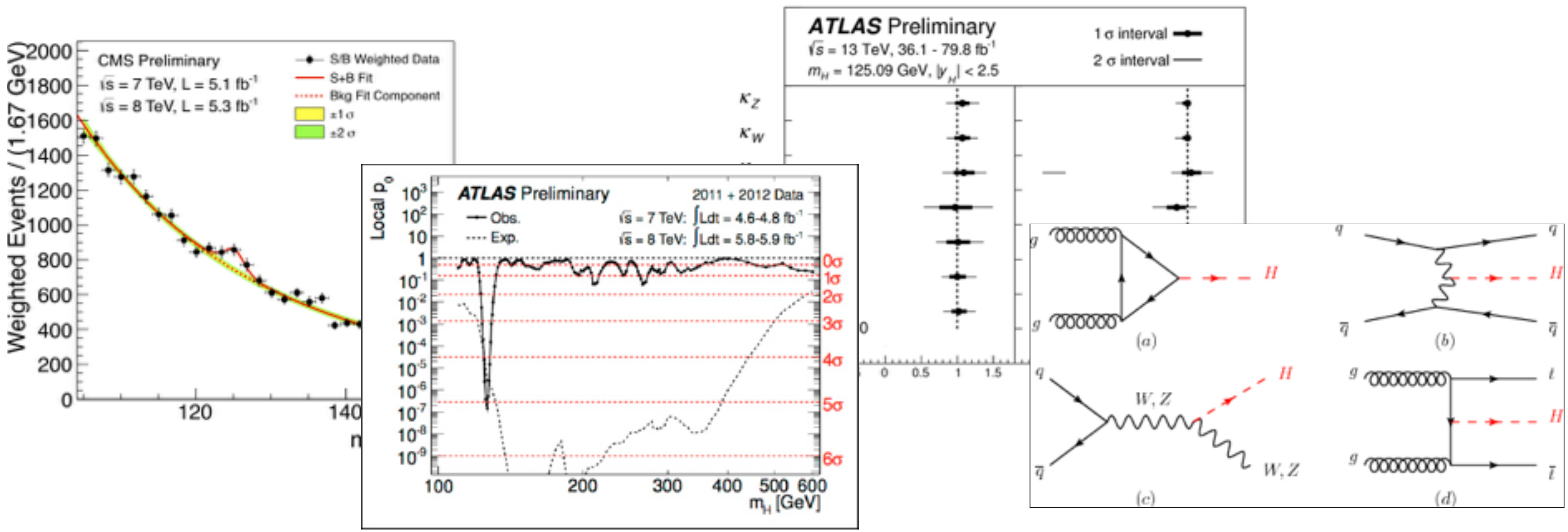
Exploring the SM EFT with diboson production

Marc Montull
(postdoc at DESY)

Based on:
1810.05149 with C. Grojean and M. Riembau
190x.xxxxx with G. Durieux and M. Riembau
190x.xxxxx with F. Bishara, P. Englert, C. Grojean, G. Panico, A. Rossia

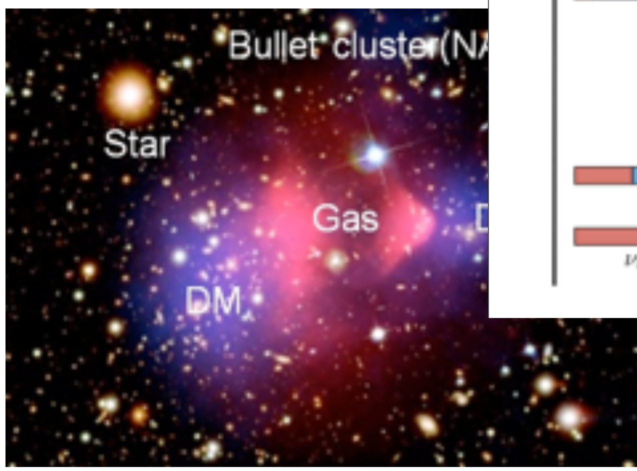
As we know, the LHC discovered the **first scalar** and *elementary* (?) particle consistent with the SM Higgs boson

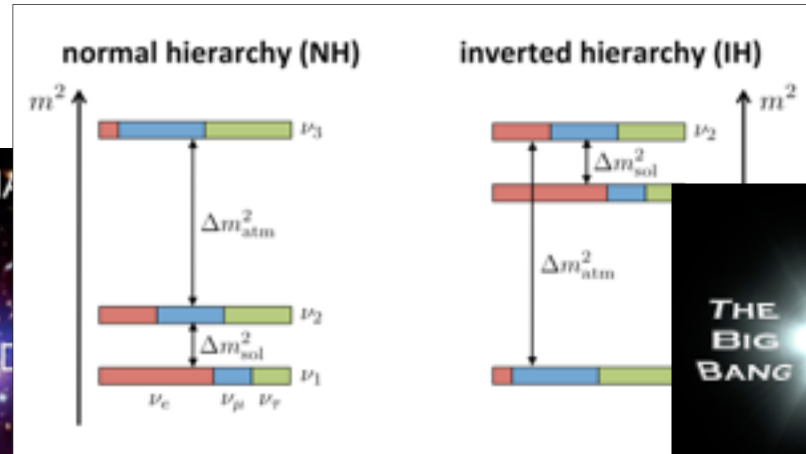


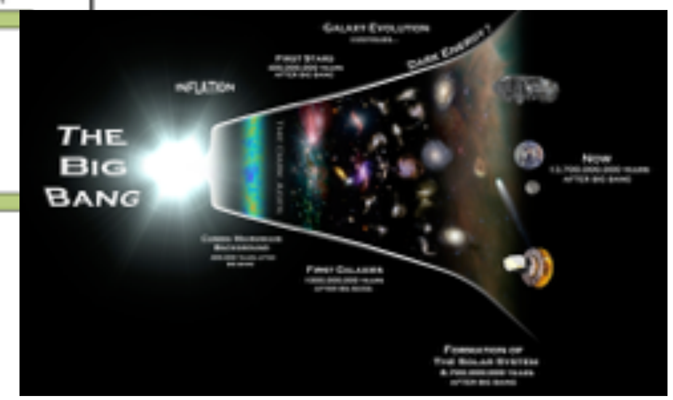
With this discovery, the SM is complete !!

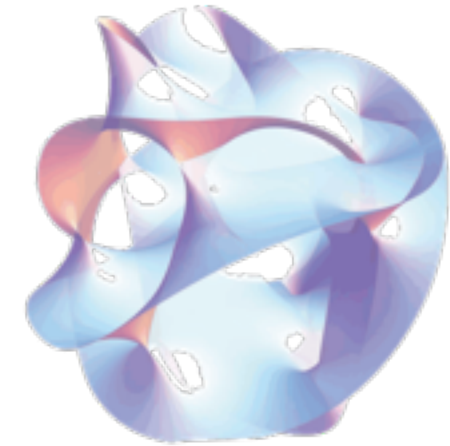
Are we done ?

No! There are still **many** things to be understood … for instance









DM

Neutrinos

Inflation

Baryon asymmetry

Gravity

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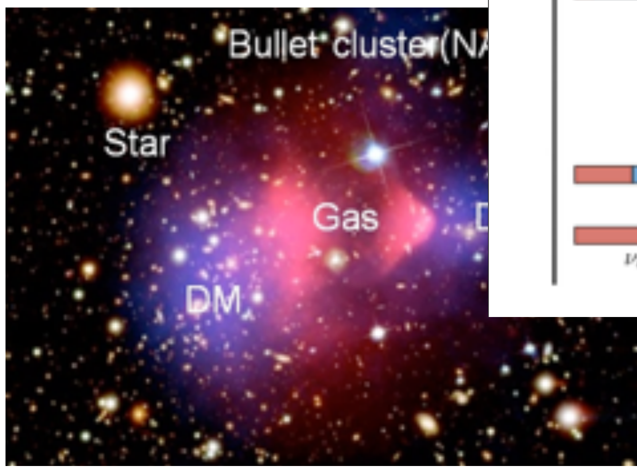

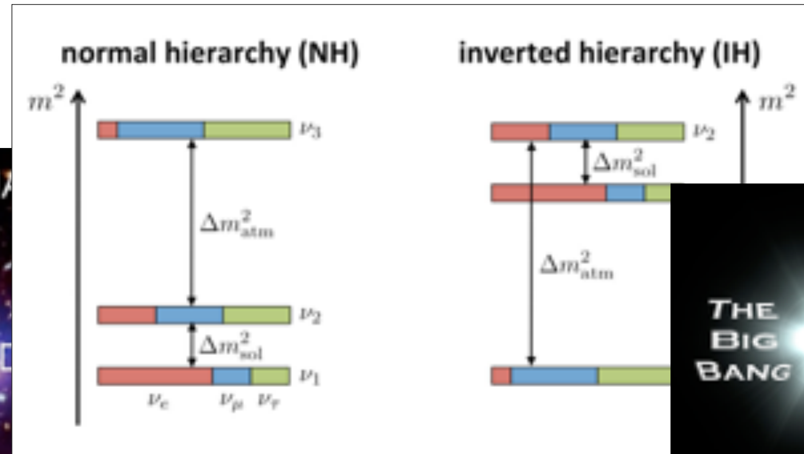

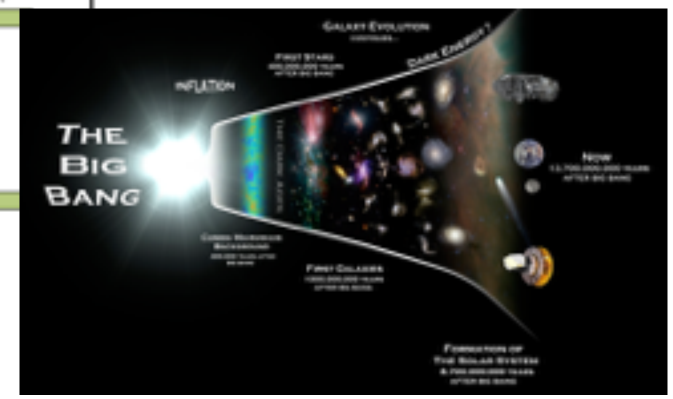

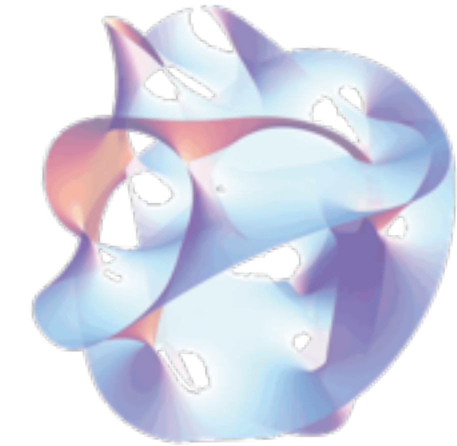

Neutrinos Inflation Gravity

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Baryon asymmetry

<u>Even more, the LHC will keep running until 2037 !</u>

New discoveries
or
New constrains

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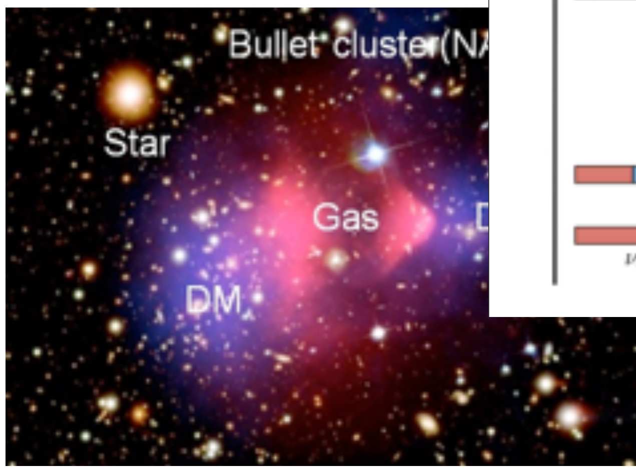

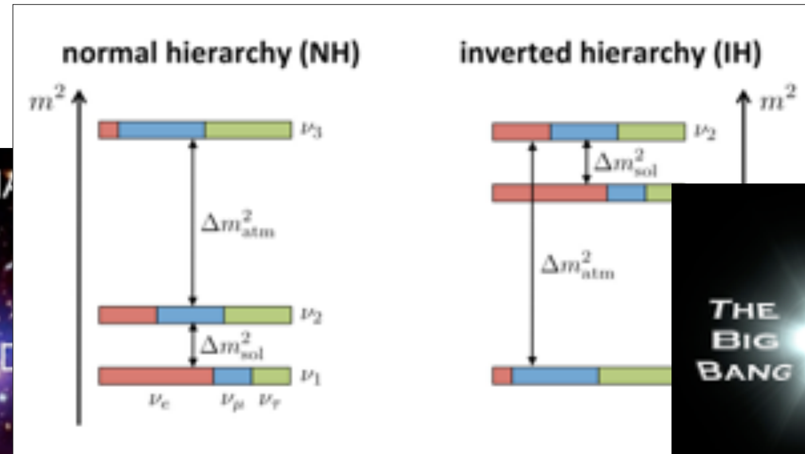

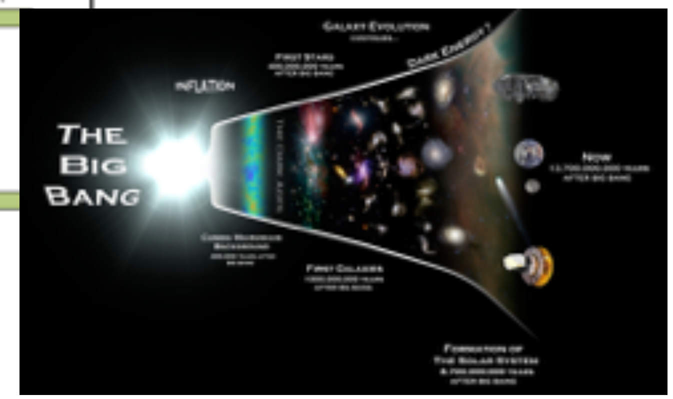

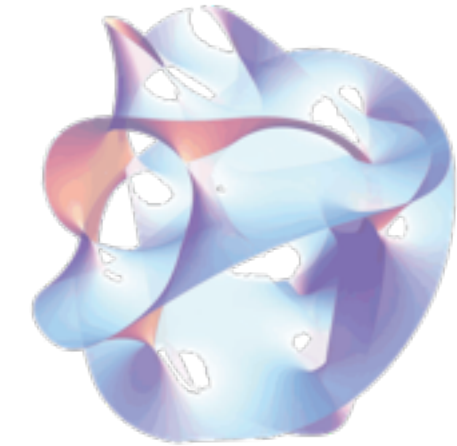

Neutrinos

Inflation

Gravity

DM

Baryon asymmetry

Even more the LHC will keep running until 2037 !

New discoveries
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In any case clues on:

All the above +

Hierarchy problem

Strong CP problem

Flavour structure

So far the LHC has not found any new physics yet…

Hence, if there is NP around the EW scale it is either:

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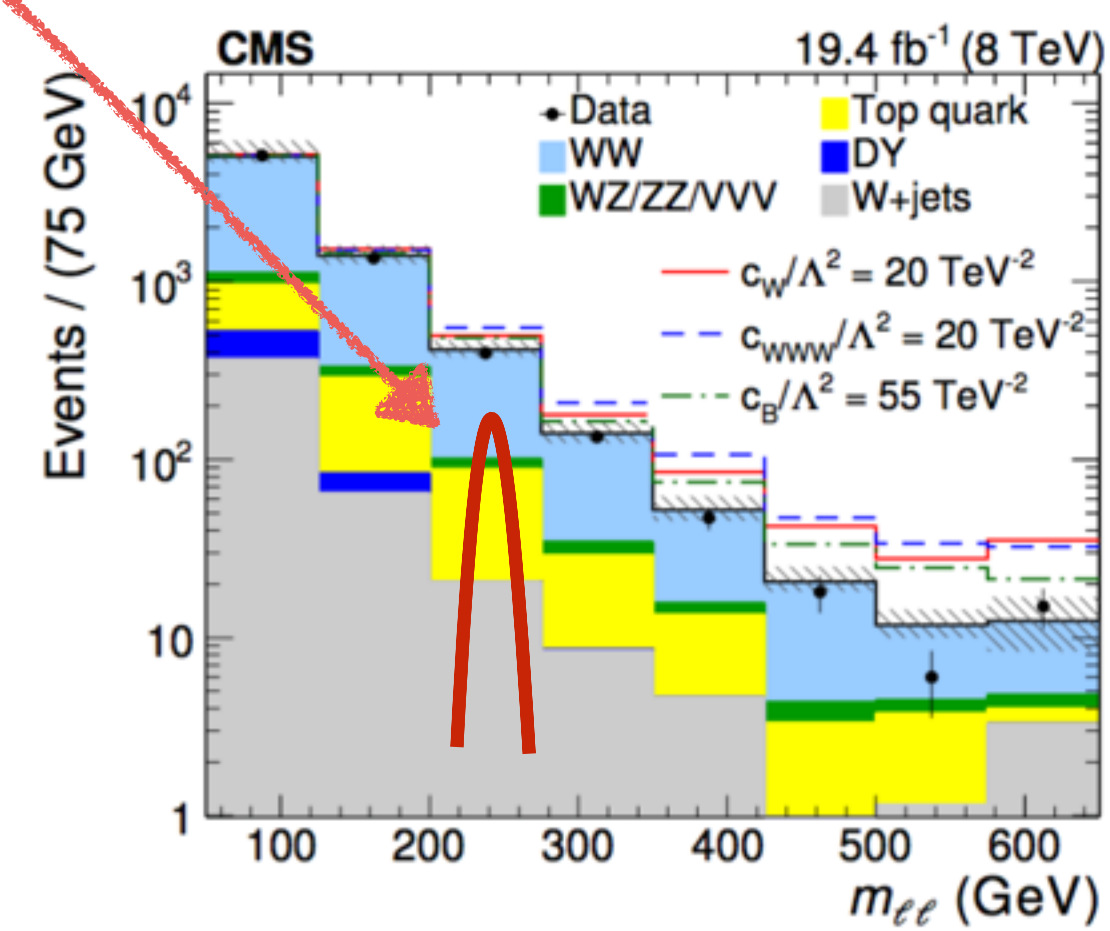
- Light (but weakly coupled)
- **Limited by systematics** (large at LHC)

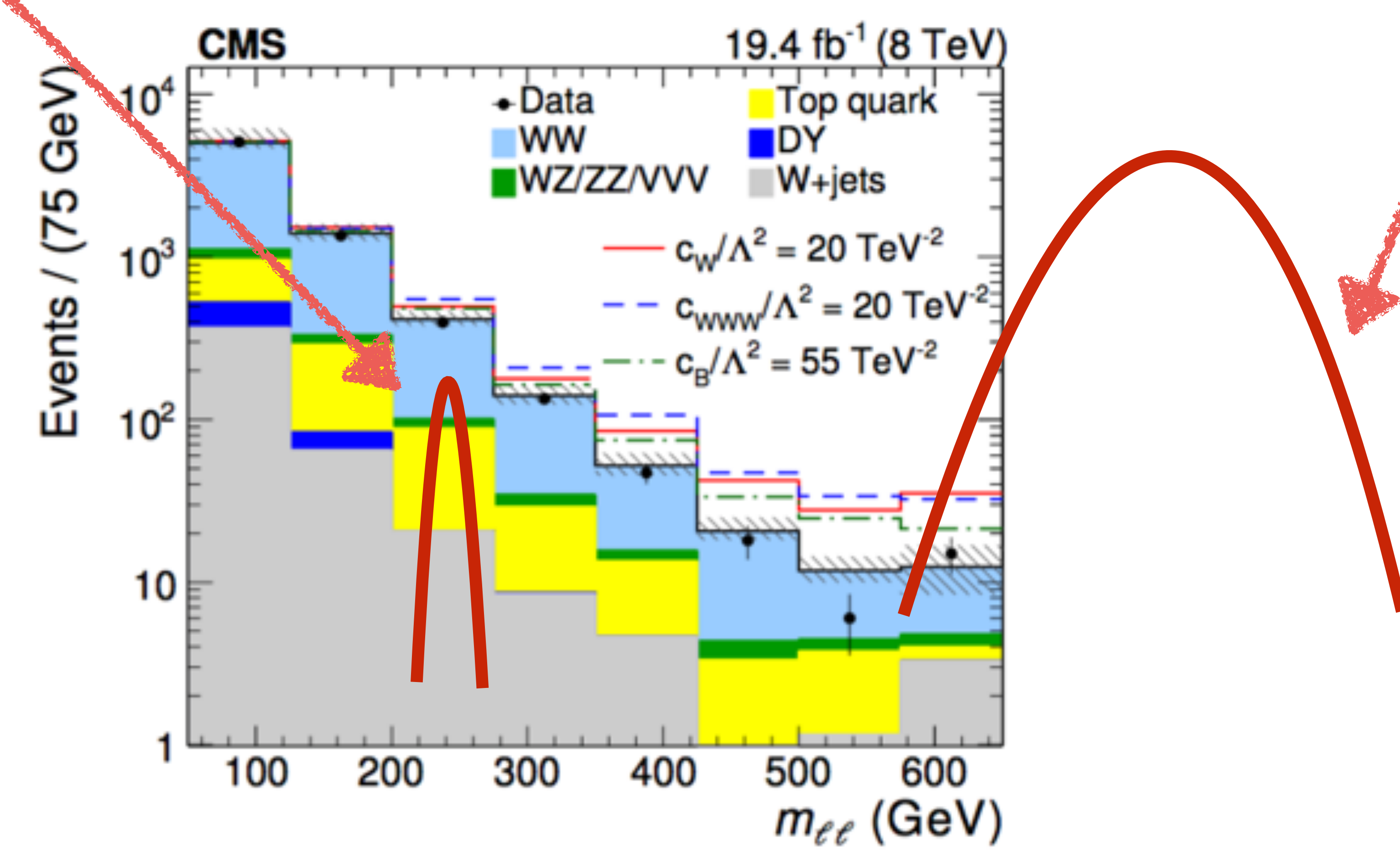


So far the LHC has not found any new physics yet…

Hence, if there is NP around the EW scale it is either:

- Light (but weakly coupled)
- **Limited by systematics** (large at LHC)

- Heavy (effects suppressed)
- **Effects can be enhanced at high energy**



What does this mean??

