TH-Institute 25-July-2016

Effective-Field-Theory Approach of the anomalous Triple Gauge Couplings at the LHC

Minho Son
KAIST

Greljo, Gonzalez-Alonso, Falkowski, Marzoca, SON in progress

Lesson from Run1, part of Run 2

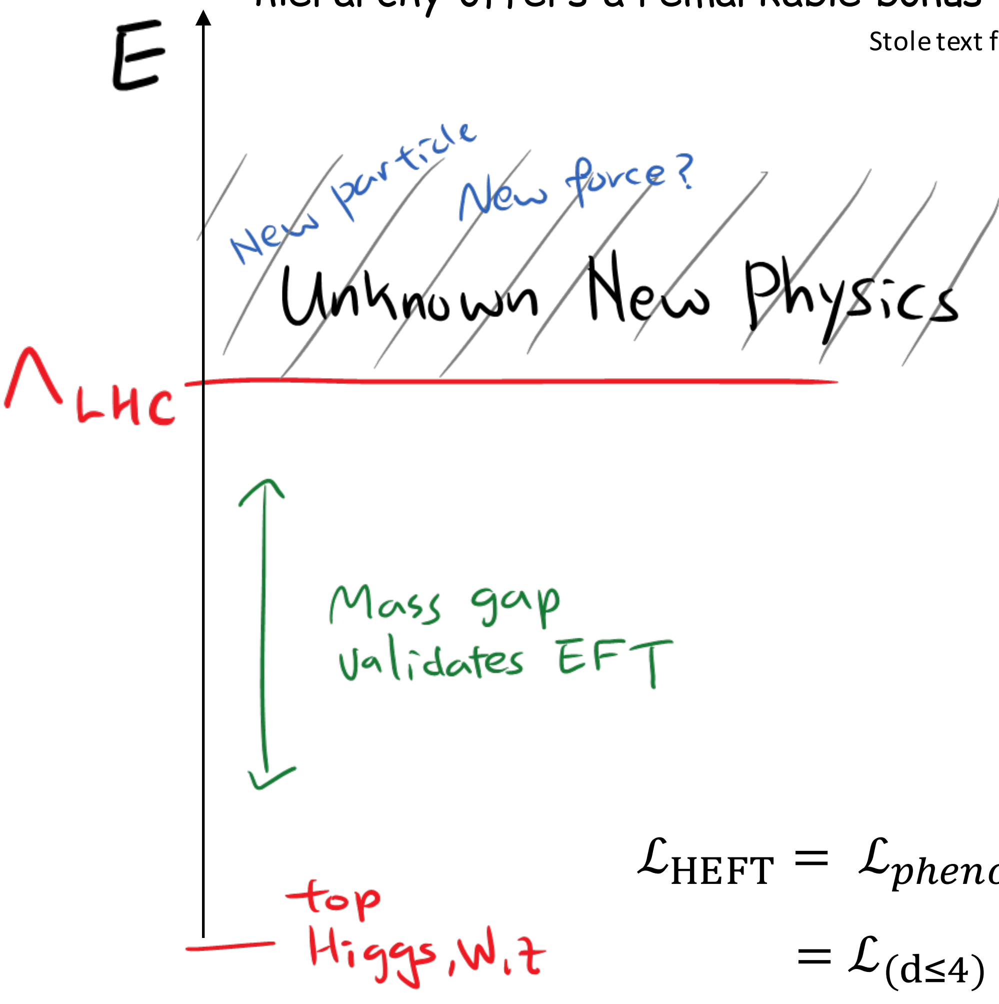
$$\Lambda_{LHC} > \mathcal{O}(\mathrm{TeV})$$

: cut-off scale
extracted from data

Higgs Effective Field Theory

Widely separated two scales, or seemingly un-natural hierarchy offers a remarkable bonus

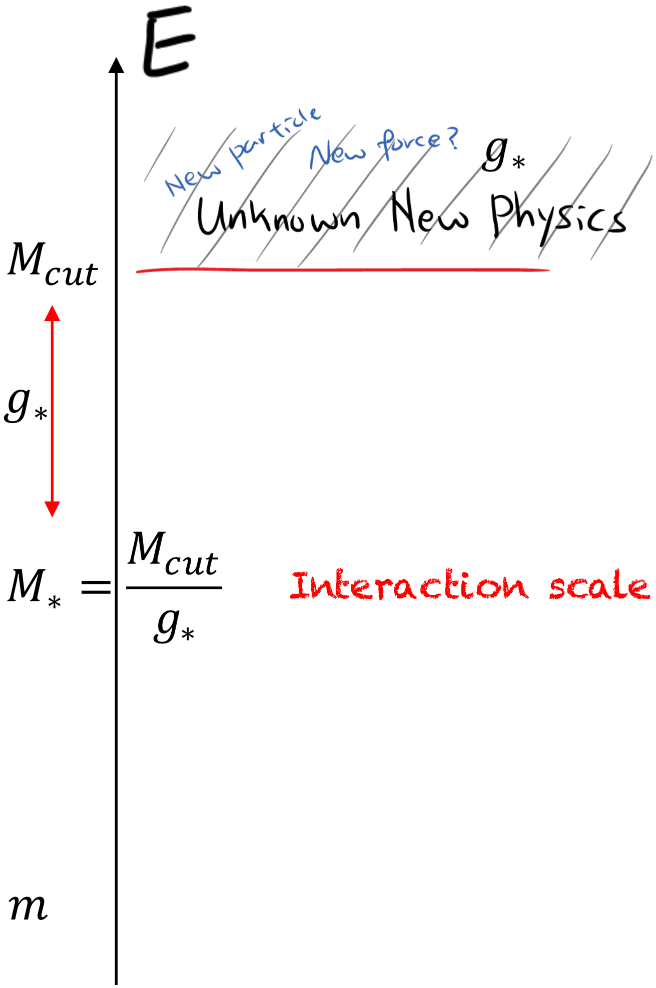
Stole text from the talk by Rattazzi



$$\mathcal{L}_{\text{HEFT}} = \mathcal{L}_{pheno.} + Higgs$$
$$= \mathcal{L}_{(\text{d}\leq 4)} + \frac{1}{\Lambda_{\text{LHC}}}\mathcal{L}_{(5)} + \frac{1}{\Lambda_{\text{LHC}}^2}\mathcal{L}_{(6)} + \cdots$$

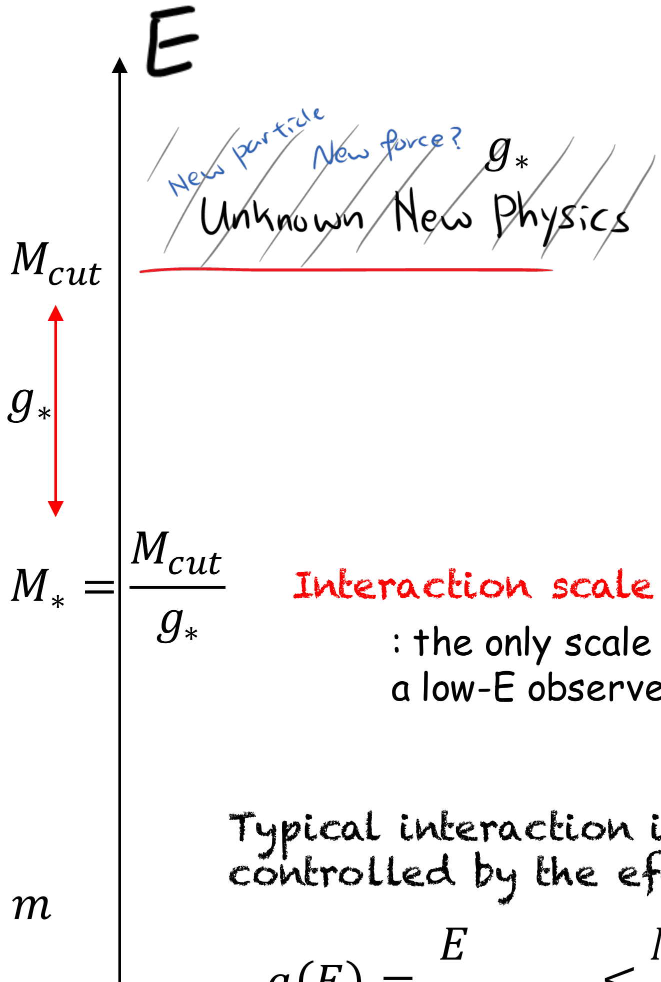
Structural picture of EFT

Racco, Wulzer, Zwirner 15'
Contino, Falkowski, Goertz, Grojean, Riva 16'



Structural picture of EFT

Racco, Wulzer, Zwirner 15'
Contino, Falkowski, Goertz, Grojean, Riva 16'



Typical interaction in EFT is controlled by the effective coupling,

$$g(E) = \frac{E}{M_*} \leq \frac{M_{cut}}{M_*} = g_*$$

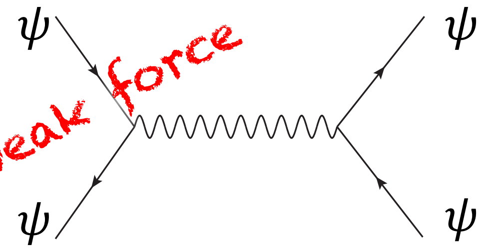
Structural picture of EFT

Racco, Wulzer, Zwirner 15'
Contino, Falkowski, Goertz, Grojean, Riva 16'

E

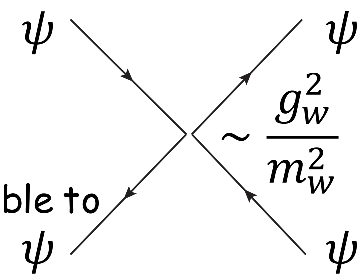
New particle
New force?
g_*
Unknown New Physics

= Weak force



M_{cut} $\rightarrow m_W$

g_* g_W



$$M_* = \frac{M_{cut}}{g_*}$$

Interaction scale

: the only scale accessible to a low-E observer

$$\rightarrow \frac{m_W}{g_W} = \frac{1}{\sqrt{G_F}}$$

m $\rightarrow m_\psi$

Typical interaction in EFT is controlled by the effective coupling,

$$g(E) = \frac{E}{M_*} \leq \frac{M_{cut}}{M_*} = g_*$$

$$g(E) = \frac{g_W}{m_W} E$$

Structural picture of EFT

Racco, Wulzer, Zwirner 15'
Contino, Falkowski, Goertz, Grojean, Riva 16'

E

New particle

New force?

g_*

Unknown New Physics

M_{cut}

g_*

$M_* = \frac{M_{cut}}{g_*}$ Interaction scale

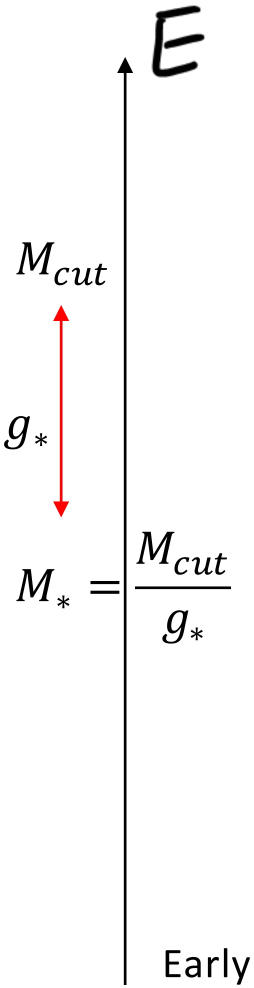
m

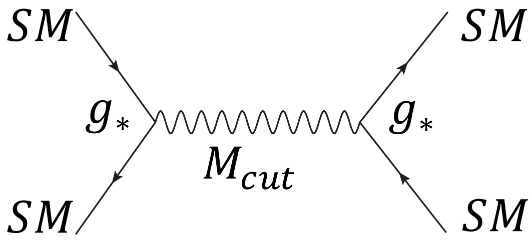
This picture fits to Higgs physics well
& also to aTGC

