EFT studies of diboson

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Multi-boson interactions, Thessaloniki, Greece, 26-28 of July 2019

Outline

1) Introduction

2) Small review on SMEFT and diboson at High E

3) Work done / ongoing

- **Diboson at LHC vs LEP** (1810.05149)

  with C. Grojean, M. Riembau

- **Study of Wh** (1910.xxxxx)

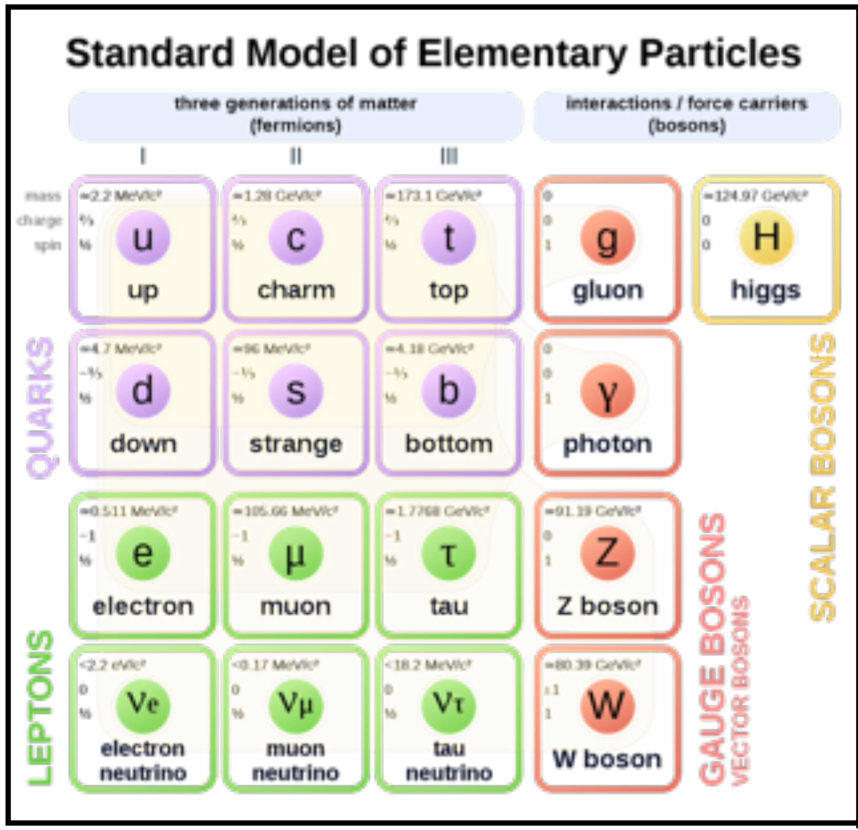
  with F. Bishara, F. Englert, C. Grojean, G. Panico

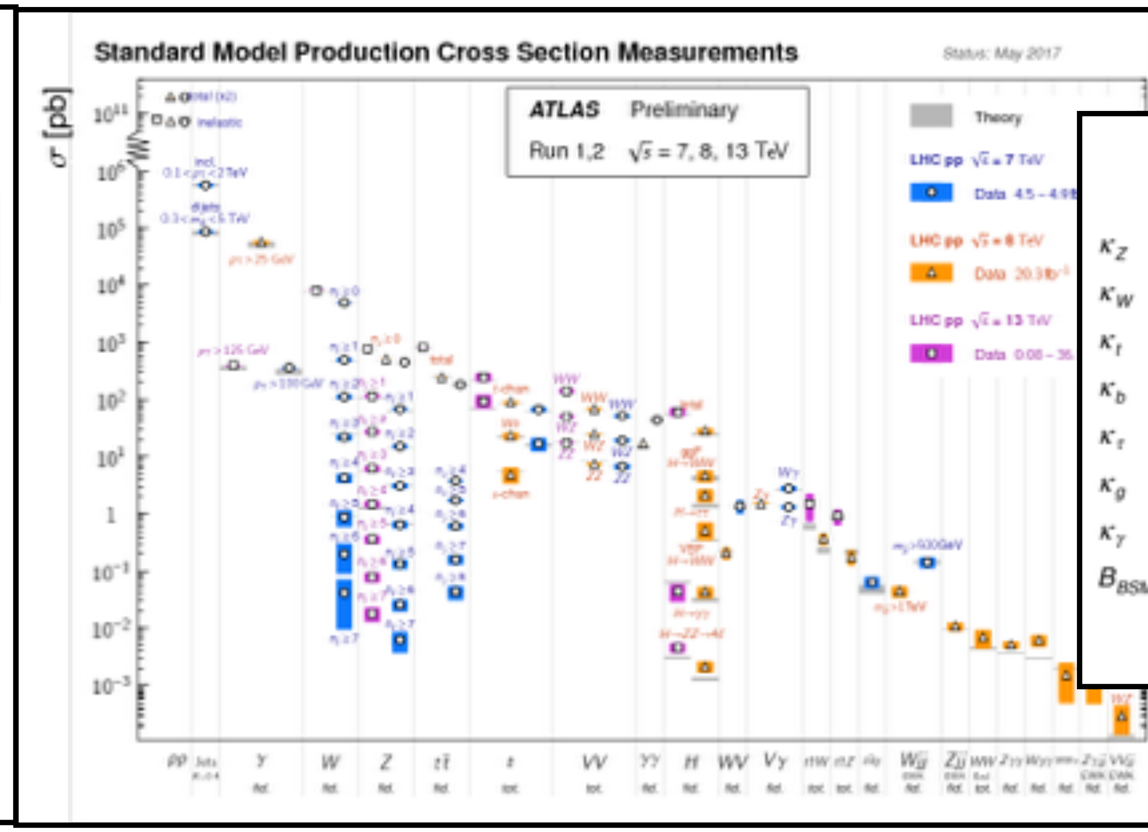
- **Study of Zjj** (1910.xxxxx)

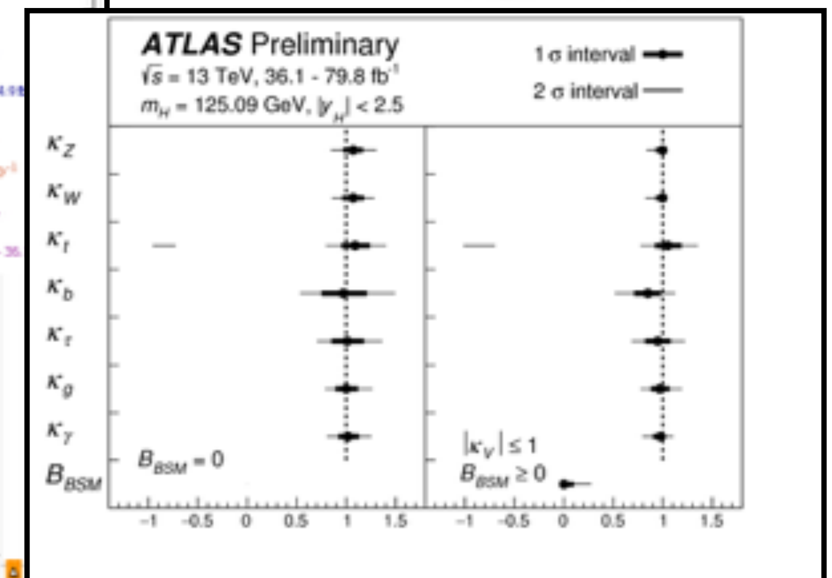
  with G. Durieux, M. Riembau

Introduction

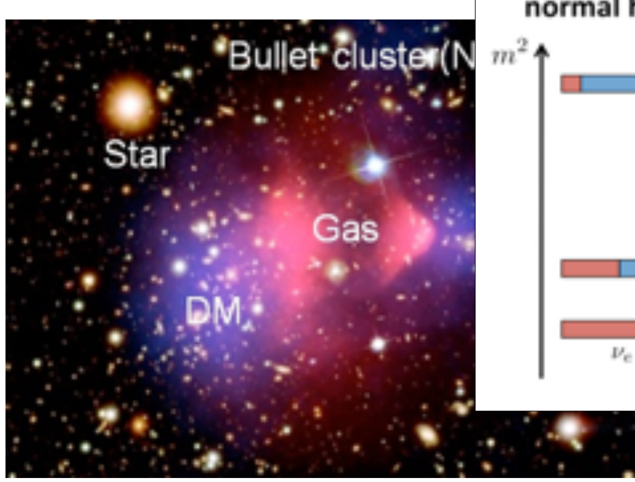
The SM seems complete

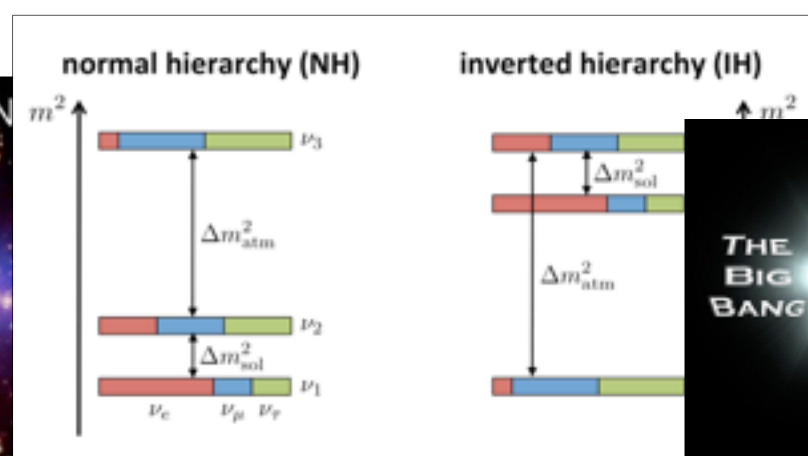


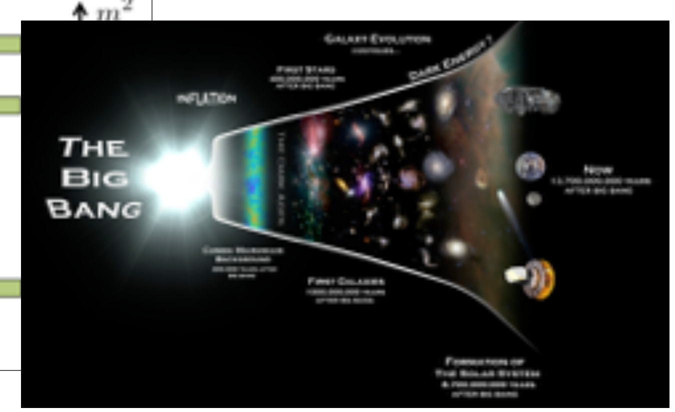


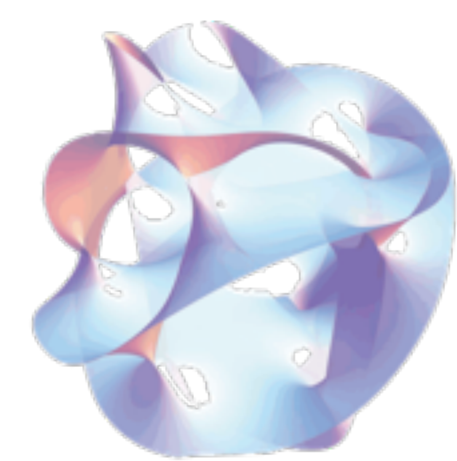


But there are still many things not understood , e.g.









Neutrinos

Inflation

Gravity

DM

Baryon asymmetry

Origin of EWSB

Naturalness

Strong CP-problem

Many of the models addressing the various issues

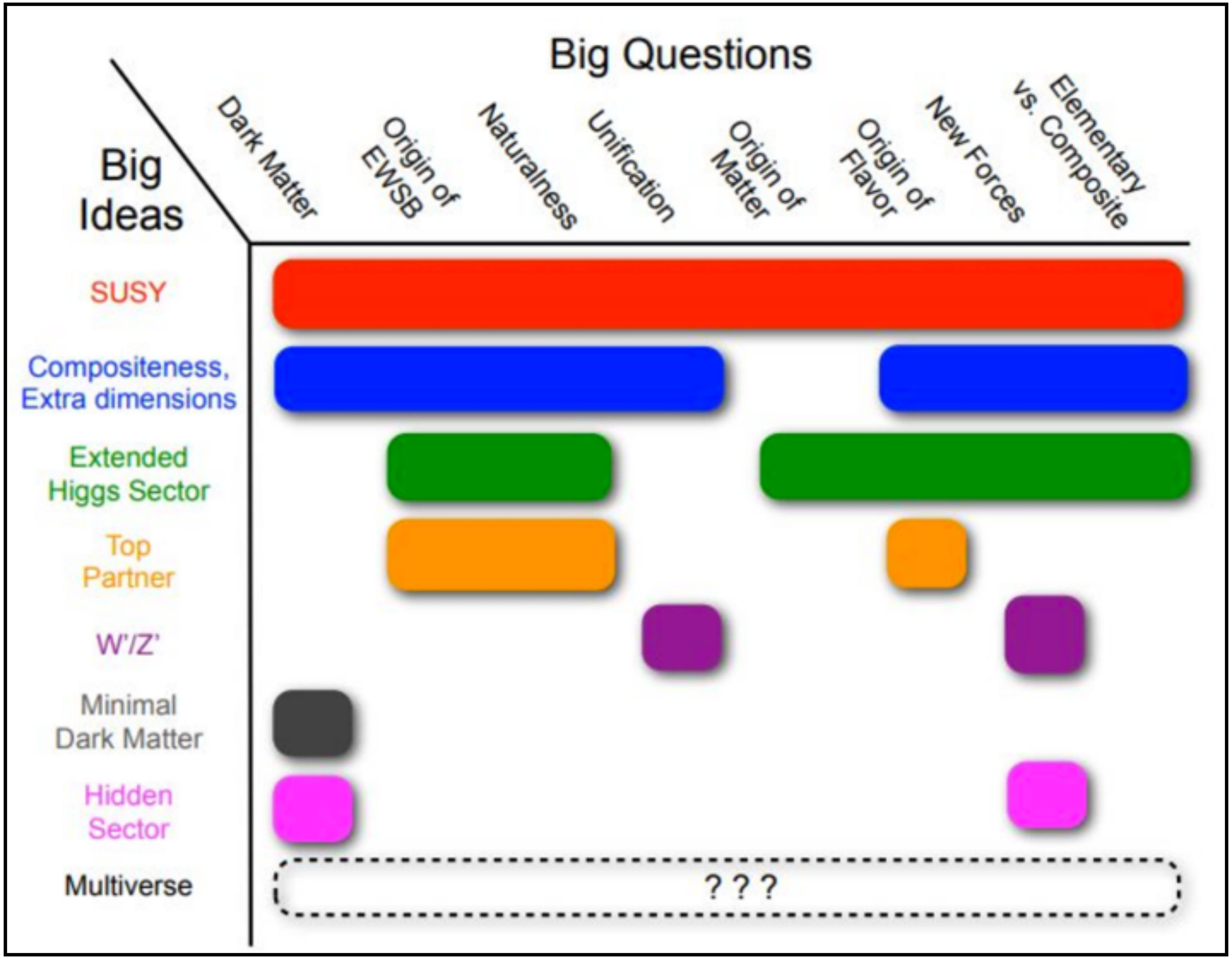
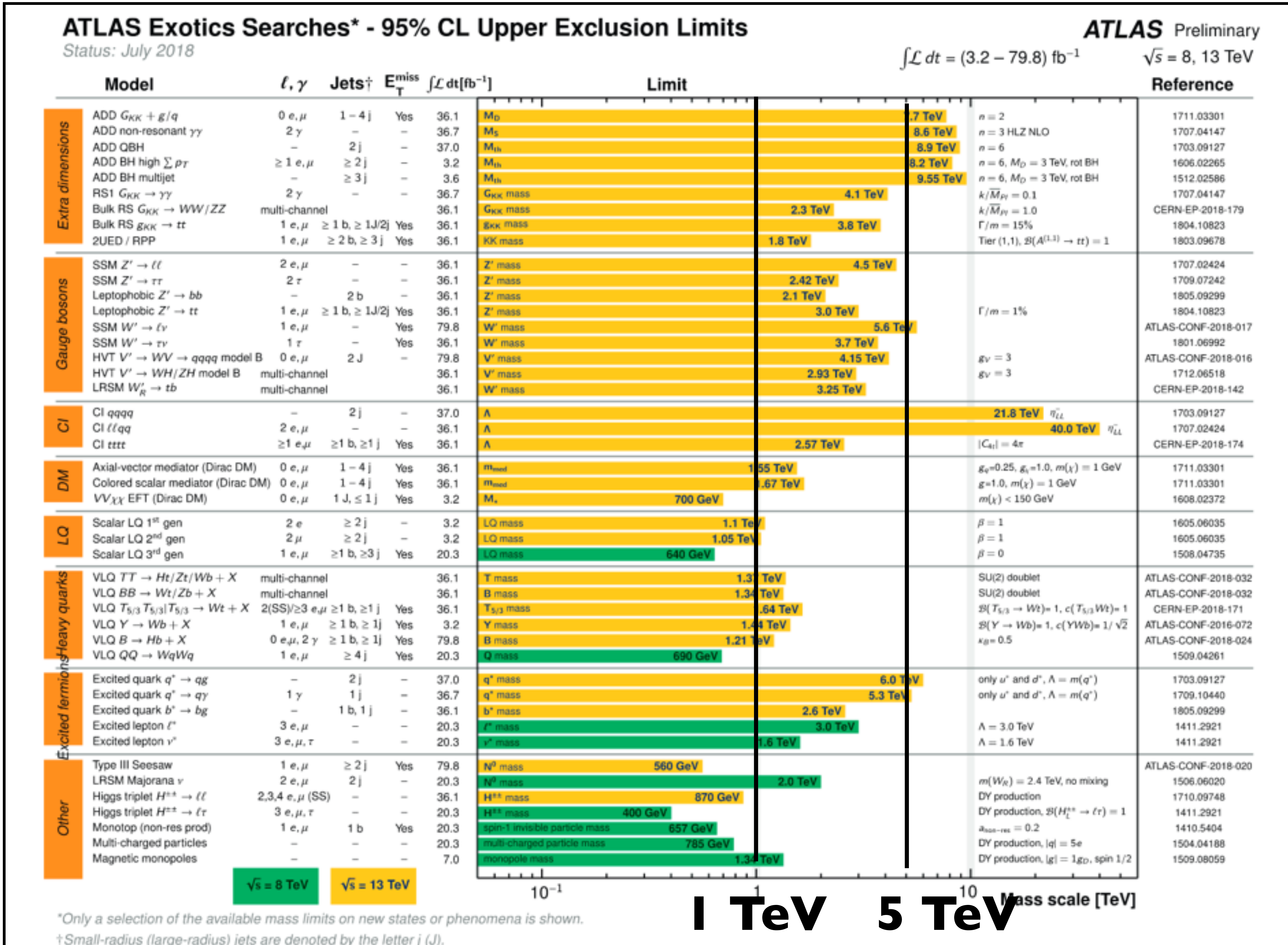


Fig. taken from Adriana Milic's talk

predict new physics at the LHC

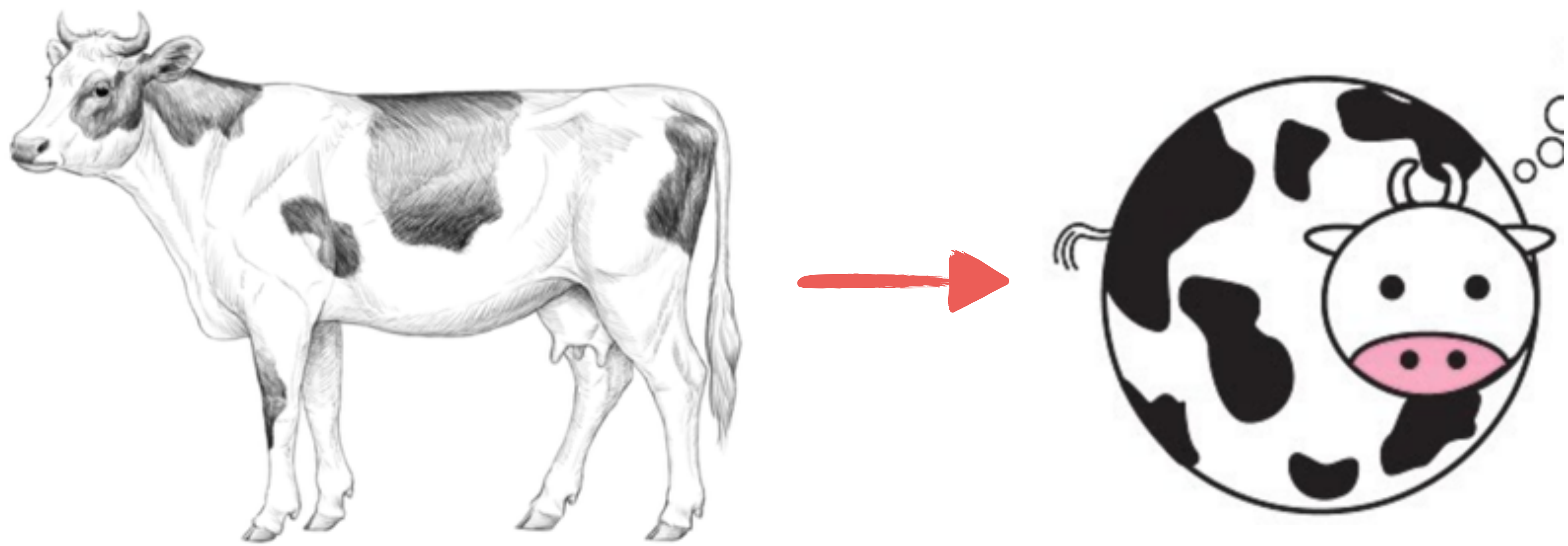
In particular in diboson processes

Nonetheless, the LHC has not found any New Physics yet

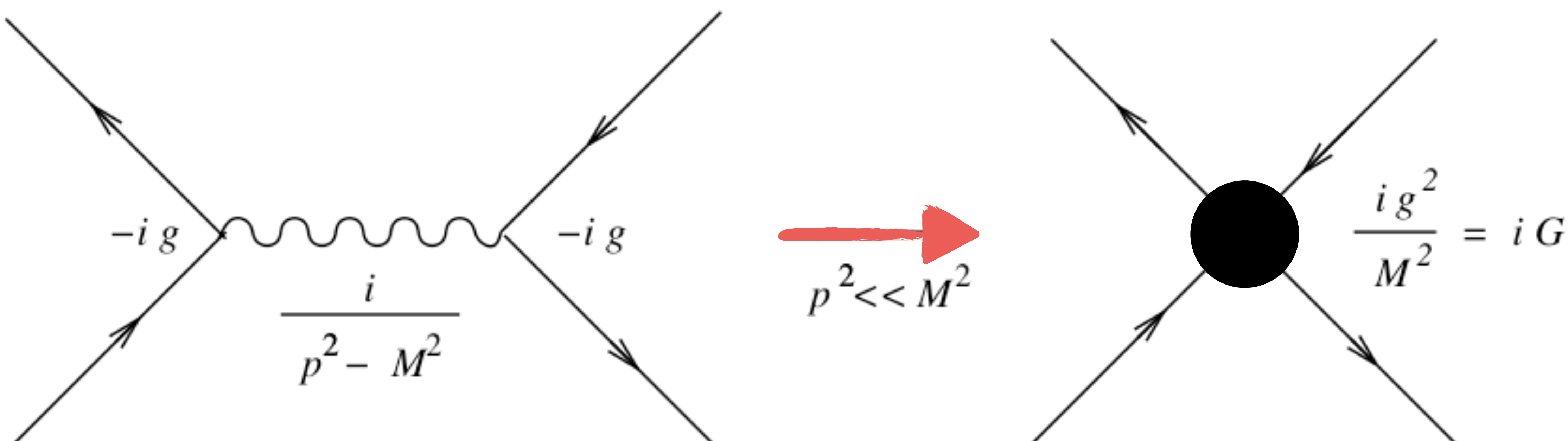


It is plausible then, that New Physics is heavy

In that case we can capture the main NP effects via an EFT



For instance as done in the Fermi theory



Assuming that the Higgs is part of an $SU(2)_L$ doublet: the SM EFT is given by

(assuming no Baryon, nor Lepton number violation)

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

SM **d=6** **d=8**

<u>It is important to remember that when working with EFTs</u>

Bounds on Wilson Coefficients strongly depend on UV assumptions

- **Power counting:** e.g. some operators negligible or zero
- **Flavour assumptions:** e.g. LEP bounds very dependent on this

56 operators at d=6 (1 flavour), **2000+** (no flavours assumptions)

(see 1503.07872)

Given the current status, an important question to ask is:

- What can we expect from the HL-LHC?
- Where can we look for signals of NP?

