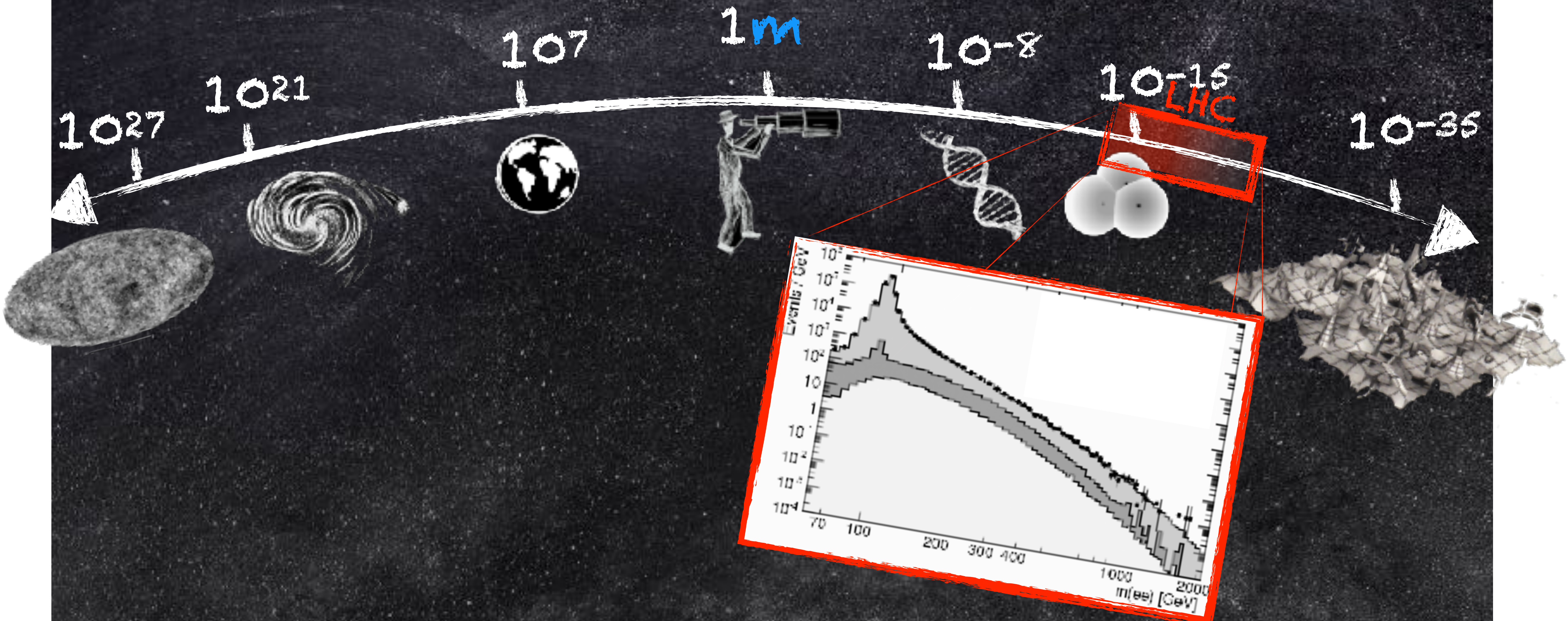
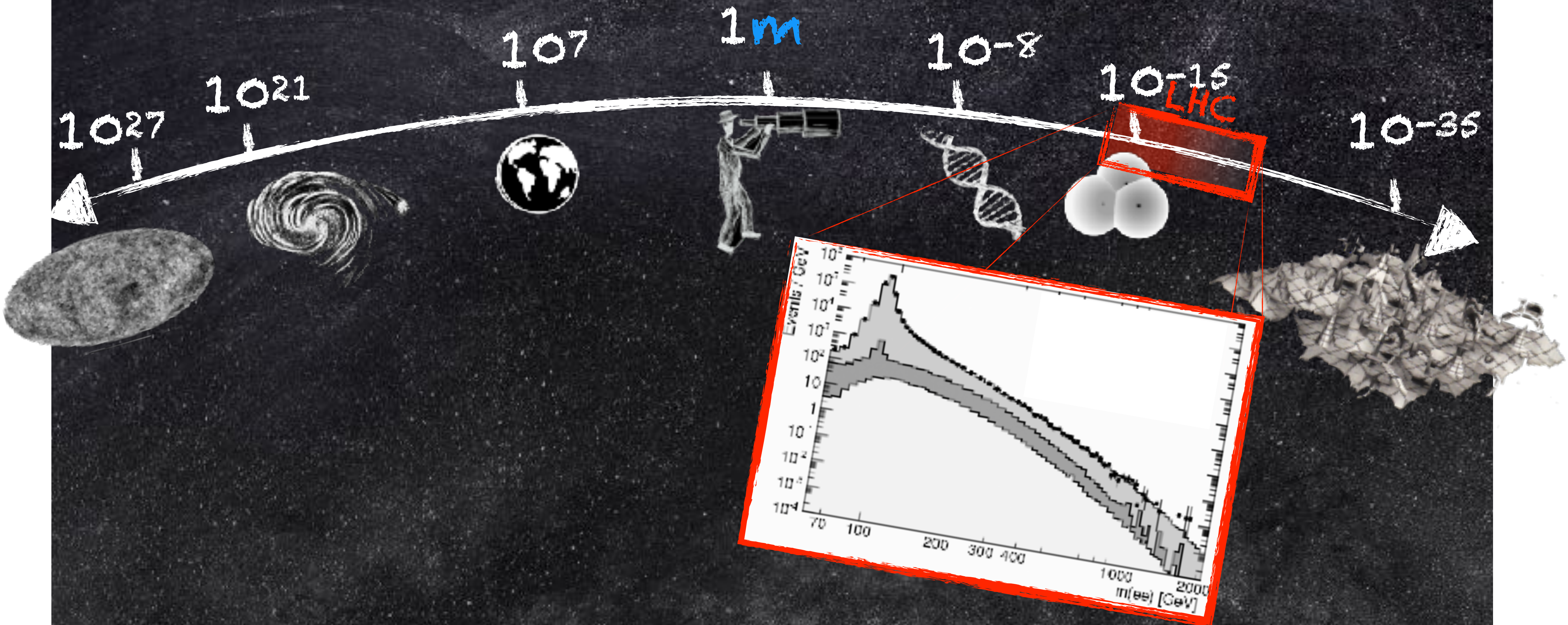
Higgs Couplings



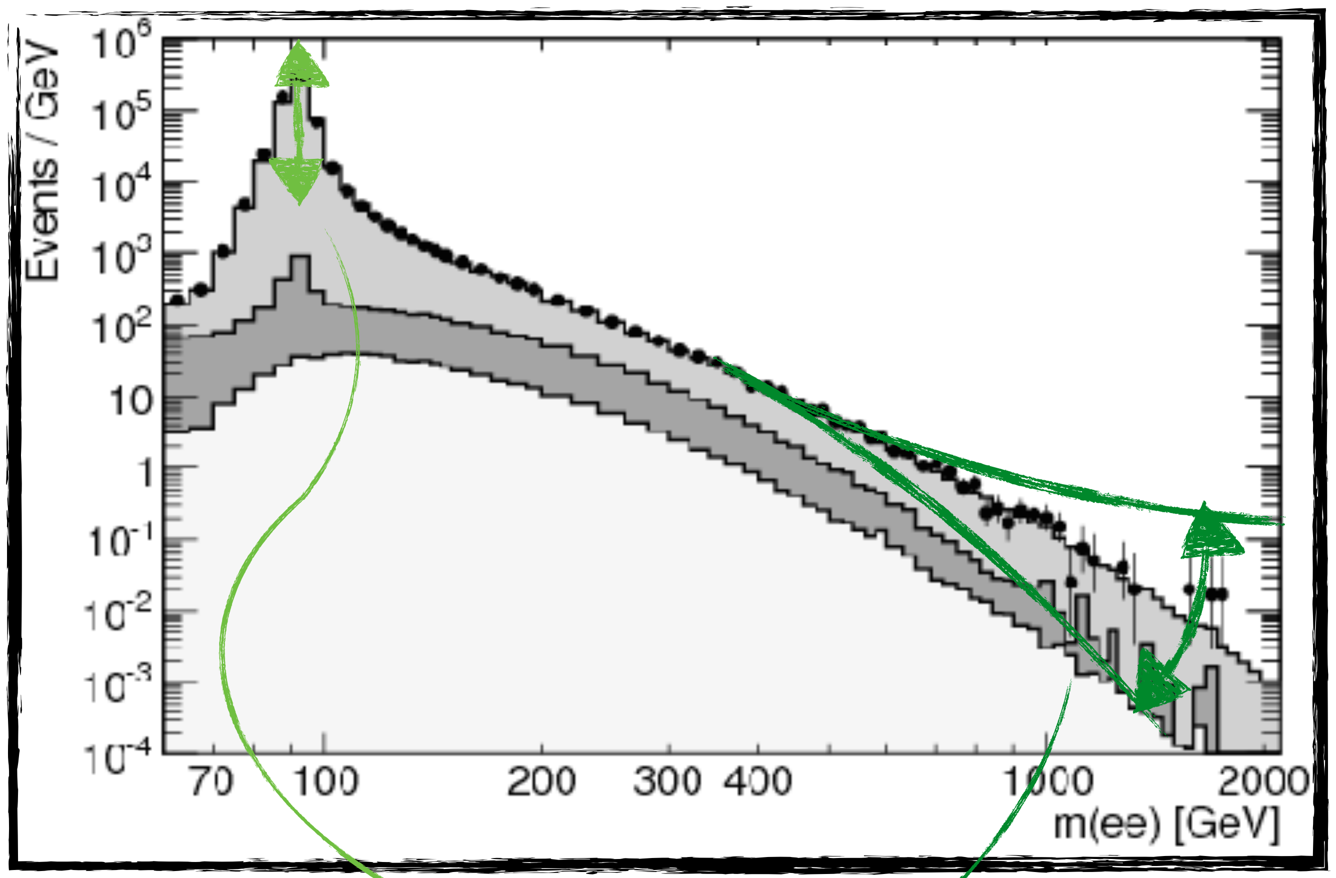
Francesco Riva
(Université de Genève)

Higgs Couplings ... without the Higgs



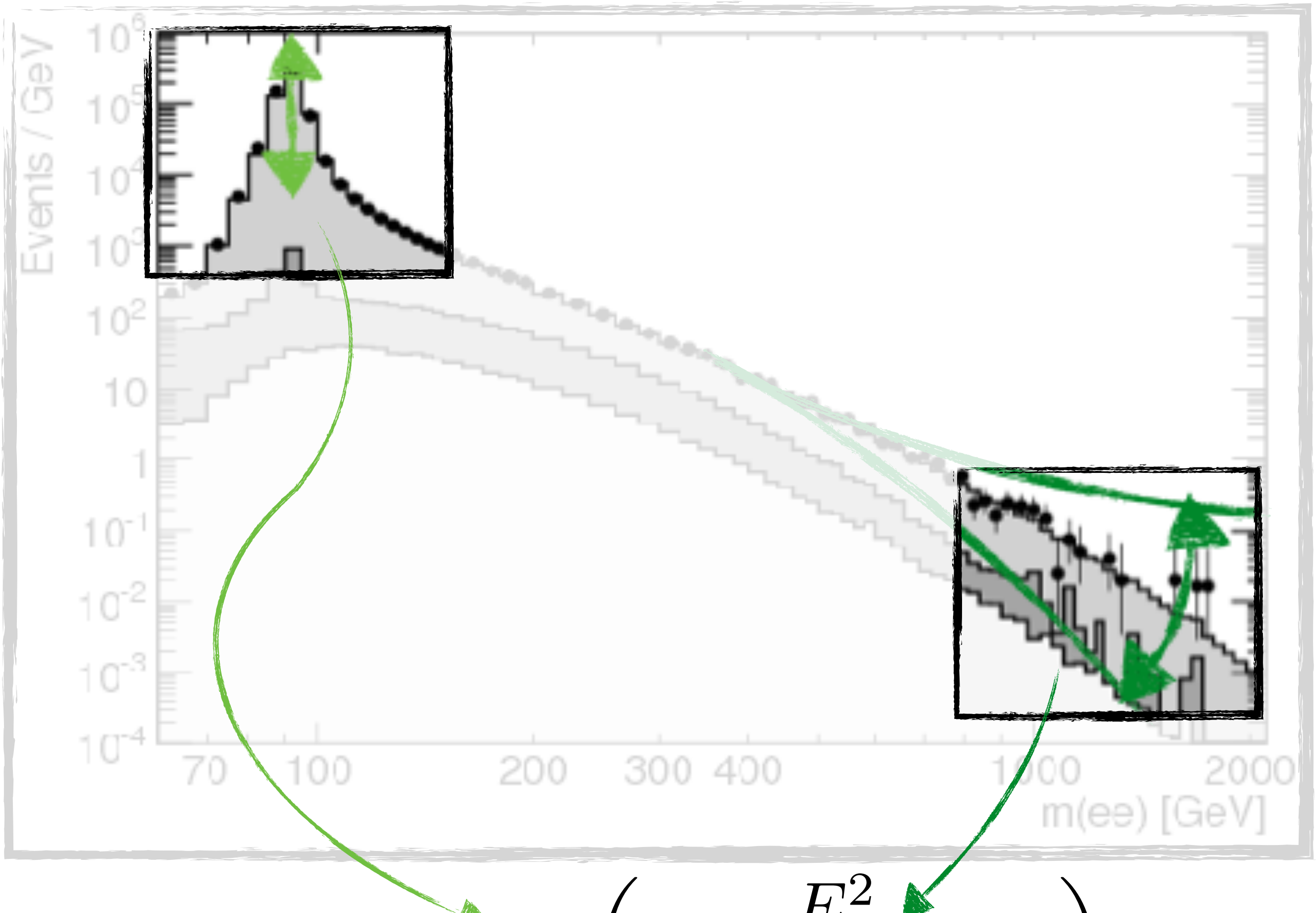
Francesco Riva
(Université de Genève)

Precision Tests



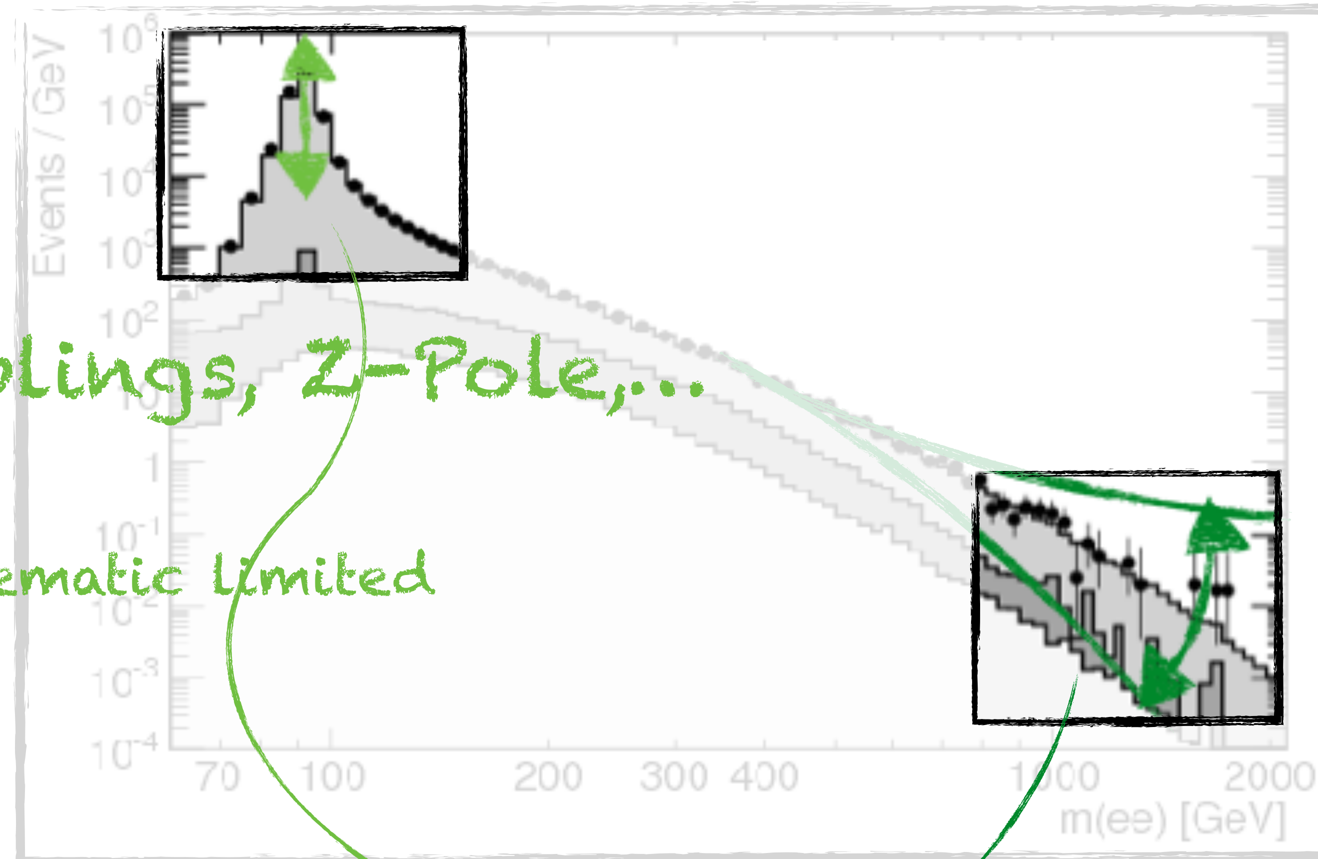
$$\sigma = \sigma_{\rm SM}\left(1 + c\frac{E^2}{\Lambda^2} + \cdots\right)$$

Precision Tests



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

Precision Tests

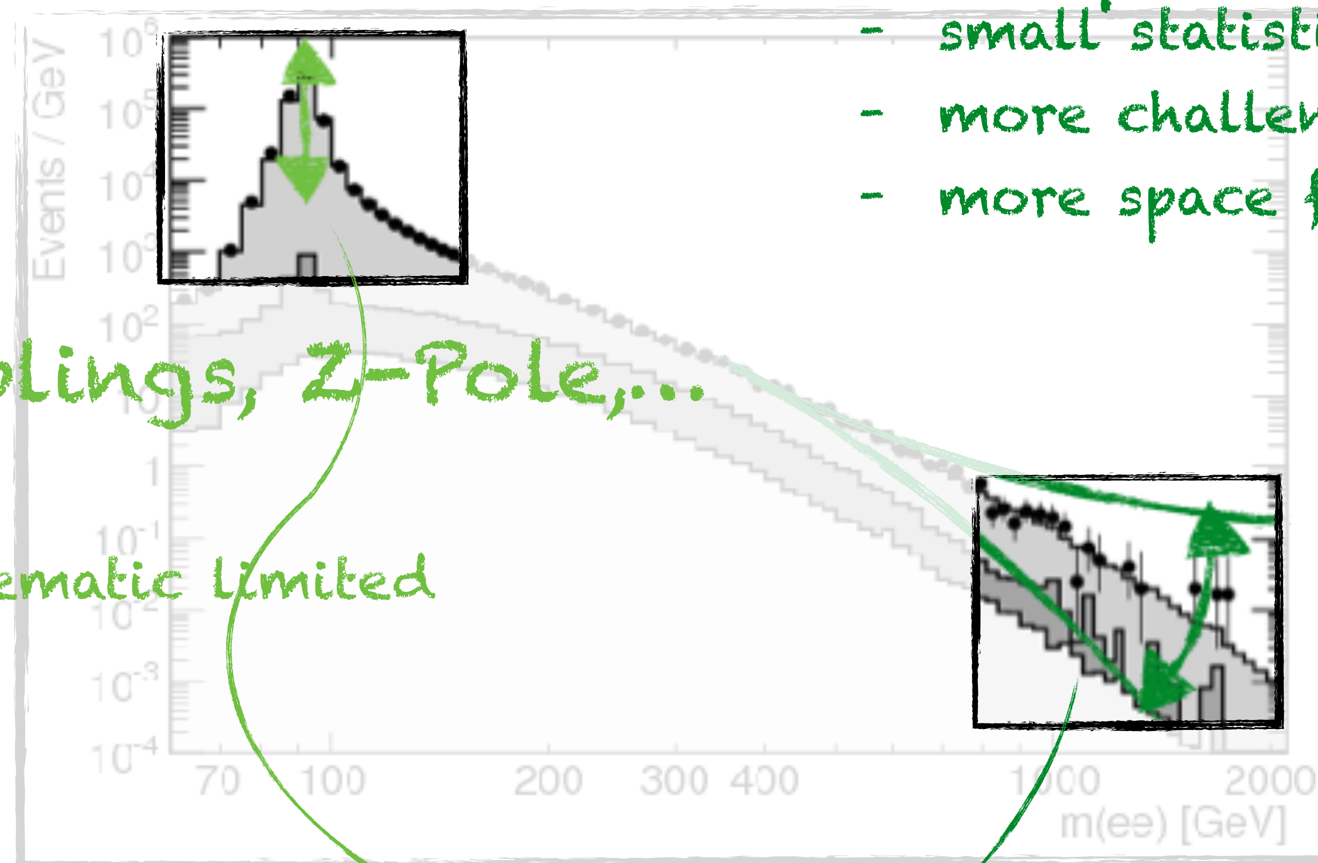


e.g. Higgs Couplings, Z-Pole,...

- big statistics
- sooner or later systematic limited

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

Precision Tests



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

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

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

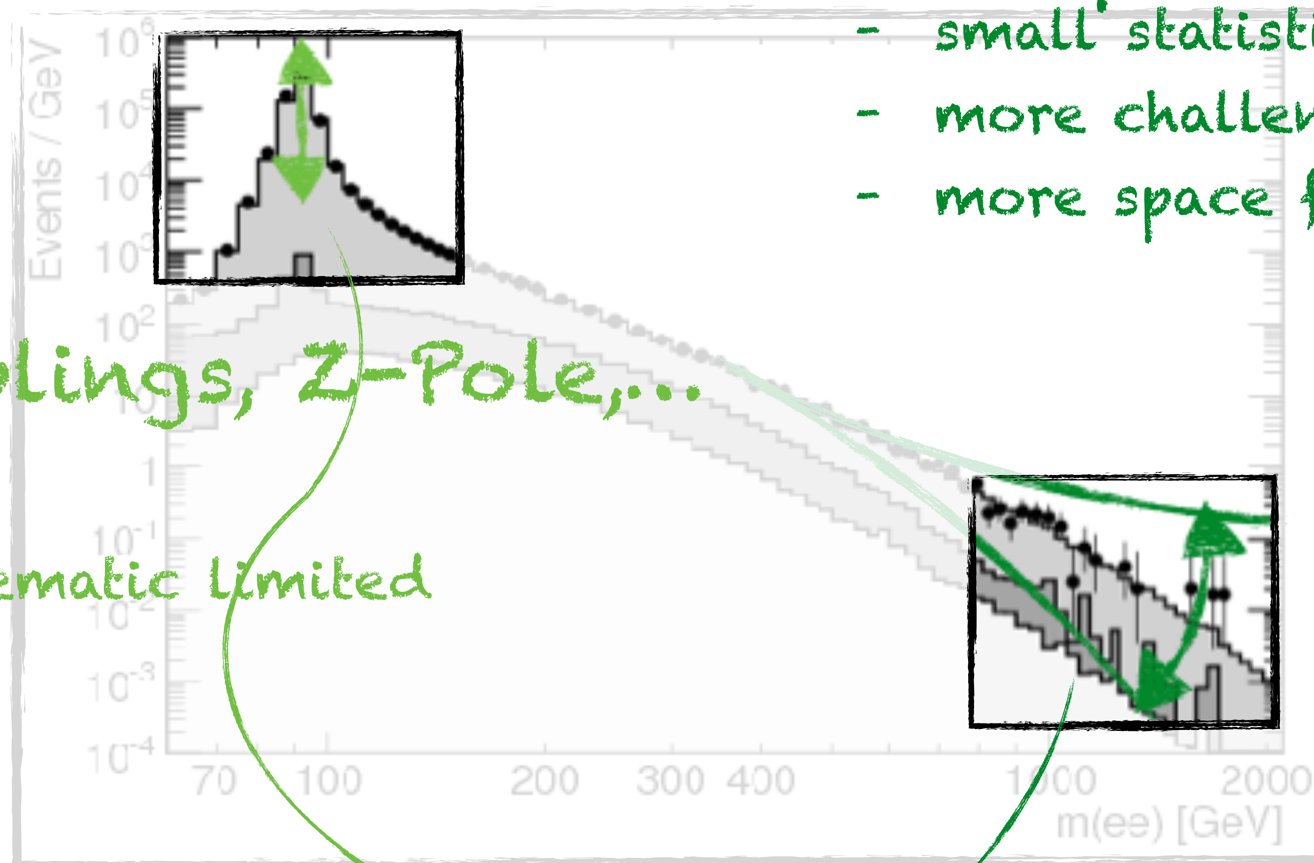
- big statistics
- sooner or later systematic limited