Typical interaction in EFT is
controlled by the effective coupling,

$$g(E) = \frac{E}{M_*} \leq \frac{M_{cut}}{M_*} = g_*$$

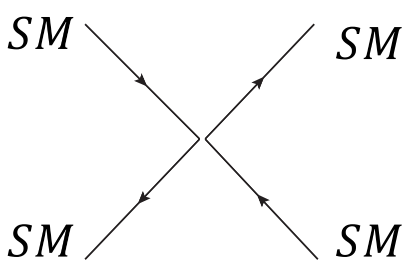
Unitarity violation in EFT





$$\mathcal{A}_{UV} \propto \frac{g_*^2 s}{s - M_{cut}^2} \quad \to \text{const. as } s \to \infty$$

$$= \frac{g_*^2 s}{M_{cut}^2} + O\left(\frac{s^2}{M_{cut}^4}\right)$$



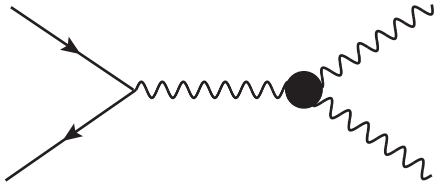
What if our collider was not strong enough to produce $\boldsymbol{M_{cut}}$?

$$\mathcal{A}_{EFT} \sim \frac{s}{M_*^2} \qquad \to \infty \text{ as } s \to \infty$$

E-growing vs. Validity of EFT

Early new physics hint in EFT approach relies on the E-growing feature due to decent $S/\sqrt{B}$.
However, this benefit should cut off at a certain energy scale, $E < M_{cut}$

Constraining HEFT via VV processes



We will parameterize BSM in the Higgs basis

See "LHC Higgs Cross Section Working Group" note

Data

↕

New interactions beyond SM

$$\mathcal{L}_{pheno\ EFT} = \mathcal{L}_{SM} + \Delta\mathcal{L}$$

- shift of the coupling strength away from SM predictions
- new tensor structures of interaction absent in SM

↕

$$\mathcal{L}_{HEFT} = \mathcal{L}_{SM} + \sum \overline{c_i} \frac{\mathcal{O}_i^{dim=6}}{v^2}$$

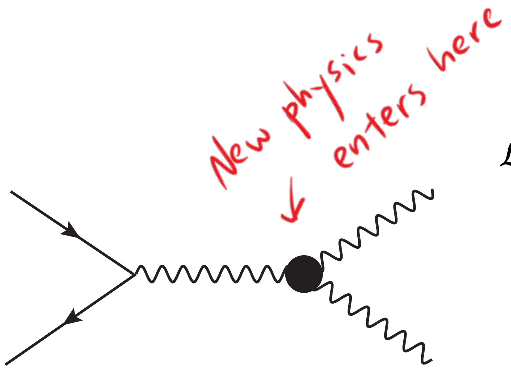
$$g^2(E) \sim O\left(g_{SM}^2 \frac{E^2}{m_W^2} \bar{c}\right)$$

↕

Warsaw, SILH bases etc with
SU(2) doublet Higgs H

BSM

Constraining HEFT via VV processes



Treat LEP measurements as inputs

$$\mathcal{L}_{TGC} = ie\left[\left(W^+_{\mu\nu}W^-_\mu - W^-_{\mu\nu}W^+_\mu\right)A_\nu + \left(1+\delta\kappa_\gamma\right)A_{\mu\nu}W^+_\mu W^-_\nu\right]$$

$$+\, ig_L\cos\theta\left[\left(1+\delta g_{1,z}\right)\left(W^+_{\mu\nu}W^-_\mu - W^-_{\mu\nu}W^+_\mu\right)Z_\nu + \left(1+\delta\kappa_z\right)Z_{\mu\nu}W^+_\mu W^-_\nu\right]$$

$$+\, ie\frac{\lambda_\gamma}{m_W^2}W^+_{\mu\nu}W^-_{\nu\rho}A_{\rho\mu} + ig_L\cos\theta\frac{\lambda_z}{m_W^2}W^+_{\mu\nu}W^-_{\nu\rho}Z_{\rho\mu}$$

$$\delta\kappa_z = \delta g_{1,z} - \frac{g_Y^2}{g_L^2}\delta\kappa_\gamma \qquad \lambda_z = \lambda_\gamma$$

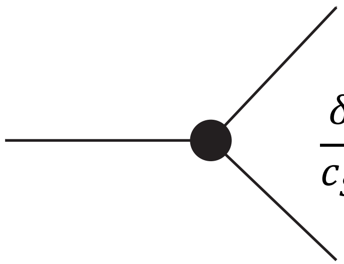
→ Three variables for VV

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

A difficulty of EFT approach:

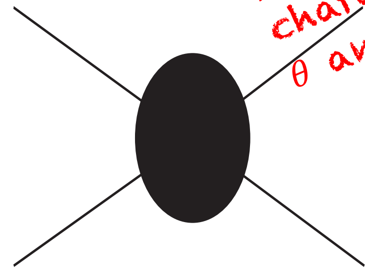
Many parameters lead to a degeneracy

Decay vs 2-to-2 scattering process



$$\frac{\delta c}{c_{SM}} \sim \left(\frac{g_*}{g_{SM}}\right)^2 \frac{m_h^2}{M_{cut}^2}$$

Main focus of Run 1



Kinematics is characterized by θ and $\sqrt{\hat{s}}$

$$\frac{\delta\sigma_{2\to2}}{\sigma_{SM}} \sim \frac{g^2(E)}{g_{SM}^2} \sim \left(\frac{g_*}{g_{SM}}\right)^2 \frac{E^2}{M_{cut}^2}$$

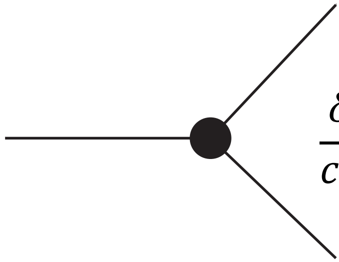
Important item of Run 2

Parameters in HEFT are $\theta, \sqrt{\hat{s}}$ -dependent

$$\frac{d\sigma}{d\sqrt{\hat{s}}}, \quad \frac{d\sigma}{d\cos\theta}, \quad \left(\frac{d\sigma}{d\sqrt{\hat{s}}}\right)_{13\text{TeV}} \Big/ \left(\frac{d\sigma}{d\sqrt{\hat{s}}}\right)_{8\text{TeV}}$$

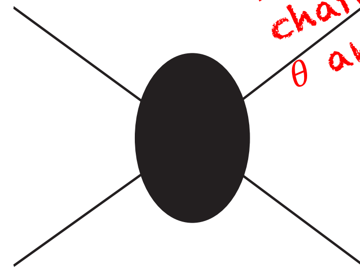
Can see more microscopic structure of BSM

Decay vs 2-to-2 scattering process



$$\frac{\delta c}{c_{SM}} \sim \left(\frac{g_*}{g_{SM}}\right)^2 \frac{m_h^2}{M_{cut}^2}$$

Main focus of Run 1



Kinematics is characterized by θ and $\sqrt{\hat{s}}$

$$\frac{\delta\sigma_{2\to 2}}{\sigma_{SM}} \sim \frac{g^2(E)}{g_{SM}^2} \sim \left(\frac{g_*}{g_{SM}}\right)^2 \frac{E^2}{M_{cut}^2}$$

Important item of Run 2

Parameters in HEFT are $\theta, \sqrt{\hat{s}}$ -dependent ➡ $\frac{d\sigma}{d\sqrt{\hat{s}}}$, $\frac{d\sigma}{dcos\theta}$, $\left(\frac{d\sigma}{d\sqrt{\hat{s}}}\right)_{13\mathrm{TeV}} \Big/ \left(\frac{d\sigma}{d\sqrt{\hat{s}}}\right)_{8\mathrm{TeV}}$

Can see more microscopic structure of BSM

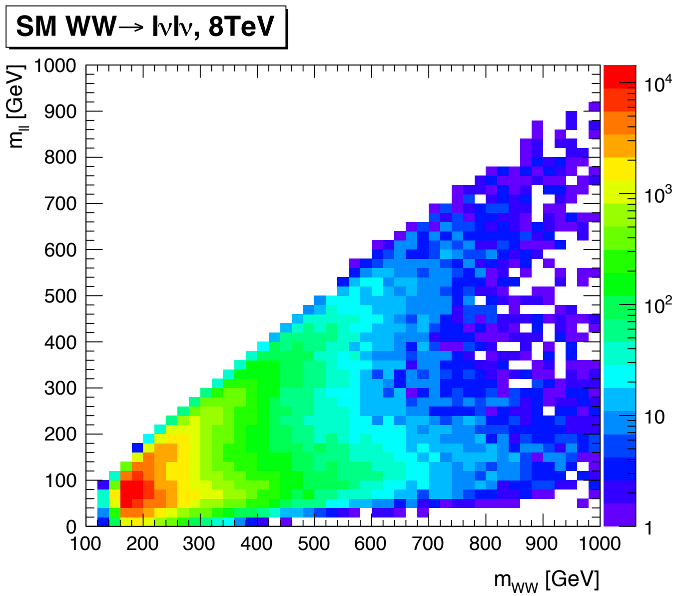
Accessing to the truth-level $\sqrt{\hat{s}}$ is non-trivial

What we want to know vs. What we currently measure

$\sqrt{\hat{s}} = m_{WW}, m_{WZ}$ Not exactly matches m_{ll}, m_{WZ}^T, p_T etc

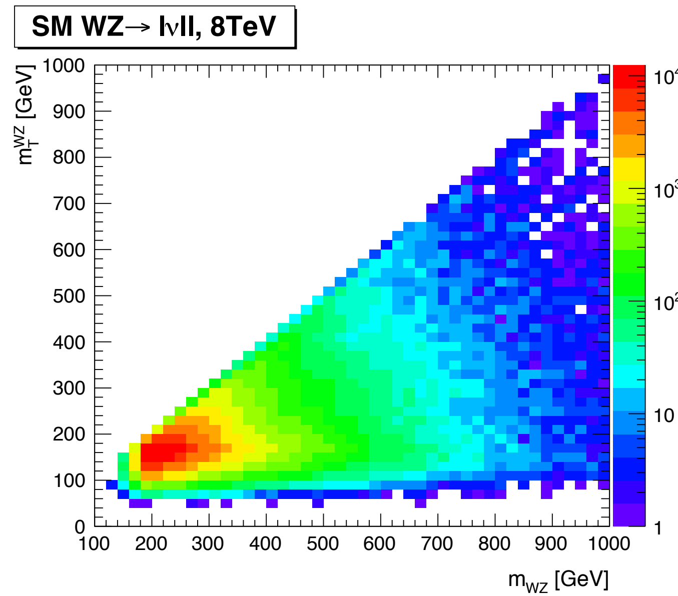
Accessing to the truth-level $\sqrt{\hat{s}}$ is non-trivial

