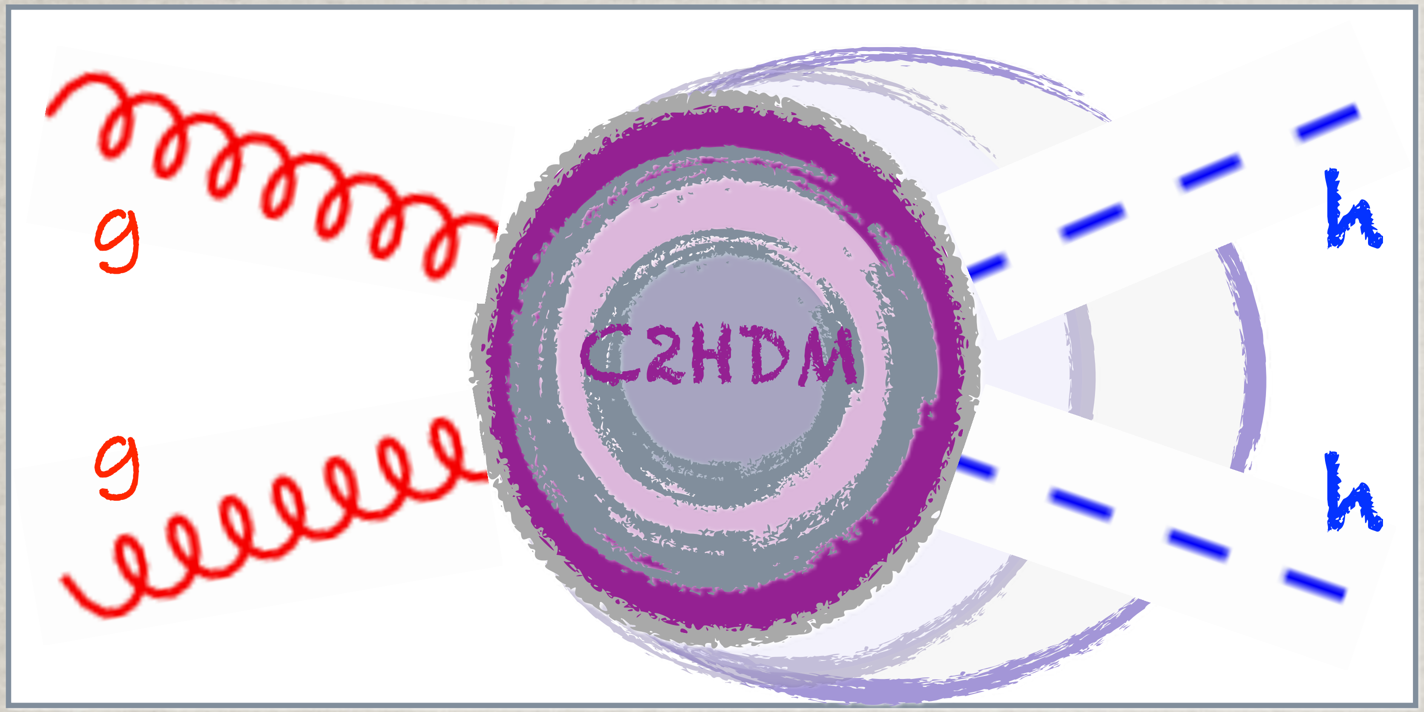
HPNP2023 The 6th International Workshop on "Higgs as a Probe of New Physics 2023"



Di-Higgs production in Composite 2HDM

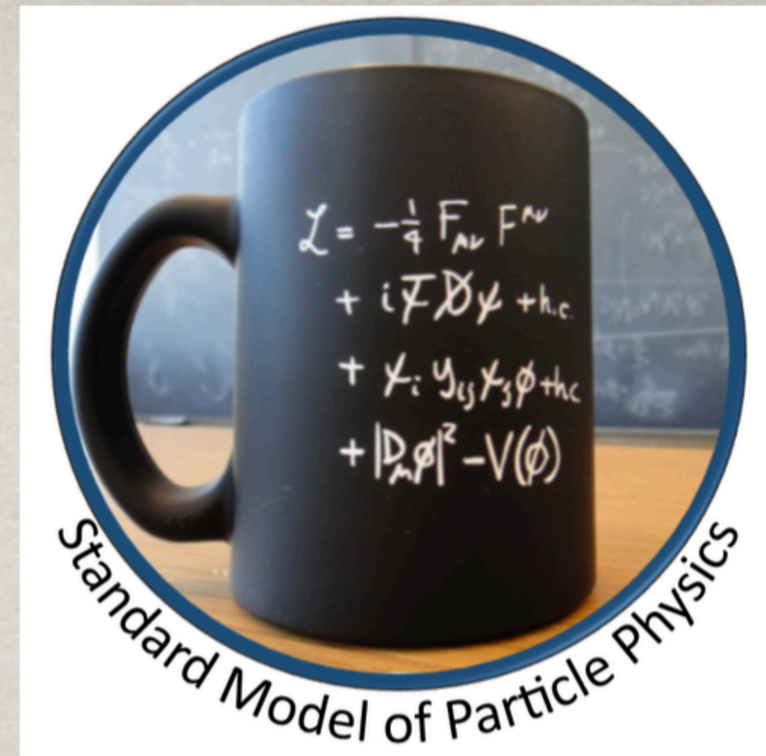
Stefania De Curtis

INFN and University of Florence

Galileo Galilei Institute for Theoretical Physics

5.-9. June 2023, Osaka University, Japan

The Standard Model



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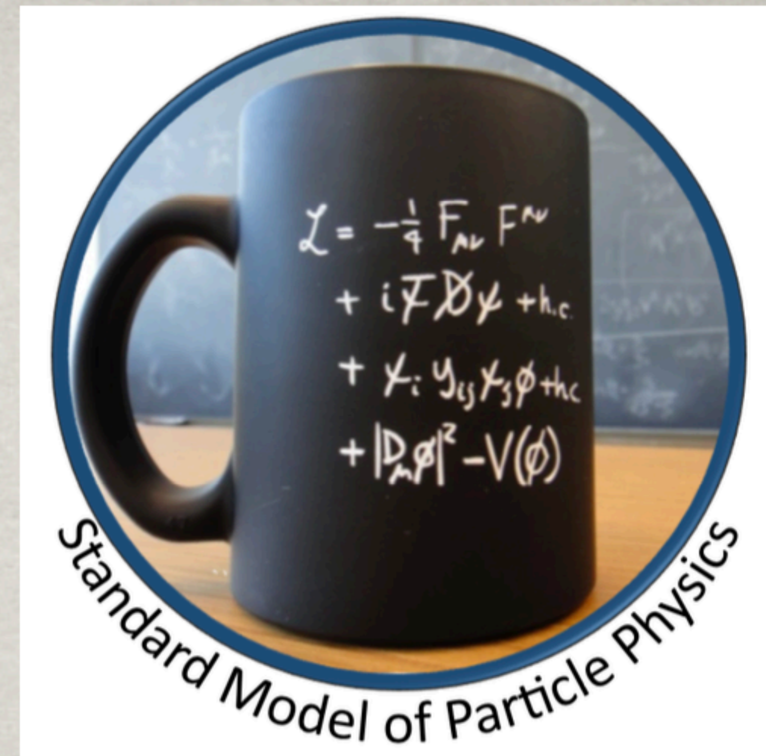
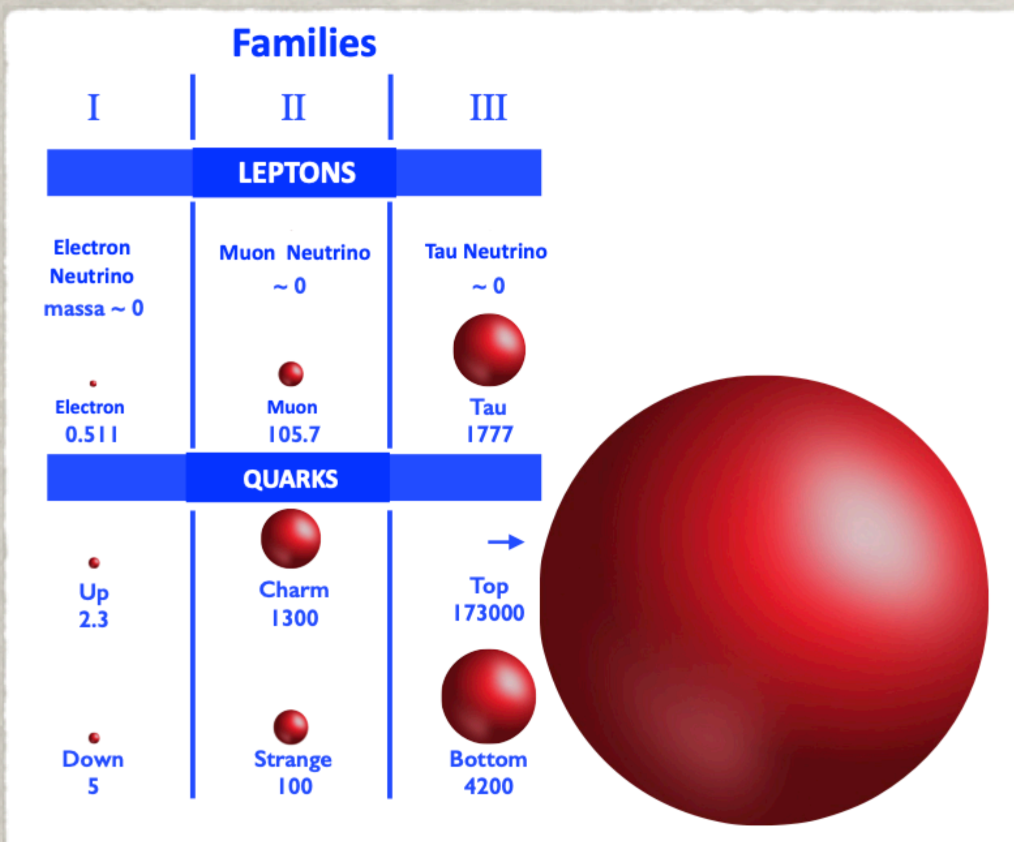
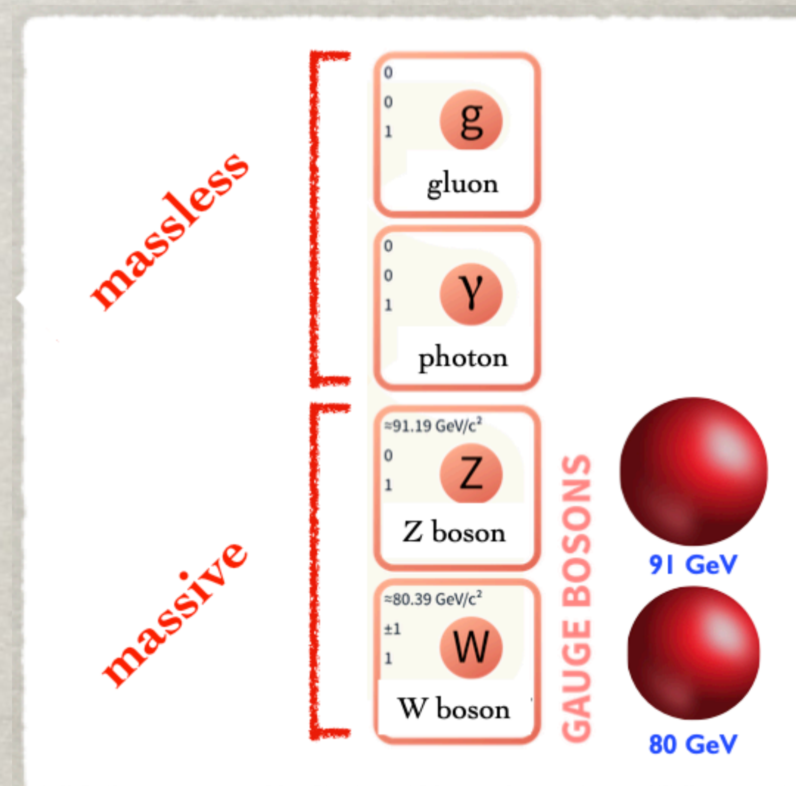




Crucial aspect
the dynamics which gives mass to the matter constituents (quarks, leptons) and the force mediators



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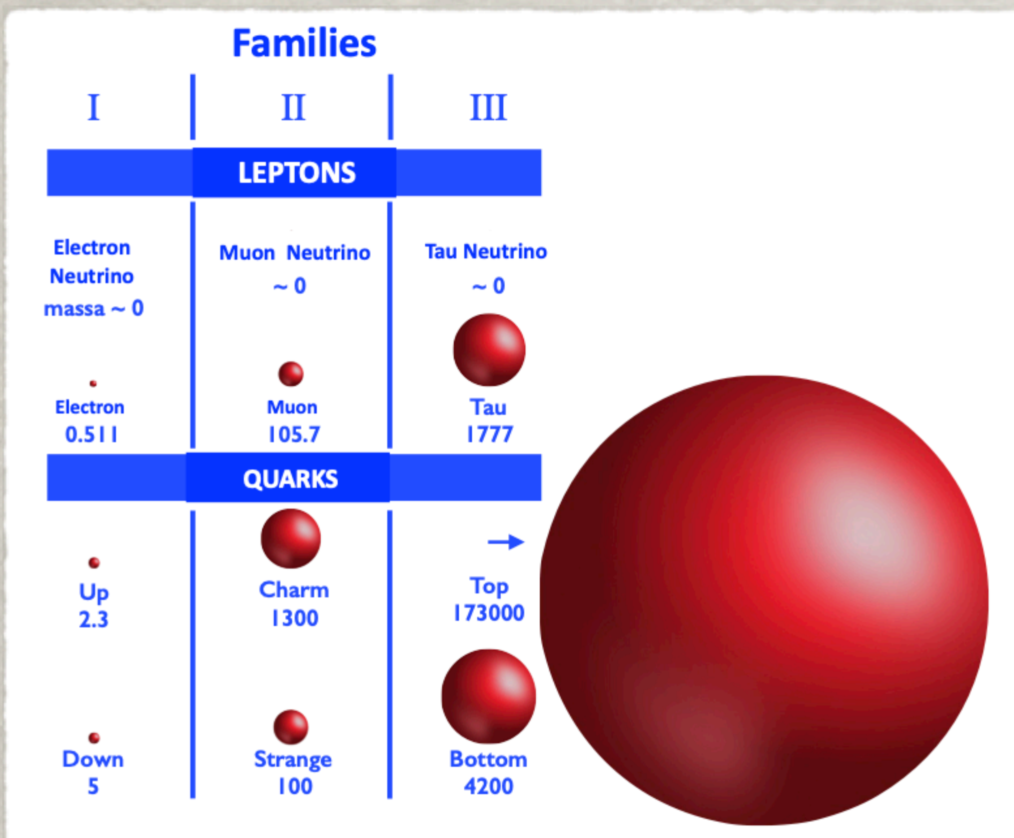

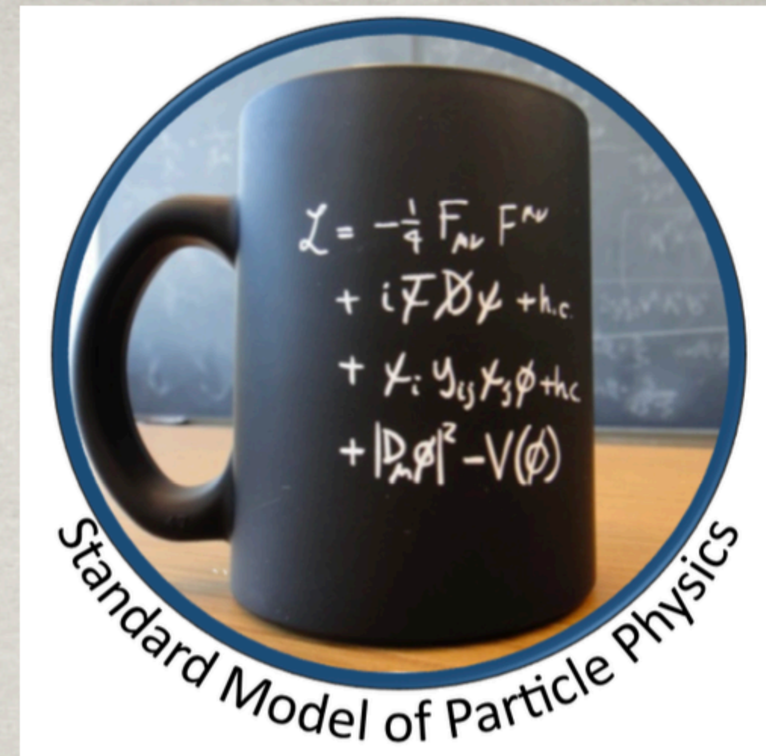

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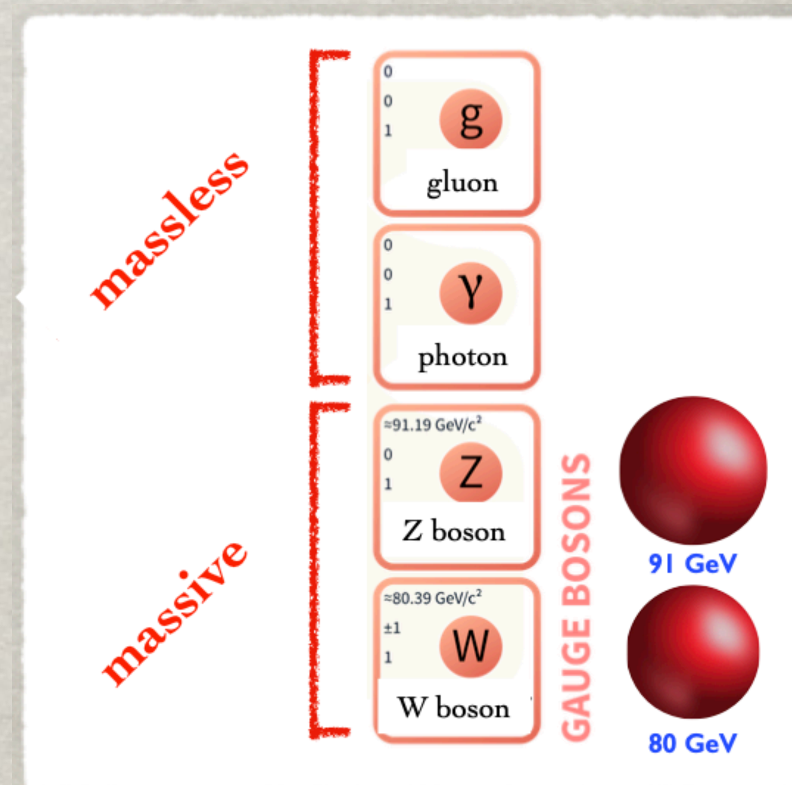

Which is the origin of the masses?

The Higgs Boson

- The fundamental interactions are regulated by "symmetry principles" which are satisfied only if the particles are massless

- R. Brout, F. Englert e P. Higgs, in 1964, introduced a mechanism to give mass to the matter constituents without violating the fundamental symmetry laws

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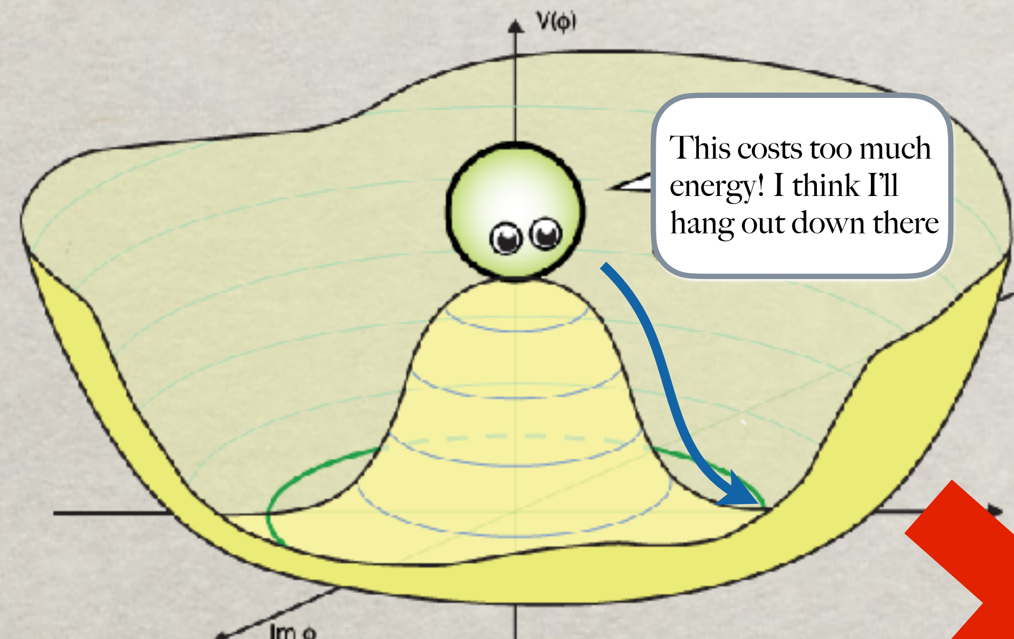
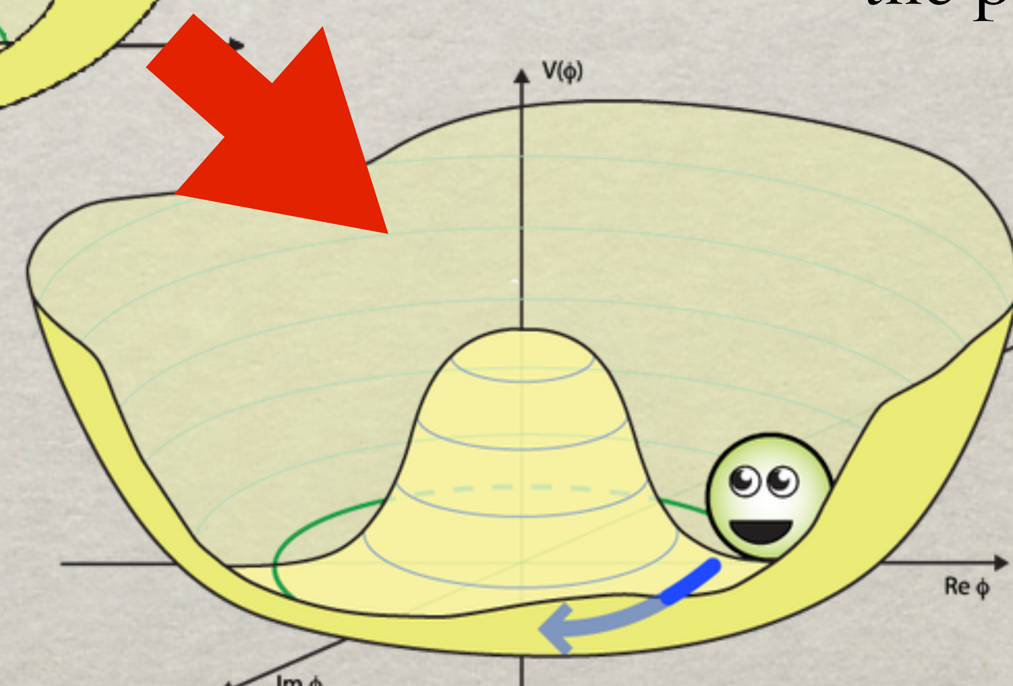


It requires the existence of a particle field ϕ (Higgs field) with peculiar properties. It moves from the origin to a constant value ($\neq 0$), to minimize the potential energy



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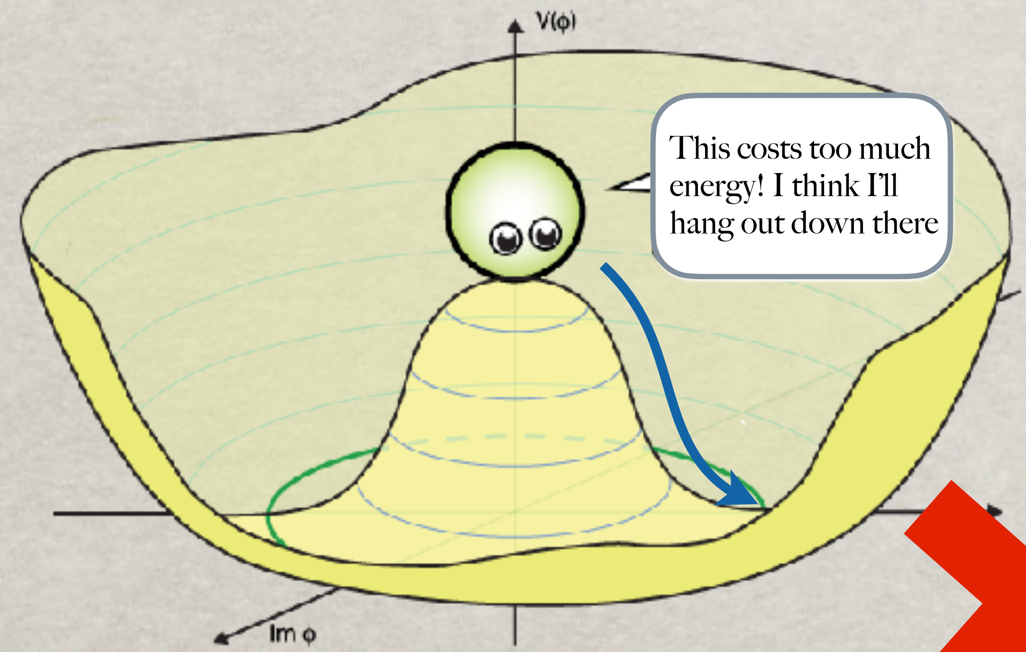

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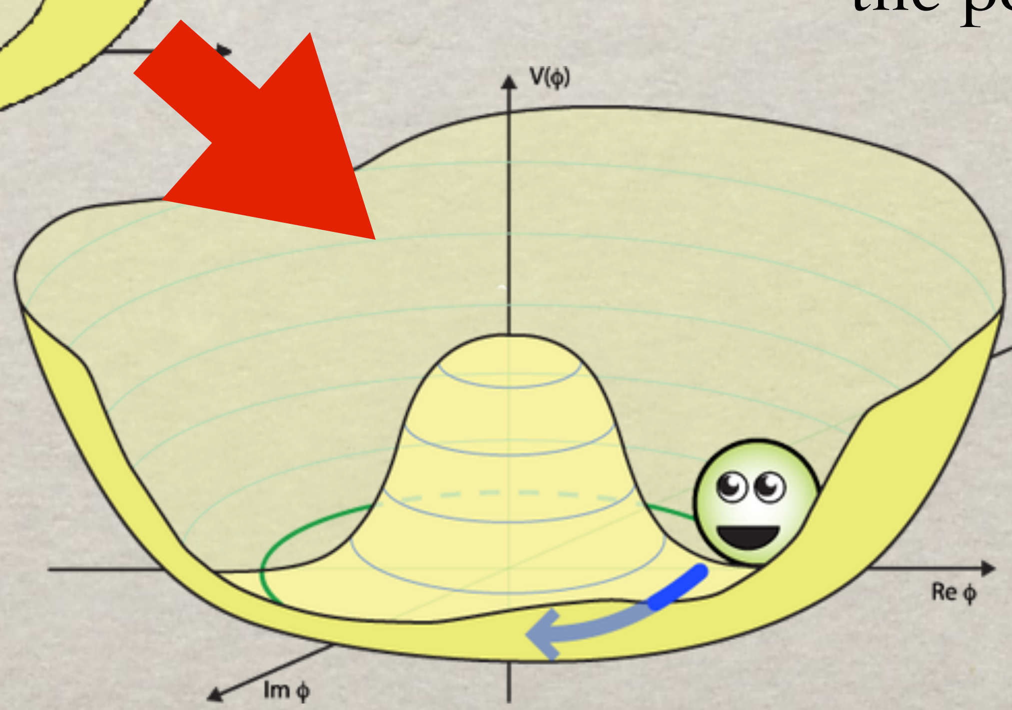

- The Higgs field permeates all the space with a constant value. Its interactions with the particles create a "friction" generating their masses

The Standard Model is a quantum theory of interacting fields. The excitations of these fields create their associated particles

The experimental test of the Higgs mechanism requires the **presence of the Higgs boson (charge=0, spin=0, m_H =?)**

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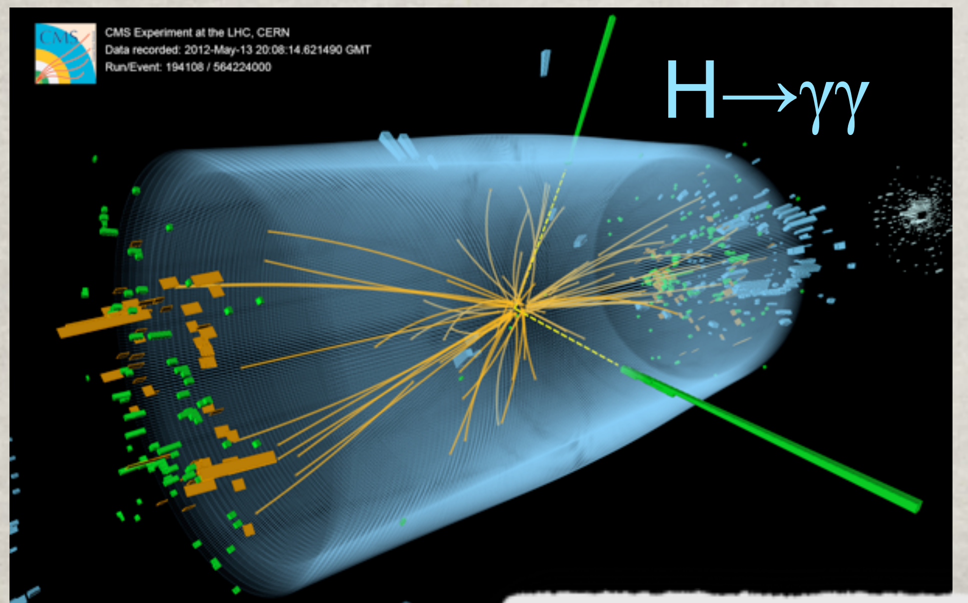
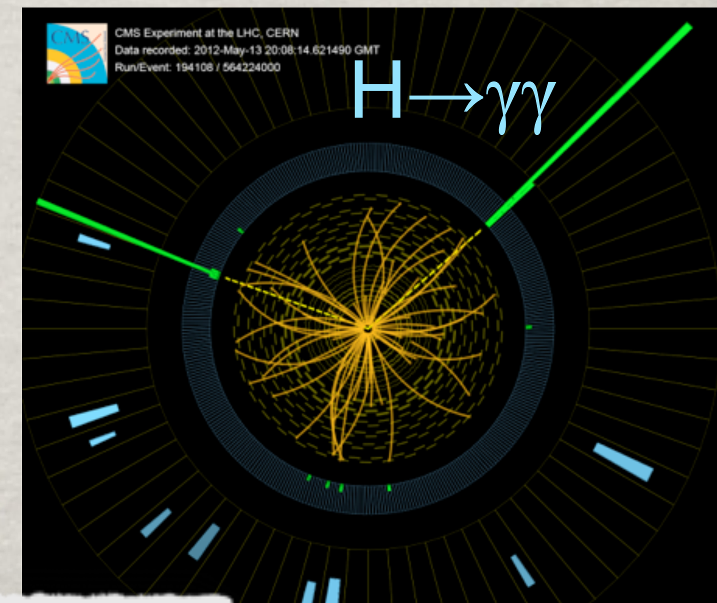
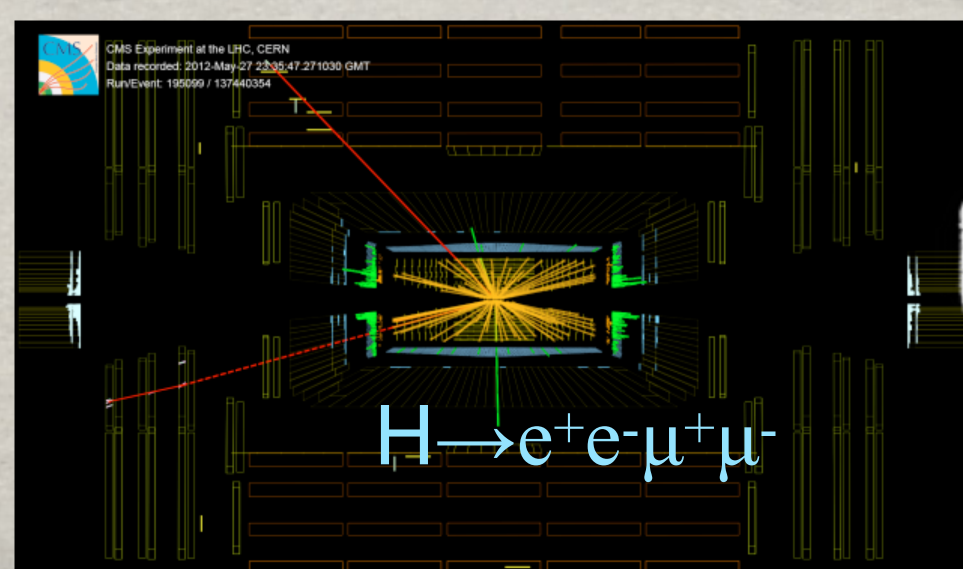




