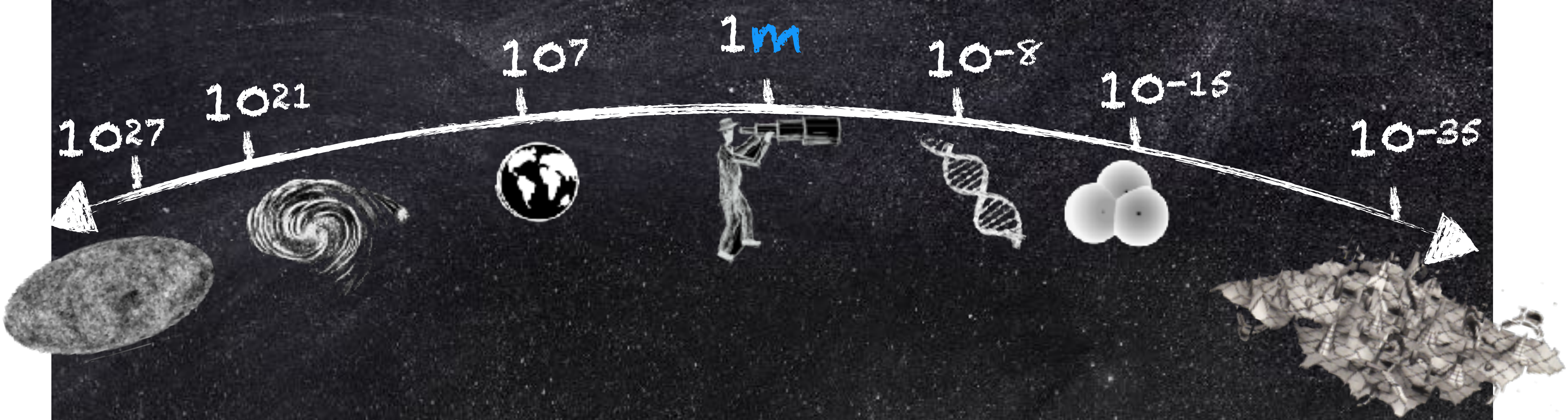
Higgs Couplings ... without the Higgs



Francesco Riva
(Geneva University)

More luminosity = New Experiment

More data:
- More high-energy events
- Access more SM distributions
- Access rare multi-particle processes

- Design searches that were impossible before!

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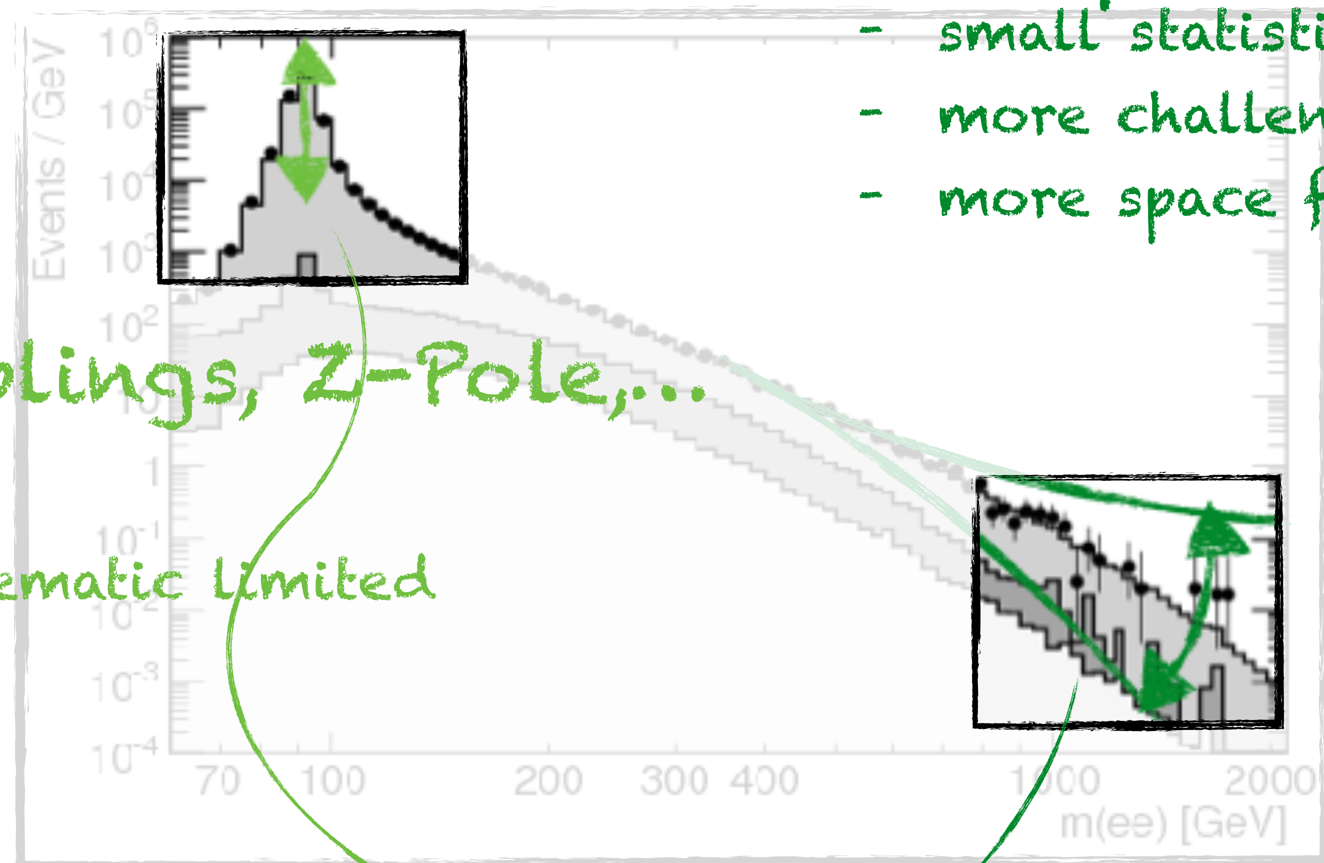
Multi-bosons to test Higgs couplings

(Higgs without Higgs)

Precision Tests of SM Distributions

e.g. 2>2 processes (WZ,ll,...)

- small statistics
- more challenging measurement
- more space for improvement



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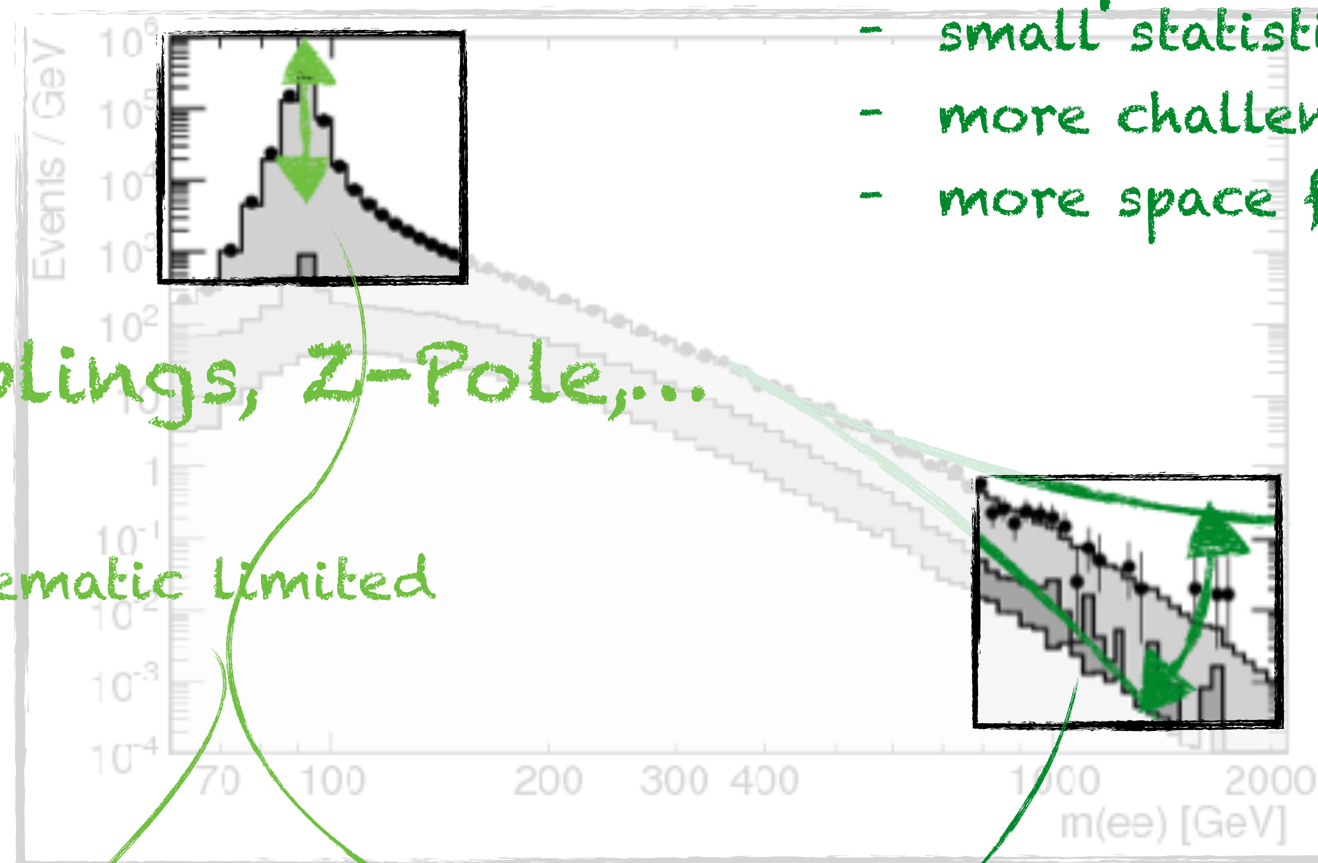

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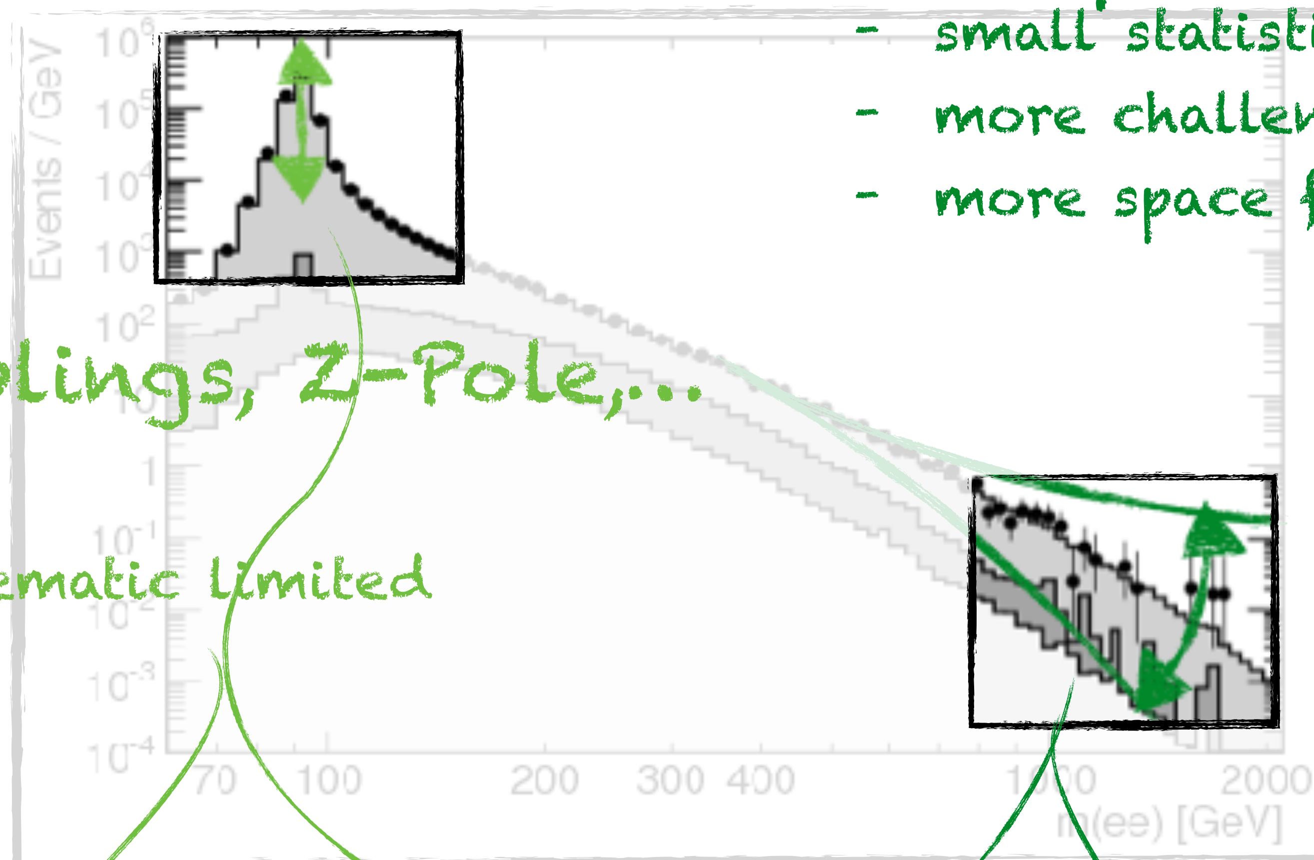

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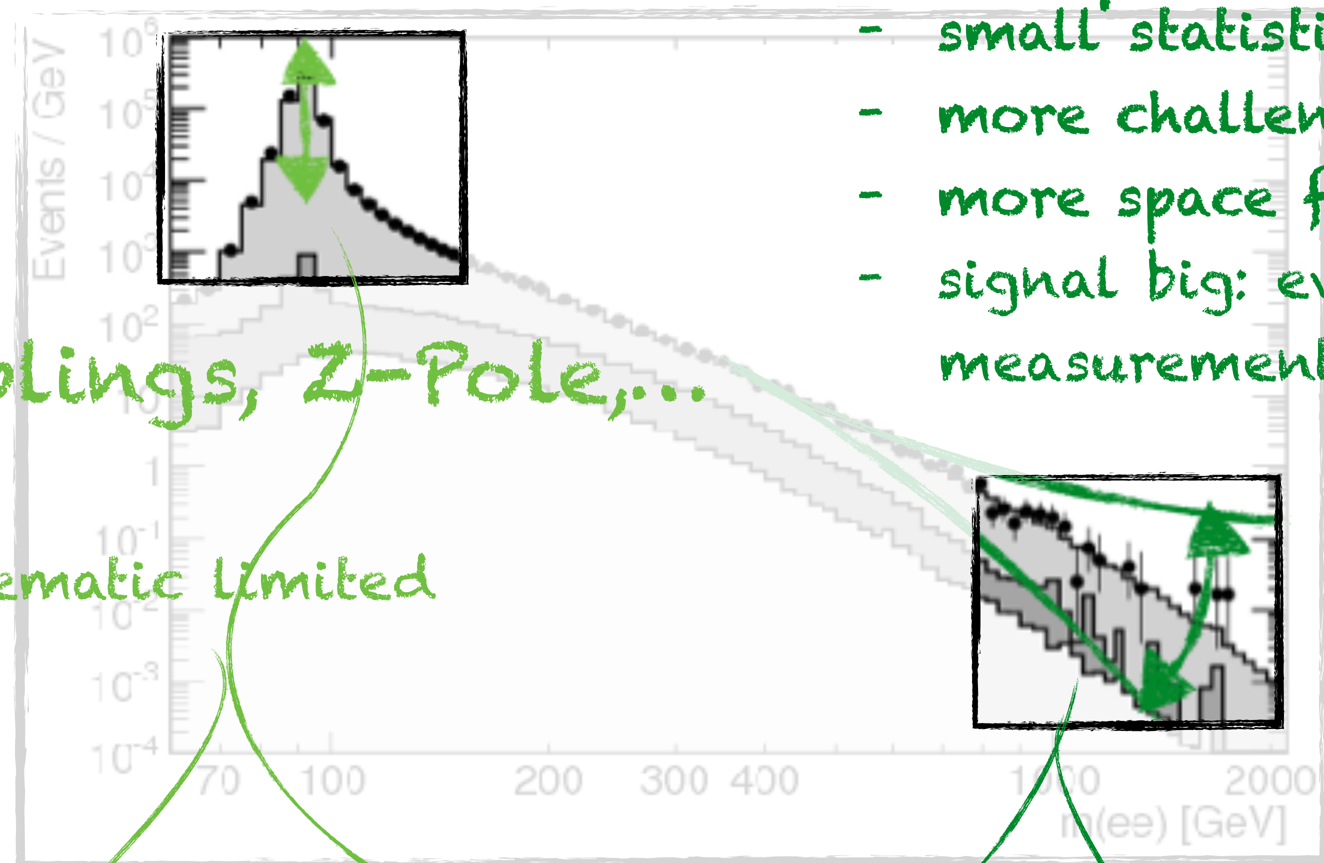

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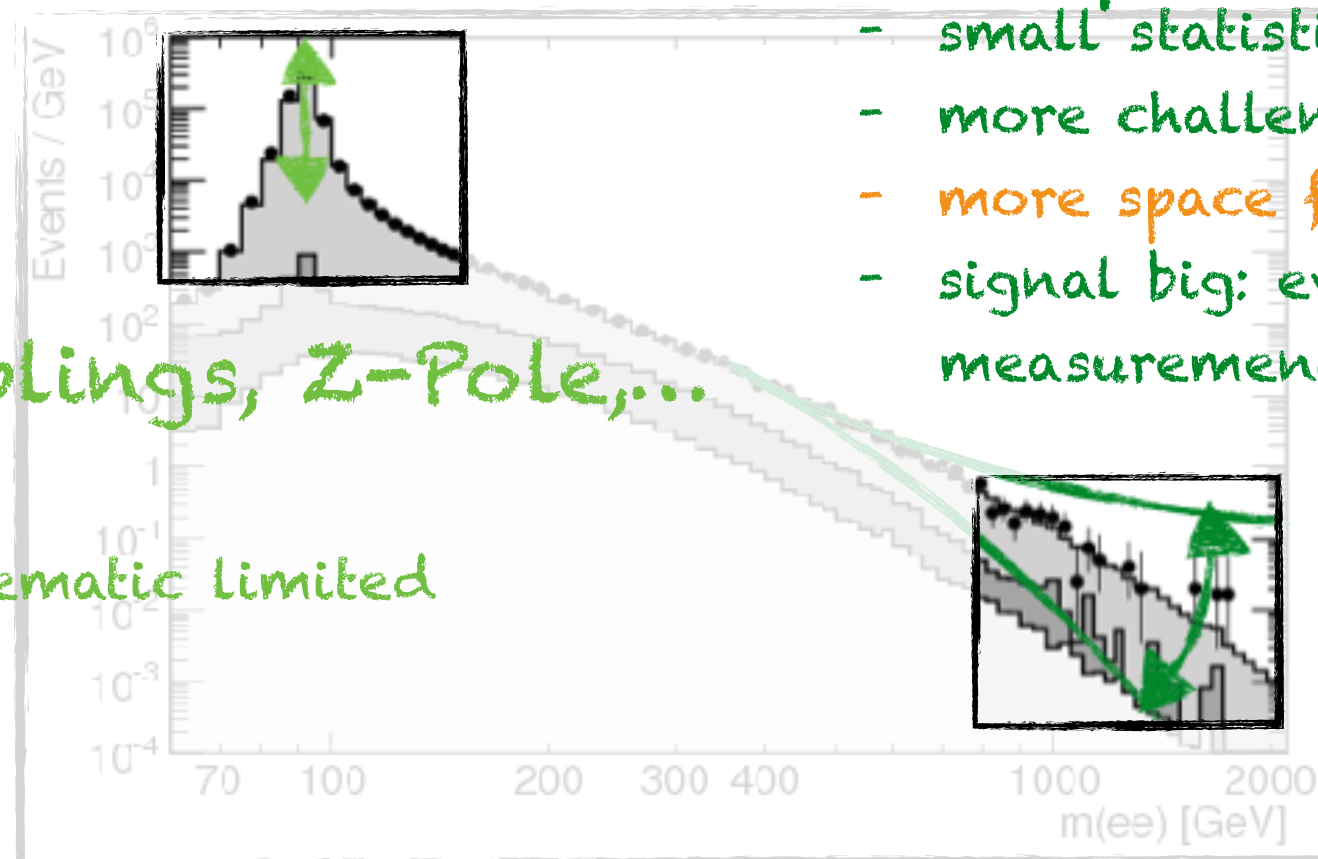

