Higgs without Higgs

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Université de Genève

CERN, October 2019

Based on
1812.09299, with **B. Henning**, **D. Lombardo** and **F. Riva**
Ongoing work with **S. Adorni, B. Henning**, **D. Lombardo**, **F. Riva** and **S. Schramm**

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

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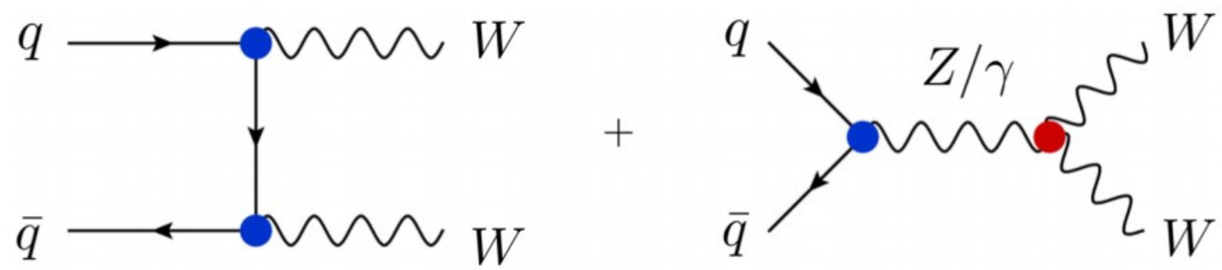
Changing any of its relation among couplings must spoil this uniqueness, and induce a pathological behaviour in some process

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

An example in diboson

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

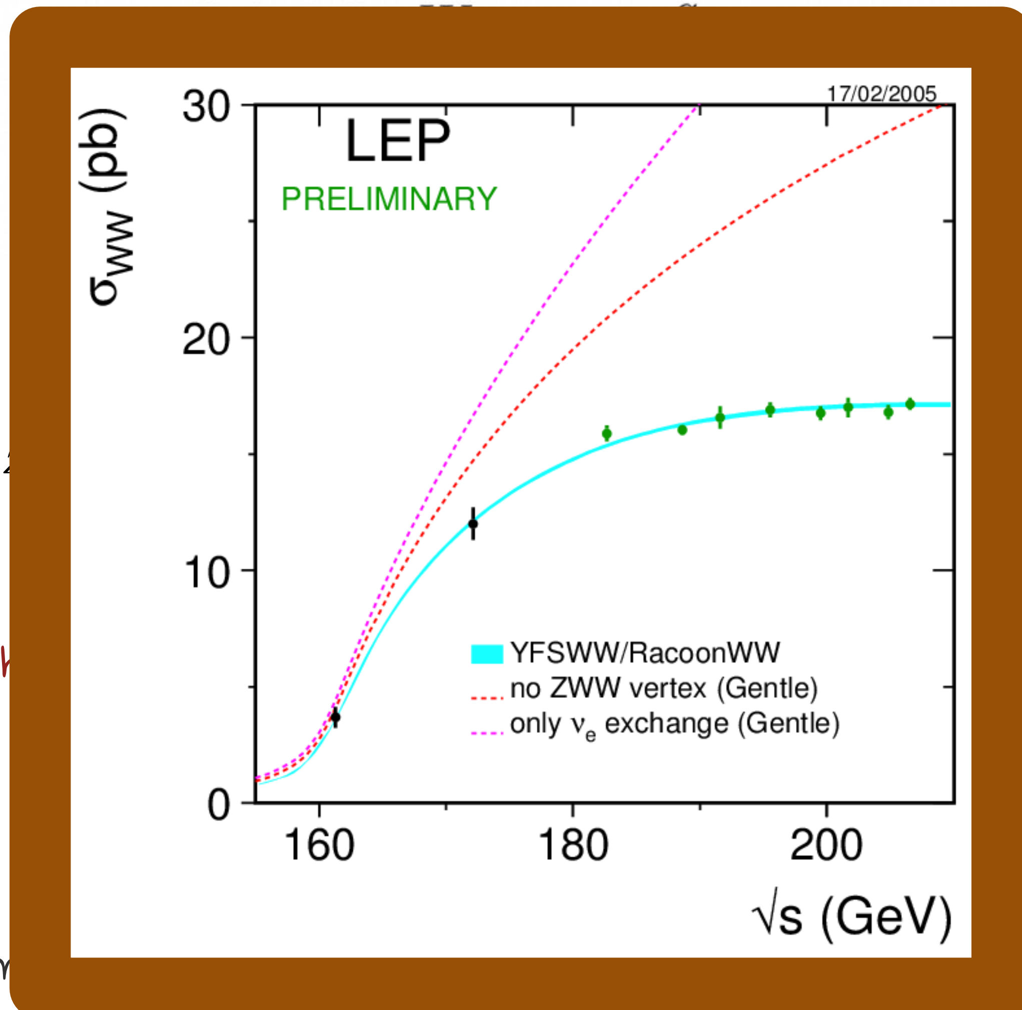
An example in diboson

An explicit example in diboson:

In the unitary gauge, and in the SM,

q ... W

$\bar{q}$ ... W



$$\mathcal{M}_\gamma + \mathcal{M}_Z \; \ldots \; - \frac{T_q^3}{s_W^2}\Big)$$

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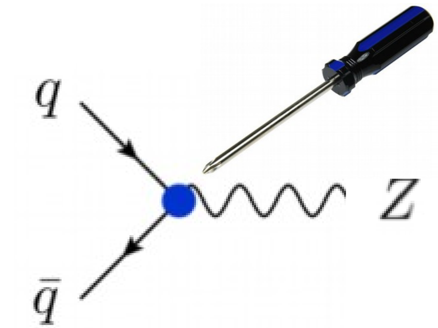
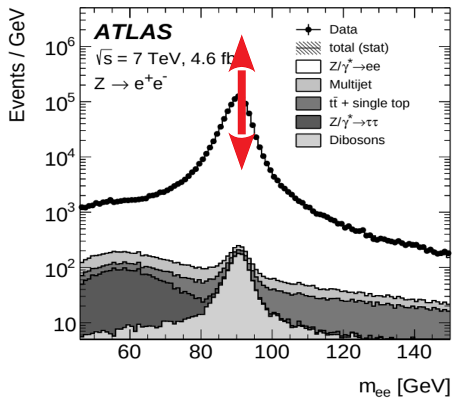
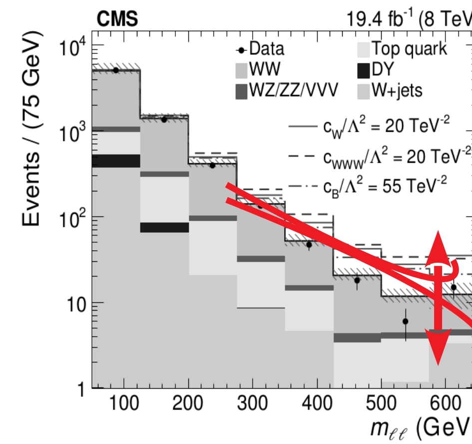
An example in diboson

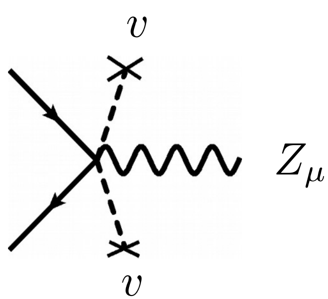


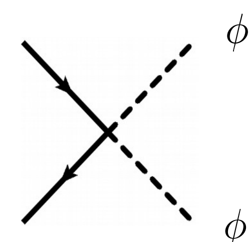


Unitary gauge



Heavy BSM = EFT





Feynman gauge

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

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

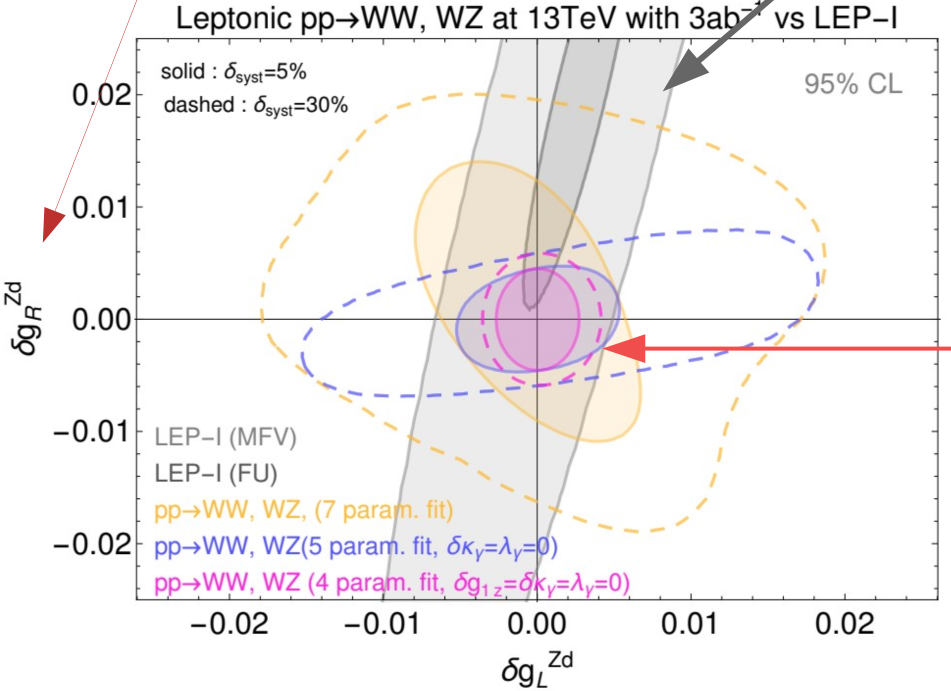
$$\bar{f}\gamma_\mu f\, H^\dagger \overleftrightarrow{D}_\mu H$$

