Precision measurement with Diboson at the LHC

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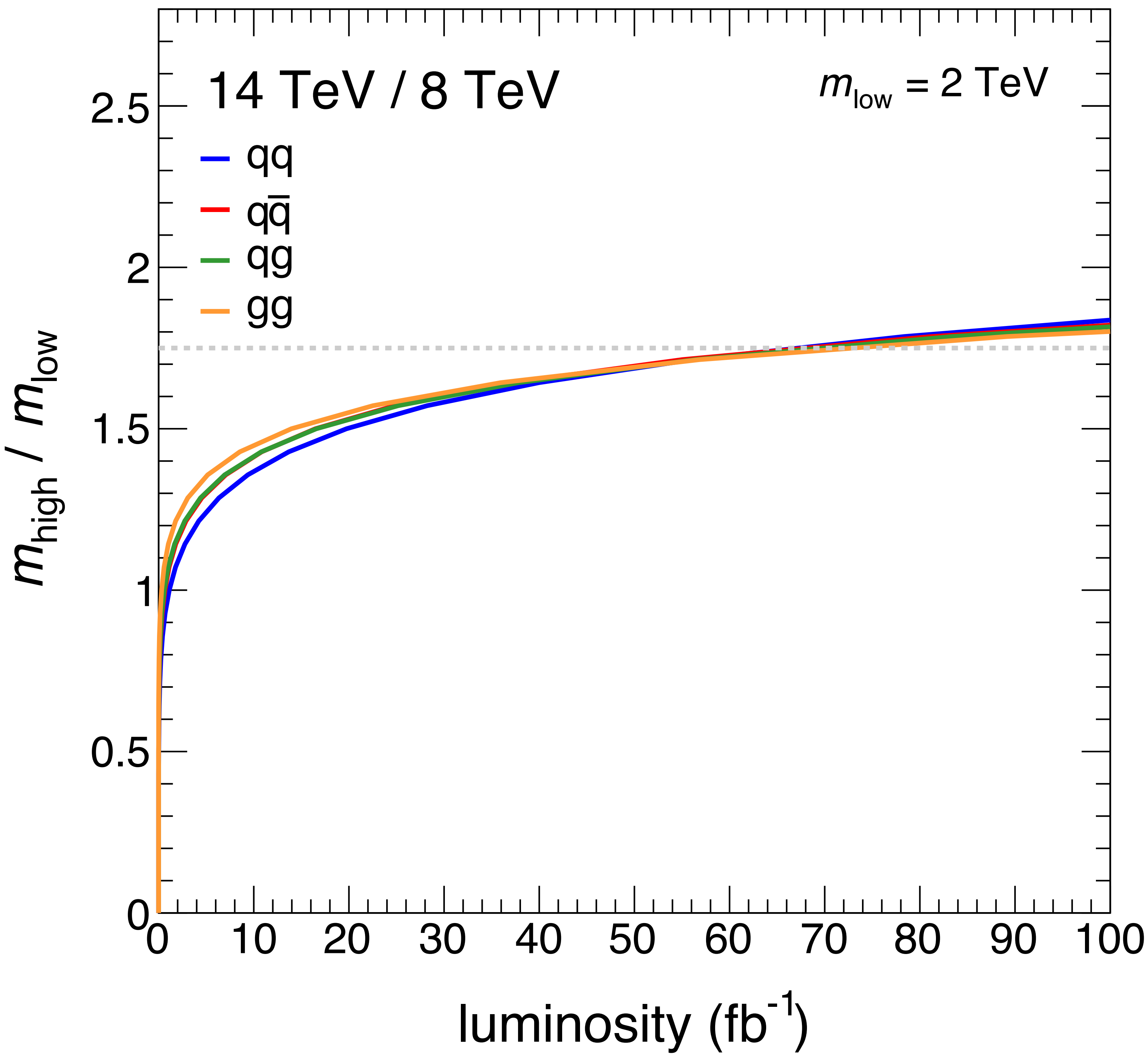
Motivation

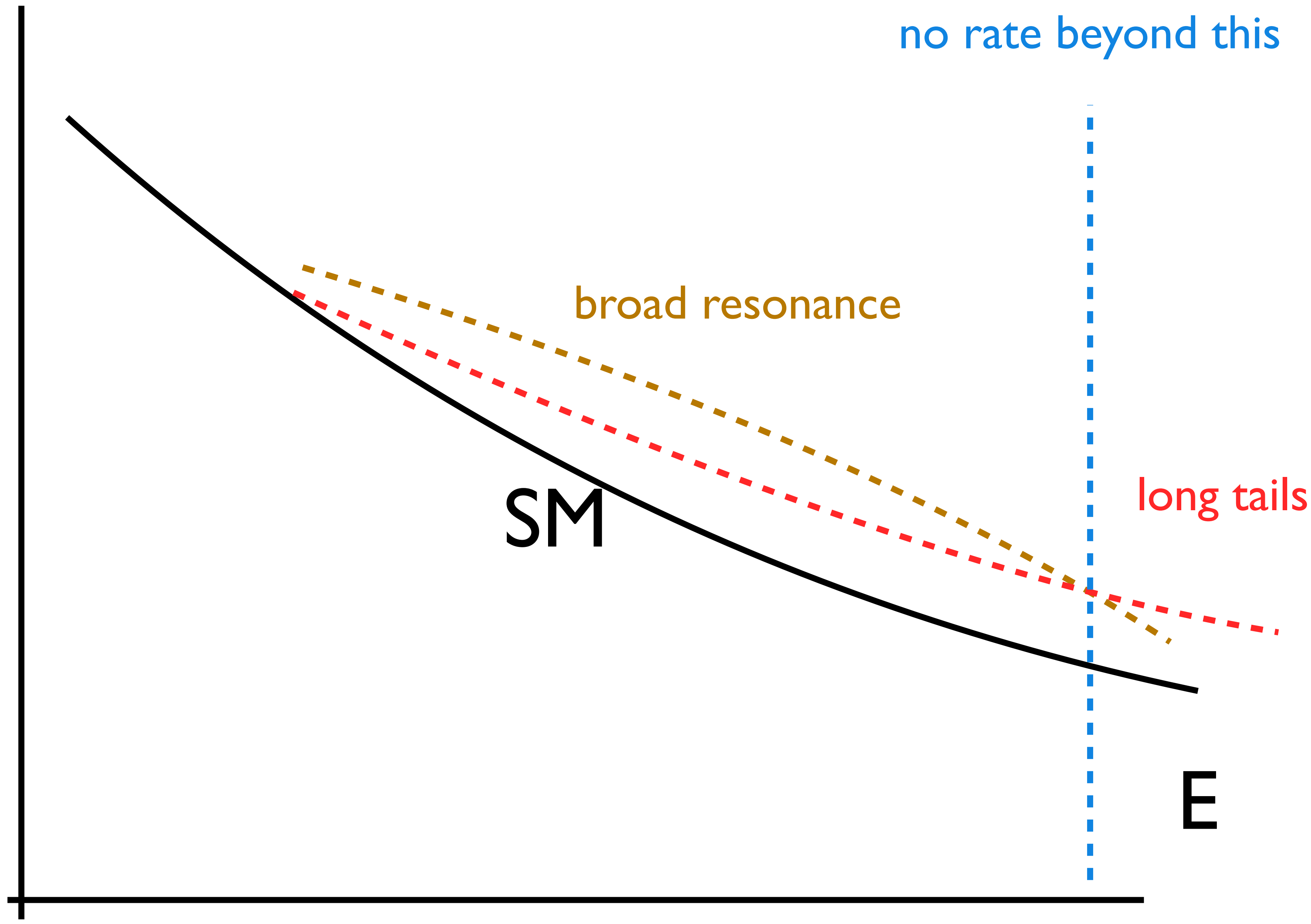
- So far, LHC (80 fb^-1) has not observed any significant excess (Maybe RK?)
- We will have 30 times more data to come.
- Precision measurement enter to a new era at the LHC.
- Some physics scenarios are more sensitive to precision measurement than direct resonance searches.

Resonance searches reach the slow phase!



Mass scale reach at the LHC

New physics too heavy to be produced?



What about LEP?

Compared with LEP, we have more energy and

$\boxed{\text{Energy helps precision!}}$

To reach the mass scale $\Lambda \sim 2\,\mathrm{TeV}$

$$\boxed{\text{LEP}}: \quad \frac{\delta\sigma}{\sigma_{SM}} \sim \frac{m_Z^2}{\Lambda^2} \sim 2.1 \times 10^{-3}$$

$$\boxed{\text{LHC}}: \quad \frac{\delta\sigma}{\sigma_{SM}} \sim \frac{E_c^2}{\Lambda^2} \sim 0.25, \qquad E_c \sim 1\,\mathrm{TeV}$$

$$\frac{\delta\sigma}{\sigma_{SM}} \sim \frac{E_c^4}{\Lambda^4} \sim 0.06$$

LHC has potential.

