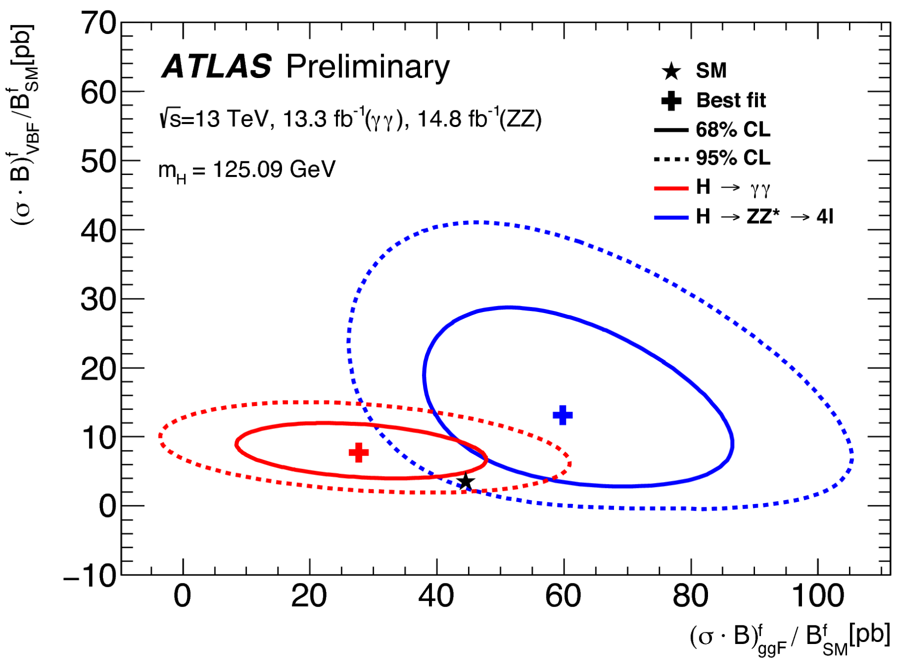
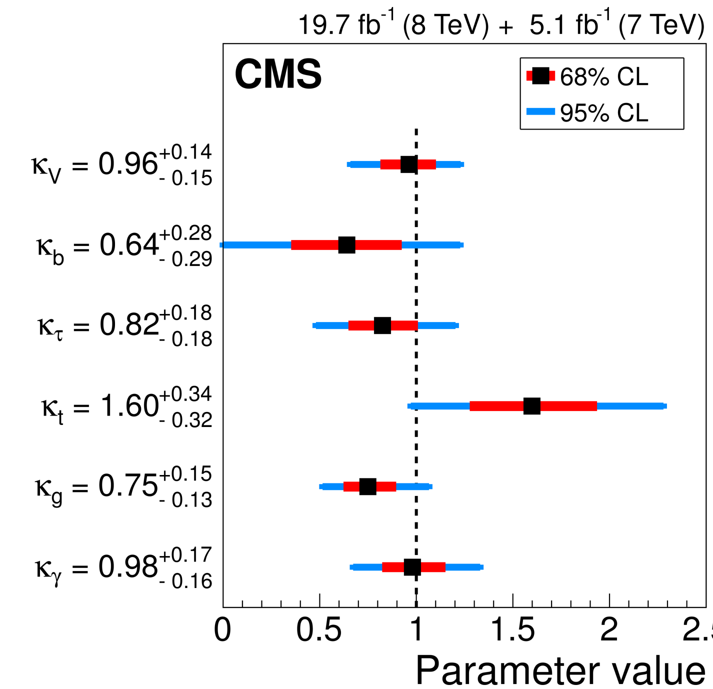
EFT probes of new physics @LHC

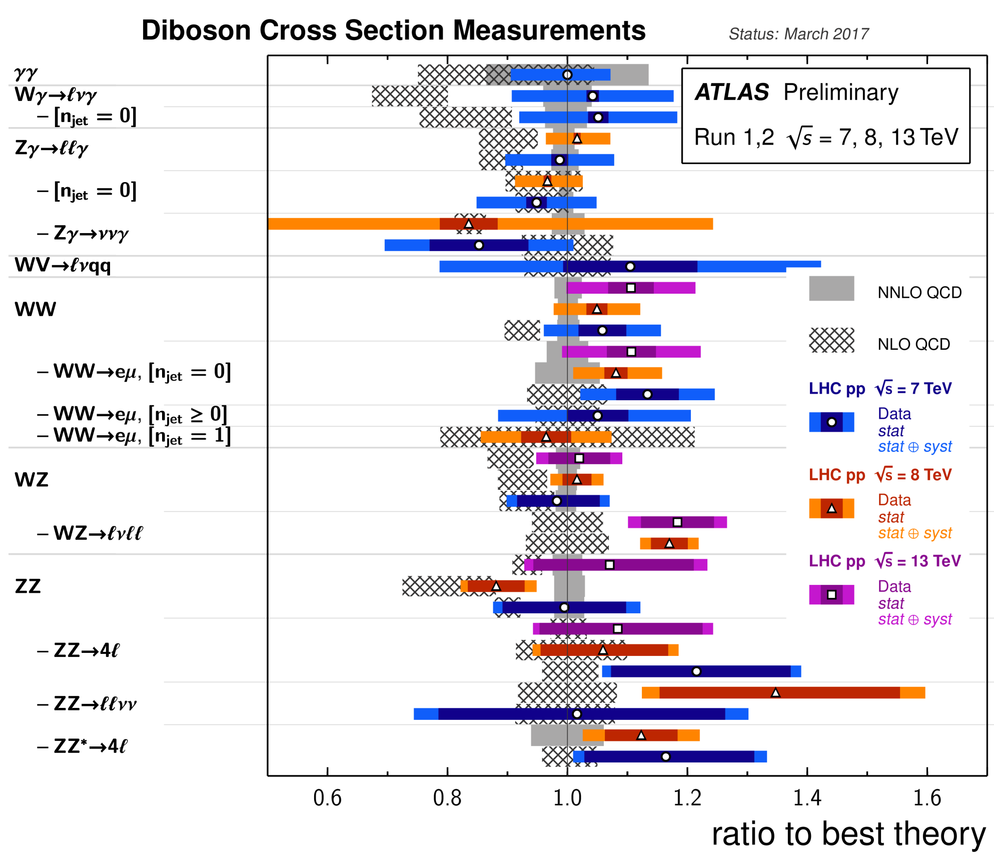
Joan Elias Miró

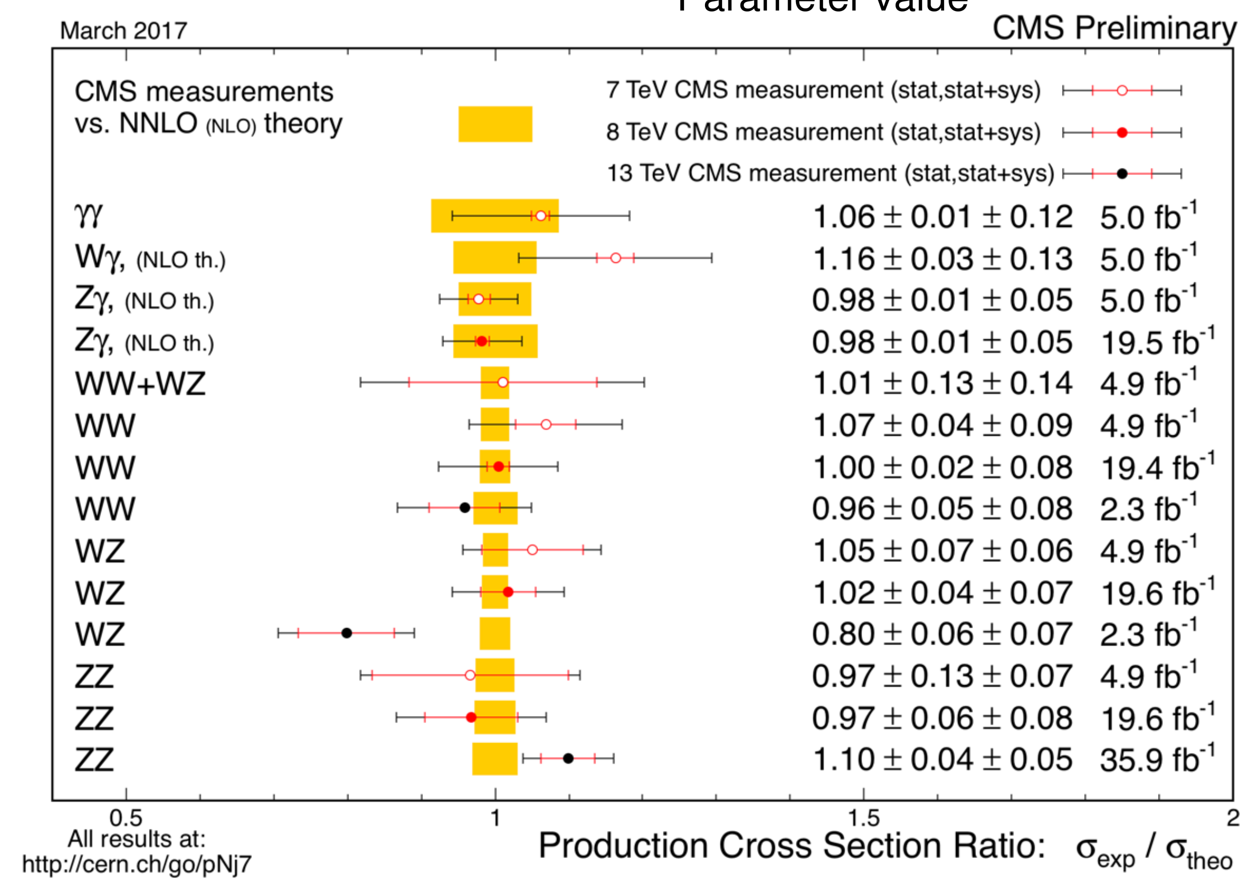
EPS Conference on High Energy Physics 2017 — Venezia

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.

must

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.

this talk

LHC searches suggest that there is a separation between the EW scale and the scale of new physics Λ.

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

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

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.

