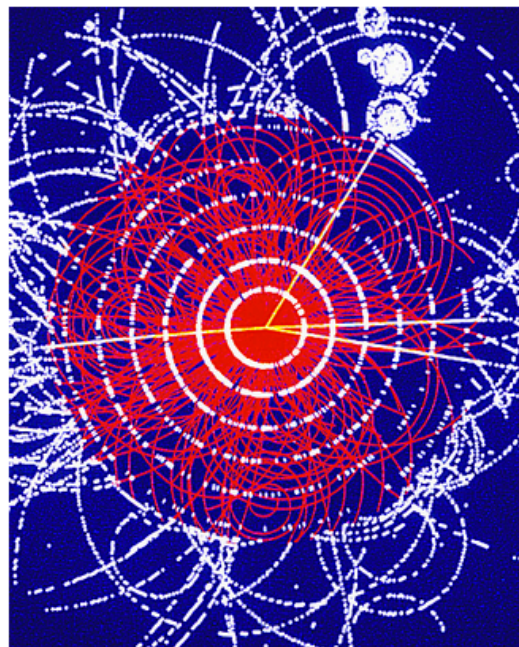
As always, TIME's editors will choose the Person of the Year, but that doesn't mean readers shouldn't have their say. Cast your vote for the person you think most influenced the news this year for better or worse. Voting closes at 11:59 p.m. on Dec. 12, and the winner will be announced on Dec. 14.

Like 1.5k Tweet 536 +1 20 Share 7

### 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

VOTE

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

Video

Poll Results

### PAST PERSONS OF THE YEAR



2011: The Protester



2010: Facebook's Mark Zuckerberg



2009: Ben Bernanke



2008: Barack Obama

Most Read

Most Emailed

- Who Should Be TIME's Person of the Year 2012?
- LIFE Behind the Picture: The Photo That Changed the Face of AIDS
- Nativity-Scene Battles: Score One for the Atheists
- The \$7 Cup of Starbucks: A Logical Extension of the Coffee Chain's Long-Term Strategy



2012 2011 2010 2009 2008

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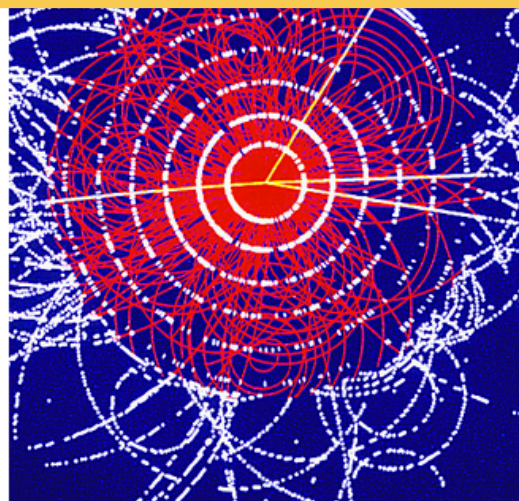
### THE CANDIDATES

## The Higgs Boson

By Jeffrey Kluger | Monday, Nov. 26, 2012

18 of 40

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



SSPL/GETTY IMAGES

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

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2012 2011 2010 2009 2008

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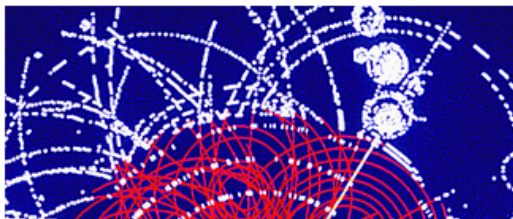
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2011: The Protester



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

# 2013: a rider with a gun

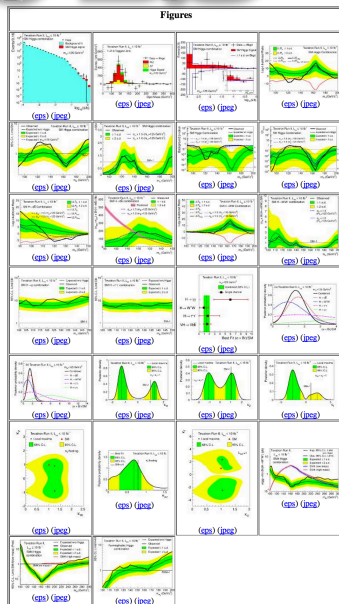
[“Lawrence of Arabia” idea from C. Grojean]

- By early 2013 a clear Higgs-like picture emerged.





# (self-inflicted) Mission: impossible



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



|          |                                                              |                            |
|----------|--------------------------------------------------------------|----------------------------|
| Oct-2013 | Z(bb)H, H -> invisible                                       | <a href="#">TWiki, PAS</a> |
| Oct-2013 | SM H -> mumu                                                 | <a href="#">TWiki, PAS</a> |
| Oct-2013 | ttH Combination                                              | <a href="#">TWiki</a>      |
| Sep-2013 | Full 8 TeV dataset: ttH, H -> multi-leptons                  | <a href="#">TWiki, PAS</a> |
| Aug-2013 | Full 8 TeV dataset: VBF H -> invisible                       | <a href="#">TWiki, PAS</a> |
| Aug-2013 | Full 7+8 TeV dataset: VBF H -> WW                            | <a href="#">TWiki, PAS</a> |
| Jul-2013 | Full 8 TeV dataset: ttH, H -> bb or tautau                   | <a href="#">TWiki, PAS</a> |
| Jul-2013 | Full 8 TeV dataset: H -> ZZ -> 2l2j                          | <a href="#">TWiki, PAS</a> |
| Jul-2013 | Full 8 TeV dataset: h -> 2a + X -> 4mu + X                   | <a href="#">TWiki, PAS</a> |
| Jul-2013 | Full 8 TeV dataset: VH, H -> invisible                       | <a href="#">TWiki, PAS</a> |
| Jul-2013 | Full 8 TeV dataset: VH, H -> WW(2l2nu) + V -> jj             | <a href="#">TWiki, PAS</a> |
| Jul-2013 | Full 7+8 TeV dataset: Higgs properties from H -> gamma gamma | <a href="#">TWiki, PAS</a> |

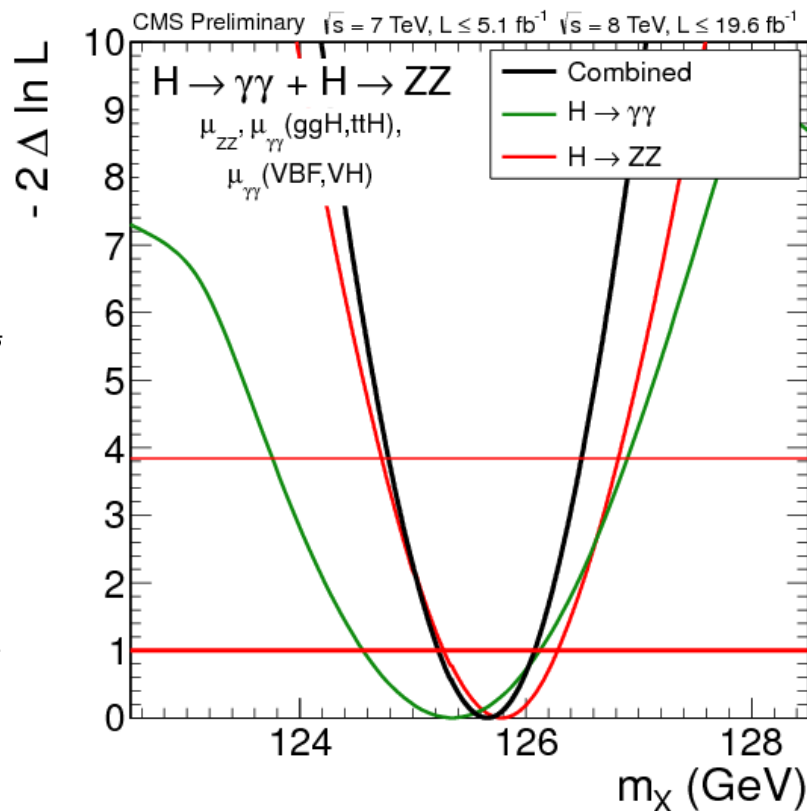
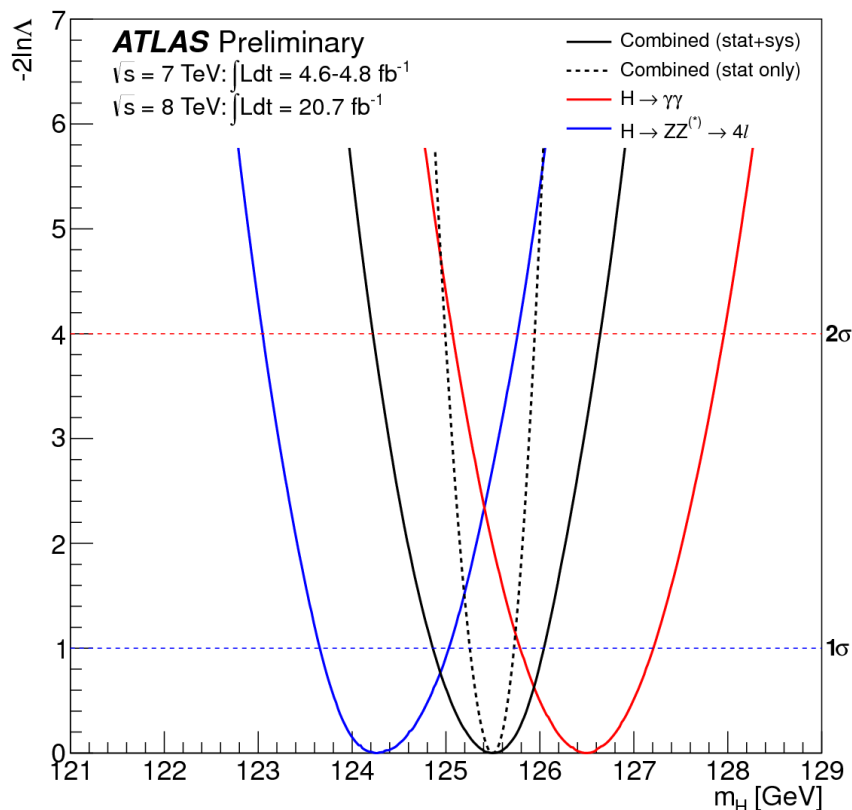
+ Moriond 2014

| Channel                | Conference note                     | L                         | Date       |
|------------------------|-------------------------------------|---------------------------|------------|
| Spin Combination       | <a href="#">ATLAS-CONF-2013-040</a> | up to 25 fb <sup>-1</sup> | 05/03/2013 |
| Couplings Combination  | <a href="#">ATLAS-CONF-2013-034</a> | up to 25 fb <sup>-1</sup> | 05/03/2013 |
| Higgs to Diphoton spin | <a href="#">ATLAS-CONF-2013-029</a> | 25 fb <sup>-1</sup>       | 11/03/2013 |
| Higgs to WW(lv) spin   | <a href="#">ATLAS-CONF-2013-031</a> | 25 fb <sup>-1</sup>       | 11/03/2013 |
| Higgs to WW(lv)        | <a href="#">ATLAS-CONF-2013-030</a> | 25 fb <sup>-1</sup>       | 11/03/2013 |
| 2HDM WW(lv)            | <a href="#">ATLAS-CONF-2013-027</a> | 13 fb <sup>-1</sup>       | 11/03/2013 |
| Combined of Mass       | <a href="#">ATLAS-CONF-2013-014</a> | up to 25 fb <sup>-1</sup> | 05/03/2013 |
| Higgs to Diphoton      | <a href="#">ATLAS-CONF-2013-012</a> | 25 fb <sup>-1</sup>       | 05/03/2013 |
| Higgs to 4 leptons     | <a href="#">ATLAS-CONF-2013-013</a> | 25 fb <sup>-1</sup>       | 05/03/2013 |
| ZH (invisible decays)  | <a href="#">ATLAS-CONF-2013-011</a> | 18 fb <sup>-1</sup>       | 05/03/2013 |
| Higgs to dimuon        | <a href="#">ATLAS-CONF-2013-010</a> | 21 fb <sup>-1</sup>       | 05/03/2013 |
| Higgs to Zgamma        | <a href="#">ATLAS-CONF-2013-009</a> | 25 fb <sup>-1</sup>       | 05/03/2013 |

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

- 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.

# First things first: the mass

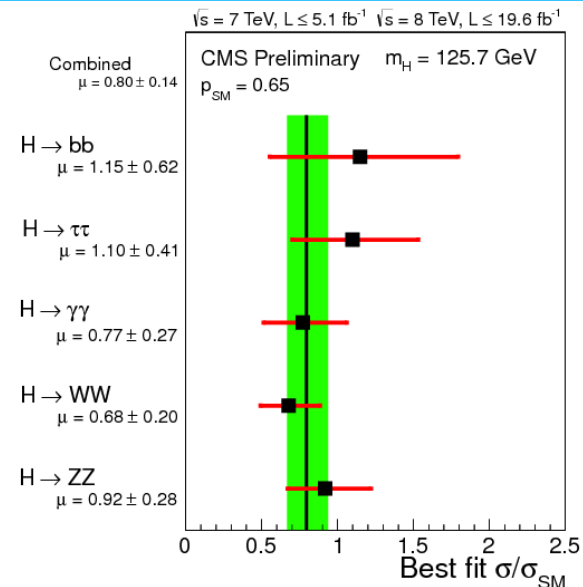
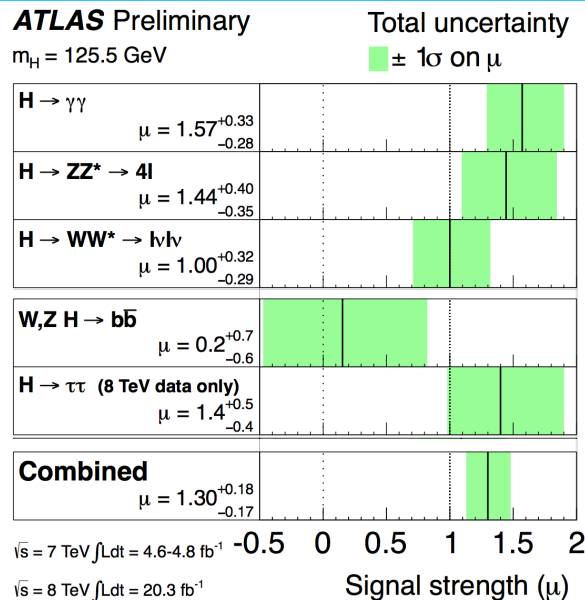
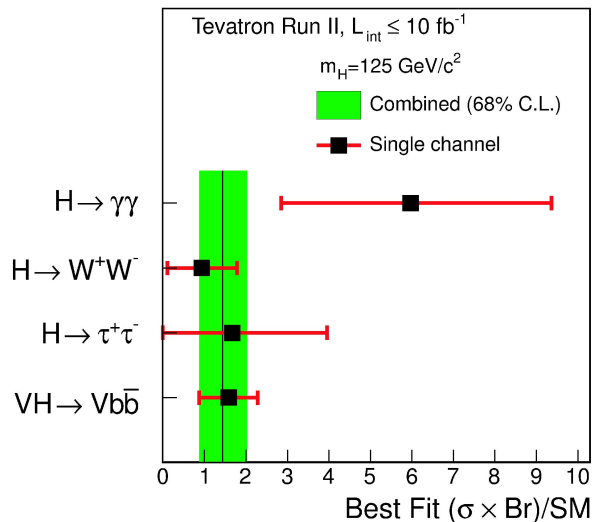

**ATLAS**
**CMS**
 $m_X$ 
 $125.5 \pm 0.2 \text{ (stat.) } {}^{+0.5}_{-0.6} \text{ (syst.) GeV}$ 
 $125.7 \pm 0.3 \text{ (stat.) } \pm 0.3 \text{ (syst.) GeV}$ 
**Naïve average:  $125.6 \pm 0.4 \text{ GeV}$**



# Relative signal strengths

14

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

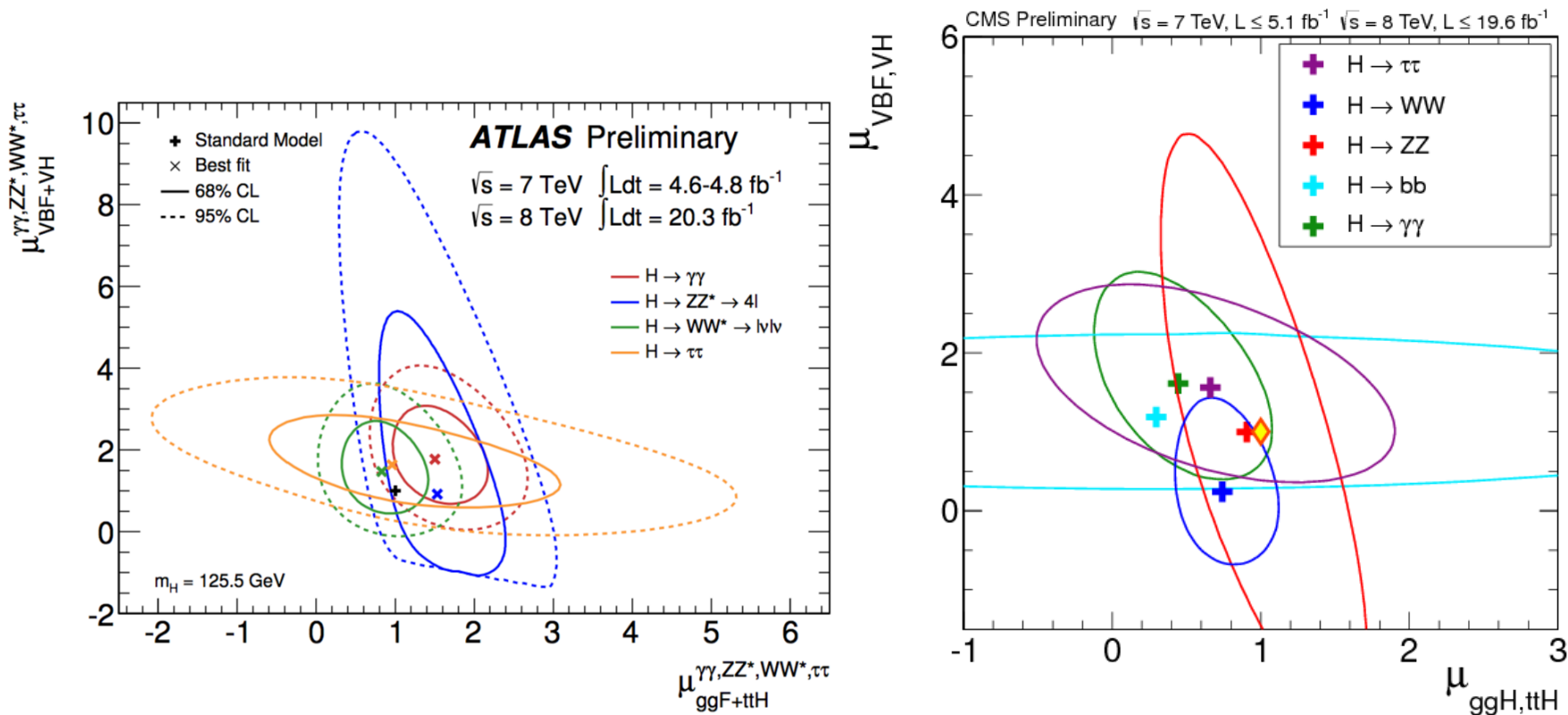


|                                                  | Tevatron               | ATLAS           | CMS             |
|--------------------------------------------------|------------------------|-----------------|-----------------|
| $m_H$                                            | 125 GeV            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

