Higgs couplings after LHC Run I

Global fit & presentation of the experimental results

Jérémy Bernon
LPSC Grenoble

Based on
« **Status of Higgs couplings after run 1 of the LHC with Lilith 1.0** »
arXiv:1409.1588

Updated

In collaboration with **Béranger Dumont** and **Sabine Kraml**

Grenoble
Laboratoire de Physique
Subatomique et de Cosmologie

Hamburg Workshop on Higgs Physics
DESY Hamburg, 23 October 2014

PHYSICS AT THE TERA SCALE
Helmholtz Alliance

Run I

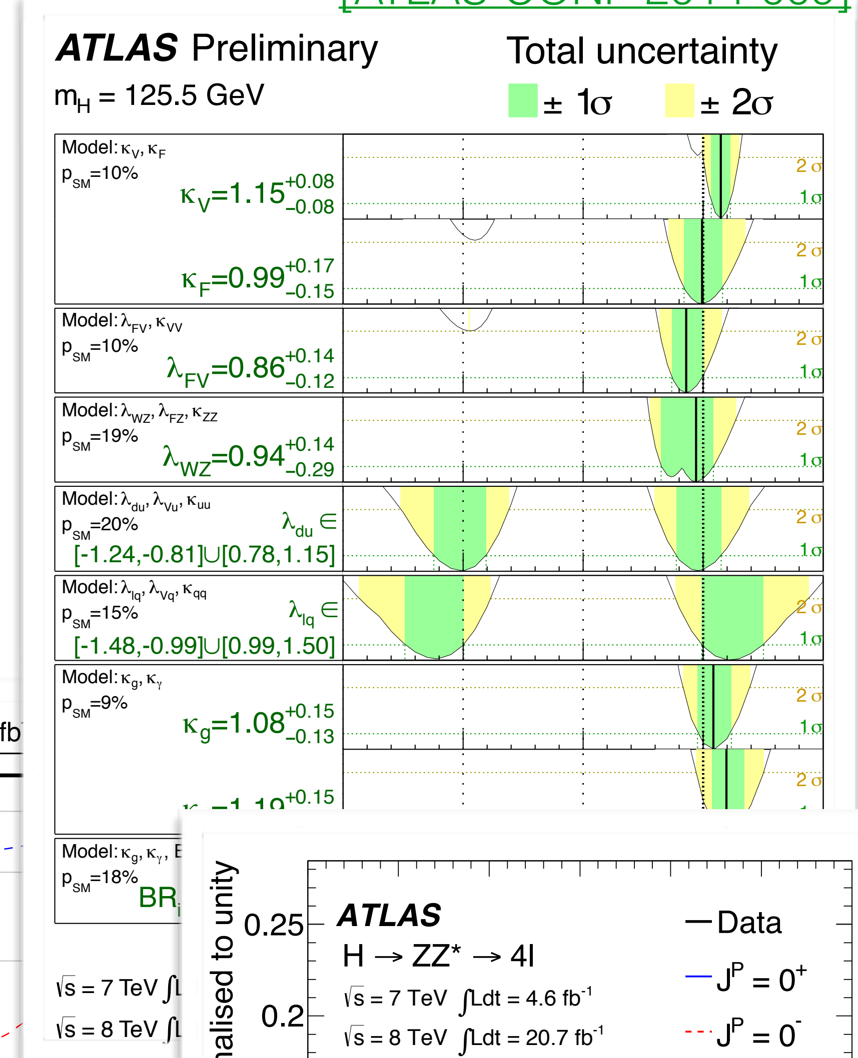
Signal strengths

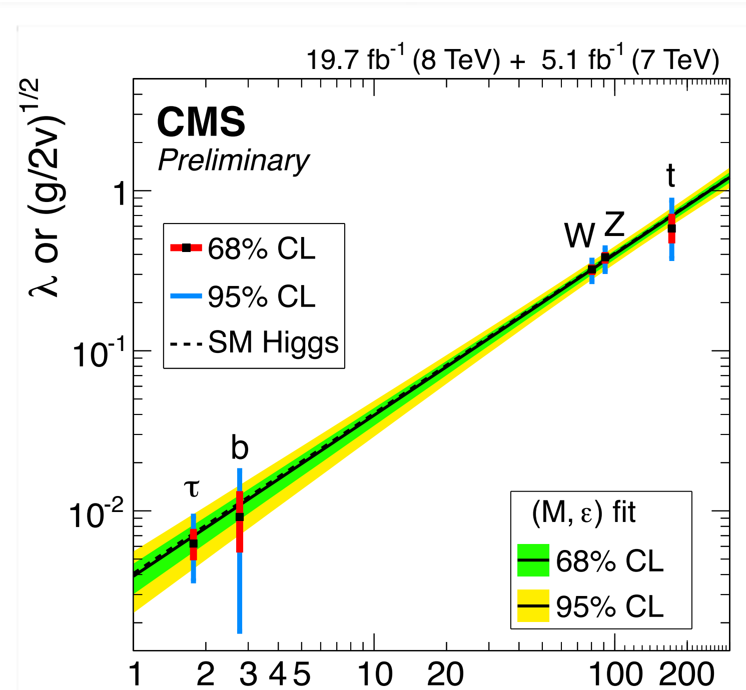
Global fit

LHC Run I and Higgs physics

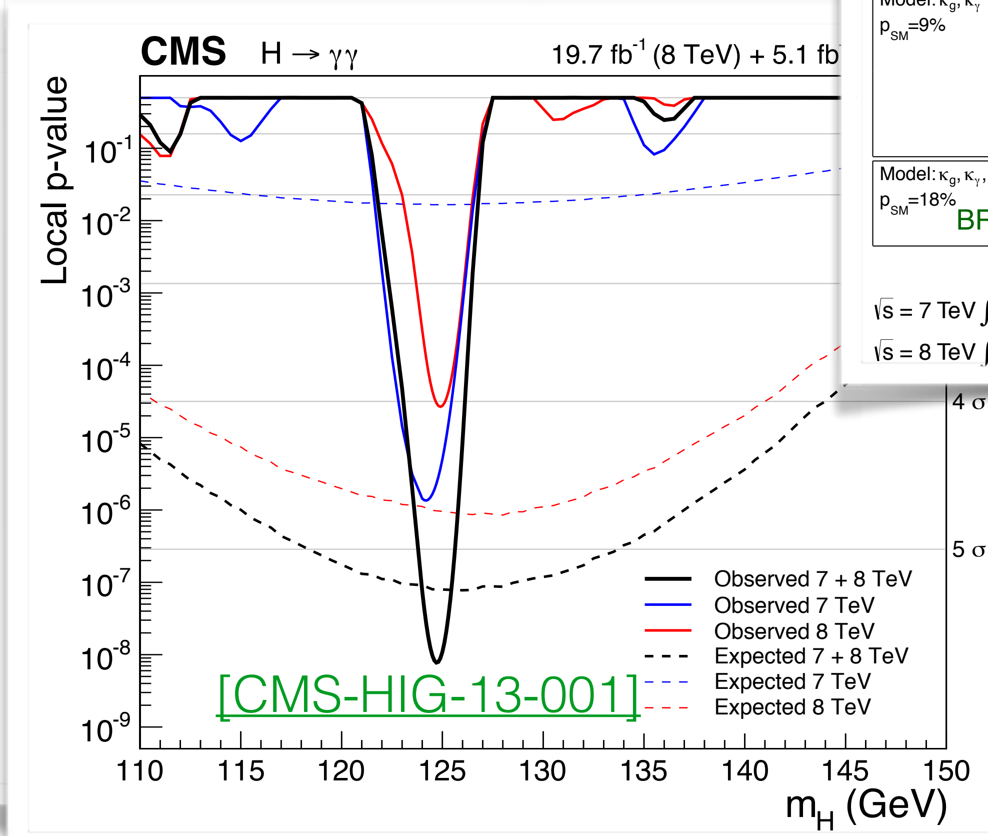
- Huge efforts during Run 1; from observation to beginning of precise measurements
- Mass, spin, couplings, cross sections…
- So far, compatible with an elementary weakly coupled SM-like Higgs

[ATLAS-CONF-2014-009]

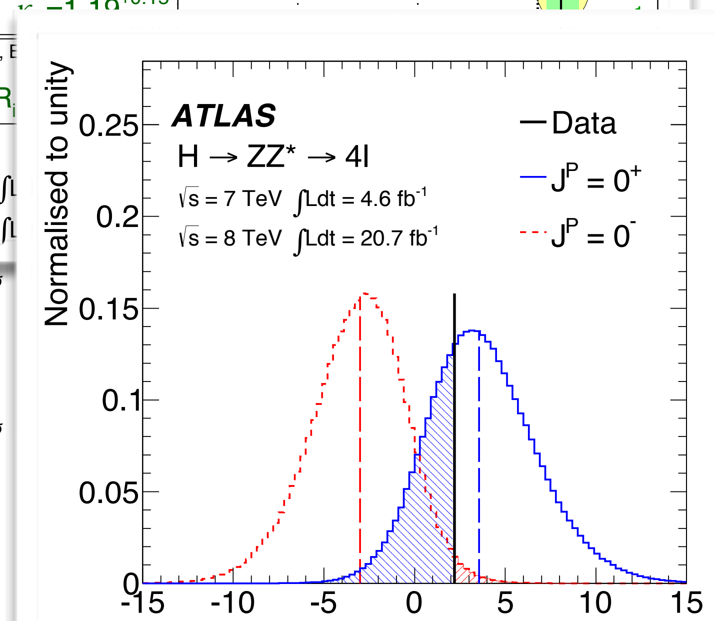




[CMS-HIG-14-009]



[CMS-HIG-13-001]



[ATLAS-HIGG-2013-01]

Run I

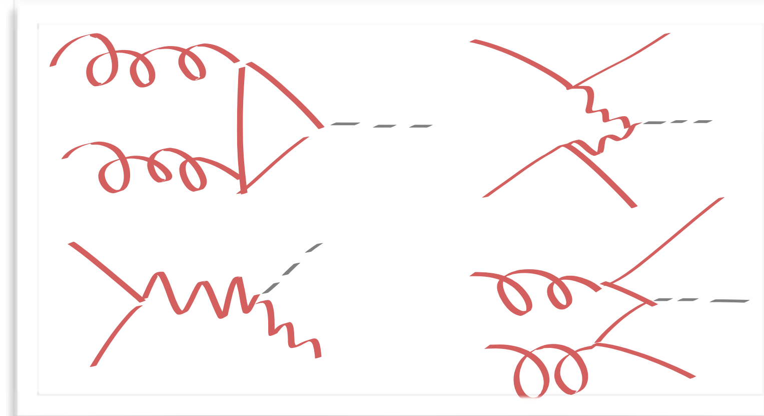
Signal strengths

Global fit

Run 1 & experimental signal strengths

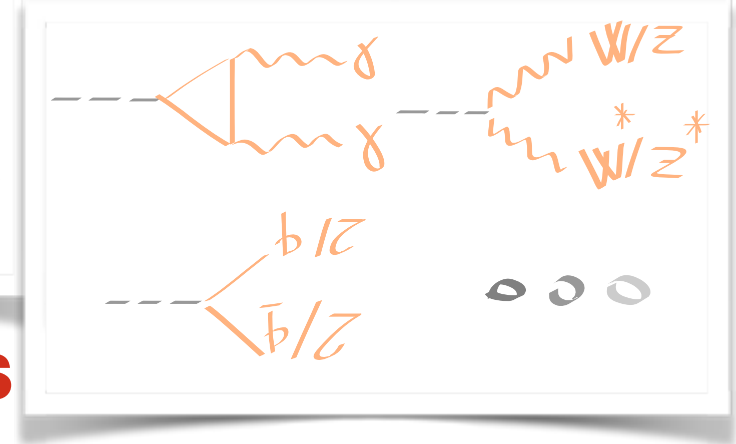
$$\mu(X,Y) = \frac{\sigma(X)BR(H \to Y)}{\sigma(X_{SM})BR(H_{SM} \to Y)}$$

Signal strength in « theory space »



Production modes

Decay modes



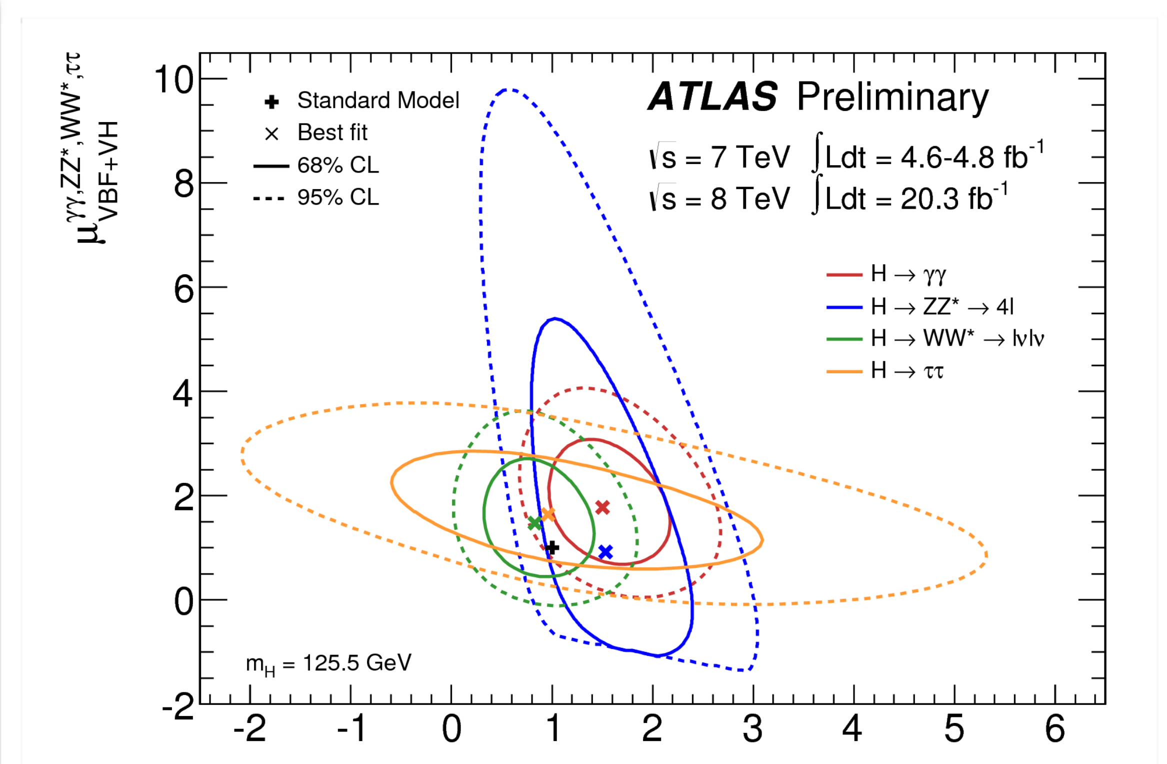
- « **Theory space** »: total decomposition in terms of production modes and decay modes

