Fitting Higgs couplings in an EFT approach

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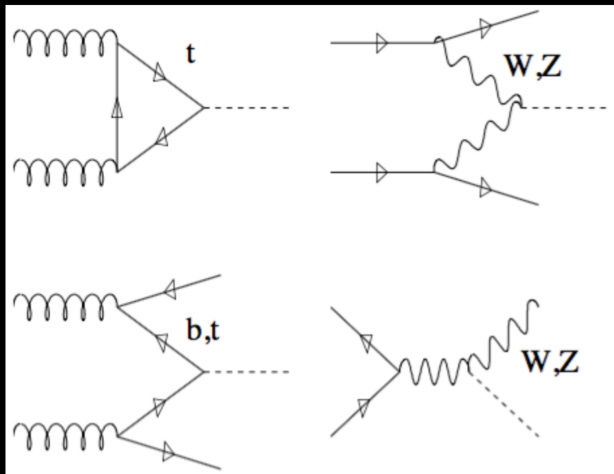
HEFT-2015

Goal: comprehensive analysis of couplings of the Higgs

- assume a narrow CP-even scalar
- use SFitter to fit available LHC data:
  [SFitter: Gonzalez-Fraile, Klute, Plehn, Rauch, Zerwas]

	production/decay mode	ATLAS	CMS
	$H \to WW$	X	X
	$H \to ZZ$	X	X
	$H \to \gamma\gamma$	X	X
	$H \to \tau\bar{\tau}$	X	X
	$H \to b\bar{b}$	X	X
	$H \to Z\gamma$	X	X
	$H \to$ invisible	X	X
[159]	$t\bar{t}H$ production	X	X
[14]	kinematic distributions	X	
[37]	off-shell rate	X	X

- frequentist likelihood everywhere
- SFitter is flexible to study theoretical uncertainties
  [flat distribution ; uncorrelated uncertainties for production]



1.How well does the SM describe the Higgs data?

[Corbett, OE, Gonçalves, Gonzalez-Fraile, Plehn, Rauch: arXiv:1505.05516]

- assume SM operators with free couplings: [nonlinear sigma model: Alonso et al.; Buchalla et al.; Brivio et al,…]

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \Delta_W \; g m_W H \; W^\mu W_\mu + \Delta_Z \; \frac{g}{2c_w} m_Z H \; Z^\mu Z_\mu - \sum_{\tau,b,t} \Delta_f \; \frac{m_f}{v} H \left(\bar{f}_R f_L + {\rm h.c.} \right)$$
$$+ \Delta_g F_G \; \frac{H}{v} \; G_{\mu\nu} G^{\mu\nu} + \Delta_\gamma F_A \; \frac{H}{v} \; A_{\mu\nu} A^{\mu\nu} + \text{invisible decays}$$

corresponding changes in the Higgs couplings:

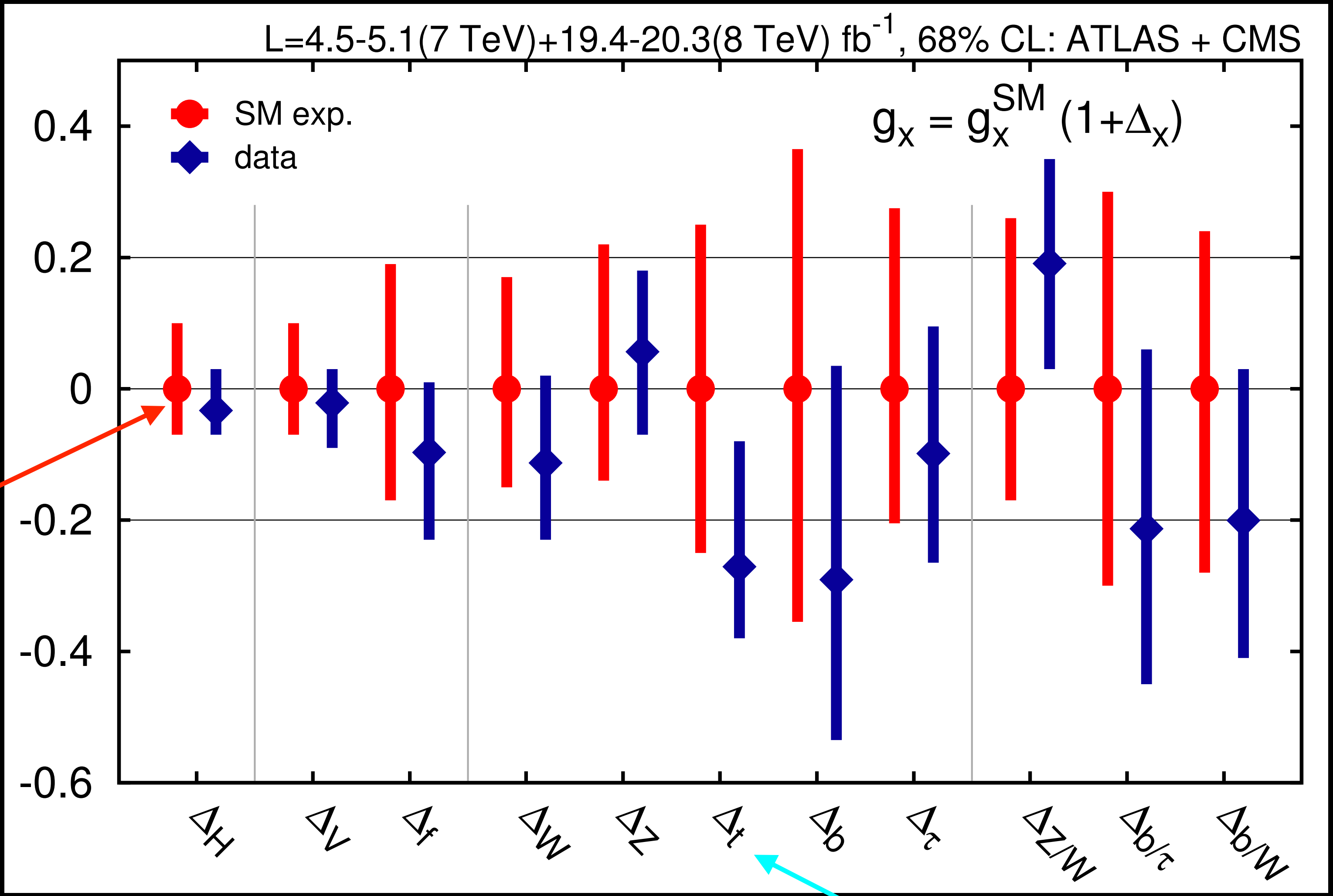
$$g_x = g_x^{\rm SM} \; (1 + \Delta_x)$$
$$g_\gamma = g_\gamma^{\rm SM} \; (1 + \Delta_\gamma^{\rm SM} + \Delta_\gamma) \equiv g_\gamma^{\rm SM} \; (1 + \Delta_\gamma^{\rm SM+NP})$$
$$g_g = g_g^{\rm SM} \; (1 + \Delta_g^{\rm SM} + \Delta_g) \equiv g_g^{\rm SM} \; (1 + \Delta_g^{\rm SM+NP})$$

tree level　　new physics

[keeping values for finite loop masses in calculations]

- $\Delta_x = -2$ flips the sign of the SM couplings
- only rate measurements (of course!)

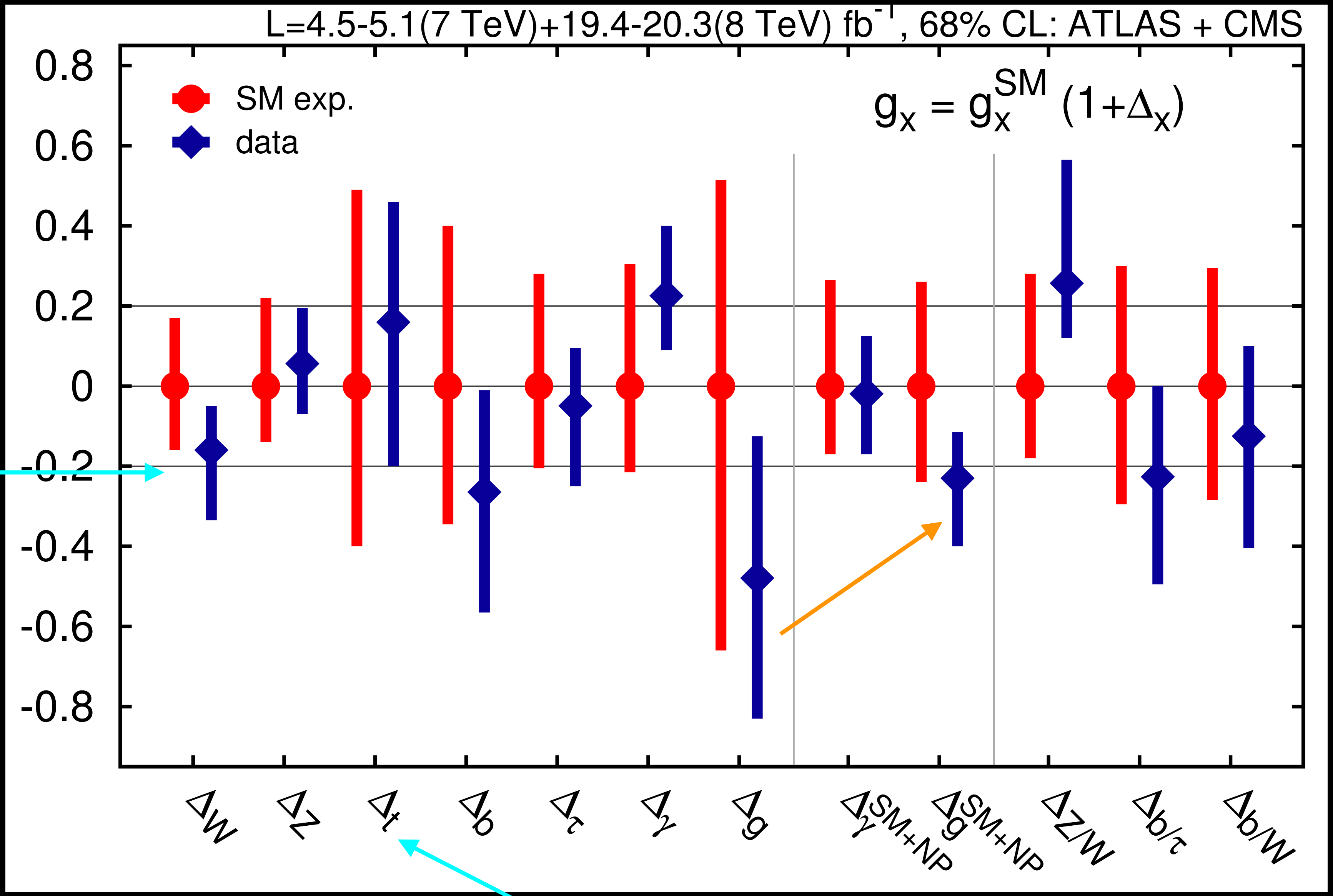
- presenting the SM like solutions with $\Delta_g = \Delta_\gamma = 0$
- slowly increasing the number of free parameters
- Δ_H equal tree level deviations



injected SM Higgs signal

controls hgg coupling (expected 15% error)

- adding new loop contributions Δ_g Δ_γ (7 parameter fit)

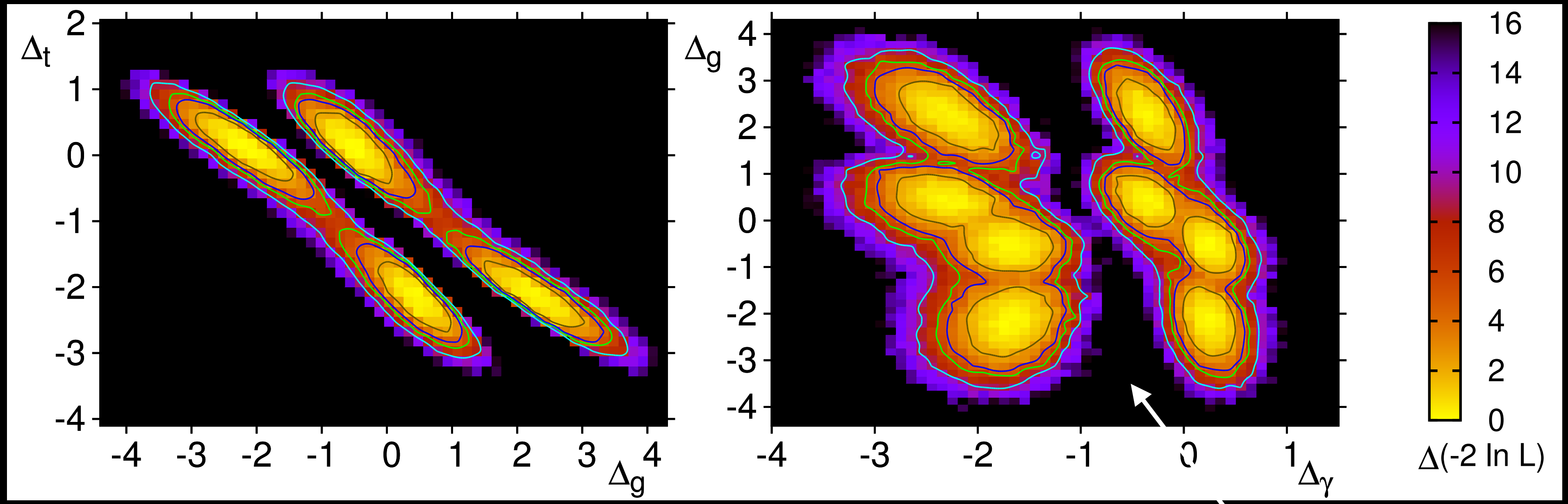


slightly decrease

effect of ttH (expected 30% error)

- analogously $\Delta_{\gamma Z} < 0.7$ (1.8) at 68% (95%) CL

- multiple solutions due to degeneracy $\Delta_x = 0 \Longleftrightarrow \Delta_x = -2$
- Δ_t and Δ_g contribute to gluon fusion production

