Lessons learned from LHC data

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January 2021

Personal and biased

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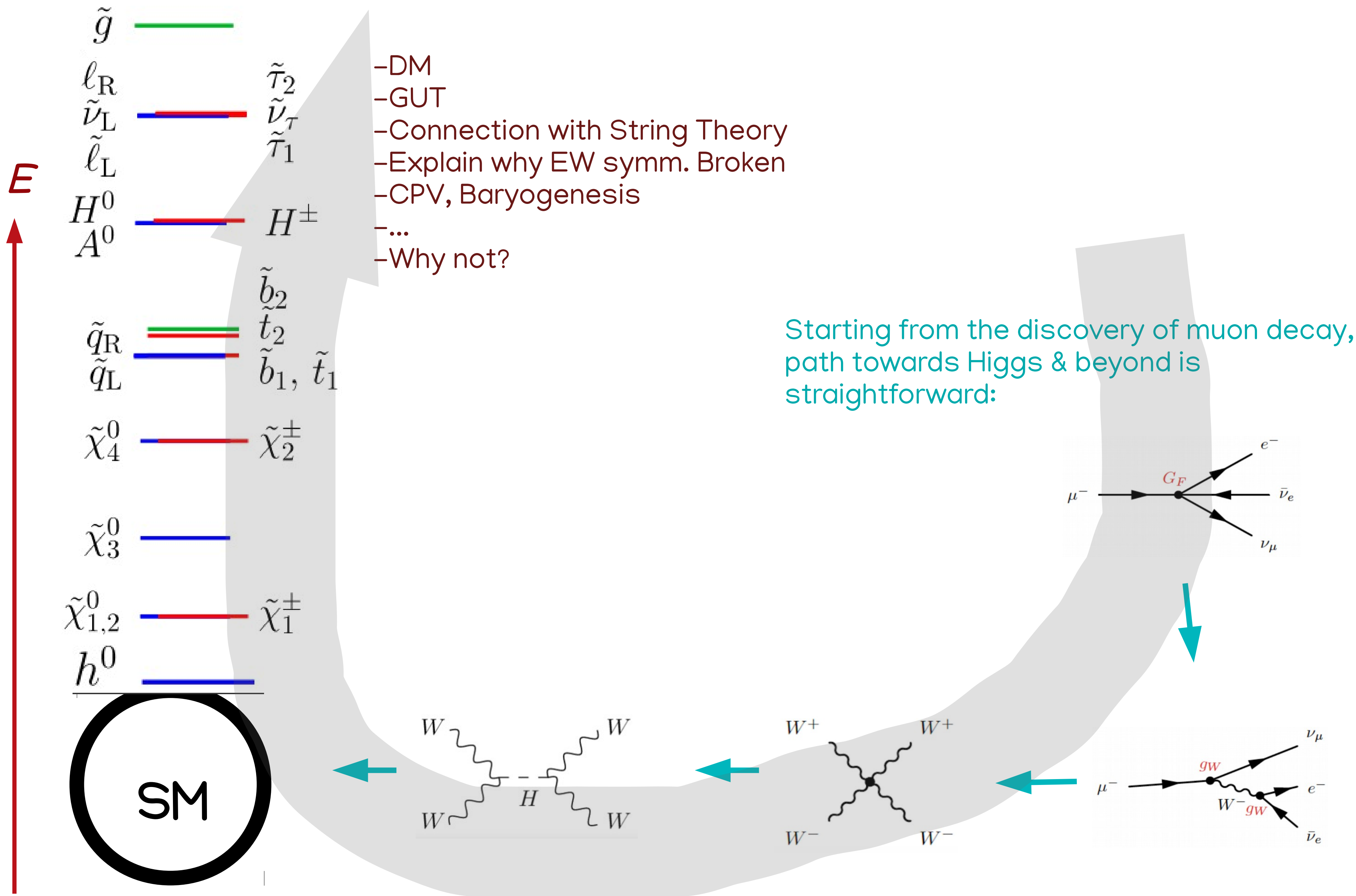
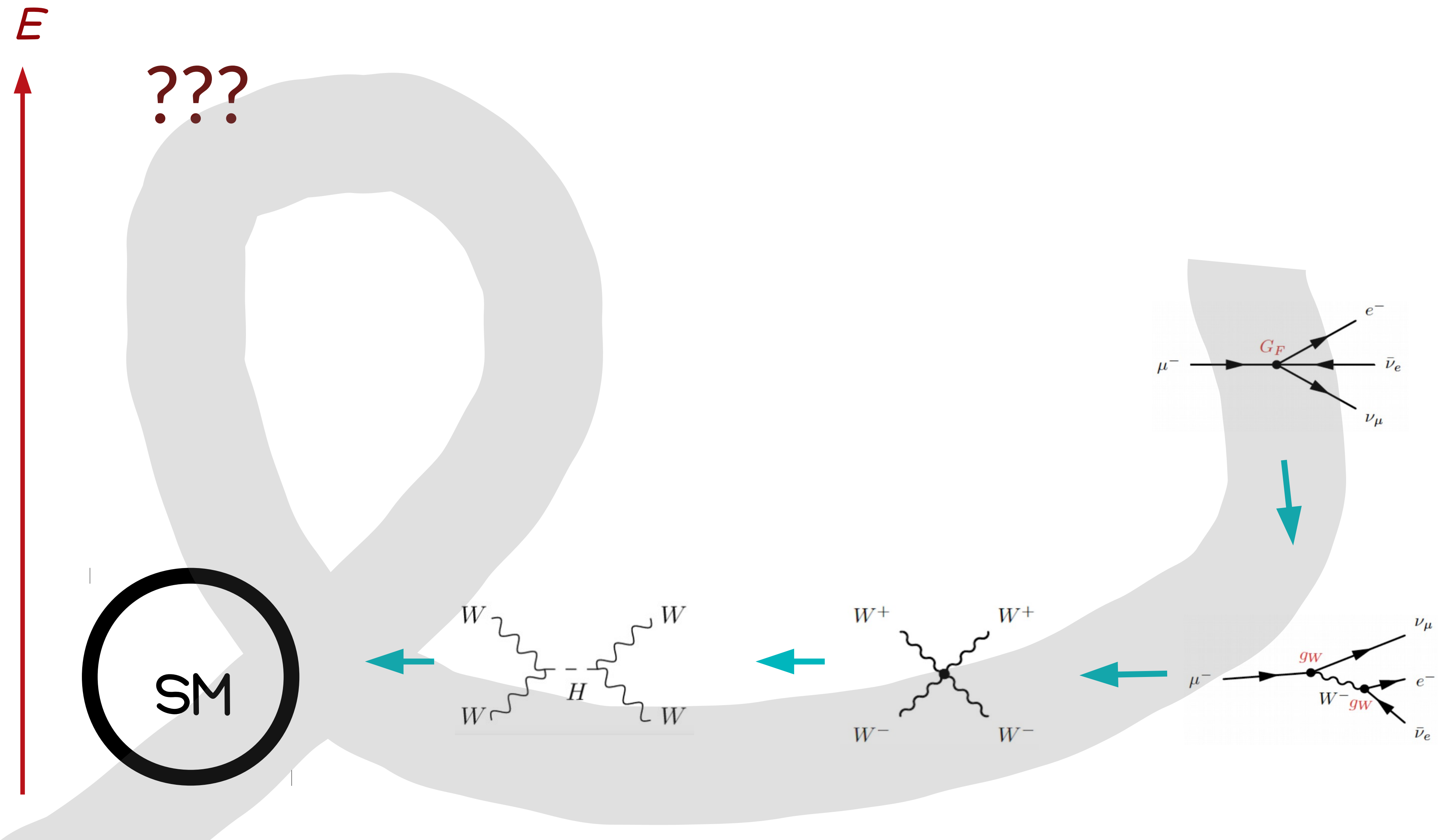
XXth Century particle physics from a XXIst Century perspective:



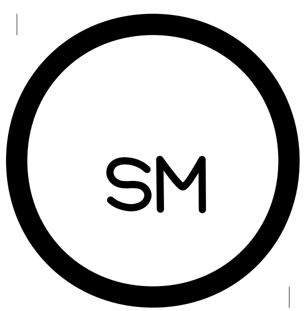


E
???
SM
W
W
H
W
W
W+
W+
W−
W−
μ−
gW
W−
gW
νμ
e−
ν̄e
μ−
GF
e−
ν̄e
νμ

$$\mathcal{L}\,?$$

E

Particle Physics is back to the origin, is again the exploration of the unknown.