- Very useful since production modes are unfolded from experimental categories, correlations within each channels taken in to account

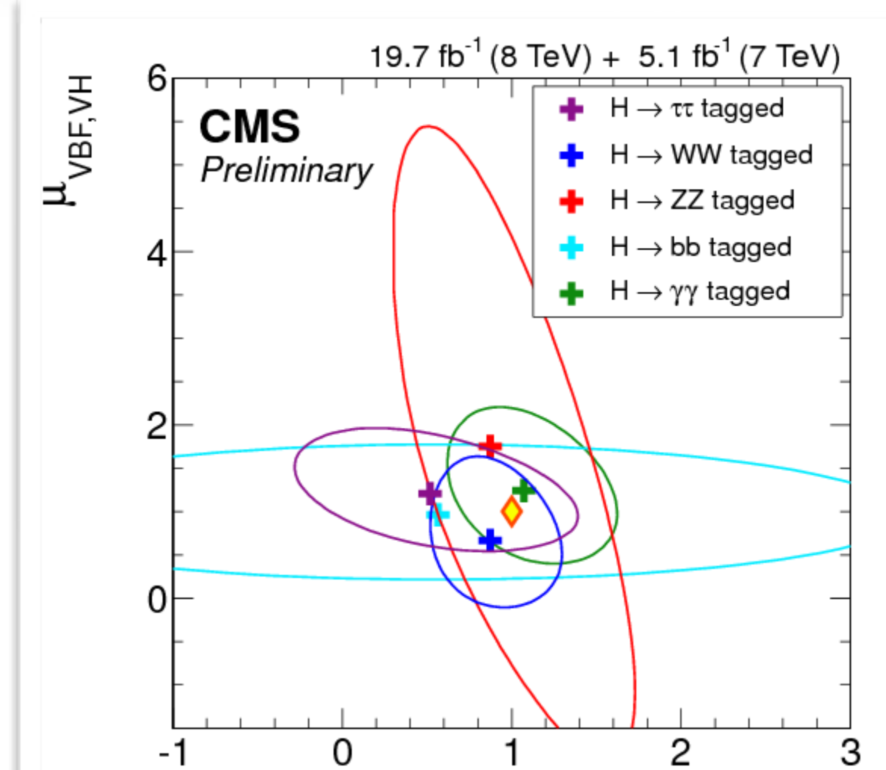
- Results given as $-2\ln\mathcal{L}$ in a $\mu(X,Y)$ vs $\mu(X',Y)$ plane

- Noticeable efforts during Run 1 from ATLAS and CMS to provide information readily usable for re-interpreting Higgs results (next slides)

Contour plots



[ATLAS-CONF-2014-009]

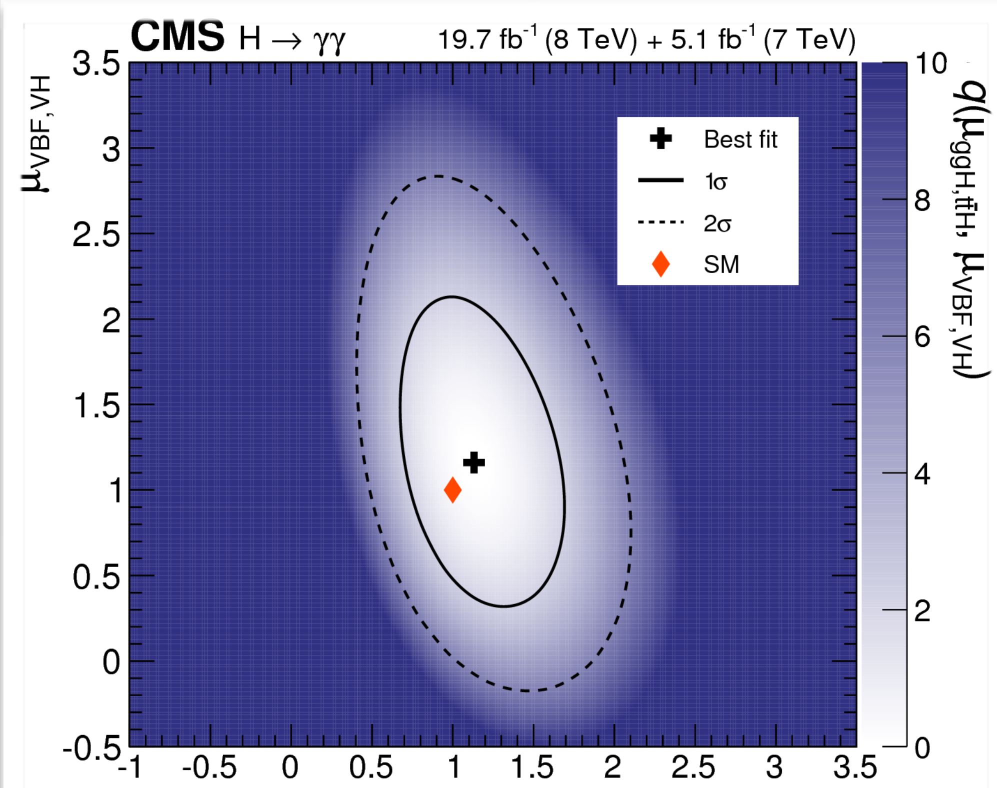


[CMS-PAS-HIG-14-009]

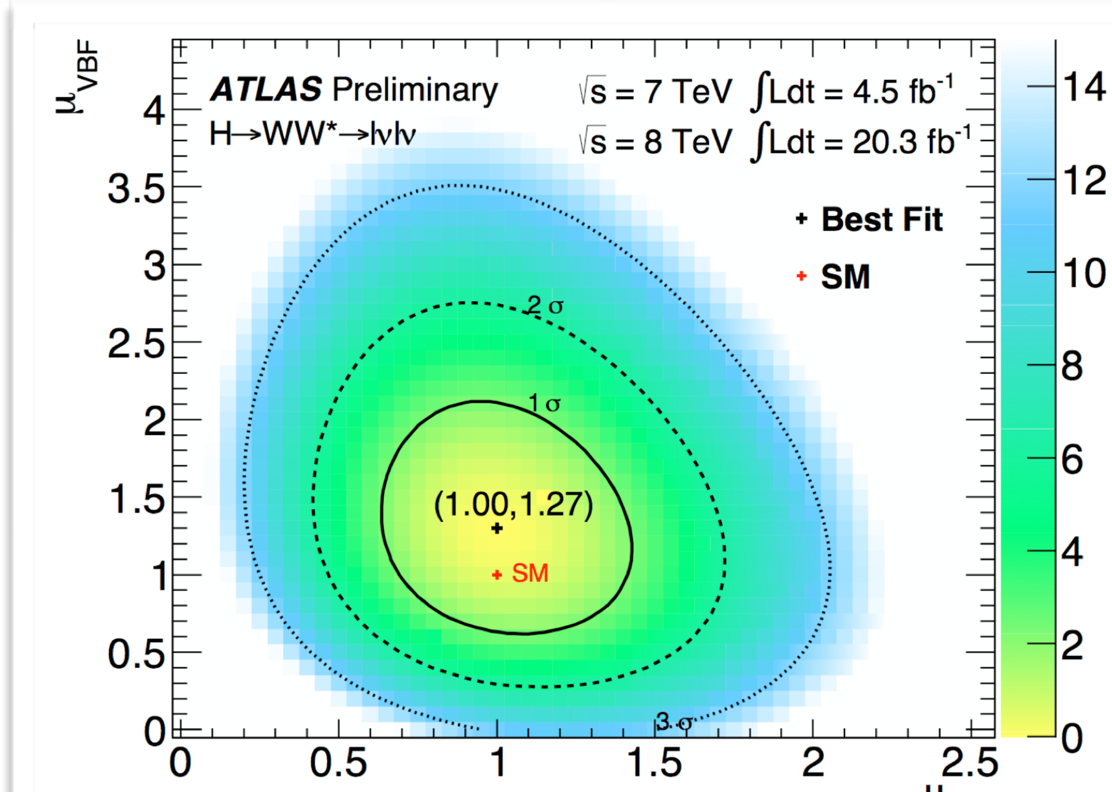
Approach first introduced by G. Cacciapaglia, A. Deandrea, G. D. La Rochelle, J.B. Flament in [arXiv:1210.8120v2]

- Standard way of presenting the results: 68.3% and 95.4% C.L. contours are given
- To reconstruct the likelihood shape one has to assume a model and fit the contours. 2D gaussian here.
- Correlation between the 2 dimensions taken into account, but validity of the approximation sometimes poor (*e.g.* ZZ channel)

Temperature plots



[CMS-HIG-13-001]



[ATLAS-CONF-14-060]

- Values of $-2\ln\mathcal{L}$ available : shape of the likelihood numerically accessible
- No assumptions on the model needed
- But still need to be digitized

A great step forward: digital likelihoods

ATLAS $H \to \gamma\gamma,\ WW,\ ZZ$

[ATLAS-HIGG-2013-002]

Informations | Références (121) | Citations (120) | Fichiers | Graphiques | HepData

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*

Jul 4, 2013 - 32 pages

$\mu_{\mathrm{ggH+ttH}}$	$\mu_{\mathrm{VH+VBF}}$	$-2\log\mathcal{L}^{exp}$
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 Higgs results
- All three ATLAS diboson analyses have been updated since then, those are unfortunately out of date now

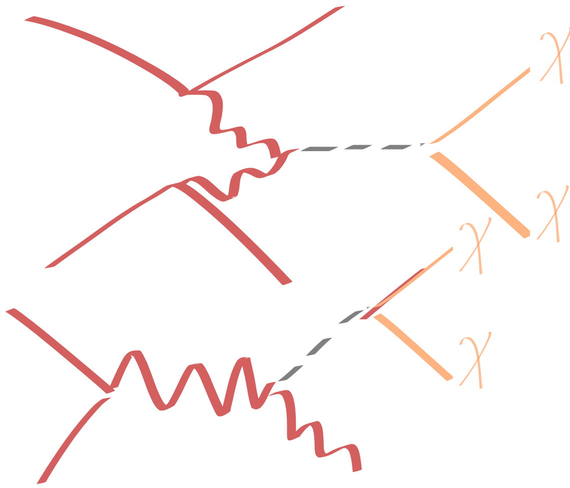
Run I

Signal strengths

Global fit

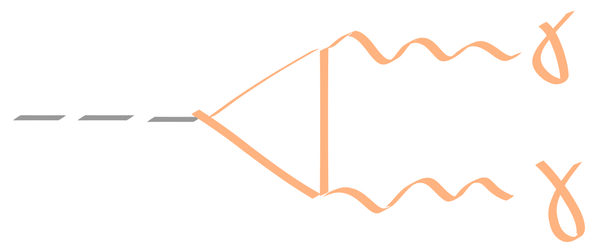
Recent results

- Considerable number of updated analyses released in the past few months



$VBF + VH, H \to \text{inv}$

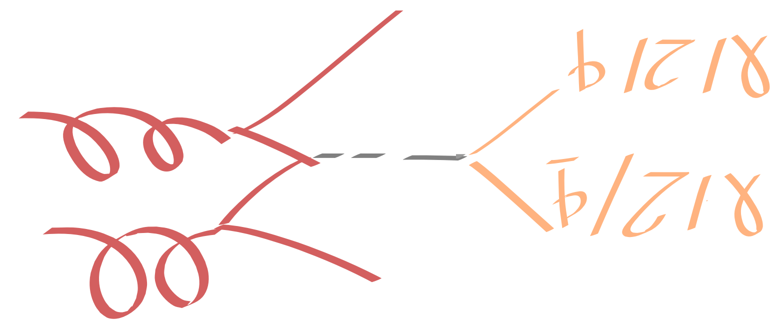
[CMS-HIG-13-030]



$H \to \gamma\gamma$

[CMS-HIG-13-001]

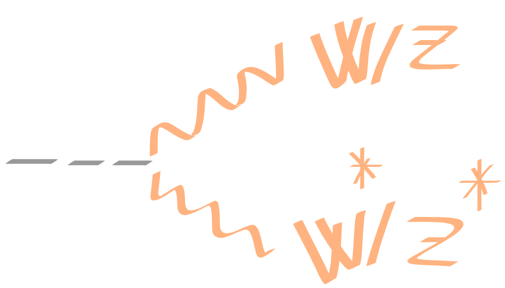
[ATLAS-HIGG-13-08]



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

[CMS-HIG-13-029]

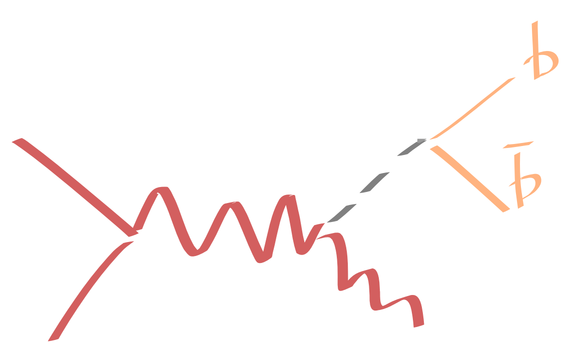
[ATLAS-HIGG-13-11,25]



$H \to WW^*/ZZ^*$

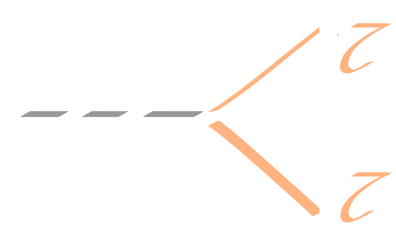
[ATLAS-CONF-14-060] *

[ATLAS-HIGG-13-21]



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

[ATLAS-HIGG-13-32] *



$H \to \tau\tau$

[ATLAS-CONF-14-061] *

Global fit

Based on previous work
by G. Belanger, B. Dumont,
U. Ellwanger, J.F. Gunion, S. Kraml in
[arXiv:1212.5244, 1302.5694, 1306.2641]

- Define reduced couplings (« κ framework »):

$$\mathcal{L} = \left[C_W m_W W^\mu W_\mu + C_Z \frac{m_Z}{\cos\theta_W} Z^\mu Z_\mu - C_U \frac{m_t}{2m_W} \bar{t}t - C_D \frac{m_b}{2m_W} \bar{b}b - C_D \frac{m_\tau}{2m_W} \bar{\tau}\tau \right] H$$

+ possible width extra-contribution (*e.g.* invisible BR)

SM particles contribution

- Effective loop-induced vertex: $C_{g,\gamma} = \overline{C}_{g,\gamma} + \Delta C_{g,\gamma}$
- Signal strengths predictions in terms of reduced couplings following LHC HXSWG recommendations [LHCHXSWG-2012-001]
- Construction of a combined likelihood
- If likelihood shape is available: no assumptions needed
- Otherwise: use the gaussian approximation
- Profile likelihood analysis

