aTGC in the EFT approach @ LHC

David Marzocca

Universität Zürich UZH

Based on:
Falkowski, Gonzalez-Alonso, Greljo, D.M., Son *1609.06312*

LHC EWK working group multi boson discussion
24.10.2016 CERN

Outline

- EFT approach(es) and aTGC
- EFT validity
- Limiting the scale of the process @LHC: how to do it.
- Example of an analysis

EFT approach

Scale of New Physics is high

$$\Lambda_{NP} \gg m_h, E_{exp}$$

Low energy theory specified by
particle content (SM) + symmetries

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$h \in$ SU(2)$_L$ doublet $\quad H = \begin{pmatrix} 0 \\ \frac{v+h}{\sqrt{2}} \end{pmatrix}$

Linear realisation: SMEFT

$$\mathcal{L}^{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_j \frac{c_j^{(8)}}{\Lambda^4}\mathcal{O}_j^{(8)} + \ldots$$

h is a singlet

Non-linear realisation: HEFT

organize operators with some power counting, e.g. NDA:

$$\frac{\Lambda^4}{16\pi^2}\left[\frac{\partial}{\Lambda}\right]^{N_p}\left[\frac{4\pi\,\phi}{\Lambda}\right]^{N_\phi}\left[\frac{4\pi\,A}{\Lambda}\right]^{N_A}\left[\frac{4\pi\,\psi}{\Lambda^{3/2}}\right]^{N_\psi}\left[\frac{g}{4\pi}\right]^{N_g}\left[\frac{y}{4\pi}\right]^{N_y}$$

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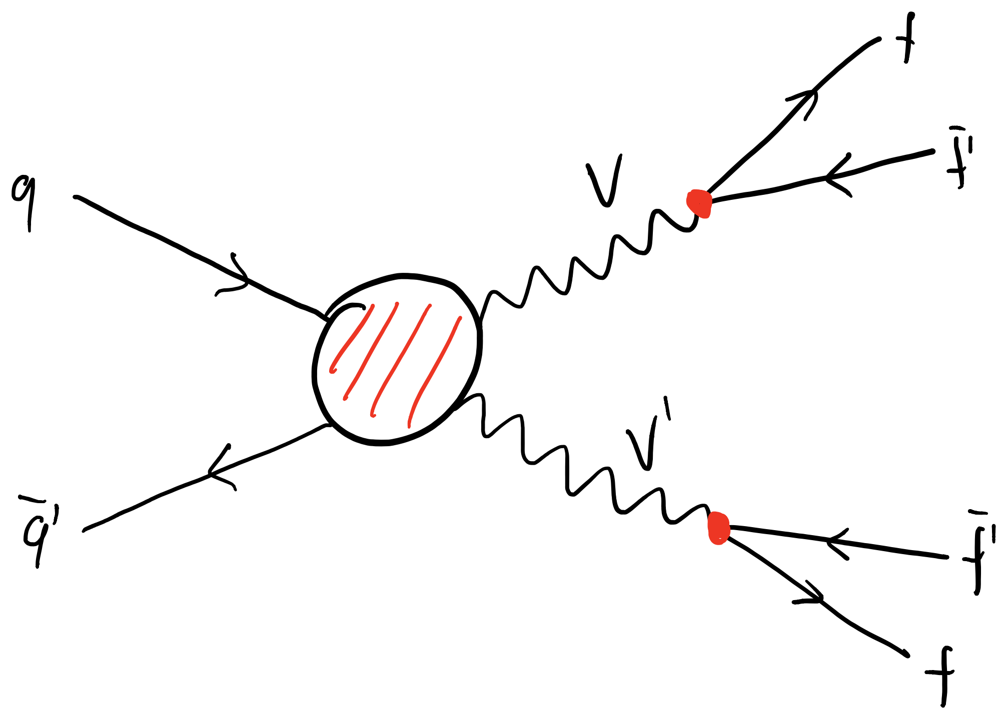
More symmetry: more constraints and relations among couplings.

In both cases: EFT description valid for experiments below **Λ**.

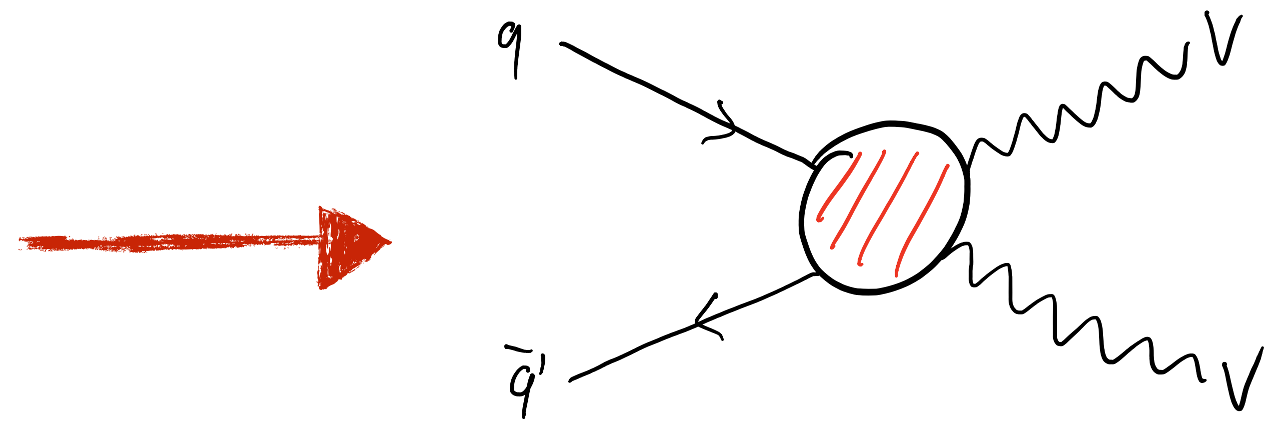
Diboson production

We are interested in the double-pole part of the on-shell process $q\,\bar{q}' \to 4f$

See M. Trott's talk and 1606.06693.



