Constraining new physics from Higgs measurements

Signal strengths, Global fits, Lilith & Applications

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PhD seminars
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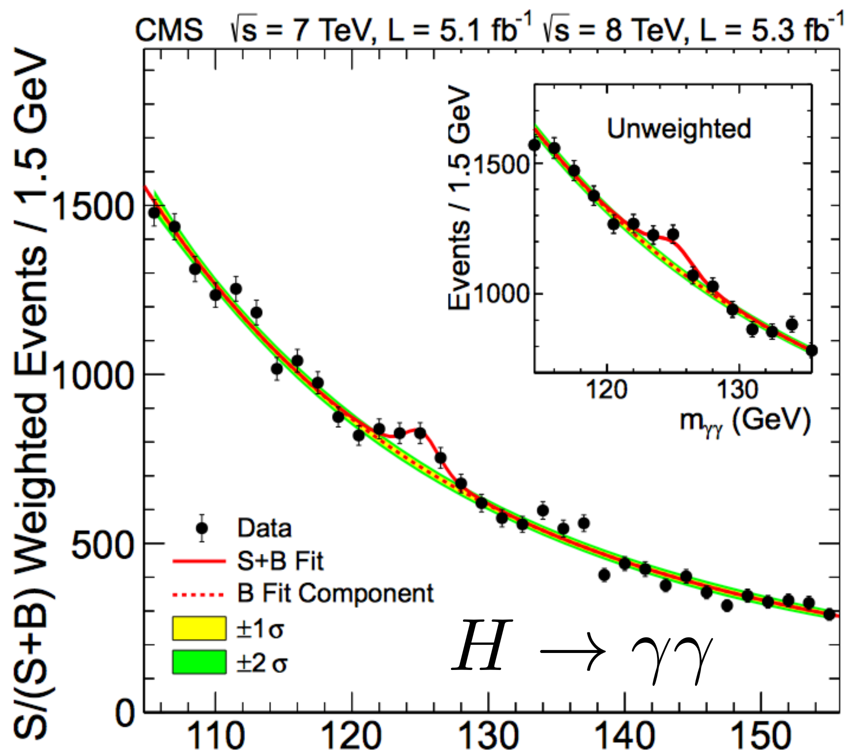
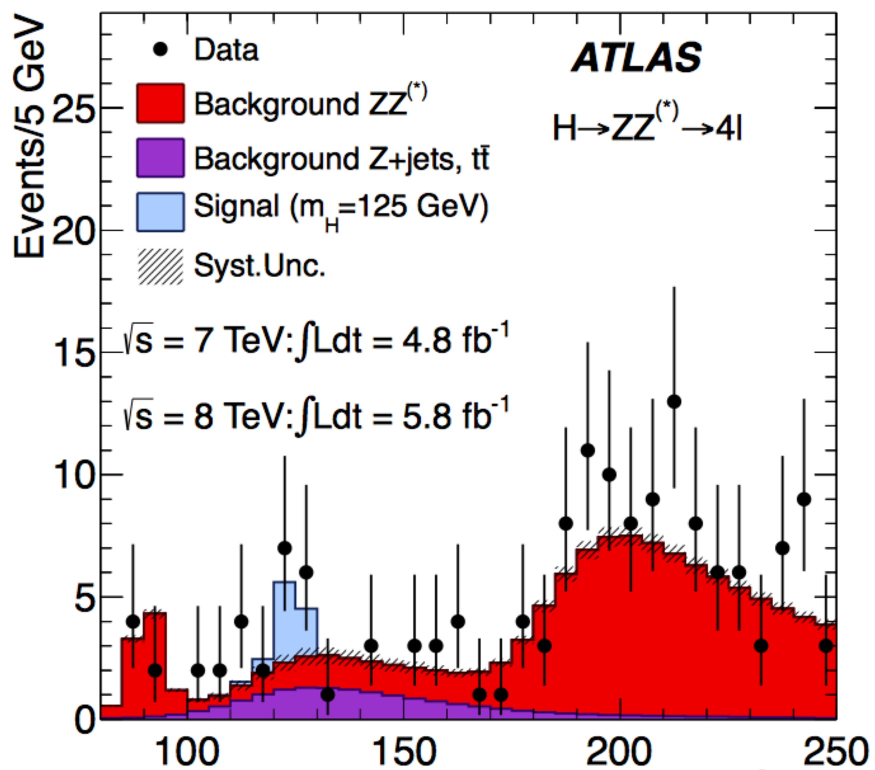
Motivations

A new particle was discovered at the LHC !



[CMS-HIG-2012-28]



[ATLAS-HIGG-2012-27]

It really seems to « walk and quack » like a
Standard Model (SM) Higgs boson

Could it really be it ?

Higgs at the LHC

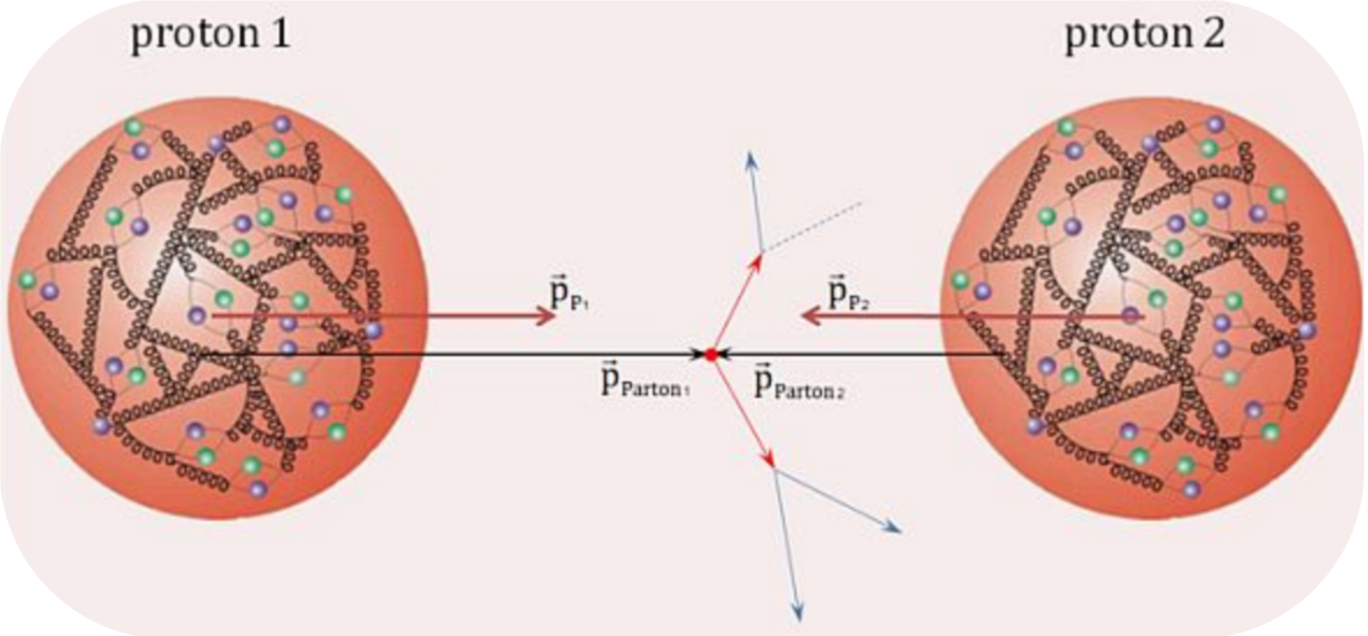
Production/decay modes in the SM

Signals strengths

Constructing our likelihood function

The LHC as a parton collider

- Due to the high energies in play, the LHC is not simply colliding protons but rather their constituant partons, *i.e.* quarks and gluons



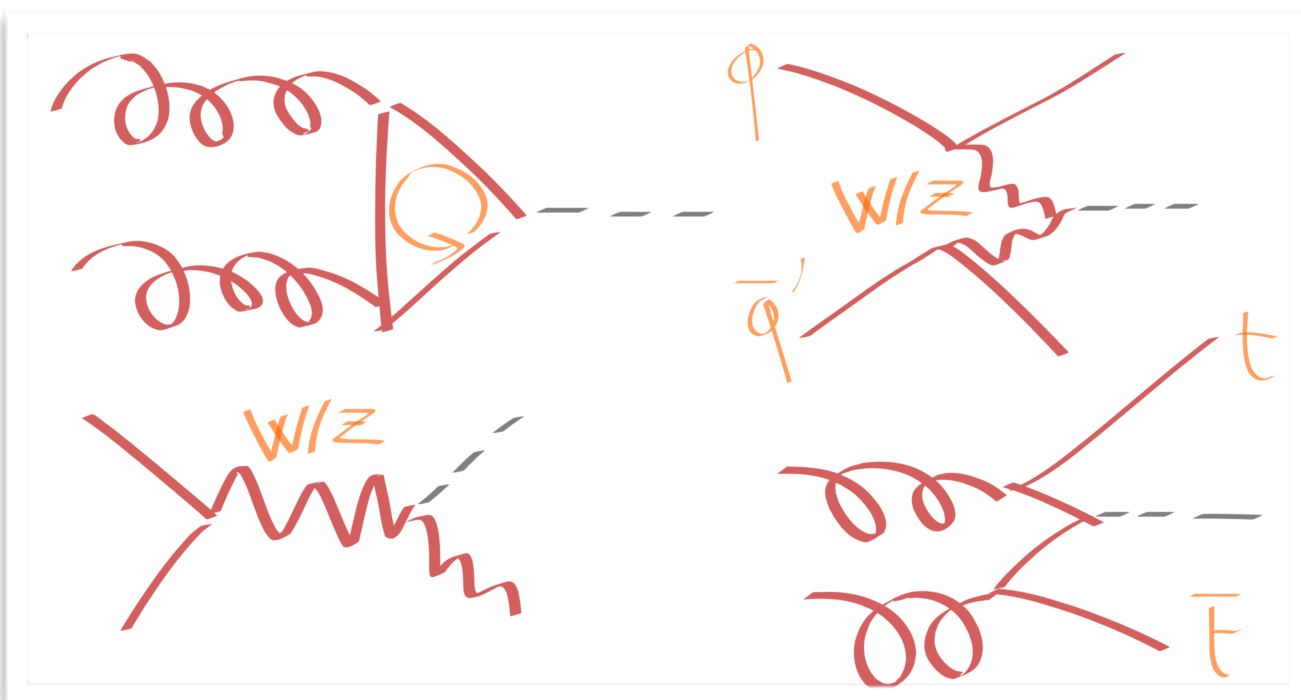
- To create a Higgs from such a collision, the initial state *has to* be composed from quarks or gluons:

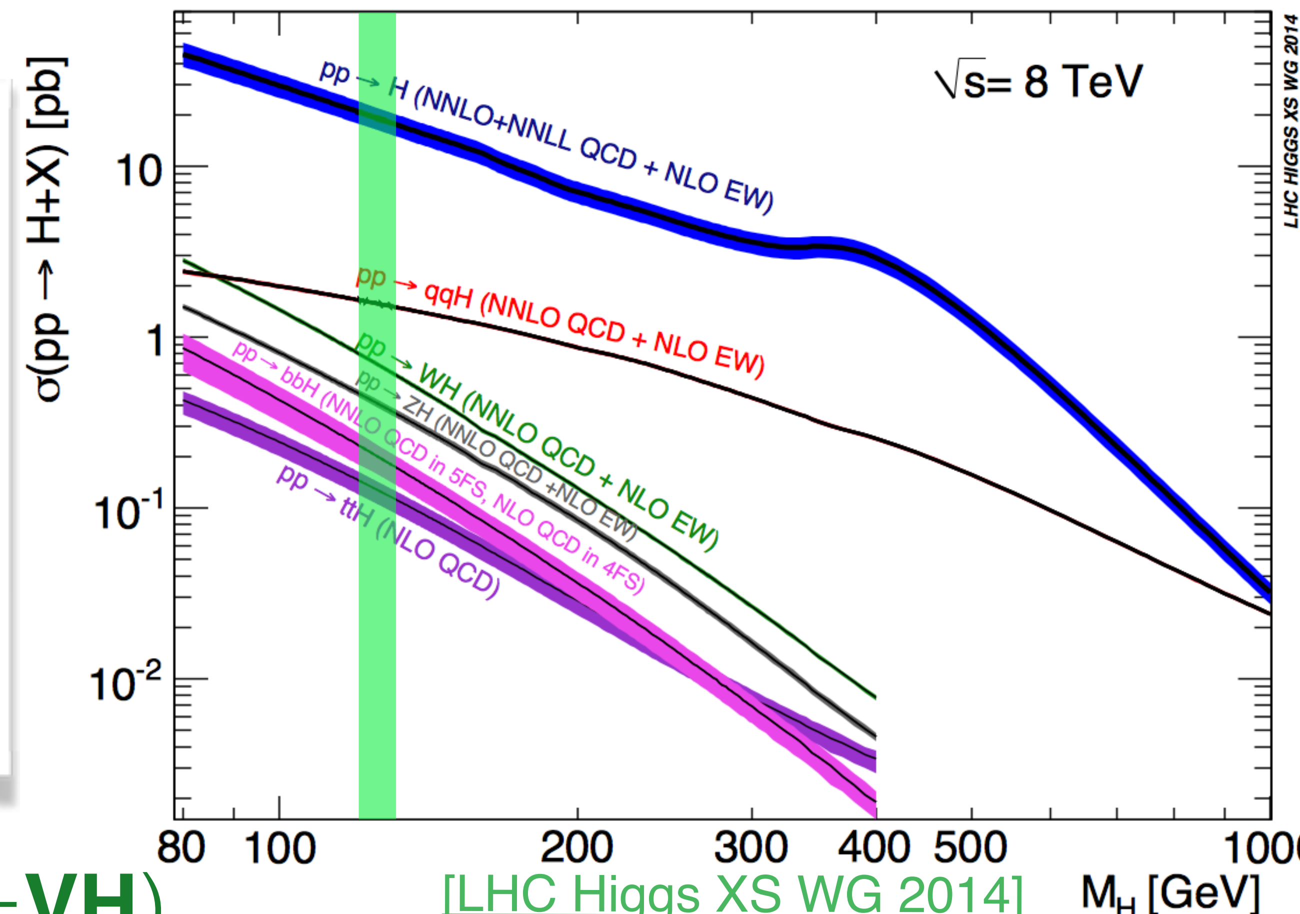
$$q\bar{q}^{(\prime)} \to H$$
$$gg \to H$$

Higgs production modes at the LHC

Vector boson fusion (**VBF**)

Gluon fusion (**ggH**)





[LHC Higgs XS WG 2014]

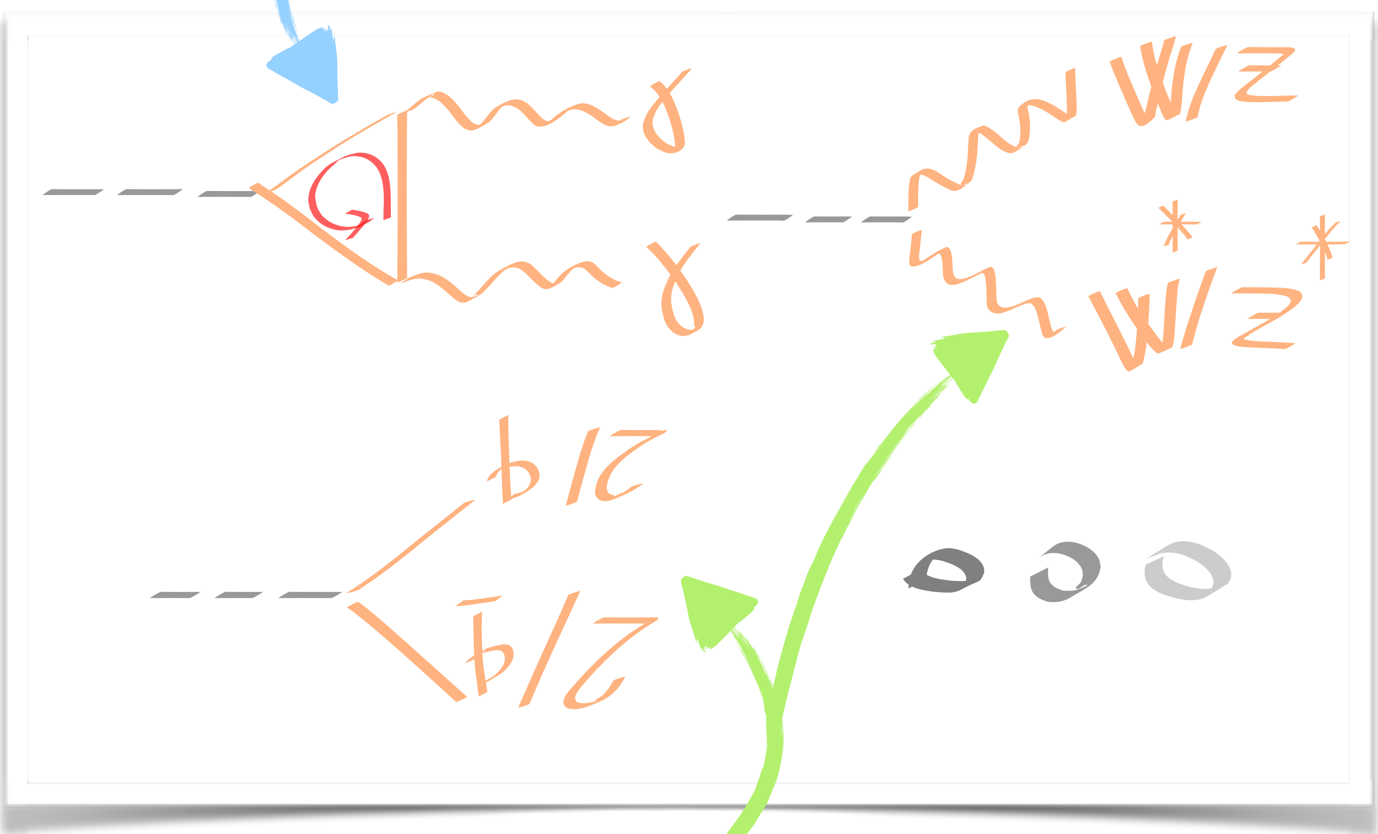
W/Z associated production (**WH+ZH=VH**)

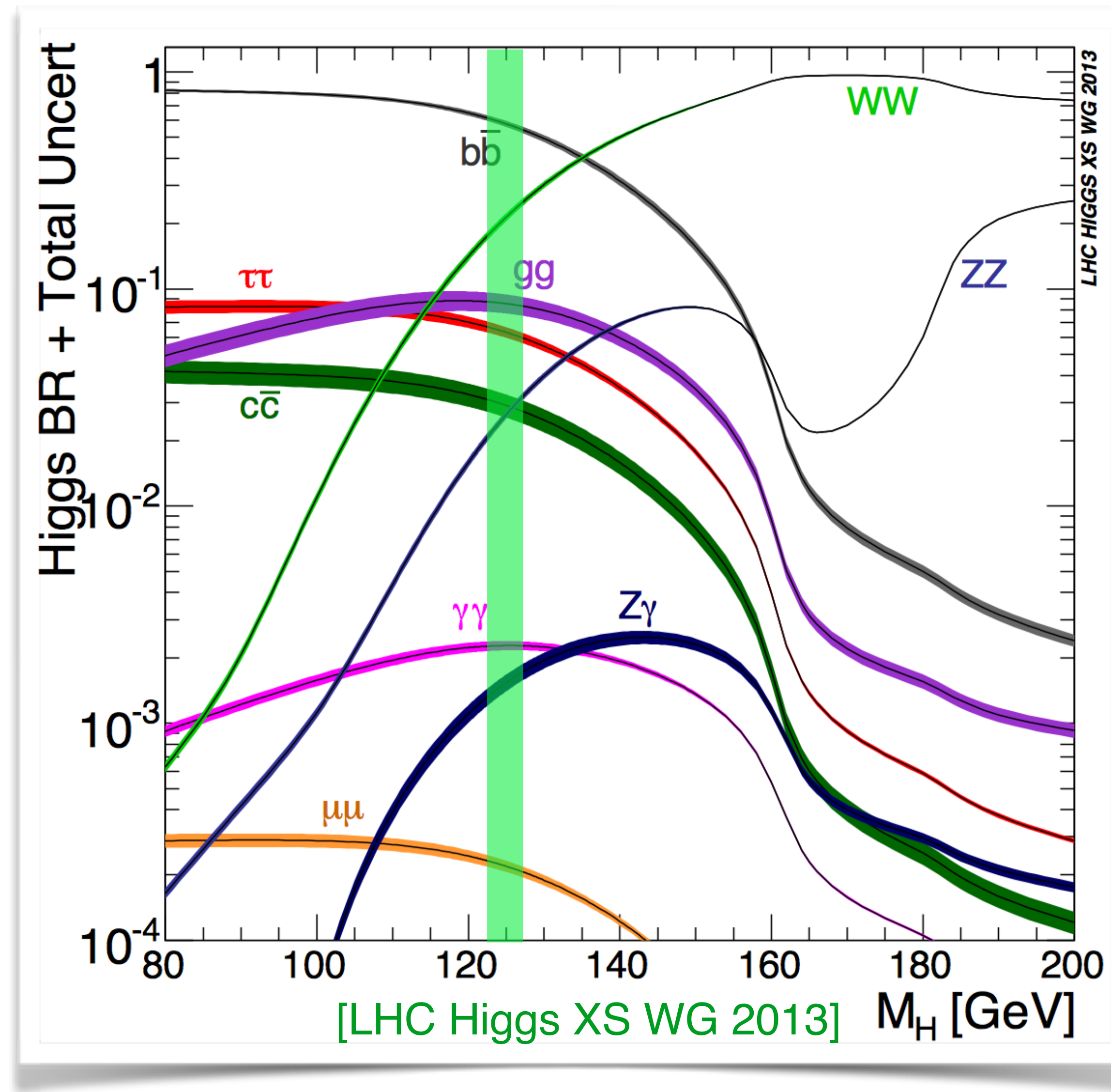
$t\bar{t}$ associated production (**ttH**)