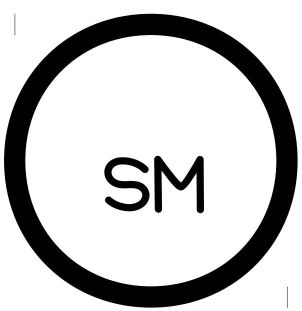


$$\mathcal{L} = \mathcal{L}_{\rm SM}$$

$$\mathcal{L}\,?$$

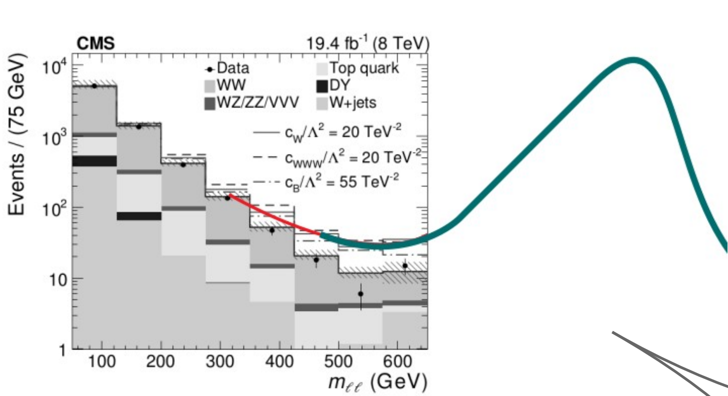
$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{c_i}{\Lambda}\mathcal{O}_i$$

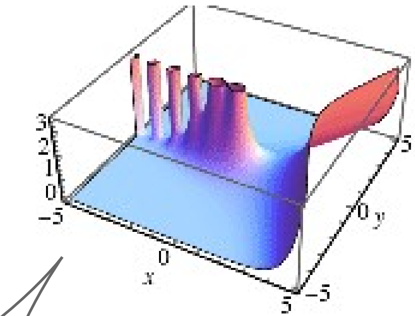
EFT operators encode information
about the heavy dynamics,
and tells us in which way
the SM is deformed.



$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}}$$

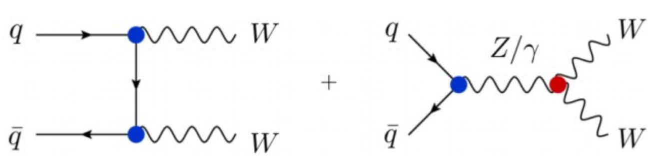
SM deformations mean an energy growth in some process





Pathological high energy behaviour

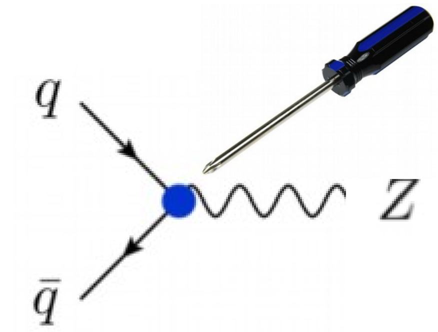
$$(\bar{q}\gamma_\mu q)(H^\dagger \overleftrightarrow{D}_\mu H),$$

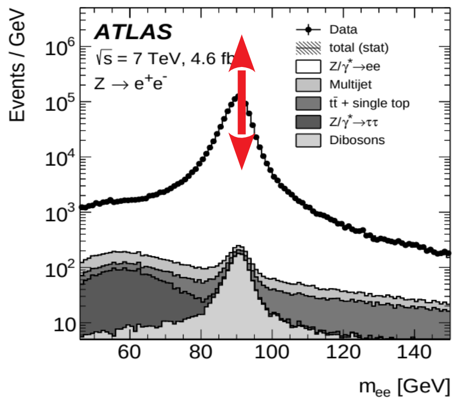


$$i\mathcal{A}(q_i^- \bar{q}_j^+ V^A V^B) = -i\frac{\langle 2|\not{p}_3 - \not{p}_4|1]}{2m_V^2}\left(\sum_{F_I}(g_L^{iF_IA}g_L^{jF_IB} - g_L^{jF_IA}g_L^{iF_IB}) - i\sum_{V_I} f^{V_I 34} g_L^{ijV_I}\right)$$

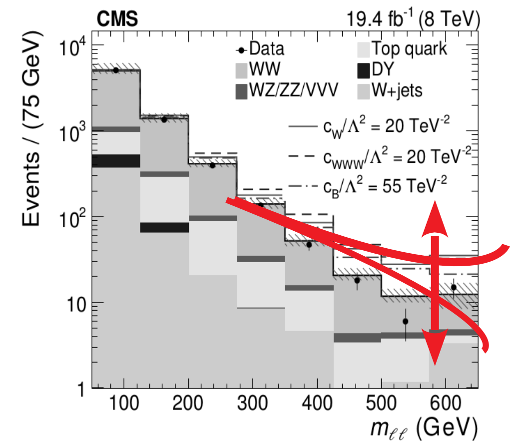
$$\mathcal{M}_\gamma + \mathcal{M}_Z + \mathcal{M}_t = -i\frac{e^2\sin\theta}{2m_W^2}\, s \left(Q_q + \frac{1}{s_W^2}(T_q^3 - s_W^2 Q_q) - \frac{T_q^3}{s_W^2}\right)$$

$$[T^A, T^B] \neq f^{ABC}T^C$$

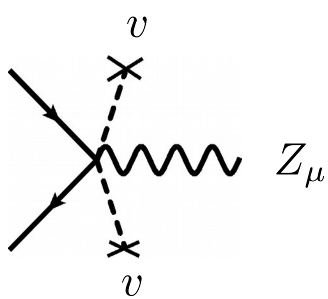


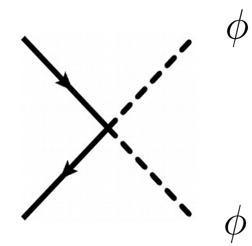


Unitary gauge



Heavy BSM = EFT





Feynman gauge

$$\delta\mathcal{A} \sim v^2/\Lambda^2$$

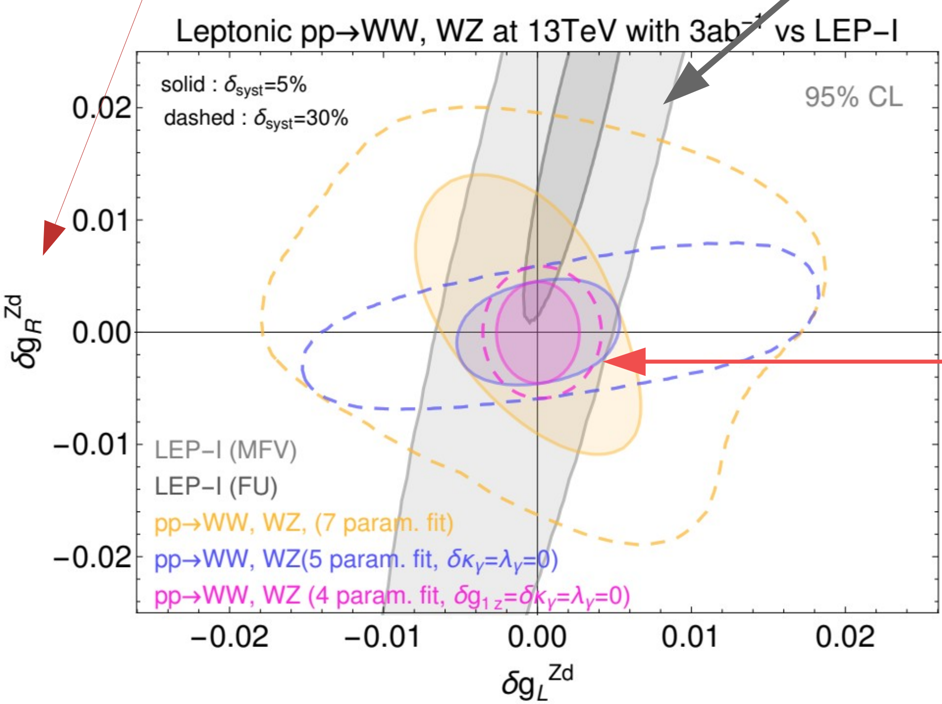
$$\delta\mathcal{A} \sim E^2/\Lambda^2$$

$$\bar{f}\gamma_\mu f \, H^\dagger \overleftrightarrow{D}_\mu H$$

Grojean, Montull, MR, '18

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

LEP, Z pole measurements



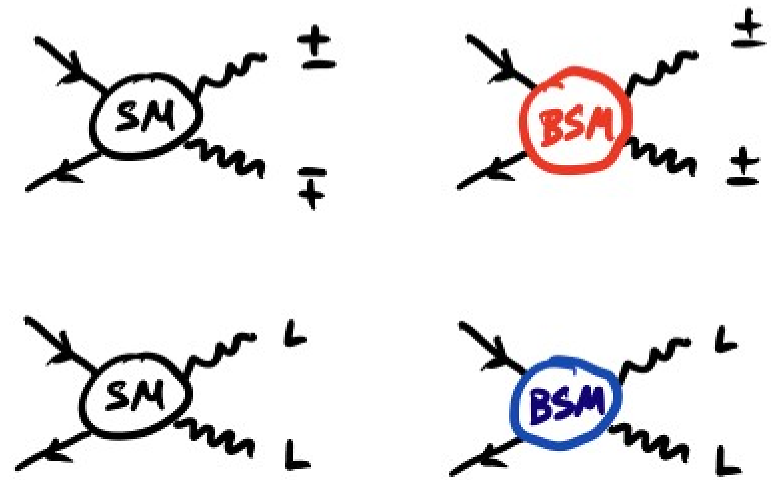
HL-LHC, diboson

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

BSM/EFT modifies kinematical distributions of diboson (and other) SM processes.
But "a process" may involve only one helicity configuration.