- **If we go to measurements dominated by systematics**

It may be hard to improve the bounds on the current scale of NP

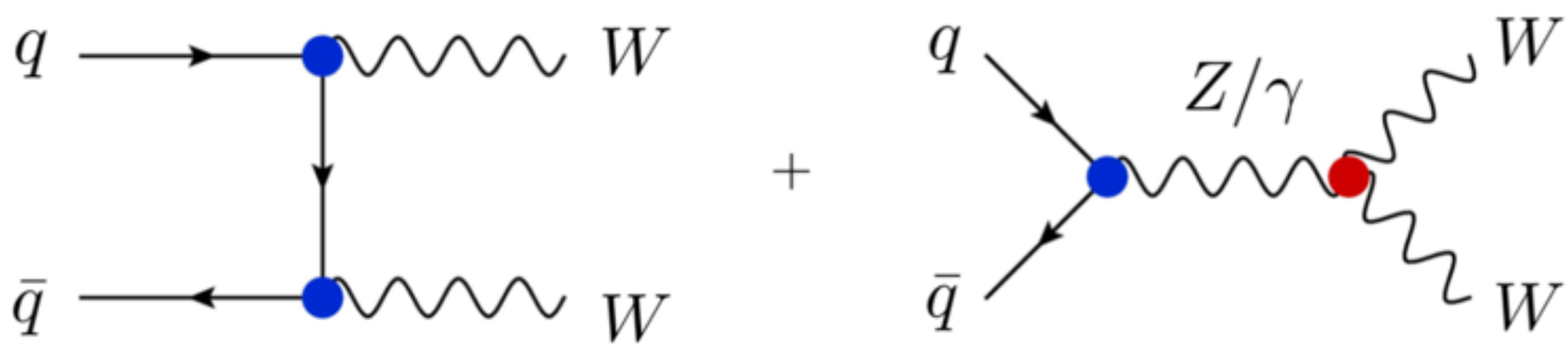
e.g. Errors on anomalous Higgs couplings stuck at the % level due to systematics

Coupling	Uncertainty (%)			
	300 fb^{-1}		3000 fb^{-1}	
	Scenario 1	Scenario 2	Scenario 1	Scenario 2
κ_γ	6.5	5.1	5.4	1.5
κ_V	5.7	2.7	4.5	1.0
κ_g	11	5.7	7.5	2.7
κ_b	15	6.9	11	2.7
κ_t	14	8.7	8.0	3.9
κ_τ	8.5	5.1	5.4	2.0

- If we focus on measurements dominated by statistics

One may be able to improve by a lot the sensitivity to NP

an example of this are diboson processes



t-channel   s-channel

How?

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

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

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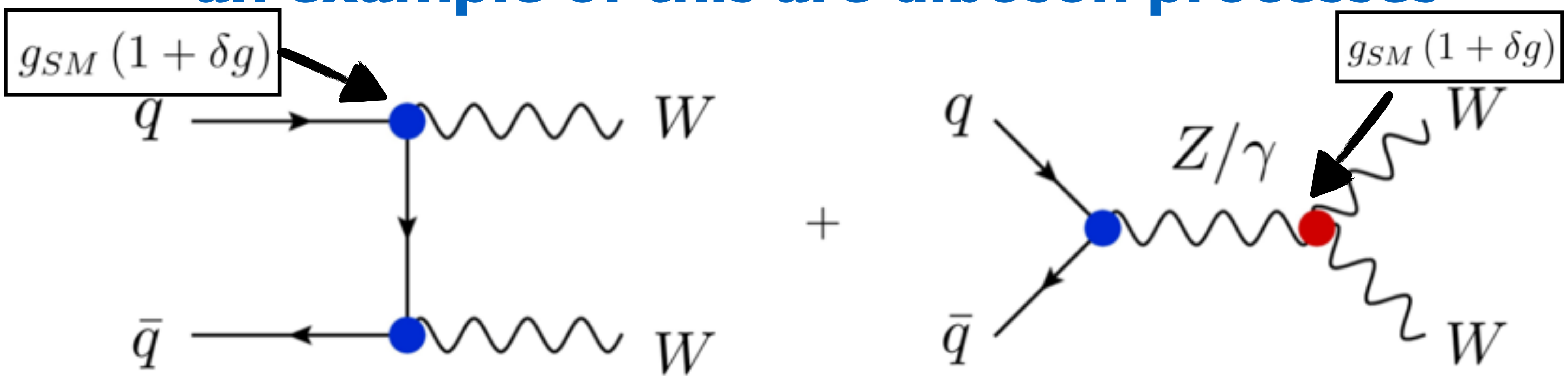

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- In the **SMEFT** the vertices are modified and the cancellations spoiled

Let us see how the BSM Energy growth increases the sensitivity to NP

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

Wilson Coefficient

Take the BSM cross for a given process and parametrize it as

$$\sigma_{BSM} = \sigma_{SM} + \delta\sigma$$

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As we have seen:

The **BSM XS** can have **different behaviours w.r.t. the SM in terms of the CME**

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

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

Performing a naive χ^2 fit we find that the bound on the Wilson C. is of order:

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

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

Error in %

What does this formula tell us?

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

If the systematic error $\Delta \sim 10\%,\ E \sim 1\,\mathrm{TeV}$ $\quad \boxed{c_i \lesssim 0.1\%}$

Permille bound $\longleftrightarrow$ **Precision physics at the LHC !!**

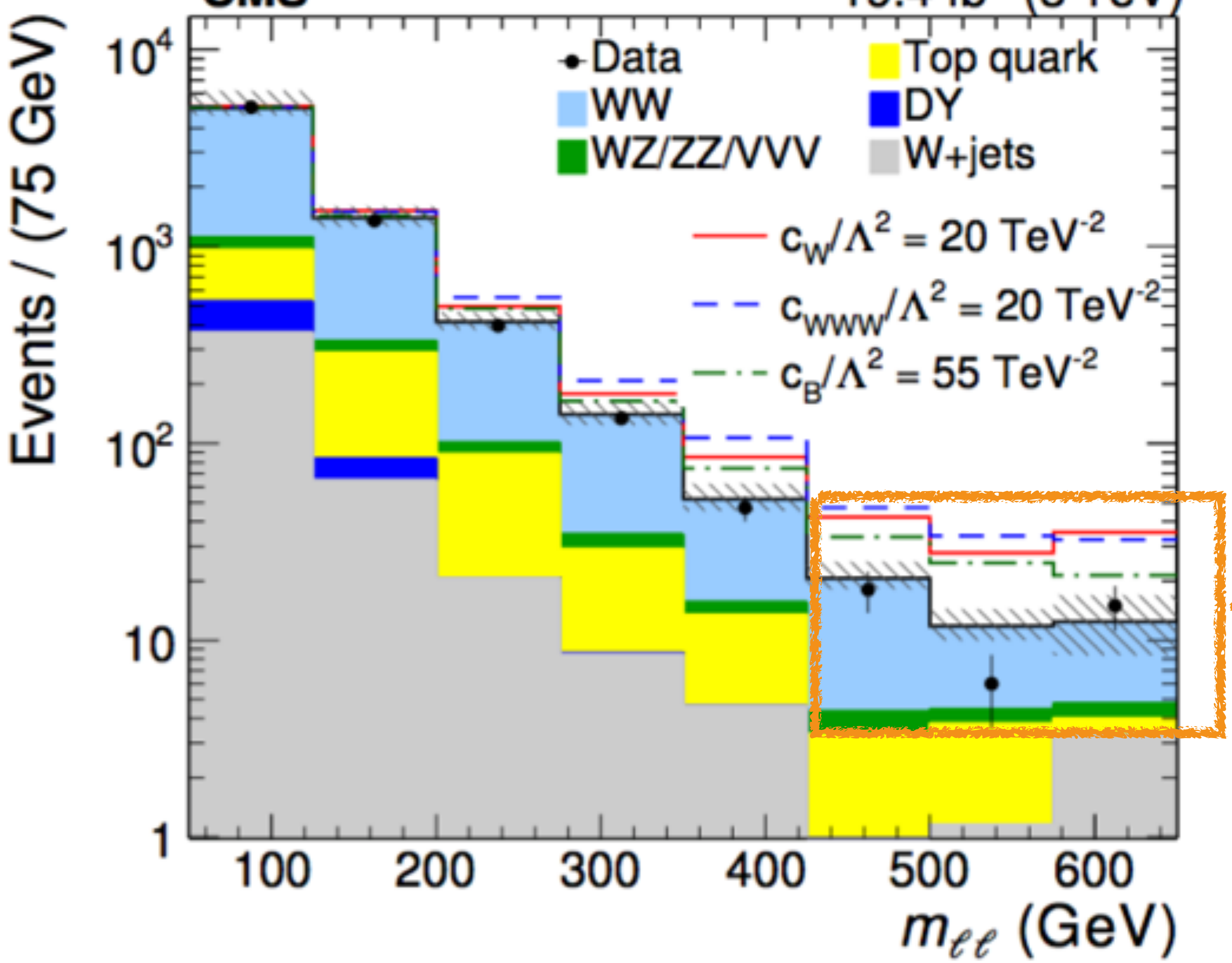
In order for this to be possible we need:

- To look into diff. distributions correlated with $\sqrt{s}$
- Need small systematic errors
- Enough statistics in the tails (where E >> mw)

It is the case, that diboson production satisfies all of these!

1507.03268

$pp \to WW$



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

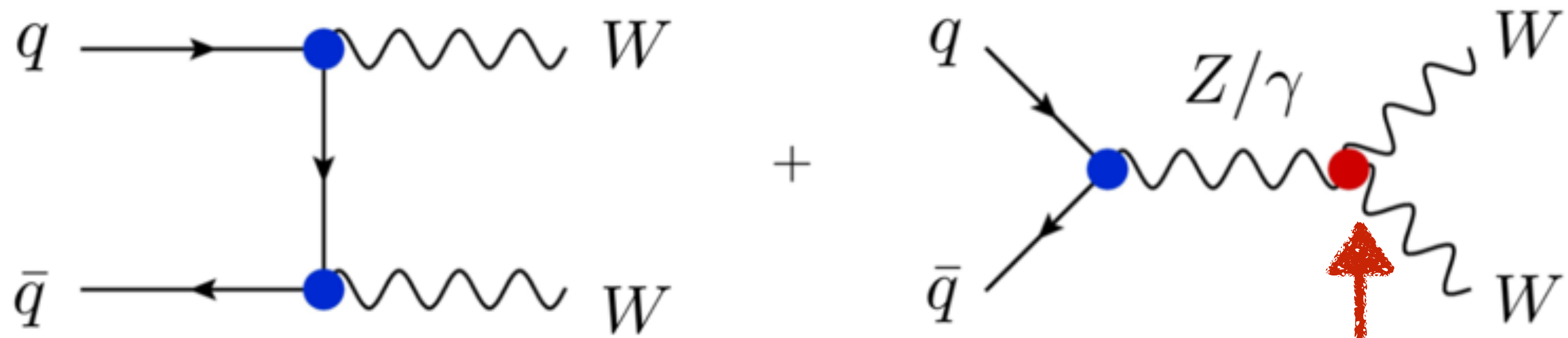
- Diboson interesting because it tests NP related to EWSB

- Hence there has been a lot of activity recently studying the sensitivity of diboson production at the LHC

Small review on the SMEFT and diboson at High E

(mostly charged diboson production WW/WZ/Zh/Wh)

Charged diboson production (WW, WZ, Wa) has traditionally been studied as a prove of the aTGC



Bounds on aTGC

Charged diboson production (WW, WZ, Wa) has traditionally been studied as a prove of the aTGC

The aTGC can be written as deviations of the SM Triple Gauge Couplings

$$\begin{aligned}\mathcal{L}_{\mathrm{TGC}} &= ie\left(W^+_{\mu\nu}W^-_\mu - W^-_{\mu\nu}W^+_\mu\right)A_\nu + ie\left[(1+\boxed{\delta\kappa_\gamma})A_{\mu\nu}\,W^+_\mu W^-_\nu\right] \\ &+ ig\,c_W\left[(1+\boxed{\delta g_{1,z}})\left(W^+_{\mu\nu}W^-_\mu - W^-_{\mu\nu}W^+_\mu\right)Z_\nu + (1+\boxed{\delta\kappa_z})\,Z_{\mu\nu}\,W^+_\mu W^-_\nu\right] \\ &+ i\frac{e}{m_W^2}\boxed{\lambda_\gamma}W^+_{\mu\nu}W^-_{\nu\rho}A_{\rho\mu} + i\frac{g\,c_W}{m_W^2}\boxed{\lambda_z}W^+_{\mu\nu}W^-_{\nu\rho}Z_{\rho\mu}\,.\end{aligned}$$

At d=6 and CP-even $\quad \delta\kappa_z = \delta g_1^z - \tan^2\theta\,\delta\kappa_\gamma \qquad \lambda_z = \lambda_\gamma \quad$ 3 independent aTGC

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At d=6 and CP-even $\delta\kappa_z = \delta g_1^z - \tan^2\theta\,\delta\kappa_\gamma$ $\lambda_z = \lambda_\gamma$ 3 independent aTGC

It was early noticed that the LHC could improve the LEP-2 bounds on the anomalous Triple Gauge Couplings

e.g.

Butter et al. 1604.03105

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

Per mille at LHC !!

Percent at LEP

From this observation various questions arise

1) Why is this happening? Naively hadron colliders less precise…

2) Need to understand the high E behaviour of the SMEFT in diboson production

3) What is the validity of the bounds?

4) Can these bounds be improved?

5) To what theories do they apply?

6) What is the interplay between LEP-1 and aTGC?

Incomplete list works addressing these questions (see refs therein)

- Anomalous Triple Gauge Couplings in the EFT Approach at the LHC — Falkowski et al. 1609.06312
- Novel measurements of anomalous triple gauge couplings for the LHC — Azatov et al. 1707.08060
- Probing Electroweak Precision Physics via boosted Higgs-strahlung at the LHC — Gupta et al. 1707.08060
- An NLO QCD effective field theory analysis of W^+W^- production at the LHC including fermionic operators — Baglio et al. 1708.03332
- Diboson Interference Resurrection — Riva et al. 1708.07823
- Electroweak Precision Tests in High-Energy Diboson Processes — Pomarol et al. 1712.01310
- Prospects for precision measurement of diboson processes in the semileptonic decay channel in future LHC runs — Liu et al. 1804.08688
- New phenomenological and theoretical perspective on anomalous ZZ and Zγ processes — Bellazzini et al. 1806.09640
- Diboson at the LHC vs LEP — MM et al. 1810.05149
- Precision diboson measurements at hadron colliders — Azatov et al. 1901.04821
- Resolving the tensor structure of the Higgs coupling to Z-bosons via Higgs-strahlung — Gupta et al. 1905.02728
- Exploring SMEFT in VH with Machine Learning — Freitas et al. 1902.05803

I) Why is this happening? Naively hadron colliders less precise…

This we saw in previous slides

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

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

Error in %

2) Behaviour of the SMEFT at High E for diboson production

One can choose a particular SMEFT basis and check the high Energy behaviour of the different operators entering diboson

$\mathcal{O}_i$	$\sigma_{SM\times dim_6}/(g_{SM}^4/E^2)$	$\sigma_{dim_6^2}/(g_{SM}^4/E^2)$
F^3	$\frac{c_1}{g_{SM}}\frac{m_W^2}{\Lambda^2}$	$\frac{c_1^2}{g_{SM}^2}\frac{E^4}{\Lambda^4}$
$\phi^2 F^2$	$\frac{c_2}{g_{SM}^2}\frac{m_W^2}{\Lambda^2}$	$\frac{c_2^2}{g_{SM}^4}\frac{m_W^2 E^2}{\Lambda^4}$
$(\phi D\phi)^2$	$\frac{c_3}{g_{SM}^2}\frac{m_W^2}{\Lambda^2}$	$\frac{c_3^2}{g_{SM}^4}\frac{m_W^4}{\Lambda^4}$
$\bar{\psi}\gamma\psi\,\phi D\phi$	$\frac{c_4}{g_{SM}^2}\frac{E^2}{\Lambda^2}$	$\frac{c_4^2}{g_{SM}^4}\frac{E^4}{\Lambda^4}$

SM x BSM   BSM x BSM

Falkowski et al. 1609.06312

From these behaviours one can also check:

-The behaviour of each helicity final state with the Energy

- How many and which combinations of operators contribute to each helicity

Following the first question:
one can find that the SM and SMEFT leading behaviours for each helicity are:

	SM	BSM
$q_{L,R}\bar{q}_{L,R} \to V_L V_L(h)$	~ 1	$\sim E^2/M^2$
$q_{L,R}\bar{q}_{L,R} \to V_\pm V_L(h)$	$\sim m_W/E$	$\sim m_W E/M^2$
$q_{L,R}\bar{q}_{L,R} \to V_\pm V_\pm$	$\sim m_W^2/E^2$	$\sim E^2/M^2$
$q_{L,R}\bar{q}_{L,R} \to V_\pm V_\mp$	~ 1	~ 1

Pomarol et al.
1712.01310

Given a generic SMEFT amplitude, one has:

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

If interference term dominates → Leading: SM x BSM = LL → E^2/M^2

If quadratic term dominates → Leading: BSM x BSM = LL, TT → E^4/M^4

Notice: Interference terms for transverse final states not enhanced by E
(non-interference effects, see Riva et al. 1607.05236)

One can also check that only **5 combinations of SMEFT operators** modify the amplitudes of the following processes at high energies

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

Amplitude	High-energy primaries	Low-energy primaries
$\bar{u}_L d_L \to W_L Z_L, W_L h$	$\sqrt{2} a_q^{(3)}$	$\sqrt{2}\frac{g^2}{m_W^2}\left[c_{\theta_W}(\delta g_{uL}^Z - \delta g_{dL}^Z)/g - c_{\theta_W}^2 \delta g_1^Z\right]$
$\bar{u}_L u_L \to W_L W_L$ $\bar{d}_L d_L \to Z_L h$	$a_q^{(1)} + a_q^{(3)}$	$-\frac{2g^2}{m_W^2}\left[Y_L t_{\theta_W}^2 \delta\kappa_\gamma + T_Z^{u_L} \delta g_1^Z + c_{\theta_W} \delta g_{dL}^Z/g\right]$
$\bar{d}_L d_L \to W_L W_L$ $\bar{u}_L u_L \to Z_L h$	$a_q^{(1)} - a_q^{(3)}$	$-\frac{2g^2}{m_W^2}\left[Y_L t_{\theta_W}^2 \delta\kappa_\gamma + T_Z^{d_L} \delta g_1^Z + c_{\theta_W} \delta g_{uL}^Z/g\right]$
$\bar{f}_R f_R \to W_L W_L, Z_L h$	a_f	$-\frac{2g^2}{m_W^2}\left[Y_{f_R} t_{\theta_W}^2 \delta\kappa_\gamma + T_Z^{f_R} \delta g_1^Z + c_{\theta_W} \delta g_{fR}^Z/g\right]$

4 longitudinal + 1 transverse

Pomarol et al. 1712.01310

Making the measures of WW, WZ, Wh and Zh are complementary

3) What is the validity of the bounds?

3.1) In many cases at the LHC the quadratic pieces of the BSM XS are non-negligible

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

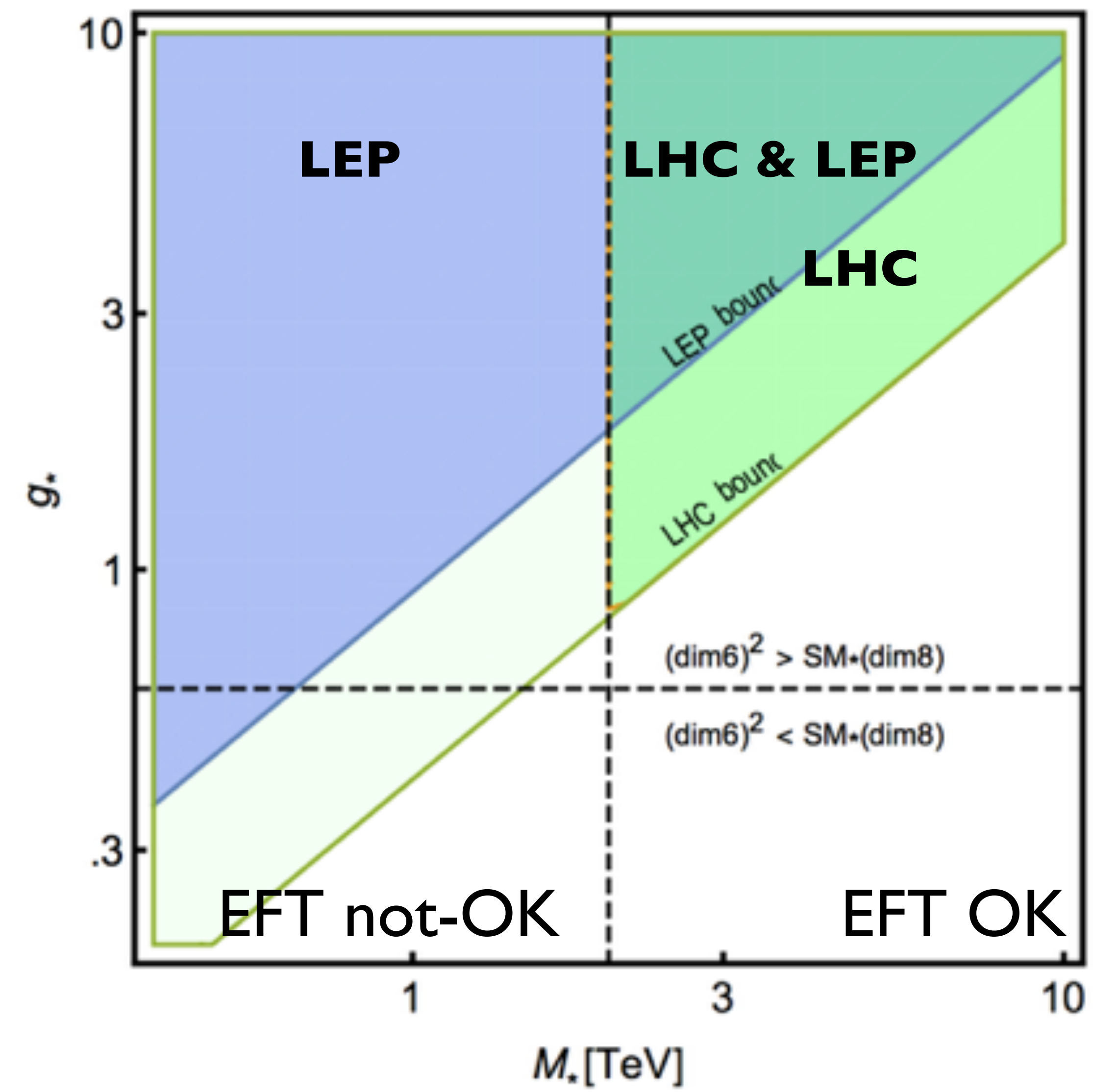
Parametrically of the same order as dim 8, but these not included in the fits

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

Need of power counting to ensure:

dimension 8 are negligible

3.2) Bounds only valid for masses larger than the max CME of any events used



strong

weak

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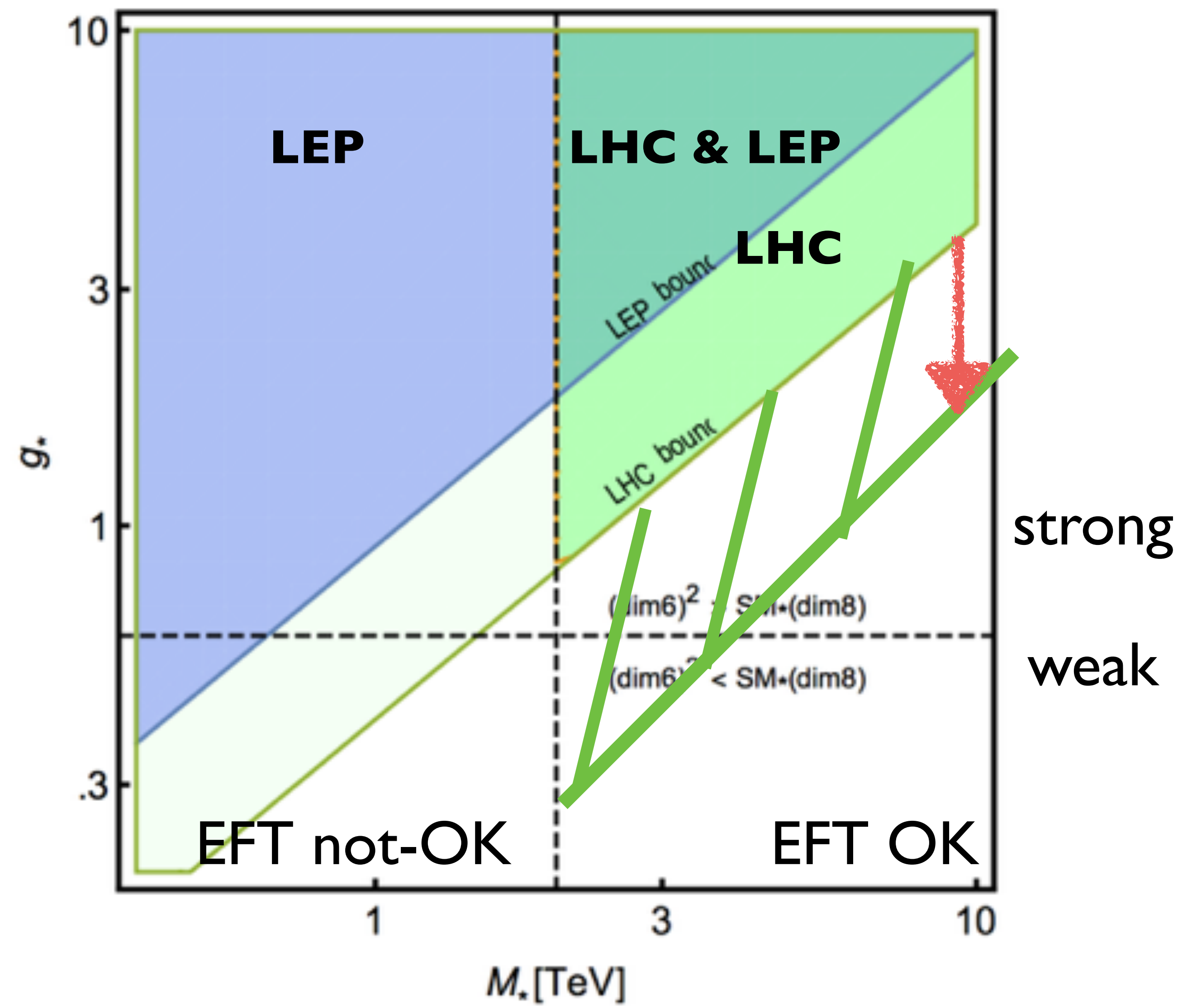

One would like to:

1) Increase the Sensitivity (constrain weakly coupled theories & neglect quad.)

