Constraining new physics from Higgs measurements

Signal strengths, Global fits & Lilith

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Based on work with
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Imperial College London

Outline

- Motivations
- From experimental results to likelihood functions
- Lilith: a tool for constraining new physics from Higgs measurements
- Some applications
- Prospects for LHC Run II
- Conclusions

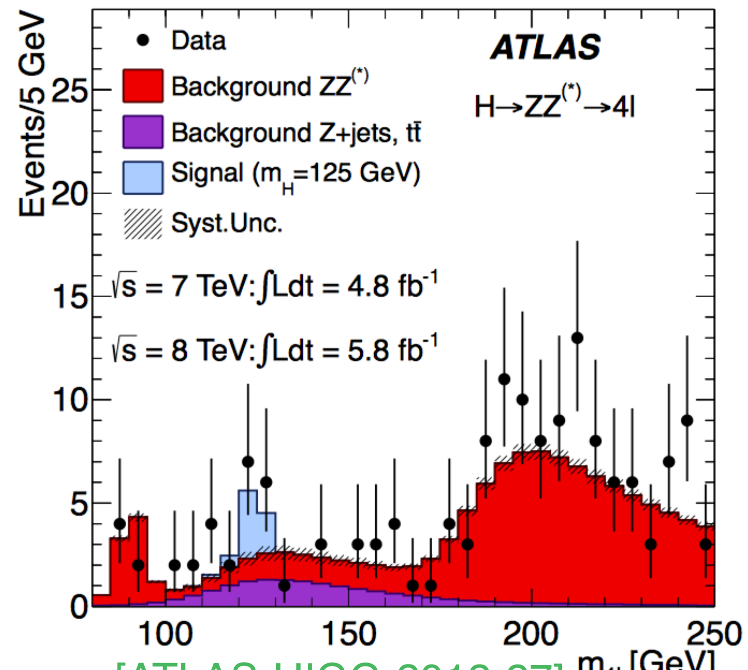
Motivations

The 2012 discovery of a **Standard Model (SM)-like Higgs boson** is the **major achievement** of the LHC Run I

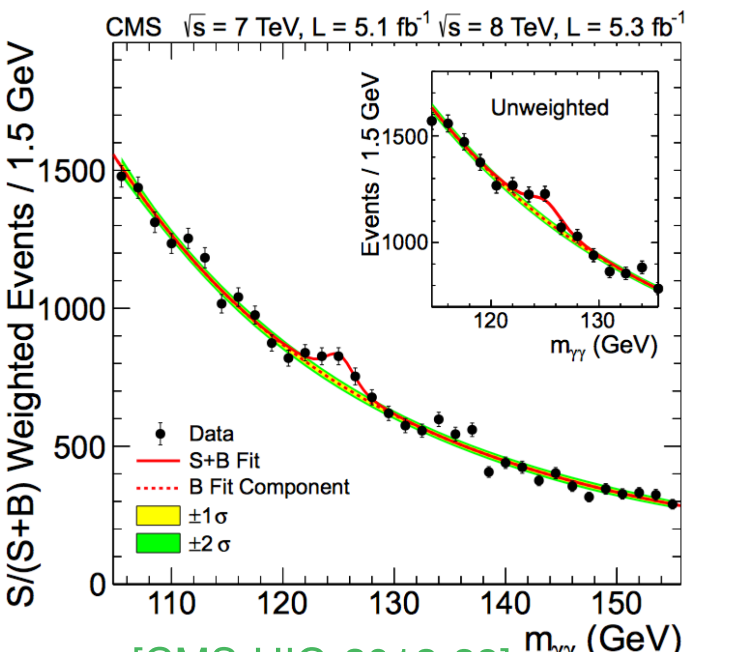
The wealth of accessible final states of a 125 GeV SM-Higgs boson allows for a **comprehensive** determination of the properties of this new state, already with the 7-8 TeV LHC datasets

Precise determination of these properties is crucial in the quest of unraveling the mechanism at the origin of the electroweak symmetry breaking

We want to use these results in order to impose **constraints** on a large class of new physics scenarios



[ATLAS-HIGG-2012-27]



[CMS-HIG-2012-28]

From experimental results to likelihood functions

Production/decay modes in the SM

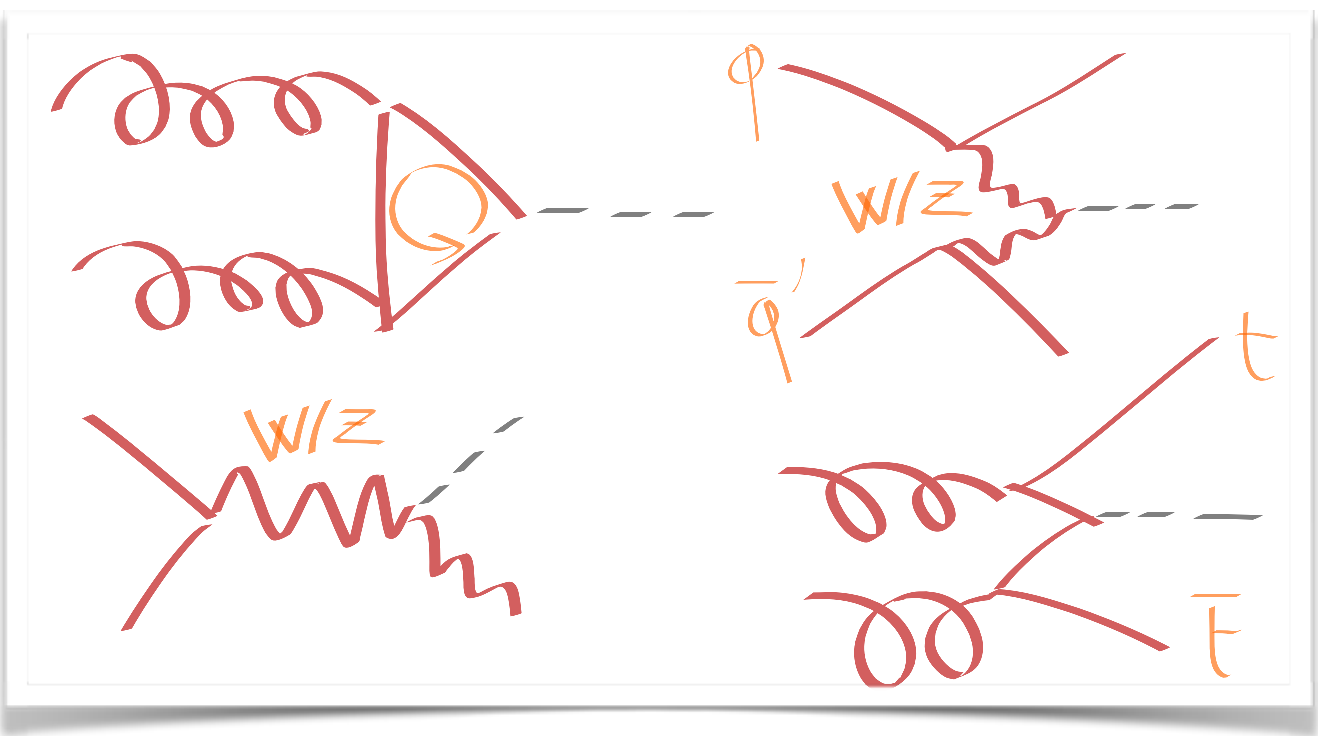
Signals strengths
Event categories
Unfolded production modes

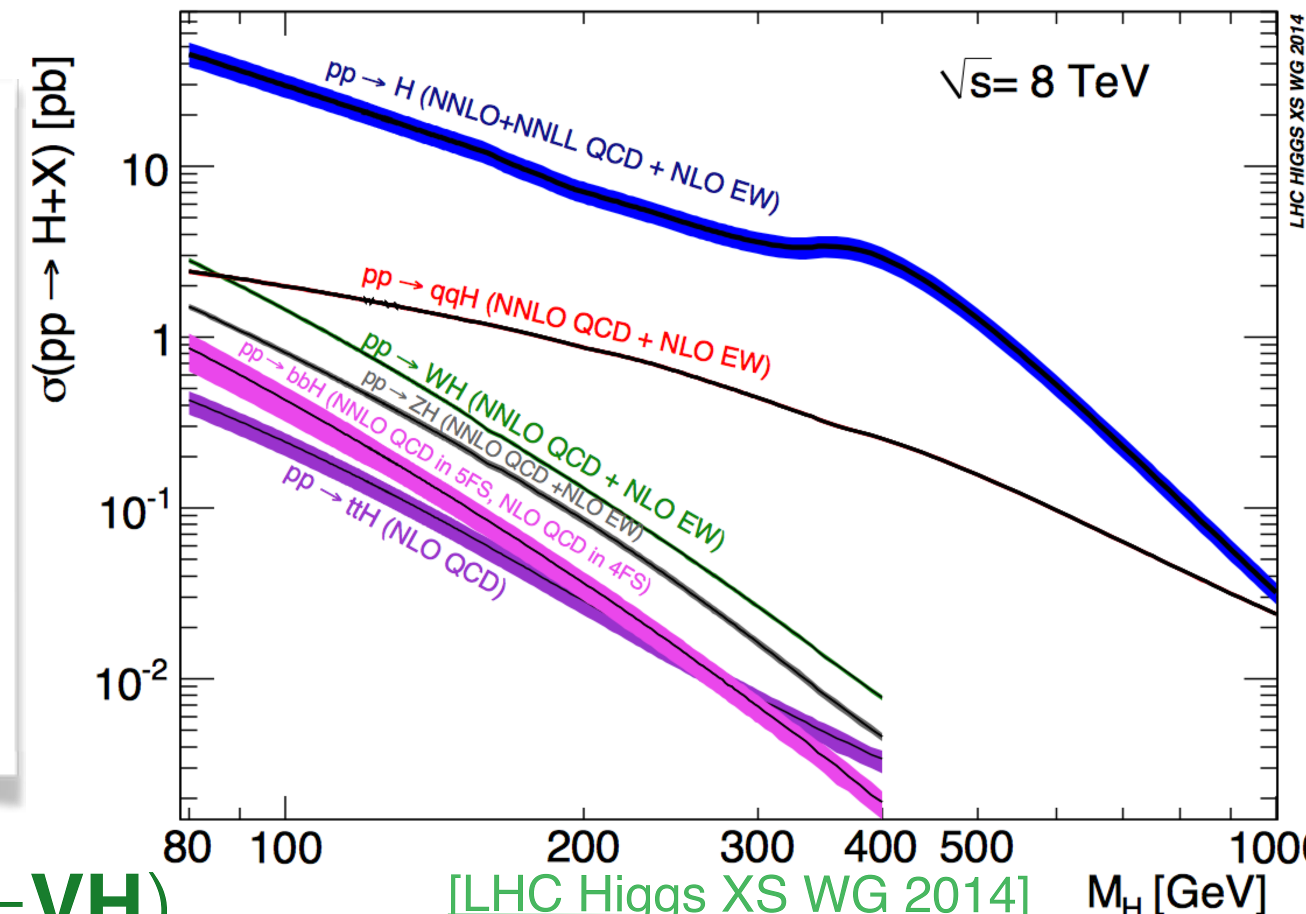
Constructing the likelihood function

SM Higgs production modes at the LHC

Vector boson fusion (**VBF**)

Gluon fusion (**ggH**)





[LHC Higgs XS WG 2014]

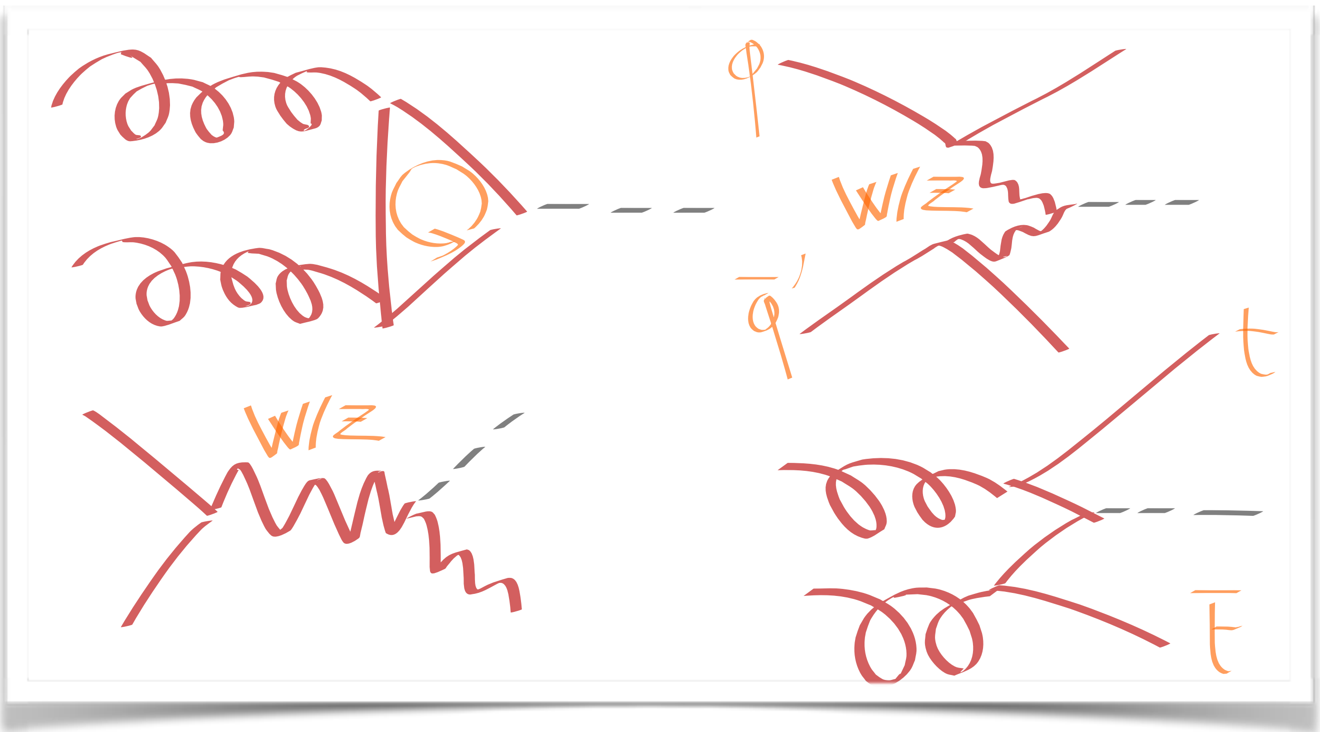
W/Z associated production (**WH+ZH=VH**)

$t\bar{t}$ associated production (**ttH**)

SM Higgs production modes at the LHC

Vector boson fusion (**VBF**)

Gluon fusion (**ggH**)



ggH: Loop-induced process; sensitive to new colored degrees of freedom

VBF, VH: determination of coupling to the EW gauge bosons, test of custodial symmetry

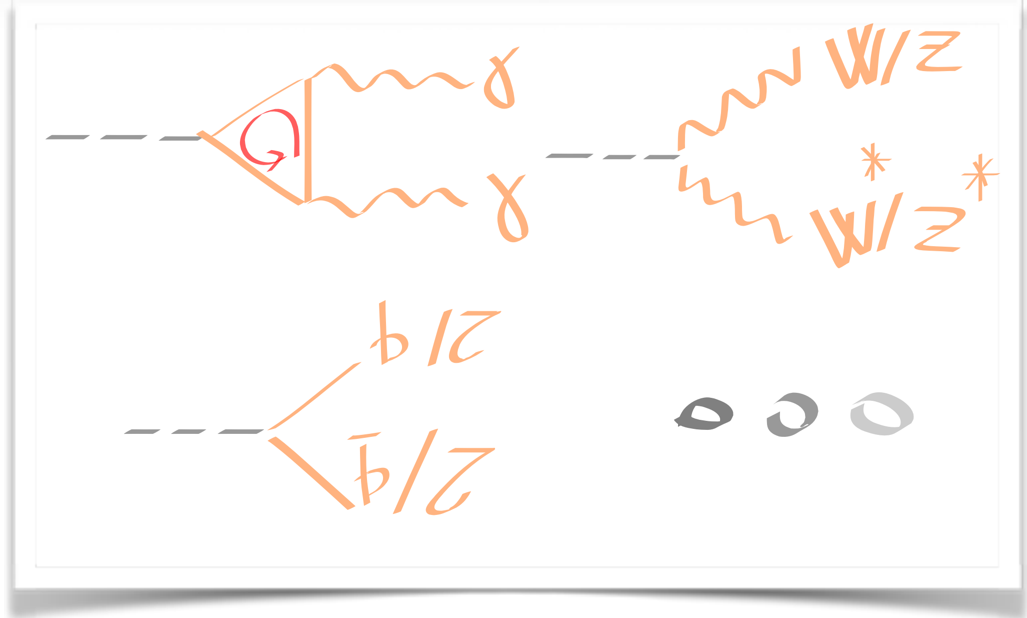
ttH: Direct access to the top Yukawa

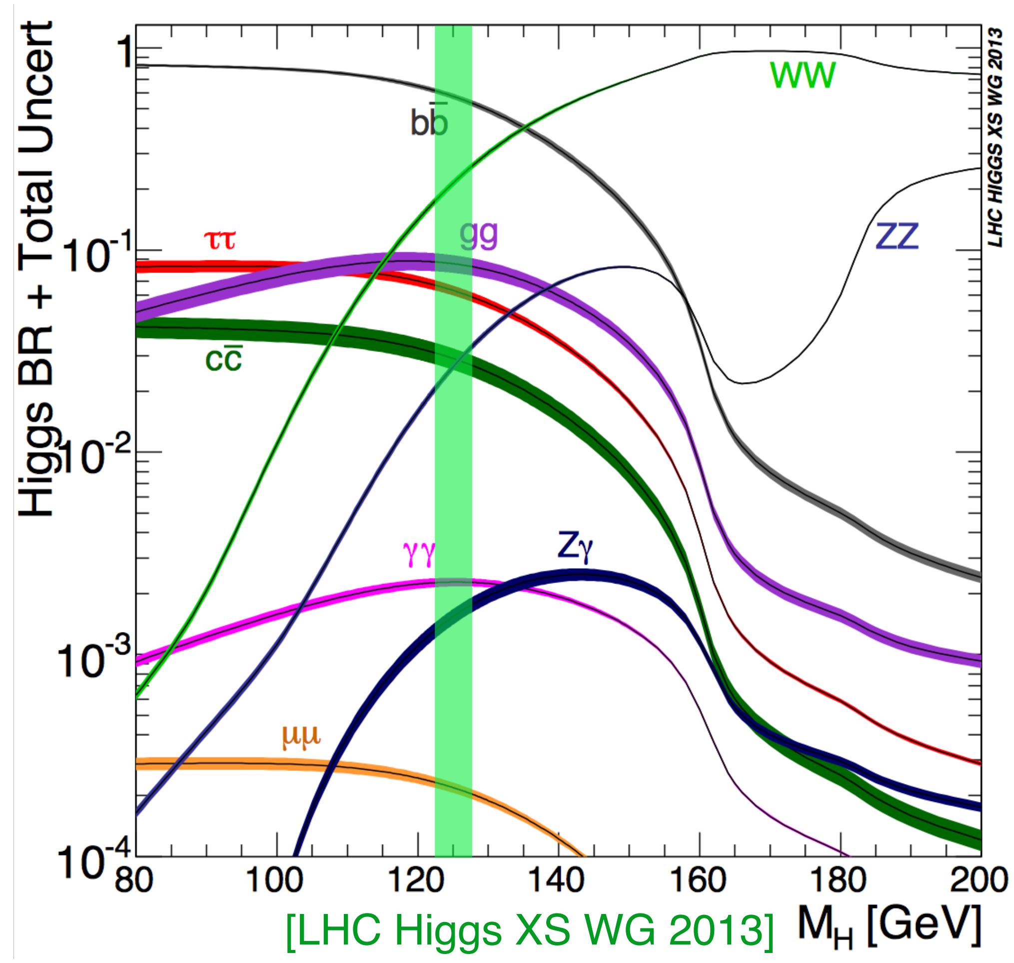
W/Z associated production (**WH+ZH=VH**)

$t\bar{t}$ associated production (**ttH**)

SM Higgs decay modes

- 125 GeV is very fortunate
- Gamma loop sensitive to electrically charged new degrees of freedom
- Small $\mathcal{B}(H \to \gamma\gamma) \sim \mathcal{O}(10^{-3})$ but very clean signature (discovery channel)
- $\mathcal{B}(H \to b\bar{b}) \sim 0.55$ dominates the total Higgs width $\Gamma_H^{125,\mathrm{SM}} = 4.1\ \mathrm{MeV}$
- Mass dependence of the Higgs couplings can be checked for gauge bosons and fermions (III, II)





Signal strengths

Experimental Higgs results are expressed in the form of **signals strengths**, for a set of selection criteria:

$$n^{\text{exp}} = \mu n_s^{\text{exp}} + n_b^{\text{exp}} \qquad \mu = \frac{\sigma \times A \times \epsilon}{[\sigma \times A \times \epsilon]^{\text{SM}}}$$

Assuming that:

-Observed signal is a sum of the SM ones: $\sigma = \sum_{X,Y} \sigma(X)\mathcal{B}(H \to Y)$

-Acceptance, efficiency same as in the SM: $(A \times \epsilon)_{X,Y} = (A \times \epsilon)^{\text{SM}}_{X,Y}$

the signal strength read

$$\mu = \sum_{X,Y} \text{eff}_{X,Y} \frac{\sigma(X)\mathcal{B}(H \to Y)}{\sigma(X)^{\text{SM}}\mathcal{B}(H \to Y)^{\text{SM}}}$$

⇒ Allow for **combination** of signal strengths from various searches

⇒ Possibility to assess compatibility of experimental results with a given model by means of a **global fit**

⇒ Construction of a **likelihood function** out of these results

Signal strengths: event categories (I/II)

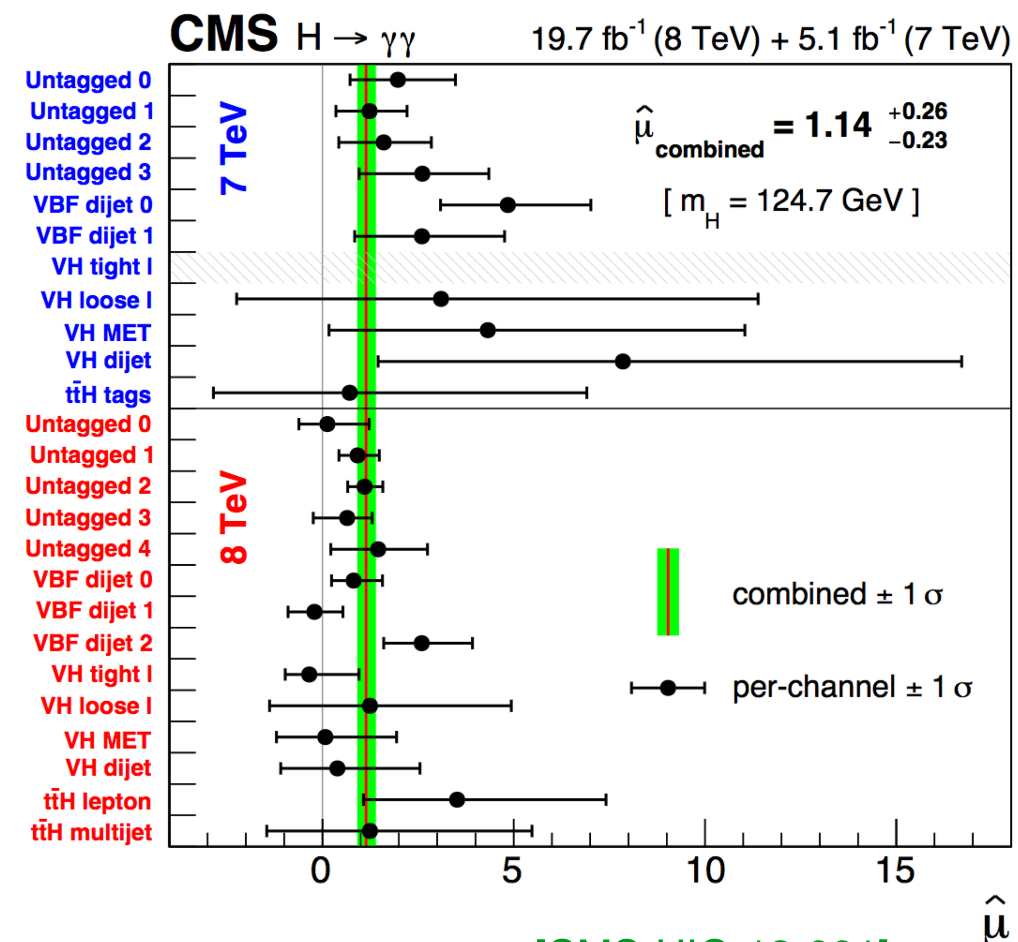
Experimental searches are split into several **event categories** designed to optimize sensitivity to a particular production mode

The signal strength best-fit and the 68% confidence level (CL) interval are reported in each category: $\hat{\mu}^{+\Delta\hat{\mu}^{+}}_{-\Delta\hat{\mu}^{-}}$

To use this information, the signal composition in each category has to be known

For each category, an approximate likelihood function can be constructed:

$$-2\log L(\mu) = \begin{cases} \left(\frac{\mu-\hat{\mu}}{\Delta\mu^{-}}\right)^2 & \text{if } \mu < \hat{\mu}\,, \\ \left(\frac{\mu-\hat{\mu}}{\Delta\mu^{+}}\right)^2 & \text{if } \mu > \hat{\mu}\,, \end{cases}$$



[CMS-HIG-13-001]

Event classes		Expected SM Higgs boson signal yield (m_H=125 GeV)								Bkg. (GeV^{-1})
		Total	ggH	VBF	WH	ZH	tt̄H	σ_{eff} (GeV)	σ_{HM} (GeV)	
7 TeV 5.1 fb^{-1}	Untagged 0	5.8	**79.8%**	9.9%	6.0%	3.5%	0.8%	1.11	0.98	11.0
	Untagged 1	22.7	**91.9%**	4.2%	2.4%	1.3%	0.2%	1.27	1.09	69.5
	Untagged 2	27.1	**91.9%**	4.1%	2.4%	1.4%	0.2%	1.78	1.40	135.
	Untagged 3	34.1	**92.1%**	4.0%	2.4%	1.3%	0.2%	2.36	2.01	312.
	VBF dijet 0	1.6	19.3%	**80.1%**	0.3%	0.2%	0.1%	1.41	1.17	0.5
	VBF dijet 1	3.0	38.1%	**59.5%**	1.2%	0.7%	0.4%	1.65	1.32	3.5
	VH tight ℓ	0.3	—	—	**77.2%**	20.6%	2.2%	1.61	1.31	0.1
	VH loose ℓ	0.2	3.6%	1.1%	**79.1%**	15.2%	1.0%	1.63	1.32	0.2
	VH $E_{\mathrm{T}}^{\mathrm{miss}}$	0.3	4.5%	1.1%	41.5%	**44.6%**	8.2%	1.60	1.14	0.2
	VH dijet	0.4	27.1%	2.8%	**43.7%**	24.3%	2.1%	1.54	1.24	0.5
	tt̄H tags	0.2	3.1%	1.1%	2.2%	1.3%	**92.3%**	1.40	1.13	0.2

Signal strengths: event categories (II/II)

Signal decomposition not always available

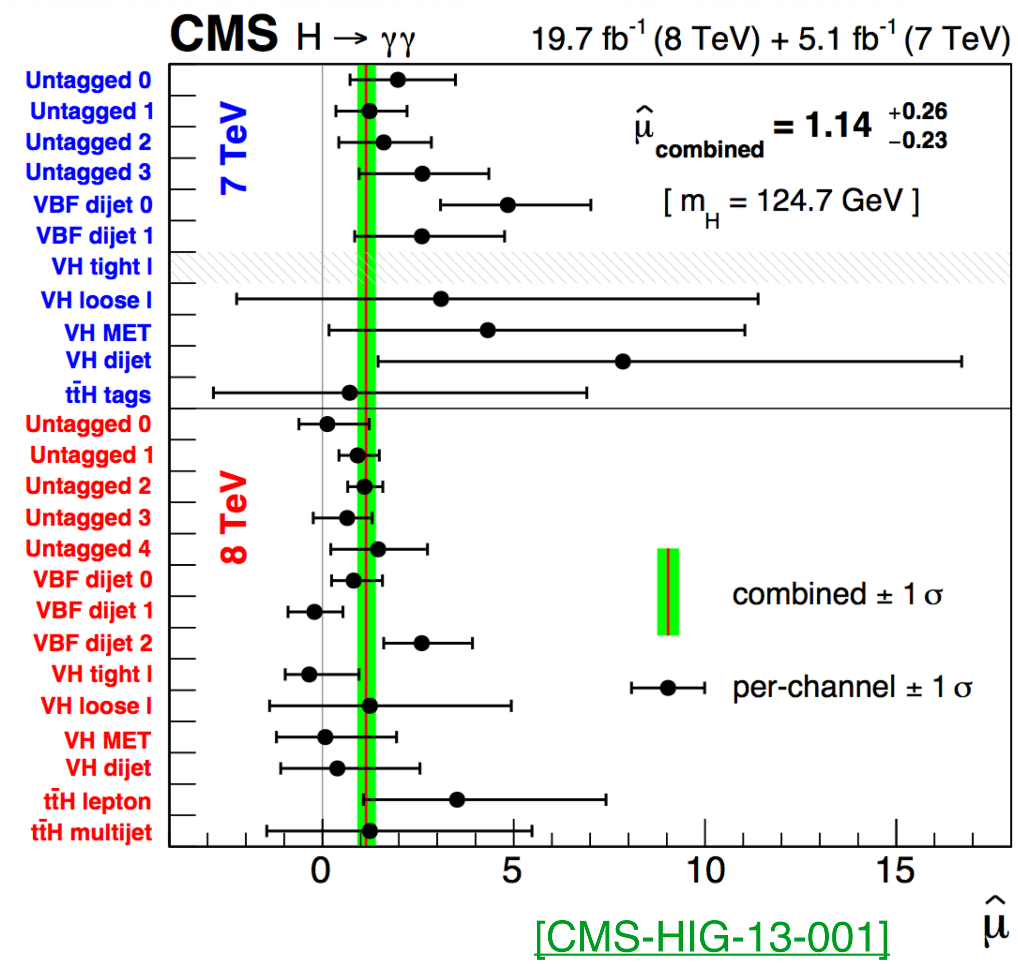
- In principle obtainable from a MC simulation but very difficult in practice

The full likelihood for every category is not available → use a gaussian approximation

Combining signal strengths for all categories:

- Correlations not available
- Simple approximation can be used:

$$L(\boldsymbol{\mu}) = \prod_{i=1}^{n} L(\mu_i) \quad \Rightarrow \quad \chi^2(\boldsymbol{\mu}) = \sum_{i=1}^{n} \chi^2(\mu_i) = \sum_{i=1}^{n} \left(\frac{\mu_i - \hat{\mu}_i}{\Delta \mu_i} \right)^2$$



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Common systematic uncertainties

- Experimental uncertainties:

  Reconstruction of the same final state, luminosity uncertainty …

- Theoretical uncertainties:

  PDF, QCD scale …

<u>In the case of the event category signal strengths:</u>

- If all measurements are well within the Gaussian regime, the likelihood has a simple, very compact expression:

$$-2\log L(\boldsymbol{\mu}) = \chi^2(\boldsymbol{\mu}) = (\boldsymbol{\mu} - \hat{\boldsymbol{\mu}})^T V^{-1} (\boldsymbol{\mu} - \hat{\boldsymbol{\mu}})$$

- Off-diagonal entries of V^{-1} are however not provided

Table 3: List of nuisance parameters for systematic uncertainties assumed to be 100% correlated between ATLAS and CMS.