Both interference and energy growing behavior crucial!

See M. Farina, G. Panico, D. Pappadopulo, J.T. Ruderman, R.Torre and A.Wulzer

Effective Operators

The model-independent way to capture the new physics effects below the cut-off:

$$\mathscr{L} = \mathscr{L}_{\mathrm{SM}} + \sum_{i \in i_6} \frac{c_i}{\Lambda^2} \mathcal{O}_i + \sum_{i \in i_8} \frac{c_i}{\Lambda^4} \mathcal{O}_i$$

- In our parametrization, Λ is the physical cut-off, i.e. the mass of the resonances.
- c_i is the dimensionless Wilson coefficients, which can be large or small (tree or loop) depending the assumptions about the physics at the cut-off.
- Dimension-eight operators maybe relevant in some scenario with:

$$c_8 \gg c_6$$

Effective Operators

We are focusing on the following dimension-six operators:

$$\mathcal{O}_W = \frac{ig}{2}\left(H^\dagger \sigma^a \overleftrightarrow{D}^\mu H\right) D^\nu W^a_{\mu\nu}, \qquad \mathcal{O}_B = \frac{ig'}{2}\left(H^\dagger \overleftrightarrow{D}^\mu H\right) \partial^\nu B_{\mu\nu}$$

$$\mathcal{O}_{2W} = -\frac{1}{2} D^\mu W^a_{\mu\nu} D_\rho W^{a\rho\nu}, \qquad \mathcal{O}_{2B} = -\frac{1}{2}\partial^\mu B_{\mu\nu}\partial_\rho B^{\rho\nu}$$

$$\mathcal{O}_{HW} = ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}, \qquad \mathcal{O}_{HB} = ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$$

$$\mathcal{O}_{3W} = \frac{1}{3!} g \epsilon_{abc} W^{a\nu}_\mu W^b_{\nu\rho} W^{c\rho\mu}, \qquad \mathcal{O}_T = \frac{g^2}{2}(H^\dagger \overleftrightarrow{D}^\mu H)(H^\dagger \overleftrightarrow{D}_\mu)H$$

$$\mathcal{O}^u_R = ig'^2 \left(H^\dagger \overleftrightarrow{D}_\mu H\right) \bar{u}_R \gamma^\mu u_R, \qquad \mathcal{O}^d_R = ig'^2 \left(H^\dagger \overleftrightarrow{D}_\mu H\right) \bar{d}_R \gamma^\mu d_R$$

$$\mathcal{O}^q_L = ig'^2 \left(H^\dagger \overleftrightarrow{D}_\mu H\right) \bar{Q}_L \gamma^\mu Q_L, \qquad \mathcal{O}^{(3)q}_L = ig^2 \left(H^\dagger \sigma^a \overleftrightarrow{D}_\mu H\right) \bar{Q}_L \sigma^a \gamma^\mu Q_L$$

$$\mathscr{L} = \mathscr{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i + \cdots$$

Power Counting of Wilson Cocoefficients

Model	$\mathcal{O}_{2W}$	$\mathcal{O}_{2B}$	$\mathcal{O}_{3W}$	$\mathcal{O}_{HW}$	$\mathcal{O}_{HB}$	$\mathcal{O}_{W,B}$	$\mathcal{O}_{BB}$
SILH	$\frac{g^2}{g_*^2}$	$\frac{g'^2}{g_*^2}$	$\frac{g^2}{16\pi^2}$	$\frac{g_*^2}{16\pi^2}$	$\frac{g_*^2}{16\pi^2}$	1	$\frac{g^2}{16\pi^2}$
Remedios	1	1	$\frac{g_*}{g}$				
Remedios+MCHM	1	1	$\frac{g_*}{g}$	1	1	1	1
Remedios+$ISO(4)$	1	1	$\frac{g_*}{g}$	$\frac{g_*}{g}$	1	1	1

- Strongly Interacting Light Higgs (SILH), OW is most relevant one for Di-boson.
- Remedios scenario: O2W, O3W enhanced!
- Remedios + ISO(4): OHW also enhanced!

Diboson helicity amplitudes

The helicity amplitudes can be decomposed as:

$$\mathcal{M}_{f_1\bar{f}_2}^{\lambda_1\lambda_2,\lambda_3\lambda_4} = \tilde{\mathcal{M}}_{f_1\bar{f}_2}^{\lambda_1\lambda_2,\lambda_3\lambda_4}(\theta)(\lambda_1-\lambda_2)(-1)^{\lambda_4} d^{J_0}_{\Delta\lambda_{12},\Delta\lambda_{34}}$$

with

$$d^{J_0}_{\Delta\lambda_{12},\Delta\lambda_{34}}, \qquad \Delta\lambda_{12} = \lambda_1 - \lambda_2, \qquad \Delta\lambda_{34} = \lambda_3 - \lambda_4, \qquad J_0 = \max(|\Delta\lambda_{12}|, |\Delta\lambda_{34}|)$$

If $\tilde{\mathcal{M}}$ is only a function of (s, t, u),
the amplitude is factorized!

Explicit formulae for d-functions

$$d^2_{1,2} = -d^2_{-1,-2} = \frac{1}{2}\sin\theta(1+\cos\theta), \qquad d^2_{1,-2} = -d^2_{-1,2} = -\frac{1}{2}\sin\theta(1-\cos\theta)$$

$$d^1_{1,1} = d^1_{-1,-1} = \frac{1}{2}(1+\cos\theta), \qquad d^1_{1,-1} = d^1_{-1,1} = \frac{1}{2}(1-\cos\theta),$$

$$d^1_{1,0} = -d^1_{-1,0} = -\frac{\sin\theta}{\sqrt{2}}$$

Diboson helicity amplitudes: TT

Subprocess	SM	NP
$u_L\bar{u}_L \to W^+_\pm W^-_\mp$	$-g^2\frac{s}{2t}$	$-\frac{g^2}{2}\frac{s^2}{\Lambda^4}c_{TWW}$
$d_L\bar{d}_L \to W^+_\pm W^-_\mp$	$-g^2\frac{s}{2u}$	$-\frac{g^2}{2}\frac{s^2}{\Lambda^4}c_{TWW}$
$u_L\bar{d}_L \to W^+_\pm Z_\mp$ $d_L\bar{u}_L \to W^-_\pm Z_\mp$	$-\frac{g}{\sqrt{2}}\left(g_Z^{d_L}\frac{s}{t}+g_Z^{u_L}\frac{s}{u}\right)$ $-\frac{g}{\sqrt{2}}\left(g_Z^{u_L}\frac{s}{t}+g_Z^{d_L}\frac{s}{u}\right)$	$\frac{gg's_w}{2\sqrt{2}}\frac{s^2}{\Lambda^4}c_{TWB}$ $\frac{gg's_w}{2\sqrt{2}}\frac{s^2}{\Lambda^4}c_{TWB}$
$u_L\bar{d}_L \to W^+_\pm \gamma_\mp$ $d_L\bar{u}_L \to W^-_\pm \gamma_\mp$	$-\frac{g}{\sqrt{2}}\left(g_\gamma^{d_L}\frac{s}{t}+g_\gamma^{u_L}\frac{s}{u}\right)$ $-\frac{g}{\sqrt{2}}\left(g_\gamma^{u_L}\frac{s}{t}+g_\gamma^{d_L}\frac{s}{u}\right)$	$-\frac{gg'c_w}{2\sqrt{2}}\frac{s^2}{\Lambda^4}c_{TWB}$ $-\frac{gg'c_w}{2\sqrt{2}}\frac{s^2}{\Lambda^4}c_{TWB}$
$f\bar{f} \to V_\pm V'_\mp$	$-g_V^f g_{V'}^f\left(\frac{s}{t}+\frac{s}{u}\right)$	$-\frac{g^2}{4}\frac{s^2}{\Lambda^4}c^{(8)}_{fVV'}$

$\tilde{\mathcal{M}}$

- The transverse WW has t-channel singularity, dominate over LL mode.
  - No interference with dim-6 as angular momentum conservation or helicity selection rules.
- WZ is antisymmetric under (t,u) exchange in the limit of vanishing hypercharge coupling, resulting inthe famous amplitude-zero.
- All can interference with dim-8 operators.