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Experimentally very appealing

Higgs Couplings

See Craig's talk

Modified Higgs sectors have modified Higgs couplings

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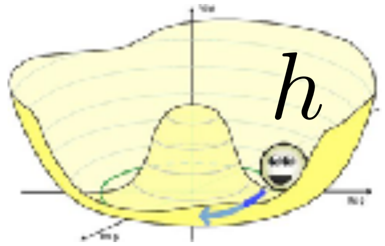
Composite Higgs Models: Higgs is a (pseudo) goldstone boson



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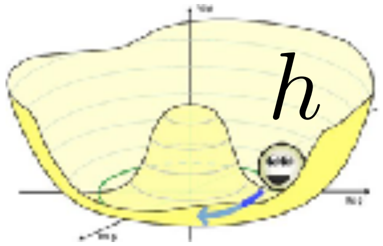

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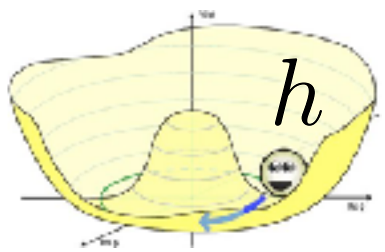

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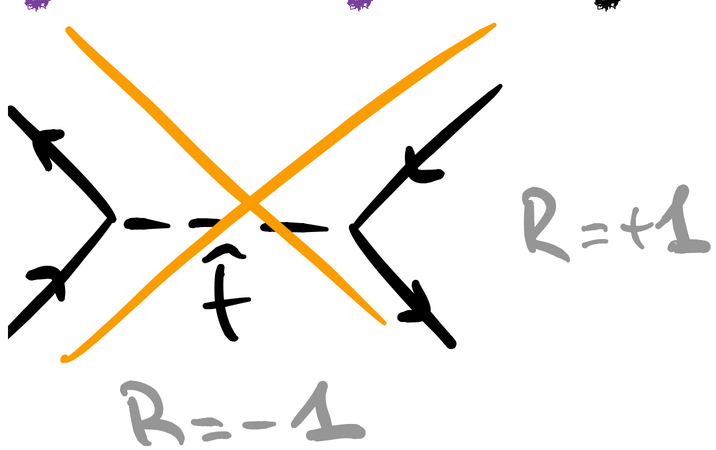
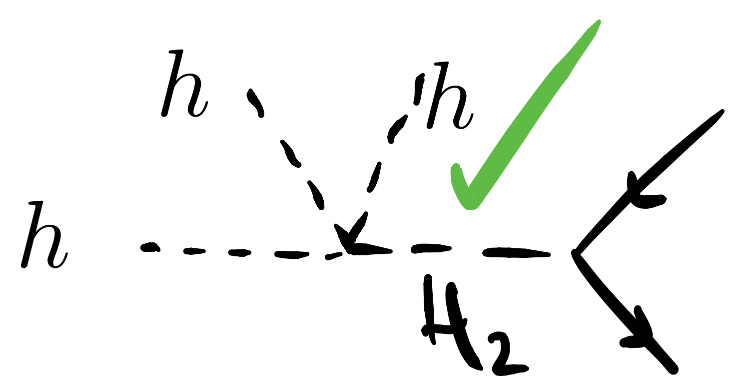
Supersymmetry: only H_2 (second Higgs) exchanged at tree-level (R-parity)





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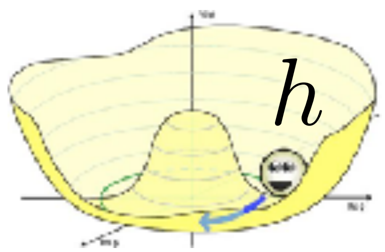

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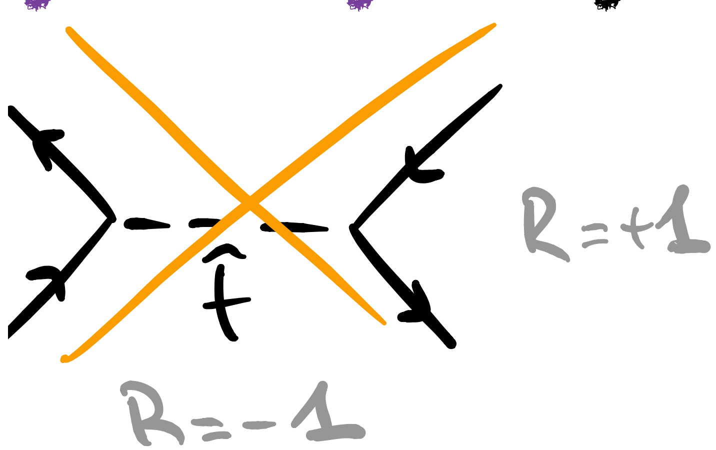

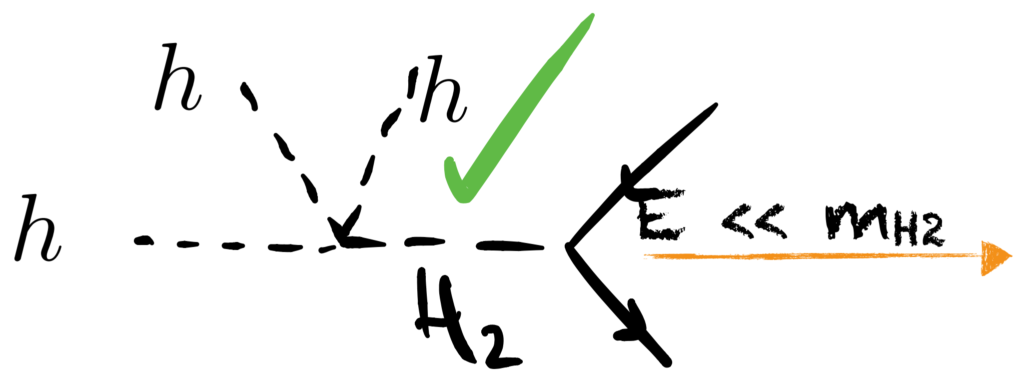

$$\frac{h^3}{m_{H_2}^2}\bar{\psi}\psi$$

Higgs couplings to top/bottom modified

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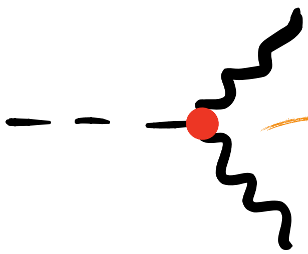

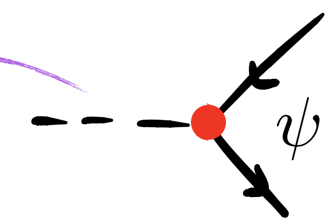

$\mathcal{O}_r = |H|^2 D_\mu H^\dagger D^\mu H$

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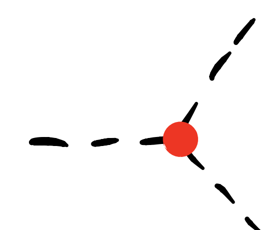
$\mathcal{O}_{WW} = g^2 |H|^2 W^a_{\mu\nu} W^{a\,\mu\nu}$

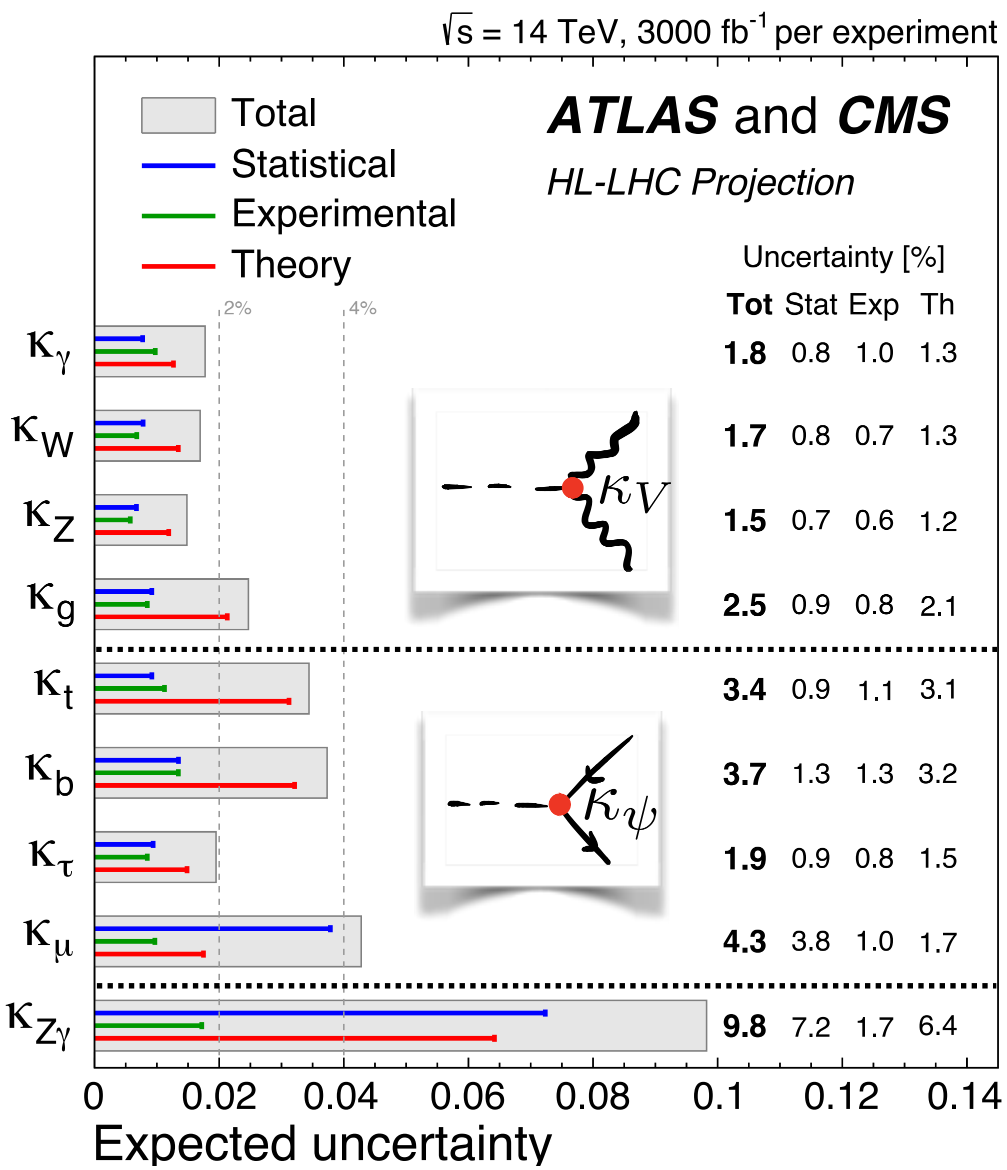
$\mathcal{O}_{GG} = g_s^2 |H|^2 G^a_{\mu\nu} G^{a\,\mu\nu}$

$\mathcal{O}_6 = |H|^6$



HL-LHC Reach (3000 fb-1)

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



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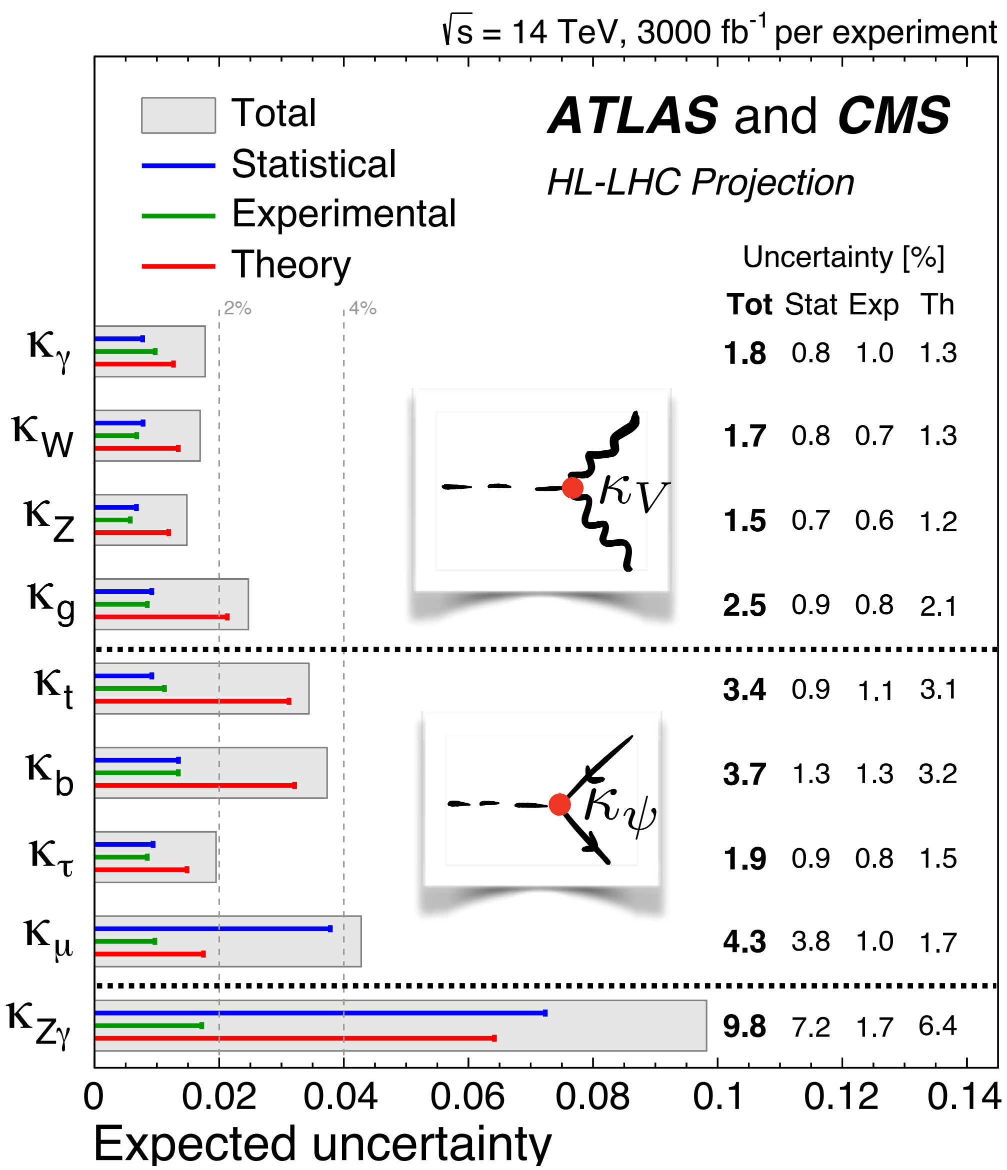

