

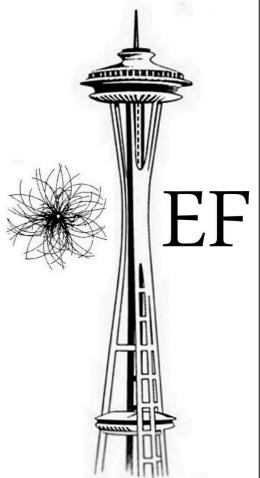


# Constraints on triple gauge boson couplings using the Higgs data

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(arXiv:1207.1344, 1211.4580 and 1304.1151)

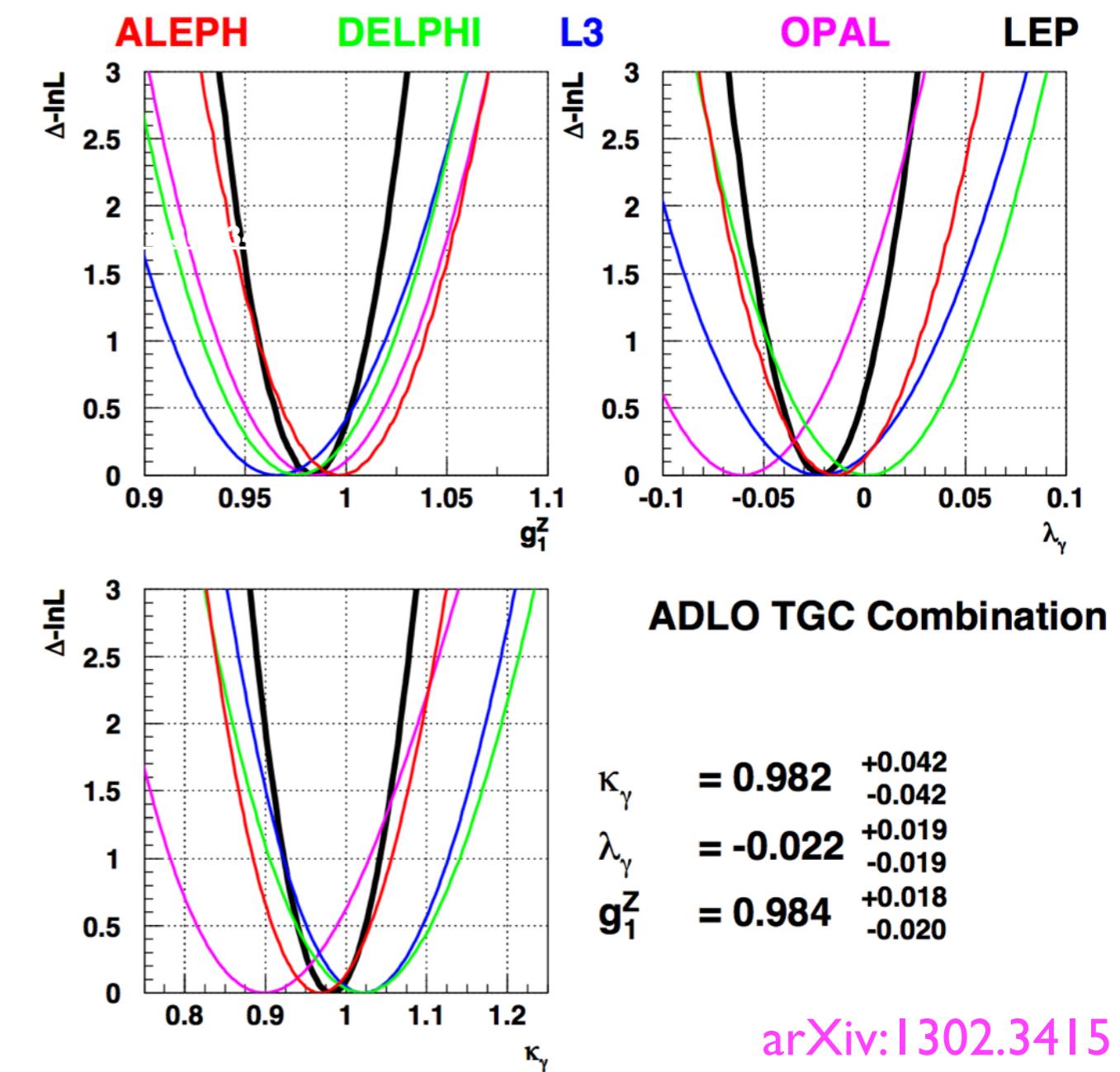
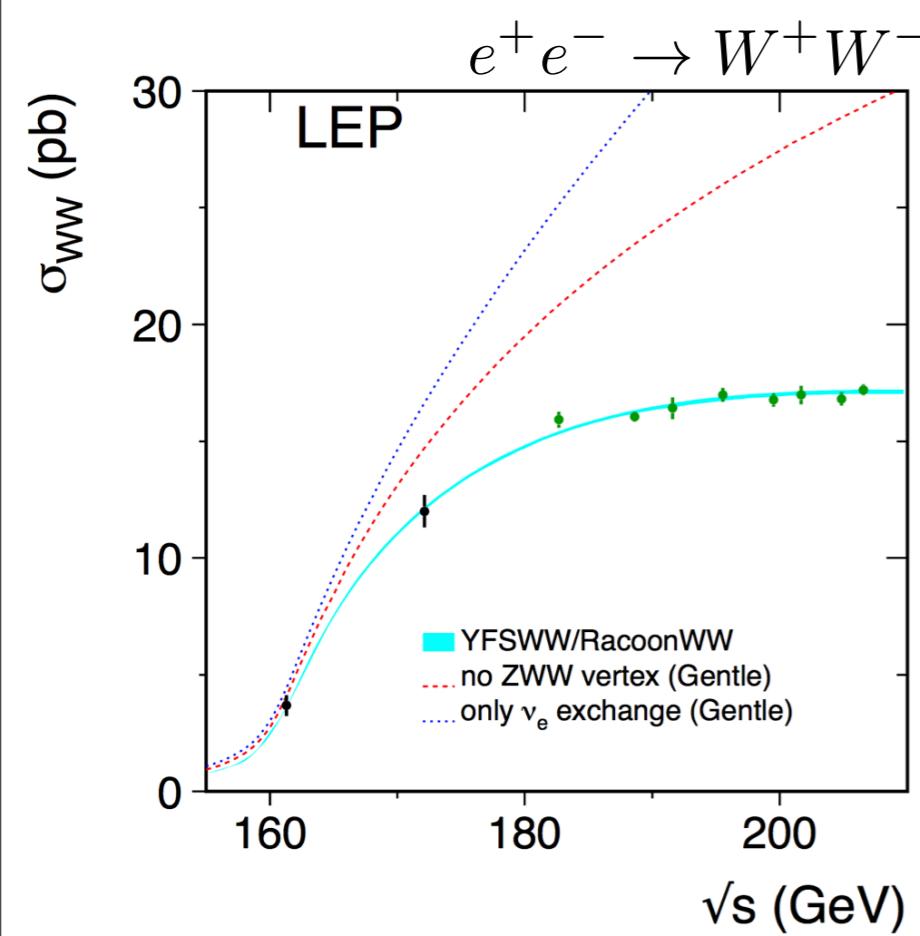


- Measurement of TGCs is an important test of the SM
- Deviations from the SM predictions can be parametrized

[Hagiwara, Hikasa, Peccei, Zeppenfeld]

$$\mathcal{L}_{WWV} = -ig_{WWV} \left\{ g_1^V \left( W_{\mu\nu}^+ W^{-\mu} V^\nu - W_\mu^+ V_\nu W^{-\mu\nu} \right) + \kappa_V W_\mu^+ W_\nu^- V^{\mu\nu} + \frac{\lambda_V}{m_W^2} W_{\mu\nu}^+ W^{-\nu\rho} V_\rho^\mu \right\}$$

SM values  $g_1^V = \kappa_V = 1$  ,  $\lambda_V = 0$



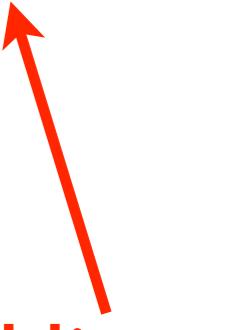
- TGCs can be studied using dimension-six operators

$$\mathcal{L}_{\text{TGC}} = \frac{f_B}{\Lambda^2} \mathcal{O}_B + \frac{f_W}{\Lambda^2} \mathcal{O}_W + \frac{f_{WWW}}{\Lambda^2} \mathcal{O}_{WWW}$$

with

$$\mathcal{O}_B = (D_\mu \Phi)^\dagger \hat{B}^{\mu\nu} D_\nu \Phi \quad , \quad \mathcal{O}_W = (D_\mu \Phi)^\dagger \hat{W}^{\mu\nu} D_\nu \Phi$$

$$\mathcal{O}_{WWW} = \text{Tr}[\hat{W}_{\mu\nu} \hat{W}^{\nu\rho} \hat{W}_\rho^\mu]$$