If new physics is heavy it can be studied with the SM EFT

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

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$$\frac{\delta\sigma}{\sigma_{SM}} \sim \boxed{c_i} \left(\frac{E}{m_W}\right)^{\beta}$$

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$$\chi^2 \sim \left(\frac{\delta\sigma}{\sigma_{SM}}\right)^2 \left(\frac{1}{\Delta}\right)^2 \lesssim 1$$

(error in %) $\Delta \equiv \sqrt{\Delta_{sys}^2 + \Delta_{stat}^2}$

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$$\chi^2 \sim \left(\frac{\delta\sigma}{\sigma_{SM}}\right)^2 \left(\frac{1}{\Delta}\right)^2 \lesssim 1 \longrightarrow \boxed{\boxed{c_i} \lesssim \Delta \left(\frac{m_W}{E}\right)^\beta}$$

(error in %) $\Delta \equiv \sqrt{\Delta_{sys}^2 + \Delta_{stat}^2}$

Bound becomes stronger at large E

Diboson production at the LHC is specially interesting

In particular,
the processes modified
by dimension 6 operators,
which are:

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

1) $pp \to WW$, 2) $pp \to WZ$, 3) $pp \to Zh$, 4) $pp \to Wh$

Why are they interesting?

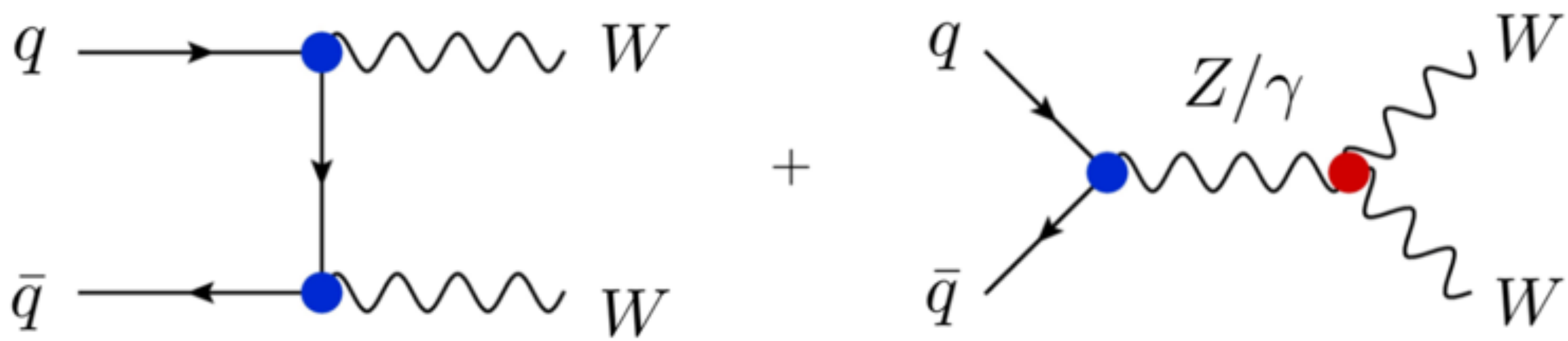
1) Sensitive to BSM physics addressing the hierarchy problem

for instance: Composite Higgs models, extra dimensions, Little Higgs

Why are they interesting?

2) The BSM contributions grow faster than the SM one

for example: $pp \to WW$,



t-channel s-channel

$$\mathcal{M}_\gamma + \mathcal{M}_Z + \mathcal{M}_t = -i\frac{e^2 \sin\theta}{2m_W^2}\underbrace{s}_{E^2}\left(\underbrace{Q_q + \frac{1}{s_W^2}(T_q^3 - s_W^2 Q_q) - \frac{T_q^3}{s_W^2}}_{=0}\right) + \ldots$$

- In the **SM** each diagram grows with CM Energy but sum **cancels**

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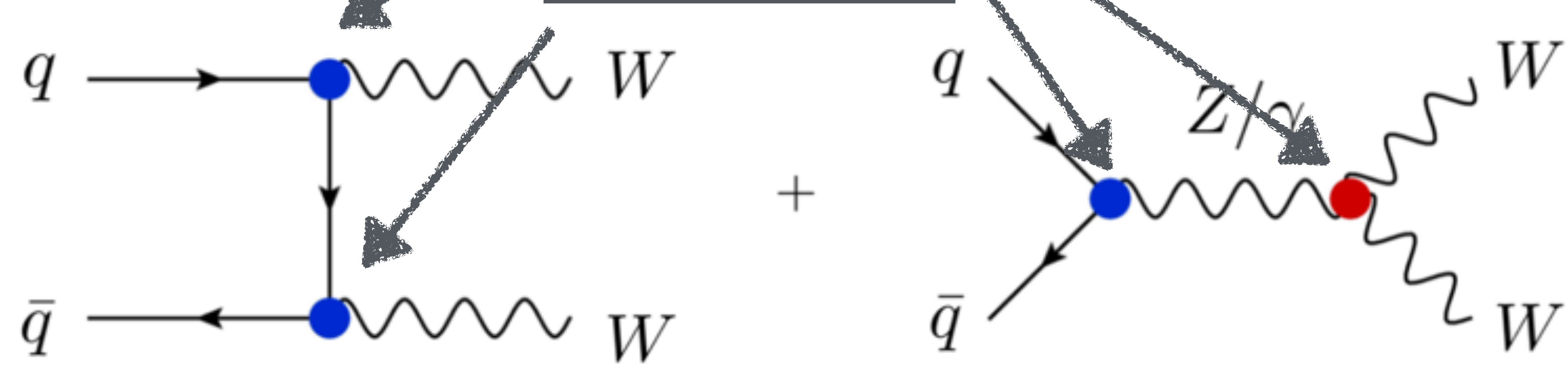
for example: $pp \to WW$, $\boxed{g_{SM}\,(1+\delta g)}$



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$$\mathcal{M}_\gamma + \mathcal{M}_Z + \mathcal{M}_t = -i\frac{e^2\sin\theta}{2m_W^2}\, s \left(Q_q + \frac{1}{s_W^2}(T_q^3 - s_W^2 Q_q) - \frac{T_q^3}{s_W^2} \right) + \ldots$$

E^2

$\boxed{\neq 0}$

- In the **SM** each diagram grows with CM Energy but sum **cancels**

- In the **SMEFT** vertices are modified, **cancellation is spoiled**
(at dimension 6)

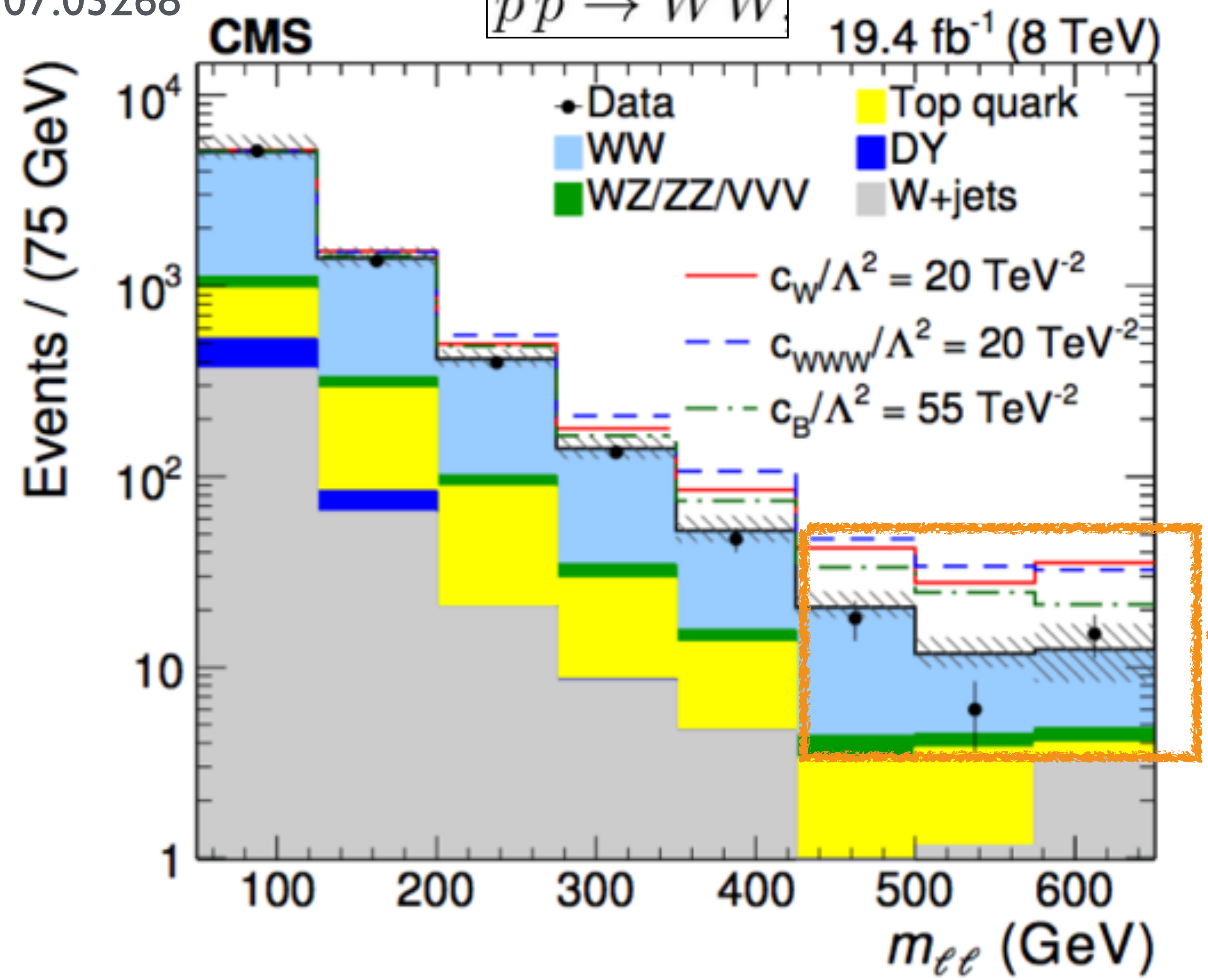
Enhanced sensitivity!

Why are they interesting?

3) Diboson errors are **small** enough to set strong bounds thanks to **E enhancement**

1507.03268

$pp \to WW$



$\Delta \sim 10\%,\ E \sim 1\,\mathrm{TeV}$

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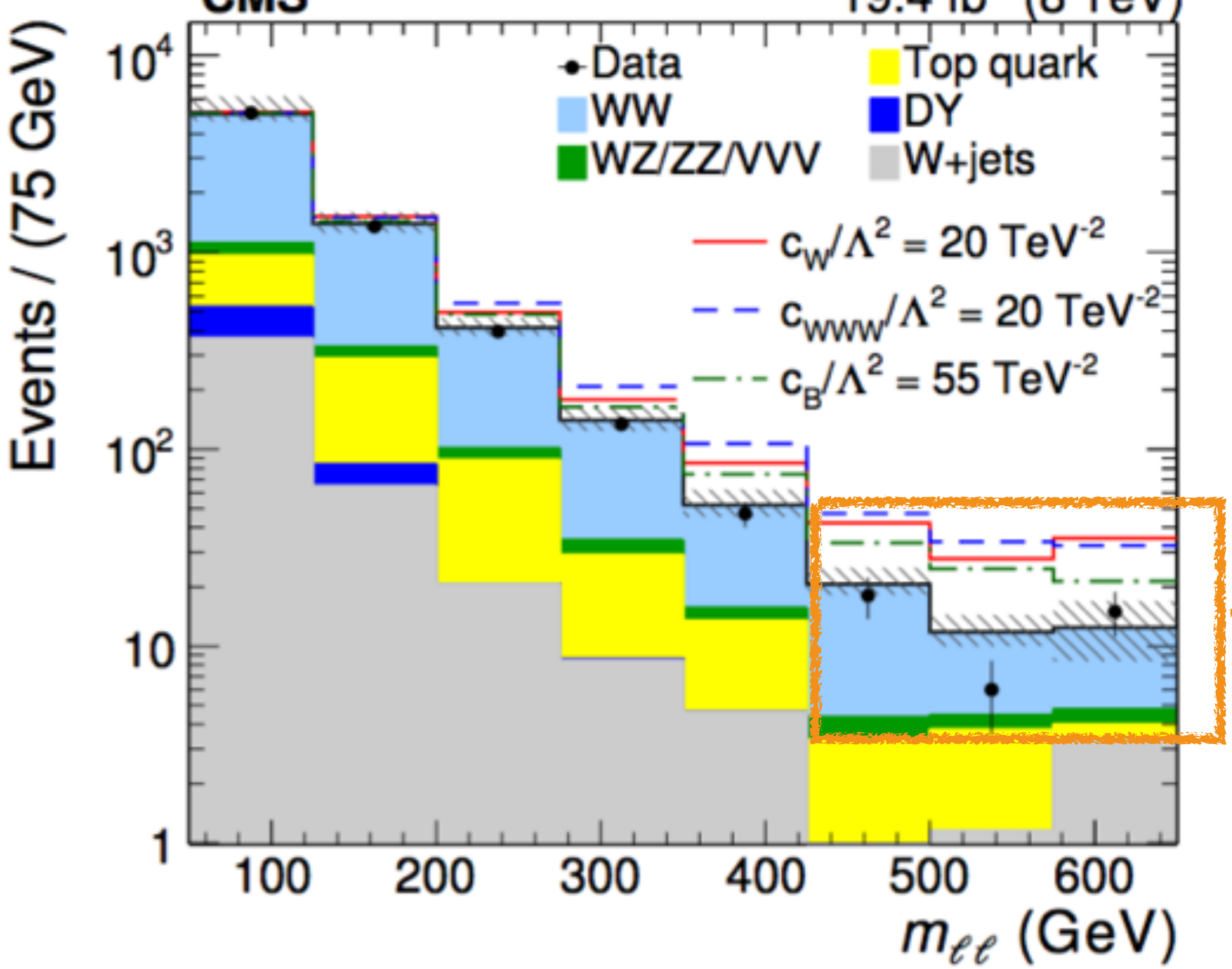


$\Delta \sim 10\%,\ E \sim 1\,\mathrm{TeV}$

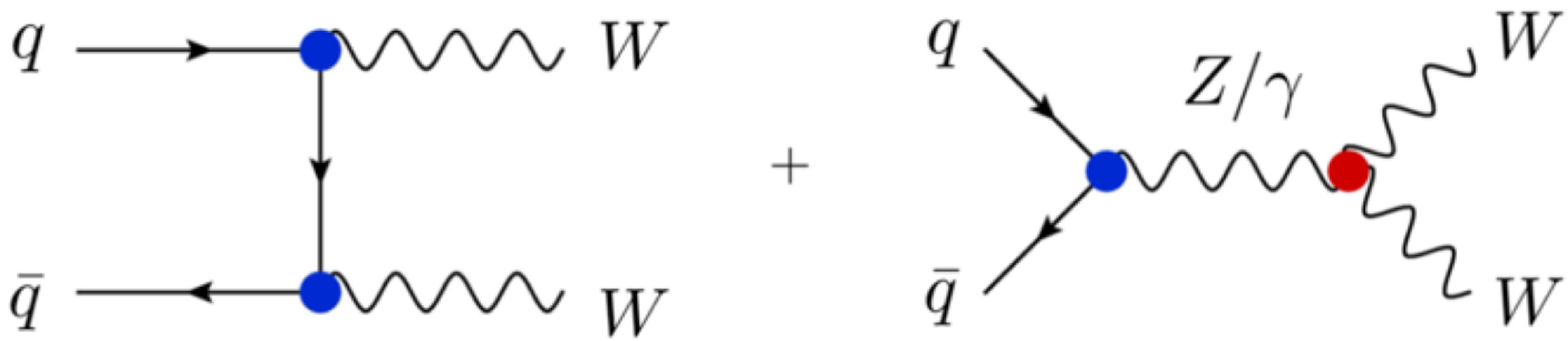
Since the **BSM** XS grows with E faster than the **SM** XS

$$c_i \lesssim \Delta \left(\frac{m_W}{E}\right)^{\beta}$$

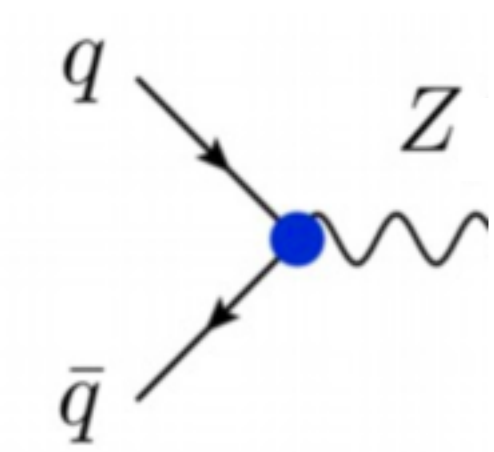
$$\Delta \sim 10\%,\ E \sim 1\,\mathrm{TeV} \xrightarrow[\beta=2]{} c_i \lesssim 0.1\%$$

Naively we expect a permille bound!!