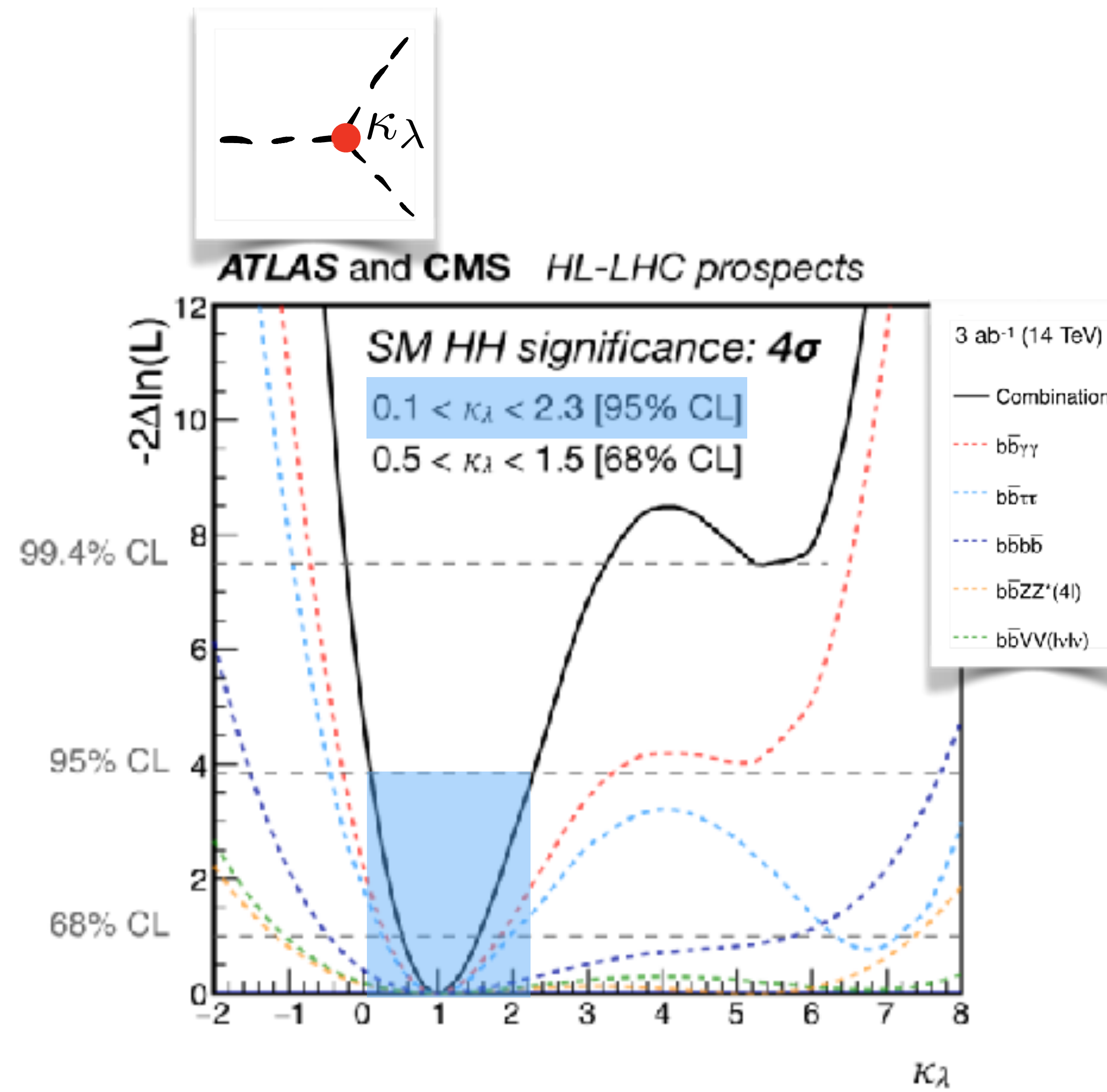

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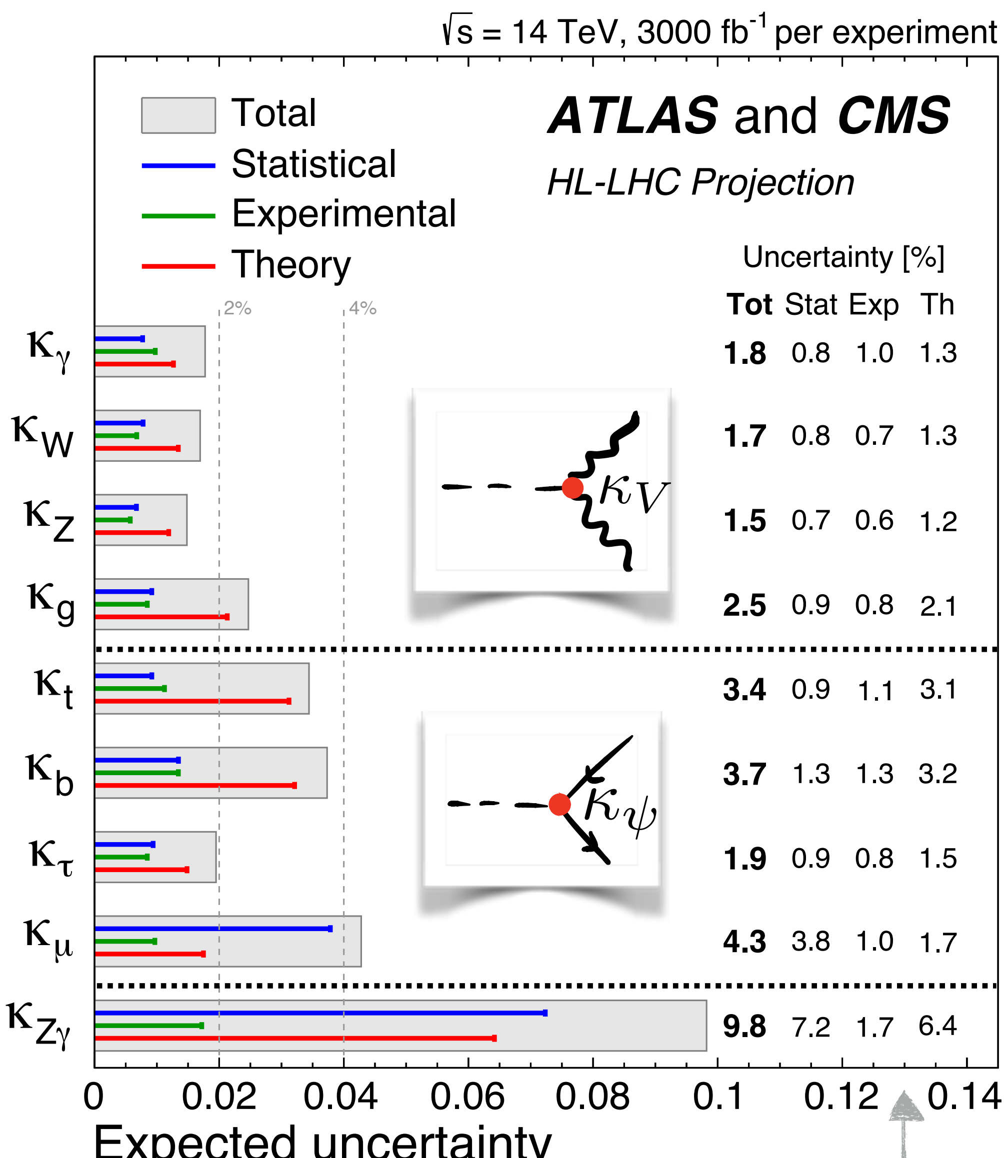
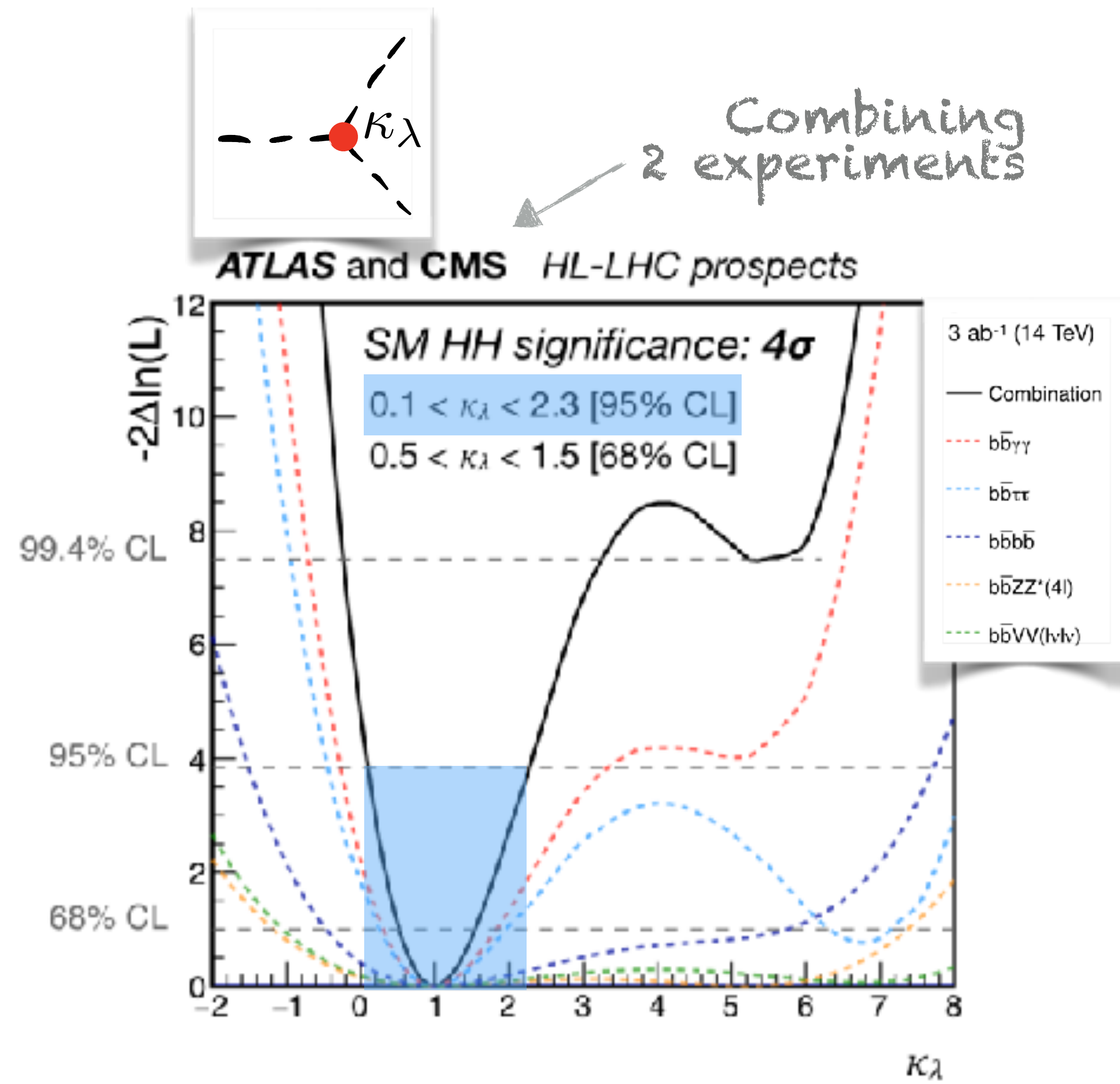


Optimistic Systematics (S2)



Combining 2 experiments

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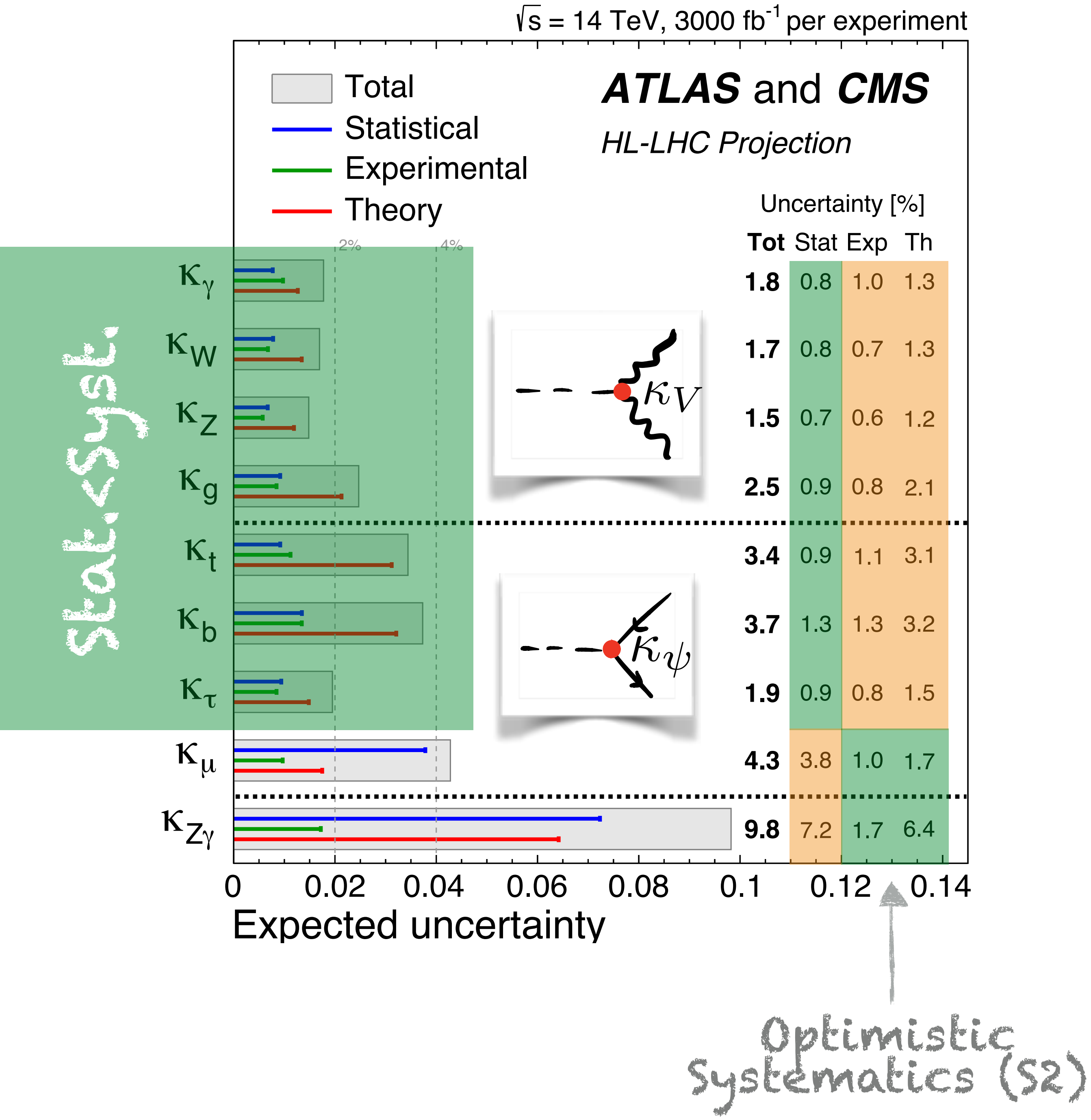
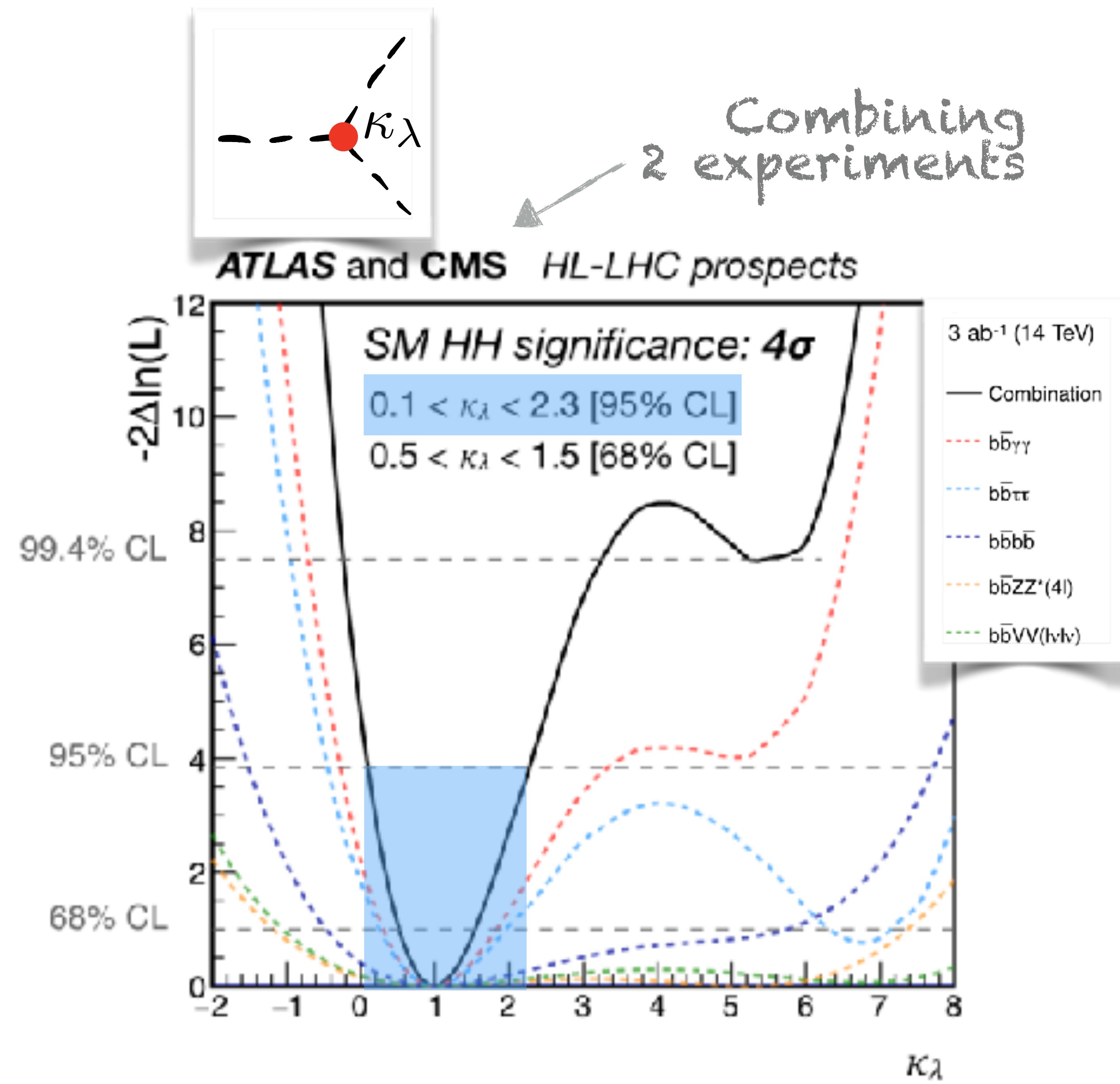


	Tot	Stat	Exp	Th
κ_γ	1.8	0.8	1.0	1.3
κ_W	1.7	0.8	0.7	1.3
κ_Z	1.5	0.7	0.6	1.2
κ_g	2.5	0.9	0.8	2.1
κ_t	3.4	0.9	1.1	3.1
κ_b	3.7	1.3	1.3	3.2
κ_τ	1.9	0.9	0.8	1.5
κ_μ	4.3	3.8	1.0	1.7
$\kappa_{Z\gamma}$	9.8	7.2	1.7	6.4



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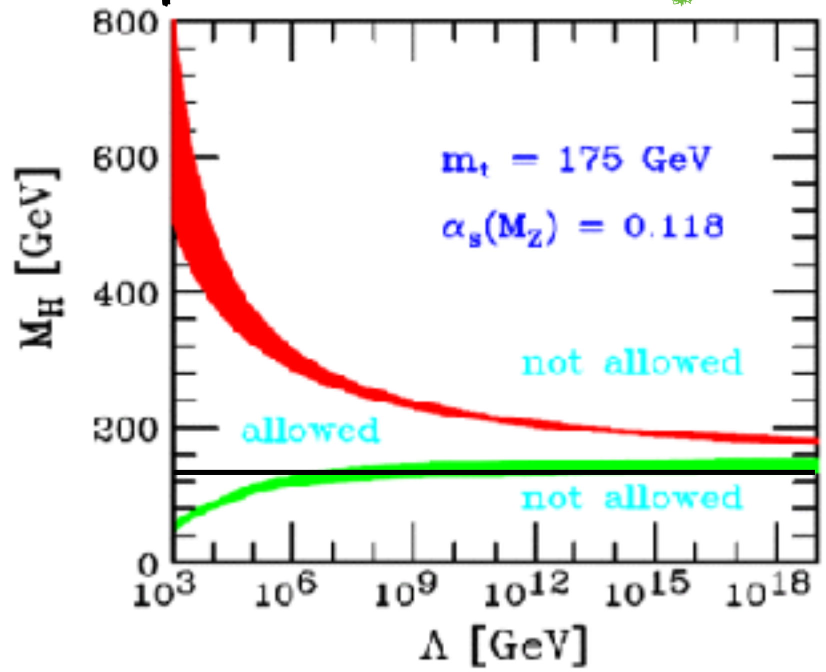

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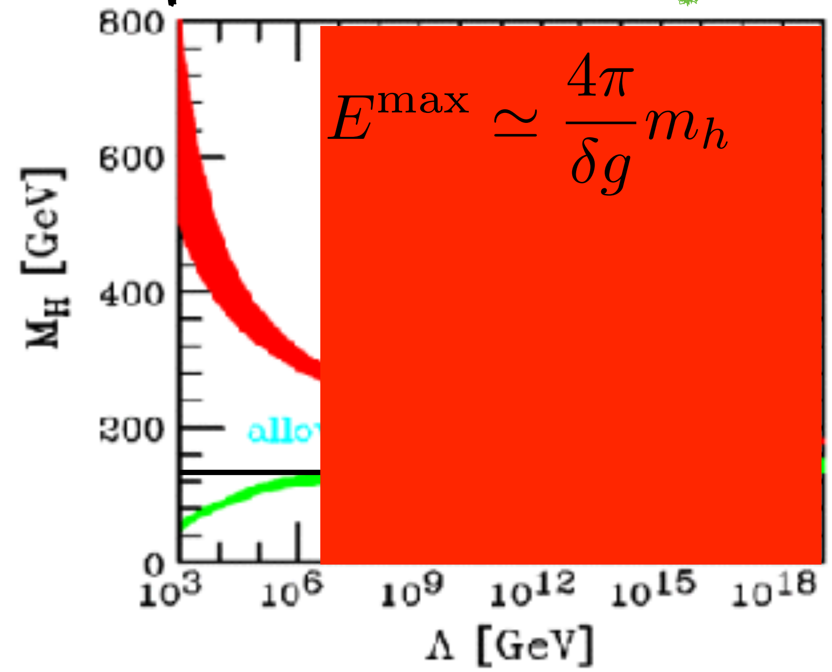


Any coupling modification must induce energy-growth in some process, reducing the validity energy-range