SM Higgs decay modes

Sensitive to new states and modified Higgs couplings

125 GeV is quite fortunate !





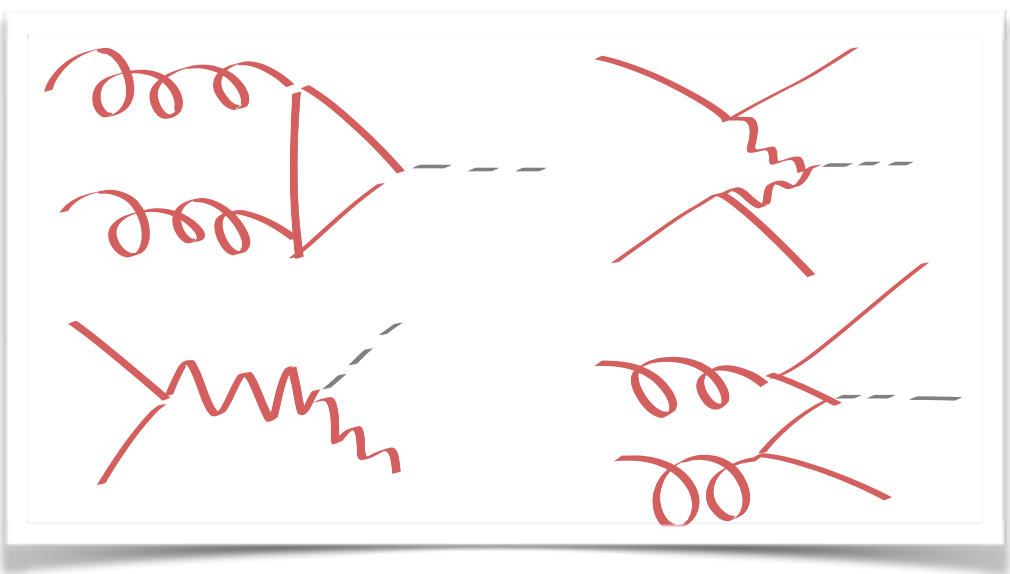
Mass dependence of the couplings accessible for W, Z and third and second generations of fermions at the LHC

Signal strengths

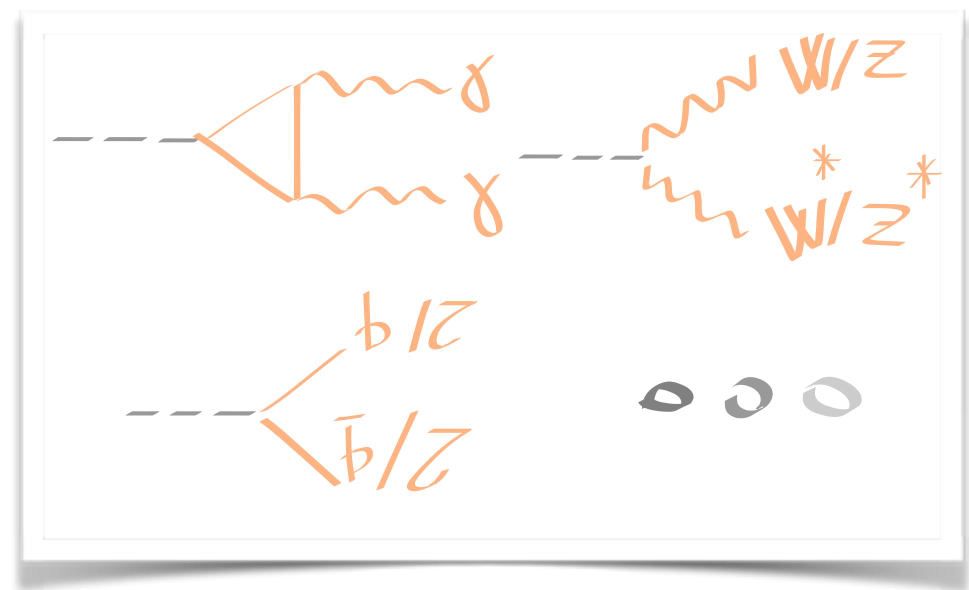
- Deviations of signal rates can be encoded in the form of **signal strengths**:

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

$X \subset$

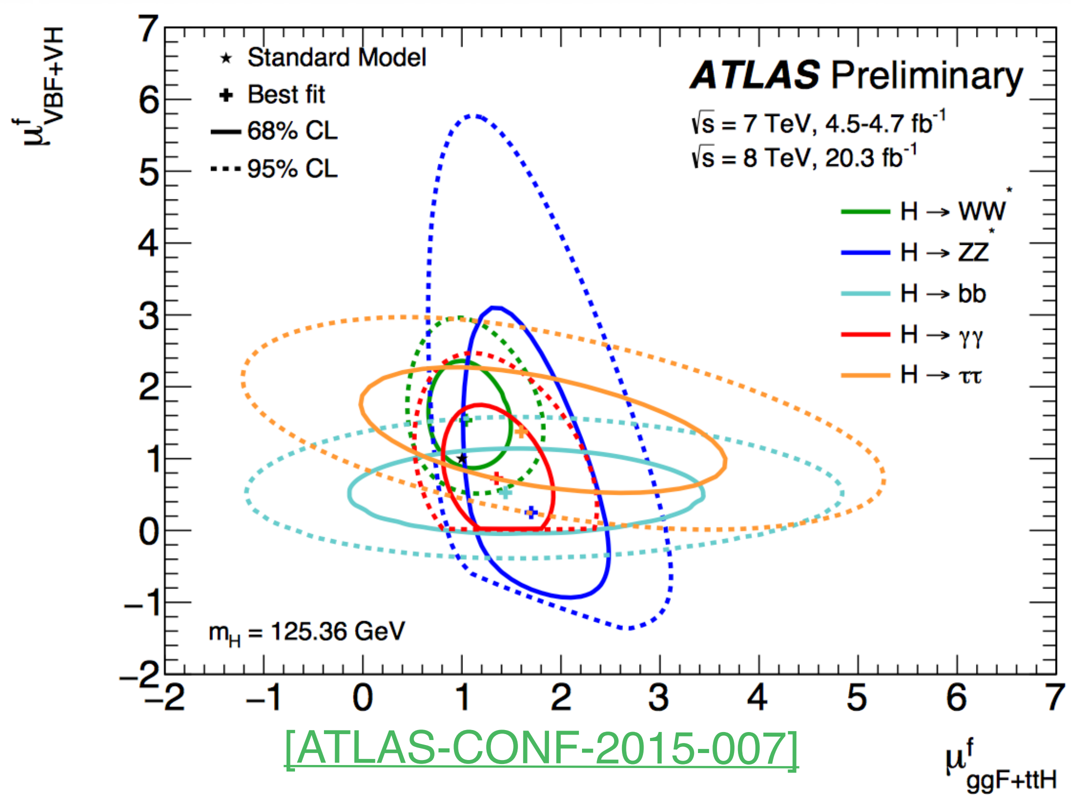


$Y \subset$

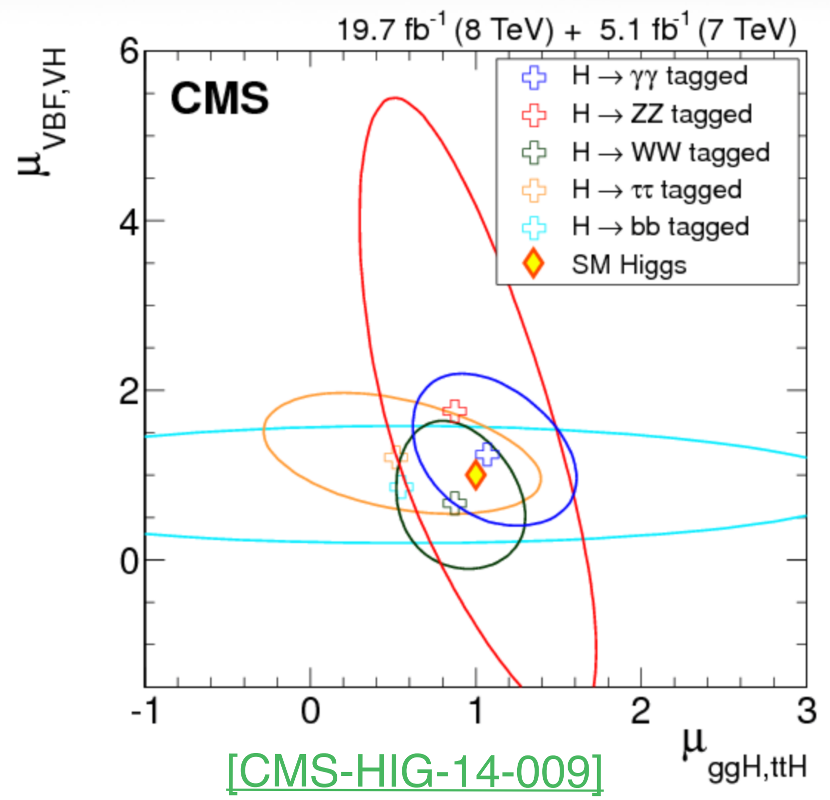


- Assumptions: small width, 0^+ state, single state
- Signal strengths are measured by ATLAS and CMS (and D0&CDF)
- We want to use these results to constraint new physics scenarios

Signal strengths at the LHC



[ATLAS-CONF-2015-007]



[CMS-HIG-14-009]

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

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

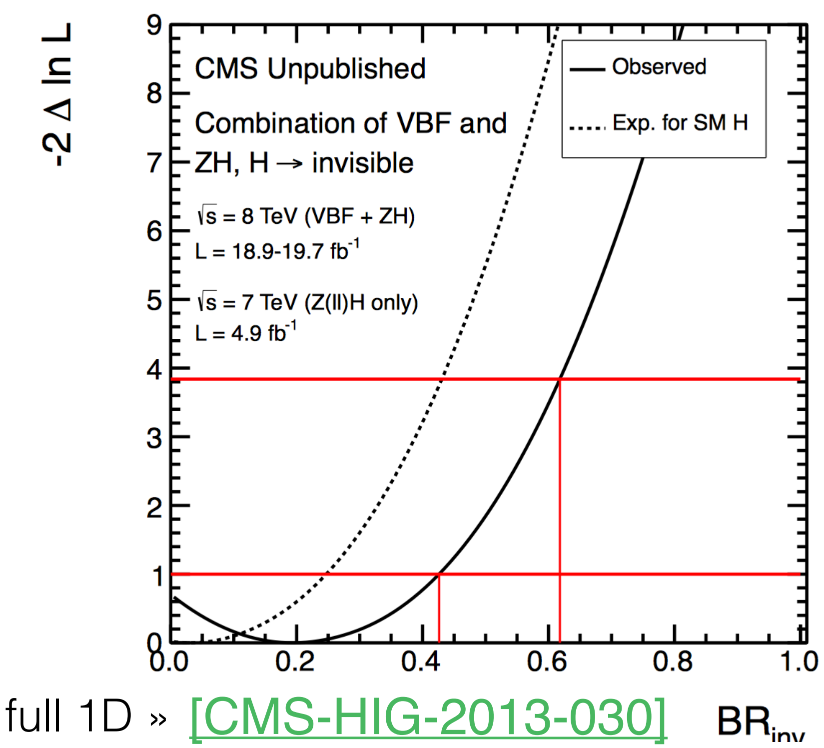
Primary experimental input used for the construction of our likelihood ✓

Latest experimental results

Collaboration	Analysis	Type	Reference
ATLAS	$H \to \gamma\gamma, ZZ^*, WW^*, \tau\tau$	2D contour	[CONF-2015-007]
	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	[HIGG-2013-027]
	ttH, $H \to \gamma\gamma$	1D interval	[HIGG-2013-08]
	ttH, $H \to$ multi-leptons	1D interval	[CONF-2015-006]
	$H \to \mu\mu$	1D interval	[CONF-2015-007]
	$H \to Z\gamma$	1D interval	[CONF-2015-007]
CMS	$H \to \gamma\gamma, ZZ^*, WW^*, \tau\tau$	2D contours	[HIG-2014-009]
	$VH, H \to b\bar{b}$	1D interval	[HIG-2014-009]
	ttH, $H \to b\bar{b}$	1D interval	[HIG-2014-010]
	ttH, $H \to \gamma\gamma, \tau\tau$	1D interval	[HIG-2014-009]
	ttH, $H \to$ multi-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]