Our framework: Lilith

- Python **public** code: obtain Higgs likelihood from the latest experimental signal strengths in terms of production modes

Lilith

LIght LIkelihood fiT for the Higgs

[JB, B. Dumont]

Information, Download:
http://lpsc.in2p3.fr/projects-th/lilith/

- All kind of signal strengths experimental formats are handled: full grid, 2D contour, 1D profile, single point measurement

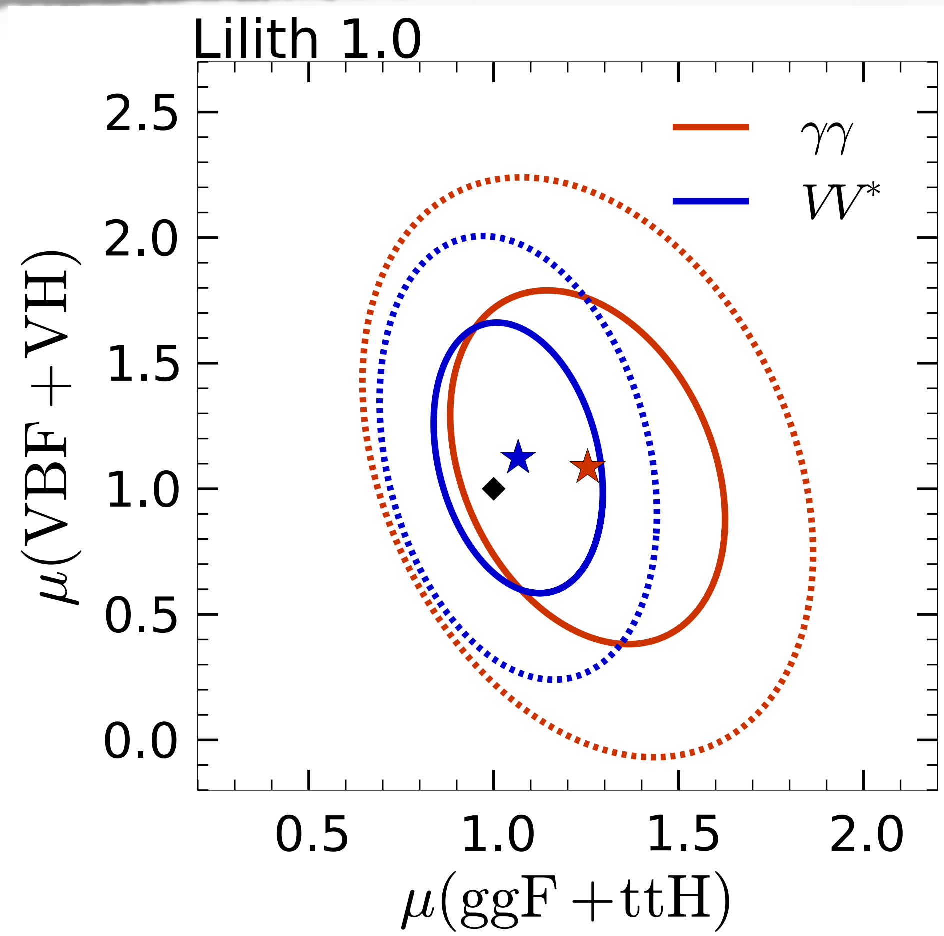
- All experimental data are stored in a flexible XML database; easy to update and add/modify results

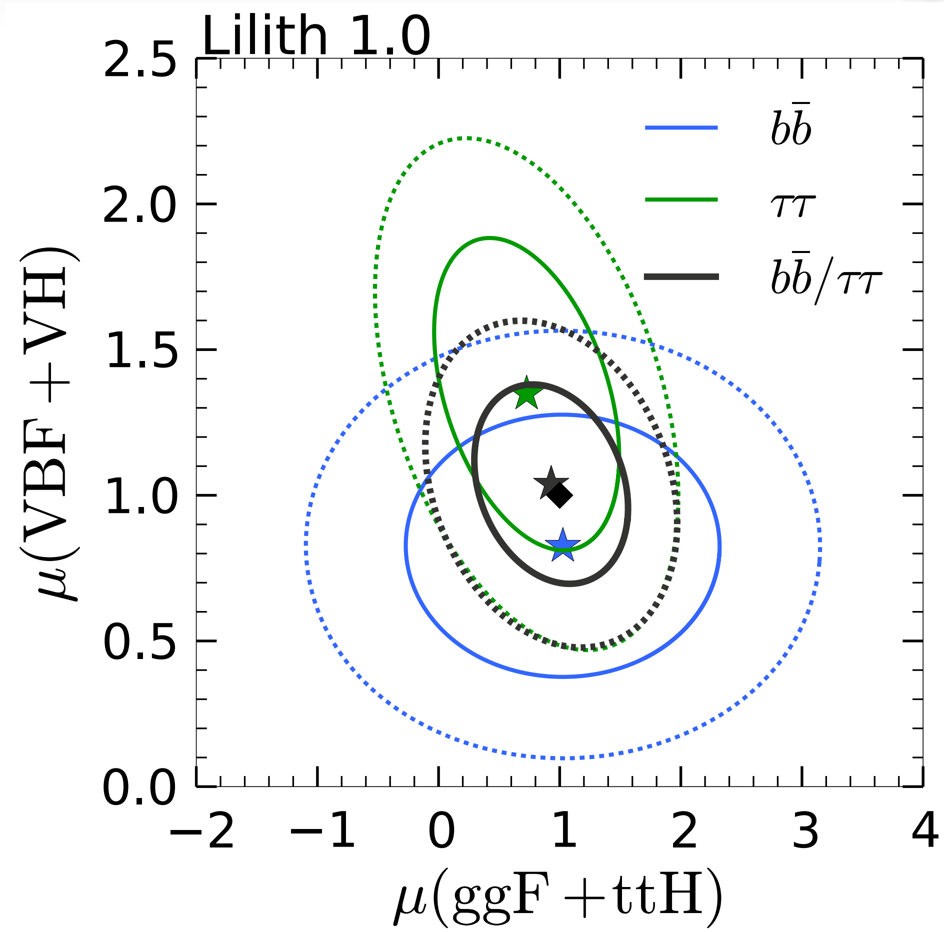
- Two user input modes:
  - → Reduced couplings as inputs
  - → Signal strengths as inputs

- Returns $-2\ln\mathcal{L}$ for each input points

The following results are based on an updated analysis of
arXiv:1409.1588
taken into account the latest ATLAS results

Signal strengths combination: LHC+Tevatron



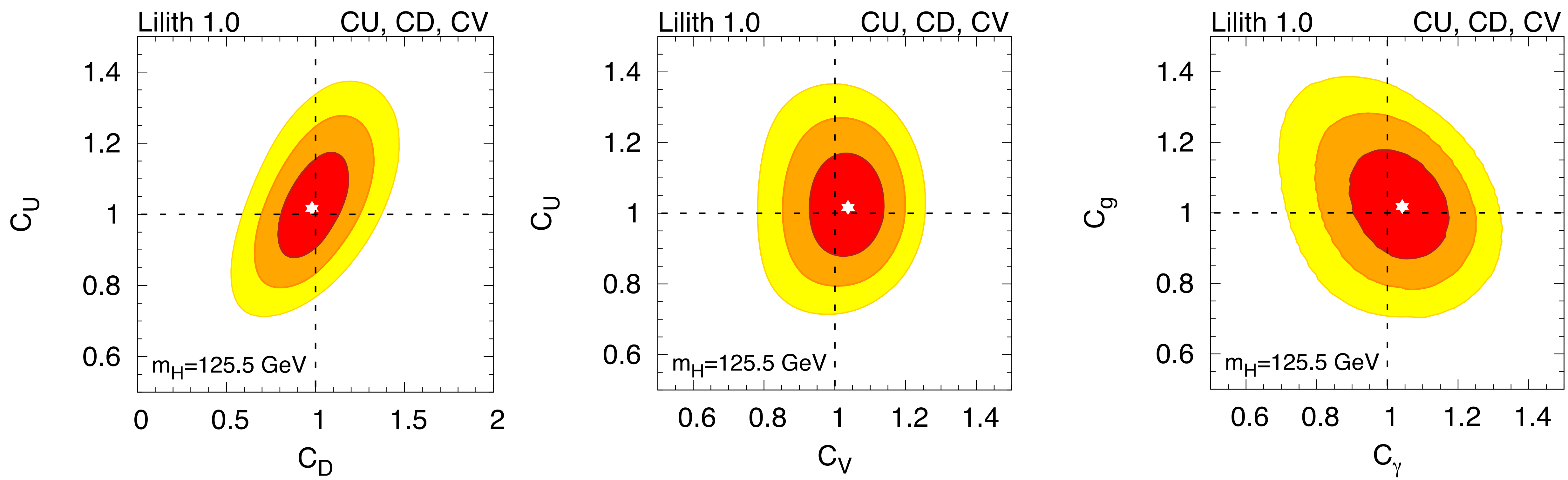


	$\hat{\mu}^{\mathrm{ggF+ttH}}$	$\hat{\mu}^{\mathrm{VBF+VH}}$	ρ
$\gamma\gamma$	1.25 ± 0.24	1.09 ± 0.46	-0.30
VV^*	1.07 ± 0.15	1.12 ± 0.36	-0.26
$b\bar{b}/\tau\tau$	0.93 ± 0.42	1.04 ± 0.23	-0.24
$b\bar{b}$	1.02 ± 0.85	0.83 ± 0.30	0
$\tau\tau$	0.73 ± 0.50	1.35 ± 0.35	-0.40

Perfectly well compatible with the SM

Reduced coupling fits

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



Profiling over other parameters:

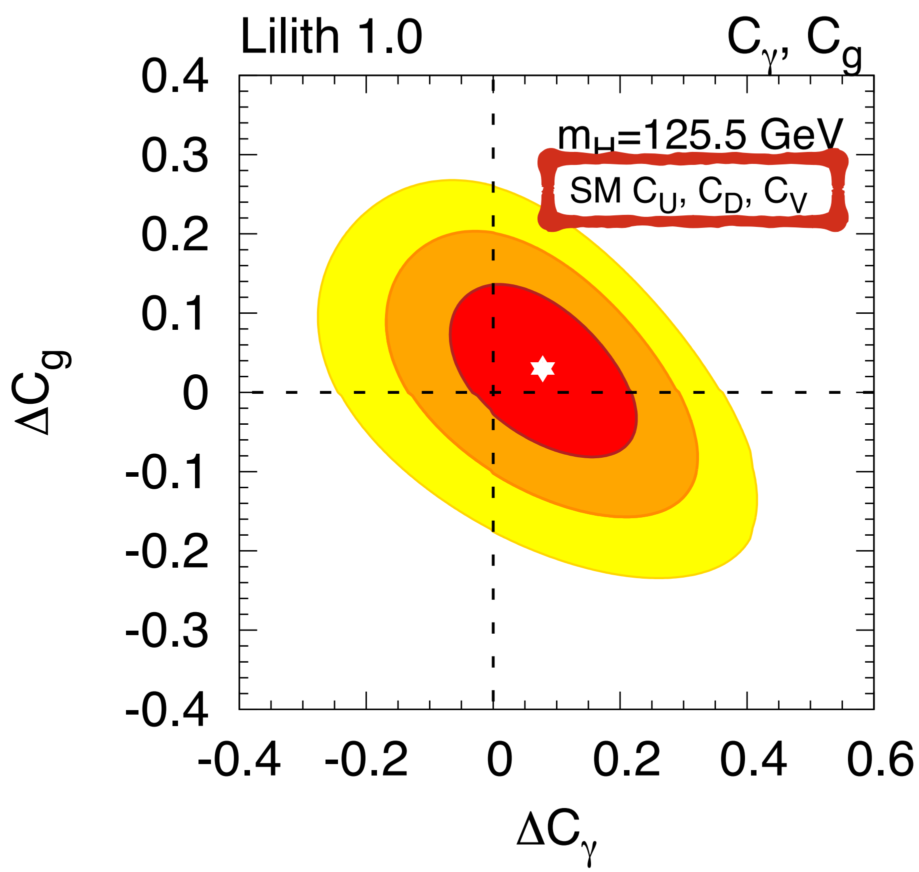
$$C_U = 1.02 \pm 0.10$$
$$C_D = 0.98 \pm 0.14$$
$$C_V = 1.04 \pm 0.07$$
$$C_\gamma = 1.04 \pm 0.11$$
$$C_g = 1.02 \pm 0.11$$

- **Fit II:** C_U, C_D, C_Z, $C_{WZ}=C_W/C_Z$, under the previous assumptions:

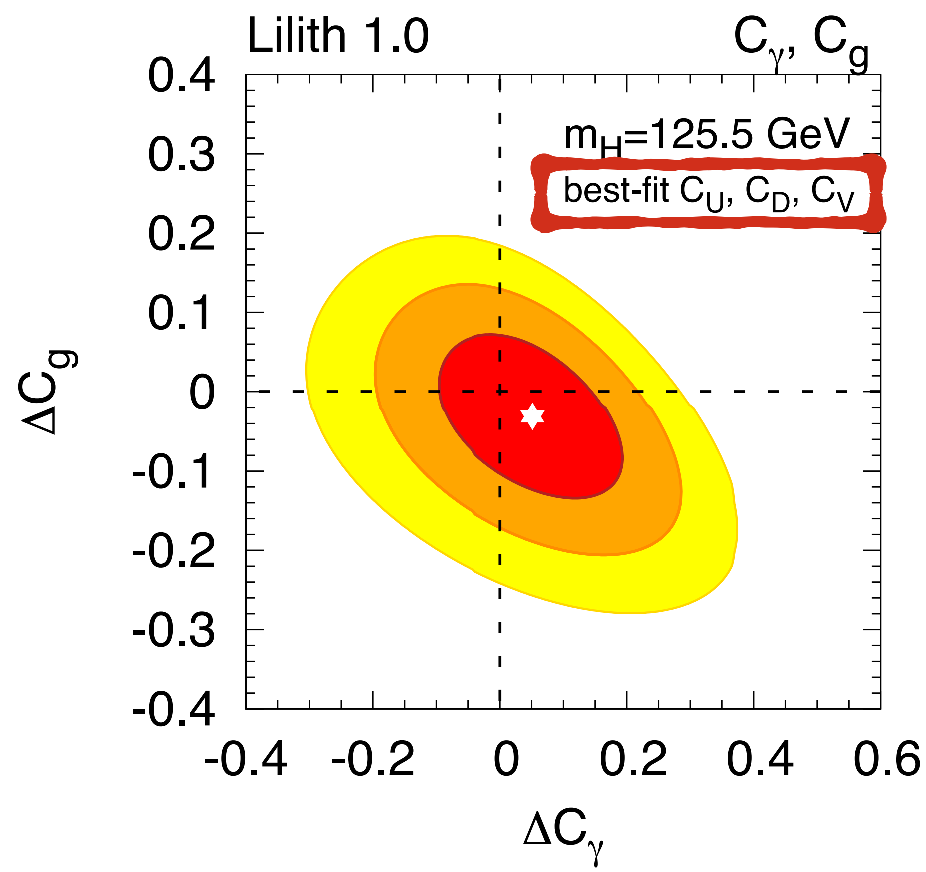
(Custodial symmetry test) $C_{WZ} = 0.94 \pm 0.10$

