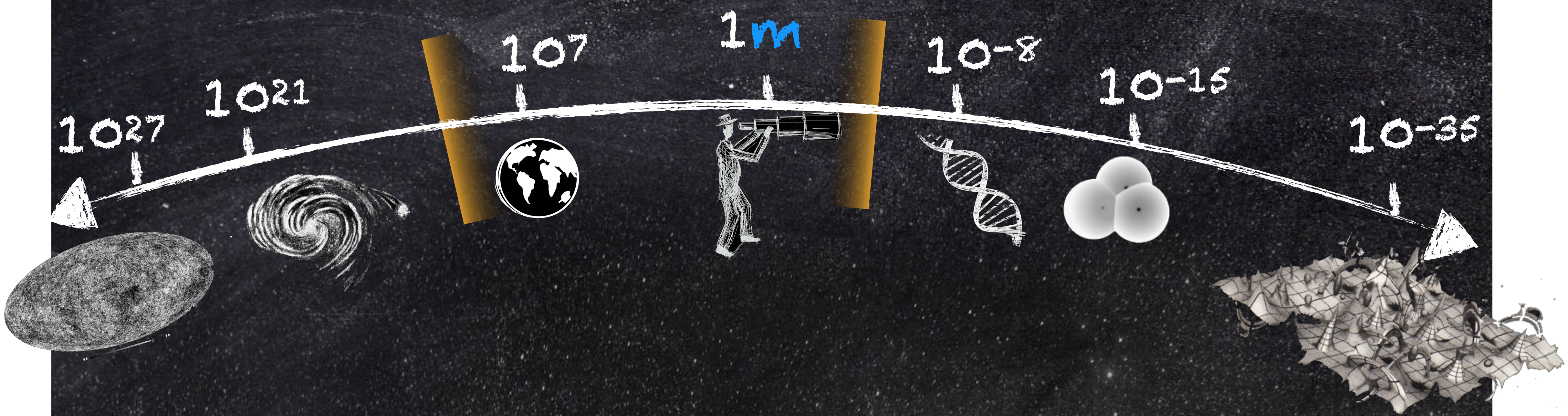
Higgs Couplings ... without the Higgs



Francesco Riva
(UNIGE)

In collaboration with
Henning, Lombardo, Riembau

arXiv: 1812.09299

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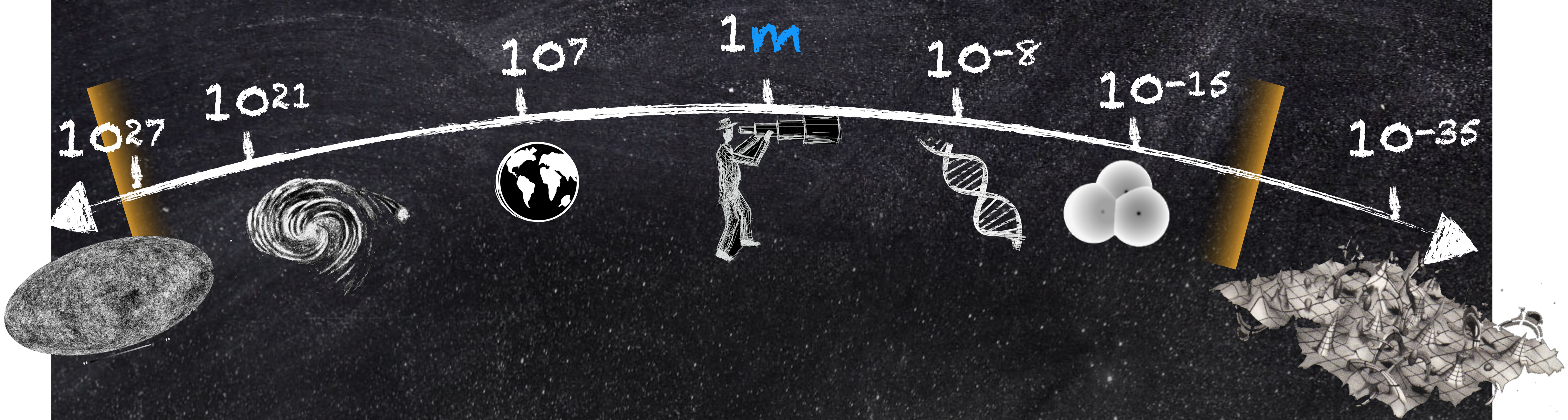

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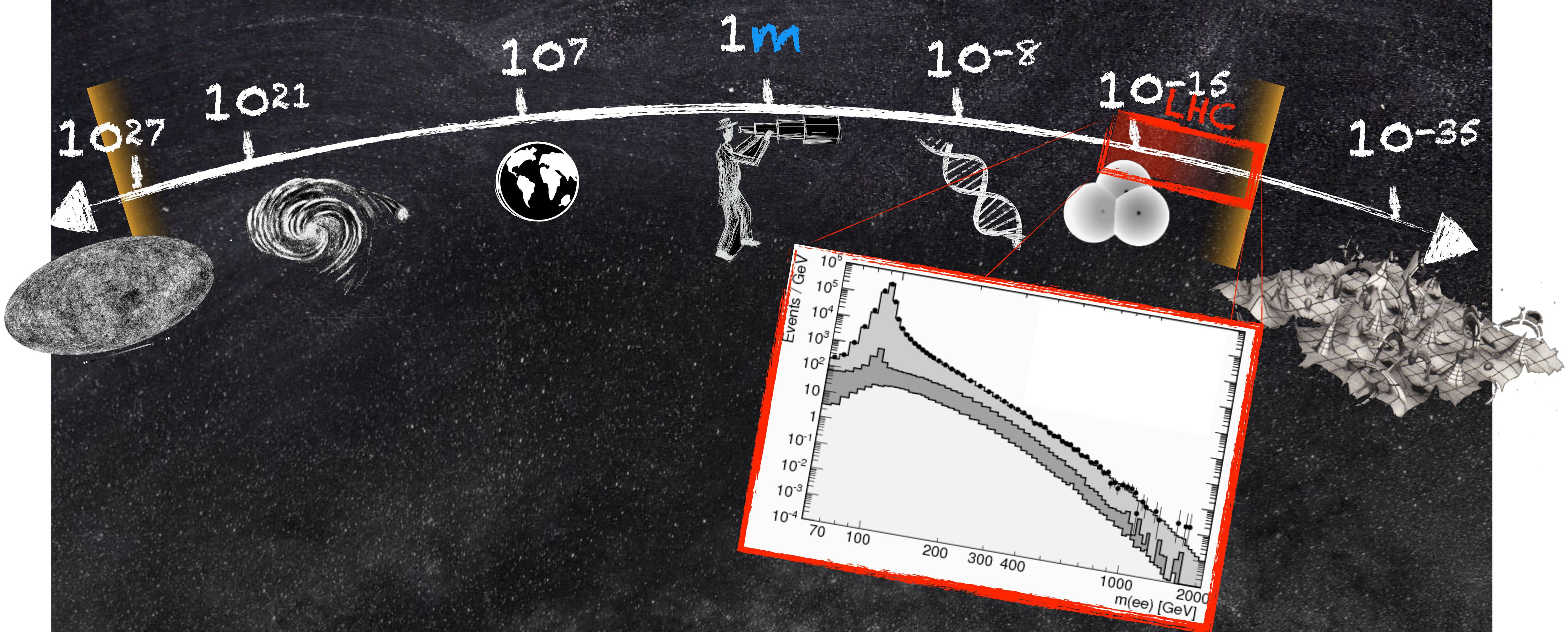

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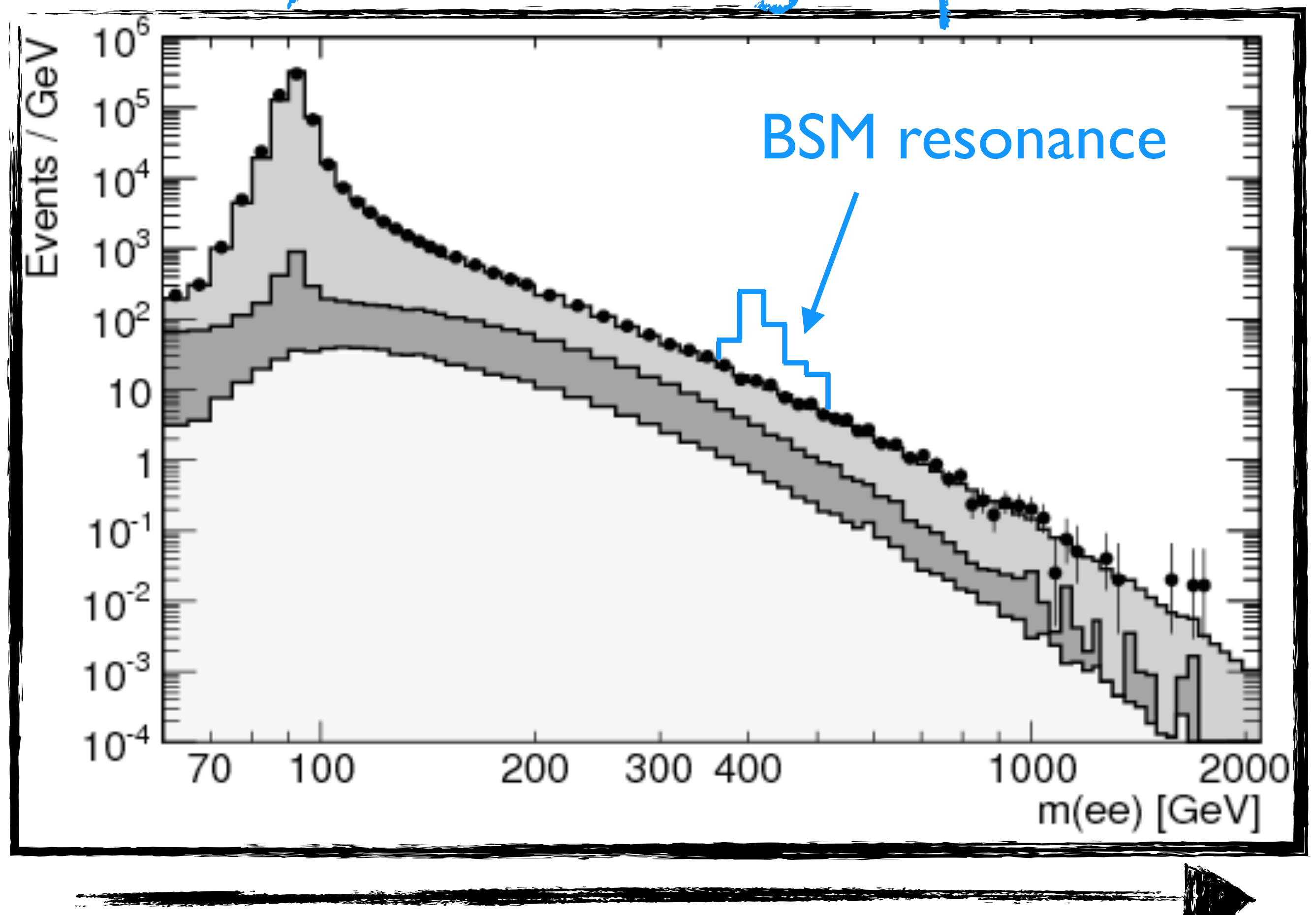
LHC Exploration

Focus so far: Search for new light particles



Energy frontier (13 TeV)

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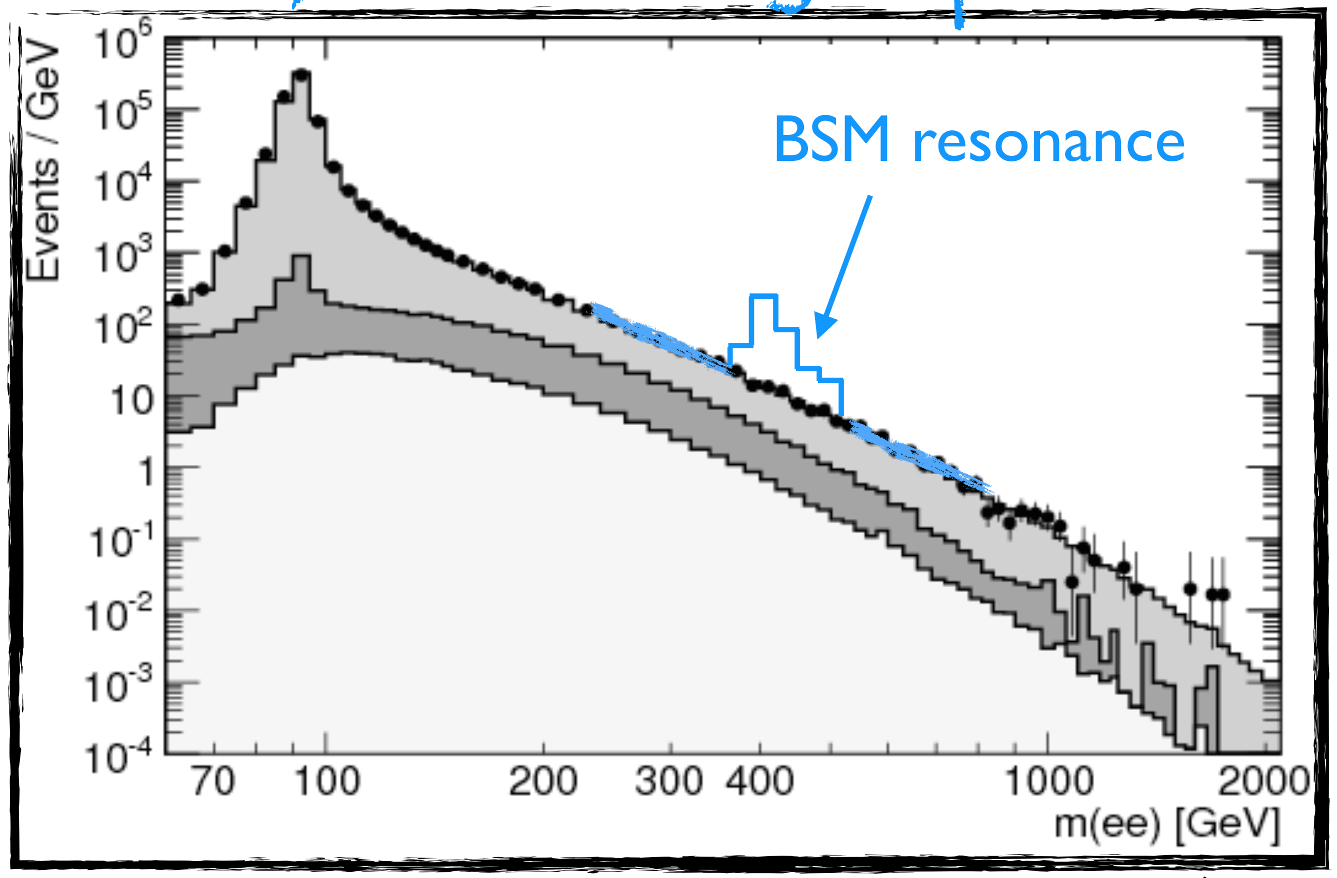


Energy frontier (13 TeV)

- Experimentally: First accessible signal/Easy to study

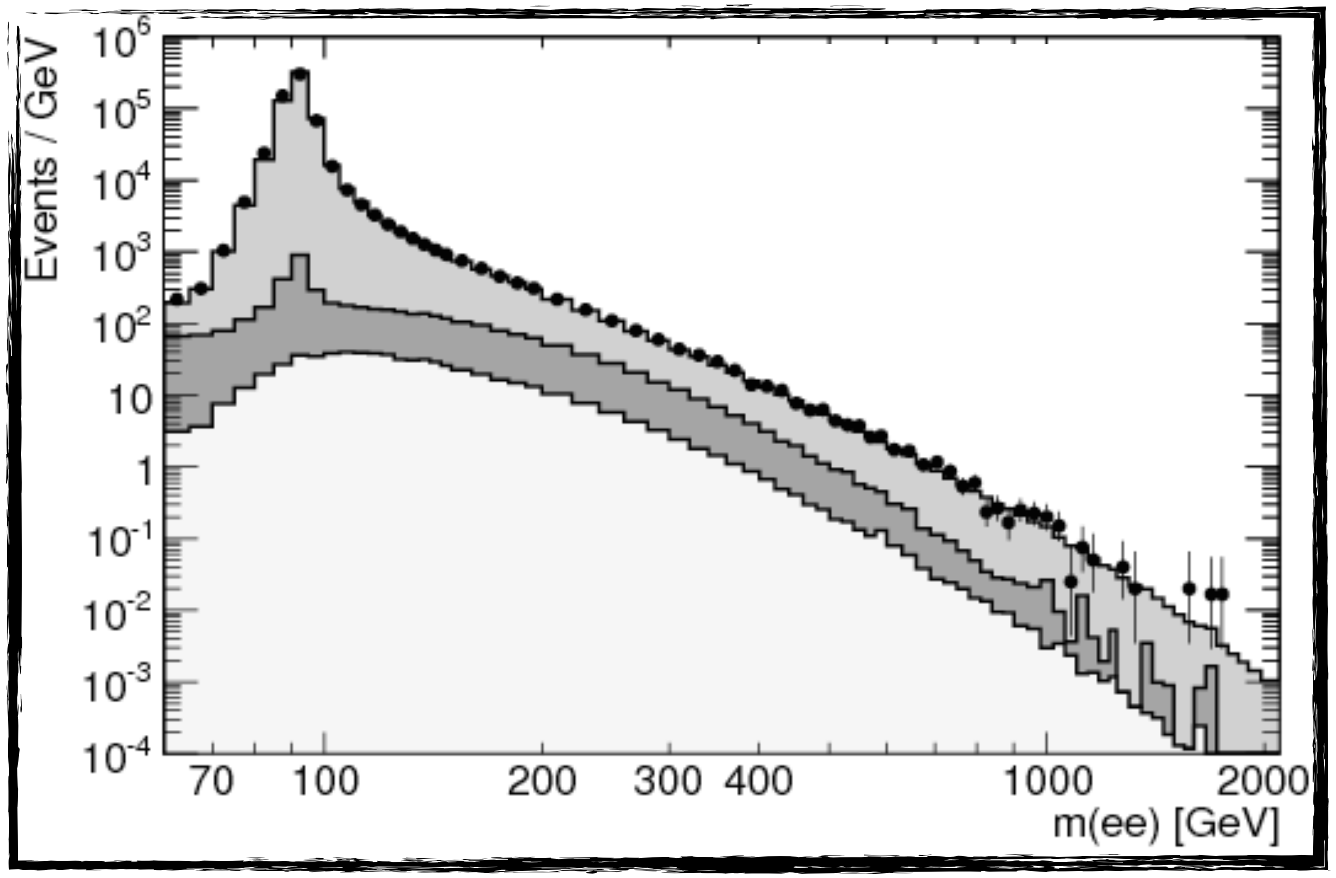
LHC Exploration

Focus now: Standard Model Precision Tests

(2035: 3000 fb-1)

intensity frontier

(2019: 65 fb-1)



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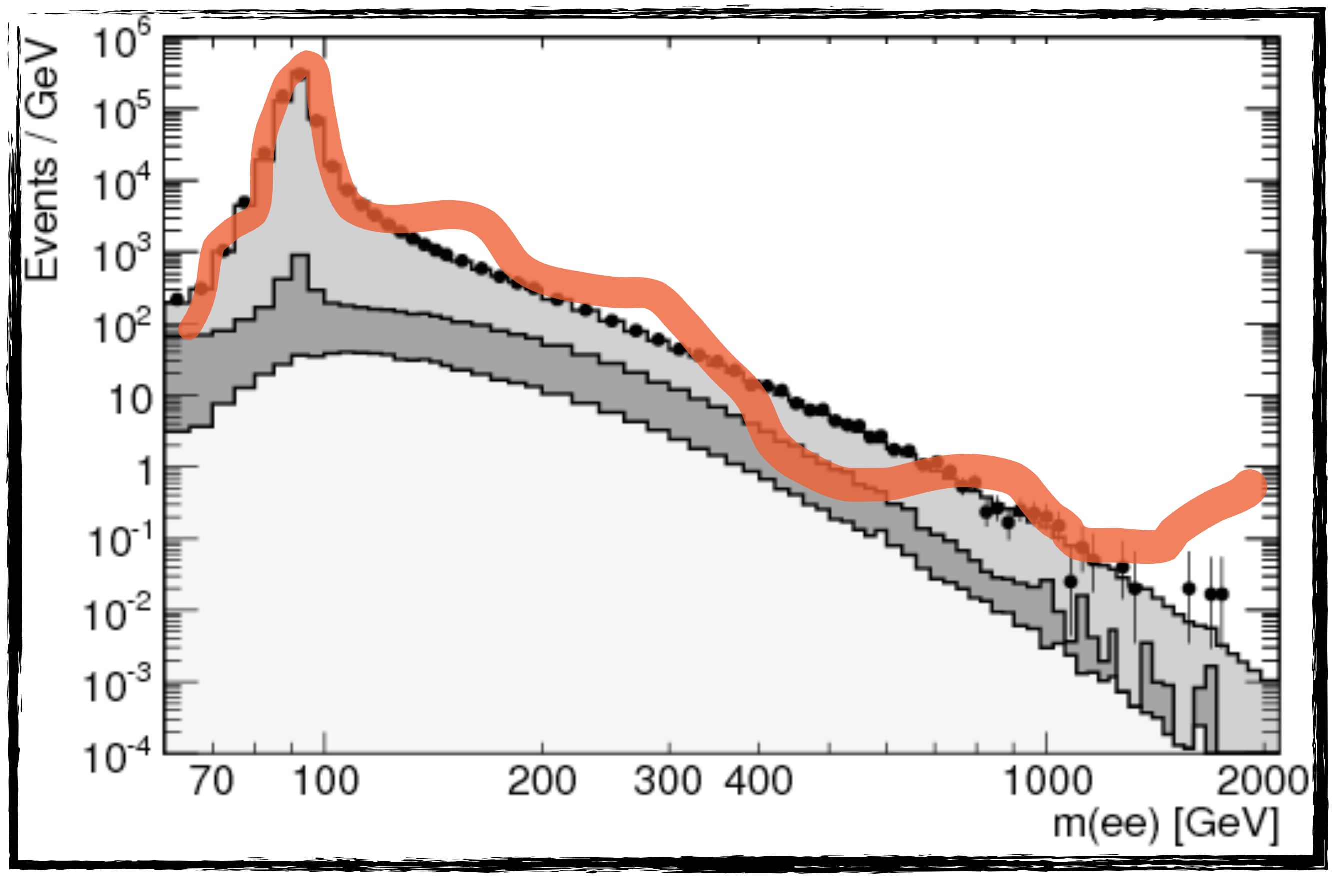

Infinite Information

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

LHC Exploration

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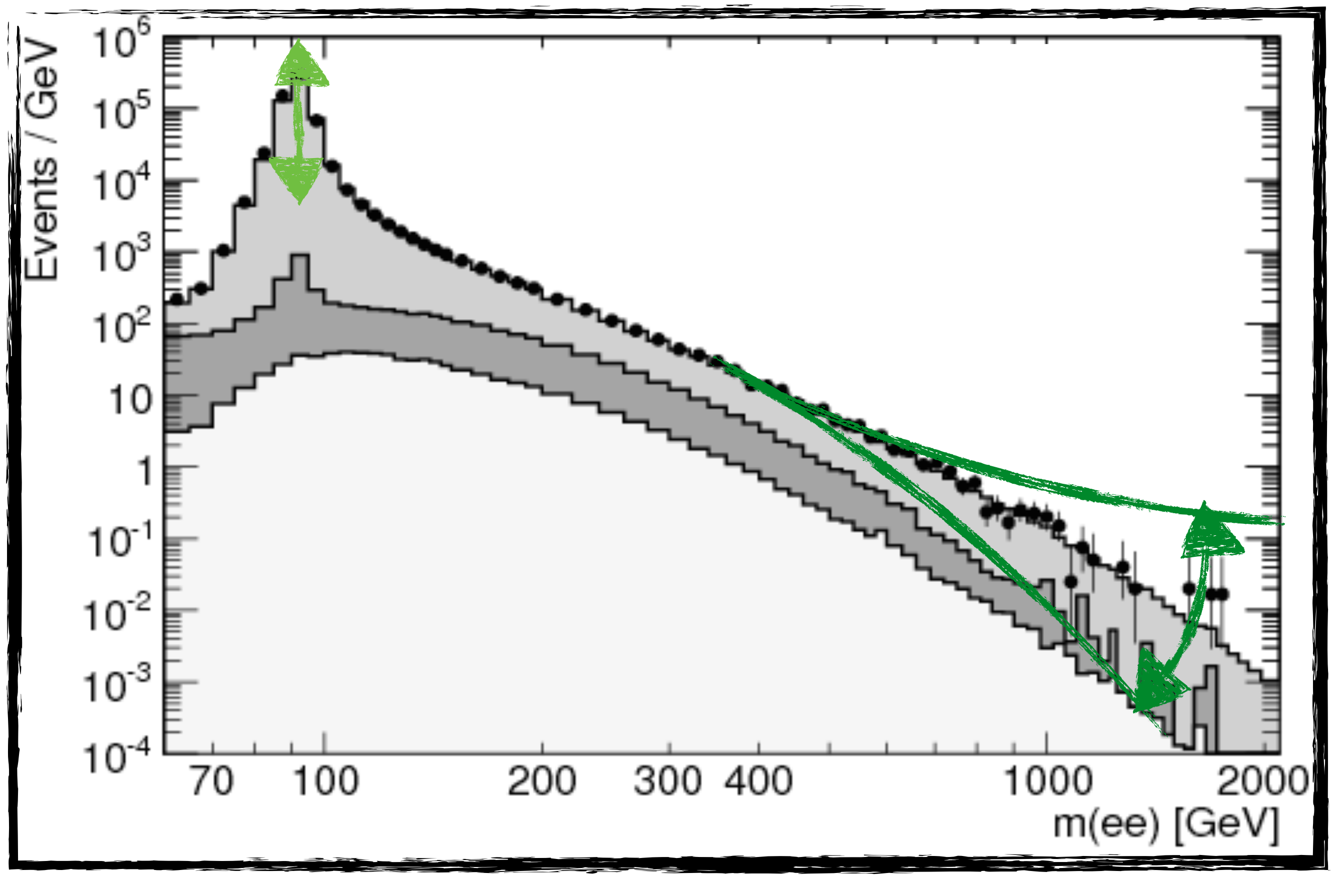

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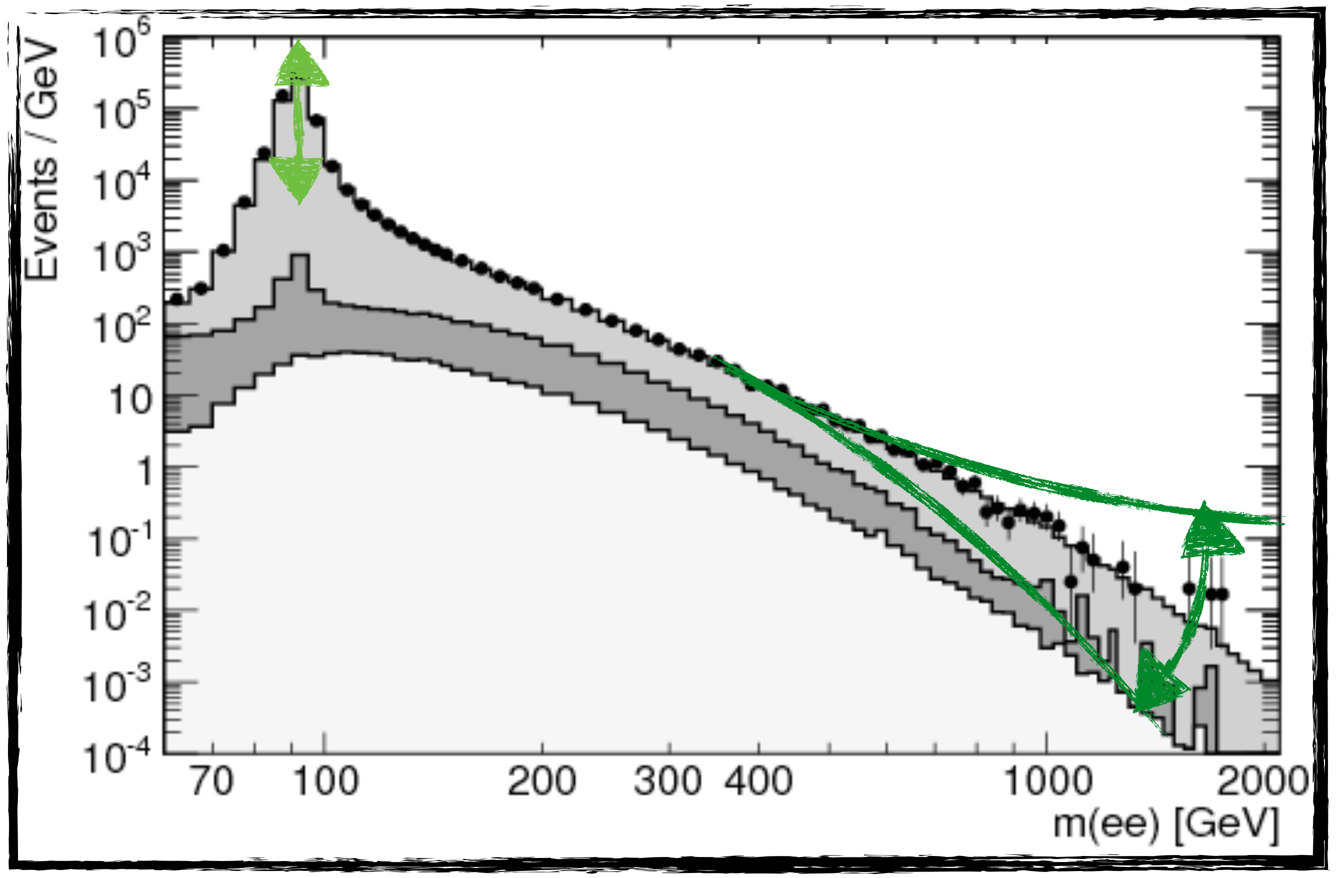

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systematic Taylor expansion for **all** observables

Effective Field Theory (EFT)

