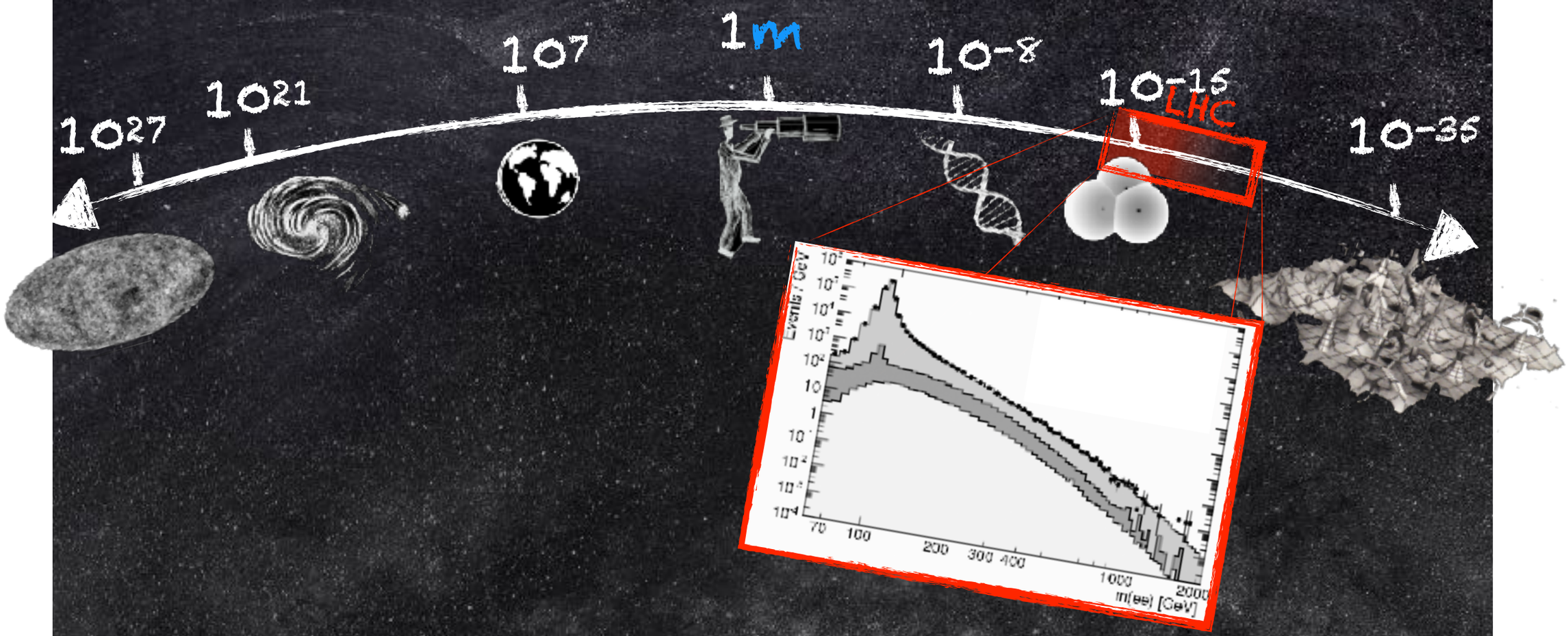
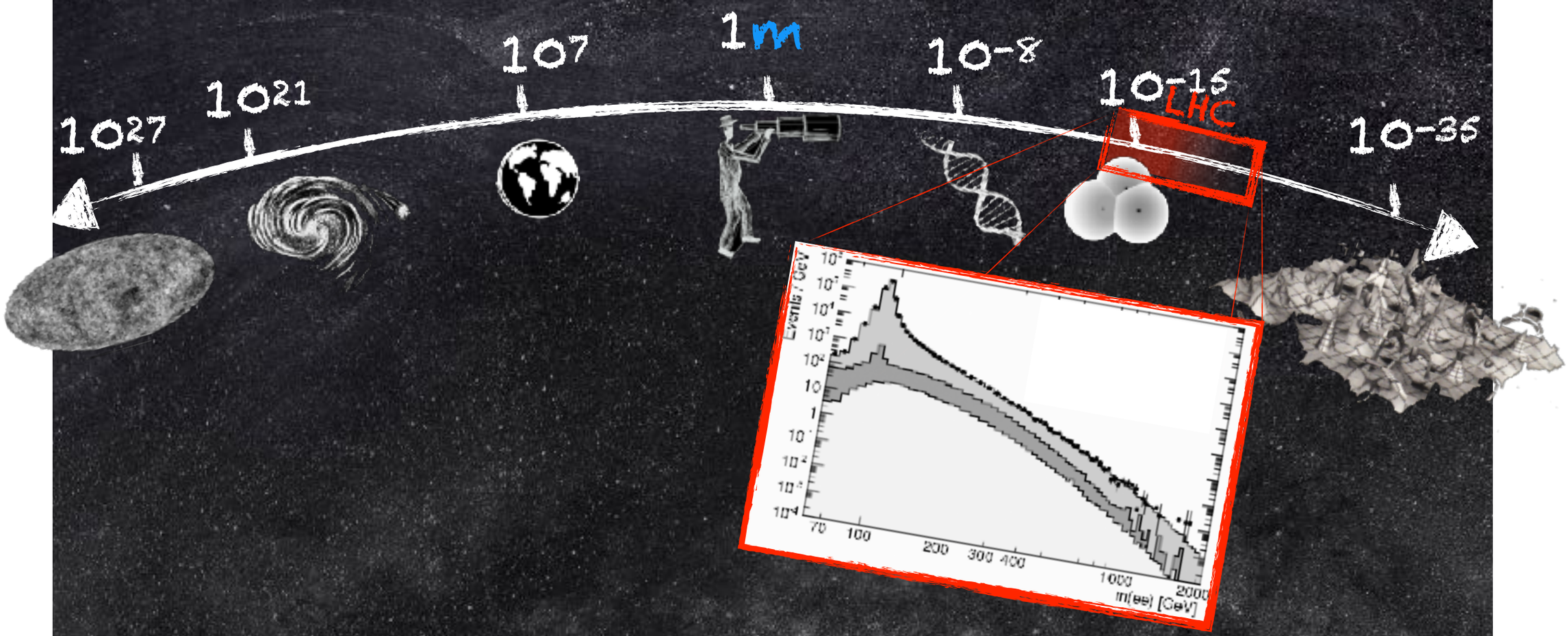
Higgs Couplings



Francesco Riva
(Université de Genève)

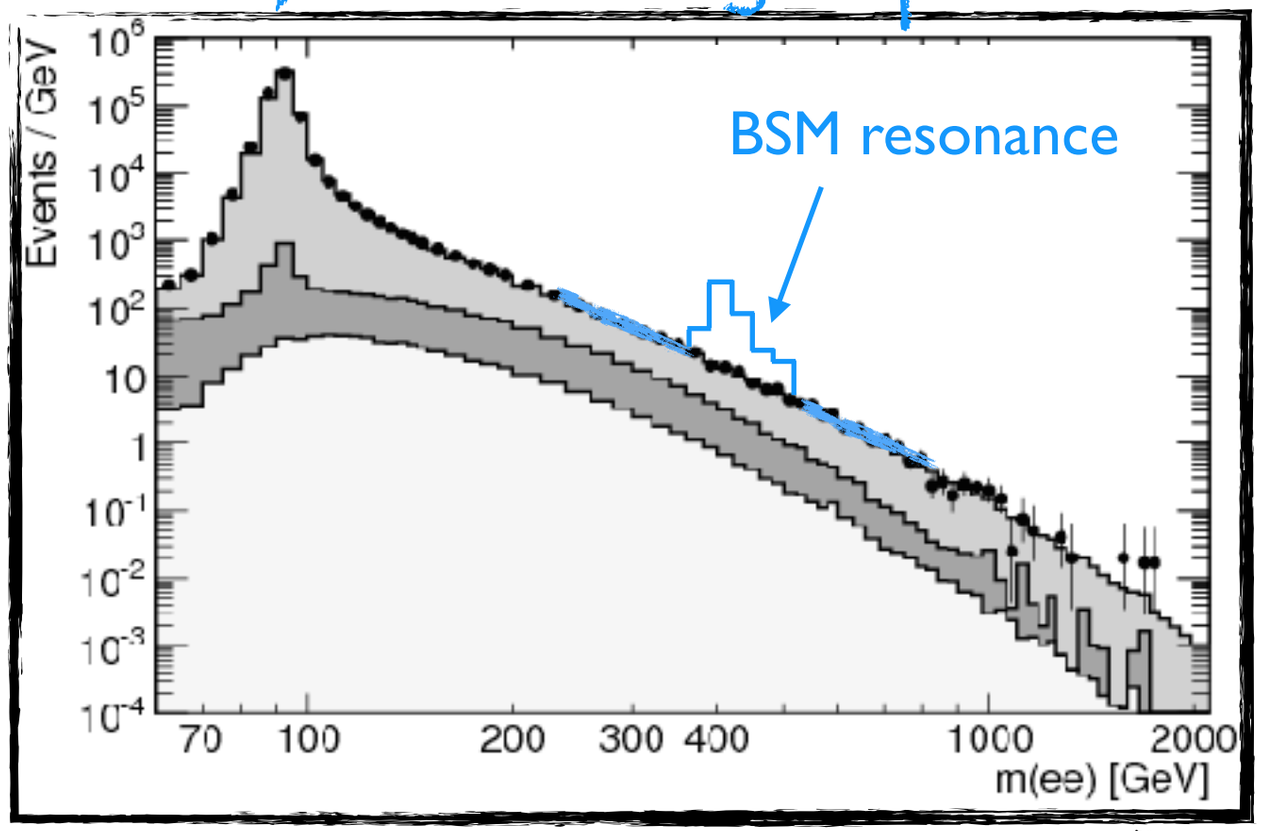
Higgs Couplings ... without the Higgs



Francesco Riva
(Université de Genève)

LHC Exploration

Focus so far: Search for new light particles



Energy frontier (13 TeV)

- Experimentally: First accessible signal/Easy to study

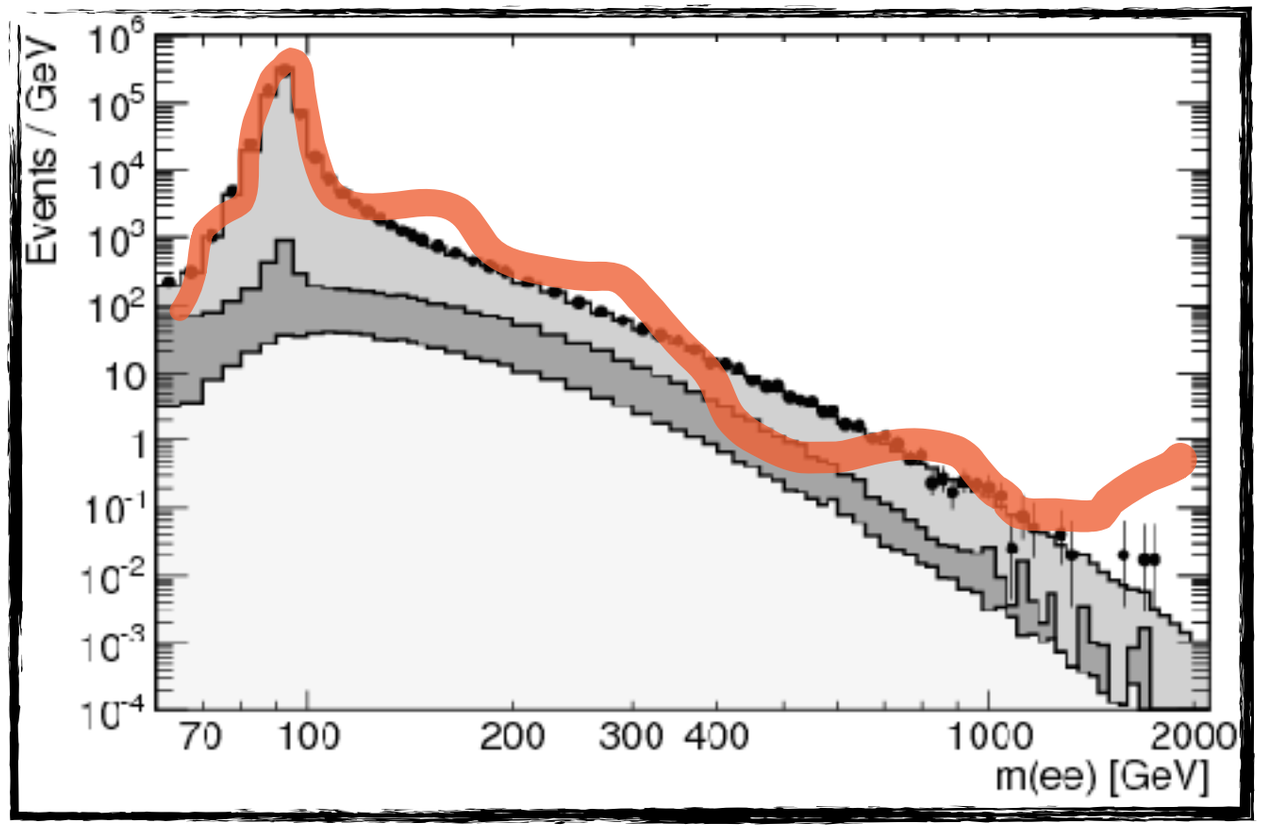
LHC Exploration

Focus now: Standard Model Precision Tests

(2035: 3000 fb^{-1})

intensity frontier

(2019: 65 fb^{-1})



