Electroweak Production of
1, 2, 3, 4
electroweak bosons

Marc Riembau
Université de Genève

LHCP, May 2019

Based on
1810.05149, with **C. Grojean** and **M. Montull**
1812.09299, with **B. Henning**, **D. Lombardo** and **F. Riva**
190x.xxxxxx, with **G. Durieux** and **M. Montull**

Electroweak Production of
1, 2, 3, ~~4~~
electroweak bosons

Marc Riembau
Université de Genève

LHCP, May 2019

Based on
1810.05149, with **C. Grojean** and **M. Montull**
1812.09299, with **B. Henning**, **D. Lombardo** and **F. Riva**
190x.xxxxxx, with **G. Durieux** and **M. Montull**

People like to say that the SM is complete...

i.e., it is possible to write down a consistent, renormalizable Lagrangian given its matter content, and it is unique

People like to say that the SM is complete…

i.e., it is possible to write down a consistent, renormalizable Lagrangian given its matter content, and it is unique

Changing any of its relation among couplings must induce a pathological behaviour in some process

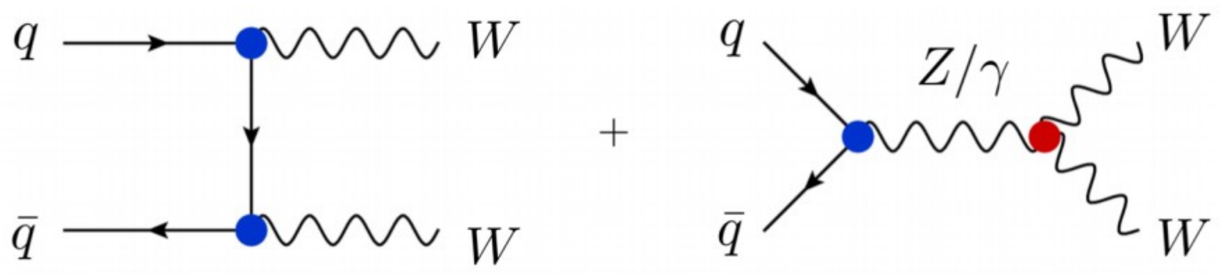
New phenomena must enter before QFT breakdown at some scale, and SM deformations classified by an EFT

Electroweak Production of 2 electroweak bosons

The role of high energies

An explicit example in diboson:

In the unitary gauge, and in the SM,



$$\mathcal{M}_\gamma + \mathcal{M}_Z + \mathcal{M}_t = -i\frac{e^2 \sin\theta}{2m_W^2}\, s \left(Q_q + \frac{1}{s_W^2}(T_q^3 - s_W^2 Q_q) - \frac{T_q^3}{s_W^2} \right)$$

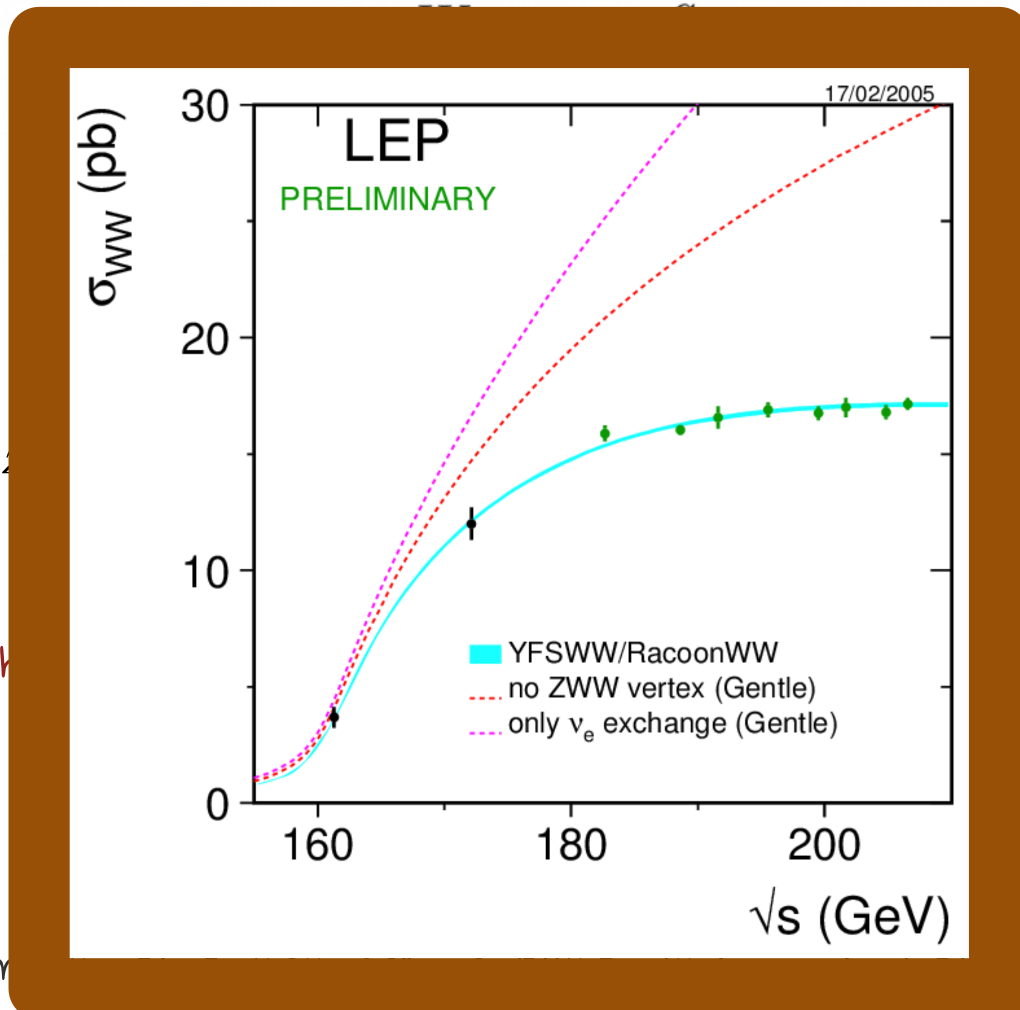
- Each of the contributions separately grows with energy

- In the SM, the couplings are such that there is no pathological growth of the amplitude

- This also means that non-SM couplings induce deviations that get amplified at high energies

An explicit example in diboson:

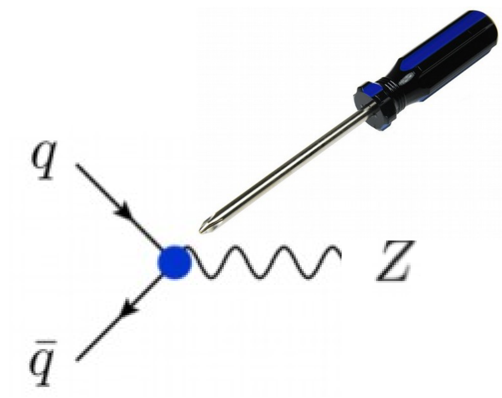
In the unitary gauge, and in the SM,

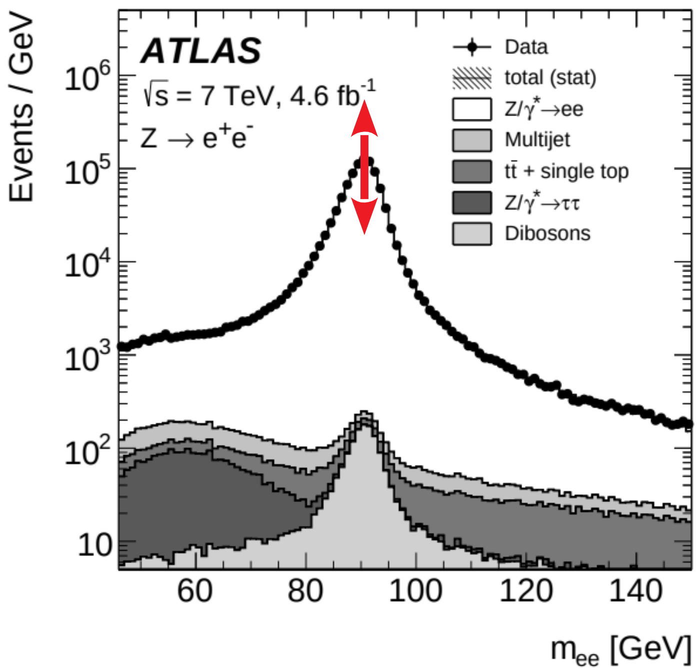


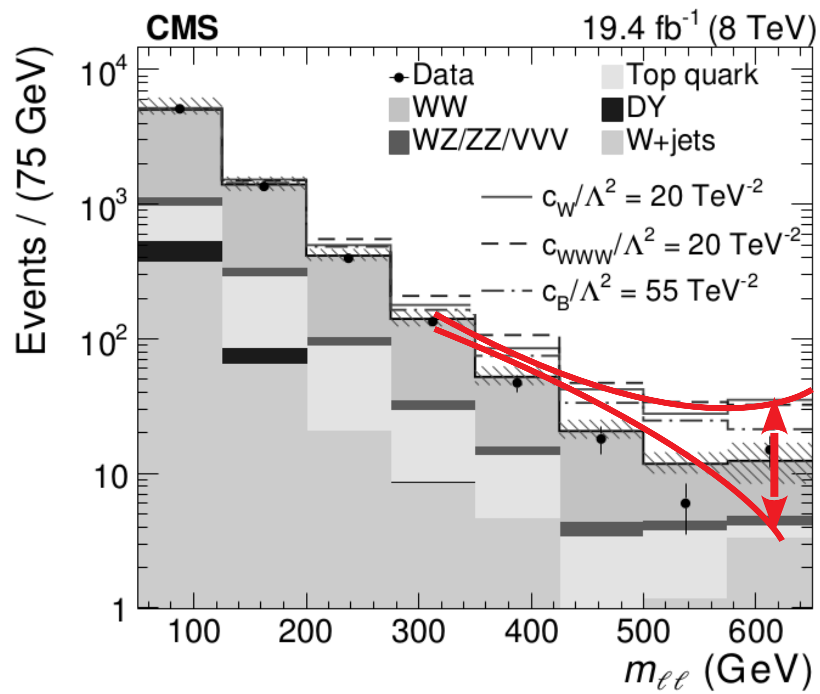
$\mathcal{M}_\gamma + \mathcal{M}$ ... $- \boxed{\frac{T_q^3}{s_W^2}}\Big)$

