Higgs couplings and implications for extended Higgs sectors

Béranger Dumont
(LPSC Grenoble)

mainly based on work with
G. Bélanger, U. Ellwanger, J. F. Gunion and S. Kraml, [arXiv:1306.2941]

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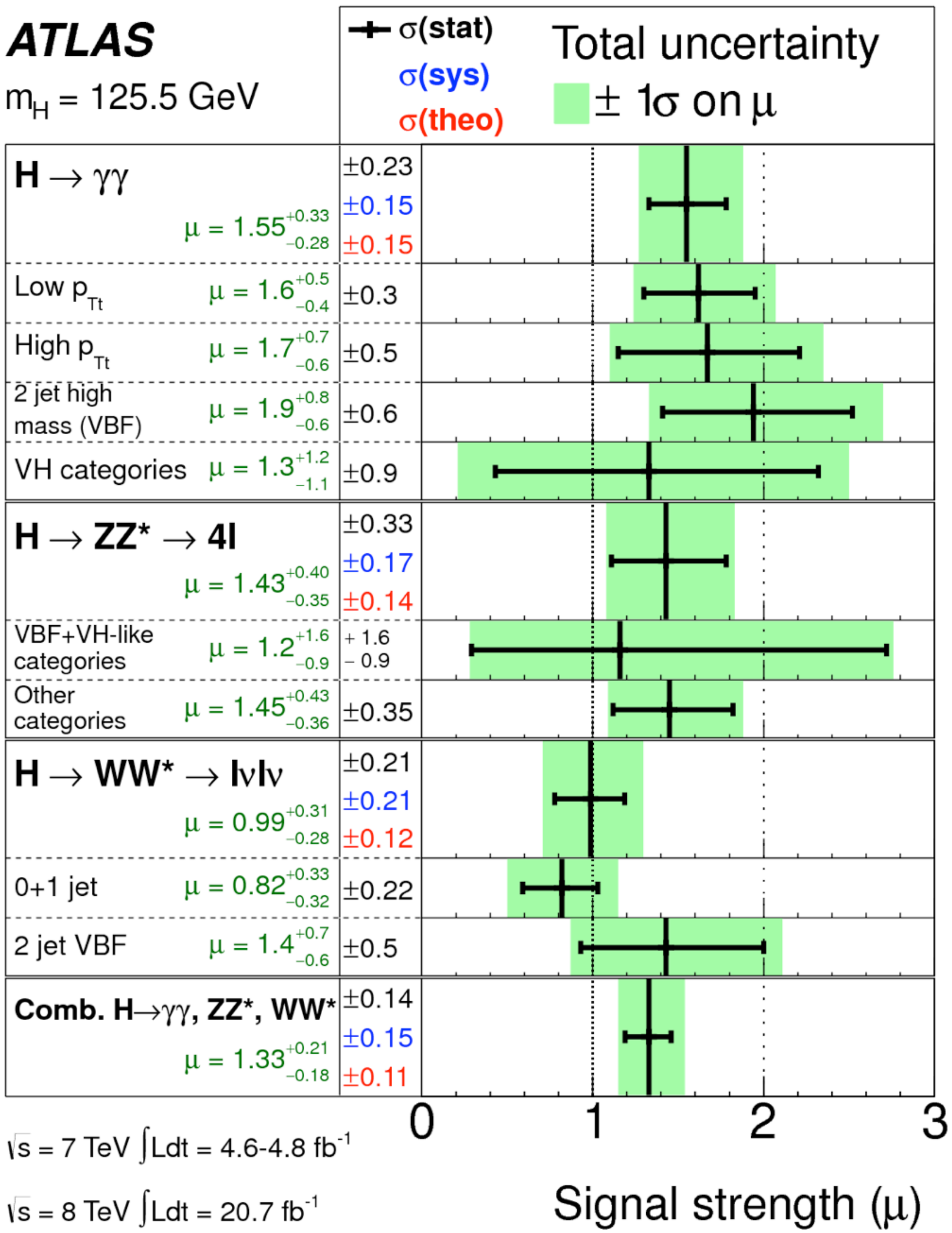
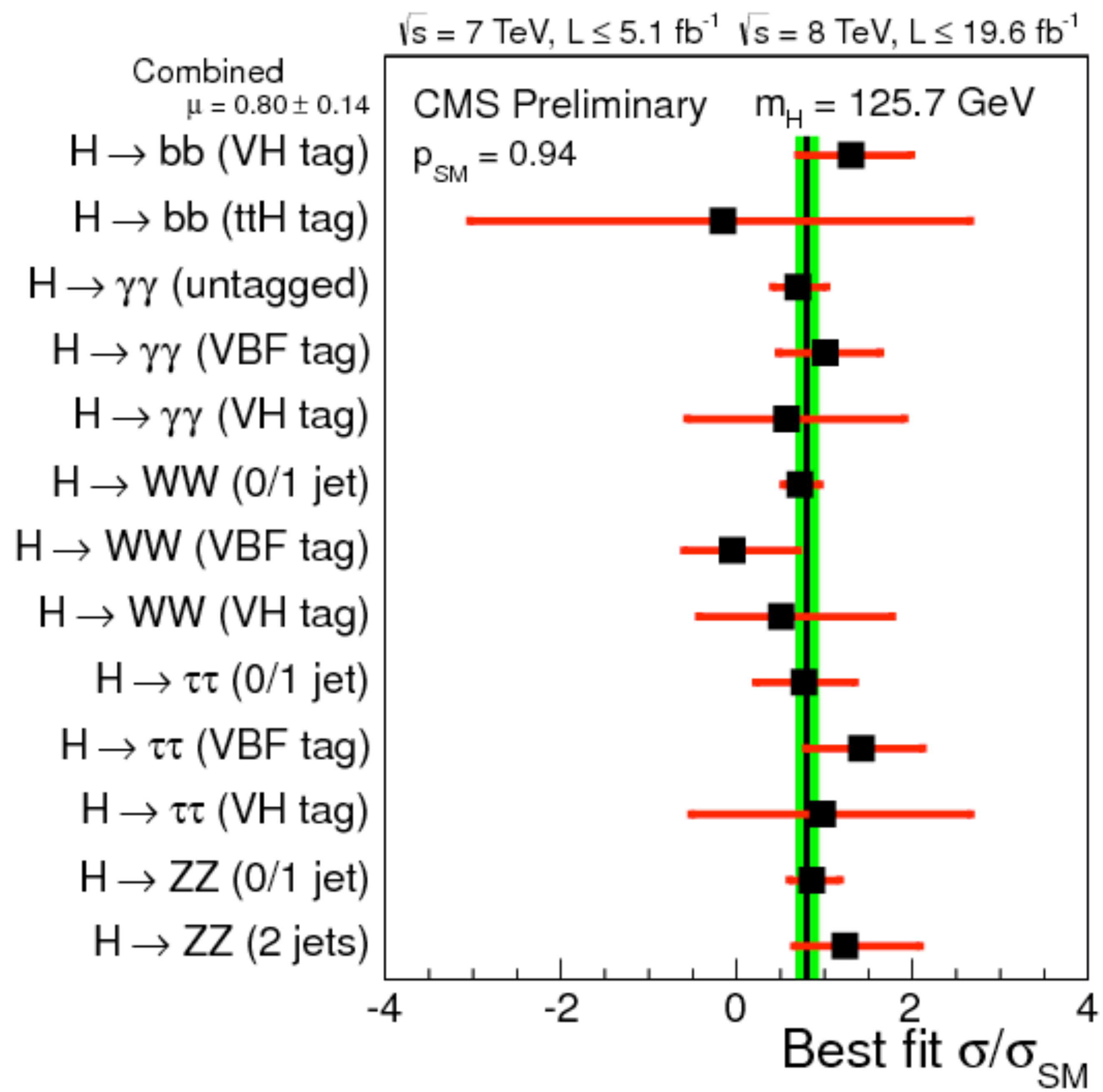
October 7, 2013

the usual signal strengths

[arXiv:1307.1427]



[CMS-PAS-HIG-13-005]



the usual signal strengths

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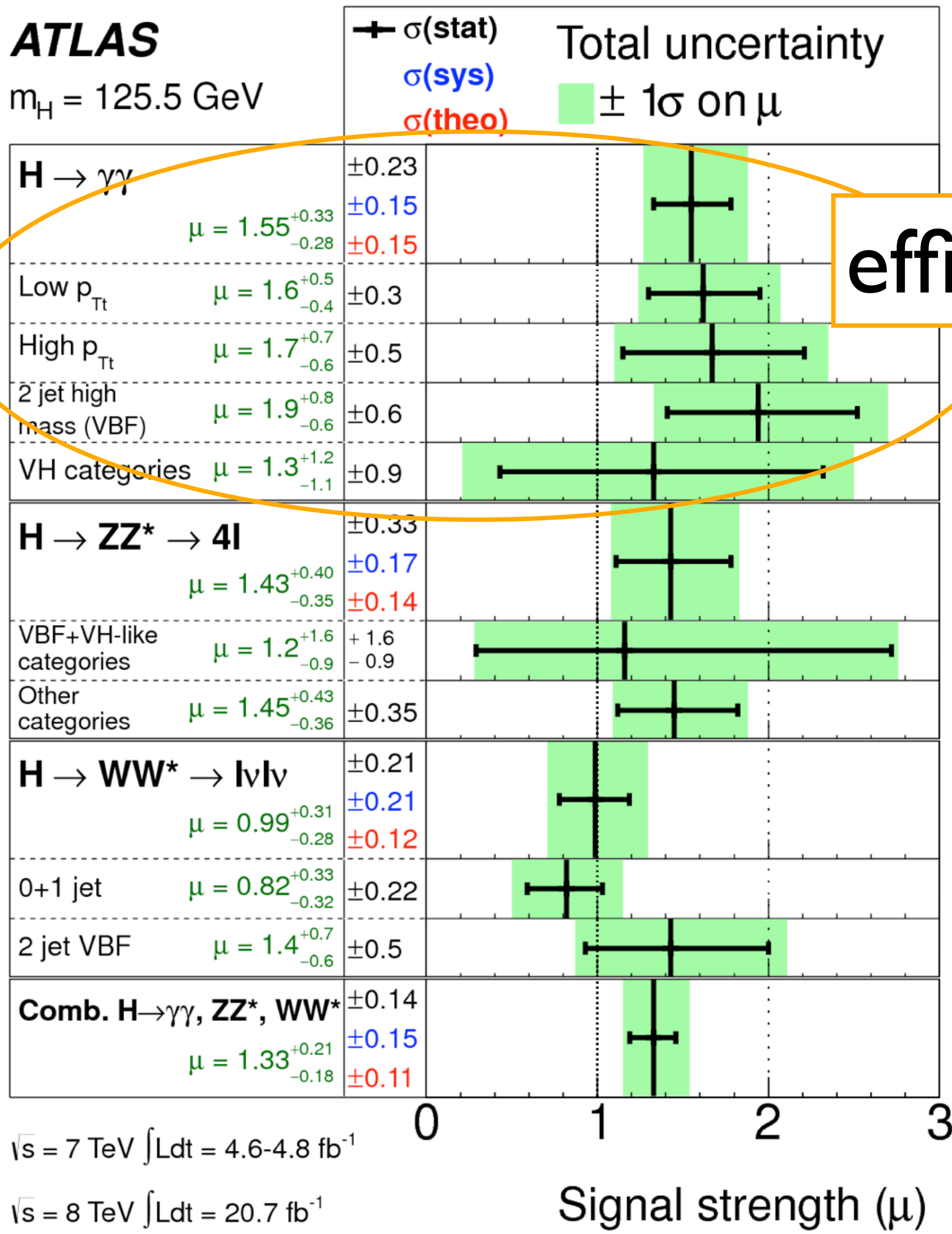
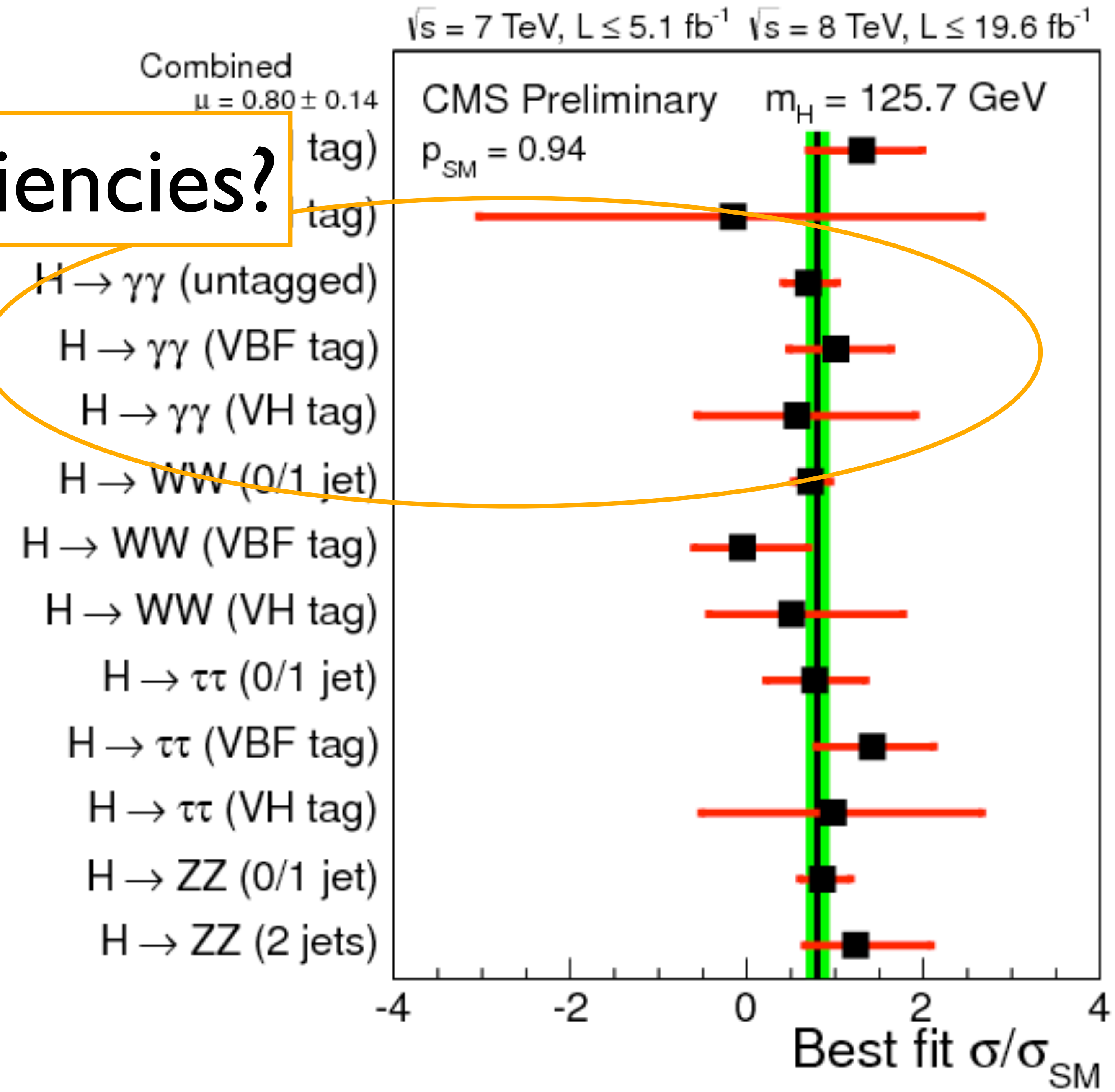