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

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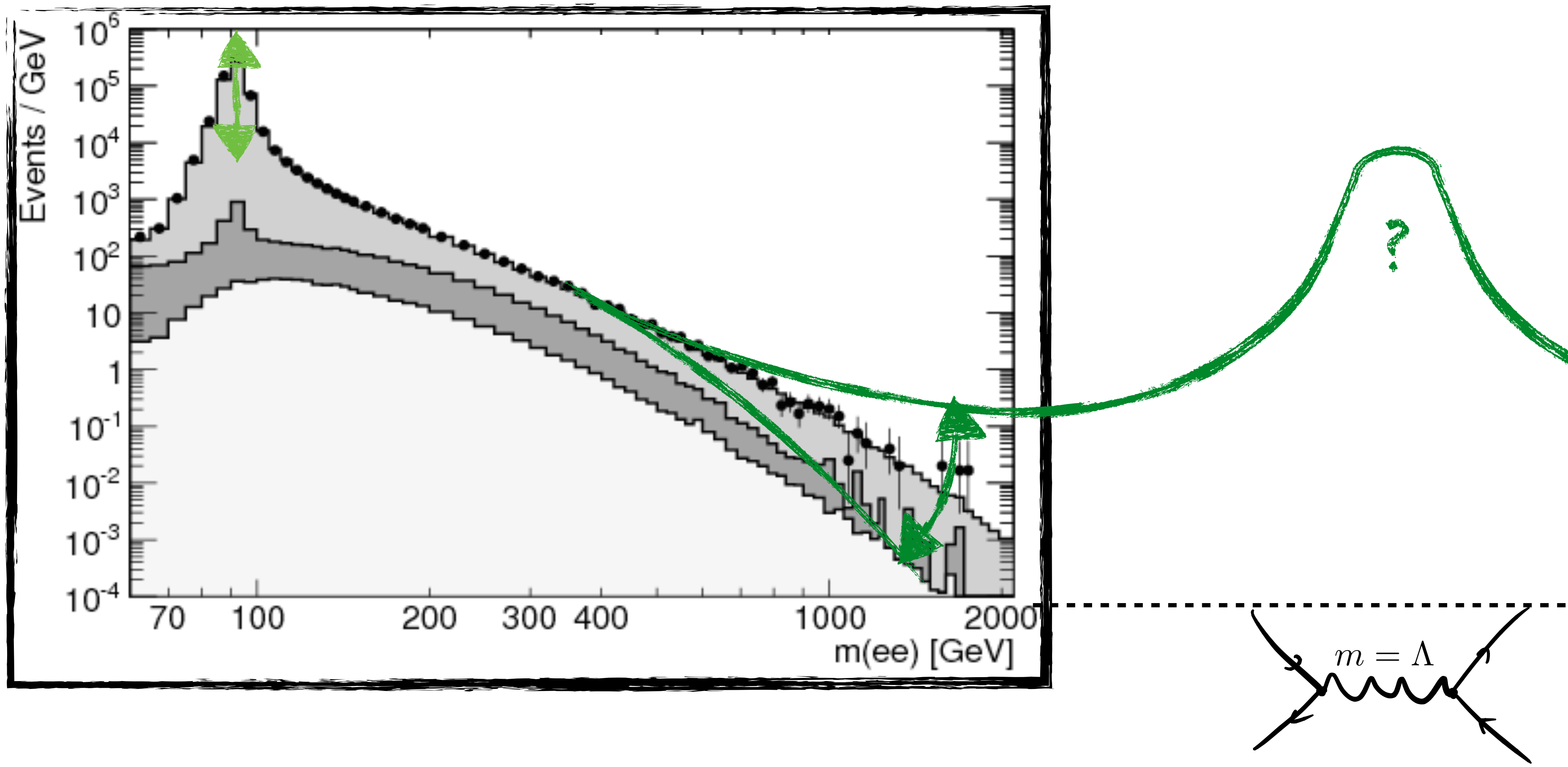

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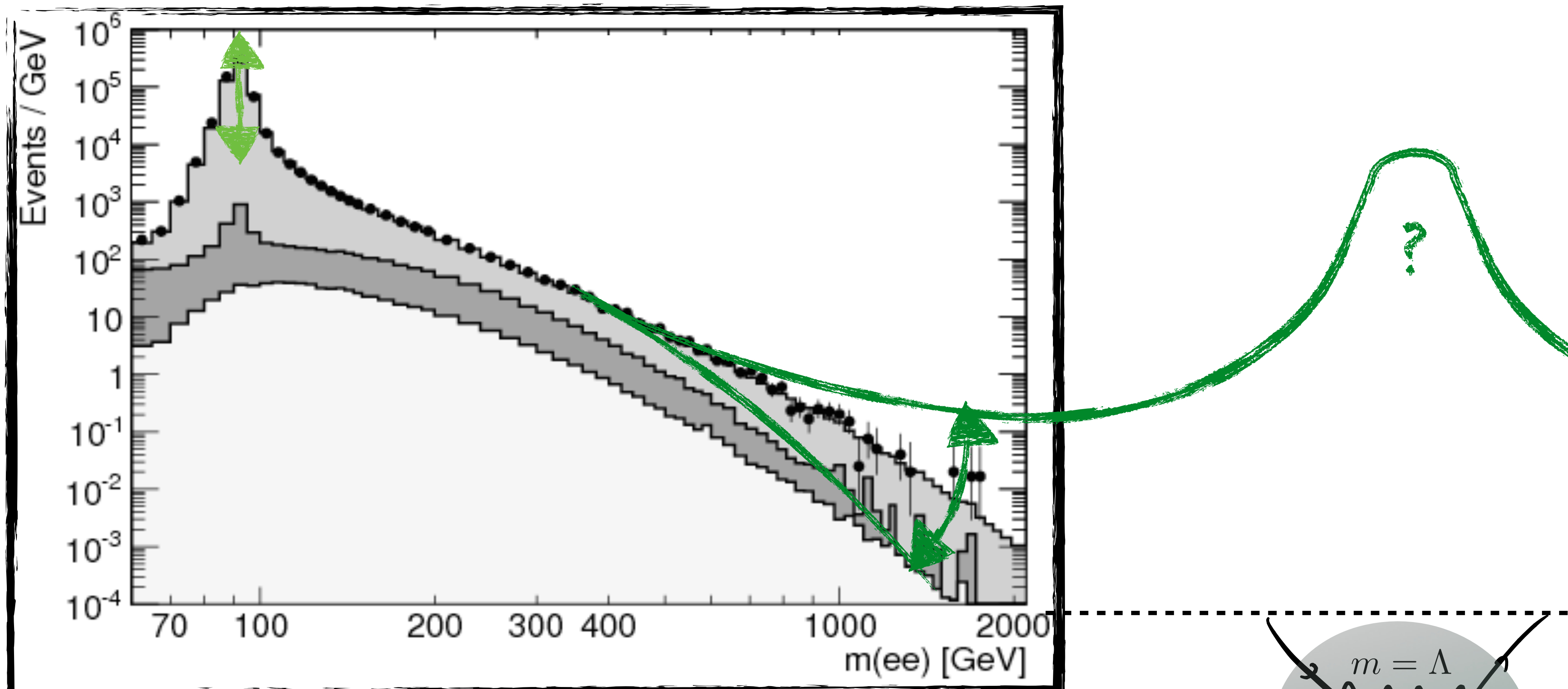

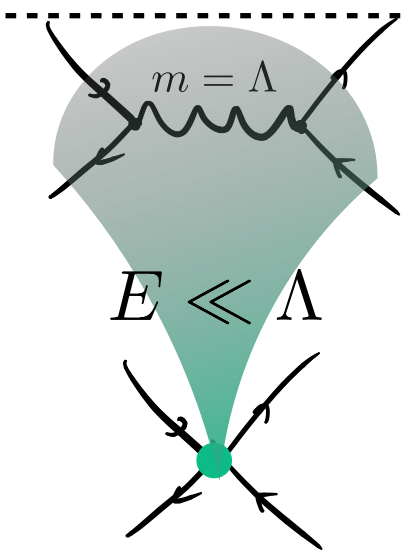

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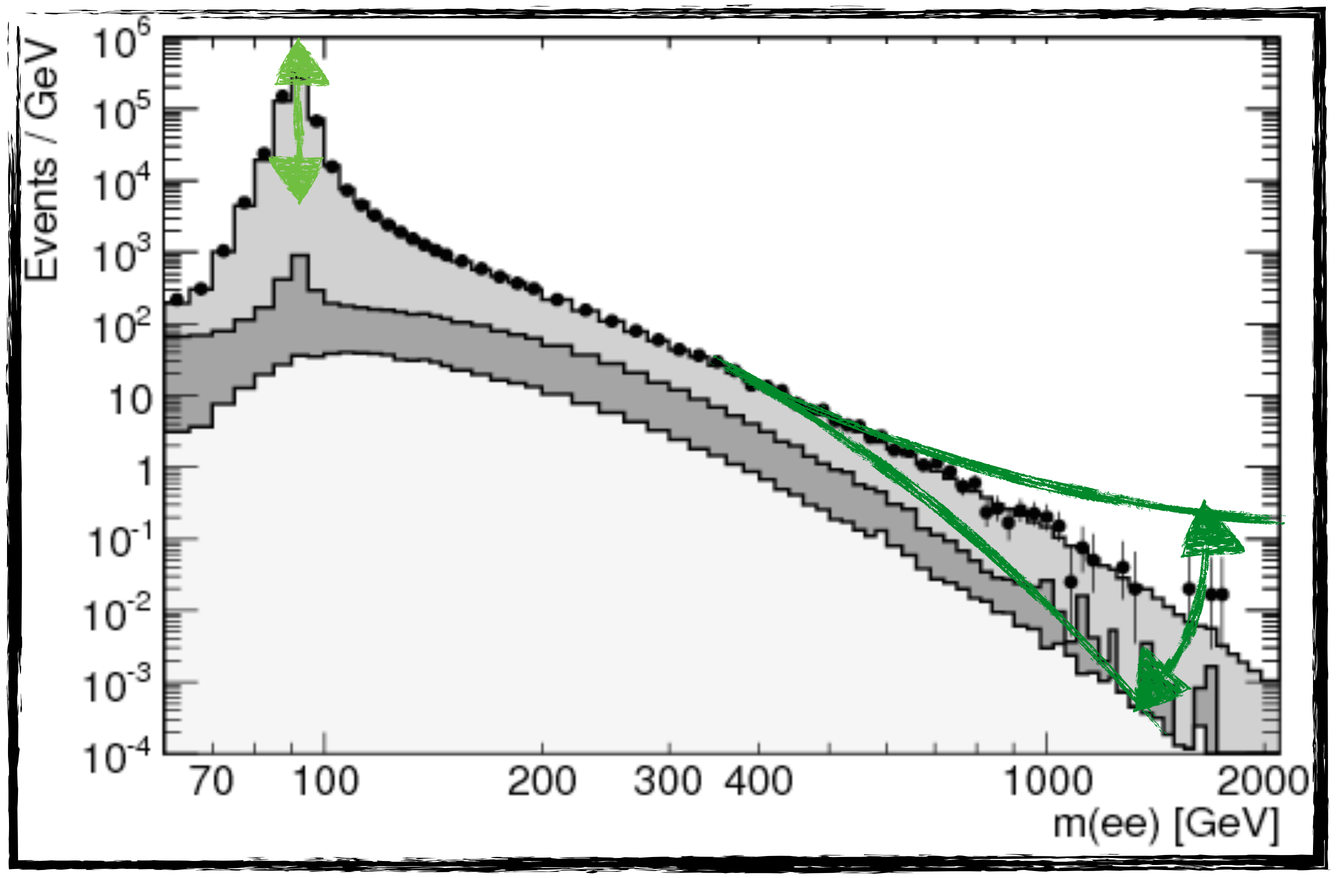
$$\mathcal{O}_i = \frac{(\bar{\psi}\gamma_\mu\psi)^2}{\Lambda^2}$$

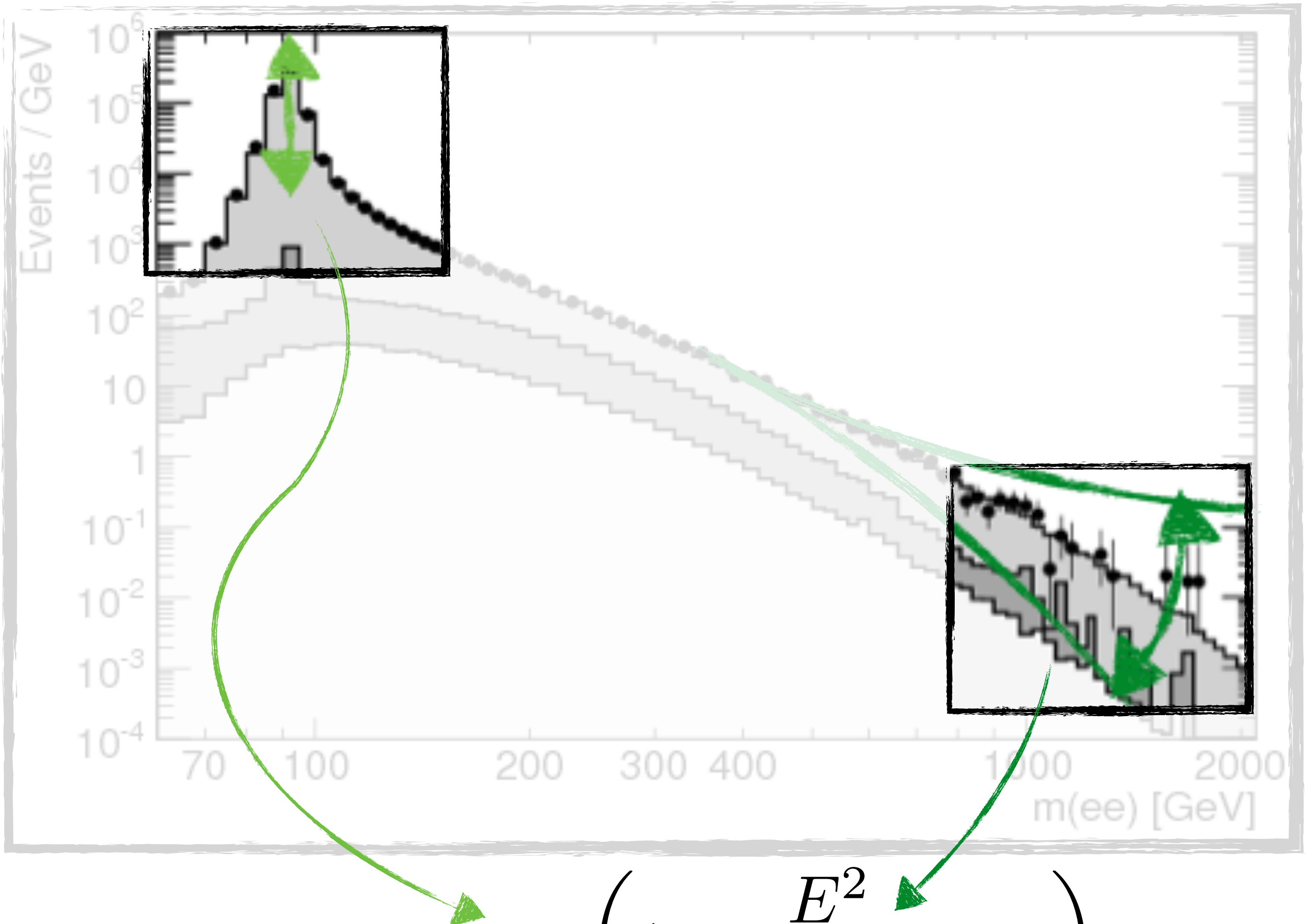
most relevant effects from **all** heavy BSM

Precision Tests



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

Precision Tests



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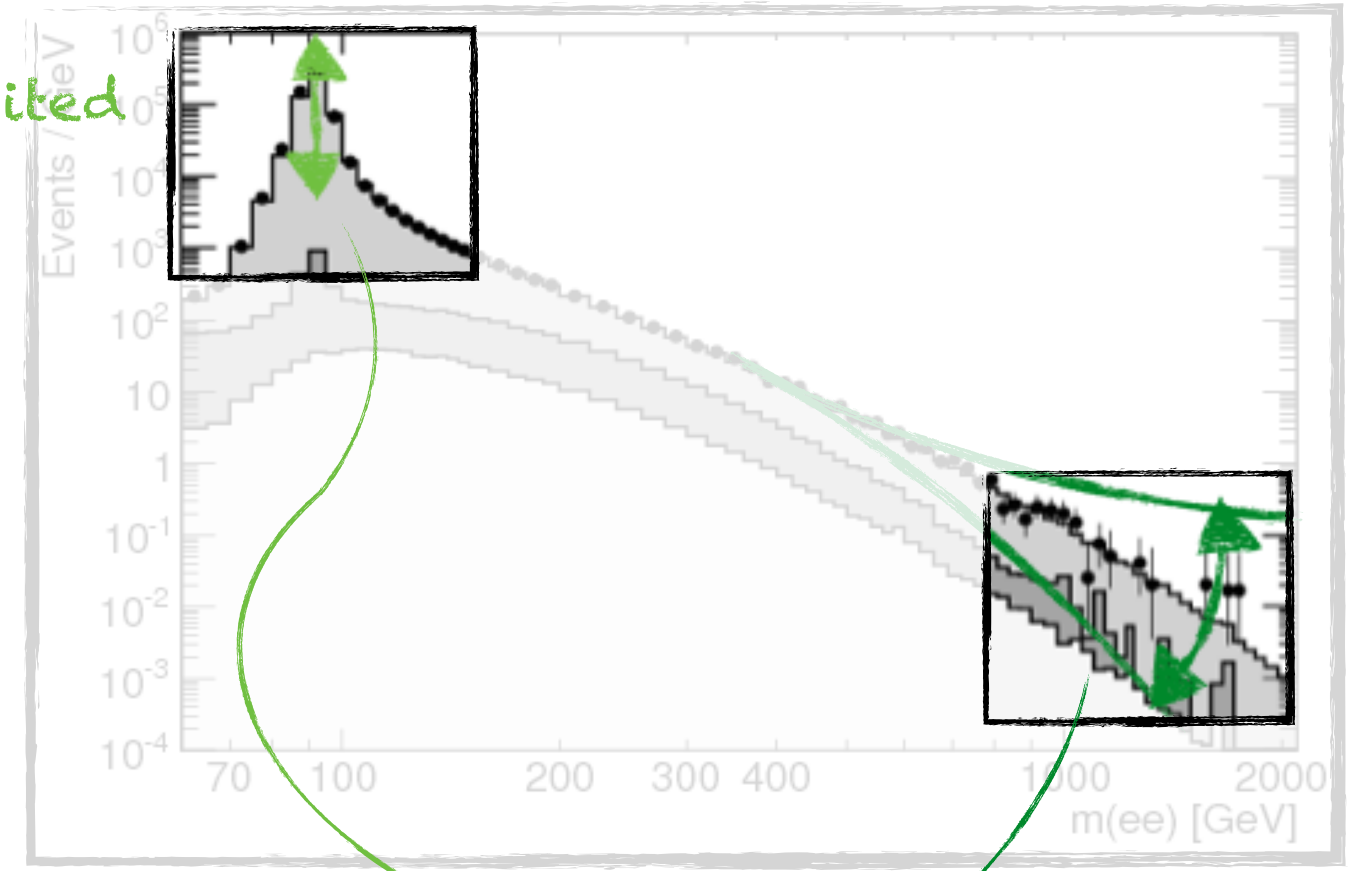
Precision Tests

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

- big statistics
- soon systematic limited



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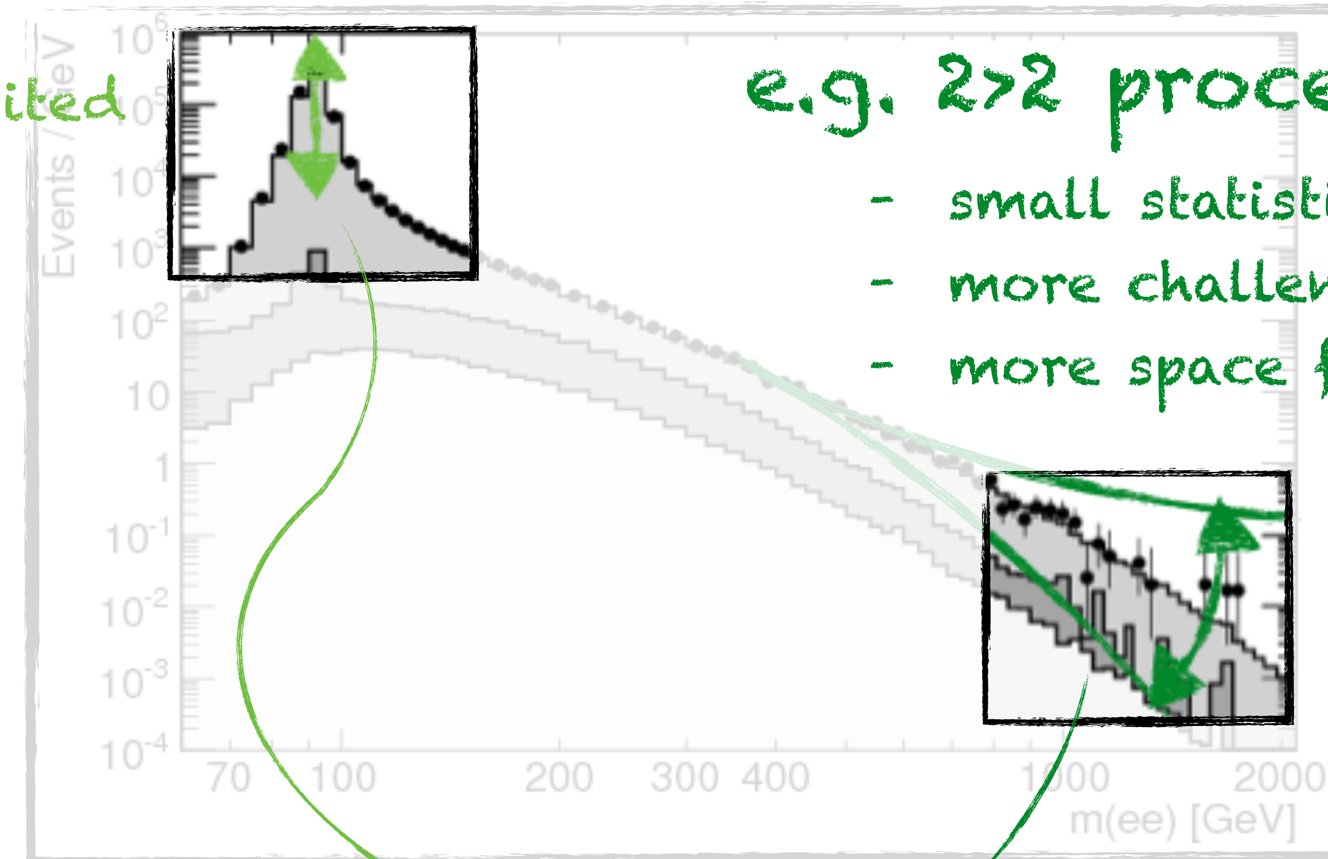

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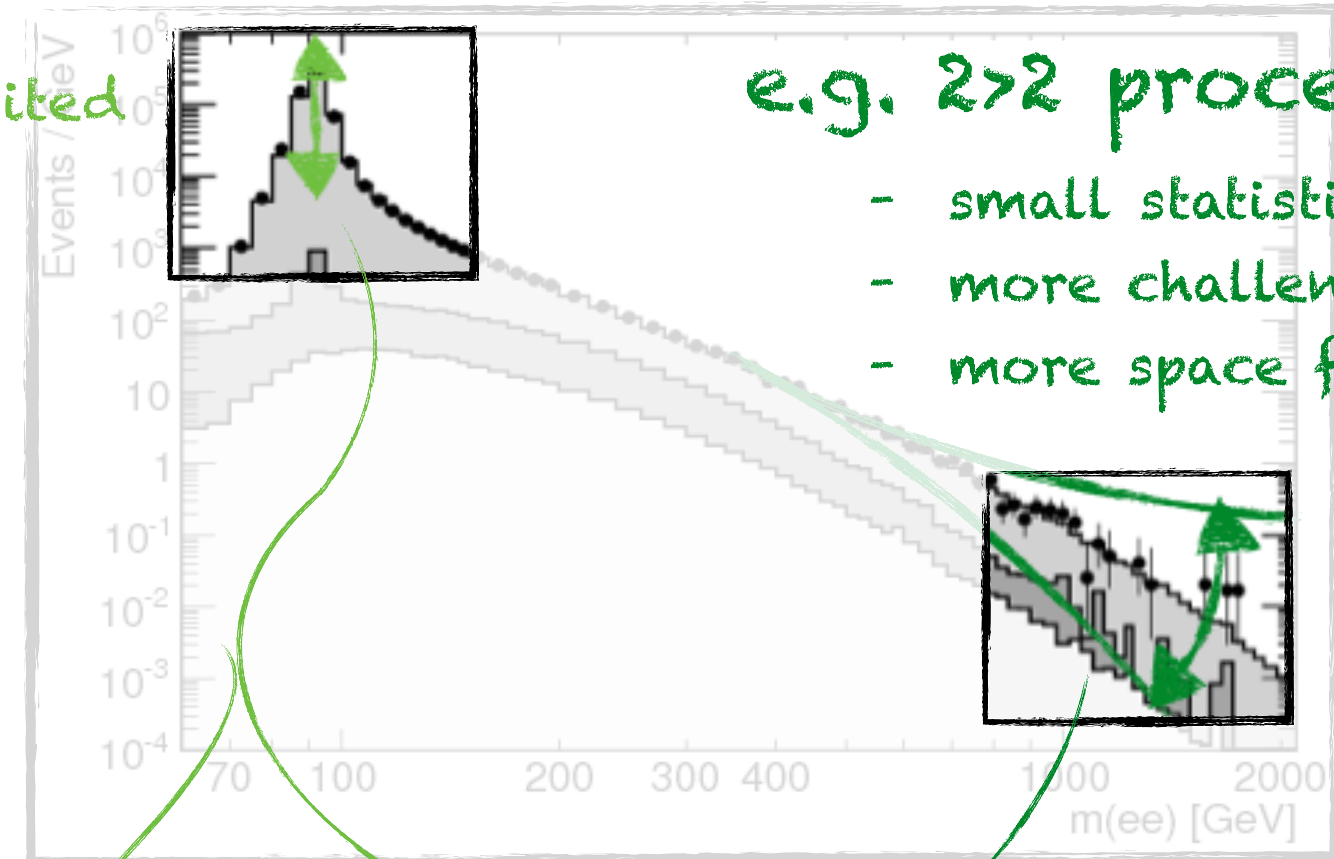

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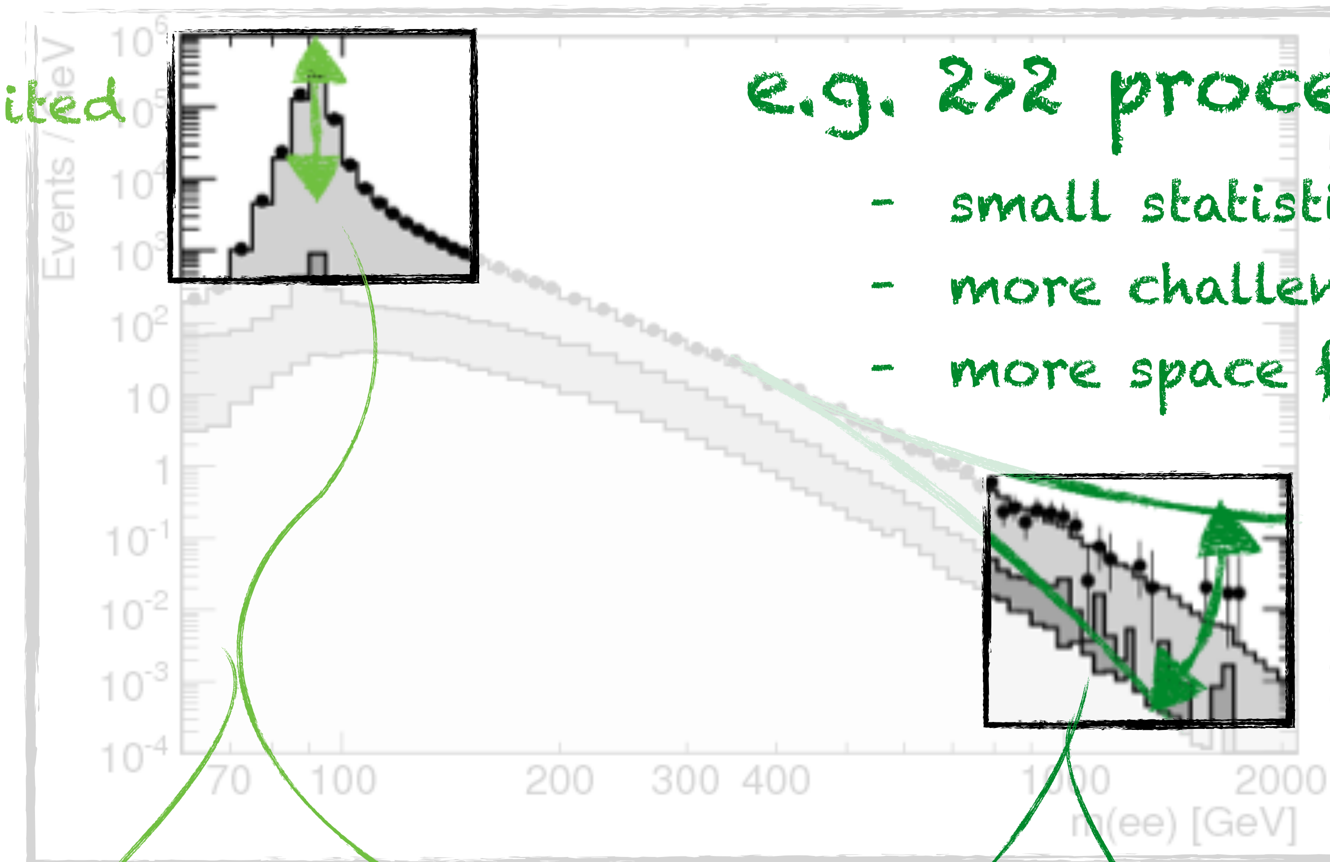

