Interplay between
Vertex Corrections and aTGC

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Ongoing collaboration with C. Grojean and M. Riembau

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The LHC has still not found any new physics yet…

Assuming new physics is heavy we can study their effects via EFT

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_i \frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_i \frac{c_i^{(8)}}{\Lambda^4}\mathcal{O}_i^{(8)} + \cdots$$

-Systematic way to test possible deformations of the SM

- Easy to match to UV

- One can make assumptions for classes of theories to simplify it

    - Power counting

    - Flavour

LEP already tested parts of the SM EFT with good accuracy

Focusing in the EW sector we have two types of operators

Operators well measured **LEP**

- Modify **Zff** error LEP $\sim 0.1\% - 1\%$ (*)

- Modify **TGC** error LEP $\sim 1\%$

Operators ONLY measured at **LHC**

- Modify **Higgs** error LHC $\sim 10\%$

if **LHC** has systematics $\sim 10\%$

Q: Can it be used to improve LEP bounds?

* depending on UV assumptions

Answer: In some cases

1) If a process has a cross section that grows with energy

$$\sigma \sim 1 + E^2/\Lambda^2$$

$$10\% \text{ precision at } \sim 2\text{TeV} \quad \longleftrightarrow \quad 0.1\% \text{ precision at } \sim 200\text{GeV}$$

2) If enough statistics, then it is possible to beat LEP

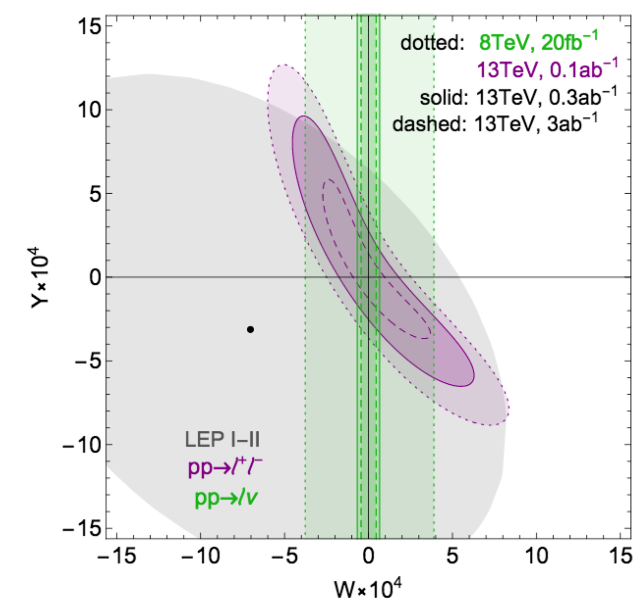
e.g.

- Drell-Yan

Farina et al 1609.08157

Parameters Y, W (4-fermions)

better than LEP



- Diboson production

Butter et al 1604.03105

anomalous Triple Gauge Couplings

better than LEP2

*for certain theories

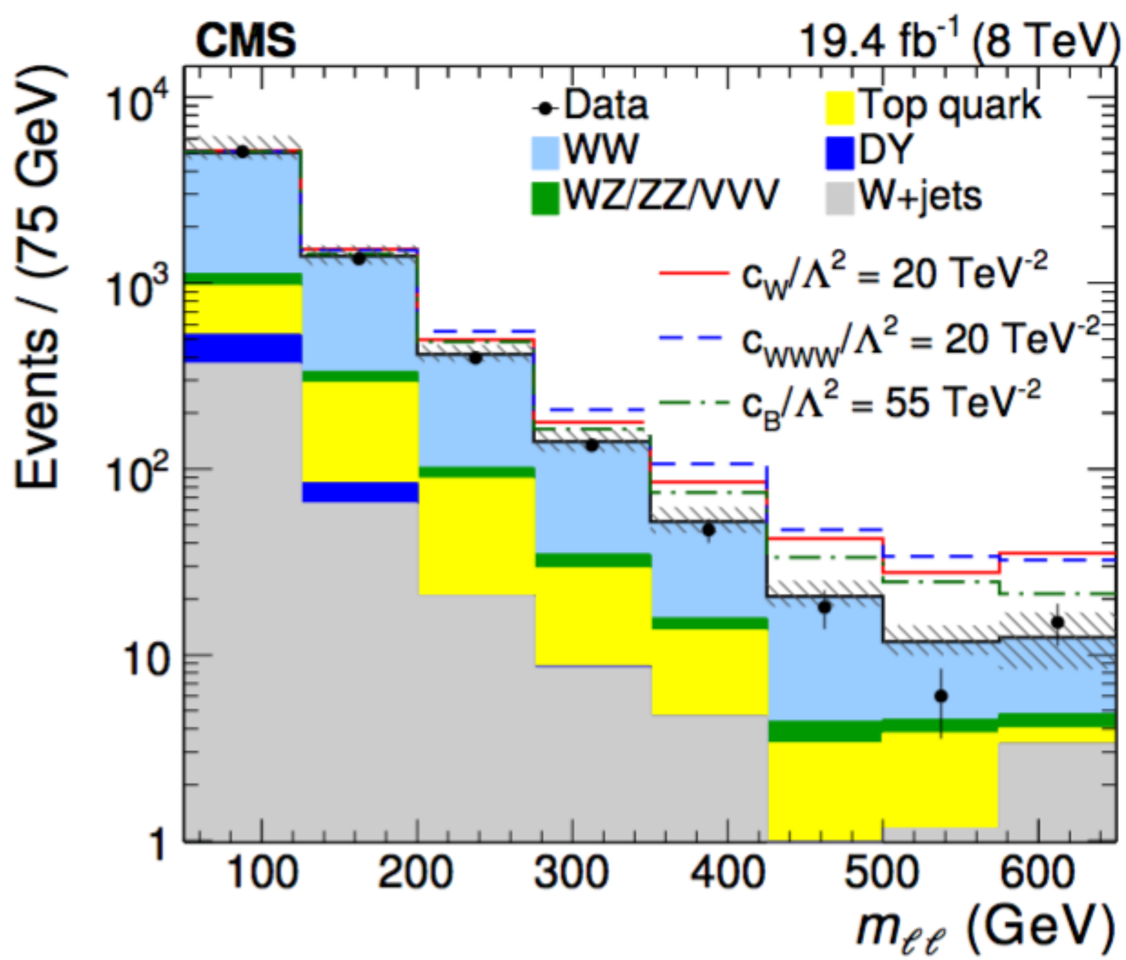
In our work we focus on **diboson production at the LHC**

In our work we focus on **diboson production at the LHC**

First, let's check that:

1) Systematics and statistics under control (at high E)

e.g. $$p\,p \to WW$$



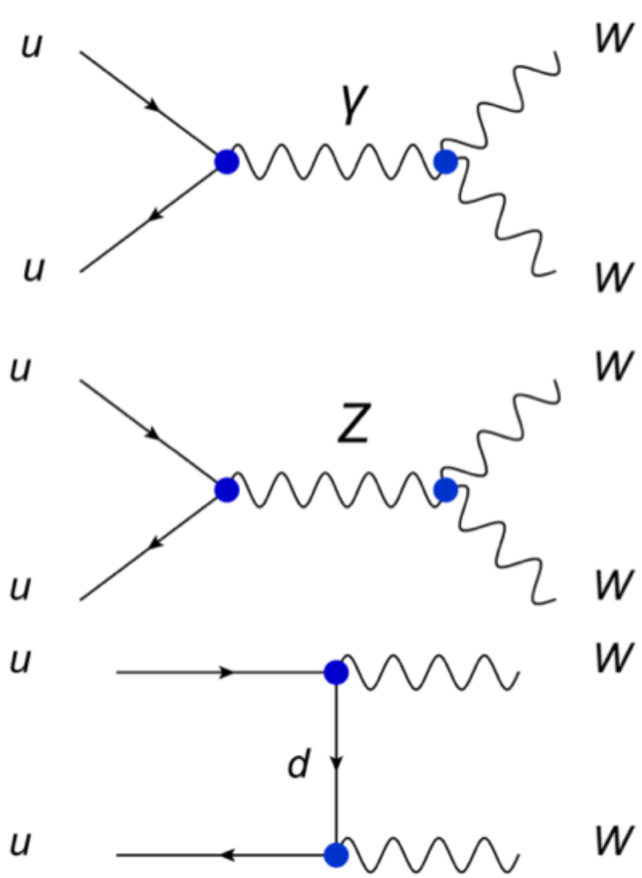
1507.03268

systematics + statistics $\sim 10\%$

2) Growth with Energy $pp \to WW$

Simple way to see it is looking at the SM contributions to

Each diagram grows with energy



$$\mathcal{M}_\gamma = -i\frac{e^2 \sin\theta}{2m_W^2}\, s\, Q_f$$

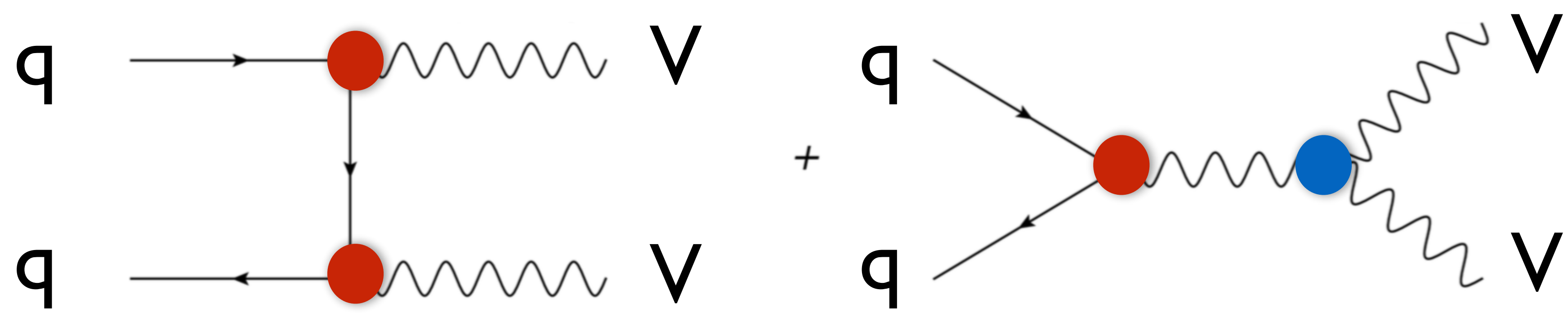
$$\mathcal{M}_Z = -i\frac{e^2 \sin\theta}{2m_W^2}\, \frac{s}{s_W^2}\, (T_f^3 - s_W^2 Q_f)$$

$$\mathcal{M}_t = +i\frac{e^2 \sin\theta}{2m_W^2}\, \frac{s}{2s_W^2}$$

Sum does not grow with energy, as expected.
However, it is obvious that any deviation from the SM relation will be amplified at large energies.

