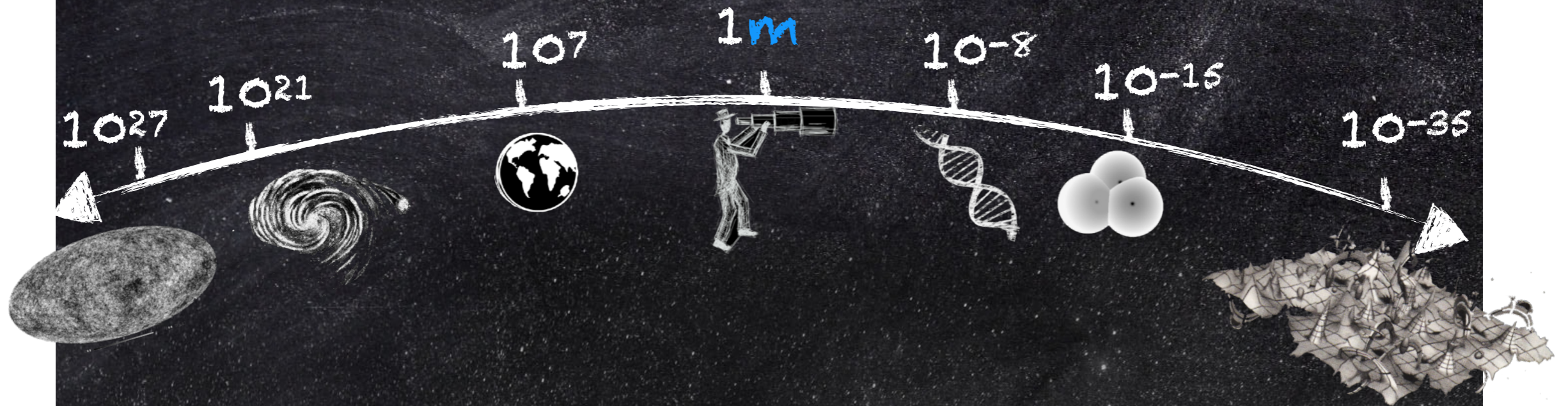


# Higgs Couplings ... without the Higgs at FCChh



Francesco Riva  
(Geneva University)

# Precision Tests of SM Distributions

Off-shell

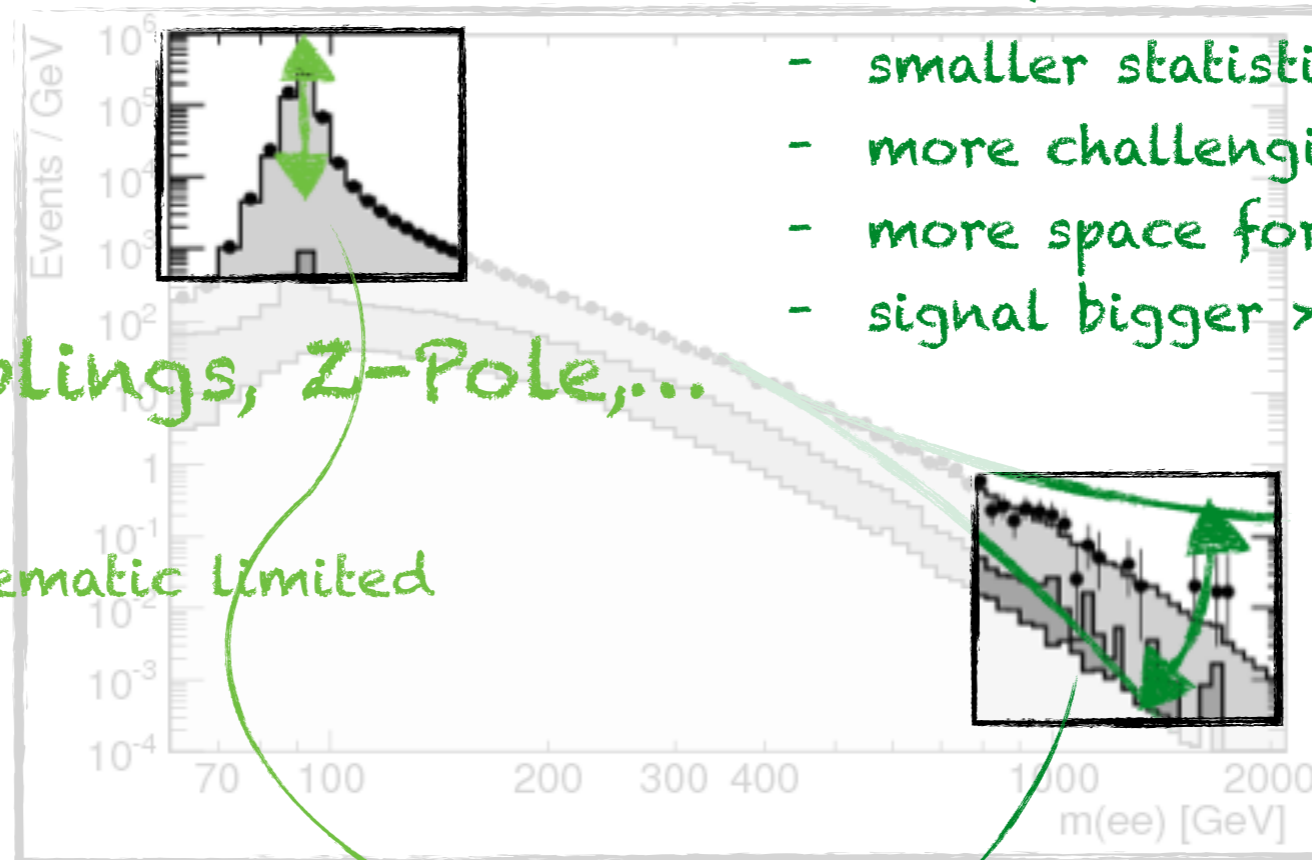
e.g.  $2 \rightarrow 2$  processes (WZ, LL, ...)

On-shell

e.g. Higgs Couplings, Z-Pole, ...

- big statistics
- sooner or later systematic limited

- smaller statistics
- more challenging measurement
- more space for improvement
- signal bigger > precise measurement



$$\sigma = \sigma_{\text{SM}} \left( 1 + c \frac{E^2}{\Lambda^2} + \dots \right)$$

# Precision Tests of SM Distributions

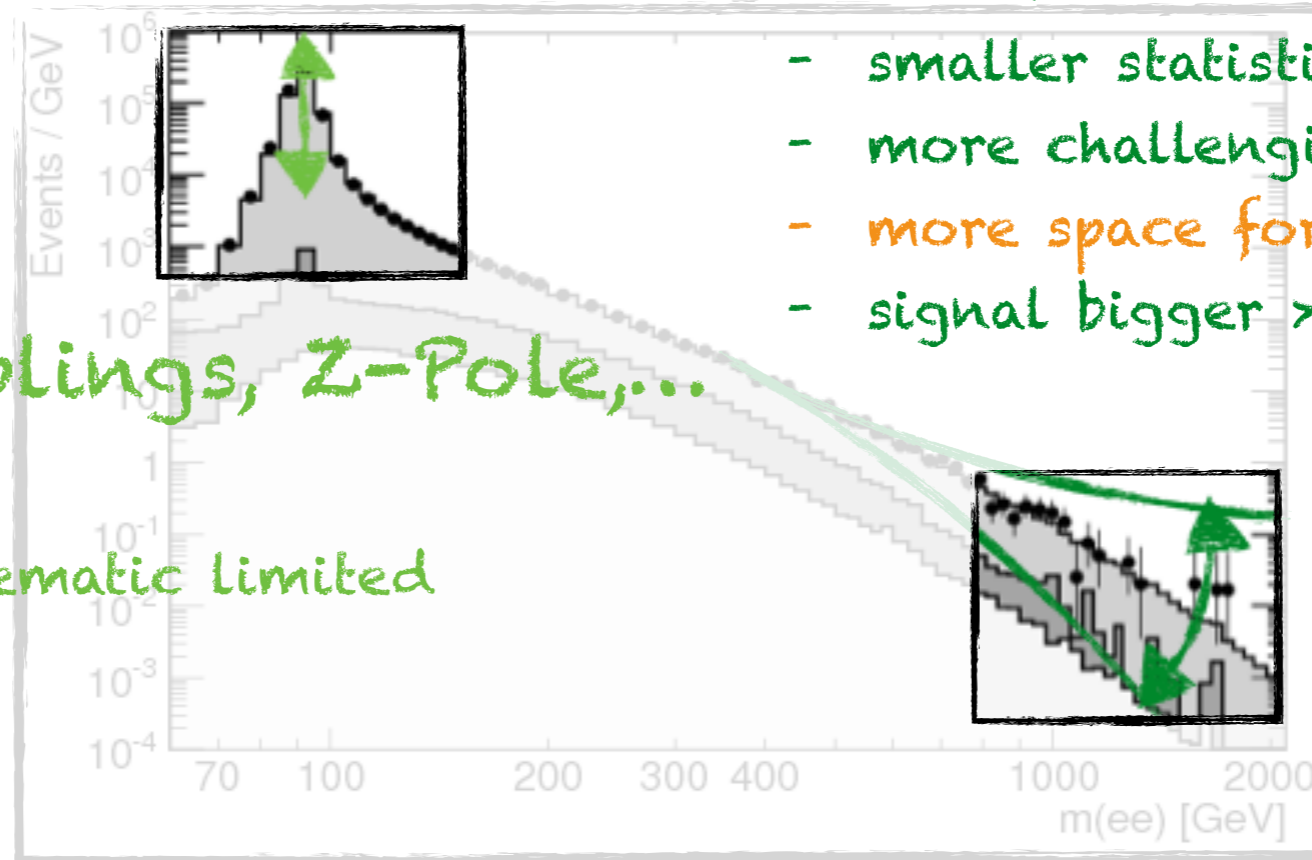
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Experimentally very appealing

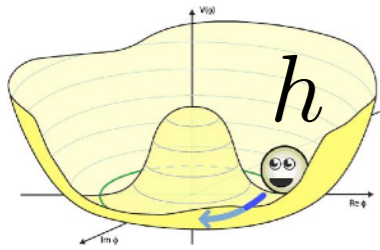
# Higgs Couplings

Modified Higgs sectors have modified Higgs couplings

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Modified Higgs sectors have modified Higgs couplings

**Composite Higgs Models:** Higgs is a (pseudo) goldstone boson



SM

$h$



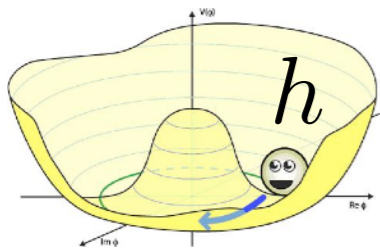
BSM

$$\sin h = \left( h - \frac{h^3}{3!} + \dots \right)$$

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$\bar{\psi}\psi h$

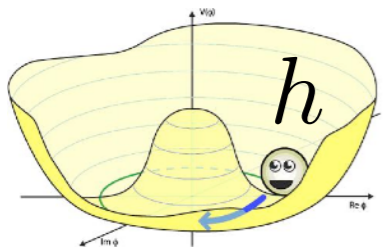
$$\bar{\psi}\psi h + c \bar{\psi}\psi h^3$$

ALL tree-level Higgs Couplings are modified

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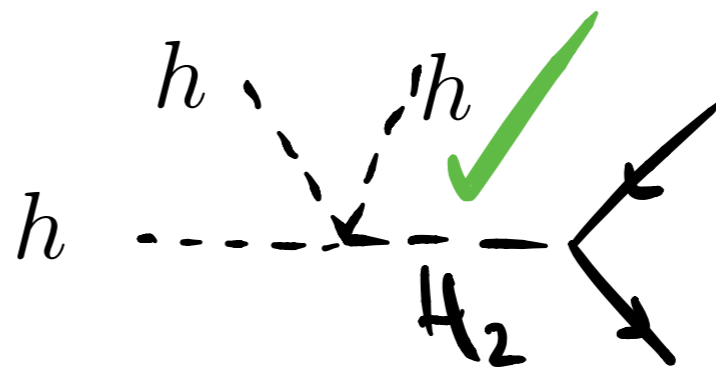
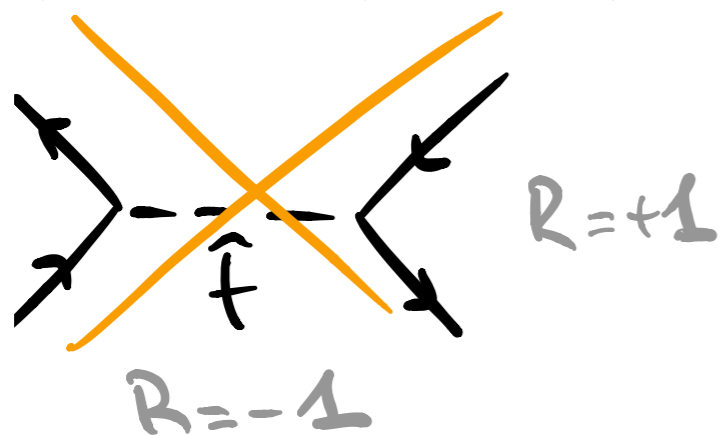
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ALL tree-level Higgs Couplings are modified

second Higgs

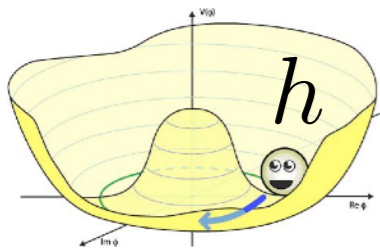
Supersymmetry: only  $H_2$  exchanged at tree-level (R-parity)



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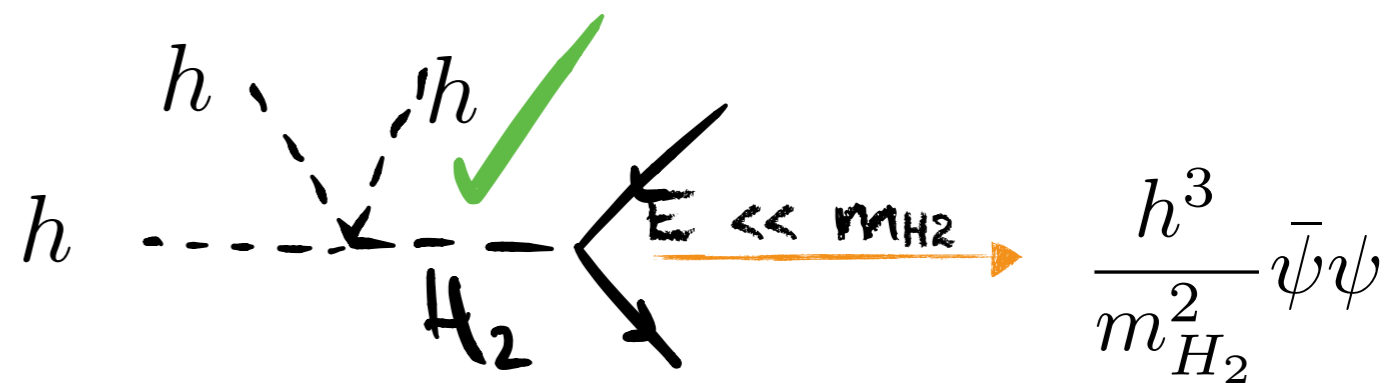
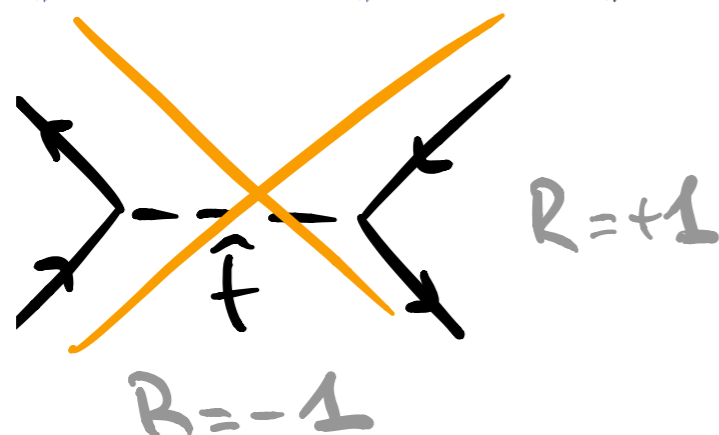
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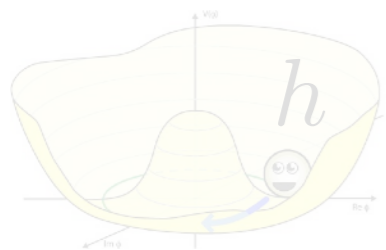
Higgs couplings to top/bottom modified