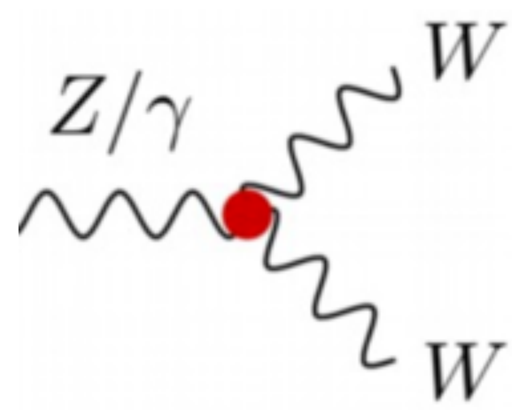
Schematically diboson production (WW,WZ):



Equivalent to study modifications to Zqq and aTGC



$$\boxed{g_{SM}\,(1+\delta g)}$$



Z couplings to quarks

anomalous TGC

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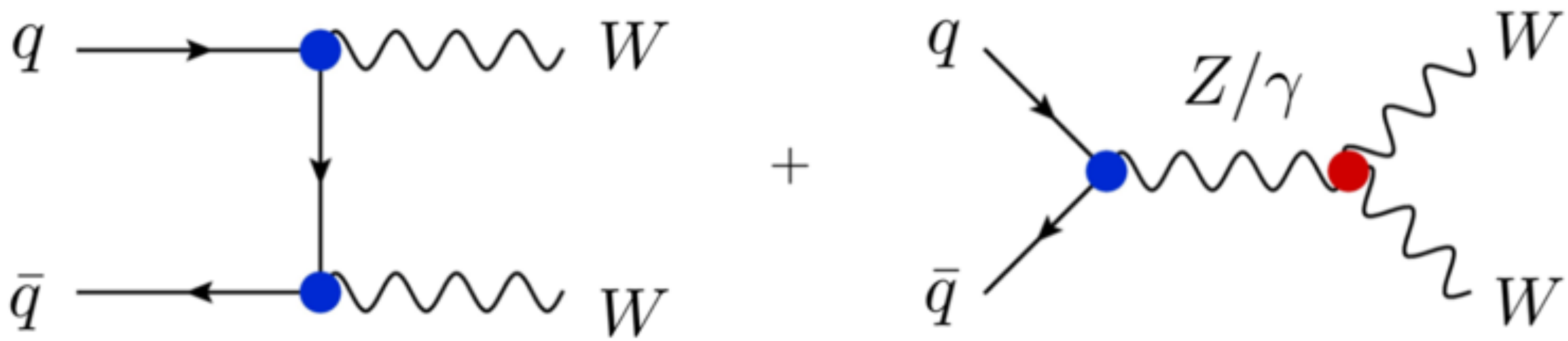

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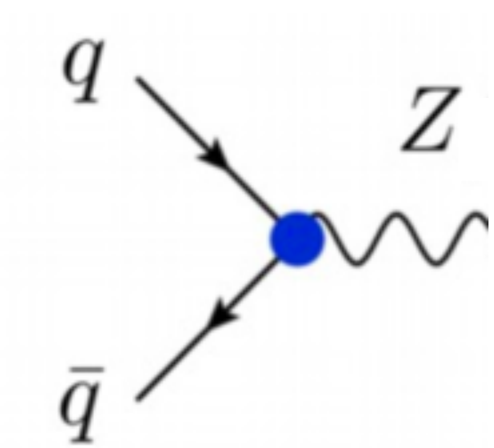

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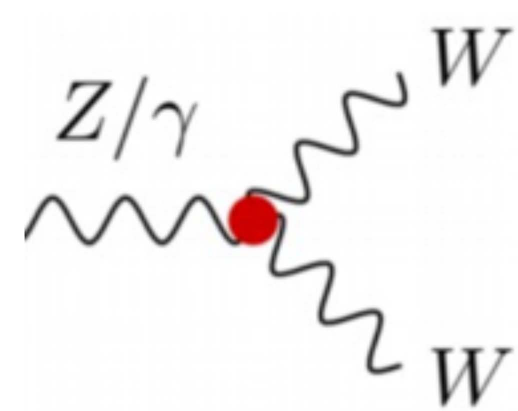

Z couplings to quarks

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At dim=6:
(Flavour Universality)

$$\boxed{\delta g_L^{Zu},\ \delta g_L^{Zd},\ \delta g_R^{Zu},\ \delta g_L^{Zd}} \qquad \boxed{\delta\kappa_\gamma,\ \delta g_{1z},\ \lambda_\gamma}$$

4 + 3 = 7 param

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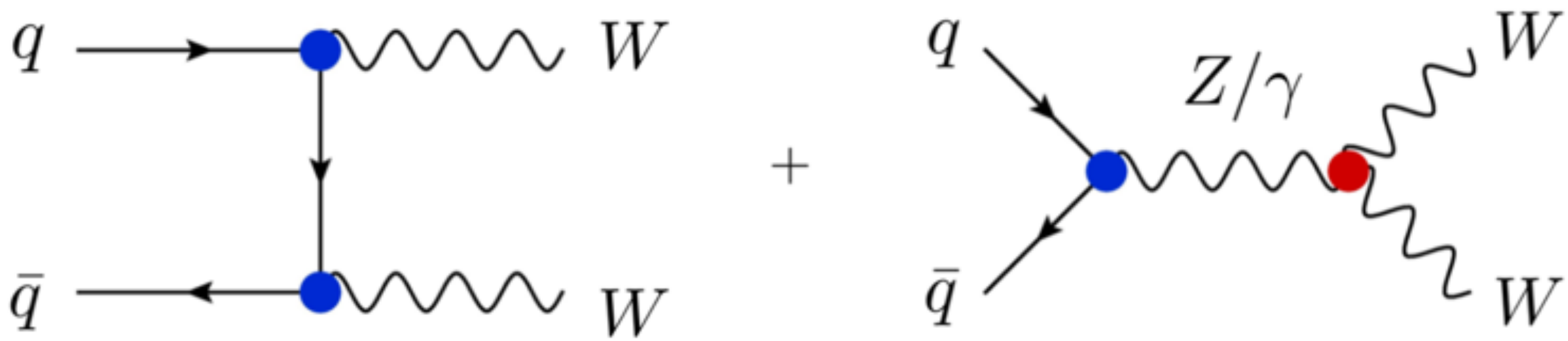

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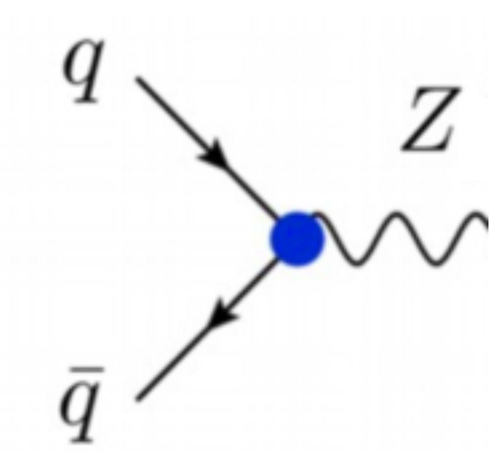

Z couplings to quarks

(**LEP-1** @ Z-pole)

$\delta g \lesssim 0.1\% - 1\%$

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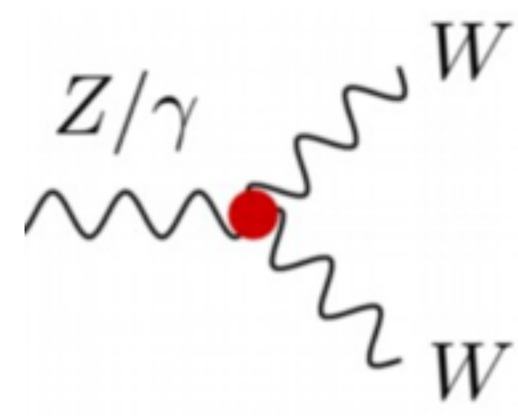

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(**LEP-2**)

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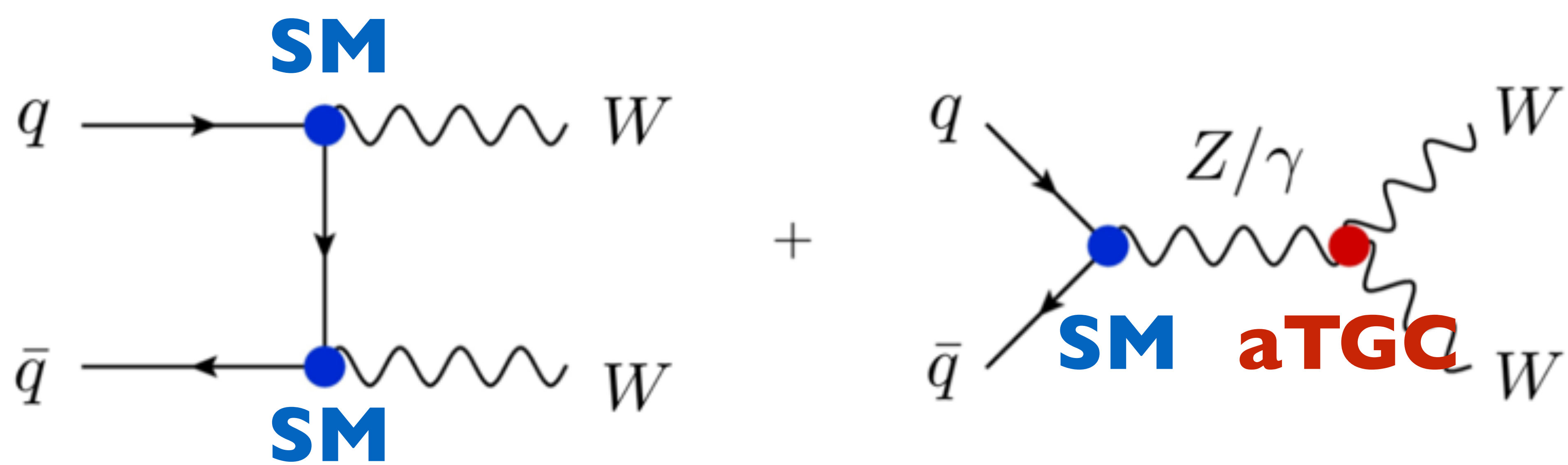

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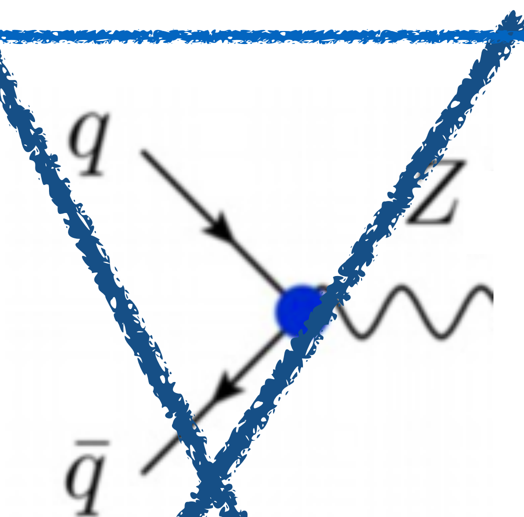

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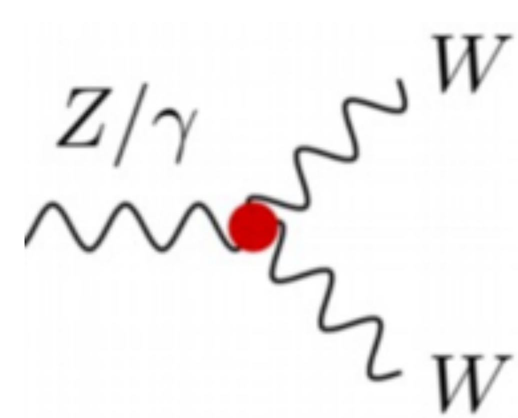

anomalous TGC

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Summary of our work on diboson:

1) 1810.05149 with C. Grojean and M. Riembau

1.1) Is it justified to neglect Zqq couplings @ LHC?

1.2) Can the LHC improve the bounds on the Zqq w.r.t LEP?

2) 190x.xxxxx with G. Durieux and M. Riembau
(ongoing)

2.1) Improving the sensitivity and range with VBF

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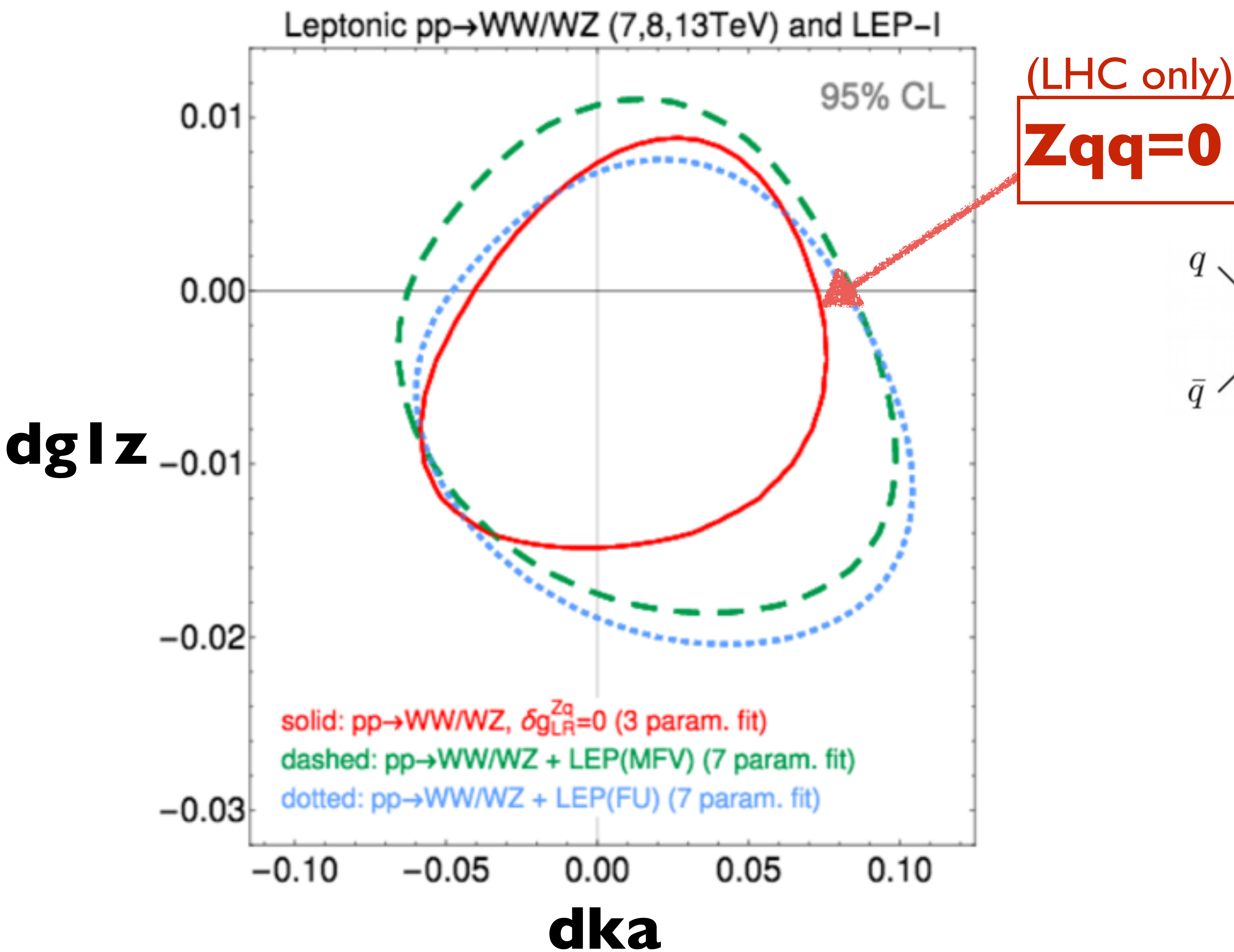
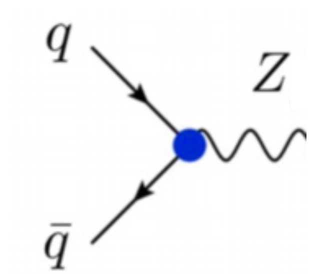
Combine current **leptonic data for WW, WZ** from CMS & ATLAS

Fit to **anomalouts Triple Gauge Couplings**





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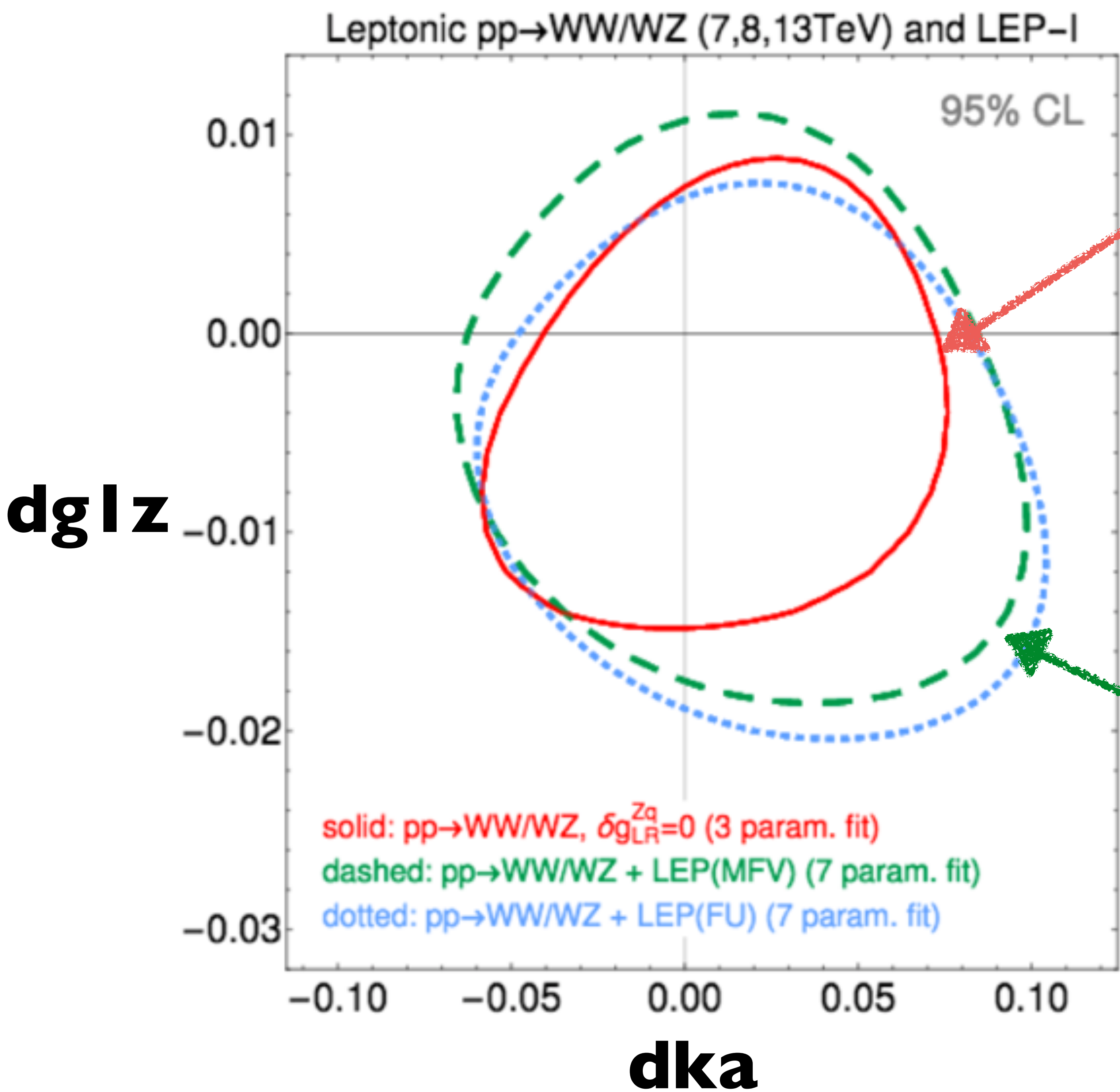
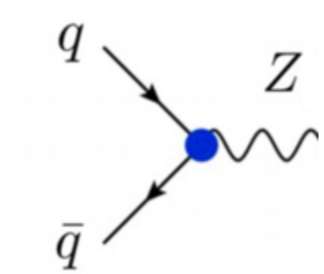


(LHC only)