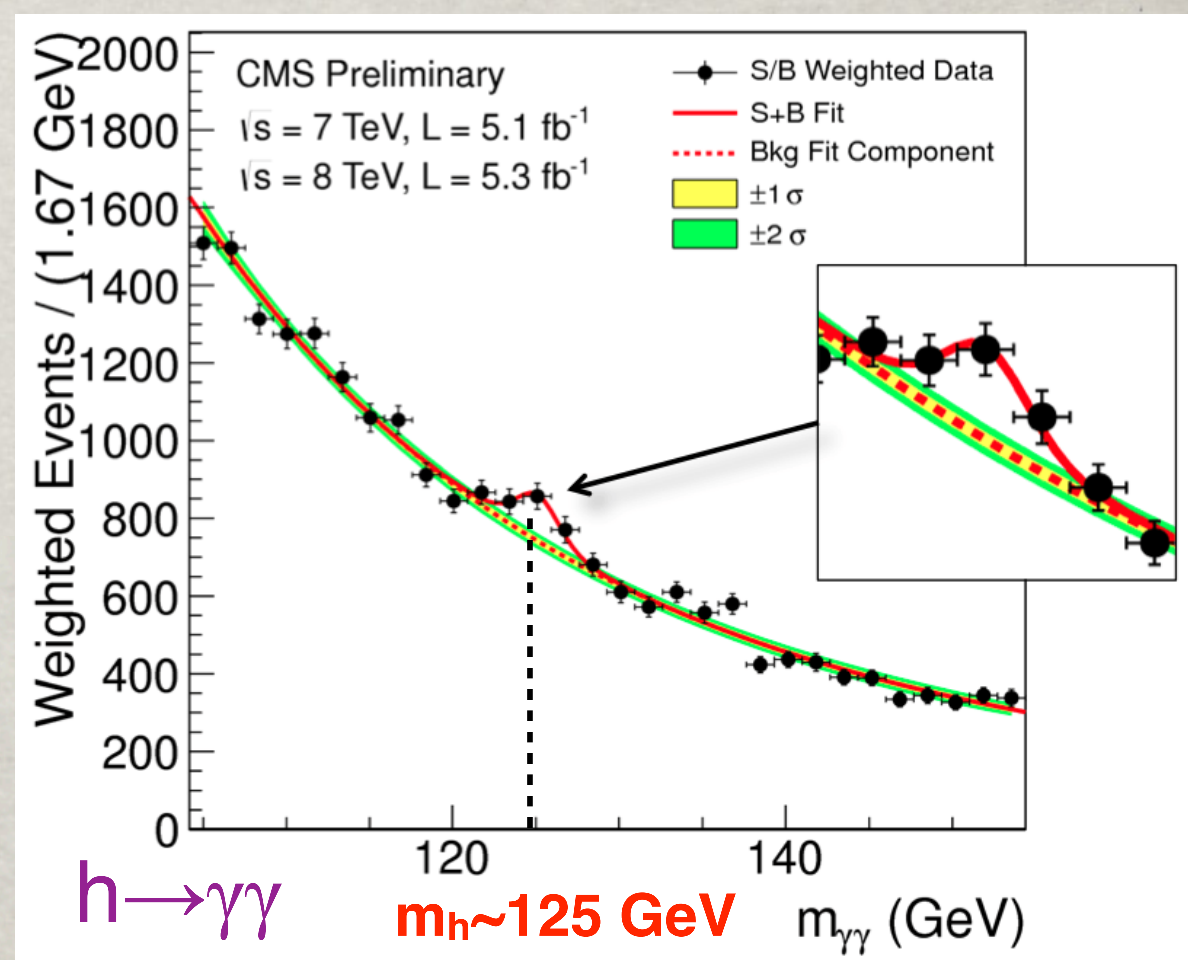
data recorded by CMS - May 13, 2012

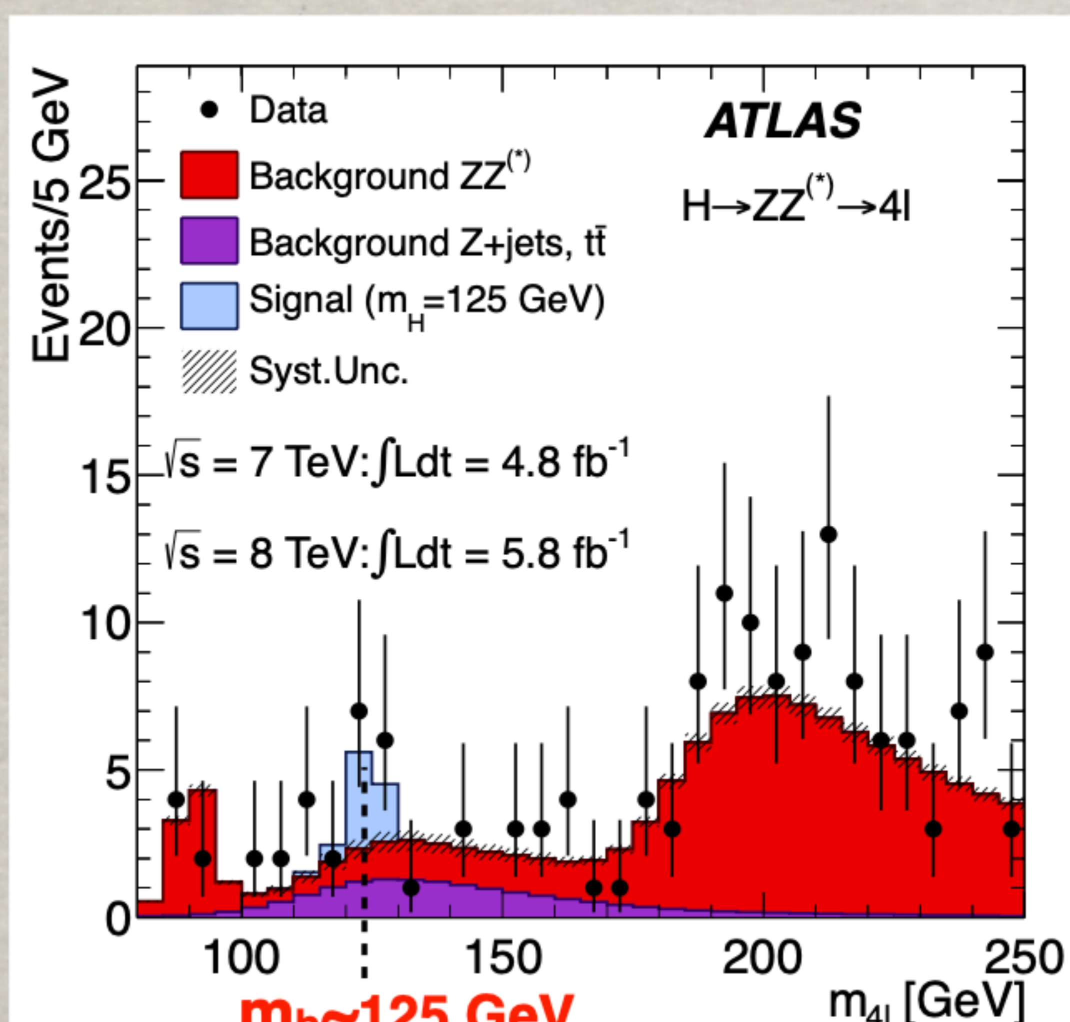
Higgs candidates at LHC (2012)



data recorded by CMS - May 27, 2012

On July 4th, 2012 the ATLAS and CMS collaborations finally announced the discovery of the Higgs boson … 48 years after its theoretical prediction (1964)





h→ZZ →4ℓ

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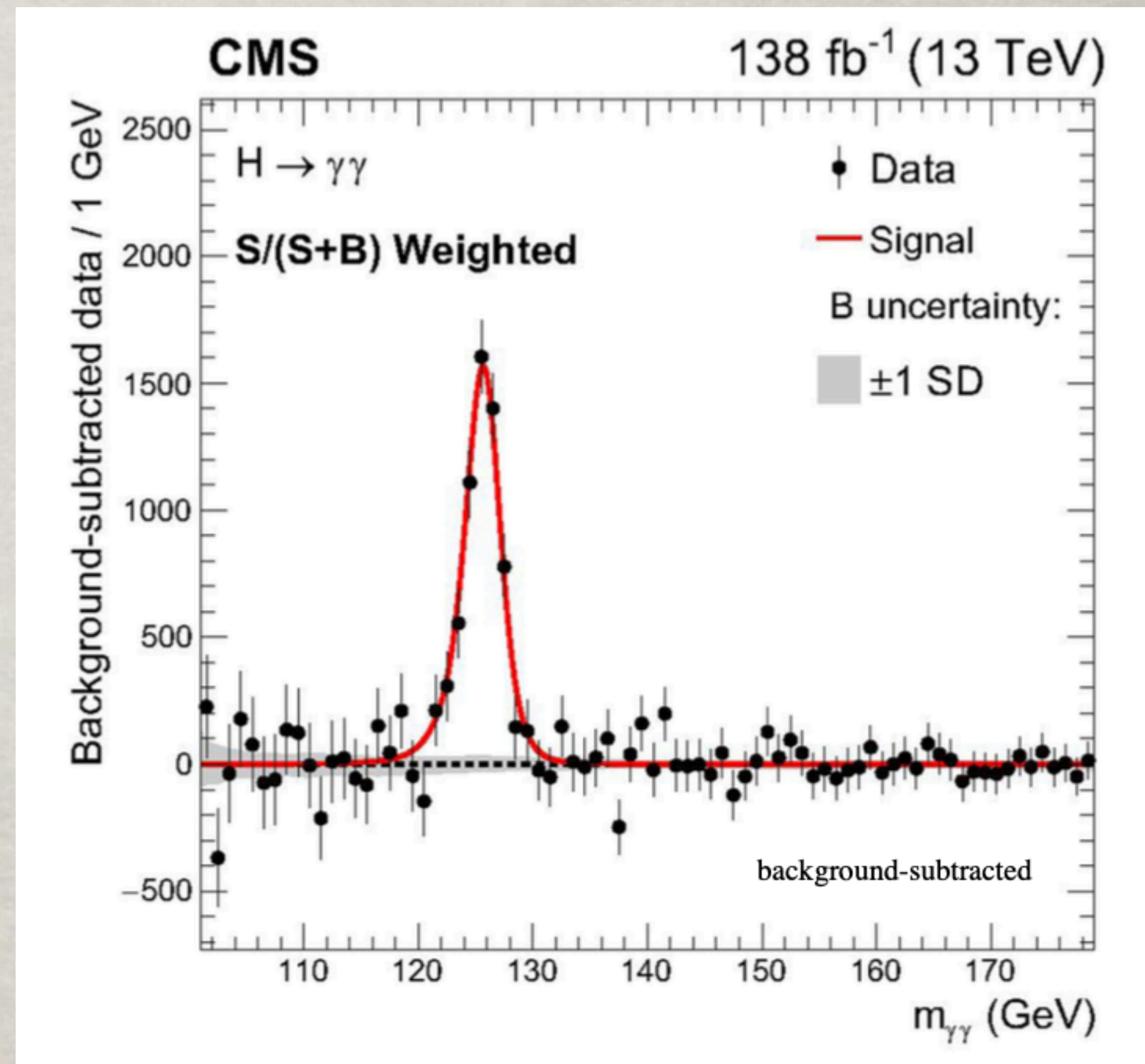

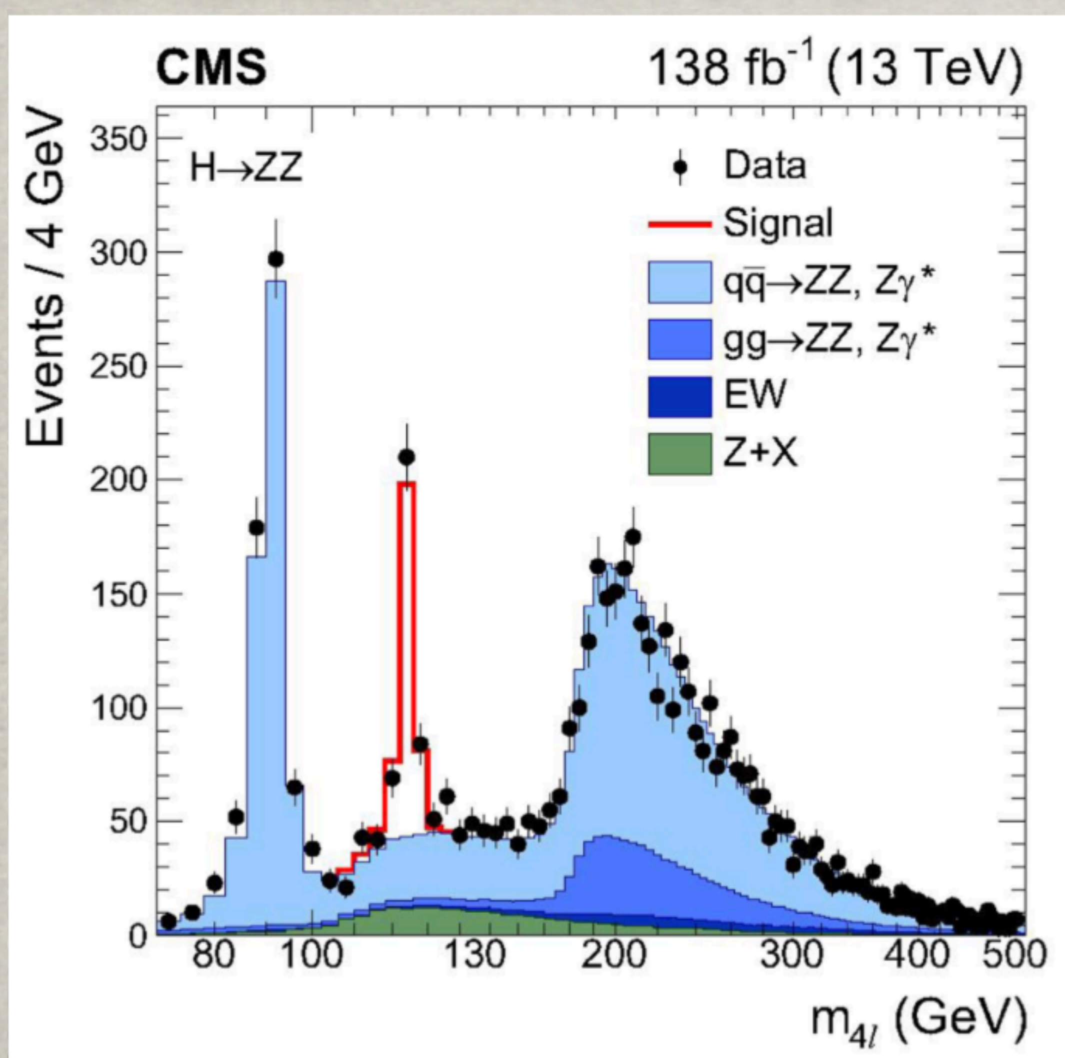

$m_h = 125.38 \pm 0.14$ GeV

+ other channels:
$h \to WW$, $h \to Z\gamma$, $h \to \mu\mu$
$h \to bb$, $h \to \tau\tau$

$h \to ZZ \to 4\ell$

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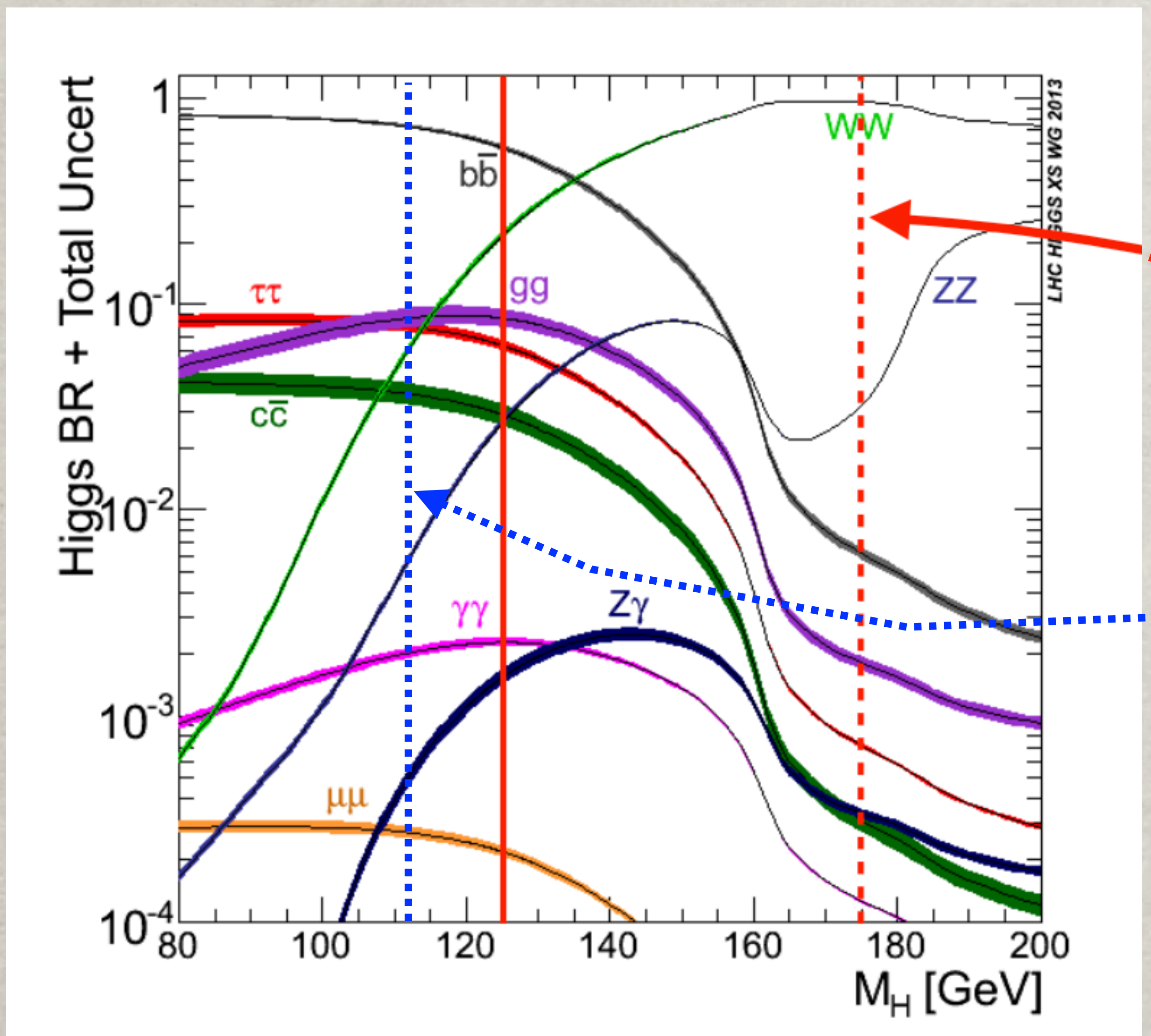
SM Higgs decay channels

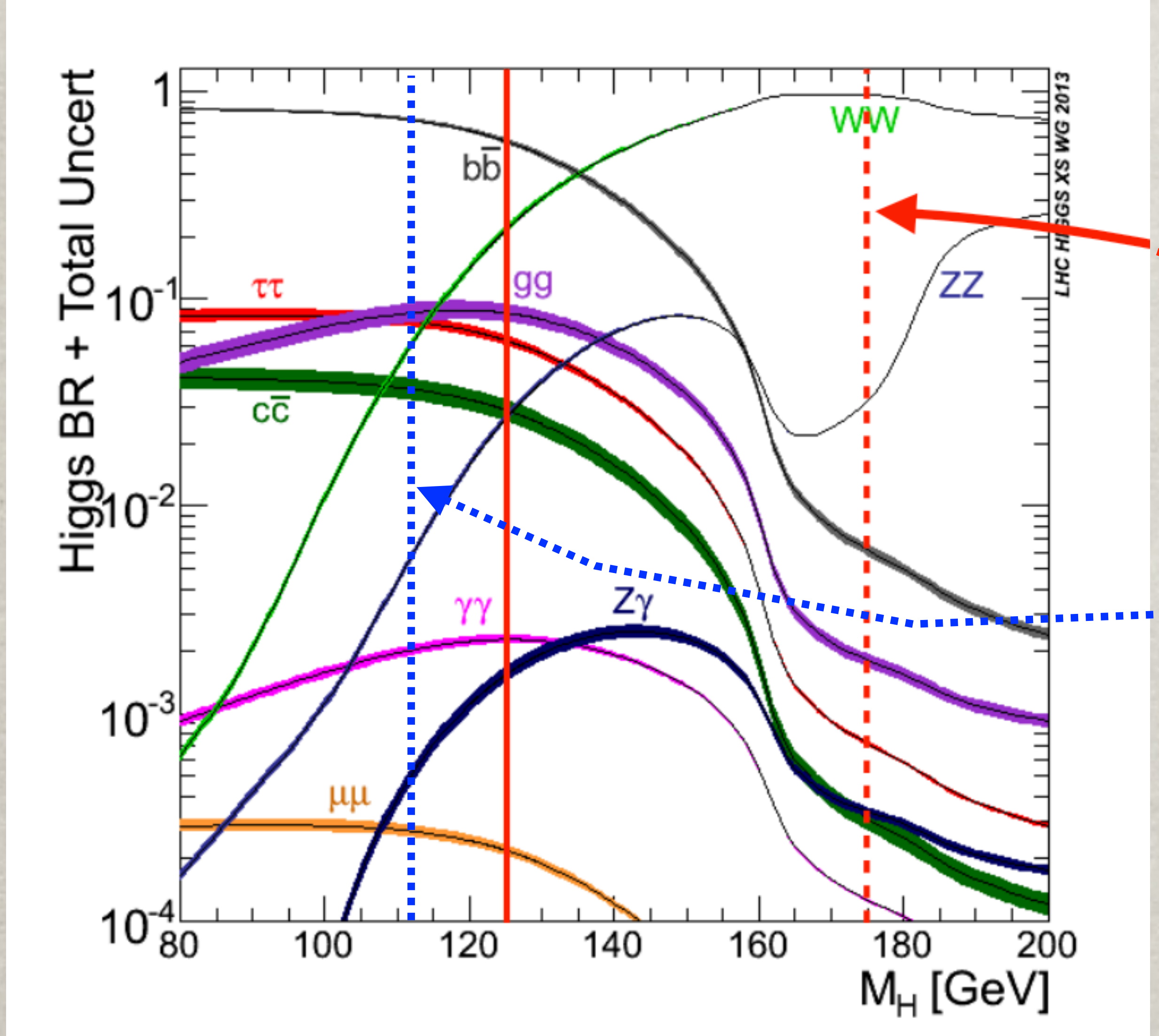


for a 50 GeV heavier Higgs only two basic decay channels WW and ZZ

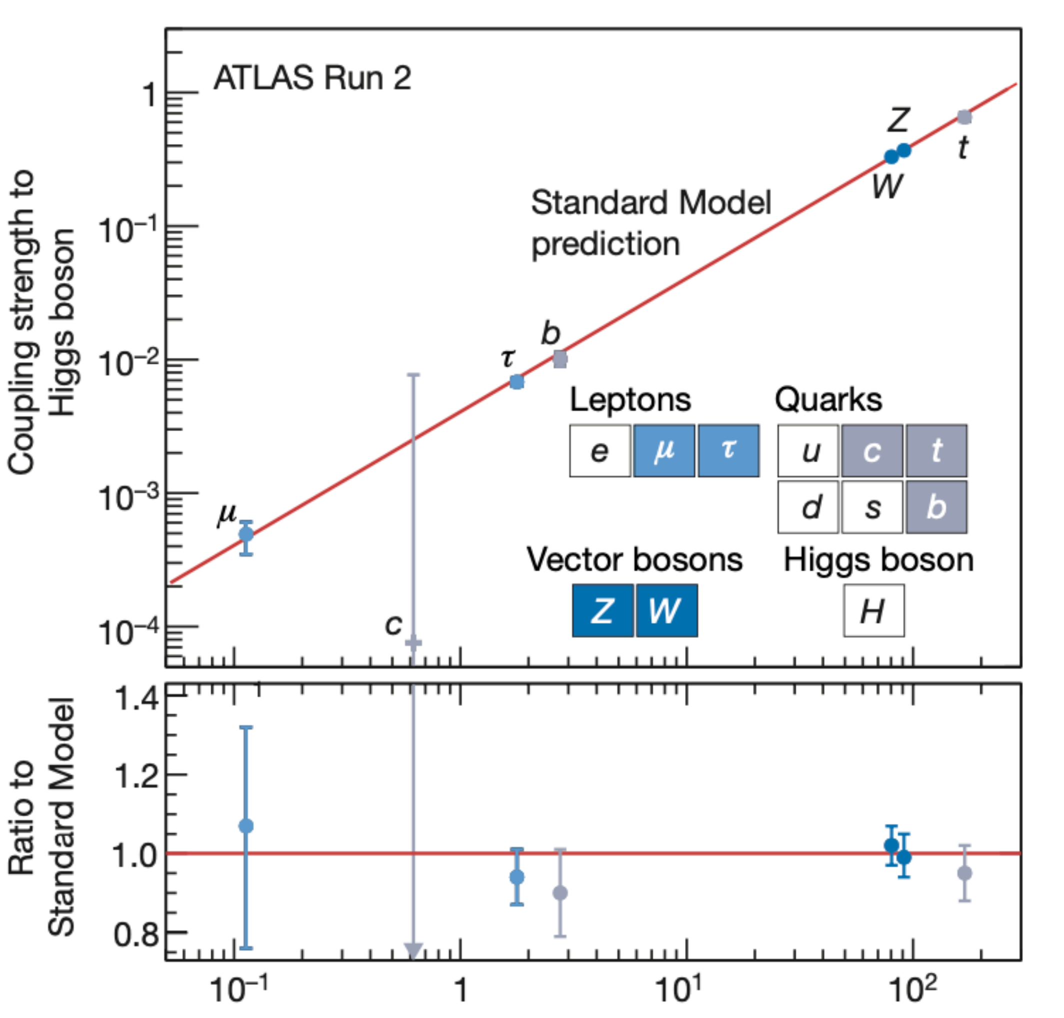
for a 10 GeV lightest Higgs the WW and ZZ decay channels would have been impossible so far

The value of the Higgs mass lies in a lucky spot, this is part of the reason because the Higgs was discovered quickly at the LHC

SM Higgs decay channels



Measured coupling strengths to Higgs boson



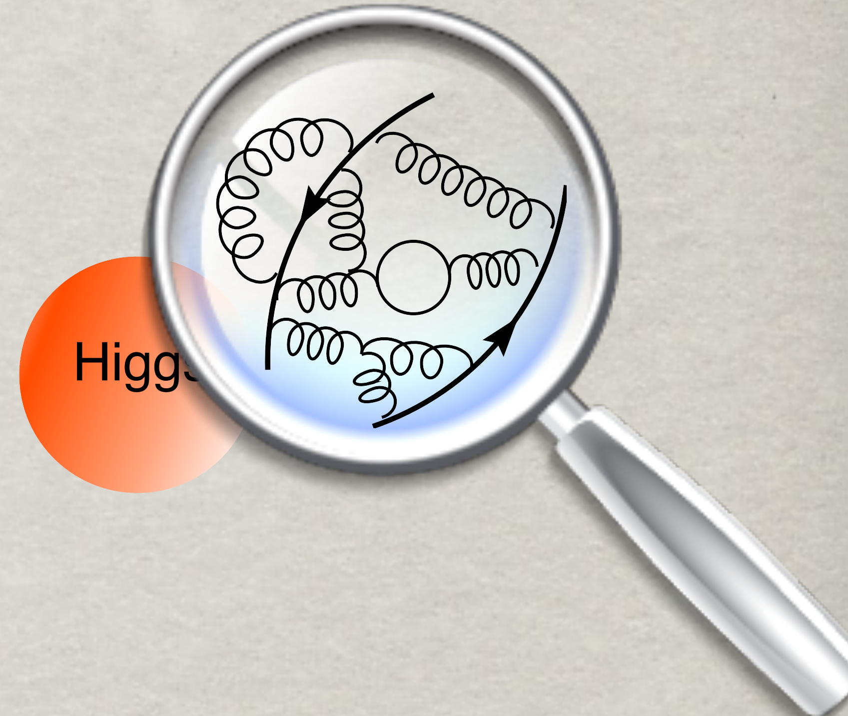
Nature, 607, 2022

The red straight line shows the agreement with the SM prediction but…. several important couplings, like hhh and htt are still very weakly constrained

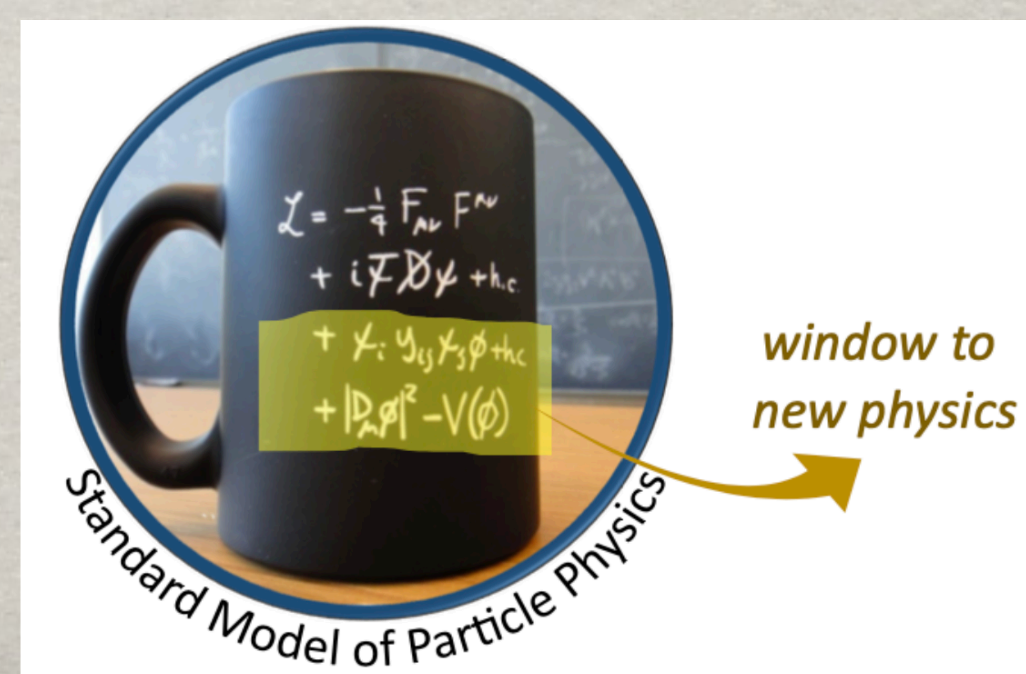
Still open fundamental questions

- Why the three quark and lepton families have so different masses?
- Why the Higgs boson mass is small?
- Why there is only matter in our Universe?
- Why the gravitational force is so much weaker with respect to the others?
- What is dark matter? Is it an unknown particle? What is dark energy?
- ……..

We found the Higgs Boson



- ☑ Is it the SM Higgs?
- ☑ Is it small mass “natural"?
- ☑ Is it an elementary or composite particle?
- ☑ Is it unique?
- ☑ Is it the first supersymmetric particle ever observed?
- ☑ Is it the only responsible for the masses of all the elementary particles?
- ☑ Is it a portal to a hidden world?



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The SM could be a "partial" description of the Nature, it could be part of a more general theory which will manifest itself at energies higher than the ones explored till now

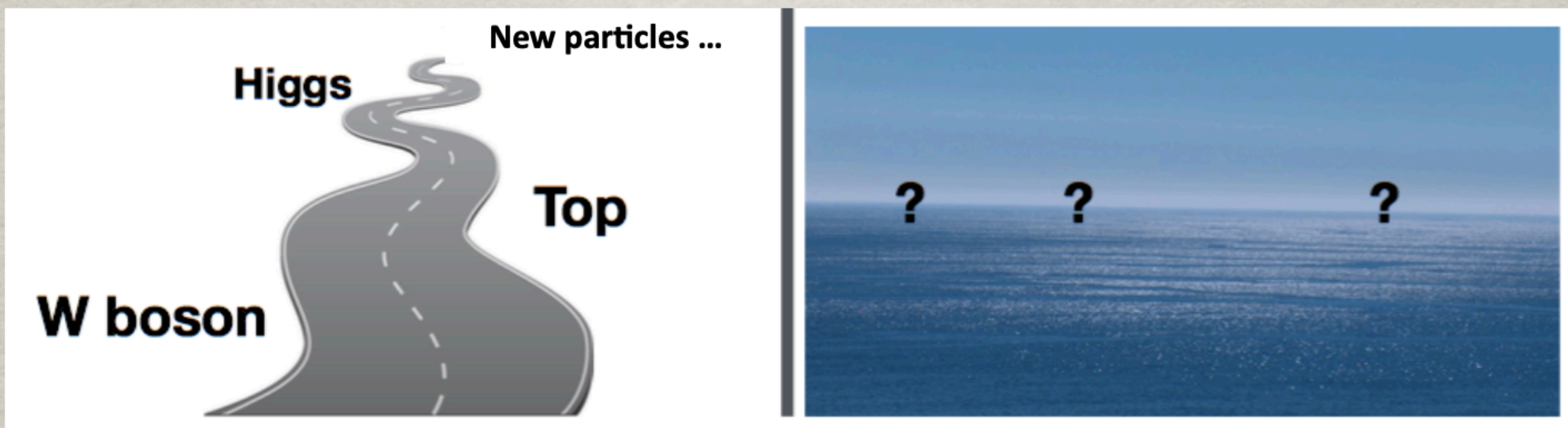
Is the ZOO of the elementary particles complete?

Is the discovered Higgs particle the last missing piece of the puzzle?