# Production mechanisms

15

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



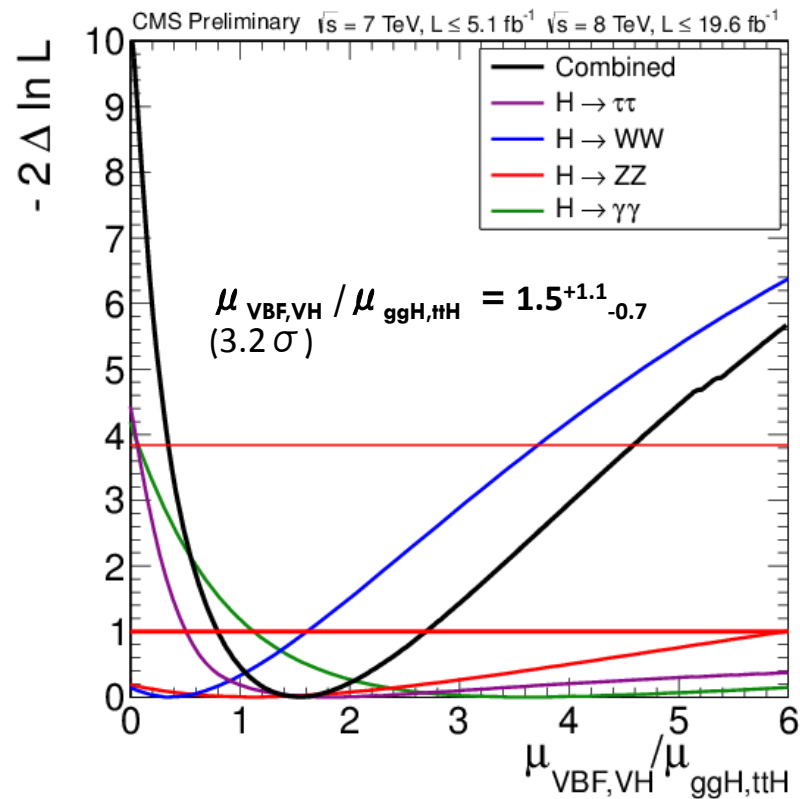
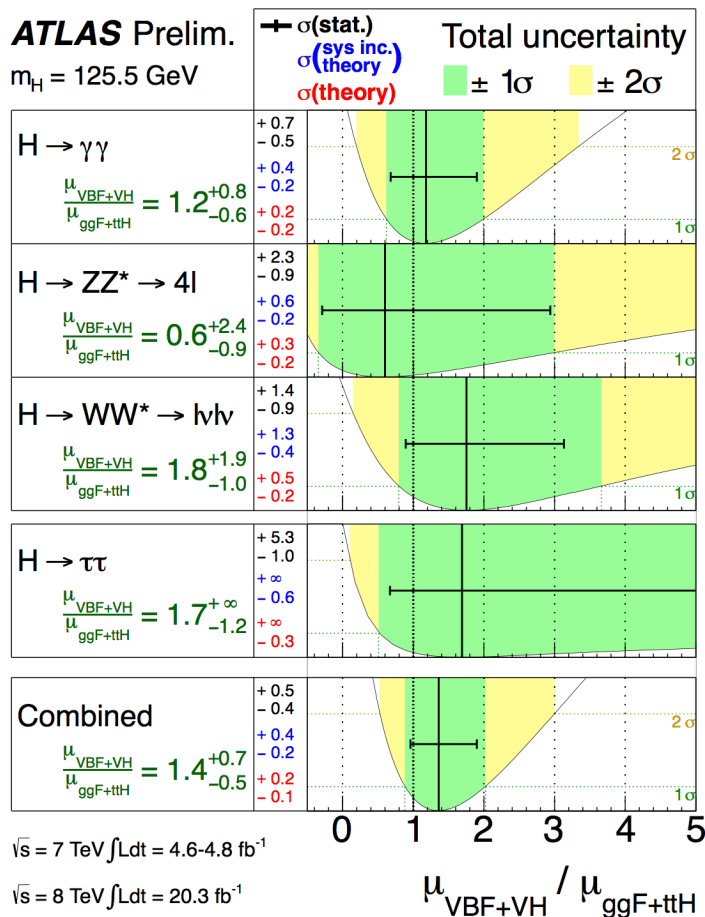
- Scale fermion-mediated (ggH & ttH) and vector-boson-mediated (VBF & VH) together.



# Production mechanisms

16

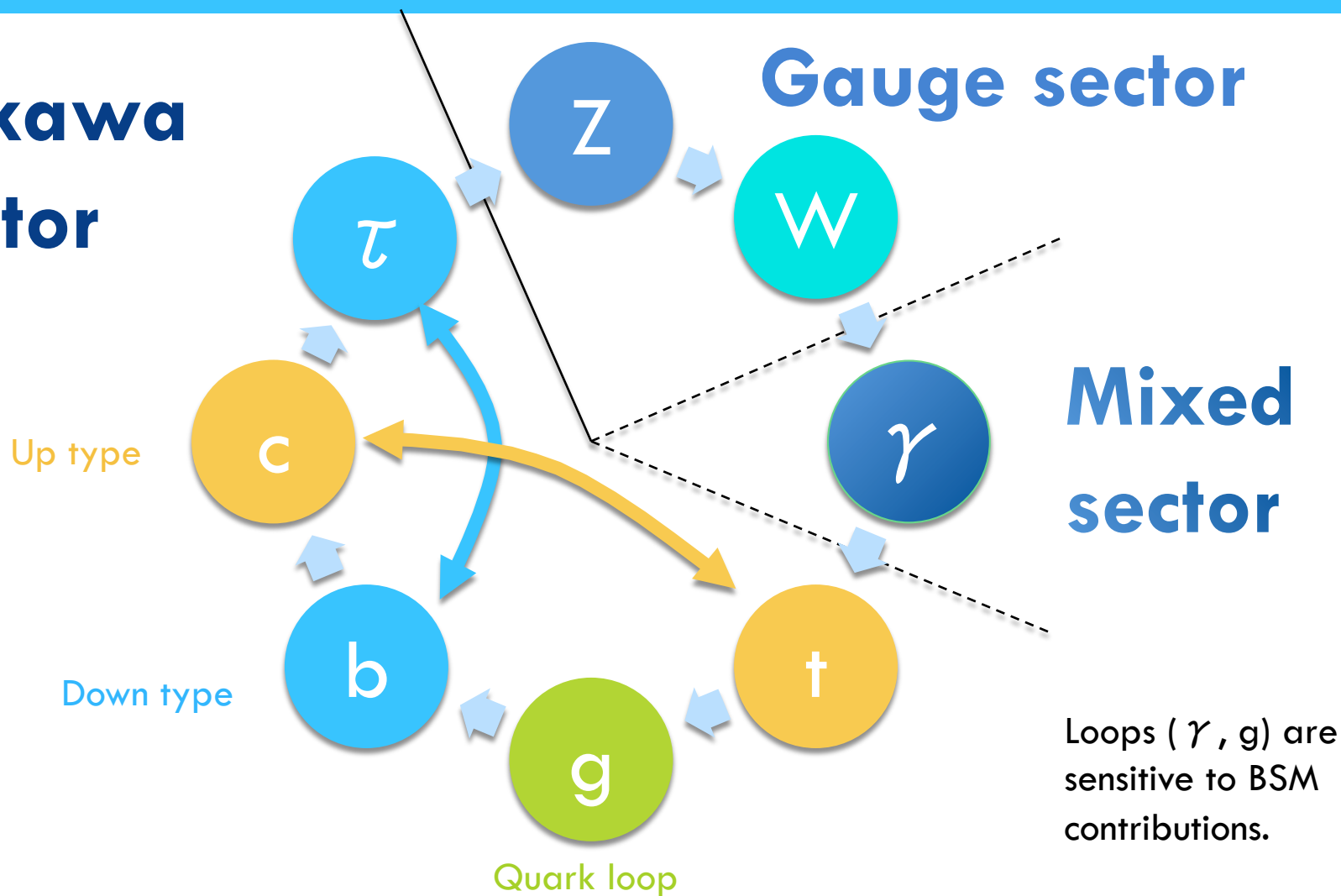
[ATLAS-CONF-2014-009] [CMS-PAS-HIG-13-005]



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

# Scalar coupling structure

## Yukawa sector



# Couplings deviations

18

[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

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

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

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

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

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

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:  $(\sigma \times \text{BR}) = \sigma \cdot \Gamma / \Gamma_H$

# Couplings deviations

19

[arXiv:1209.0040]

## Production modes

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

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

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

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

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

## Detectable decay modes

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

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

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

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

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

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

## Currently undetectable decay modes

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

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

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

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

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

## 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”.

# 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           | $\frac{\kappa_f^2 \cdot \kappa_V^2 (\kappa_t^2, \kappa_b^2, \kappa_V^2)}{\kappa_H^2(\kappa_i)}$ | $\frac{\kappa_f^2 \cdot \kappa_V^2}{\kappa_H^2(\kappa_i)}$ |                          | $\frac{\kappa_f^2 \cdot \kappa_f^2}{\kappa_H^2(\kappa_i)}$ |                              |
| t $\bar{t}$ H |                                                                                                 |                                                            |                          |                                                            |                              |
| VBF           | $\frac{\kappa_V^2 \cdot \kappa_f^2 (\kappa_t^2, \kappa_b^2, \kappa_V^2)}{\kappa_H^2(\kappa_i)}$ | $\frac{\kappa_V^2 \cdot \kappa_V^2}{\kappa_H^2(\kappa_i)}$ |                          | $\frac{\kappa_V^2 \cdot \kappa_f^2}{\kappa_H^2(\kappa_i)}$ |                              |
| WH            |                                                                                                 |                                                            |                          |                                                            |                              |
| ZH            |                                                                                                 |                                                            |                          |                                                            |                              |

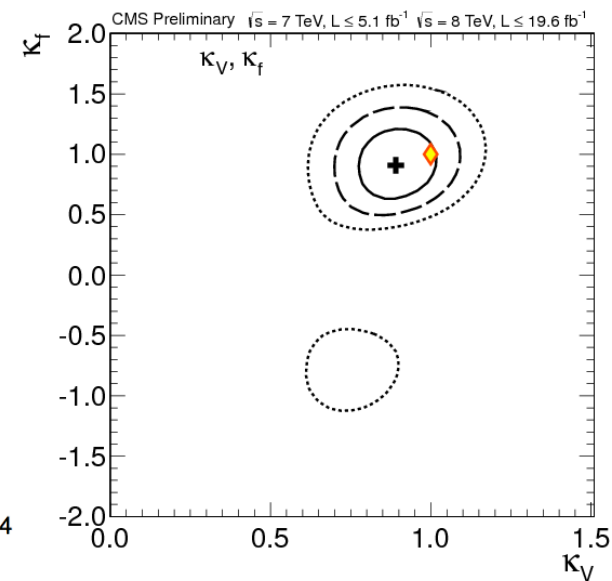
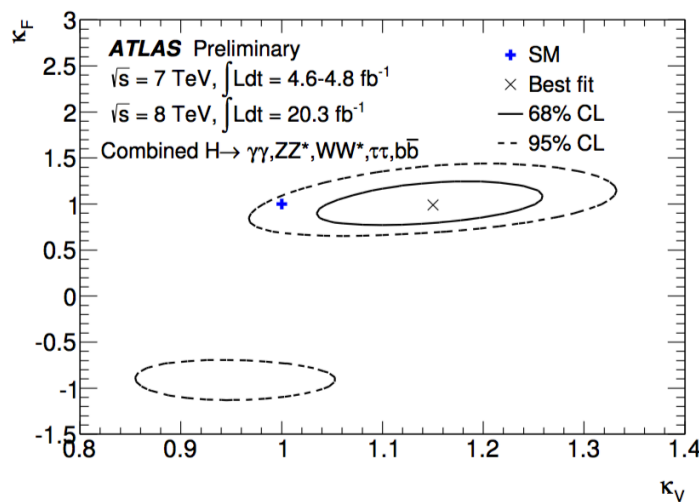
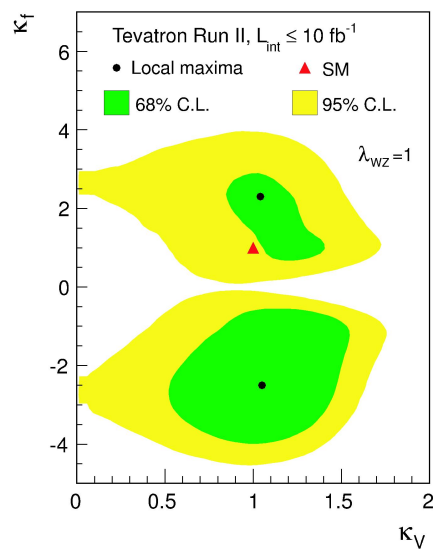
$H \rightarrow \gamma \gamma$  resolved into  
top-loop, b-loop,  $\tau$ -loop,  
and **W-loop**.



# Weak bosons and fermions

21

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



|       | Tevatron | ATLAS | CMS          |
|-------|----------|-------|--------------|
| p(SM) | -        | 10%   | $< 1 \sigma$ |

# Composite (R.Contino)

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

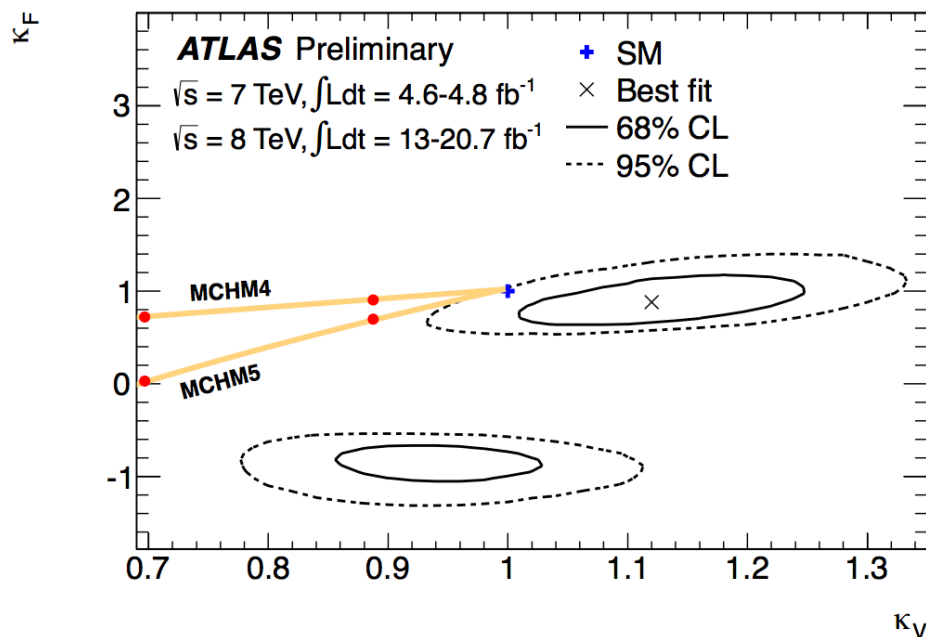
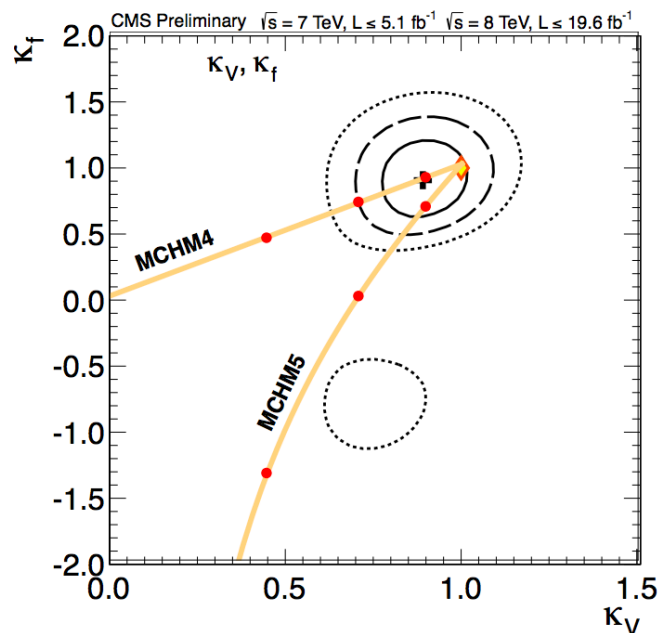
## Leading effects in tree-level couplings and $Z\gamma$ rate

$$c_V, c_u, c_d = 1 + O\left(\frac{v^2}{f^2}\right)$$

$$\frac{\Gamma(h \rightarrow Z\gamma)}{\Gamma_{SM}} = 1 + O\left(\frac{v^2}{f^2}\right)$$