Zqq=0



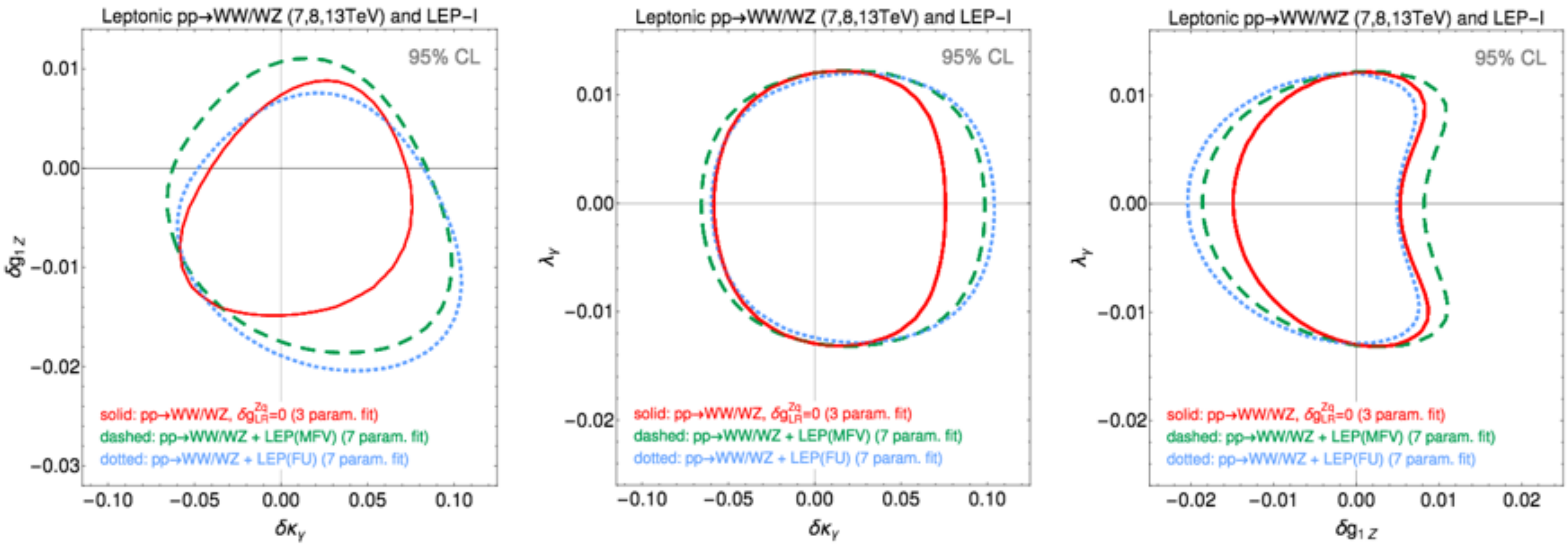
Zqq $\neq$ 0

+

Global fit w/ LEP

(LHC + LEP-1)

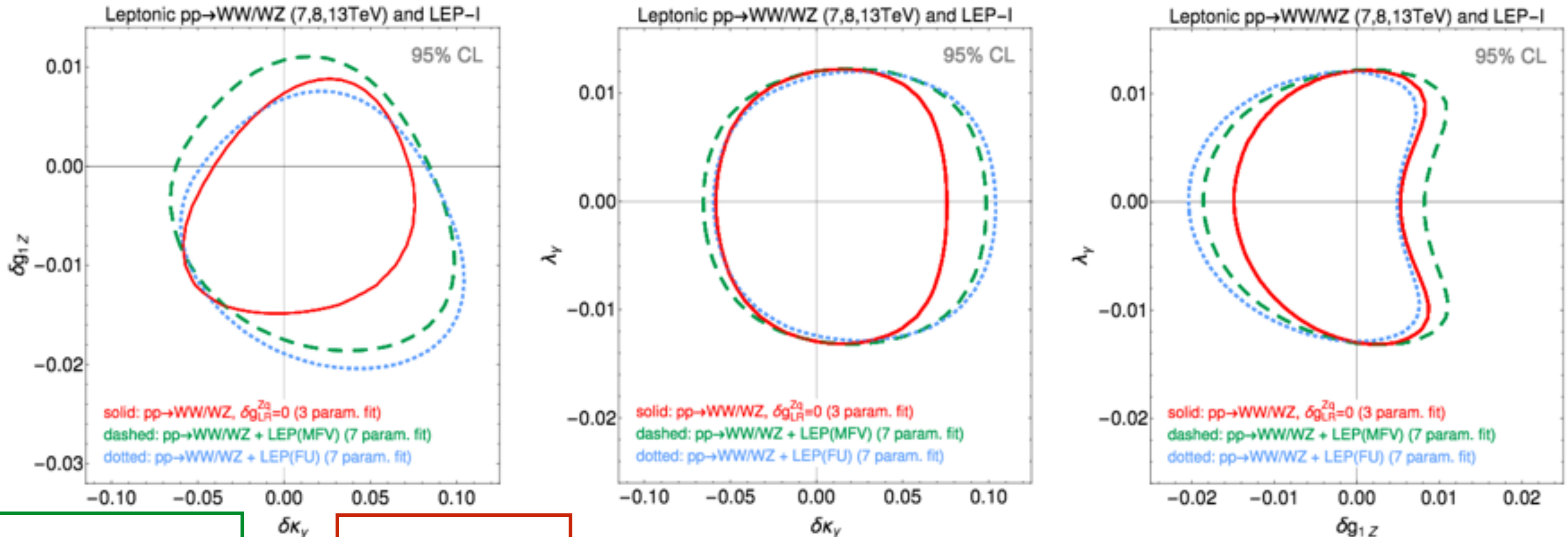
LHC NOW



- Difference between considering Zqq non-zero or zero is of order 20%

(+ global fit w/ LEP)

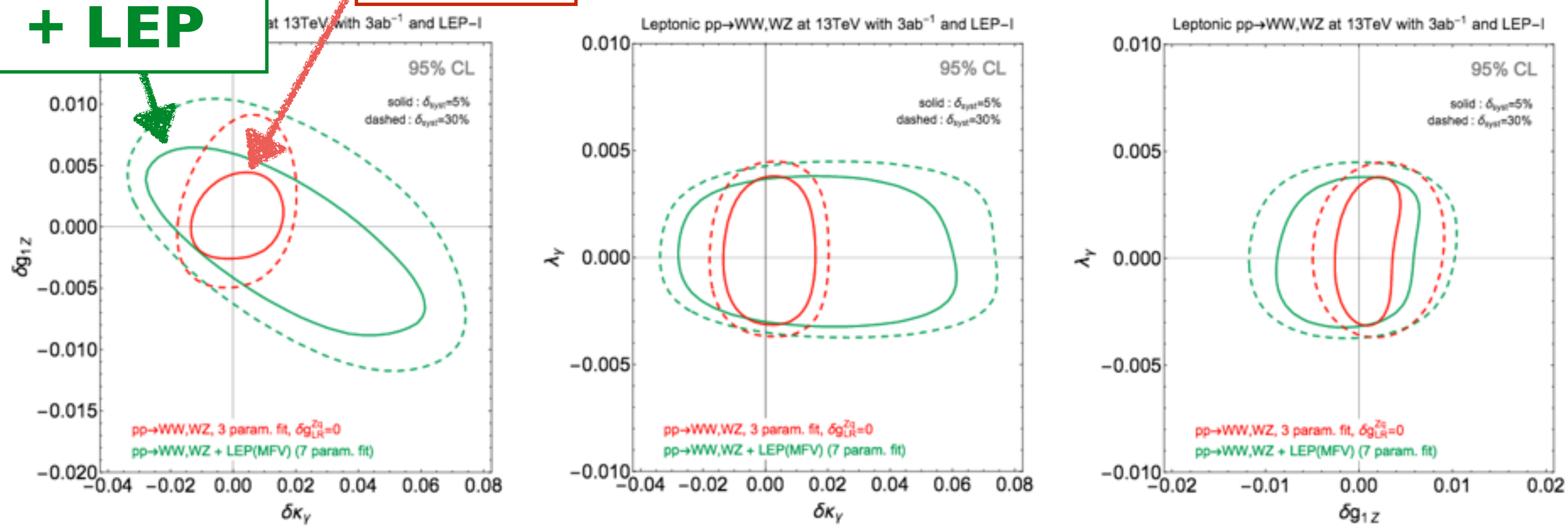
LHC NOW



Zqq ≠ 0 + LEP

Zqq=0

HL-LHC 3 ab^{-1}

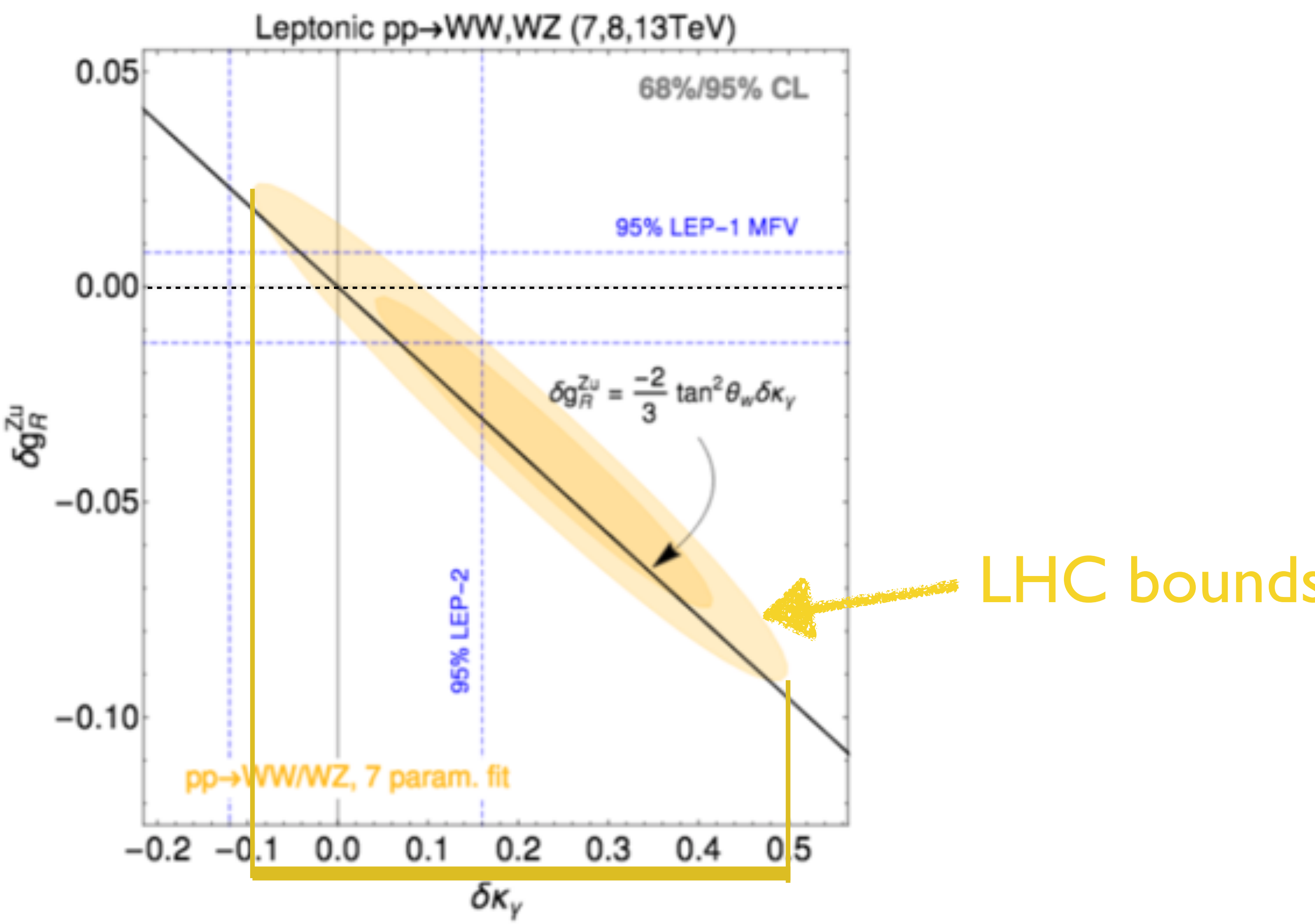


- Difference > 100% @ HL-LHC: **Not Justified to Neglect Zqq!**

At high energies WW, WZ only test 5 directions

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}

but depend on **7 parameters**: 4 Zqq couplings and 3 aTGC



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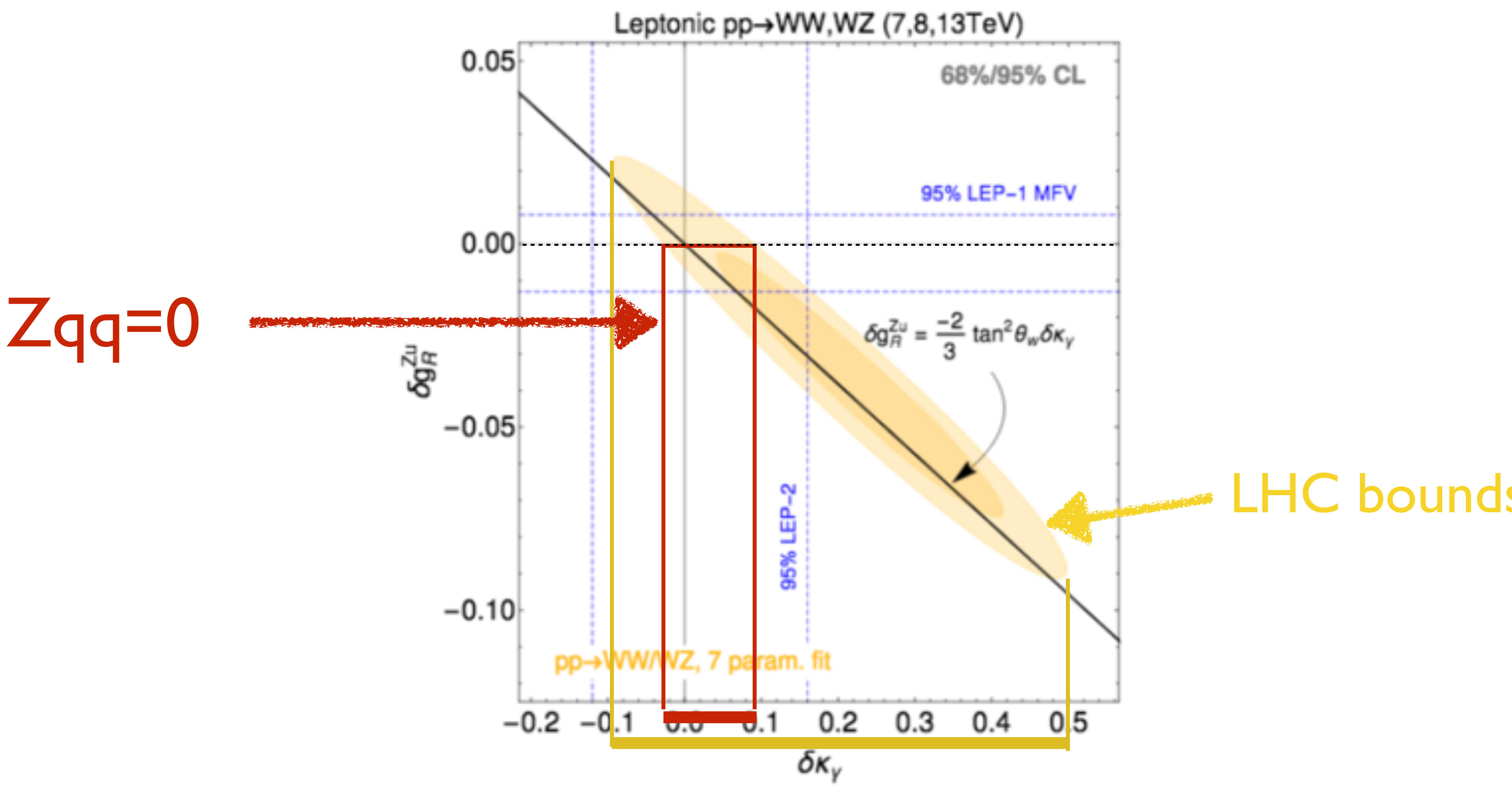
$\bar{u}_R u_L \to W_L^+ W_L^-$	$-2\delta g_L^{Zu} - 0.69\delta g_{1z} - 0.1\delta\kappa_\gamma$	$c_{Hq}^{(1)} + c_{Hq}^{(3)}$
$\bar{d}_R d_L \to W_L^+ W_L^-$	$-2\delta g_L^{Zd} + 0.85\delta g_{1z} - 0.1\delta\kappa_\gamma$	$c_{Hq}^{(1)} - c_{Hq}^{(3)}$
$\bar{u}_L u_R \to W_L^+ W_L^-$	$-2\delta g_R^{Zu} + 0.31\delta g_{1z} - 0.4\delta\kappa_\gamma$	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}

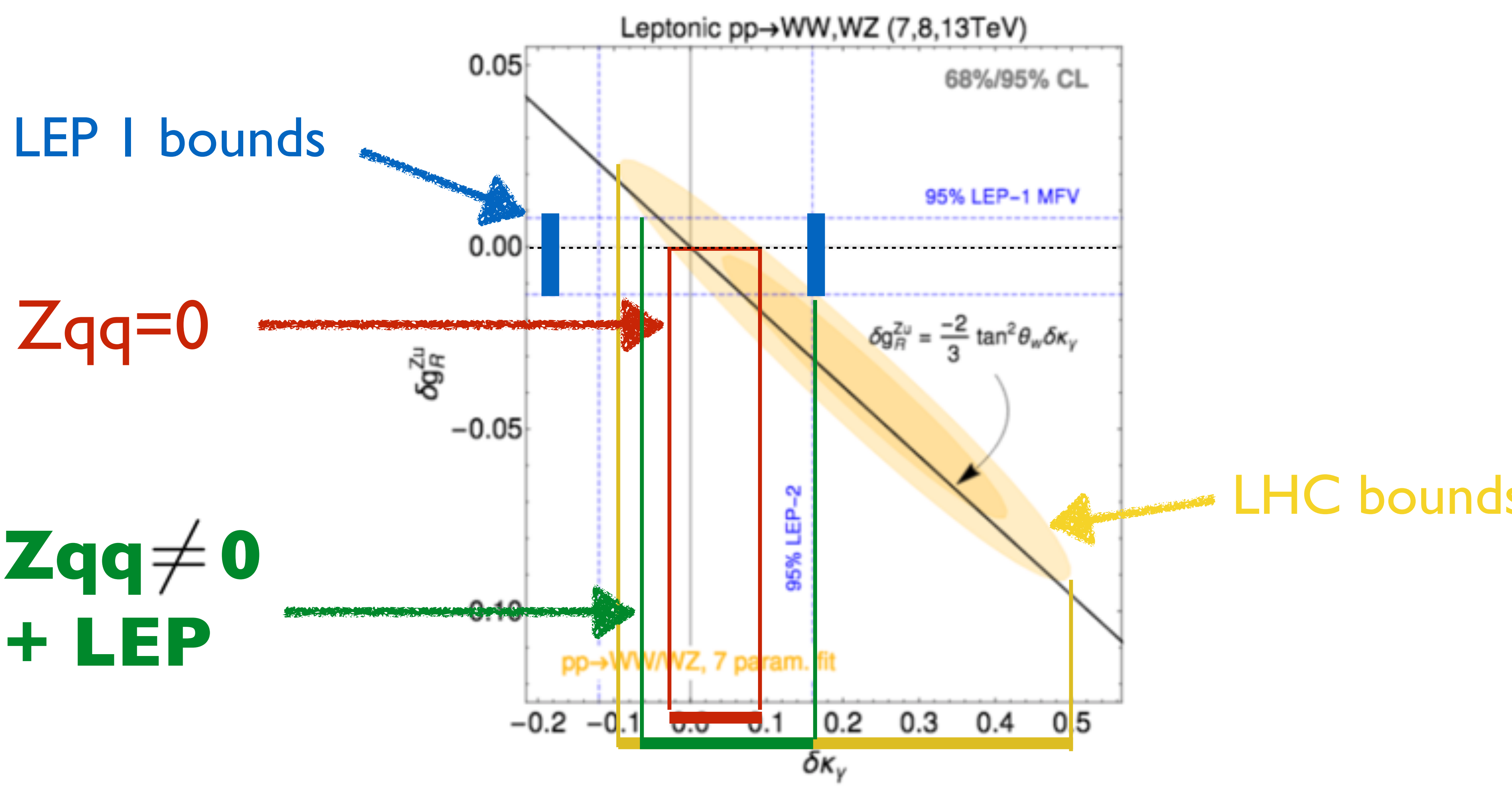
but depend on **7 parameters**: 4 Zqq couplings and 3 aTGC



At high energies WW, WZ only test 5 directions

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}

but depend on **7 parameters**: 4 Zqq couplings and 3 aTGC



1.2) Can the LHC improve the bounds on the Zqq w.r.t LEP?