slide by M. Riembau

In the Higgs basis we have one or more coefficients modifying each vertex



TGC vertices

$$\begin{aligned}\mathcal{L}_{\rm tgc} &= ie\left(W^+_{\mu\nu}W^-_\mu - W^-_{\mu\nu}W^+_\mu\right)A_\nu + ie\left[(1+\delta\kappa_\gamma)A_{\mu\nu}\,W^+_\mu W^-_\nu\right]\\ &+ igc_\theta\left[(1+\delta g_{1,z})\left(W^+_{\mu\nu}W^-_\mu - W^-_{\mu\nu}W^+_\mu\right)Z_\nu + (1+\delta\kappa_z)\,Z_{\mu\nu}\,W^+_\mu W^-_\nu\right]\\ &+ i\frac{e}{m_W^2}\left[\lambda_\gamma W^+_{\mu\nu}W^-_{\nu\rho}A_{\rho\mu}\right] + i\frac{gc_\theta}{m_W^2}\left[\lambda_z W^+_{\mu\nu}W^-_{\nu\rho}Z_{\rho\mu}\right],\end{aligned}$$

SM-like

Not in SM (they grow due more derivaties)

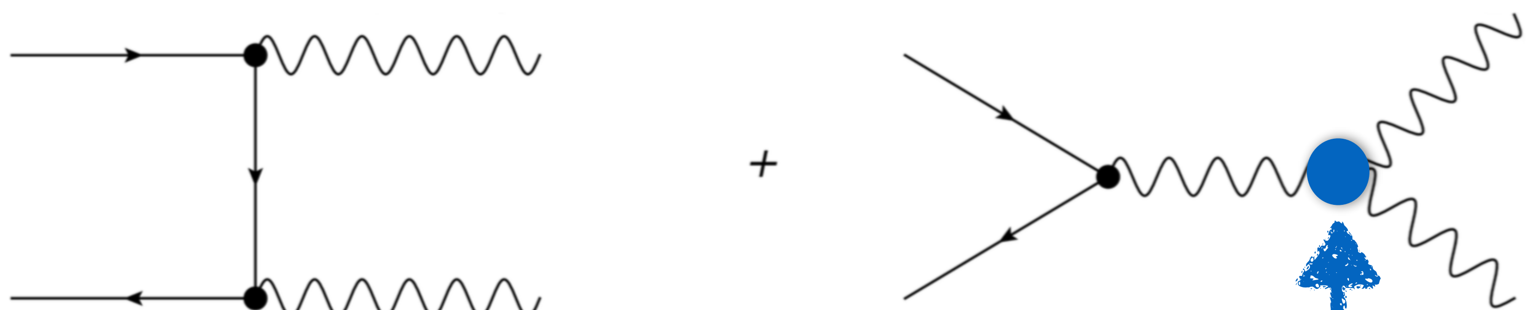
Zqq vertices

Not in SM

$$\begin{aligned}\mathcal{L}_{\rm vertex} &= \frac{g}{\sqrt{2}}\left(W^+_\mu\bar{\nu}_L\gamma_\mu\left(I_3+\delta g_L^{W\ell}\right)e_L + W^+_\mu\bar{u}_L\gamma_\mu\left(I_3+\delta g_L^{Wq}\right)d_L + W^+_\mu\bar{u}_R\gamma_\mu\delta g_R^{Wq}d_R + \text{h.c.}\right)\\ &+ \sqrt{g^2+g'^2}Z_\mu\left[\sum_{f\in u,d,e,\nu}\bar{f}_L\gamma_\mu\left(T^3_f - s^2_\theta Q_f + \delta g_L^{Zf}\right)f_L + \sum_{f\in u,d,e}\bar{f}_R\gamma_\mu\left(-s^2_\theta Q_f + \delta g_R^{Zf}\right)f_R\right]\end{aligned}$$

1) dipoles neglected (MFV) | 2) Ops. are dim. 6 | 3) Mw shift neglected

In the Higgs basis we have one or more coefficients modifying each vertex



TGC vertices

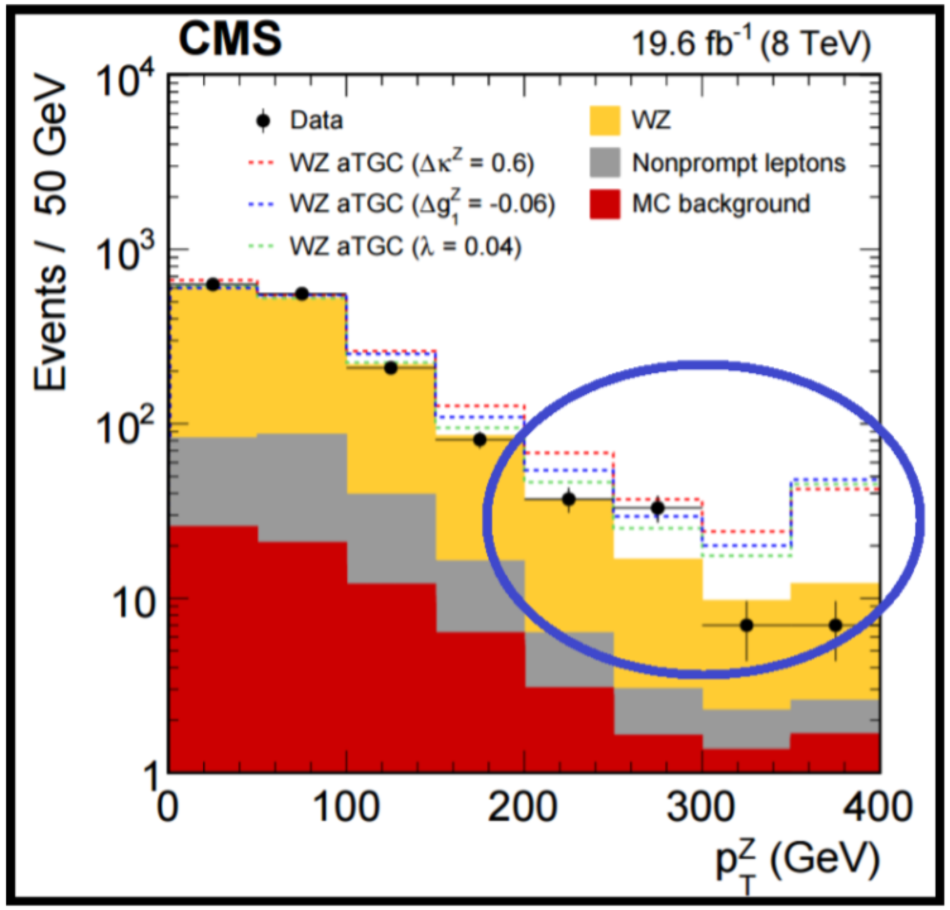
$$
\begin{aligned}
\mathcal{L}_{\rm tgc} \;=\;& ie\left(W^+_{\mu\nu}W^-_\mu - W^-_{\mu\nu}W^+_\mu\right)A_\nu + ie\left[(1+\delta\kappa_\gamma)A_{\mu\nu}\,W^+_\mu W^-_\nu\right] \\
+\;& igc_\theta\left[(1+\delta g_{1,z})\left(W^+_{\mu\nu}W^-_\mu - W^-_{\mu\nu}W^+_\mu\right)Z_\nu + (1+\delta\kappa_z)\,Z_{\mu\nu}\,W^+_\mu W^-_\nu\right] \\
+\;& i\frac{e}{m_W^2}\left[\lambda_\gamma W^+_{\mu\nu}W^-_{\nu\rho}A_{\rho\mu}\right] + i\frac{gc_\theta}{m_W^2}\left[\lambda_z W^+_{\mu\nu}W^-_{\nu\rho}Z_{\rho\mu}\right],
\end{aligned}
$$

