# Diboson pair production

Joan Elias Miró

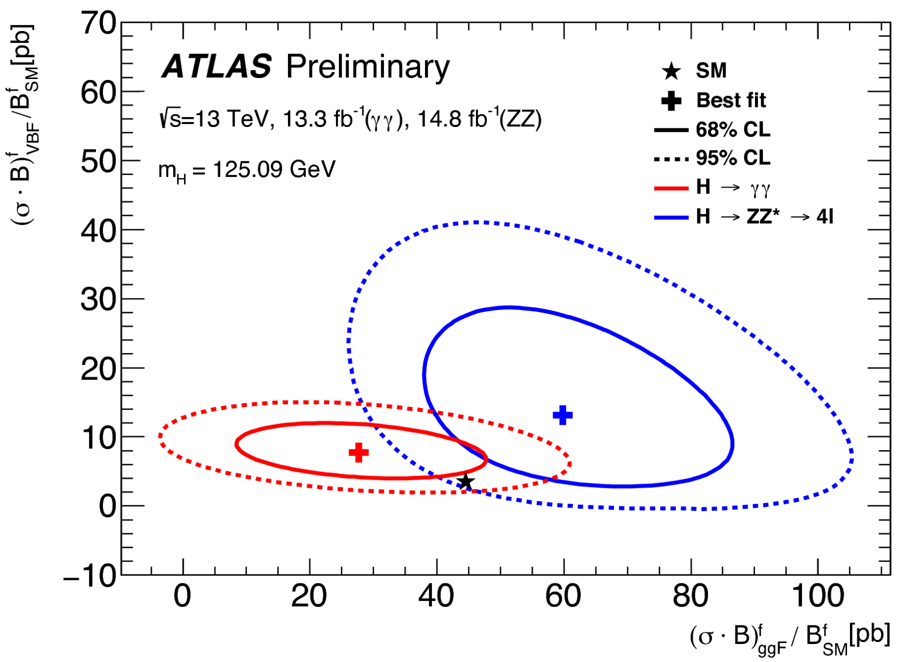
*Physics of the HL-LHC, and perspectives at a high energy LHC* — CERN

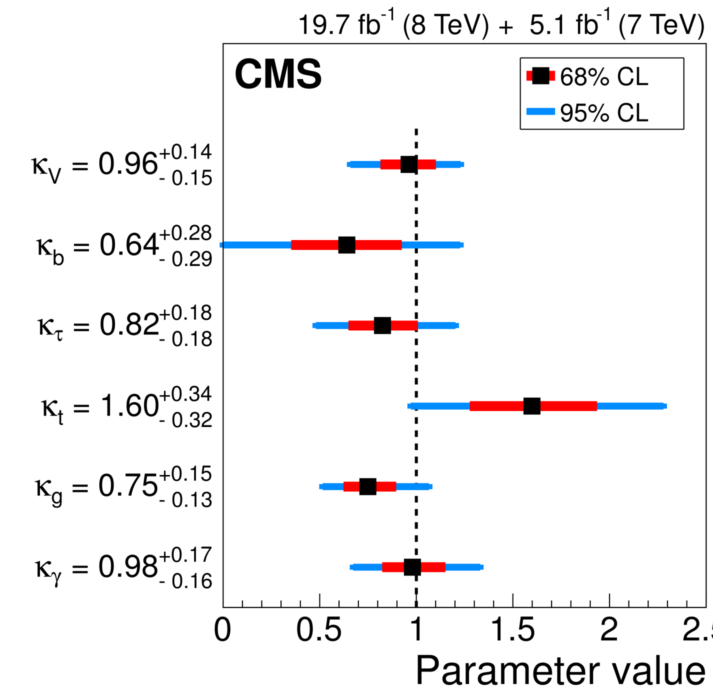
1/11/2017

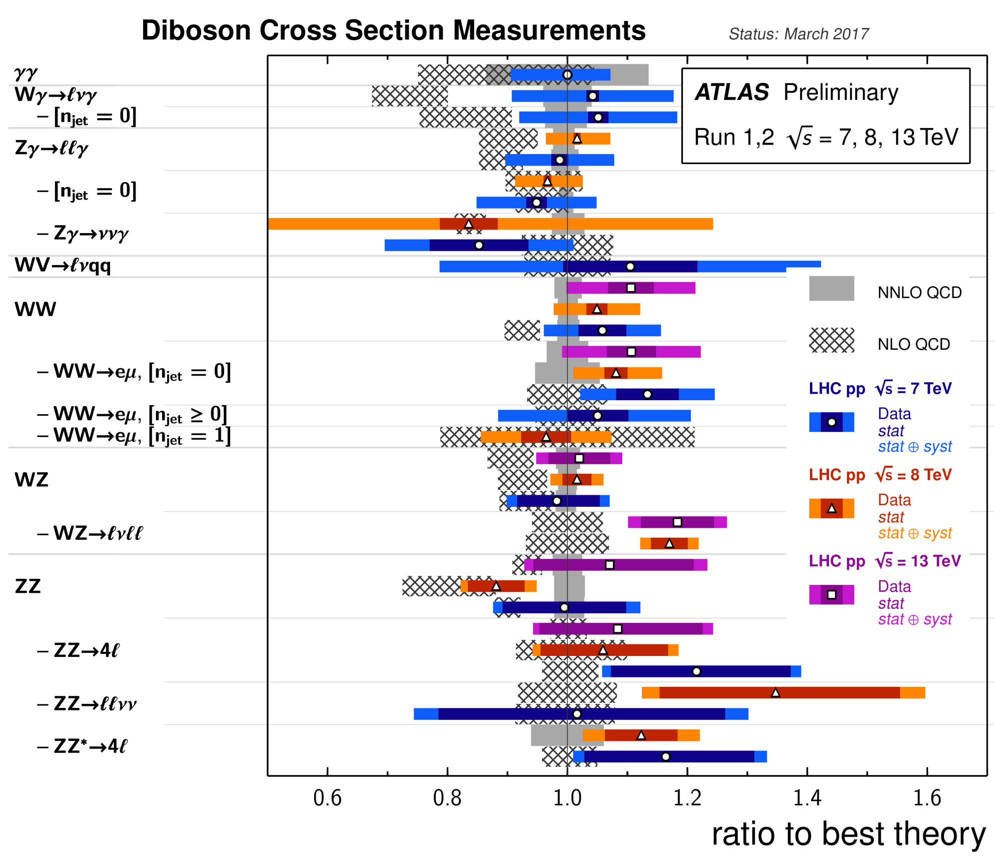
**1707.08060 w/ Azatov, Reyimuaji, Venturini**

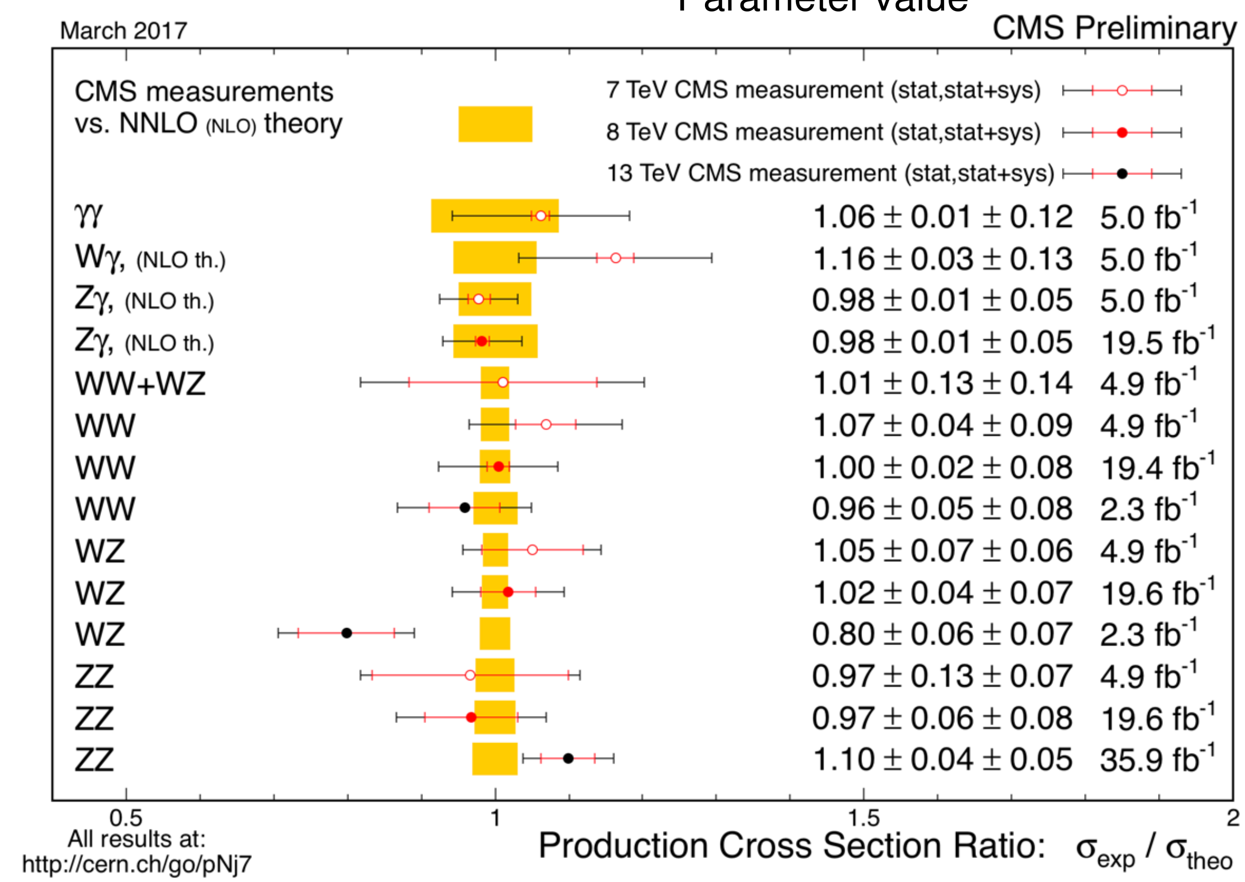
ma per seguir virtute e canoscenza
SISSA

# LHC is performing great…




… but no new particles, no significant deviations in the data.

## *We should understand the consequences of that*

Two complementary avenues towards achieving this goal:

a) Model building — paradigm change.

b) Detailed understanding of the real pressure — the LHC legacy.

*We ~~should~~ must understand the consequences of that*

Two complementary avenues towards achieving this goal:

a) Model building — paradigm change.

b) Detailed understanding of the real pressure — the LHC legacy.

this talk

LHC searches suggest that there is a separation between the EW scale and the scale of new physics $\mathit{\Lambda}$.

$$\frac{M_W^2}{\Lambda^2} \ll 1$$

*EFT approach is convenient to organize the lessons we learn from LHC.*

# *What does the EFT approach buys for us? — SM EFT philosophy*

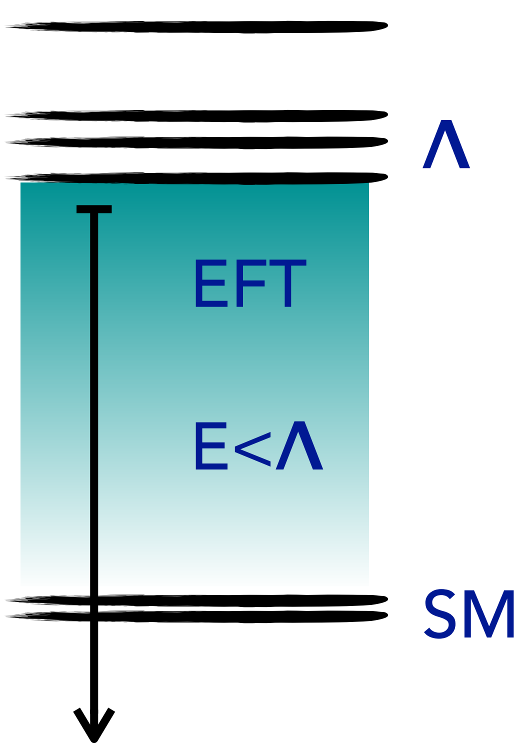
* Consistent framework for the parametrization of BSMs.