Beyond Standard Model Theories

before LHC

after LHC run II



LHC has not shown any evidence for new particles and/or interactions

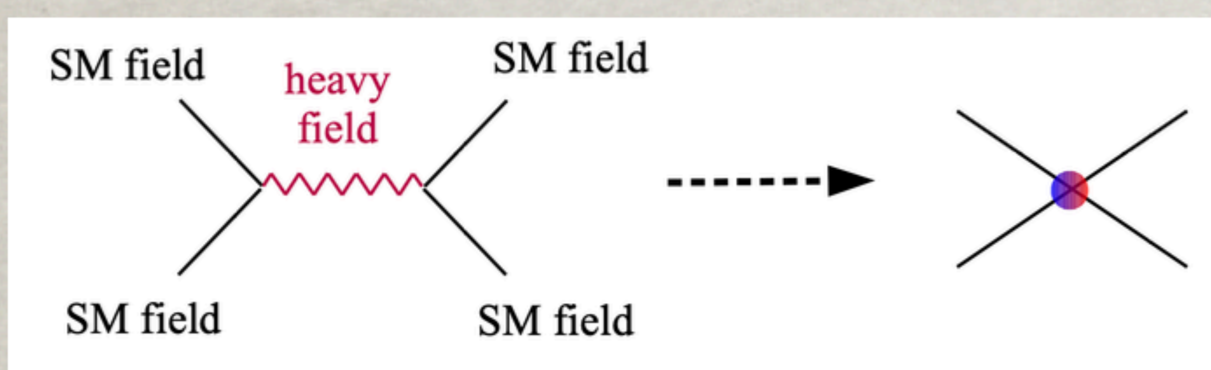
After the Higgs discovery, there is not a clear path to follow for the discovery of new particles

Two main attitudes in the particle theory community:

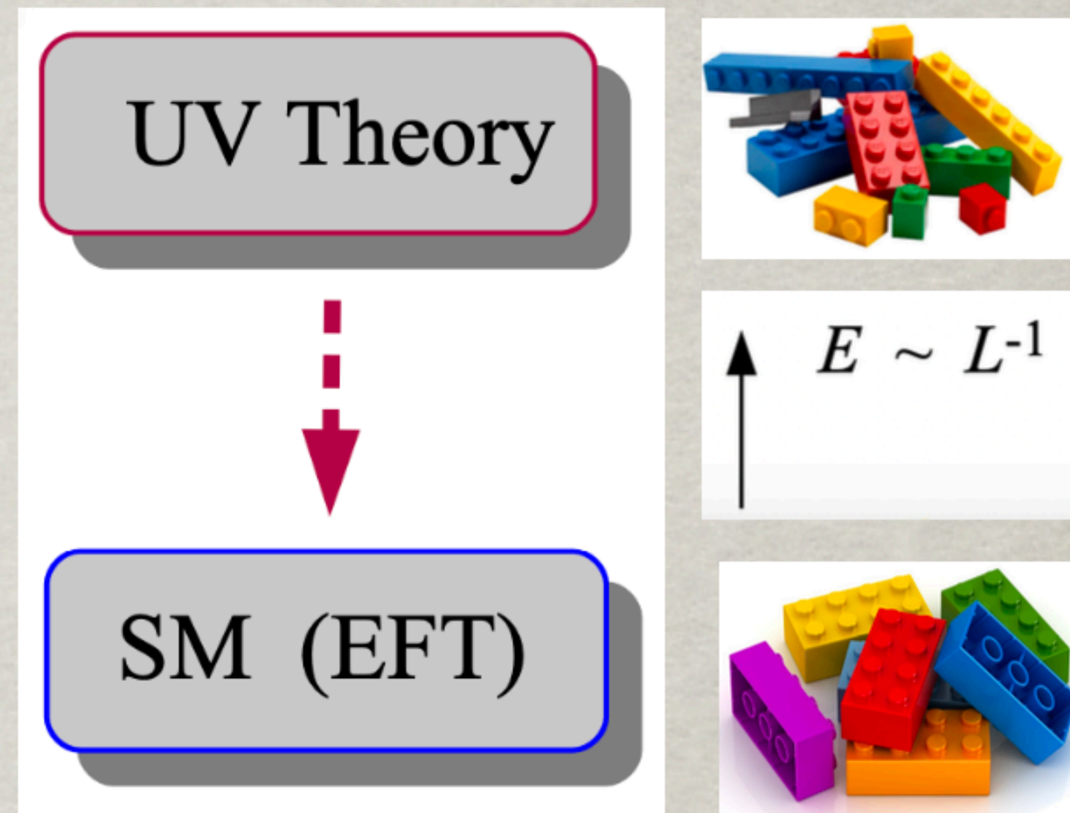
1. SM as an effective theory, deviations encoded in higher dimension operators
2. explore alternative paradigms

SM as an Effective Field Theory

Low energy limit of a more fundamental theory with new particles and/or interactions



ex. Fermi theory



courtesy G.Isidori

$$\mathscr{L}_{\text{SM-EFT}} = \mathscr{L}_{\text{gauge}} + \mathscr{L}_{\text{Higgs}} + \sum_{d,i} \frac{c_i^{[d]}}{\Lambda^{d-4}} O_i^{d\geq 5}$$

Natural: dictated by gauge symmetry

Non trivial UV imprints: M_H and Y_{ij} (they span 5 orders of magnitude)

Higher dimensional operators can capture the residual effects of a non SM-Higgs: its interactions not included in the SM, its composite nature, etc.


BSM Theory after LHC Run II
fermionic partners
massive vectors
extended Higgs sectors
phase transitions
stops
gluinos
axions
dark photons
long-lived particles
gravitational waves
neutral naturalness
low-energy SUSY
compositeness
extra-dimensions
relaxion
landscape
UV-naturalness
Un-Naturalness
Naturalness
Modified Naturalness
G. Panico, talk EPS-HEP 2019

an important question to answer

Can the value of the Higgs mass be explained by an UV theory?

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Why Beyond the Standard Model ?

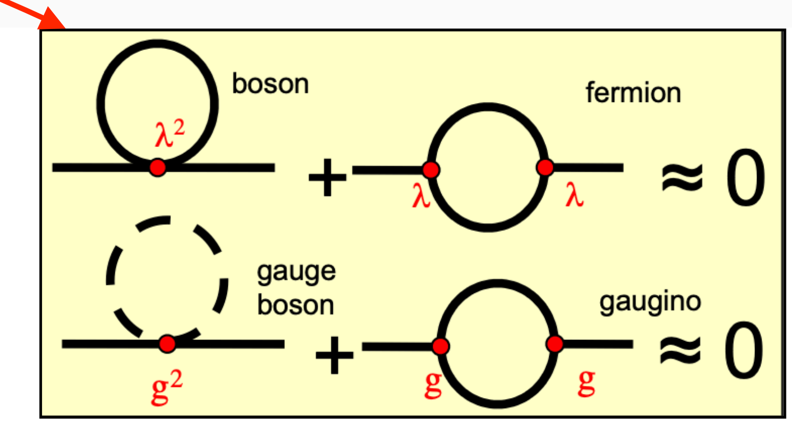
Naturalness is a very deep question

$\sim \Lambda^2 H^\dagger H$

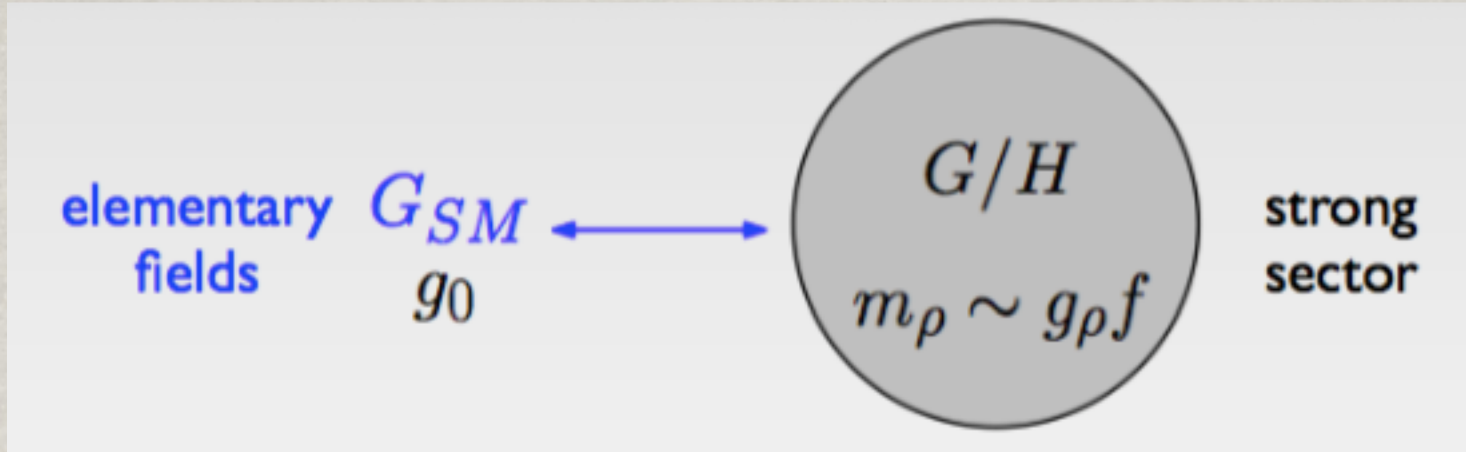
In the SM, Higgs is not naturally light.

New paradigms...

- Supersymmetry
- Strong dynamics near the TeV scale
  - Technicolor
  - Extra Dimensions
  - Higgsless
  - Composite Higgs Models



Higgs as a Composite pseudo Nambu Goldstone Boson



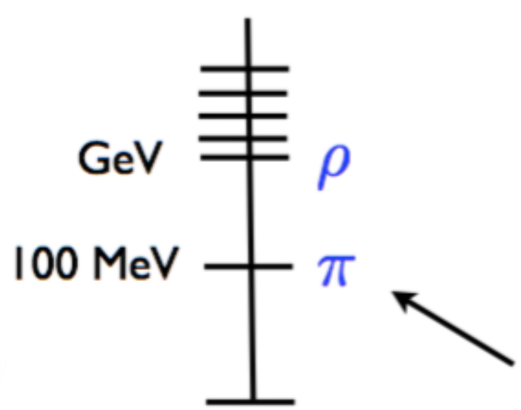
The basic idea

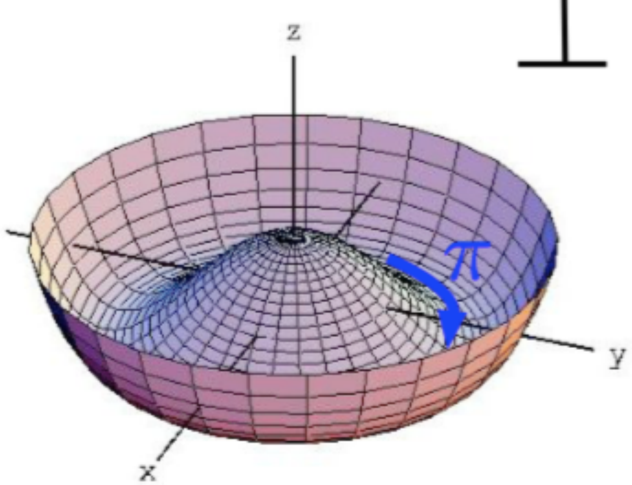
- Higgs as Goldstone Boson of G/H in a **strong** sector

(Georgi, Kaplan '80s)

inspired by QCD where one observes that the (pseudo) scalar are the lightest states

Spectrum:





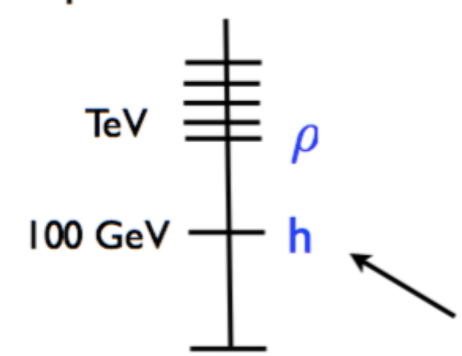
Are Pseudo-Goldstone bosons (PGB)

Mass protected by the global QCD symmetry!

$$\pi \to \pi + \alpha$$

→ **Can the light Higgs be a kind of a pion from a new strong sector?**

We'd like the spectrum of the new strong sector to be:



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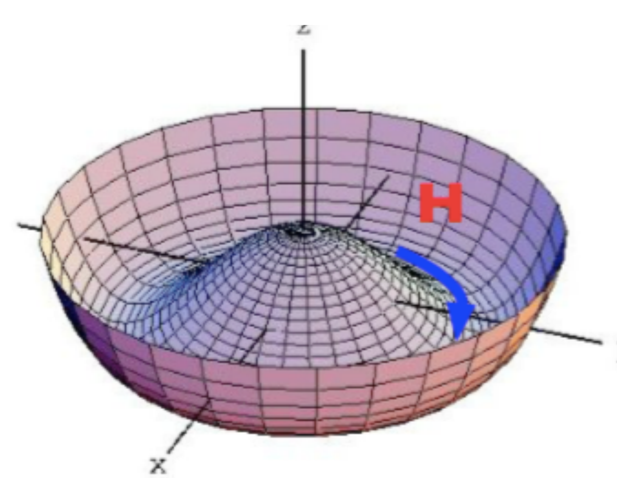


e.g. SO(5) → SO(4)

4 Goldstones

↓

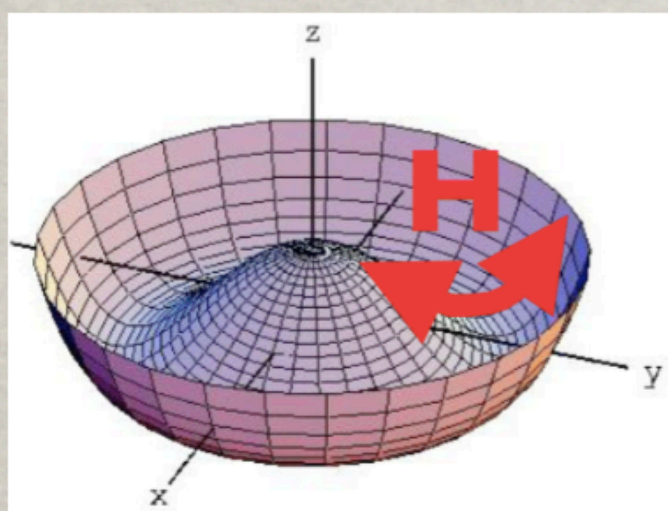
Higgs doublet

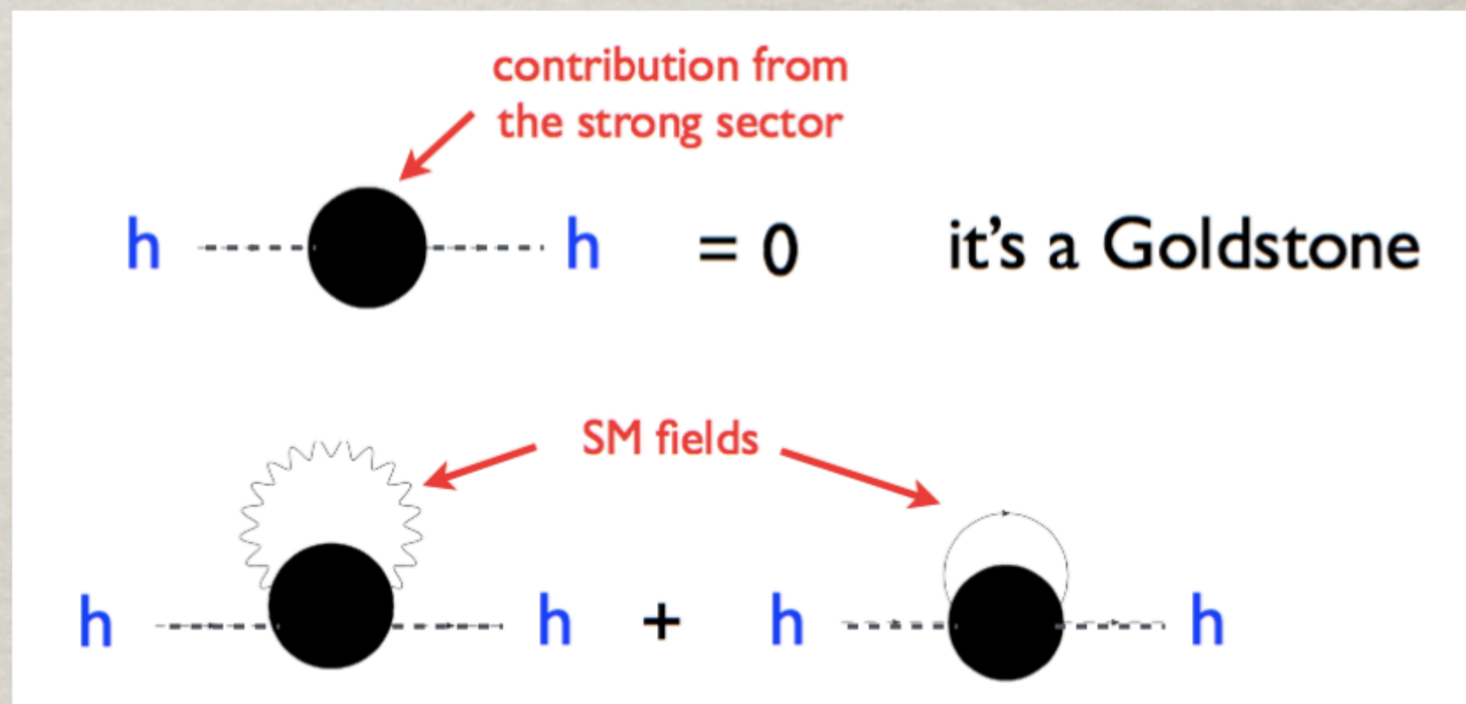
Higgs as a Composite pseudo Nambu Goldstone Boson

How to get an Higgs mass?

- G is only an approximate global symmetry $g_0 \rightarrow V(h)$

SM-field couplings to the strong sector
break the global G
SM loop effects $\rightarrow$ EWSB minimum





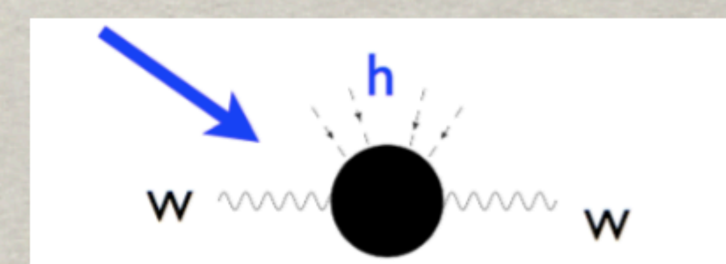
- EWSB as in the SM
- And the hierarchy problem?
  no Higgs mass term at tree level

$$\rightarrow \delta m_h^2 \sim \frac{g_0^2}{16\pi^2}\Lambda_{com}^2$$

V(h) triggers the EWSB

EW scale from m_W^2:

$$v^2 = f^2 \sin^2 \frac{\langle h \rangle}{f}$$



Encode the strong-sector contribution
to the gauge propagator
in the h-background

to recap:

	Pion Physics	Composite pNGB Higgs
Fundamental Theory	QCD	QCD-like theory
Spontaneous sym. breaking	$SU(2)_L \times SU(2)_R \to SU(2)_V$	$G \to H$ (spontaneous at compositeness scale f)
pNGB modes	$(\pi^0, \pi^\pm) \sim 135$ MeV	$h \sim 125$ GeV
Other resonances	$\rho \sim 770$ MeV, $\cdots$	New spin 1 and ½ states $\sim$ Multi-TeV

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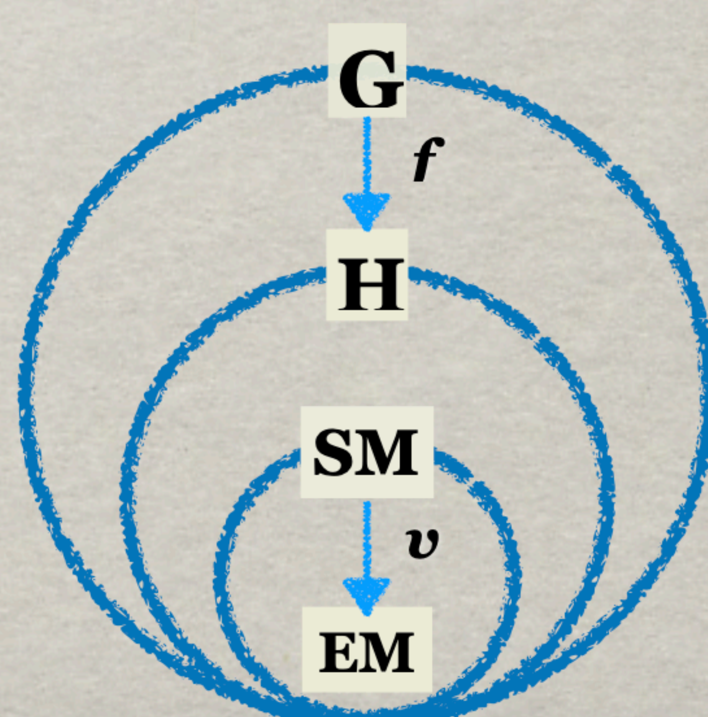
Basic rules for explicit composite pNGB models

- ☑ Need to choose the correct $G \rightarrow H$ (spontaneous) breaking at f (~ TeV) to have the required NGBs (≥ 4)
- ☑ Need to break H (explicitly, so pNGBs) via g_0 (gauge) and Y (Yukawa) couplings to generete the one-loop effective potential for EWSB
- ☑ Need to include new composite resonances from the confining strong dynamics



Composite Higgs Models

Elementary Sector		Strong Sector
$A_\mu, \psi \in SU(2) \times U(1)_Y$	$\mathcal{L}_{\text{mix}} = g_0 A_\mu J^\mu_\rho + \Delta \bar{\psi} \Psi$	$\rho_\mu, \Psi \in G_{\text{strong}}$
$g_0 < 1$		$m_\rho,\ 1 < g_\rho < 4\pi$

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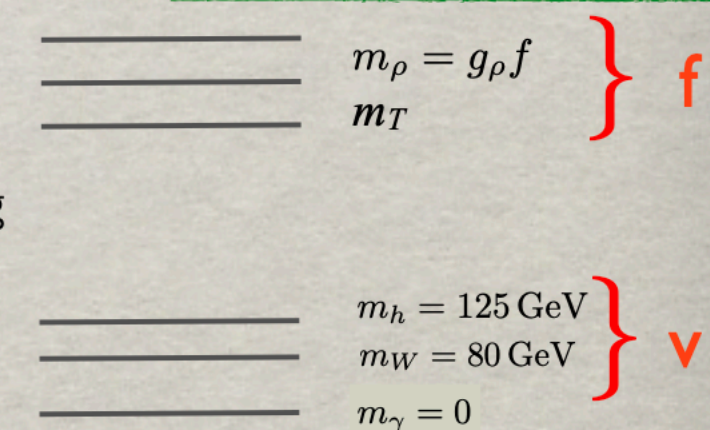
Strong sector: resonances + Higgs bound state

Extra particle content:

- Spin 1 resonances ρ
- 1/2 resonances T

Spectrum :



g_ρ = strong coupling

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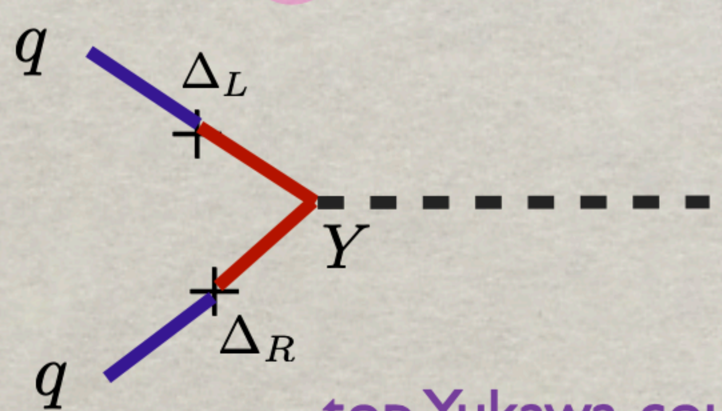
partial compositeness

Linear elementary-composite fermion mixings

→ for the 3rd generation quarks

$$\Delta_R \bar{q}_R \mathcal{O}_L + \Delta_L \bar{q}_L \mathcal{O}_R + Y \bar{\mathcal{O}}_L H \mathcal{O}_R$$



top Yukawa coupling

$$m_t \sim \frac{v}{\sqrt{2}} \frac{\Delta_{t_L}}{m_T} \frac{\Delta_{t_R}}{m_{\tilde{T}}} \frac{Y_T}{f}$$

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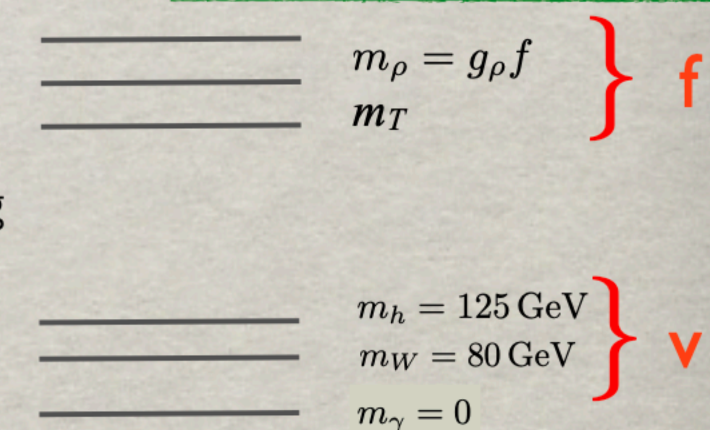

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$g_0 < 1$		$m_\rho,\ 1 < g_\rho < 4\pi$

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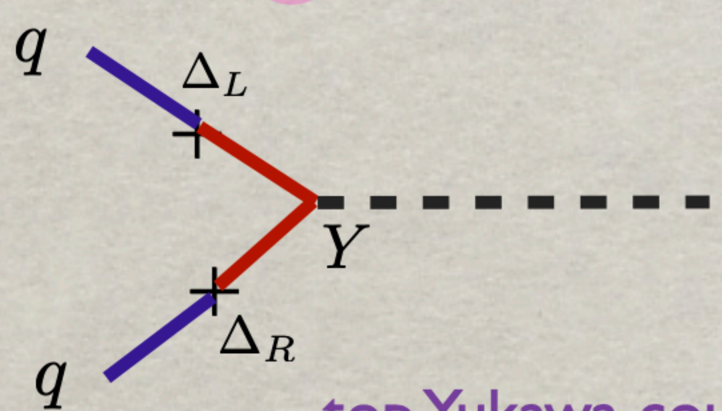

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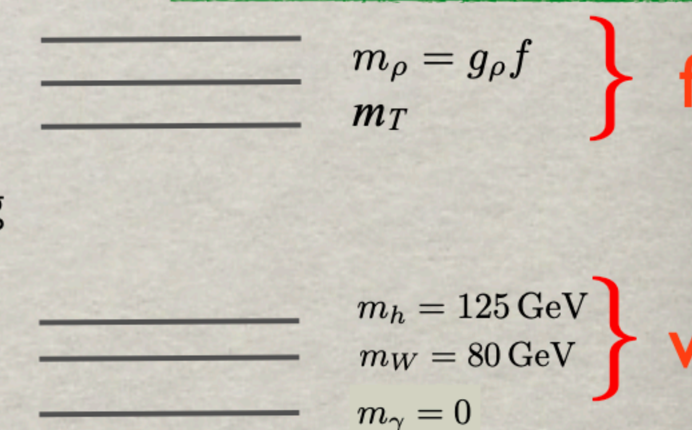
- 1/2 resonances T

Spectrum :



g_ρ = strong coupling

SM hierarchies are generated by the mixings:
light quarks mostly elementary, top mostly composite

Extended Composite Higgs Models

Models with a larger Higgs structure with respect to the SM have been largely discussed

Supersymmetry requires two Higgs doublets with specific Yukawa and potential terms

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Look for a pNGB realisation of extended Higgs scenarios

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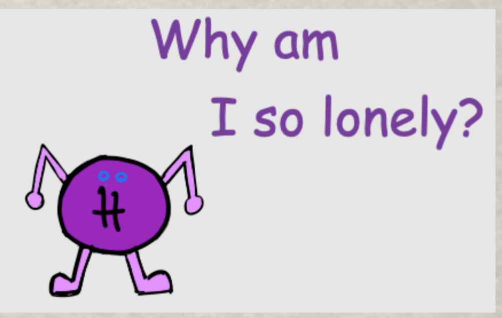

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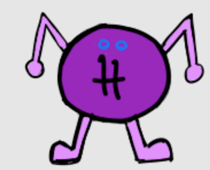
The structure of the Higgs sector is determined by the coset G/H

G	H	PGB
SO(5)	SO(4)	4=(2,2)
SO(6)	SO(5)	5=(2,2)+(1,1)
SO(6)	SO(4)xSO(2)	8=(2,2)+(2,2)
SO(7)	SO(6)	6=(2,2)+(1,1)+(1,1)
	G_2	7=(1,3)+(2,2)
...	...	...



- ➠ Minimal = One Doublet
  DC,Red,Tesi 12
- ➠ Doublet + Singlet
  Gripaios et al.09; Redi,Tesi 12; DC et al.19
- ➠ Two Doublets
  Mrazek et al.11
  Bertuzzo et al.13
  DC et al. 16; 18

SU(5) →SU(4) x U(1)

New players in the game

Composite 2-Higgs Doublet Model (C2HDM)

J.Mrazek et al. '11; DC,Moretti,Yagyu,Yildirim '16, DC,Delle Rose,Moretti,Yagyu '18

- The model construction follows the same steps of the minimal 4DCHM (two-site model).
  All the parameters real → CP invariant scenario

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$$
\begin{aligned}
\mathcal{L}_{\rm mix} + \mathcal{L}_{\rm strong} \;\; &= \;\; \Delta_L^I \bar{q}_L^{\bf 6} \Psi_R^I + \Delta_R^I \bar{t}_R^{\bf 6} \Psi_L^I \; + h.c. \\
&+ \;\; \bar{\Psi}^I i \not{D} \Psi^I - \bar{\Psi}_L^I M_\Psi^{IJ} \Psi_R^J - \bar{\Psi}_L^I \left(Y_1^{IJ} \Sigma + Y_2^{IJ} \Sigma^2 \right) \Psi_R^J
\end{aligned}
$$

$$\Sigma = U_1 \Sigma_2 U_1^T$$

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$$f, \quad \Delta_L^{1,2}, \quad \Delta_R^{1,2}, \quad Y_{1,2}^{IJ}, \quad M_\Psi^{IJ}, \quad I,J=1,2$$

(partial compositeness for the top)

scale of compositeness, linear mixings, Yukawas, heavy fermion mass parameters

2-Higgs Doublets as pNGBs

Aligned 2HDM realised in a composite scenario

- Same physical Higgs states as in the elementary 2HDM: $h, H, A, H^{\pm}$ (h=SM-like Higgs)

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  $m_h \sim v \quad m_H \sim f + O(v) \qquad \xi = v^2/f^2$

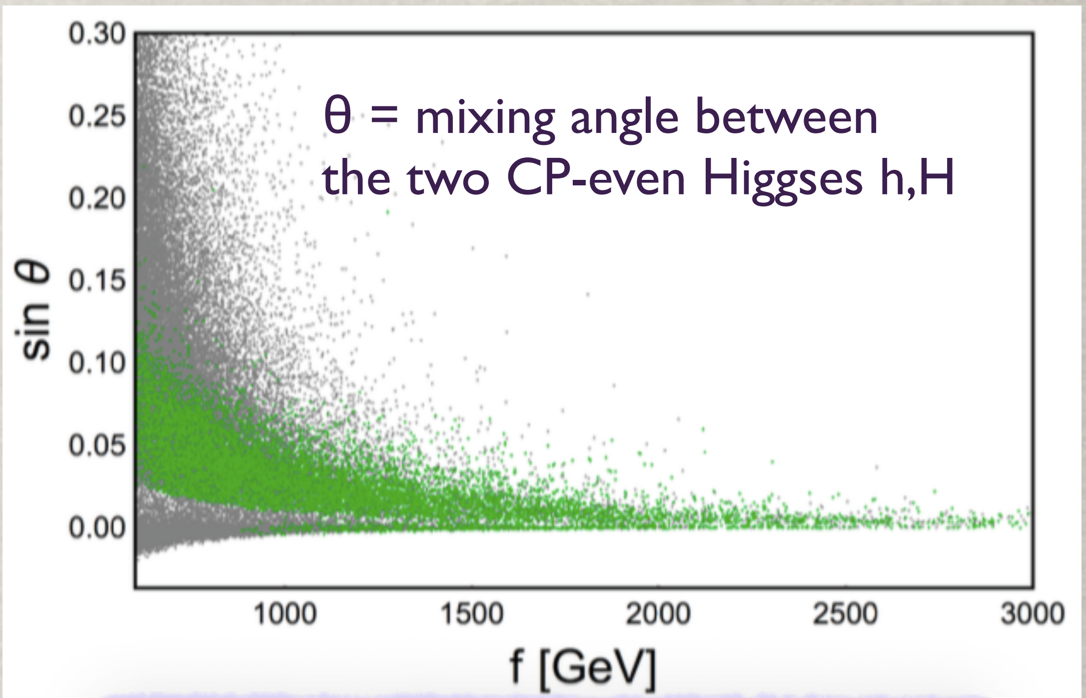
  θ is predicted to be small: O(ξ) for large f