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

Precision Tests

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

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



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

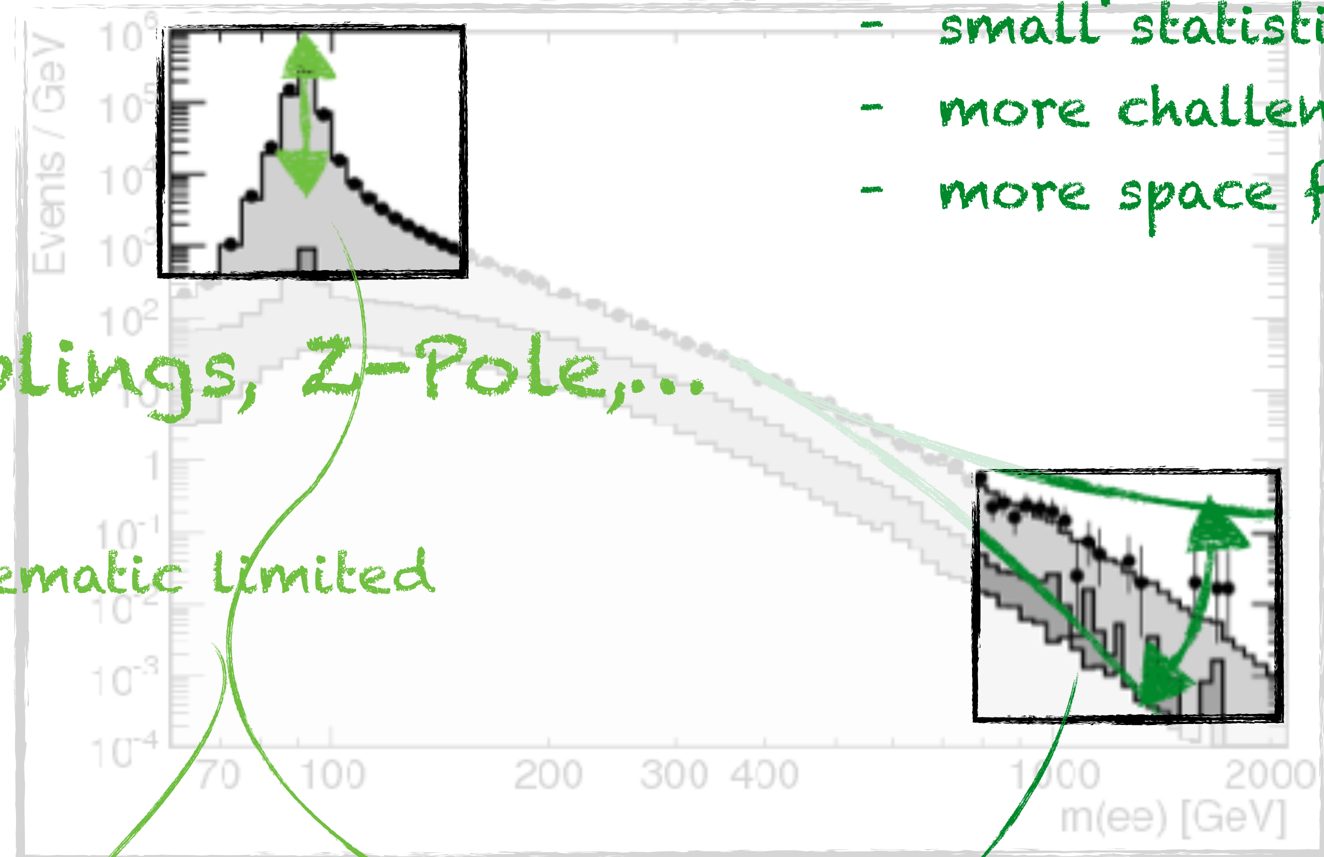
- big statistics
- sooner or later systematic limited

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

Precision Tests

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

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



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

- big statistics
- sooner or later systematic limited

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

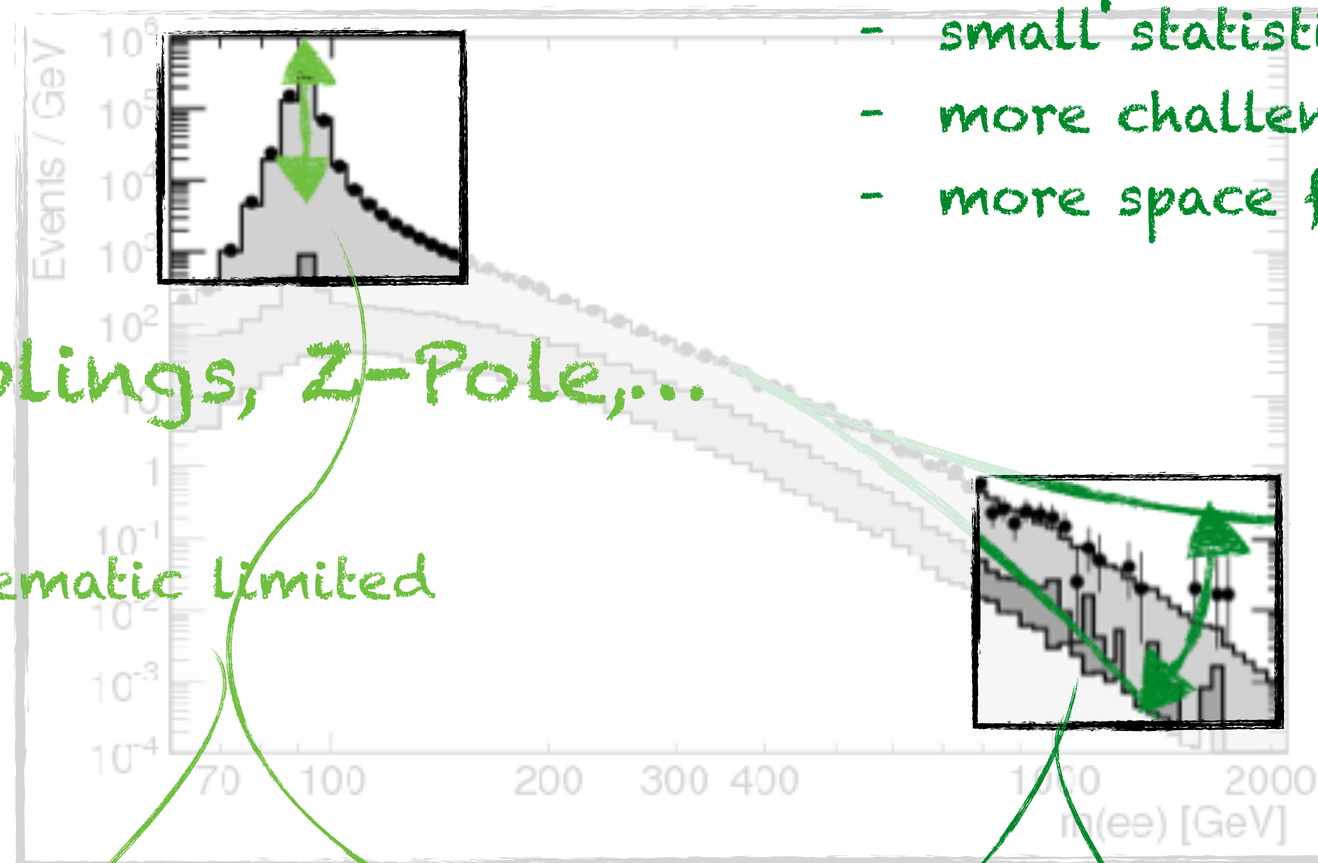
Imagine measuring $\left.\frac{\delta\sigma}{\sigma_{\rm SM}}\right|_{\sqrt{s}=m_Z} \sim 10^{-4}$

(surely a precise measurement)

Precision Tests

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

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



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

- big statistics
- sooner or later systematic limited

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

Imagine measuring $\left.\frac{\delta\sigma}{\sigma_{\rm SM}}\right|_{\sqrt{s}=m_Z} \sim 10^{-4}$

(surely a precise measurement)

... equivalent to $\left.\frac{\delta\sigma}{\sigma_{\rm SM}}\right|_{\sqrt{s}=3\,\rm TeV} \sim 10\%$

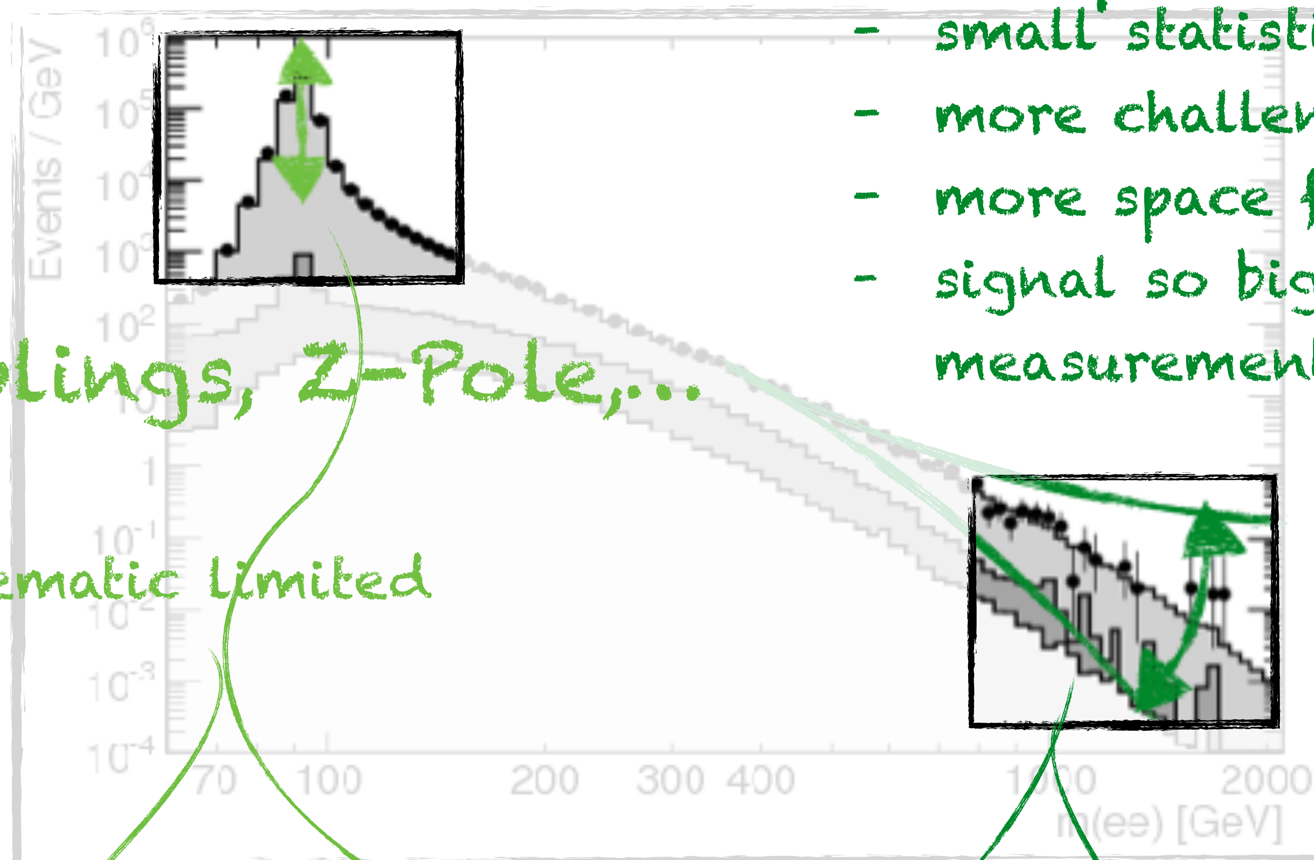
(naively not so precise)

Effect grows ≈ E^2: $\left(\frac{3000}{91.2}\right)^2 \approx 1000$

Precision Tests

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

- small statistics
- more challenging measurement
- more space for improvement
- signal so big that even a poor measurement can be precise



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

- big statistics
- sooner or later systematic limited

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

Imagine measuring $\left.\frac{\delta\sigma}{\sigma_{\rm SM}}\right|_{\sqrt{s}=m_Z} \sim 10^{-4}$

(surely a precise measurement)

... equivalent to $\left.\frac{\delta\sigma}{\sigma_{\rm SM}}\right|_{\sqrt{s}=3\,\rm TeV} \sim 10\%$

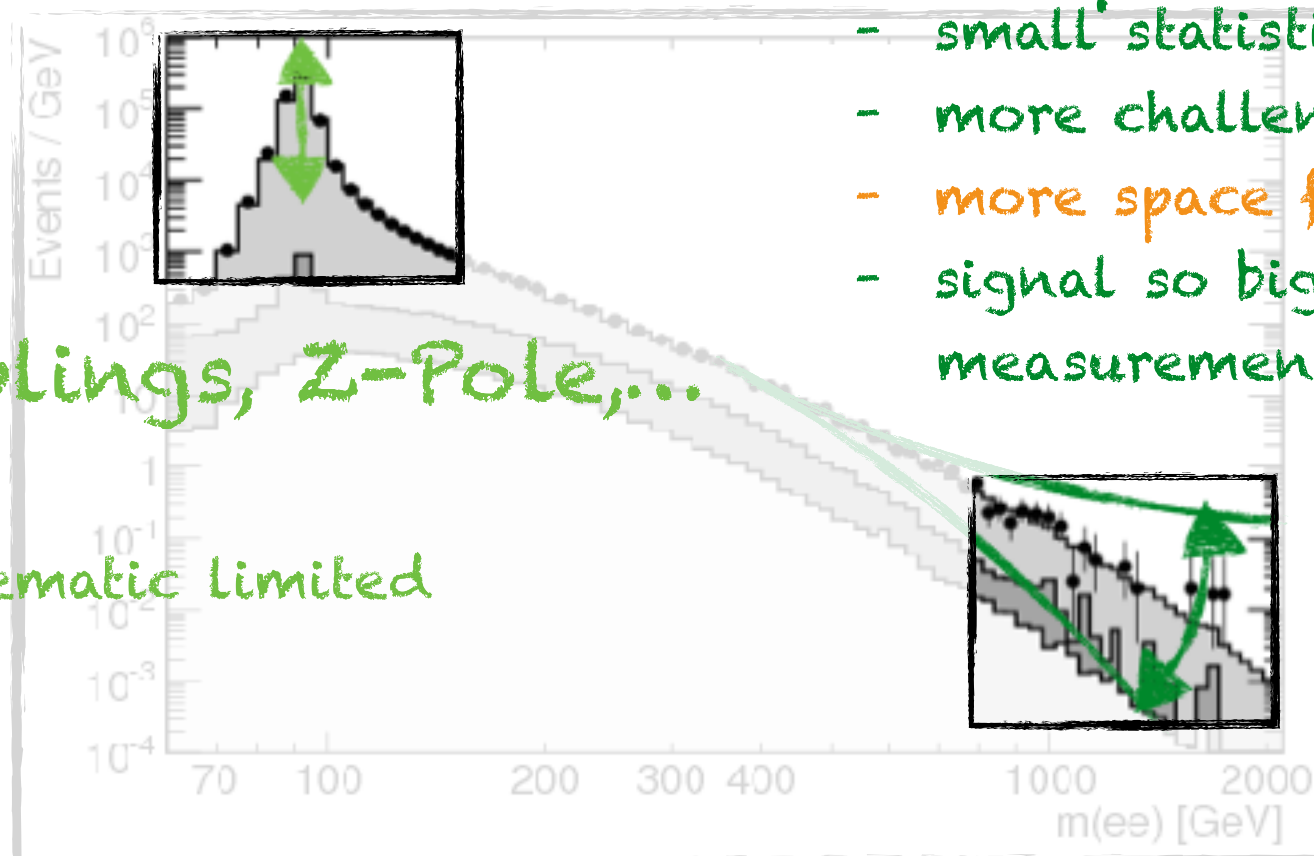
(naively not so precise)

Effect grows ≈ E²: $\left(\frac{3000}{91.2}\right)^2 \approx 1000$

Precision Tests

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

- small statistics
- more challenging measurement
- more space for improvement
- signal so big that even a poor measurement can be precise



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

- big statistics
- sooner or later systematic limited

Experimentally very appealing

Higgs Couplings

LHC and future collider priority: Higgs Couplings

Higgs Couplings

LHC and future collider priority: Higgs Couplings

Modifications of Higgs couplings in EFT language:

Higgs Couplings

LHC and future collider priority: Higgs Couplings

Modifications of Higgs couplings in EFT language:

$$\mathcal{O}_r = |H|^2 \partial_\mu H^\dagger \partial^\mu H \qquad \mathcal{O}_{y_\psi} = Y_\psi |H|^2 \psi_L H \psi_R$$
$$\mathcal{O}_{BB} = g'^{\,2} |H|^2 B_{\mu\nu} B^{\mu\nu} \qquad \mathcal{O}_{WW} = g^2 |H|^2 W^a_{\mu\nu} W^{a\,\mu\nu}$$
$$\mathcal{O}_{GG} = g_s^2 |H|^2 G^a_{\mu\nu} G^{a\,\mu\nu} \qquad \mathcal{O}_6 = |H|^6$$

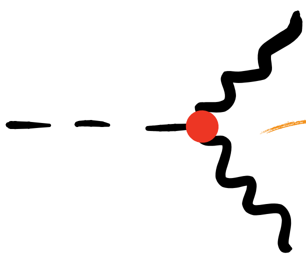
$\mathcal{L}_{\rm SM} \times |H|^2$ has no effect in vacuum <H>=v

$$\frac{1}{g_s^2} G_{\mu\nu} G^{\mu\nu} + \frac{|H|^2}{\Lambda^2} G_{\mu\nu} G^{\mu\nu} = \left(\frac{1}{g_s^2} + \frac{v^2}{\Lambda^2} \right) G_{\mu\nu} G^{\mu\nu} + h \frac{2v}{\Lambda^2} G_{\mu\nu} G^{\mu\nu} + \cdots$$

Higgs Couplings

LHC and future collider priority: Higgs Couplings

Modifications of Higgs couplings in EFT language:



$V = W, Z, \gamma, g$

$$\mathcal{O}_r = |H|^2 \partial_\mu H^\dagger \partial^\mu H \qquad \mathcal{O}_{y_\psi} = Y_\psi |H|^2 \psi_L H \psi_R$$

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

$$\mathcal{O}_{GG} = g_s^2 |H|^2 G^a_{\mu\nu} G^{a\,\mu\nu} \qquad \mathcal{O}_6 = |H|^6$$

$\mathcal{L}_{\rm SM} \times |H|^2$ has no effect in vacuum <H>=v

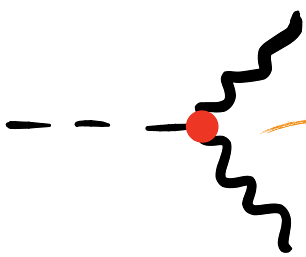
modifies single-Higgs processes

$$\frac{1}{g_s^2} G_{\mu\nu} G^{\mu\nu} + \frac{|H|^2}{\Lambda^2} G_{\mu\nu} G^{\mu\nu} = \left(\frac{1}{g_s^2} + \frac{v^2}{\Lambda^2} \right) G_{\mu\nu} G^{\mu\nu} + h \frac{2v}{\Lambda^2} G_{\mu\nu} G^{\mu\nu} + \cdots$$

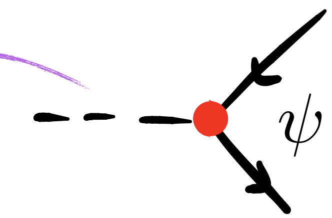
Higgs Couplings

LHC and future collider priority: Higgs Couplings

Modifications of Higgs couplings in EFT language:



$V = W, Z, \gamma, g$



$\psi = t, b, \tau$

$$\mathcal{O}_r = |H|^2 \partial_\mu H^\dagger \partial^\mu H \qquad \mathcal{O}_{y_\psi} = Y_\psi |H|^2 \psi_L H \psi_R$$

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

$$\mathcal{O}_{GG} = g_s^2 |H|^2 G^a_{\mu\nu} G^{a\,\mu\nu} \qquad \mathcal{O}_6 = |H|^6$$

$\mathcal{L}_{\rm SM} \times |H|^2$ has no effect in vacuum <H>=v

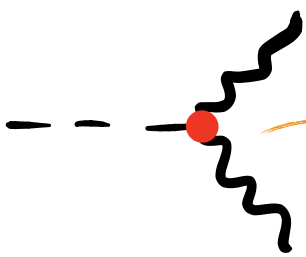
modifies single-Higgs processes

$$\frac{1}{g_s^2} G_{\mu\nu} G^{\mu\nu} + \frac{|H|^2}{\Lambda^2} G_{\mu\nu} G^{\mu\nu} = \left(\frac{1}{g_s^2} + \frac{v^2}{\Lambda^2}\right) G_{\mu\nu} G^{\mu\nu} + h \frac{2v}{\Lambda^2} G_{\mu\nu} G^{\mu\nu} + \cdots$$

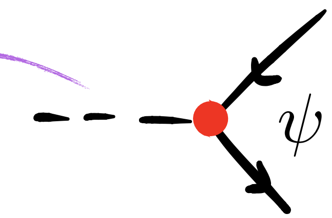
Higgs Couplings

LHC and future collider priority: Higgs Couplings

Modifications of Higgs couplings in EFT language:



$V = W, Z, \gamma, g$



$\psi = t, b, \tau$

$\mathcal{O}_r = |H|^2 \partial_\mu H^\dagger \partial^\mu H$

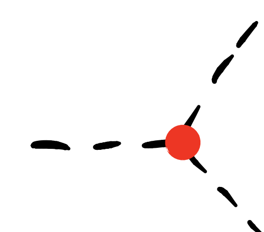
$\mathcal{O}_{y_\psi} = Y_\psi |H|^2 \psi_L H \psi_R$

$\mathcal{O}_{BB} = g'^2 |H|^2 B_{\mu\nu} B^{\mu\nu}$

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

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

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



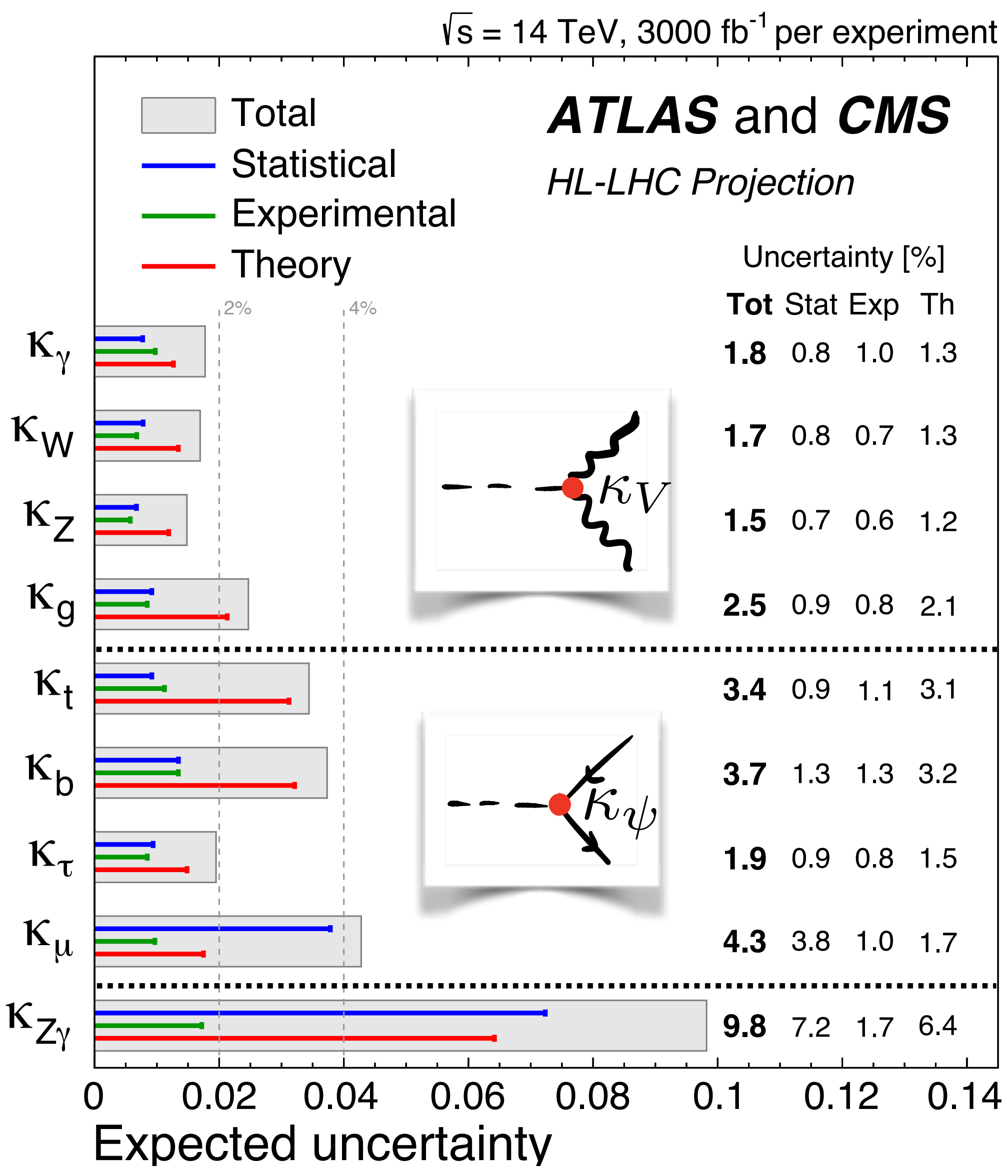
$\mathcal{L}_{\rm SM} \times |H|^2$ has no effect in vacuum <H>=v

modifies single-Higgs processes

$$\frac{1}{g_s^2} G_{\mu\nu} G^{\mu\nu} + \frac{|H|^2}{\Lambda^2} G_{\mu\nu} G^{\mu\nu} = \left(\frac{1}{g_s^2} + \frac{v^2}{\Lambda^2}\right) G_{\mu\nu} G^{\mu\nu} + h \frac{2v}{\Lambda^2} G_{\mu\nu} G^{\mu\nu} + \cdots$$