Diboson helicity amplitudes: LL

Subprocess	SM	NP
$u_L\bar{u}_L \to W^+_L W^-_L$ $d_L\bar{d}_L \to Z_L h$	$\frac{1}{\sqrt{2}}\left(\frac{g^2}{2}+\frac{g'^2}{6}\right)$	$\frac{1}{\sqrt{2}}\frac{s}{\Lambda^2}\left(\frac{g^2}{2}c^{(3)}_{q_L}+\frac{g'^2}{6}c^{(1)}_{u_L}\right)$
$d_L\bar{d}_L \to W^+_L W^-_L$ $u_L\bar{u}_L \to Z_L h$	$\frac{1}{\sqrt{2}}\left(-\frac{g^2}{2}+\frac{g'^2}{6}\right)$	$\frac{1}{\sqrt{2}}\frac{s}{\Lambda^2}\left(-\frac{g^2}{2}c^{(3)}_{q_L}+\frac{g'^2}{6}c^{(1)}_{d_L}\right)$
$u_R\bar{u}_R \to W^+_L W^-_L$	$\frac{\sqrt{2}}{3}g'^2$	$\frac{\sqrt{2}}{3}g'^2\frac{s}{\Lambda^2}c^{(1)}_{u_R}$
$u_R\bar{u}_R \to W^+_L W^-_L$	$\frac{\sqrt{2}}{3}g'^2$	$\frac{\sqrt{2}}{3}g'^2\frac{s}{\Lambda^2}c^{(1)}_{u_R}$
$d_R\bar{d}_R \to W^+_L W^-_L$	$-\frac{\sqrt{2}}{6}g'^2$	$-\frac{\sqrt{2}}{6}g'^2\frac{s}{\Lambda^2}c^{(1)}_{d_R}$
$u_L\bar{d}_L \to W^+_L Z_L(h)$ $d_L\bar{u}_L \to W^-_L Z_L(h)$	$-\frac{g^2}{2}$	$-\frac{g^2}{2}\frac{s}{\Lambda^2}c^{(3)}_{q_L}$

$\tilde{\mathcal{M}}$

$$c^{(3)}_{q_L} = c_W + c_{HW} - c_{2W} + 4c^{(3)q}_L$$
$$c^{(1)}_{u_L} = c_B + c_{HB} - c_{2B} + 4c^q_L$$
$$c^{(1)}_{d_L} = c_B + c_{HB} - c_{2B} - 4c^q_L$$
$$c^{(1)}_{u_R} = c_B + c_{HB} - c_{2B} + 3c_{u_R}$$
$$c^{(1)}_{d_R} = c_B + c_{HB} - c_{2B} - 6c_{d_R}$$

- Because of the smallness of hyper-charge couplings the dominant contribution comes from the combination $c^{(3)}_{q_L}$
- Wh Zh no transverse backgrounds, but suffer from W+jets and Z+jets.

See R.Franceschini, G.Panico, A.Pomarol, F.Riva and A.Wulzer, [arXiv:1712.01310 [hep-ph]].

$$\mathcal{O}_{3W} = \frac{1}{3!} g \epsilon_{abc} W_{\mu}^{a\nu} W_{\nu\rho}^{b} W^{c\rho\mu},$$

- Helicity selection rules tells us this only contribute to ++ helicity final states (see Azatov et al.)