* Deformation of the SM in a way where the assumptions taken tend to be clear ("model independence").

* With suitable parameterizations one can learn about broad classes of models (e.g. SILH, univ. BSM, MFV, ...).

* The dim>4 operators connect further physics that are otherwise more independent (e.g. learn Higgs physics from LEP measurements, information about TGC from Higgs measurements, etc.).

* ...



The prevailing point of view is that the SM is an EFT — as any other theory of nature discovered so far.

$$
\begin{aligned}
\mathcal{L}^{E<TeV}_{\text{nature}} = \overbrace{\mathcal{L}^{\text{dim}\leq 4}_{\text{SM}}}^{\checkmark} &+ \frac{c}{\Lambda} \overbrace{\tilde{H}^T \Psi_L \bar{\Psi}^* H}^{\text{dim. five}} + \\
&+ \frac{1}{\Lambda^2} \overbrace{\left(c_1 \bar{\psi}_L F_{\mu\nu} \psi_R H + c_2 |H|^2 W_{\mu\nu} W^{\mu\nu} + \cdots\right)}^{\text{dimension six } ?} \\
&+ \frac{1}{\Lambda^4} \overbrace{\left(c_3 \psi_L \gamma^\mu \psi_L D^\mu W_{\tau\sigma} W^{\tau\sigma} + \cdots\right)}^{\text{dimension eight. } ?} \\
&+ \ldots
\end{aligned}
$$

Any heavy particle of mass $m > g_{NP}\Lambda$ is integrated out.

$$
\sigma \sim SM^2 + \frac{SM \times BSM_6}{\Lambda^2} + \frac{BSM_6^2}{\Lambda^4} + \frac{SM \times BSM_8}{\Lambda^4} + \cdots
$$

*Plan of the talk:*

*Precise measurements of Triple Gauge Couplings (TGC) within EFT approach.*

## *Triple gauge couplings, what do we know?*

In the SM, there is a single TGC which can be breakdown as

$$\mathcal{L}_{TGC} \;=\; ig\,(W^{+\,\mu\nu}W^{-}_{\mu}\,W^{3}_{\nu} + \,W^{\mu\nu}_{3}W^{+}_{\mu}W^{-}_{\nu}) \sim \partial WWW$$

where $W^3_\mu = c_\theta Z_\mu + s_\theta A_\mu$

Beyond the SM, what ops. can we write at d=6 level? (weak coupling)

Only two type of **CP even** interactions are possible:

$$\mathcal{L}_{aTGC} \sim v^2\,\partial WWW + \partial W\partial W\partial W$$

2.- Different momentum and helicity interaction

1.- Deformation of existing TGC

# a(nomalous)TGC of the 1st kind

$$\mathcal{L}_{TGC} = ig\, W^{+\,\mu\nu} W^-_\mu \,(c_\theta Z_\nu + s_\theta A_\nu) + ig\,(c_\theta Z^{\mu\nu} + s_\theta A^{\mu\nu}) W^+_\mu W^-_\nu$$

$$\downarrow$$

$$\mathcal{L}^{1st}_{aTGC} = ig\, W^{+\,\mu\nu} W^-_\mu \,(c_\theta\, \delta g_{1,z}\, Z_\nu + s_\theta\, \cancel{\delta g_{1,\gamma}}\, A_\nu) + ig\,(c_\theta\, \delta\kappa_z\, Z^{\mu\nu} + s_\theta\, \delta\kappa_\gamma\, A^{\mu\nu}) W^+_\mu W^-_\nu$$

gauge inv.

At d=6 level, gauge invariance implies $\delta\kappa_z = \delta g_{1,z} - s_\theta^2/c_\theta^2\, \delta\kappa_\gamma$

# aTGC of the 2nd kind

$$\mathcal{L}^{2nd}_{aTGC} = \lambda_z \frac{ig}{m_W^2} W^{+\,\mu_2}_{\mu_1} W^{-\,\mu_3}_{\mu_2} W^{3\,\mu_1}_{\mu_3}$$

**All in all, we have 3 CP-even aTGC** $\delta g_{1,z}\,,\ \delta\kappa_\gamma\,,\ \lambda_z$

Gaemers, Gounaris 78'
Hagiwara, Peccei, Zeppenfeld, Hikasa 86'

## Famous LEP-II % measurements

$$\begin{aligned} \delta g_{1,z} &= -0.016^{+.018}_{-.020} \\ \delta\kappa_\gamma &= -0.018 \pm 0.042 \\ \lambda_z &= -0.022 \pm 0.019 \end{aligned}$$

* Derived from diboson production.
* Fixed collision energy.
* EFT interpretation is straightforward.

LEP [1302.3415]

One can perform a global analysis of *all* SM dim6 operators.

After constraints from W/Z pole observables only **3** parameters

to describe **possible deviations** of diboson production $\delta g_{1,z}\ ,\ \ \delta\kappa_\gamma\ ,\ \ \lambda_z$

These are matched into **4** unconstrained **Wilson coefficients**.

**3<4 ⇒ flat direction** — can be lifted with Higgs physics data.

EM, Espinosa, Masso, Pomarol [1308.1879]
Riva, Pomarol [1308.2803]
Falkowski, Riva [1411.0669]

# *TGC, diboson, EFT and the LHC*

In summary, our limits are consistent with the SM prediction and improve upon the sensitivity of the fully leptonic 8 TeV results [6, 7] and the combined LEP experiments [37, 42].

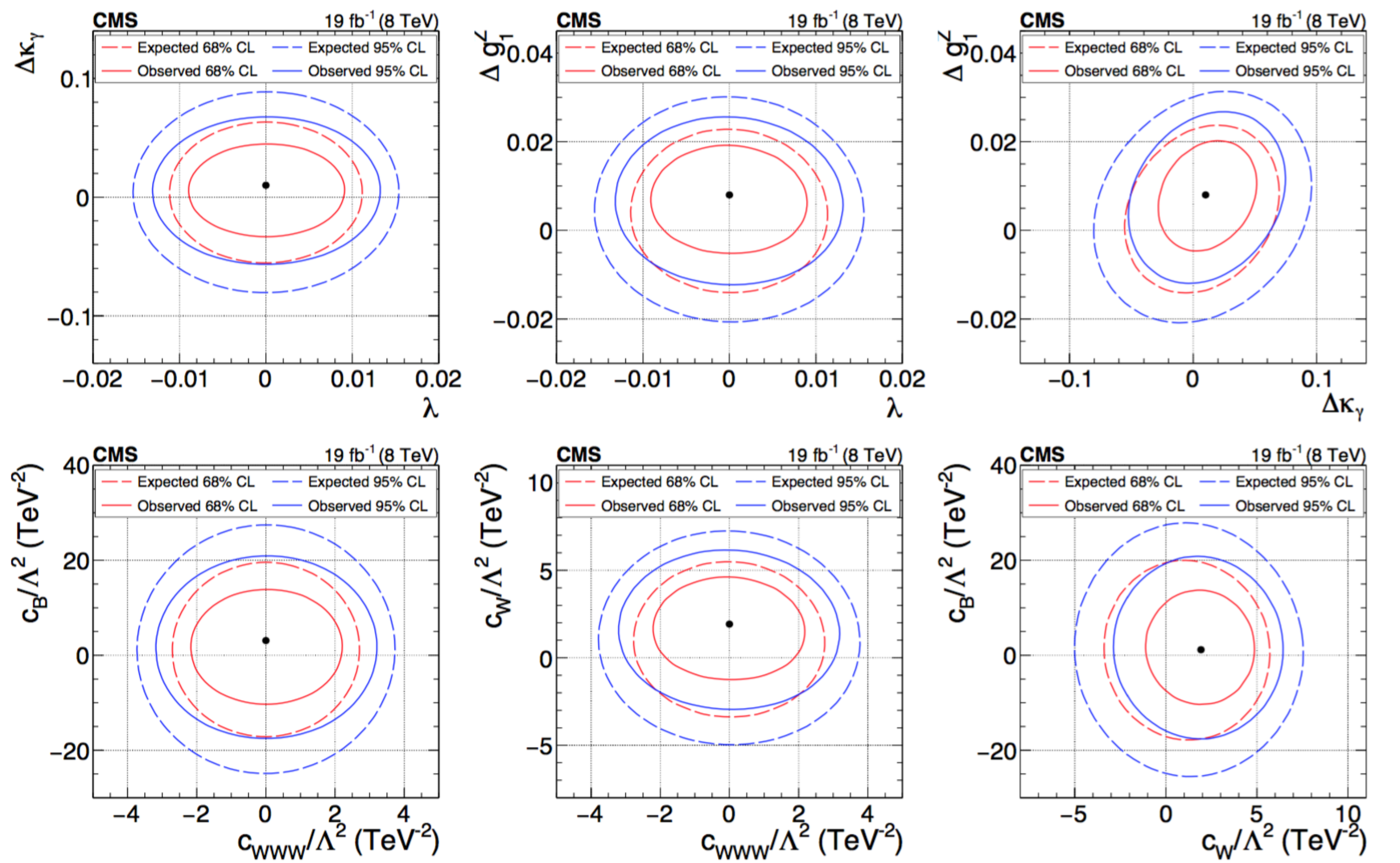


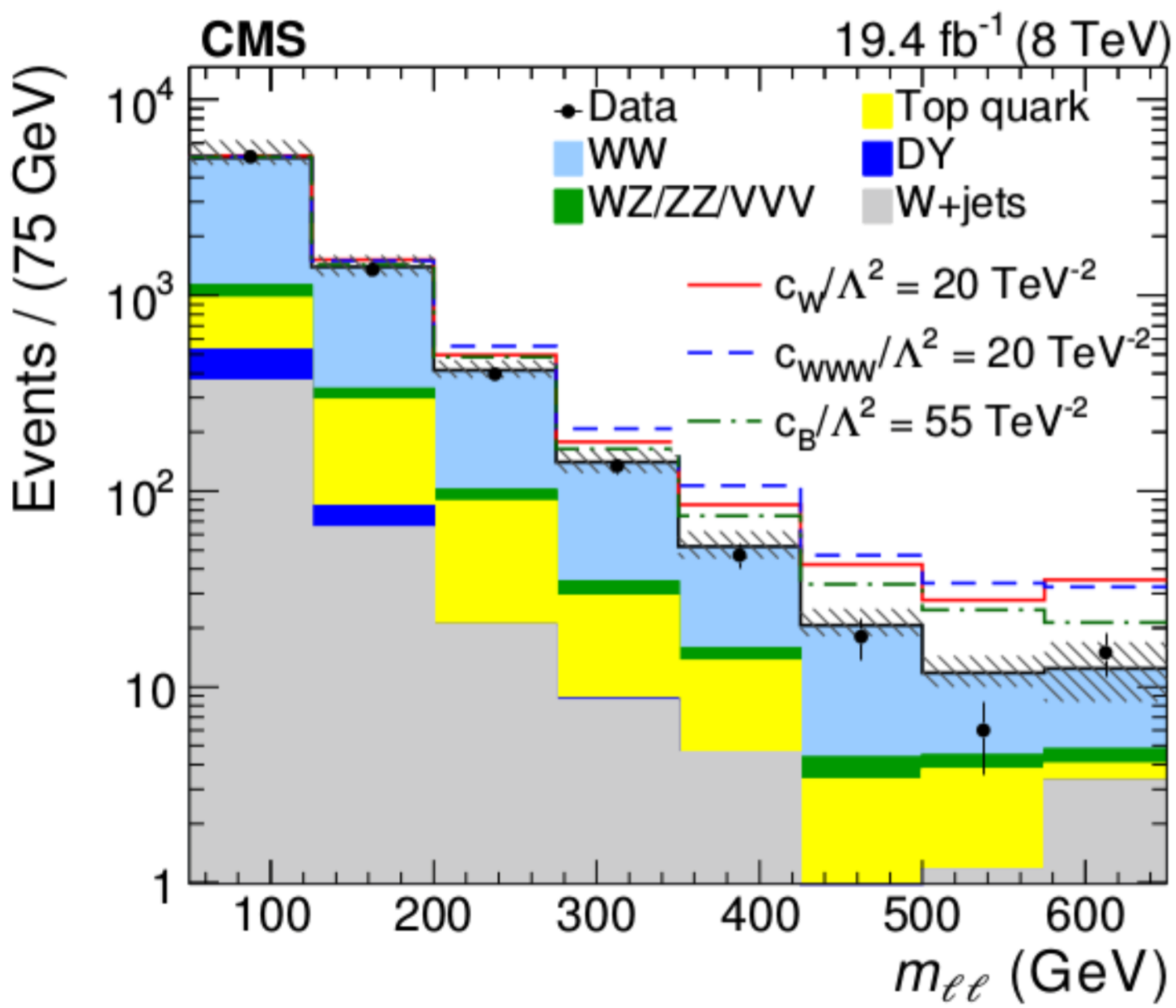

Figure 3: The 68 and 95% CL observed and expected exclusion contours in ΔNLL are depicted for three pairwise combinations of the aTGC parameters in the LEP parametrization (top) and in the EFT formulation (bottom). The black dot represents the best fit point.