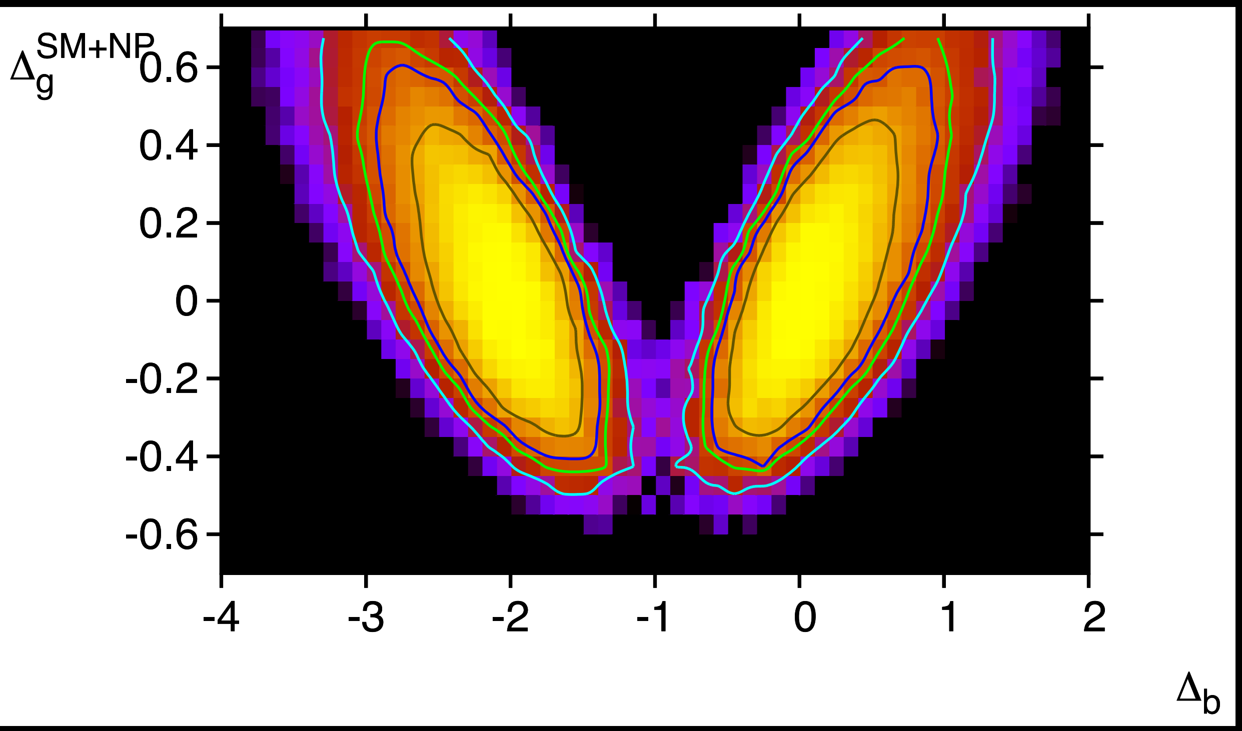


Δ_t plays indirect role

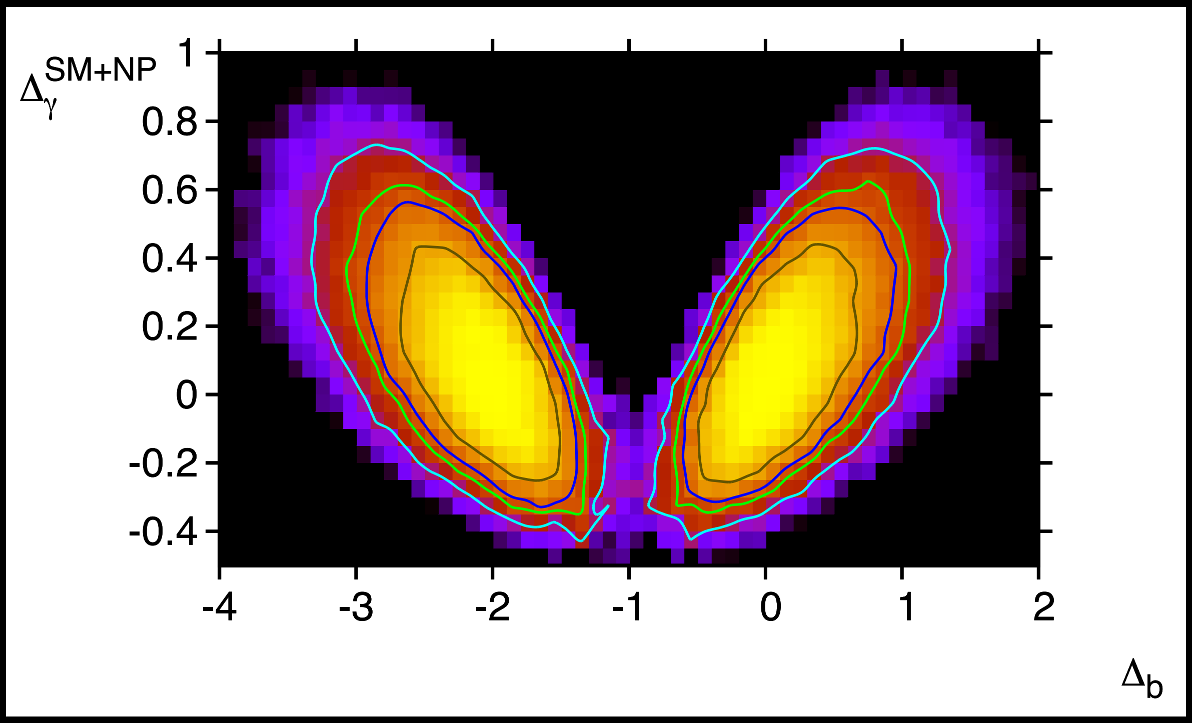
7 parameter fit

$\Delta_W > -1$

- further interesting correlations due to $\sigma(pp \to h \to \gamma\gamma)$



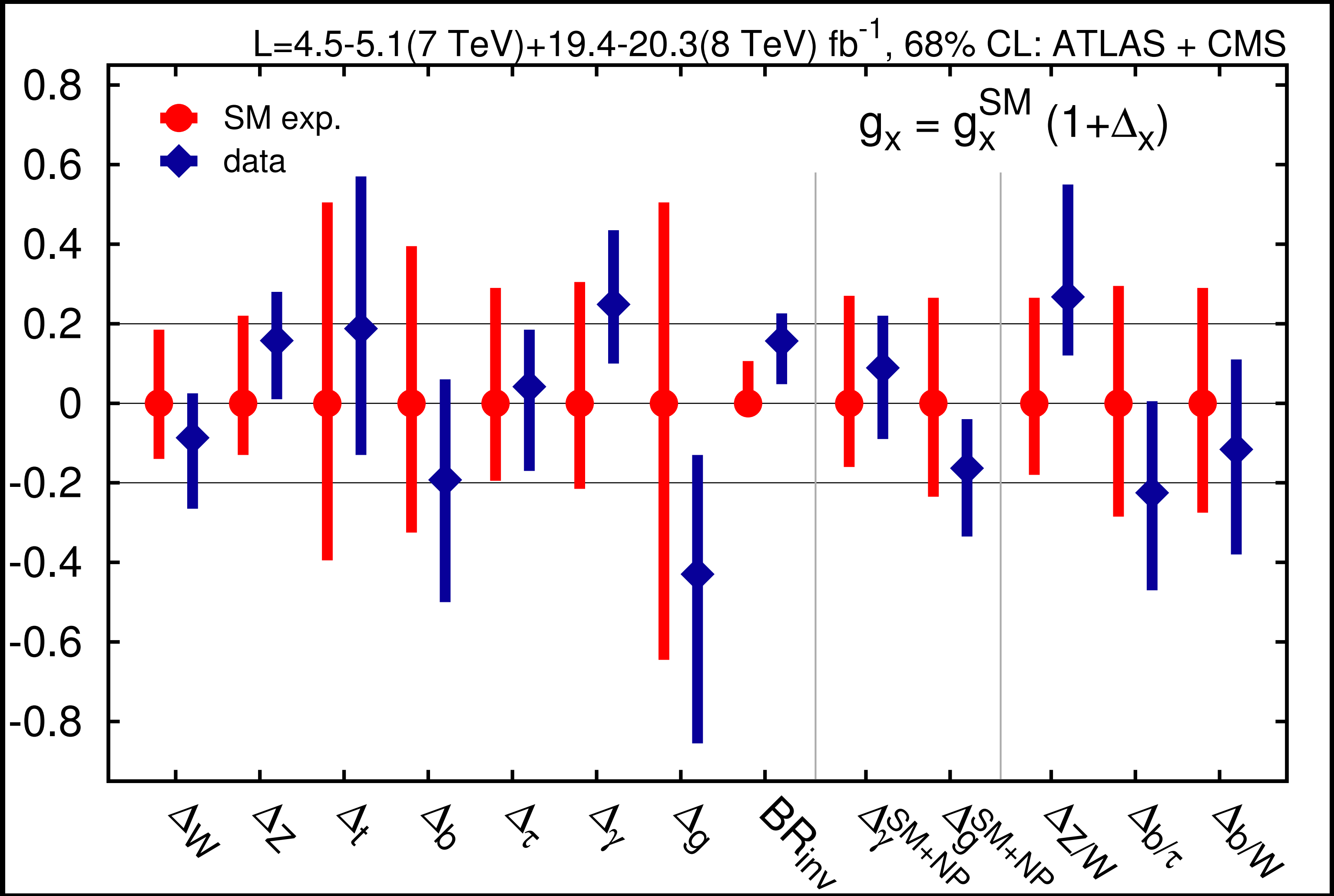
Δ_t and Δ_g



$\Delta_t \quad \Delta_W \quad \text{and} \quad \Delta_\gamma$

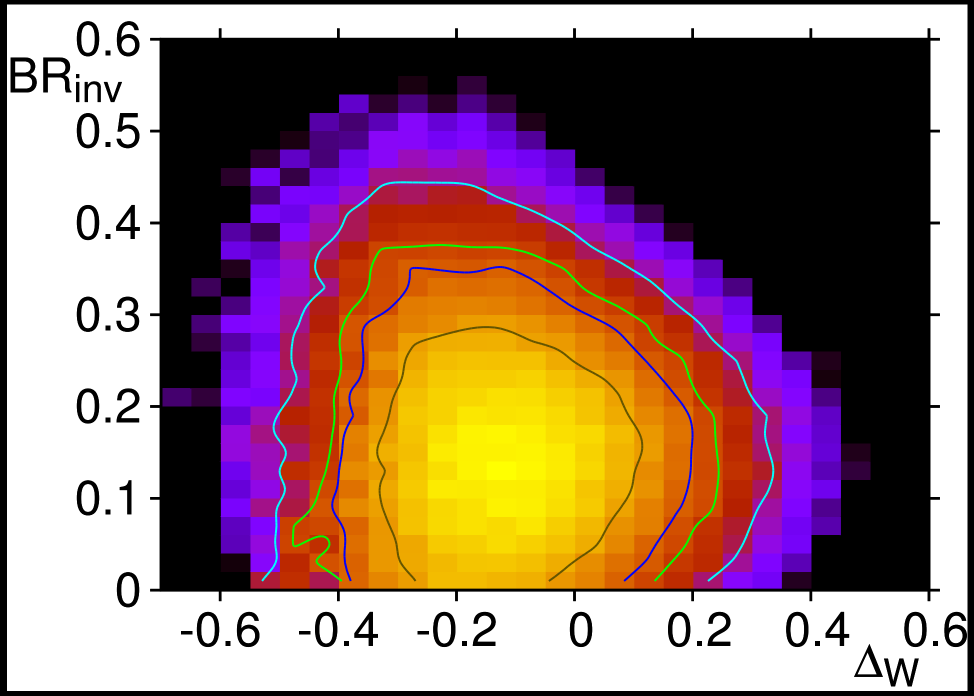
$$\sigma^{\text{on-shell}}_{i \to H \to f} \propto \frac{g_i^2(m_H)\, g_f^2(m_H)}{\Gamma_H}$$

- adding invisible decays (8 parameter fit)



$\mathrm{BR}_{\mathrm{inv}} < 0.31$ at 95% CL

no correlation with $\Delta_{W,Z}$

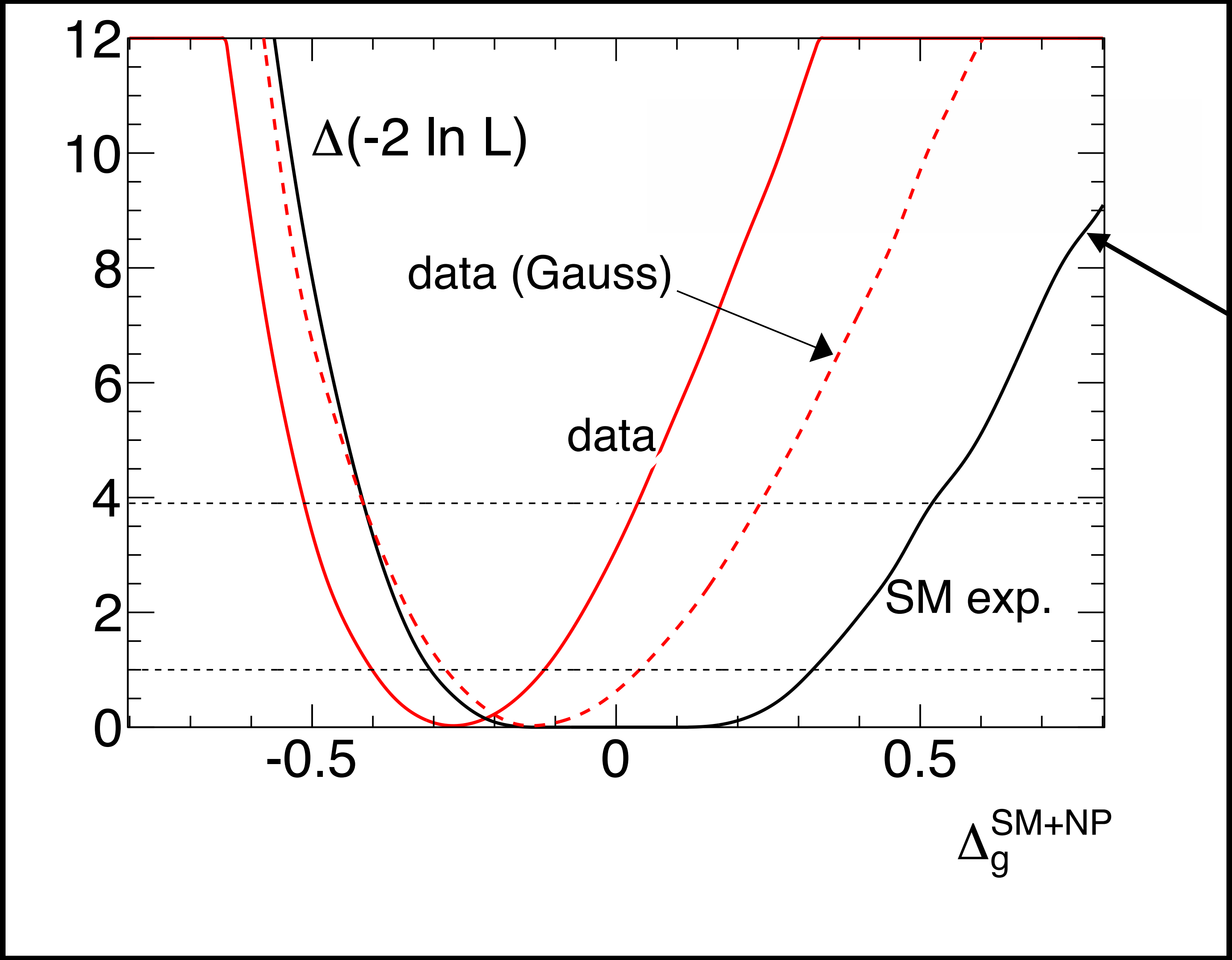


$$\sigma^{\text{on-shell}}_{i\to H\to f} \propto \frac{g_i^2(m_H)\, g_f^2(m_H)}{\Gamma_H}$$