– Each of th ... couplings separately ... ere is no energy ... wth of

– This also m ... s that get amplified at high energies







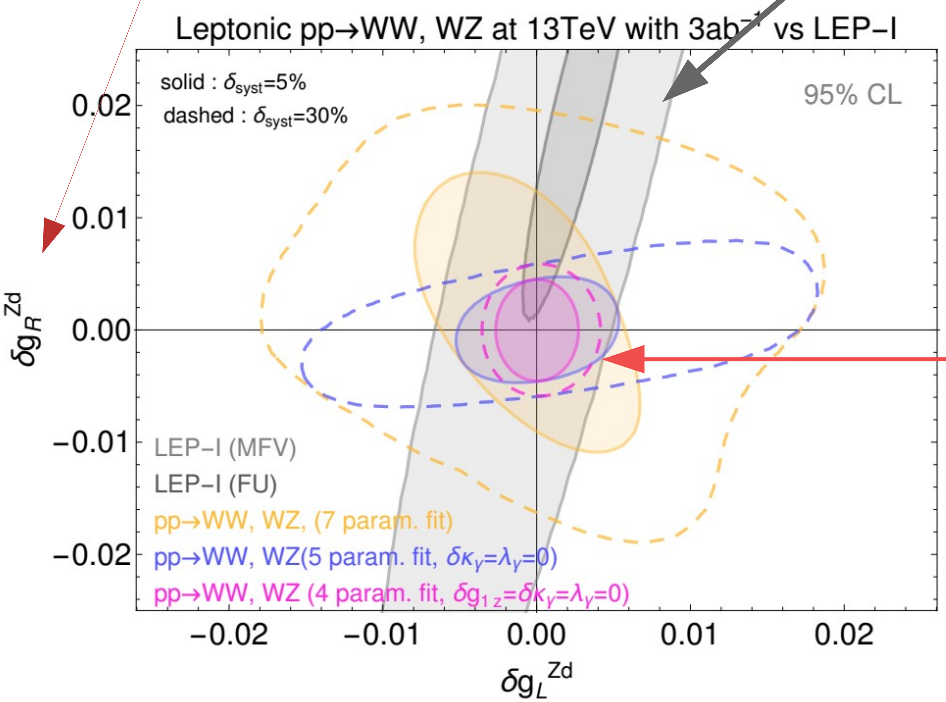
Constant shift of cross section
Limited by systematics

Effects enhanced at high energies
Limited by statistics

Grojean, Montull, MR, 1810.05149

$$\sqrt{g^2+g'^2}Z_\mu \bar{f}_R\gamma_\mu\left(-s_W^2 Q_f + \delta g_R^{Zf}\right) f_R$$

LEP, Z pole measurements

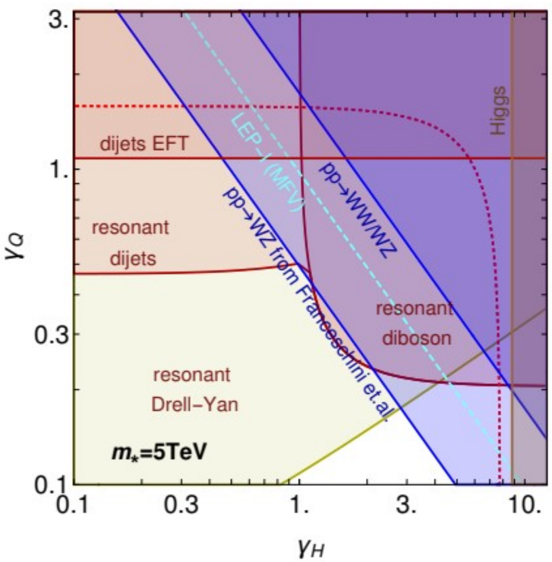


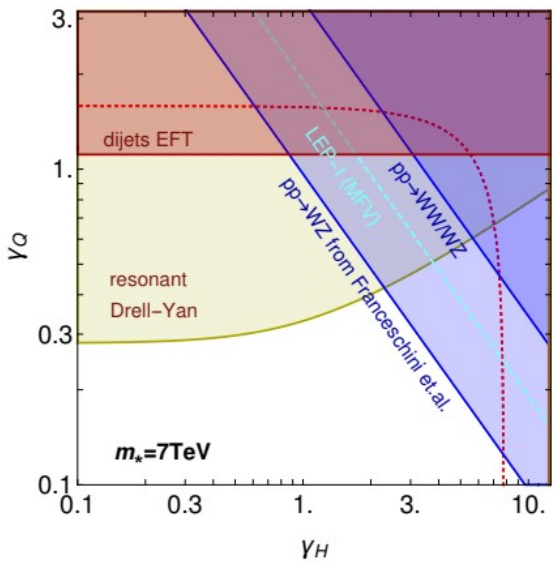
HL-LHC, diboson

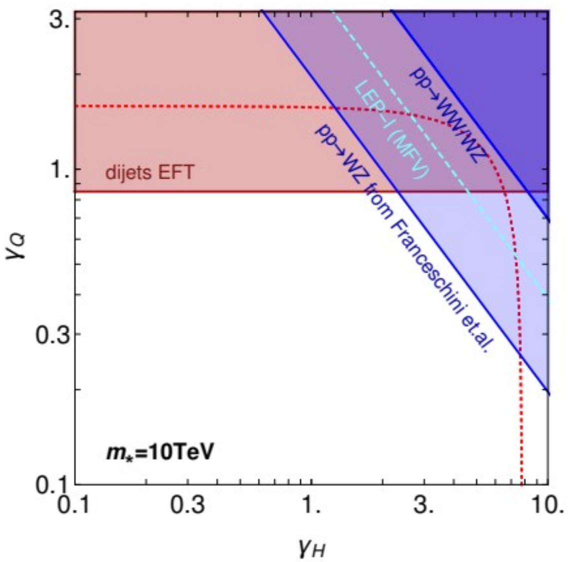
$$\sqrt{g^2+g'^2}Z_\mu \bar{f}_L\gamma_\mu\left(T_f^3-s_W^2 Q_f + \delta g_L^{Zf}\right) f_L$$

Grojean, Montull, MR, 1810.05149

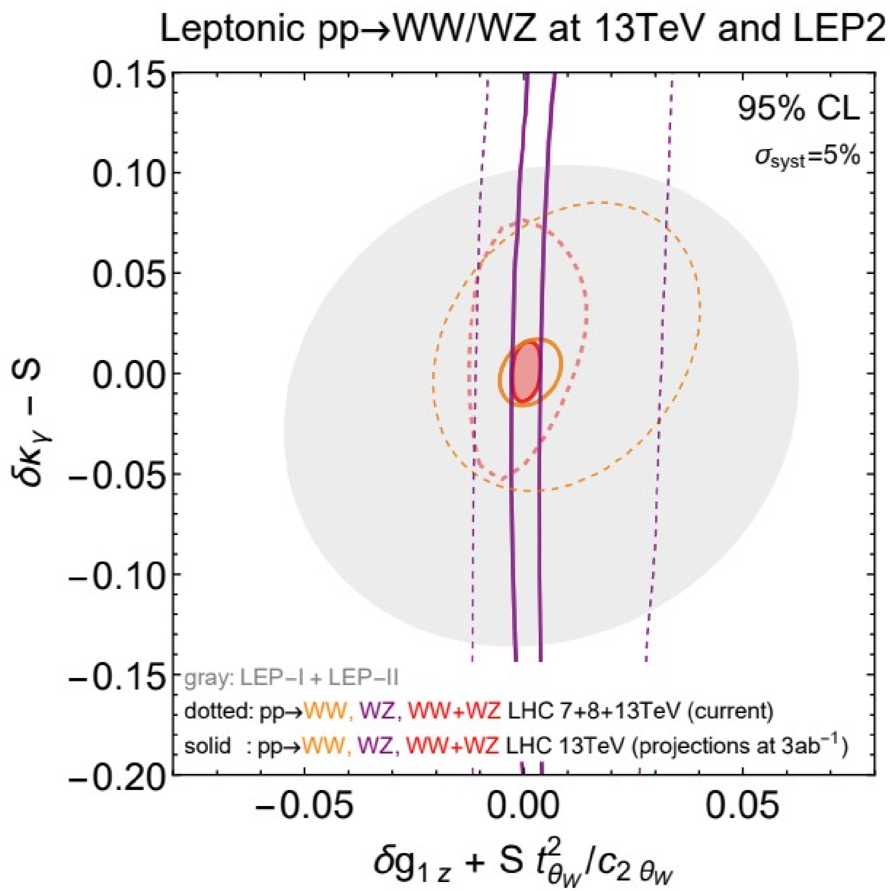
Complementarity between direct and indirect probes for an explicit model:

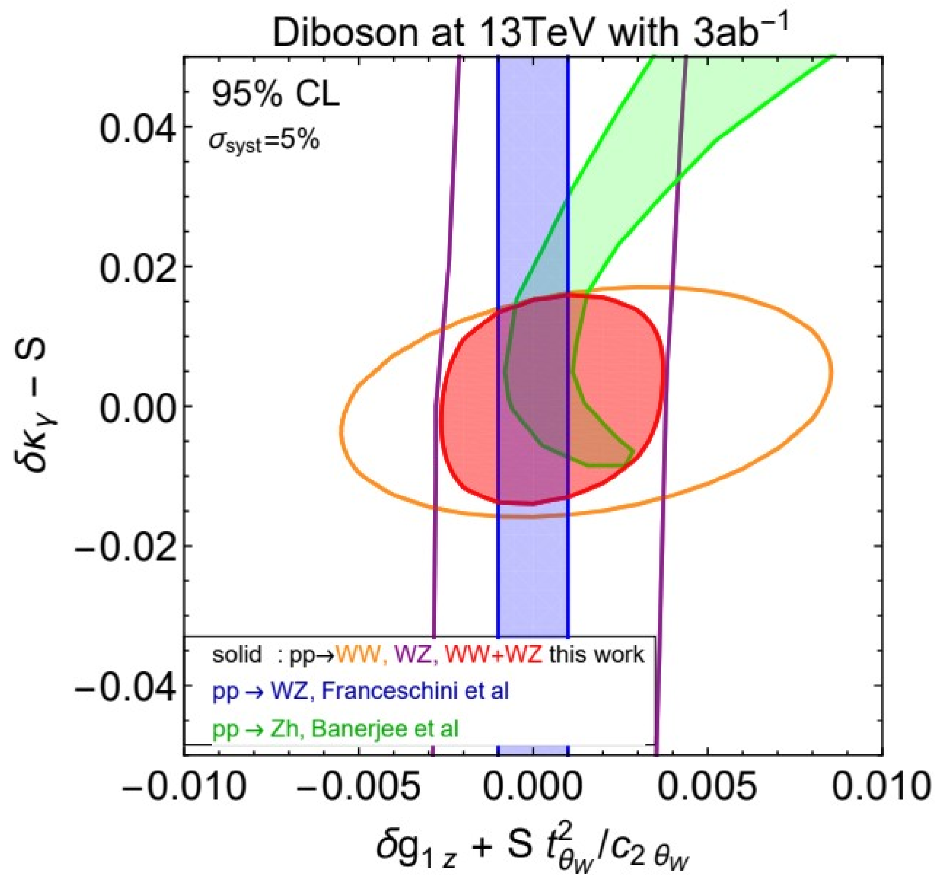




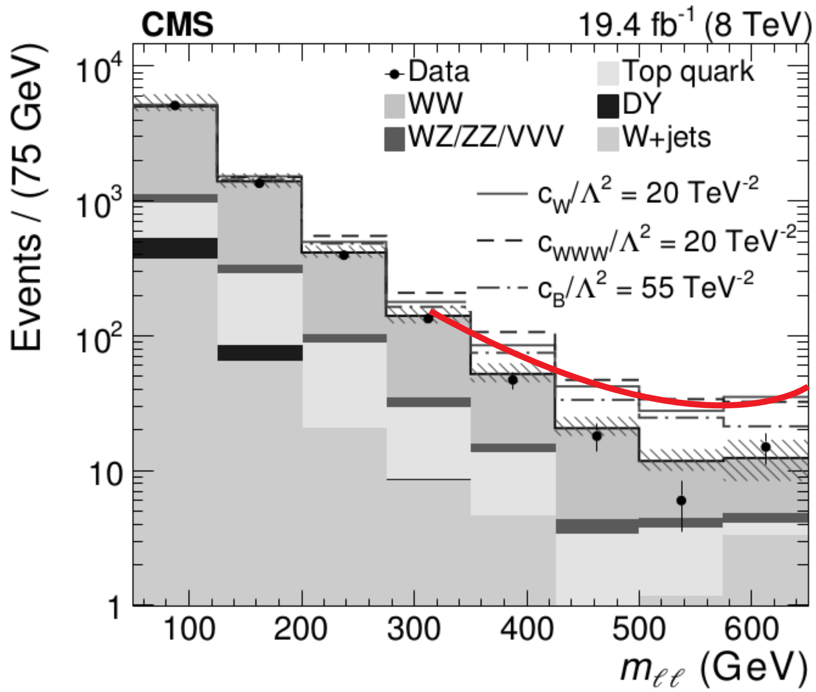


Grojean, Montull, MR, 1810.05149





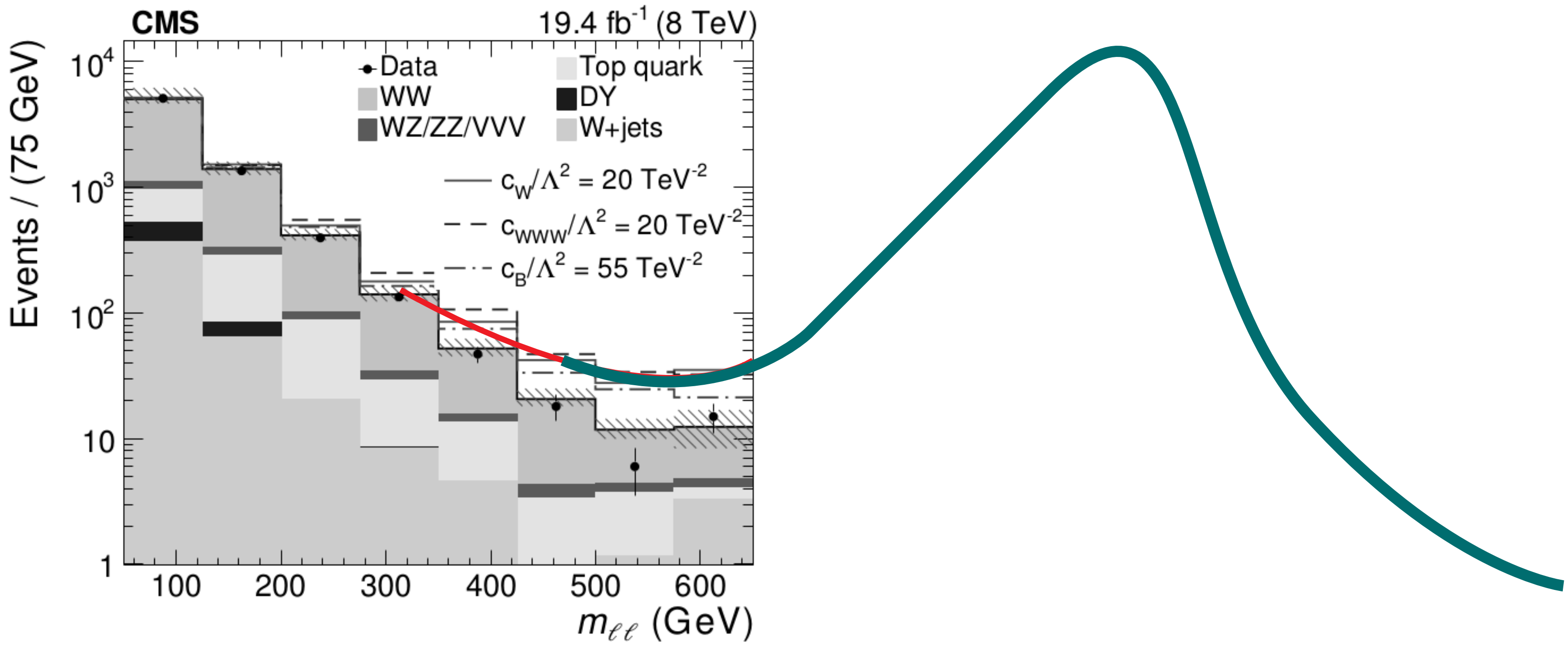
The role of precision



We look for enhancement at tails of high energy processes, and set constraints to parameters

$$\delta g_{1z} < 0.01$$

The role of precision

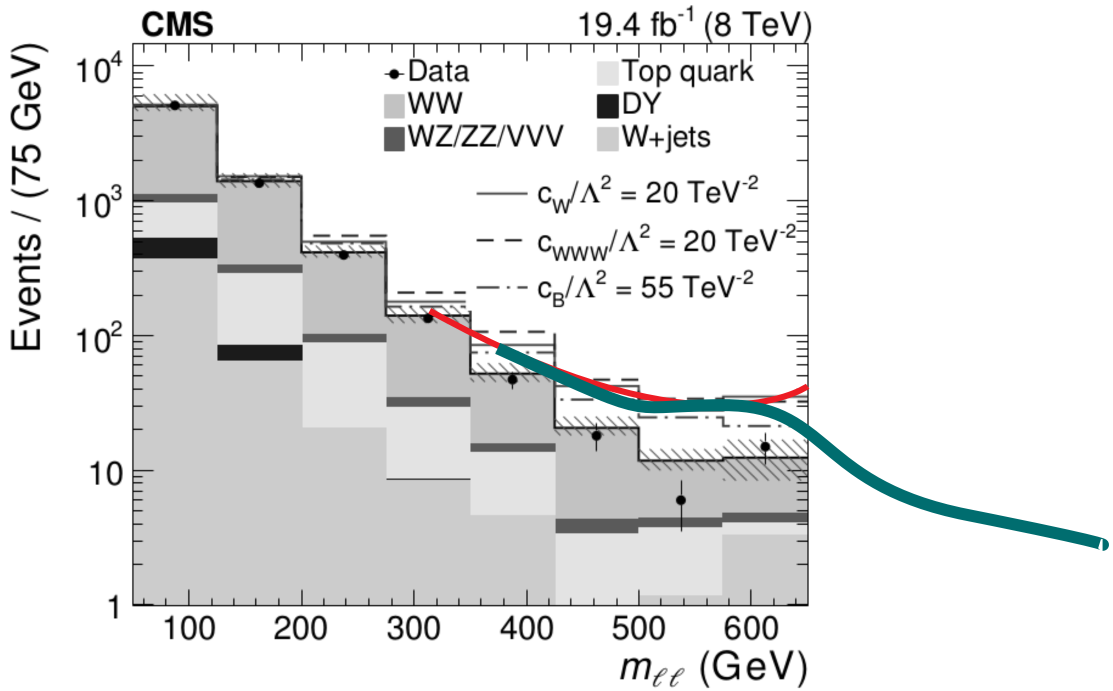


We look for enhancement at tails of high energy processes, and set constraints to parameters

$$\delta g_{1z} \sim g_\star \frac{v^2}{M_\star^2} < 0.01 \;\rightarrow\; M_\star > g_\star \cdot 3\,TeV$$

Big effects are generically well described by an EFT

The role of precision



We look for enhancement at tails of high energy processes, and set constraints to parameters

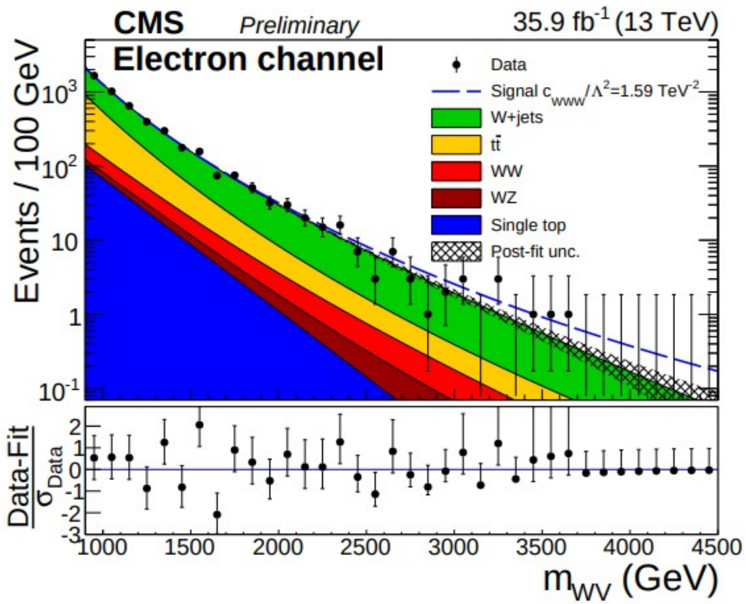
$$\delta g_{1z} \sim g_\star \frac{v^2}{M_\star^2} < 0.01 \;\rightarrow\; M_\star > g_\star \cdot 3\,TeV$$

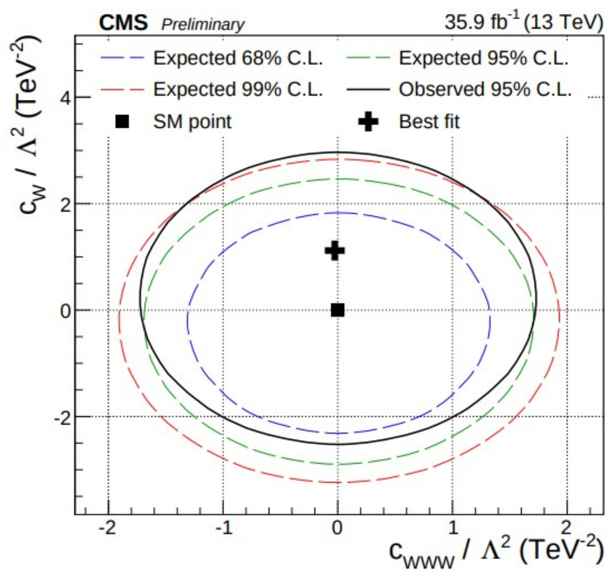
Small effects are not!