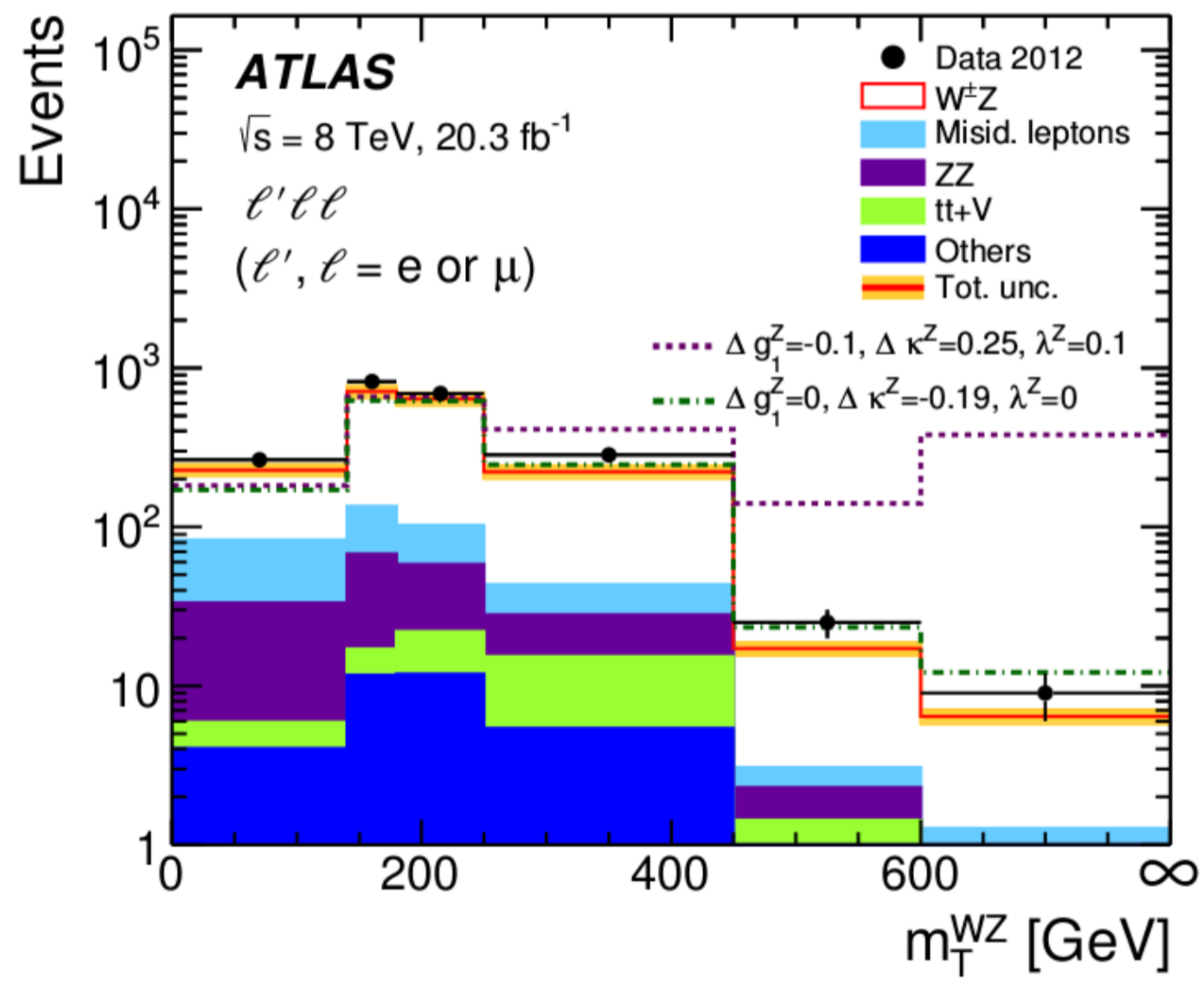
CMS [1703.06095]

LHC has surpassed the precision of LEP on TGC,

but which theories are this bounds proving?

Most of its sensitivity comes from the tails, where the EFT description can break.



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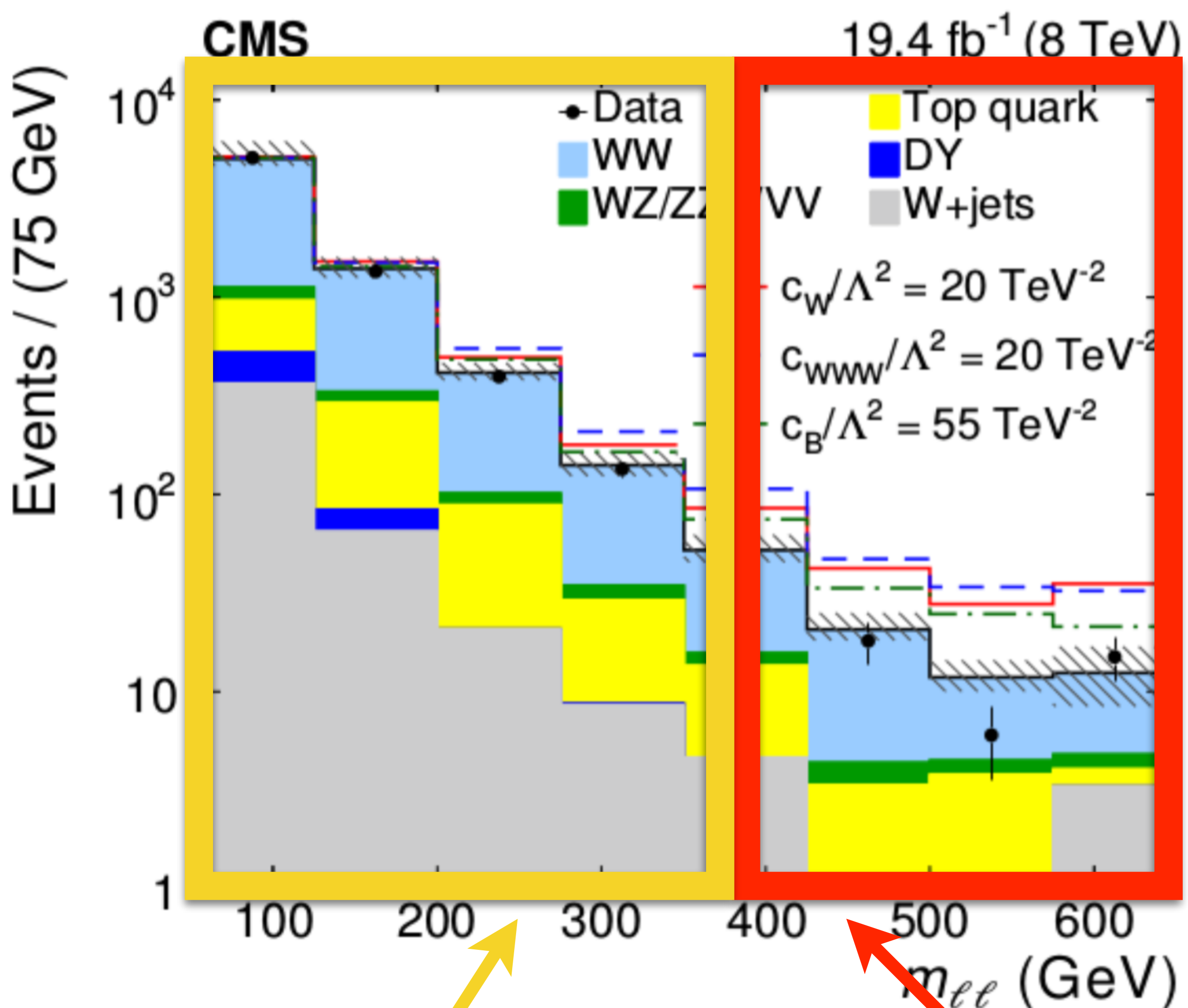
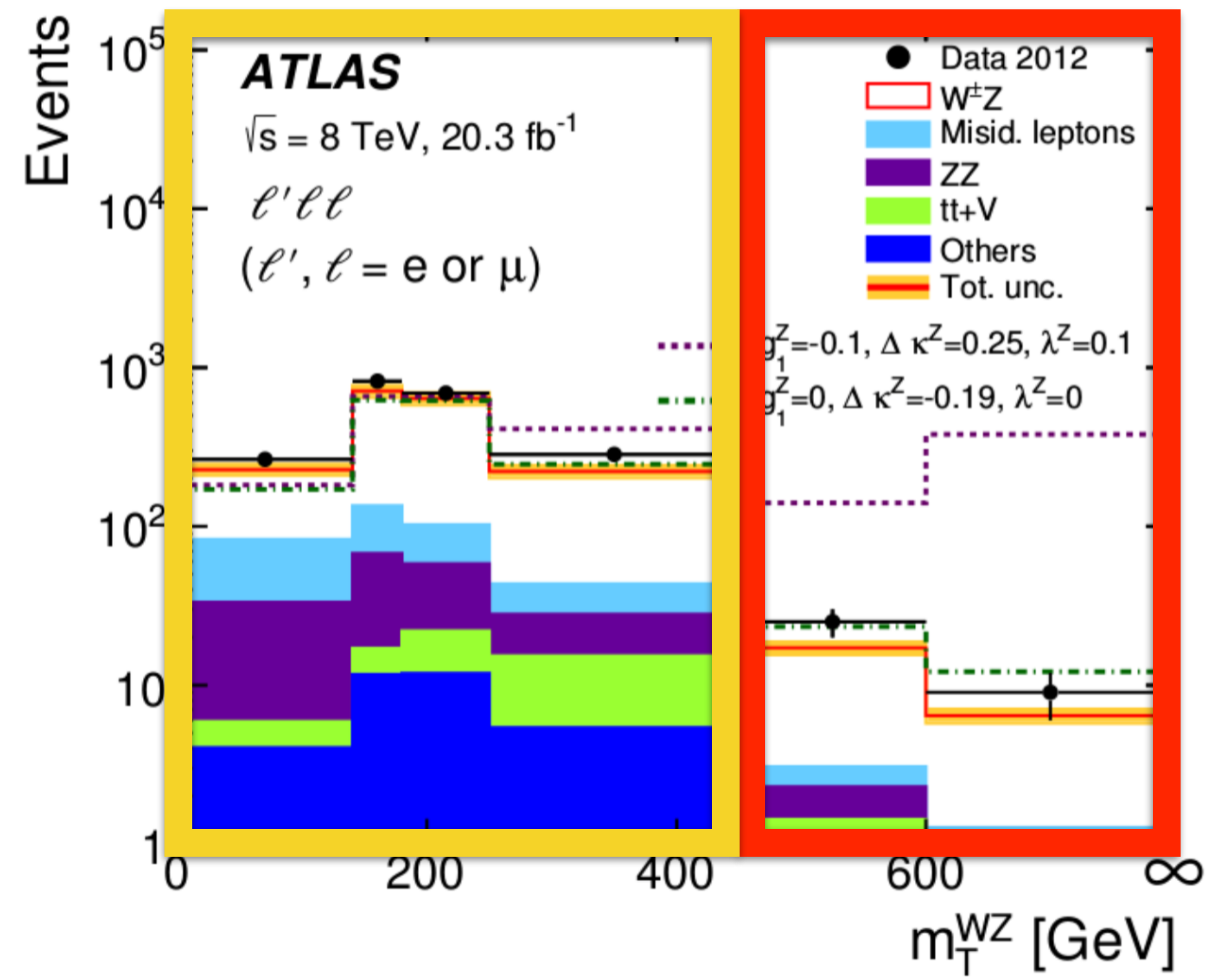