- CP-odd states: $A, H^{\pm}$

  $m_A \sim m_{H\pm} \sim f + O(v)$

$f \to \infty$ SM limit

$H, A, H^{\pm}$ decouple
$h \to h^{SM}$



green points satisfy the bounds from direct and indirect Higgs searches

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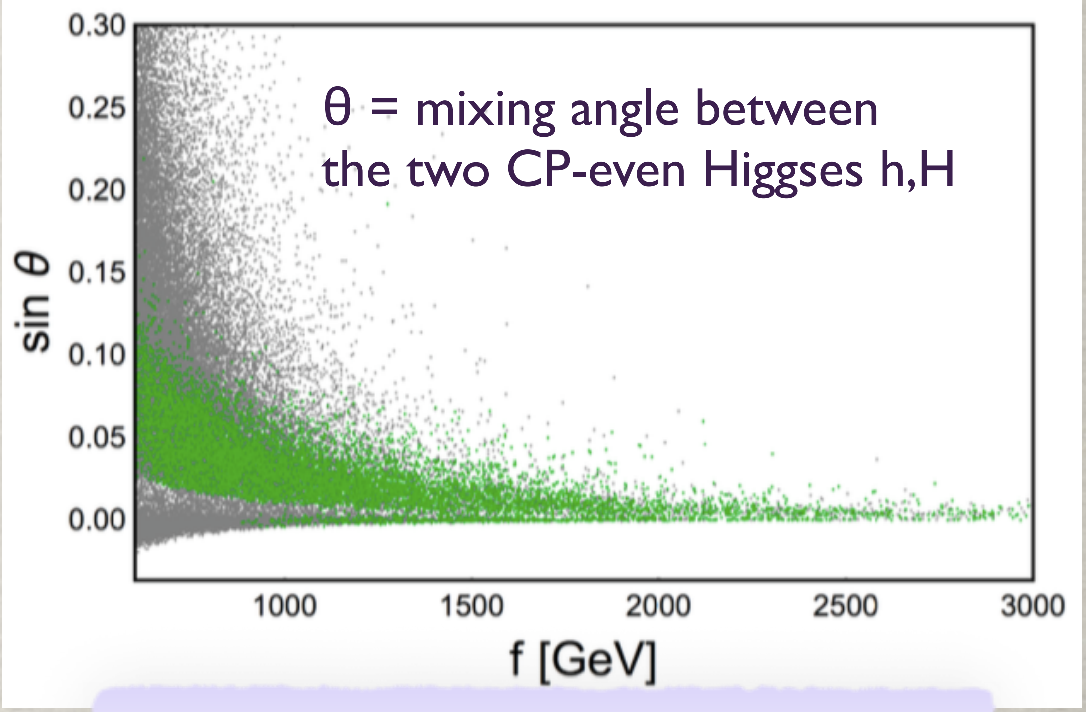

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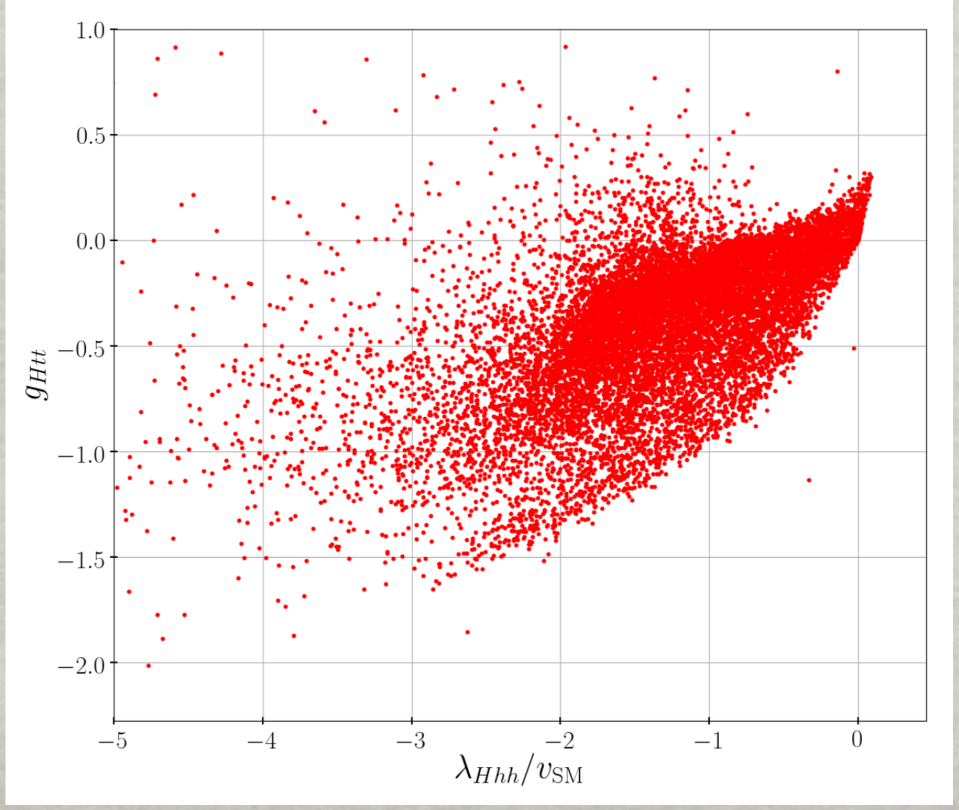


in the C2HDM the Higgs sector parameters are correlated and carry the imprint of compositeness

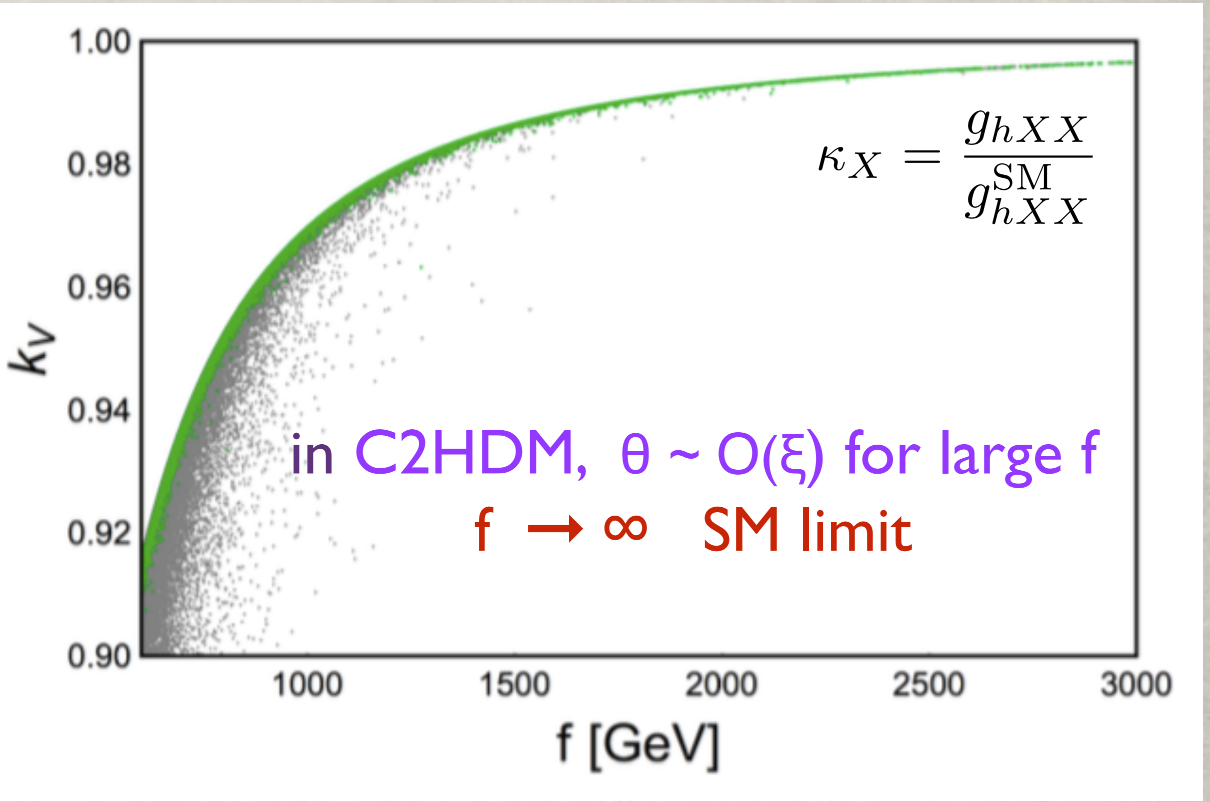
→ Ex: Htt and Hhh

C2HDM - facing the data

- h couplings to SM particles:

dictated by symmetries (as in QCD chiral Lagrangian) Ex: corrections of order ξ to the hVV couplings. Also modified by the mixing angle θ

$k_V \simeq (1-\xi/2)\cos\theta$ V=W,Z $\xi = v^2/f^2$



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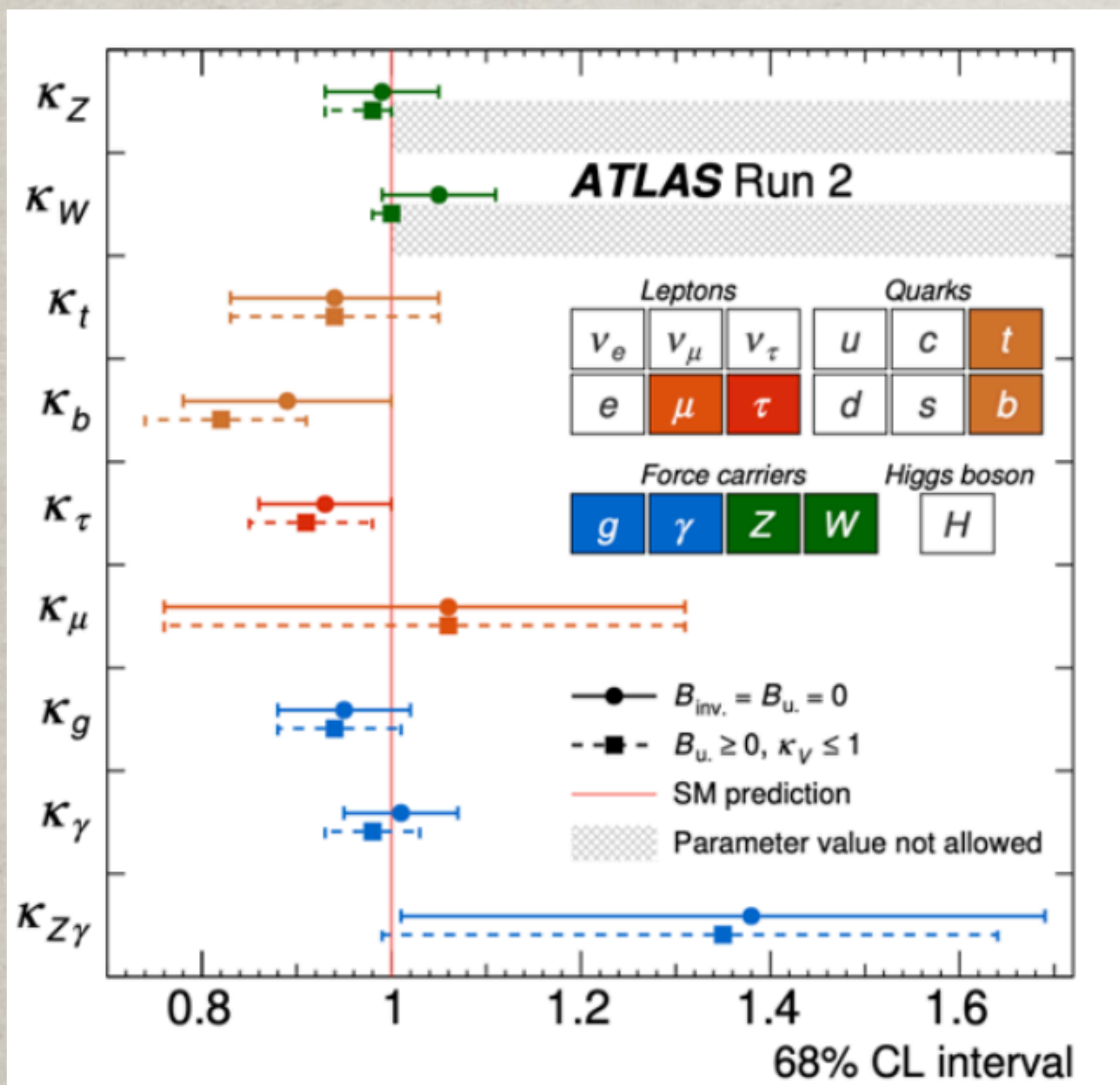

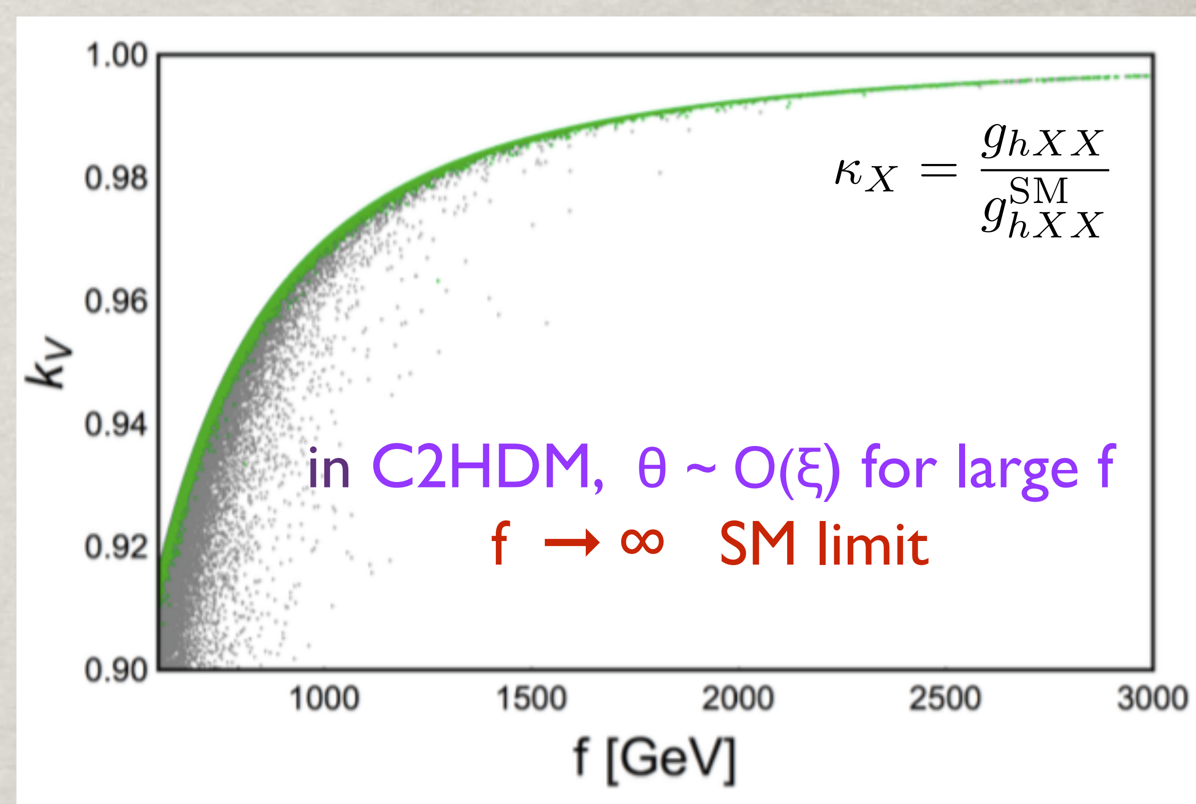

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NOW: the Higgs couplings are constrained at 10-20% level

$\xi \leq 0.1$ $f \geq 750$ GeV

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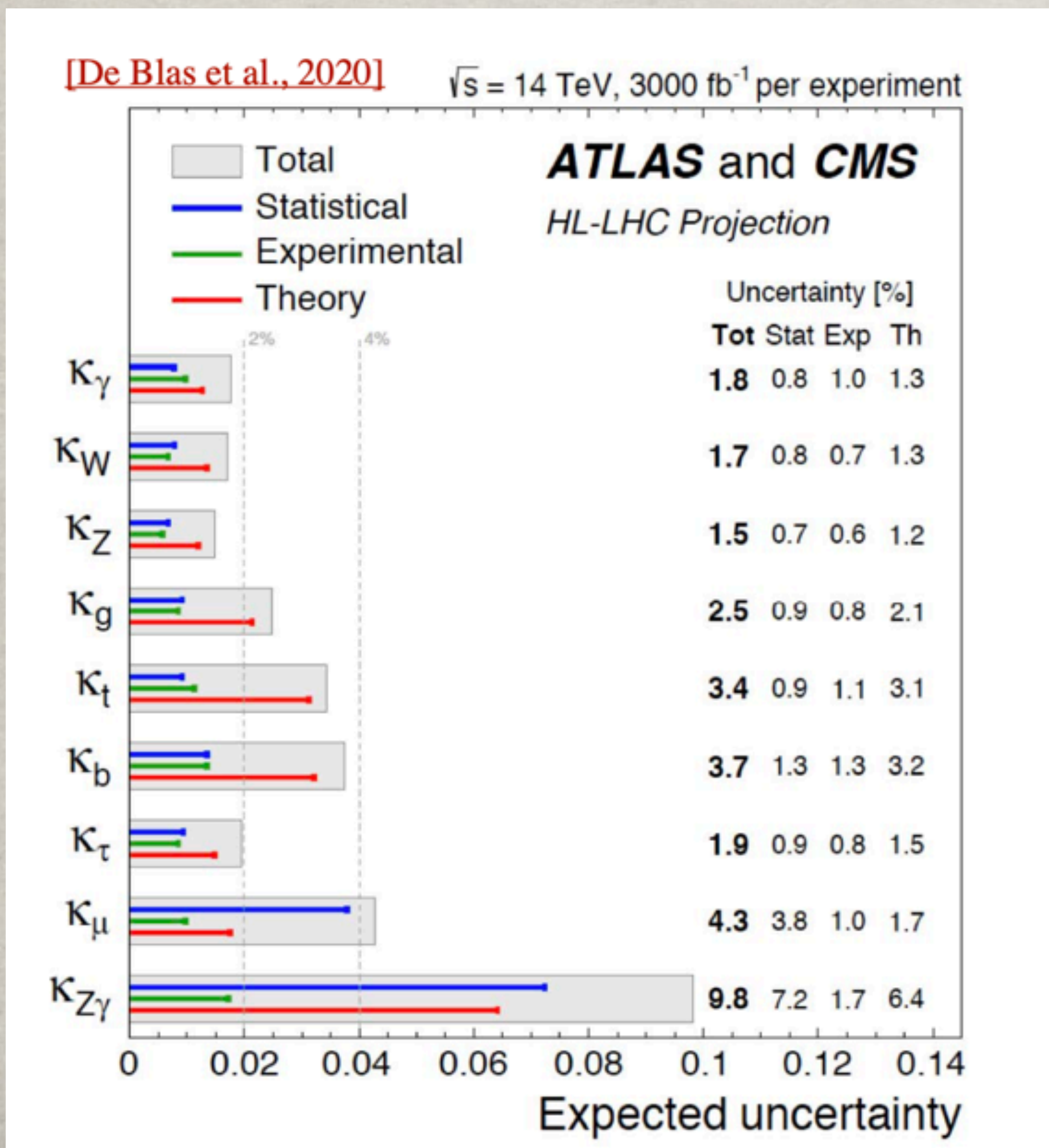

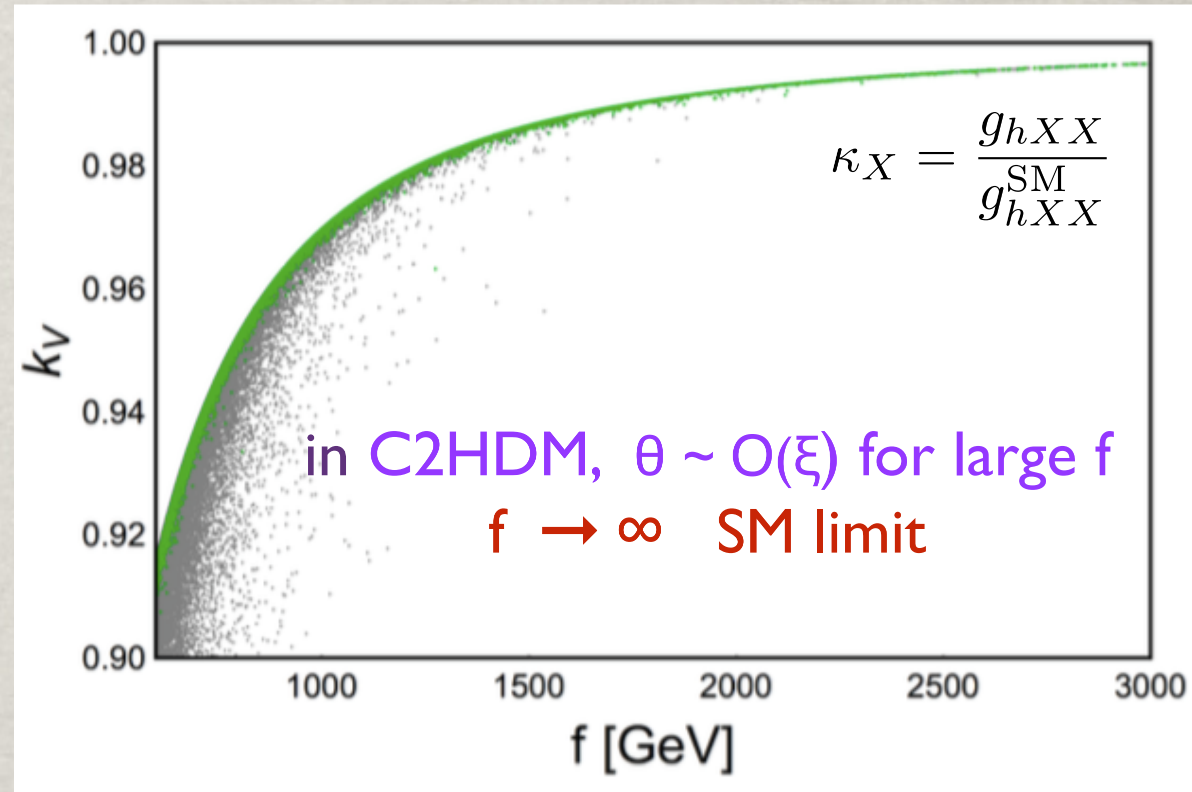

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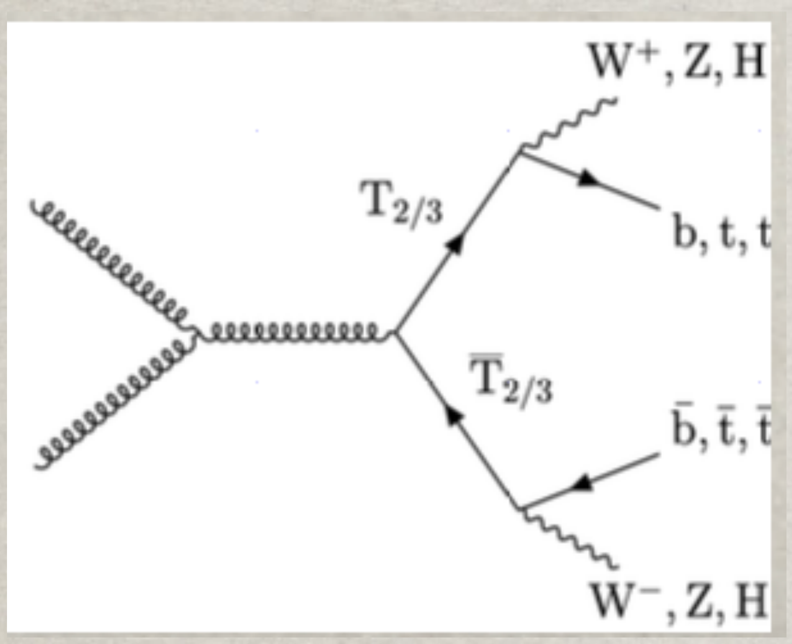
HL-LHC : the Higgs couplings will be constrained at 2-4% level

ξ ≤ 0.04 f ≥ 1200 GeV

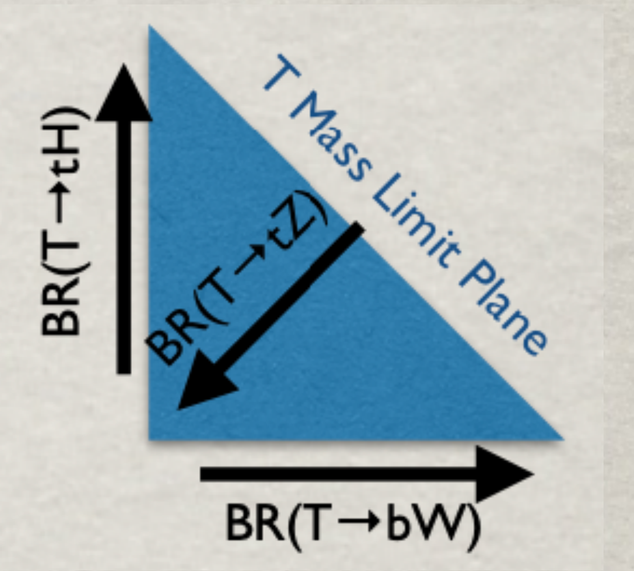
CHMs NOT ruled out

Mass bounds on new heavy fermions: $T_{2/3}$, $B_{-1/3}$, $X_{5/3}$



Pair production searches set σ x BR limits depending on the extra-fermion mass and on the BR assumption

← only SM decay channels considered →



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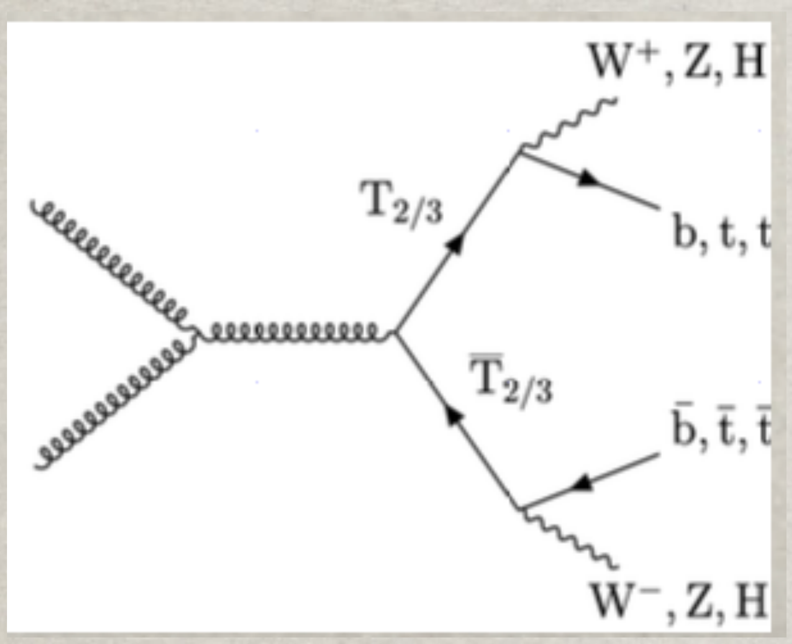

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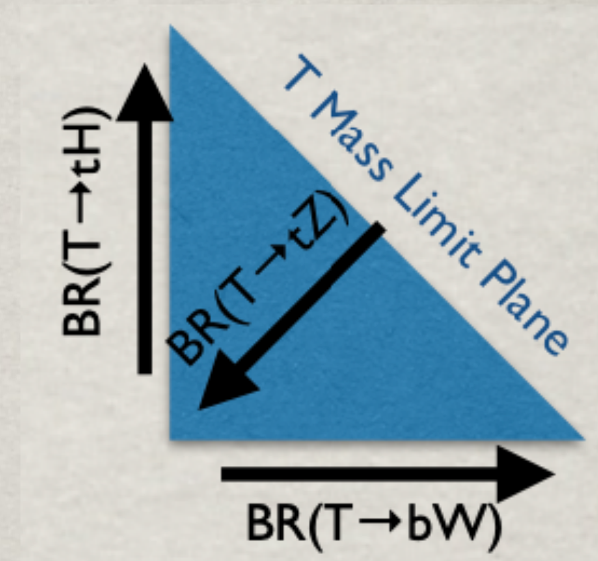

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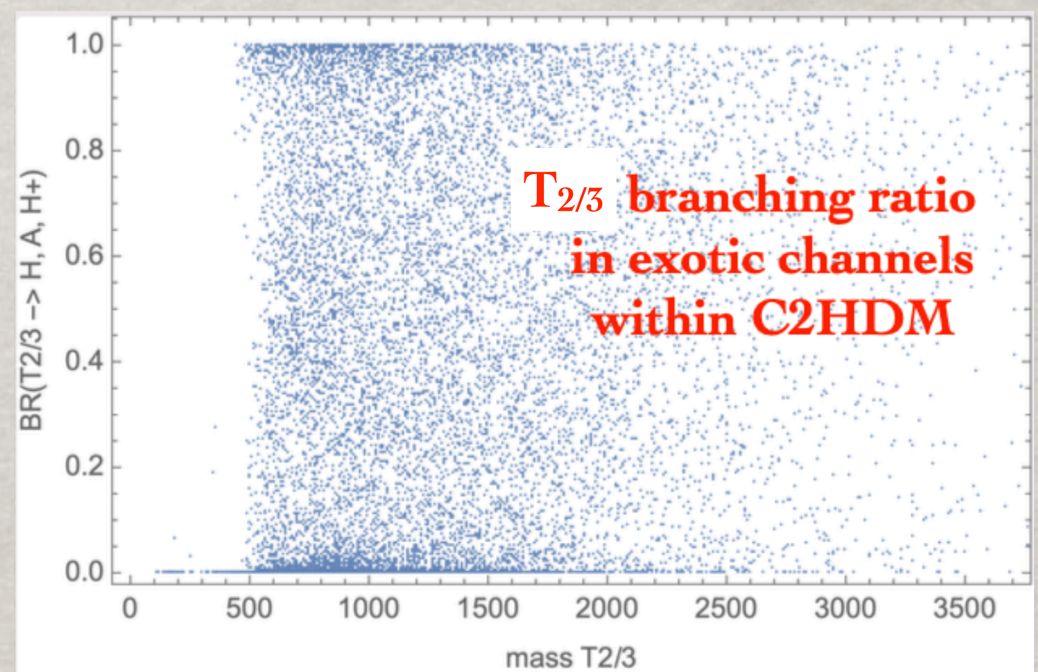

A recasting of the bounds is under study

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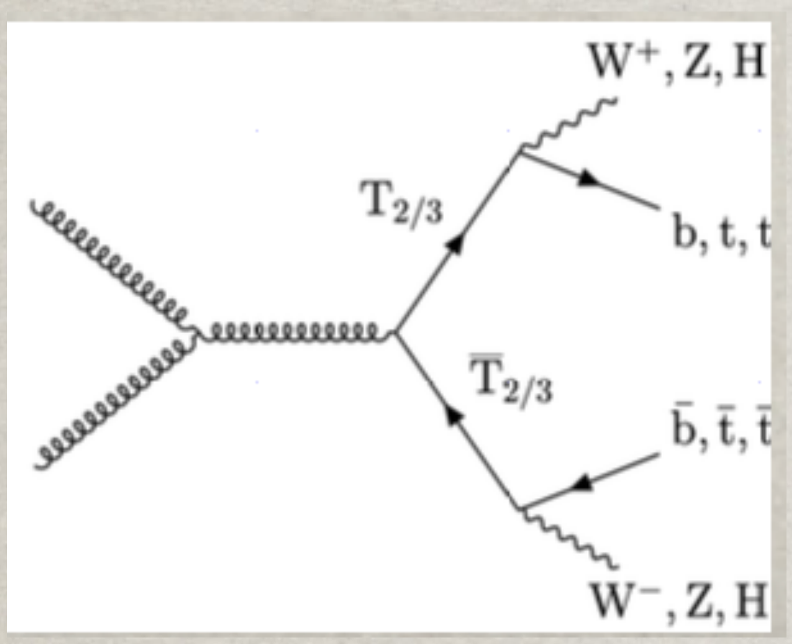

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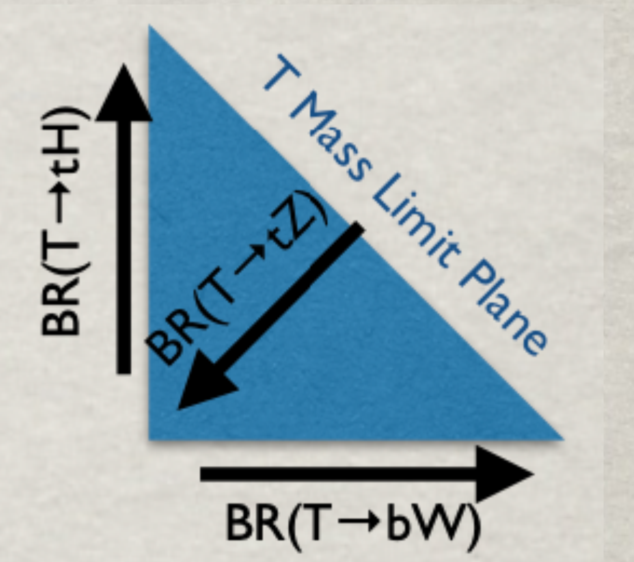

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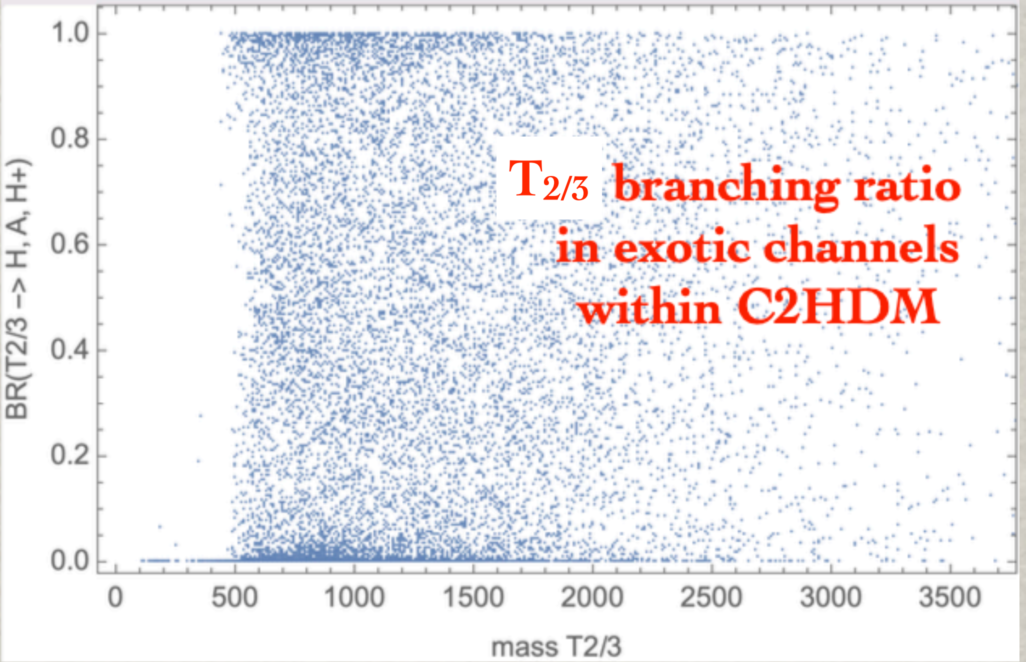
However, from a recent ATLAS analysis [hep-exp 2212.05263] seems difficult to allow $M_{T2/3}$ < 1.3 TeV

