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anomalous Triple Gauge Coupling & associated Higgs production in the EFT approach

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

Azatov, Goertz, Falkowski, SON in progress

Lesson from Run1, part of 2

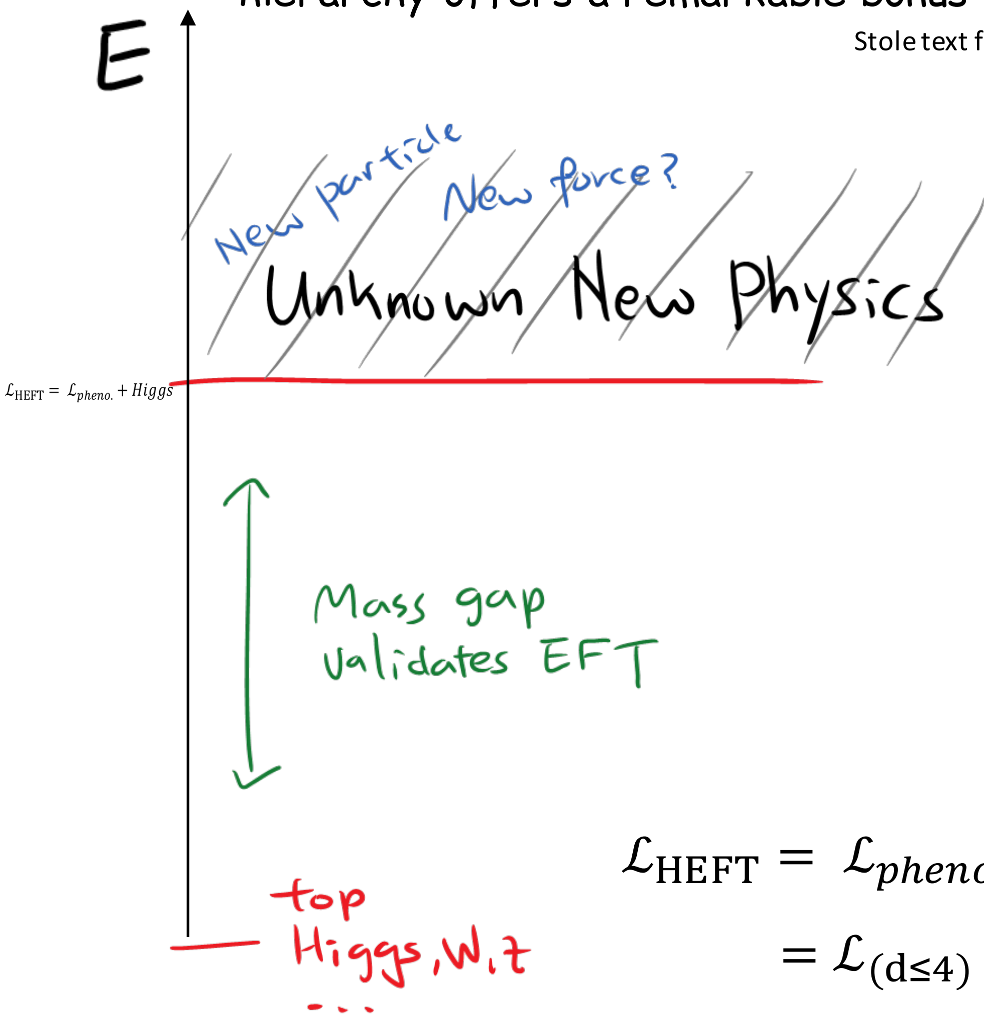
$$\Lambda_{LHC} \geq m_{new} > \mathcal{O}(\mathrm{TeV})$$

: cut-off scale in bottom-up approach

Higgs Effective Field Theory

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

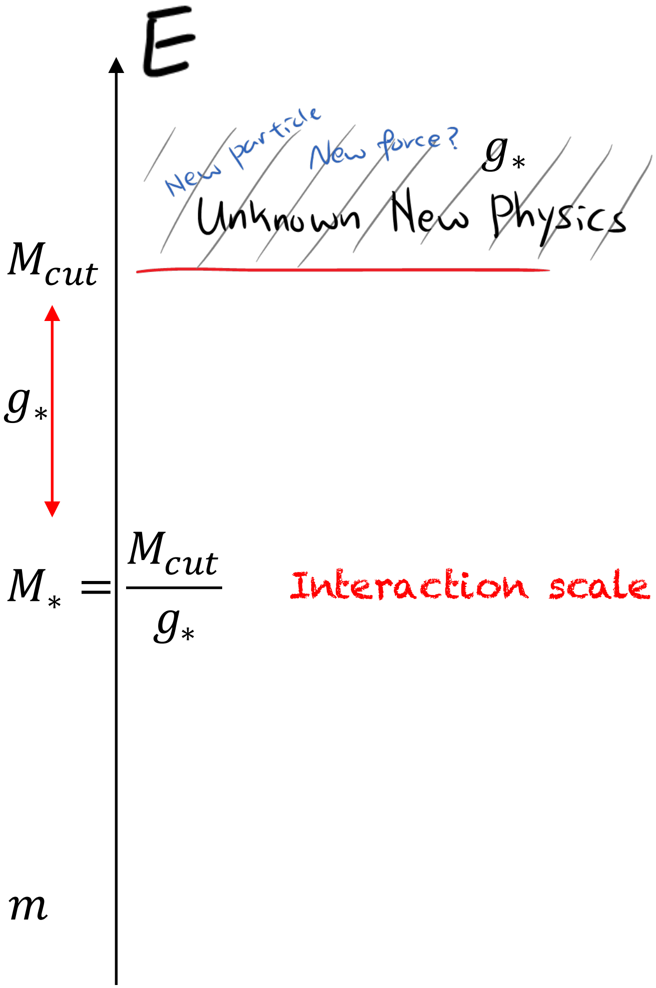
Stole text from the talk by Rattazzi



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

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'

E

New particle New force? g_*

Unknown New Physics

M_{cut}

g_*

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

Interaction scale

: the only scale accessible to
a low-E observer

m

Typical interaction in EFT is
controlled by the effective coupling,

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

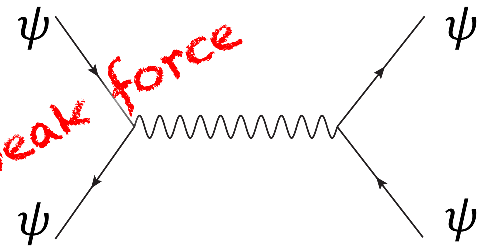
Structural picture of EFT

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

E

New particle
New force?
g_*
Unknown New Physics

= Weak force

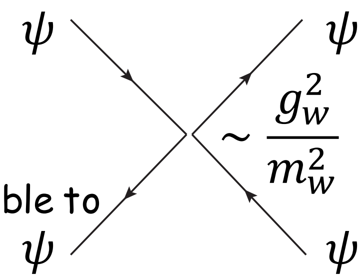


M_{cut} $\rightarrow m_W$

g_* g_W

$M_* = \dfrac{M_{cut}}{g_*}$ **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,

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

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

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_*

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

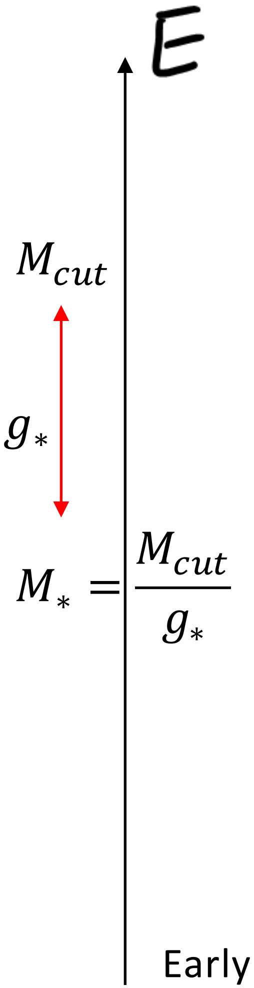
This picture fits to Higgs physics well

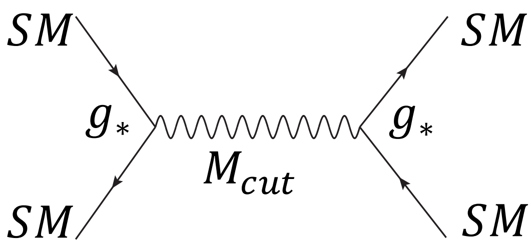
m

Typical interaction in EFT is controlled by the effective coupling,

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

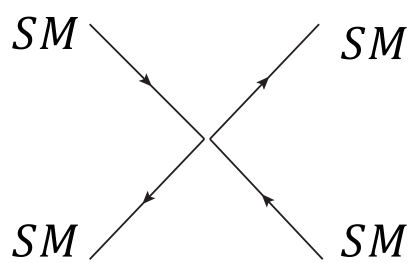
Unitarity violation in EFT





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

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



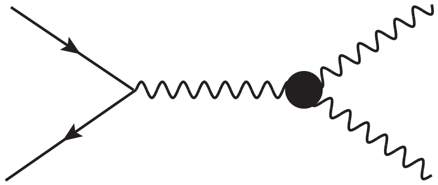
What if our collider was not strong enough to produce $\boldsymbol{M_{cut}}$?

