New Physics searches in EW physics

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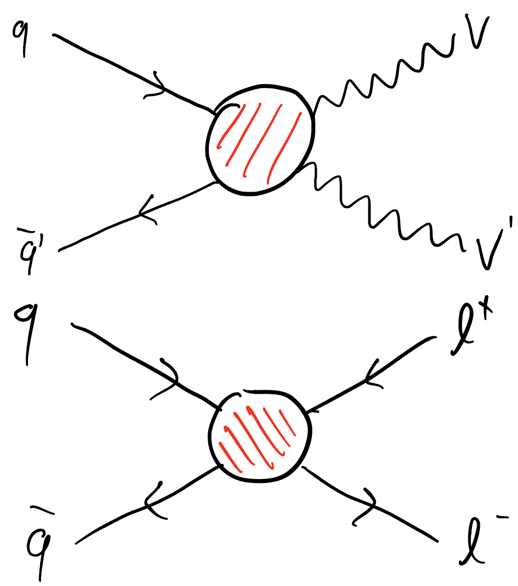
Outline

- Introduction
- Which EW processes @LHC offer the best sensitivity to New Physics?
  - Diboson production
  - Dilepton production (Drell-Yan)



- Present bounds, EFT validity, prospects.
- Application to neutral-current B-physics anomalies

Indirect searches of New Physics

Precision measurements of SM processes can allow to test New Physics at scales not reachable by direct searches.

The SM EFT allows to describe the low-energy effects of heavy New Physics

SM + heavy New Physics

$$E, m_Z \ll \Lambda \qquad \mathcal{L}^{\text{eff}} = \mathcal{L}_{\text{SM}} + \boxed{\sum_i \frac{c_i^{(6)}}{\Lambda^2} \mathcal{O}_i^{(6)}} + \sum_j \frac{c_j^{(8)}}{\Lambda^4} \mathcal{O}_j^{(8)} + \dots$$

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For example:

- constraint on custodial symmetry violation,
- heavy states coupled to Higgs and/or fermion currents,
- deviations in Higgs couplings to SM gauge bosons,
- …

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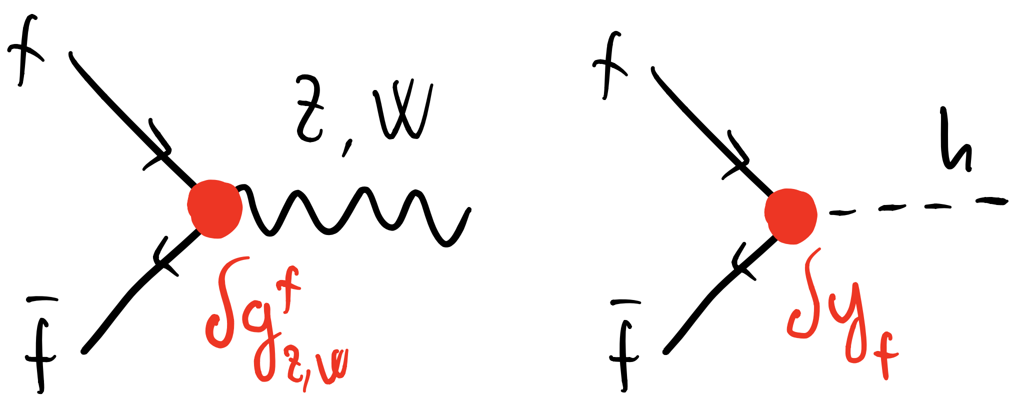
What are the electroweak processes at the LHC which offer the best sensitivity to such heavy New Physics?

New Physics @ LHC

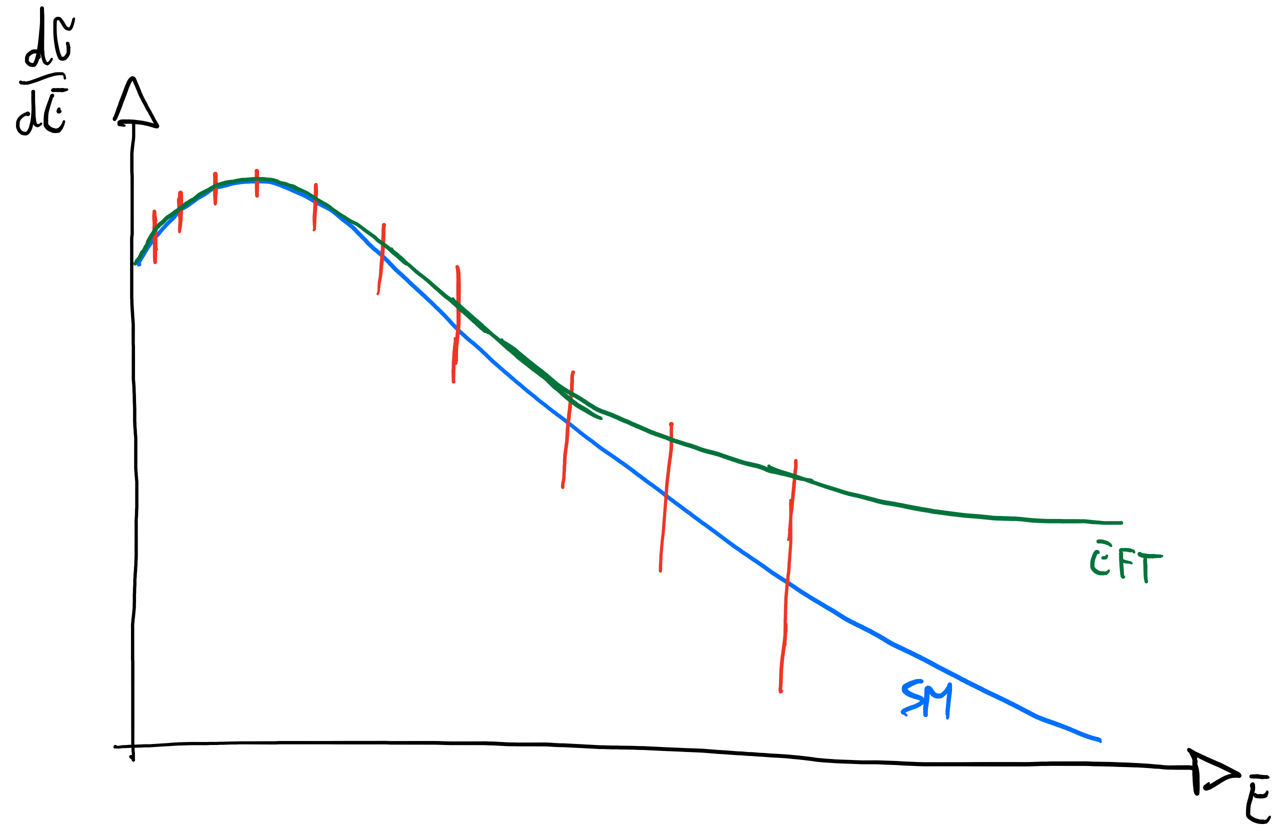
Excluding direct searches and flavour physics

Two broad strategies for looking for deviations from the SM

1) Deviations in on-shell* couplings between SM particles



2)



Deviations in the tails of differential distributions

$$A_{BSM} / A_{SM} \sim E^2$$

New Physics @ LHC

Excluding direct searches and flavour physics

1) ***Z(W)-pole** observables, **Higgs** couplings,..*

$c_i \sim g_*^2 \qquad \delta_{\rm pole} \sim \mathcal{O}\left(g_*^2 \frac{m_Z^2}{\Lambda^2} \right)$ LEP-I: $\delta_{\rm pole} \lesssim 10^{-3} \xrightarrow{g_* \sim 1}$ **$\Lambda \gtrsim 3$ TeV**

At LHC these measurements are limited by systematic (incl. theory) uncertainties.

Not much room for improvement beyond ~ (few) % level
[few exceptions, e.g. m_W]

New Physics @ LHC

Excluding direct searches and flavour physics

2) *Deviations in the **tails of 2 → 2 processes***

$$\delta_{\rm tail} \sim \mathcal{O}\left(g_*^2 \frac{p^2}{\Lambda^2} \right) \qquad \delta_{\rm tail} \lesssim 10^{-1} \xrightarrow[g_* \sim 1]{p \sim 2\ \mathrm{TeV}} \Lambda \gtrsim 6\ \mathrm{TeV}$$

'*Energy helps accuracy'* [see e.g. Farina et al. 1609.08157]

New Physics @ LHC

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Less precise measurements at high energy can be competitive with very precise ones at low energy.

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We focus on **operators**
whose interfering amplitude with the SM
grows quadratically with the energy

EFT validity

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;
...

Any experimental limit in the EFT approach will be on the combination

$$c_i \sim g_*^2$$

$$\boxed{v^2 \frac{c}{\Lambda^2} < \delta_{prec.}}$$

$$\begin{cases} c < \frac{\Lambda^2}{v^2}\, \delta_{prec.} \\ c \lesssim 4\pi \\ \Lambda \gg E_{exp} \end{cases}$$

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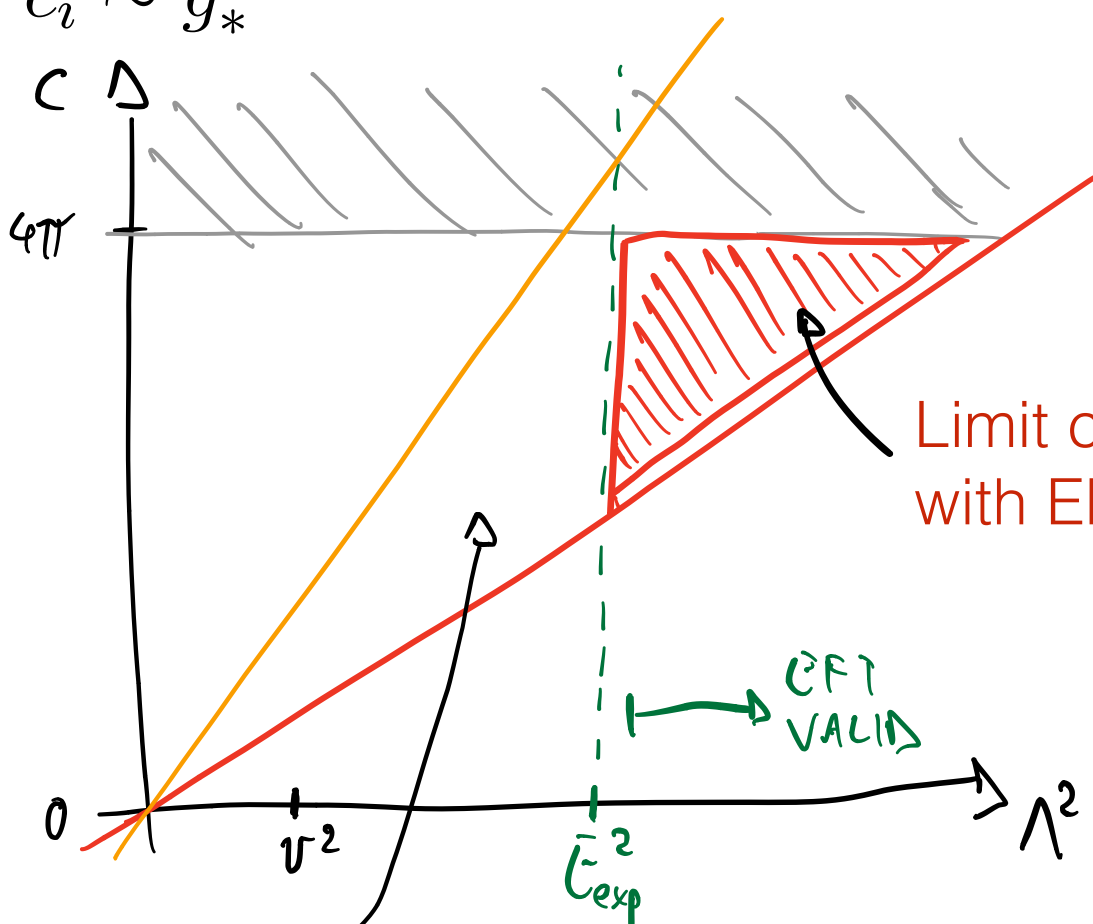


Limit consistent with EFT

This region is possibly excluded by same search, but using a ‘direct search’ approach.

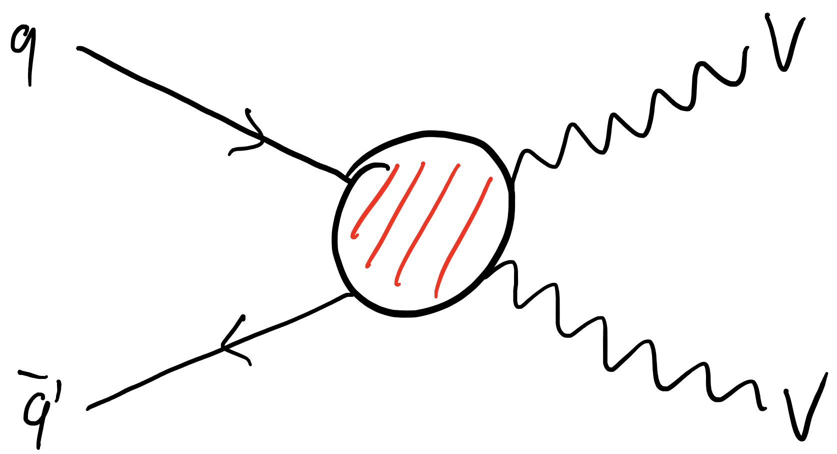
Bad precision at high energy could mean that no scenario is being probed consistently with the EFT.

Increasing the precision enlarges the size of the triangle, accessing more weakly coupled models.

2 → 2 processes at high-p_T

In this talk I will focus on:

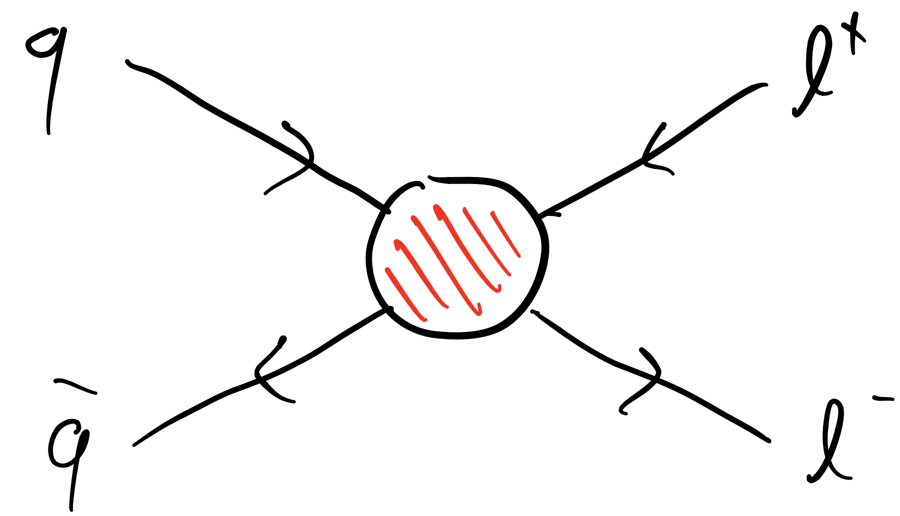
Diboson (and VH) production



Constraints on
qqHD$_\mu$H operators.