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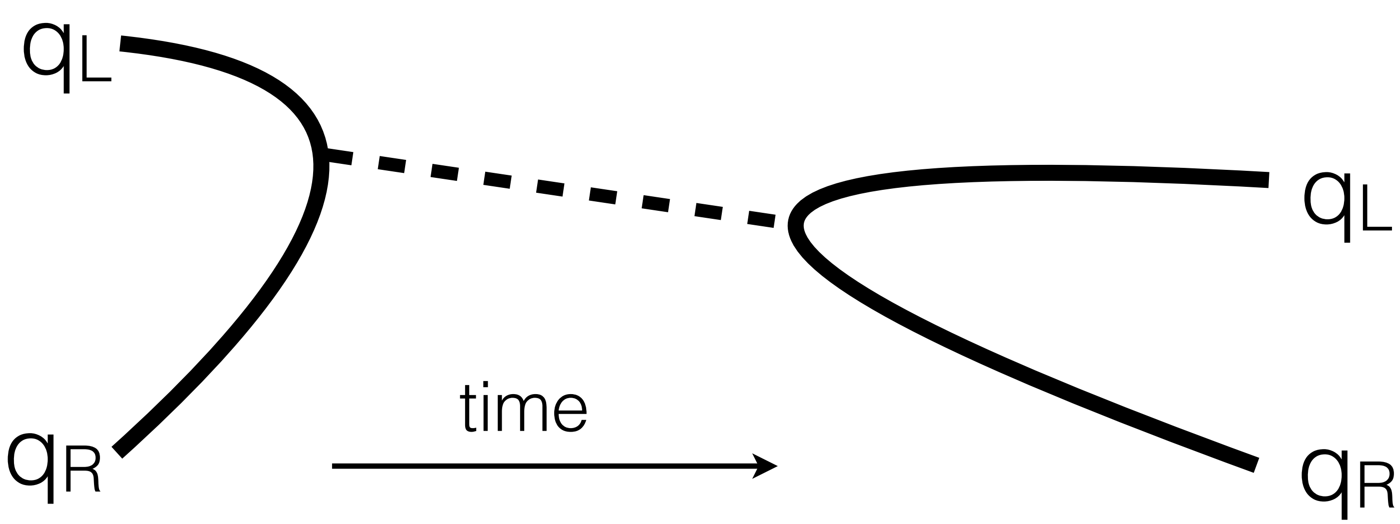
dim. five

For instance, integrating a second heavy Higgs doublet



gives a four fermion, among other ops.

Any hea

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$$
\begin{aligned}
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$$

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

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

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

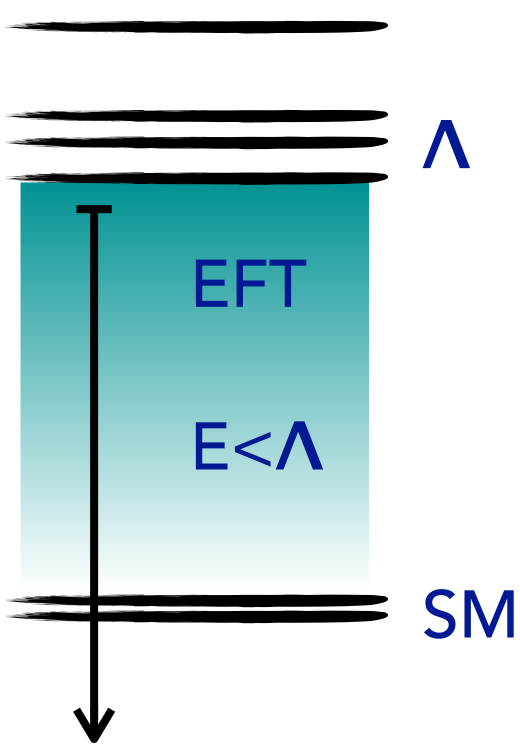
* Consistent framework for the parametrization of BSMs.

* 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.).

* ...



Plan of the talk:

I will exemplify many aspect of the use of EFT in the context of Higgs physics, Triple Gauge Couplings and the LHC.

Triple gauge couplings, what do we know?

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

$$\mathcal{L}_{TGC} \;=\; ig\,(W^{+\,\mu\nu}W^-_\mu\,W^3_\nu + W_3^{\mu\nu}W^+_\mu W^-_\nu) \sim \partial WWW$$

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

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

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

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

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2.- Different momentum and helicity interaction

1.- Deformation of existing TGC

a(nomalous)TGC of the 1st kind

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

$$\downarrow$$

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

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

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gauge inv.

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

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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 $\quad \delta g_{1,z}\,,\ \delta\kappa_\gamma\,,\ \lambda_z$

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

Famous LEP-II % measurements

$$\delta g_{1,z} = -0.016^{+.018}_{-.020}$$

$$\delta\kappa_\gamma = -0.018 \pm 0.042$$

$$\lambda_z = -0.022 \pm 0.019$$

* 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]

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Fit revisited in 1405.1617, 1411.0669

Working linearly w/ the aTGC the constraints are **O(10) weaker due to a flat direction** $\delta g_{1,z} \approx -\lambda$ **.**
Thus strong sensitivity to quadratic terms — EFT 🙁?!

Can be "lifted" by considering:

* Higgs observables — it bounds $g_{1,z}$
* other diboson c.m. energy — λ_z dep. scales different

EM, Espinosa, Masso, Pomarol [1308.1879]
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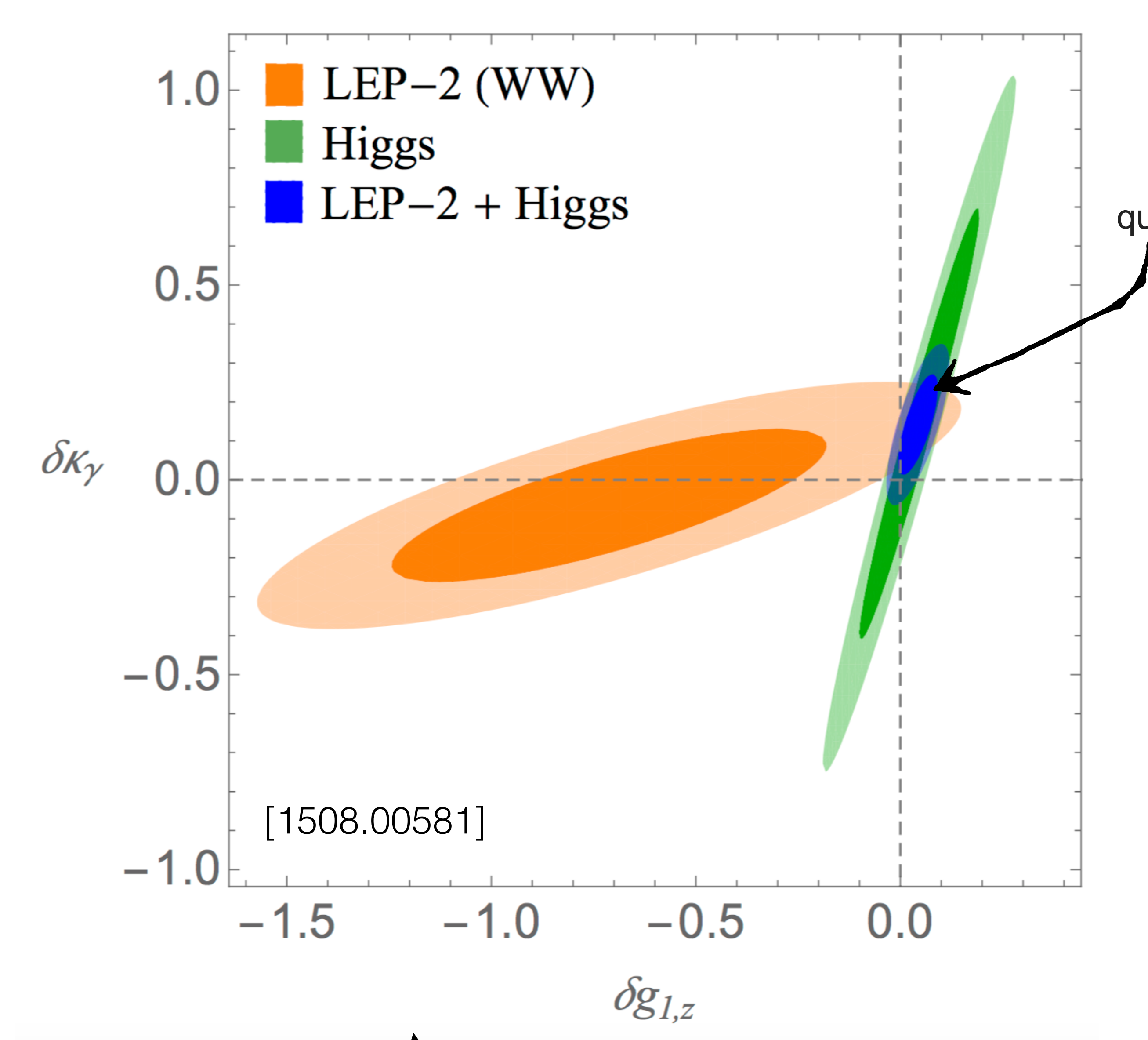
Fan

δ

quadratic fit ≈ linear fit



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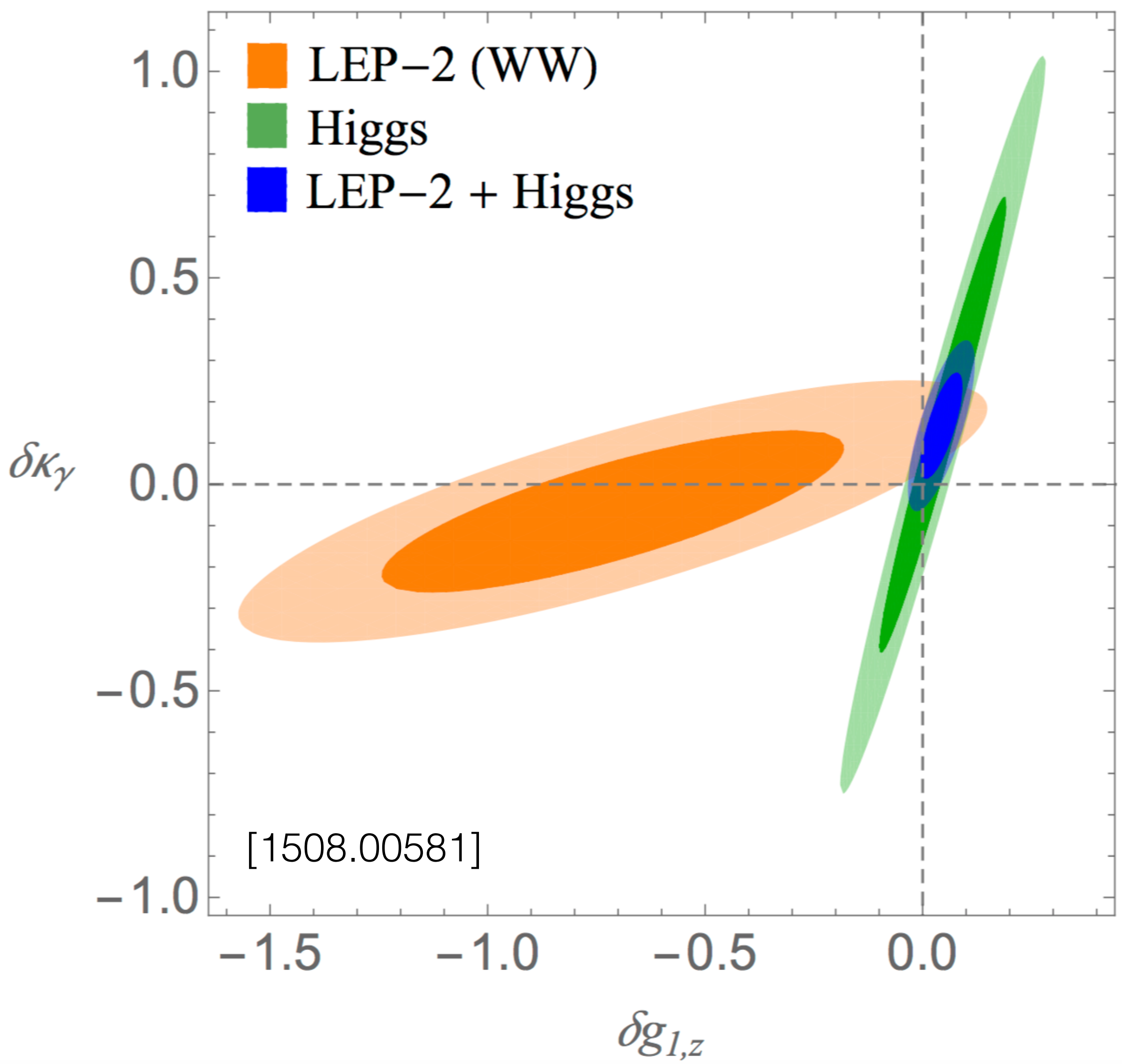