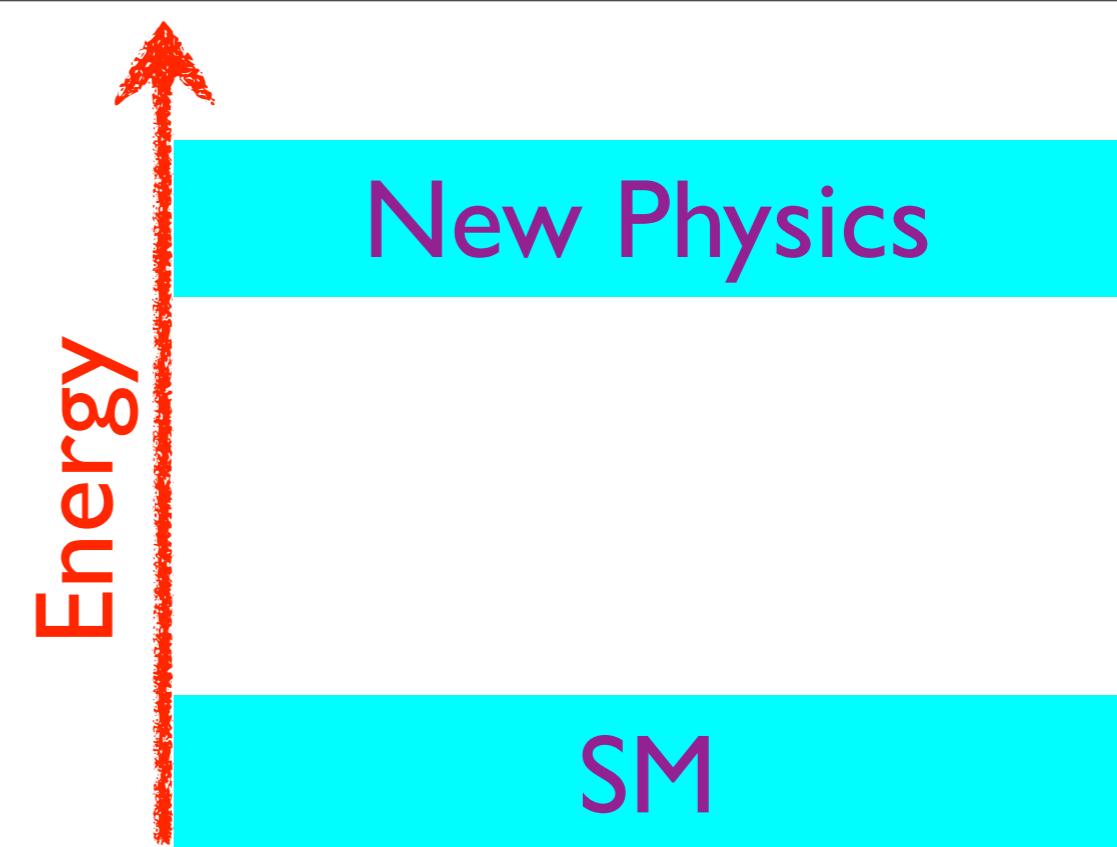


Higgs

we want to explore the connection between Higgs physics and TGCs

# Reasonable assumptions

- There is a mass gap between SM and NP
- one new state: CP even and spin 0
- new state belongs to SU(2) doublet  $\Phi$
- $SU(2) \times U(1)$  realized linearly as in the SM
- Building blocks of  $\mathcal{L}_{\text{eff}}$



$\Phi$

$D_\mu \Phi$

$$\hat{B}_{\mu\nu} = i\frac{g'}{2}B_{\mu\nu} \quad \hat{W}_{\mu\nu} = i\frac{g}{2}\sigma^a W_{\mu\nu}^a \quad G_{\mu\nu}^a$$

...

...

...

- To measure departures of the SM predictions we write

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

dimension-6 operators  
summarizing NP effects

- There are 59 “independent” dimension-six operators

[Buchmuller & Wyler; Grzadkowski et al. arXiv: 1008.4884]

- There is a freedom in choosing the operator basis

- We picked the basis to make better use of all available data

Our goal: study deviations from SM predictions using  
a bottom-up approach and largest possible dataset

- The Higgs interactions with gauge bosons are modified by

$$\mathcal{O}_{GG} = \Phi^\dagger \Phi G_{\mu\nu}^a G^{a\mu\nu} ,$$

$$\mathcal{O}_{WW} = \Phi^\dagger \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \Phi \quad \longleftrightarrow \quad \mathcal{O}_{BB} = \Phi^\dagger \hat{B}_{\mu\nu} \hat{B}^{\mu\nu} \Phi ,$$

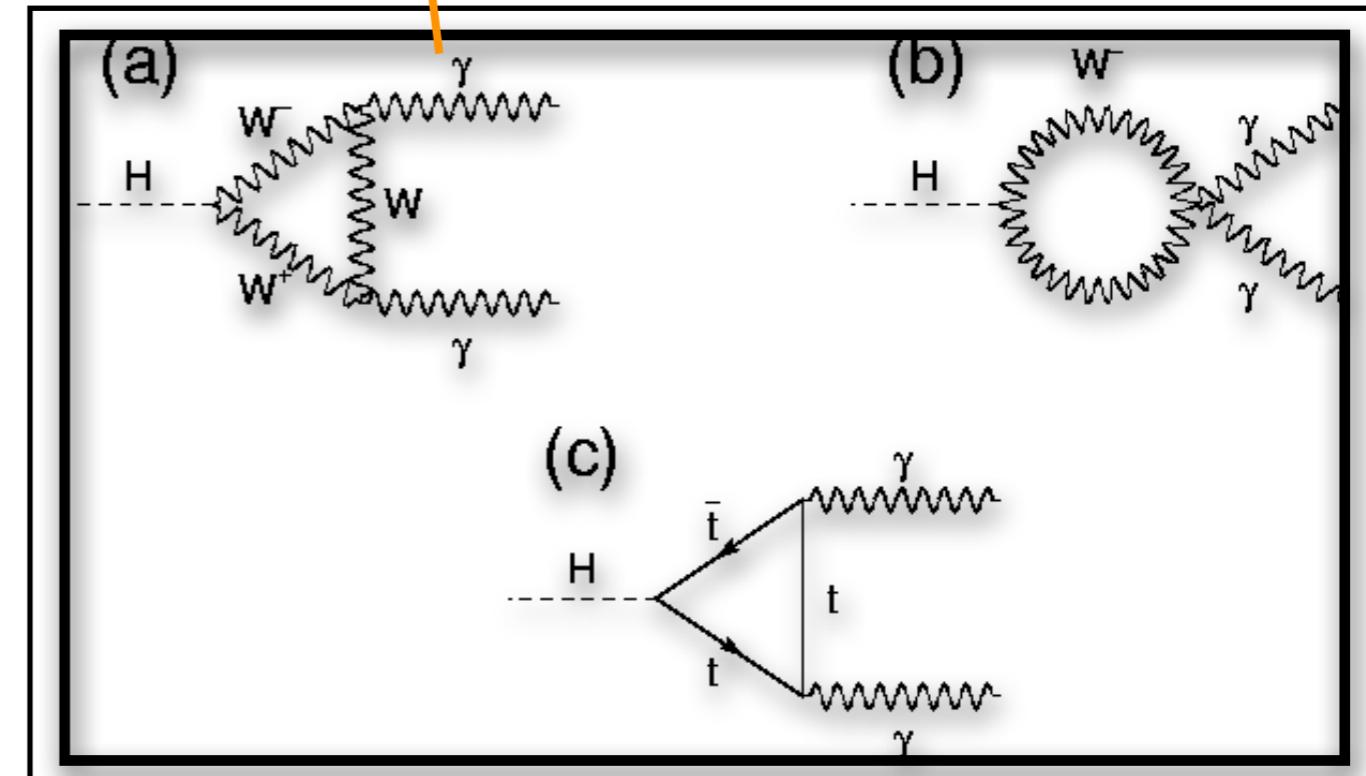
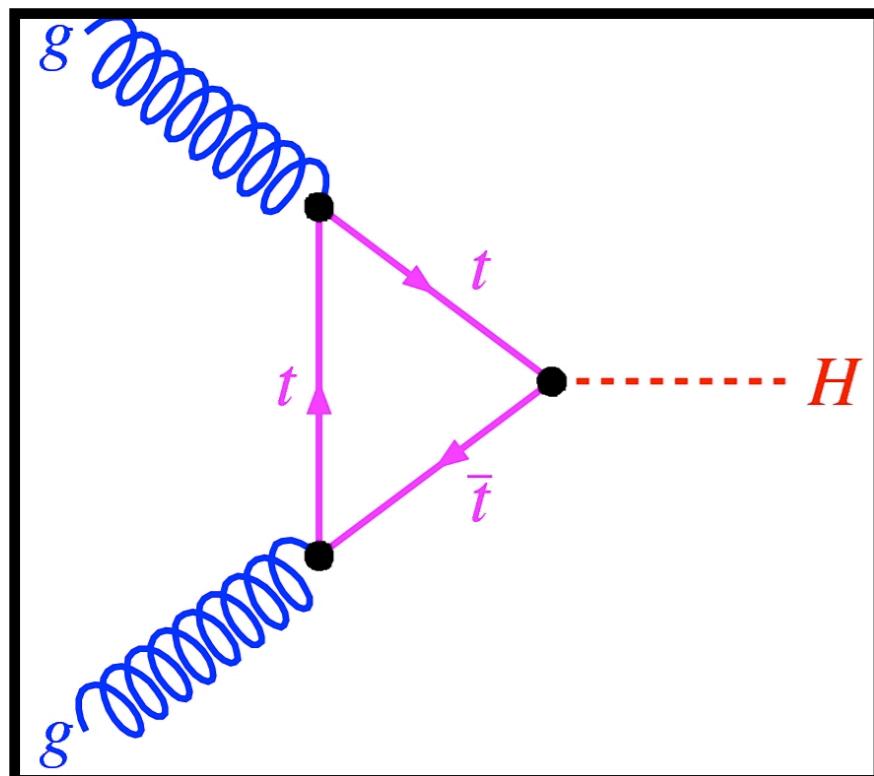
$$\mathcal{O}_{BW} = \Phi^\dagger \hat{B}_{\mu\nu} \hat{W}^{\mu\nu} \Phi ,$$

$$\mathcal{O}_W = (D_\mu \Phi)^\dagger \hat{W}^{\mu\nu} (D_\nu \Phi) ,$$

$$\mathcal{O}_B = (D_\mu \Phi)^\dagger \hat{B}^{\mu\nu} (D_\nu \Phi) ,$$

$$\mathcal{O}_{\Phi,1} = (D_\mu \Phi)^\dagger \Phi \Phi^\dagger (D^\mu \Phi) , \quad \mathcal{O}_{\Phi,2} = \frac{1}{2} \partial^\mu (\Phi^\dagger \Phi) \partial_\mu (\Phi^\dagger \Phi) ,$$

$$\mathcal{O}_{\Phi,4} = (D_\mu \Phi)^\dagger (D^\mu \Phi) (\Phi^\dagger \Phi) ,$$



$$\Delta S \propto f_{BW}$$

$$\Delta T \propto f_{\Phi,1}$$

$$H = h \left[ 1 + \frac{v^2}{2\Lambda^2} (f_{\Phi,1} + 2f_{\Phi,2} + f_{\Phi,4}) \right]^{1/2}$$