Loop-induced vertices fits: ΔC_γ, ΔC_g

- **Fit:** ΔC_γ, ΔC_g, assuming C_U, C_D, C_V fixed at their SM or best-fit values & no extra width contribution



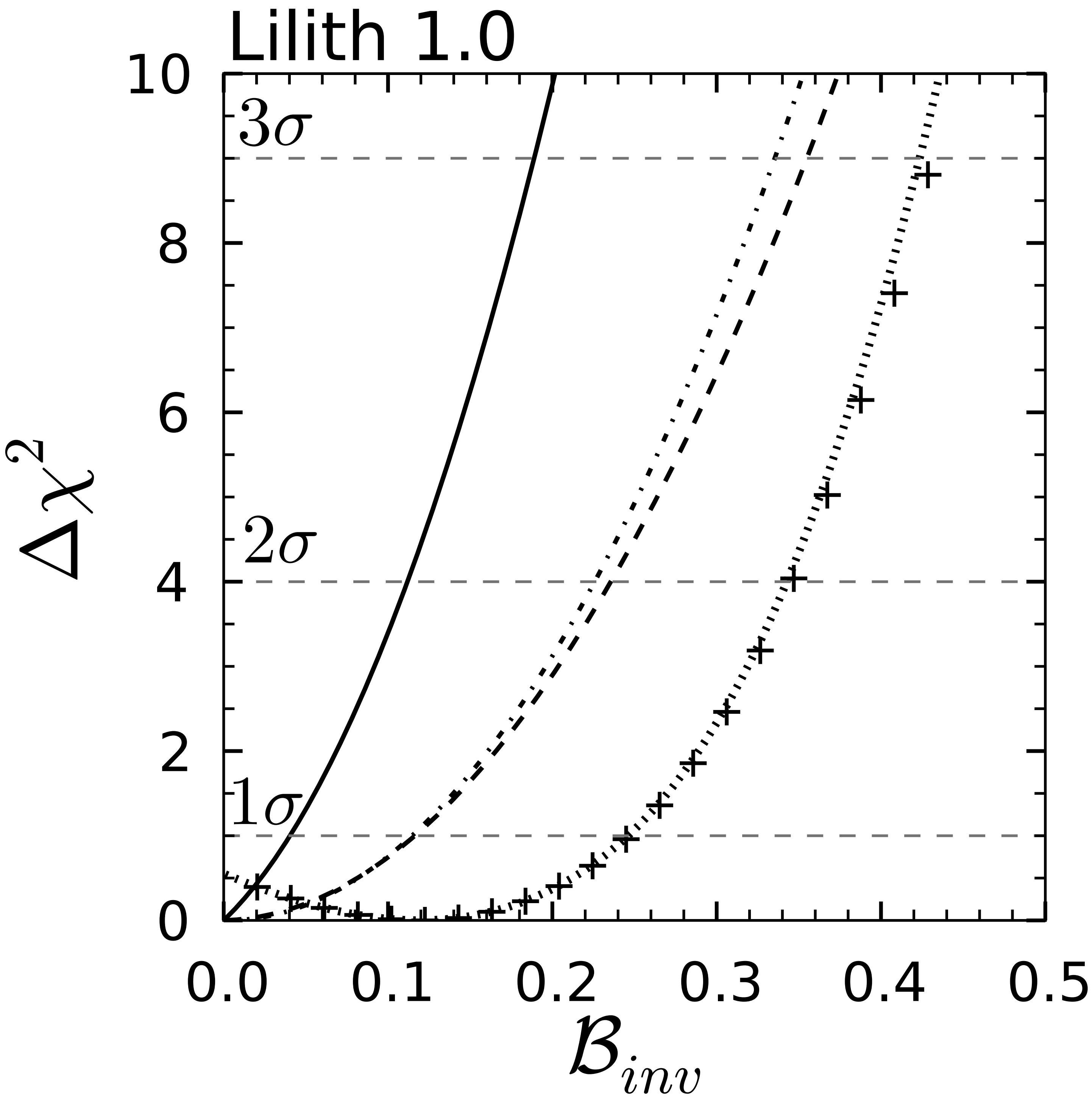
$$C_U = C_D = C_V = 1$$



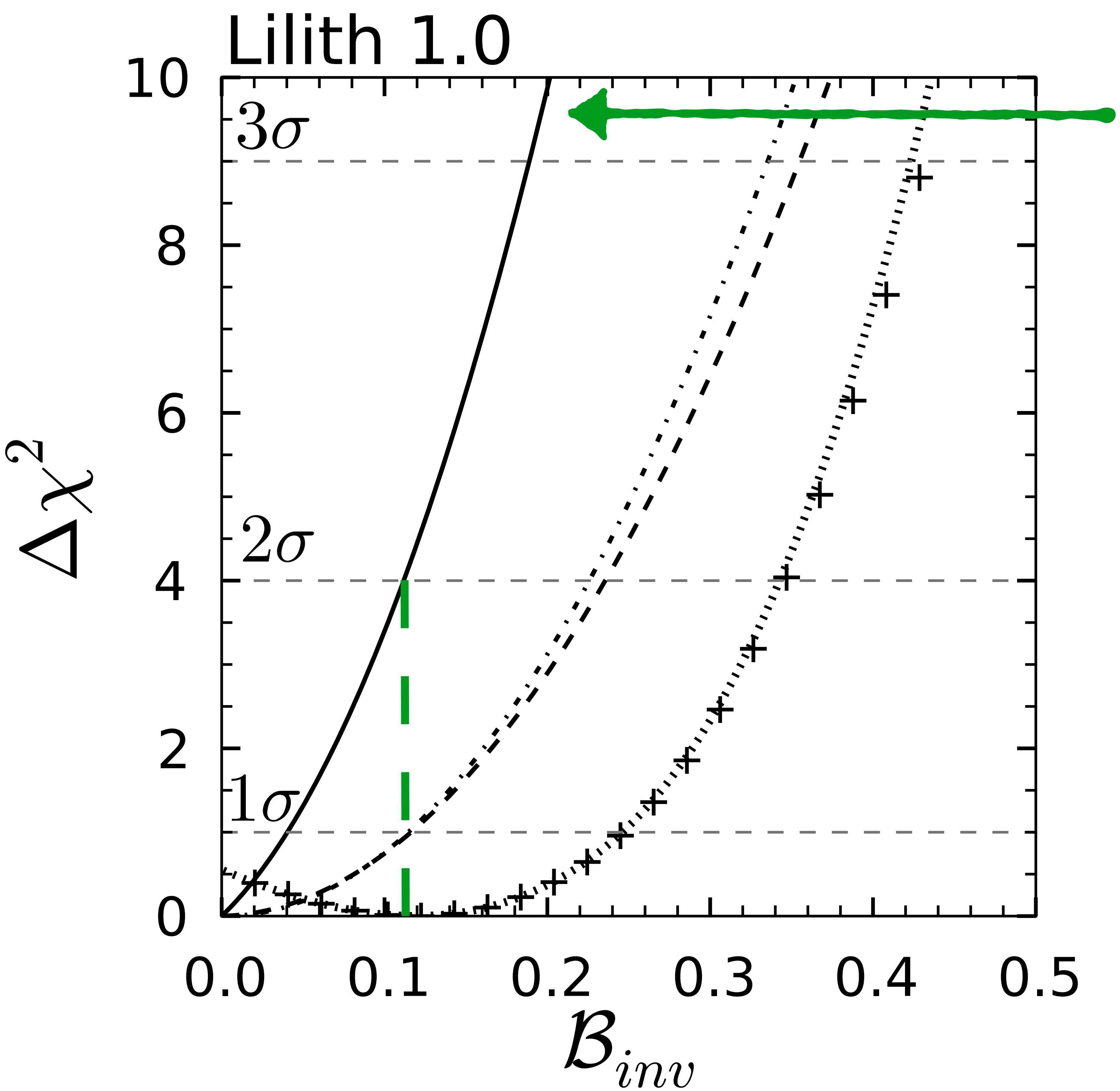
$$C_U = 1.02 \; , C_D = 0.98 \; , C_V = 1.04$$

✓Loop-induced processes well compatible with SM particle contributions only

Invisible branching ratio fits



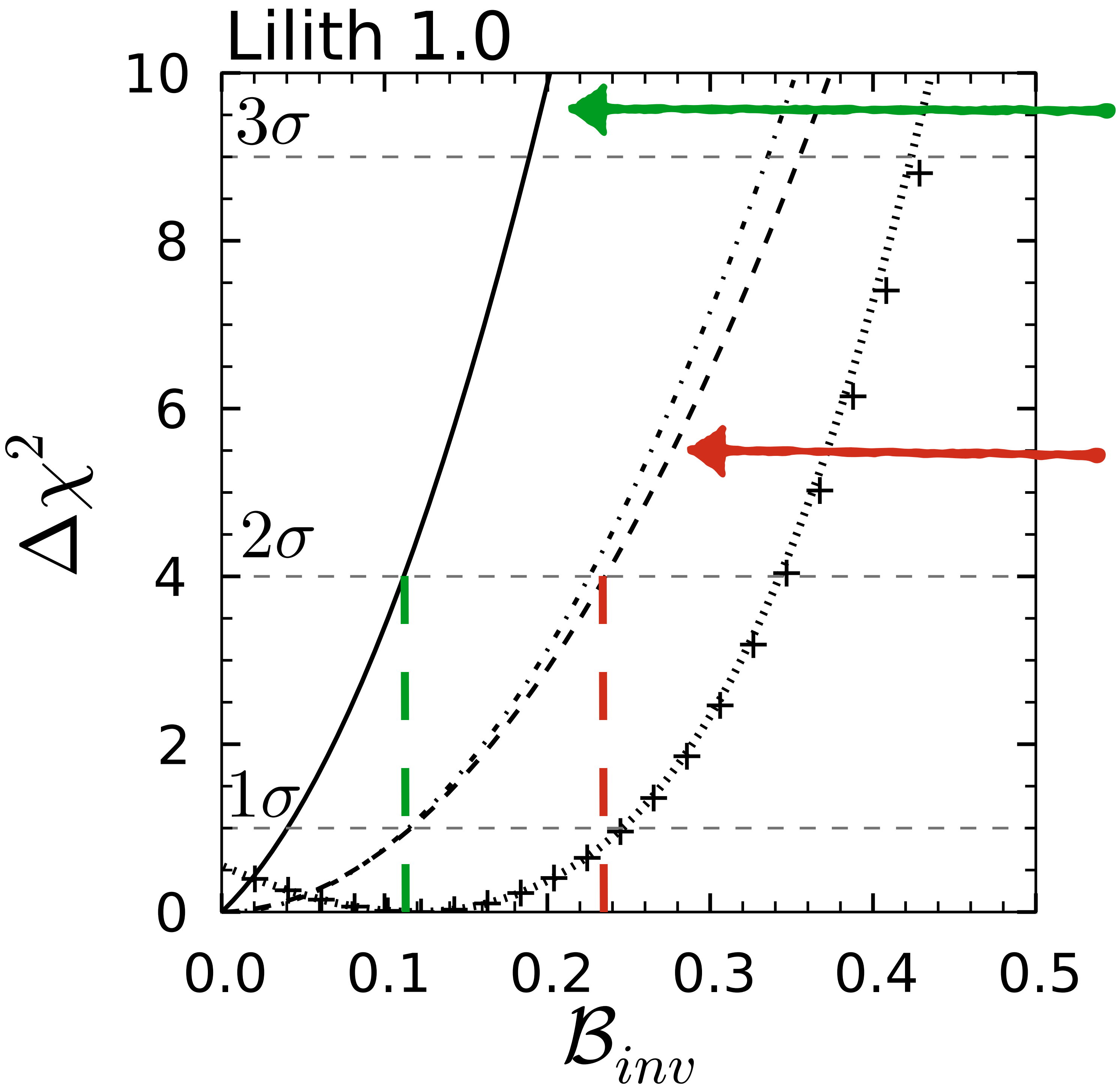
Invisible branching ratio fits



SM+invisible

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

Invisible branching ratio fits



SM+invisible

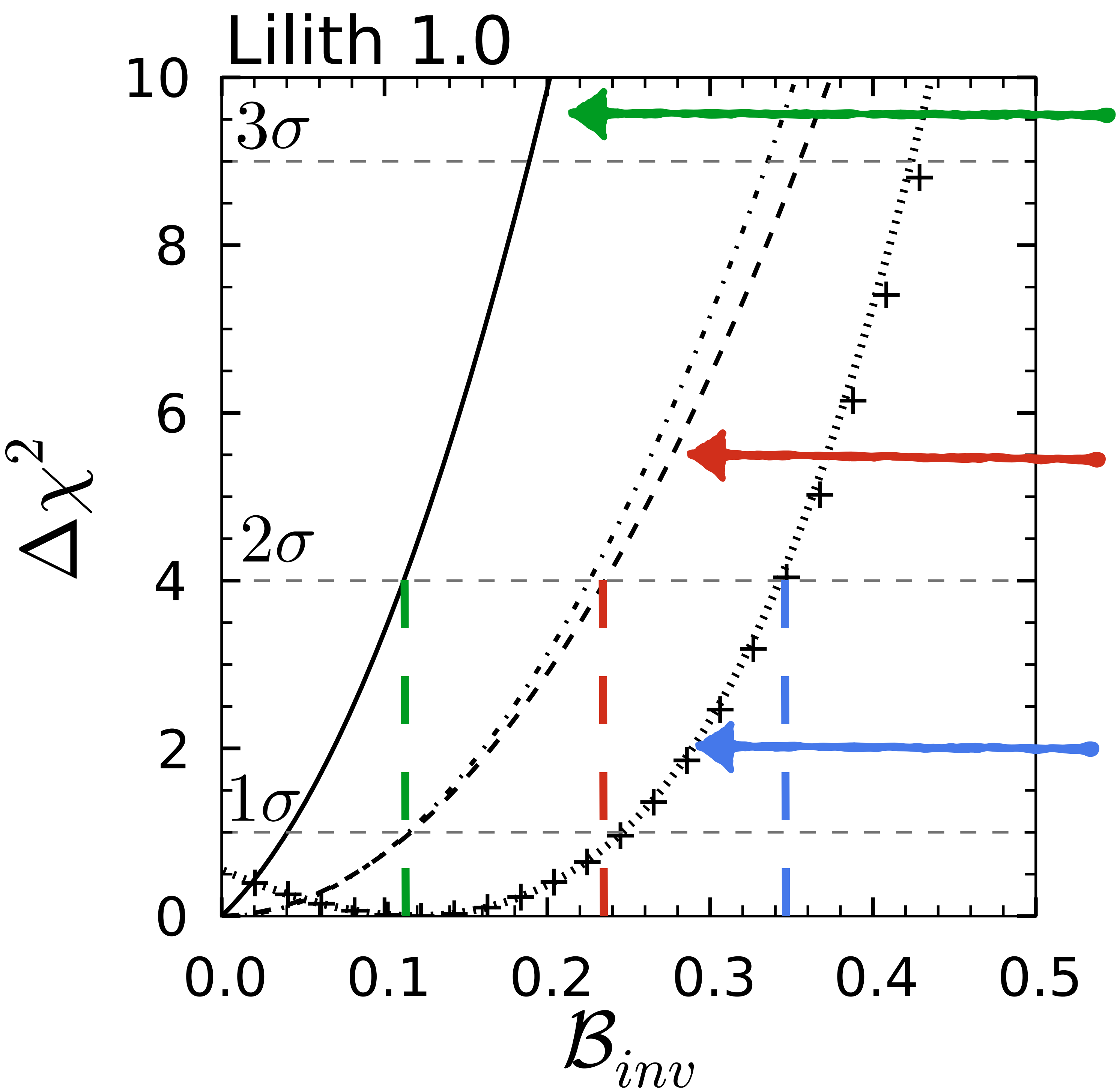
$\mathcal{B}_{inv} < 0.11$ at 95.4% C.L.