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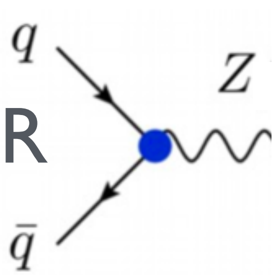
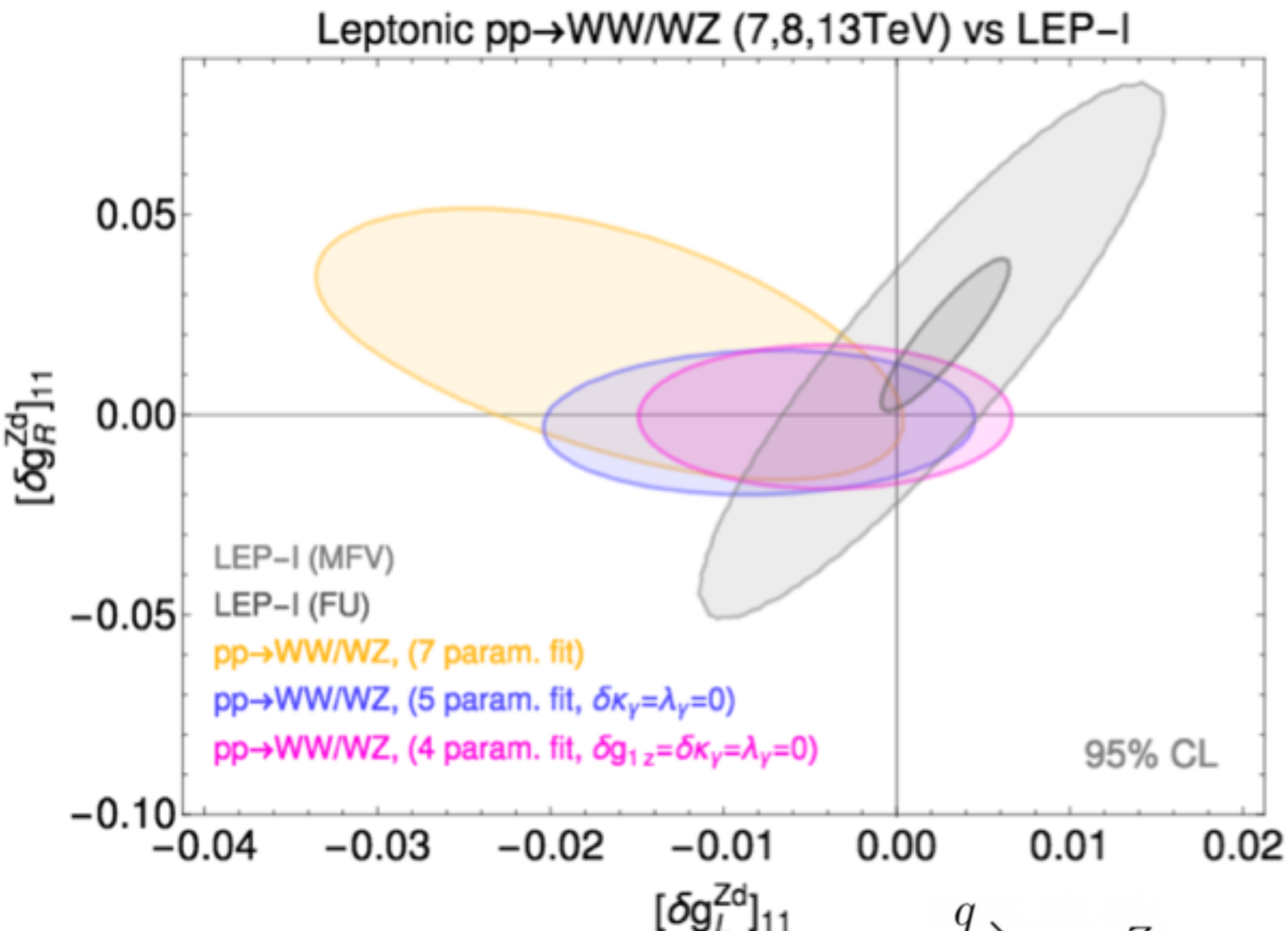
Combine current **leptonic data for WW, WZ** from CMS & ATLAS

Fit to **Zqq vertex corrections**

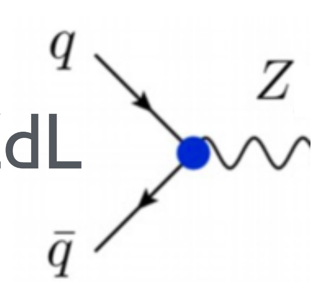
Z to **down** type q

ZdR





ZdL



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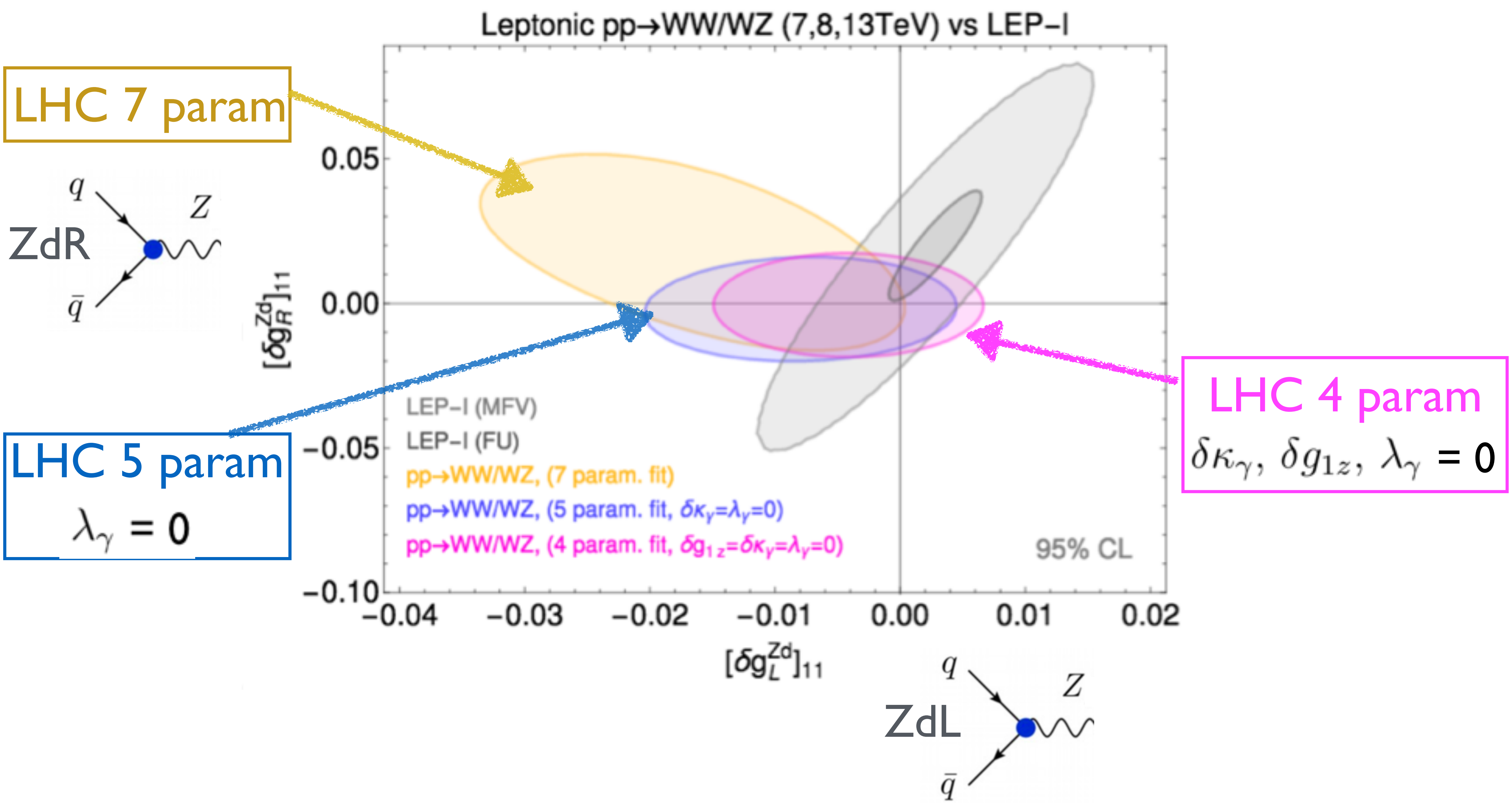

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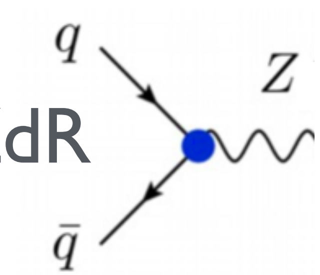
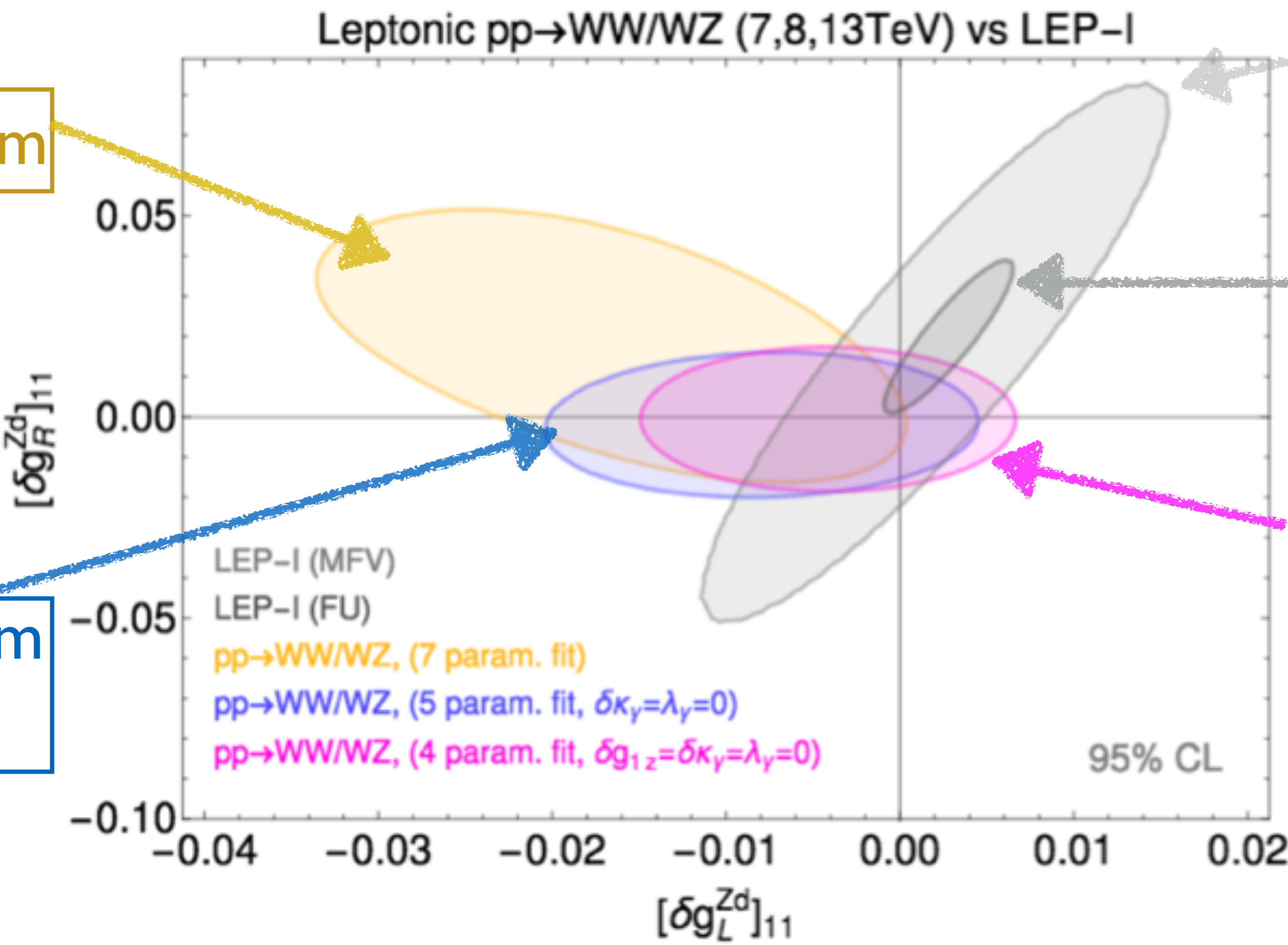
LHC 7 param

ZdR



LHC 5 param

$\lambda_\gamma = 0$



LEP - MFV

LEP - Flavour Universal

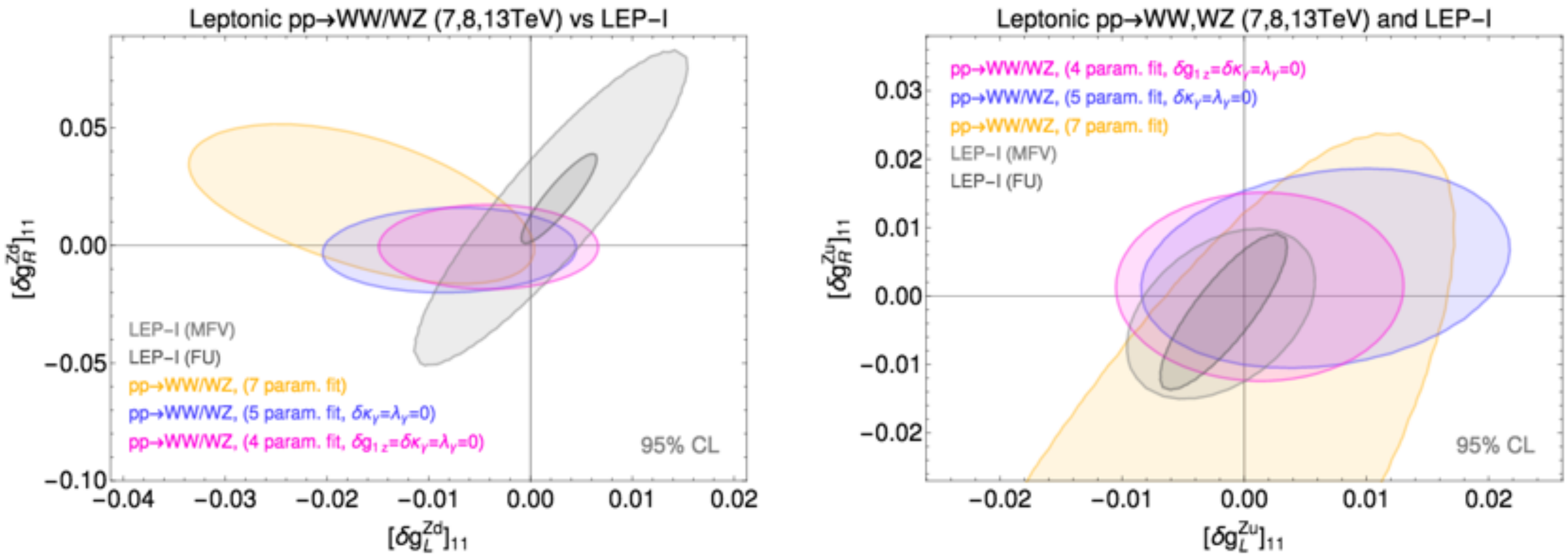
LHC 4 param

$\delta\kappa_\gamma,\ \delta g_{1z},\ \lambda_\gamma = 0$

- Current data is competitive with LEP setting bounds to Zqq down type q!

LHC NOW

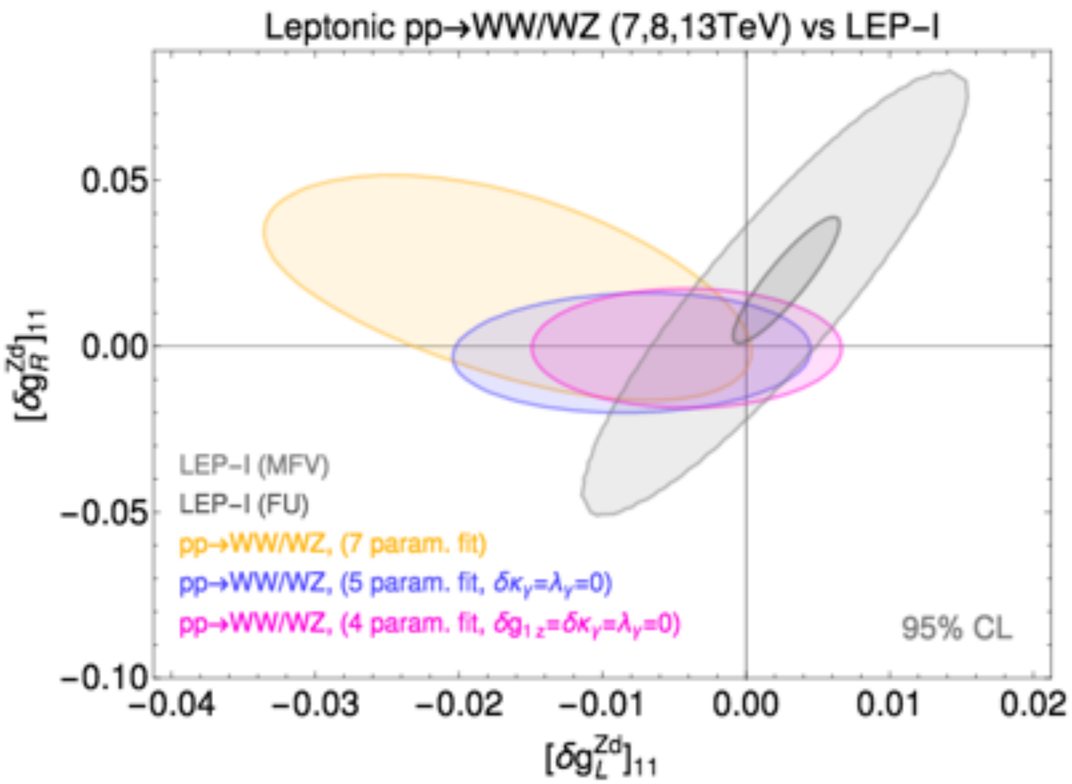
Z to **down** type q — Z to **up** type q



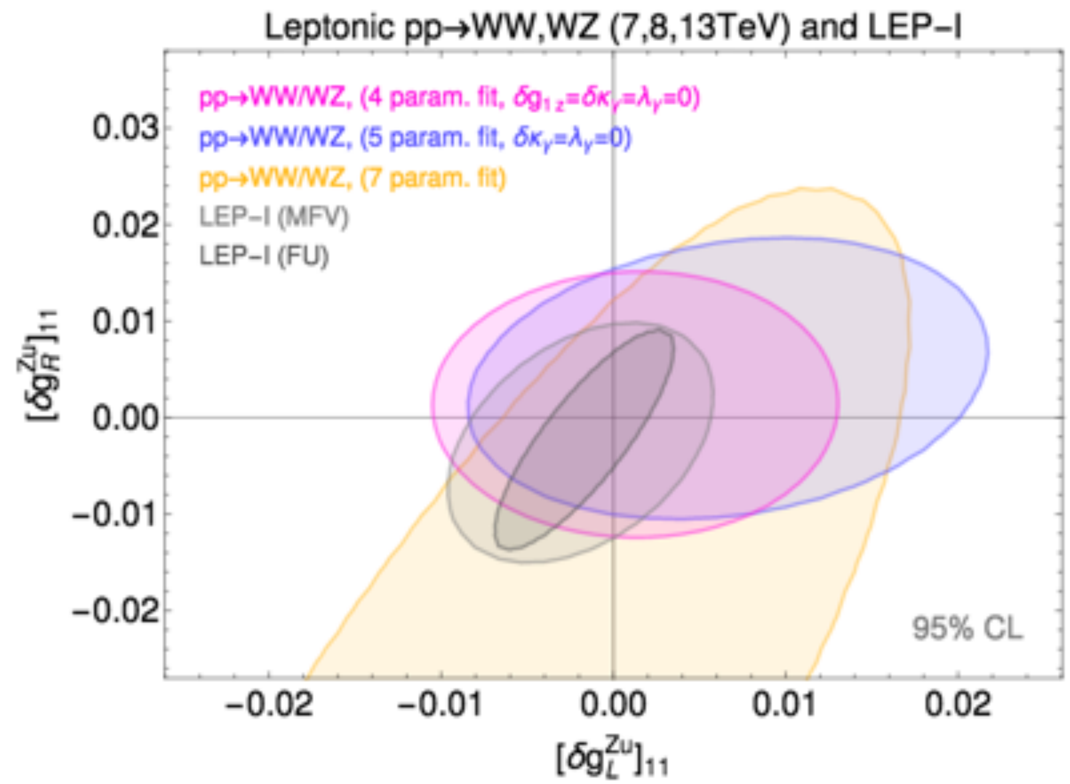
- For the up type corrections, the LHC is still not competitive with LEP