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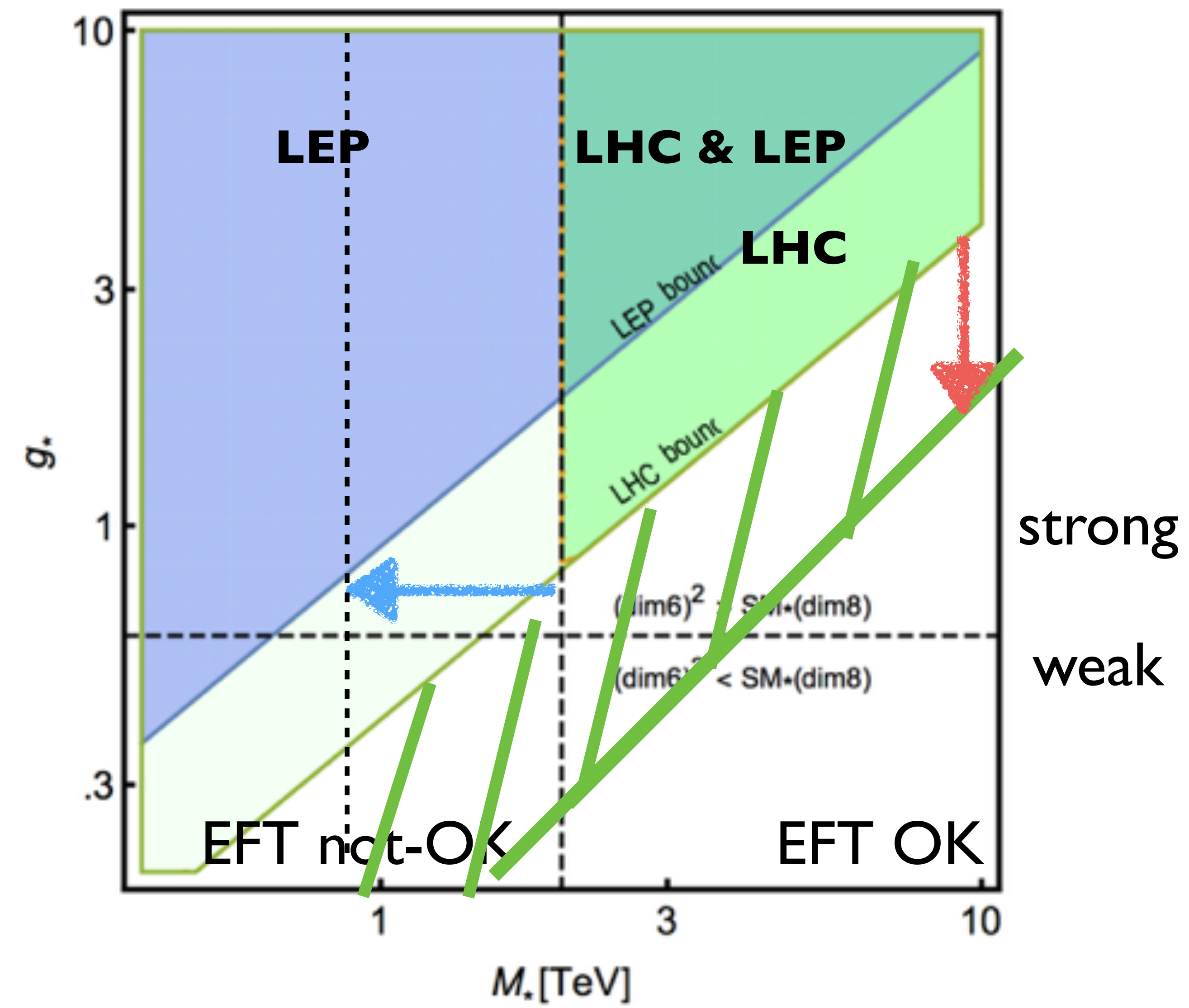

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1) Increase the Sensitivity (constrain weakly coupled theories & neglect quad.)

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

4) Can these bounds be improved?

4.1) To increase the Sensitivity

- Need to find observables with better signal/bkg ratio

- Deal with non-interference effects

4.2) To lower the cutoff (increase range of the bounds)

- Need a way to reconstruct the final states 4-momenta

and only use events in the fit with $\sqrt{s} \ll M$

(conservative approximations possible if exact 4-momenta not available)

4.1) Some work has already been done to improve the diboson sensitivity

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)
+ …

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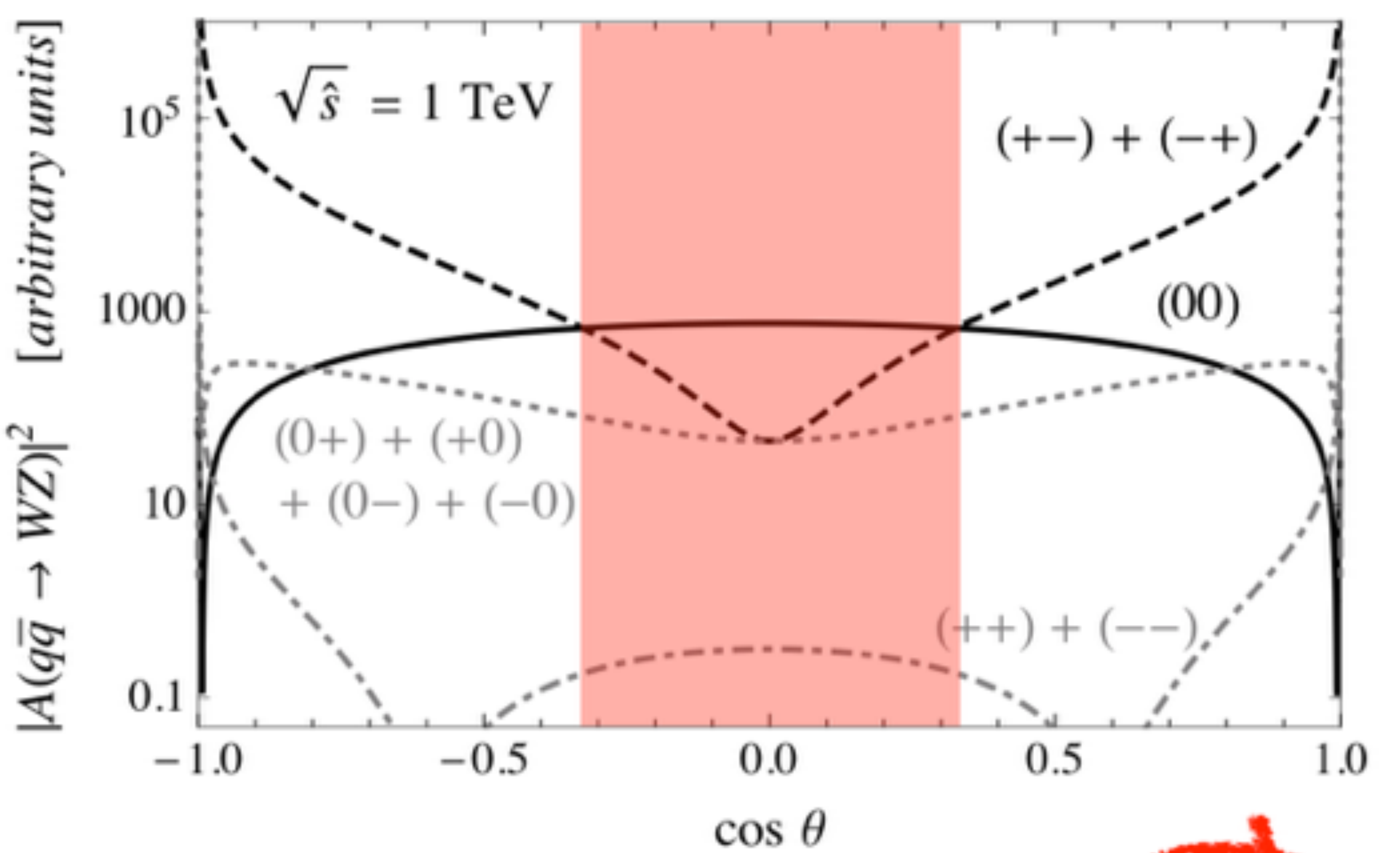
+ ...

Concrete example: Franceschini et al. (1712.01310)



13 TeV		σ_{tot}	σ_{LL}	σ_{LL}/σ_{tot}
$\lvert\cos\theta\rvert < 0.5$	$\sqrt{\hat{s}} > 300$ GeV	630 fb	230 fb	37%
$\lvert\cos\theta\rvert < 0.5$	$\sqrt{\hat{s}} > 500$ GeV	80 fb	34 fb	42%

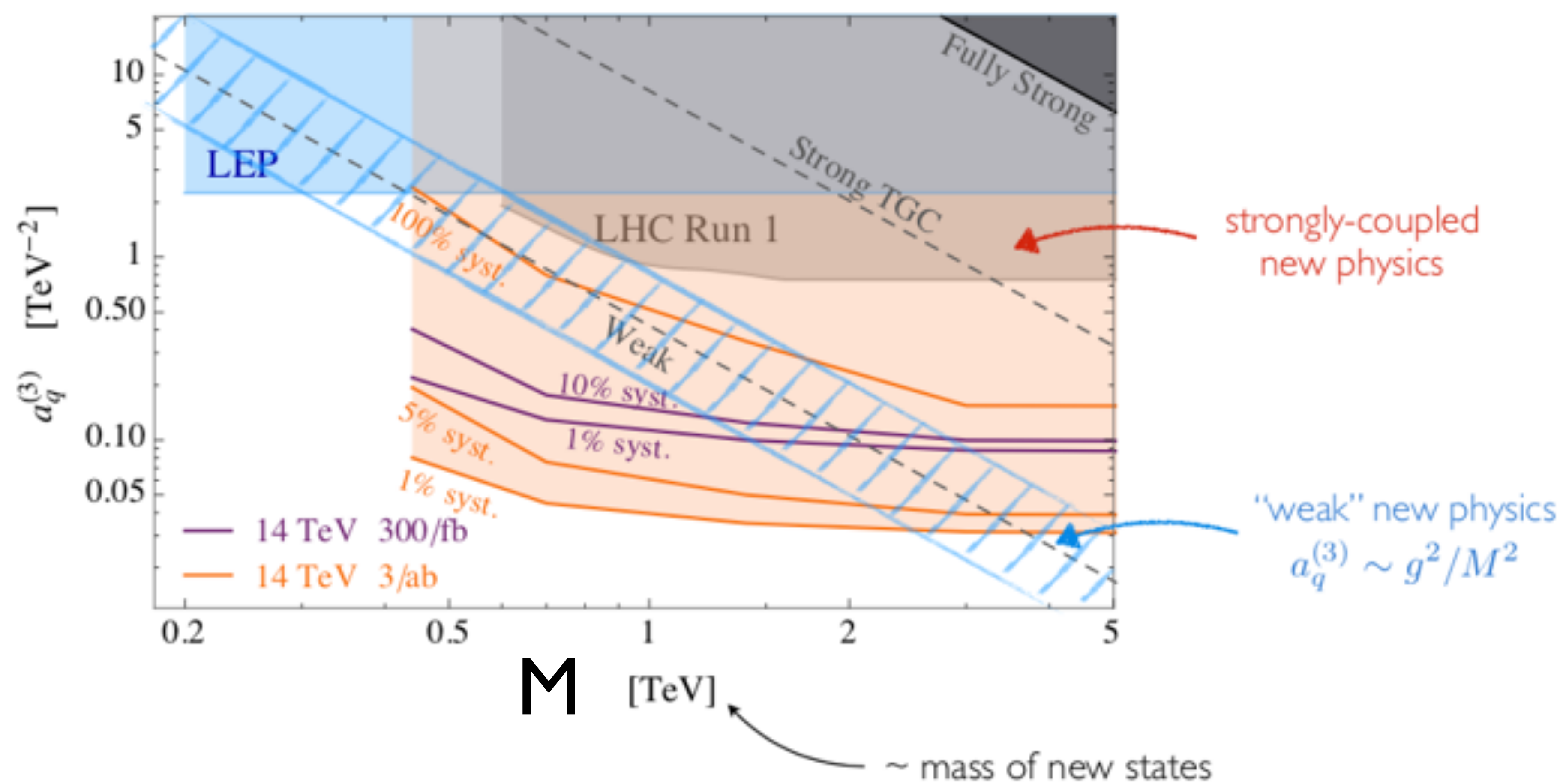
Look at the Helicity Amplitudes w.r.t. scattering angle and use it to reduce the SM background

Slide taken from A. Pomerol

WZ production: LHC

Estimate of the bounds on $a_q^{(3)}(\bar{q}_L\sigma^a\gamma^\mu q_L)(iH^\dagger\sigma^a\overleftrightarrow{D}_\mu H)$

[Franceschini, GP, Pomarol, Riva, Wulzer '17]



The enhanced sensitivity will allow (at the HL-LHC) to set bounds on regions where BSM has a weak coupling interpretation

(larger spectrum of theories covered)

Other works increase sensitivety/non-interference effects by looking at:

Panico et al. 1708.07823

- Other angular observables
- Double differential distributions
- Optimal observables
- Machine Learning techniques

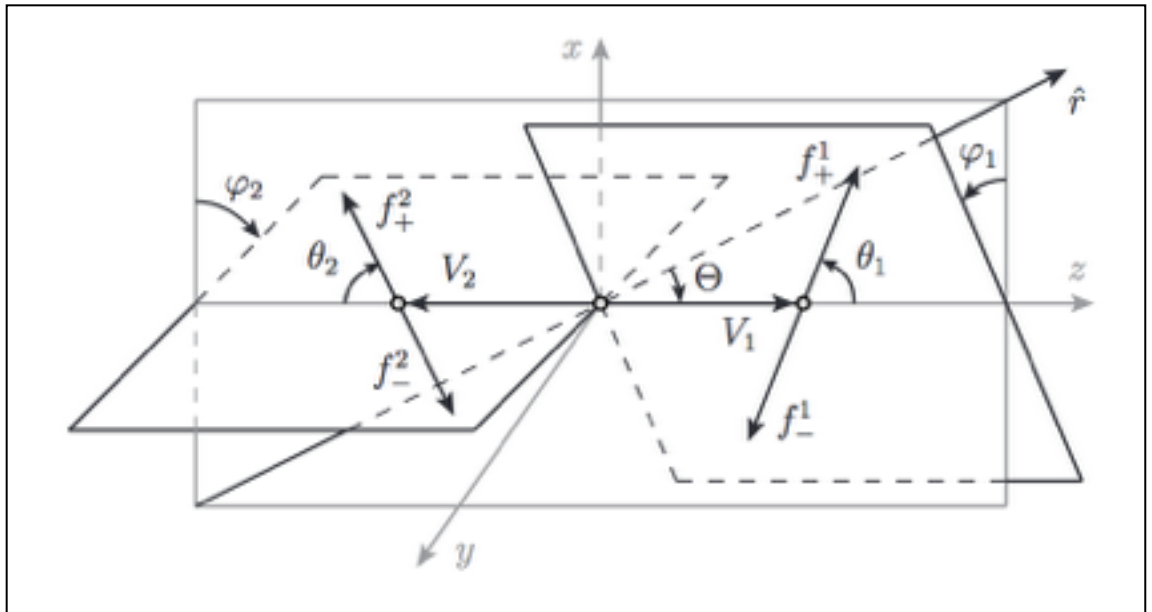
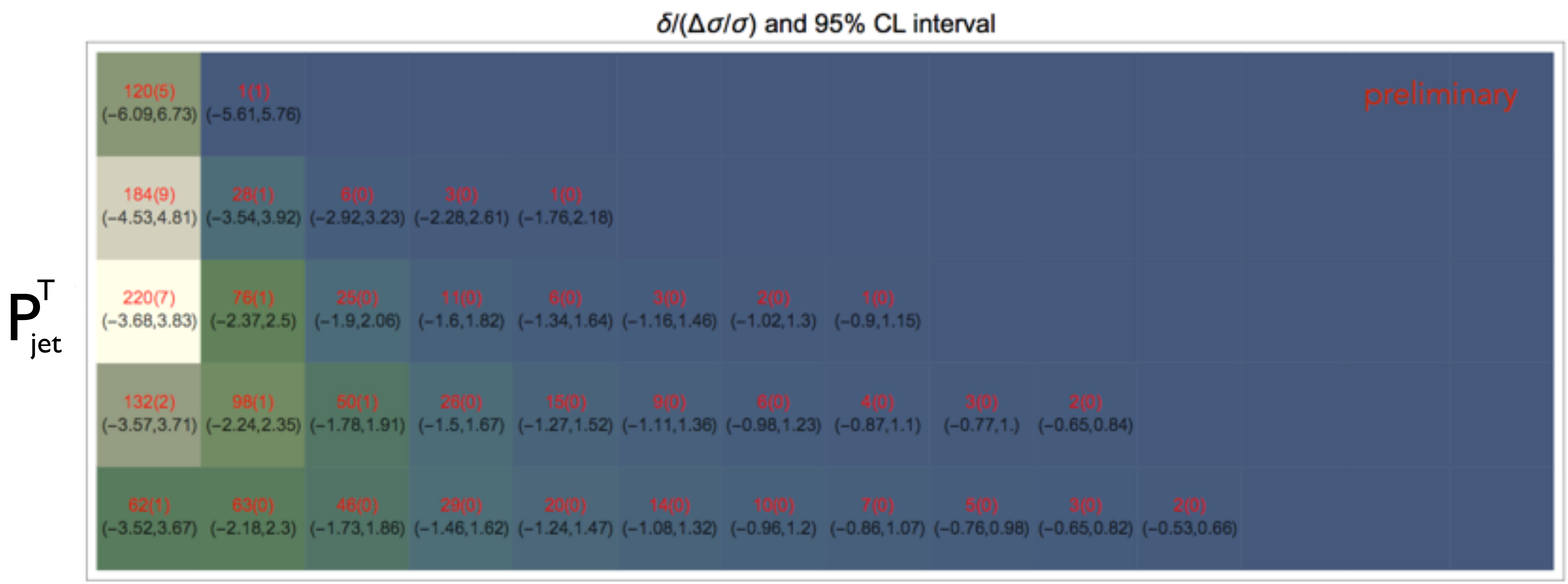


Figure 1: Definition of the decay angles for the diboson system.



M_{WZ}^T

Azatov et al. 1707.08060

4.2) To increase the range of EFT validity (i.e. bounds valid for lower Masses)

- Leptonic WZ
- Wh(bb)

Franceschini et al. (1712.01310)

ongoing

Assume Miss ET = neutrino
+
Reconstruct with conservative solution

Banerjee et al. (1807.01796)

- Zh (2 leptons + bb)

It can be fully reconstructed

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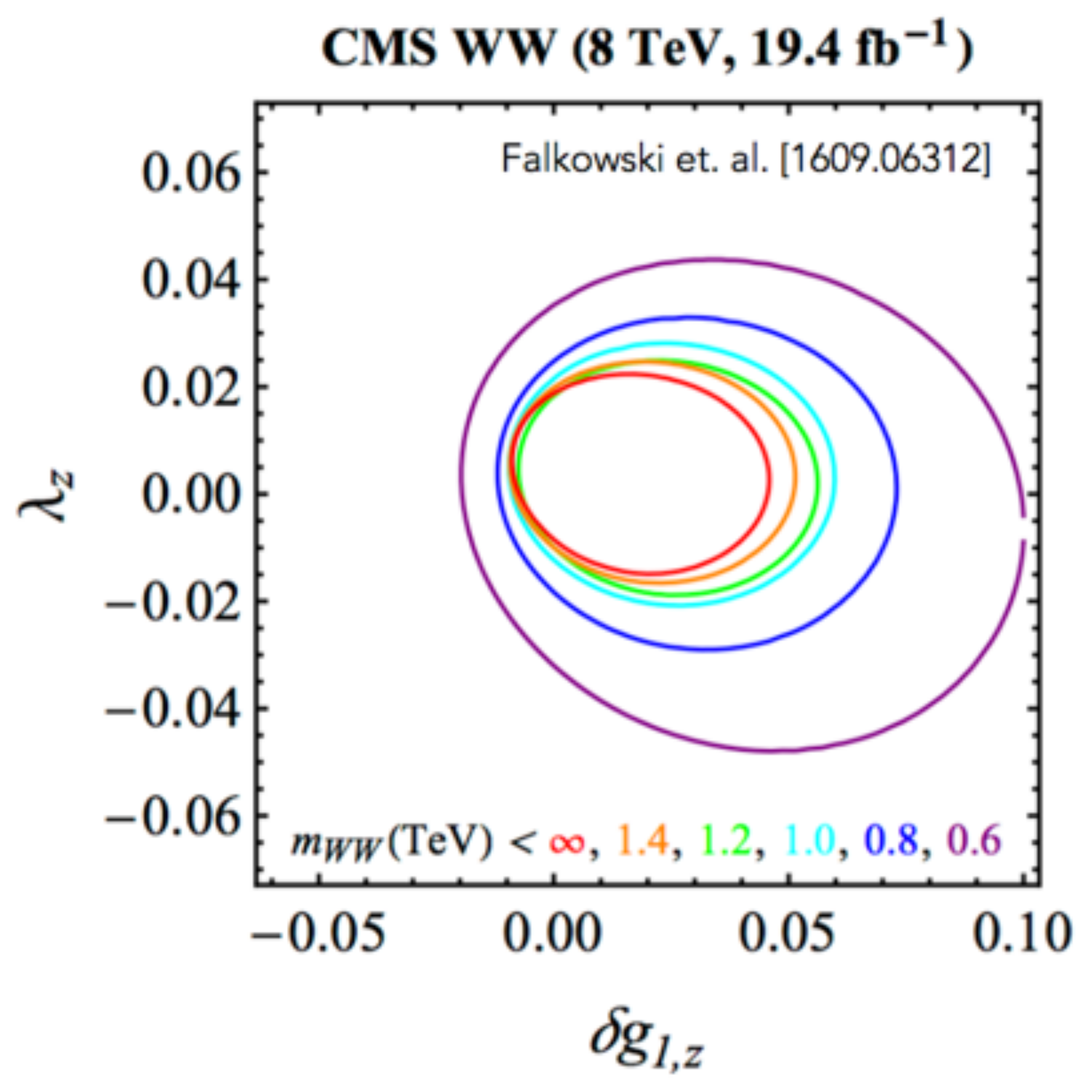