## ■ The operators $(\mathcal{O}_B, \mathcal{O}_W)$ modify the TGV

$$\mathcal{O}_W = (D_\mu \Phi)^\dagger \hat{W}^{\mu\nu} (D_\nu \Phi) , \quad \mathcal{O}_B = (D_\mu \Phi)^\dagger \hat{B}^{\mu\nu} (D_\nu \Phi)$$

$$\mathcal{L}_{WWV} = -ig_{WWV} \left\{ g_1^V \left( W_{\mu\nu}^+ W^{-\mu} V^\nu - W_\mu^+ V_\nu W^{-\mu\nu} \right) + \kappa_V W_\mu^+ W_\nu^- V^{\mu\nu} \right\} + \dots$$

[Hagiwara, Hikasa, Peccei, Zeppenfeld]

with

$$\Delta g_1^Z = g_1^Z - 1 = \frac{g^2 v^2}{8c^2 \Lambda^2} f_W$$

$$\Delta \kappa_\gamma = \kappa_\gamma - 1 = \frac{g^2 v^2}{8\Lambda^2} (f_W + f_B)$$

$$\Delta \kappa_Z = \kappa_Z - 1 = \frac{g^2 v^2}{8c^2 \Lambda^2} (c^2 f_W - s^2 f_B)$$

there are data on that.

- The Higgs the couplings to fermions are modified by

$$\mathcal{O}_{e\Phi,ij} = (\Phi^\dagger \Phi)(\bar{L}_i \Phi e_{R_j})$$

$$\mathcal{O}_{u\Phi,ij} = (\Phi^\dagger \Phi)(\bar{Q}_i \tilde{\Phi} u_{R_j})$$

$$\mathcal{O}_{d\Phi,ij} = (\Phi^\dagger \Phi)(\bar{Q}_i \Phi d_{R_j})$$

$$\mathcal{O}_{\Phi L,ij}^{(1)} = \Phi^\dagger (i \overleftrightarrow{D}_\mu \Phi) (\bar{L}_i \gamma^\mu L_j)$$

$$\mathcal{O}_{\Phi Q,ij}^{(1)} = \Phi^\dagger (i \overleftrightarrow{D}_\mu \Phi) (\bar{Q}_i \gamma^\mu Q_j)$$

$$\mathcal{O}_{\Phi e,ij}^{(1)} = \Phi^\dagger (i \overleftrightarrow{D}_\mu \Phi) (\bar{e}_{R_i} \gamma^\mu e_{R_j})$$

$$\mathcal{O}_{\Phi u,ij}^{(1)} = \Phi^\dagger (i \overleftrightarrow{D}_\mu \Phi) (\bar{u}_{R_i} \gamma^\mu u_{R_j})$$

$$\mathcal{O}_{\Phi d,ij}^{(1)} = \Phi^\dagger (i \overleftrightarrow{D}_\mu \Phi) (\bar{d}_{R_i} \gamma^\mu d_{R_j})$$

$$\mathcal{O}_{\Phi ud,ij}^{(1)} = \tilde{\Phi}^\dagger (i \overleftrightarrow{D}_\mu \Phi) (\bar{u}_{R_i} \gamma^\mu d_{R_j})$$

$$\mathcal{O}_{\Phi L,ij}^{(3)} = \Phi^\dagger (i \overleftrightarrow{D}_\mu^a \Phi) (\bar{L}_i \gamma^\mu \sigma_a L_j)$$

$$\mathcal{O}_{\Phi Q,ij}^{(3)} = \Phi^\dagger (i \overleftrightarrow{D}_\mu^a \Phi) (\bar{Q}_i \gamma^\mu \sigma_a Q_j)$$

these modify the Yukawa couplings

these modify the couplings of gauge bosons to fermions

- there are also four-fermion operators and

$$\mathcal{O}_{WWW} = \text{Tr}[\hat{W}_{\mu\nu} \hat{W}^{\nu\rho} \hat{W}_\rho^\mu]$$

- all these operators are NOT independent when we consider the equations of motion

- The right of choice

- Idea: operators related by EOM lead to the same S matrix elements [Politzer; Georgi; Artz; Simma]

- The EOM lead to the relations

$$2\mathcal{O}_{\Phi,2} - 2\mathcal{O}_{\Phi,4} = \sum_{ij} (y_{ij}^e \mathcal{O}_{e\Phi,ij} + y_{ij}^u \mathcal{O}_{u\Phi,ij} + y_{ij}^d (\mathcal{O}_{d\Phi,ij})^\dagger + \text{h.c.})$$

$$2\mathcal{O}_B + \mathcal{O}_{WB} + \mathcal{O}_{BB} + g'^2 (\mathcal{O}_{\Phi,1} - \frac{1}{2}\mathcal{O}_{\Phi,2}) = \frac{g'^2}{2} \sum_i \left( \frac{1}{2}\mathcal{O}_{\Phi L,ii}^{(1)} - \frac{1}{6}\mathcal{O}_{\Phi Q,ii}^{(1)} + \mathcal{O}_{\Phi e,ii}^{(1)} - \frac{2}{3}\mathcal{O}_{\Phi u,ii}^{(1)} + \frac{1}{3}\mathcal{O}_{\Phi d,ii}^{(1)} \right)$$

$$2\mathcal{O}_W + \mathcal{O}_{WB} + \mathcal{O}_{WW} + g^2 (\mathcal{O}_{\Phi,4} - \frac{1}{2}\mathcal{O}_{\Phi,2}) = -\frac{g^2}{4} \sum_i \left( \mathcal{O}_{\Phi L,ii}^{(3)} + \mathcal{O}_{\Phi Q,ii}^{(3)} \right)$$

with this we can further eliminate 3 operators

- Very large operator basis → we must choose it to take full advantage of the available data
- Avoid theoretical prejudice (tree vs loop, etc)
- Care is needed in the interpretation

- we choose the basis:

$$\left\{ \mathcal{O}_{GG}, \quad \mathcal{O}_{BW}, \quad \mathcal{O}_{WW}, \quad \mathcal{O}_W, \quad \mathcal{O}_B, \quad \mathcal{O}_{\Phi,1}, \quad \mathcal{O}_{f\Phi}, \quad \mathcal{O}_{\Phi f}^{(1)}, \quad \mathcal{O}_{\Phi f}^{(3)} \right\}$$

- we choose the basis:

$$\left\{ \mathcal{O}_{GG} , \cancel{\mathcal{O}_{BW}} , \mathcal{O}_{WW} , \mathcal{O}_W , \mathcal{O}_B , \cancel{\mathcal{O}_{\Phi,1}} , \cancel{\mathcal{O}_{f\Phi}} , \cancel{\mathcal{O}_{\Phi f}^{(1)}} , \cancel{\mathcal{O}_{\Phi f}^{(3)}} \right\}$$

- we choose the basis:

$$\left\{ \mathcal{O}_{GG}, \cancel{\mathcal{O}_{BW}}, \mathcal{O}_{WW}, \mathcal{O}_W, \mathcal{O}_B, \cancel{\mathcal{O}_{\Phi,1}}, \cancel{\mathcal{O}_{f\Phi}}, \cancel{\mathcal{O}_{\Phi f}^{(1)}}, \cancel{\mathcal{O}_{\Phi f}^{(3)}} \right\}$$

- after discarding the constrained operators  $\rightarrow$  13:
  - too many!
- 9 fermions:  $\mathcal{O}_{e\Phi,jj}, \mathcal{O}_{u\Phi,jj}, \mathcal{O}_{d\Phi,jj}$ 
  - neglecting the effects of couplings to first two generations
  - due to small statistics we trade  $f_{top} \rightarrow f_g$  and  $f_{WW}$
- gauge bosons:  $\mathcal{O}_W, \mathcal{O}_B, \mathcal{O}_{WW}, \mathcal{O}_{GG}$

- Summarizing:

coefficients related by gauge invariance

	$hgg$	$h\gamma\gamma$	$h\gamma Z$	$hZZ$	$hW^+W^-$	$\gamma W^+W^-$	$ZW^+W^-$
$\mathcal{O}_{GG}$	✓						
$\mathcal{O}_{WW}$		✓	✓	✓	✓		
$\mathcal{O}_B$			✓	✓		✓	✓
$\mathcal{O}_W$			✓	✓	✓	✓	✓

supplemented by shifts in the Yukawa couplings (3rd family)

nice feature: dimension-six operators lead to relations between anomalous couplings