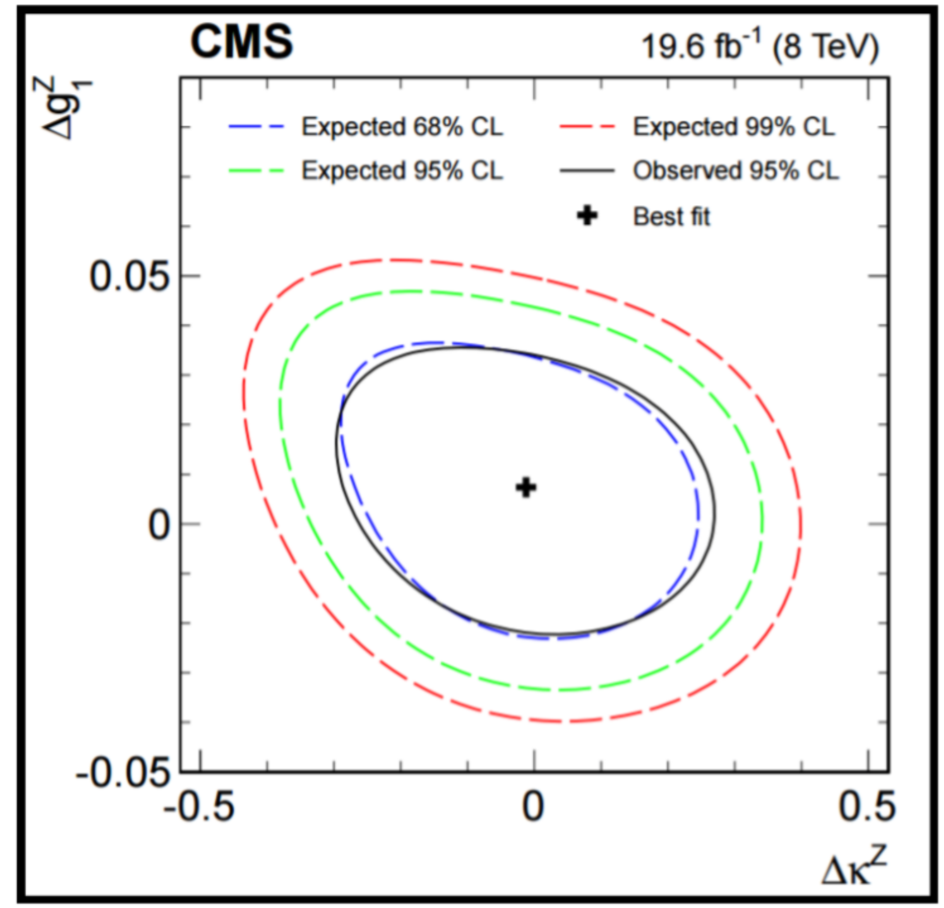
Zqq vertices

$$
\begin{aligned}
\mathcal{L}_{\rm vertex} \;=\;& \frac{g}{\sqrt{2}}\left(W^+_\mu\bar{\nu}_L\gamma_\mu\left(I_3+\delta g_L^{W\ell}\right)e_L + W^+_\mu\bar{u}_L\gamma_\mu\left(I_3+\delta g_L^{Wq}\right)d_L + W^+_\mu\bar{u}_R\gamma_\mu\delta g_R^{Wq}d_R + \text{h.c.}\right) \\
+\;& \sqrt{g^2+g'^2}Z_\mu\left[\sum_{f\in u,d,e,\nu}\bar{f}_L\gamma_\mu\left(T^3_f - s^2_\theta Q_f + \delta g_L^{Zf}\right)f_L + \sum_{f\in u,d,e}\bar{f}_R\gamma_\mu\left(-s^2_\theta Q_f + \delta g_R^{Zf}\right)f_R\right]
\end{aligned}
$$

dipoles neglected (MFV)

aTGC fits are being done neglecting those contributions





likelihood method, Wald gaussian approximation, and Wilks' theorem [59] are used to derive 1D and 2D limits at a 95% confidence level (CL) on each of the three aTGC parameters and every combination of two aTGC parameters, respectively, while all other parameters are set to their SM values. No significant deviation from the SM expectation is observed. Results can be found in Tables 8 and 9, and in Figs. 8, 9, and 10.

Is this still justified?

Previous works raised doubts: Falkowski 1508.00581, Zhang 1610.01618,

First we look at the Diboson amplitudes *WW, WZ* at High E (most sensitive)

Process	Higgs basis	Warsaw basis
$\bar{f}_L f_L \to W_T^\pm + Z_T$	λ_γ	c_{3W}
$\bar{d}_R u_L \to W_L^+ Z_L$ $\bar{u}_R d_L \to W_L^- Z_L$	$2\,(\delta g_L^{Zd} - \delta g_L^{Zu}) + \cos\theta_W\,\delta g_{1z}$	$c_{Hq}^{(3)}$
$\bar{f}_R f_L \to W_T^+ W_T^-$	λ_γ	c_{3W}
$\bar{u}_R u_L \to W_L^+ W_L^-$	$-2\delta g_L^{Zu} - 0.69\delta g_{1z} - 0.1\delta\kappa_\gamma$	$c_{Hq}^{(1)} + c_{Hq}^{(3)}$
$\bar{d}_R d_L \to W_L^+ W_L^-$	$-2\delta g_L^{Zd} + 0.85\delta g_{1z} - 0.1\delta\kappa_\gamma$	$c_{Hq}^{(1)} - c_{Hq}^{(3)}$
$\bar{u}_L u_R \to W_L^+ W_L^-$	$-2\delta g_R^{Zu} + 0.31\delta g_{1z} - 0.4\delta\kappa_\gamma$	c_{Hu}
$\bar{d}_L d_R \to W_L^+ W_L^-$	$-2\delta g_R^{Zd} - 0.15\delta g_{1z} + 0.2\delta\kappa_\gamma$	c_{Hd}

Zff vertices

TGCs

Bounds on Zff anomalous couplins (from LEP)

Flavour Universality

$$[\delta g_R^{Zu}]_{ij} = A\,\delta_{ij}$$

$$\begin{aligned}
\delta g_L^{Zu} &= -0.0017 \pm 0.002 \\
\delta g_R^{Zu} &= -0.0023 \pm 0.005 \\
\delta g_L^{Zd} &= 0.0028 \pm 0.0015 \\
\delta g_R^{Zd} &= 0.019 \pm 0.008
\end{aligned}$$

MFV

$$[\delta g_R^{Zu}]_{ij} = \left(A + B\frac{m_i}{m_3}\right)\delta_{ij}$$

$$\begin{aligned}
\delta g_L^{Zu} &= -0.002 \pm 0.003 \\
\delta g_R^{Zu} &= -0.003 \pm 0.005 \\
\delta g_L^{Zd} &= 0.002 \pm 0.005 \\
\delta g_R^{Zd} &= 0.016 \pm 0.027
\end{aligned}$$

Falkowski et al. 1503.07872

Bounds on aTGC

	LHC Run I				LEP			
	68 % CL	Correlations			68 % CL	Correlations		
Δg_1^Z	0.010 ± 0.008	1.00	0.19	−0.06	$0.051^{+0.031}_{-0.032}$	1.00	0.23	−0.30
$\Delta\kappa_\gamma$	0.017 ± 0.028	0.19	1.00	−0.01	$-0.067^{+0.061}_{-0.057}$	0.23	1.00	−0.27
λ	0.0029 ± 0.0057	−0.06	−0.01	1.00	$-0.067^{+0.036}_{-0.038}$	−0.30	0.27	1.00

Butter, et al.1604.03105

First we look at the diboson amplitudes WW, WZ at High E

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$\bar{f}_L f_L \to W_T^{\pm} + Z_T$	λ_γ	c_{3W}
$\bar{d}_R u_L \to W_L^+ Z_L$ $\bar{u}_R d_L \to W_L^- Z_L$	$2\,(\delta g_L^{Zd} - \delta g_L^{Zu}) + \cos\theta_W\,\delta g_{1z}$	$c_{Hq}^{(3)}$
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Notice the order of magnitude in the size of the coefficients

1) Do Zff corrections affect aTGC fits?

2) Does Diboson give us any information on Zff corrections?

Notice that in the Higgs basis there are 7 parameters
(but we only have 5 directions) => we will find 2 correlated directions

To find this, we redo the fits with and without the vertices

1) Current data

We chose the most significant leptonic channels

Detector	$\mathcal{L}[\text{fb}^{-1}]$	$\sqrt{s}$	Process	Obs.	Ref.
ATLAS	4.6	7TeV	$WW \to \ell\nu\ell\nu$	$p_{T\ell}^{(1)}$	[5]
ATLAS	20.3	8TeV	$WW \to \ell\nu\ell\nu$	$p_{T\ell}^{(1)}$	[6]
CMS	19.4	8TeV	$WW \to \ell\nu\ell\nu$	$m_{\ell\ell}$	[7]
ATLAS	20.3	8TeV	$WZ \to \ell\nu\ell\ell$	p_{TZ}	[8]
CMS	19.6	8TeV	$WZ \to \ell\nu\ell\ell$	p_{TZ}	[9]
ATLAS	13	13TeV	$WZ \to \ell\nu\ell\ell$	m_{WZ}	[10]

2) Future projections

single channel

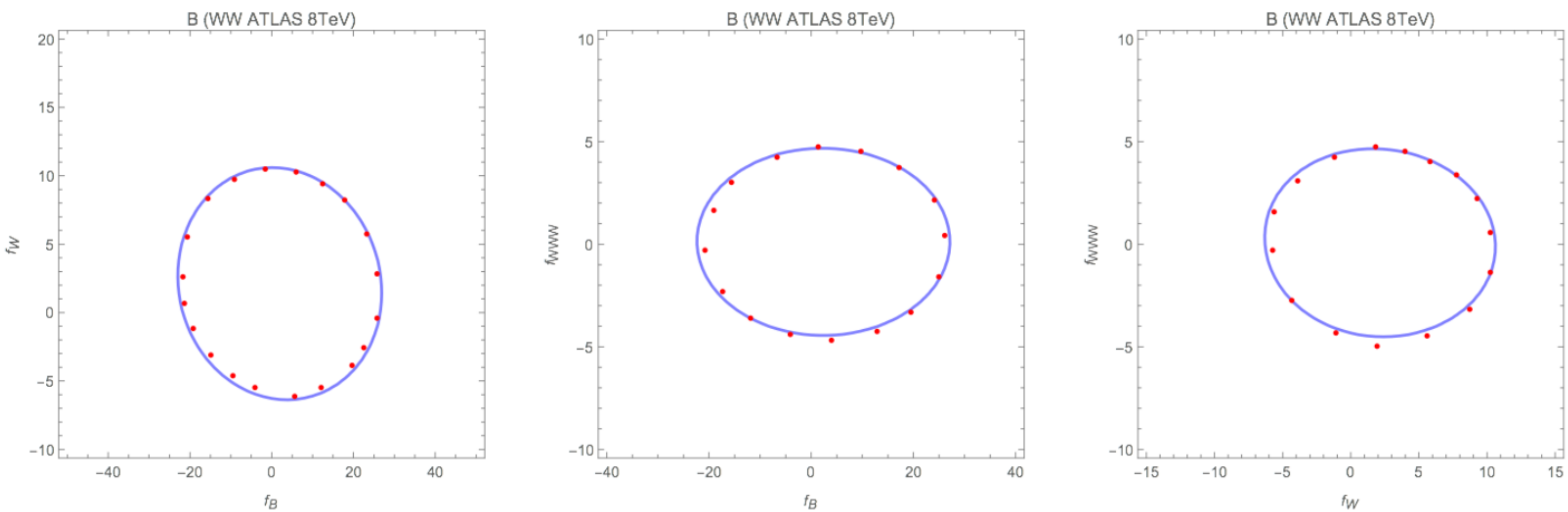
Used MadGraph5_aMC@NLO to get BSM cross section and fit

