IRN@ZOOM

Constraining new physics from Higgs measurements with *Lilith-2*

Sabine Kraml

in collaboration with

Tran Quang Loc, Dao Thi Nhung, and Le Duc Ninh

arXiv:1908.03952 — SciPost Phys. 7, 052 (2019) — GitHub

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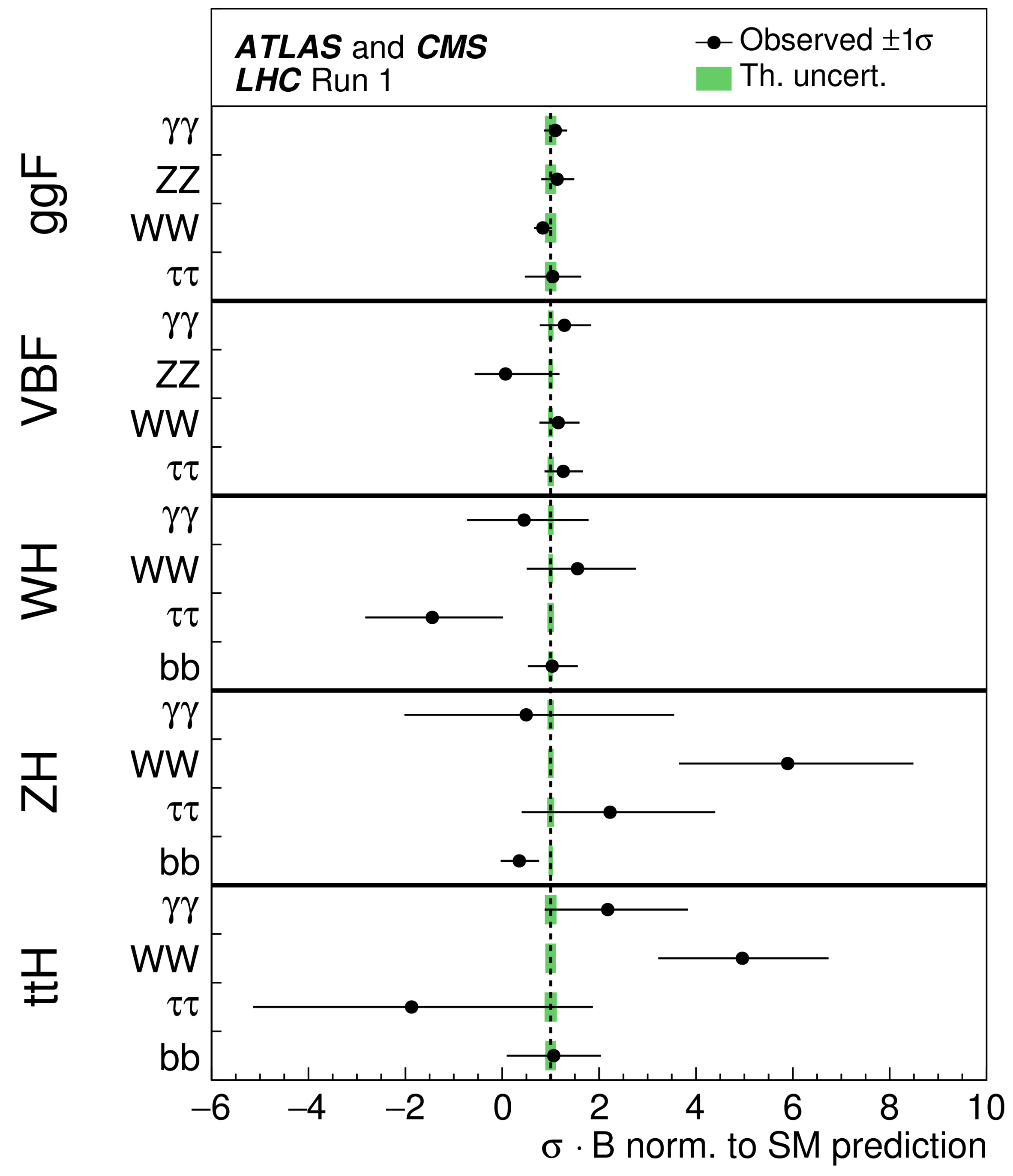
Motivation

- The LHC runs at 8 and 13 TeV have led to a **wealth of experimental results** on the 125 GeV Higgs boson.
- **Increasingly precise picture** of the various **Higgs production & decay processes**, and consequently of the **Higgs couplings** to the SM gauge bosons and (3rd generation) fermions.
- BSM theories typically predict deviations from the SM expectations (mixing effects in enlarged Higgs sectors, loop contributions from new particles, higher-order EFT effects, new decay modes, ….).
- The Higgs data therefore provide **strong constraints** and have become a major guideline **for BSM theories.**

Bernon, Dumont, arXiv:1502.04138
SK, Loc, Nhung, Ninh, arXiv:1908.03952

Lilith : Light Likelihood fit for the Higgs

- Lilith is a **light and easy-to-use Python tool** for constraining new physics from signal strength measurements of the 125 GeV Higgs boson.
- The **Higgs likelihood** is evaluated from the user input, given in XML format **in terms of reduced couplings or signal strengths**.
- Based on experimental results from ATLAS and CMS stored in an **easily extensible XML database**.



https://github.com/sabinekraml/Lilith-2

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- The **Higgs likelihood** is evaluated from the user input, given in XML format **in terms of reduced couplings or signal strengths**.
- Based on experimental results from ATLAS and CMS stored in an **easily extensible XML database**.

Features of Lilith-2 :

- Use of variable Gaussian and generalized Poisson likelihoods for a **better treatment of asymmetric uncertainties**.
- Use of **N-dim correlation matrices** for ordinary and variable Gaussian likelihoods.
- Database 19.09 contains the published ATLAS and CMS Run 2 results for 36/fb as of Sep 2019.
- Update for full Run-2 luminosity results in progress.

https://github.com/sabinekraml/Lilith-2

Signal strength framework

decay mode: *Y* ∈ ($\gamma\gamma$, *ZZ**, *WW**, *bb*, $\tau\tau$,…)

$$\mu(X,Y) \equiv \frac{\sigma(X)\,\mathrm{BR}(H \to Y)}{\sigma^{\mathrm{SM}}(X)\,\mathrm{BR}^{\mathrm{SM}}(H \to Y)}$$

production mode: *X* ∈ (ggH, VBF, ZH, WH, ttH, …)

nb, here the fundamental production modes are unfolded from the experimental categories

The likelihood in terms of μ(*X,Y*) allows for reinterpretation of the results in **models where the signal acceptances** for the (*X,Y*) are to good approximation the **same as in the SM**:

- SM tensor structure
- no new production modes

Signal strength framework

… in this case, new physics results only in the scaling of SM Higgs processes

$$\mu(X,Y) \equiv \frac{\sigma(X)\,\mathrm{BR}(H\to Y)}{\sigma^{\mathrm{SM}}(X)\,\mathrm{BR}^{\mathrm{SM}}(H\to Y)} = \frac{\mathbf{C}_X^2\,\mathbf{C}_Y^2}{\sum_Y \mathbf{C}_Y^2\,\mathrm{BR}^{\mathrm{SM}}(H\to Y)}$$

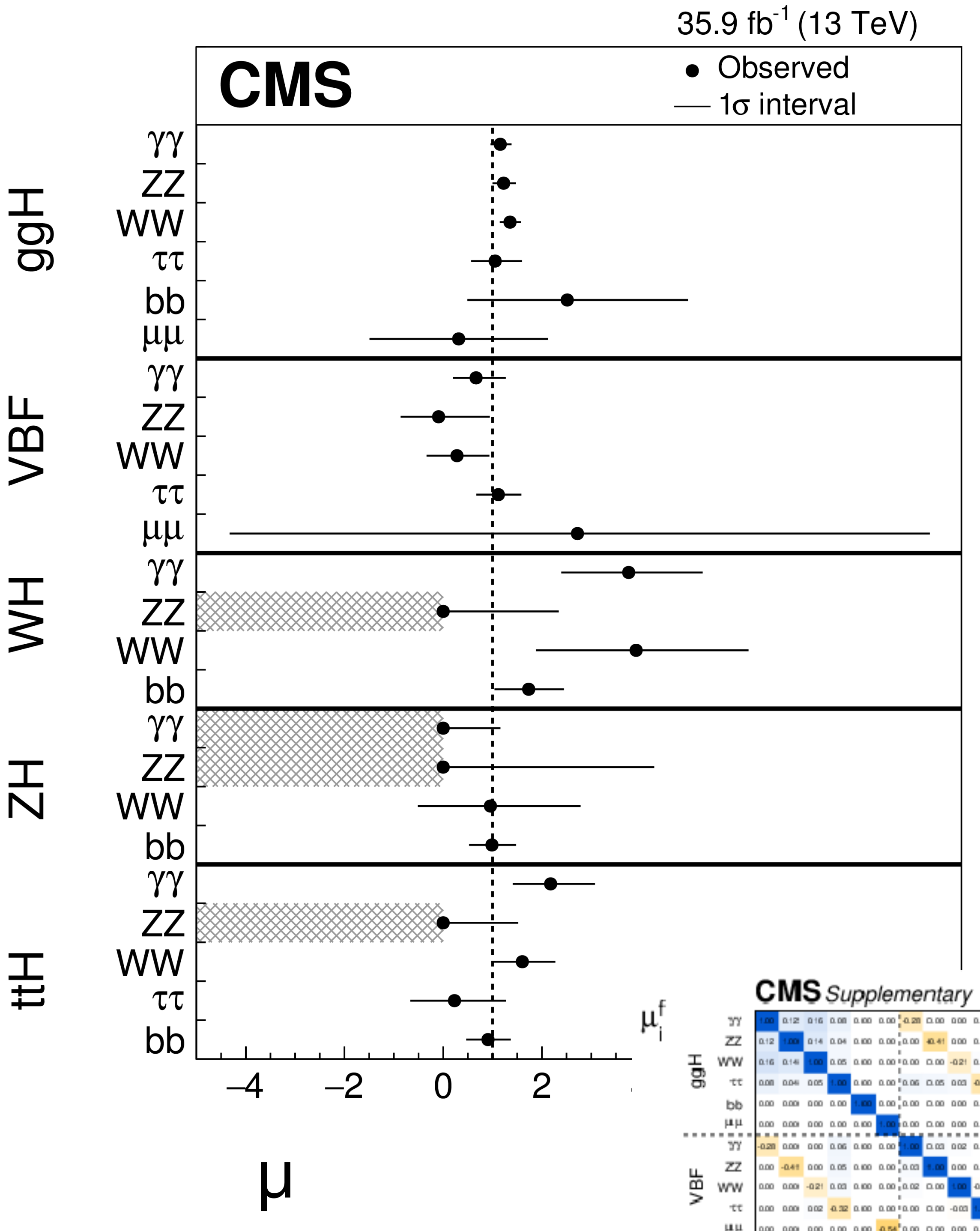
The factors $\mathbf{C}_X$ and $\mathbf{C}_Y$ can be identified to (or derived from) "**reduced couplings**" appearing in an effective Lagrangian:

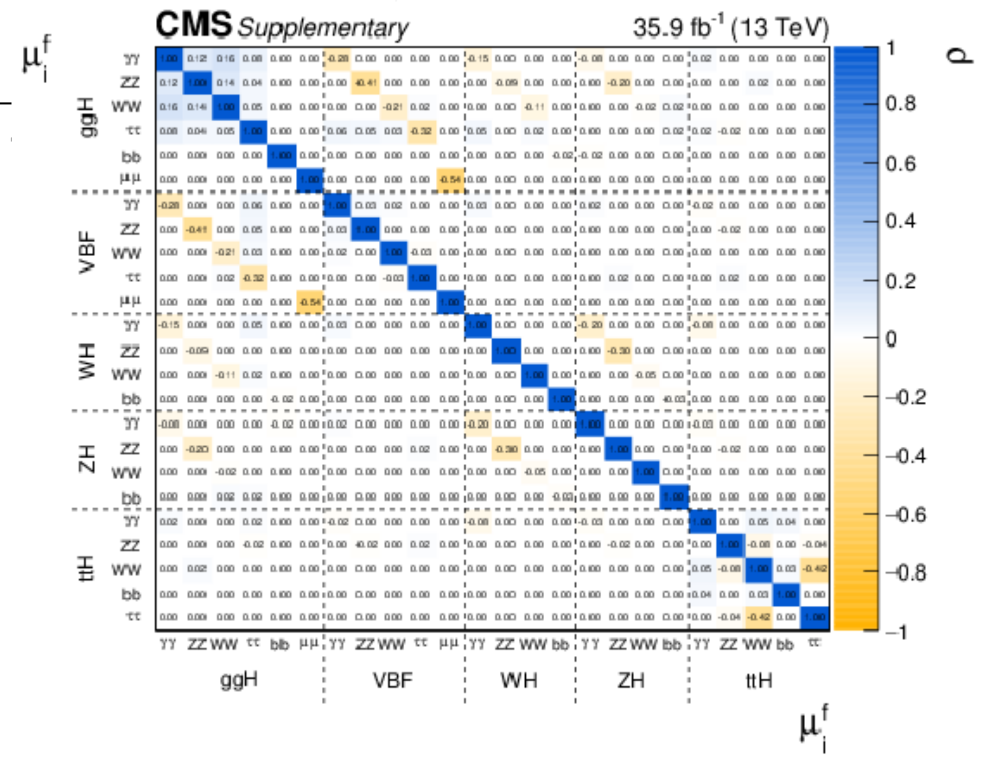
$$\mathcal{L} = g\left[C_W m_W W^\mu W_\mu + C_Z \frac{m_Z}{\cos\theta_W} Z^\mu Z_\mu - \sum_f C_f \frac{m_f}{2m_W} f\bar{f}\right] H$$

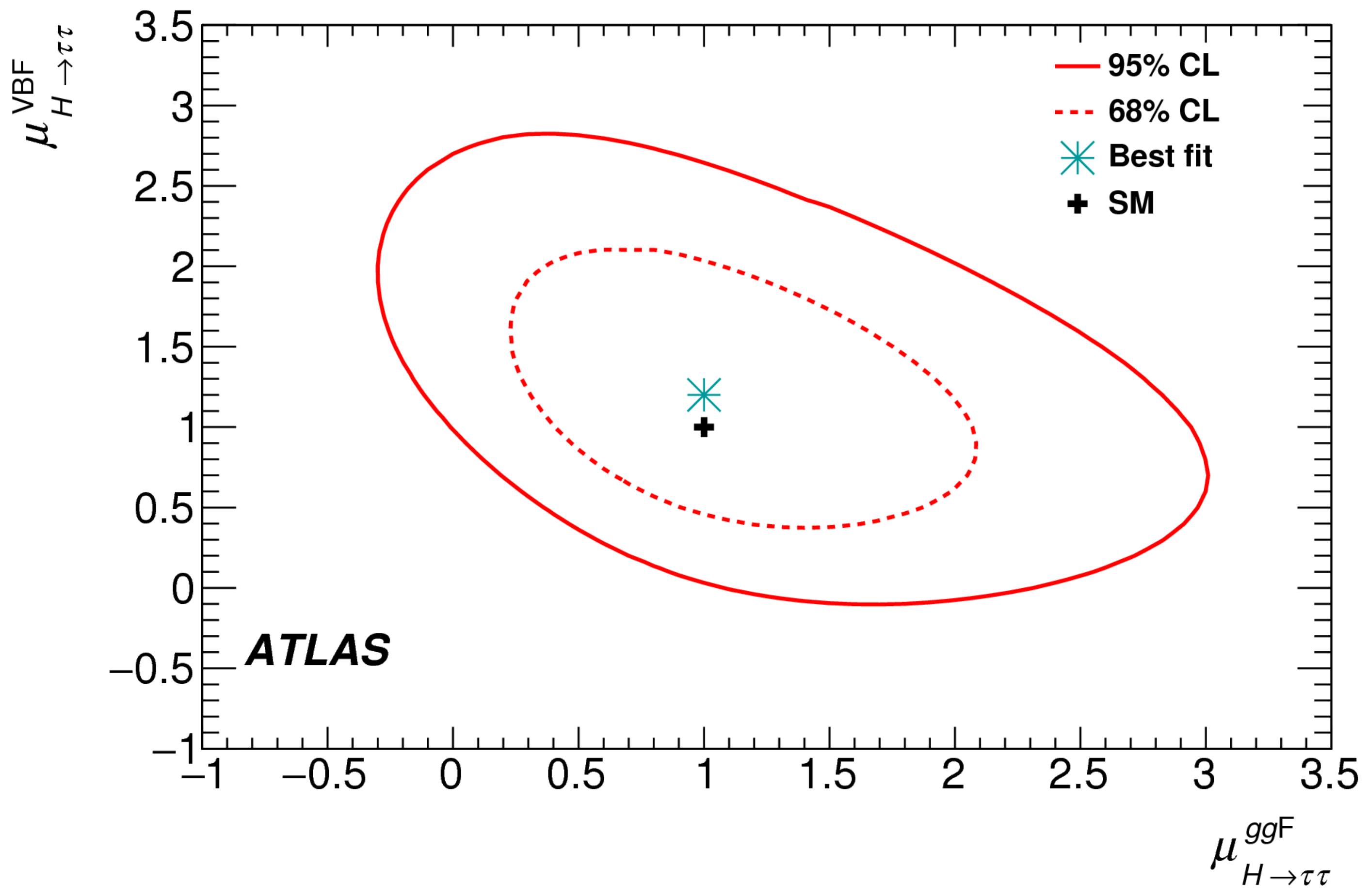
In addition, we define the loop-induced couplings C_g and C_γ of the Higgs to gluons and photons.