What is measured



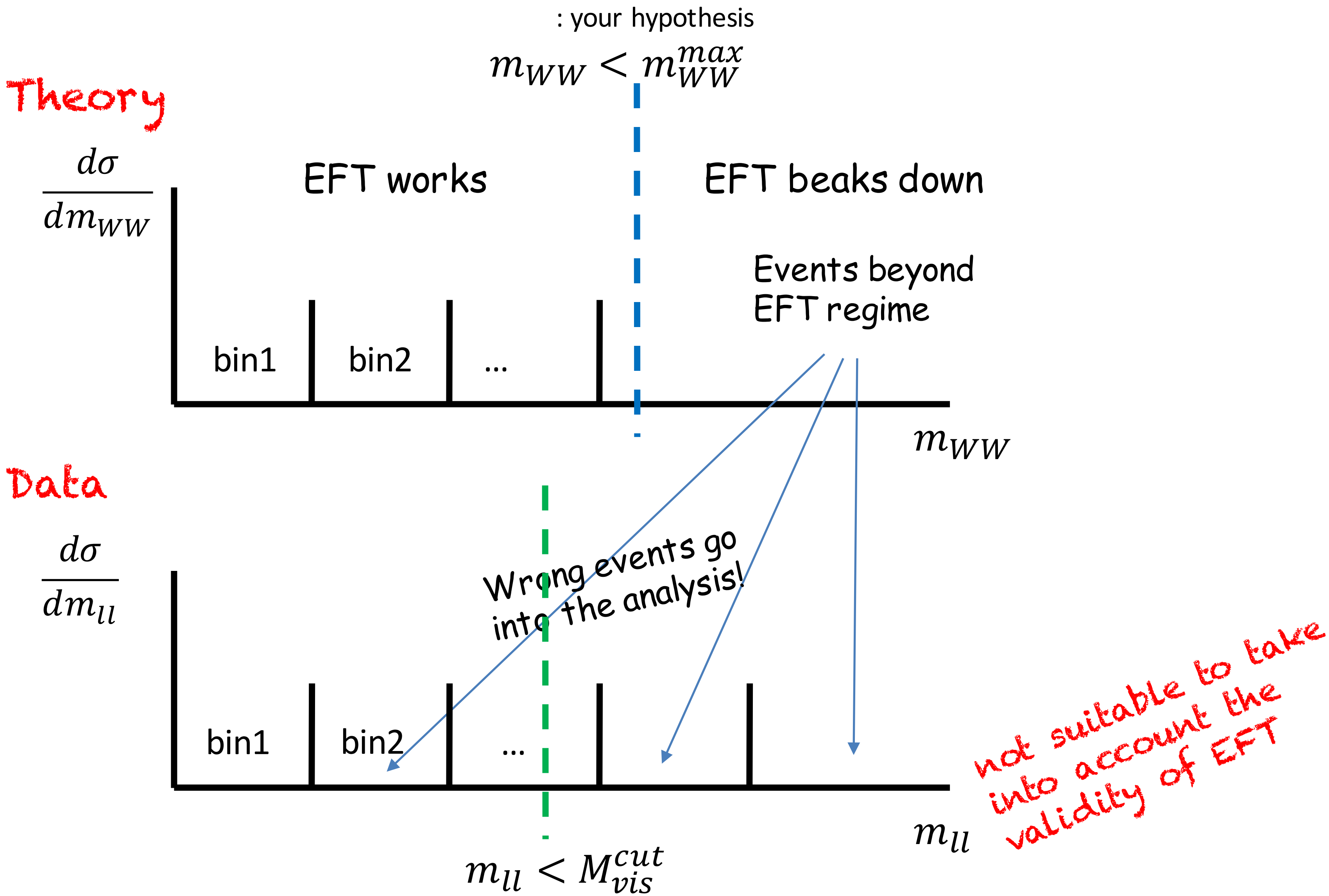
What we want to know

What is measured

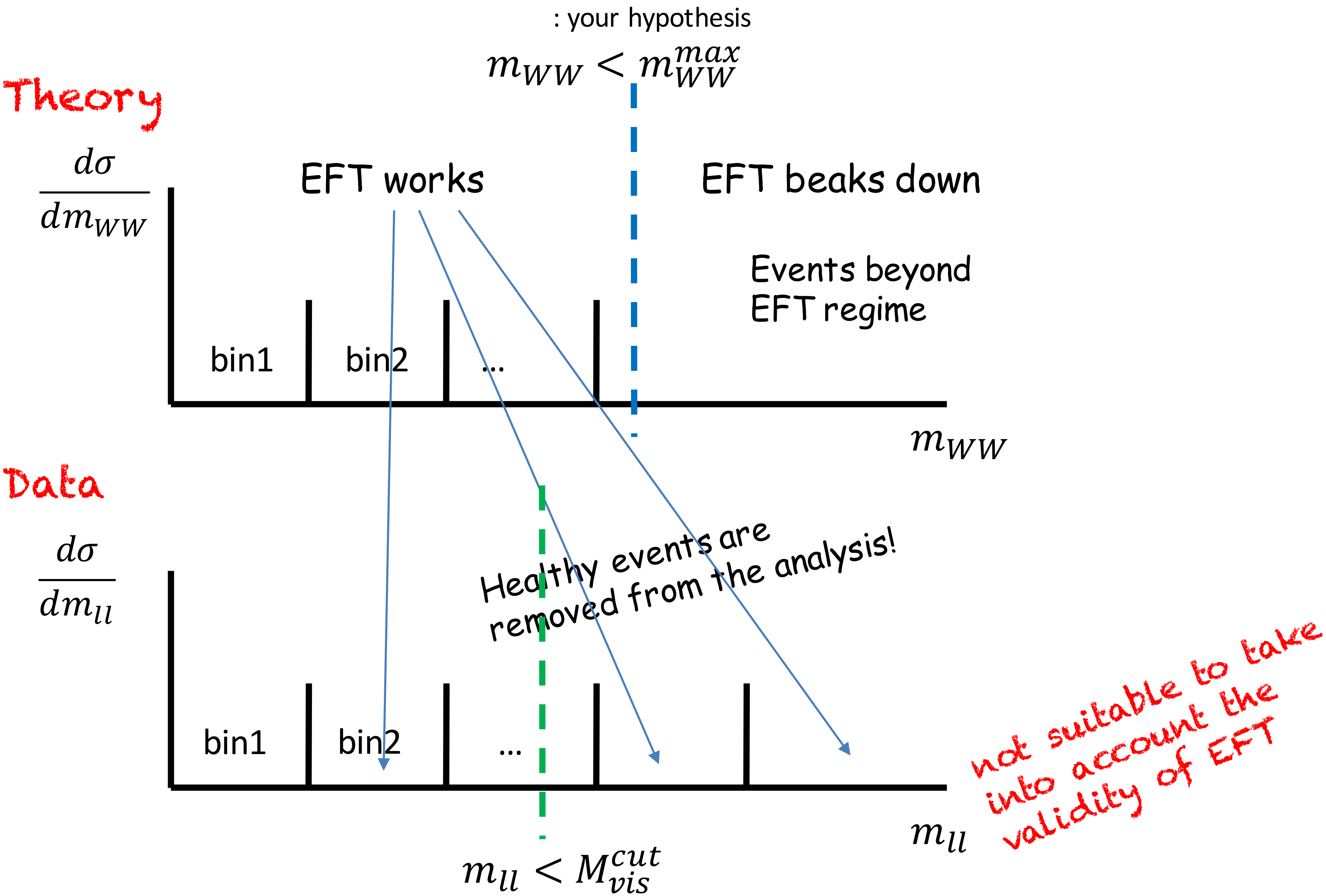


What we want to know

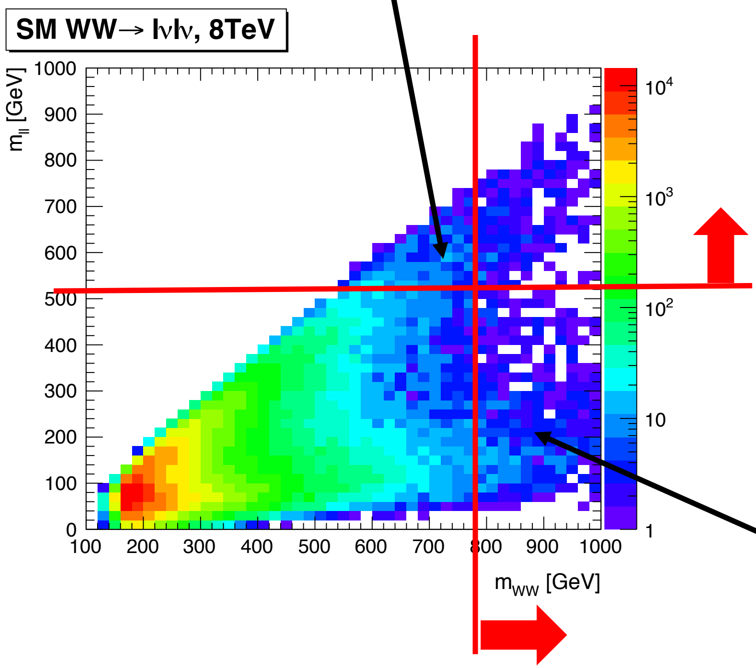
Pollution from the wrong events



Removal of the healthy events



You wrongly kill healthy events



What is measured

You cut here on m_{ll}

You fail to remove these wrong events

m_{WW}^{max}

What controls EFT validity

$$\int_0^{m_{VV}^{max}} dm_{VV} \frac{d\sigma}{dm_{VV}} \neq \int_0^{M_{vis}^{cut}} dm_{vis} \frac{d\sigma}{dm_{vis}}$$

Cutting on m_{ll} is not justified. What do we do?

In principle, if we can access to $m_{VV} \equiv \sqrt{\hat{s}}$

$$(\sigma_{SM}+\sigma_{BSM})(m_{VV} < m_{VV}^{max}) \qquad \sigma_{obs}\,(m_{VV} < m_{VV}^{max})$$

In mass situations, we do not have access to $m_{VV} \equiv \sqrt{\hat{s}}$

We only hope to set a conservative bound

$$(\sigma_{obs} - \sigma_{SM}) - \Delta\sigma \leq \underline{\sigma_{BSM}} \leq (\sigma_{obs} - \sigma_{SM}) + \Delta\sigma$$

$$\sigma_{BSM}^{m_{VV} < m_{VV}^{max}} + \sigma_{BSM}^{m_{VV} > m_{VV}^{max}}$$

Inspired by Racco, Wulzer, Zwirner 15'

For general discussion for Validity of EFT
Biekötter, Krämer, Liu, Riva 15'
Contino, Falkowski, Goertz, Grojean, Riva 16'

setting a conservative bound

$$(\sigma_{obs} - \sigma_{SM}) - \Delta\sigma \leq \sigma_{BSM} \leq (\sigma_{obs} - \sigma_{SM}) + \Delta\sigma$$

$$\sigma_{BSM}^{m_{VV}<m_{VV}^{max}} + \sigma_{BSM}^{m_{VV}>m_{VV}^{max}}$$

Inspired by Racco, Wulzer, Zwirner 15'

For general discussion for Validity of EFT
Biekötter, Krämer, Liu, Riva 15'
Contino, Falkowski, Goertz, Grojean, Riva 16'

If $\sigma_{BSM}^{m_{VV}<m_{VV}^{max}} > 0$ && $\sigma_{BSM}^{m_{VV}>m_{VV}^{max}} > 0$ && No excess

$$(\sigma_{obs} - \sigma_{SM}) - \Delta\sigma \leq \sigma_{BSM}^{m_{VV}<m_{VV}^{max}} \leq (\sigma_{obs} - \sigma_{SM}) + \Delta\sigma$$

setting a conservative bound

$$(\sigma_{obs}-\sigma_{SM}) - \Delta\sigma \leq \sigma_{BSM} \leq (\sigma_{obs}-\sigma_{SM}) + \Delta\sigma$$

$$\sigma_{BSM}^{m_{VV}<m_{VV}^{max}} + \sigma_{BSM}^{m_{VV}>m_{VV}^{max}}$$

Inspired by Racco, Wulzer, Zwirner 15'

For general discussion for Validity of EFT
Biekötter, Krämer, Liu, Riva 15'
Contino, Falkowski, Goertz, Grojean, Riva 16'

If $\sigma_{BSM}^{m_{VV}<m_{VV}^{max}} > 0$ && $\sigma_{BSM}^{m_{VV}>m_{VV}^{max}} > 0$ && No excess

$$(\sigma_{obs} - \sigma_{SM}) - \Delta\sigma \leq \sigma_{BSM}^{m_{VV}<m_{VV}^{max}} \leq (\sigma_{obs}-\sigma_{SM}) + \Delta\sigma$$

- ✓ In the absence of the interference between SM and BSM
- ✓ In the presence of the interference
  - Incomplete justification

$$\sigma_{BSM} \propto (\mathcal{A}_{SM}^{*}\mathcal{A}_{BSM} + h.c.) + |\mathcal{A}_{BSM}|^2$$

$$\left|\frac{\mathcal{A}_{BSM}}{\mathcal{A}_{SM}}\right| \sim \left(\frac{g_*}{g_{SM}}\right)^2 \left(\frac{E}{m_{VV}^{max}}\right)^2 > 1 \qquad \text{for } E > m_{VV}^{max}$$