PDF+α_s uncertainties

nuisance	groups of physics processes
pdf_gg	$gg \to H$, $t\bar{t}H$, VQQ, $t\bar{t}$, tW, tb (s-channel), $gg \to VV$
pdf_qqbar	VBF H, VH, V, VV, $\gamma\gamma$
pdf_qg	tbq (t-channel), γ+jets

QCD scale uncertainties

nuisance	groups of physics processes
QCDscale_ggH	total inclusive $gg \to H$
QCDscale_ggH1in	inclusive $gg/qg \to H + \geq 1$ jets
QCDscale_ggH2in	inclusive $gg/qg \to H + \geq 2$ jets
QCDscale_qqH	VBF H
QCDscale_VH	associate VH
QCDscale_ttH	$t\bar{t}H$
QCDscale_V	W and Z
QCDscale_VV	WW, WZ, and ZZ up to NLO
QCDscale_ggVV	$gg \to WW$ and $gg \to ZZ$
QCDscale_ZQQ	Z with heavy flavor $q\bar{q}$-pair
QCDscale_WQQ	W with heavy flavor $q\bar{q}$-pair
QCDscale_ttbar	$t\bar{t}$, single top productions are lumped here for simplicity

Phenomenological uncertainties

nuisance	groups of physics processes
UEPS	all processes sensitive to modeling of UE and PS

Acceptance uncertainties

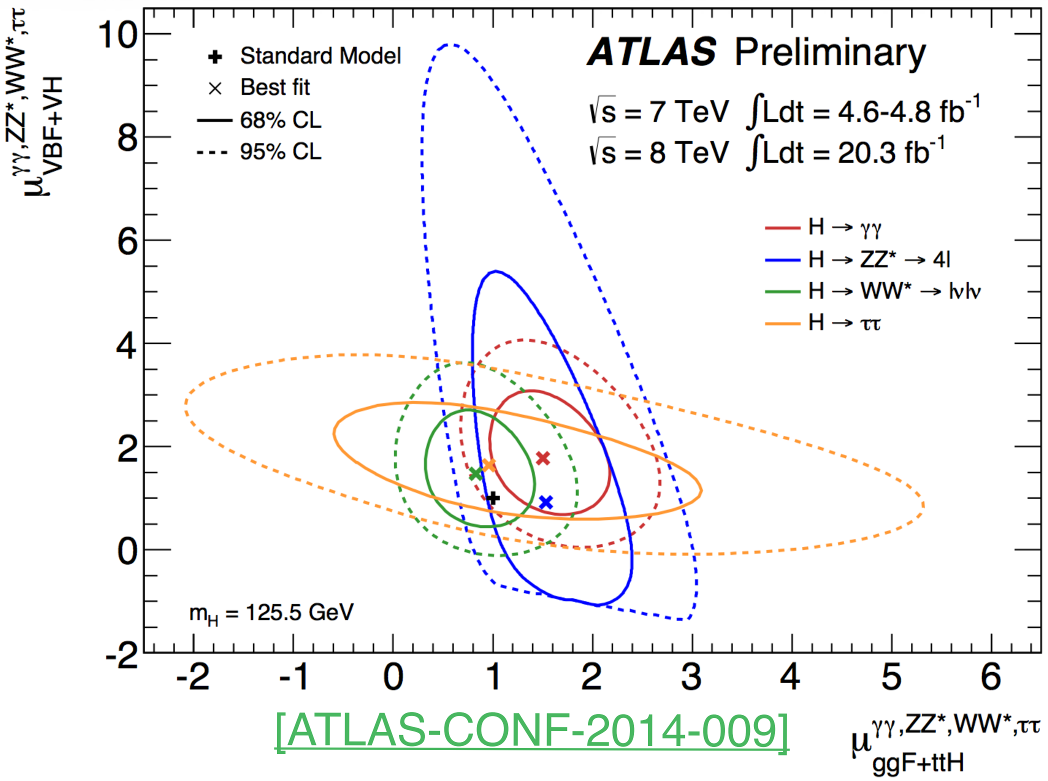
nuisance	comments
QCDscale_WW_EXTRAP	extrap. factor α for deriving WW bkgd in HWW analysis
QCDscale_ttbar_EXTRAP	extrap. factor α for deriving $t\bar{t}$ bkgd in HWW analysis

Instrumental uncertainties

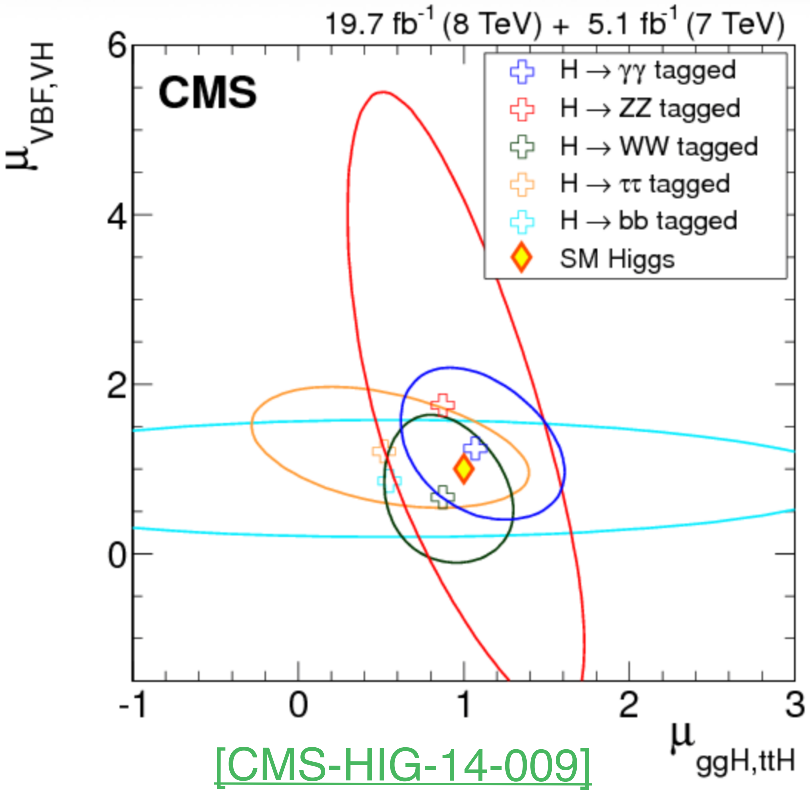
nuisance	comments
lumi	uncertainties in luminosities

[CMS-NOTE-2011-005;ATL-PHYS-PUB-2011-11]

Signal strengths: unfolded production modes (I/II)



[ATLAS-CONF-2014-009]



[CMS-HIG-14-009]

$$\mu(X,Y) = \frac{\sigma(X)\mathcal{B}(H \to Y)}{\sigma(X)^{\mathrm{SM}}\mathcal{B}(H \to Y)^{\mathrm{SM}}}$$

- Signal strengths in $\mu(X,Y)$ vs $\mu(X',Y)$ planes: production modes unfolded from event categories. Usually $X = \mathrm{ggH{+}ttH}$, $X' = \mathrm{VBF{+}VH}$
- All systematic uncertainties for a given channel taken into account
- 68% (95%) CL contours provided, *i.e.* isolines of $-2\log L$

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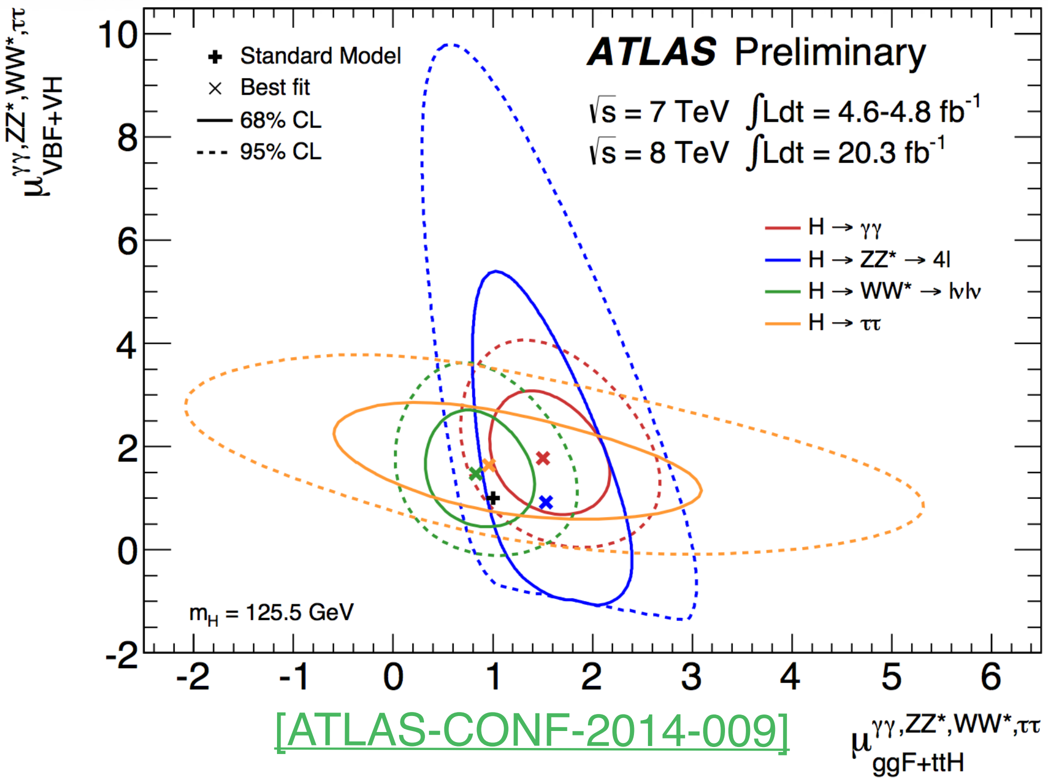

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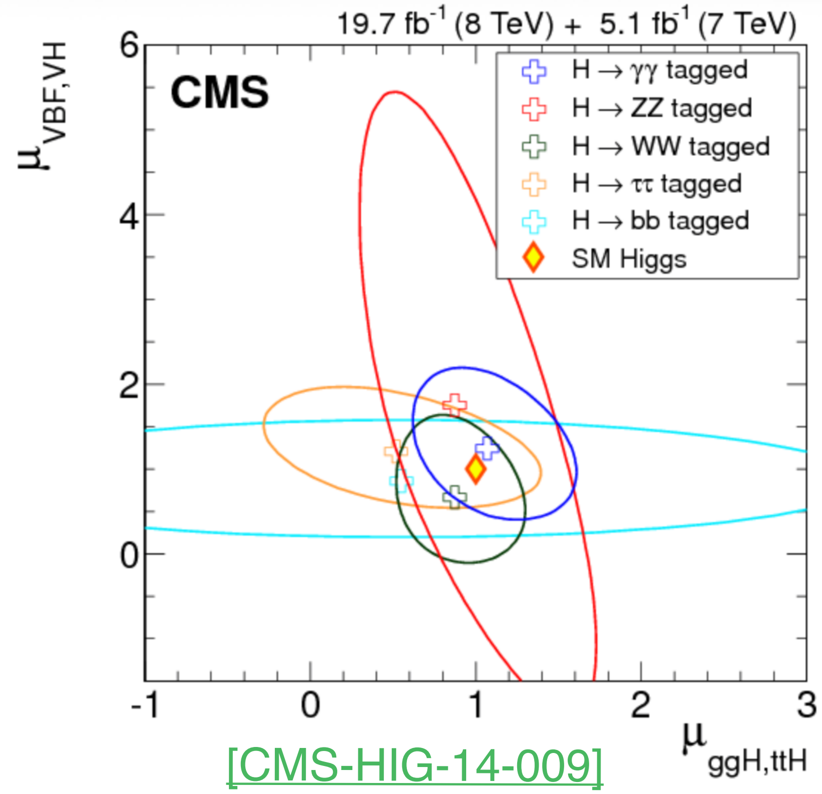

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- All systematic uncertainties for a given channel taken into account
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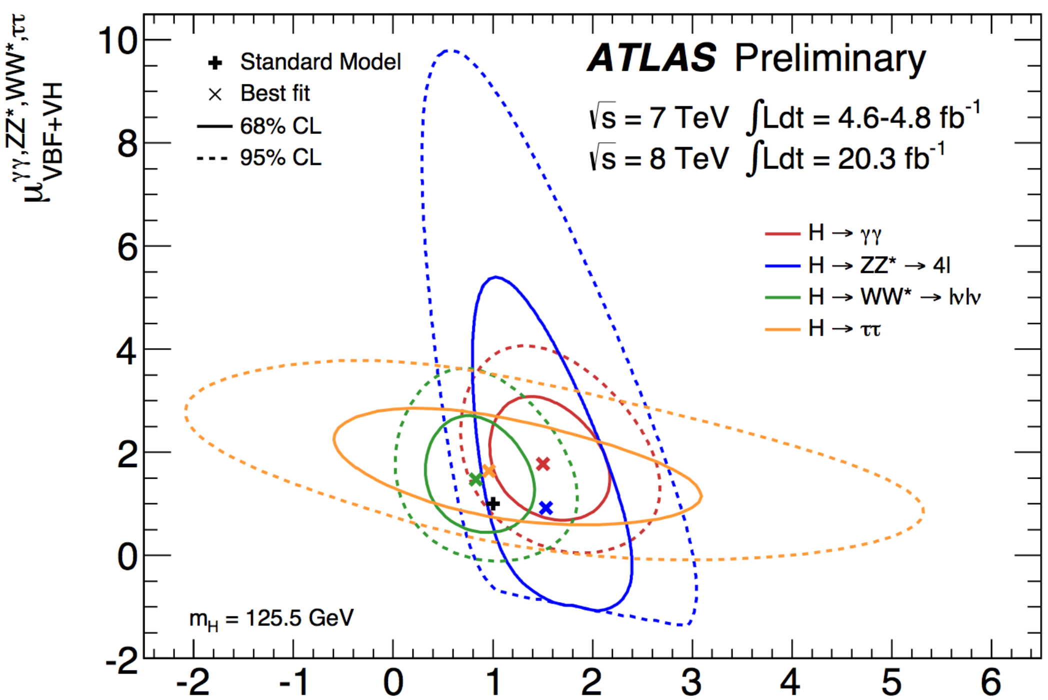
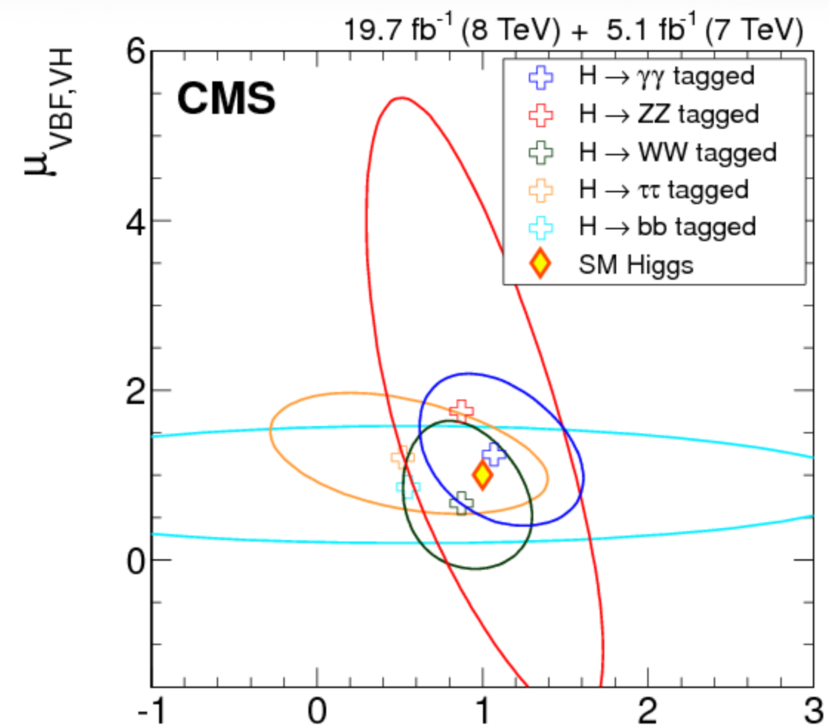
Primary experimental input used for the construction of our likelihood ✓

Signal strengths: unfolded production modes (II/II)



[ATLAS-CONF-2014-009]



[CMS-HIG-14-009]

- Using this information requires reconstructing $-2\log L$ in the full plane
- The bivariate normal approximation is usually well motivated:

[Cacciapaglia, Deandrea, Drieu La Rochelle, Flament] [arXiv:1210.8120v2]

$$-2\log L(\boldsymbol{\mu}) = (\boldsymbol{\mu} - \hat{\boldsymbol{\mu}})^T C^{-1} (\boldsymbol{\mu} - \hat{\boldsymbol{\mu}}) \qquad C^{-1} = \begin{pmatrix} a & b \\ b & c \end{pmatrix}$$

- Best-fit point and covariance matrix obtained from a fit to 68% CL contour
- If available the 95% CL contour can be used for validation (see later)

A step forward: digital likelihoods

ATLAS $H \to \gamma\gamma,\ WW,\ ZZ$ [ATLAS-HIGG-2013-002]

Informations | Références (121) | Citations (328) | Fichiers | Graphiques | Données

Measurements of Higgs boson production and couplings in diboson final states with the ATLAS detector at the LHC

ATLAS Collaboration (Georges Aad (Freiburg U.) *et al.*) *Afficher les 2923 auteurs*

$\mu_{\mathrm{ggH+ttH}}$	$\mu_{\mathrm{VH+VBF}}$	$-2\log L$
1.83000000e+00	2.25000000e+00	1.43921400e+00
1.88200000e+00	2.25000000e+00	1.69128200e+00
1.93400000e+00	2.25000000e+00	1.96610000e+00
1.98600000e+00	2.25000000e+00	2.26150400e+00
2.03800000e+00	2.25000000e+00	2.57528000e+00
2.09000000e+00	2.25000000e+00	2.90927600e+00
2.14200000e+00	2.25000000e+00	3.25943400e+00
2.19400000e+00	2.25000000e+00	3.62660000e+00
2.24600000e+00	2.25000000e+00	4.01081600e+00

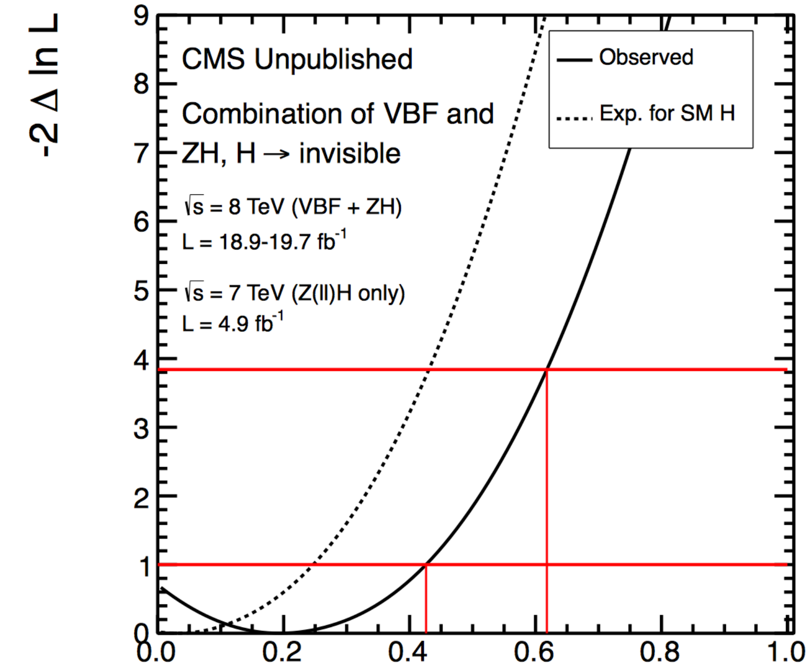
- First digital likelihoods available (and last ones so far)
- Extremely useful, allow for direct reinterpretation of the Higgs results
- All three ATLAS diboson analyses have been updated since then, however the corresponding digital likelihoods have not been published

Latest experimental results

Collaboration	Analysis	Type	Reference
ATLAS	$H \to \gamma\gamma$	2D contour	[HIGG-2013-008]
	$H \to ZZ^*$	2D contour	[HIGG-2013-021]
	$H \to WW^*$	2D contour	[HIGG-2013-013]
	$H \to \tau\tau$	2D contour	[HIGG-2013-032]
	VH, $H \to b\bar{b}$	2D contour	[HIGG-2013-023]
	ZH, $H \to$ invisible	full 1D	[HIGG-2013-003]
	ttH, $H \to b\bar{b}$	1D interval	[CONF-2014-011]
	ttH, $H \to \gamma\gamma$	1D interval	[HIGG-2013-008]
CMS	$H \to \gamma\gamma, ZZ^*, WW^*, b\bar{b}, \tau\tau$	2D contours	[HIG-2014-009]
	ttH, $H \to \gamma\gamma, \tau\tau$	1D interval	[HIG-2014-009]
	ttH, $H \to$ leptons	1D interval	[HIG-2013-029]
	ZH + VBF, $H \to$ invisible	full 1D	[HIG-2013-030]
CDF & D0	VH, $H \to b\bar{b}$	1D interval	[PUB-2013-081]

$$\mu(\text{ttH}, b\bar{b}) = 1.4 \pm 1.7$$

« 1D interval » [ATLAS-CONF-2014-011]



« full 1D » [CMS-HIG-2013-030]

- Final likelihood is the product of the individual 1D and 2D likelihoods
- Validity of this approximation and possible improvements for LHC Run II addressed later

Predicting signal strengths

$$-2\log L = -2\log L(\boldsymbol{\mu})$$

$\Longrightarrow$ need prediction of the signal strengths

Direct computation in a given model ?

$$\mu(X,Y) = \frac{\sigma(X)\mathcal{B}(H\to Y)}{\sigma(X)^{\rm SM}\mathcal{B}(H\to Y)^{\rm SM}}$$

- Need $\sigma(X)$, $\sigma^{\rm SM}(X)$, $\mathcal{B}(H\to Y)$, and $\mathcal{B}^{\rm SM}(H\to Y)$
- Computation should be performed using the same parton distribution functions, QCD scale, order, (renormalization scheme)…
- Most new physics scenarios are only known at leading order (LO)
- $\mu^{(n)}$ and $\mu^{(n+1)}$ (n: order in perturbation theory) will generally differ since the relative SM particle contributions to the process may change

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$\Longrightarrow$ **Feasible but easily inaccurate**

Reduced couplings "κ framework"

- Alleviating the previous problems by introducing **reduced couplings**:

$$\mathcal{L} = g\left[C_W m_W W^\mu W_\mu + C_Z \frac{m_Z}{\cos\theta_W} Z^\mu Z_\mu\right] H - g \sum_{f=t,b,c,\tau} C_f \frac{m_f}{2m_W} f\bar{f}H$$

$$\Longrightarrow \mu(X,Y) = \frac{C_X^2 C_Y^2}{\sum_Y C_Y^2 \mathcal{B}^{\mathrm{SM}}(H\to Y)}$$

- Couplings for processes involving more than one SM particle (ggH, VBF, gg, $\gamma\gamma$, $Z\gamma$) can be obtained as, *e.g.*,

$$C_{\mathrm{ggH}}^2 = \frac{\sum\limits_{i,j=t,b,c} C_i C_j\, \sigma_{ij}^{\mathrm{SM}}(\mathrm{ggH})}{\sum\limits_{i,j=t,b,c} \sigma_{ij}^{\mathrm{SM}}(\mathrm{ggH})}$$

[LHCHXSWG-2012-001]

- If new decay modes into **invisible** or **undetected** particles are open, the signal strengths are modified as

$$\mu(X,Y) \to (1-\mathcal{B}_{\mathrm{invisible/undetected}})\mu(X,Y)$$

Lilith: a tool for constraining new physics from Higgs measurements

Presentation

Validation

Meet Lilith

- **Python tool**: evaluate the Higgs likelihood from the latest experimental signal strengths

- Based on earlier works on Higgs fits:

  Higgs Couplings at the End of 2012: Bélanger, Dumont, Ellwanger Gunion, Kraml. arXiv:1212.5244

  Status of invisible Higgs decays: Bélanger et al. arXiv:1302.5694

  Global fit to Higgs signal strengths and couplings and implications for extended Higgs sectors: Bélanger et al. arXiv:1306.2941

Lilith

LIght LIkelihood fiT for the Higgs

[JB, B. Dumont] [arXiv:1502.04138]

Information, Download:

http://lpsc.in2p3.fr/projects-th/lilith/

(Google: lilith higgs)

- All formats of experimental signal strengths are handled: full 2D, 2D contours, full 1D, 1D intervals

- All experimental results are stored in a flexible **XML database** (updated as new results are published)

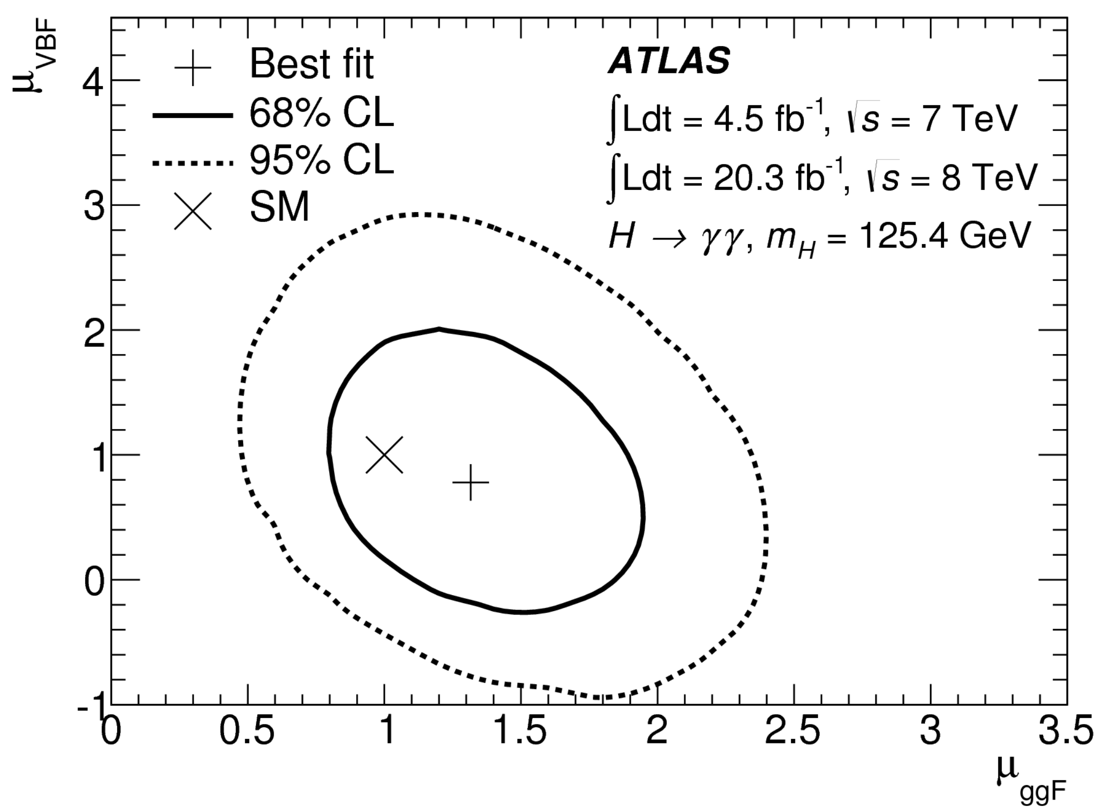
- Two user input modes:
  - → Reduced couplings as inputs
  - → Signal strengths as inputs

