University of Zurich[UZH]

LABORATOIRE DE L'ACCÉLÉRATEUR LINÉAIRE

LHC Physics: Higgs and beyond

(*a personal selection of topics in the wast domain of LHC physics*)

Gino Isidori
[*University of Zürich*]

- Lecture I: *What we learned from run-I*
  [The SM as an effective theory & the "ghost" of the anthropic principle]

- Lecture II: *What we can hope to learn from run-II (at high-pT)*
  [Future prospects in Higgs physics and direct NP searches]

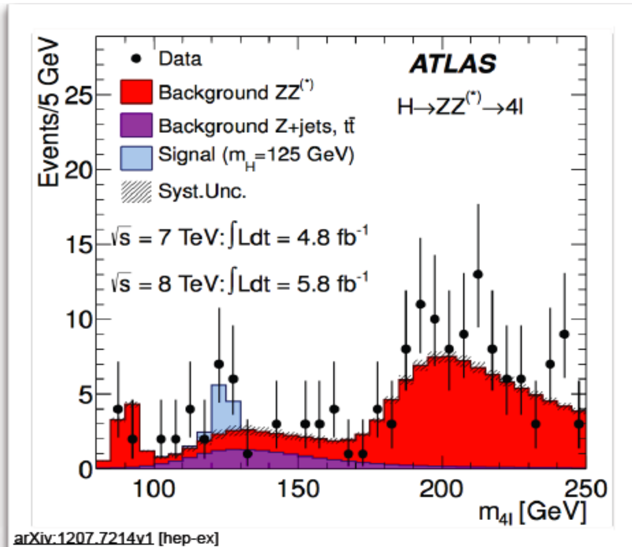
- Lecture III: *Indirect searches for NP*
  [Flavor physics beyond the SM]

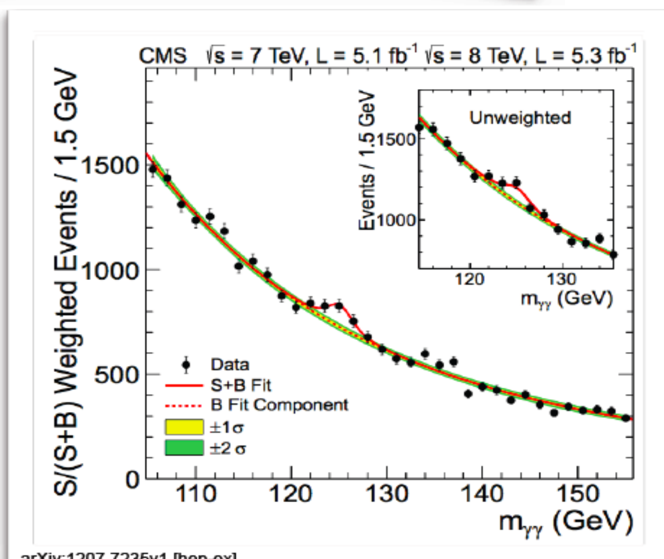
Lecture II: *What we can hope to learn from run-II* (*at high-pT*)
[Future prospects in Higgs physics and direct NP searches]

- Future prospects in Higgs physics
  - *Pseudo Observables in Higgs physics*
  - *The $h \to 4l$ case*
  - *PO in EW production*
  - *EFT approaches to Higgs physics vs. PO*
- SUSY
  - *Higgs and SUSY*
  - *Few comments on direct SUSY searches*
- Some comments on the “750 GeV di-photon excess”