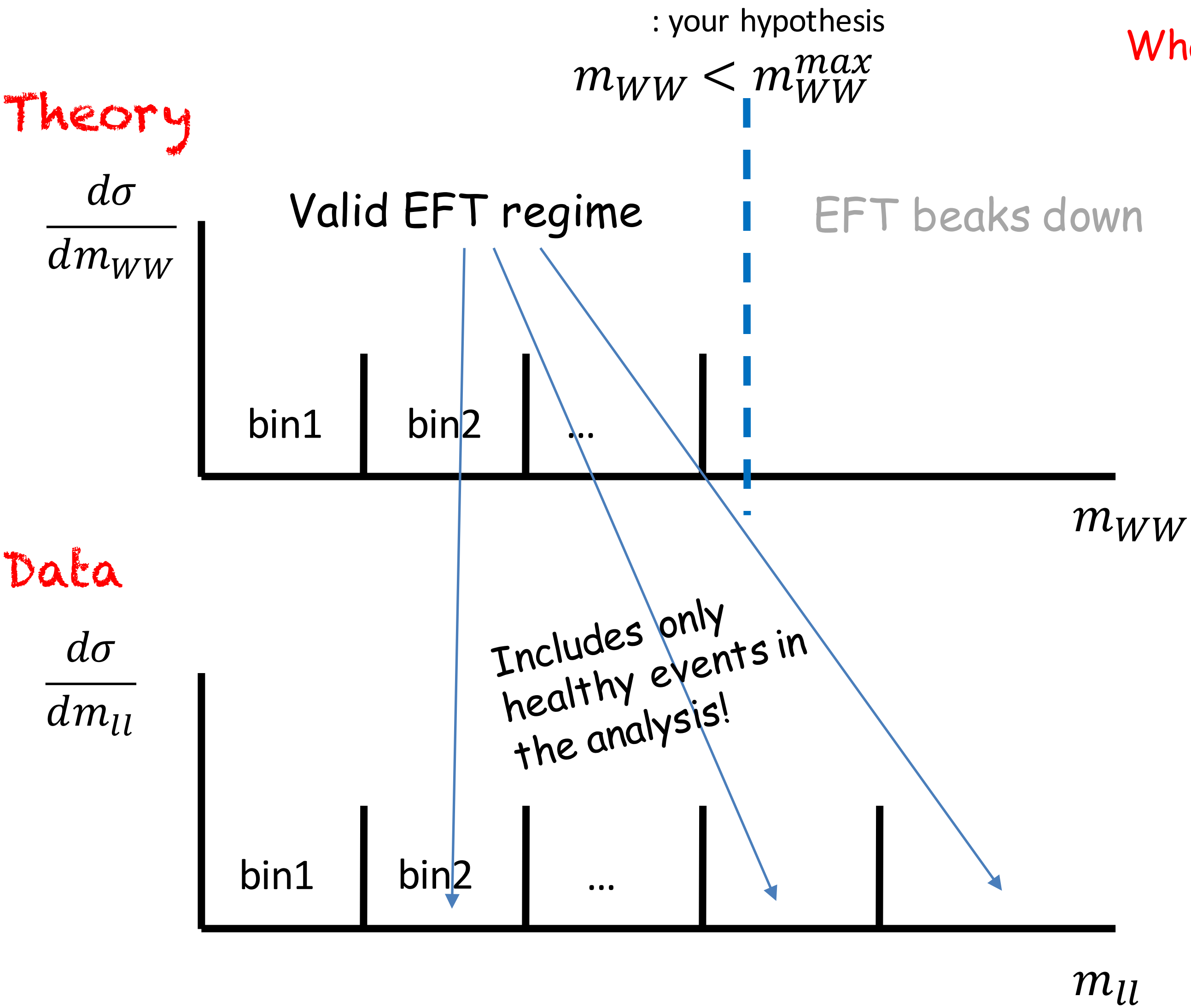
If a theory is strongly coupled, $g_* \gg g_{SM}$

  - Suppression of interference by hidden selection rules

$$\sigma_{BSM} \propto (\mathcal{A}_{SM}^{*}\mathcal{A}_{BSM} + h.c.) + |\mathcal{A}_{BSM}|^2 \sim |\mathcal{A}_{BSM}|^2$$

-> This is what's happening in aTGC

No excess scenario

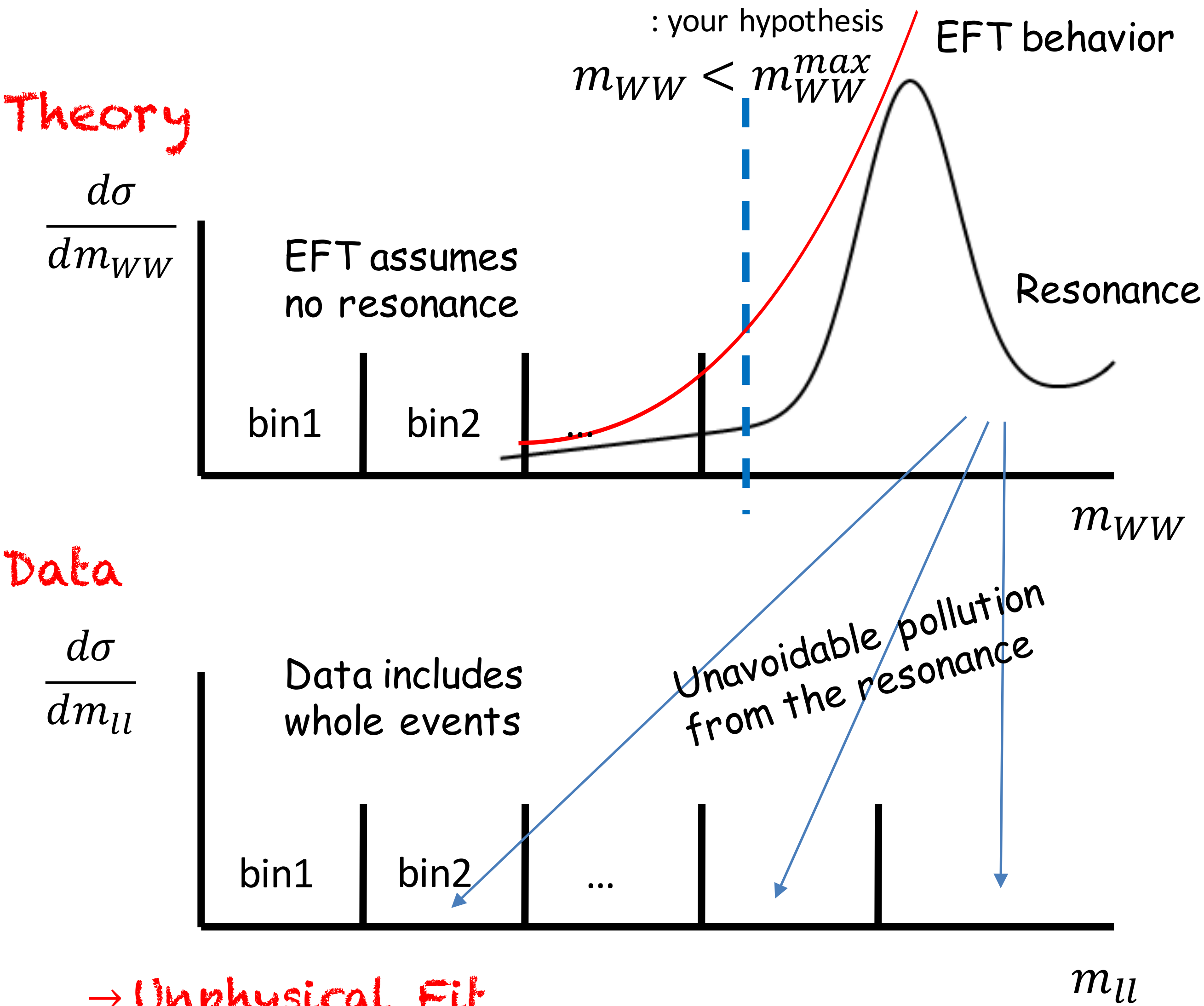


What we propose

1. Assume possible cut-off scale
2. Remove events from $\sigma_{BSM}^{m_{VV}>m_{VV}^{max}}$ in your simulation
3. recast data in entire m_{ll} distribution
4. Repeat 1-3 for different choice of cut-off scales

$$(\sigma_{obs} - \sigma_{SM}) - \Delta\sigma \leq \sigma_{BSM}^{m_{VV}<m_{VV}^{max}} \leq (\sigma_{obs} - \sigma_{SM}) + \Delta\sigma$$

Complication in Resonance scenario



→ Unphysical Fit

$$(\sigma_{obs} - \sigma_{SM}) - \Delta\sigma \leq \sigma_{BSM}^{m_{VV}<m_{VV}^{max}} \leq (\sigma_{obs} - \sigma_{SM}) + \Delta\sigma$$

will be overestimated

* Can be fixed if we recover full $\sqrt{\hat{s}} = m_{WW}$

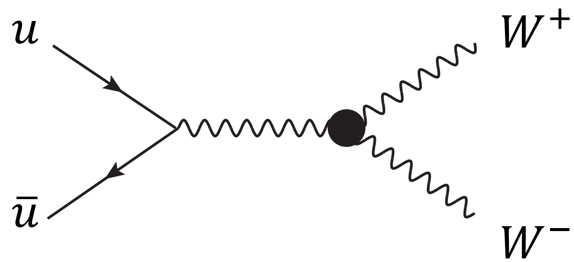
✓ In this case, we might just switch to resonance search than relying on EFT

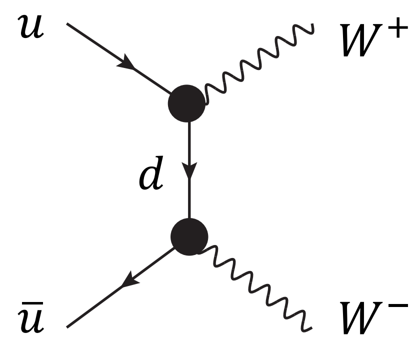
aTGC Amplitude

aTGC in WW

Anomalous Triple Gauge couplings

T, U channels participate in
Unitarity restoration in SM





Perfect cancellation of E-growing pieces

S-channel → T

$$\mathcal{A}_{0,0}^{SM} \sim \frac{\sin\theta}{2}\left[\left((T_u^3 - s_{\theta_w}^2 Q_u)g^2 + e^2 Q_u\right) - \frac{g^2}{2}\right]\frac{s}{m_W^2} = 0$$