EFT with smaller cutoff may apply

Large cutoff, implies sensitivity to large coupling

To prove less *exotic* theories we need better sensitivity

Two effects we may worry about the EFT measurement:

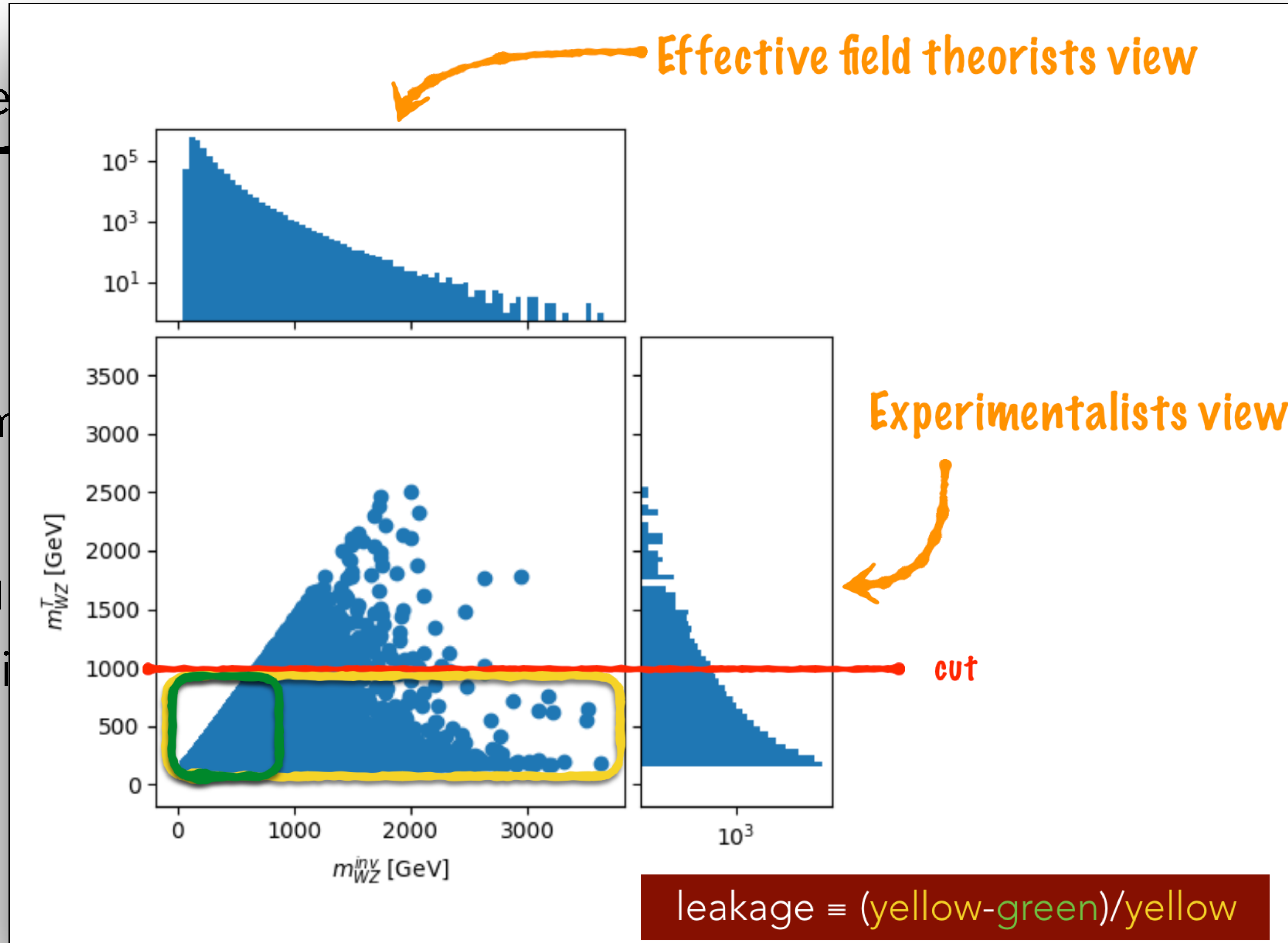
* Leakage of high invariant mass events
* Strong sensitivity to quadratic terms vs linear ones.

To prove

Two effects we m

* Leakage of hig

* Strong sensitivi




I won't discuss it today, see the studies
1609.06312 — Falkowski, Gonzalez-Alonso, Greljo, Marzocca, Son
1707.08060 — Azatov, Elias-Miro, Reyimuaji, Venturni

To prove less *exotic* theories we need better sensitivity

Two effects we may worry about the EFT measurement:

* Leakage of high invariant mass events
* Strong sensitivity to quadratic terms vs linear ones.

# An obstruction to precision

$$\sigma \sim SM^2 + \frac{SM \times BSM_6}{\Lambda^2} + \frac{BSM_6^2}{\Lambda^4} + \frac{SM \times BSM_8}{\Lambda^4} + \cdots$$

Helicity selection rules. In some cases the interference term vanishes, at tree-level.

**Which ops. can interfere?**

## Two groups of dim6 operators

[for any basis]

1) "Current-current ops.":

Those that **can** be resolved by the tree-level exchange of a spin s≤1 resonance.

2) "Loop ops.":

Those that **can't** be resolved by the tree-level exchange of a spin s≤1 resonance.

# An obstruction to precision

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**Which ops. can interfere?**

**Two groups of dim6 operators** [for any basis]

1) "Current-current ops.":

Those that **can** be resolved by the tree-level exchange of a spin s≤1 resonance.

**⇒ they can mediate processes with same helicity configuration as in the SM.**

2) "Loop ops.":

Those that **can't** be resolved by the tree-level exchange of a spin s≤1 resonance.

**⇒ require case by case analysis.** (maybe can be classified with susy? spurion vev sucks helicity of the process and that's why some of them lead to MHV amplitudes…)

See Azatov, Contino, Machado, Riva [1607.05236] for thorough analysis — classification there is based on different logic.

$W^3{}_{\mu\nu}$ is of the second group.

Azatov, Contino, Machado, Riva [1607.05236]
Dixon, Shadmi [9312363]

Does not lead to 2->2 amplitudes with same helicity as in the SM ⇒ thus interference vanishes.

$$O_{3W} \propto w_{\alpha}{}^{\beta} w_{\beta}{}^{\gamma} w_{\gamma}{}^{\alpha} + \bar{w}_{\dot{\alpha}}{}^{\dot{\beta}} \bar{w}_{\dot{\beta}}{}^{\dot{\gamma}} \bar{w}_{\dot{\gamma}}{}^{\dot{\alpha}}$$

# Energy growth of the BSM amplitudes

thanks to A. Azatov for the slide

We start with dimension six operators

$$O_{HB} = ig'(D^\mu H)^\dagger D^\nu H B_{\mu\nu},\, O_{HW} = ig(D^\mu H)^\dagger \sigma^a D^\nu H W^a_{\mu\nu}$$
$$O_{3W} = \frac{g}{3!}\epsilon_{abc} W^{a\,\nu}_{\mu} W^{b\,\rho}_{\nu} W^{c,\mu}_{\rho}$$

Goldstone equivalence theorem relates $\boxed{H \Rightarrow W_L, Z_L}$

$$\begin{aligned}
O_{HB} &\supset \partial W_L \partial Z_T \partial W_L + v W_T \partial Z_T \partial W_L + v^2 W_T \partial Z_T W_T + \ldots \\
O_{HW} &\supset \partial V_L \partial V_T \partial V_L + v V_T \partial V_T \partial V_L + v^2 V_T \partial V_T V_T + \ldots \\
O_{3W} &\supset \partial V_T \partial V_T \partial V_T + \ldots
\end{aligned}$$

**Leading energy scaling can be estimated by noting that the light quarks couple mostly to transverse gauge bosons:**

$$\mathcal{M}\left(q\bar{q} \to W_L^- W_L^+\right) \sim E^2/\Lambda^2\ c_{HB} + E^2/\Lambda^2\ c_{HW} \sim E^2/m_W^2\ \delta g_{1,Z} + E^2/m_W^2\ \delta\kappa_Z$$
$$\mathcal{M}\left(q\bar{q} \to Z_L W_L^+\right) \sim E^2/\Lambda^2\ c_{HW} = E^2/m_Z^2\ \delta g_{1,Z}\ ,$$
$$\mathcal{M}\left(q\bar{q} \to V_T W_T^+\right) \sim E^2/\Lambda^2\ c_{3W} = E^2/m_W^2\ \lambda_Z$$