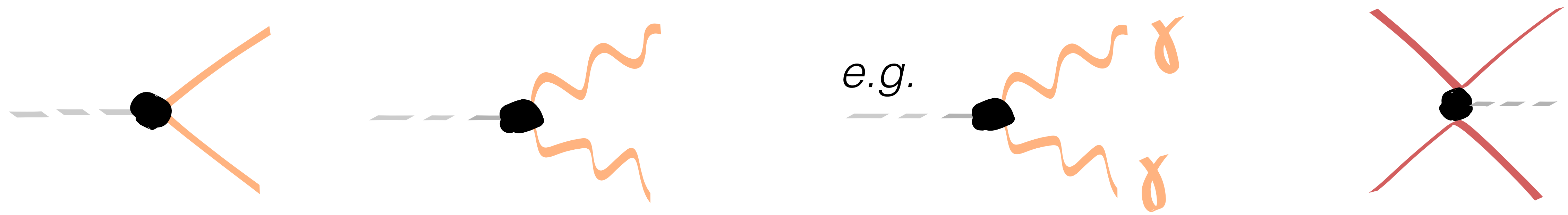
- Final likelihood is the product of the individual 1D and 2D likelihoods
- Good approximation at LHC Run I ! (illustrated later)
- At LHC Run II, systematic uncertainties will dominate over statistical ones → calls for a **consistent** treatment of the systematics

[LHCHXSWG-2012-001]

Parametrizing the likelihood function

- Introducing **reduced couplings**:

$C_t,\ C_b,\ C_c,\ C_\tau$ $\qquad$ $C_W,\ C_Z$ $\qquad$ $C_{\gamma\gamma}, C_{gg}, C_{Z\gamma}$ $\qquad$ $C_{\rm VBF}$



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

- If new decay modes into **invisible** or **undetected** particles are open (direct Higgs/Dark matter interplay at the LHC), the signal strengths are modified as

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

$\Longrightarrow$ Put constraints on the Higgs couplings, exotic branching ratios

$\Longrightarrow$ More generally: test new physics scenarios

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:

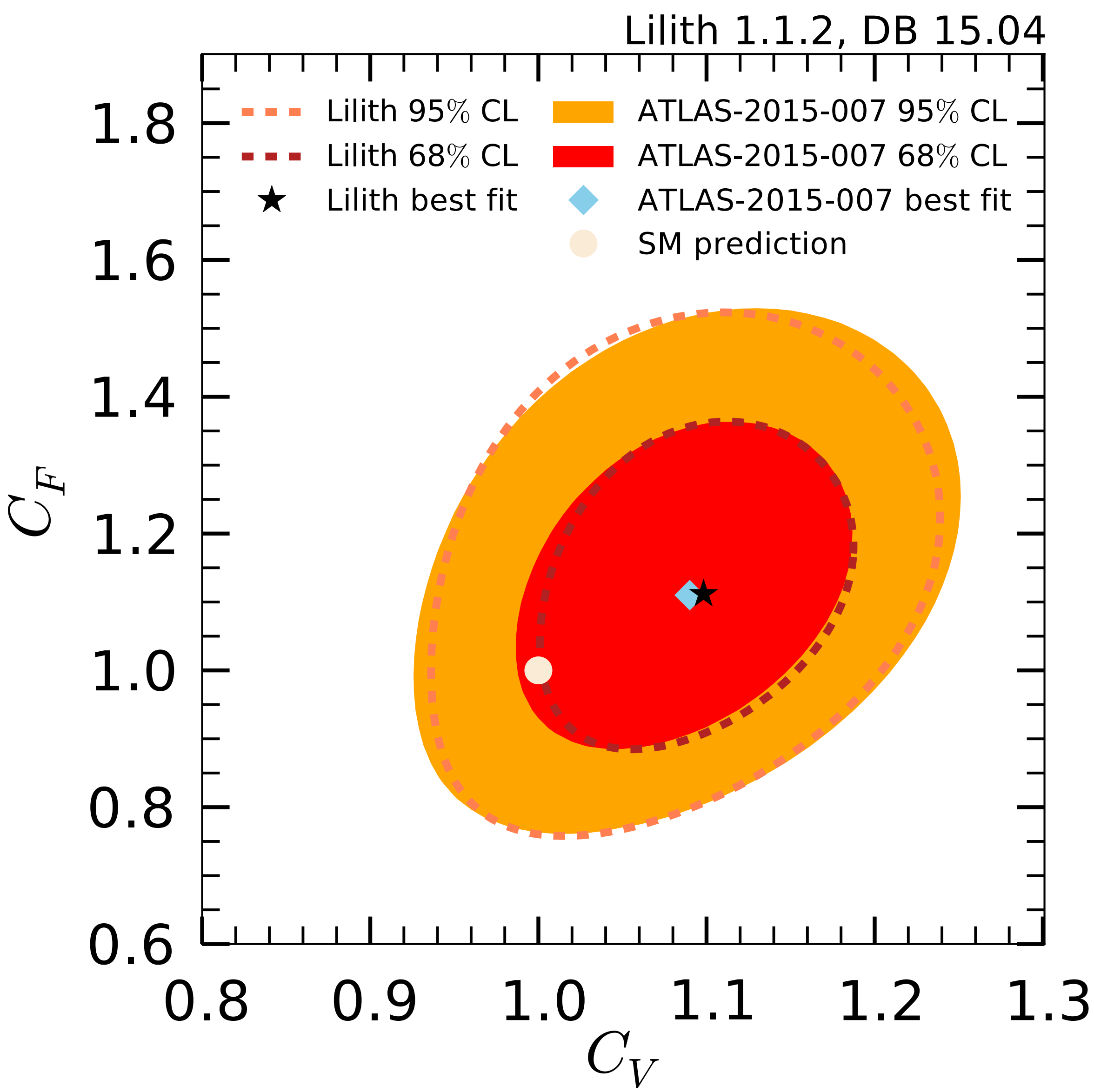
http://lpsc.in2p3.fr/projects-th/lilith/

(Google: lilith higgs)

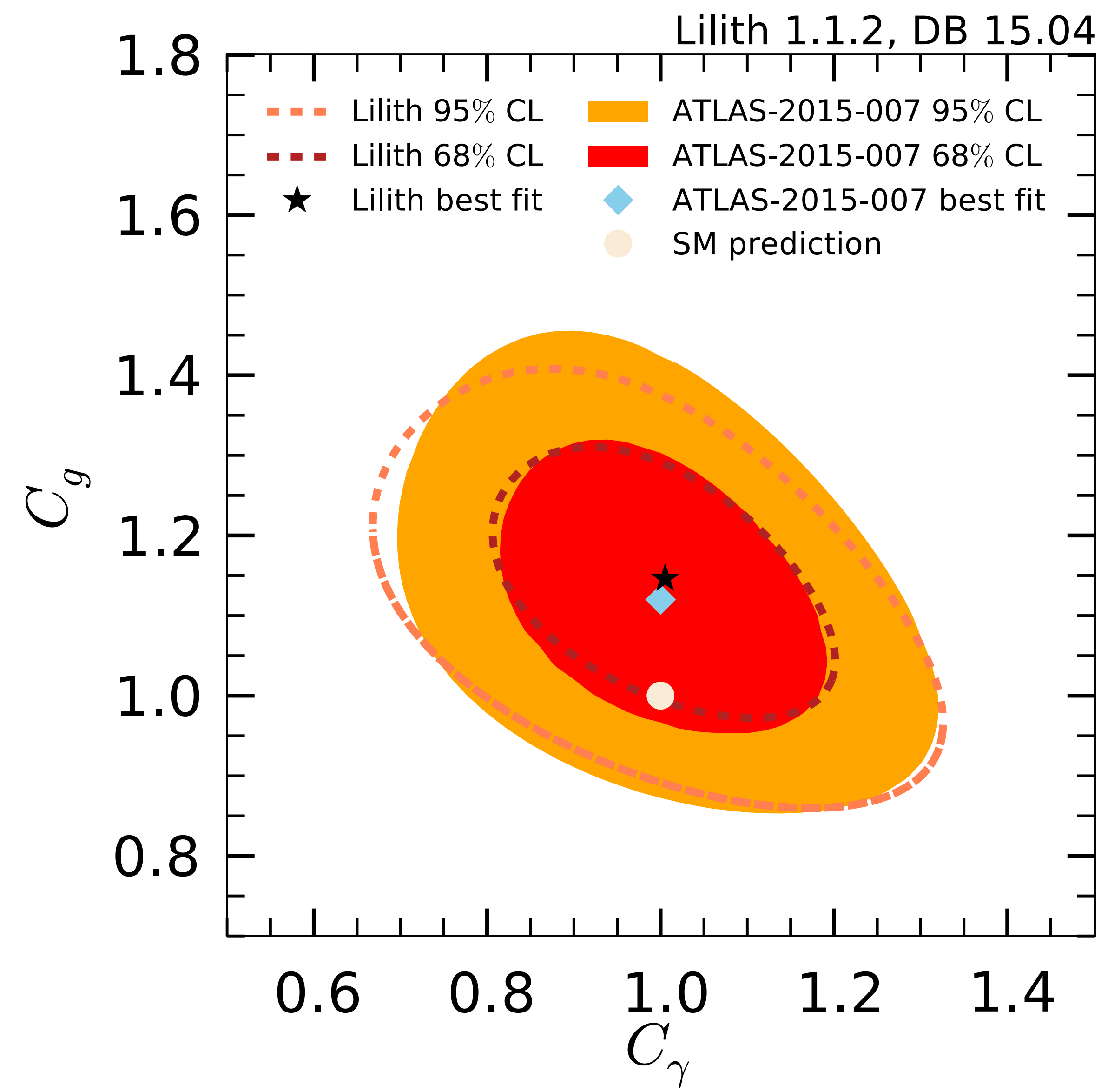
- All formats of experimental signal strengths are handled
- All experimental results are stored in a flexible XML database (updated as new results are published, last update: Moriond 2015)
- Two user input modes:
  → Reduced couplings as inputs
  → Signal strengths as inputs
- Evaluate $-2\log L$ for each input points, allow for a statistical interpretation in the frequentist or bayesian approach