Imperfect cancellation picks up E-growing behavior

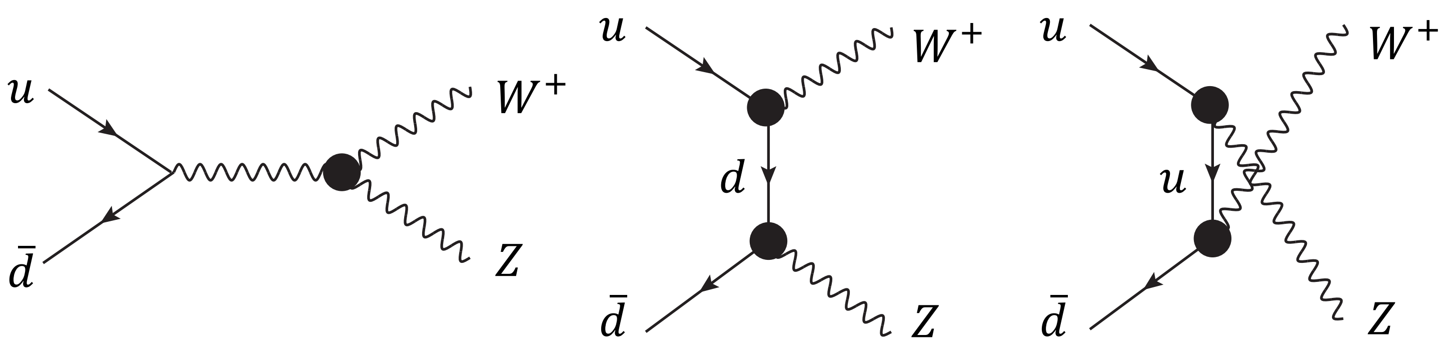
$$\mathcal{A}_{0,0} \sim \frac{\sin\theta}{2}\left[g^2\left(T_u^3 - s_{\theta_w}^2 Q_u\right)\delta\kappa_z + e^2 Q_u\,\delta\kappa_\gamma\right]\frac{s}{m_W^2}$$

$$\mathcal{A}_{L/R,0} \sim \frac{\mp 1 - \cos\theta}{2\sqrt{2}}\left[g^2\left(T_u^3 - s_{\theta_w}^2 Q_u\right)(\delta g_{1z} + \delta\kappa_z + \lambda_z) + e^2 Q_u(\delta\kappa_\gamma + \lambda_\gamma)\right]\frac{\sqrt{s}}{m_W}$$

aTGC in WZ

Anomalous Triple Gauge couplings

T, U channels participate in Unitarity restoration in SM



Perfect cancellation of E-growing pieces

S-channel T U

$$\mathcal{A}^{SM}_{0,0} \sim \sin\theta \, \frac{g^2}{2\sqrt{2}c_{\theta_w}}\left[c^2_{\theta_w} + (T^3_d - s^2_{\theta_w} Q_d) - (T^3_u - s^2_{\theta_w} Q_u)\right]\frac{s}{m_W m_Z} = 0$$

Imperfect cancellation picks up E-growing behavior

$$\mathcal{A}_{0,0} \sim \sin\theta \, \frac{g^2}{2\sqrt{2}c_{\theta_w}}\left[c^2_{\theta_w}\ \delta g_{1,z}\right]\frac{s}{m_W m_Z}$$

$$\mathcal{A}_{L/R,R/L} \sim -\sin\theta \frac{c_{\theta_w}\ g^2}{2\sqrt{2}}\lambda_z \frac{s}{m_W^2}$$

$$\mathcal{A}_{L/R,0} \sim (\pm 1 + \cos\theta)\, \frac{g^2}{4c_{\theta_w}}\left[2\ c^2_{\theta_w}\ \ \delta g_{1,z} + \lambda_z\right]\frac{\sqrt{s}}{m_Z}$$

$$\mathcal{A}_{0,R/L} \sim (\mp 1 + \cos\theta)\, \frac{g^2}{4c_{\theta_w}}\left[c^2_{\theta_w}\ \ (\delta g_{1,z} + \delta\kappa_z + \lambda_z)\ \right]\frac{\sqrt{s}}{m_W}$$

✓ Accessing to the polarizations could give us further discriminating power

Quadratic vs Linear fit

$$\sigma/\sigma_{SM} = 1 + B_a\kappa_a + C_{ab}\kappa_a\kappa_b$$

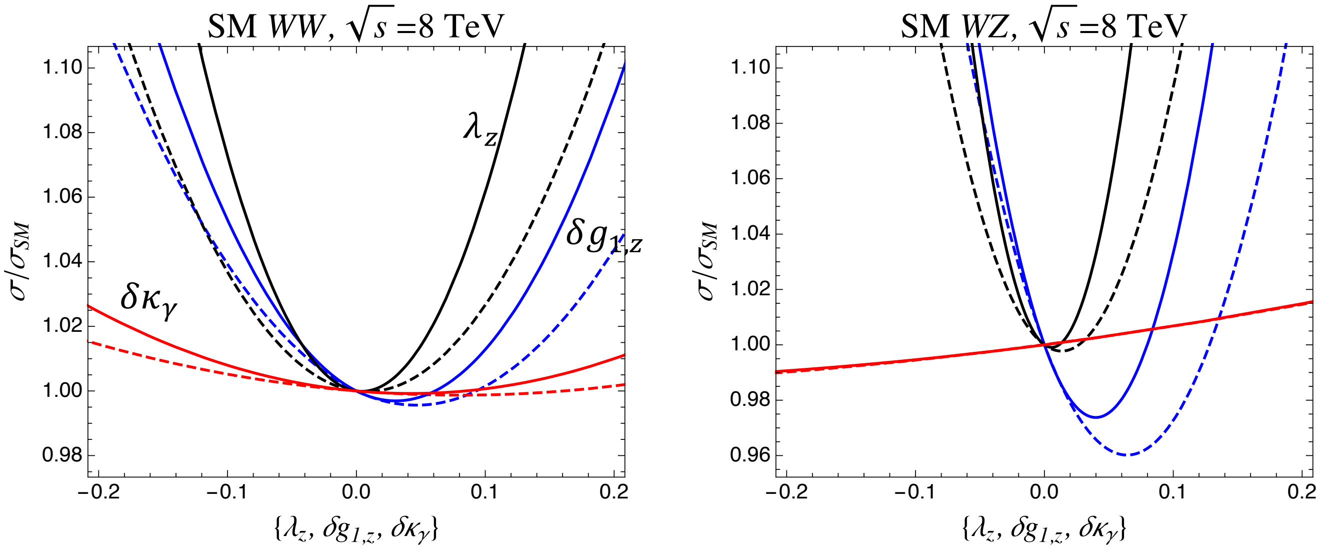
$$\kappa_a = \{\lambda_z, \delta g_{1,z}, \delta\kappa_\gamma\}$$

Linear: dim-6*SM $\sim \mathcal{O}(\Lambda^{-2})$

Quadratic : dim-6*dim-6 $\sim \mathcal{O}(\Lambda^{-4})$

[dim-8*SM $\sim \mathcal{O}(\Lambda^{-4})$]

Inclusive cross sections
Varying one aTGC at a time (no cross-term included)



Solid Lines: $\sqrt{\hat{s}} < \infty$

Dashed Lines: $\sqrt{\hat{s}} < 600$ GeV

: Quadratic terms stay being dominant for any cut value on $\sqrt{\hat{s}}$-cut

Interference terms appear to be suppressed

Deeper insight comes from Helicity Amplitude

Structural difference between WW and WZ

Helicity Amplitude

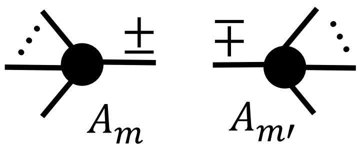
Deeper insight into the suppressed interference

Azatov, Contino, Machado, Riva 16'
Cheung, Shen 15'

In the massless limit

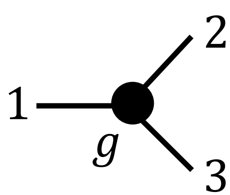
$$p_{a\dot{b}} = -|p]_a \langle p|_{\dot{b}}, \qquad p^{\dot{a}b} = -|p\rangle^{\dot{a}} [p|^b$$

I. Gluing amplitudes to get n-pt amplitude



$$h(A_n) = h(A_m) + h(A_{m'})$$

II. 3-pt amplitude



Little Group scaling uniquely fixes the 3-point amplitudes

$$A_3(1^{h_1}2^{h_2}3^{h_3}) = g \begin{cases} \langle 12\rangle^{h_3-h_1-h_2}\langle 13\rangle^{h_2-h_1-h_3}\langle 23\rangle^{h_1-h_2-h_3} & \text{for } \sum h_i < 0 \\ [12]^{h_1+h_2-h_3}[13]^{h_1+h_3-h_2}[23]^{h_2+h_3-h_1} & \text{for } \sum h_i > 0 \end{cases}$$

Little group + NDA

$$\rightarrow |\textstyle\sum h_i| \equiv |h| = 1 - [g]$$

E.g.

$$SM \qquad |h(A_3^{SM})| = 1 - [g] = 1$$

$$\mathcal{O}_{3W} = \mathrm{tr}(W^3) \qquad |h(A_3^{BSM})| = 1 - [c_{3W}] = 3$$

III. Some of SM 4-pt amplitude with $|h(A_4^{SM})| = 2$ vanish

$$A_4(V^+V^+V^+V^-) = A_4(V^+V^+\psi^+\psi^-) = A_4(V^+V^+\phi\phi) = A_4(V^+\psi^+\psi^-\phi) = 0$$

A_4	$\lvert h(A_4^{\rm SM})\rvert$	$\lvert h(A_4^{\rm BSM})\rvert$
$VVVV$	0	4,2
$VV\phi\phi$	0	2
$VV\psi\psi$	0	2
$V\psi\psi\phi$	0	2
$\psi\psi\psi\psi$	2,0	2,0
$\psi\psi\phi\phi$	0	0
$\phi\phi\phi\phi$	0	0

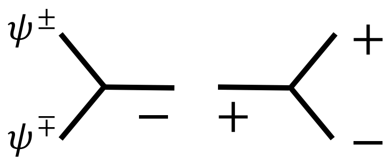
Azatov, Contino, Machado, Riva 16'

Illustrative example

A_4	$\lvert h(A_4^{\rm SM})\rvert$	$\lvert h(A_4^{\rm BSM})\rvert$
$VVVV$	0	4,2
$VV\phi\phi$	0	2
$VV\psi\psi$	0	2
$V\psi\psi\phi$	0	2
$\psi\psi\psi\psi$	2,0	2,0
$\psi\psi\phi\phi$	0	0
$\phi\phi\phi\phi$	0	0

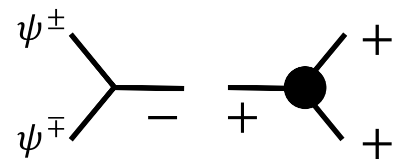
Azatov, Contino, Machado, Riva 16'

Helicity selection rule: total helicity should match



$h\left(A_4^{SM}\right) = 0$

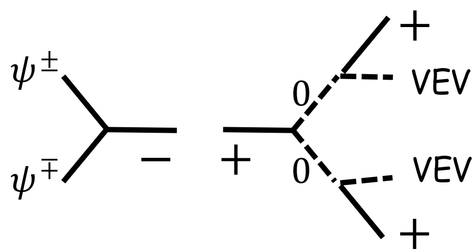
SM amplitude



$h\left(A_4^{BSM}\right) = 2$

BSM amplitude
with insertion of $\mathcal{O}_{3W} \sim \mathrm{tr}(W^3)$

How to interfere? Flip the helicity via VEV insertion (finite mass effect)



$h\left(A_6^{SM}\right) = 2 \quad \propto \left(\frac{m_W}{E}\right)^2$

Channel	SM	BSM$_6$
$++++$	ε_V^4	ε_V^0
$+++-$	ε_V^2	ε_V^0
$++--$	ε_V^0	ε_V^2
$+\frac{1}{2}-\frac{1}{2}++$	ε_V^2	ε_V^0
$+\frac{1}{2}-\frac{1}{2}+-$	ε_V^0	ε_V^2
$+\frac{1}{2}-\frac{1}{2}\,0+$	ε_V^1	ε_V^1
$+\frac{1}{2}-\frac{1}{2}\,0\,0$	ε_V^0	ε_V^0

Channel	SM	BSM$_6$
$0+++$	ε_V^3	ε_V^1
$0++-$	ε_V^1	ε_V^1
$0\,0++$	ε_V^2	ε_V^0
$0\,0+-$	ε_V^0	ε_V^2
$0\,0\,0+$	ε_V^1	ε_V^1
$0\,0\,0\,0$	ε_V^0	ε_V^0

Azatov, Contino, Machado, Riva 16'