# Higgs Couplings

Modified Higgs sectors have modified Higgs couplings

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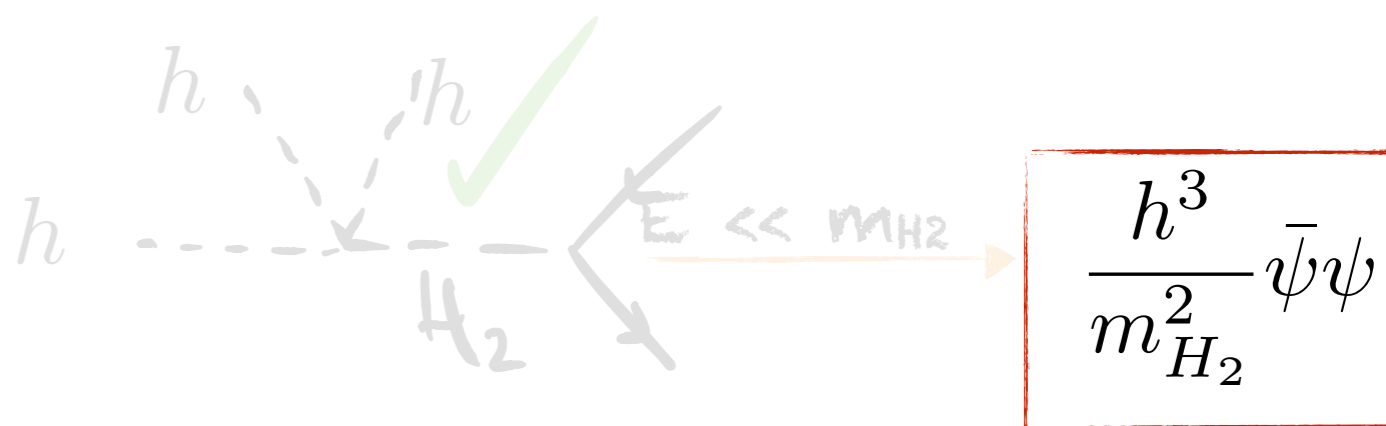
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All tree-level Higgs Couplings are modified

second Higgs

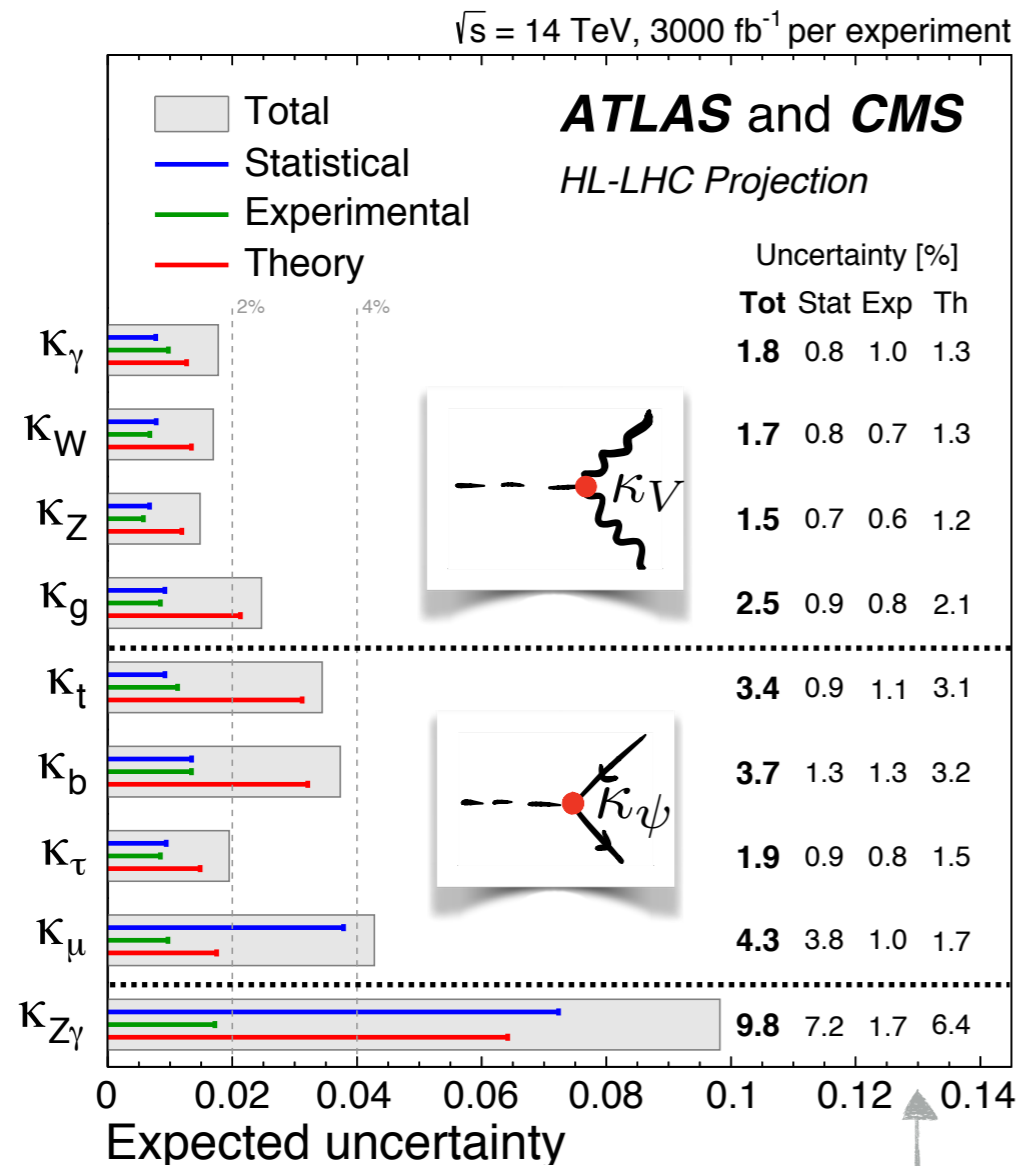
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# Higgs Couplings Reach

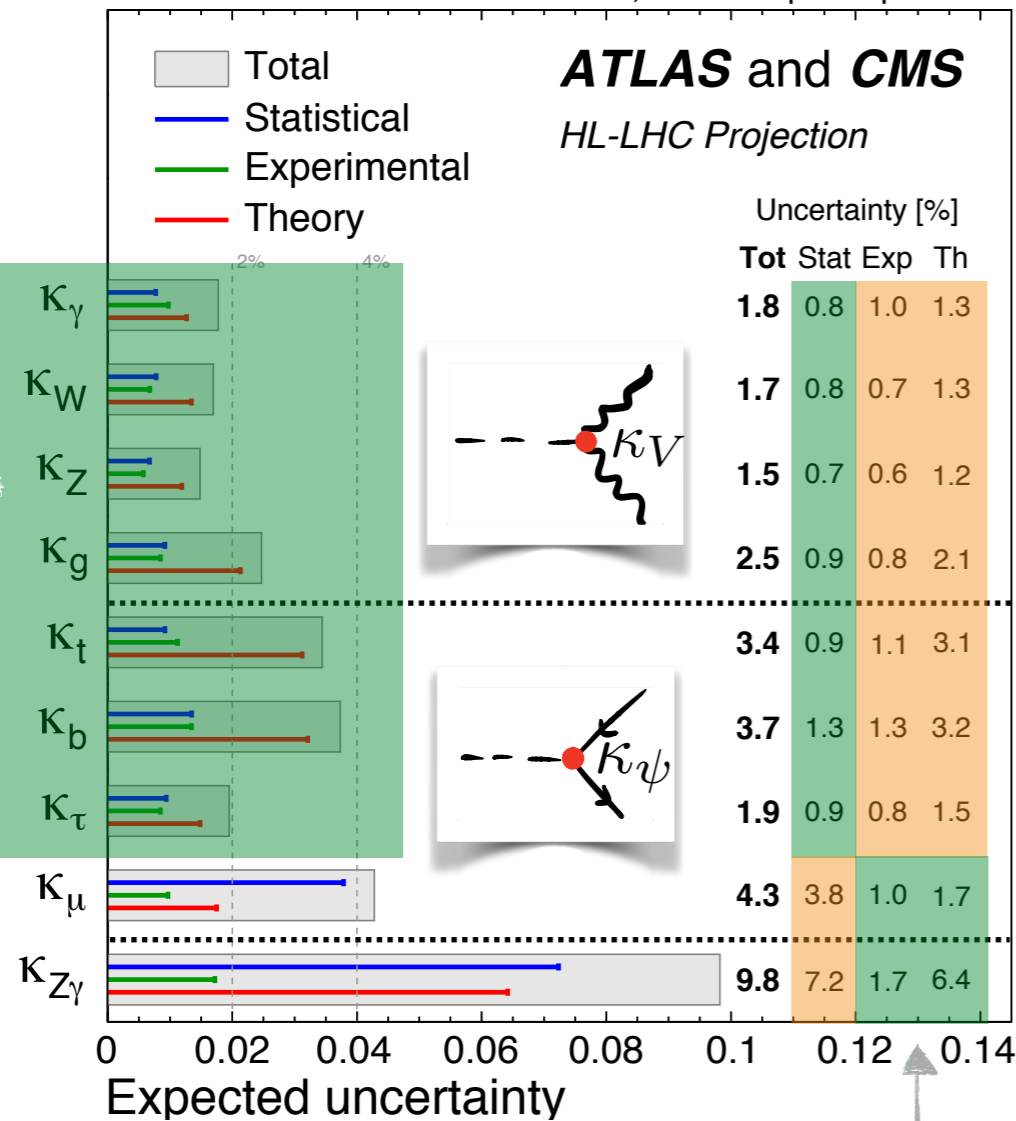
Higgs couplings (HC) are measured in processes with on-shell Higgs ( $E=125$  GeV)



# Higgs Couplings Reach

Higgs couplings (HC) are measured in processes with on-shell Higgs ( $E=125$  GeV)

$\sqrt{s} = 14$  TeV,  $3000 \text{ fb}^{-1}$  per experiment



stat. < syst.

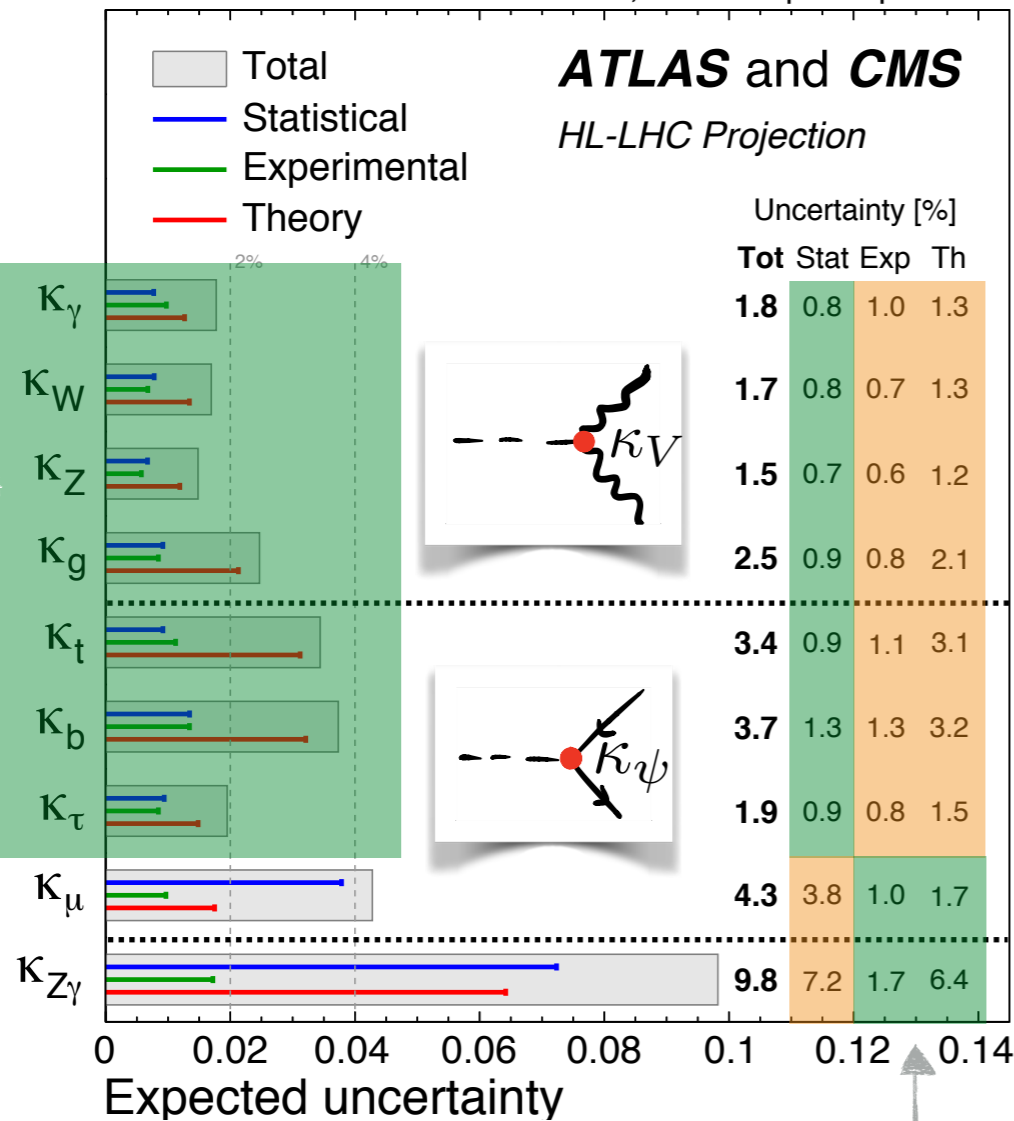
Optimistic Systematics (S2)

# Higgs Couplings Reach

Higgs couplings (HC) are measured in processes with on-shell Higgs ( $E=125$  GeV)

$\sim 1/10$

$\sqrt{s} = 14$  TeV,  $3000 \text{ fb}^{-1}$  per experiment



kappa-0	HL-LHC	FCC-ee		FCC-ee/eh/hh
		240	365	
$\kappa_W$ [%]	1.7	1.3	0.43	0.14
$\kappa_Z$ [%]	1.5	0.20	0.17	0.12
$\kappa_g$ [%]	2.3	1.7	1.0	0.49
$\kappa_\gamma$ [%]	1.9	4.7	3.9	0.29
$\kappa_{Z\gamma}$ [%]	10.	81*	75*	0.69
$\kappa_c$ [%]	—	1.8	1.3	0.95
$\kappa_t$ [%]	3.3	—	—	1.0
$\kappa_b$ [%]	3.6	1.3	0.67	0.43
$\kappa_\mu$ [%]	4.6	10	8.9	0.41
$\kappa_\tau$ [%]	1.9	1.4	0.73	0.44

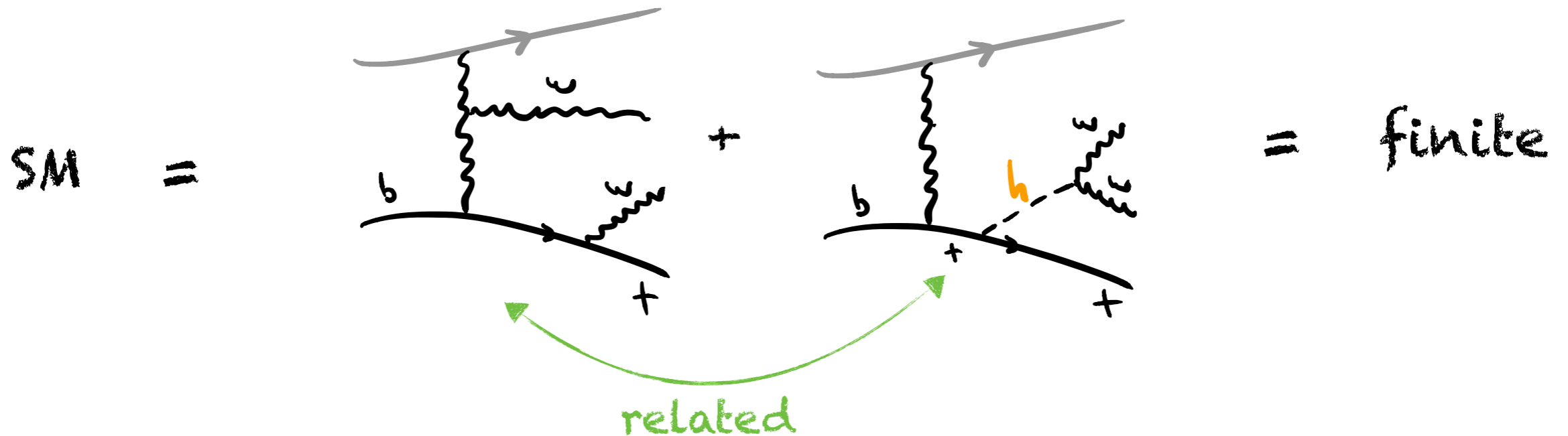
# Higgs Couplings... without a Higgs (HWH)

Henning, Lombardo, Riembau, FR' 19

It would be nice if Higgs Couplings would also deform distributions!

Any modifications of Higgs couplings induces also  $E^2$  growth in some process with longitudinal W,Z bosons!

One way of seeing this:



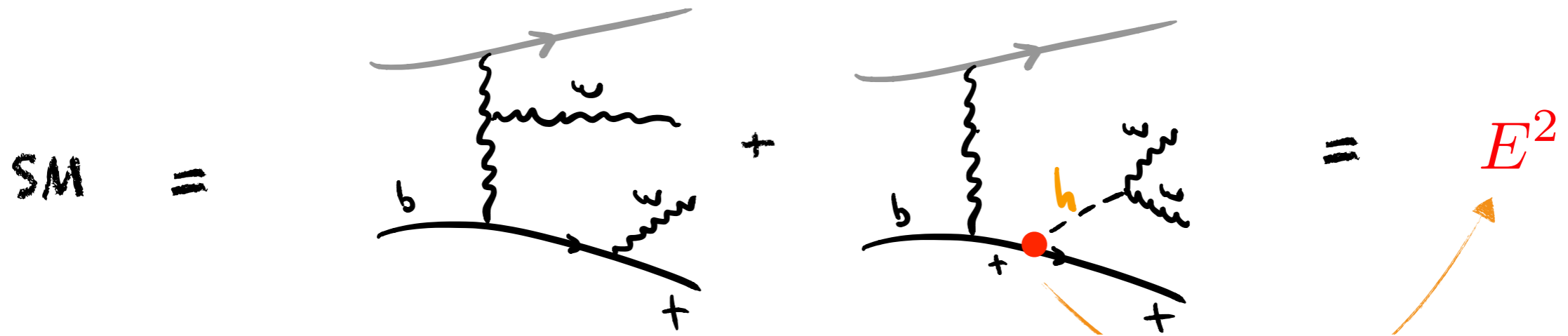
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One way of seeing this:



modification of top-yukawa  
compromises gauge cancellations in the SM  
►  $E^2$ -growth

Cornwall, Levin, Tiktopoulos'74

# Top Yukawa... without a Higgs

Another way of understanding E-growth:

$$\text{modified Top-Yukawa } \kappa_t \iff \frac{|H|^2 Q \tilde{H} t_R}{\Lambda^2}$$

# Top Yukawa... without a Higgs

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modified Top-Yukawa  $K_t$



$$\frac{|H|^2}{\Lambda^2} Q \tilde{H} t_R$$

$$H = \begin{pmatrix} \phi^+ \\ h + i\phi^0 \end{pmatrix}$$

Goldstones =  $W_L, Z_L$

$$|H|^2 = \frac{1}{2} (v^2 + 2hv + h^2 + 2\phi^+\phi^- + (\phi^0)^2)$$



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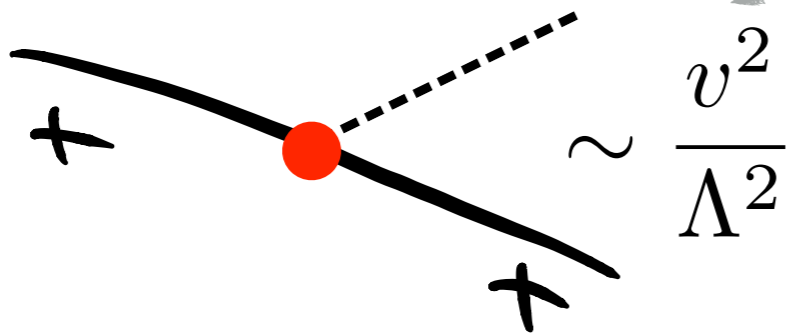