**We have an additional $E^2$ compared to the SM amplitudes, as expected from dimensional analysis**

# Energy growth of the BSM amplitudes

thanks to A. Azatov for the slide

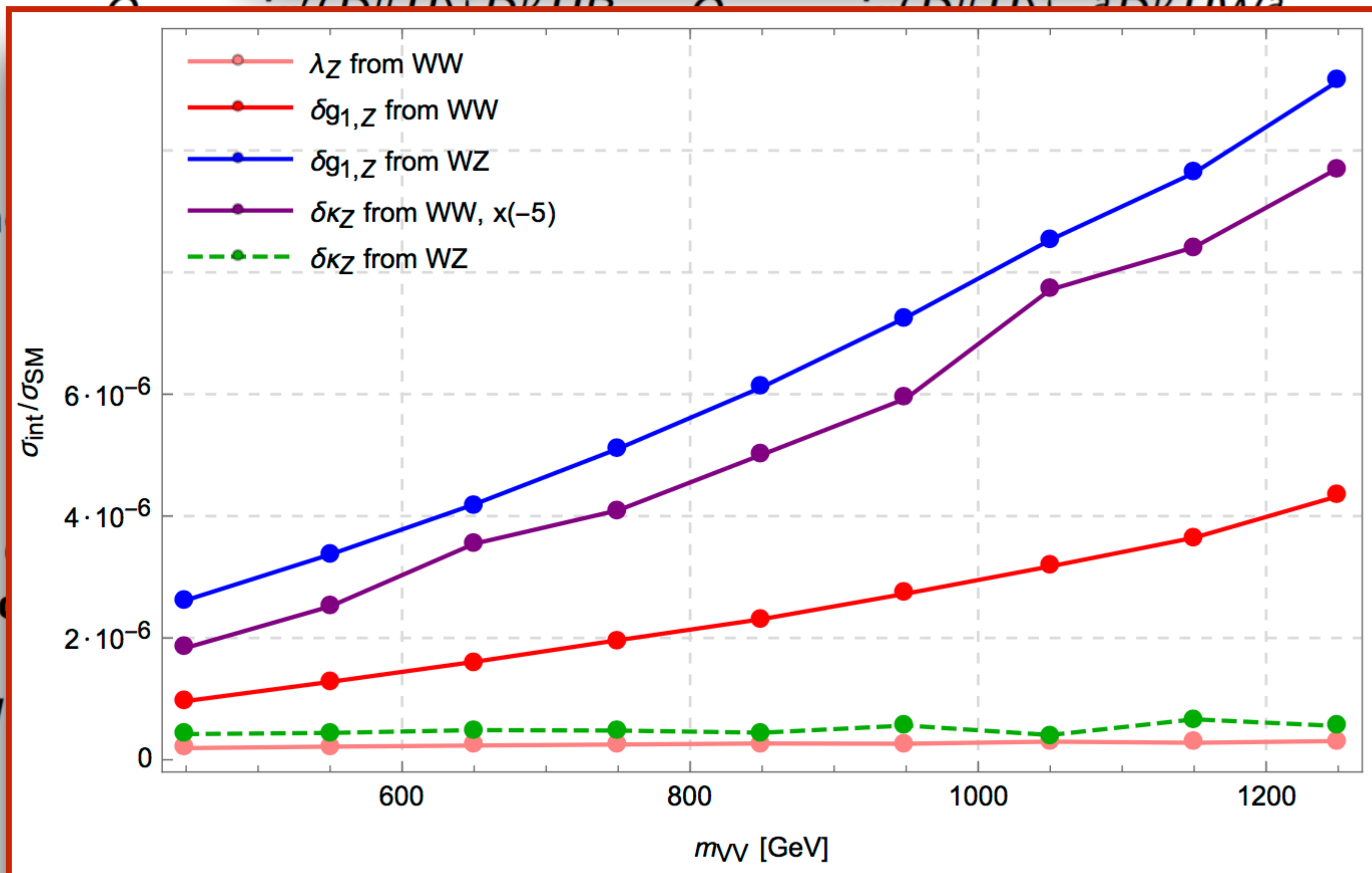
**Interference over SM**

We start with dimens

Goldston

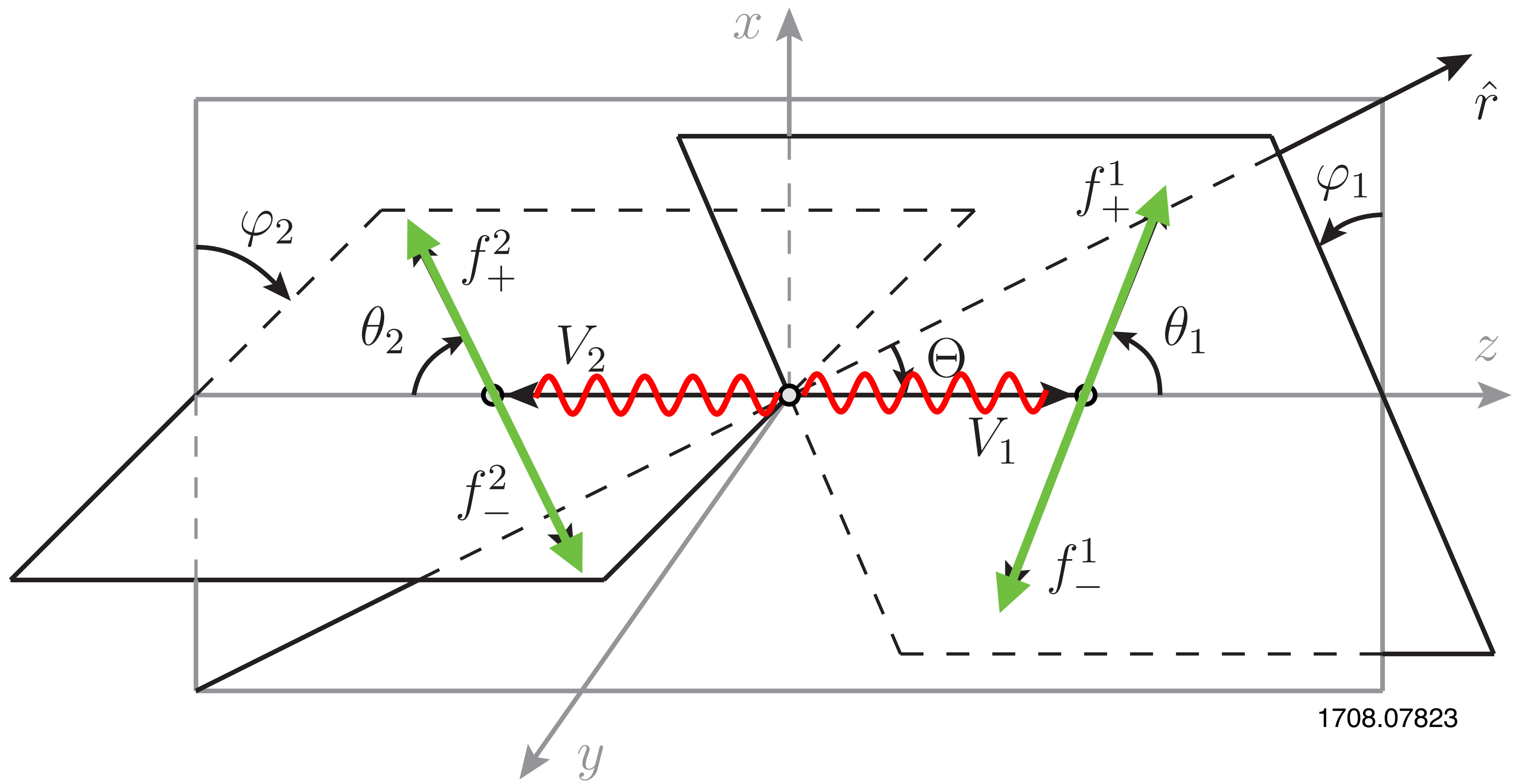
**Leading** **ouple**
**mostly t**

$\mathcal{M}\left(q\right.$ $m_W^2\ \delta\kappa_Z$



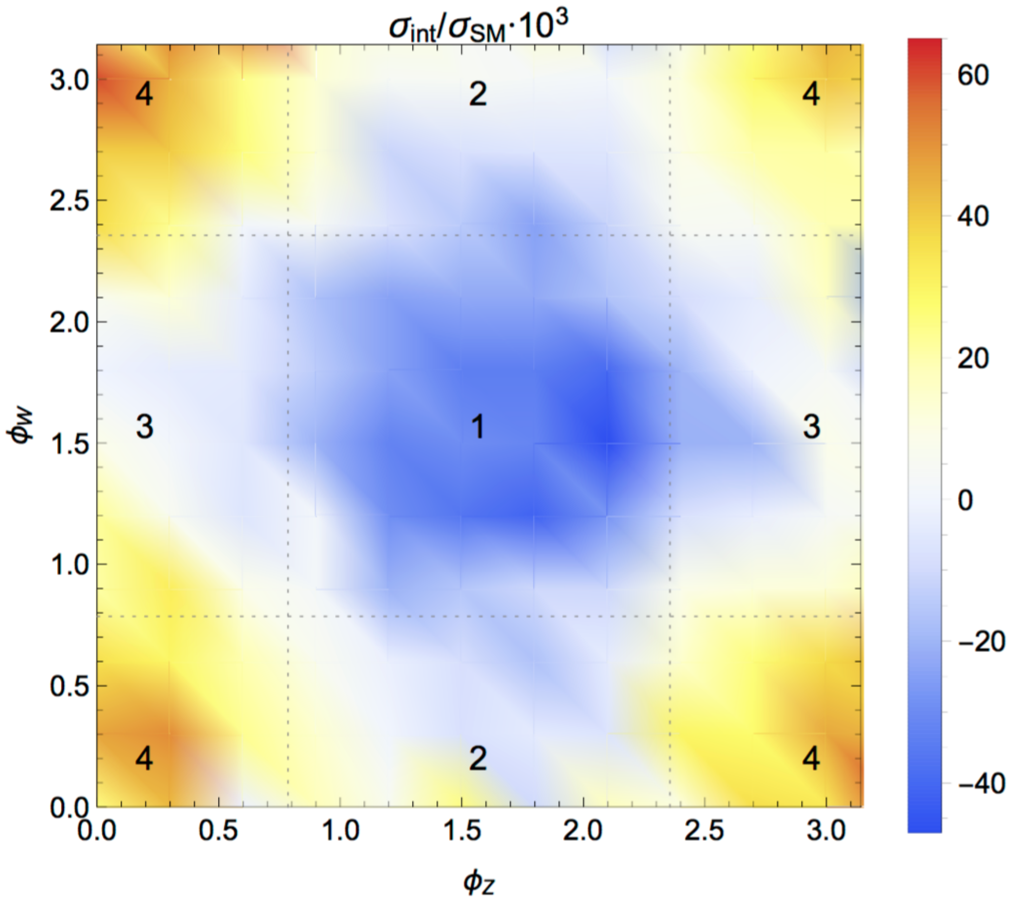

**We have an additional $E^2$ compared to the SM amplitudes, as expected from dimensional analysis**

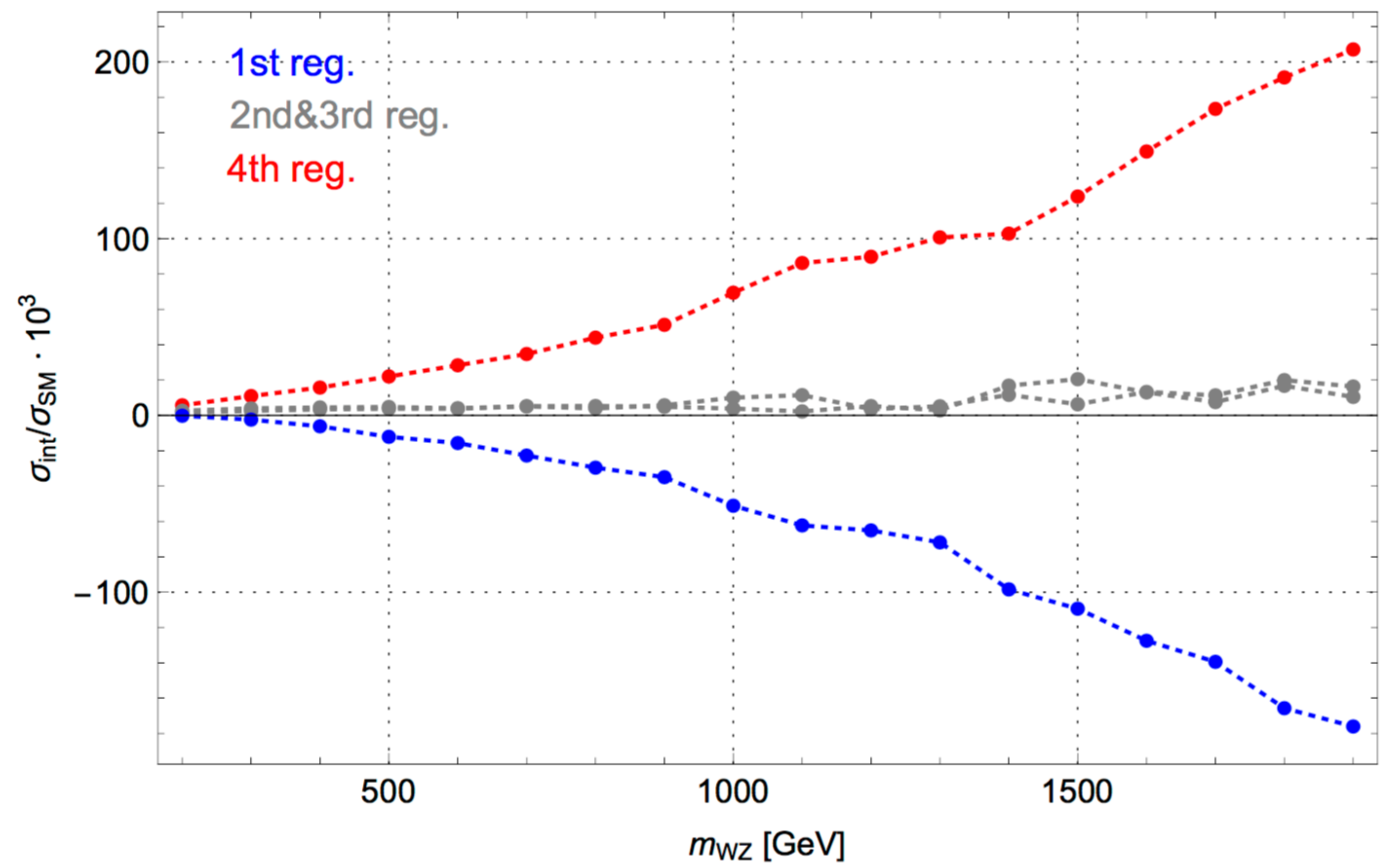
**Solution:** binning on azimuthal angles of the decay products allows to recover de energy worth of the interference term.




$$\frac{d\sigma(q\bar{q}\to W_{T_+} l_- \bar{l}_+)}{d\mathrm{LIPS}} = \frac{1}{2s} \frac{\left| \sum_i (\mathcal{M}^{\mathrm{SM}}_{q\bar{q}\to W_{T_+} Z_i} + \mathcal{M}^{\mathrm{BSM}}_{q\bar{q}\to W_{T_+} Z_i}) \mathcal{M}_{Z_i \to l_- \bar{l}_+} \right|^2}{(k_Z^2 - m_Z^2)^2 + m_Z^2 \Gamma_Z^2} \propto \cos(2\phi_Z)$$