- Evaluate $-2\log L$ for each input points, allow for a statistical interpretation in the frequentist or bayesian approach

XML experimental database

- All latest experimental results from ATLAS and CMS (presented earlier) are available in the Lilith database, superseded results as well
- For clarity one XML file corresponds to one experimental result, for instance,

[ATLAS-HIGG-2013-008]

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  <experiment>ATLAS</experiment>
  <source type="published">HIGG-2013-08</source>
  <sqrts>7+8</sqrts>
  <mass>125.4</mass>
  <CL>68%</CL>

  <eff axis="x" prod="ggH">1</eff>
  <eff axis="y" prod="VBF">1</eff>

  <bestfit>
    <x>1.361</x>
    <y>0.858</y>
  </bestfit>

  <param>
    <a>7.393</a>
    <b>0.998</b>
    <c>1.951</c>
  </param>
</expmu>
```

/Lilith-1.1/data/ATLAS/Run1/HIGG-2013-08_ggH-VBF_gammagamma_n68.xml

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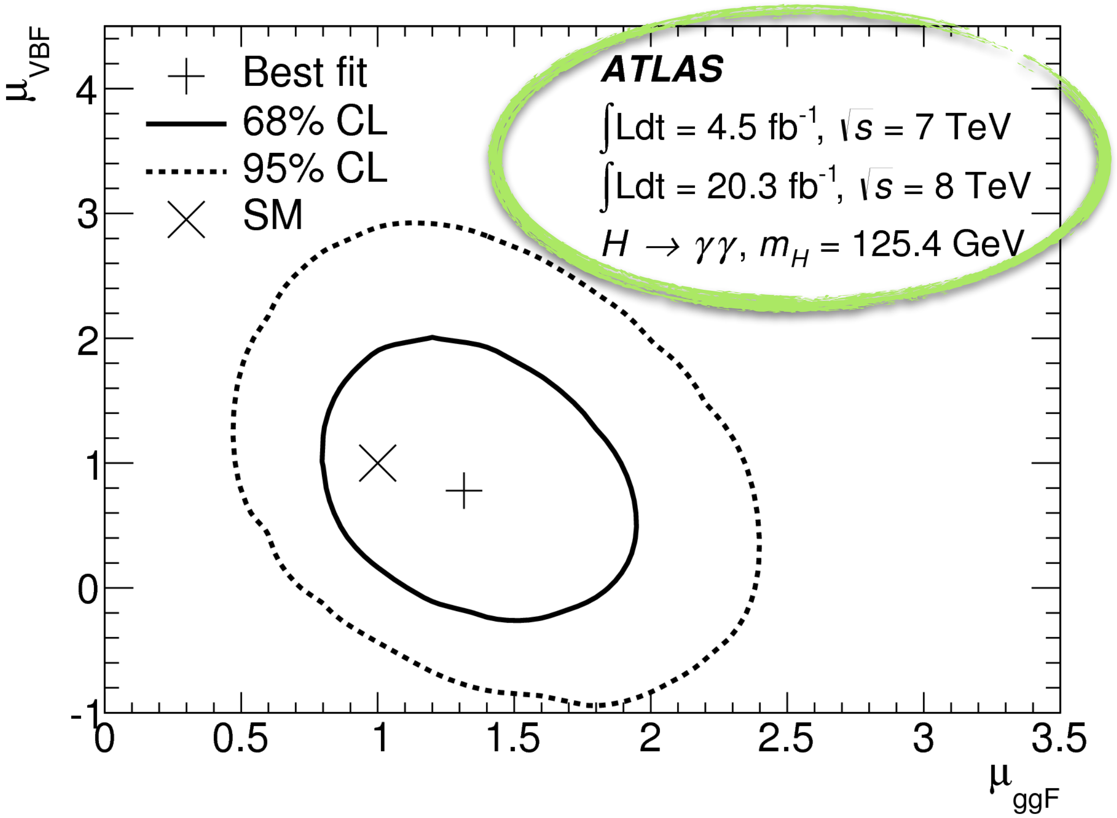
- For clarity one XML file corresponds to one experimental result, for instance,

[ATLAS-HIGG-2013-008]



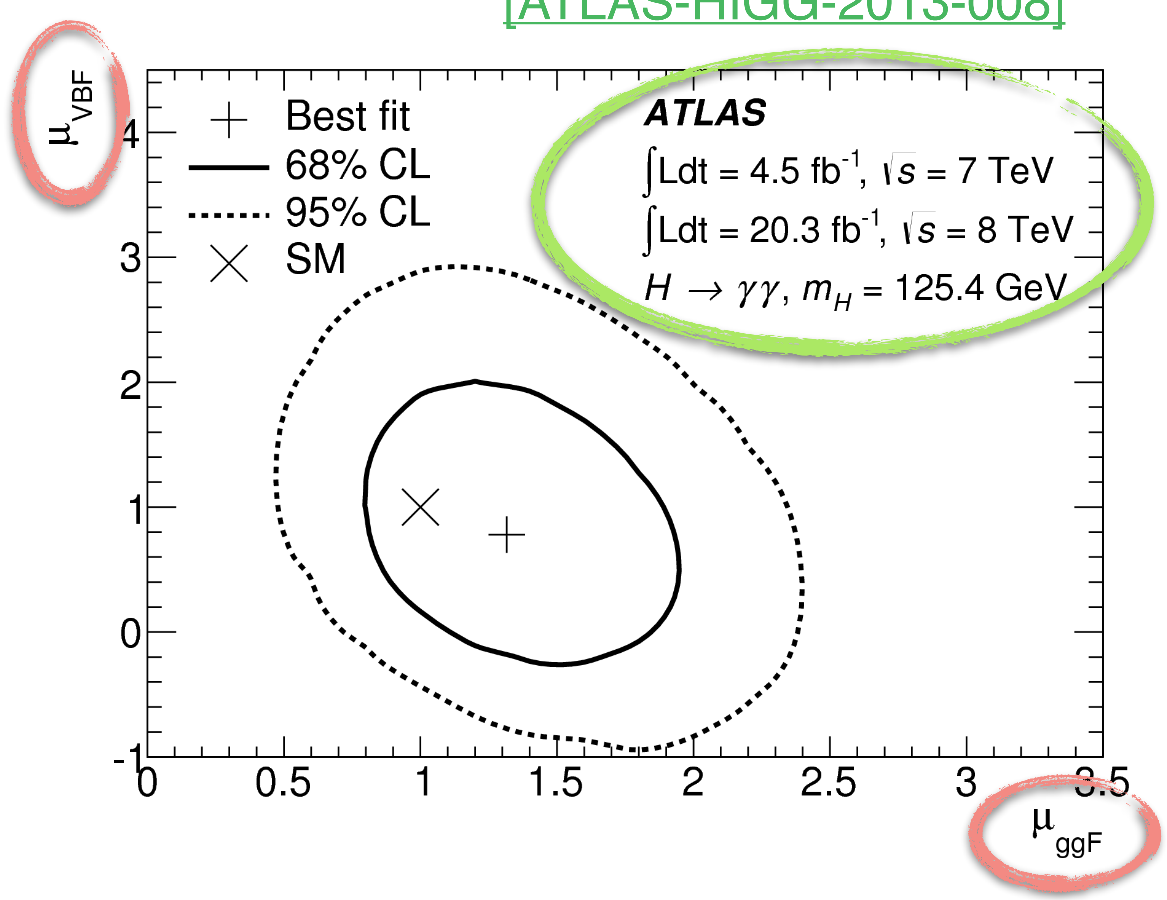

```xml
<expmu decay="gammagamma" dim="2" type="n">
  <experiment>ATLAS</experiment>
  <source type="published">HIGG-2013-08</source>
  <sqrts>7+8</sqrts>
  <mass>125.4</mass>
  <CL>68%</CL>

  <eff axis="x" prod="ggH">1</eff>
  <eff axis="y" prod="VBF">1</eff>

  <bestfit>
    <x>1.361</x>
    <y>0.858</y>
  </bestfit>

  <param>
    <a>7.393</a>
    <b>0.998</b>
    <c>1.951</c>
  </param>
</expmu>
```

/Lilith-1.1/data/ATLAS/Run1/HIGG-2013-08_ggH-VBF_gammagamma_n68.xml

XML experimental database

- All latest experimental results from ATLAS and CMS (presented earlier) are available in the Lilith database, superseded results as well
- For clarity one XML file corresponds to one experimental result, for instance,

[ATLAS-HIGG-2013-008]




```xml
<expmu decay="gammagamma" dim="2" type="n">
  <experiment>ATLAS</experiment>
  <source type="published">HIGG-2013-08</source>
  <sqrts>7+8</sqrts>
  <mass>125.4</mass>
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  <eff axis="x" prod="ggH">1</eff>
  <eff axis="y" prod="VBF">1</eff>

  <bestfit>
    <x>1.361</x>
    <y>0.858</y>
  </bestfit>

  <param>
    <a>7.393</a>
    <b>0.998</b>
    <c>1.951</c>
  </param>
</expmu>
```

/Lilith-1.1/data/ATLAS/Run1/HIGG-2013-08_ggH-VBF_gammagamma_n68.xml

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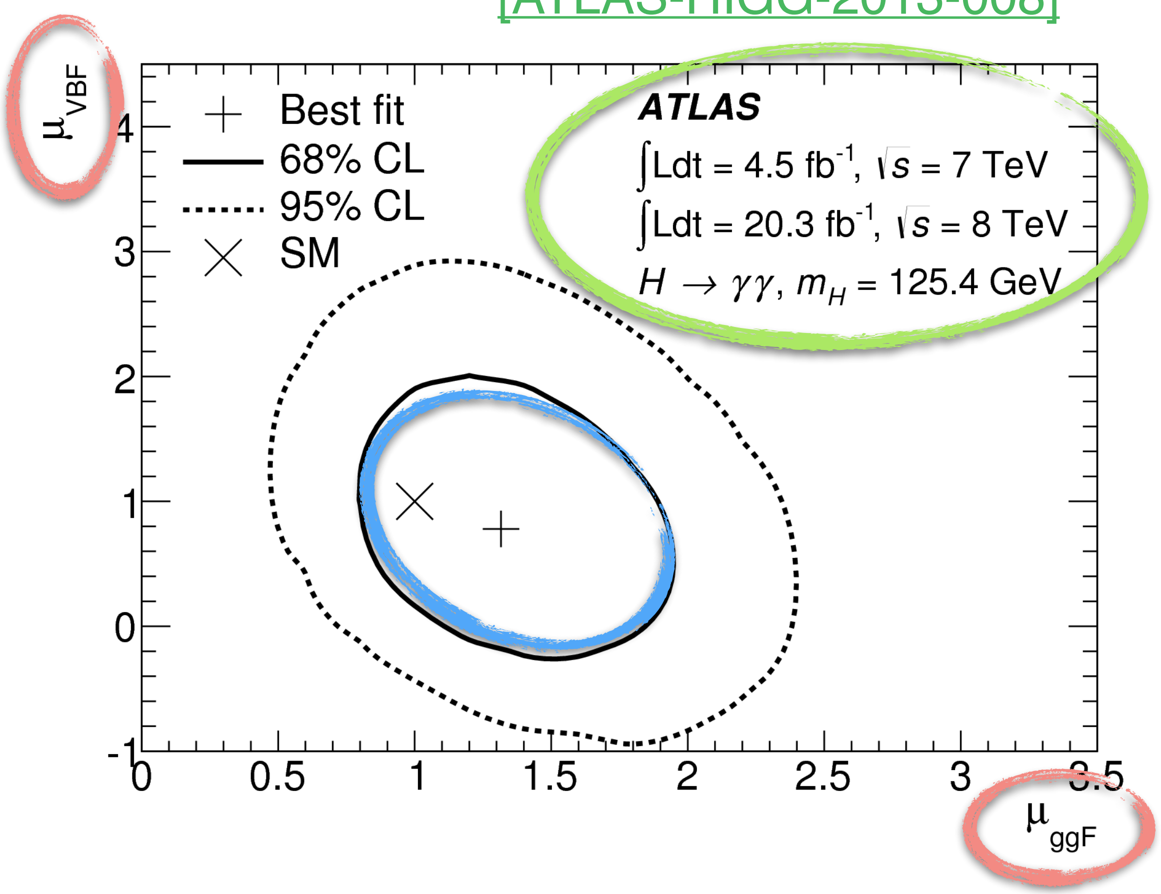
[ATLAS-HIGG-2013-008]




```xml
<expmu decay="gammagamma" dim="2" type="n">
  <experiment>ATLAS</experiment>
  <source type="published">HIGG-2013-08</source>
  <sqrts>7+8</sqrts>
  <mass>125.4</mass>
  <CL>68%</CL>

  <eff axis="x" prod="ggH">1</eff>
  <eff axis="y" prod="VBF">1</eff>

  <bestfit>
    <x>1.361</x>
    <y>0.858</y>
  </bestfit>

  <param>
    <a>7.393</a>
    <b>0.998</b>
    <c>1.951</c>
  </param>
</expmu>
```

Bivariate normal distribution parametrization (best-fit+C^{-1})

/Lilith-1.1/data/ATLAS/Run1/HIGG-2013-08_ggH-VBF_gammagamma_n68.xml

XML user input: reduced coupling mode

```xml
<?xml version="1.0"?>

<lilithinput>
  <reducedcouplings>
    <mass>125</mass>

    <C to="tt">1.0</C>
    <C to="cc">1.0</C>
    <C to="bb">1.0</C>
    <C to="tautau">1.0</C>
    <C to="ZZ">1.0</C>
    <C to="WW">1.0</C>

    <C to="gammagamma">1.0</C>
    <C to="Zgamma">1.0</C>
    <C to="gg">1.0</C>
    <C to="VBF">1.0</C>

    <precision>BEST-QCD</precision>

    <extraBR>
      <BR to="invisible">0.0</BR>
      <BR to="undetected">0.0</BR>
    </extraBR>

  </reducedcouplings>
</lilithinput>
```

/Lilith-1.1_released/userinput/example_couplings.xml

Higgs mass [123-128] GeV

$$\mathcal{L} = g\left[C_W m_W W^\mu W_\mu + C_Z \frac{m_Z}{\cos\theta_W} Z^\mu Z_\mu\right] H - g \sum_{f=t,b,c,\tau} C_f \frac{m_f}{2m_W} f\bar{f}H$$

Multi-labels also defined: uu=(tt, cc), VV= (WW, ZZ) etc

If not given, computed internally assuming SM particles only, at a given *precision* with cross sections and partial widths from HIGLU, HDECAY, VBFNLO

Invisible, undetected branching ratios

$$\mu(X,Y) \rightarrow (1 - \mathcal{B}_{\text{invisible/undetected}})\mu(X,Y)$$

Possibility to also define CP-violating couplings and arbitrary number of Higgs states

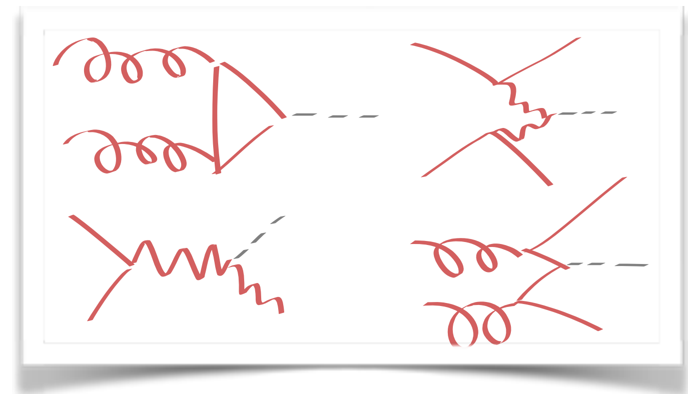
XML user input: signal strengths mode

```xml
<?xml version="1.0"?>

<lilithinput>
  <signalstrengths part="h">
    <mass>125</mass>

    <mu prod="ggH" decay="gammagamma">1.0</mu>
    <mu prod="ggH" decay="VV">1.0</mu>
    <mu prod="ggH" decay="bb">1.0</mu>
    <mu prod="ggH" decay="tautau">1.0</mu>

    <mu prod="VVH" decay="gammagamma">1.0</mu>
    <mu prod="VVH" decay="VV">1.0</mu>
    <mu prod="VVH" decay="bb">1.0</mu>
    <mu prod="VVH" decay="tautau">1.0</mu>

    <mu prod="ttH" decay="gammagamma">1.0</mu>
    <mu prod="ttH" decay="VV">1.0</mu>
    <mu prod="ttH" decay="bb">1.0</mu>
    <mu prod="ttH" decay="tautau">1.0</mu>

    <redxsBR prod="ZH" decay="invisible">0.0</redxsBR>
    <redxsBR prod="VBF" decay="invisible">0.0</redxsBR>
  </signalstrengths>
</lilithinput>
```

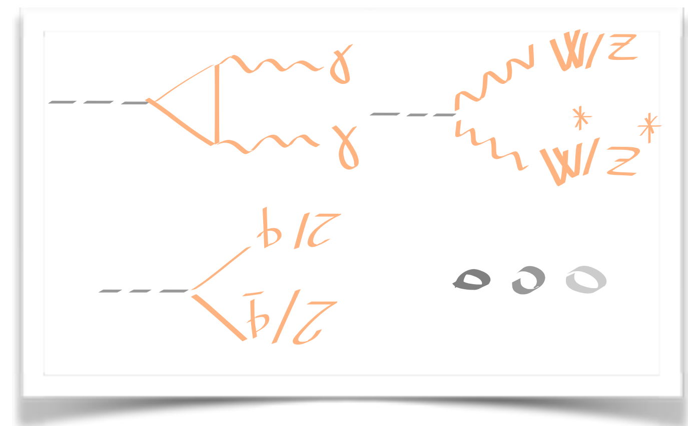
/Lilith-1.1_released/userinput/example_mu.xml

$$\mu(X,Y) = \frac{\sigma(X)\mathcal{B}(H \to Y)}{\sigma(X)^{\rm SM}\mathcal{B}(H \to Y)^{\rm SM}}$$

$X \subset$



$Y \subset$



$$\mu(X,\text{invisible}) \equiv C_X^2 \mathcal{B}_{\rm invisible}$$

Running Lilith

- As a **Python library** (recommended way):

Several methods (read input, format of output..) and attributes of the class Lilith accessible to the user. Fully documented.

~/mylilithtest.py

```
import lilith
lilithObj = lilith.Lilith()
lilithObj.readexpinput()
lilithObj.readuserinputfile("userinput/
example_couplings.xml")
lilithObj.computelikelihood()
print "-2logL =", lilithObj.l
```

```
bernon@Jeremy:~/Projects/Higgs/Lilith-1.1$ python mylilithtest.py
-2logL = 20.2445863392
```

- Through the **command line interface**:

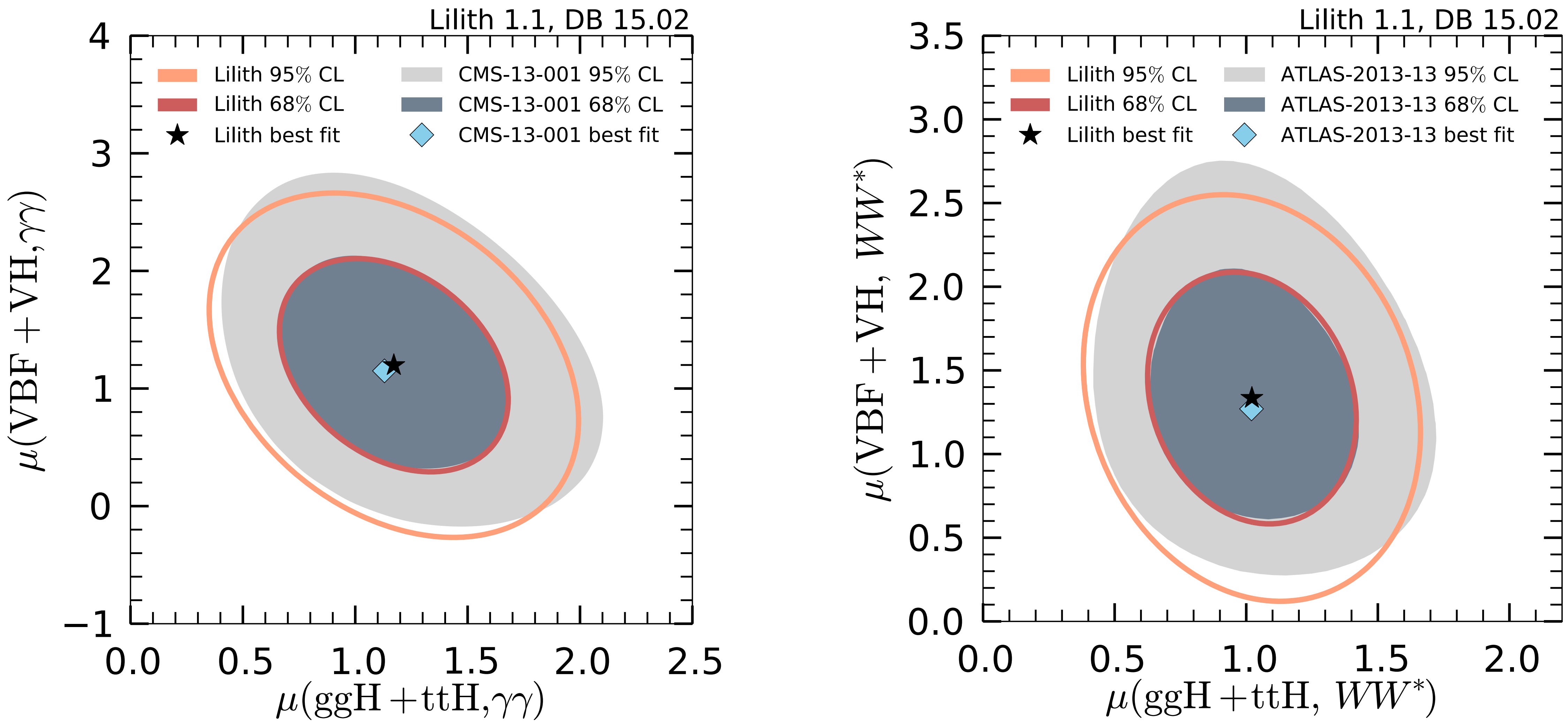
```
bernon@Jeremy:~/Projects/Higgs/Lilith-1.1$ python run_lilith.py userinput/example_mu.xml
                  <><><><><><><><><><><><><>
                     Lilith version 1.1
                    database version 15.02
                  <><><><><><><><><><><><><>