$f$  = Higgs decay constant

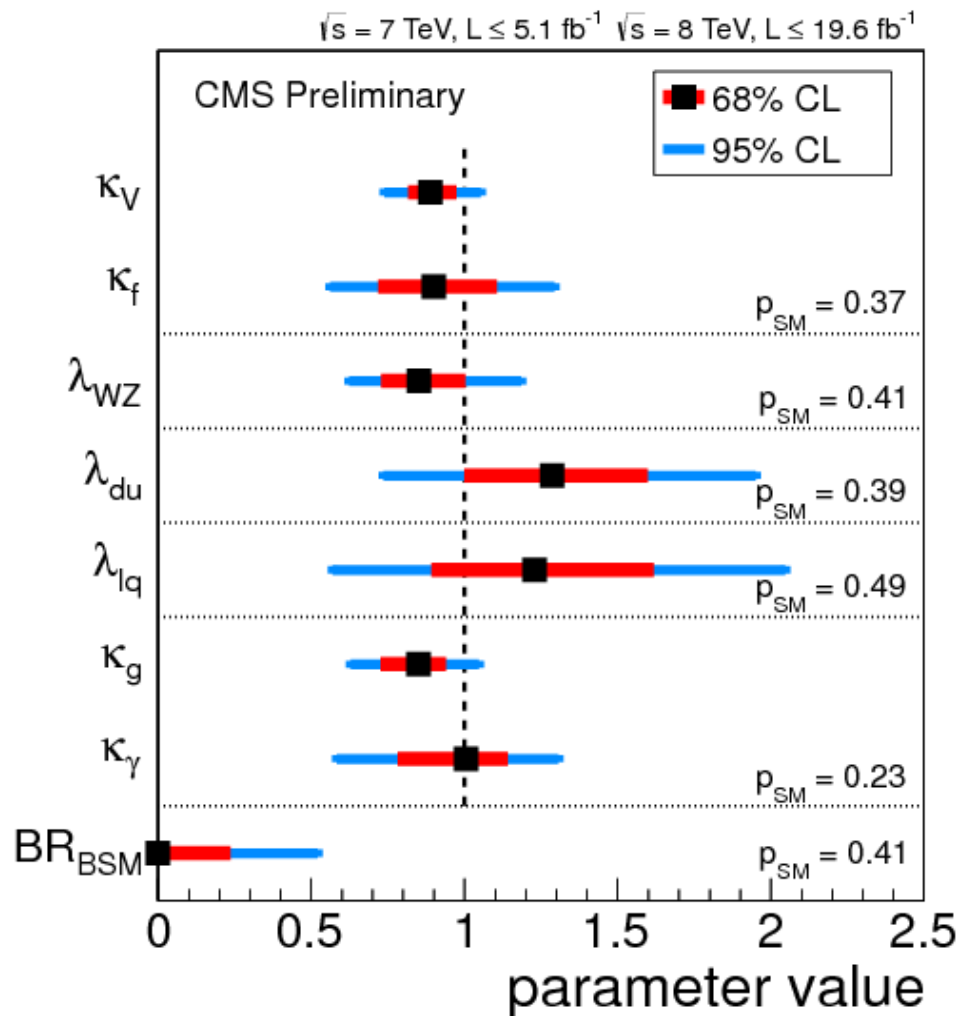
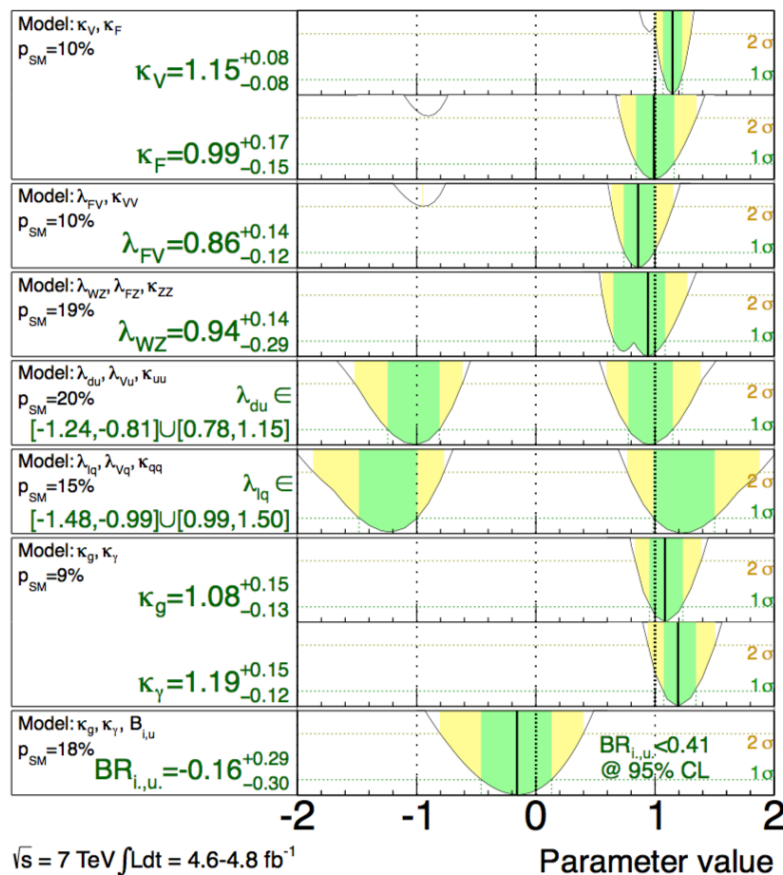
$$m_{\text{new}} = g_* f \lesssim 4\pi f$$



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

# The deviations that we do not (yet) see

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

**ATLAS Preliminary**
 $m_H = 125.5 \text{ GeV}$ 
**Total uncertainty**
■  $\pm 1\sigma$  ■  $\pm 2\sigma$ 


# Spin is so much more than a number

[arXiv:1208.4018]

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

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

# Spin is so much more than a number

[arXiv:1208.4018]

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

$$\begin{aligned}
 A(X \rightarrow V_1 V_2) = \Lambda^{-1} & \left[ 2g_1^{(2)} t_{\mu\nu} f^{*(1)\mu\alpha} f^{*(2)\nu\alpha} + \cancel{2g_2^{(2)} t_{\mu\nu} f^{*(1)\mu\alpha} f^{*(2)\nu\alpha}} + \cancel{g_3^{(2)} \frac{\tilde{a}^\beta \tilde{a}^\alpha}{\Lambda^2} (f^{*(1)\mu\nu} f^{*(2)\mu\nu} - f^{*(1)\mu\alpha} f^{*(2)\mu\alpha})} \right. \\
 & + \cancel{g_4^{(2)} \frac{\tilde{a}^\nu \tilde{a}^\mu}{\Lambda^2} f^{*(1)\mu\alpha} f^{*(2)\nu\alpha}} + m_V^2 \left( 2g_5^{(2)} t_{\mu\nu} \epsilon_1^{*\mu} \epsilon_2^{*\nu} + \cancel{2g_6^{(2)} \frac{\tilde{a}^\mu q_\alpha}{\Lambda^2} (f^{*(1)\mu\nu} f^{*(2)\nu\alpha} - f^{*(1)\alpha\nu} f^{*(2)\mu\nu})} + \cancel{g_7^{(2)} \frac{\tilde{a}^\mu \tilde{a}^\nu}{\Lambda^2} t_{\mu\nu} \epsilon_1^{*\alpha} \epsilon_2^{*\alpha}} \right) \\
 & + \cancel{g_8^{(2)} \frac{\tilde{a}_\mu \tilde{a}_\nu}{\Lambda^2} f^{*(1)\mu\alpha} f^{*(2)\nu\alpha}} + m_V^2 \left( \cancel{g_9^{(2)} \frac{t_{\mu\alpha} \tilde{a}^\alpha}{\Lambda^2} \epsilon_1^{*\mu} \epsilon_2^{*\alpha}} + \cancel{g_{10}^{(2)} \frac{t_{\mu\alpha} \tilde{a}^\alpha}{\Lambda^2} \epsilon_1^{*\mu} \epsilon_2^{*\alpha}} + \cancel{g_{11}^{(2)} \frac{t_{\mu\alpha} \tilde{a}^\alpha}{\Lambda^2} \epsilon_1^{*\mu} \epsilon_2^{*\alpha}} \right) \Big], \quad (18)
 \end{aligned}$$

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



# $J^P$ : a simplified picture

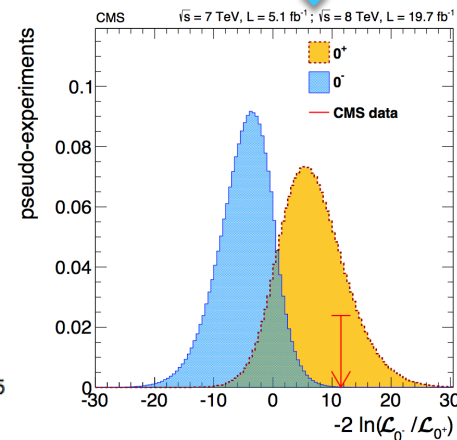
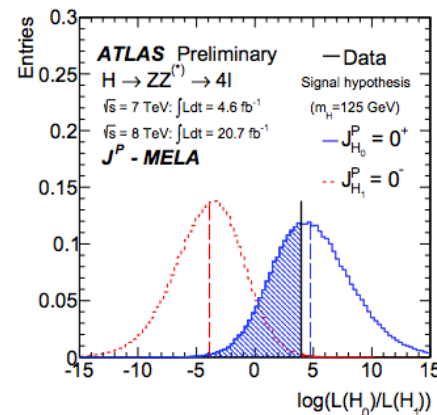
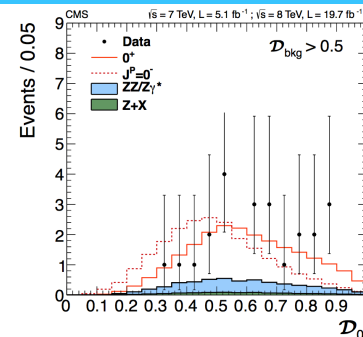
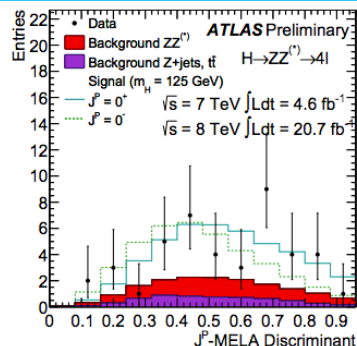
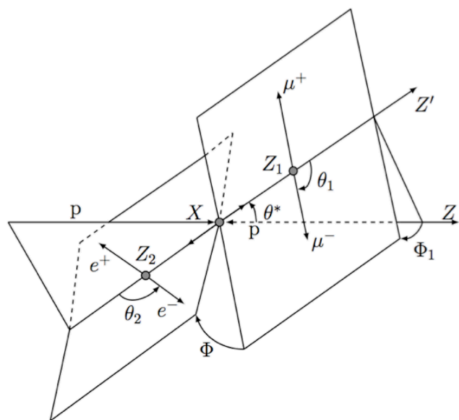
[arXiv:1208.4018]

- 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              | $X \rightarrow ZZ$ | $X \rightarrow WW$ | $X \rightarrow \gamma\gamma$ |
|-----------------------|--------------------|--------------------|------------------------------|
| $0_m^+$ 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 $2_h^+$    | $\sim 5$           | 1.1                | 3.1                          |
| $0_m^+$ vs $2_h^-$    | $\sim 5$           | 2.5                | 3.1                          |

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

[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.

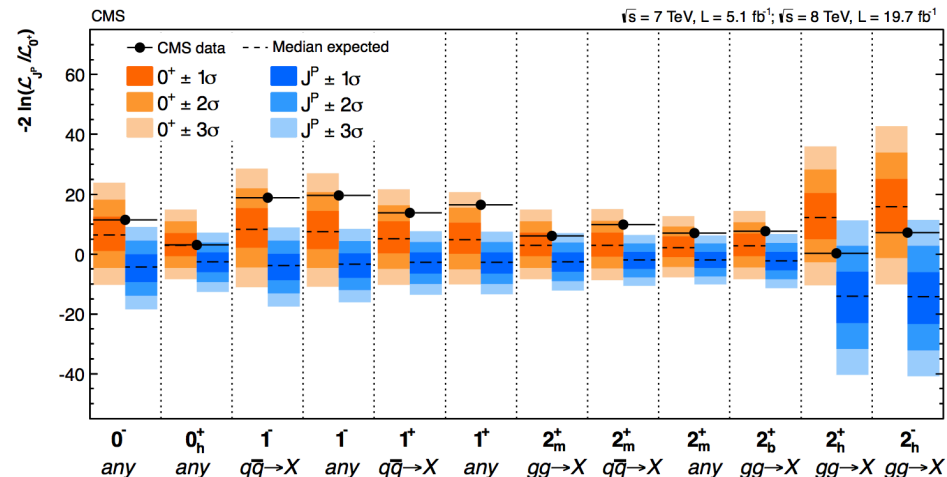
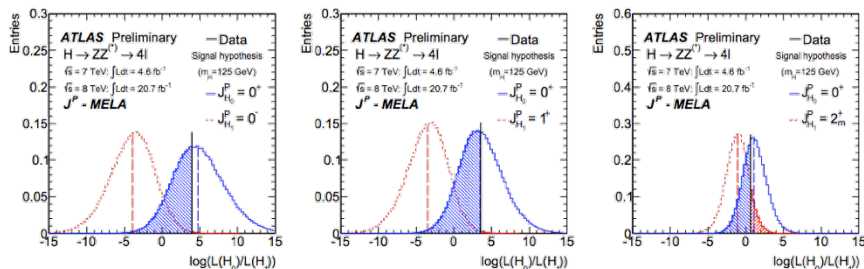
|                        | ATLAS        | CMS           |
|------------------------|--------------|---------------|
| $CL_s$                 | 0.37%        | 0.09%         |
| $P(\text{obs.}   0^+)$ | $0.2 \sigma$ | $-0.9 \sigma$ |
| $P(\text{obs.}   0^-)$ | $2.8 \sigma$ | $3.6 \sigma$  |



# Other $J^P$ in $H \rightarrow ZZ \rightarrow 4\ell$

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



| J <sup>P</sup> -MELA analysis |                |                                                     |          |                                                     |                 |
|-------------------------------|----------------|-----------------------------------------------------|----------|-----------------------------------------------------|-----------------|
|                               |                | tested J <sup>P</sup> for an assumed 0 <sup>+</sup> |          | tested 0 <sup>+</sup> for an assumed J <sup>P</sup> | CL <sub>s</sub> |
|                               |                | expected                                            | observed | observed*                                           |                 |
| 0 <sup>-</sup>                | p <sub>0</sub> | 0.0011                                              | 0.0022   | 0.40                                                | 0.004           |
| 1 <sup>+</sup>                | p <sub>0</sub> | 0.0031                                              | 0.0028   | 0.51                                                | 0.006           |
| 1 <sup>-</sup>                | p <sub>0</sub> | 0.0010                                              | 0.027    | 0.11                                                | 0.031           |
| 2 <sup>+</sup> <sub>m</sub>   | p <sub>0</sub> | 0.064                                               | 0.11     | 0.38                                                | 0.182           |
| 2 <sup>-</sup>                | p <sub>0</sub> | 0.0032                                              | 0.11     | 0.08                                                | 0.116           |

| J <sup>P</sup> model        | J <sup>P</sup> production | Expected (μ = 1) | Obs. 0 <sup>+</sup> | Obs. J <sup>P</sup> | CL <sub>s</sub> |
|-----------------------------|---------------------------|------------------|---------------------|---------------------|-----------------|
| 0 <sup>-</sup>              | any                       | 2.4σ (2.7σ)      | -0.9σ               | +3.6σ               | 0.09%           |
| 0 <sup>+</sup> <sub>h</sub> | any                       | 1.7σ (1.9σ)      | -0.0σ               | +1.8σ               | 7.1%            |
| 1 <sup>-</sup>              | q $\bar{q}$ → X           | 2.6σ (2.7σ)      | -1.4σ               | +4.8σ               | 0.001%          |
| 1 <sup>-</sup>              | any                       | 2.6σ (2.6σ)      | -1.7σ               | +4.9σ               | 0.001%          |
| 1 <sup>+</sup>              | q $\bar{q}$ → X           | 2.1σ (2.3σ)      | -1.5σ               | +4.1σ               | 0.03%           |
| 1 <sup>+</sup>              | any                       | 2.0σ (2.1σ)      | -1.9σ               | +4.5σ               | 0.01%           |
| 2 <sup>+</sup> <sub>m</sub> | gg → X                    | 1.7σ (1.8σ)      | -0.8σ               | +2.6σ               | 1.9%            |
| 2 <sup>+</sup> <sub>m</sub> | q $\bar{q}$ → X           | 1.6σ (1.7σ)      | -1.6σ               | +3.6σ               | 0.03%           |
| 2 <sup>+</sup> <sub>m</sub> | any                       | 1.5σ (1.5σ)      | -1.3σ               | +3.0σ               | 1.4%            |
| 2 <sup>+</sup> <sub>b</sub> | gg → X                    | 1.6σ (1.8σ)      | -1.2σ               | +3.1σ               | 0.9%            |
| 2 <sup>+</sup> <sub>h</sub> | gg → X                    | 3.7σ (4.0σ)      | +1.8σ               | +1.9σ               | 3.1%            |
| 2 <sup>-</sup> <sub>h</sub> | gg → X                    | 4.0σ (4.5σ)      | +1.0σ               | +3.0σ               | 1.7%            |

ATLAS

CMS

Worse CL<sub>s</sub> for J ≠ 0

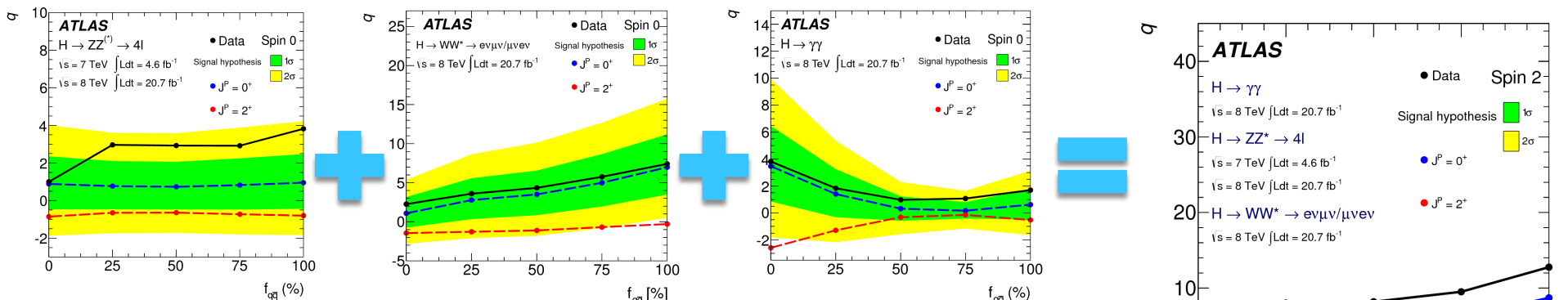
< 18.2%

< 3.1%

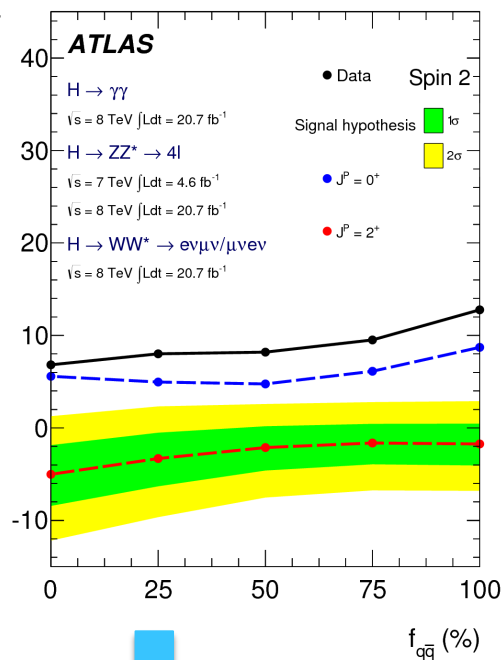
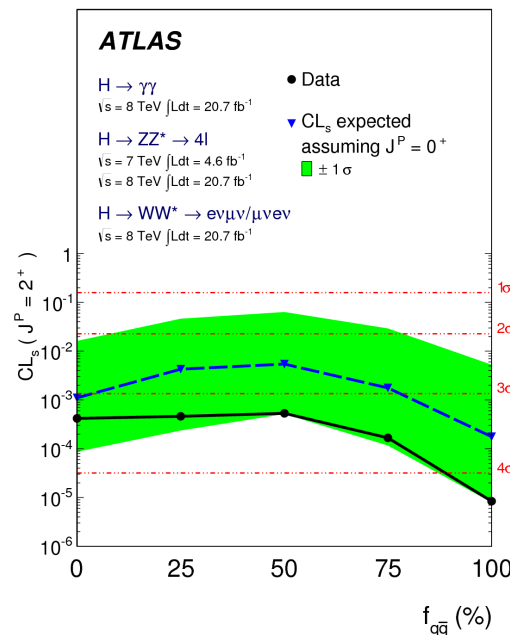
# ATLAS: combination against $2^+_{\text{m}}$

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[arXiv:1307.1432]



- Combined  $H \rightarrow ZZ$ ,  $WW$ , and  $\gamma\gamma$ .
- Scan for fraction of  $(gg/q\bar{q}) \rightarrow 2^+_{\text{m}}$ :
  - $\text{CL}_s < 0.06\% \quad \forall f_{q\bar{q}}$ .