C_U, C_D, C_V <1

SM+ΔC_γ, ΔC_g +invisible

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

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

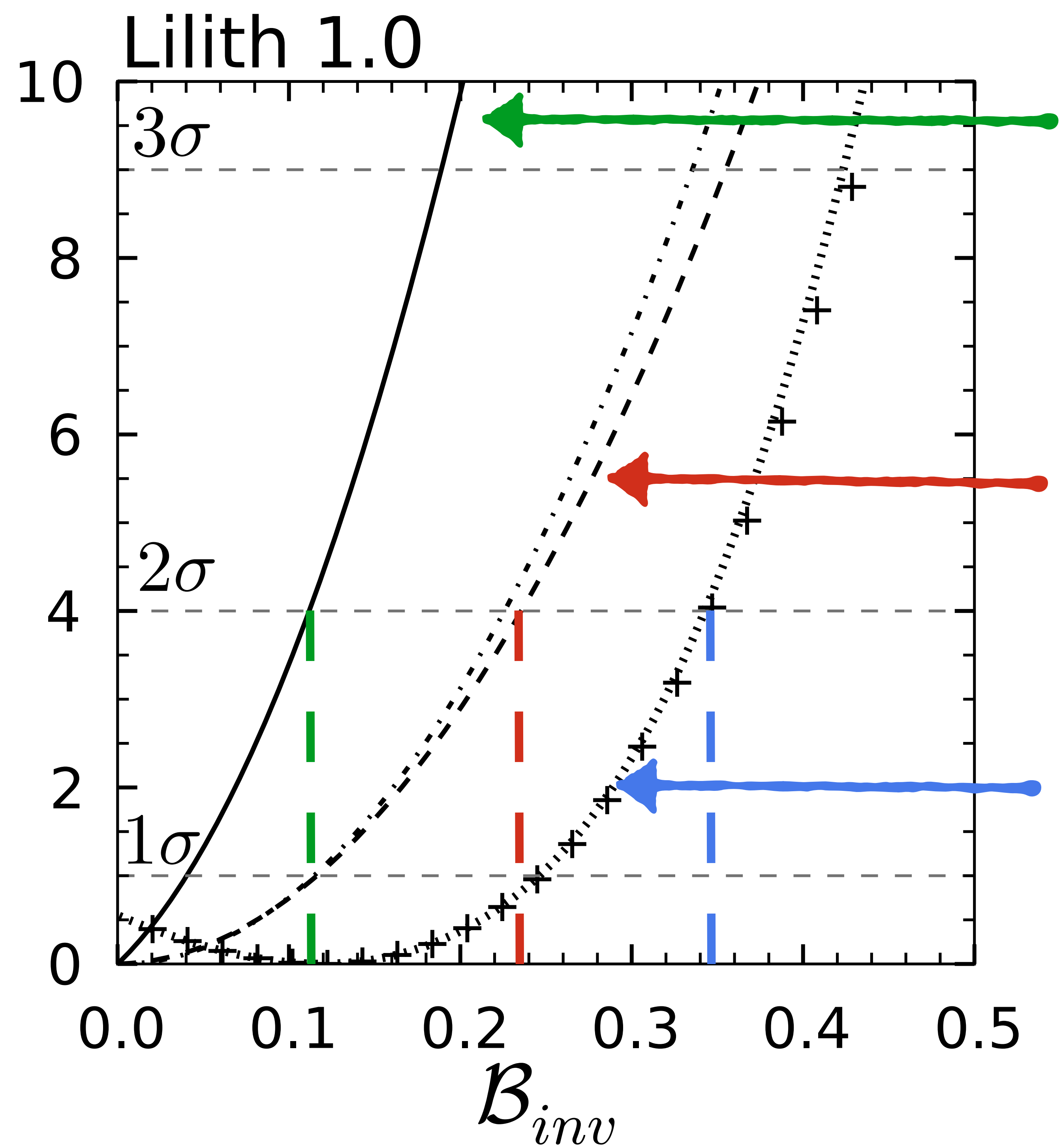
$\mathcal{B}_{inv} \lesssim 0.24$ at 95.4% C.L.

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.

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.

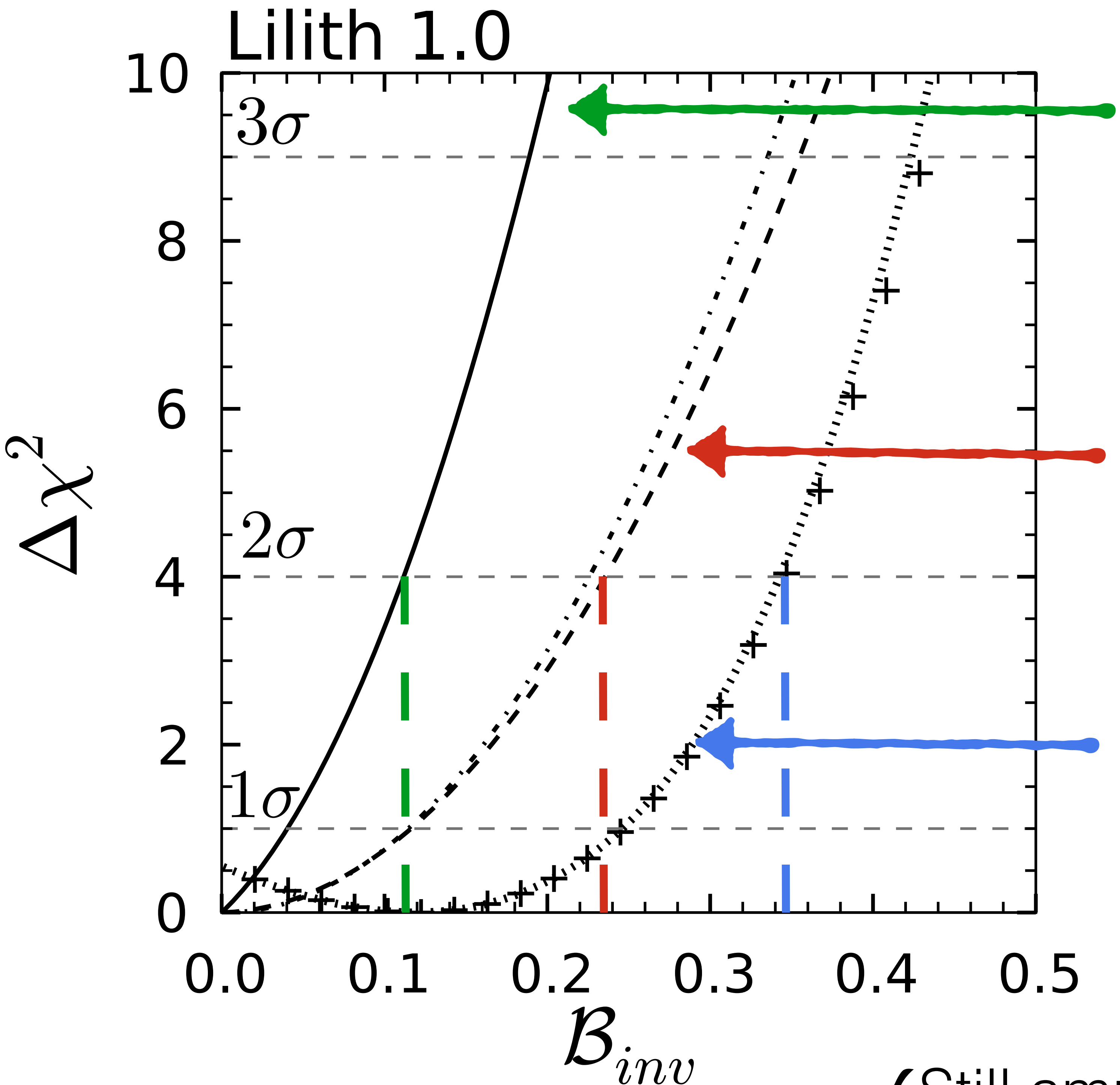
Roughly the same limits for undetected BR

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.

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.

Roughly the same limits for undetected BR

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

After Run I

Pursuing the Run I efforts

- Possible and desirable to go beyond the κ framework in Run 2 to reinterpret Higgs results in more complex cases (*e.g.* non SM-like tensor structure), nevertheless it is still valid for most cases of interest.

- Pursuing the ATLAS and CMS efforts during Run 1, signal strengths results should **systematically** come in numerical form

- This is **necessary** to the community to make the most out of the Higgs results by re-interpreting them in various models without need to make crude assumptions

- ATLAS showed that it is possible

Going forward

- Total breakdown of the production modes is highly desirable and will become necessary as more data is collected
- Introduce mass dependence
  - Publication of a 6D likelihood function for each decay mode, center of mass energy

$$\mathcal{L}(m_H, \mu_{ggH}, \mu_{ttH}, \mu_{VBF}, \mu_{ZH}, \mu_{WH})$$

Digital grid ?
Simplified likelihood ?
Full model ?

See « **On the presentation of the LHC Higgs results »**
F. Boudjema et al
[arXiv:1307.5865v2]

- Treatment of systematic uncertainties, in particular theoretical, will be crucial during Run 2: possibility to decouple them

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

Conclusions

Conclusions

- Run 1 showed impressive performance; large amount of data collected, lot of results available
- The observed state looks really SM-like, but there is still room for deviations
- Better understanding of the data if more information is given in a systematical way
- First steps have been initiated by both ATLAS and CMS collaborations
- Necessity to pursue in that direction and go beyond
- This is the only way to fully make sense of the data

Backup

Before/after the recent ATLAS updates

Before

	$\hat{\mu}^{\text{ggF}}$	$\hat{\mu}^{\text{VBF}}$	ρ
$\gamma\gamma$	1.25 ± 0.24	1.09 ± 0.46	-0.30
VV^*	1.03 ± 0.17	1.12 ± 0.41	-0.29
$b\bar{b}/\tau\tau$	0.83 ± 0.41	1.14 ± 0.27	-0.27
$b\bar{b}$	1.02 ± 0.85	0.92 ± 0.38	0
$\tau\tau$	0.64 ± 0.50	1.40 ± 0.40	-0.42

$$\mu^{\text{VH}}_{b\bar{b}} = 0.2^{+0.7}_{-0.6}$$

$$\mu^{\text{ggF+ttH}}_{\tau\tau} \simeq 1.20 \pm 1.19$$

$$\mu^{\text{VH+VBF}}_{\tau\tau} \simeq 1.66 \pm 0.76$$

$$\mu^{\text{ggF+ttH}}_{WW^*} \simeq 0.82 \pm 0.35$$

$$\mu^{\text{VH+VBF}}_{WW^*} \simeq 1.67 \pm 0.76$$

After

	$\hat{\mu}^{\text{ggF+ttH}}$	$\hat{\mu}^{\text{VBF+VH}}$	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

$$\mu^{\text{VH}}_{b\bar{b}} = 0.51^{+0.40}_{-0.37}$$

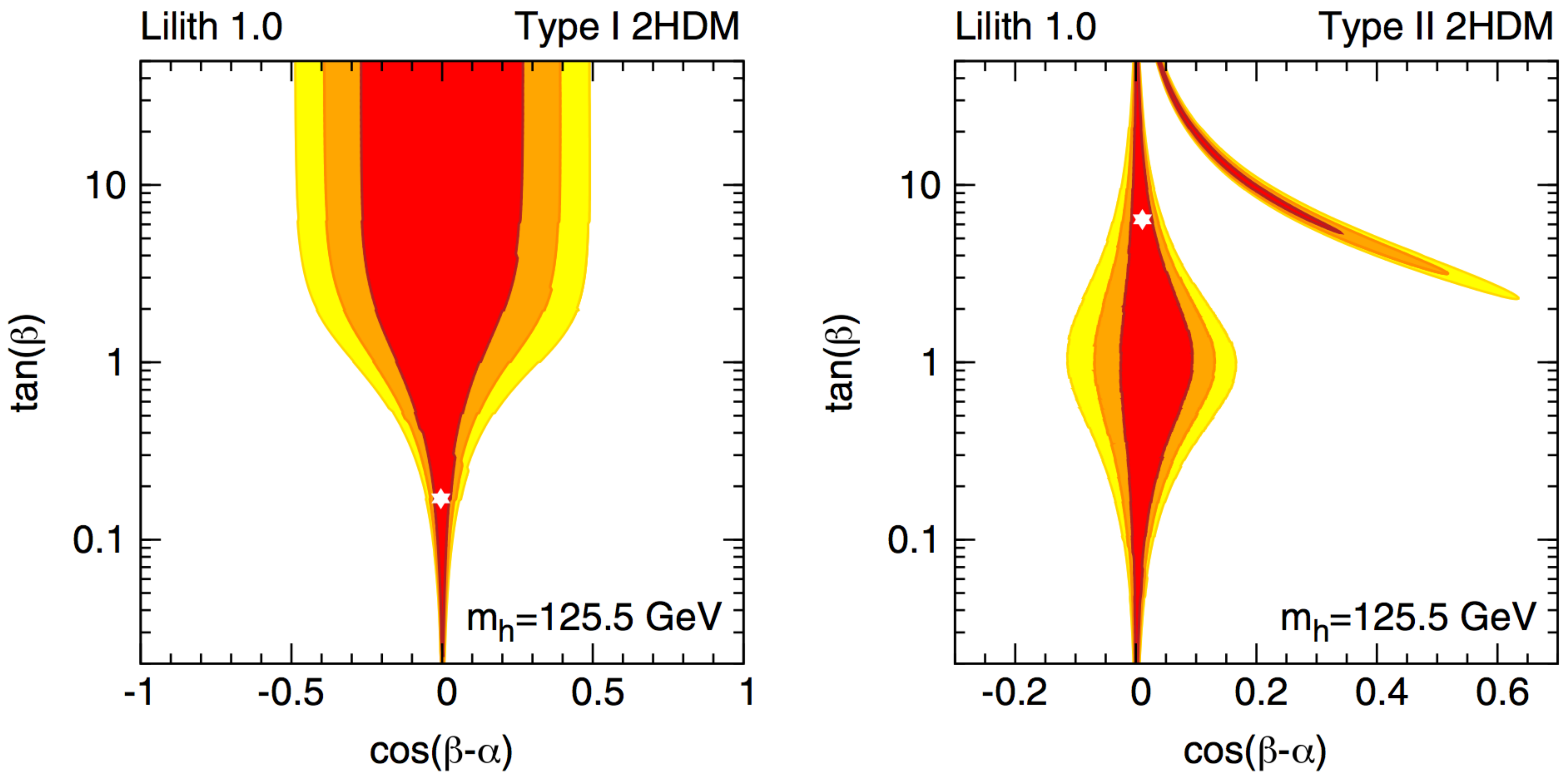
$$\mu^{\text{ggF+ttH}}_{\tau\tau} \simeq 2.17 \pm 1.35$$