Azatov, EM, Reyimuaji, Venturini [1707.08060]
Panico, Riva, Wulzer [1708.07823]



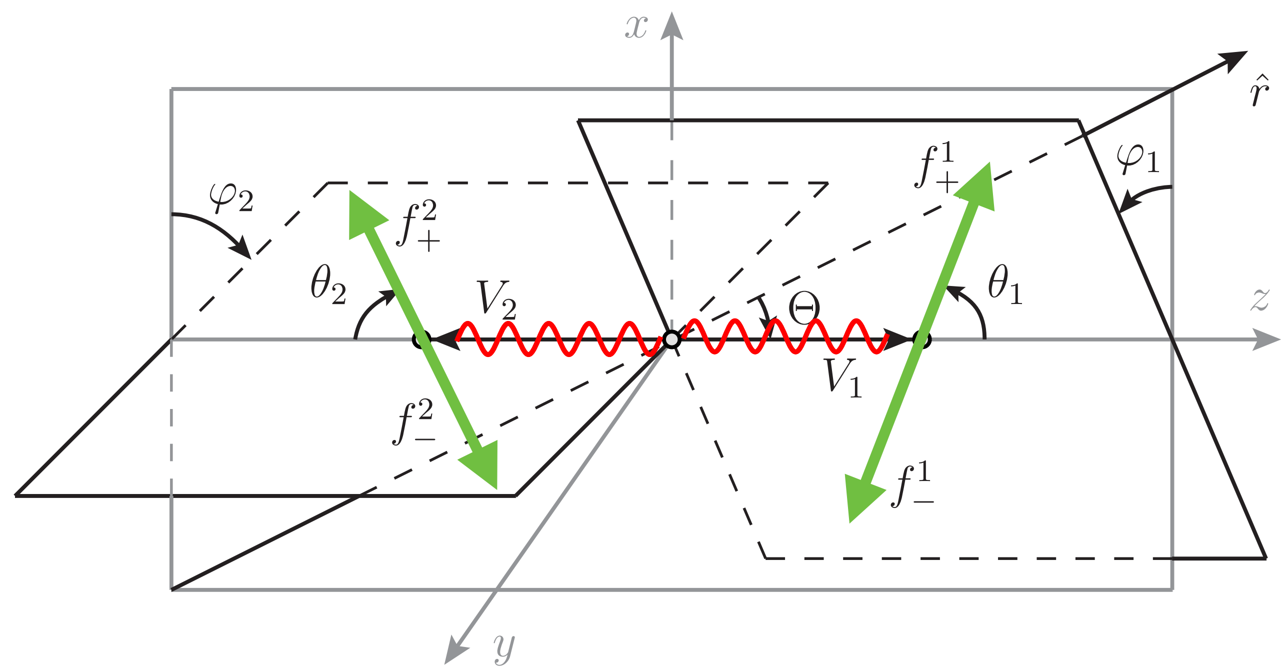

- Gives a better handle on the interference amplitude.

- Energy growth is recovered.

- Sensitivity to the sign of the Wilson coefficient

Azatov, EM, Reyimuaji, Venturini

More generally,




Panico, Riva, Wulzer [1708.07823]

$$I^{V_1V_2}_{\mathbf{h}\otimes\mathbf{h}'} = T^{V_1V_2}_{\mathbf{h}\mathbf{h}'}\left[\mathcal{A}^{\rm SM}_{\mathbf{h}}\mathcal{A}^{\rm BSM+}_{\mathbf{h}'} + \mathcal{A}^{\rm BSM+}_{\mathbf{h}}\mathcal{A}^{\rm SM}_{\mathbf{h}'}\right]\cos\left[\mathbf{\Delta h}\cdot\boldsymbol{\varphi}\right]$$ (cp-even)

Angles of charged leptons can be fully reconstructed but not the helicity, thus reconstruction subject to the ambiguity

$$\{\theta_{1(2)}, \varphi_{1(2)}\} \leftrightarrow \{\pi - \theta_{1(2)}, \varphi_{1(2)} + \pi\}$$

Angles of W boson decays subject to neutrino momentum reconstruction ambiguity

$$\cot\varphi = \frac{1}{\sin[\phi_\nu - \phi_l]}\left[\sinh[\eta_l - \eta_\nu] + \mathcal{O}\left(\frac{m_W^2}{p_{\perp l}p_{\perp\nu}}\right)\right]$$

± ambiguity

$$\{\theta_{1(2)}, \varphi_{1(2)}\} \leftrightarrow \{\theta_{1(2)}, \pi - \varphi_{1(2)}\}$$

(boosted W)

# HL-LHC

| | Lumi. 300 fb$^{-1}$ 95% CL | Lumi. 300 fb$^{-1}$ 68% CL | Lumi. 3000 fb$^{-1}$ 95% CL | Lumi. 3000 fb$^{-1}$ 68% CL | $Q$ [TeV] |
|---|---|---|---|---|---|
| Excl. | [-1.06,1.11] | [-0.59,0.61] | [-0.44,0.45] | [-0.23,0.23] | 1 |
| Excl., linear | [-1.50,1.49] | [-0.76,0.76] | [-0.48,0.48] | [-0.24,0.24] | |
| No $\phi_Z$ binning | [-1.19,1.20] | [-0.69,0.70] | [-0.57,0.57] | [-0.32,0.31] | |
| No $\phi_Z$ binning, linear | [-2.28,2.22] | [-1.15,1.14] | [-0.74,0.73] | [-0.38,0.38] | |
| No $p_j^T$ binning | [-1.14,1.17] | [-0.64,0.67] | [-0.50,0.51] | [-0.27,0.27] | |
| No $p_j^T$ binning, linear | [-1.80,1.81] | [-0.91,0.92] | [-0.57,0.57] | [-0.29,0.29] | |
| Incl. | [-1.29,1.27] | [-0.77,0.76] | [-0.69,0.67] | [-0.40,0.39] | |
| Incl., linear | [-4.27,4.27] | [-2.17,2.17] | [-1.37,1.37] | [-0.70,0.70] | |
| Excl. | [-0.69,0.78] | [-0.39,0.45] | [-0.31,0.35] | [-0.17,0.18] | 1.5 |
| Excl., linear | [-1.22,1.19] | [-0.61,0.61] | [-0.39,0.39] | [-0.20,0.20] | |
| No $\phi_Z$ binning | [-0.75,0.82] | [-0.43,0.49] | [-0.37,0.43] | [-0.21,0.25] | |
| No $\phi_Z$ binning, linear | [-2.02,1.95] | [-1.02,1.00] | [-0.65,0.64] | [-0.33,0.33] | |
| No $p_j^T$ binning | [-0.73,0.80] | [-0.41,0.49] | [-0.34,0.38] | [-0.19,0.20] | |
| No $\phi_Z$ binning., linear | [-1.43,1.40] | [-0.72,0.71] | [-0.45,0.45] | [-0.23,0.23] | |
| Incl. | [-0.79,0.85] | [-0.46,0.52] | [-0.41,0.47] | [-0.24,0.29] | |
| Incl., linear | [-3.97,3.92] | [-2.01,2.00] | [-1.27,1.26] | [-0.64,0.64] | |
| Excl. | [-0.47,0.54] | [-0.27,0.31] | [-0.22,0.26] | [-0.12,0.14] | 2 |
| Excl., linear | [-1.03,0.99] | [-0.52,0.51] | [-0.33,0.32] | [-0.17,0.17] | |
| No $\phi_Z$ binning | [-0.50,0.56] | [-0.28,0.34] | [-0.25,0.30] | [-0.14,0.18] | |
| No $\phi_Z$ binning, linear | [-1.84,1.73] | [-0.92,0.89] | [-0.59,0.58] | [-0.30,0.30] | |
| No $p_j^T$ binning | [-0.49,0.55] | [-0.28,0.32] | [-0.23,0.27] | [-0.13,0.15] | |
| No $p_j^T$ binning, linear | [-1.18,1.12] | [-0.60,0.58] | [-0.37,0.37] | [-0.19,0.19] | |
| Incl. | [-0.52,0.57] | [-0.30,0.34] | [-0.27,0.31] | [-0.15,0.19] | |
| Incl., linear | [-3.55,3.41] | [-1.79,1.75] | [-1.12,1.11] | [-0.57,0.57] | |