# 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

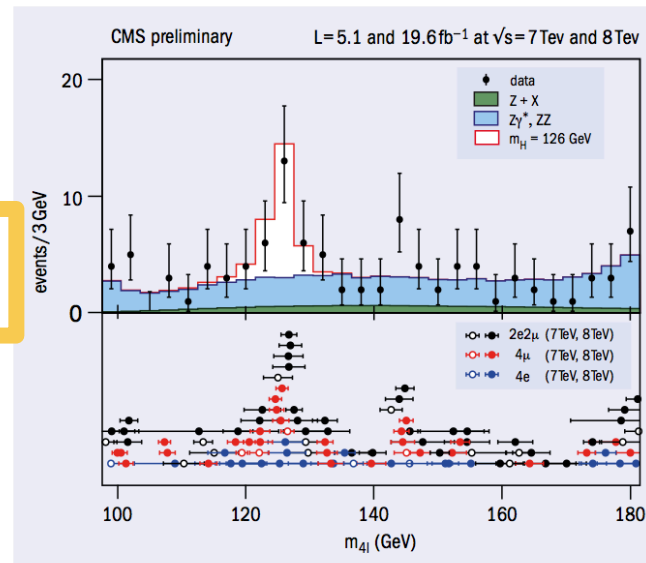
March, giving the particle-physics community enough evidence to name this new boson “a Higgs boson”.

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.





# Entry in the PDG

## $H^0$ (Higgs Boson)

The observed signal is called a Higgs Boson in the following, although its detailed properties and in particular the role that the new particle plays in the context of electroweak symmetry breaking need to be further clarified. The signal was discovered in searches for a Standard Model (SM)-like Higgs. See the following section for mass limits obtained from those searches.

## $H^0$ MASS

[INSPIRE search](#)

| Value (GeV)                                                              | Document ID                             | TECN                   | Comment                 |
|--------------------------------------------------------------------------|-----------------------------------------|------------------------|-------------------------|
| 125.9 $\pm 0.4$                                                          | <b>OUR AVERAGE</b>                      |                        |                         |
| 125.8 $\pm 0.4 \pm 0.4$                                                  | <a href="#">CHATRCHYAN</a> <sup>1</sup> | <a href="#">2013J</a>  | CMS $pp$ , 7 and 8 TeV  |
| 126.0 $\pm 0.4 \pm 0.4$                                                  | <a href="#">AAD</a> <sup>2</sup>        | <a href="#">2012AI</a> | ATLS $pp$ , 7 and 8 TeV |
| *** We do not use the following data for averages, fits, limits, etc *** |                                         |                        |                         |
| 126.2 $\pm 0.6 \pm 0.2$                                                  | <a href="#">CHATRCHYAN</a> <sup>3</sup> | <a href="#">2013J</a>  | CMS $pp$ , 7 and 8 TeV  |
| 125.3 $\pm 0.4 \pm 0.5$                                                  | <a href="#">CHATRCHYAN</a> <sup>4</sup> | <a href="#">2012N</a>  | CMS $pp$ , 7 and 8 TeV  |

<sup>1</sup> Combined value from  $ZZ$  and  $\gamma\gamma$  final states.

<sup>2</sup> AAD 2012AI obtain results based on  $4.6 - 4.8 \text{ fb}^{-1}$  of  $pp$  collisions at  $E_{\text{cm}} = 7 \text{ TeV}$  and  $5.8 - 5.9 \text{ fb}^{-1}$  at  $E_{\text{cm}} = 8 \text{ TeV}$ . An excess of events over background with a local significance of  $5.9 \sigma$  is observed at  $m_{H^0} = 126 \text{ GeV}$ . See also AAD 2012DA.

<sup>3</sup> Result based on final states in  $5.1 \text{ fb}^{-1}$  of  $pp$  collisions at  $E_{\text{cm}} = 7 \text{ TeV}$  and  $12.2 \text{ fb}^{-1}$  at  $E_{\text{cm}} = 8 \text{ TeV}$ .

<sup>4</sup> CHATRCHYAN 2012N obtain results based on  $4.9 - 5.1 \text{ fb}^{-1}$  of  $pp$  collisions at  $E_{\text{cm}} = 7 \text{ TeV}$  and  $5.1 - 5.3 \text{ fb}^{-1}$  at  $E_{\text{cm}} = 8 \text{ TeV}$ . An excess of events over background with a local significance of  $5.0 \sigma$  is observed at about  $m_{H^0} = 125 \text{ GeV}$ . See also CHATRCHYAN 2012BY.

## References

| Document Id      | Journal Name                   |
|------------------|--------------------------------|
| CHATRCHYAN 2013J | <a href="#">PRL 110 081803</a> |
| AAD 2012AI       | <a href="#">PL B716 1</a>      |
| CHATRCHYAN 2012N | <a href="#">PL B716 30</a>     |

**NB: the mass measurement alone “cleared up”  
a huge chunk of BSM space.**



# 2013: “killer” news

- SM-like: the Swedish academy shot the prize at Englert and Higgs.

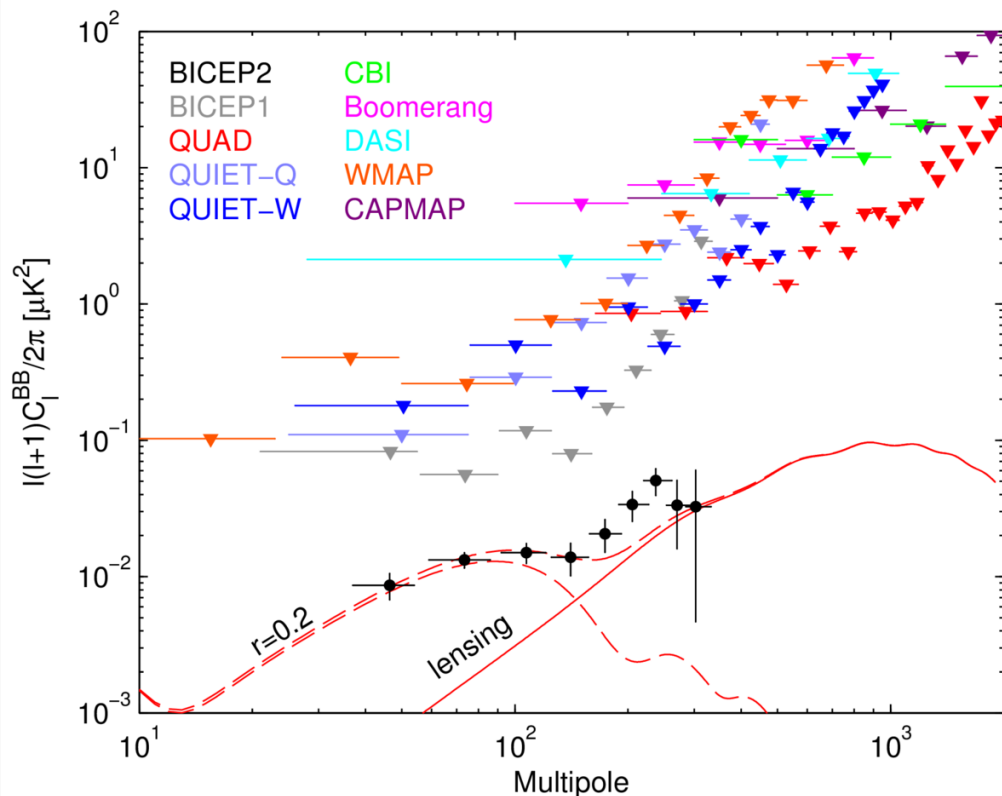




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# Flexing your BICEP2 muscles

[arXiv:1403.3985]



□ Who knows ?

## 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- 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 Higgs Inflation is 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



## 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  $r \approx 0.13 - 0.16$ , 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 ordered a pipette?

## Particles smaller than the Higgs boson exist?

By PTI | 23 Mar, 2014, 01.52PM IST

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LONDON: There are unknown particles floating around the universe that may be even smaller than the Higgs boson, the 'God particle' discovered in 2012, scientists say.

The so-called techni-quarks can be the yet unseen particles, smaller than the Higgs particle that will form a natural extension of the Standard Model which includes three generations of quarks and leptons.

These particles together with the



*Ryttov referred to the theories that have been put forward over the last five years for the existence of particles in the universe that are smaller than the Higgs particle.*

# A very long way to go...

## Decay Modes

| $\Gamma_i$ | Mode                           | Fraction ( $\Gamma_i / \Gamma$ ) | Scale Factor/<br>Confidence<br>Level | P<br>(MeV/c) |
|------------|--------------------------------|----------------------------------|--------------------------------------|--------------|
| $\Gamma_1$ | $H^0 \rightarrow WW^*$         | seen                             |                                      |              |
| $\Gamma_2$ | $H^0 \rightarrow ZZ^*$         | seen                             |                                      |              |
| $\Gamma_3$ | $H^0 \rightarrow \gamma\gamma$ | seen                             |                                      |              |
| $\Gamma_4$ | $H^0 \rightarrow b\bar{b}$     | possibly seen                    |                                      |              |
| $\Gamma_5$ | $H^0 \rightarrow \tau^+\tau^-$ | possibly seen                    |                                      |              |

## $H^0$ SIGNAL STRENGTHS IN DIFFERENT CHANNELS

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

## Decay Modes

| $\Gamma_i$    | Mode                                               | Fraction ( $\Gamma_i / \Gamma$ )     | Scale Factor/<br>Confidence<br>Level | P<br>(MeV/c) |
|---------------|----------------------------------------------------|--------------------------------------|--------------------------------------|--------------|
| $\Gamma_1$    | $Z \rightarrow e^+e^-$                             | $3.363 \pm 0.004 \%$                 |                                      | 45594        |
| $\Gamma_2$    | $Z \rightarrow \mu^+\mu^-$                         | $3.366 \pm 0.007 \%$                 |                                      | 45594        |
| $\Gamma_3$    | $Z \rightarrow \tau^+\tau^-$                       | $3.370 \pm 0.008 \%$                 |                                      | 45559        |
| $\Gamma_4$    | $Z \rightarrow \ell^+\ell^-$                       | $3.3658 \pm 0.0023 \%$               |                                      |              |
| $\Gamma_5$    | $Z \rightarrow \ell^+\ell^-\ell^+\ell^-$           | $(4.2^{+0.9}_{-0.8}) \times 10^{-6}$ |                                      | 45594        |
| $\Gamma_6$    | $Z \rightarrow \text{invisible}$                   | $(2.000 \pm .006) \times 10^{-1}$    |                                      |              |
| $\Gamma_7$    | $Z \rightarrow \text{hadrons}$                     | $(6.991 \pm .006) \times 10^{-1}$    |                                      |              |
| $\Gamma_8$    | $Z \rightarrow (u\bar{u} + c\bar{c})/2$            | $.116 \pm .006$                      |                                      |              |
| $\Gamma_9$    | $Z \rightarrow (d\bar{d} + s\bar{s} + b\bar{b})/3$ | $.156 \pm .004$                      |                                      |              |
| $\Gamma_{10}$ | $Z \rightarrow c\bar{c}$                           | $(1.203 \pm .021) \times 10^{-1}$    |                                      |              |
| $\Gamma_{11}$ | $Z \rightarrow b\bar{b}$                           | $(1.512 \pm .005) \times 10^{-1}$    |                                      |              |
| $\Gamma_{12}$ | $Z \rightarrow b\bar{b}b\bar{b}$                   | $(3.6 \pm 1.3) \times 10^{-4}$       |                                      |              |

# The future

["Lawrence of Arabia" idea from C. Grojean]

- We must examine this Higgs to the fullest extent !
  - ▣ It may be the only clue to leave the SM oasis and cross the desert.



# The future in a nutshell

- Boson “solo gigs”:
  - ▣ Beyond spin hypotheses tests.
  - ▣ Theory uncertainties and ratios.
  - ▣ The adventure of unfolding: going differential.
  - ▣ Statistics-limited:  $t\bar{t}H$ ,  $tH$ , invisible.
  - ▣ Total width interferometry.
  - ▣ 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  $\mathcal{K}$ -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

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[ATLAS-CONF-2014-009]

- PDFs not dominating on  $\mu$ .
  - ▣ ggH vs VBF+VH.
  - ▣ PDF4LHC prescription too conservative?
  - ▣ PDG  $\sigma(\alpha_s)$  too aggressive?
- NNLO+NNLL not enough to tame large QCD corrections in gluon-fusion?

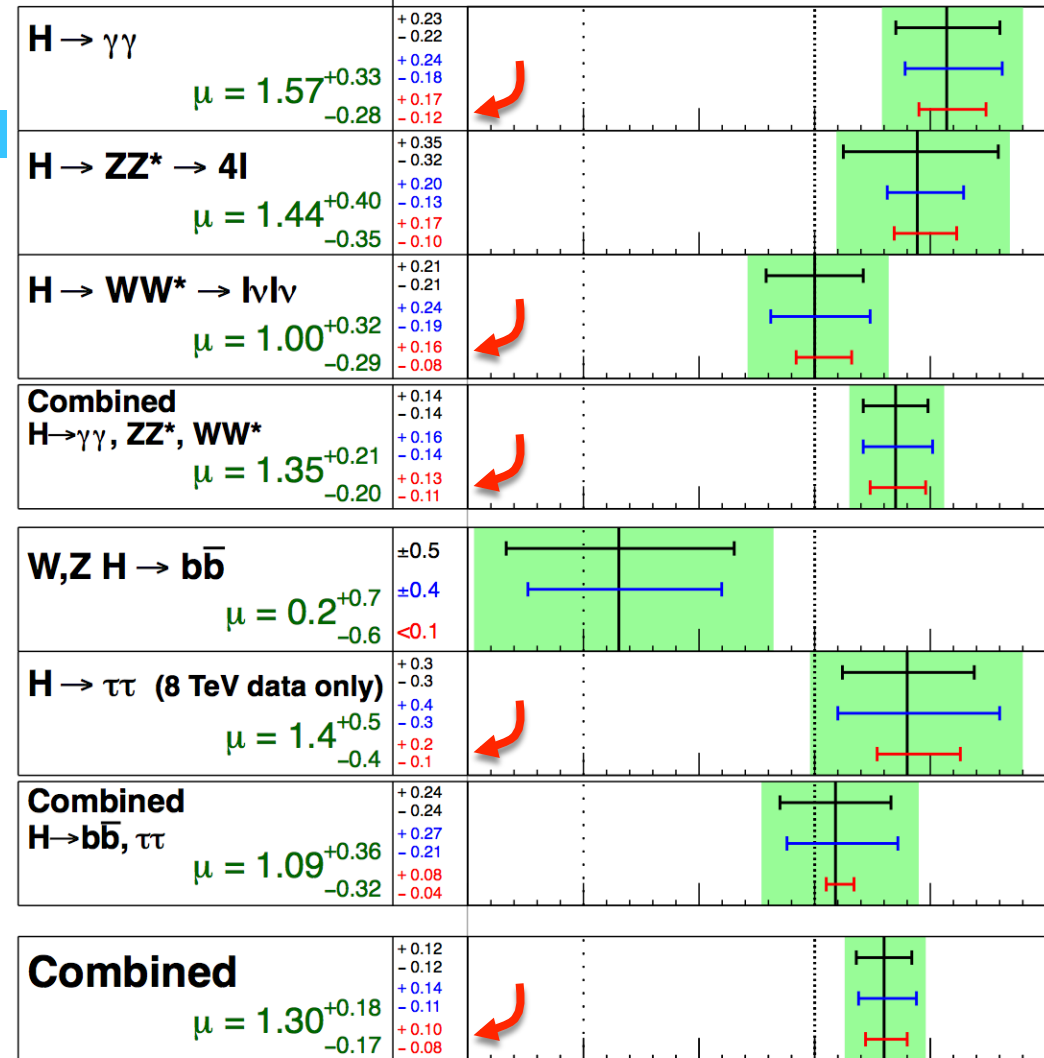
**ATLAS Prelim.**

$m_H = 125.5 \text{ GeV}$

—  $\sigma(\text{stat.})$   
 —  $\sigma(\text{sys inc.})$   
 —  $\sigma(\text{theory})$

Total uncertainty

■  $\pm 1\sigma$  on  $\mu$



$\sqrt{s} = 7 \text{ TeV} \int \mathcal{L} dt = 4.6\text{-}4.8 \text{ fb}^{-1}$

$\sqrt{s} = 8 \text{ TeV} \int \mathcal{L} dt = 20.3 \text{ fb}^{-1}$

Signal strength ( $\mu$ )

# Theory uncertainties: MHOU

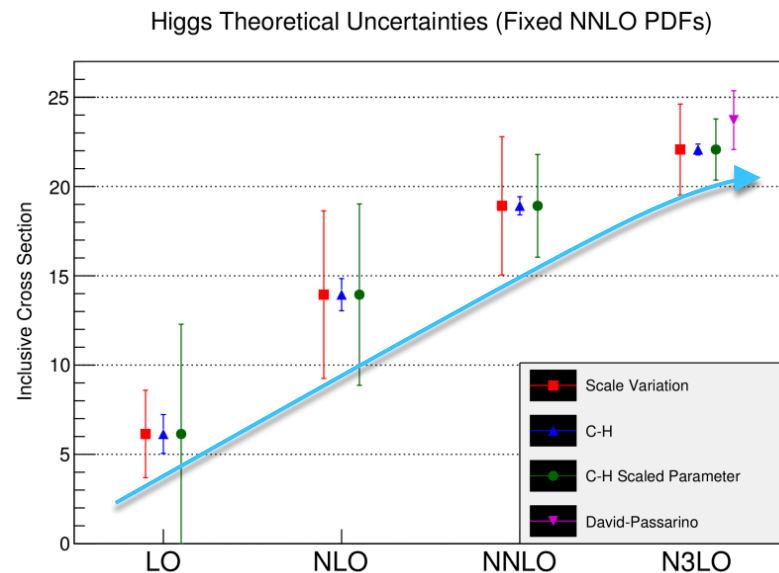
[arXiv:1307.1843] [http://cern.ch/go/V8xJ]

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

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

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

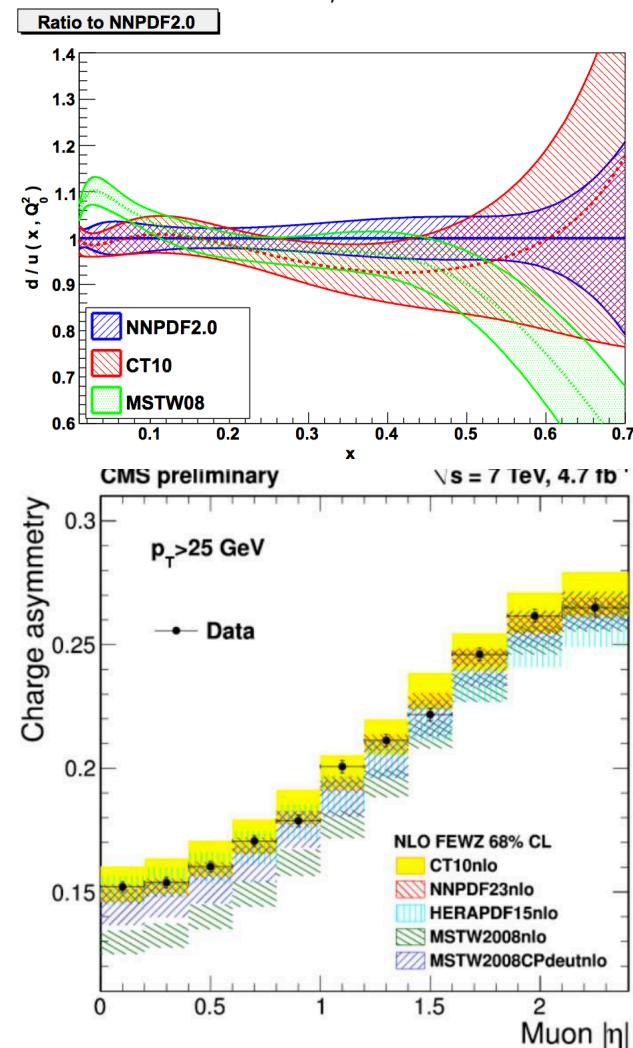
- Take gluon-gluon fusion:
  - ▣ All series terms are positive.
  - ▣ We can try and complete the series instead of **always** being off.



