Experimental limits on anomalous TGC couplings and future plans

Workshop on Implications of LHC results for TeV-scale physics

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August 30, 2011

Outline

What is an anomalous coupling?

Adding (general) deviations to the SM

- If the SM is not an exact description of Nature, the Lagrangian that we feel at low energies is:

$$\mathcal{L}(\sqrt{s} \ll \Lambda) = \mathcal{L}_{SM} + \sum_{n=5}^{\infty} \frac{1}{\Lambda^{n-4}} \left(\sum_j f_{nj} \, \mathcal{O}_{nj} \right)$$

where:

- $\mathcal{O}_{nj}$ are terms containing SM fields
- f_{nj} are adimensional couplings of order "1"
- Λ is large, of the order of the scale of new physics
- Corrections to the SM are suppressed by powers of $\frac{\sqrt{s}}{\Lambda}$ (and also $\frac{v}{\Lambda}$, with $v = 246\ \mathrm{GeV}$)
- Dominant terms respecting the $SU(2)_L \times U(1)_Y$ symmetry of the SM were collected already in 1986 (W. Buchmüller and D. Wyler, Nucl.Phys.B268:621,1986)

Examples of deviations

- Only dimension-5 operator respecting SM symmetries:

$$\frac{1}{\Lambda} \epsilon_{ij} \; \epsilon_{kl} \; (\phi^j \; \phi^l) \; (\overline{\ell}_R^{ci} \; \ell_L^k)$$

  - Gives neutrino masses consistent with experimental results if $\Lambda \sim 10^{15}$ GeV

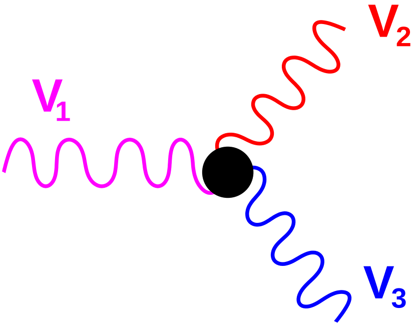
- Four-fermion contact interactions:

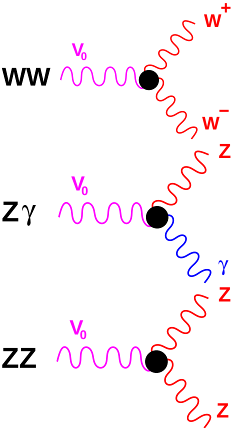
$$\frac{1}{\Lambda^2} \; (\overline{q} \Gamma_\mu q) \; \overline{\Psi} \Gamma^\mu \Psi)$$

- Operators containing WWZ and $WW\gamma$ anomalous couplings (of λ type in this example):

$$\frac{1}{\Lambda^2} \; \epsilon_{IJK} \; W_\mu^{I\nu} \; W_\nu^{J\rho} \; W_\rho^{K\mu}$$

Triple anomalous boson gauge vertices





$V^* WW$ anomalous vertex

(Hagiwara *et al.*, Nucl.Phys.B282:253,1987, only C,P conserving couplings shown)

$$
\begin{aligned}
\Gamma^{\alpha\beta\mu}_{WWV} &= g_{WWV}\ (1+\Delta g_1^V)[(q_1-q_2)^\mu g^{\alpha\beta} - q_1^\beta g^{\mu\alpha} + q_2^\alpha g^{\mu\beta}] \\
&+ (1+\Delta\kappa_V)[q_2^\alpha g^{\mu\beta} - q_1^\beta g^{\mu\alpha}] \\
&+ \frac{\lambda_V}{m_{\mathrm{W}}^2}\ (q_1-q_2)^\mu\ [\frac{s}{2} g^{\alpha\beta} - q_2^\alpha q_1^\beta]
\end{aligned}
$$

- Note that the presence of "m_{W}^2" in the denominator of λ is just historical. In reality, this should have been "Λ^2".
- Also, the fact that g_{WWV} is associated to Δ*coupling* is arbitrary (no reason to assume the SM coupling strength)
- It can be seen that $\lambda, \Delta g_1, \Delta\kappa_\gamma$ terms behave at least as $(v/\Lambda)^2$ (v is the Higgs vacuum expectation value, 246 GeV).
- SM symmetries at dimension 6 require: $\Delta g_1^Z - \Delta\kappa_z = \tan^2\theta_w\ \Delta\kappa_\gamma;\ \lambda_\gamma = \lambda_Z;\ \Delta g_1^\gamma = 0$