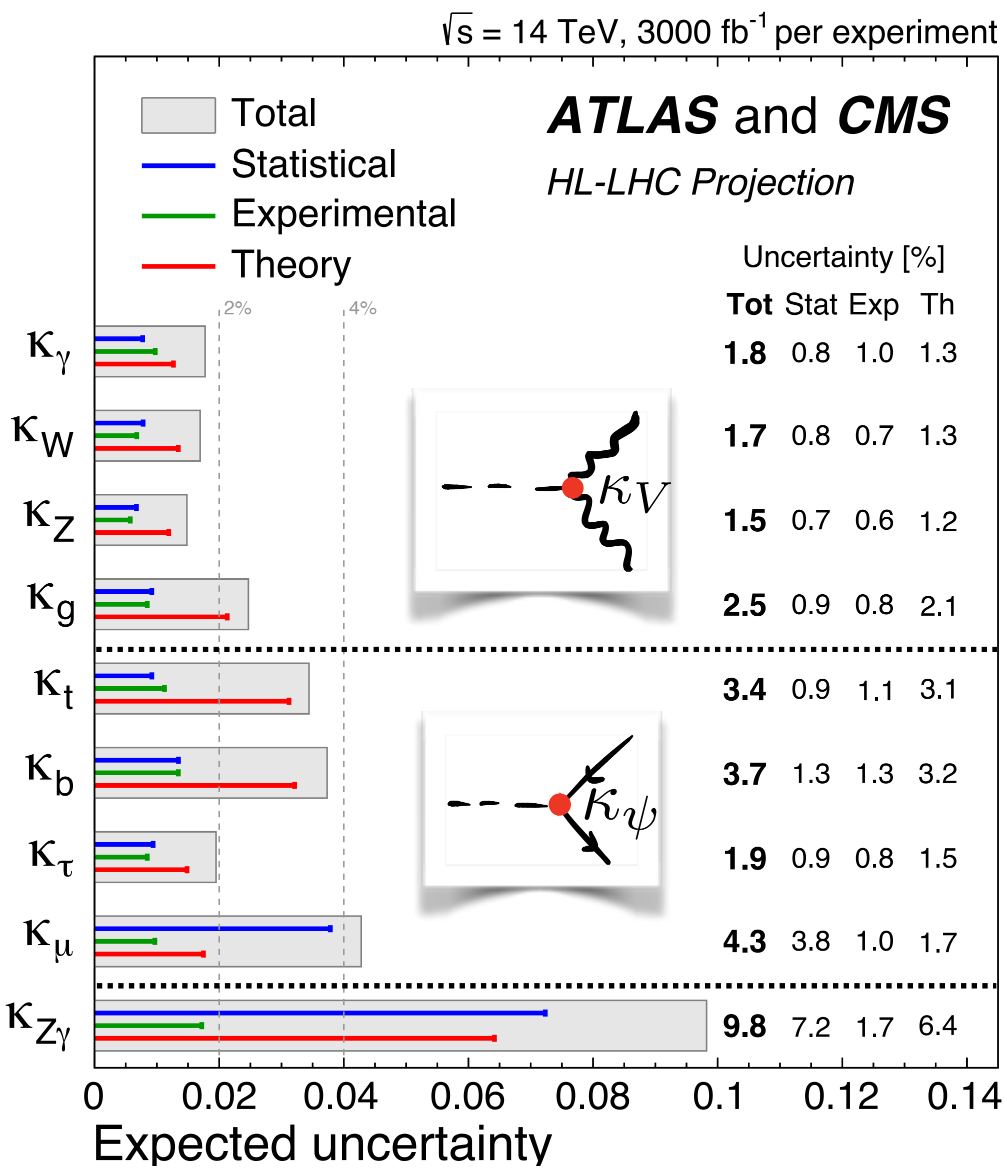
HL-LHC Reach (3000 fb-1)

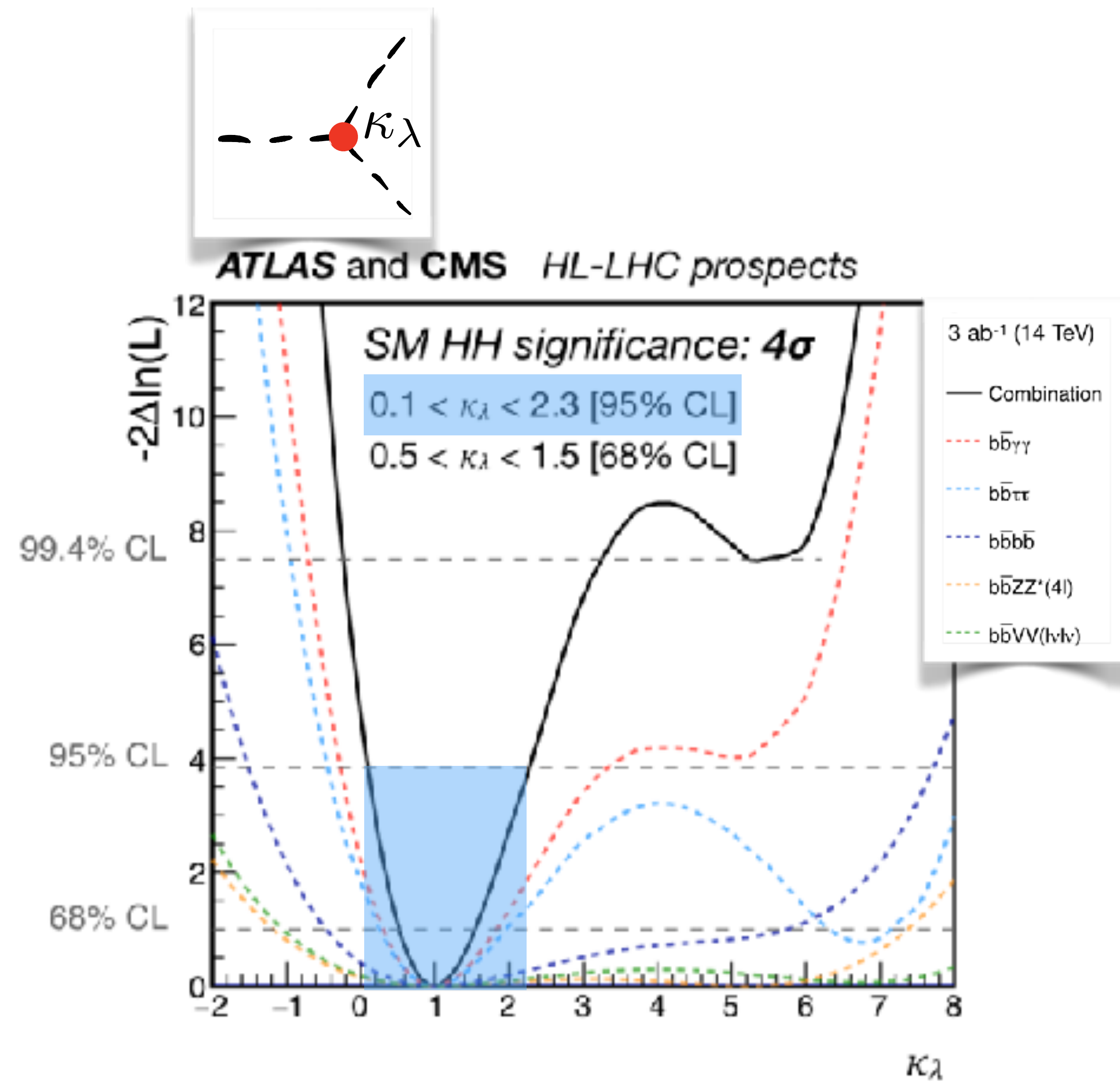
Higgs couplings: measured in processes with on-shell Higgs (E=125 GeV)



HL-LHC Reach (3000 fb-1)

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

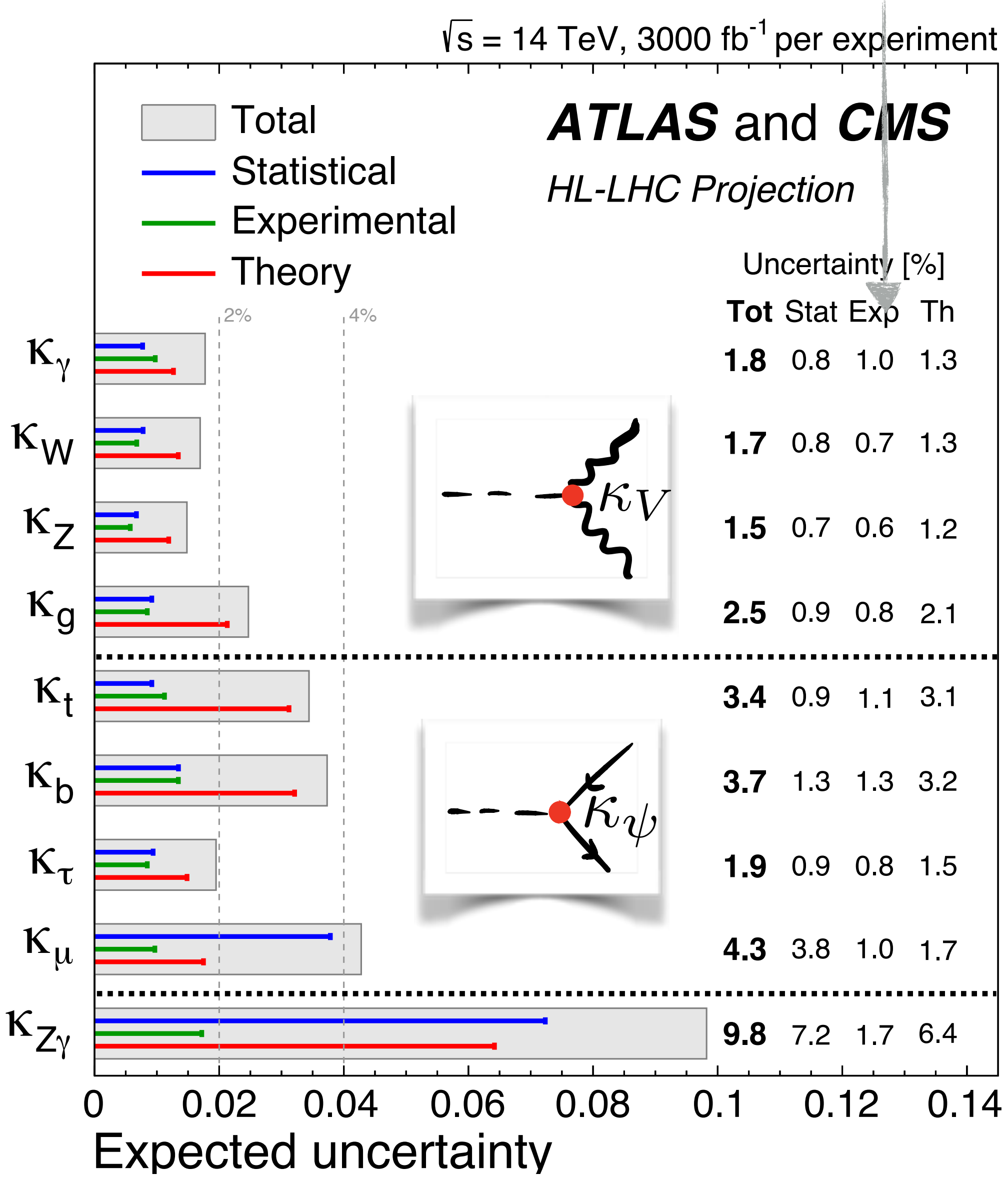




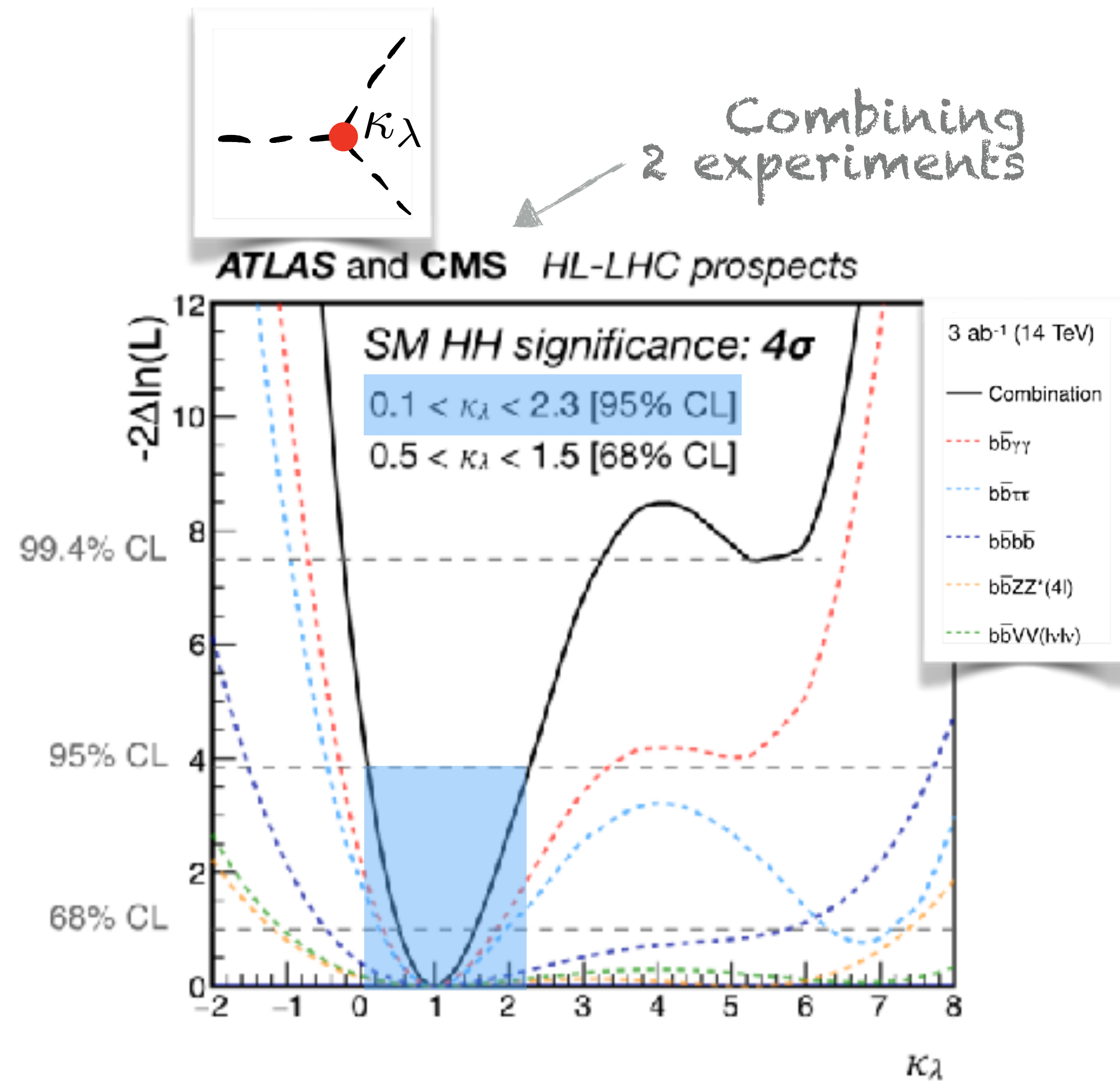
HL-LHC Reach (3000 fb-1)

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

Optimistic Systematics (S2)



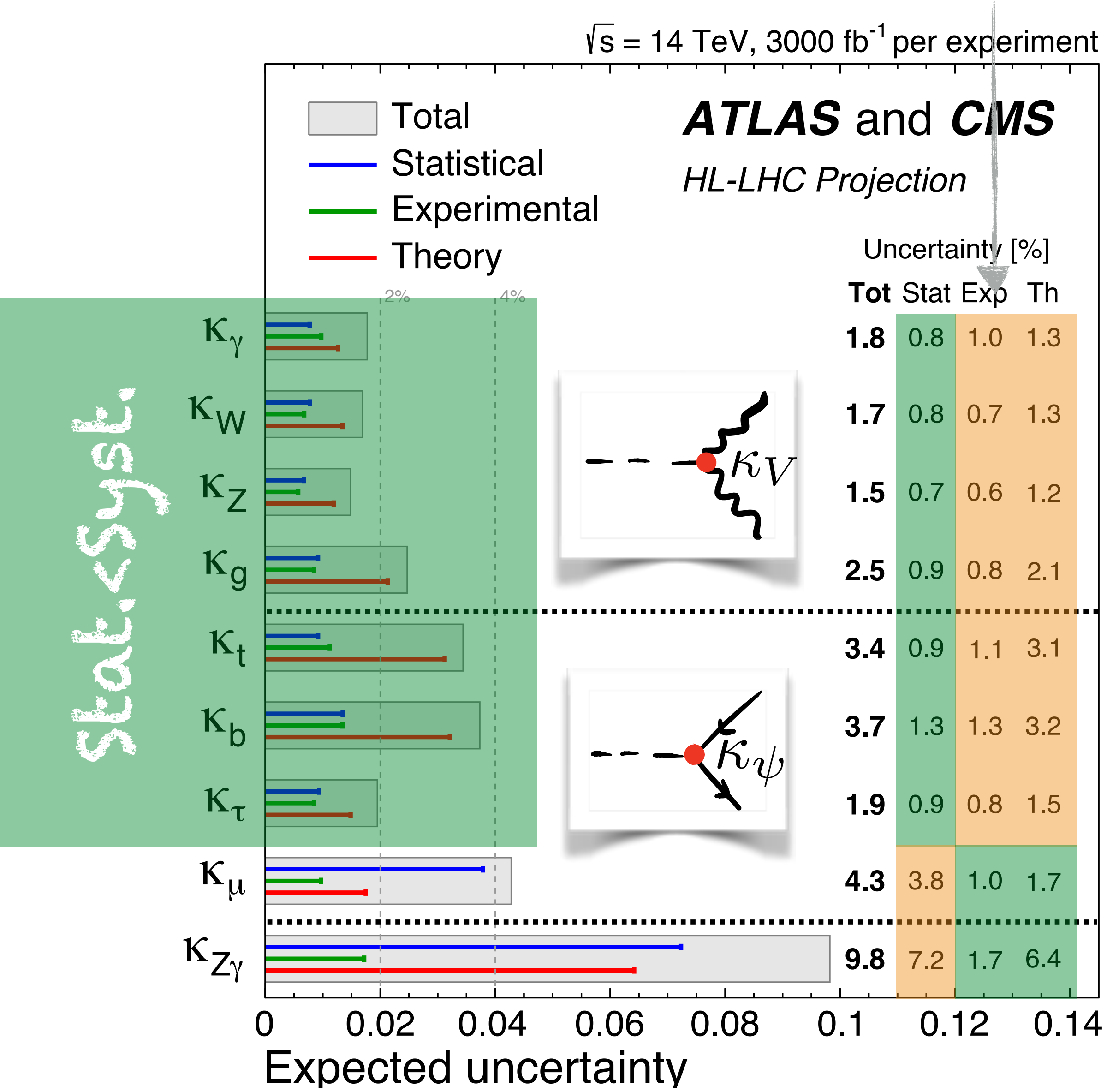
Combining 2 experiments



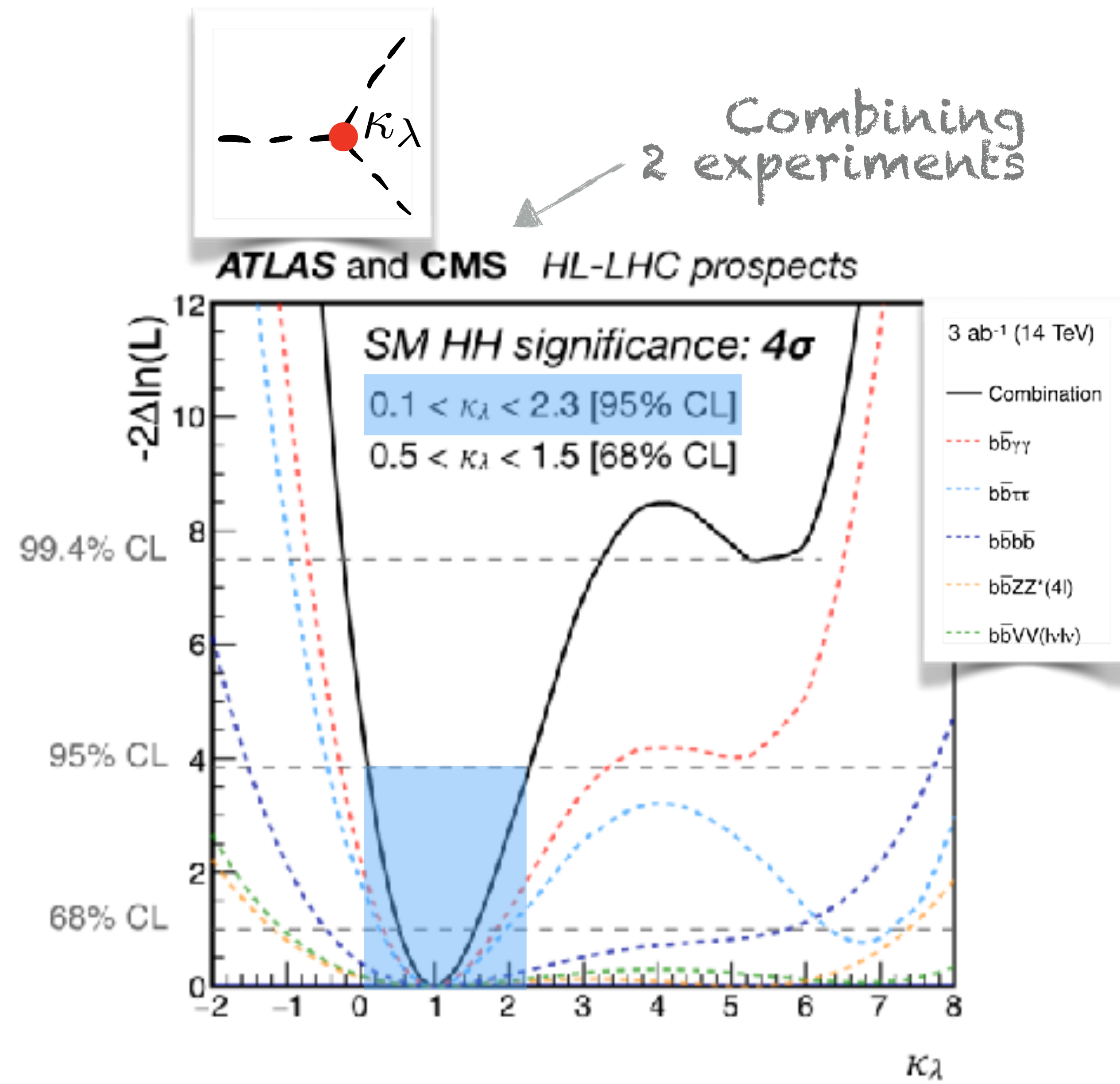
HL-LHC Reach (3000 fb-1)

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

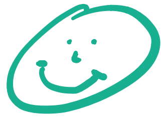
Optimistic Systematics (S2)



Combining 2 experiments



Higgs Couplings at High-Energy

Higgs couplings: Theoretically Interesting 

Experimentally not High-E measurements 

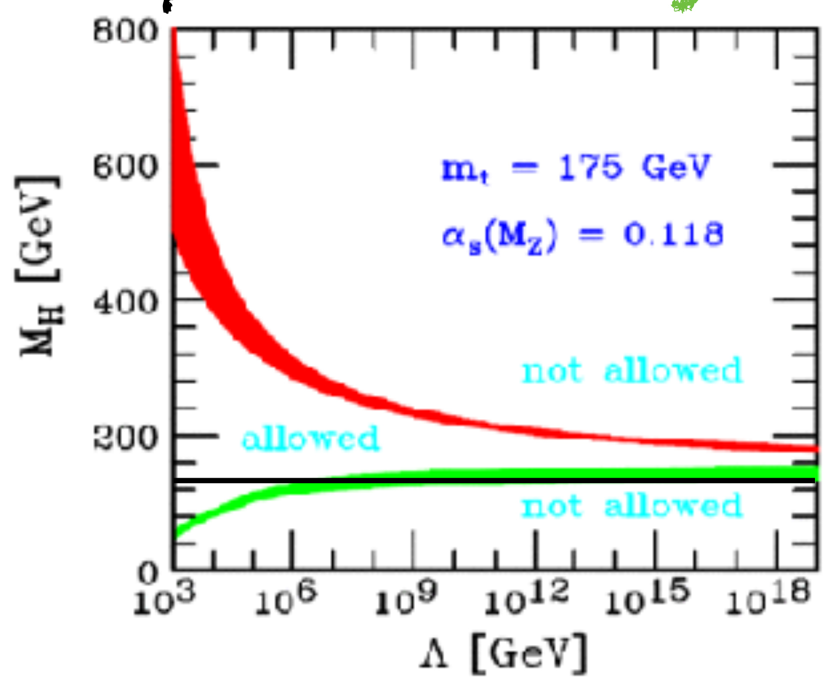
Higgs Couplings at High-Energy

Higgs couplings: Theoretically Interesting

Experimentally not High-E measurements

but...