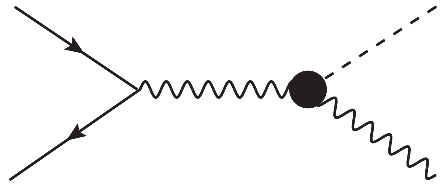
$$\mathcal{A}_{EFT} \sim \frac{s}{M_*^2} \quad \to \infty \text{ as } s \to \infty$$

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, VH 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

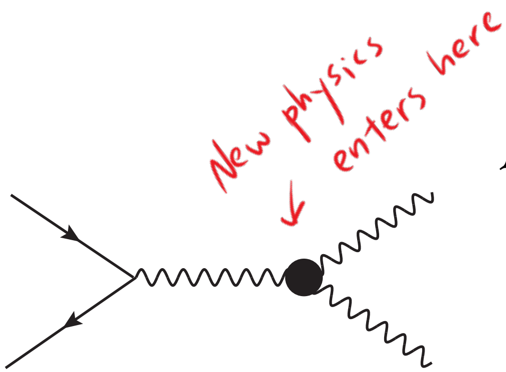
$$\mathcal{L}_{HEFT} = \mathcal{L}_{SM} + \sum \bar{c}_i \frac{\mathcal{O}_i^{dim=6}}{v^2}$$

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

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

BSM

Constraining HEFT via VH, VV processes

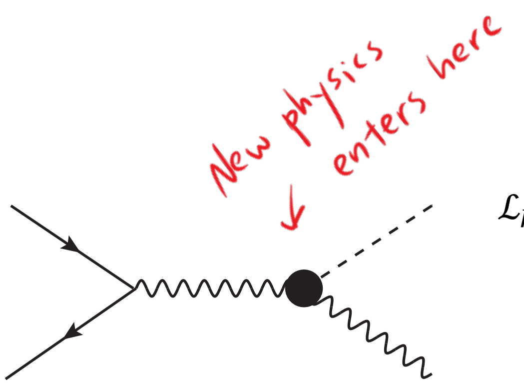


$$\mathcal{L}_{TGC} = ie\left[\left(W^+_{\mu\nu}W^-_\mu - W^-_{\mu\nu}W_\mu^+\right)A_\nu + \left(1+\delta\kappa_\gamma\right)A_{\mu\nu}W_\mu^+W_\nu^-\right]$$
$$+ ig_L\cos\theta\left[\left(1+\delta g_{1,z}\right)\left(W^+_{\mu\nu}W^-_\mu - W^-_{\mu\nu}W_\mu^+\right)Z_\nu + \left(1+\delta\kappa_z\right)Z_{\mu\nu}W_\mu^+W_\nu^-\right]$$
$$+ ie\frac{\lambda_\gamma}{m_W^2}W^+_{\mu\nu}W^-_{\nu\rho}A_{\rho\mu} + ig_L\cos\theta\frac{\lambda_z}{m_W^2}W^+_{\mu\nu}W^-_{\nu\rho}Z_{\rho\mu}$$

Treat LEP measurements as inputs

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

→ Three variables for VV



$$\mathcal{L}_h = \frac{h}{v}\left[\left(1+\delta c_w\right)\frac{g^2v^2}{2}W_\mu^+W^{-\mu} + c_{ww}\frac{g^2}{2}W^+_{\mu\nu}W^{-\mu\nu}\right.$$
$$\left. + c_{w\square}g^2\left(W_\mu^-\partial_\nu W^{+\mu\nu} + h.c.\right) + \cdots\right]$$

$$\boxed{\delta c_w, \quad c_{ww}, \quad c_{w\square}}$$

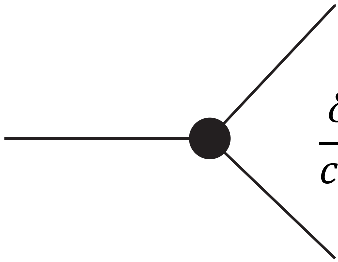
Similiarly for Z boson

→ Three variables for Wh

A difficulty of EFT approach:

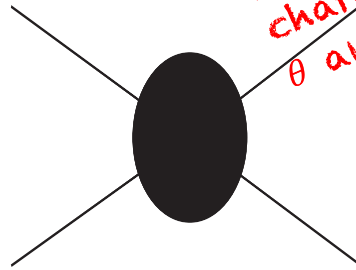
Many parameters lead to a degeneracy

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 $\sqrt{\hat{s}}$

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

Important item of Run 2

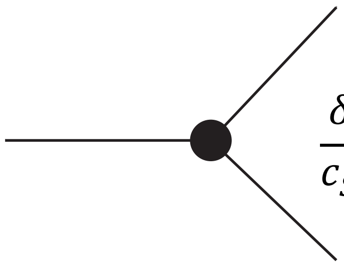
Parameters in HEFT are $\theta, \sqrt{\hat{s}}$ -dependent

$\Rightarrow$

$$\frac{d\sigma}{d\sqrt{\hat{s}}}, \quad \frac{d\sigma}{d\cos\theta}$$

can break degeneracy

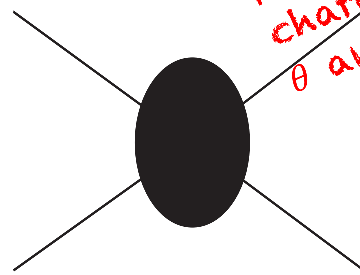
Decay vs 2 to 2 scattering process



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

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 $\Rightarrow$ $\frac{d\sigma}{d\sqrt{\hat{s}}}, \quad \frac{d\sigma}{dcos\theta}$

can break degeneracy

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

What we want to know vs. What we currently measure

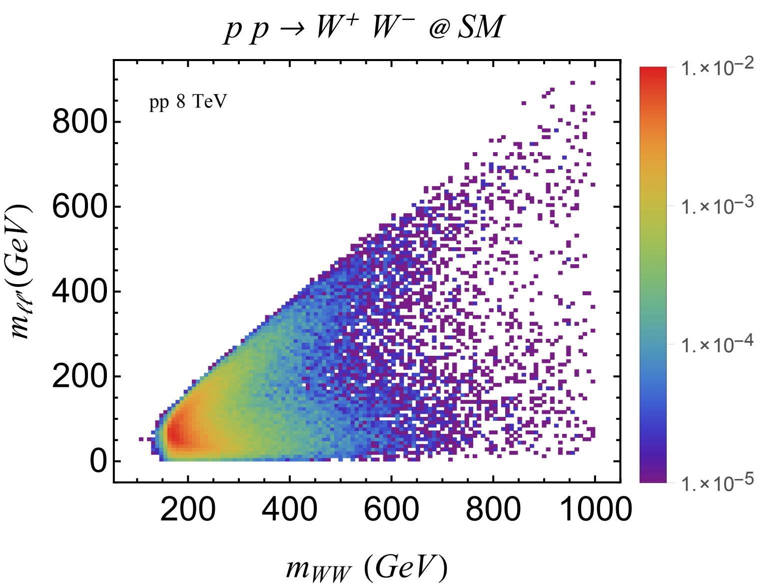
$$\sqrt{\hat{s}} = m_{WW}, m_{WZ}$$

Not exactly matches

$$m_{ll}, m_{lll}$$

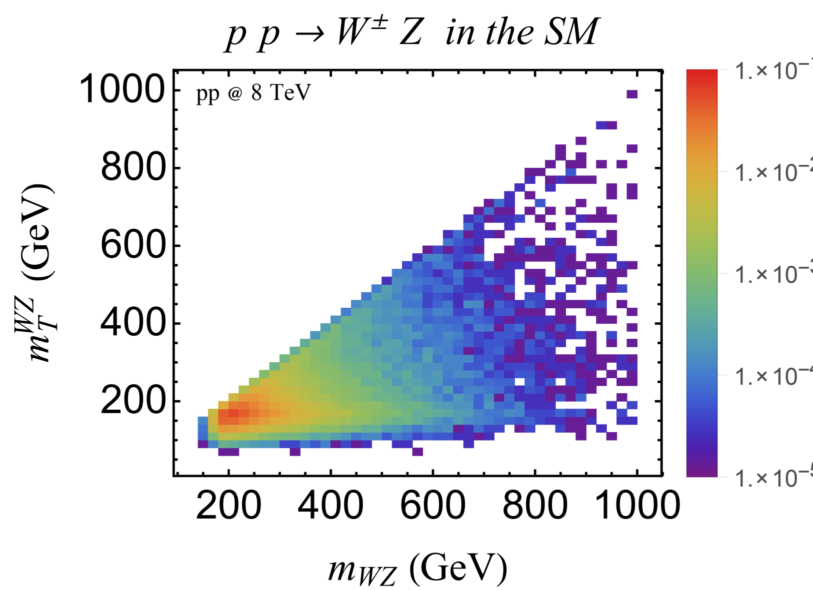
Accessing to the truth-level $\sqrt{\hat{s}}$ is non-trivial