Validation of the Lilith likelihood against ATLAS results

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



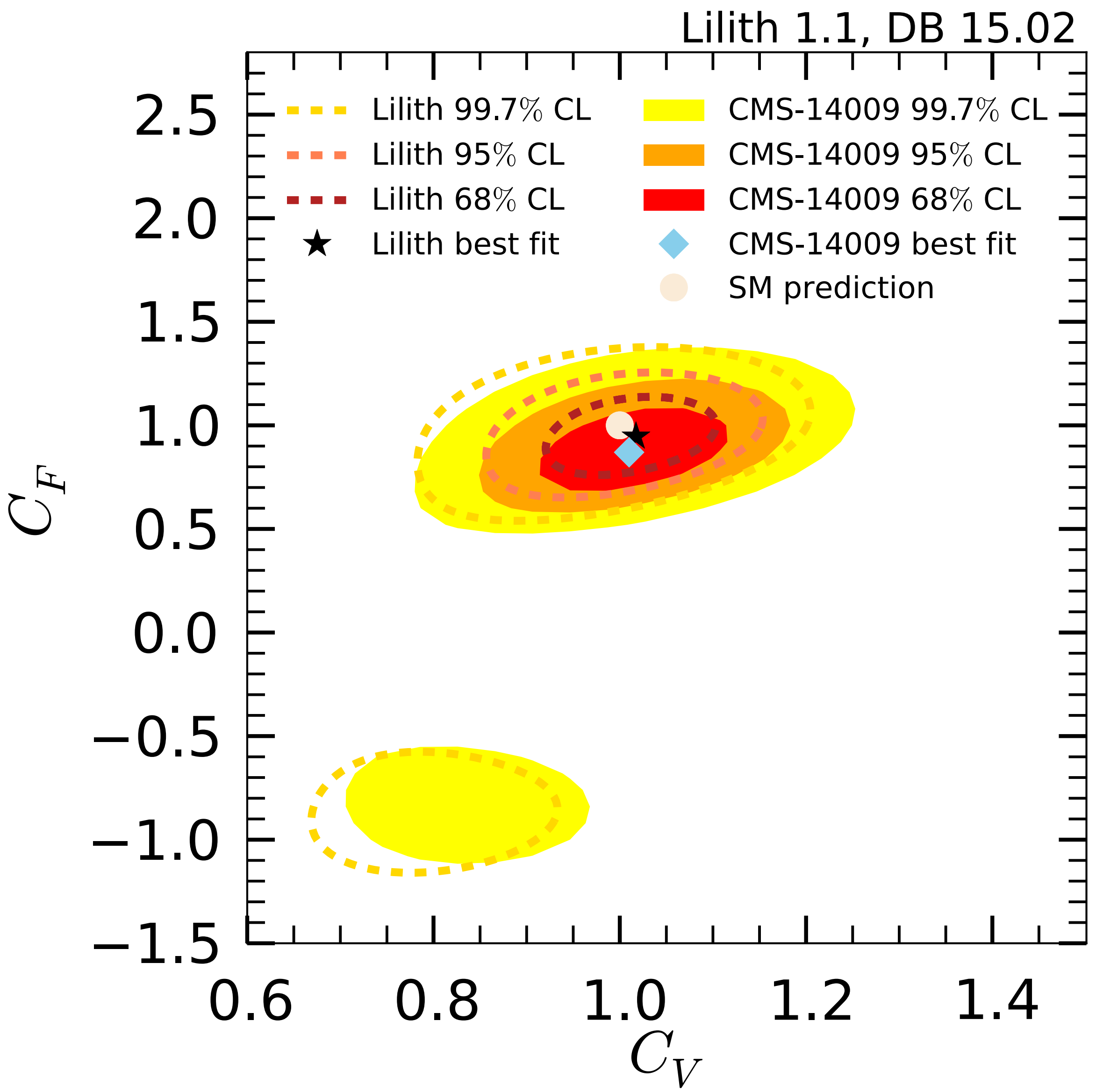
(C_V, C_F) benchmark scenario



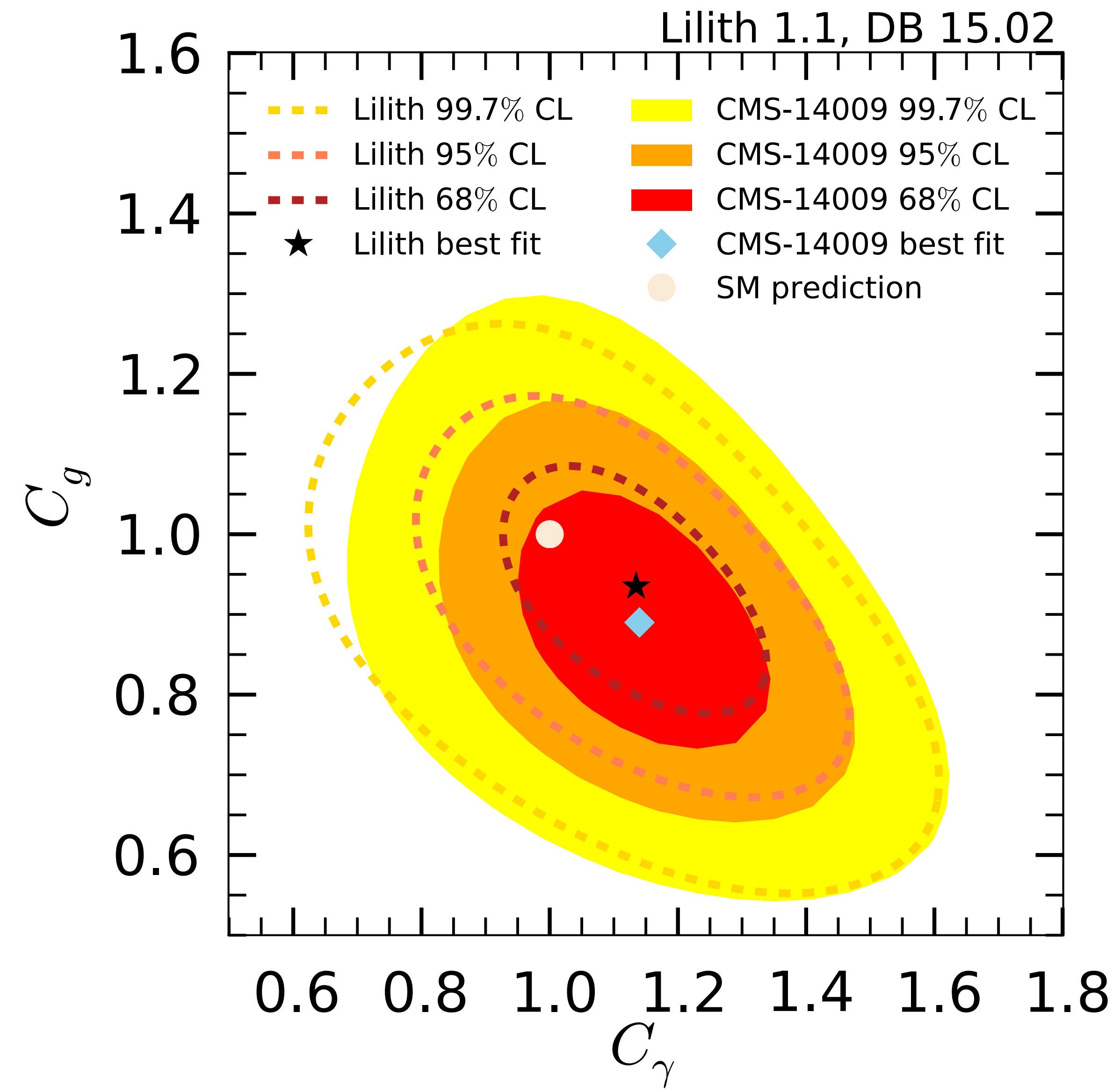
$(C_\gamma, C_g, C_{Z\gamma})$ benchmark scenario

Validation of the Lilith likelihood against CMS results

- Trying to reproduce the official 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

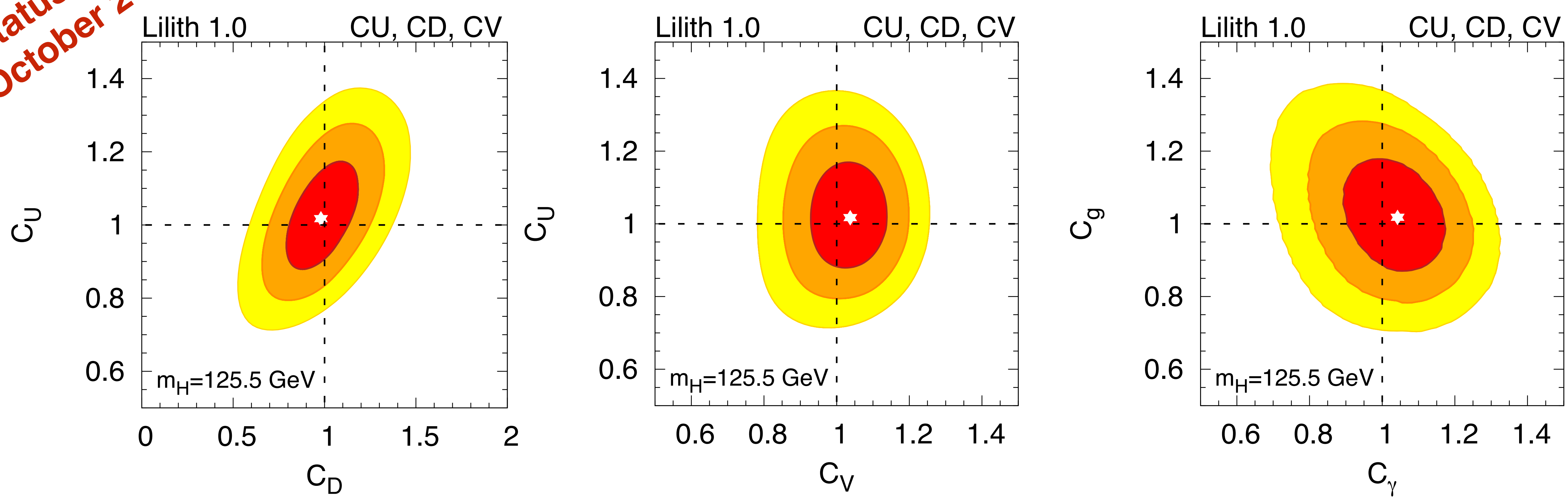
Global fit

Phenomenological study of a 2HDM

Simple model fit

- **Model :** C_U, C_D, C_V, without any 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 (PRD)]

Constraining extended Higgs sectors: a 2HDM example

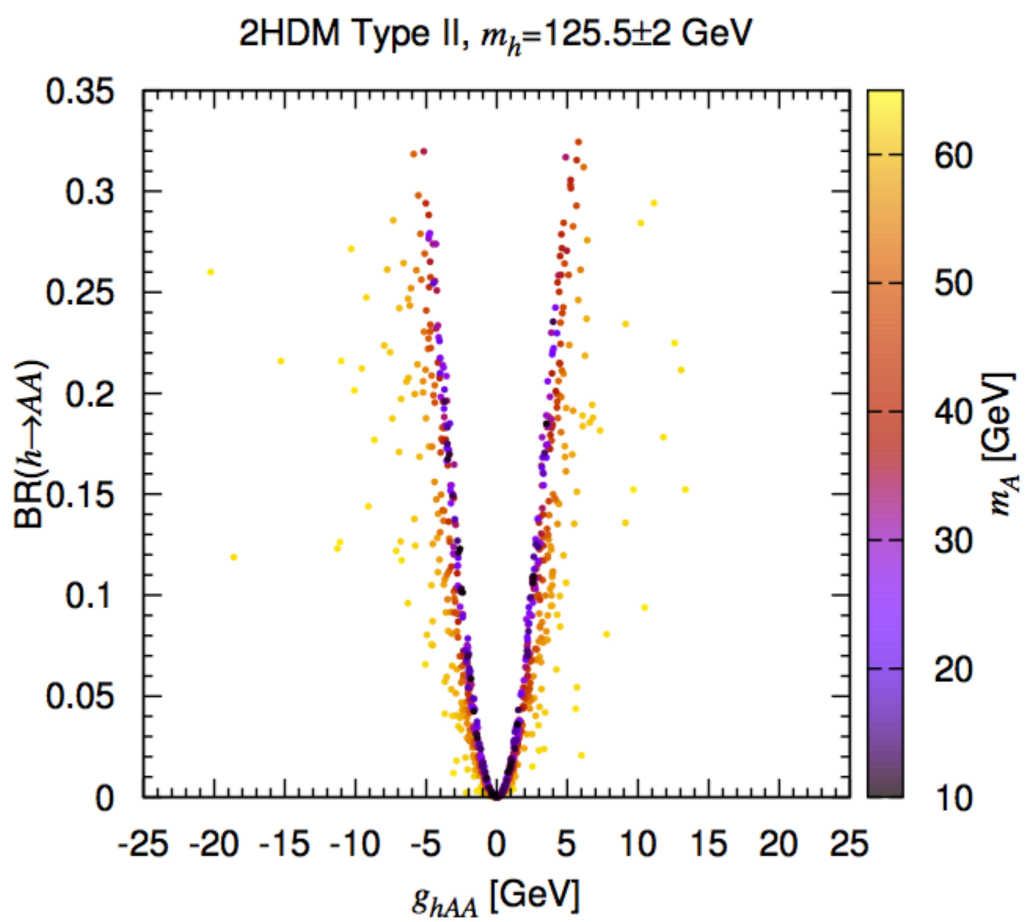
- **Two Higgs doublet model** (2HDM): Minimal extension of the SM, including a second Y=+1 Higgs doublet