- minor upward shift of all couplings due to correlation with total width
- there is no significant deviations from the SM predictions

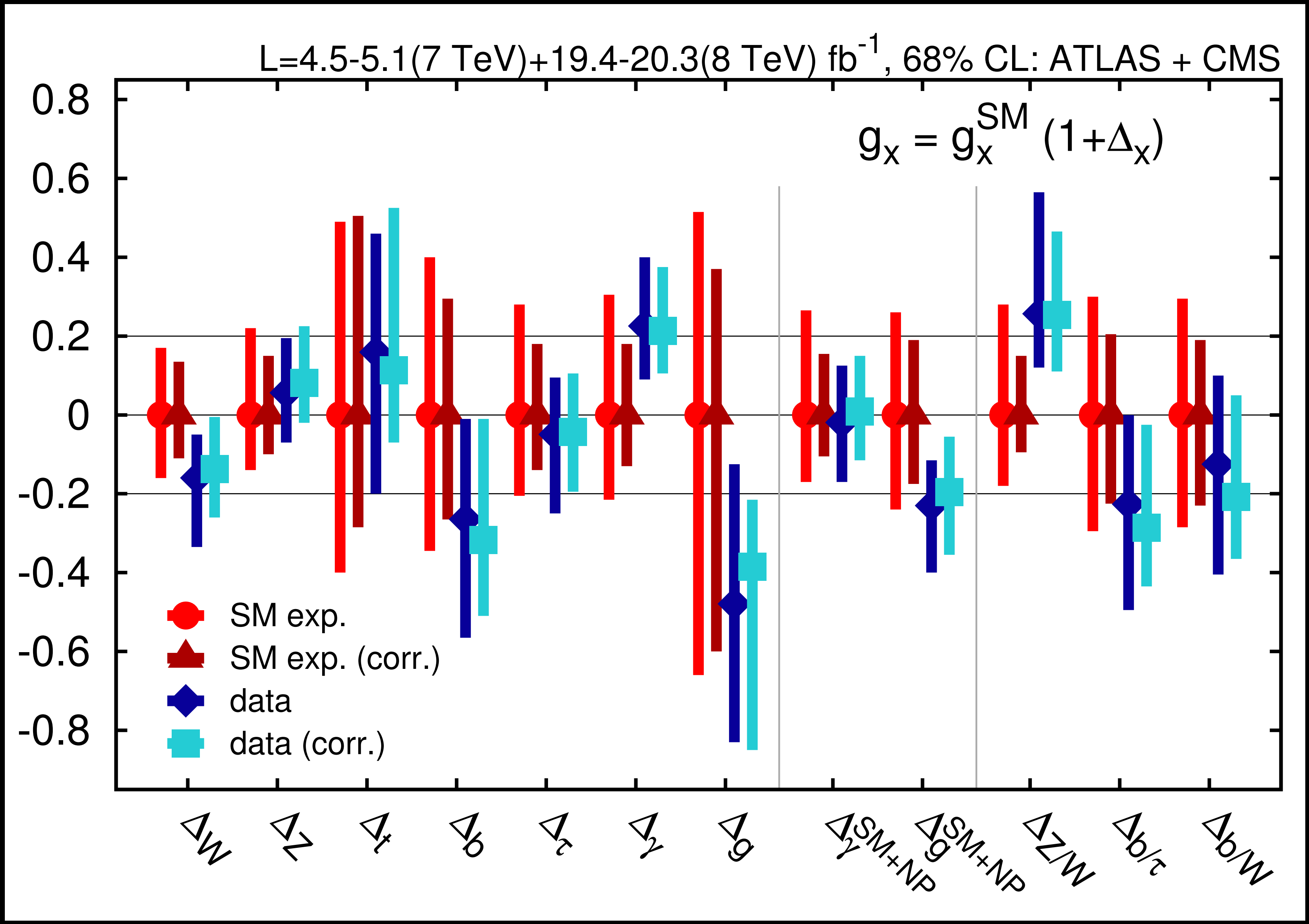
details of the theoretical uncertainty treatment

- flat vs gaussian distributions for the theoretical uncertainties



- presently statistical errors dominate
- gaussian distributions lead to slightly larger 68% CL bands

- correlated vs uncorrelated uncertainties (7 parameter fit):



- correlated uncertainties lead to slightly smaller errors

2. Linear effective lagrangians to describe the LHC data?

- new state belongs to SU(2) doublet
- consider SU(2) x U(1) invariant dimension-6 lagrangian

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \sum_n \frac{f_n}{\Lambda^2}\mathcal{O}_n + \cdots$$

- There are 59 "independent" dimension-six operators [Buchmuller & Wyler; Grzadkowski]
- our choice for the boson operators is [Corbett, OE, Gonzalez-Fraile, Gonzalez-Garcia]

[Hagiwara, Ishihara, Szalapski, Zeppenfeld]

$$\mathcal{O}_{GG} = \Phi^\dagger\Phi\, G^a_{\mu\nu}G^{a\mu\nu} \qquad \mathcal{O}_{WW} = \Phi^\dagger\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\Phi \qquad \mathcal{O}_{BB} = \Phi^\dagger\hat{B}_{\mu\nu}\hat{B}^{\mu\nu}\Phi$$

$$\mathcal{O}_{BW} = \Phi^\dagger\hat{B}_{\mu\nu}\hat{W}^{\mu\nu}\Phi \qquad \mathcal{O}_{W} = (D_\mu\Phi)^\dagger\hat{W}^{\mu\nu}(D_\nu\Phi) \qquad \mathcal{O}_{B} = (D_\mu\Phi)^\dagger\hat{B}^{\mu\nu}(D_\nu\Phi)$$

$$\mathcal{O}_{\Phi,1} = (D_\mu\Phi)^\dagger\,\Phi\;\Phi^\dagger\,(D^\mu\Phi) \qquad \mathcal{O}_{\Phi,2} = \frac{1}{2}\partial^\mu\left(\Phi^\dagger\Phi\right)\partial_\mu\left(\Phi^\dagger\Phi\right) \qquad \mathcal{O}_{\Phi,4} = (D_\mu\Phi)^\dagger\,(D^\mu\Phi)\left(\Phi^\dagger\Phi\right)$$

with $$D_\mu\Phi = \left(\partial_\mu + ig'B_\mu/2 + ig\sigma_a W^a_\mu/2\right)\Phi \qquad \hat{W}_{\mu\nu} = ig\sigma^a W^a_{\mu\nu}/2$$

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eliminated with EOM

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constrained by EWPD

eliminated with EOM

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constrained by EWPD

eliminated with EOM

$$\mathcal{L}_{\rm eff}^{HVV} = -\frac{\alpha_s}{8\pi}\frac{f_{GG}}{\Lambda^2}\mathcal{O}_{GG} + \frac{f_{BB}}{\Lambda^2}\mathcal{O}_{BB} + \frac{f_{WW}}{\Lambda^2}\mathcal{O}_{WW} + \frac{f_B}{\Lambda^2}\mathcal{O}_B + \frac{f_W}{\Lambda^2}\mathcal{O}_W + \frac{f_{\Phi,2}}{\Lambda^2}\mathcal{O}_{\Phi,2}$$

- 10 effective HVV couplings are generated

$$
\begin{aligned}
\mathcal{L}^{HVV} &= g_{Hgg}\; H G^{a}_{\mu\nu} G^{a\mu\nu} + g_{H\gamma\gamma}\; H A_{\mu\nu} A^{\mu\nu} + g^{(1)}_{HZ\gamma}\; A_{\mu\nu} Z^{\mu} \partial^{\nu} H + g^{(2)}_{HZ\gamma}\; H A_{\mu\nu} Z^{\mu\nu} \\
&+ g^{(1)}_{HZZ}\; Z_{\mu\nu} Z^{\mu} \partial^{\nu} H + g^{(2)}_{HZZ}\; H Z_{\mu\nu} Z^{\mu\nu} + g^{(3)}_{HZZ}\; H Z_{\mu} Z^{\mu} \\
&+ g^{(1)}_{HWW}\; \left(W^{+}_{\mu\nu} W^{-\,\mu} \partial^{\nu} H + \text{h.c.} \right) + g^{(2)}_{HWW}\; H W^{+}_{\mu\nu} W^{-\,\mu\nu} + g^{(3)}_{HWW}\; H W^{+}_{\mu} W^{-\,\mu}
\end{aligned}
$$

that depend on 6 Wilson coefficients

$$g_{Hgg} = -\frac{\alpha_s}{8\pi} \frac{f_{GG} v}{\Lambda^2}$$

$$g_{H\gamma\gamma} = -\frac{g^2 v s_w^2}{2\Lambda^2}\; \frac{f_{BB} + f_{WW}}{2}$$

$$g^{(1)}_{HZZ} = \frac{g^2 v}{2\Lambda^2}\; \frac{c_w^2 f_W + s_w^2 f_B}{2 c_w^2}$$

$$g^{(2)}_{HZZ} = -\frac{g^2 v}{2\Lambda^2}\; \frac{s_w^4 f_{BB} + c_w^4 f_{WW}}{2 c_w^2}$$

$$g^{(3)}_{HZZ} = m_Z^2 (\sqrt{2} G_F)^{1/2} \left(1 - \frac{v^2}{2\Lambda^2} f_{\Phi,2} \right)$$

$$g^{(1)}_{HZ\gamma} = \frac{g^2 v}{2\Lambda^2}\; \frac{s_w (f_W - f_B)}{2 c_w}$$

$$g^{(2)}_{HZ\gamma} = \frac{g^2 v}{2\Lambda^2}\; \frac{s_w (2 s_w^2 f_{BB} - 2 c_w^2 f_{WW})}{2 c_w}$$

$$g^{(1)}_{HWW} = \frac{g^2 v}{2\Lambda^2}\; \frac{f_W}{2}$$

$$g^{(2)}_{HWW} = -\frac{g^2 v}{2\Lambda^2}\; f_{WW}$$

$$g^{(3)}_{HWW} = m_W^2 (\sqrt{2} G_F)^{1/2} \left(1 - \frac{v^2}{2\Lambda^2} f_{\Phi,2} \right)$$

- Summarizing

coefficients related by gauge invariance

potential correlations

	Hgg	$H\gamma\gamma$	$H\gamma Z$	HZZ	HW^+W^-	γW^+W^-	ZW^+W^-
$\mathcal{O}_{GG}$	$\surd$						
$\mathcal{O}_{BB}$		$\surd$	$\surd$	$\surd$			
$\mathcal{O}_{WW}$		$\surd$	$\surd$	$\surd$	$\surd$		
$\mathcal{O}_{B}$			$\surd$	$\surd$		$\surd$	$\surd$
$\mathcal{O}_{W}$			$\surd$	$\surd$	$\surd$	$\surd$	$\surd$
$\mathcal{O}_{\Phi,2}$				$\surd$	$\surd$		

- we should also include fermionic operators for the third generation

$$\mathcal{O}_{e\Phi,33} = (\Phi^\dagger\Phi)(\bar{L}_3\Phi e_{R,3}) \qquad \mathcal{O}_{u\Phi,33} = (\Phi^\dagger\Phi)(\bar{Q}_3\tilde{\Phi} u_{R,3}) \qquad \mathcal{O}_{d\Phi,33} = (\Phi^\dagger\Phi)(\bar{Q}_3\Phi d_{R,3})$$

leading to

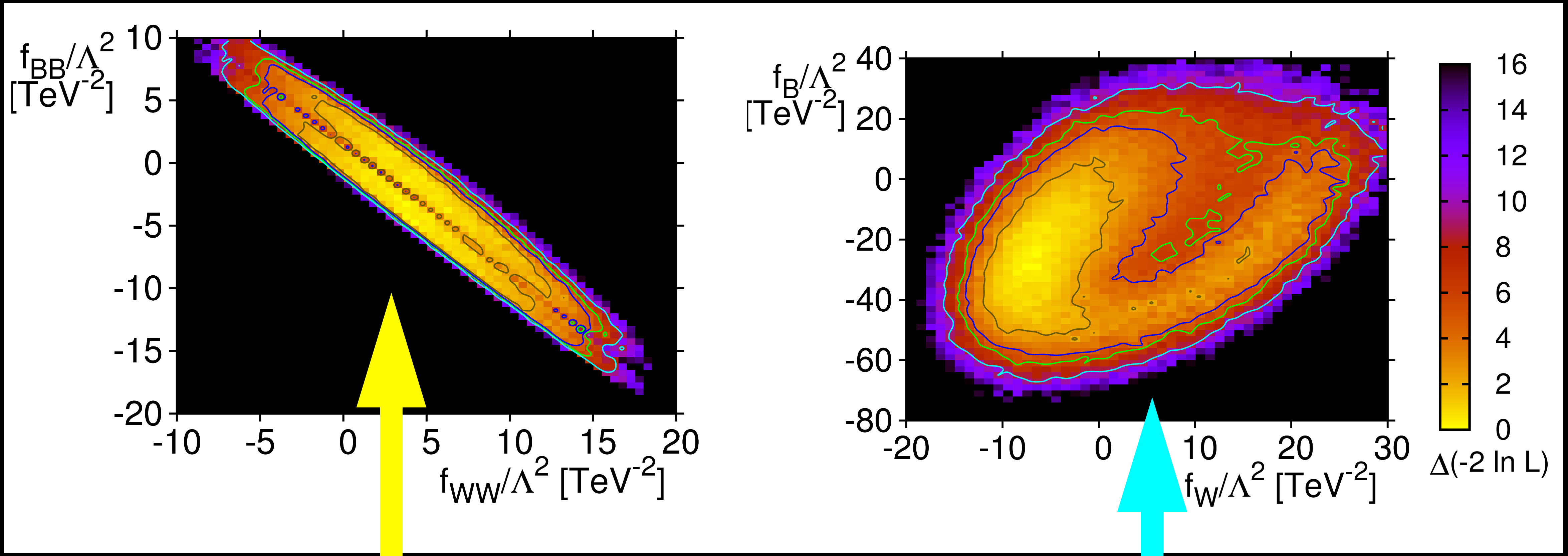
$$\mathcal{L}_{\text{eff}}^{Hff} = \frac{f_\tau m_\tau}{v\Lambda^2}\mathcal{O}_{e\Phi,33} + \frac{f_b m_b}{v\Lambda^2}\mathcal{O}_{d\Phi,33} + \frac{f_t m_t}{v\Lambda^2}\mathcal{O}_{u\Phi,33} + \frac{f_{\Phi,2}}{\Lambda^2}\mathcal{O}_{\Phi,2}$$

implying that

$$\mathcal{L}^{Hff} = g_f H \bar{f}_L f_R + \text{h.c.} \qquad \text{with} \quad g_f = -\frac{m_f}{v}\left(1 - \frac{v^2}{2\Lambda^2}f_{\Phi,2} - \frac{v^2}{\sqrt{2}\Lambda^2}f_f\right)$$