$$\mu^{\text{VBF+VH}}_{\tau\tau} \simeq 1.28 \pm 0.56$$

$$\mu^{\text{ggF+ttH}}_{WW^*} \simeq 1.02 \pm 0.26$$

$$\mu^{\text{VBF}}_{WW^*} \simeq 1.36 \pm 0.49$$

2HDM of Type I & II fit

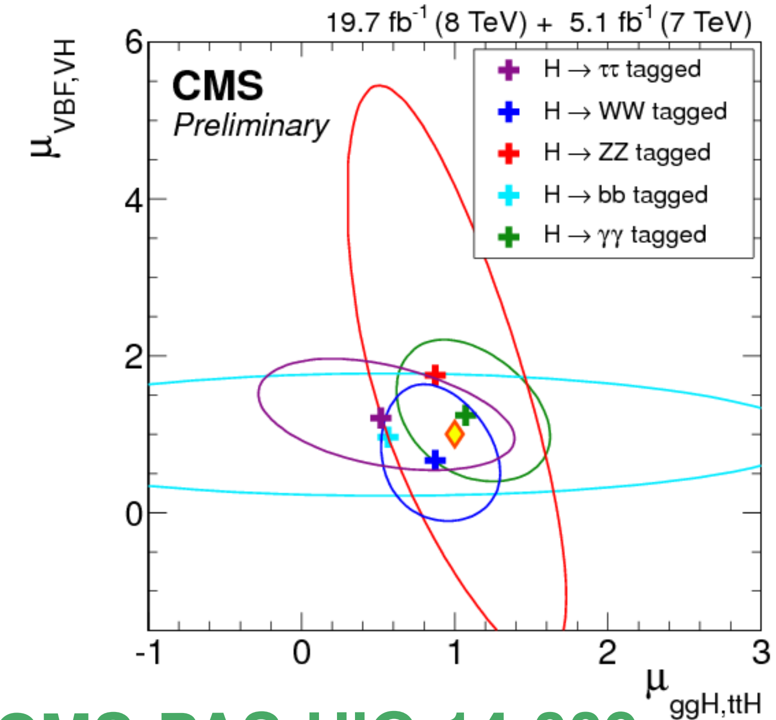


(Do not include the latest ATLAS updates)