Search for pair-produced vector-like quarks using events with exactly one lepton (e or μ), at least four jets including at least one b-tagged jet, and large missing transverse momentum

(upgrade of a previous analysis using 139 fb^{-1} and neural networks trained at several BRs)



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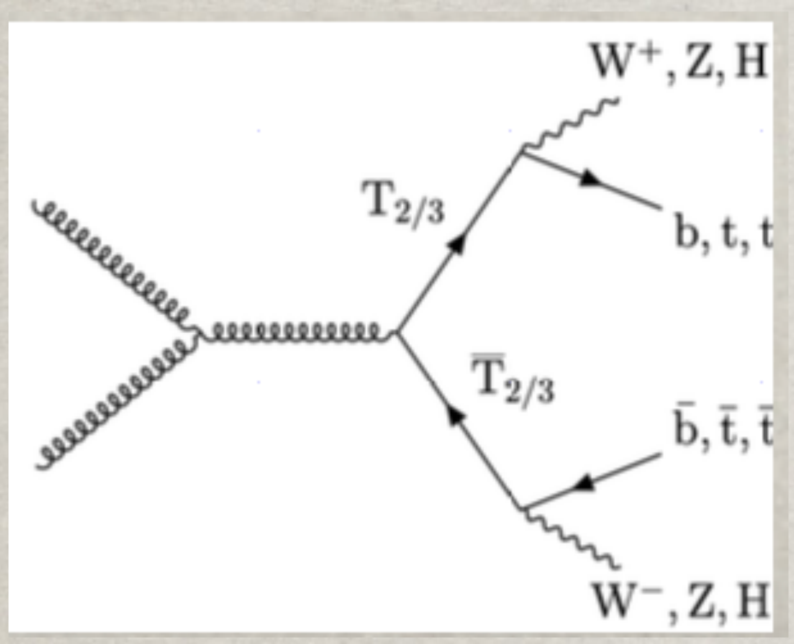

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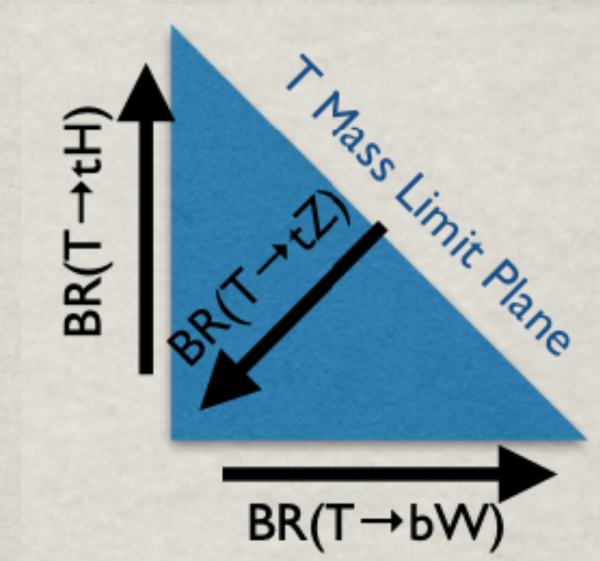

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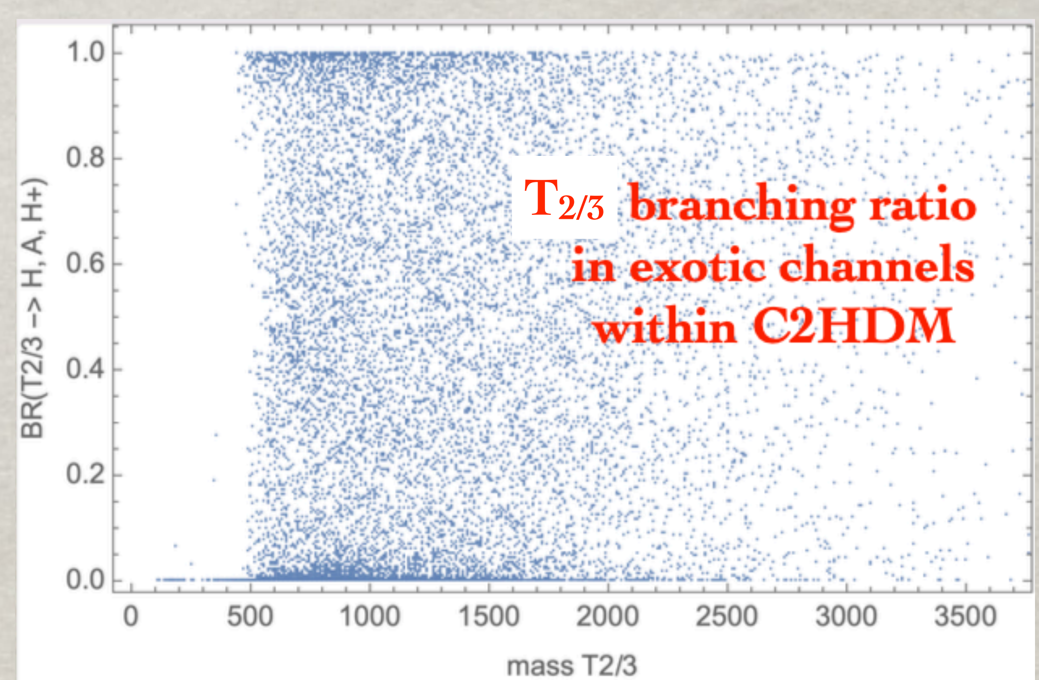

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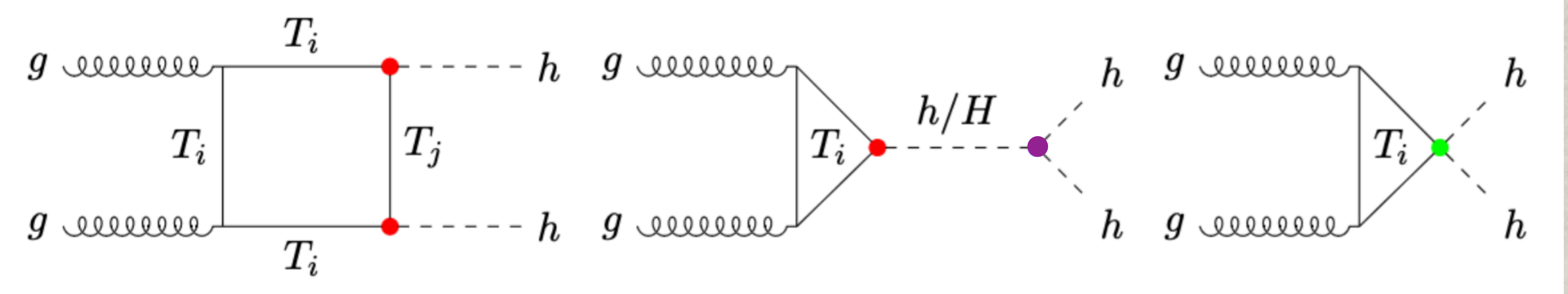
For the phenomenological analysis we take $M_{T2/3} \geq 1.3$ TeV

Can di-Higgs production at LHC reveal the underlying EWSB?

Signals of New Physics in gg → hh



In C2HDM : both resonant and non-resonant modes yield to a change in the integrated cross-section and to peculiar kinematic features in its differential distributions

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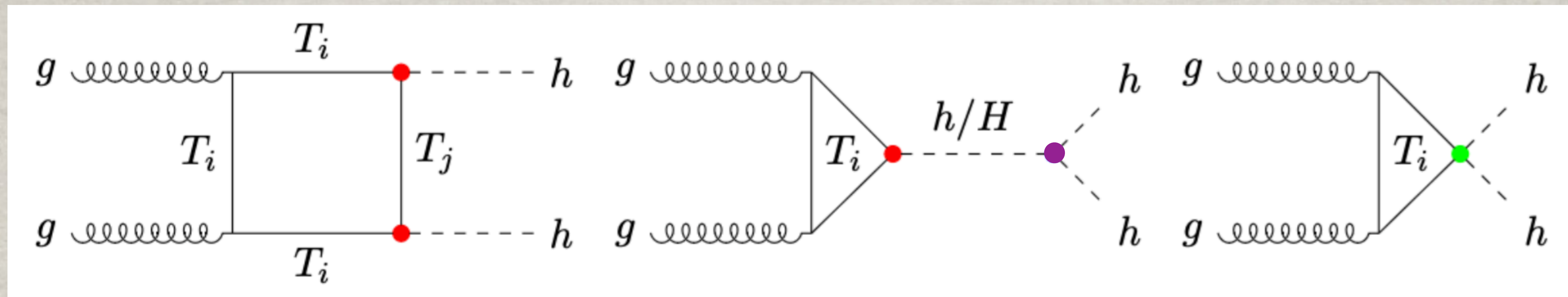

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INGREDIENTS: s-channel H exchange + distortions due to the interference effects with new topologies (quartic hhTT)
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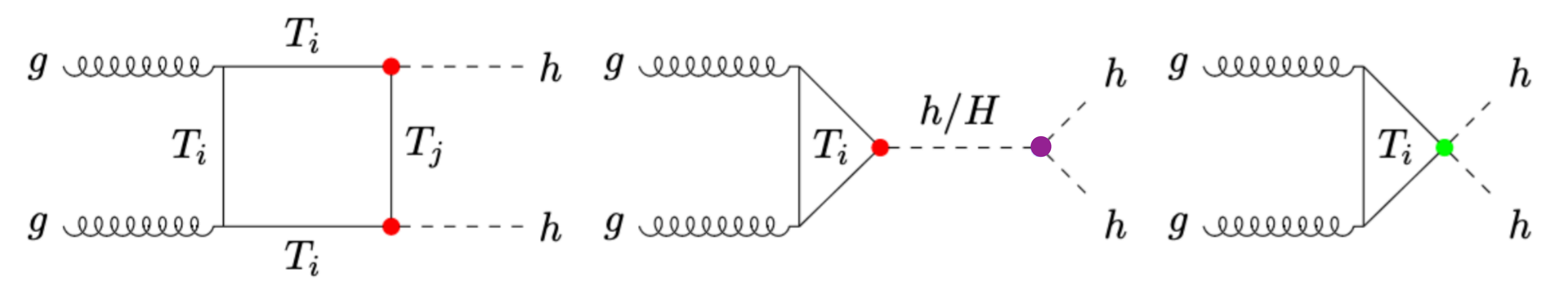

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analysis within the C2HDM (no EFT: large mass limit, nor simplified model: couplings and masses are free parameters without correlations

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1. modified hhh (κ_λ), tth couplings (κ_t)
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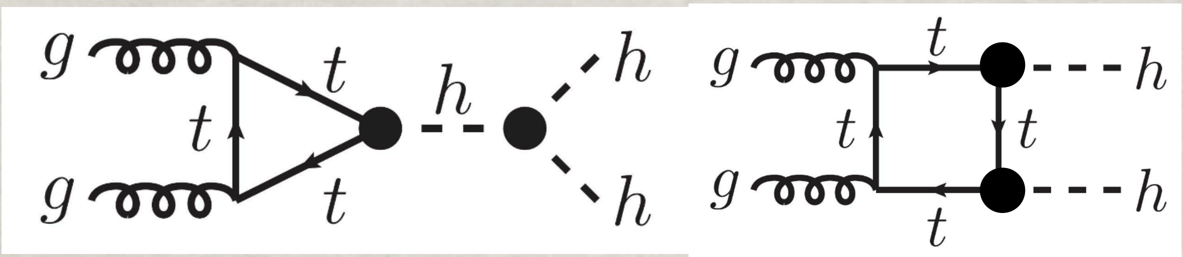
1. 

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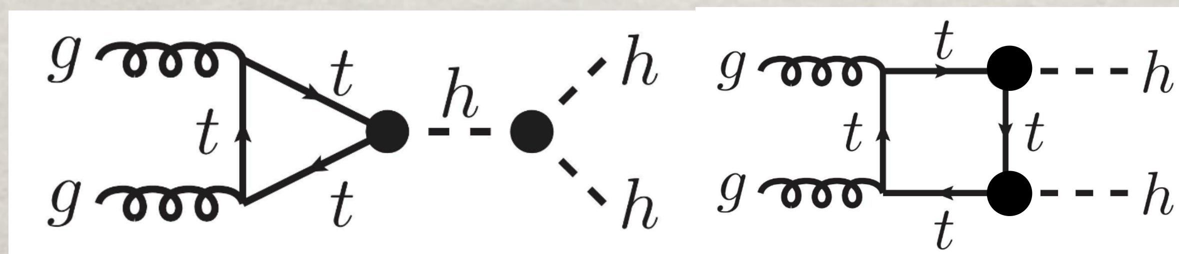

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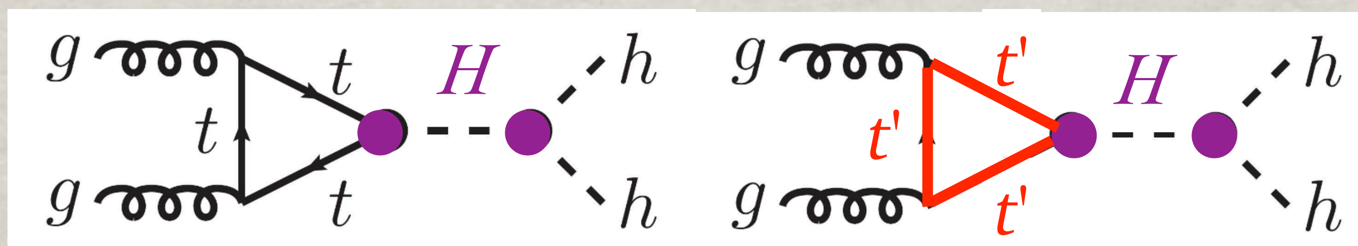

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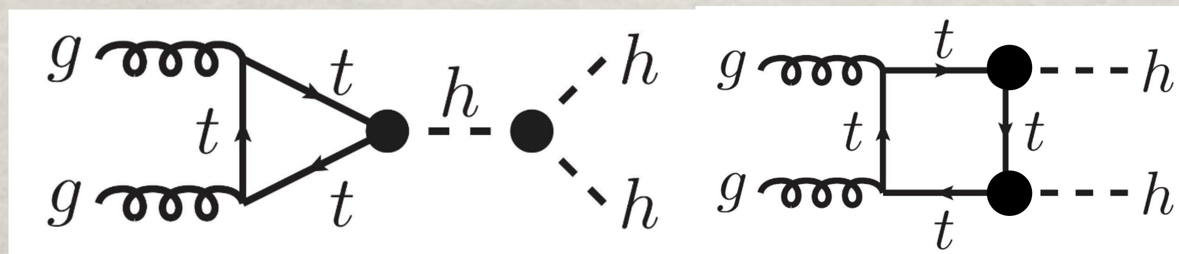

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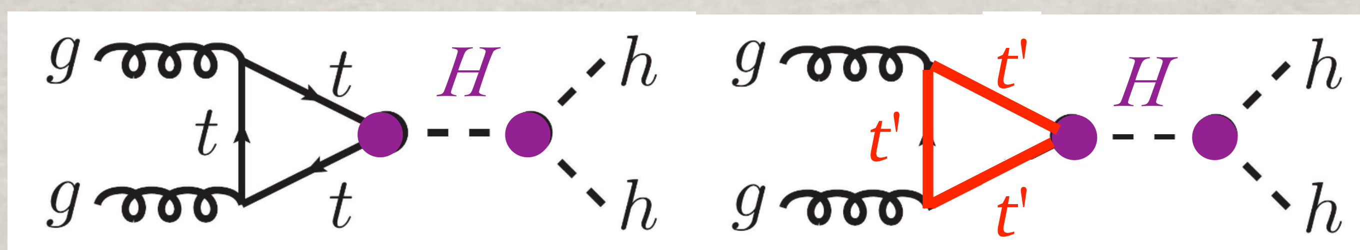

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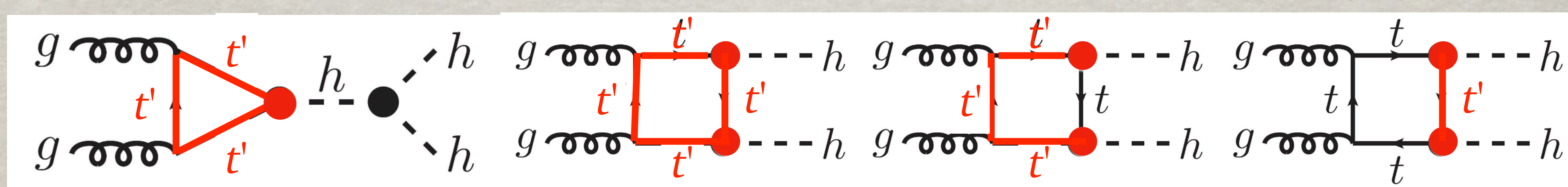

Heavy Tops' Triangle   Heavy Tops' Box   Mixed Boxes

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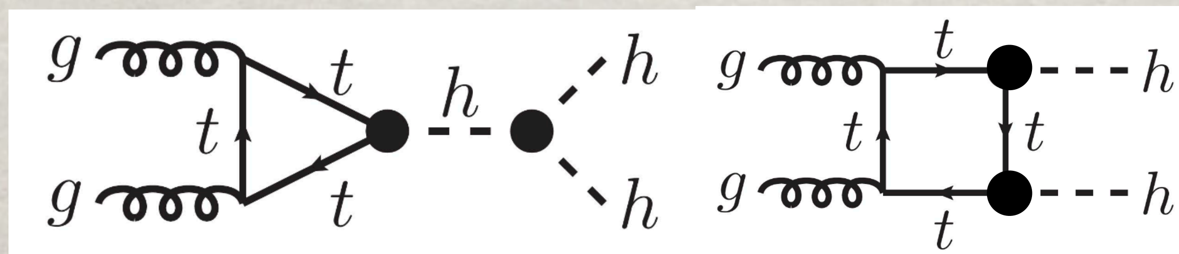
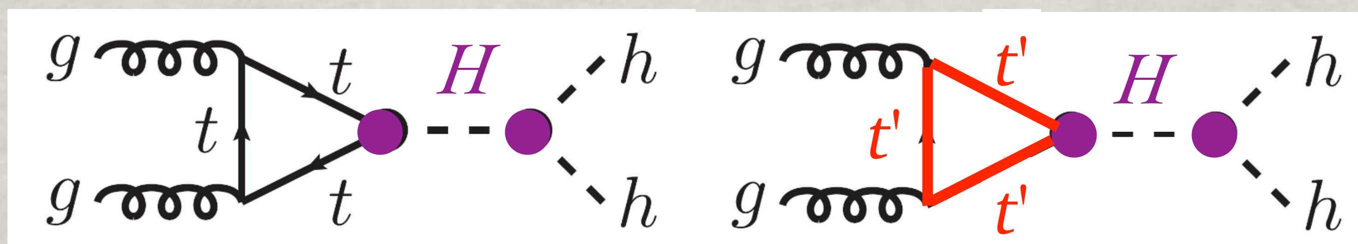
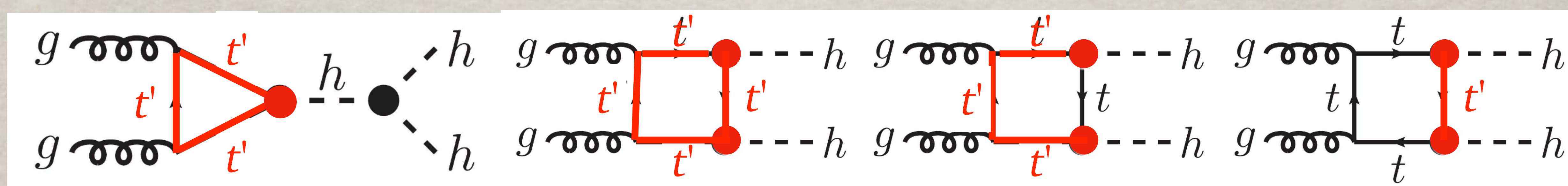
1. 

2. 

3. 

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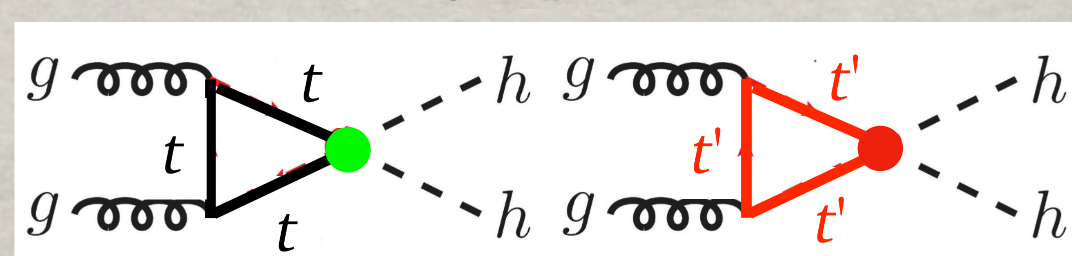

Quartic tthh
Quartic T_iT_jhh

h-top Yukawa and h-trilinear couplings in the C2HDM

scan over the model parameters $700 \leq f(\text{GeV}) \leq 3000$, $0 \leq \Delta, Y, M_\psi \leq 10f$

with the constraints to reconstruct v_{SM}, m_h, m_{top} exp. values, and $M_T \geq 1.3$ TeV

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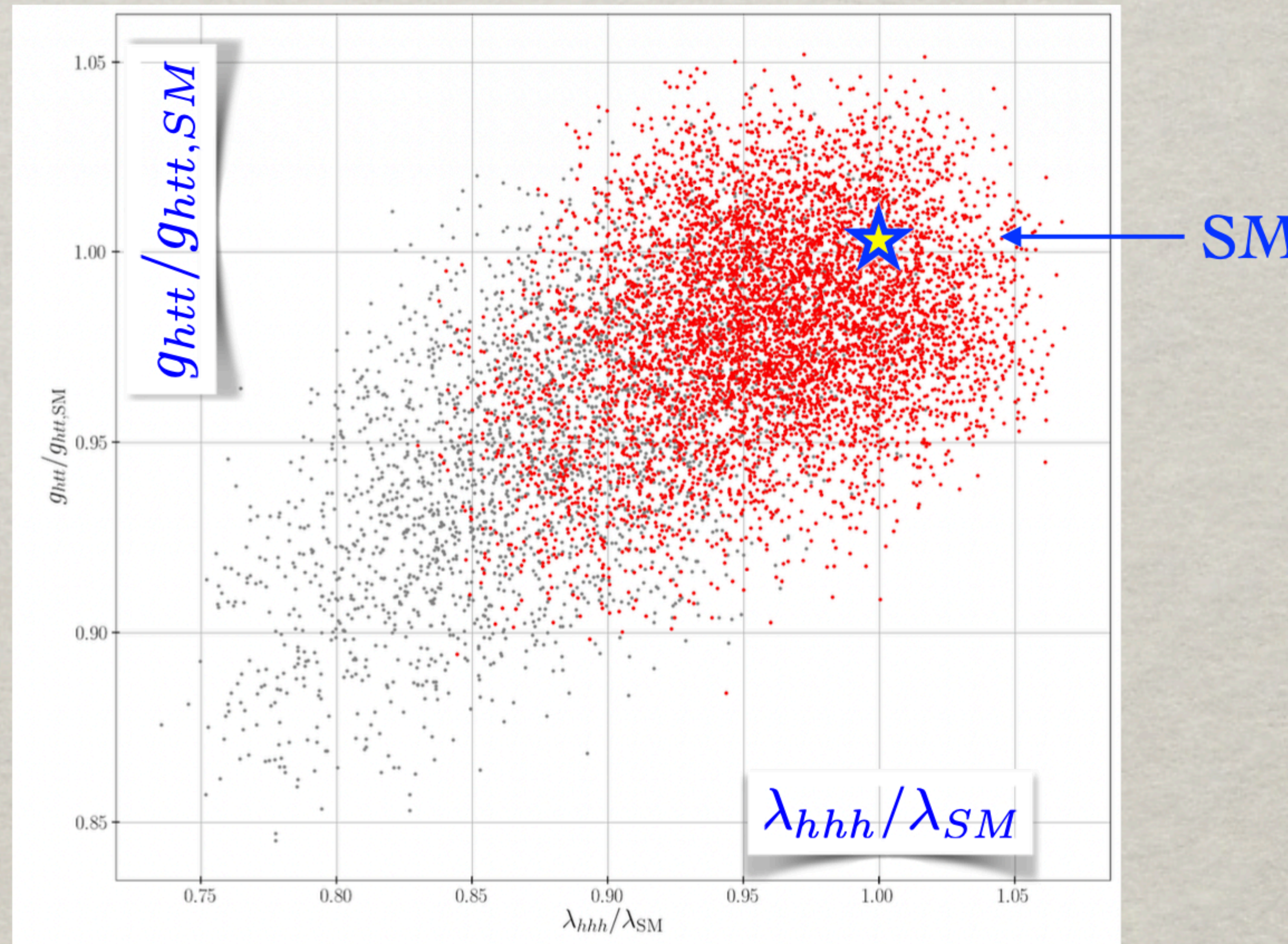
the grey points are **excluded** by the present **direct and indirect Higgs searches** (HiggsBounds and HiggsSignals Tools)



h-top Yukawa and h-trilinear couplings in the C2HDM

scan over the model parameters $700 \leq f(\text{GeV}) \leq 3000$, $0 \leq \Delta, Y, M_\psi \leq 10f$

with the constraints to reconstruct v_{SM}, m_h, m_{top} exp. values, and $M_T \geq 1.3$ TeV

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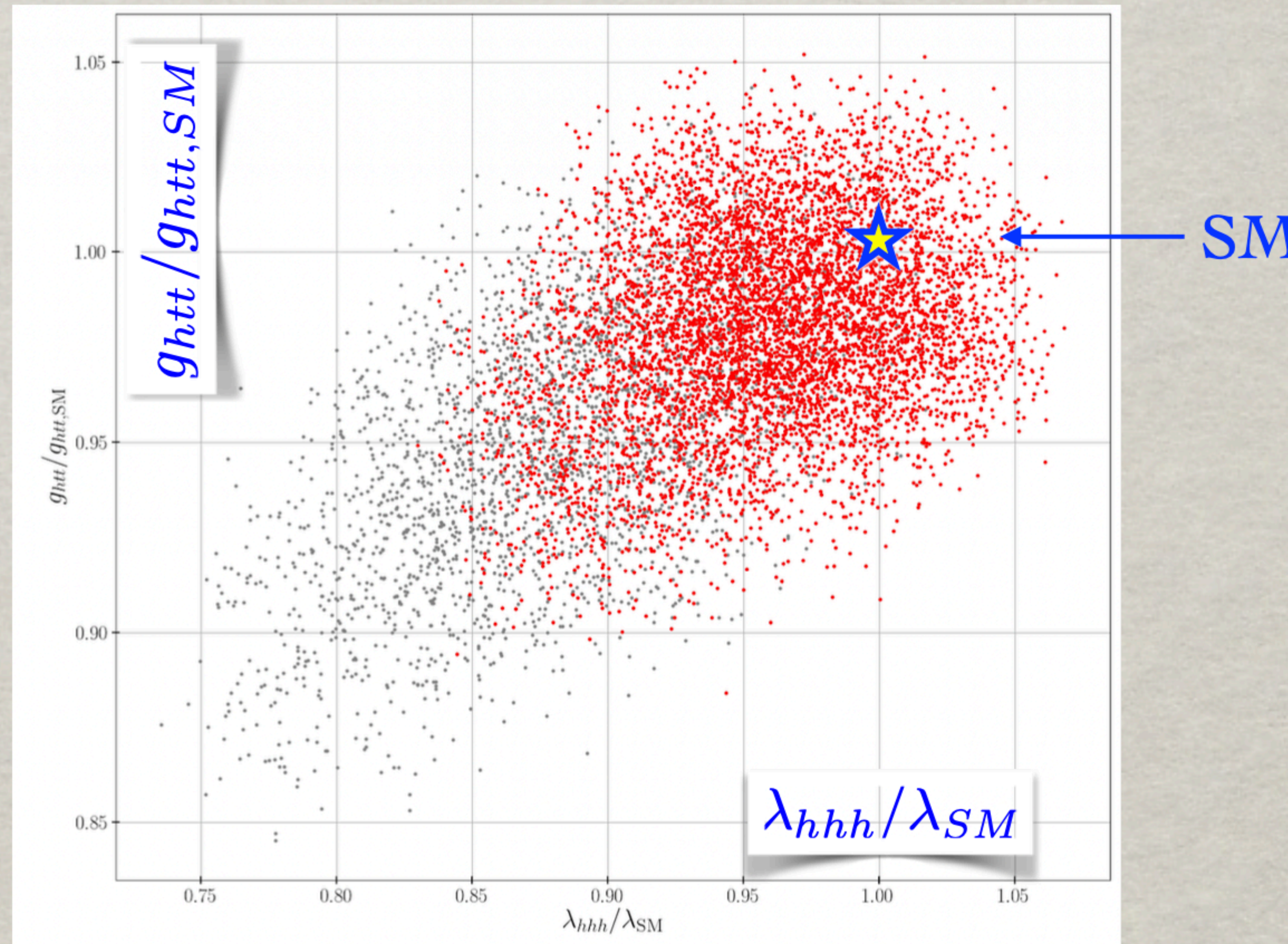

deviations up to 10% in g_{htt} and 15% in λ_{hhh}

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DC, Delle Rose, Egle, Mühlleitner, Moretti, Sakurai, in preparation

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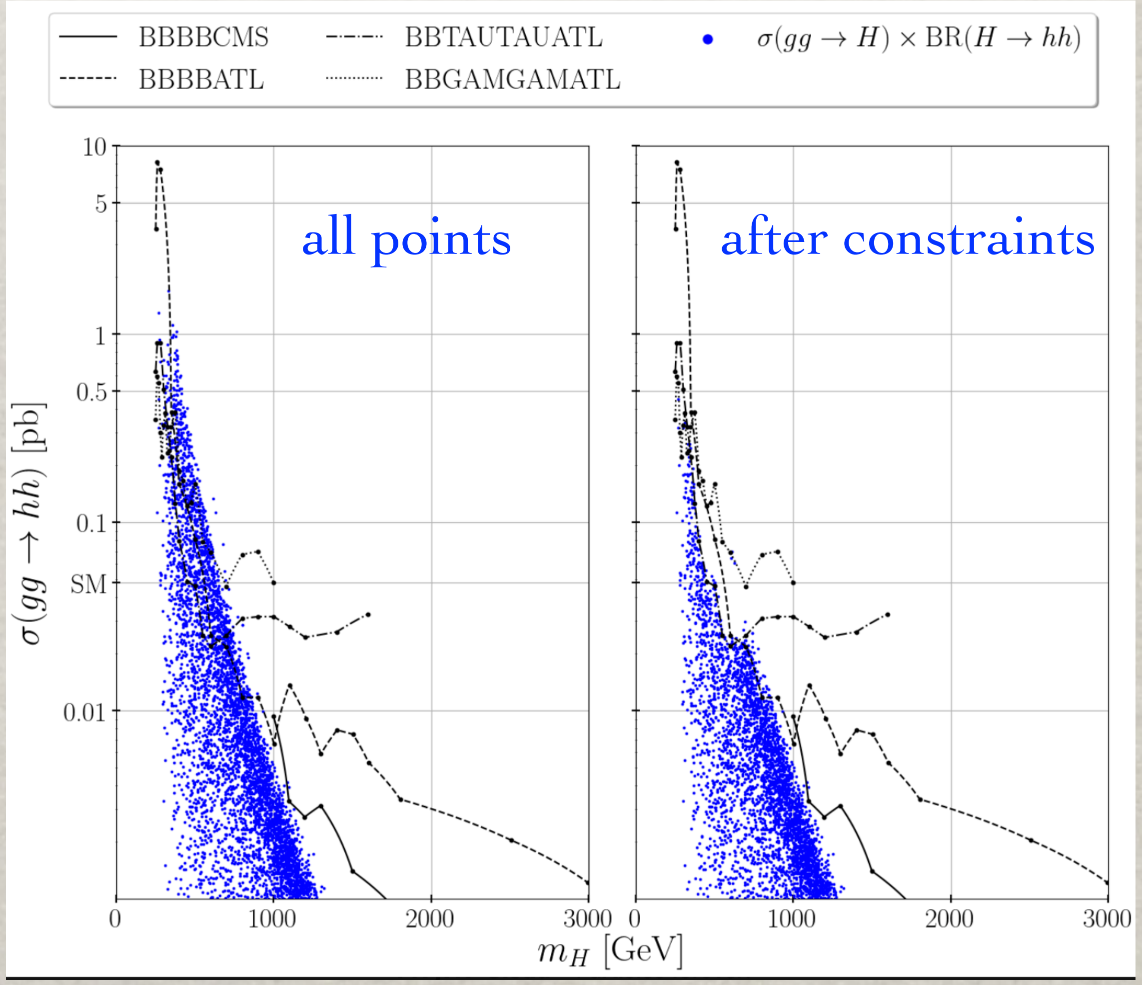