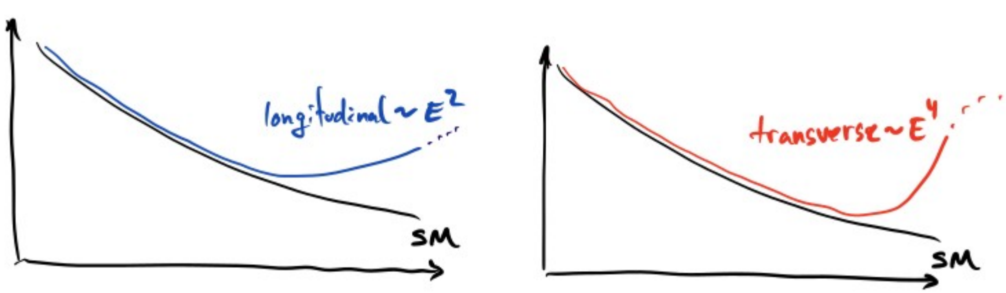
Azatov, Contino, Machado, FR

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



The production of longitudinal modes through BSM physics is the same as in SM and do interfere

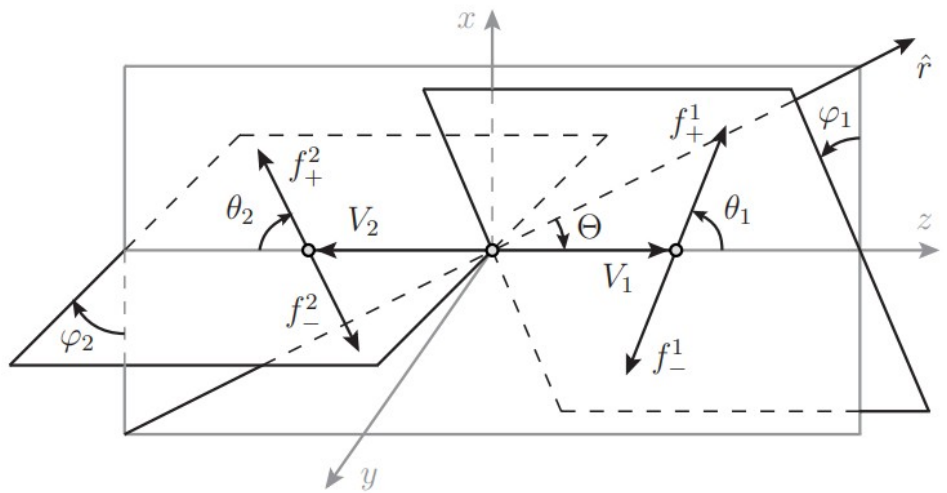
The production of transverse modes through BSM physics is different, and does not interfere!



(The larger the energy growth, the more important is the analysis of EFT validity!)

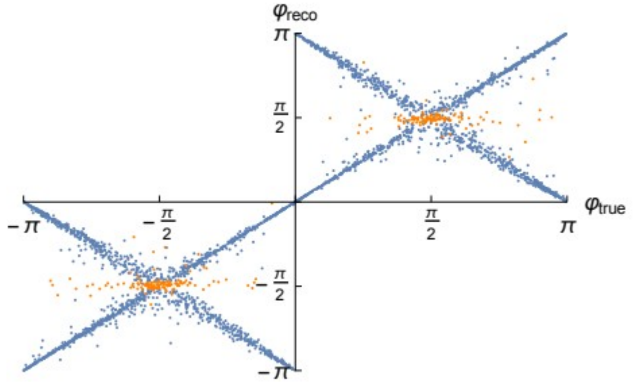
However, interference can be recovered using differential information

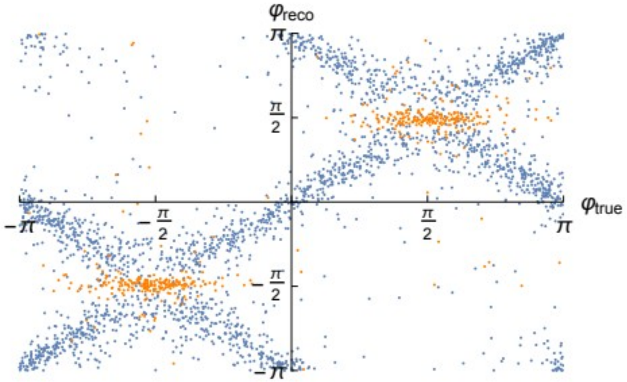
Panico, Wulzer, FR



$$\mathcal{A} \propto g_1 g_2 \sum_{h_{1,2}} \mathcal{A}_{h_1 h_2} e^{i h_1 \varphi_1} e^{i h_2 \varphi_2} d_{h_1}(\theta_1) d_{h_2}(\theta_2) \longrightarrow |\mathcal{A}|^2 \propto e^{i\phi_1(h_1 - h_1')}$$

Inclusive quantities integrate over the azimutal angles and there is no interference between different helicities.
However, differential quantities carry information about the interference.





$$\mathcal{L}_{\rm TGC} = ie\left(W^+_{\mu\nu}W^-_\mu - W^-_{\mu\nu}W^+_\mu\right)A_\nu + ie\left[(1+\delta\kappa_\gamma)A_{\mu\nu}\,W^+_\mu W^-_\nu\right]$$
$$+\; ig\,c_W\left[(1+\delta g_{1,z})\left(W^+_{\mu\nu}W^-_\mu - W^-_{\mu\nu}W^+_\mu\right)Z_\nu + (1+\delta\kappa_z)Z_{\mu\nu}\,W^+_\mu W^-_\nu\right]$$
$$+\; i\frac{e}{m_W^2}\lambda_\gamma W^+_{\mu\nu}W^-_{\nu\rho}A_{\rho\mu} + i\frac{g\,c_W}{m_W^2}\lambda_z W^+_{\mu\nu}W^-_{\nu\rho}Z_{\rho\mu}\,.$$

$$\mathcal{L}_{V\bar{q}q} = \sqrt{g^2+g'^2}Z_\mu\left[\sum_{f\in u,d}\bar{f}_L\gamma_\mu\left(T^3_f - s^2_W Q_f + \delta g^{Zf}_L\right)f_L + \sum_{f\in u,d}\bar{f}_R\gamma_\mu\left(-s^2_W Q_f + \delta g^{Zf}_R\right)f_R\right]$$
$$+\; \frac{g}{\sqrt{2}}\left(W^+_\mu \bar{u}_L\gamma_\mu\left(I_3 + \delta g^{Wq}_L\right)d_L + \text{h.c.}\right)\,.$$

$\longleftrightarrow$

$$\mathcal{O}_W = \frac{ig}{2}\left(H^\dagger\sigma^a \overleftrightarrow{D}^\mu H\right)D^\nu W^a_{\mu\nu}$$
$$\mathcal{O}_B = \frac{ig'}{2}\left(H^\dagger \overleftrightarrow{D}^\mu H\right)\partial^\nu B_{\mu\nu}$$
$$\mathcal{O}_{HW} = ig(D^\mu H)^\dagger\sigma^a(D^\nu H)W^a_{\mu\nu}$$
$$\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger(D^\nu H)B_{\mu\nu}$$
$$\mathcal{O}_{fH} = \bar{f}\gamma_\mu f H^\dagger D_\mu H$$

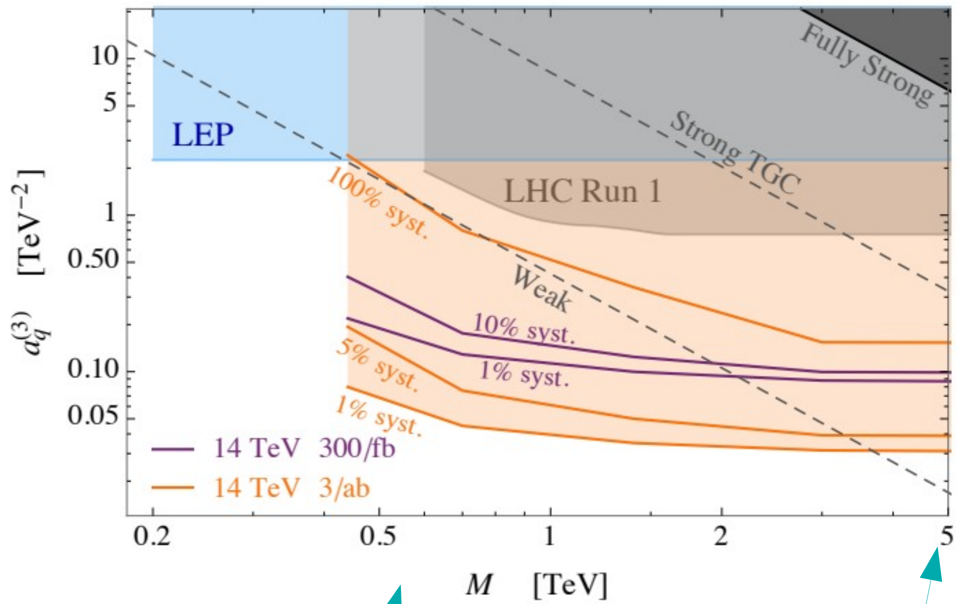
The Lagrangian parameters can be put in correspondence with helicity amplitudes:

Franceschini, Panico, Pomarol, Riva, Wulzer, '17

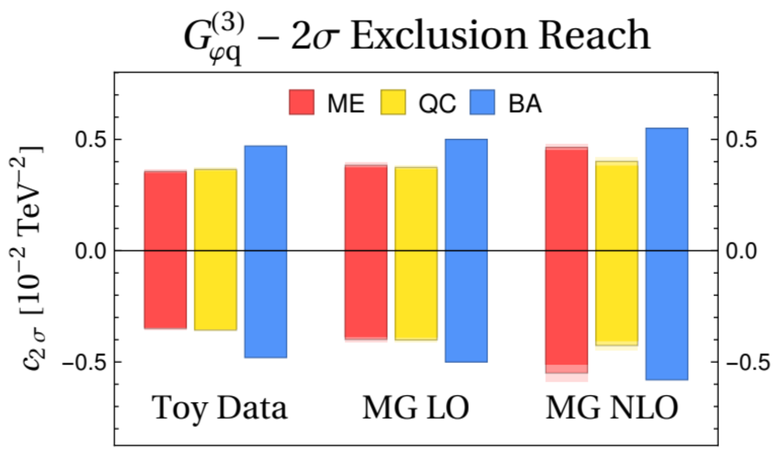
Amplitude	High-energy primaries	Low-energy primaries
$\bar{u}_L d_L \to W_L Z_L, W_L h$	$\sqrt{2}a_q^{(3)}$	$\sqrt{2}\frac{g^2}{m_W^2}\left[c_{\theta_W}(\delta g^Z_{uL} - \delta g^Z_{dL})/g - c^2_{\theta_W}\delta g^Z_1\right]$
$\bar{u}_L u_L \to W_L W_L$ $\bar{d}_L d_L \to Z_L h$	$a_q^{(1)} + a_q^{(3)}$	$-\frac{2g^2}{m_W^2}\left[Y_L t^2_{\theta_W}\delta\kappa_\gamma + T_Z^{u_L}\delta g^Z_1 + c_{\theta_W}\delta g^Z_{dL}/g\right]$
$\bar{d}_L d_L \to W_L W_L$ $\bar{u}_L u_L \to Z_L h$	$a_q^{(1)} - a_q^{(3)}$	$-\frac{2g^2}{m_W^2}\left[Y_L t^2_{\theta_W}\delta\kappa_\gamma + T_Z^{d_L}\delta g^Z_1 + c_{\theta_W}\delta g^Z_{uL}/g\right]$
$\bar{f}_R f_R \to W_L W_L, Z_L h$	a_f	$-\frac{2g^2}{m_W^2}\left[Y_{f_R} t^2_{\theta_W}\delta\kappa_\gamma + T_Z^{f_R}\delta g^Z_1 + c_{\theta_W}\delta g^Z_{fR}/g\right]$

They consist on the leading high energy behaviour,
and measurements are mostly sensitive to those combinations

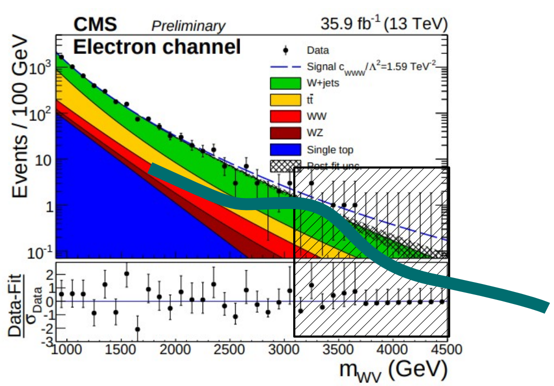
Franceschini, Panico, Pomarol, Riva, Wulzer, '17

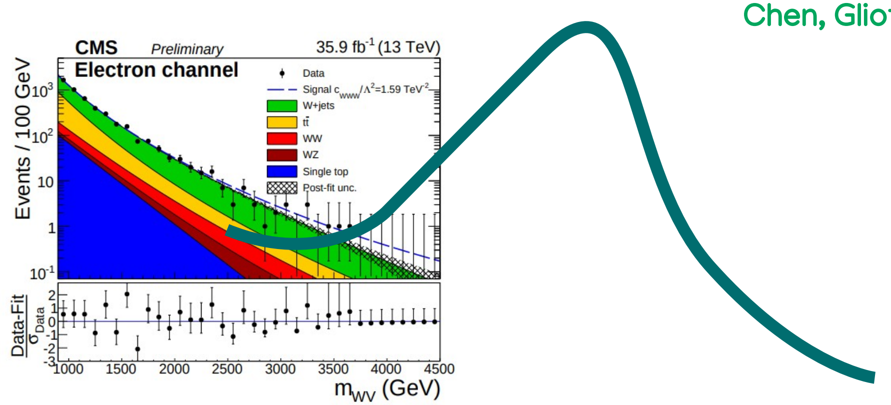


Improved using full kinematical information with ML techniques



Chen, Glioti, Panico, Wulzer, '20





Grojean, Montull, MR, '18

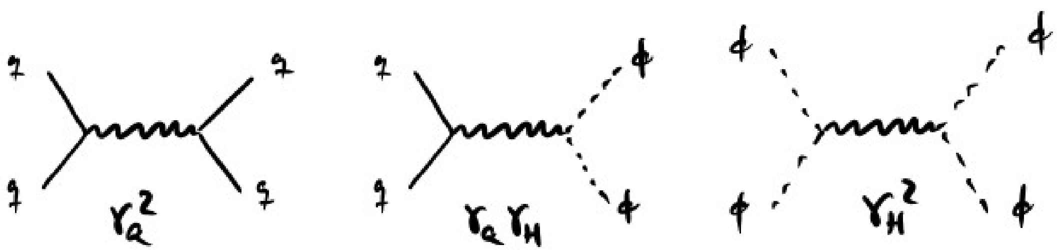
What does this mean for a full model?

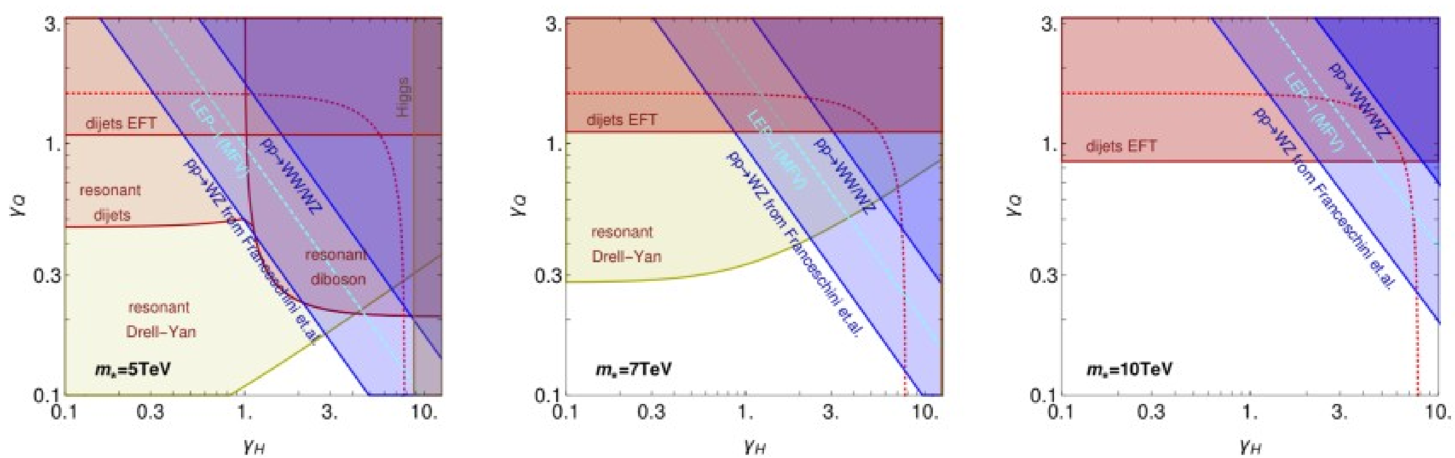
$$\mathcal{L}_{int} = L^a_\mu\left(\gamma_H J^{Ha}_\mu + \gamma_V J^a_\mu + \sum_f \gamma_f J^{fa}_\mu\right) + R^0_\mu\left(\delta_H J^H_\mu + \delta_V J_\mu + \sum_f \delta_f J^f_\mu\right) + \frac{1}{\sqrt{2}}(\delta_H R^+_\mu J^{-H}_\mu + h.c.)$$

$$\bar{c}_B = \frac{m_W^2}{m_\star^2}\frac{\delta_H\delta_V}{g'^2}\,, \quad \bar{c}_W = \frac{m_W^2}{m_\star^2}\frac{\gamma_H\gamma_V}{g^2}\,, \quad \bar{c}_H = 3\frac{m_W^2}{m_\star^2}\frac{\delta_H^2+\gamma_H^2}{g^2}\,,$$

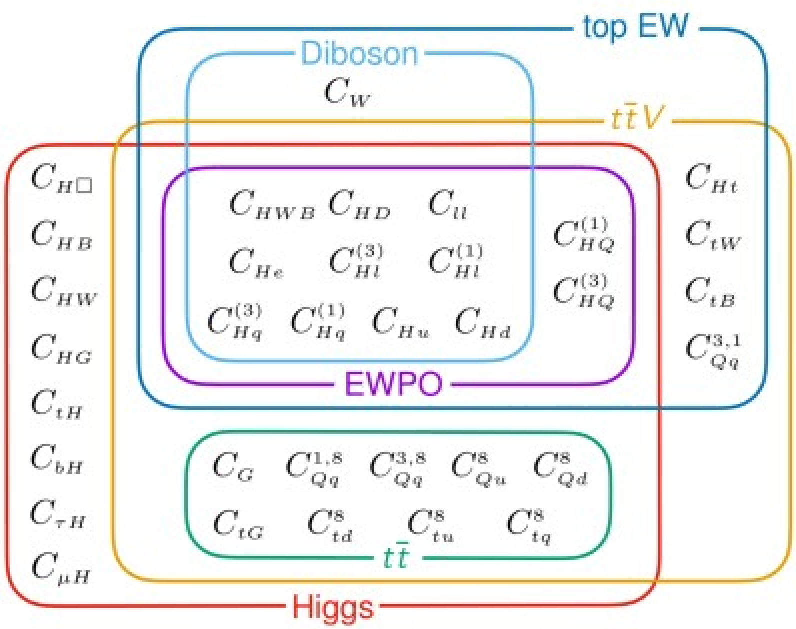
$$\bar{c}_{2B} = \frac{m_W^2}{4m_\star^2}\frac{\delta_V^2}{g'^2}\,, \quad \bar{c}_{2W} = \frac{m_W^2}{4m_\star^2}\frac{\gamma_V^2}{g^2}\,, \quad \bar{c}_{Hf} = \frac{m_W^2}{m_\star^2}\frac{2}{g^2}(-\delta_H\delta_f + \delta_V\delta_f)\,,$$