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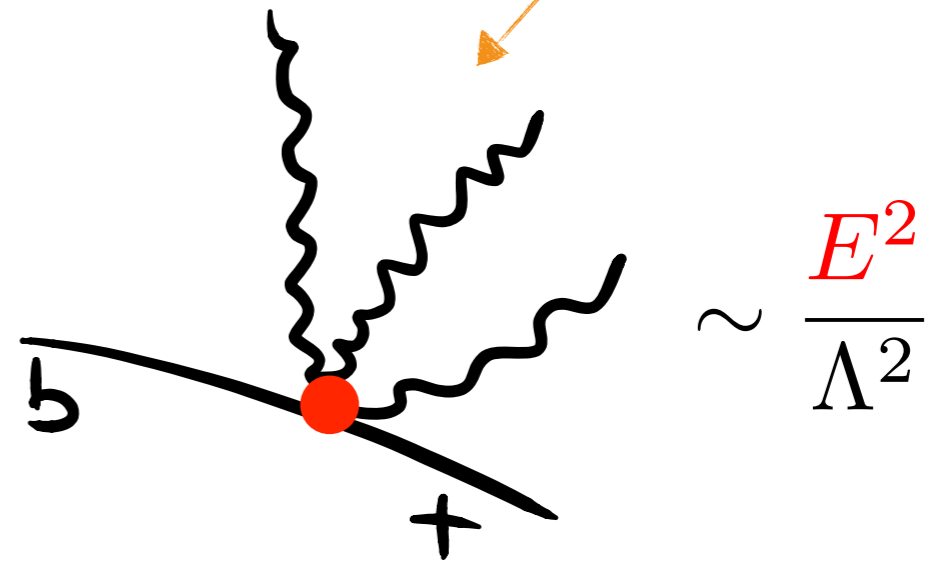
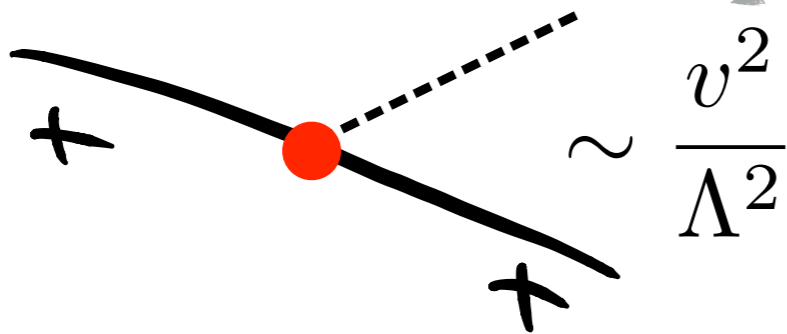


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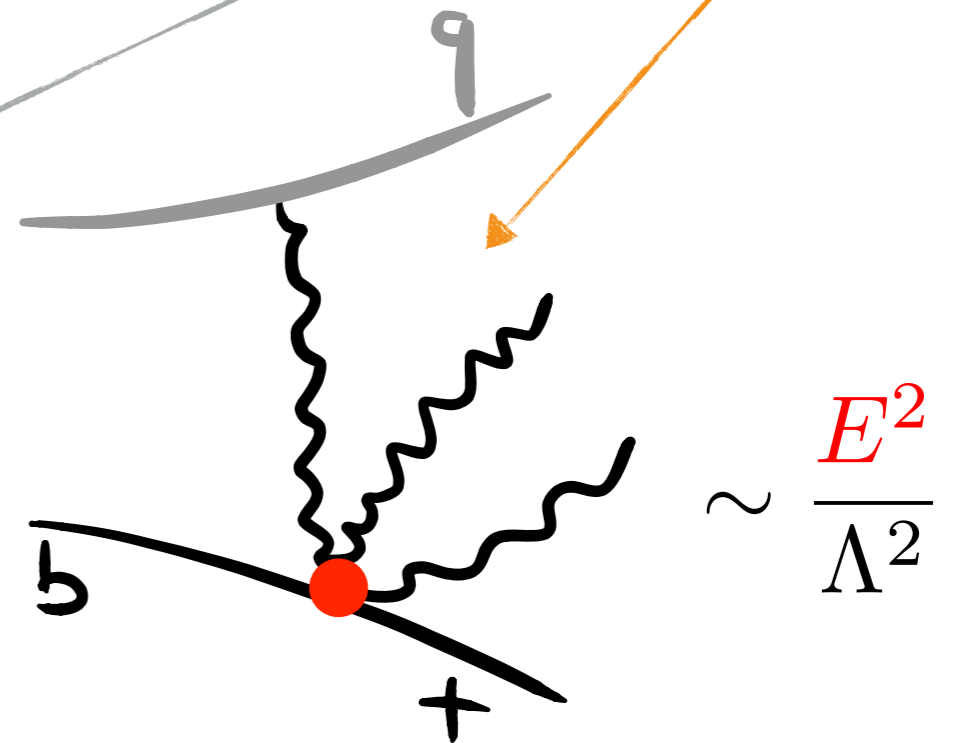
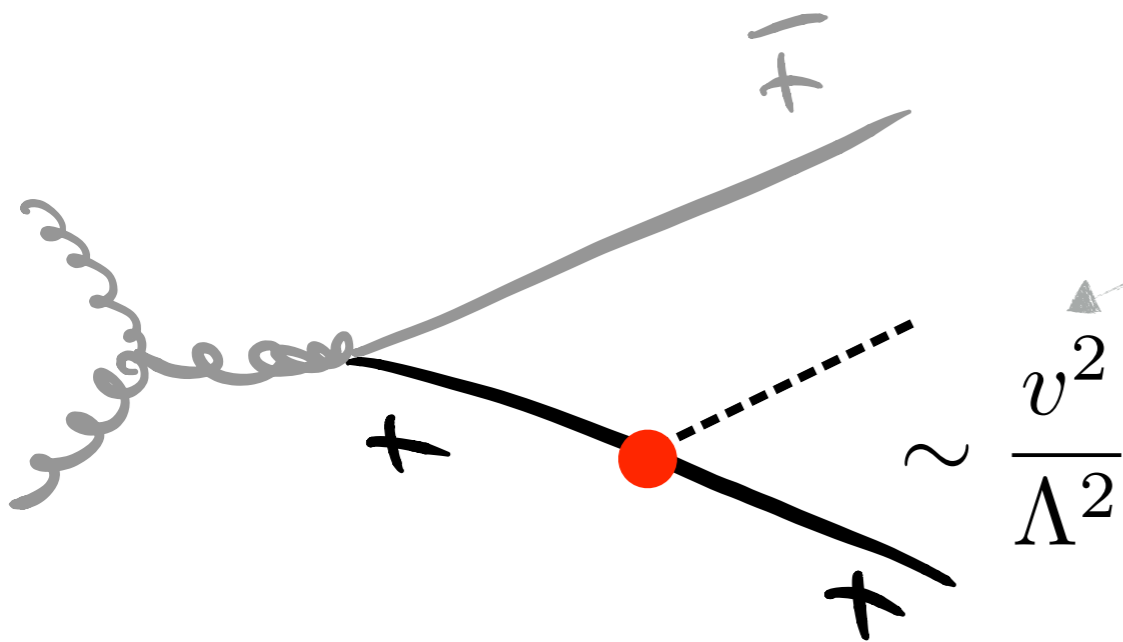


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statistics  
signal



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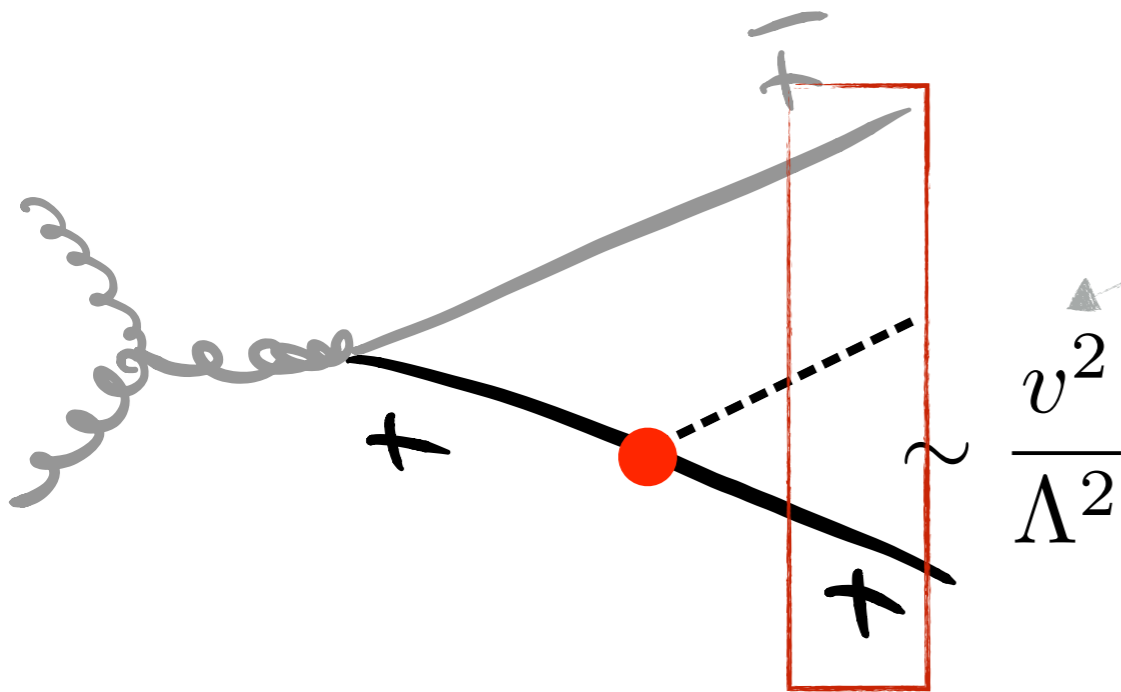


$$\frac{|H|^2}{\Lambda^2} Q \tilde{H} t_R$$

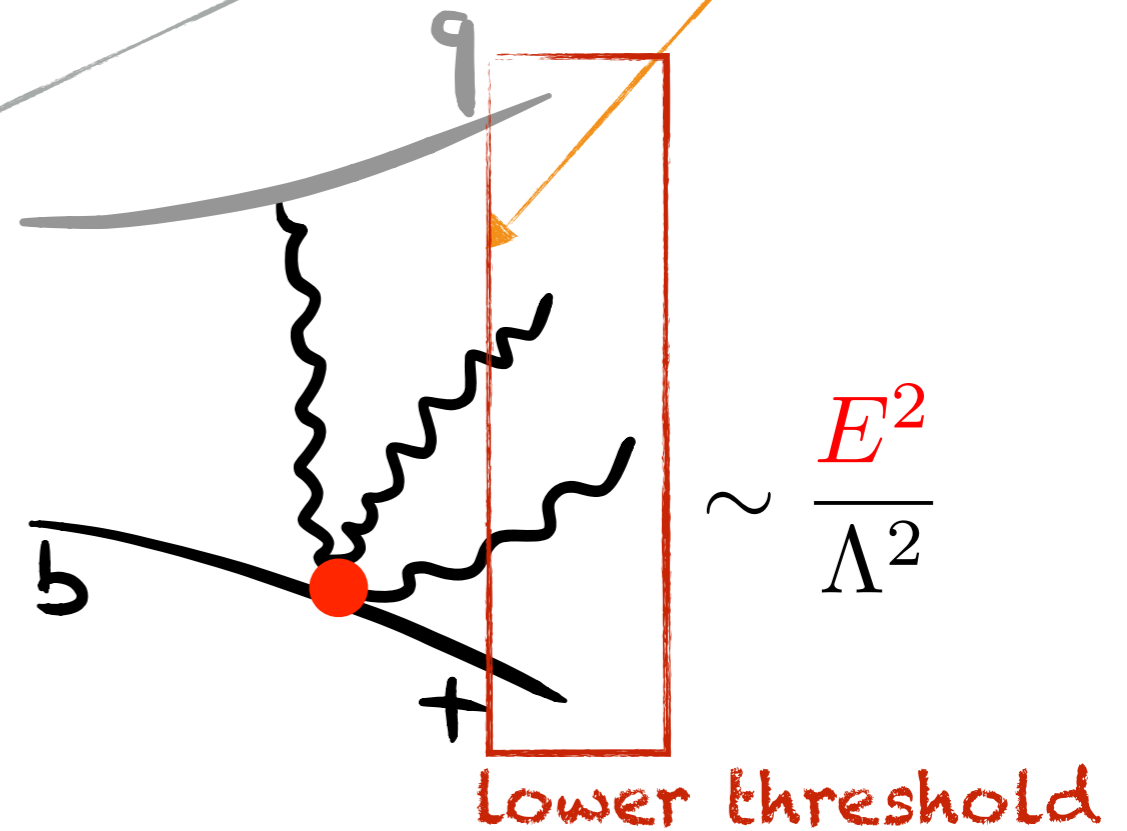
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$$|H|^2 = \frac{1}{2} (v^2 + 2hv + h^2 + 2\phi^+\phi^- + (\phi^0)^2)$$



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



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

Lower threshold

statistics  
signal



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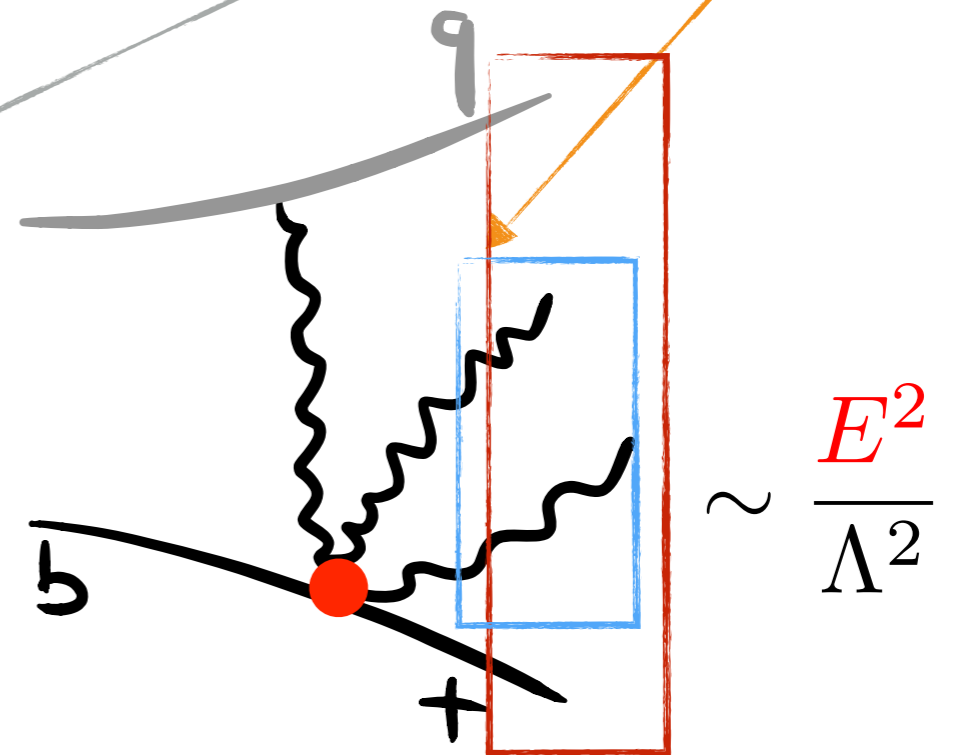
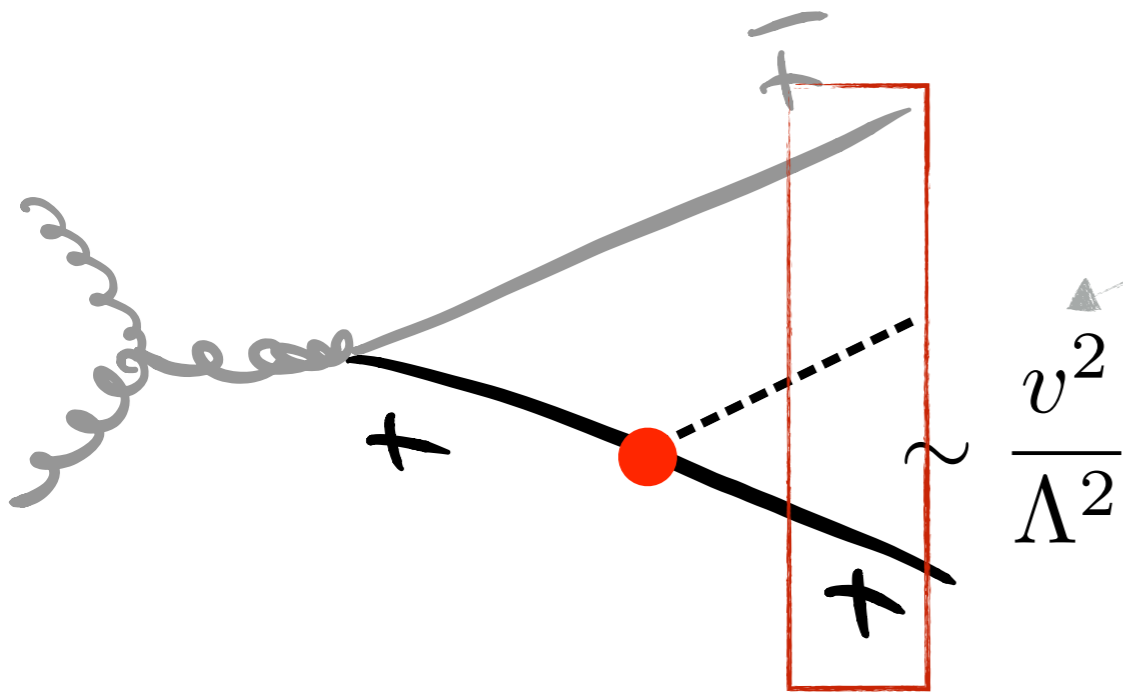


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Lower threshold

Many final states ( $WW, WZ, ZZ$ )