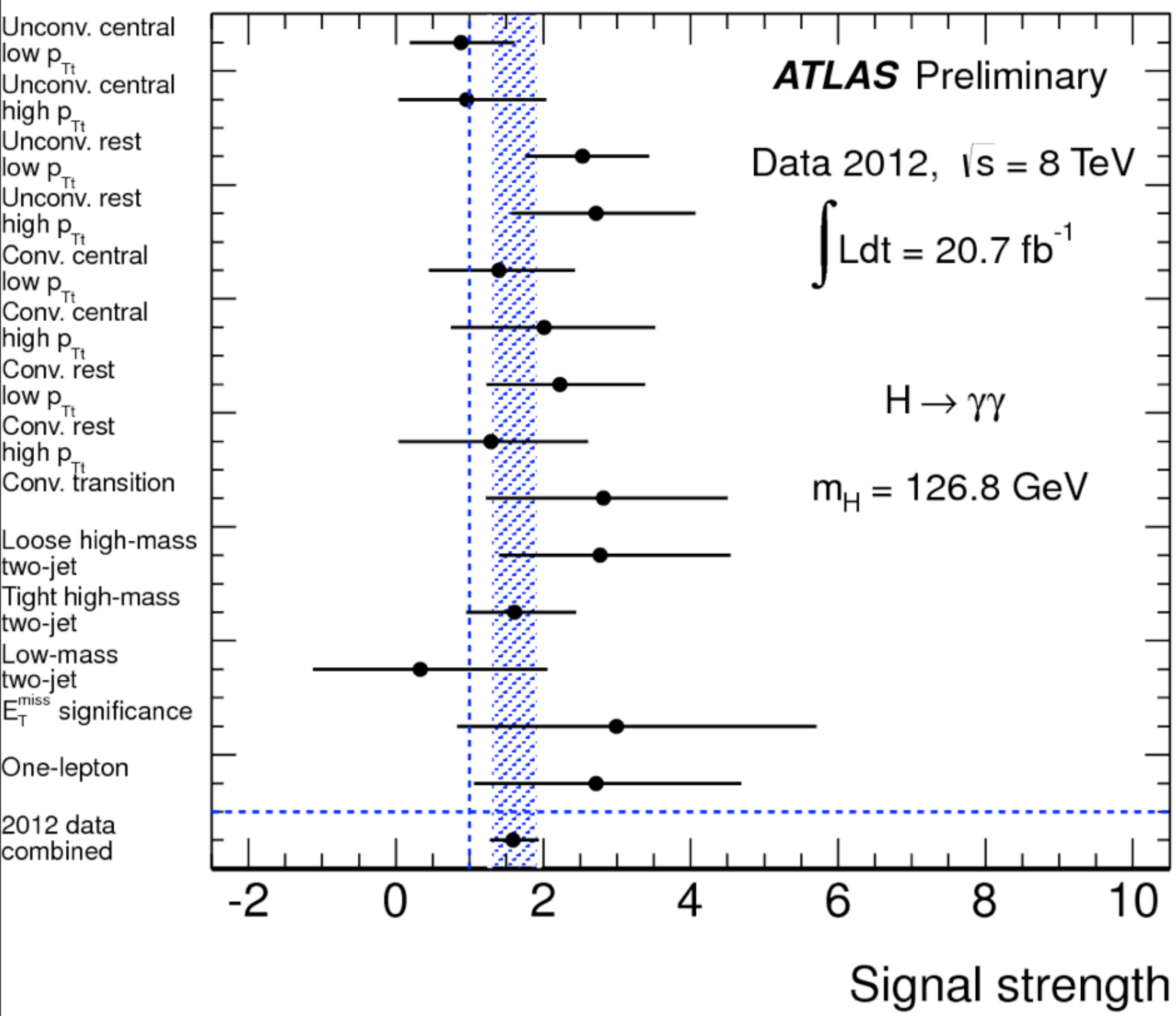
efficiencies?

[CMS-PAS-HIG-13-005]



one example: ATLAS H→γγ

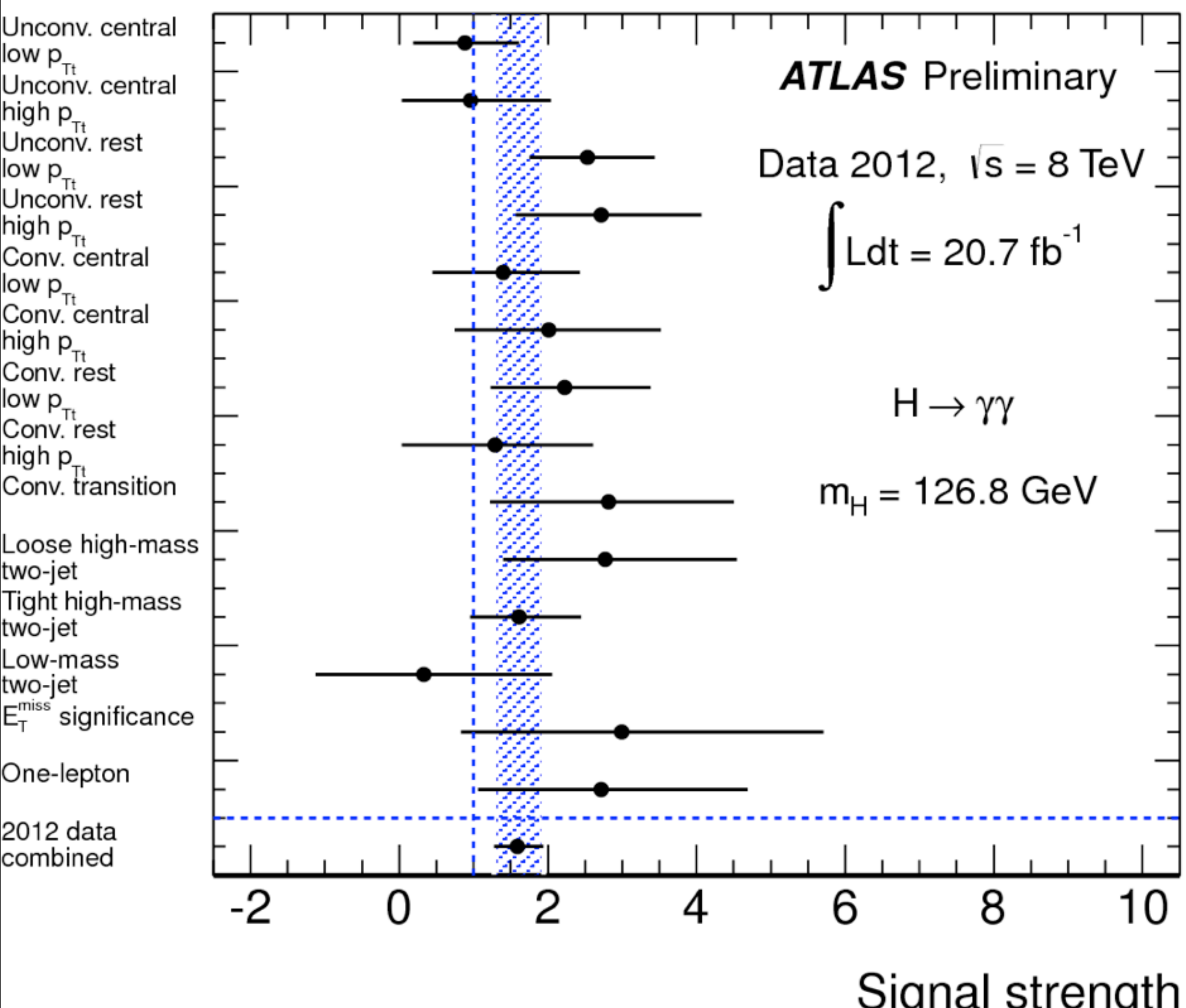
[ATLAS-CONF-2013-012]



$\sqrt{s}$	8 TeV						
Category	N_D	N_S	$gg \to H$ [%]	VBF [%]	WH [%]	ZH [%]	ttH [%]
Unconv. central, low p_{Tt}	10900	51.8	93.7	4.0	1.4	0.8	0.2
Unconv. central, high p_{Tt}	553	7.9	79.3	12.6	4.1	2.5	1.4
Unconv. rest, low p_{Tt}	41236	107.9	93.2	4.0	1.6	1.0	0.1
Unconv. rest, high p_{Tt}	2558	16.0	78.1	13.3	4.7	2.8	1.1
Conv. central, low p_{Tt}	7109	33.1	93.6	4.0	1.3	0.9	0.2
Conv. central, high p_{Tt}	363	5.1	78.9	12.6	4.3	2.7	1.5
Conv. rest, low p_{Tt}	38156	97.8	93.2	4.1	1.6	1.0	0.1
Conv. rest, high p_{Tt}	2360	14.4	77.7	13.0	5.2	3.0	1.1
Conv. transition	14864	40.1	90.7	5.5	2.2	1.3	0.2
Loose high-mass two-jet	276	5.3	45.0	54.1	0.5	0.3	0.1
Tight high-mass two-jet	136	8.1	23.8	76.0	0.1	0.1	0.0
Low-mass two-jet	210	3.3	48.1	3.0	29.7	17.2	1.9
E_T^{miss} significance	49	1.3	4.1	0.5	35.7	47.6	12.1
One-lepton	123	2.9	2.2	0.6	63.2	15.4	18.6
All categories (inclusive)	118893	395.0	88.0	7.3	2.7	1.5	0.5

one example: ATLAS H→γγ

[ATLAS-CONF-2013-012]



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correlations between categories?

can we safely neglect them?
probably not...

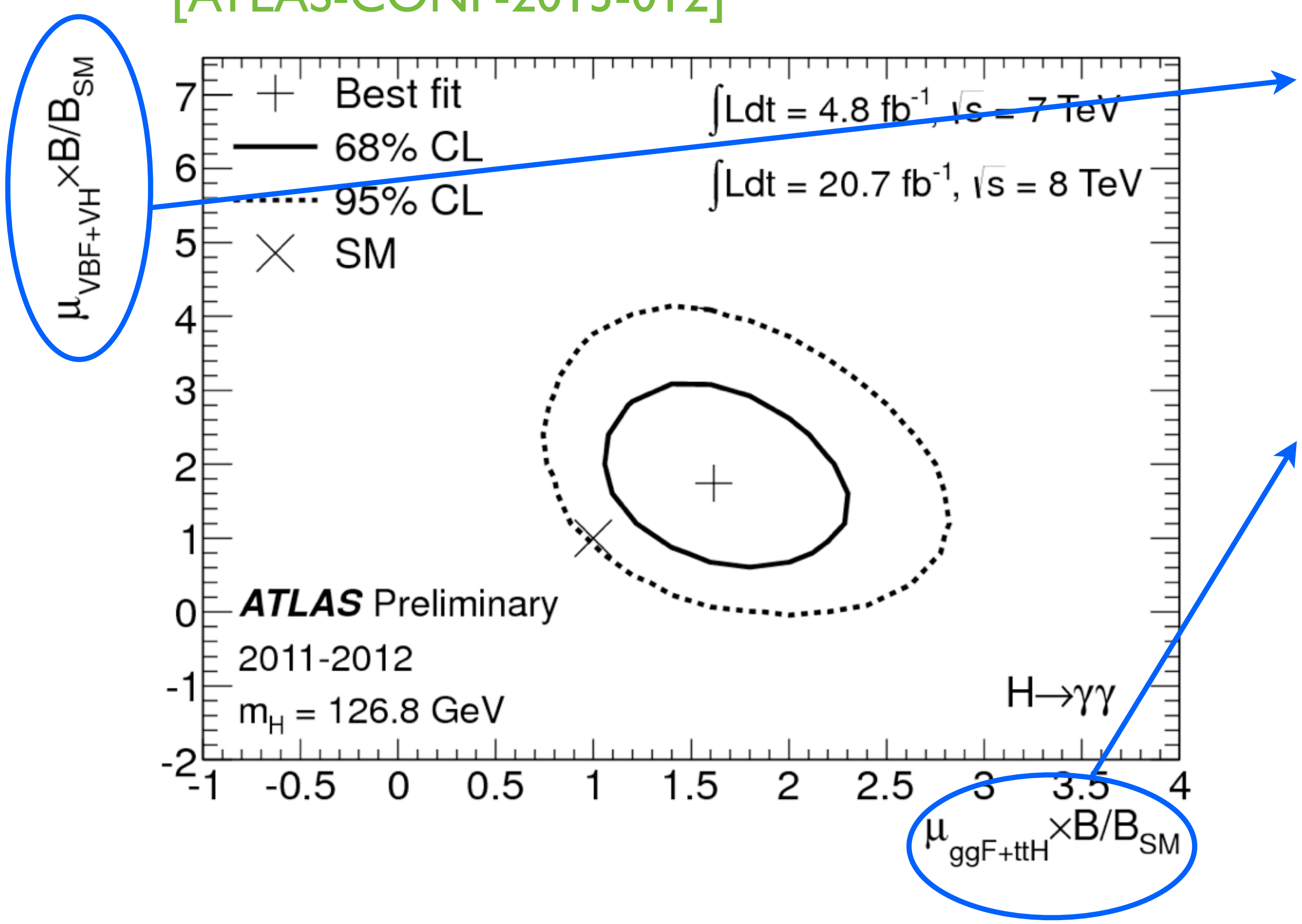
signal strengths in theory space

also possible to consider signal strengths in the (X,Y) theory space:

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

$$X = {\rm ggF, VBF, WH, ZH, ttH}$$
$$Y = \gamma\gamma, ZZ, \tau\tau, \ldots$$

[ATLAS-CONF-2013-012]



$\mu({\rm VBF+VH}, \gamma\gamma)$

→ mostly ok (custodial symmetry)

$\mu({\rm ggF+ttH}, \gamma\gamma)$

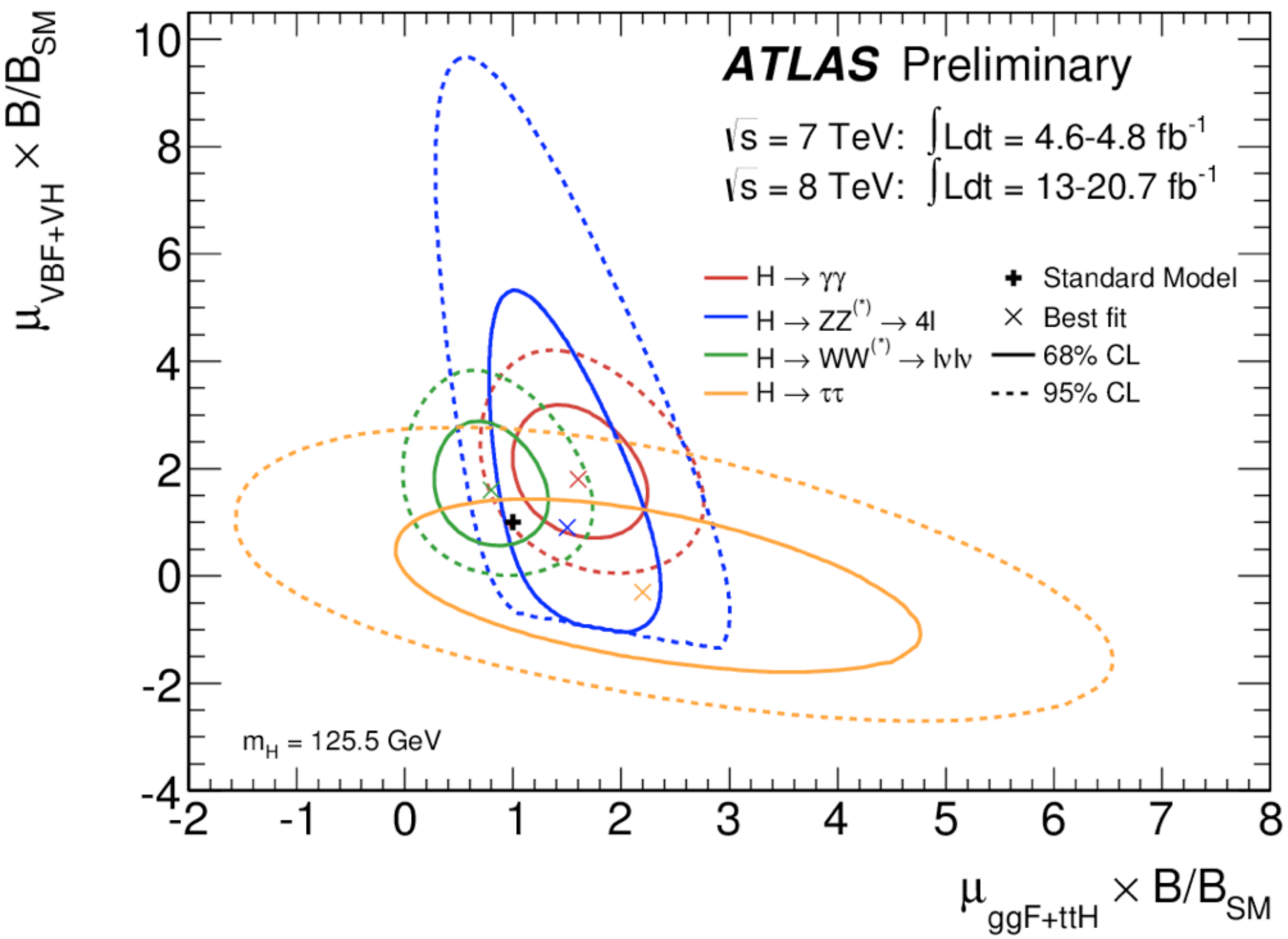
→ ok as long as ttH is poorly probed

- correlations between categories already been taken into account
- no need for efficiencies

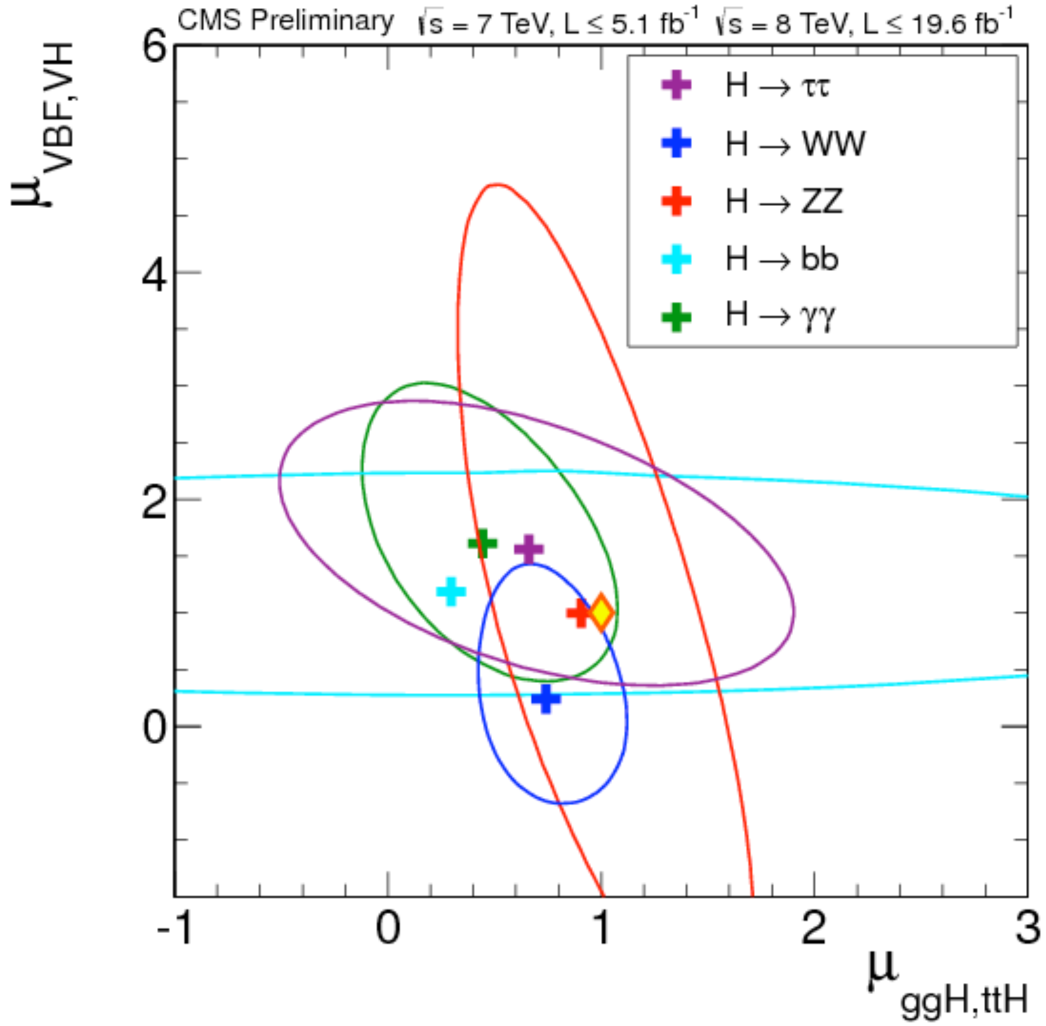
μ(X, Y) from ATLAS and CMS

now exists for all channels!

[ATLAS-CONF-2013-034]



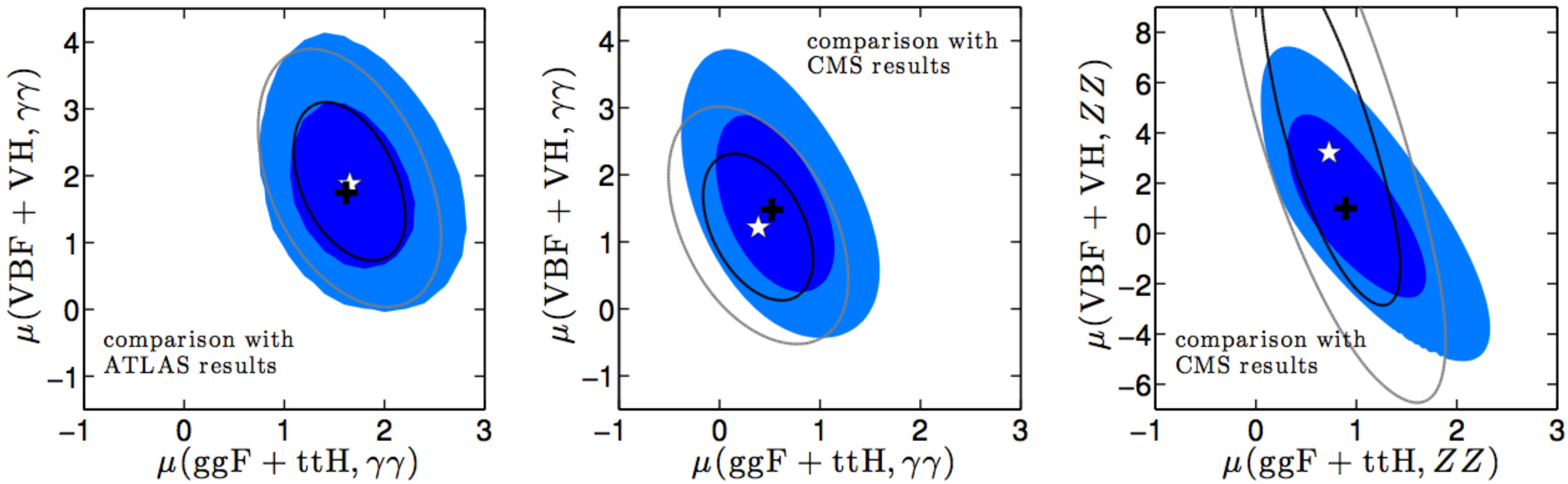
[CMS-PAS-HIG-13-005]



(

reconstructing ($\mu_{ggF+ttH}$, μ_{VBF+VH})

we want to use the ($\mu_{ggF+ttH}$, μ_{VBF+VH}) information directly.
but how well is this reconstructed from the categories?



from "On the presentation of the LHC Higgs Results", [arXiv:1307.5865]