- BSMC package Fuks et al

We did a simple analysis

- Leading order
- No Pythia (we checked didn't affect much)
- No correlation between bins

Cross check with CMS and ATLAS is OK, e.g.

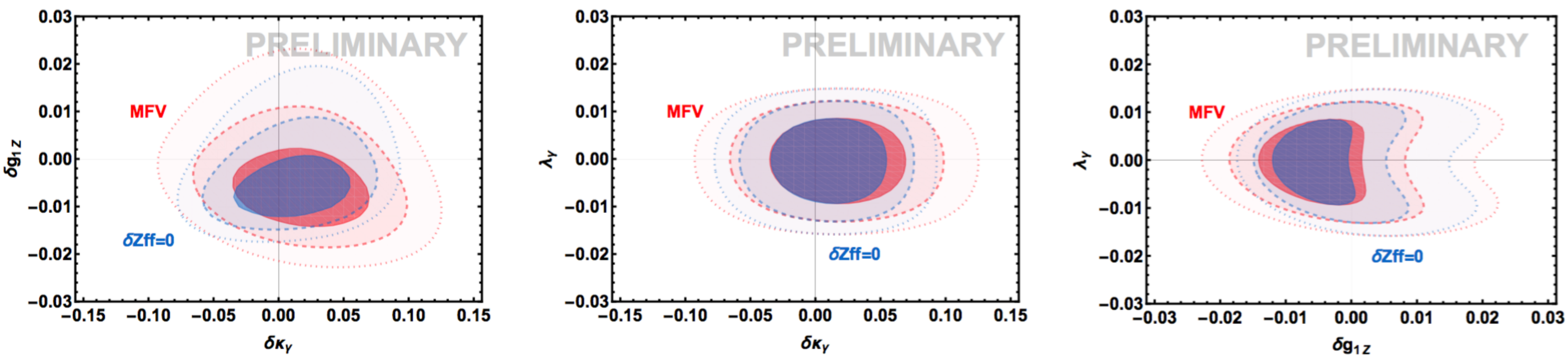


ATLAS	20.3	8TeV	$WZ \to \ell\nu\ell\ell$	p_{TZ}	[8]

Global fit: aTGC for the MFV case

3 parameter fit : χ^2_{TGC}

3+4 parameter fit : $\chi^2_{TGC} + \chi^2_{LEP1}$



- Variation 20% - 30% difference for $\delta g_{1z} - \delta\kappa_\gamma$
- λ_γ is unaffected due to affecting different polarizations

For the case of Flavor Universality we see almost negligible deviations

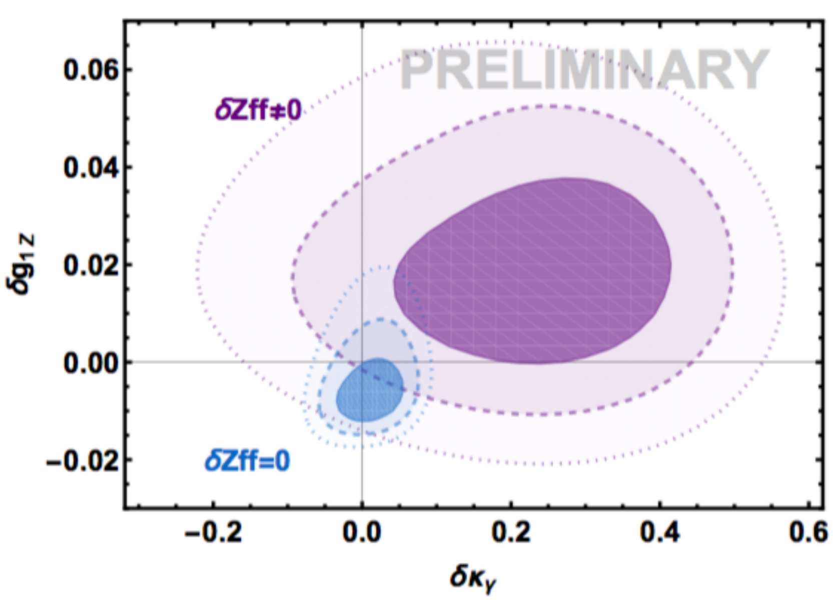
Preliminary

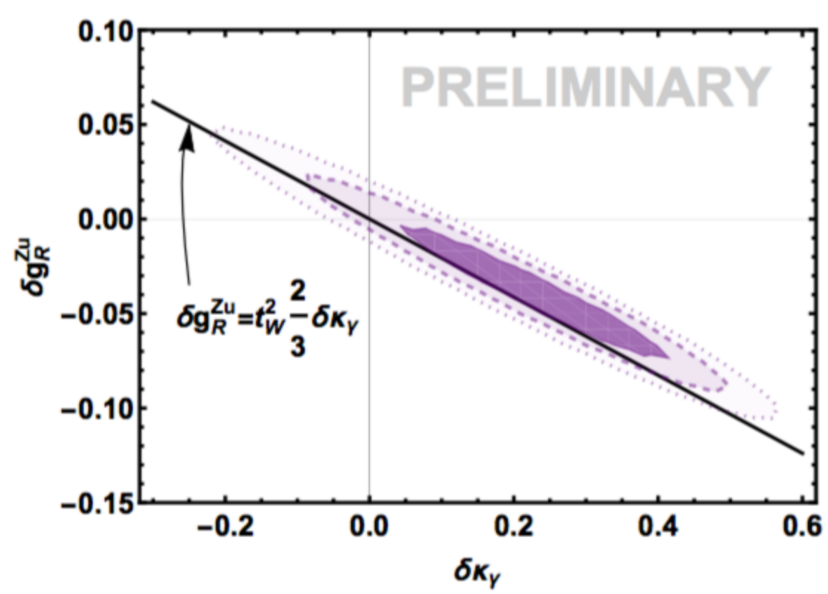
We need to include LEP1 due to 2 flat directions

Fit with 7 parameters and only LHC

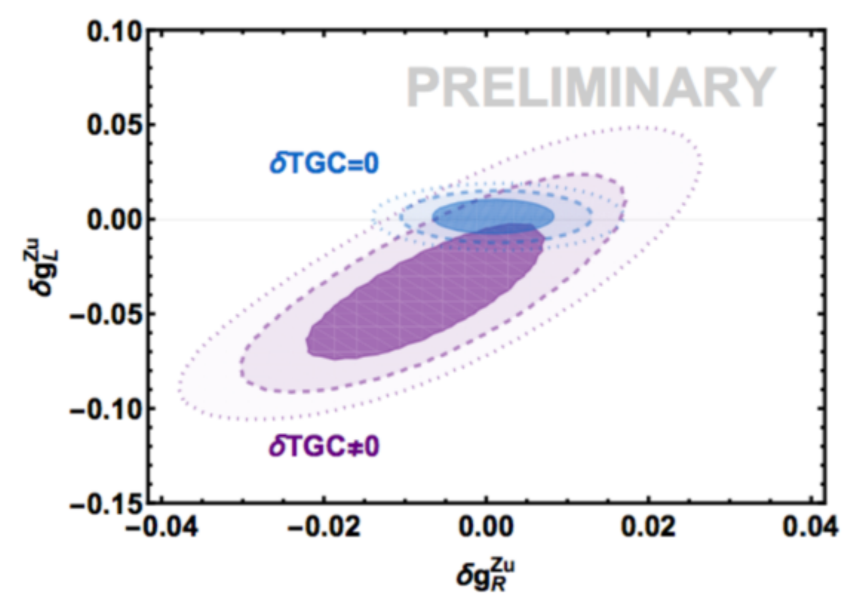
All bounds become huge

TGC bounds





Zqq bounds (up)