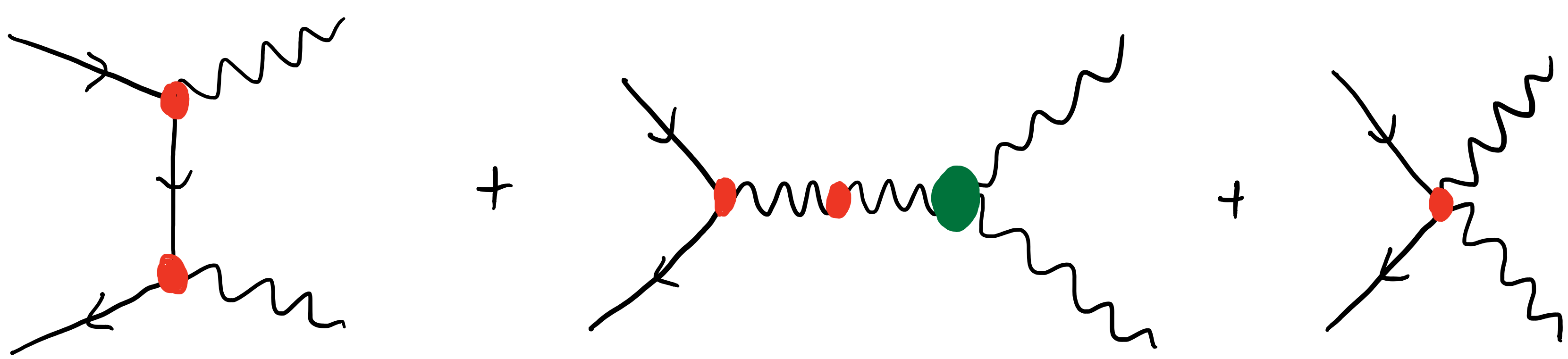
take on-shell* $q\,\bar{q}' \to V\,V'$



*in the NWA for the vector bosons $\Gamma_W\,/\,m_W \sim 0.02 \ll 1$.

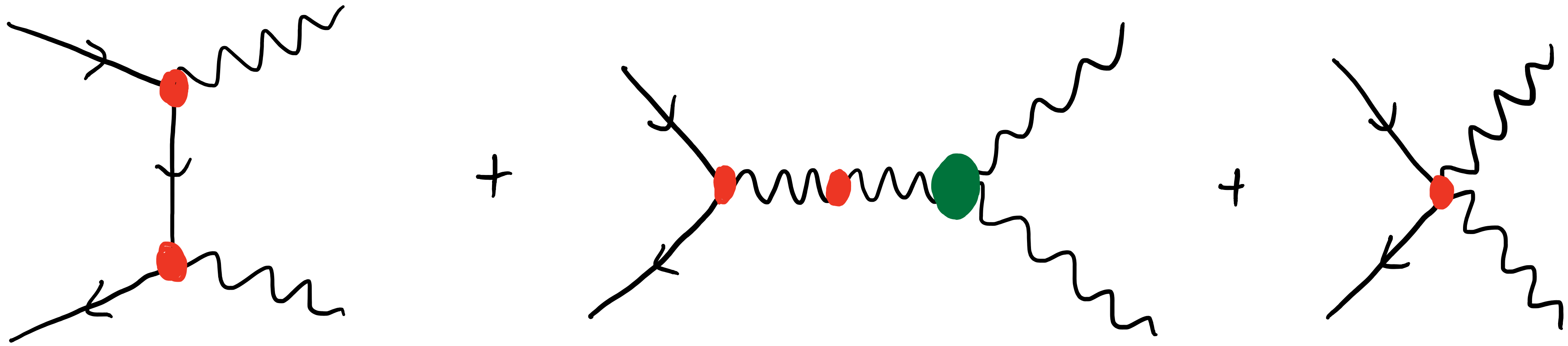
We look directly at the SMEFT.

Higher dim operators can contribute in many places



The only physical (basis indep.) quantity is the total on-shell amplitude

Diboson production



In the SMEFT, in any basis,
assuming vertex (Vff) and oblique corrections vanish*,
only 3 linear combinations of coefficients remain unconstrained.
It is always possible to identify those as the 3 aTGC.