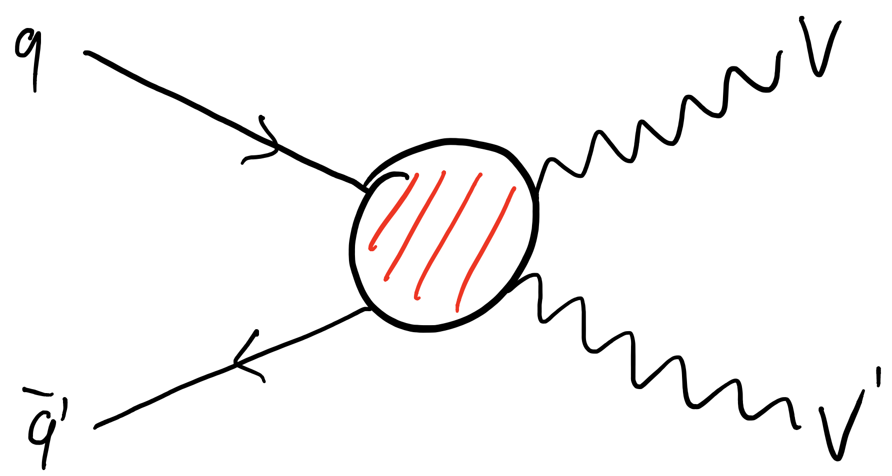
or anomalous triple-gauge couplings
(aTGC)

Dilepton production
at high $m_{\ell\ell}$



Constraints on $qq\ell\ell$
four-fermion operators

Diboson production



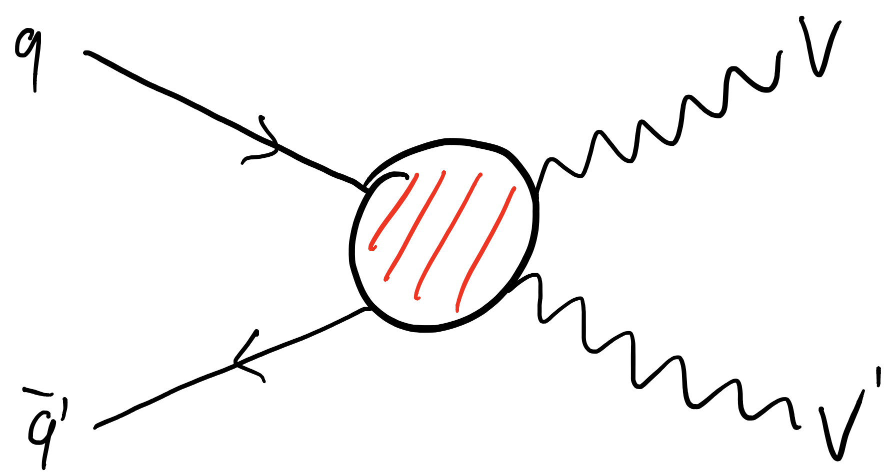
The only SM-BSM interference term growing as E^2 is in longitudinal gauge bosons

$$q\,\bar{q} \to V_L\, V_L \ \ (\text{i.e. } H\, H)$$

[Azatov et al. 1607.05236, Falkowski et al. 1609.06312, Franceschini et al 1712.01310]

eg: $\delta\mathcal{A}(\bar{q}q' \to WZ) \sim a_q^{(3)} E^2$

Diboson production



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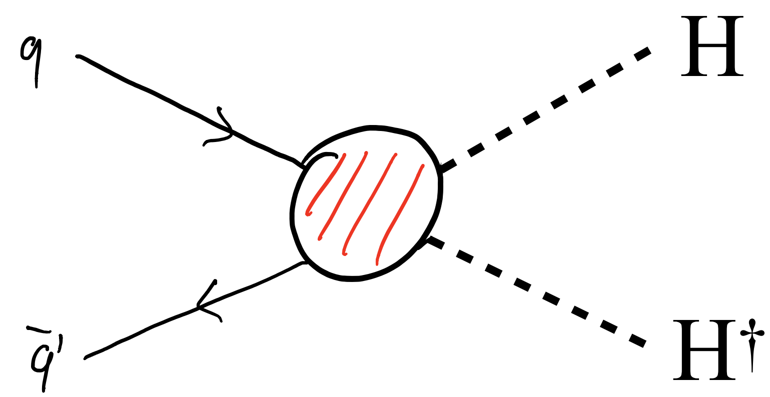
eg: $\delta\mathcal{A}(\bar{q}q' \to WZ) \sim a_q^{(3)} E^2$

Due to:

$$\frac{c_q^1}{\Lambda^2}(\bar{q}\gamma^\mu q)(H^\dagger \overleftrightarrow{D}_\mu H)$$

$$\frac{c_q^3}{\Lambda^2}(\bar{q}_L\gamma^\mu \sigma^a q_L)(H^\dagger \sigma^a \overleftrightarrow{D}_\mu H)$$



Assuming universal new physics, these correspond to combinations of aTGC and oblique parameters:

$$a_q^{(3)} = -\frac{g^2}{m_W^2}\left(c_{\theta_W}^2 \delta g_1^Z + W\right)\,, \qquad a_q^{(1)} = \frac{g'^2}{3m_W^2}\left(\hat{S} - \delta\kappa_\gamma + c_{\theta_W}^2 \delta g_1^Z - Y\right)$$

Controlling the EFT (I)

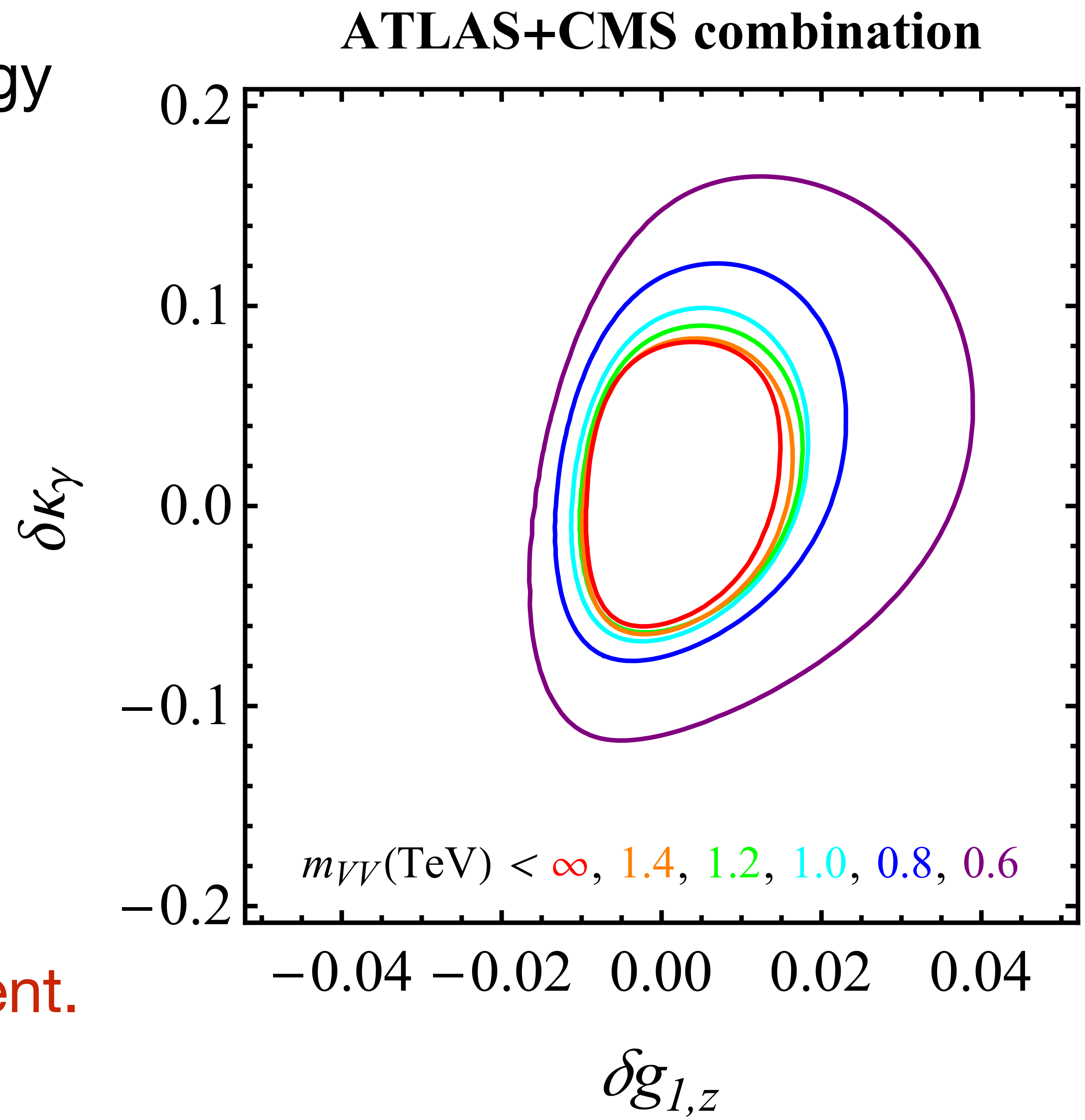
Falkowski, Gonzalez-Alonso, Greljo, D.M., Son [1609.06312]

Perform a fit keeping only low-energy events (below some cut)

$$\boxed{m_{VV} < m_{VV}^{\max}}$$

We fit a selection of 8 TeV (20fb^{-1}) +13 TeV (3.2fb^{-1})
ATLAS and CMS WW and WZ data

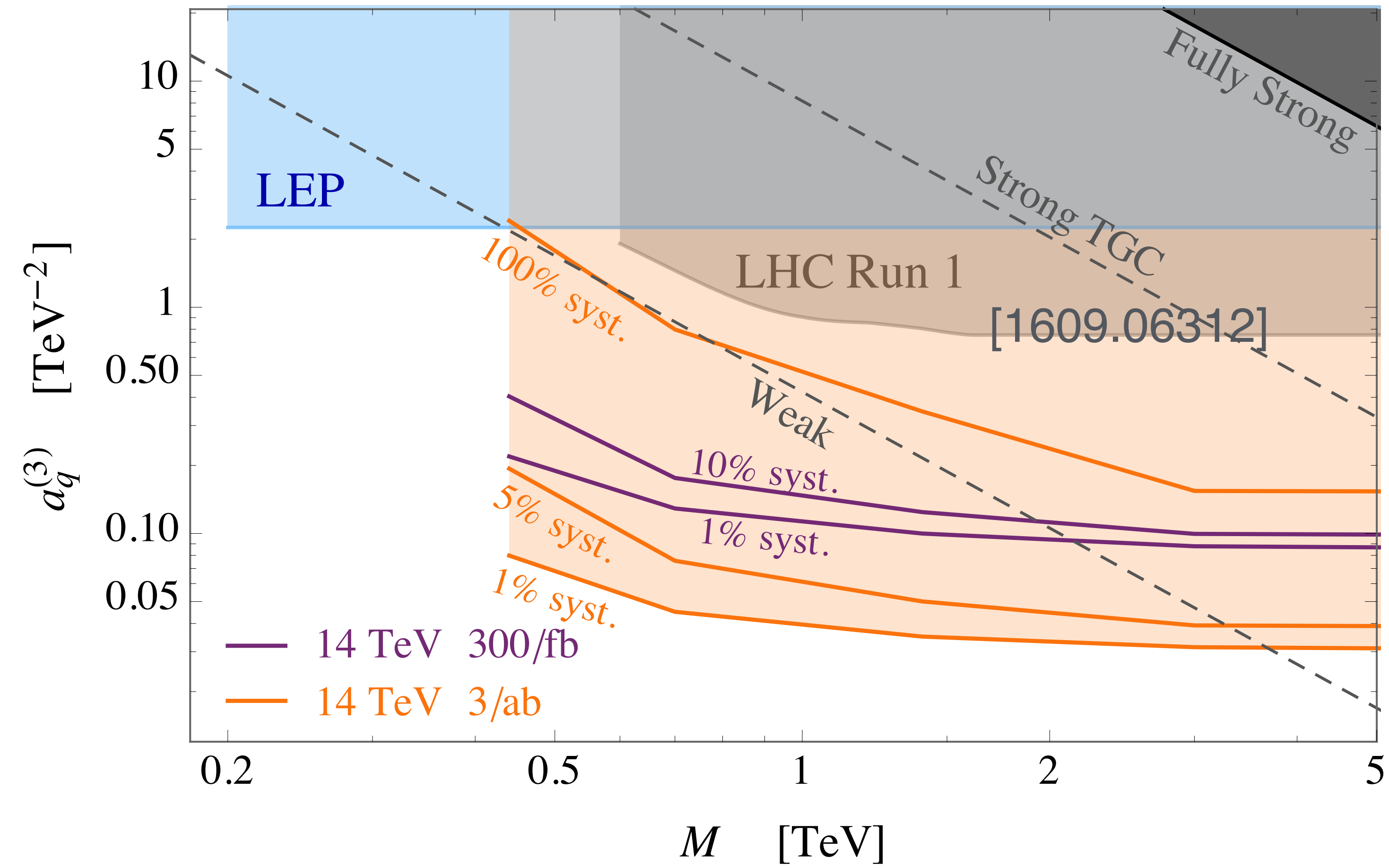
Fits saturate at $m_{VV}^{\max} \sim 1\,\mathrm{TeV}$:
typical energy scale of the measurement.