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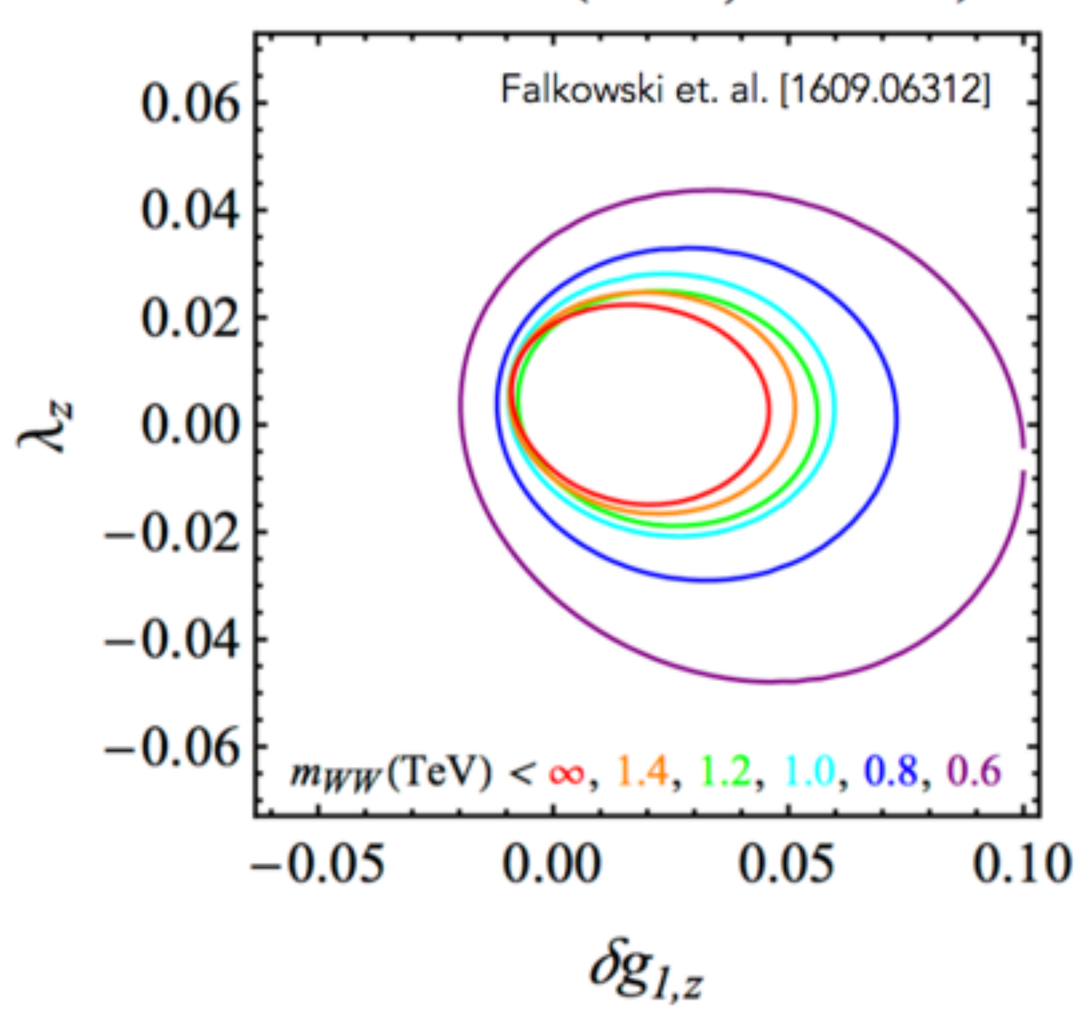
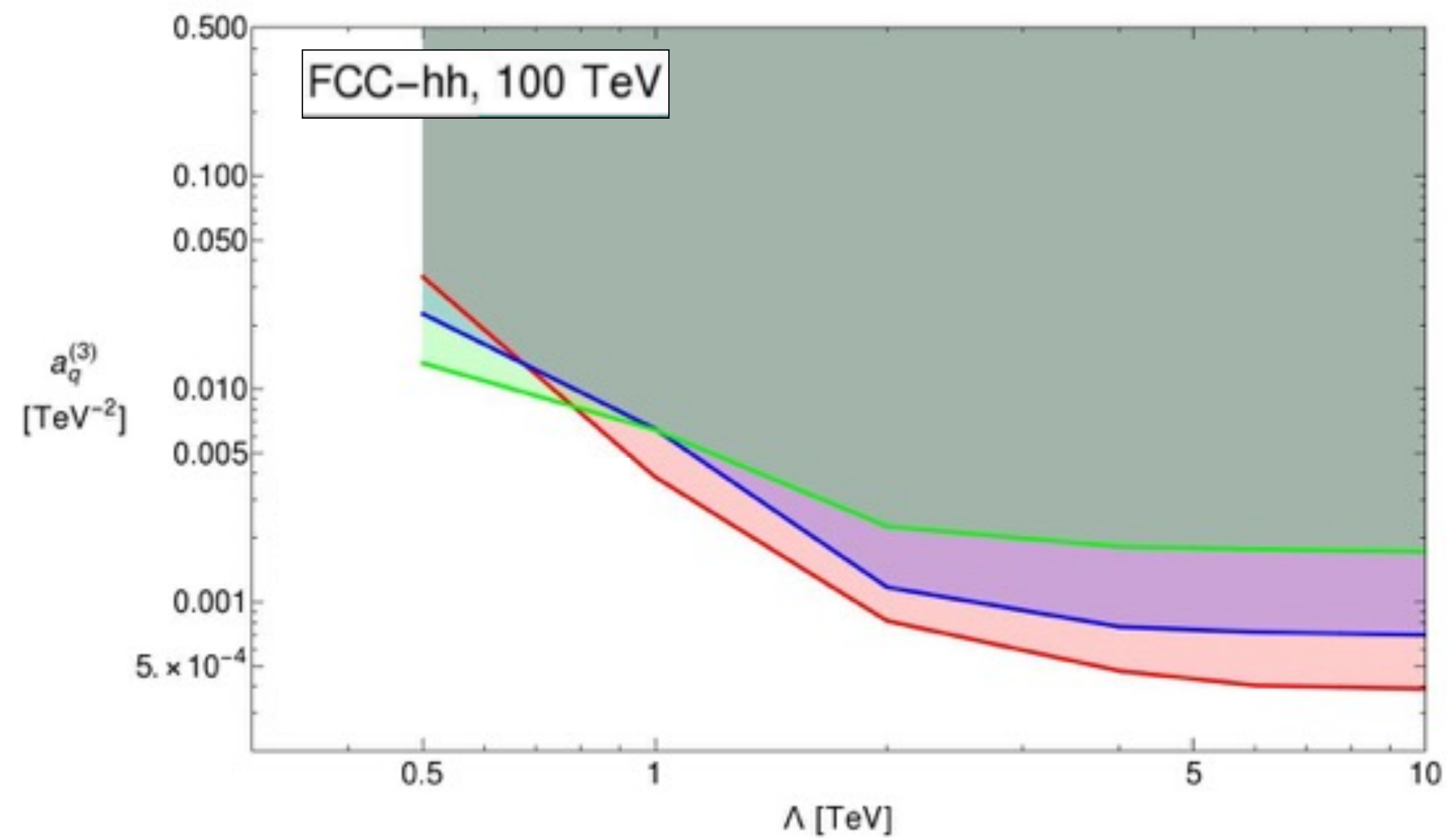


Wh(bb) @ FCC (20ab-1)



(preliminary)

5) To what theories do the LHC DB bounds apply

One needs to be careful when interpreting the bounds:

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

Currently, the quadratic pieces dominate the amplitudes, hence the bounds only apply to theories where the BSM deviations can be large

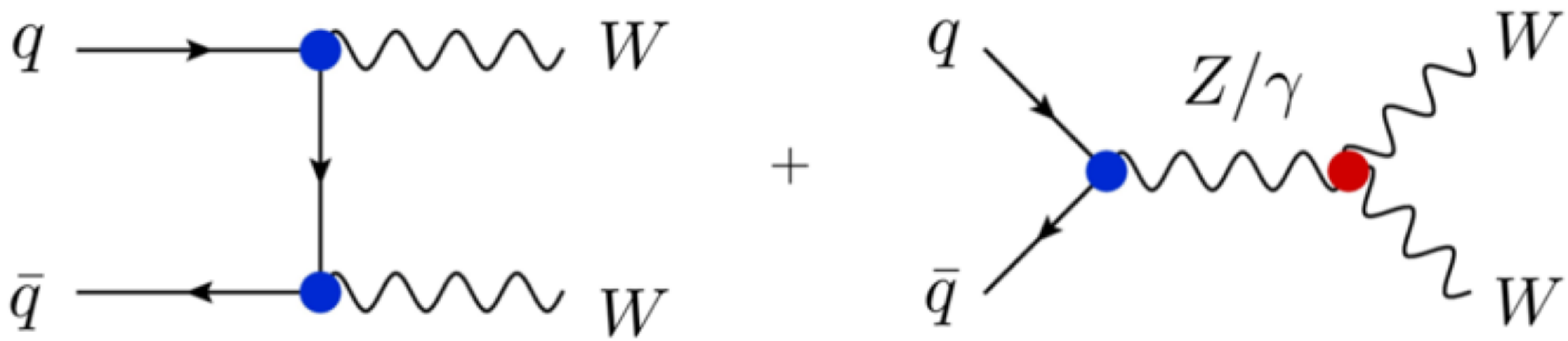
For instance, for aTGC:

- No BSM theories exist where $\delta\kappa_z$, λ_γ are large (always loop)

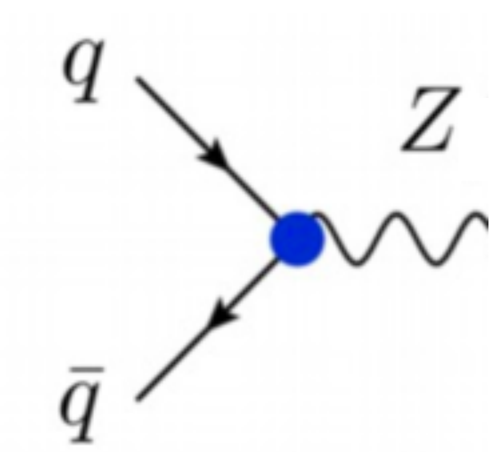
- Nonetheless see Remedios paper by Rattazzi et al. 1603.03064 showing possible power countings where these are tree level size

6) What is the interplay between LEP-1 and aTGC

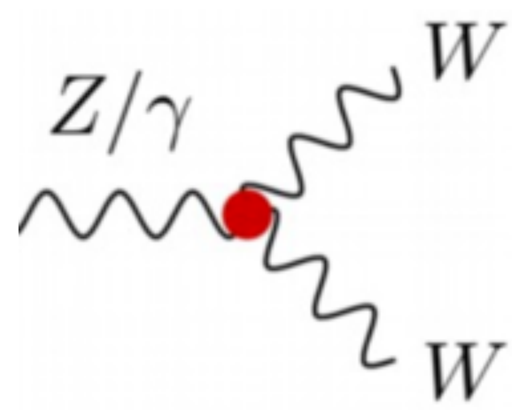
Schematically diboson production (WW, WZ):



Equivalent to study modifications to Zqq and aTGC



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



Z couplings to quarks

anomalous TGC

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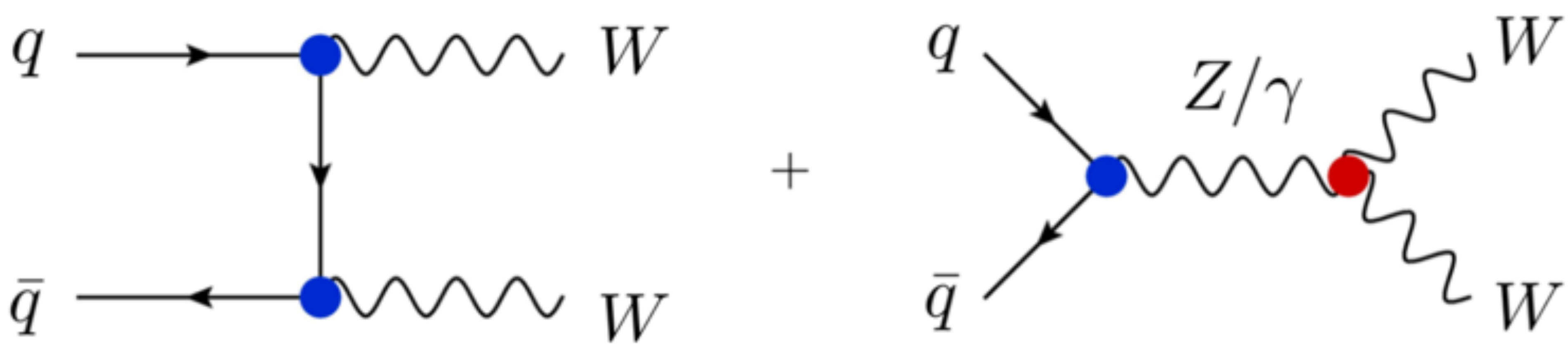

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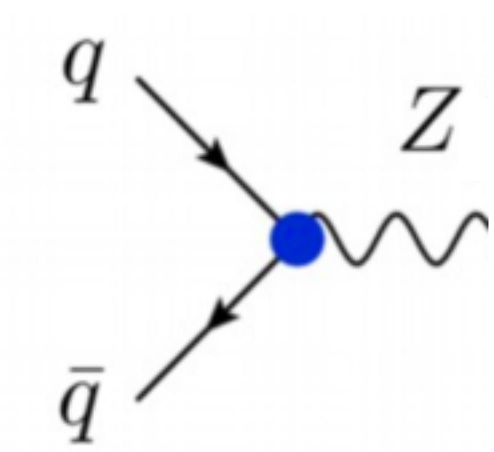

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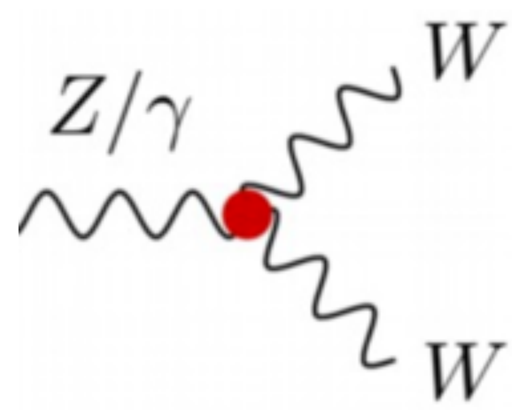

Z couplings to quarks

anomalous TGC

At dim=6:

(Flavour Universality)

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

4 + 3 = 7 param

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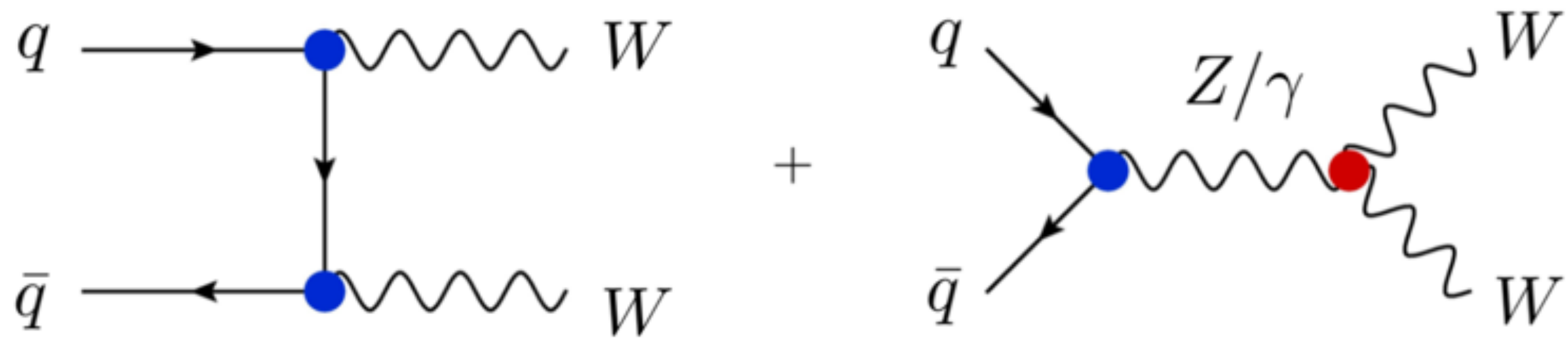

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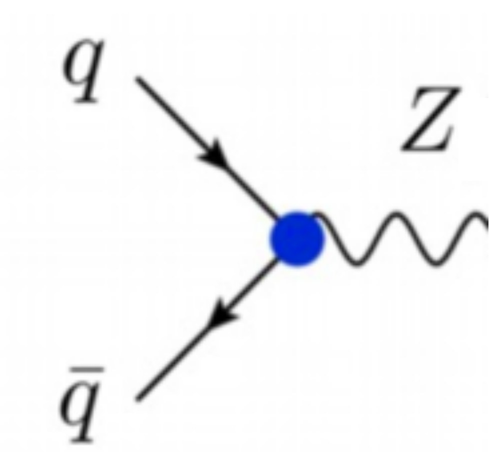
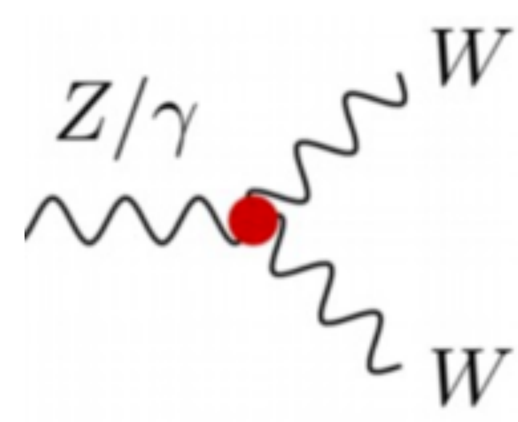


Z couplings to quarks

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

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

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



anomalous TGC

(**LEP-2**)

$$\delta g \lesssim 1\% - 10\%$$

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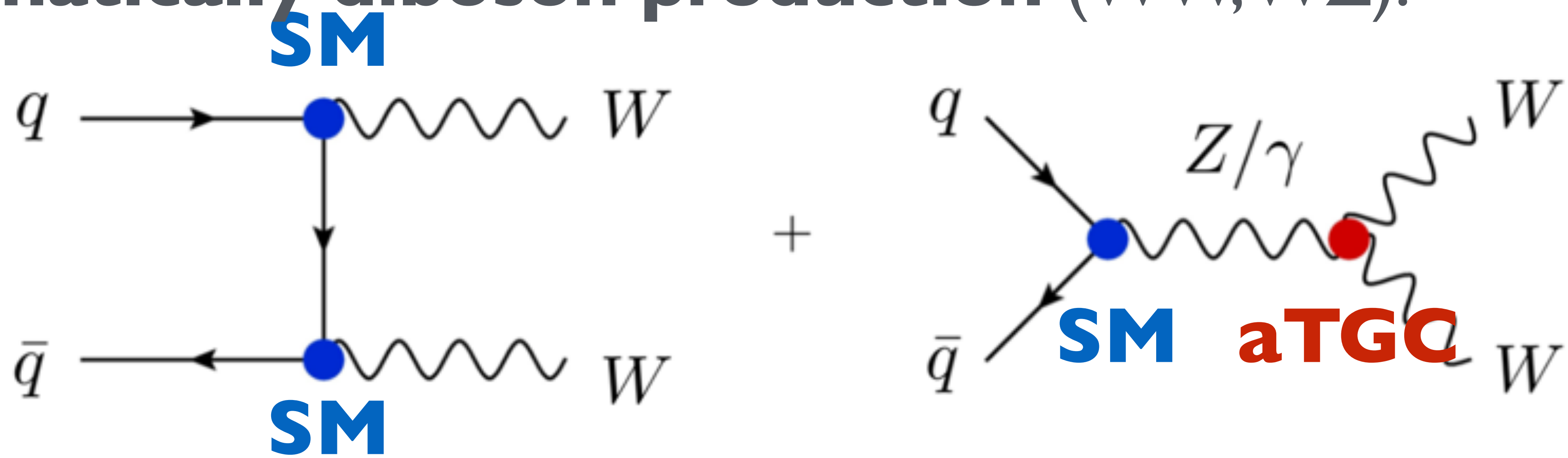
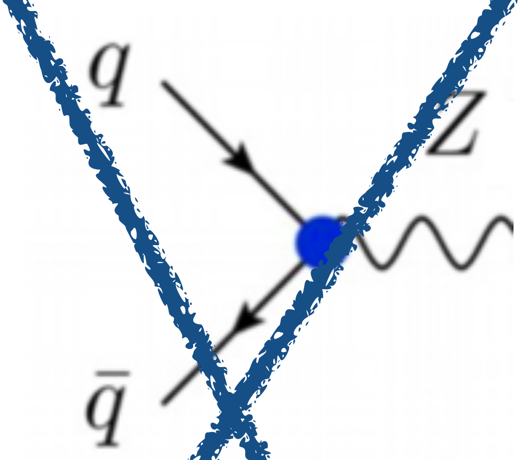


Equivalent to study modifications to Zqq and aTGC



~~Z couplings to quarks~~

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

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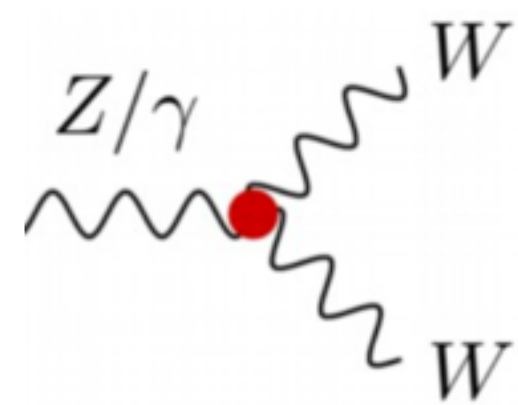
$g_{SM}\,(1 + \delta g)$

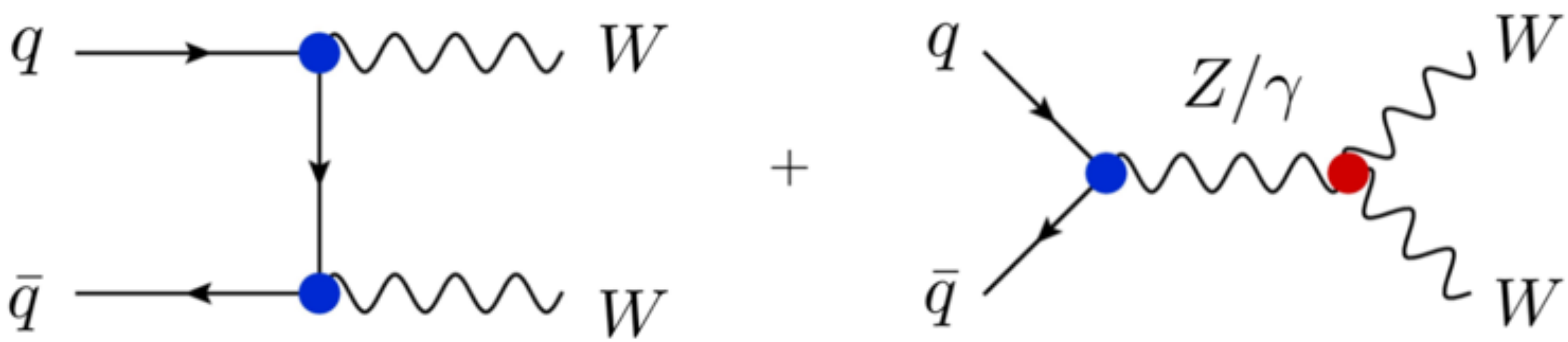


anomalous TGC

(**LEP-2**)

$\delta g \lesssim 1\% - 10\%$

Interplay between LEP-1 and the LHC for aTGC



- Is it justified to **neglect Zqq** couplings @ LHC?

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

- What is the sensitivity of WW, WZ vs other LHC channels?

3) Work done / ongoing

Is it justified to neglect Zqq couplings @ LHC?

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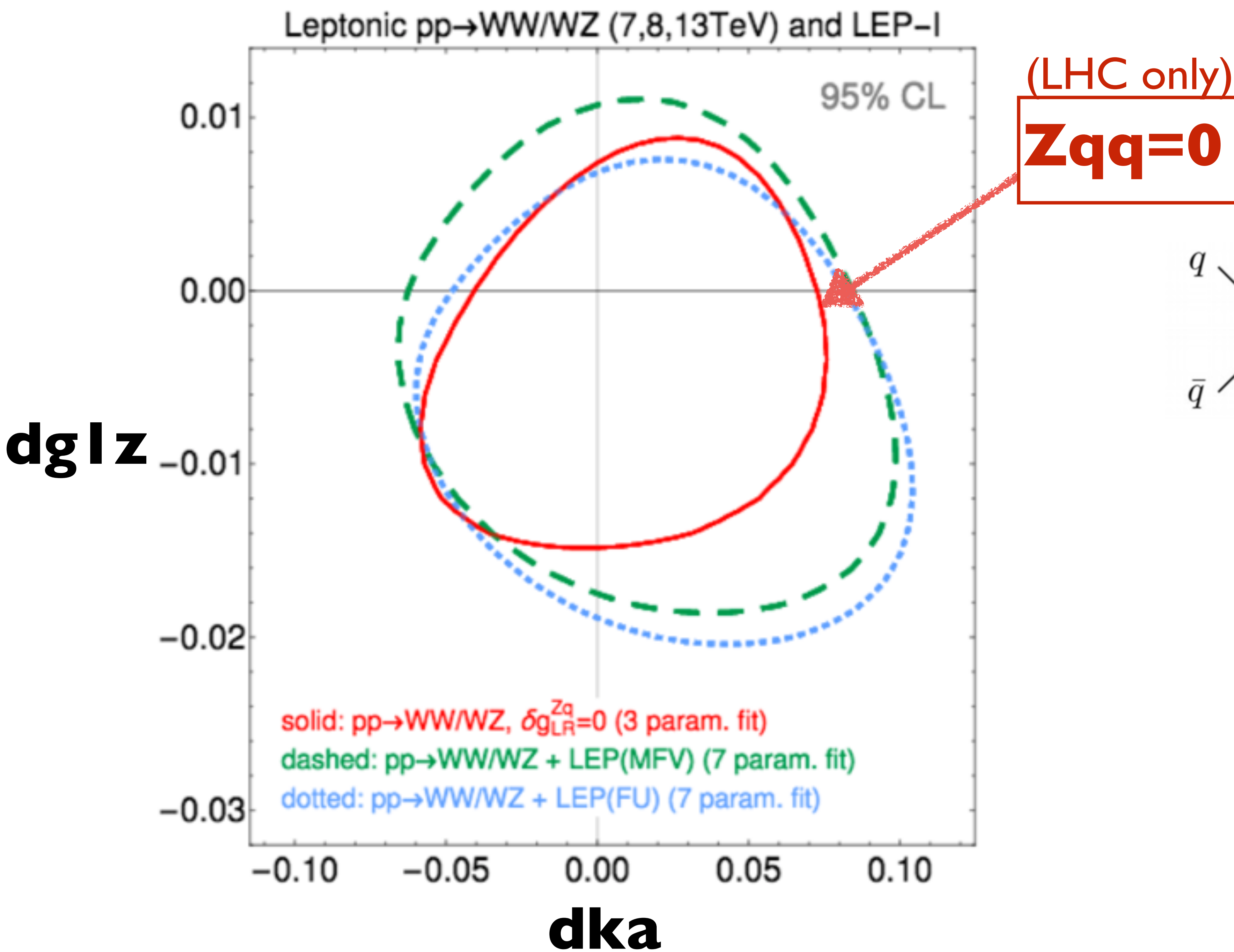
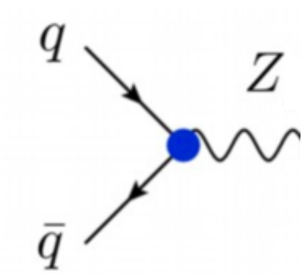
Combine current **leptonic data for WW, WZ** from CMS & ATLAS