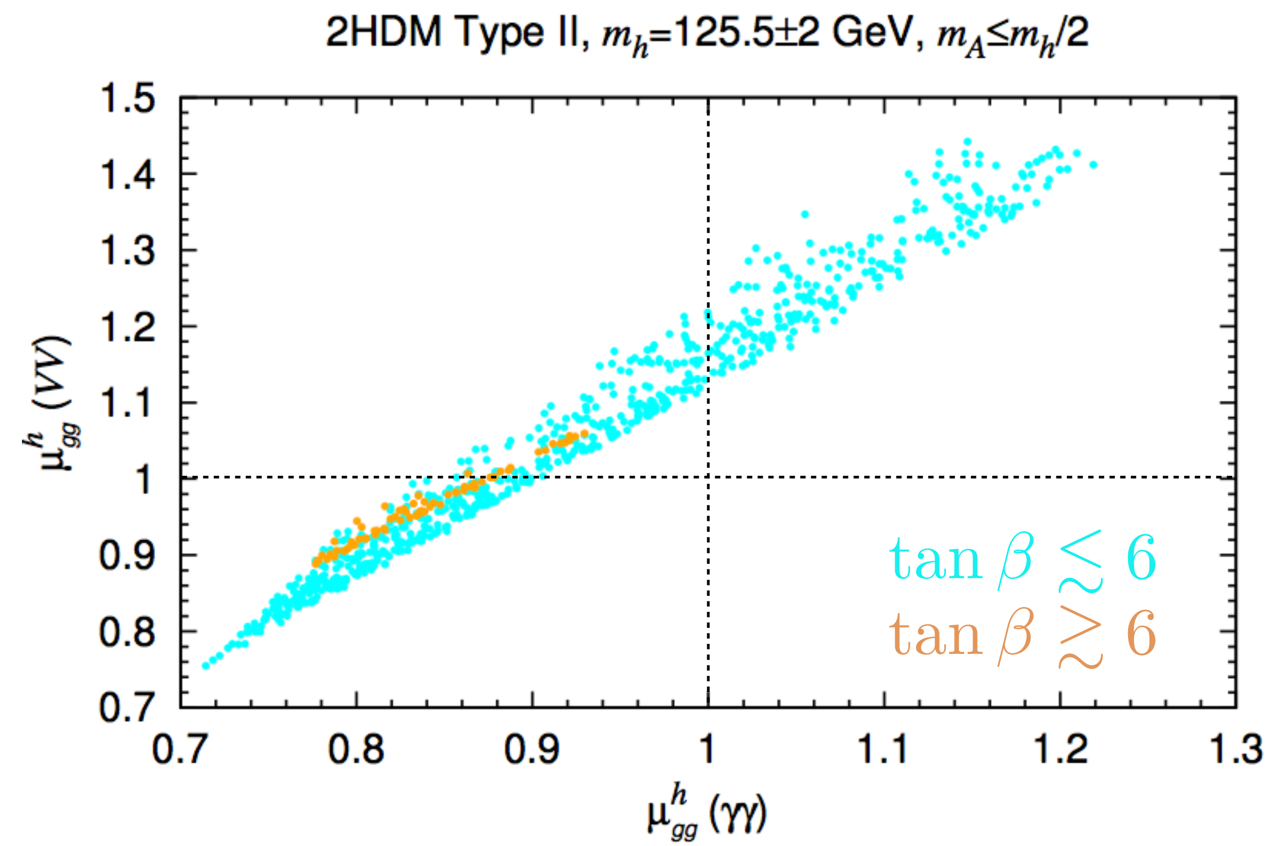
$$
\begin{aligned}
\mathcal{V} = & m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 - [m_{12}^2\Phi_1^\dagger\Phi_2 + \mathrm{h.c.}] \\
& + \tfrac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \tfrac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2)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

- Hypotheses: no CP-violation, no tree level flavor changing neutral current (so-called Type II model in the following)
- Five physical degrees of freedom: 2 CP-even (h, H), 1 CP-odd (A), 2 charged (H^+ ,H^-) states
- Impose constraints from: theory (stability, perturbativity…), STU parameters, flavor, direct Higgs searches (light and heavy), signal strengths at 125 GeV

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

h→AA decay mode is open
Possibility to probe at the LHC





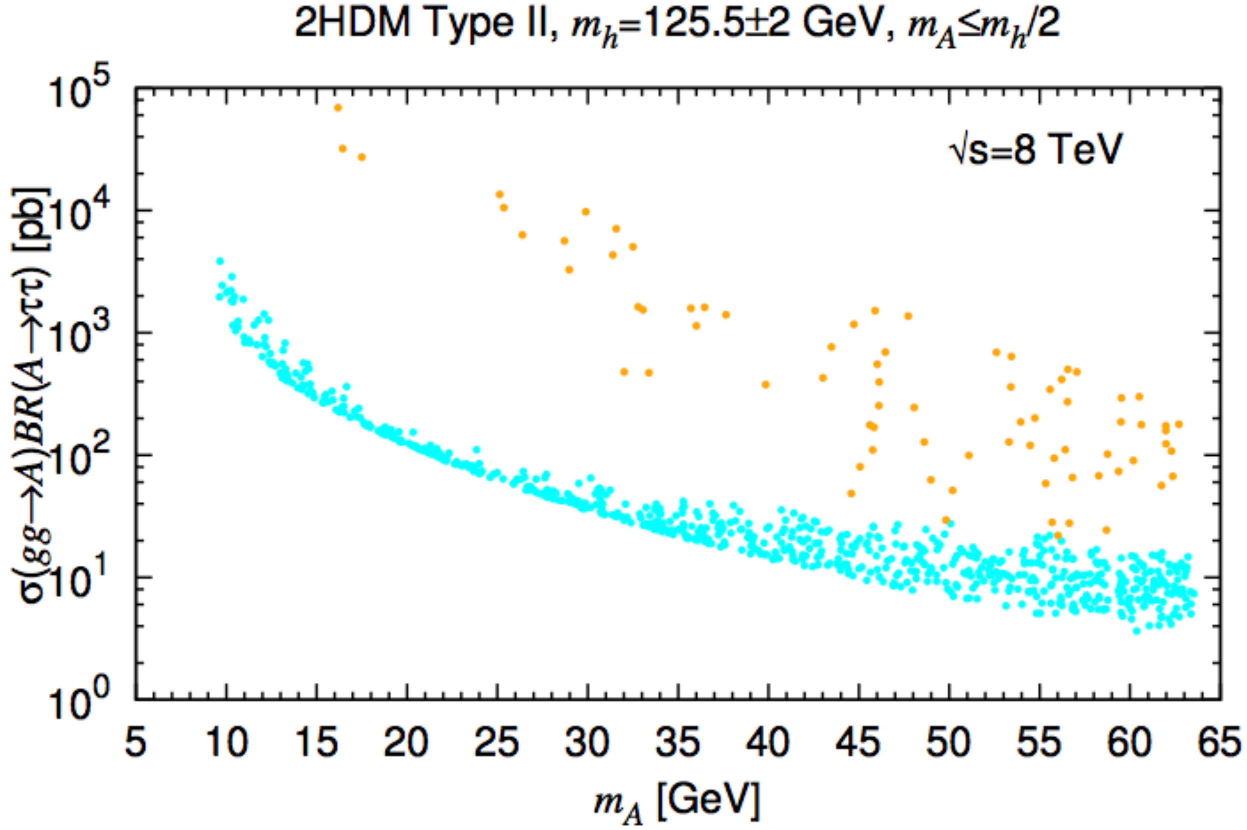
Strong constraints on h125→AA branching ratio from the Higgs signal strengths

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

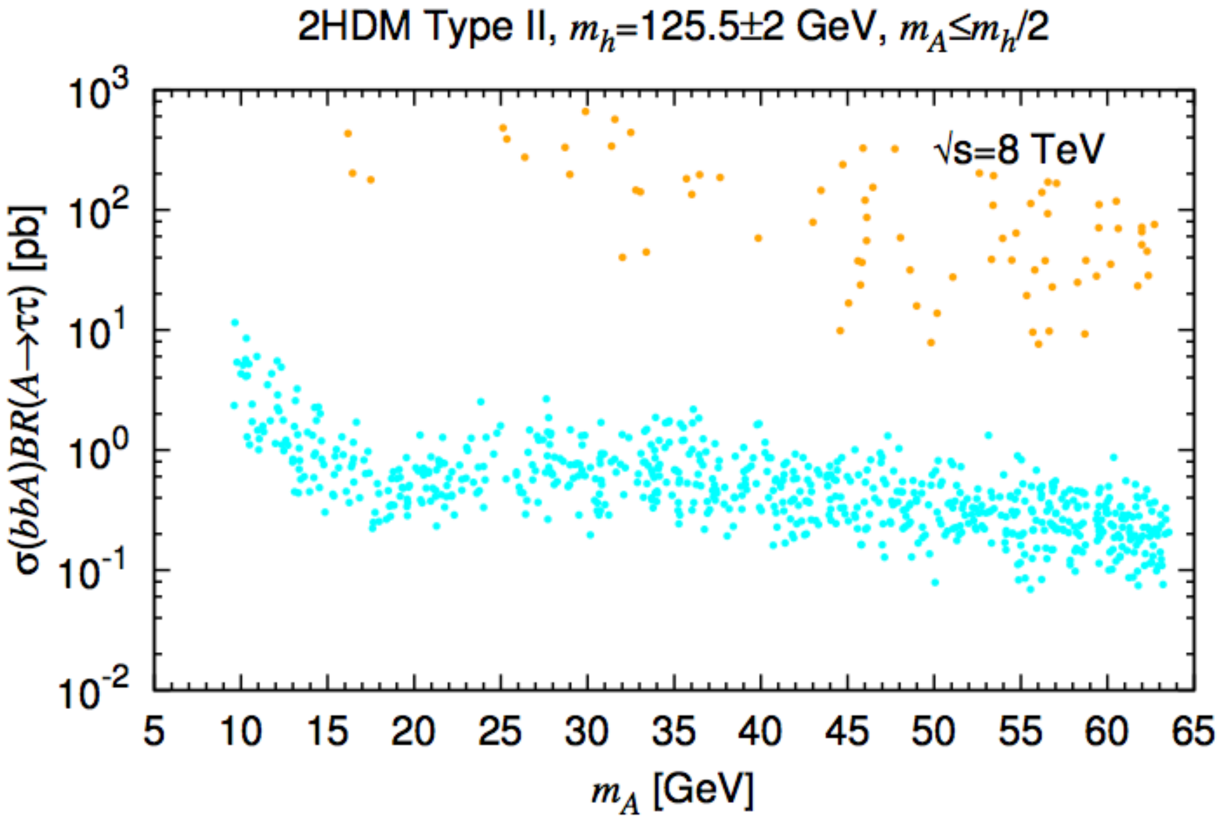
[JB, J.F. Gunion, Y. Jiang, S. Kraml; arXiv:1412.3385 (PRD)]

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

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



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



Very large cross sections over the full m_A range: should produce readily observable peaks

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 (PRD)]

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

LIght LIkelihood fiT for the Higgs

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

(Google: lilith higgs)

Work in progress!!

check back soon...