What is measured



What we want to know

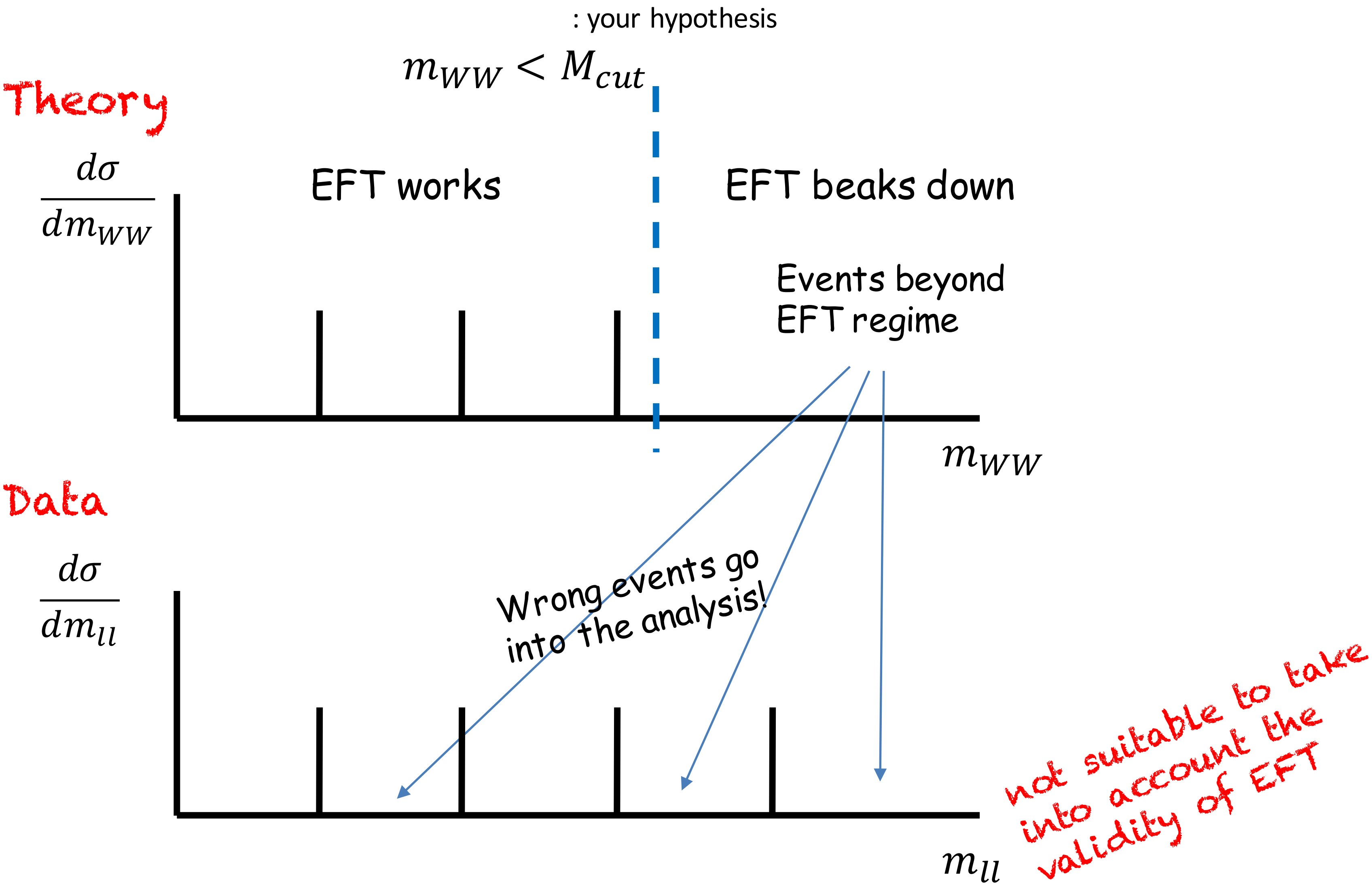
What is measured



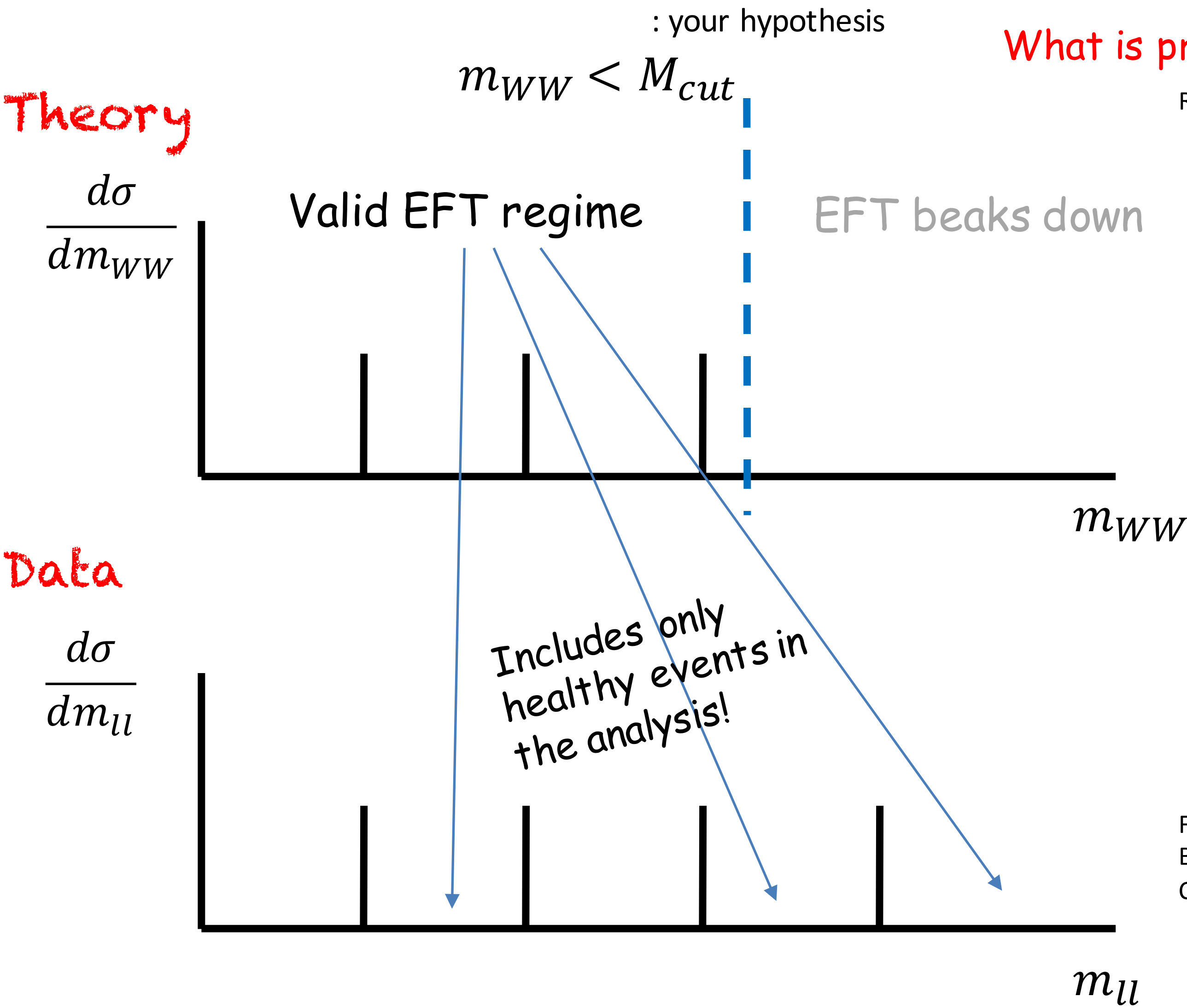
What we want to know

- ✓ Recovering exact neutrino four-vectors is important ingredient for better correlation