An example in diboson

Grojean, Montull, MR, '18

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

LEP, Z pole measurements



HL-LHC, diboson

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

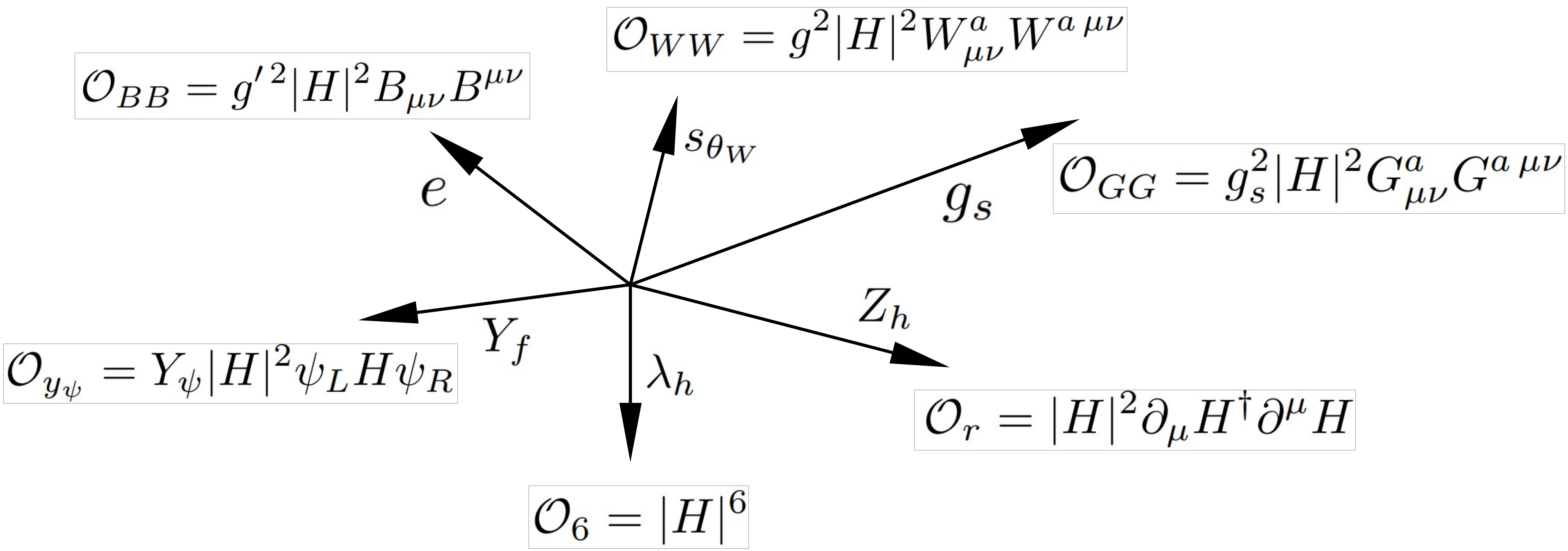
Higgs with Higgs

Gupta, Pomarol, Riva, ‘14
Masso, ‘14

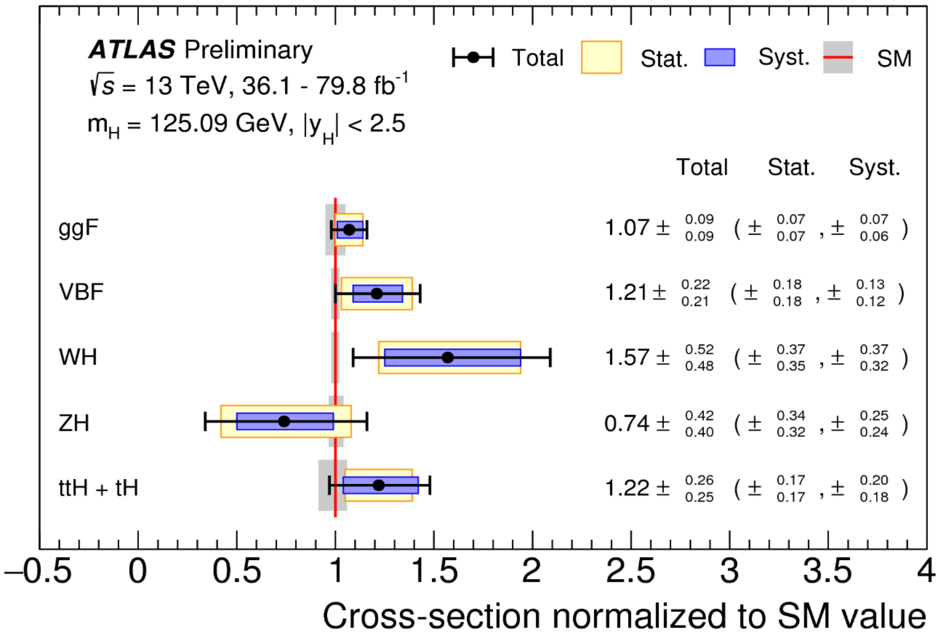
The Higgs probes a sector untested before:

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

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

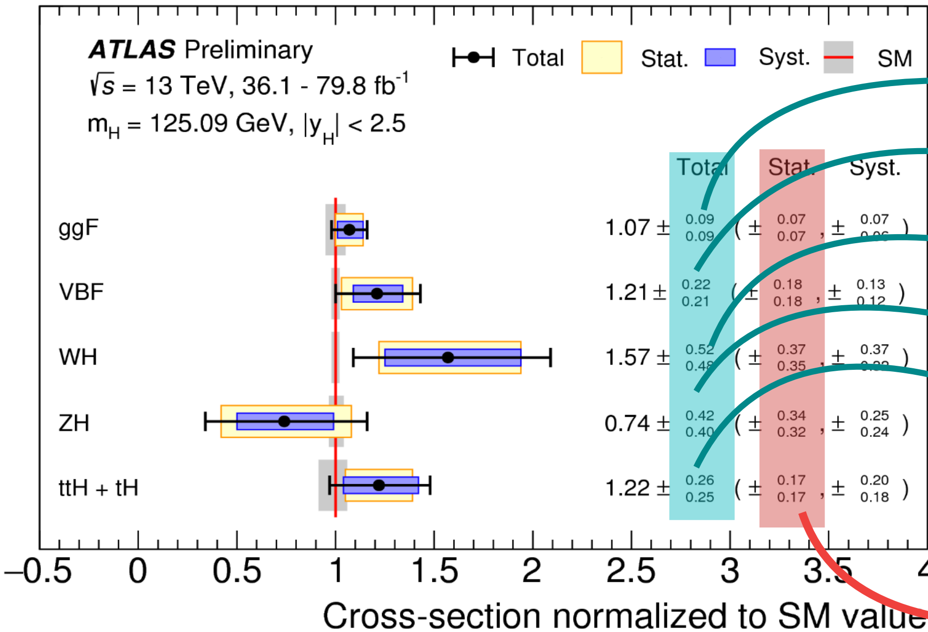


Higgs with Higgs



The directions defined by these Higgs operators are constrained by measuring the *on-shell* Higgs production rates and its branching ratios

Higgs with Higgs



HL-LHC projections:

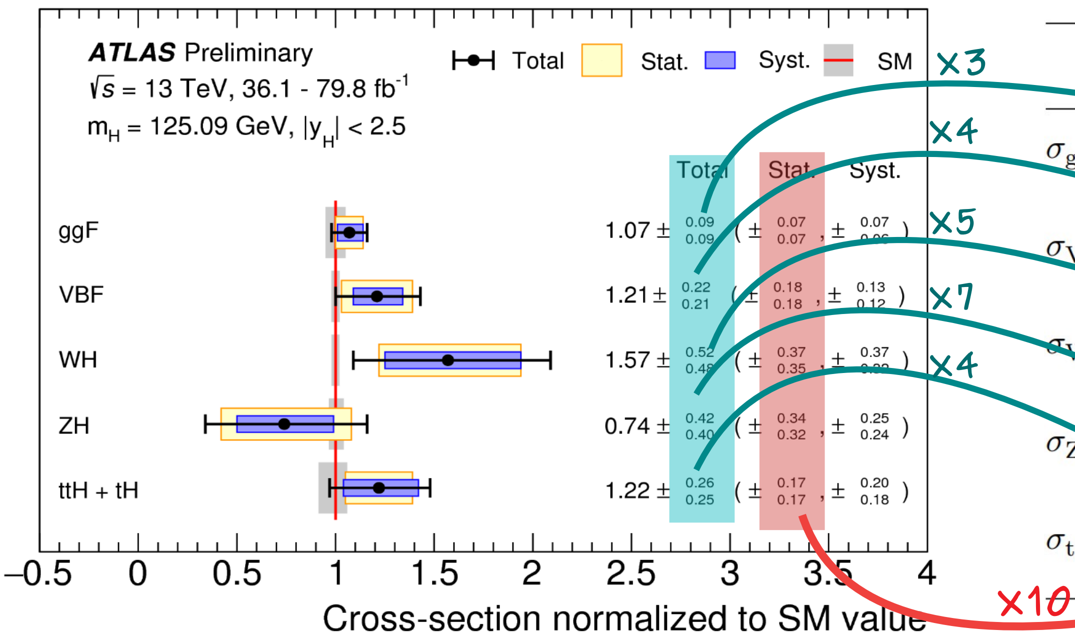
		ATLAS				
		3000 fb^{-1} uncertainty [%]				
		Total	Stat	Exp	SigTh	BkgTh
σ_{ggH}	S1	3.5	0.8	2.1	2.1	1.6
	S2	2.4	0.8	1.7	1.2	1.0
σ_{VBF}	S1	5.5	2.0	2.7	3.7	2.1
	S2	4.2	2.0	2.3	2.2	1.7
σ_{WH}	S1	9.3	4.0	4.0	5.1	5.4
	S2	7.7	4.0	3.4	3.3	4.5
σ_{ZH}	S1	6.2	3.4	2.4	3.4	3.0
	S2	4.8	3.4	1.8	2.0	2.1
σ_{ttH}	S1	6.7	1.9	3.1	3.7	4.3
	S2	5.3	1.9	2.8	2.4	3.3

On-shell Higgs coupling (HC) measurements will be saturated by systematics:

> will not benefit from collecting more luminosity

> inclusive rates will not benefit from going to higher collider energies

Higgs with Higgs



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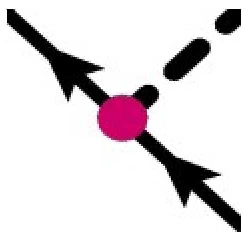
This talk is about measure Higgs properties in a way that

- It is limited by statistics, i.e., it does benefit from larger luminosities
- It benefits from going at higher collider energies, crucial for HE-LHC, CLIC, FCC/SppC

Higgs without Higgs

Tha same logic we applied to diboson can be applied to Higgs couplings:



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

$$|H|^2 \bar{f}_L H f_R$$

there must be some process where
an anomalous Yukawa induces
a pathological growth in energy…

Higgs without Higgs

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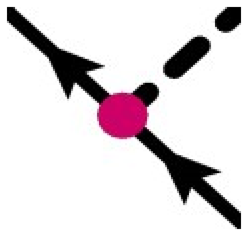
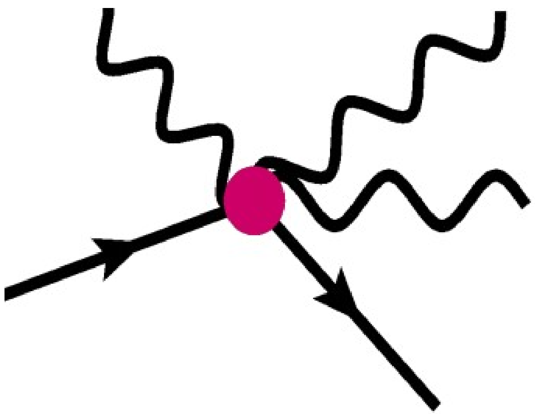