The role of precision

This effect can be important, specially in semileptonic decays:
See Chang's talk this morning!

CMS, SMP-18-008-pas



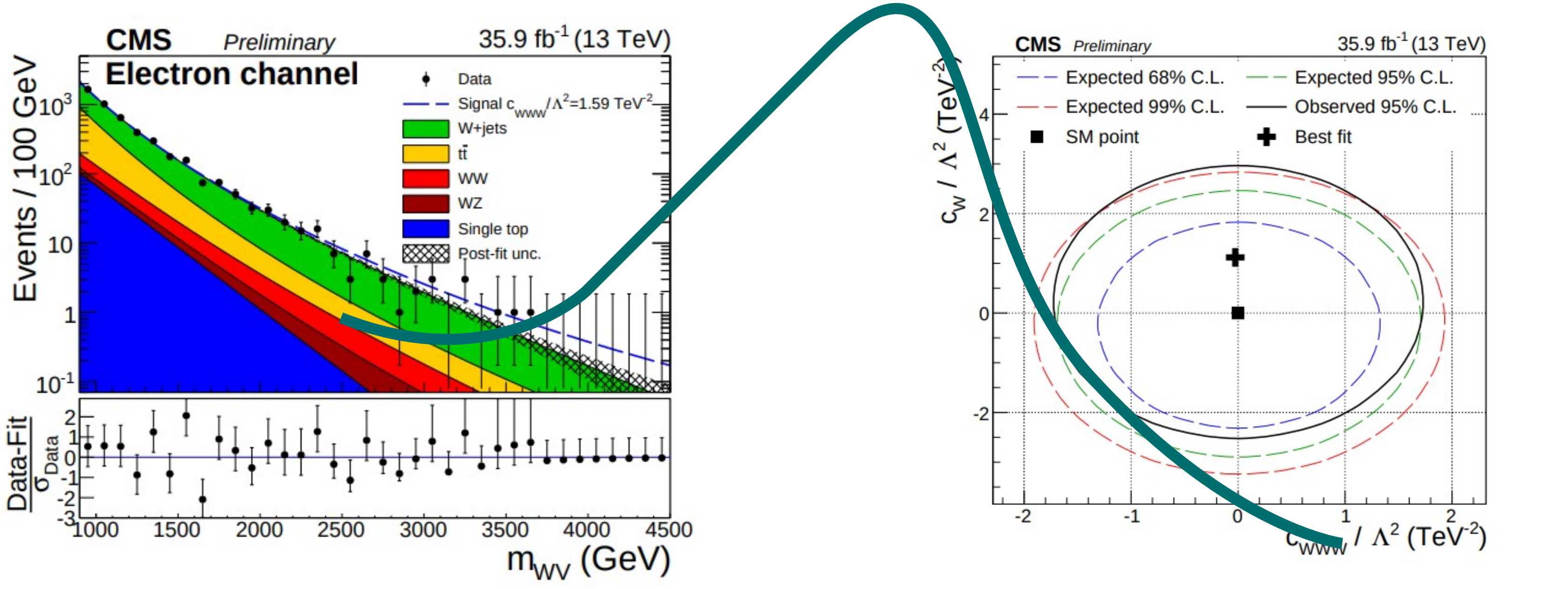


However, $c_{WWW} \sim \dfrac{g_\star^2}{M_\star^2} \lesssim \dfrac{1}{TeV^2} \oplus M_\star > 5TeV \;\rightarrow\; g_\star > 5$

The role of precision

This effect can be important, specially in semileptonic decays:
See Changs's talk this morning!

CMS, SMP-18-008-pas

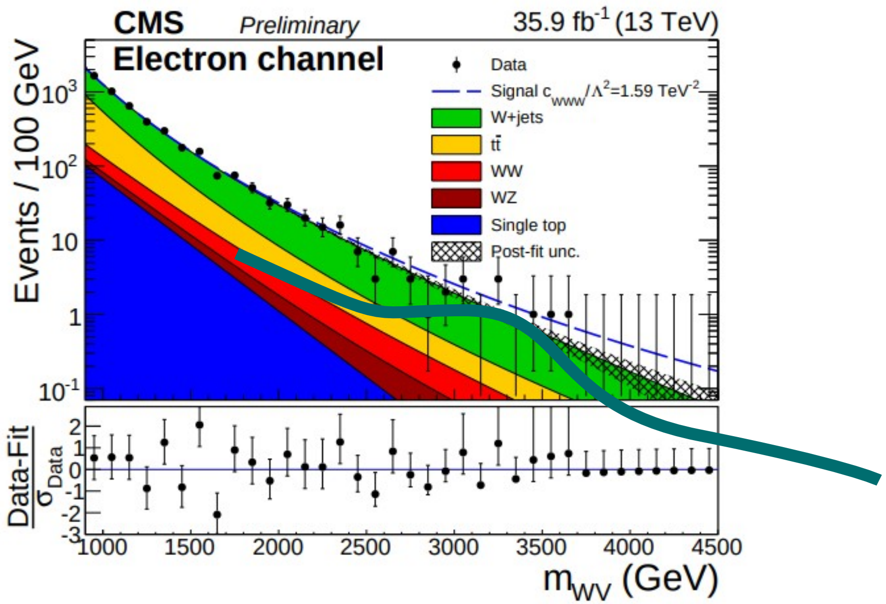


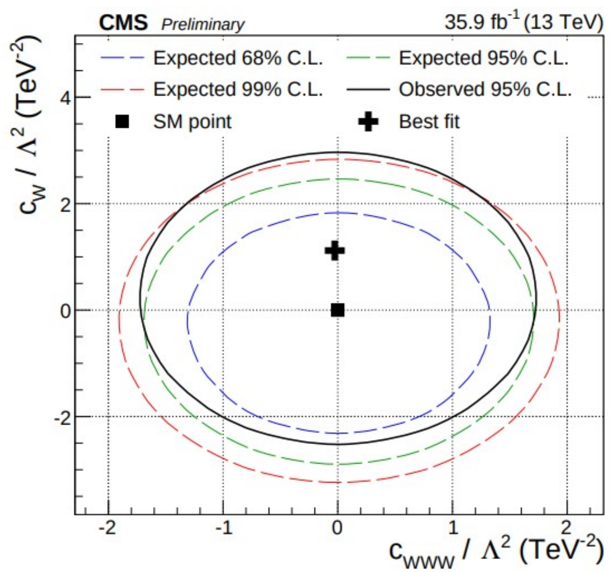
However, $c_{WWW} \sim \frac{g_\star^2}{M_\star^2} \lesssim \frac{1}{TeV^2} \oplus M_\star > 5TeV \to g_\star > 5$

The role of precision

This effect can be important, specially in semileptonic decays:
See Changs's talk this morning!

CMS, SMP-18-008-pas



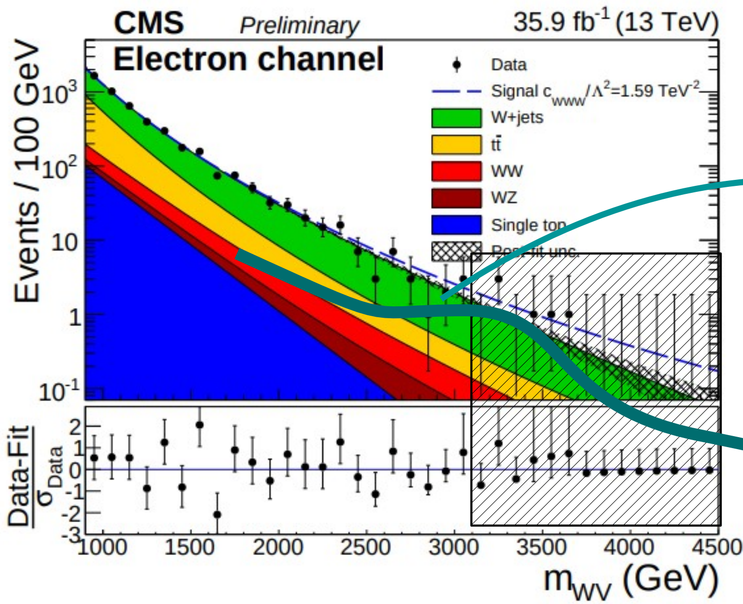


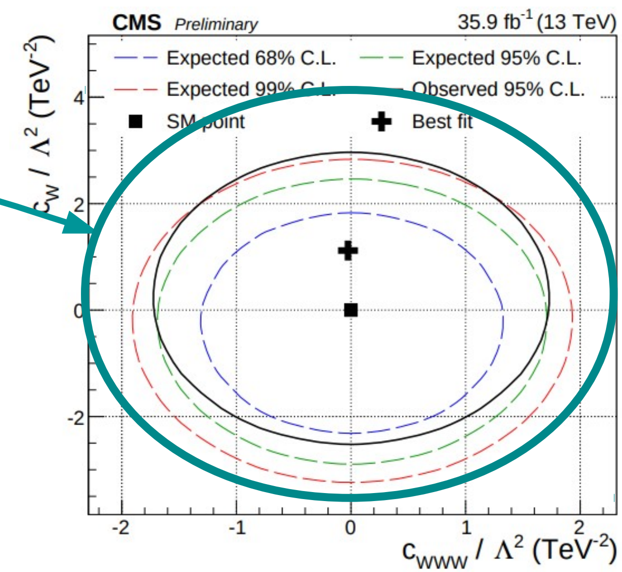
However, $c_{WWW} \sim \frac{g_\star^2}{M_\star^2} \lesssim \frac{1}{TeV^2} \oplus M_\star > 5TeV \;\to\; g_\star > 5$

The role of precision

This effect can be important, specially in semileptonic decays:
See Chang's talk this morning!