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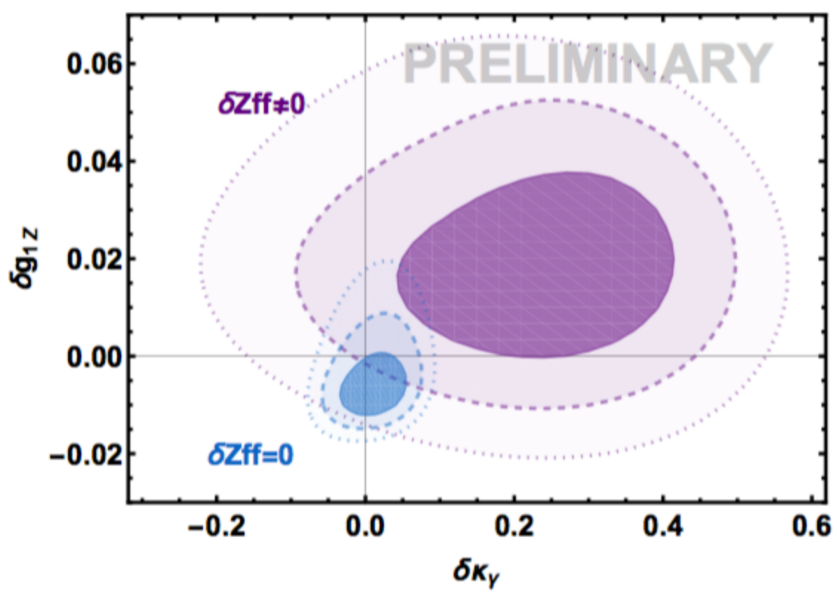
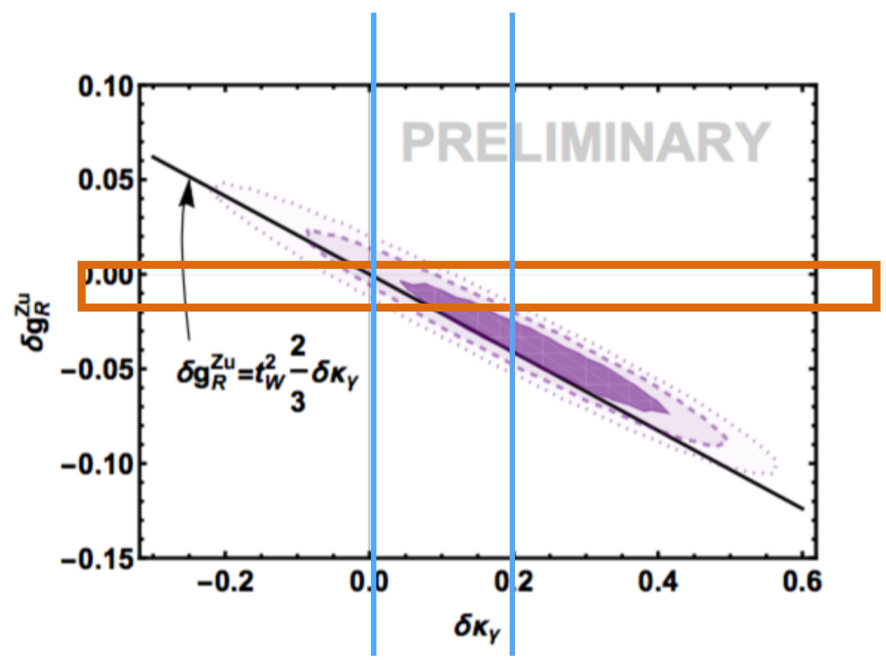
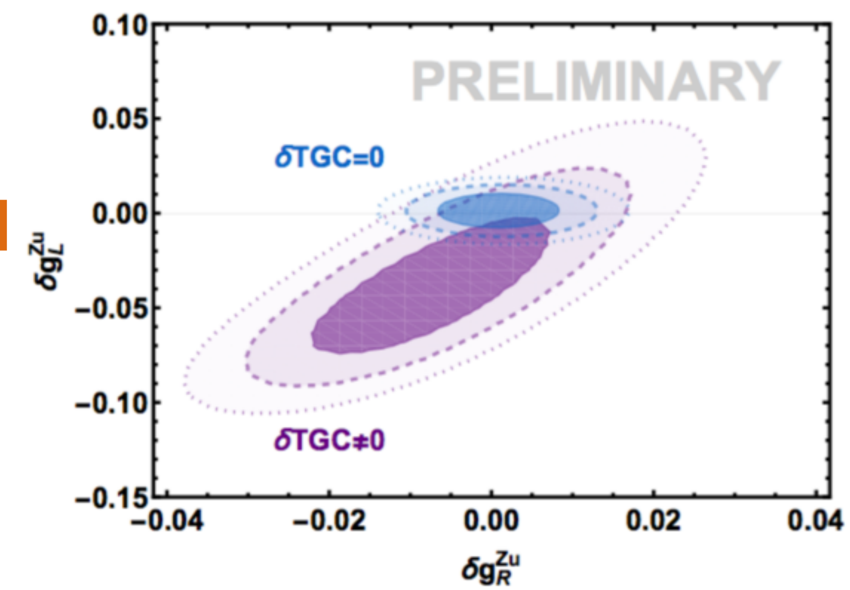




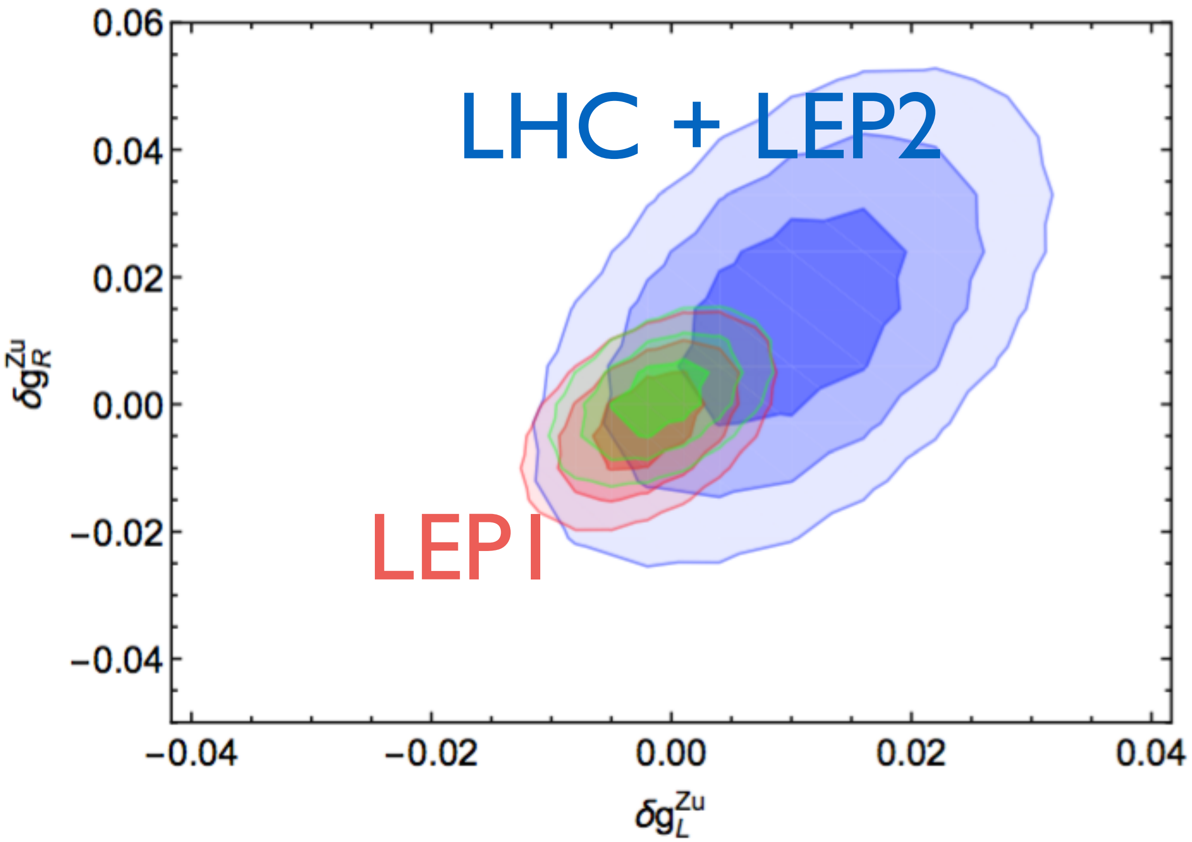
Zqq bounds (up)