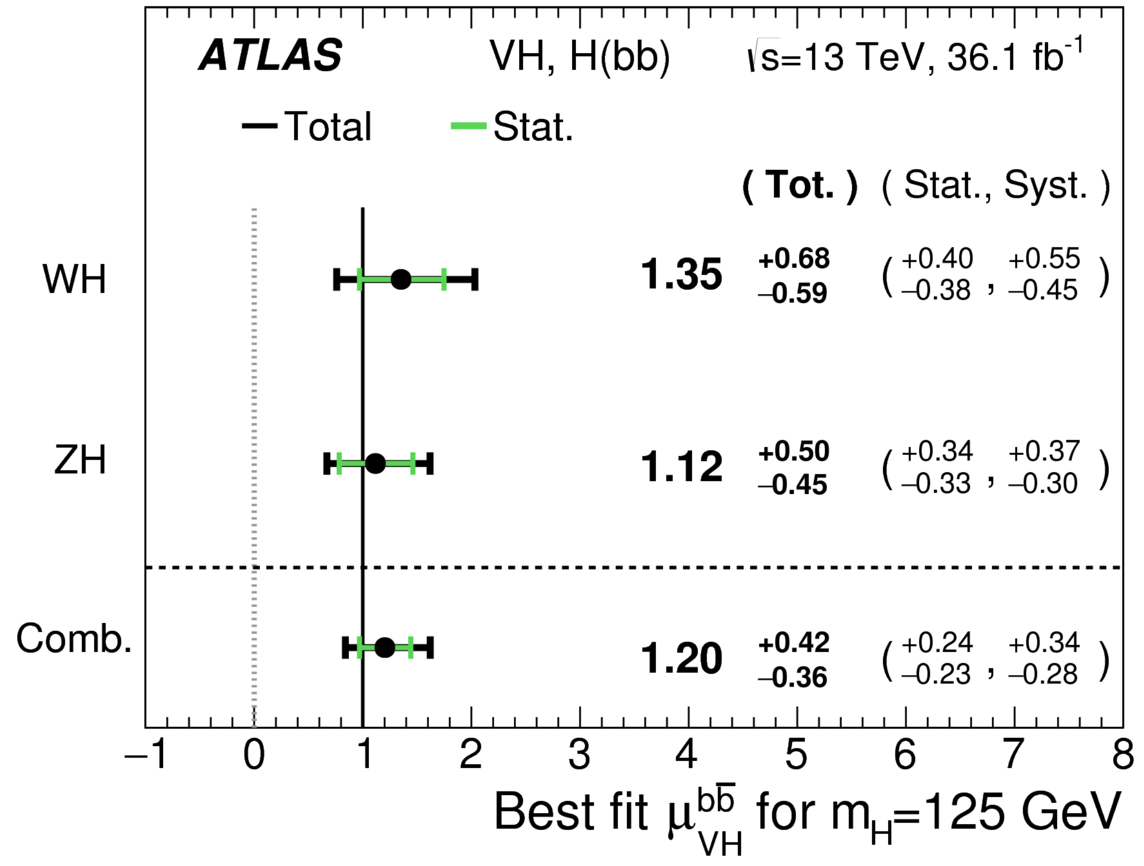
Belanger, Dumont, Ellwanger, Gunion, SK, arXiv:1212.5244;
equivalent to κ framework of HXSWG, arXiv:1307.1347.

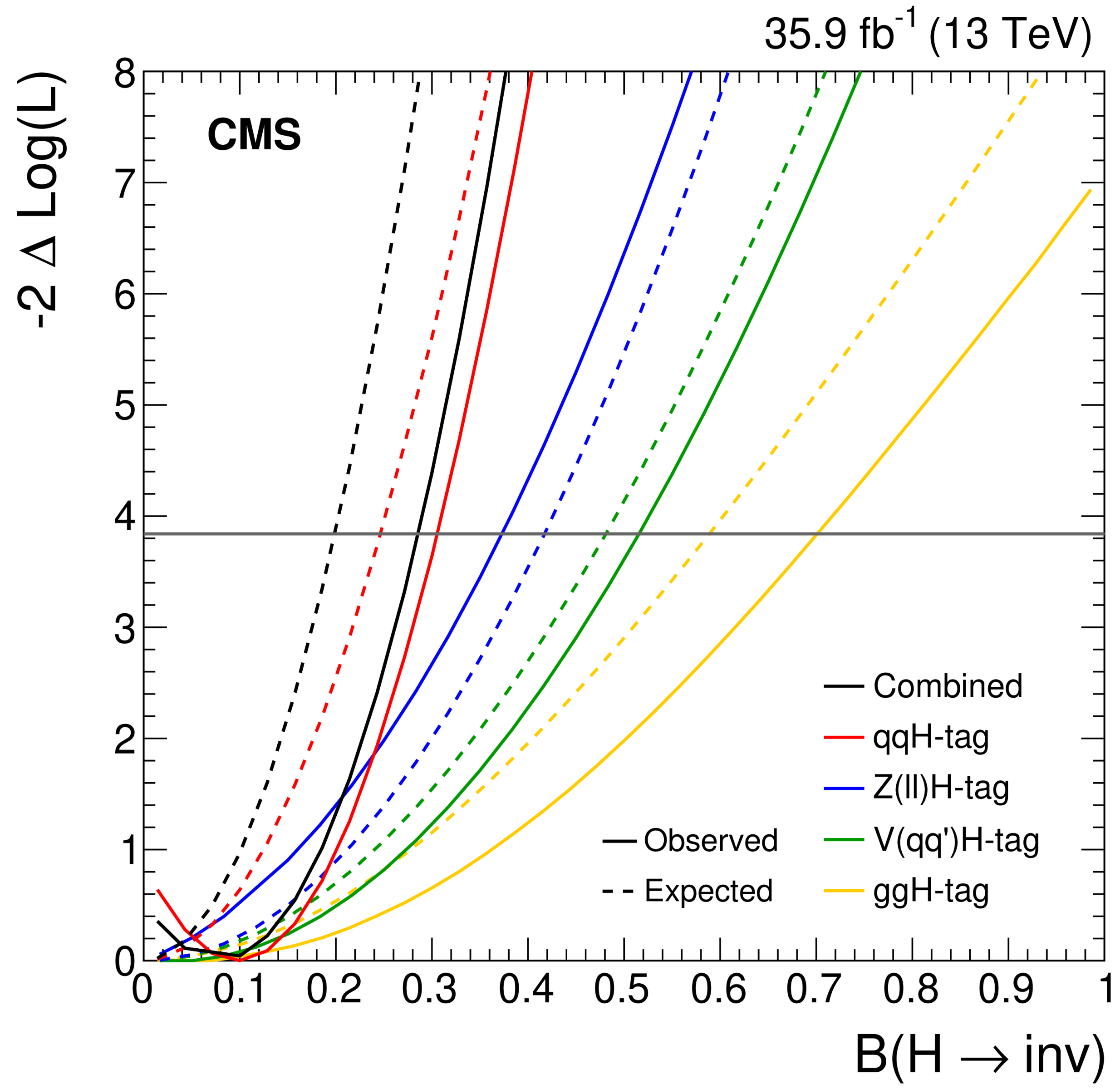
Types of results used in Lilith (examples)











Unfortunately often not available on HEPData; need to digitize “by hand”

Likelihood calculation

following R. Barlow, physics/0406120
see arXiv:1908.03952 for details

- **Variable Gaussian**

1-dim: $$\log L(\mu) = \frac{(\mu - \hat{\mu})^2}{\sigma^+\sigma^- + (\sigma^+ - \sigma^-)(\mu - \hat{\mu})}$$

n-dim: $$\log L(\mu) = (\mu - \hat{\mu})^T V^{-1} (\mu - \hat{\mu})$$

covariance matrix

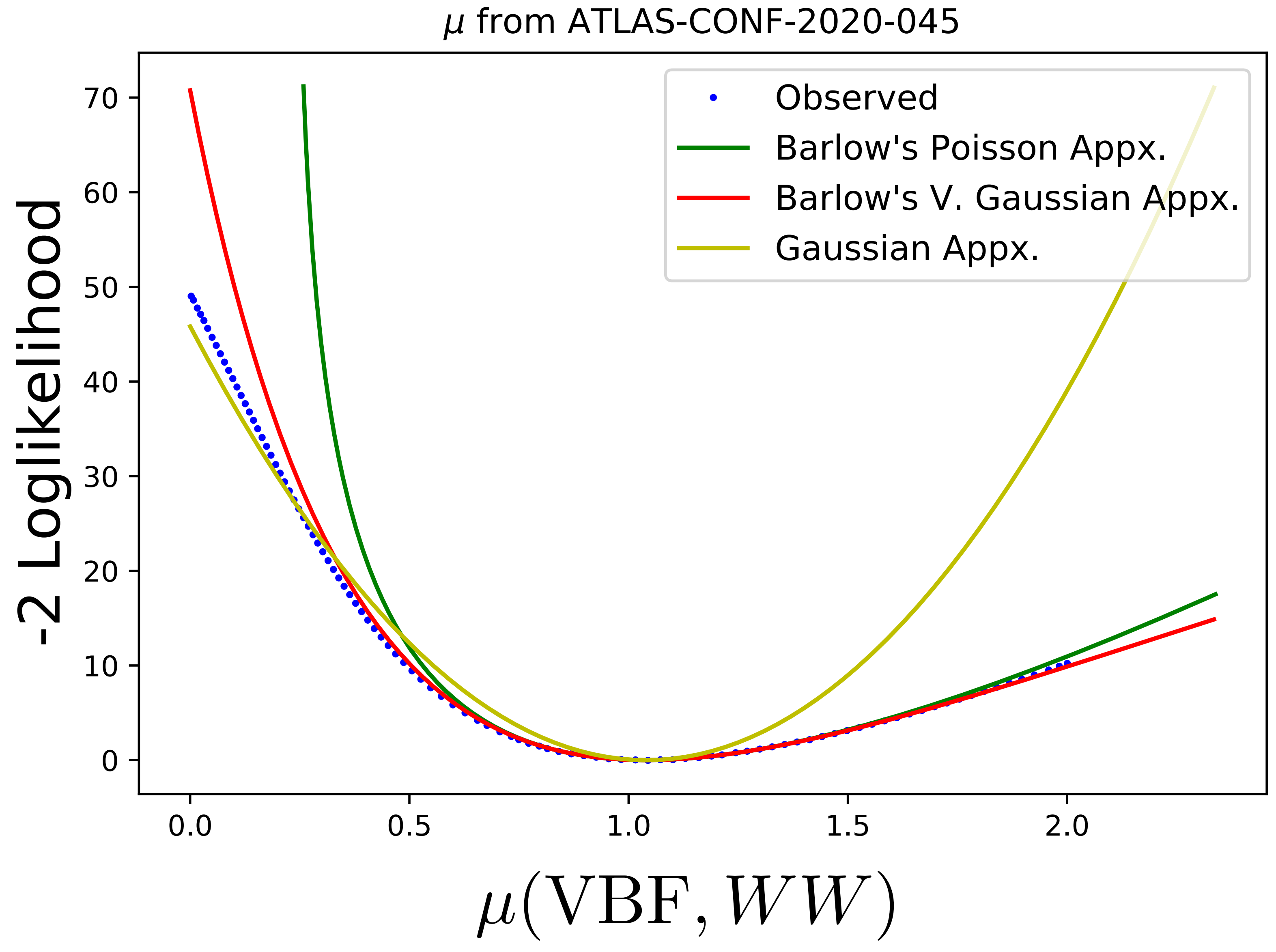
- **Generalized Poisson**

1-dim: $$\log L(\mu) = -\nu\gamma(\mu - \hat{\mu}) + \nu \log[1 + \gamma(\mu - \hat{\mu})]$$

$$\frac{1-\gamma\sigma^-}{1+\gamma\sigma^+} = e^{-\gamma(\sigma^+ + \sigma^-)}, \quad \nu = \frac{1}{2(\gamma\sigma^+ - \log(1+\gamma\sigma^+))}$$