EFT interpretation of LHC data

Available analyses

Channel	Distribution	# bins	Data
$WW \to \ell^+\ell'^- + \not{E}_T\ (0j)$	Leading lepton p_T	4	ATLAS 8 TeV, 20.3 fb^{-1}
$WW \to \ell^+\ell^{(\prime)-} + \not{E}_T\ (0j)$	$m_{\ell\ell^{(\prime)}}$	8	CMS 8 TeV, 19.4 fb^{-1}
$WZ \to \ell^+\ell^-\ell^{(\prime)\pm}$	m_T^{WZ}	6	ATLAS 8 TeV, 20.3 fb^{-1}
$WZ \to \ell^+\ell^-\ell^{(\prime)\pm} + \not{E}_T$	Z candidate $p_T^{\ell\ell}$	10	CMS 8 TeV, 19.6 fb^{-1}
$WV \to \ell^\pm jj + \not{E}_T$	V candidate p_T^{jj}	12	ATLAS 7 TeV, 4.6 fb^{-1}
$WV \to \ell^\pm jj + \not{E}_T$	V candidate p_T^{jj}	10	CMS 7 TeV, 5.0 fb^{-1}
$WZ \to \ell^+\ell^-\ell^{(\prime)\pm} + \not{E}_T$	Z candidate $p_T^{\ell\ell}$	7	ATLAS 7 TeV, 4.6 fb^{-1}
$WZ \to \ell^+\ell^-\ell^{(\prime)\pm} + \not{E}_T$	Z candidate $p_T^{\ell\ell}$	8	CMS 7 TeV, 4.9 fb^{-1}

Butter et al. 16’

EFT interpretation of LHC data

Available analyses

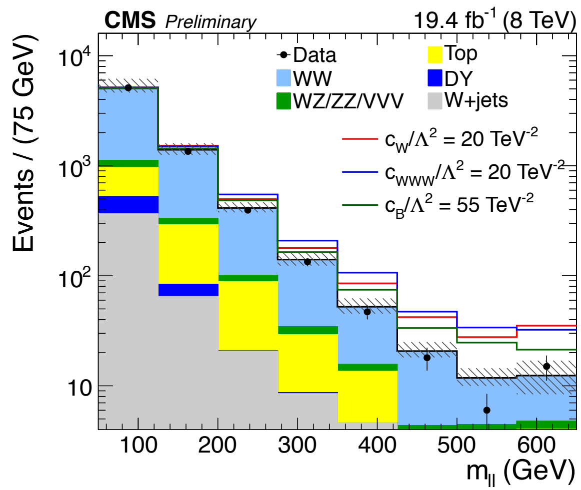
Channel	Distribution	# bins	Data
$WW \to \ell^+\ell'^- + \not{E}_T\ (0j)$	Leading lepton p_T	4	ATLAS 8 TeV, 20.3 fb^{-1}
$WW \to \ell^+\ell^{(\prime)-} + \not{E}_T\ (0j)$	$m_{\ell\ell^{(\prime)}}$	8	CMS 8 TeV, 19.4 fb^{-1}
$WZ \to \ell^+\ell^-\ell^{(\prime)\pm}$	m_T^{WZ}	6	ATLAS 8 TeV, 20.3 fb^{-1}
$WZ \to \ell^+\ell^-\ell^{(\prime)\pm} + \not{E}_T$	Z candidate $p_T^{\ell\ell}$	10	CMS 8 TeV, 19.6 fb^{-1}
$WV \to \ell^\pm jj + \not{E}_T$	V candidate p_T^{jj}	12	ATLAS 7 TeV, 4.6 fb^{-1}
$WV \to \ell^\pm jj + \not{E}_T$	V candidate p_T^{jj}	10	CMS 7 TeV, 5.0 fb^{-1}
$WZ \to \ell^+\ell^-\ell^{(\prime)\pm} + \not{E}_T$	Z candidate $p_T^{\ell\ell}$	7	ATLAS 7 TeV, 4.6 fb^{-1}
$WZ \to \ell^+\ell^-\ell^{(\prime)\pm} + \not{E}_T$	Z candidate $p_T^{\ell\ell}$	8	CMS 7 TeV, 4.9 fb^{-1}

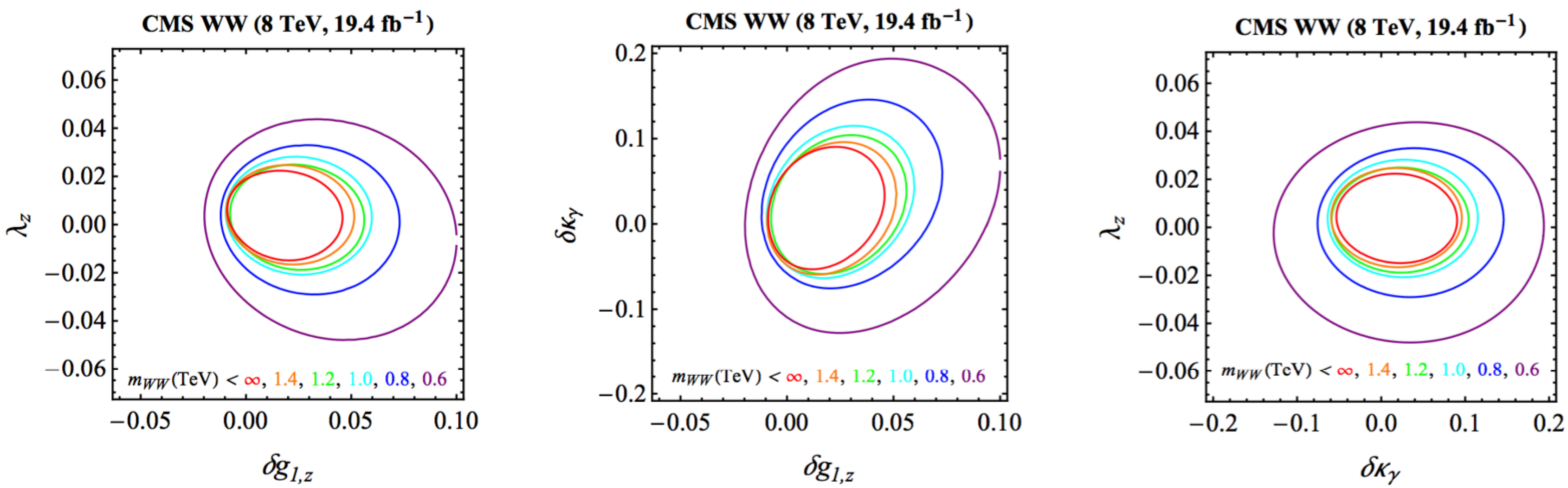
Butter et al. 16'

We choose these to make our point,
e.g. for illustrative purpose

Recasting WW-lvlv CMS analysis at 8TeV

CMS-SMP-14-016

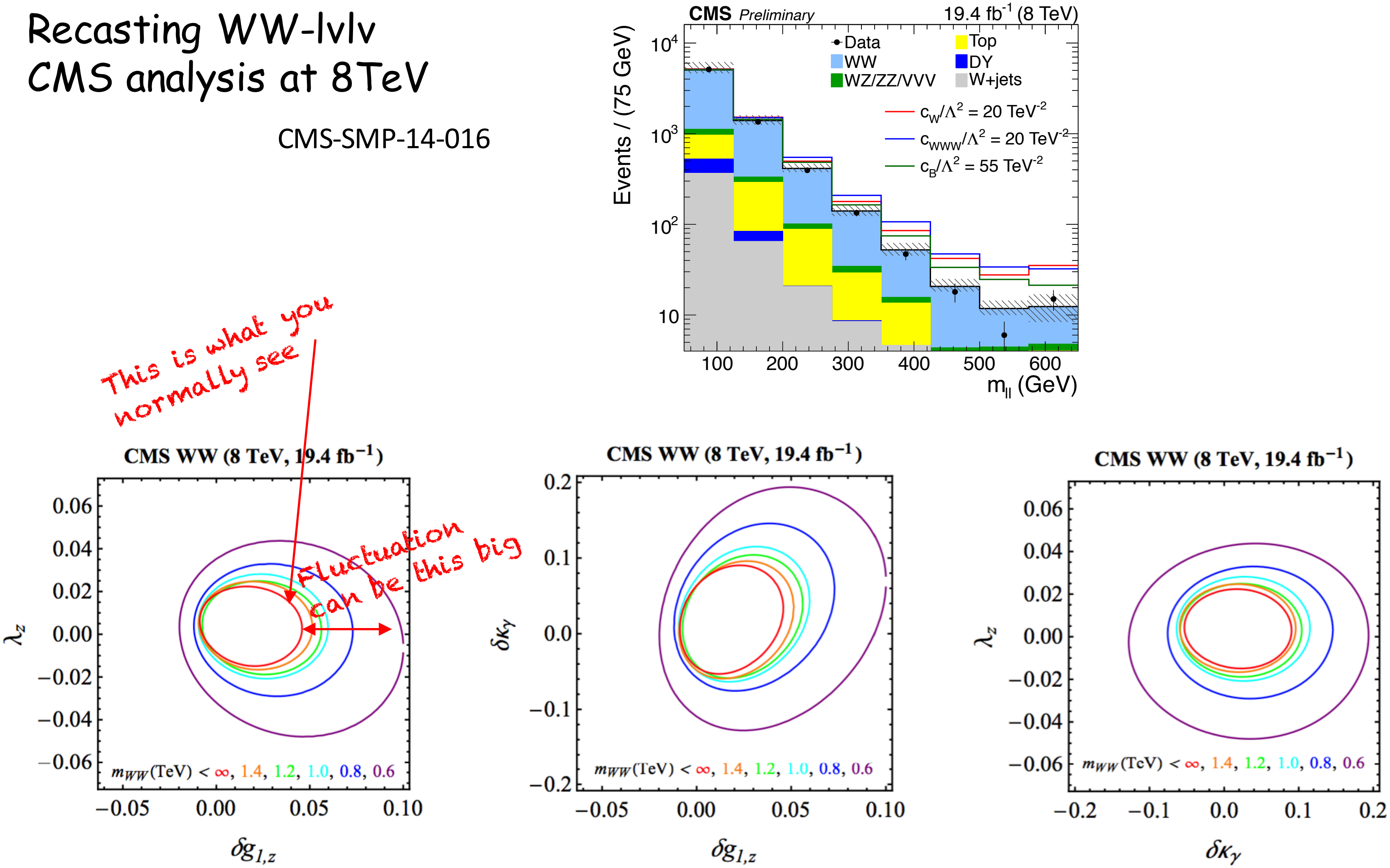




- ✓ Weak correlation among aTGC
- ✓ $m_{VV} < \infty$ is roughly similar to $m_{VV} < \mathcal{O}$(TeV). Weakening is pronounced for $m_{VV} < \mathcal{O}$(sub-TeV)