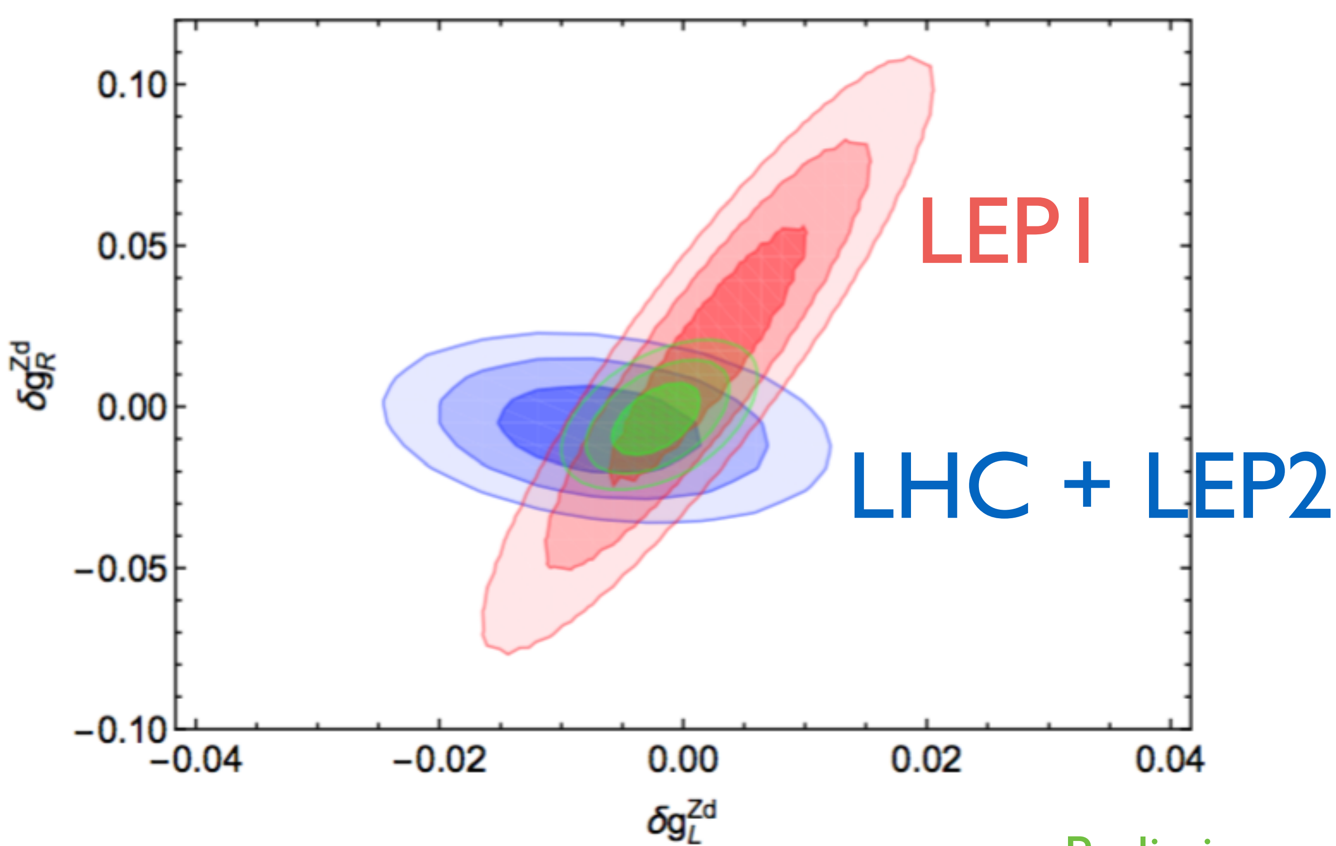
- LEP limits the runaway direction

Global fit: Zqq for the MFV case

Zqq bounds (up)



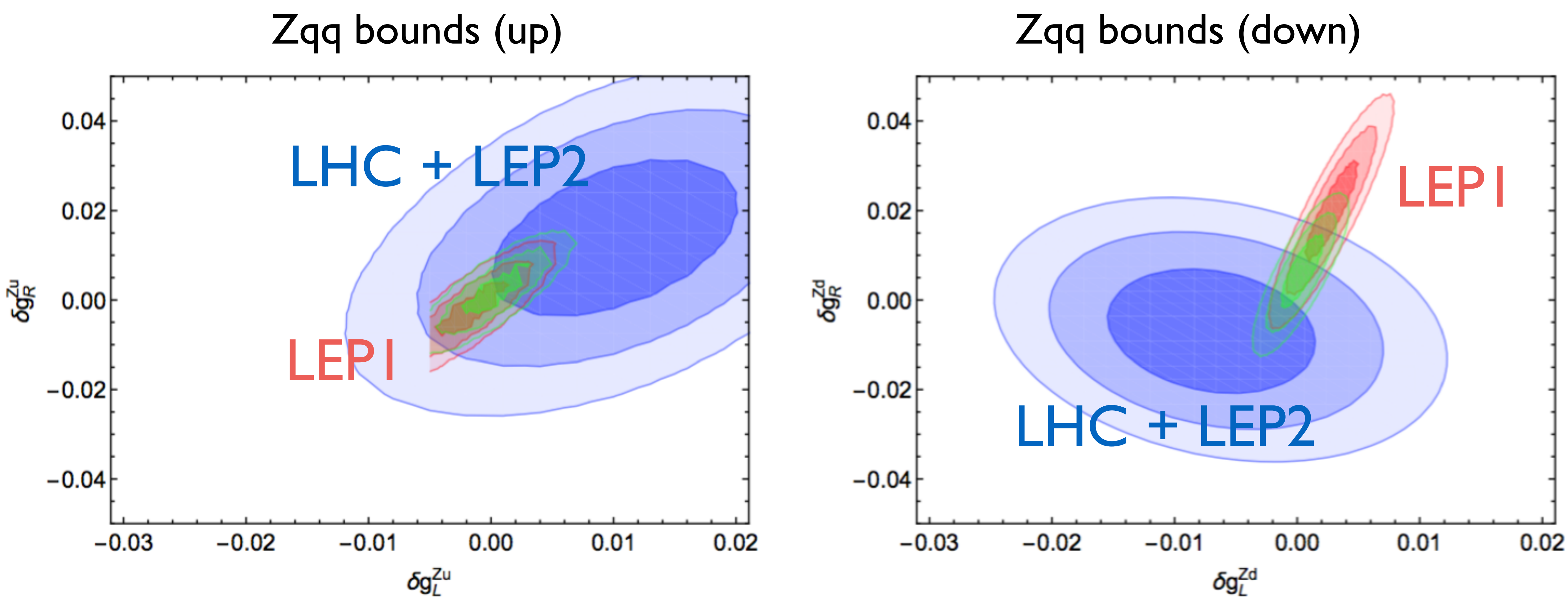
Zqq bounds (down)



Preliminary

- Big improvement in down type constrains

Global fit: Zqq for the Flavor Universality case



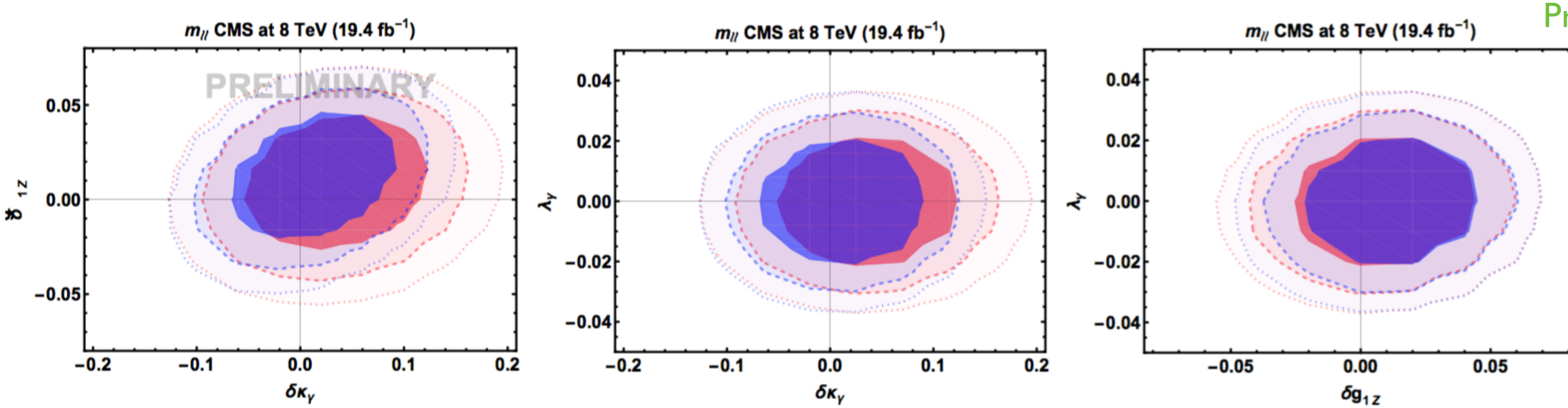
Preliminary

- Including TGC info doesn't improve much

- Diminishes the $\sim 2\sigma$ tension in down right coupling

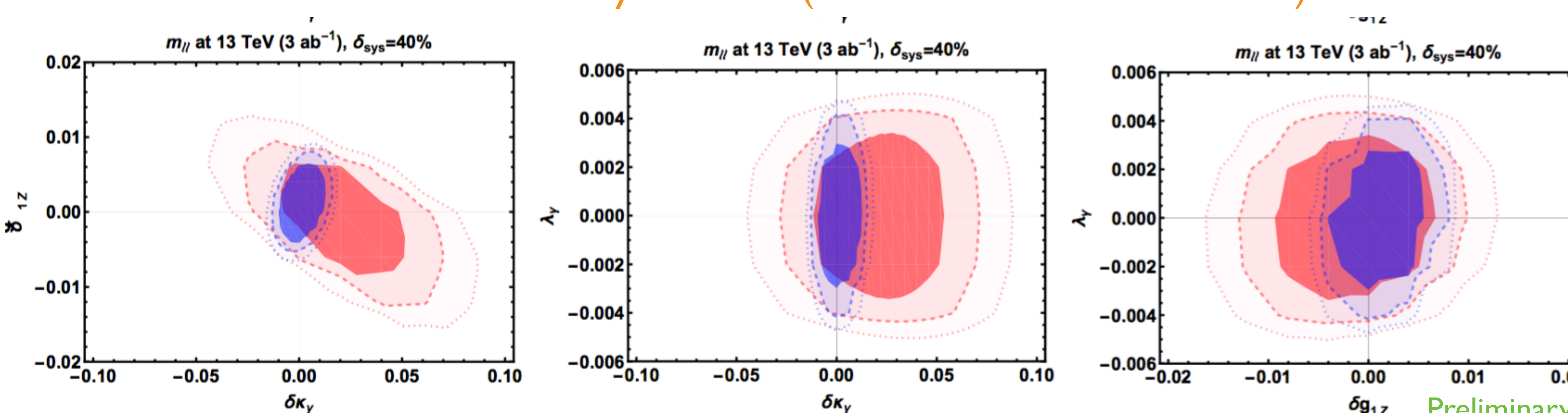
Single Channel: aTGC for MFV case NOW

Preliminary



Single Channel: aTGC for MFV case 3 ab

Assumed 40% systematics (similar to what we have now)