Rate-based analysis

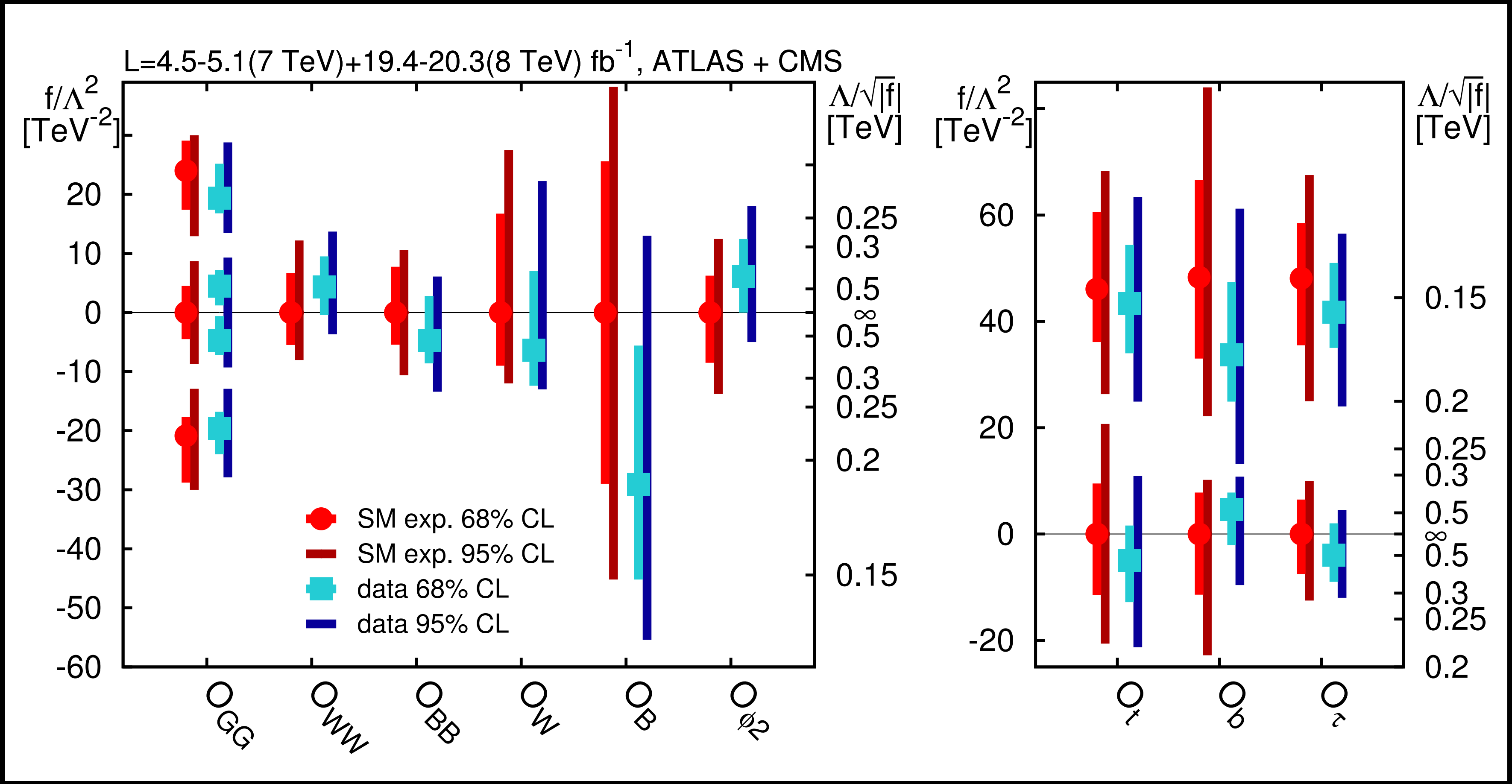
- decays and cross sections evaluated with FeynRules+MadGraph
- SM K-factors
- difference to previous analyses: f_t
- there are new correlations in addition to $f_{\rm GG} \times f_t$



strongest correlation due to $H \to \gamma\gamma$

f_B suppressed by s_w^2 improved with $H \to Z\gamma$

- the 9 parameter fit leads to



- strongest constraints on f_{WW} and f_{BB}
- next are f_W and $f_{\phi,2}$

Kinematic distributions [Ellis & Sanz & You;…],

- $(\mathcal{O}_B\ ,\ \mathcal{O}_W\ ,\ \mathcal{O}_{BB}\ ,\ \mathcal{O}_{WW})$ lead to new Lorentz structures
- limited to fully documented distributions
- using VH and WBF
- unitarity might be an issue:

  ✓ take the results at face value (with care!)
  ✓ introduce ad-hoc form factors
  ✓ keep only the phase space region not sensitive to UV completion

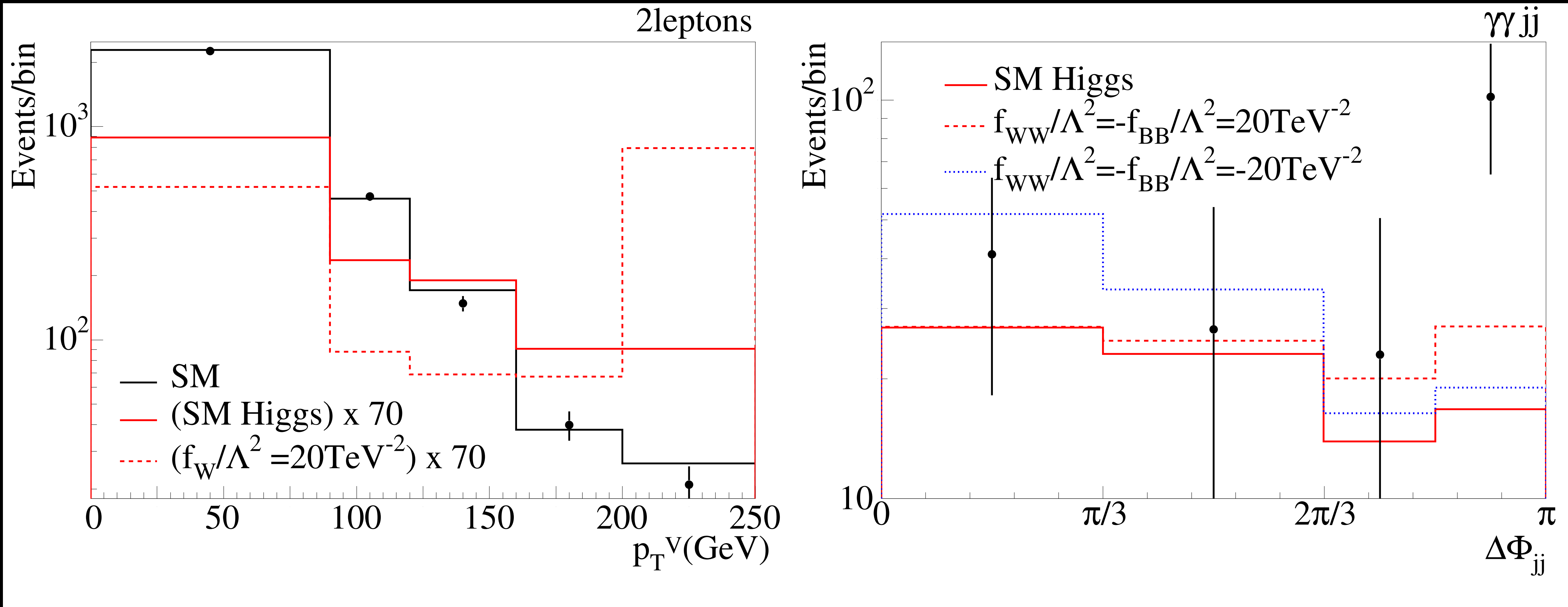
  we adopted the 1st and 3rd strategies

- To avoid double counting we used asymmetries in VH:

$$A_i = \frac{\mathrm{bin}_{i+1} - \mathrm{bin}_i}{\mathrm{bin}_{i+1} + \mathrm{bin}_i}$$

- FeynRules + MadGraph + Pythia + PGS4/DELPHES

- we used ATLAS results for VH (0,1,2 leptons) and WBF $\gamma\gamma jj$

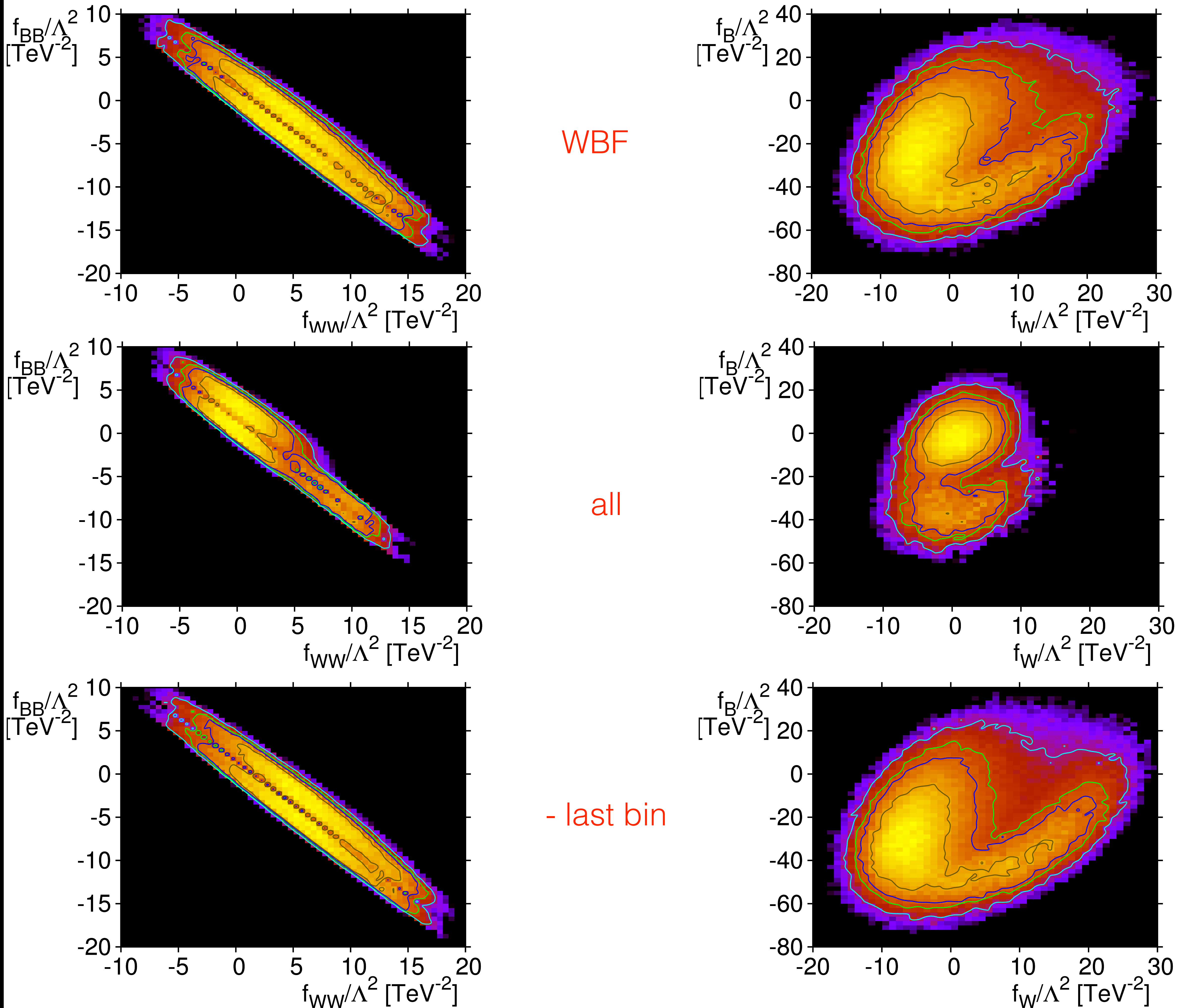


- for the WBF analysis

$$A_1 = \frac{\sigma(\Delta\phi_{jj} < \frac{\pi}{3}) + \sigma(\Delta\phi_{jj} > \frac{2\pi}{3}) - \sigma(\frac{\pi}{3} < \Delta\phi_{jj} < \frac{2\pi}{3})}{\sigma(\Delta\phi_{jj} < \frac{\pi}{3}) + \sigma(\Delta\phi_{jj} > \frac{2\pi}{3}) + \sigma(\frac{\pi}{3} < \Delta\phi_{jj} < \frac{2\pi}{3})} ,$$