CMS, SMP-18-008-pas



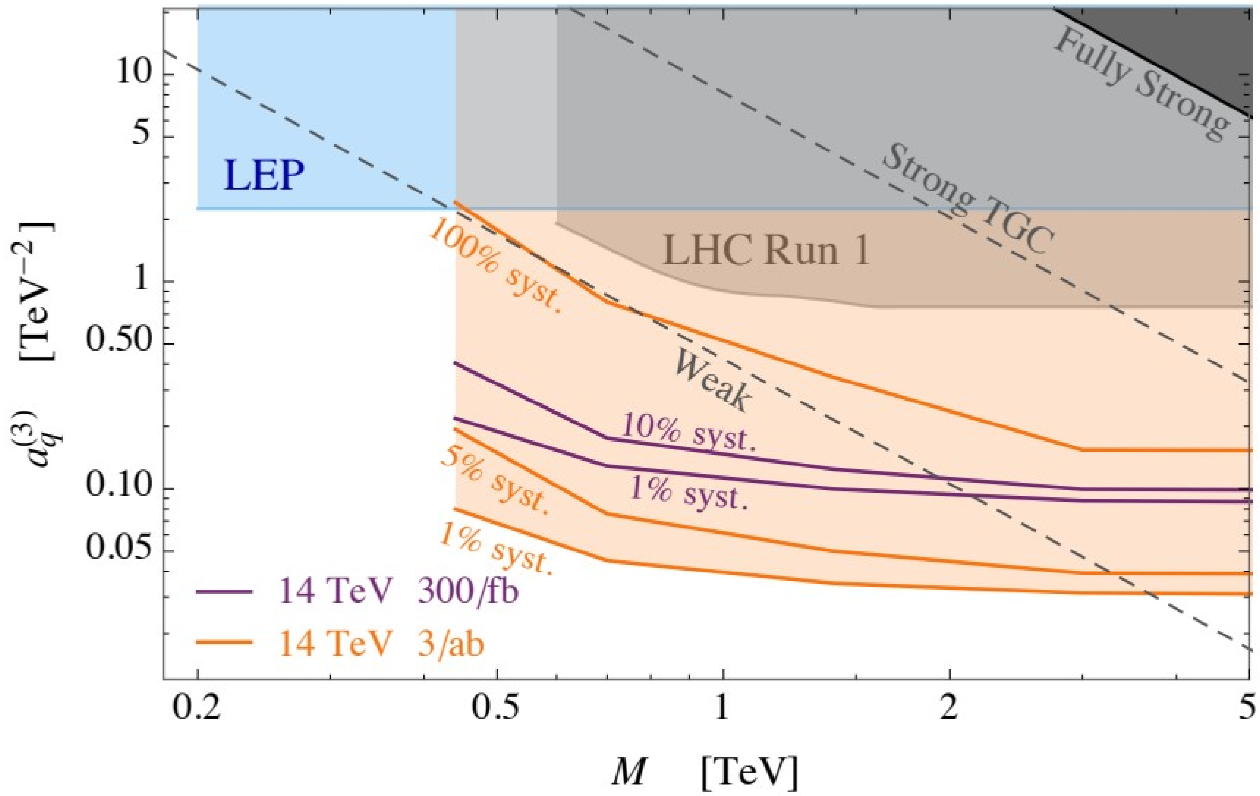


?

However, $c_{WWW} \sim \frac{g_\star^2}{M_\star^2} \lesssim \frac{1}{TeV^2} \oplus M_\star > 5TeV \;\rightarrow\; g_\star > 5$

The role of precision

R. Franceschini, G. Panico, A. Pomarol, F. Riva, A. Wulzer, 1712.01310

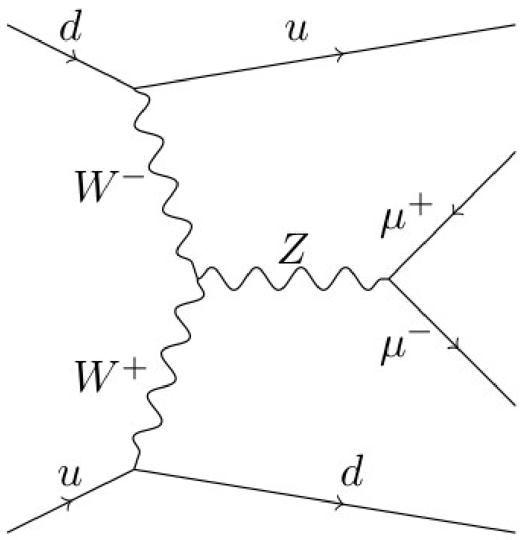


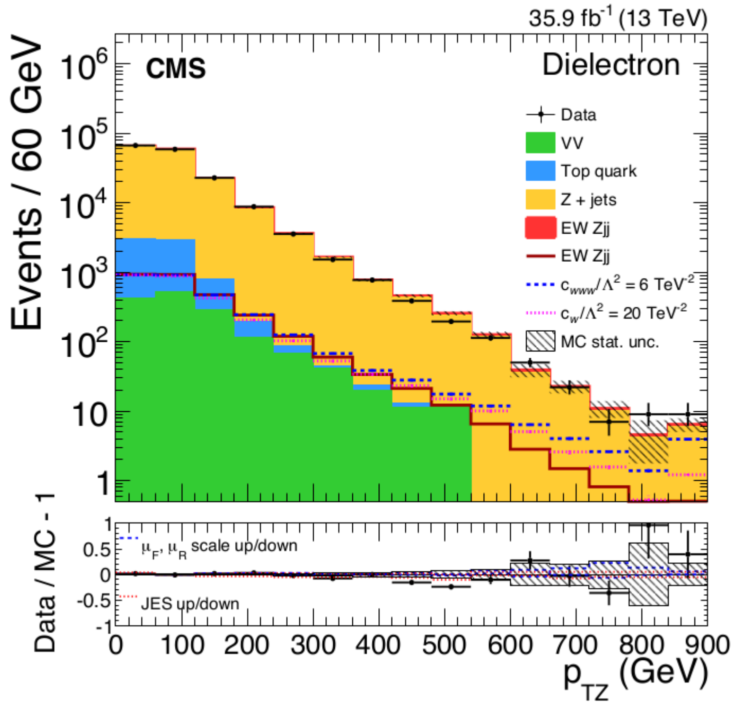
Range of EFT analysis can be enhanced by considering events only below given energy, so the analysis covers a broader class of theories

Electroweak Production of
1
electroweak bosons

EW bosons can be produced by VBF

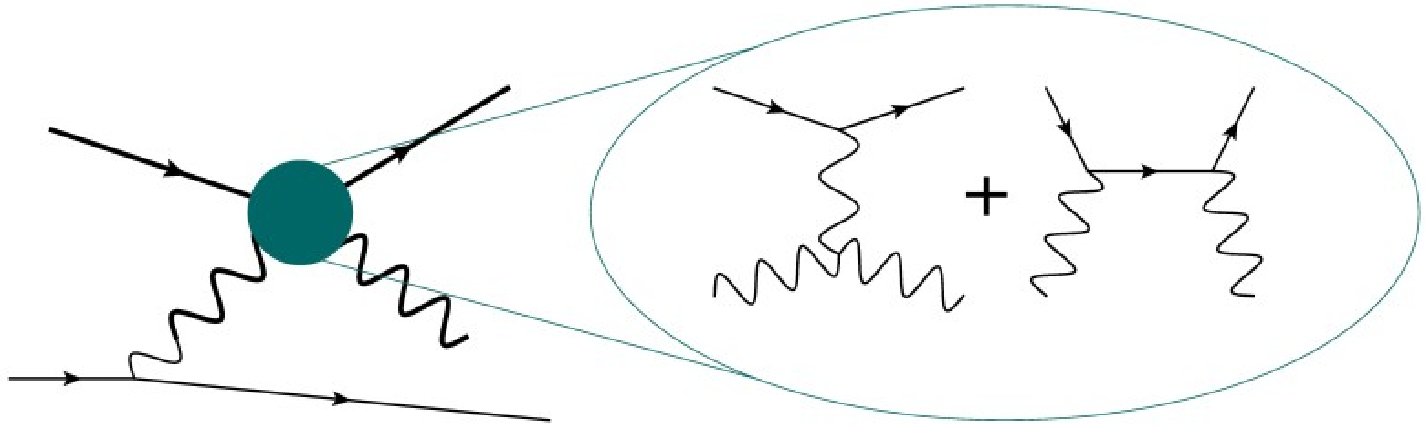
CMS-SMP-16-018





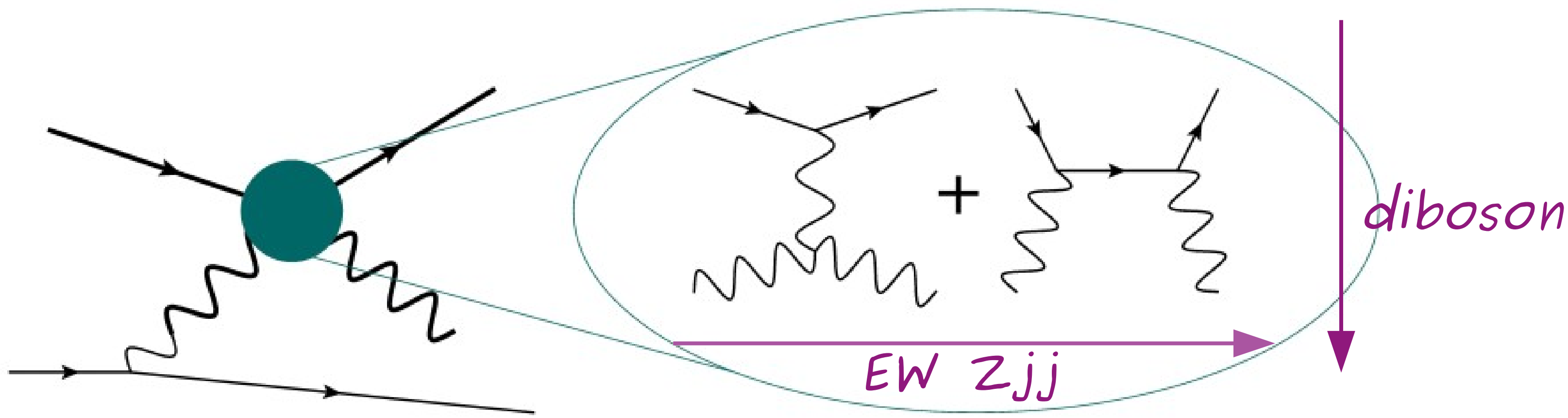
If TGC is deviated from the SM, there is a useful way to understand this process:

G. Durieux, M. Montull, MR, in progress

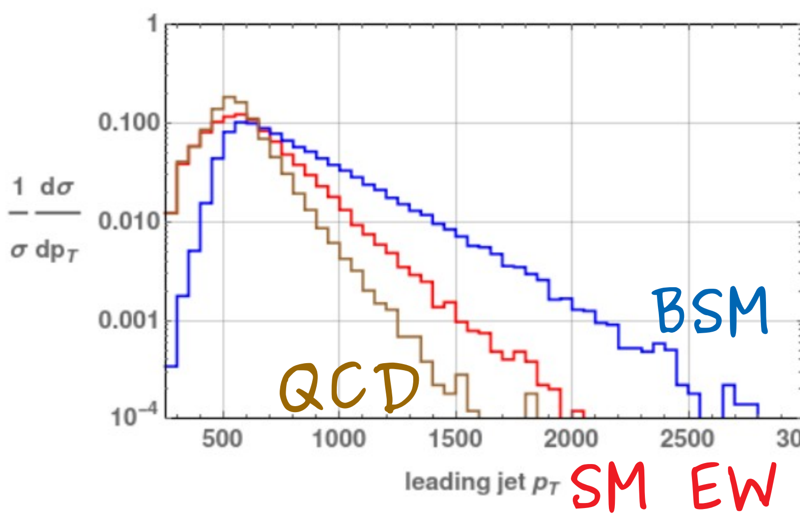


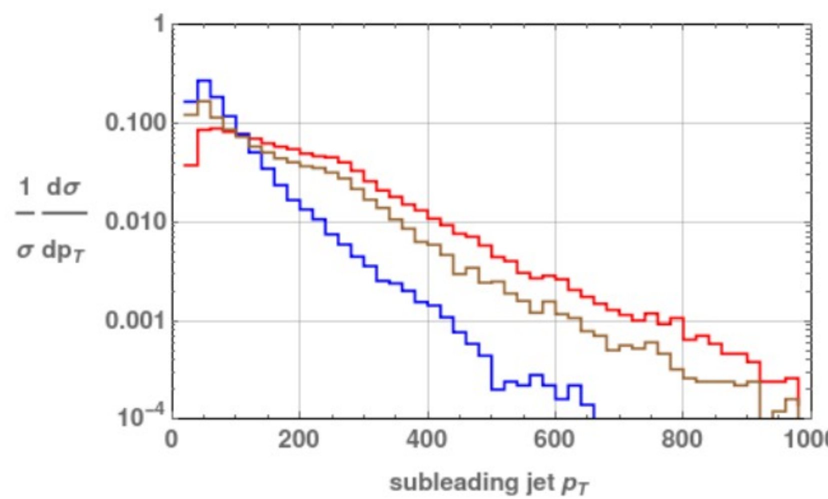
The process has two scales: a soft scale and a hard scale

G. Durieux, M. Montull, MR, in progress



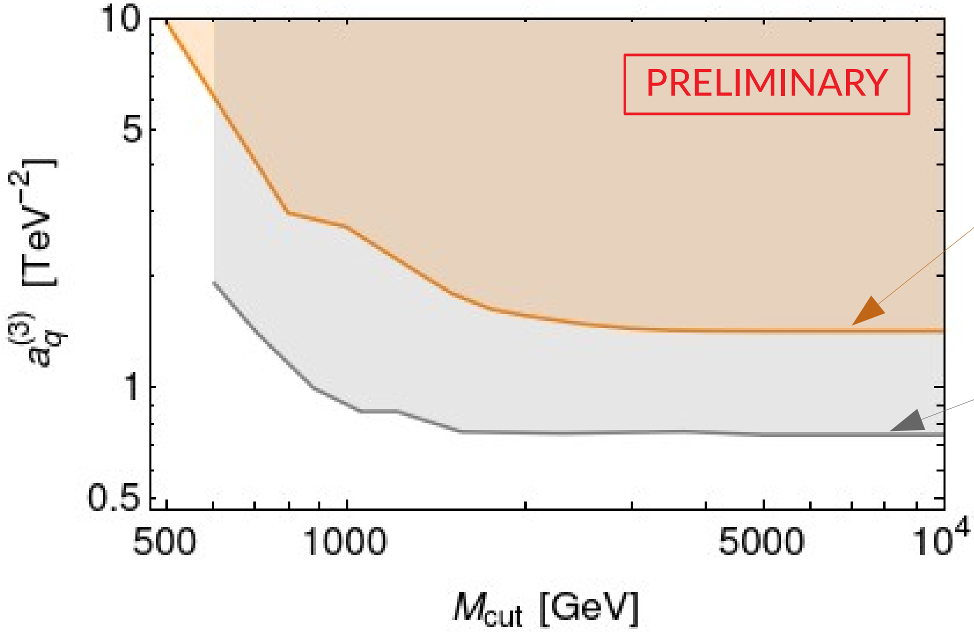
The process has two scales: a soft scale and a hard scale
So it factorizes as a soft radiation times *t-channel diboson*





Current constraints/projections

G. Durieux, M. Montull, MR, in progress



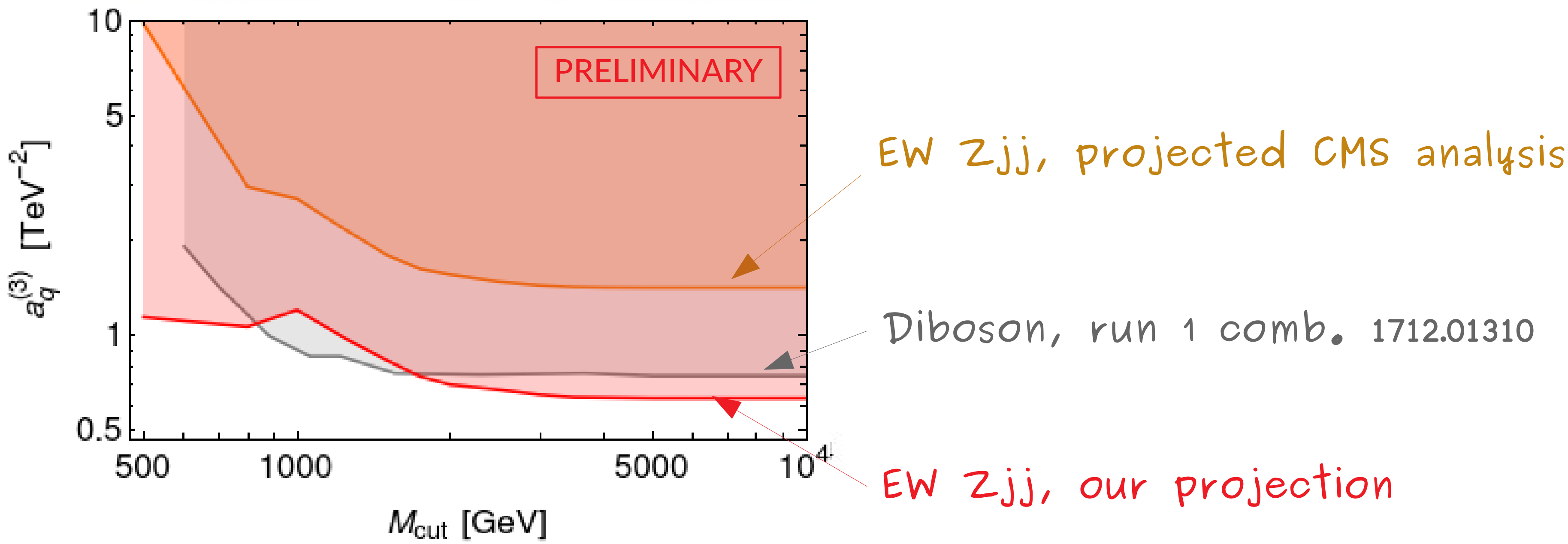
EW Zjj, projected CMS analysis

Diboson, run 1 comb. 1712.01310

EFT validity controlled by $M_{cut}^2 = -t_{2\to 2} = -(p^{in,jet} - p^{fin,jet})^2$

G. Durieux, M. Montull, MR, in progress

Current constraints/projections



Using jet imbalance variable enhances sensitivity and EFT coverage

$$\mathcal{I}p_{T,jj} = \frac{|p_{T,j_1} - p_{T,j_2}|}{p_{T,j_1} + p_{T,j_2}}$$

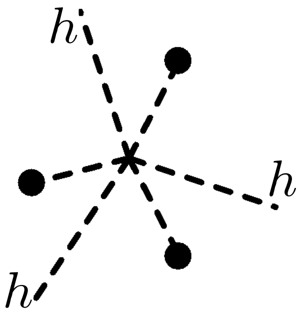
Z polarization further enhances sensitivity, BDT approach under study

Electroweak Production of
3
electroweak bosons

B. Henning, D. Lombardo, MR, F. Riva, 1812.09299

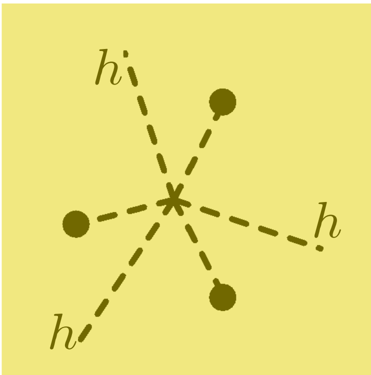
Higgs self-coupling

$$\frac{1}{\Lambda^2}|H|^6 \supset \frac{1}{\Lambda^2}(\,v^3 h^3 \qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad)$$

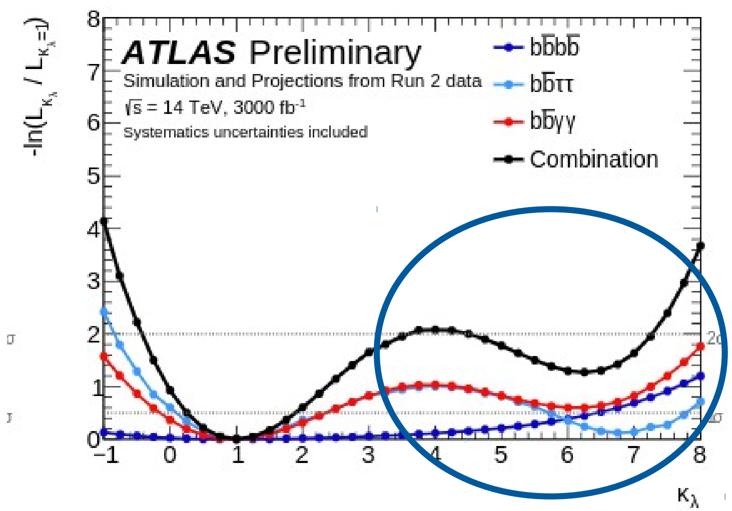


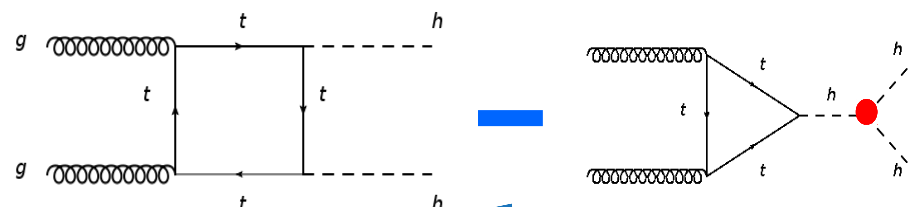
Higgs self-coupling

$$\frac{1}{\Lambda^2}|H|^6 \supset \frac{1}{\Lambda^2}(v^3h^3 \qquad\qquad)$$



$$\frac{\sigma(pp\to hh)}{\sigma(pp\to h)} \sim 10^{-3} \qquad \mathrm{Br}(h\to b\bar{b})\times \mathrm{Br}(h\to\gamma\gamma)\sim 60\%\times 0.1\%$$