# 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

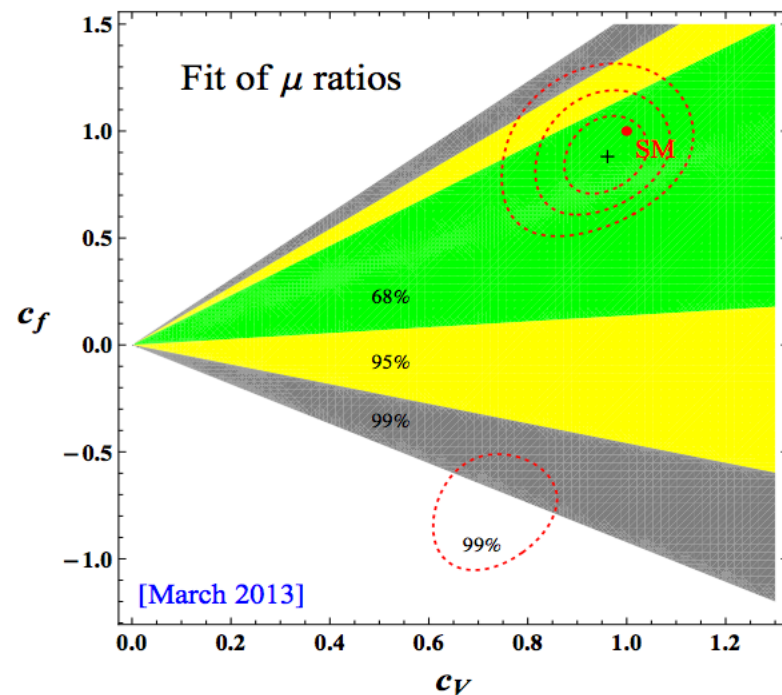
- Bottom-line for Run2:
  - Consider measurements that constrain PDF fits.
  - For higher orders, more than precision, also a matter of accuracy.
    - Need to work with theorists to get these right, also differentially.
- Or you can try to dodge them with ratios...

# Ratios to the rescue?

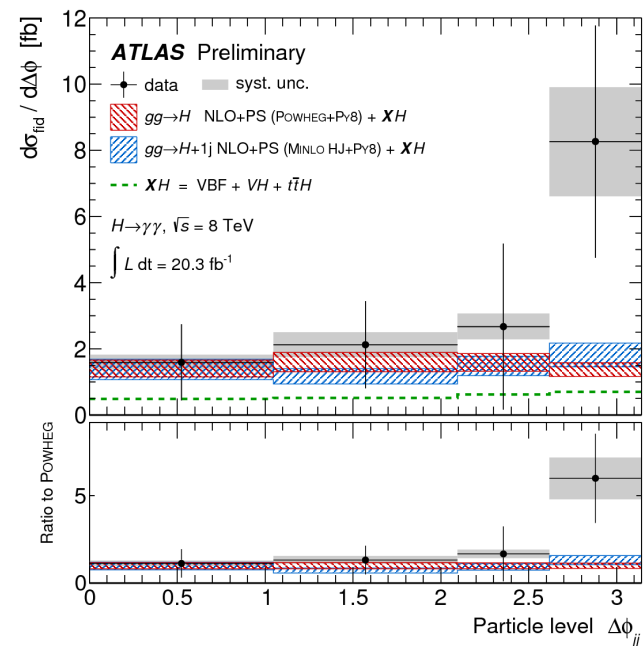
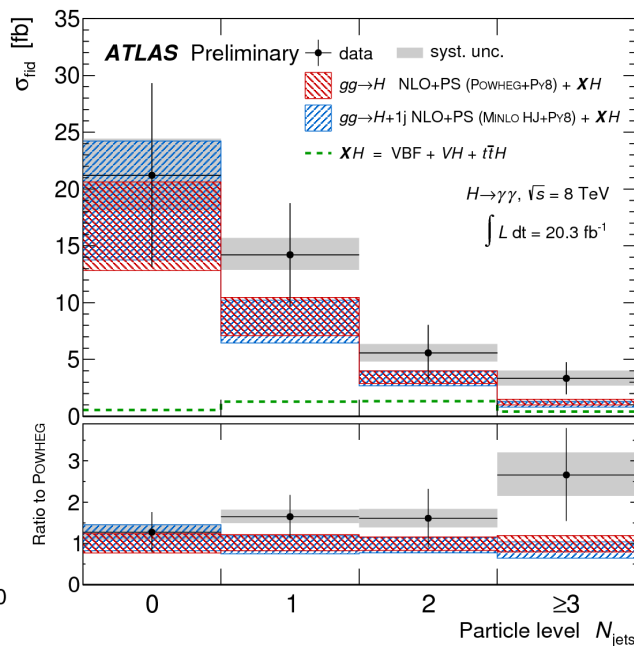
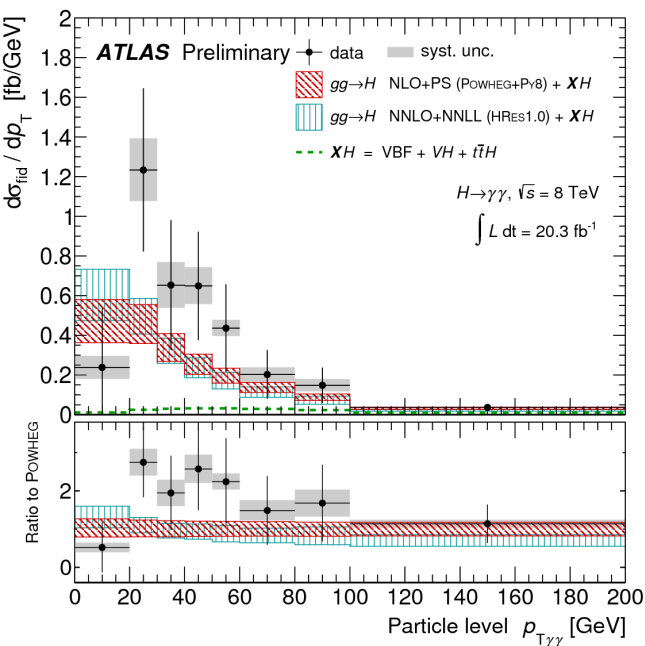
[arXiv:1303.6591] [http://cern.ch/go/gLP9]

- 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.**

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



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





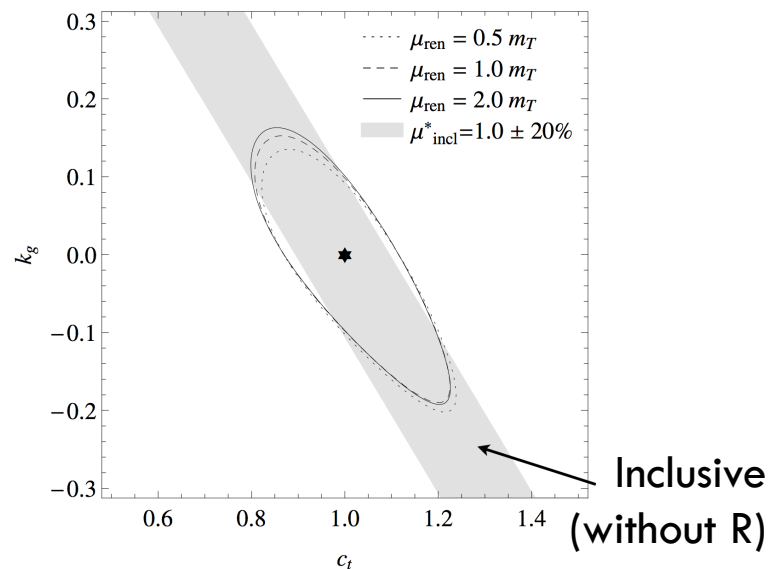
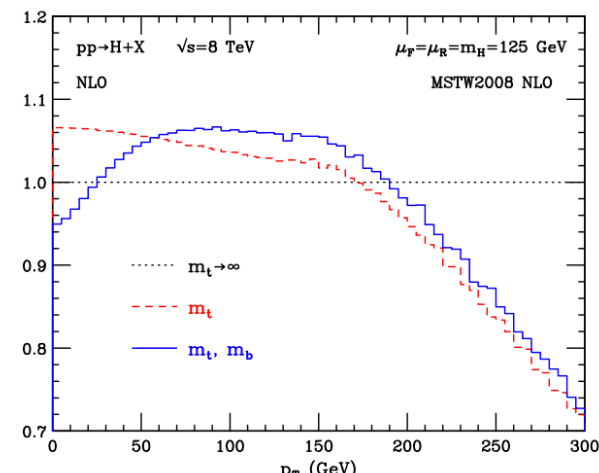
# Boosted Higgs + Ratios

[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”:

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

- ▣ But it's a 3000/fb venture.



# Oversimplified big picture

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

| <div> <div>★ “seen”</div> <div>☆ “tried”</div> <div>- “impossible”</div> </div> | $H \rightarrow b\bar{b}$ |   |   | $H \rightarrow \tau\tau$ |   |   | $H \rightarrow WW$ |   |   | $H \rightarrow ZZ$ |   |   | $H \rightarrow \gamma\gamma$ |   |   | $H \rightarrow Z\gamma$ |   |   | $H \rightarrow \text{inv.}$ |   |   | $H \rightarrow \mu\mu$ |   |   | $H \rightarrow c\bar{c}$<br>$H \rightarrow HH$ |   |   |
|---------------------------------------------------------------------------------|--------------------------|---|---|--------------------------|---|---|--------------------|---|---|--------------------|---|---|------------------------------|---|---|-------------------------|---|---|-----------------------------|---|---|------------------------|---|---|------------------------------------------------|---|---|
|                                                                                 | 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                                                                             |                          | ☆ | ☆ | ☆                        |   | ★ | ☆                  |   | ★ |                    |   | ★ |                              | ★ | ★ | -                       |   |   |                             |   |   | -                      |   |   | -                                              |   |   |

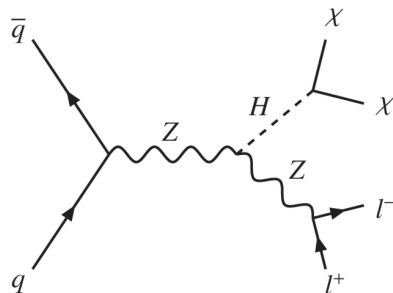
□ **Still much to explore on the rarer ends.**

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

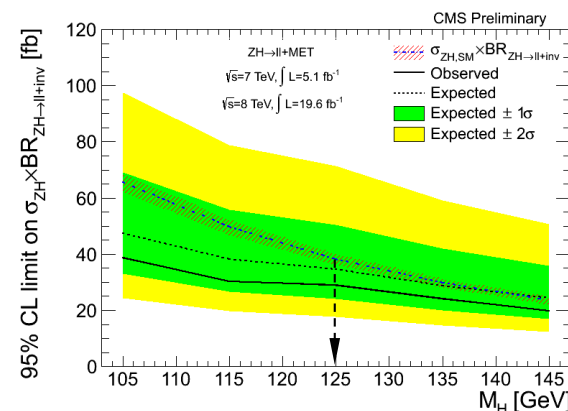
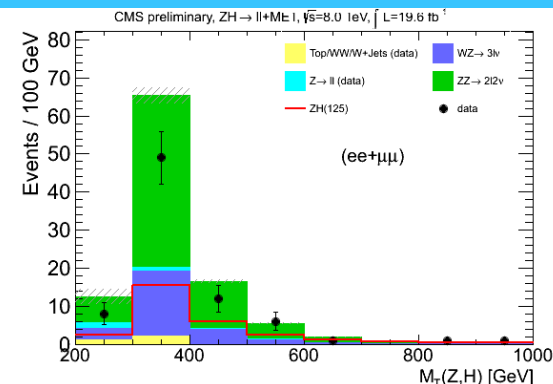
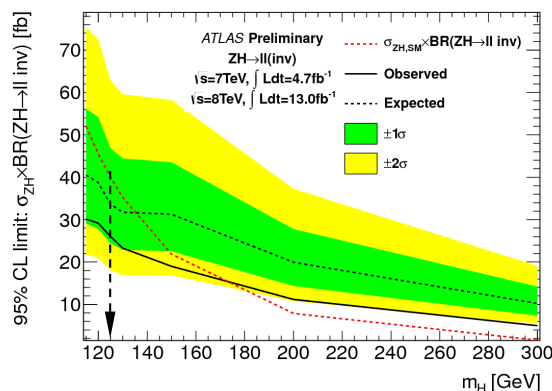
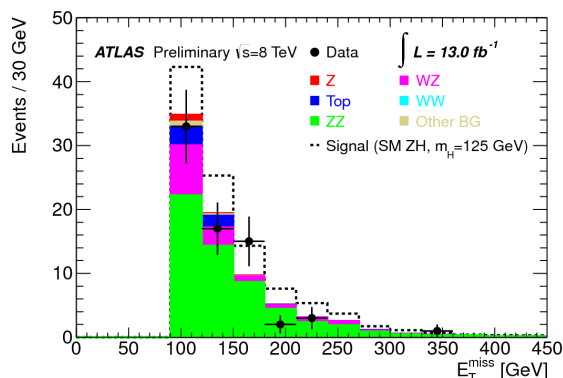
# ★ $ZH \rightarrow \ell\ell + \text{invisible}$

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[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  $Z \rightarrow b\bar{b}$  in CMS.



Obs. (exp.)

**BR<sub>inv.</sub> at 125 GeV (95% CL)**

**ATLAS**

**< 0.65 (0.84)**

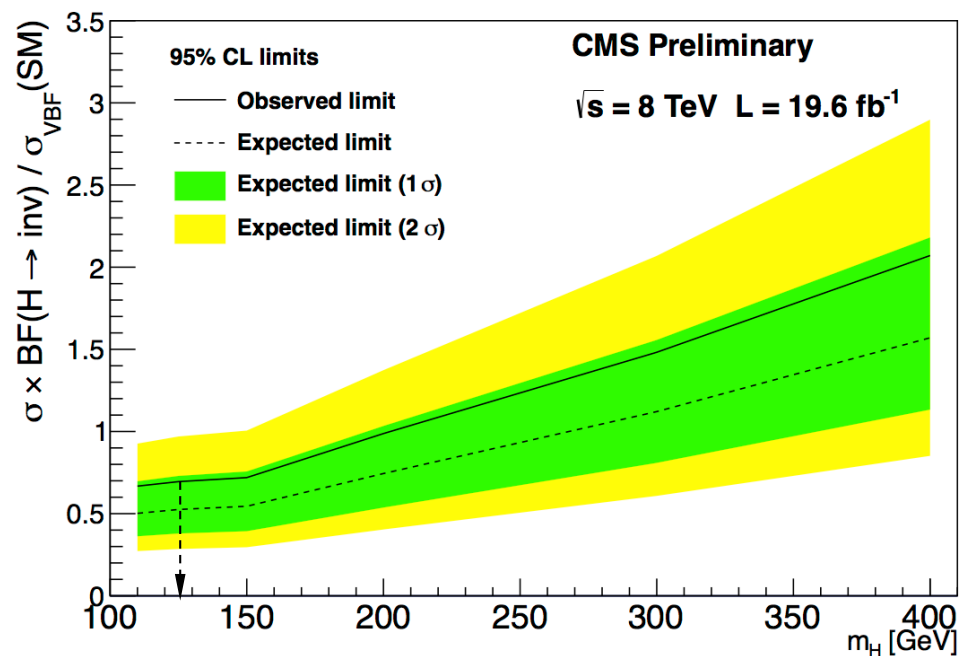
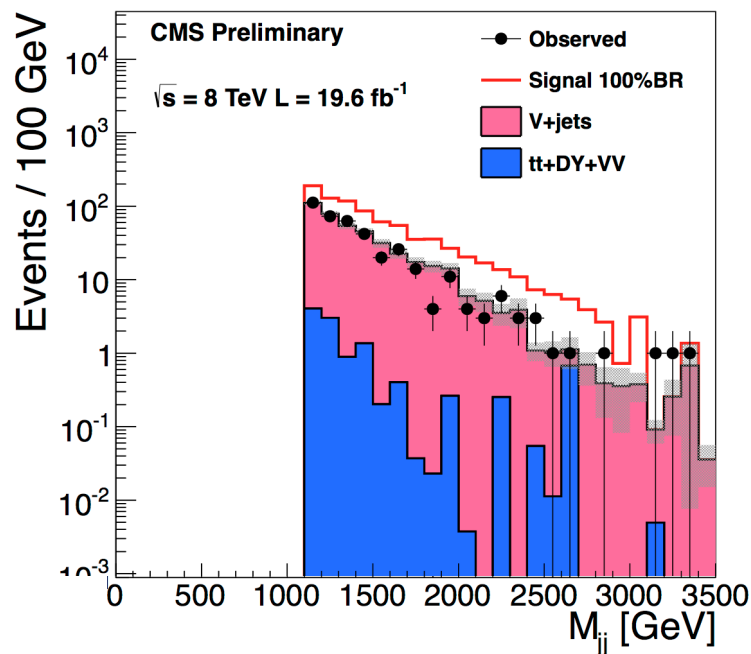
**CMS**

**< 0.75 (0.91)**

# ★ VBF, $H \rightarrow \text{invisible}$

47

[CMS-PAS-HIG-13-013]