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

$$\delta\kappa_z = \delta g_{1,z} - \frac{s_\theta^2}{c_\theta^2}\delta\kappa_\gamma.$$

$$\delta g_{1,z},\ \delta\kappa_\gamma,\ \lambda_z\ \sim c^{(6)}\frac{m_W^2}{\Lambda^2}$$

* due to EWPD. However, some Zq_Rq_R vertices have still large uncertainties and their impact is important. [Zhang 1610.01618]

aTGC

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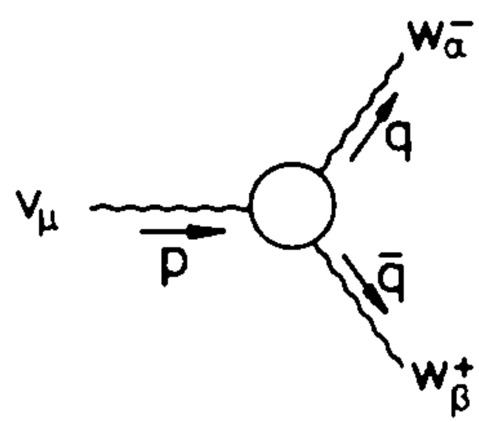
Gaemers, Gounaris (1979) + Hagiwara at al. (1987)

This is an **effective Lagrangian** parametrising the possible Lorentz structures of triple gauge couplings.
It can be extended by adding terms with more derivatives: $\Box^n V^\mu$

It is just a way of parametrising the 3-point vertex



$= i\, g_{WWV}\, \Gamma_V^{\alpha\beta\mu}\quad(q,\bar{q},p)$

Starting from the on-shell amplitude it is also possible to define the aTGC as pseudo-observables. Falkowski, Riva 2014

The extension of this approach to LHC introduces more parameters: in progress.

aTGC

$$\delta g_{1,z},\ \delta\kappa_\gamma,\ \lambda_z$$

In the SMEFT (or any other EFT) the aTGC are given by combinations of coefficients, for example in the SILH basis:

$$\delta g_{1z} = -\frac{g_L^2 + g_Y^2}{g_L^2 - g_Y^2}\left[\frac{g_L^2 - g_Y^2}{g_L^2}\bar{c}_{HW} + \bar{c}_W + \bar{c}_{2W} + \frac{g_Y^2}{g_L^2}\bar{c}_B + \frac{g_Y^2}{g_L^2}\bar{c}_{2B} - \frac{1}{2}\bar{c}_T\right]$$

$$\delta\kappa_\gamma = -\bar{c}_{HW} - \bar{c}_{HB}\ , \qquad \lambda_z = -6 g_L^2 \bar{c}_{3W}\ ,$$

note that here $\bar{c}_i \sim \frac{m_W^2}{\Lambda^2} c_i$

and analogous combinations in other basis, like Warsaw, etc..

Not only 3 operators contribute to diboson production!