← statistics

→ signal

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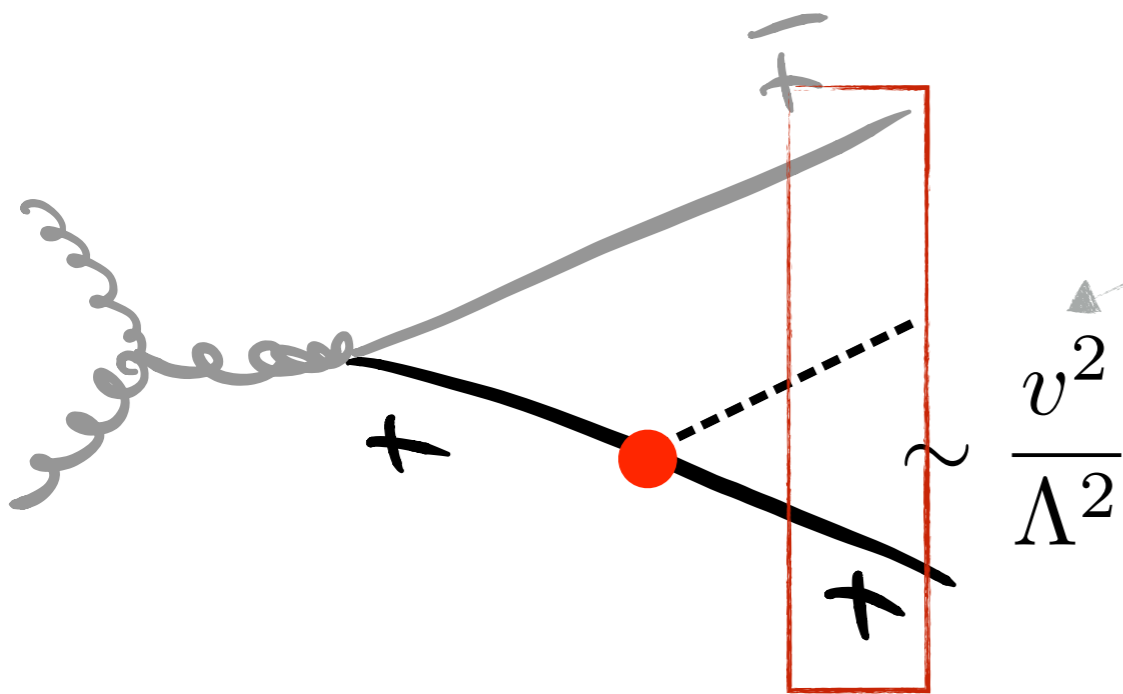


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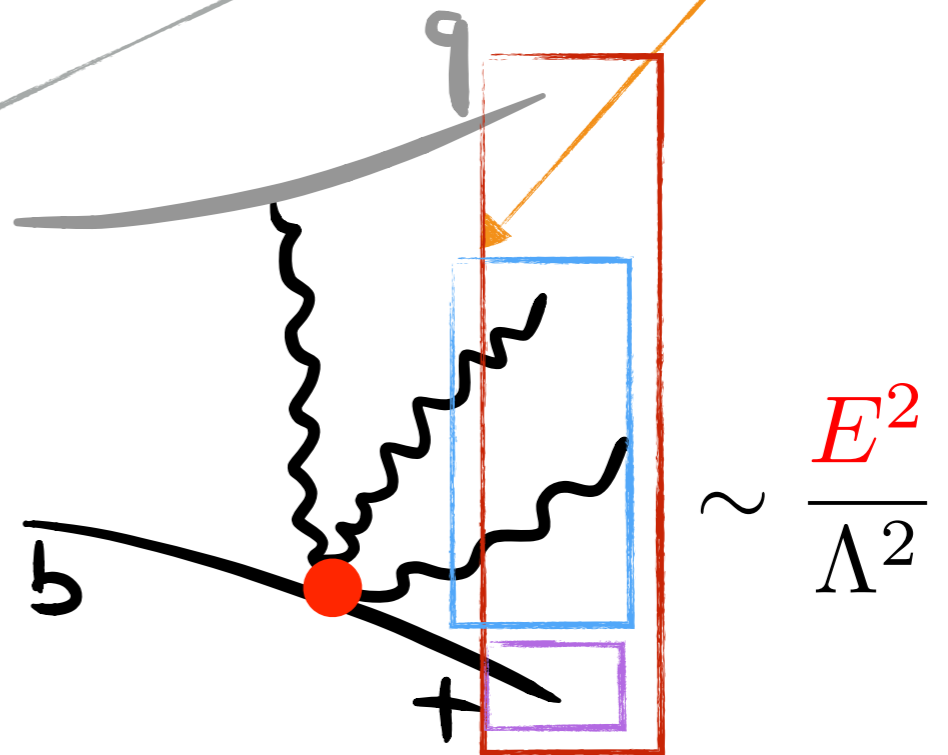
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$$\sim \frac{v^2}{\Lambda^2}$$



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

Lower threshold

Many final states ( $WW, WZ, ZZ$ )

Boosted top

statistics  
signal



# Top Yukawa... without a Higgs

$$pp \rightarrow VVjt$$

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SM signal classified by #leptons:

Process	0l	1l	$l^\pm l^\mp$	$l^\pm l^\pm$	3l(4l)
$W^\pm W^\mp$	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)

$p_T^t > 250 \text{ GeV} / p_T^t > 500 \text{ GeV}$



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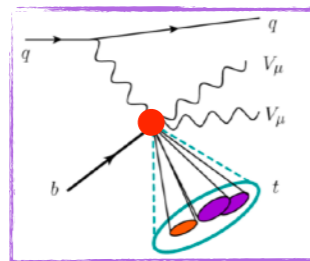
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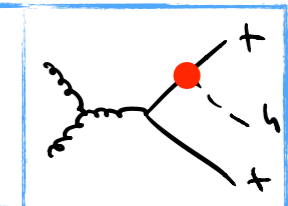
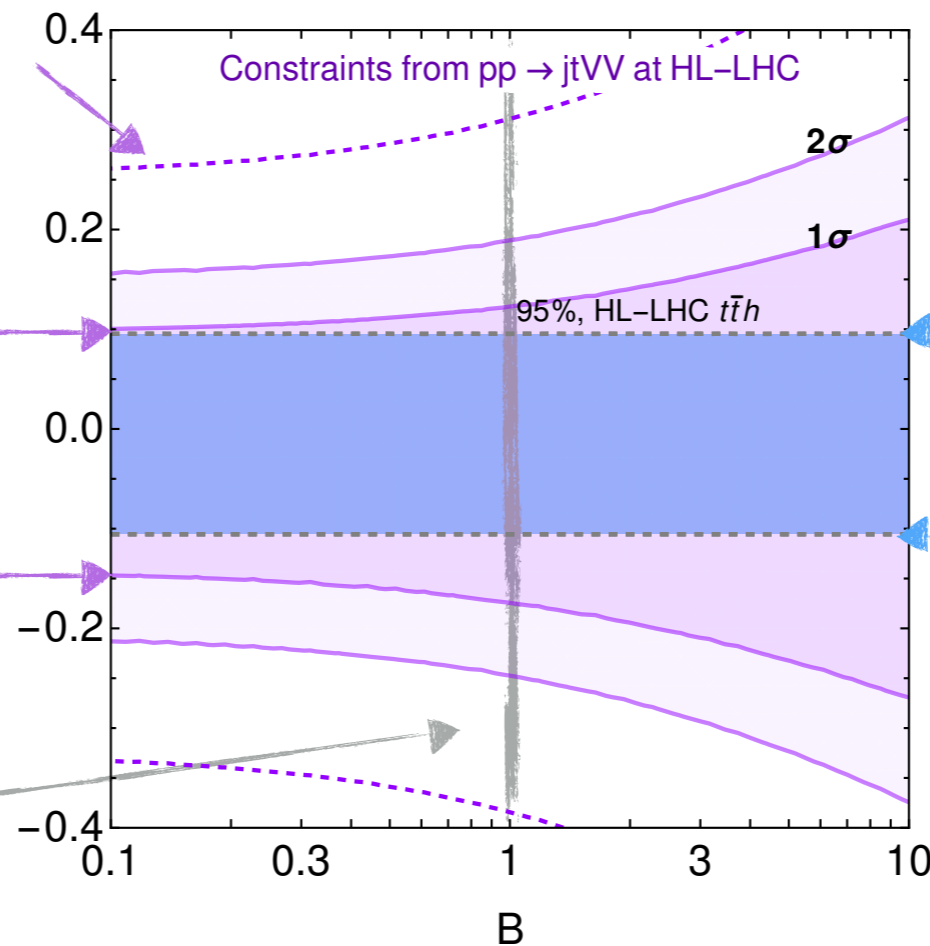
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$p_T^t > 250 \text{ GeV} / p_T^t > 500 \text{ GeV}$

only channels with >2 leptons (small B)



$\delta y_t$



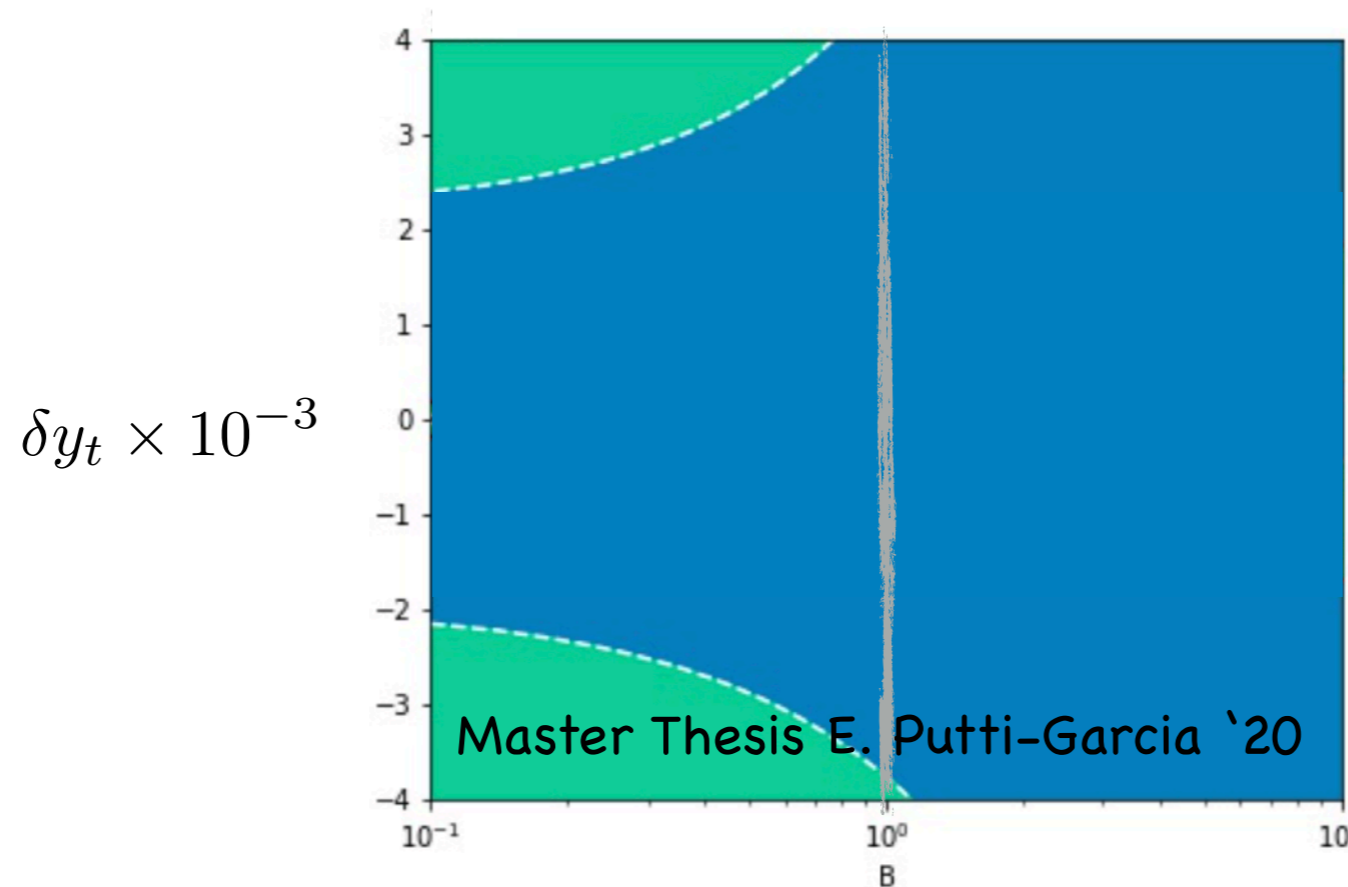
Background = SM signal

▶ Competitive with standard!

# Top Yukawa... without a Higgs

$$pp \rightarrow VVjt$$

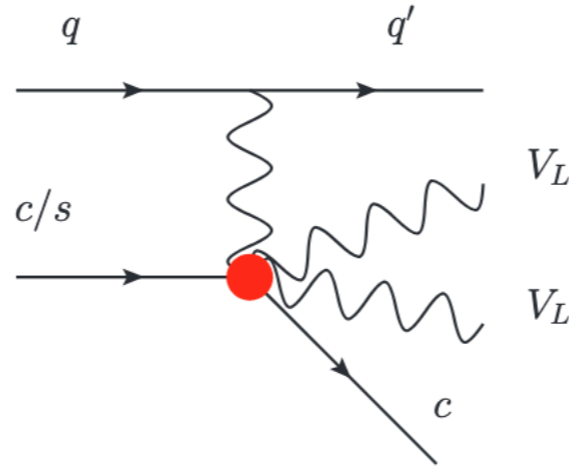
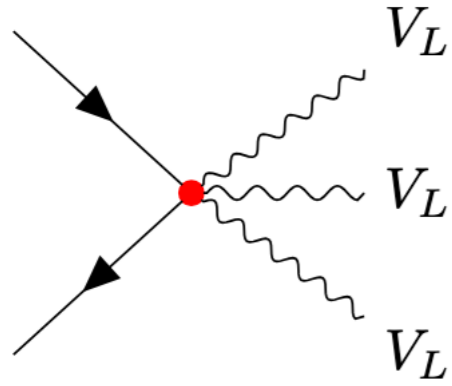
FCC-hh bounds from E. Putti-Garcia master thesis  
...very preliminary



A factor 100x improvement? More detailed analysis required...

# Light Yukawas in tribosons

Falkowski, Ganguly, Gras, No, Tobioka, Vignaroli, You'20  
Vignaroli'20

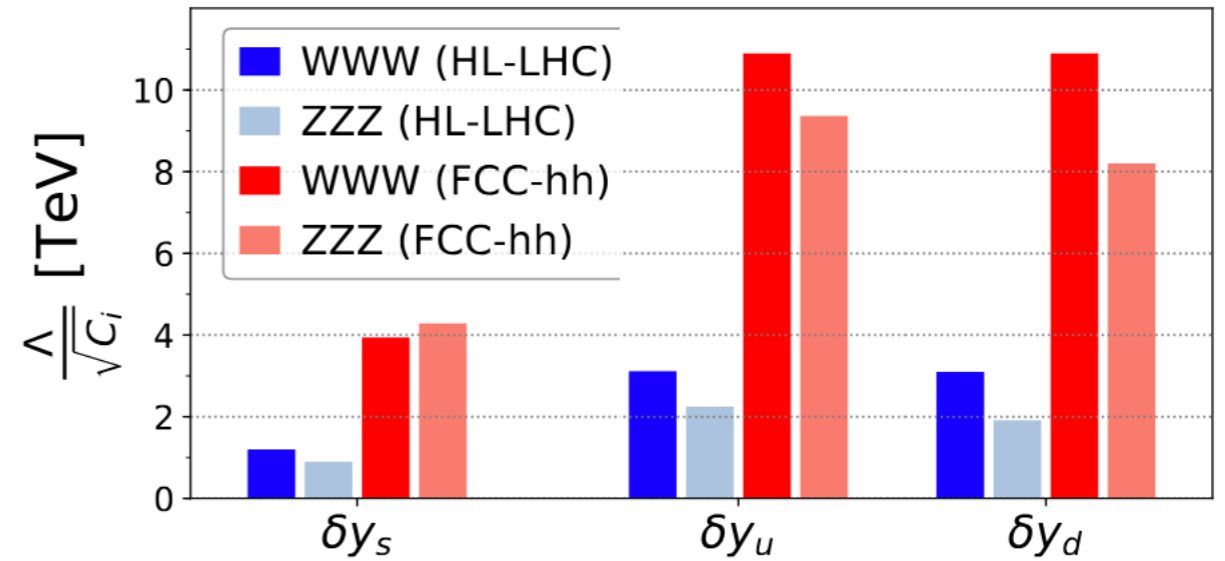
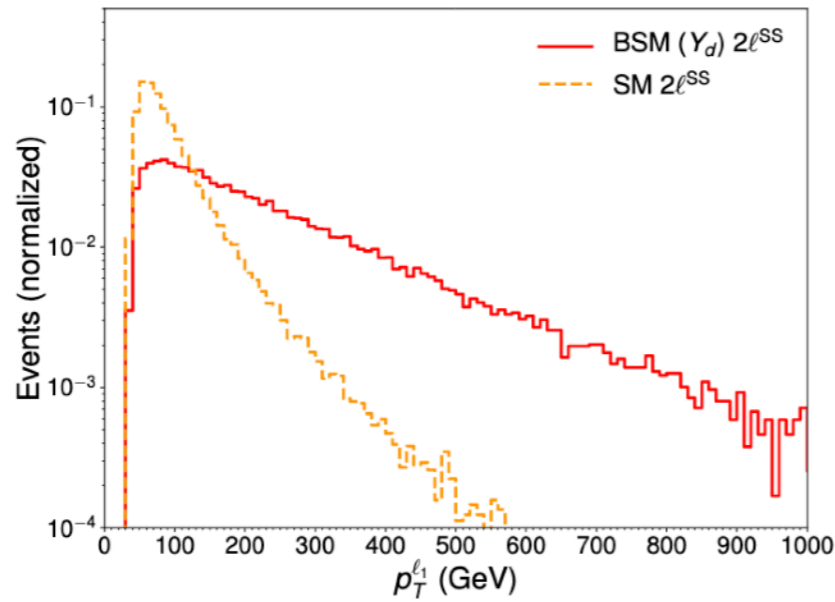


On-shell:

$$\delta y_d \lesssim 340, \quad \delta y_u \lesssim 700, \quad \delta y_s \lesssim 17 \quad (\text{HL-LHC}).$$

Assumes only one modification  
Signal suppressed  
Systematics important

Off-shell:



	WWW			ZZZ		
	$l^\pm l^\pm + 2\nu + 2j$	$l^\pm l^\pm l^\mp + 3\nu$	Comb.	$4l + 2\nu$	$4l + 2j$	Comb.
$\delta y_d$	430 (36)	840 (54)	420 (34)	1500 (65)	1300 (93)	1100 (60)
$\delta y_u$	850 (71)	1700 (110)	830 (68)	2300 (100)	1800 (140)	1600 (92)
$\delta y_s$	150 (13)	230 (33)	140 (13)	300 (12)	290 (16)	250 (11)