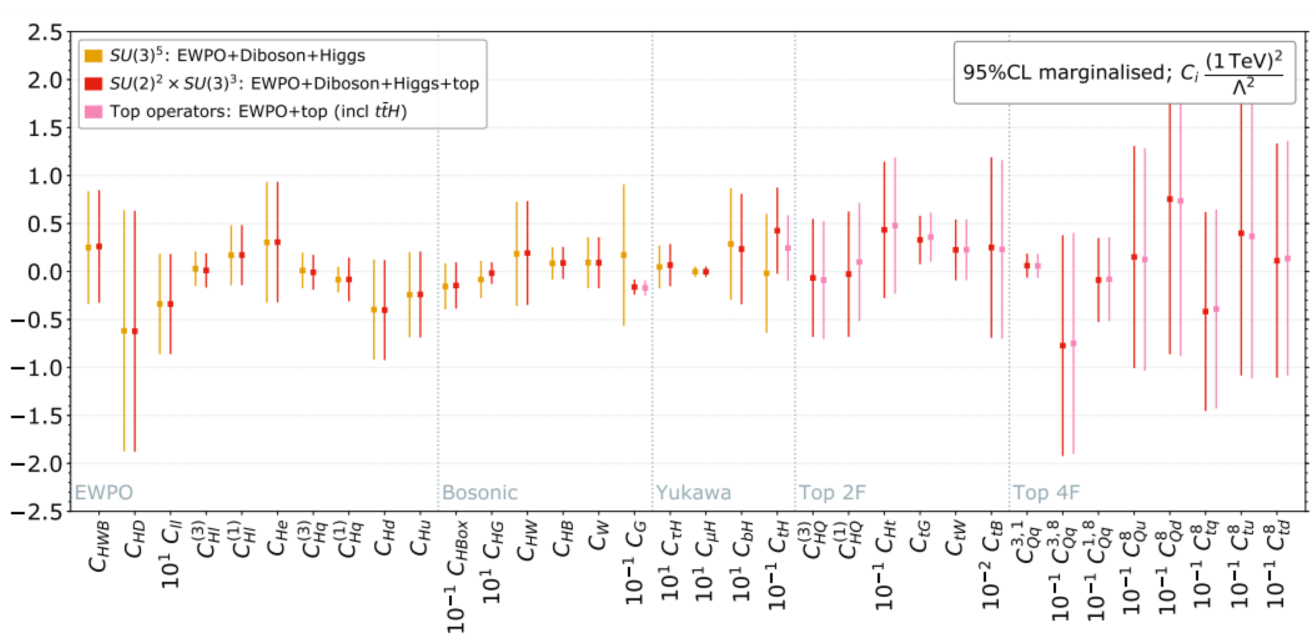
$$\bar{c}^{(3)}_{Hf} = \frac{m_W^2}{m_\star^2}\frac{2}{g^2}(-\gamma_H\gamma_f + \gamma_V\gamma_f)\,, \quad \bar{c}_{ff'} = -\frac{m_W^2}{2m_\star^2}\frac{1}{g^2}\delta_f\delta_{f'}\,, \quad \bar{c}^{(3)}_{ff'} = -\frac{m_W^2}{2m_\star^2}\frac{1}{g^2}\gamma_f\gamma_{f'}$$