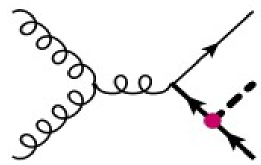
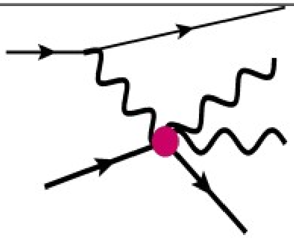
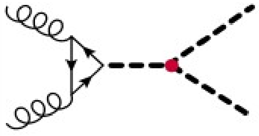
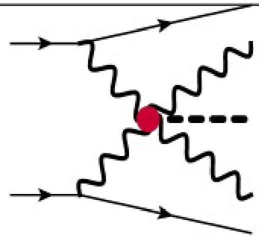
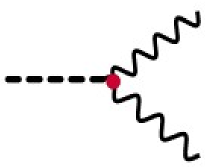
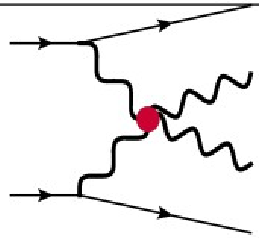
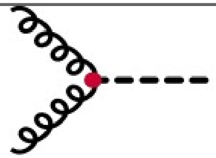
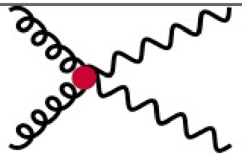
$$\delta\mathcal{A}/\mathcal{A} \sim v^2/\Lambda^2$$

$$|H|^2 \bar{f}_L H f_R$$

unanchor the Higgs from its vev

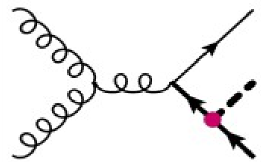
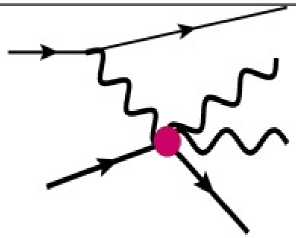
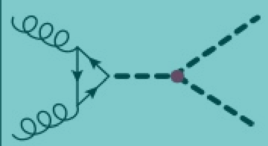
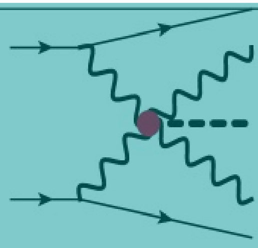
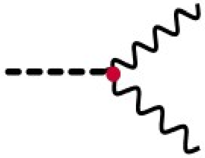
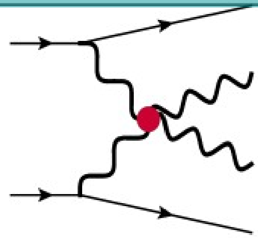
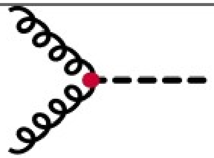
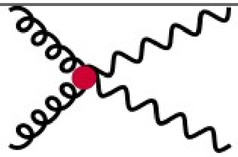


$$\boxed{\delta\mathcal{A}/\mathcal{A} \sim E^2/\Lambda^2}$$

		HC	HwH	Growth
κ_t	$\mathcal{O}_{y_t}$			$\sim \frac{E^2}{\Lambda^2}$
κ_λ	$\mathcal{O}_6$			$\sim \frac{vE}{\Lambda^2}$
$\kappa_{Z\gamma}$ $\kappa_{\gamma\gamma}$ κ_V	$\mathcal{O}_{WW}$ $\mathcal{O}_{BB}$ $\mathcal{O}_r$			$\sim \frac{E^2}{\Lambda^2}$
κ_g	$\mathcal{O}_{gg}$			$\sim \frac{E^2}{\Lambda^2}$

This puts in correspondence Higgs operators with
High Energy, multiboson processes with enhanced sensitivity

Higgs self-coupling

		HC	HwH	Growth
κ_t	$\mathcal{O}_{y_t}$			$\sim \frac{E^2}{\Lambda^2}$
κ_λ	$\mathcal{O}_6$			$\sim \frac{vE}{\Lambda^2}$
$\kappa_{Z\gamma}$ $\kappa_{\gamma\gamma}$ κ_V	$\mathcal{O}_{WW}$ $\mathcal{O}_{BB}$ $\mathcal{O}_r$			$\sim \frac{E^2}{\Lambda^2}$
κ_g	$\mathcal{O}_{gg}$			$\sim \frac{E^2}{\Lambda^2}$

Higgs self-coupling

$$\frac{1}{\Lambda^2}|H|^6 \supset \frac{1}{\Lambda^2}\left(v^5 h + v^4 h^2 + v^3 h^3 + 3v^2 h^2 \phi^2 + 3vh\phi^4 + \phi^6 + \ldots\right)$$

Can be absobed by redefining v and mh

Higgs self-coupling

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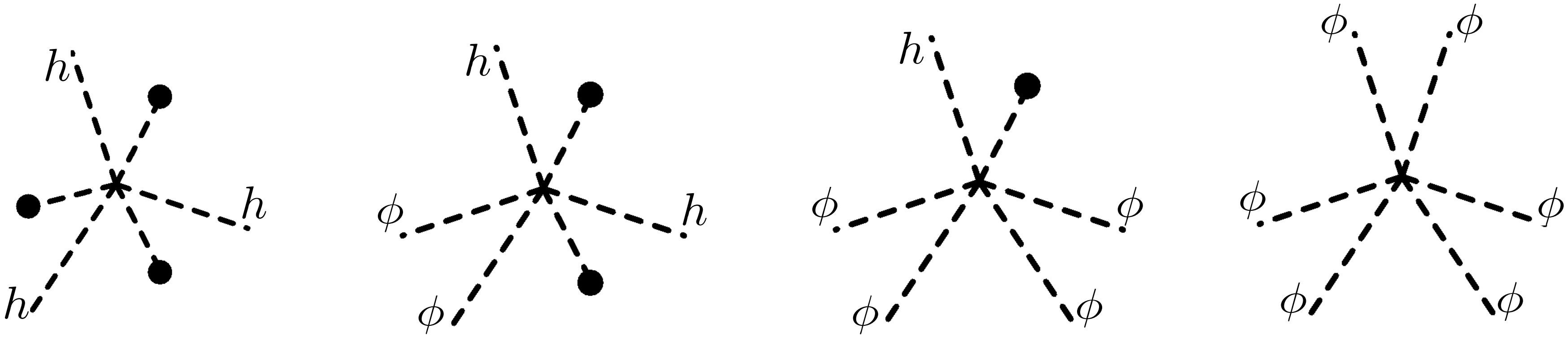

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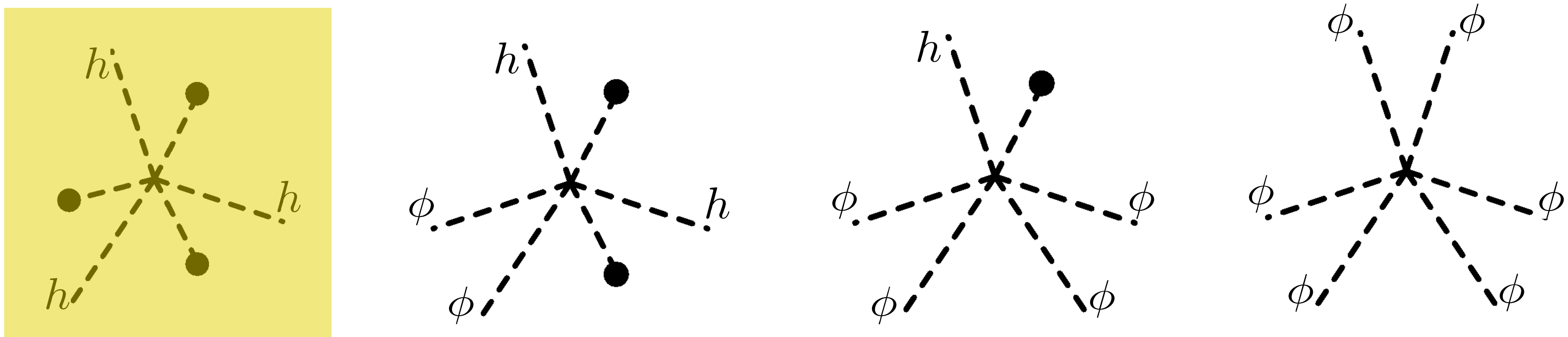
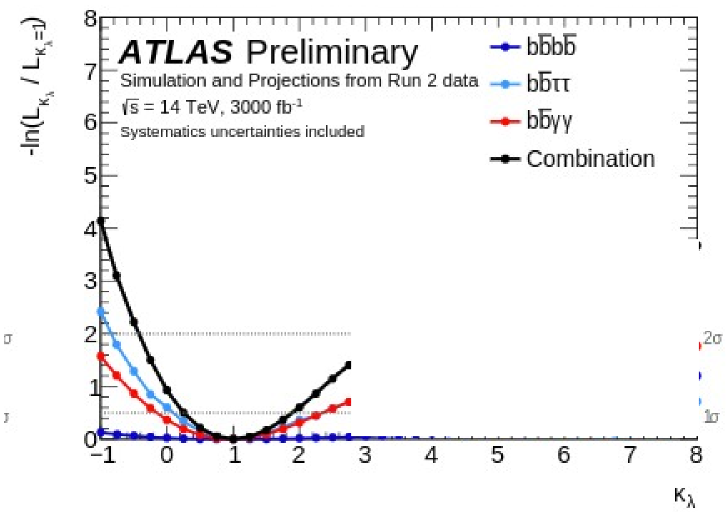


$$\frac{\sigma(pp \to hh)}{\sigma(pp \to h)} \sim 10^{-3} \qquad \mathrm{Br}(h \to b\bar{b}) \times \mathrm{Br}(h \to \gamma\gamma) \sim 60\% \times 0.1\%$$



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

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

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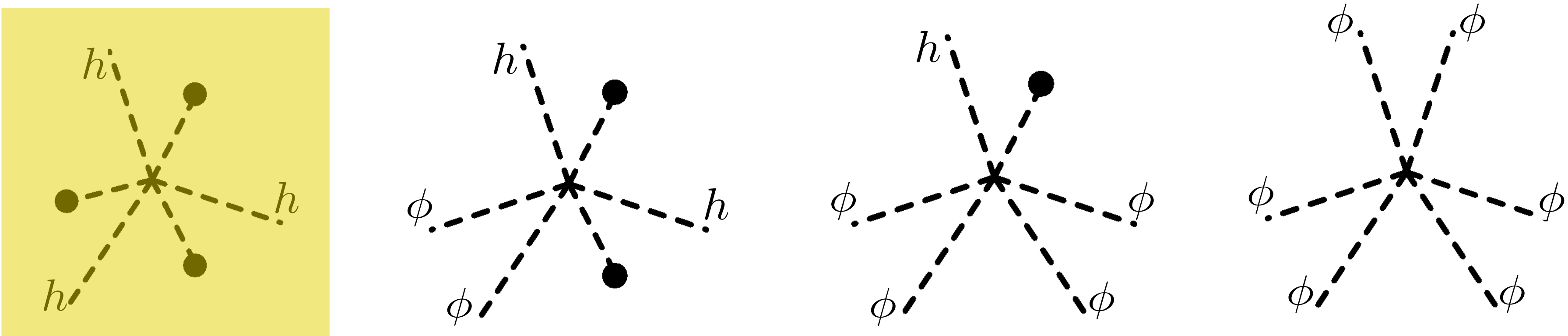

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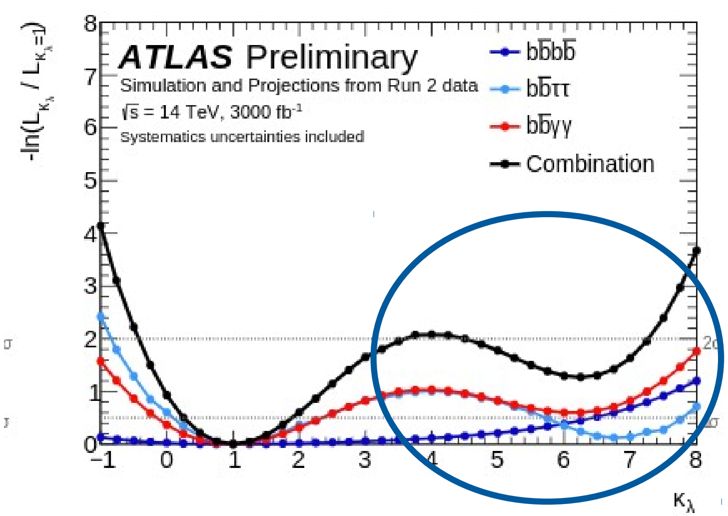