Limits and prospects

[Franceschini, Panico, Pomarol, Riva, Wulzer 1712.01310]

Only from the leptonic WZ



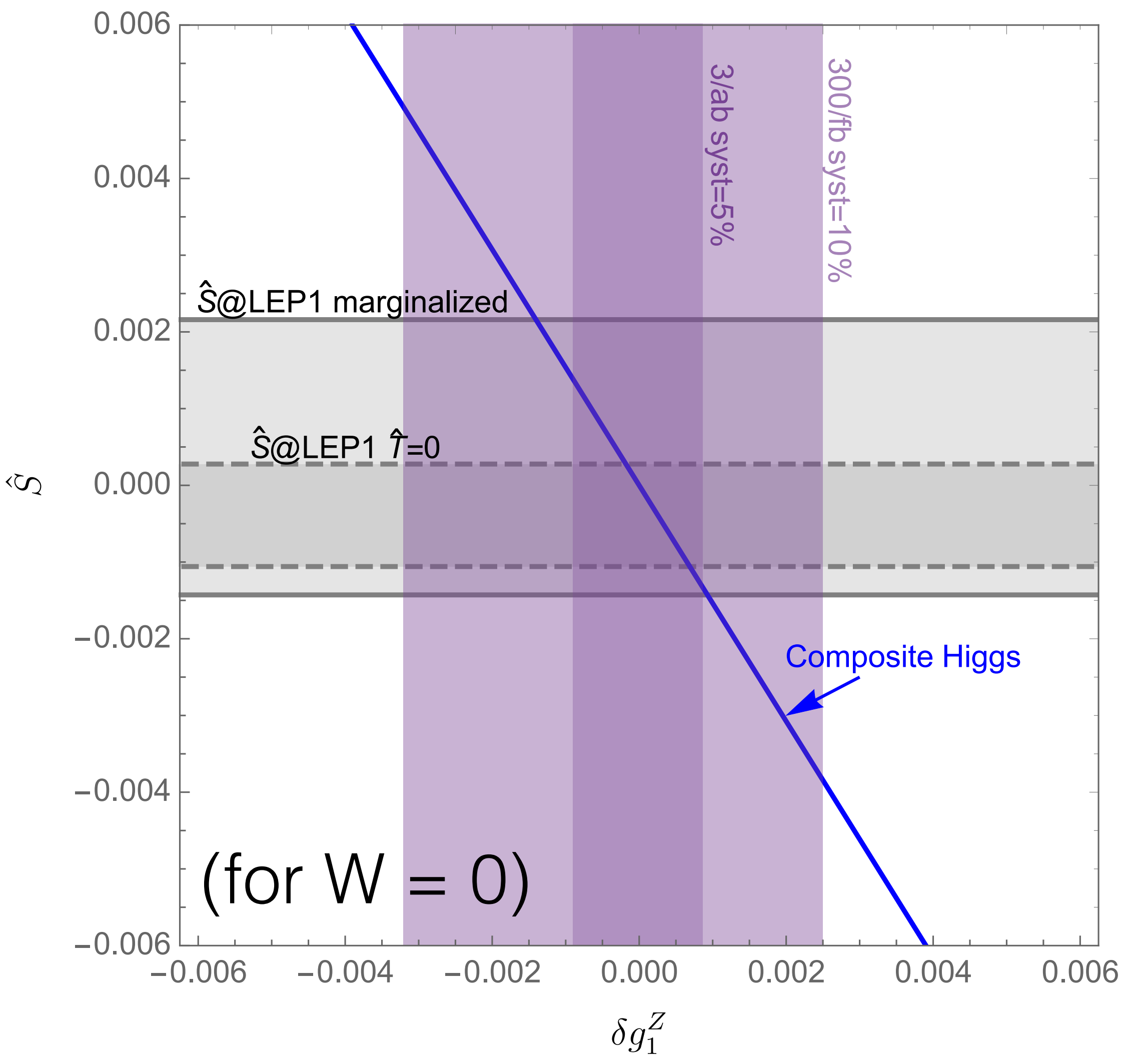
$$a_q^{(3)} = -\frac{g^2}{m_W^2}\left(c_{\theta_W}^2 \delta g_1^Z + W\right)$$

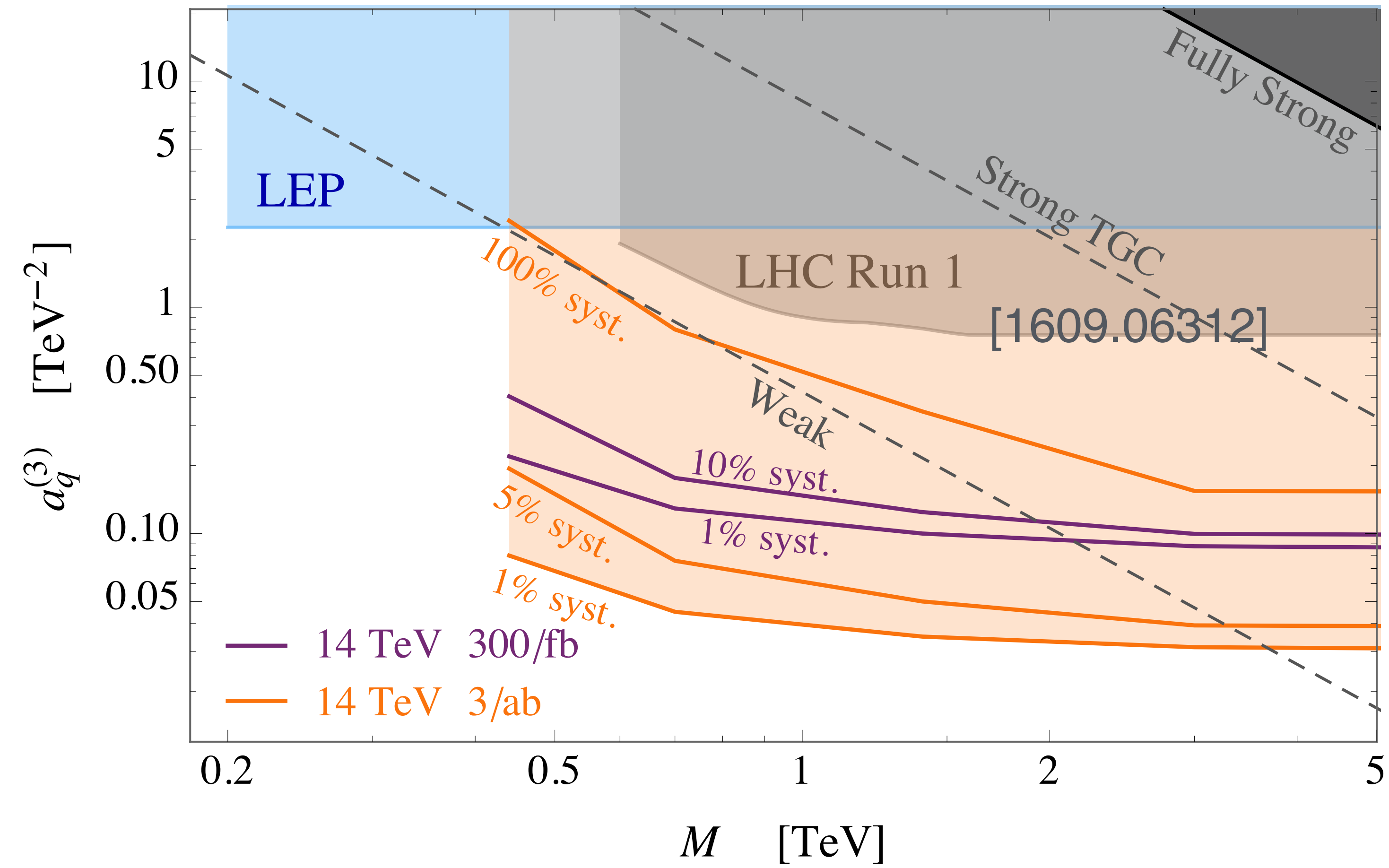
Limits and prospects

[Franceschini, Panico, Pomarol, Riva, Wulzer 1712.01310]

Only from the leftonic WZ

The HL-LHC prospect corresponds to:

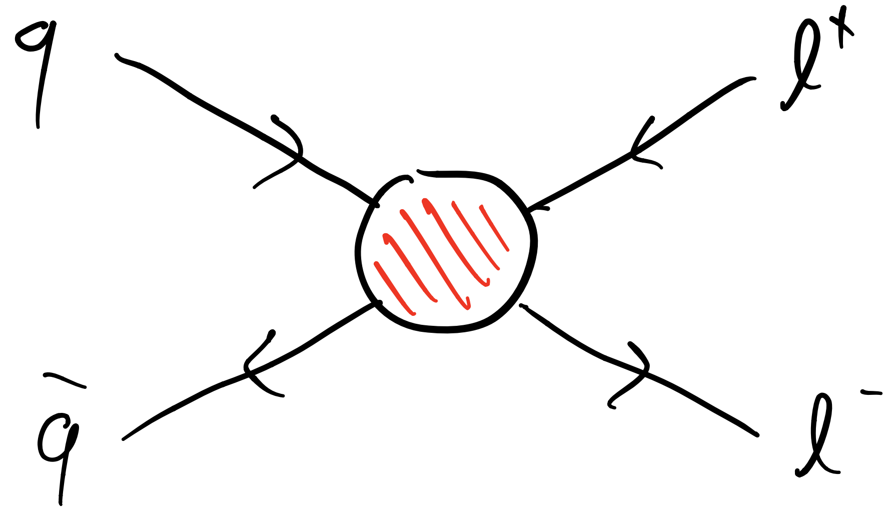




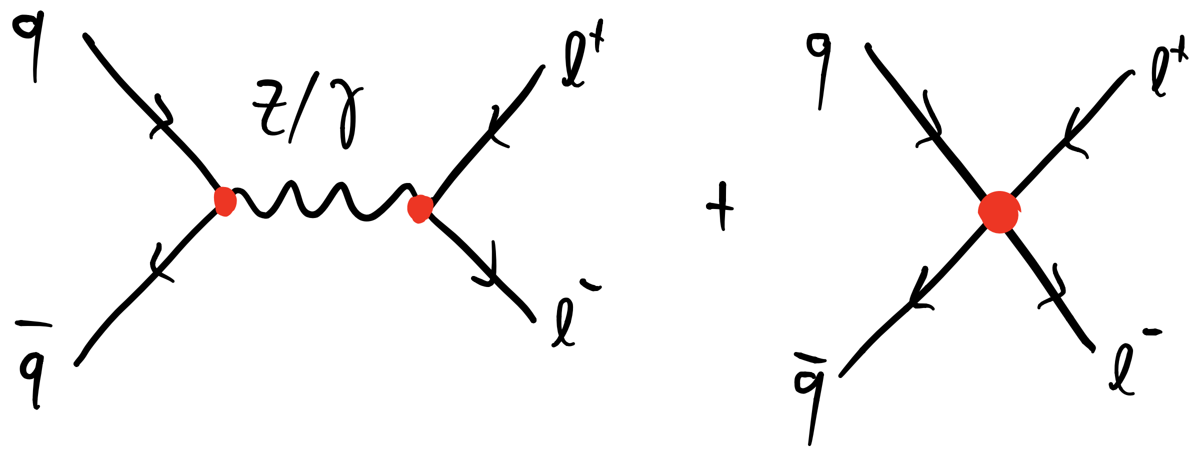
$$a_q^{(3)} = -\frac{g^2}{m_W^2}\left(c_{\theta_W}^2 \delta g_1^Z + W\right)$$

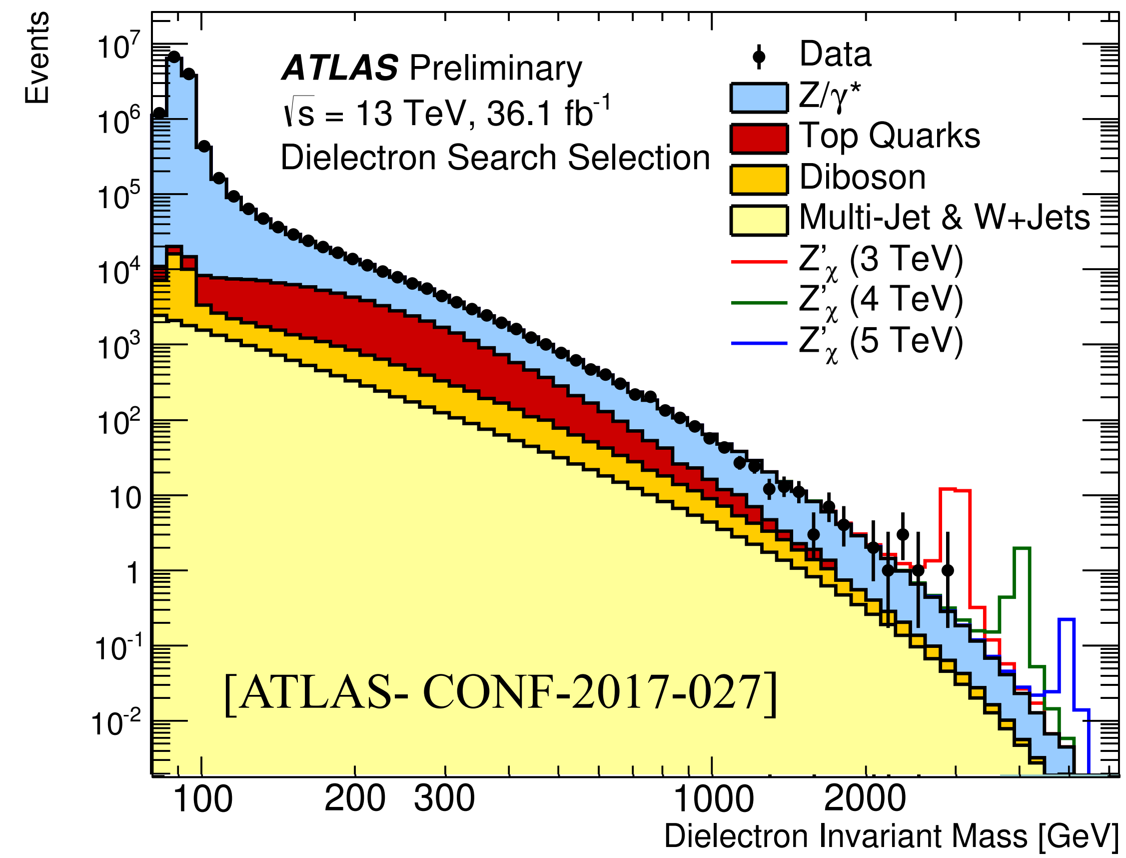
Particularly relevant for states with strong coupling to SM fermions and Higgs currents.