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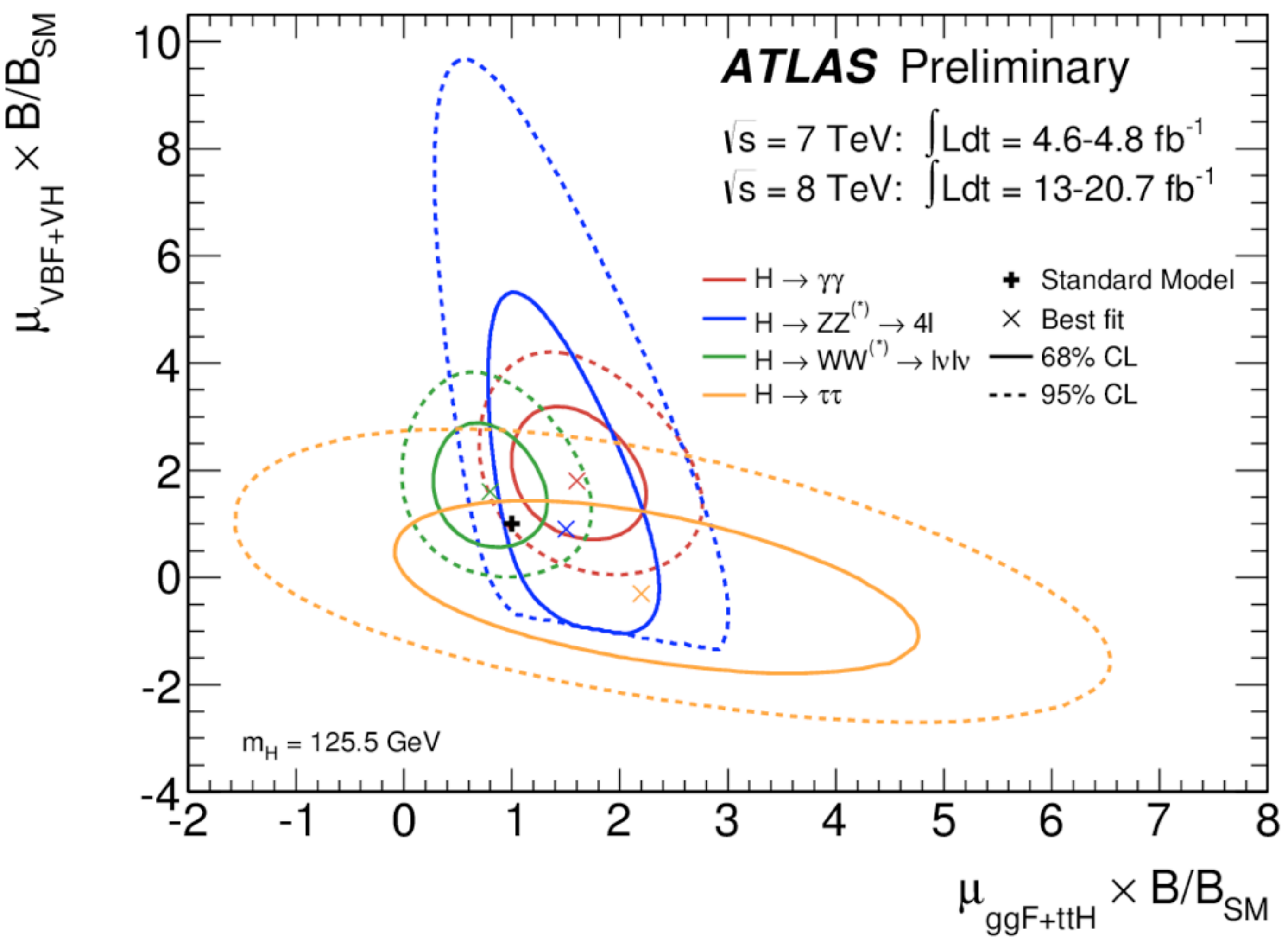
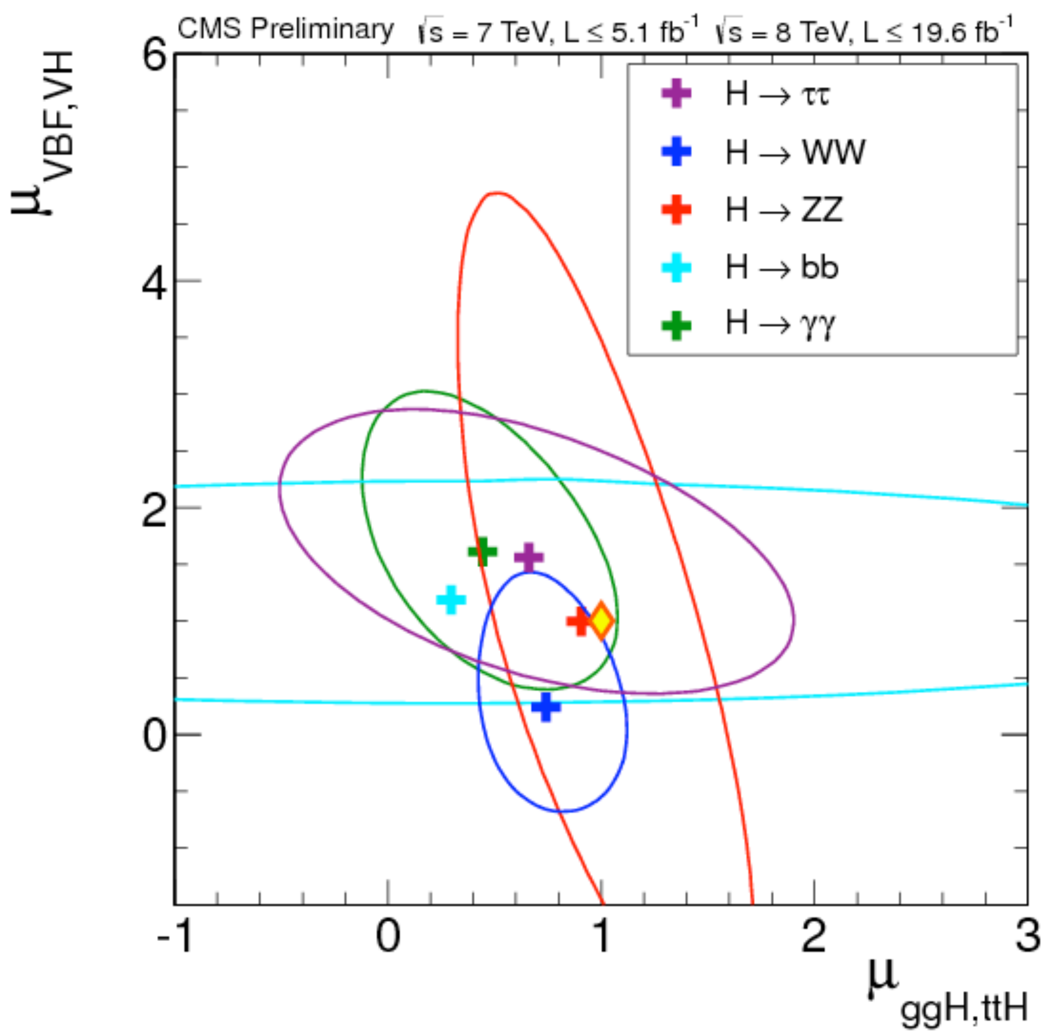
μ(X,Y) from ATLAS and CMS

[ATLAS-CONF-2013-034]



[CMS-PAS-HIG-13-005]



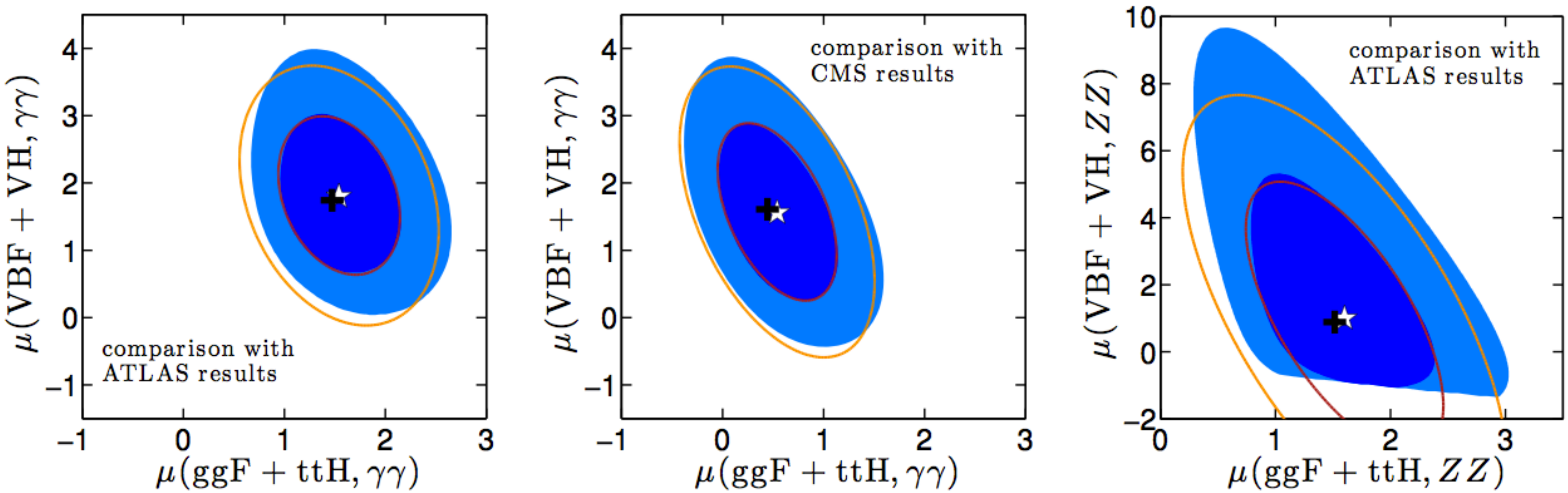
in order to construct a likelihood, one can:

i) fit a 2D Gaussian using the 68% CL contour for each final state

ii) combine the measurements from ATLAS and CMS final state by final state

μ(X,Y) from ATLAS and CMS

from "On the presentation of the LHC Higgs Results", [arXiv:1307.5865]



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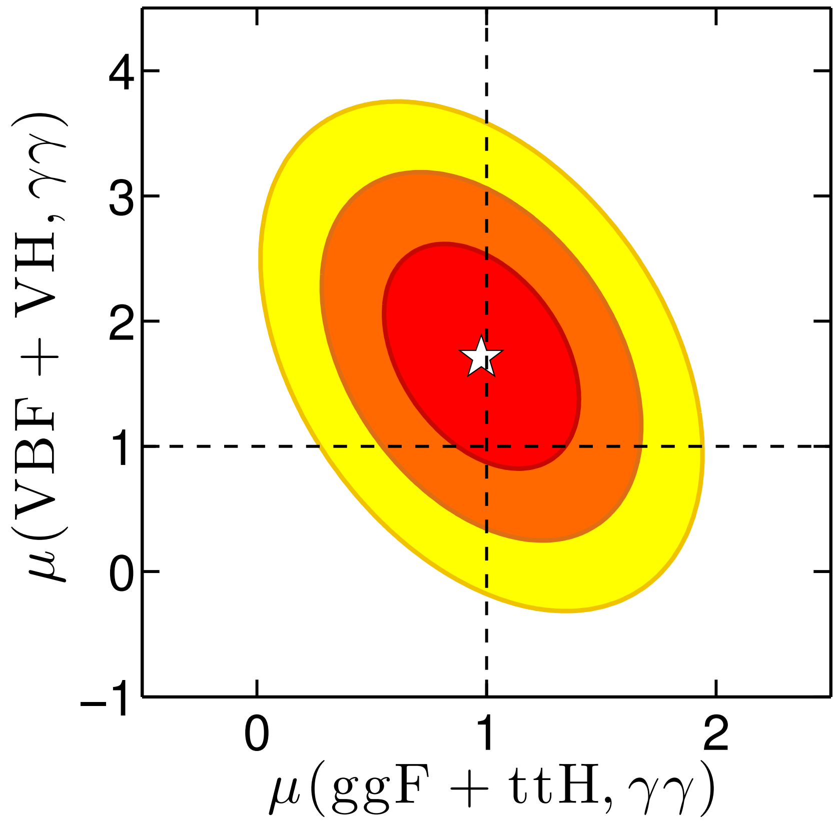
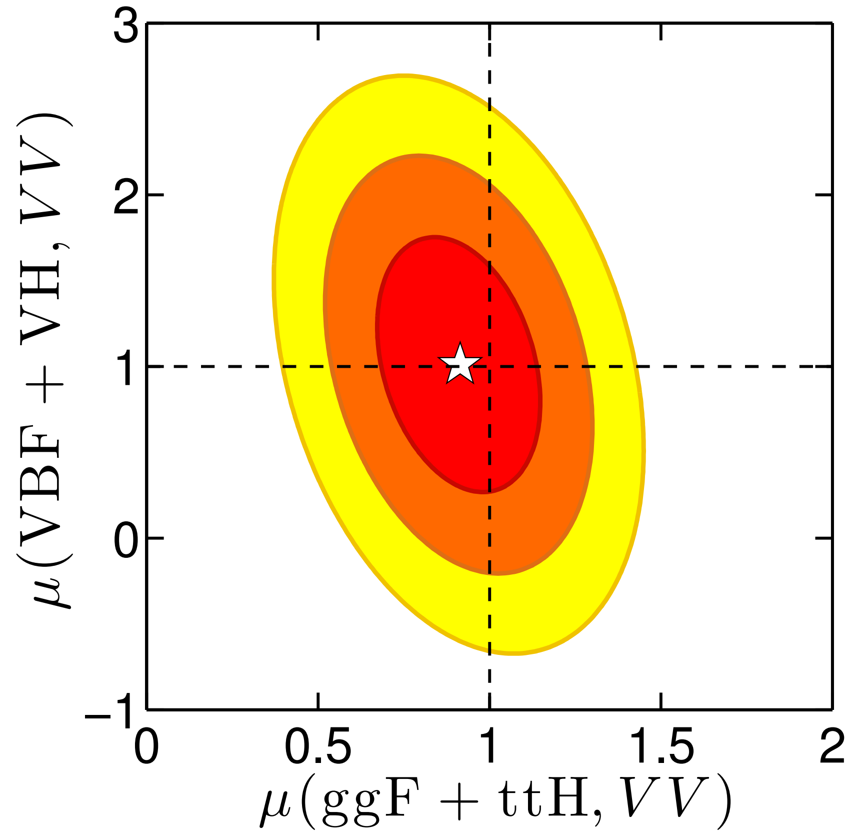
combined 2D μ plots – bosonic