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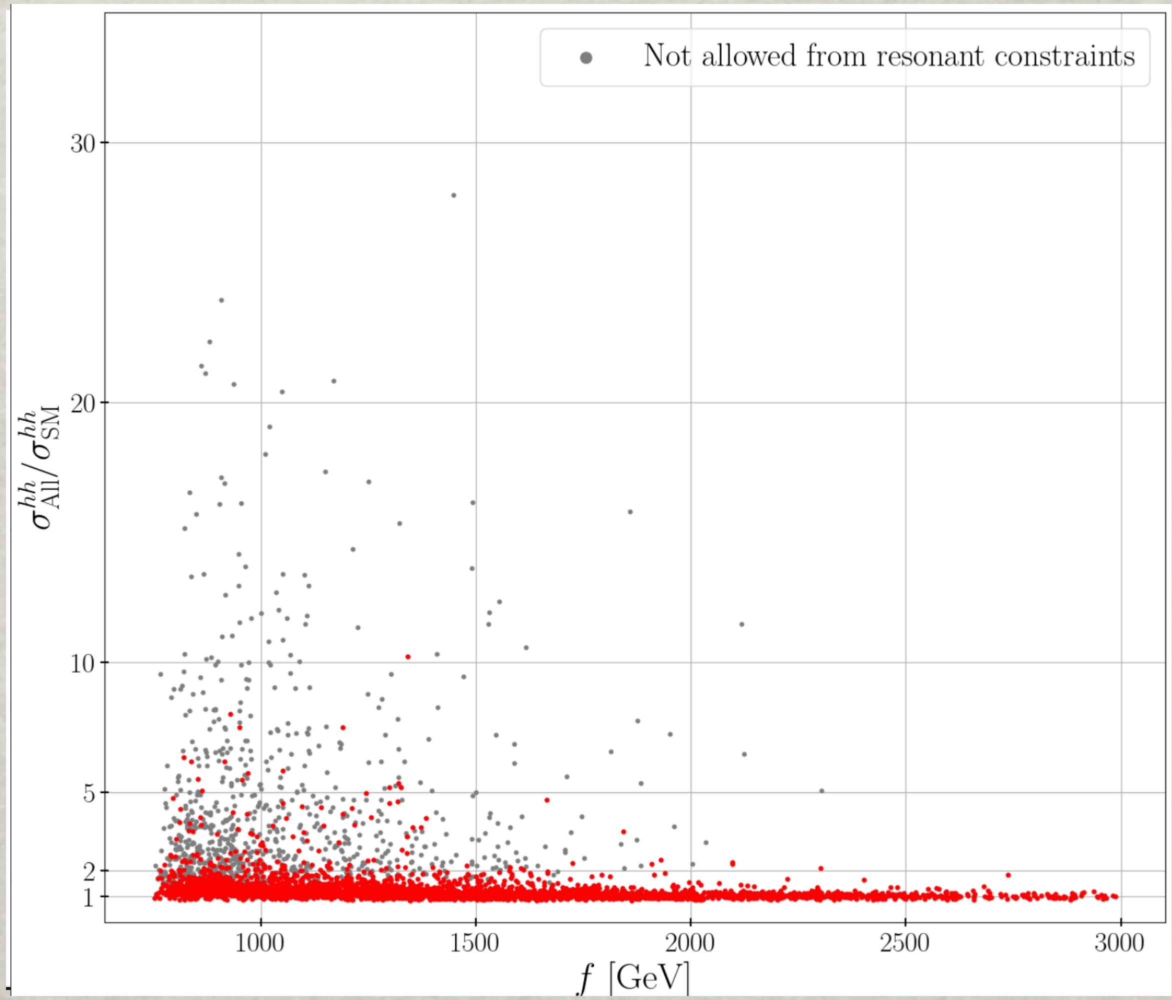

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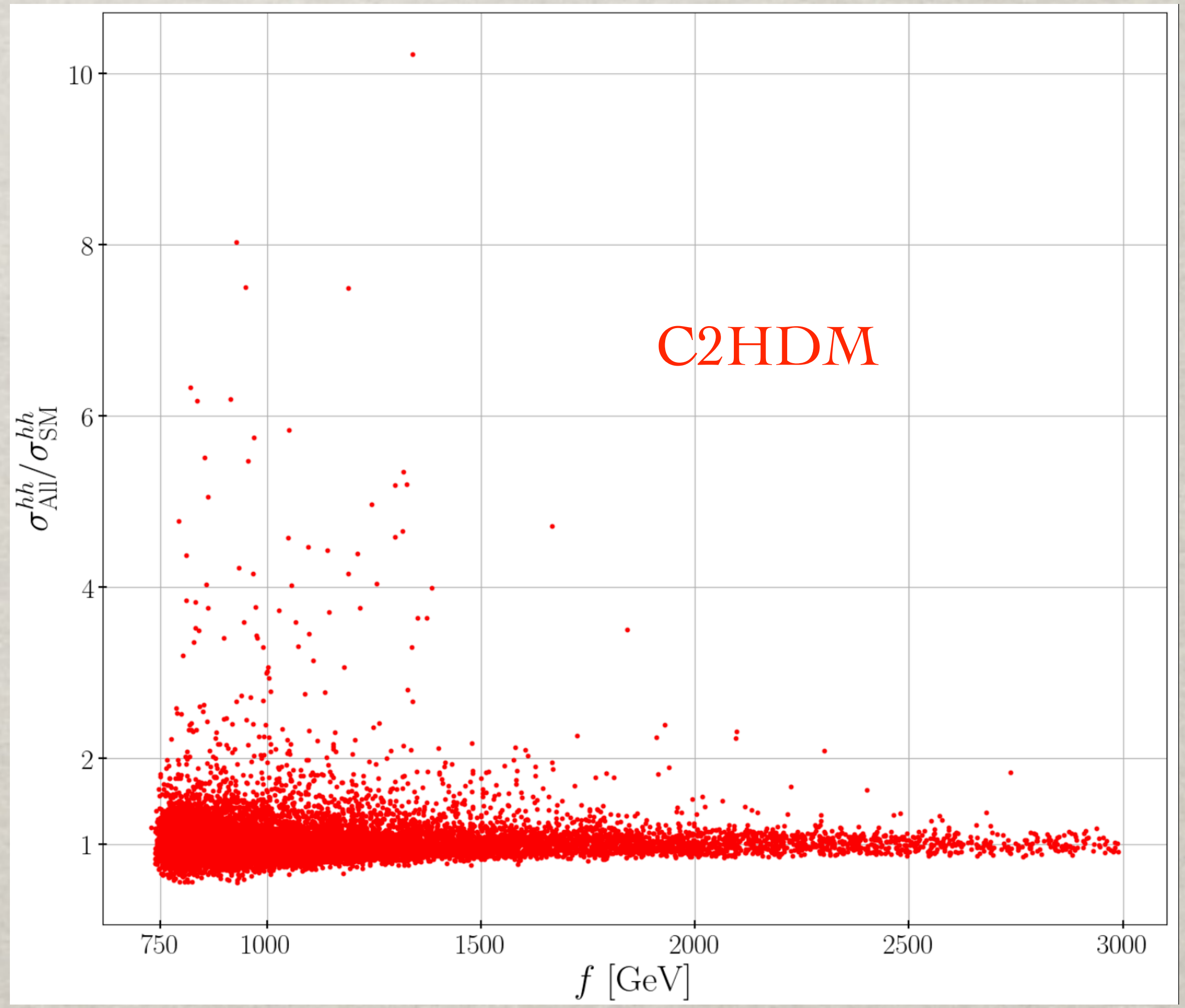

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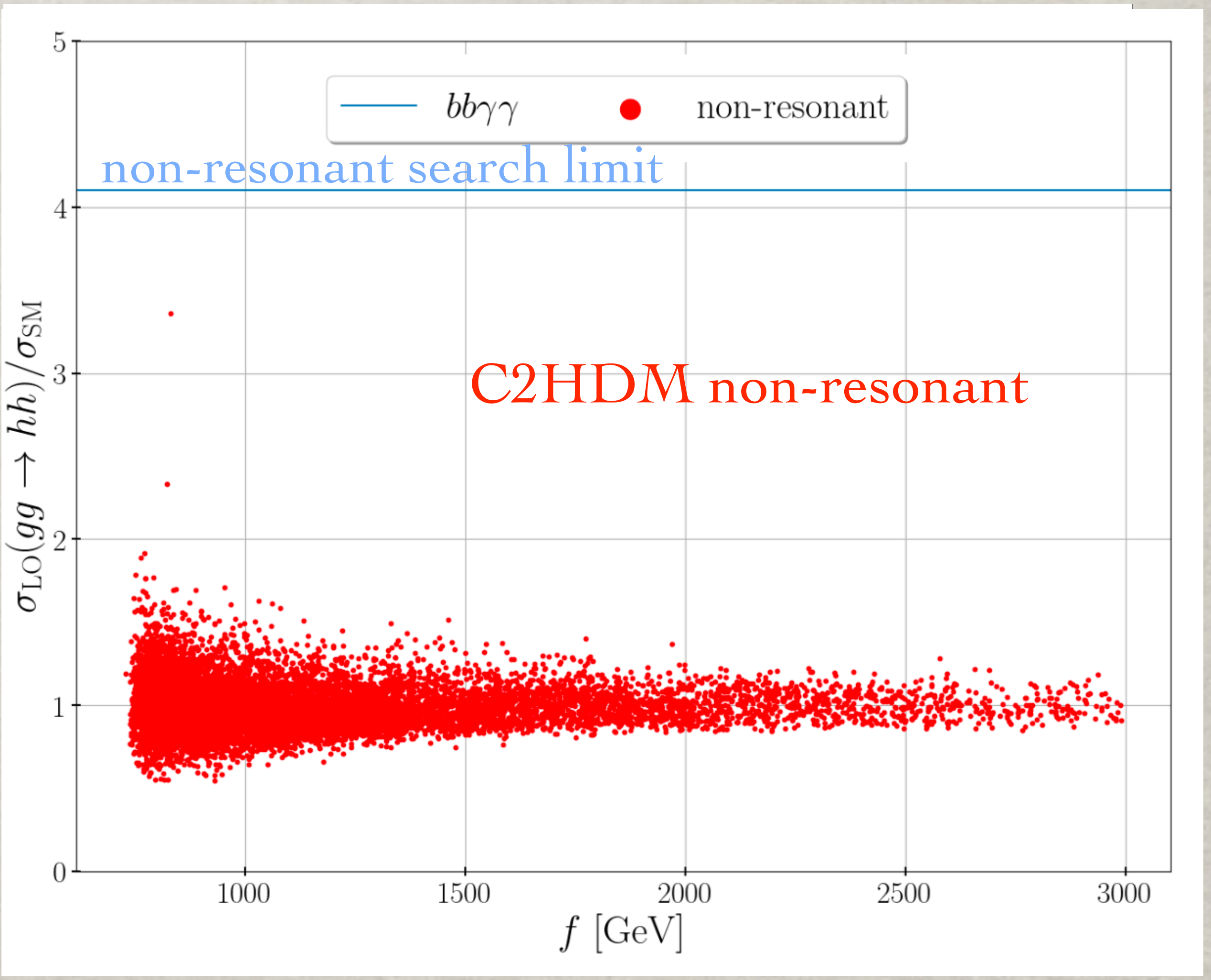
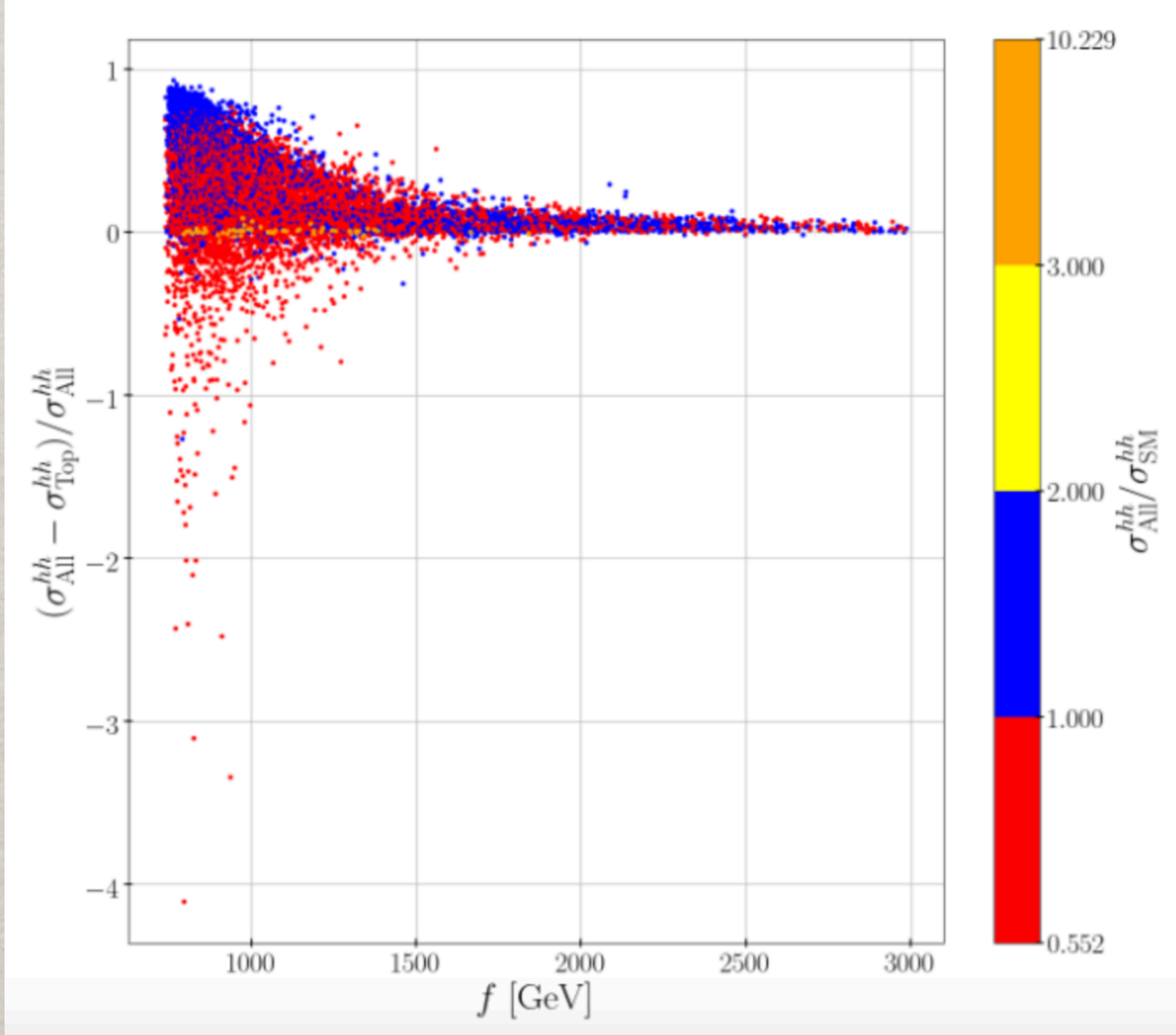
The resonant contribution may be very suppressed if the involved couplings are small, the H is very heavy, its total width is large, or if there are destructive interferences between different diagrams

NON-RESONANT MODE :
$\sigma(gg\to H)\mathrm{xBR}(H\to hh)/\sigma(gg\to hh) < 0.1$



The single and double Higgs production cross sections are given for √s = 14 TeV - pdfset: CT14lo/nlo

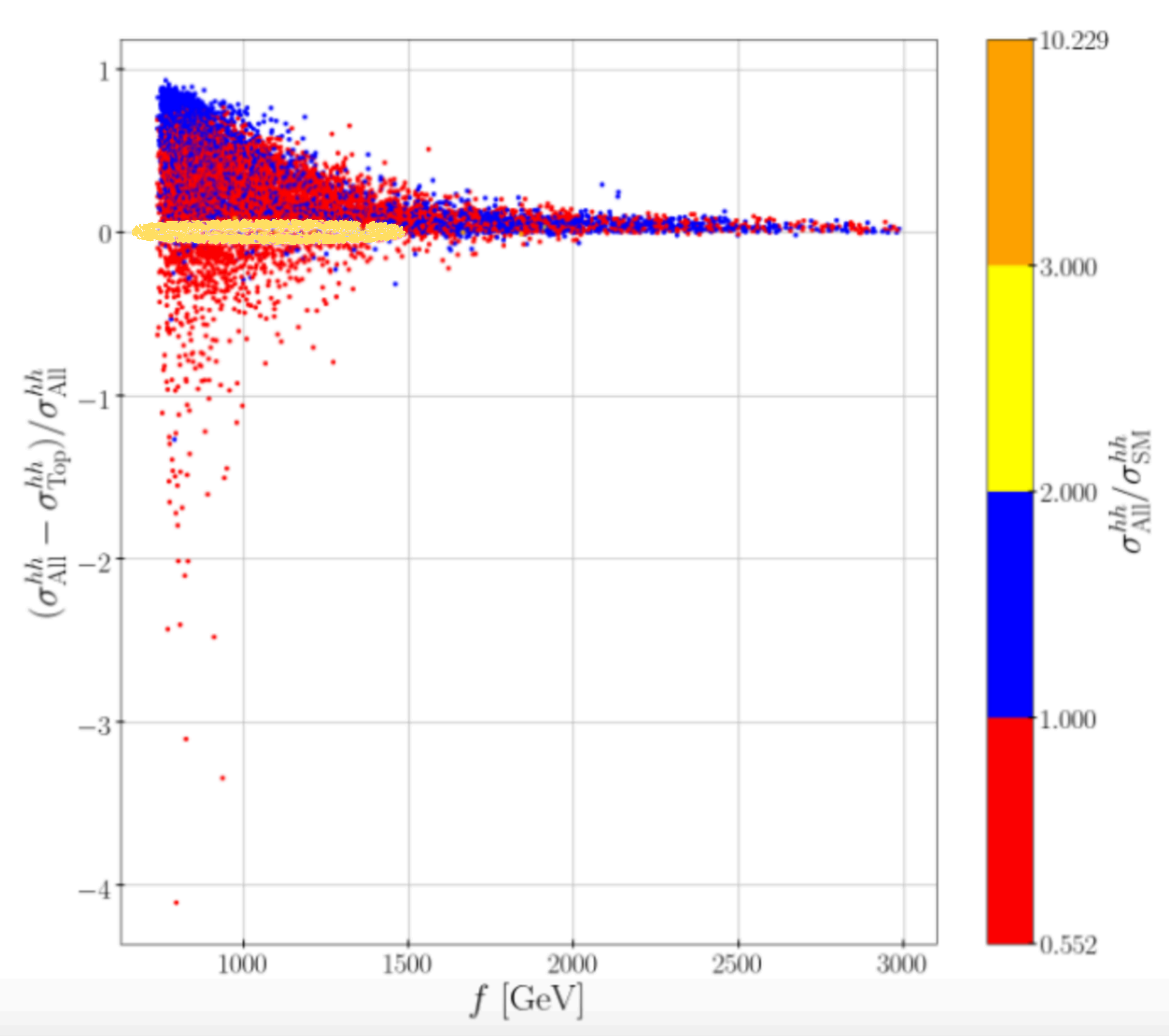
Heavy Tops' contribution



Relative difference of the full di-Higgs cross section and the one obtained with only the top quark in the loops (no heavy top partners) normalized to the full cross section

Heavy Tops' contribution

the resonant cross-section (yellow and orange BPs) does not change by including the heavy tops



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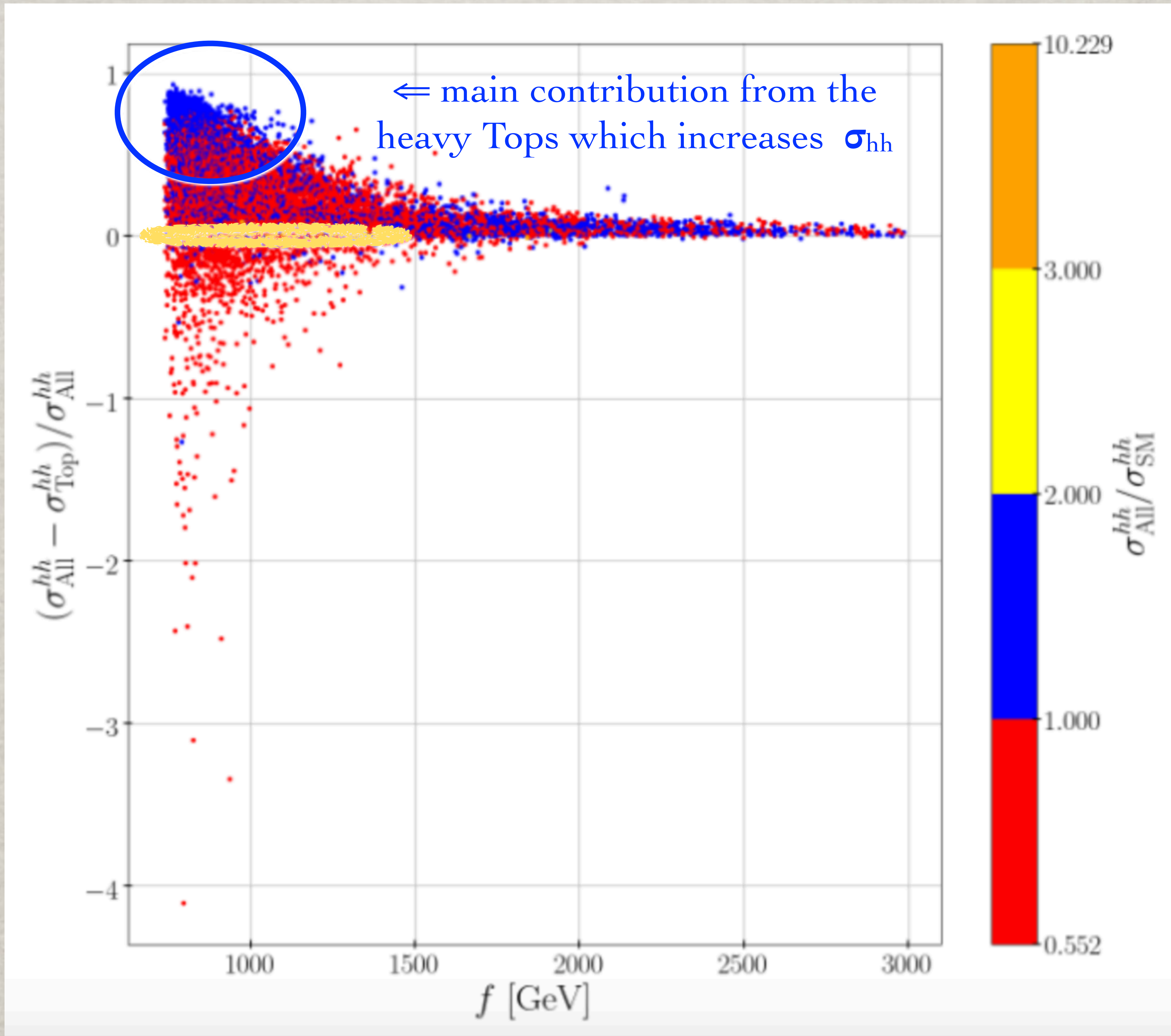

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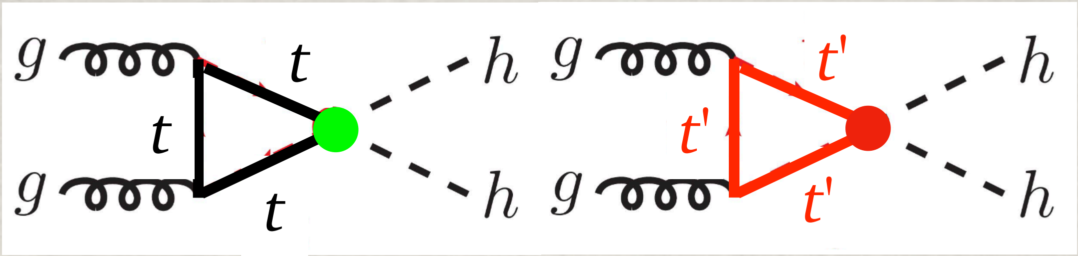
New quartic couplings naturally present in CHMs



Quartic tthh

Quartic T_iT_jhh

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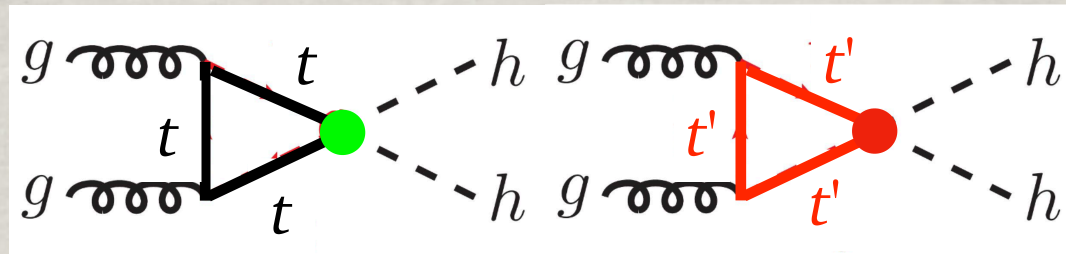
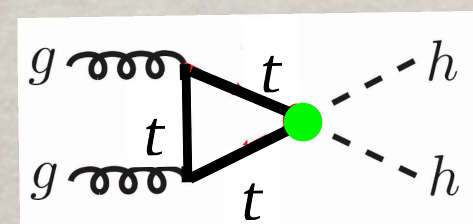
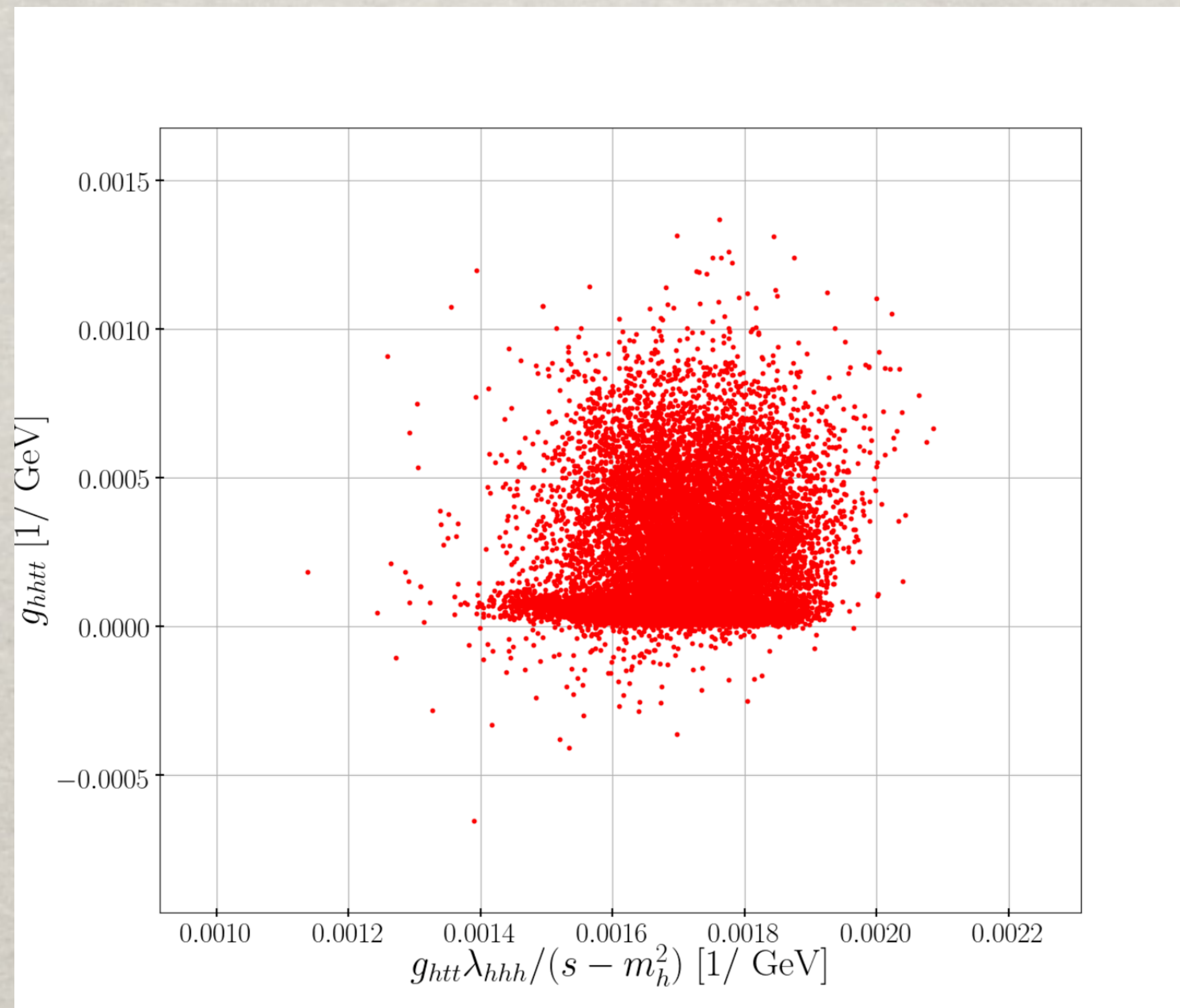
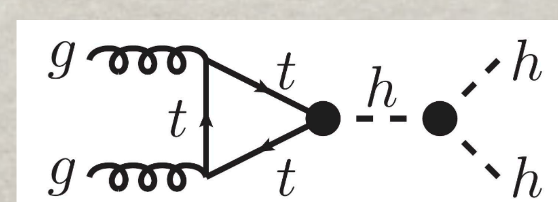


Quartic tthh | Quartic T_iT_jhh







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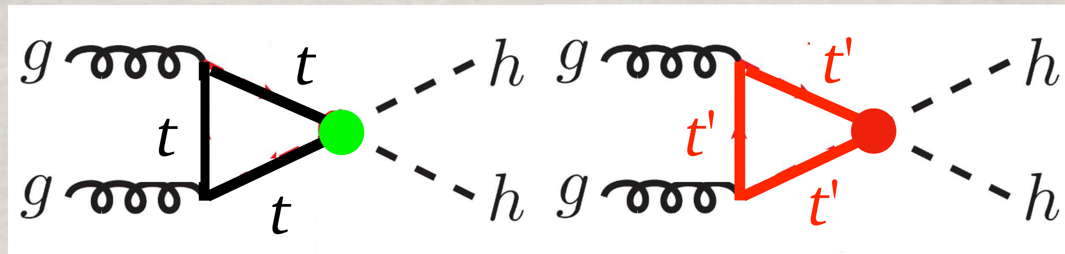

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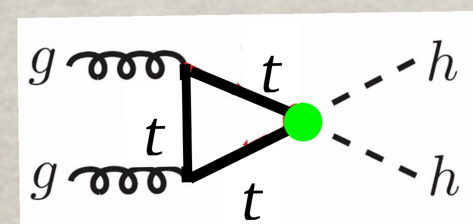
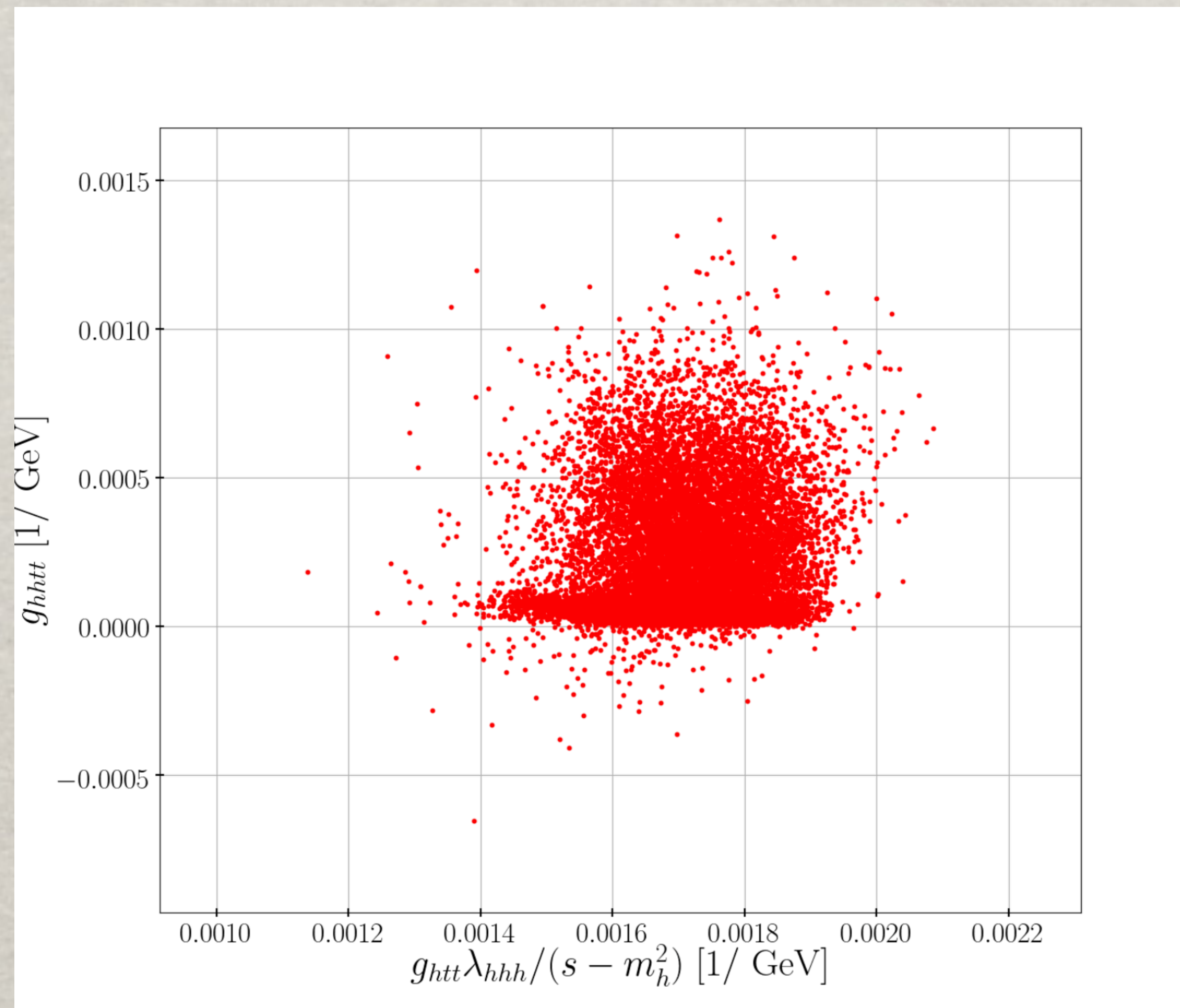
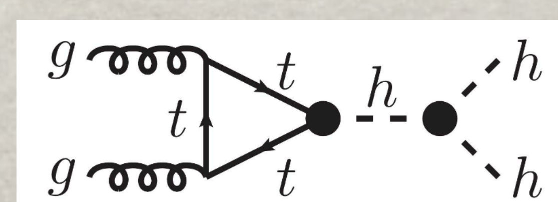