Pollution from the wrong events



A. No excess scenario



What is proposed

Racco, Wulzer, Zwirner 15'

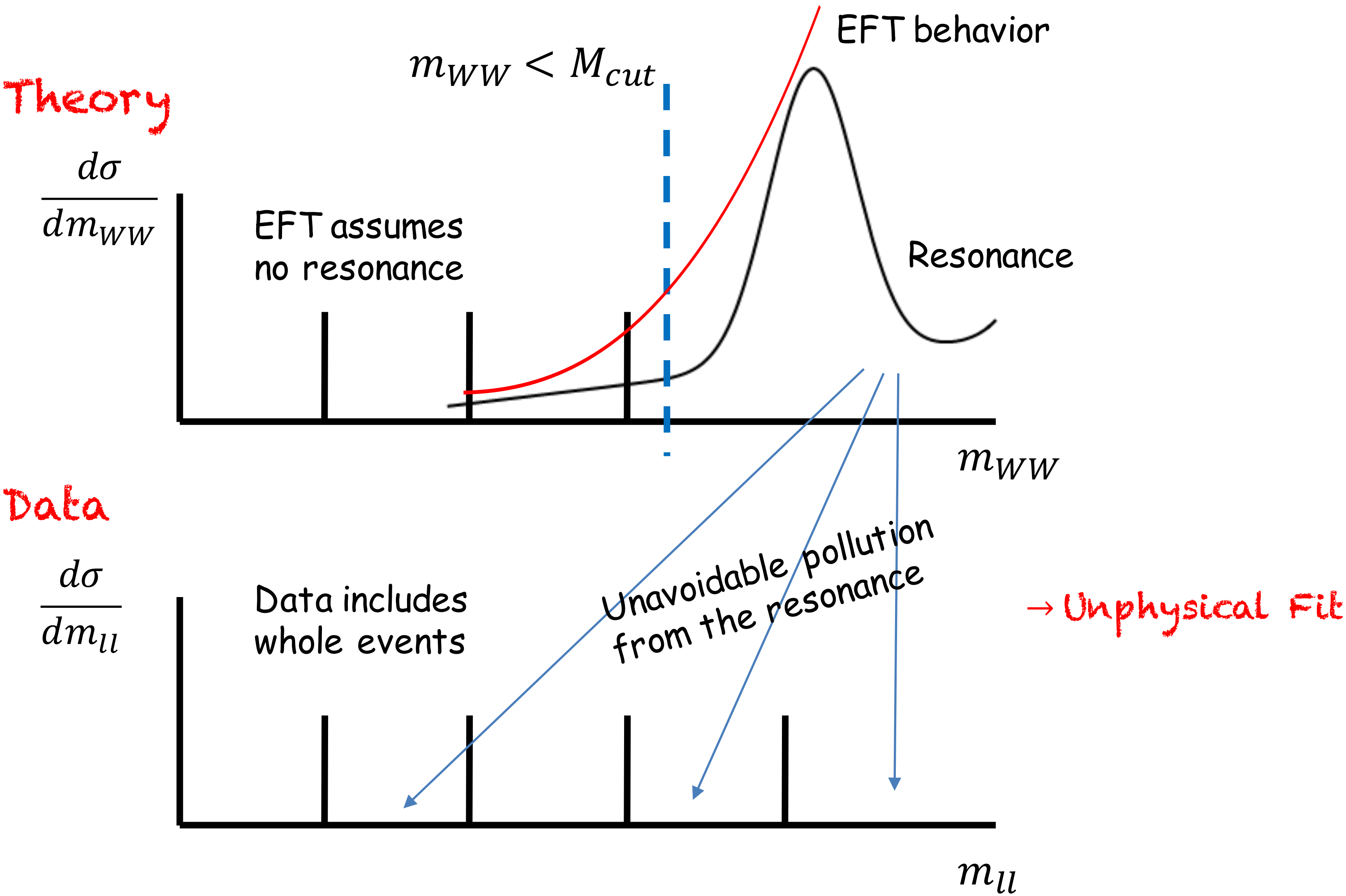
1. Assume possible cut-off scale
2. Remove events beyond it at truth-level
3. Recast with m_{ll}
4. Repeat 1-3 for different choice of cut-off scales

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

$\sigma^S_{EFT}|_{E_{cm} \le M_{cut}} < \sigma^S_{true} < \sigma_{exclusion}$ for null result

Always conservative

B. Complication in Resonance scenario

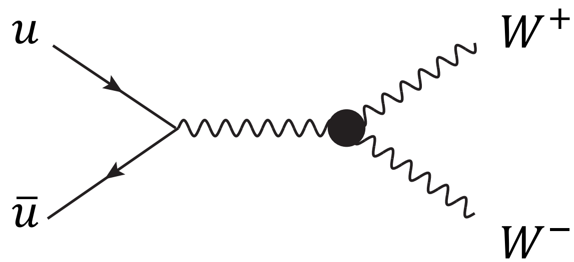


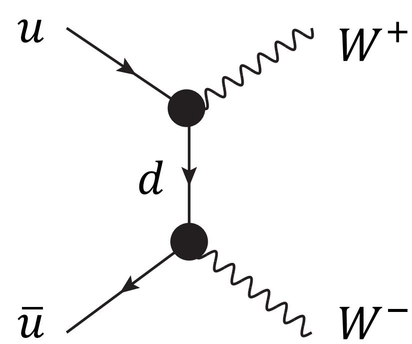
We will not consider this case

* There are nothing we can do for this case if we do not recover full $\sqrt{\hat{s}} = m_{WW}$??

aTGC in WW

Anomalous Triple Gauge couplings





Perfect cancellation of E-growing pieces

S-channel T

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

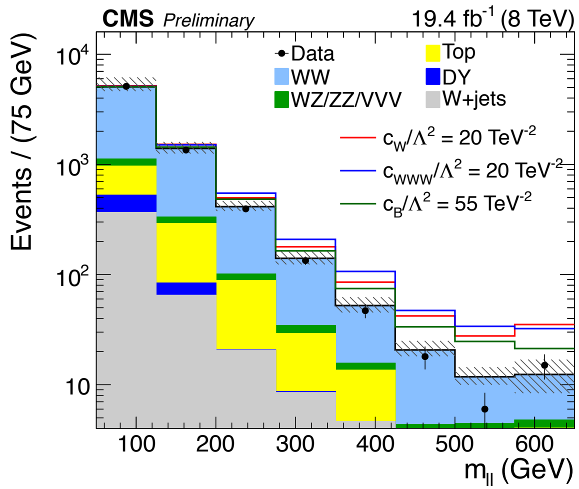
Imperfect cancellation picks up E-growing behavior

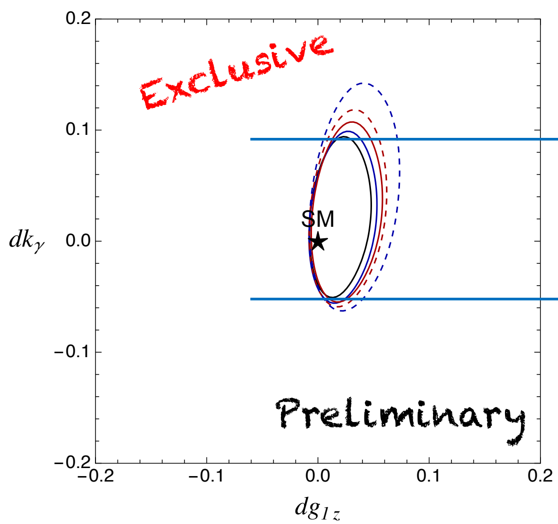
$$\mathcal{A}_{0,0} \sim \frac{\sin\theta}{2}\left[g^2\left(T_u^3 - s_{\theta_w}^2 Q_u\right)\delta\kappa_z + e^2 Q_u\,\delta\kappa_\gamma\right]\frac{s}{m_W^2}$$