Dilepton production



The new frontier of 'precision': Drell-Yan @ LHC





Parametrisation of the amplitude

Neglecting chirality-flipping terms (Yukawa suppressed)

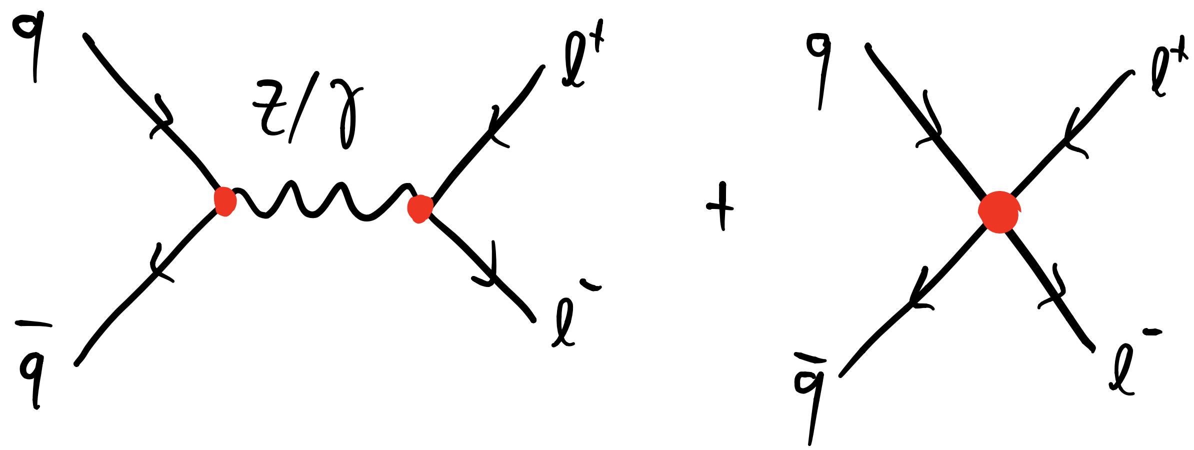
[Greljo, D.M. 1704.09015]

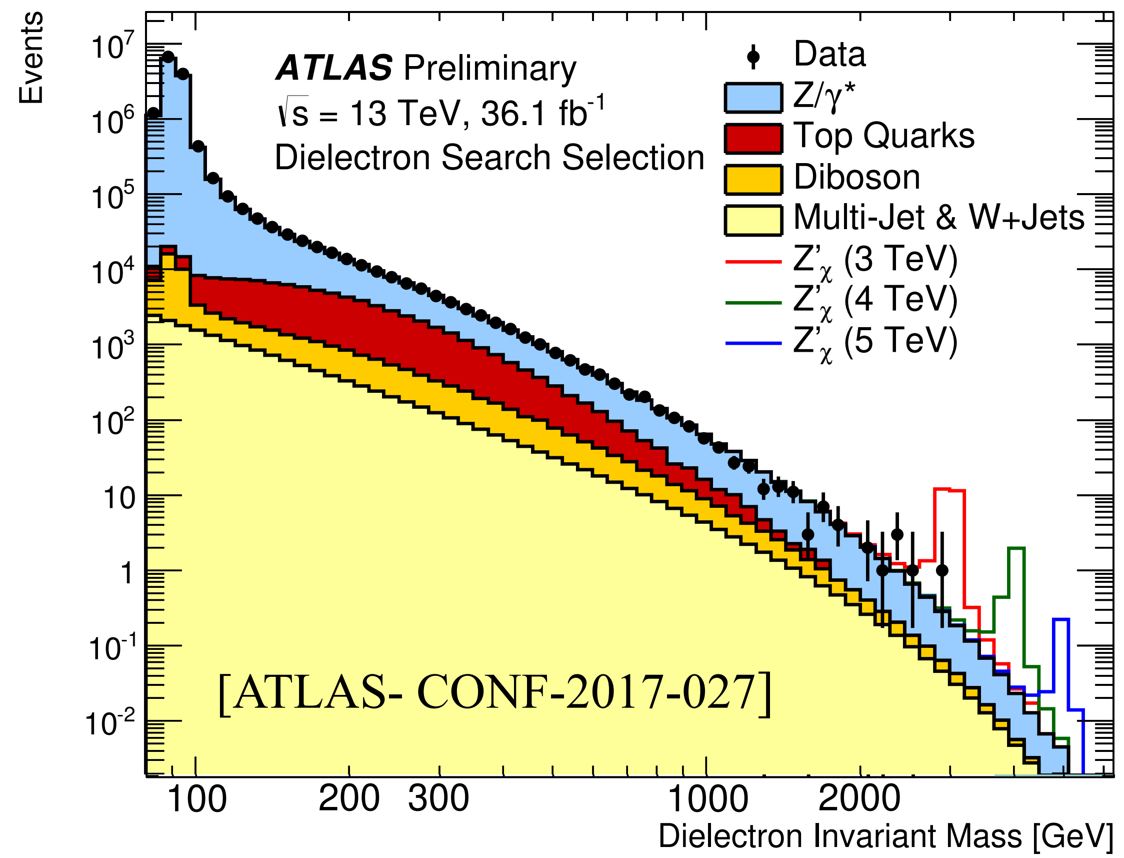
$$\mathscr{A}(q^i_{p_1}\bar{q}^j_{p_2} \to \ell^-_{p_1'}\ell^+_{p_2'}) = i\sum_{q_L,q_R}\sum_{\ell_L,\ell_R}(\bar{q}^i\gamma^\mu q^j)\,(\bar{\ell}\gamma_\mu\ell)\,F_{q\ell}(p^2)$$

$$F_{q\ell}(p^2) = \delta^{ij}\frac{e^2 Q_q Q_\ell}{p^2} + \delta^{ij}\frac{g_Z^q g_Z^\ell}{p^2 - m_Z^2 + i m_Z \Gamma_Z} + \frac{\epsilon^{q\ell}_{ij}}{v^2}$$

Local interactions, i.e. 4-fermion operators.

The new frontier of 'precision': Drell-Yan @ LHC





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$$F_{q\ell}(p^2) = \delta^{ij}\frac{e^2 Q_q Q_\ell}{p^2} + \delta^{ij}\frac{g_Z^q g_Z^\ell}{p^2 - m_Z^2 + i m_Z \Gamma_Z} + \frac{\epsilon_{ij}^{q\ell}}{v^2}$$

Local interactions, i.e. 4-fermion operators.

Convolute with parton lumi:

$$\boxed{\frac{d\sigma}{d\tau} = \left(\frac{d\sigma}{d\tau}\right)_{\rm SM} \times \frac{\sum_{q,\ell}\mathscr{L}_{q\bar{q}}(\tau,\mu_F)|F_{q\ell}(\tau s_0)|^2}{\sum_{q,\ell}\mathscr{L}_{q\bar{q}}(\tau,\mu_F)|F^{\rm SM}_{q\ell}(\tau s_0)|^2}}$$

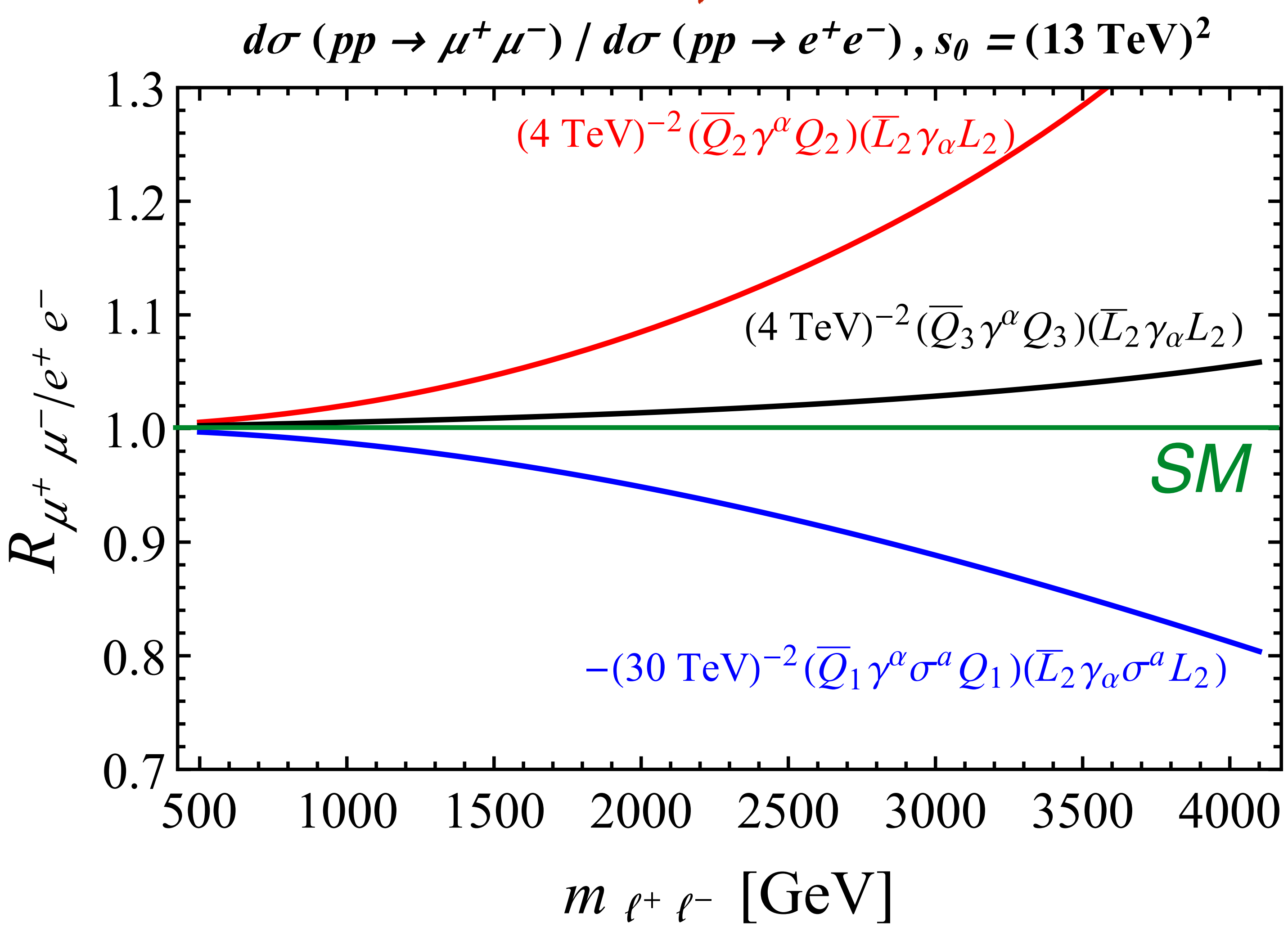
$$\tau \equiv m^2_{\ell^+\ell^-}/s_0$$

Lepton Flavour Universality ratio

Differential LFU ratio

$$R_{\mu^+\mu^-/e^+e^-}(m_{\ell\ell}) \equiv \frac{d\sigma_{\mu\mu}}{dm_{\ell\ell}} \Big/ \frac{d\sigma_{ee}}{dm_{\ell\ell}} = \frac{\sum_{q,\mu} \mathcal{L}_{q\bar{q}}(m_{\ell\ell}^2/s_0, \mu_F)|F_{q\mu}(m_{\ell\ell}^2)|^2}{\sum_{q,e} \mathcal{L}_{q\bar{q}}(m_{\ell\ell}^2/s_0, \mu_F)|F_{qe}(m_{\ell\ell}^2)|^2}$$

[Greljo, D.M. 1704.09015]

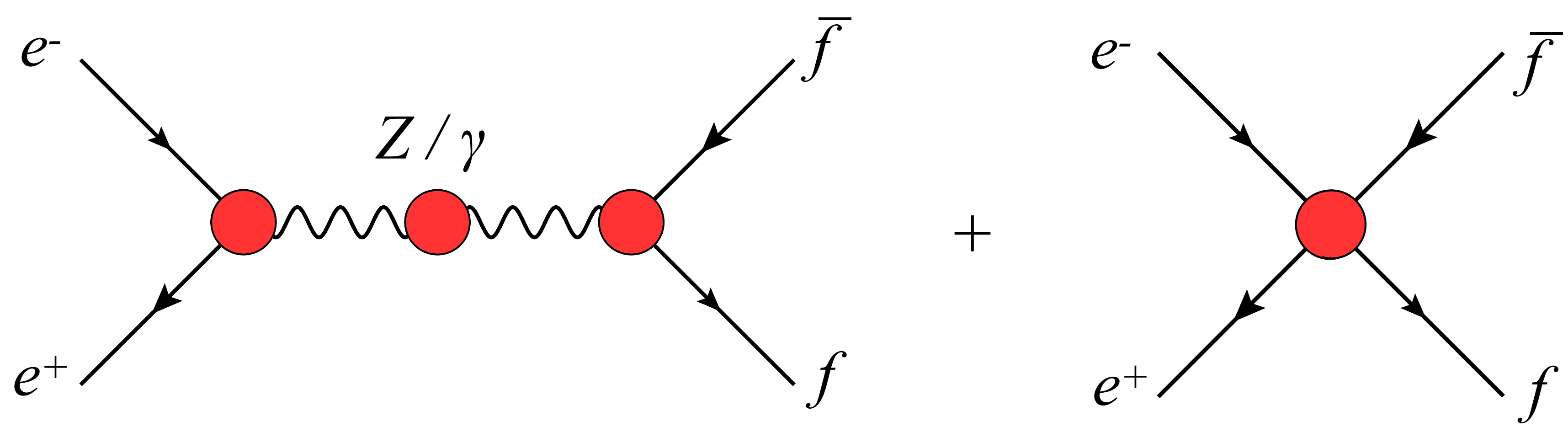


QCD and EW corrections are flavour universal: such ratios will reduce theory uncertainties in the SM prediction.

Tests of LFU are strongly motivated by the B-physics anomalies.