include all results up to the LHCP 2013 conference

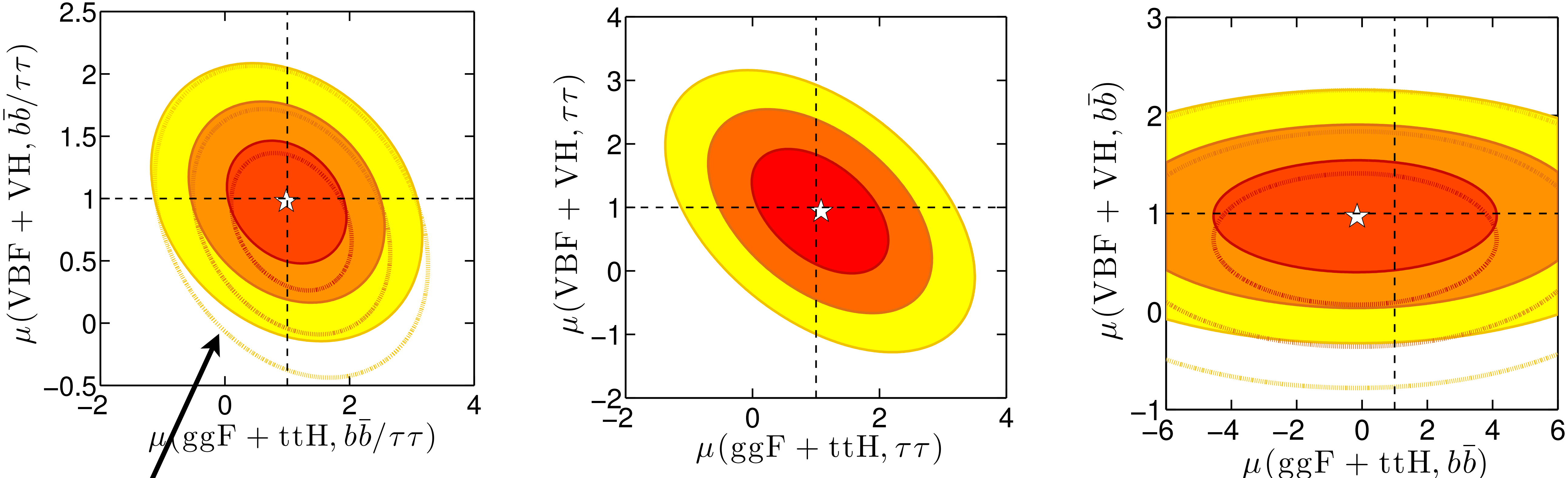




	$\hat{\mu}(\mathrm{ggF}+\mathrm{ttH},Y)$	$\hat{\mu}(\mathrm{VBF}+\mathrm{VH},Y)$	ρ
$\gamma\gamma$	0.98 ± 0.28	1.72 ± 0.59	-0.38
VV	0.91 ± 0.16	1.01 ± 0.49	-0.30

combined 2D μ plots – fermionic

include all results up to the LHCP 2013 conference



without Tevatron

	$\hat{\mu}(\mathrm{ggF}+\mathrm{ttH}, Y)$	$\hat{\mu}(\mathrm{VBF}+\mathrm{VH}, Y)$	ρ
$b\bar{b}/\tau\tau$	0.98 ± 0.63	0.97 ± 0.32	-0.25
$b\bar{b}$	-0.23 ± 2.86	0.97 ± 0.38	0
$\tau\tau$	1.07 ± 0.71	0.94 ± 0.65	-0.47

χ^2 from 2D μ's

equivalently:

$$\chi_i^2 = a_i(\mu_i^{\rm ggF} - \hat{\mu}_i^{\rm ggF})^2 + 2b_i(\mu_i^{\rm ggF} - \hat{\mu}_i^{\rm ggF})(\mu_i^{\rm VBF} - \hat{\mu}_i^{\rm VBF}) + c_i(\mu_i^{\rm VBF} - \hat{\mu}_i^{\rm VBF})^2$$

where $i = \gamma\gamma, VV^{(*)}, b\bar{b}, \tau\tau$ (or $b\bar{b} = \tau\tau$)
and ggF = (ggF+ttH), VBF = (VBF+VH)

	$\hat{\mu}^{\rm ggF}$	$\hat{\mu}^{\rm VBF}$	a	b	c
$\gamma\gamma$	0.98	1.72	14.94	2.69	3.34
VV	0.91	1.01	44.59	4.24	4.58
$b\bar{b}/\tau\tau$	0.98	0.97	2.67	1.31	10.12
$b\bar{b}$	-0.23	0.97	0.12	0	7.06
$\tau\tau$	1.07	0.94	2.55	1.31	3.07

can be used to constrain a broad class of New Physics models!

coupling fits

- We first need to specify a Lagrangian. Our choice:

$$\mathcal{L} = g\left[C_V\left(M_W W_\mu W^\mu + \frac{M_Z}{\cos\theta_W} Z_\mu Z^\mu\right) - C_U \frac{m_t}{2M_W}\bar{t}t - C_D \frac{m_b}{2M_W}\bar{b}b - C_D \frac{m_\tau}{2M_W}\bar{\tau}\tau\right] H$$

Scaling factors C parametrize deviations from the SM ($C_U=C_D=C_V=1$ is the SM)

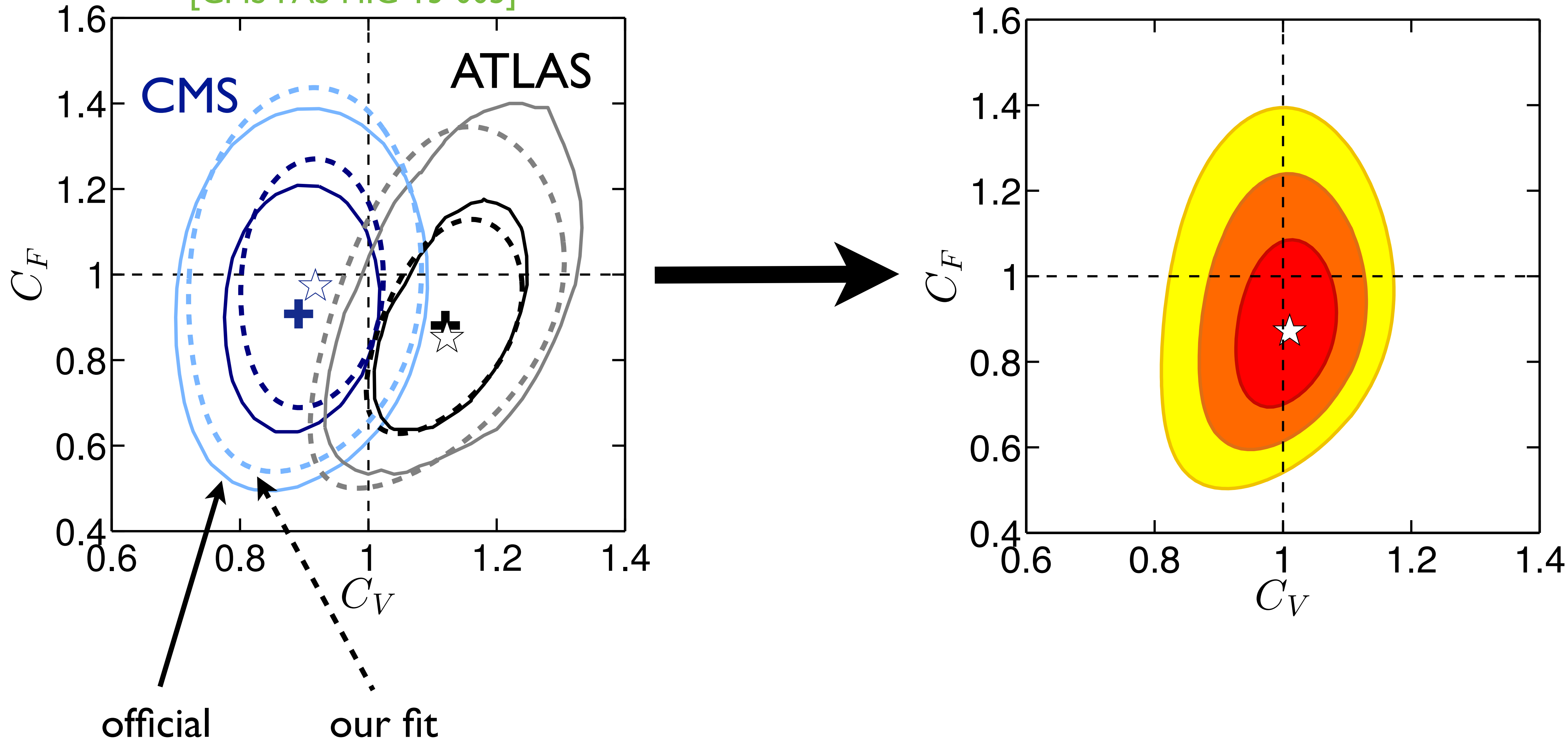
- We compute $\overline{C_g}$ (for gluon-gluon fusion) and $\overline{C_\gamma}$ (for $H\rightarrow\gamma\gamma$) from C_U, C_D, C_V and we allow for additional particles in the loop: ΔC_g and ΔC_γ
$\rightarrow$ $C_g = \overline{C_g} + \Delta C_g$ and $C_\gamma = \overline{C_\gamma} + \Delta C_\gamma$

- Total Higgs width: not accessible at the LHC. We consider two cases:
i) only SM Higgs decay modes are open
ii) new decay modes are invisible at the LHC (would be seen as MET)
  (...possibly dark matter!)

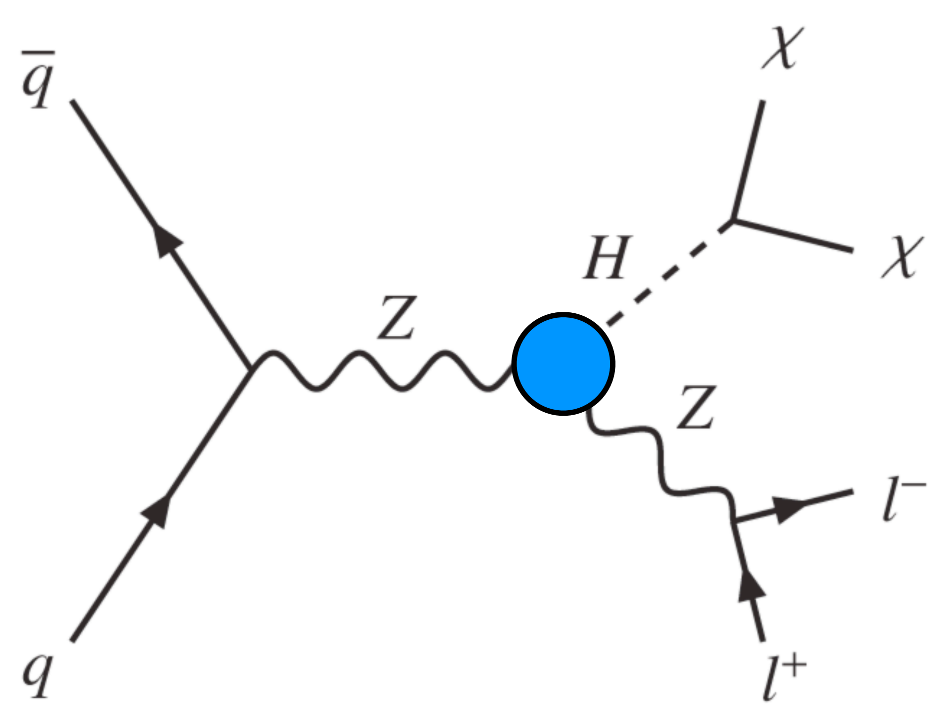
validation with ATLAS and CMS

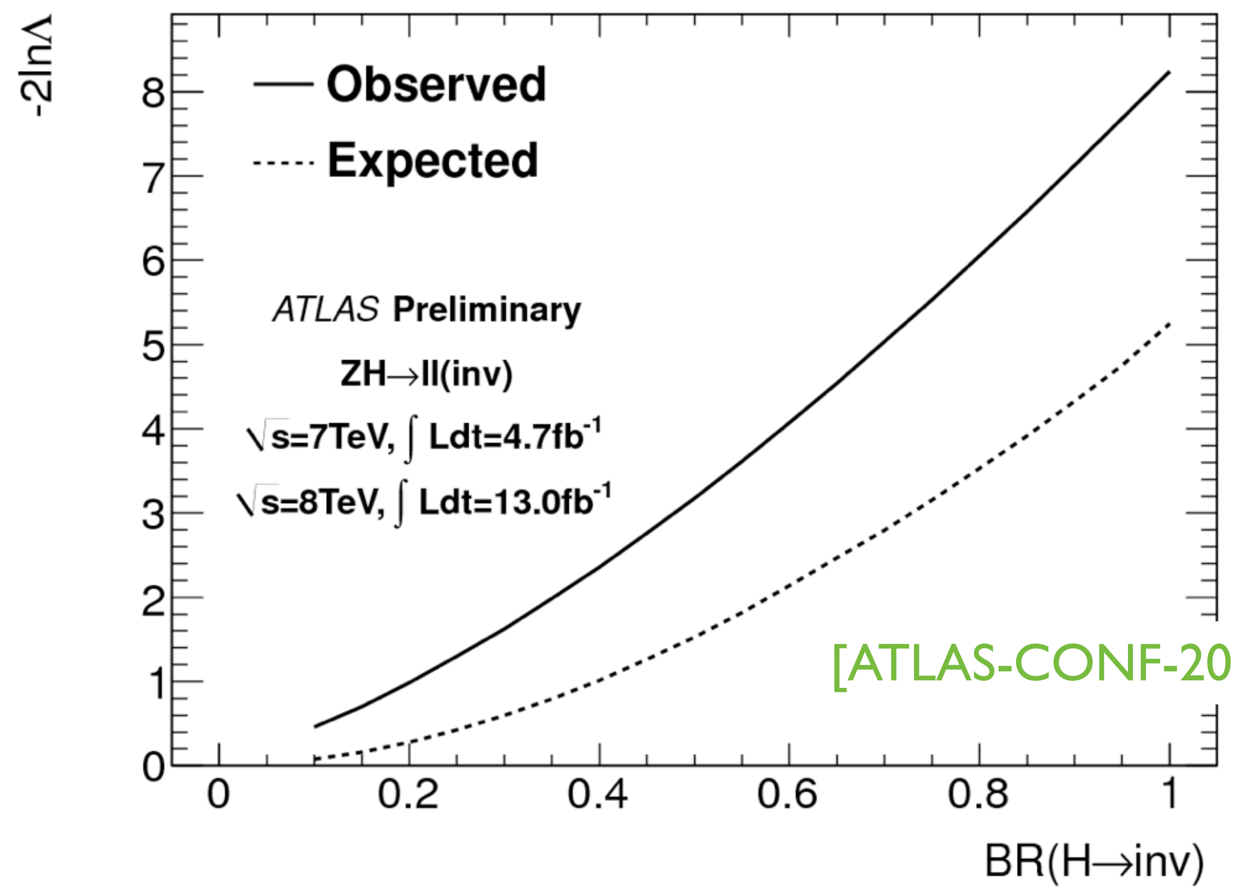
validation with benchmark scenarios of the ATLAS and CMS couplings fits