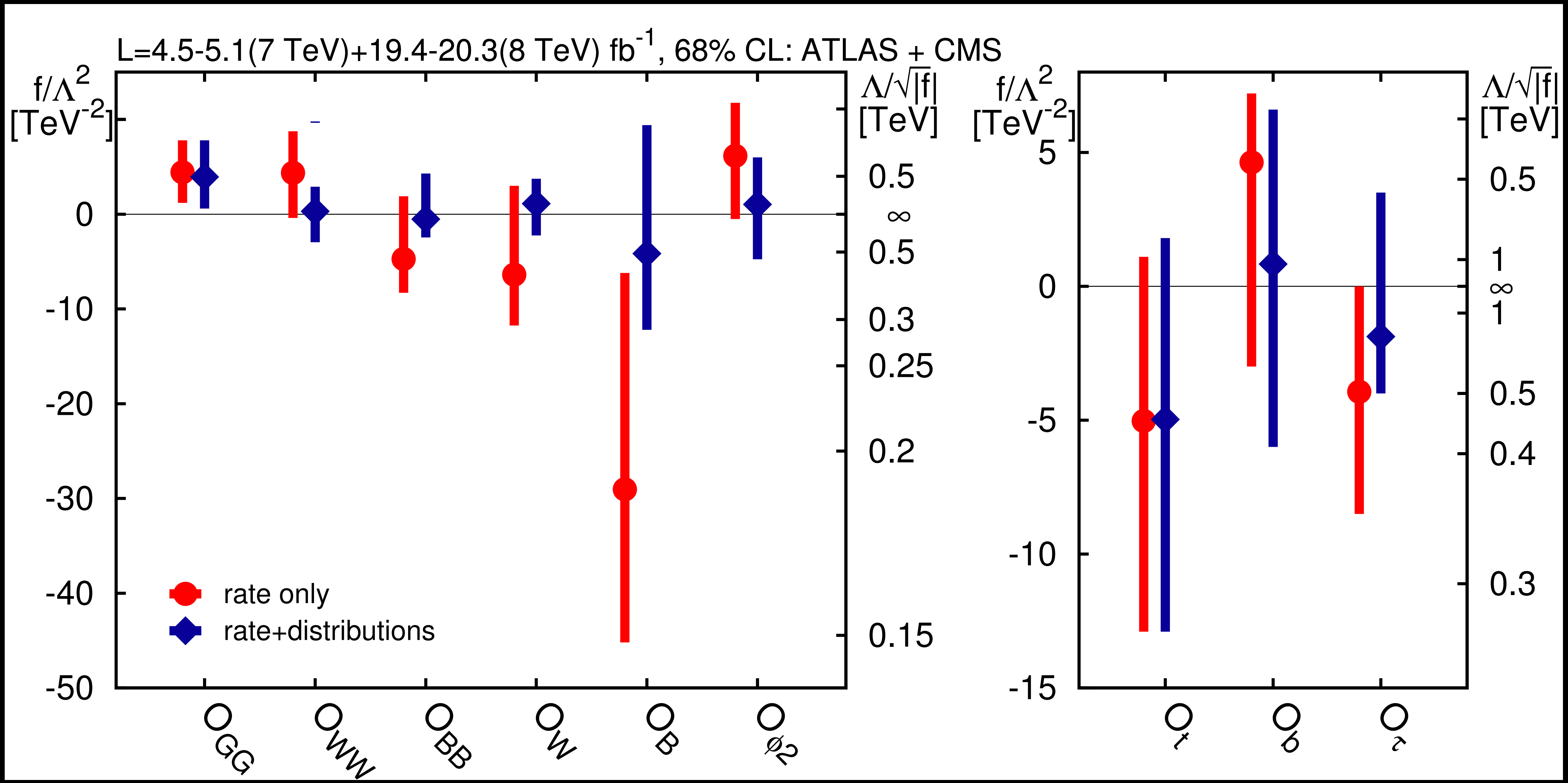
$$A_2 = \frac{\sigma(\Delta\phi_{jj} > \frac{2\pi}{3}) - \sigma(\Delta\phi_{jj} < \frac{\pi}{3})}{\sigma(\Delta\phi_{jj} > \frac{2\pi}{3}) + \sigma(\Delta\phi_{jj} < \frac{\pi}{3})} ,$$

$$A_3 = \frac{\sigma(\Delta\phi_{jj} > \frac{5\pi}{6}) - \sigma(\frac{2\pi}{3} < \Delta\phi_{jj} < \frac{5\pi}{6})}{\sigma(\Delta\phi_{jj} > \frac{5\pi}{6}) + \sigma(\frac{2\pi}{3} < \Delta\phi_{jj} < \frac{5\pi}{6})}$$



WBF
all
- last bin
f_BB/Λ^2 [TeV^-2]
f_WW/Λ^2 [TeV^-2]
f_B/Λ^2 [TeV^-2]
f_W/Λ^2 [TeV^-2]

- Presently the distributions impact mainly $\mathcal{O}_B$ and $\mathcal{O}_W$



take this is a proof of principle for the use of distributions!

- EFT range of validity from unitarity violation [Corbett, OE, Gonzalez-Garcia] [Renard & Gounaris; Baur & Zeppenfeld; ….]

$$\begin{aligned}
\left|\frac{f_{\Phi 2}}{\Lambda^2}s\right| &\leq 105 && \Longrightarrow \sqrt{s} < 2.3\ \text{TeV}\\
\left|\frac{f_{W}}{\Lambda^2}s\right| &\leq 205 && \Longrightarrow \sqrt{s} < 5.3\ \text{TeV}\\
\left|\frac{f_{B}}{\Lambda^2}s\right| &\leq 640 && \Longrightarrow \sqrt{s} < 3.7\ \text{TeV}\\
\left|\frac{f_{WW}}{\Lambda^2}s\right| &\leq 200 && \Longrightarrow \sqrt{s} < 2.6\ \text{TeV}\\
\left|\frac{f_{BB}}{\Lambda^2}s\right| &\leq 880 && \Longrightarrow \sqrt{s} < 9.4\ \text{TeV}
\end{aligned}$$

$$VV \to VV \text{ and } f\bar{f} \to VV$$

3. TGC from Higgs measurements

[Corbett, OE, Gonzalez-Fraile, Gonzalez-Garcia: arXiv:1304.1151]

- the operators $\mathcal{O}_B$ and $\mathcal{O}_W$ modify TGC's

$$\begin{aligned}
\Delta\kappa_\gamma &= \frac{g^2v^2}{8\Lambda^2}\Big(f_W + f_B\Big) \\
\Delta g_1^Z &= \frac{g^2v^2}{8c^2\Lambda^2} f_W \\
\Delta\kappa_Z &= \frac{g^2v^2}{8c^2\Lambda^2}\Big(c^2 f_W - s^2 f_B\Big)
\end{aligned}$$

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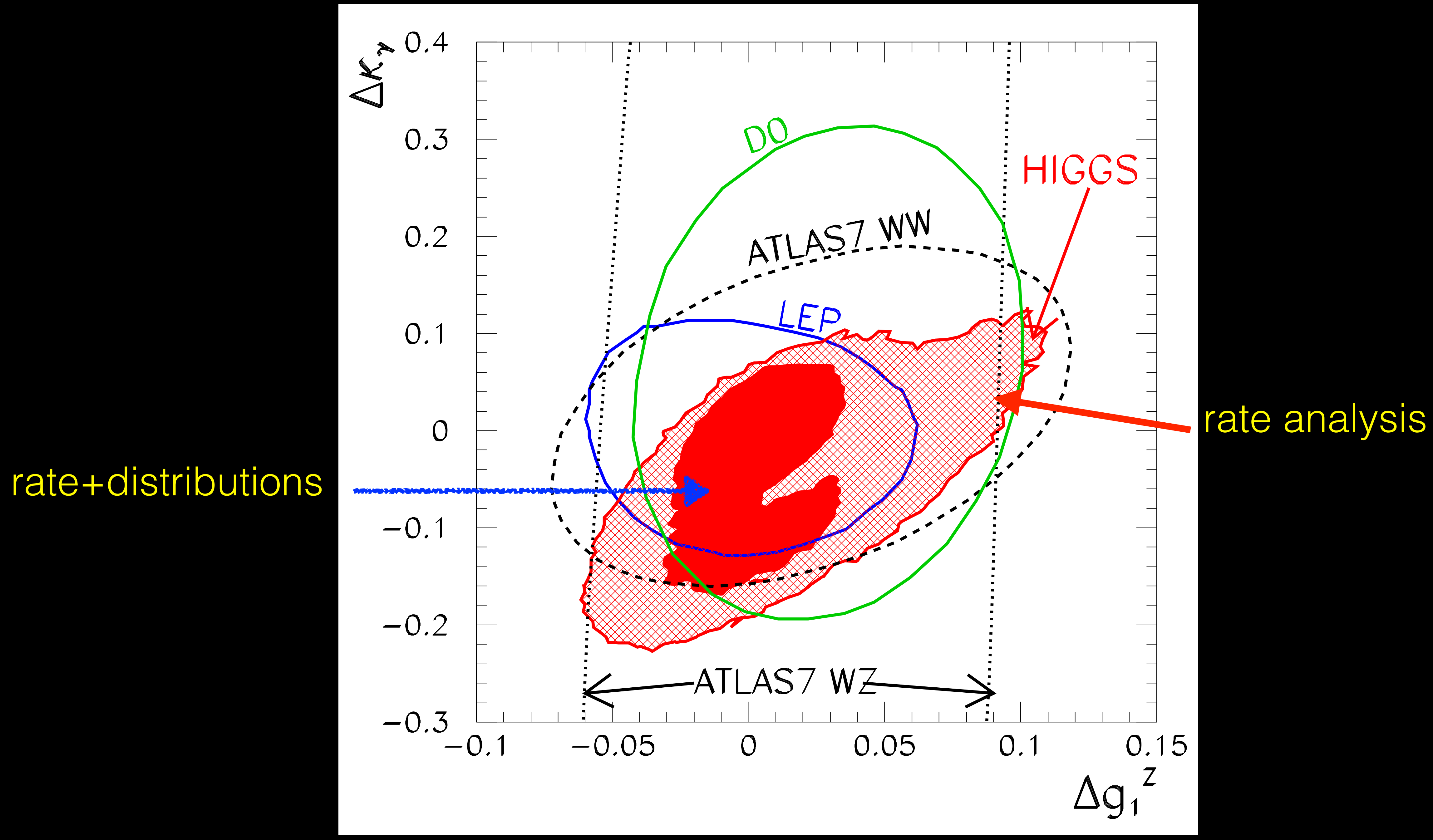

- nice interplay between TGC and Higgs physics
- side effect: TGC data still not good enough to decouple $\mathcal{O}_B$ and $\mathcal{O}_W$

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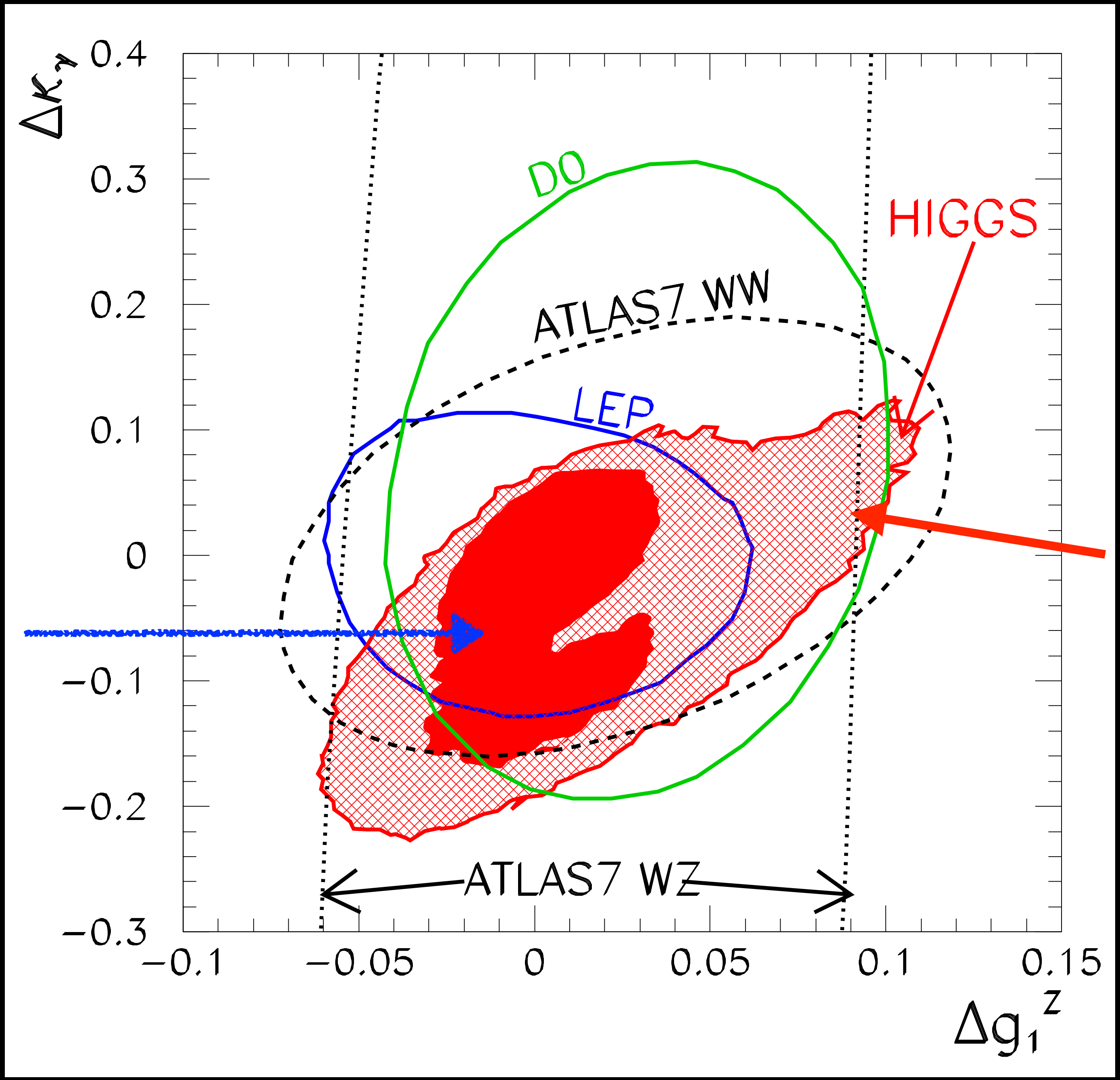
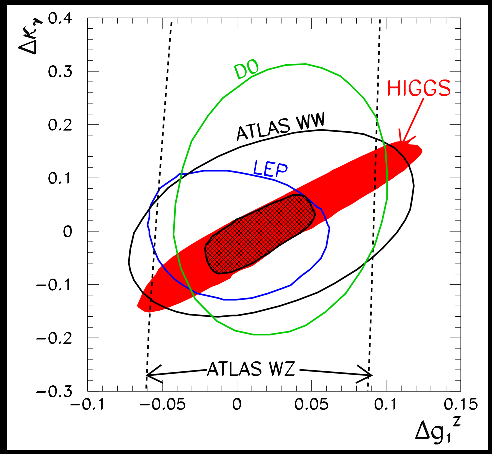
- the operators $\mathcal{O}_B$ and $\mathcal{O}_W$ modify TGC's

rate+distributions



rate analysis



- nice interplay between TGC and Higgs physics
- side effect: TGC data still not good enough to decouple $\mathcal{O}_B$ and $\mathcal{O}_W$