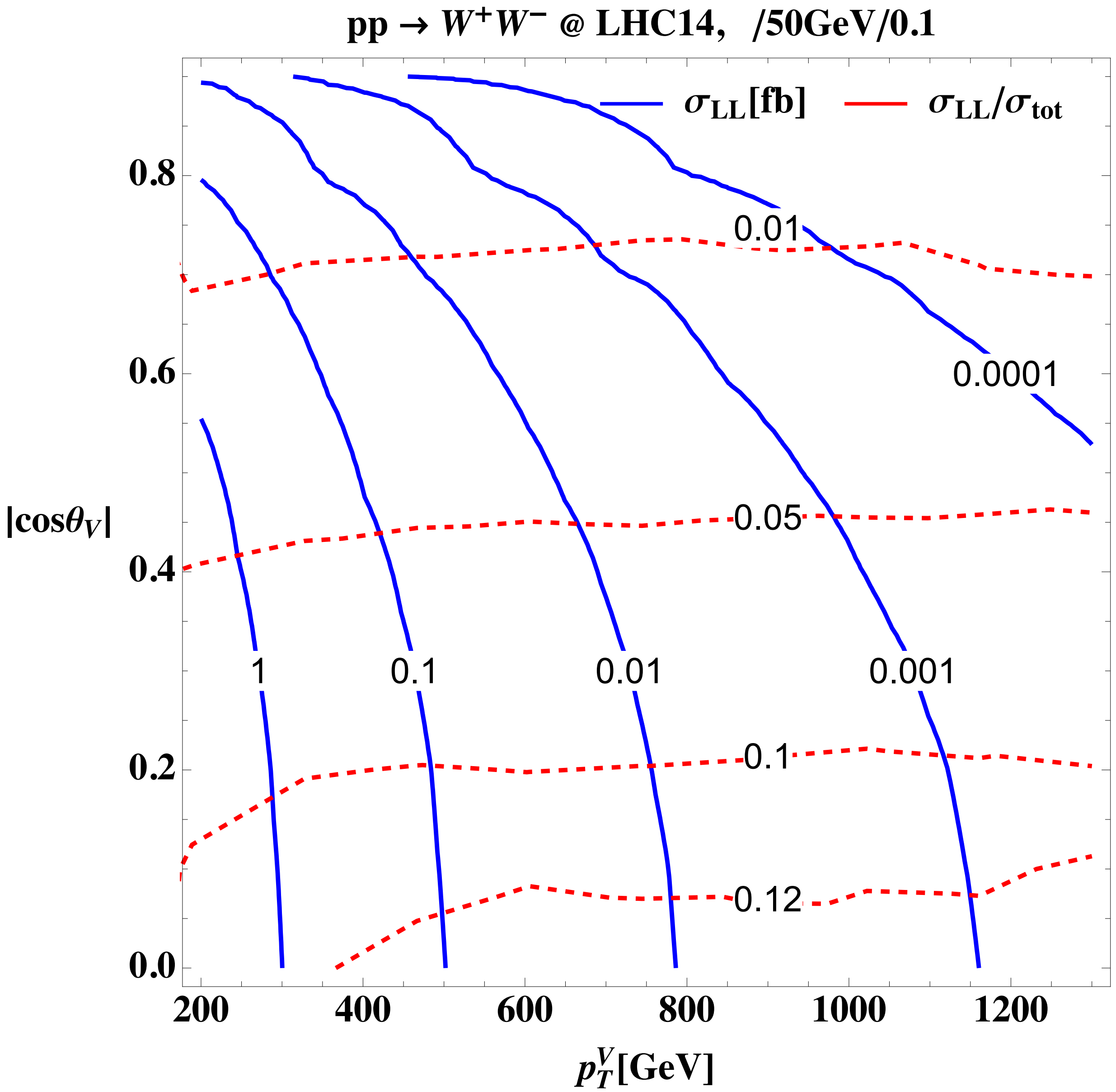
$$|h(A_3)| = 1 - [g] \, .$$

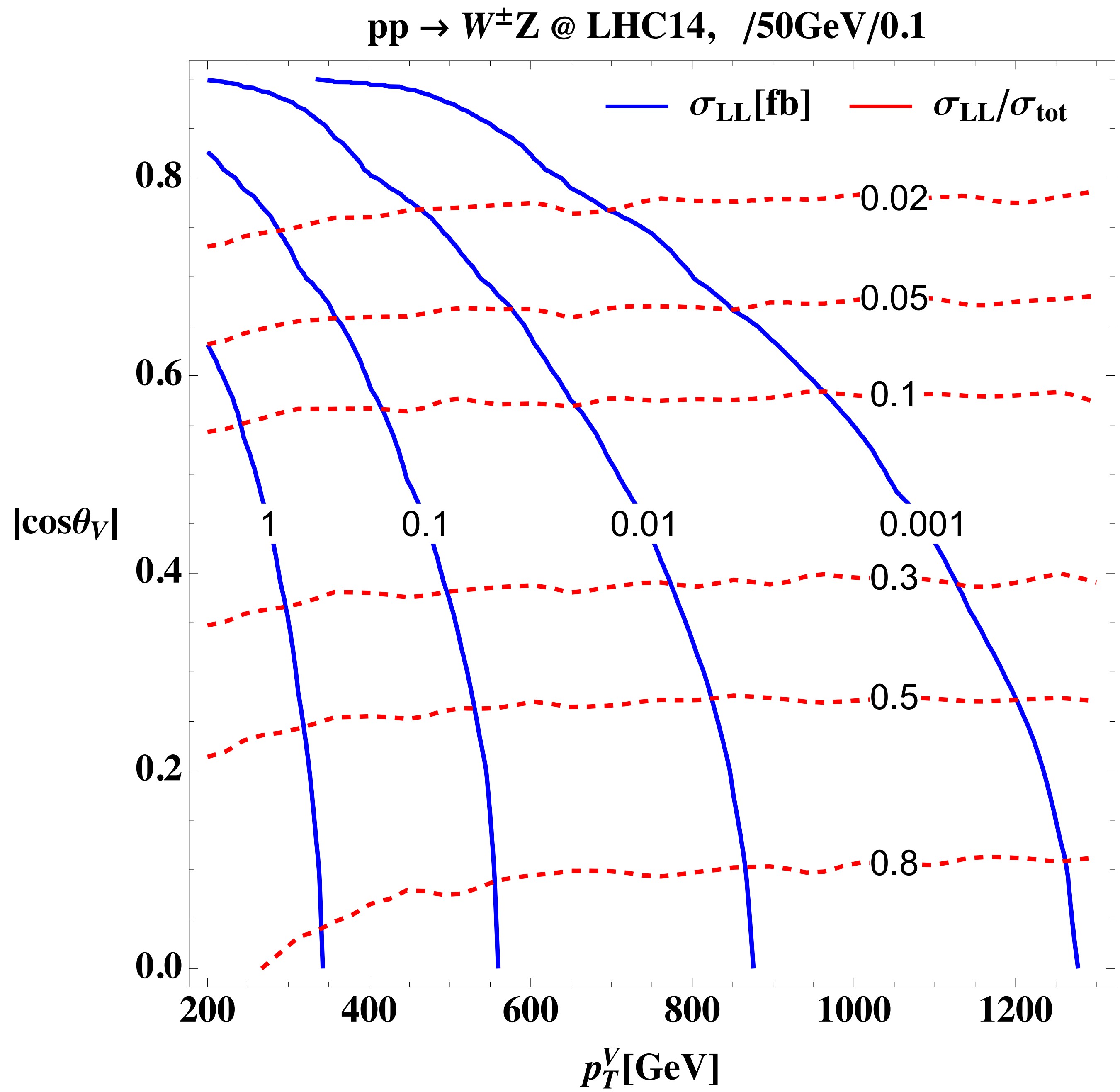
- Underlying SUSY ward identity for gauge interactions at tree level ensure ++ SM amplitudes are zero (the same reason as the vanishing of the ++++ four gluon amplitudes)

- Interference with SM not growing with energy, hard to probe at the hadron collider

- Can be improved by explore the azimuthal angles of decay products (See Azatov et al. and Panico et al.)

WW and WZ at the LHC





Focusing on the central region improves the significance

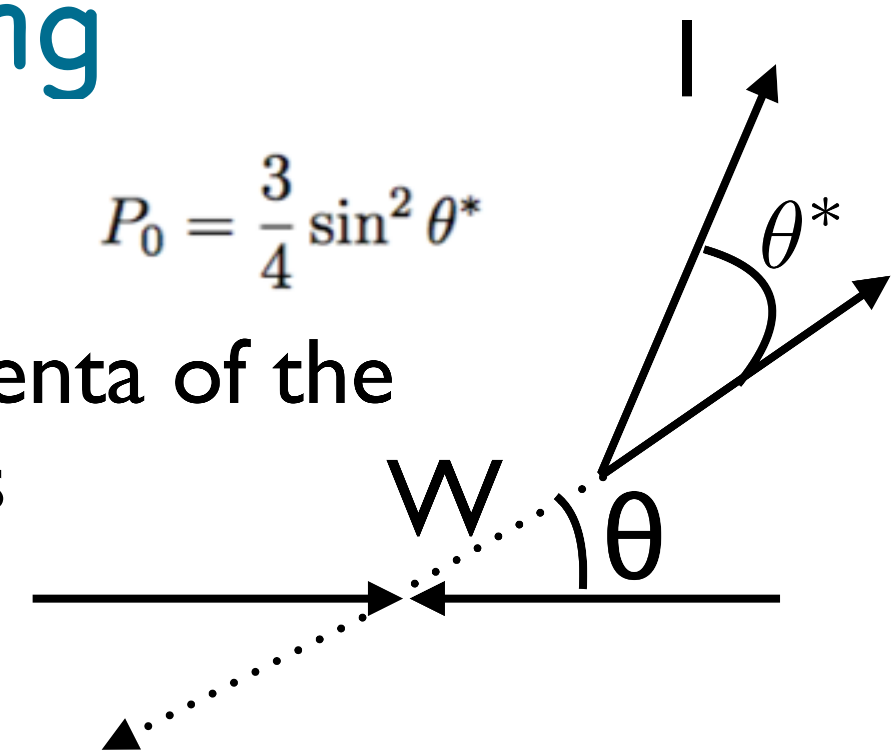
We are focusing on the semi-leptonically decaying channels

$$pp \to WV \to \ell\nu q\bar{q}, \qquad \mathrm{BR}(W^+W^- \to \ell\nu q\bar{q}) = 29.2\%, \qquad \mathrm{BR}(W^\pm Z \to \ell\nu q\bar{q}) = 15.1\%$$
$$pp \to Wh \to \ell\nu b\bar{b}, \qquad \mathrm{BR} = 12.6\%$$
$$pp \to Zh \to \ell^+\ell^- b\bar{b}, \qquad \mathrm{BR} = 3.92\%$$
$$pp \to Zh \to \nu\bar{\nu} b\bar{b}, \qquad \mathrm{BR} = 11.6\%$$

- Compared with fully leptonical channels, these have one oder of magnitude larger rate.
- Although suffered from reducible backgrounds V +jets, a lot of data can make big difference here!
- Jet substructure methods play an important role to suppress the reducible backgrounds.
- 13 TeV W-jet tagging has been improved by a factor of 2 with 8 TeV.