EFT validity

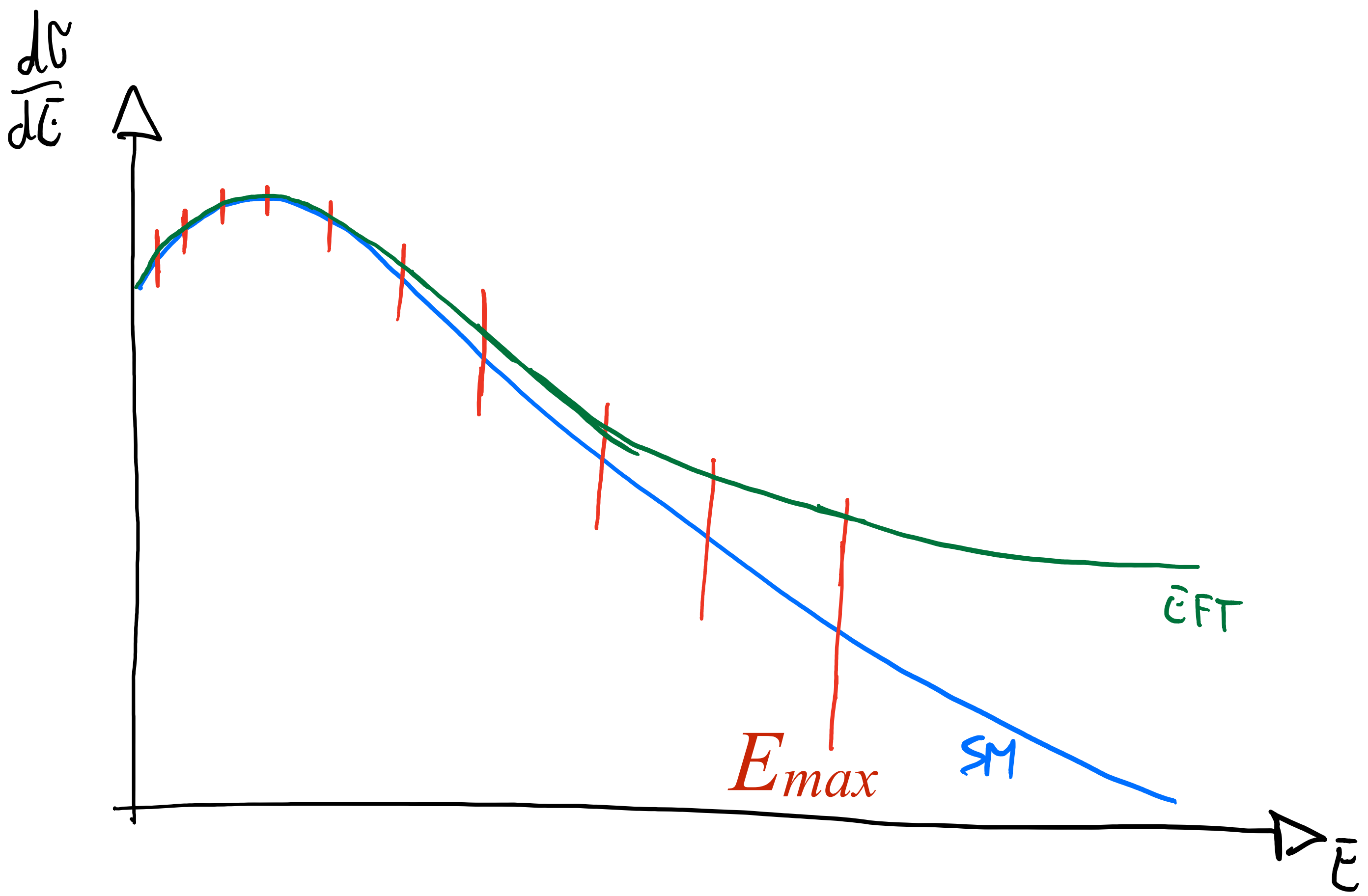
$$E_{exp} \ll \Lambda$$

Ellis, Sanz 1410.7703;
Greljo et al. 1512.06135;
Plehn et al. 1510.03443,1602.05202;
Contino et al. 1604.06444;
Falkowski et al. 1609.06312;
…

From low energy experiments the scale Λ is unknowable: depends on the model, not on the data.

Example: from muon decay we can only extract G_F, not the value of m_W.

What depends on the data is the scale which we can probe in a consistent way: $\Lambda \gg E_{max}$.



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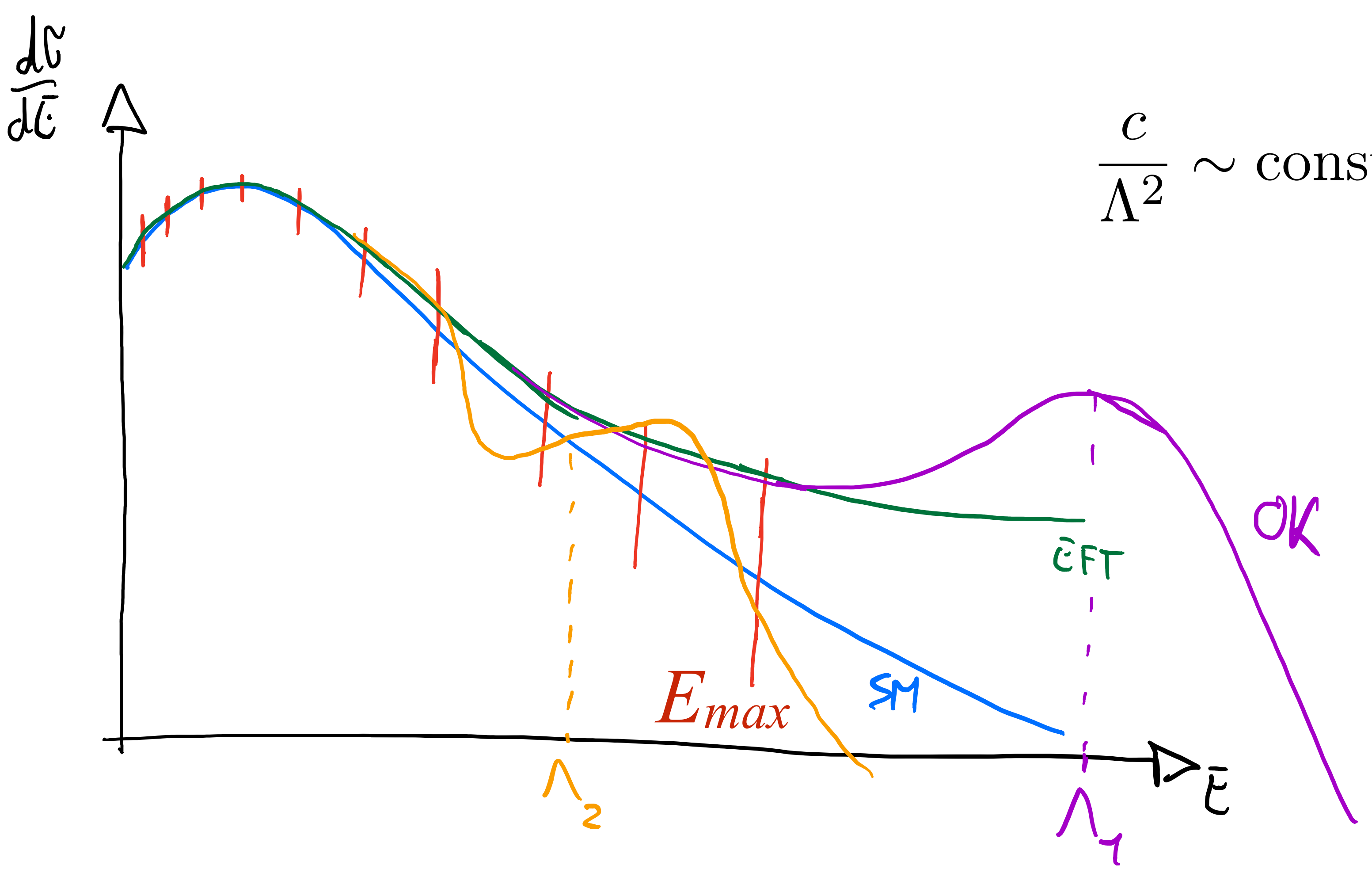

$$\frac{c}{\Lambda^2} \sim \text{const}$$

Both models generate the same dim-6 coefficient

Model 1 is clearly consistent with the EFT analysis.