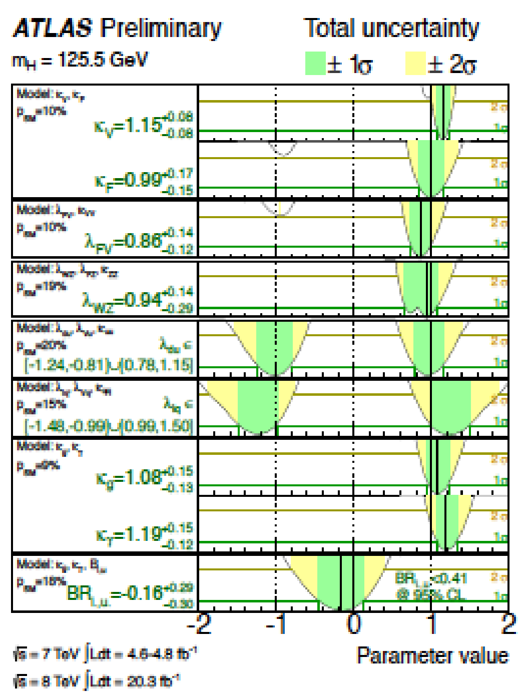
Future prospects in Higgs physics

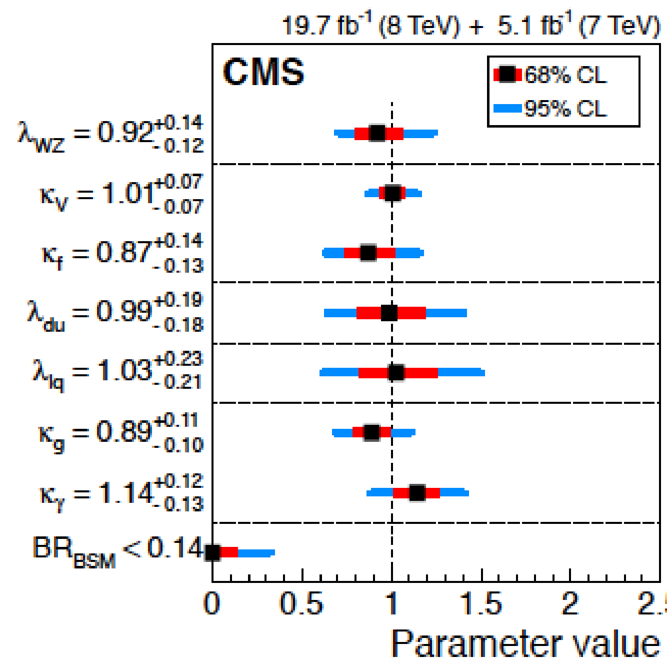
After the exciting discovery phase...





...we are entering into the era of precise measurements of the properties of the "Higgs particle" observed at 125 GeV.





Future prospects in Higgs physics

It's already quite clear (*both from the values of the Higgs couplings and by the consistency of* m_h *with EPWO*) that this particle is well compatible with the massive excitation of the Higgs field postulated within the SM:

$$\mathscr{L}_{\rm higgs}(\phi, A_a, \psi_i) = D\phi^+ D\phi - V(\phi)$$

$$V(\phi) = -\mu^2 \phi^+\phi + \lambda(\phi^+\phi)^2 + Y^{ij}\, \psi_L^{\,i}\, \psi_R^{\,j}\, \phi + \ldots$$

...but we are far from having established that there is nothing else beside the SM, or better that the cut-off of SM viewed as an effective theory is very high.

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⬇

On general grounds, it is natural to expect possible deviations from the SM in the Higgs sector
(origin of the main "problems" of the SM...)

⬇

High-precision Higgs physics

→ I. precise measurements of SM allowed processes (production & decay)

→ II. search for rare/exotic h decay modes

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On general grounds, it is natural to expect possible deviations from the SM in the Higgs sector
(origin of the main "problems" of the SM...)

Given the absence of clear NP directions, it's important to make these studies in general terms
(with minimum theoretical bias)

I. precise measurements of SM allowed processes (production & decay)

II. search for rare/exotic h decay modes

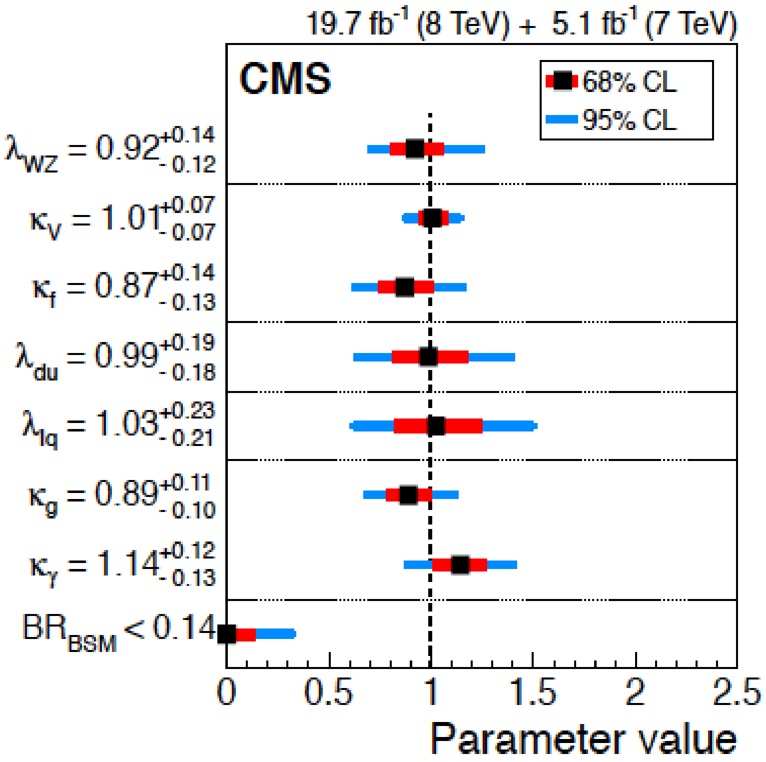
Future prospects in Higgs physics

So far, possible non-standard properties of the Higgs boson (in process with a leading SM amplitude) have been analyzed from the experimental point of view using the so-called "kappa-formalism":

$$\sigma(ii \to h+X) \times BR(h \to ff) = \sigma_{ii} \frac{\Gamma_{ff}}{\Gamma_h} = \frac{\kappa_{ii}^2 \kappa_{ff}^2}{\kappa_h^2} \sigma_{SM} \times BR_{SM}$$