. User input: userinput/example_mu.xml

. Experimental input: latest LHC results [data/latest.list]
                      (20 files, Ndof = 29)
-2log(likelihood) = 20.244586
```

- Through the **C/C++/Root interface** (C/Python API):

Several functions defined, working example shipped with the code.

Validity of the bivariate normal approximation (I/II)

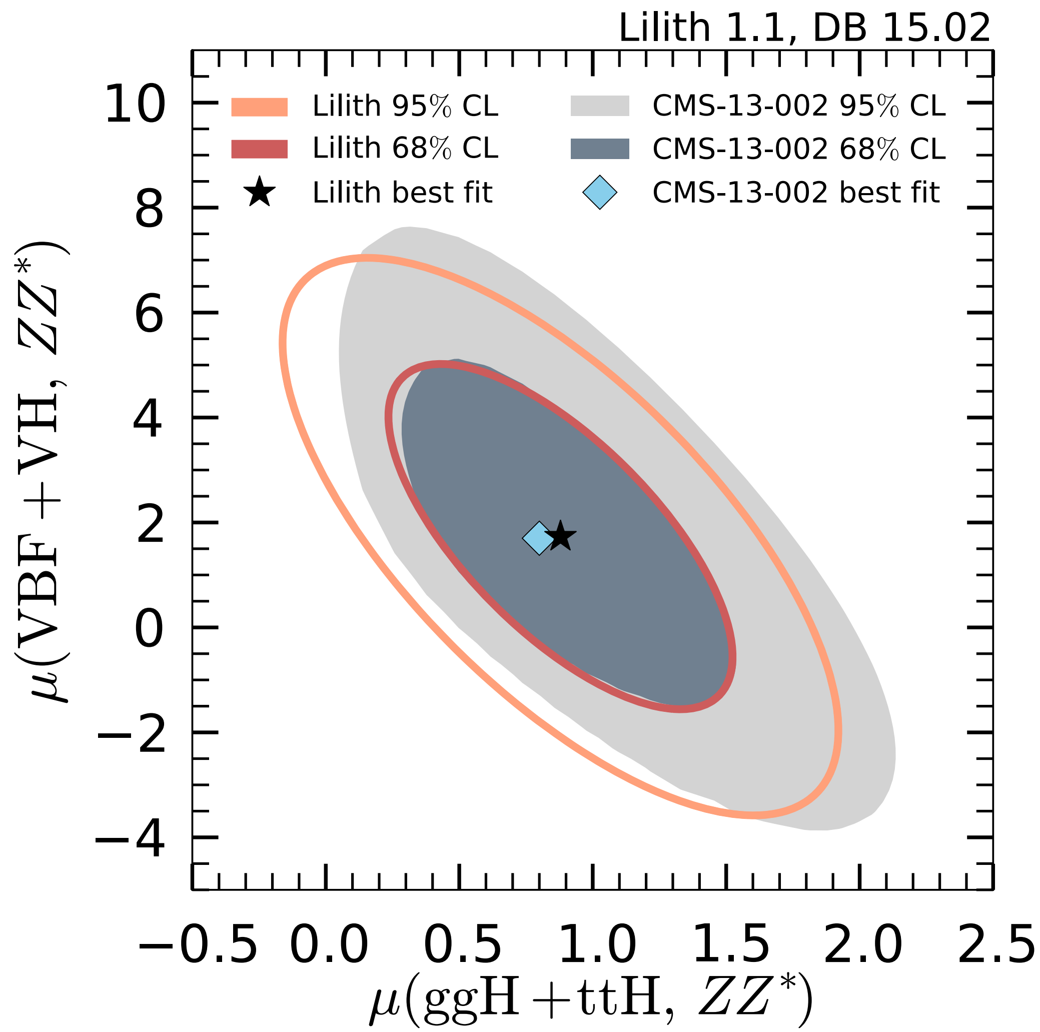
- When only the 68% CL contours in the signal strength planes are provided, we use a bivariate normal distribution to reconstruct the likelihood
- We compare the reconstruction and the official results to assess the validity of this approximation

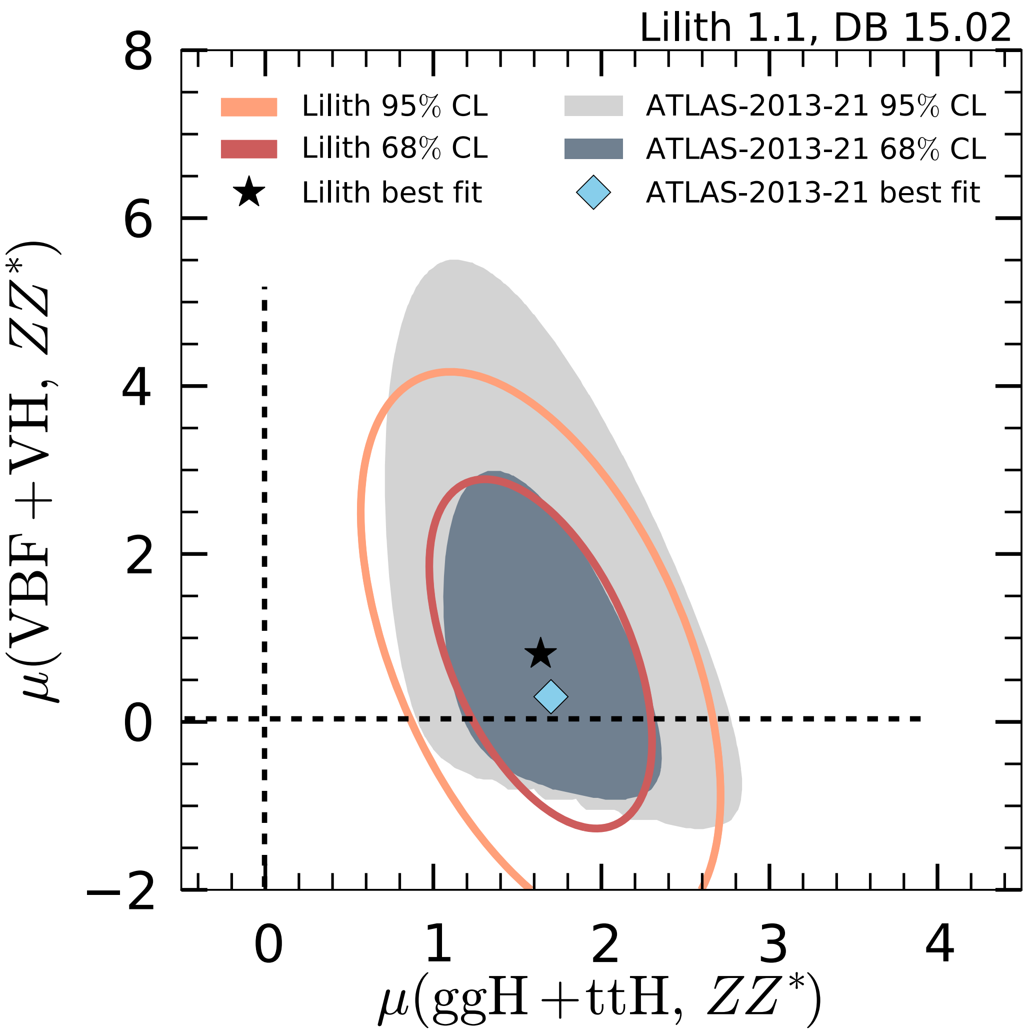


Generally very good ✓

Validity of the bivariate normal approximation (II/II)

- Deviations from the bivariate normal approximation are however expected for channels with low statistics, as the Poisson distribution describing the counting experiment has not yet entered the Gaussian regime, typically: ZZ^*

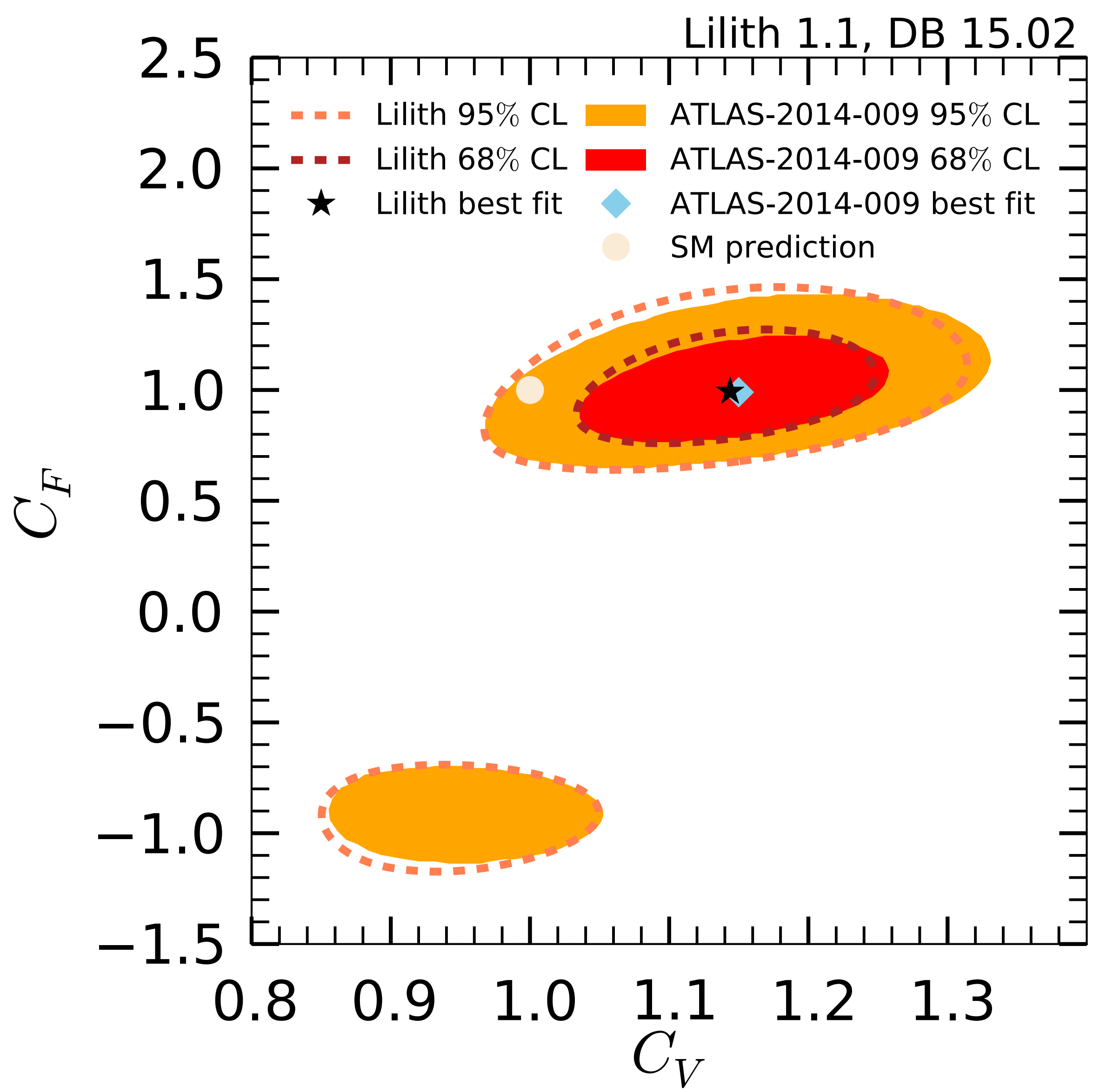




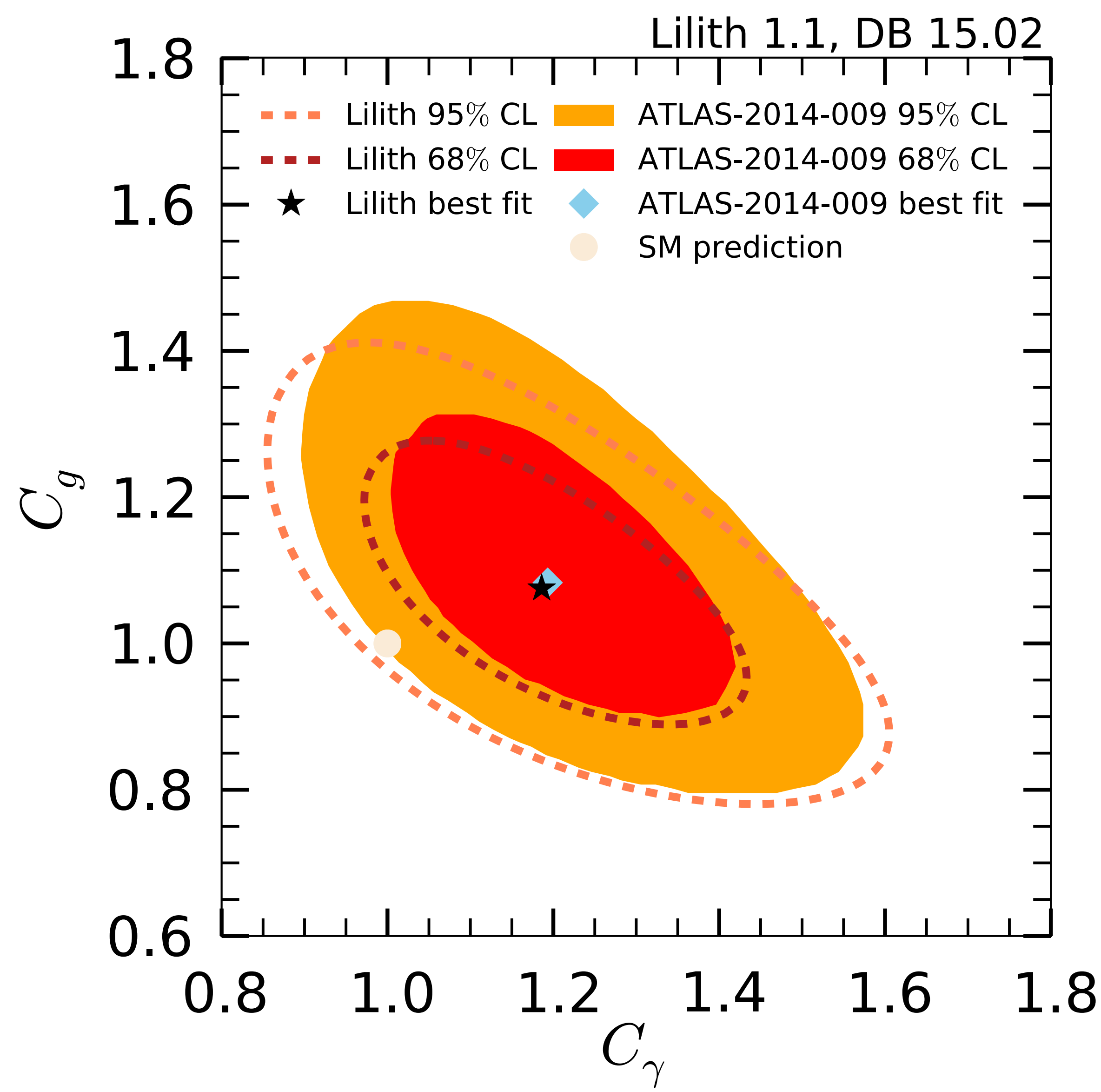
- Publication of the full likelihood function would make this approximation unnecessary

Validation of the Lilith likelihood against ATLAS results

- Trying to reproduce the official ATLAS and CMS coupling fits (profile likelihood ratio to derive the confidence intervals)



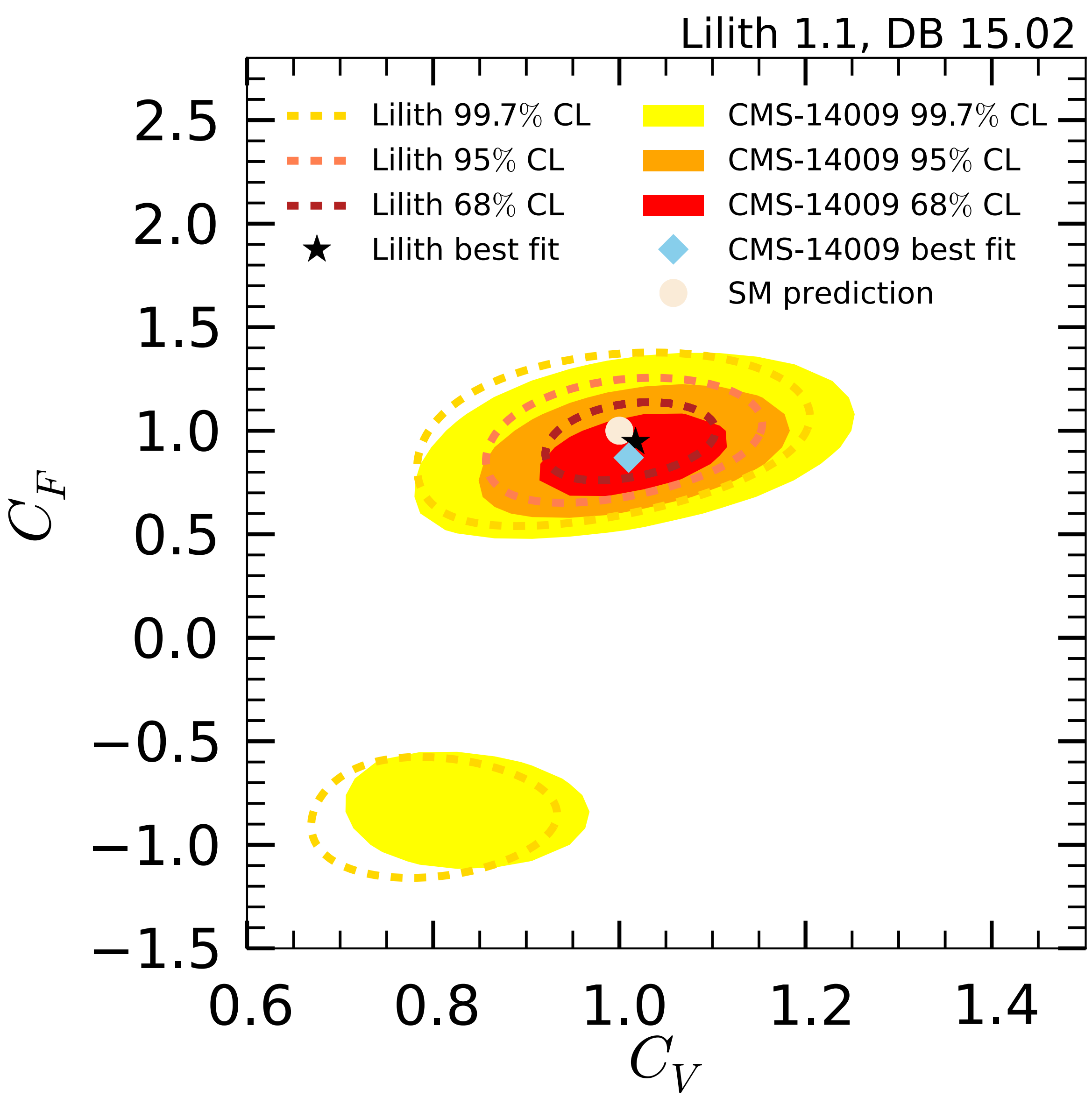
(C_V, C_F) benchmark scenario



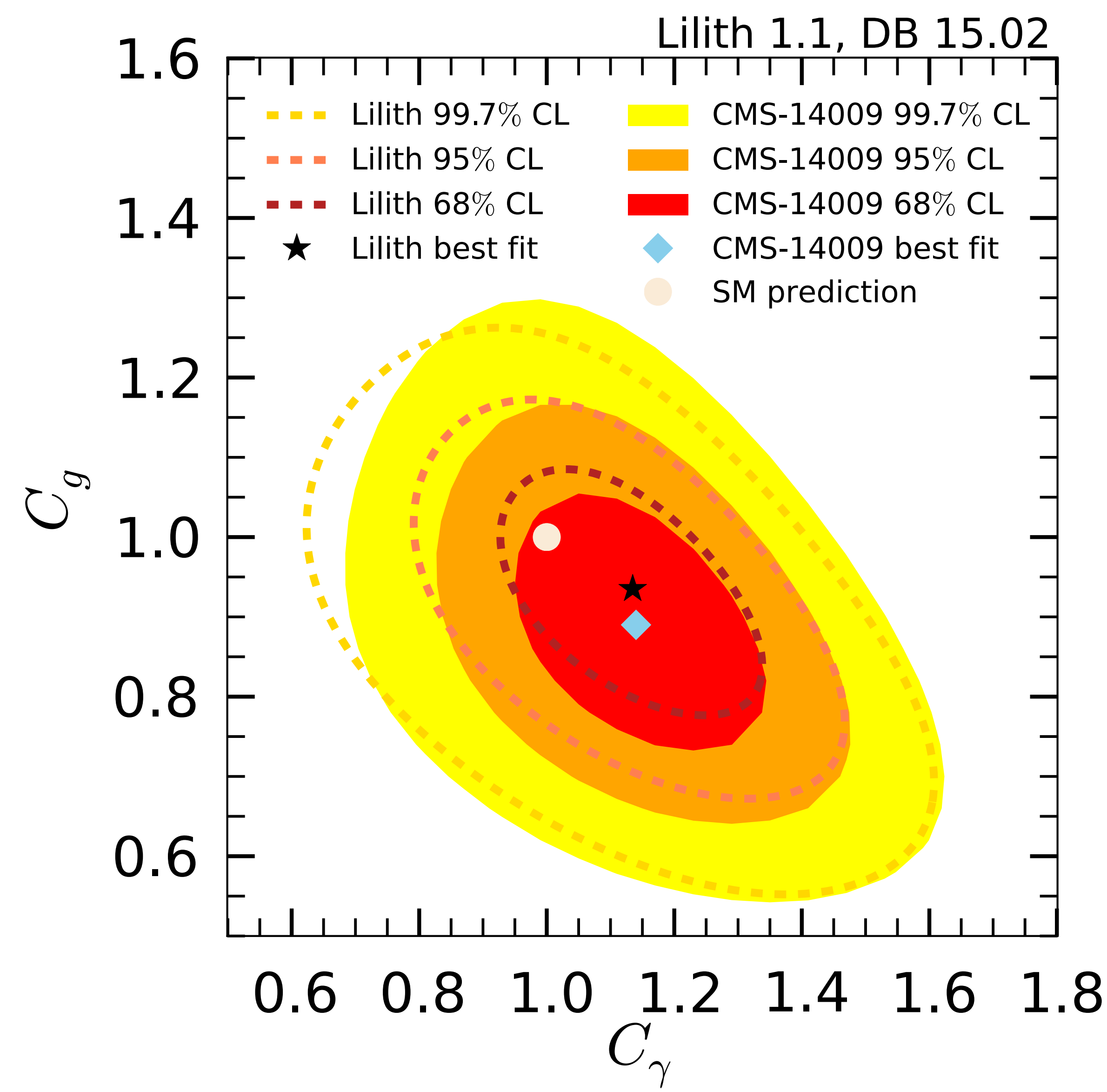
(C_γ, C_g) benchmark scenario

Validation of the Lilith likelihood against CMS results

- Trying to reproduce the official ATLAS and CMS coupling fits (profile likelihood ratio to derive the confidence intervals)



(C_V, C_F) benchmark scenario



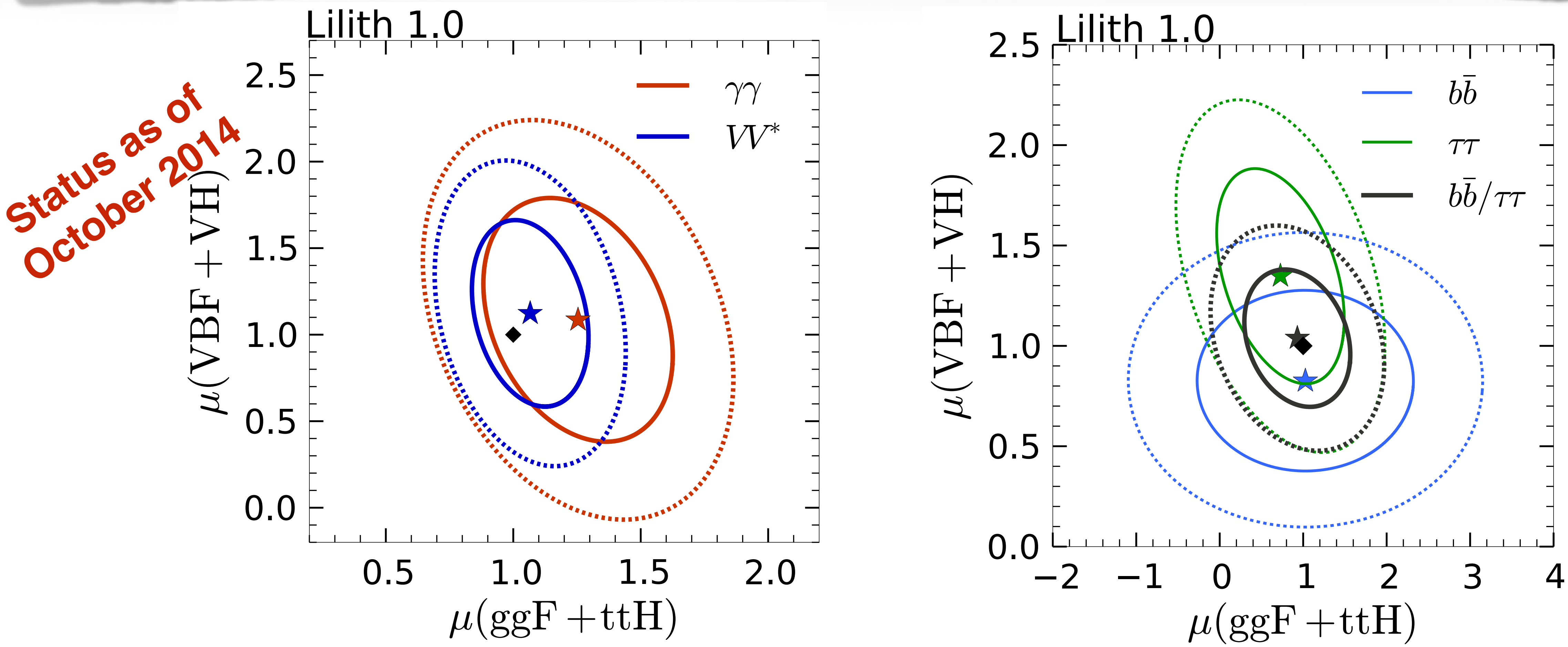
(C_γ, C_g) benchmark scenario

Some applications

Global fit

Phenomenological study of a 2HDM

Signal strengths combination: LHC+Tevatron



	$\hat{\mu}^{\mathrm{ggF+ttH}}$	$\hat{\mu}^{\mathrm{VBF+VH}}$	ρ
$\gamma\gamma$	1.25 ± 0.24	1.09 ± 0.46	-0.30
VV^*	1.07 ± 0.15	1.12 ± 0.36	-0.26
$b\bar{b}/\tau\tau$	0.93 ± 0.42	1.04 ± 0.23	-0.24
$b\bar{b}$	1.02 ± 0.85	0.83 ± 0.30	0
$\tau\tau$	0.73 ± 0.50	1.35 ± 0.35	-0.40

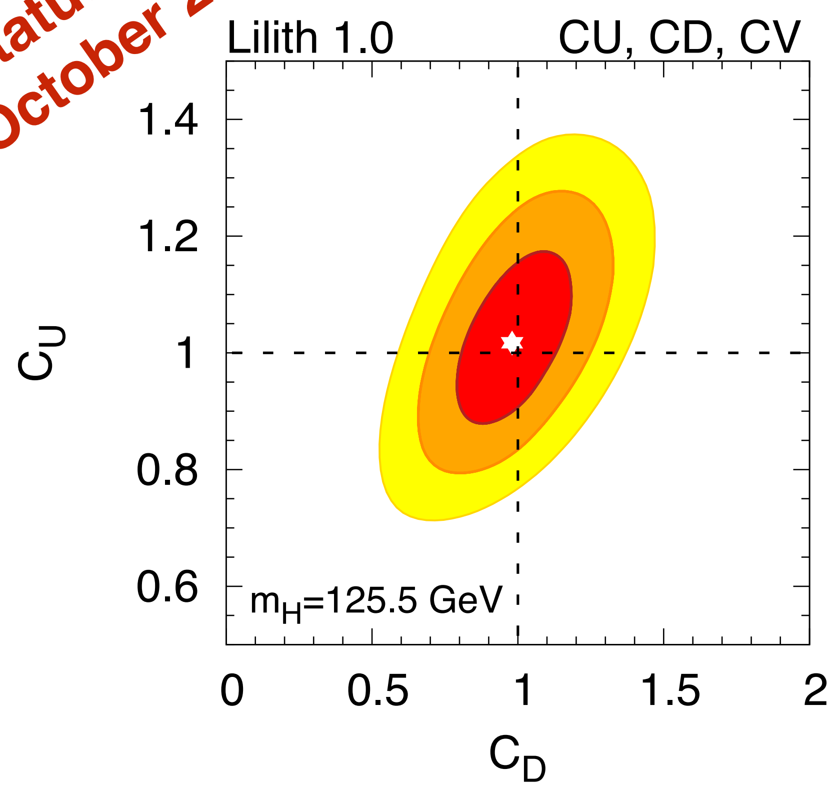
Perfectly well compatible with the SM

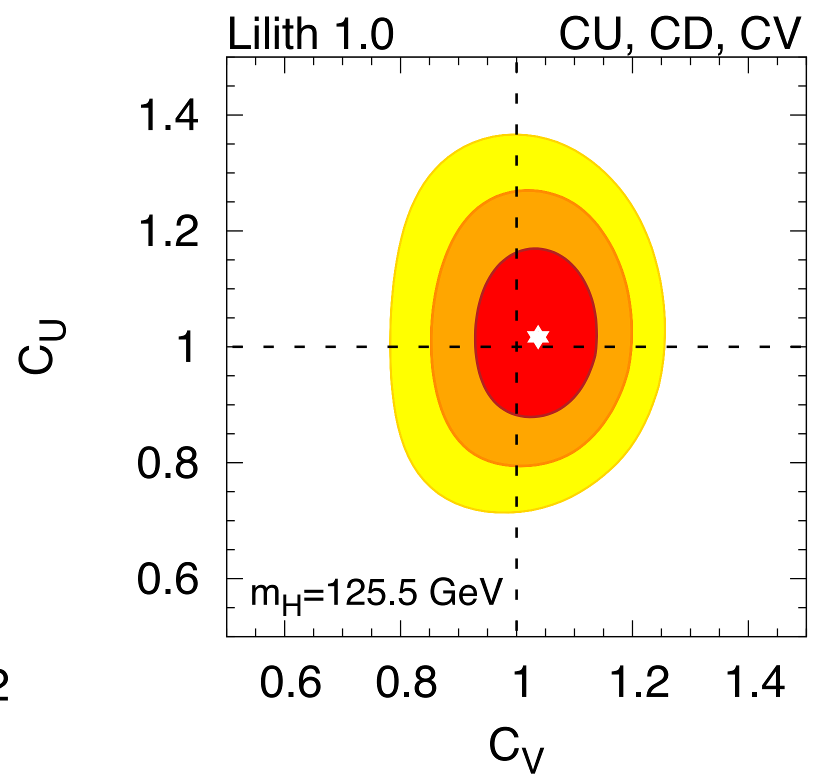
[JB, B. Dumont, S. Kraml] [arXiv:1409.1588]

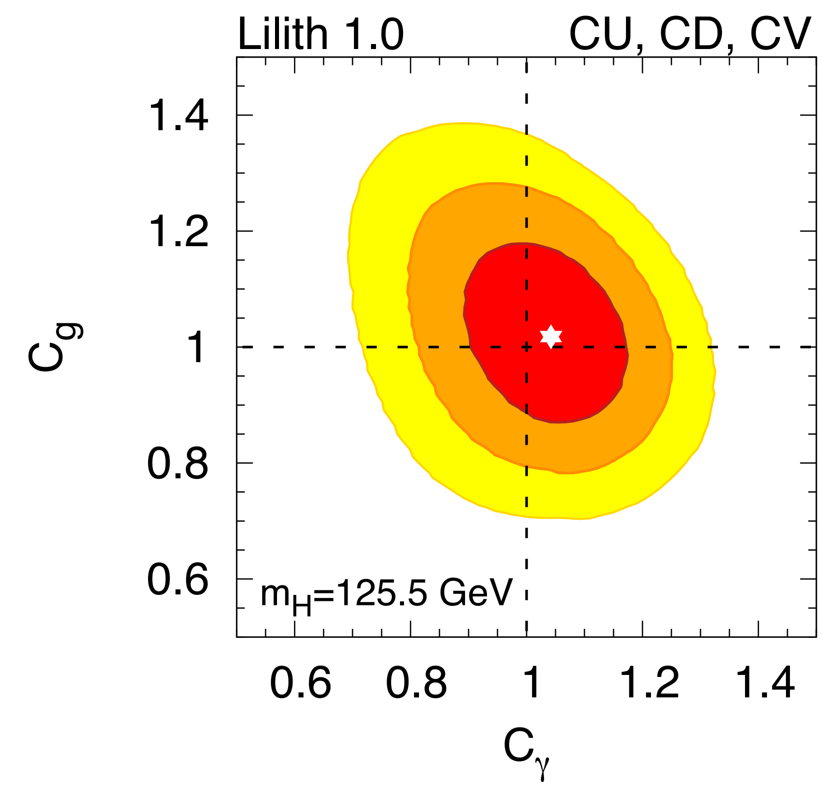
Simple model fit

- **Model :** C_U, C_D, C_V , assuming no extra BSM loop or width contributions

Status as of October 2014







In 1D (profiling over other parameters):

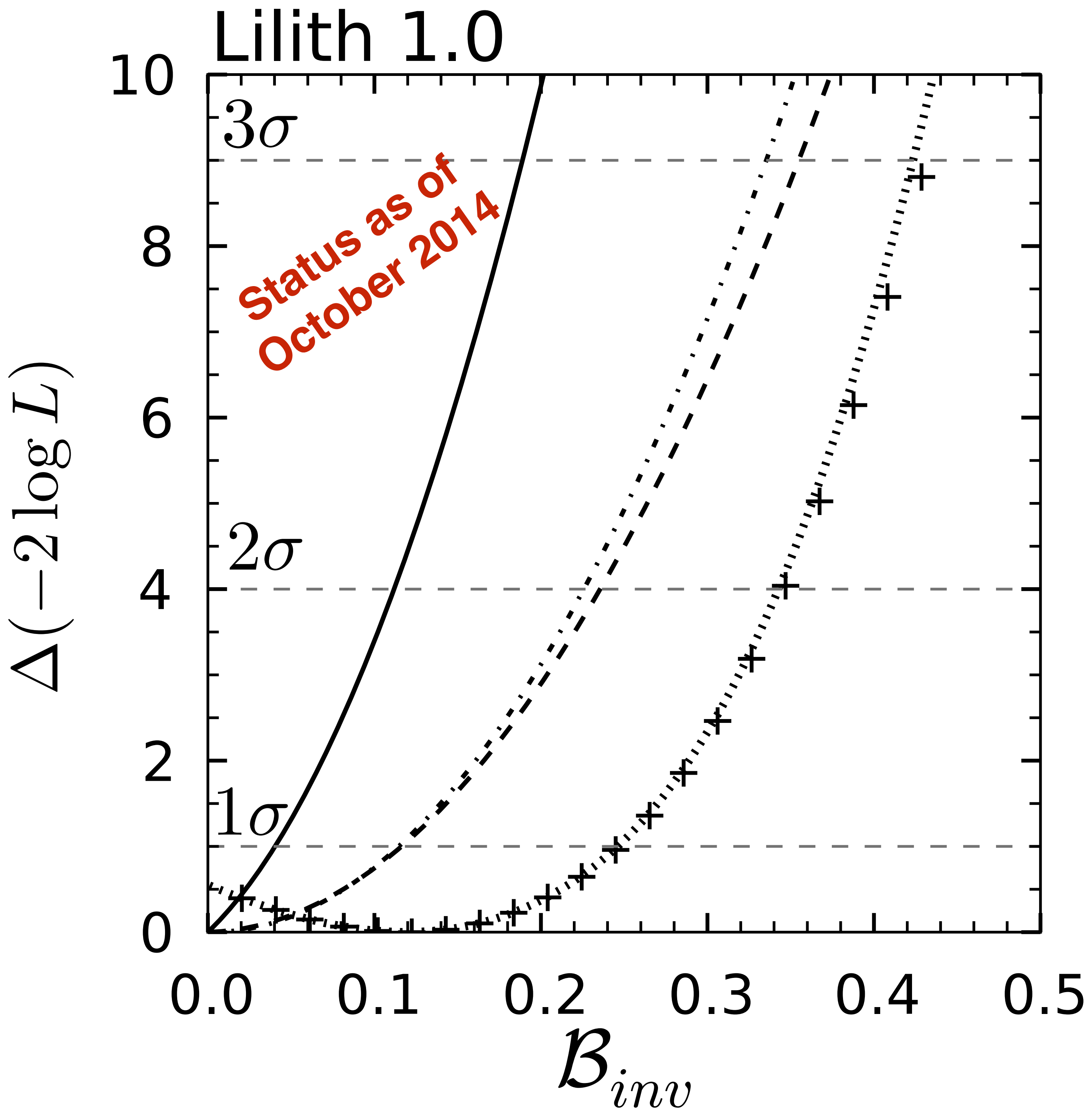
$$C_U = 1.02 \pm 0.10$$
$$C_D = 0.98 \pm 0.14$$

$$C_V = 1.04 \pm 0.07$$

$$C_\gamma = 1.04 \pm 0.11$$