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

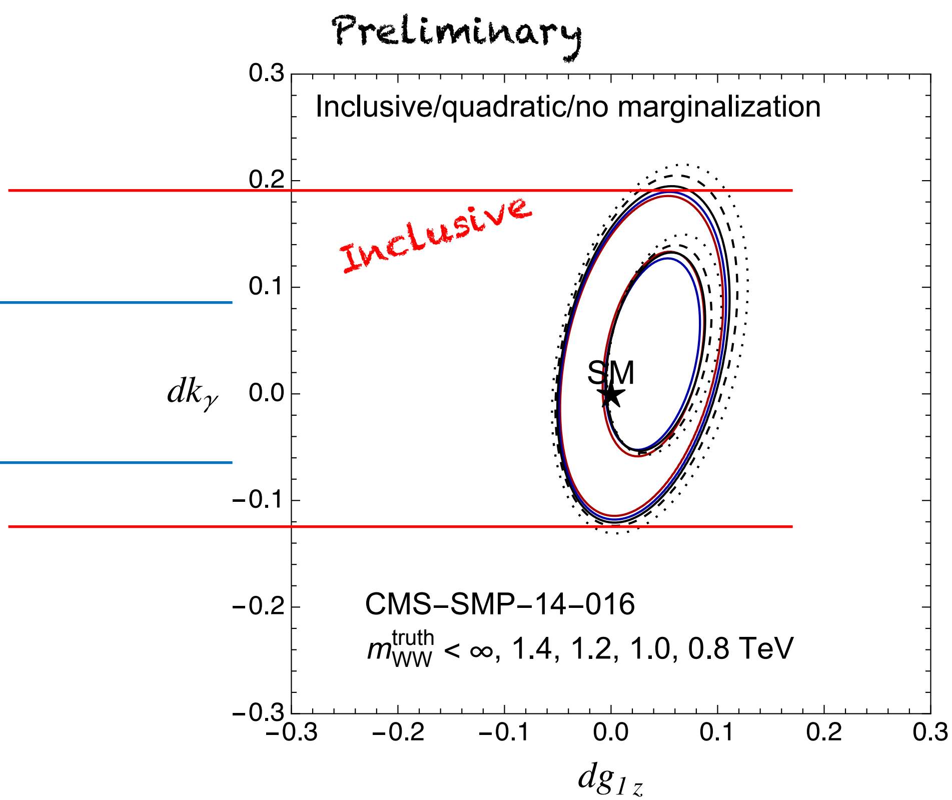
Recasting WW-lvlv CMS analysis at 8TeV

CMS-SMP-14-016





$m_{WW}^{\text{truth}} < \infty, 1.4, 1.2, 1.0, 0.8$ TeV



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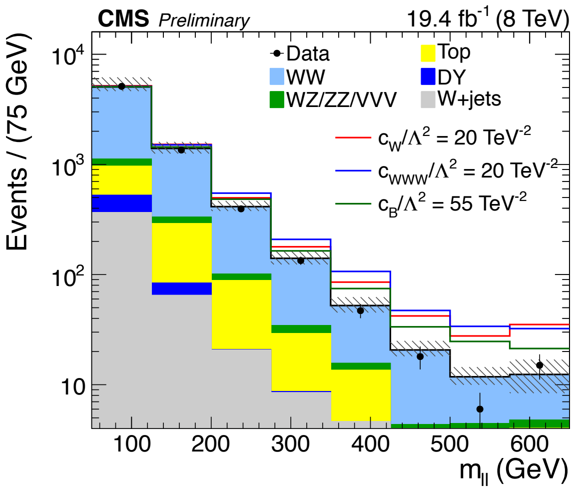

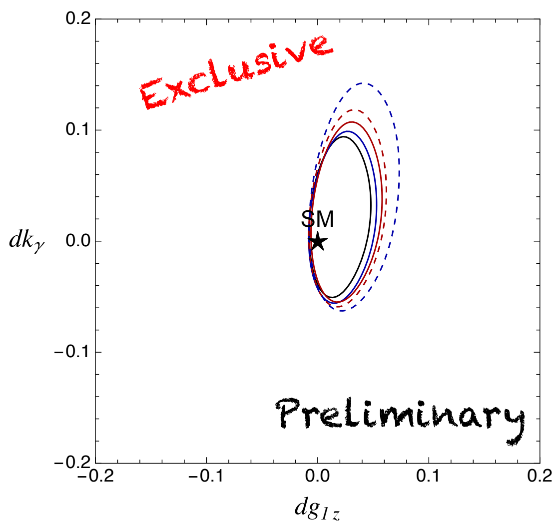

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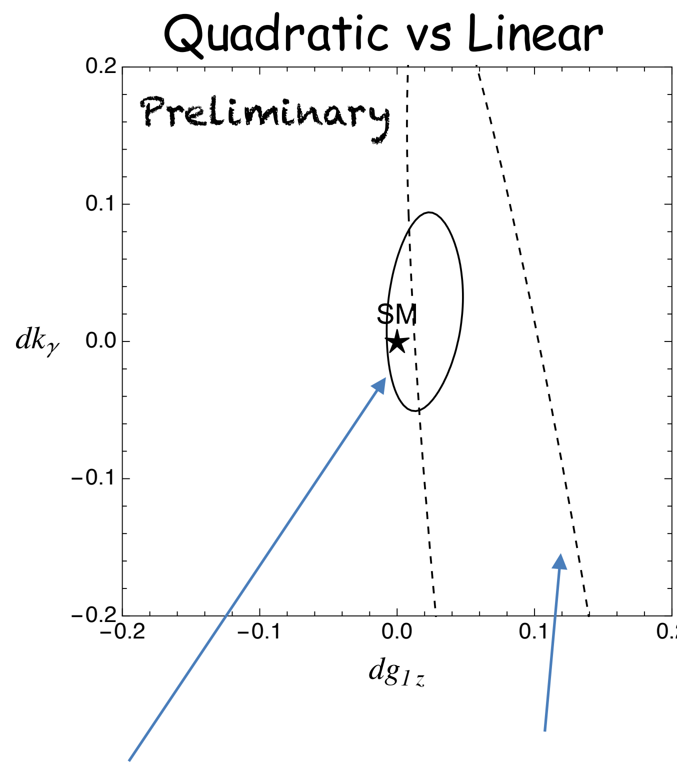
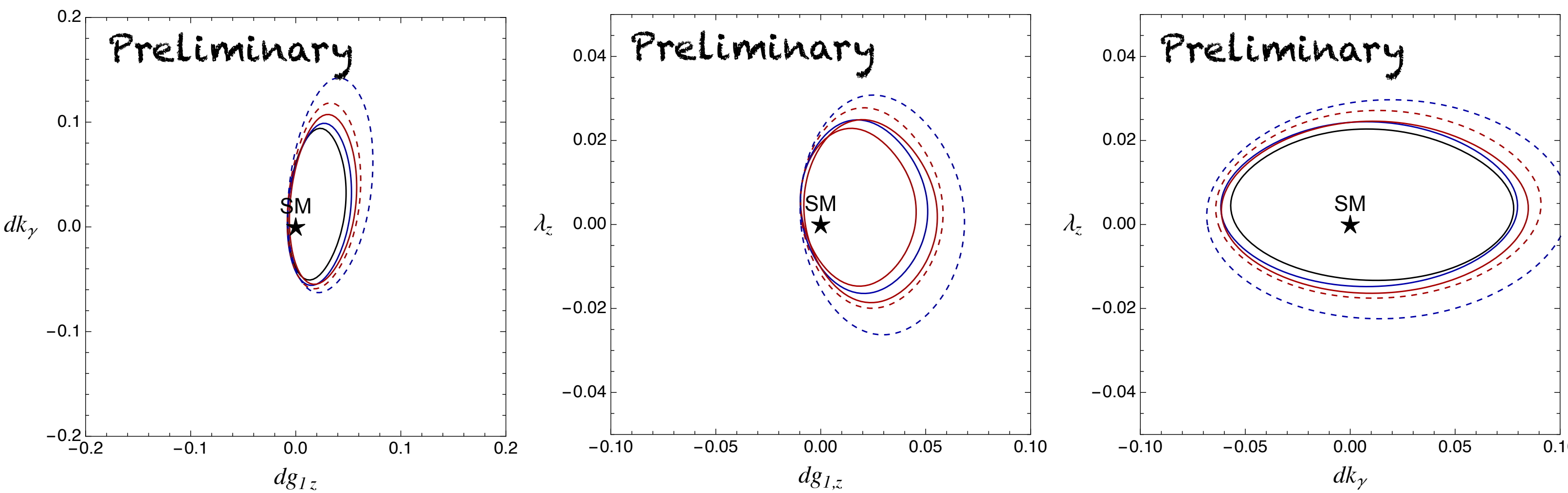