Infinite Information

$$function(E^2) = f(0) + f'(0)E^2 + f''(0)E^4 + \cdots$$

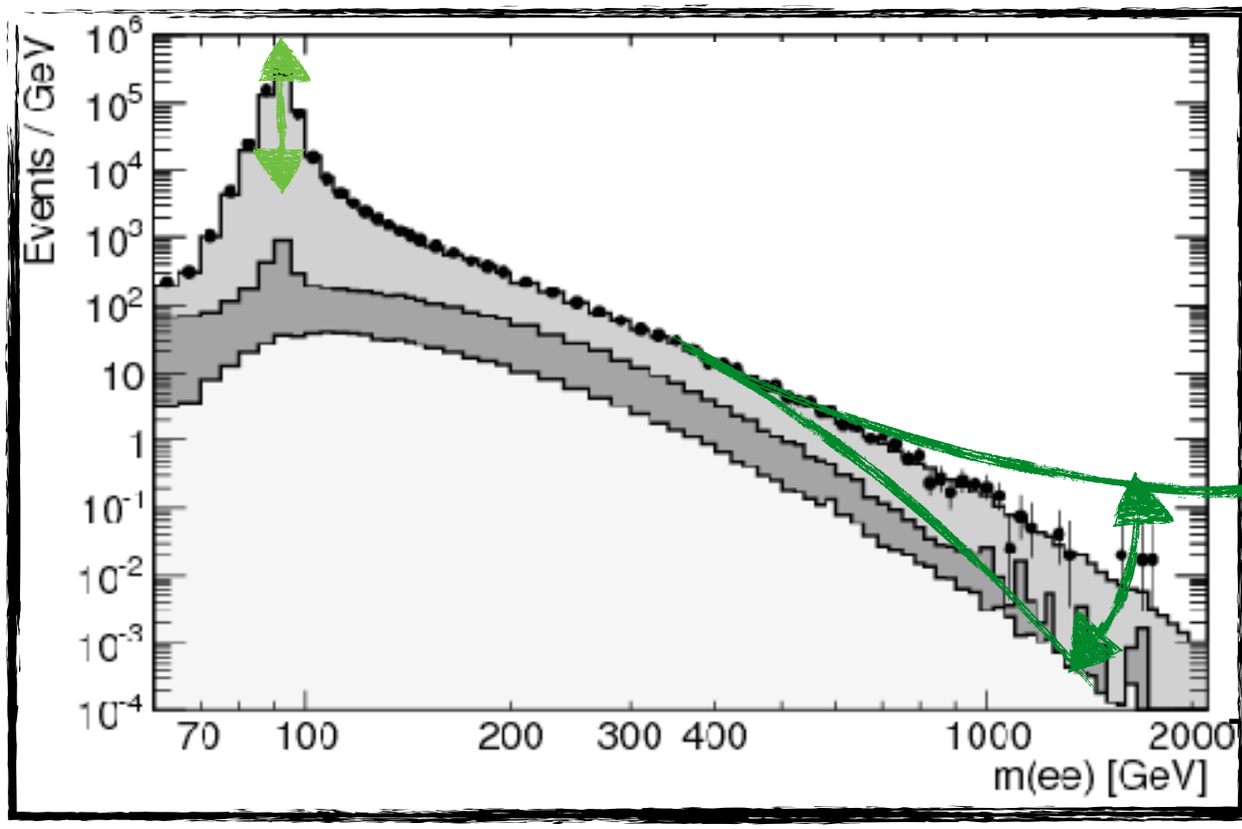
LHC Exploration

Focus now: Standard Model Precision Tests

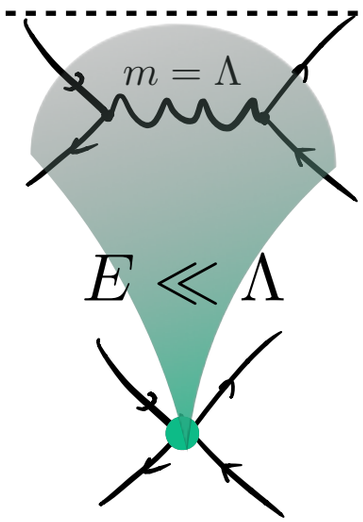
(2035: 3000 fb^{-1})

intensity frontier

(2019: 65 fb^{-1})



?



finite
~~Infinite~~ Information

$$function(E^2) = f(0) + f'(0)E^2 + f''(0)E^4 + \cdots$$

systematic Taylor expansion for all observables

Effective Field Theory (EFT)

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda^2}\sum_i c_i \mathcal{O}_i + \cdots$$

$$\mathcal{O}_i = \frac{(\bar\psi\gamma_\mu\psi)^2}{\Lambda^2}$$

most relevant effects from all heavy BSM

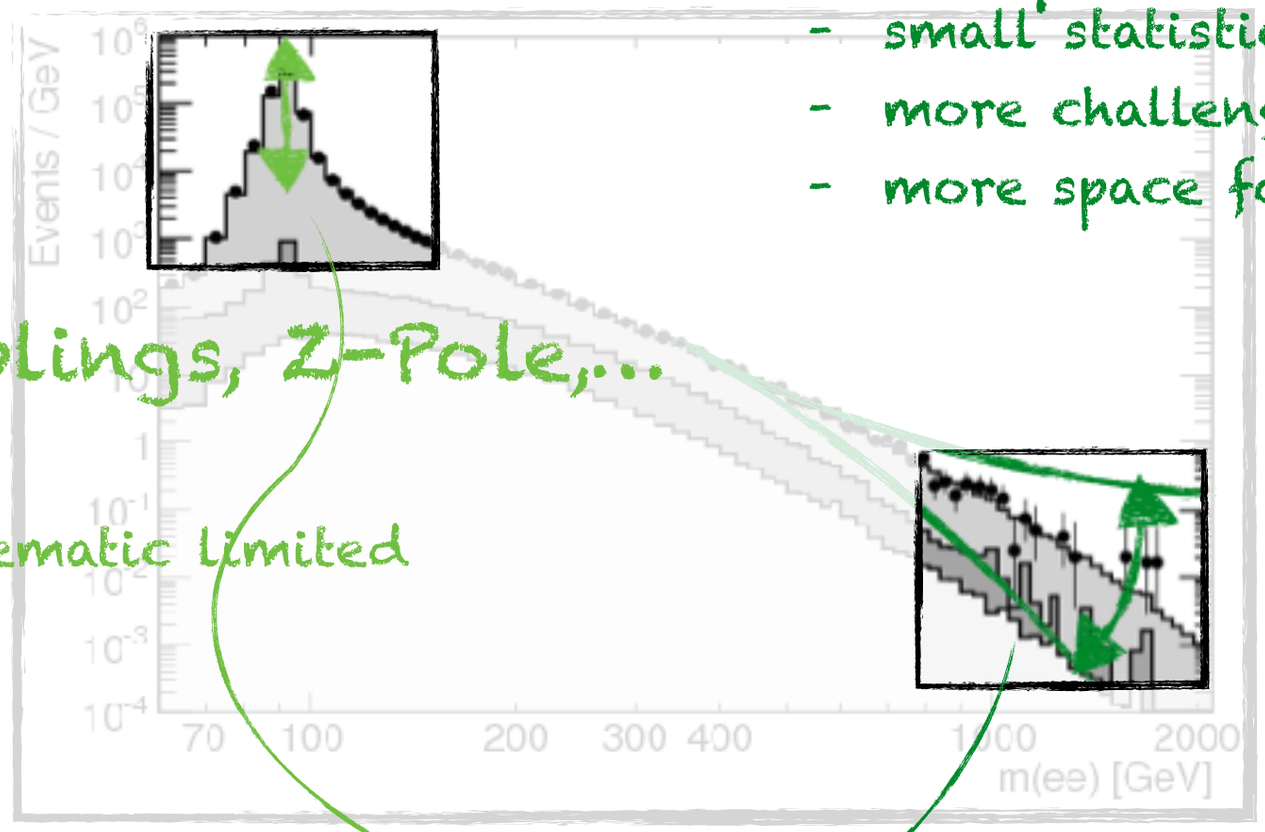
Precision Tests

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



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

Precision Tests

e.g. Hig

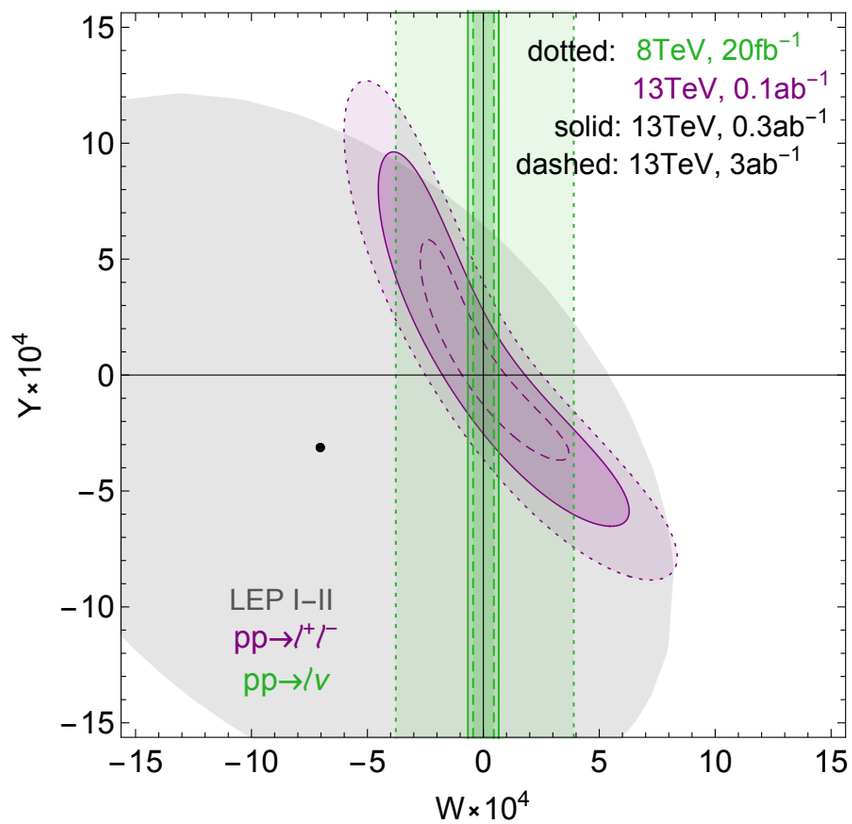
- big stati
- sooner c

,LL,...)

ement

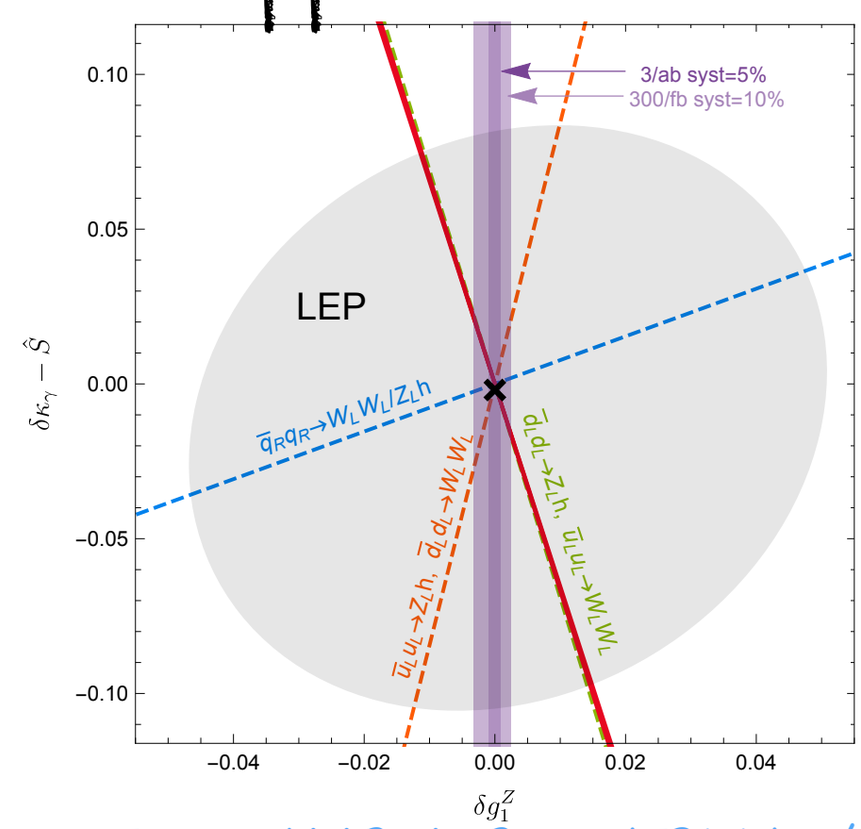
ent

Drell-Yann



Farina,Panico,Pappadopulo,Rudermann,Torre,Wulzer'16

pp -> WZ



Franceschini,Panico,Pomarol,FR,Wulzer'17
(pp>ZH: Banarjee,Englert,Gupta,Spannowsky'18)
and more...

In some processes, LHC more precise than LEP

Why?