- Getting ready for LHC Run II: thoughts about consistent treatment of systematic uncertainties

- Study of the alignment limits of the 2HDMs

[JB, J.F. Gunion, H.E. Haber, Y. Jiang, S. Kraml; in preparation]

Other aspect of the thesis: Baryon number violation, Minimal flavor violation and R-parity violation

[JB, C. Smith; arXiv:1404.5496 (JHEP)]

Backup

Lilith

Running Lilith

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

~/mylilithtest.py
```python
import lilith
lilithObj = lilith.Lilith()
lilithObj.readexpinput("data/latest.list")
lilithObj.readuserinputfile("userinput/example_couplings.xml")
lilithObj.computelikelihood()
print "-2logL =", lilithObj.l
```

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

```
bernon@Jeremy:~/Projects/LilithVersions/Code/Lilith-1.1.2$ python mylilithtest.py
-2logL = 24.1189771501
```

- Through the **command line interface**:

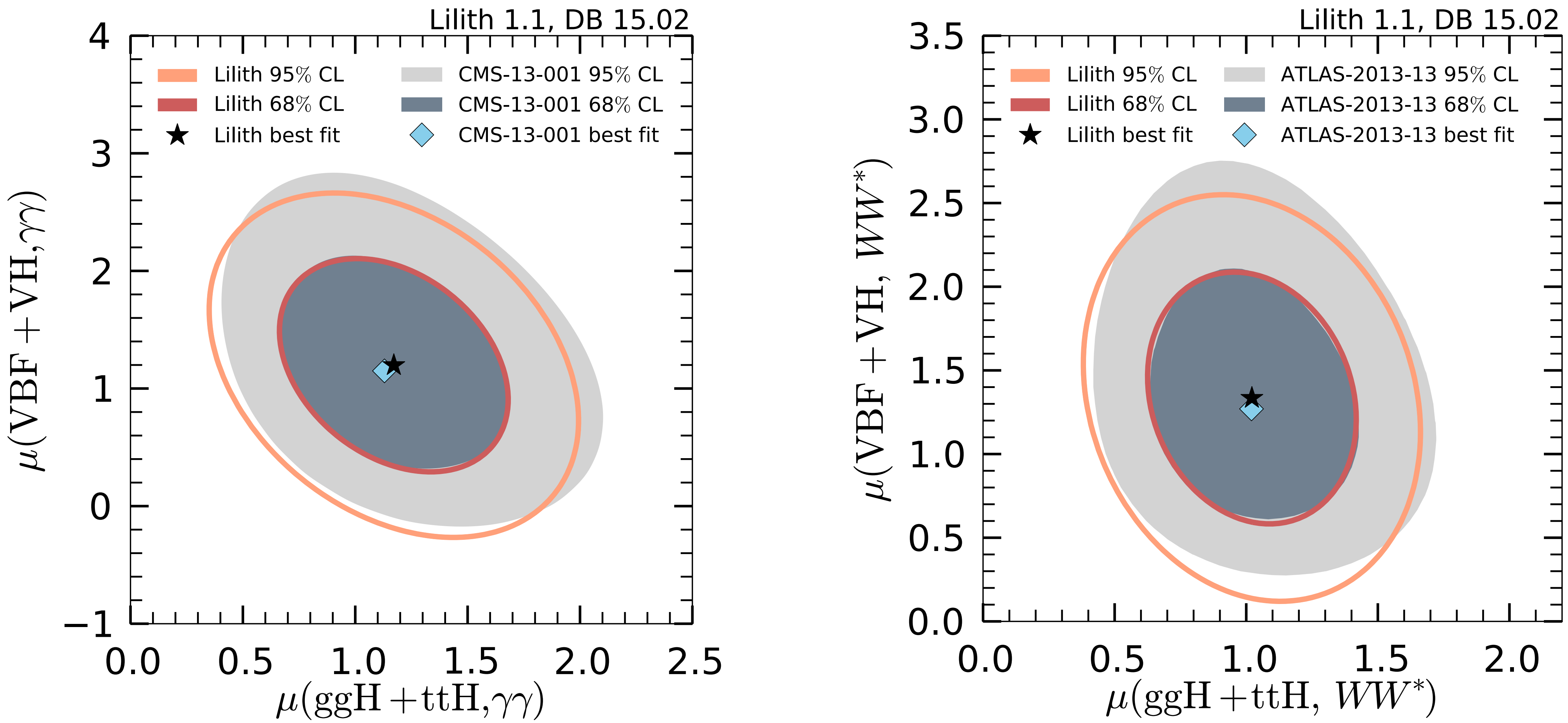
```
bernon@Jeremy:~/Projects/LilithVersions/Code/Lilith-1.1.2$ ./run_lilith.py userinput/example_mu.xml
                    <><><><><><><><><><><><><><><>
                        Lilith version 1.1.2
                       database version 15.04
                    <><><><><><><><><><><><><><><>
. User input: userinput/example_mu.xml

. Experimental input: latest LHC results [data/latest.list]
                      (28 files, Ndof = 36)
-2log(likelihood) = 24.118977
```

- 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)

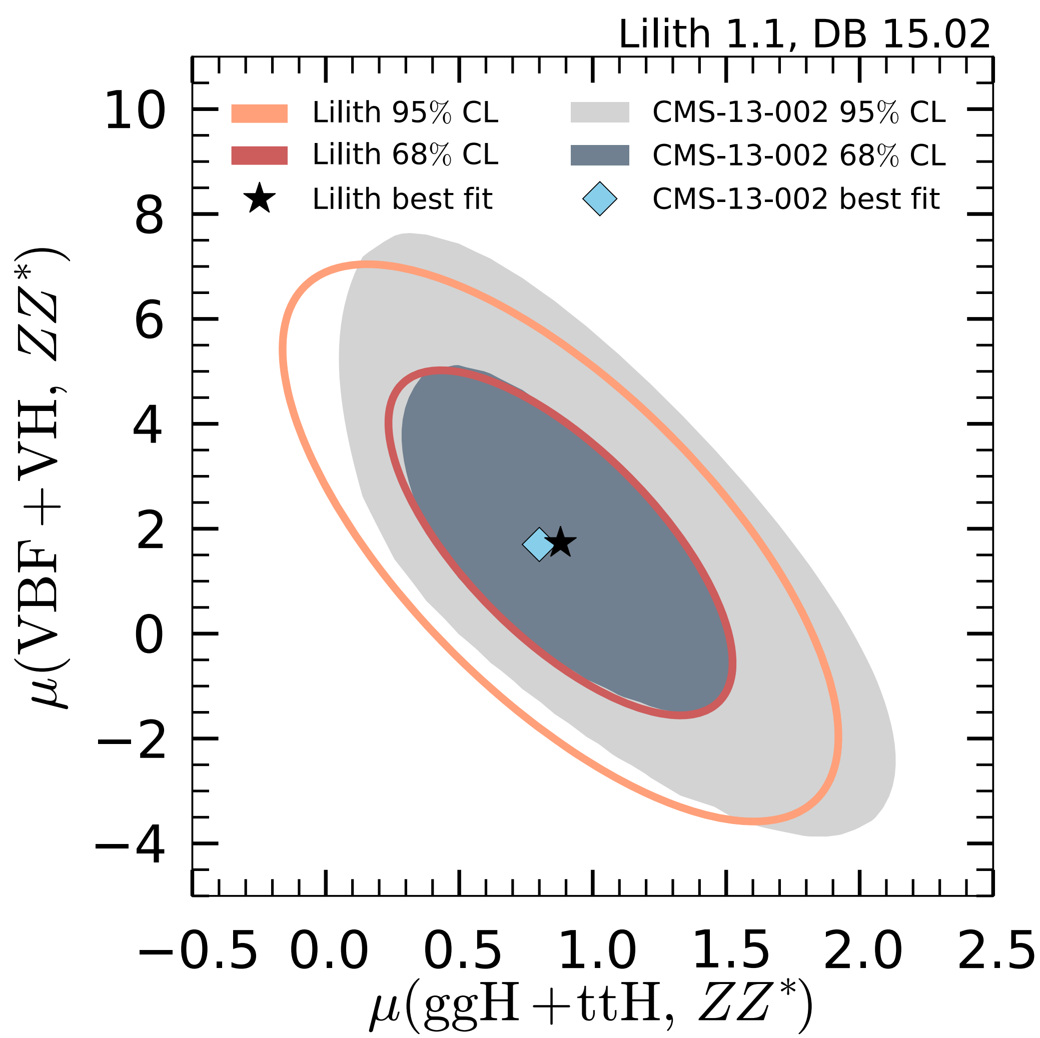
- When only the 68% CL contours in the signal strength planes are provided, we use a bivariate normal distribution to reconstruct the likelihood
- We compare the reconstruction and the official results to assess the validity of this approximation