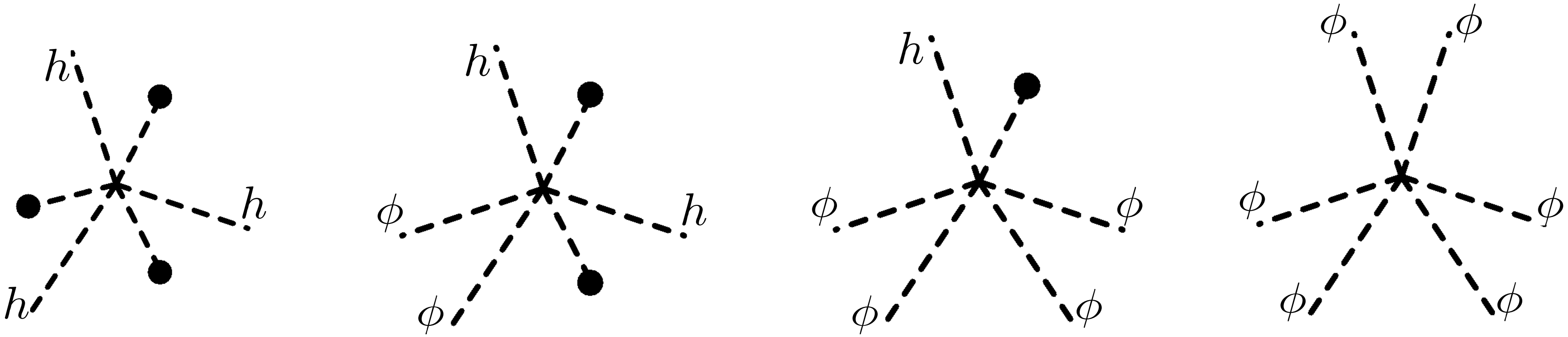
HL-LHC @ 3 ab^{-1}, 95% CL

$$\kappa_\lambda \in\sim [-0.5, \cancel{3}]\ ?$$

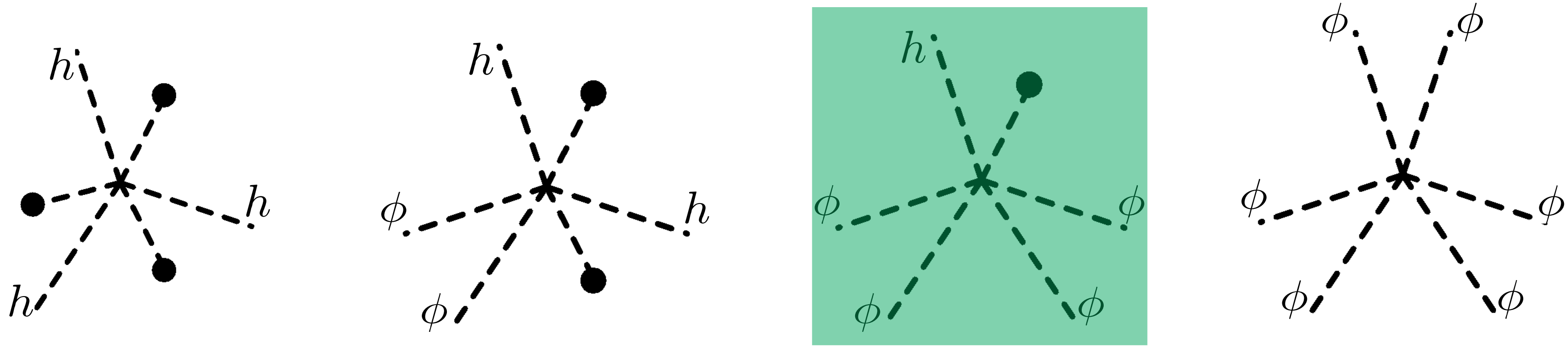
7!

Higgs self-coupling

$$\frac{1}{\Lambda^2}|H|^6 \supset \frac{1}{\Lambda^2}\left(v^3h^3 + 3v^2h^2\phi^2 + 3vh\phi^4 + \phi^6 + \ldots \right)$$



$$\frac{1}{\Lambda^2}|H|^6 \supset \frac{1}{\Lambda^2}\left(v^3h^3 + 3v^2h^2\phi^2 + \boxed{3vh\phi^4} + \phi^6 + \ldots\right)$$



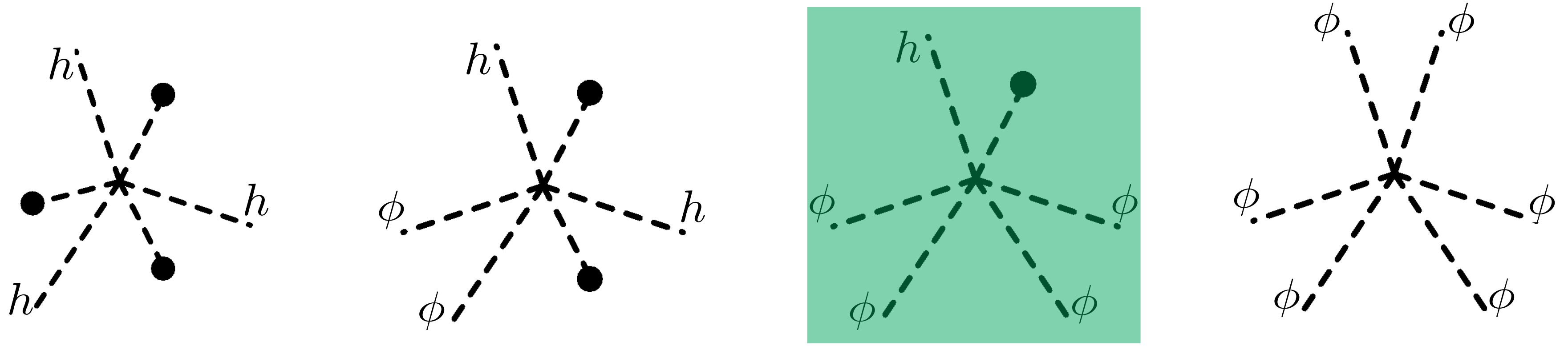
$$\frac{\mathcal{A}(\phi^+\phi^-\phi^+\phi^-h)}{\mathcal{A}(\phi^+\phi^-\phi^+\phi^-h)_{SM}} \sim \frac{c_6 v/\Lambda^2}{v/E^2} \sim c_6\frac{E^2}{\Lambda^2}$$

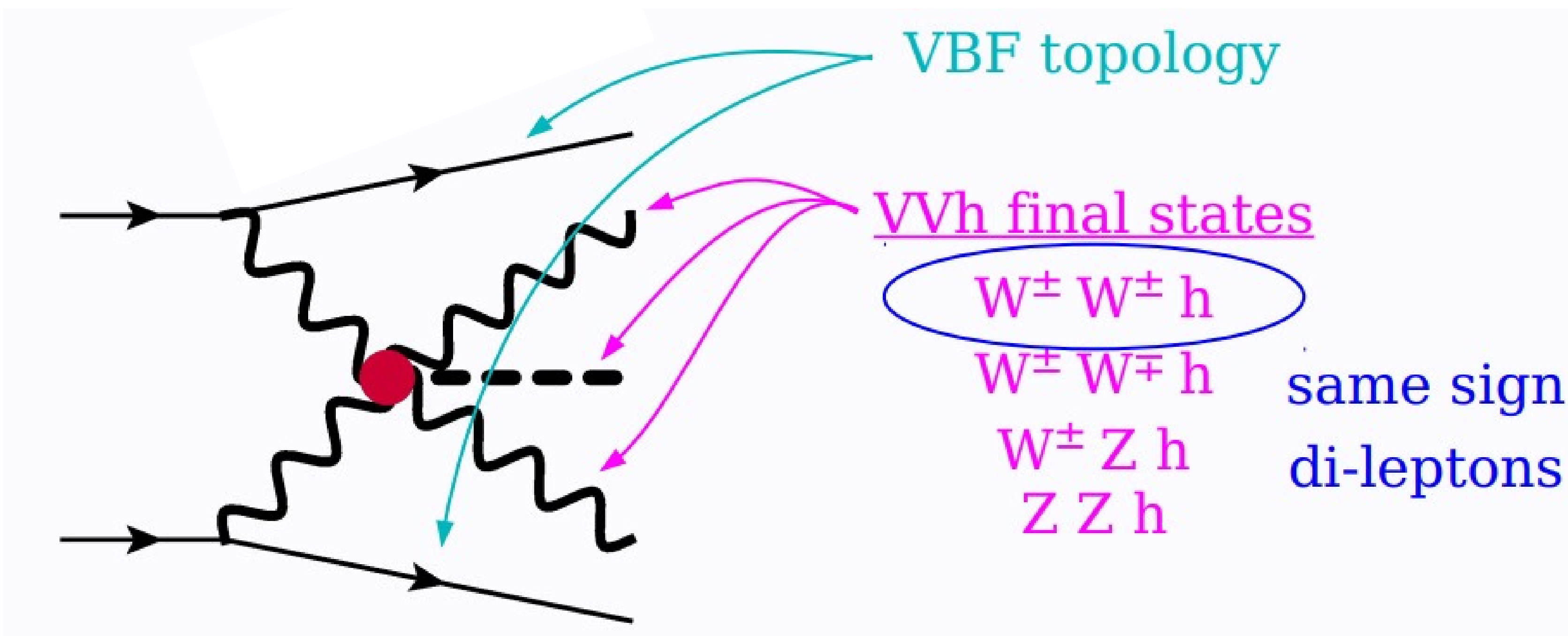
but,

$$\frac{\mathcal{A}(\phi^+\phi^-\phi^+\phi^-h)}{\mathcal{A}(W_T^+W_T^-W_T^+\phi^-h)_{SM}} \sim \frac{c_6 v/\Lambda^2}{p\cdot\epsilon/E^2} \sim c_6\frac{vE}{\Lambda^2}$$

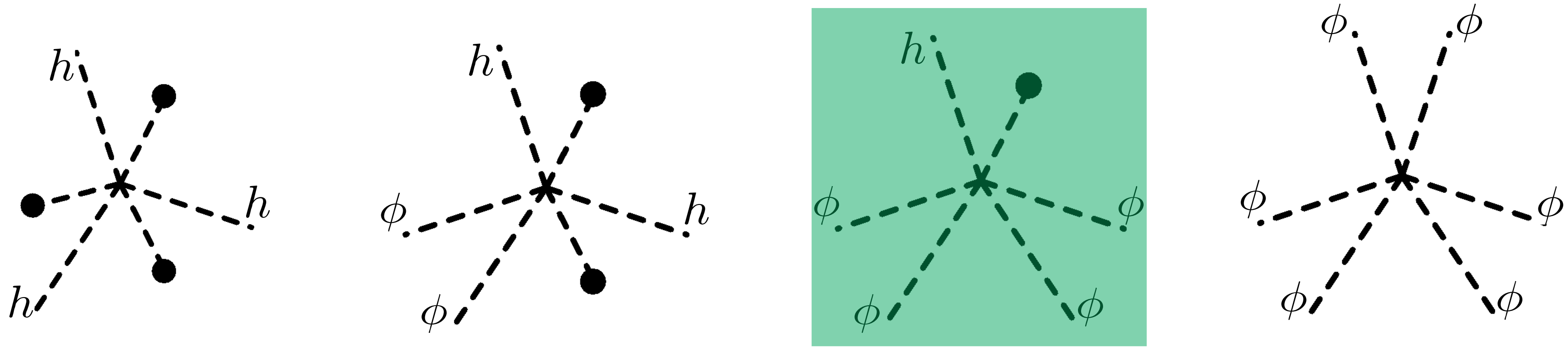
Transverse modes scale as 1/E and become an important background

$$\frac{1}{\Lambda^2}|H|^6 \supset \frac{1}{\Lambda^2}\left(v^3h^3 + 3v^2h^2\phi^2 + \boxed{3vh\phi^4} + \phi^6 + \dots \right)$$