HL-LHC FCC-hh

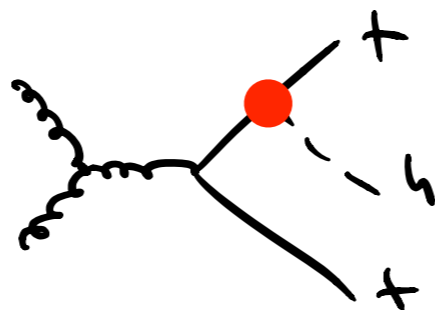
# HwH Program

$\sim \text{const}$

$\sim E^2$

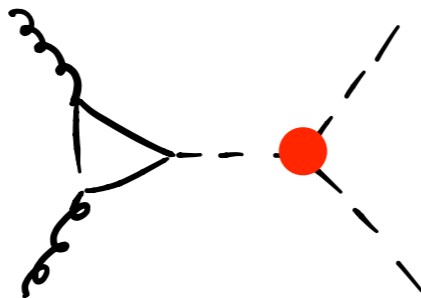
$\kappa_t$

$$|H|^2 Q \tilde{H} t_R$$



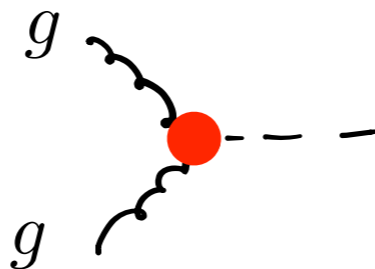
$\kappa_\lambda$

$$|H|^6$$



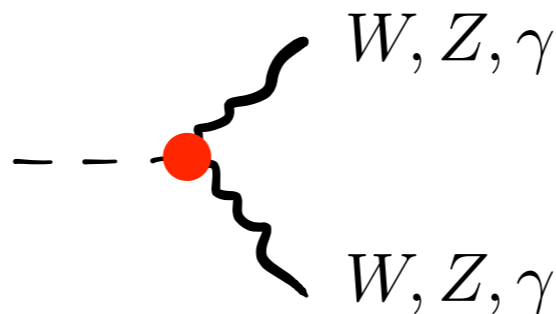
$\kappa_G$

$$|H|^2 G_{\mu\nu}^a G^{a\mu\nu}$$



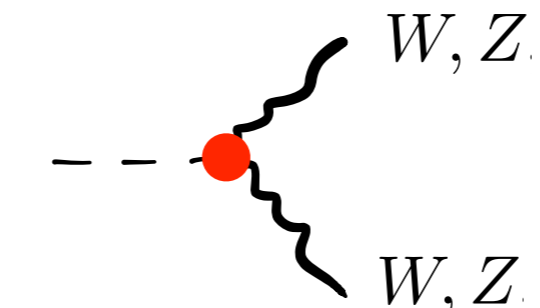
$\kappa_\gamma$

$$|H|^2 B_{\mu\nu} B^{\mu\nu}$$



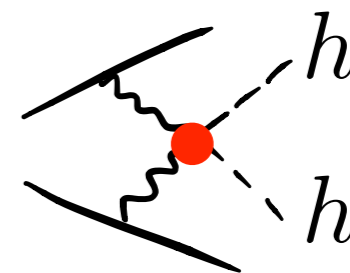
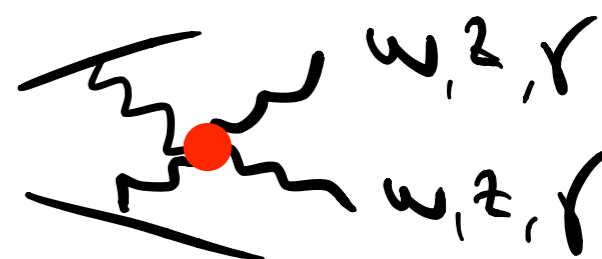
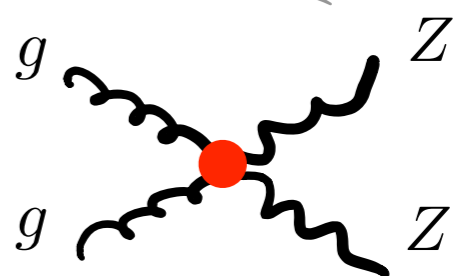
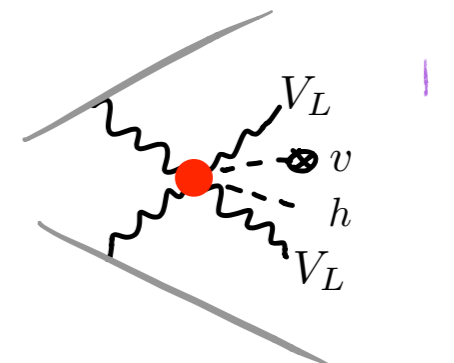
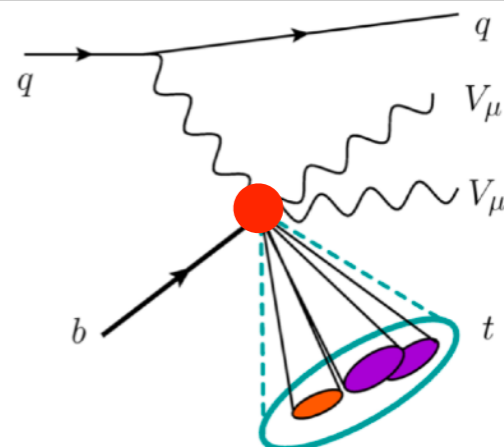
$\kappa_{Z\gamma}$

$$|H|^2 W_{\mu\nu}^a W^{a\mu\nu}$$



$\kappa_V$

$$|H|^2 \partial_\mu H^\dagger \partial^\mu H$$



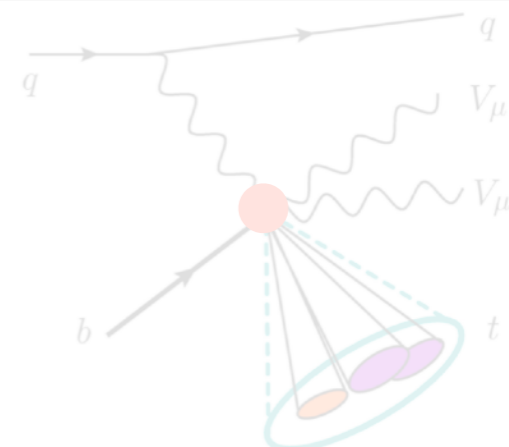
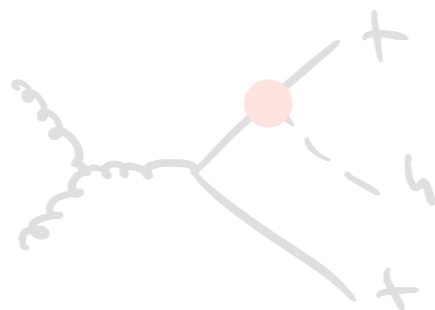
# HWH Program

$\sim \text{const}$

$\sim E^2$

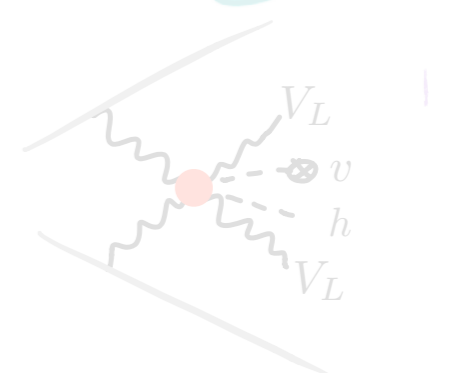
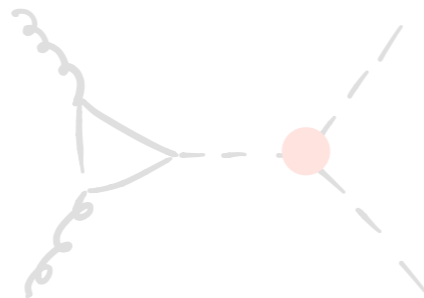
$\kappa_t$

$$|H|^2 Q \tilde{H} t_R$$



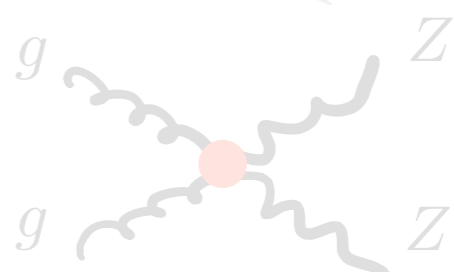
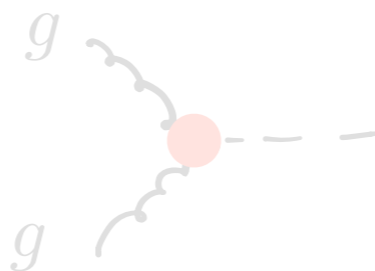
$\kappa_\lambda$

$$|H|^6$$



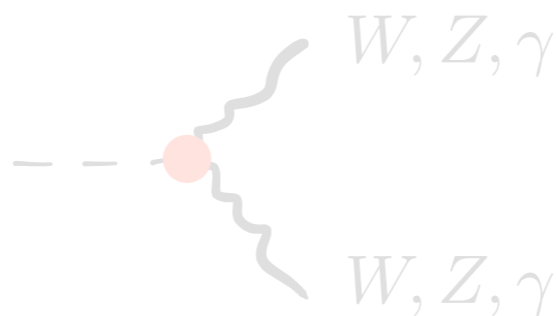
$\kappa_G$

$$|H|^2 G_{\mu\nu}^a G^{a\mu\nu}$$



$\kappa_\gamma$

$$|H|^2 B_{\mu\nu} B^{\mu\nu}$$

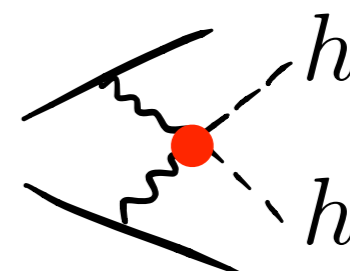
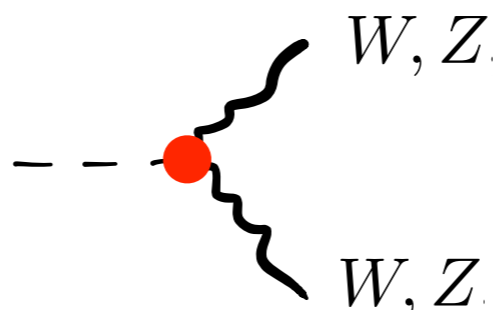


$\kappa_{Z\gamma}$

$$|H|^2 W_{\mu\nu}^a W^{a\mu\nu}$$

$\kappa_V$

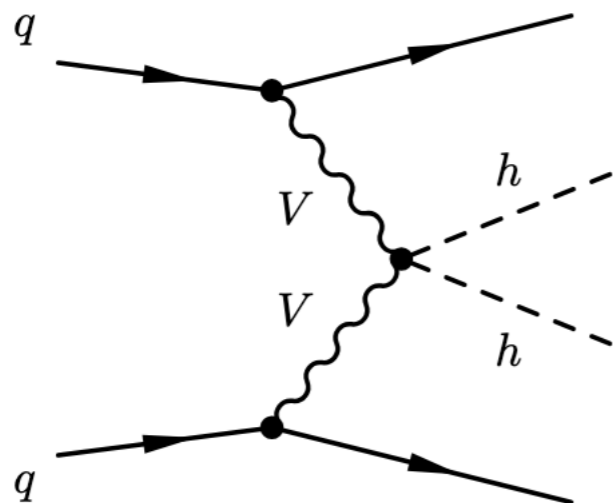
$$|H|^2 \partial_\mu H^\dagger \partial^\mu H$$



# $\kappa_V$ in di-Higgs

Bishara, Contino, Rojo'16

(see also Contino, Grojean, Moretti, Piccinini, Rattazzi'10)



VBS cuts:

Central jet veto:  $|\Delta y_{jj}| \geq 5.0$   
 $m_{jj} \text{ (GeV)} \geq 1000$   
 $p_{Tj_3} \text{ (GeV)} \leq 65$   
 $m_{hh} > 1000 \text{ GeV.}$

Off-shell:

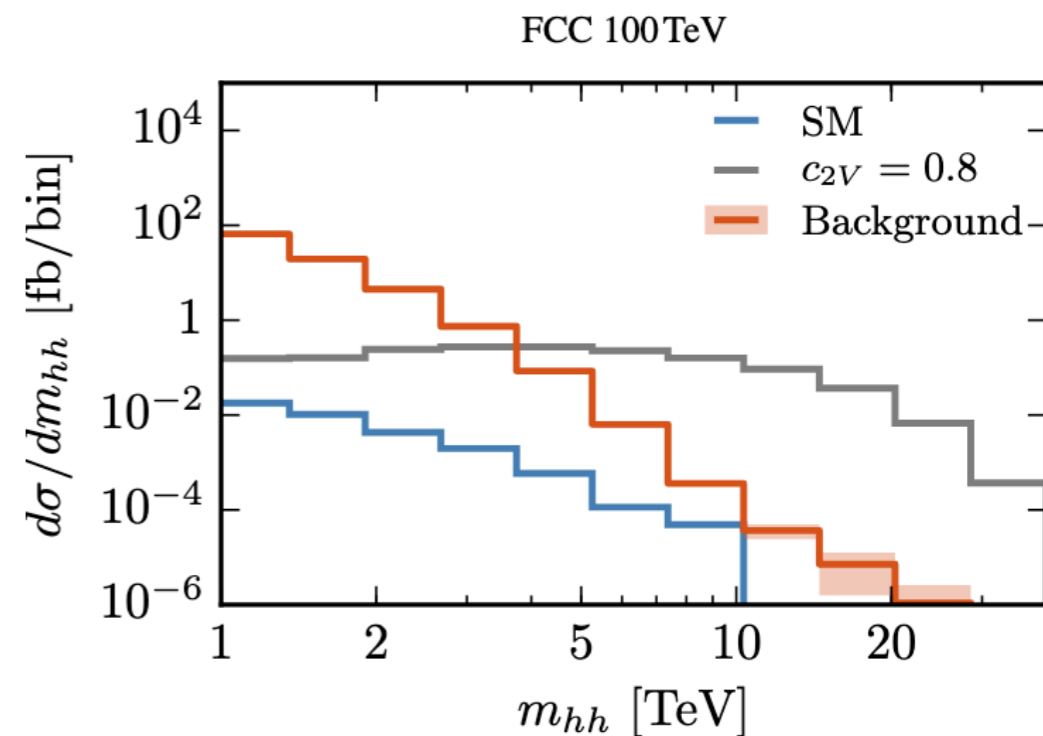
	68% probability interval on $\delta_{c_{2V}}$	
	$1 \times \sigma_{\text{bkg}}$	$3 \times \sigma_{\text{bkg}}$
LHC <sub>14</sub>	[-0.37, 0.45]	[-0.43, 0.48]
HL-LHC	[-0.15, 0.19]	[-0.18, 0.20]
FCC <sub>100</sub>	[0, 0.01]	[-0.01, 0.01]

HL-LHC

FCC<sub>hh</sub>

On-shell:

kappa-0	HL-LHC	FCC-ee		FCC-ee/eh/hh
		240	365	
$\kappa_W$ [%]	1.7	1.3	0.43	0.14
$\kappa_Z$ [%]	1.5	0.20	0.17	0.12