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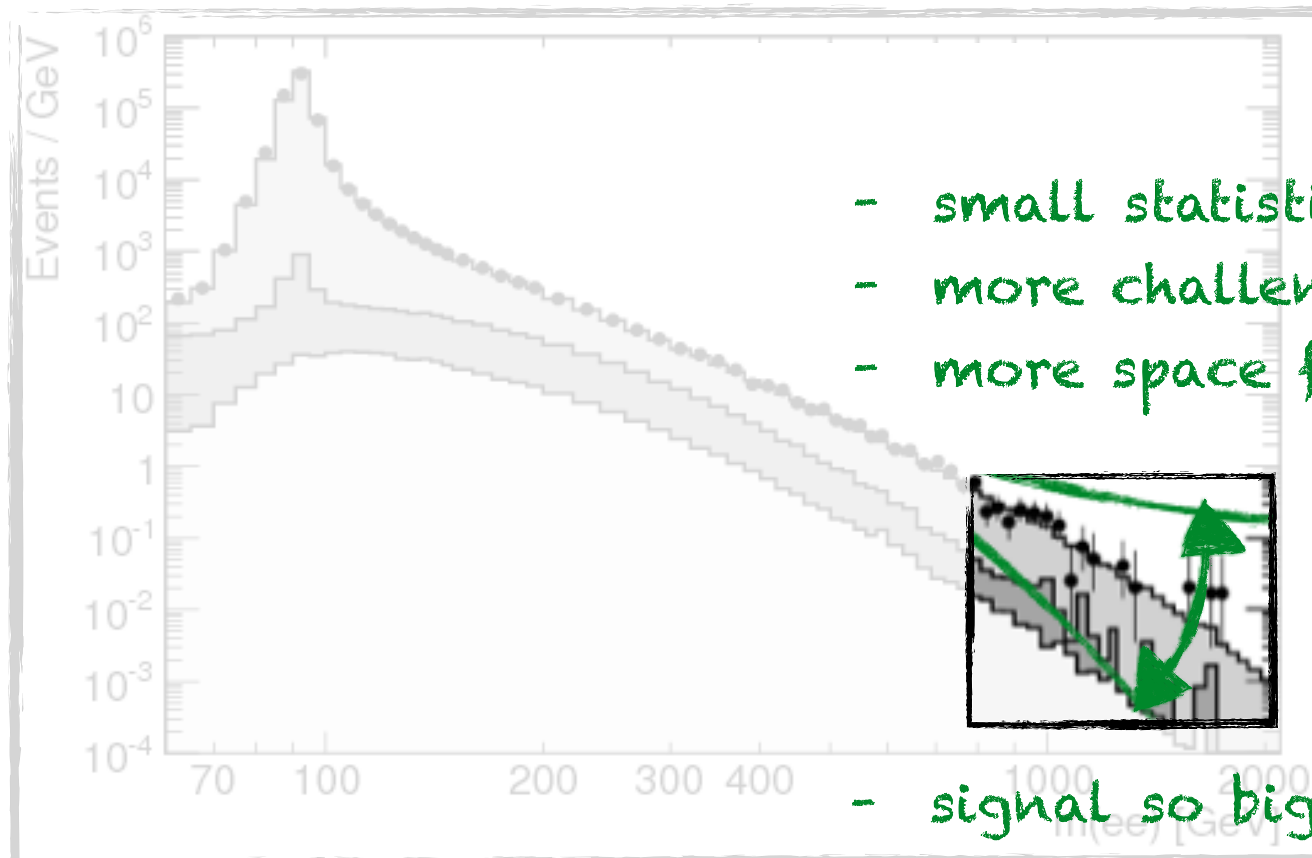
... equivalent to $\left.\dfrac{\delta\sigma}{\sigma_{\rm SM}}\right|_{\sqrt{s}=3\,\rm TeV} \sim 10\%$

(naively not so precise)

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

Precision Tests



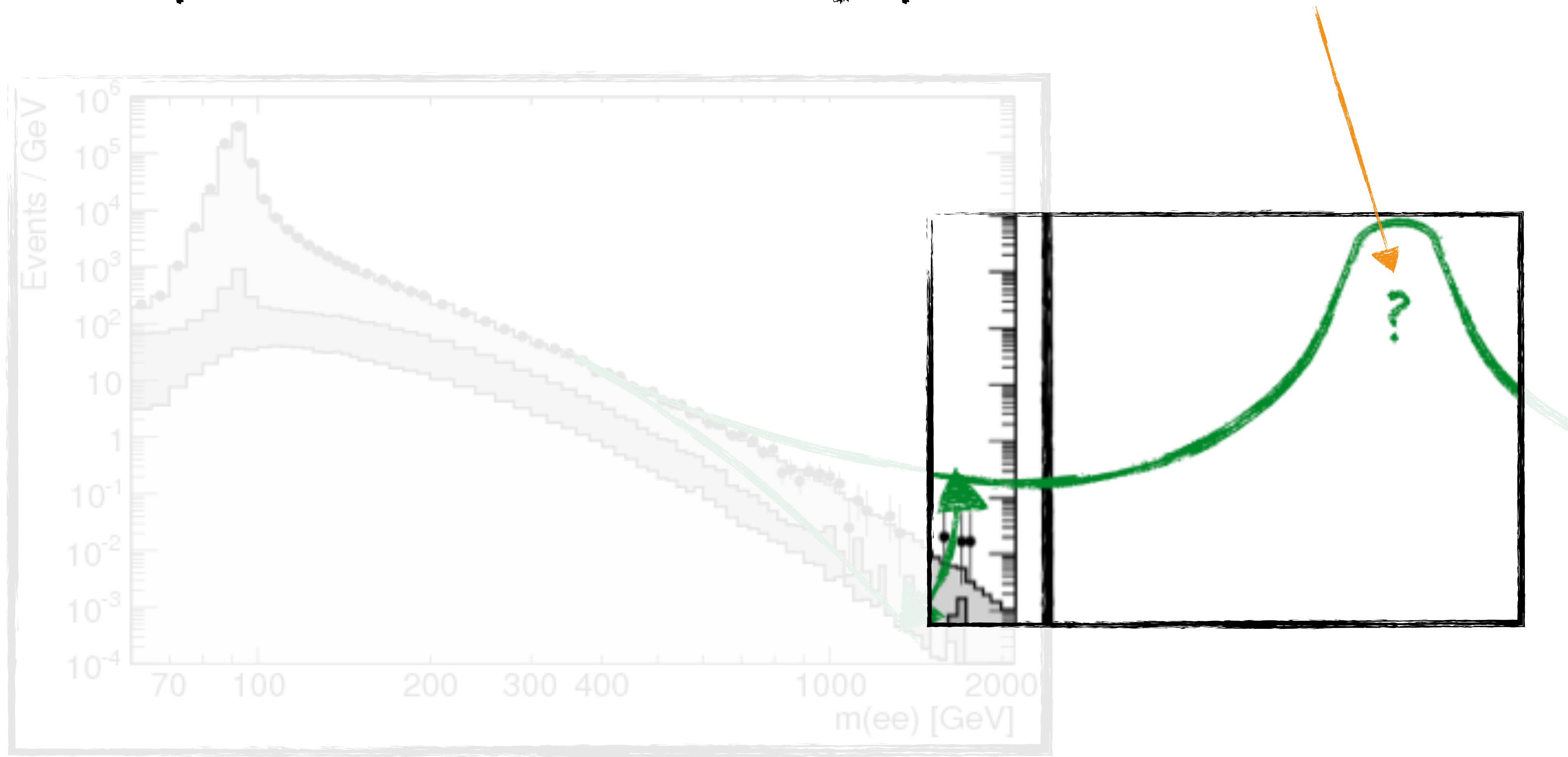
- small statistics
- more challenging measurement
- more space for improvement

- signal so big that even a poor measurement can be precise

Experimentally very appealing

BSM Perspective

What do we expect from a theory point of view?



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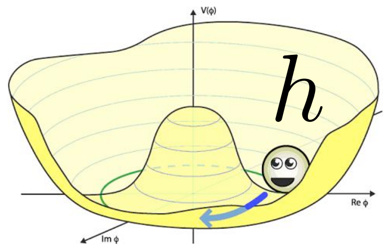
What do we expect from a theory point of view?

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

(it's natural, because a Pion is natural)



Giudice,Grojean,Pomarol,Rattazzi'08;
Pomarol,FR'12

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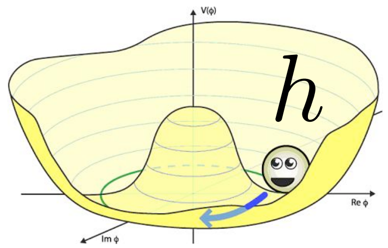

SM

BSM

$$h \longrightarrow \sin h = (h - \frac{h^3}{3!} + \cdots)$$

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

Giudice,Grojean,Pomarol,Rattazzi'08;
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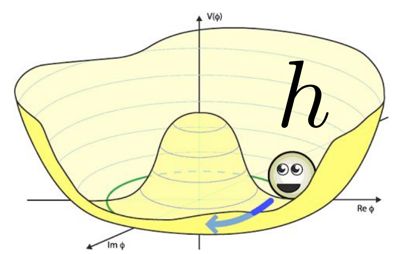
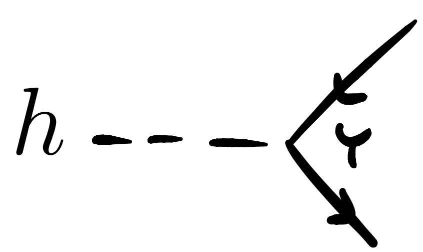
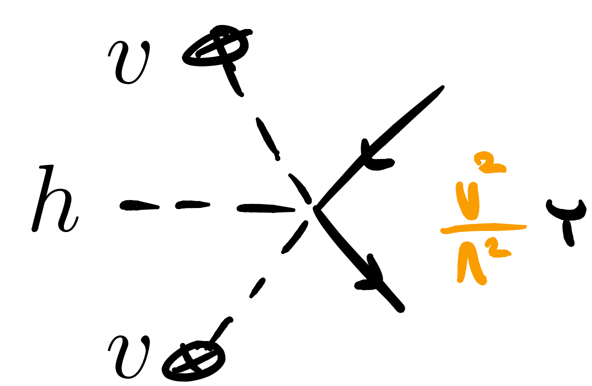


SM		BSM
h	$\longrightarrow$	$\sin h \;=(h-\dfrac{h^3}{3!}+\cdots)$
$\bar\psi\psi h$		$\bar\psi\psi h \;+c\,\bar\psi\psi h^3$





All tree-level Higgs Couplings are modified

Giudice,Grojean,Pomarol,Rattazzi'08;
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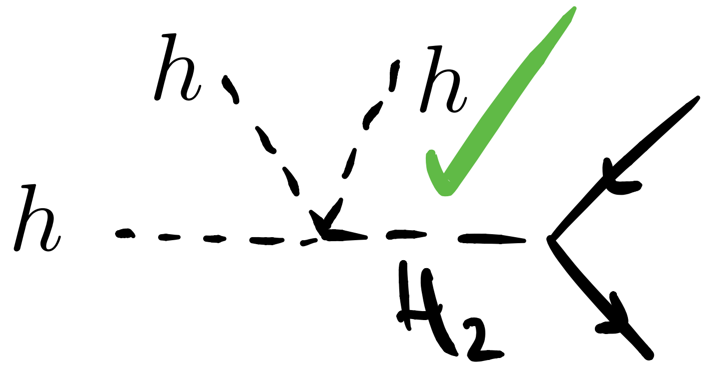
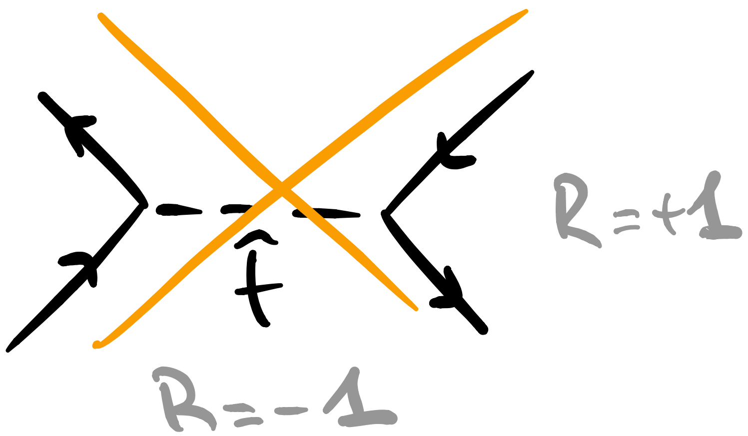
Supersymmetry: only H_2 (second Higgs) exchanged at tree-level (R-parity)





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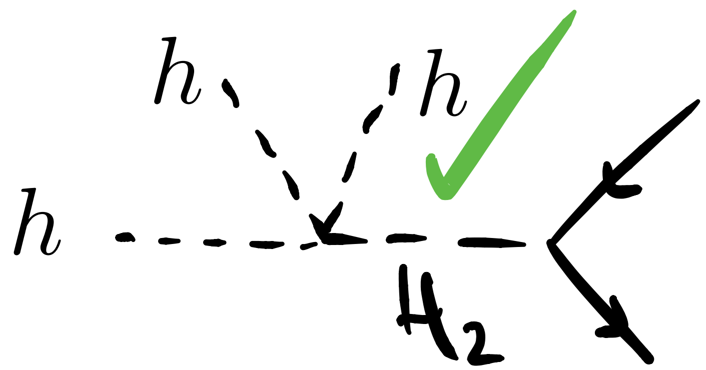
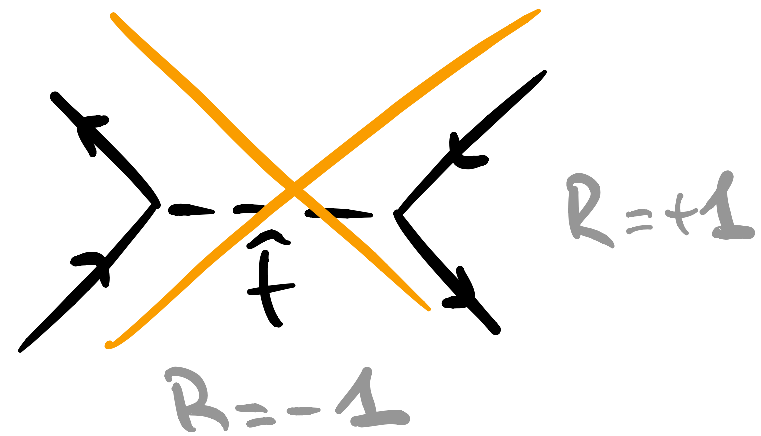
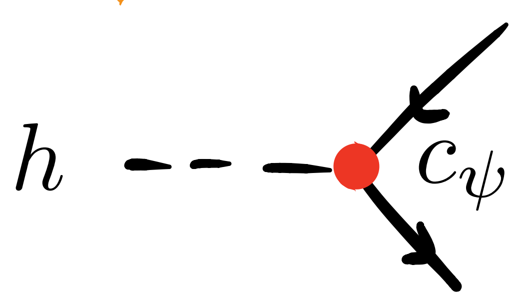




$E \ll m_{H2}$



$$c_{b,\tau} \approx 1 - 4\tan\beta\,\delta\,\frac{v^2}{m_{H_2}^2}\,,$$
$$c_t \approx 1 + 4\cot\beta\,\delta\,\frac{v^2}{m_{H_2}^2}\,.$$

Gupta, Montull, FR'12

Higgs couplings to top/bottom are modified

BSM Perspective

What do we expect from a theory point of view?

▼

Higgs couplings

Are among the most important tests of new physics

(reasons: hierarchy problem, h-sector unexplored)

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

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

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

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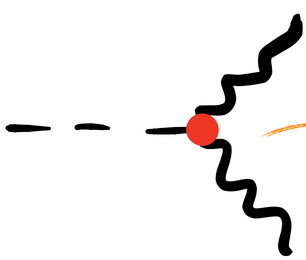

$V = W, Z, \gamma, g$

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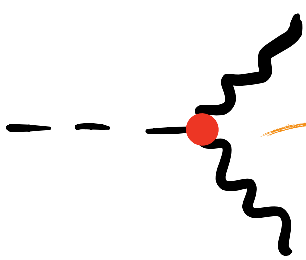

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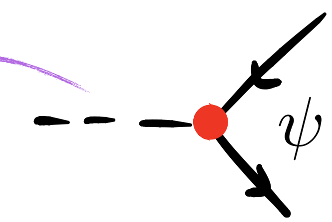

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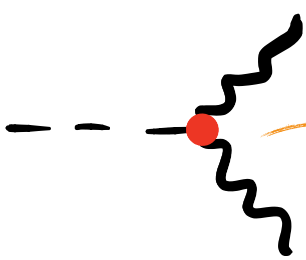

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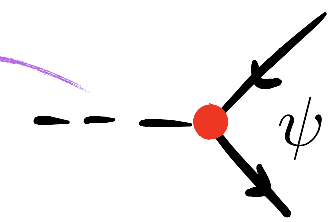

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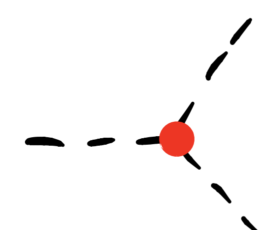

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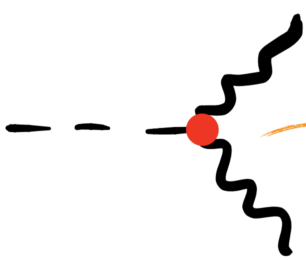

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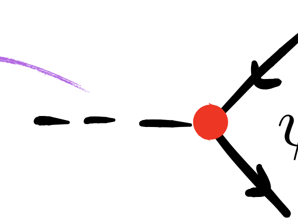

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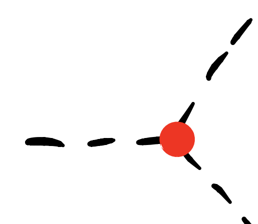

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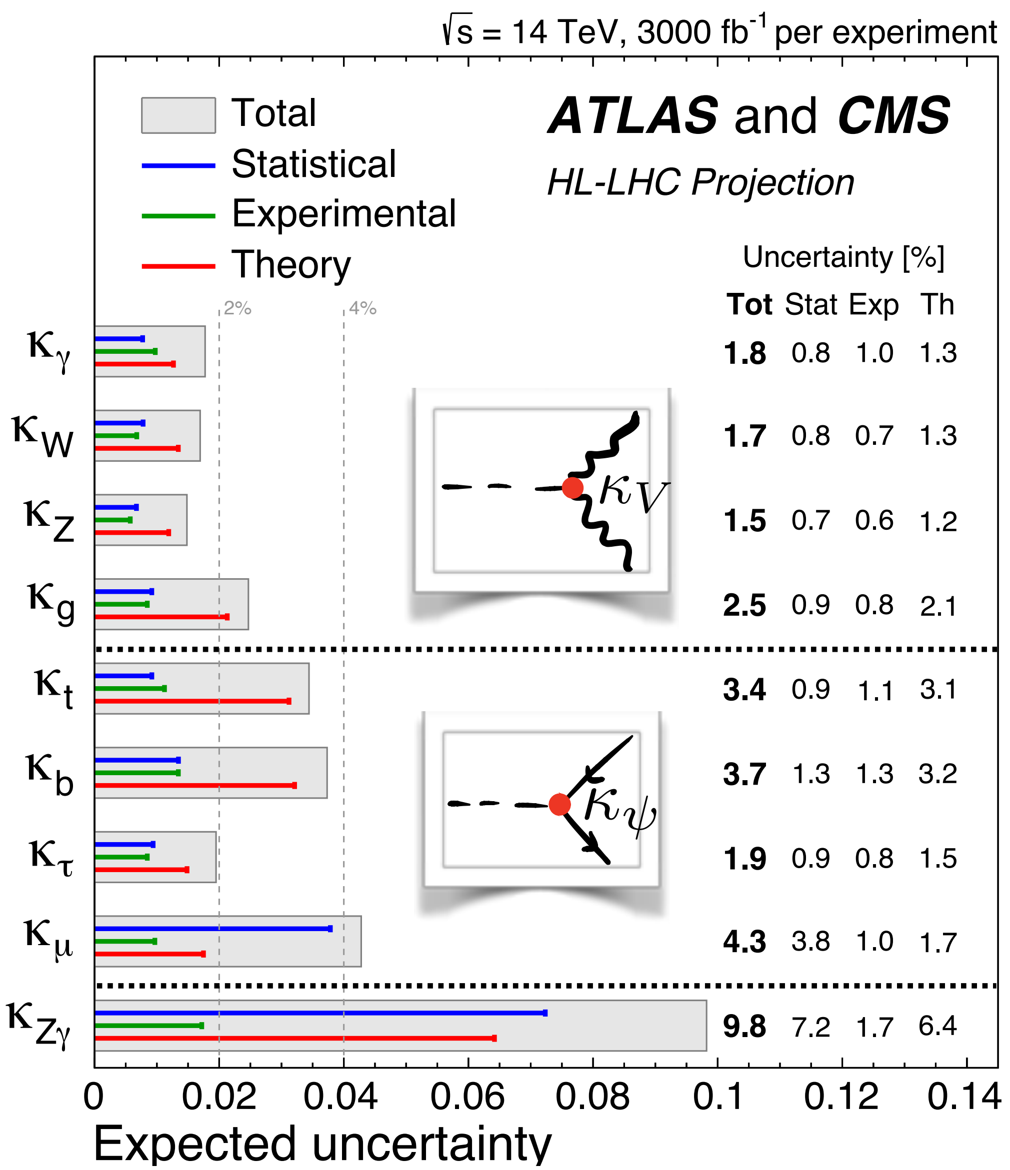
...and more

HL-LHC Reach (3000 fb-1)

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



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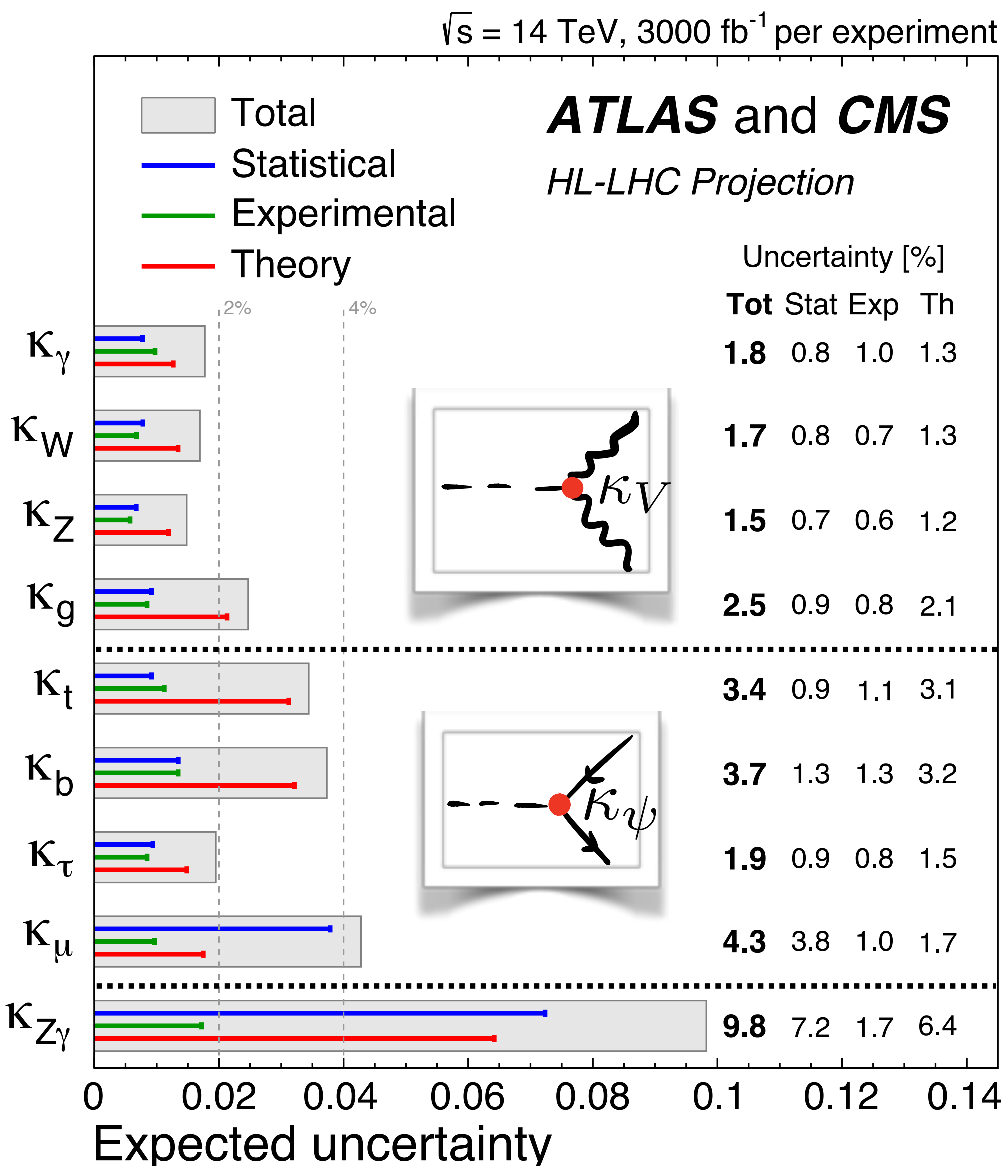