Model 2 is not.

The EFT analysis can't be used to put consistent limits on Model 2.

Should we worry?

$$\sigma = \sigma^{\mathrm{SM}} + \sum_i \left(\frac{c_i^{(6)}}{\Lambda^2} \sigma_i^{(6\times\mathrm{SM})} + \mathrm{h.c.} \right) + \sum_{ij} \frac{c_i^{(6)} c_j^{(6)*}}{\Lambda^4} \sigma_{ij}^{(6\times6)} + \sum_j \left(\frac{c_j^{(8)}}{\Lambda^4} \sigma_j^{(8\times\mathrm{SM})} + \mathrm{h.c.} \right) + \ldots$$

Ideally the dim-6 interference is expected to dominate,
while quadratic terms and interference of dim-8 are equally suppressed.

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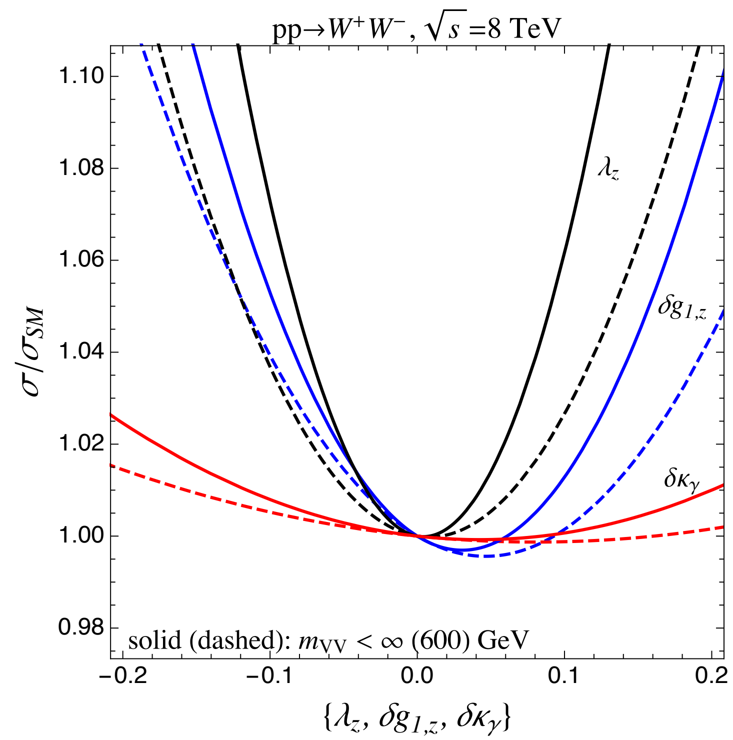
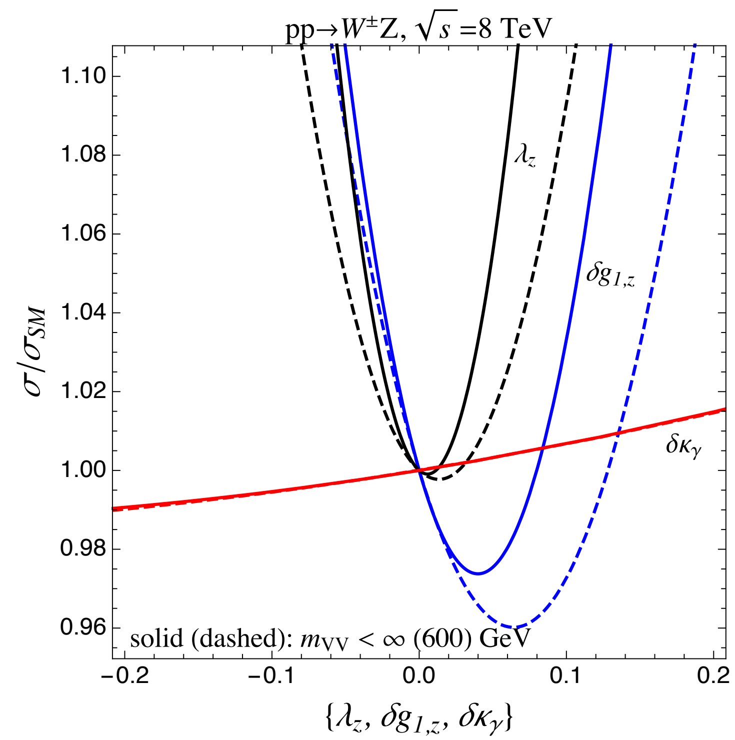
In practice: even with a few-percent precision, quadratic terms dominate.

Neglected interference of dim-8 could have a sizeable impact.





The analysis will be valid only for those models where dim-8 do not conspire in such a way, e.g. if:

$$c_i^{(6)} \sim c_j^{(8)} \sim g_*^2 \gg 1$$

Unitarity?

Any EFT is valid **only** for $E_{exp} \ll \Lambda$

- Problems with unitarization of the scattering amplitudes start to appear at the scale Λ, i.e. where the EFT ceases to be a valid description.
If the experimental analysis is sensitive to such effects, then the EFT approach is not a good one to interpret the data.

- Imposing a form-factor-like suppression to EFT coefficients in order to avoid unitarity violations at scales E ~ Λ corresponds to choosing some specific UV model.