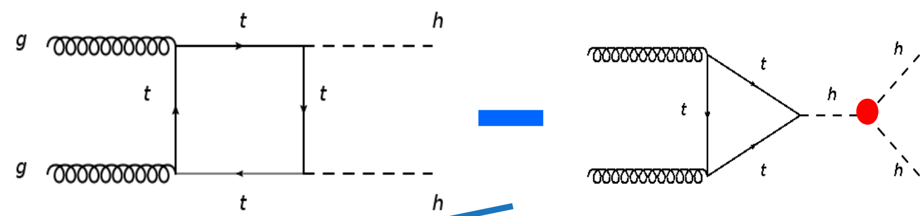

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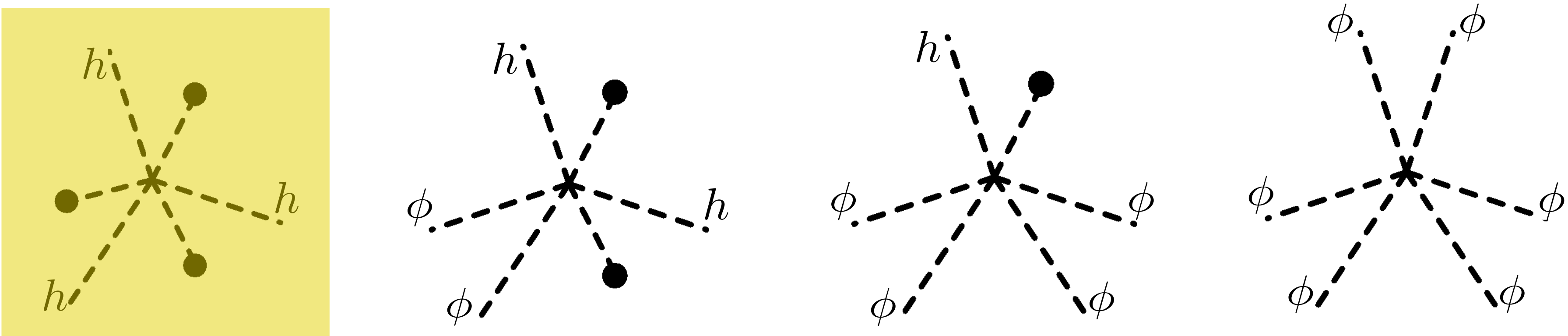

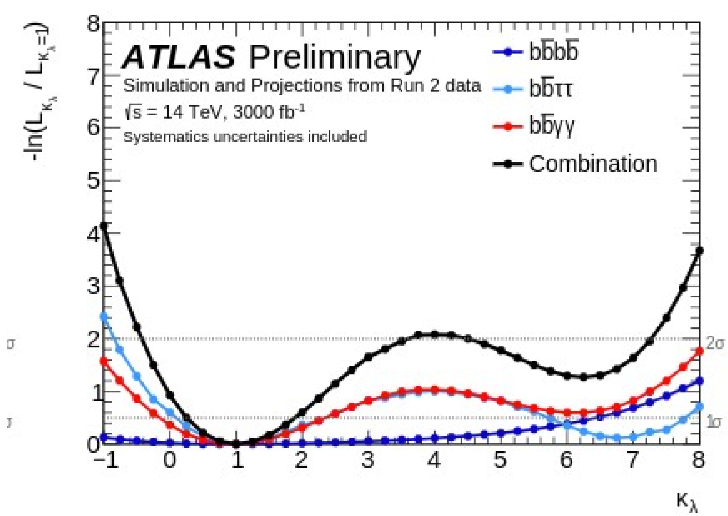

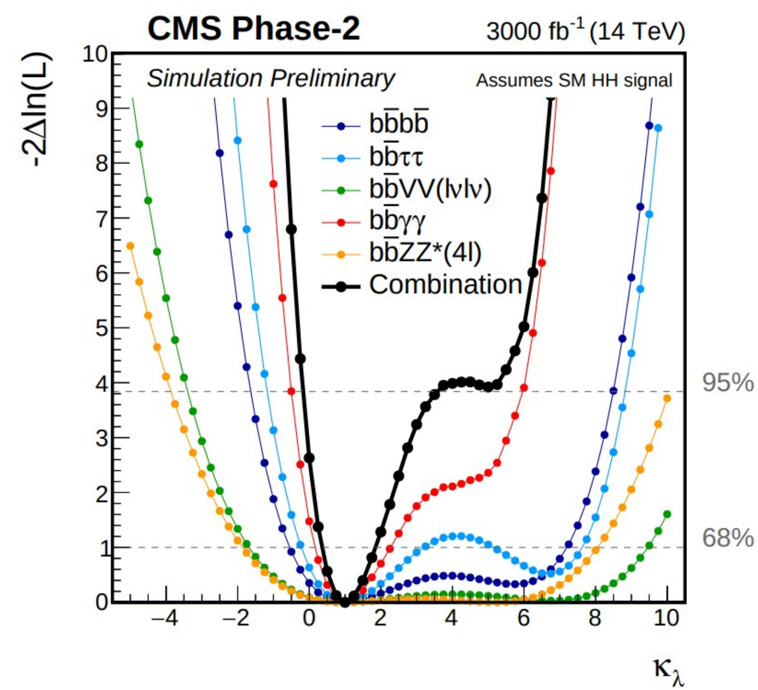

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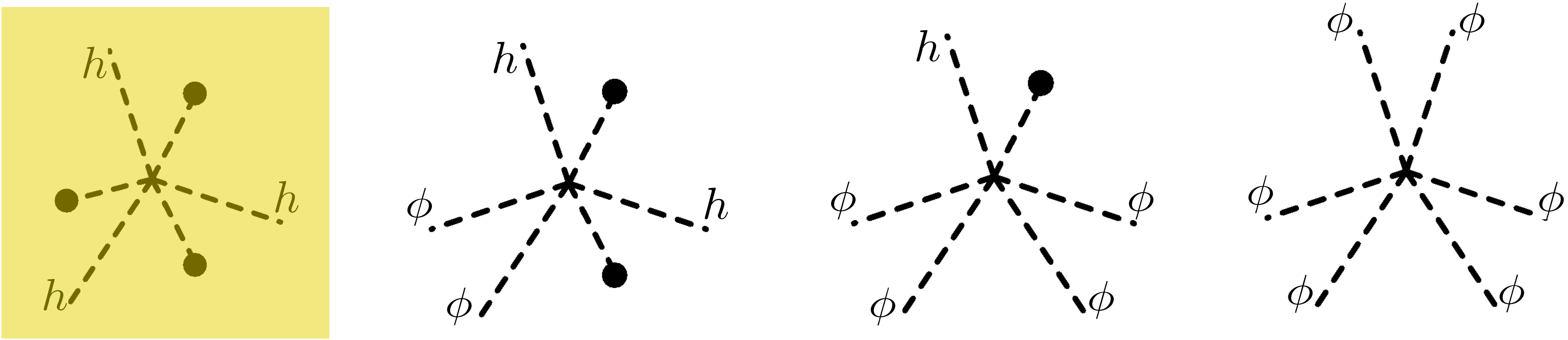

A. Azatov, R. Contino, G. Panico, M. Son, '16

$m_{hh}^{\rm reco}$ [GeV]	250 – 400	400 – 550	550 – 700	700 – 850	850 – 1000	1000–
hh	2.14	6.34	2.86	0.99	0.33	0.17
$\gamma\gamma b\bar{b}$	7.69	10.1	3.35	1.38	1.18	0.59
$\gamma\gamma jj$	0.66	0.95	0.31	0.16	0.08	0.045
$t\bar{t}h$	3.33	4.53	1.41	0.41	0.16	0.043
$b\bar{b}h$	0.20	0.16	0.03	0.0054	0.0022	0.00054
Zh	0.13	0.19	0.067	0.021	0.009	0.0009

TABLE V: Expected number of events after all cuts at $\sqrt{s} = 14\,\text{TeV}$ in each of the six $m_{hh}^{\rm reco}$ categories considered, assuming an integrated luminosity $L = 3000\,\text{fb}^{-1}$. The last category is inclusive.

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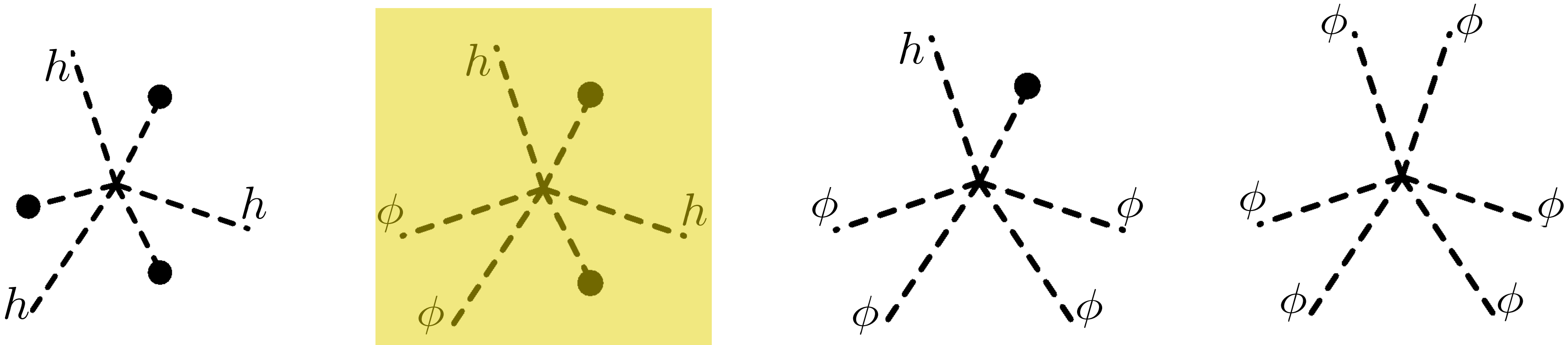
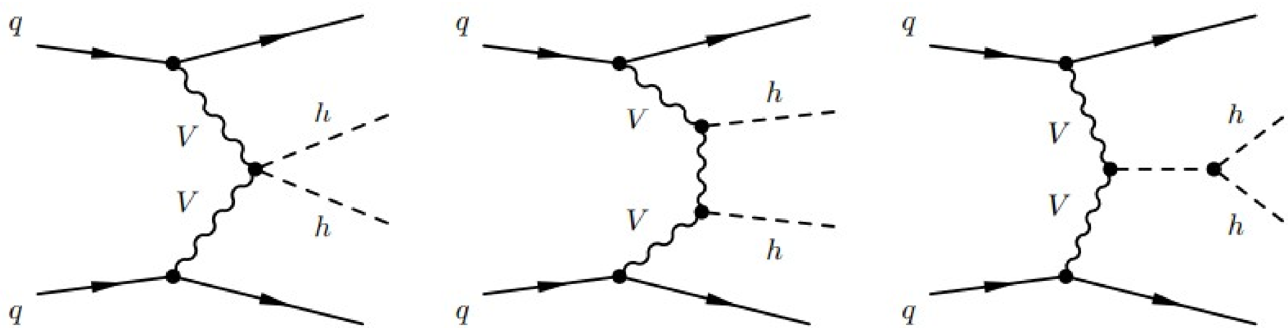


Bishara, Contino, Rojo, '16



No growth with energy, not really competitive with gluon production
Nonetheless, focus of the paper is not in the trilinear