Schematically

$$\left\{\begin{matrix} HHBB \\ HHWB \\ HHWW \\ cW\text{-}cB \\ WWW \end{matrix}\right\}$$

* **4** Higgs deformations
* **3** measurements
  hγγ, hZZ, hWZ, (hγZ)
* Each fermion decay/prod. mode has possible deformation.
* **4-3=1**

* **3** aTGC
* **2** measurements at linear level.
* **3-2=1**

After constraints from W/Z po

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TGC, diboson, EFT and the LHC

CMS [1703.06095]

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].

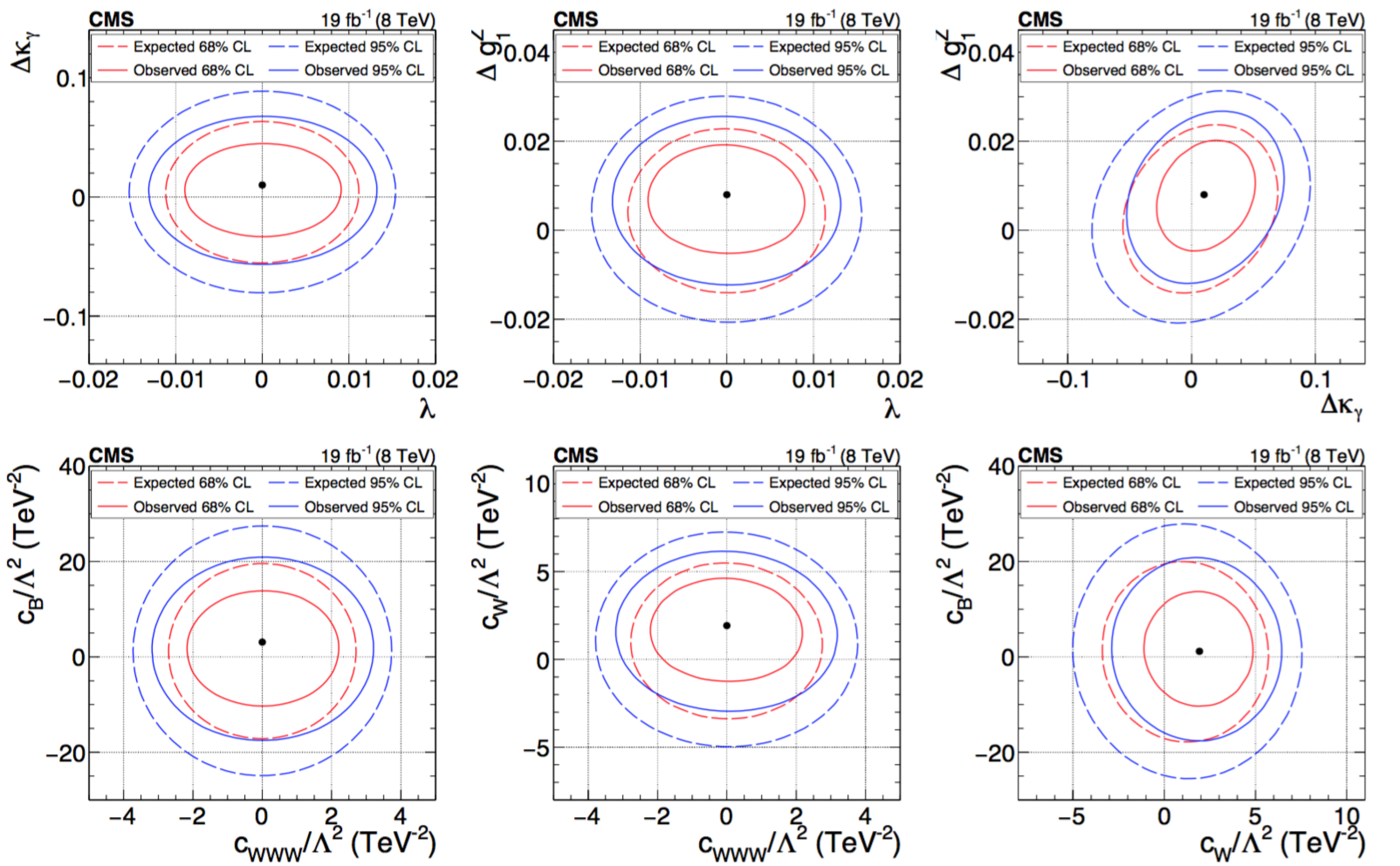
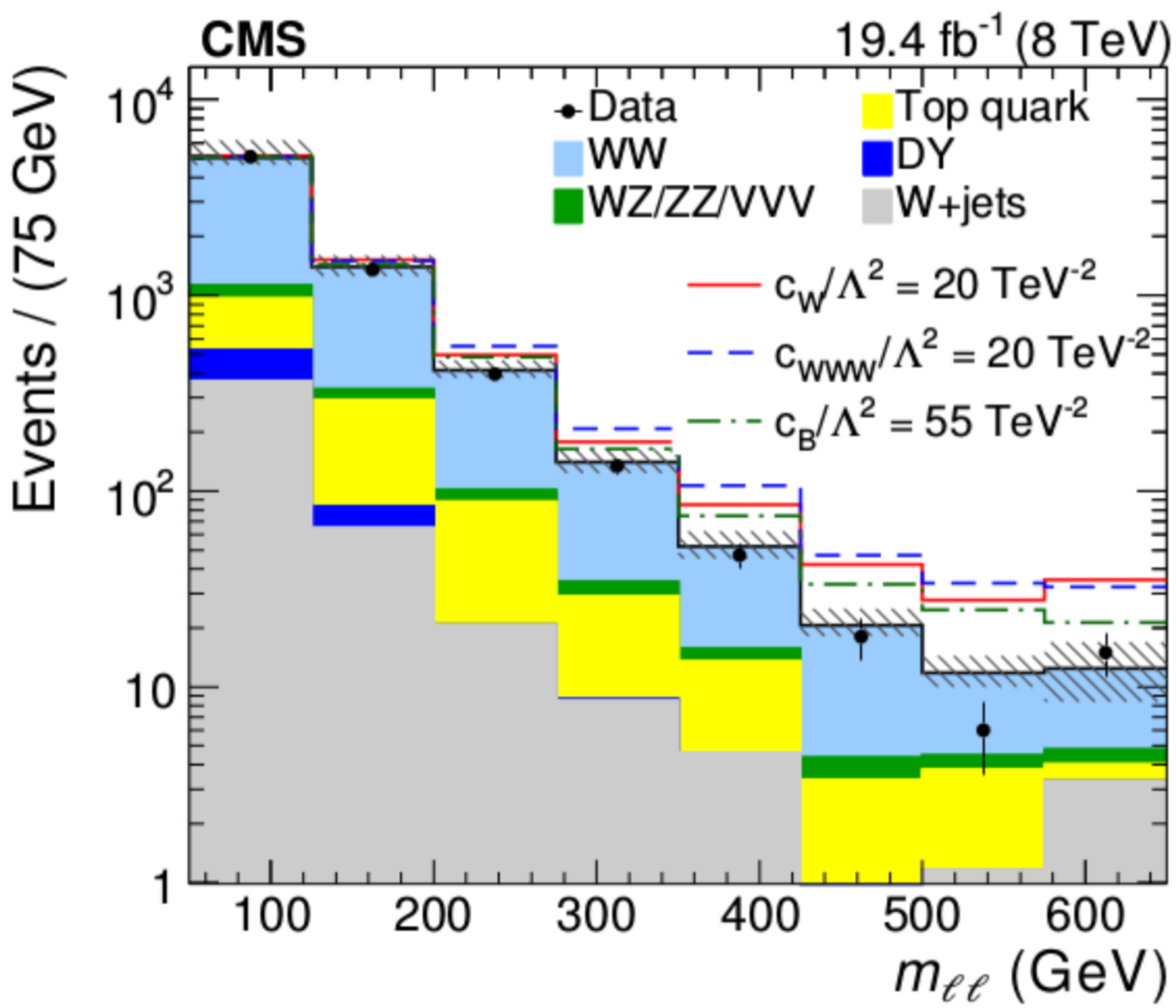
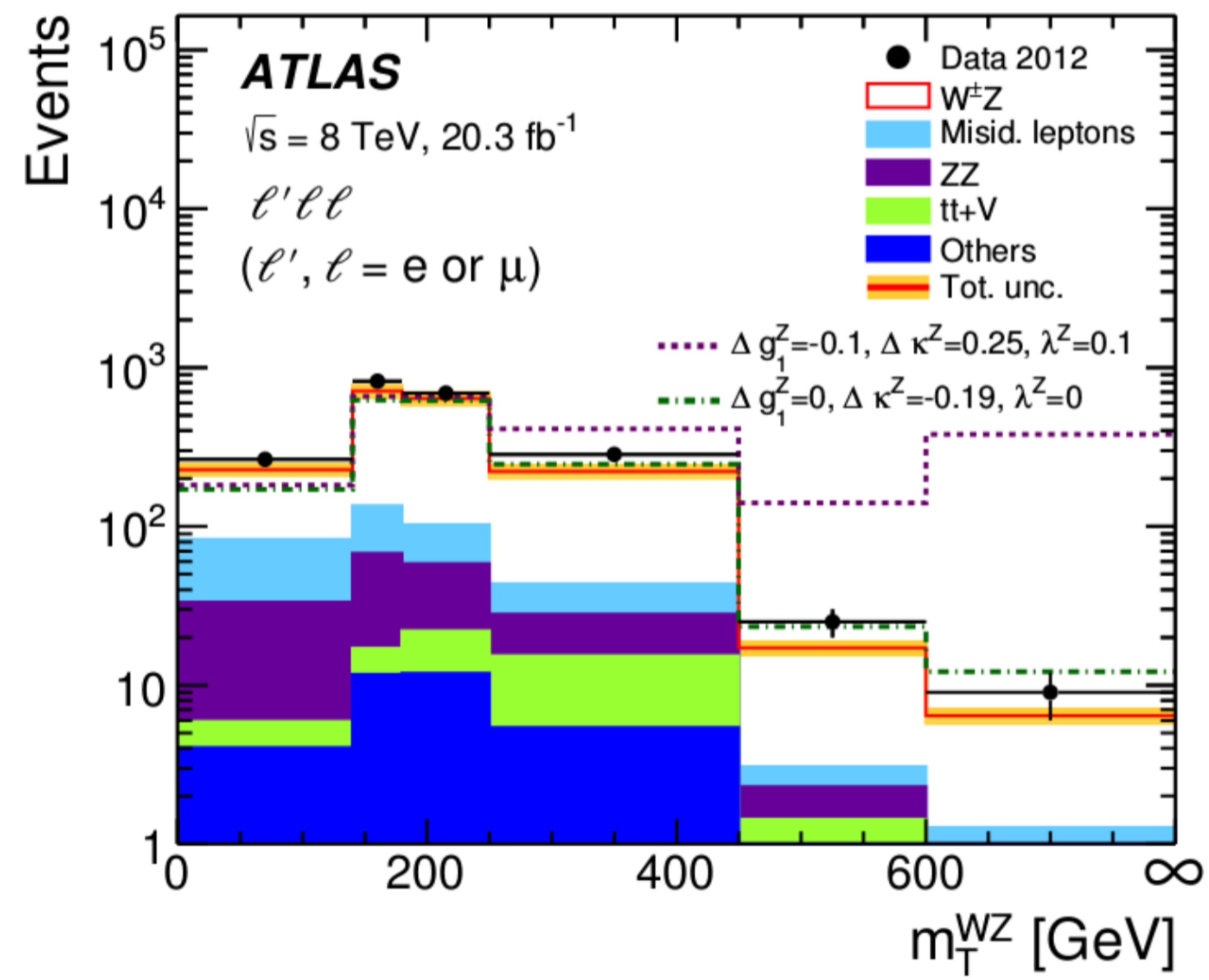