+ 2-dim implementation

$$\mu(\mathrm{VBF}, WW) = 1.04^{+0.24}_{-0.20}$$



- **Interpolated data grid**

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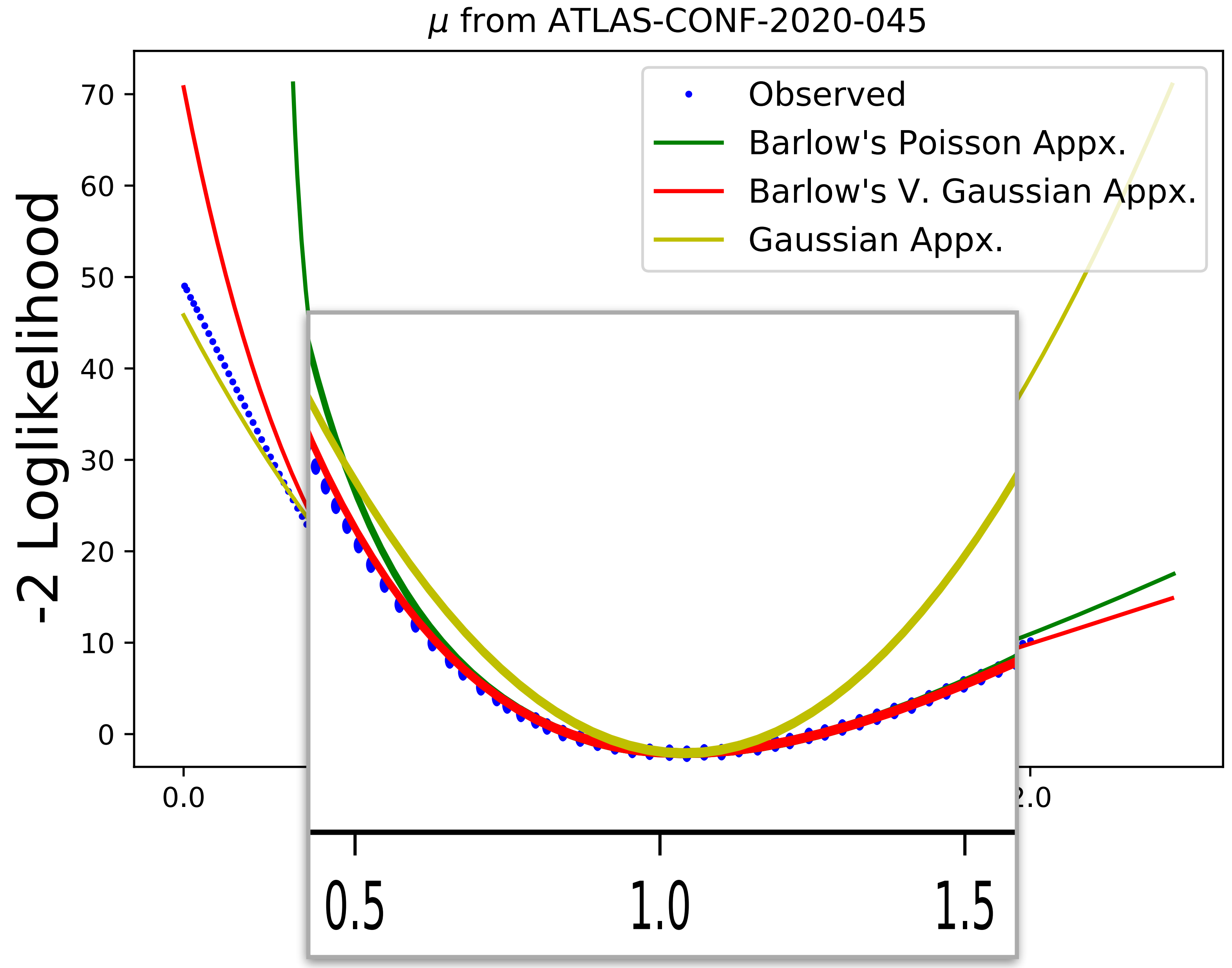


- **Interpolated data grid**

ATLAS Run-2 36/fb results in DB 19.09

<table>
<tr><th></th><th>$\gamma\gamma$</th><th>ZZ</th><th>WW</th><th>$\tau\tau$</th><th>bb</th><th>μμ</th><th>inv.</th></tr>
<tr><td>ggH</td><td rowspan="5">HIGG-2016-21</td><td rowspan="4">HIGG-2016-22</td><td rowspan="2">2016-07</td><td rowspan="2">2017-07</td><td>—</td><td rowspan="4">HIGG-2016-10</td><td>—</td></tr>
<tr><td>VBF</td><td>2016-30</td><td>2018-54</td></tr>
<tr><td>WH</td><td rowspan="2">2017-14</td><td>—</td><td rowspan="2">2016-29</td><td>—</td></tr>
<tr><td>ZH</td><td>—</td><td>2016-28</td></tr>
<tr><td>ttH</td><td colspan="4">HIGG-2017-02</td><td>—</td><td>—</td></tr>
</table>

Paper ID’s: ATLAS-HIGG-yyyy-nn

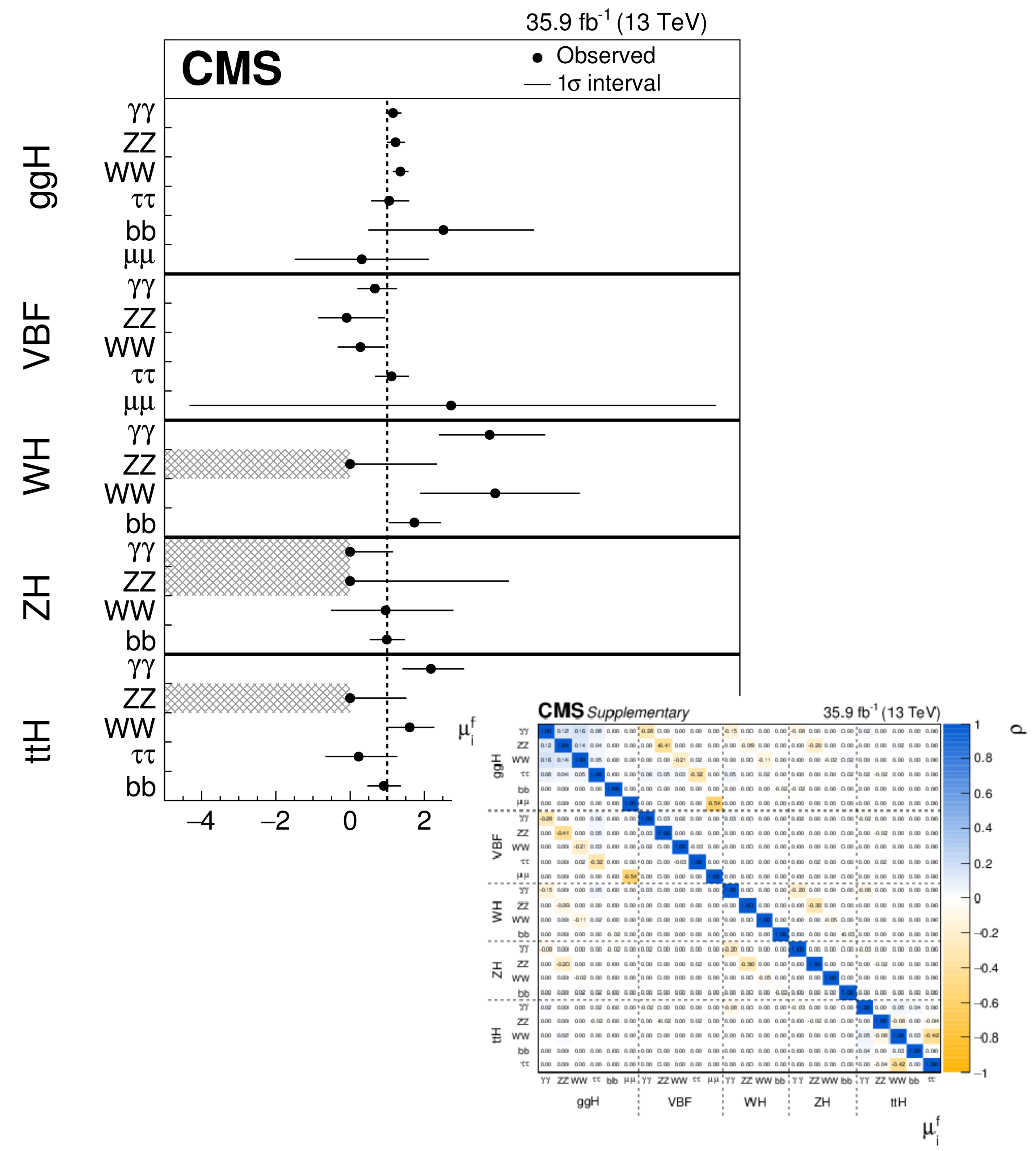
CMS Run-2 36/fb results in DB 19.09

	$\gamma\gamma$	ZZ	WW	$\tau\tau$	bb	μμ	inv.
ggH							
VBF							
WH							
ZH							
ttH							