Quadratic vs. Linear fit

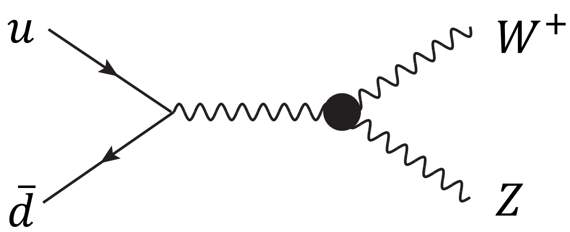


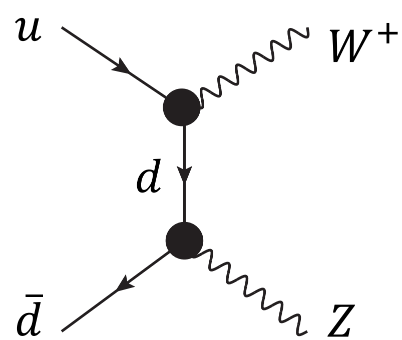
$m_{WW}^{\mathrm{truth}} < \infty, 1.4, 1.2, 1.0, 0.8$ TeV

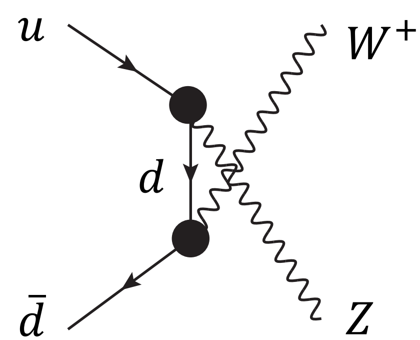
aTGC in WZ

Anomalous Triple Gauge couplings

T, U channels participate in Unitarity restoration in SM







Perfect cancellation of E-growing pieces

S-channel T U

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

Imperfect cancellation picks up E-growing behavior

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

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

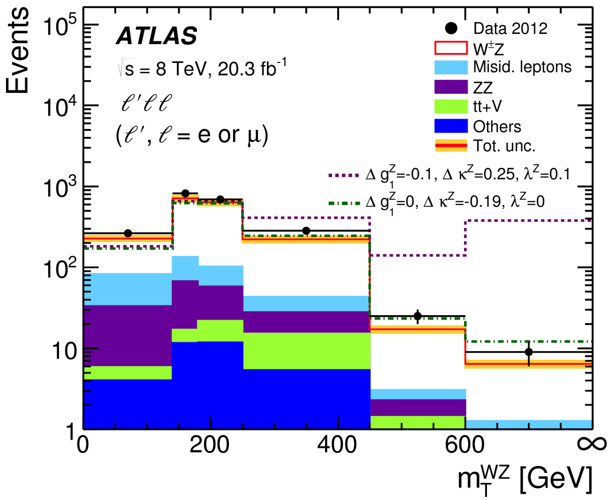
$$\mathcal{A}_{L/R,0} \sim (\pm 1 + \cos\theta) \, \frac{g^2}{4 c_{\theta_w}} \left[2 \, c_{\theta_w}^2 \; \delta g_{1,z} + \lambda_z \right] \frac{\sqrt{s}}{m_Z}$$

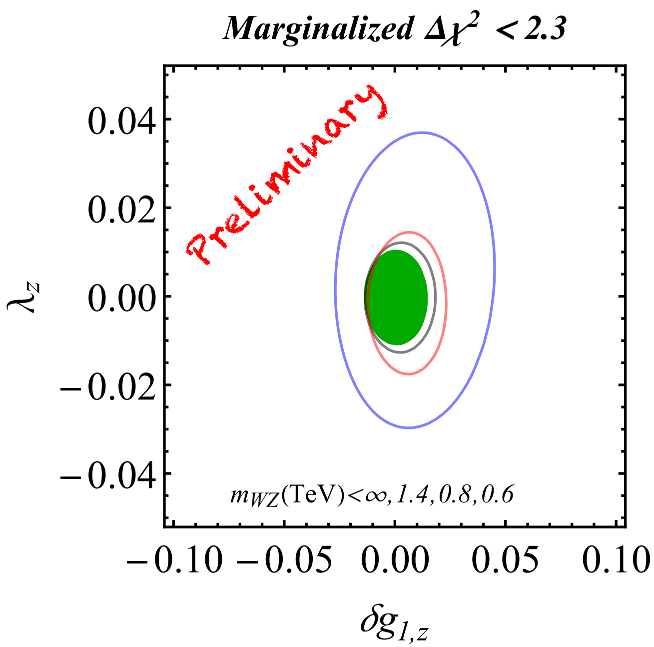
$$\mathcal{A}_{0,L/R} \sim (\mp 1 + \cos\theta) \, \frac{g^2}{4 c_{\theta_w}} \left[c_{\theta_w}^2 \; (\delta g_{1,z} + \delta\kappa_z + \lambda_z) \right] \frac{\sqrt{s}}{m_W}$$

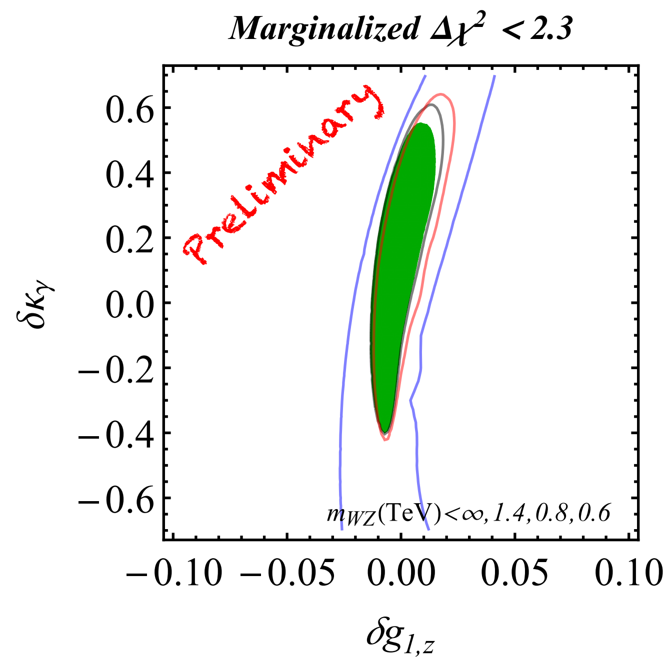
✓ Accessing to the polarizations could give us further discriminating power