V^*WW anomalous vertices via deviations from SM

$$\begin{aligned} \Delta g_1^Z &\rightarrow i \frac{f}{\Lambda^2}(D_\mu\Phi)^\dagger(\vec{\tau}\vec{W^{\mu\nu}})(D_\nu\Phi) \\ \Delta k_Z &\rightarrow i \frac{f}{\Lambda^2}(D_\mu\Phi)^\dagger B^{\mu\nu}(D_\nu\Phi) \\ \lambda_\gamma &\rightarrow \frac{f}{\Lambda^2}\, \epsilon_{IJK}\; W_\mu^{I\nu}\; W_\nu^{J\rho}\; W_\rho^{K\mu} \end{aligned}$$

- Every $D_\mu\Phi$ gives a v and a vector boson. These terms lead to the same type of terms presented in the previous page, but changing m_W by Λ and adding $(v/\Lambda)^2$ when no Λ is present.
- Δg_1^Z and Δk_γ are connected to the Higgs field at this order (they also provide Higgs-boson-boson anomalous couplings). We have also set limits on these anomalous Higgs couplings at LEP (L3).
- Note at margin: it is not so easy to produce trilinear anomalous couplings (D. Rújula et al., Nucl. Phys. B384 (1992) 3).

$V^*Z\gamma$ anomalous vertex

(Hagiwara *et al.*, Nucl.Phys.B282 (1987) 253 (+ missing "*i*" factor))

$$\Gamma^{\alpha\beta\mu}_{Z\gamma V} = i\ e\frac{q_V^2 - m_V^2}{m_Z^2}\{\ h_1^V\ (q_\gamma^\mu g^{\alpha\beta} - q_\gamma^\alpha g^{\beta\mu})$$
$$+\ h_2^V\ \frac{q_V^\alpha}{m_Z^2}\ (q_\gamma q_V\ g^{\beta\mu} - q_\gamma^\mu\ q_V^\beta)$$
$$+h_3^V\ \epsilon^{\alpha\beta\mu\rho}\ q_{\gamma\rho}$$
$$+\ h_4^V\ \frac{q_V^\alpha}{m_Z^2}\ \epsilon^{\mu\beta\rho\sigma}\ q_{V\rho}\ q_{\gamma\sigma}\ \}$$

- Note again the presence of m_Z in the denominators. And of e as an arbitrary coupling constant, In reality, Λ and a generic coupling constant should have been used instead.
- So $h_{1,3}$ behave at least as Λ^{-2} and $h_{2,4}$ at least as Λ^{-4}. Actually, all must behave at least as Λ^{-4} if $SU(2) \times U(1)$ symmetry is preserved (J. A., Phys. Rev. D65 (2002) 075020).

$V^{*}\mathrm{ZZ}$ anomalous vertex

(Hagiwara *et al.*, Nucl.Phys.B282:253,1987)

$$\Gamma^{\alpha\beta\mu}_{\mathrm{Z}_1\mathrm{Z}_2 V} = i\ e\frac{q_V^2 - m_V^2}{m_\mathrm{Z}^2}\left\{\ f_4^V\ (q_V^\alpha\ g^{\beta\mu} + q_V^\beta\ g^{\mu\alpha}) + \ f_5^V\ \epsilon^{\alpha\beta\mu\rho}\ (q_{\mathrm{Z}_1\rho} - q_{\mathrm{Z}_2\rho})\ \right\}$$

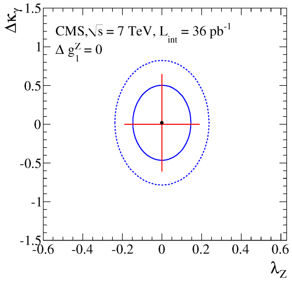
- Similarly to the previous cases, $f_{4,5}$ behave at least as Λ^{-2} (well, rather like Λ^{-4} if we respect SM symmetries).
- Again, according to the initial discussion, it would have been more reasonable to measure/set limits on $coupling/\Lambda_h^n$ and $coupling/\Lambda_f^n$ (and there are even papers that can be used as references).
- This is indeed the approach used in the case of four-fermion contact interactions, quartic couplings (which were defined more recently).