Higgs self-coupling

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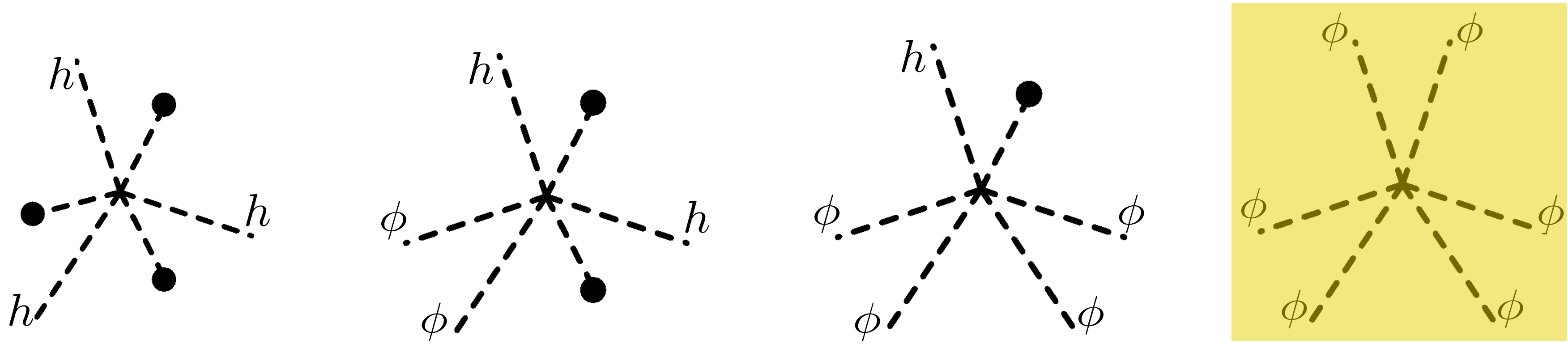
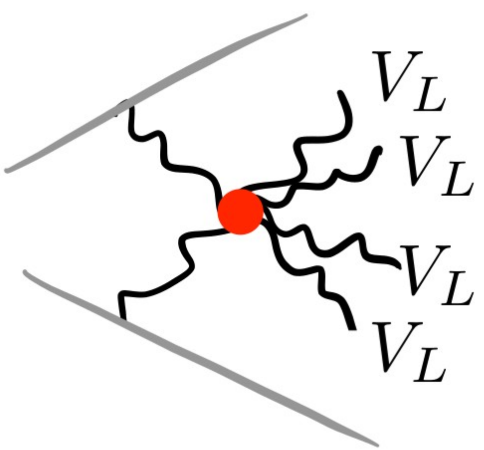


(In progress w/ experimental group in U. Geneve)



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

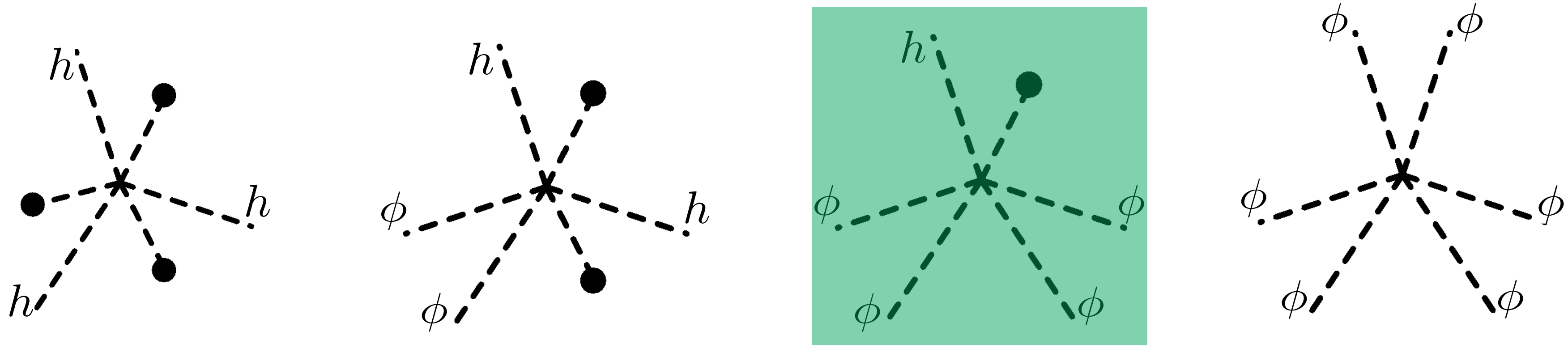
final state

W^+	W^+	W^+	W^+	W^+	W^+	W^+	W^-	W^+	W^-	Z
W^-	W^-	W^-	W^-	W^-	W^-	W^+	W^-	Z	Z	Z
W^+	W^+	W^-	Z	W^+	W^-	Z	Z	Z	Z	Z
W^-	Z	Z	Z	W^+	W^-	Z	Z	Z	Z	Z

```
MG5_aMC>define pm = u u~ d d~
MG5_aMC>generate pm pm > pm pm w+ w- w+ w- QCD=0
Total: 12 processes with 118182 diagrams
Generated helas calls for 12 subprocesses (118182 diagrams) in 379.720 s
Wrote files for 127986 helas calls in 4715.227 s
```

Higgs self-coupling

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



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

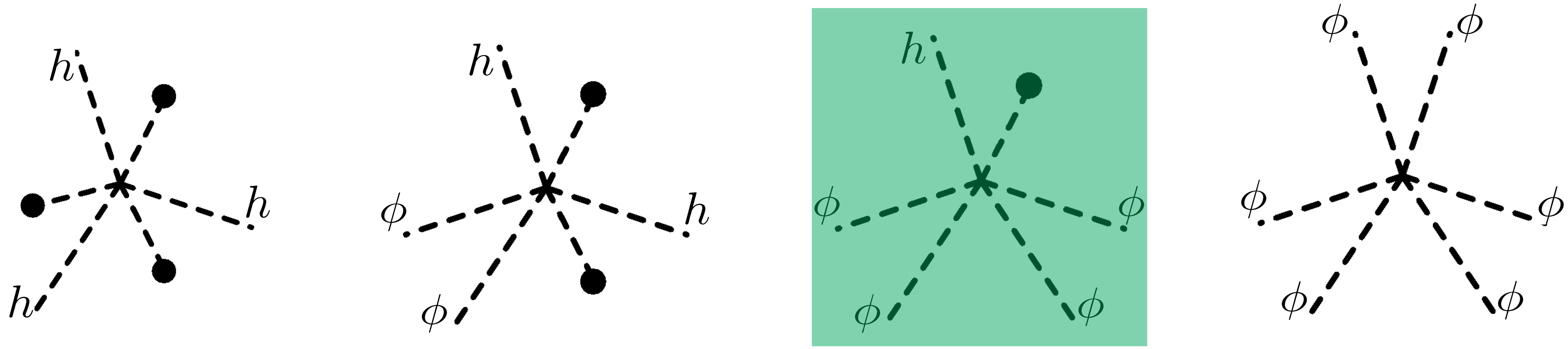
but,

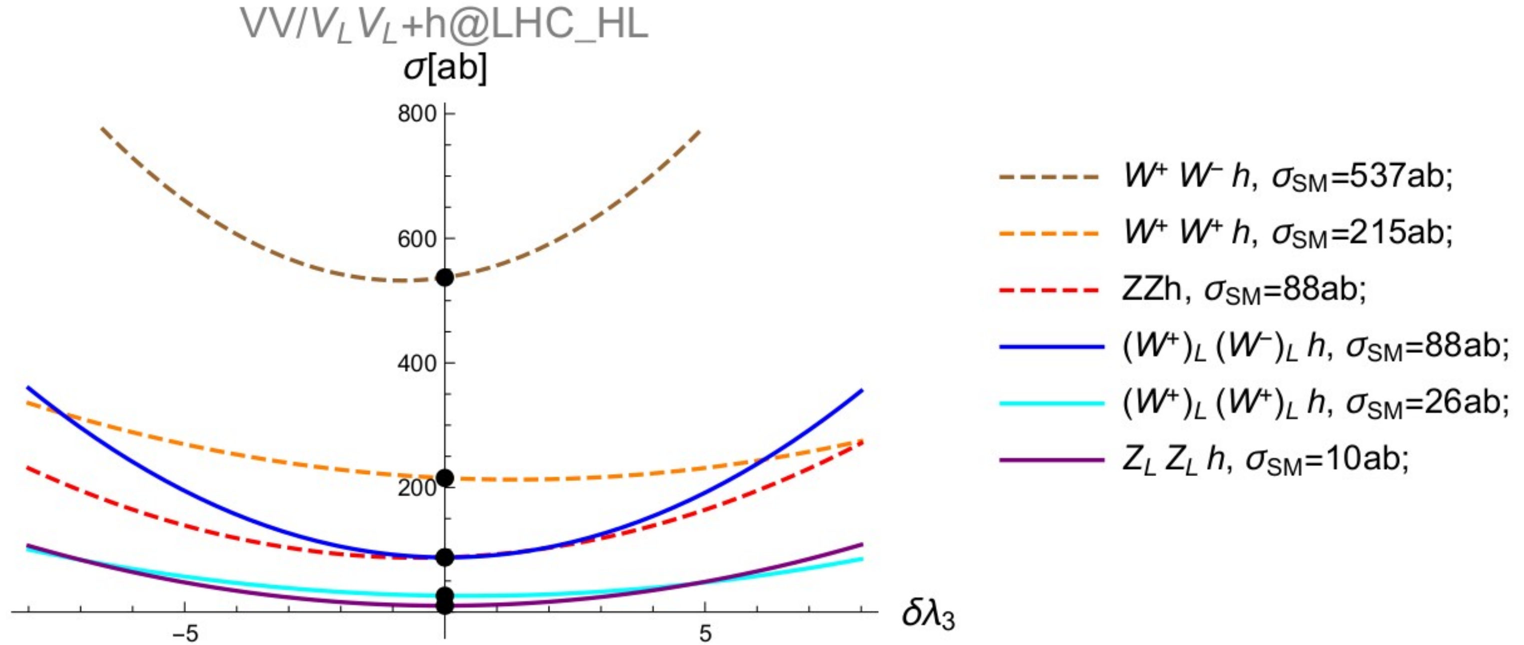
$$\frac{\mathcal{A}(\phi^+\phi^-\phi^+\phi^-h)}{\mathcal{A}(W_T^+W_T^-W_T^+\phi^-h)_{SM}} \sim \frac{c_6 v/\Lambda^2}{p\cdot\epsilon/E^2} \sim c_6\frac{vE}{\Lambda^2}$$