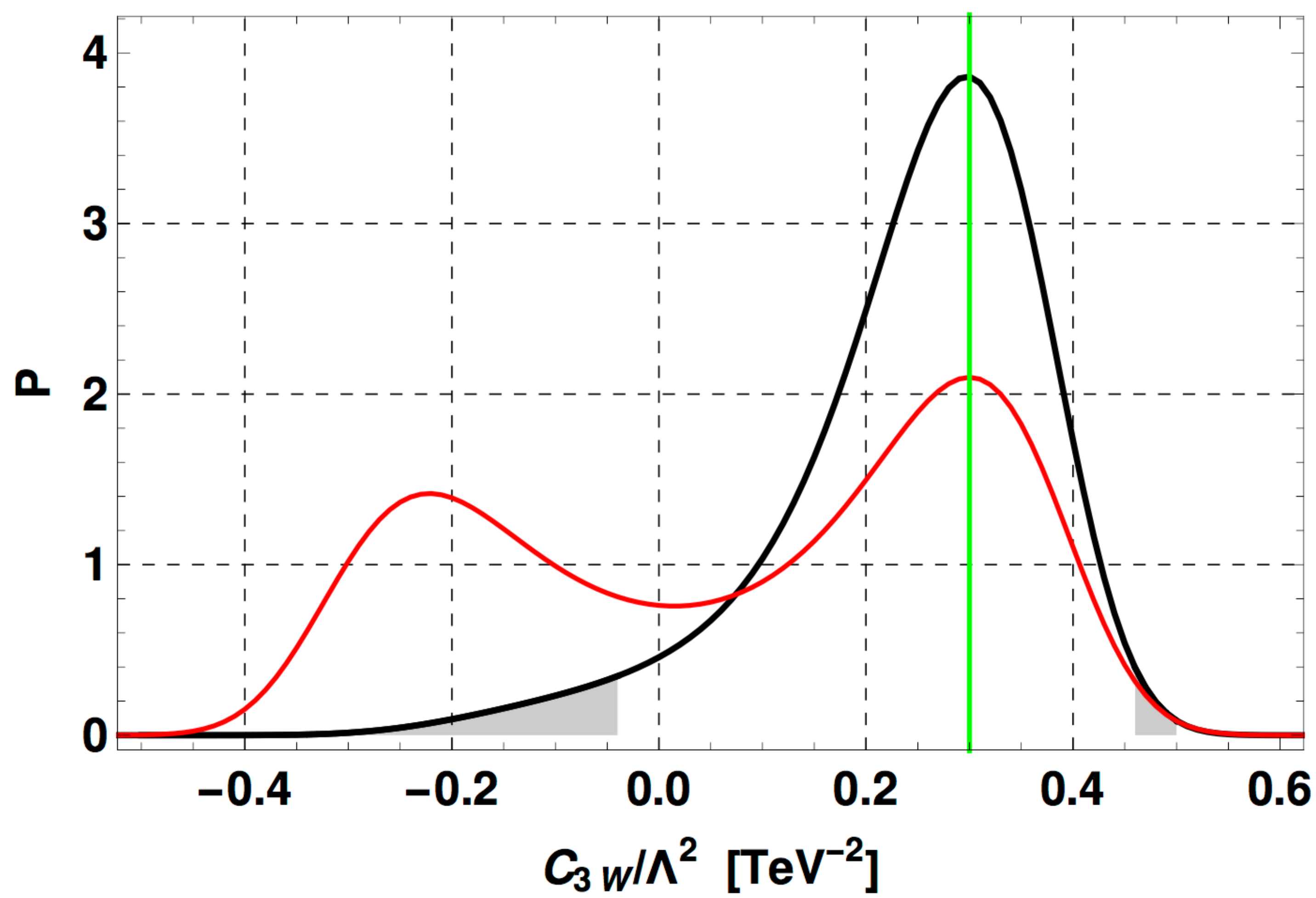
+17%

+166%

**Table 3:** Bounds on $c_{3W}/\Lambda^2$. The total leakage in the various bins of $m_{WZ}^T$ is $\lesssim 5\%$.

Azatov, EM, Reyimuaji, Venturini

**qualitatively different:** with the azimuthal angle binning we access the sign and regime of EFT validity is larger.



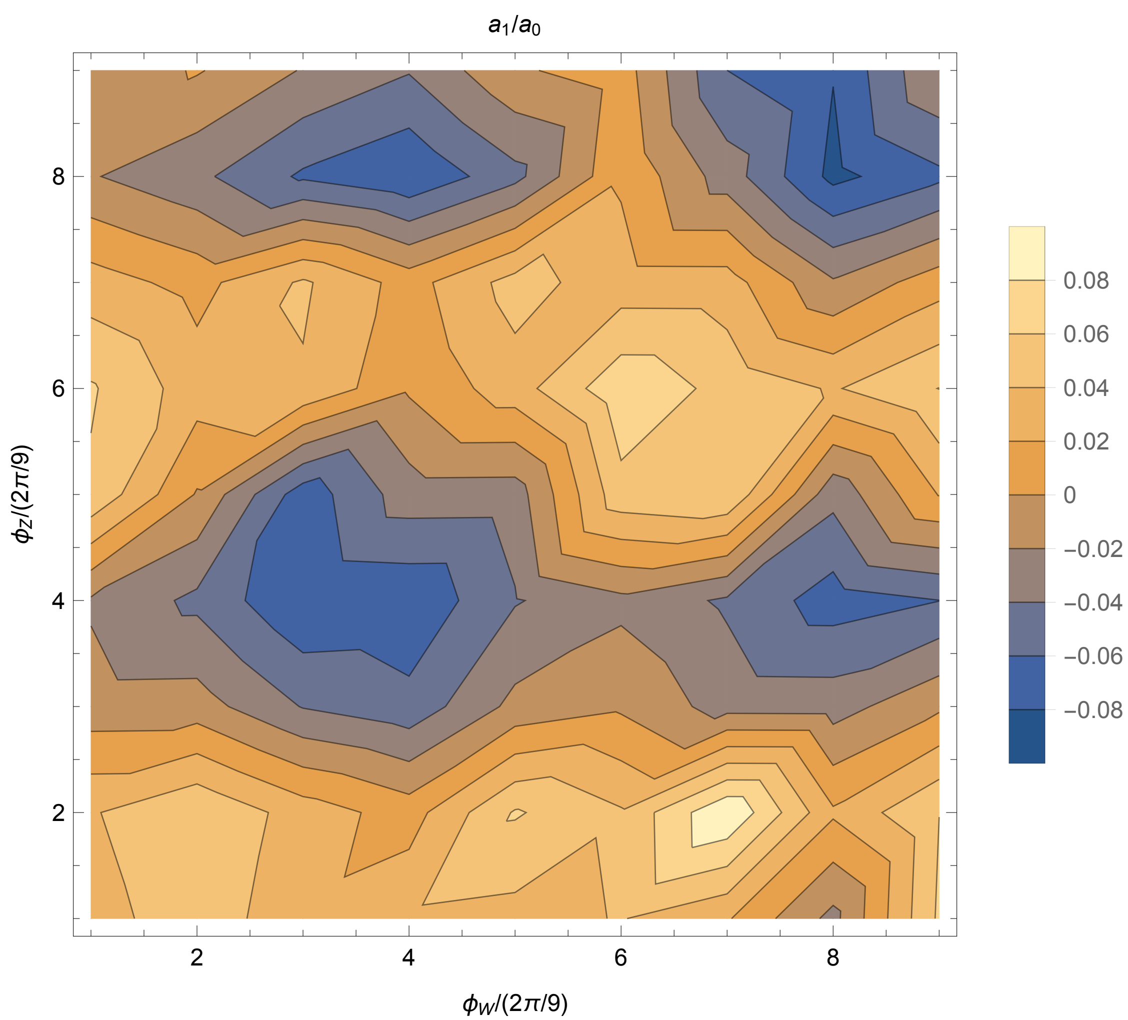

Azatov, EM, Reyimuaji, Venturini

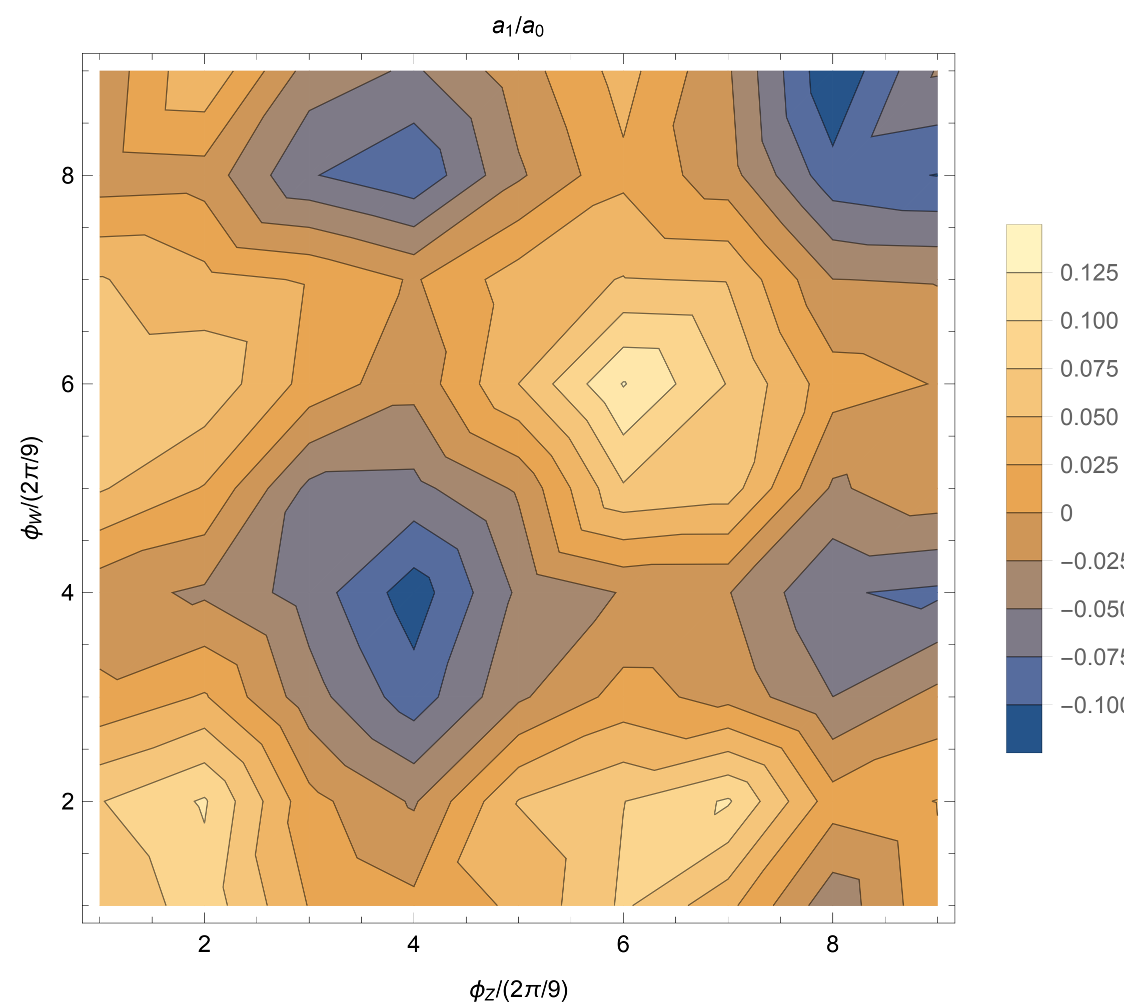
**CP odd**

$$I^{V_1V_2}_{\mathbf{h}\otimes\mathbf{h}'} = iT^{V_1V_2}_{\mathbf{h}\mathbf{h}'}[\mathcal{A}^{\rm SM}_{\mathbf{h}}\mathcal{A}^{\rm BSM-}_{\mathbf{h}'} - \mathcal{A}^{\rm BSM-}_{\mathbf{h}}\mathcal{A}^{\rm SM}_{\mathbf{h}'}]\sin[\mathbf{\Delta h}\cdot\varphi]$$

Panico, Riva, Wulzer [1708.07823]

One can access the azimuthal modulation of the Z decays. While W boson decays are buried in the neutrino ambiguity reconstruction.




thanks to Venturini for these plots

[-0.127347, 0.128206], phiZ binning
[-0.19845, 0.198181], phiZ binning (linear)

[-0.144279, 0.146636], no phiZ binning;
[-3.7873, 3.72596], no phiZ binning (linear)

## *Summary*

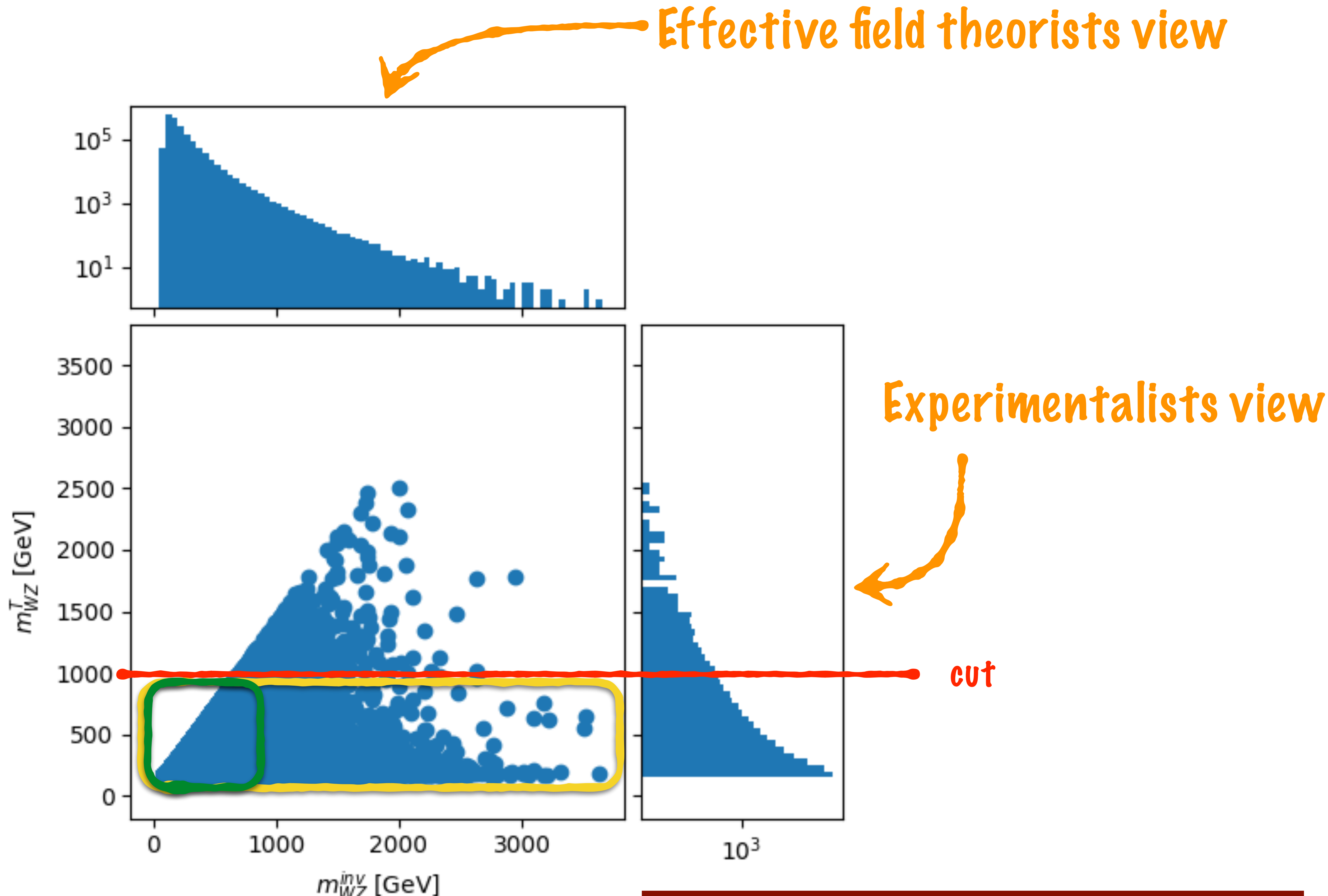
* At LHC we must be careful with EFT interpretation.