Ex:
$g_{hhtt} \sim 10^{-3}$ /GeV
comparable with
top triangle +
higgs exchange
at $\sqrt{s}$ = 300 GeV



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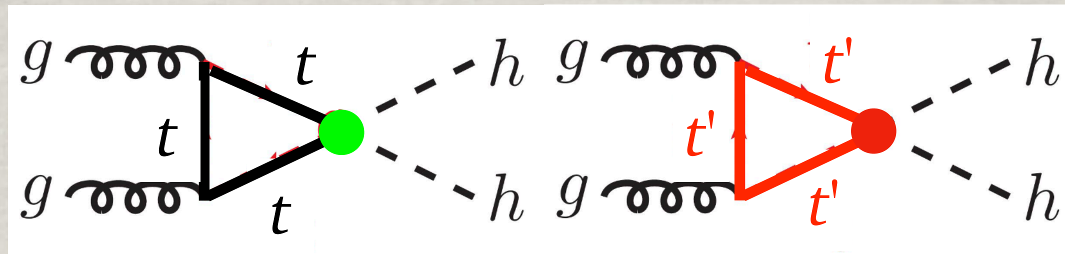

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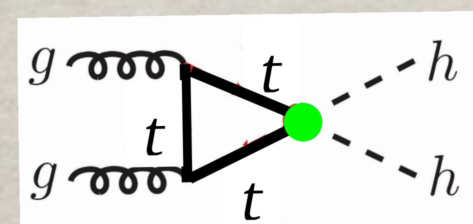

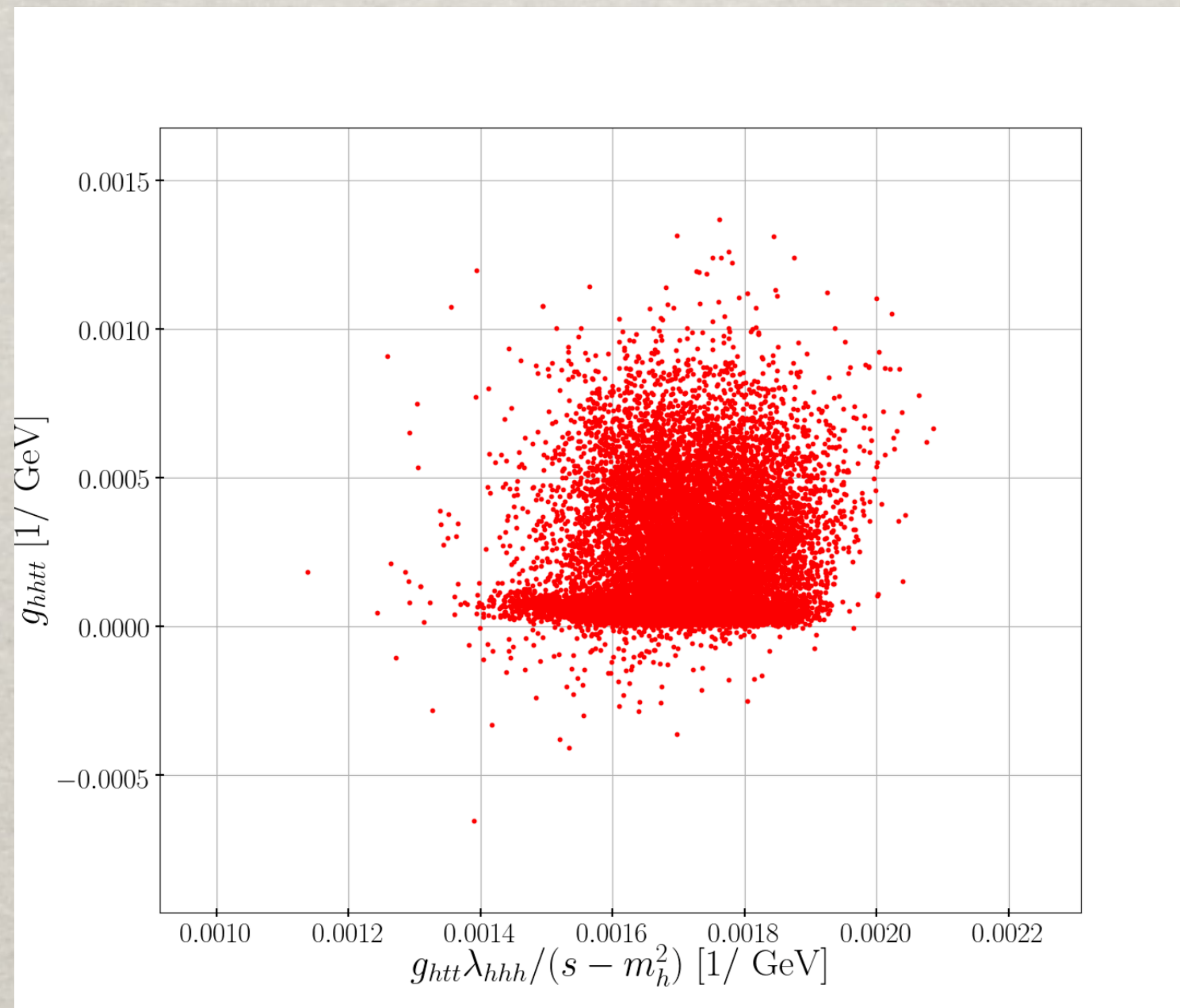

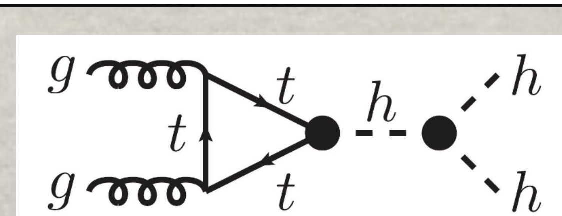

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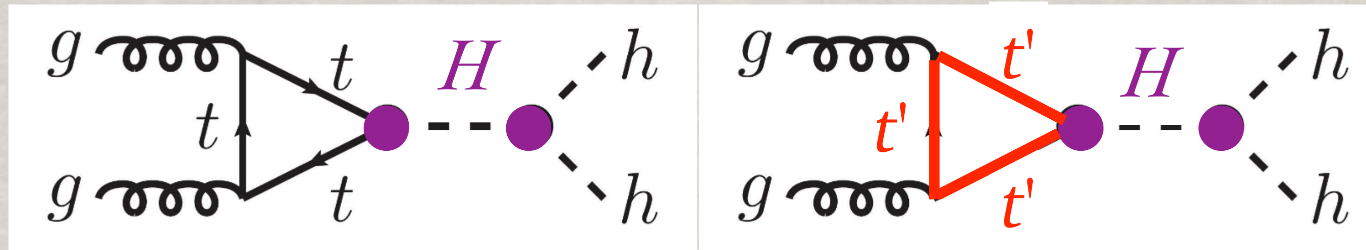
sizeable
interference
effects

H contribution



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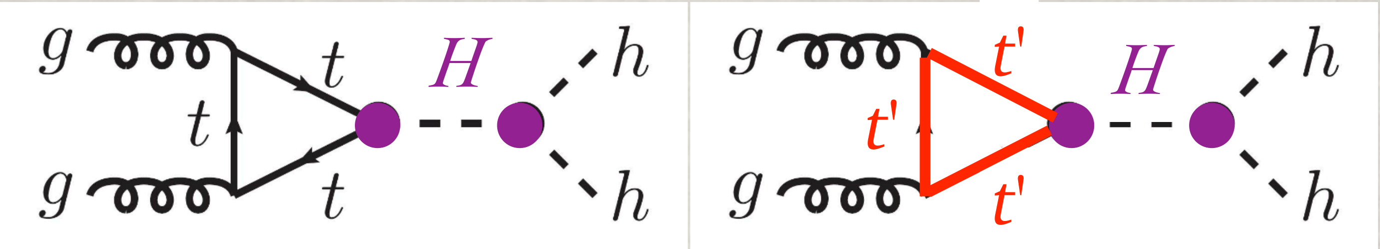
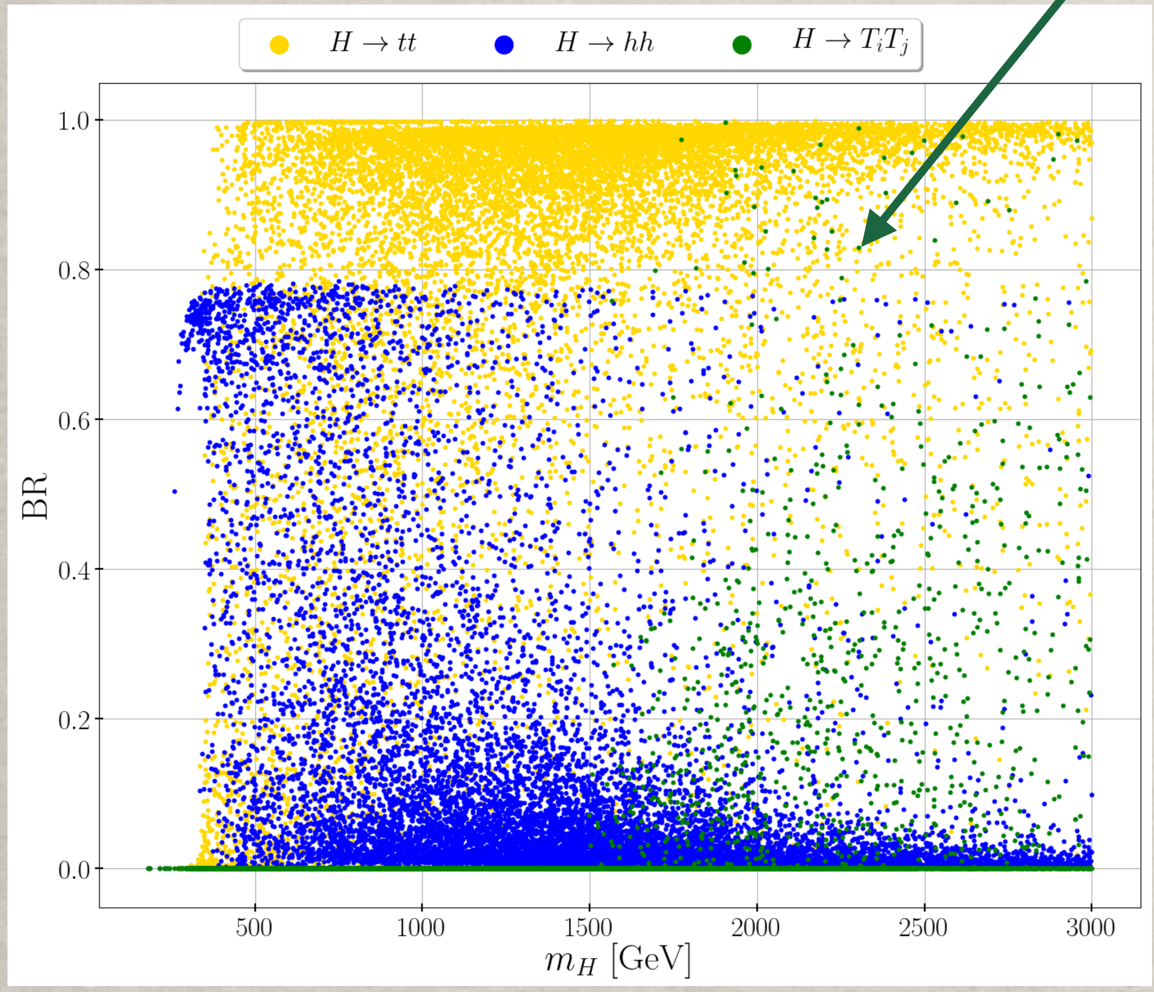


the **heavy Higgs H** can have a **sizeable BR in $T_9T_{8,7}$**

T_9=top, $T_{8,7}$= lightest heavy tops



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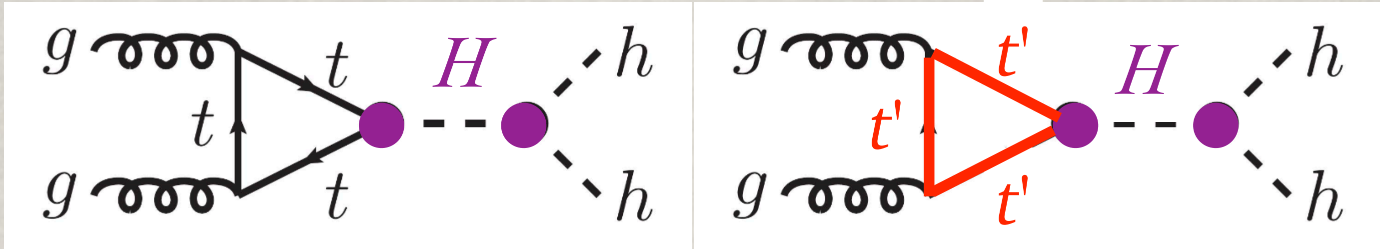

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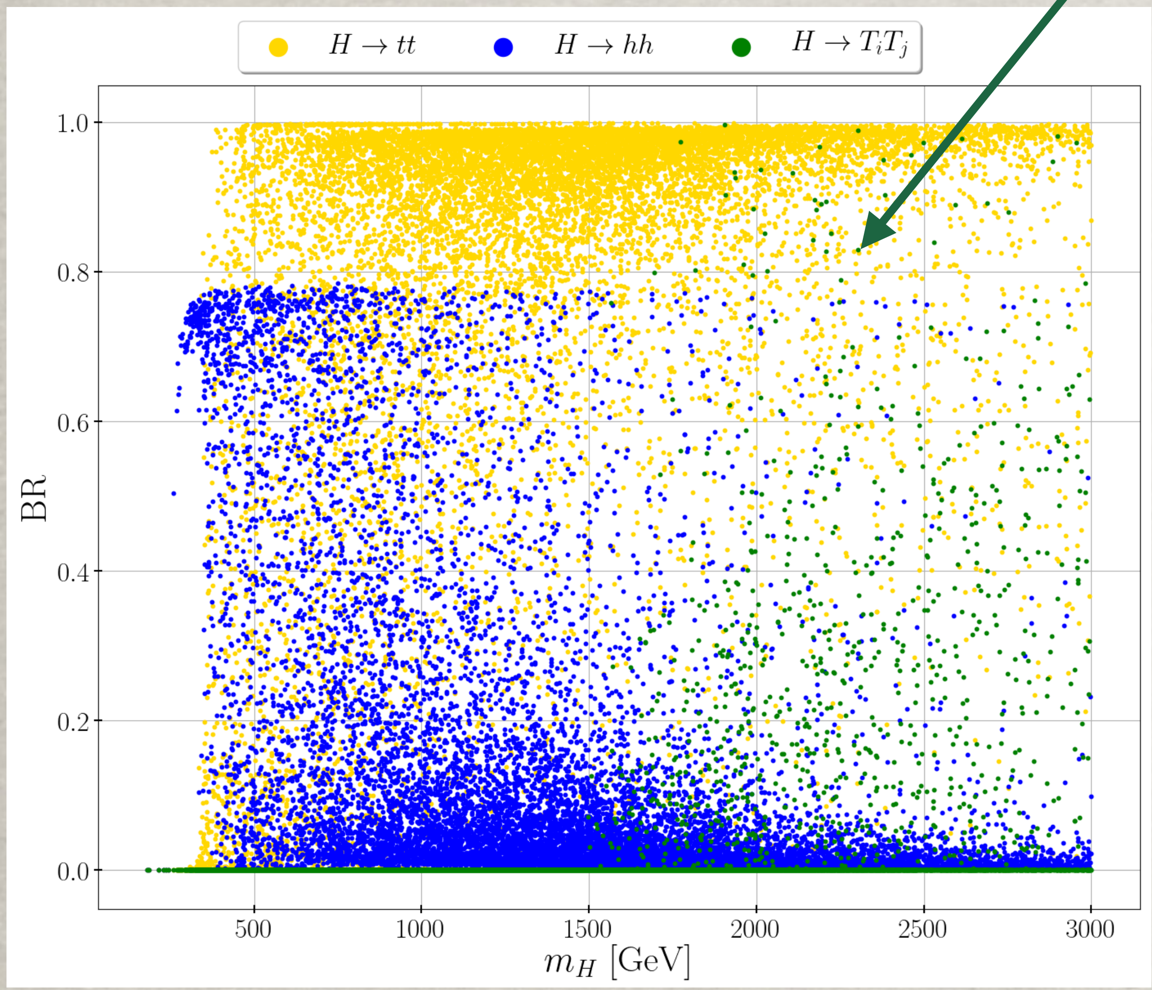

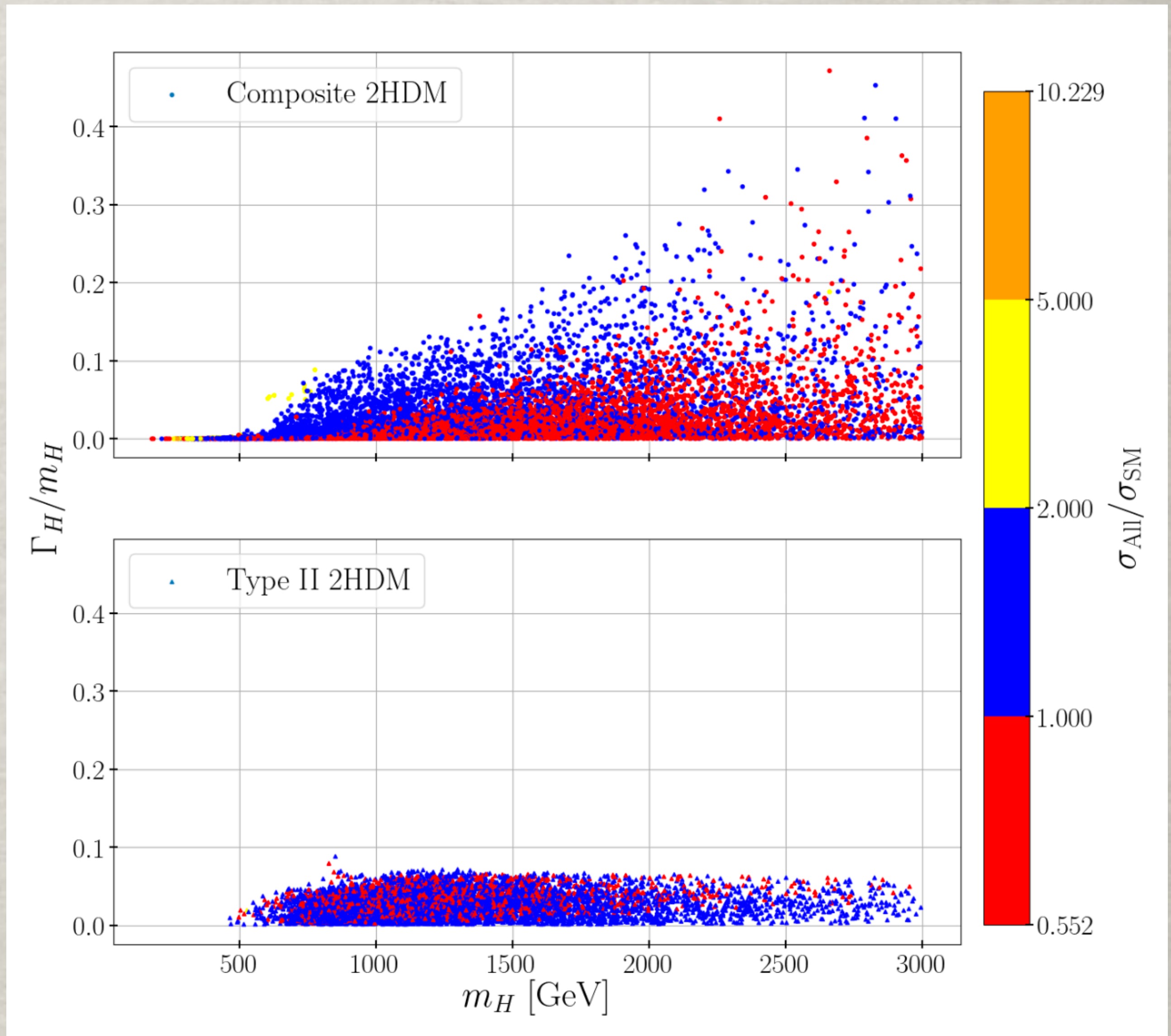

Peculiar feature of the C2HDM: Γ_H/M_H can be ~10-20%

enhancement of σ_{hh}, great impact on the shape modification of the differential distributions due to the large interference effects

di-Higgs production in C2HDM

1. modified hhh (k_λ), tth couplings (k_t) → small deviations
2. H contribution → present in several BSM schemes (MSSM, 2HDM, ..)
3. Heavy Tops' contributions ($t' = T_i$ i=1,..,8) + quartic tthh → naturally present in CHMs

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Can we see the heavy tops' loop effects by looking at the invariant mass and/or p_t distributions?

recall triangle vs box cancellation in the SM - loops are not really subleading

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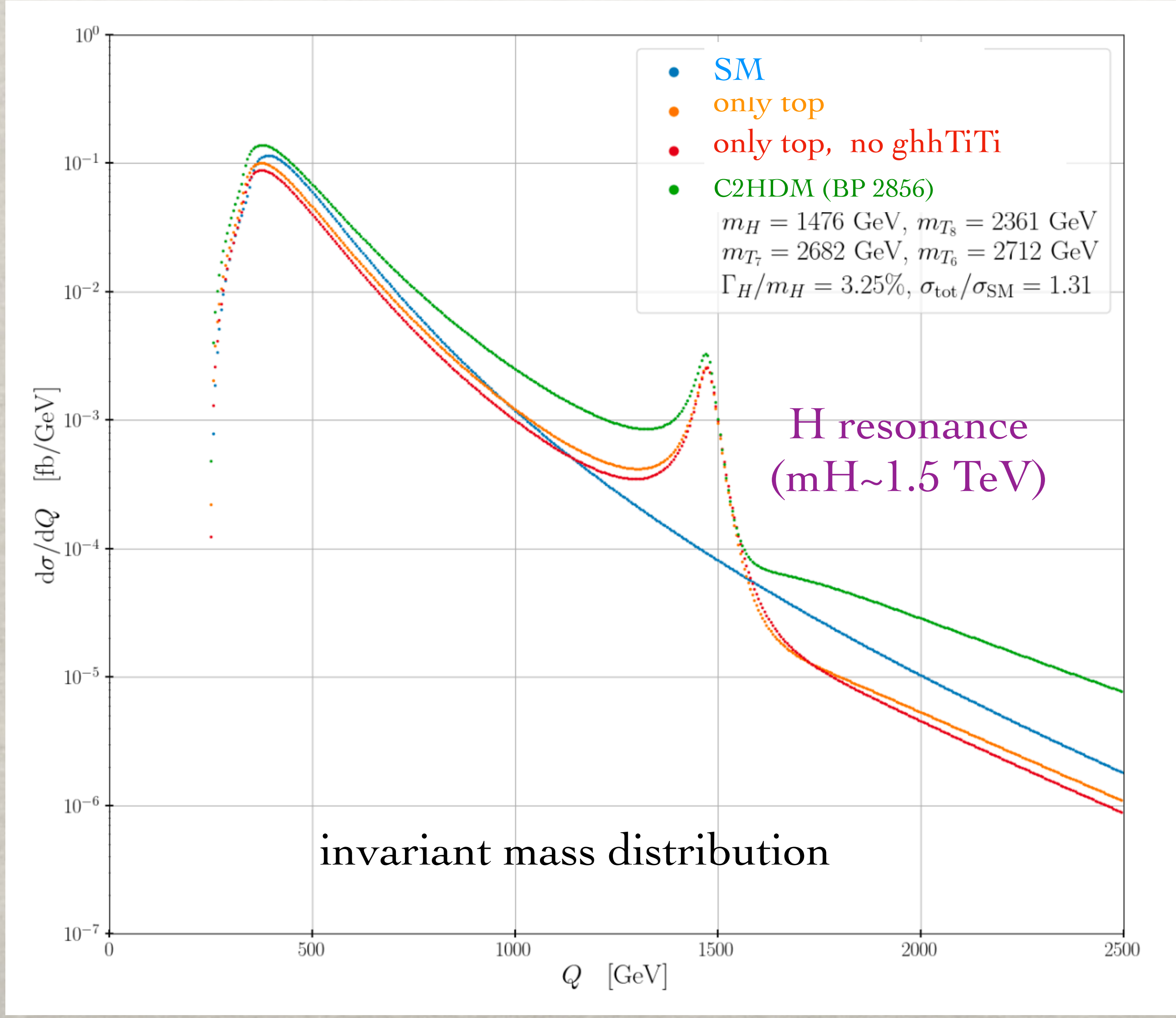

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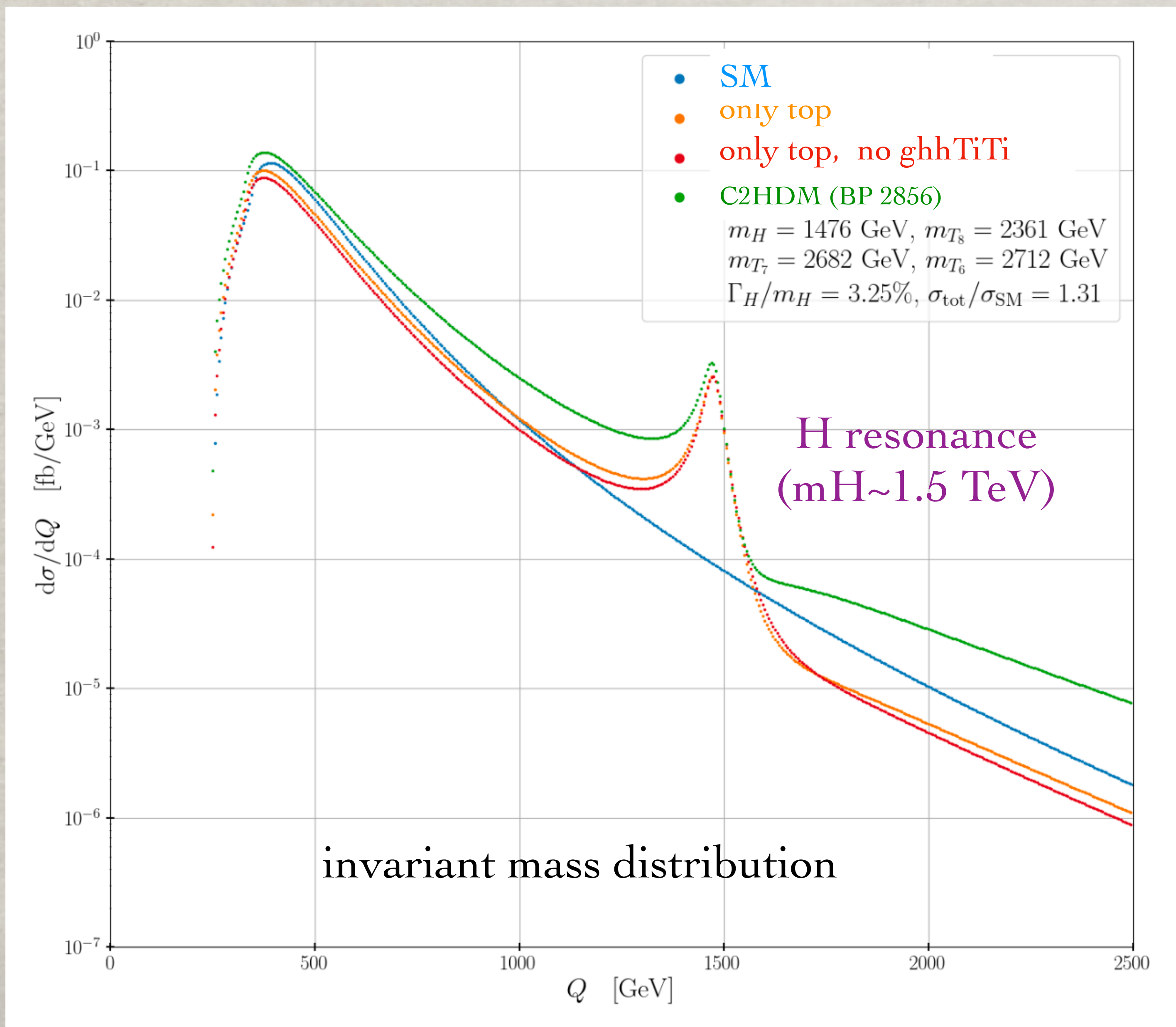

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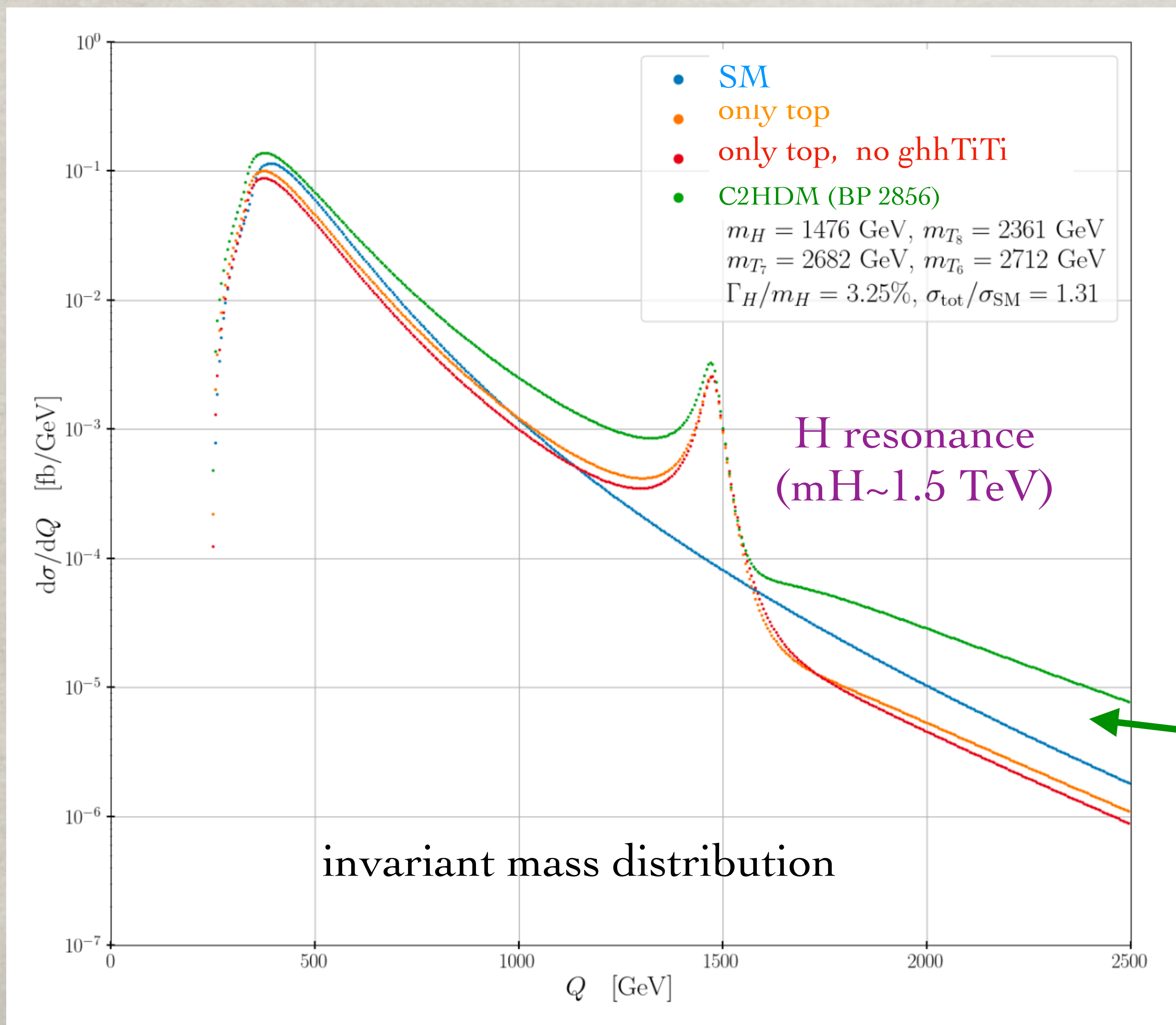