Recasting WW-lvlv CMS analysis at 8TeV

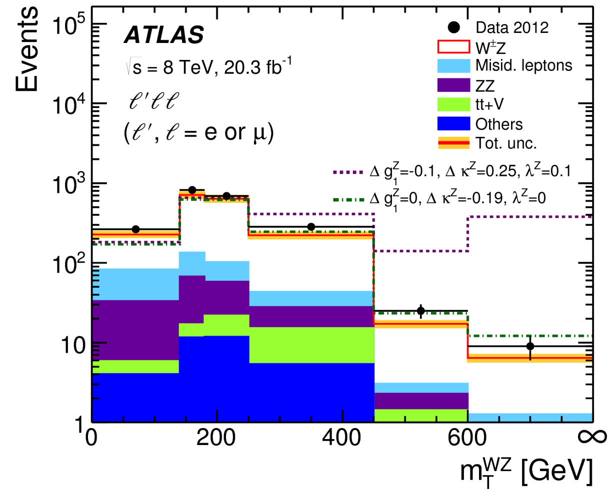
CMS-SMP-14-016

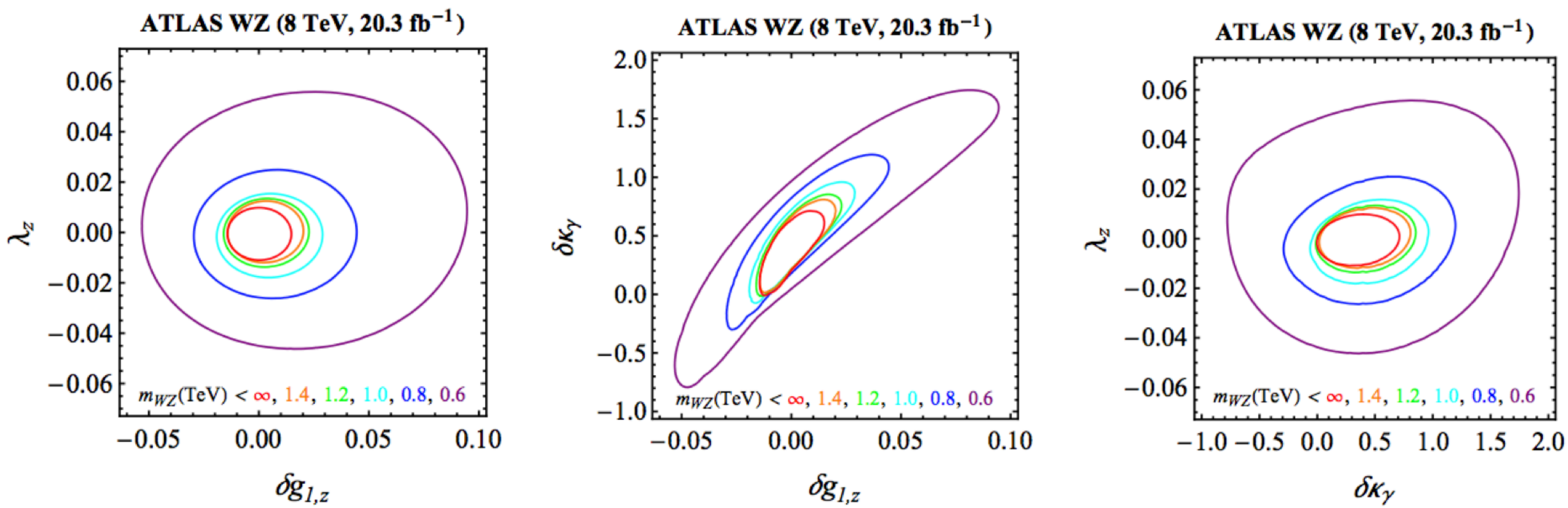


- ✓ Weak correlation among aTGC
- ✓ $m_{VV} < \infty$ is roughly similar to $m_{VV} < \mathcal{O}$(TeV). Weakening is pronounced for $m_{VV} < \mathcal{O}$(sub-TeV)

Recasting WZ-lvll ATLAS analysis at 8TeV

ATLAS arXiv:1603.02151





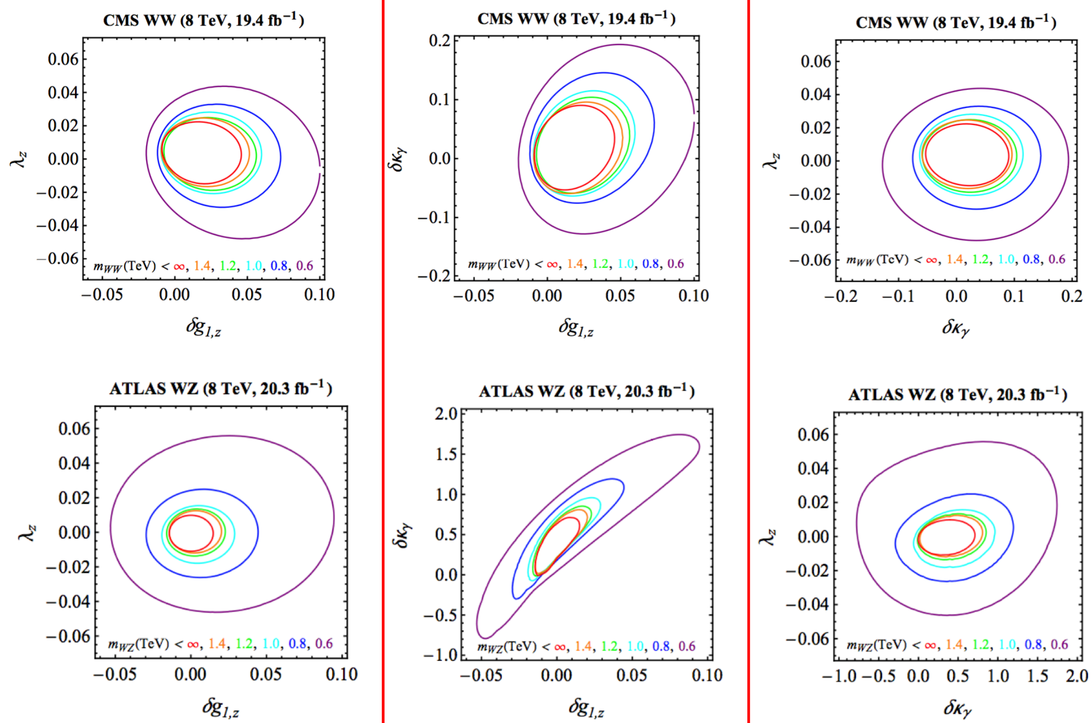
- ✓ Strong correlation among aTGC
- ✓ $m_{VV} < \infty$ is roughly similar to $m_{VV} < \mathcal{O}$(TeV). Weakening is pronounced for $m_{VV} < \mathcal{O}$(sub-TeV)

WW

CMS-SMP-14-016

WZ

ATLAS
1603.02151

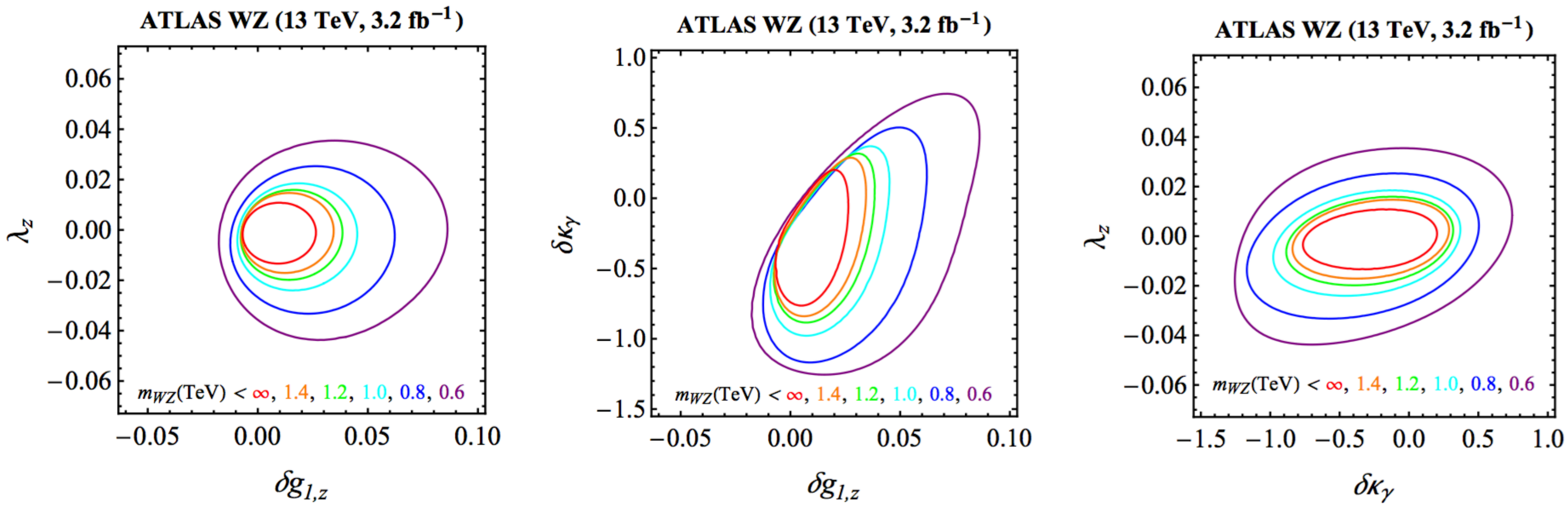


✓ $\delta\kappa_\gamma$ is strongly constrained by WW, not by WZ

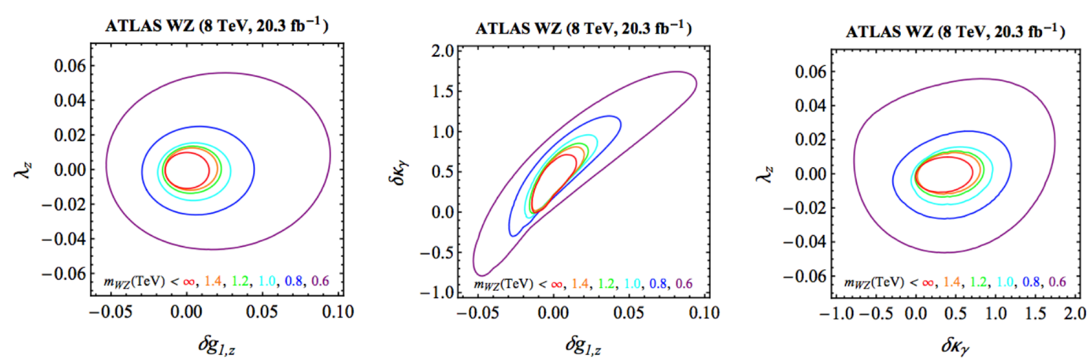
'First' recasting of 13TeV data on aTGC

arXiv:1606.04017

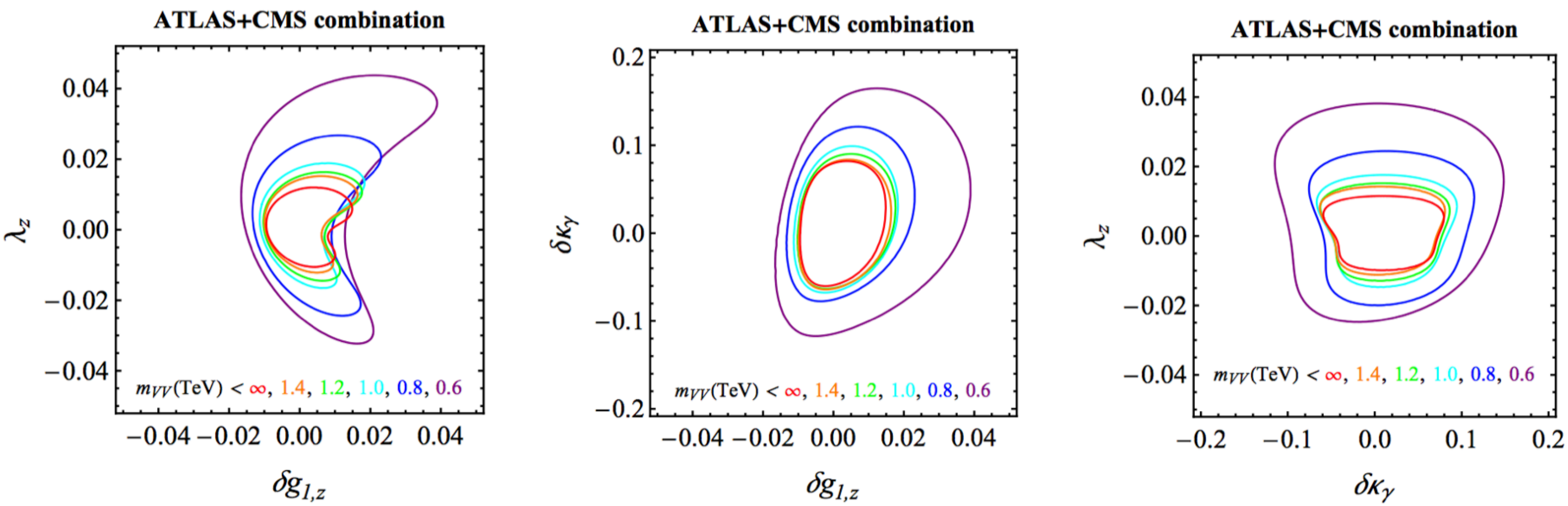
WZ ATLAS analysis



✓ No dramatic improvement. More or less similar to 8 TeV case.