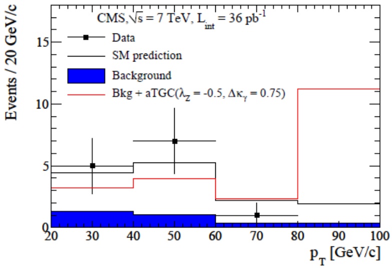
Experimental results at the LHC

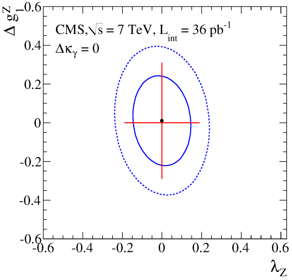
- Since effects increase with $\sqrt{\hat{s}}$:
  - WW, WZ, ZZ, $W\gamma$, $Z\gamma$ cross section must increase. The sensitivity is huge compared to previous experiments (LEP, Tevatron), simply due to the large center-of-mass energy of the LHC: $\sqrt{s}\uparrow \Rightarrow \sqrt{\hat{s}}\uparrow$
  - And cross section is particularly enhanced in regions of phase space that imply high $\sqrt{\hat{s}}$: visible transverse activity, very high photon or lepton p_T, ...
- With more than 2 fb^{-1} already collected, the LHC sensitivity to anomalous triple gauge couplings is already beyond Tevatron reach

WW channel

- CMS uses the high-p_T lepton region to enhance sensitivity (SHERPA, NLO effects studied with MCFM)
- Sensitivity to AC not far from Tevatron with just 36 pb^{-1}
- No use of any additional form factors (more on this later)

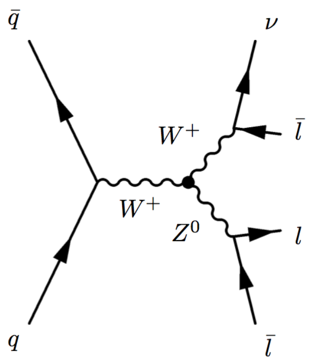


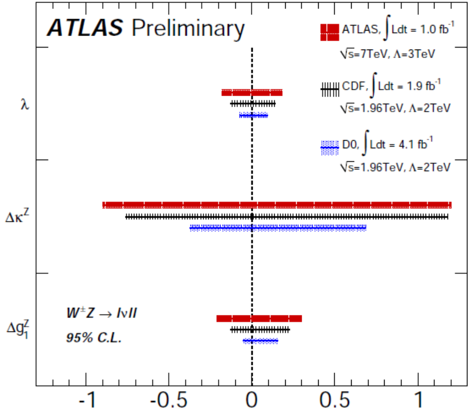




WZ channel

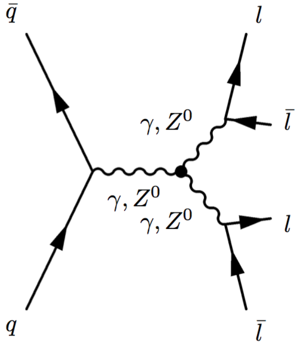
- ATLAS limits based on just the total cross section measurement (MC@NLO, aTGC effects via reweighting methods)
- Sensitivity slightly worse than Tevatron with 1 fb^{-1}
- Several additional form factors (more on this later)

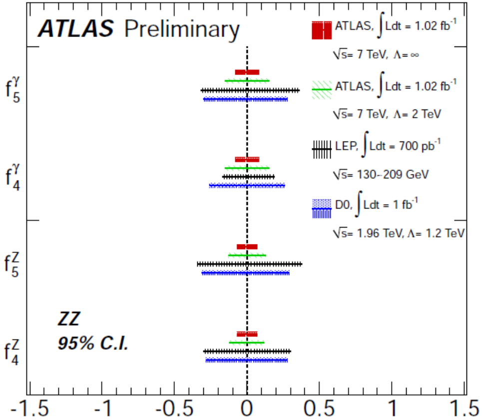




ZZ channel

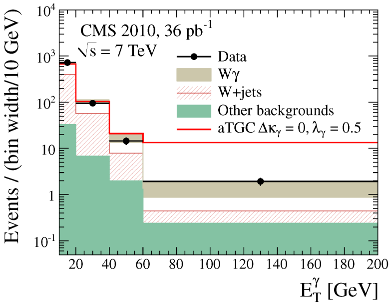
- ATLAS limits based on just the total cross section measurement (PYTHIA, aTGC effects via reweighting to Baur's predictions)
- Sensitivity slightly better than Tevatron with 1 fb^{-1}
- Several additional form factors (more on this later)