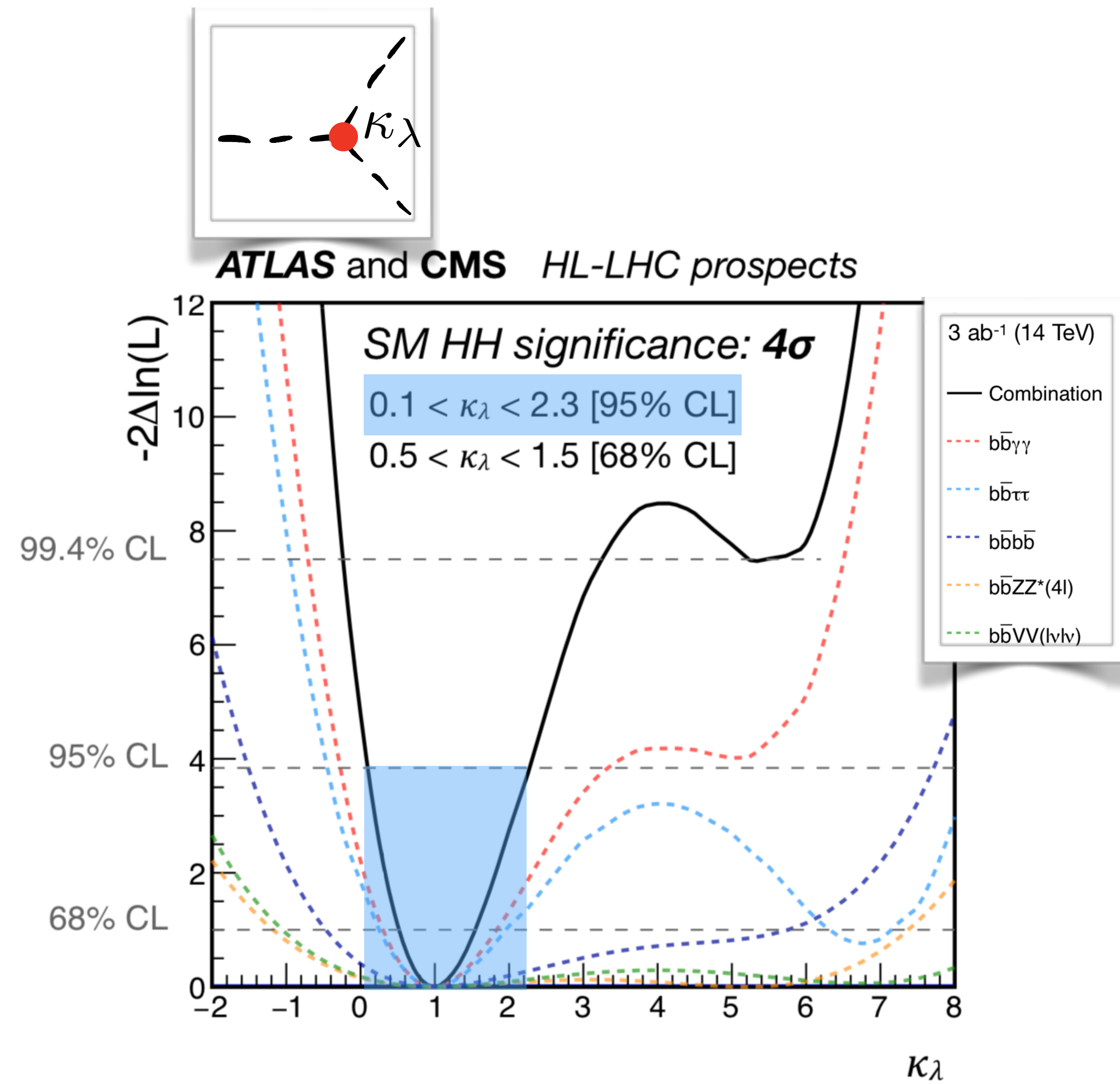

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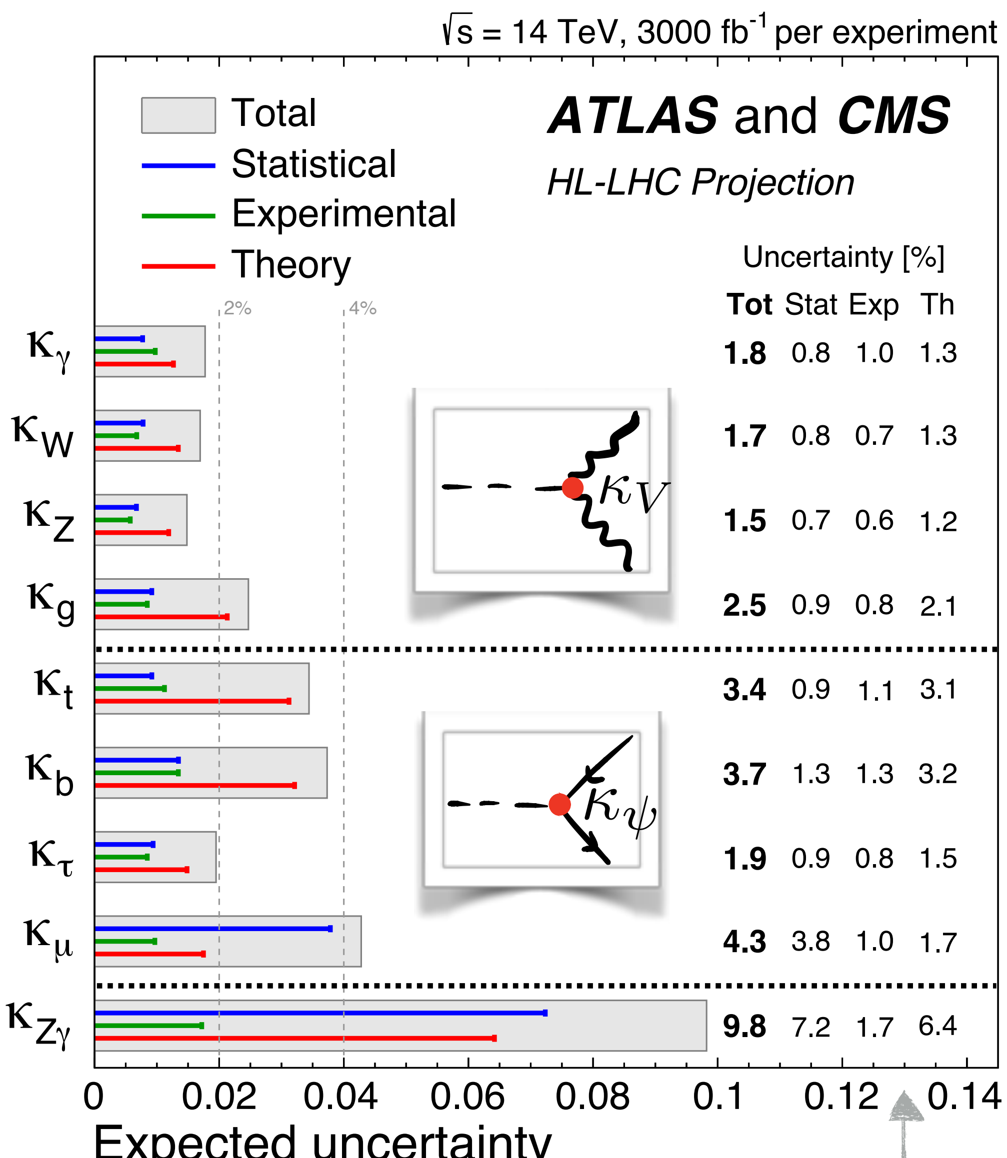
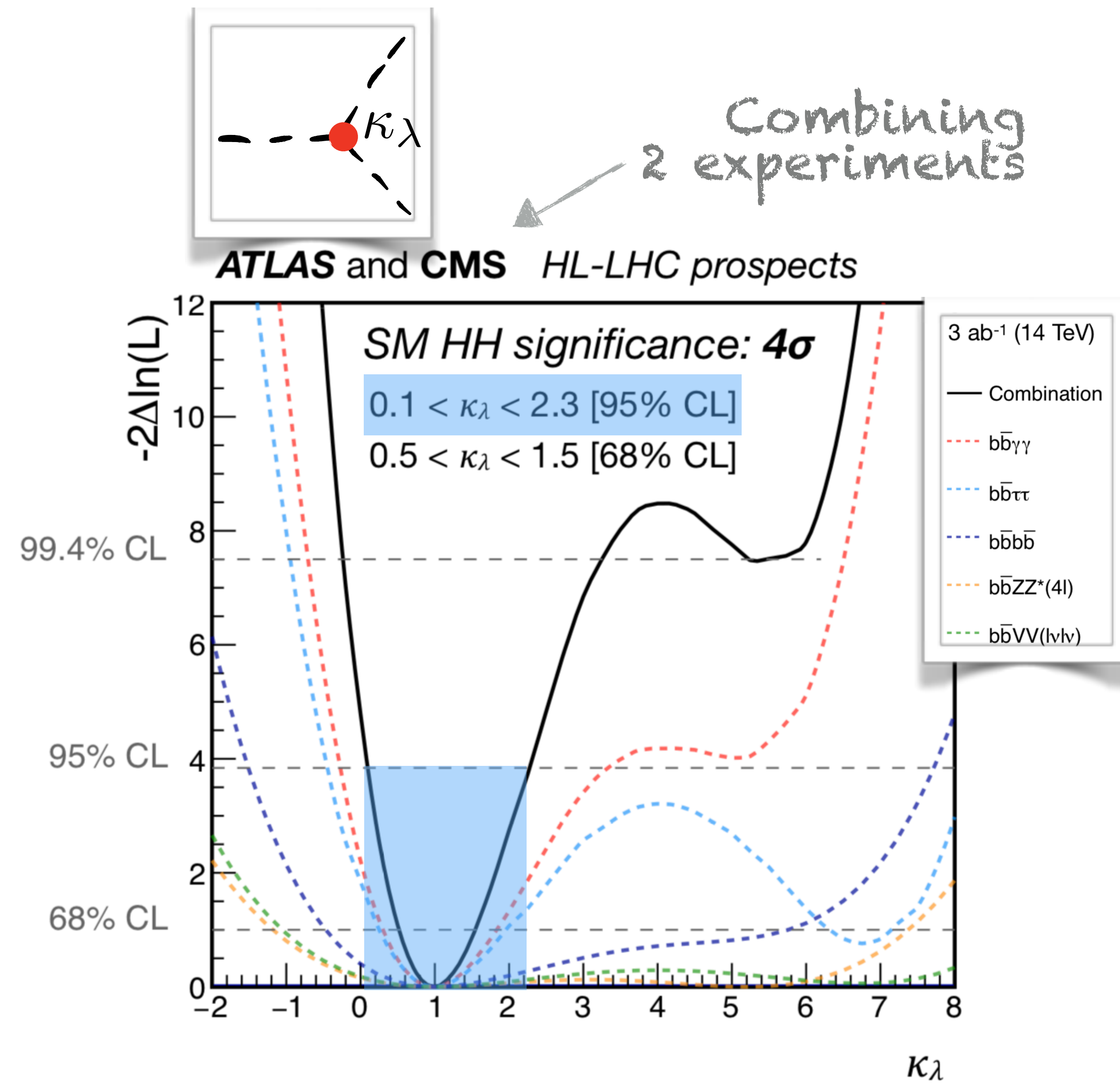


Optimistic Systematics (S2)



Combining 2 experiments

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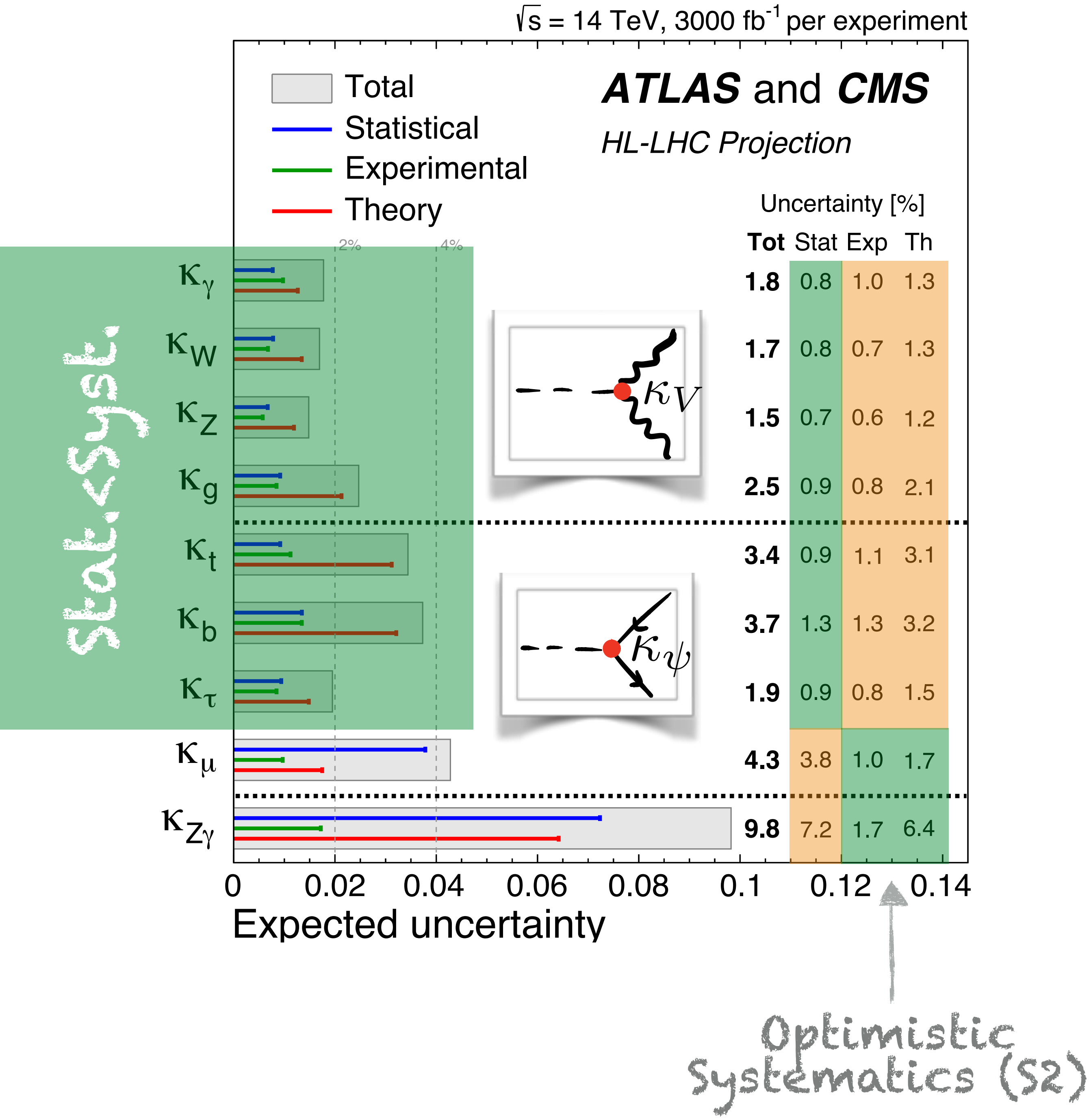
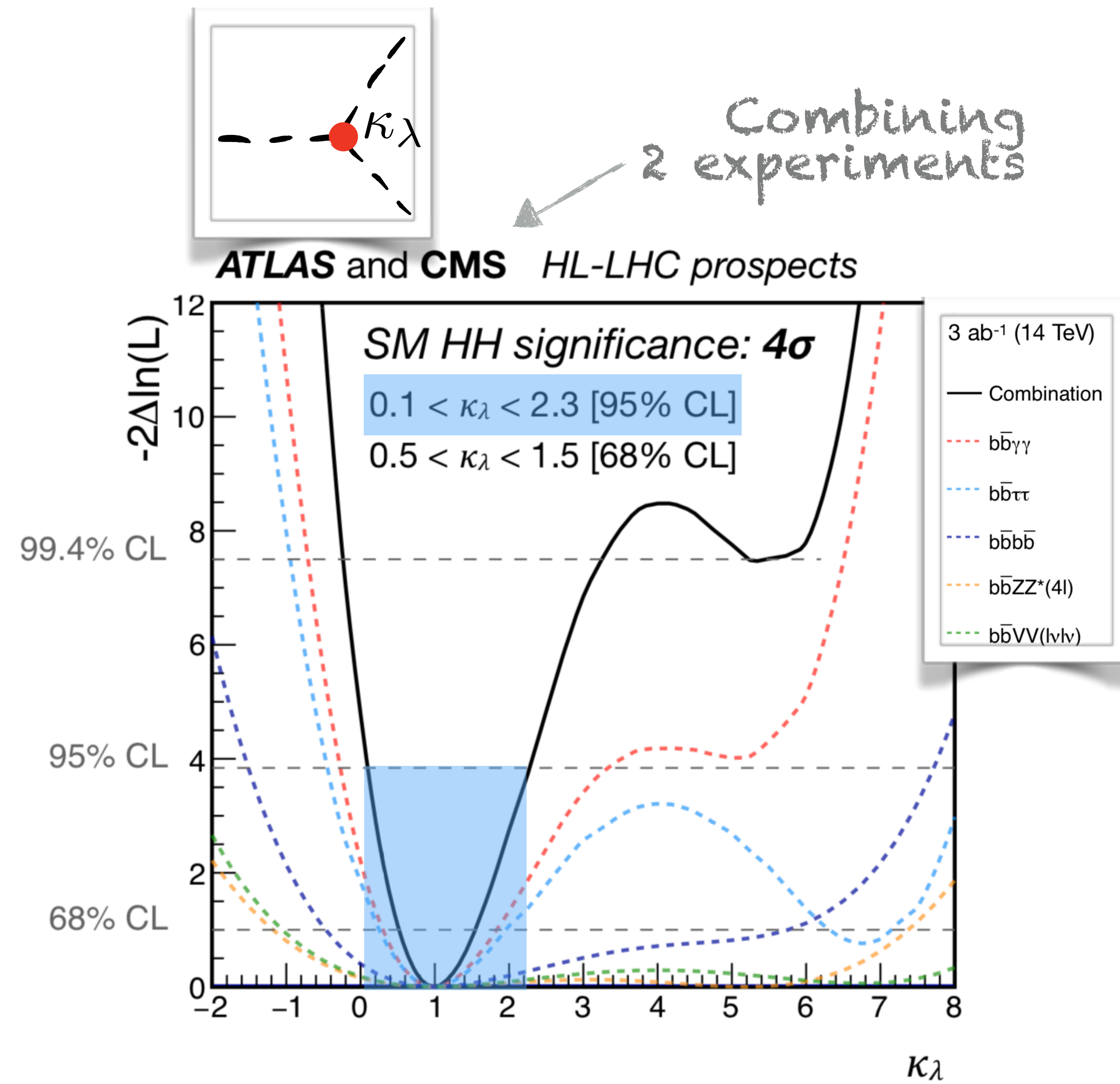
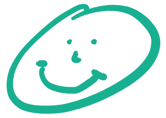




Higgs Couplings at High-Energy

Higgs couplings: Theoretically Interesting 

Experimentally not High-E measurements 

ZH, WH or VBF at high-E? Higgs Couplings: no Energy-growth in Higgs processes

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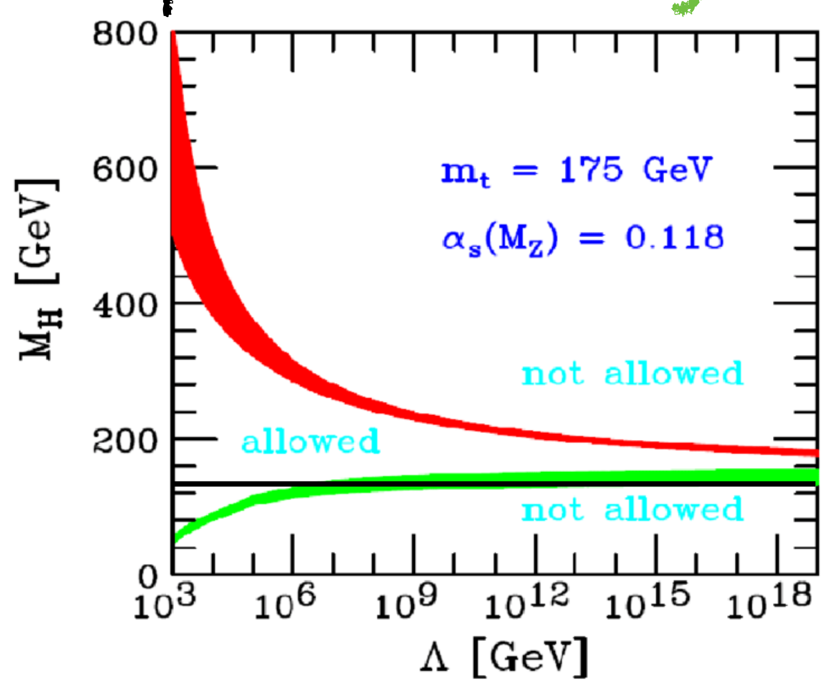
SM is the unique theory, with its particle content, valid up to arbitrary energy:



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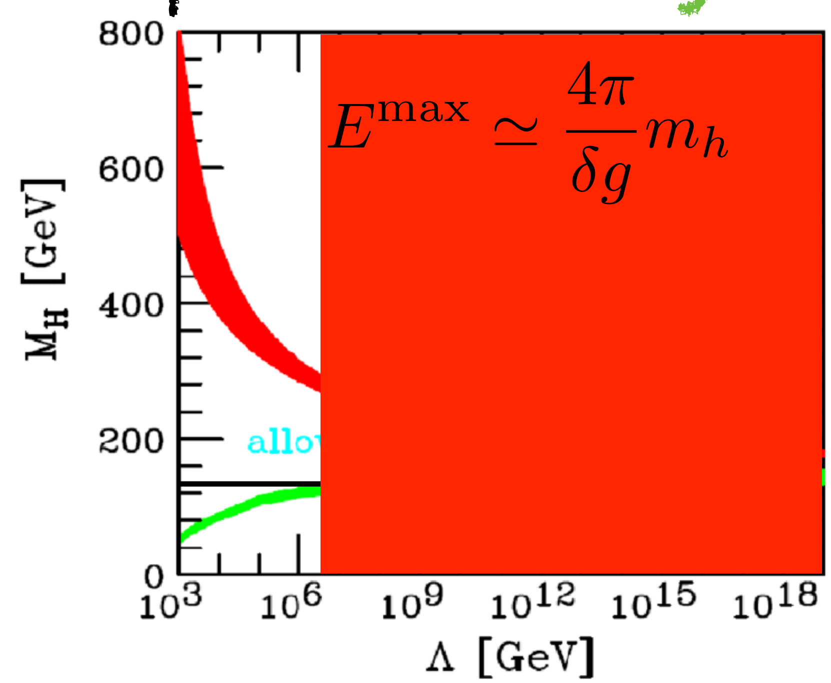

Any coupling modification must induce energy-growth in some process, reducing the validity energy-range

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!

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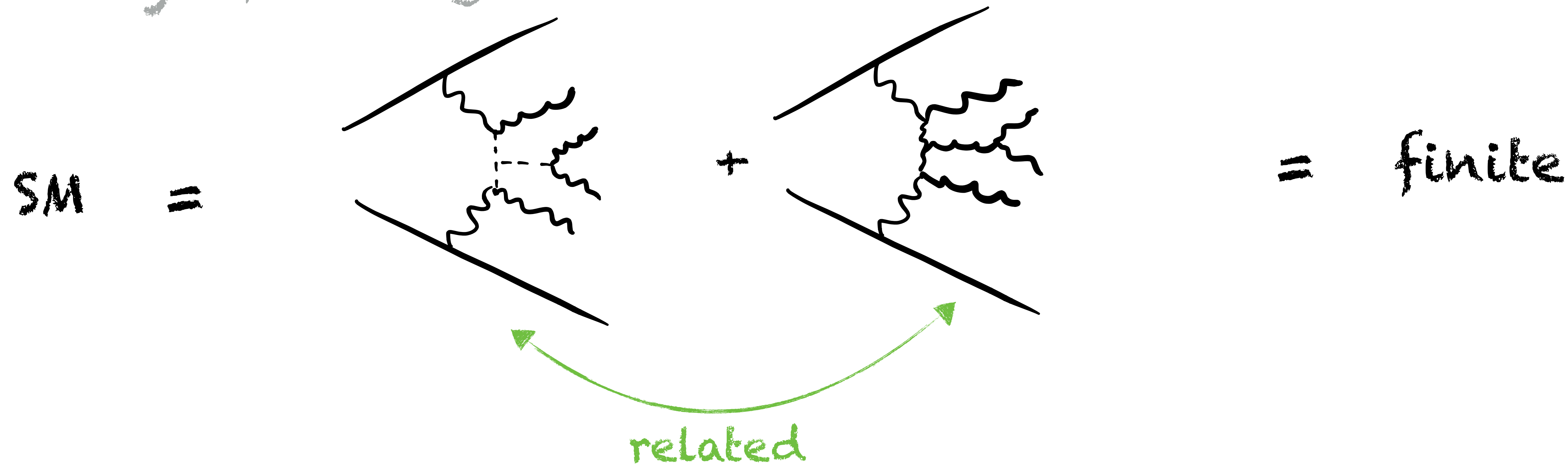

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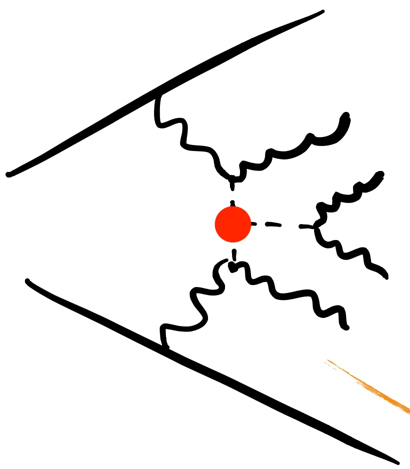
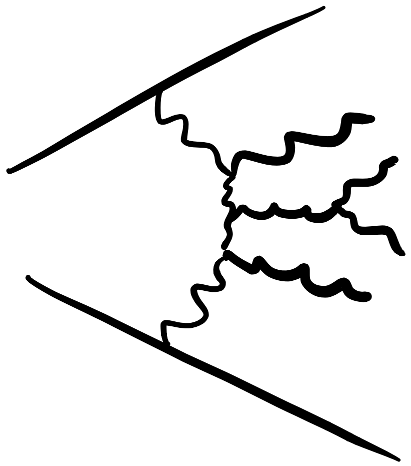


+



= 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

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

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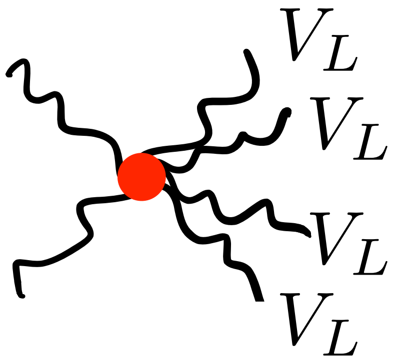

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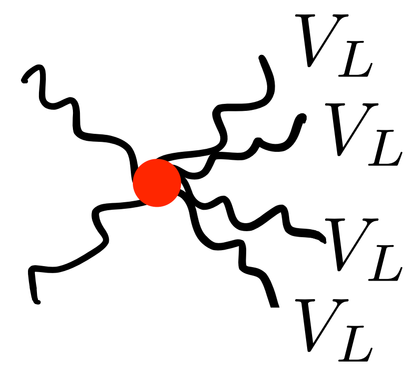

$\sim \frac{E^2}{\Lambda^2}$ w.r.t SM

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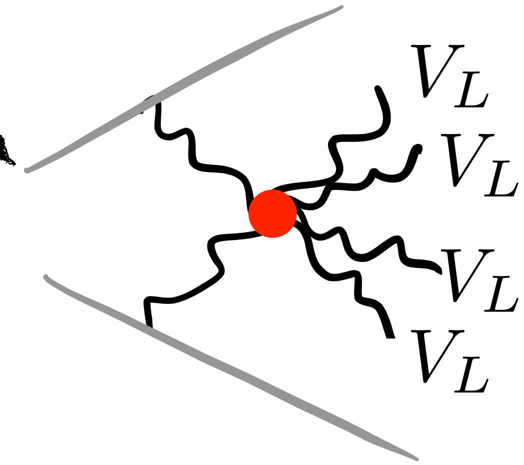

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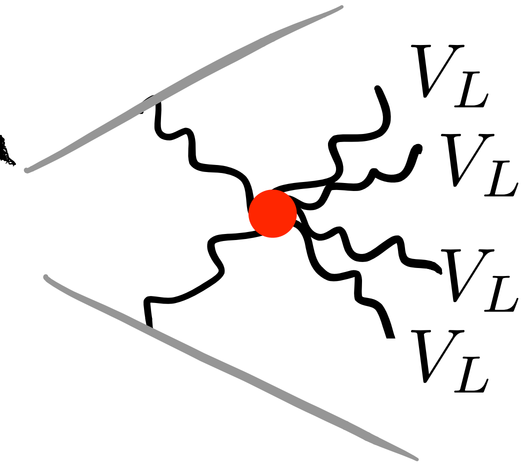

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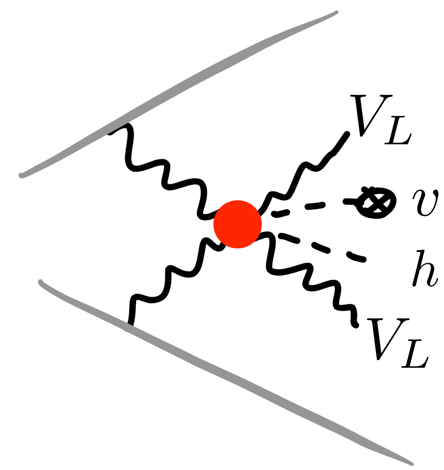

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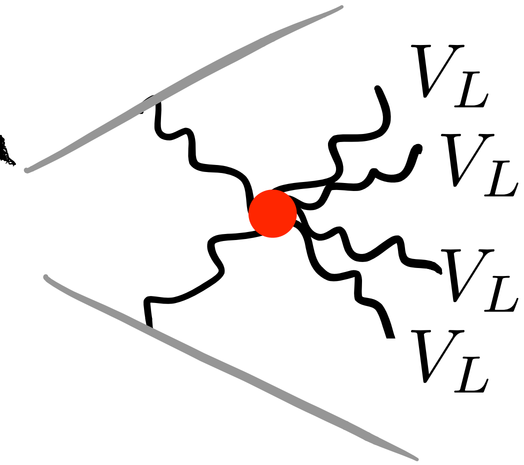

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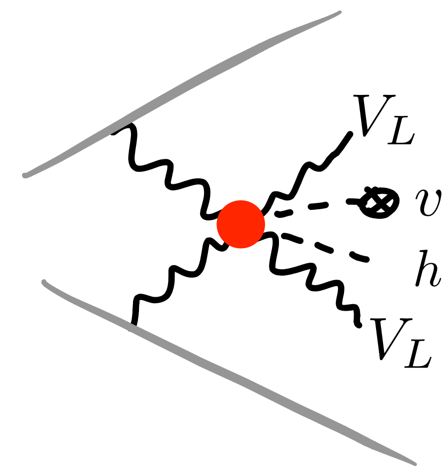

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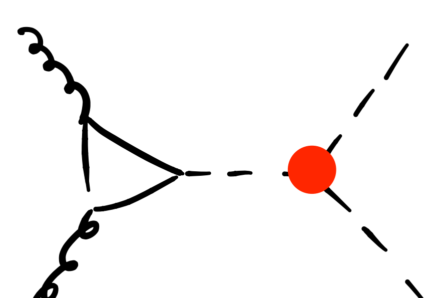
$pp \to jjh + V_L V'_L$

with 3 Higgs v.e.v.s

(= traditional Higgs Coupling measurement)



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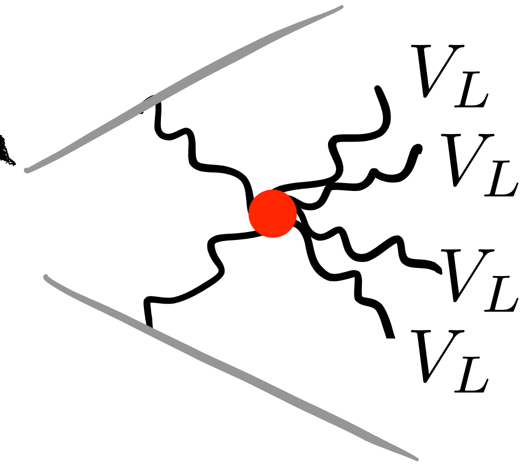

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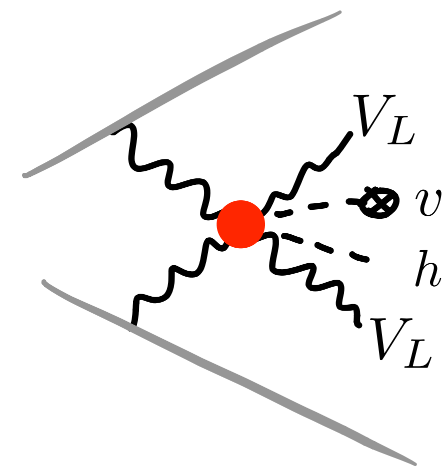

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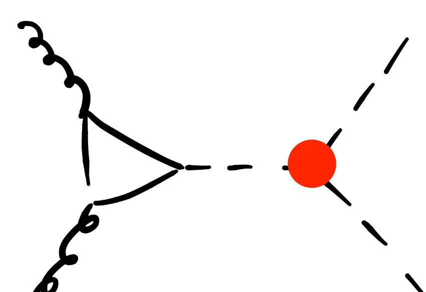

$\sim \frac{v^2}{\Lambda^2}$

signal

statistics

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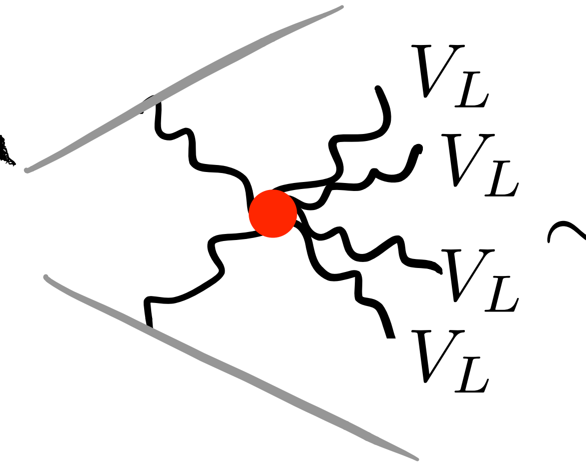

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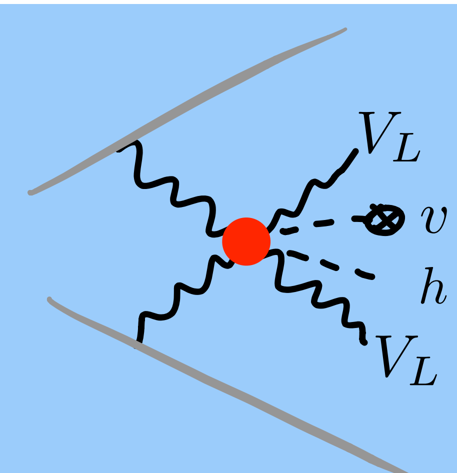

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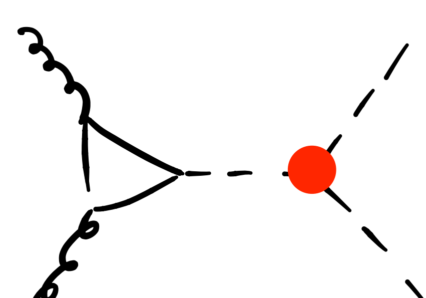

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Higgs Self Coupling

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

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$W \to l + \nu$ → Same-sign leptons