ATLAS-CONF-2017-064

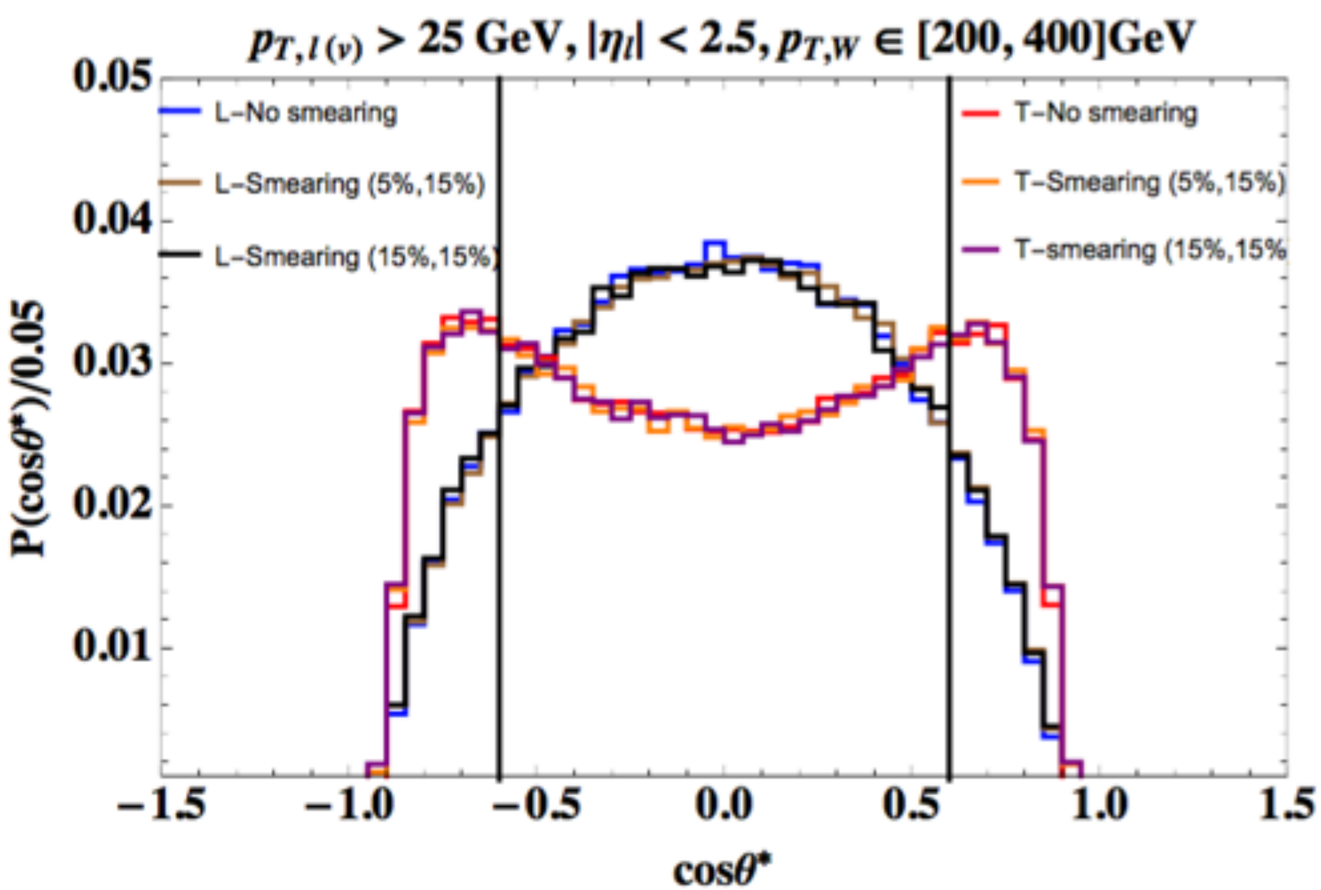
Polarization tagging

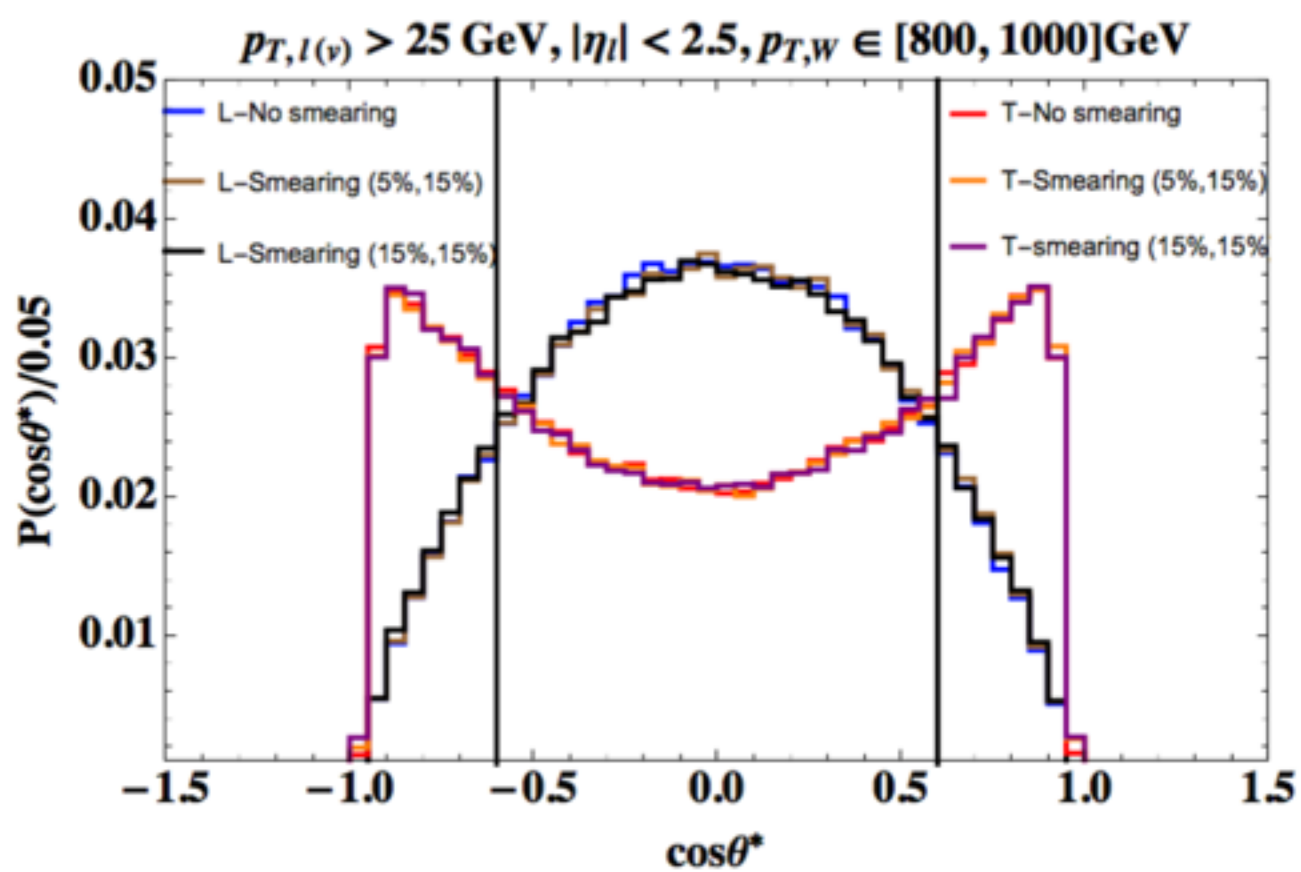


$$P_+ = \frac{3}{8}(1-\cos\theta^*)^2, \qquad P_- = \frac{3}{8}(1+\cos\theta^*)^2, \qquad P_0 = \frac{3}{4}\sin^2\theta^*$$

$\cos\theta^*$ can be determined by the momenta of the leptons and neutrinos

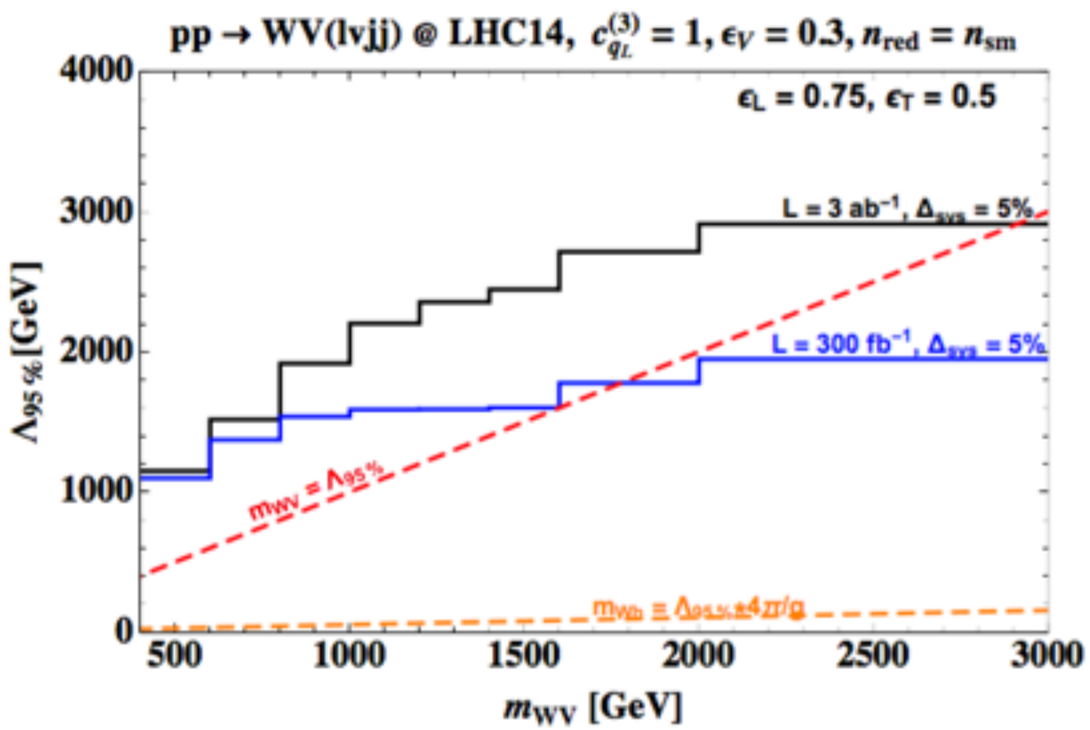
$$\cos\theta^* = \frac{E_\ell - E_\nu}{|\vec{p}_\ell + \vec{p}_\nu|}.$$