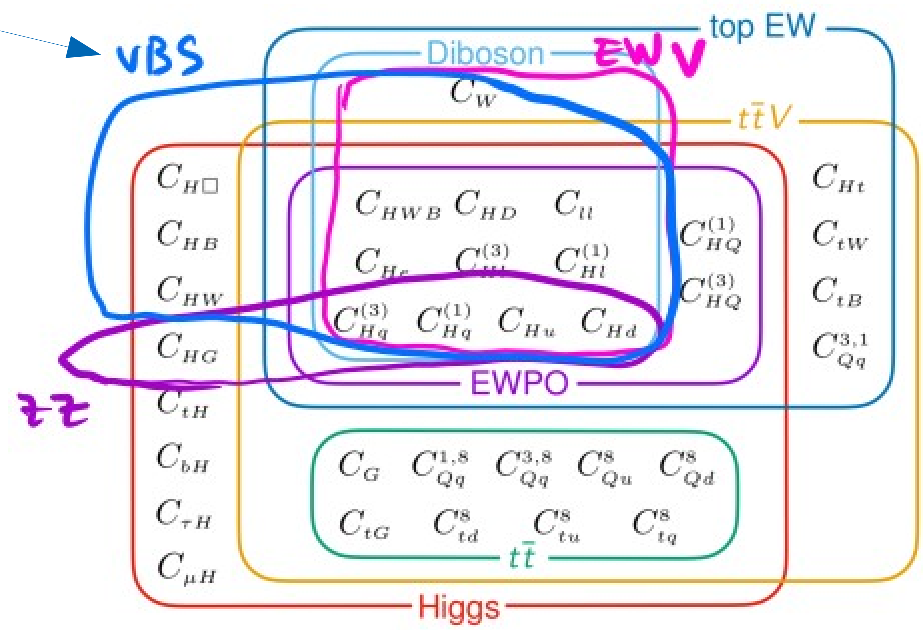
Ellis, Madigan, Mimasu, Sanz, You, '20

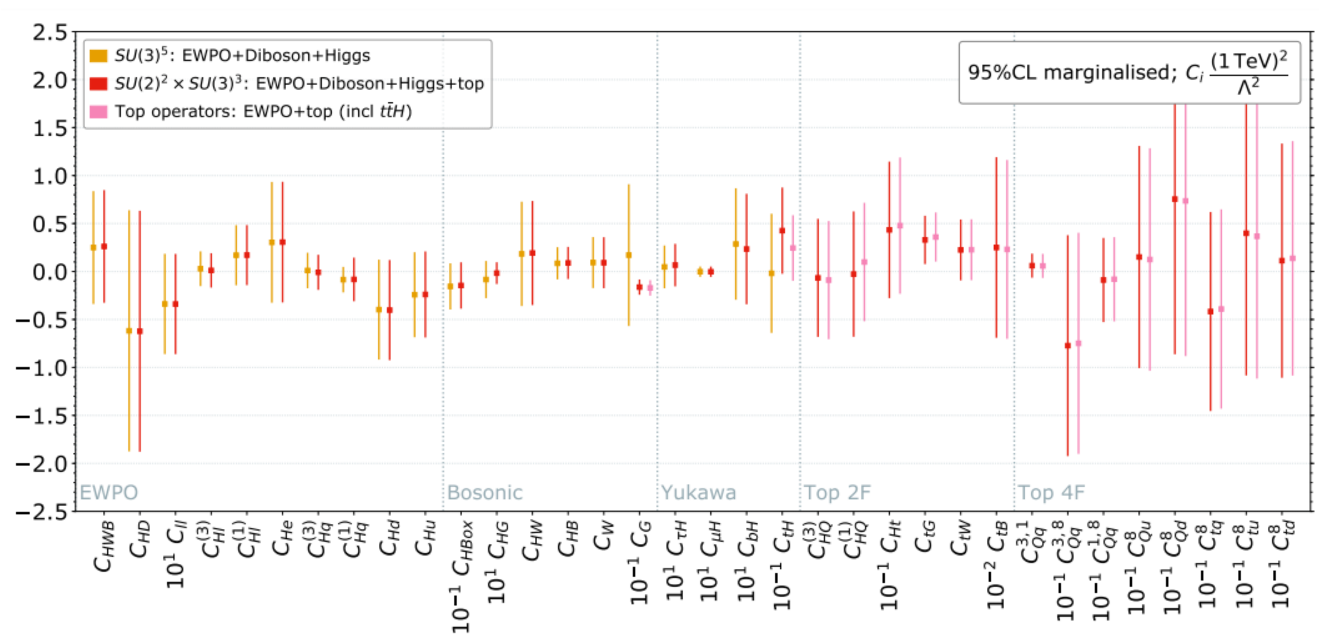


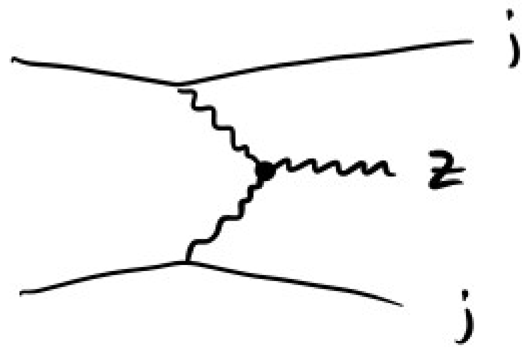


Ellis, Madigan, Mimasu, Sanz, You, '20

More in Raquel's talk on Thursday

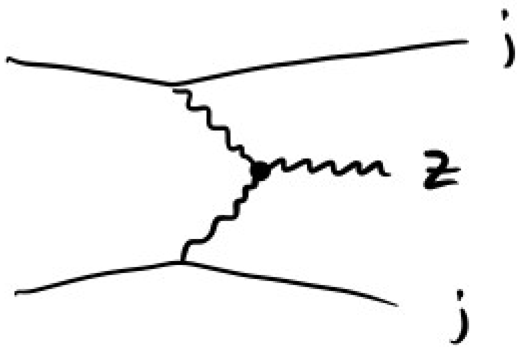






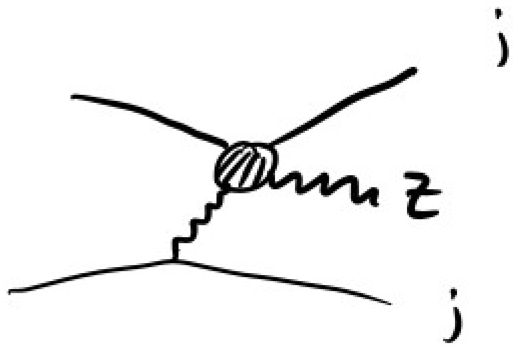
EW Zjj production

EW production of single EW bosons



EW Zjj production

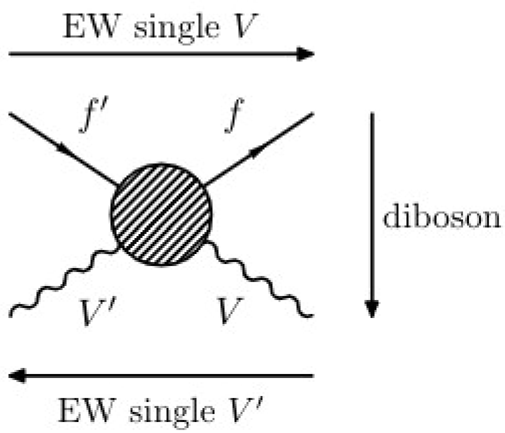
If dim 6 EFT operators are present

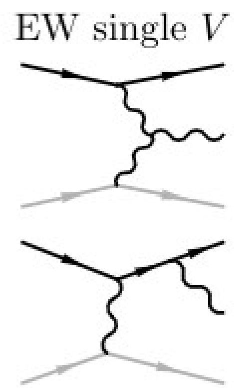


Diboson in the t-channel

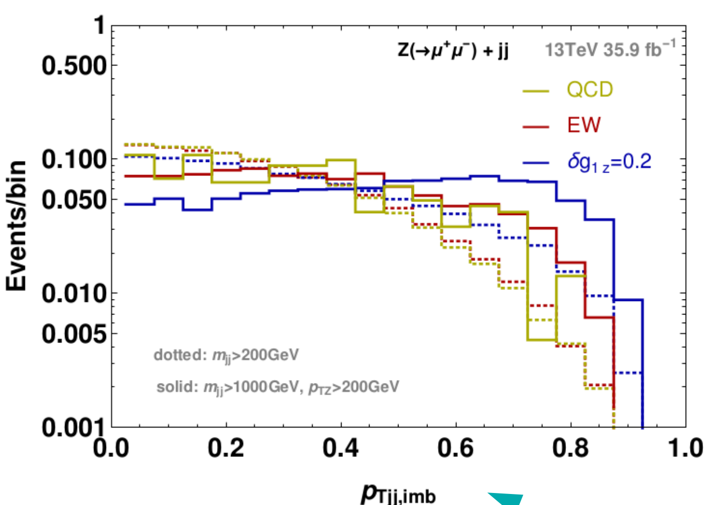
G. Durieux, M. Montull, MR, in progress

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



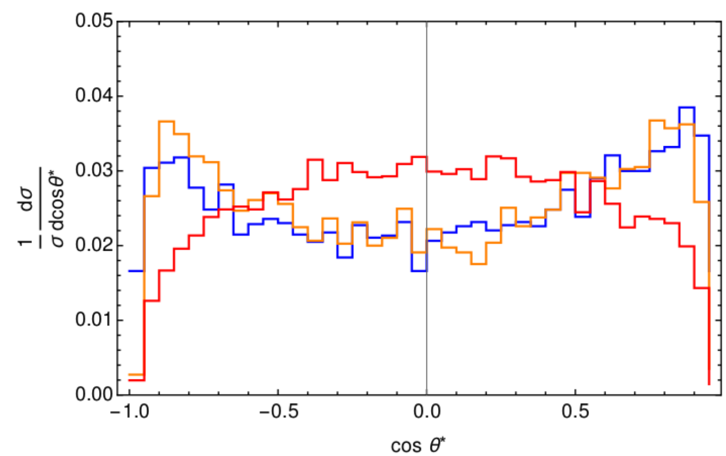


The EFT operator gives a large jet pT imbalance



$$p_{T,imb} = \frac{|p_T^{j_1} - p_T^{j_2}|}{p_T^{j_1} + p_T^{j_2}}$$

Signal is mostly on longitudinal polarizations



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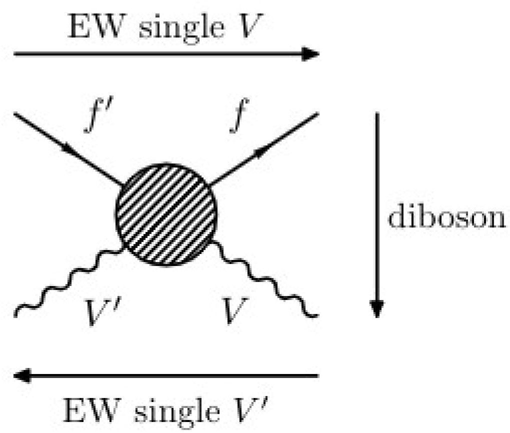
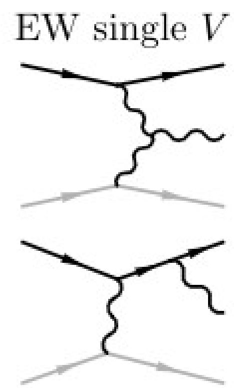




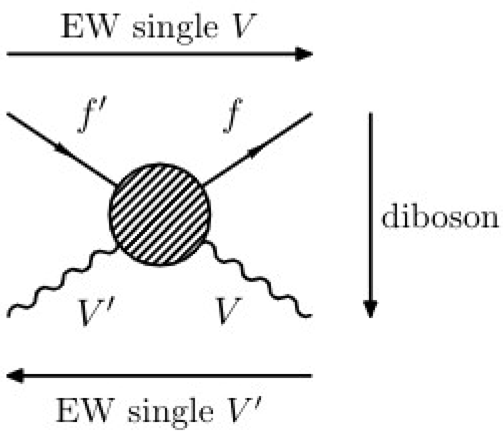
arXiv: 2006.15458

See yesterday's talk by Joany

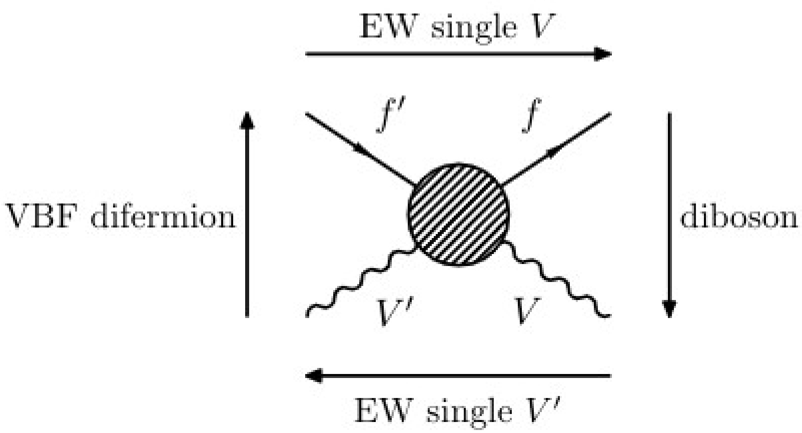
Wilson coefficient	Includes $\|\mathcal{M}_{d6}\|^2$	95% confidence interval [TeV^{-2}] Expected	Observed	p-value (SM)
c_W/Λ^2	no	[−0.30, 0.30]	[−0.19, 0.41]	45.9%
	yes	[−0.31, 0.29]	[−0.19, 0.41]	43.2%
$\tilde{c}_W/\Lambda^2$	no	[−0.12, 0.12]	[−0.11, 0.14]	82.0%
	yes	[−0.12, 0.12]	[−0.11, 0.14]	81.8%
c_{HWB}/Λ^2	no	[−2.45, 2.45]	[−3.78, 1.13]	29.0%
	yes	[−3.11, 2.10]	[−6.31, 1.01]	25.0%
$\tilde{c}_{HWB}/\Lambda^2$	no	[−1.06, 1.06]	[0.23, 2.34]	1.7%
	yes	[−1.06, 1.06]	[0.23, 2.35]	1.6%

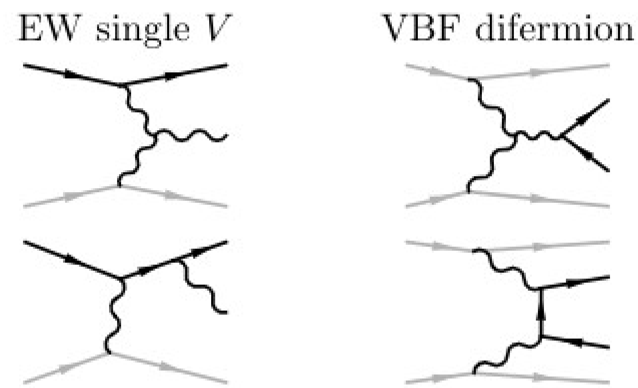
This is a serious competitor of diboson for the HEP parameters!