Recasting WZ-lvll ATLAS analysis at 8TeV

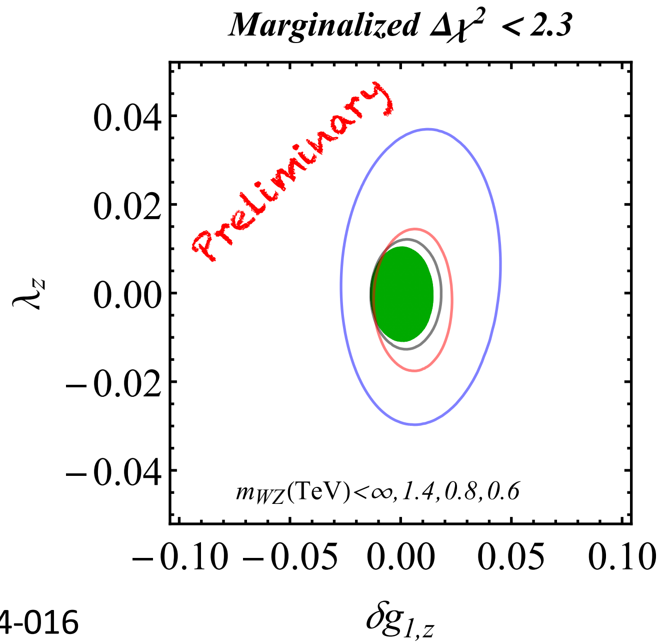
ATLAS arXiv:1603.02151

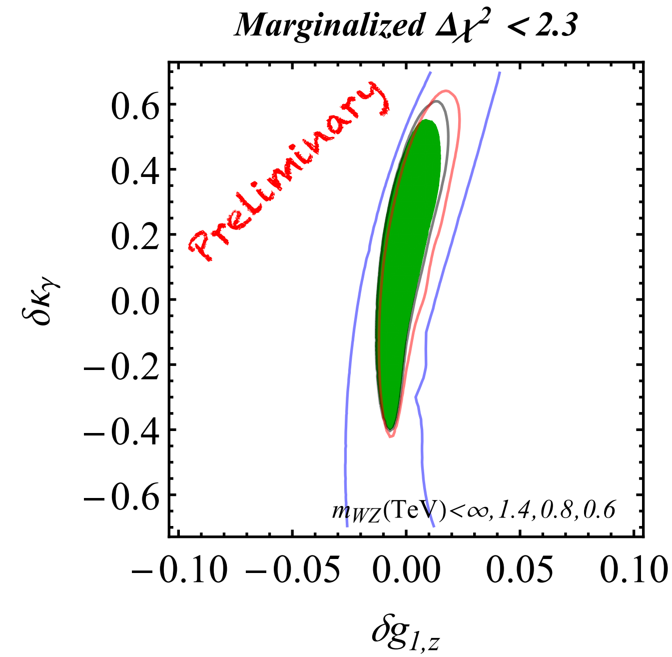




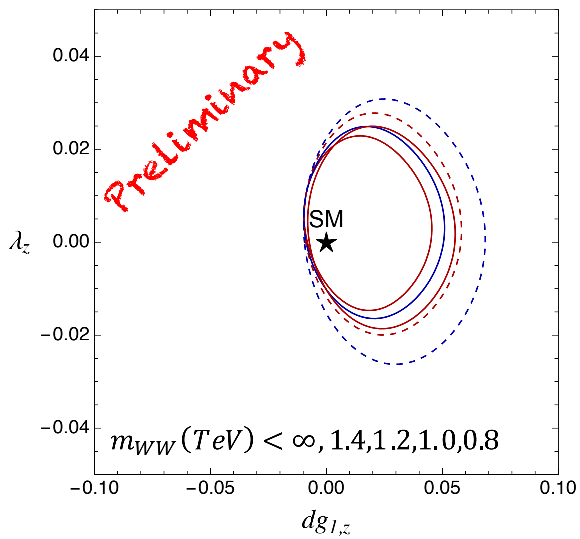


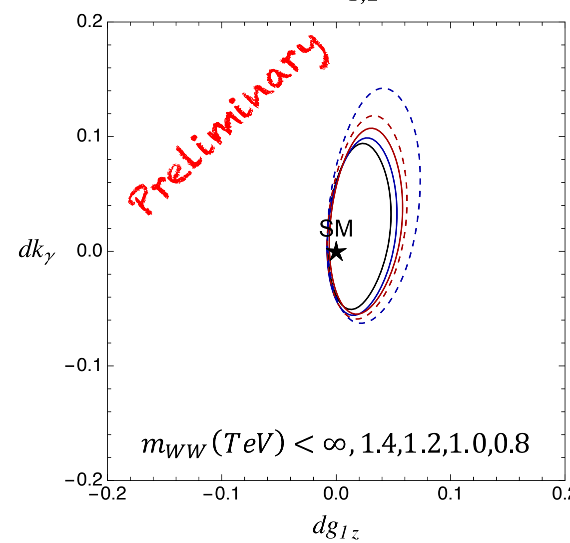
ATLAS
1603.02151
WZ



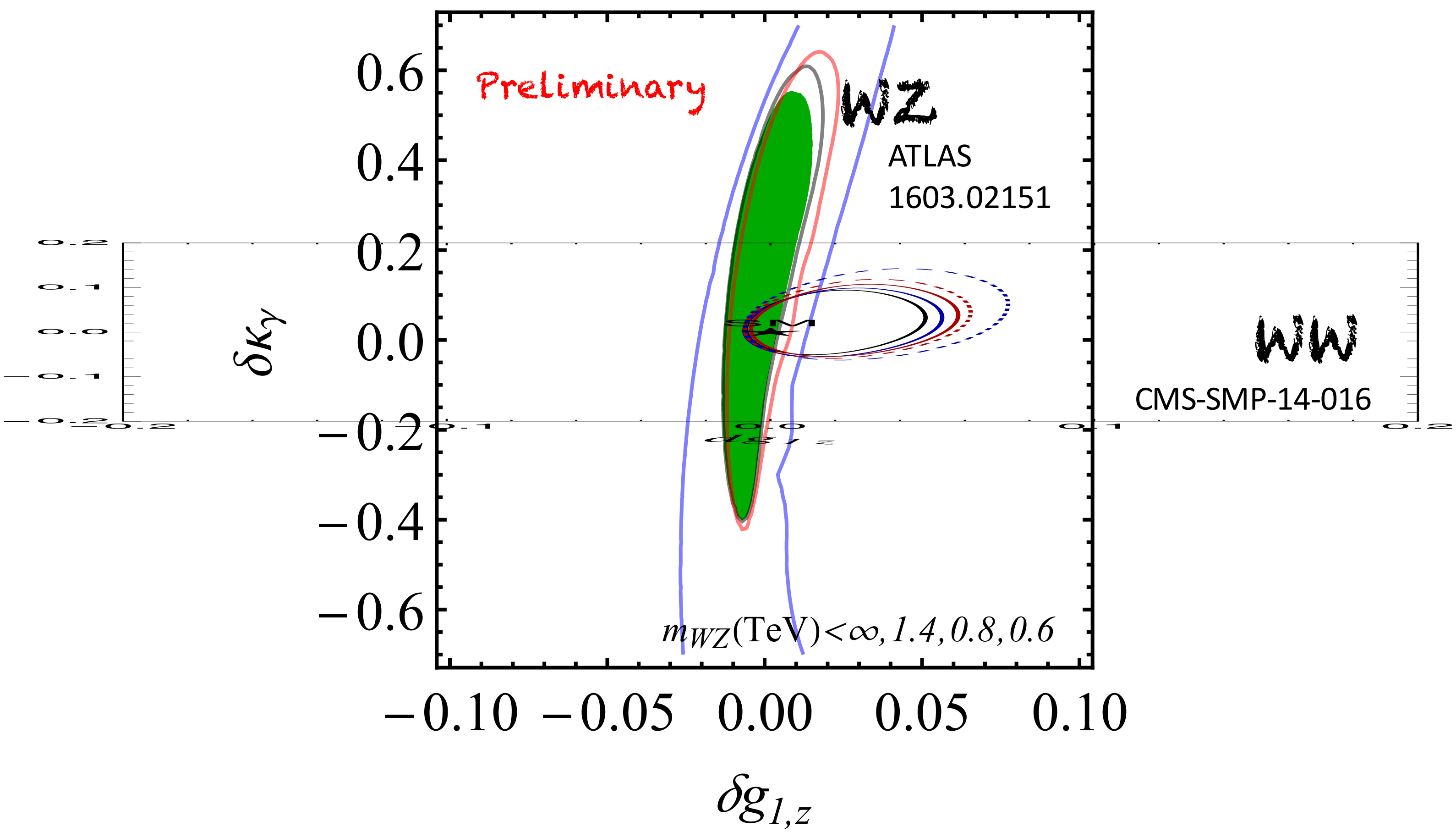


CMS-SMP-14-016
WW

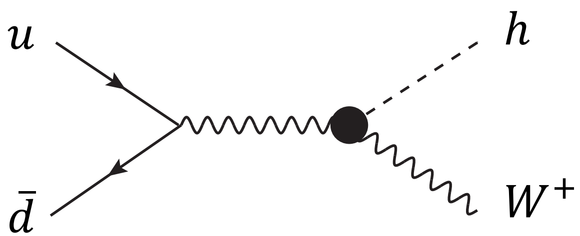




Marginalized $\Delta\chi^2 < 2.3$



VH process



$$\mathcal{A}_{L/R}^{SM} \sim (\pm 1 + \cos\theta)\,\frac{g^2}{2}\,\frac{m_W\sqrt{s}}{s - m_W^2} \qquad \sim \frac{1}{E}$$

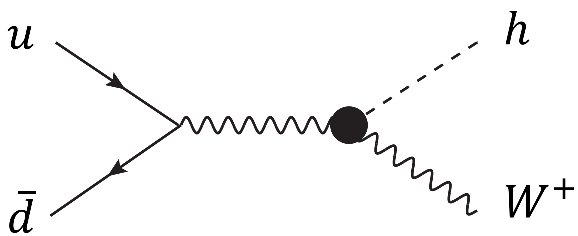
$$\mathcal{A}_0^{SM} \sim \sin\theta\,\frac{g^2}{2\sqrt{2}}\,\frac{s - m_h^2 + m_W^2}{s - m_W^2} \qquad \sim const$$