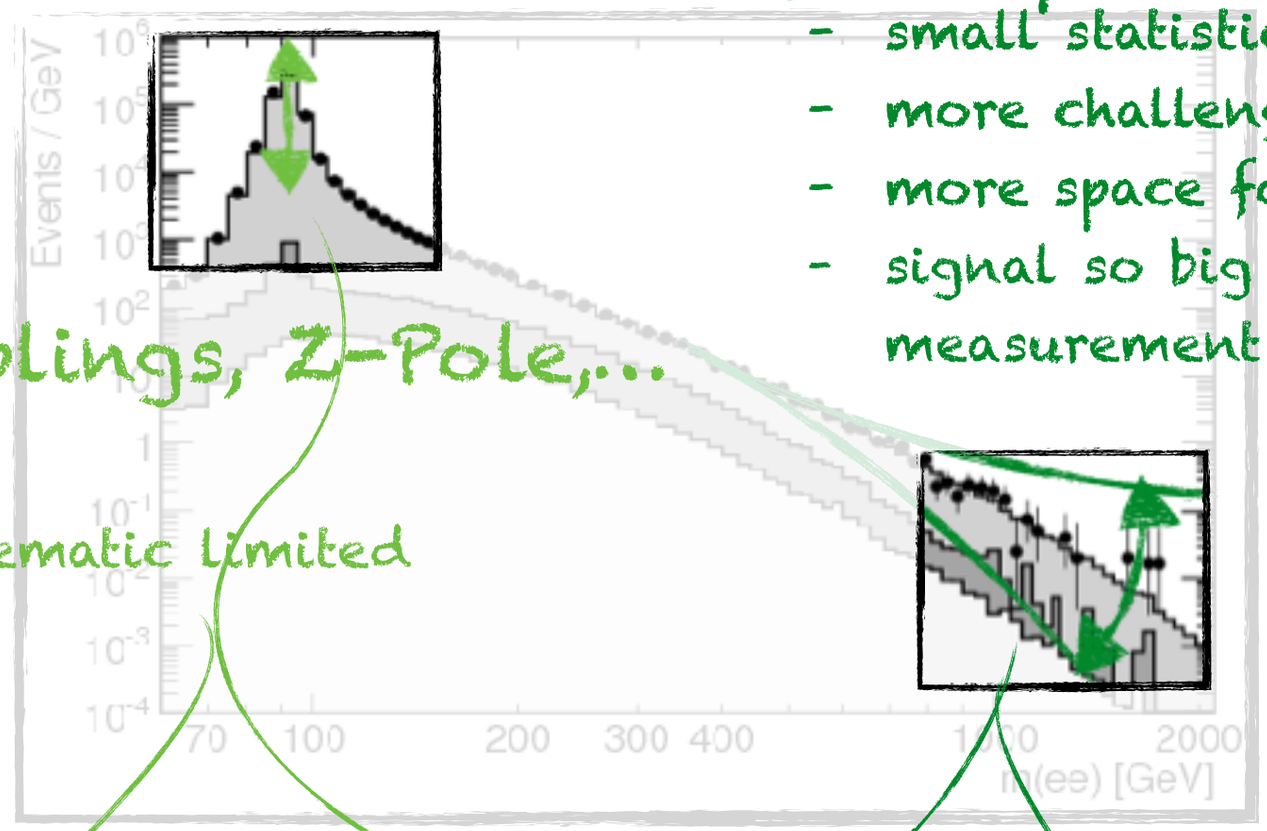
Precision Tests

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

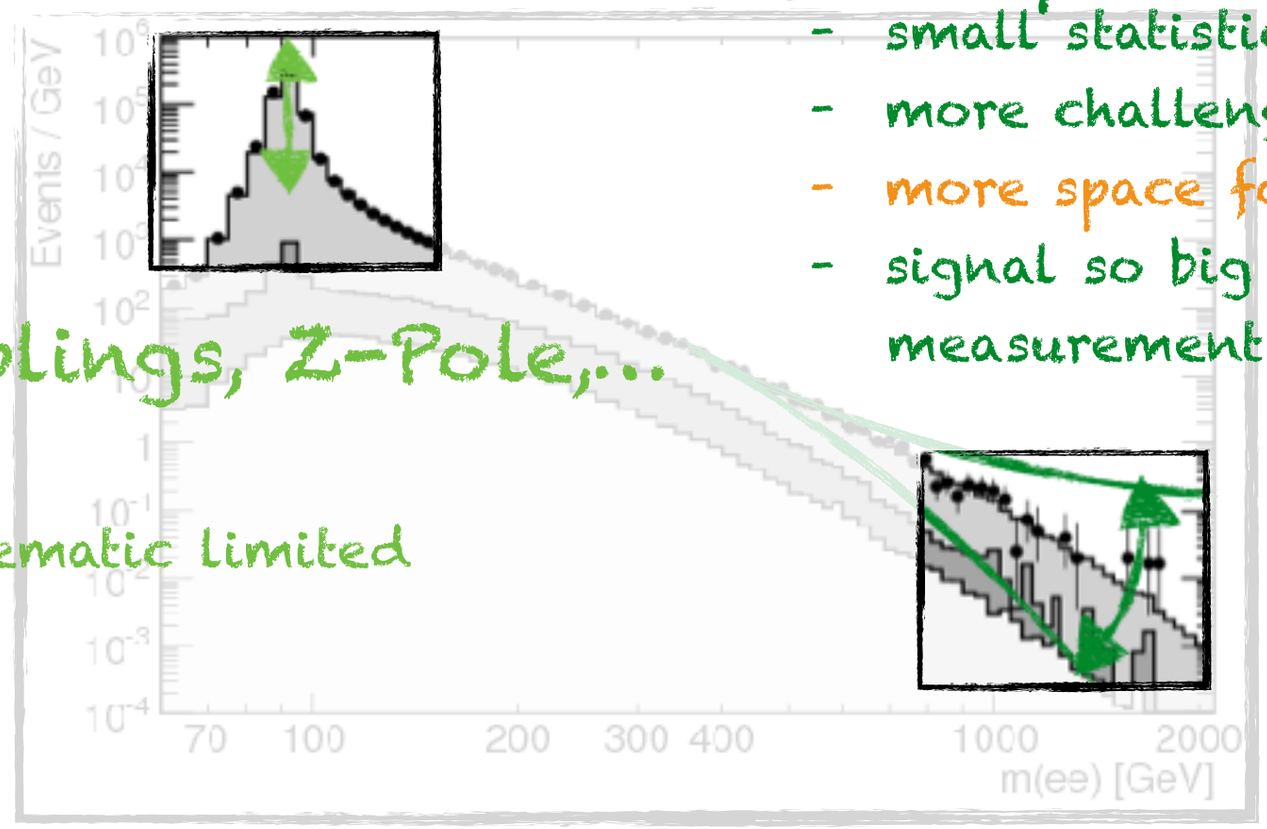
Precision Tests

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

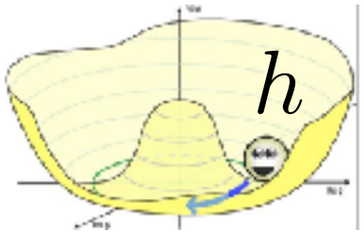


Experimentally very appealing

What to expect from a theory viewpoint?

Higgs Compositeness: Higgs must be a (pseudo)goldstone boson

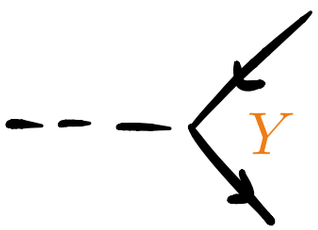
(like pions)



SM

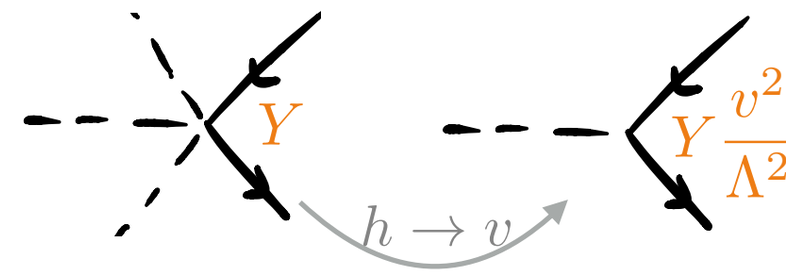
BSM

$$h \longrightarrow \Lambda \sin \frac{h}{\Lambda} = h - \frac{h^3}{3!\Lambda^2} + \cdots$$



$\bar{\psi}\psi h$

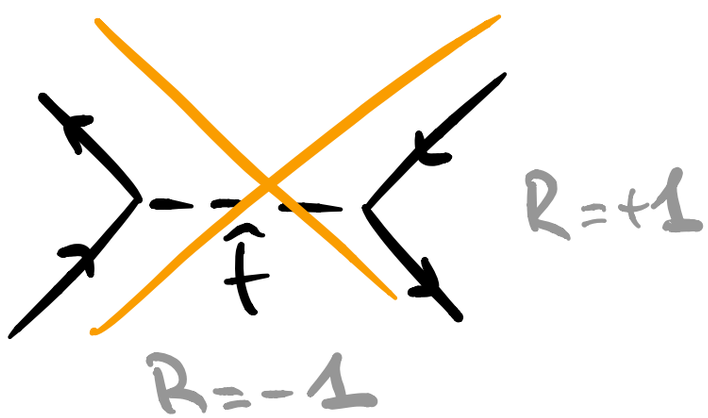
$\bar{\psi}\psi h + \bar{\psi}\psi h^3/\Lambda^2$

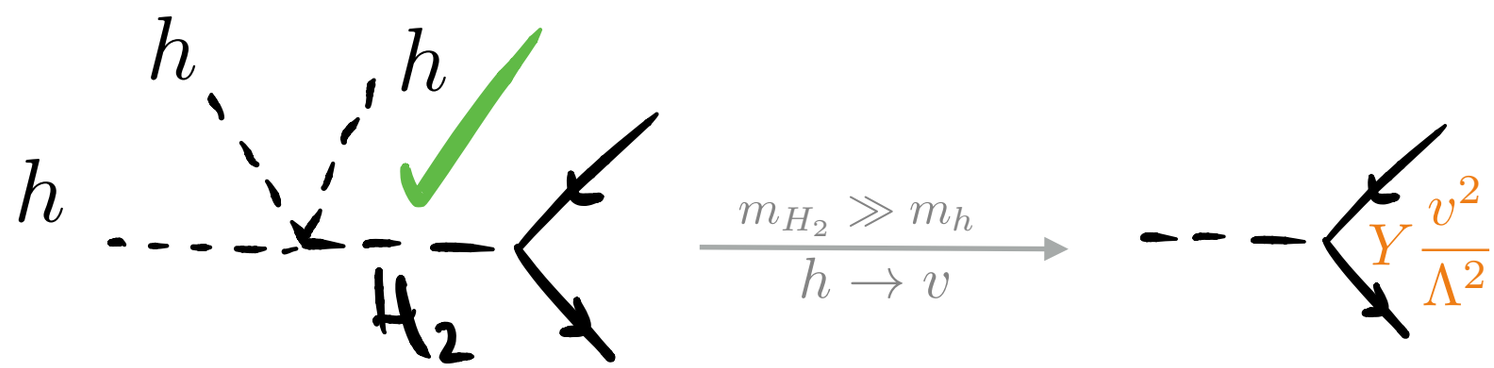


Giudice,Grojean,Pomarol,Rattazzi'08;

second Higgs

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

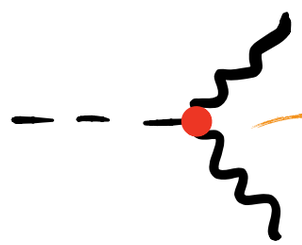




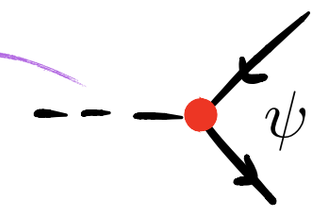
Higgs Couplings are modified

Higgs Couplings

Modifications of Higgs couplings in EFT language:



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



$\psi = t, b, \tau$

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

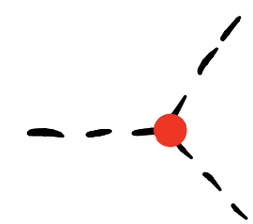
$\mathcal{O}_{y_\psi} = Y_\psi |H|^2 \psi_L H \psi_R$

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

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

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

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



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

modifies single-Higgs processes

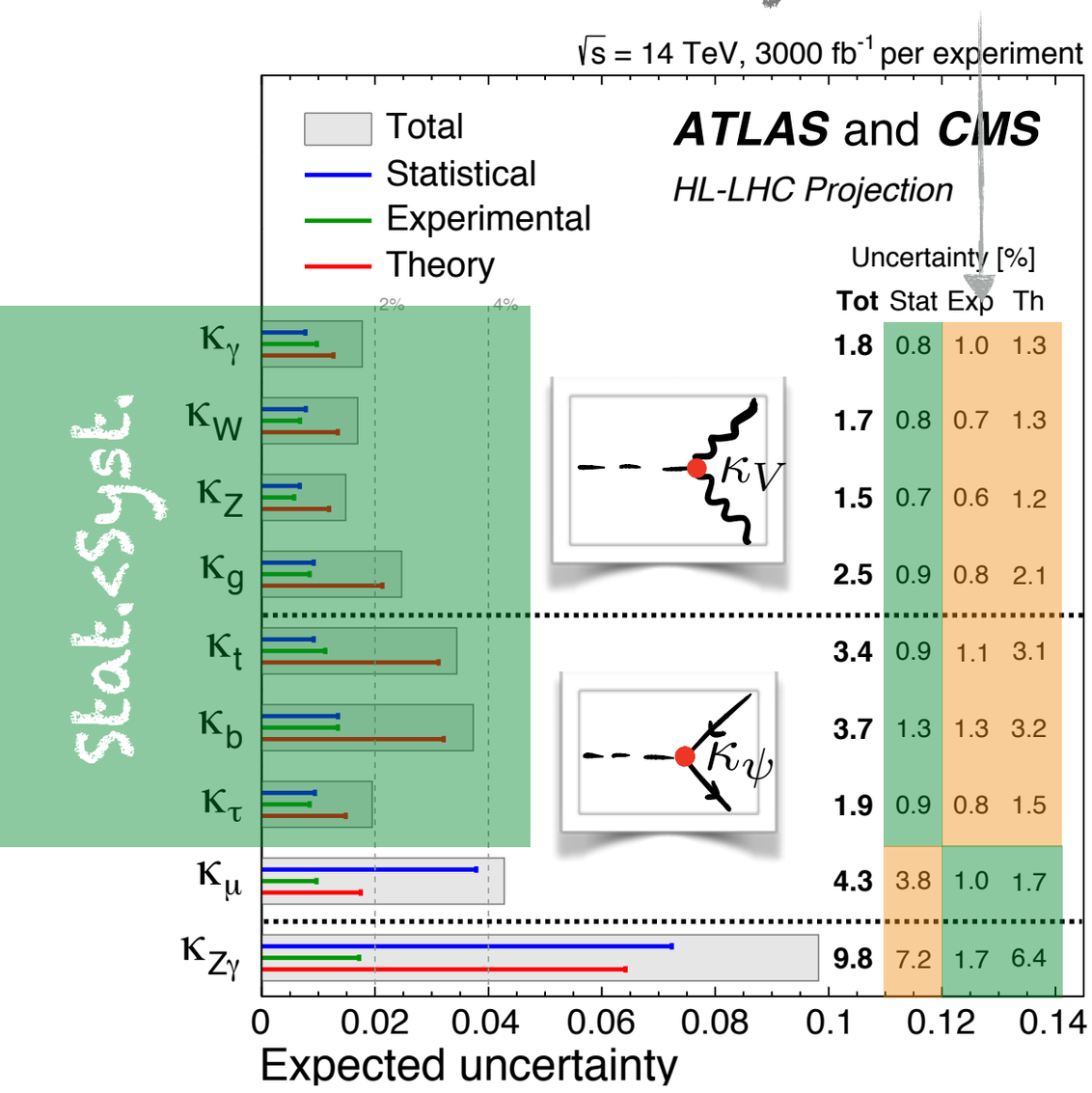
$$\frac{1}{g_s^2} G_{\mu\nu} G^{\mu\nu} + \frac{|H|^2}{\Lambda^2} G_{\mu\nu} G^{\mu\nu} = \left(\frac{1}{g_s^2} + \frac{v^2}{\Lambda^2} \right) G_{\mu\nu} G^{\mu\nu} + h \frac{2v}{\Lambda^2} G_{\mu\nu} G^{\mu\nu} + \cdots$$

HL-LHC Reach (3000 fb^{-1})