Fit to **anomalouts Triple Gauge Couplings**





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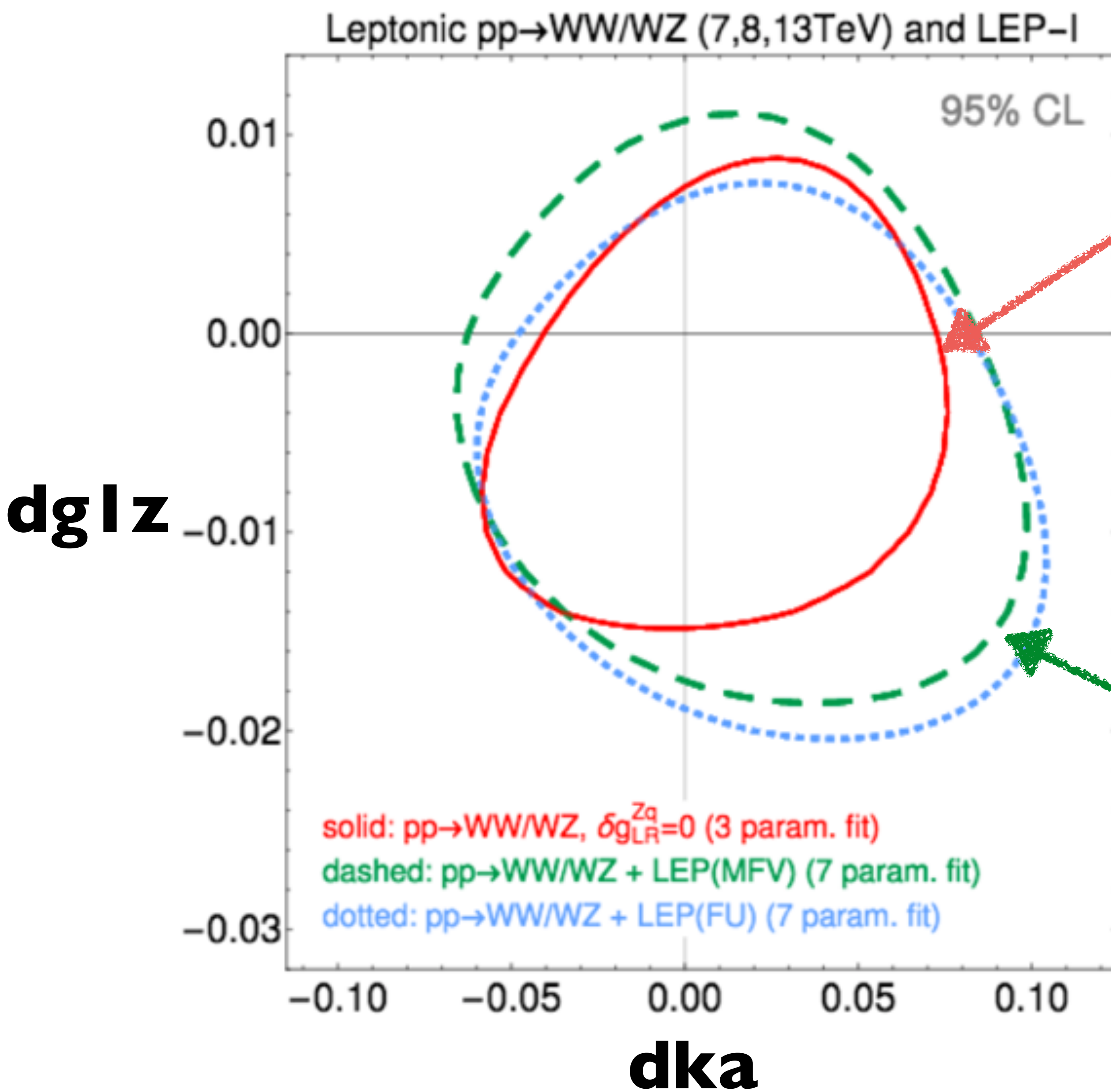
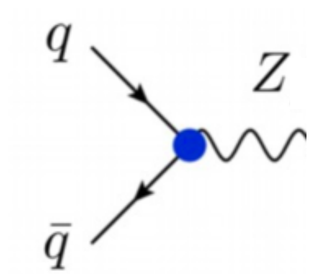


(LHC only)

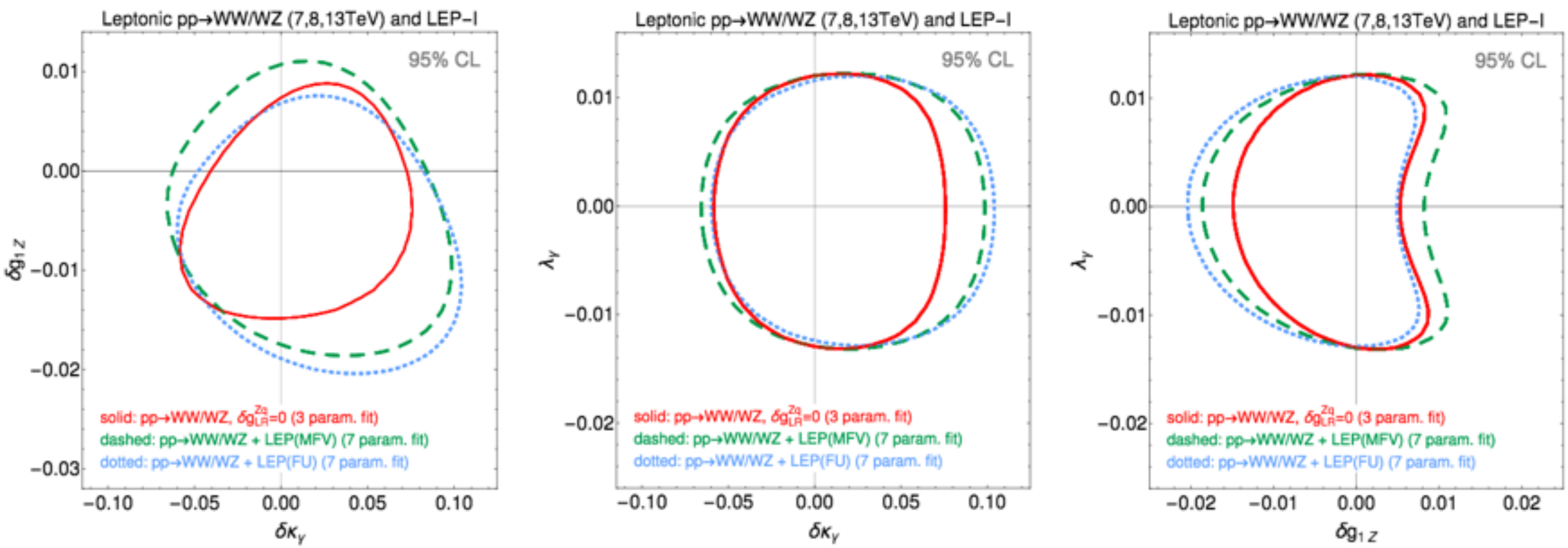
Zqq=0



Zqq $\neq$ 0
+
Global fit w/ LEP

(LHC + LEP-1)

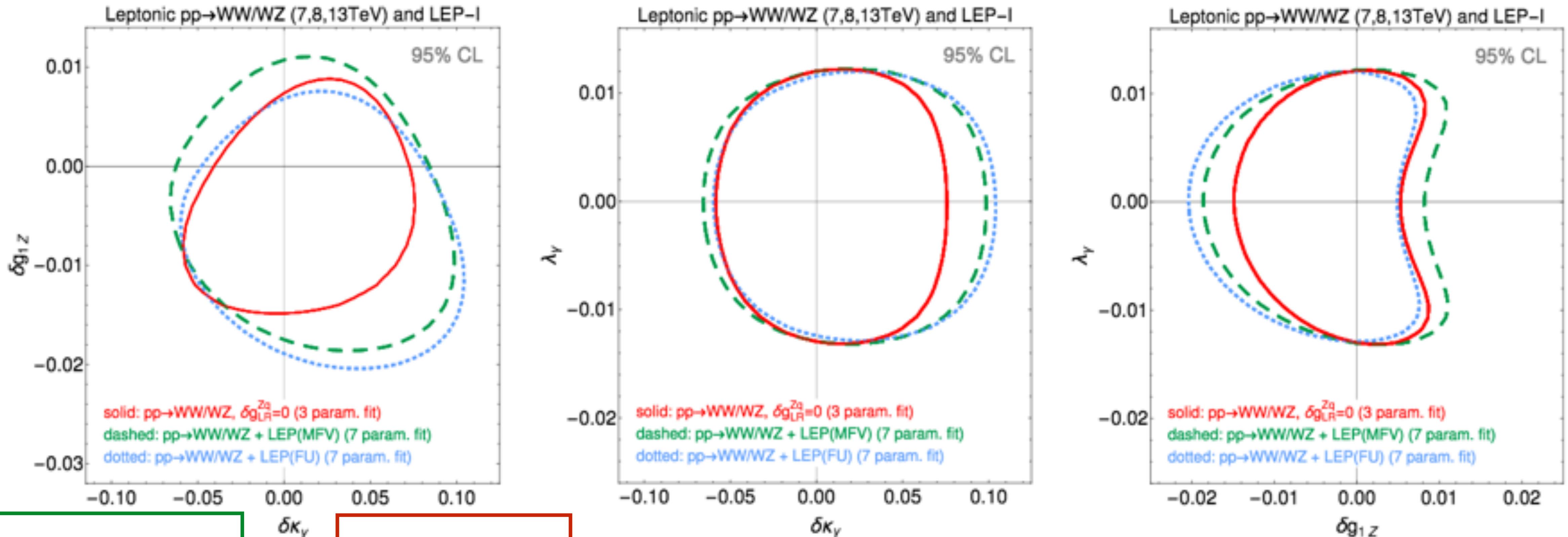
LHC NOW



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

(+ global fit w/ LEP)

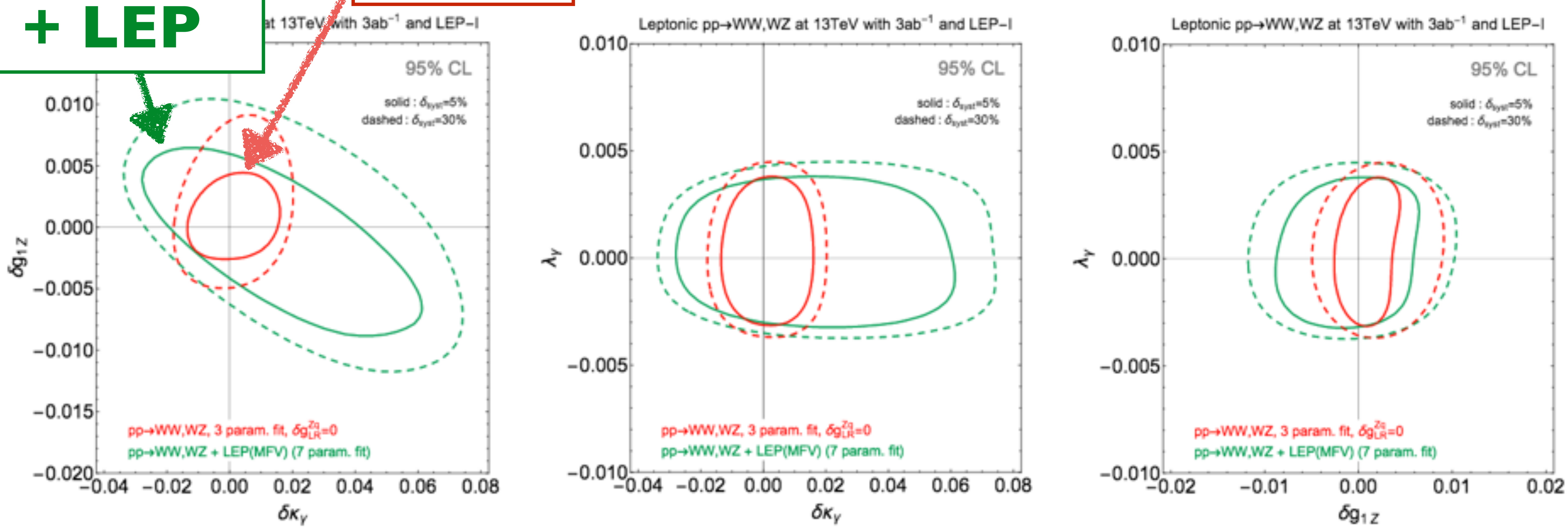
LHC NOW



Zqq ≠ 0 + LEP

Zqq=0

HL-LHC 3 ab^{-1}

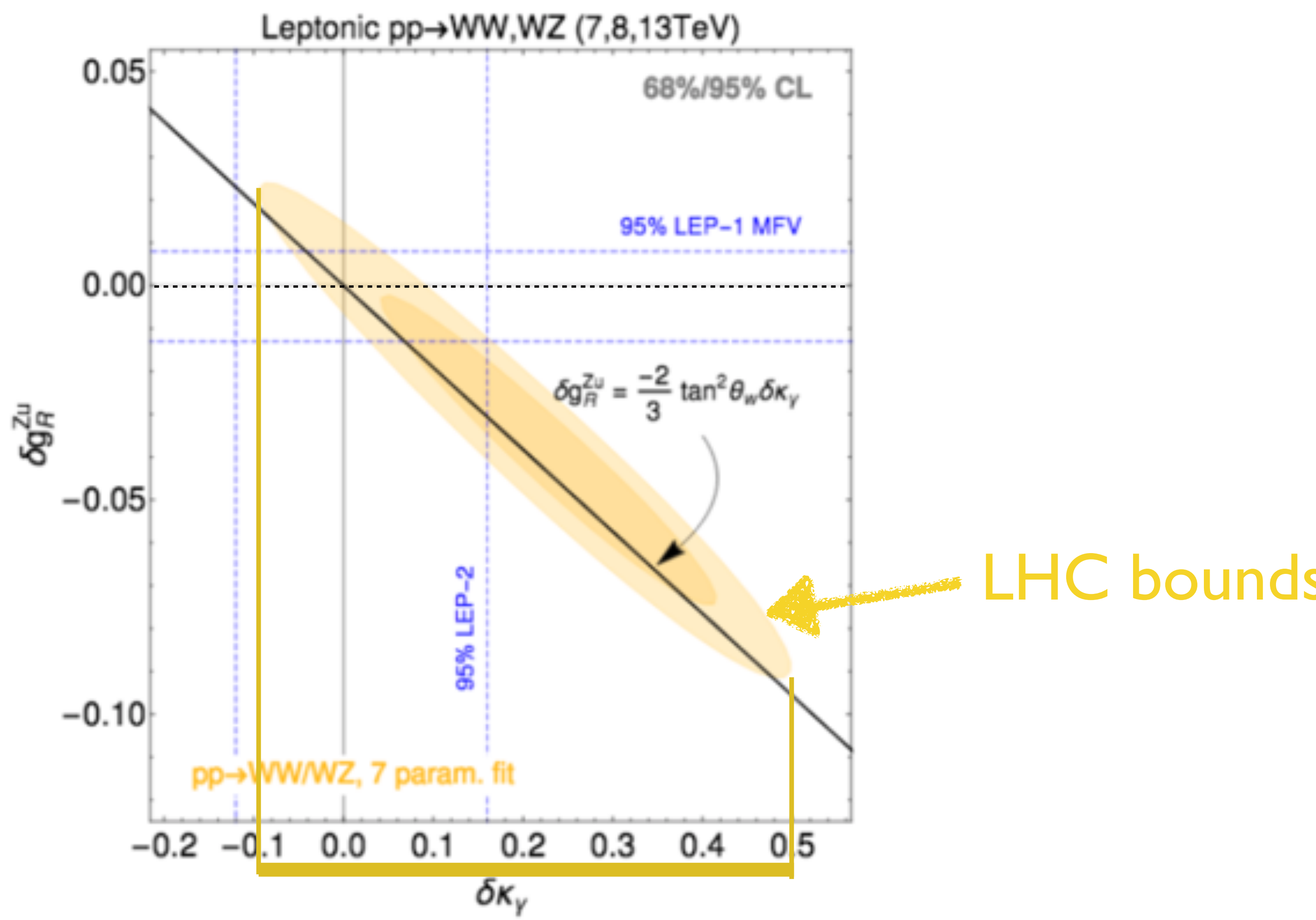


- Difference > 100% @ HL-LHC: **Not Justified to Neglect Zqq!**

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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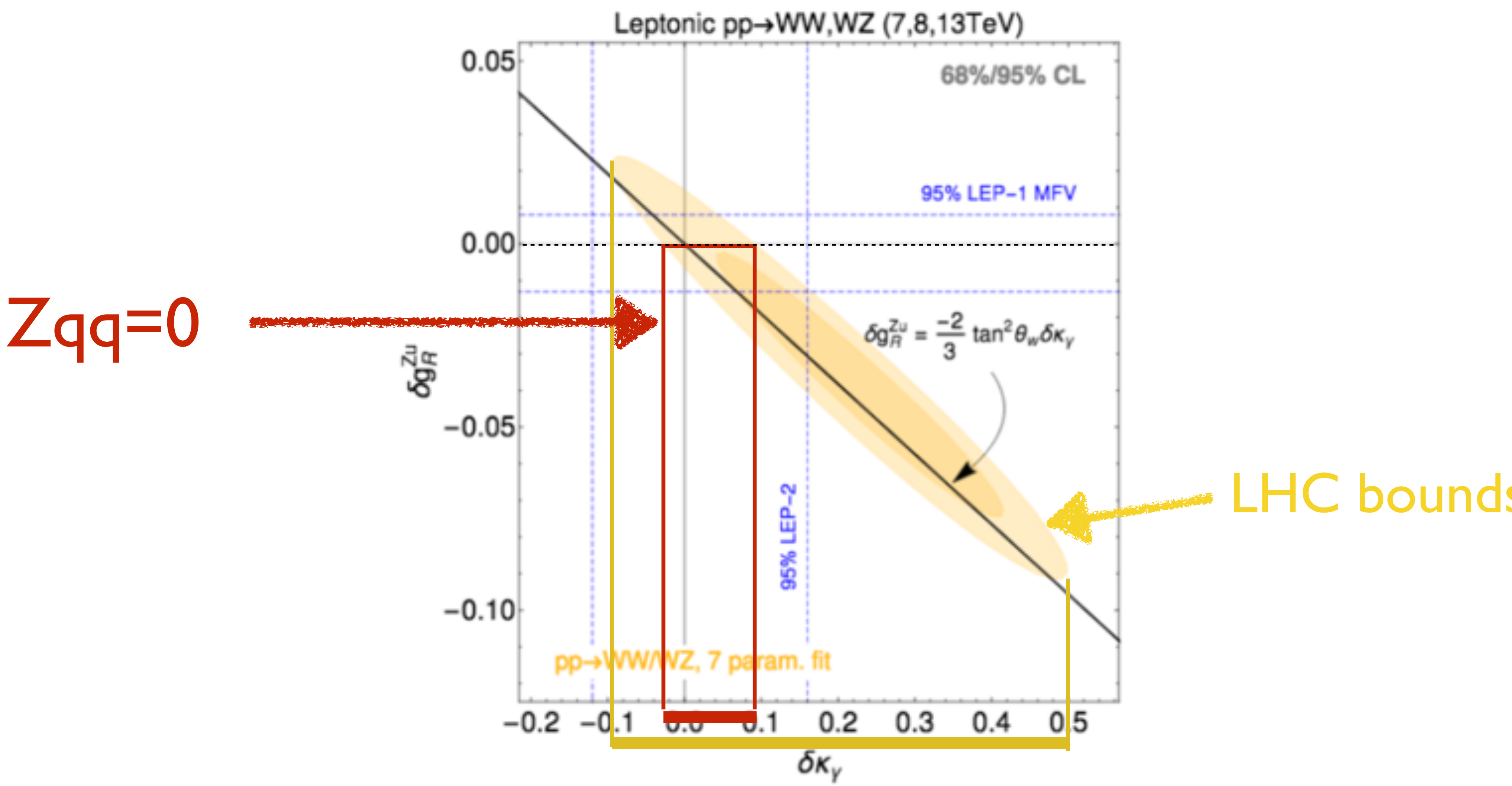

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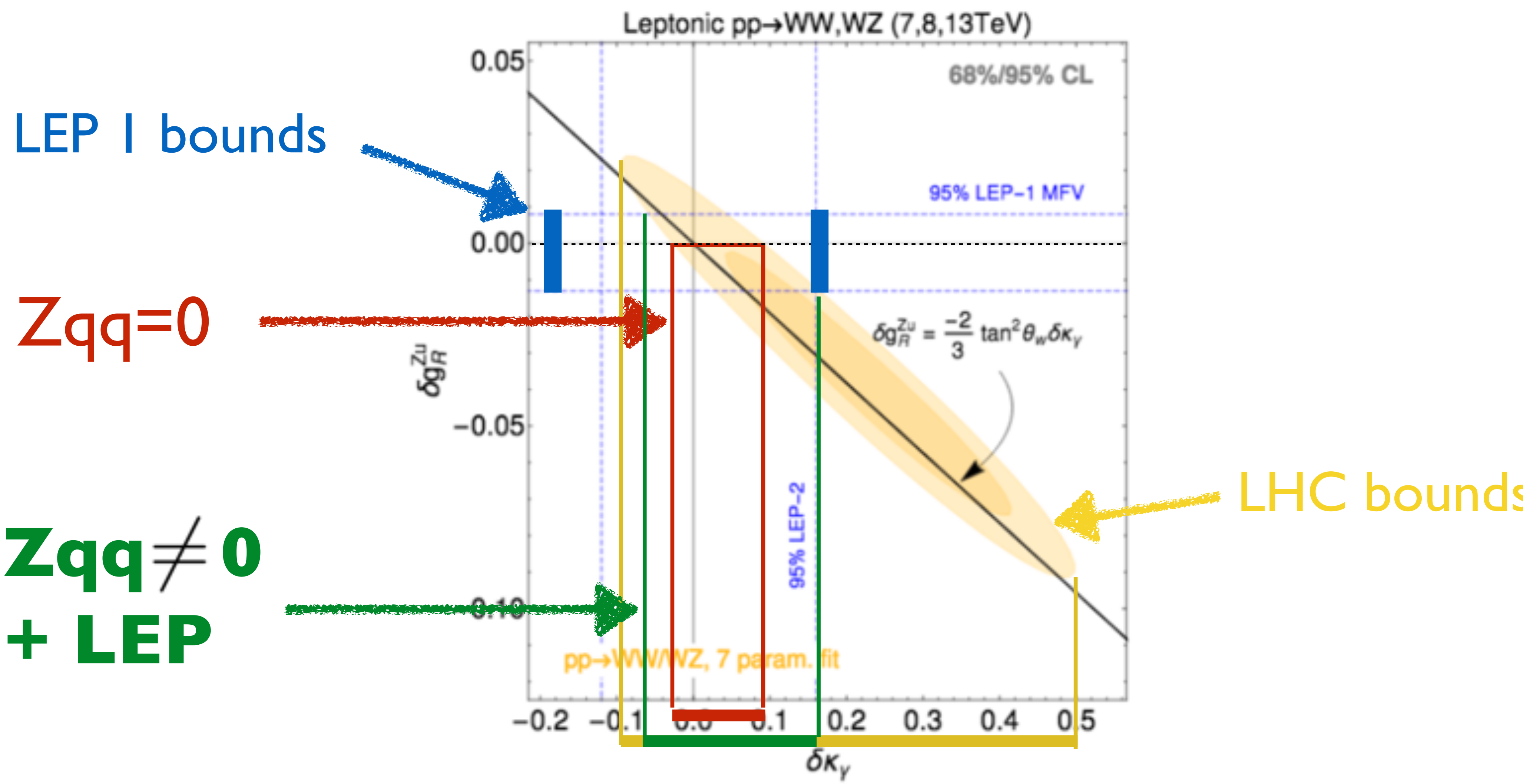

Can the LHC improve the bounds on the Zqq w.r.t LEP?