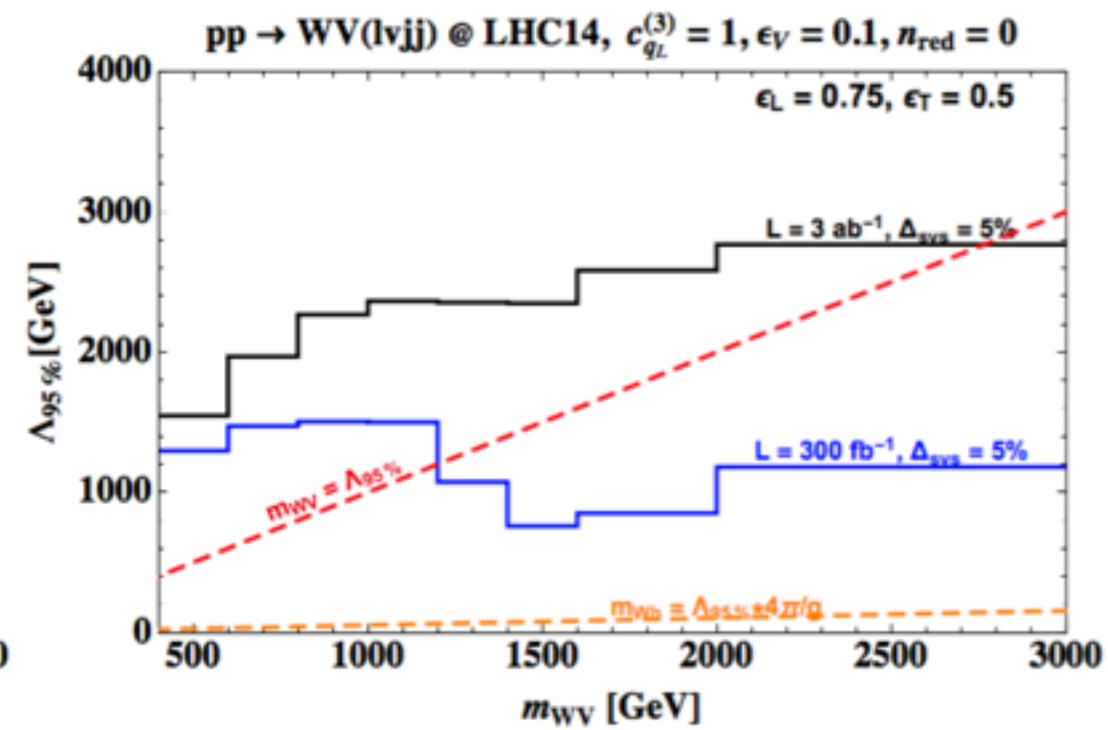


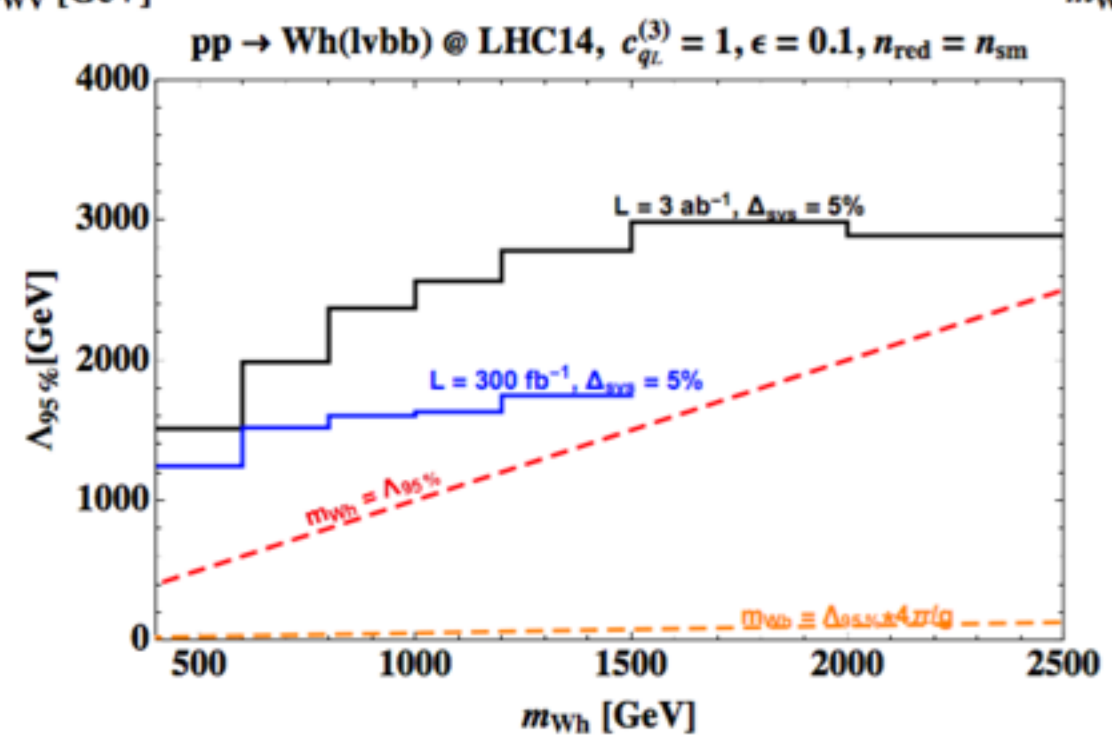


$$\epsilon_L \equiv \epsilon^L_{p_T,\eta} \times \epsilon^L_{\cos\theta^*} = 0.75, \qquad \epsilon_T \equiv \epsilon^T_{p_T,\eta} \times \epsilon^T_{\cos\theta^*} = 0.5.$$