LEP-2 $f\bar{f}$ data

The Z (or γ) is off-shell



This bounds four-fermion operators

See [Falkowski et al. 1511.07434] for global fit of 4-lepton operators

Assuming "universality" (i.e. only Z,W propagators are affected)

	universal form factor ($\mathcal{L}$)	contact operator ($\mathcal{L}'$)
W	$-\frac{\mathrm{W}}{4m_W^2}(D_\rho W^a_{\mu\nu})^2$	$-\frac{g_2^2\mathrm{W}}{2m_W^2} J_L{}^a_\mu J_L{}^\mu_a$
Y	$-\frac{\mathrm{Y}}{4m_W^2}(\partial_\rho B_{\mu\nu})^2$	$-\frac{g_1^2\mathrm{Y}}{2m_W^2} J_Y{}_\mu J_Y{}^\mu$

W and Y parameters of

[Barbieri et al. hep-ph/0405040]

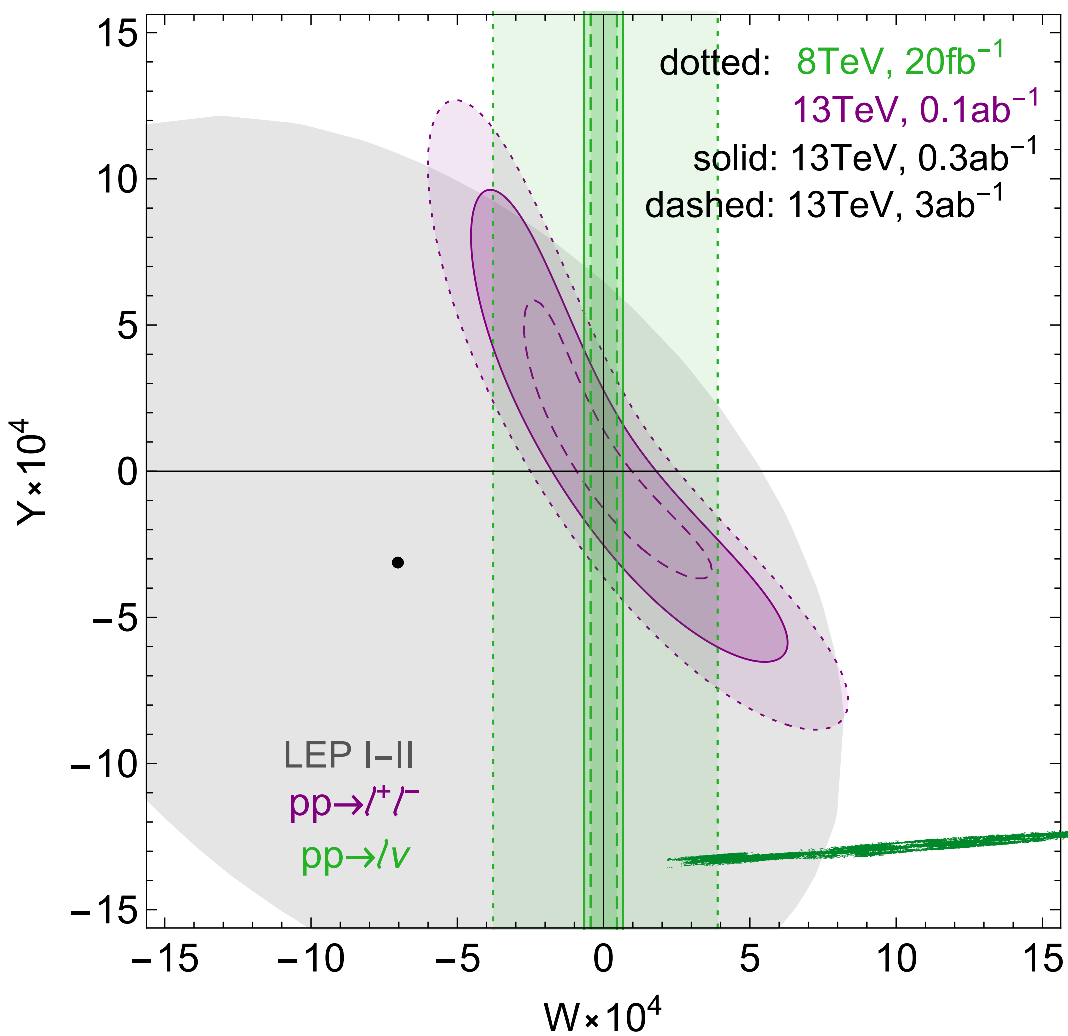
$\sim 10^{-3}$ *precision from LEP*

Assuming Universality

[Farina, Panico, Pappadopulo, Ruderman, Torre, Wulzer 1609.08157]

All 4-fermion operators aligned with the W and B currents:

$$-\frac{g_2^2 \mathrm{W}}{2m_W^2} J_{L\,\mu}^{\;a} J_{L\,a}^{\;\mu} \quad -\frac{g_1^2 \mathrm{Y}}{2m_W^2} J_{Y\,\mu} J_Y^{\;\mu}$$



Limits from LHC are already competitive/better than those from LEP and will improve even more with more data.

$pp \to \ell v$ has also potential to provide strong bounds!

Limits on 36 4-fermion operators

[Greljo, D.M. 1704.09015]

Limits in the Warsaw basis, shown here one operator at a time.
We have the complete Likelihood function and checked: no sizable correlations since different operators do not interfere (different flavours and chirality).

C_i	ATLAS 36.1 fb^{-1}	3000 fb^{-1}
$C^{(1)}_{Q^1L^1}$	[-0.0, 1.75] $\times 10^{-3}$	[-1.01, 1.13] $\times 10^{-4}$
$C^{(3)}_{Q^1L^1}$	[-8.92, -0.54] $\times 10^{-4}$	[-3.99, 3.93] $\times 10^{-5}$
$C_{u_RL^1}$	[-0.19, 1.92] $\times 10^{-3}$	[-1.56, 1.92] $\times 10^{-4}$
$C_{u_Re_R}$	[0.15, 2.06] $\times 10^{-3}$	[-7.89, 8.23] $\times 10^{-5}$
$C_{Q^1e_R}$	[-0.40, 1.37] $\times 10^{-3}$	[-1.8, 2.85] $\times 10^{-4}$
$C_{d_RL^1}$	[-2.1, 1.04] $\times 10^{-3}$	[-7.59, 4.23] $\times 10^{-4}$
$C_{d_Re_R}$	[-2.55, 0.46] $\times 10^{-3}$	[-3.37, 2.59] $\times 10^{-4}$
$C^{(1)}_{Q^2L^1}$	[-6.62, 4.36] $\times 10^{-3}$	[-3.31, 1.92] $\times 10^{-3}$
$C^{(3)}_{Q^2L^1}$	[-8.24, 2.05] $\times 10^{-3}$	[-8.87, 7.90] $\times 10^{-4}$
$C_{Q^2e_R}$	[-4.67, 6.34] $\times 10^{-3}$	[-2.11, 3.30] $\times 10^{-3}$
$C_{s_RL^1}$	[-7.4 , 5.9] $\times 10^{-3}$	[-3.96, 2.8] $\times 10^{-3}$
$C_{s_Re_R}$	[-8.17, 5.06] $\times 10^{-3}$	[-3.82, 2.13] $\times 10^{-3}$
$C_{c_RL^1}$	[-0.83, 1.13] $\times 10^{-2}$	[-3.74, 5.77] $\times 10^{-3}$
$C_{c_Re_R}$	[-0.67, 1.27] $\times 10^{-2}$	[-2.59, 4.17] $\times 10^{-3}$
$C_{b_LL^1}$	[-1.93, 1.19] $\times 10^{-2}$	[-8.62, 4.82] $\times 10^{-3}$
$C_{b_Le_R}$	[-1.47, 1.67] $\times 10^{-2}$	[-7.29, 8.99] $\times 10^{-3}$
$C_{b_RL^1}$	[-1.65, 1.49] $\times 10^{-2}$	[-8.86, 7.48] $\times 10^{-3}$
$C_{b_Re_R}$	[-1.73, 1.40] $\times 10^{-2}$	[-9.38, 6.63] $\times 10^{-3}$

C_i	ATLAS 36.1 fb^{-1}	3000 fb^{-1}
$C^{(1)}_{Q^1L^2}$	[-5.73, 14.2] $\times 10^{-4}$	[-1.30, 1.51] $\times 10^{-4}$
$C^{(3)}_{Q^1L^2}$	[-7.11, 2.84] $\times 10^{-4}$	[-5.25, 5.25] $\times 10^{-5}$
$C_{u_RL^2}$	[-0.84, 1.61] $\times 10^{-3}$	[-2.00, 2.66] $\times 10^{-4}$
$C_{u_R\mu_R}$	[-0.52, 1.36] $\times 10^{-3}$	[-1.04, 1.08] $\times 10^{-4}$
$C_{Q^1\mu_R}$	[-0.82, 1.27] $\times 10^{-3}$	[-2.25, 4.10] $\times 10^{-4}$
$C_{d_RL^2}$	[-2.13, 1.61] $\times 10^{-3}$	[-8.98, 5.11] $\times 10^{-4}$
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$C_{Q^2\mu_R}$	[-7.53, 8.67] $\times 10^{-3}$	[-2.58, 3.73] $\times 10^{-3}$
$C_{s_RL^2}$	[-1.04 , 0.93] $\times 10^{-2}$	[-4.42, 3.33] $\times 10^{-3}$
$C_{s_R\mu_R}$	[-1.09 , 0.87] $\times 10^{-2}$	[-4.67, 2.73] $\times 10^{-3}$
$C_{c_RL^2}$	[-1.33, 1.52] $\times 10^{-2}$	[-4.58, 6.54] $\times 10^{-3}$
$C_{c_R\mu_R}$	[-1.21, 1.62] $\times 10^{-2}$	[-3.48, 6.32] $\times 10^{-3}$
$C_{b_LL^2}$	[-2.61, 2.07] $\times 10^{-2}$	[-11.1, 6.33] $\times 10^{-3}$
$C_{b_L\mu_R}$	[-2.28, 2.42] $\times 10^{-2}$	[-8.53, 10.0] $\times 10^{-3}$
$C_{b_RL^2}$	[-2.41, 2.29] $\times 10^{-2}$	[-9.90, 8.68] $\times 10^{-3}$
$C_{b_R\mu_R}$	[-2.47, 2.23] $\times 10^{-2}$	[-10.5, 7.97] $\times 10^{-3}$

$$C_x \equiv \frac{v^2}{\Lambda^2} c_x$$

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$\sim 10^{-3}$ - 10^{-2} *precision now*

$$C = \frac{g_*^2 v^2}{M^2} \xrightarrow{g_* = 1} M \gtrsim 8\ \text{TeV}$$

a *5-10* -fold improvement at HL-LHC

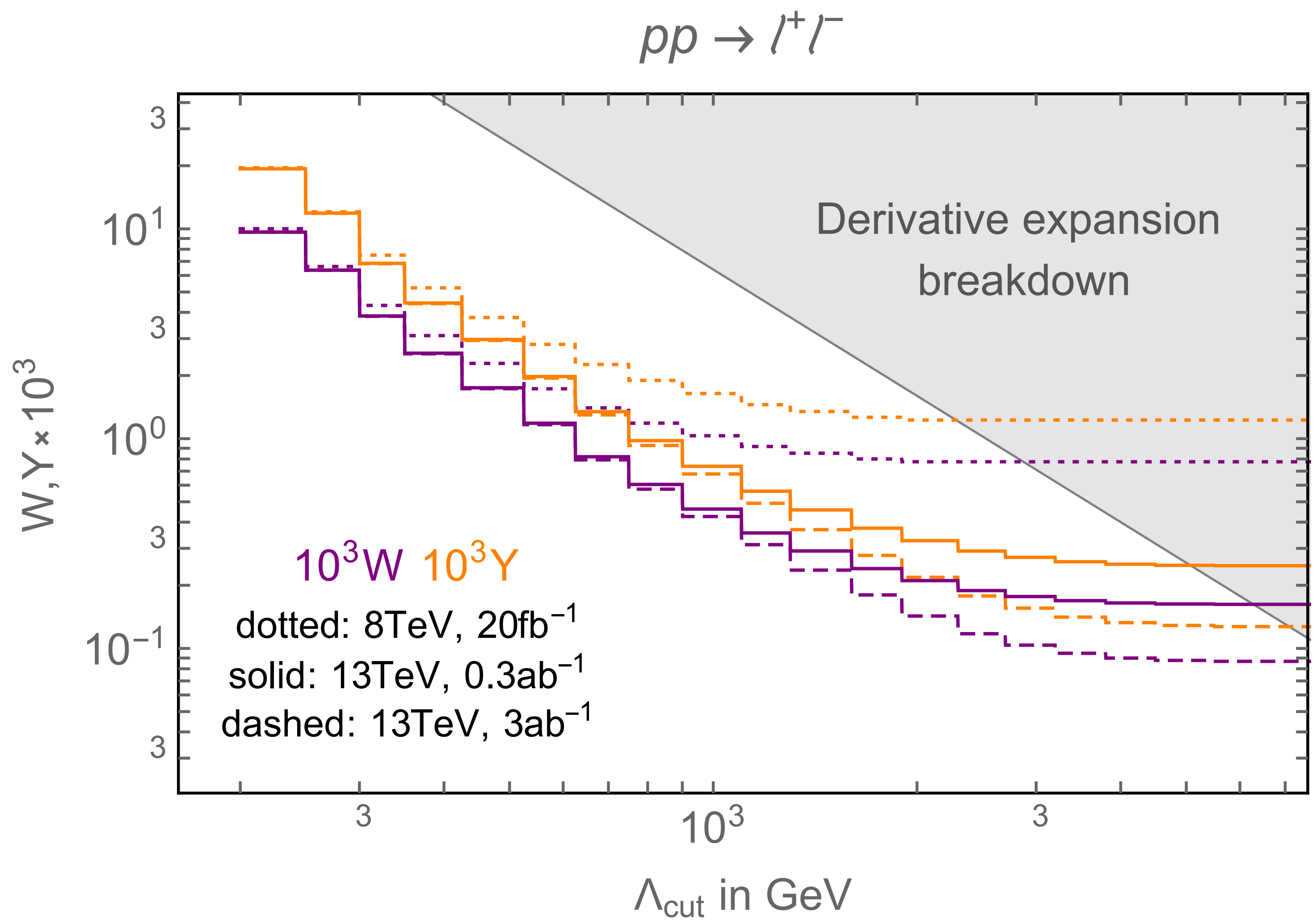
C_i	ATLAS 36.1 fb^{-1}				
$C^{(1)}_{Q^1L^1}$	[-0.0, 1.75] $\times 10^{-3}$				
$C^{(3)}_{Q^1L^1}$	[-8.92, -0.54] $\times 10^{-4}$				
$C_{u_RL^1}$	[-0.19, 1.92] $\times 10^{-3}$				
$C_{u_Re_R}$	[0.15, 2.06] $\times 10^{-3}$				
$C_{Q^1e_R}$	[-0.40, 1.37] $\times 10^{-3}$				
$C_{d_RL^1}$	[-2.1, 1.04] $\times 10^{-3}$				
$C_{d_Re_R}$	[-2.55, 0.46] $\times 10^{-3}$				
$C^{(1)}_{Q^2L^1}$	[-6.62, 4.36] $\times 10^{-3}$				
$C^{(3)}_{Q^2L^1}$	[-8.24, 2.05] $\times 10^{-3}$				
$C_{Q^2e_R}$	[-4.67, 6.34] $\times 10^{-3}$				
$C_{s_RL^1}$	[-7.4 , 5.9] $\times 10^{-3}$				
$C_{s_Re_R}$	[-8.17, 5.06] $\times 10^{-3}$	[-3.82, 2.13] $\times 10^{-3}$	$C_{s_R\mu_R}$	[-1.09 , 0.87] $\times 10^{-2}$	[-4.67, 2.73] $\times 10^{-3}$
$C_{c_RL^1}$	[-0.83, 1.13] $\times 10^{-2}$	[-3.74, 5.77] $\times 10^{-3}$	$C_{c_RL^2}$	[-1.33, 1.52] $\times 10^{-2}$	[-4.58, 6.54] $\times 10^{-3}$
$C_{c_Re_R}$	[-0.67, 1.27] $\times 10^{-2}$	[-2.59, 4.17] $\times 10^{-3}$	$C_{c_R\mu_R}$	[-1.21, 1.62] $\times 10^{-2}$	[-3.48, 6.32] $\times 10^{-3}$
$C_{b_LL^1}$	[-1.93, 1.19] $\times 10^{-2}$	[-8.62, 4.82] $\times 10^{-3}$	$C_{b_LL^2}$	[-2.61, 2.07] $\times 10^{-2}$	[-11.1, 6.33] $\times 10^{-3}$
$C_{b_Le_R}$	[-1.47, 1.67] $\times 10^{-2}$	[-7.29, 8.99] $\times 10^{-3}$	$C_{b_L\mu_R}$	[-2.28, 2.42] $\times 10^{-2}$	[-8.53, 10.0] $\times 10^{-3}$
$C_{b_RL^1}$	[-1.65, 1.49] $\times 10^{-2}$	[-8.86, 7.48] $\times 10^{-3}$	$C_{b_RL^2}$	[-2.41, 2.29] $\times 10^{-2}$	[-9.90, 8.68] $\times 10^{-3}$
$C_{b_Re_R}$	[-1.73, 1.40] $\times 10^{-2}$	[-9.38, 6.63] $\times 10^{-3}$	$C_{b_R\mu_R}$	[-2.47, 2.23] $\times 10^{-2}$	[-10.5, 7.97] $\times 10^{-3}$

$$C_x \equiv \frac{v^2}{\Lambda^2} c_x$$

Controlling the EFT (II)

[Farina, Panico, Pappadopulo, Ruderman, Torre, Wulzer 1609.08157]

How do the limits vary when using only events with $m_{\ell\ell} < \Lambda_{\text{cut}}$?