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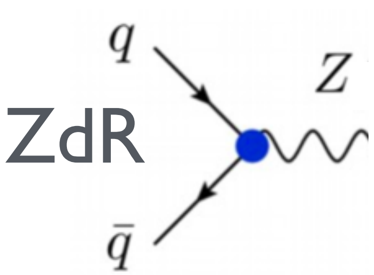
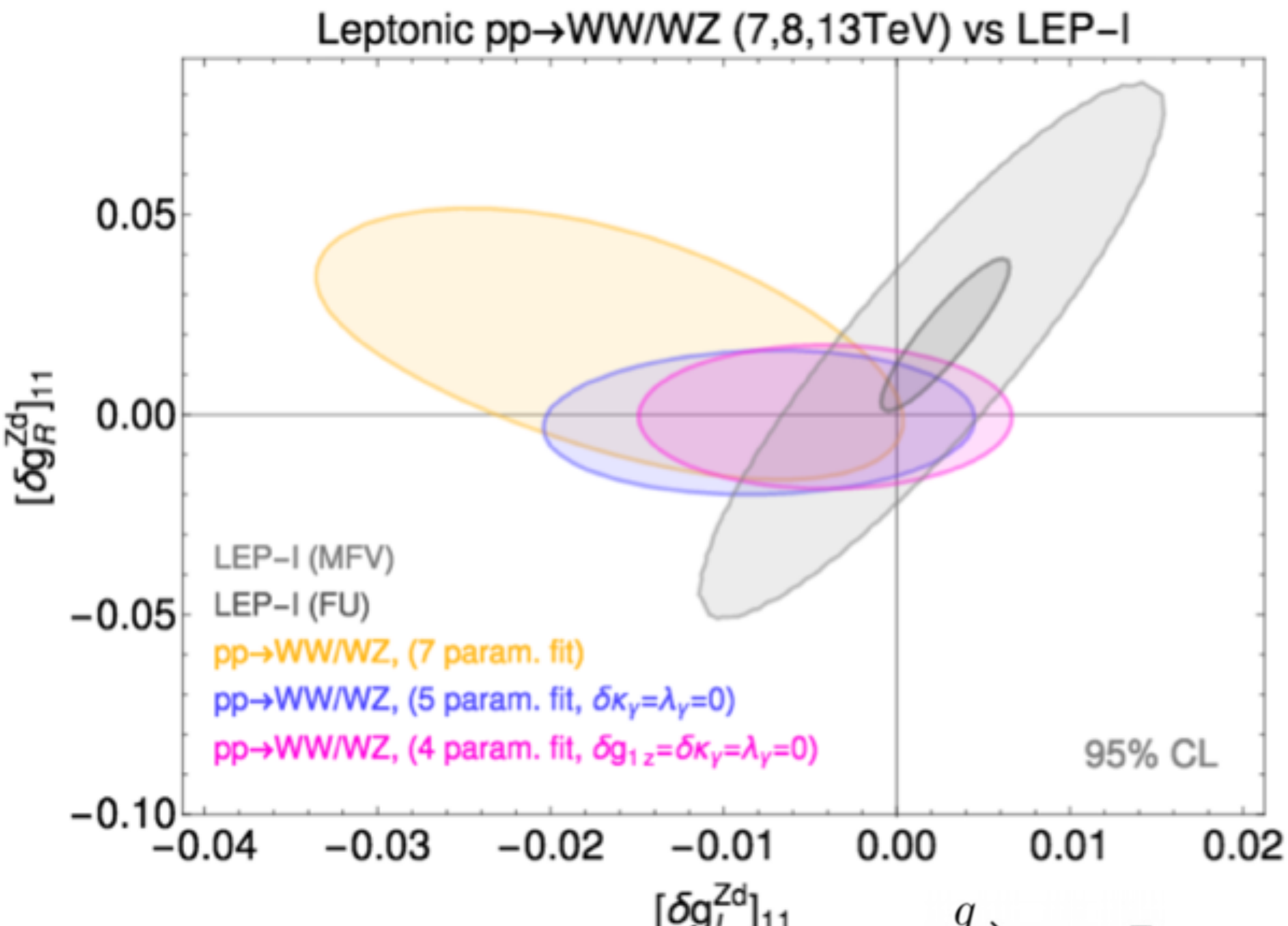
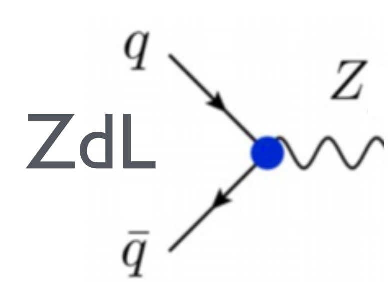
Combine current **leptonic data for WW, WZ** from CMS & ATLAS

Fit to **Zqq vertex corrections**

Z to **down** type q







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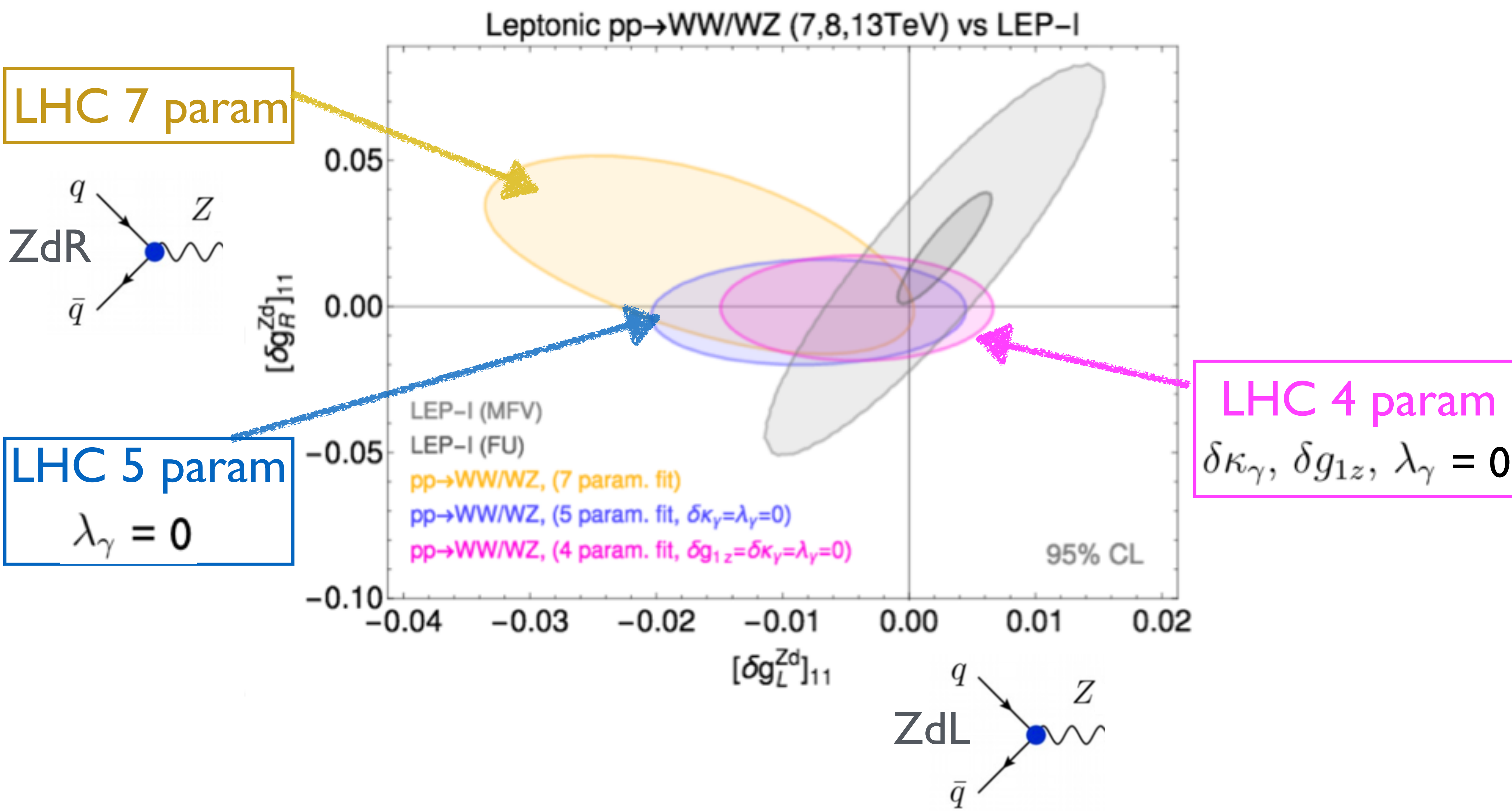

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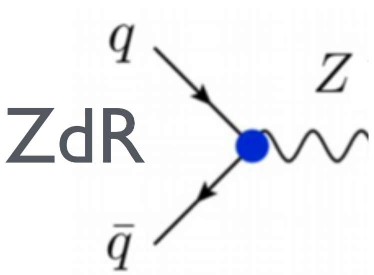
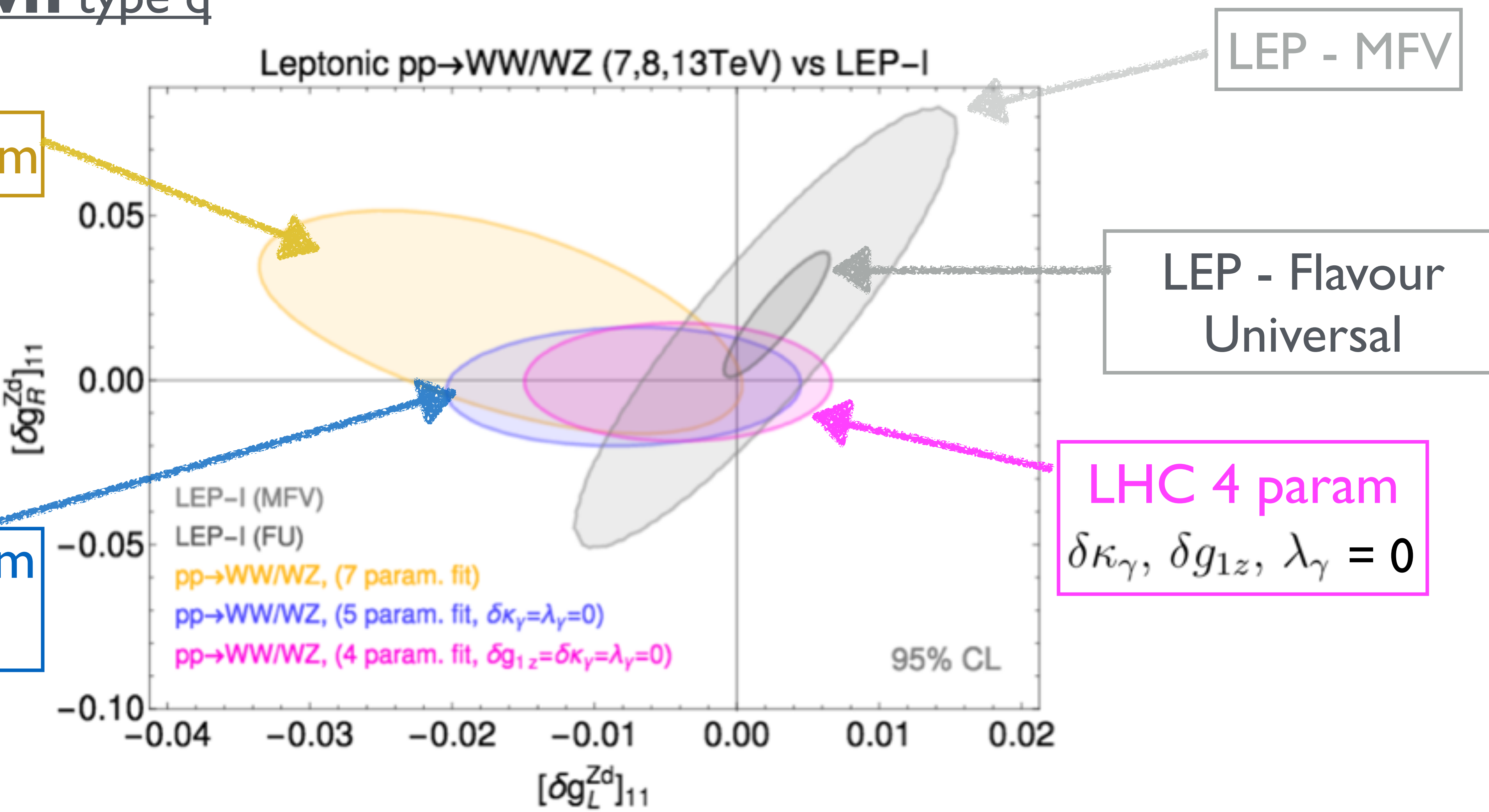
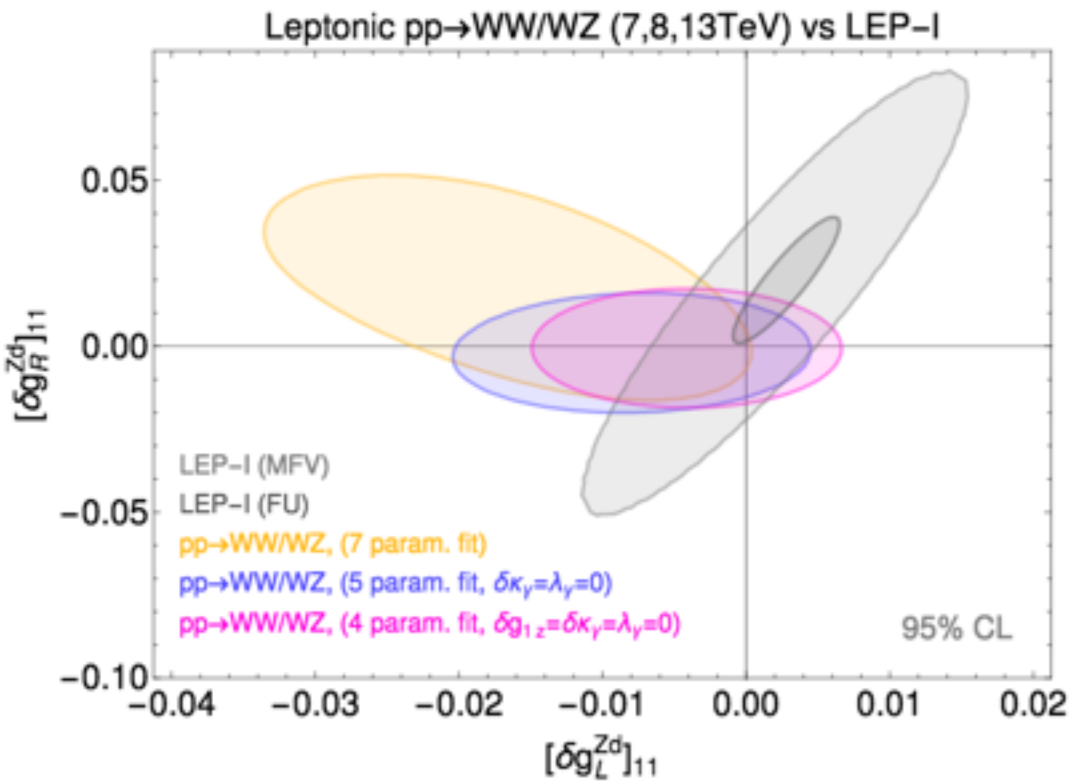




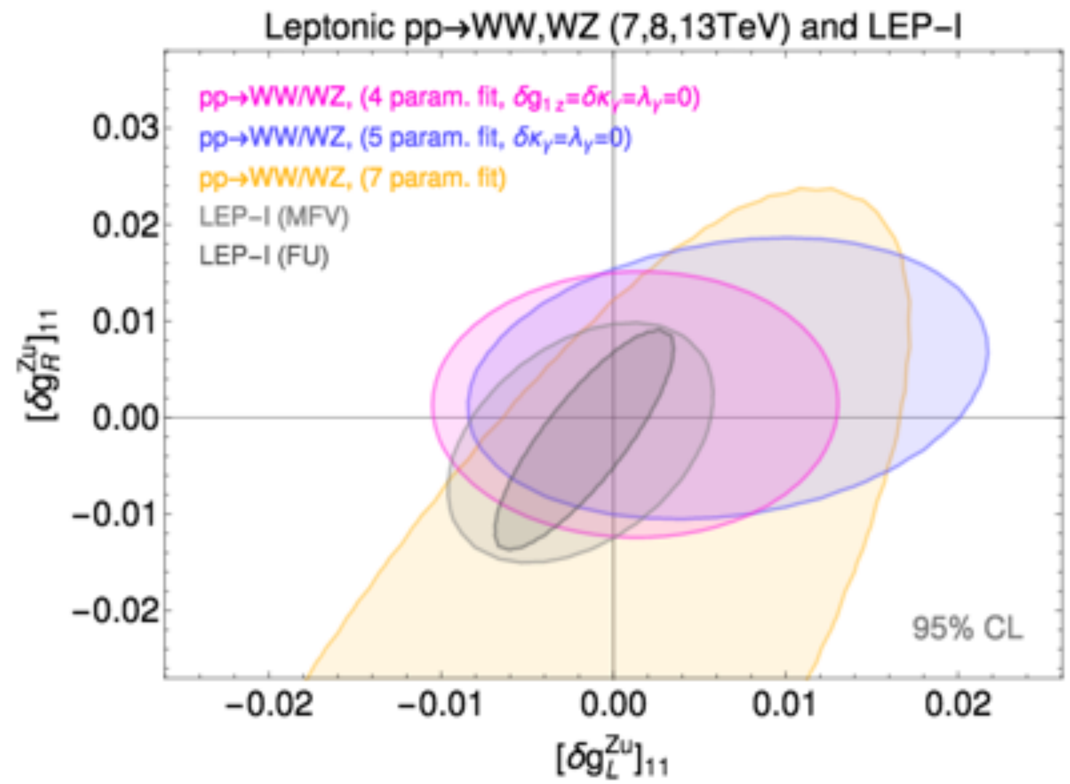
- **Current data is competitive with LEP** setting bounds to Zqq down type q!

LHC NOW

Z to **down** type q



Z to **up** type q

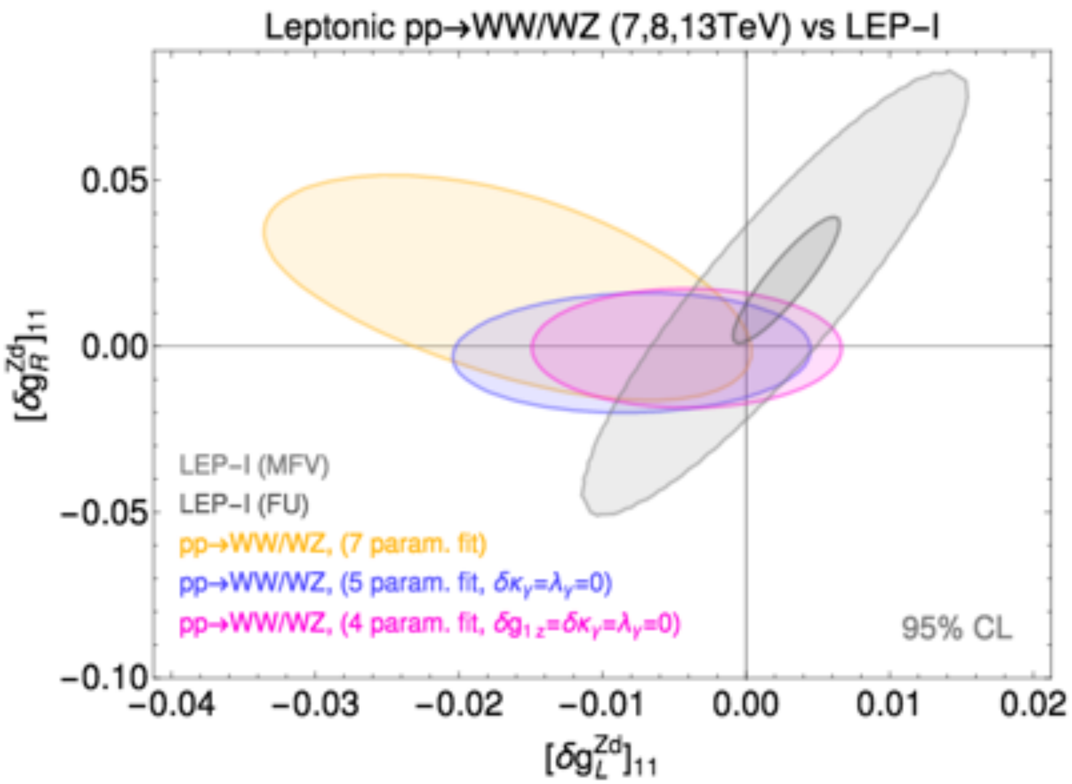


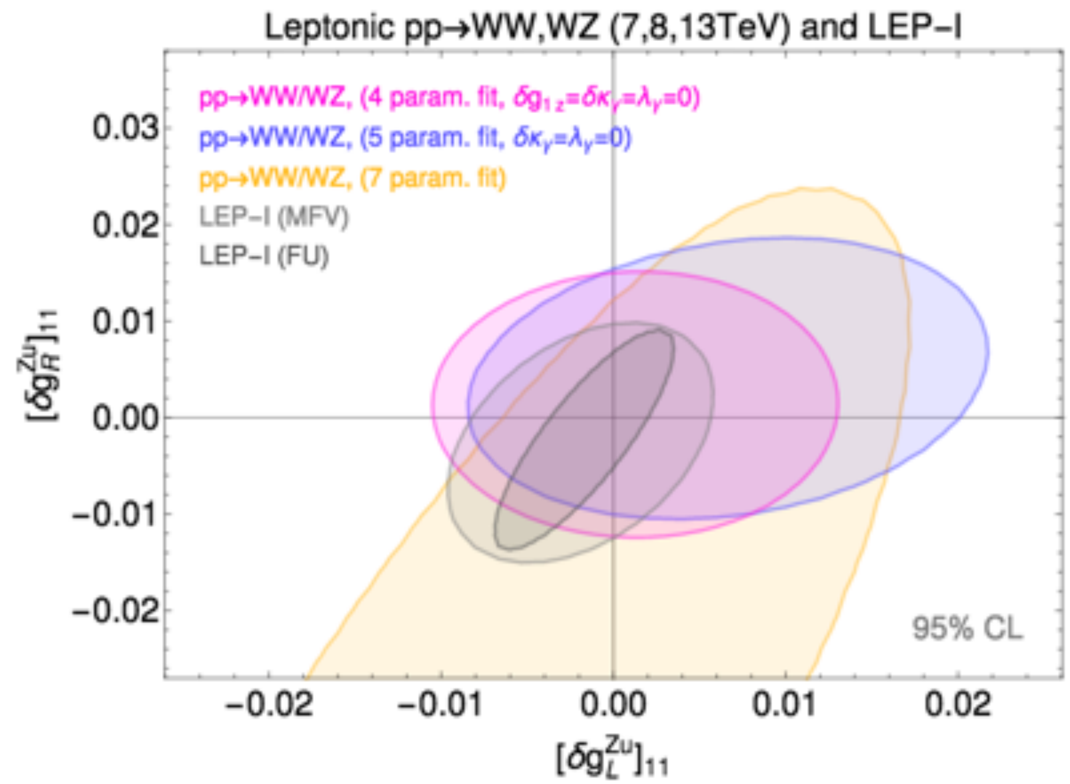
- For the up type corrections, the LHC is still not competitive with LEP

LHC NOW

Z to **down** type q

Z to **up** type q

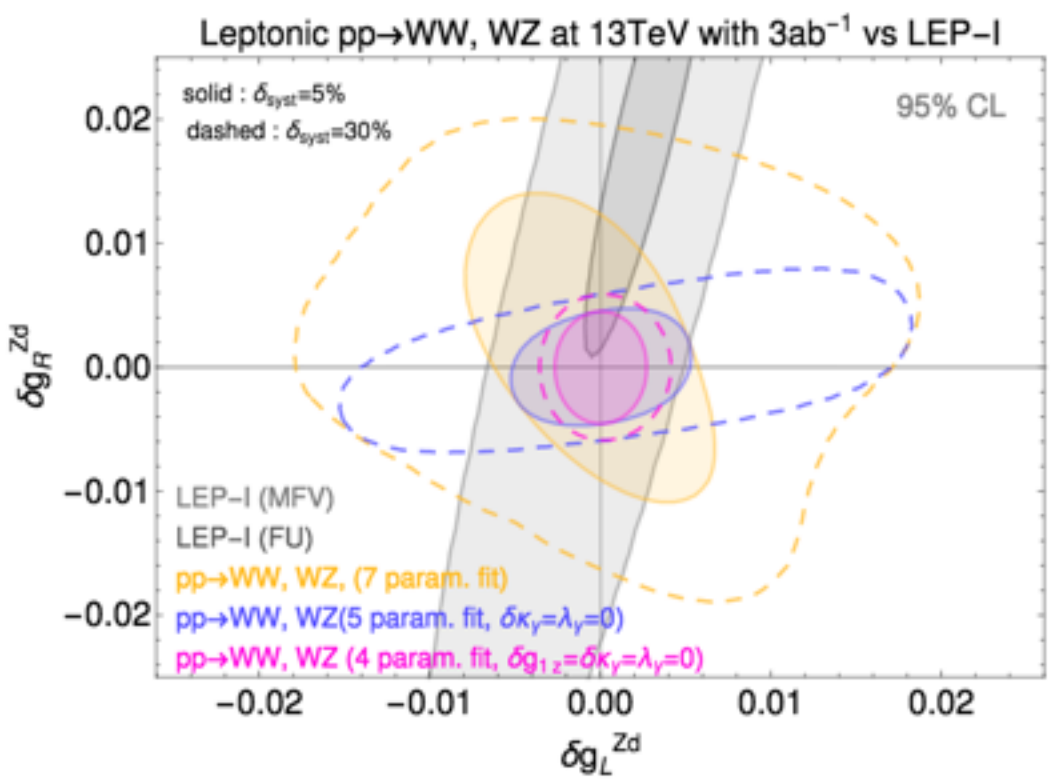


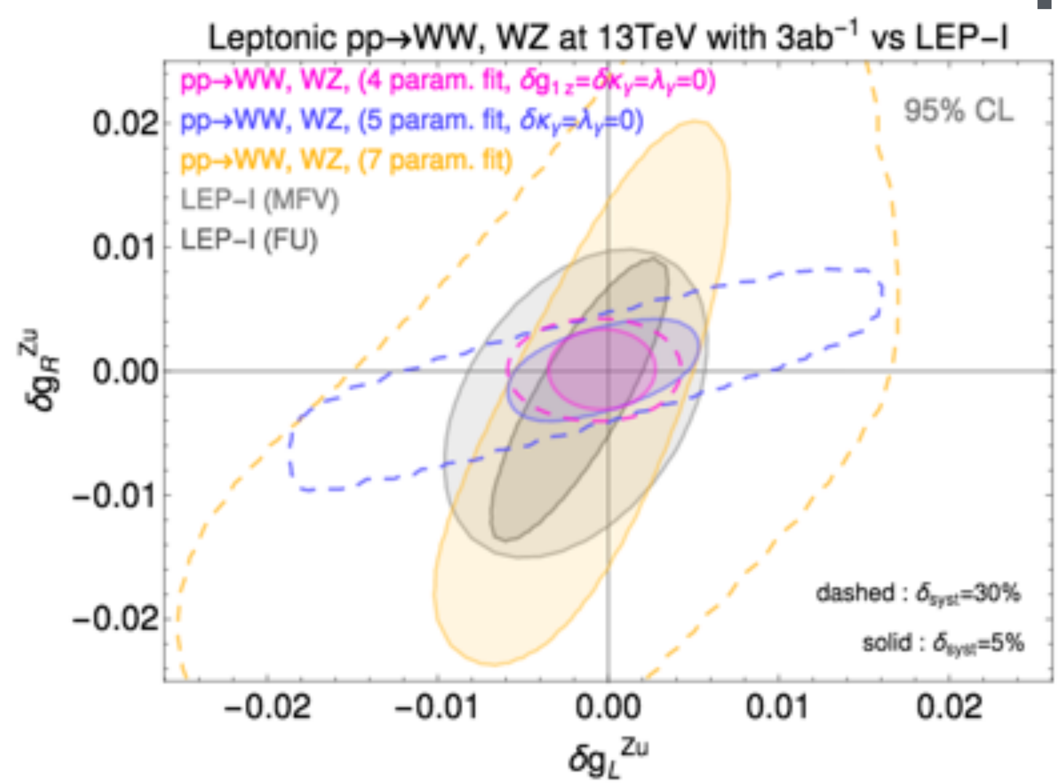


HL-LHC 3 ab^{-1}

Z to **down** type q

Z to **up** type q





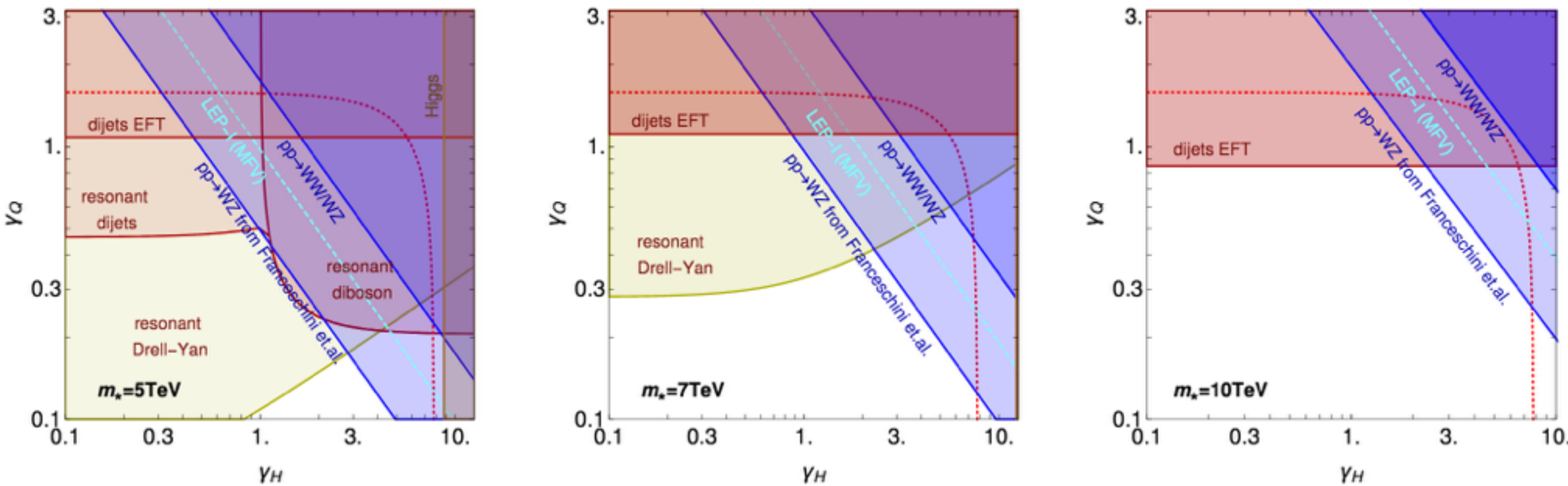
- DB @ HL-LHC may **improve** the bounds on all the Zqq vertices **w.r.t LEP**!