## • Summarizing:

coefficients related by gauge invariance

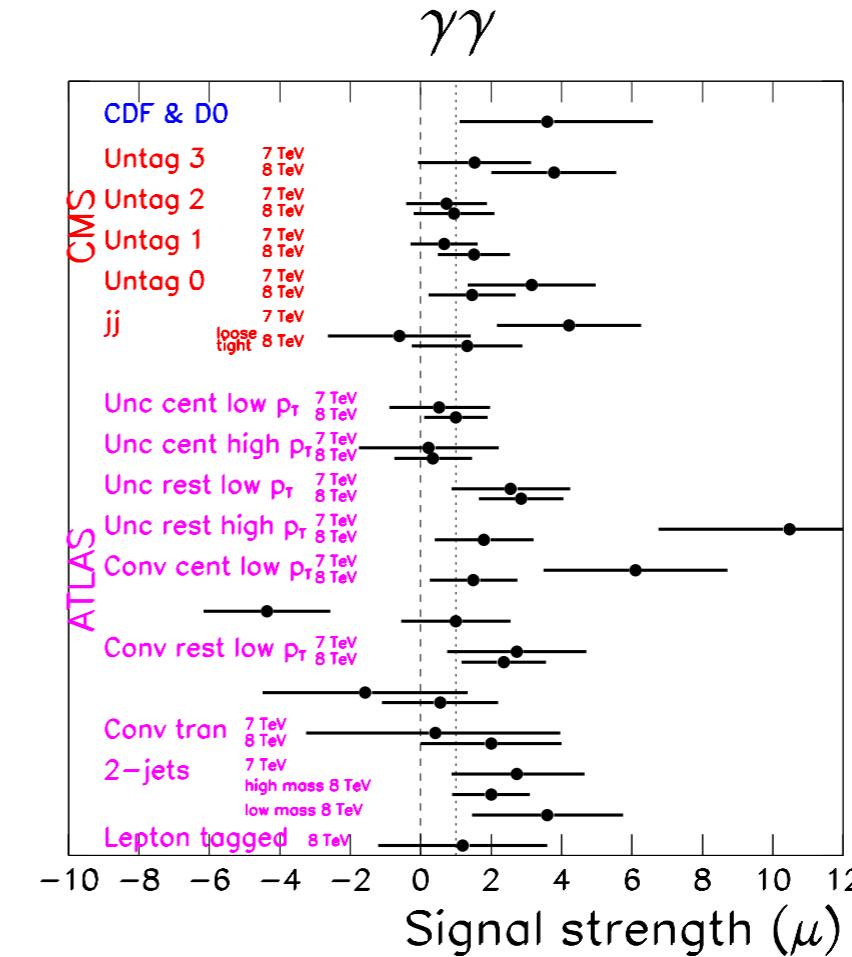
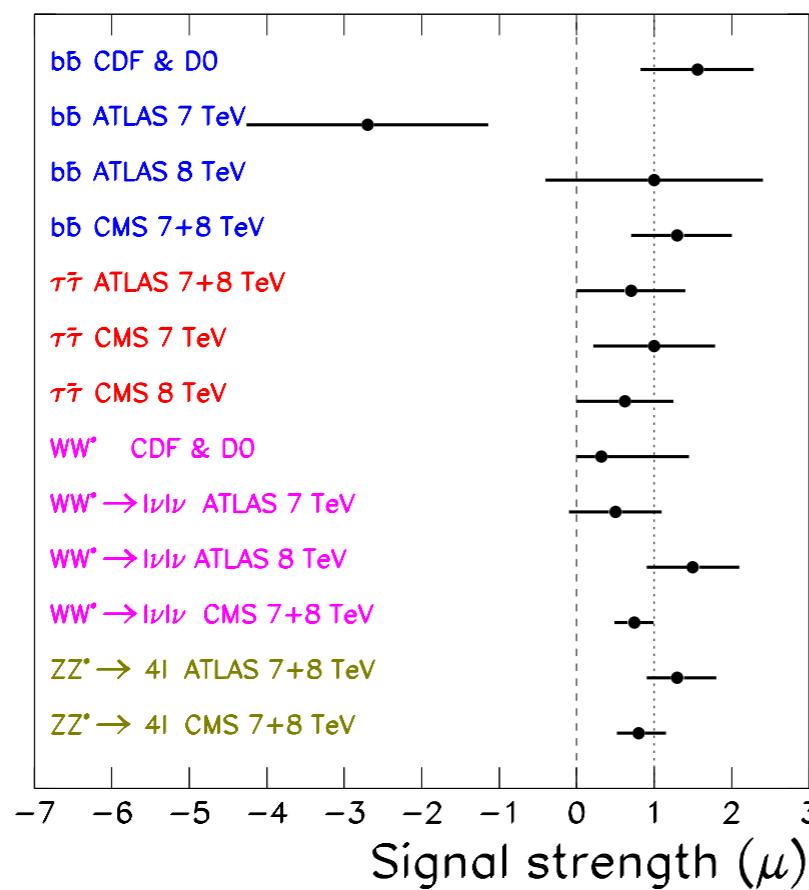
	$hgg$	$h\gamma\gamma$	$h\gamma Z$	$hZZ$	$hW^+W^-$	$\gamma W^+W^-$	$ZW^+W^-$
$\mathcal{O}_{GG}$	✓						
$\mathcal{O}_{WW}$		✓	✓	✓	✓		
$\mathcal{O}_B$		✓	✓	✓		✓	✓
$\mathcal{O}_W$		✓	✓	✓	✓	✓	✓

supplemented by shifts in the Yukawa couplings (3rd family)

$$\mathcal{L}_{eff} = -\frac{\alpha_s v}{8\pi} \frac{f_g}{\Lambda^2} \mathcal{O}_{GG} + \frac{f_{WW}}{\Lambda^2} \mathcal{O}_{WW} + \frac{f_W}{\Lambda^2} \mathcal{O}_W + \frac{f_B}{\Lambda^2} \mathcal{O}_B + \frac{f_{bot}}{\Lambda^2} \mathcal{O}_{d\Phi,33} + \frac{f_\tau}{\Lambda^2} \mathcal{O}_{e\Phi,33}$$

# Fitting procedure

- Inputs: signal strength for the different channels  $\mu = \frac{\sigma_{obs}}{\sigma_{SM}}$
- using all available data



- The statistical analyses were done using

$$\chi^2 = \min_{\xi_{pull}} \sum_j \frac{(\mu_j - \mu_j^{\exp})^2}{\sigma_j^2} + \sum_{pull} \left( \frac{\xi_{pull}}{\sigma_{pull}} \right)^2$$

- we also can use the data on

**EWPT:**

$$\Delta S_{PDG} = 0.00 \pm 0.10$$

$$\Delta T_{PDG} = 0.02 \pm 0.11$$

$$\Delta U_{PDG} = 0.03 \pm 0.09$$

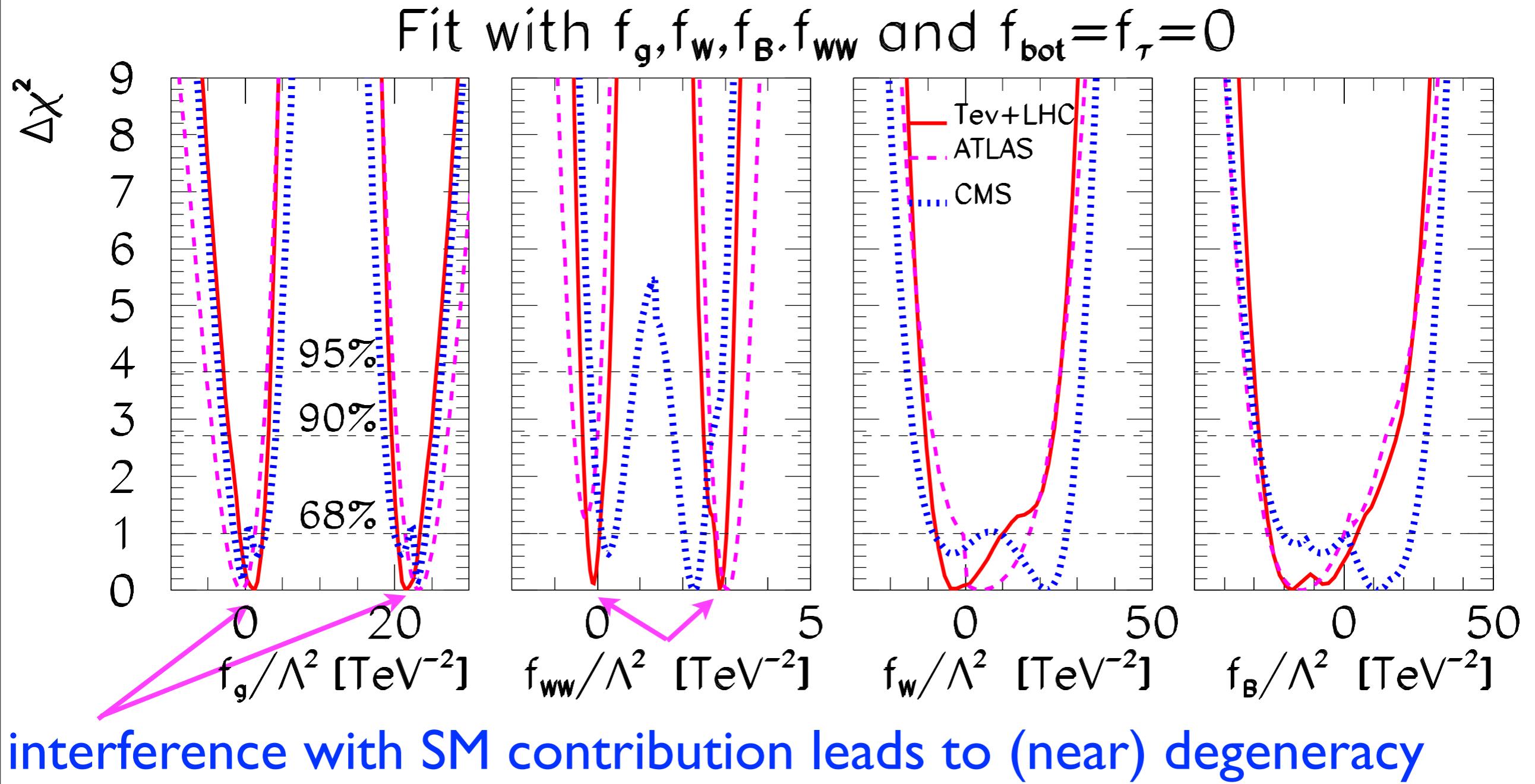
$$\rho = \begin{pmatrix} 1 & 0.89 & -0.55 \\ 0.89 & 1 & -0.8 \\ -0.55 & -0.8 & 1 \end{pmatrix}$$