$$C_g = 1.02 \pm 0.11$$

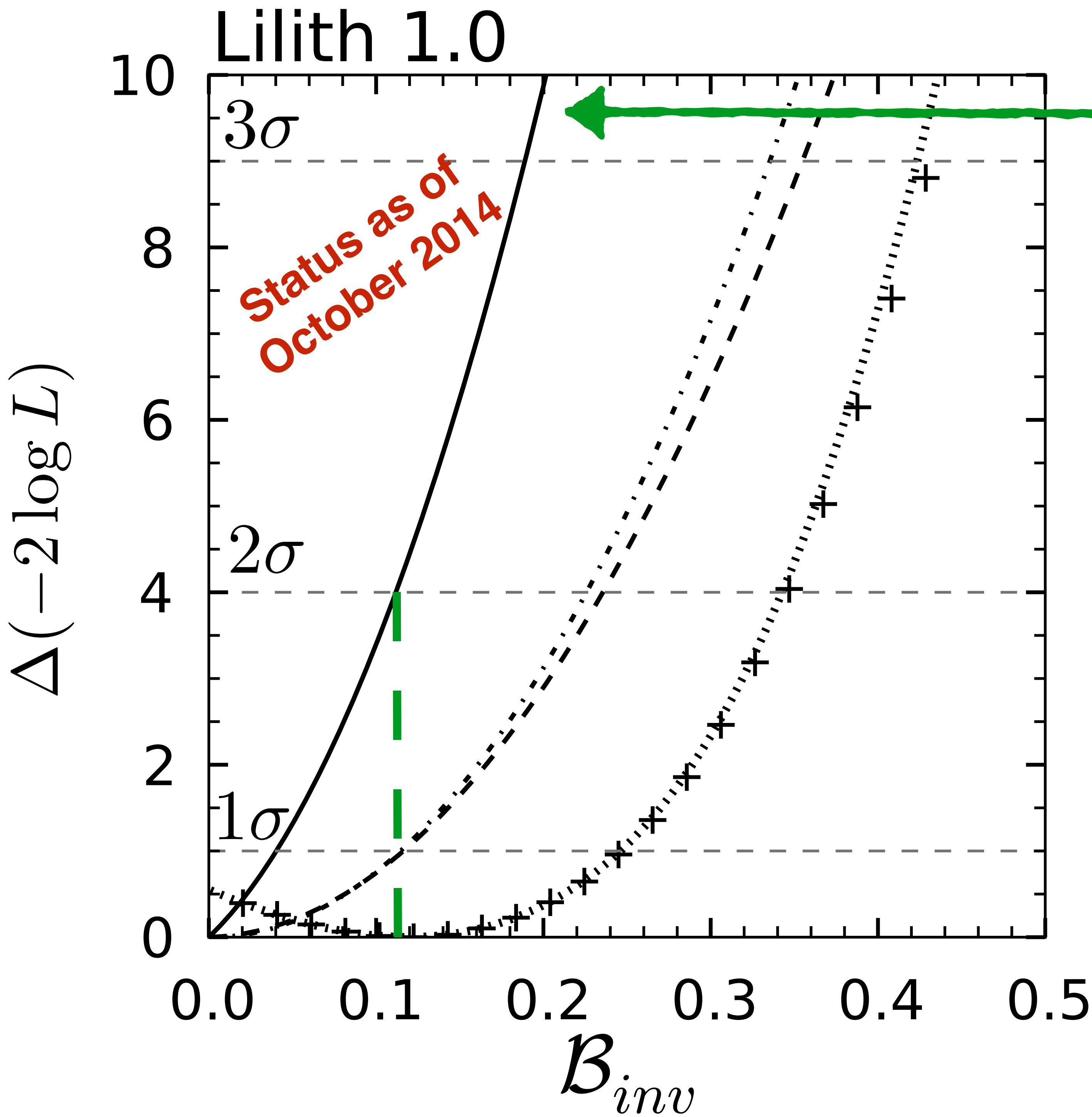
[JB, B. Dumont, S. Kraml] [arXiv:1409.1588]

Invisible branching ratio fits



[JB, B. Dumont, S. Kraml] [arXiv:1409.1588]

Invisible branching ratio fits

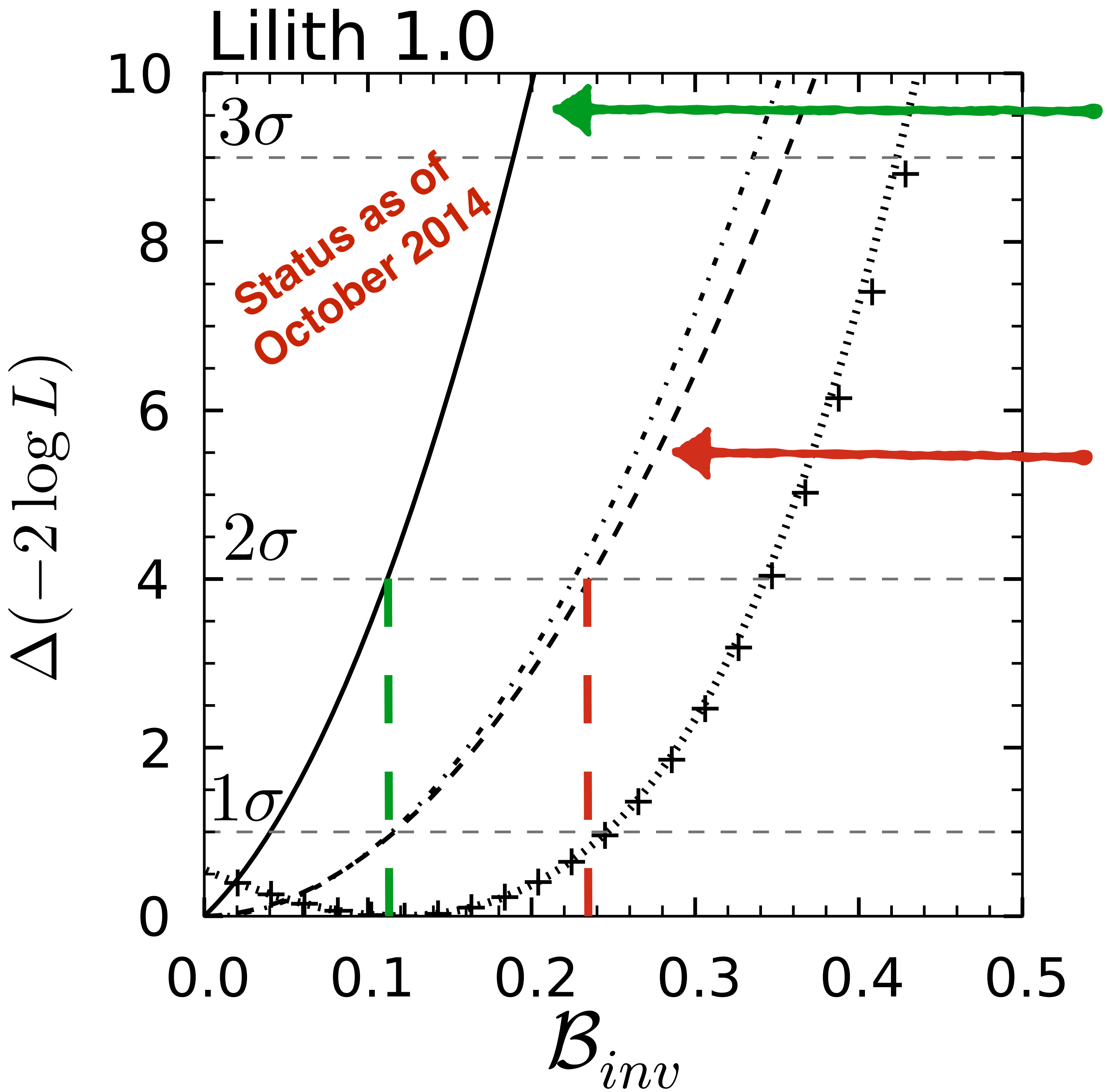


SM+invisible

$\mathcal{B}_{inv} < 0.11$ at 95.4% C.L.

[JB, B. Dumont, S. Kraml] [arXiv:1409.1588]

Invisible branching ratio fits



SM+invisible

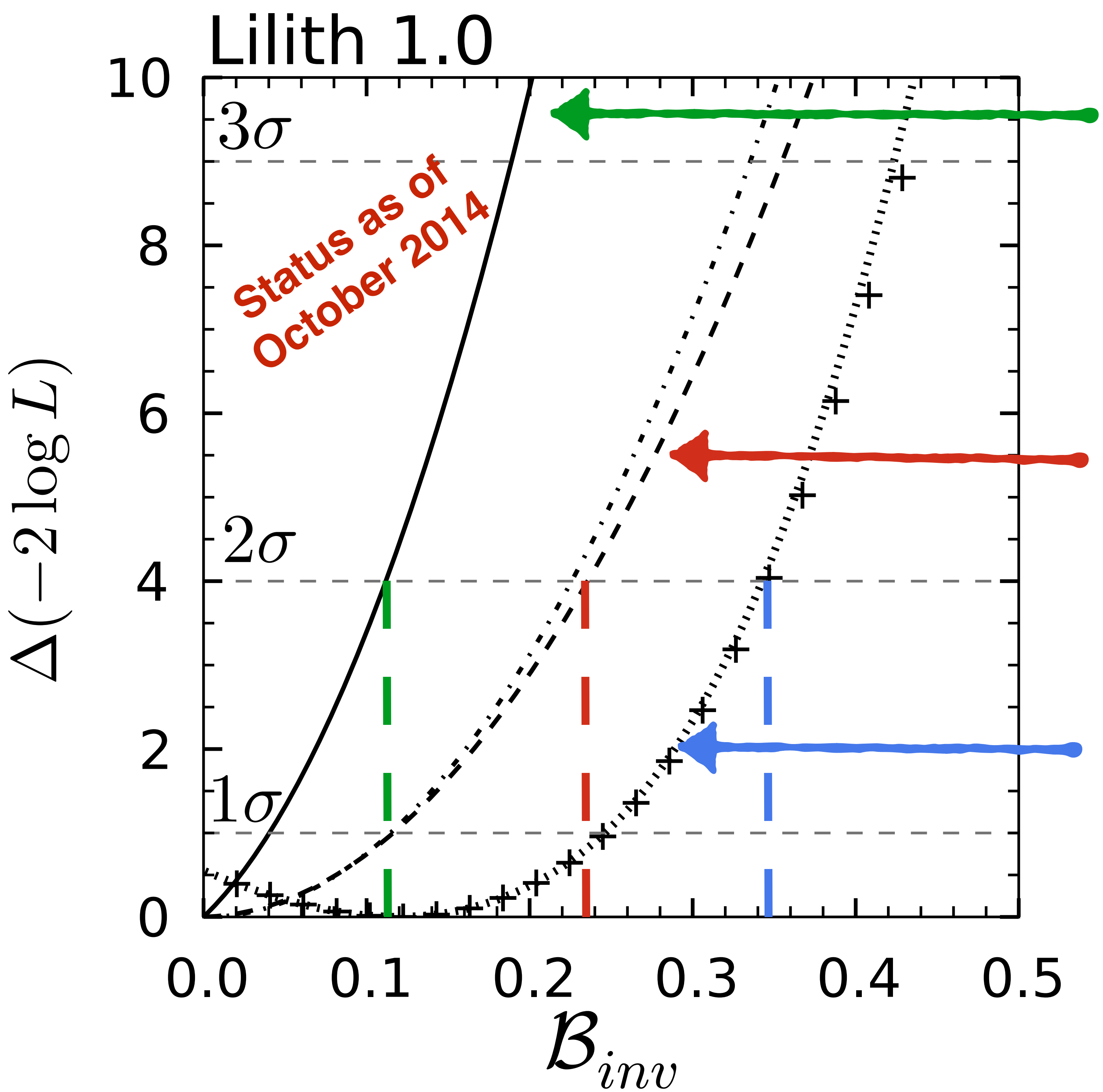
$\mathcal{B}_{inv} < 0.11$ at 95.4% C.L.

C_U, C_D, C_V <1
SM+ΔC_γ, ΔC_g +invisible

$\mathcal{B}_{inv} \lesssim 0.24$ at 95.4% C.L.

[JB, B. Dumont, S. Kraml] [arXiv:1409.1588]

Invisible branching ratio fits



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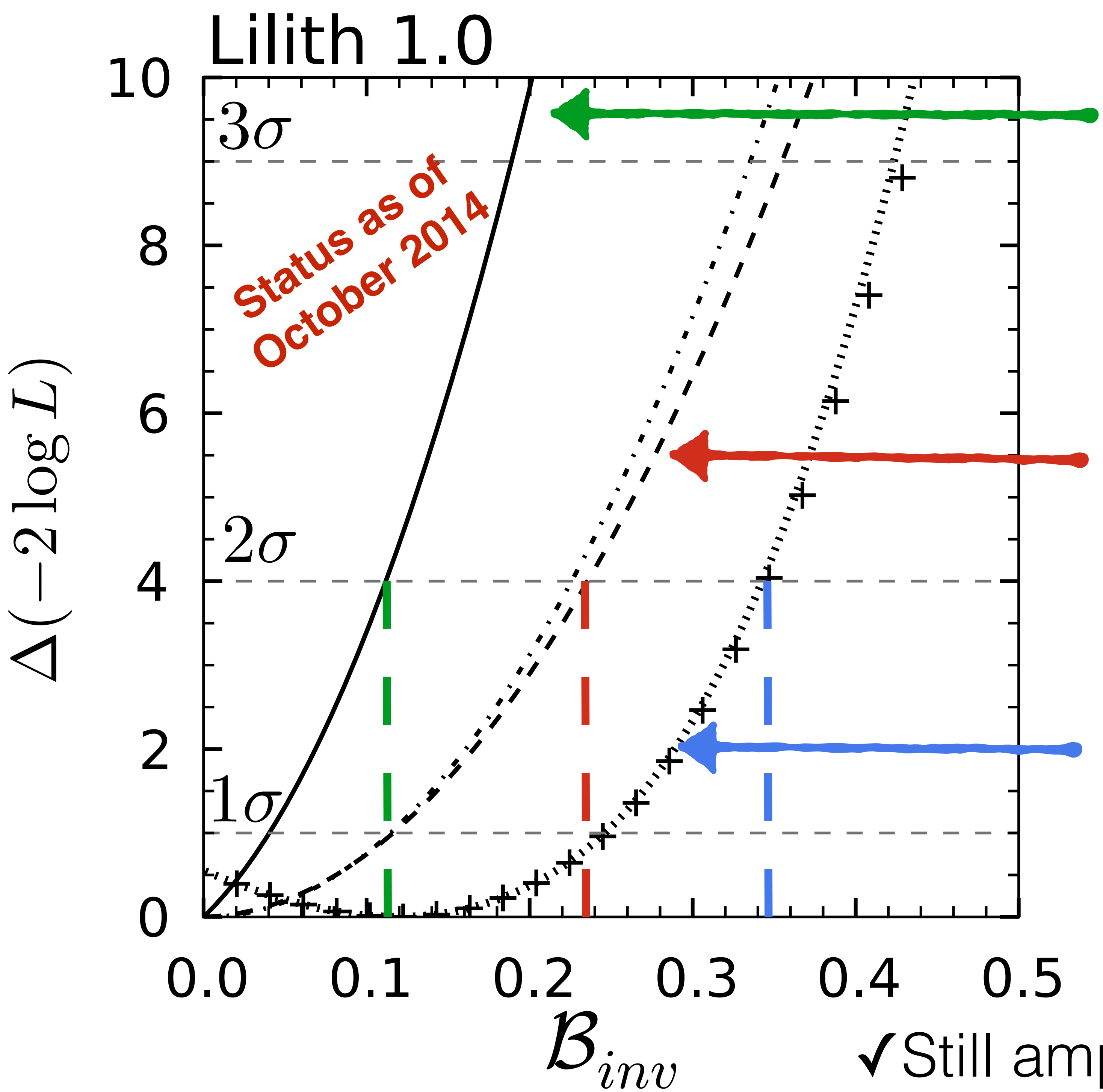
C_U, C_D, C_V
C_U, C_D, C_V, ΔC_γ, ΔC_g +invisible

$\mathcal{B}_{inv} \lesssim 0.34$ at 95.4% C.L.

[JB, B. Dumont, S. Kraml] [arXiv:1409.1588]

Invisible branching ratio fits



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C_U, C_D, C_V
C_U, C_D, C_V, ΔC_γ, ΔC_g +invisible

$\mathcal{B}_{inv} \lesssim 0.34$ at 95.4% C.L.

✓Still ample room for new decay modes

[JB, B. Dumont, S. Kraml] [arXiv:1409.1588]

Constraining extended Higgs sectors: a 2HDM example

- **Two Higgs doublet model** (2HDM): Minimal extension of the SM, including a second Y=+1 Higgs doublet

$$\mathcal{V} = m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 - [m_{12}^2\Phi_1^\dagger\Phi_2 + \text{h.c.}]$$
$$+\tfrac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \tfrac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1)$$
$$+\left\{\tfrac{1}{2}\lambda_5(\Phi_1^\dagger\Phi_2)^2 + [\lambda_6(\Phi_1^\dagger\Phi_1) + \lambda_7(\Phi_2^\dagger\Phi_2)]\Phi_1^\dagger\Phi_2 + \text{h.c.}\right\}.$$

$\Phi_1 \to \Phi_1, \Phi_2 \to -\Phi_2$

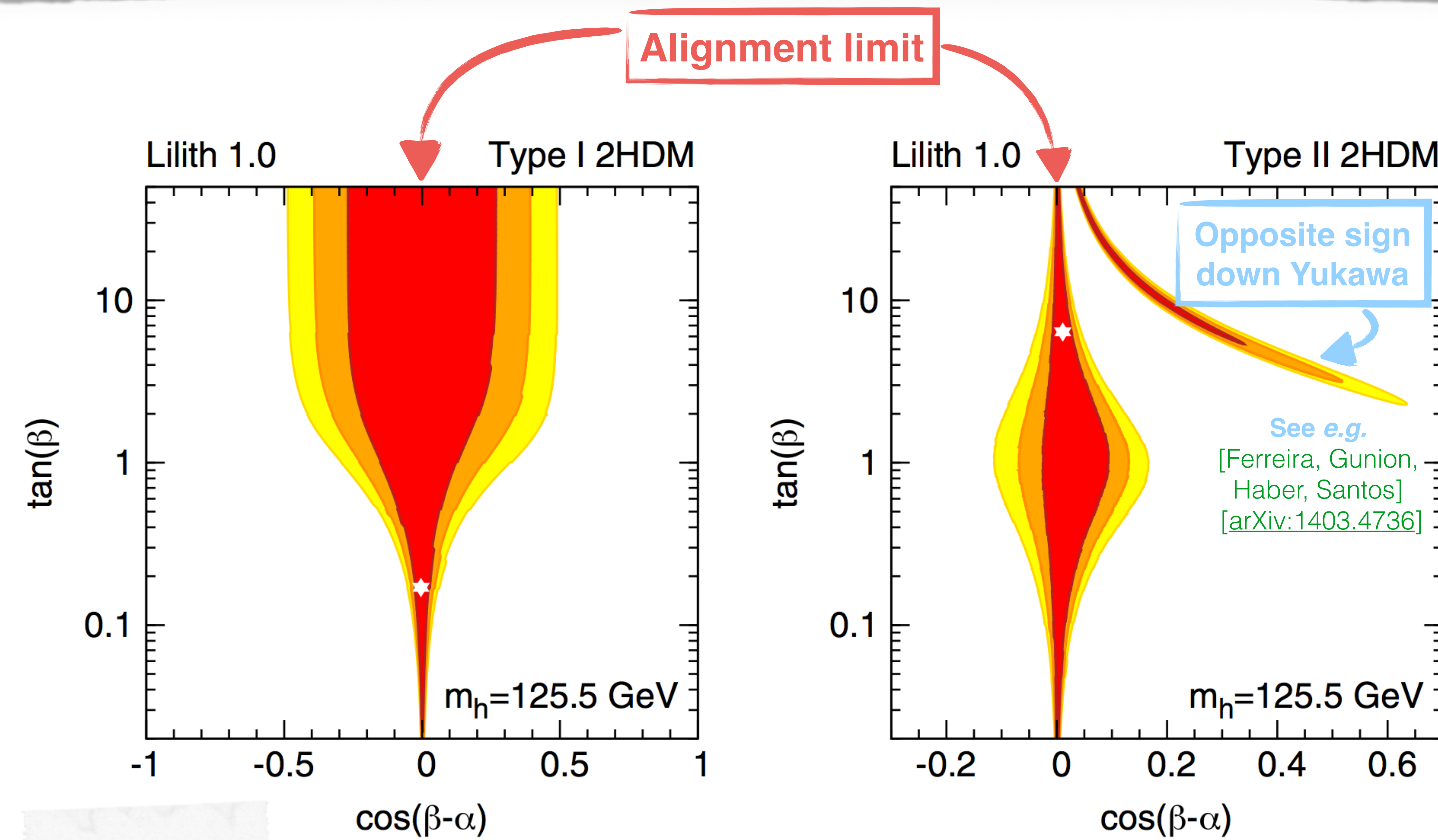
- Hypotheses: Softly broken Z2 symmetry, no CP-violation, no flavor changing neutral current (we consider the so-called Type I and II models)

- Five physical degrees of freedom: 2 CP-even (h, H), 1 CP-odd (A), 2 charged (H^+ ,H^-) states

- Free parameters: $m_h, m_H, m_A, m_{H^\pm}, \tan\beta, \sin(\alpha), m_{12}^2$
$\tan\beta$: ratio of the 2 Higgs vevs, α : mixing angle of the CP-even mass matrix

- Impose constraints from: theory (stability, perturbativity…), STU parameters, flavor, direct Higgs searches (light and heavy), signal strengths at 125 GeV

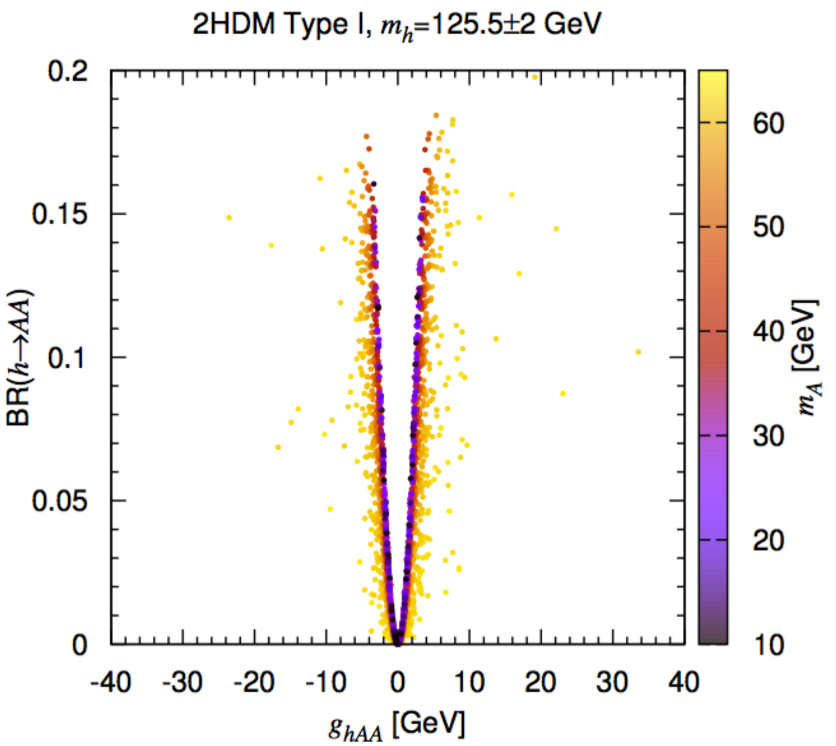
Signal strengths constraints in the 2HDM

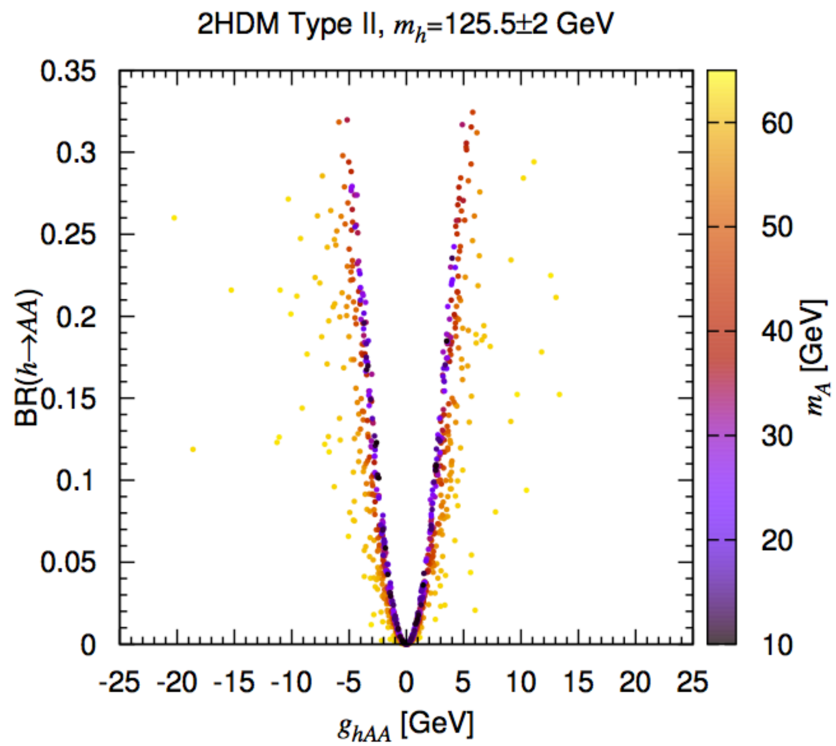


	Type I and II	Type I		Type II	
Higgs	C_V	C_U	C_D	C_U	C_D
h	$\sin(\beta-\alpha)$	c_α/s_β	c_α/s_β	c_α/s_β	$-s_\alpha/c_\beta$