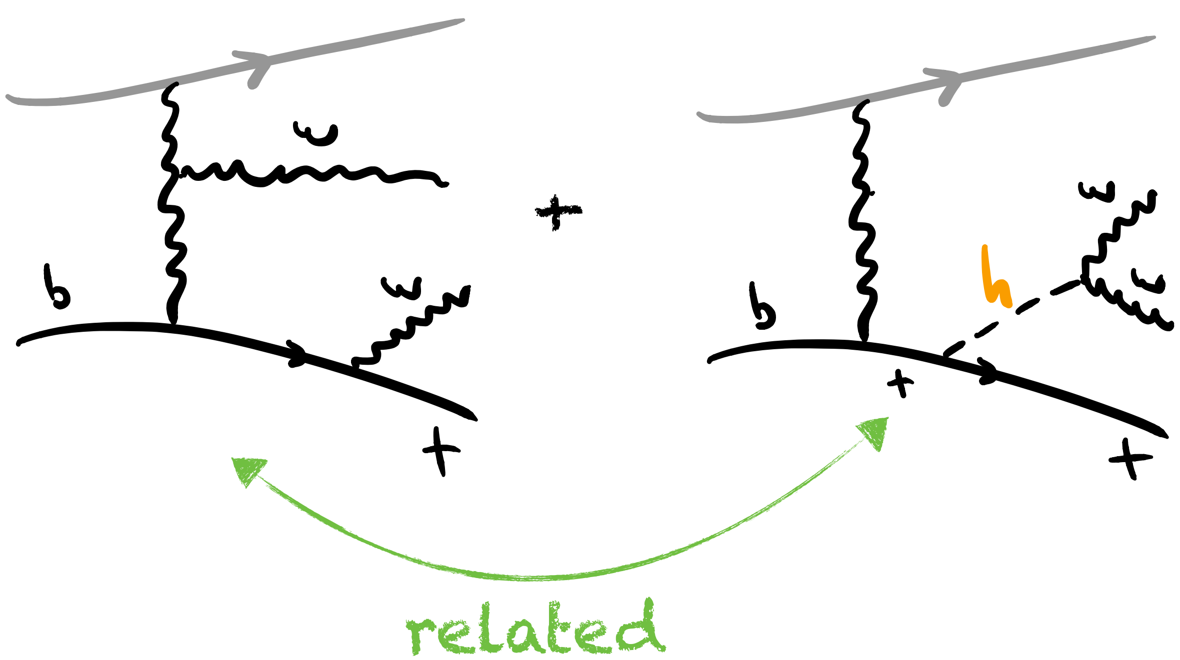
Higgs Couplings… without a Higgs (HwH)

Henning,Lombardo,Riembau,FR - PRL'19

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

One way of seeing this:

SM =



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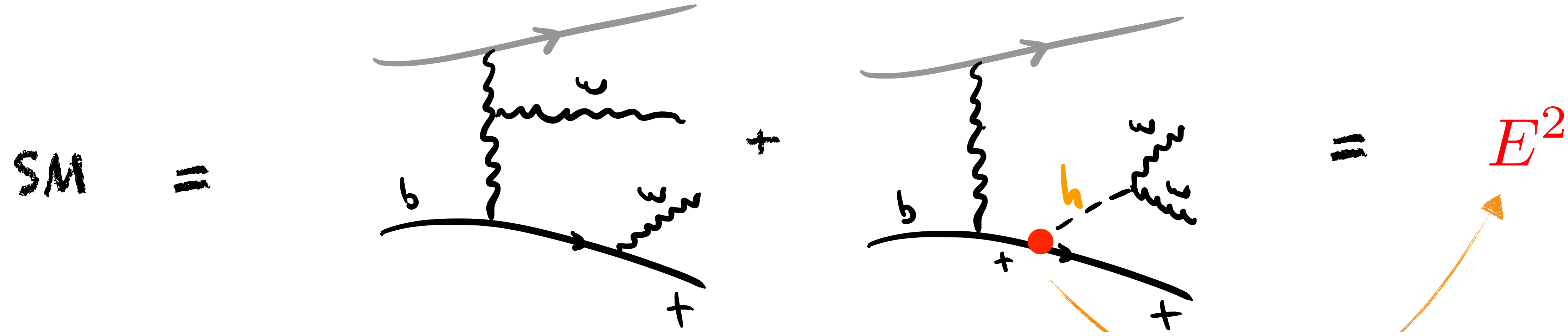

modification of top-yukawa
compromises gauge cancellations in the SM
▶ E-growth

Top Yukawa... without a Higgs

Another way of understanding E-growth:

modified Top-Yukawa κ_t $\Longleftrightarrow$ $\frac{|H|^2 Q\tilde{H}t_R}{\Lambda^2}$

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

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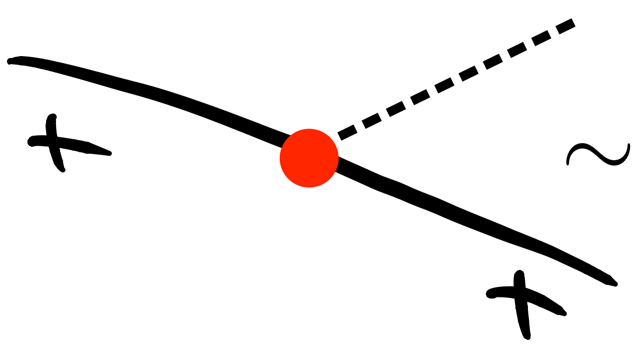

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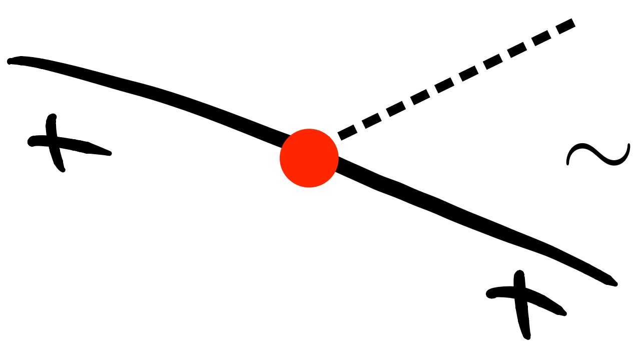

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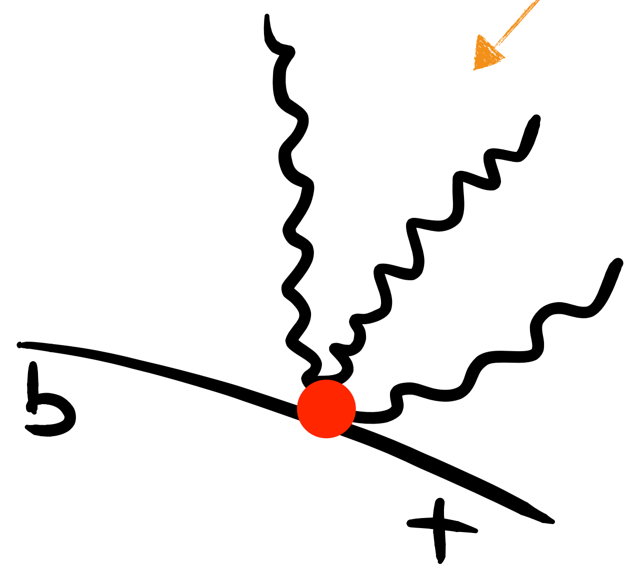

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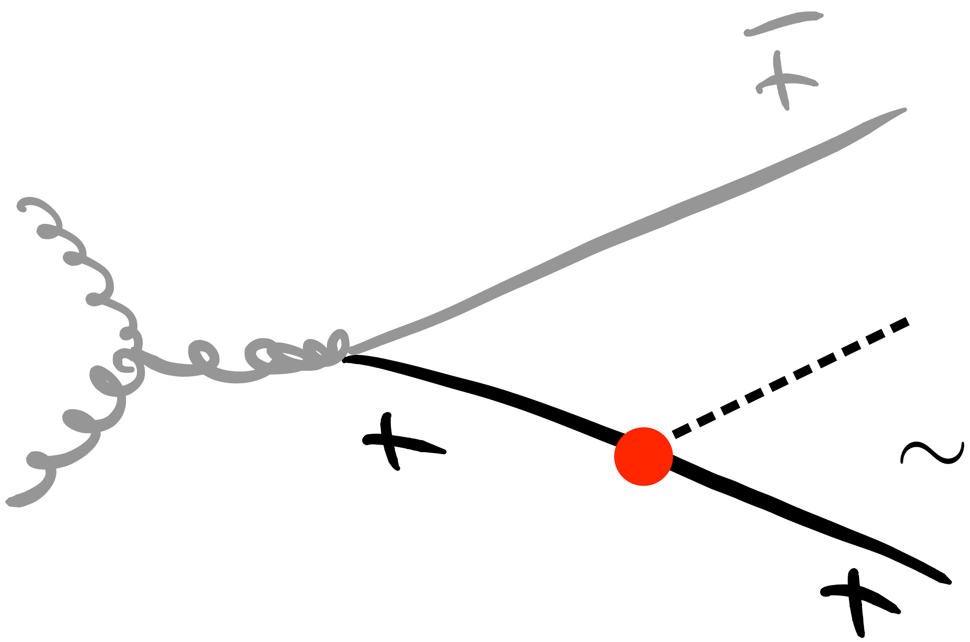

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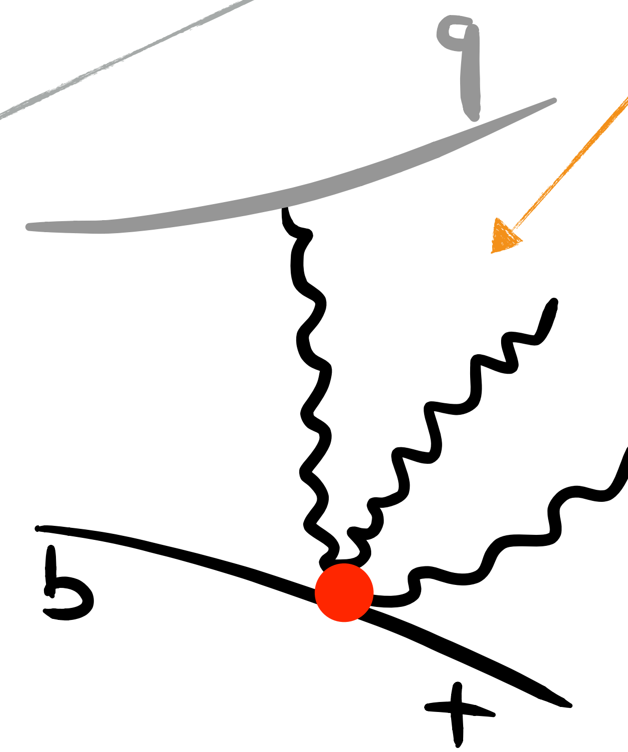

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statistics ←

signal →

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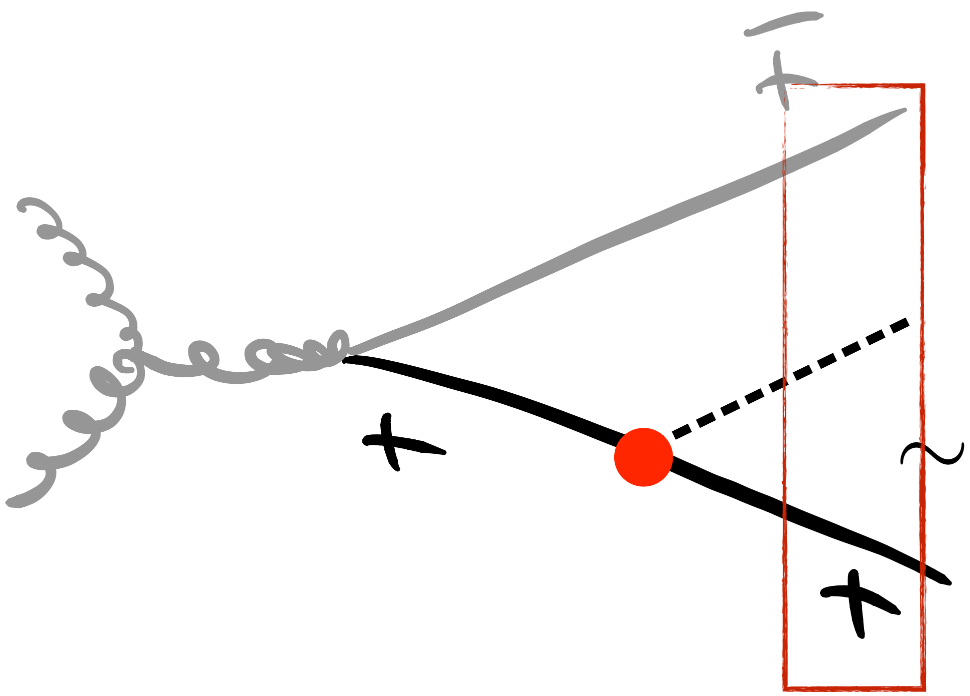

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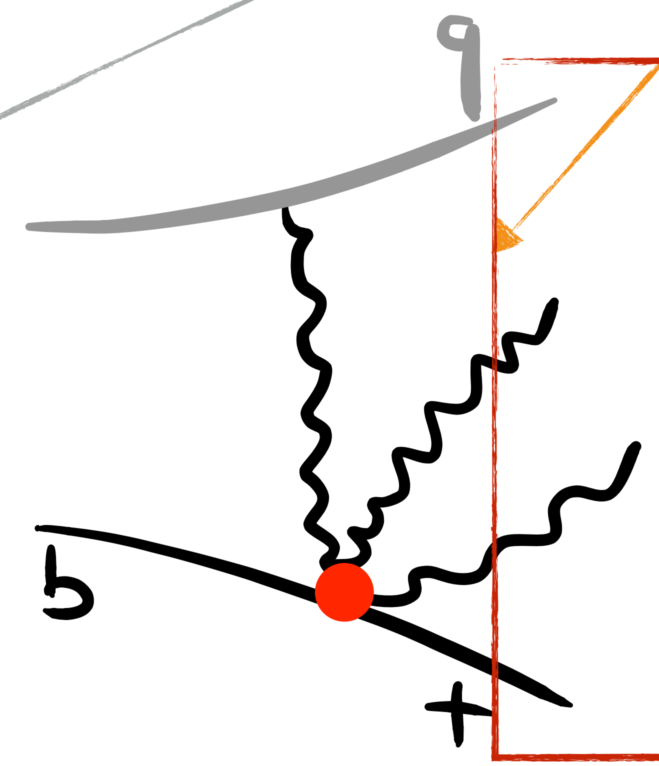

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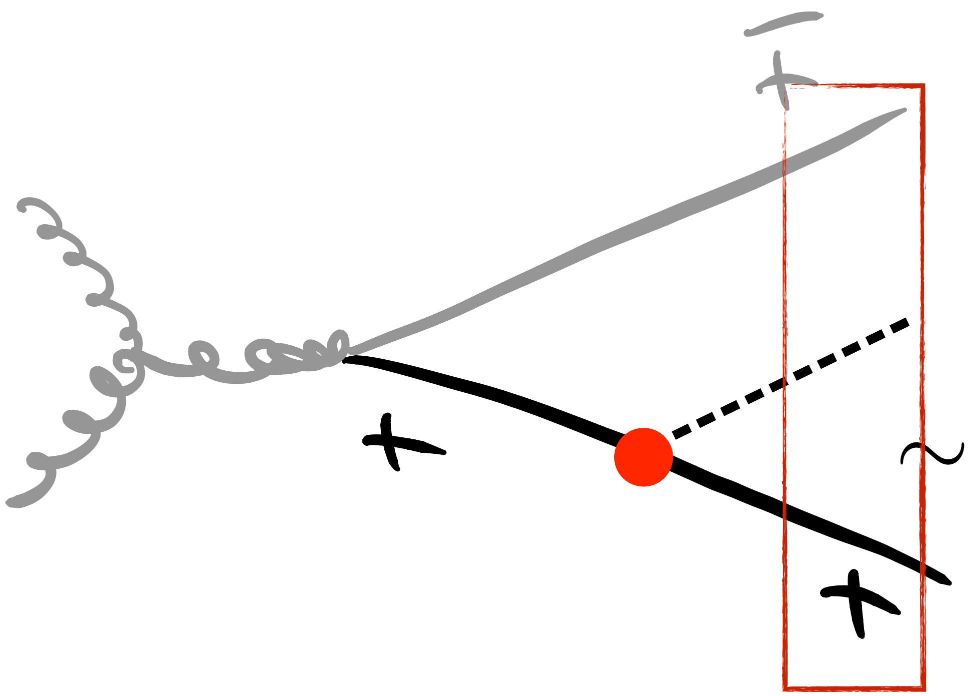

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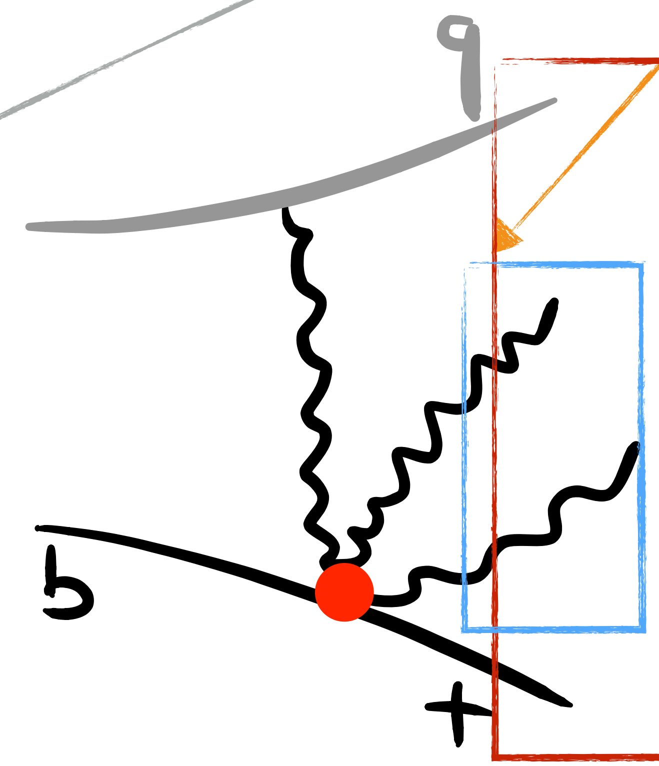

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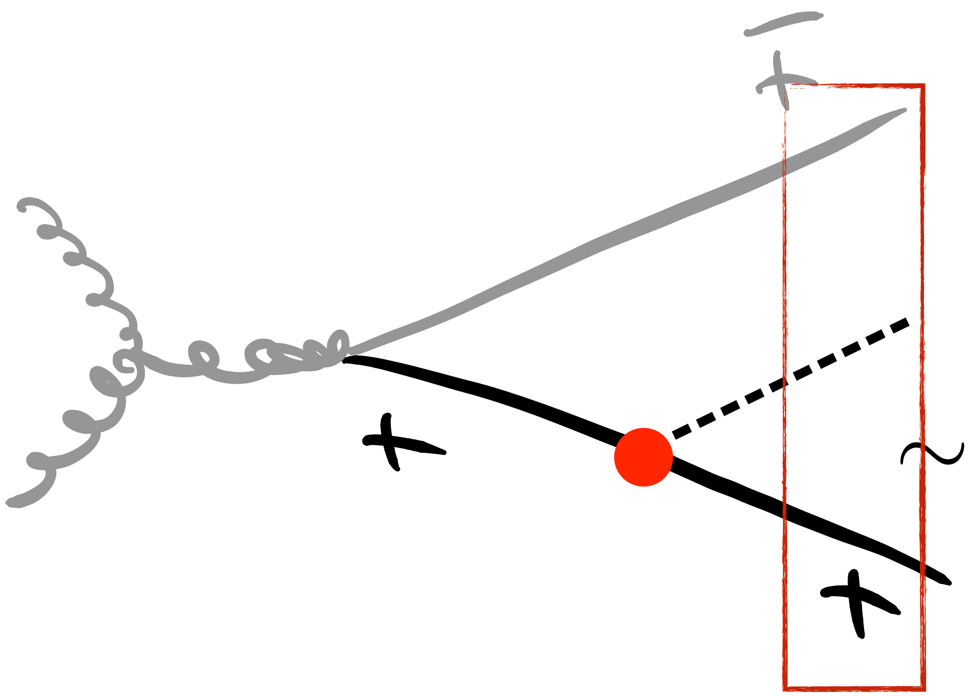