HIG-17-031

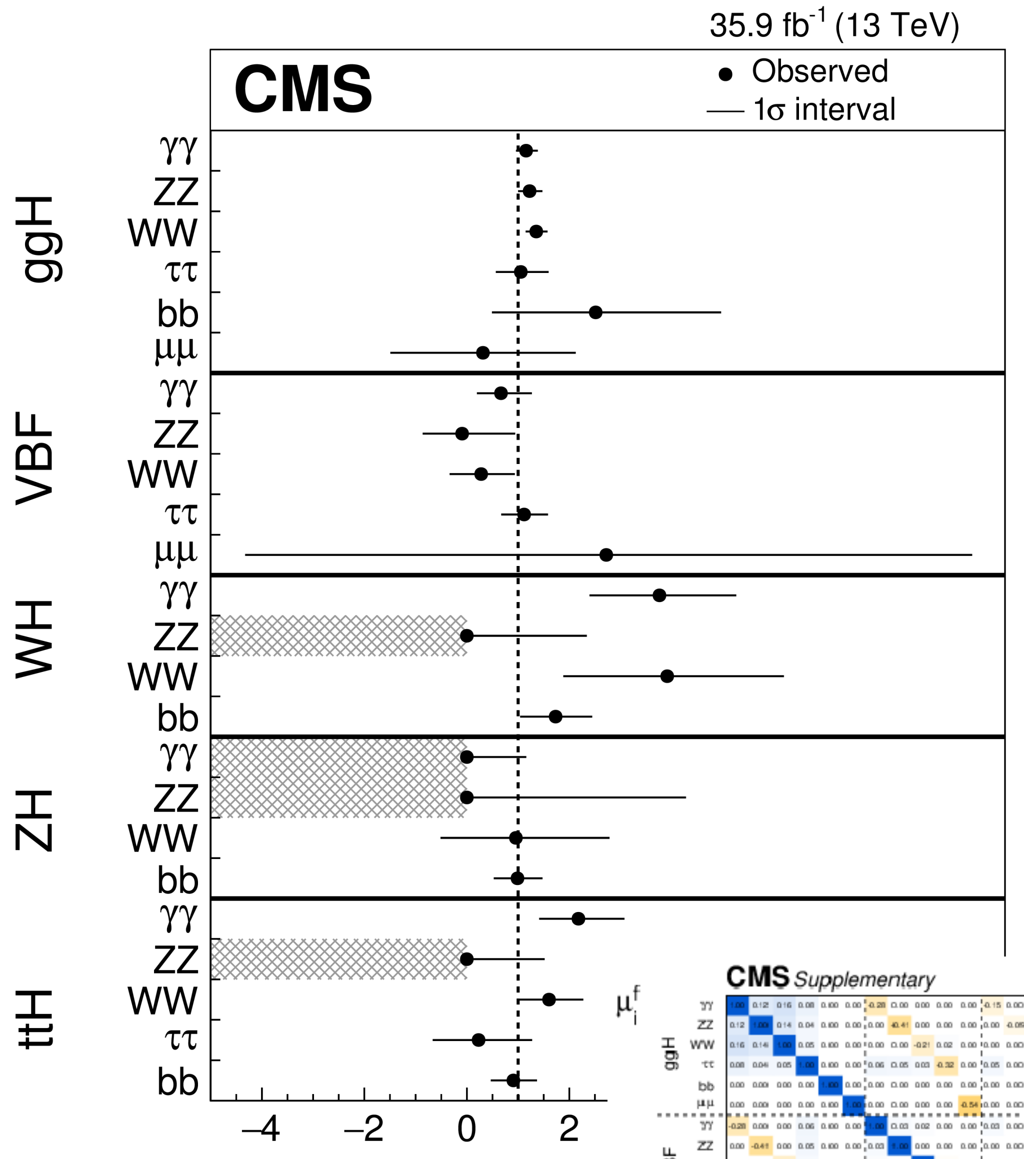
18-007

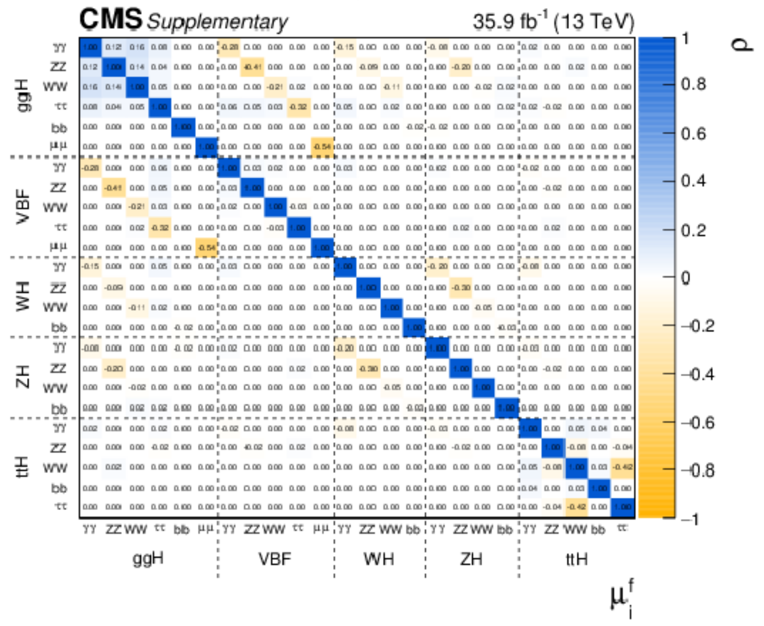
HIG-17-023



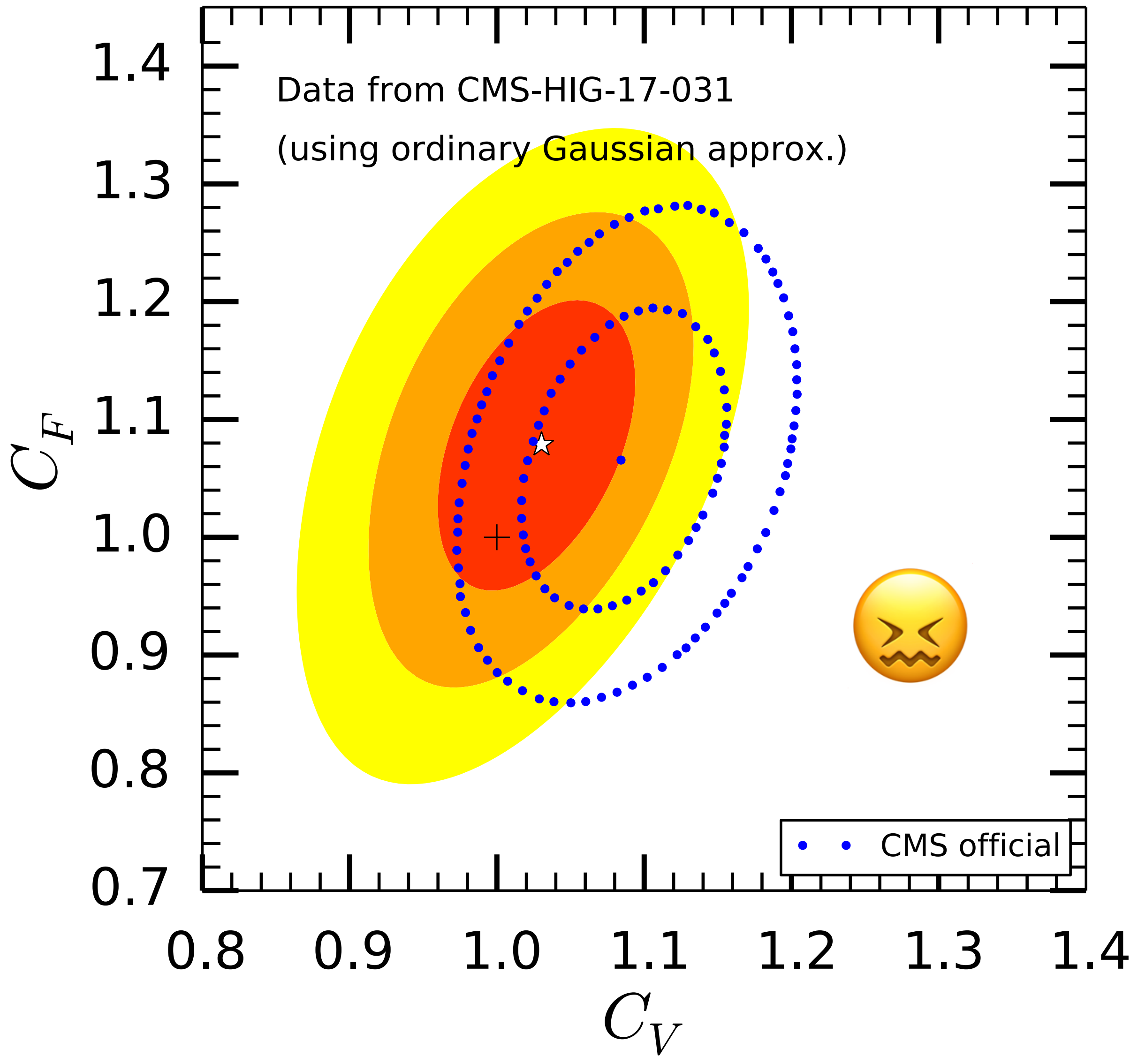
Paper ID's: CMS-HIG-yy-nnn

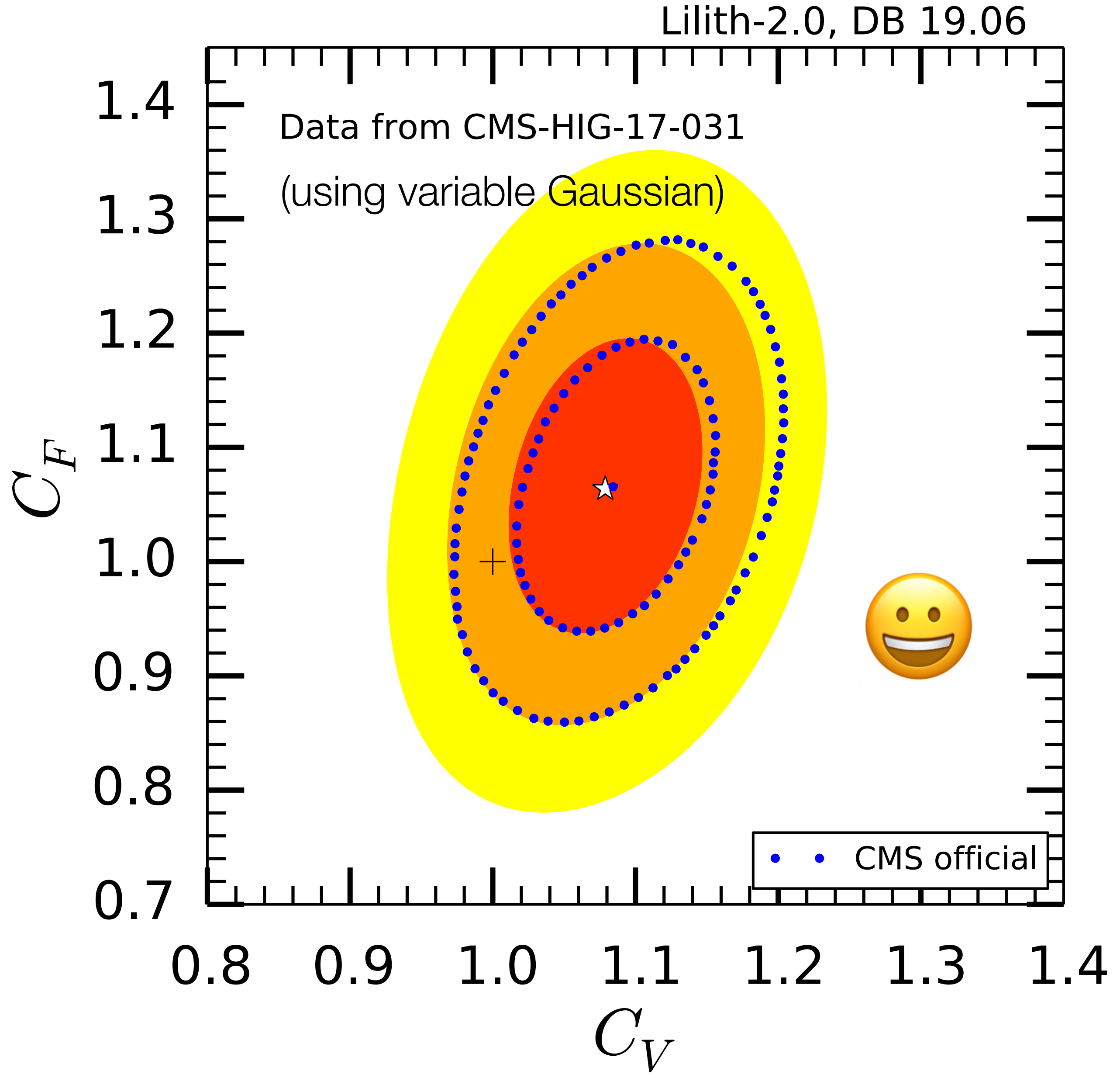
Validation examples - CMS combination





24 channels!



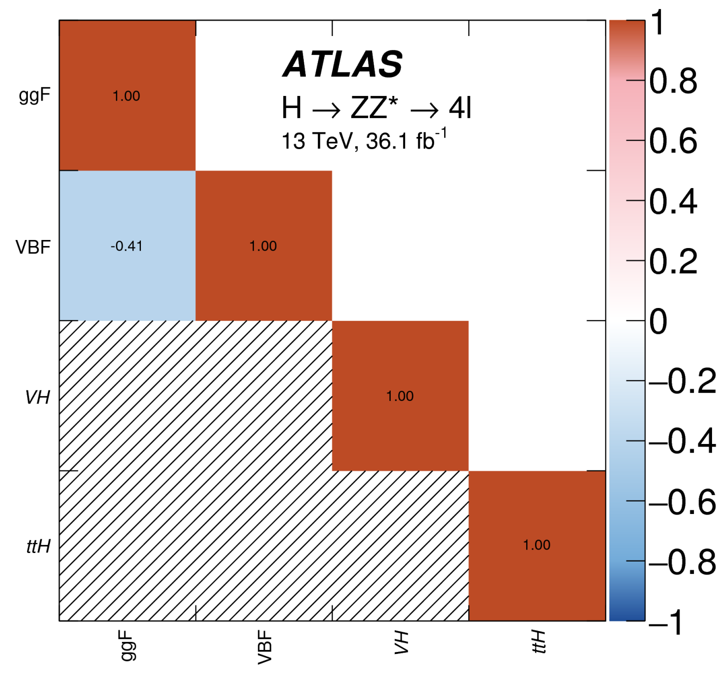


Validation examples - ATLAS H→ZZ*→4l

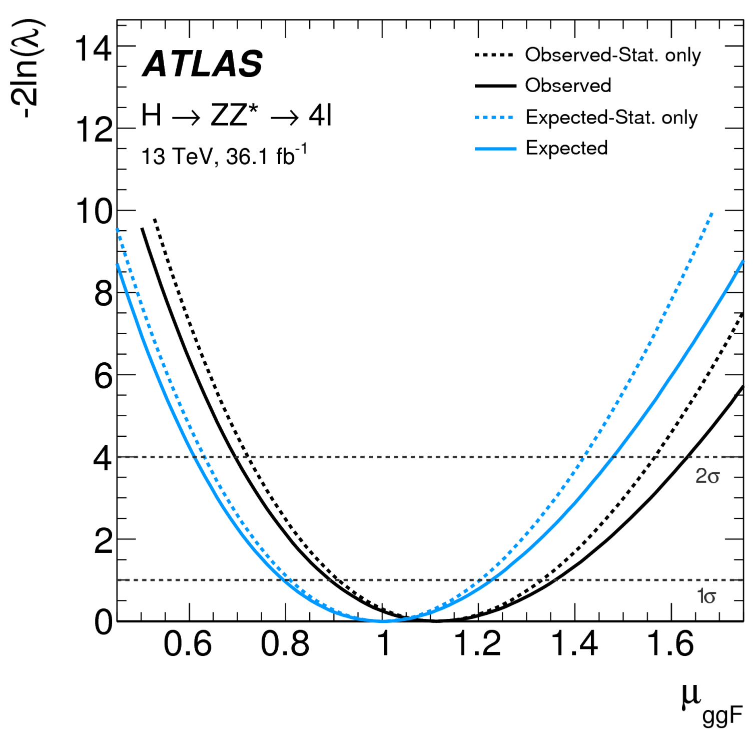
Table 9

Production bin	Cross section $(\sigma \cdot B)$ [pb]		$(\sigma \cdot B)/(\sigma \cdot B)_{\mathrm{SM}}$
	SM expected	Observed	Observed
Inclusive production, $\|y_H\| < 2.5$			
	1.34 ± 0.09	$1.73^{+0.24+0.10}_{-0.23-0.08}\pm0.04$	$1.29^{+0.18+0.07}_{-0.17-0.06}\pm0.03$
Stage-0 production bins, $\|y_H\| < 2.5$			
ggF	1.18 ± 0.08	$1.31^{+0.26+0.09}_{-0.24-0.07}\pm0.05$	$1.11^{+0.22+0.07}_{-0.20-0.06}\pm0.04$
VBF	0.0928 ± 0.0028	$0.37^{+0.15}_{-0.13}\pm0.03\pm0.03$	$4.0^{+1.7}_{-1.4}\pm0.3\pm0.3$
VH	$0.053^{+0.003}_{-0.005}$	< 0.20	< 3.7
ttH	$0.0154^{+0.0011}_{-0.0016}$	< 0.12	< 7.5