[JB, B. Dumont, S. Kraml] [arXiv:1409.1588]

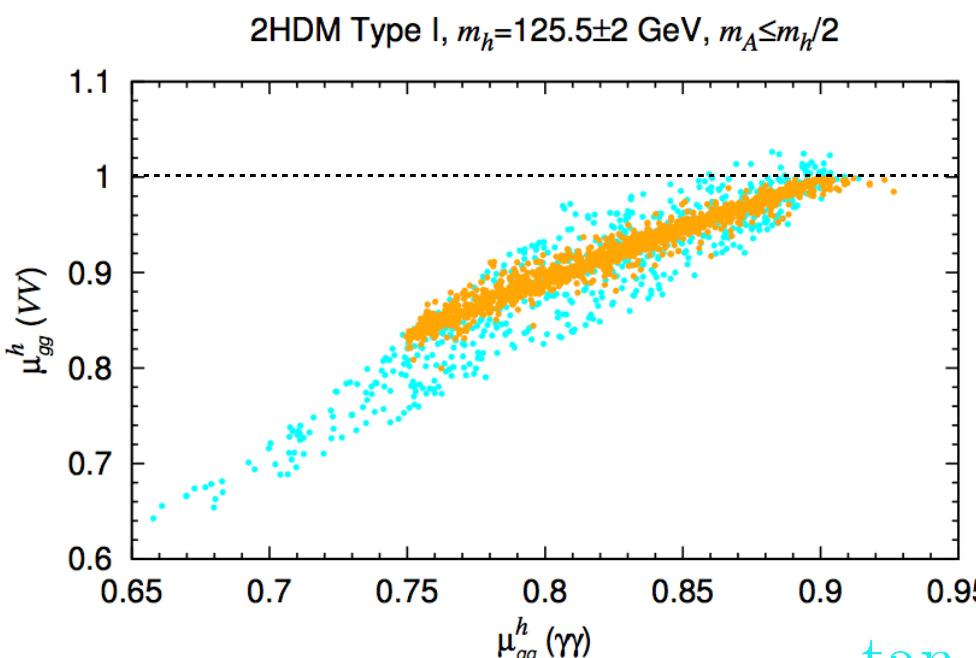
Light pseudo-scalar in the 2HDM: $m_A<m_h/2$

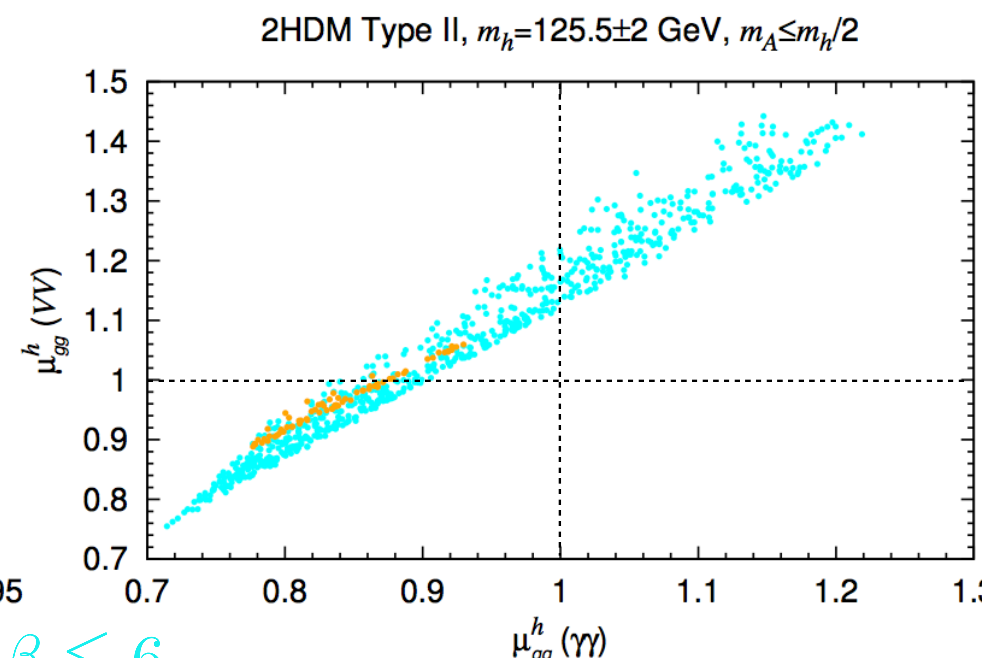




$$m_h = 125.5 \pm 2\ \text{GeV}$$

Strong constraints on h125→AA branching ratio from the Higgs signal strengths





$\tan\beta \lesssim 6$

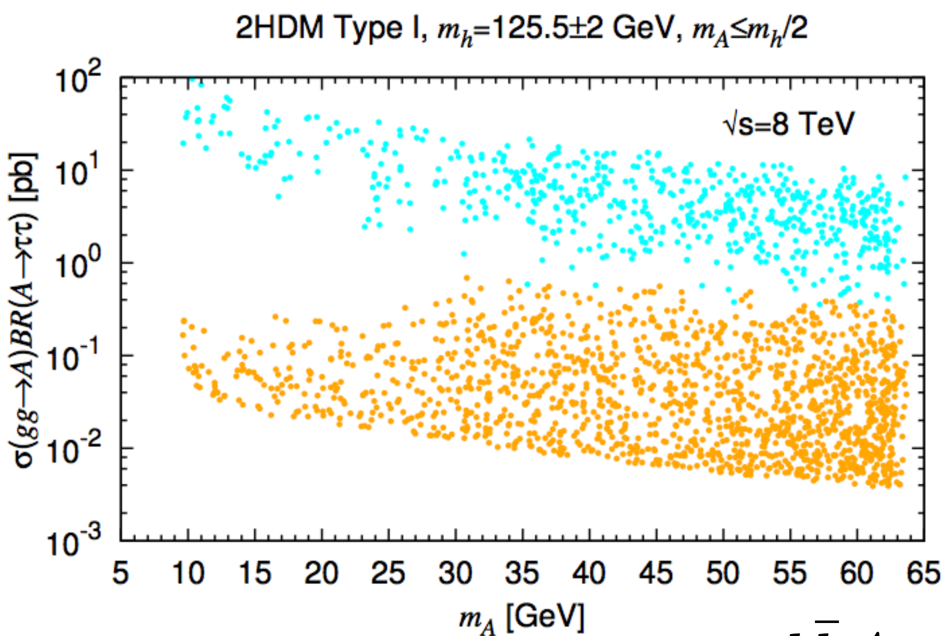
$\tan\beta \gtrsim 6$

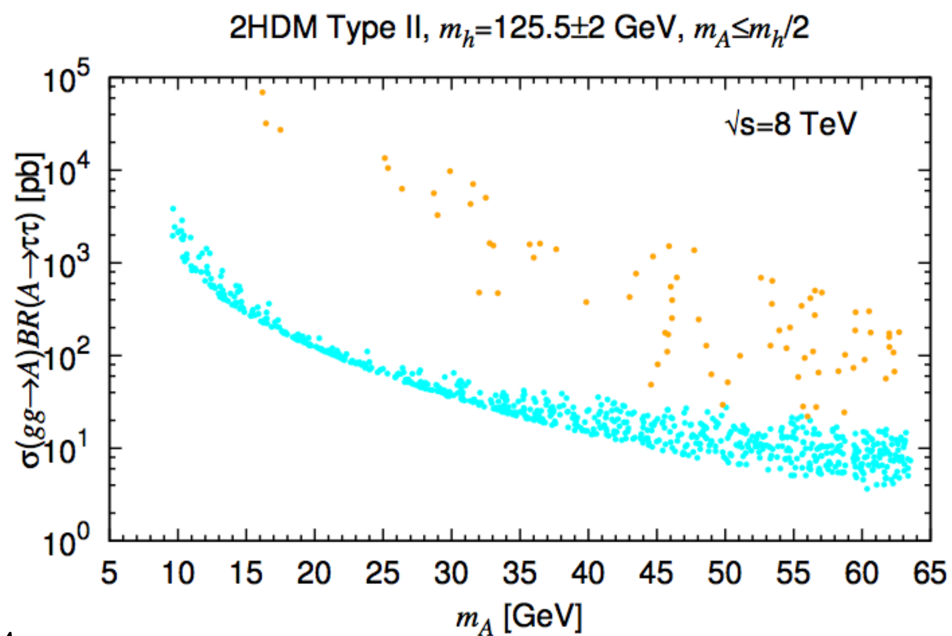
Impossible to achieve SM μ(gg,VV) and μ(gg,$\gamma\gamma$) simultaneously.
LHC Run II will be able to test these scenarios

[JB, J.F. Gunion, Y. Jiang, S. Kraml] [arXiv:1412.3385]

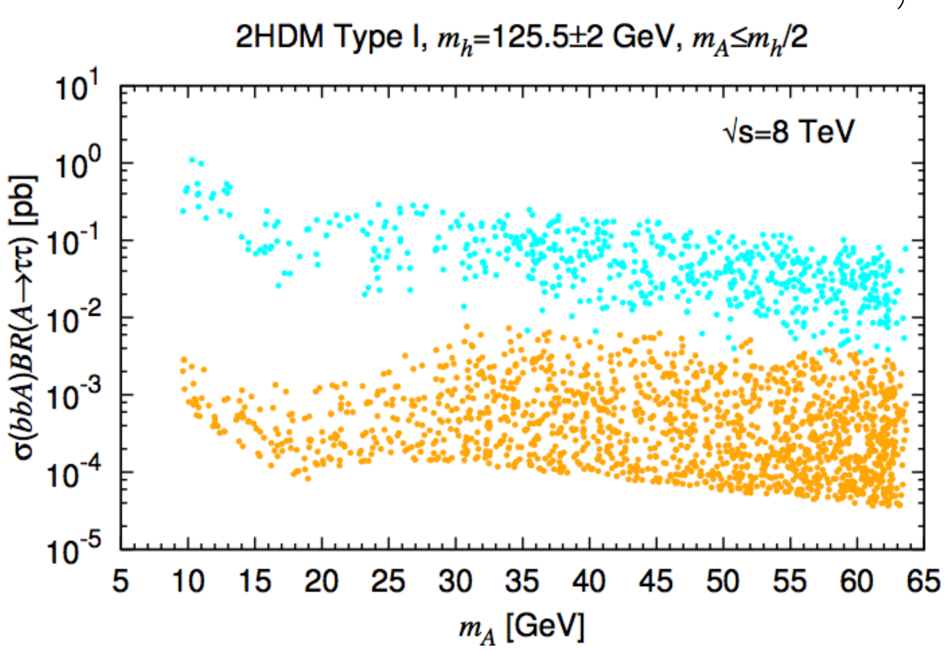
Light pseudo-scalar in the 2HDM: A→ττ cross-section at LHC8

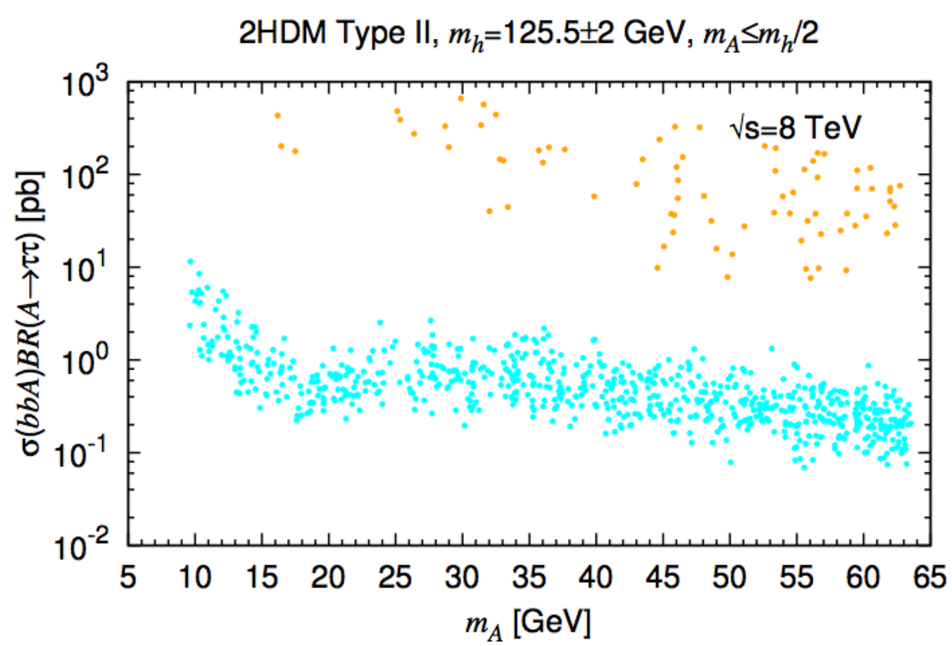
$$gg \to A \to \tau\tau$$





$$b\bar{b}A,\, A \to \tau\tau$$





$\tan\beta \lesssim 6$

$\tan\beta \gtrsim 6$

Very large cross sections in the Type II model over the full m_A range: should produce readily observable peaks

$\mathcal{O}(10)$ pb should be observable in the current dataset

A→μμ: same shape, factor 100 smaller

At 14 TeV: gain of factor~2 in cross section

[JB, J.F. Gunion, Y. Jiang, S. Kraml] [arXiv:1412.3385]

Prospects for LHC Run II

Prospects for LHC Run II

- The likelihood obtained from the LHC Run I measurements has been **well validated** against ATLAS and CMS results, however this could change with LHC Run II results where *systematic uncertainties are expected to dominate over the statistical ones*.
- As more (X,Y) combinations will be probed with higher precision, a **total breakdown** of the signal strength in terms of the 5 production modes would be needed
- **Mass dependence** of the likelihood can also provide important information
- We advocate the experimental collaborations to provide the signal strengths in the **largest *relevant* space** in a numerical form, *i.e.* possibly

$$(m_H, \mu(\mathrm{ggH}, Y), \mu(\mathrm{ttH}, Y), \mu(\mathrm{VBF}, Y), \mu(\mathrm{ZH}, Y), \mu(\mathrm{WH}, Y))$$

- Proposals to **decouple** common systematic uncertainties from the published results and re-inject them in a later stage have been proposed, *e.g.*,

« **A novel approach to Higgs Coupling Measurements** »
K. Cranmer et al
[arXiv:1401.0080v1]

Conclusions

Conclusions

- **Strong constraints** on the Higgs sector already arise from the LHC precise Higgs measurements
- Global fits are necessary since experimental collaborations cannot cover all new physics scenarios
- **Lilith** is a Python tool that allows to impose the **up-to-date constraints** coming from the LHC and Tevatron and has been **thoroughly validated**
- Lilith can be used as a Python library, through a command line interface or a C/C++/Root interface