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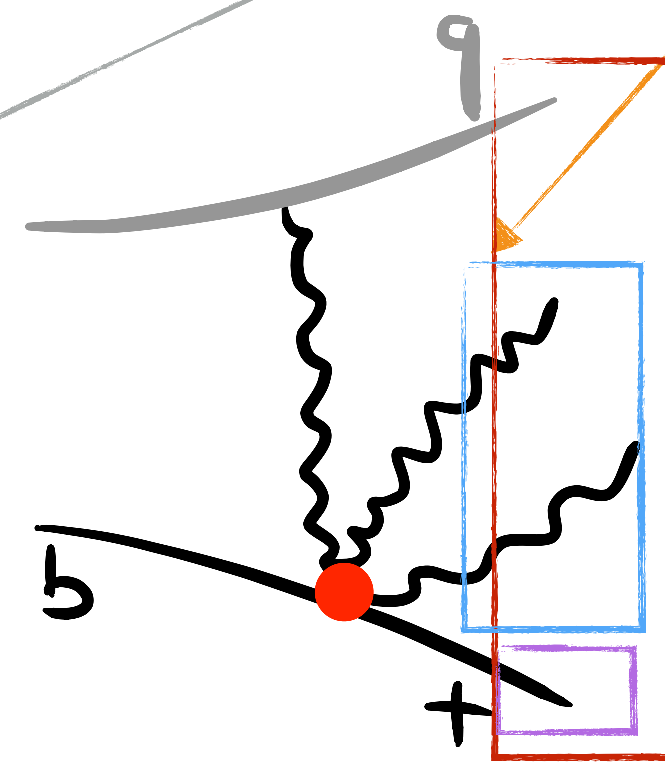

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Boosted top

statistics

signal

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$$pp \to VVjt$$

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SM signal classified by #leptons:

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

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SM signal classified by #leptons:

≥2l: Small Background

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

Top Yukawa... without a Higgs

$$pp \to VVjt$$

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$ttjj \to tWbjj$ ($bj \sim W$) background 10^6 larger... but manageable

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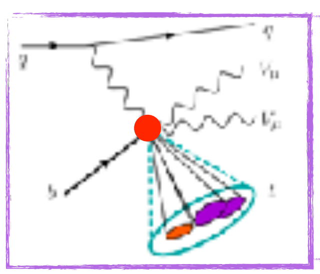
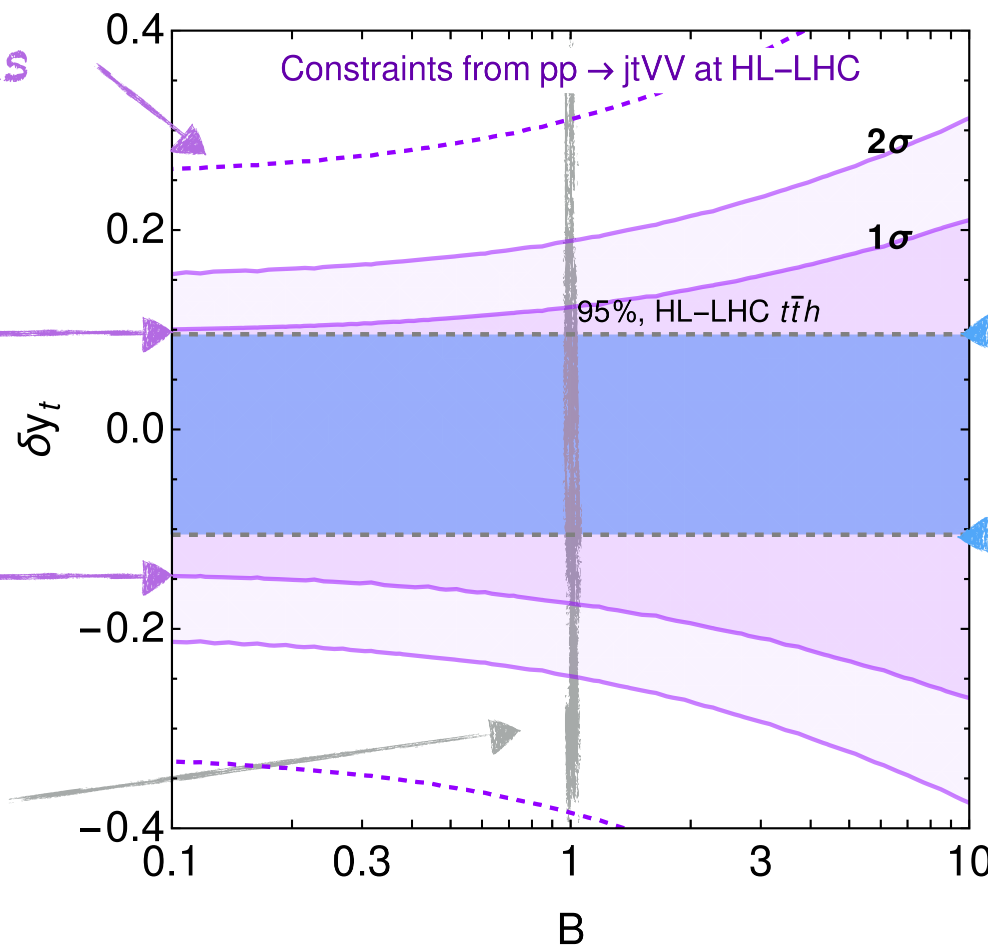
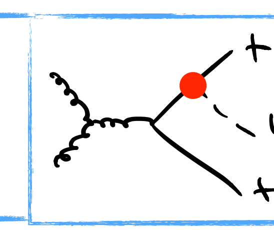
$p_T^t > 250$ GeV / $p_T^t > 500$ GeV

only channels with >2 leptons (small B)







Background = SM signal

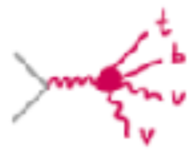
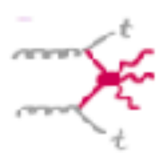
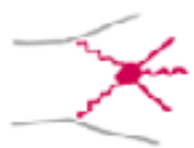
▶ Competitive with standard!

WANTED

Top Yukawa... improvements

...work in progress...

Same amplitude enters in many channels...

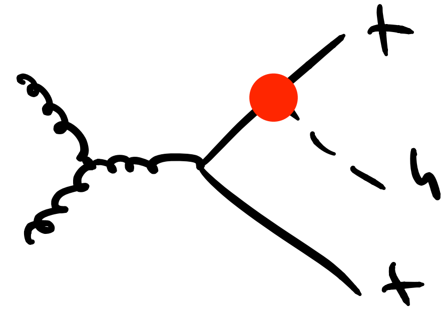
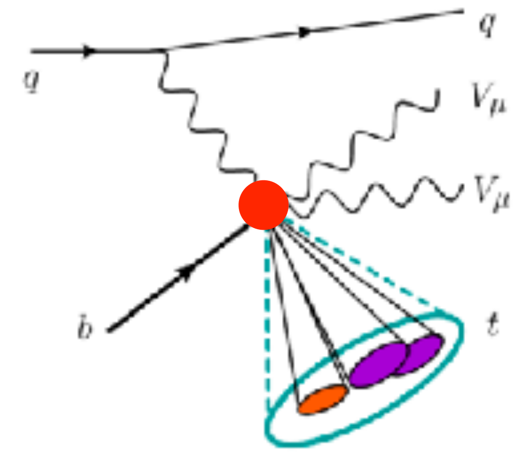
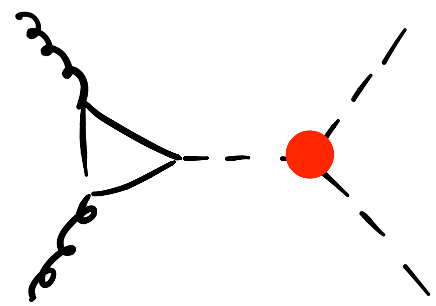
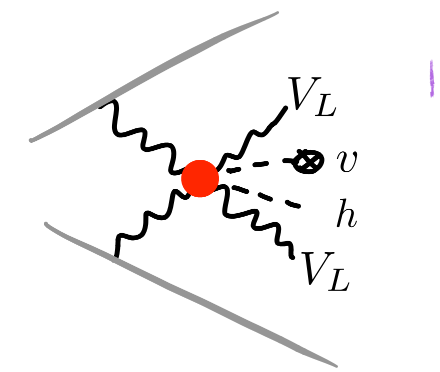
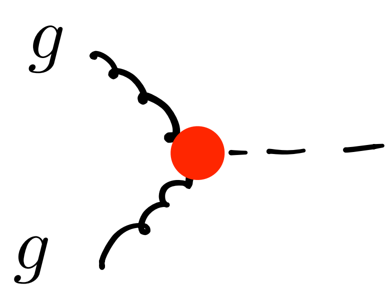
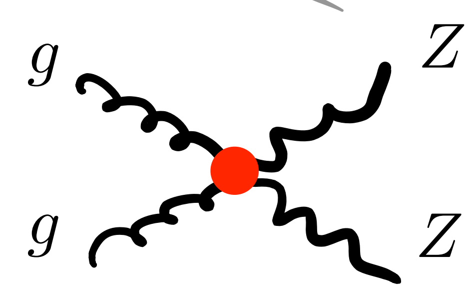
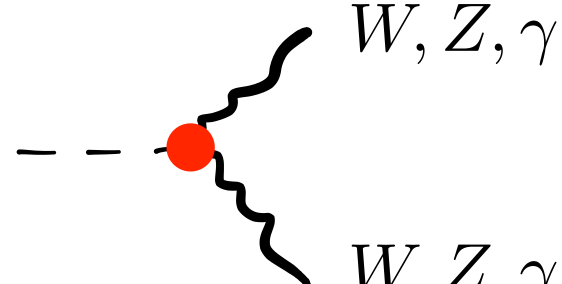
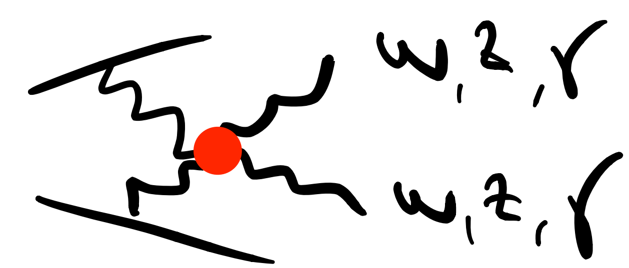
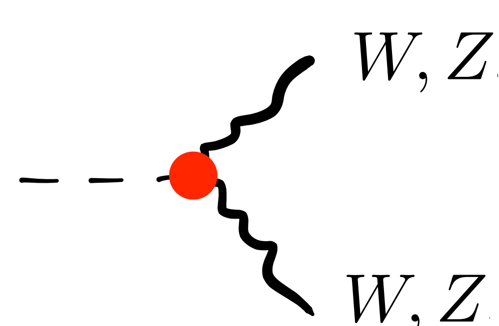
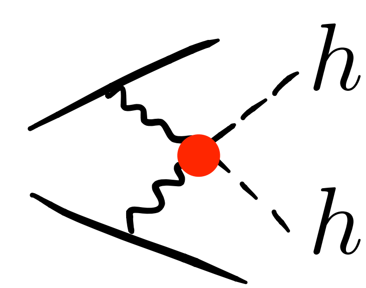
Legs	Order	Diagram	Channels	Xsec[fb]	QCD bgnd	L/T
$1 \to 4$	QCD		$tW^\pm W^\pm W^\mp$	0.7	/	0.03
			$tW^\pm ZZ$	0.4	/	0.03
	EW		$tbW^\pm W^\pm$	3.5	/	0.10
			$tbW^\pm W^\mp$	3.5	/	0.20
			$tbW^\pm Z$	3.8	/	0.11
			$tbZZ$	0.02	0	0.09
$2 \to 3$	QCD^2		$ttZWW$	0.083	/	0.03
			$ttZZZ$	0.008	/	0.04
			$tbWWW$	19	/	0.04
			$tbWZZ$	3.8	/	0.07
	EW^2		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		$\sim const$	$\sim E^2$
κ_t	$\lvert H\rvert^2 Q\tilde{H} t_R$		
κ_λ	$\lvert H\rvert^6$		
κ_G	$\lvert H\rvert^2 G^a_{\mu\nu} G^{a\,\mu\nu}$		
κ_γ $\kappa_{Z\gamma}$	$\lvert H\rvert^2 B_{\mu\nu} B^{\mu\nu}$ $\lvert H\rvert^2 W^a_{\mu\nu} W^{a\,\mu\nu}$		
κ_V	$\lvert H\rvert^2 \partial_\mu H^\dagger \partial^\mu H$		

HwH: Higgs Self Coupling

E-growth from a modified self-coupling:

$$h^3 \in \frac{|H|^6}{\Lambda^2}$$

Golstones = W_L, Z_L

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

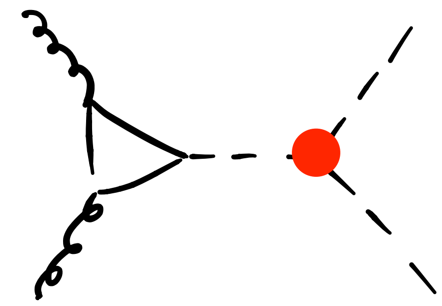
HwH: Higgs Self Coupling

E-growth from a modified self-coupling:

$$h^3 \in \frac{|H|^6}{\Lambda^2}$$

with 3 Higgs v.e.v.s

(= traditional Higgs Coupling measurement)



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

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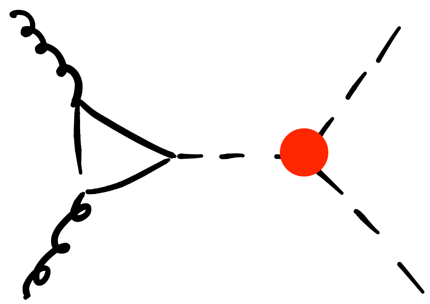

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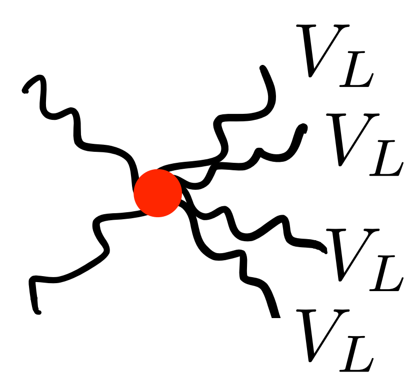
with No Higgs v.e.v.s

Contact Interaction Among W_L, Z_L



$$\sim \frac{1}{\Lambda^2}$$

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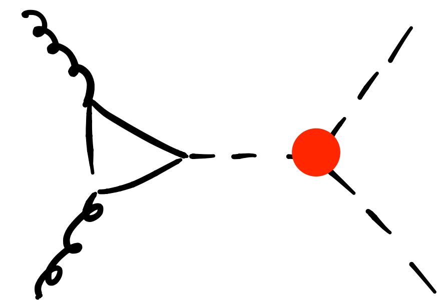

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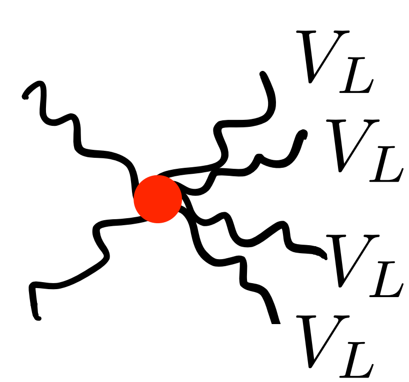

$$\sim \frac{E^2}{\Lambda^2}$$ w.r.t SM

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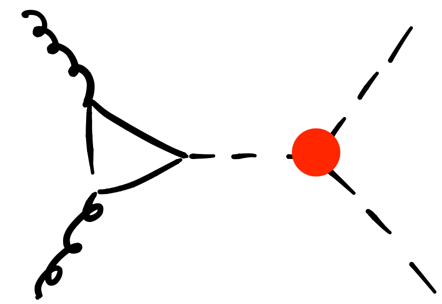

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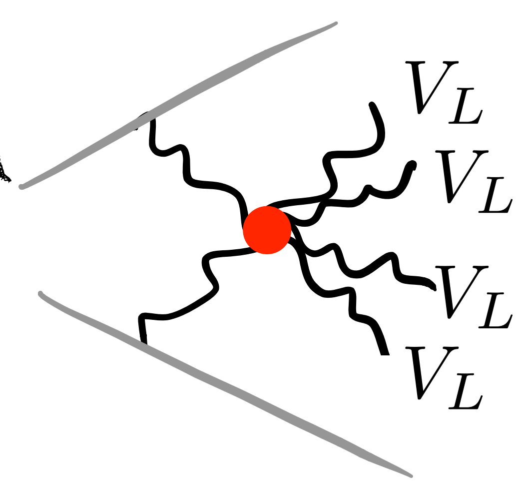

$$\sim \frac{E^2}{\Lambda^2} \text{ w.r.t SM}$$

$$pp \to jj + 4V_L$$

HwH: Higgs Self Coupling

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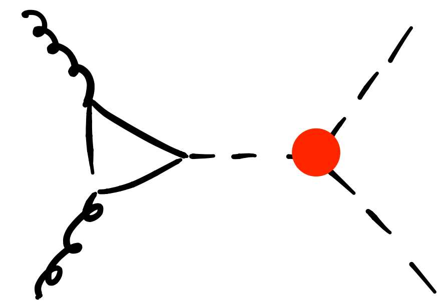

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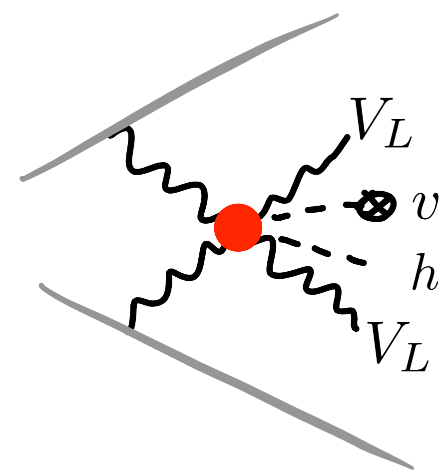
with 1 Higgs v.e.v.