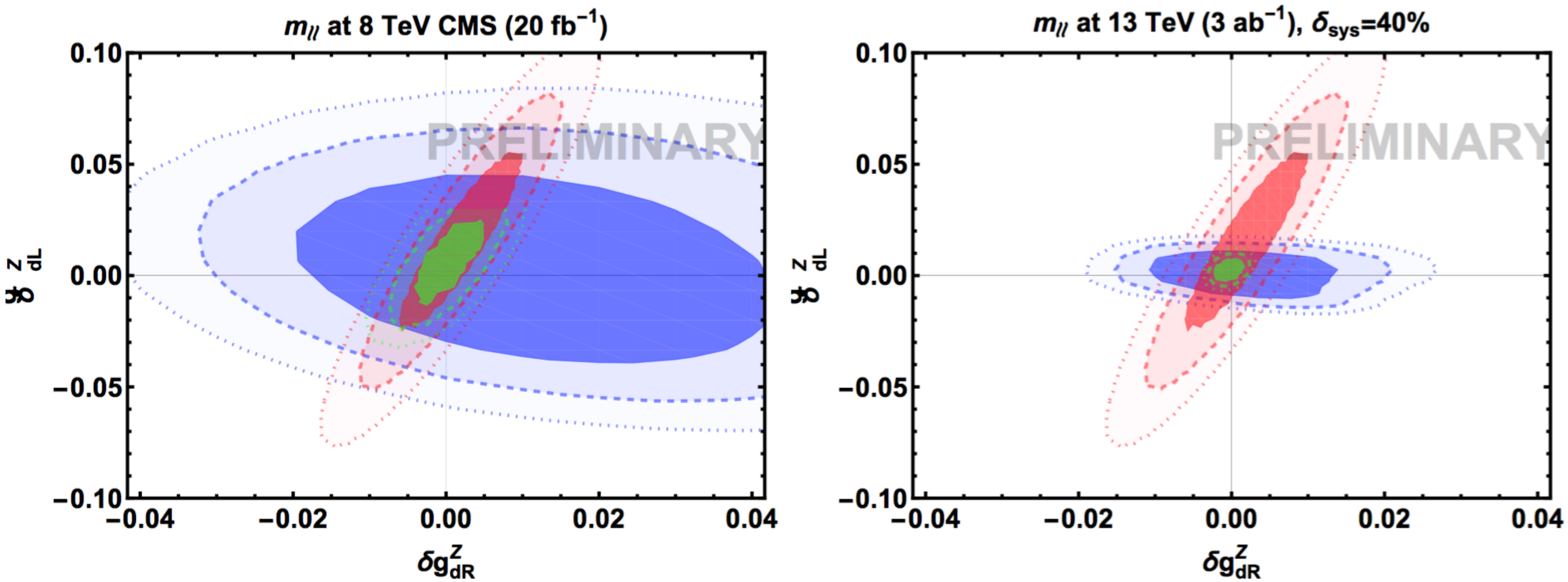


Preliminary

- Huge difference to the aTGC bounds in the future!

Single channel: Zqq down type for the MFV case

NOW 3 ab



- Big improvement in down type constrains
- It would be interesting adding more channels

Interpreting the bounds

In these fits, the quadratic pieces are non-negligible

$$|\mathcal{M}|^2 \sim |\mathcal{M}_{SM}|^2 + \mathcal{M}_{SM}\,\mathcal{M}_6 + |\mathcal{M}_6|^2$$

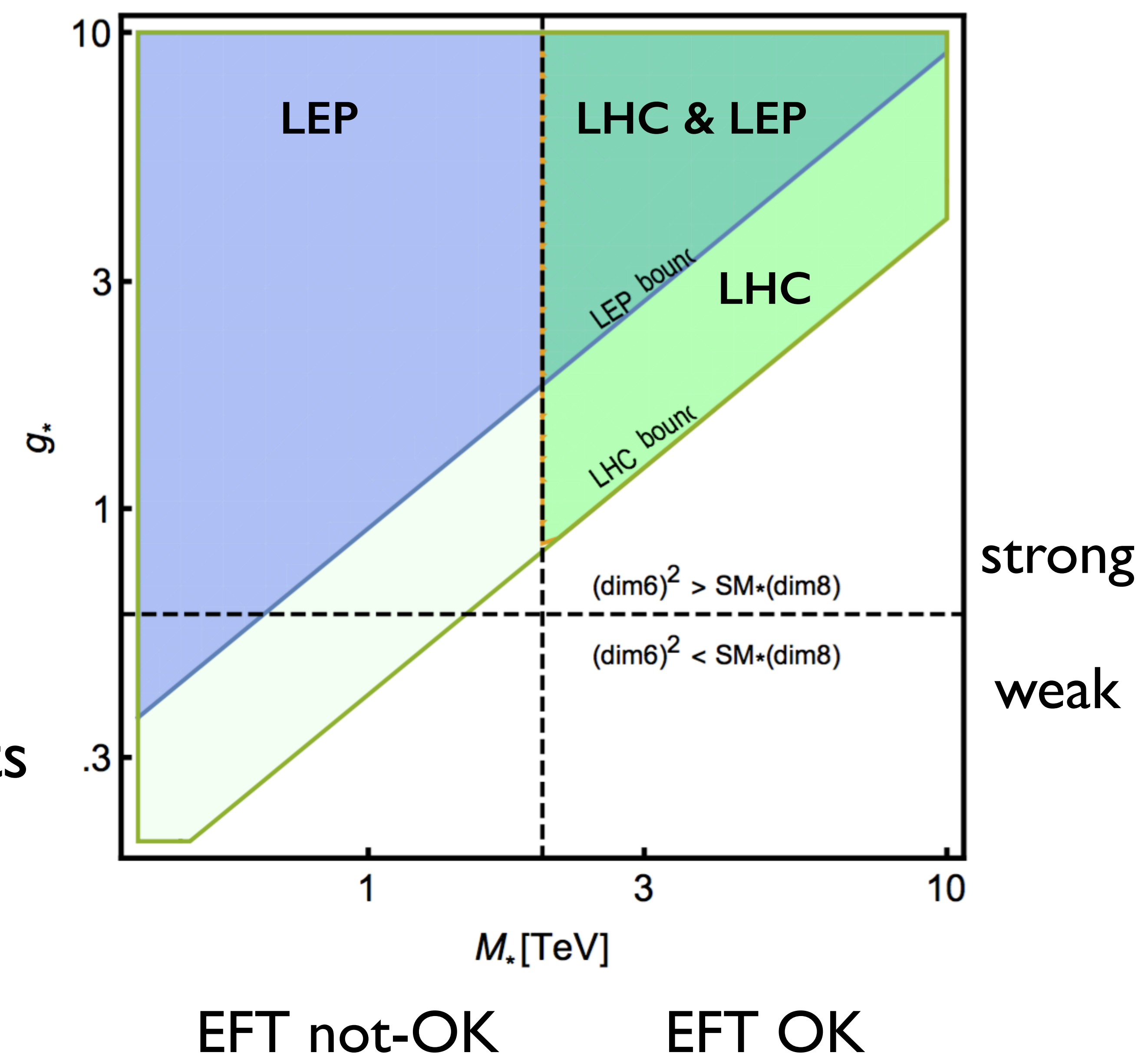
so they are of the same order as dim 8

$$|\mathcal{M}_6|^2 \sim \frac{1}{\Lambda^4} \sim \mathcal{M}_{SM}\,\mathcal{M}_8$$

Need of power counting to ensure:

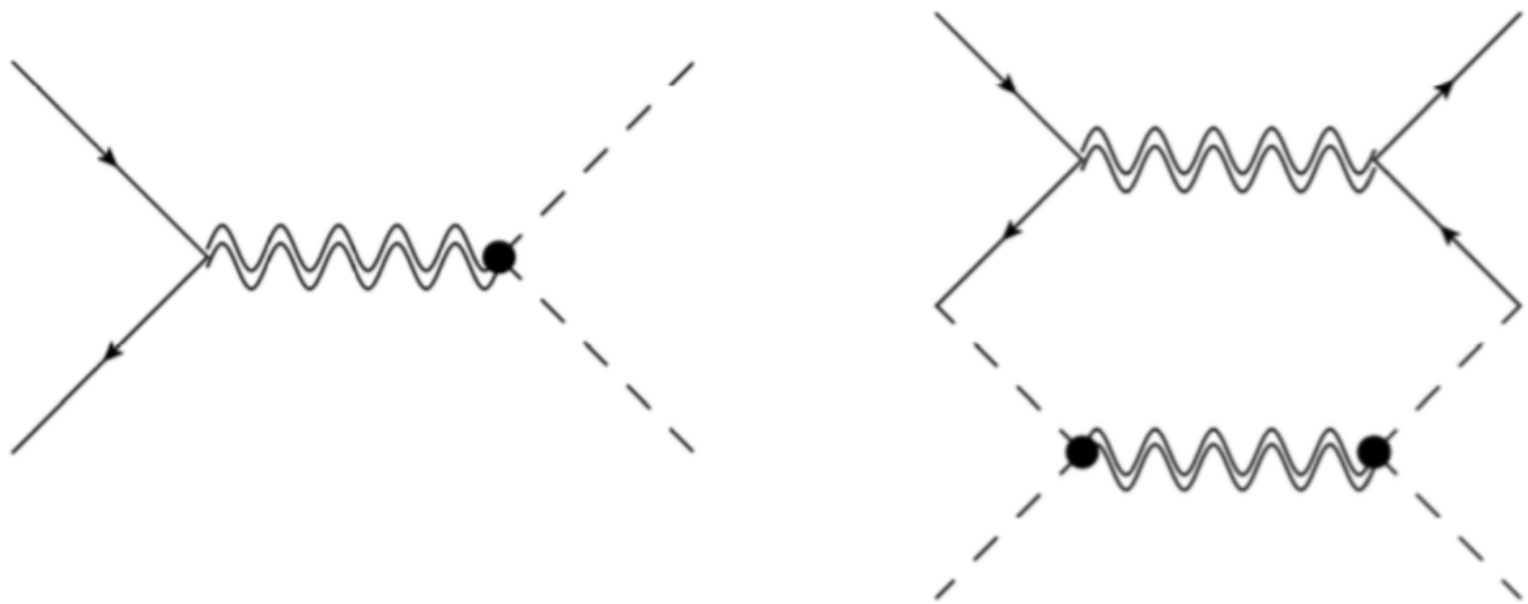
1) dimension 8 are negligible

2) physical mass larger than Energy events



Toy Model to get more intuition

A simple toy model: $SU(2)_R$ triplet so that respects custodial.