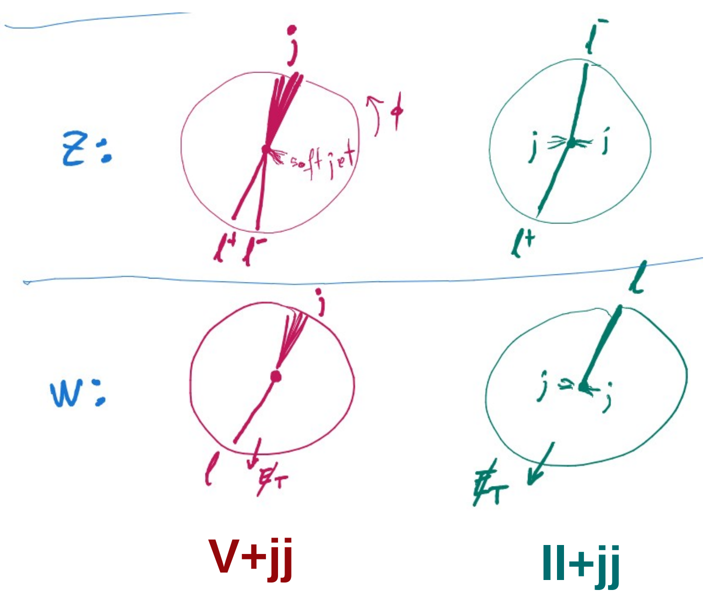
G. Durieux, M. Montull, MR, in progress



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







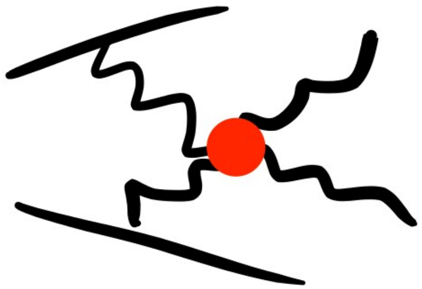
Crude estimate:

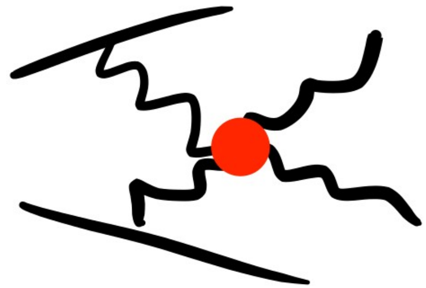
Events at HL-LHC for ll+jj, mjj>500GeV, mll>1.5TeV:

$$40 + 110\delta g^{Ze_R} + 48000(\delta g^{Ze_R})^2$$

Implies order 1% constraint on coupling

- Not competitive for Zee couplings, but perhaps interesting for Wlnu, only at %
- Only way to test the leptonic HE parameters at hadron colliders.





dim 6 operators

dim 8 operators

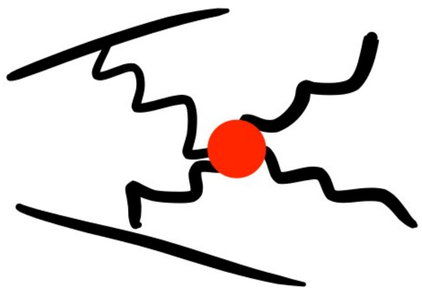
Interplay among dim 6 and dim 8 is crucial,
and will be covered by Raquel on Thursday

Anything beyond TGCs?

Vector boson scattering

Henning, Lombardo, Riva, MR, '18

Usually, VBS is interpreted in terms of dimension 8 operators.
But they recieve contributions from Higgs operators



$$|H|^2 W^a_{\mu\nu} W^a_{\mu\nu} \qquad \kappa_{\gamma\gamma} h A_{\mu\nu} A_{\mu\nu}$$

$$|H|^2 B_{\mu\nu} B_{\mu\nu} \qquad \kappa_{Z\gamma} h Z_{\mu\nu} A_{\mu\nu}$$

$$\phi^+ \phi^-$$

Recall that the Higgs doublet also contains the Goldstone modes,
So the operators also give contact interactions for the longitudinal vectors!

VBS probes dynamics that were thought to be only probed by Higgs physics!

Vector boson scattering

Henning, Lombardo, Riva, MR, '18

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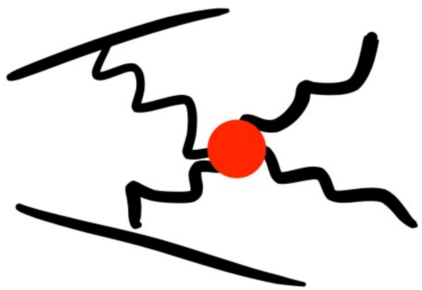


$$|H|^2 W^a_{\mu\nu} W^a_{\mu\nu} \quad \longleftrightarrow \quad \kappa_{\gamma\gamma} h A_{\mu\nu} A_{\mu\nu}$$

$$|H|^2 B_{\mu\nu} B_{\mu\nu} \quad \longleftrightarrow \quad \kappa_{Z\gamma} h Z_{\mu\nu} A_{\mu\nu}$$

We project analysis on W+W+, WZ, ZZ and Zγ

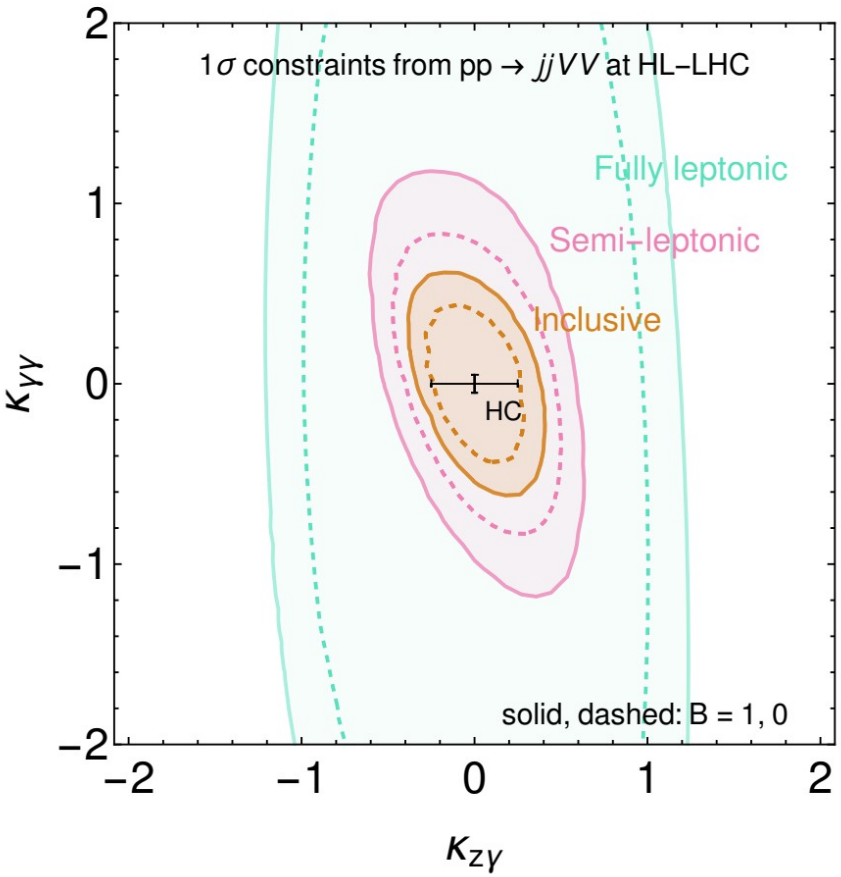
e.g., ATLAS, 1405.6241
ATLAS, 1705.01966

Other channels, W+W−, W+γ, γγ are left for future study.

Hardness of 2→2 characterized by scalar sum of vectors' pT, we bin on it.