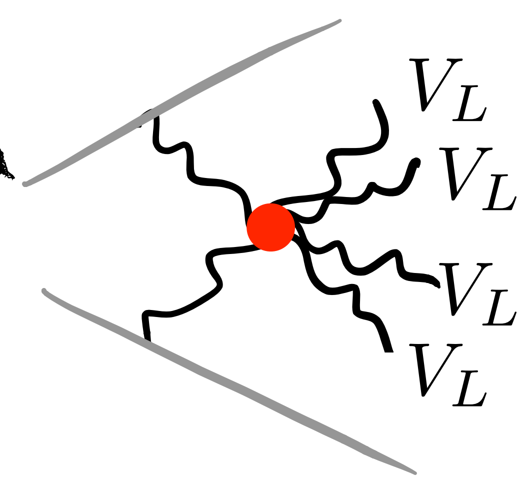


$$\sim \frac{v\,E}{\Lambda^2}$$

$pp \to jjh + V_L V_L'$

with No Higgs v.e.v.s

▶ Contact Interaction Among W_L, Z_L



$$\sim \frac{E^2}{\Lambda^2}$$ w.r.t SM

$pp \to jj + 4V_L$

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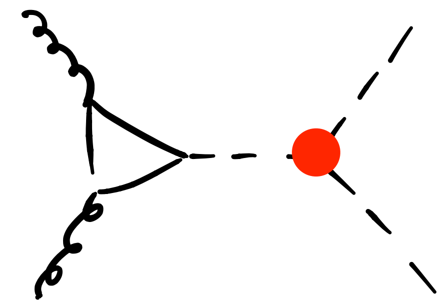
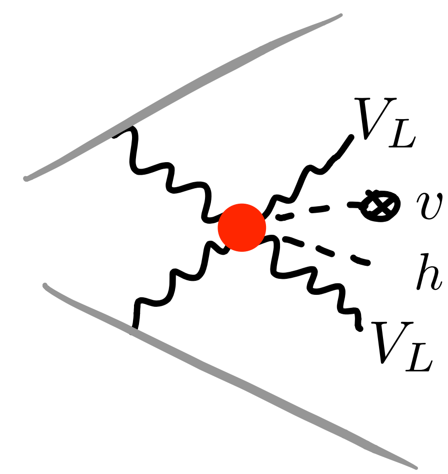
with 3 Higgs v.e.v.s
(= traditional Higgs Coupling measurement)



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

with 1 Higgs v.e.v.

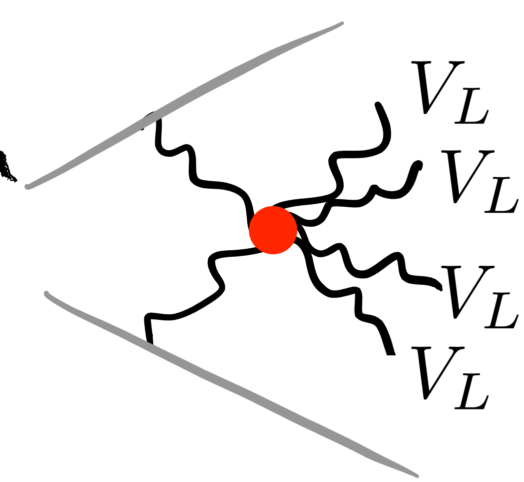


$$\sim \frac{v\,E}{\Lambda^2}$$

$pp \to jjh + V_L V'_L$

with No Higgs v.e.v.s

Contact Interaction Among W_L, Z_L



$$\sim \frac{E^2}{\Lambda^2}$$ w.r.t SM

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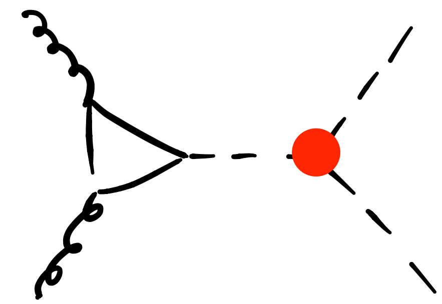

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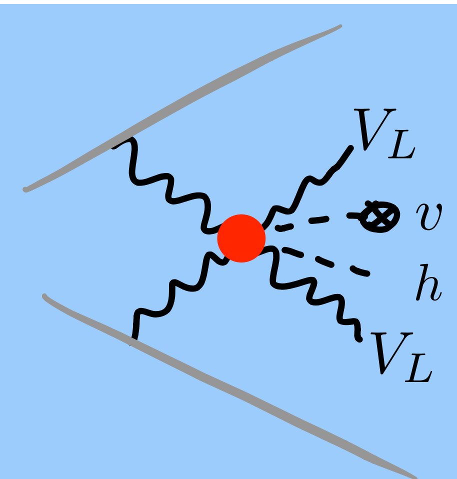

$$\sim \frac{v\,E}{\Lambda^2}$$

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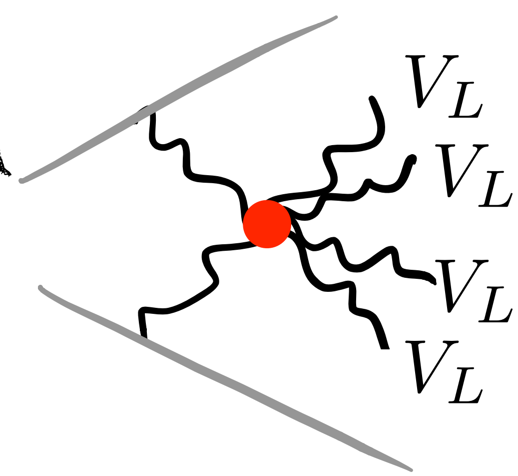
with No Higgs v.e.v.s

Contact Interaction Among W_L, Z_L



$$\sim \frac{E^2}{\Lambda^2}$$ w.r.t SM

$pp \to jj + 4V_L$

signal

statistics

HwH: Higgs Self Coupling

Henning,Lombardo,Riembau,PRL'19

$$pp \to jjh + W^{\pm}W^{\pm}$$

HwH: Higgs Self Coupling

Henning,Lombardo,Riembau,PRL'19

$W \to l + \nu$ → Same-sign leptons

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HwH: Higgs Self Coupling

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$W \to l + \nu$ → Same-sign leptons

$$pp \to jjh + W^{\pm}W^{\pm}$$

$h \to \bar{b}b$

→ VBF topology

HwH: Higgs Self Coupling

Henning,Lombardo,Riembau,PRL'19

$$pp \to jjh + W^{\pm}W^{\pm}$$

- $W \to l + \nu$ → Same-sign leptons
- $h \to \bar{b}b$
- → VBF topology

- Enough events
  (50 events @ 3000 fb-1)
- Low background B
  - ttjj ✓
  - fake leptons ?

HwH: Higgs Self Coupling

Henning,Lombardo,Riembau,PRL'19

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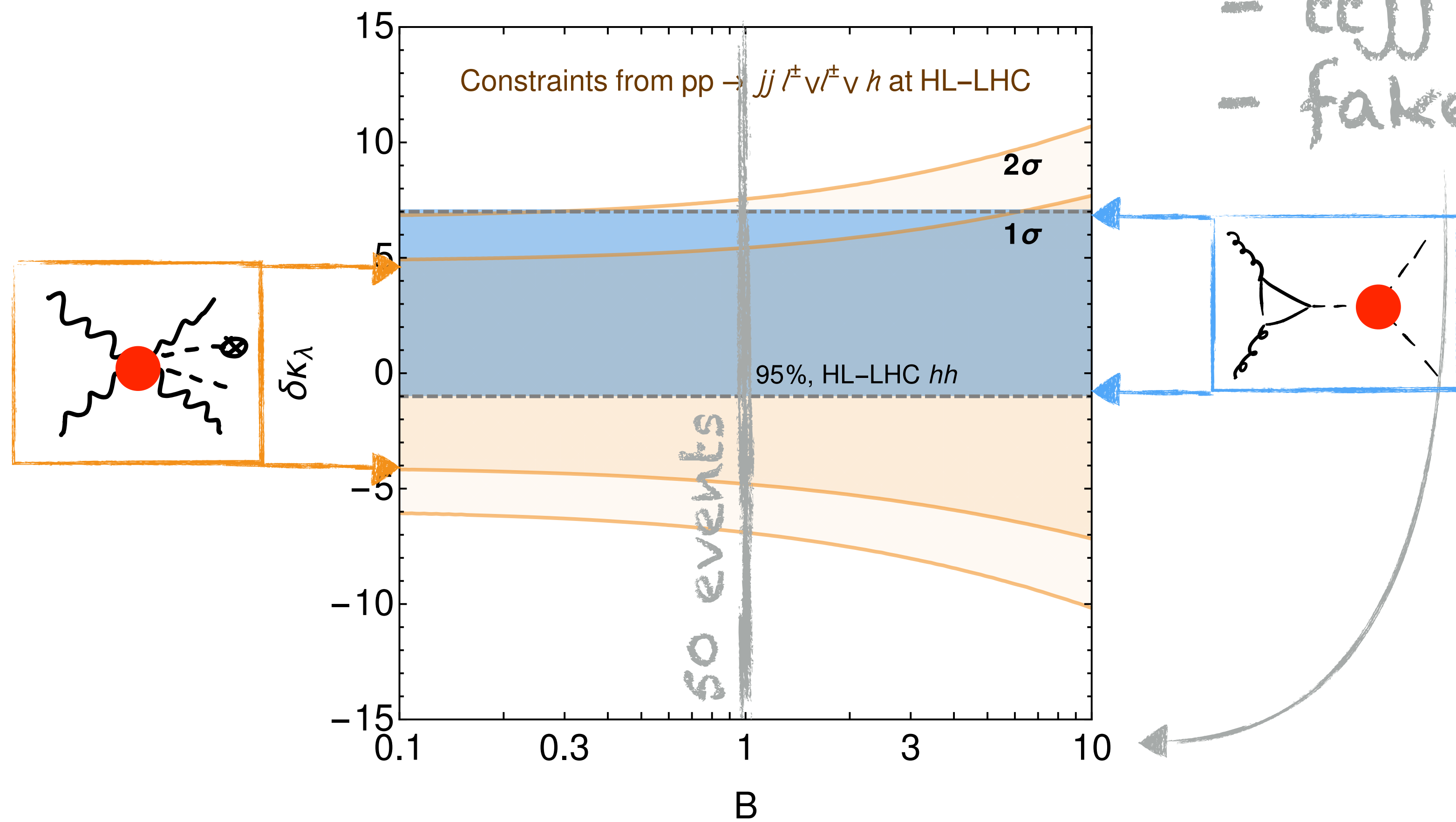

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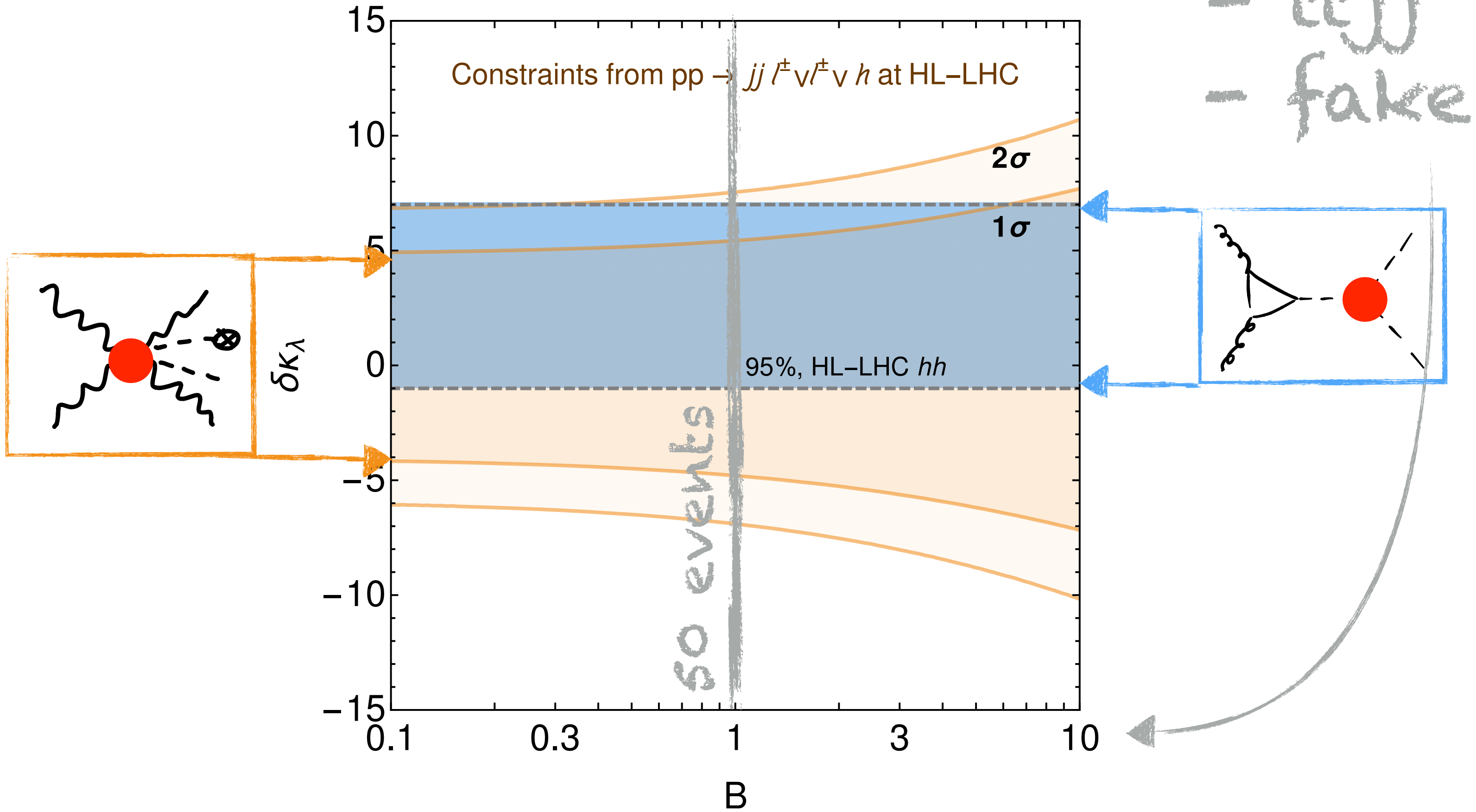
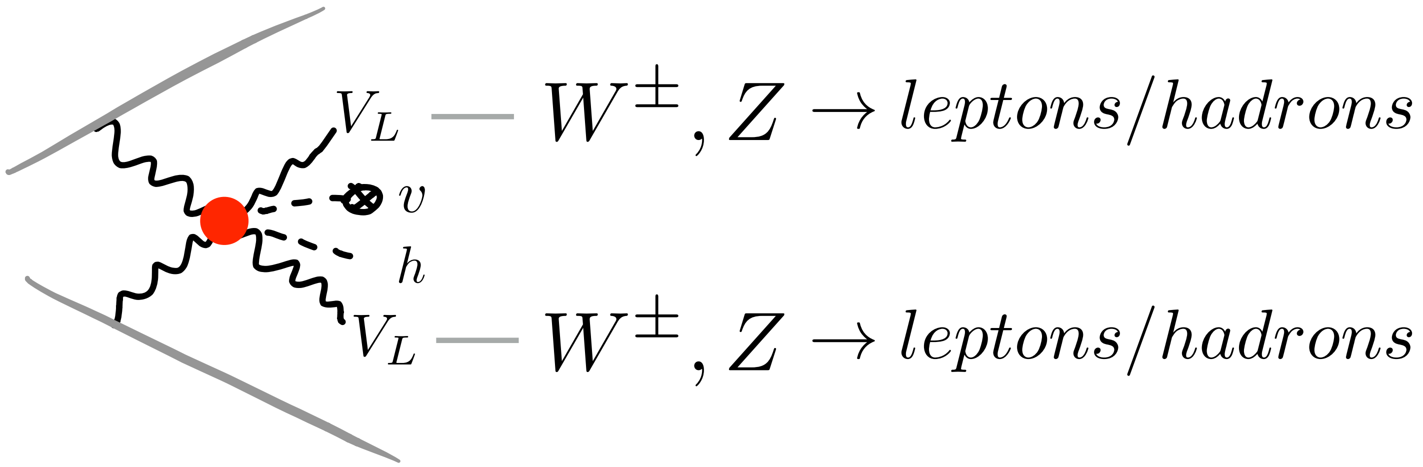


- HwH: single channel, simple analysis, competitive with HC!

HwH: Higgs Self Coupling

... many possibilities of improvement ...

- More Final states



HwH: Higgs Self Coupling

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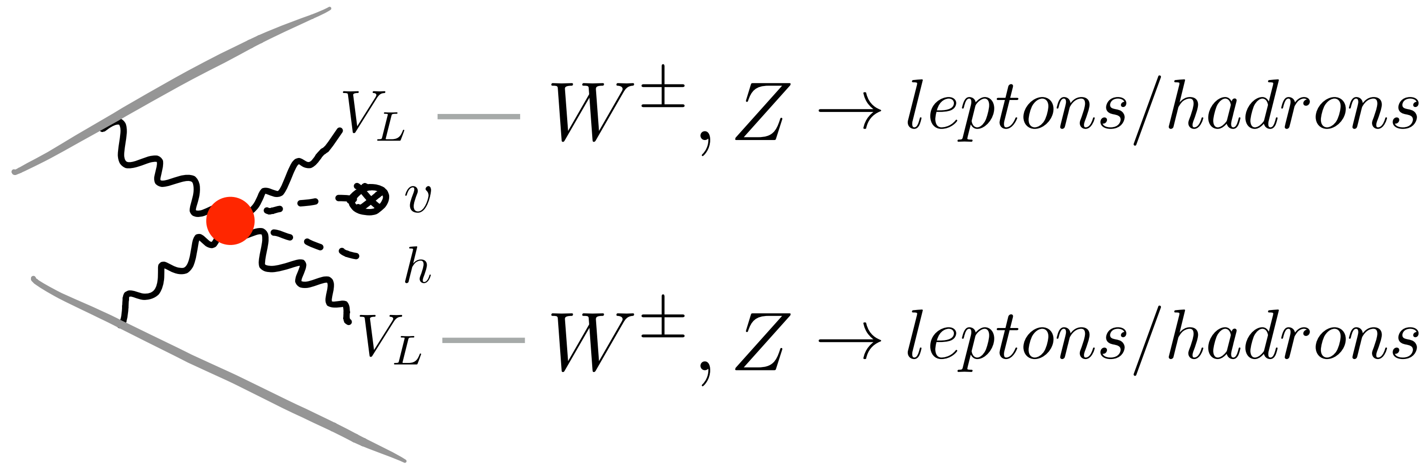
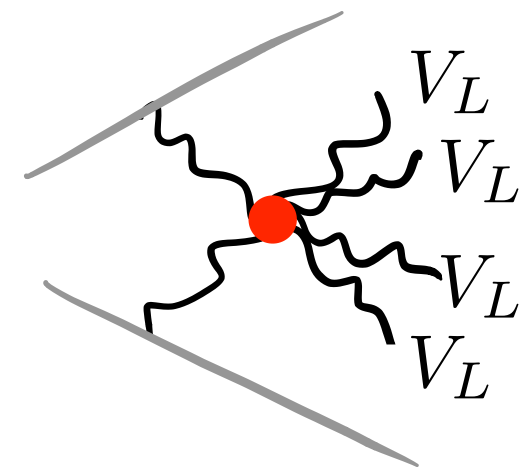