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

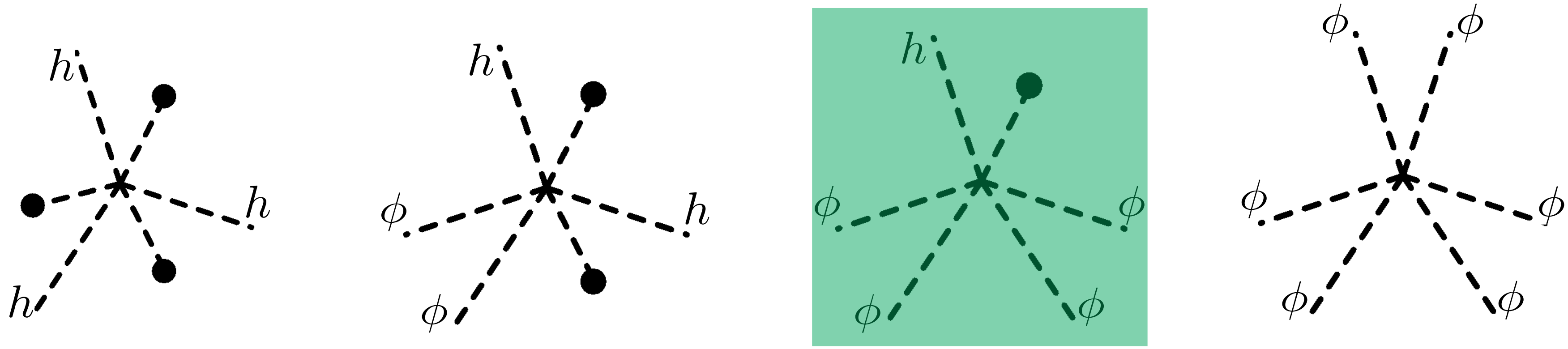
Higgs self-coupling

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





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

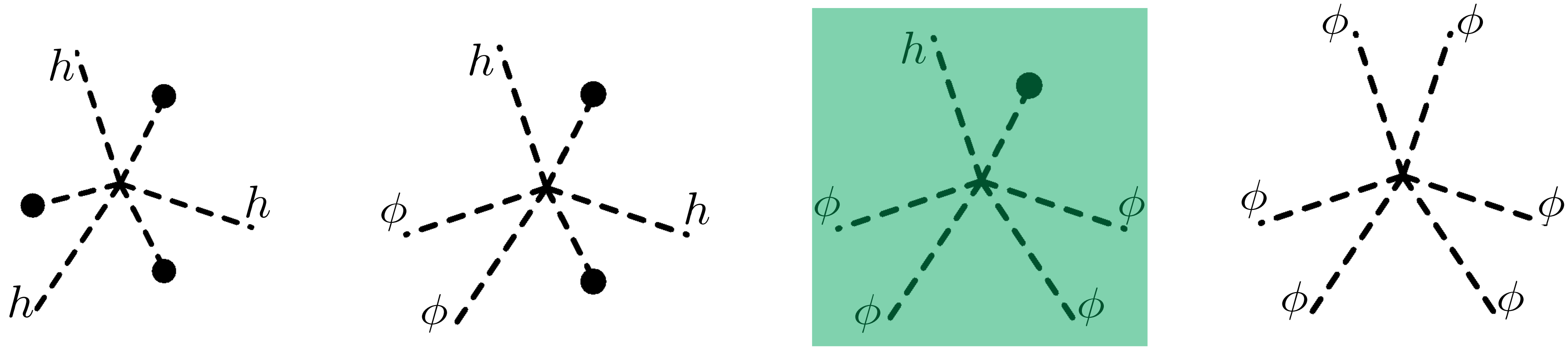


Number of events at 14TeV with 3/ab (mjj>500GeV):

	4j	$2j\ell^\pm\nu$	$2j\ell^\pm\ell^\mp$	$2j\nu\nu$	4ℓ	$3\ell\nu$	$\ell^\pm\ell^\mp\nu\nu$	$\ell^\pm\ell^\pm\nu\nu$	4ν
$W^\pm W^\mp$	732	464	0	0	0	0	73	0	0
$W^\pm W^\pm$	372	235	0	0	0	0	0	37	0
$W^\pm Z$	467	148	45	134	0	14	0	0	0
ZZ	129	0	25	74	1	0	7	0	11
total	1700	847	70	207	1	14	80	37	11

Higgs self-coupling

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



Number of events at 14TeV with 3/ab (mjj>500GeV, no detector):

	4j	$2j\ell^\pm\nu$	$2j\ell^\pm\ell^\mp$	$2j\nu\nu$	4ℓ	$3\ell\nu$	$\ell^\pm\ell^\mp\nu\nu$	$\ell^\pm\ell^\pm\nu\nu$	4ν
$W^\pm W^\mp$	732	464	0	0	0	0	73	0	0
$W^\pm W^\pm$	372	235	0	0	0	0	0	37	0
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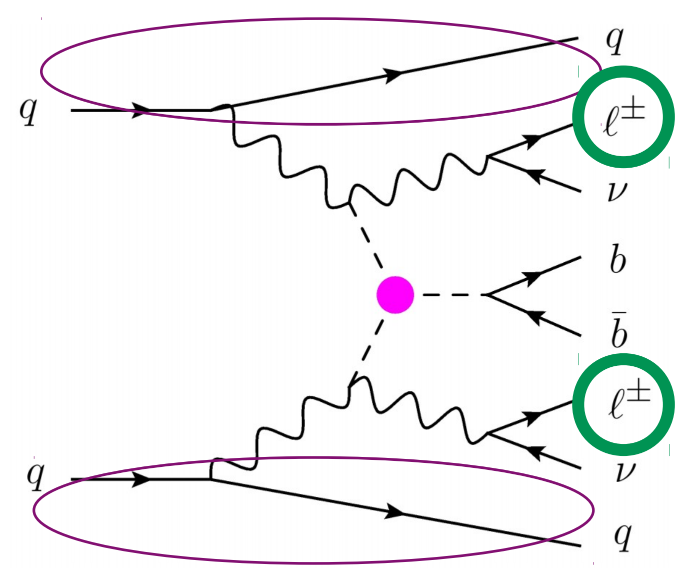
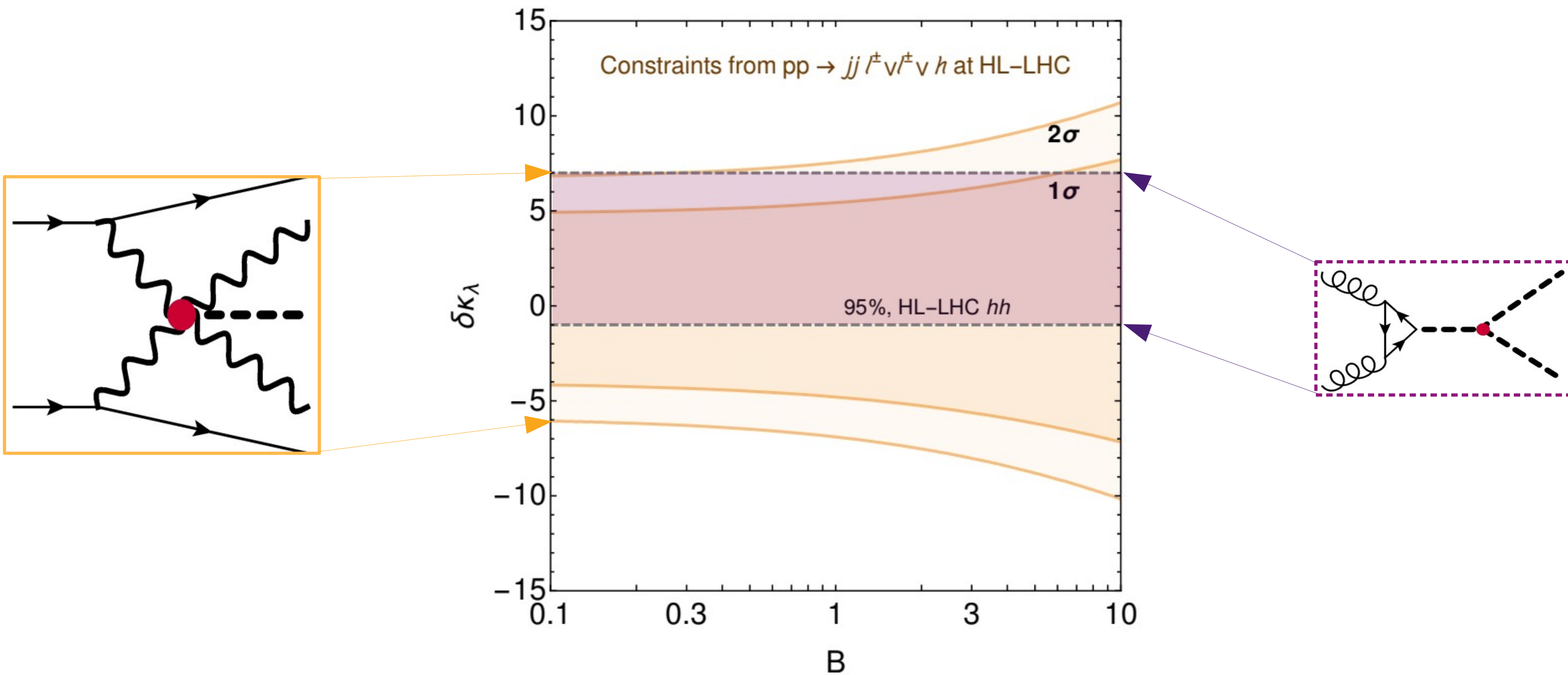


Higgs self-coupling

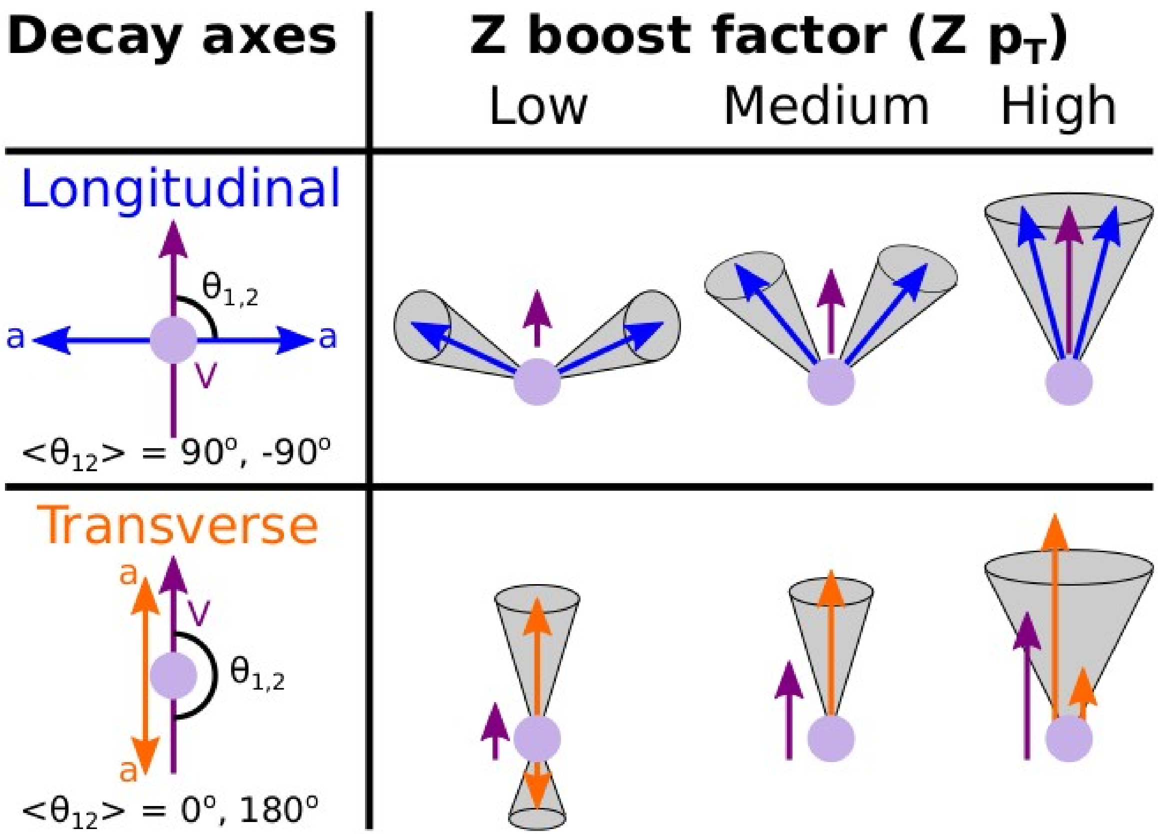


- Irreducible background negligible
- Background from ttjj with lepton misidentification negligible for muons, under control for electrons
- Backgorund from fake leptons is potentially the dominant one. We parametrize it with #back = B x #signal.
- Rough cut-and-count analysis gives competitive results with double higgs production
- Future colliders? $\sigma(W^{\pm}W^{\pm}h + jj)$ *at 13, 27, 100 TeV : 0.2fb, 1.4fb, 13.5fb*