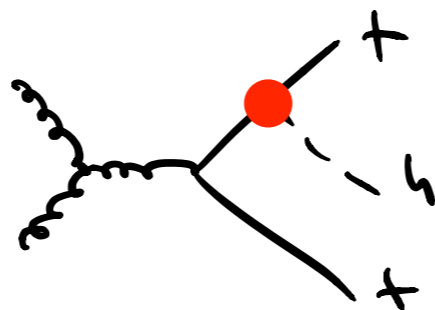
# HwH Program

$\sim \text{const}$

$\sim E^2$

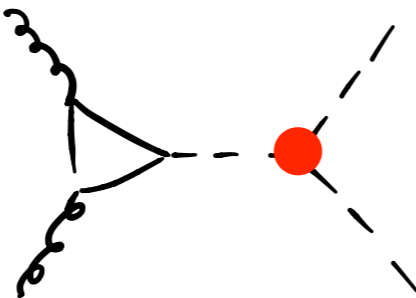
$\kappa_t$

$$|H|^2 Q \tilde{H} t_R$$



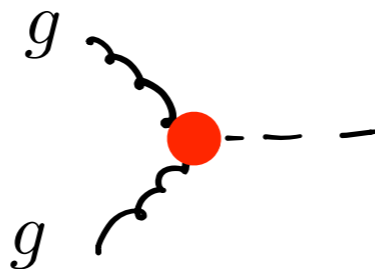
$\kappa_\lambda$

$$|H|^6$$



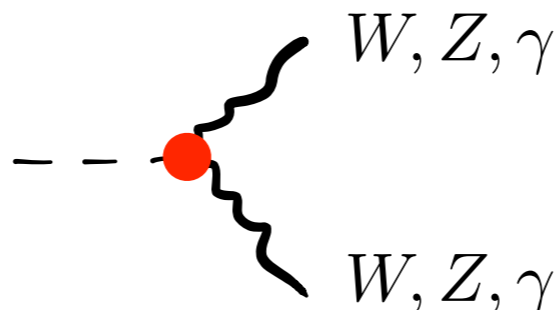
$\kappa_G$

$$|H|^2 G_{\mu\nu}^a G^{a\mu\nu}$$



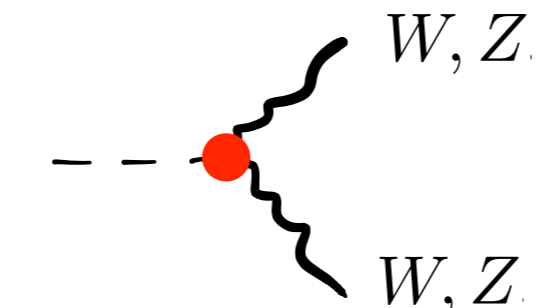
$\kappa_\gamma$

$$|H|^2 B_{\mu\nu} B^{\mu\nu}$$



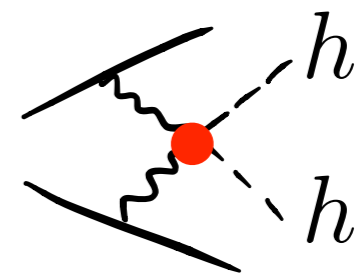
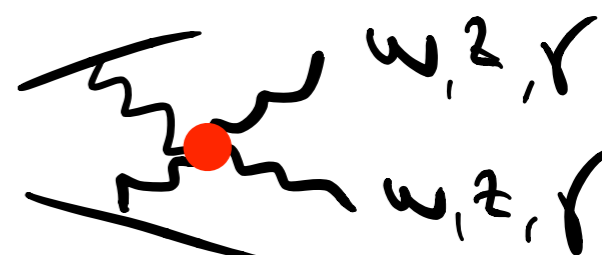
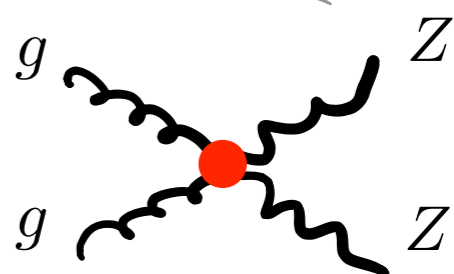
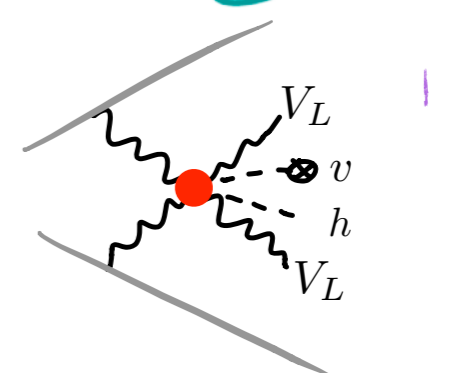
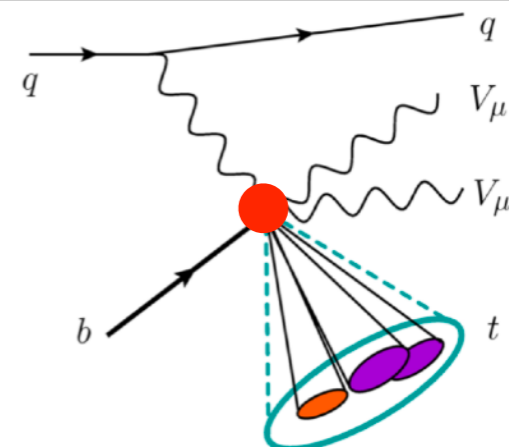
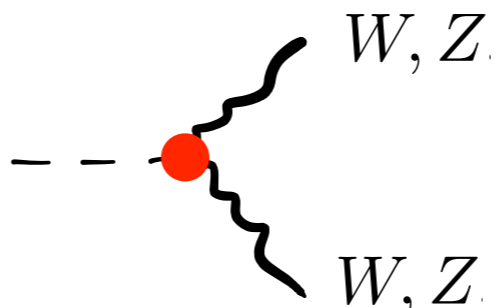
$\kappa_{Z\gamma}$

$$|H|^2 W_{\mu\nu}^a W^{a\mu\nu}$$



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$$|H|^2 \partial_\mu H^\dagger \partial^\mu H$$



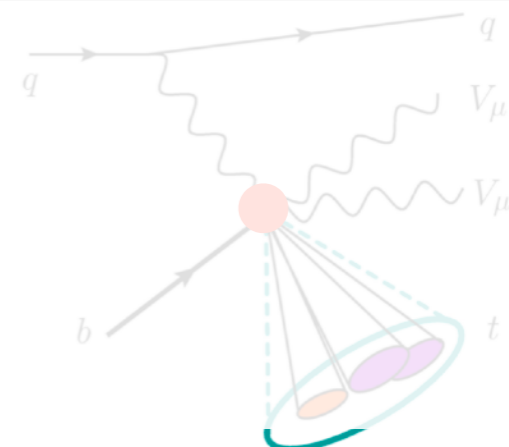
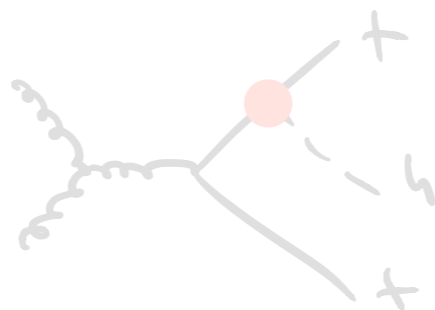
# HWH Program

$\sim \text{const}$

$\sim E^2$

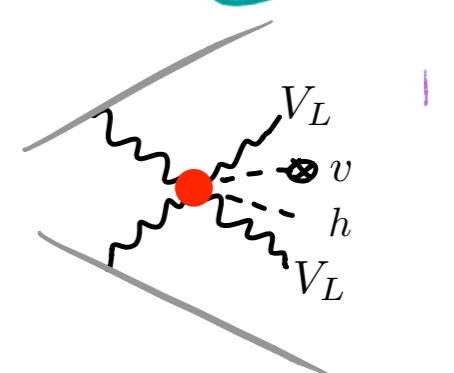
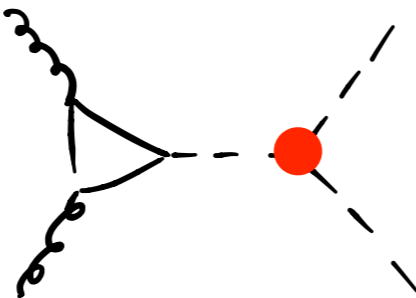
$\kappa_t$

$$|H|^2 Q \tilde{H} t_R$$



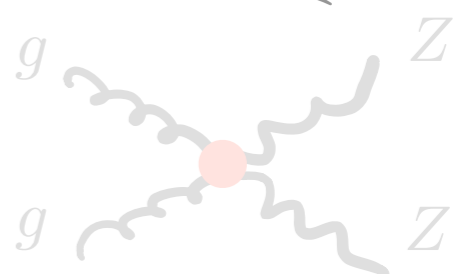
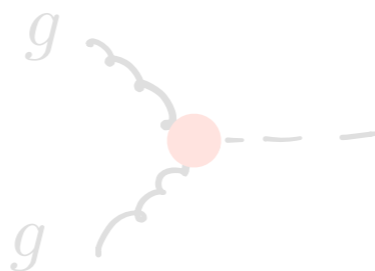
$\kappa_\lambda$

$$|H|^6$$



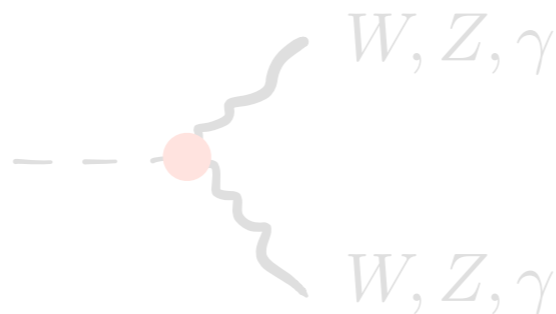
$\kappa_G$

$$|H|^2 G_{\mu\nu}^a G^{a\mu\nu}$$



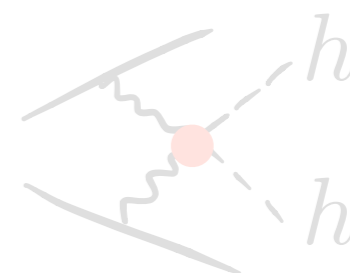
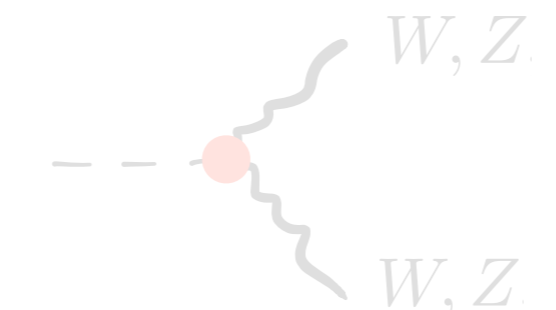
$\kappa_\gamma$

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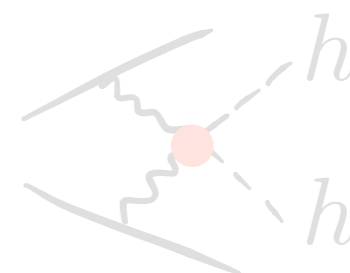
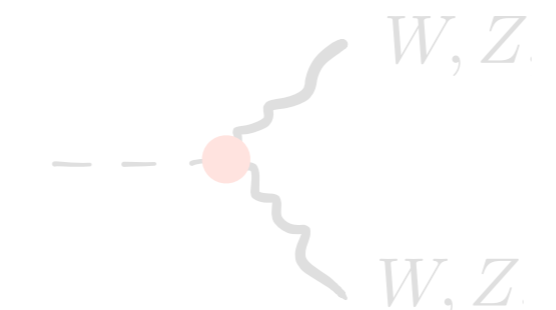
$\kappa_{Z\gamma}$

$$|H|^2 W_{\mu\nu}^a W^{a\mu\nu}$$



$\kappa_V$

$$|H|^2 \partial_\mu H^\dagger \partial^\mu H$$



# HWH: Higgs Self Coupling

Henning, Lombardo, Riembau, PRL'19

$$pp \rightarrow jjh + W^\pm W^\pm$$

# HWH: Higgs Self Coupling

Henning, Lombardo, Riembau, PRL'19

$pp \rightarrow jjh + W^\pm W^\pm$   $\xrightarrow{W \rightarrow l + \nu}$  Same-sign leptons

# HWH: Higgs Self Coupling

Henning, Lombardo, Riembau, PRL'19

$$pp \rightarrow jjh + W^\pm W^\pm$$

$W \rightarrow l + \nu$   $\rightarrow$  Same-sign leptons

$h \rightarrow \bar{b}b$

VBF topology

# HWH: Higgs Self Coupling

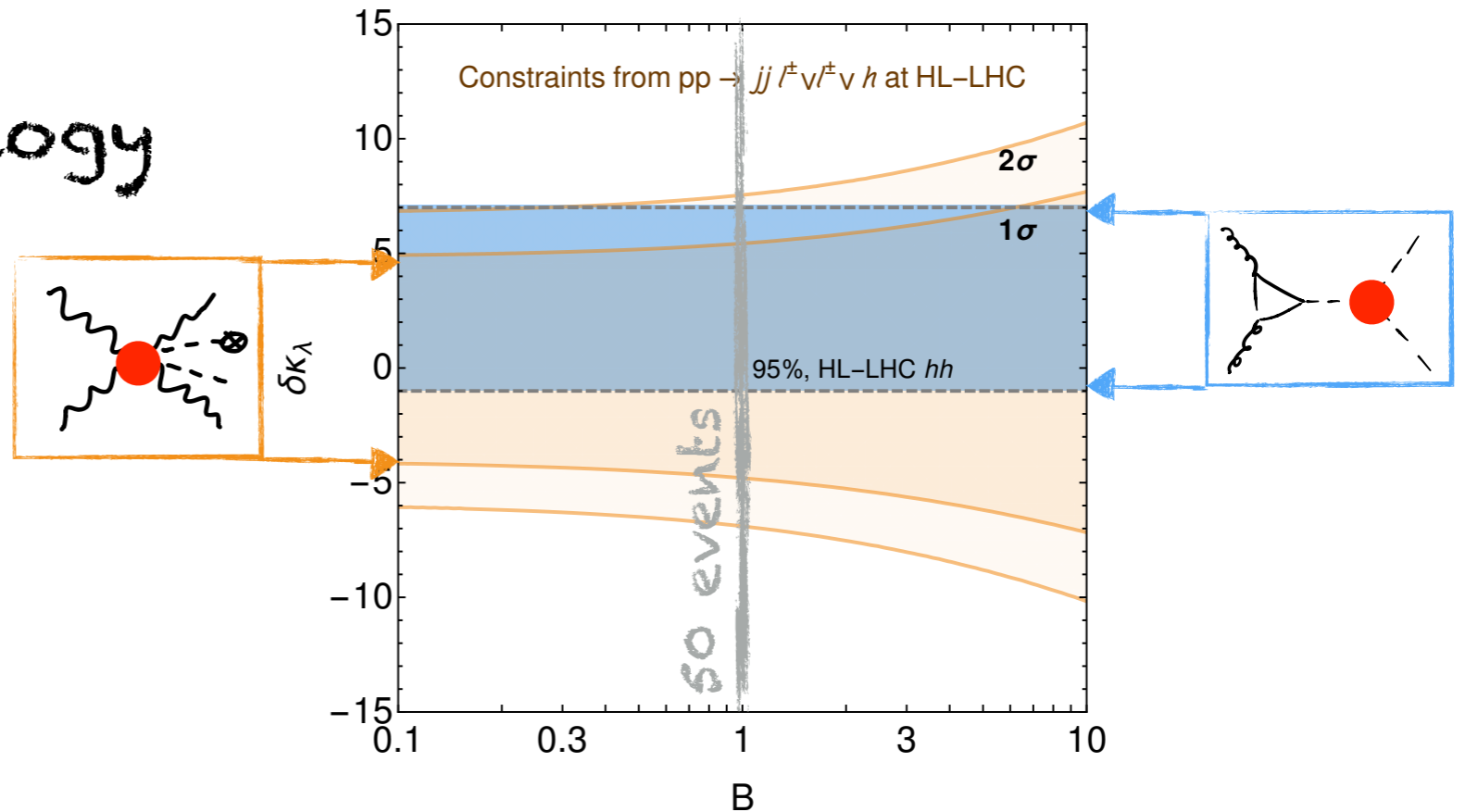
Henning, Lombardo, Riemann, PRL'19

$pp \rightarrow jjh + W^\pm W^\pm$

$W \rightarrow l + \nu$  → Same-sign leptons

$h \rightarrow \bar{b}b$

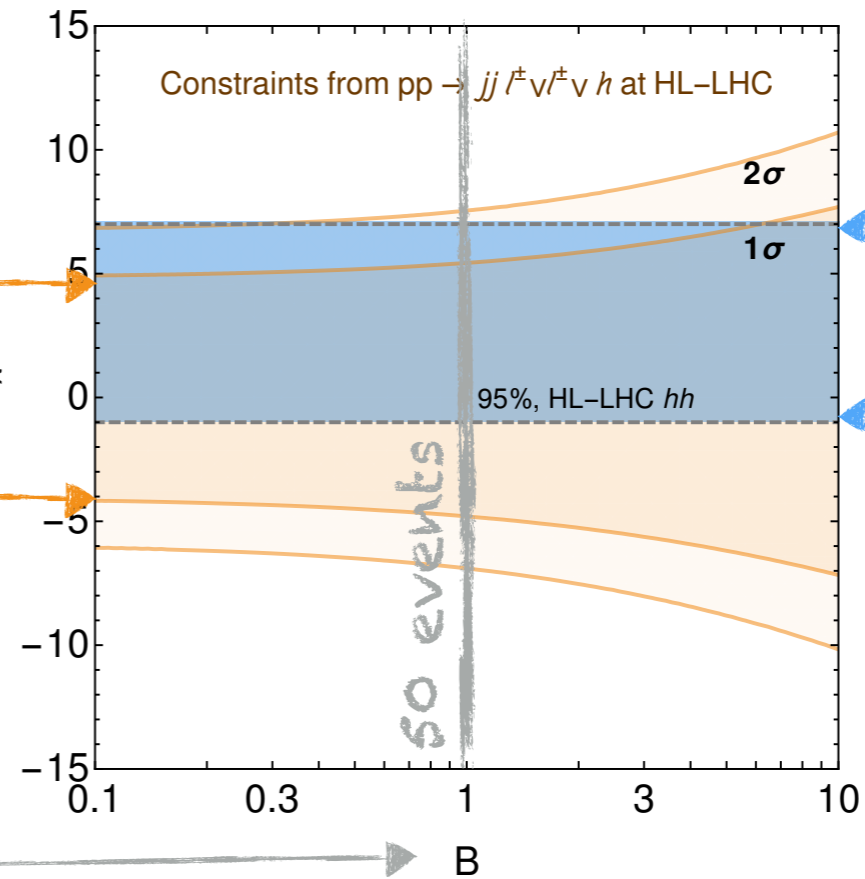
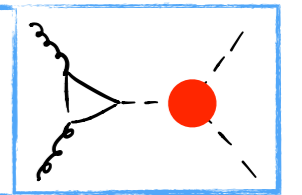
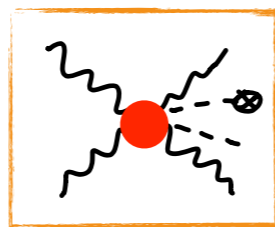
VBF topology



# HWH: Higgs Self Coupling

Henning, Lombardo, Riemann, PRL'19

$pp \rightarrow jjh + W^\pm W^\pm$   
 $W \rightarrow l + \nu$  → Same-sign leptons  
 $h \rightarrow \bar{b}b$   
 VBF topology



► Low background B

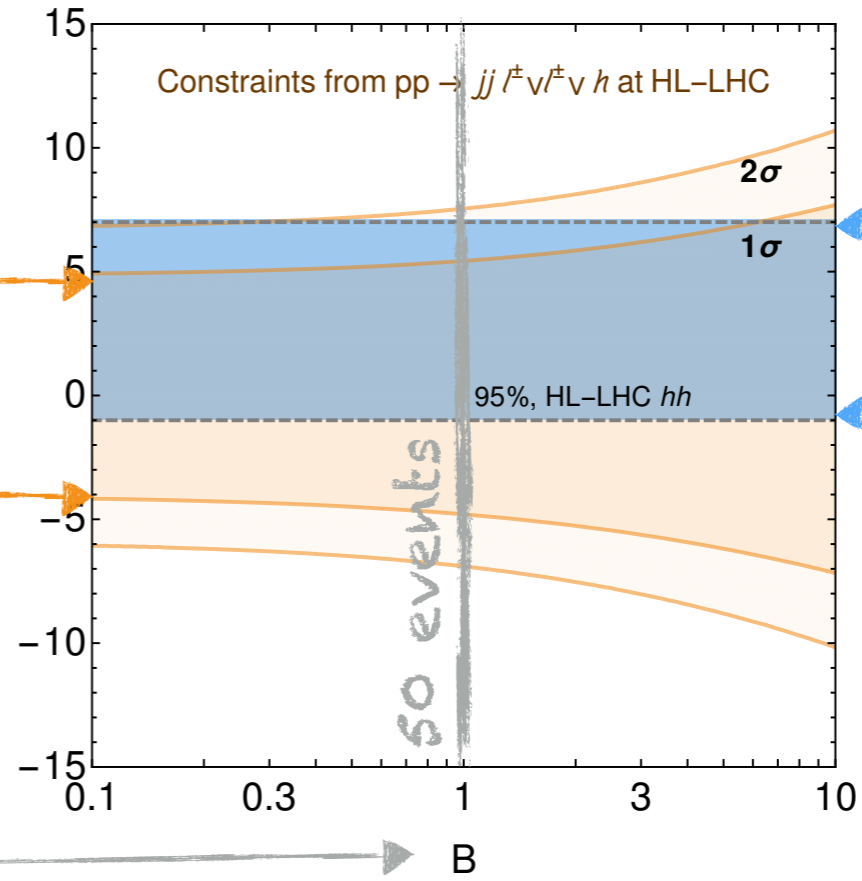
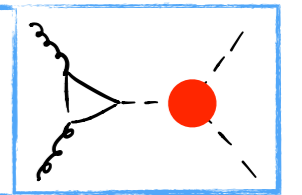
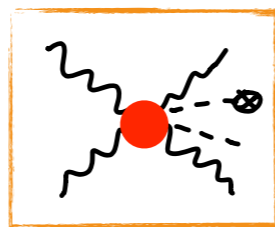
- $t\bar{t}jj$  ✓
- fake leptons ? → B

# HWH: Higgs Self Coupling

Henning, Lombardo, Riemann, PRL'19

$pp \rightarrow jjh + W^\pm W^\pm$   
 $W \rightarrow l + \nu$  → Same-sign leptons  
 $h \rightarrow \bar{b}b$

VBF topology



- ▶ Low background B
  - ttjj ✓
  - fake leptons ?