Experimental data

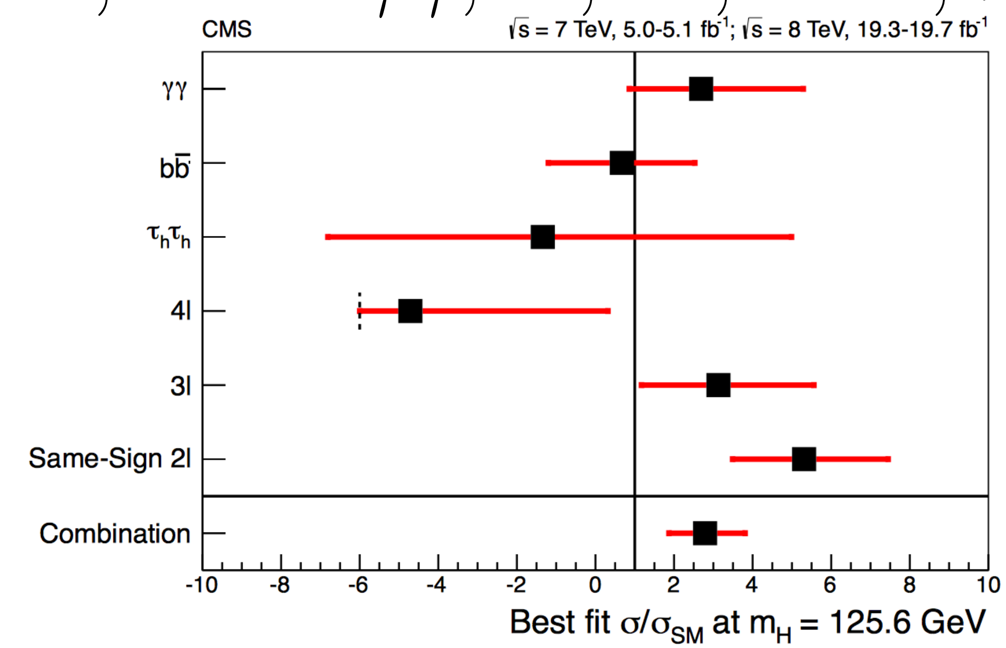
Data: CMS

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

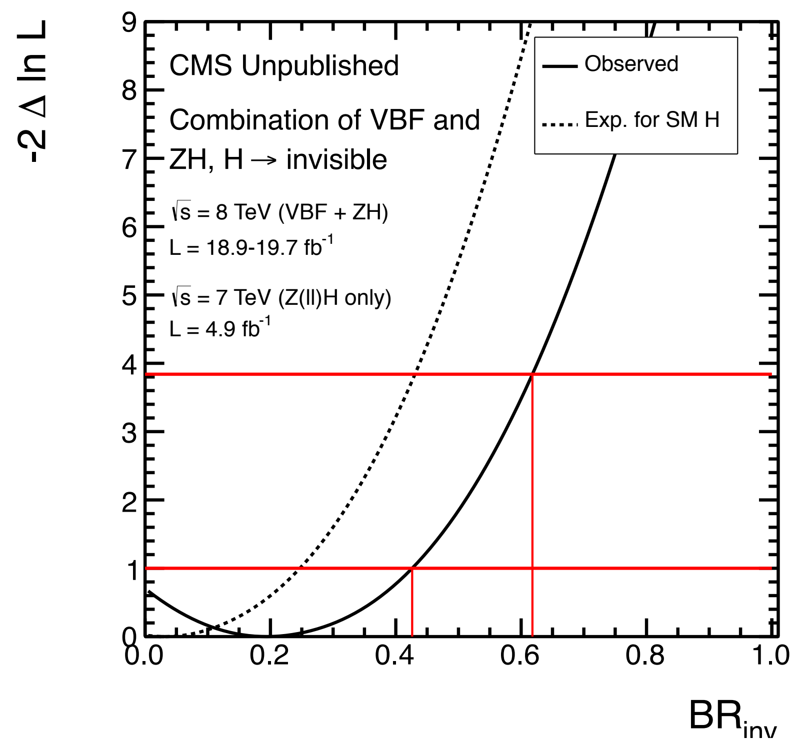


CMS-PAS-HIG-14-009

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



CMS-HIG-13-015

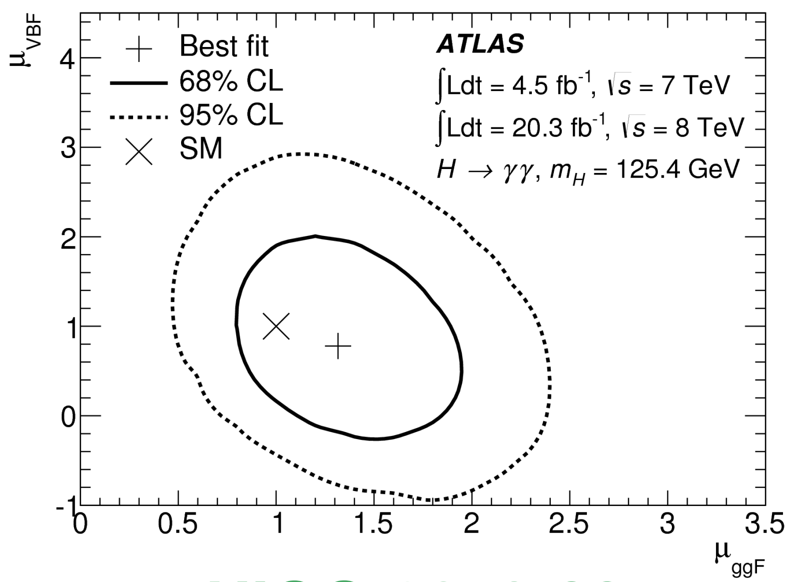


CMS-HIG-13-030

$\text{VBF} + \text{VH},\ H \to \text{invisible}$

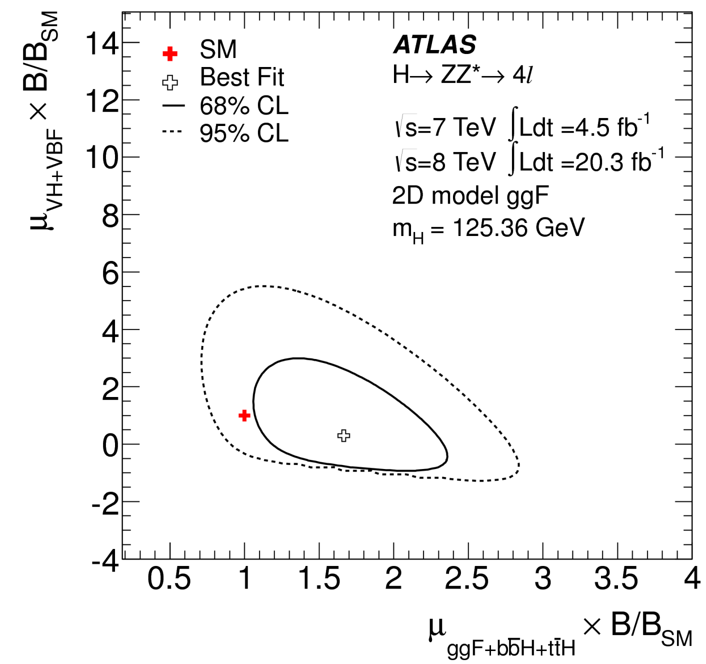
Data: ATLAS

$H \to \gamma\gamma$



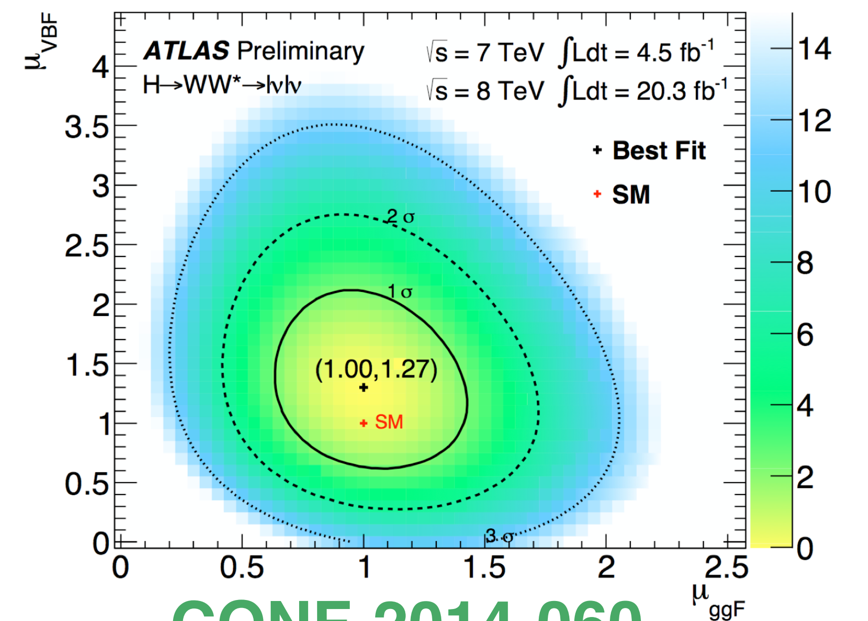
HIGG-2013-08

$H \to ZZ^*$



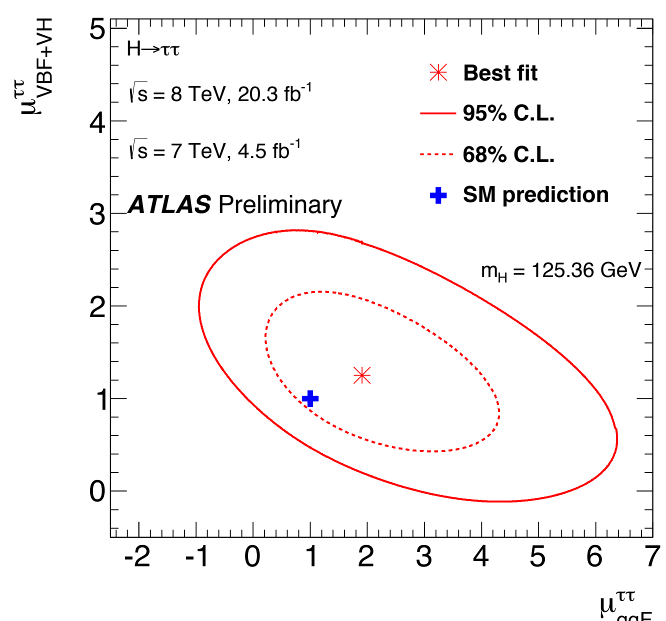
HIGG-2013-21

$H \to WW^*$



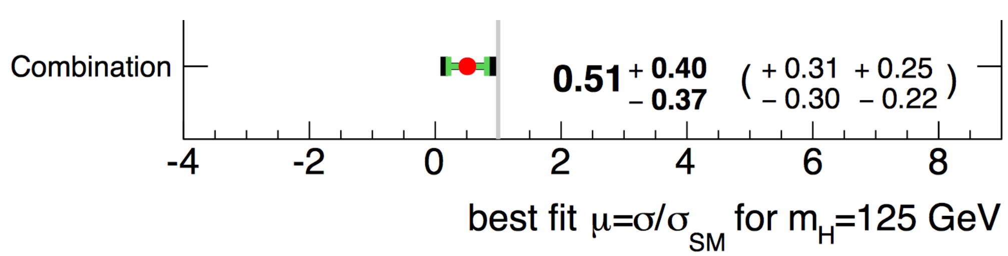
CONF-2014-060

$H \to \tau\tau$



CONF-2014-061

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

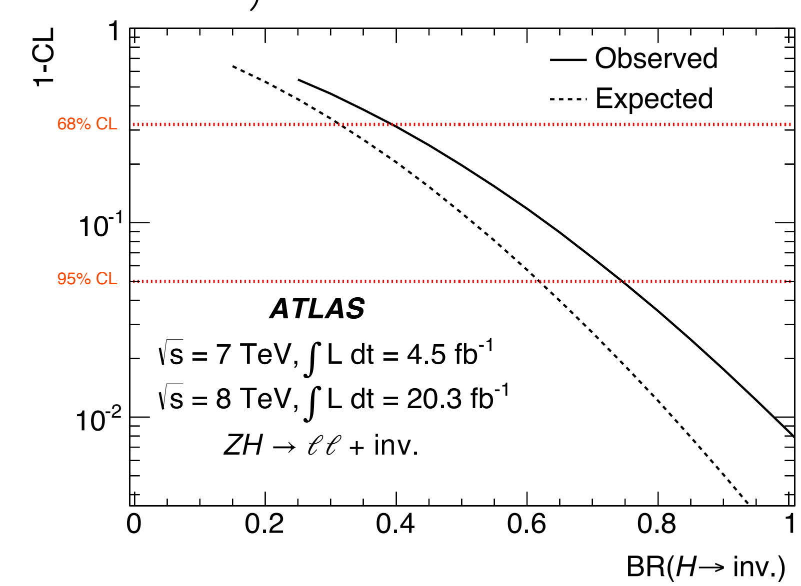


HIGG-2013-23

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

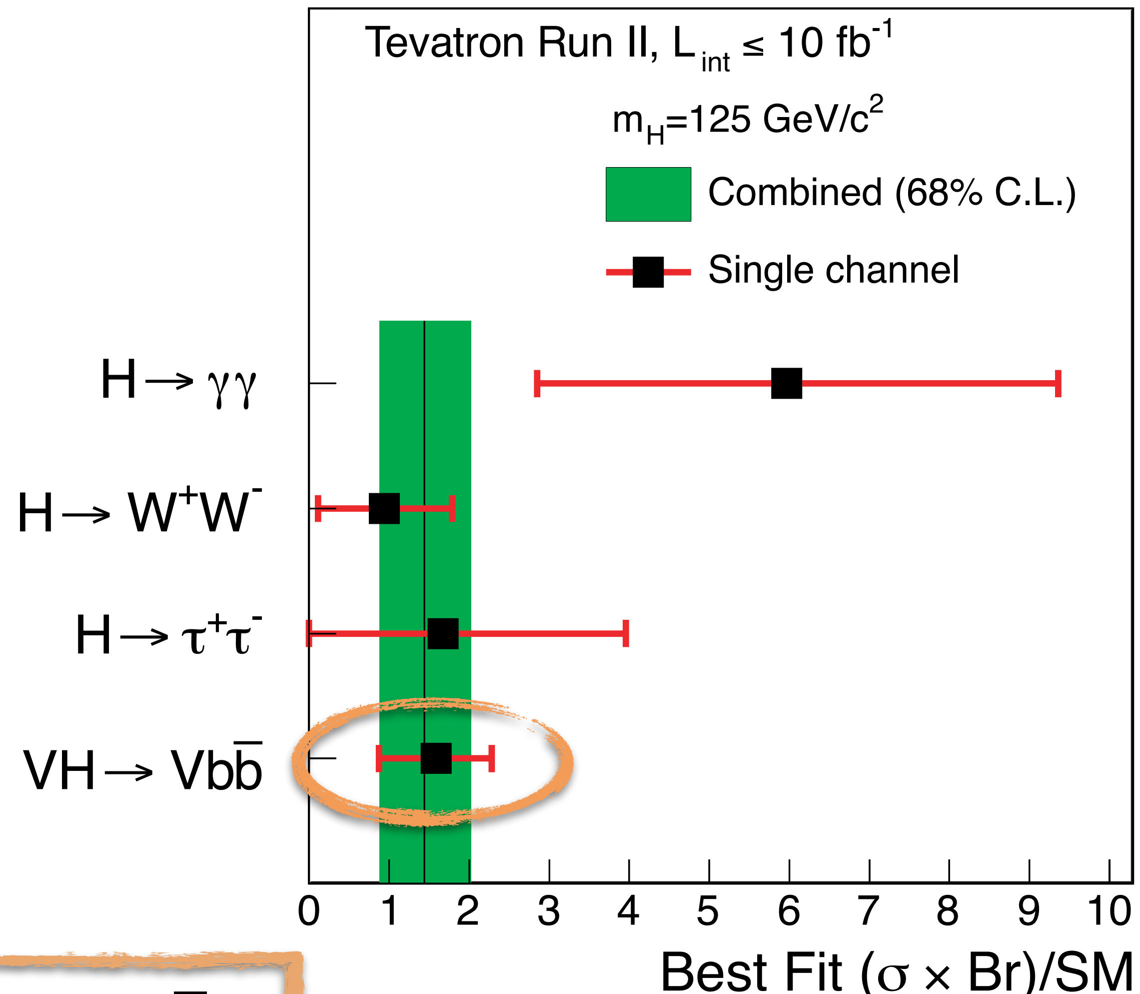
HIGG-2013-08, CONF-2014-

VH, $H \to$ invisible



CONF-2013-079

Data: Tevatron



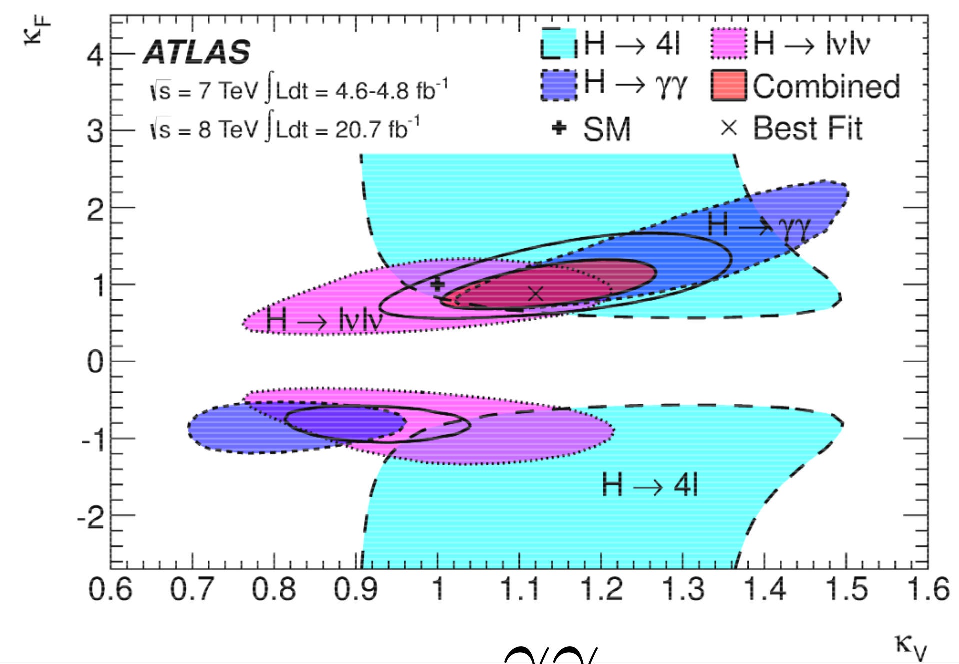
Only $VH, H \to b\bar{b}$ is competitive with the LHC results

FERMILAB-PUB-13-081-E

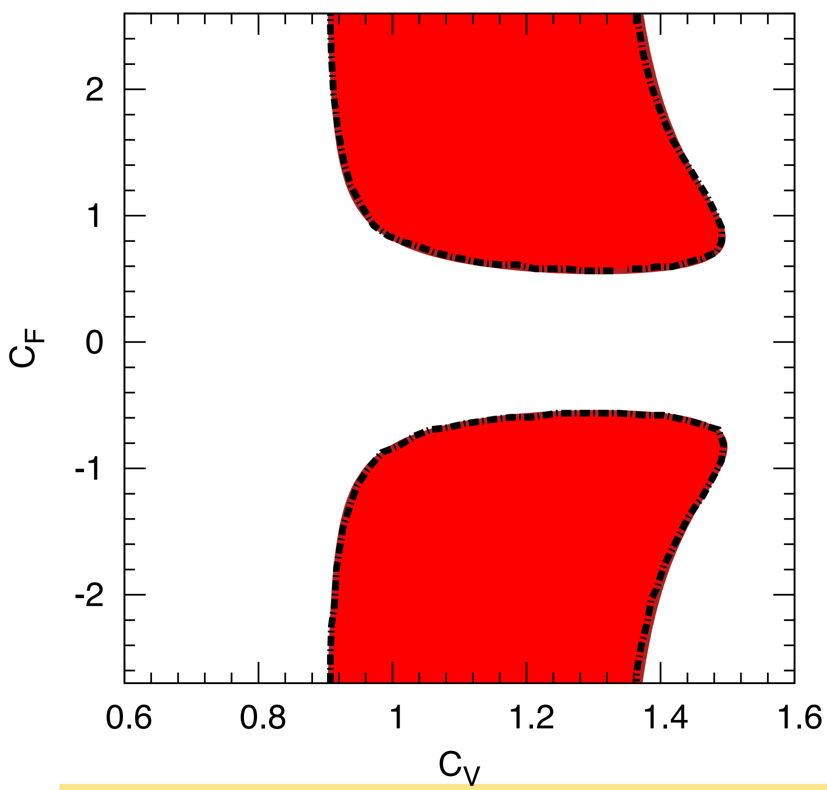
Validation

ATLAS: Diboson

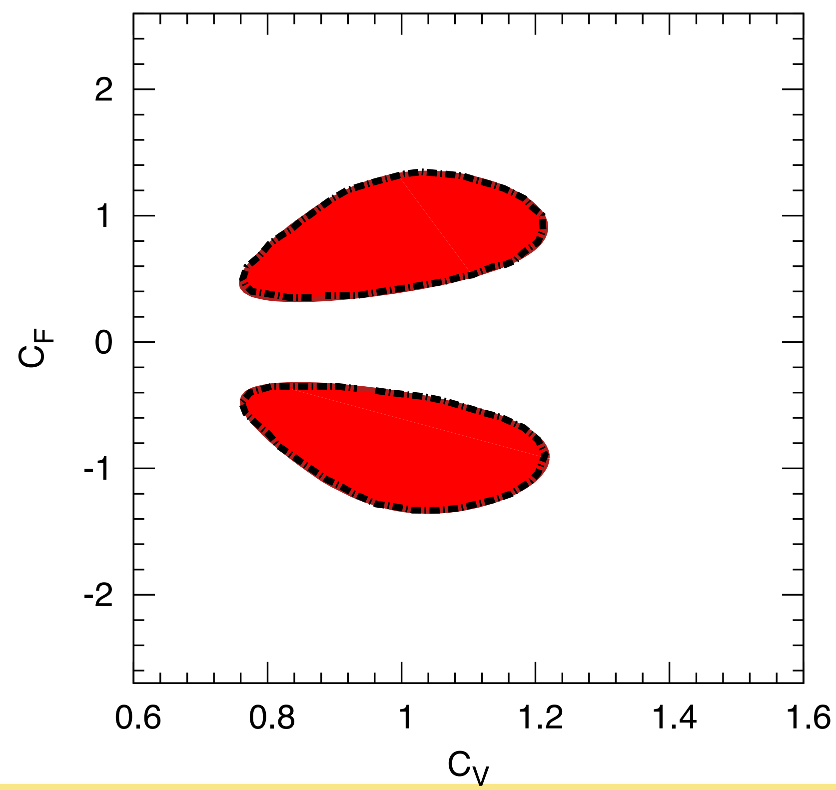
- Data set: Digitized likelihood
- 2 parameters fit: $(C_V,\ C_F)$