SM is the unique theory, with its particle content, valid up to arbitrary energy:

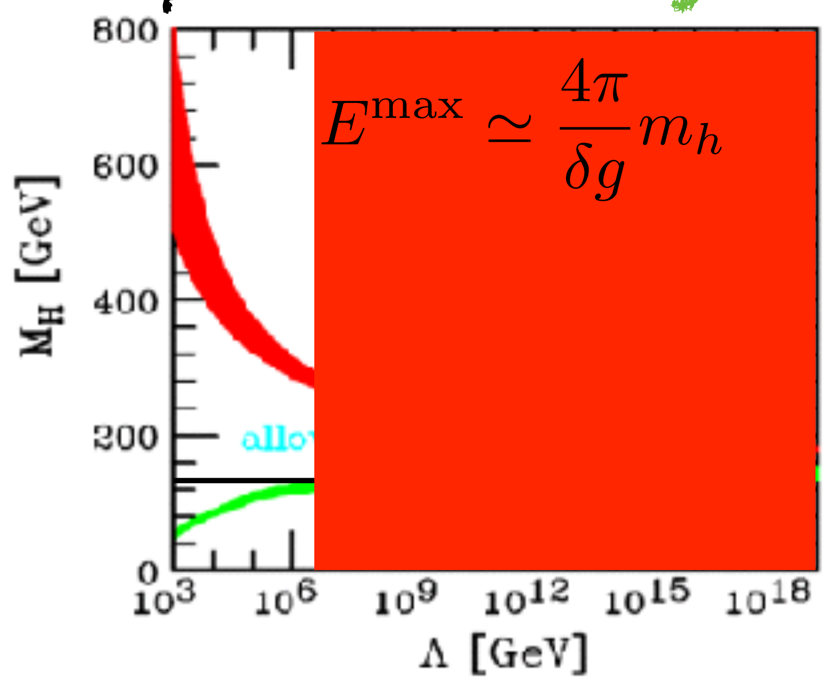


Higgs Couplings at High-Energy

Higgs couplings: Theoretically Interesting
Experimentally not High-E measurements

but...

SM is the unique theory, with its particle content, valid up to arbitrary energy:



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

Higgs Couplings… without a Higgs

Henning,Lombardo,Riembau,FR'18

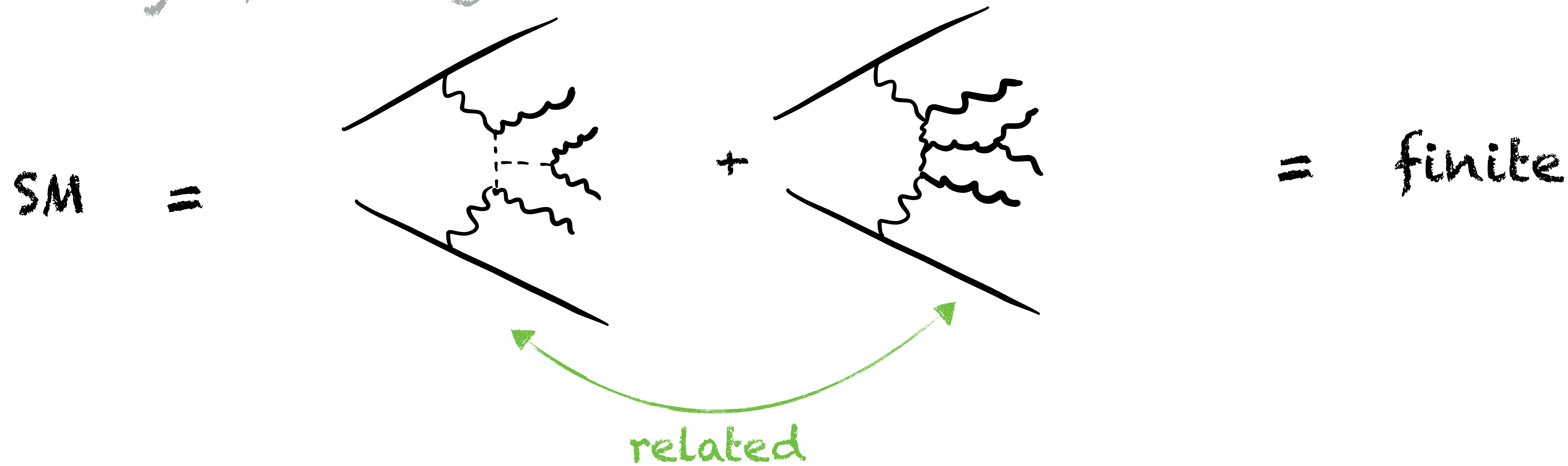
Any modifications of Higgs couplings induces
E^2 growth in some process with longitudinal W,Z bosons!

Higgs Couplings... without a Higgs

Henning,Lombardo,Riembau,FR'18

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

One way of seeing this:



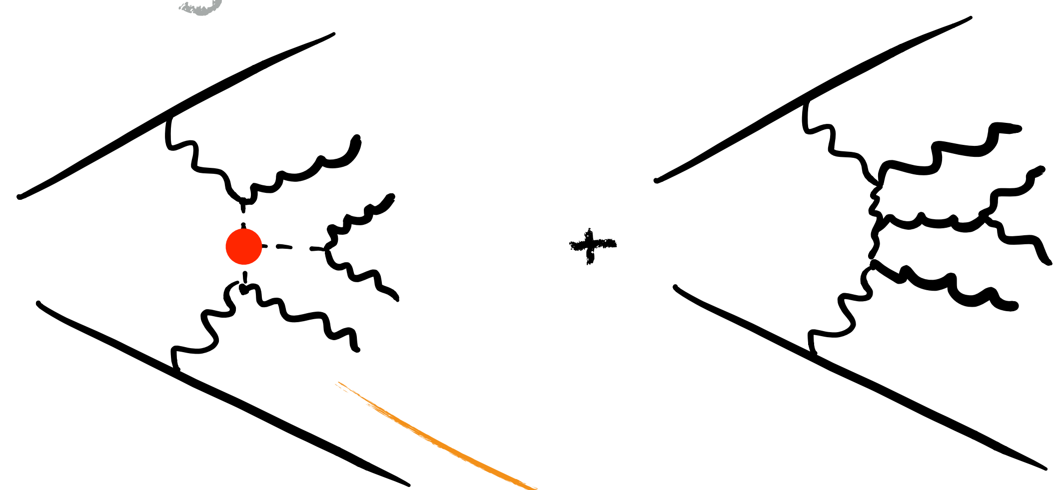
Higgs Couplings… without a Higgs

Henning,Lombardo,Riembau,FR'18

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

One way of seeing this:

SM =



= E^2

modification of a coupling (h^3) compromises gauge cancellations in the SM

Higgs Self Coupling

Another way of understanding E-growth:

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

Golstones = W_L, Z_L

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

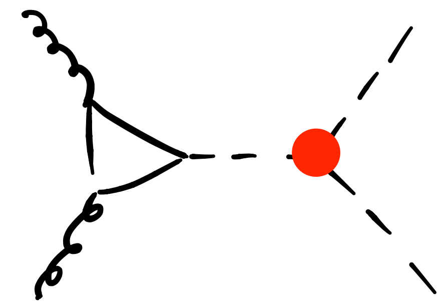
Higgs Self Coupling

Another way of understanding E-growth:

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

with 3 Higgs v.e.v.s

(= traditional Higgs Coupling measurement)



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

Golstones = W_L, Z_L

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

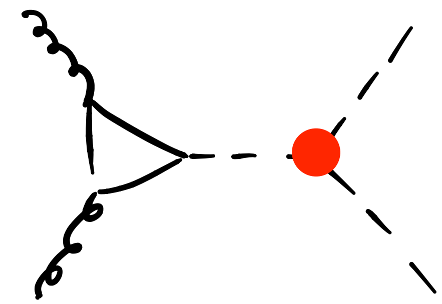
Higgs Self Coupling

Another way of understanding E-growth:

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

with 3 Higgs v.e.v.s

(= traditional Higgs Coupling measurement)



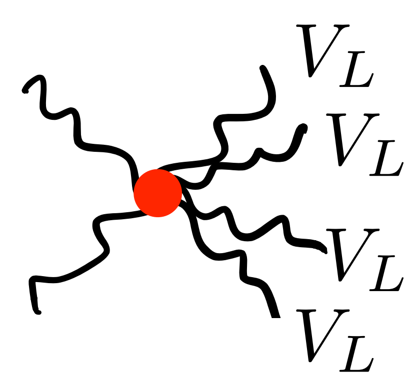
$$\sim \frac{v^2}{\Lambda^2}$$

Golstones = W_L, Z_L

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

with No Higgs v.e.v.s

▶ Contact Interaction Among W_L, Z_L



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

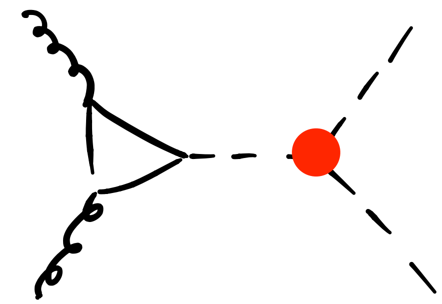
Higgs Self Coupling

Another way of understanding E-growth:

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

with 3 Higgs v.e.v.s

(= traditional Higgs Coupling measurement)



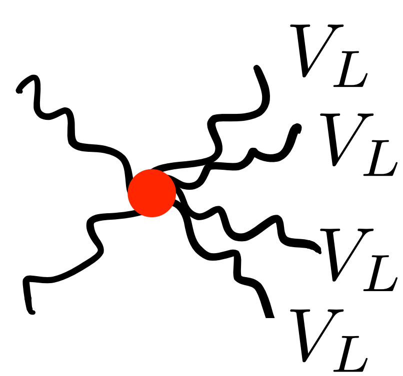
$$\sim \frac{v^2}{\Lambda^2}$$

Golstones = W_L, Z_L

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

with No Higgs v.e.v.s

▶ Contact Interaction Among W_L, Z_L



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

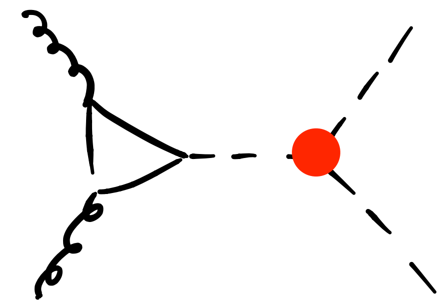
Higgs Self Coupling

Another way of understanding E-growth:

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

with 3 Higgs v.e.v.s

(= traditional Higgs Coupling measurement)



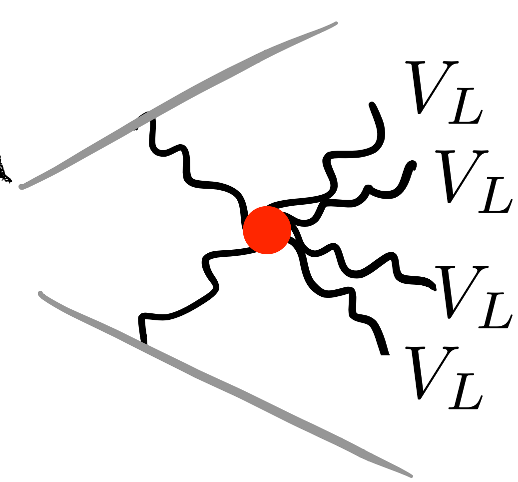
$$\sim \frac{v^2}{\Lambda^2}$$

Golstones = W_L, Z_L

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

with No Higgs v.e.v.s

▶ Contact Interaction Among W_L, Z_L



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

$pp \to jj + 4V_L$

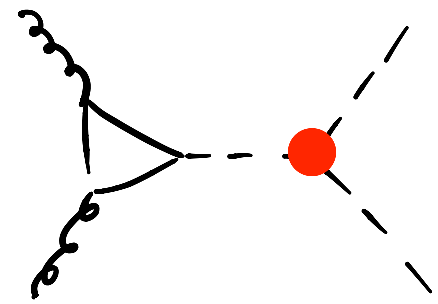
Higgs Self Coupling

Another way of understanding E-growth:

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

with 3 Higgs v.e.v.s

(= traditional Higgs Coupling measurement)

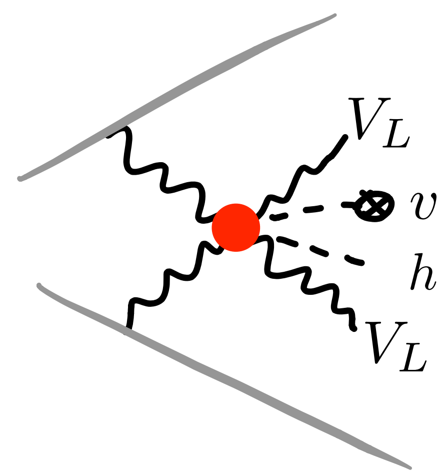


$$\sim \frac{v^2}{\Lambda^2}$$

Golstones = W_L, Z_L

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

with 1 Higgs v.e.v.

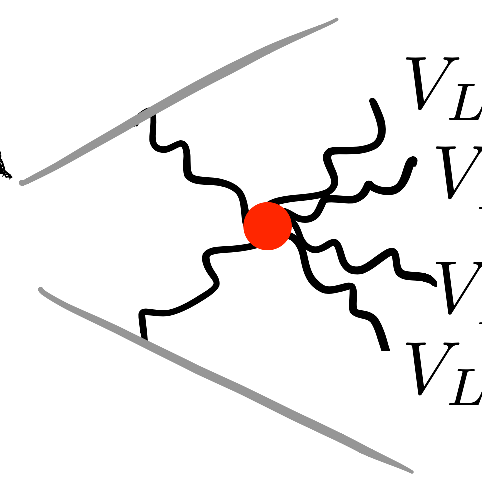


$$\sim \frac{v\,E}{\Lambda^2}$$

$pp \to jjh + V_L V_L'$

with No Higgs v.e.v.s

▶ Contact Interaction Among W_L, Z_L



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

$pp \to jj + 4V_L$

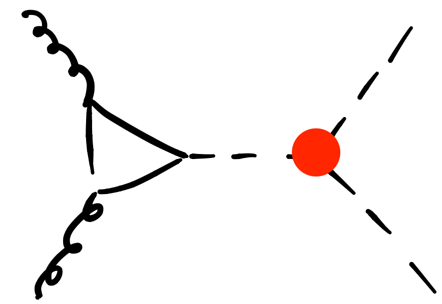
Higgs Self Coupling

Another way of understanding E-growth:

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

with 3 Higgs v.e.v.s

(= traditional Higgs Coupling measurement)

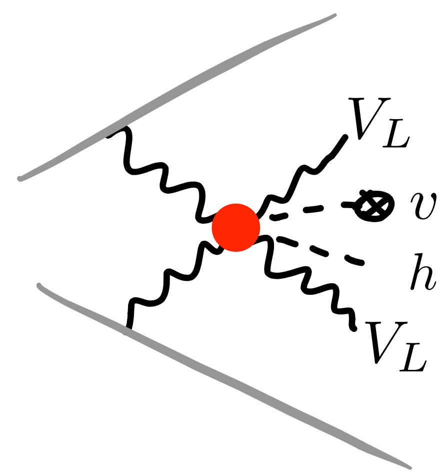


$$\sim \frac{v^2}{\Lambda^2}$$

Golstones = W_L, Z_L

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

with 1 Higgs v.e.v.

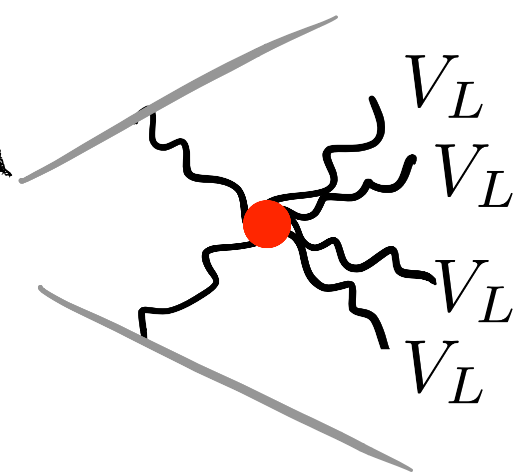


$$\sim \frac{v\,E}{\Lambda^2}$$

$pp \to jjh + V_L V_L'$

with No Higgs v.e.v.s

Contact Interaction Among W_L, Z_L



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

$pp \to jj + 4V_L$

signal

statistics

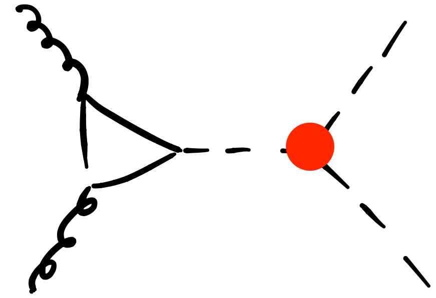
Higgs Self Coupling

Another way of understanding E-growth:

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

with 3 Higgs v.e.v.s

(= traditional Higgs Coupling measurement)

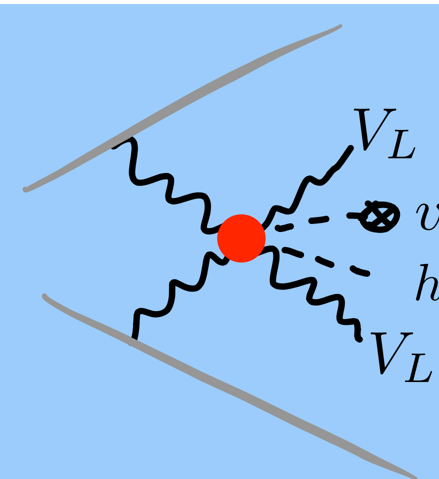


$$\sim \frac{v^2}{\Lambda^2}$$

Golstones = W_L, Z_L

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

with 1 Higgs v.e.v.

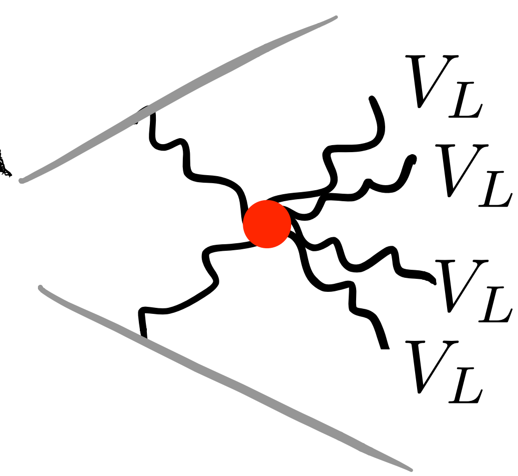


$$\sim \frac{v\,E}{\Lambda^2}$$

$pp \to jjh + V_L V_L'$

with No Higgs v.e.v.s

Contact Interaction Among W_L, Z_L



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

$pp \to jj + 4V_L$

signal

statistics

Higgs Self Coupling

Henning,Lombardo,Riembau,FR'18

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

Higgs Self Coupling

Henning,Lombardo,Riembau,FR'18

$W \to l + \nu$ → Same-sign leptons

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

Higgs Self Coupling

Henning,Lombardo,Riembau,FR'18

$W \to l + \nu$ → Same-sign leptons

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

$h \to \bar{b}b$

→ VBF topology

Higgs Self Coupling

Henning,Lombardo,Riembau,FR'18

$W \to l + \nu$ → Same-sign leptons

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

$h \to \bar{b}b$

→ VBF topology

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

Higgs Self Coupling

Henning,Lombardo,Riembau,FR'18

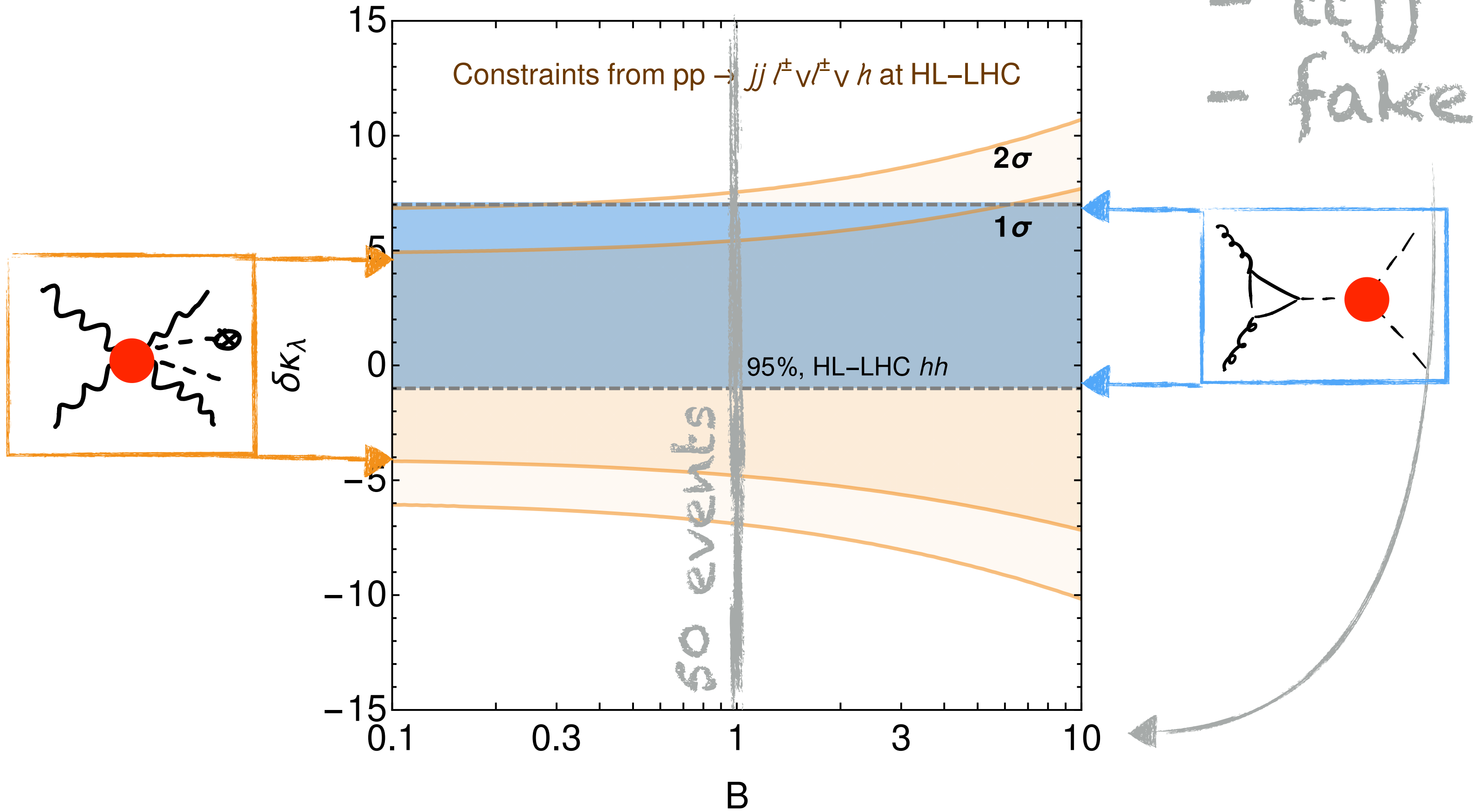
$W \to l + \nu$ → Same-sign leptons

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

$h \to \bar{b}b$

→ VBF topology

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



Higgs Self Coupling

Henning, Lombardo, Riembau, FR'18

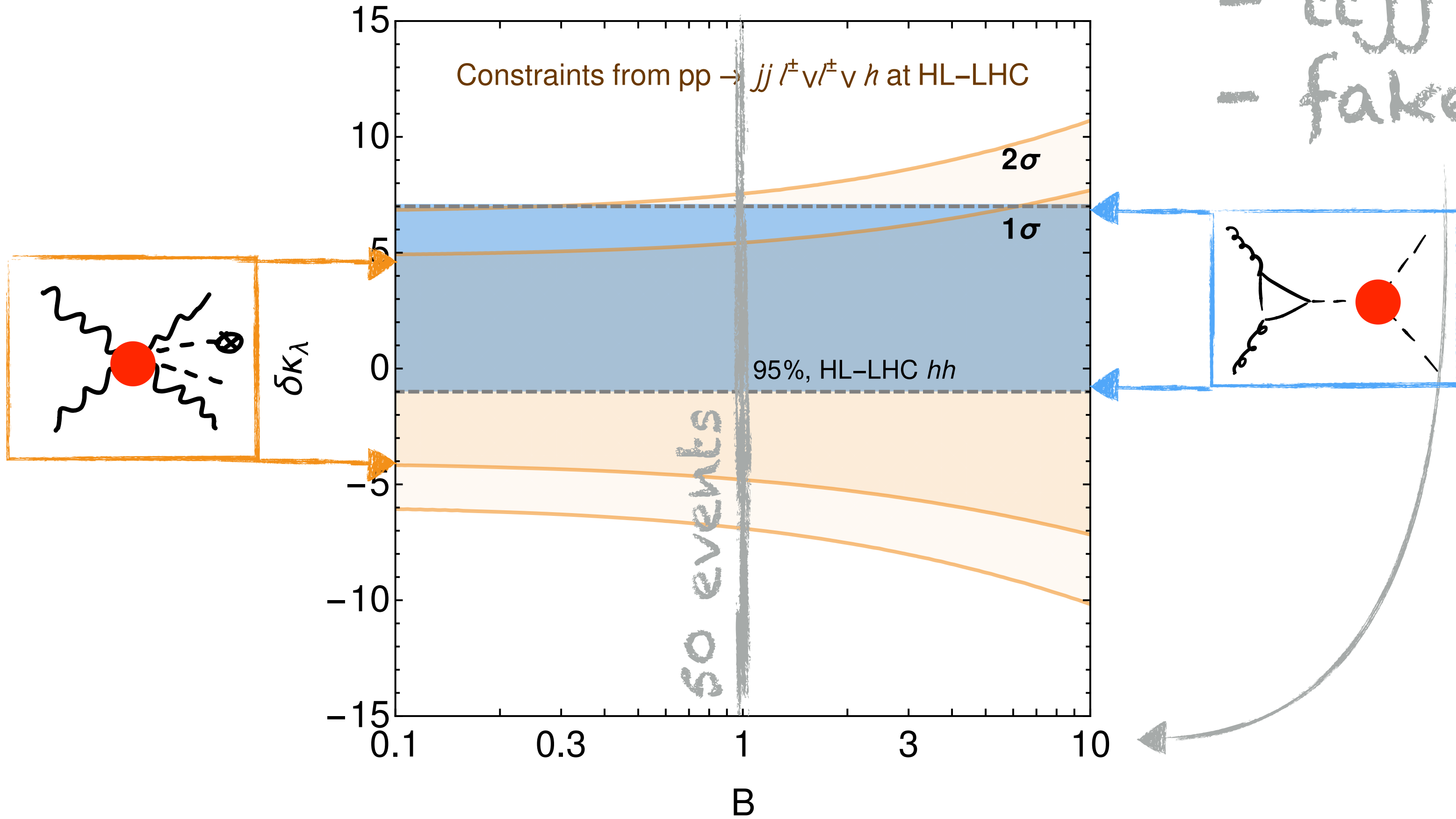
$$pp \to jjh + W^{\pm}W^{\pm}$$

$W \to l + \nu$ → Same-sign leptons

$h \to \bar{b}b$

→ VBF topology

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

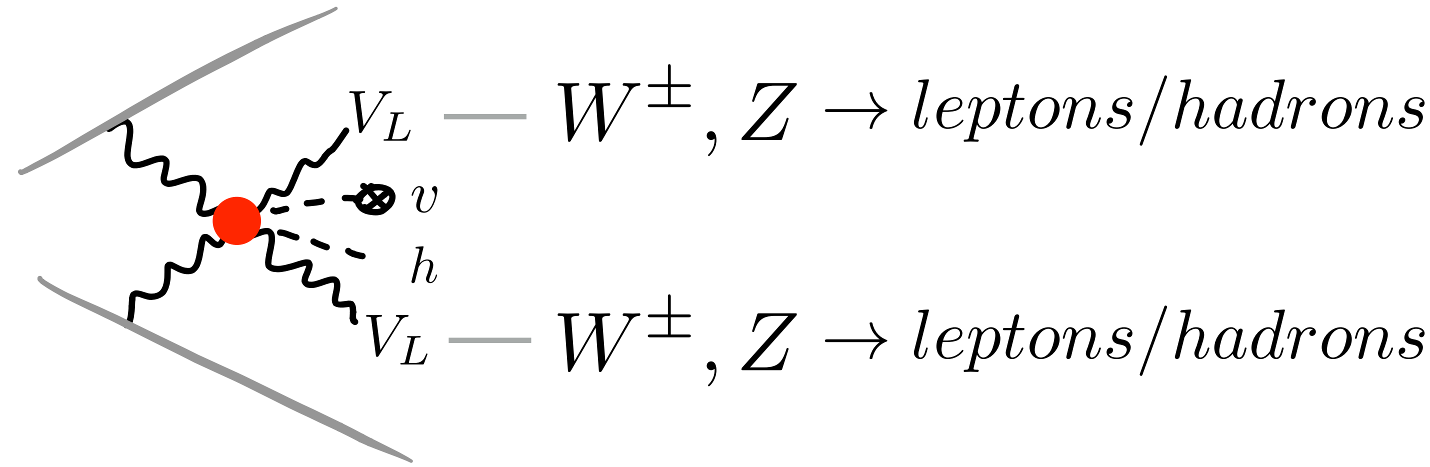


- HwH: single channel, simple analysis, competitive with HC!