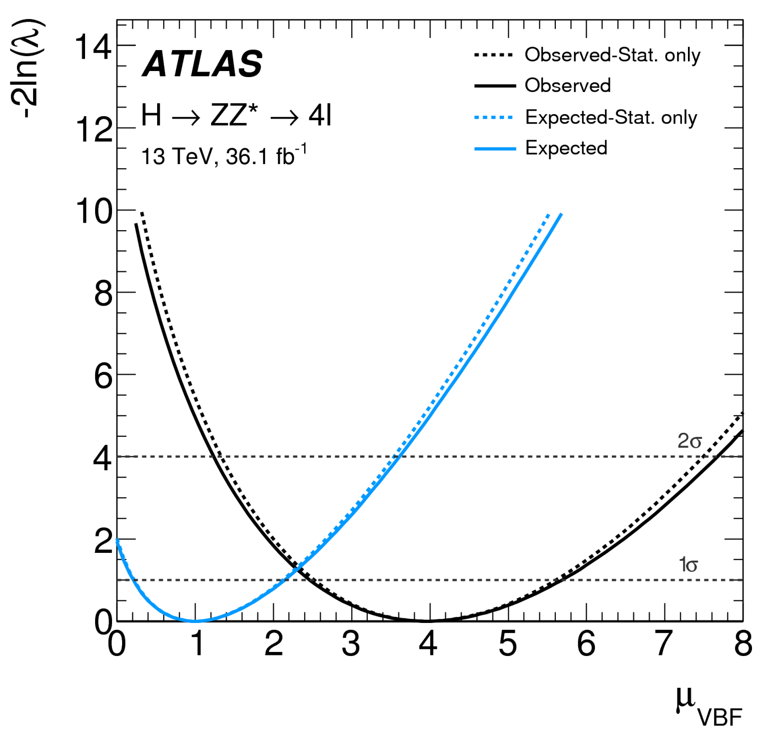
Aux.Fig. 4c

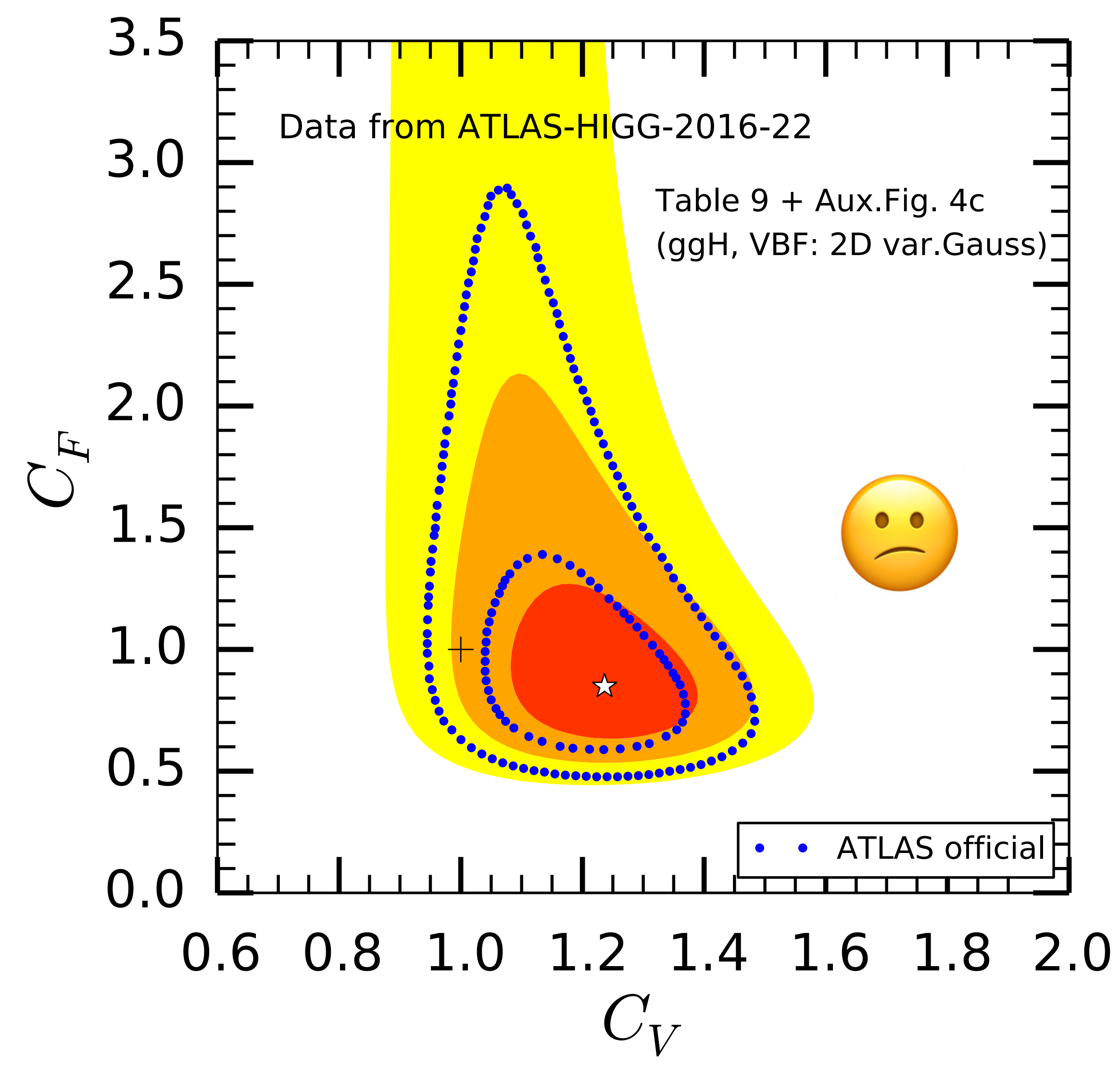


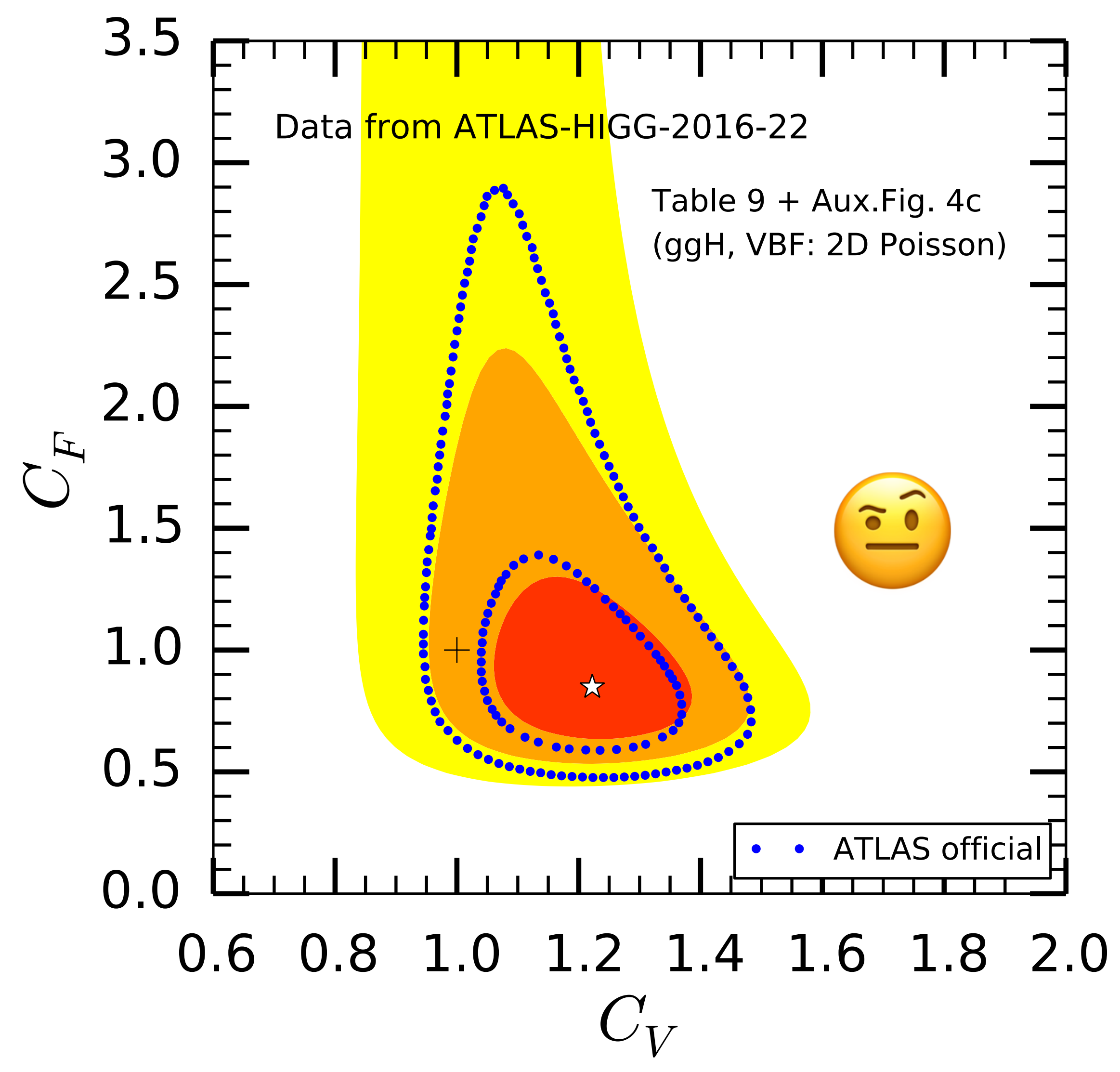
Aux.Fig. 7a

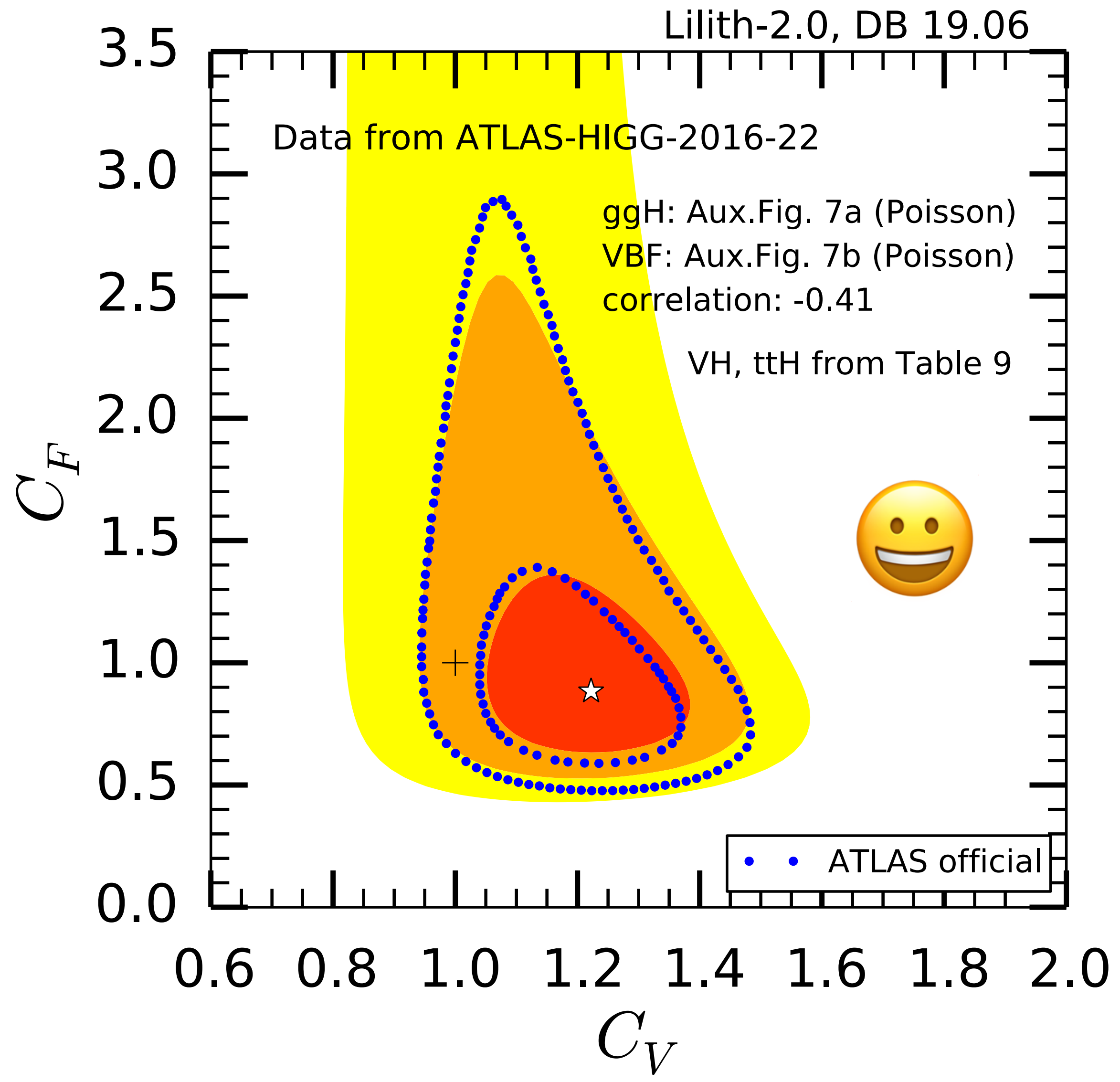


Aux.Fig. 7b

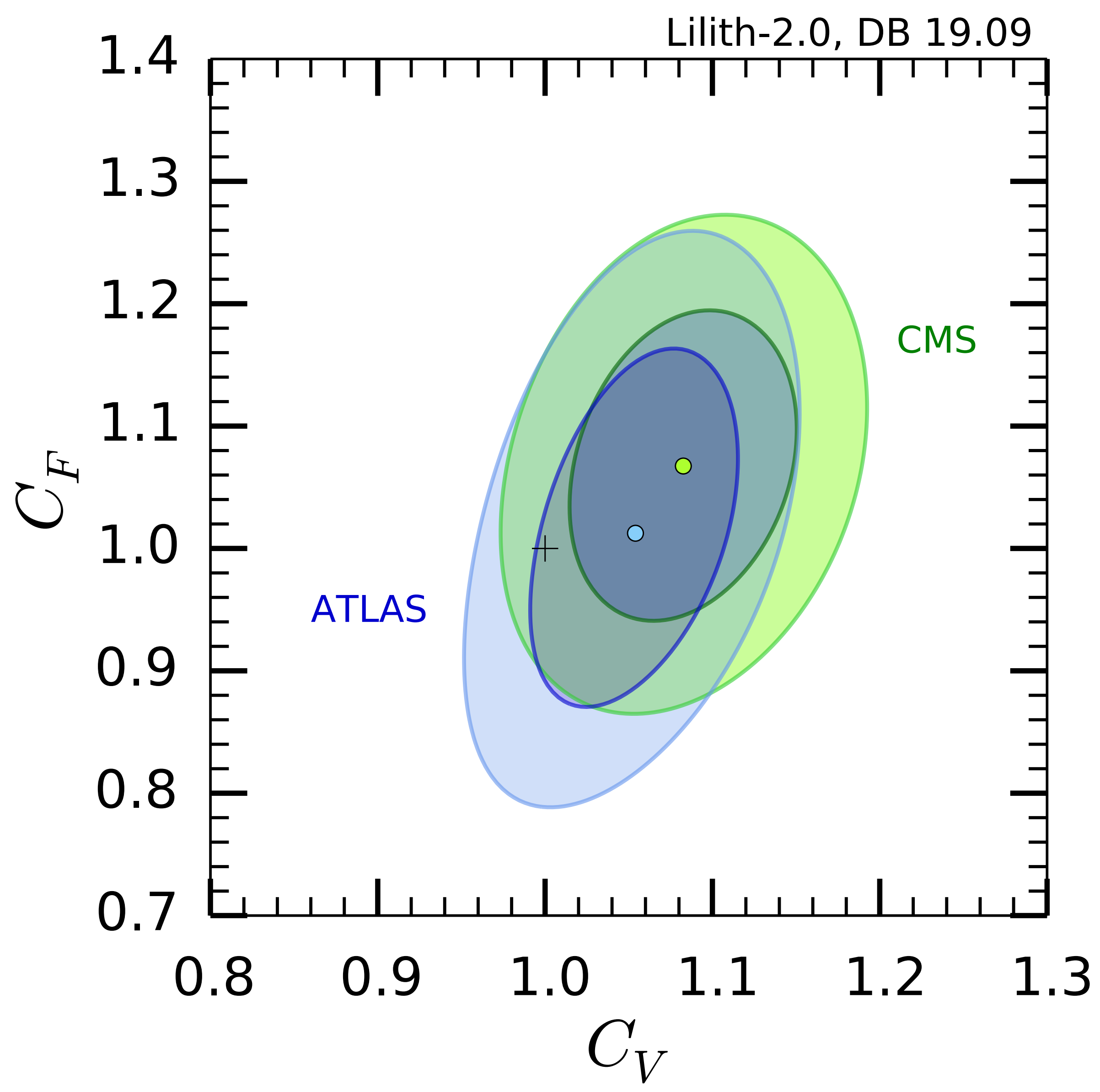


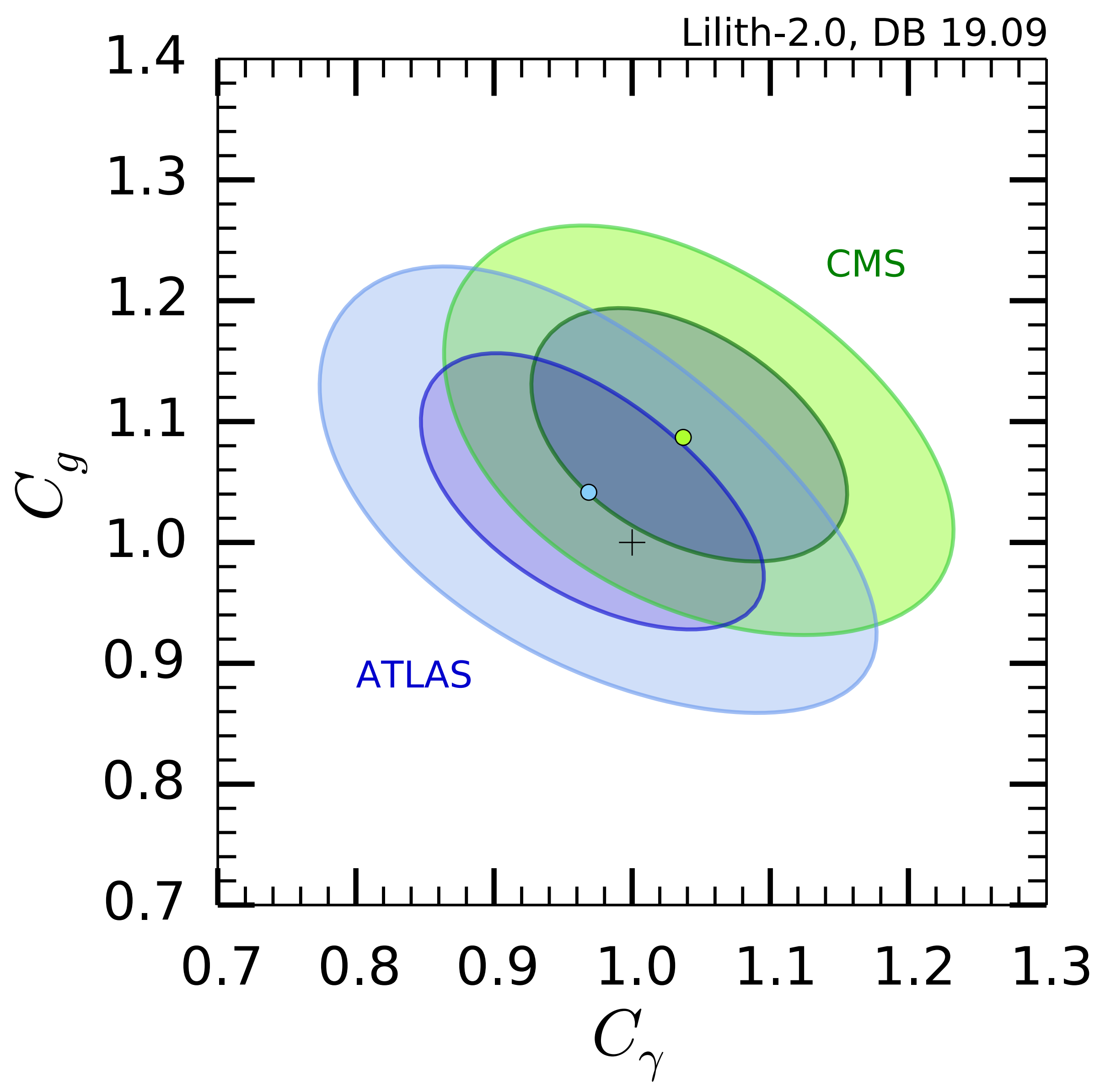






Constraints on couplings - status Sep. 2019





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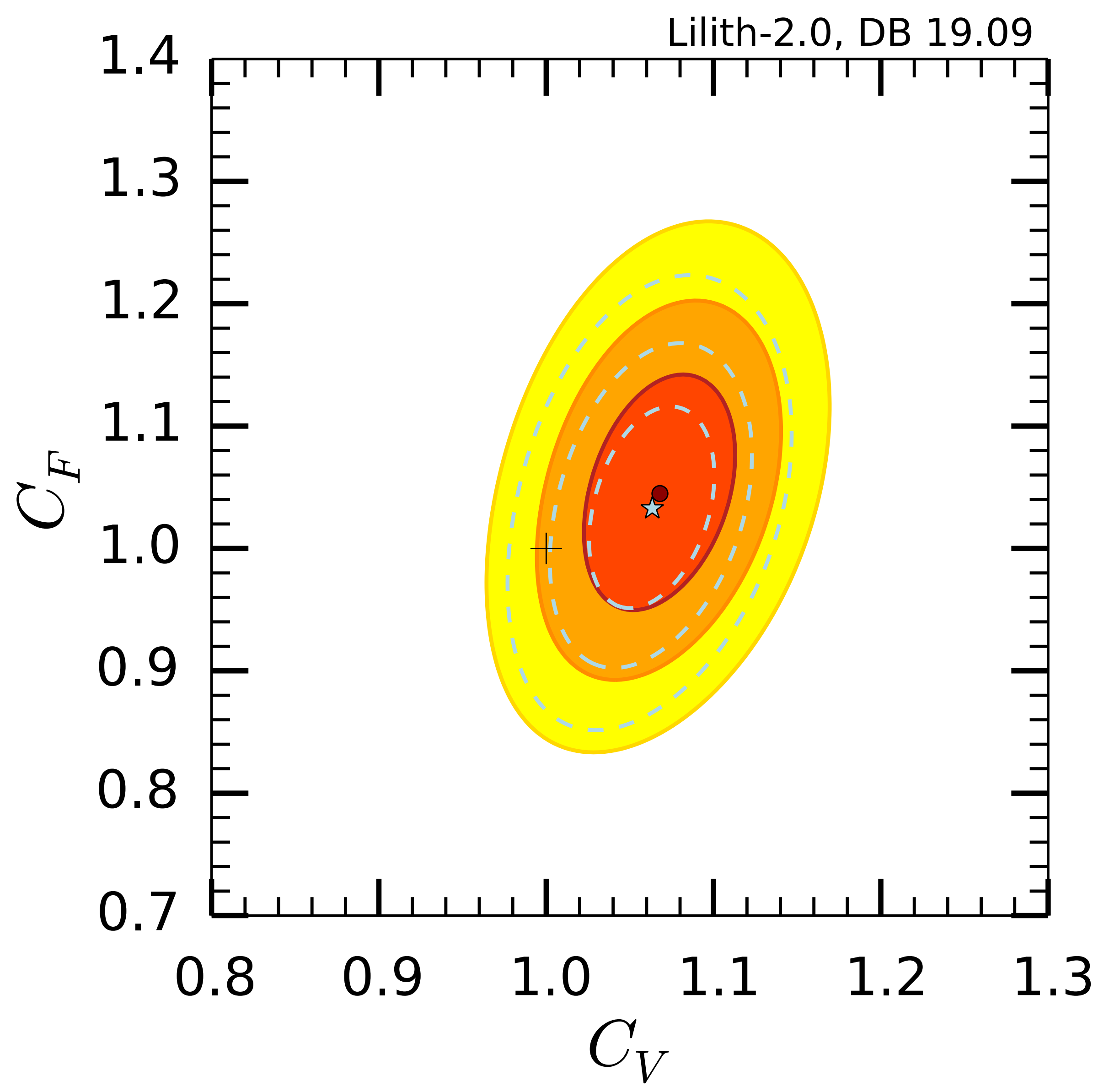
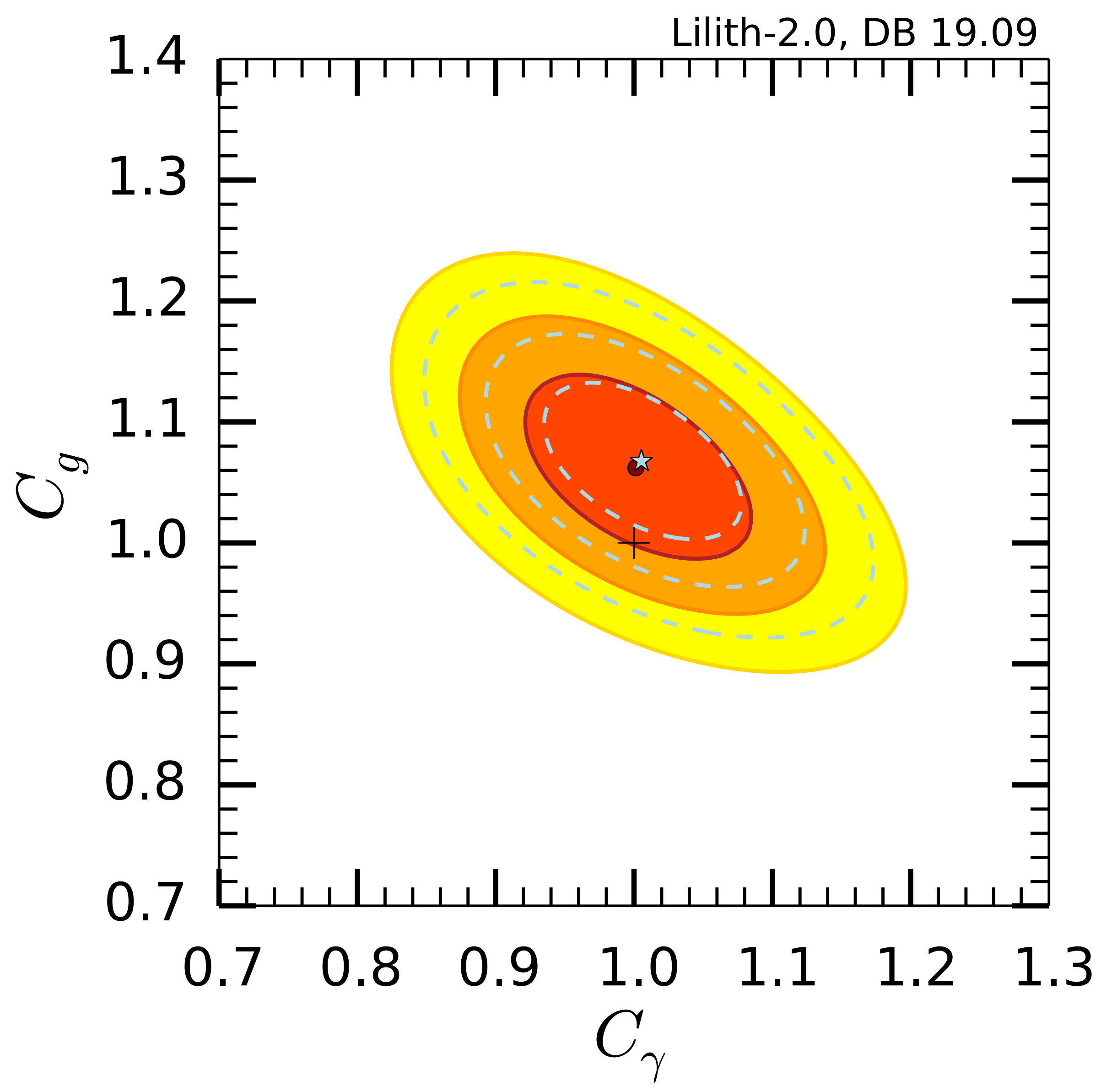
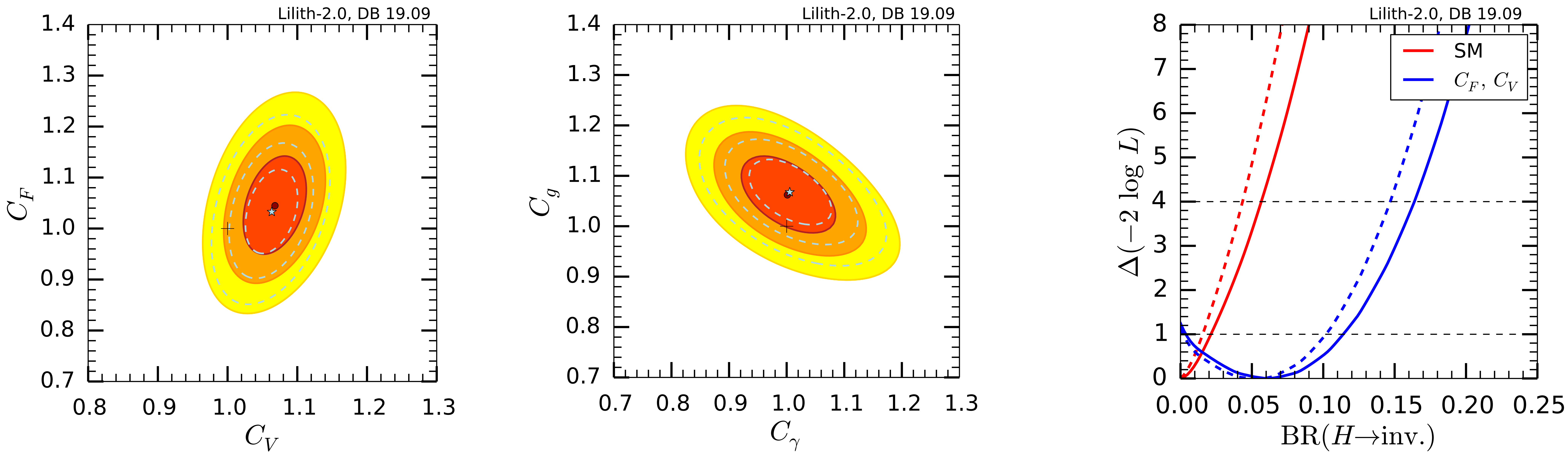




full contours: Run 2
dashed contours: Run1 + Run2