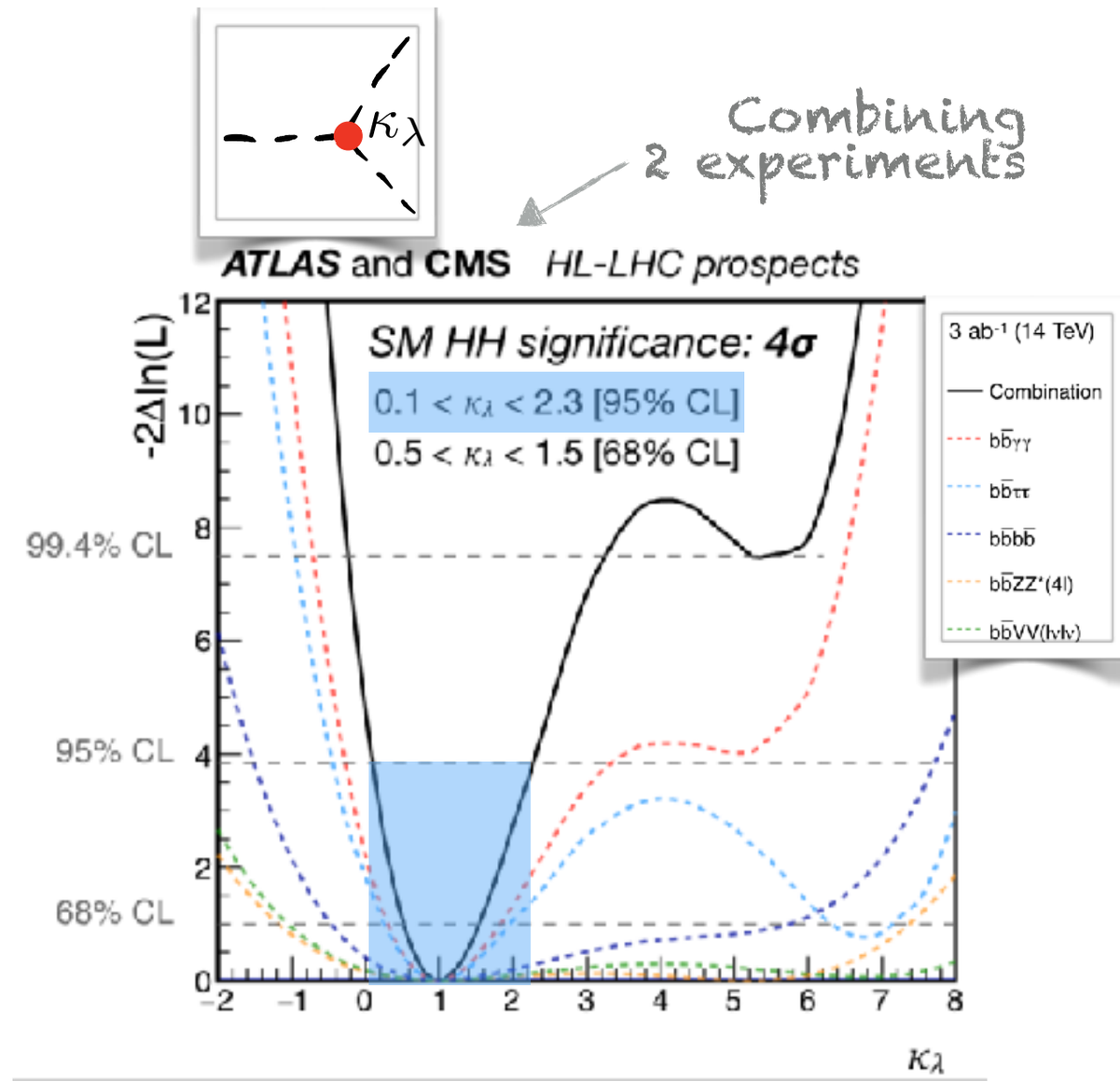
See this morning talks

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

Optimistic Systematics (S2)



Combining 2 experiments



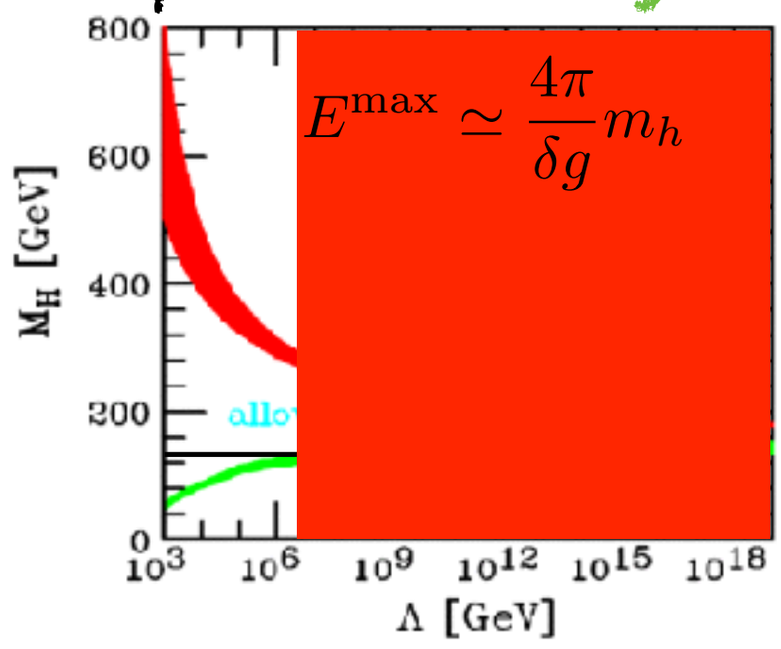
Higgs Couplings at High-Energy

Higgs couplings: Theoretically Interesting

Experimentally not High-E measurements

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

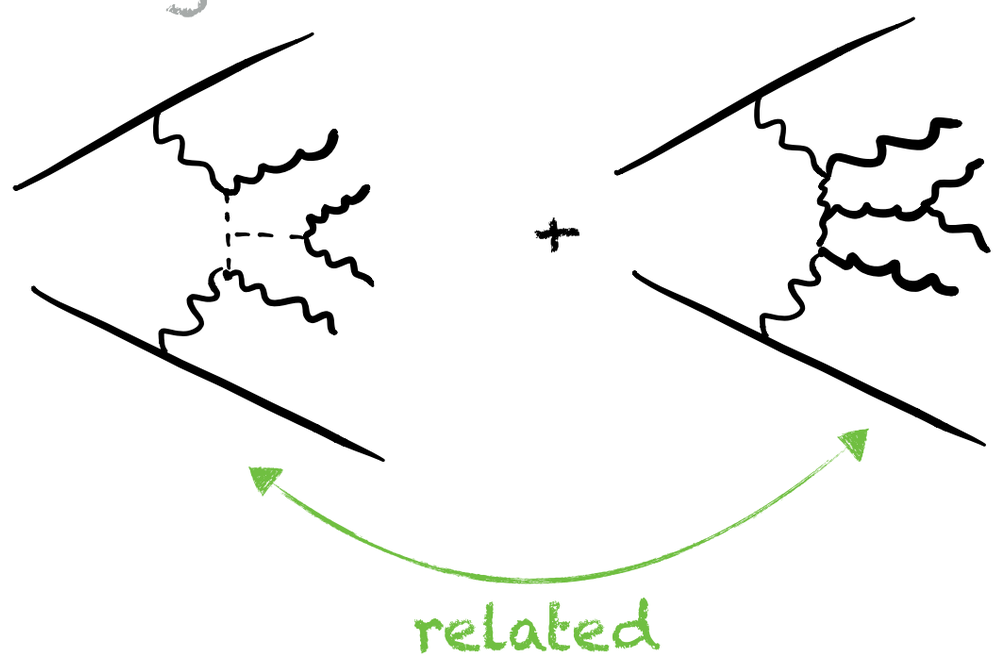
Higgs Couplings... without a Higgs

Henning,Lombardo,Riembau,FR'18

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

One way of seeing this:

SM =



= finite

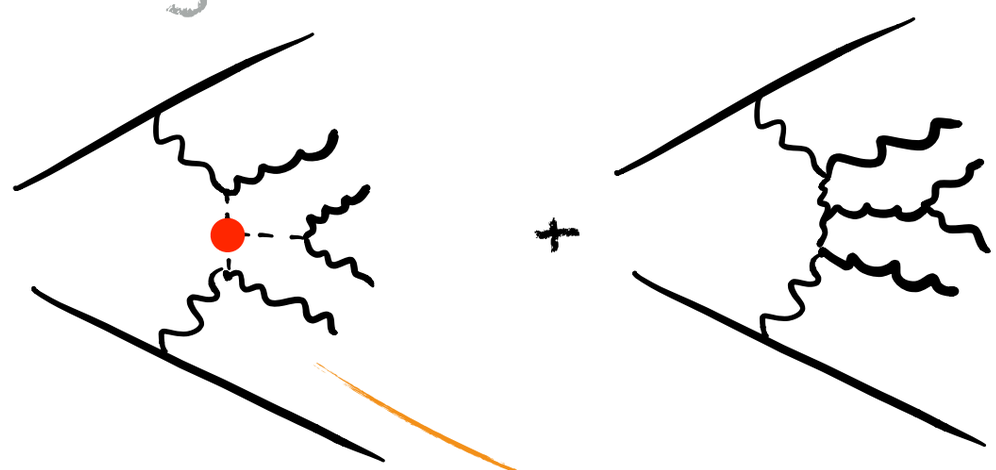
Higgs Couplings... without a Higgs

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 =



$= E^2$

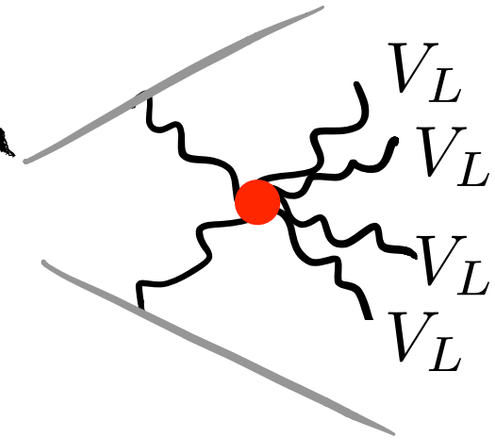
modification of a coupling (h^3) compromises gauge cancellations in the SM

Higgs Self Coupling

Another way of understanding E-growth:

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

Contact Interaction Among W_L, Z_L



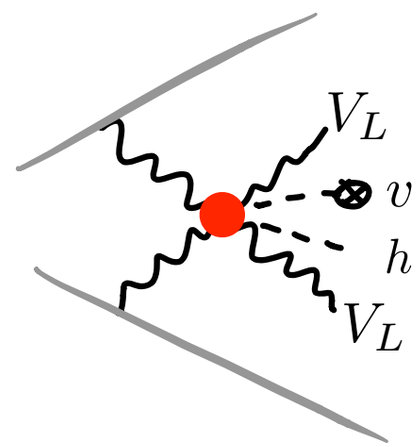
$$\sim \frac{E^2}{\Lambda^2} \text{ w.r.t SM}$$

$pp \to jj + 4V_L$

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.

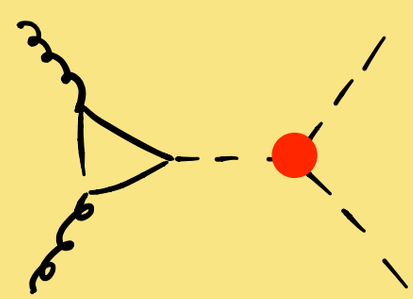


$$\sim \frac{v\,E}{\Lambda^2}$$

$pp \to jjh + V_L V_L'$

with 3 Higgs v.e.v.s

(= traditional Higgs Coupling measurement)



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

signal

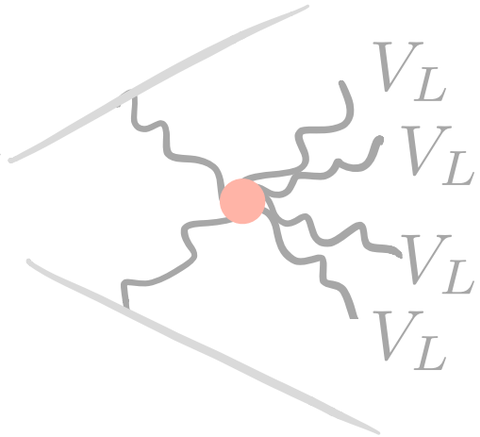
statistics

Higgs Self Coupling

Another way of understanding E-growth:

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

Contact Interaction Among W_L, Z_L

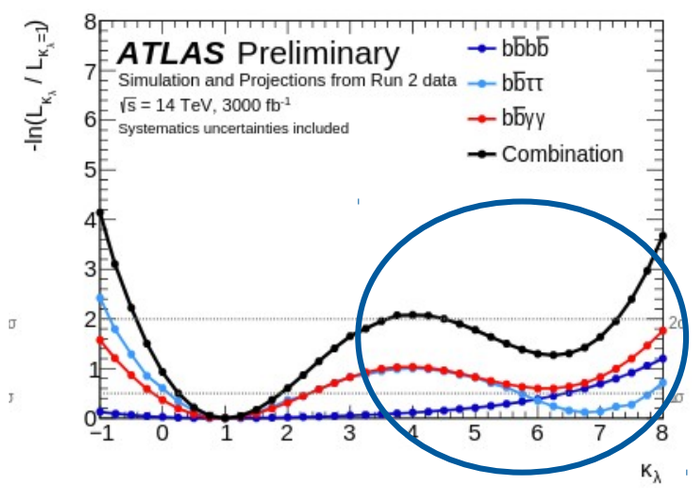


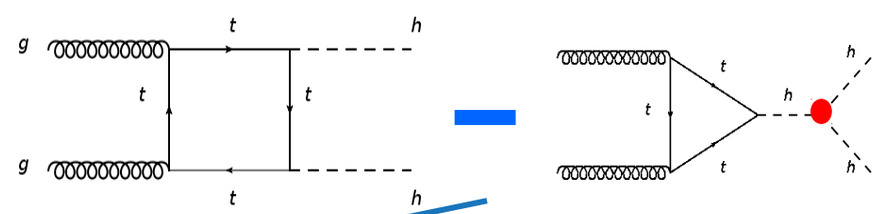
$$\sim \frac{E^2}{\Lambda^2} \text{ w.r.t SM}$$

Golstones = W_L, Z_L

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

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





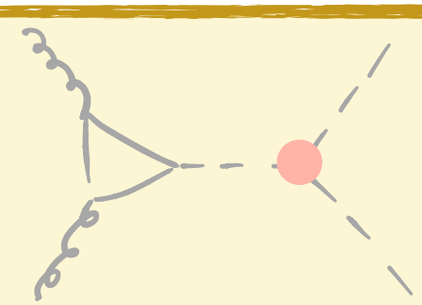
HL-LHC @ 3 ab^{-1}, 95% CL

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

7!

with 3 Higgs v.e.v.s

(= traditional Higgs Coupling measurement)



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

signal

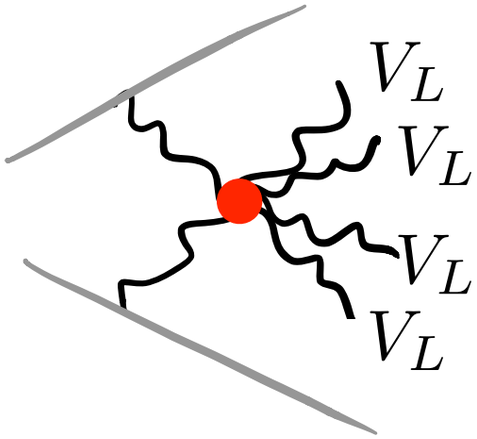
statistics

Higgs Self Coupling

Another way of understanding E-growth:

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

Contact Interaction Among W_L, Z_L



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

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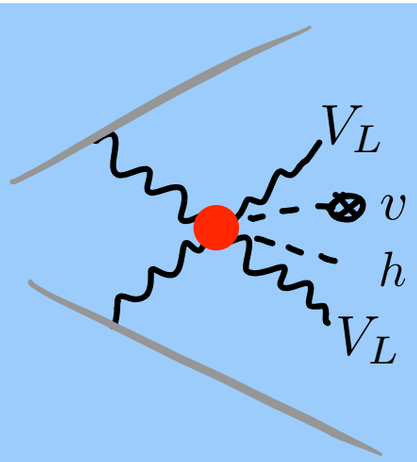
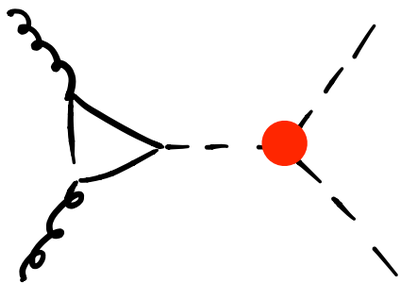


$$\sim \frac{v\,E}{\Lambda^2}$$

$$pp \to jjh + V_L V_L'$$

with 3 Higgs v.e.v.s

(= traditional Higgs Coupling measurement)



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

signal

statistics

Higgs Self Coupling

Henning,Lombardo,Riembau,FR'18

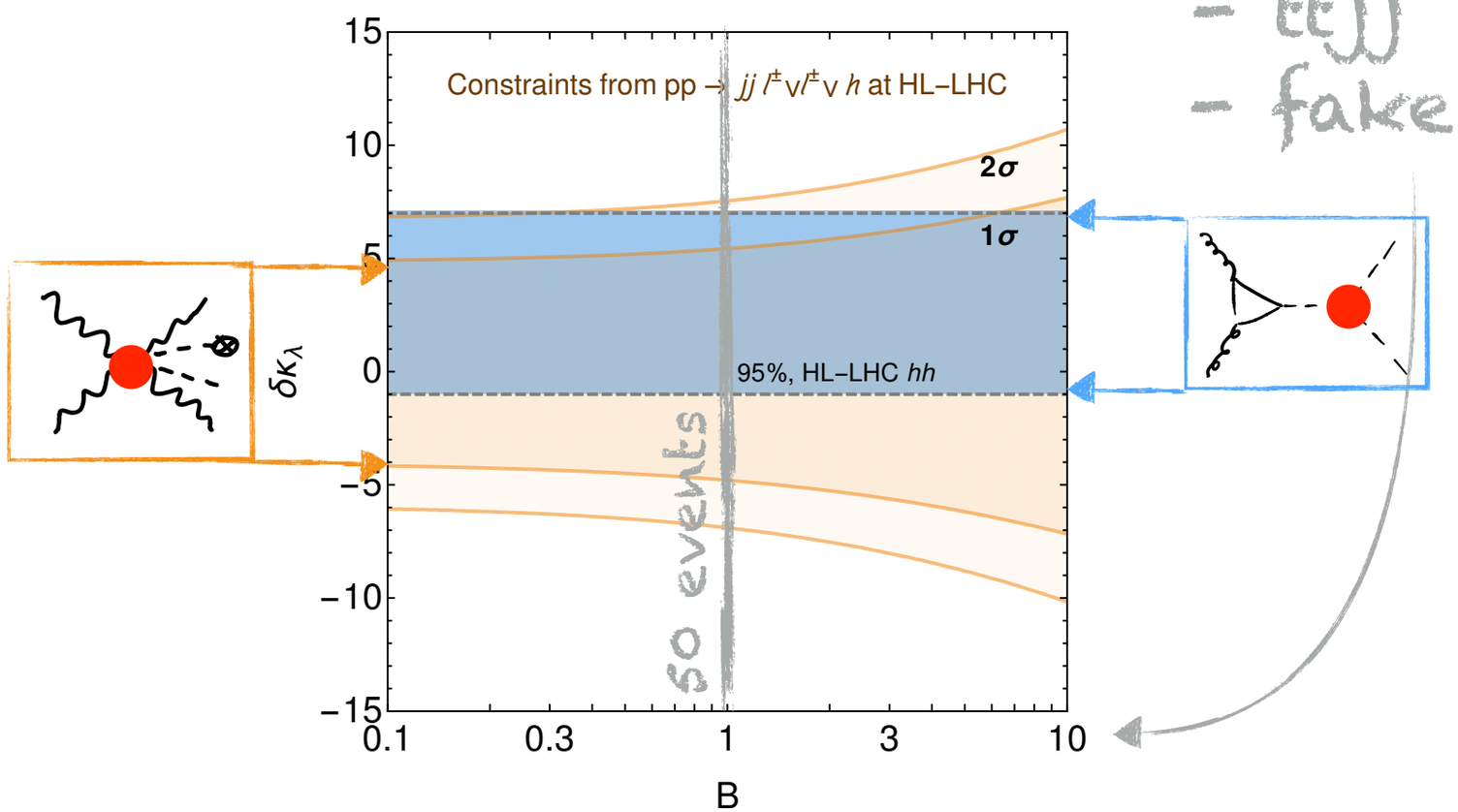
$W \to l + \nu$ → Same-sign leptons

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

$h \to \bar{b}b$

VBF topology

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

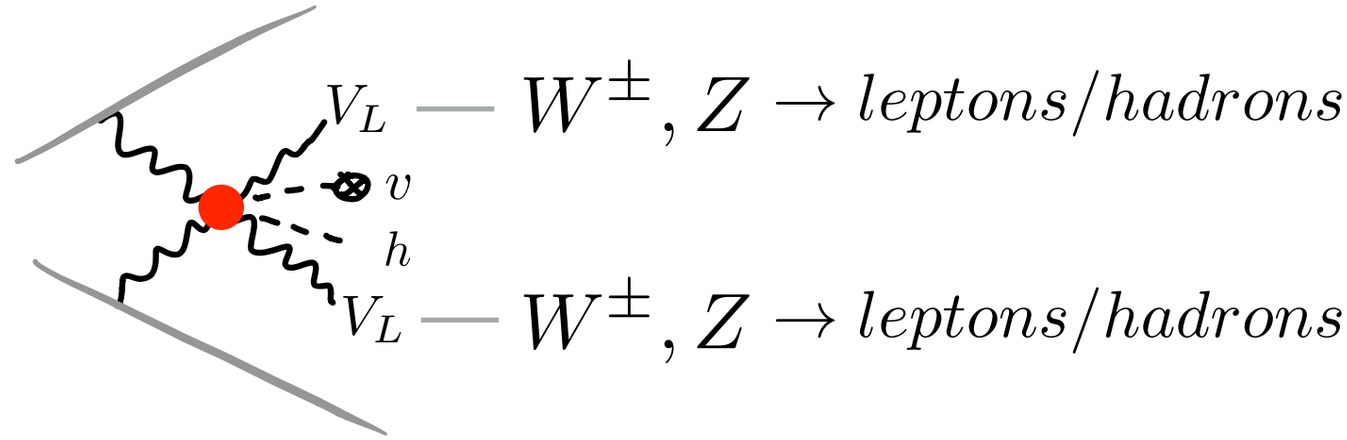


- HwH: single channel, simple analysis, competitive with HC!

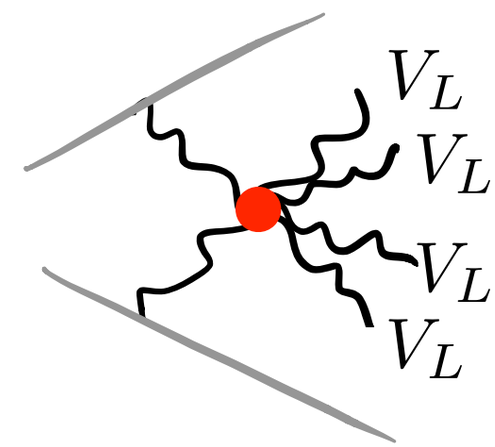
Higgs Self Coupling

... endless possibilities of improvement ...

- More Final states



- Look also at E^2-growing processes



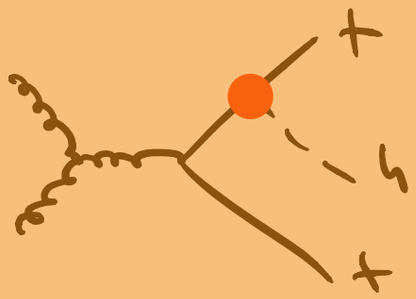
- Keep differential information to exploit E-growth

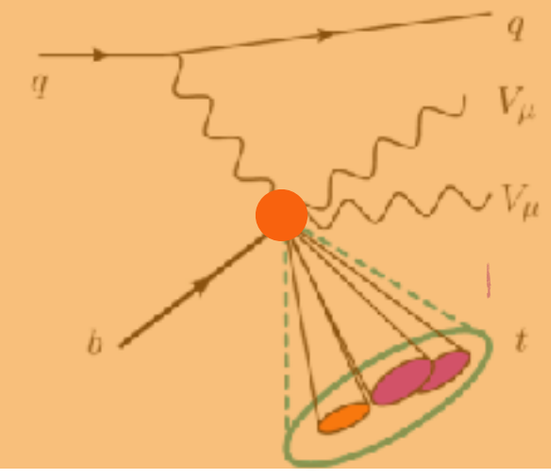
- Develop polarization-sensitive analysis (see Panico,FR,Wulzer'17)
  (SM V_T final states large and not interfering)

"Higgs without Higgs" Program

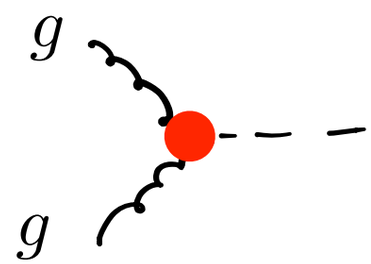
$\sim const$ | $\sim E^2$

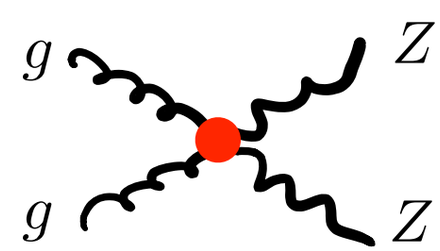
κ_t
$|H|^2 Q \tilde{H} t_R$



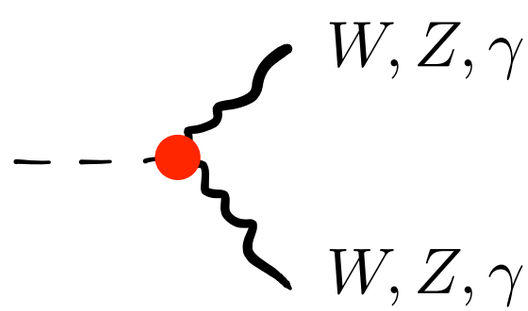


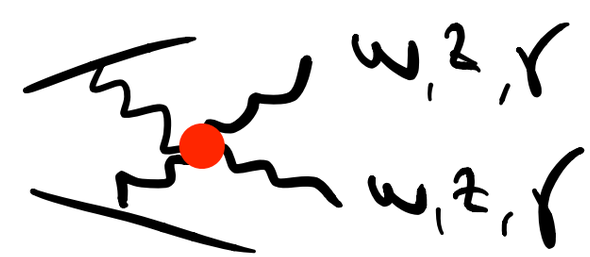
κ_G
$|H|^2 G^a_{\mu\nu} G^{a\,\mu\nu}$



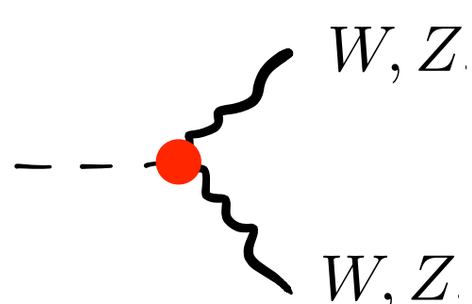


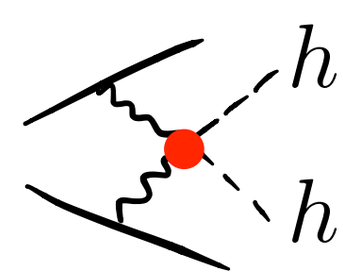
$\kappa_\gamma \quad |H|^2 B_{\mu\nu} B^{\mu\nu}$
$\kappa_{Z\gamma} \; |H|^2 W^a_{\mu\nu} W^{a\,\mu\nu}$





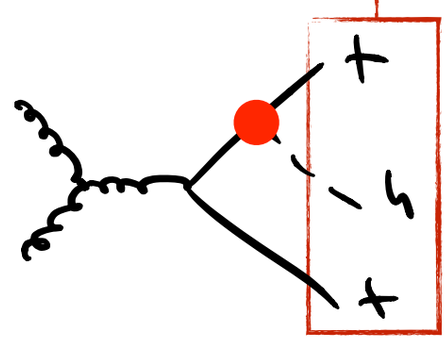
$\kappa_V \quad |H|^2 \partial_\mu H^\dagger \partial^\mu H$





HwH Program: top Yukawa

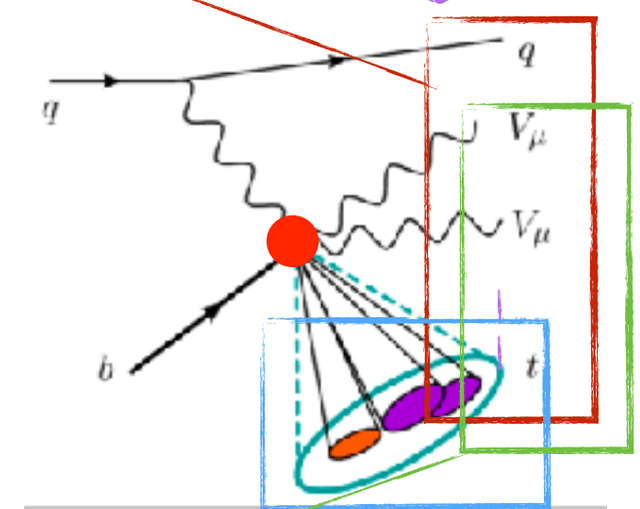
κ_t
$|H|^2 Q \tilde{H} t_R$



lower threshold

$\sim E^2$

signal enhanced



many final states

boosted top:
good discriminant,
easier to reconstruct

Signal classified by #leptons:

$ttjj \to tW\boxed{bj}j$ ($\sim W$)

background manageable

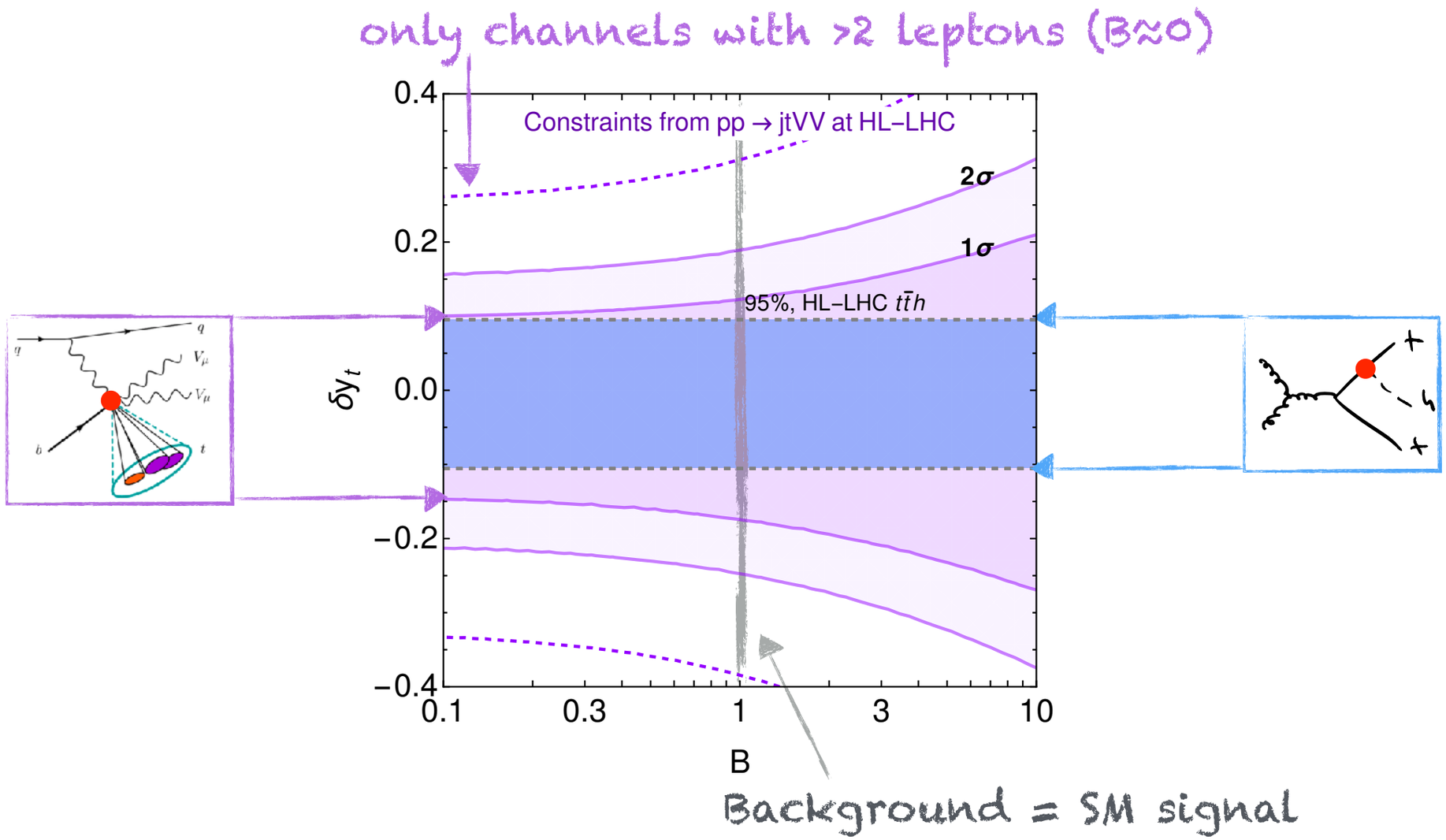
Process	0ℓ	1ℓ	$\ell^\pm\ell^\mp$	$\ell^\pm\ell^\pm$	$3\ell(4\ell)$
$W^\pm W^\mp$	3449/567	1724/283	216/35	-	-
$W^\pm W^\pm$	2850/398	1425/199	-	178/25	-
$W^\pm Z$	3860/632	965/158	273/45	-	68/11
ZZ	2484/364	-	351/49	-	(12/2)

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

>2l: Small Background

Henning,Lombardo,Riembau,FR'18

HωH Program: top Yukawa



- HωH competitive with HC!

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

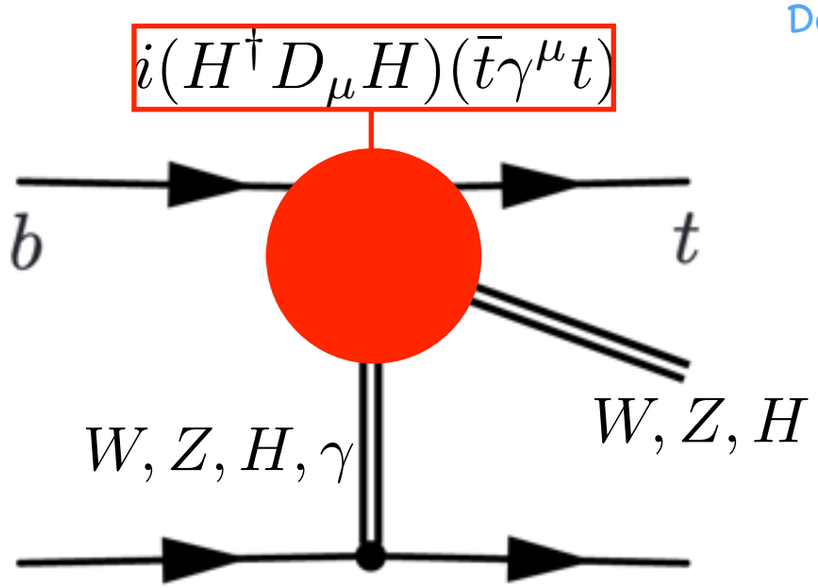
More Top and Higgs at High-Energy

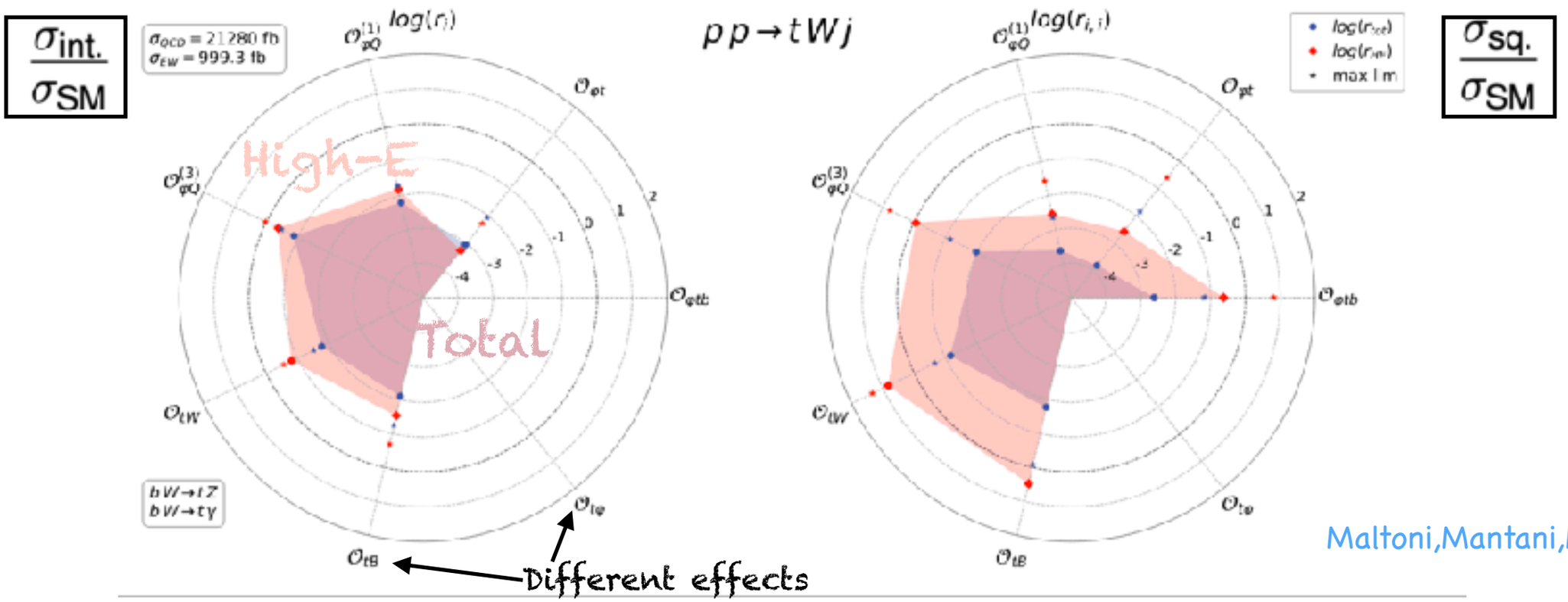
Top-Higgs: well motivated by naturalness

Other Top-Higgs effects grow in single-top

Dror,Farina,Salvioni,Serra'16

Degrande,Maltoni,Mimasu,Vryonidou,Zhang'18





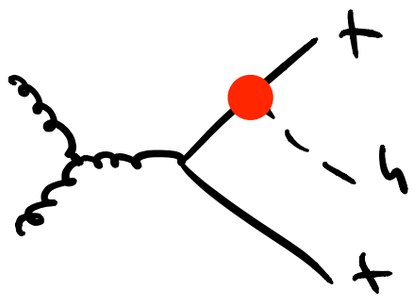
Maltoni,Mantani,Mimasu'19

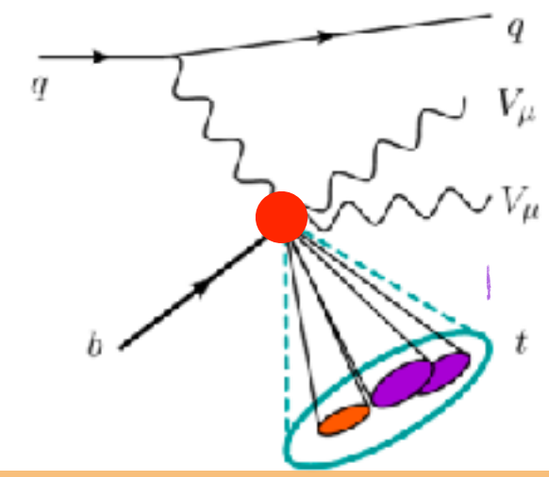
HwH Program

$\sim const$

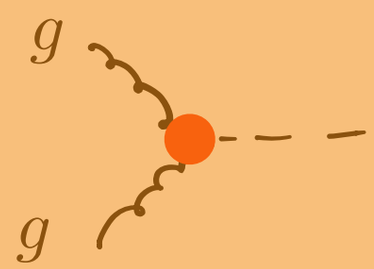
$\sim E^2$

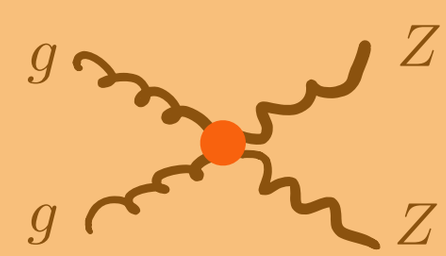
κ_t
$|H|^2 Q \tilde{H} t_R$



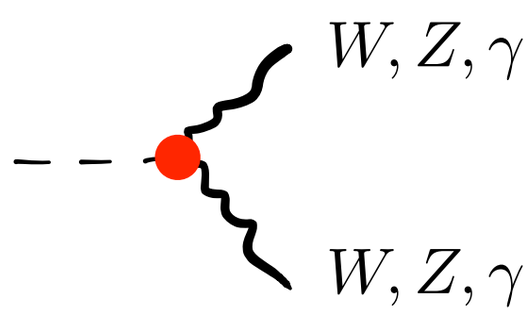


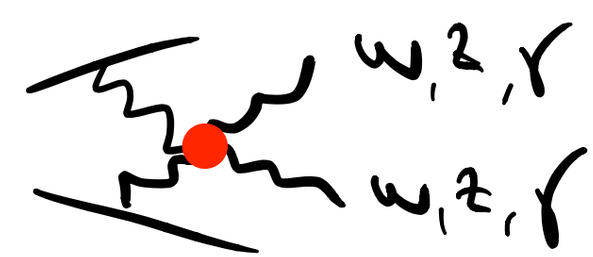
κ_G
$|H|^2 G^a_{\mu\nu} G^{a\,\mu\nu}$



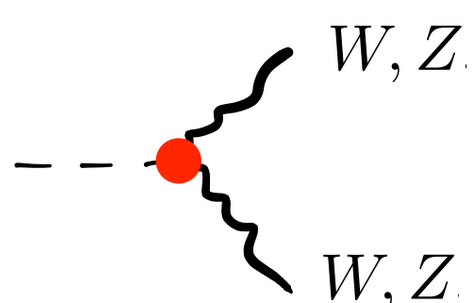


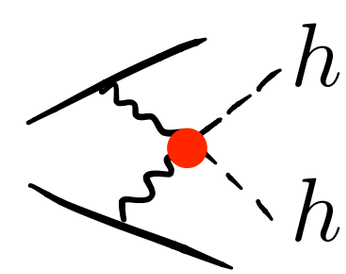
$\kappa_\gamma \quad |H|^2 B_{\mu\nu} B^{\mu\nu}$
$\kappa_{Z\gamma} \; |H|^2 W^a_{\mu\nu} W^{a\,\mu\nu}$