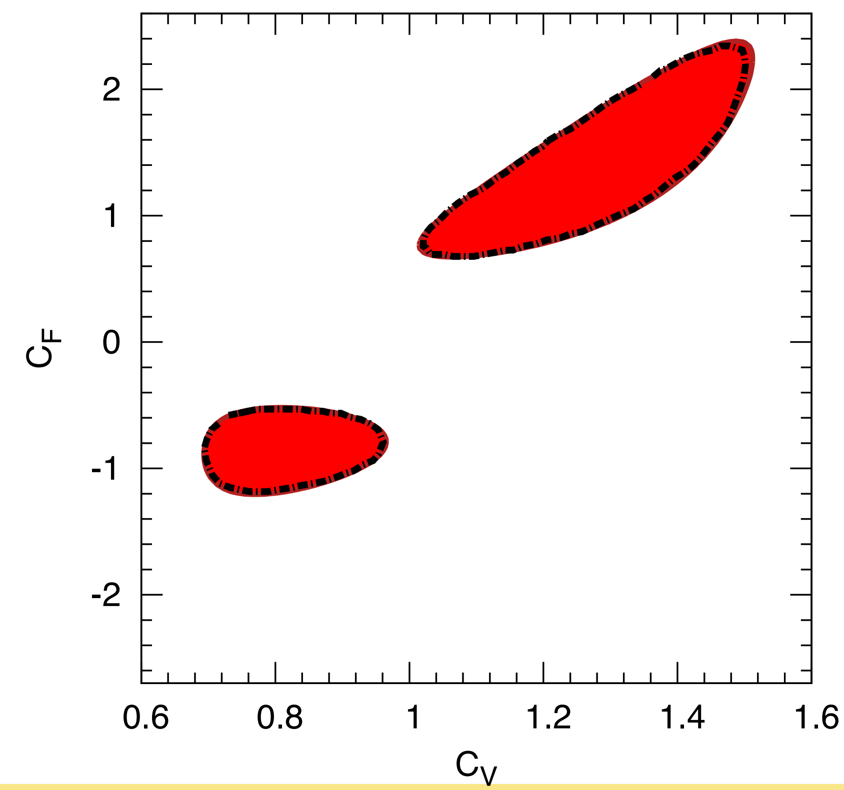
ZZ



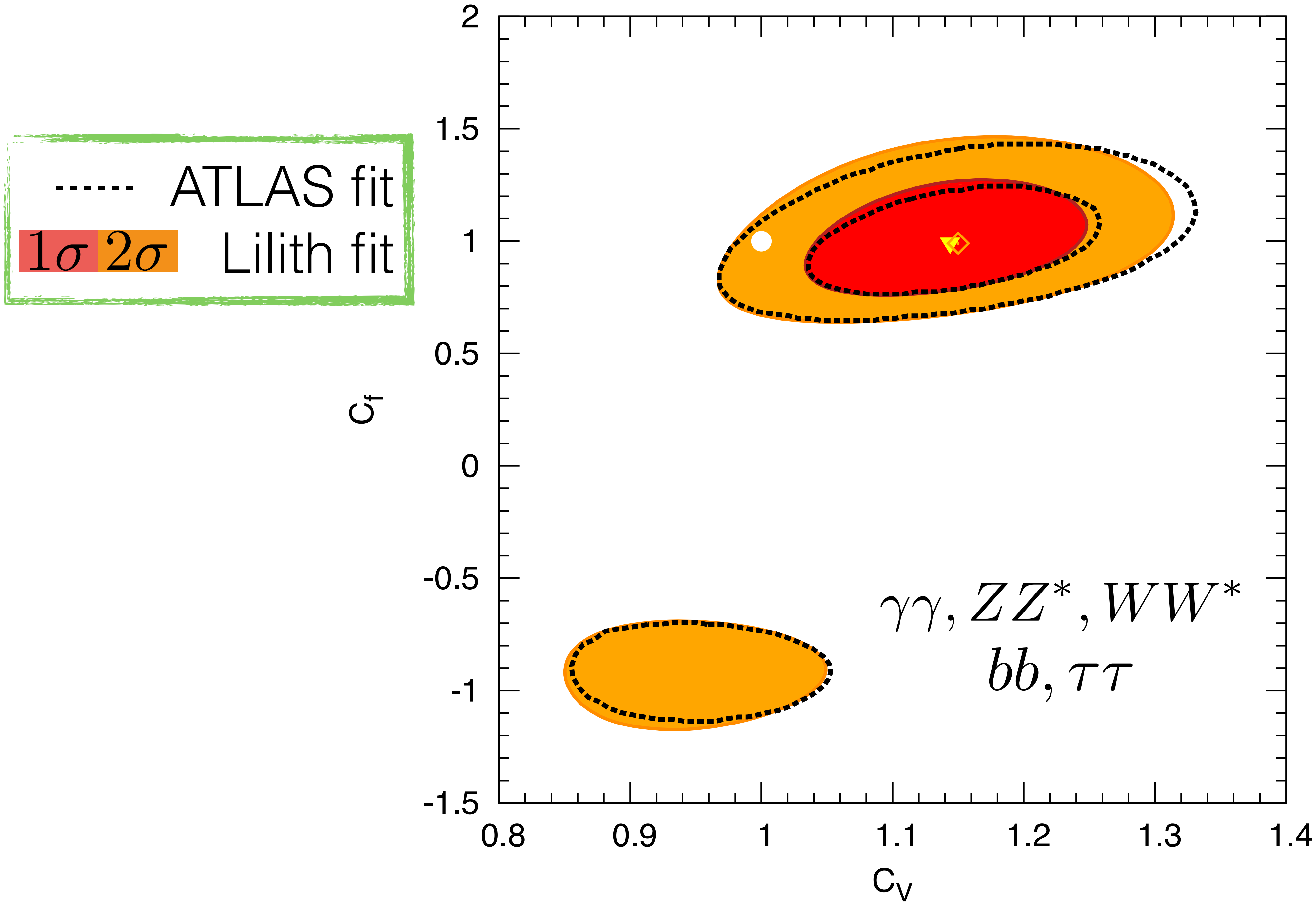
WW



$\gamma\gamma$



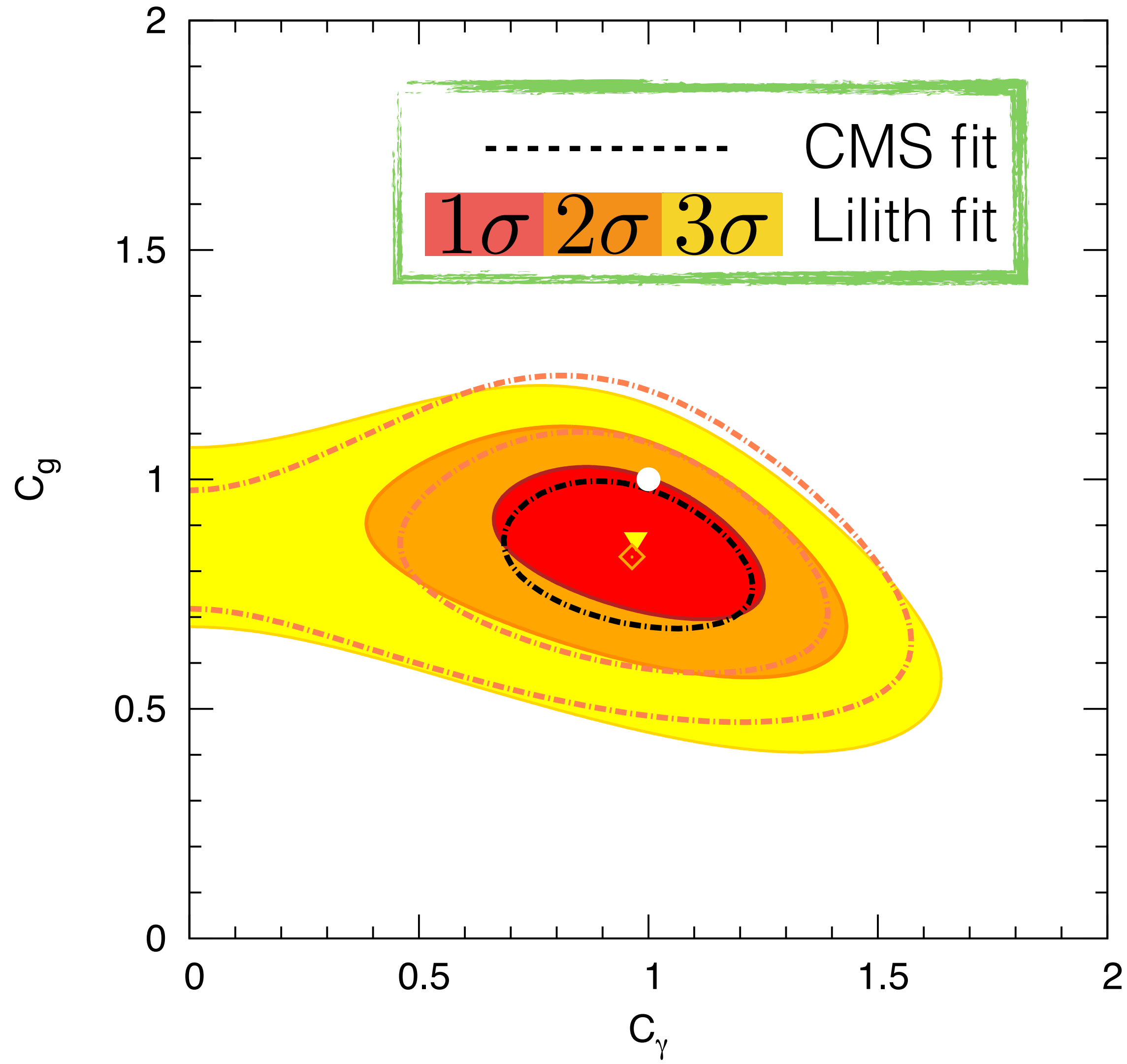
ATLAS: Moriond14 fit



CMS

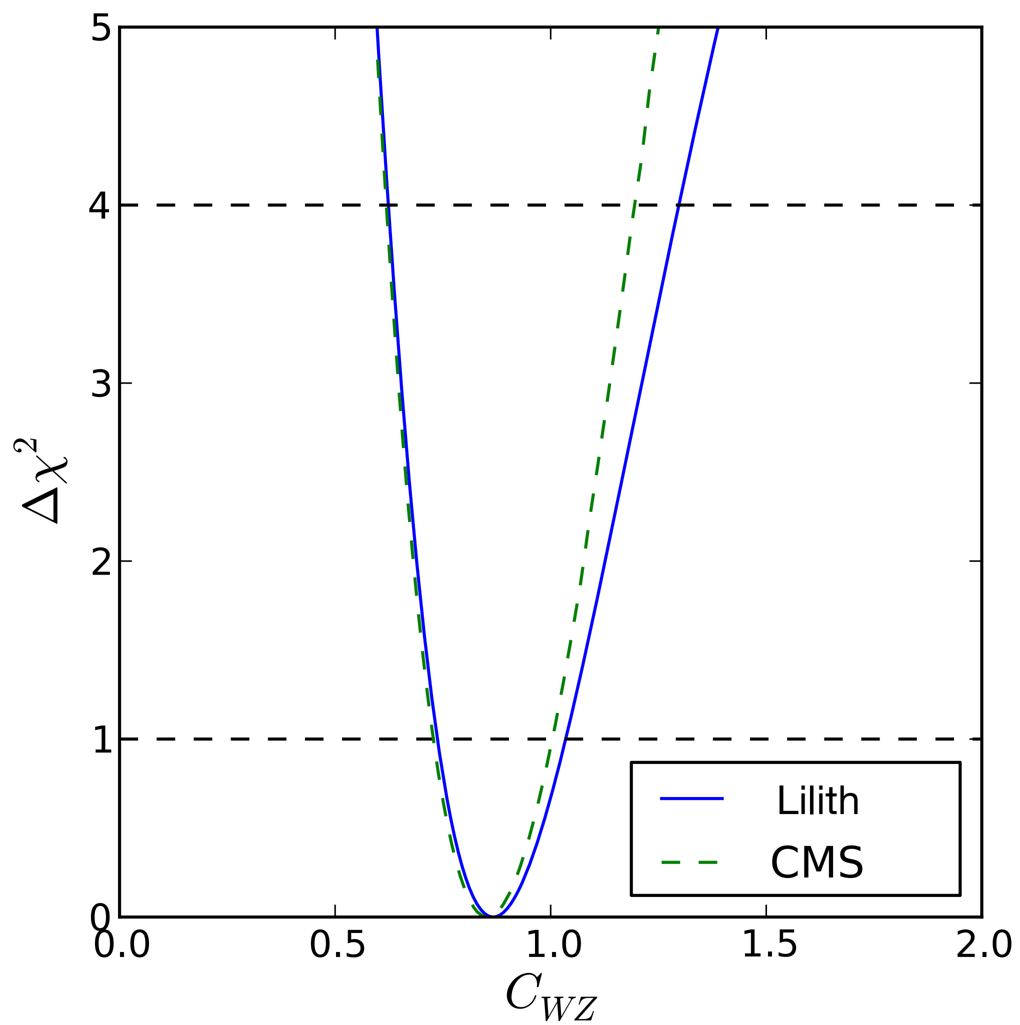
- Dataset: Data from the analysis note

$(C_\gamma,\ C_g)$ fit



Loop structure

$(C_{WZ} = C_W/C_Z,\ C_Z,\ C_F)$ fit

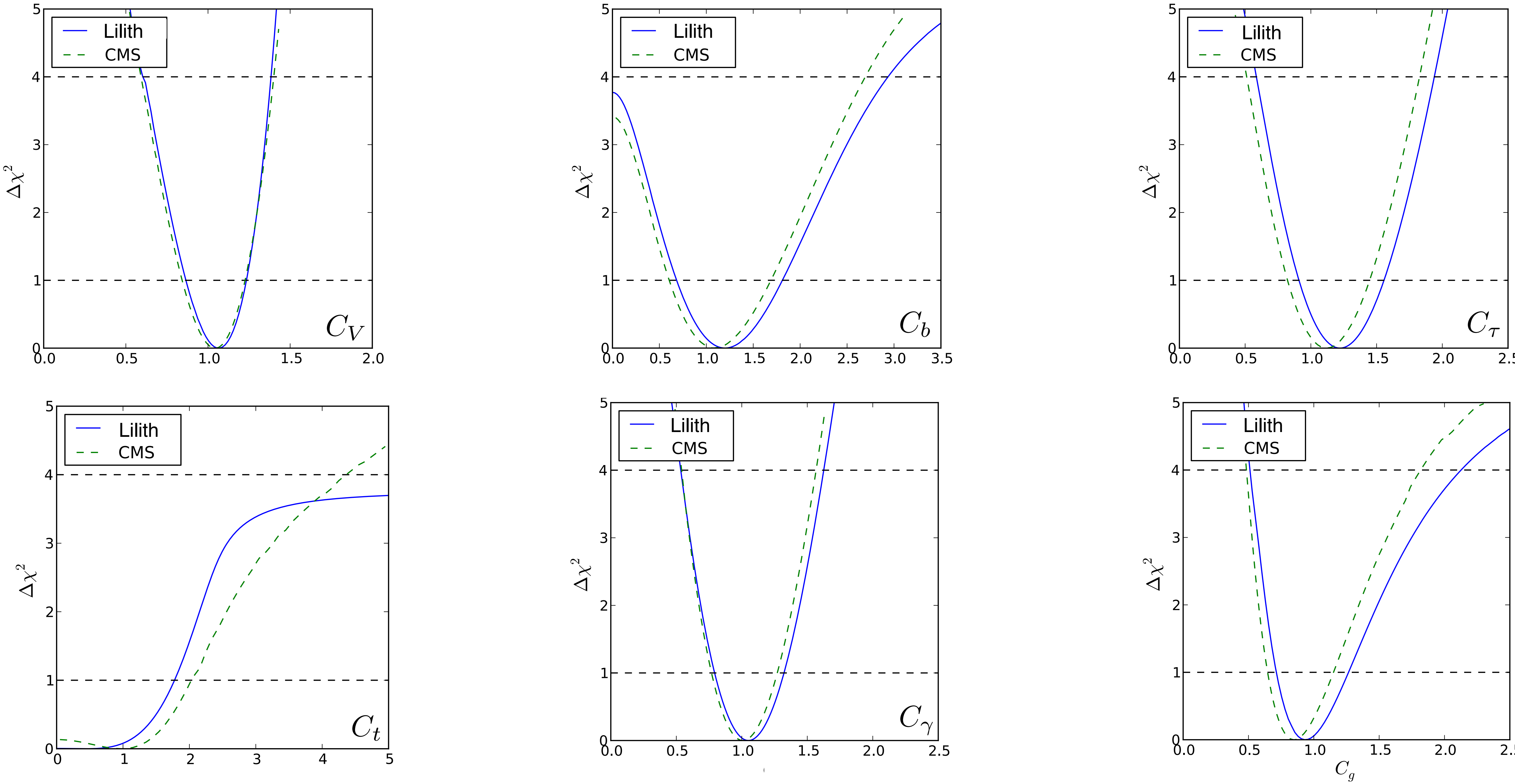


W/Z couplings

[CMS-HIG-2013-005]

CMS

$(C_V,\ C_b\ ,C_\tau,\ C_t,\ C_\gamma,\ C_g)$ fit



CMS

$(C_V,\ C_b,\ C_\tau,\ C_t,\ C_\gamma,\ C_g,\ BR_{BSM})$ fit