Higgs Self Coupling

... endless possibilities of improvement ...

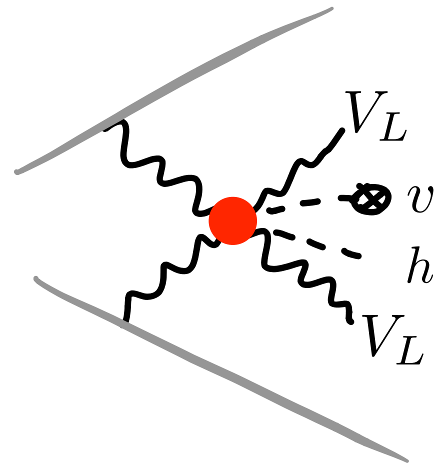
- More Final states



Higgs Self Coupling

... endless possibilities of improvement ...

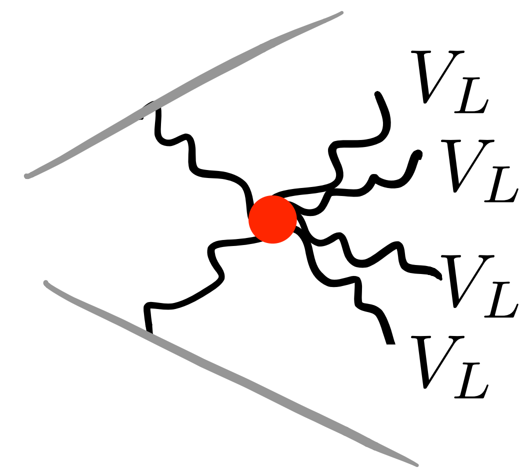
- More Final states



$W^{\pm}, Z \to leptons/hadrons$

$W^{\pm}, Z \to leptons/hadrons$

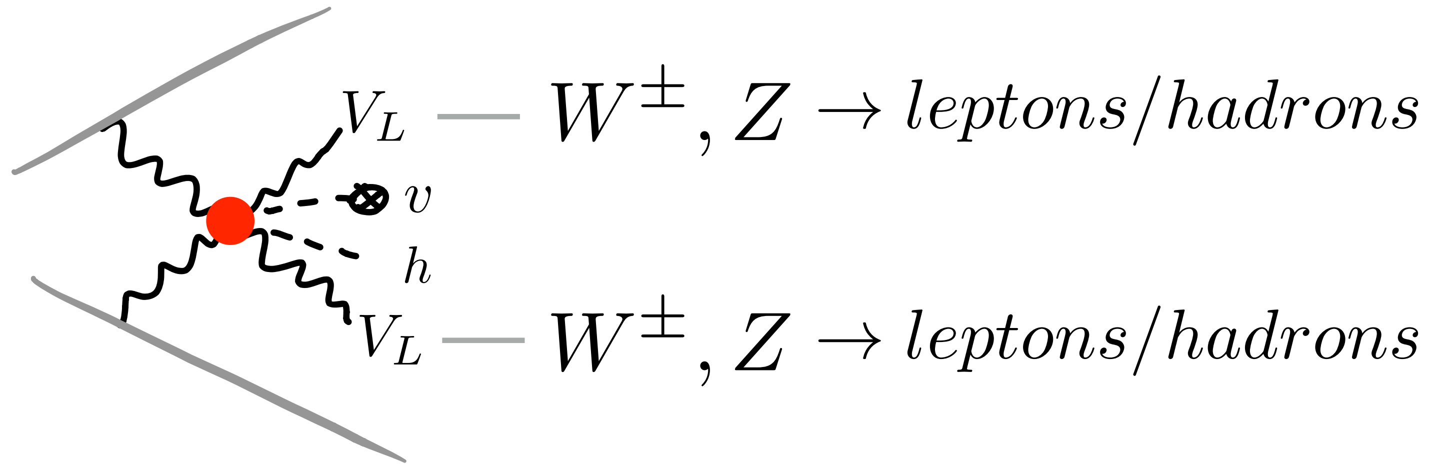
- Look also at E^2-growing processes



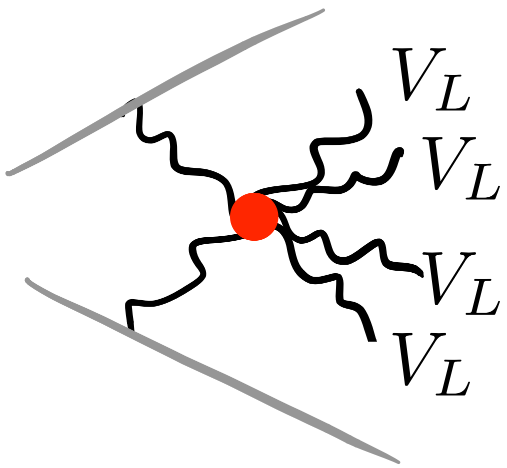
Higgs Self Coupling

... endless possibilities of improvement ...

- More Final states



- Look also at E^2-growing processes

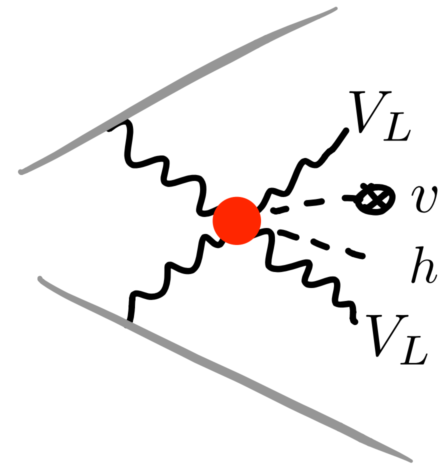


- Keep differential information to exploit E-growth

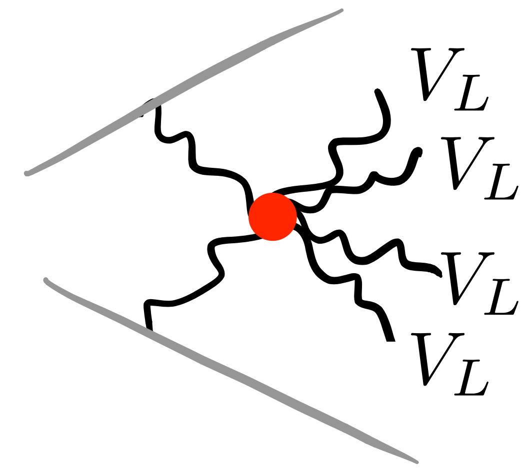
Higgs Self Coupling

… endless possibilities of improvement …

- More Final states



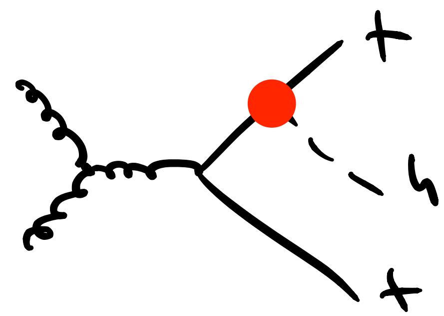
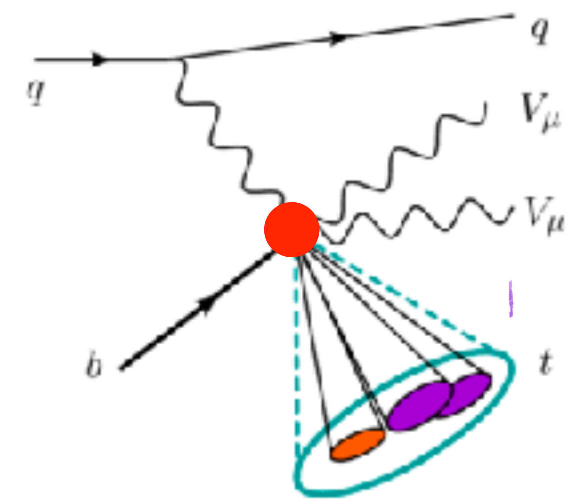
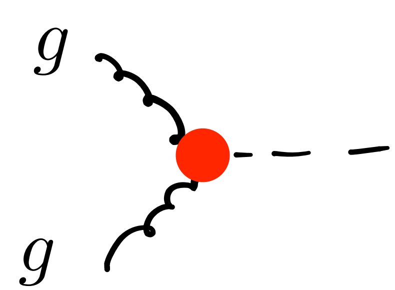
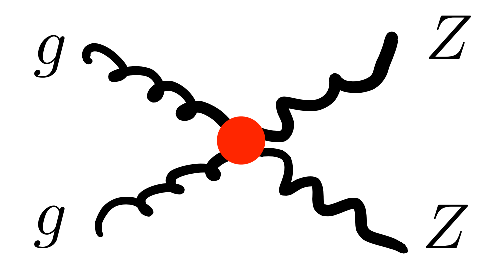
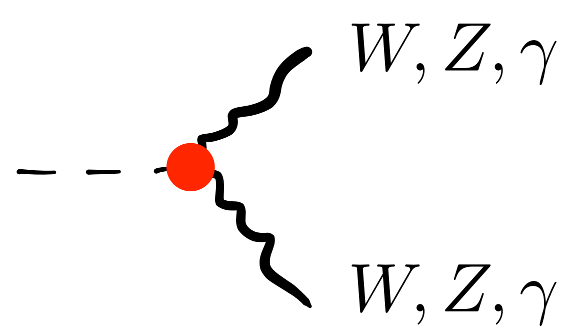
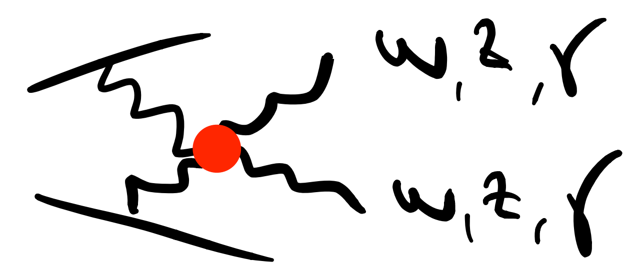
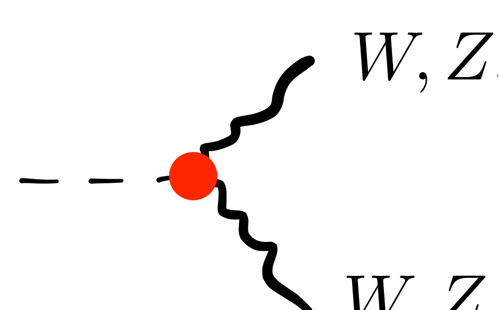
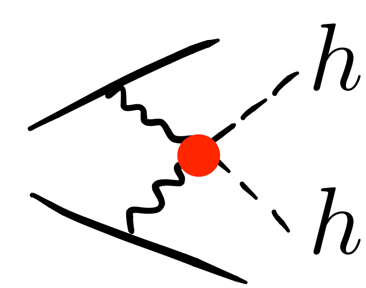
- Look also at E^2-growing processes



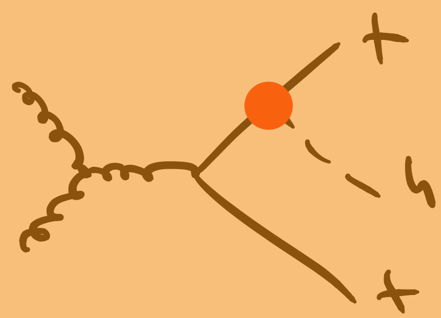
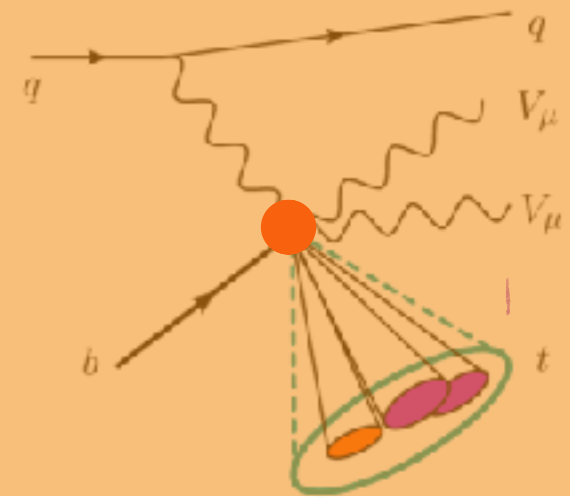
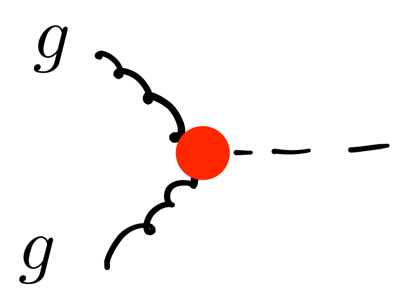
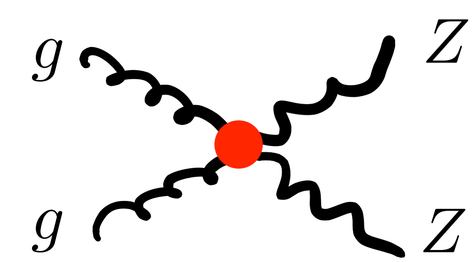
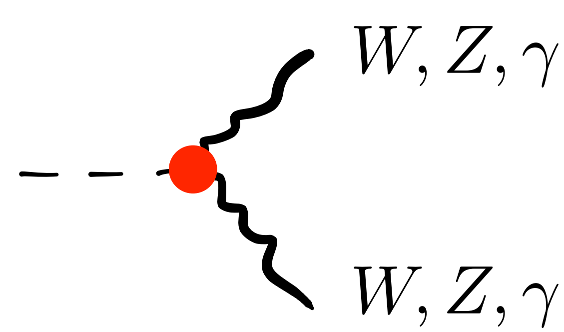
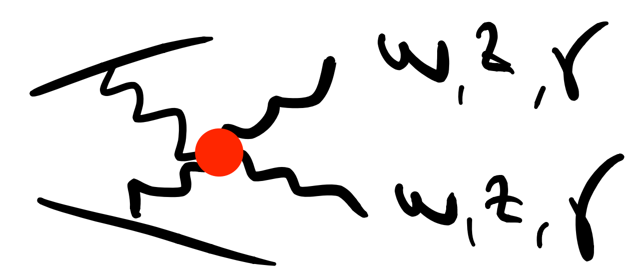
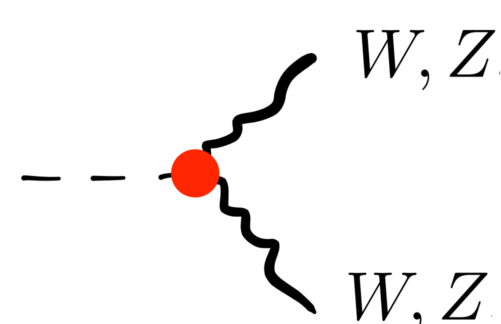
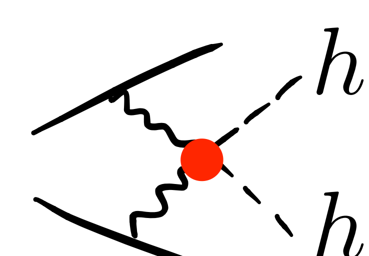
- Keep differential information to exploit E-growth

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

"Higgs without Higgs" Program

	$\sim const$	$\sim E^2$
κ_t $\lvert H\rvert^2 Q\tilde{H}t_R$		
κ_G $\lvert H\rvert^2 G^a_{\mu\nu}G^{a\,\mu\nu}$		
κ_γ $\lvert H\rvert^2 B_{\mu\nu}B^{\mu\nu}$ $\kappa_{Z\gamma}$ $\lvert H\rvert^2 W^a_{\mu\nu}W^{a\,\mu\nu}$		
κ_V $\lvert H\rvert^2 \partial_\mu H^\dagger \partial^\mu H$		

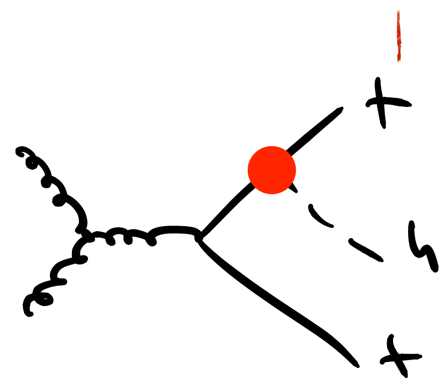
"Higgs without Higgs" Program

	$\sim const$	$\sim E^2$
κ_t $\|H\|^2 Q\tilde{H}t_R$		
κ_G $\|H\|^2 G^a_{\mu\nu}G^{a\,\mu\nu}$		
κ_γ $\|H\|^2 B_{\mu\nu}B^{\mu\nu}$ $\kappa_{Z\gamma}$ $\|H\|^2 W^a_{\mu\nu}W^{a\,\mu\nu}$		
κ_V $\|H\|^2 \partial_\mu H^\dagger \partial^\mu H$		