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

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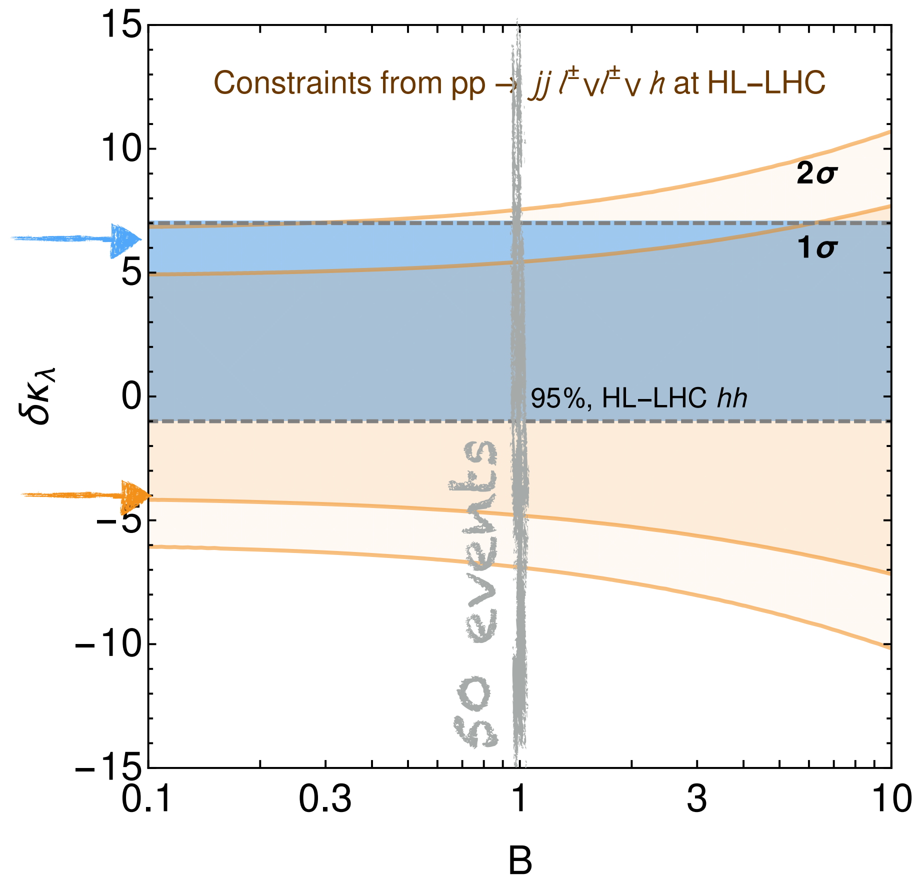
Standard Higgs Coupling Measurements (HC)

High-E Higgs without Higgs (HwH)



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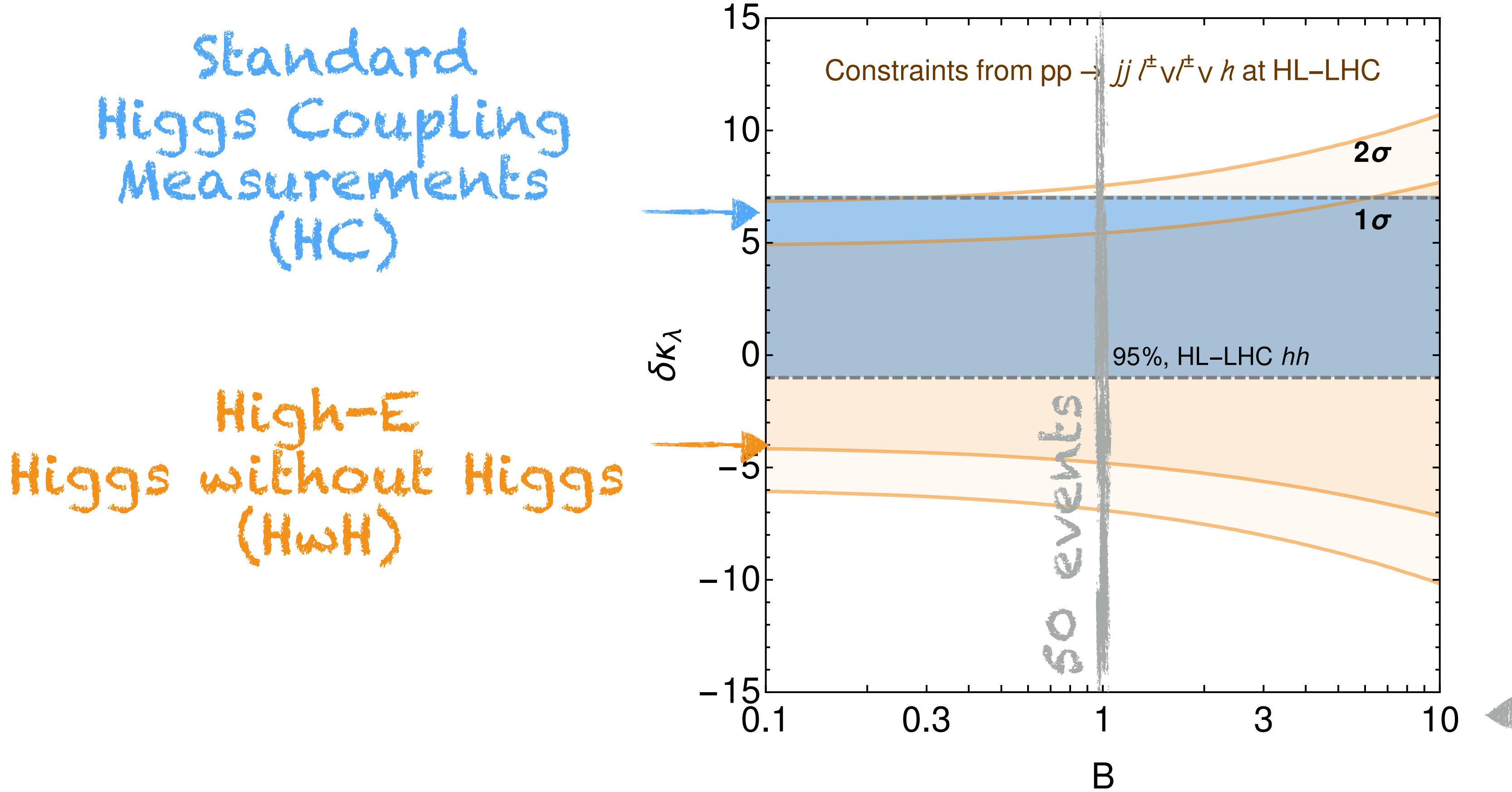
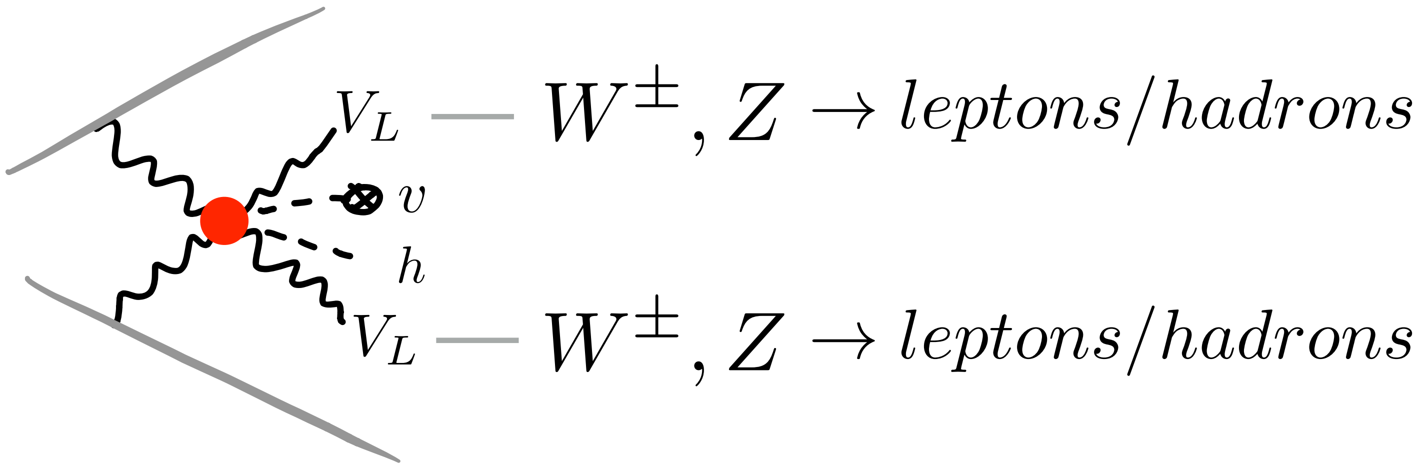


- HwH: single channel, simple analysis, competitive with HC!

Higgs Self Coupling

... endless possibilities of improvement ...

- More Final states



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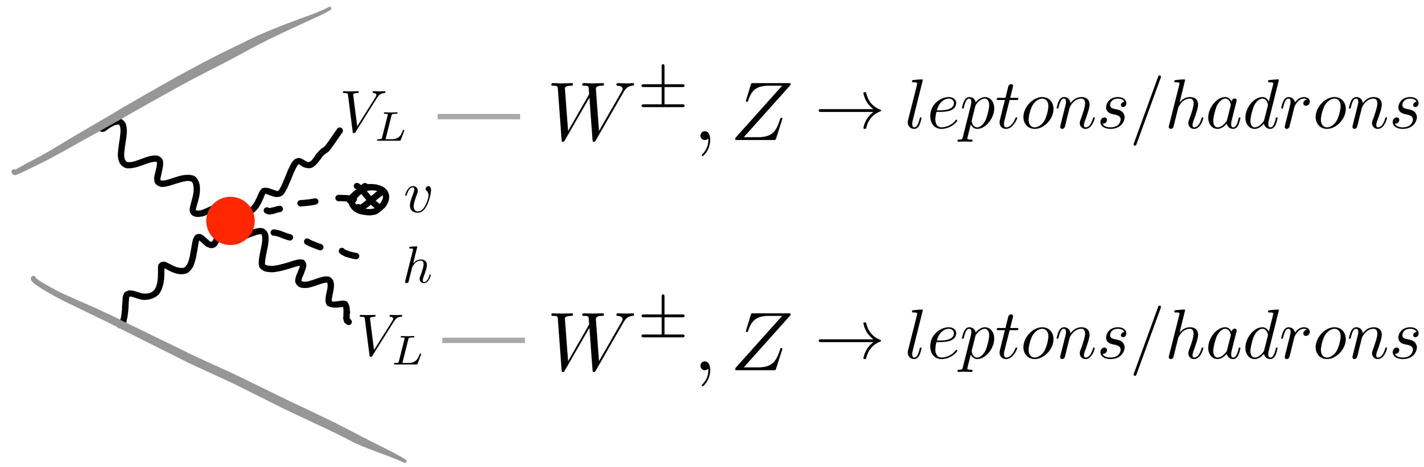
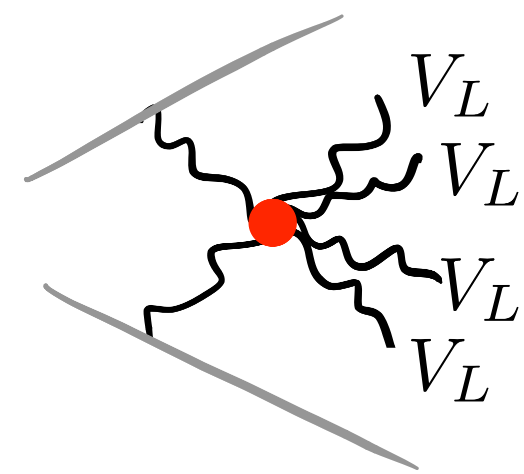


- Look also at E²-growing processes



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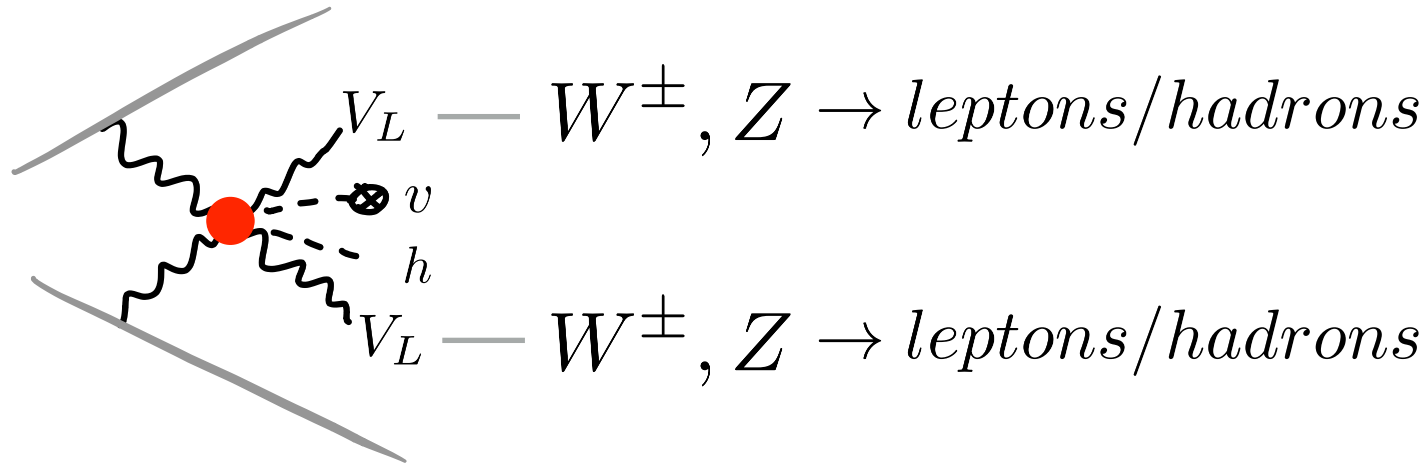

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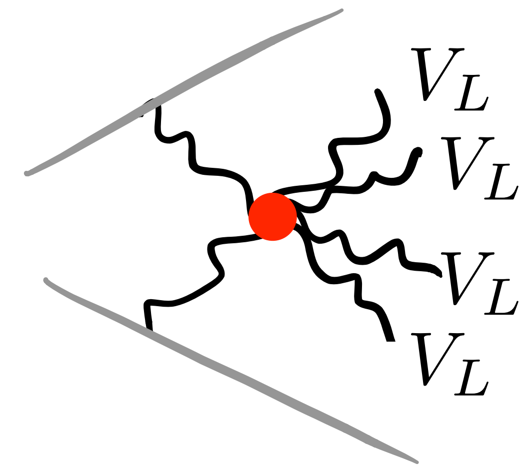

- Keep differential information to exploit E-growth

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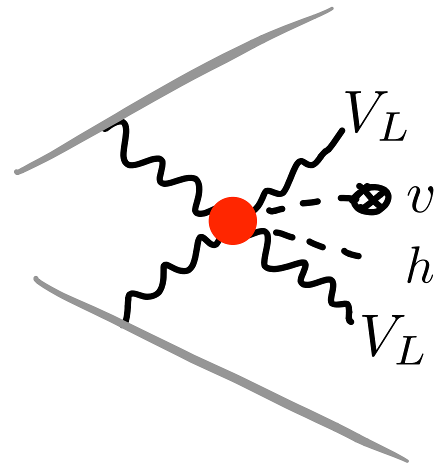
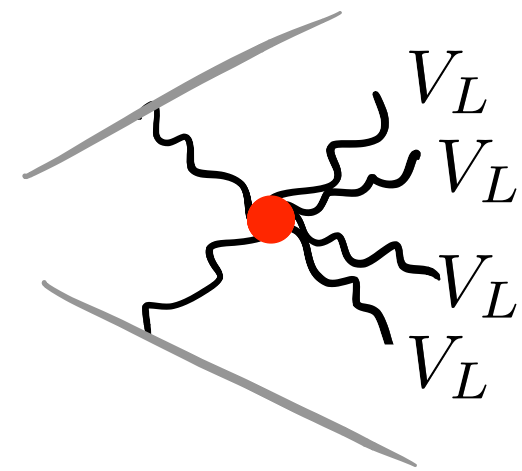


- Look also at E^2-growing processes



- Keep differential information to exploit E-growth

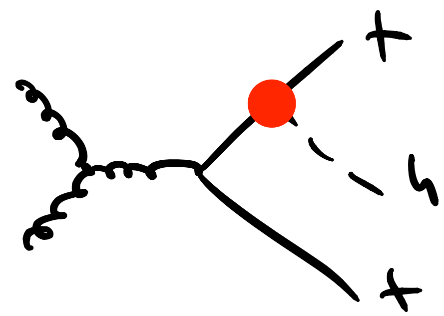
- Develop polarization-sensitive analysis (see Panico,FR,Wulzer'17)
  (SM V_T final states large and not interfering)

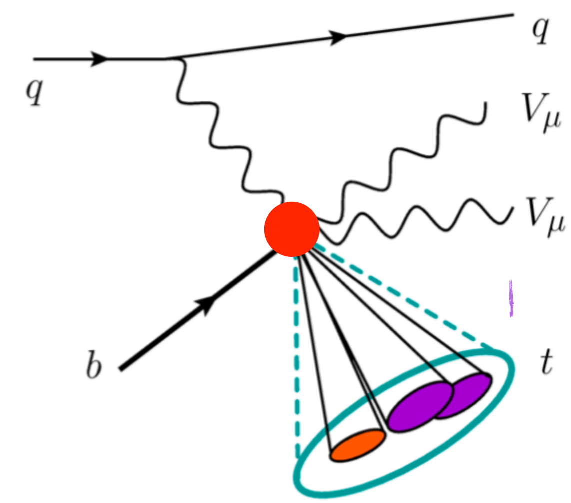
HwH Program

$\sim const$

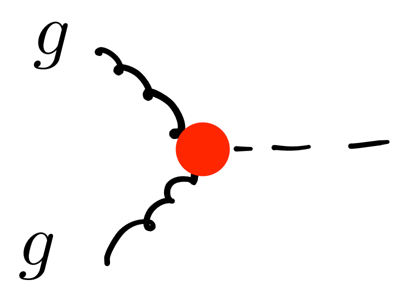
$\sim E^2$

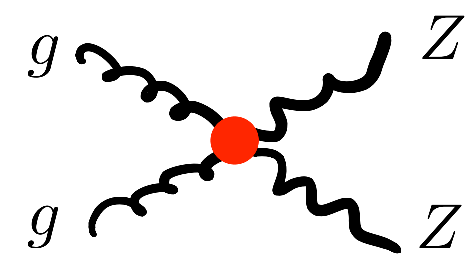
κ_t
$|H|^2 Q\tilde{H} t_R$



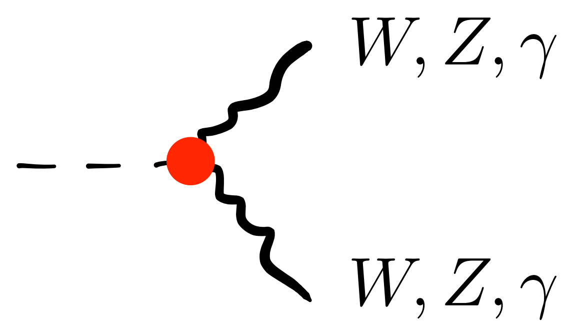


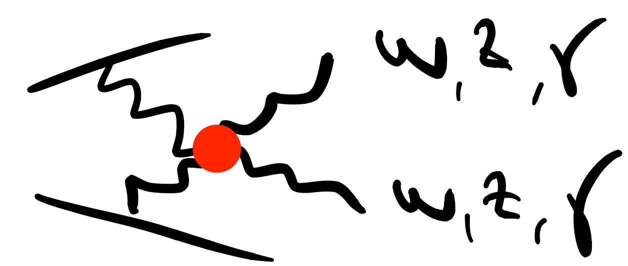
κ_G
$|H|^2 G^a_{\mu\nu} G^{a\,\mu\nu}$



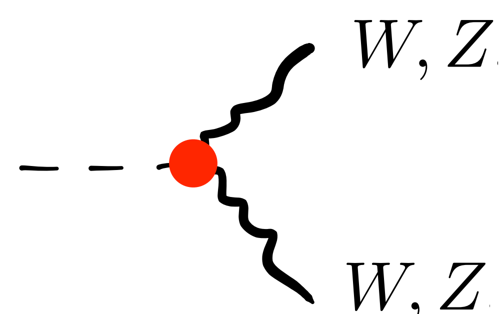


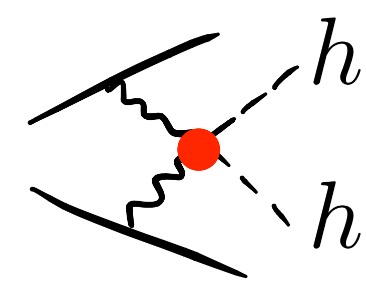
$\kappa_\gamma \quad |H|^2 B_{\mu\nu} B^{\mu\nu}$
$\kappa_{Z\gamma} \; |H|^2 W^a_{\mu\nu} W^{a\,\mu\nu}$





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





HwH Program: top Yukawa

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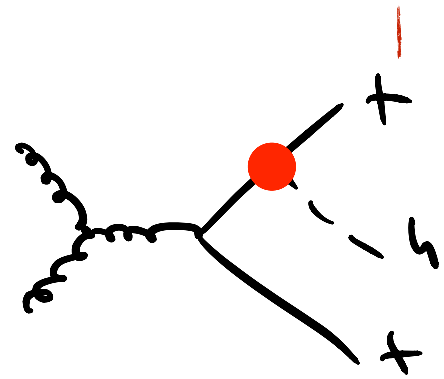
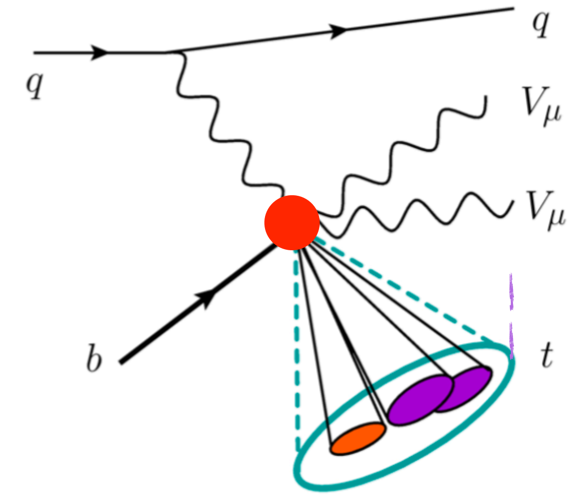
$|H|^2 Q\tilde{H} t_R$



$\sim E^2$

signal enhanced

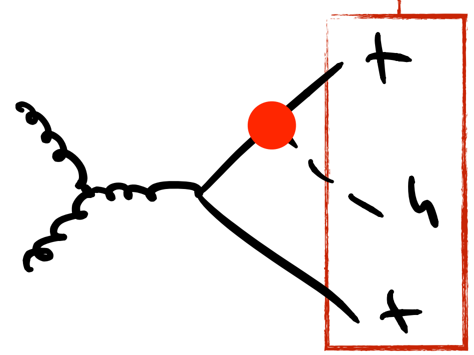


HwH Program: top Yukawa

κ_t

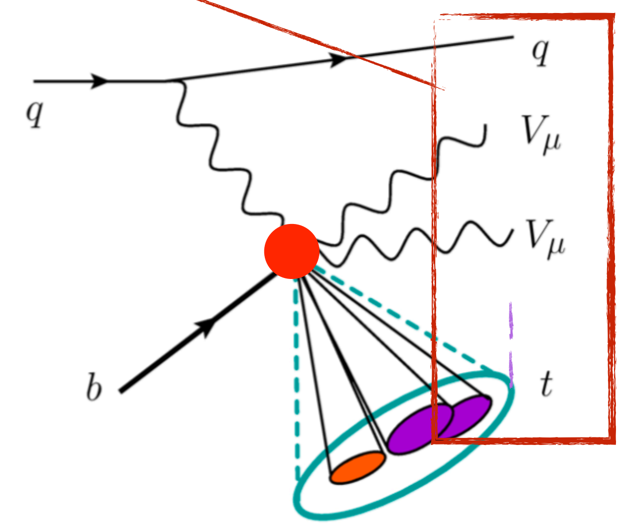
$|H|^2 Q\tilde{H} t_R$

lower threshold



$\sim E^2$

signal enhanced



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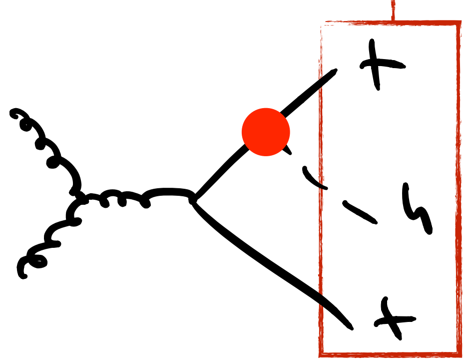

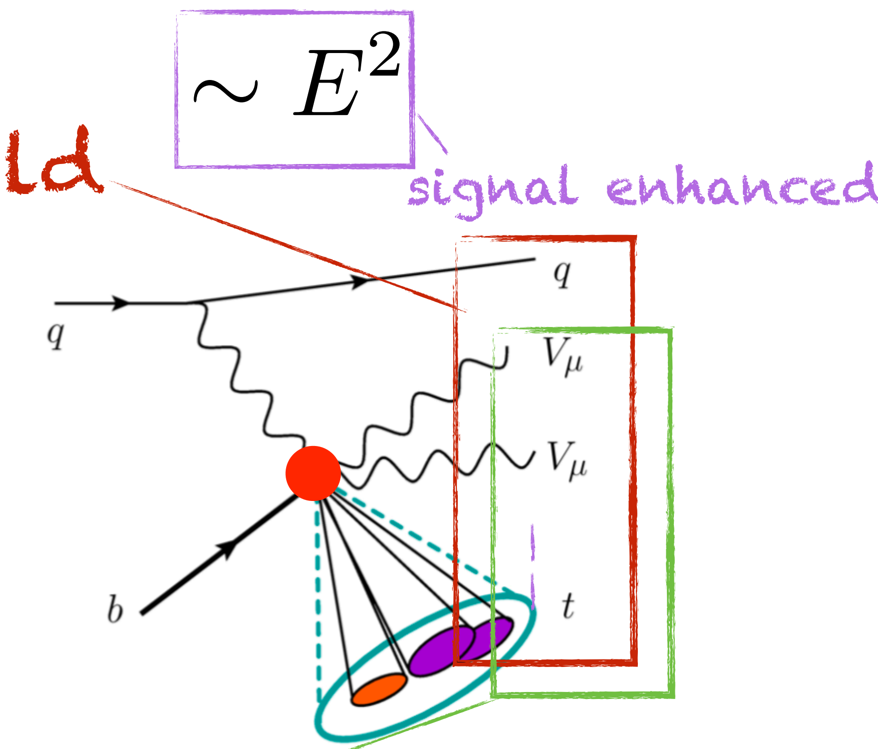

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κ_t

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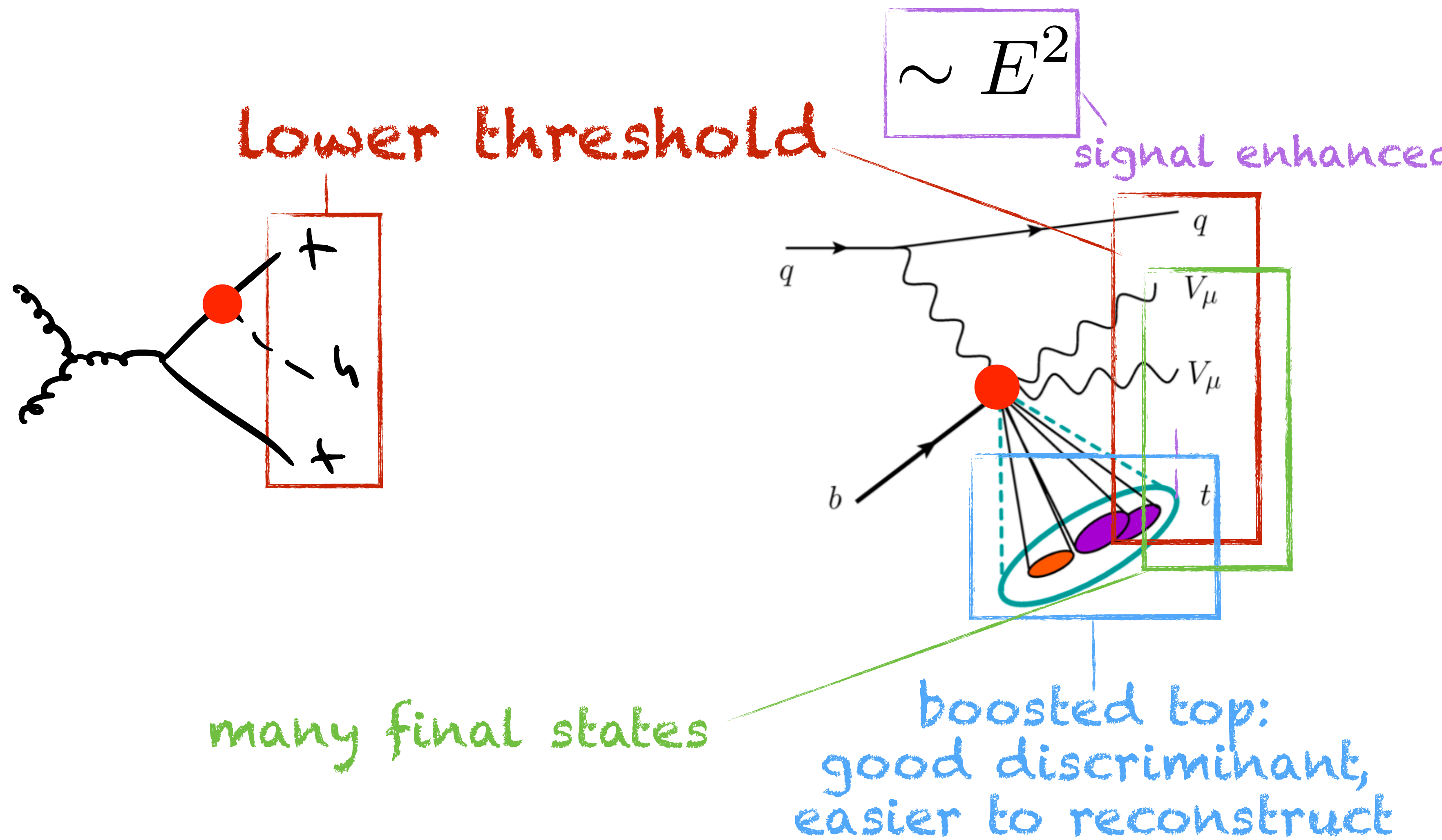
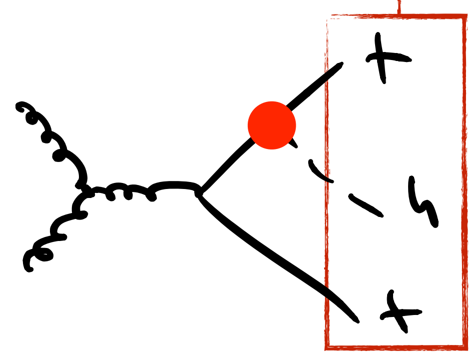