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start to see the threshold shape

di-Higgs production in C2HDM

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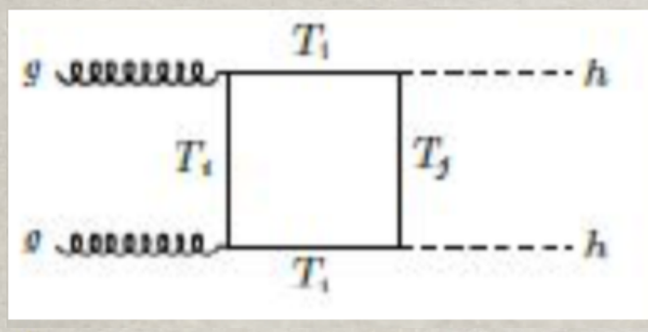
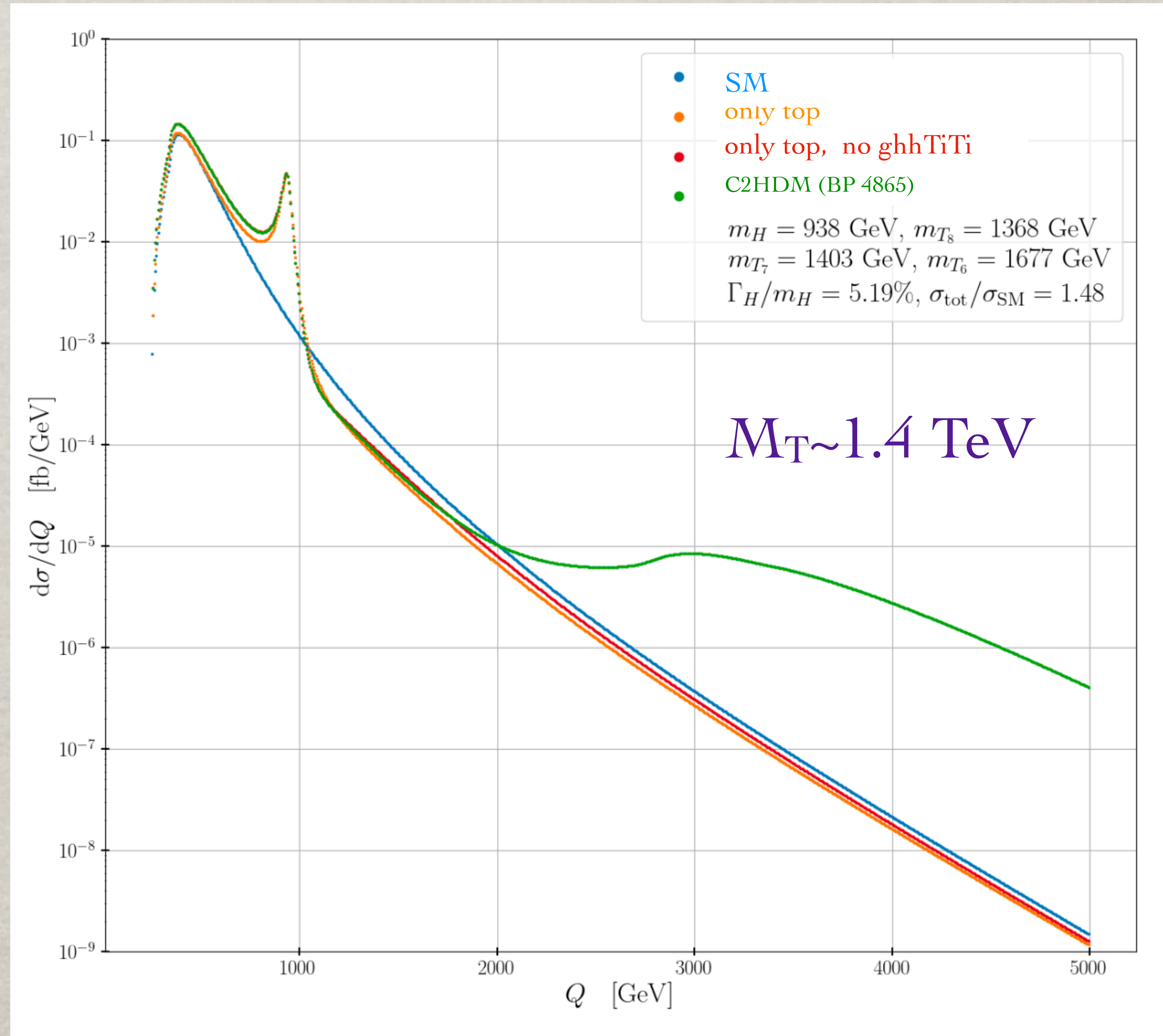


Boxes can induce thresholds at $2M_T$ and low-mass tail, different from squark loop effects (PV functions, spin)



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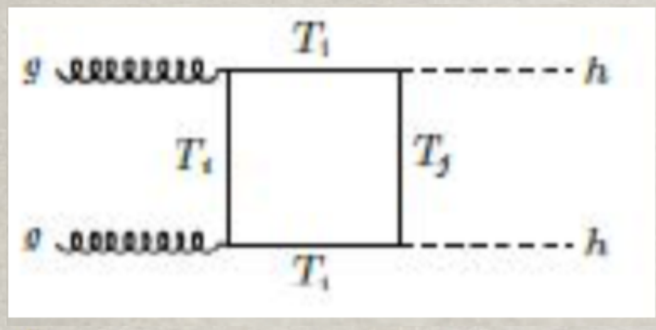

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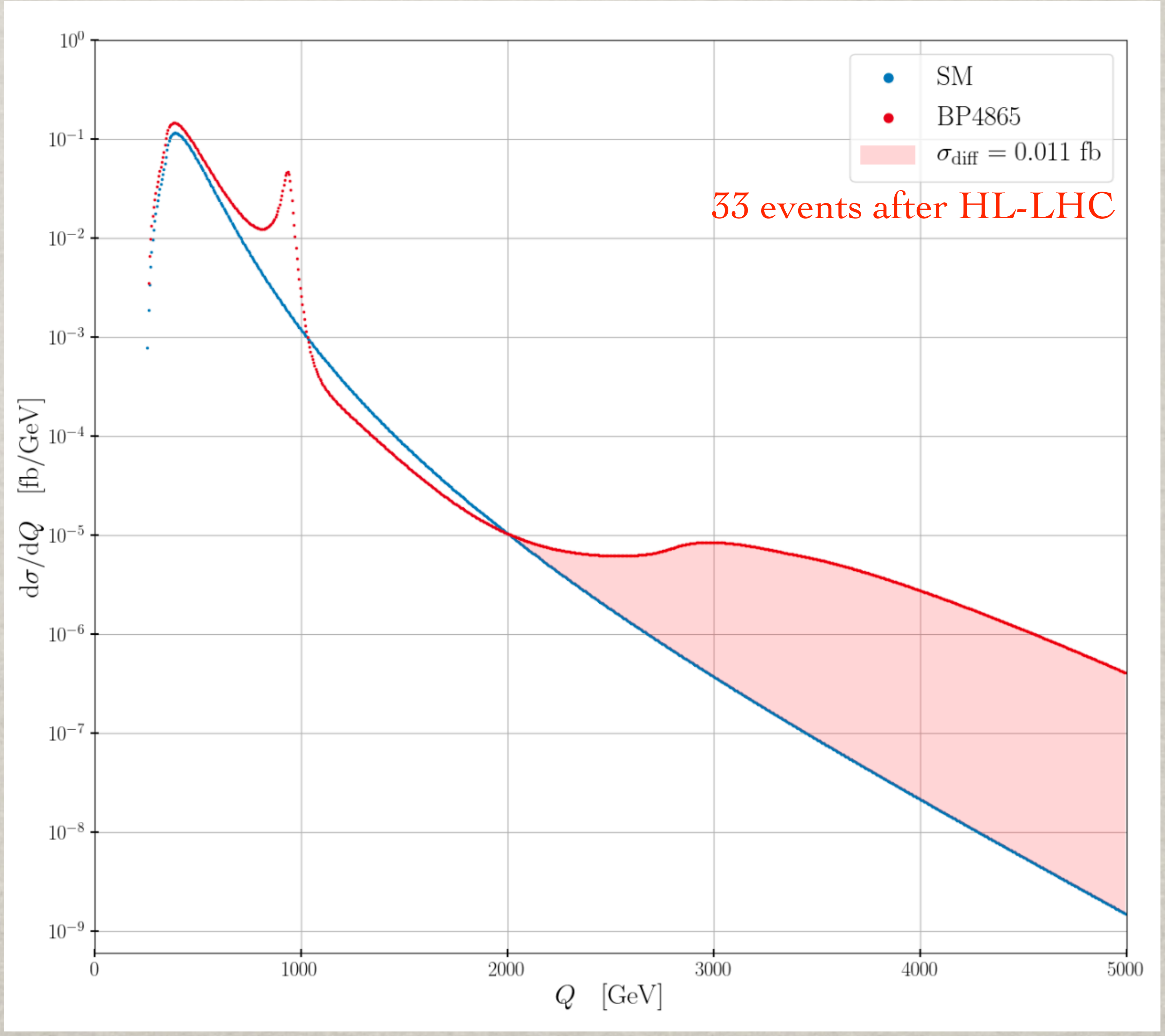

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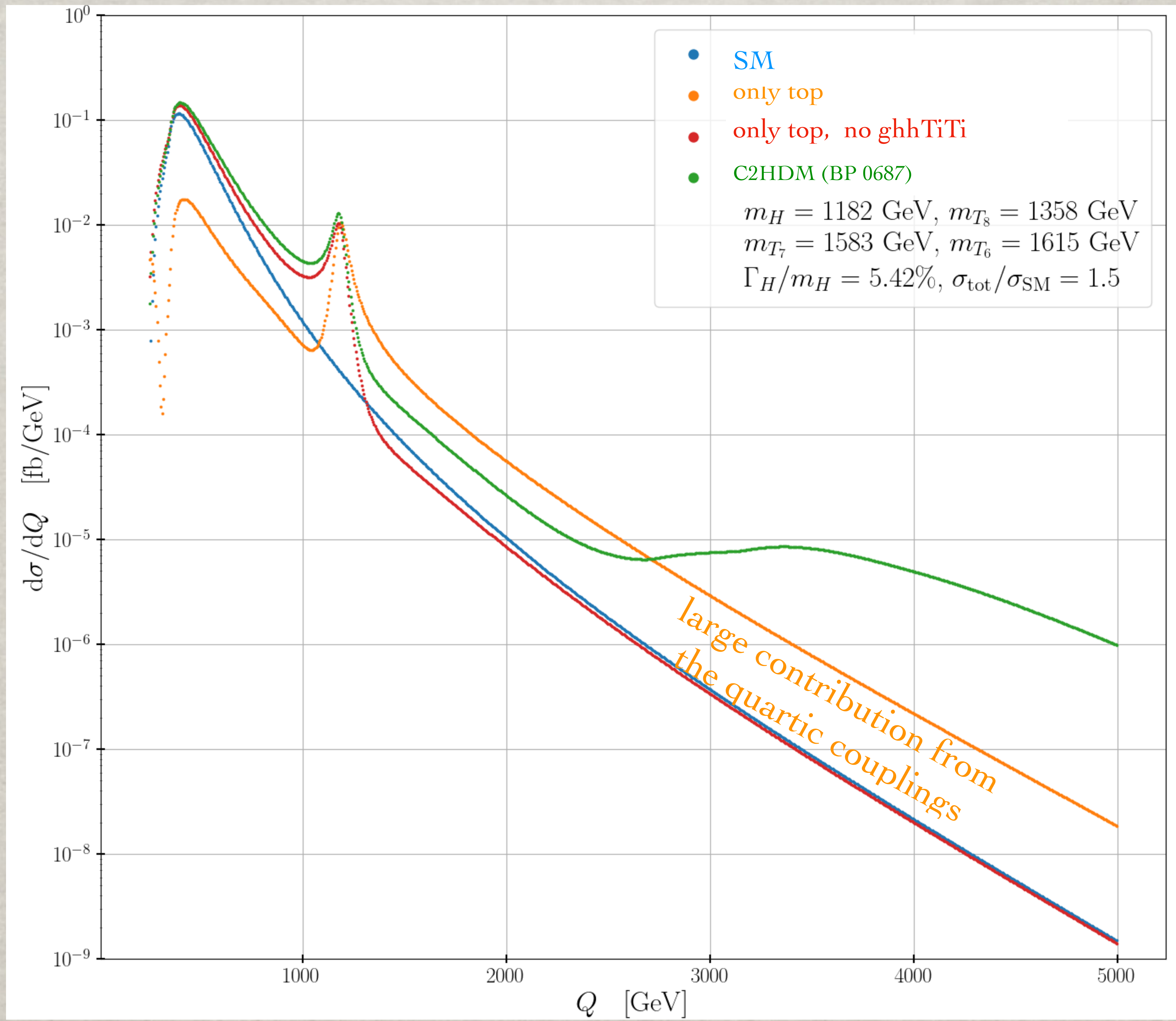

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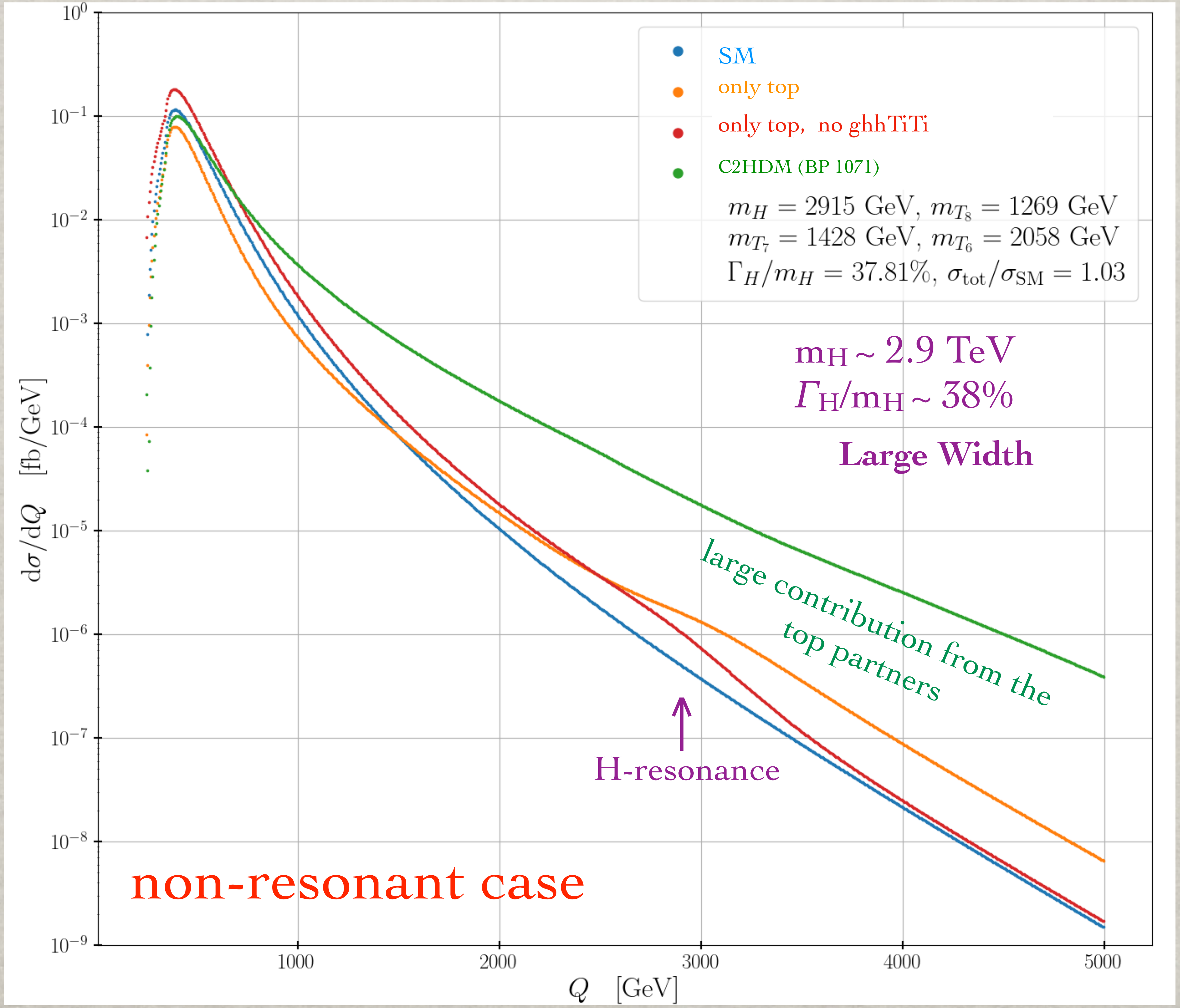

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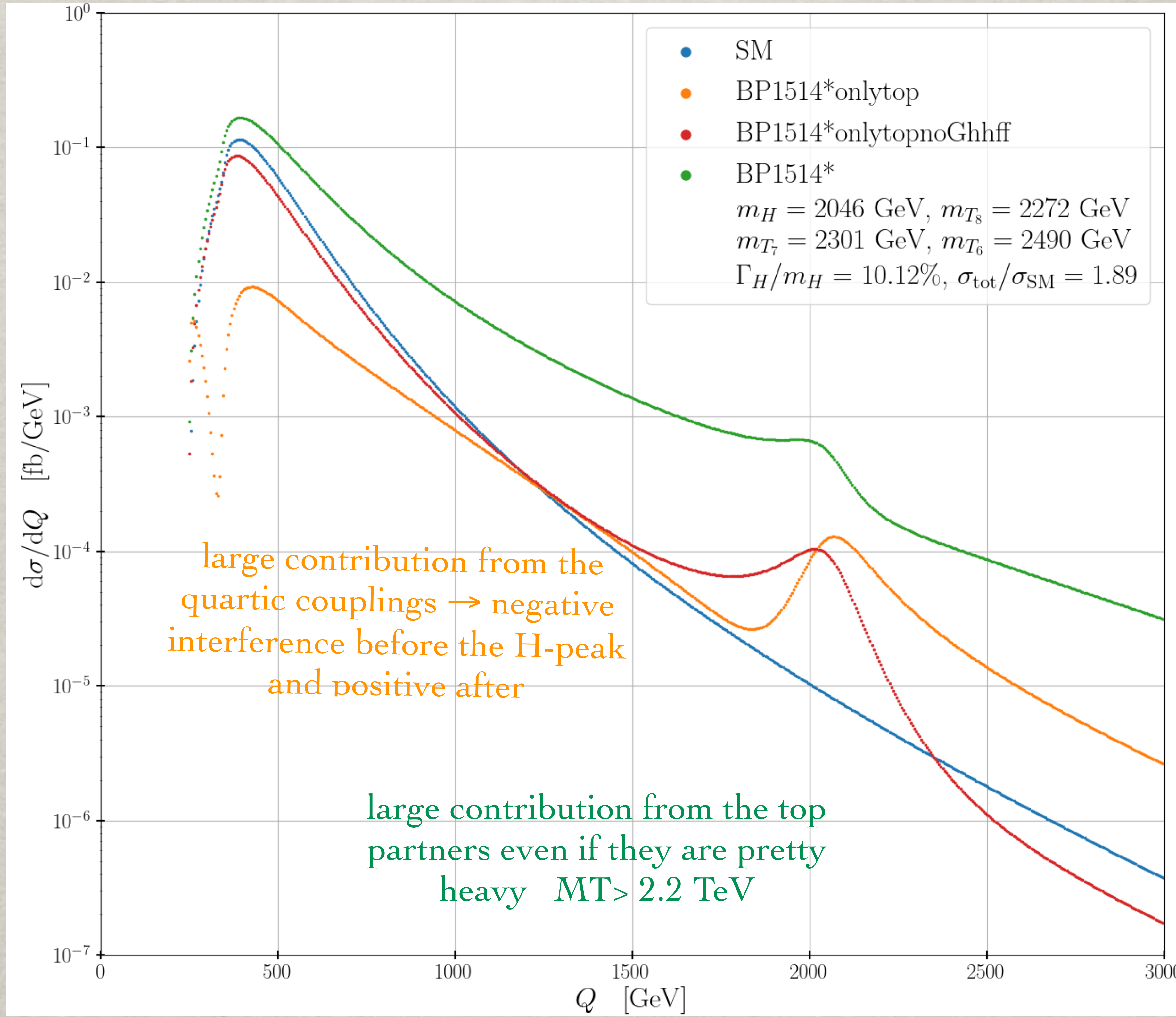

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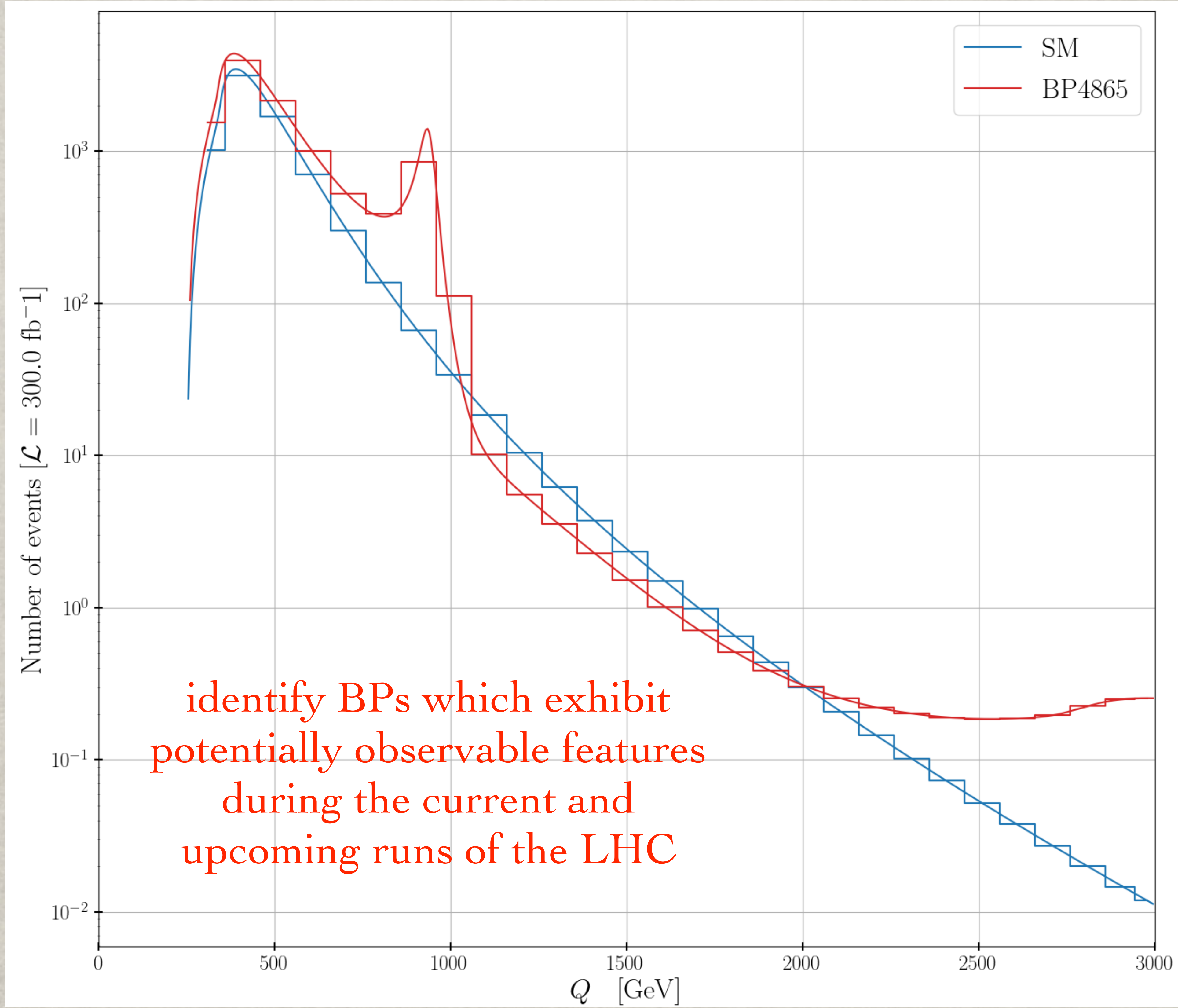

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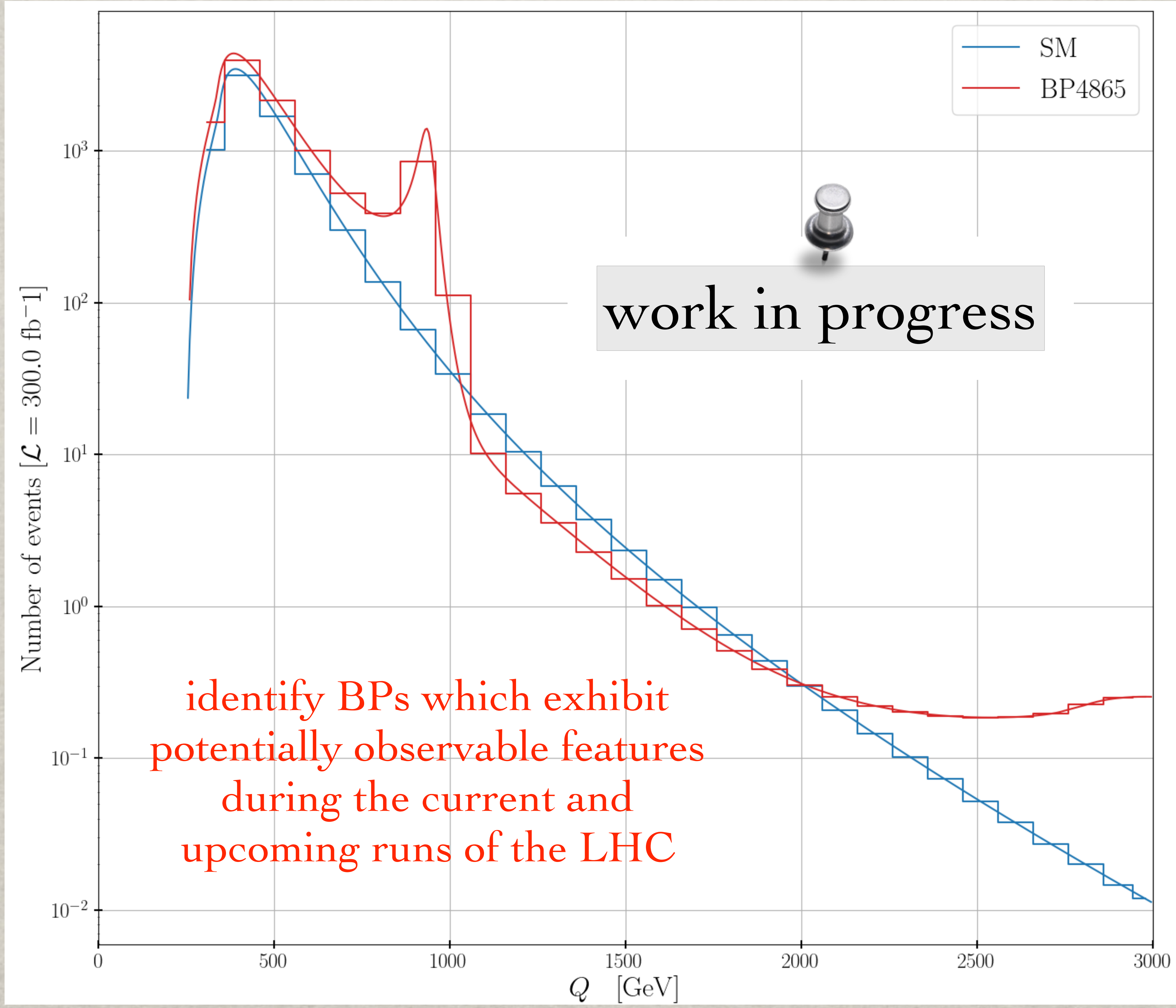

Conclusions

- ☑ di-Higgs production is a target process for the LHC, within the SM it is the experimental signature of the Higgs self-interaction, but also a probe for BSM scenarios

- ☑ We analysed $gg \to hh$ within the C2HDM with an approach which enables to disentangle the different NP ingredients: coupling modifications, new resonance exchange, heavy fermions in the loops, and the extra quartic couplings

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Sizeable effects both in the **integrated cross-section** and in the **differential distributions** open the prospect of **using di-Higgs production at the LHC as a probe for NP** with the possibility to **disentangle among different BSM schemes**

BACKUP SLIDES

C2HDM versus MSSM

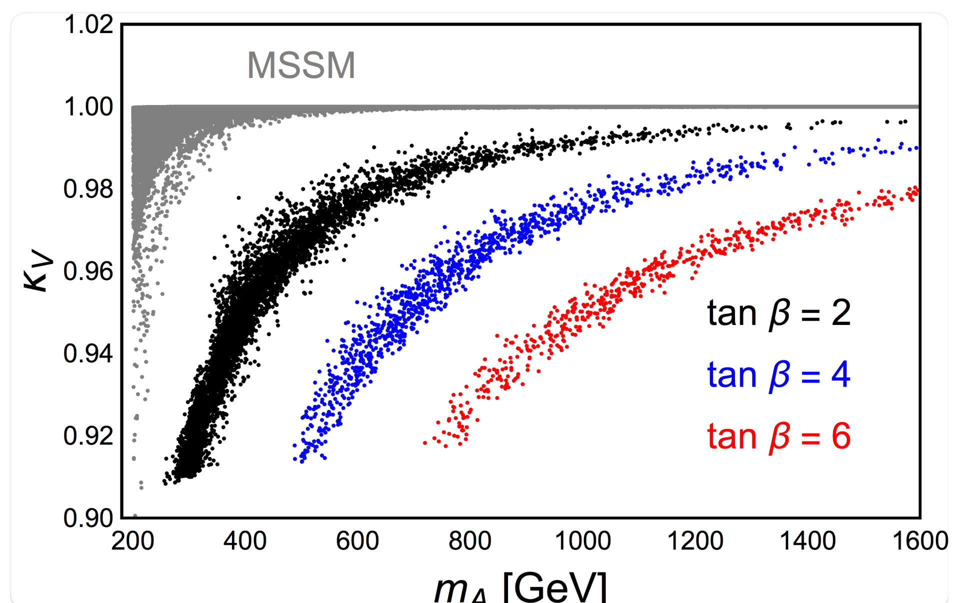
	Supersymmetry	Compositeness
dynamics	*weak*	*strong*
nature of the Higgs	*elementary*	*bound state* $\varphi \sim \langle \bar{\Psi}\Psi \rangle$
quadratic divergences	*fermion/boson interplay*	*no elementary scalars*
lightness of the Higgs	$m_\varphi \sim m_Z$	*pseudo Nambu-Goldstone*
Higgs structure	*2HDM required*	*2HDM depending on the (broken) global symmetry*

Can we distinguish the two paradigms by looking at the 2HDM dynamics?

Several observables can be used to discriminate between ℂ2HDM and MSSM:

- k_V (delayed decoupling)
- mass spectrum
- heavy Higgses' decay patterns
- (lightest) top partner spectrum

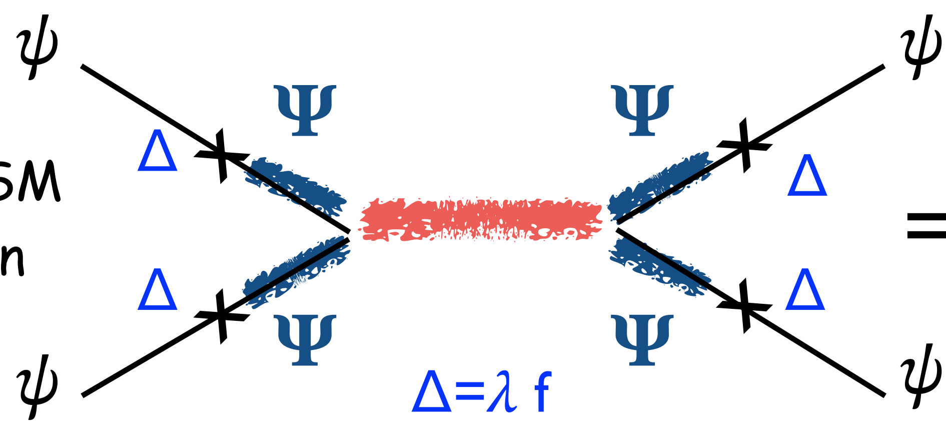
(DC, Delle Rose, Moretti, Yagyu, '18)



Composite Higgs and Flavour

In composite scenarios four-fermion operators are generated integrating out the composite fermions and vectors

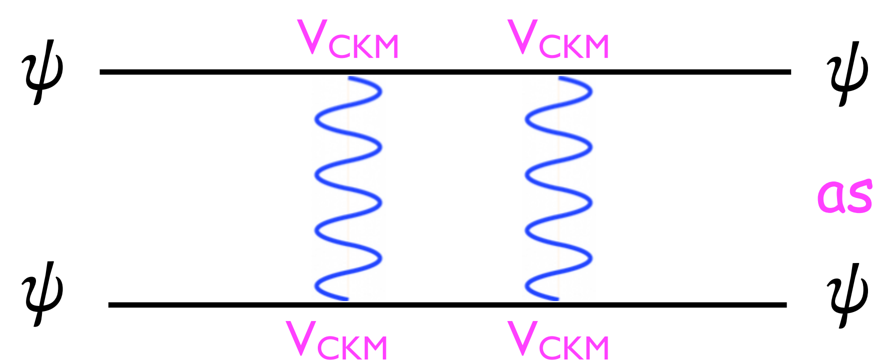
ψ is a SM fermion



$$\Rightarrow \quad \frac{x_{ijkl}}{f^2}\psi_i\psi_j\psi_k\psi_l$$

They can mediate FCNCs at tree-level if the flavour coefficients $x^{ijkl} \sim (\lambda\lambda)^{ij}\,(\lambda\lambda)^{kl}$ are generic

These effects are suppressed if a partial alignment of λ^{ij} with the CKM matrix is realised
(Redi,Weiler 11; Barbieri et al.12)



as in the SM

We will work under these assumptions to realise a flavour symmetric composite sector