Figure 3: The 68 and 95% CL observed and expected exclusion contours in ΔNLL are depicted for three pairwise combinations of the aTGC parameters in the LEP parametrization (top) and in the EFT formulation (bottom). The black dot represents the best fit point.

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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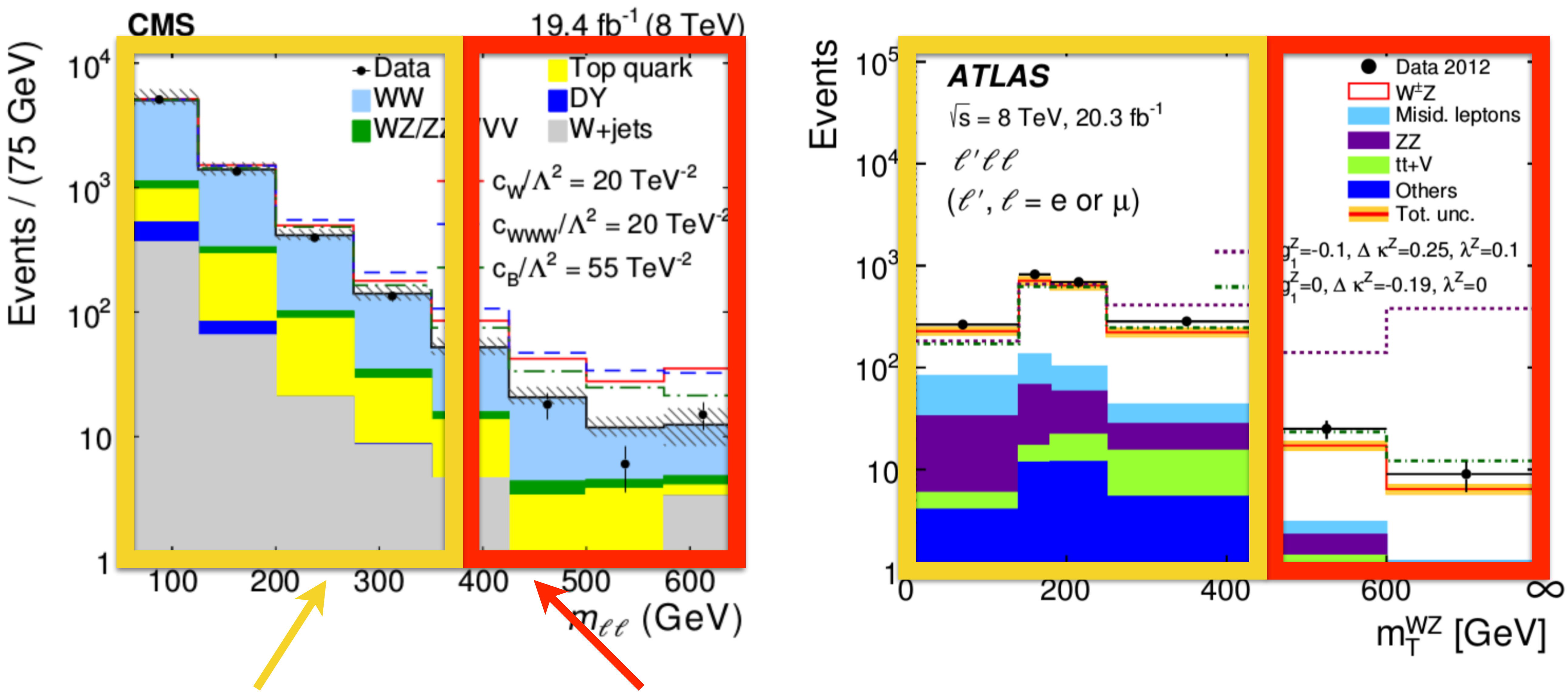