Lilith

LIght LIkelihood fiT for the Higgs

http://lpsc.in2p3.fr/projects-th/lilith/

- With more data to be collected during LHC Run II, the construction of a combined likelihood would require more detailed experimental inputs
- We strongly advocate the experimental collaborations to *pursue* the efforts initiated during Run I to make the Higgs measurement results **accessible** and **usable** by the **whole 3-PAC community**

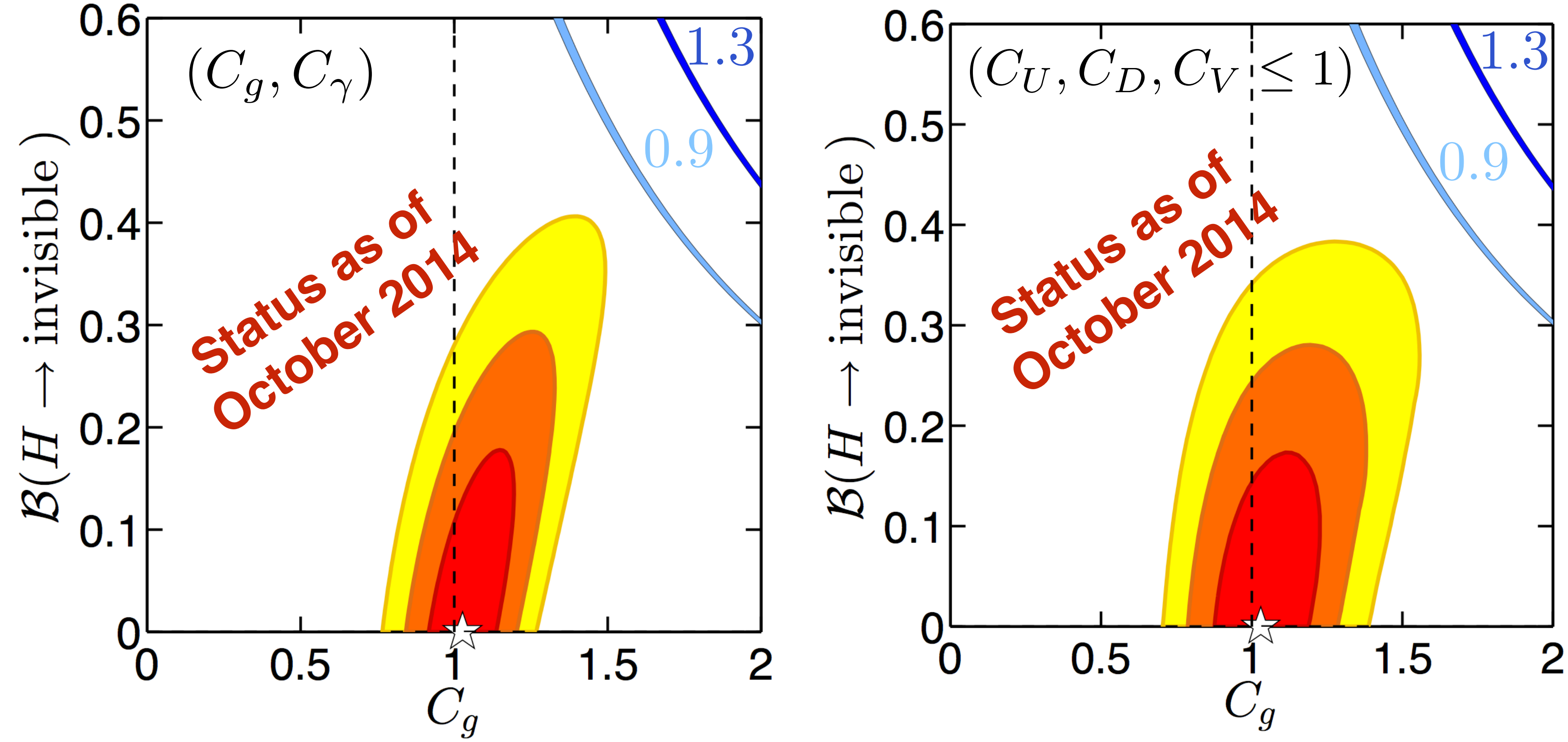
Backup

Some applications

Higgs direct search/mono-jet interplay

- Signal strengths measurements constraint the Higgs invisible branching ratio: $$\mu(X,Y) \to (1-\mathcal{B}_{\text{invisible}})\mu(X,Y)$$
- Mono-jet searches can provide competitive constraints (gg→H+1-2j, VBF): $$R_{\text{invisible}} \equiv \left(\tfrac{2}{3}C^2_{\text{ggH}} + \tfrac{1}{3}C^2_{\text{VBF}}\right)\mathcal{B}_{\text{invisible}} < 1.1 \text{ at } 95\% \text{ CL}$$

[Djouadi, Falkowski, Mambrini, Quevillon] [arXiv:1205.3169]



[Bélanger, Dumont, Ellwanger, Gunion, Kraml] [arXiv:1302.5694]

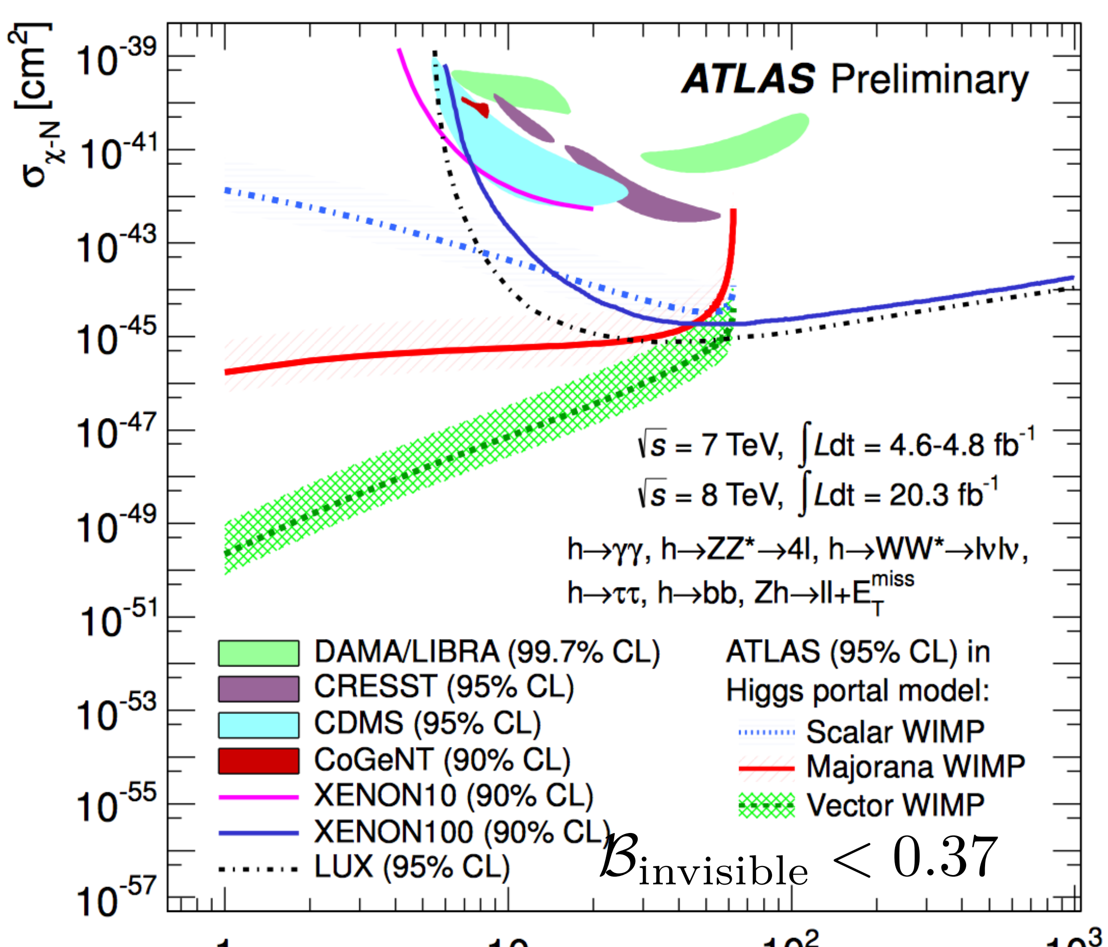
Higgs/dark matter direct searches interplay

- Higgs portal scenarios with scalar, vector or Majorana dark matter χ:

$$\Delta\mathcal{L}_S = -\frac{1}{2}m_S^2 S^2 - \frac{1}{4}\lambda_S S^4 - \frac{1}{4}\lambda_{hSS} H^\dagger H S^2 \,,$$
$$\Delta\mathcal{L}_V = \frac{1}{2}m_V^2 V_\mu V^\mu + \frac{1}{4}\lambda_V (V_\mu V^\mu)^2 + \frac{1}{4}\lambda_{hVV} H^\dagger H V_\mu V^\mu \,,$$
$$\Delta\mathcal{L}_f = -\frac{1}{2}m_f f f - \frac{1}{4}\frac{\lambda_{hff}}{\Lambda} H^\dagger H f f + \text{h.c.} \,.$$

- The invisible branching ratio only depends on the DM mass and the spin independent cross-section

$$\mathcal{B}_{\text{invisible}} = \frac{\Gamma(H \to \chi\chi)}{\Gamma(H \to \chi\chi) + \Gamma(H \to \text{SM-SM})}$$

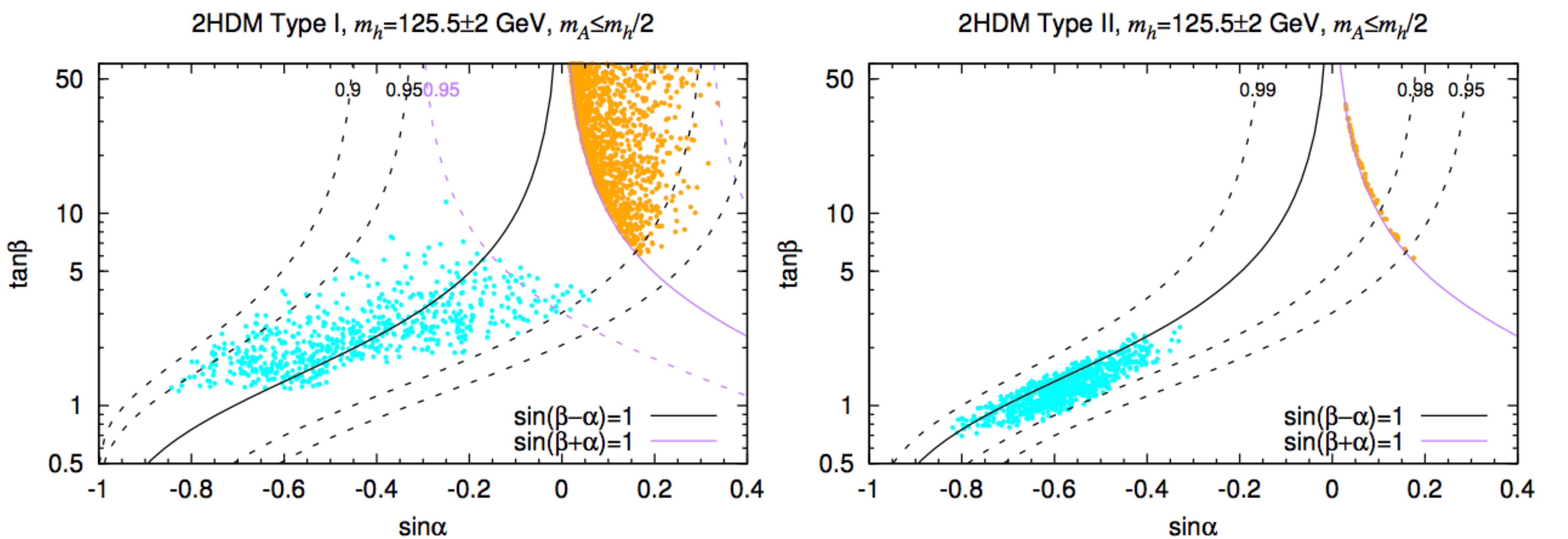


[ATLAS-CONF-2014-010]

Such simple scenarios do not account for the correct relic density
Generally need ≲100 GeV
extra particles to account for it

[Greljo, Julio, Kamenik, Smith, Zupan]
[arXiv:1302.5694]

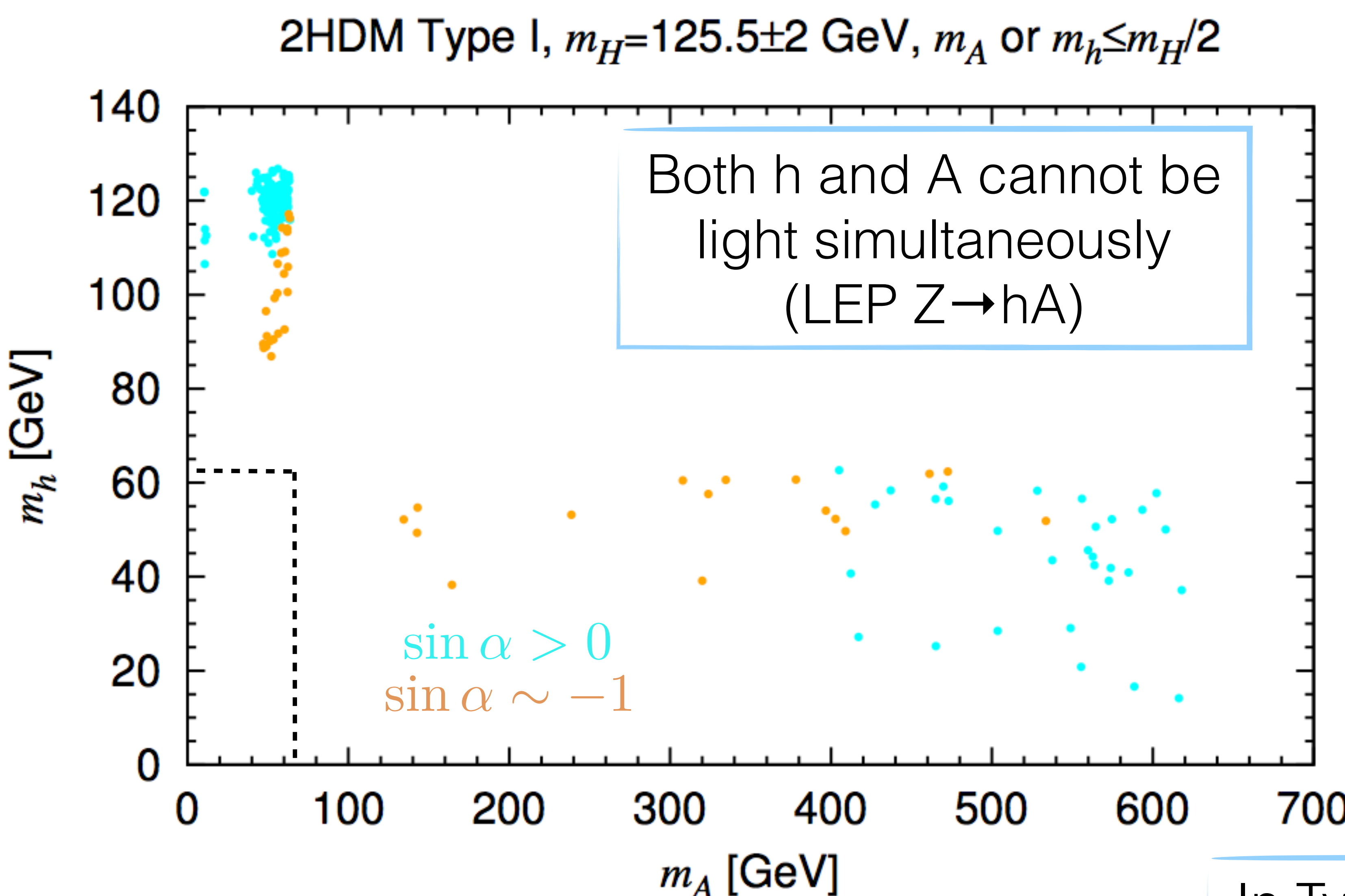
Light scalars in the 2HDM: m_h=125 GeV case



$$g_{hAA} = \frac{1}{2v}\left[\left(2m_A^2 - m_h^2\right)\frac{\cos(\alpha-3\beta)}{\sin 2\beta} + \left(8m_{12}^2 - \sin 2\beta\left(2m_A^2+3m_h^2\right)\right)\frac{\cos(\beta+\alpha)}{\sin^2 2\beta}\right]$$

[JB, J.F. Gunion, Y. Jiang, S. Kraml] [arXiv:1412.3385]

Light scalars in the 2HDM: m_H=125 GeV case



Both h and A cannot be light simultaneously (LEP Z→hA)

In Type II, B-physics require $m_A \gtrsim 200$ GeV

[JB, J.F. Gunion, Y. Jiang, S. Kraml] [arXiv:1412.3385]

Light scalars in the 2HDM: m_H=125 GeV case