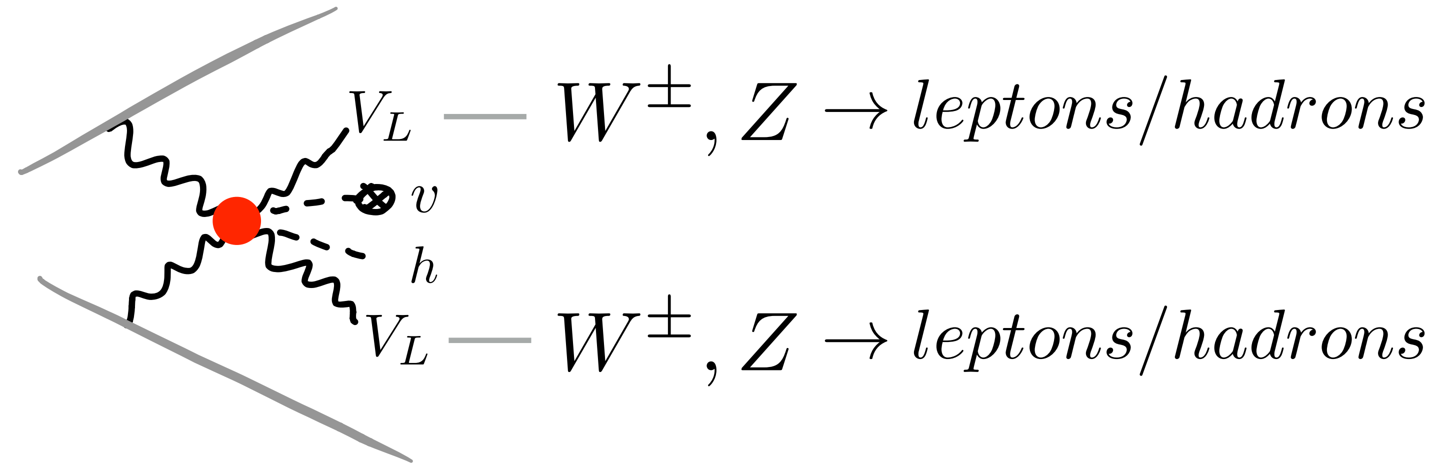
- Look also at E²-growing processes



HwH: Higgs Self Coupling

… many possibilities of improvement …

- More Final states



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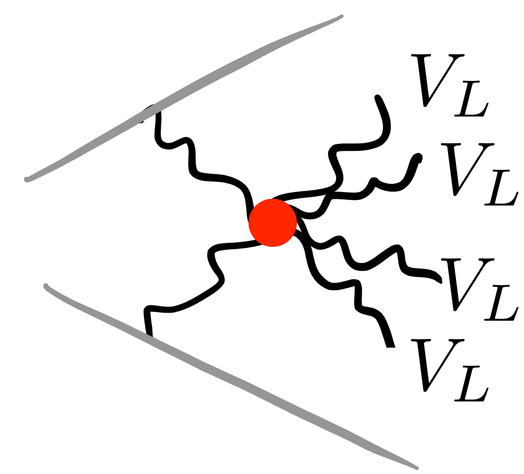
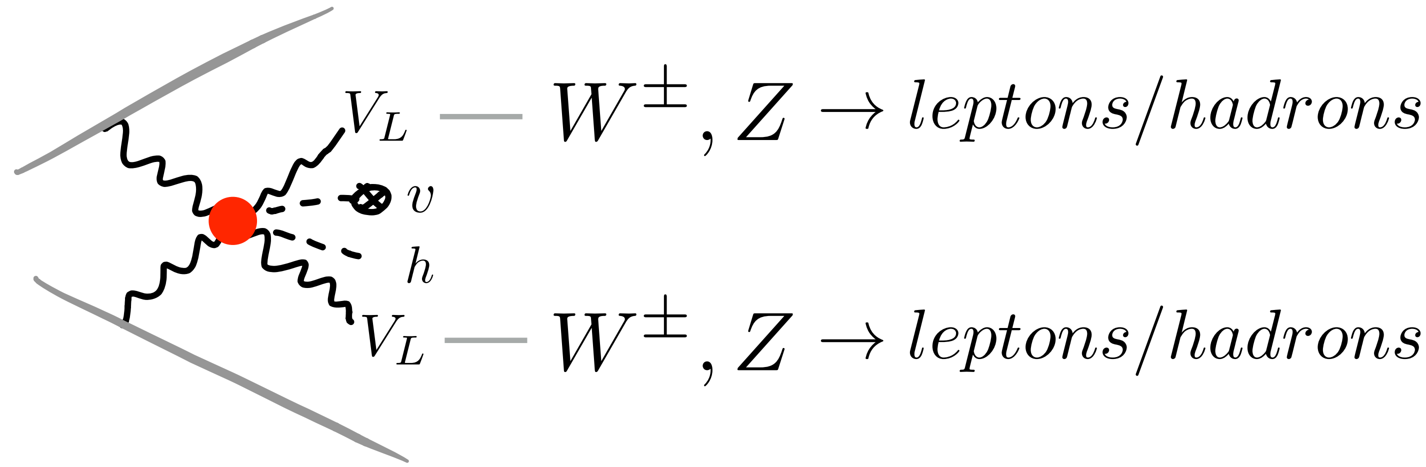


- Keep differential information to exploit E-growth

HwH: Higgs Self Coupling

… many possibilities of improvement …

- More Final states



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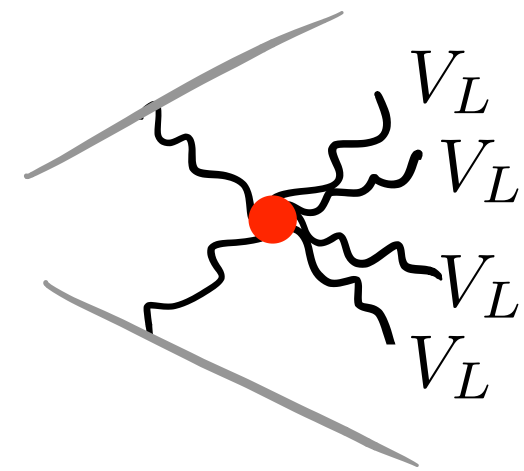


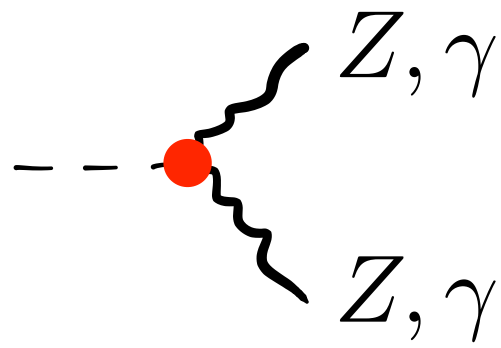
- Keep differential information to exploit E-growth

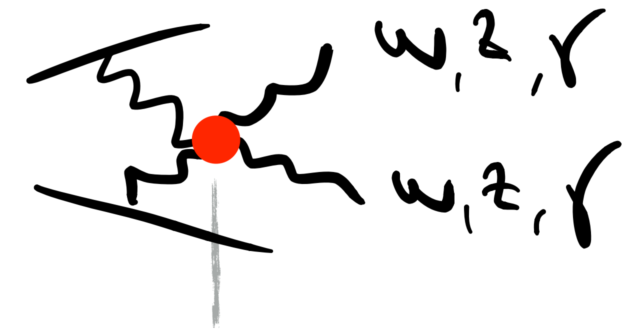
- Develop polarization-sensitive analysis (see Panico,FR,Wulzer'17)
  (SM V_T final states large and not interfering)

HwH Program: h to gauge bosons

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

$$\kappa_{Z\gamma} \; |H|^2 W^a_{\mu\nu} W^{a\,\mu\nu}$$





So far interpreted with dim-8 operators (aQGC)

HwH Program: h to gauge bosons

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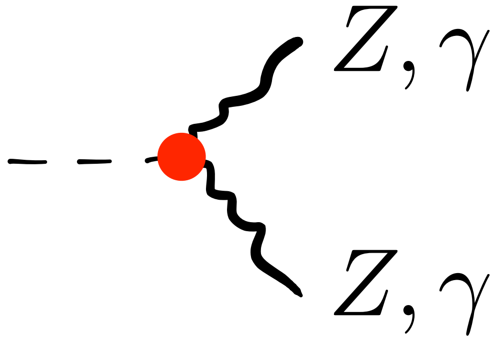

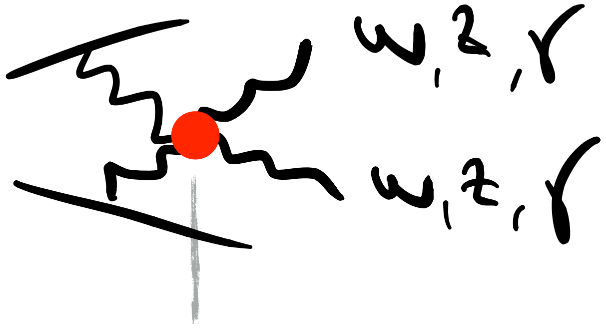

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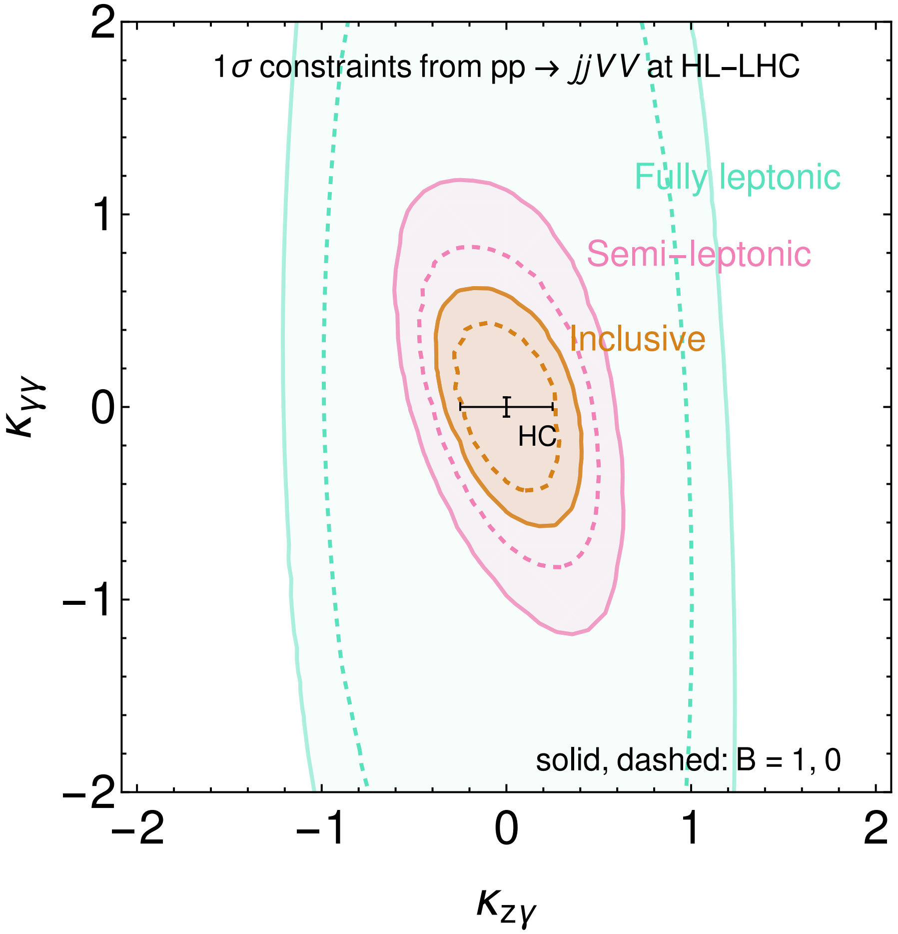

Simple analysis:

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

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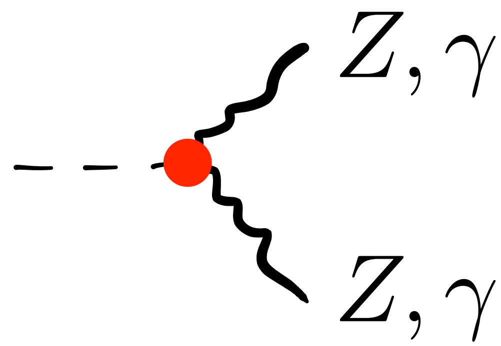

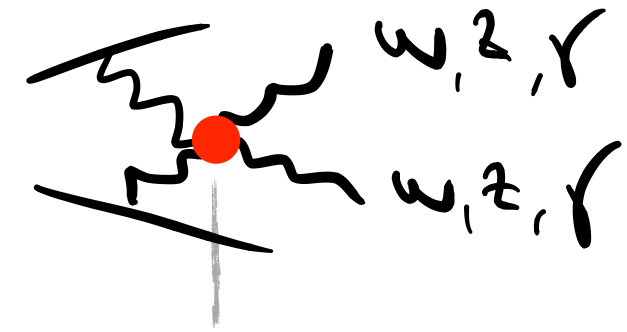

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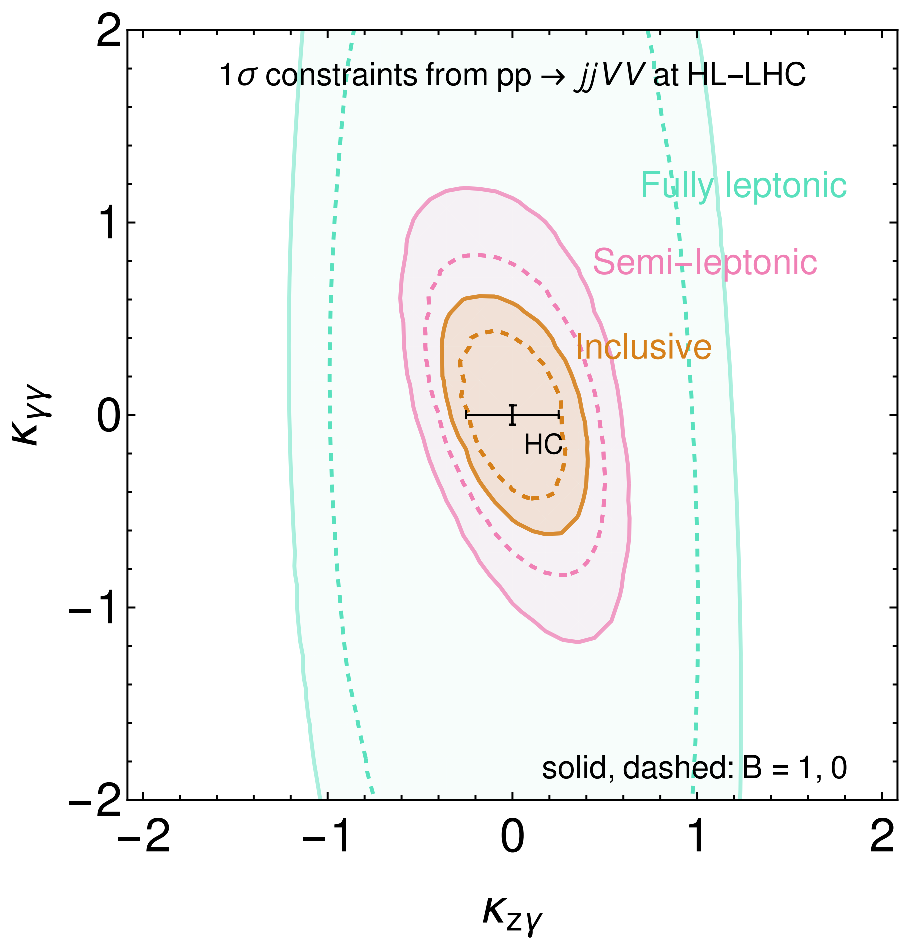

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Unfortunately SM/BSM-interference small: reach poor.

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

Azatov,Contino,Machado,FR'17

Prospects to "resurrect" interference with exclusive azimuthal angle measurement

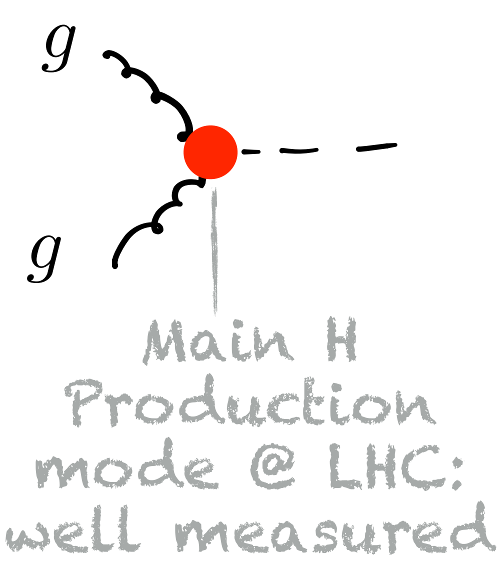
Panico,FR,Wulzer'18

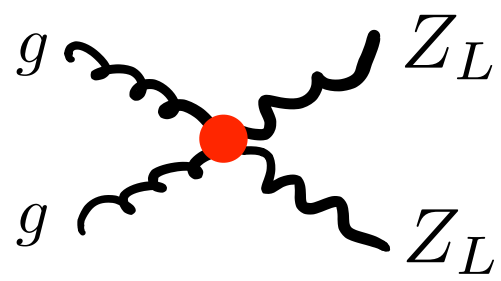
HwH Program: Higgs-Gluons

see also Azatov, Grojean, Paul, Salvioni'14

κ_G

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





Non-resonant!