HwH Program: top Yukawa

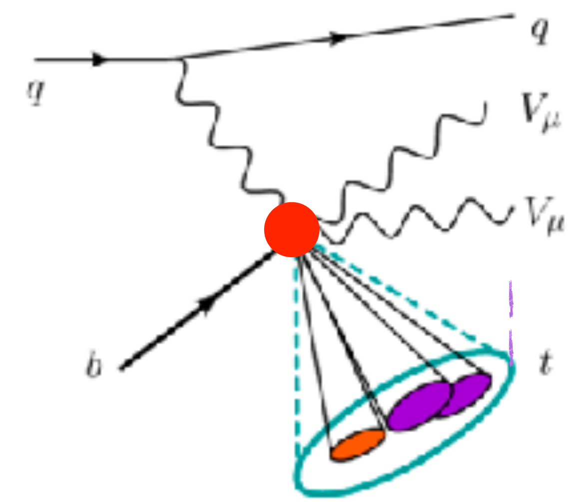
κ_t

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



$\sim E^2$

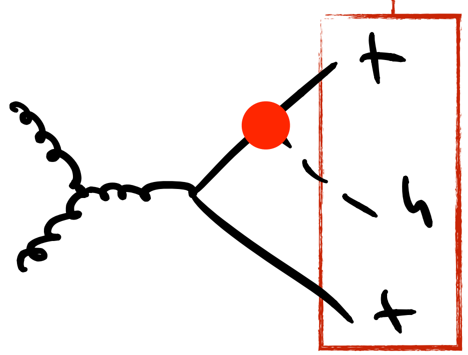
signal enhanced

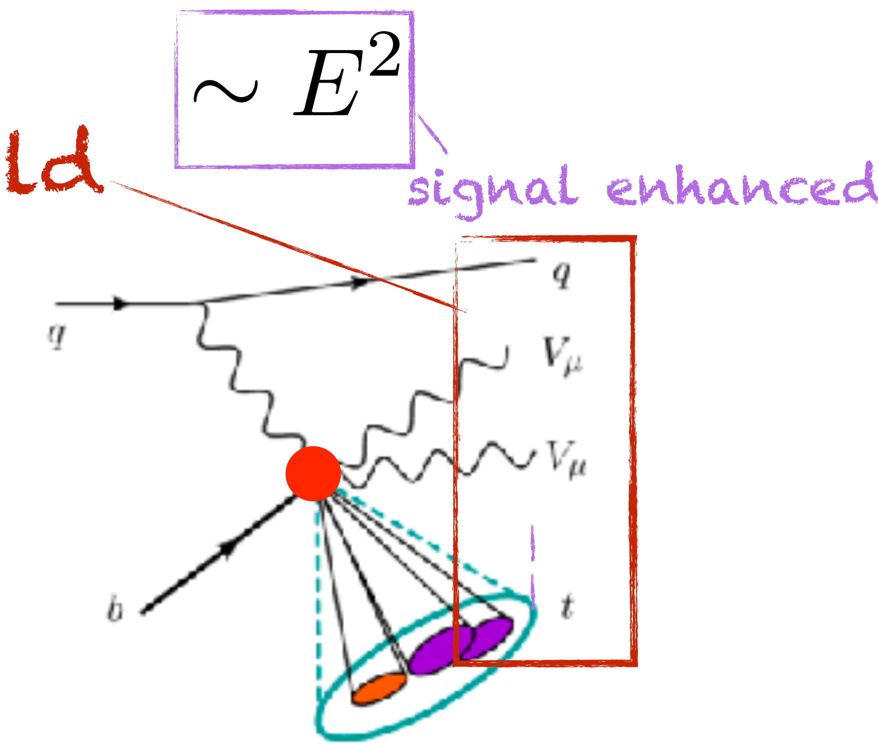


Henning,Lombardo,Riembau,FR'18

HwH Program: top Yukawa

κ_t
$|H|^2 Q\tilde{H} t_R$

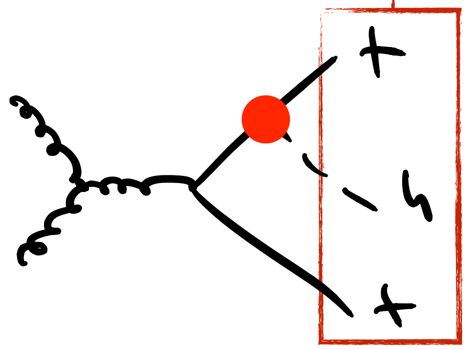


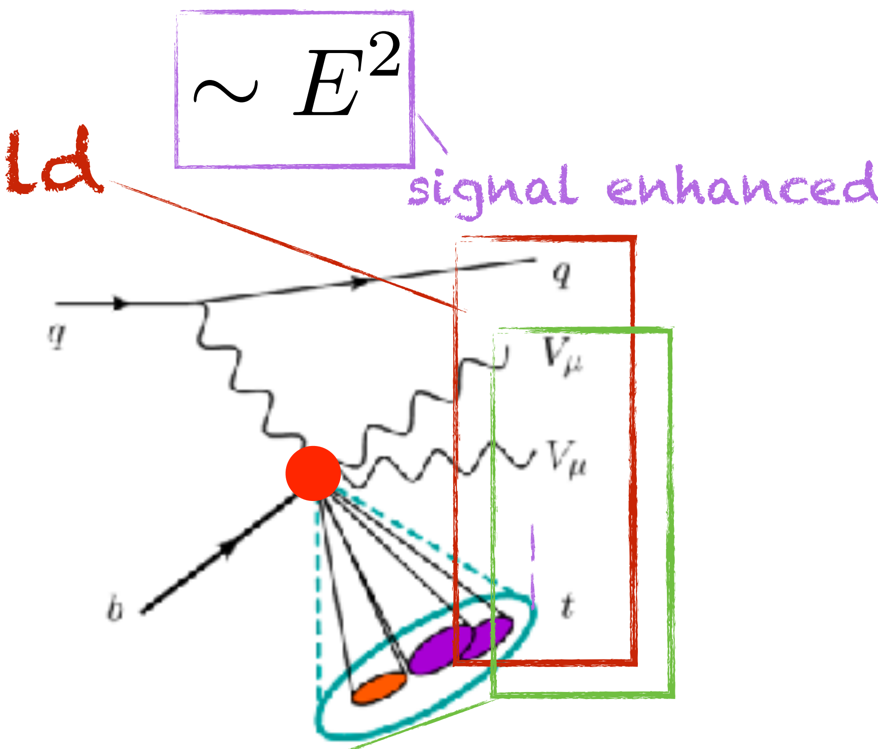


Henning,Lombardo,Riembau,FR'18

HwH Program: top Yukawa

κ_t
$|H|^2 Q\tilde{H}t_R$





Henning,Lombardo,Riembau,FR'18

HwH Program: top Yukawa

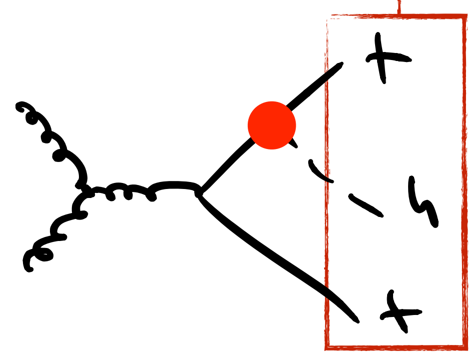
κ_t

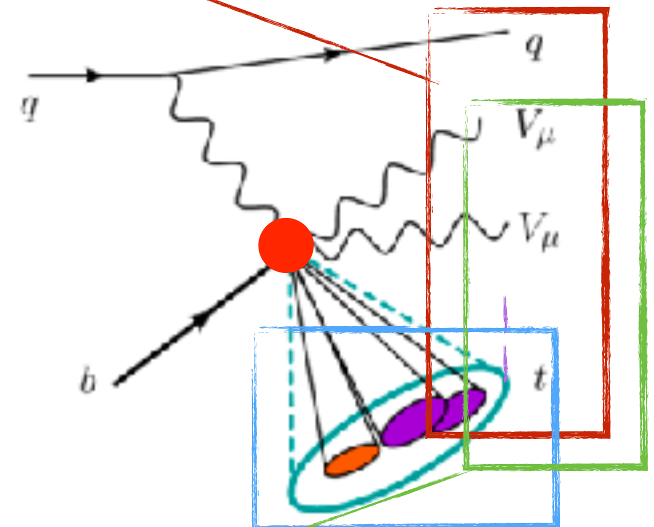
$|H|^2 Q\tilde{H} t_R$

$\sim E^2$

signal enhanced

lower threshold





many final states

boosted top:
good discriminant,
easier to reconstruct

Henning,Lombardo,Riembau,FR'18

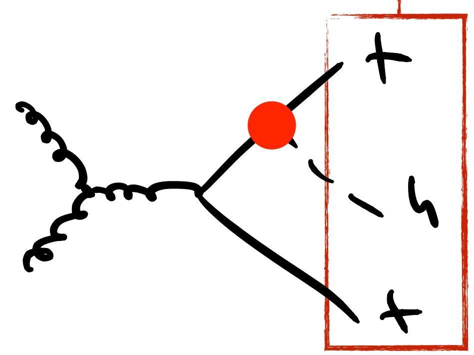
HwH Program: top Yukawa

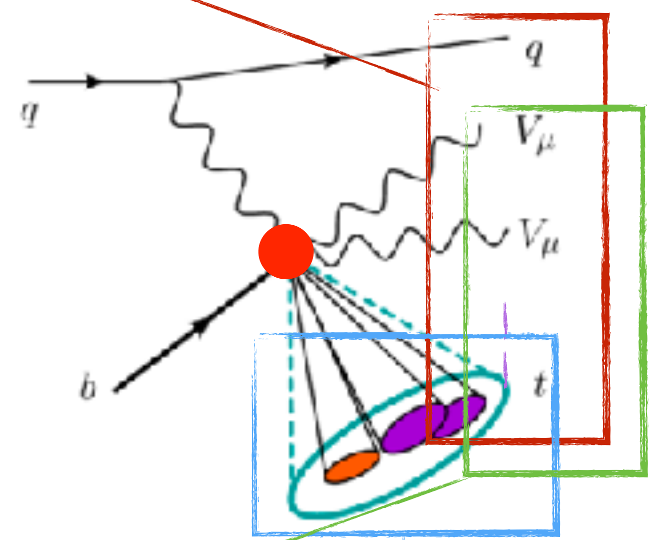
κ_t
$|H|^2 Q\tilde{H}t_R$

lower threshold

$\sim E^2$

signal enhanced





many final states

boosted top:
good discriminant,
easier to reconstruct

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)

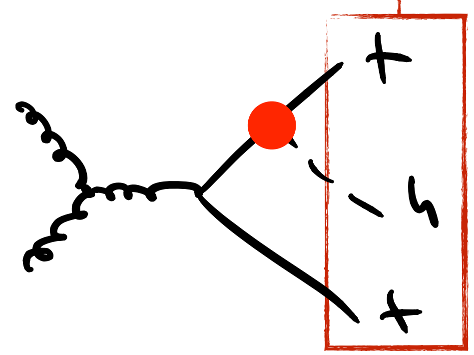
$p_T^t > 250$ GeV / $p_T^t > 500$ GeV

Henning,Lombardo,Riembau,FR'18

HwH Program: top Yukawa

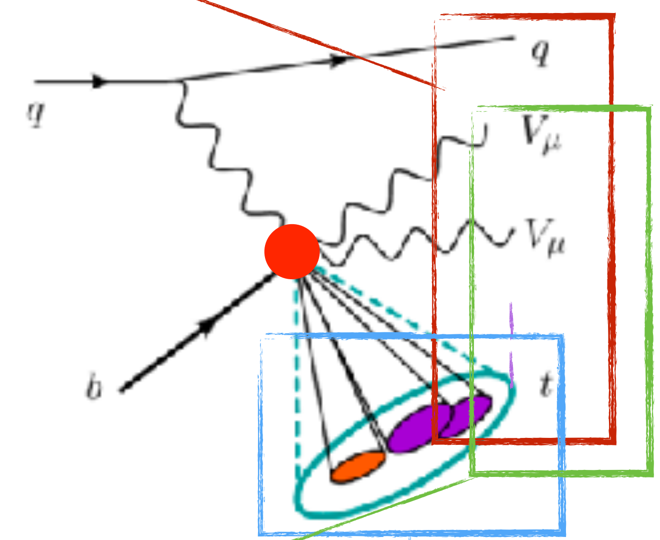
κ_t
$|H|^2 Q\tilde{H}t_R$

lower threshold



$\sim E^2$

signal enhanced



many final states

boosted top:
good discriminant,
easier to reconstruct

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

>2l: Small Background

Henning,Lombardo,Riembau,FR'18

HwH Program: top Yukawa

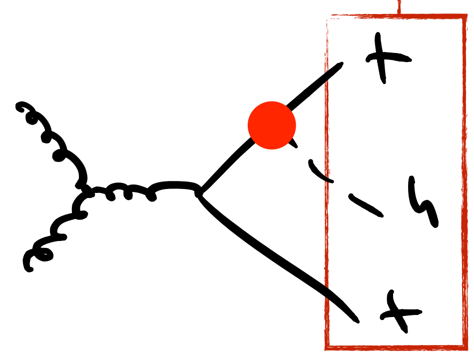
κ_t

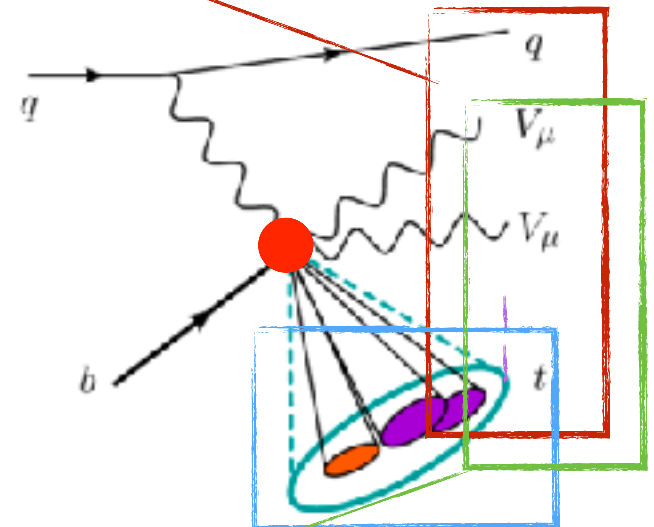
$|H|^2 Q\tilde{H}t_R$

lower threshold

$\sim E^2$

signal enhanced





many final states

boosted top:
good discriminant,
easier to reconstruct

Signal classified by #leptons:

$ttjj \to tW\,bj\,j$ ($bj \sim W$)

background manageable

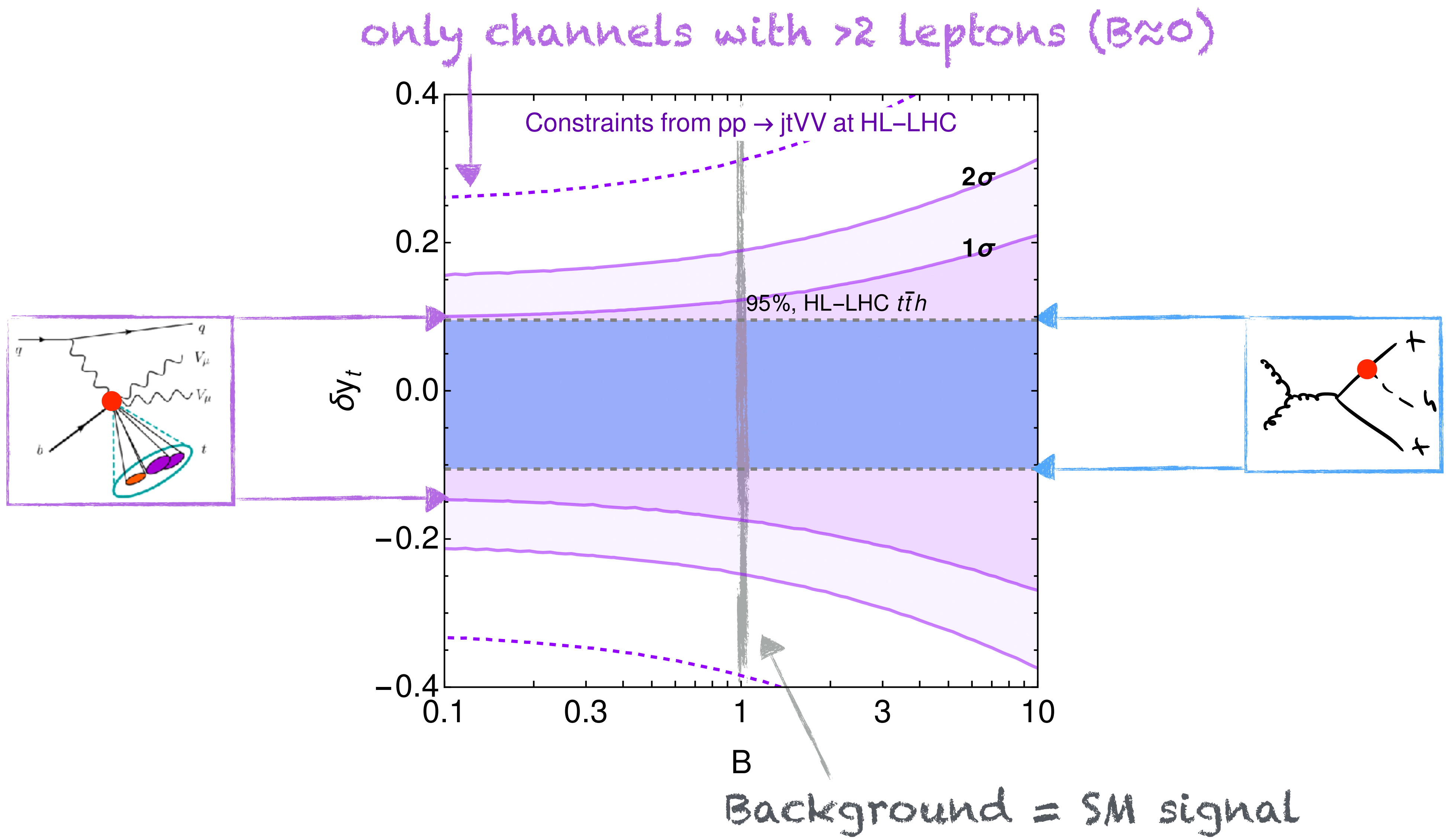
Process	0ℓ	1ℓ	$\ell^\pm\ell^\mp$	$\ell^\pm\ell^\pm$	$3\ell(4\ell)$
$W^\pm W^\mp$	3449/567	1724/283	216/35	-	-
$W^\pm W^\pm$	2850/398	1425/199	-	178/25	-
$W^\pm Z$	3860/632	965/158	273/45	-	68/11
ZZ	2484/364	-	351/49	-	(12/2)

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

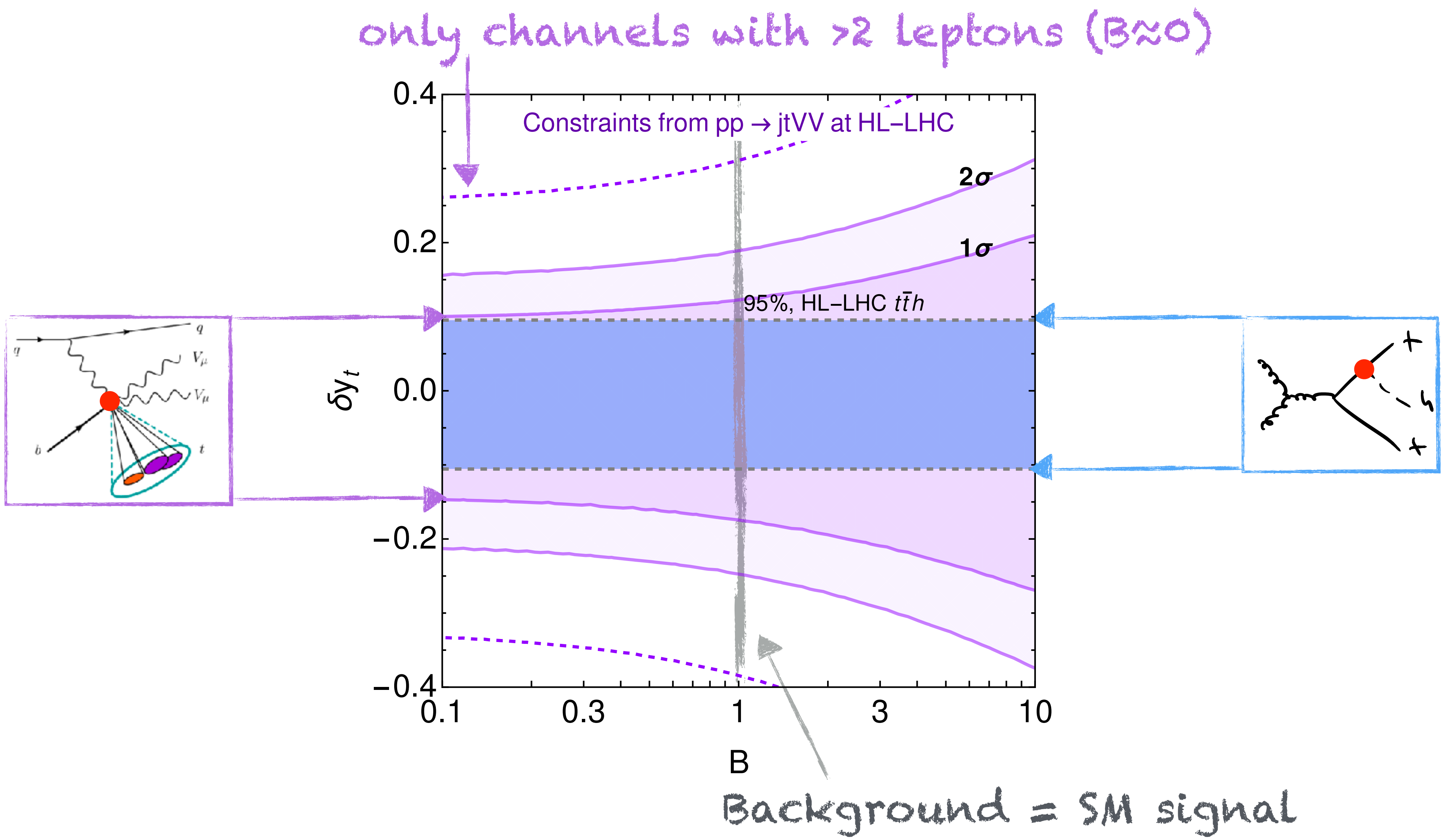
>2l: Small Background

Henning,Lombardo,Riembau,FR'18

HwH Program: top Yukawa



HwH Program: top Yukawa



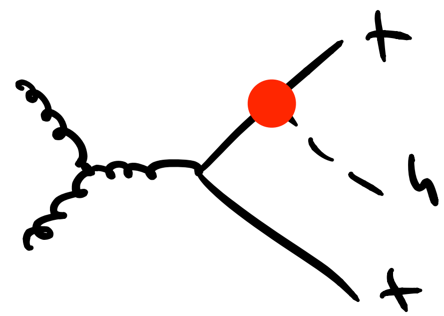
- HwH competitive with HC!

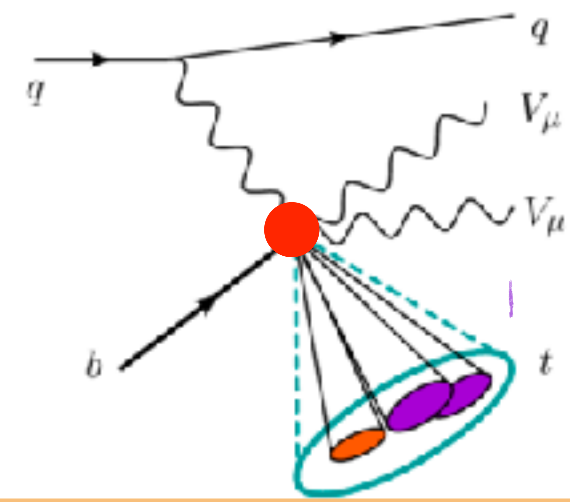
Further improvements: differential distributions (into larger E^2)
better background estimate

HwH Program

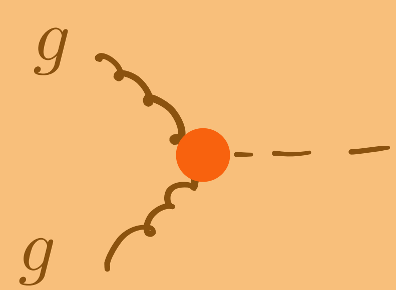
	$\sim const$	$\sim E^2$

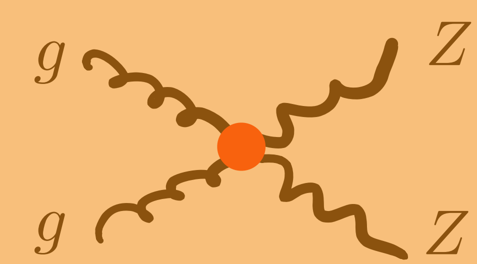
κ_t
$|H|^2 Q\tilde{H} t_R$



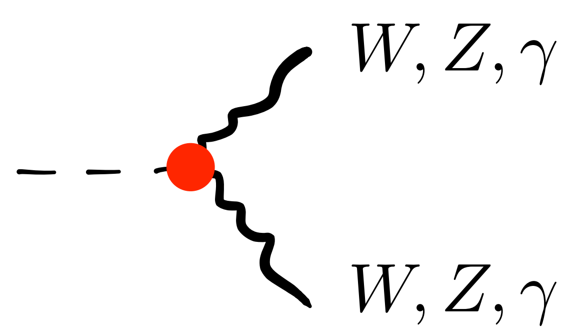


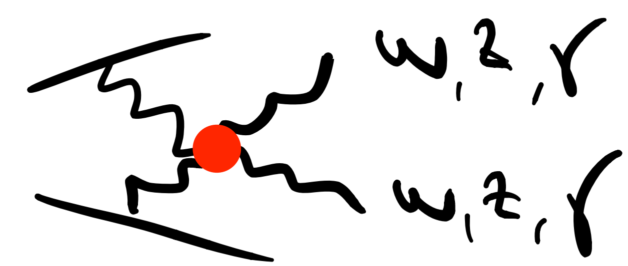
κ_G
$|H|^2 G^a_{\mu\nu} G^{a\,\mu\nu}$



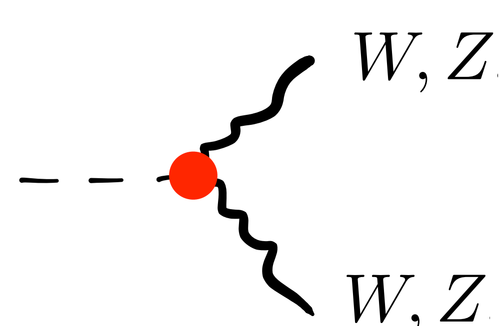


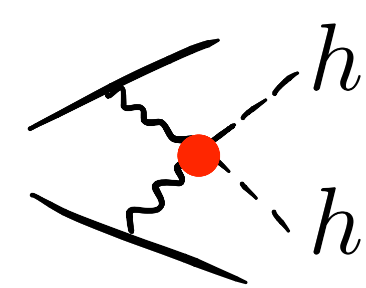
$\kappa_\gamma \quad |H|^2 B_{\mu\nu} B^{\mu\nu}$
$\kappa_{Z\gamma} \; |H|^2 W^a_{\mu\nu} W^{a\,\mu\nu}$





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



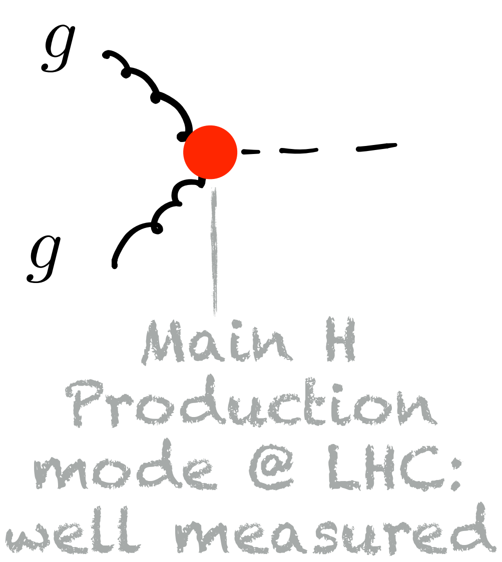


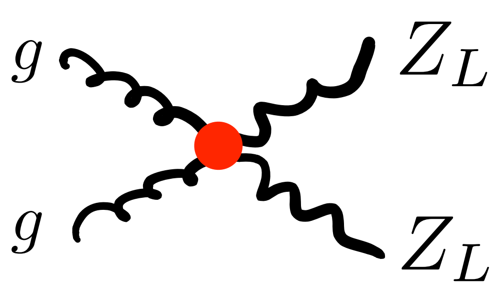
HwH Program: Higgs-Gluons

Azatov, Grojean, Paul, Salvioni'14

κ_G

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





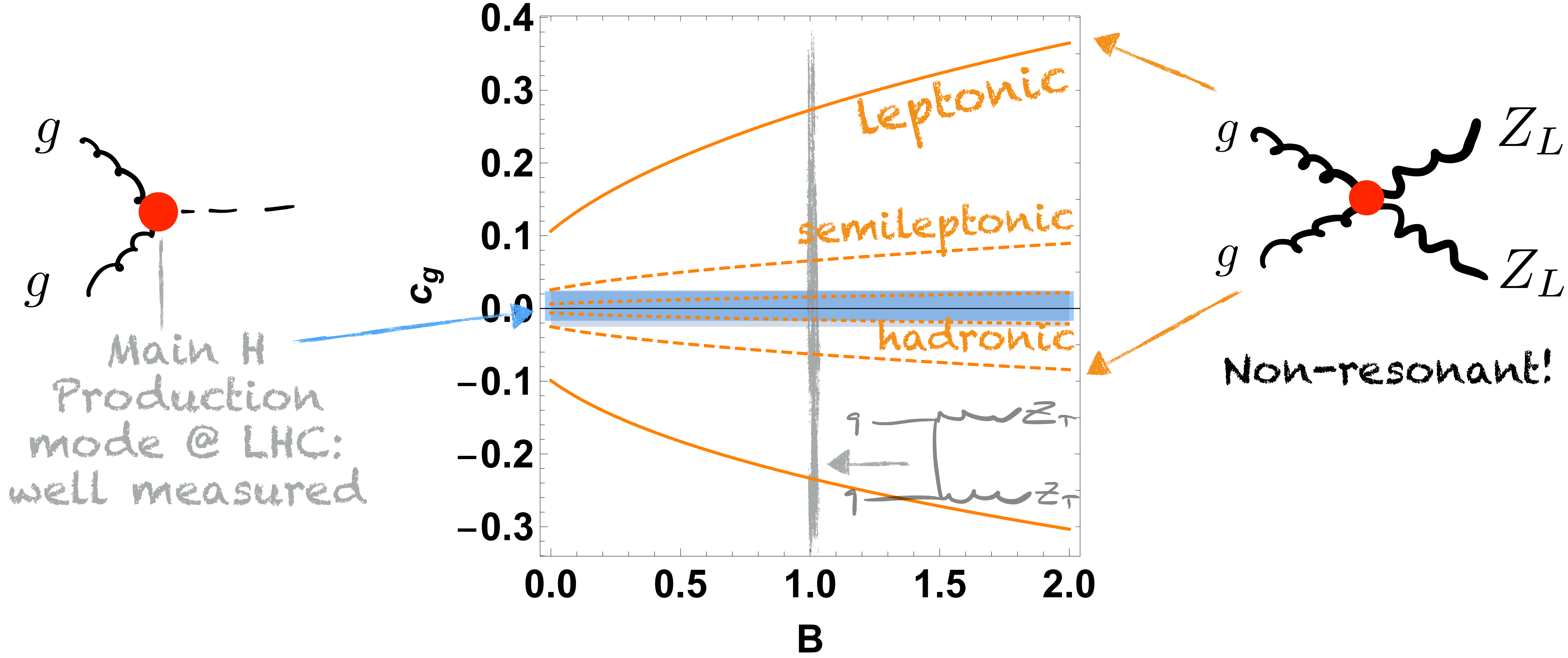
Non-resonant!