**TGV bounds:**

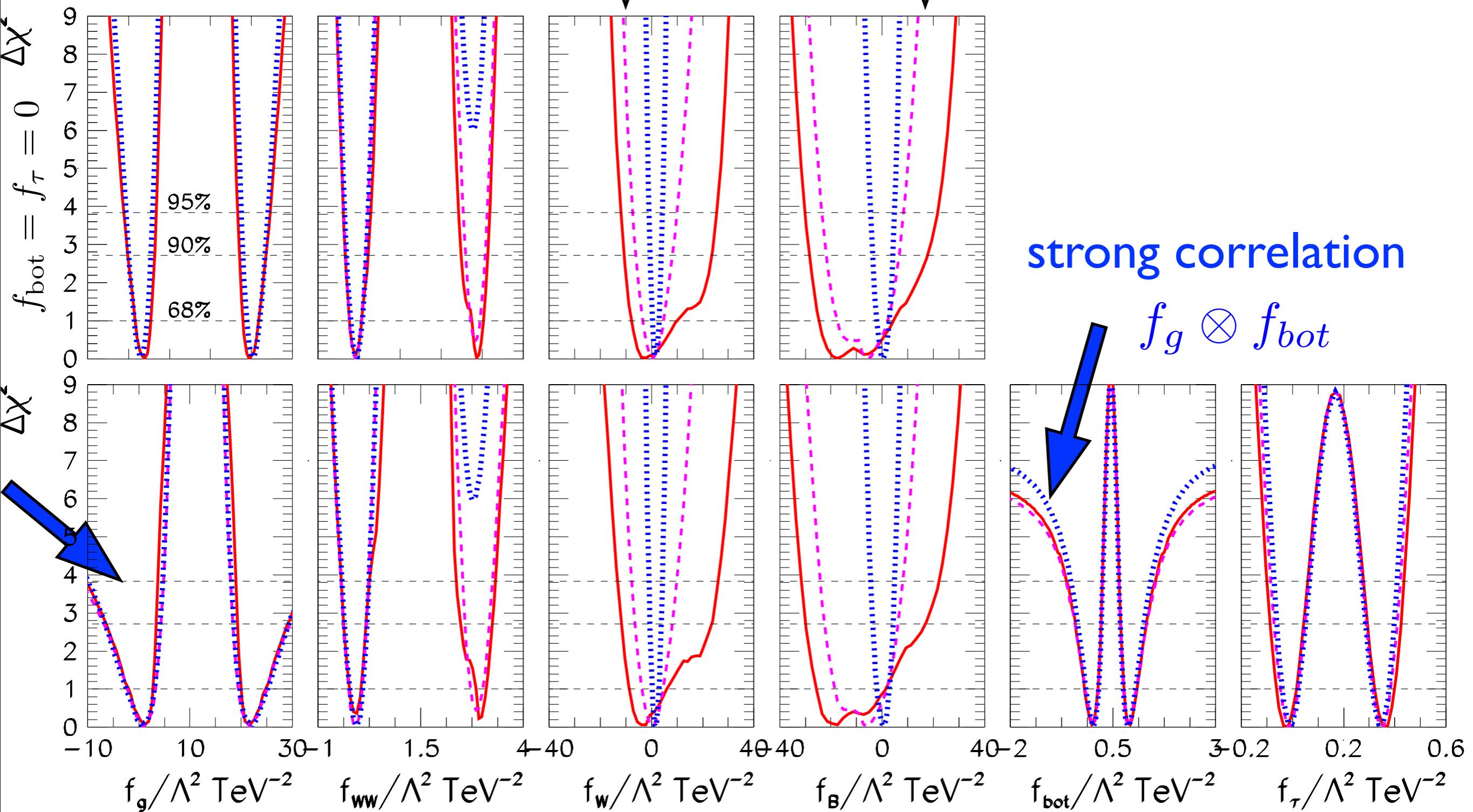
$g_1^Z$	$\kappa_\gamma$	$\kappa_Z$	Ref	Asummption
$0.984^{+0.022}_{-0.019}$	$0.973^{+0.044}_{-0.045}$	$0.924^{+0.059}_{-0.056}$	PDG	1-par fit (others SM)
$1.004^{+0.024}_{-0.025}$	$0.984^{+0.049}_{-0.049}$	GI: $\kappa_Z = g_1^Z - (\kappa_\gamma - 1)s^2/c^2$	LEPEWWG	2-par fit with GI, $\rho = 0.11$

# Results

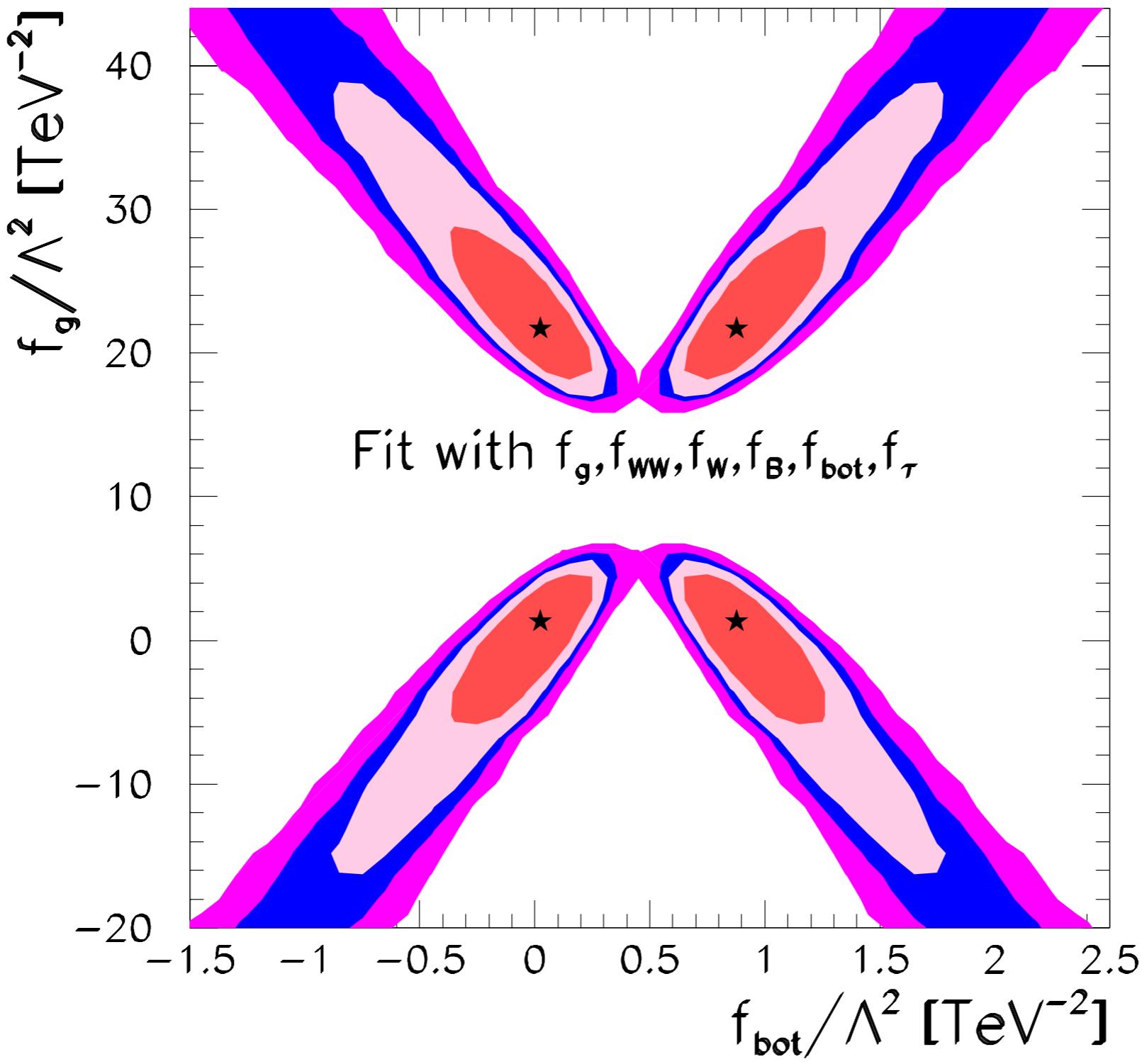
- Comparison of the fits to ATLAS and CMS data