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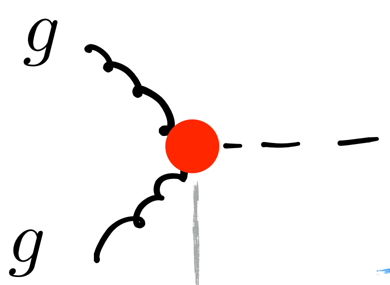
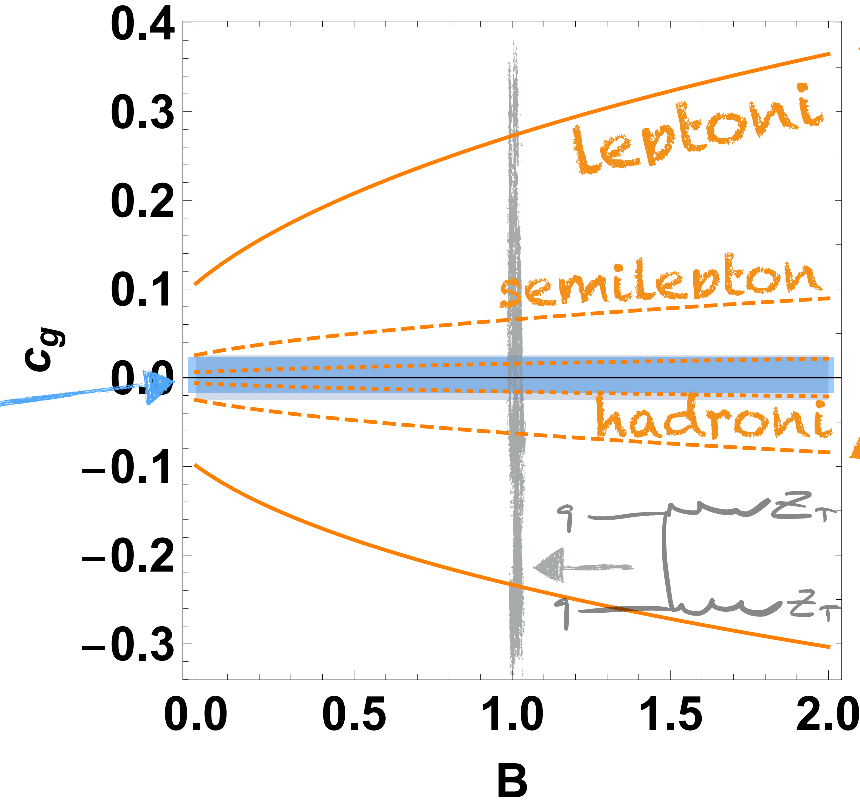
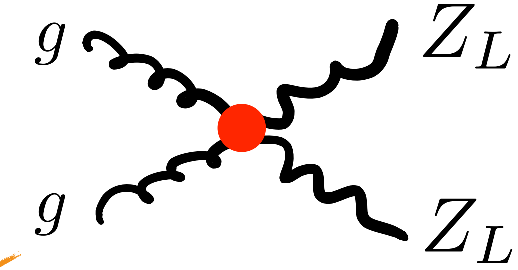


Main H Production mode @ LHC: well measured





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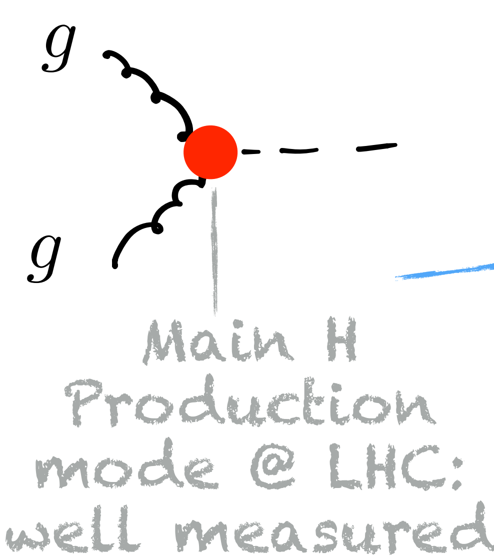
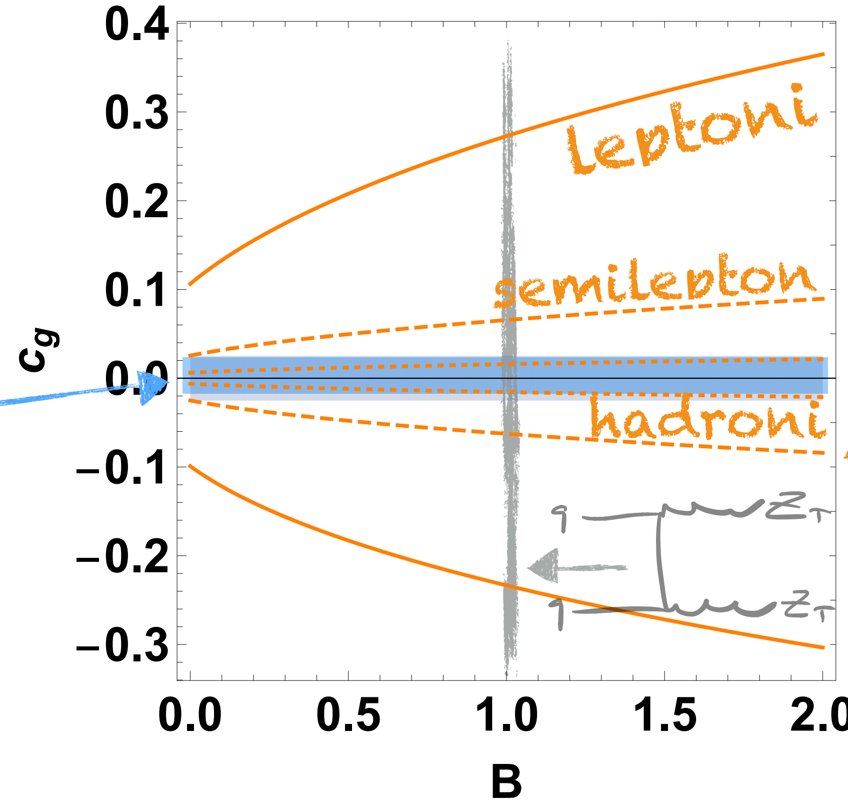
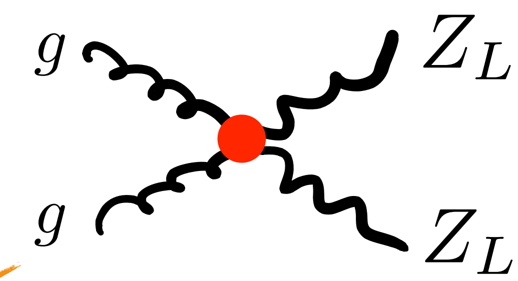
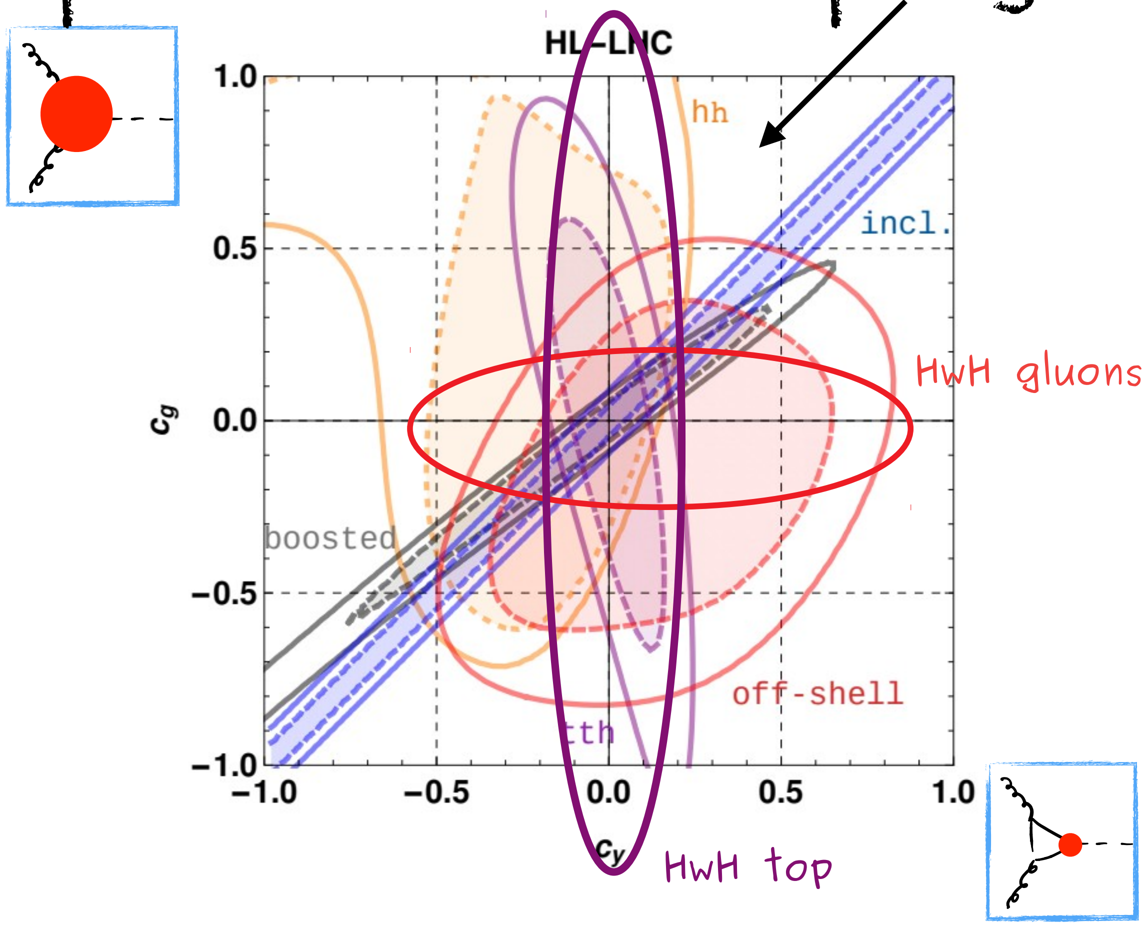






Non-resonant!

Important since Coupling measurements leave degeneracies...

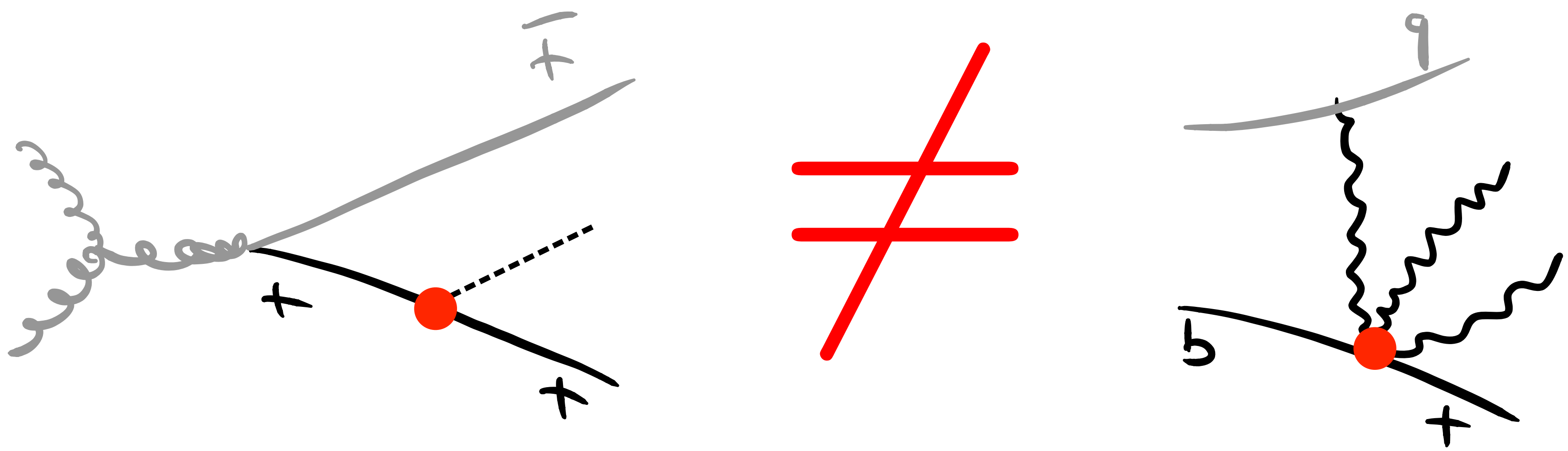


HwH offer new observables, orthogonal to previous ones!

HwH: probing the EWSB sector

Possible that BSM has extra EWSB sources or non-decoupling - HEFT

e.g Galloway,Luty,Tsai,Zhao'13; Falkowski,Rattazzi'19; Brivio,Corbett,Eboli,Gavela,Gonzalez-Fraile,Gonzalez-Garcia,Merlo,Rigolin'13; ...



HC and HwH ~~competitive~~ complementary

HwH processes will be the most sensitive to test this hypothesis!

Message

- More luminosity -> access to new observables: high-energy tails
  - Challenging
  - More improvements

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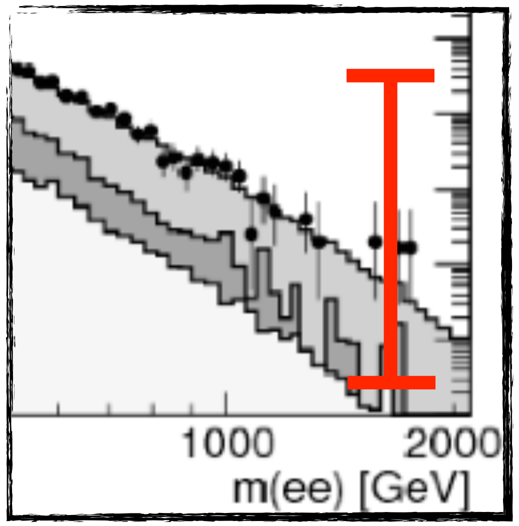

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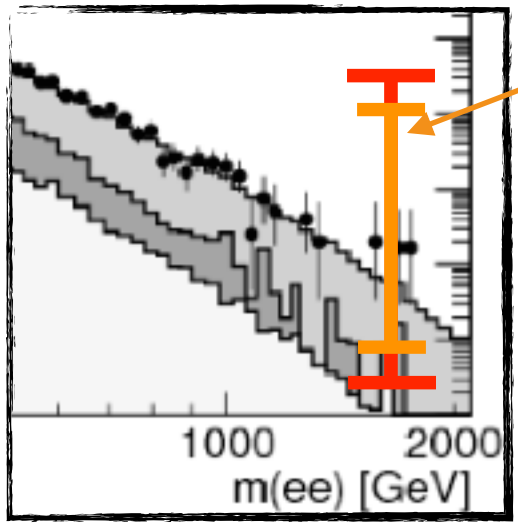

Precise SM theoretical predictions

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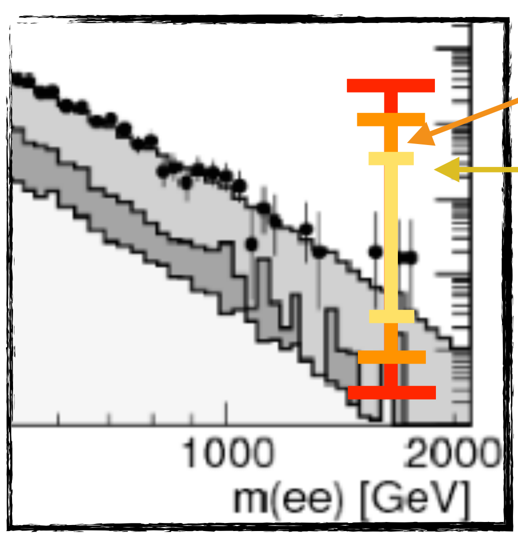

Precise SM theoretical predictions

LHC Experimental control of systematics

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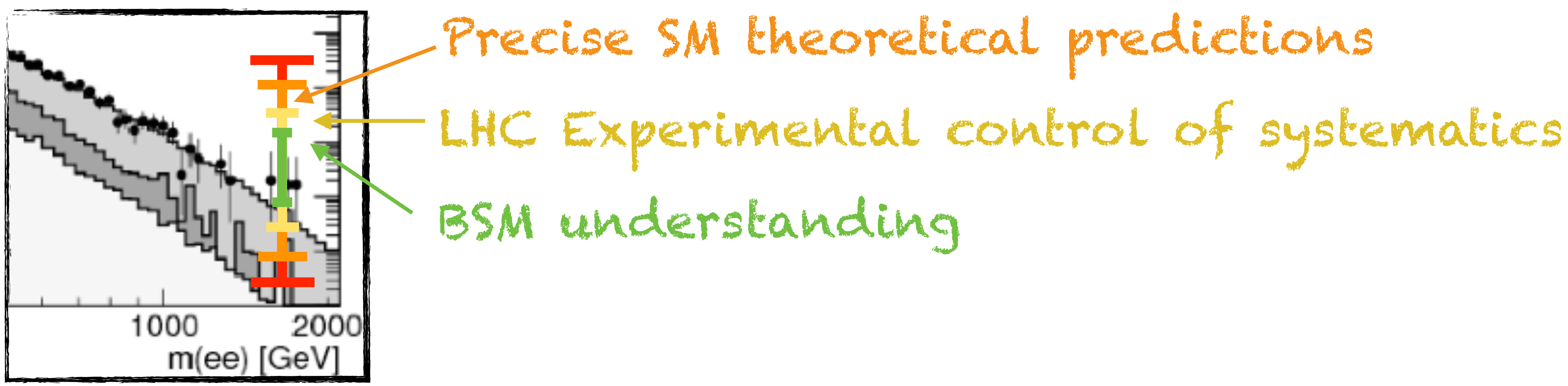

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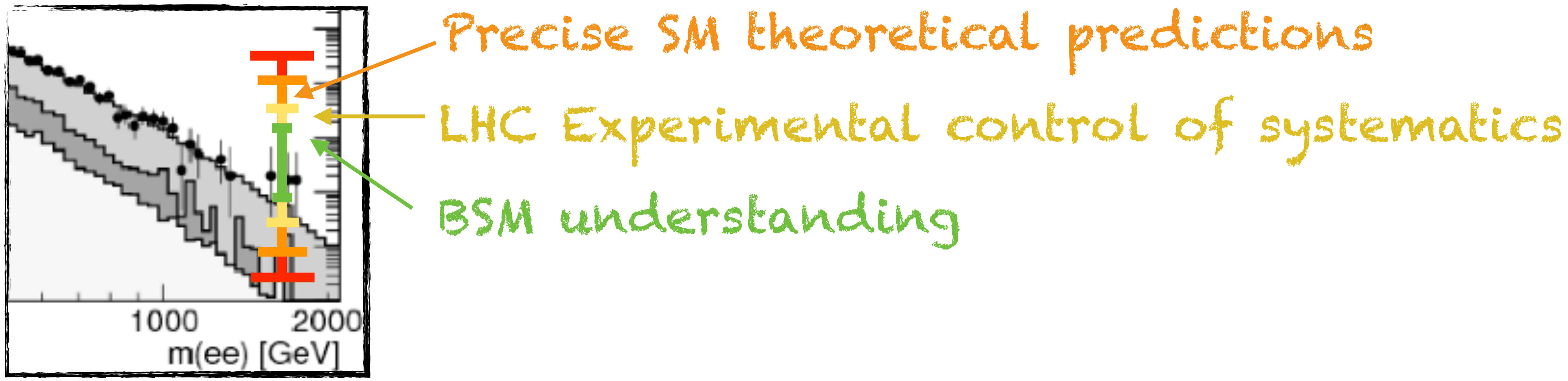
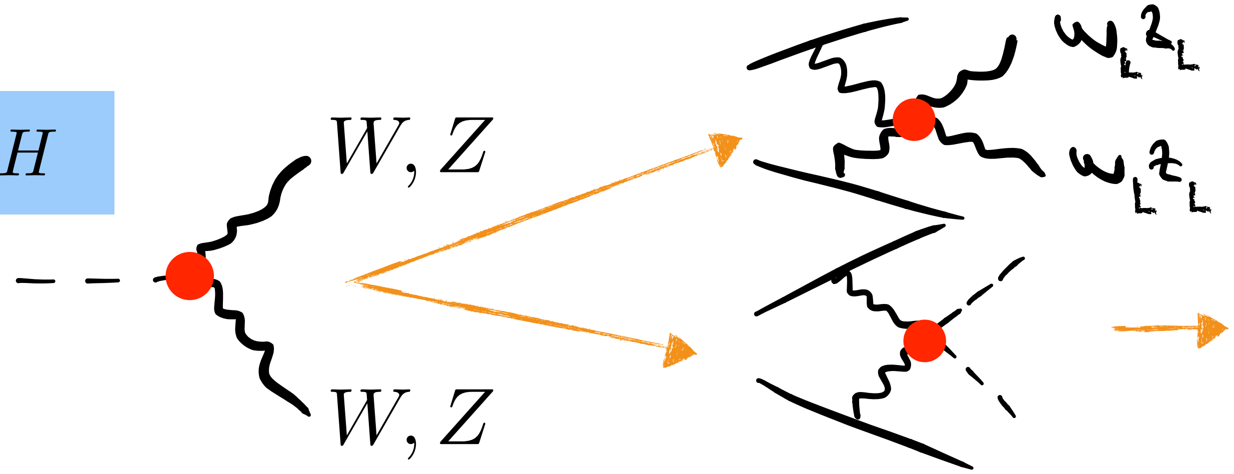


- Important for future colliders (HE-LHC,CLIC,FCC,...)

HwH Program: h to gauge bosons 2

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



In SM V_L suppressed by ≈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