Higgs self-coupling

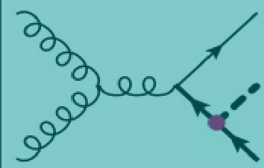
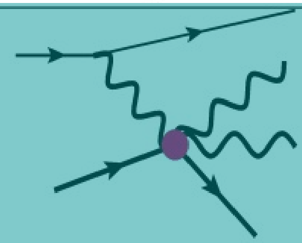
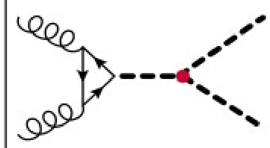
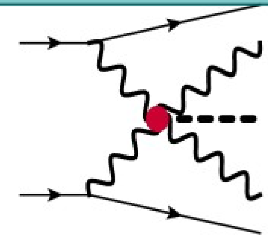
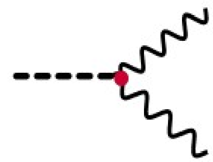
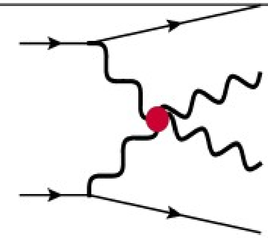
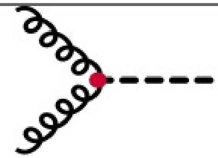
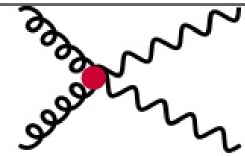
Longitudinal and transverse vectors are two different beasts with different dynamics that happen to be mixed by a mass term.
A tagger to separate them would be a huge step forward.

- High boson p_{T} = "boosted" or "merged" regime
  - This is the realm of **jet substructure**



Slide by Steven Schramm

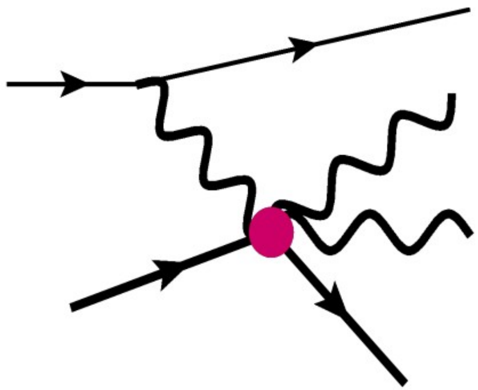
Top Yukawa

		HC	HwH	Growth
κ_t	$\mathcal{O}_{y_t}$			$\sim \frac{E^2}{\Lambda^2}$
κ_λ	$\mathcal{O}_6$			$\sim \frac{vE}{\Lambda^2}$
$\kappa_{Z\gamma}$ $\kappa_{\gamma\gamma}$ κ_V	$\mathcal{O}_{WW}$ $\mathcal{O}_{BB}$ $\mathcal{O}_r$			$\sim \frac{E^2}{\Lambda^2}$
κ_g	$\mathcal{O}_{gg}$			$\sim \frac{E^2}{\Lambda^2}$

Top Yukawa

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

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



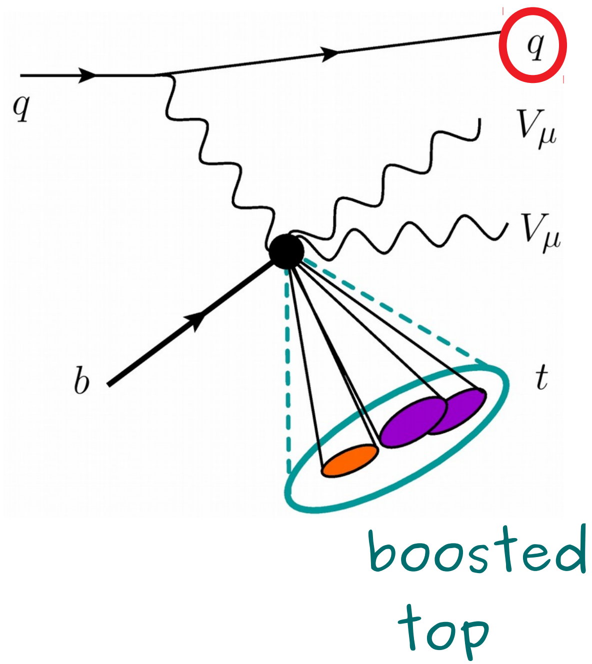
$$\sim \frac{E^2}{\Lambda^2}$$

Many final states, many decays… just if we had something to simplify the analysis…

Top Yukawa

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

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



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

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)

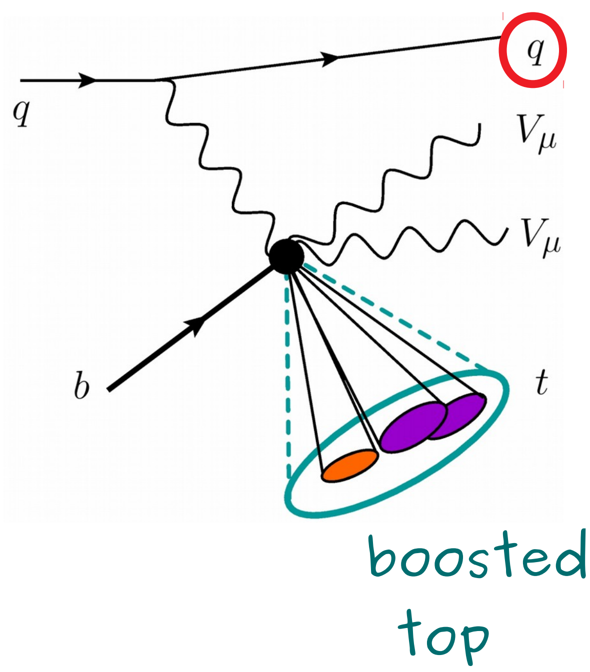
$p_T^t > 250$ GeV / $p_T^t > 500$ GeV

Strategy: look for a single boosted top + forward jet,
then just count leptons!

Top Yukawa

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

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



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$W^\pm Z$	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

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

small background

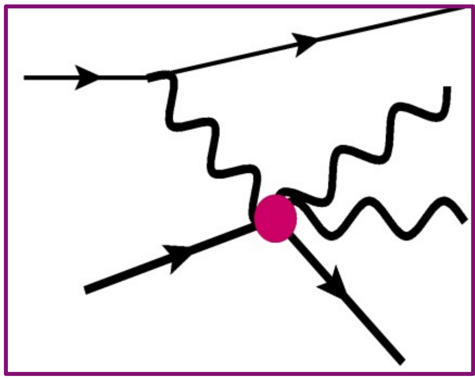
Top Yukawa

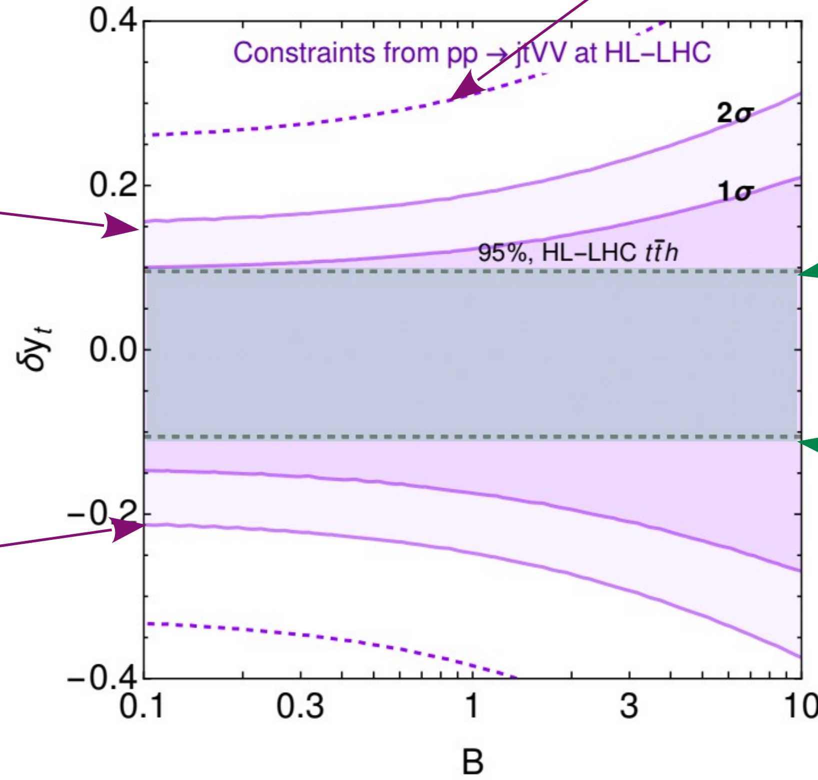
$t\bar{t}jj \to tWbjj$ background estimation:

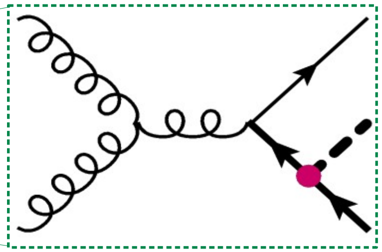
	$p_T^t > 250$ GeV	$p_T^t > 500$ GeV
$\lvert\eta_j\rvert > 2.5, p_T^j > 30\text{GeV}, E_j > 300\text{GeV}$	470fb (80xsignal)	22fb (20xsignal)
$b \to j$ missid: 10% for 90% light j acceptance (ATLAS-PHYS-PUB-2017-013 (2017))	47fb (8xsignal)	2fb (2xsignal)
Vector boson tagging: 10^2 rej for 40% acceptance (ATLAS-CONF-2018-016 (2018))	B~S	B<~S

Top Yukawa

>2 leptons only





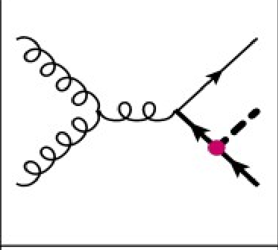
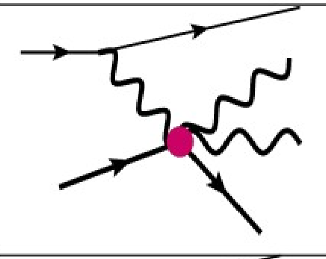
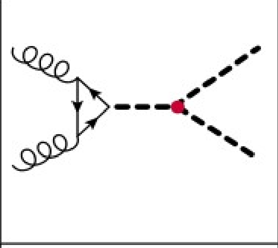
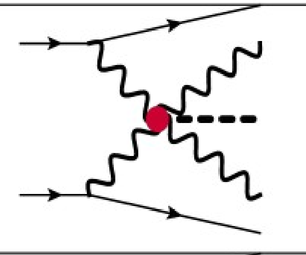
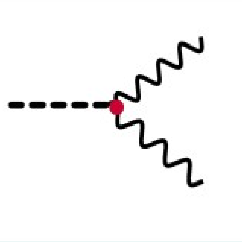
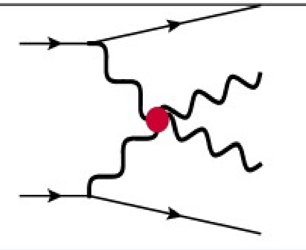
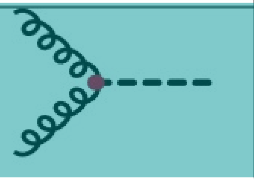
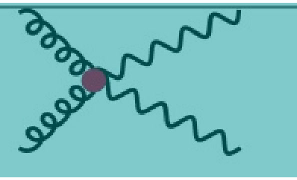