Reach in different energy bins

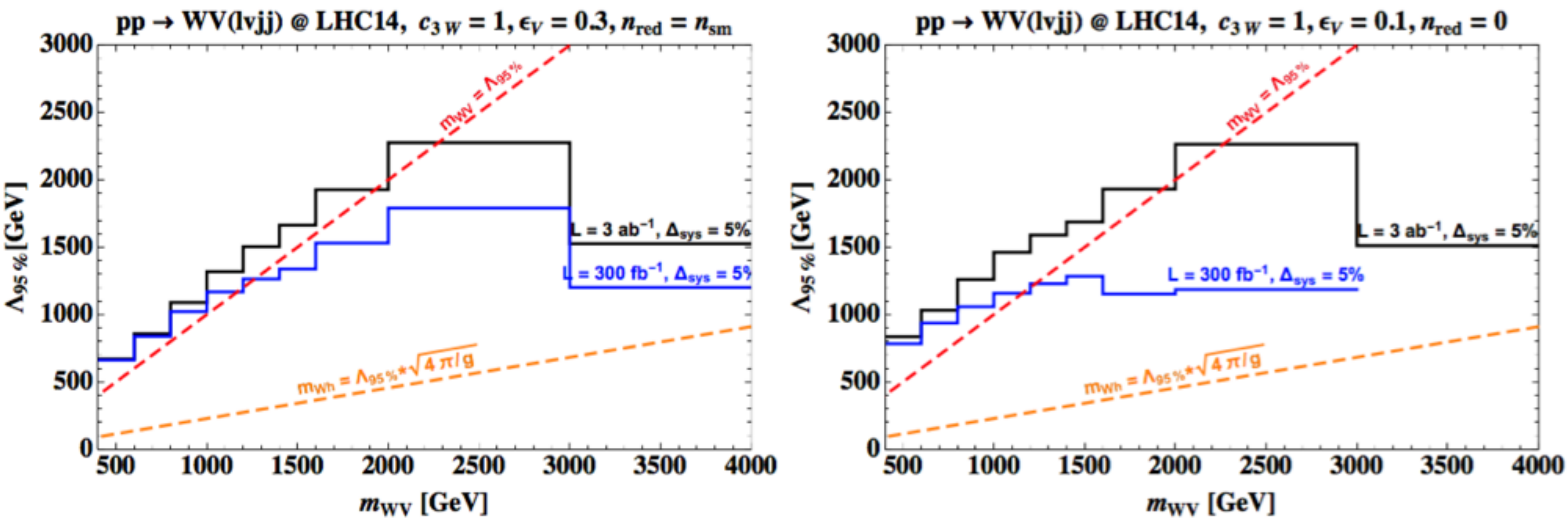






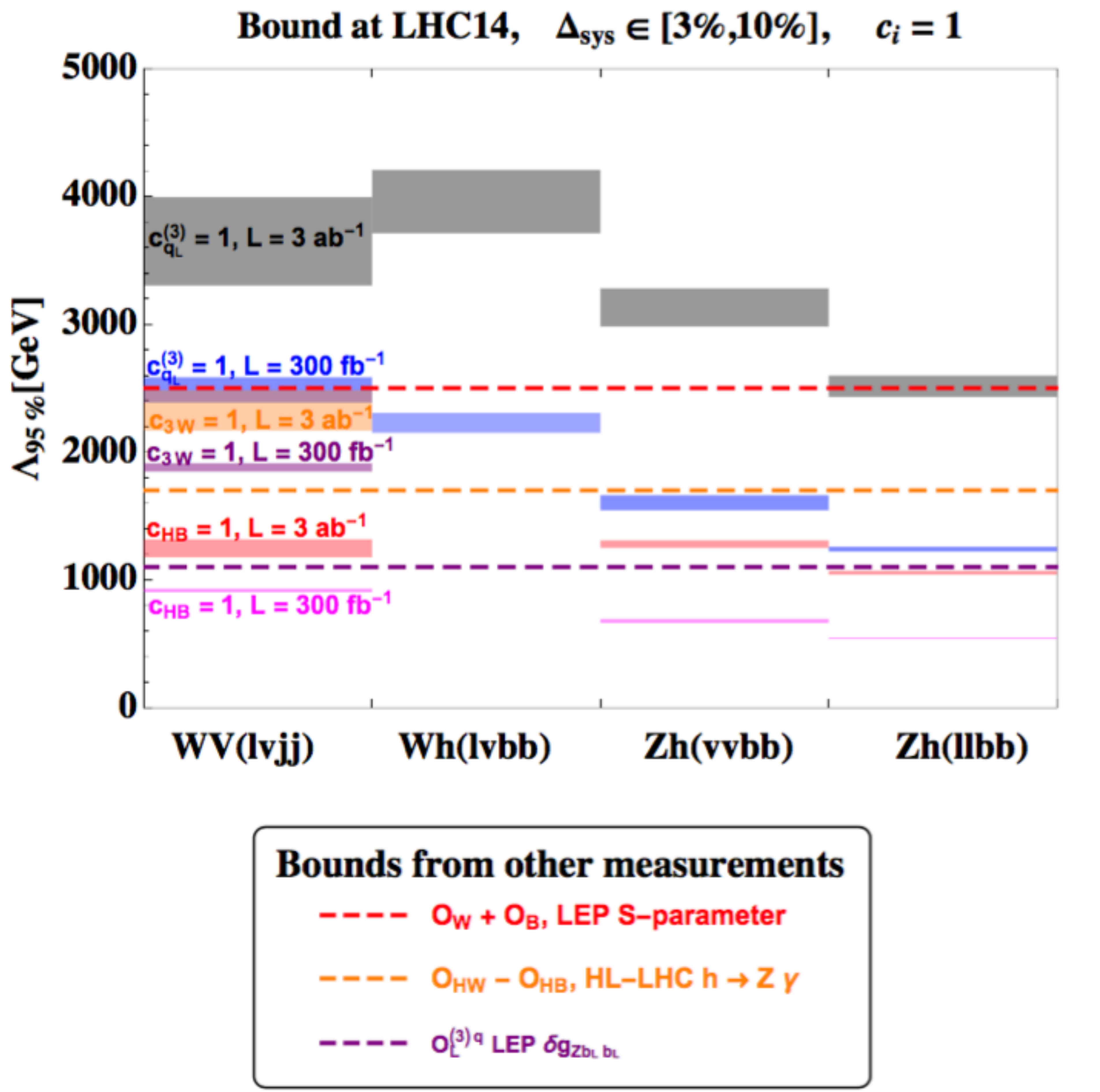
With HL, weakly coupled EFT consistent!

Bounds on O3W



- Bounds are in tension with weakly coupled EFT.

- Still useful for strongly coupled case, e.g. Strong multi-pole interactions.



Bound at LHC14, $\Delta_{sys} \in [3\%, 10\%]$, $c_i = 1$
$\Lambda_{95\%}$[GeV]
5000
4000
3000
2000
1000
0
$c_{q_L}^{(3)} = 1$, L = 3 ab^{-1}
$c_{q_L}^{(3)} = 1$, L = 300 fb^{-1}
$c_{3W} = 1$, L = 3 ab^{-1}
$c_{3W} = 1$, L = 300 fb^{-1}
$c_{HB} = 1$, L = 3 ab^{-1}
$c_{HB} = 1$, L = 300 fb^{-1}
WV(lvjj)
Wh(lvbb)
Zh(vvbb)
Zh(llbb)
Bounds from other measurements
$O_W + O_B$, LEP S–parameter
$O_{HW} - O_{HB}$, HL–LHC $h \to Z\gamma$
$O_L^{(3)q}$ LEP $\delta g_{Zb_L b_L}$

Mass scale reach in different scenarios

Model	Di-boson	S-parameter	LHC $h \to Z\gamma$	LHC $h \to \gamma\gamma$	LHC dilepton
SILH	4.0	2.5	$1.7\sqrt{\frac{g_*}{4\pi}}$	0.34	$0.69\sqrt{\frac{4\pi}{g_*}}$
Remedios	$10.6\sqrt{\frac{g_*}{4\pi}}$				13.4
Remedios+MCHM	$10.6\sqrt{\frac{g_*}{4\pi}}$	2.5	1.7	6.5	13.4
Remedios+$ISO(4)$	$17.6\sqrt{\frac{g_*}{4\pi}}$	2.5	$7.5\sqrt{\frac{g_*}{4\pi}}$	6.5	13.4

- Strongly Interacting Light Higgs (SILH), Di-boson can beat the LEP EWPT.

- Pure Strong multi-pole interactions, LHC dilepton bounds on O2W maybe the most relevant ones.

- Remedios+ISO(4), Di-boson can be better for large coupling g* > 7.

Conclusion

- New physics may only show its tail at the LHC, it is important to do the precision measurement.

- The EFT is a convenient and model-independent way to capture the effects.

- With high energy at hand, LHC can beat LEP precision.

- Non-resonant, broad features. Difficult. But a lot data can make a significant difference here!

Back-up Slides

Helicity structure for WW

$$q_L \bar{q}_R \to W^+ W^-$$

(h_{W^+}, h_{W^-})	SM	$\mathcal{O}_W$	$\mathcal{O}_{HW}$	$\mathcal{O}_B$	$\mathcal{O}_{HB}$	$\mathcal{O}_{3W}$
$(\pm, \mp)$	1	0	0	0	0	0
$(0, 0)$	1	$\frac{E^2}{\Lambda^2}$	$\frac{E^2}{\Lambda^2}$	$\frac{E^2}{\Lambda^2}$	$\frac{E^2}{\Lambda^2}$	0
$(0, \pm), (\pm, 0)$	$\frac{m_W}{E}$	$\frac{E m_W}{\Lambda^2}$	$\frac{E m_W}{\Lambda^2}$	$\frac{E m_W}{\Lambda^2}$	$\frac{E m_W}{\Lambda^2}$	$\frac{E m_W}{\Lambda^2}$
$(\pm, \pm)$	$\frac{m_W^2}{E^2}$	$\frac{m_W^2}{\Lambda^2}$	$\frac{m_W^2}{\Lambda^2}$	$\frac{m_W^2}{\Lambda^2}$	0	$\frac{E^2}{\Lambda^2}$

$$q_R \bar{q}_L \to W^+ W^-$$

(h_{W^+}, h_{W^-})	SM	$\mathcal{O}_W$	$\mathcal{O}_{HW}$	$\mathcal{O}_B$	$\mathcal{O}_{HB}$	$\mathcal{O}_{3W}$
$(\pm, \mp)$	0	0	0	0	0	0
$(0, 0)$	1	$\frac{m_W^2}{\Lambda^2}$	$\frac{m_W^2}{\Lambda^2}$	$\frac{E^2}{\Lambda^2}$	$\frac{E^2}{\Lambda^2}$	0
$(0, \pm), (\pm, 0)$	$\frac{m_W}{E}$	$\frac{m_W^2 m_Z^2}{\Lambda^2 E^2}$	$\frac{E m_W}{\Lambda^2}$	$\frac{E m_W}{\Lambda^2}$	$\frac{E m_W}{\Lambda^2}$	$\frac{m_W^2 m_Z^2}{\Lambda^2 E^2}$
$(\pm, \pm)$	$\frac{m_W^2}{E^2}$	$\frac{m_W^2}{\Lambda^2}$	$\frac{m_W^2}{\Lambda^2}$	$\frac{m_W^2}{\Lambda^2}$	0	$\frac{m_W^2}{\Lambda^2}$

- Whether interference or not depends on polarization of WW. Polarization differentiation can be crucial.