* Larger sensitivity to interference term is more *EFT save*:
less dependence on quadratic terms and dim8 ops — field redefinitions of $O(1/\Lambda^2)$ differ at $O(1/\Lambda^4)$.

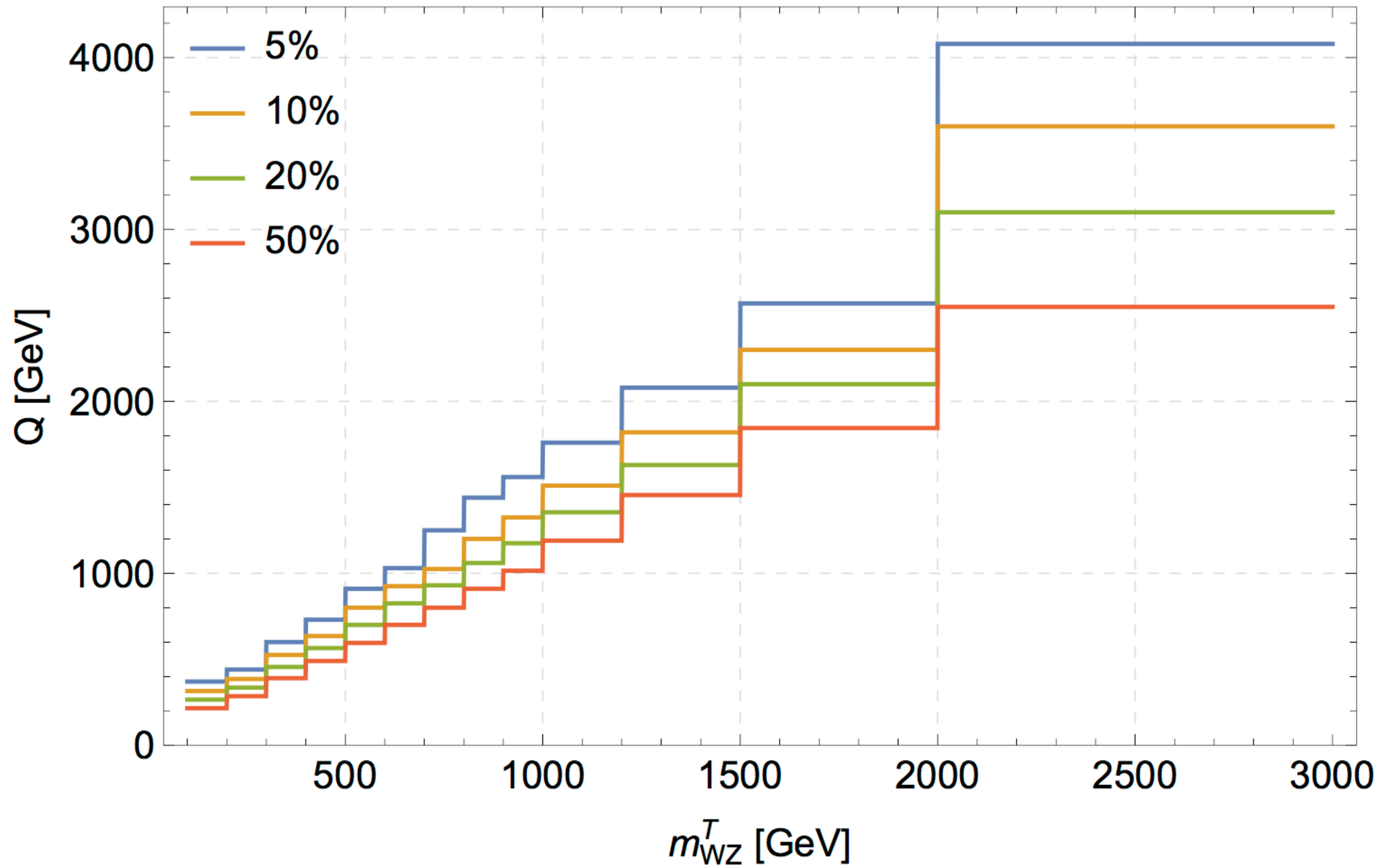
* Resurrect energy growth through angular distributions.

## *To do*

* Apply same strategy to other ops. HL-LHC will allow us to do cool measurements of the EFT.



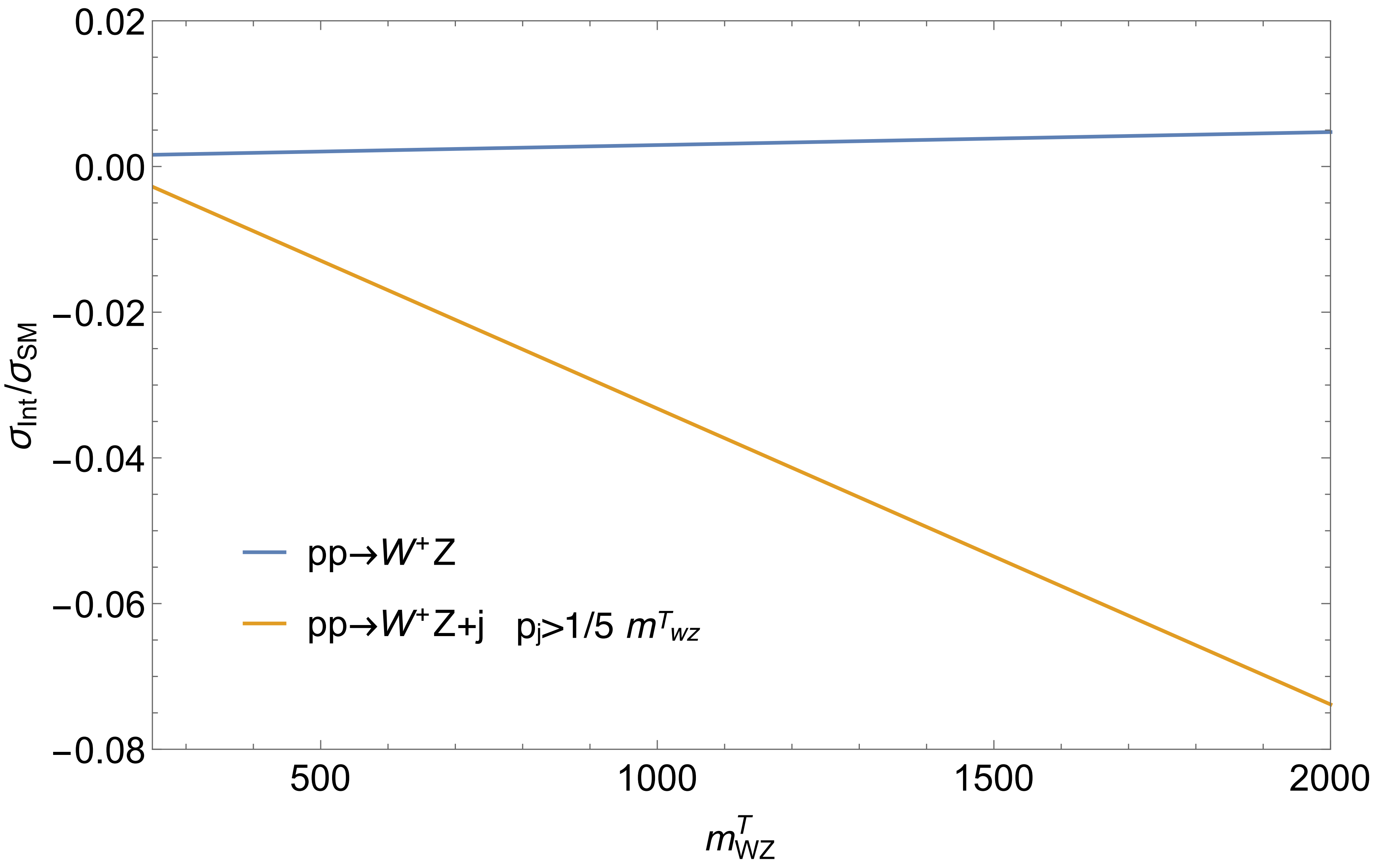

leakage ≡ (yellow-green)/yellow




$$\text{Leakage} = \frac{N_i(m_{VW} > Q)}{N_i} \times 100$$

# $pp \to W^+Z+j$

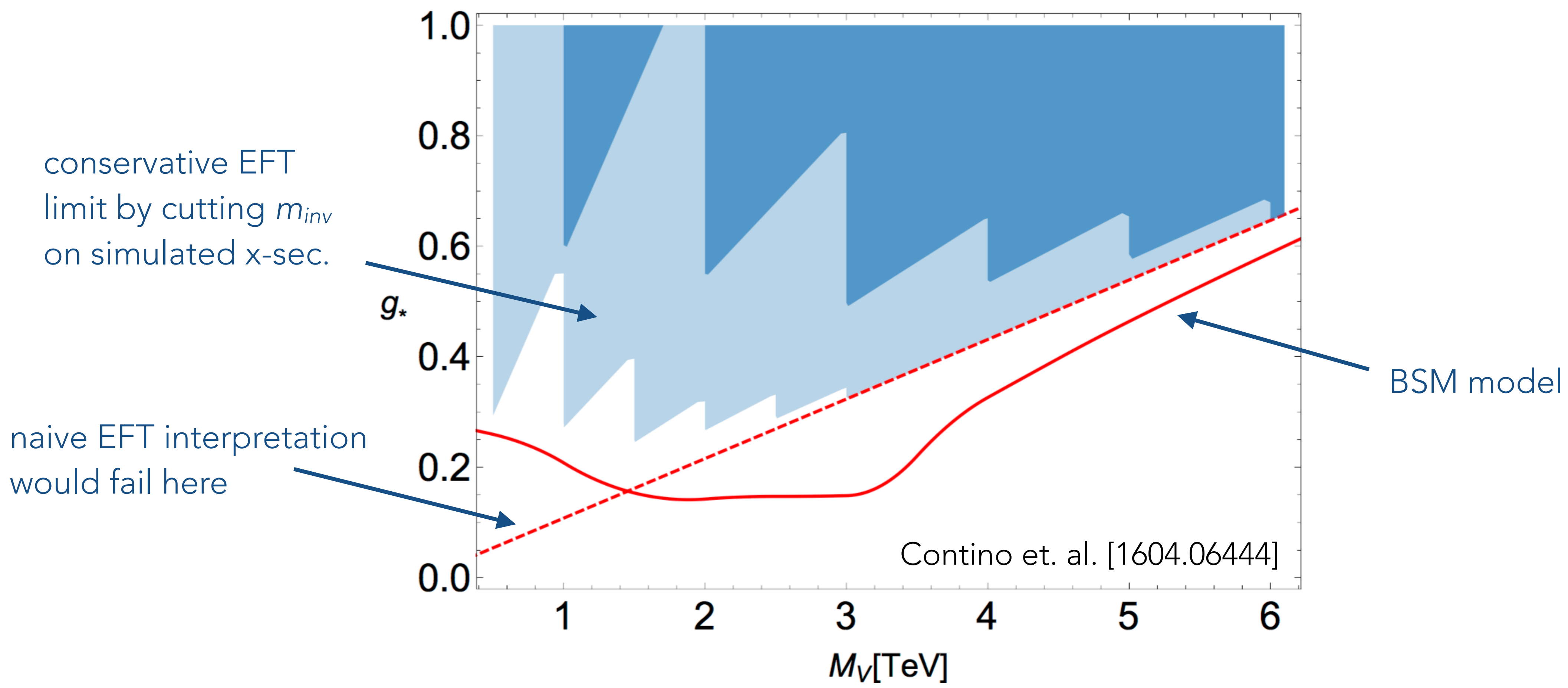
* Sensitive to $\lambda_z$ interference.




* Requiring extra hard jet helps in interference!

# Power counting examples

# Example



conservative EFT limit by cutting $m_{inv}$ on simulated x-sec.
naive EFT interpretation would fail here
BSM model
Contino et. al. [1604.06444]
$g_*$
$M_V$[TeV]
1.0
0.8
0.6
0.4
0.2
0.0
1
2
3
4
5
6