[ATLAS-CONF-2013-034]
[CMS-PAS-HIG-13-005]



invisible decays of the Higgs boson





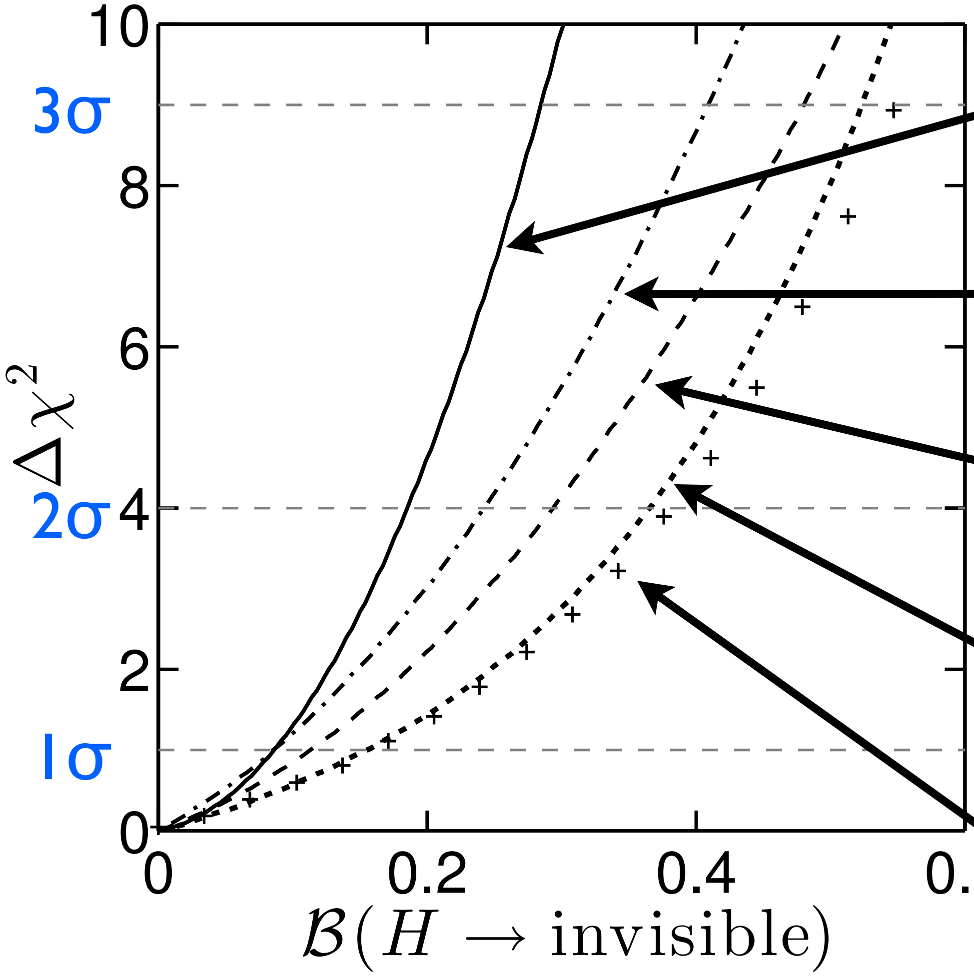
[ATLAS-CONF-2013-011]

$$C_V^2 \mathcal{B}(H \to \text{inv.}) < 0.65 \text{ at } 95\% \text{ CL}$$

see also CMS limit on ZH→ll+invisible [HIG-13-018]
and on VBF→invisible [HIG-13-013]

invisible decays of the Higgs boson

[arXiv:1302.5694, arXiv:1306.2941]



SM+invisible
$\mathcal{B}(H \to \text{inv.}) < 0.19$ at 95% CL

SM+C_U+C_D+($C_V \leq 1$)+invisible
$\mathcal{B}(H \to \text{inv.}) < 0.24$ at 95% CL

SM+ΔC_g+ΔC_γ+invisible
$\mathcal{B}(H \to \text{inv.}) < 0.29$ at 95% CL

SM+C_U+C_D+C_V+invisible
$\mathcal{B}(H \to \text{inv.}) < 0.36$ at 95% CL

SM+C_U+C_D+C_V+ΔC_g+ΔC_γ+invisible
$\mathcal{B}(H \to \text{inv.}) < 0.38$ at 95% CL

mainly from global μ fit

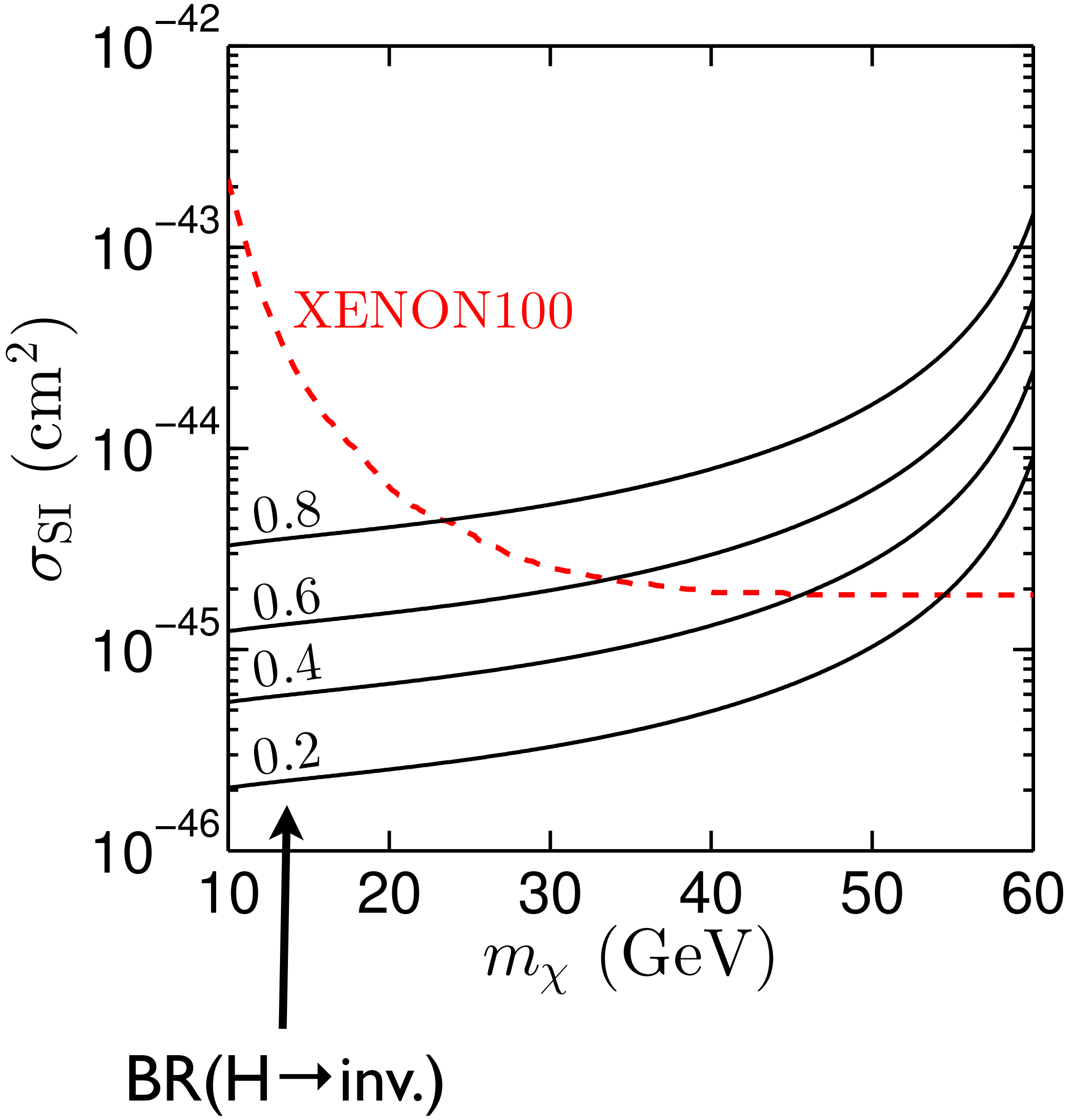
mainly from searches for invisible

invisible decays & dark matter

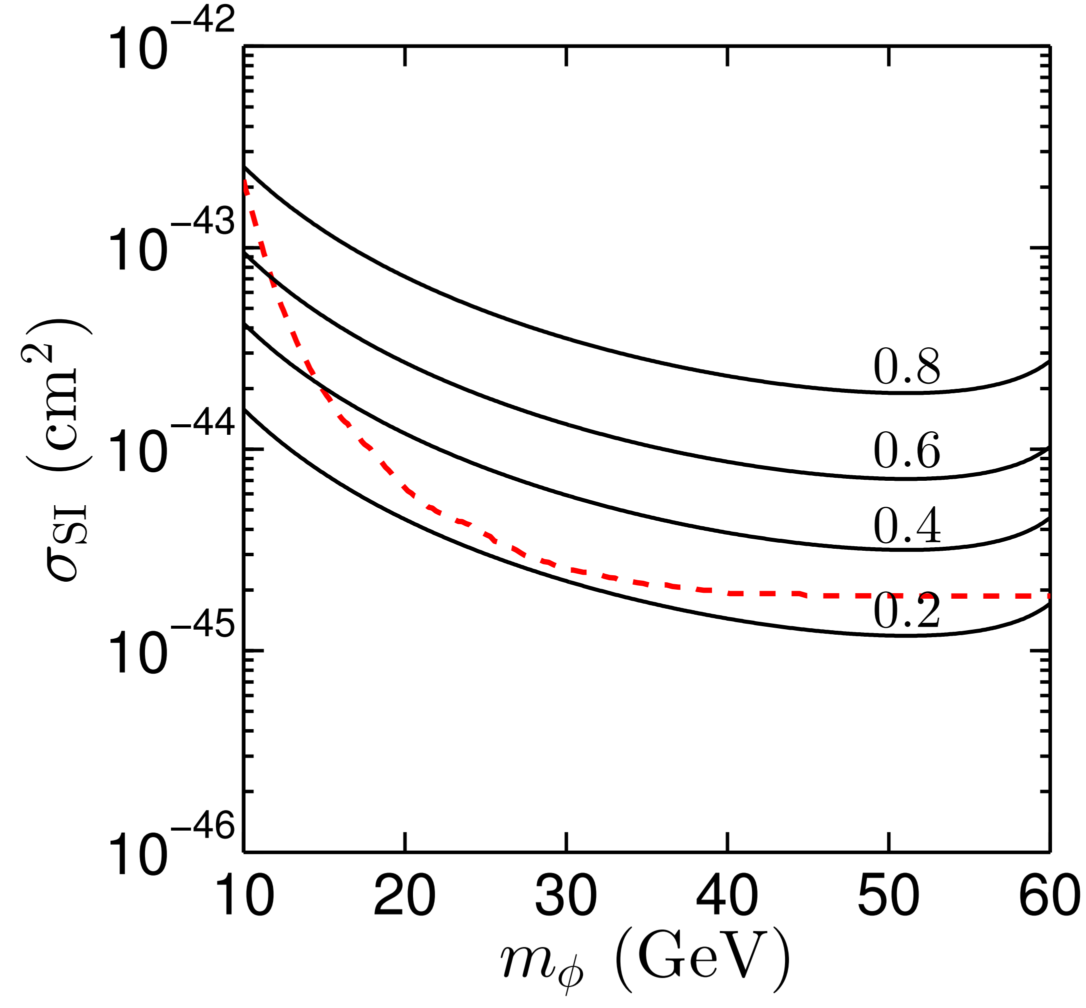
if invisible = dark matter interacting via Higgs:
interplay between direct searches and H→invisible

[arXiv:1302.5694]