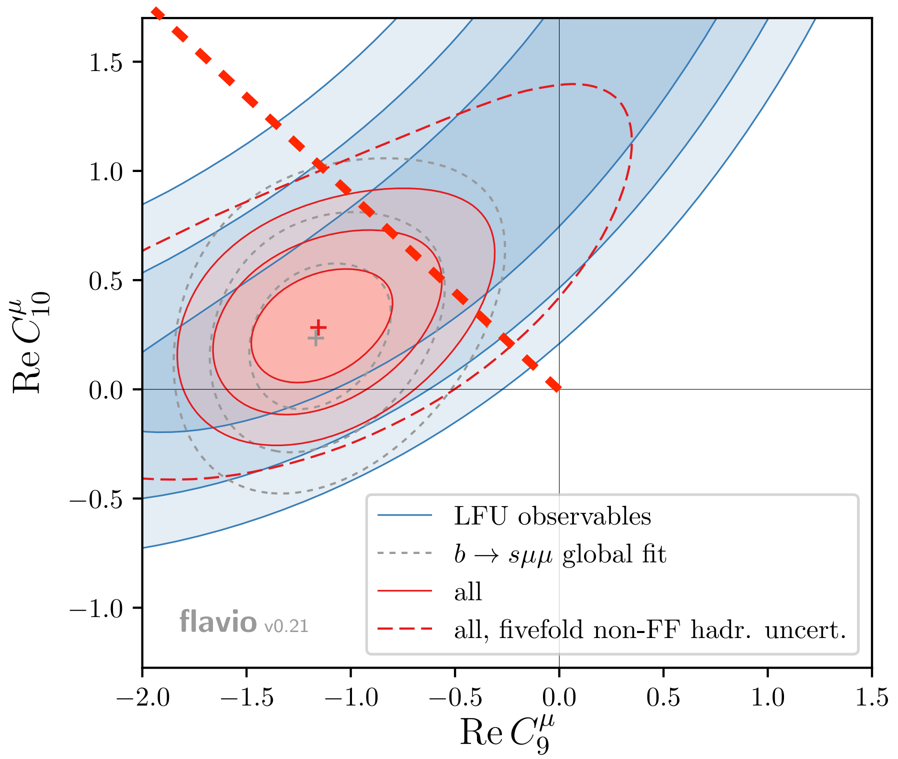


Limits saturate at $\Lambda_{\text{cut}} \sim$ 2-3 TeV at 13TeV.

(more luminosity → more events at high energy)

Application to B anomalies

Altmannshofer, Stangl, Straub 2017; etc….



The result of the fit is compatible with the observed anomaly in P'₅.

Required EFT operator

$$\mathcal{L} \supset \frac{C_{bs\mu}}{v^2}(\bar{b}_L \gamma_\mu s_L)(\bar{\mu}_L \gamma^\mu \mu_L) + h.c.$$

$$C_{bs\mu} = \frac{\alpha}{\pi} V_{tb} V_{ts}^* \Delta C_9^\mu \simeq 9.3 \times 10^{-5} \Delta C_9^\mu$$

$$\boxed{\Delta C_9^\mu = -\Delta C_{10}^\mu = -0.61 \pm 0.12}$$

This is a 'measurement' of non-zero $C_{bs\mu}$.

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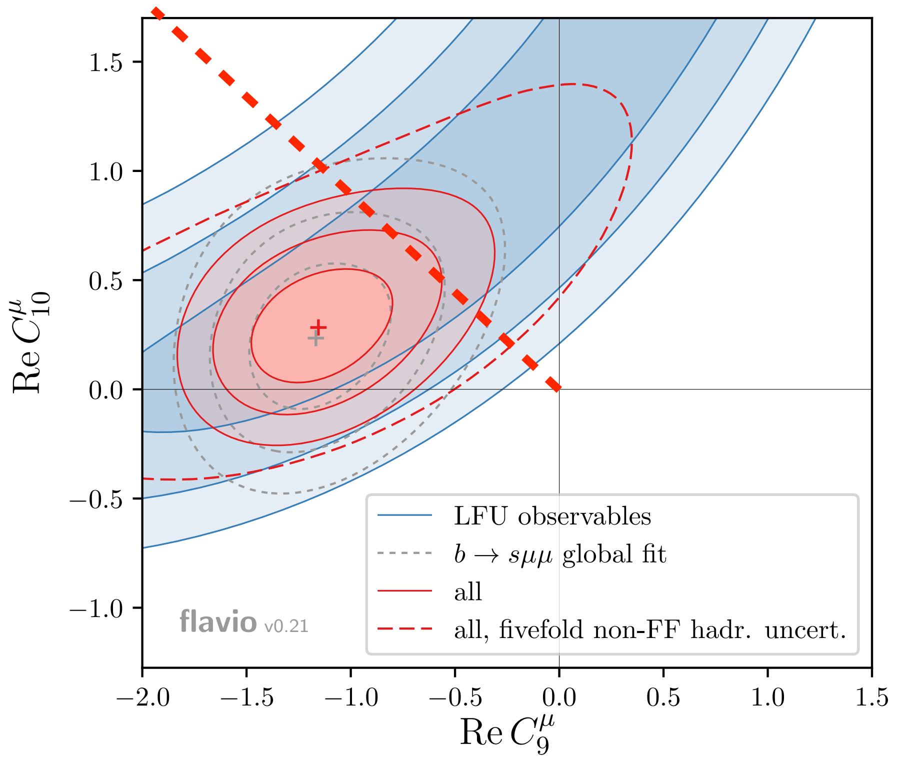


The result of the fit is compatible with the observed anomaly in P'5.

Required EFT operator

$$\mathcal{L} \supset \frac{C_{bs\mu}}{v^2}(\bar{b}_L \gamma_\mu s_L)(\bar{\mu}_L \gamma^\mu \mu_L) + h.c.$$

$$C_{bs\mu} = \frac{\alpha}{\pi} V_{tb} V_{ts}^* \Delta C_9^\mu \simeq 9.3 \times 10^{-5} \Delta C_9^\mu$$

$$\boxed{\Delta C_9^\mu = -\Delta C_{10}^\mu = -0.61 \pm 0.12}$$

This is a 'measurement' of non-zero $C_{bs\mu}$.

In the SM EFT at the EW scale:

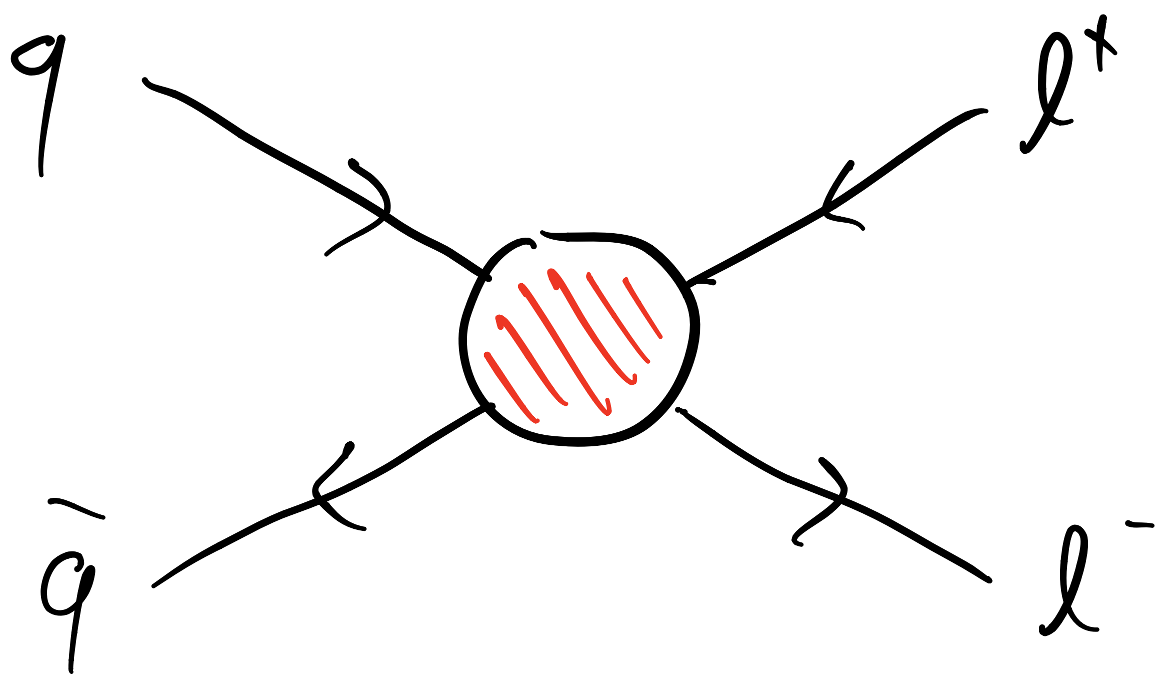
$$\boxed{C_T\ (\bar{Q}_L^i \gamma_\mu \sigma^a Q_L^j)(\bar{L}_L^\alpha \gamma^\mu \sigma^a L_L^\beta) + C_S\ (\bar{Q}_L^i \gamma_\mu Q_L^j)(\bar{L}_L^\alpha \gamma^\mu L_L^\beta)}$$

Flavor in dimuon tails?

The present (future) direct bound on ΔC_9^{μ} from ATLAS dimuon search

$$|\Delta C_9{}^{\mu}| = \left| \frac{\pi}{\alpha V_{tb} V_{ts}^*} C_{bs\mu} \right| < 100\ (39)$$

No sensitivity.



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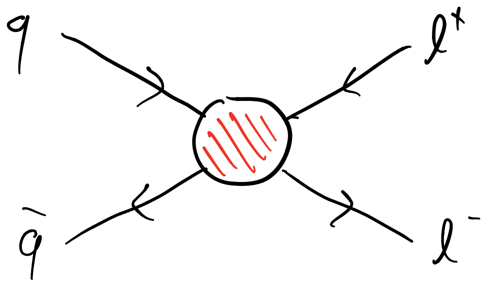

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In a complete flavour model, such a flavour-violating operator will be related to the flavour-conserving ones:

$$\mathscr{L}^{\rm eff} \supset \frac{\mathbf{C}_{ij}^{U\mu}}{v^2} (\bar{u}_L^i \gamma_\mu u_L^j)(\bar{\mu}_L \gamma^\mu \mu_L) + \frac{\mathbf{C}_{ij}^{D\mu}}{v^2} (\bar{d}_L^i \gamma_\mu d_L^j)(\bar{\mu}_L \gamma^\mu \mu_L)$$

$$\mathbf{C}_{ij}^{U\mu} = \begin{pmatrix} C_{u\mu} & 0 & 0 \\ 0 & C_{c\mu} & 0 \\ 0 & 0 & C_{t\mu} \end{pmatrix}, \quad \mathbf{C}_{ij}^{D\mu} = \begin{pmatrix} C_{d\mu} & 0 & 0 \\ 0 & C_{s\mu} & C_{bs\mu}^* \\ 0 & C_{bs\mu} & C_{b\mu} \end{pmatrix}$$

This structure is predicted in a given model.