LHC NOW

Z to **down** type q

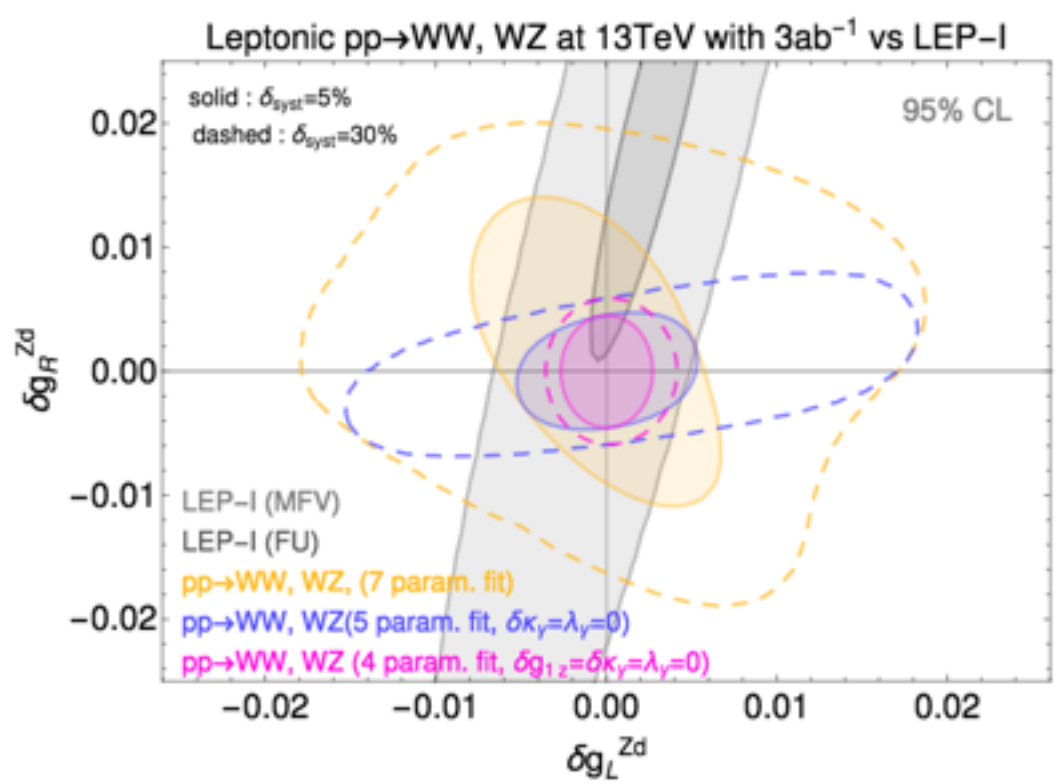


Z to **up** type q

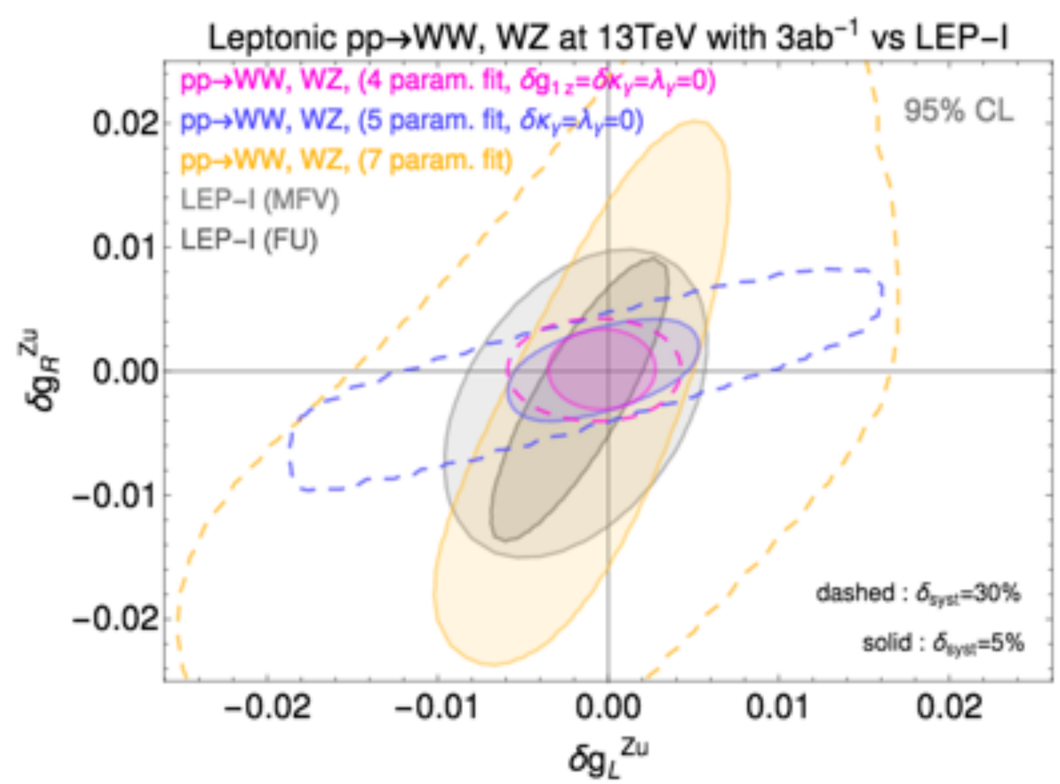


HL-LHC 3 ab^{-1}

Z to **down** type q



Z to **up** type q

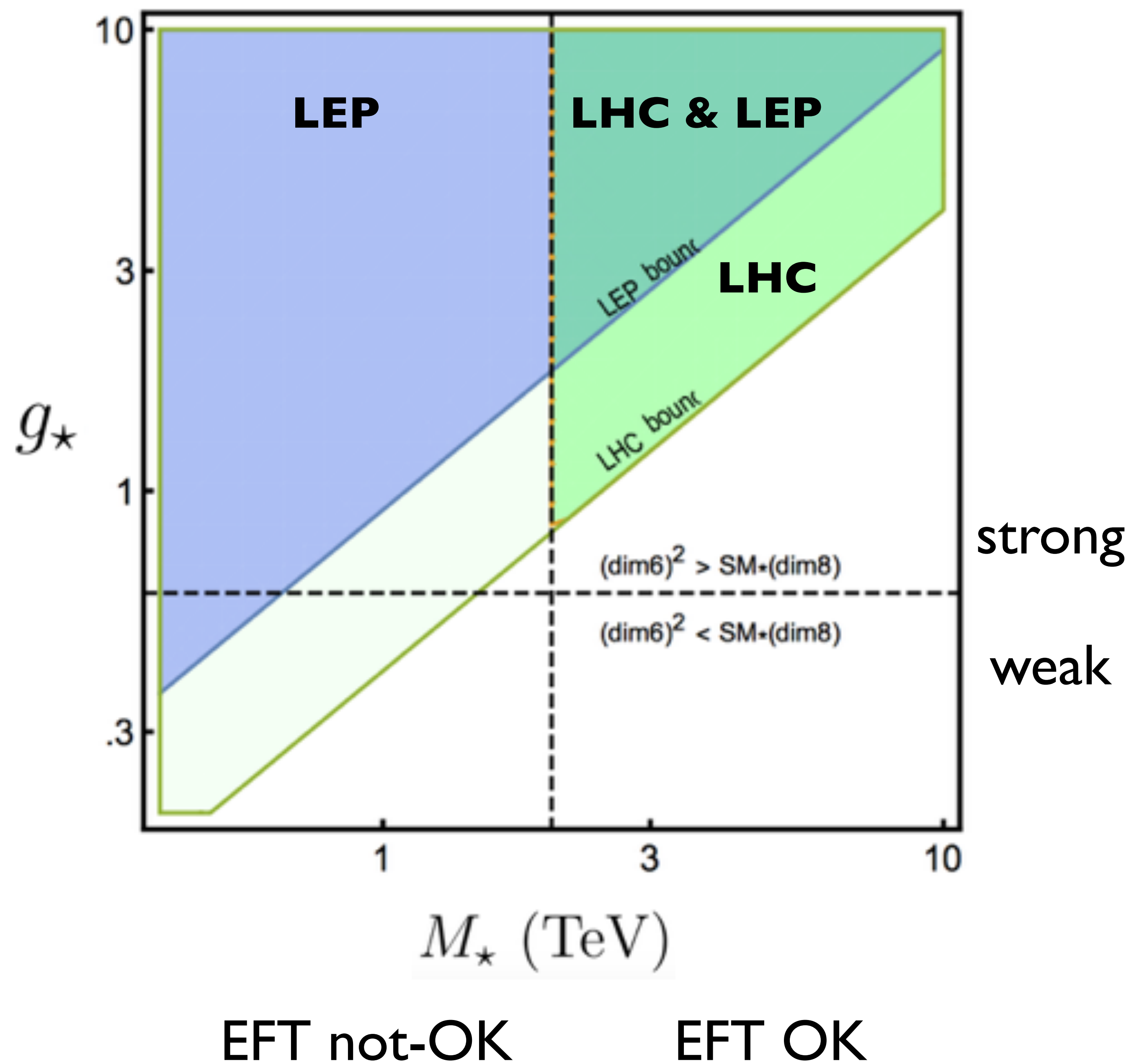


- WV @ HL-LHC may **improve** the bounds on all the Zqq vertices **w.r.t LEP**!

Interpreting the bounds

Our LHC bounds on the BSM parameters are only valid for large BSM masses

In our case this means that we can only constrain theories where $g_\star > g_{SM}$



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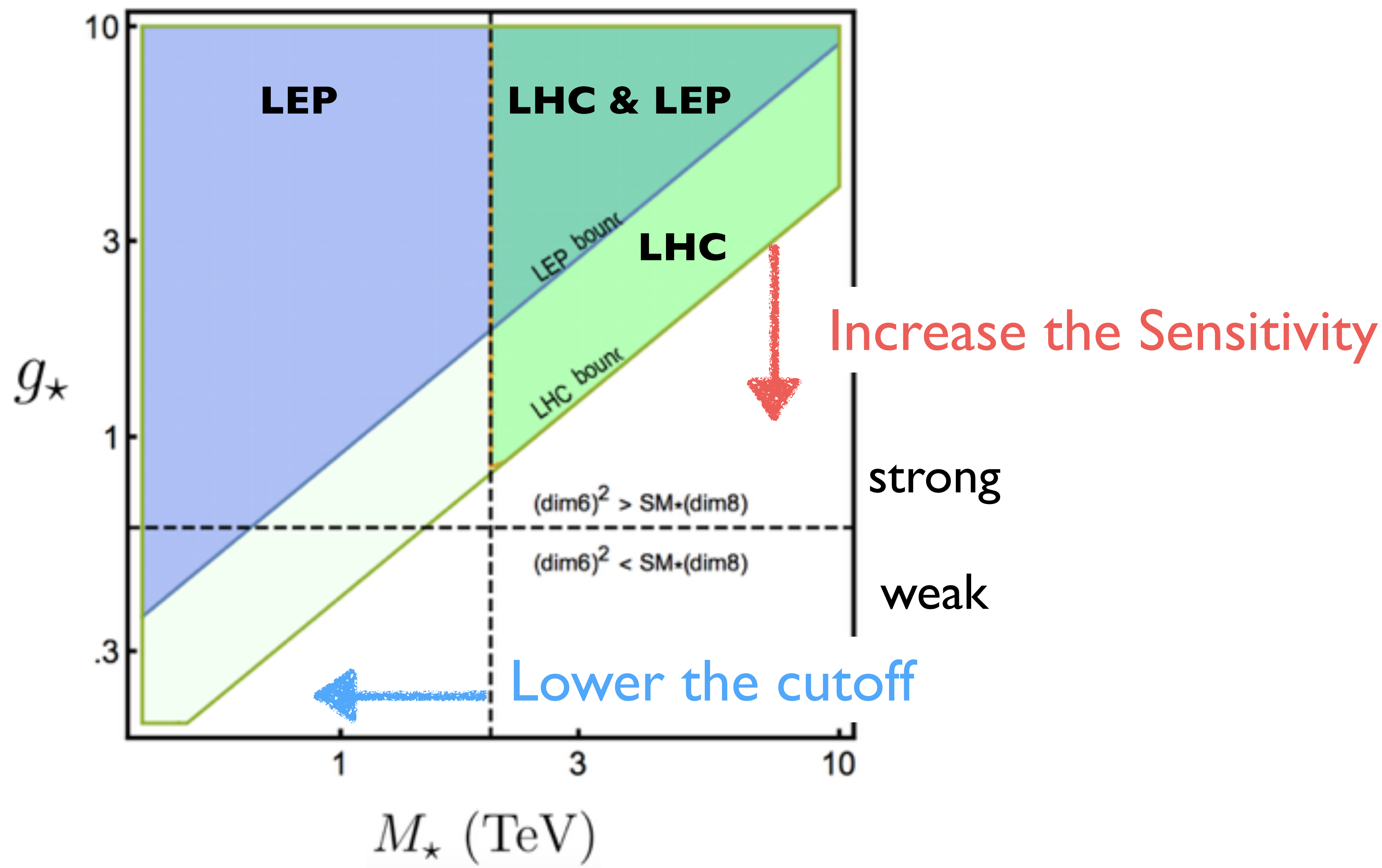


EFT not-OK EFT OK

<u>We would like to:</u>

1) Increase the Sensitivity (constrain weakly coupled theories)

2) Lower the cutoff (increase range of the bounds)

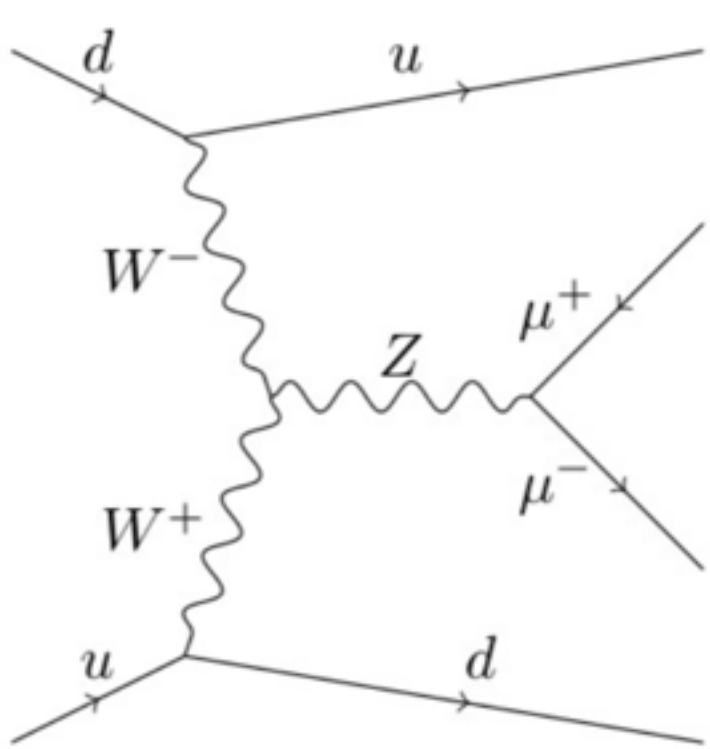
Many work done on diboson to improve the bounds, e.g.

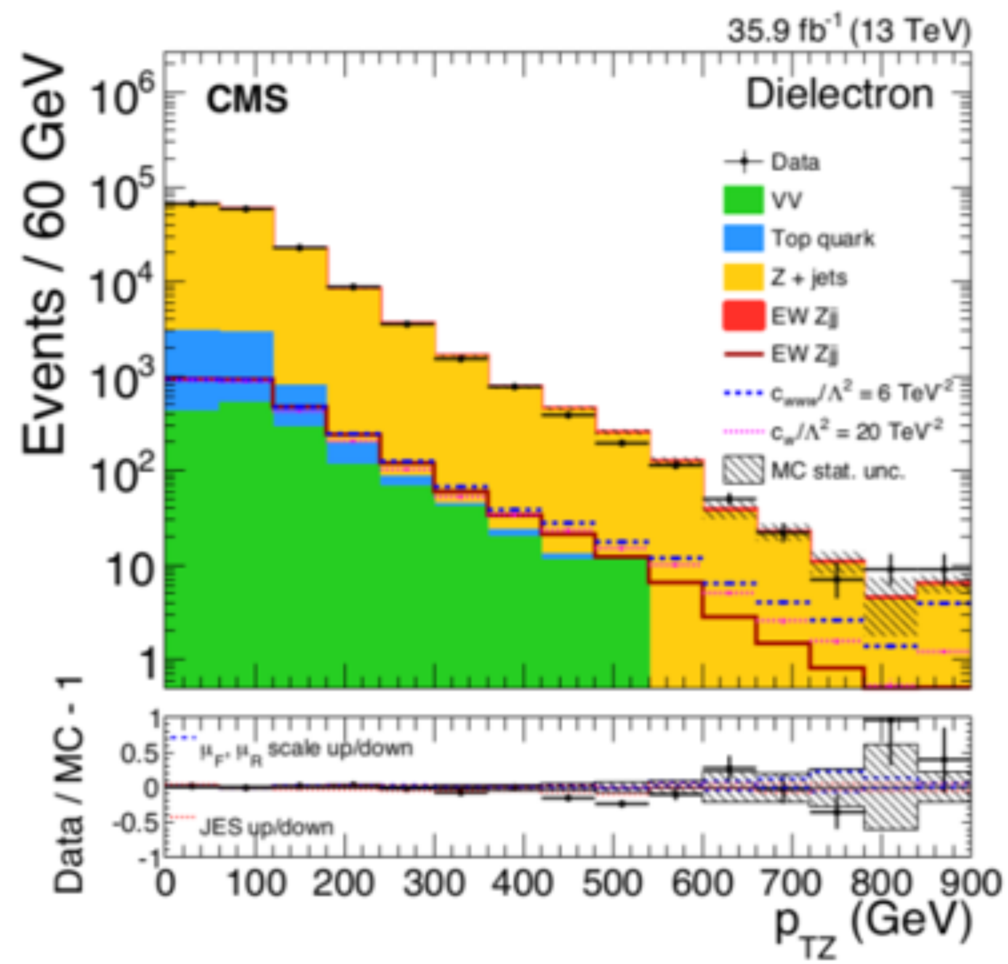
Falkowski et al. (1609.06312)
Azatov et. al (1707.08060)
Panico et al. (1708.07823)
Franceschini et al. (1712.01310)

Bellazzini et al. (1806.09640)
Azatov et. al (1901.04821)
Banerjee et. al (1905.02728)
+ …

(ongoing work with G. Durieux and M. Riembau)

2.1) Improving the sensitivity and range with VBF?

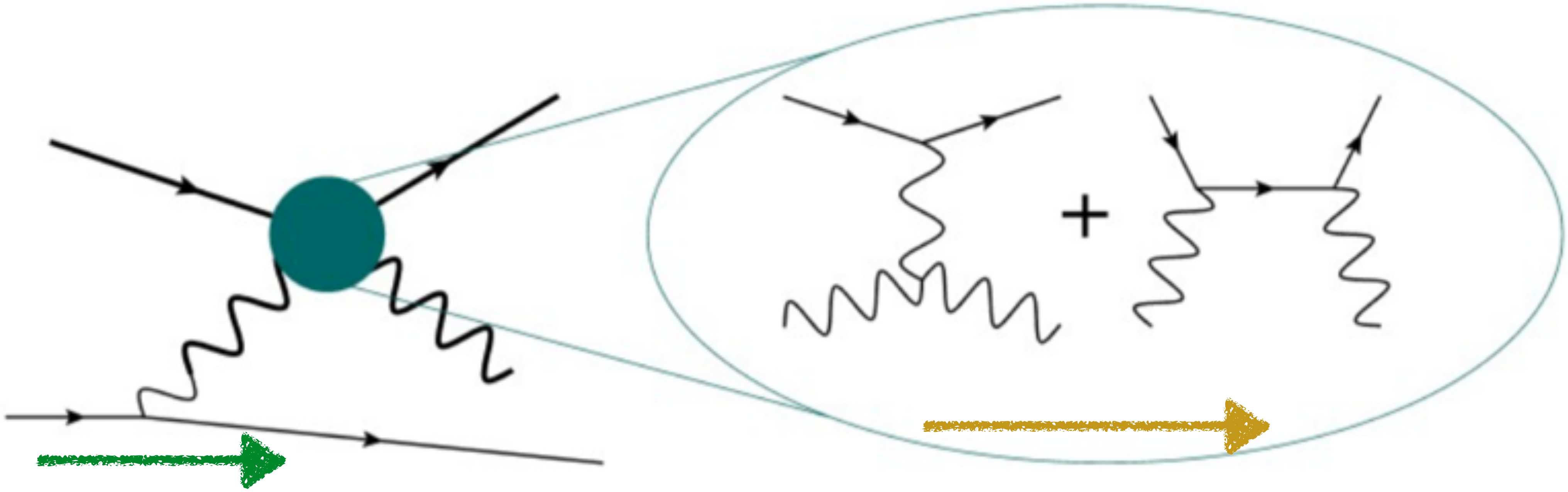




Why study VBF?