A concrete toy model, left handed gauge triplets

(appearing in Composite Higgs models and other BSM extensions)

$$\mathcal{L}_{int} = L_\mu^a \left(\gamma_H J_\mu^{Ha} + \gamma_V J_\mu^a + \sum_f \gamma_f J_\mu^{fa} \right)$$

We compare diboson vs dijets, direct searches and Higgs couplings

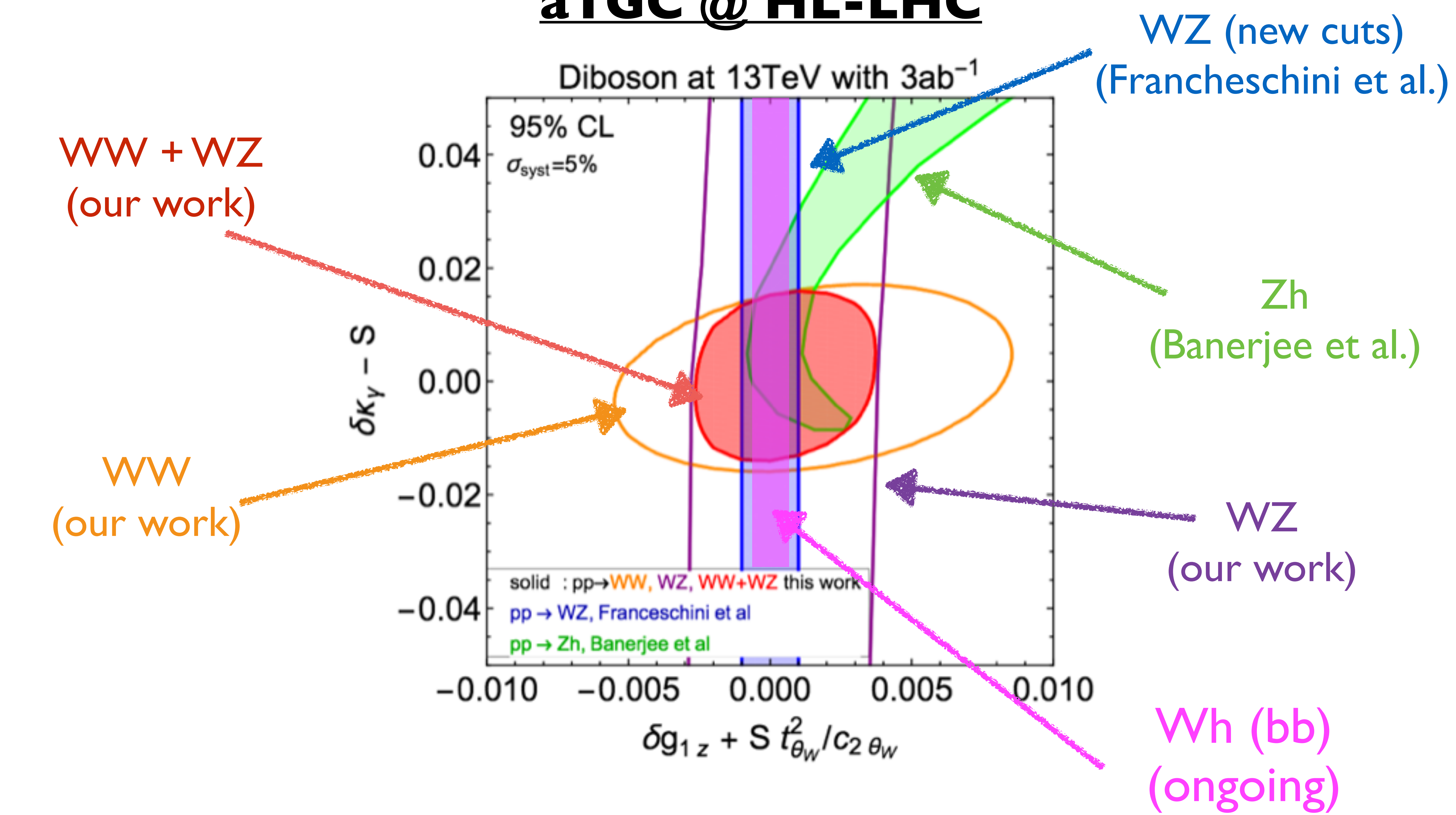


WW and WZ able to cover untested parts of the parameter space and improve w.r.t. LEP-1

(most useful when the coupling to the Higgs is large, and small to quarks)

Bounds from diboson to aTGC (for Univ. Th.)

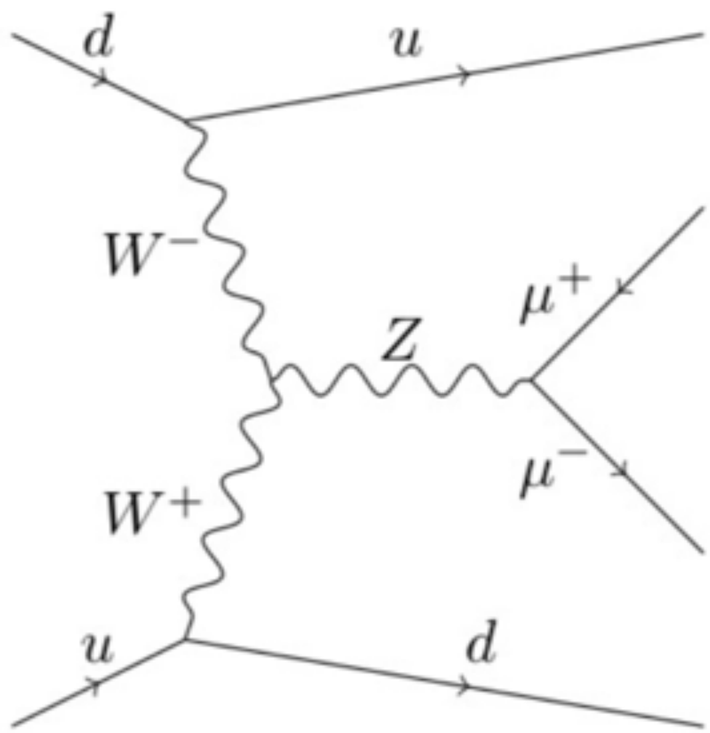
aTGC @ HL-LHC

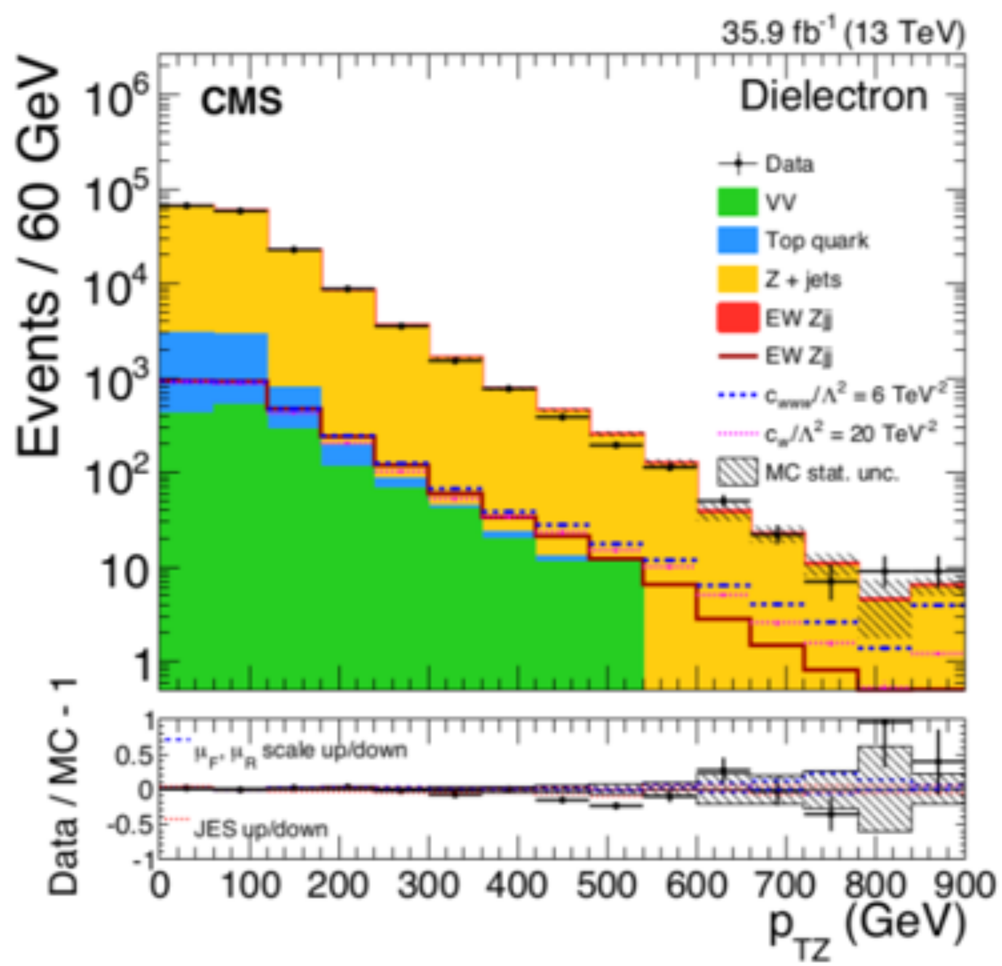


Wh(bb) may be even better than WW & WZ

Improving the sensitivity and range with VBF?

(ongoing with G. Durieux and M. Riembau)

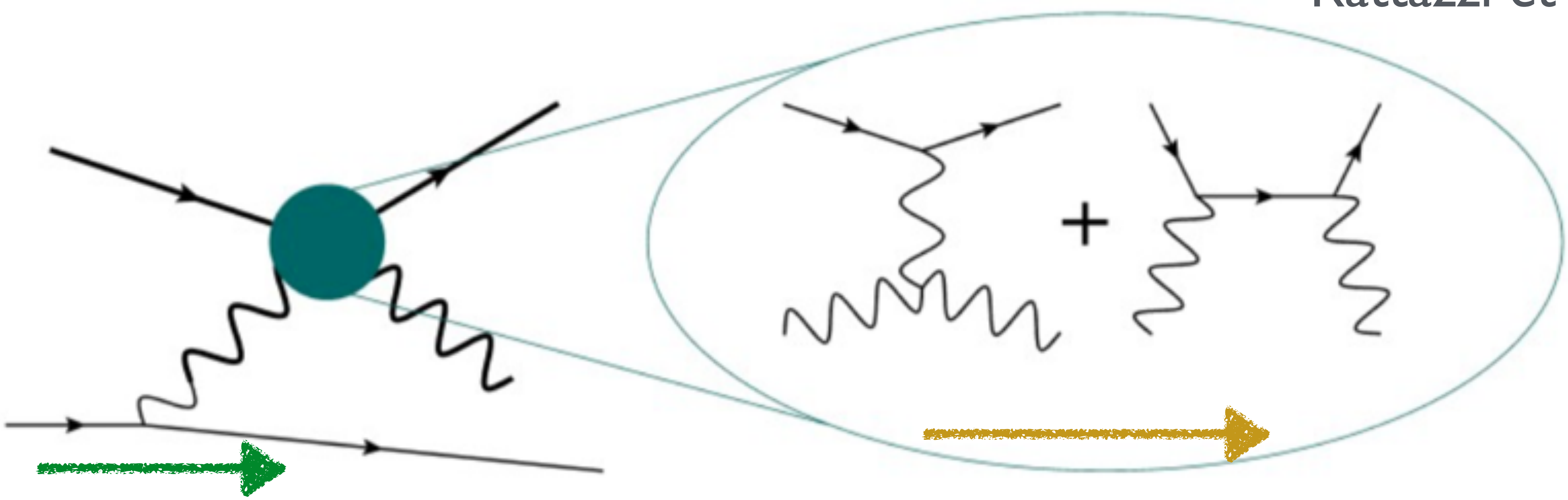




Why study VBF?

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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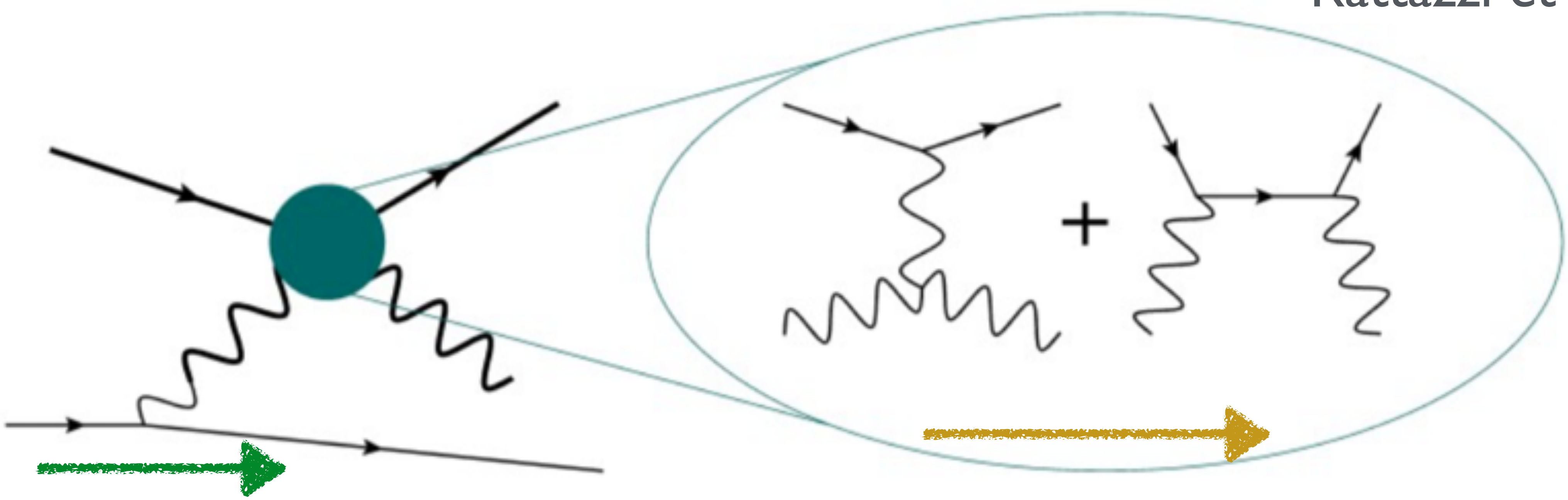

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Diboson has the same diagrams as the 2->2 channel rotated 90 degrees

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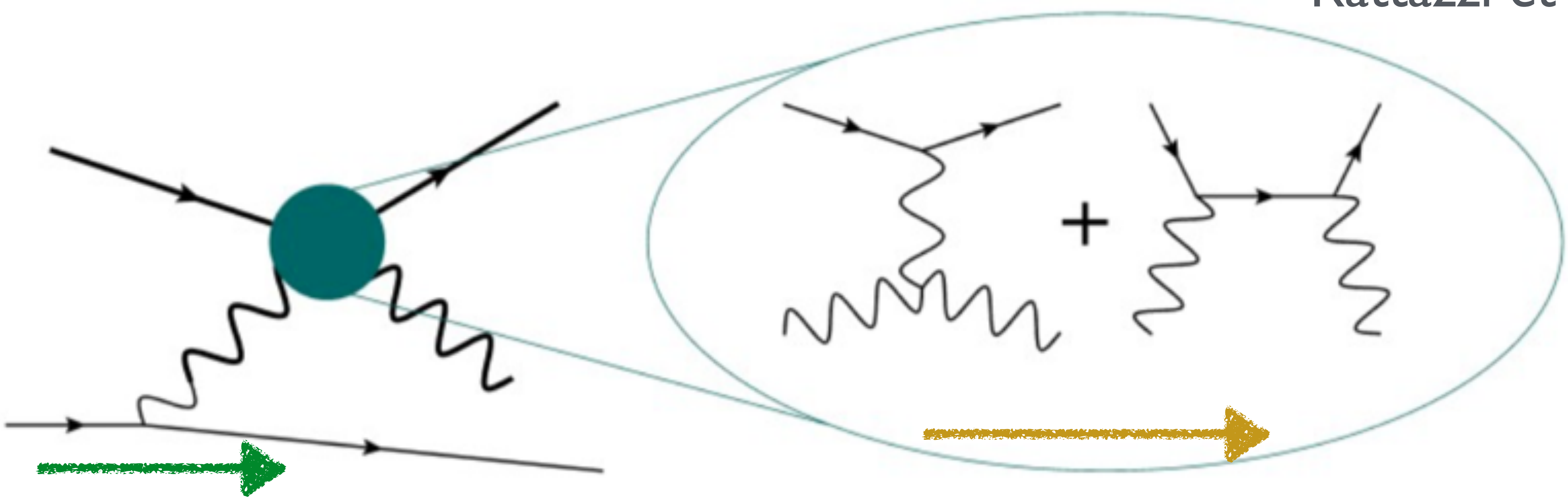

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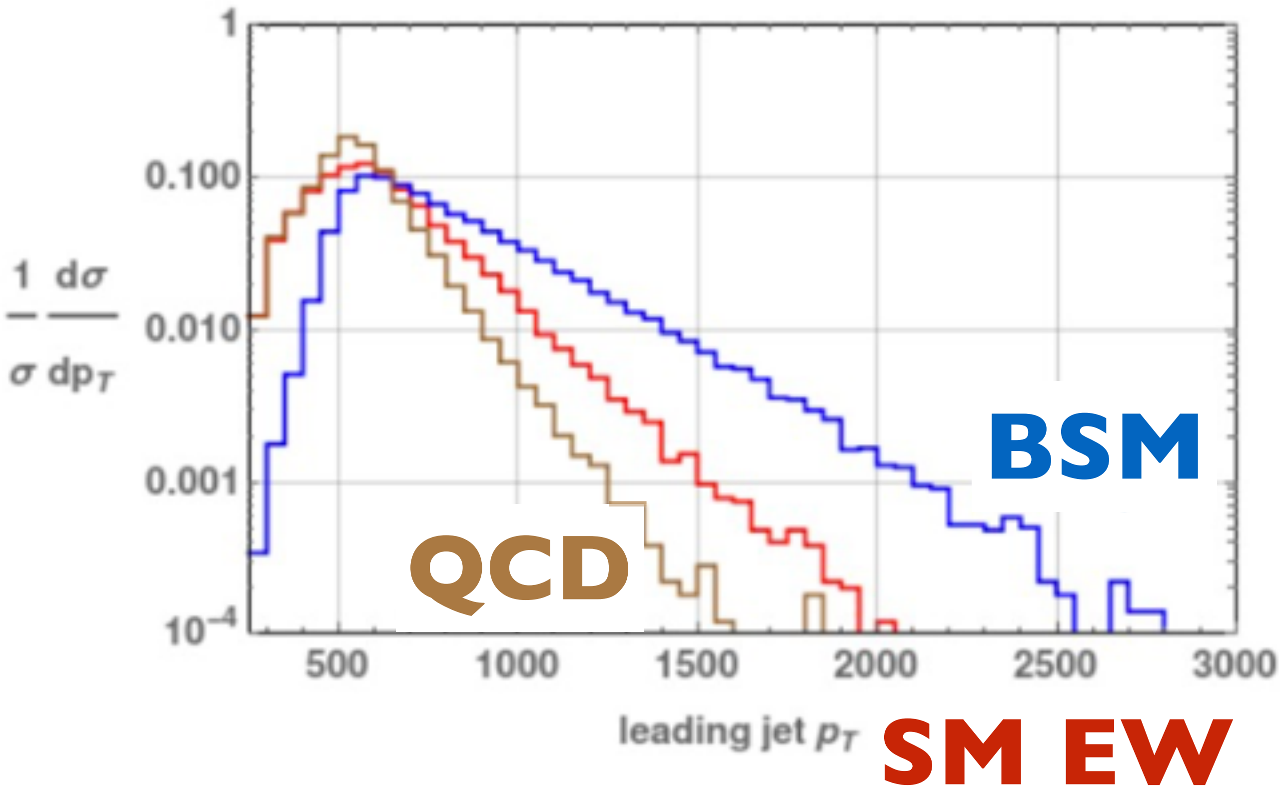
2) VBF is sensitive to the same operators as diboson

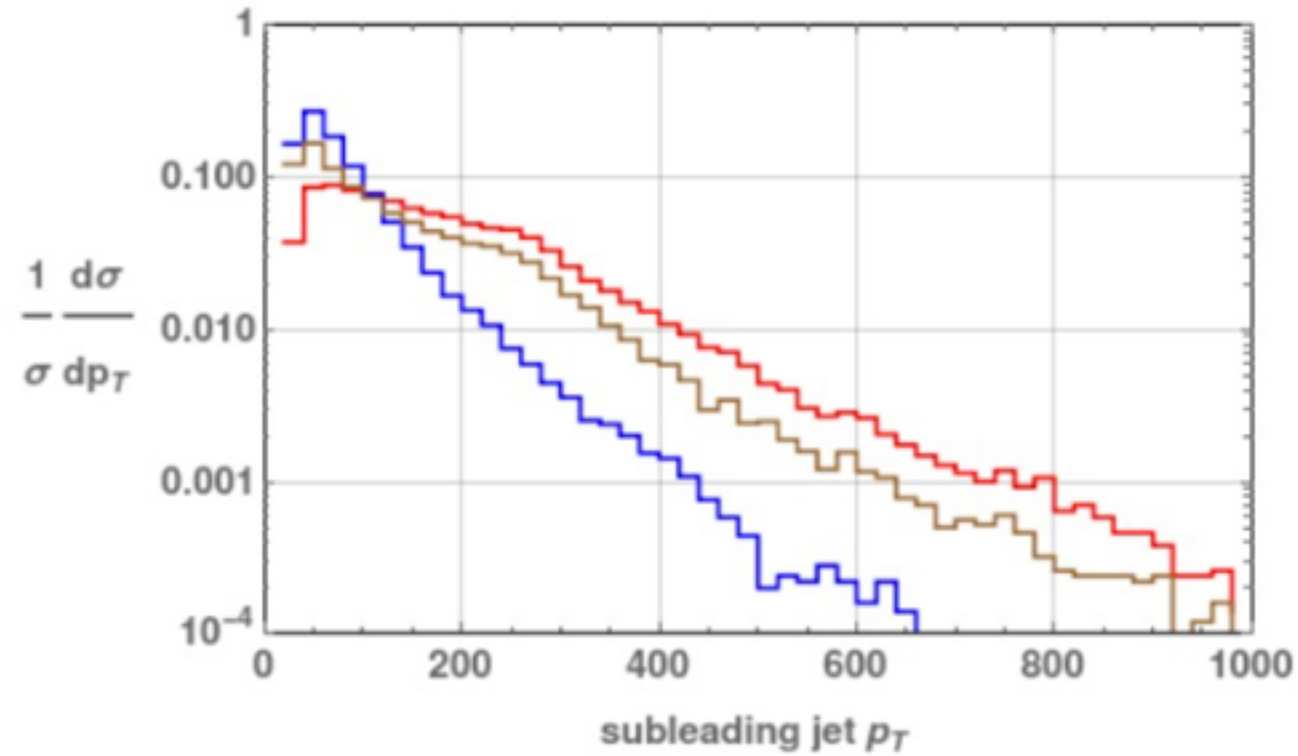
Diboson has the same diagrams as the 2->2 channel rotated 90 degrees