Operator relations

- Equation of motion or field redefinition

$$
\begin{aligned}
D^\nu W^a_{\mu\nu} &= igH^\dagger \frac{\sigma^a}{2} \overleftrightarrow{D}_\mu H + g\sum_f \bar{f}_L \frac{\sigma^a}{2}\gamma_\mu f_L\,, \\
\partial^\nu B_{\mu\nu} &= ig' Y_H H^\dagger \overleftrightarrow{D}_\mu H + g'\sum_f \left[Y^f_L \bar{f}_L \gamma_\mu f_L + Y^f_R \bar{f}_R \gamma_\mu f_R\right] \\
D^\nu G^A_{\mu\nu} &= g_s \sum_q \bar{q} T^A \gamma_\mu q\,,
\end{aligned}
$$

- Partial integral

$$
\mathcal{O}_B = \mathcal{O}_{HB} + \frac{1}{4}\mathcal{O}_{BB} + \frac{1}{4}\mathcal{O}_{WB}\,, \qquad \mathcal{O}_{WW} = g^2|H|^2 W^a_{\mu\nu}W^{\mu\nu\,a}
$$

$$
\mathcal{O}_W = \mathcal{O}_{HW} + \frac{1}{4}\mathcal{O}_{WW} + \frac{1}{4}\mathcal{O}_{WB}\,. \qquad , \mathcal{O}_{WB} = g' g H^\dagger \sigma^a H W^a_{\mu\nu} B^{\mu\nu}
$$

- We can use them to rewrite the more derivative operators with more fields -> Warsaw basis.

$$
\mathcal{O}_W = -\frac{3}{2}\mathcal{O}_H + 2\mathcal{O}_6 + \frac{1}{2}(\mathcal{O}_{y_u} + \mathcal{O}_{y_d} + \mathcal{O}_{y_e}) + \frac{1}{4}\sum_f \mathcal{O}^{(3)f}_L
$$

$$
\mathcal{O}_B = -\frac{1}{2}\mathcal{O}_T + \frac{1}{2}\sum_f \left(Y^f_L \mathcal{O}^f_L + Y^f_R \mathcal{O}^f_R\right)
$$

see for example Elias-Miro et al.

Phenomenology of the effective operators

$\boxed{\text{hVV contact interactions, } V = W, Z, A}$

$$\mathcal{L}_h = \frac{2m_W^2}{\Lambda^2}\left(\frac{h}{v}+\frac{h^2}{2v^2}\right)\left\{(\hat{c}_W W_\mu^- \mathcal{D}^{\mu\nu} W_\nu^+ + h.c.) + Z_\mu \mathcal{D}^{\mu\nu}\left[\hat{c}_Z Z_\nu + \left(\frac{2\hat{c}_W}{\sin 2\theta_W} - \frac{\hat{c}_Z}{\tan\theta_W}\right) A_\nu\right]\right\}$$
$$- 4\frac{m_W^2}{\Lambda^2}\left(\frac{h}{v}+\frac{h^2}{2v^2}\right)\left\{\frac{c_{HW}}{2} W^{+\mu\nu} W^-_{\mu\nu} + \frac{c_{HW} + \tan^2\theta_W c_{HB}}{4} Z^{\mu\nu} Z_{\mu\nu} - 2\sin^2\theta_W c_{\gamma Z} A^{\mu\nu} Z_{\mu\nu}\right\}$$

$$\mathcal{D}^{\mu\nu} = \partial^\mu\partial^\nu - \Box\eta^{\mu\nu}, \quad \hat{c}_W = c_W + c_{HW}, \quad \hat{c}_Z = \hat{c}_W + \tan^2\theta_W\,(c_B + c_{HB}), \quad c_{\gamma Z} = -\frac{c_{HW} - c_{HB}}{4\sin 2\theta_W}$$

- OW and OB don't contribute to on-shell photon production

- OHW and OHB contribute to $hZ\gamma$, loop level generated in minimal coupled theory

Phenomenology of the effective operators

$\boxed{\text{TGC:}}$

$$\mathcal{L}_V = -\frac{\tan\theta_W}{2}\hat{S}W^{(3)}_{\mu\nu}B^{\mu\nu} + ig\cos\theta_W\delta g_1^Z\left(W^+_{\mu\nu}W^{-\mu} - W^-_{\mu\nu}W^{+\mu}\right)Z^\nu$$

$$+\, ig\left(\cos\theta_W\delta\kappa_Z Z^{\mu\nu} + \sin\theta_W\delta\kappa_\gamma A^{\mu\nu}\right)W^+_\mu W^-_\nu + ig\cos\theta_W\frac{\lambda_Z}{m_W^2}W^+_{\lambda\mu}W^{-\mu}{}_\nu Z^{\nu\lambda} + +ie\frac{\lambda_\gamma}{m_W^2}W^+_{\lambda\mu}W^{-\mu}{}_\nu A^{\nu\lambda}$$

$$\hat{S} = (c_W + c_B)\frac{m_W^2}{\Lambda^2}, \qquad \delta g_1^Z = -\frac{c_W + c_{HW}}{\cos^2\theta_W}\frac{m_W^2}{\Lambda^2}, \qquad \delta\kappa_\gamma = -\left(c_{HW} + c_{HB}\right)\frac{m_W^2}{\Lambda^2}$$

$$\delta\kappa_Z = \delta g_1^Z - \tan^2\theta_W\delta\kappa_\gamma, \qquad \lambda_Z = \lambda_\gamma = c_{3W}\frac{m_W^2}{\Lambda^2}$$

- OW and OB contribute to the S parameter, constrained by LEP

- O3W modify the magnetic dipole and to the electric quadrupole of the W, can only arise from loop level in minimal coupled theory

Phenomenology of the effective operators

Fermion couplings:

$$\mathcal{L}_f = \frac{4m_W^2}{\Lambda^2}\left(1+\frac{h}{v}\right)^2\Big[\frac{g}{\sqrt{2}}c_L^{(3)q}W_\mu^+\bar{u}_L\gamma^\mu d_L + h.c.$$
$$-\frac{g}{2c_w}Z_\mu\left(c_R^u\bar{u}_R\gamma^\mu u_R + c_R^d\bar{d}_R\gamma^\mu d_R + (c_L^q - c_L^{(3)q})\bar{u}_L\gamma^\mu u_L + (c_L^q + c_L^{(3)q})\bar{d}_L\gamma^\mu d_L\right)\Big]$$

- Contribute to the Z-pole variables.
- We will consider the flavour-universal effects
- Contact interactions between ffVh, longitudinal modes growing with energy.

Phenomenology of the effective operators

$\boxed{\text{Dimension-eight:}}$

$$\mathcal{L}_8 = \frac{1}{\Lambda^4} T_f^{\mu\nu} \Big[c_{TWW} g^2 (W^+_{\mu\rho} W_\nu^{-\rho} + W^+_{\nu\rho} W_\mu^{-\rho}) + (c_{TWW} g^2 c_w^2 + c_{TBB} g'^2 s_w^2 - 2T_f^3 c_{TWB} g g' s_w c_w) Z_{\mu\rho} Z_\nu{}^\rho$$
$$+ (c_{TWW} + c_{TBB} + 2T_f^3 c_{TWB}) e^2 A_{\mu\rho} A_\nu{}^\rho + (2 c_w s_w (c_{TWW} g^2 - c_{TBB} g'^2) + 2T_f^3 c_{TWB} g g' (c_w^2 - s_w^2)) Z_{\mu\rho} A_\nu{}^\rho$$
$$+ \frac{1}{2} (c_{TH} - 2T_f^3 c_{TH}^{(3)}) g^2 \left(\partial_\mu h \partial_\nu h + m_Z^2 Z_\mu Z_\nu \right) + (c_{TH} + 2T_f^3 c_{TH}^{(3)}) g^2 m_W^2 W_\mu^- W_\nu^+ \Big]$$
$$+ c_{TWB} \frac{\sqrt{2} g g'}{\Lambda^4} \left(T_{f_L}^{+\mu\nu} W^+_{\mu\rho} + T_{f_L}^{-\mu\nu} W^-_{\mu\rho} \right) (-s_w Z_\nu{}^\rho + c_w A_\nu{}^\rho)$$
$$+ c_{TH}^{(3)} \frac{\sqrt{2} g^2 m_W}{\Lambda^4} \left(T_{f_L}^{+\mu\nu} W_\mu^+ (-i\partial_\nu h - m_Z Z_\nu) + T_{f_L}^{-\mu\nu} W_\mu^- (i\partial_\nu h - m_Z Z_\nu) \right)$$

- New signatures: $ZZ, \gamma\gamma$
- Interference with SM: $\frac{\delta\sigma}{\sigma_{\rm SM}} \sim \frac{E^4}{\Lambda^4}$
- Can be enhanced by strong coupling