Constraints on couplings - status Sep. 2019



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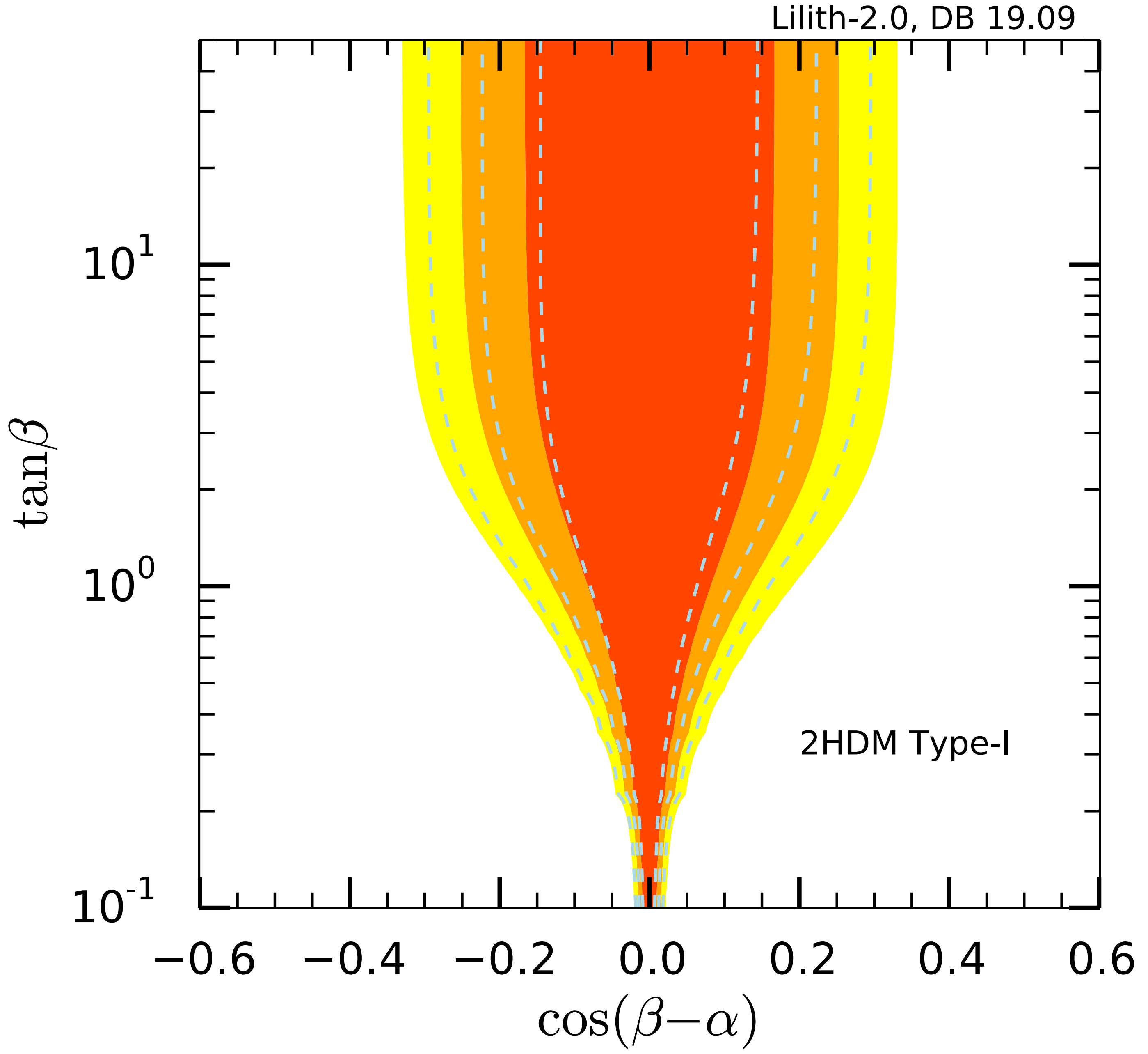

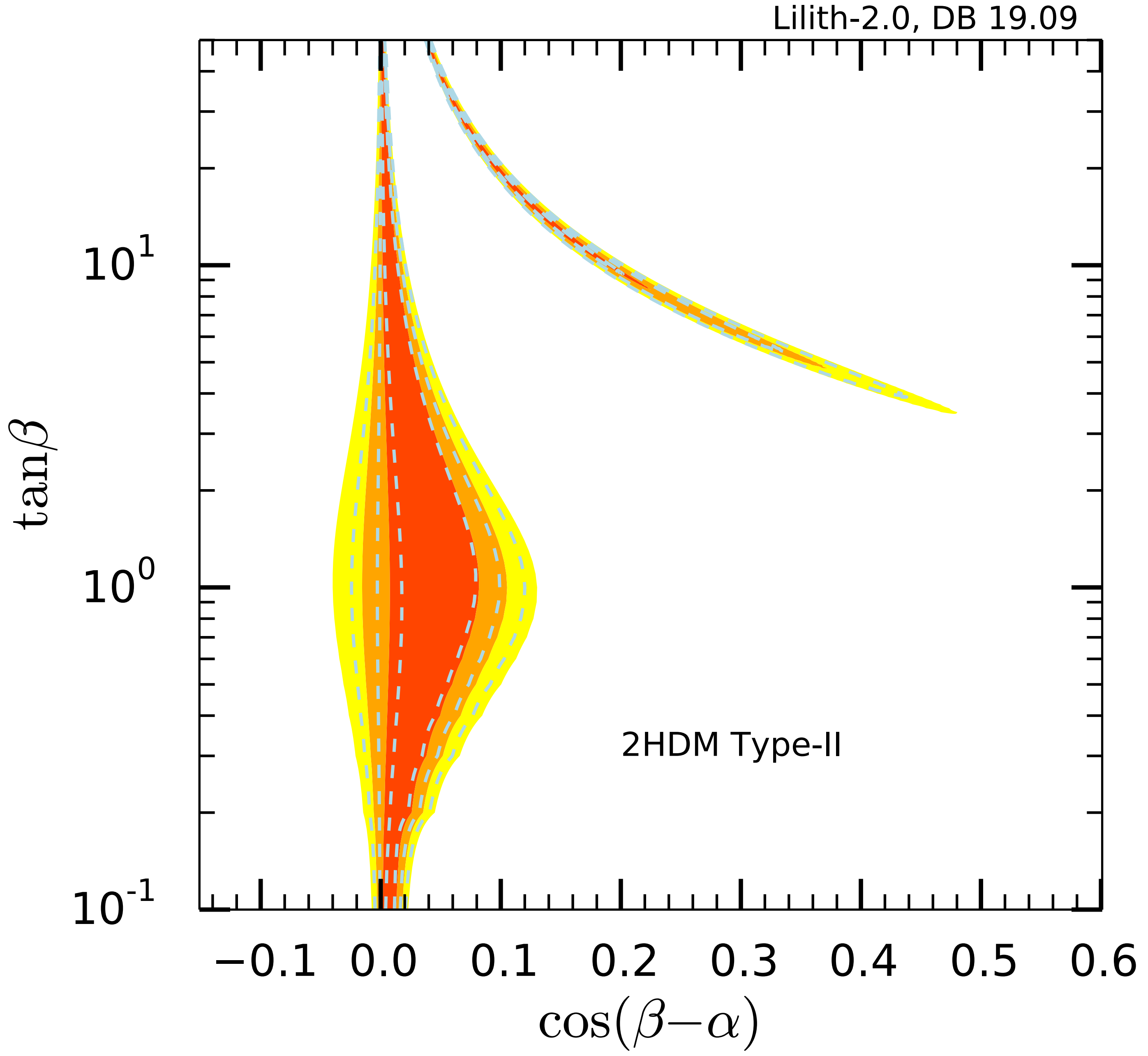

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Ongoing developments

- The code has recently been translated from Python 2 to Python 3 (M1 internship of Marius Bertrand)
  public release of new **Python 3 version** to come soon
- We are heavily working on a **database update for full Run 2 luminosity** (~140/fb) results;
  not at all straightforward …. often no validation material, or other problems