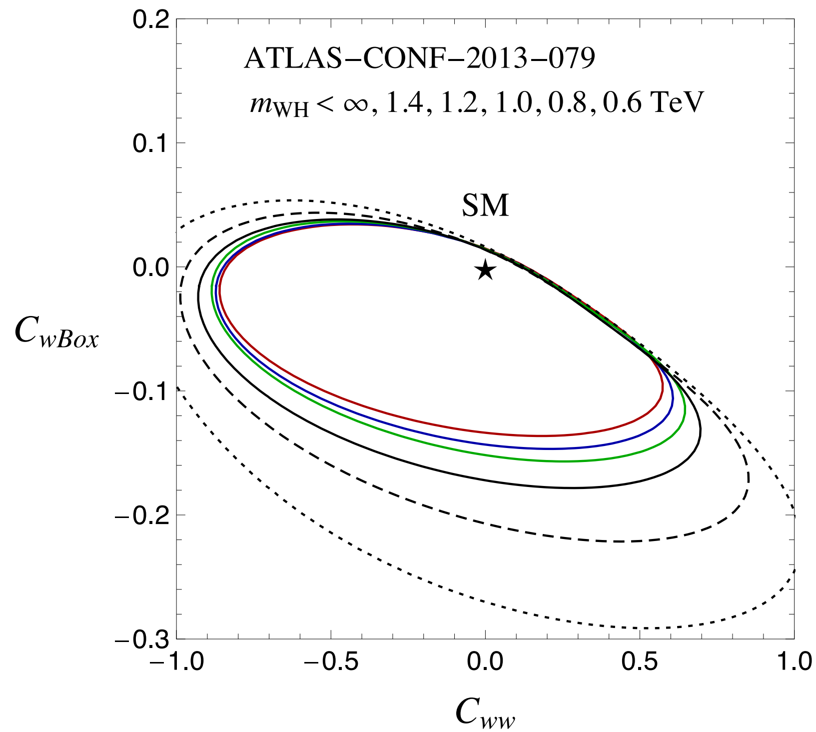
BSM picks up E-growing behavior

$$\mathcal{A}_{L/R} \sim (\pm 1 + \cos\theta)\,\frac{1}{\sqrt{2}}\,(g^2 c_{w\Box} + g^2 c_{ww})\,\frac{\sqrt{s}}{v}$$

$$\mathcal{A}_0 \sim \sin\theta\,\frac{1}{\sqrt{2}}\,g^2 c_{w\Box}\,\frac{s}{v^2}$$

VH process





$$\mathcal{A}^{SM}_{L/R} \sim (\pm 1 + \cos\theta)\,\frac{g^2}{2}\frac{m_W\sqrt{s}}{s-m_W^2}$$

$$\mathcal{A}^{SM}_{0} \sim \sin\theta\,\frac{g^2}{2\sqrt{2}}\frac{s-m_h^2+m_W^2}{s-m_W^2}$$

BSM picks up E-growing behavior

$$\mathcal{A}_{L/R} \sim (\pm 1 + \cos\theta)\,\frac{1}{\sqrt{2}}\underline{(g^2 c_{w\Box} + g^2 c_{ww})\frac{\sqrt{s}}{v}}$$

$$\mathcal{A}_{0} \sim \sin\theta\,\frac{1}{\sqrt{2}}\,\underline{g^2 c_{w\Box}\frac{s}{v^2}}$$

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

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

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

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

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

Assumed LEP bound is perfect

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

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

Both triplet and singlet are required to have dm = 0

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

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

$$\delta c_{w\Box} = \frac{\kappa_H^2}{g'^2}\frac{m_W^2}{m_V^2}$$

EFT vs UV model (strongly vs weakly)

$SU(2)_L$ triplet + singlet

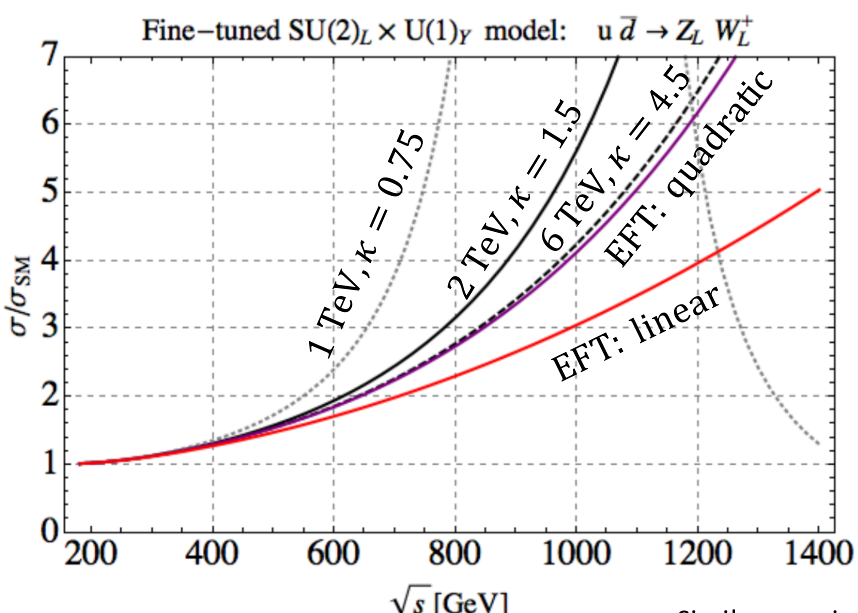
$$\mathcal{L}_{int} = V_\mu^a \left(\frac{i}{2} g \kappa'_H J_H^{a\,\mu} + \frac{g}{2} \kappa'_{fJ} J_f^{a\,\mu} \right) + V_\mu^0 \left(-\frac{i}{2} g \kappa_H J_H^\mu + \frac{g}{2} \kappa_{fJ} J_f^\mu \right)$$

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

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

Weakly coupled

Strongly coupled



EFT works better for a strongly coupling

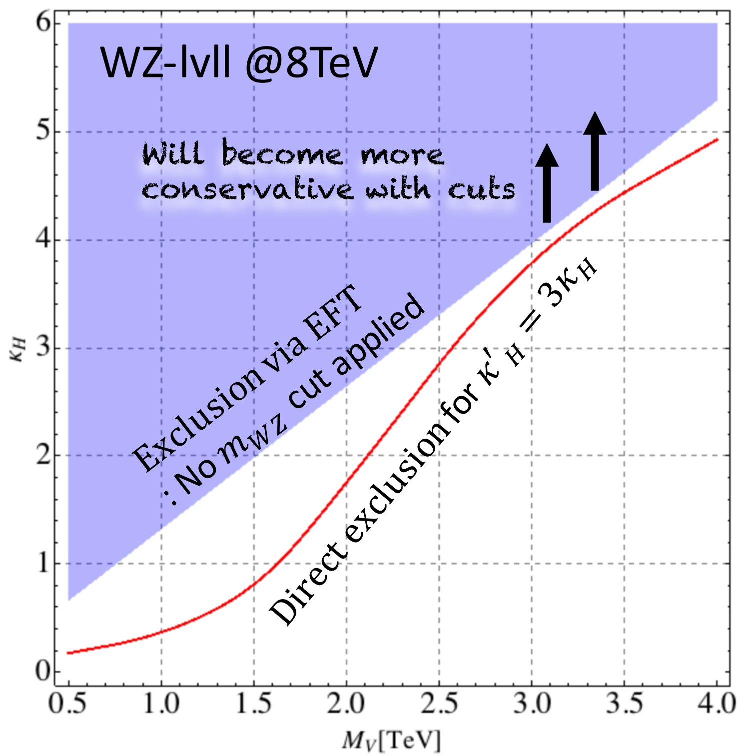
Similar exercise for Wh appeared in
Contino, Falkowski, Goertz, Grojean, Riva 16’

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 ${}^{\kappa_H}/_{m_V}$



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

Summary

We reviewed a general structure of EFT and subtle issues

Technical aspects of EFT

✓ Recovering full $\sqrt{\hat{s}}$-dep is tough.

1. Makes EFT interpretation hard, e.g. resonance scenario
2. Bounds get weaker when imposing a proper $\sqrt{\hat{s}}$-cut (e.g. since sensitivity relies on E-growing)
3. Any progress on this seems very important

✓ Can we do something cool with diff angular distribution as well ?

What are missing in this talk and coming soon

1. Comparison/combination with LEP
2. (HL) LHC projections
3. Sensitivity in terms of parameters in Warsaw, SILH basis etc
4. UV model where EFT can do better job than direct bound