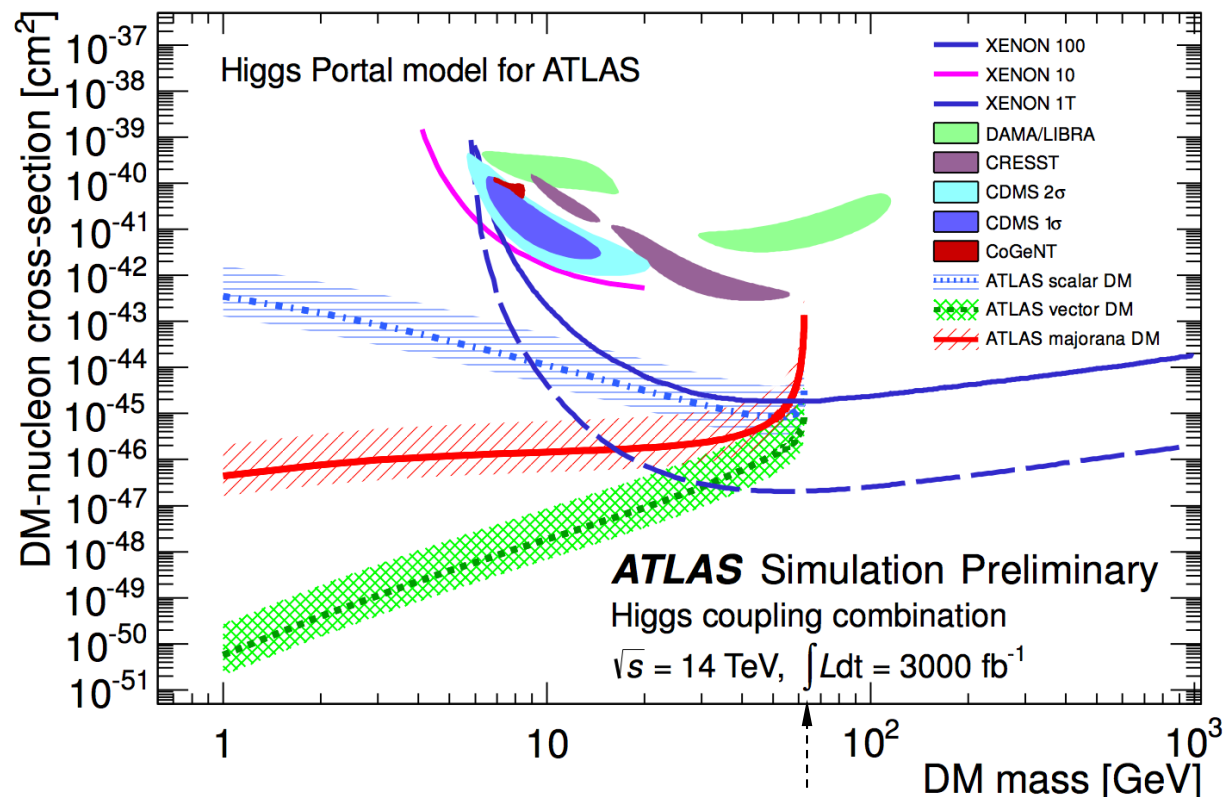


□ At  $m_H = 125 \text{ GeV}$ ,  
 $\text{BR}_{\text{inv.}} < 0.69 \text{ (0.53)} \text{ (95\%CL), obs.(exp.)}$ .

# Statistics-limited: invisible

[ATL-PHYS-PUB-2013-015]

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

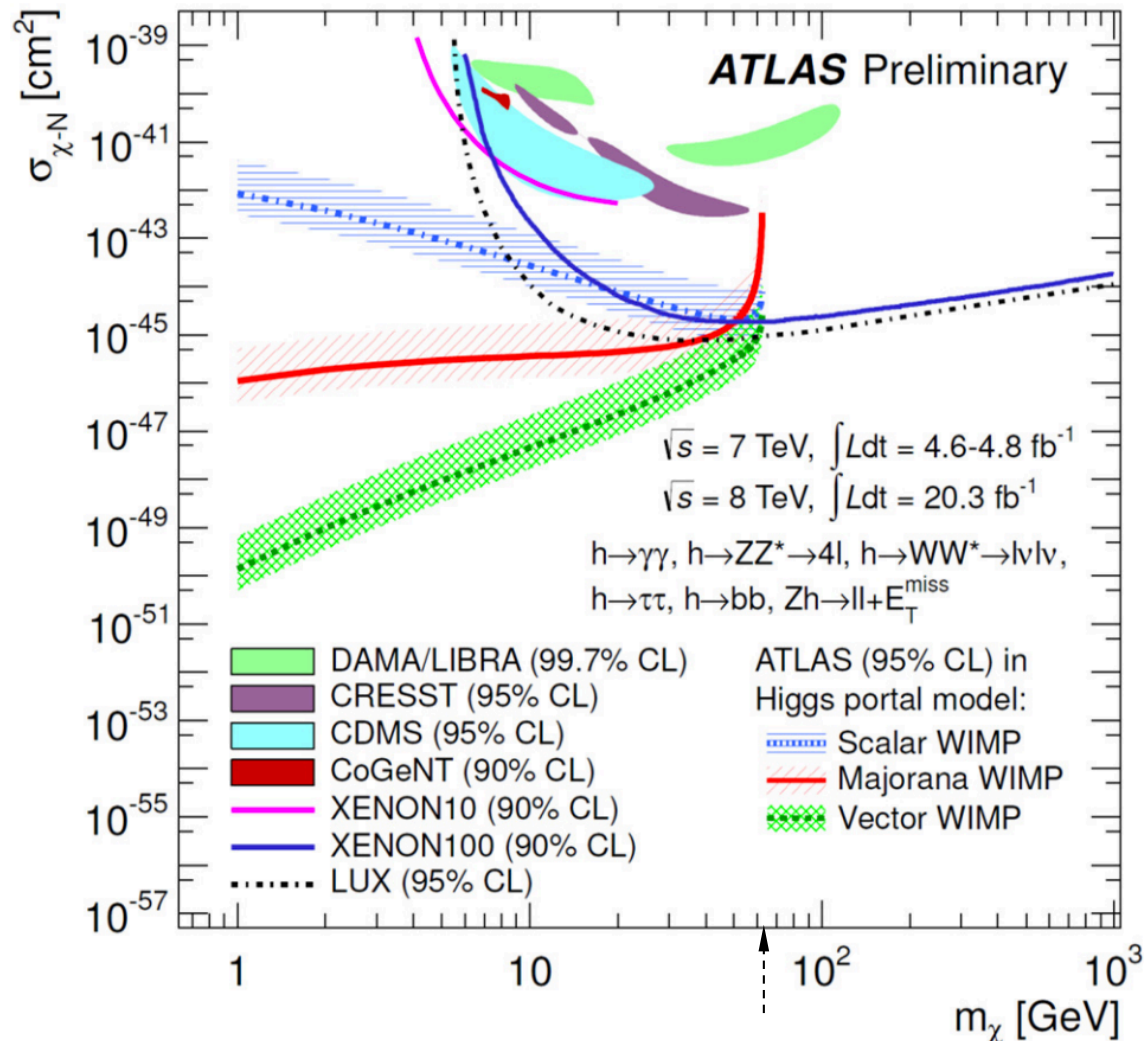


# Direct and indirect combined

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

- Shown by ATLAS at Moriond 2014.
- Combination
  - ▣  $\text{BR}_{\text{inv}} < 0.37 \text{ (0.39)}$  (95% CL), obs.(exp.)
  - ▣ Dominated by constraints from the visible decays.





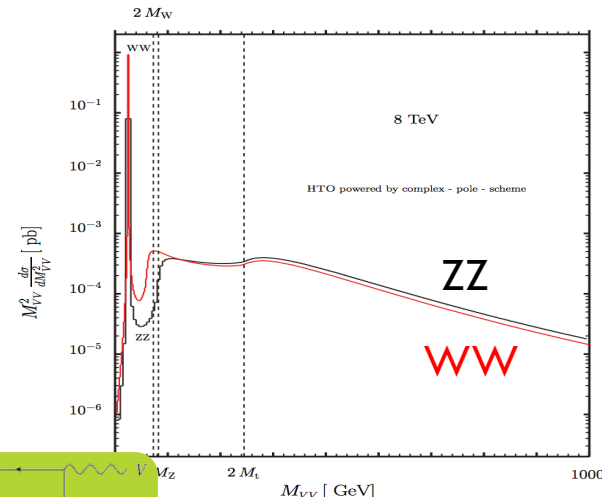
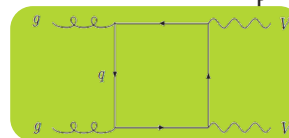
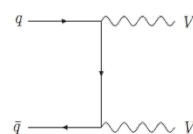
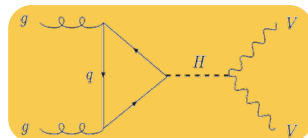
# Total width: interferometry

[arXiv:1206.4803] [arXiv:1211.3736] [arXiv:1305.3854]

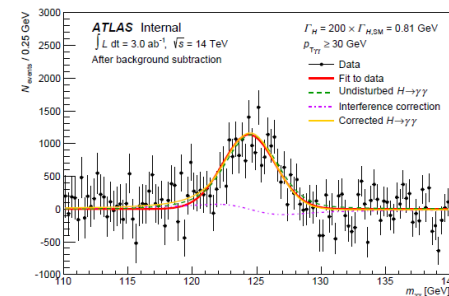
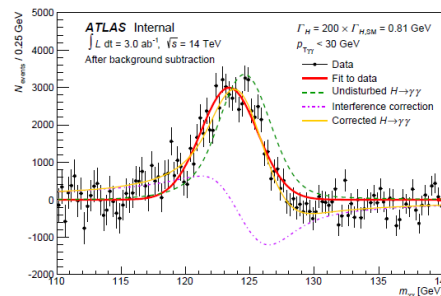
- Kauer-Passarino note that:

$$\left( \frac{d\sigma}{dM_{VV}} \right)_{\text{ZWA}} = \sigma_{H,\text{ZWA}} \frac{M_H \Gamma_H}{\pi} \frac{2M_{VV}}{(M_{VV}^2 - M_H^2)^2 + (M_H \Gamma_H)^2}$$

- $\sigma$  above ZZ threshold is independent of the on-shell total width.
- Caola-Melnikov propose analysis in  $ZZ \rightarrow 4\ell$  and estimate  $\Gamma_H < 90$  MeV for LHC Run1.
- $gg \rightarrow H^* \rightarrow VV$  off-shell production interferes with  $gg \rightarrow \text{non-}H \rightarrow VV$ .



- Dixon-Siu show how total width affects signal-background interference in  $\gamma\gamma$ .
  - ATLAS HL-LHC projection:  $\Gamma_H < 100$  MeV.



# $H^*$ : constraining the width of H

- Define  $r = \Gamma_H / \Gamma_H^{\text{SM}}$
- On-mass-shell we have

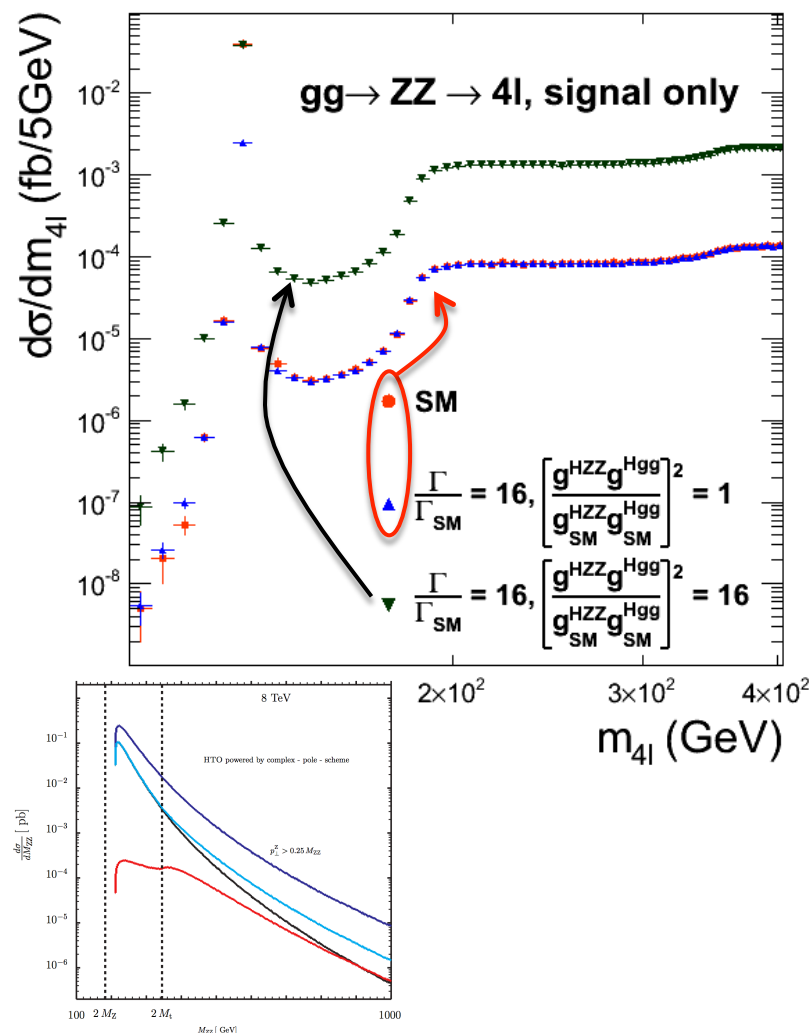
$$\sigma_{\text{gg} \rightarrow \text{H} \rightarrow \text{ZZ}}^{\text{on-peak}} = \frac{\kappa_g^2 \kappa_Z^2}{r} (\sigma \cdot \mathcal{B})_{\text{SM}} \equiv \mu (\sigma \cdot \mathcal{B})_{\text{SM}}$$

- Off-mass-shell there is no  $r$ :

$$\frac{d\sigma_{\text{gg} \rightarrow \text{H} \rightarrow \text{ZZ}}^{\text{off-peak}}}{dm_{\text{ZZ}}} = \kappa_g^2 \kappa_Z^2 \cdot \frac{d\sigma_{\text{gg} \rightarrow \text{H} \rightarrow \text{ZZ}}^{\text{off-peak, SM}}}{dm_{\text{ZZ}}} = \mu r \frac{d\sigma_{\text{gg} \rightarrow \text{H} \rightarrow \text{ZZ}}^{\text{off-peak, SM}}}{dm_{\text{ZZ}}}$$

- Can make inference on  $r$  assuming:
  - $\mu = 0.93 \pm 0.25$  (arXiv:1312.5353)
  - Only SM processes  $\rightarrow \text{ZZ}$ :

- $\text{gg} \rightarrow \text{H}^*$
- $\text{gg} = |\text{gg} \rightarrow \text{H}^*| + |\text{gg} \rightarrow \text{non-H}|^2$
- $|\text{gg} \rightarrow \text{H}^*|^2 + |\text{gg} \rightarrow \text{non-H}|^2$
- Total** =  $\text{gg} + \text{q}\bar{\text{q}}$

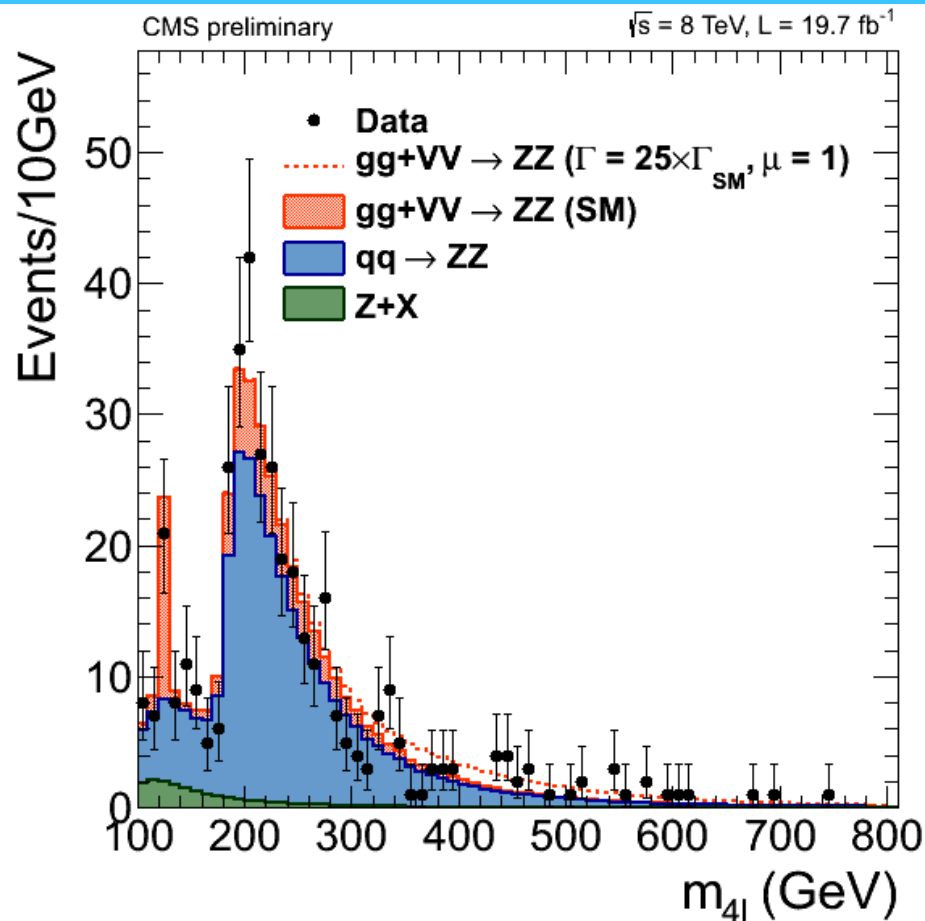


# $H^*$ : constraining the width of H

□ Two channels exploited:

□  $ZZ \rightarrow 4\ell$

■ 2D:  $m_{4\ell}$  + MECLA(gg vs.  $q\bar{q}$ )