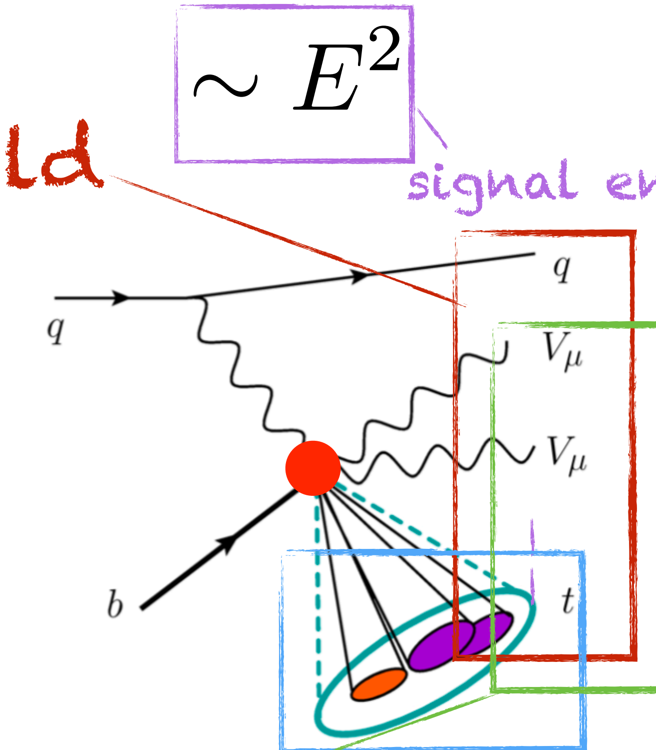
HwH Program: top Yukawa

κ_t

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

lower threshold





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

HwH Program: top Yukawa

κ_t
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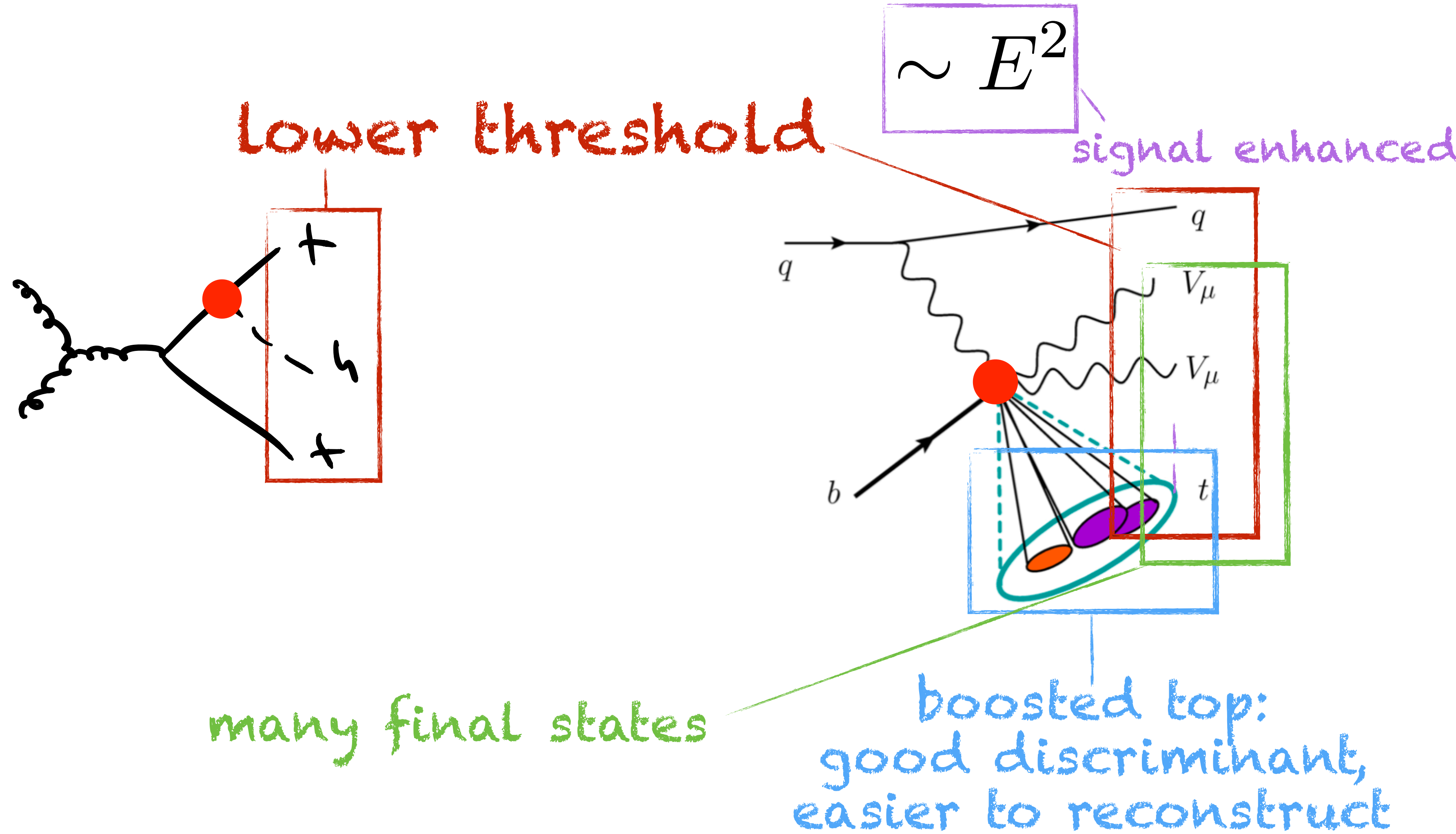

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>2l: Small Background

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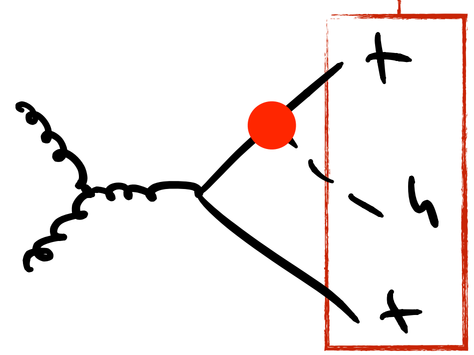

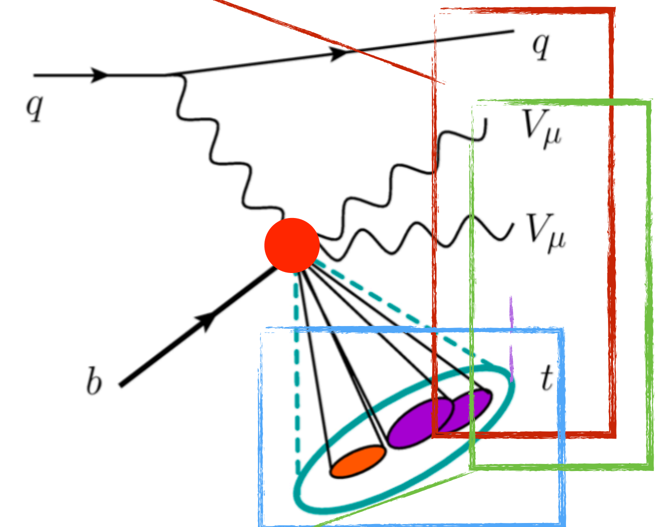

Signal classified by #leptons:

$\sim W$

$ttjj \to tWbjj$

background

10^6 larger...

but 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	-	-
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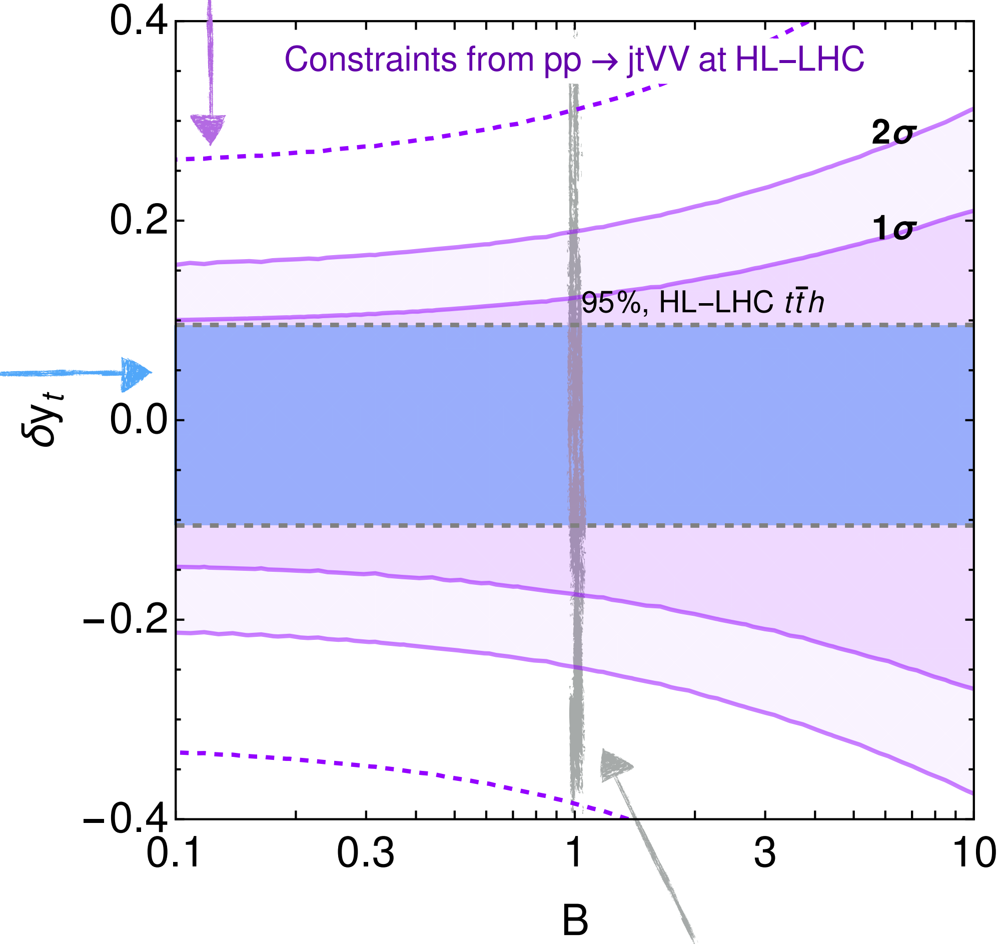
HwH Program: top Yukawa

only channels with >2 leptons (B≈0)

Standard Higgs Couplings



Background = SM signal

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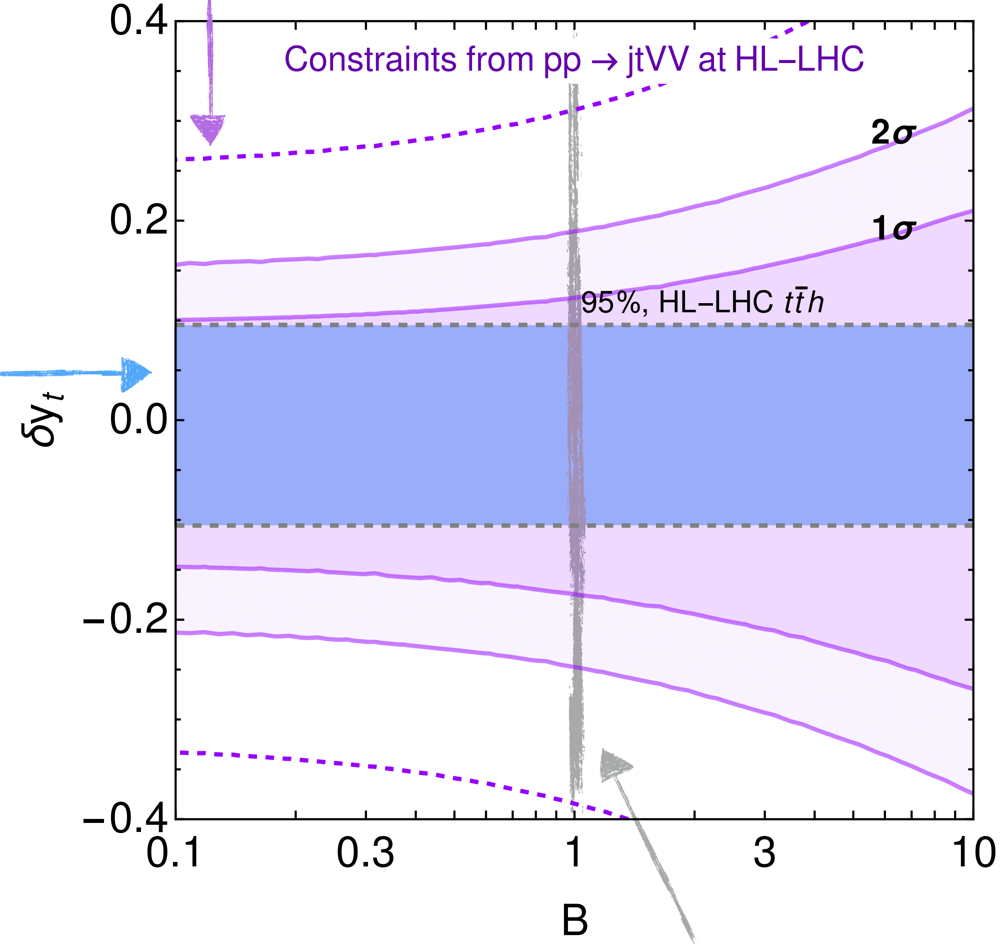


Background = SM signal

▸ HwH competitive with HC!

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

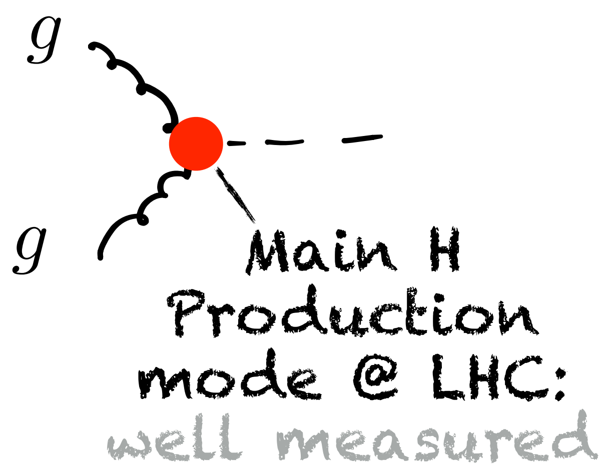
background estimate

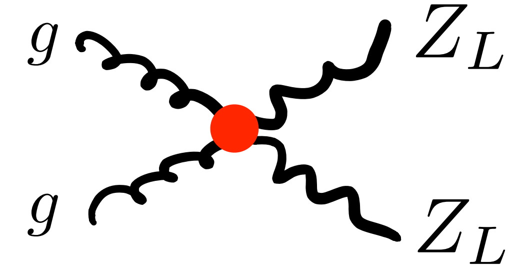
HwH Program: Higgs-Gluons

See also, Azatov, Grojean, Paul, Salvioni'14

κ_G

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





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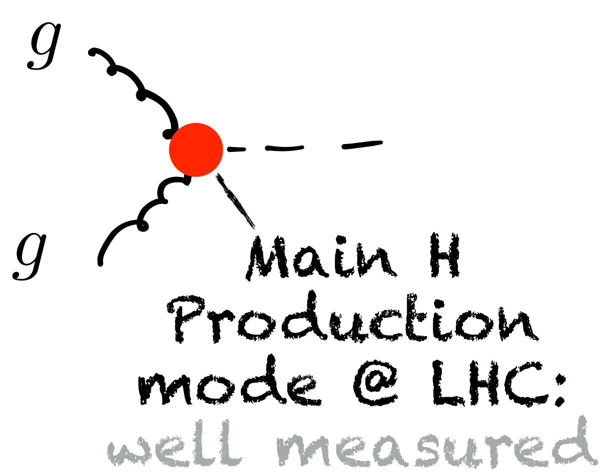

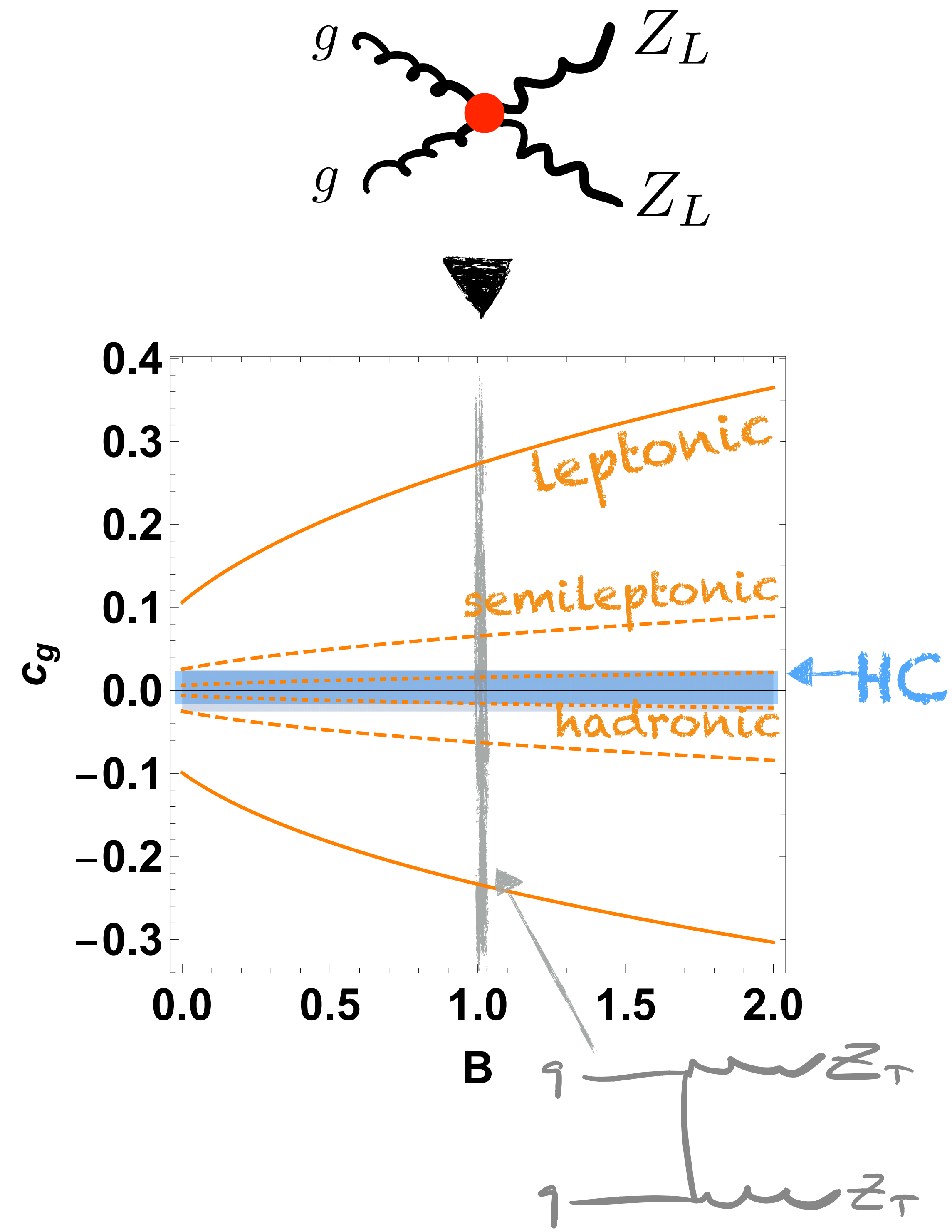

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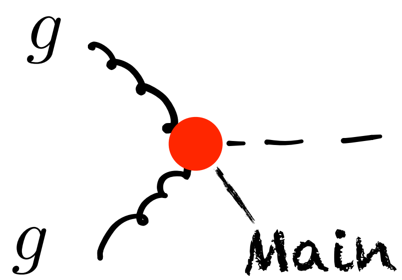
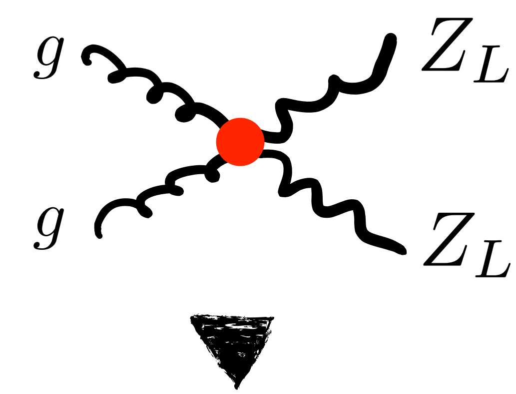
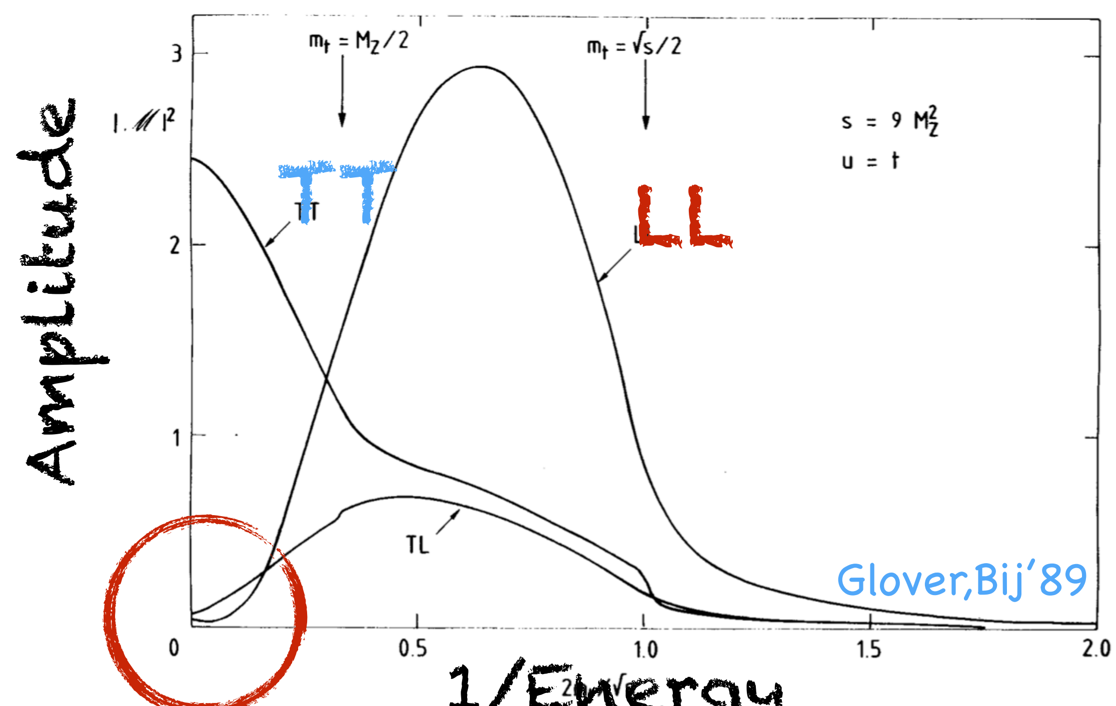
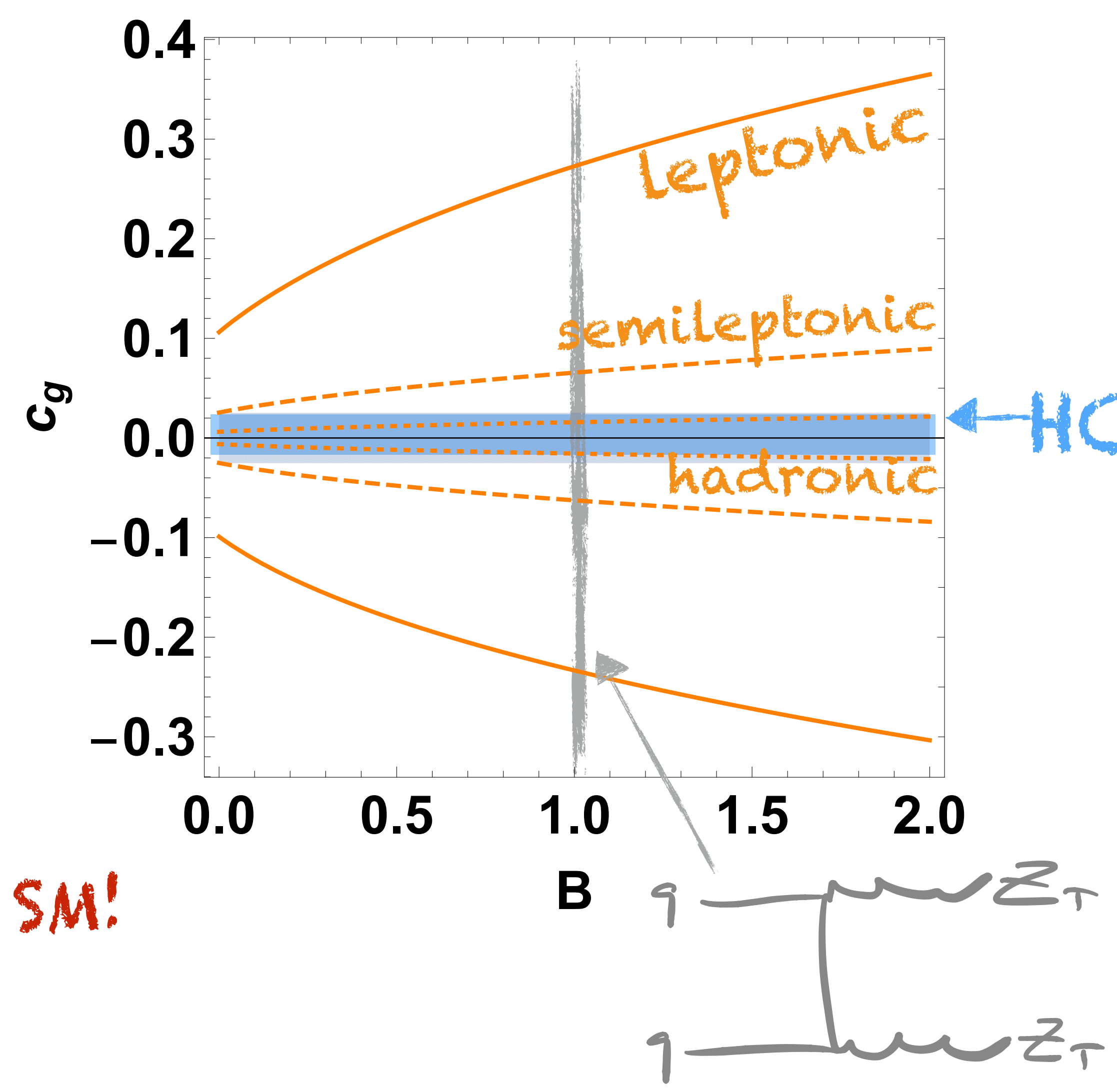


Main H Production mode @ LHC: well measured







Unfortunately LL vanishes at high-E in SM!

SM/BSM-interference small: reach poor.