# Higgs + TGC + EWPT



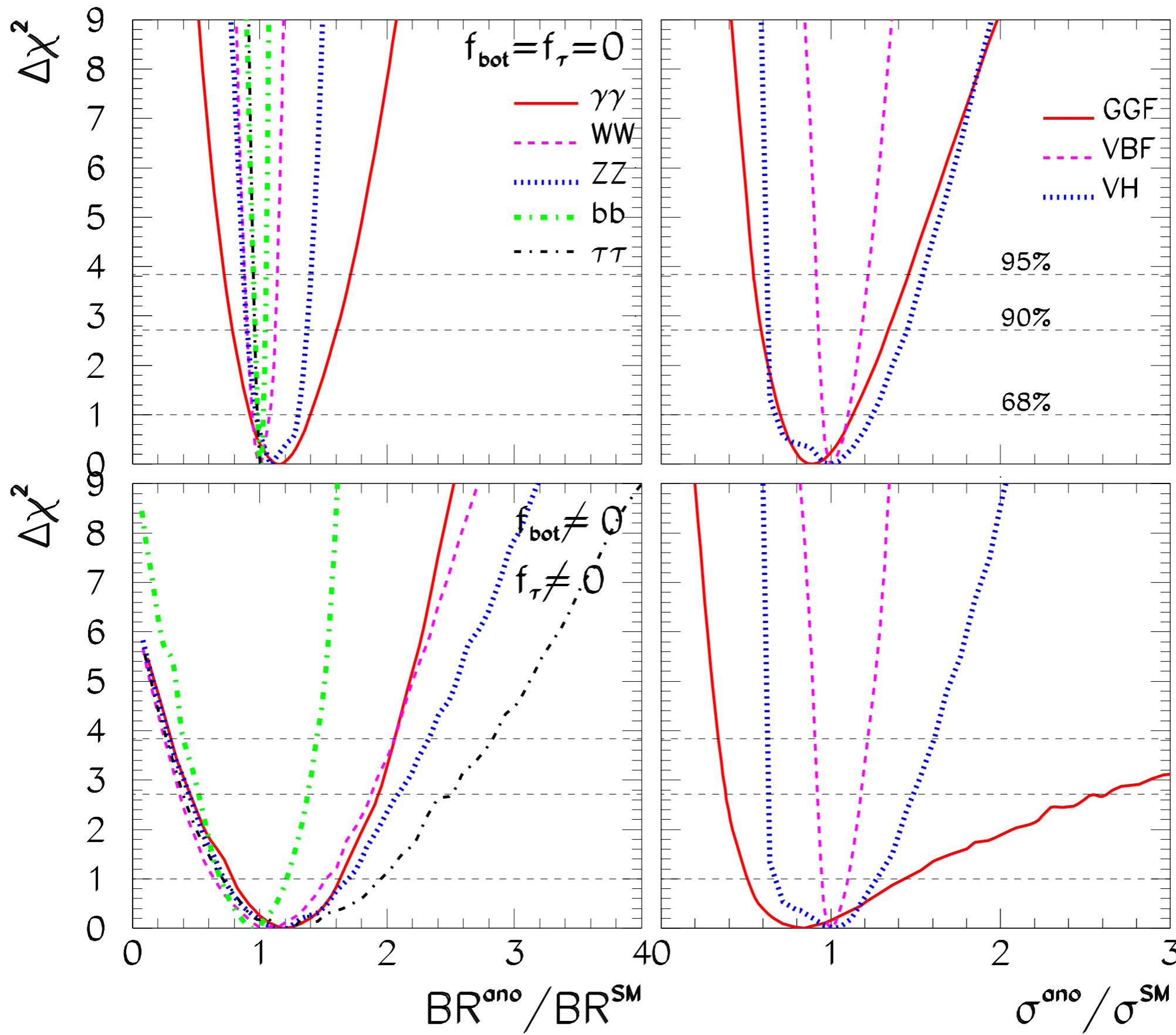
Tevatron+LHC+TGV



$$\sigma(pp \rightarrow h \rightarrow \gamma\gamma) \propto \frac{f_g^2}{f_{\text{bot}}^2}$$

# cross sections and branching ratios

Tevatron+LHC+TGV

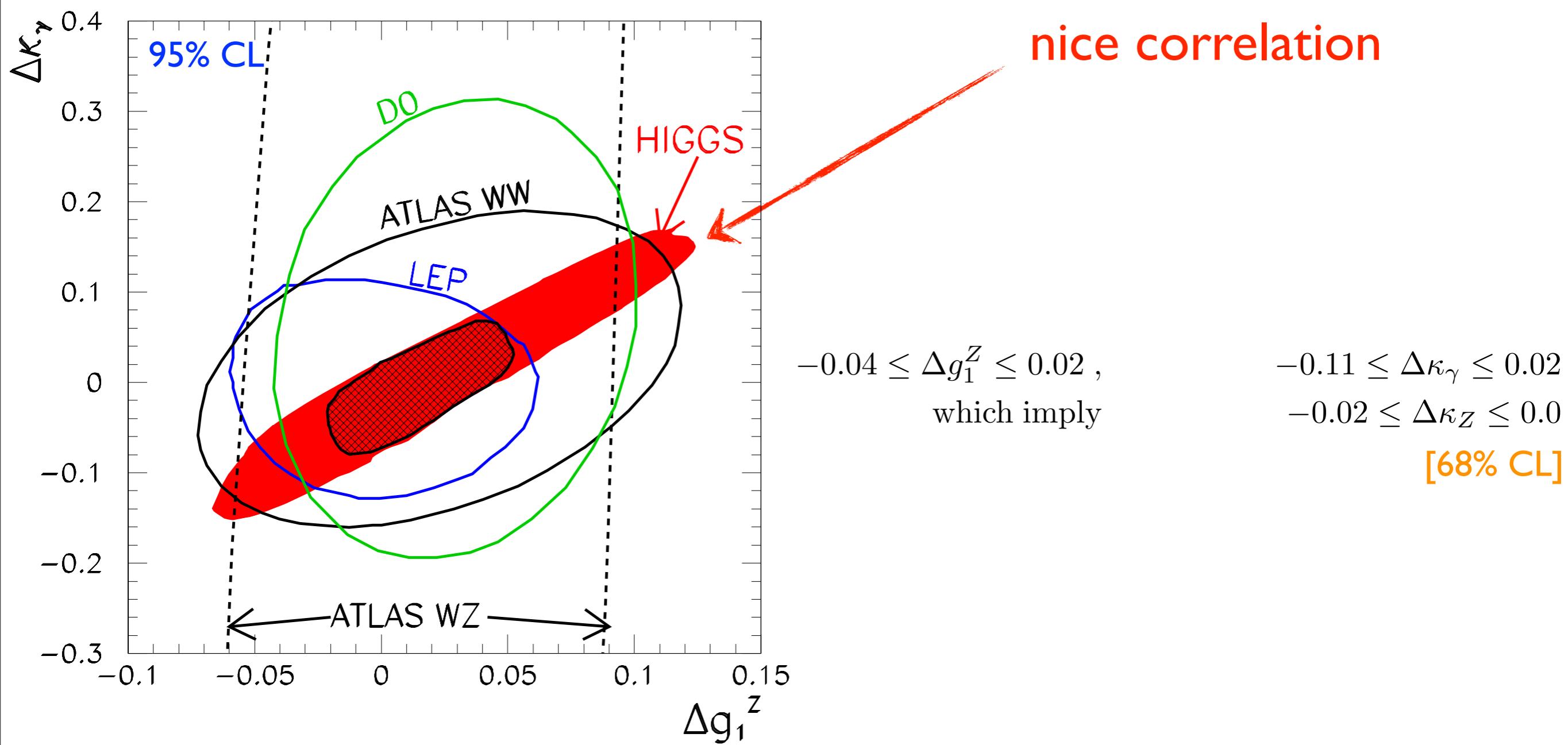


# Impact on the TGCs

[Campos, Gonzalez-Garcia, Novaes]