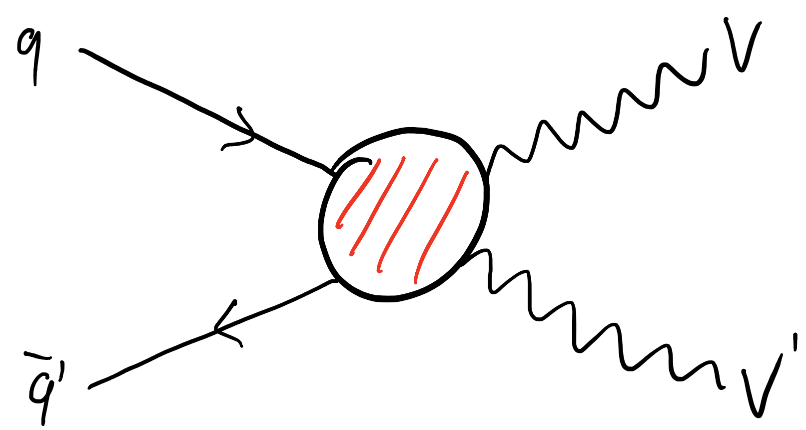
It is then difficult (impossible) to interpret results of such analyses in a model-independent way.

When doing EFT, worry about EFT validity, not about unitarity.

Limit the energy

Ideally, one would like to fix the perfect value of E_{max} for each Λ considered, in order to maximise sensitivity while retaining consistency.

In practice, the experimental analysis could be done for a few different values of E_{max}.



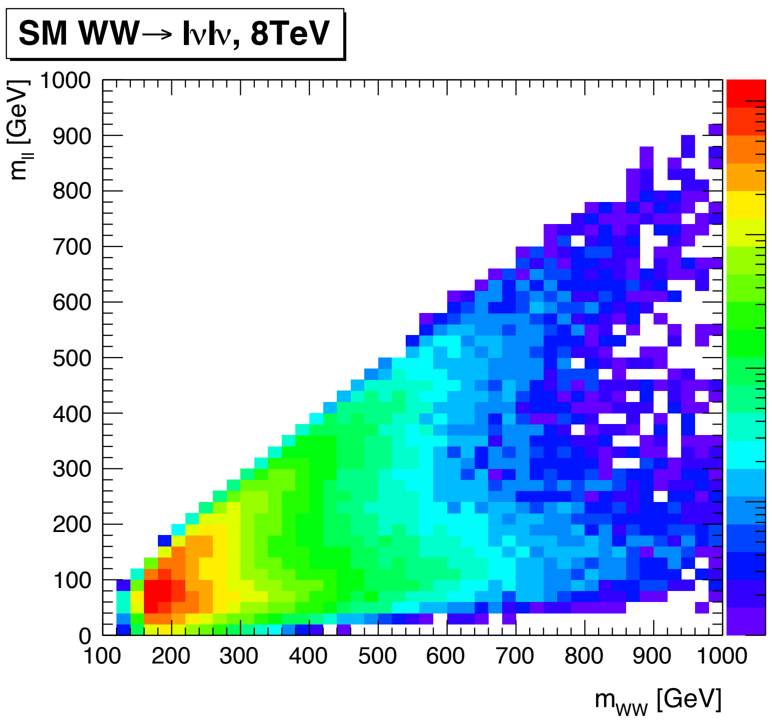
In diboson production the relevant variable is