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



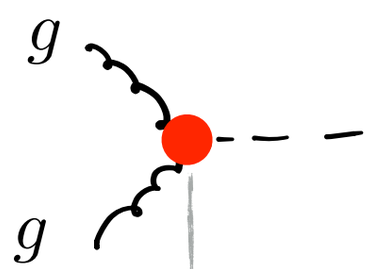


HwH Program: Higgs-Gluons

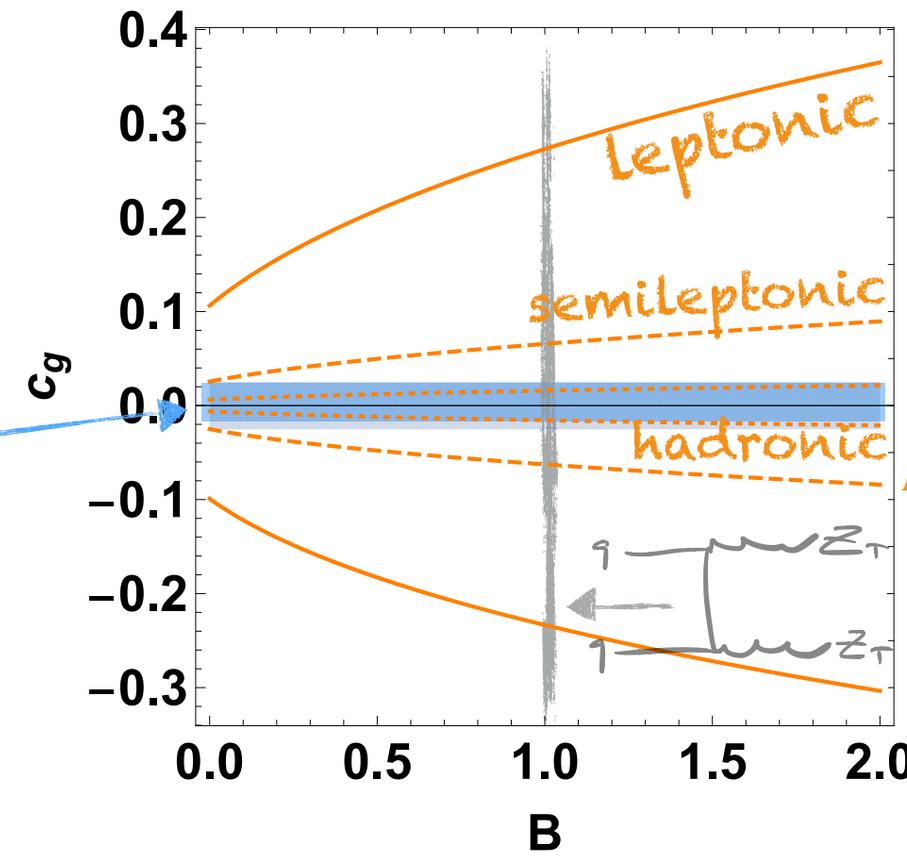
Azatov, Grojean, Paul, Salvioni'14

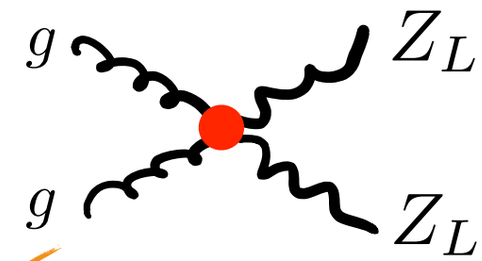
κ_G

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



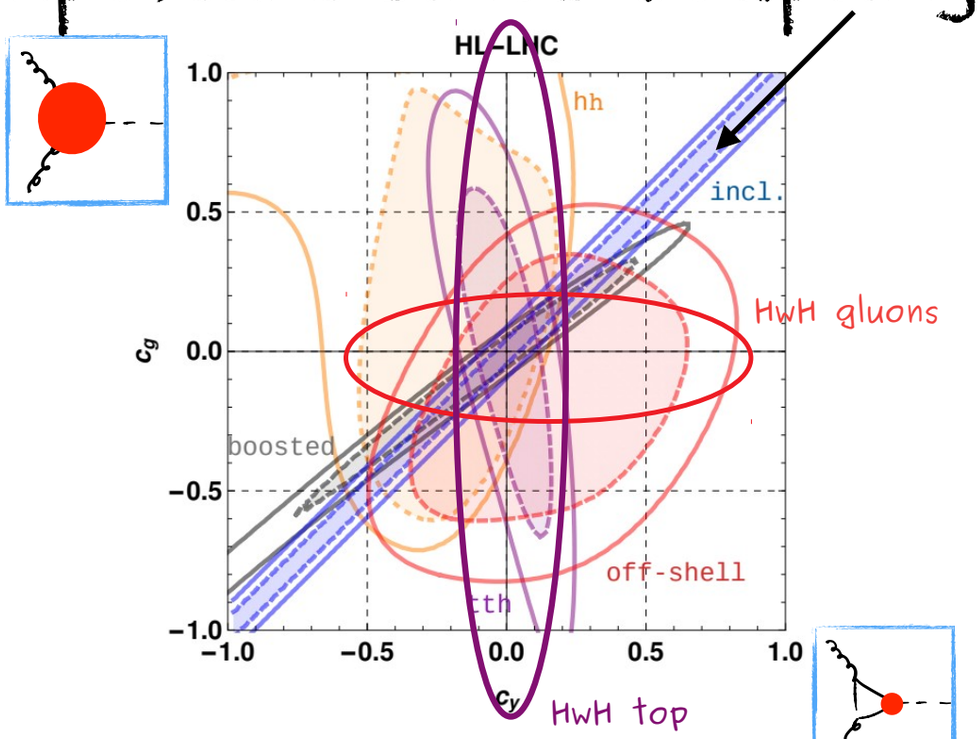
Main H Production mode @ LHC: well measured





Non-resonant!

Important since Coupling measurements leave degeneracies...



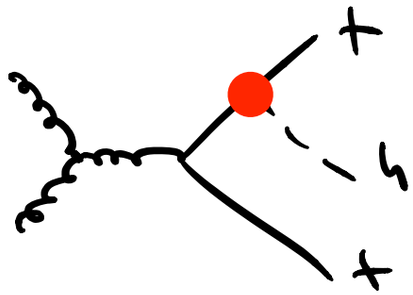
HwH offer new observables, orthogonal to previous ones!

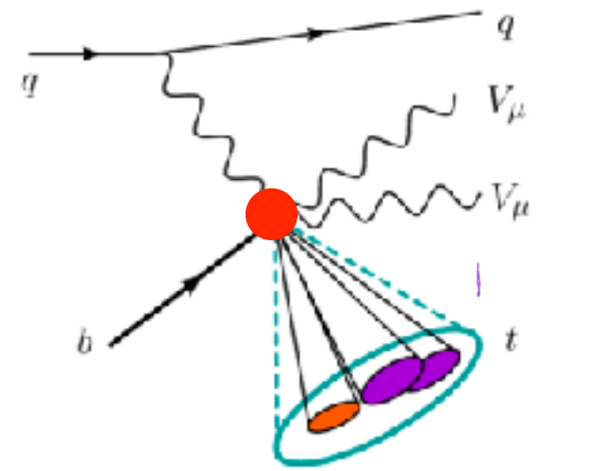
HwH Program

$\sim const$

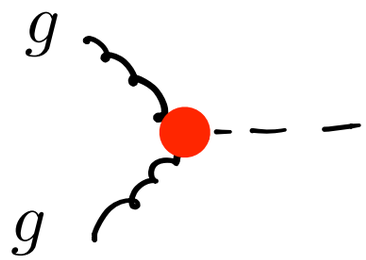
$\sim E^2$

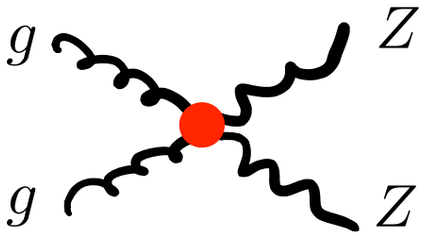
κ_t
$|H|^2 Q \tilde{H} t_R$



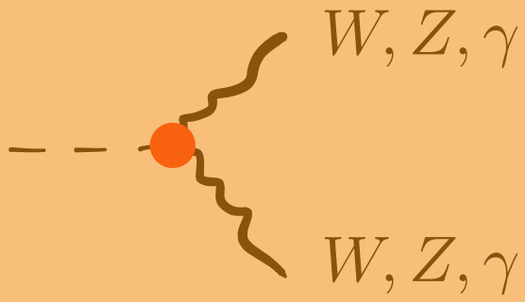


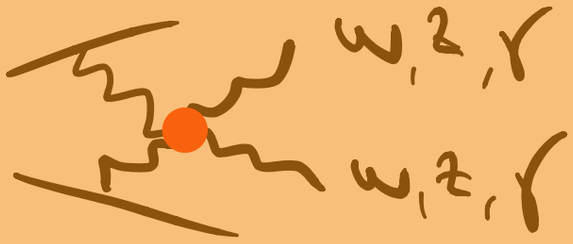
κ_G
$|H|^2 G^a_{\mu\nu} G^{a\,\mu\nu}$



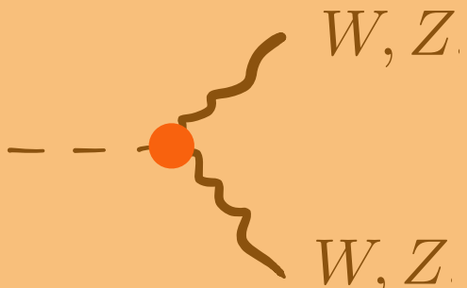


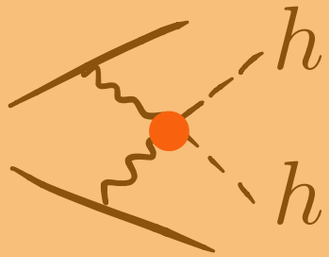
$\kappa_\gamma \quad |H|^2 B_{\mu\nu} B^{\mu\nu}$
$\kappa_{Z\gamma} \; |H|^2 W^a_{\mu\nu} W^{a\,\mu\nu}$





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

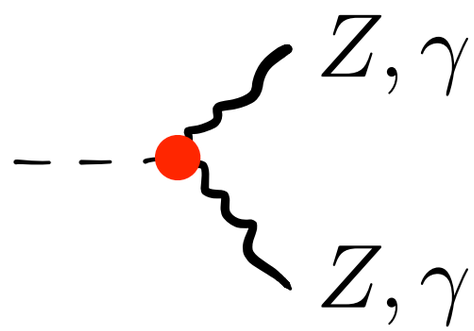


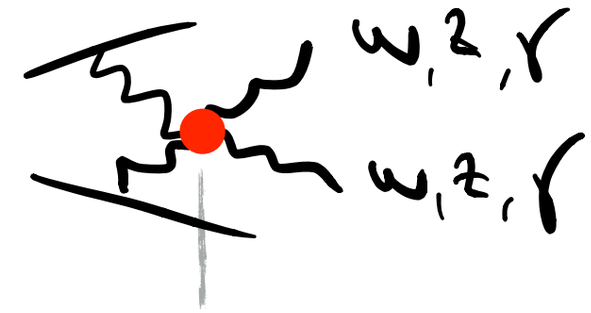


HwH Program: h to gauge bosons

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

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

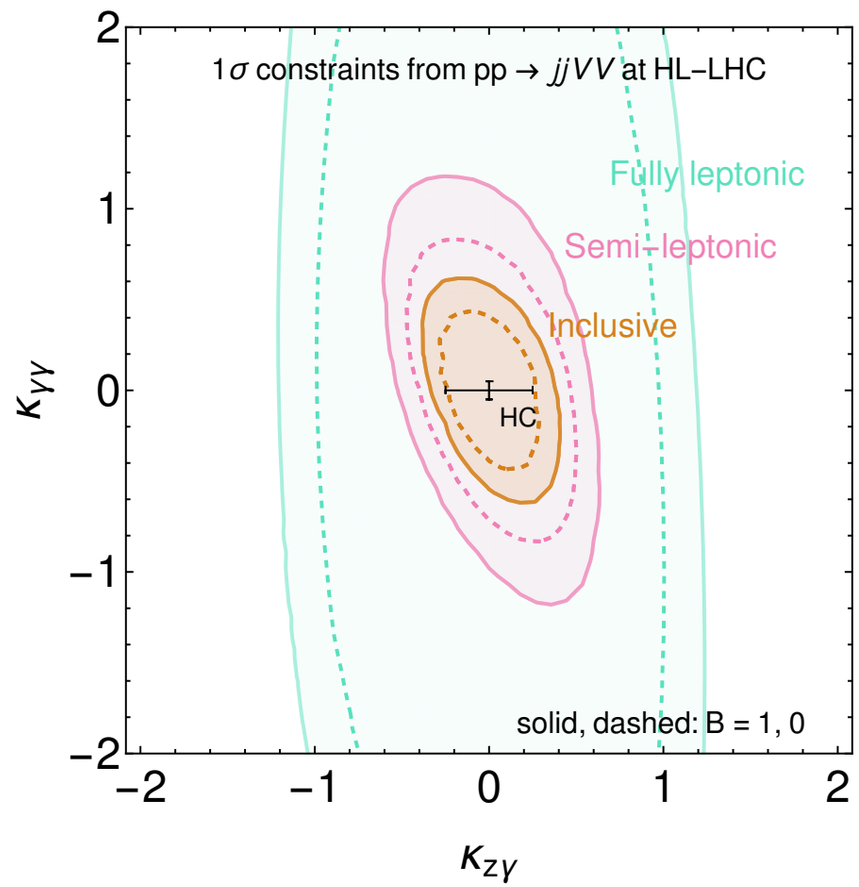




So far interpreted with dim-8 operators (aQGC)

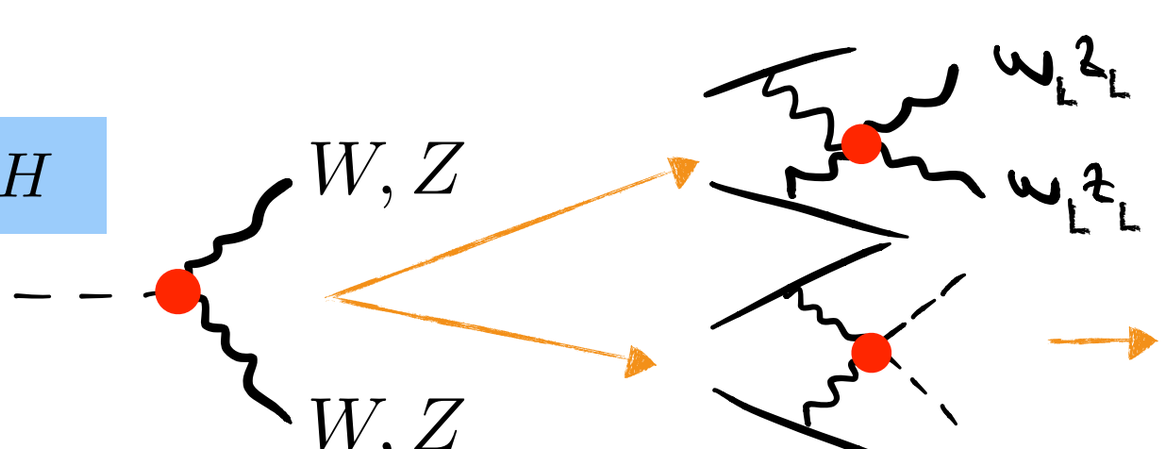
Simple analysis:

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



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

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



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

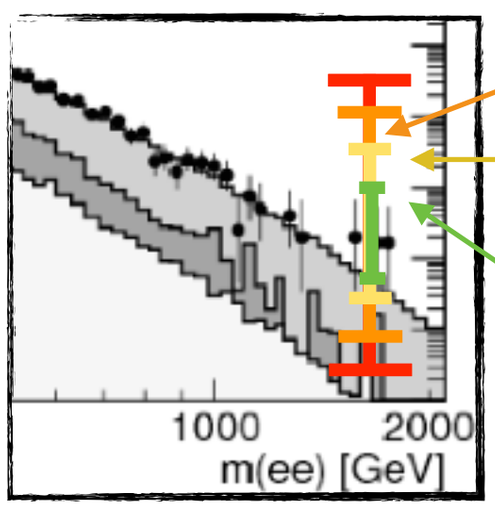
Contino,Grojean,Moretti,Piccinini,Rattazzi'10

$\delta\kappa_V \lesssim 8\%$, (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
- Multiboson (HwH): Competitive/Complementary to HC measurements
- Many opportunities for improvement (contrary to HC):



Precise SM theoretical predictions

Experimental control of systematics/backgrounds

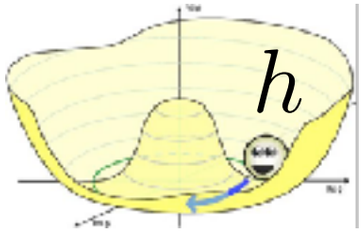
Understanding of relevant kinematics, handle on transverse/longitudinal