4. Off-shell Higgs measurements

- Off-shell Higgs measurements are a window into its width:
  [Kauer & Passarino; Caola & Melnikov; Ellis & Williams]

$$\sigma^{\text{on-shell}}_{i\to H\to f} \propto \frac{g_i^2(m_H)\, g_f^2(m_H)}{\Gamma_H} \qquad \text{vs} \qquad \sigma^{\text{off-shell}}_{i\to H^*\to f} \propto g_i^2(m_{4\ell})\, g_f^2(m_{4\ell})$$

- $m_{4\ell}$ is also useful to break the $\Delta_t \times \Delta_g$ degeneracy

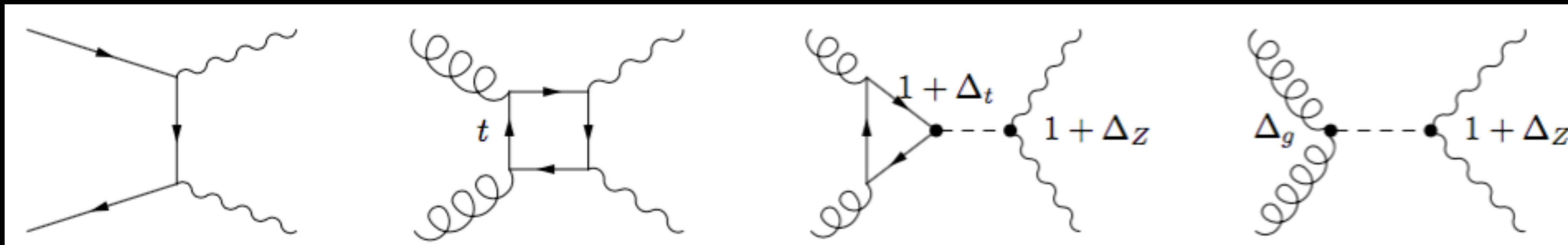
  [Buschmann, Gonçalves, Kuttimalai, Schönherr, Kraus, Plehn]

- In this analysis we worked in the delta framework

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \Delta_W\; g m_W H\; W^\mu W_\mu + \Delta_Z\; \frac{g}{2c_w} m_Z H\; Z^\mu Z_\mu - \sum_{\tau,b,t} \Delta_f\; \frac{m_f}{v} H\left(\bar{f}_R f_L + \text{h.c.}\right)$$
$$+ \Delta_g F_G\; \frac{H}{v}\; G_{\mu\nu}G^{\mu\nu} + \Delta_\gamma F_A\; \frac{H}{v}\; A_{\mu\nu}A^{\mu\nu} + \text{invisible decays} + \text{unobservable decays}$$

additional contribution!

- sample of Feynman diagrams



leading to

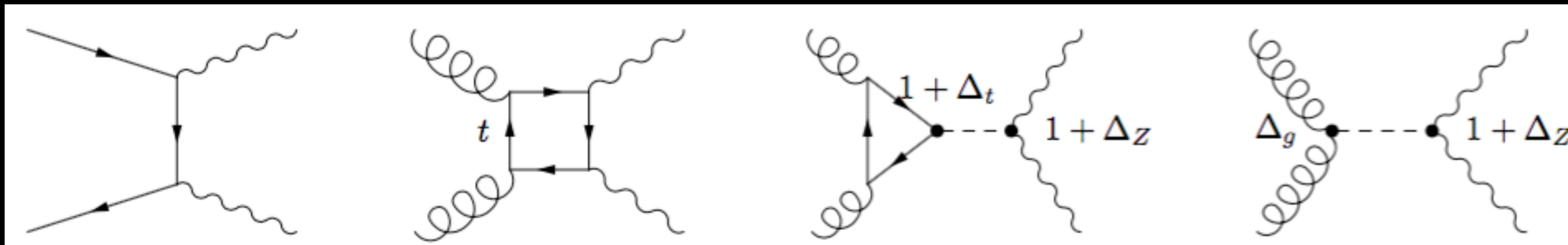
$$\mathcal{M}_{gg\to ZZ} = (1+\Delta_Z)\left[(1+\Delta_t)\mathcal{M}_t + \Delta_g \mathcal{M}_g\right] + \mathcal{M}_c$$

$$\frac{d\sigma}{dm_{4\ell}} = (1+\Delta_Z)\left[(1+\Delta_t)\frac{d\sigma_{tc}}{dm_{4\ell}} + \Delta_g \frac{d\sigma_{gc}}{dm_{4\ell}}\right] + (1+\Delta_Z)^2\left[(1+\Delta_t)^2\frac{d\sigma_{tt}}{dm_{4\ell}} + (1+\Delta_t)\Delta_g\frac{d\sigma_{tg}}{dm_{4\ell}} + \Delta_g^2\frac{d\sigma_{gg}}{dm_{4\ell}}\right] + \frac{d\sigma_c}{dm_{4\ell}}$$

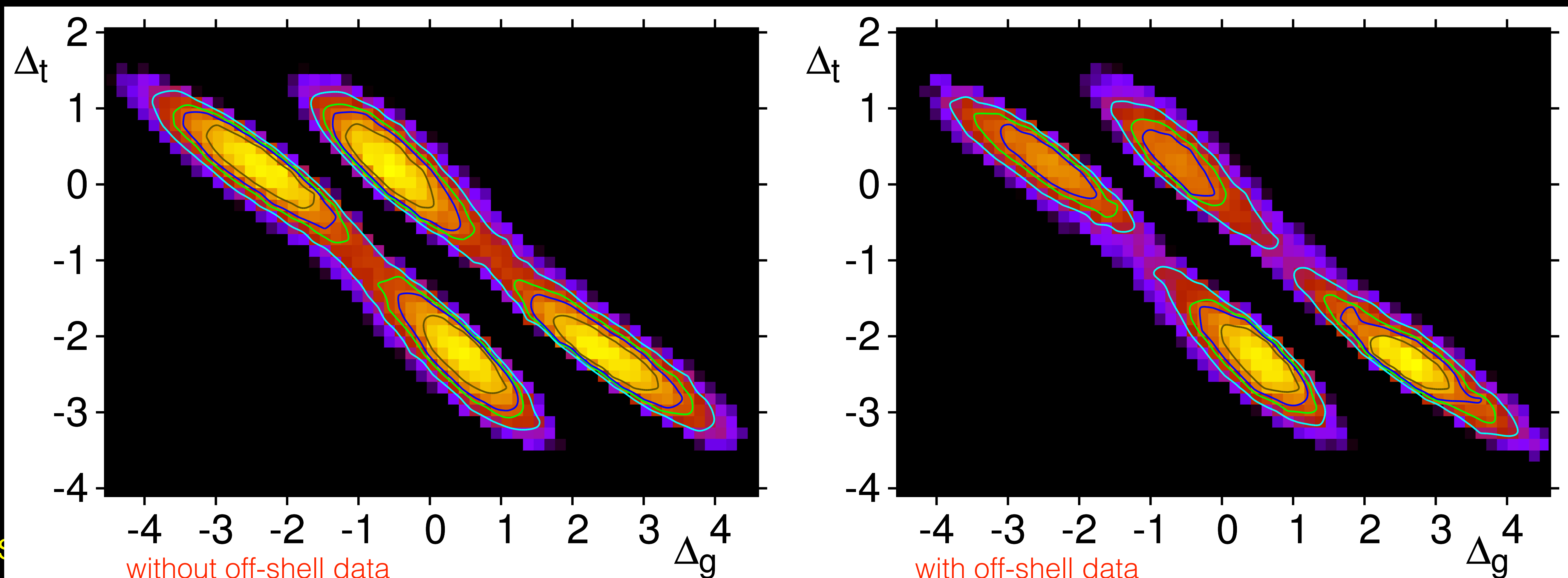
sensitive to the sign!