Majorana dark matter

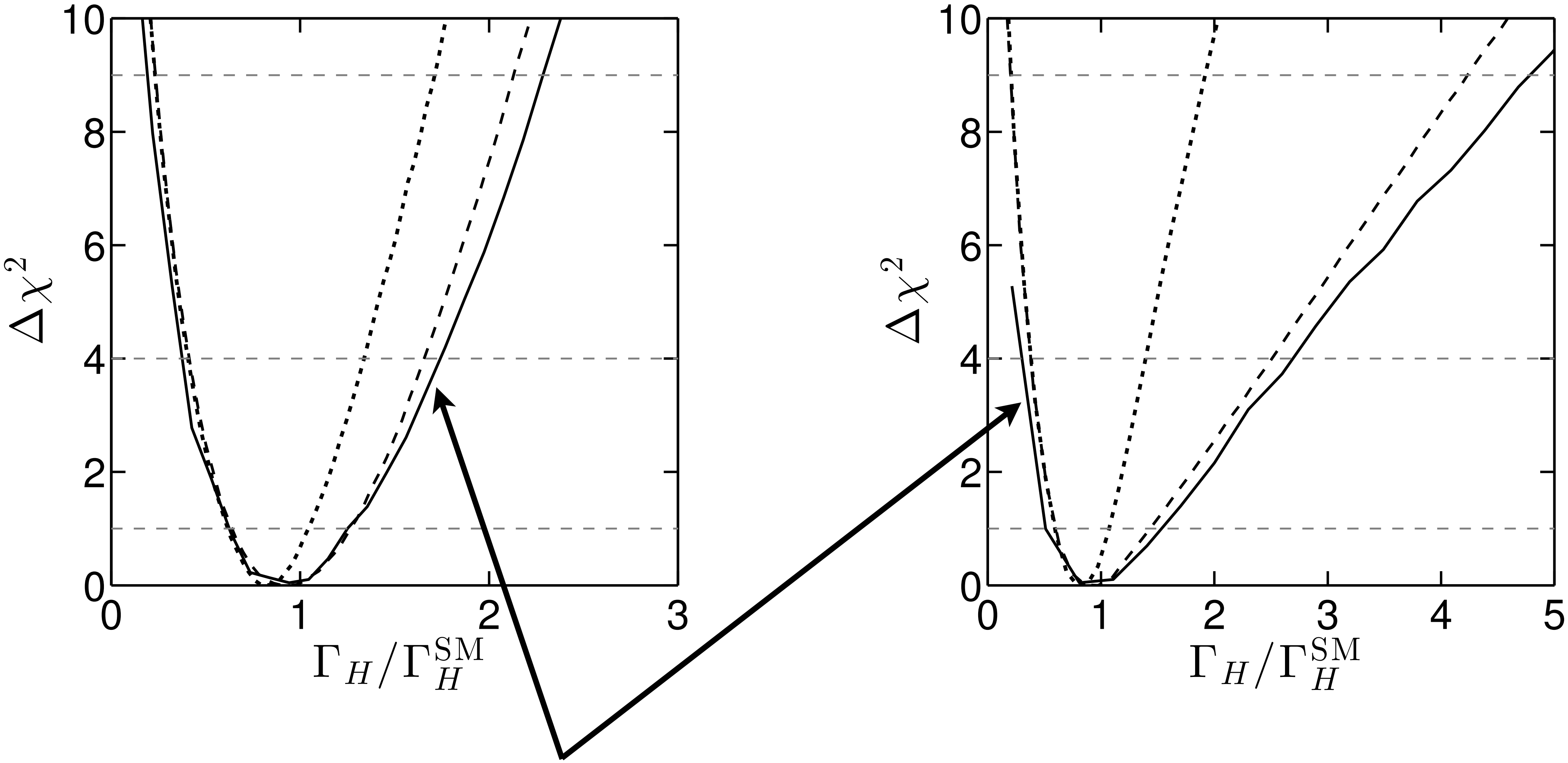


scalar dark matter



total Higgs decay width

without invisible decays | allowing for invisible decays



$SM+C_U+C_D+C_V+\Delta C_g+\Delta C_\gamma$(+invisible)

$$\Gamma_H \in [0.4, 1.7-2.7] \times \Gamma_H^{\rm SM} \text{ at } 95\% \text{ CL}$$

Inert Doublet Model

new Higgs doublet, odd under a Z_2 symmetry ($\rightarrow$ no coupling to pairs of SM particles)

$$\begin{aligned} V &= \mu_1^2|H_1|^2 + \mu_2^2|\tilde{H}_2|^2 + \lambda_1|H_1|^4 + \lambda_2|\tilde{H}_2|^4 + \lambda_3|H_1|^2|\tilde{H}_2|^2 \\ &\quad + \lambda_4|H_1^\dagger \tilde{H}_2|^2 + \frac{\lambda_5}{2}\left[\left(H_1^\dagger \tilde{H}_2\right)^2 + \text{h.c.}\right] \end{aligned}$$

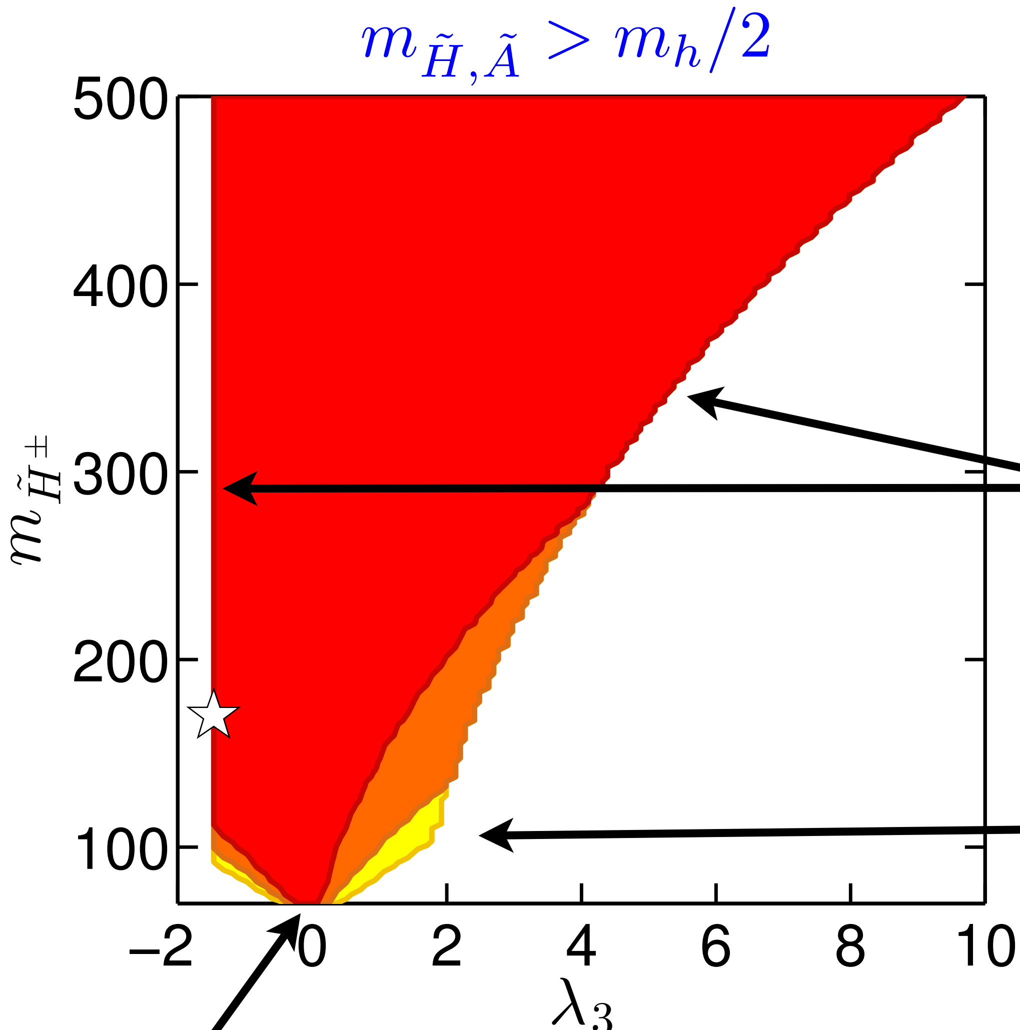
4 new particles: $\tilde{H}$ (scalar) $\tilde{A}$ (pseudoscalar) $\tilde{H}^\pm$

dark matter candidate

only modification to the Higgs couplings: charged Higgs contribution to $h\rightarrow\gamma\gamma$

Inert Doublet Model: w/out inv.

$$V = \mu_1^2|H_1|^2 + \mu_2^2|\tilde{H}_2|^2 + \lambda_1|H_1|^4 + \lambda_2|\tilde{H}_2|^4 + \lambda_3|H_1|^2|\tilde{H}_2|^2 + \lambda_4|H_1^\dagger \tilde{H}_2|^2 + \frac{\lambda_5}{2}\left[\left(H_1^\dagger \tilde{H}_2\right)^2 + \text{h.c.}\right]$$



$g_{h\tilde{H}^+\tilde{H}^-} \propto -\lambda_3$

vacuum stability + perturbative unitarity

$$\mu_2^2 = m_{\tilde{H}^\pm}^2 - \frac{1}{2}\lambda_3 v^2$$

where Higgs measurements matter

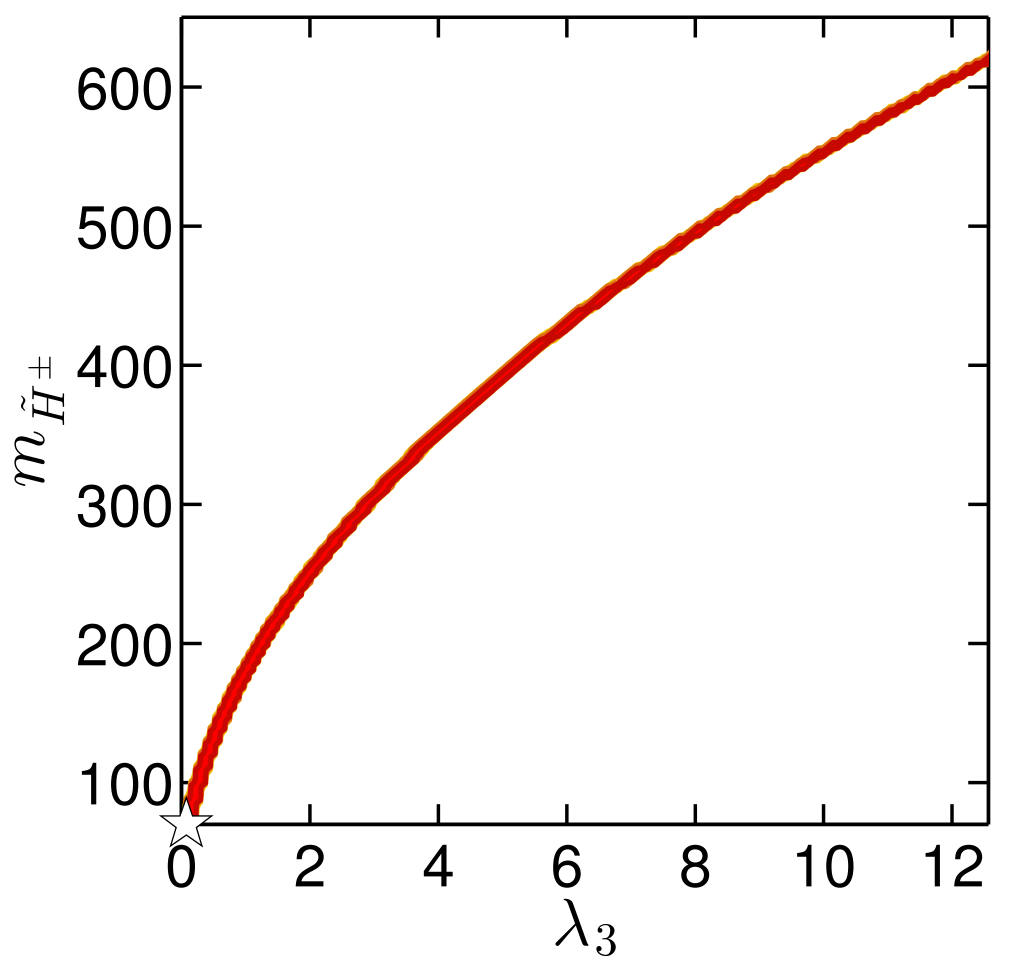
$m_{\tilde{H}^\pm} \gtrsim$

Inert Doublet Model: with inv.

$$V = \mu_1^2|H_1|^2 + \mu_2^2|\tilde{H}_2|^2 + \lambda_1|H_1|^4 + \lambda_2|\tilde{H}_2|^4 + \lambda_3|H_1|^2|\tilde{H}_2|^2 + \lambda_4|H_1^\dagger\tilde{H}_2|^2 + \frac{\lambda_5}{2}\left[\left(H_1^\dagger\tilde{H}_2\right)^2 + \text{h.c.}\right]$$