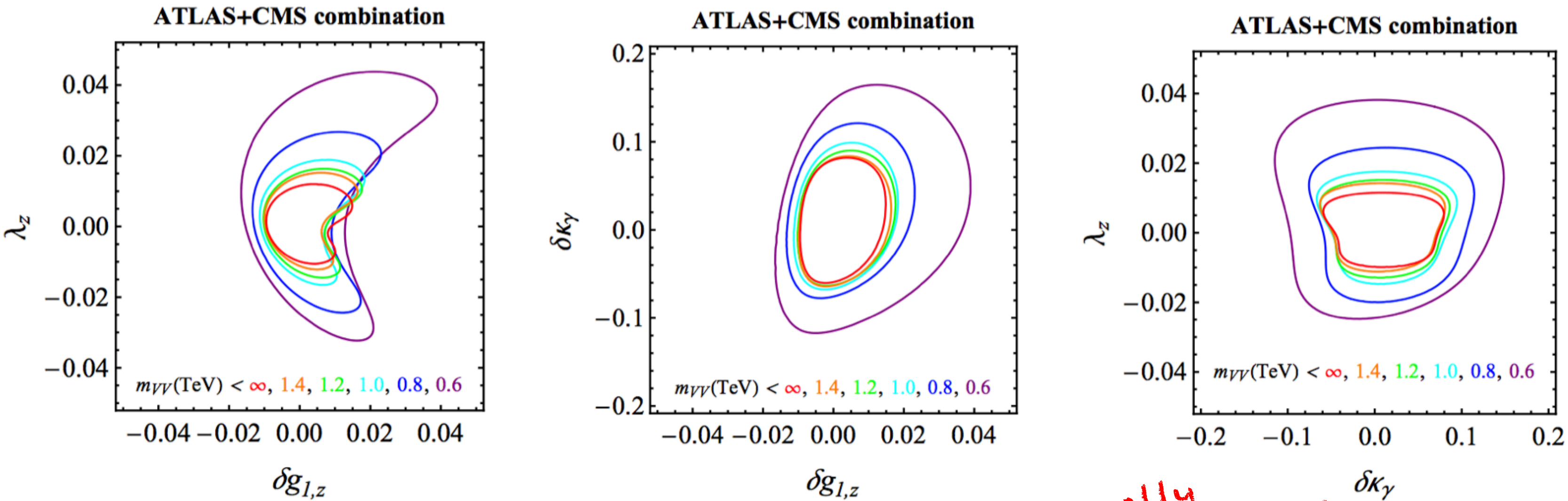
Combine all (8TeV CMS + ATLAS and 13TeV ATLAS)



Profiled 95% CL bounds on the each aTGC from our combined fit with diff. mVV cut

$m_{VV}^{\max}$ [GeV]	∞	1400	1200
$\delta g_{1,z}$ (%)	[−1.2, 2.0]	[−1.2, 2.2]	[−1.3, 2.4]
$\delta\kappa_\gamma$ (%)	[−7.8, 9.9]	[−8.3, 10]	[−8.4, 11]
λ_z (%)	[−1.3, 1.3]	[−1.5, 1.7]	[−1.8, 1.8]
m_{VV}^{cut} [GeV]	1000	800	600
$\delta g_{1,z}$ (%)	[−1.4, 2.5]	[−1.7, 3.2]	[−2.1, 5.4]
$\delta\kappa_\gamma$ (%)	[−9.0, 11]	[−10, 15]	[−15, 21]
λ_z (%)	[−2.1, 2.1]	[−2.9, 3.0]	[−4.2, 4.8]

Combine all (8TeV CMS + ATLAS and 13TeV ATLAS)



What is usually reported in literature

$m_{VV}^{\max}$ [GeV]	∞	1400	1200
$\delta g_{1,z}$ (%)	[−1.2, 2.0]	[−1.2, 2.2]	[−1.3, 2.4]
$\delta\kappa_\gamma$ (%)	[−7.8, 9.9]	[−8.3, 10]	[−8.4, 11]
λ_z (%)	[−1.3, 1.3]	[−1.5, 1.7]	[−1.8, 1.8]
$m_{VV}^{\rm cut}$ [GeV]	1000	800	600
$\delta g_{1,z}$ (%)	[−1.4, 2.5]	[−1.7, 3.2]	[−2.1, 5.4]
$\delta\kappa_\gamma$ (%)	[−9.0, 11]	[−10, 15]	[−15, 21]
λ_z (%)	[−2.1, 2.1]	[−2.9, 3.0]	[−4.2, 4.8]

Profiled 95% CL bounds on the each aTGC from our combined fit with diff. mVV cut

Can be widely different

EFT vs UV model

Contino, Falkowski, Goertz, Grojean, Riva 16'
for similar discussion

$SU(2)_L$ triplet + singlet

$$\mathcal{L}_{int} = V_\mu^a \left(\frac{i}{2} g \kappa'_H J_H^{a\,\mu} + \frac{g}{2} \kappa'_{fJ} J_f^{a\,\mu} \right) + V_\mu^0 \left(-\frac{i}{2} g \kappa_H J_H^\mu + \frac{g}{2} \kappa_{fJ} J_f^\mu \right)$$

Integrate out Triplet and Singlet and match to
EFT coefficients

$$c_{WB} = 0 \quad c_T = \frac{\kappa_H^2}{2} \frac{m_W^2}{m_V^2} \quad c_H = \frac{3\kappa'_H}{2} \frac{m_W^2}{m_V^2} \quad c_6 = -4\lambda \kappa'^2_H \frac{m_W^2}{m_V^2} \quad c_\psi = \kappa'^2_H \frac{m_W^2}{m_V^2}$$

$$\delta g_{1,z} = \frac{g^2 + g'^2}{g^2 - g'^2} (c_T - \delta v)$$

$$\delta v = \frac{1}{2}([c'_{Hl}]_{11} + [c'_{Hl}]_{22}) - \frac{1}{4}[c_{ll}]_{1221} = -\kappa'_H \kappa'_l \frac{m_W^2}{m_V^2}$$

$$[c'_{Hl}]_{11} = [c'_{Hl}]_{22} = -\kappa'_H \kappa'_l \frac{m_W^2}{m_V^2}$$

$$[c_{ll}]_{1221} = -2\kappa'^2_l \frac{m_W^2}{m_V^2} + \Delta \quad = \quad 0$$

$$\delta m = \frac{1}{g^2 - g'^2} (g^2 c_T - g'^2 \delta v) \quad = \quad 0 \quad \rightarrow \quad \kappa'_H \kappa'_f = -\frac{g^2}{2\,g'^2} \kappa_H^2$$

Assumed LEP bound is perfect

Both triplet and singlet are
required to have dm = 0

$$\delta g_{1,z} = -\kappa_H^2 \frac{g^2 + g'^2}{2\,g'^2} \frac{m_W^2}{m_V^2}$$

$$\delta \kappa_\gamma = \lambda_z = 0$$

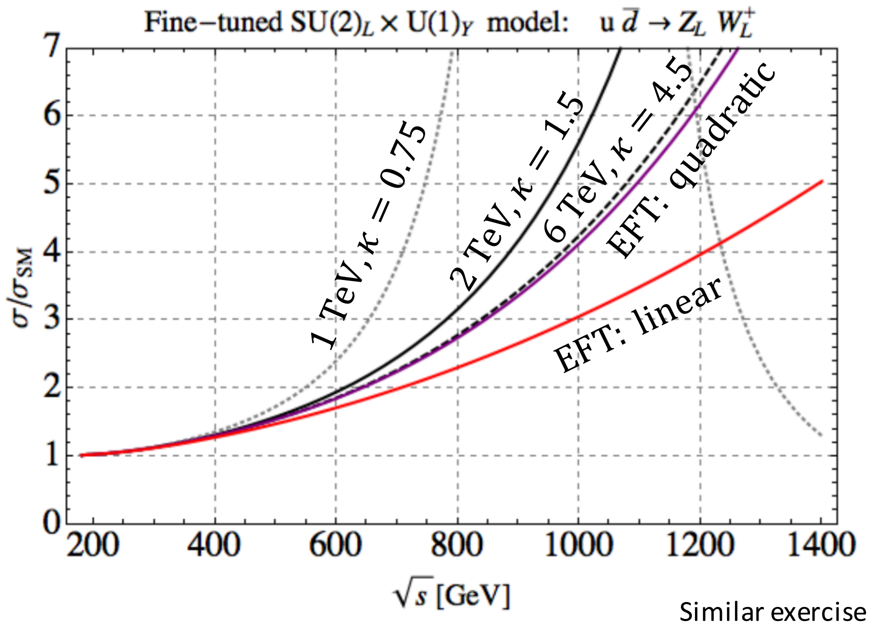
EFT vs UV model (strongly vs weakly)

$SU(2)_L$ triplet + singlet

$$\mathcal{L}_{int} = V_\mu^a \left(\frac{i}{2} g \kappa'_H J_H^{a\,\mu} + \frac{g}{2} \kappa'_{fJ} J_f^{a\,\mu} \right) + V_\mu^0 \left(-\frac{i}{2} g \kappa_H J_H^\mu + \frac{g}{2} \kappa_{fJ} J_f^\mu \right)$$

$$\delta g_{1,z} = -\kappa_H^2 \frac{g^2 + g'^2}{2\, g'^2} \frac{m_W^2}{m_V^2} \propto -\frac{\kappa_H^2}{m_V^2}$$

$$\delta g_{1,z} = -0.009 \qquad \leftrightarrow \qquad \frac{\kappa_H}{m_V} = \frac{0.75}{1\ \text{TeV}} = \frac{1.5}{2\ \text{TeV}} = \frac{4.5}{6\ \text{TeV}}$$



Weakly coupled

Strongly coupled

EFT works better for a strong coupling

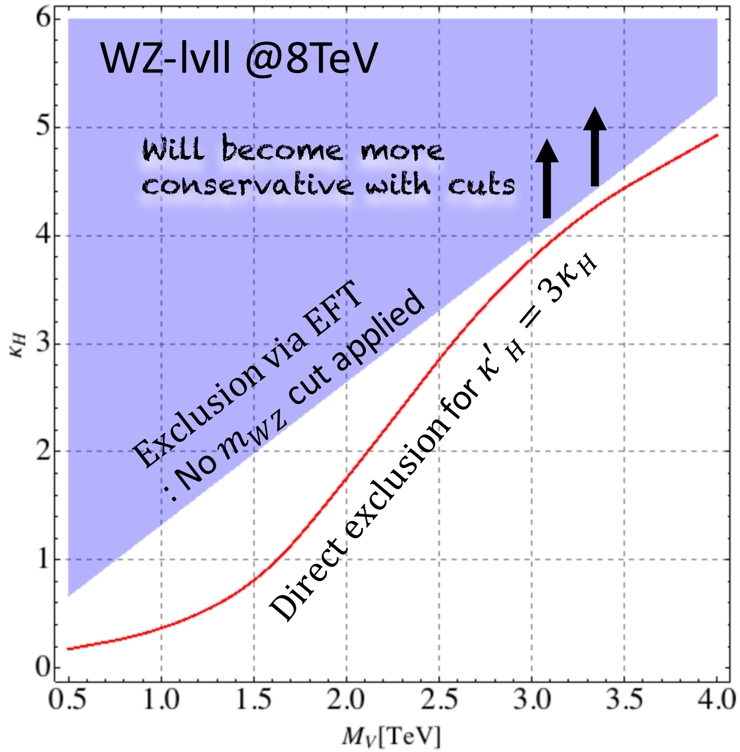
Similar exercise for Wh appeared in
Contino, Falkowski, Goertz, Grojean, Riva 16’

Illustration of EFT vs Direct

$SU(2)_L$ triplet + singlet

$$\mathcal{L}_{int} = V_\mu^a \left(\frac{i}{2} g \kappa'_H J_H^{a\,\mu} + \frac{g}{2} \kappa'_{fJ} J_f^{a\,\mu} \right) + V_\mu^0 \left(-\frac{i}{2} g \kappa_H J_H^\mu + \frac{g}{2} \kappa_{fJ} J_f^\mu \right)$$

$$\delta g_{1,z} = -\kappa_H^2 \frac{g^2 + g'^2}{2\, g'^2} \frac{m_W^2}{m_V^2} \propto -\frac{\kappa_H^2}{m_V^2}$$: EFT constrains κ_H / m_V



Similar exercise for Wh appeared in
Contino, Falkowski, Goertz, Grojean, Riva 16’