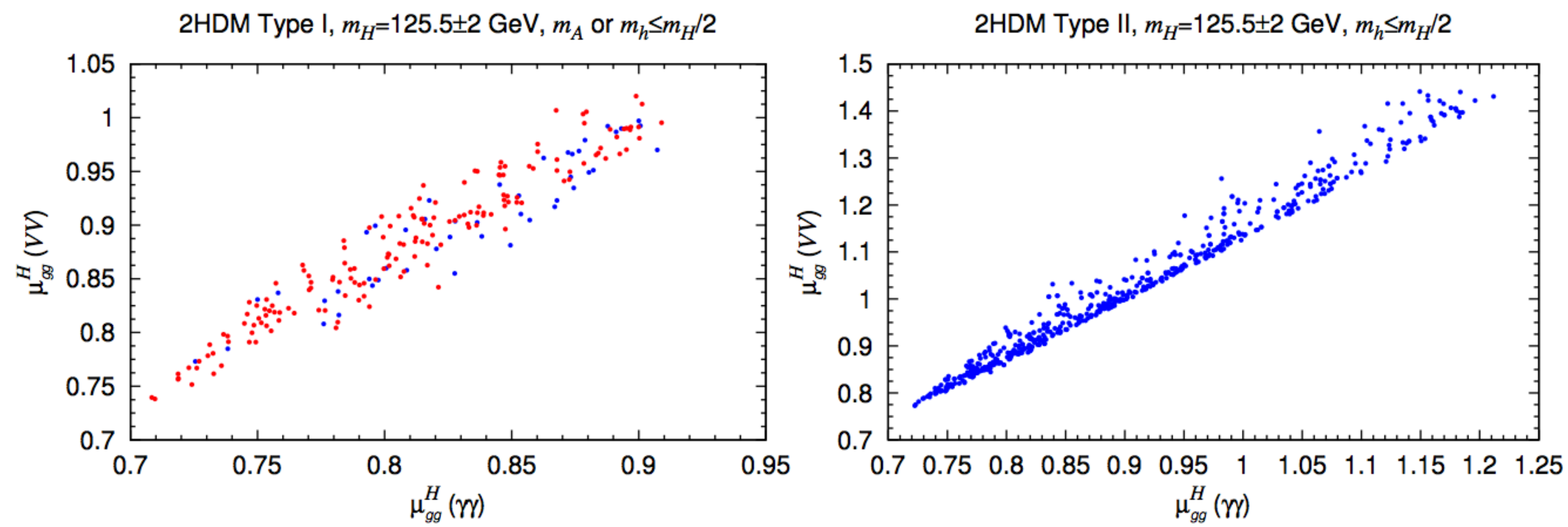


FIG. 13: Signal strengths $\mu^H_{gg}(VV)$ vs. $\mu^H_{gg}(\gamma\gamma)$ for the Type I and Type II models. Points with $m_A \leq m_H/2$ are shown in red and points with $m_h \leq m_H/2$ in blue.

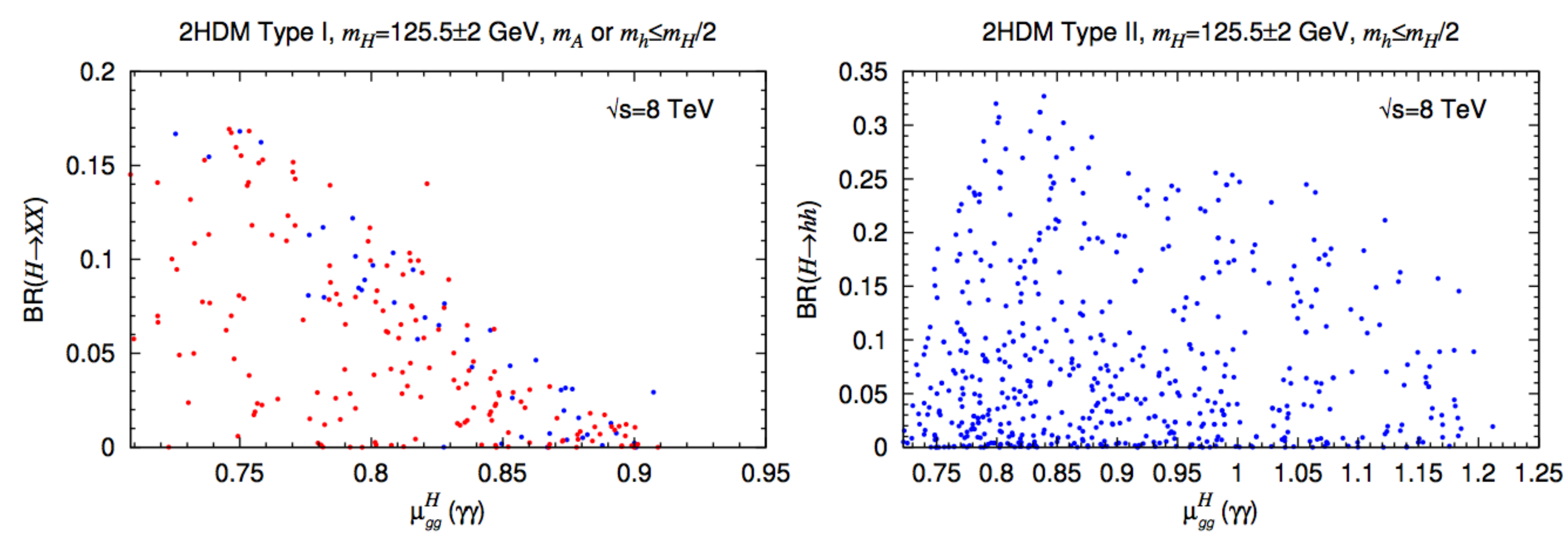
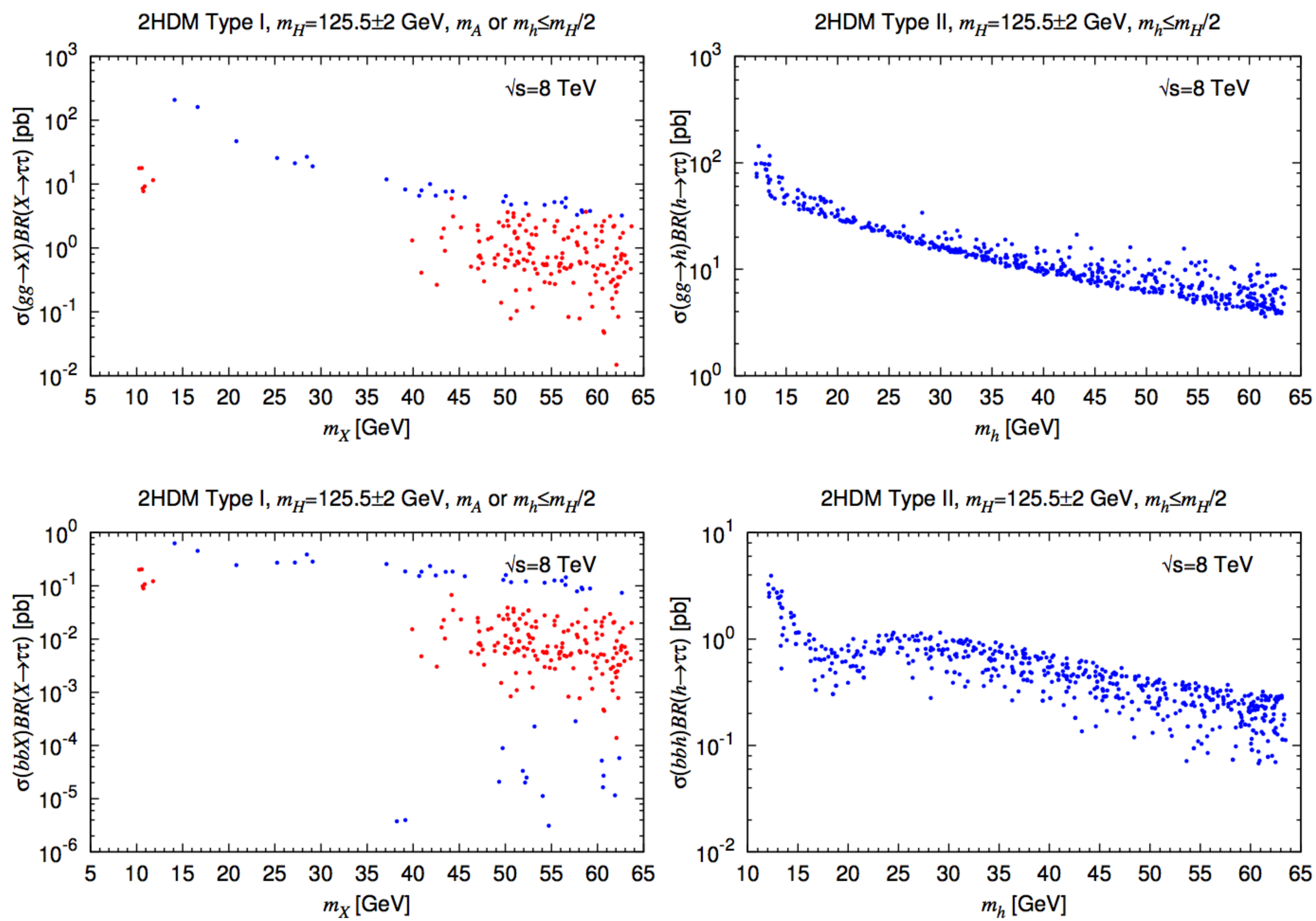


FIG. 14: Branching ratios of $H \to XX$ $(X = h, A)$ decays vs. $\mu^H_{gg}(\gamma\gamma)$ for the Type I and Type II models. Points with $m_A \leq m_H/2$ are shown in red and points with $m_h \leq m_H/2$ in blue.

[JB, J.F. Gunion, Y. Jiang, S. Kraml] [arXiv:1412.3385]

Light scalars in the 2HDM: m_H=125 GeV case

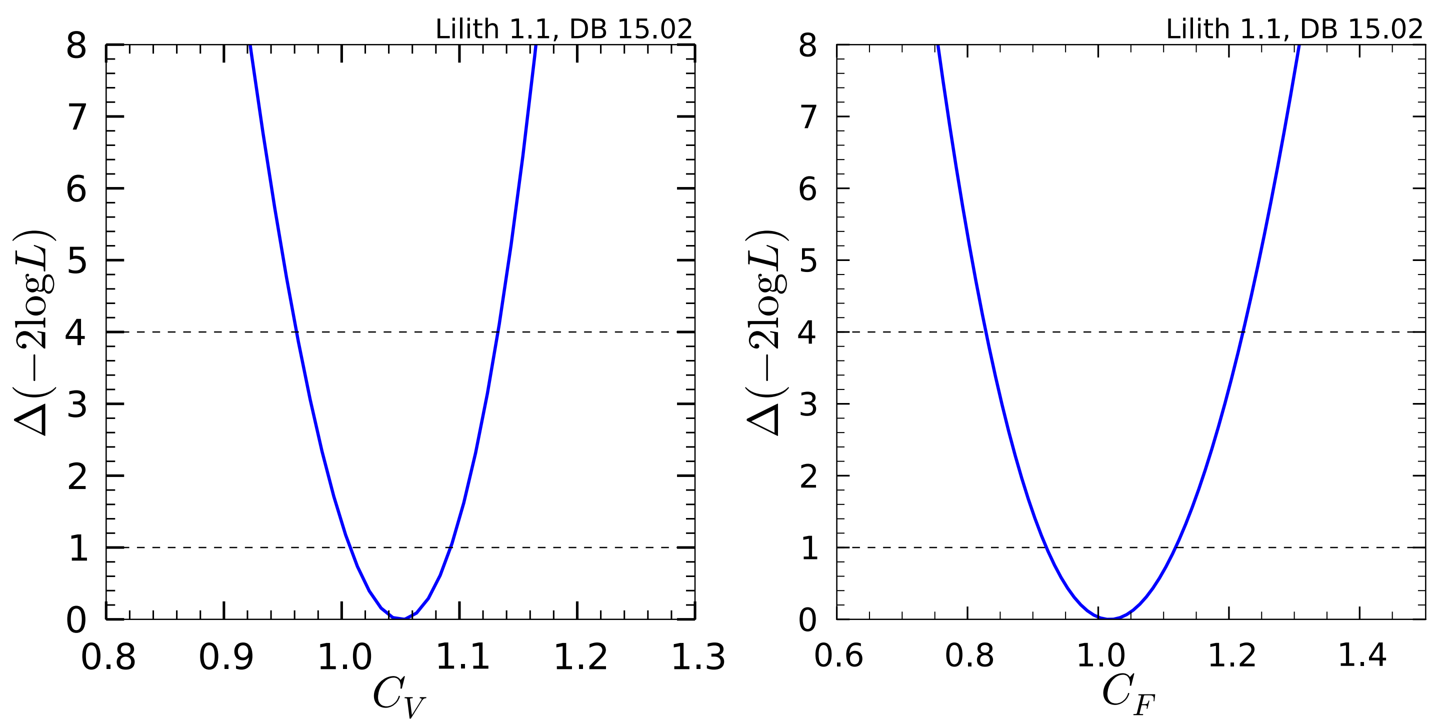


[JB, J.F. Gunion, Y. Jiang, S. Kraml] [arXiv:1412.3385]

Coupling fit with Lilith

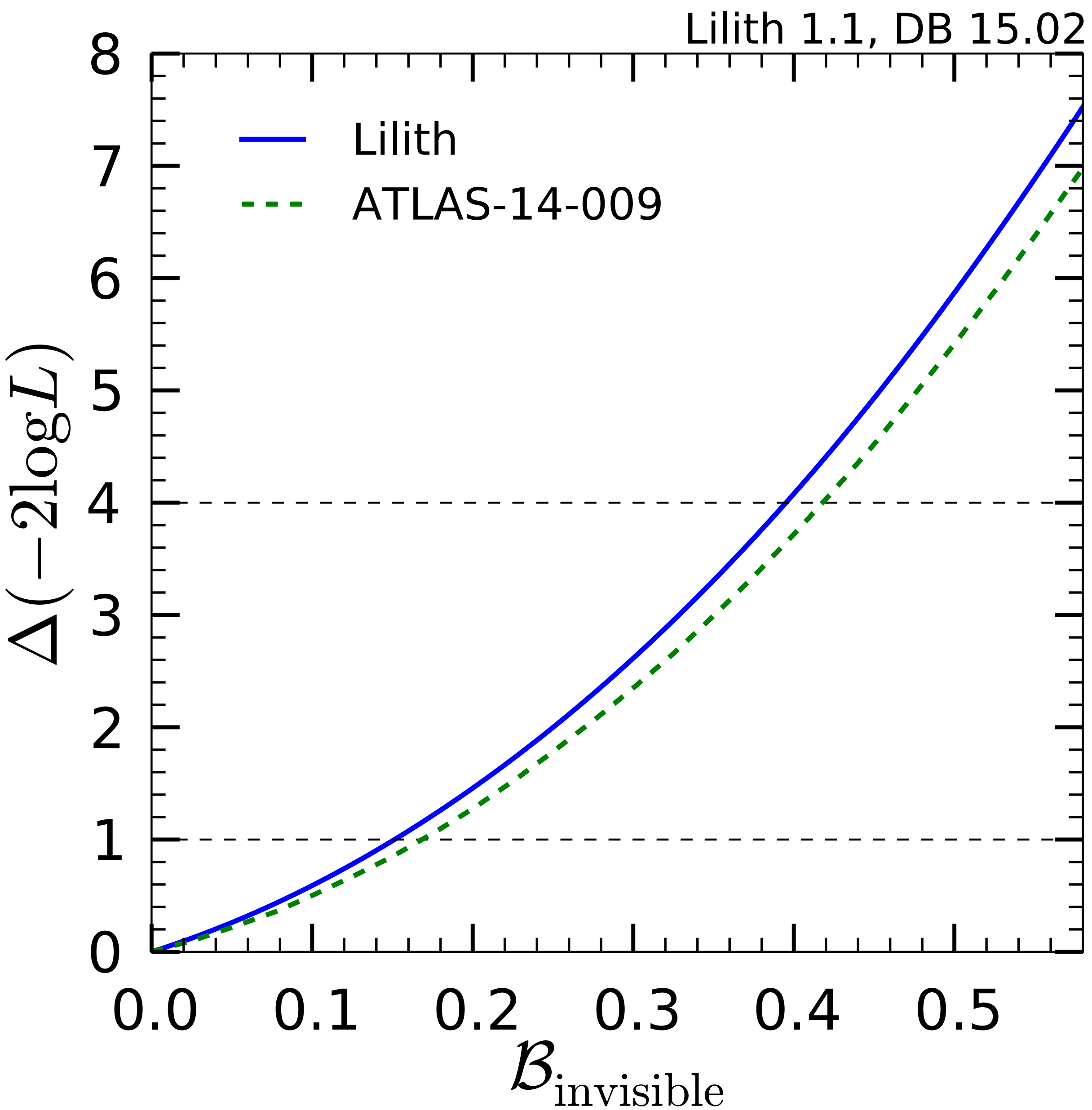
- Example provided: Lilith-1.1/examples/python/CVCF_1dprofile.py: (CV,CF) benchmark scenario fit
- Using Lilith as Python library + **Iminuit** (minimization) + **matplotlib** (plotting) is very straightforward

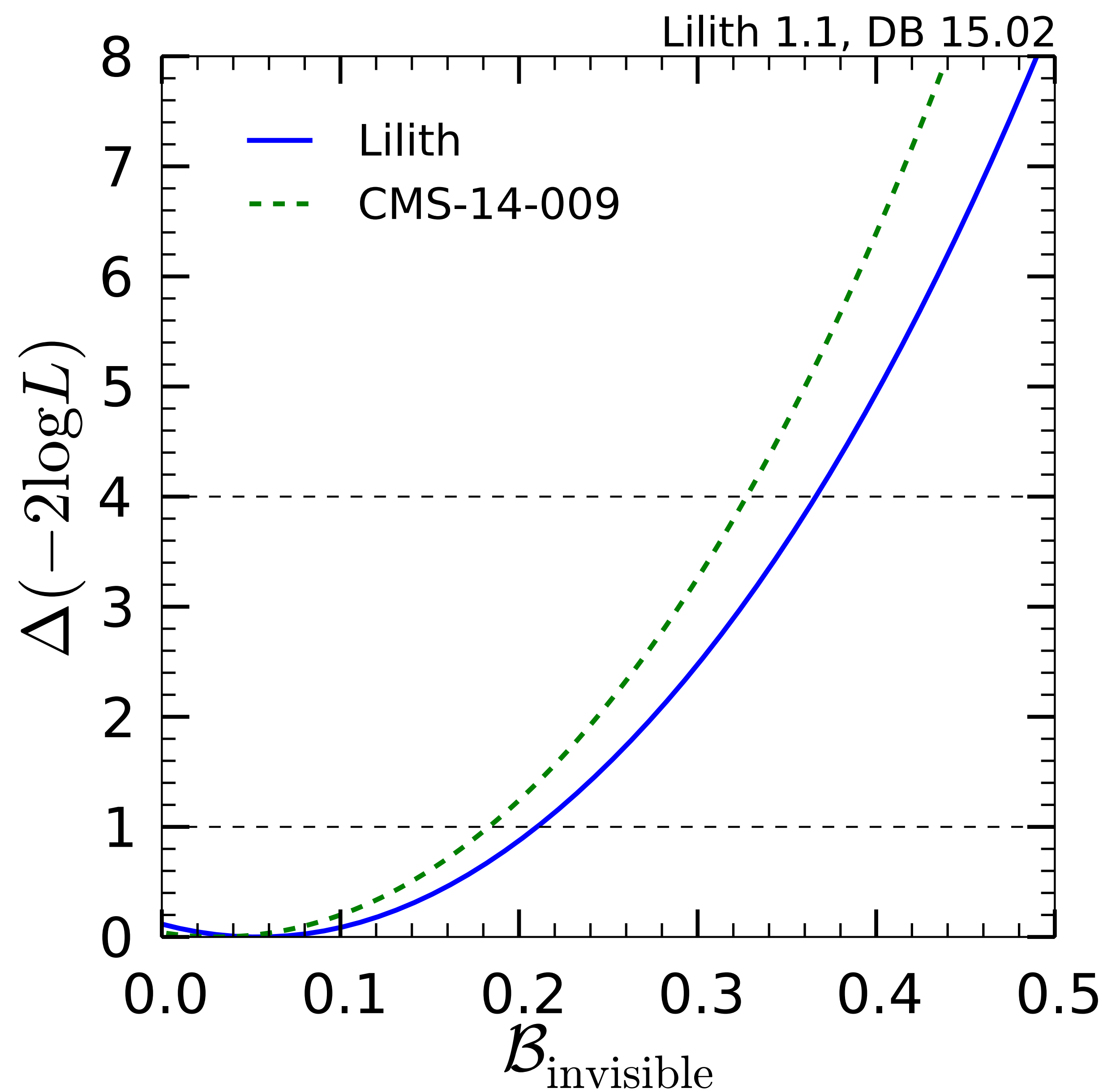
```
m = Minuit(getL, CV=1, limit_CV=(0,3), CF=1, limit_CF=(0,3))
m.migrad()
xV,yV,rV = m.mnprofile('CV', bins=300, bound=(0., 3), subtract_min=True)
xF,yF,rF = m.mnprofile('CF', bins=300, bound=(0., 3), subtract_min=True)
```



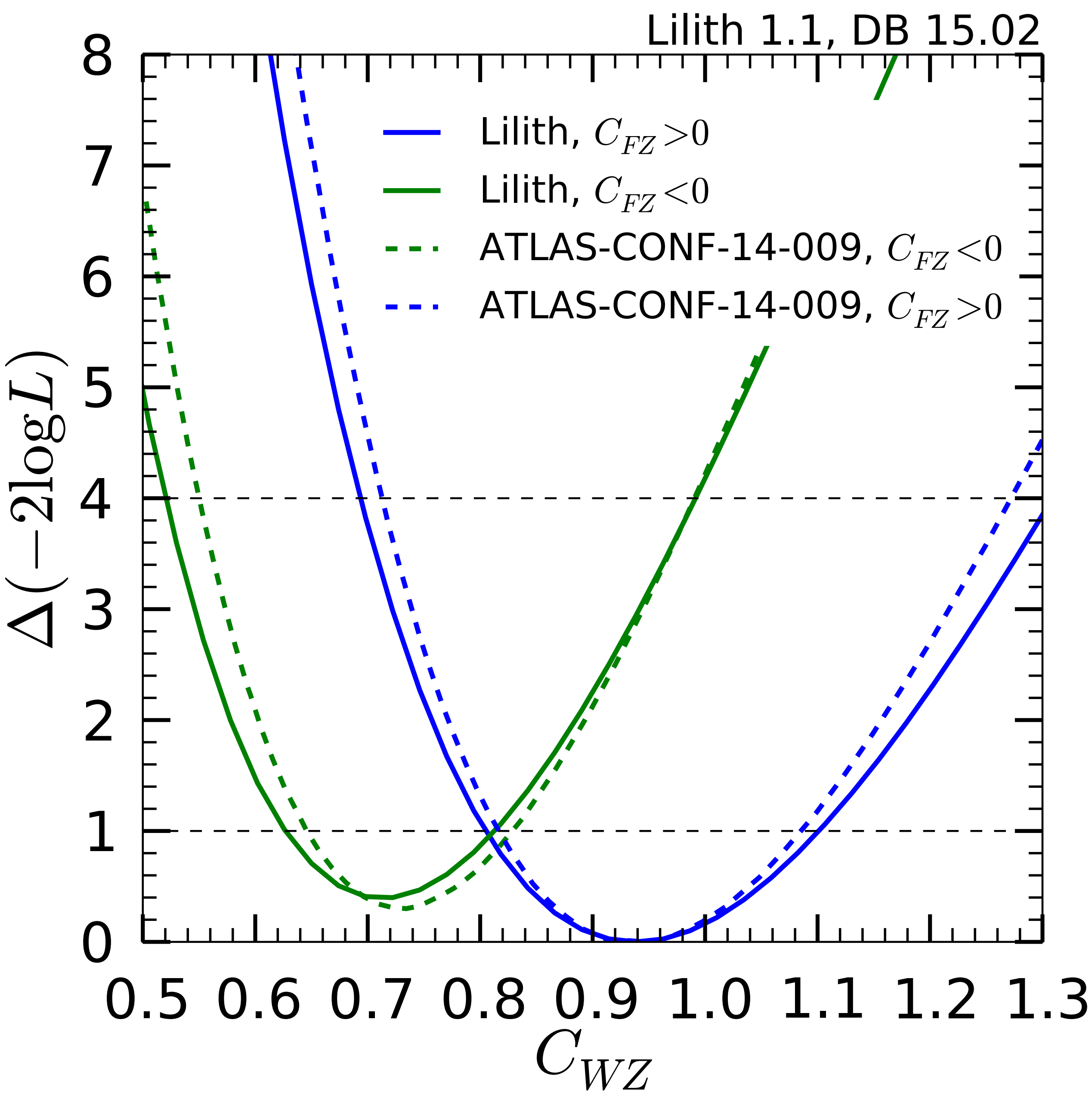
Validation

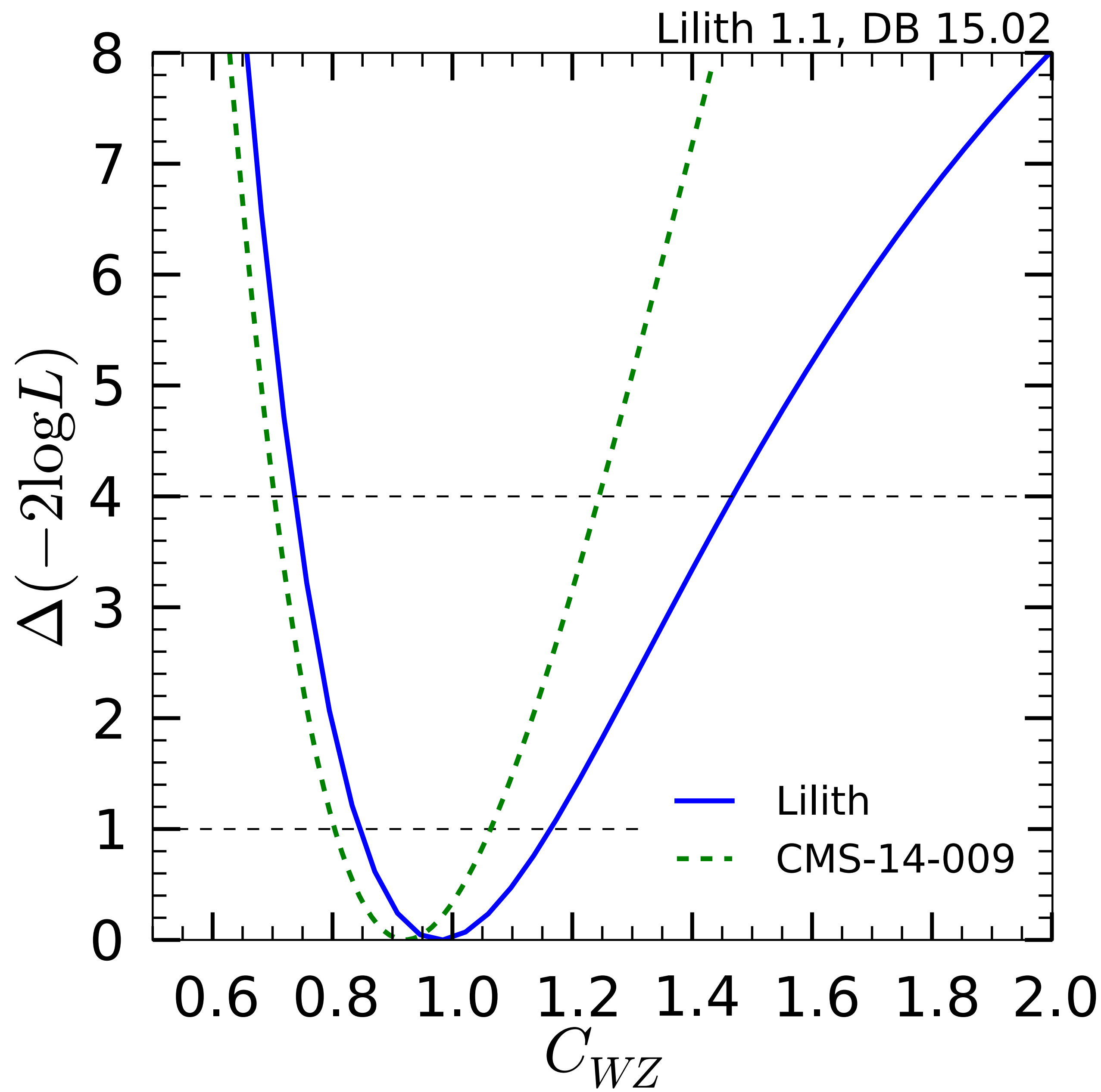
Validation: (C_γ, C_g, $BR_{invisible}$) fit





Validation: (C_F, C_Z, C_{WZ}) fit

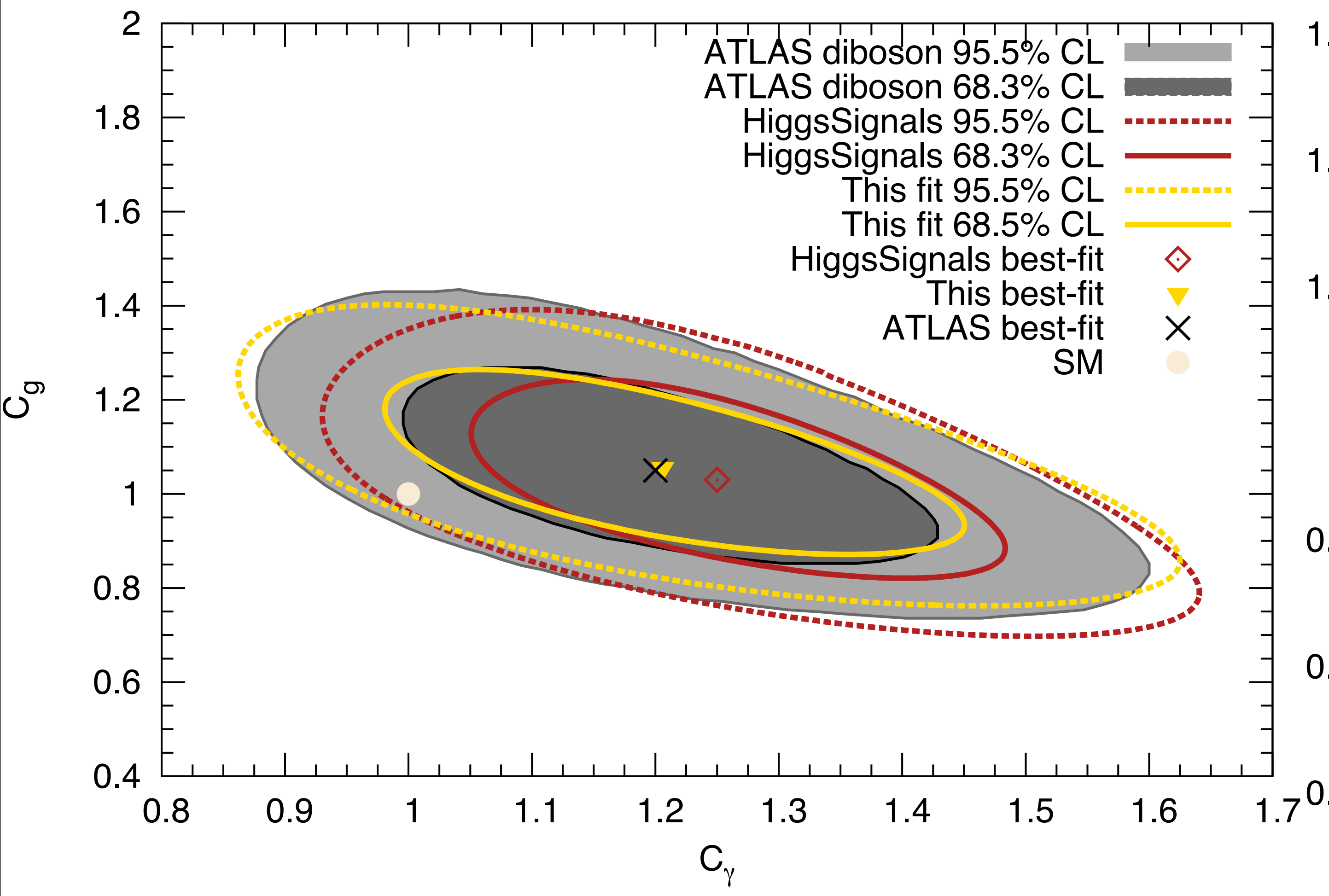




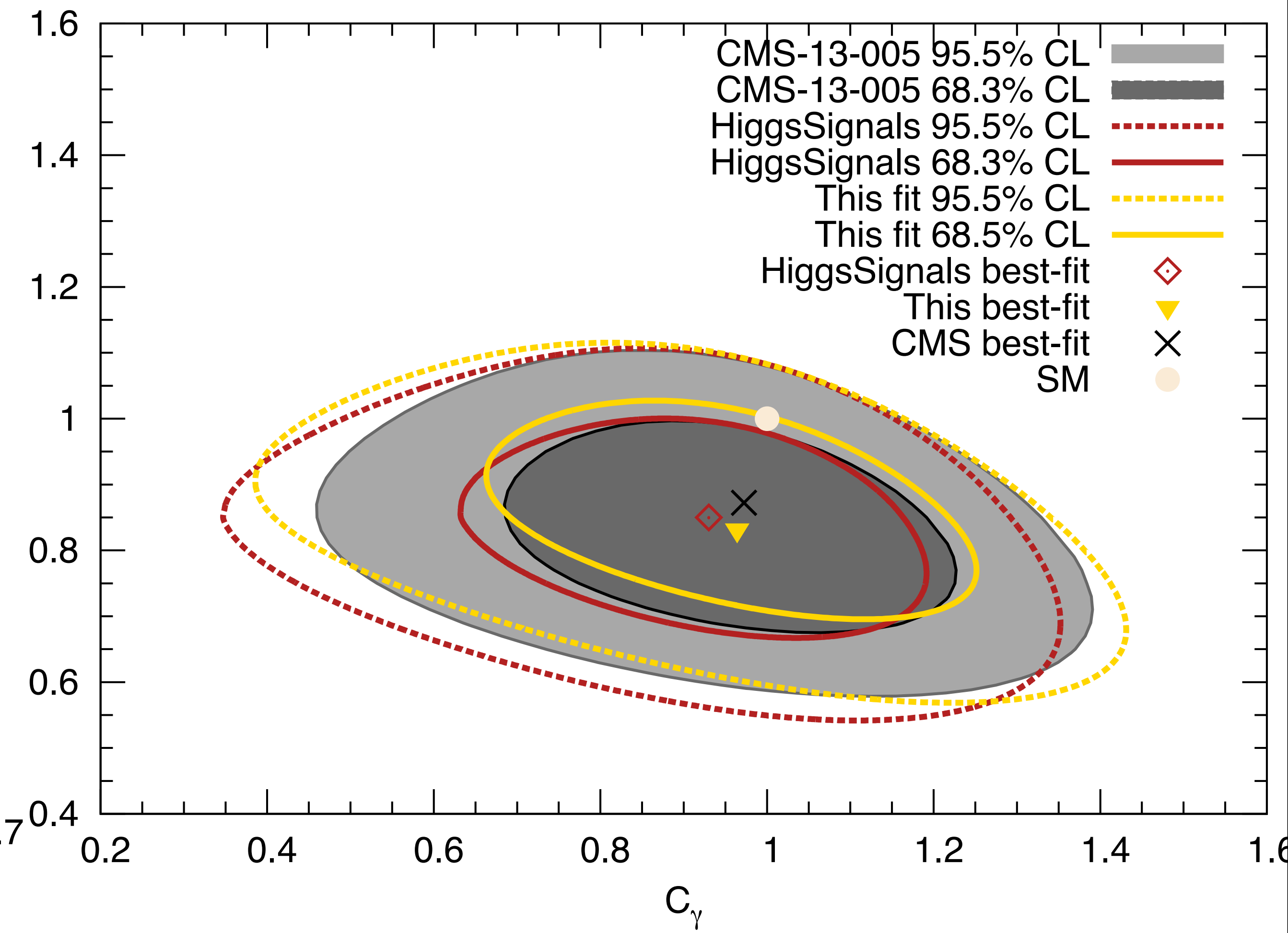
Comparison with HiggsSignals

- $$(C_\gamma,\ C_g)\ \text{fit}$$

[ATLAS-HIGG-2013-02]



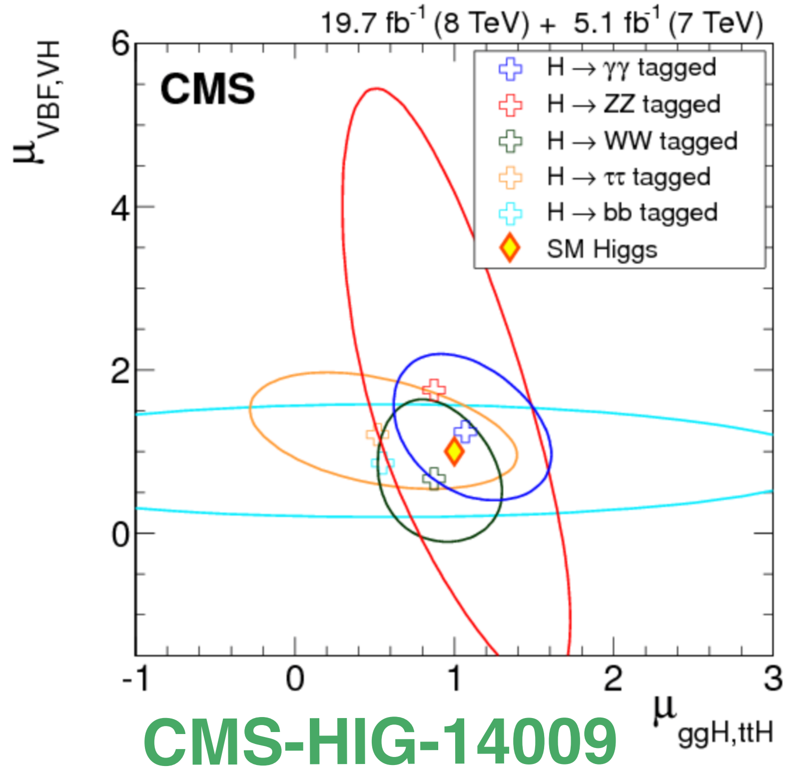
[CMS-HIG-2013-005]



Experimental data

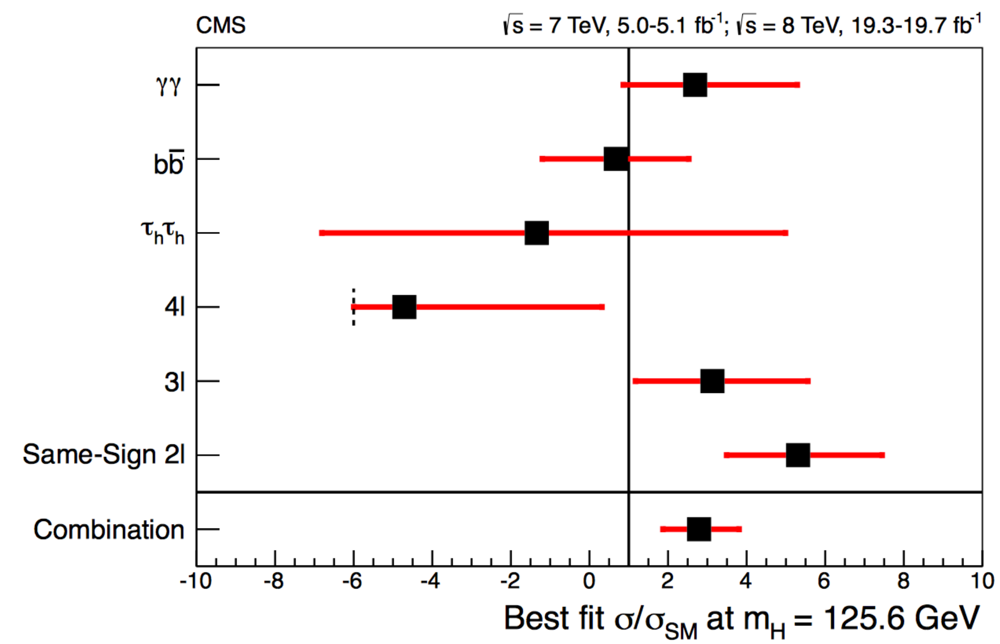
Data: CMS

$H \to \gamma\gamma, ZZ^*, WW^*, \tau\tau, b\bar{b}$

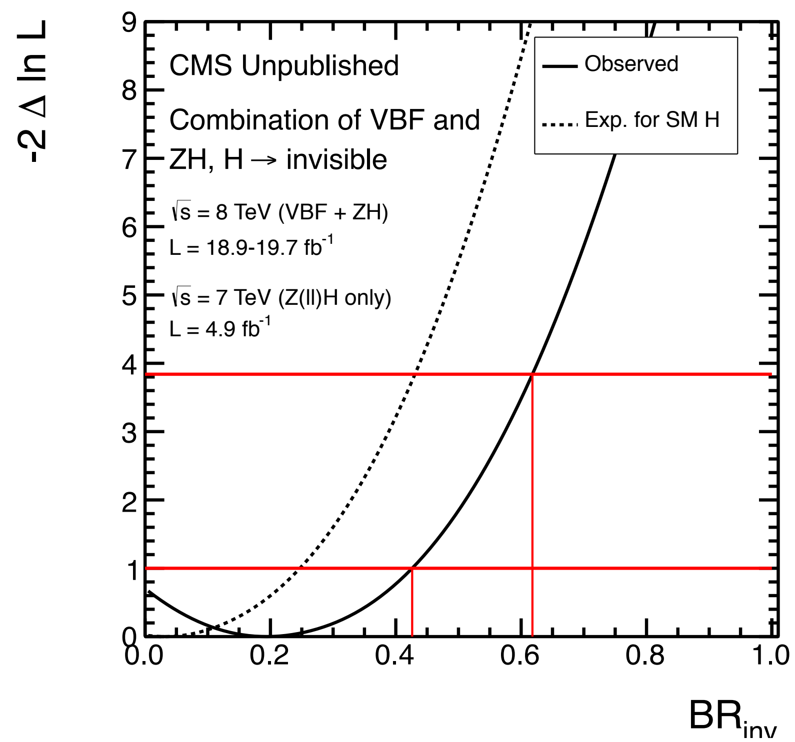


CMS-HIG-14009

ttH



CMS-HIG-13-015

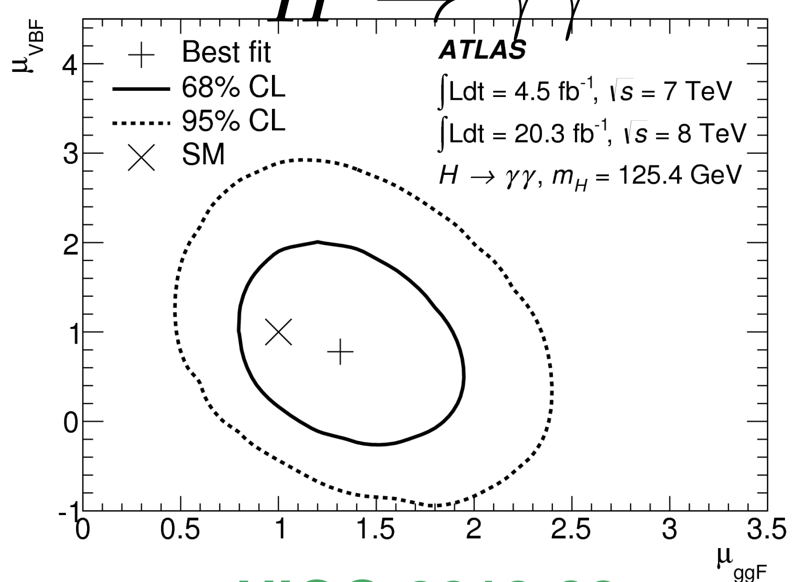


CMS-HIG-13-030

VBF + VH, $H \to$ invisible

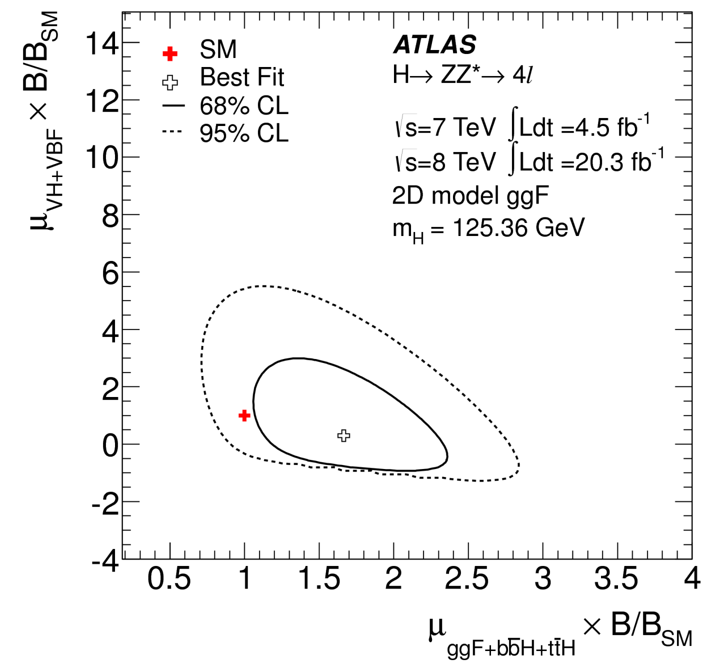
Data: ATLAS

$H \to \gamma\gamma$



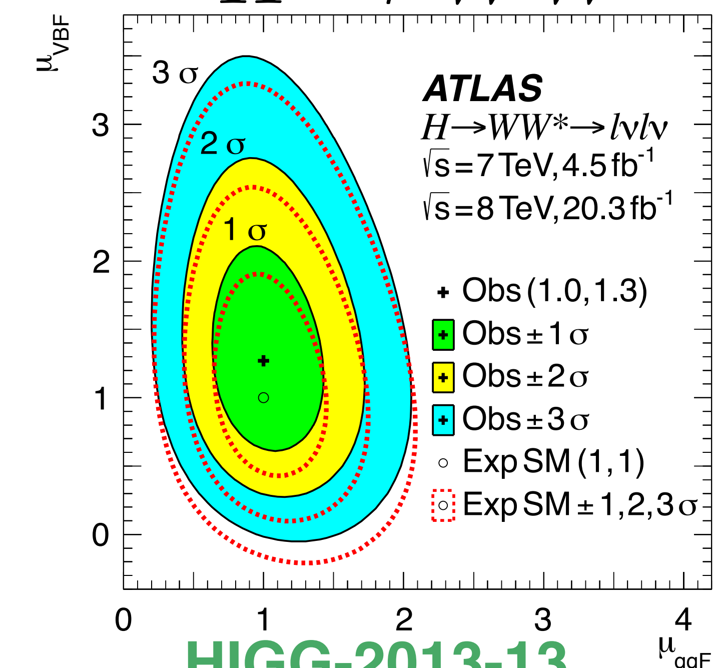
HIGG-2013-08

$H \to ZZ^*$



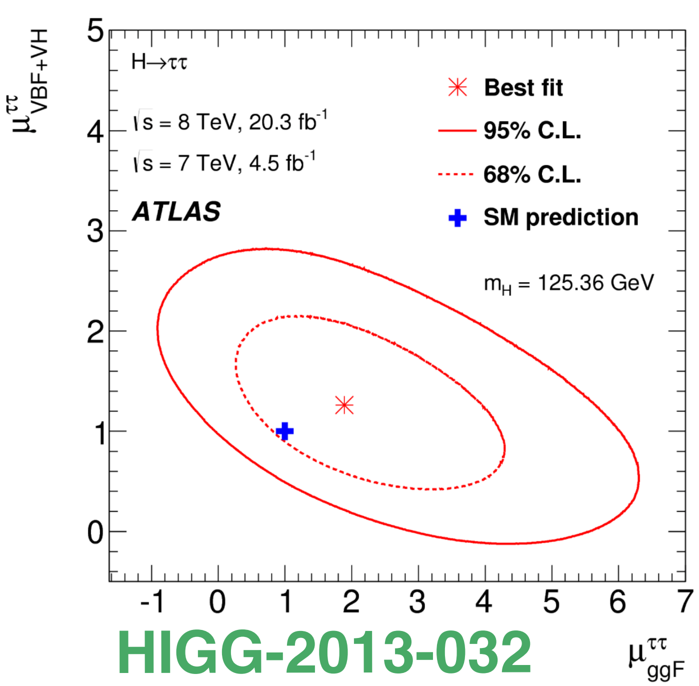
HIGG-2013-21

$H \to WW^*$



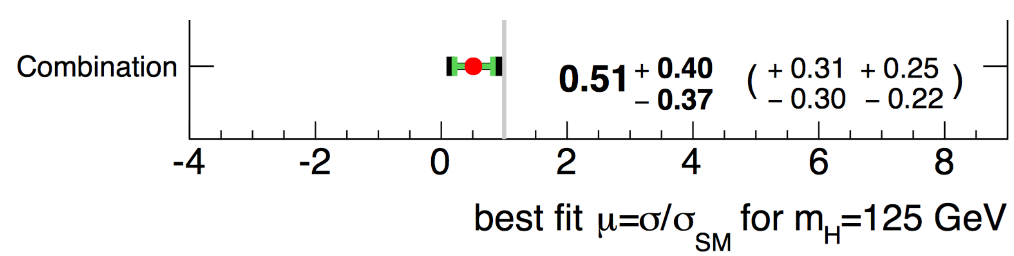
HIGG-2013-13

$H \to \tau\tau$



HIGG-2013-032

$VH, H \to b\bar{b}$

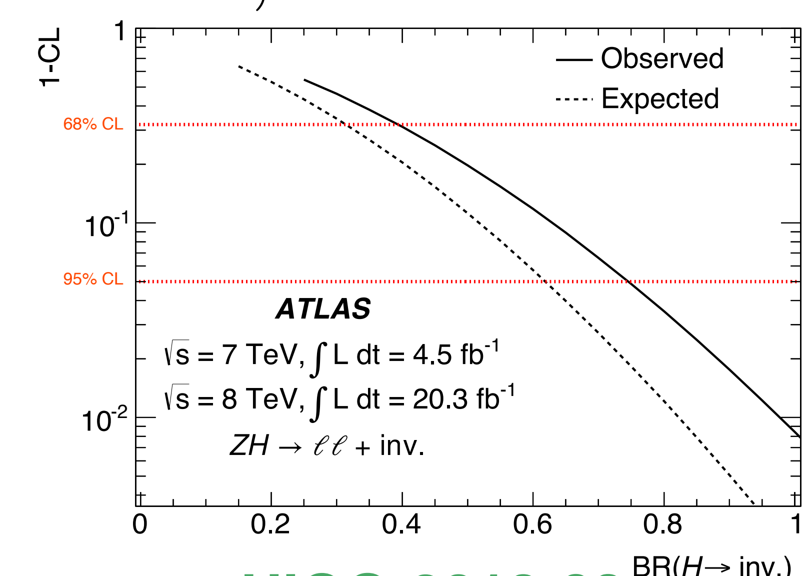


HIGG-2013-23

$ttH, H \to \gamma\gamma, b\bar{b}$

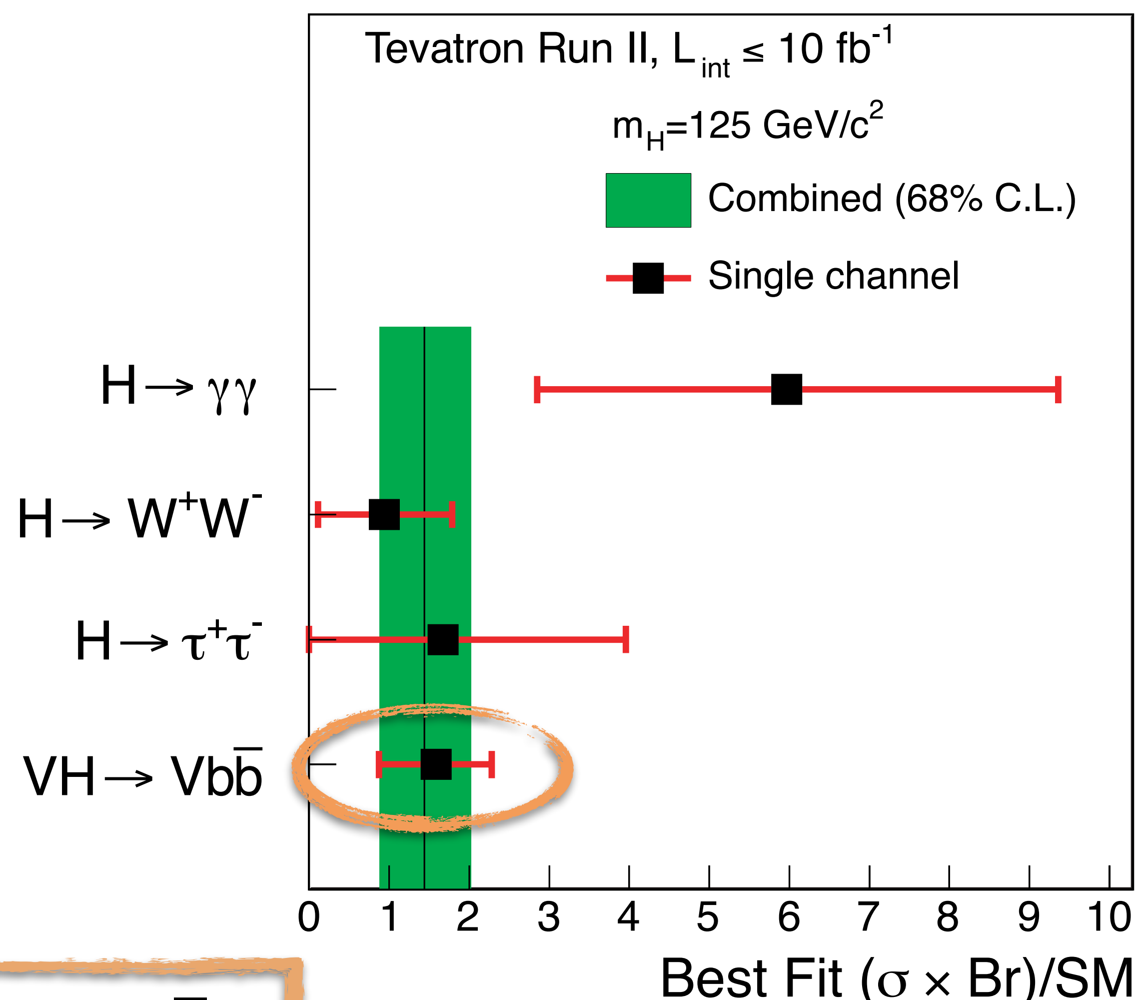
HIGG-2013-08, CONF-2014-

VH, $H \to$ invisible



HIGG-2013-03

Data: Tevatron



Only $VH, H \to b\bar{b}$ is competitive with the LHC results

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