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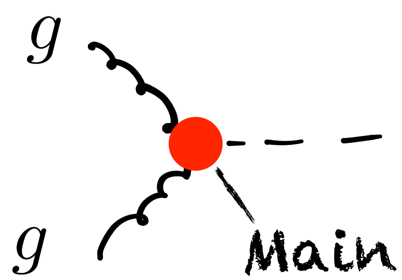

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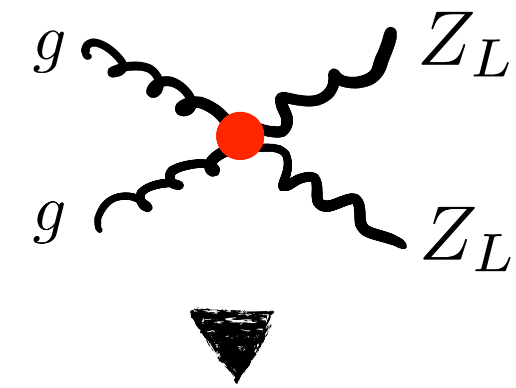
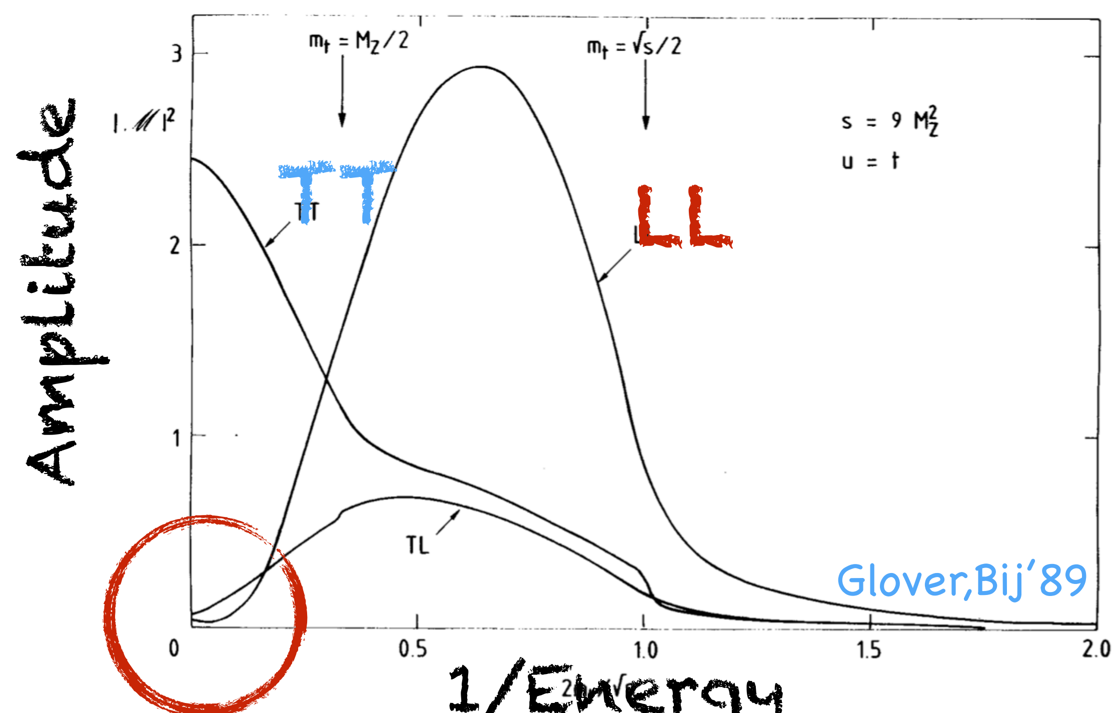
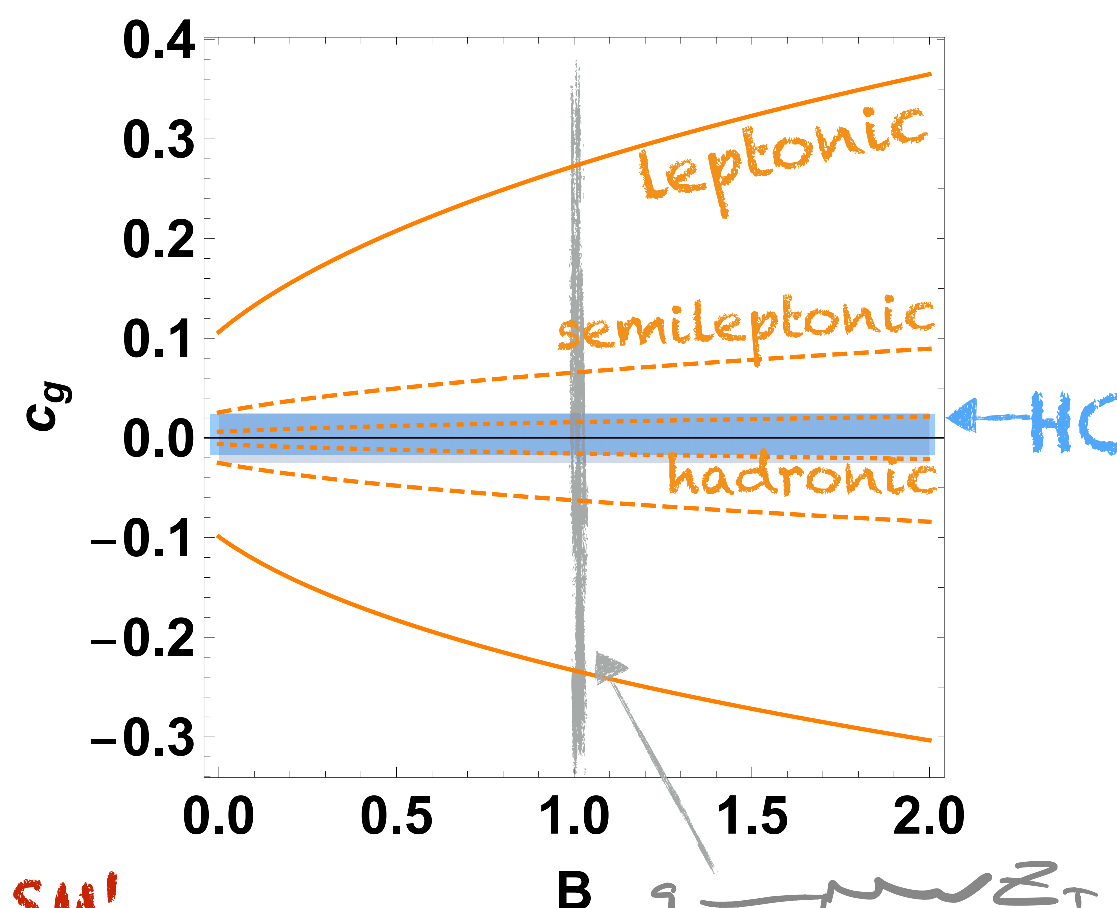
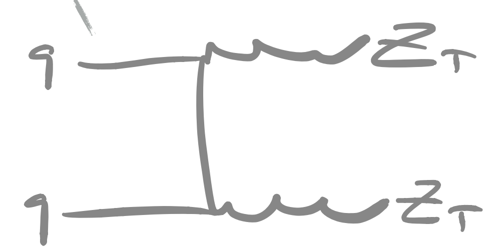








Unfortunately LL vanishes at high-E in SM!

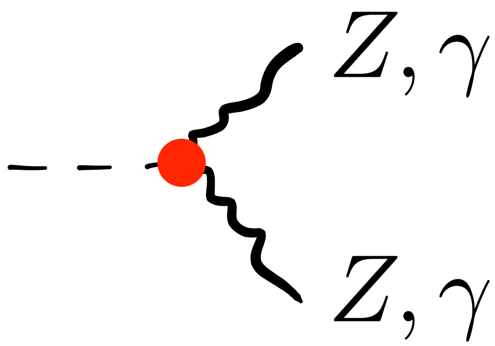
SM/BSM-interference small: reach poor.

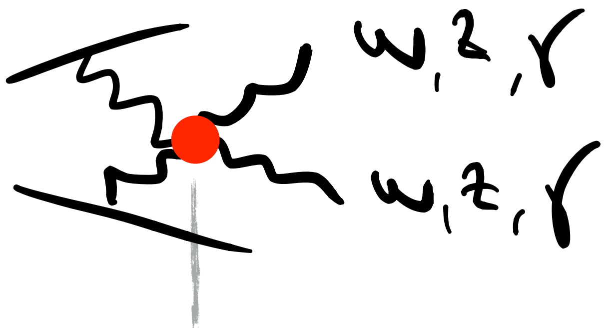
Competitive. Improvable?

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)

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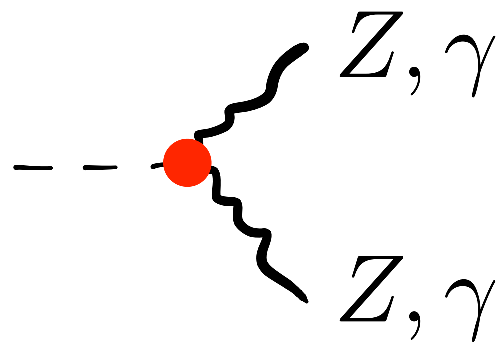

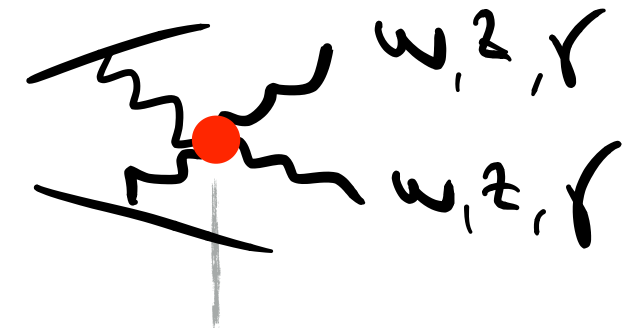

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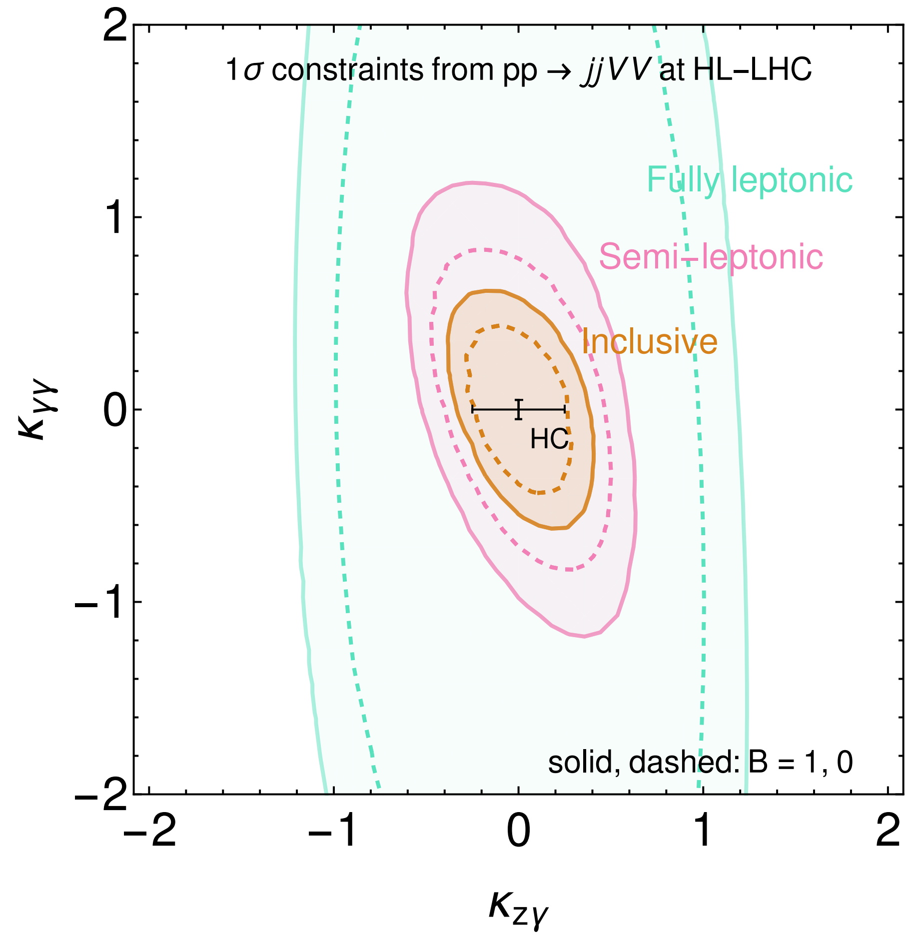
Simple analysis:
- VBF cuts
- Binning $\sum |p_T^V|$



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

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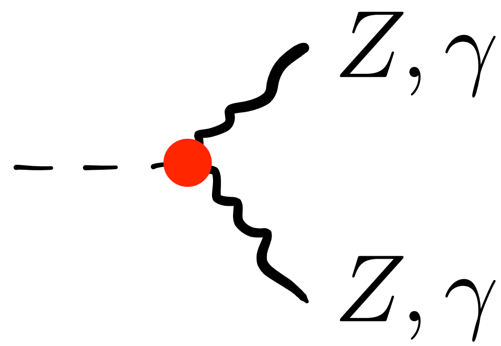

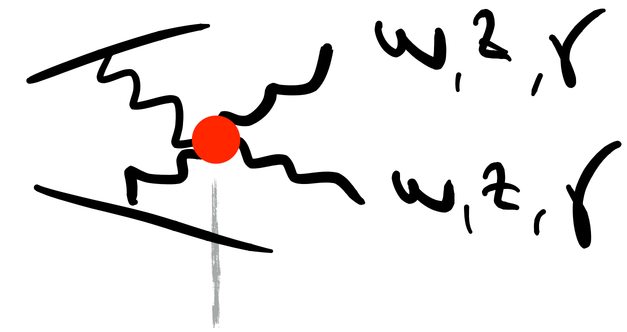

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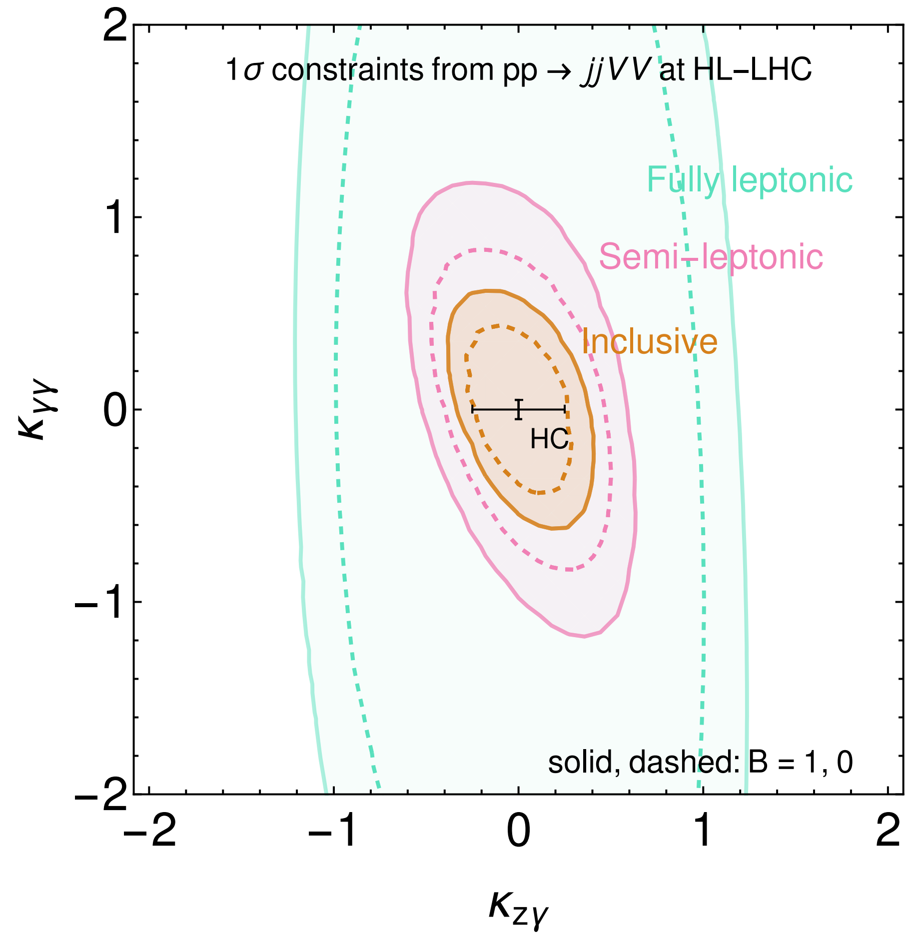
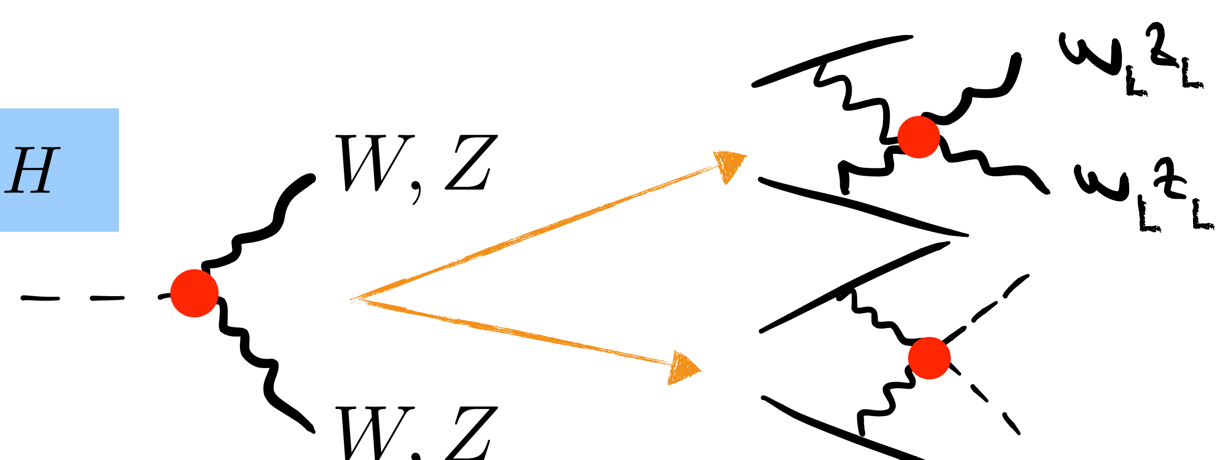


$\kappa_{Z\gamma}$ **competitive,** κ_γ **not**

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



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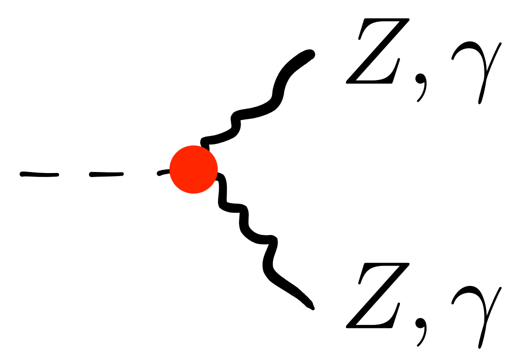

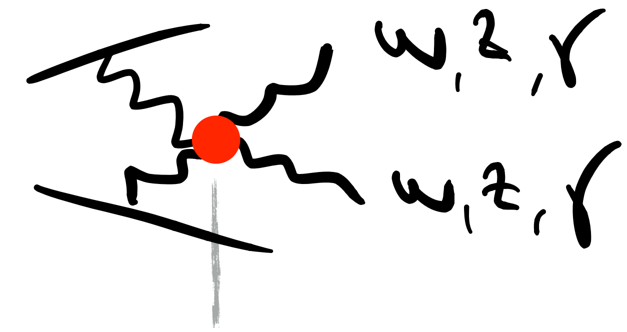

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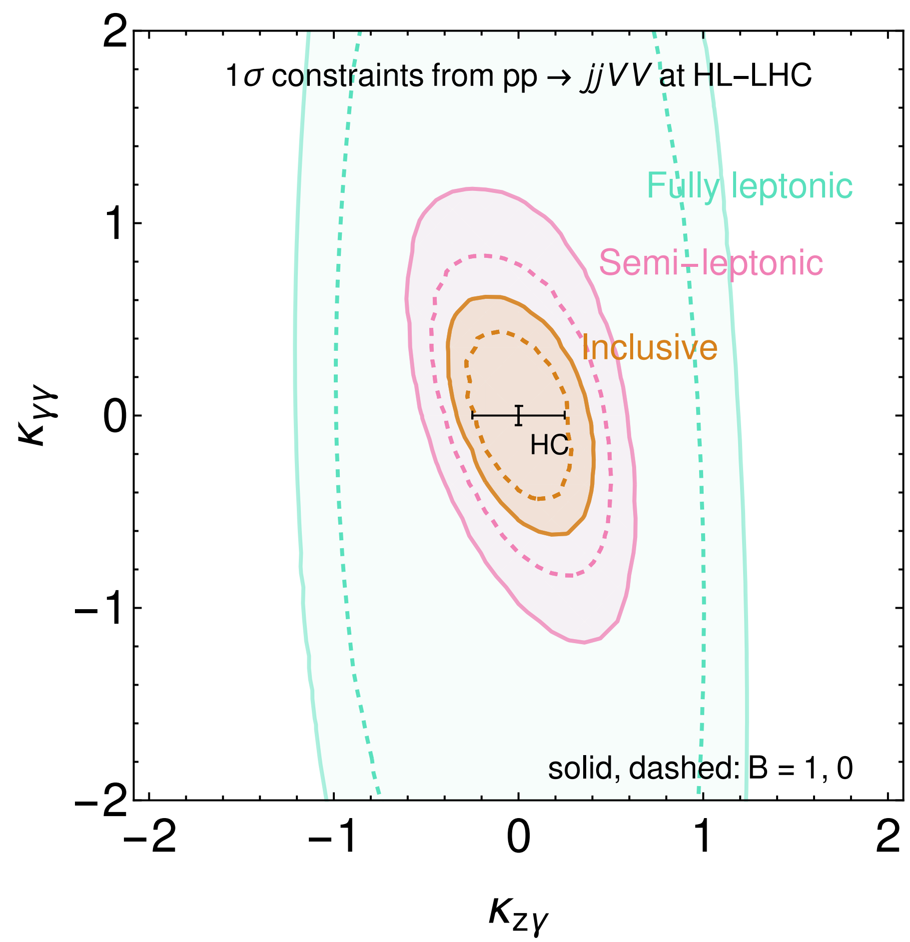

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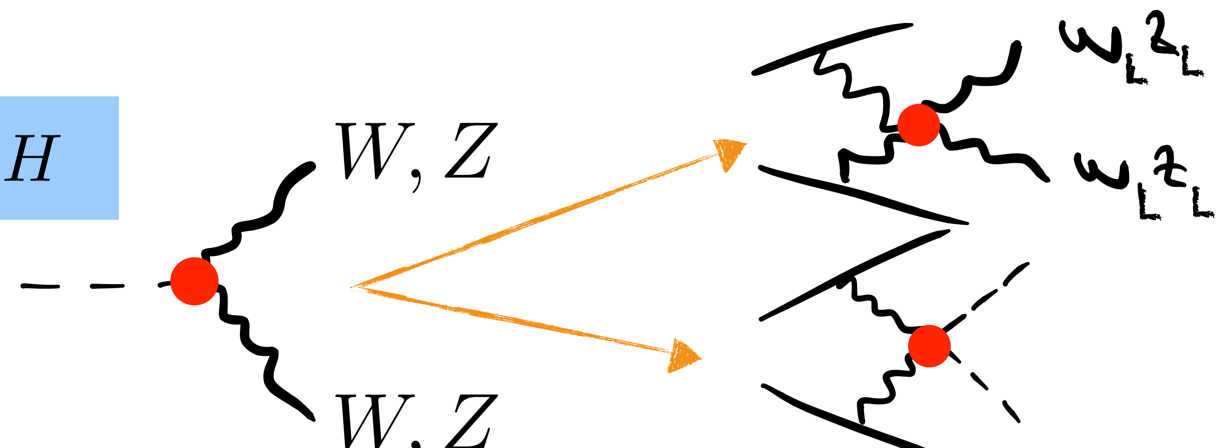

In SM V_L suppressed by ≈1/1000 w.r.t V_T

Contino,Grojean,Moretti,Piccinini,Rattazzi'10

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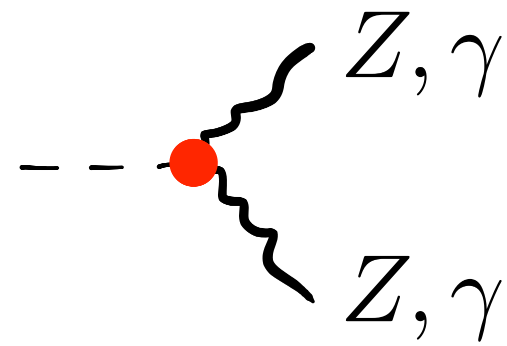

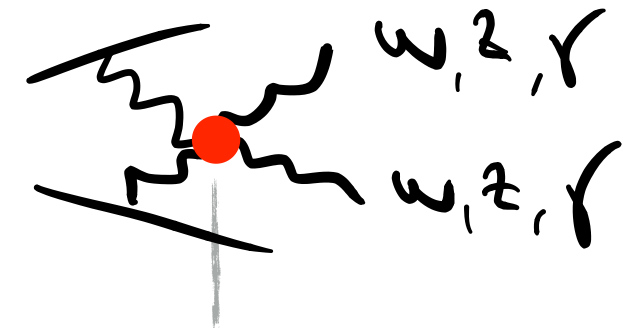

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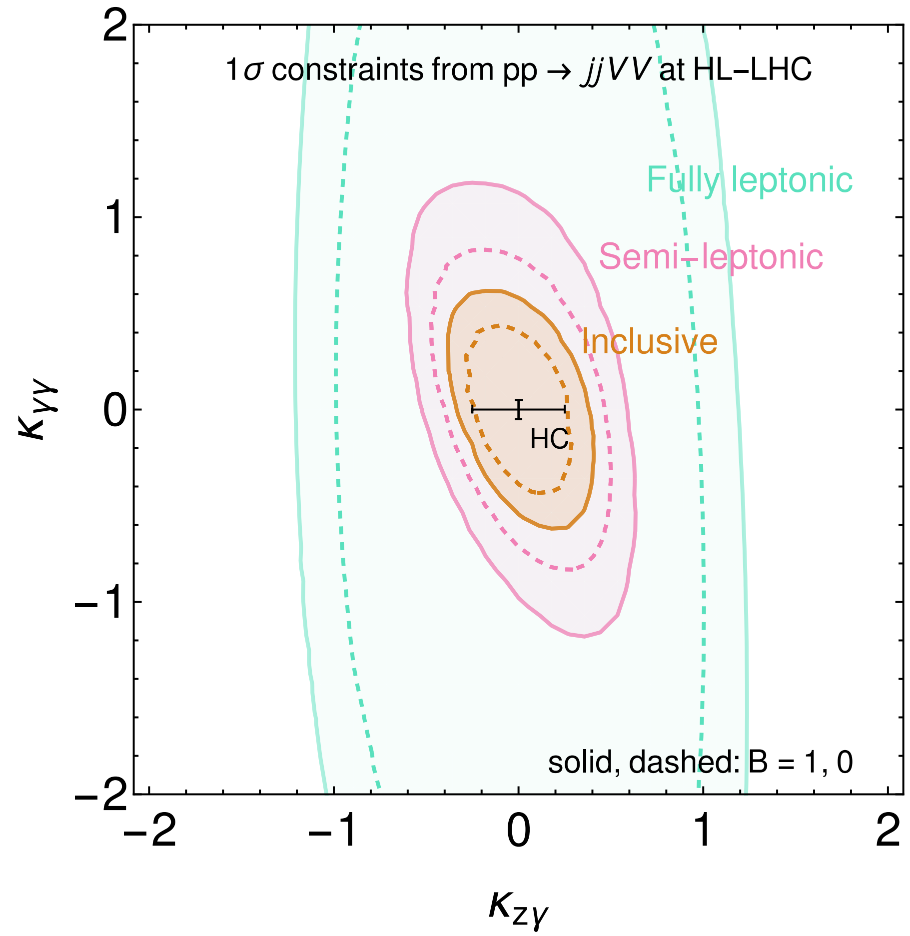

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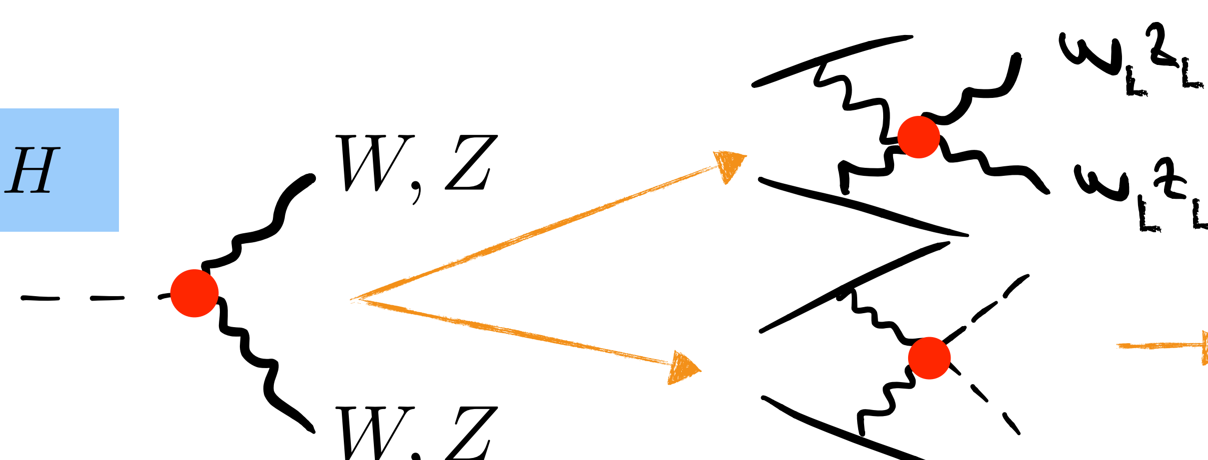

In SM V_L suppressed by ≈1/1000 w.r.t V_T
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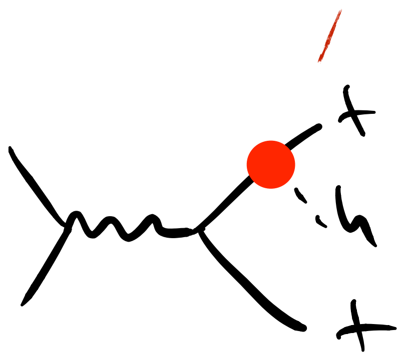
→ $\delta\kappa_V \lesssim 8\%$, (HwH) $\delta\kappa_V \lesssim 5\%$ (HC)
Bishara,Contino,Rojo'17

HwH Program at Lepton Colliders
(different w.r.t LHC)

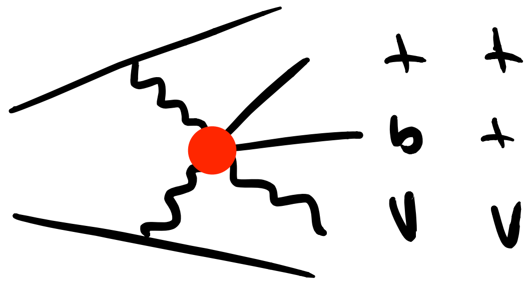
w.r.t. LEP: $\left(\frac{3000}{91.2}\right)^2 \approx 1000$ times larger

κ_t

HC



HwH $\sim E^2$



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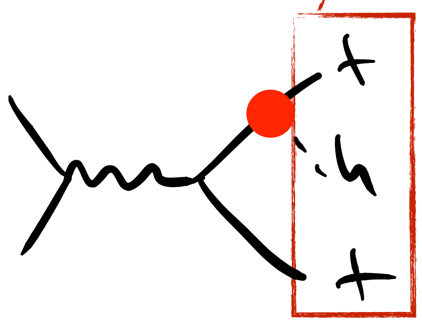
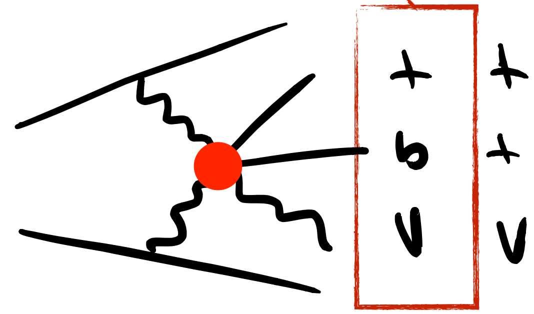
lower threshold