Vector boson scattering

Henning, Lombardo, Riva, MR, '18



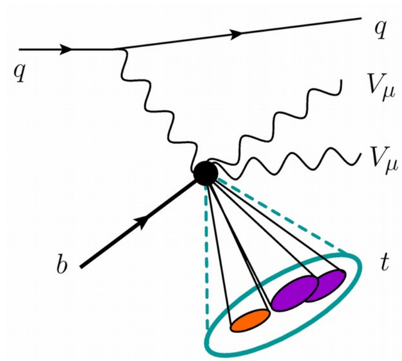
- Competitive for Zγ, not for γγ
- If VBS with W+fat jet, W+W− will also enter

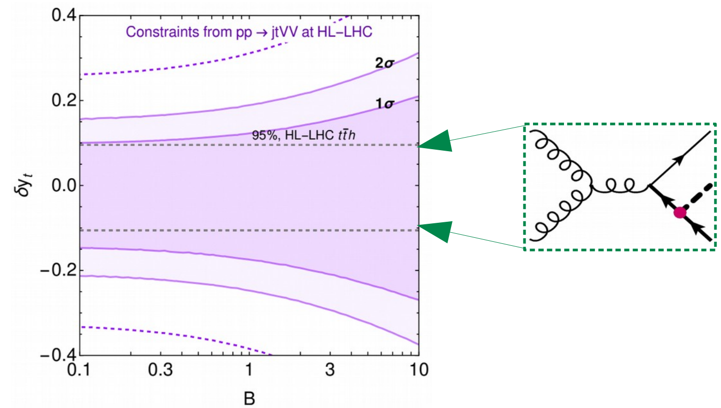
Henning, Lombardo, Riva, MR, '18

Each SM input defines a direction only probed by Higgs physics, they look like

$$|H|^2 \mathcal{O}_{SM}$$

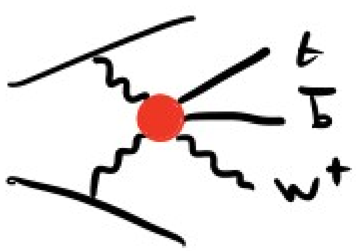
This makes VBS more connected to Higgs physics than it was thought:





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

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



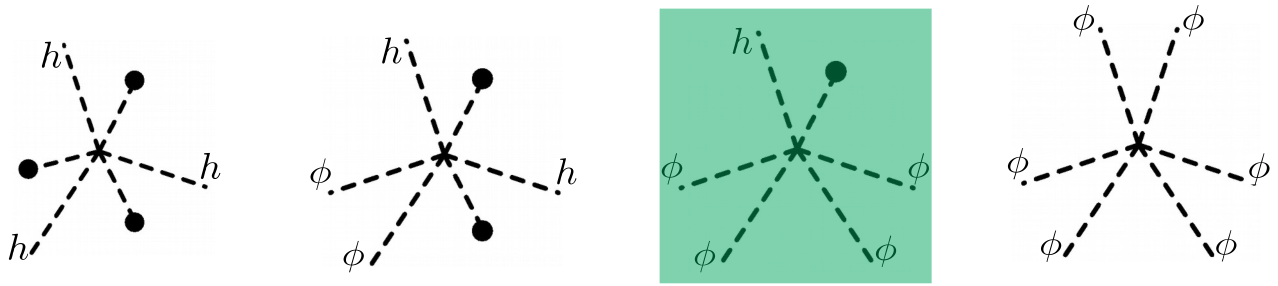
?

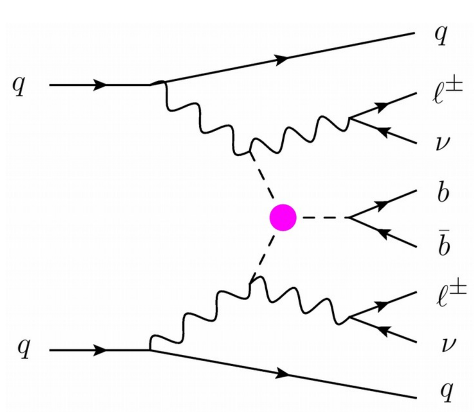
Each SM input defines a direction only probed by Higgs physics, they look like

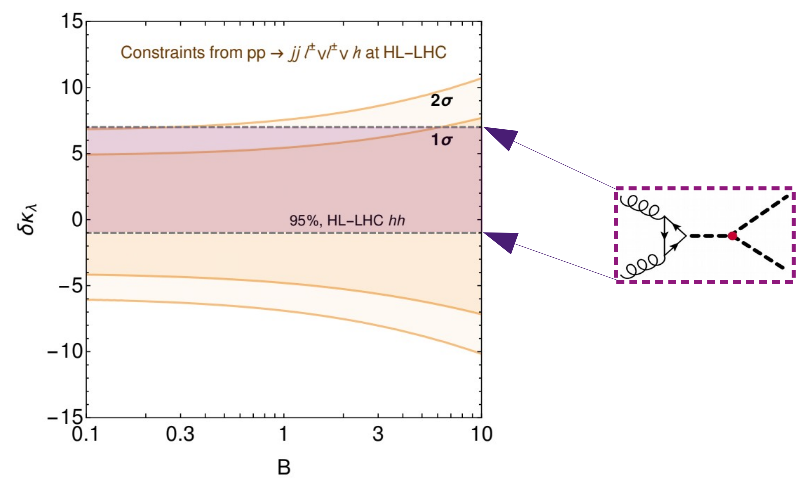
$$|H|^2\mathcal{O}_{SM}$$

This makes VBS more connected to Higgs physics than it was thought:

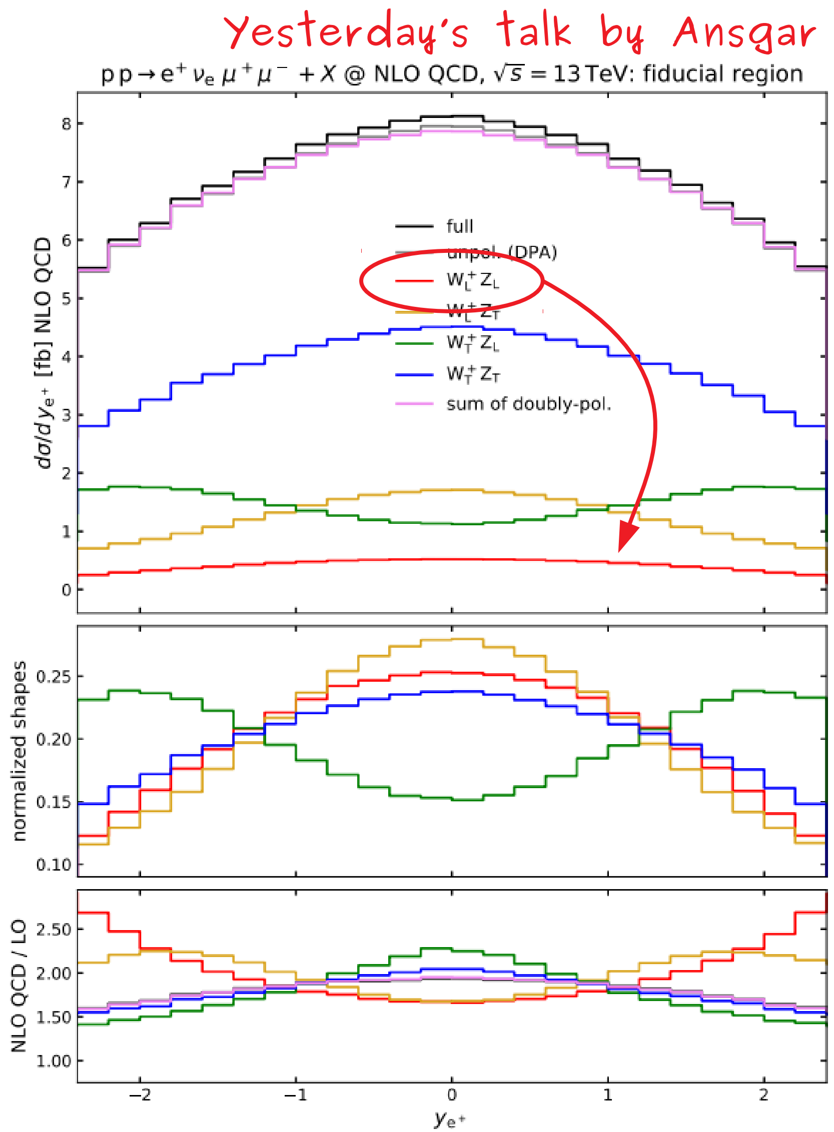
$$\frac{1}{\Lambda^2}|H|^6 \supset \frac{1}{\Lambda^2}(v^3h^3 + 3v^2h^2\phi^2 + 3vh\phi^4 + \phi^6 + \ldots)$$







A common theme is that the interesting physics is in the longitudinal modes, and the production of transverse polarizations acts like a background



A better understanding and better tools to discriminate longitudinal and transverse would make a technical and conceptual progress

The ideology can be summarized with this:

LEP showed us that left- and right- handed fermions are two different animals, that happen to be mixed through a mass term

The entire ideology can be summarized with this:

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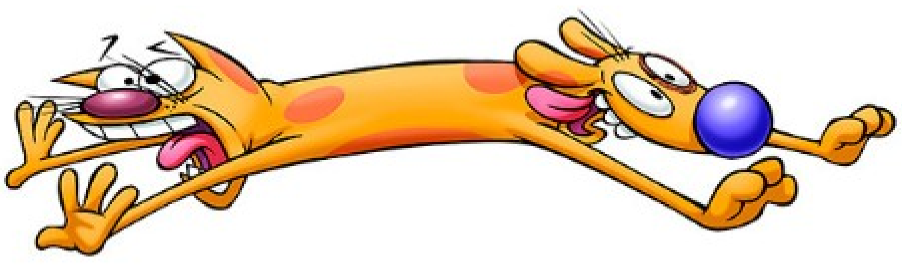

The higher we go in energy, the more relevant the same statement is for the massive vectors:

Longitudinal and transverse polarizations are two different animals, with different dynamics,
that happen to be mixed through a mass term

Conclusions:

LHC is producing an unprecedented amount of data, which implies

... access to relevant physical effects waiting to be understood and studied

... that advanced computational techniques can and should be used to extract all the rich kinematics in the process, which enhances the sensitivity to EFT operators.

... allows to perform precision measurements in processes like VBS

... that correlations and synergies between very different processes can be studied