big effort by Tran Quang Loc

	$\gamma\gamma$	ZZ	WW	$\tau\tau$	bb	μμ	inv.	combination
ATLAS	CONF: 2020-026 2019-004	HIGG-2018-28	CONF-2020-045		HIGG-2018-51	HIGG-2019-14		CONF-2020-027
CMS	PAS-19-015 HIG-19-013			PAS-19-010		HIG-19-006		HIG-19-005

issues with validation, no validation material, looks ok

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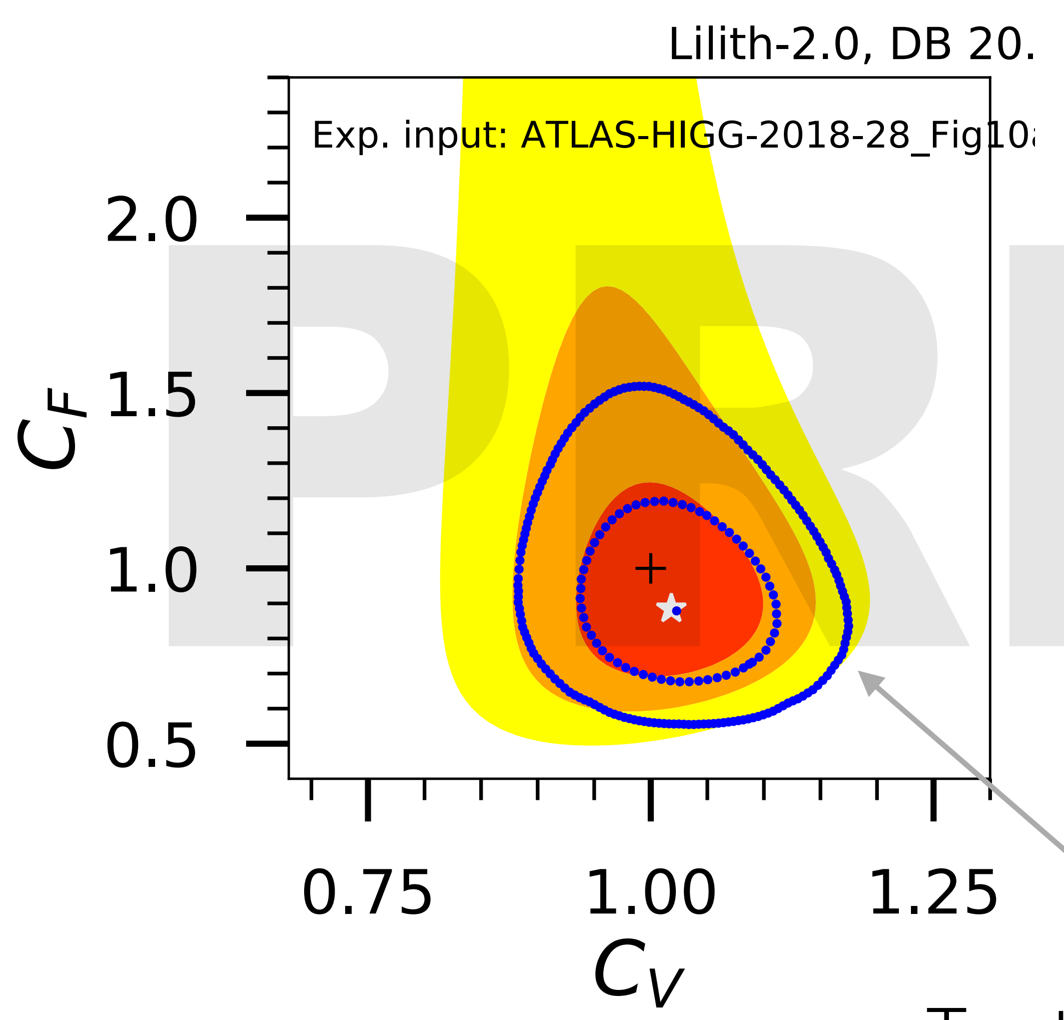
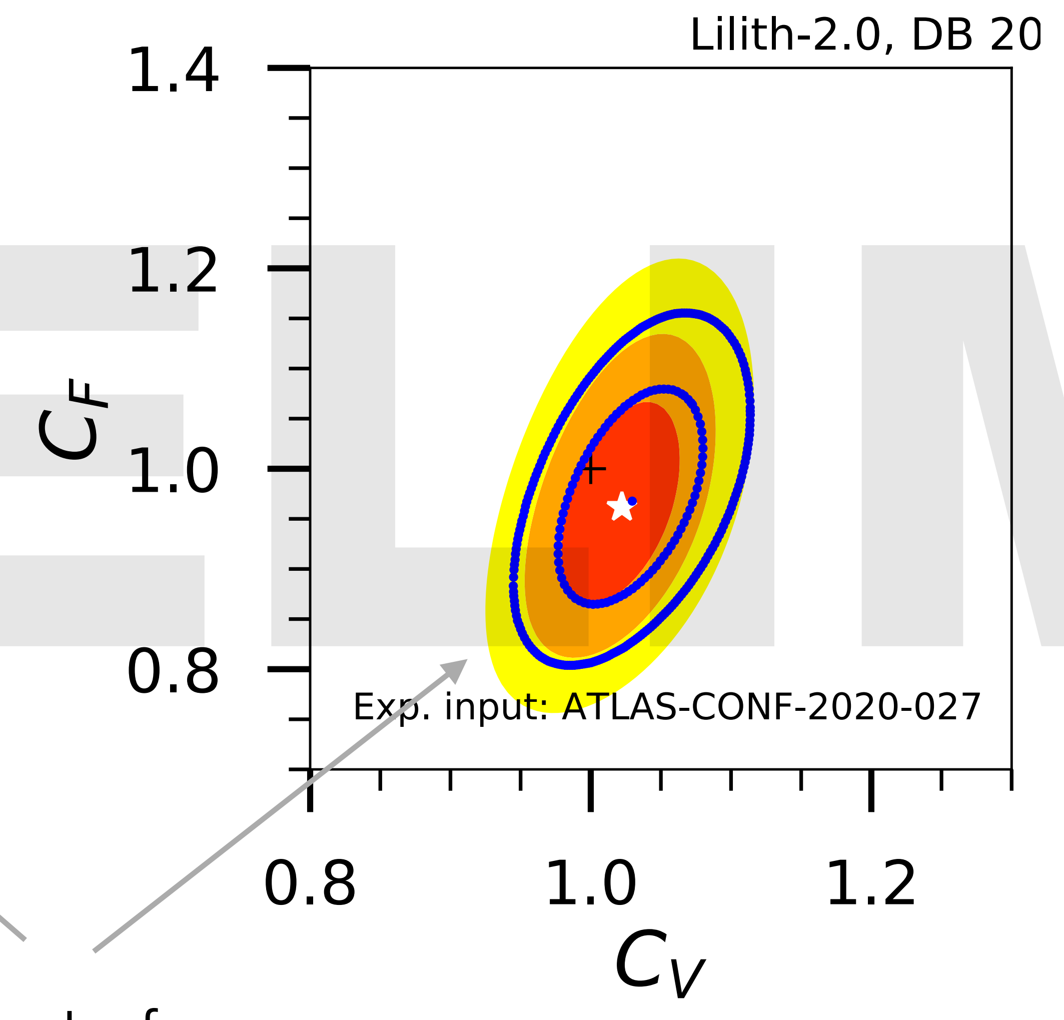
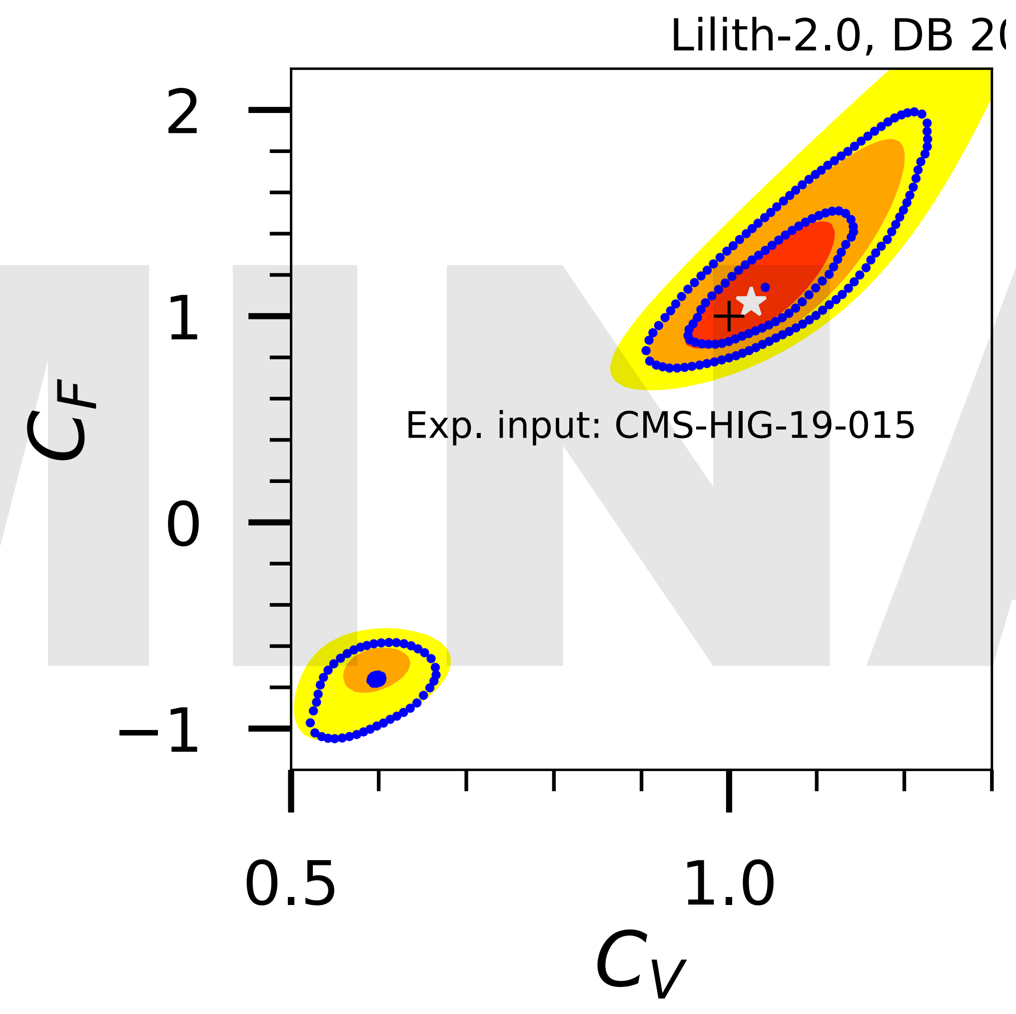
ATLAS H→ZZ*→4l



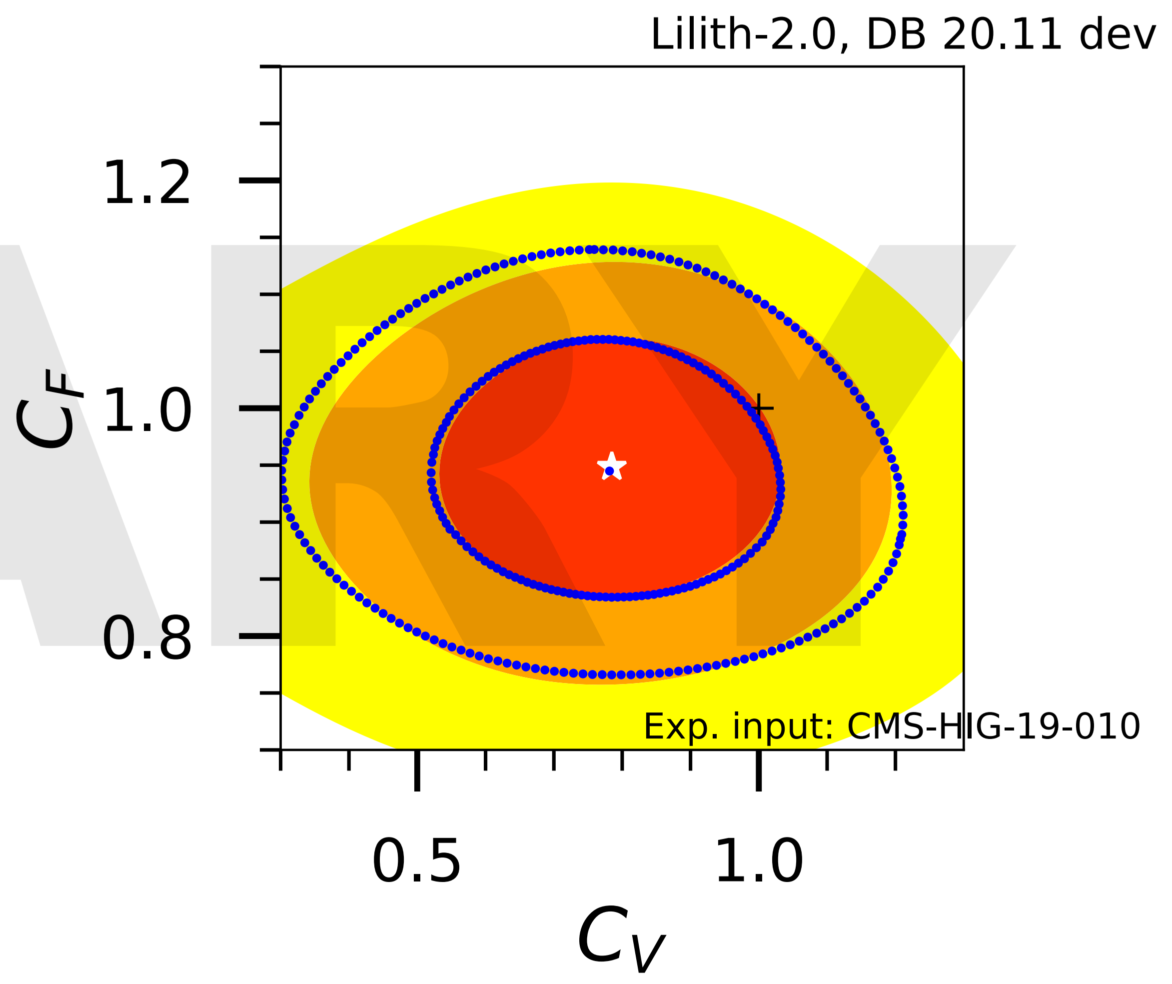
ATLAS comb.