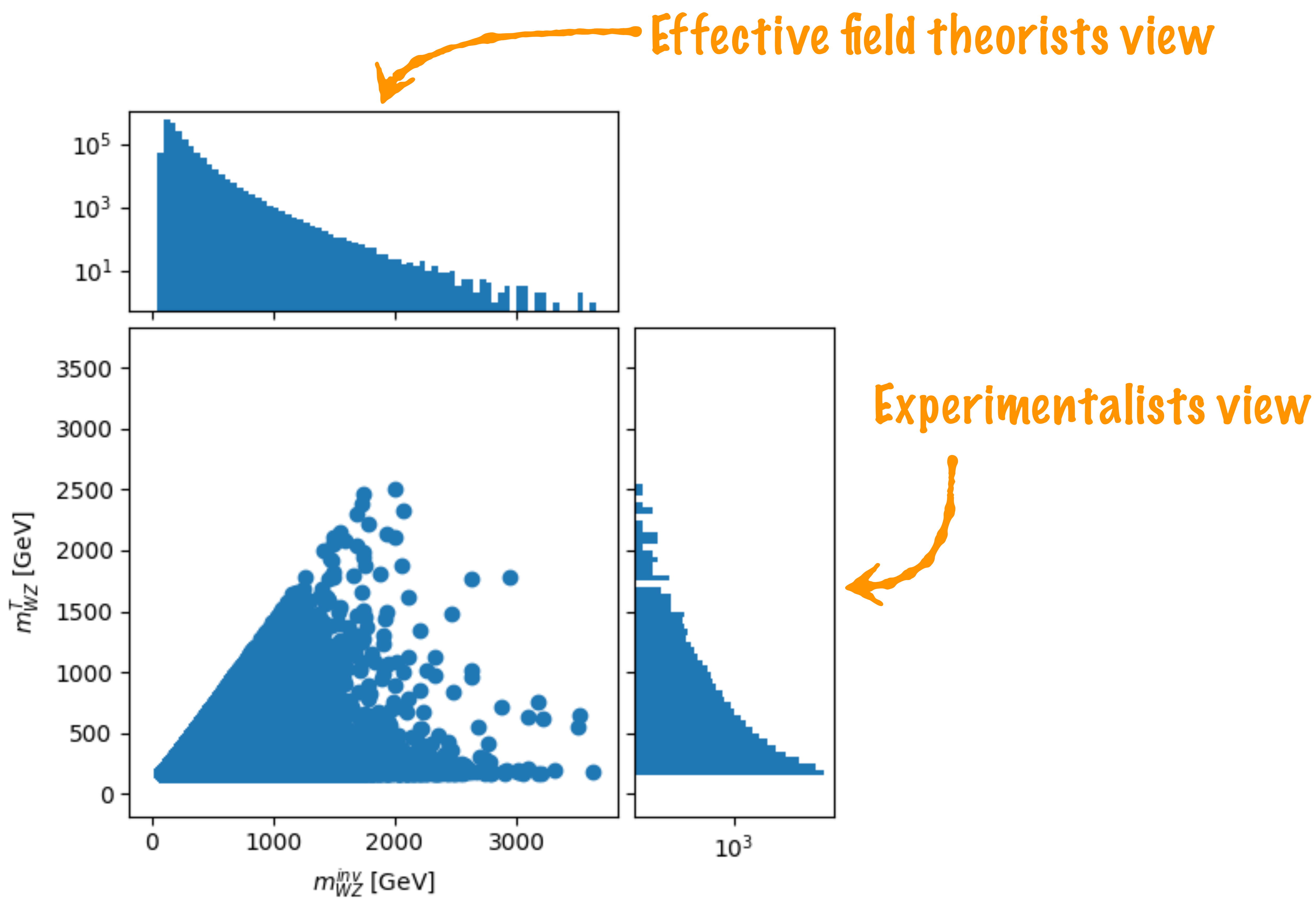
EFT with smaller cutoff may apply

Large cutoff, implies sensitivity to large coupling

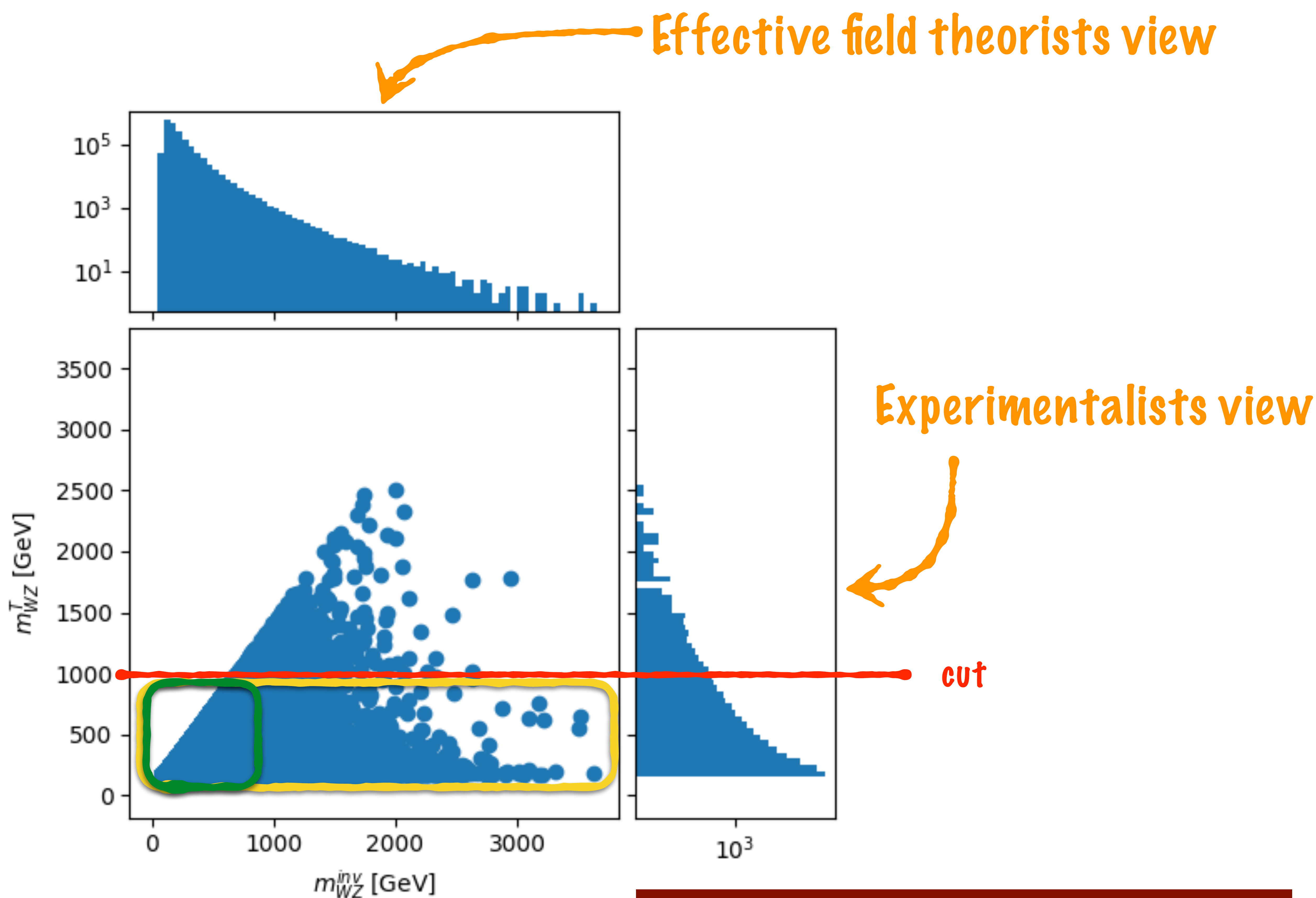
To prove less *exotic* theories we need better sensitivity

Two effects we may worry about the EFT measurement:

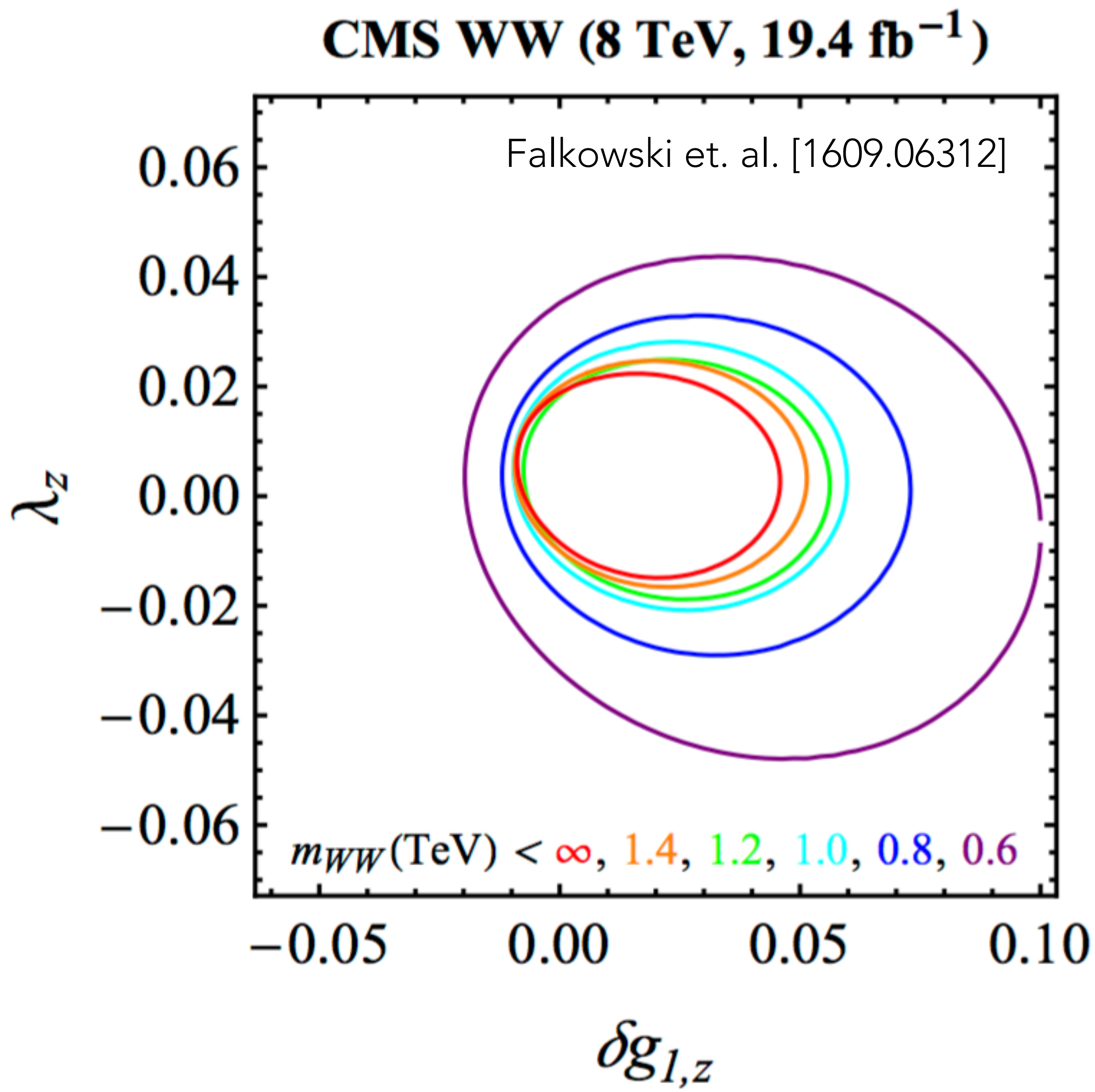
* Leakage of high invariant mass events
* Strong sensitivity to quadratic terms vs linear ones.



Effective field theorists view
Experimentalists view
10^5
10^3
10^1
3500
3000
2500
2000
1500
1000
500
0
m_{WZ}^{T} [GeV]
0
1000
2000
3000
m_{WZ}^{inv} [GeV]
10^3



leakage ≡ (yellow-green)/yellow



Looking at low categories only, LEP bounds are still stronger.

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.

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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…)

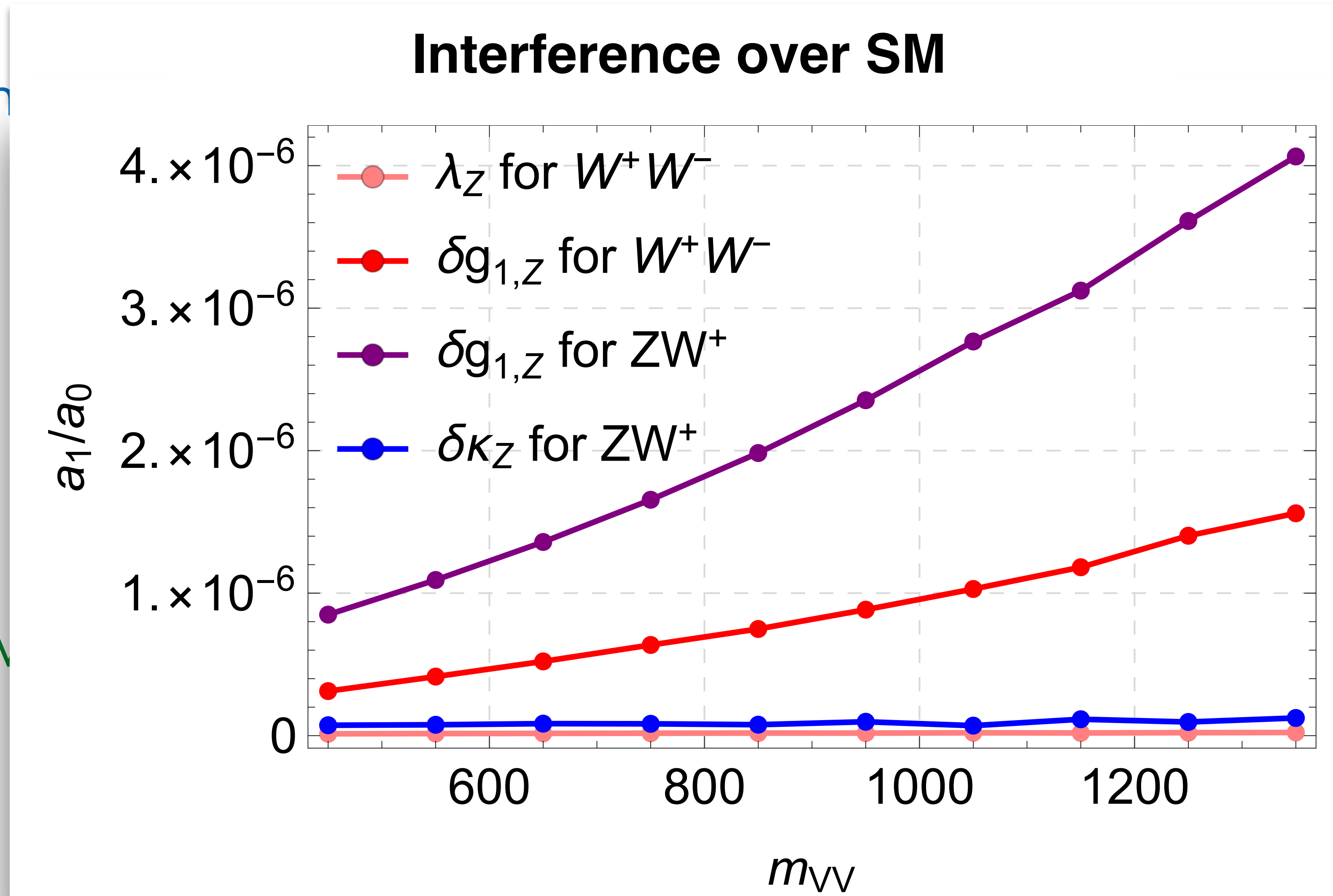
See Azatov, Contino, Machado, Riva [1607.05236] for thorough analysis — classification there is based on different logic.