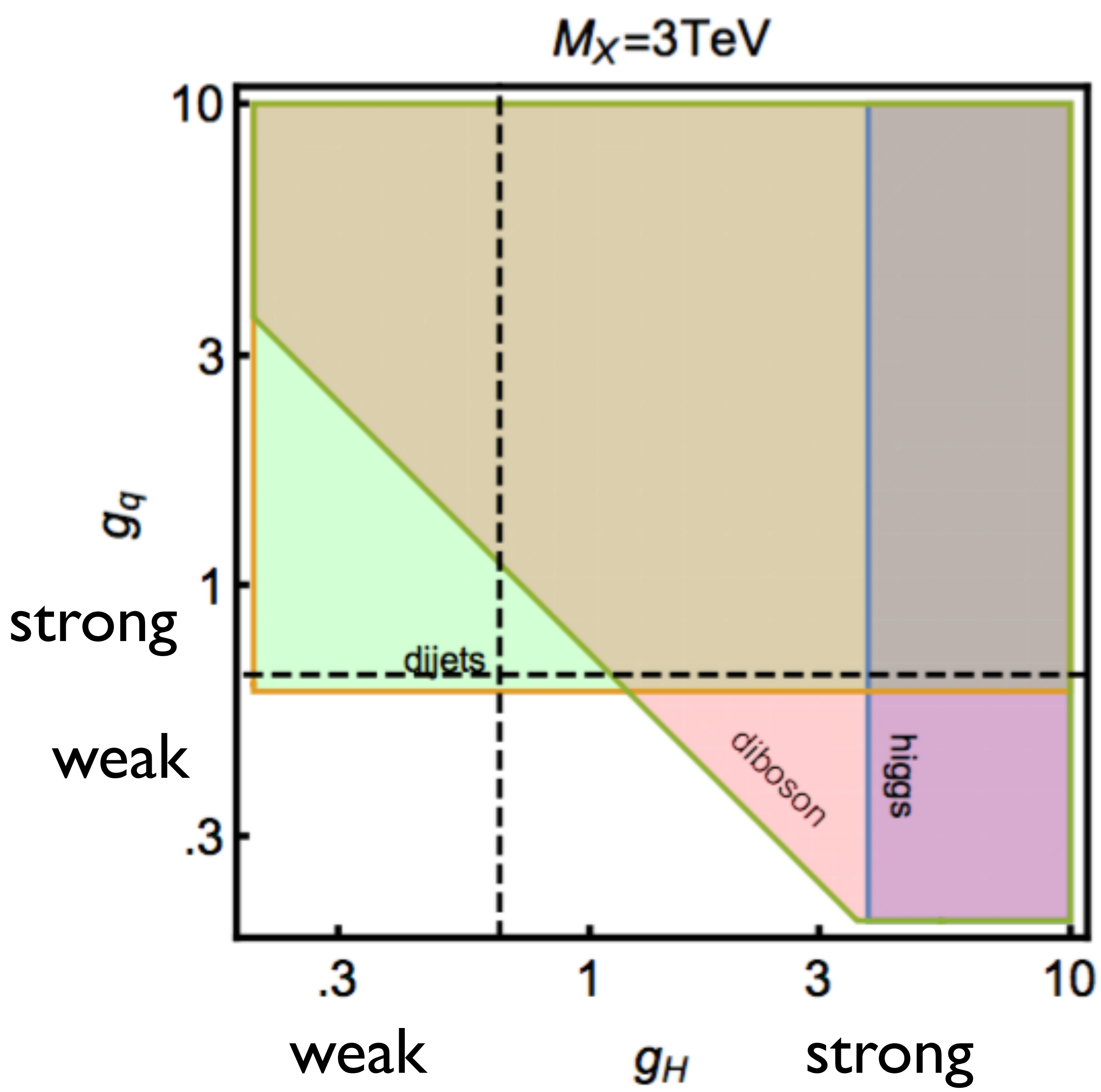
$$\mathcal{L} \supset -m_X^2 V^2 + i g_H V_\mu^i H^\dagger \sigma^i D_\mu H + g_q V_\mu^i \bar{q} \gamma_\mu \sigma^i q$$

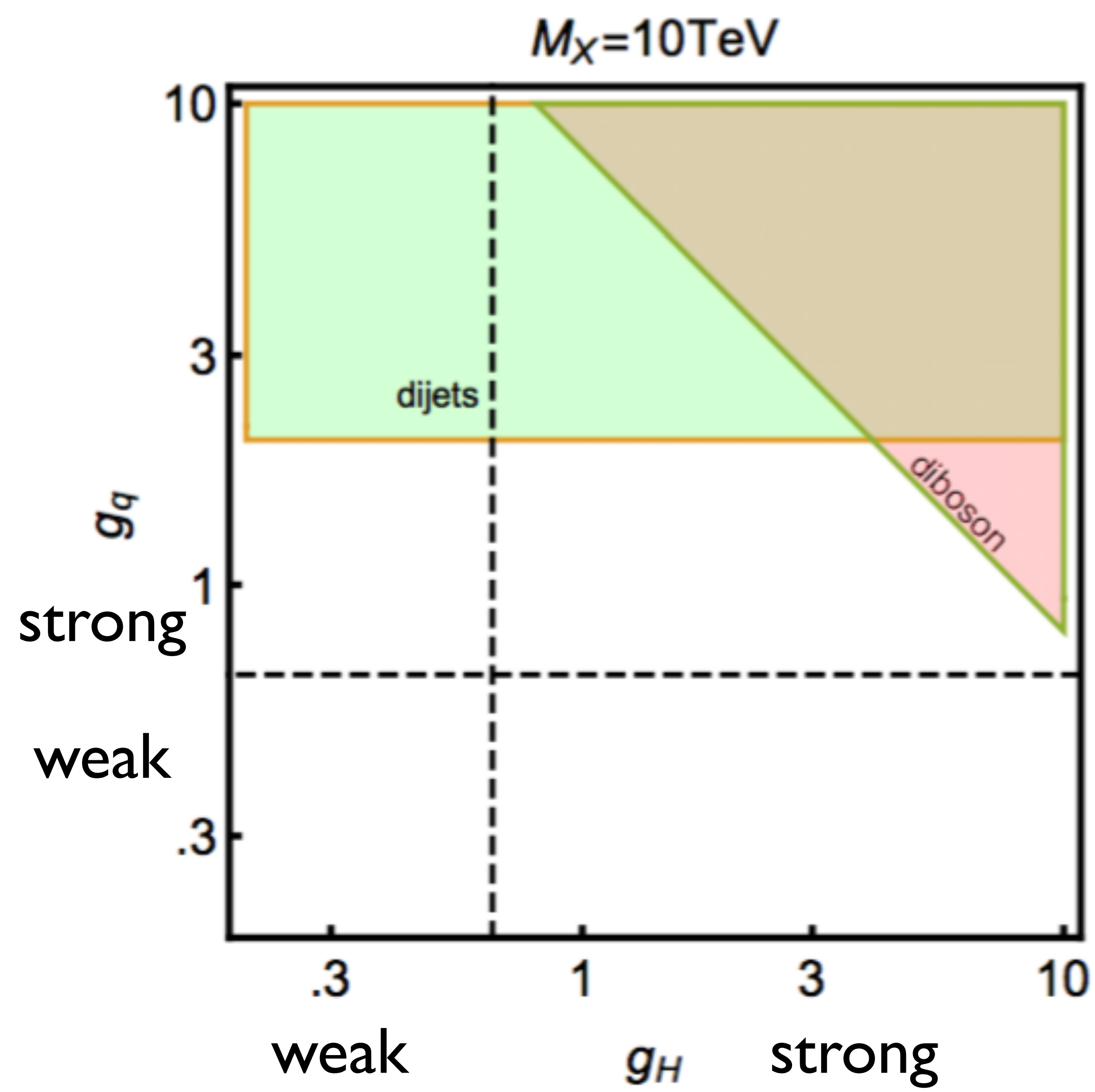
$$\frac{g_q^2}{M_X^2} \bar{f} f \bar{f} f \quad + \quad \frac{g_q g_H}{M_X^2} \bar{f} \gamma_\mu f H D_\mu H \quad + \quad \frac{g_H^2}{M_X^2} H^2 D_\mu H^\dagger D_\mu H$$

dijets: $\frac{g_q^2}{M_X^2} \leq \frac{0.04}{TeV^2}$, higgs: $\frac{g_H^2}{M_X^2} \leq \frac{1.6}{TeV^2}$

combined: $\frac{g_H g_q}{M_X^2} \leq \frac{\sqrt{0.04 \cdot 1.6}}{TeV^2} \sim \frac{0.25}{TeV^2}$

diboson: $\frac{g_H g_q}{M_X^2} \leq \frac{0.08}{TeV^2}$





Conclusions

- aTGC fits at the LHC will need to include Zqq corrections soon
(unless other processes at the LHC can bound them better)

- Flavor assumptions may be important for aTGC fits
(at the moment, to neglect or not the Zqq corrections)

- Diboson data from LHC can help improve the bounds
for Zqq for down type quarks (*for some theories)

- For our toy model, the diboson channel is useful even if in some
regions other LHC processes are more sensitive

Thanks