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

BSM

Composite Higgs Models: $\kappa \sim \frac{v^2}{\Lambda^2} \lesssim (1-5)\%$ $\quad m_{\rm NP} \sim g_* \Lambda \sim 30\,{\rm TeV}$

$g_* \sim 4\pi$

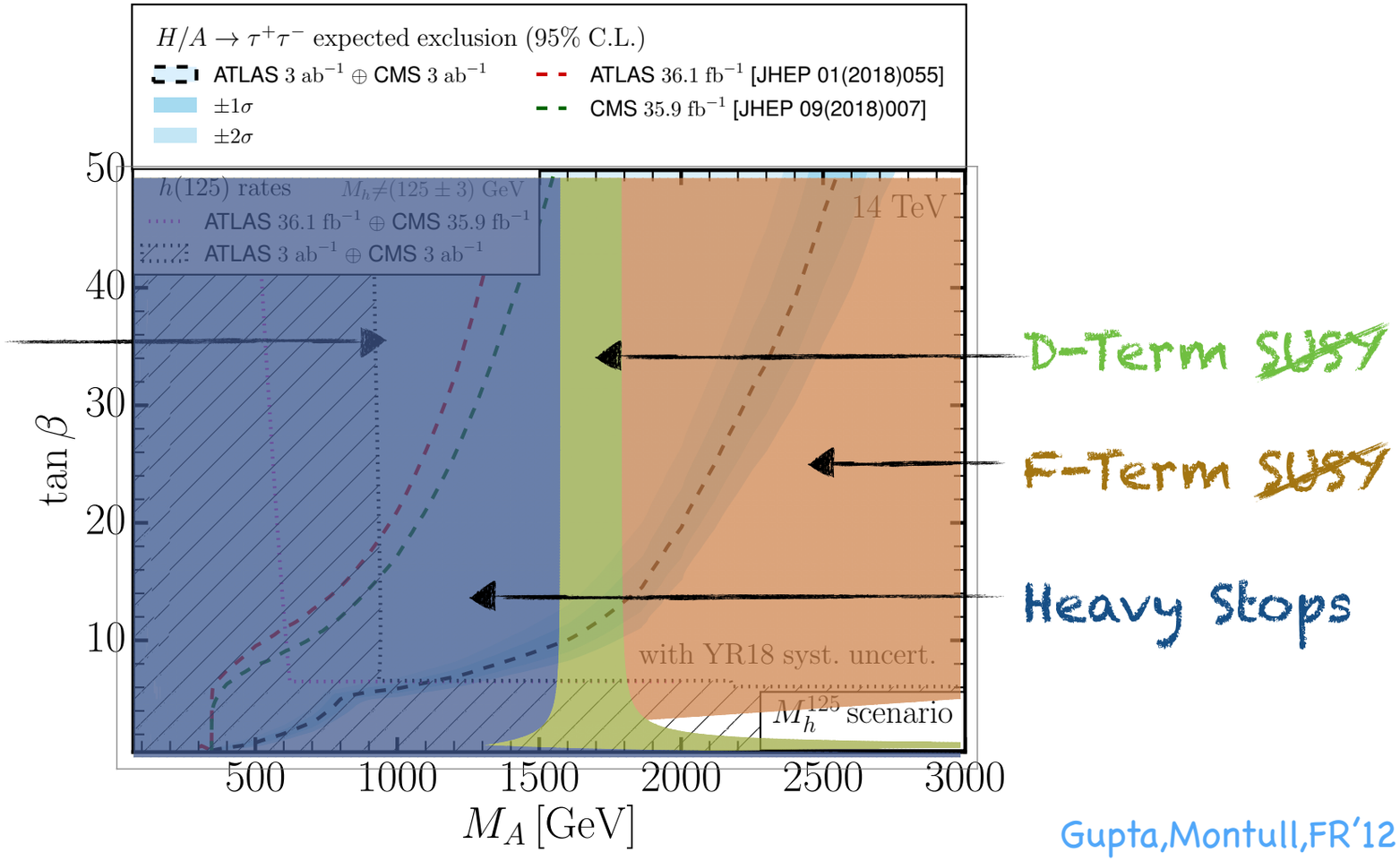


Here Λ analog of pion decay constant f

(Direct Searches Poor for large g* $3\,{\rm TeV}$)

Supersymmetry:

$H/A \to \tau\tau$



Gupta,Montull,FR'12 - updated

... on similar lines

Chang,Luty'19
Falkowski,Rattazzi'19

Modifications of the SM induce unitarity violation in some channel...

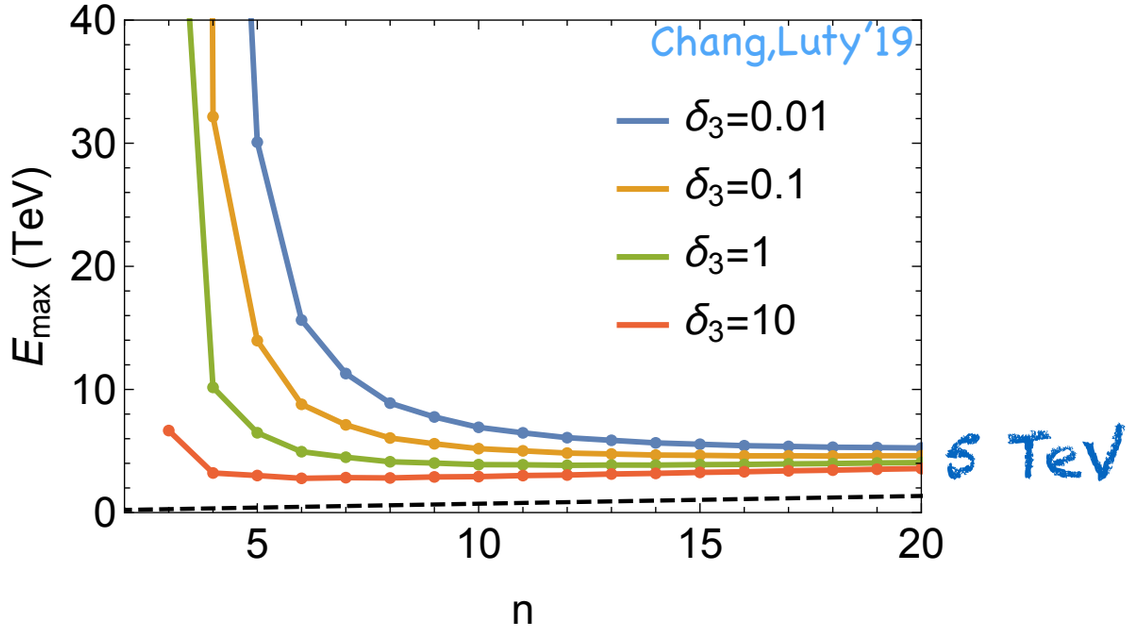
which channel first?

$$\delta V(h) = \sum_{n=3}^{\infty} \frac{\delta\lambda_n}{n!} h^n.$$

only δ_3

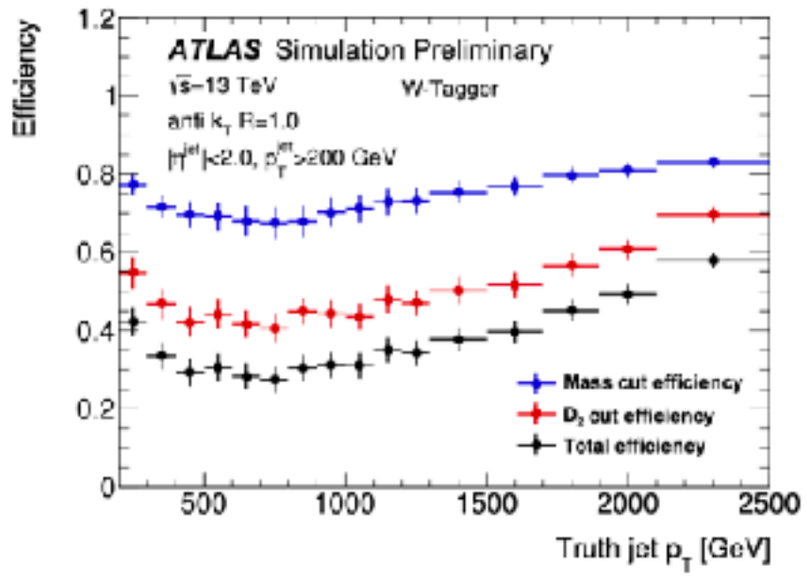
all δ_n (more conservative)

$Z_L^2 h^n$

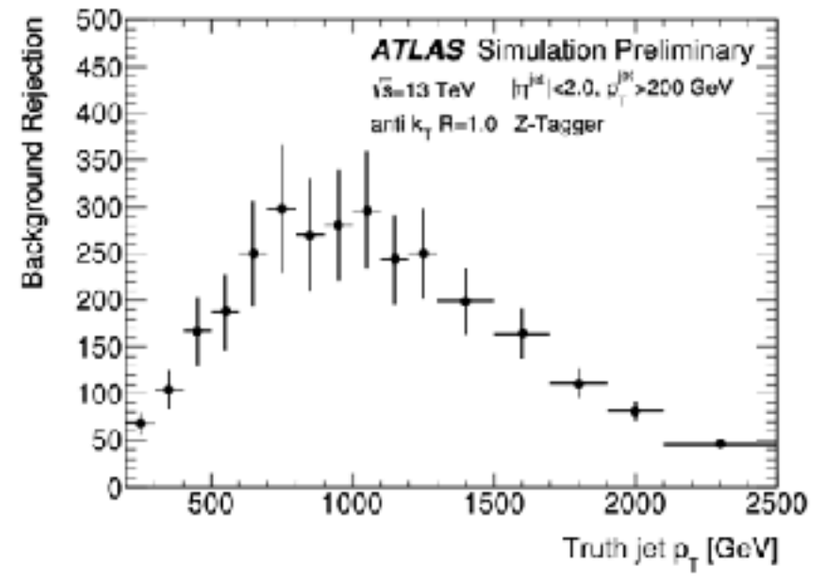


Process	Unitarity Violating Scale
$h^2 Z_L \leftrightarrow h Z_L$	$66.7\ \text{TeV}/\lvert\delta_3 - \frac{1}{3}\delta_4\rvert$
$h Z_L^2 \leftrightarrow Z_L^2$	$94.2\ \text{TeV}/\lvert\delta_3\rvert$
$h W_L Z_L \leftrightarrow W_L Z_L$	$141\ \text{TeV}/\lvert\delta_3\rvert$
$h Z_L^2 \leftrightarrow h Z_L^2$	$9.1\ \text{TeV}/\sqrt{\lvert\delta_3 - \frac{1}{5}\delta_4\rvert}$
$h W_L Z_L \leftrightarrow h W_L Z_L$	$11.1\ \text{TeV}/\sqrt{\lvert\delta_3 - \frac{1}{5}\delta_4\rvert}$
$Z_L^3 \leftrightarrow Z_L^3$	$15.7\ \text{TeV}/\sqrt{\lvert\delta_3\rvert}$
$Z_L^2 W_L \leftrightarrow Z_L^2 W_L$	$20.4\ \text{TeV}/\sqrt{\lvert\delta_3\rvert}$
$h Z_L^3 \leftrightarrow Z_L^3$	$6.8\ \text{TeV}/\lvert\delta_3 - \frac{1}{6}\delta_4\rvert^{\frac{1}{3}}$
$h Z_L^2 W_L \leftrightarrow Z_L^2 W_L$	$8.0\ \text{TeV}/\lvert\delta_3 - \frac{1}{6}\delta_4\rvert^{\frac{1}{3}}$
$Z_L^4 \leftrightarrow Z_L^4$	$6.1\ \text{TeV}/\lvert\delta_3 - \frac{1}{6}\delta_4\rvert^{\frac{1}{4}}$

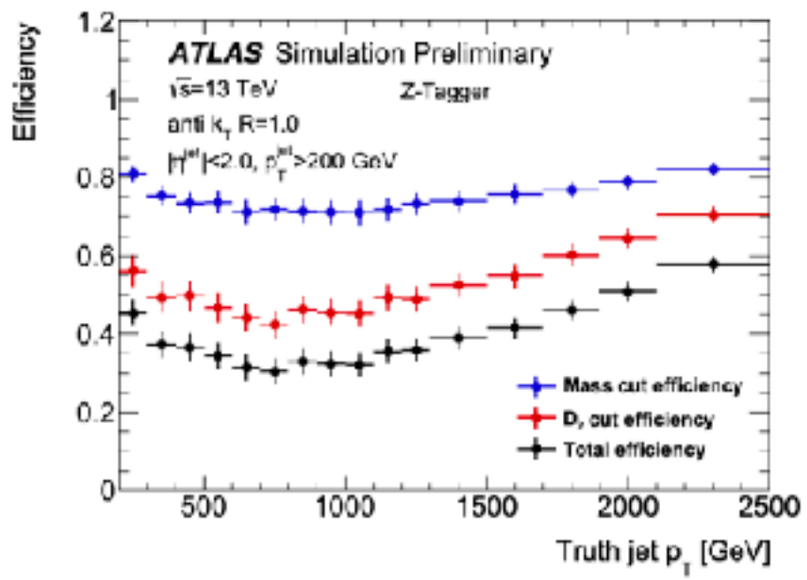
Generic models valid to 5 TeV



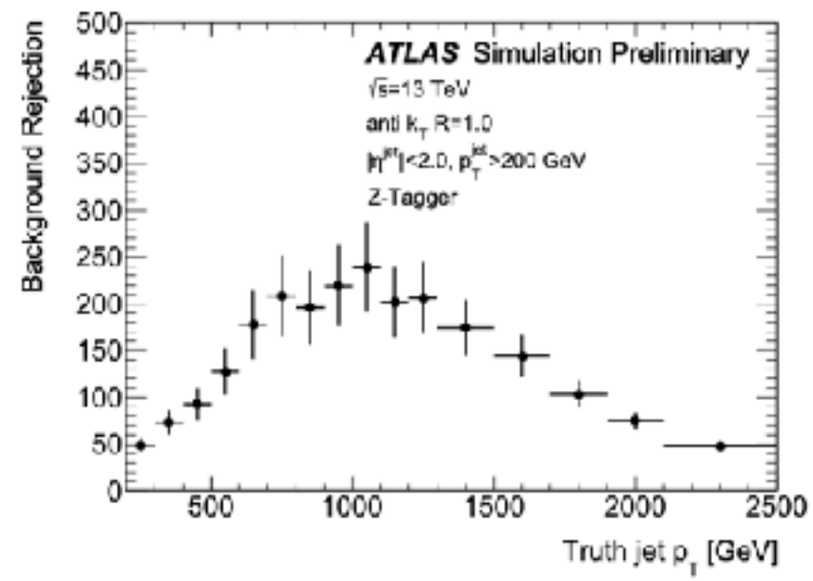
(a) W-tagger: signal efficiency



(b) W-tagger: background rejection



(c) Z-tagger: signal efficiency



(d) Z-tagger: background rejection

ATLAS-CONF-2018-016