3) It is possible to completely reconstruct final state

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

First naive attempt: Separating soft vs hard processes



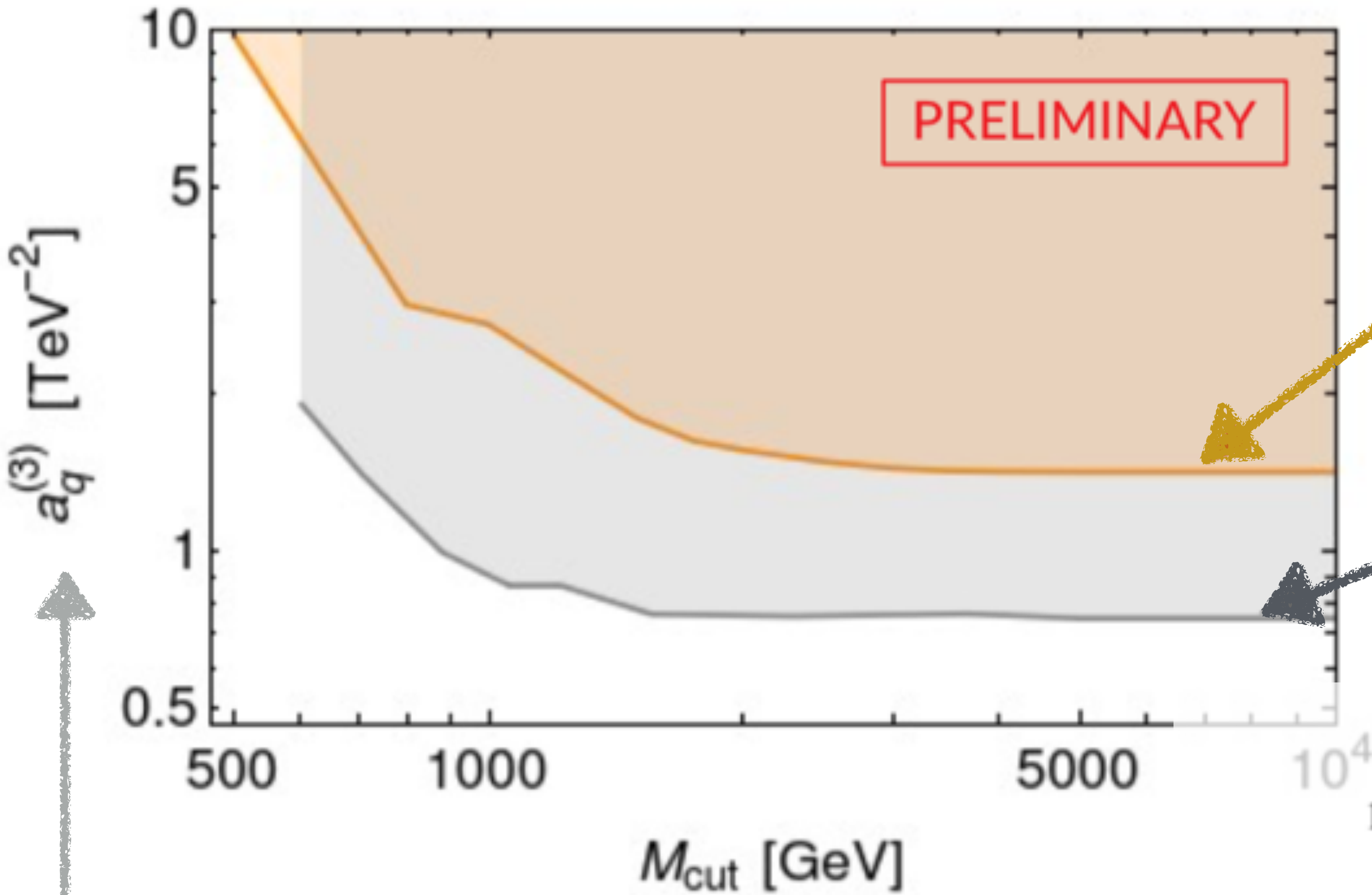


We can define a jet imbalance variable given by:

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

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

Comparing to other works with cuts that increase sensitivity

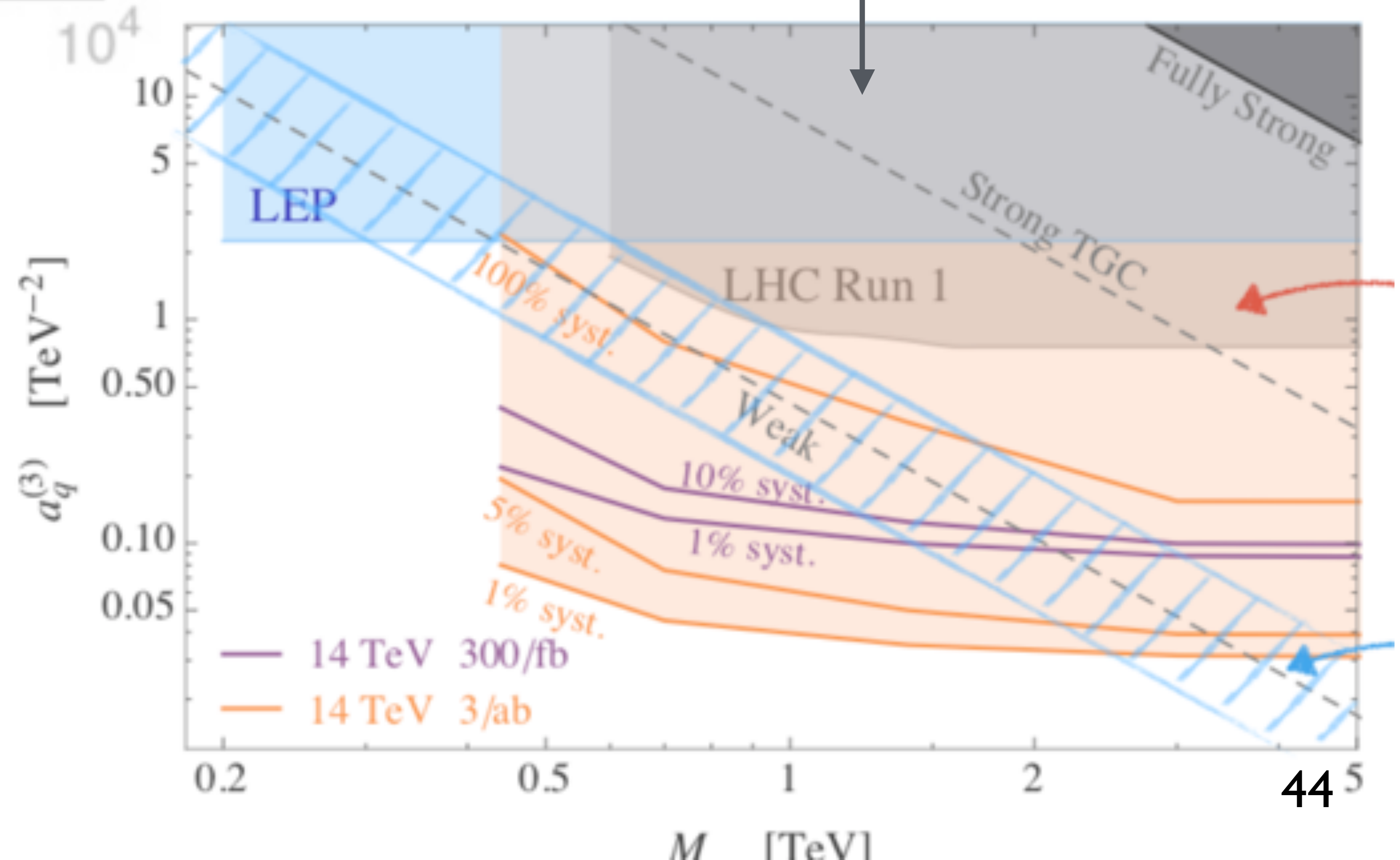


CMS VBF analysis adding CM E cuts only

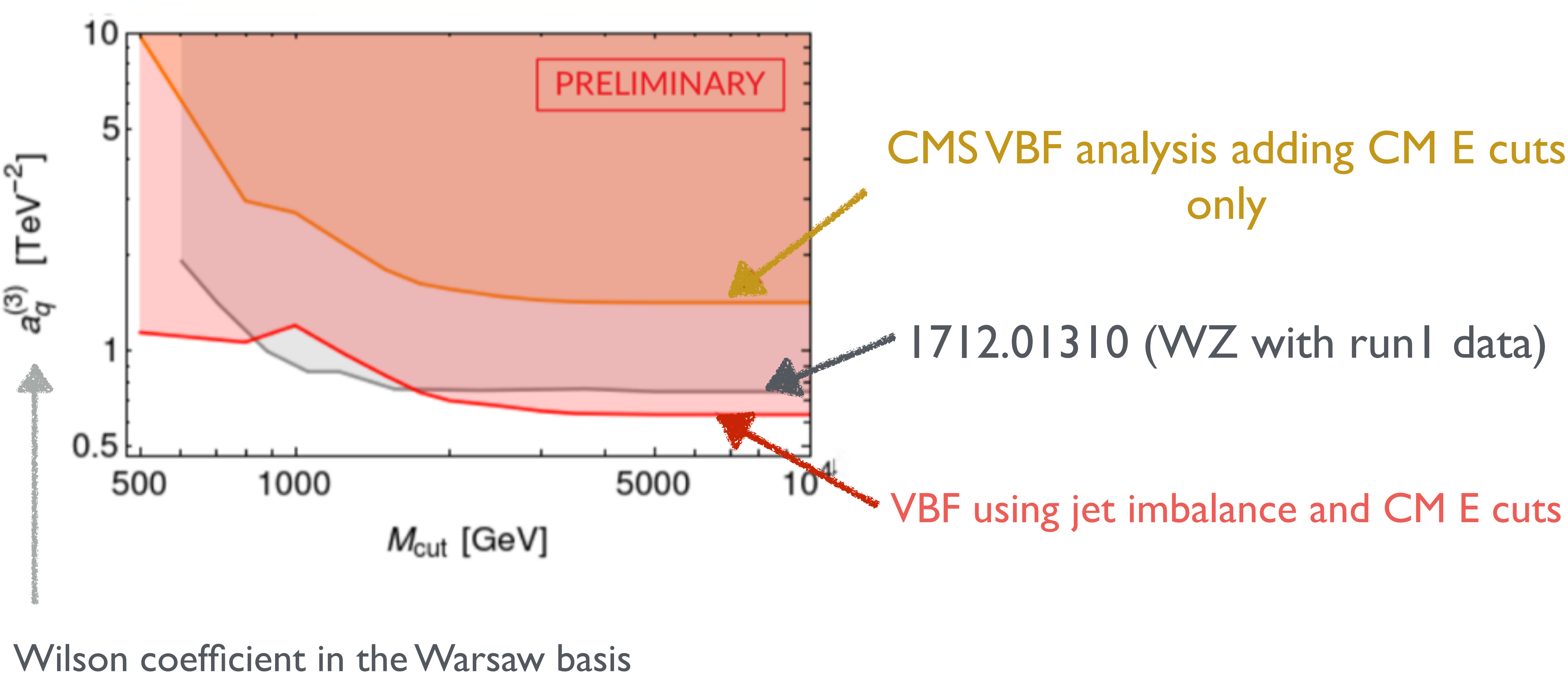
1712.01310 (WZ with run1 data)

Wilson coefficient in the Warsaw basis

$$a_q^{(3)}(\bar{q}_L\sigma^a\gamma^\mu q_L)(iH^\dagger\sigma^a\overleftrightarrow{D}_\mu H)$$



Comparing to other works with cuts that increase sensitivity



- Simple analysis already very powerful

Increased sensitivity and range to lower scales

- Possibility to further improve it with angular distributions, BDT

Conclusions

1) BSM processes that grow with CME @ LHC powerful to constrain NP

- Need of further study with other channels and more sensitive cuts

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

- At least under the MFV or FU assumptions

4) New possibilities to test diboson operators with VBF

Thanks

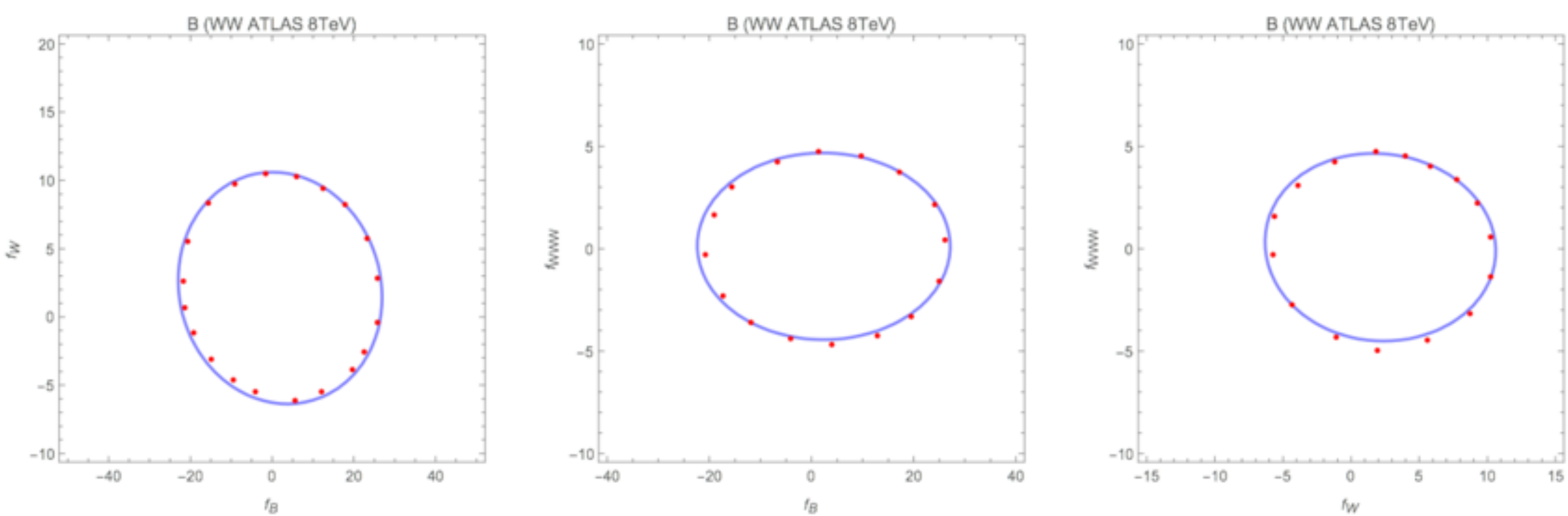
Used MadGraph5_aMC@NLO to get BSM cross section and fit

- 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]

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

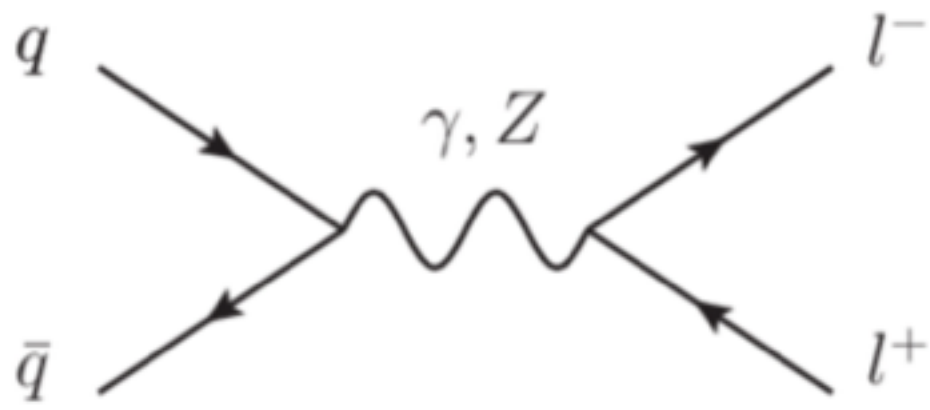
We chose the most significant leptonic channels

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]

Example 1: Drell-Yan

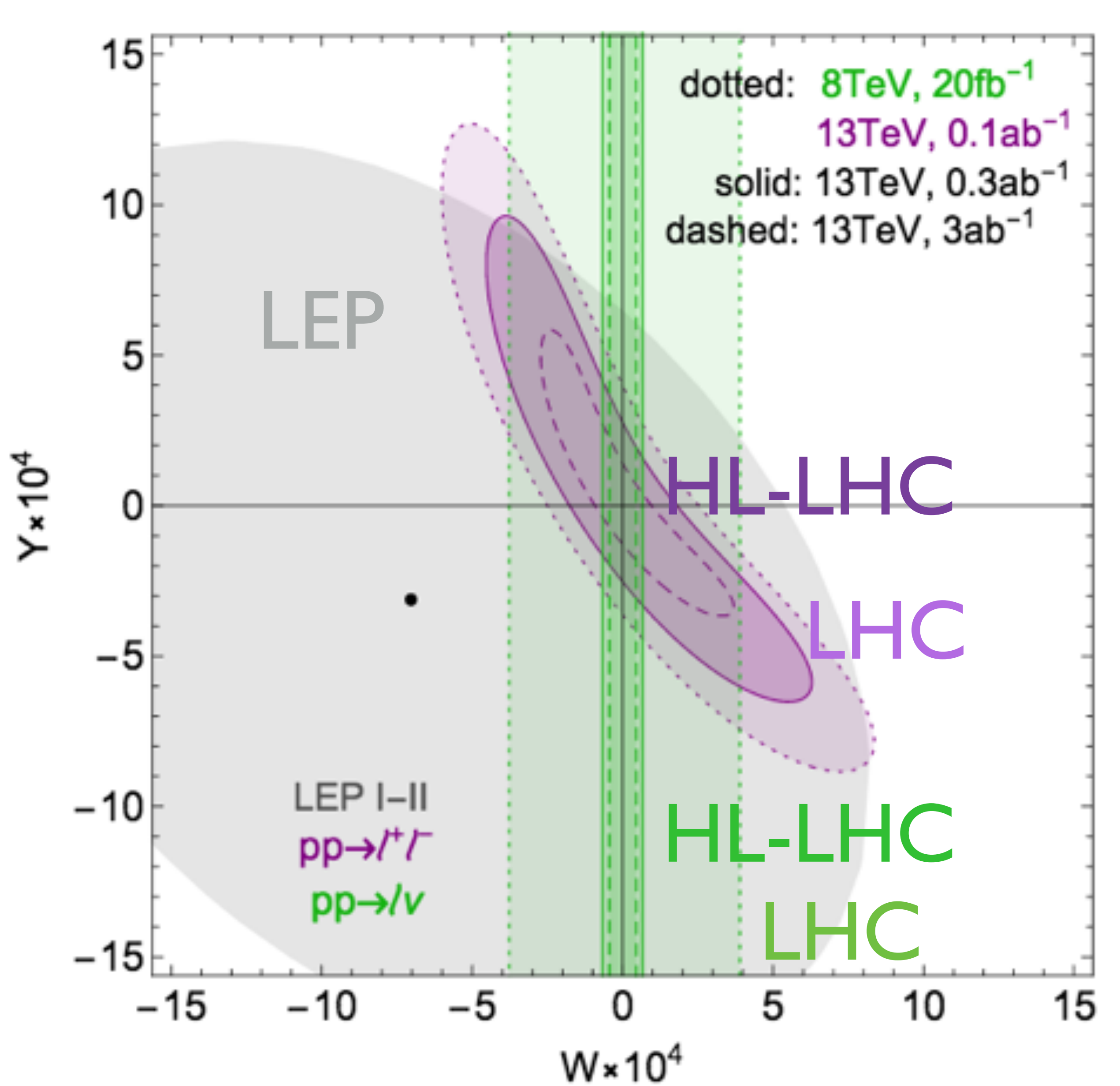
The sensitivity enhancement at the LHC has already been used to **expand previous LEP bounds**

Farina et al 1609.08157



Used to improve LEP bounds on **Universal Parameters W, Y**

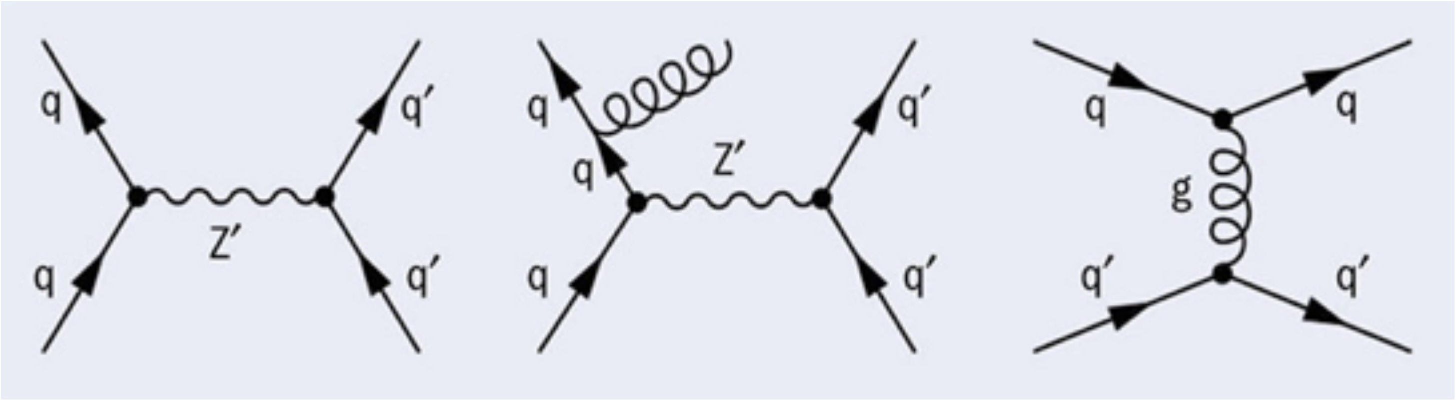
	universal form factor ($\mathcal{L}$)
W	$-\frac{\mathrm{W}}{4m_W^2}(D_\rho W^a_{\mu\nu})^2$
Y	$-\frac{\mathrm{Y}}{4m_W^2}(\partial_\rho B_{\mu\nu})^2$



This bounds can be translated for instance to masses of SU(2)$_L$ triplets

CH models, Little Higgs, extra dimensions, extended gauge symmetry

Example 3: Dijets



Constrains on Four quark interactions

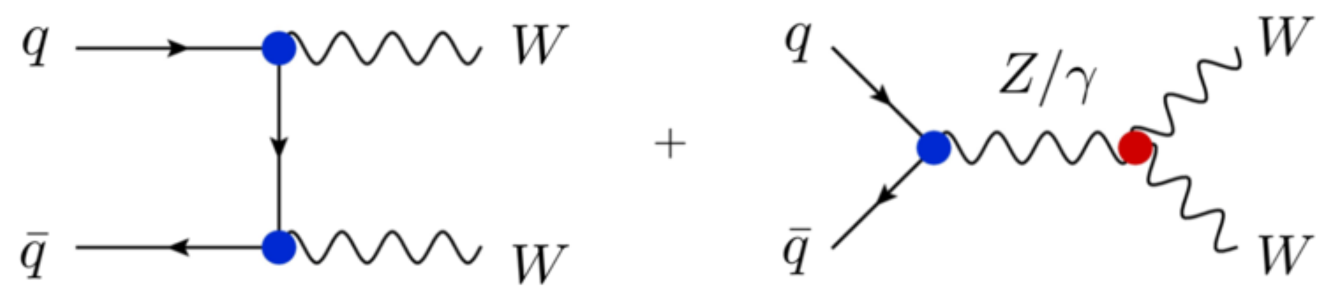
$$
\begin{aligned}
\mathcal{O}_{uu}^{(1)} &= (\bar{u}_R\gamma^\mu u_R)(\bar{u}_R\gamma_\mu u_R) \\
\mathcal{O}_{dd}^{(1)} &= (\bar{d}_R\gamma^\mu d_R)(\bar{d}_R\gamma_\mu d_R) \\
\mathcal{O}_{ud}^{(1)} &= (\bar{u}_R\gamma^\mu u_R)(\bar{d}_R\gamma_\mu d_R) \\
\mathcal{O}_{ud}^{(8)} &= (\bar{u}_R\gamma^\mu T^A u_R)(\bar{d}_R\gamma_\mu T^A d_R)
\end{aligned}
$$

$$
\begin{aligned}
\mathcal{O}_{qq}^{(1)} &= (\bar{q}_L\gamma^\mu q_L)(\bar{q}_L\gamma_\mu q_L) \\
\mathcal{O}_{qq}^{(8)} &= (\bar{q}_L\gamma^\mu T^A q_L)(\bar{q}_L\gamma_\mu T^A q_L) \\
\mathcal{O}_{qu}^{(1)} &= (\bar{q}_L\gamma^\mu q_L)(\bar{u}_R\gamma_\mu u_R) \\
\mathcal{O}_{qu}^{(8)} &= (\bar{q}_L\gamma^\mu T^A q_L)(\bar{u}_R\gamma_\mu T^A u_R) \\
\mathcal{O}_{qd}^{(1)} &= (\bar{q}_L\gamma^\mu q_L)(\bar{d}_R\gamma_\mu d_R) \\
\mathcal{O}_{qd}^{(8)} &= (\bar{q}_L\gamma^\mu T^A q_L)(\bar{d}_R\gamma_\mu T^A d_R)
\end{aligned}
$$

Can be translated for instance to bounds on
Quark Compositeness, Heavy gauge bosons, KK-gluons, Axigluons
(> 1 TeV)

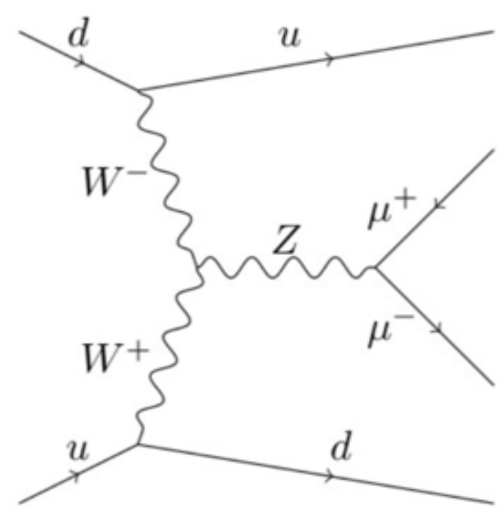
In the DESY-ph group we have focused on diboson at High E:

1) 1810.05149 with C. Grojean and M. Riembau



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

(ongoing)



3) 190x.xxxxx with F. Bishara, P. Englert, C. Grojean, G. Panico, A. Rossia

(ongoing)