$\lambda_{bs}^q \equiv C_{bs\mu} / C_{q\mu}$ → ~ fixed in a model,
~ V_{ts} in MFV

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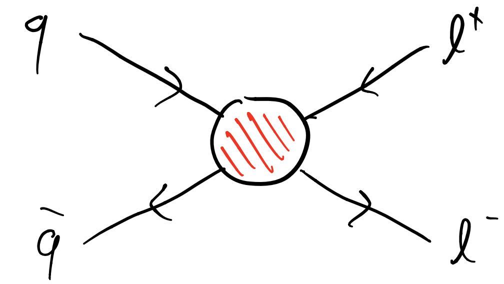

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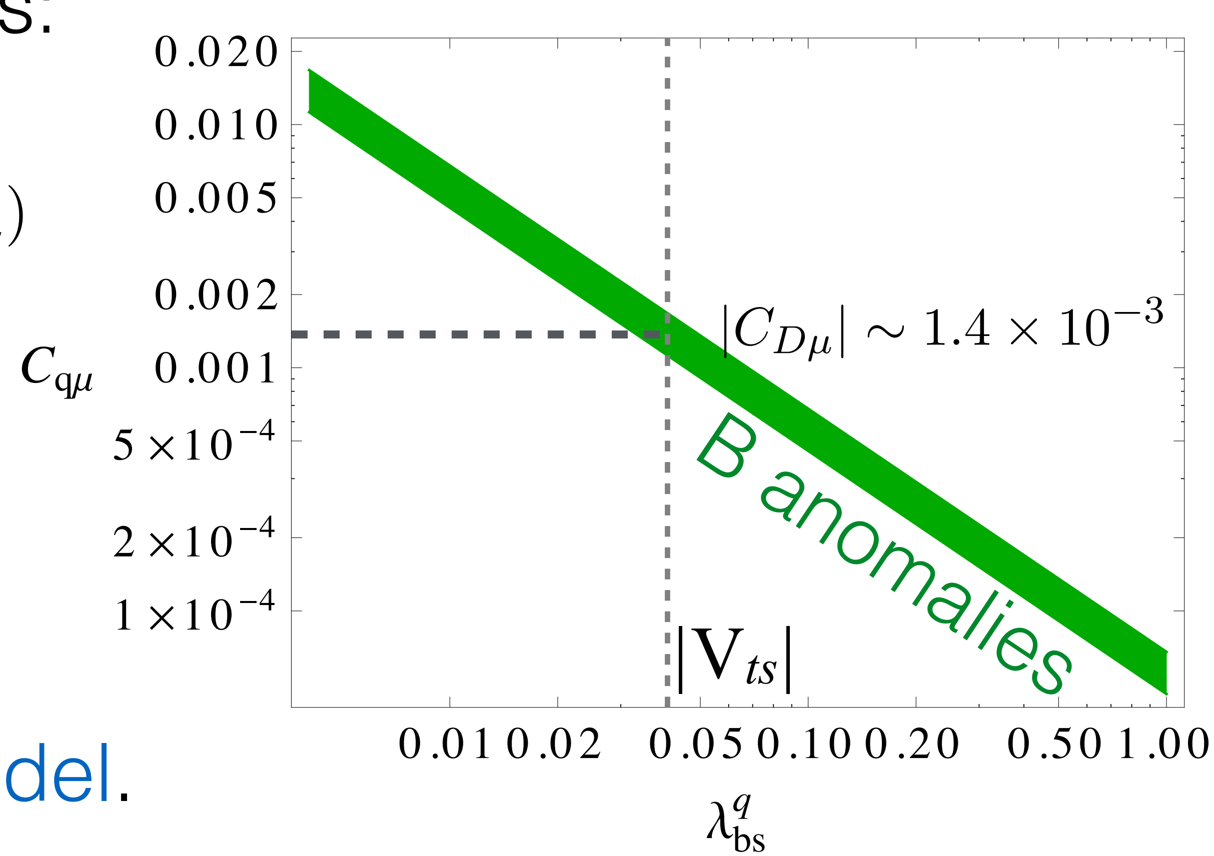

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We might test the flavour-diagonal ones.

Minimal Flavour Violation

Assumption: The only breaking of the SU(3)^5 flavour symmetry is via the SM Yukawas.

$$\mathbf{C}_{ij}^{U\mu} = \begin{pmatrix} C_{u\mu} & 0 & 0 \\ 0 & C_{c\mu} & 0 \\ 0 & 0 & C_{t\mu} \end{pmatrix}, \quad \mathbf{C}_{ij}^{D\mu} = \begin{pmatrix} C_{d\mu} & 0 & 0 \\ 0 & C_{s\mu} & C_{bs\mu}^* \\ 0 & C_{bs\mu} & C_{b\mu} \end{pmatrix}$$

$$C_{u\mu} = C_{c\mu} = C_{t\mu} \equiv C_{U\mu}$$
$$C_{d\mu} = C_{s\mu} = C_{b\mu} \equiv C_{D\mu}$$
$$|C_{bs\mu}| \sim |V_{tb} V_{ts}^* y_t^2 C_{D\mu}|$$

We get a <u>prediction</u> for $C_{D\mu}$ (which is tested by LHC)

$$|C_{D\mu}| \sim 1.4 \times 10^{-3}$$

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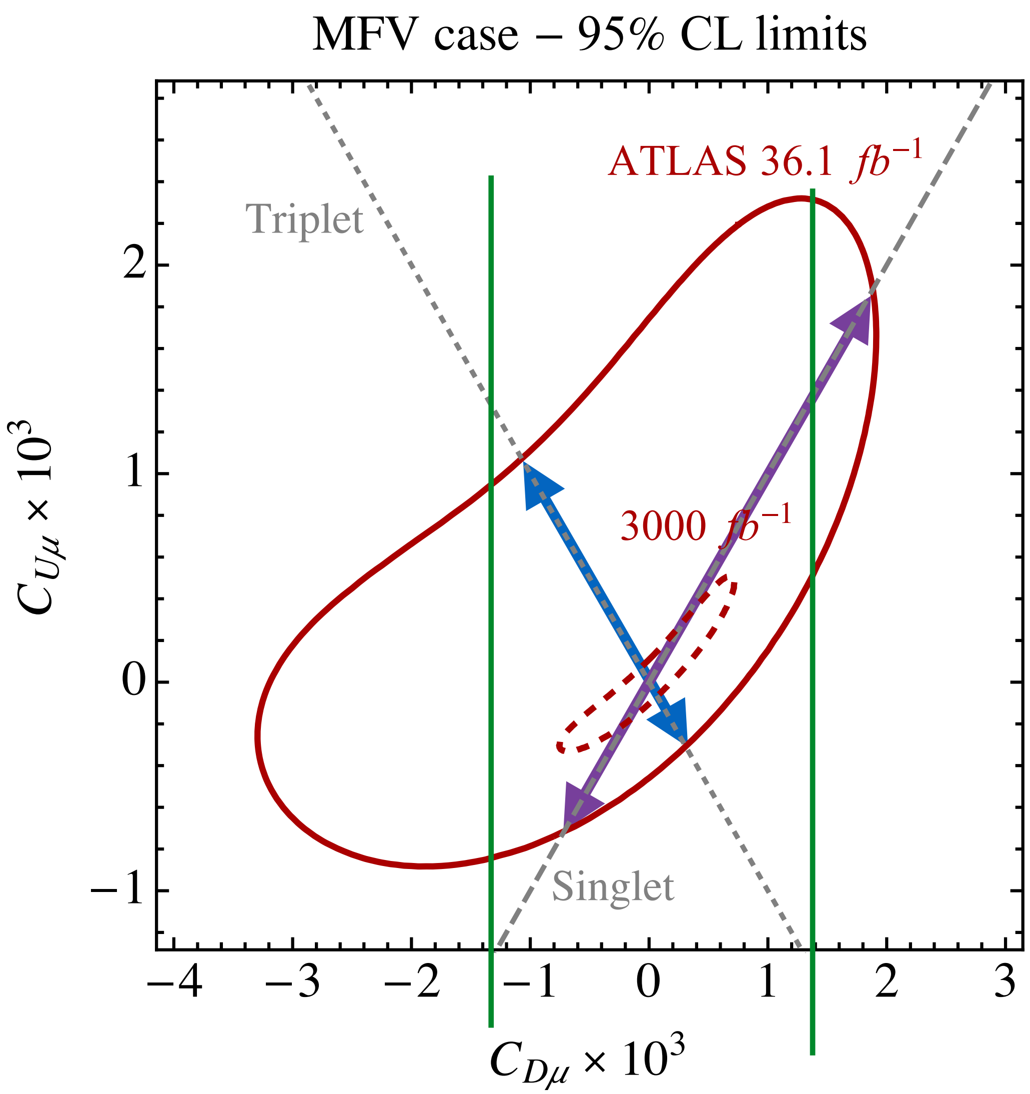
$$\boxed{\begin{aligned} C_{u\mu} &= C_{c\mu} = C_{t\mu} \equiv C_{U\mu} \\ C_{d\mu} &= C_{s\mu} = C_{b\mu} \equiv C_{D\mu} \\ |C_{bs\mu}| &\sim |V_{tb} V^*_{ts} y_t^2 C_{D\mu}| \end{aligned}}$$



We get a prediction for $C_{D\mu}$ (which is tested by LHC)

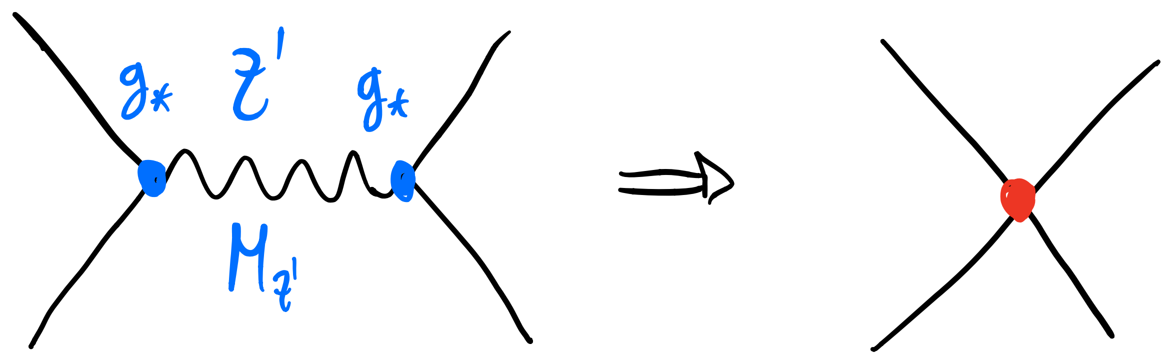
$$|C_{D\mu}| \sim 1.4 \times 10^{-3}$$

qqμμ operators with valence quarks are tested better than per-mille level.

The MFV solution is already in strong tension with LHC

Compare to explicit model

Model with a **spin-1 singlet: Z'**.



$$\frac{C}{v^2} = -\frac{g_*^2}{M_{Z'}^2}$$

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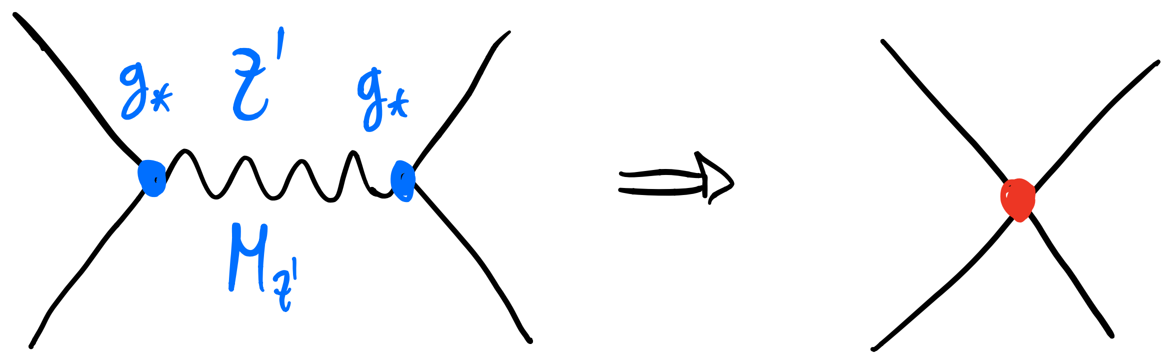
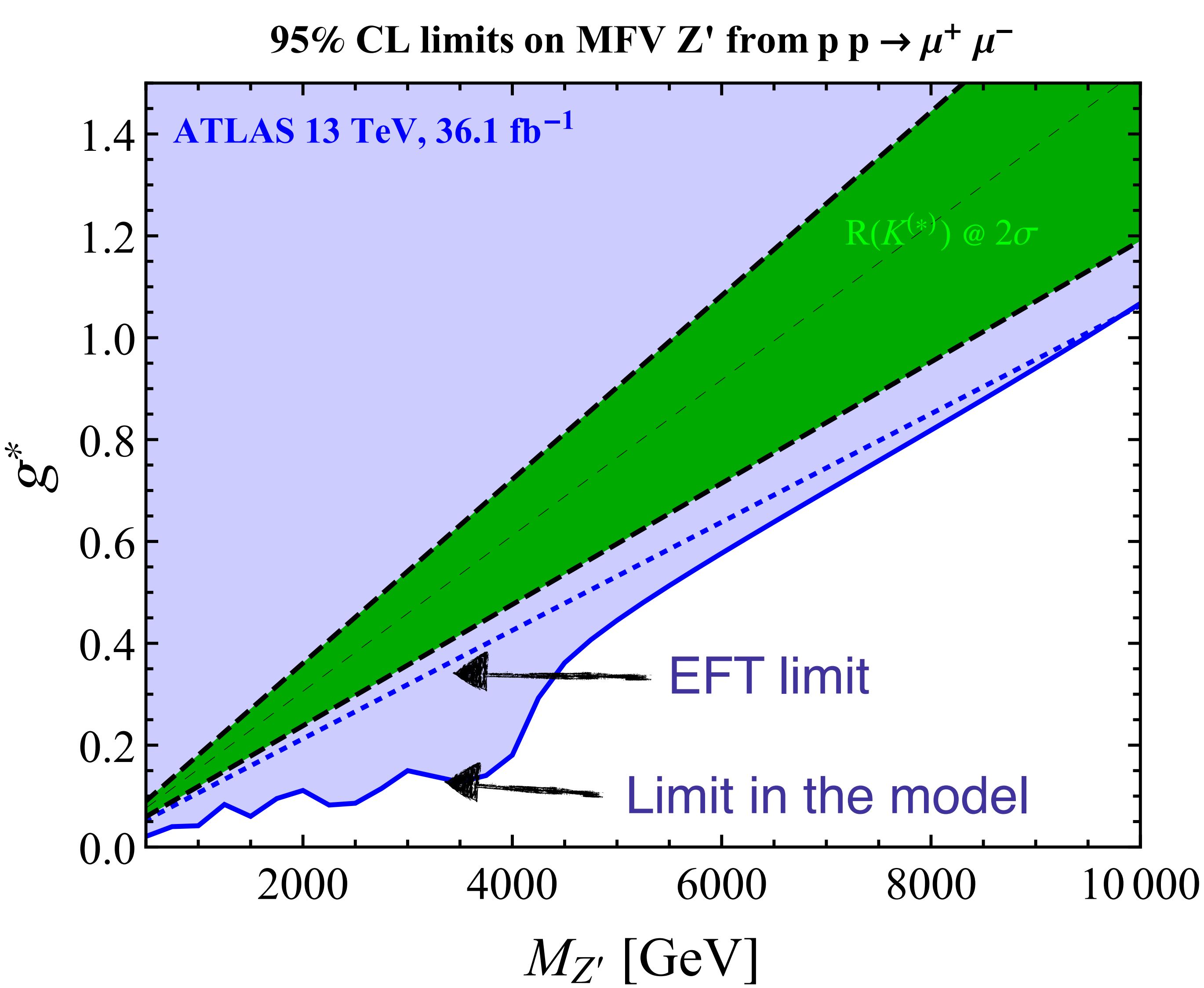


$$\frac{c}{v^2} = -\frac{g_*^2}{M_{Z'}^2}$$



Such an explanation of the anomalies is excluded for any mass.