1) Analytic simplification is possible via Equivalent EW bosons

Rattazzi et al. 1202.1904



The process factorises into a:

- soft scale (radiated W)
- hard scale (2->2 scattering)

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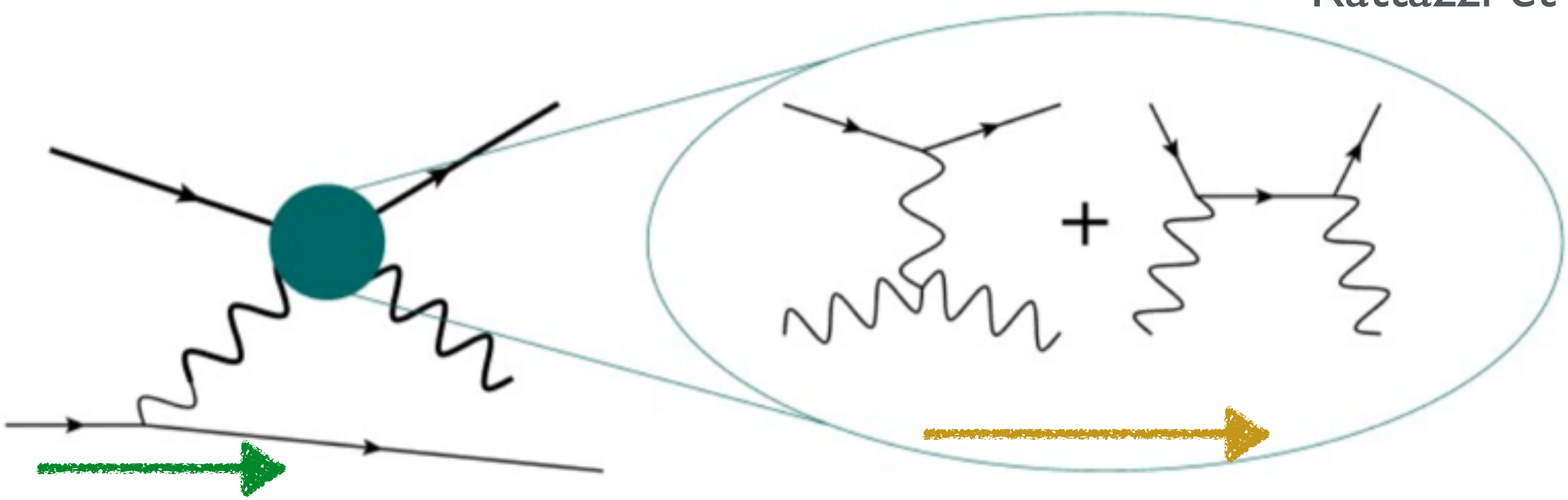

The process factorises into a:

- soft scale (radiated W)
- hard scale (2->2 scattering)

2) VBF is sensitive to the same operators as diboson

Diboson has the same diagrams as the 2->2 channel rotated 90 degrees

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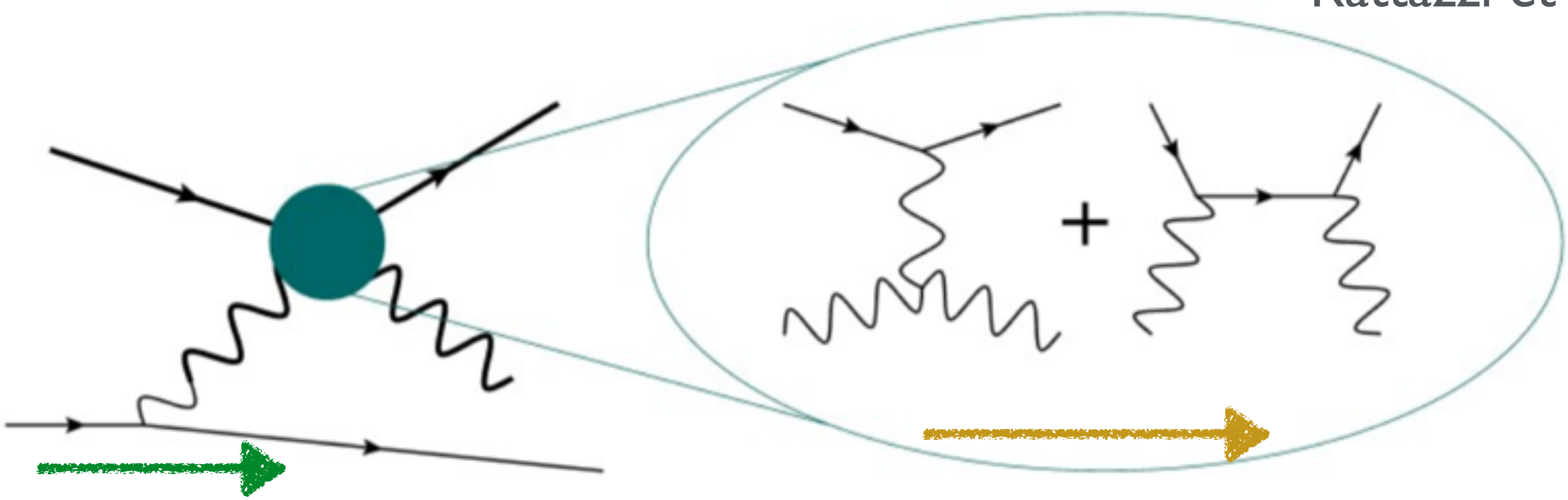


The process factorises into a:
- soft scale (radiated W)
- hard scale (2->2 scattering)

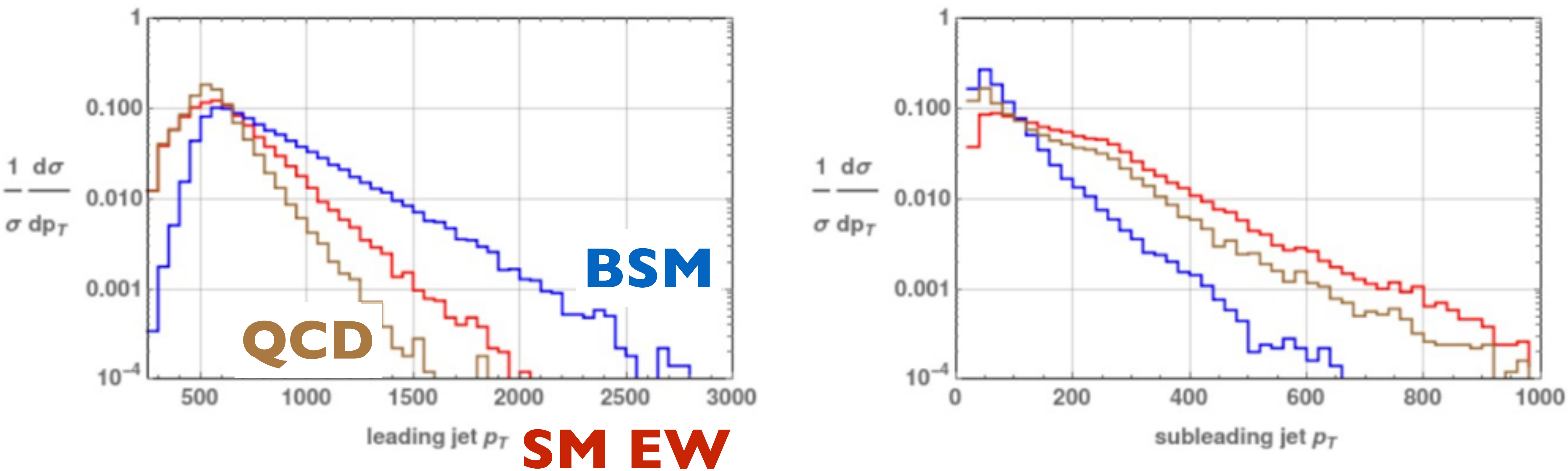
2) VBF is sensitive to the same operators as diboson

Diboson has the same diagrams as the 2->2 channel rotated 90 degrees

3) It is possible to completely reconstruct final state

Implement cuts on CM Energy + cuts to increase sensitivity (angular distr)

First naive attempt: Separating of soft vs hard processes

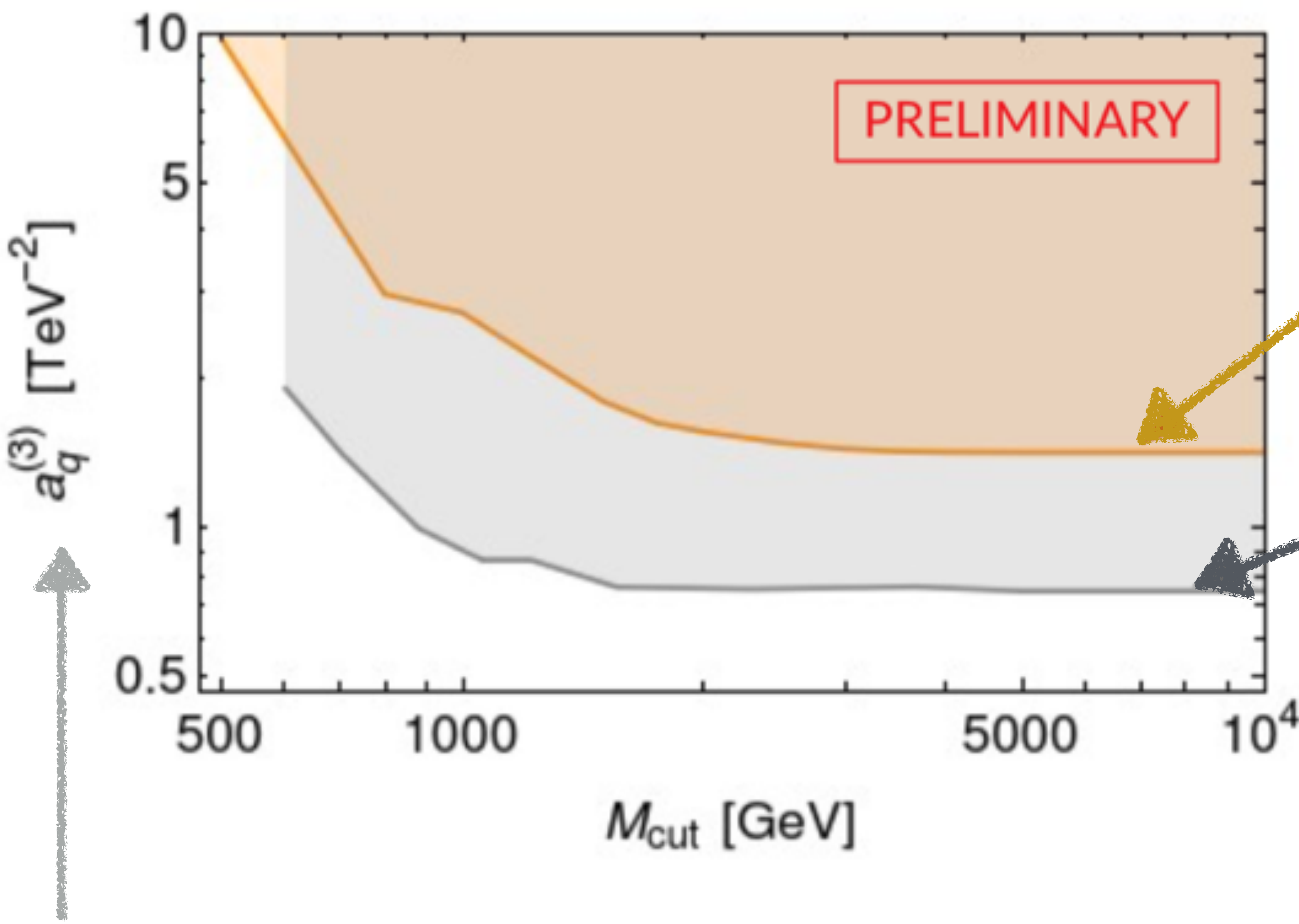


We can define a jet imbalance variable given by:

$$\mathcal{I}p_{T,jj} = \frac{|p_{T,j_1} - p_{T,j_2}|}{p_{T,j_1} + p_{T,j_2}}$$

which we checked has a good discriminating power between signal and bkg

Comparing to other works with cuts that increase sensitivity

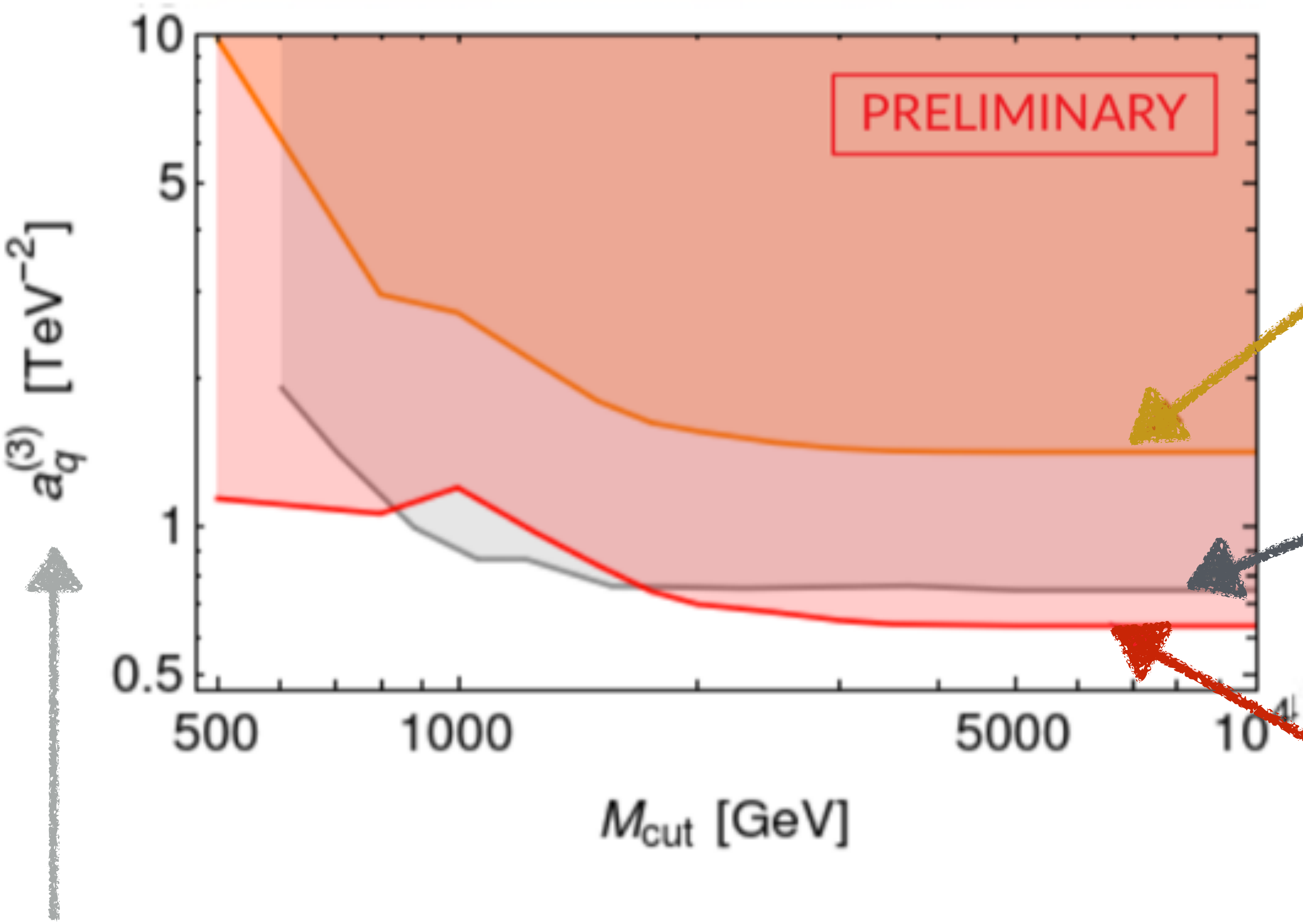


CMS VBF analysis adding CM E cuts only

1712.01310 (WZ with run1 data)

Wilson coefficient in the Warsaw basis

Comparing to other works with cuts that increase sensitivity



CMS VBF analysis adding CM E cuts only

1712.01310 (WZ with run1 data)

VBF using jet imbalance and CM E cuts

Wilson coefficient in the Warsaw basis

- **Simple analysis already very powerful**

  Increased sensitivity and range to lower scales

- Possibility to further improve it with angular distributions, BDT

Conclusions

1) CMS and ATLAS aTGC fits will need to include Zqq corrections soon

- At least under the MFV or FU assumptions

2) Diboson @ LHC can improve the LEP bounds on the Zqq corrections

- Need of further study with other channels and more sensitive cuts
- Would be interesting if CMS and ATLAS would try to do it

3) New possibilities to test diboson operators with VBF

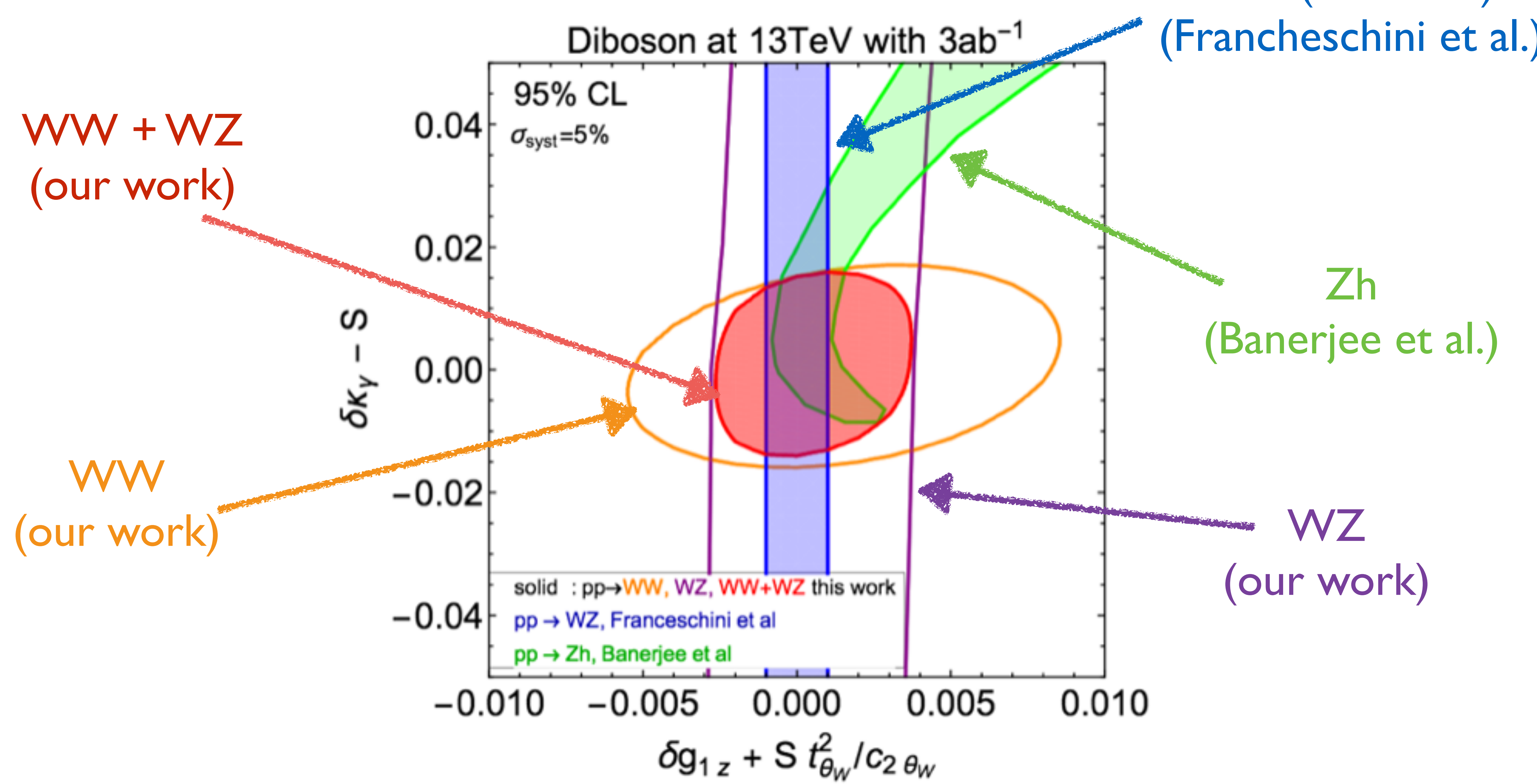
- Results hopefully coming soon

Thanks

We studied WW, WZ channels using the same cuts as CMS/ATLAS

Possible to improve bounds with other cuts/channels

aTGC @ HL-LHC



- **Wh** hasn't been studied in detail yet.
- Preliminary results seem competitive (ongoing work)