HwH Program: Higgs-Gluons

Azatov, Grojean, Paul, Salvioni'14

κ_G

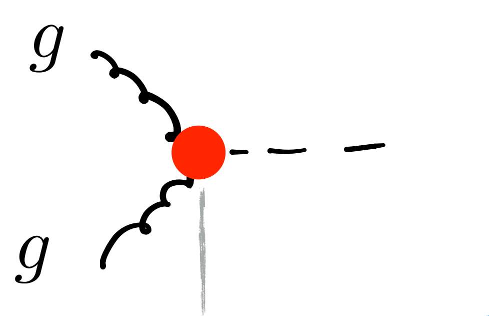
$|H|^2 G^a_{\mu\nu} G^{a\,\mu\nu}$

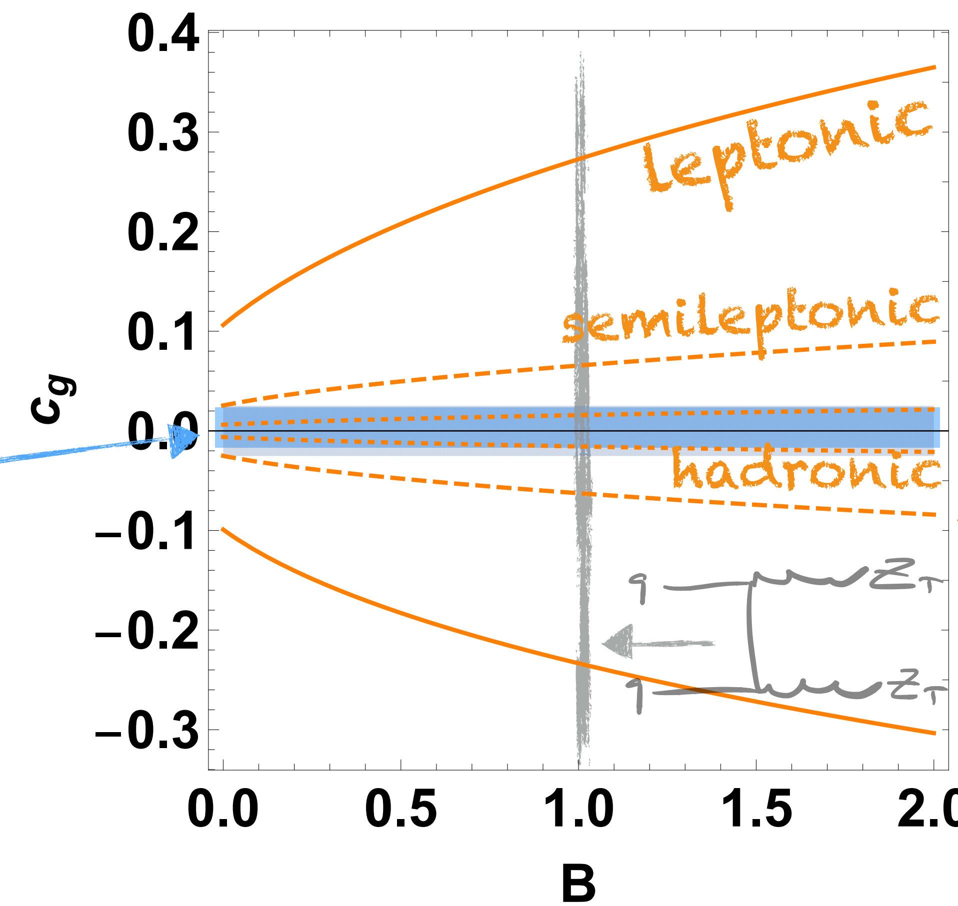


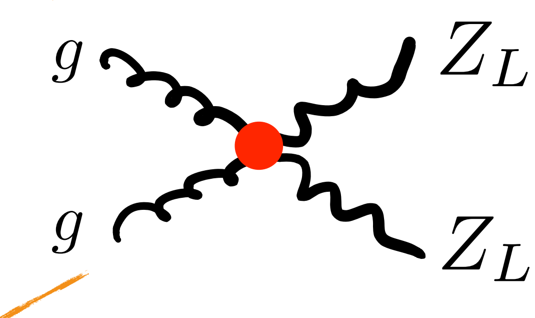
HwH Program: Higgs-Gluons

Azatov, Grojean, Paul, Salvioni'14

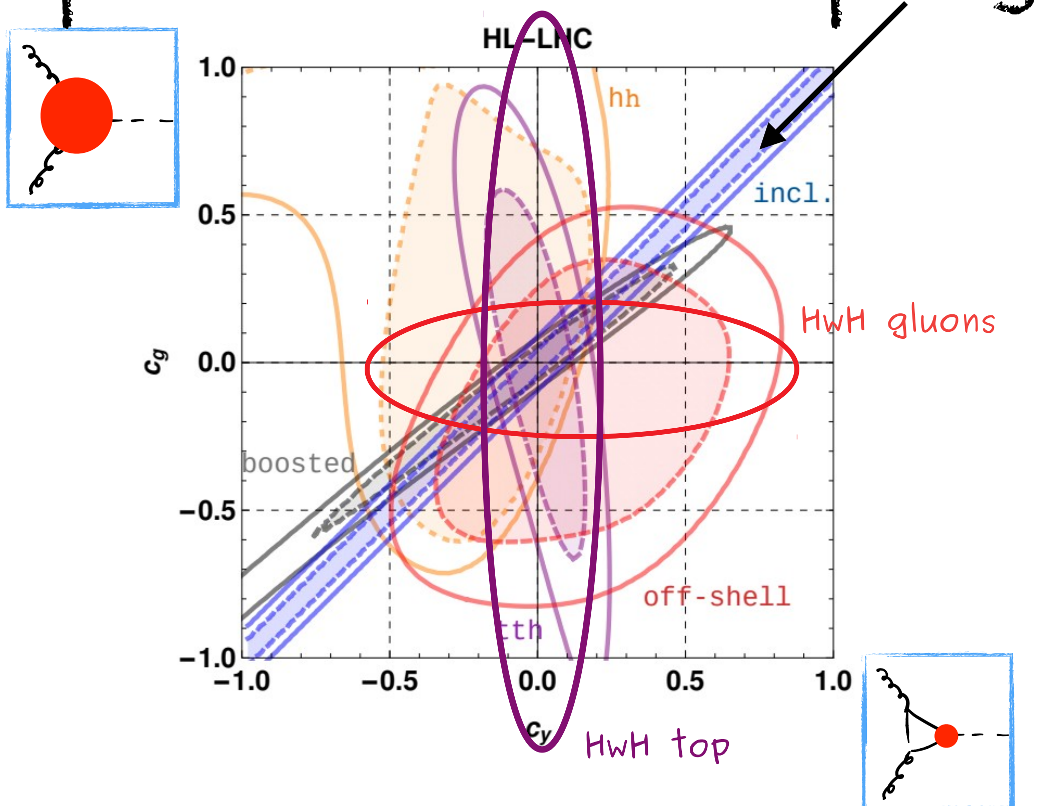
κ_G
$|H|^2 G^a_{\mu\nu} G^{a\,\mu\nu}$





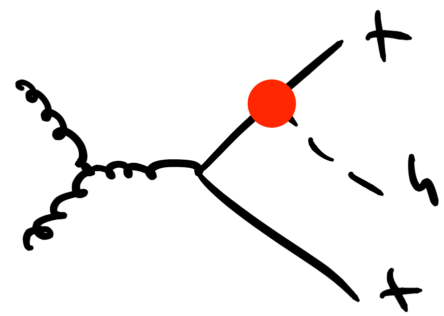
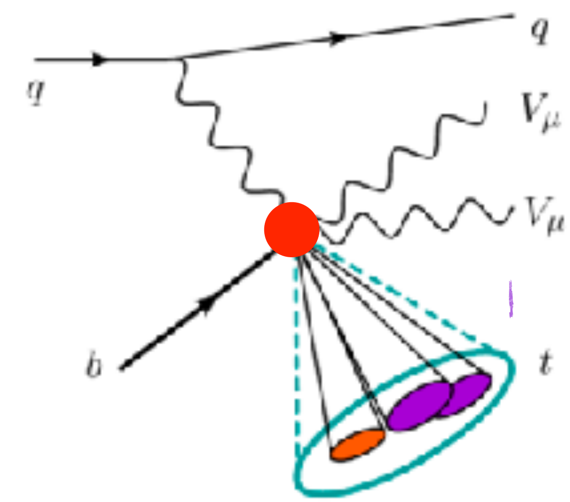
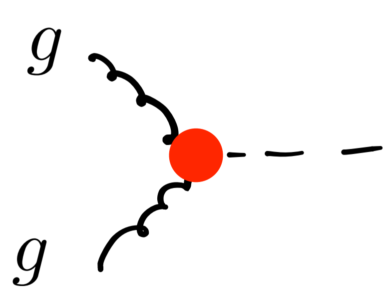
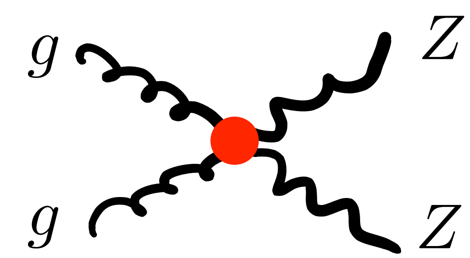
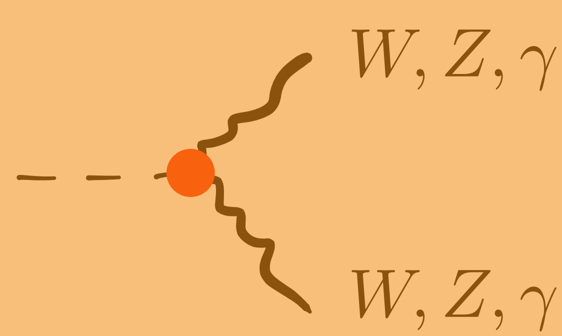
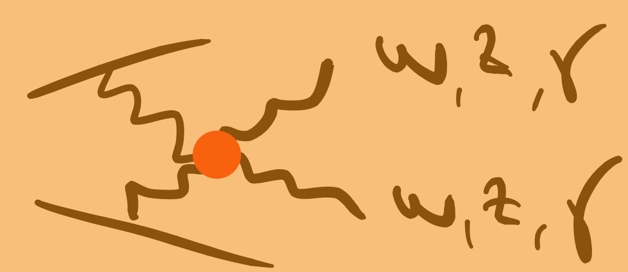
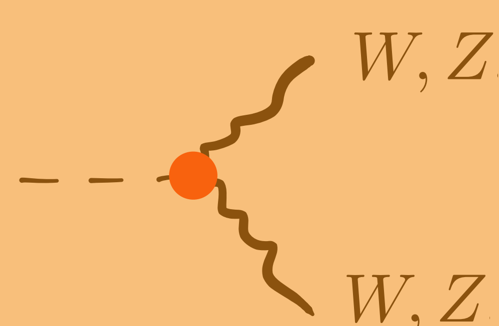
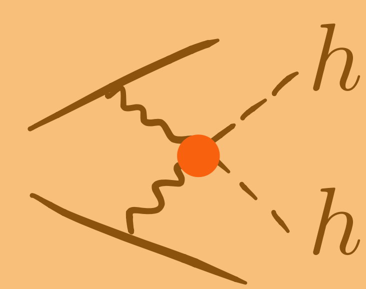


Important since Coupling measurements leave degeneracies...



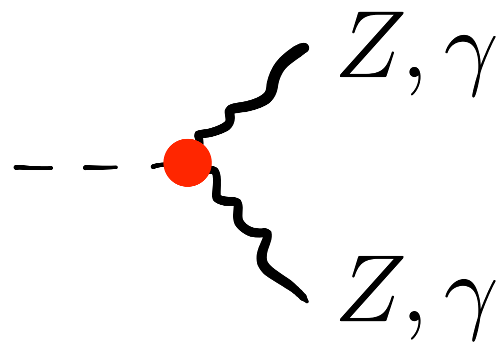
HwH offer new observables, orthogonal to previous ones!

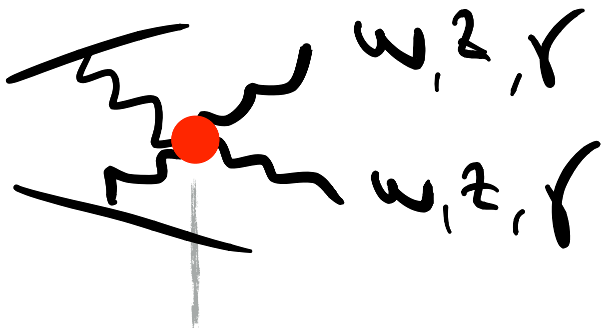
HwH Program

	$\sim const$	$\sim E^2$
κ_t $\lvert H\rvert^2 Q\tilde{H} t_R$		
κ_G $\lvert H\rvert^2 G^a_{\mu\nu} G^{a\,\mu\nu}$		
κ_γ $\lvert H\rvert^2 B_{\mu\nu} B^{\mu\nu}$ $\kappa_{Z\gamma}$ $\lvert H\rvert^2 W^a_{\mu\nu} W^{a\,\mu\nu}$		
κ_V $\lvert H\rvert^2 \partial_\mu H^\dagger \partial^\mu H$		

HwH Program: h to gauge bosons

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

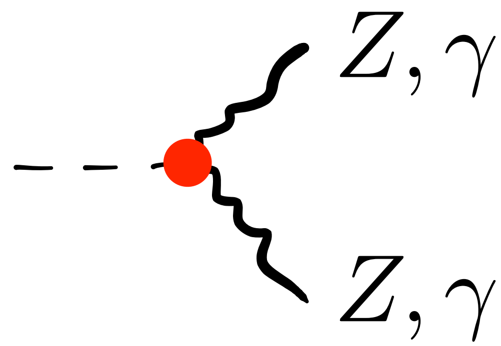


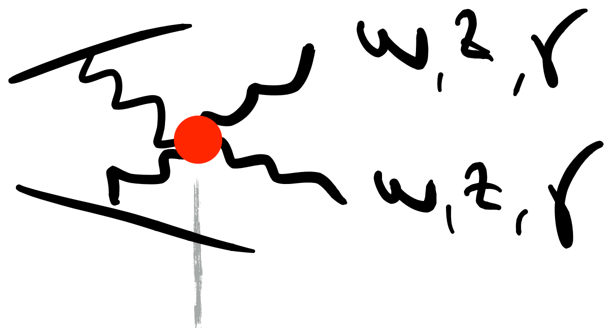


So far interpreted with dim-8 operators (aQGC)

HwH Program: h to gauge bosons

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

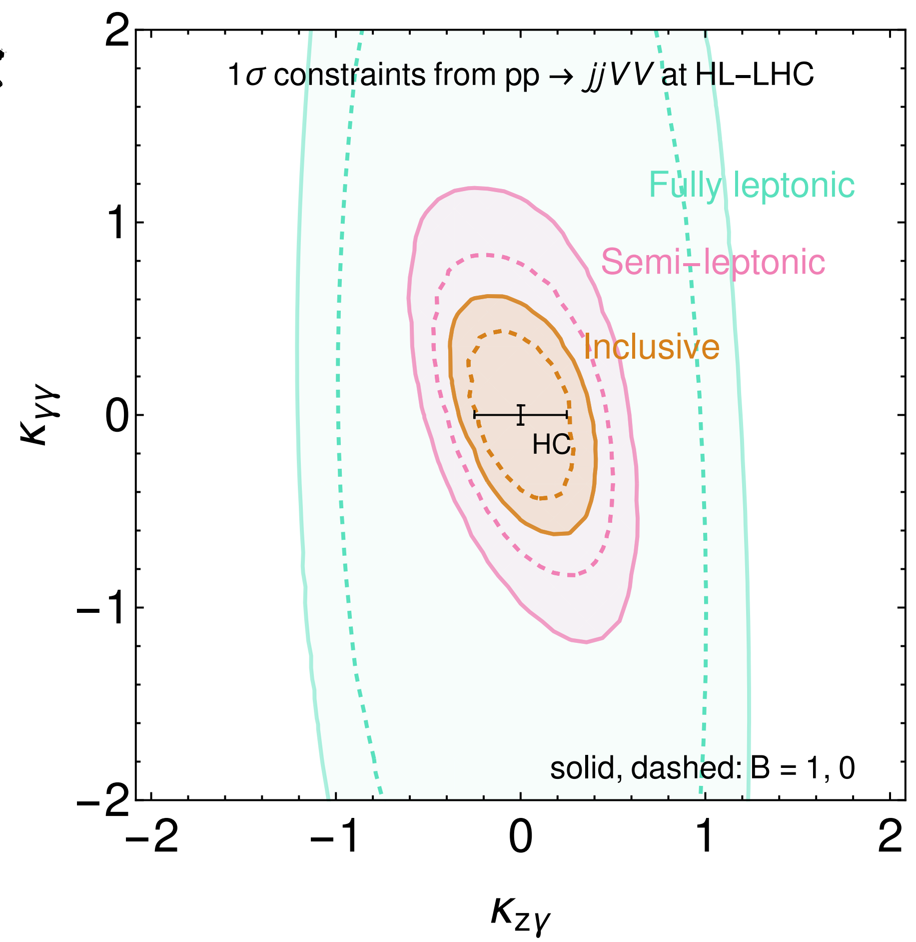




So far interpreted with dim-8 operators (aQGC)

Simple analysis:

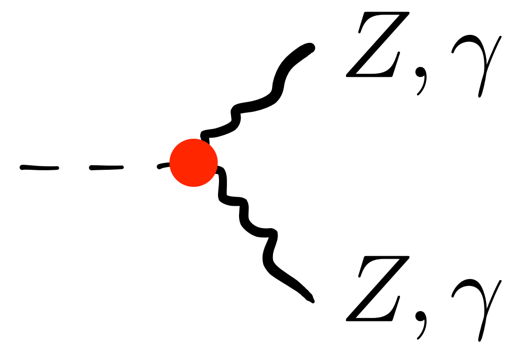
- VBF cuts
- Binning $\sum |p_T^V|$

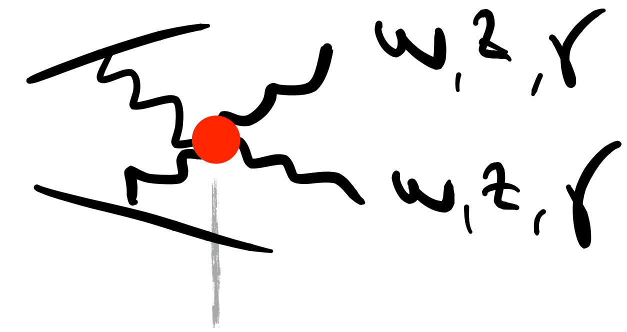


$\kappa_{Z\gamma}$ **competitive,**
κ_γ **not**

HwH Program: h to gauge bosons

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

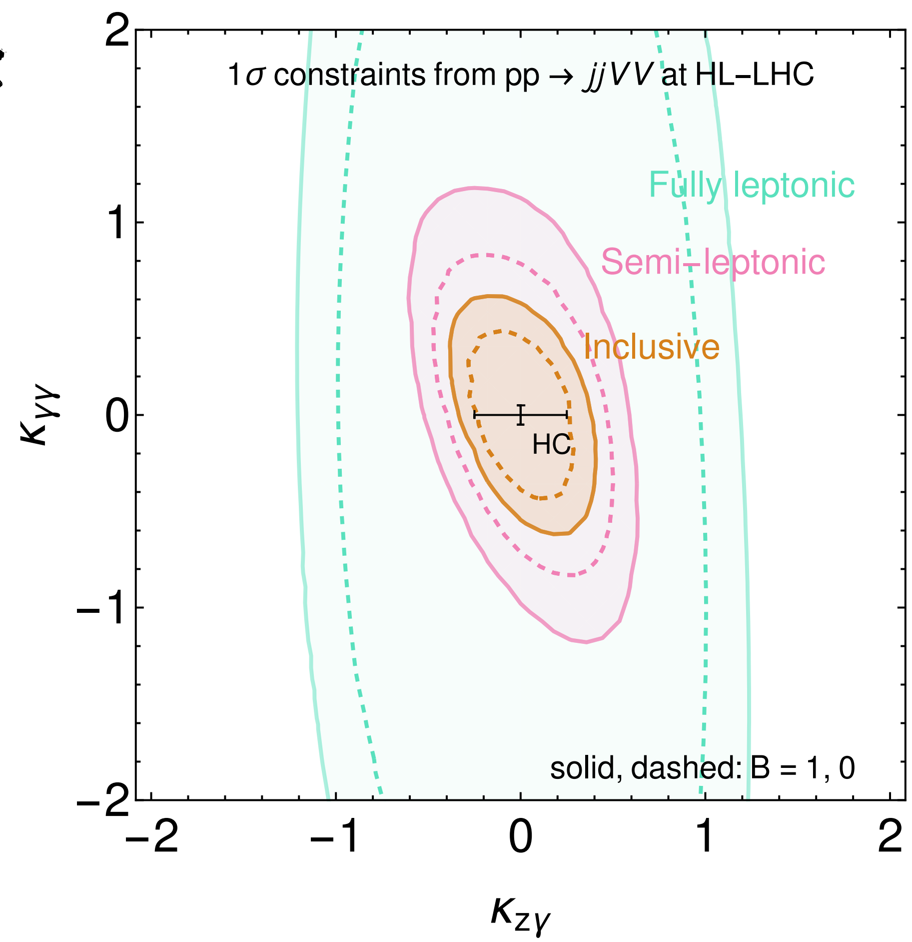




So far interpreted with dim-8 operators (aQGC)

Simple analysis:

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



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

!No Interference of 2>2 Amplitude!