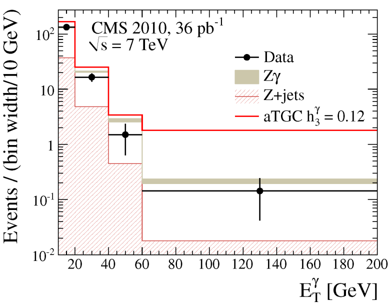




$V\gamma$ channel

- CMS uses high-E_T photons to enhance the sensitivity (MadGraph, aTGC effects via k-factors to MCFM or Baur's program)
- No form factors used (more on this later)





$V\gamma$ channel

- CMS uses high-E_T photons to enhance the sensitivity
- Sensitivity not so far from Tevatron with just 36 pb^{-1} (specially on h_4 due to the $\sqrt{s}$ increase)
- No form factors used (more on this later)

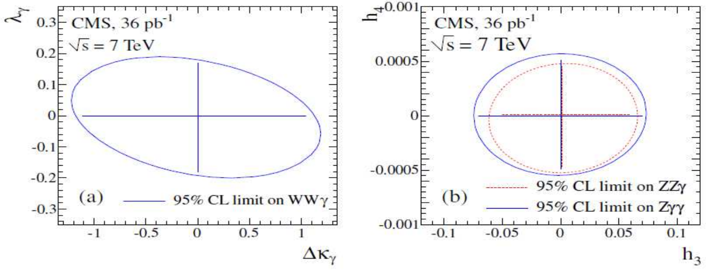
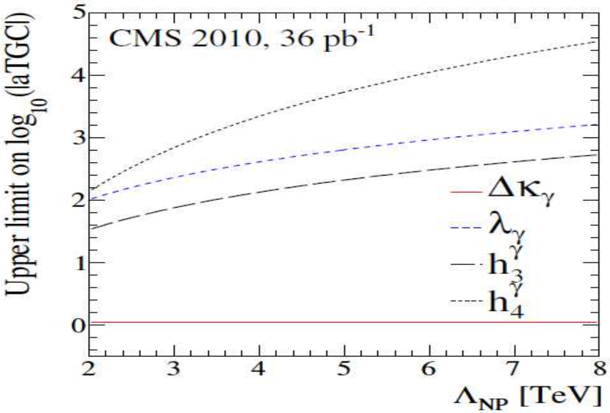


Table 2: One dimensional 95% CL limits on $WW\gamma$, $ZZ\gamma$, and $Z\gamma\gamma$ aTGCs.

$WW\gamma$	$ZZ\gamma$	$Z\gamma\gamma$
$-1.11 < \Delta\kappa_\gamma < 1.04$	$-0.05 < h_3 < 0.06$	$-0.07 < h_3 < 0.07$
$-0.18 < \lambda_\gamma < 0.17$	$-0.0005 < h_4 < 0.0005$	$-0.0005 < h_4 < 0.0006$

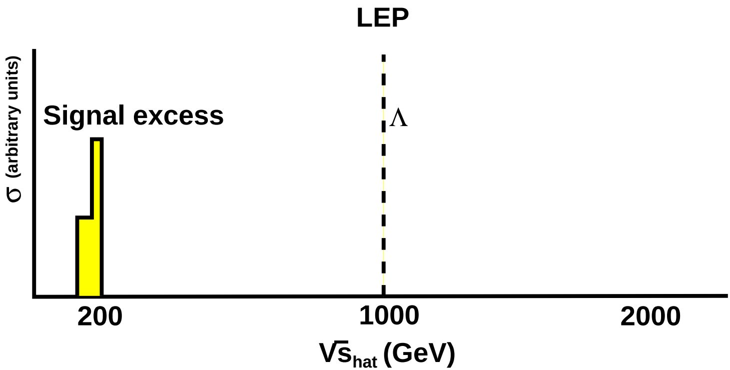
$V\gamma$ channel

- Results also expressed in terms of scales: $\frac{\sqrt{\alpha_{QED}}\ h}{m_Z^n} \equiv \frac{aTGC}{\Lambda_{NP}^n}$.
- ($n = 0$ used for $\Delta\kappa_\gamma$, but actually $\sqrt{\alpha_{QED}}\ \Delta\kappa_\gamma \equiv \frac{aTGC\ v^2}{\Lambda_{NP}^2}$)



Form factors for anomalous couplings?