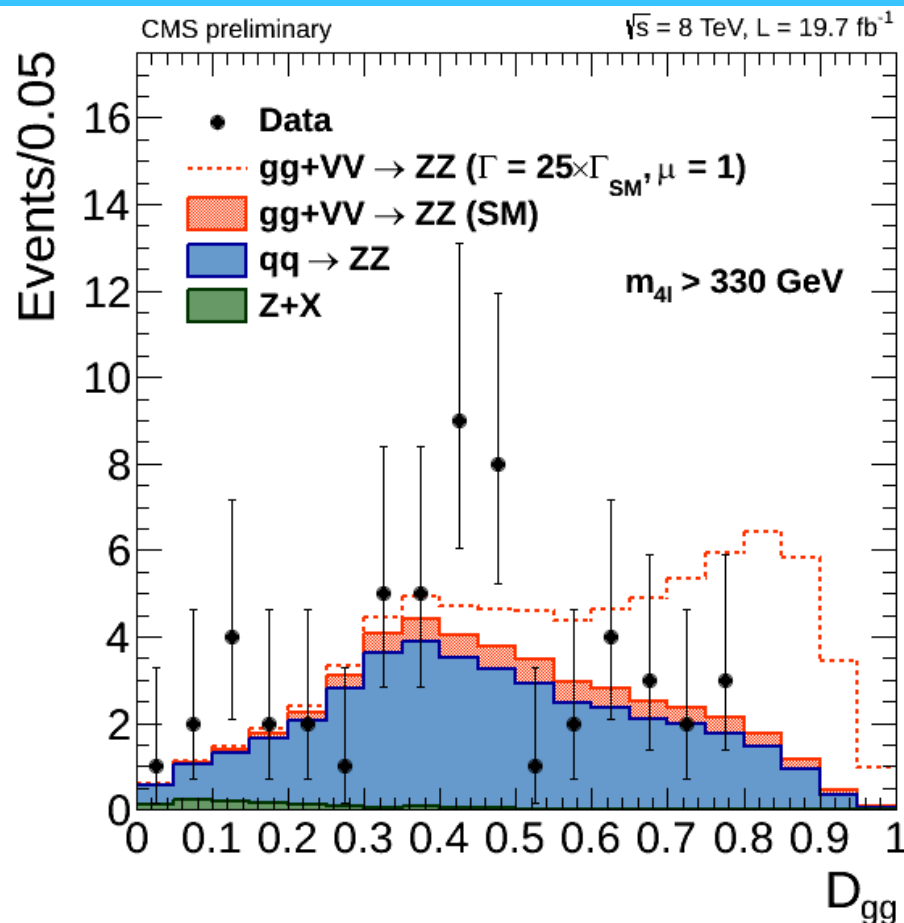


# $H^*$ : constraining the width of H

□ Two channels exploited:

□  $ZZ \rightarrow 4\ell$

■ 2D:  $m_{4\ell} + \text{MELA}(gg \text{ vs. } q\bar{q})$



# $H^*$ : constraining the width of H

## Two channels exploited:

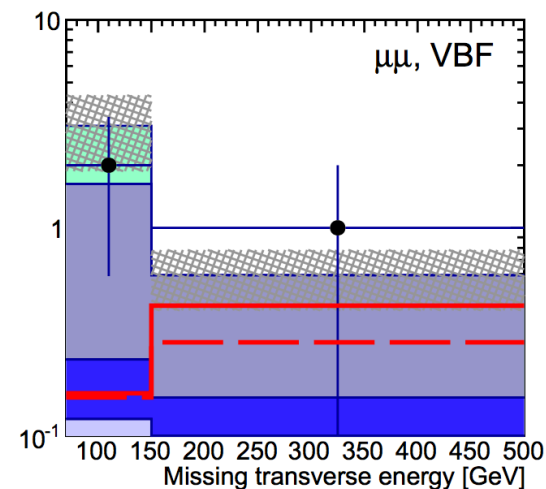
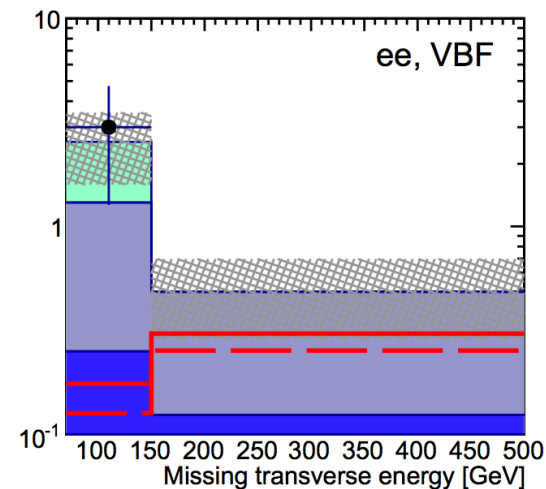
### $ZZ \rightarrow 4\ell$

- 2D:  $m_{4\ell} + \text{MELA}(gg \text{ vs. } q\bar{q})$

### $ZZ \rightarrow 2\ell 2\nu$

- MET shape in  $2j\text{-VBF}$ ,**
- $m_T$  shape in 0 jet, and  $\geq 1$  jet

CMS preliminary,  $\sqrt{s}=8.0$  TeV,  $|\mathcal{L}|=19.7 \text{ fb}^{-1}$



# $H^*$ : constraining the width of H

## Two channels exploited:

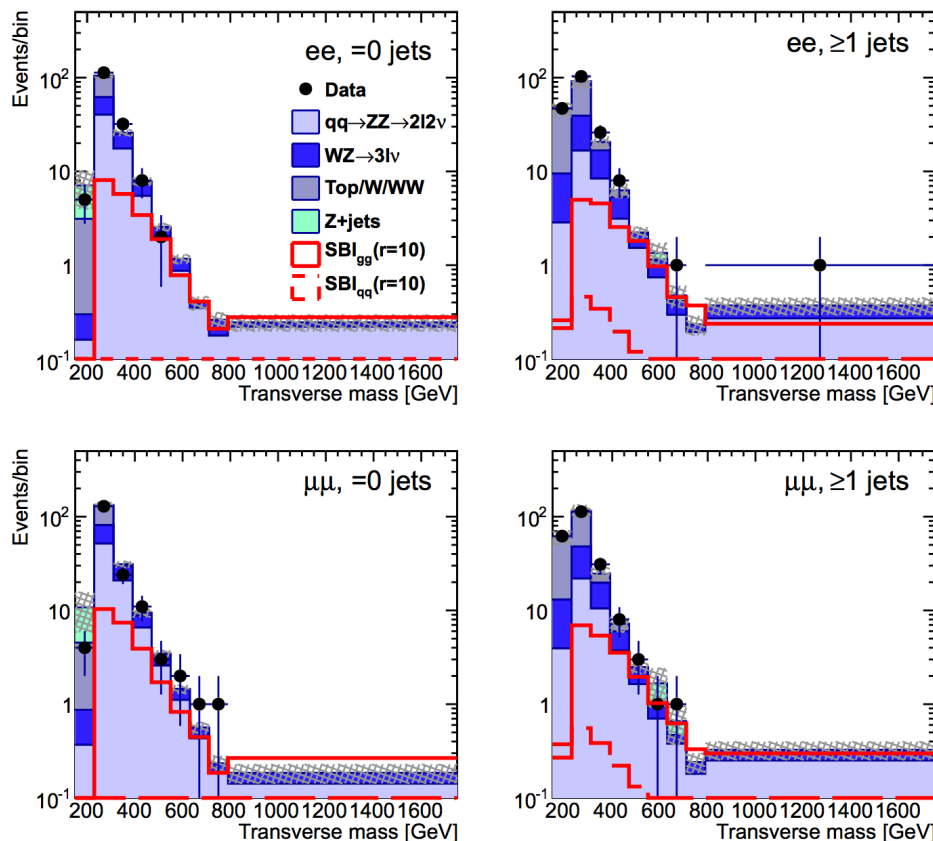
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CMS preliminary,  $\sqrt{s}=8.0$  TeV,  $|\mathcal{L}|=19.7 \text{ fb}^{-1}$



# $H^*$ : constraining the width of H

## Two channels exploited:

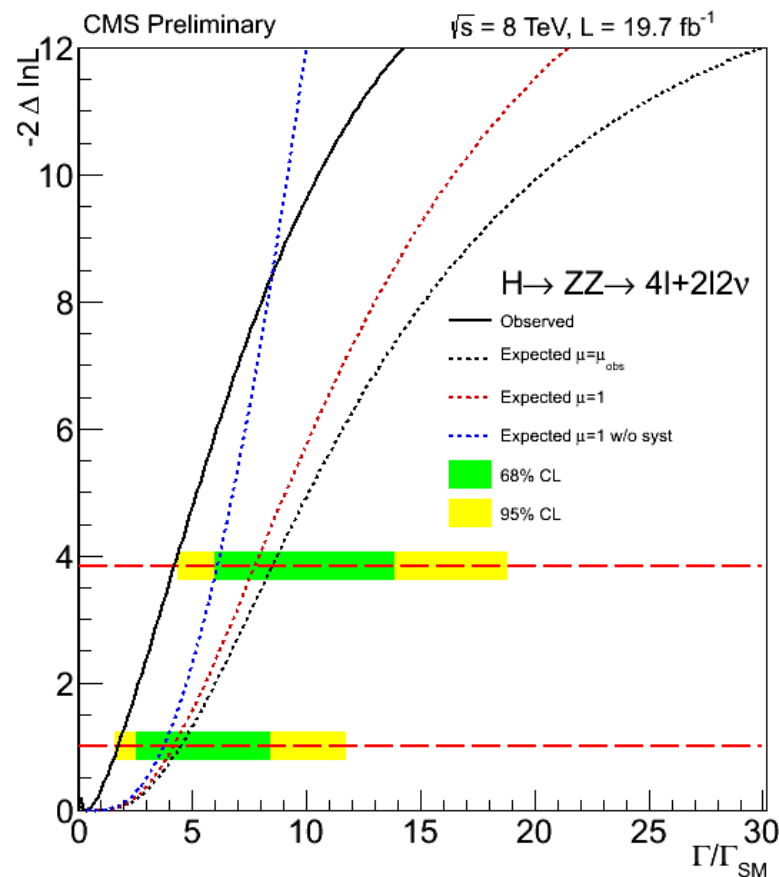
### $ZZ \rightarrow 4\ell$

- 2D:  $m_{4\ell} + \text{MELA}(gg \text{ vs. } q\bar{q})$

### $ZZ \rightarrow 2\ell 2\nu$

- MET shape in  $2j\text{-VBF}$ ,
- $m_T$  shape in 0 jet, and  $\geq 1$  jet

## Observed limit lower than expected ( $p=0.02$ )



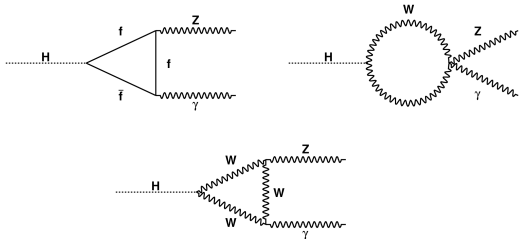
| Obs. (exp.)                                | $4\ell$        | $2\ell 2\nu$   | Combined      |
|--------------------------------------------|----------------|----------------|---------------|
| $\Gamma_H / \Gamma_H^{\text{SM}}$ (95% CL) | $< 6.6$ (11.5) | $< 6.4$ (10.7) | $< 4.2$ (8.5) |



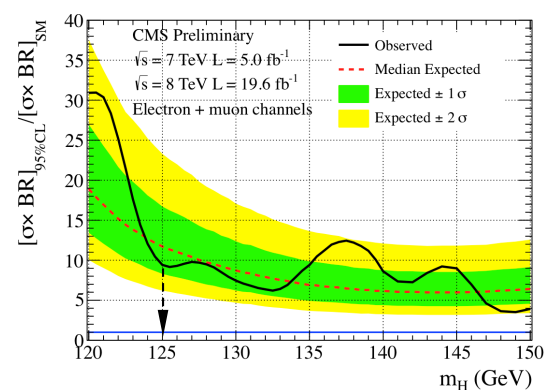
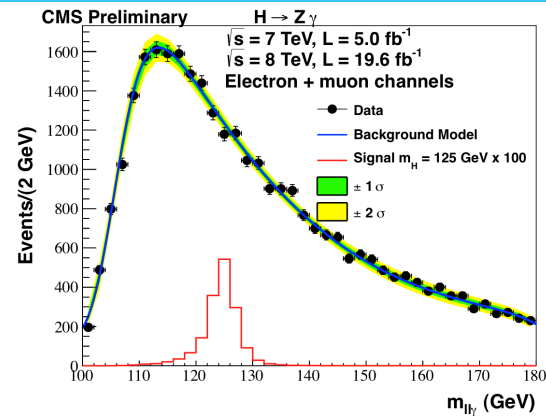
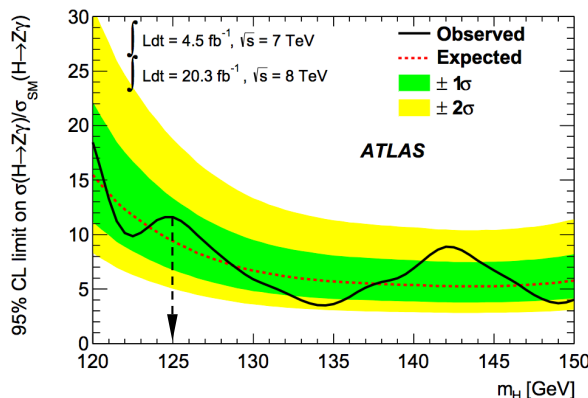
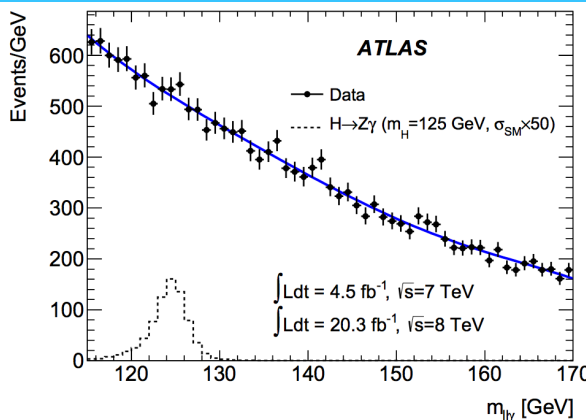
# ★ $H \rightarrow Z \gamma \rightarrow \ell\ell \gamma$

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[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.)

$\mu$  at 125 GeV (95% CL)

ATLAS

< 11 (9)

CMS

< 9 (12)

# From deviations to EFTs

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

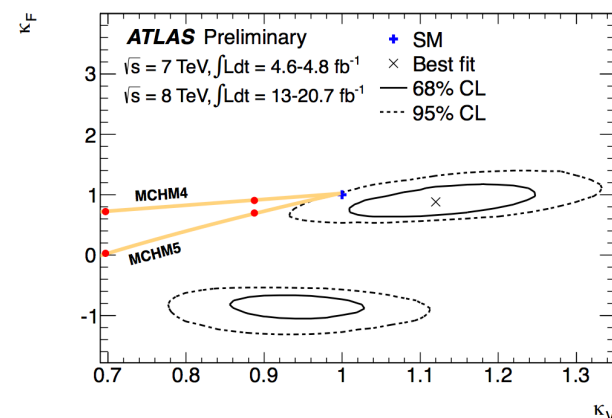
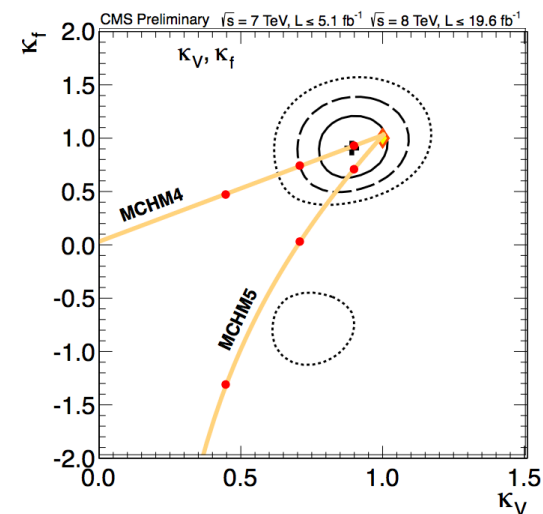
- Today we talk about deviations from the SMH.

- ▣ 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 ( $\tan \beta = 5$ ):

$$\frac{g_{hbb}}{g_{h_{SM}bb}} = \frac{g_{h\tau\tau}}{g_{h_{SM}\tau\tau}} \simeq 1 + 1.7\% \left( \frac{1 \text{ TeV}}{m_A} \right)^2$$

□ Composite Higgs:

$$\frac{g_{hff}}{g_{h_{SM}ff}} \simeq \frac{g_{hVV}}{g_{h_{SM}VV}} \simeq 1 - 3\% \left( \frac{1 \text{ TeV}}{f} \right)^2$$

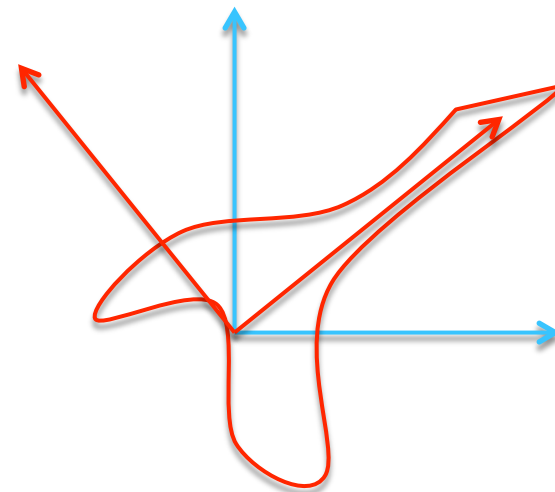
□ Top partners:

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

# 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?**



# EFT: one possible basis

- Multiple sectors affected:

- Electroweak precision data.**

- Anomalous triple gauge couplings.**

- Higgs only.**

- Global fit should be possible.

$$19 = 8 + 3 + 8$$

change Higgs  
kin. term:  
 $VV \rightarrow h$

$h \rightarrow \gamma\gamma$

$GG \rightarrow h$

$h \rightarrow f\bar{f}$

$$\begin{aligned} \mathcal{O}_H &= \frac{1}{2}(\partial^\mu |H|^2)^2 \\ \mathcal{O}_T &= \frac{1}{2}(H^\dagger \overleftrightarrow{D}_\mu H)^2 \\ \mathcal{O}_6 &= \lambda |H|^6 \\ \mathcal{O}_W &= \frac{ig}{2}(H^\dagger \sigma^a \overleftrightarrow{D}_\mu H) D^\nu W_{\mu\nu}^a \\ \mathcal{O}_B &= \frac{ig'}{2}(H^\dagger \overleftrightarrow{D}_\mu H) \partial^\nu B_{\mu\nu} \\ \mathcal{O}_{HW} &= ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W_{\mu\nu}^a \\ \mathcal{O}_{HB} &= ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu} \\ \mathcal{O}_{BB} &= g'^2 |H|^2 B_{\mu\nu} B^{\mu\nu} \\ \mathcal{O}_{GG} &= g_s^2 |H|^2 G_{\mu\nu}^A G^{A\mu\nu} \\ \mathcal{O}_{3W} &= \frac{1}{3!} g \epsilon_{abc} W_\mu^{a\nu} W_\nu^b W_\rho^c W^{\rho\mu} \end{aligned}$$

Affects  $h^3$ :  
It can be measured  
in the far future by  
 $GG \rightarrow h\bar{h}$