For $M_{Z'} \gtrsim$ **4-5 TeV** the EFT expansion is OK (still weak coupling).

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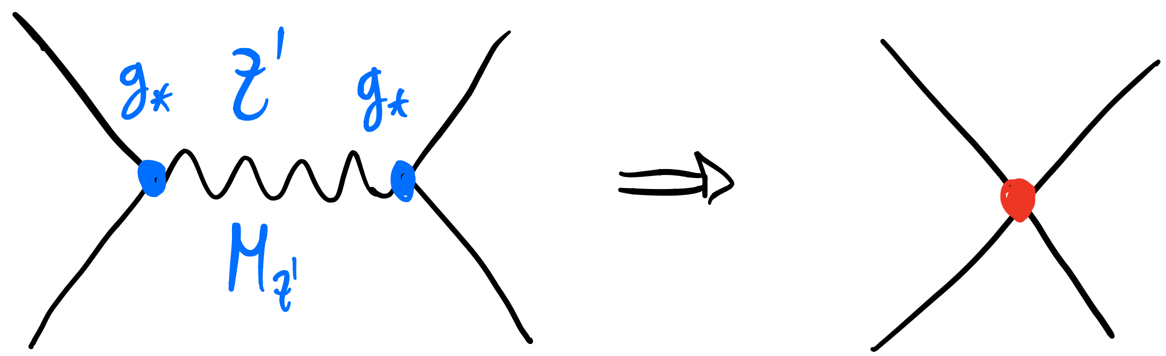
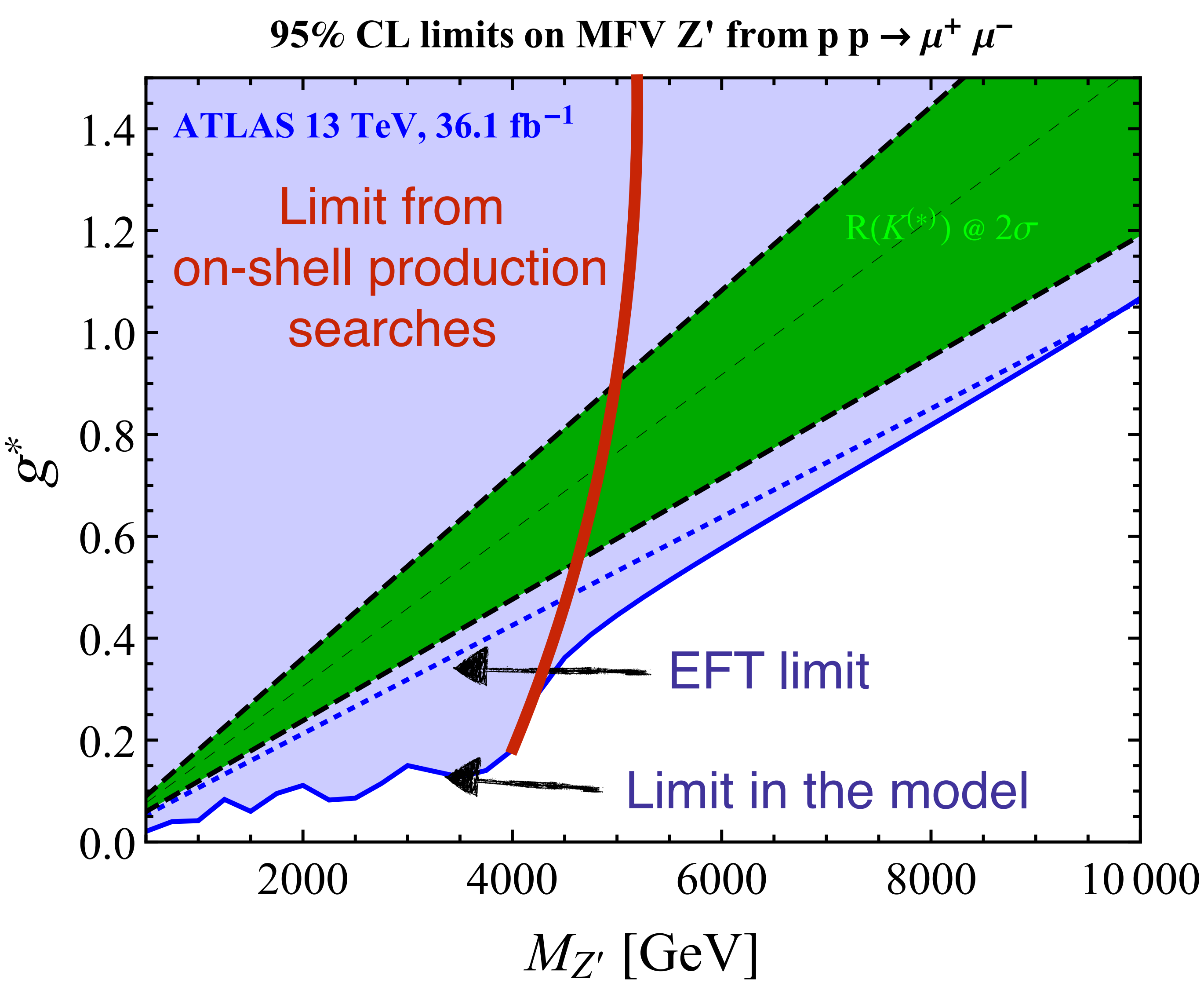


$$\frac{C}{v^2} = -\frac{g_*^2}{M_{Z'}^2}$$



Such an explanation of the anomalies is **excluded for any mass**.

For $M_{Z'} \gtrsim$ **4-5 TeV** the EFT expansion is OK (still weak coupling).

Conclusions

- LHC measurements of **high-p_T tails** of $2 \rightarrow 2$ processes offer **strong probes of new physics**,
  complementing (and often surpassing) limits derived from LEP.

- Care must be taken to understand the typical energy scale of the experiment and making sure that, at the interpretation level,

$$E_{exp} \ll \Lambda_{NP}$$

- This allows us to probe mass scales often higher than the reach of direct searches.

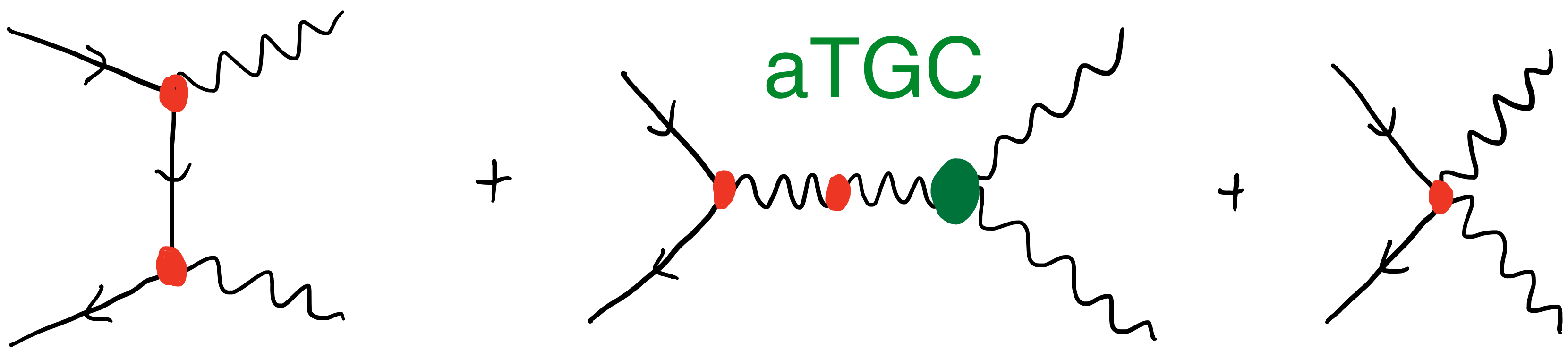
- The limits are already relevant for models addressing B-anomalies.

Thank you!

Backup

SMEFT contributions

We study BSM effects in the SMEFT (for the moment at LO).
Dimension-6 operators can contribute in many ways:



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

I take Z(W)-pole bounds and **approximate**:
fix those SMEFT directions as SM-like.

Note that this is a basis-independent statement.
Indeed, in our work we use both SILH and Warsaw bases.

SMEFT contributions

After imposing Z(W)-pole limits, **Three unconstrained combinations** of SMEFT coefficients contribute to the process:

Warsaw basis:

$$\delta g_{1,z} = -\frac{v^2}{\Lambda^2}\frac{g_L^2+g_Y^2}{4(g_L^2-g_Y^2)}\left(4\frac{g_Y}{g_L}w_{\phi WB} + w_{\phi D} - [w_{\ell\ell}]_{1221} + 2[w_{\phi\ell}^{(3)}]_{11} + 2[w_{\phi\ell}^{(3)}]_{22}\right)$$

$$\delta\kappa_\gamma = \frac{v^2}{\Lambda^2}\frac{g_L}{g_Y}w_{\phi WB}\ , \qquad \lambda_z = -\frac{v^2}{\Lambda^2}\frac{3}{2}g_L w_W\ ,$$

SILH basis:

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

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

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

Falkowski, Gonzalez-Alonso, Greljo, D.M., Son JHEP [1609.06312]

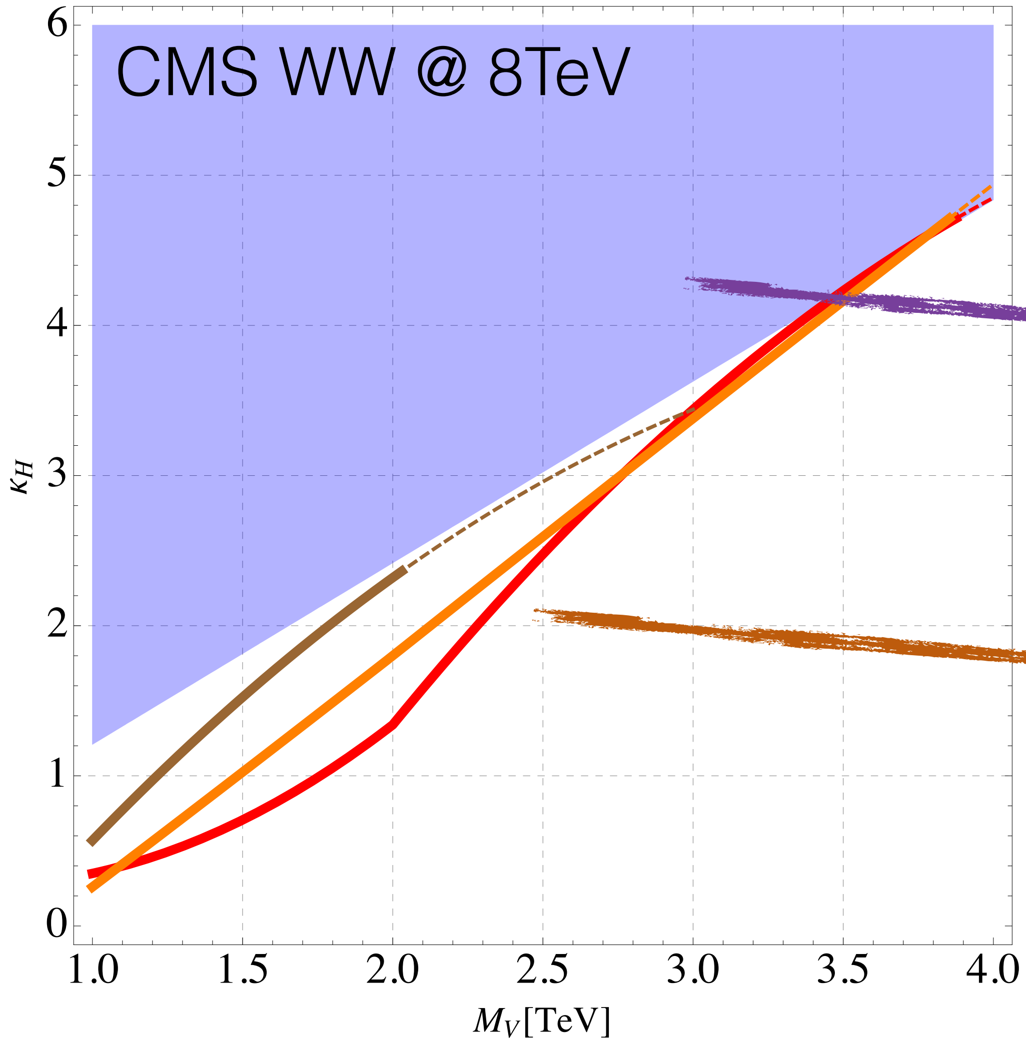
Not only 3 operators contribute to diboson production, but **the independent, unconstrained, combinations are 3 (in any basis)**.

Let us call them:

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

Applications & Validity

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



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

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

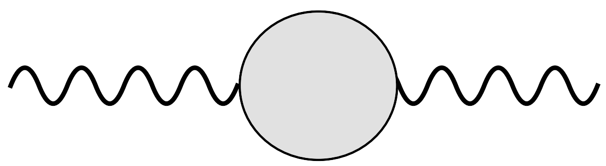
Limits directly from the model
(different benchmarks points
with same low energy EFT)

1) For $\mathbf{M_V \gtrsim 3}$**TeV** the EFT approximates well the model.
2) For lower masses, the EFT gives conservative bounds (in this case).

Universal Scenario

i.e. oblique corrections

Assuming that New Physics is "universal" — *affects only gauge boson self-energies*



$$\Pi_V(q^2) \simeq \Pi_V(0) + q^2\Pi'_V(0) + \frac{(q^2)^2}{2!}\Pi''_V(0) + \cdots$$

$$\langle V_\mu(-q)V'_\nu(q)\rangle \propto \Pi_{VV'}(q^2)$$

[Altarelli and Barbieri '91, Peskin and Takeuchi '92, Barbieri et al. hep-ph/0405040]

At dim-6 in SM EFT only these are generated:

$$\begin{aligned} g^{-2}\widehat{S} &= \Pi'_{W_3B}(0) \\ g^{-2}M_W^2\widehat{T} &= \Pi_{W_3W_3}(0) - \Pi_{W^+W^-}(0) \\ 2g'^{-2}M_W^{-2}Y &= \Pi''_{BB}(0) \\ 2g^{-2}M_W^{-2}W &= \Pi''_{W_3W_3}(0) \end{aligned}$$

$S = 4s_{\rm W}^2\widehat{S}/\alpha \approx 119\,\widehat{S},\; T = \widehat{T}/\alpha \approx 129\,\widehat{T}$