Form factors?



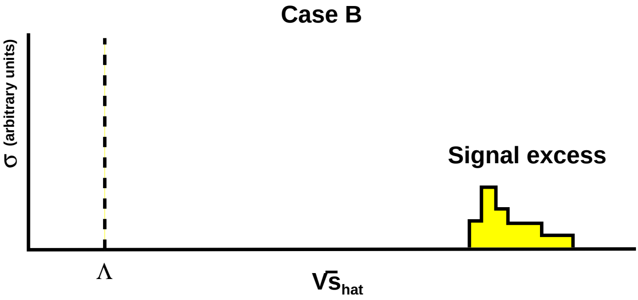
- If $\sqrt{s} \ll \Lambda$ no higher order terms must be considered:

$$\frac{\text{Anomalous coupling}}{\Lambda^n} \equiv \frac{f}{\Lambda^n}$$

which does not depend on $\sqrt{s}_{hat}$

- This is the ONLY SENSIBLE CONTEXT for these "couplings"

Form factors?

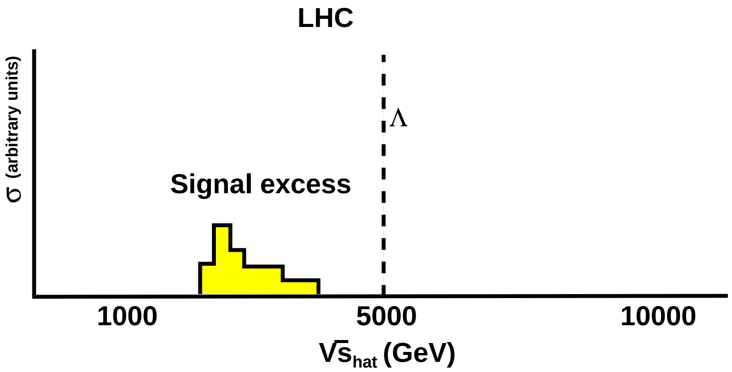


- Infinite higher orders $\frac{\sqrt{s}}{\Lambda^n}$ must be resummed. Unitary can not be violated: $\sigma(\sqrt{s}) \sim\rightarrow \frac{1}{s}$, which allows an ansatz of the type:

$$\frac{\text{Anomalous coupling}}{\Lambda^n} \rightarrow \frac{f}{\Lambda^n} \times (\text{Form factor}) \rightarrow \frac{f}{\Lambda^n \left[1 + (s_{hat}/\Lambda^2)\right]^m}$$

- Similarities with Λ_{QCD} and QCD form factors
- In this context WE SHOULD KNOW THE UNDERLYING THEORY, I.E. WE SHOULD HAVE SEEN NEW PHYSICS ALREADY

The real case



- In this case, there is no way to know the exact functional shape (resonances, interferences, ...). One needs to know exactly the "underlying" new physics theory near threshold (SUSY AROUND THE CORNER could be an example).

Confirmation...

J. Wudka, UCRHEP-T164, hep-ph/9606478, "The meaning of anomalous couplings":

3.1.1 Form factors

It has been customary to use form factors to insure the theory does not violate unitarity. I will not do this here for the following reasons:

(*i*) The effective lagrangian approach should not be extended to scales close to a threshold. All attempts at modifying the formalism to this end are *extremely* model dependent and no general conclusions can be derived from them.

(*ii*) The form factors are usually chosen so that there are no poles in *any* physical process. This is unreasonable: even if in certain processes no poles occur, they will appear in the crossed channels.

As an example, the (expected) bounds $h_3^Z \lesssim 0.005$, $h_4^Z \lesssim 10^{-4}$ have been obtained for the LHC [12] using the $p\bar{p} \to Z\gamma \to e^+e^-\gamma$ reaction assuming that the CM energy was 14 TeV while the scale of the form factor was 1.5 TeV. These values, however, imply that we have enough energy to observe directly the heavy physics ($1.5 \ll 14$). The effective lagrangian approach breaks down in this region and no reliable information can be derived from this approach, but this is of little importance: the new physics would be directly observable.

There are also experimental arguments...