KHW-KHB

$h \rightarrow Z\gamma$

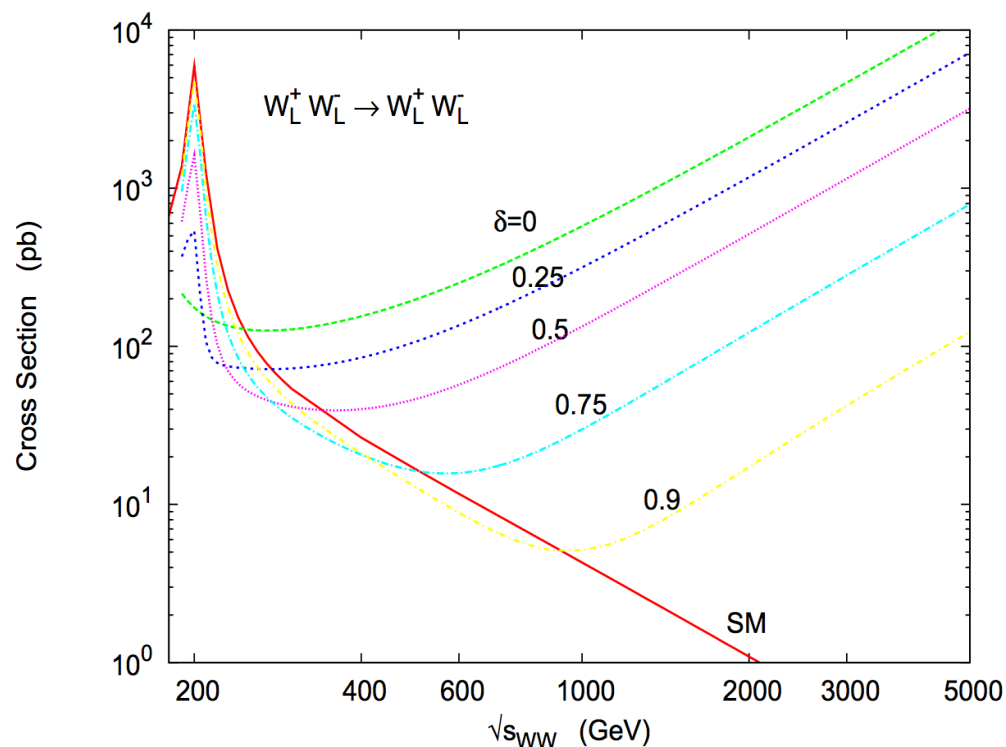
|                                                                                                                |                                                                                         |                                                                                                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

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

# 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  $\sim$  Energy.**



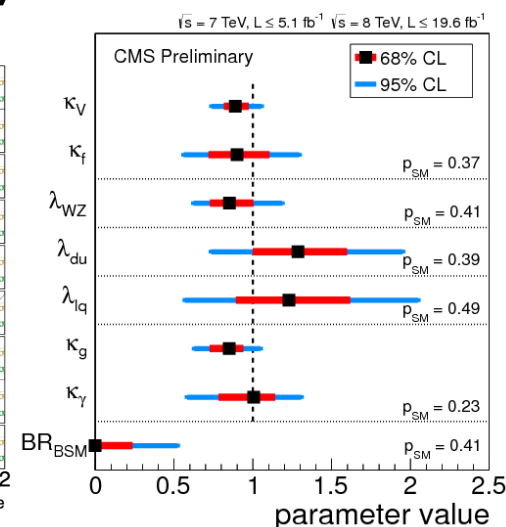
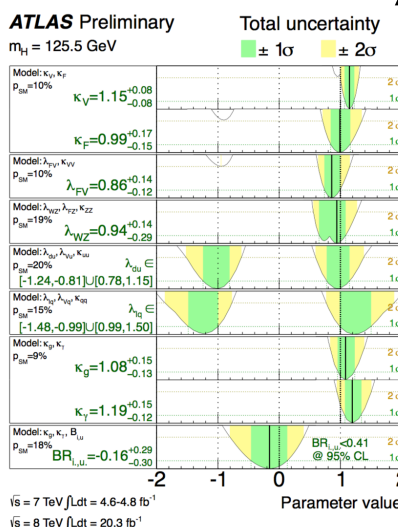
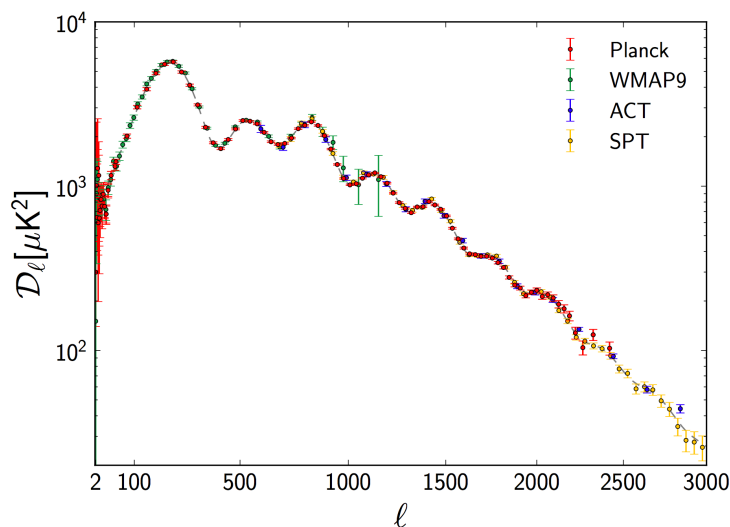
# Summary



- **LHC13: last chance before a “BSM desert”.**
  - Tevatron: Run I  $\rightarrow$  top discovery, Run II  $\rightarrow$  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  $\mathcal{K}$  fits to global EWK EFT fits.
  
- **We have a long way to go.**  
**All it takes is one deviation.**



- **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, ...**

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# References

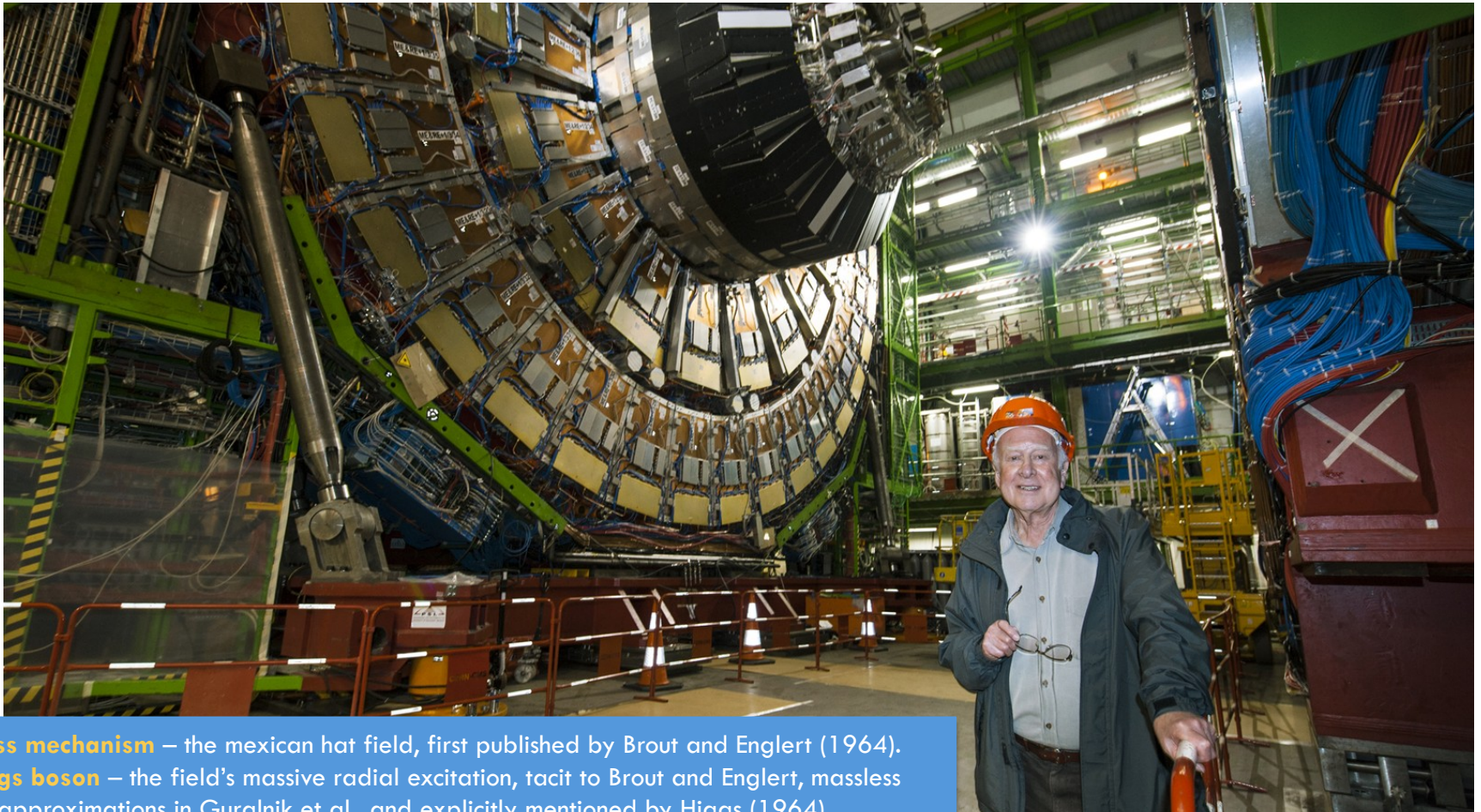
# “...and references therein.”

- 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>

# 67 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).



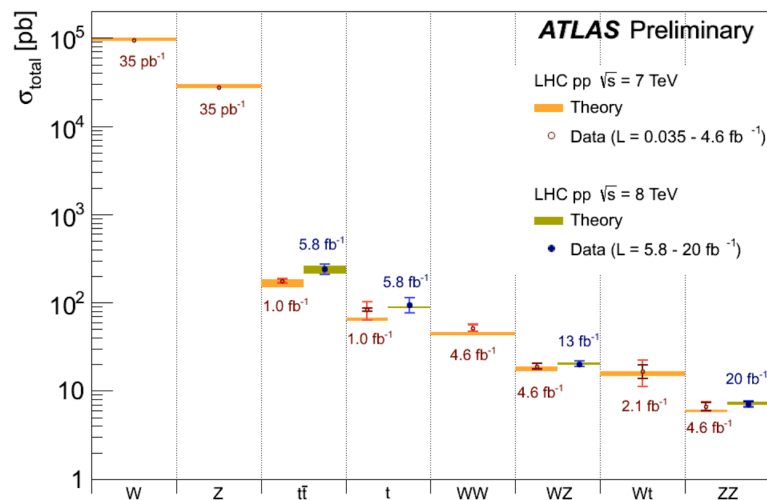
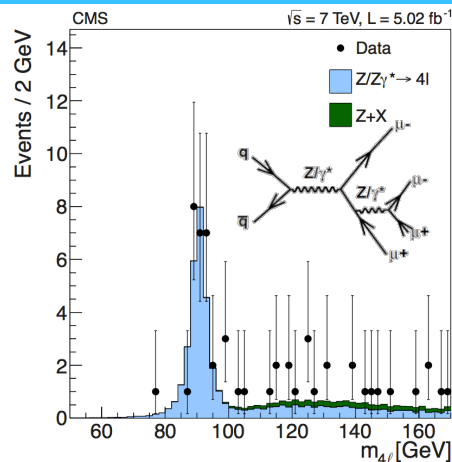
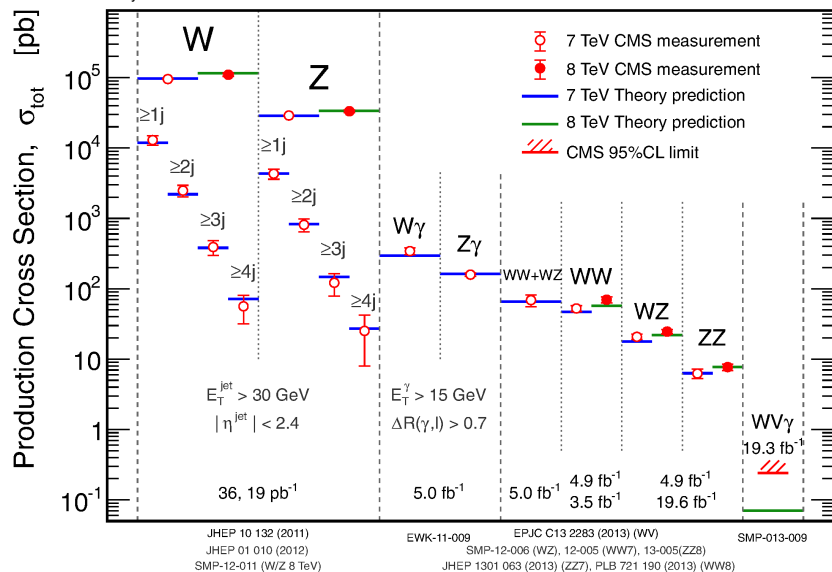
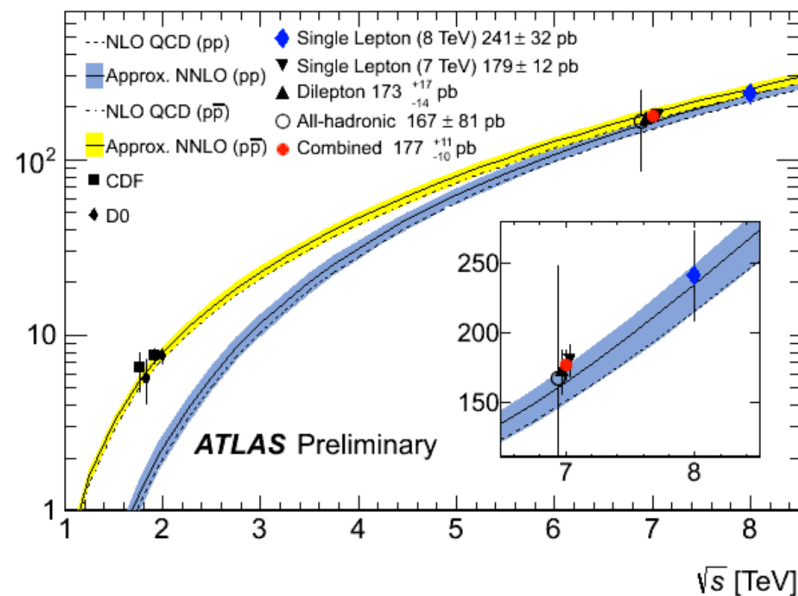
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# A tribute to those doing SM calculations

"Yesterday's discovery is today's calibration, and tomorrow's background." – V. L. Telegdi

July 2013

CMS

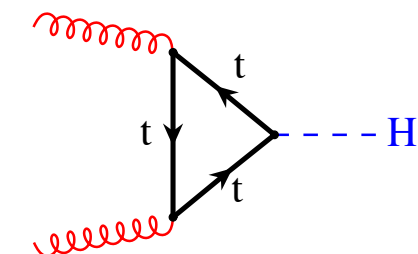
 $\sigma_{t\bar{t}}$  [pb][a.david@cern.ch](mailto:a.david@cern.ch)

Higgs and DM - Grenoble 2014

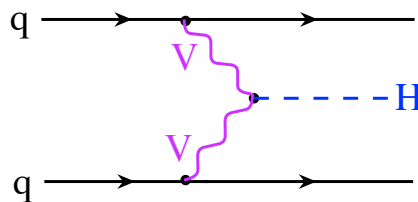
# How SM Higgses are born

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

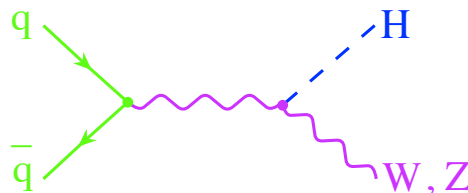
□ **Gluon fusion**



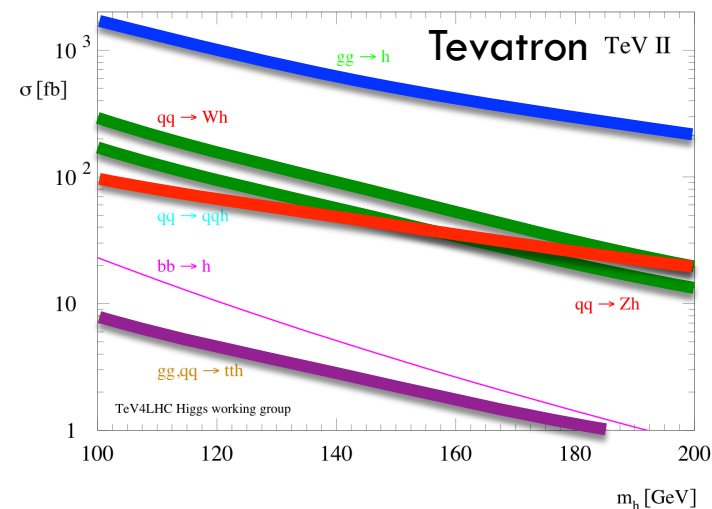
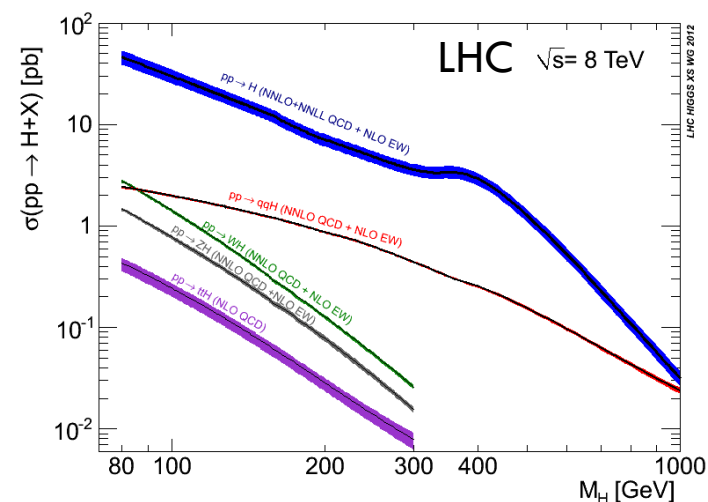
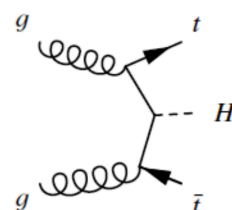
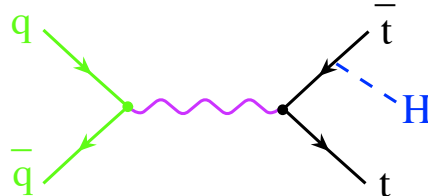
□ **VBF**



□ **VH**



□  **$t\bar{t}H$**

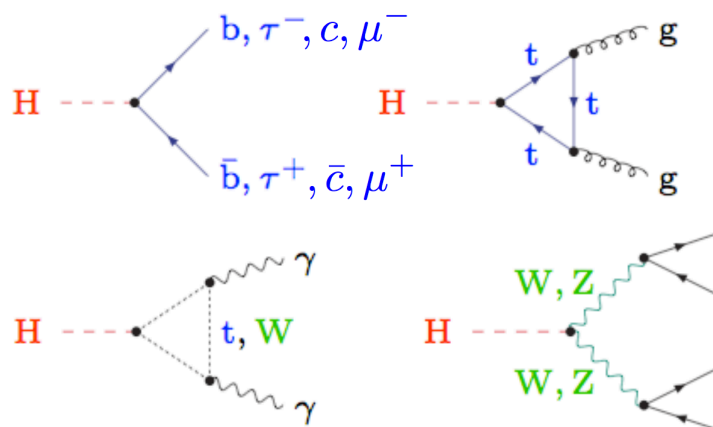




# How SM Higgses die

□ 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  $\Pi BR_i \rightarrow$