- top mass effects are different for Δ_g and Δ_t

- sample of Feynman diagrams

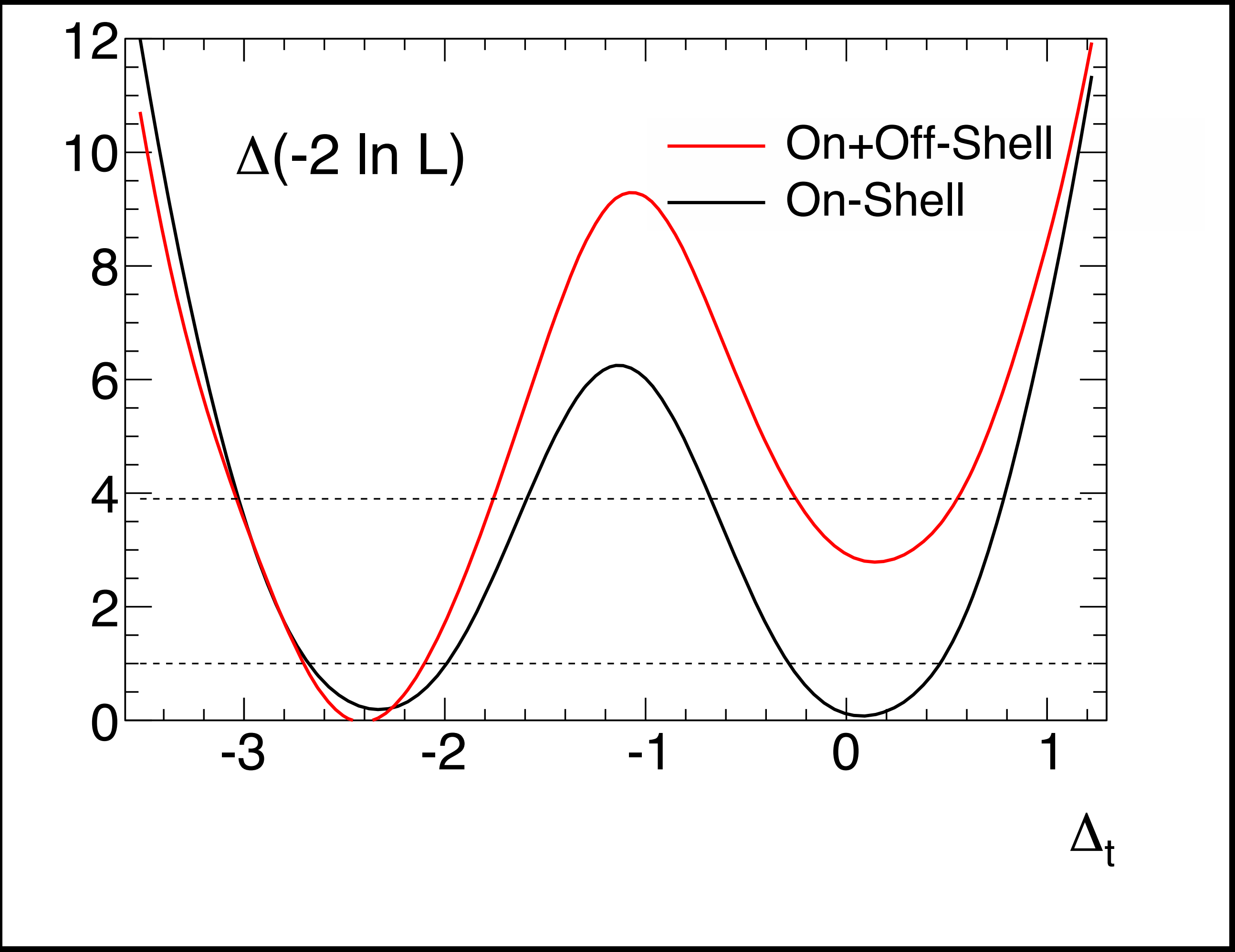


leading to

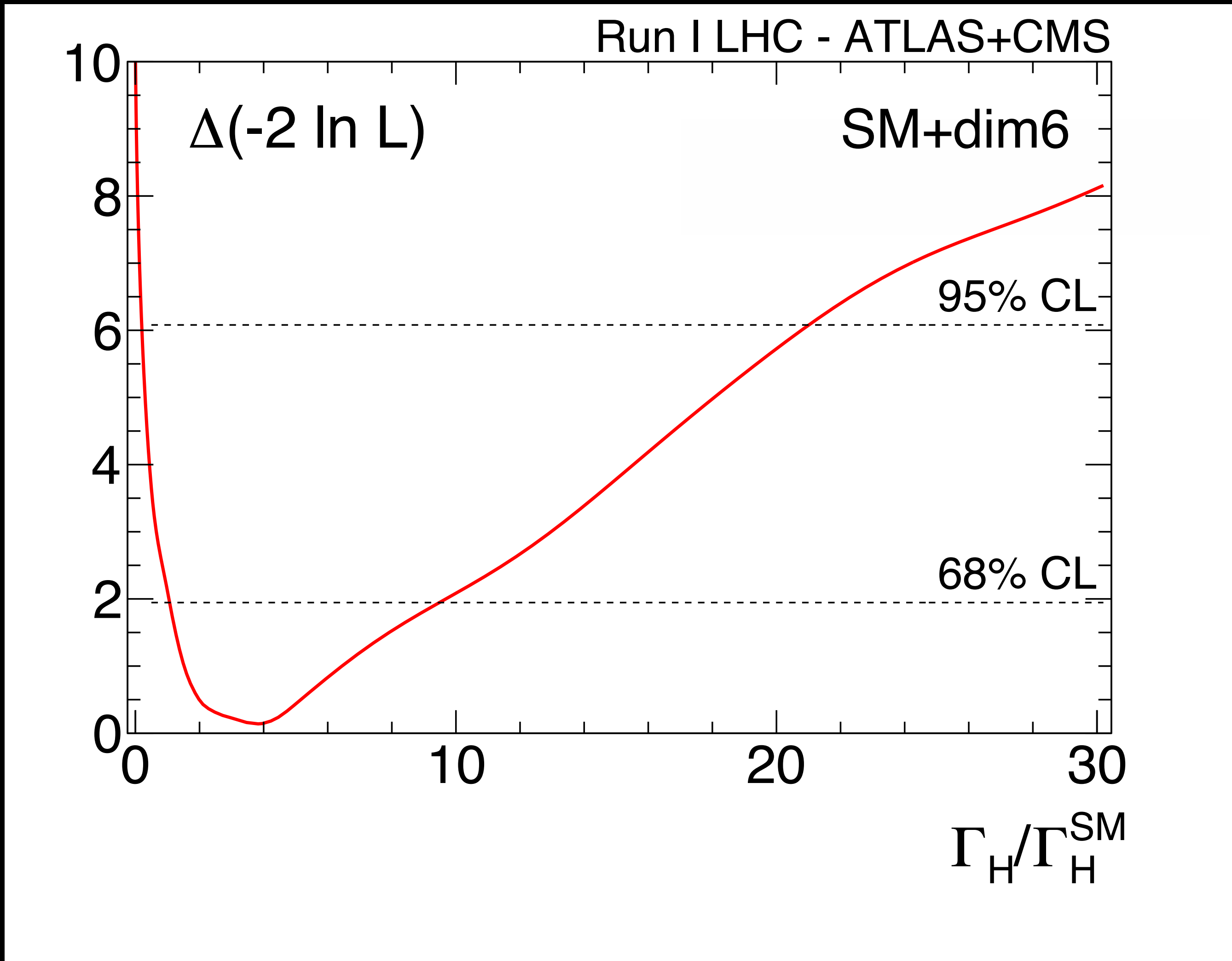


- top mass effects are different for Δ_g and Δ_t

- it is interesting to look at 1d profile likelihoods



slight preference for flipped-sign solution



$$\Gamma_H < 9.3\ \Gamma_H^{\mathrm{SM}}\ \text{at } 68\%\mathrm{CL}$$

5. Final remarks

- The observed Higgs is fully consistent with the SM

$\mathrm{BR_{inv}} < 0.31$ at 95% CL $\qquad\qquad \Gamma_H < 9.3\ \Gamma_H^{\mathrm{SM}}$ at 68%CL

- kinematic distributions and off-shell measurements can play a major role
- We tested different ways to include the theoretical uncertainties.

5. Final remarks

- The observed Higgs is fully consistent with the SM

$\mathrm{BR_{inv}} < 0.31$ at 95% CL $\qquad\qquad \Gamma_H < 9.3\ \Gamma_H^{\mathrm{SM}}$ at 68%CL

- kinematic distributions and off-shell measurements can play a major role
- We tested different ways to include the theoretical uncertainties.

THANK YOU

backup slides

- We can also analyze distributions in the non-linear sigma model
[Brivio, et al, arXiv: 1311.1823]

$$\mathcal{P}_C(h) = -\frac{v^2}{4}\mathrm{Tr}(\mathbf{V}^\mu \mathbf{V}_\mu)\mathcal{F}_C(h)$$

$$\mathcal{P}_T(h) = \frac{v^2}{4}\mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu)\mathrm{Tr}(\mathbf{T}\mathbf{V}^\mu)\mathcal{F}_T(h)$$

$$\mathcal{P}_H(h) = \frac{1}{2}(\partial_\mu h)(\partial^\mu h)\mathcal{F}_H(h)$$

$$\mathcal{P}_W(h) = -\frac{g^2}{4}W^a_{\mu\nu}W^{a\mu\nu}\mathcal{F}_W(h)$$

$$\mathcal{P}_G(h) = -\frac{g_s^2}{4}G^a_{\mu\nu}G^{a\mu\nu}\mathcal{F}_G(h)$$

$$\mathcal{P}_B(h) = -\frac{g'^2}{4}B_{\mu\nu}B^{\mu\nu}\mathcal{F}_B(h)$$

$$\mathcal{P}_{\Box H} = \frac{1}{v^2}(\partial_\mu\partial^\mu h)^2\mathcal{F}_{\Box H}(h)$$

$$\mathcal{P}_1(h) = gg'B_{\mu\nu}\mathrm{Tr}(\mathbf{T}W^{\mu\nu})\mathcal{F}_1(h)$$

$$\mathcal{P}_2(h) = ig'B_{\mu\nu}\mathrm{Tr}(\mathbf{T}[\mathbf{V}^\mu, \mathbf{V}^\nu])\mathcal{F}_2(h)$$

$$\mathcal{P}_3(h) = ig\mathrm{Tr}(W_{\mu\nu}[\mathbf{V}^\mu, \mathbf{V}^\nu])\mathcal{F}_3(h)$$

$$\mathcal{P}_4(h) = ig'B_{\mu\nu}\mathrm{Tr}(\mathbf{T}\mathbf{V}^\mu)\partial^\nu\mathcal{F}_4(h)$$

$$\mathcal{P}_5(h) = ig\mathrm{Tr}(W_{\mu\nu}\mathbf{V}^\mu)\partial^\nu\mathcal{F}_5(h)$$

$$\mathcal{P}_6(h) = (\mathrm{Tr}(\mathbf{V}_\mu\mathbf{V}^\mu))^2\mathcal{F}_6(h)$$

$$\mathcal{P}_7(h) = \mathrm{Tr}(\mathbf{V}_\mu\mathbf{V}^\mu)\partial_\nu\partial^\nu\mathcal{F}_7(h)$$

$$\mathcal{P}_8(h) = \mathrm{Tr}(\mathbf{V}_\mu\mathbf{V}_\nu)\partial^\mu\mathcal{F}_8(h)\partial^\nu\mathcal{F}'_8(h)$$

$$\mathcal{P}_9(h) = \mathrm{Tr}((\mathcal{D}_\mu\mathbf{V}^\mu)^2)\mathcal{F}_9(h)$$

$$\mathcal{P}_{10}(h) = \mathrm{Tr}(\mathbf{V}_\nu\mathcal{D}_\mu\mathbf{V}^\mu)\partial^\nu\mathcal{F}_{10}(h)$$

,

$$\frac{v^2}{2}\frac{f_{BB}}{\Lambda^2} = a_B\,, \qquad \frac{v^2}{2}\frac{f_{WW}}{\Lambda^2} = a_W\,, \qquad \frac{v^2}{(4\pi)^2}\frac{f_{GG}}{\Lambda^2} = a_G\,,$$
$$\frac{v^2}{8}\frac{f_B}{\Lambda^2} = a_4\,, \qquad -\frac{v^2}{4}\frac{f_W}{\Lambda^2} = a_5\,, \qquad v^2\frac{f_{\phi,2}}{\Lambda^2} = c_H\,,$$
$$v^2\frac{f_t}{\Lambda^2} = a'_t\,, \qquad v^2\frac{f_b}{\Lambda^2} = a'_b\,, \qquad v^2\frac{f_\tau}{\Lambda^2} = a'_\tau\,.$$

$$\mathcal{O}_{BB} = \frac{v^2}{2}\mathcal{P}_B(h)\,, \qquad \mathcal{O}_{WW} = \frac{v^2}{2}\mathcal{P}_W(h)\,,$$

$$\mathcal{O}_{GG} = -\frac{2v^2}{g_s^2}\mathcal{P}_G(h)\,, \qquad \mathcal{O}_{BW} = \frac{v^2}{8}\mathcal{P}_1(h)\,,$$

$$\mathcal{O}_{B} = \frac{v^2}{16}\mathcal{P}_2(h) + \frac{v^2}{8}\mathcal{P}_4(h)\,, \qquad \mathcal{O}_{W} = \frac{v^2}{8}\mathcal{P}_3(h) - \frac{v^2}{4}\mathcal{P}_5(h)\,,$$

$$\mathcal{O}_{\Phi,1} = \frac{v^2}{2}\mathcal{P}_H(h) - \frac{v^2}{4}\mathcal{F}(h)\mathcal{P}_T(h)\,, \qquad \mathcal{O}_{\Phi,2} = v^2\mathcal{P}_H(h)\,,$$

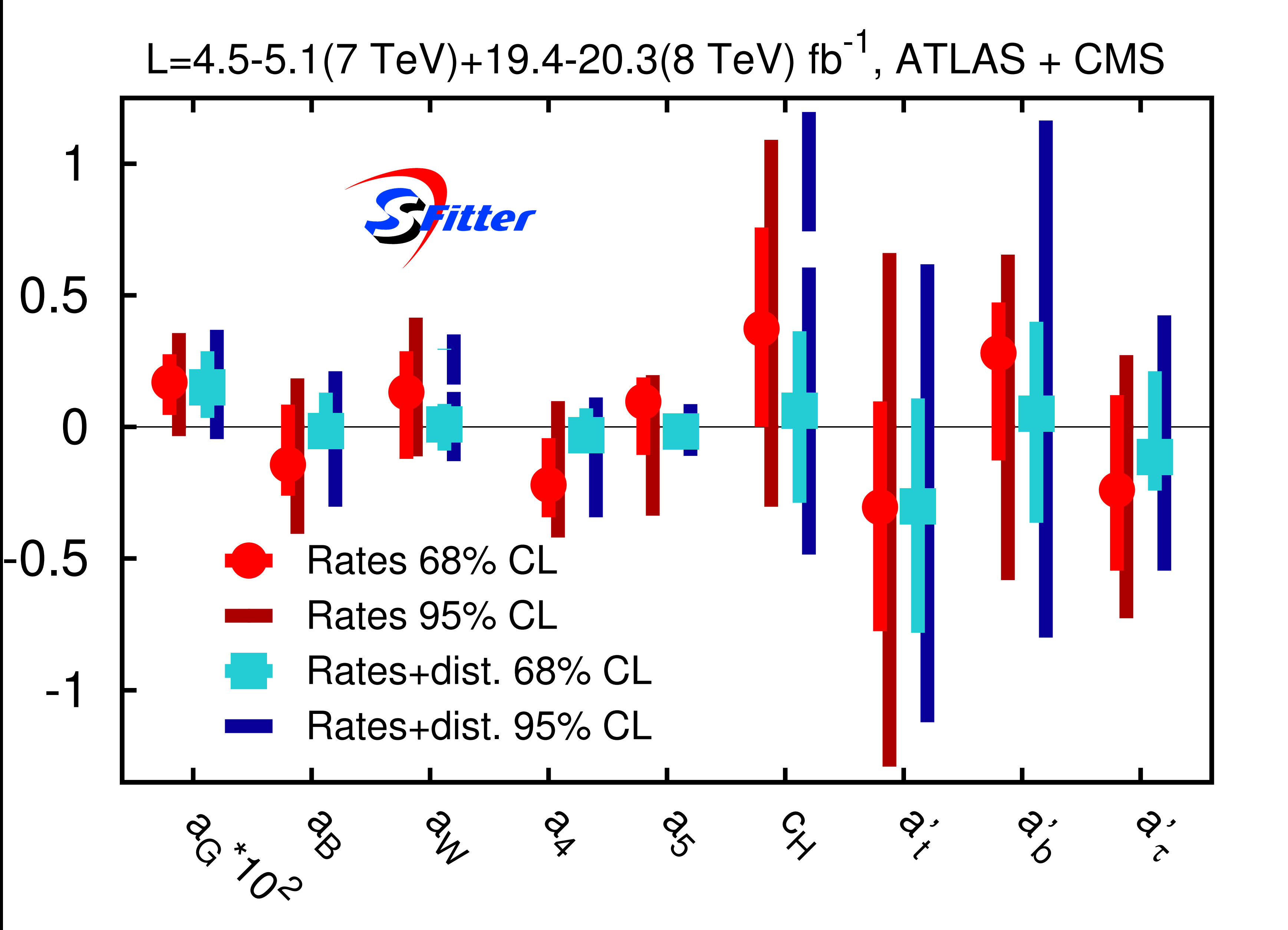
$$\mathcal{O}_{\Phi,4} = \frac{v^2}{2}\mathcal{P}_H(h) + \frac{v^2}{2}\mathcal{F}(h)\mathcal{P}_C(h)\,,$$

$$\mathcal{O}_{\Box\Phi} = \frac{v^2}{2}\mathcal{P}_{\Box H}(h) + \frac{v^2}{8}\mathcal{P}_6(h) + \frac{v^2}{4}\mathcal{P}_7(h) - v^2\mathcal{P}_8(h) - \frac{v^2}{4}\mathcal{P}_9(h) - \frac{v^2}{2}\mathcal{P}_{10}(h)$$

$$\frac{v^2}{2}\frac{f_{BB}}{\Lambda^2} = a_B\,, \qquad \frac{v^2}{2}\frac{f_{WW}}{\Lambda^2} = a_W\,, \qquad \frac{v^2}{(4\pi)^2}\frac{f_{GG}}{\Lambda^2} = a_G\,,$$

$$\frac{v^2}{8}\frac{f_B}{\Lambda^2} = a_4\,, \qquad -\frac{v^2}{4}\frac{f_W}{\Lambda^2} = a_5\,, \qquad v^2\frac{f_{\phi,2}}{\Lambda^2} = c_H\,,$$

$$v^2\frac{f_t}{\Lambda^2} = a'_t\,, \qquad v^2\frac{f_b}{\Lambda^2} = a'_b\,, \qquad v^2\frac{f_\tau}{\Lambda^2} = a'_\tau\,.$$



L=4.5-5.1(7 TeV)+19.4-20.3(8 TeV) fb^{-1}, ATLAS + CMS
SFitter
1
0.5
0
-0.5
-1
Rates 68% CL
Rates 95% CL
Rates+dist. 68% CL
Rates+dist. 95% CL
a_G *10^2
a_B
a_W
a_4
a_5
c_H
a'_t
a'_b
a'_τ