- ▶ HWH: single channel, simple analysis, competitive with HC!
- ▶ Improvements: Background, Distributions, More final States, Polarisation, ...

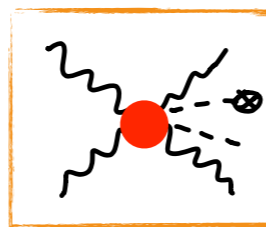


# HWH: Higgs Self Coupling

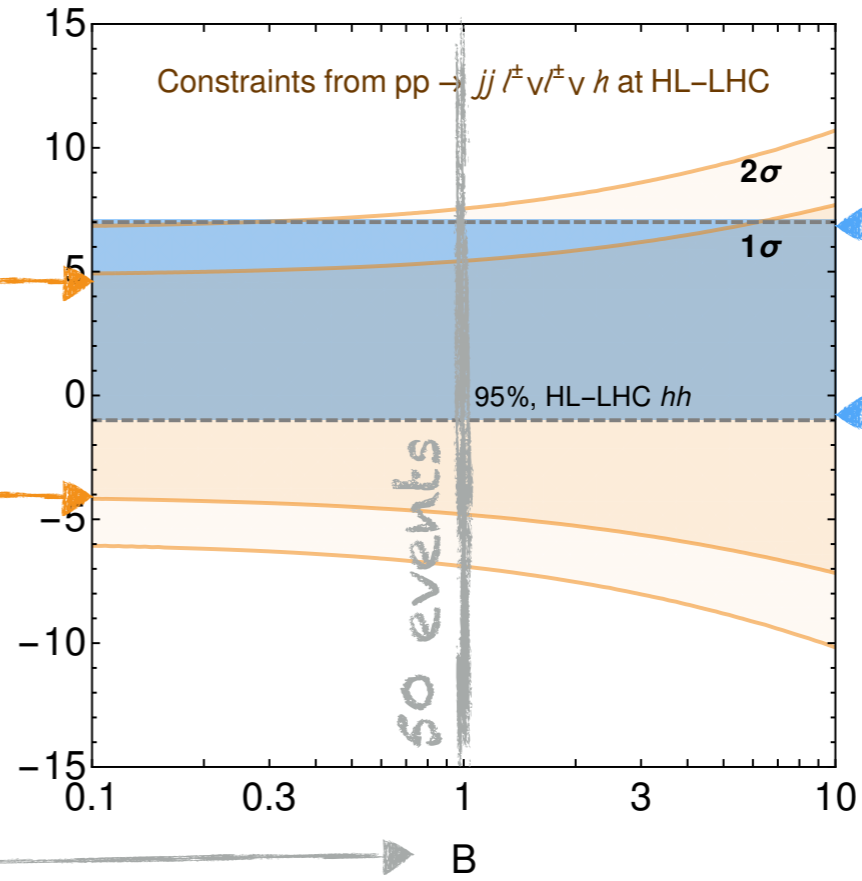
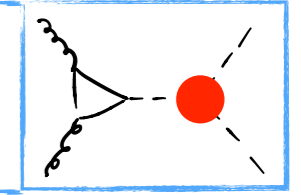
Henning, Lombardo, Riemann, PRL'19

$pp \rightarrow jjh + W^\pm W^\pm$ 
  
 $W \rightarrow l + \nu$  → Same-sign leptons

$h \rightarrow \bar{b}b$ 
  
 VBF topology



$\delta\kappa_\lambda$



- ▶ Low background B
  - ttjj ✓
  - fake leptons ? →

- ▶ HWH: single channel, simple analysis, competitive with HC!
- ▶ Improvements: Background, Distributions, More final States, Polarisation, ...

and for FCChh?

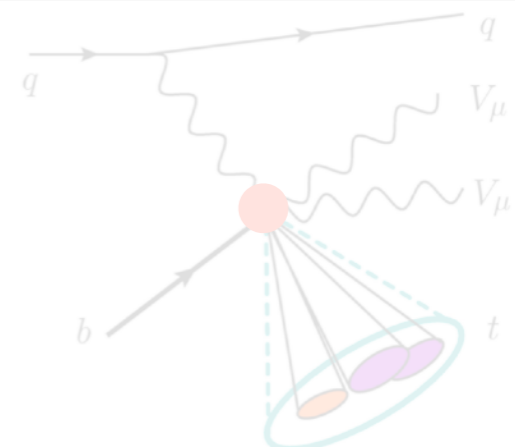
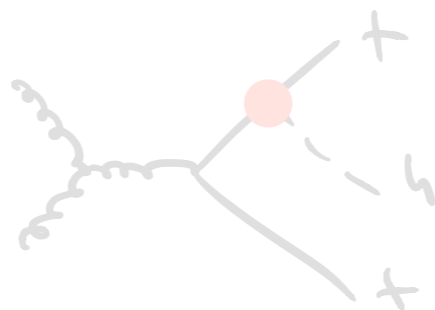
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$\sim const$

$\sim E^2$

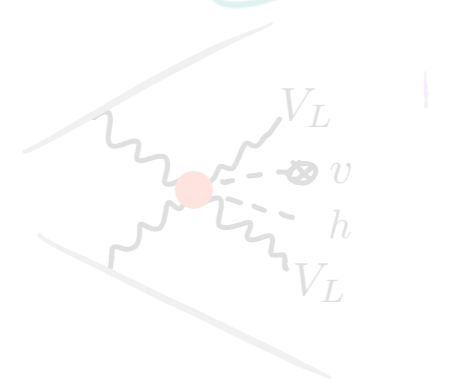
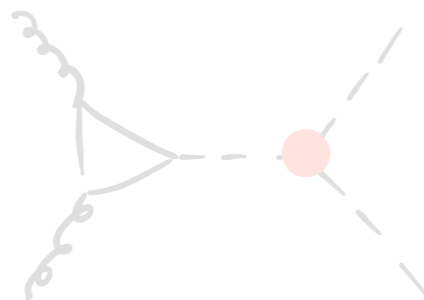
$\kappa_t$

$$|H|^2 Q \tilde{H} t_R$$



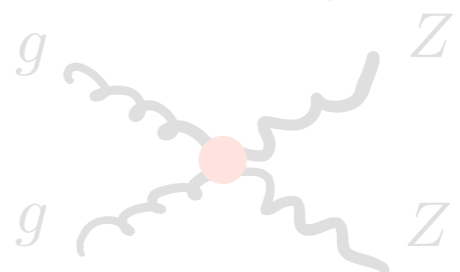
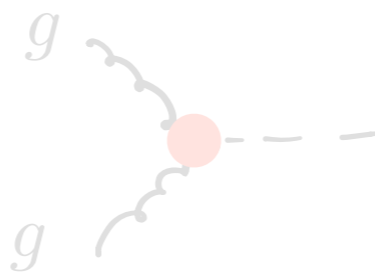
$\kappa_\lambda$

$$|H|^6$$



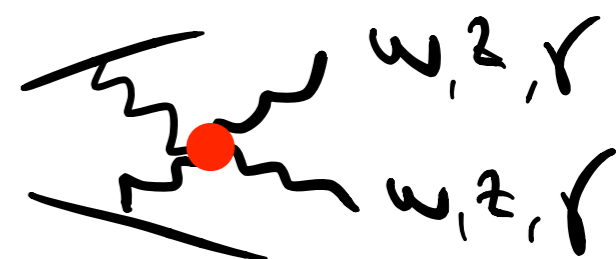
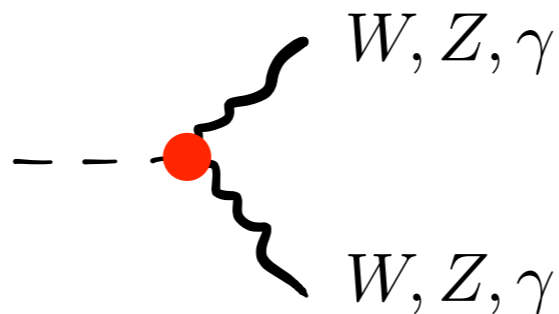
$\kappa_G$

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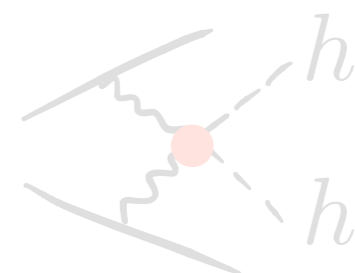
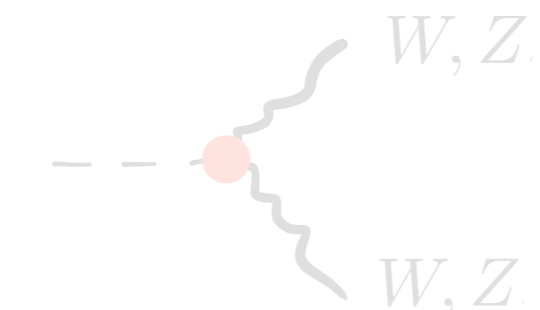
$\kappa_\gamma$

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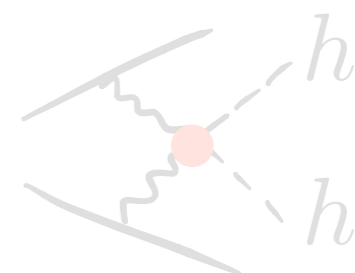
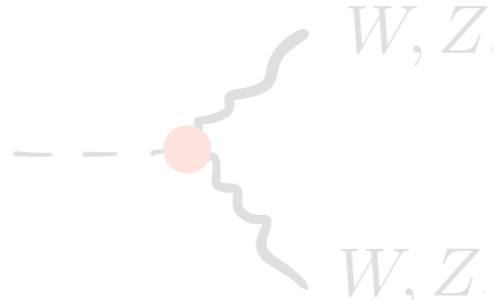
$\kappa_{Z\gamma}$

$$|H|^2 W_{\mu\nu}^a W^{a\mu\nu}$$



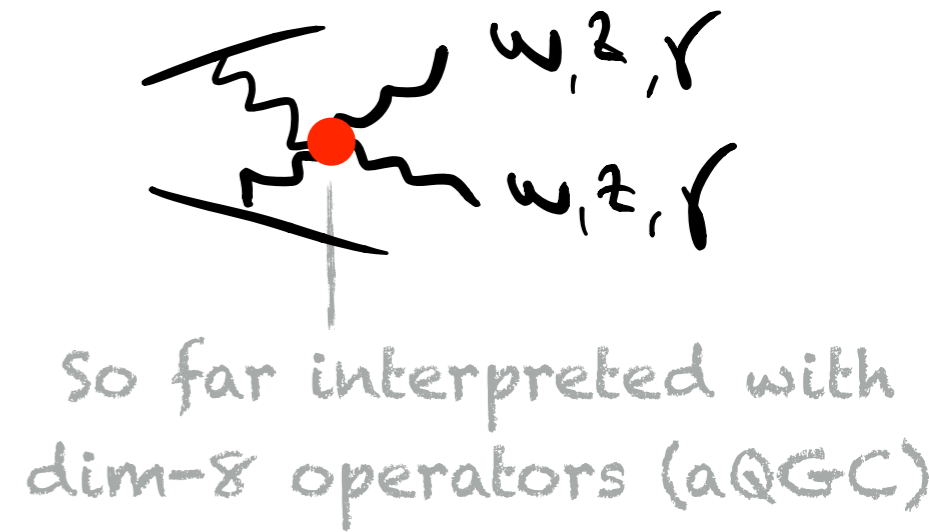
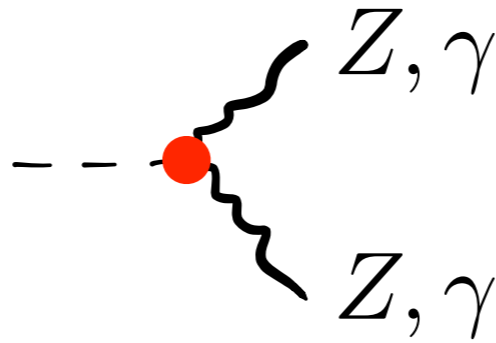
$\kappa_V$

$$|H|^2 \partial_\mu H^\dagger \partial^\mu H$$



# HWH Program: h to gauge bosons

$$\kappa_\gamma |H|^2 B_{\mu\nu} B^{\mu\nu}$$
$$\kappa_{Z\gamma} |H|^2 W_{\mu\nu}^a W^{a\mu\nu}$$

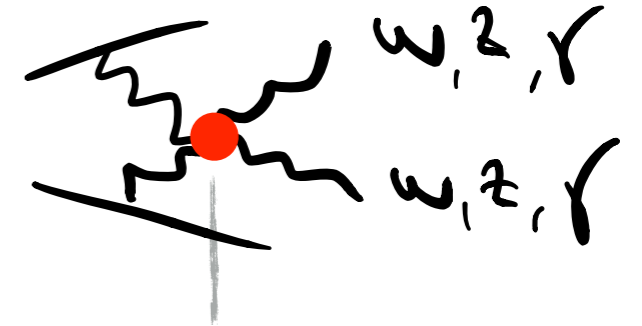
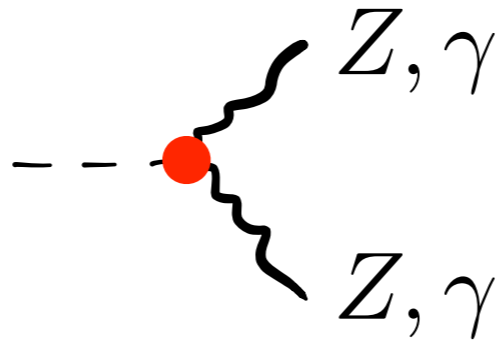


and for FCChh?

# HWH Program: h to gauge bosons

$$\kappa_\gamma |H|^2 B_{\mu\nu} B^{\mu\nu}$$

$$\kappa_{Z\gamma} |H|^2 W_{\mu\nu}^a W^{a\mu\nu}$$

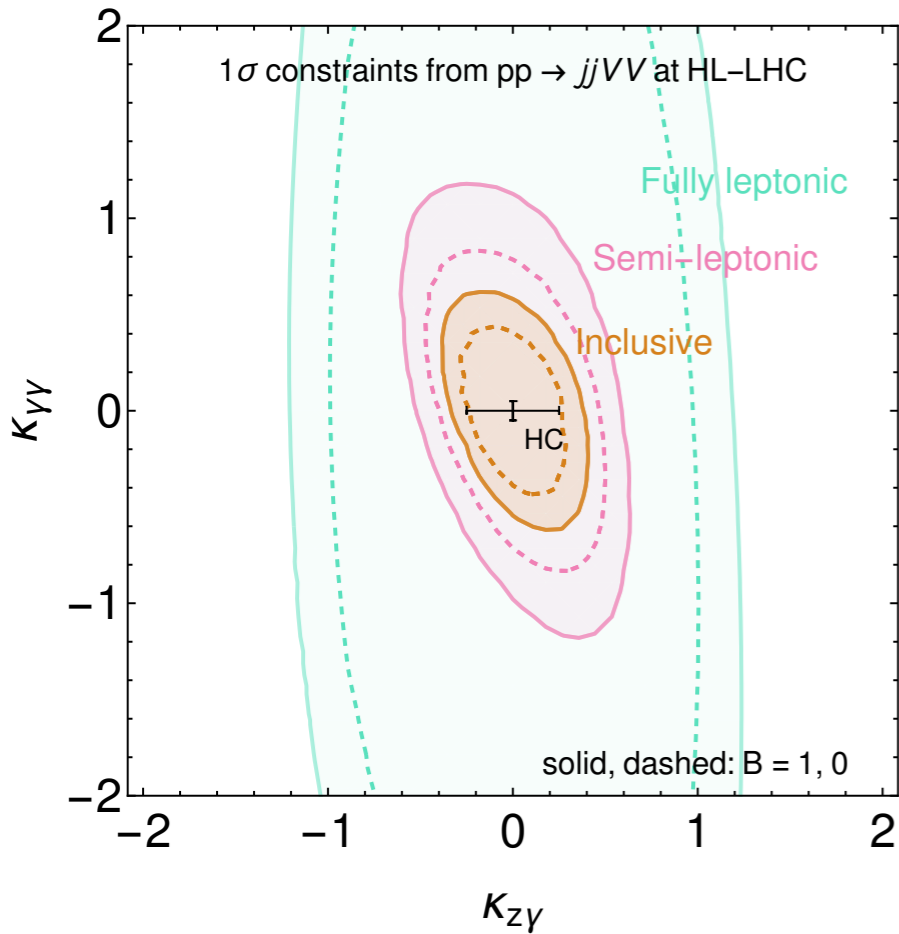


So far interpreted with dim-8 operators (aQGC)

Simple analysis:

- VBF cuts
- Binning  $\sum |p_T^V|$

$\kappa_{Z\gamma}$  competitive,  $\kappa_\gamma$  not



and for FCChh?