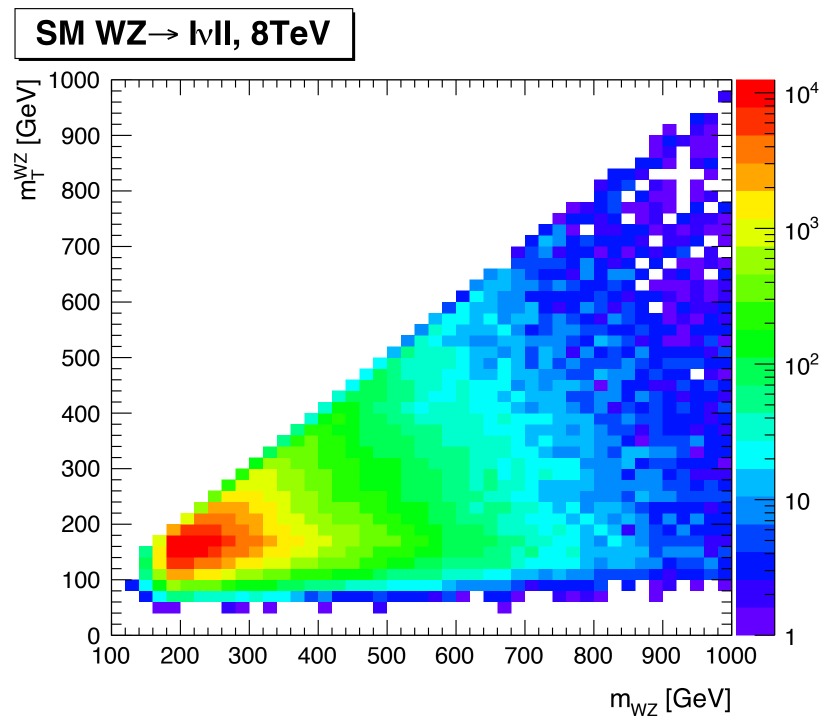
$$\sqrt{\hat{s}} = m_{VV}$$

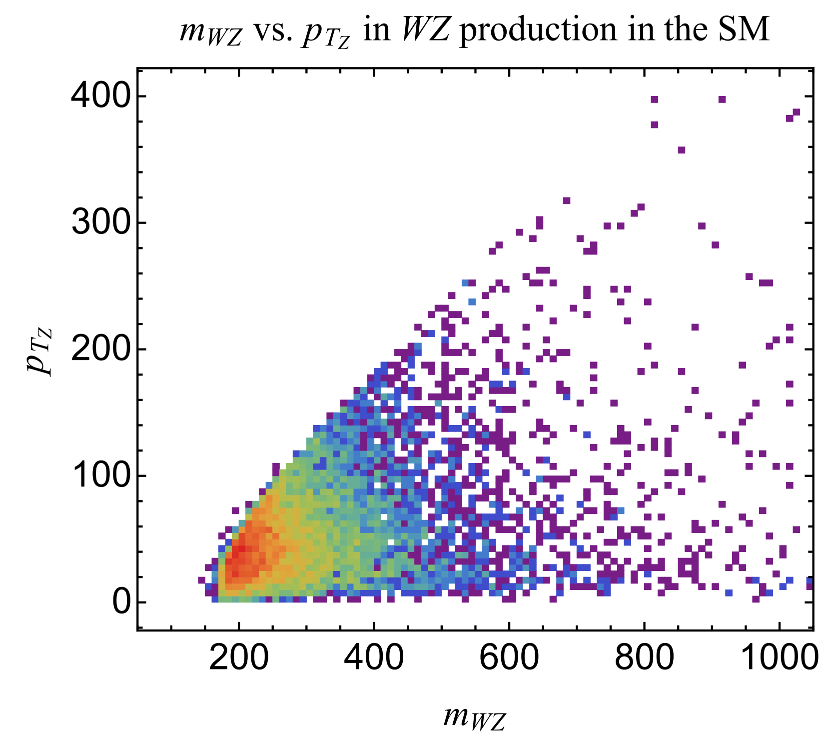
However, in WW (2ℓ2ν) this is not available, while in WZ (3ℓν) it has a bad resolution.

We need a proxy, ideally with the best correlation possible: maybe $m_{\ell\ell}$ or m_T^{WZ} ?

Limit the energy







A cut on any of these variables will still allow a large fraction of (unwanted) high-energy events.

Proposal for WZ (3ℓν): cut data using the available m_{WZ} resolution, then analyse the $m_T{}^{WZ}$ distribution.

How can we impose the cut on m_{VV} if no variable is correlated enough with it?

Same problem appeared in LHC DM searches with the EFT approach.

Racco, Wulzer, Zwirner 1502.04701

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If **both terms are positive*** and **no significant excess** from the SM is observed then removing the high-E part provides **conservative limits** on the coefficients.

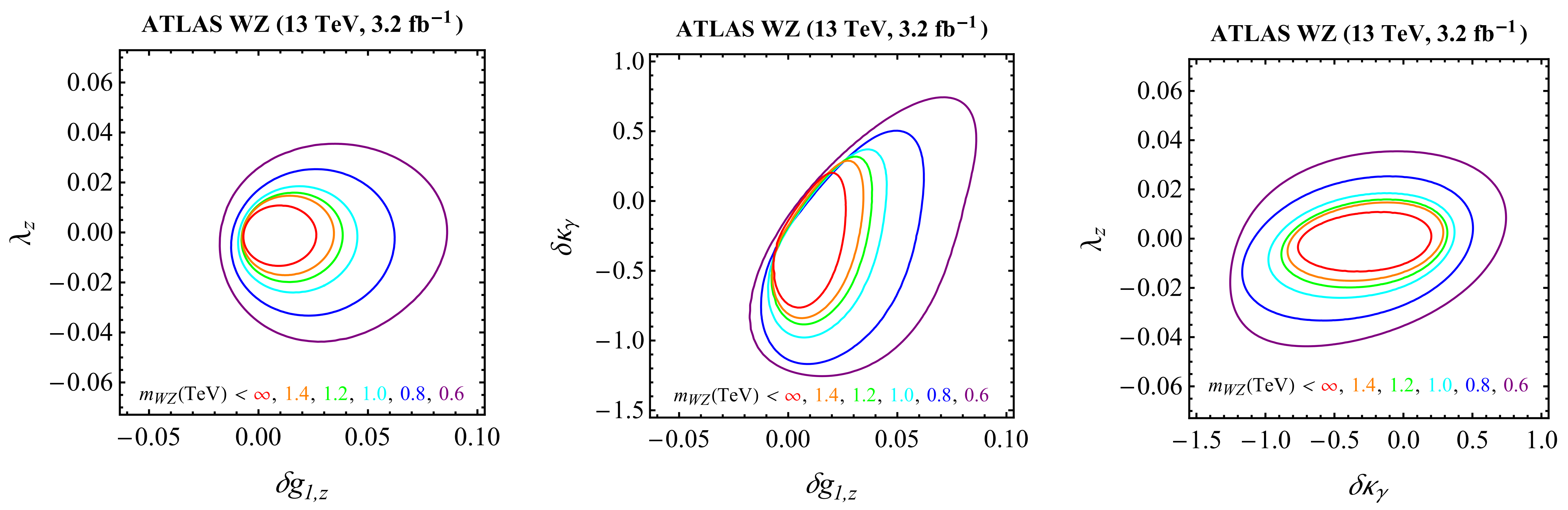
$$\sigma_{obs} - \sigma_{\rm SM} - \Delta\sigma < \sigma_{\rm BSM}^{m_{VV}<m_{VV}^{\rm max}} < \sigma_{obs} - \sigma_{\rm SM} + \Delta\sigma$$

* in practice in LHC diboson production the interference with SM is small, BSM is dominated by quadratic terms.