There are many operators at this order

$$\mathcal{P}_W = -\frac{g^2}{4} W^a_{\mu\nu} W^{a\mu\nu} \mathcal{F}_W(h)$$
$$\mathcal{P}_B = -\frac{g'^2}{4} B_{\mu\nu} B^{\mu\nu} \mathcal{F}_B(h)$$
$$\mathcal{P}_G = -\frac{g_s^2}{4} \mathcal{G}^A_{\mu\nu} \mathcal{G}^{A\mu\nu} \mathcal{F}_G(h)$$
$$\mathcal{P}_H = \frac{1}{2} \partial_\mu h \partial^\mu h \mathcal{F}_H(h)$$
$$\mathcal{P}_C = -\frac{v^2}{4} \mathrm{Tr}(\mathbf{V}^\mu \mathbf{V}_\mu) \mathcal{F}_C(h)$$
T $\mathcal{P}_T = \frac{v^2}{4} \mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu)\, \mathrm{Tr}(\mathbf{T}\mathbf{V}^\mu) \mathcal{F}_T(h)$

S $\mathcal{P}_1 = g g' B_{\mu\nu}\, \mathrm{Tr}(\mathbf{T} W^{\mu\nu}) \mathcal{F}_1(h)$

$$\mathcal{P}_2 = i g' B_{\mu\nu}\, \mathrm{Tr}(\mathbf{T}[\mathbf{V}^\mu, \mathbf{V}^\nu]) \mathcal{F}_2(h)$$
TGV
$$\mathcal{P}_3 = i g\, \mathrm{Tr}(W_{\mu\nu}[\mathbf{V}^\mu, \mathbf{V}^\nu]) \mathcal{F}_3(h)$$
$$\mathcal{P}_4 = i g' B_{\mu\nu}\, \mathrm{Tr}(\mathbf{T}\mathbf{V}^\mu) \partial^\nu \mathcal{F}_4(h)$$
$$\mathcal{P}_5 = i g\, \mathrm{Tr}(W_{\mu\nu} \mathbf{V}^\mu) \partial^\nu \mathcal{F}_5(h)$$
QGV $\mathcal{P}_6 = (\mathrm{Tr}(\mathbf{V}_\mu \mathbf{V}^\mu))^2 \mathcal{F}_6(h)$
$$\mathcal{P}_7 = \mathrm{Tr}(\mathbf{V}_\mu \mathbf{V}^\mu) \partial_\nu \partial^\nu \mathcal{F}_7(h)$$
$$\mathcal{P}_8 = \mathrm{Tr}(\mathbf{V}_\mu \mathbf{V}_\nu) \partial^\mu \mathcal{F}_8(h) \partial^\nu \mathcal{F}'_8(h)$$
$$\mathcal{P}_9 = \mathrm{Tr}((\mathcal{D}_\mu \mathbf{V}^\mu)^2) \mathcal{F}_9(h)$$
$$\mathcal{P}_{10} = \mathrm{Tr}(\mathbf{V}_\nu \mathcal{D}_\mu \mathbf{V}^\mu) \partial^\nu \mathcal{F}_{10}(h)$$

$\mathcal{P}_{11} = (\mathrm{Tr}(\mathbf{V}_\mu \mathbf{V}_\nu))^2 \mathcal{F}_{11}(h)$ QGV
$$\mathcal{P}_{12} = g^2\, \mathrm{Tr}(\mathbf{T} W_{\mu\nu}))^2 \mathcal{F}_{12}(h)$$
$$\mathcal{P}_{13} = i g\, \mathrm{Tr}(\mathbf{T} W_{\mu\nu})\, \mathrm{Tr}(\mathbf{T}[\mathbf{V}^\mu, \mathbf{V}^\nu]) \mathcal{F}_{13}(h)$$
$$\mathcal{P}_{14} = g \varepsilon^{\mu\nu\rho\lambda}\, \mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu)\, \mathrm{Tr}(\mathbf{V}_\nu W_{\rho\lambda}) \mathcal{F}_{14}(h)$$
$$\mathcal{P}_{15} = \mathrm{Tr}(\mathbf{T}\mathcal{D}_\mu \mathbf{V}^\mu)\, \mathrm{Tr}(\mathbf{T}\mathcal{D}_\nu \mathbf{V}^\nu) \mathcal{F}_{15}(h)$$
$$\mathcal{P}_{16} = \mathrm{Tr}([\mathbf{T}, \mathbf{V}_\nu]\mathcal{D}_\mu \mathbf{V}^\mu)\, \mathrm{Tr}(\mathbf{T}\mathbf{V}^\nu) \mathcal{F}_{16}(h)$$
$$\mathcal{P}_{17} = i g\, \mathrm{Tr}(\mathbf{T} W_{\mu\nu})\, \mathrm{Tr}(\mathbf{T}\mathbf{V}^\mu) \partial^\nu \mathcal{F}_{17}(h)$$
$$\mathcal{P}_{18} = \mathrm{Tr}(\mathbf{T}[\mathbf{V}_\mu, \mathbf{V}_\nu])\, \mathrm{Tr}(\mathbf{T}\mathbf{V}^\mu) \partial^\nu \mathcal{F}_{18}(h)$$
$$\mathcal{P}_{19} = \mathrm{Tr}(\mathbf{T}\mathcal{D}_\mu \mathbf{V}^\mu)\, \mathrm{Tr}(\mathbf{T}\mathbf{V}_\nu) \partial^\nu \mathcal{F}_{19}(h)$$
$$\mathcal{P}_{20} = \mathrm{Tr}(\mathbf{V}_\mu \mathbf{V}^\mu) \partial_\nu \mathcal{F}_{20}(h) \partial^\nu \mathcal{F}'_{20}(h)$$
$$\mathcal{P}_{21} = (\mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu))^2 \partial_\nu \mathcal{F}_{21}(h) \partial^\nu \mathcal{F}'_{21}(h)$$
$$\mathcal{P}_{22} = \mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu)\, \mathrm{Tr}(\mathbf{T}\mathbf{V}_\nu) \partial^\mu \mathcal{F}_{22}(h) \partial^\mu \mathcal{F}'_{22}(h)$$
$$\mathcal{P}_{23} = \mathrm{Tr}(\mathbf{V}_\mu \mathbf{V}^\mu)(\mathrm{Tr}(\mathbf{T}\mathbf{V}_\nu))^2 \mathcal{F}_{23}(h)$$
QGV
$$\mathcal{P}_{24} = \mathrm{Tr}(\mathbf{V}_\mu \mathbf{V}_\nu)\, \mathrm{Tr}(\mathbf{T}\mathbf{V}^\mu)\, \mathrm{Tr}(\mathbf{T}\mathbf{V}^\nu) \mathcal{F}_{24}(h)$$
$$\mathcal{P}_{25} = (\mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu))^2 \partial_\nu \partial^\nu \mathcal{F}_{25}(h)$$
$$\mathcal{P}_{26} = (\mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu)\, \mathrm{Tr}(\mathbf{T}\mathbf{V}_\nu))^2 \mathcal{F}_{26}(h)$$

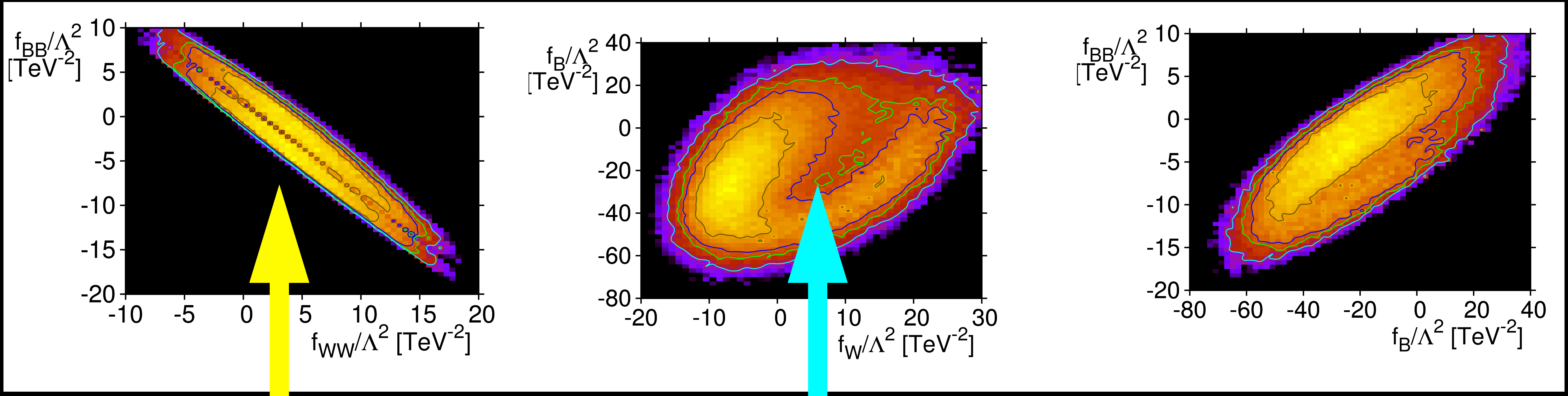
generalization of the Appelquist-Bernard-Longhitano basis

- Limits on the Higgs couplings

	7 parameter analysis			8 parameter analysis		
	Best fit	68% CL intervals	95% CL intervals	Best fit	68% CL intervals	95% CL intervals
Δ_W	-0.160	$(-0.335, -0.05)$	$(-0.46, 0.085)$	-0.0867	$(-0.265, 0.025)$	$(-0.38, 0.155)$
Δ_Z	0.0559	$(-0.07, 0.195)$	$(-0.205, 0.305)$	0.158	$(0.01, 0.28)$	$(-0.125, 0.405)$
Δ_t	0.159	$(-0.2, 0.46)$	$(-0.585, 0.75)$	0.188	$(-0.13, 0.57)$	$(-0.505, 0.845)$
Δ_b	-0.265	$(-0.565, -0.01)$	$(-0.82, 0.295)$	-0.193	$(-0.5, 0.06)$	$(-0.77, 0.375)$
Δ_τ	-0.0492	$(-0.25, 0.095)$	$(-0.395, 0.28)$	0.0417	$(-0.17, 0.185)$	$(-0.33, 0.375)$
Δ_γ	0.226	$(0.09, 0.40)$	$(-0.065, 0.555)$	0.248	$(0.1, 0.435)$	$(-0.055, 0.595)$
Δ_g	-0.479	$(-0.83, -0.125)$	$(-1, 0.37)$	-0.430	$(-0.855, -0.13)$	$(-1, 0.385)$
$\mathrm{BR_{inv}}$	—	—	—	0.157	$(0.048, 0.226)$	$(0., 0.306)$
$\Delta_\gamma^{\mathrm{SM+NP}}$	-0.0191	$(-0.17, 0.125)$	$(-0.295, 0.285)$	0.0892	$(-0.09, 0.22)$	$(-0.22, 0.395)$
$\Delta_g^{\mathrm{SM+NP}}$	0.230	$(-0.4, 0.115)$	$(-0.51, 0.35)$	-0.163	$(-0.335, 0.04)$	$(-0.45, 0.115)$
	$(-2\ln L)_{\mathrm{min}} = 66.4,\ (-2\ln L)_{\mathrm{SM}} = 72.1$			$(-2\ln L)_{\mathrm{min}} = 63.4,\ (-2\ln L)_{\mathrm{SM}} = 72.1$		

	Rate-based analysis			Analysis with kinematic distributions		
	Best fit	68% CL intervals	95% CL intervals	Best fit	68% CL intervals	95% CL intervals
f_{GG}/Λ^2 (TeV^{-2})	-19.6	$(-24, 16.8)$	$(-27.9, -12.9)$	-24.39	$(-27, -18.9)$	$(-30, -14.1)$
	-4.79	$(-7.2, 0.6)$	$(-9.3, 9.3)$	-3.75	$(-7.2, -1.2)$	$(-9.6, 9.6)$
	4.42	$(1.2, 7.2)$	$(13.5, 28.8)$	3.94	$(0.6, 7.8)$	$(15.3, 30)$
	19.35	$(16.8, 25.1)$		24.18	$(19.2, 27)$	
f_{WW}/Λ^2 (TeV^{-2})	4.36	$(-0.4, 9.5)$	$(-3.7, 13.7)$	0.296	$(-2.95, 2.9)$, $(9.65, 9.8)$	$(-4.3, 4.4)$, $(15.3, 30)$
f_{BB}/Λ^2 (TeV^{-2})	-4.72	$(-8.6, 2.8)$	$(-13.4, 6.1)$	-0.518	$(-2.45, 4.3)$	$(-10, 7)$
$f_{\phi,2}/\Lambda^2$ (TeV^{-2})	6.15	$(0, 12.5)$	$(-5, 18)$	1.03	$(-4.75, 6)$	$(-8, 10)$, $(12.25, 19.75)$
f_W/Λ^2 (TeV^{-2})	-6.38	$(-12.4, 7)$	$(-13, 22.5)$	1.12	$(-2.25, 3.75)$	$(-5.75, 7.25)$
f_B/Λ^2 (TeV^{-2})	-29.04	$(-45.2, -5.6)$	$(-55.4, 13)$	-4.16	$(-12.2, 9.4)$	$(-45.2, 14.8)$
f_b/Λ^2 (TeV^{-2})	4.63	$(-2.1, 7.8)$	$(-9.6, 10.8)$	0.83	$(-6, 6.6)$	$(-13.2, 19.2)$
	33.7	$(24.9, 47.3)$	$(13.2, 61.2)$	46.4	$(33, 56.4)$	$(24, 67.8)$
f_τ/Λ^2 (TeV^{-2})	-3.94	$(-9, 2)$	$(-12, 4.5)$	-1.88	$(-4, 3.5)$	$(-9, 7)$
	41.7	$(35, 51)$	$(24, 56.5)$	43.9	$(39, 53.5)$	$(23.5, 60)$
f_t/Λ^2 (TeV^{-2})	-5.03	$(-12.8, 1.6)$	$(-21.3, 10.9)$	-4.97	$(-12.9, 1.8)$	$(-18.5, 10.2)$
	43.4	$(34, 54.4)$	$(24.9, 63.4)$	53.37	$(41, 59.9)$	$(24.2, 66.9)$
	$(-2\ln L)_{\rm min} = 66.7$, $(-2\ln L)_{\rm SM} = 72.1$			$(-2\ln L)_{\rm min} = 88.4$, $(-2\ln L)_{\rm SM} = 91.9$		

- decays and cross sections evaluated with FeynRules+MadGraph
- SM K-factors
- difference to previous analyses: f_t
- there are new correlations in addition to $f_{\rm GG} \times f_t$



strongest correlation
due to $H \to \gamma\gamma$

f_B suppressed by s_w^2
improved with $H \to Z\gamma$