1. We are never going to violate unitarity experimentally. It is only the interpretation which can violate unitarity. We should only ensure unitarity at the $\sqrt{s'}$ values that we test, and this is not an issue in practice when anomalous couplings are sufficiently small.
2. It also leads to non-sense conclusions. If we see some excess at $\sqrt{s'}$ that could be attributed to this, the last thing that we want to do is to hide the excess to set a conservative limit, assuming that what we see at $\sqrt{s'}$ must be weighted down by a form factor of ~ 16 (in the best case!). Simply we will not set any limit and try to look for possible explanations (not necessarily AC). And if we do not see an excess, there are no unitarity issues (the limit may be trivial if it is too poor: that's all). Last but not least, limits without form factors are always a sensible quantification for all $\Lambda \gg \sqrt{s'}$.

What are we doing today for anomalous couplings in $Z\gamma$ production?

- We are using form factors of the type:

$$F(s/\Lambda^2) = \frac{1}{(1 + s/\Lambda^2)^N}$$

  $N = 3$ for couplings of type $h_{1,3}$ and $N = 4$ for couplings of type $h_{2,4}$.
- First of all, there is no fundamental reason why the form factor should have this explicit form (dipole form factor), and even less when $\sqrt{s'} \sim \Lambda$, the only real case of interest.
- Second, in order not to violate unitarity when $\sqrt{s} \to \infty$, one should just ensure that $N > 3/2$ and $N > 5/2$, respectively.
- Which is the original justification for this?

Original justification for the usage of form factors in $Z\gamma V$

U. Baur, E.L. Berger, Phys. Rev. D47 (1993) 4889, "Probing the weak-boson sector in $Z\gamma$ production at hadron colliders":

> choices guarantee that unitarity is preserved and that terms proportional to $h^V_{20,40}$ have the same high-energy behavior as those proportional to $h^V_{10,30}$. Furthermore, if exponents sufficiently above the minimum values of $\frac{3}{2}$ and $\frac{5}{2}$ are selected, one ensures that $Z\gamma$ production is suppressed at energies $\sqrt{\hat{s}} \gg \Lambda \gg m_Z$, where novel phenomena such as multiple weak boson, or resonance production, are expected to dominate.

What is written is correct, but a) this has nothing to do with the true experimental scenario $\sqrt{\hat{s}} \lesssim \Lambda$ and b) one can not a priori experimentally penalize an AC interpretation assuming that other NP interpretations are more likely to happen.

PROPOSAL 1

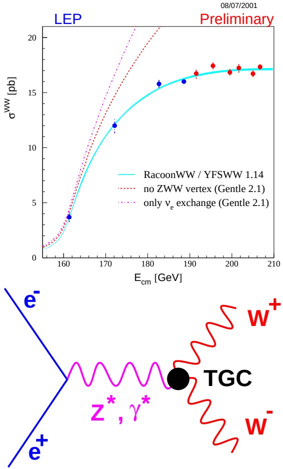
- At least for "neutral" trilinear anomalous gauge couplings, we should set limits on f/Λ^n terms FROM THE START to decouple from the current convention and avoid confusion. This has already been done already (L3 and now CMS). There are references for the new convention (Mery, Perrotet, Renard, Z.Phys. C38 (1988) 579).
- We can add an interpretation in terms of the old anomalous coupling convention at the end for the sake of comparison with previous results. BUT THE CONVERSION IS TRIVIAL: $\sqrt{\alpha_{QED}}\ h/m_Z^n \equiv f/\Lambda^n$.
- This will be more difficult for WWV couplings, due to the too well established convention, but nothing prevents us from providing Λ limits too.

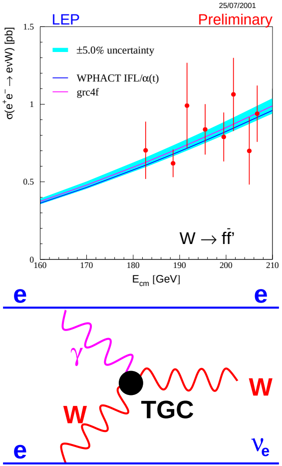
PROPOSAL 2

- We should not use form factors to quote limits. The use of form factors in the context of anomalous couplings at hadron colliders is inconvenient (hard for combinations), arbitrary (just a tentative choice) and out of context (they refer to the process in a limit that is not the one tested experimentally). The proposed form factors make sense only in the limit $\sqrt{\hat{s}} \gg \Lambda_{NP}$. For $\sqrt{\hat{s}} \ll \Lambda_{NP}$ there is no form factor and for $\sqrt{\hat{s}} \sim \Lambda_{NP}$ one requires a detailed knowledge of the new physics Lagrangian.
- Experimentally, we do not use form factors anywhere else when looking for new physics deviations (contact interactions, low scale gravity, quartic couplings, ...). So why in this context?
- I am aware that this is a big change in the logic, but we should address this problem NOW, not later.
- We are already following this approach in CMS.