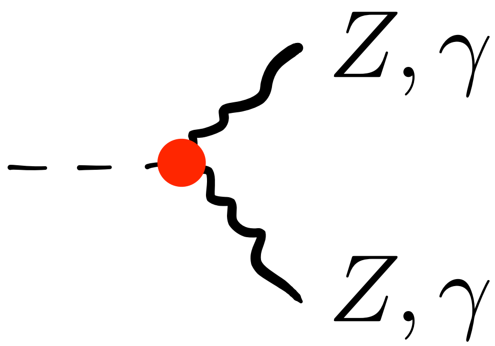
Azatov,Contino,Machado,FR'16

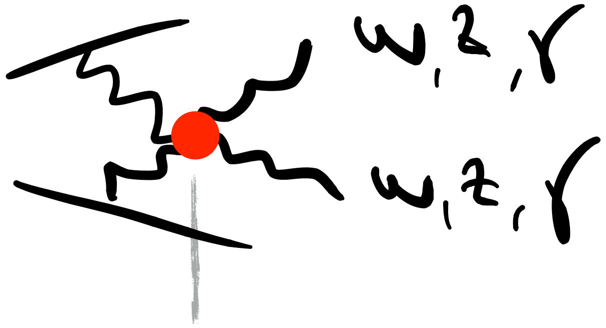
Azimuthal distributions might help

Panico,FR,Wulzer'17

HwH Program: h to gauge bosons

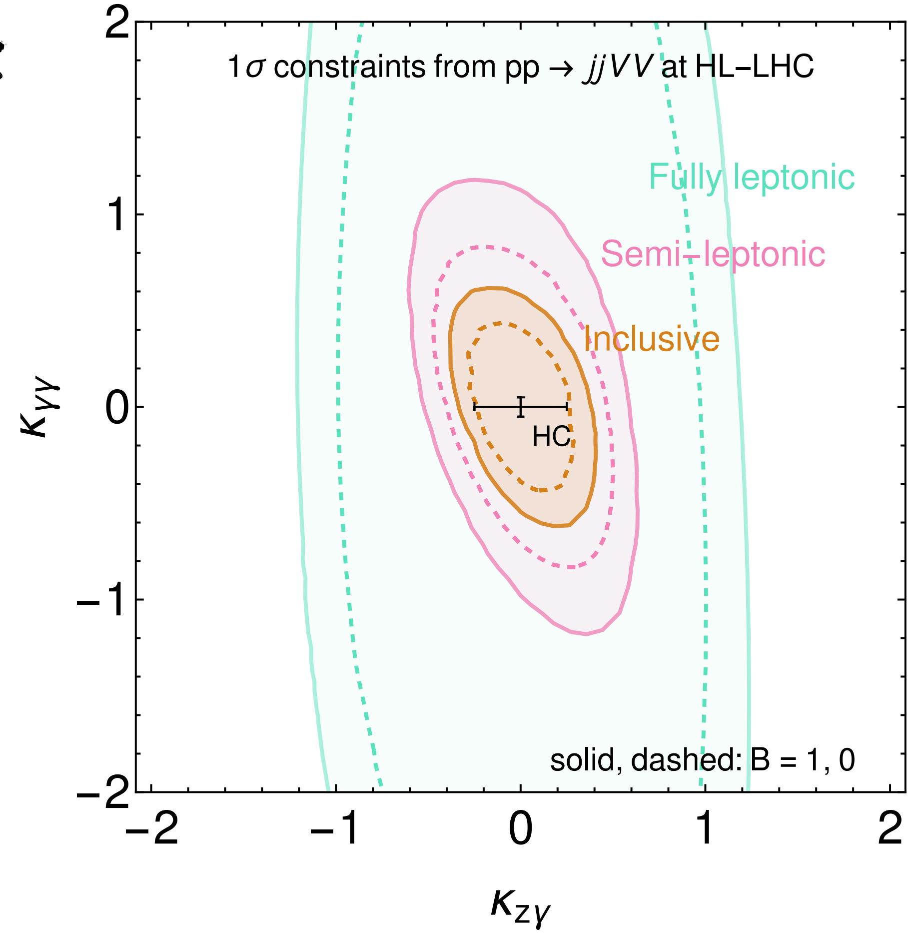
$\kappa_\gamma \quad |H|^2 B_{\mu\nu} B^{\mu\nu}$
$\kappa_{Z\gamma} \; |H|^2 W^a_{\mu\nu} W^{a\,\mu\nu}$





So far interpreted with dim-8 operators (aQGC)

Simple analysis:
- VBF cuts
- Binning $\sum |p_T^V|$



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

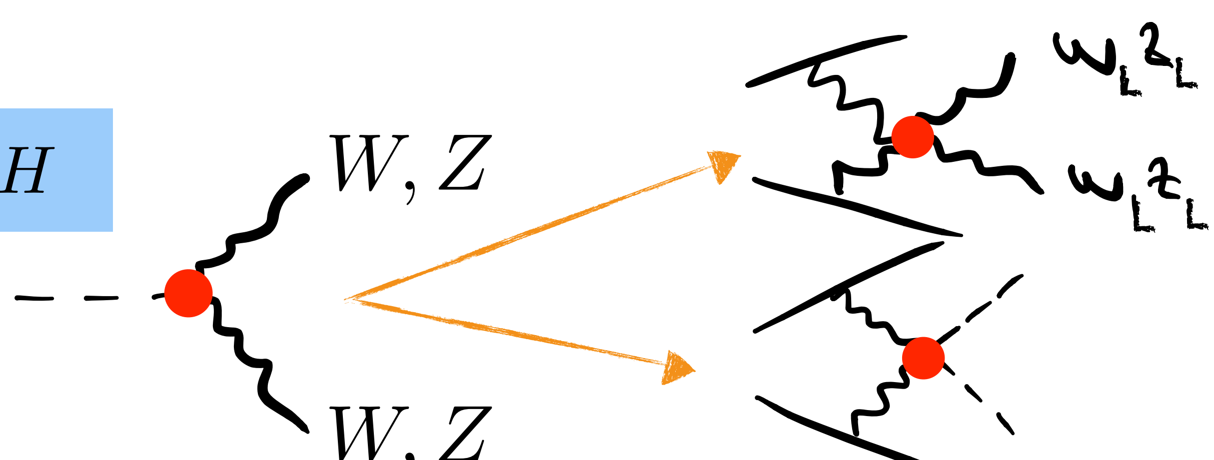
!No Interference of 2>2 Amplitude!

Azatov,Contino,Machado,FR'16

Azimuthal distributions might help

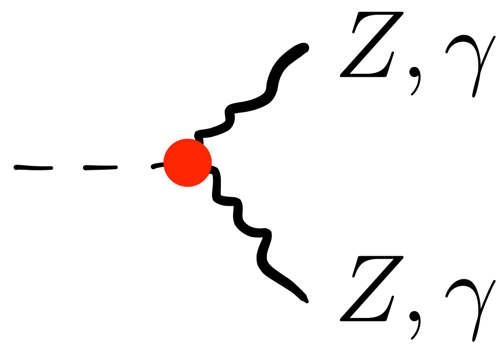
Panico,FR,Wulzer'17

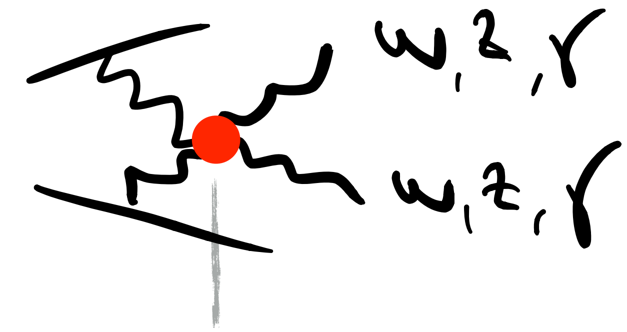
$\kappa_V \quad |H|^2 \partial_\mu H^\dagger \partial^\mu H$



HwH Program: h to gauge bosons

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



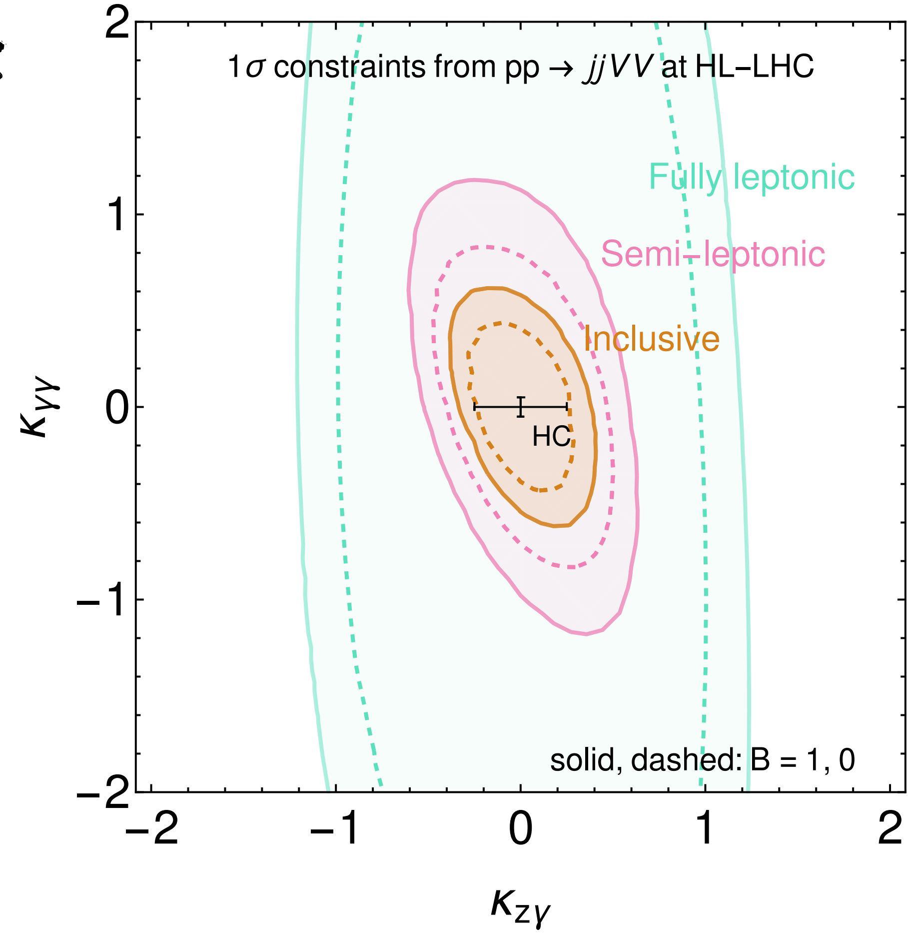


So far interpreted with dim-8 operators (aQGC)

Simple analysis:

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

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



!No Interference of 2>2 Amplitude!

Azatov,Contino,Machado,FR'16

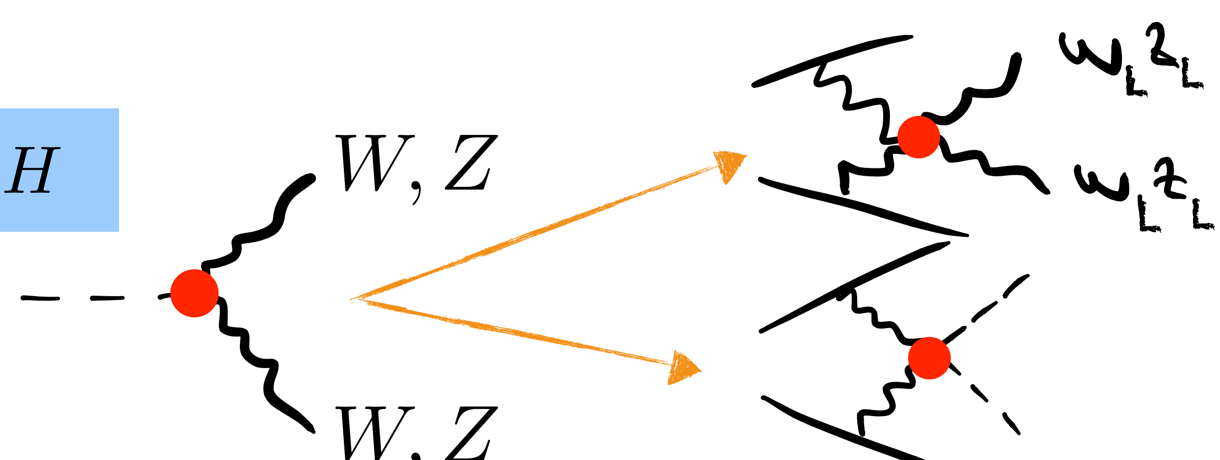
Azimuthal distributions might help

Panico,FR,Wulzer'17

In SM V_L suppressed by ≈1/1000 w.r.t V_T

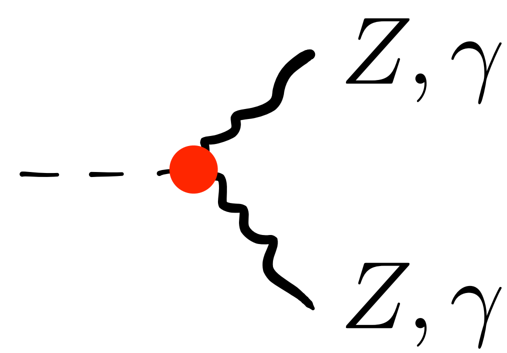
Contino,Grojean,Moretti,Piccinini,Rattazzi'10

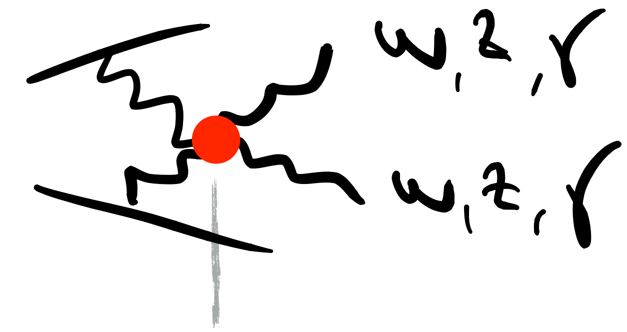
$\kappa_V \quad |H|^2 \partial_\mu H^\dagger \partial^\mu H$



HwH Program: h to gauge bosons

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

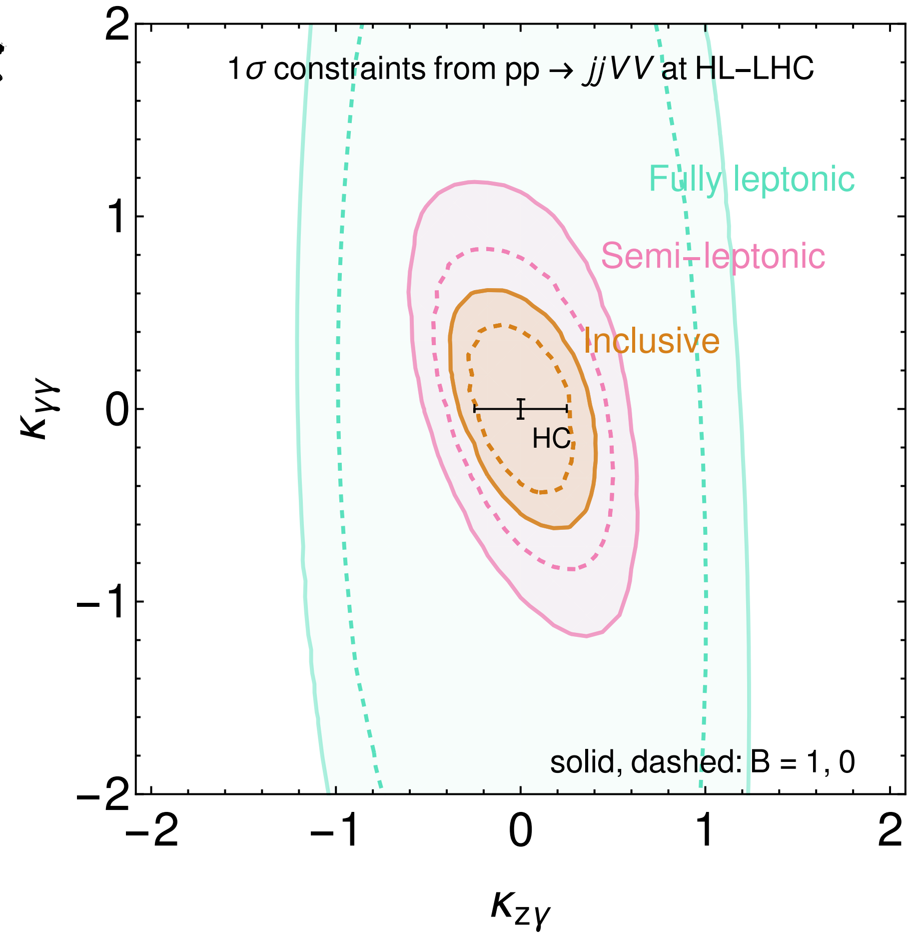




So far interpreted with dim-8 operators (aQGC)

Simple analysis:
- VBF cuts
- Binning $\sum |p_T^V|$

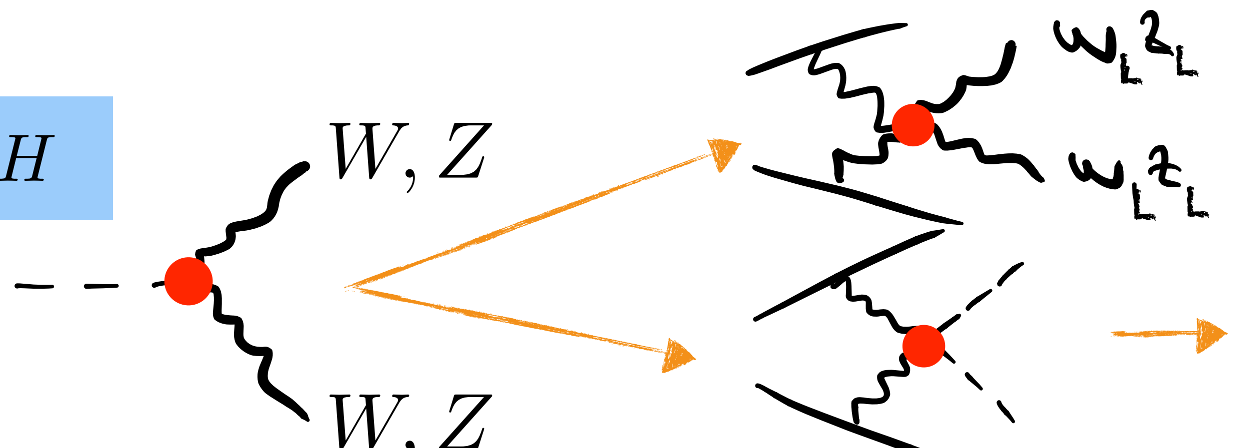
$\kappa_{Z\gamma}$ competitive, κ_γ not



!No Interference of 2>2 Amplitude!
Azatov,Contino,Machado,FR'16

Azimuthal distributions might help
Panico,FR,Wulzer'17

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



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

Message

- Higgs Coupling (HC) modifications: crucial for BSM
- High-Energy precision tests: appealing experimental program

Message

- Higgs Coupling (HC) modifications: crucial for BSM
- High-Energy precision tests: appealing experimental program
- Multiboson (HwH): Competitive/Complementary to HC measurements

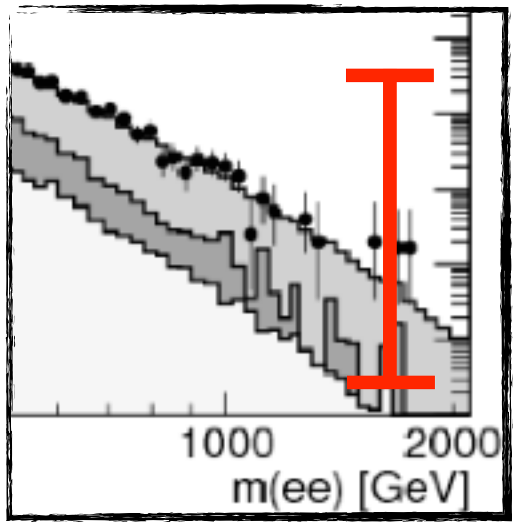
Message

- Higgs Coupling (HC) modifications: crucial for BSM

- High-Energy precision tests: appealing experimental program

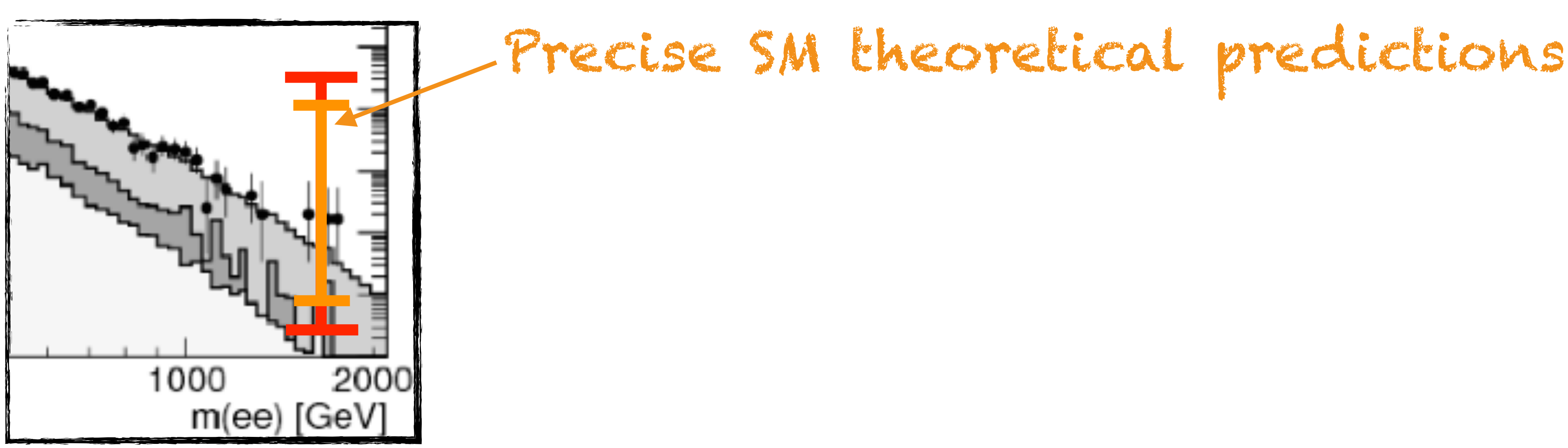
- Multiboson (HwH): Competitive/Complementary to HC measurements

- Many opportunities for improvement (contrary to HC):



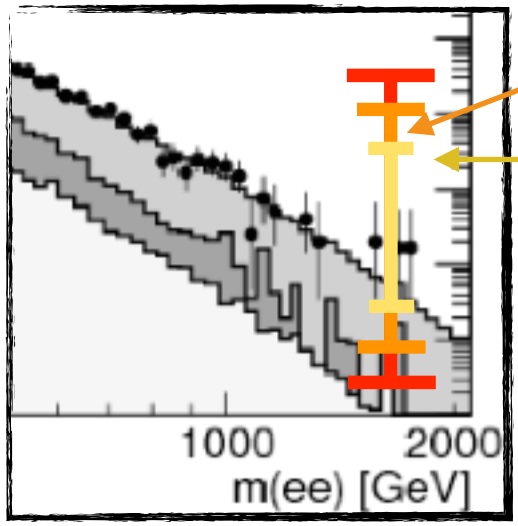
Message

- Higgs Coupling (HC) modifications: crucial for BSM
- High-Energy precision tests: appealing experimental program
- Multiboson (HwH): Competitive/Complementary to HC measurements
- Many opportunities for improvement (contrary to HC):



Message

- Higgs Coupling (HC) modifications: crucial for BSM
- High-Energy precision tests: appealing experimental program
- Multiboson (HwH): Competitive/Complementary to HC measurements
- Many opportunities for improvement (contrary to HC):

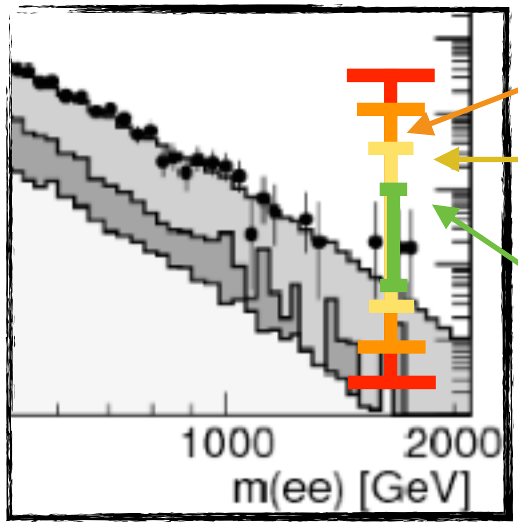


Precise SM theoretical predictions

Experimental control of systematics/backgrounds

Message

- Higgs Coupling (HC) modifications: crucial for BSM
- High-Energy precision tests: appealing experimental program
- Multiboson (HwH): Competitive/Complementary to HC measurements
- Many opportunities for improvement (contrary to HC):



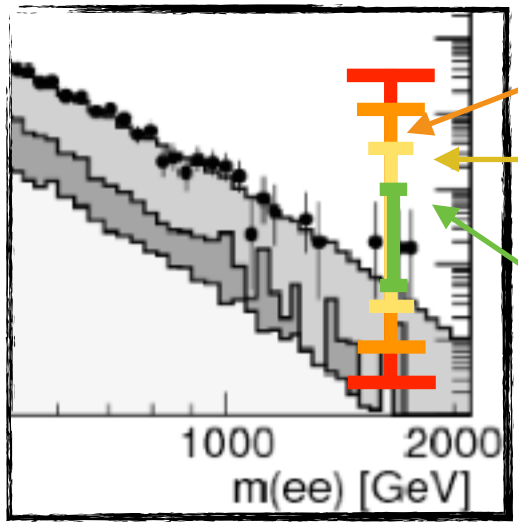
Precise SM theoretical predictions

Experimental control of systematics/backgrounds

Understanding of relevant kinematics,
handle on transverse/longitudinal

Message

- Higgs Coupling (HC) modifications: crucial for BSM
- High-Energy precision tests: appealing experimental program
- Multiboson (HwH): Competitive/Complementary to HC measurements
- Many opportunities for improvement (contrary to HC):

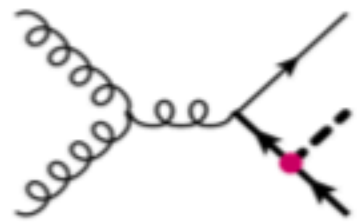
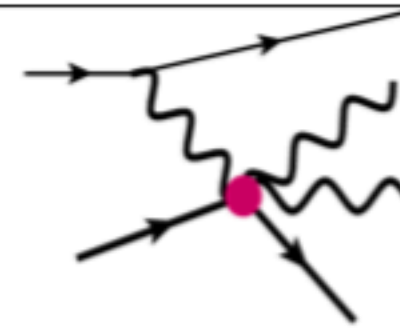
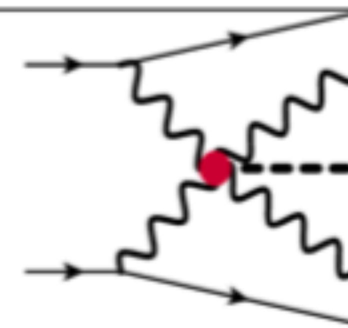
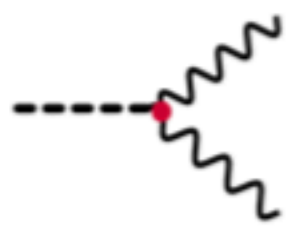
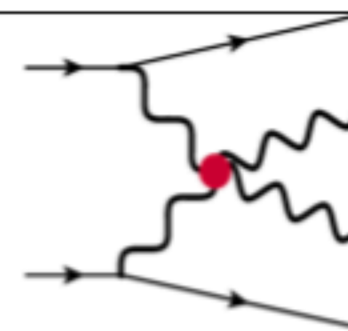
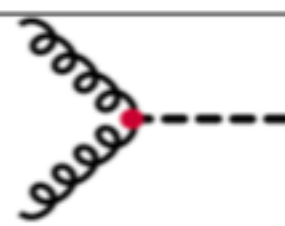
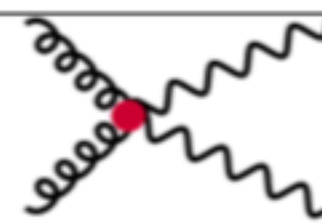


Precise SM theoretical predictions

Experimental control of systematics/backgrounds

Understanding of relevant kinematics, handle on transverse/longitudinal

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

		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	$\mathcal{O}_{gg}$			$\sim \frac{E^2}{\Lambda^2}$