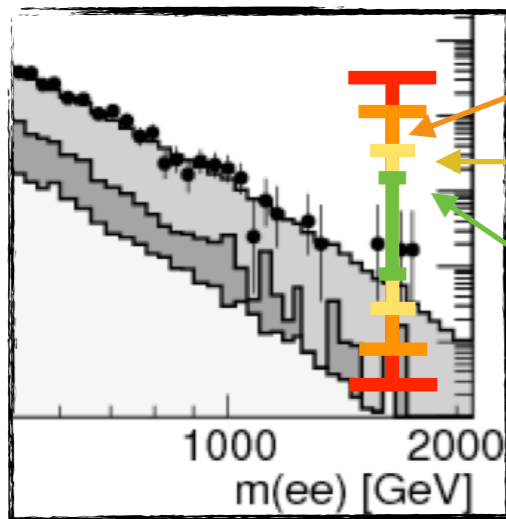
# Message

▶ Multiboson HWH: Competitive/Complementary to HC measurements

Probe EW sector

Break degeneracies

▶ Many opportunities for improvement (contrary to HC):



Precise SM theoretical predictions

LHC Experimental control of systematics

BSM understanding

▶ Thorough study/potential for FCChh important but still not fully explored



# Top Yukawa... improvements

Same amplitude enters in many channels...

Legs	Order	Diagram	Channels	Xsec[fb]	QCD bgnd	L/T
1 → 4	QCD		$tW^\pm W^\pm W^\mp$	0.7	/	0.03
			$tW^\pm ZZ$	0.4	/	0.03
	EW		$tbW^\pm W^\pm$	3.5	/	0.10
			$tbW^\pm W^\mp$	3.5	/	0.20
			$tbW^\pm Z$	3.8	/	0.11
			$tbZZ$	0.02	0	0.09
2 → 3	QCD <sup>2</sup>		$ttZWW$	0.083	/	0.03
			$ttZZZ$	0.008	/	0.04
			$tbWWW$	19	/	0.04
			$tbWZZ$	3.8	/	0.07
	EW <sup>2</sup>		$ttZ$	0.1	/	0.29
			$ttW^\pm$	0.3	/	0.32
			$tbZ$	0.2	/	0.31
			$tbW^\pm(SS)$	0.9	2	0.29
			$tbW^\pm(OS)$	19	/	0.45
	EW * QCD		$tbW^\pm W^\mp$	75	467	0.15
			$tbW^\pm W^\pm$	75	458	0.13
			$tbW^\pm Z$	26	215	0.15
			$tbZZ$	4	0	0.07
			$tW^\pm W^\mp W^\pm$	0.7	/	0.03
			$tW^\pm ZZ$	0.4	/	0.03
	$tW^\pm W^\mp$	9	7.15	0.09		
	$tW^\pm W^\pm$	8	6.44	0.10		
	$tW^\pm Z$	9	75.4	0.07		
	$tZZ$	5	2.64	0.07		

signal in longitudinal polarizations

t-channel gluon

so far

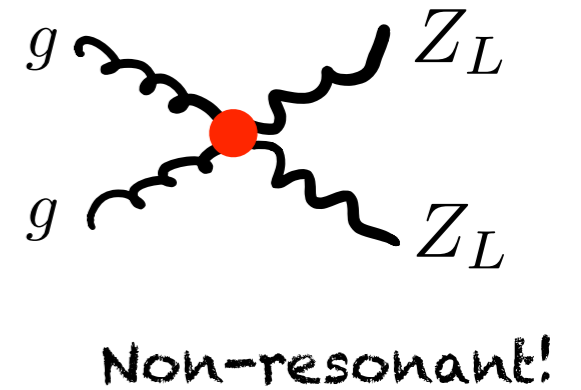
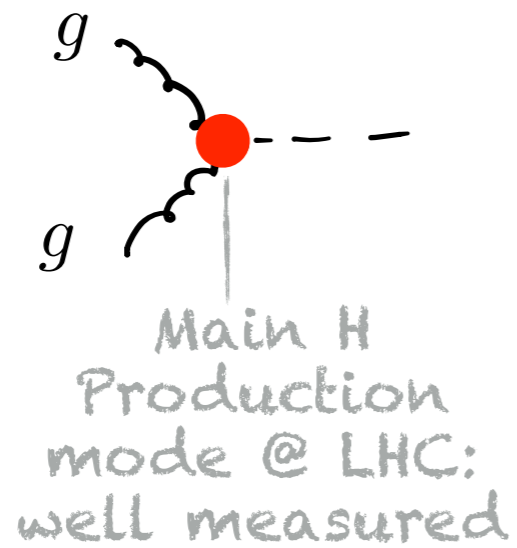
Further improvements:

- more channels
- background estimate
- differential distributions (into larger  $E^2$ )

# HWH Program: Higgs-Gluons

see also Azatov, Grojean, Paul, Salvioni'14

$$\kappa_G$$
$$|H|^2 G_{\mu\nu}^a G^{a\mu\nu}$$

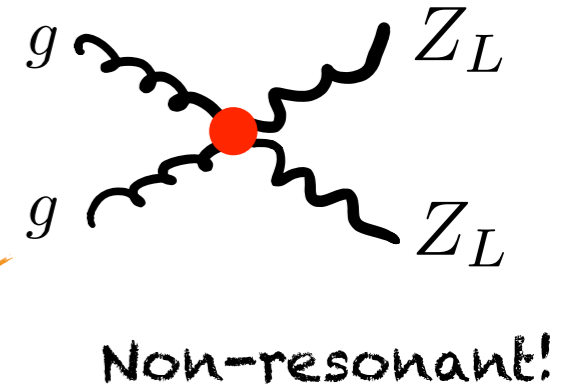
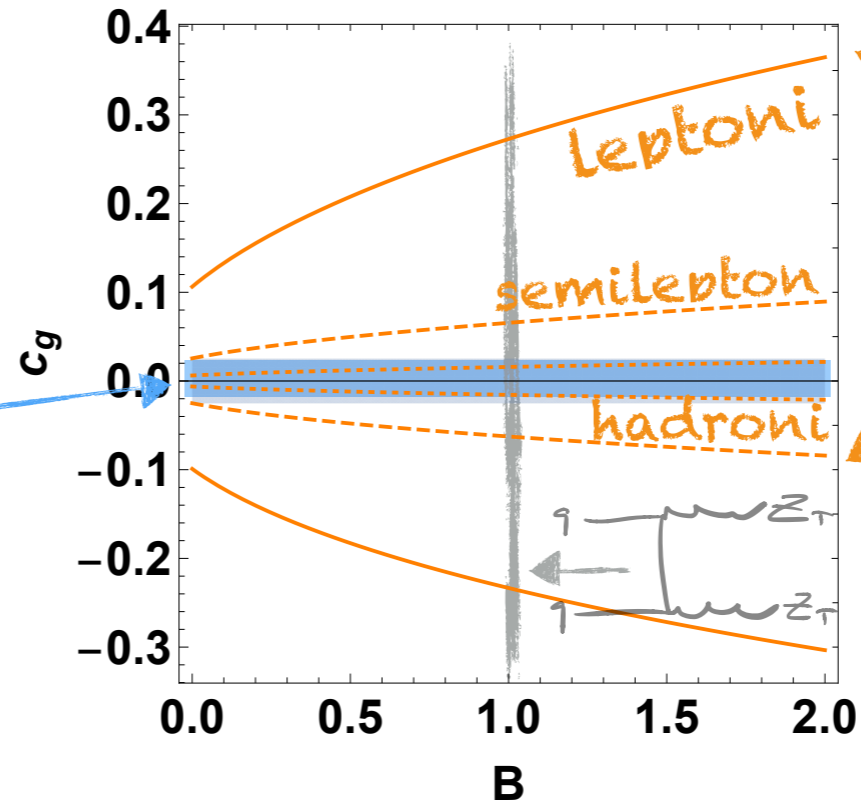
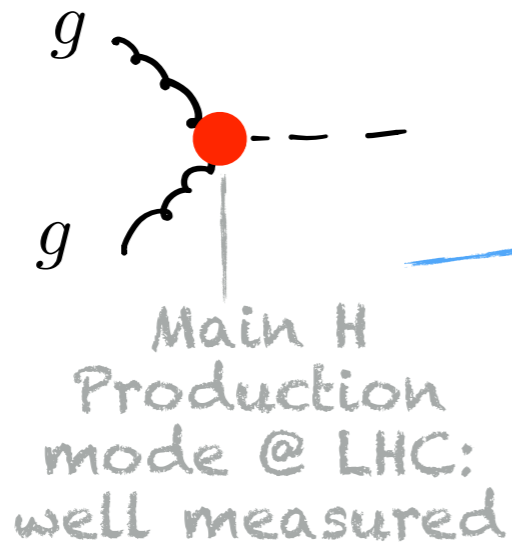


# HWH Program: Higgs-Gluons

see also Azatov, Grojean, Paul, Salvioni'14

$$\kappa_G$$

$$|H|^2 G_{\mu\nu}^a G^{a\mu\nu}$$

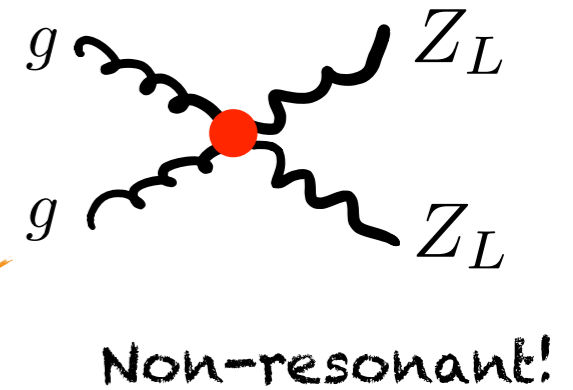
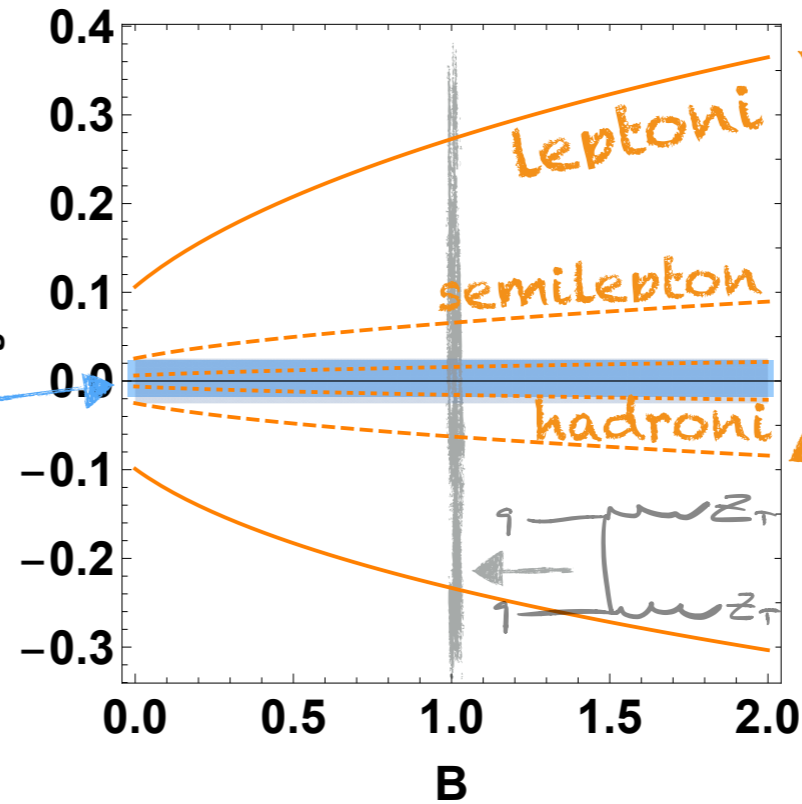
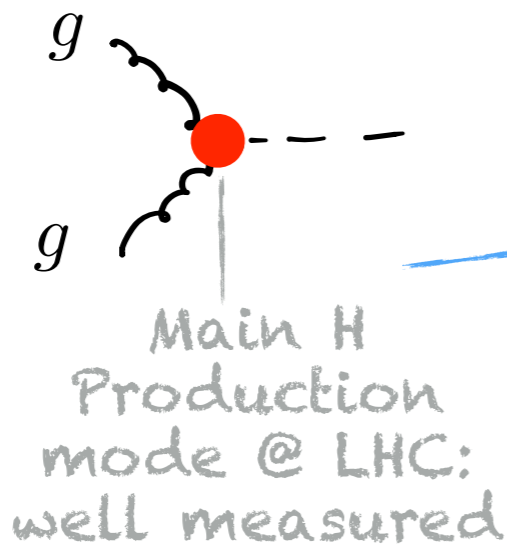




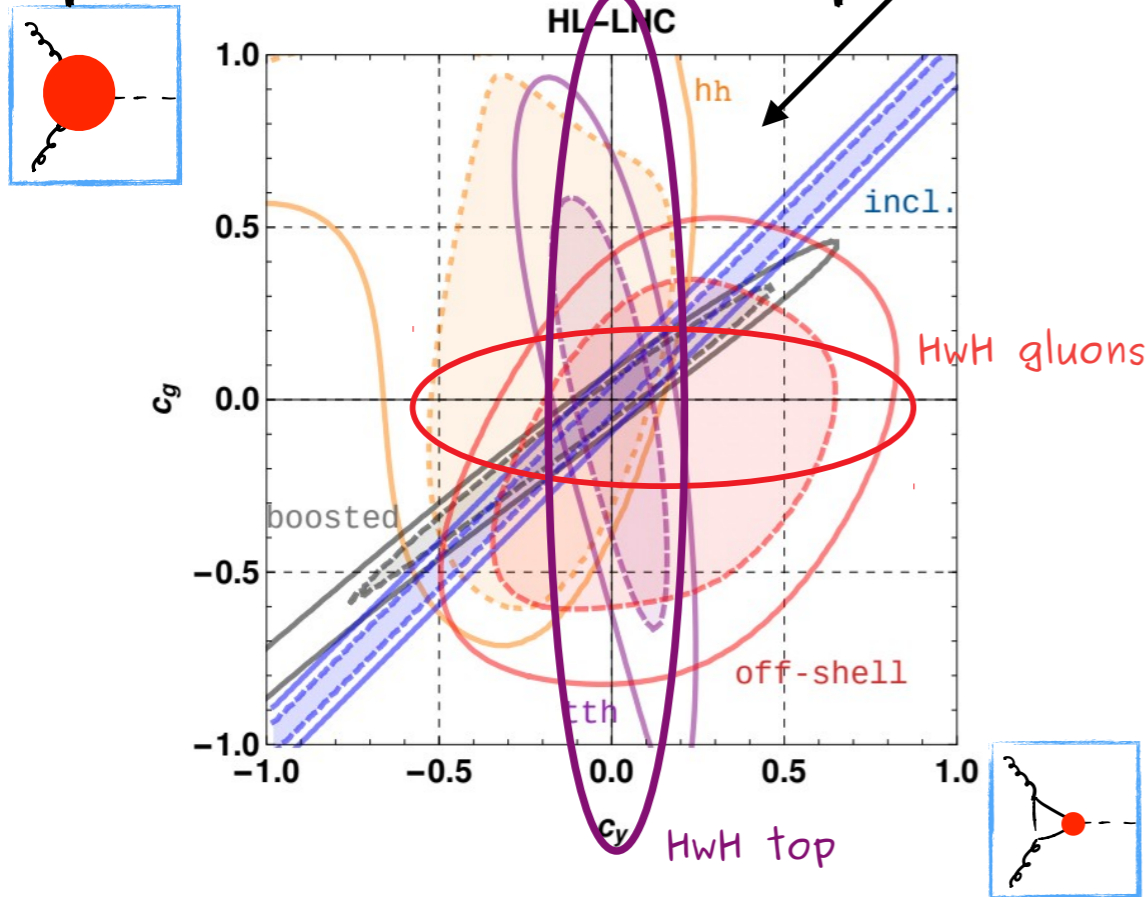
# HWH Program: Higgs-Gluons

see also Azatov, Grojean, Paul, Salvioni'14

$$\kappa_G |H|^2 G_{\mu\nu}^a G^{a\mu\nu}$$



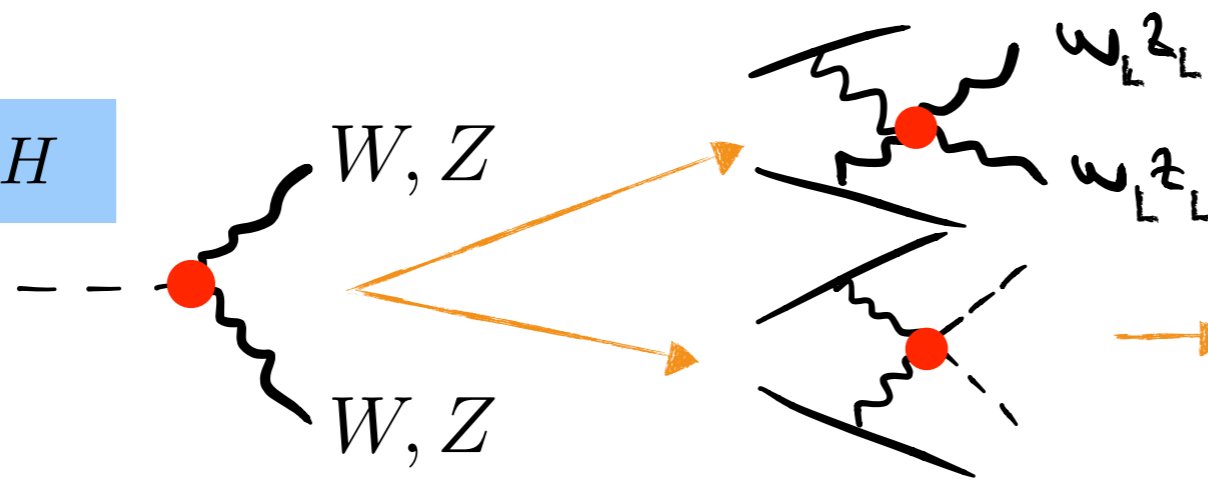
Important since Coupling measurements leave degeneracies...



HWH offer new observables, orthogonal to previous ones!

# HwH Program: h to gauge bosons 2

$$\kappa_V |H|^2 \partial_\mu H^\dagger \partial^\mu H$$



In SM  $V_L$  suppressed  
by  $\approx 1/1000$  w.r.t  $V_T$   
Contino, Grojean, Moretti, Piccinini, Rattazzi'10

$\delta\kappa_V \lesssim 8\%$ , (HwH)  $\delta\kappa_V \lesssim 5\%$  (HC)  
Bishara, Contino, Rojo'17