Recasting exp. analyses

We recast some WW and WZ ATLAS and CMS 8 and 13TeV analyses fixing different $m_{VV}^{\max}$ cuts.

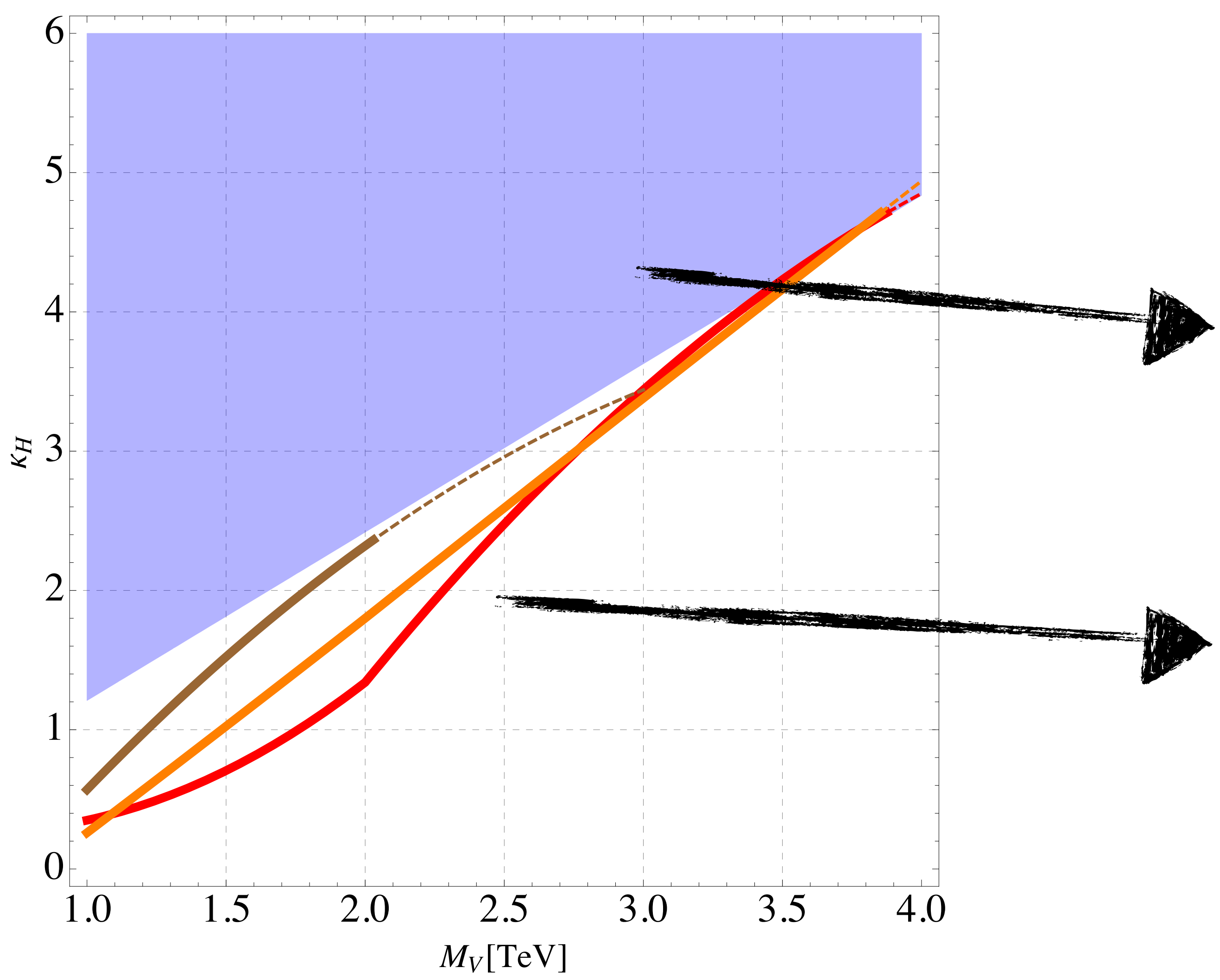
For example:



Validation: the red limits (no cuts) are in agreement with those from the collaborations and from other th. fits.

Comparing EFT and model

Model with a vector triplet + singlet. No vertex corrections, at low energy only



$$\delta g_{1,z} = -\kappa_H^2 \frac{m_W^2}{2 s_\theta^2 m_V^2}$$

Limits from EFT (no high-E cut) from CMS WW @ 8TeV.

Different lines: limits obtained simulating directly the model with different parameters with same low energy EFT.

Only for masses ≳ 3TeV the EFT and model limits are compatible.
In this case the EFT gives always conservative limits, not always so lucky.

Conclusions

- aTGC offer an efficient parametrization of BSM in diboson production within an EFT setup, if vertex corrections can be taken SM-like.
- It is important to take control of the EFT validity by doing analyses with different cuts on the invariant mass: relevant impact at the interpretation level.
- Violation of unitarity is not a problem if the EFT approach itself can be applied.