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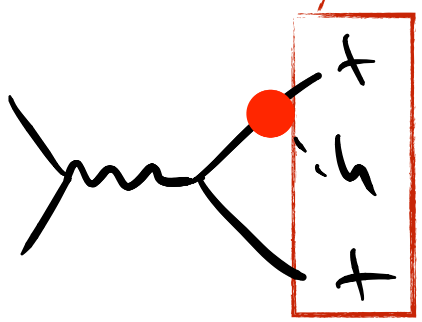
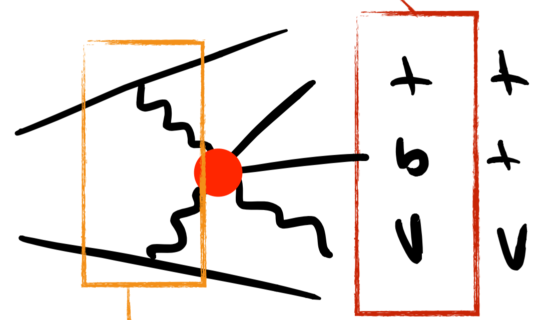
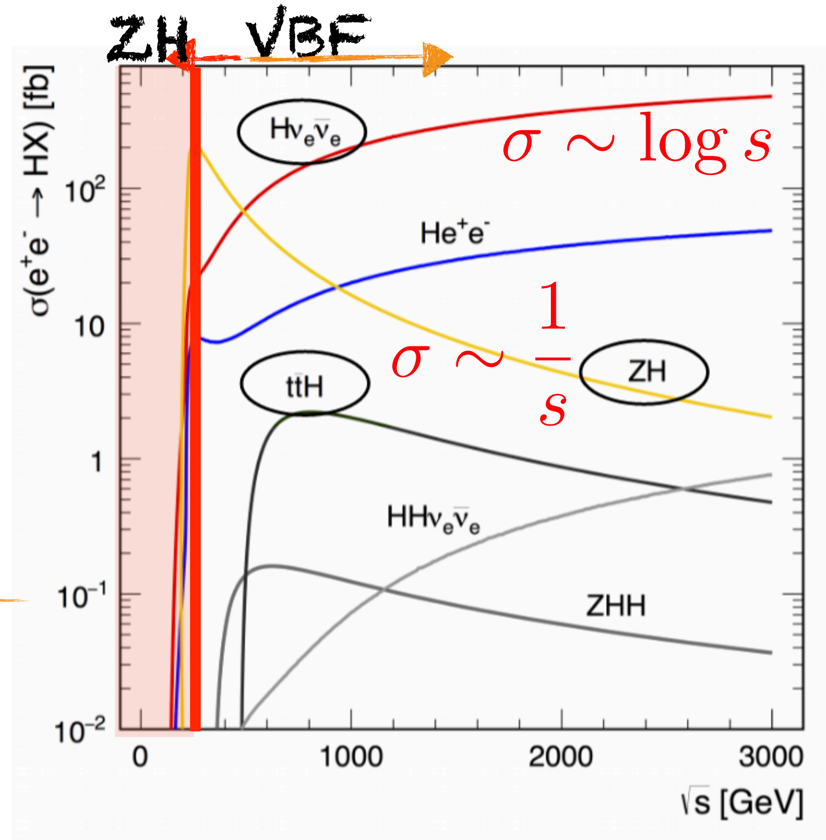




VBF xsec larger



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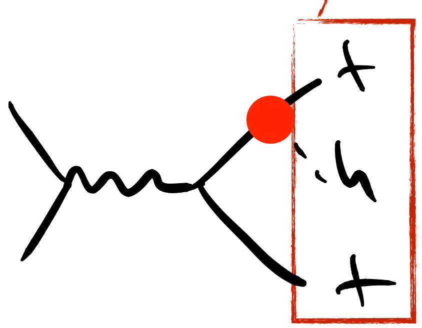
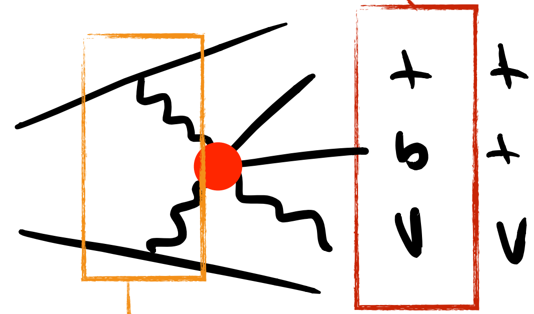
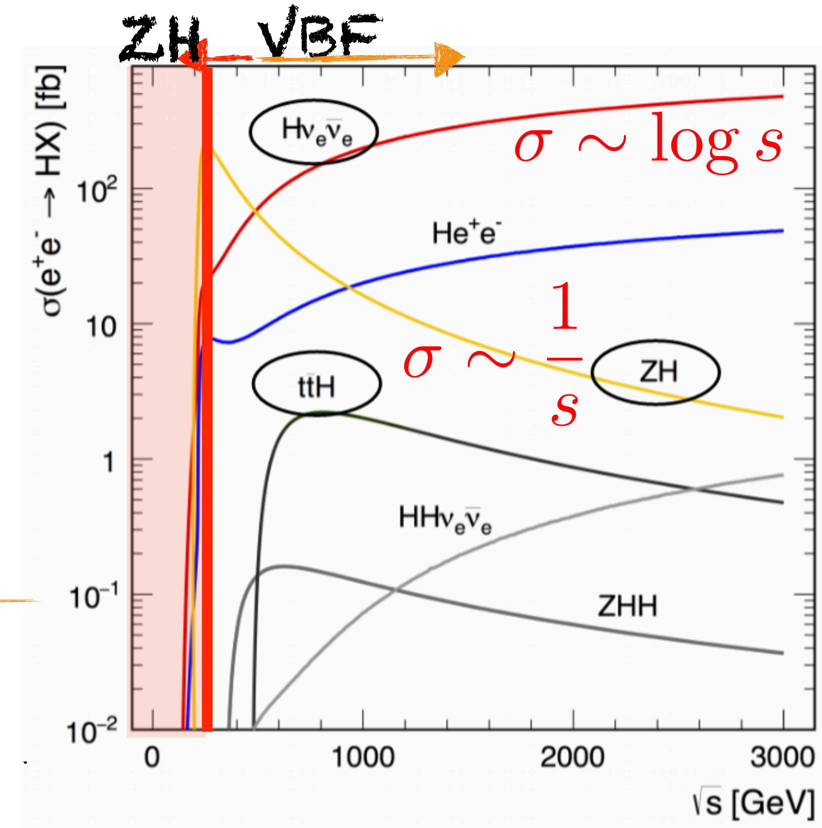
lower threshold

κ_t



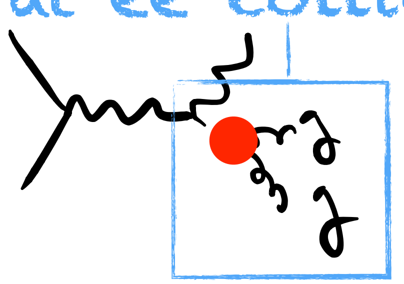


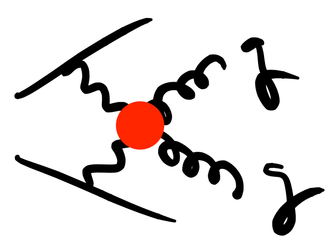
VBF xsec larger



Poorly measured at ee-colliders

κ_G





Beam Polarization:
Enhance LL?

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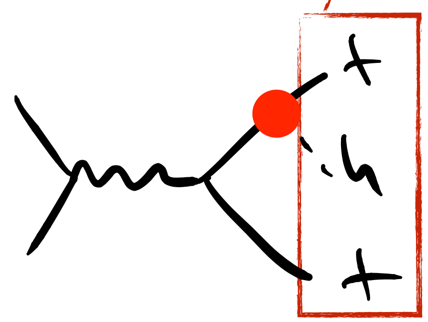
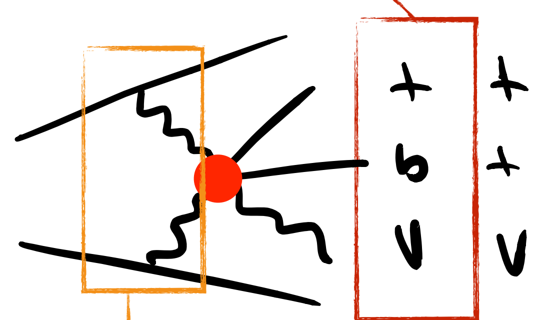
HC

HwH $\sim E^2$

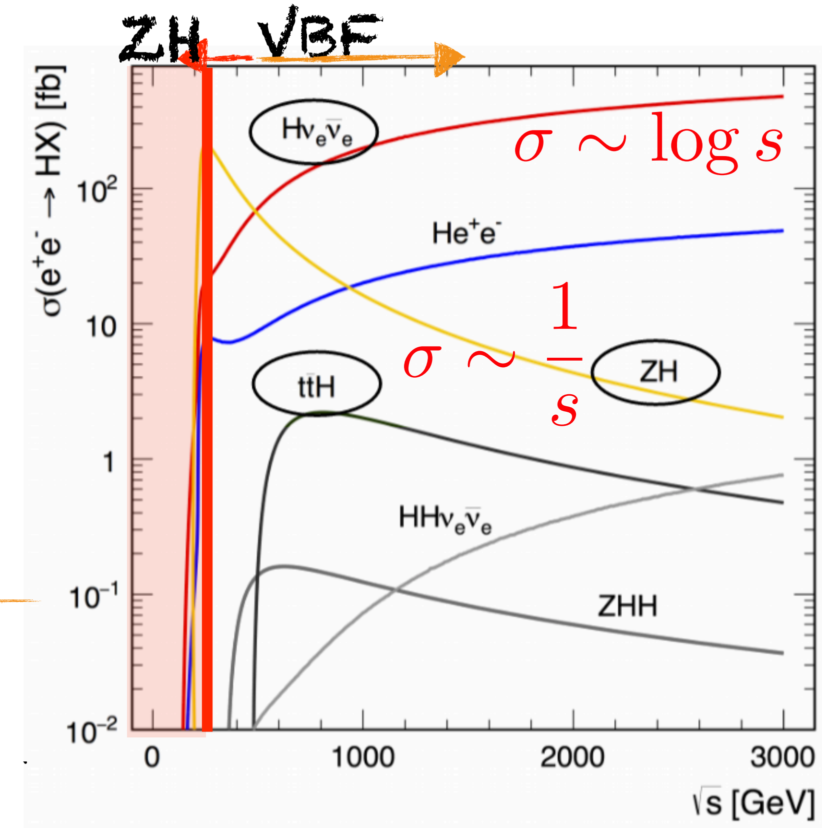
lower threshold

κ_t





VBF xsec larger



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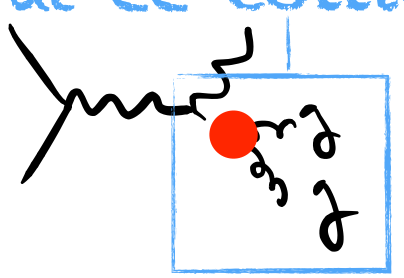
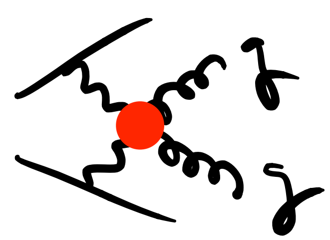
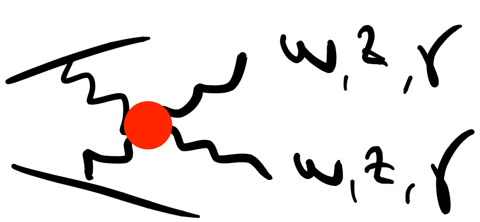
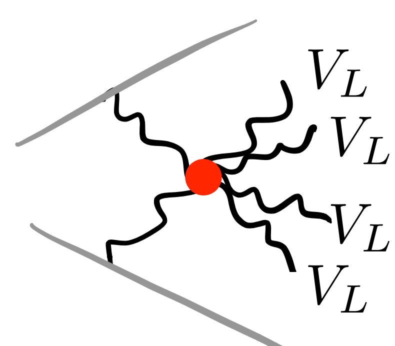


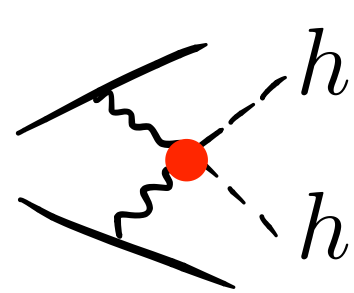


Beam Polarization:
Enhance LL?

κ_γ
$\kappa_{Z\gamma}$
κ_V
κ_λ



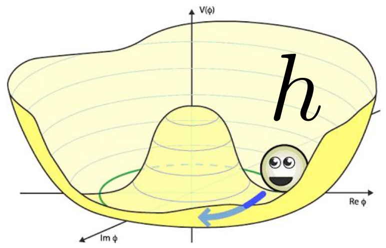




Similar to LHC

BSM

Composite Higgs Models: $\kappa \sim \frac{v^2}{\Lambda^2} \lesssim 1\%$



Here Λ analog of pion decay constant f

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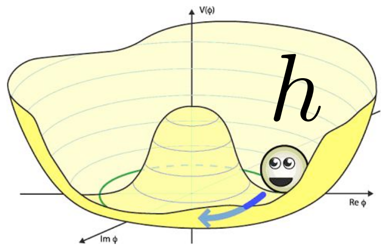
Composite Higgs Models: $\kappa \sim \dfrac{v^2}{\Lambda^2} \lesssim 1\%$ $\qquad m_{\rm NP} \sim g_* \Lambda \sim 30\,\text{TeV}$

$g_* \sim 4\pi$



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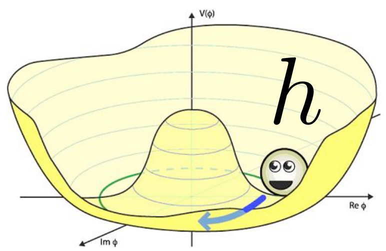

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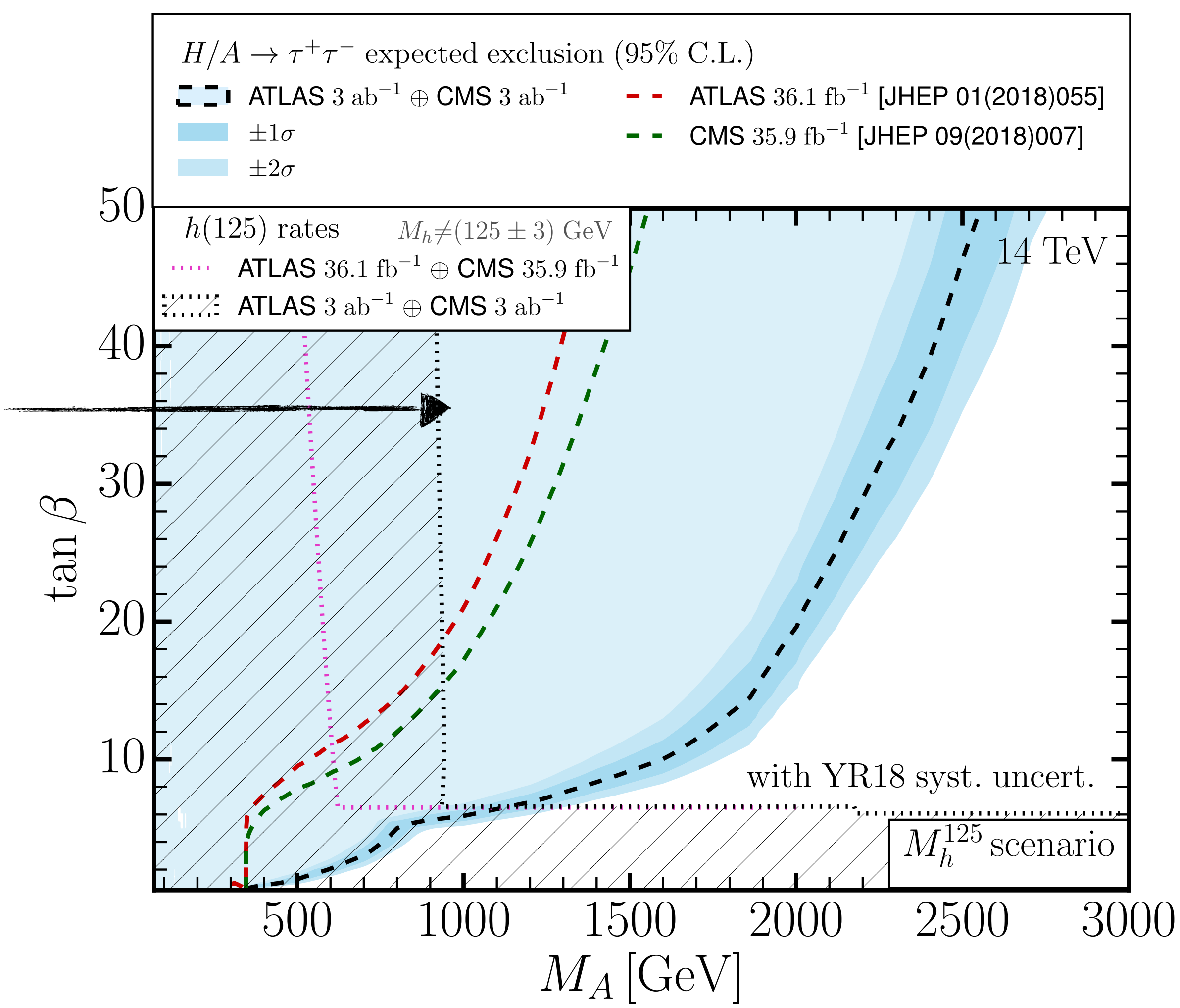

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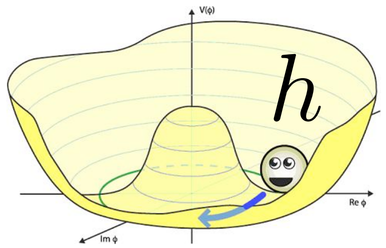

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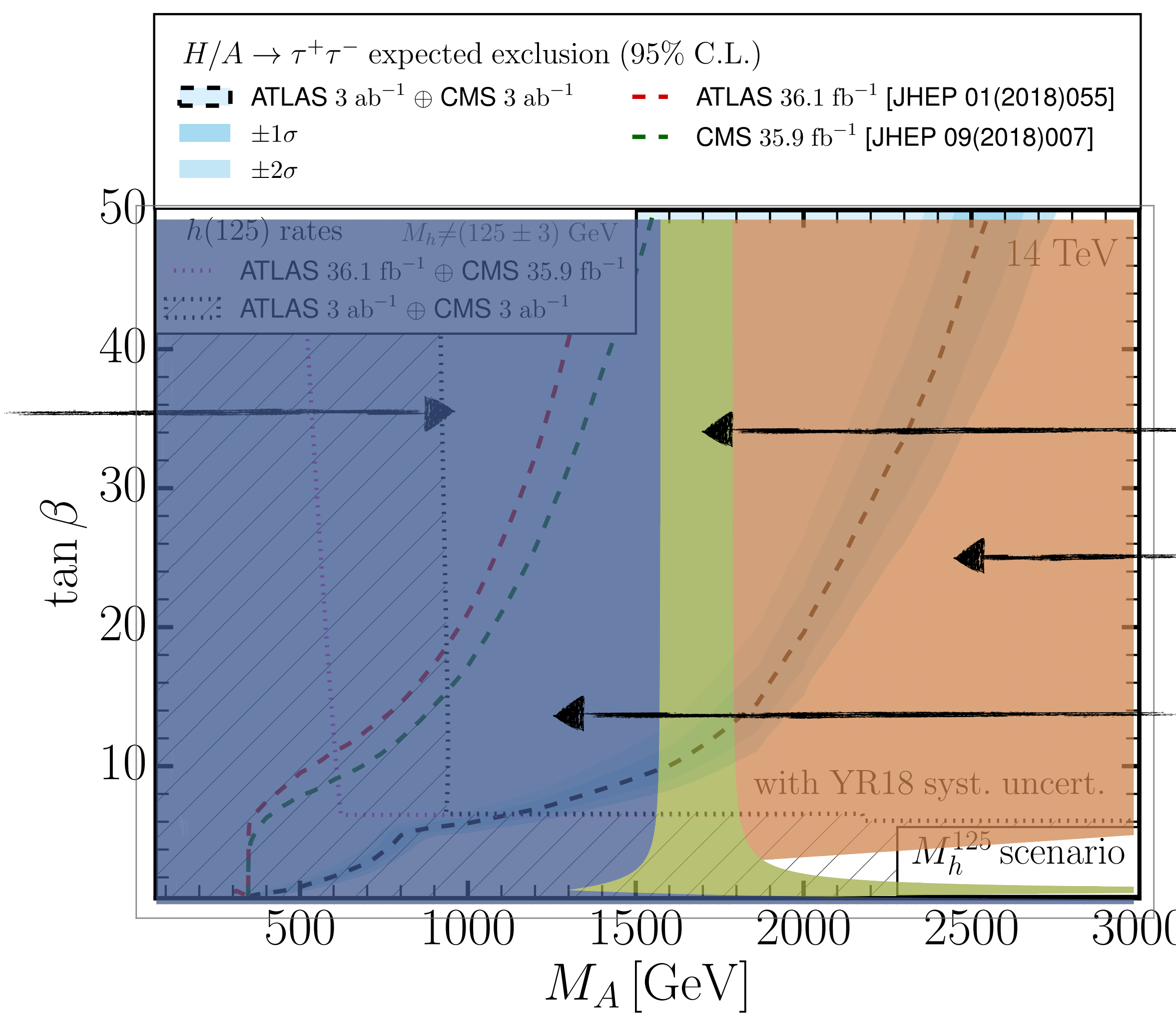

D-Term SUSY

F-Term SUSY

Heavy Stops

Gupta,Montull,FR'12 - updated

Message

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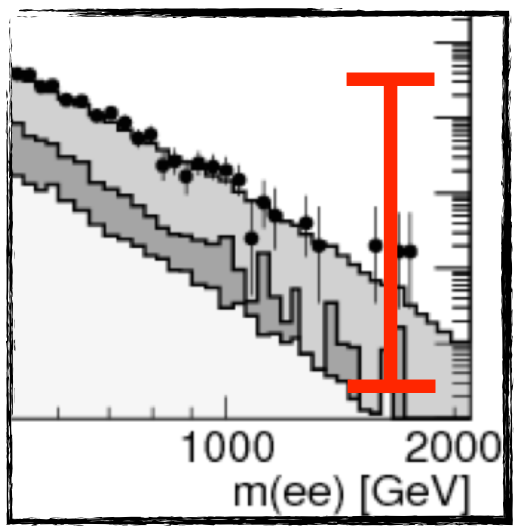

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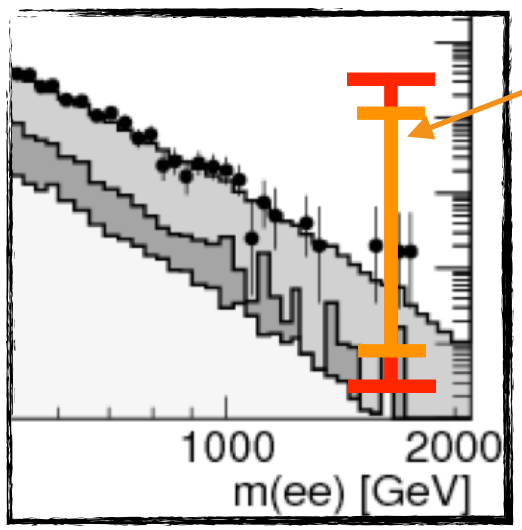

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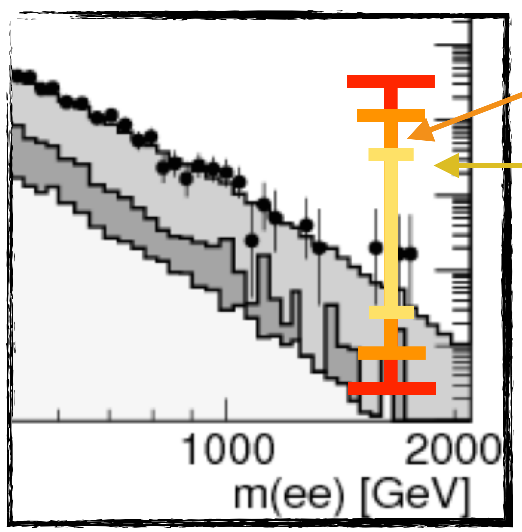

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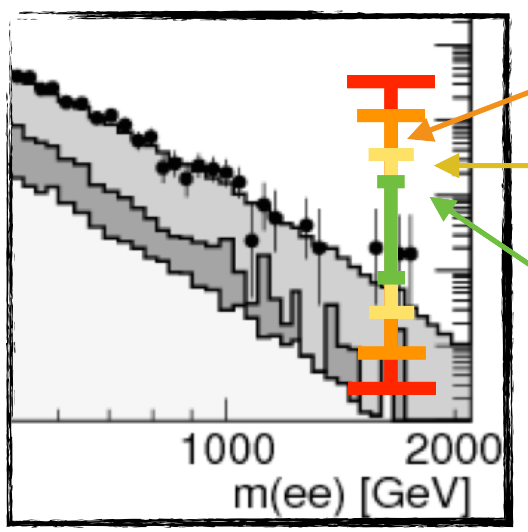

Precise SM theoretical predictions

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BSM understanding

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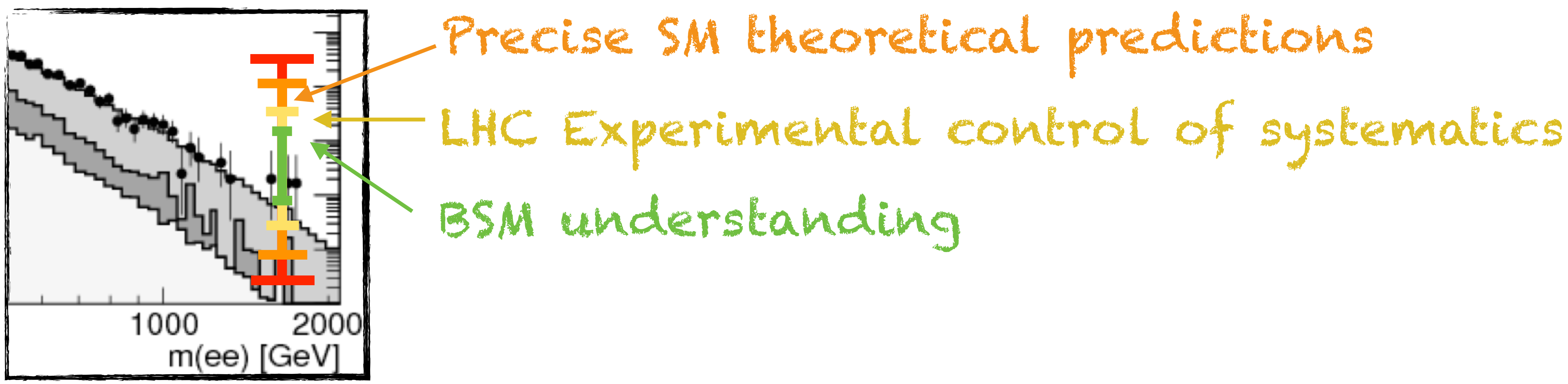

- Important for future colliders (HE-LHC,CLIC,FCC,...)

HC: Present Reach vs HL-LHC

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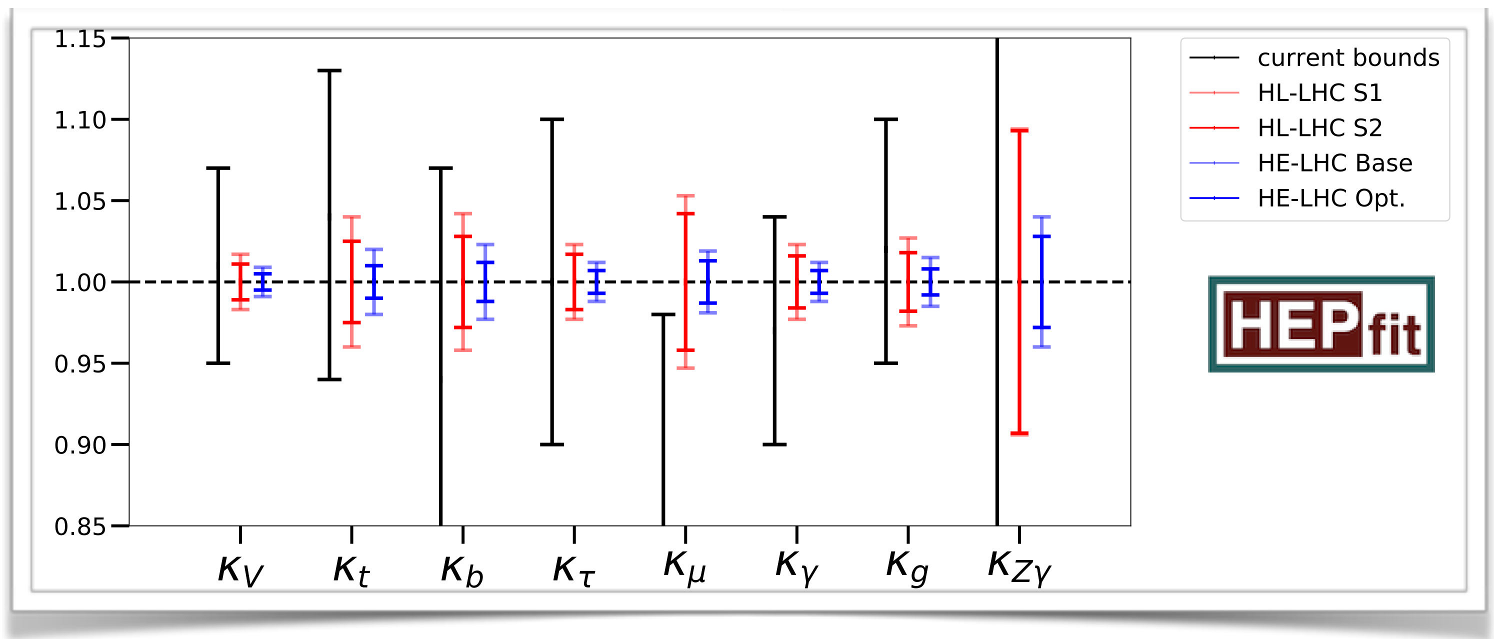

Why Interference?

When SM and BSM contribute to the same amplitude:

$$Amp = SM + BSM = SM(1 + \delta_{BSM})$$

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- $\sigma \propto |Amp|^2 \simeq SM^2(1 + \delta_{BSM} + \delta^2_{BSM})$

For small BSM effects $1 \gg \delta_{BSM}$,

interference dominates $\delta_{BSM} \gg \delta^2_{BSM}$

Non-Interference?

If SM and BSM contribute to different amplitudes:

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interference vanishes

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If SM and BSM contribute to different amplitudes:

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The leading effects BSM are $O\left(\frac{1}{\Lambda^4}\right)$

- Small effects, even smaller!