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

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

It turns out that $W^3_{\mu\nu}$ does not lead to 2->2 amplitudes with same helicity as in the SM ⇒ thus interference vanishes.

$W^3_{\mu\nu}$ is of th



It turns out … me helicity

as in the SM

Azatov, EM, Reyimuaji, Venturini

Can we enlarge the sensitivity to $W^3_{\mu\nu}$ in the region where the EFT is valid?

We want to prove this term

* In general $\sigma = \sigma_{\rm SM} + \sigma_{\rm int} c + \sigma_{\rm BMS^2} c^2$

diboson measurements
sensitive to this function

* We can look at the parameter $\delta = \dfrac{\sigma_{\rm int}}{\sigma_{SM}} \times \dfrac{\sigma_{\rm int}}{\sigma_{\rm BMS^2}}$

EFT 🙂?

sensitive to NP?

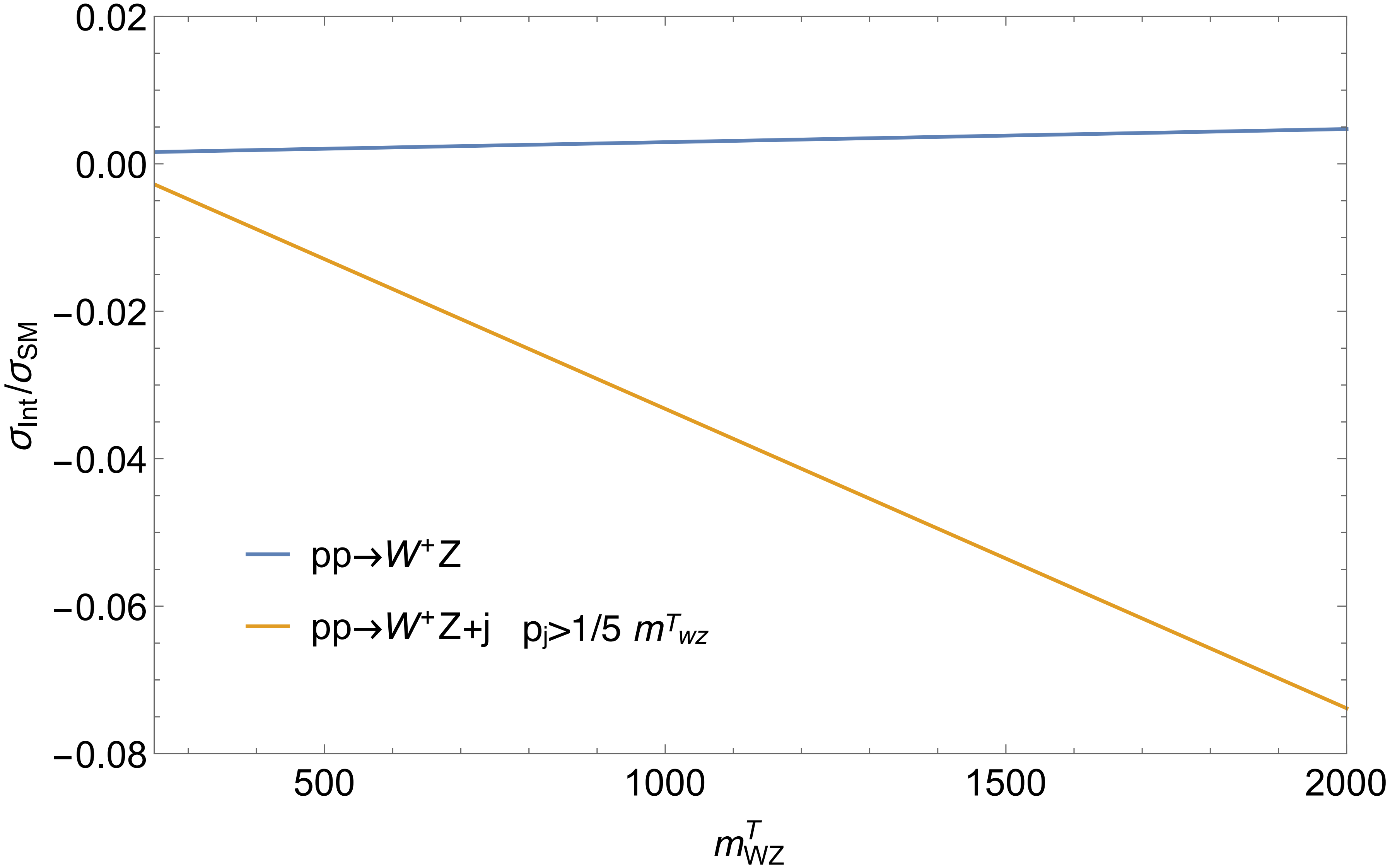
* For the deviations of the SM cross sections less than $\Delta\sigma_{\rm obs} \leq \delta \times \sigma_{\rm SM}$
we are still dominated by the interference term.

⇒ **We should design searches that maximize δ**

1st solution

$pp \to W^+Z+j$

* Sensitive to λ_z interference.



* Requiring extra hard jet helps in interference!

Azatov, EM, Reyimuaji, Venturini

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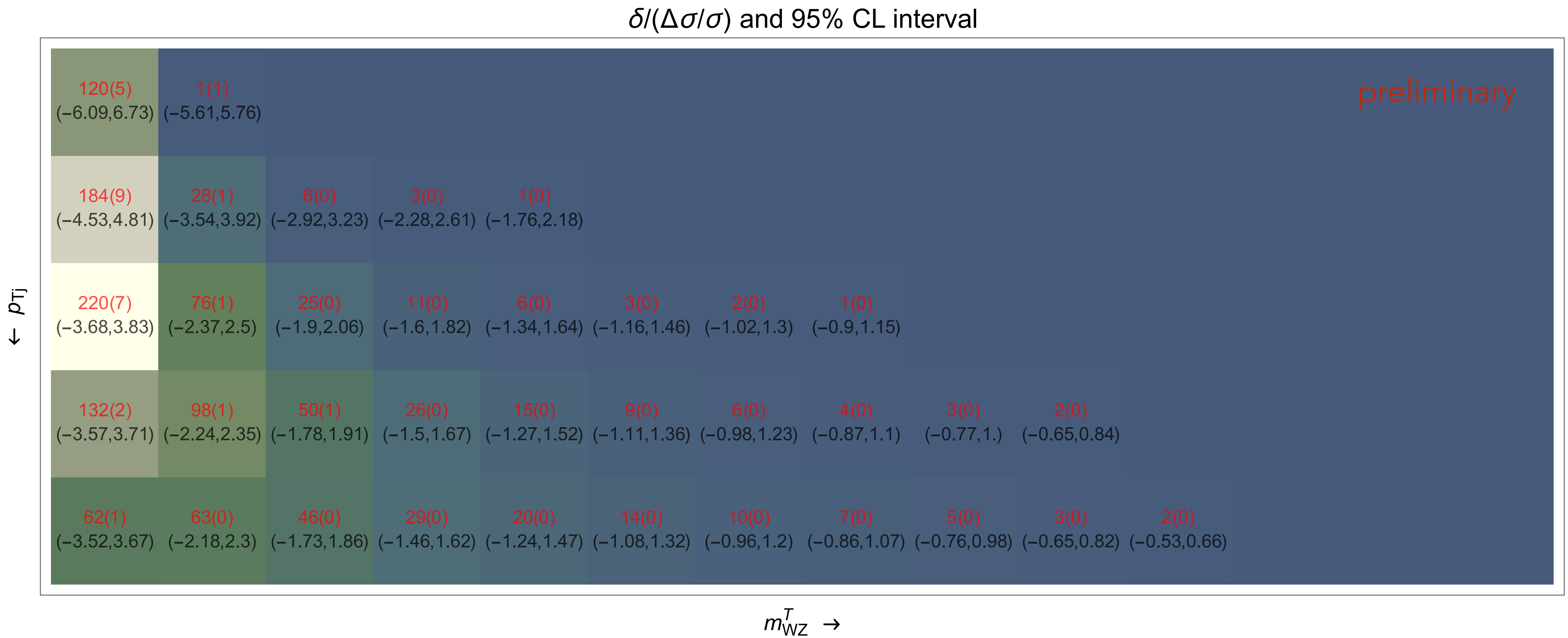
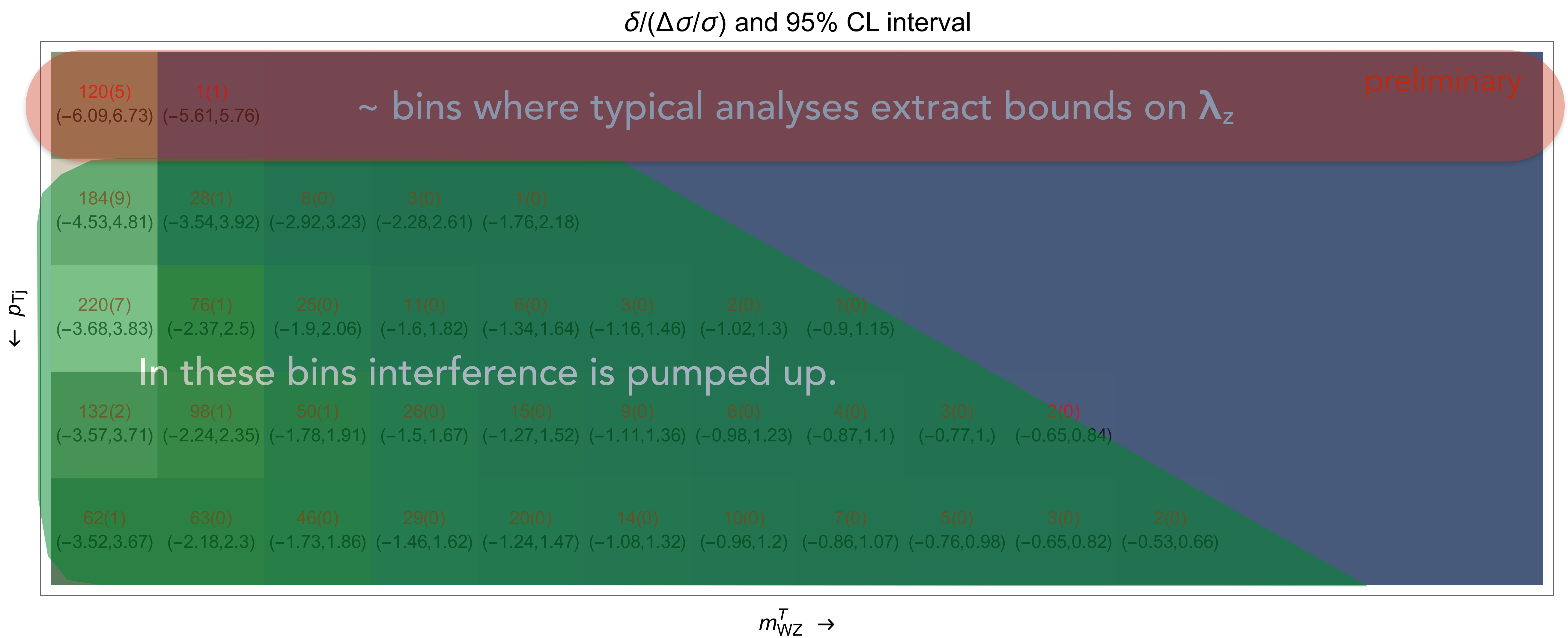


CL obtained integrating over lower bin categories.