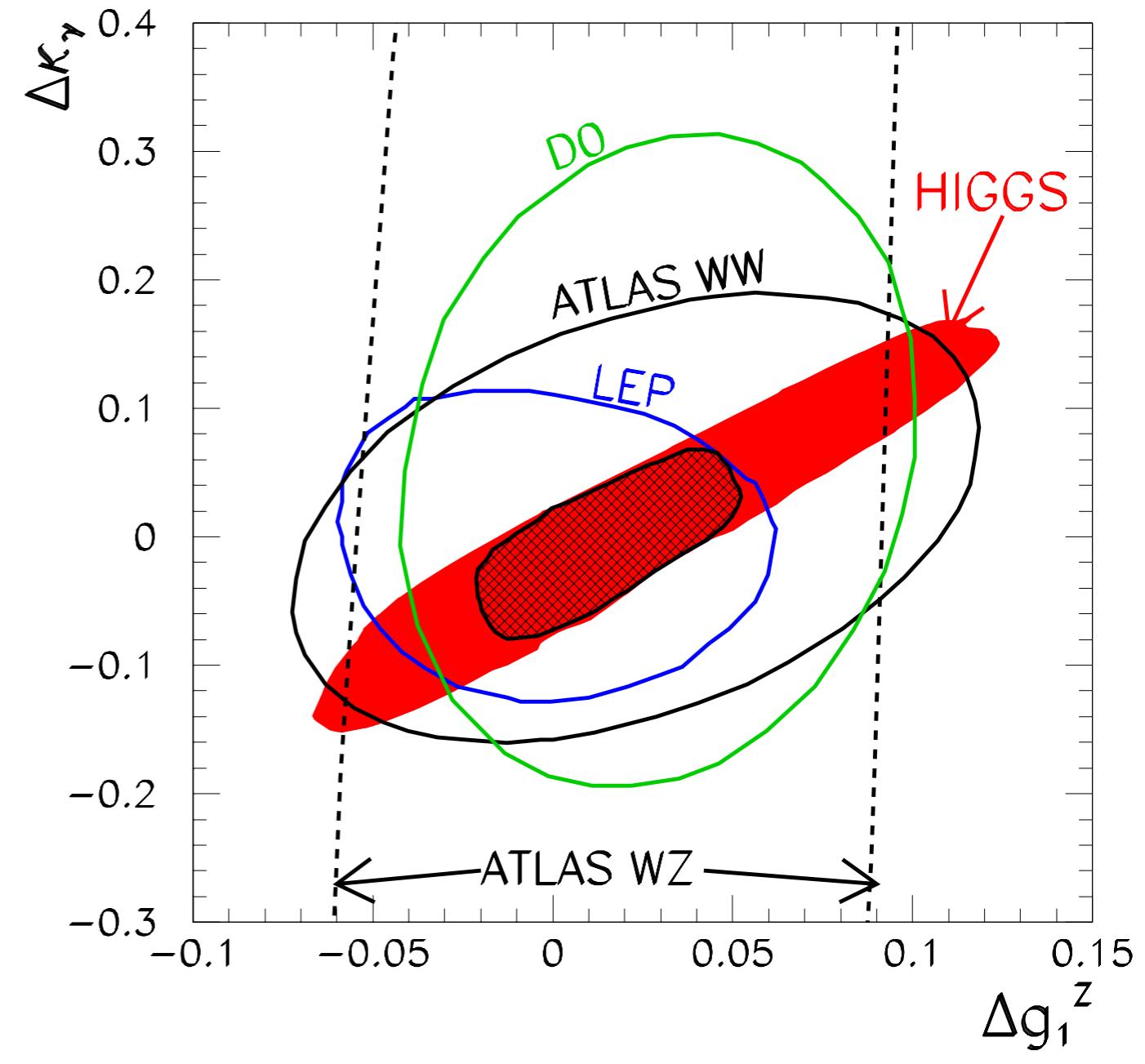
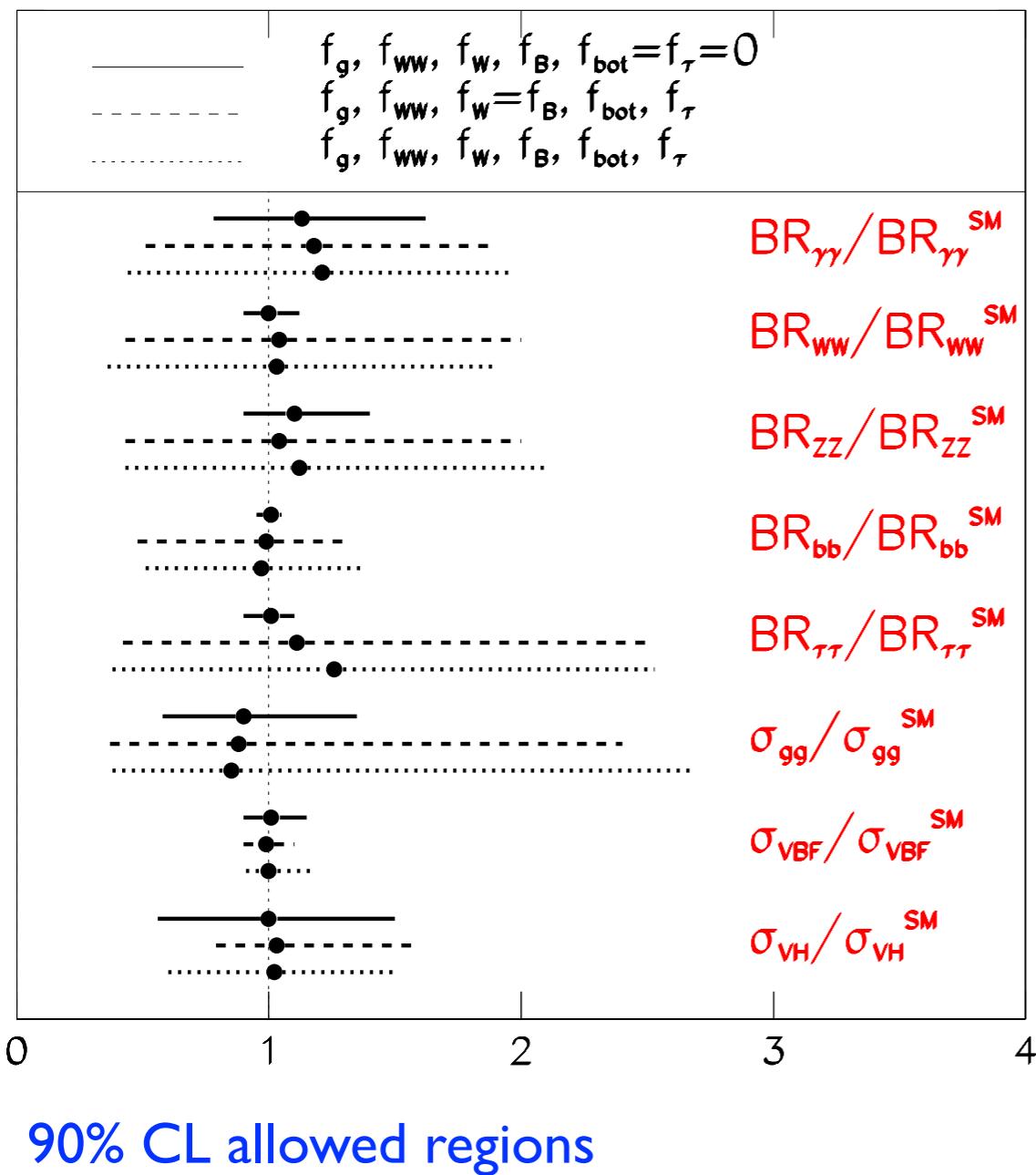
- We performed the fitting to Higgs data without TGC data

$$\Delta\chi^2_H(\Delta\kappa_\gamma, \Delta g_1^Z) = \min_{f_g, f_{WW}, f_{\text{bot}}, f_\tau} \Delta\chi^2_H(f_g, f_{WW}, f_{\text{bot}}, f_\tau, f_B, f_W)$$



# Conclusion

- we can constrain Higgs couplings and TGCs as well.  
both measurements can profit from the basis choice



$$\Delta g_1^Z = 0.012^{+0.014}_{-0.015}, \quad \Delta \kappa_\gamma = -0.006^{+0.04}_{-0.03}$$

# THANK YOU

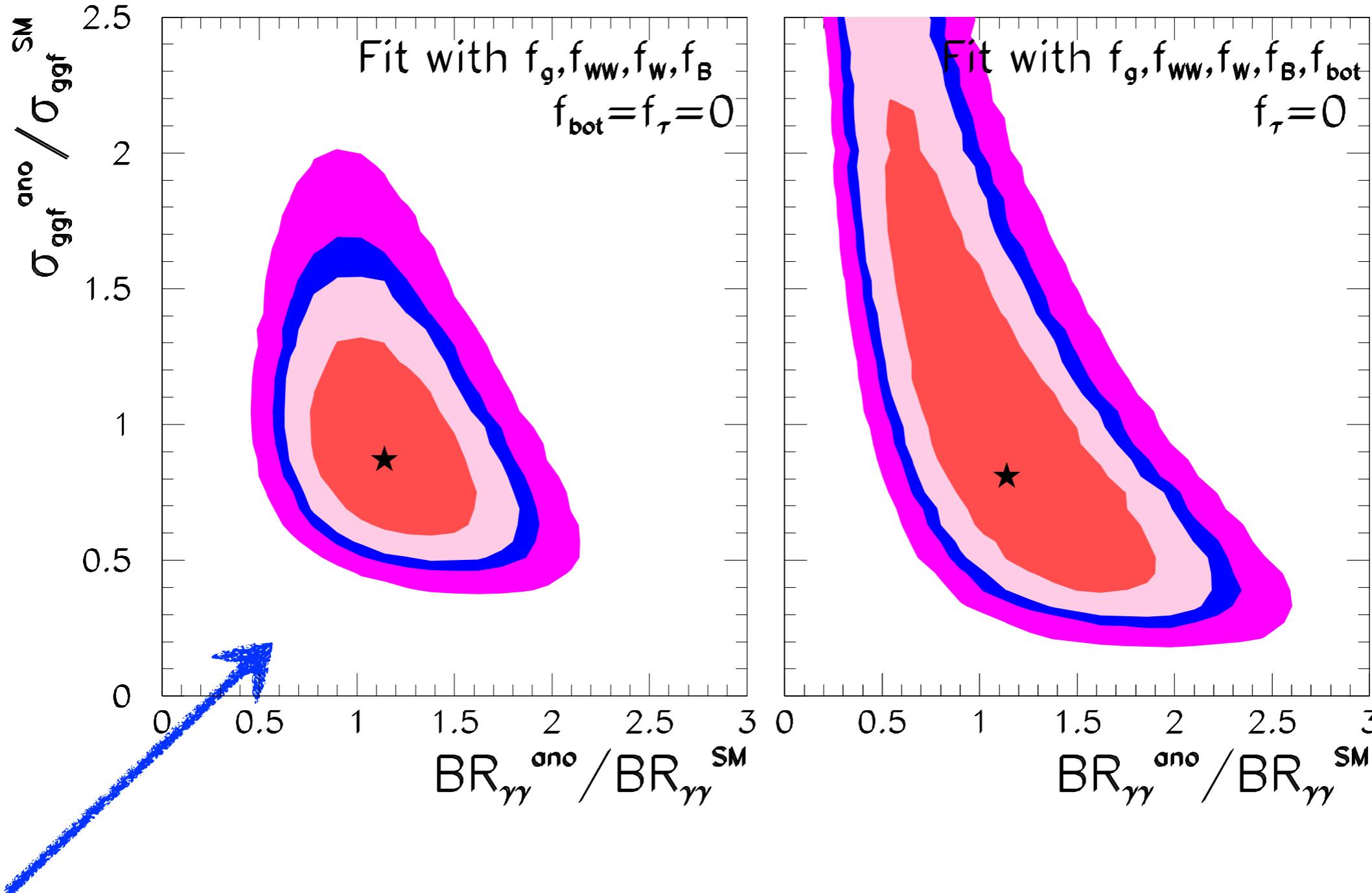
updated results at <http://hep.if.usp.br/Higgs>