Again, we parametrize background with B x signal

Competitive with on-shell Higgs measurements

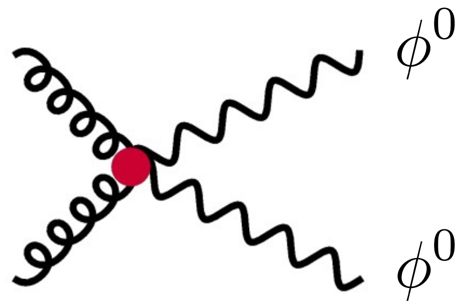
Further improvements: background characterization, specially for hadronic,
differential information, larger E^2,
get rid of transverse polarizations

H to gluons

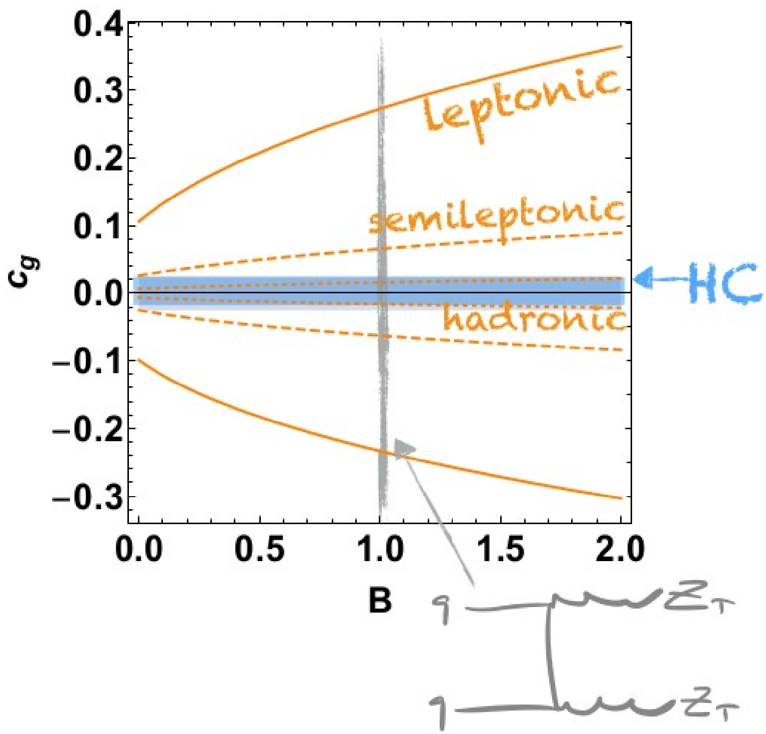
		HC	HwH	Growth
κ_t	$\mathcal{O}_{y_t}$			$\sim \frac{E^2}{\Lambda^2}$
κ_λ	$\mathcal{O}_6$			$\sim \frac{vE}{\Lambda^2}$
$\kappa_{Z\gamma}$ $\kappa_{\gamma\gamma}$ κ_V	$\mathcal{O}_{WW}$ $\mathcal{O}_{BB}$ $\mathcal{O}_r$			$\sim \frac{E^2}{\Lambda^2}$
κ_g	$\mathcal{O}_{gg}$			$\sim \frac{E^2}{\Lambda^2}$

H to gluons

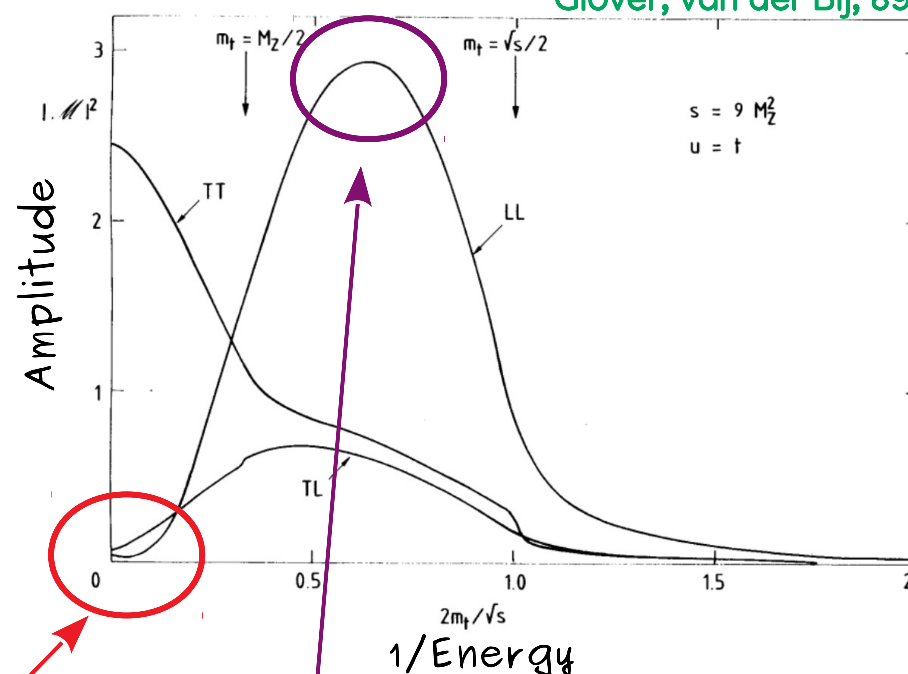
Azatov, Grojean, Paul, Salvioni, '14



Contraints looking only at rates:



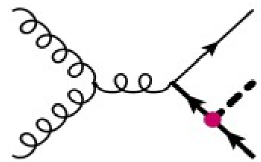
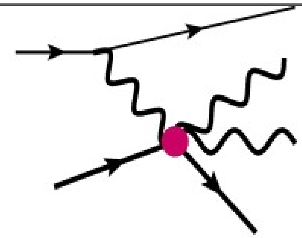
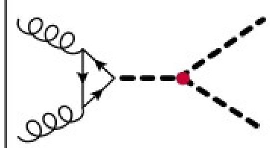
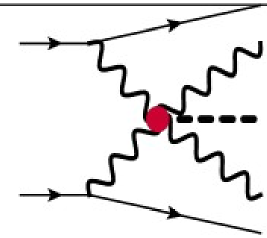
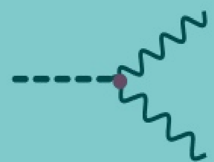
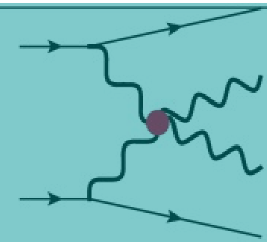
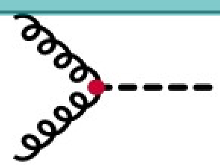
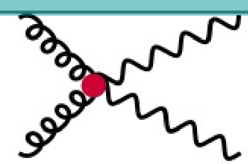
Glover, van der Bij, 89



Production of longitudinal modes goes to zero at high energies (similar to send quarks mass to zero)

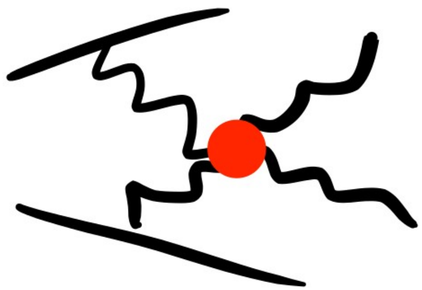
Should be possible to 'sit' at this maximum and dig out the longitudinals to improve constraints & be sensitive to linear terms only

Vector boson scattering

		HC	HwH	Growth
κ_t	$\mathcal{O}_{y_t}$			$\sim \frac{E^2}{\Lambda^2}$
κ_λ	$\mathcal{O}_6$			$\sim \frac{vE}{\Lambda^2}$
$\kappa_{Z\gamma}$ $\kappa_{\gamma\gamma}$ κ_V	$\mathcal{O}_{WW}$ $\mathcal{O}_{BB}$ $\mathcal{O}_r$			$\sim \frac{E^2}{\Lambda^2}$
κ_g	$\mathcal{O}_{gg}$			$\sim \frac{E^2}{\Lambda^2}$

Vector boson scattering

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



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

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

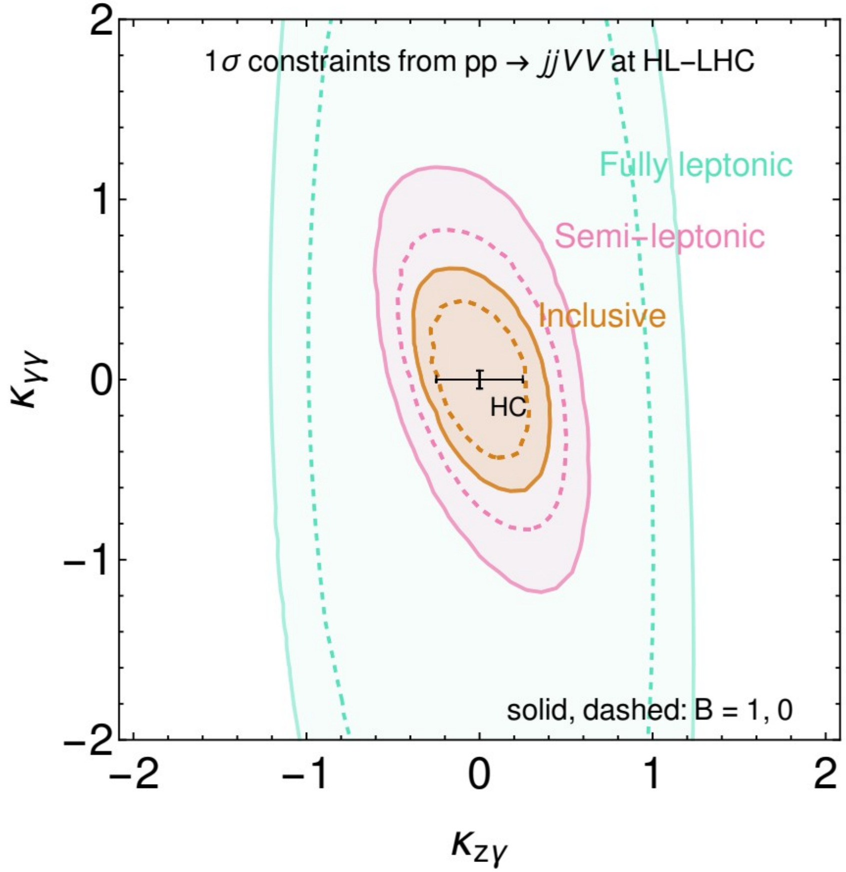
We project current analysis on W+W+, WZ, ZZ and Zγ

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



–Competitive for Zγ, not for γγ

–If VBS with W+fat jet, W+W– will also enter

Conclusions

Conclusions

- Characterization of Higgs is crucial
- HwH processes competitive and complementary to HC measurements
- Endless oportunities for improvements:
  - Precise theoretical predictions
  - Understanding of relevant kinematics
  - Experimental control of systematics and backgrounds
  - Theoretical understanding of longitudinal vs transverse gauge bosons
  - Experimental handle on longitudinal vs transverse gauge bosons
  - BSM interpretation
- Important for future high energy colliders, HE-LHC, CLIC, FCC/SppC