CMS H→$\gamma\gamma$



CMS H→$\tau\tau$

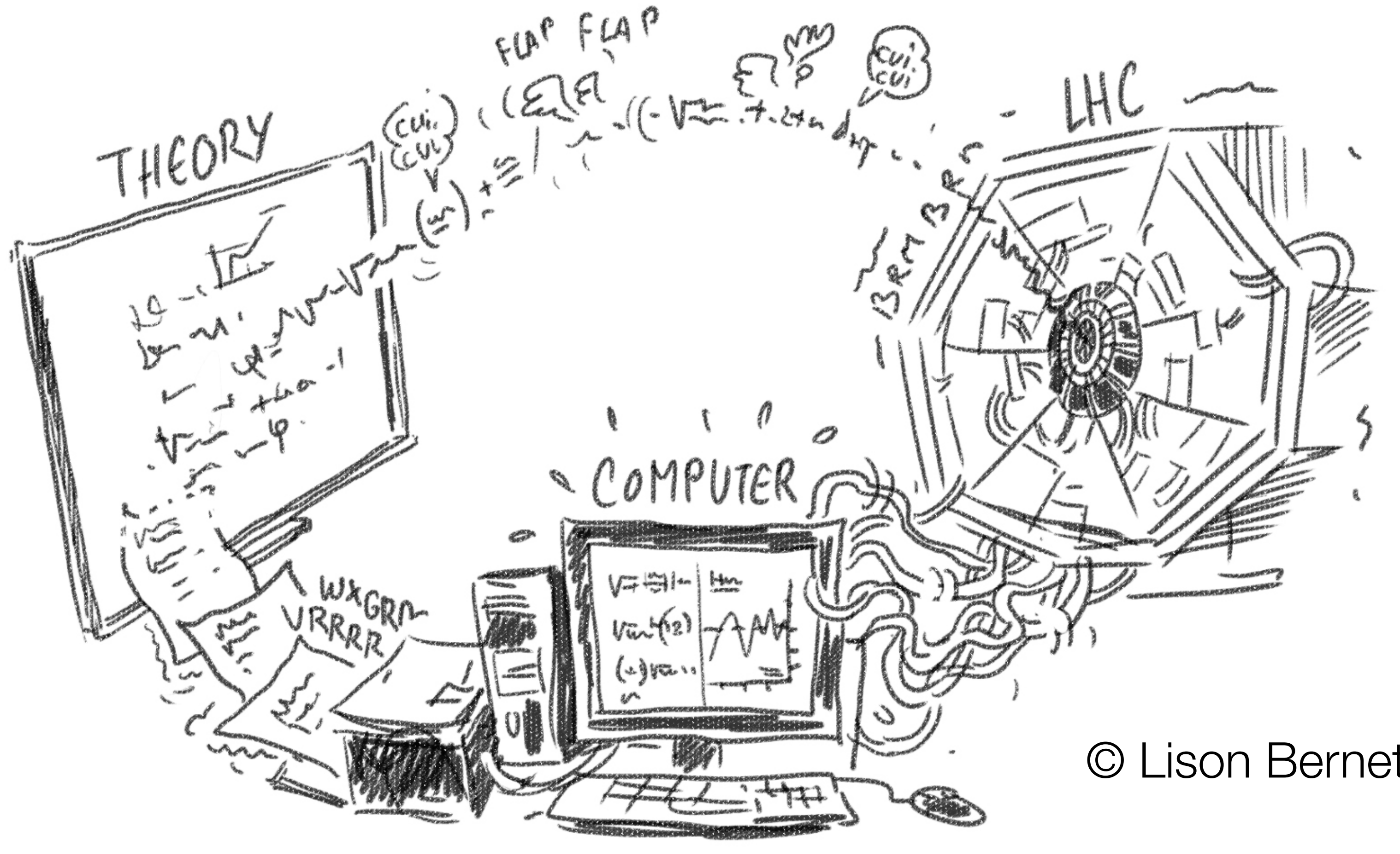


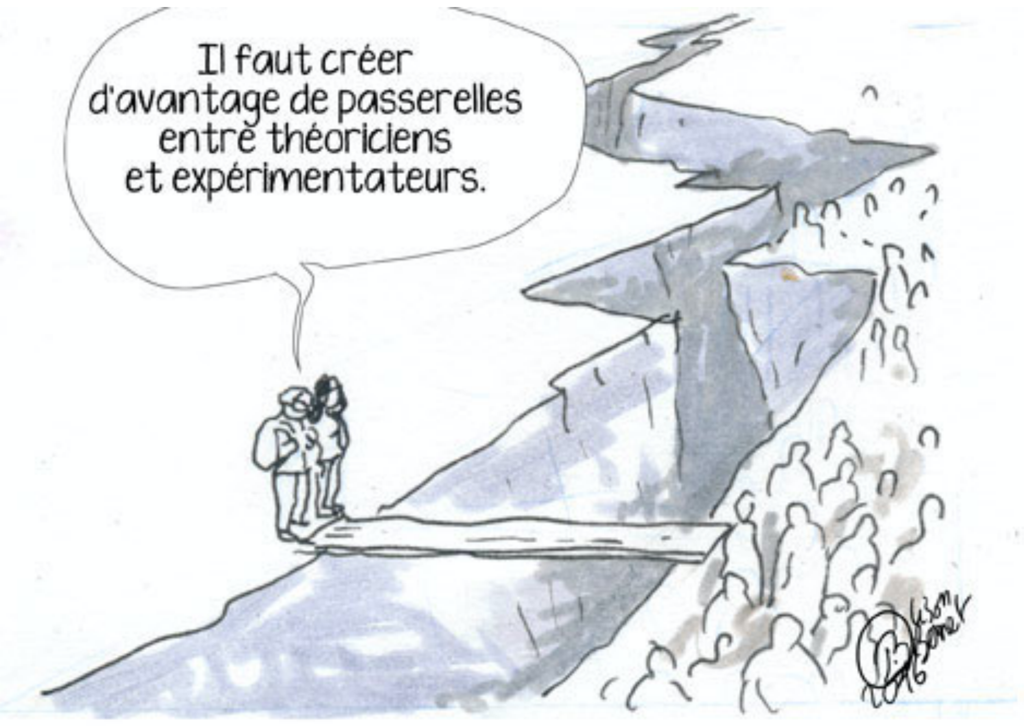
PRELIMINARY

Treatment of
SM uncertainties??

Lilith : Light Likelihood fit for the Higgs

- Light and easy-to-use Python tool for **constraining new physics from signal strength measurements** of the 125 GeV Higgs boson.
- v2.0 features a better treatment of **asymmetric uncertainties** and **correlations**: variable Gaussian and generalized Poisson likelihoods; use of N-dim correlation matrices (for v.Gauss.).
- Database 19.09 contains the published **ATLAS and CMS Run 2 results for 36/fb** as of Sep 2019.
- Currently Python 2, **beta version for Python 3**
- **Update for full Run-2** luminosity results **in progress**.





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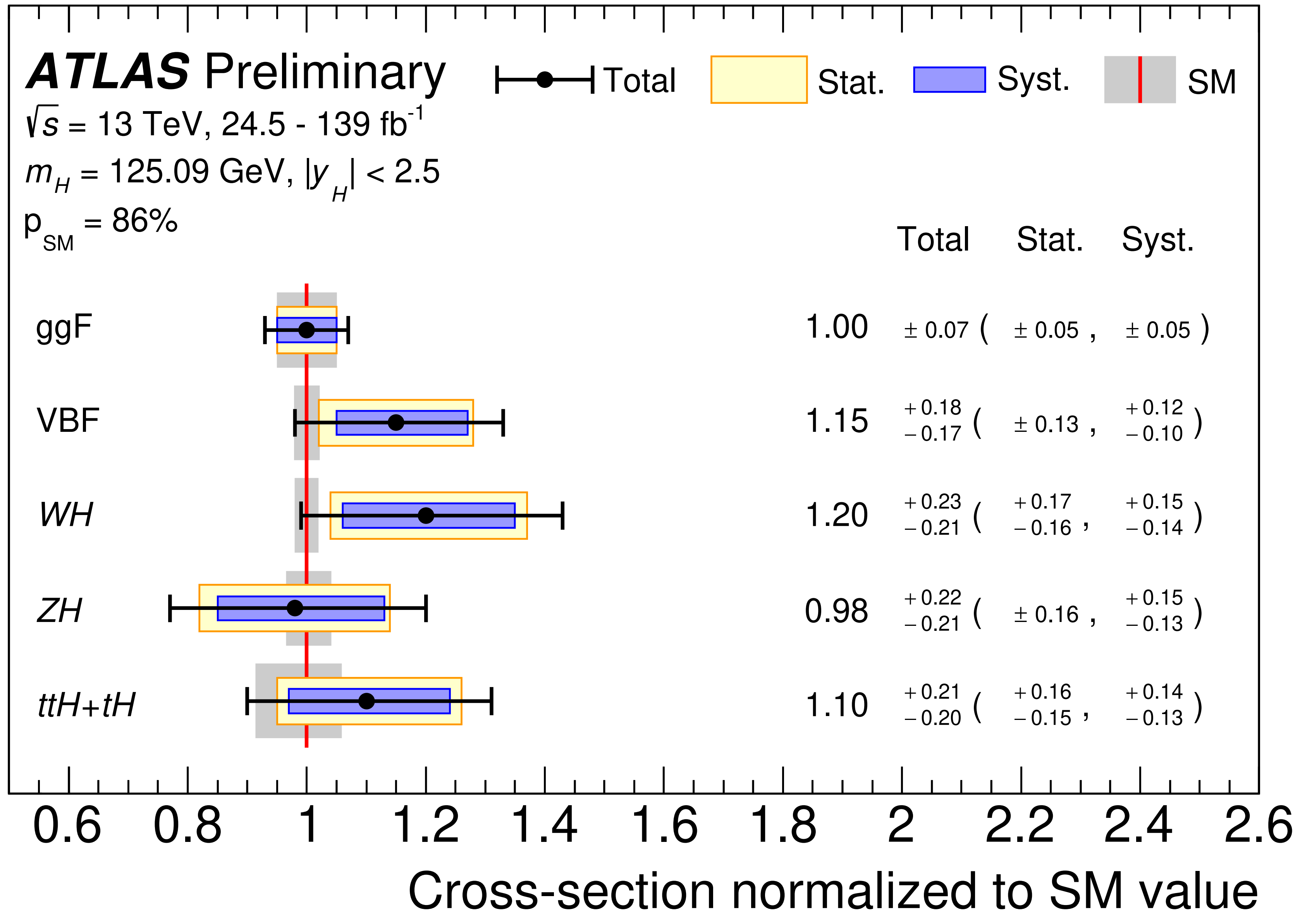
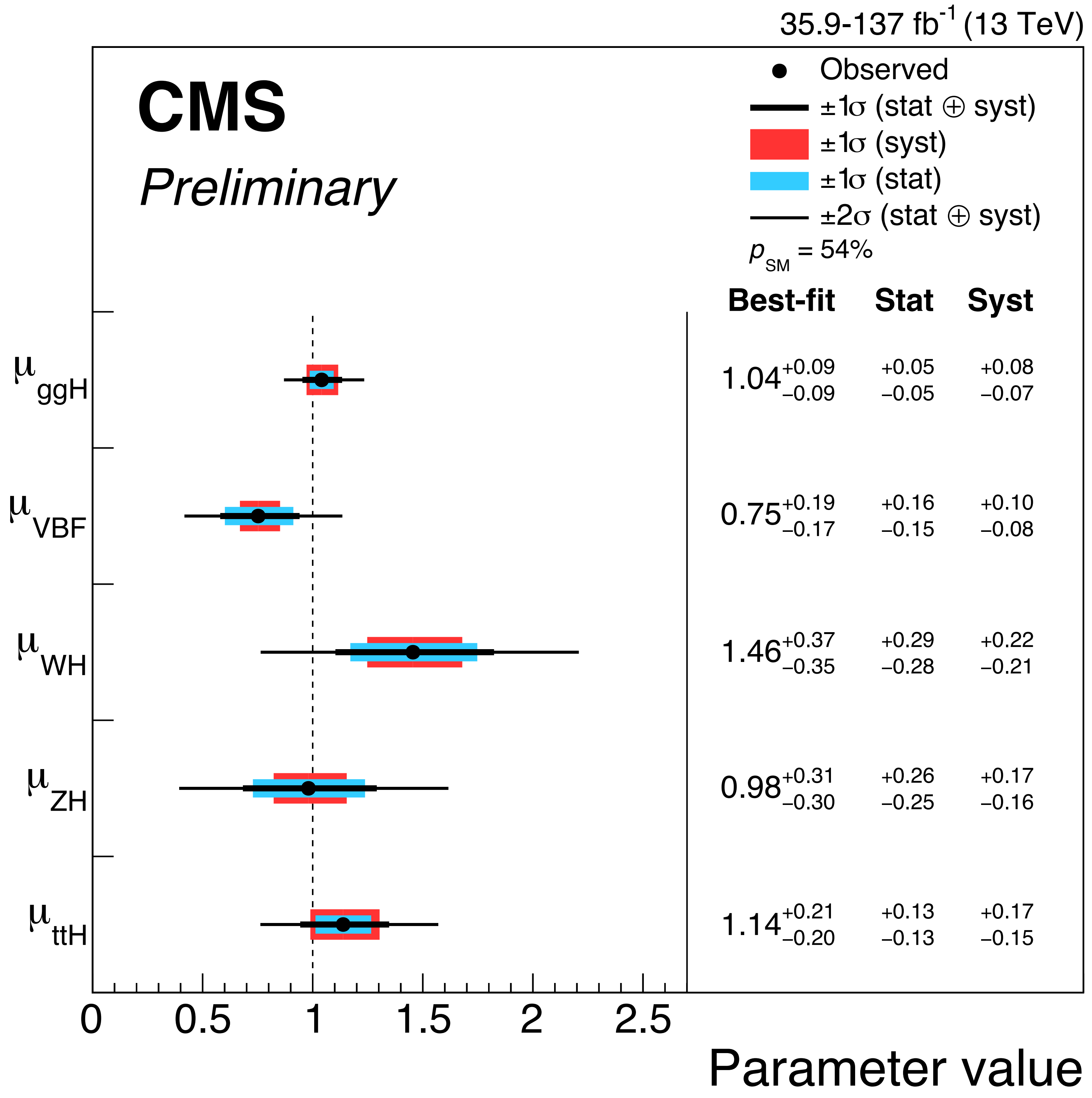
BACKUP

Production mode results

ATLAS measures σ_i while CMS measures signal strength μ_i

- difference in the treatment of theoretical uncertainties
  - in the first case, factorize out theory uncertainty on cross-section and include in SM prediction





ATLAS: significance $> 5\sigma$ for all production modes

Very good agreement with SM, both $p_{SM} > 50\%$

Started becoming systematic dominated, ggH precision $\sim$ theory uncertainty

Recommendations from the Reinterpretation Forum

arXiv:2003.07868

The **signal strength framework remains of high interest because of its power and ease of use** in constraining new physics […]. We **encourage the experimental collaborations to continue to provide detailed Higgs signal strength multiplier results** (“μ values”) in addition to STXS and differential fiducial cross-sections.

For optimal usefulness, we would appreciate:

- **best-fit μ’s and uncertainties** for the experimental reconstructed event categories and for the pure, unfolded Higgs production×decay modes (allowing for negative μ values in order to have an unbiased estimator);
- **channel-by-channel correlation** or covariance matrices, separately for experimental and theoretical uncertainties, as well as **for the total (combined) uncertainties**;
- **reference values** (normalisation) of the corresponding SM predictions, or a clear reference where these values can be found, in the same binning as the experimental results;
- **signal efficiencies per signal channel** (i.e. each production×decay mode), assuming SM Higgs kinematics; for combinations of production and/or decay modes, their relative contributions wherever possible.