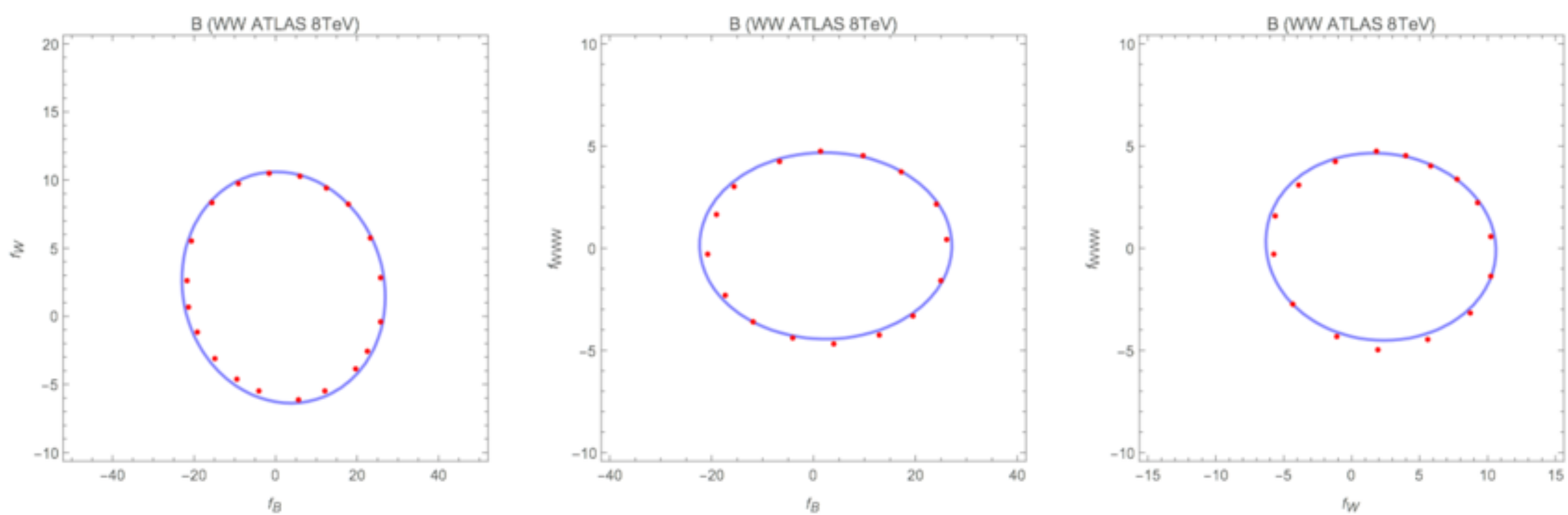
Used MadGraph5_aMC@NLO to get BSM cross section and fit

- 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]

Interpreting the bounds

In these fits, the quadratic pieces are non-negligible

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

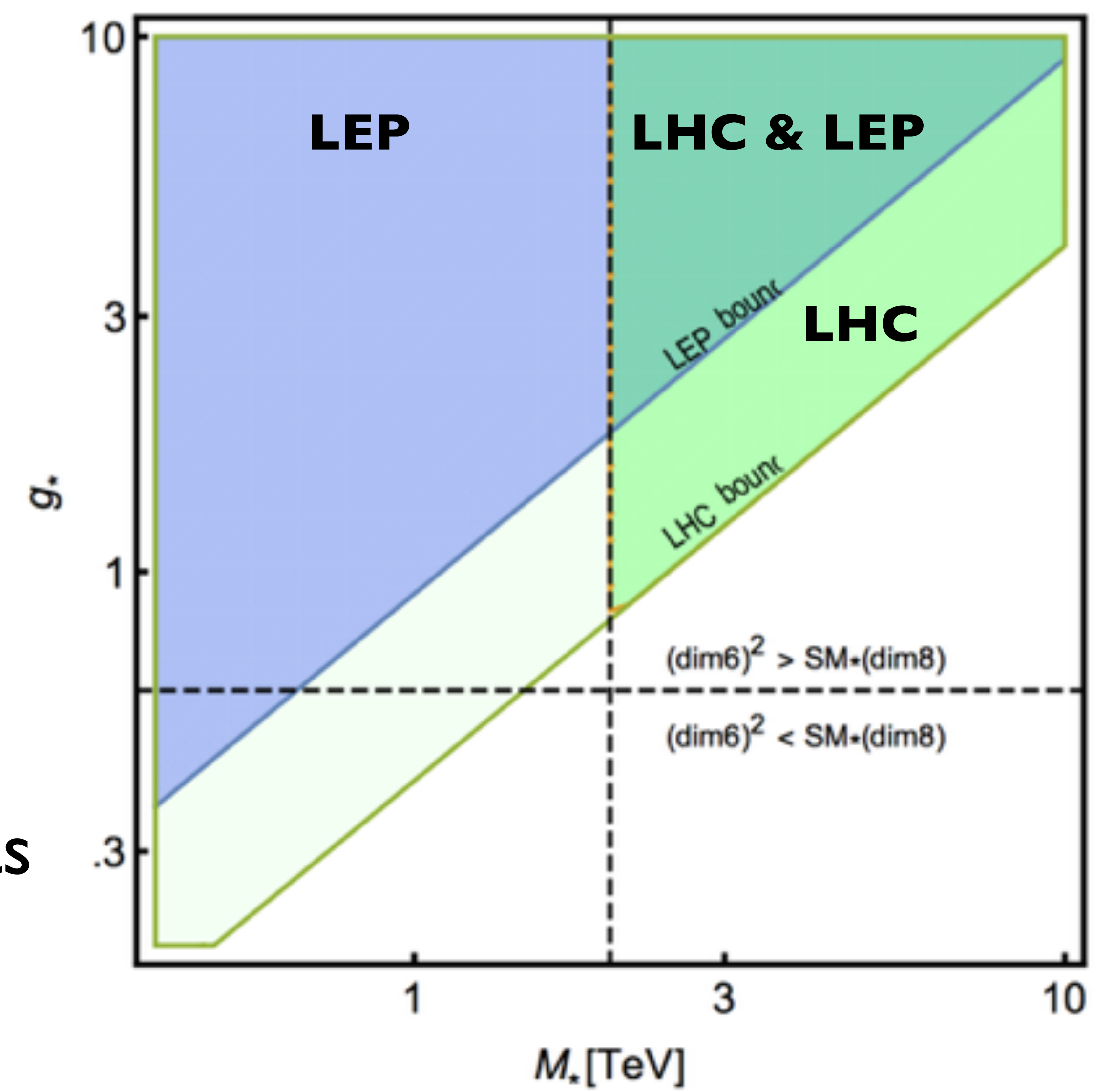
so they are of the same order as dim 8

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

Need of power counting to ensure:

1) dimension 8 are negligible

2) physical mass larger than Energy events



strong

weak

EFT not-OK EFT OK

At dimension six

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

59 operators (Flavour Universality)

$1: X^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
Q_W	$\epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$
$Q_{\widetilde W}$	$\epsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$

$2: H^6$	
Q_H	$(H^\dagger H)^3$

$3: H^4 D^2$	
$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
Q_{HD}	$\left(H^\dagger D_\mu H\right)^* \left(H^\dagger D_\mu H\right)$

$5: \psi^2 H^3 + \mathrm{h.c.}$	
Q_{eH}	$(H^\dagger H)(\bar l_p e_r H)$
Q_{uH}	$(H^\dagger H)(\bar q_p u_r \widetilde H)$
Q_{dH}	$(H^\dagger H)(\bar q_p d_r H)$

$4: X^2 H^2$	
Q_{HG}	$H^\dagger H\, G^A_{\mu\nu} G^{A\mu\nu}$
$Q_{H\widetilde G}$	$H^\dagger H\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$
Q_{HW}	$H^\dagger H\, W^I_{\mu\nu} W^{I\mu\nu}$
$Q_{H\widetilde W}$	$H^\dagger H\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$
Q_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$
$Q_{H\widetilde B}$	$H^\dagger H\, \widetilde B_{\mu\nu} B^{\mu\nu}$
Q_{HWB}	$H^\dagger \tau^I H\, W^I_{\mu\nu} B^{\mu\nu}$
$Q_{H\widetilde W B}$	$H^\dagger \tau^I H\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$

$6: \psi^2 X H + \mathrm{h.c.}$	
Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r) \tau^I H W^I_{\mu\nu}$
Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r) H B_{\mu\nu}$
Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r) \widetilde H\, G^A_{\mu\nu}$
Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r) \tau^I \widetilde H\, W^I_{\mu\nu}$
Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r) \widetilde H\, B_{\mu\nu}$
Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r) H\, G^A_{\mu\nu}$
Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r) \tau^I H\, W^I_{\mu\nu}$
Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r) H\, B_{\mu\nu}$

$7: \psi^2 H^2 D$	
$Q_{Hl}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar l_p \gamma^\mu l_r)$
$Q_{Hl}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar l_p \tau^I \gamma^\mu l_r)$
Q_{He}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar e_p \gamma^\mu e_r)$
$Q_{Hq}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar q_p \gamma^\mu q_r)$
$Q_{Hq}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar q_p \tau^I \gamma^\mu q_r)$
Q_{Hu}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar u_p \gamma^\mu u_r)$
Q_{Hd}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar d_p \gamma^\mu d_r)$
Q_{Hud} + h.c.	$i(\widetilde H^\dagger D_\mu H)(\bar u_p \gamma^\mu d_r)$

$8: (\bar L L)(\bar L L)$	
Q_{ll}	$(\bar l_p \gamma_\mu l_r)(\bar l_s \gamma^\mu l_t)$
$Q_{qq}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar q_s \gamma^\mu q_t)$
$Q_{qq}^{(3)}$	$(\bar q_p \gamma_\mu \tau^I q_r)(\bar q_s \gamma^\mu \tau^I q_t)$
$Q_{lq}^{(1)}$	$(\bar l_p \gamma_\mu l_r)(\bar q_s \gamma^\mu q_t)$
$Q_{lq}^{(3)}$	$(\bar l_p \gamma_\mu \tau^I l_r)(\bar q_s \gamma^\mu \tau^I q_t)$

$8: (\bar R R)(\bar R R)$	
Q_{ee}	$(\bar e_p \gamma_\mu e_r)(\bar e_s \gamma^\mu e_t)$
Q_{uu}	$(\bar u_p \gamma_\mu u_r)(\bar u_s \gamma^\mu u_t)$
Q_{dd}	$(\bar d_p \gamma_\mu d_r)(\bar d_s \gamma^\mu d_t)$
Q_{eu}	$(\bar e_p \gamma_\mu e_r)(\bar u_s \gamma^\mu u_t)$
Q_{ed}	$(\bar e_p \gamma_\mu e_r)(\bar d_s \gamma^\mu d_t)$
$Q_{ud}^{(1)}$	$(\bar u_p \gamma_\mu u_r)(\bar d_s \gamma^\mu d_t)$
$Q_{ud}^{(8)}$	$(\bar u_p \gamma_\mu T^A u_r)(\bar d_s \gamma^\mu T^A d_t)$

$8: (\bar L L)(\bar R R)$	
Q_{le}	$(\bar l_p \gamma_\mu l_r)(\bar e_s \gamma^\mu e_t)$
Q_{lu}	$(\bar l_p \gamma_\mu l_r)(\bar u_s \gamma^\mu u_t)$
Q_{ld}	$(\bar l_p \gamma_\mu l_r)(\bar d_s \gamma^\mu d_t)$
Q_{qe}	$(\bar q_p \gamma_\mu q_r)(\bar e_s \gamma^\mu e_t)$
$Q_{qu}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar u_s \gamma^\mu u_t)$
$Q_{qu}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar u_s \gamma^\mu T^A u_t)$
$Q_{qd}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar d_s \gamma^\mu d_t)$
$Q_{qd}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar d_s \gamma^\mu T^A d_t)$

$8: (\bar L R)(\bar R L) + \mathrm{h.c.}$	
Q_{ledq}	$(\bar l_p^j e_r)(\bar d_s q_{tj})$

$8: (\bar L R)(\bar L R) + \mathrm{h.c.}$	
$Q_{quqd}^{(1)}$	$(\bar q_p^j u_r) \epsilon_{jk} (\bar q_s^k d_t)$
$Q_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r) \epsilon_{jk} (\bar q_s^k T^A d_t)$
$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r) \epsilon_{jk} (\bar q_s^k u_t)$
$Q_{lequ}^{(3)}$	$(\bar l_p^j \sigma_{\mu\nu} e_r) \epsilon_{jk} (\bar q_s^k \sigma^{\mu\nu} u_t)$

Toy Model to get more intuition

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

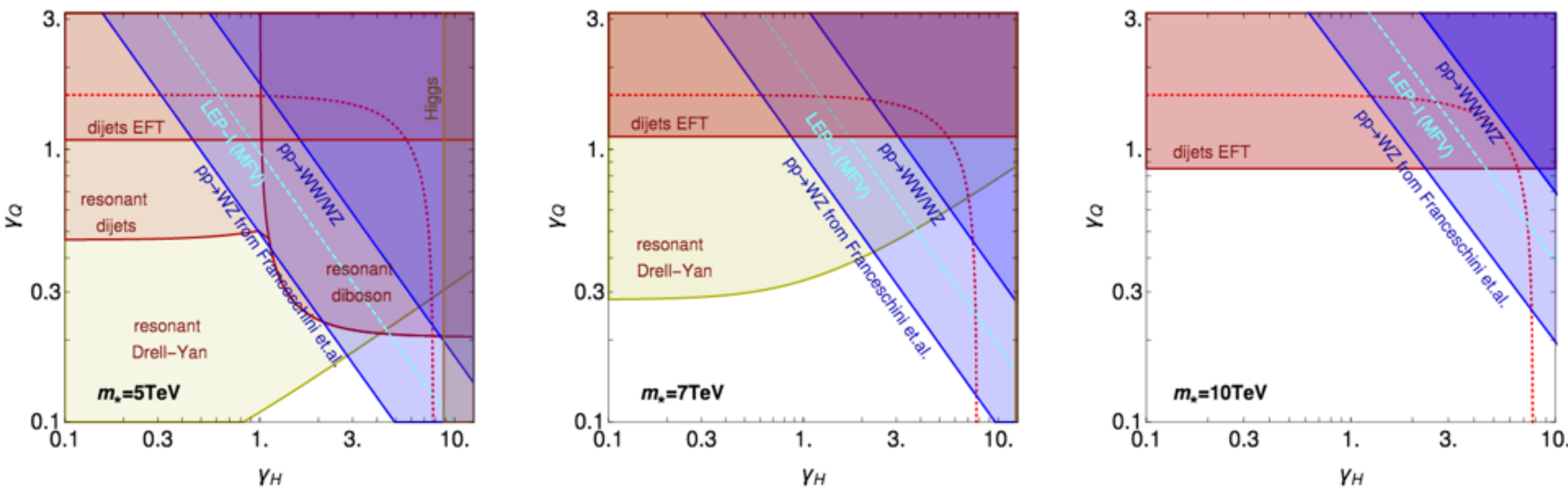


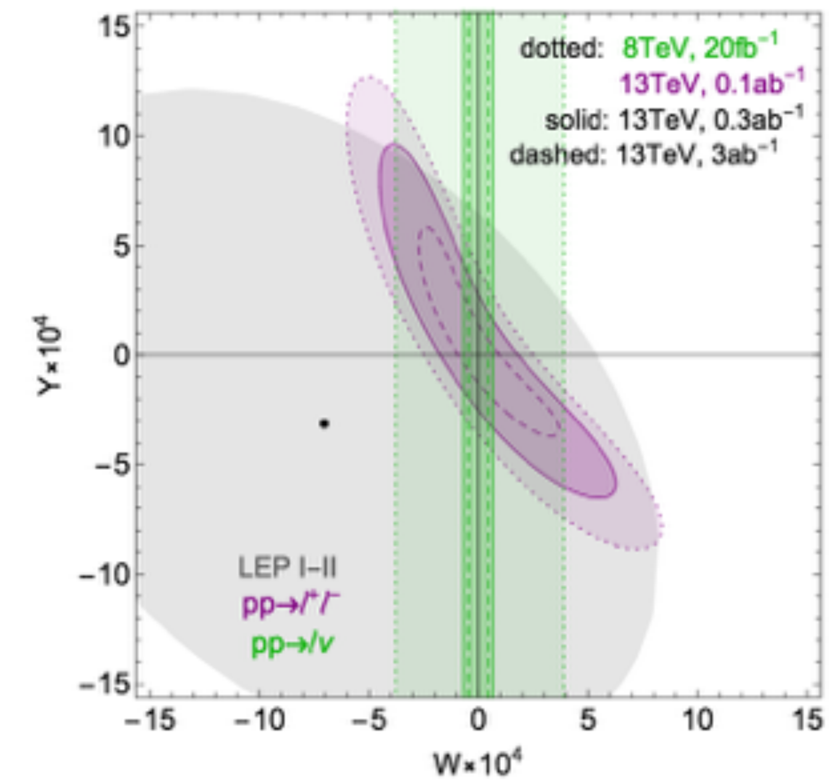
Figure 9: 95% CL exclusion regions in the (γ_H, γ_Q) plane for various values of the resonance masses. In blue, the projected constraints from diboson data at HL-LHC, using our projections (dark shade) or the refined analysis strategy of Ref. [12]. The other constraints come from a recast of the studies in Refs. [21, 60–63] and are commented in detail in the text.

Sensitivity enhancement already used to
expand previous LEP bounds

1) Drell-Yan

Farina et al 1609.08157

Improving LEP bounds on
Universal Parameters W, Y

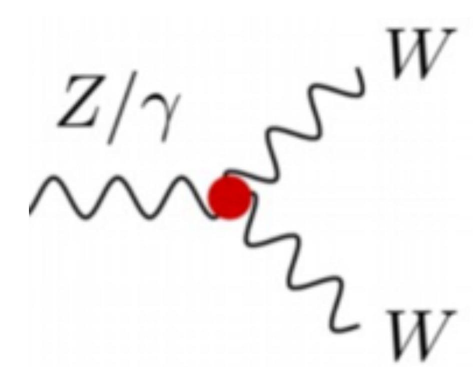


2) Diboson production

Butter et al 1604.03105

Azatov et al 1707.08060

Improving LEP-2 bounds on
anomalous Triple Gauge Couplings



Bounds on Zff anomalous couplins (from LEP)

Flavour Universality

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

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

MFV

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

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

Falkowski et al. 1503.07872

Bounds on aTGC

	LHC Run I				LEP			
	68 % CL	Correlations			68 % CL	Correlations		
Δg_1^Z	$0.010 \pm \underline{0.008}$	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

1) Data used

We chose the most significant leptonic channels

Detector	$\mathcal{L}[\mathrm{fb}^{-1}]$	$\sqrt{s}$	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]