LHC @14TeV
pTj: veto <50, [50,100], [100,300], [300,500], >500
mwzT: [100,200], …, [900,1000], [1000,1200], [1200,1500], [1500,2000], [2000,2500], >2500

Azatov, EM, Reyimuaji, Venturini



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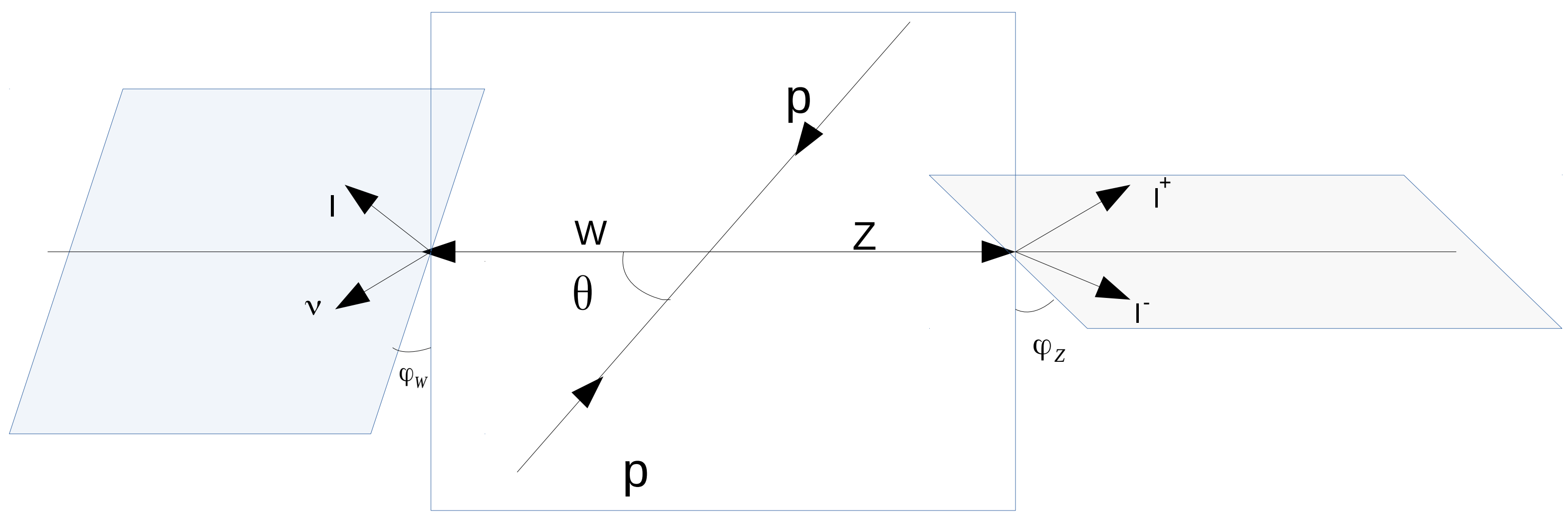
2nd solution binning on azimuthal angles of the decay products

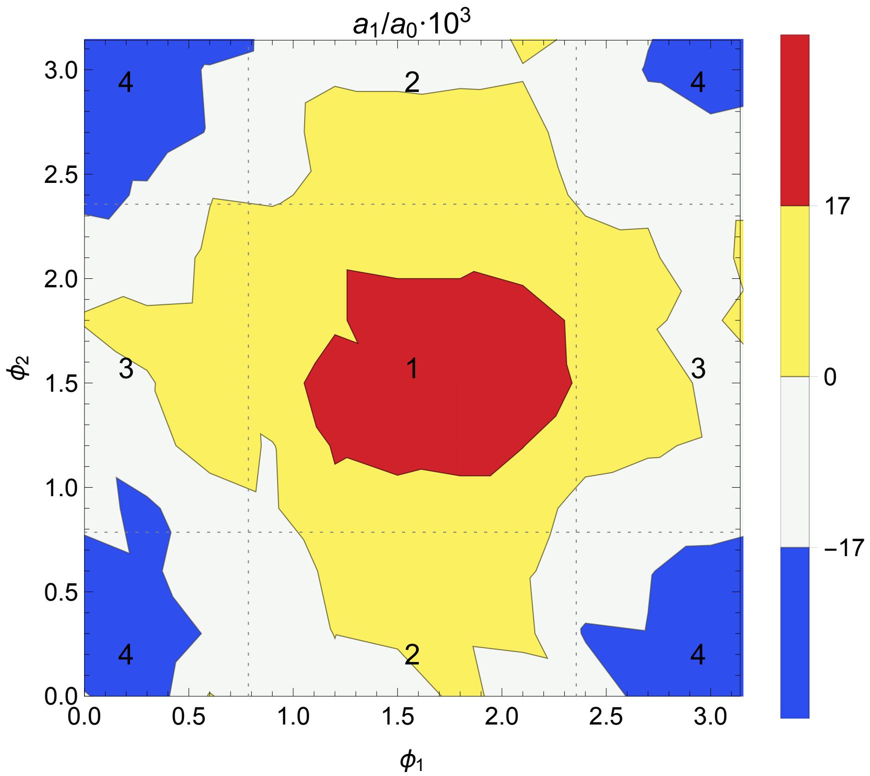


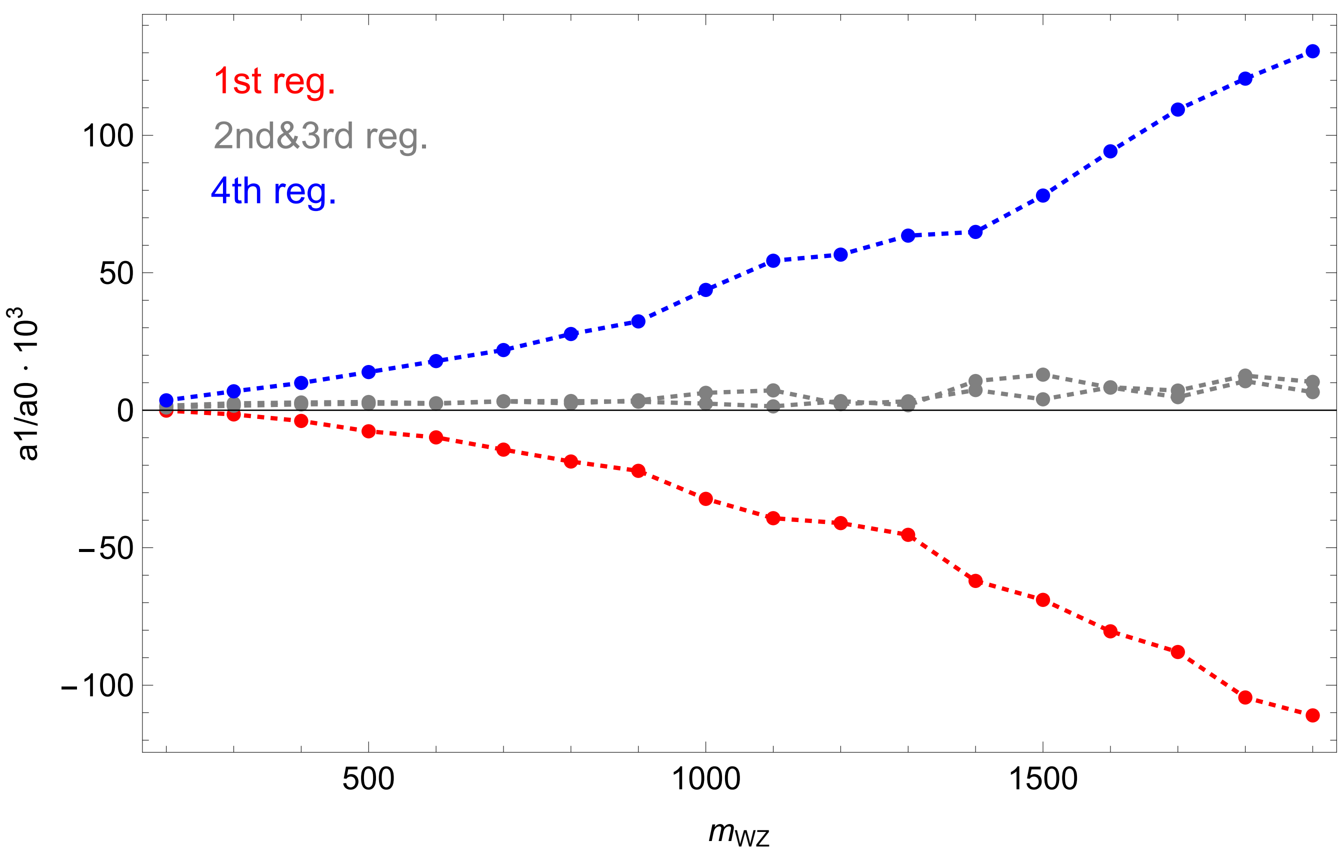
Azatov, EM, Reyimuaji, Venturini

- Gives a better handle on the interference amplitude.

- Energy growth is recovered.