# **BACKUP SLIDES**

	Fit with $f_{bot} = f_\tau = 0$		Fit with $f_{bot}$ and $f_\tau$	
	Best fit	90% CL allowed range	Best fit	90% CL allowed range
$f_g/\Lambda^2$ (TeV $^{-2}$ )	0.64, 22.1	[-1.8, 2.7] $\cup$ [20, 25]	0.92, 21.8	[-7.1, 4.4] $\cup$ [18, 30]
$f_{WW}/\Lambda^2$ (TeV $^{-2}$ )	-0.083	[-0.35, 0.15] $\cup$ [2.6, 3.05]	-0.11	[-0.40, 0.18] $\cup$ [2.6, 3.2]
$f_W/\Lambda^2$ (TeV $^{-2}$ )	0.35	[-6.2, 8.4]	-0.032	[-6.7, 8.3]
$f_B/\Lambda^2$ (TeV $^{-2}$ )	-5.9	[-22, 6.7]	-6.2	[-23, 6.5]
$f_{bot}/\Lambda^2$ (TeV $^{-2}$ )	—	—	0.01, 0.89	[-0.44, 0.22] $\cup$ [0.68, 1.3]
$f_\tau/\Lambda^2$ (TeV $^{-2}$ )	—	—	-0.02, 0.36	[-0.07, 0.05] $\cup$ [0.29, 0.41]
$BR_{\gamma\gamma}^{ano}/BR_{\gamma\gamma}^{SM}$	1.13	[0.78, 1.62]	1.21	[0.44, 1.95]
$BR_{WW}^{ano}/BR_{WW}^{SM}$	1.00	[0.9, 1.12]	1.03	[0.36, 1.9]
$BR_{ZZ}^{ano}/BR_{ZZ}^{SM}$	1.10	[0.9, 1.4]	1.12	[0.43, 2.1]
$BR_{bb}^{ano}/BR_{bb}^{SM}$	1.01	[0.95, 1.05]	0.97	[0.51, 1.38]
$BR_{\tau\tau}^{ano}/BR_{\tau\tau}^{SM}$	1.01	[0.9, 1.1]	1.26	[0.38, 2.5]
$\sigma_{gg}^{ano}/\sigma_{gg}^{SM}$	0.90	[0.58, 1.35]	0.85	[0.38, 2.7]
$\sigma_{VH}^{ano}/\sigma_{VH}^{SM}$	1.0	[0.56, 1.5]	1.02	[0.6, 1.5]

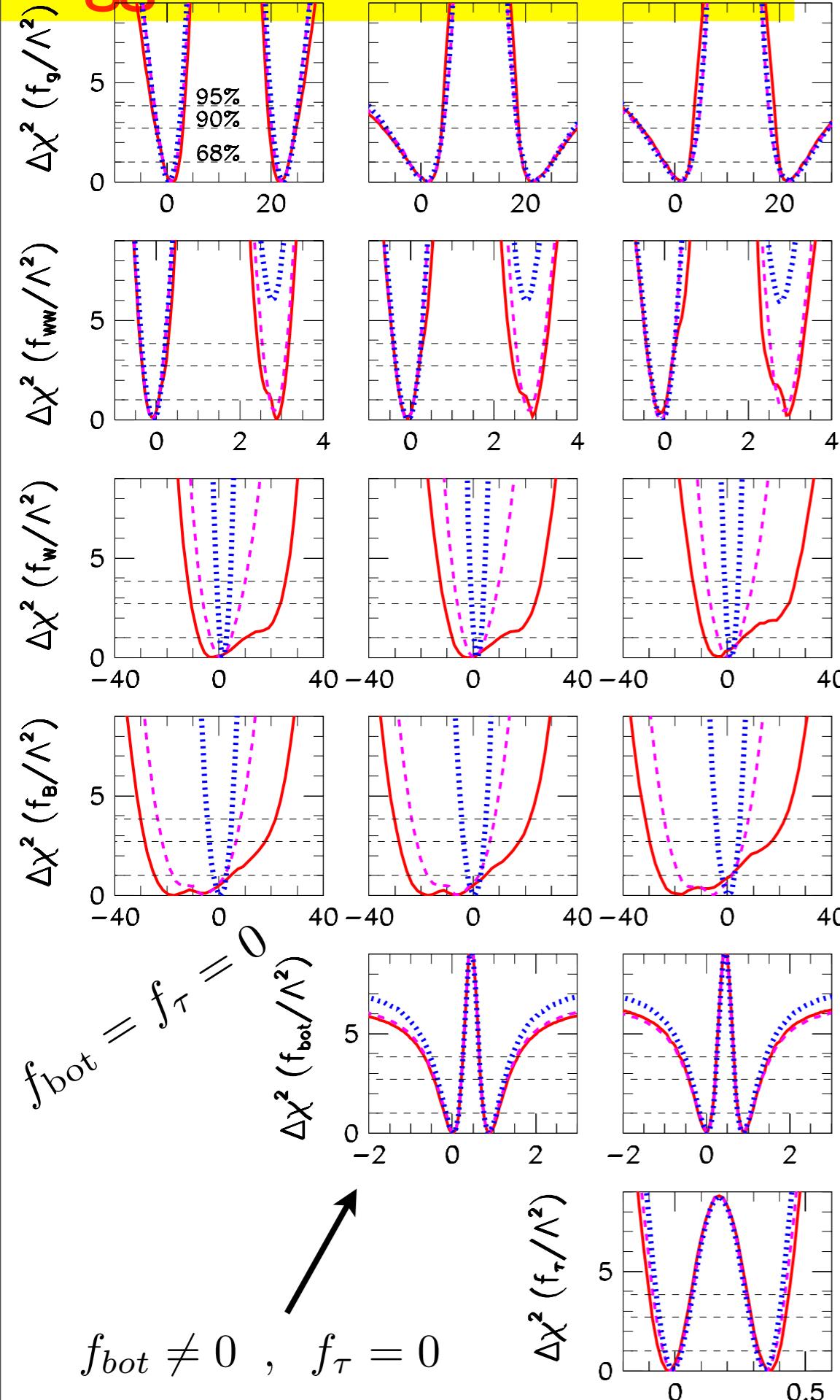
# interesting correlations

Tevatron+LHC+TGV

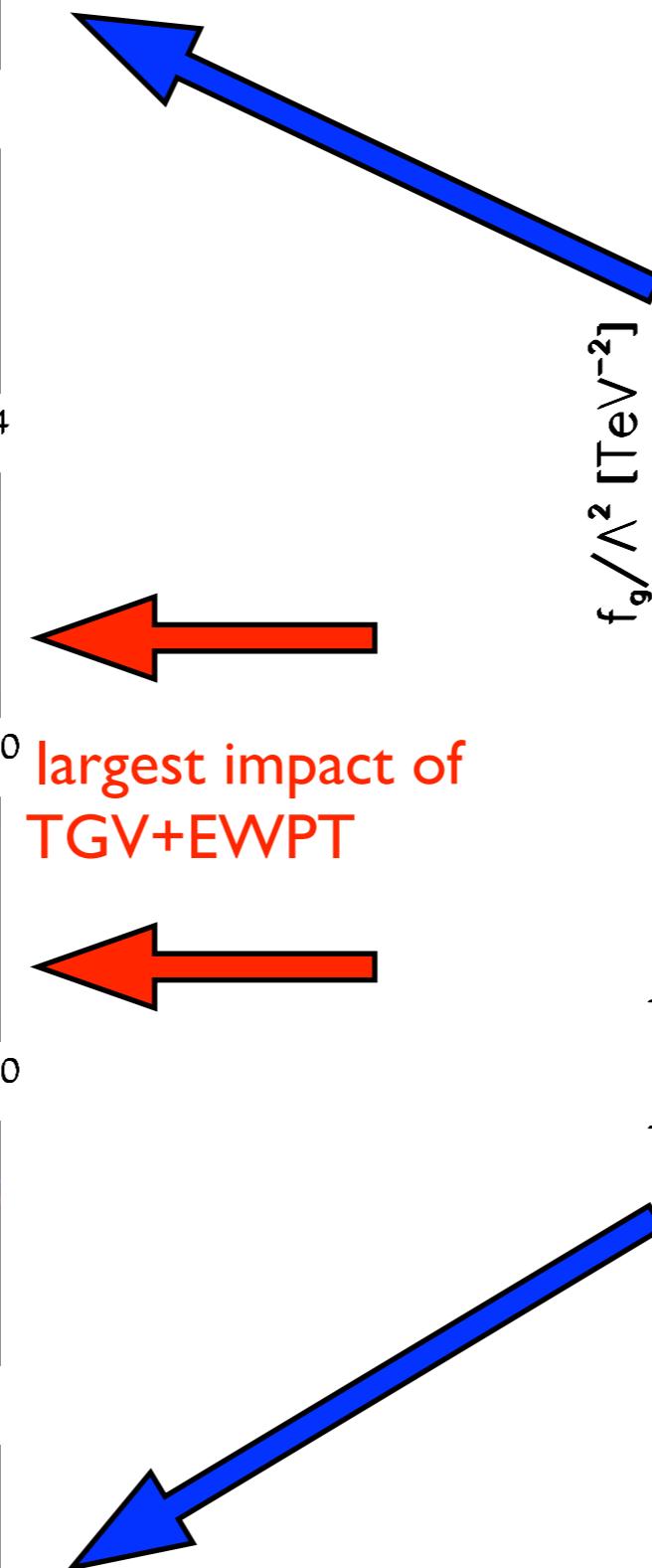
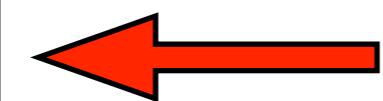


due to the diphoton channel

# Higgs + TGV + EWPT



largest impact of  
TGV+EWPT



strong correlation

$$\sigma(pp \rightarrow h \rightarrow \gamma\gamma) \propto \frac{f_g^2}{f_{bot}^2}$$

$$f_g \otimes f_{bot}$$

$$\frac{f_g^2}{f_{bot}^2}$$