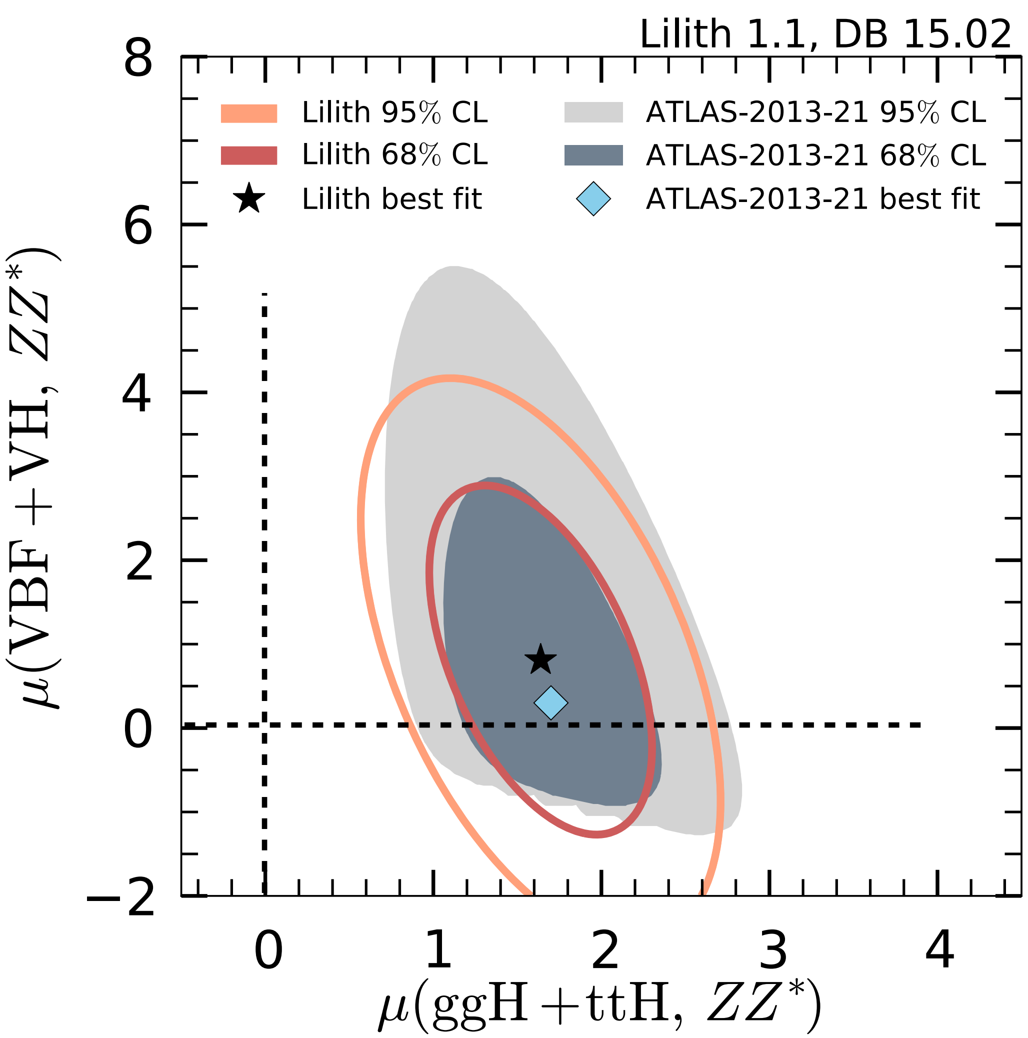


Generally very good ✓

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^*



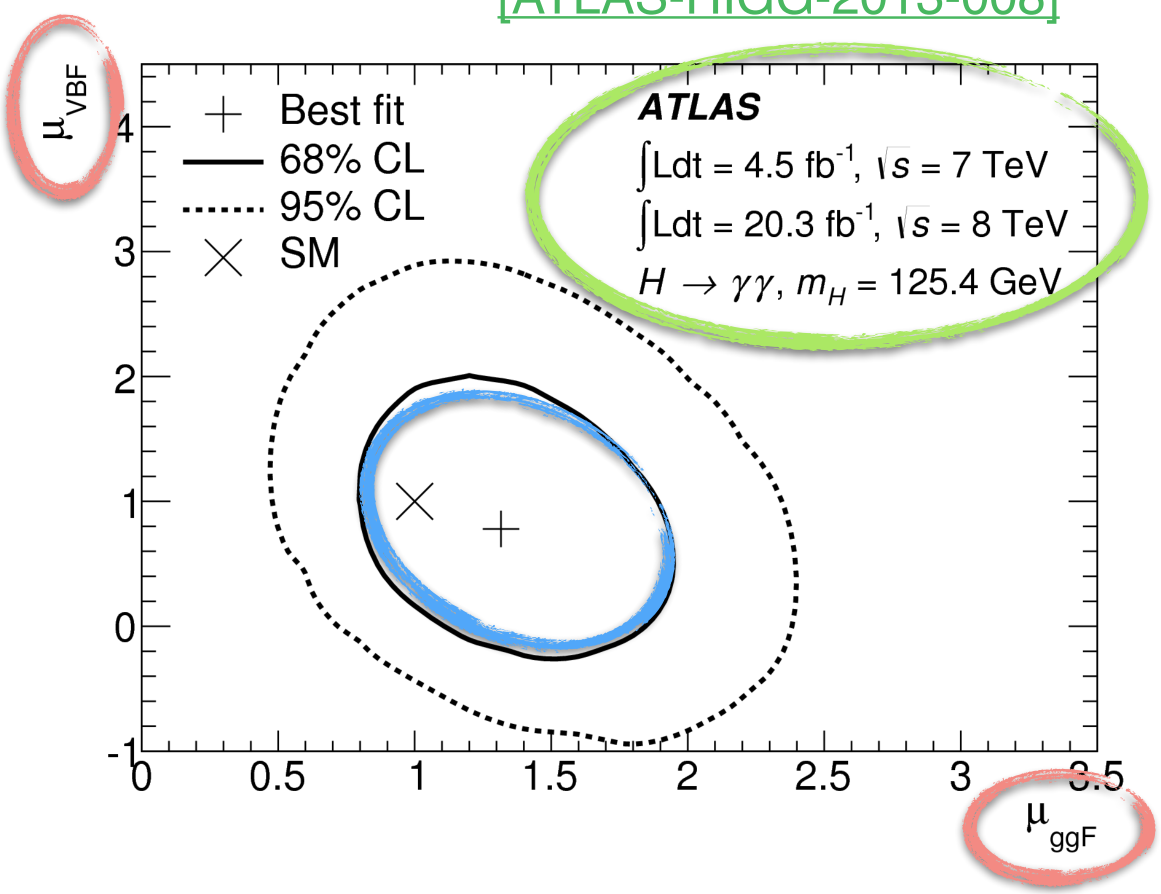


- Publication of the full likelihood function would make this approximation unnecessary

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>
  <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 particle contributions only, at a given *precision* with cross sections and partial widths from HIGLU, HDECAY, VBFNLO

Invisible, undetected branching ratios

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

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

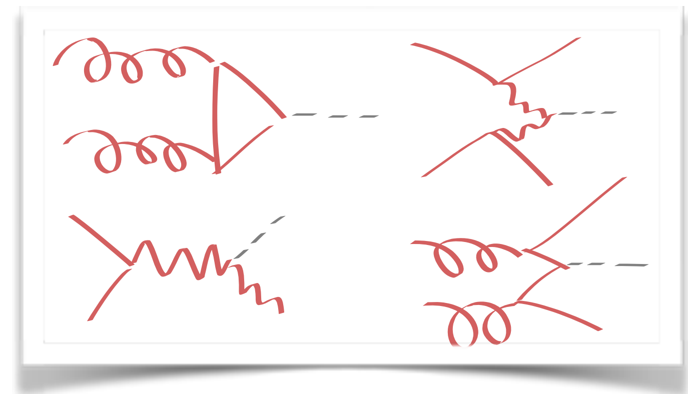
XML user input: signal strengths mode

```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>
```

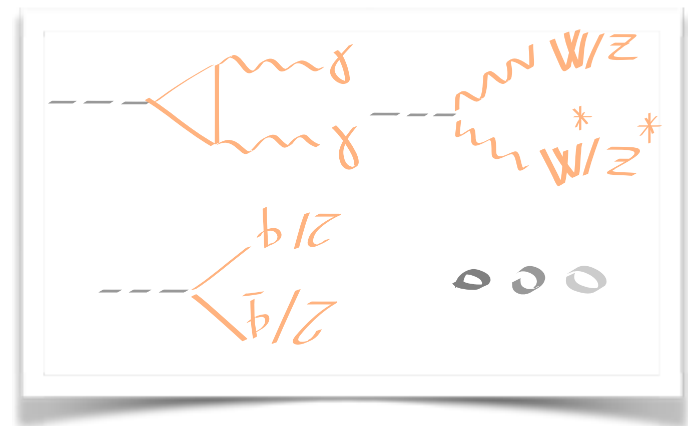
/Lilith-1.1_released/userinput/example_mu.xml

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

$X \subset$



$Y \subset$



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

Signal strengths

Signal strengths

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

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

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: $(A \times \epsilon)_{X,Y} = (A \times \epsilon)^{\rm SM}_{X,Y}$

the signal strength read

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

✓ 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

Drawbacks of the Run I approach

- Multiplying the likelihoods together leads to a **multi-counting** of **shared systematic uncertainties**
- The profiling of common systematics may not be consistent: different channels may pull the profiling towards different directions

$\Longrightarrow$ need a **consistent** treatment of the systematics

- Theoretical systematic uncertainties are time-dependent, analyses should not be re-performed for every new calculation

$\Longrightarrow$ **decouple** shared systematic uncertainties from experimental results (luminosity, inclusive ggH cross-section, ggH+2-jets,…)

$\Longrightarrow$

« **A novel approach to Higgs Coupling Measurements** »
K. Cranmer, S. Kreiss, D. Lopez-Val, T. Plehn
[arXiv:1401.0080]

Kyle's slide

Effective Likelihoods

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Start with the full likelihood function

yield · shape · systematics

$$L_{\text{full}}(\boldsymbol{\mu},\boldsymbol{\alpha}) = \underbrace{\prod_{c\in\text{category}} \left[\text{Pois}(n_c|\nu_c(\boldsymbol{\mu},\boldsymbol{\alpha})) \prod_{e=1}^{n_c} f_c(x_e|\boldsymbol{\mu},\boldsymbol{\alpha}) \right]}_{\equiv L_{\text{main}}(\boldsymbol{\mu},\boldsymbol{\alpha})} \underbrace{\prod_{i\in\text{syst}} f_i(a_i|\alpha_i)}_{\equiv L_{\text{constr}}(\boldsymbol{\alpha})}$$

Subscripts
c … category
p … production
d … decay

Expected number of events ν has signal strength μ that scales a signal yield s which depends on **α**

$$\nu_c(\boldsymbol{\mu},\boldsymbol{\alpha}) = \sum_{p,d} \mu_{pd}\, s_{cpd}(\boldsymbol{\alpha}) + b_c(\boldsymbol{\alpha})$$

Introduce μ^{eff} that scales with respect to some fixed theoretical reference at $\boldsymbol{\alpha}_0$.
Absorb **α**-dependence into $\mu^{\text{eff}}(\mu,\alpha)$

$$\nu_c(\boldsymbol{\mu},\boldsymbol{\alpha}) \rightarrow \sum_{p,d} \mu^{\text{eff}}_{cpd}(\boldsymbol{\mu},\boldsymbol{\alpha})\, s_{cpd}(\boldsymbol{\alpha}_0) + b_c(\boldsymbol{\alpha}_0)$$

$$L_{\text{eff}}(\boldsymbol{\mu}_{\text{eff}}) = L_{\text{main}}(\boldsymbol{\mu} = \boldsymbol{\mu}_{\text{eff}}, \boldsymbol{\alpha}_0)$$

Here $\mu^{\text{eff}}(\mu,\alpha)$ is a function that absorbs the dependence on α, but we can also think of μ^{eff} as a parameter on its own and measure $L_{\text{eff}}(\mu^{\text{eff}})$

$$L_{\text{full}}(\boldsymbol{\mu},\boldsymbol{\alpha}) \approx L_{\text{recouple}}(\boldsymbol{\mu},\boldsymbol{\alpha}) \equiv L_{\text{eff}}(\boldsymbol{\mu}^{\text{eff}}(\boldsymbol{\mu},\boldsymbol{\alpha})) \cdot L_{\text{constr}}(\boldsymbol{\alpha})$$

Need a **reparametrization template** $\mu^{\text{eff}}(\mu,\alpha)$ with parameters η and a **method** to determine the ηs such that L_{recouple} approximates L_{full}:

$$\mu^{\text{eff}}_{pd}(\boldsymbol{\mu},\boldsymbol{\alpha}) = \mu_{pd} + \sum_{i,p'} \mu_{p'd}\, \eta^{p'}_{pi}\, (\alpha_i - \alpha_{0,i}) + \sum_i \phi_i(\alpha_i - \alpha_{0,i})$$