- Sensitivity to the sign of the Wilson coefficient





Azatov, EM, Reyimuaji, Venturini

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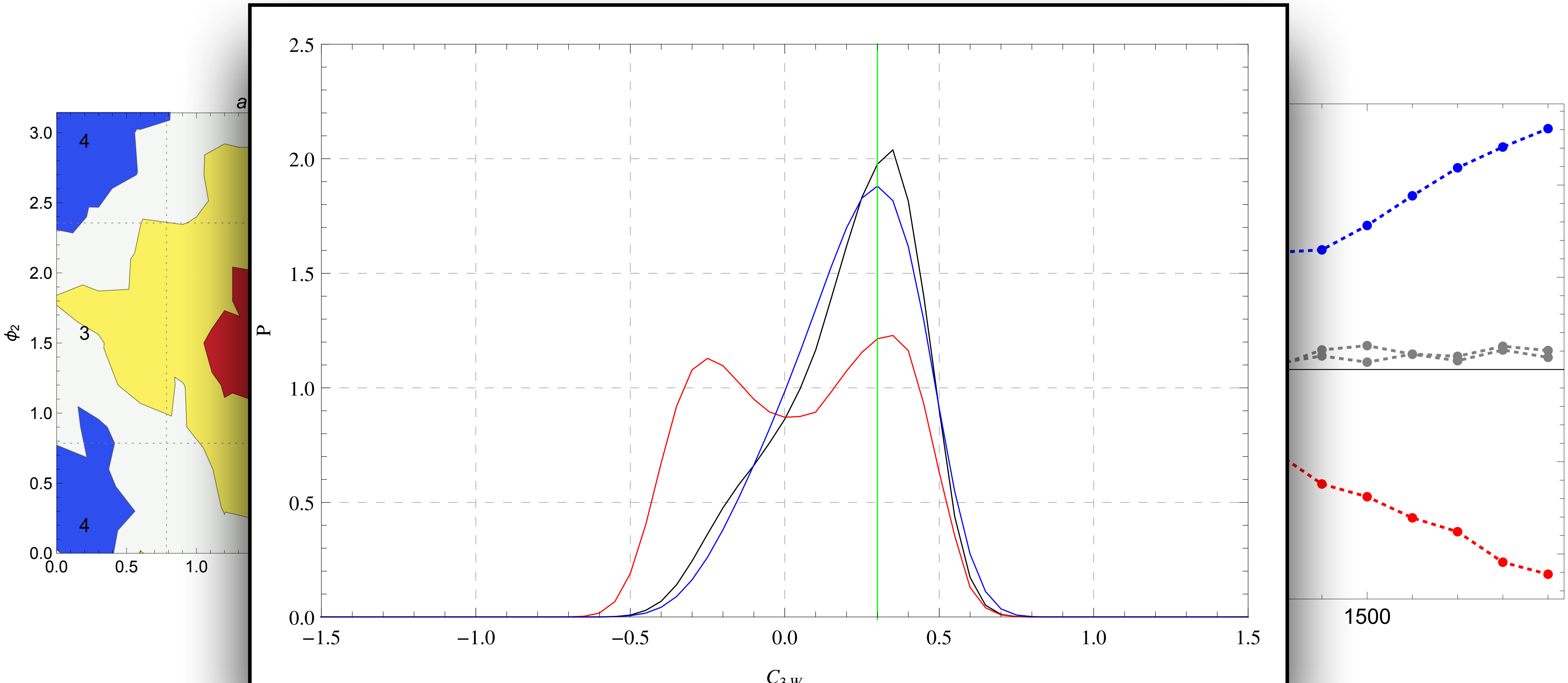
qualitatively different: with this binning we access the sign and regime of EFT validity is larger.



Azatov, EM, Reyimuaji, Venturini

Summary

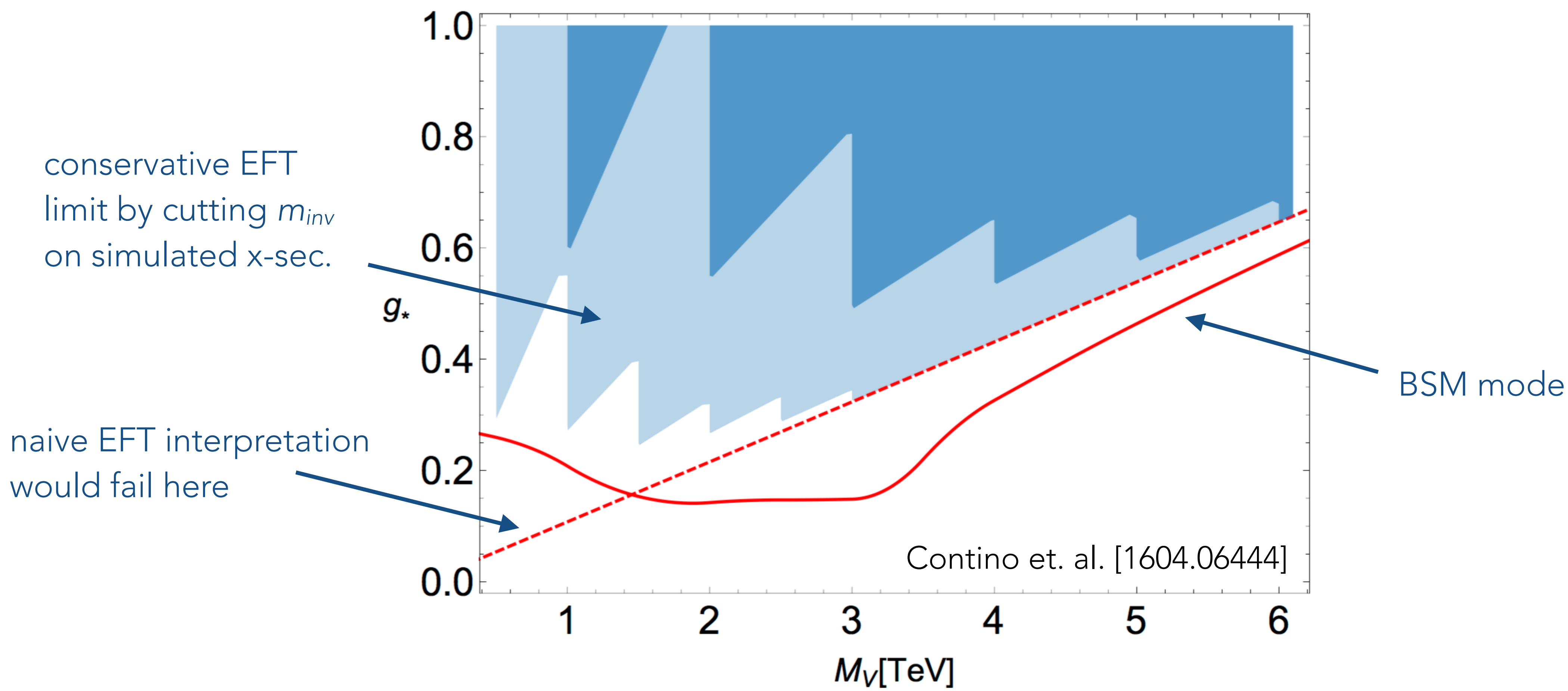
* At LHC we must be careful with EFT interpretation.

* Analysis of aTGC. The main motivation is bottom up, better sensitivity to NP from diboson measurement.

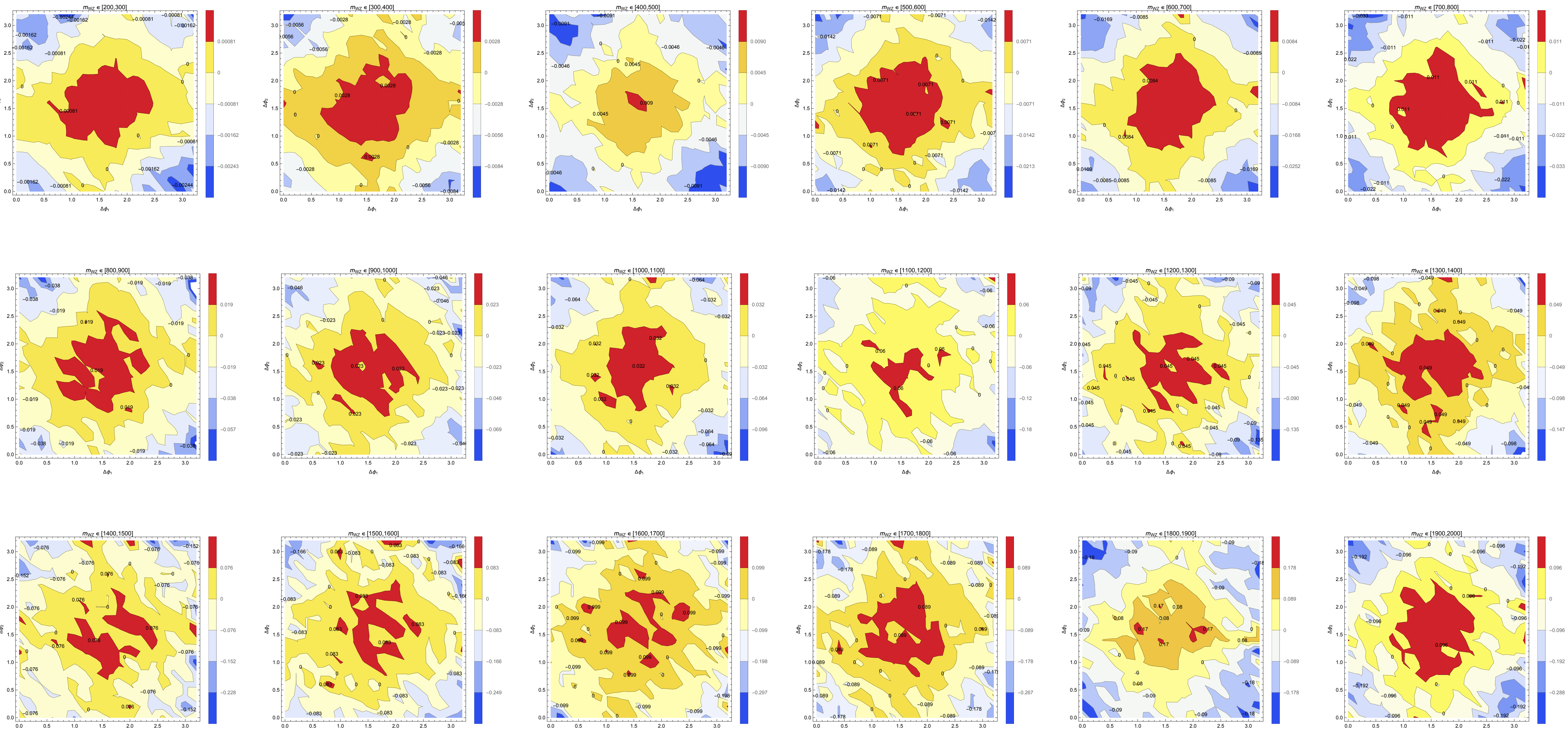
* Larger sensitivity to interference term is more *EFT save*:
less dependence on quadratic terms and dim8 ops — field redefinitions of $O(1/\Lambda^2)$ differ at $O(1/\Lambda^4)$.

* We gain sensitivity for λ_z by
    - looking at 2->3 process instead of 2->2.
    - binning on azimuthal angles of decay products.

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


$m_{WZ} \in [200,300]$
$m_{WZ} \in [300,400]$
$m_{WZ} \in [400,500]$
$m_{WZ} \in [500,600]$
$m_{WZ} \in [600,700]$
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$m_{WZ} \in [1100,1200]$
$m_{WZ} \in [1200,1300]$
$m_{WZ} \in [1300,1400]$
$m_{WZ} \in [1400,1500]$
$m_{WZ} \in [1500,1600]$
$m_{WZ} \in [1600,1700]$
$m_{WZ} \in [1700,1800]$
$m_{WZ} \in [1800,1900]$
$m_{WZ} \in [1900,2000]$
$\Delta\phi_1$
$\Delta\phi_2$