$m_{\tilde{H}} < m_h/2, m_{\tilde{A}} > m_h/2$

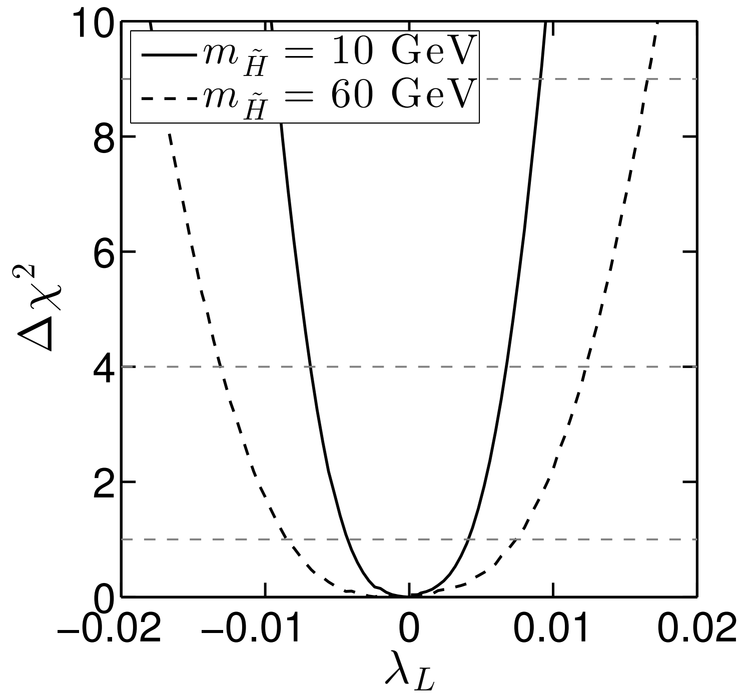
profiled over $m_{\tilde{H}} \in [1, 60]$ GeV

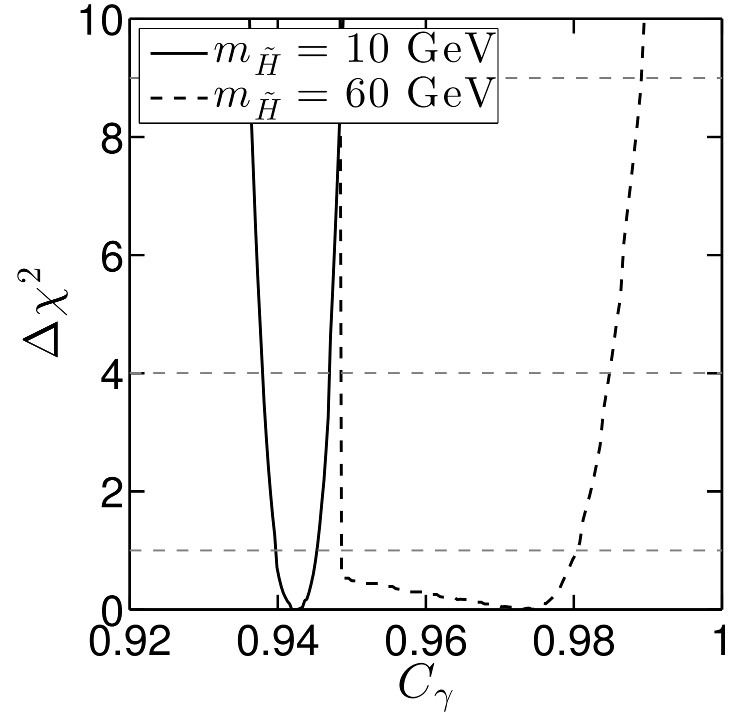


$$g_{h\tilde{H}\tilde{H}} \propto \lambda_L = \frac{1}{2}(\lambda_3 + \lambda_4 + \lambda_5)$$

$$\frac{\lambda_3}{2} = \frac{1}{v^2}\left(m^2_{\tilde{H}^+} - m^2_{\tilde{H}}\right) + \lambda_L \quad \to C_\gamma \lesssim 1$$

≈0





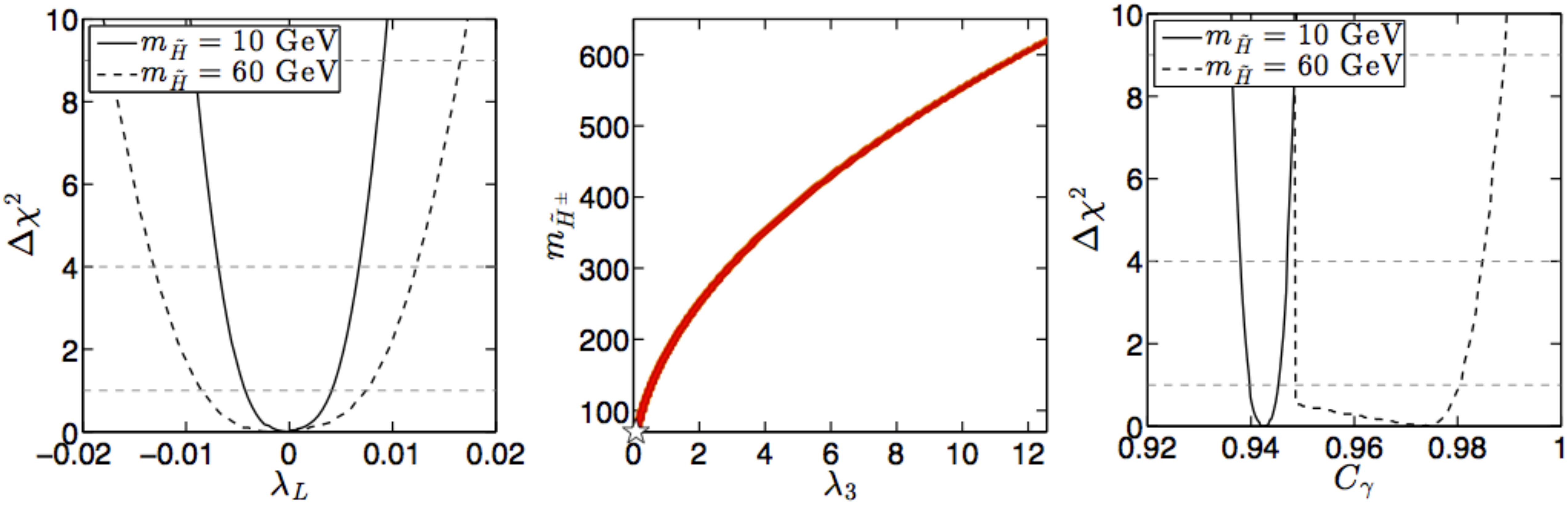
conclusion

• 2D μ’s: powerful and simple way to test a very wide class of models of New Physics against Higgs measurements

• even if the observed Higgs is SM-like, lots of implications for New Physics scenarios are still to be explored

Backup slides

Inert Doublet Model: with inv.



bonus

[arXiv:1307.1427]

On the presentation of the LHC Higgs Results

Conclusions and suggestions from the workshops "Likelihoods for the LHC Searches", 21–23 January 2013 at CERN, "Implications of the 125 GeV Higgs Boson", 18–22 March 2013 at LPSC Grenoble, and from the 2013 Les Houches "Physics at TeV Colliders" workshop.

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bonus

[arXiv:1307.1427]

ory beyond the SM. It is therefore of utmost importance that the Higgs results be usable by the whole high-energy-physics community. To this end, we put forth the following suggestions regarding the presentation of the Higgs results:

- For each Higgs decay mode Y ($\gamma\gamma$, WW, ZZ, $b\bar{b}$, $\tau\tau$ are currently considered) provide the likelihood $\mathcal{L}$ of the signal strengths in the $(\mu(X,Y), \mu(X',Y))$ plane, as shown in Figure 3. The grouping $X = \mathrm{ggF} + \mathrm{ttH}$, $X' = \mathrm{VBF} + \mathrm{VH}$ is well motivated, but additional choices of X and X' should be considered when appropriate for the given analysis. The content of the plots should *always* be provided also in numerical form, *e.g.*, as a `ROOT` file or as a simple text file with a grid. In addition to the combined results, results should also be given separately for each $\sqrt{s}$.
- To go a step further and overcome the limitations induced by 2D projections and/or combining production modes, provide the signal strength likelihood as a function of m_H, separated into all five production modes ggF, ttH, VBF, ZH and WH; *i.e.* for each decay mode considered give the likelihood in the 6D form $\mathcal{L}(m_H, \mu_{\mathrm{ggF}}, \mu_{\mathrm{ttH}}, \mu_{\mathrm{VBF}}, \mu_{\mathrm{ZH}}, \mu_{\mathrm{WH}})$. Ideally, this should again also be done separately for each $\sqrt{s}$.
- Concerning searches for additional Higgs-like states with masses above or below 125 GeV, provide the results including the injection of a signal with the properties of a SM-like Higgs boson at 125–126 GeV. Moreover, always present the results as bounds on pure $(\sigma \times \mathcal{B})$ in addition to any model interpretation.

bonus

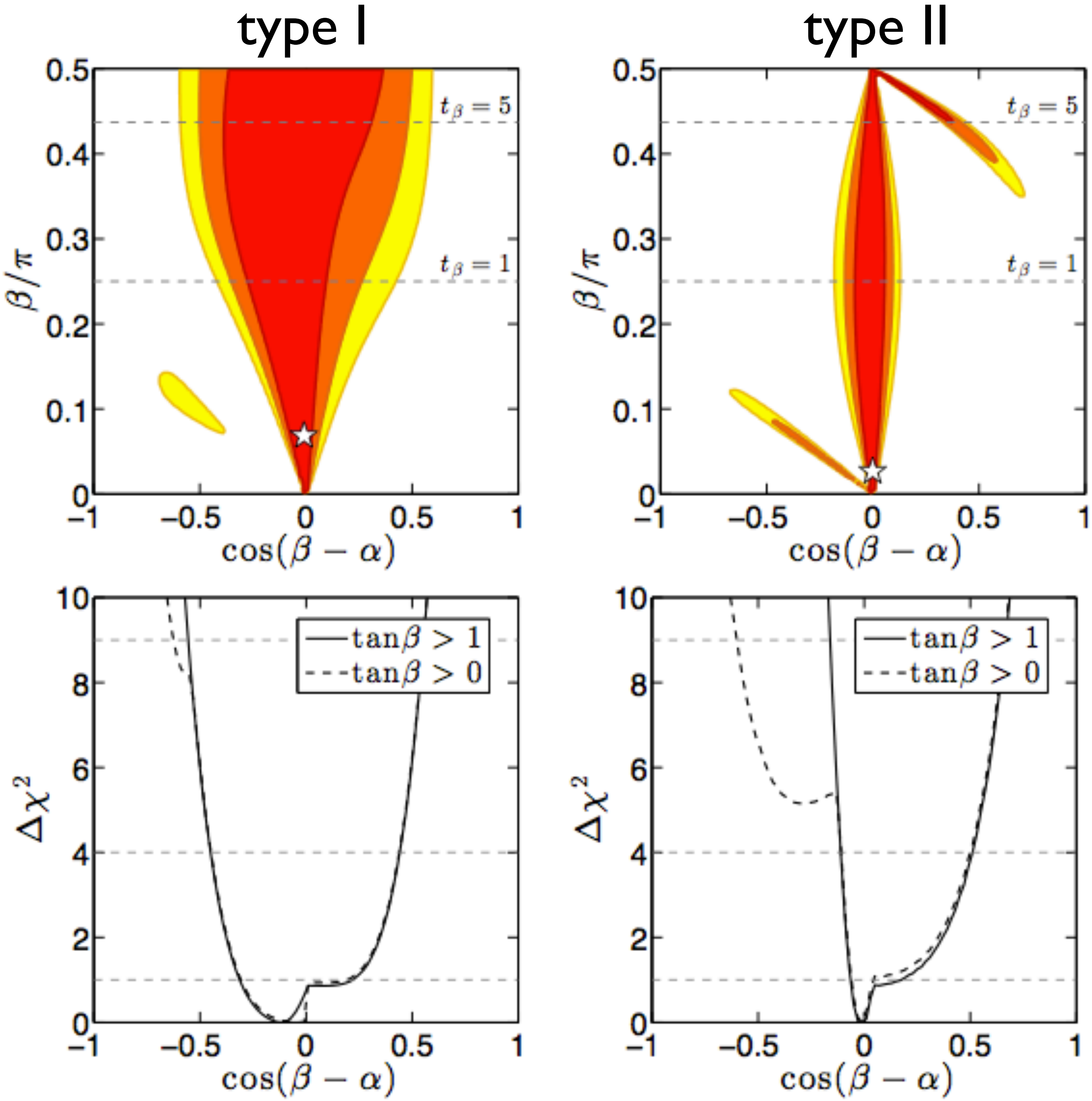
[arXiv:1307.1427]

- Whenever possible, provide kinematic event selection criteria that can approximately be reproduced by phenomenologists, *e.g.*, using Monte Carlo event generators.[2] The desired information is: the complete cut flow, estimated number of background events, expected event yields for all the SM Higgs processes, and the observed number of signal events or limits thereon. For MVA-based analyses, it would be of great value if a simplified version of the final MVA could be given.
- In addition to direct model-dependent interpretations of data, the long-term goal should be to develop a consistent scheme for publishing fiducial cross sections ($\sigma^{\rm fid} \times \mathcal{B}$), either measurements or limits for null search results, as done conventionally for SM processes.
- We suggest that this supplementary material is made available via INSPIRE [50]. This way the complete set of information will be searchable, citable, and accessible from a single point.

2HDM

	Type I and II	Type I		Type II	
Higgs	VV	up quarks	down quarks & leptons	up quarks	down quarks & leptons
h	$\sin(\beta-\alpha)$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
H	$\cos(\beta-\alpha)$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$
A	0	$\cot\beta$	$-\cot\beta$	$\cot\beta$	$\tan\beta$

2HDM



type I
type II
$t_\beta = 5$
$t_\beta = 1$
β/π
$\cos(\beta-\alpha)$
$\Delta\chi^2$
$\tan\beta > 1$
$\tan\beta > 0$