BACKUP

- The extra couplings lead to increases of the cross section with energy

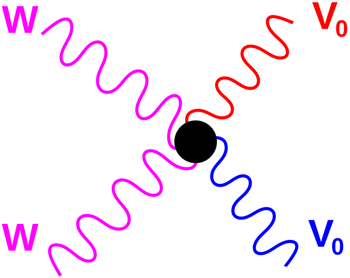




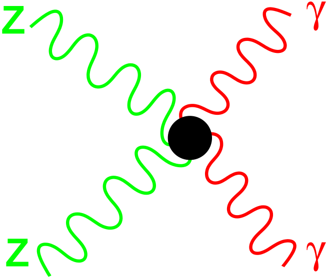
Quartic gauge couplings

- Window to new physics scales, maybe related to the symmetry breaking mechanism of the SM

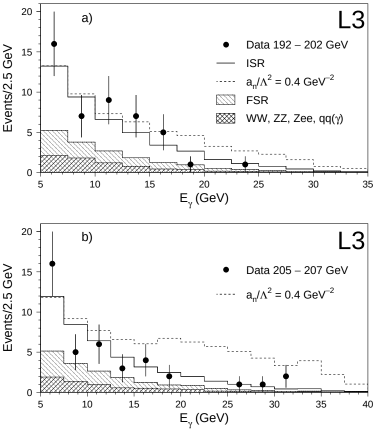
In SM:

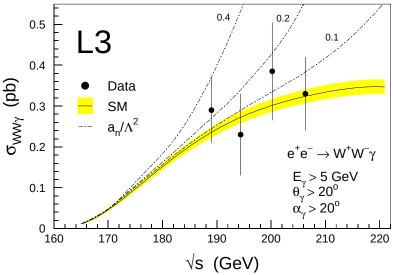


Not in SM:



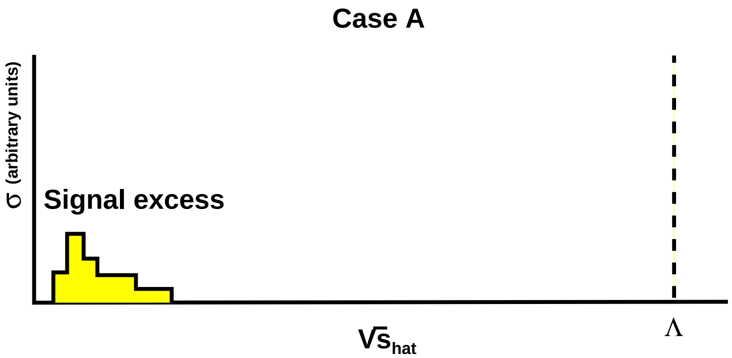
WW$V\gamma$ coupling searches





We have always been setting limits on $\frac{f}{\Lambda^2}$ in this case !!

Form factors?



- If $\sqrt{s} \ll \Lambda$ no higher order terms must be considered:

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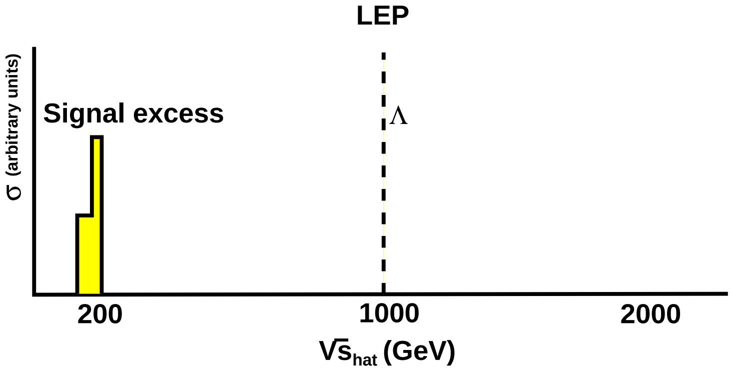
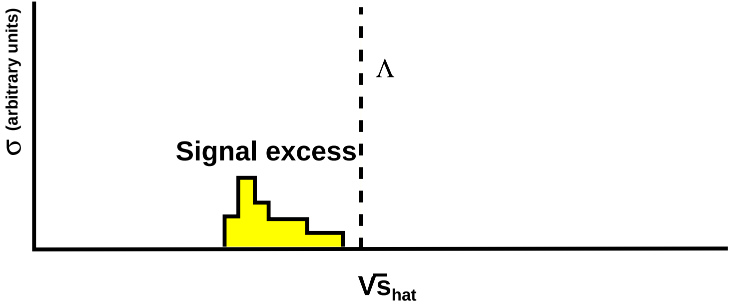
Real cases



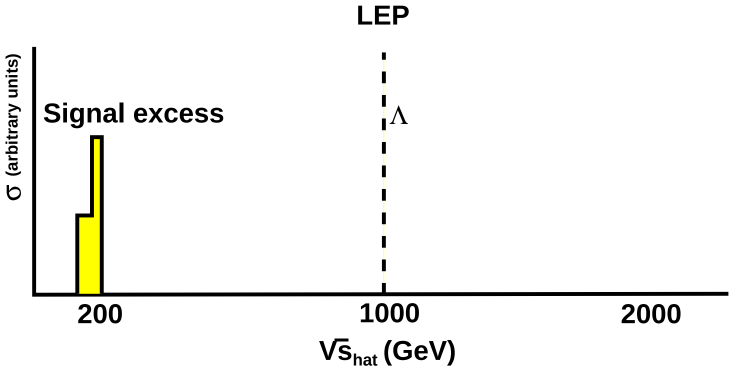
- This is clearly related with Case A before. Note that LEP is not measuring any "constant" form factor, but the "naked" anomalous coupling. Corrections due to higher orders should be small.

Form factors?



- In this case, there is no clear recipe. One needs to know exactly the "underlying" new physics theory near threshold (SUSY AROUND THE CORNER could be an example).

Real cases



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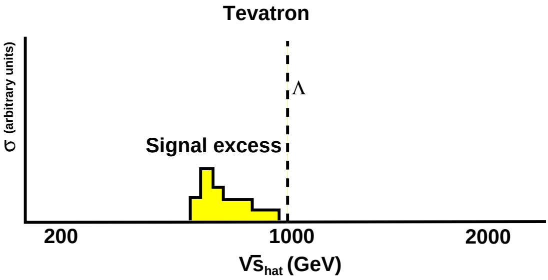
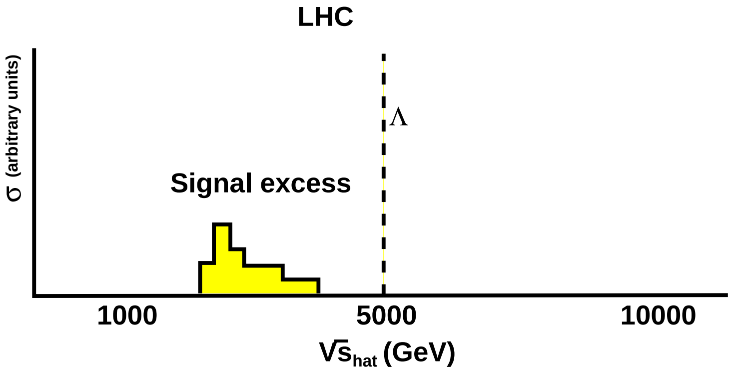
Real cases



- At Tevatron, people use a form factor $F(s/\Lambda^2)$. The functional form of F is chosen to guarantee that $\sigma(\sqrt{s}) \sim\longrightarrow \frac{1}{s}$ or even smaller when $\sqrt{s} \to \infty$: UNITARITY.
- BUT note that there is no experimental justification for this. We are not at $\sqrt{s} \to \infty$, just $\sqrt{s'} < 7$ TeV, and the scales that we are probing can not be much lower than $\sqrt{s}$ BECAUSE WE SHOULD HAVE SEEN NEW PHYSICS OTHERWISE.

Real cases



- Not so different from the Tevatron case, obviously.