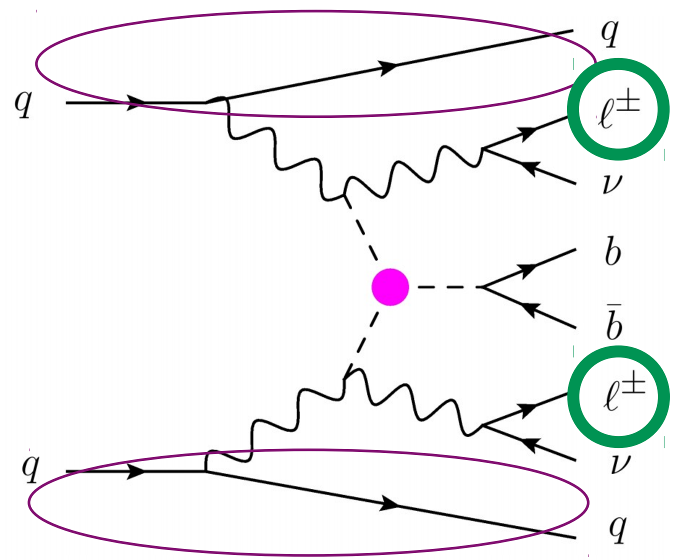


$$\frac{1}{\Lambda^2}|H|^6 \supset \frac{1}{\Lambda^2}\left(v^3h^3 + 3v^2h^2\phi^2 + \boxed{3vh\phi^4} + \phi^6 + \ldots\right)$$

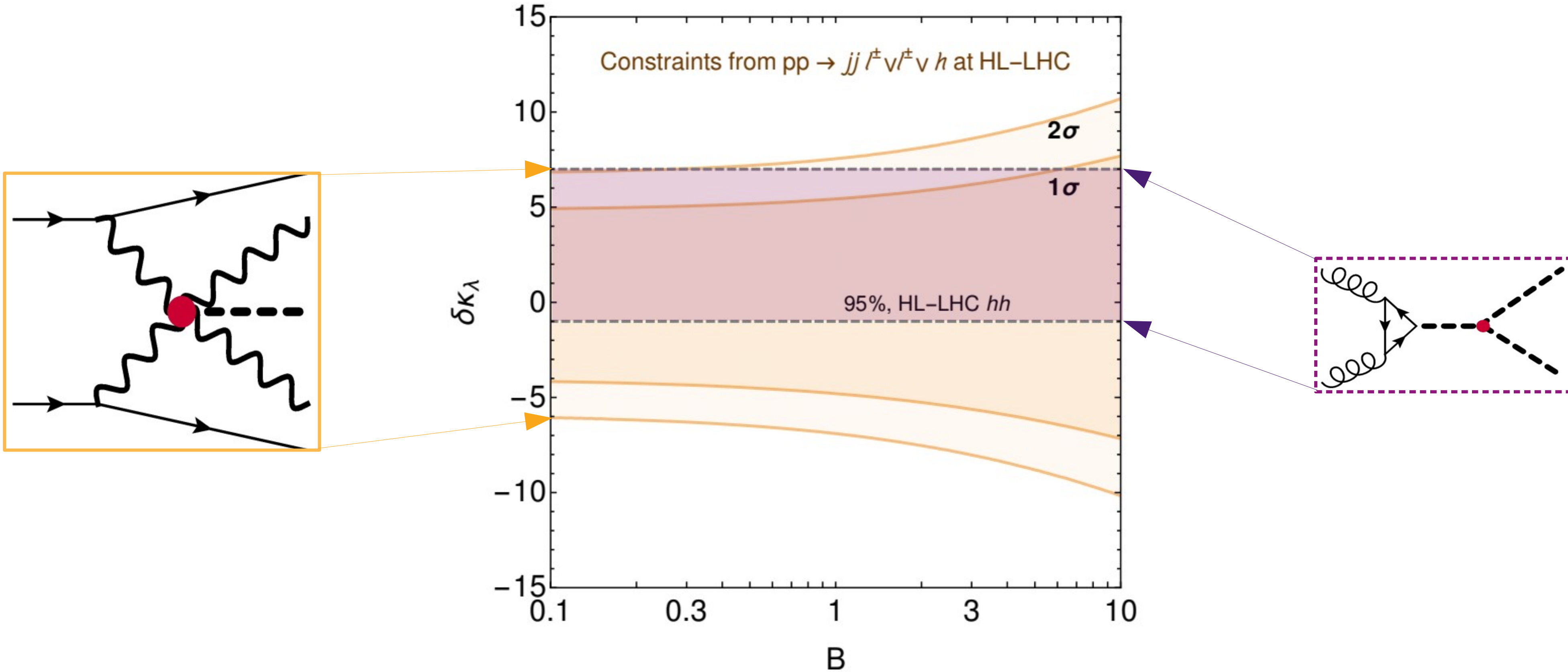


Signal enhanced only with a single power of energy,
but extremelly attractive and clean process experimentally!

VBF topology



Same sign leptons!



- 50-ish events in the SM
- Irreducible background negligible
- Background from ttjj with lepton misidentification under control
- Backgorund from fake leptons is potentially the dominant one.
  We parametrize it with #back = B x #signal.
- Rough cut-and-count analysis gives competitive results with double higgs production

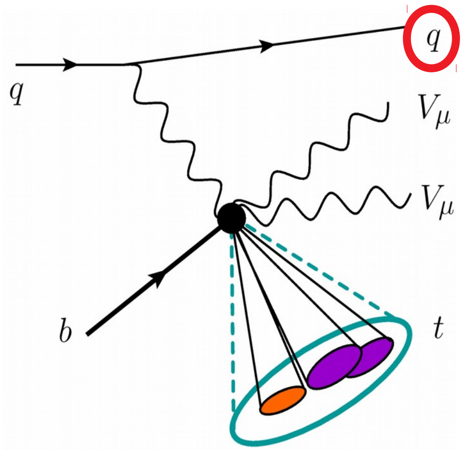
Since it is a top parallel...

Top Yukawa

$$\mathcal{L} \supset \frac{c_t}{\Lambda^2} y_t |H|^2 \bar{q}_L H t_R$$

$$\phi^+\phi^- \qquad b_L \phi^+ t_R$$

$|\eta_j| > 2.5, p_T^j > 30\mathrm{GeV}, E_j > 300\mathrm{GeV}$



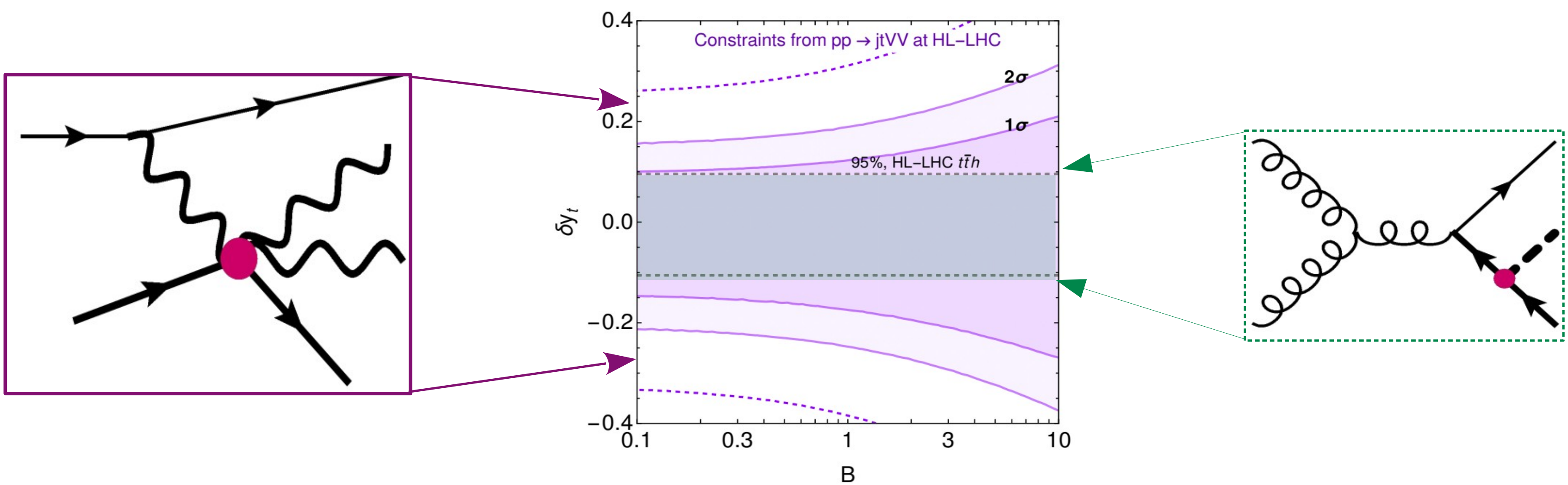
events @ HL-LHC

Process	0ℓ	1ℓ	$\ell^\pm\ell^\mp$	$\ell^\pm\ell^\pm$	$3\ell(4\ell)$
$W^\pm W^\mp$	3449/567	1724/283	216/35	-	-
$W^\pm W^\pm$	2850/398	1425/199	-	178/25	-
$W^\pm Z$	3860/632	965/158	273/45	-	68/11
ZZ	2484/364	-	351/49	-	(12/2)

$p_T^t > 250$ GeV / $p_T^t > 500$ GeV

small background

Large background from ttjj, but manageable.
Going to larger top pT's possible



Conclusions

Deviations from SM couplings are not harmless, they induce
Energy growth in some process

This can be used in our favor in hadronic machines to develop
a precision program, but beaware of validity and energies involved

Many physics yet to be studied from both theoretical and
experimental sides

Conclusions

Deviations from SM couplings are not harmless, they induce
Energy growth in some process

This can be used in our favor in hadronic machines to develop
a precision program, but beaware of validity and energies involved

Many physics yet to be studied from both theoretical and
experimental sides

Thank you