Main virtues:

- Clean SM limit [best up-to-date TH predictions recovered for $\kappa_i \to 1$]
- Well-defined both on TH and EXP sides
- (*almost*) Model independent



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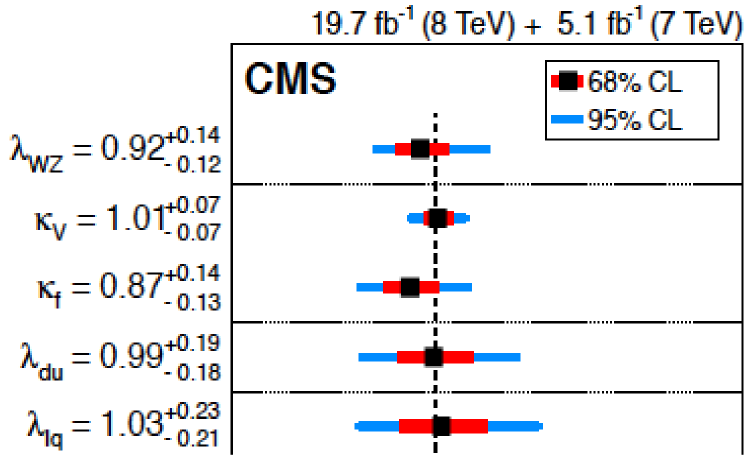

Main problem:

- Loss of information on possible NP effects modifying the kinematical distributions

N.B.: *easy to conceive NP effects showing up mainly in kin. effects rather than in total rates* (e.g. CPV)

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Main problem:

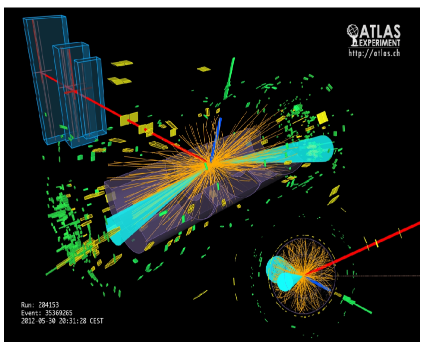
- Loss of information on possible NP effects modifying the kinematical distributions

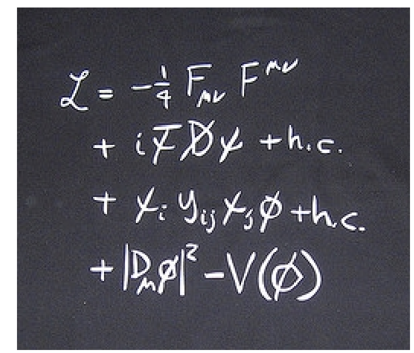
→ We need to identify a larger set of "pseudo-observables" able to characterize NP in the Higgs sector in general terms

Pseudo Observables in Higgs physics

- The goal of the PO is to provide a general encoding of the exp. results in terms of a limited number of "simplified" (idealized) observables of easy th. interpretation [*old idea - heavily used and developed at LEP times*]

- The experimental determination of an appropriate set of PO will "help" and not "replace" any explicit NP approach to Higgs physics (*including the EFT*)





Experimental data	Pseudo Observables	Lagrangian parameters
raw data, fiducial cross-sections, ...	masses, widths, slopes, ...	Wilson coefficients, renormalization scale, running masses, ...

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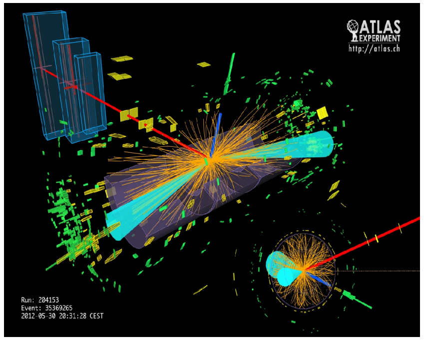

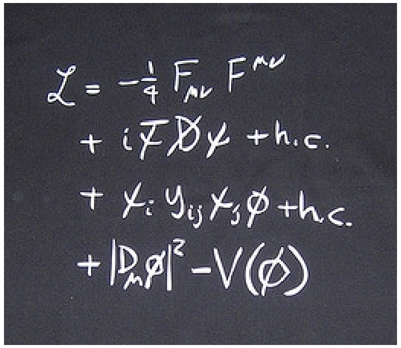

Experimental data Pseudo Observables Lagrangian parameters

The PO can be computed in terms of Lagrangian parameters in any specific th. framework (SM, SM-EFT, SUSY, ...)

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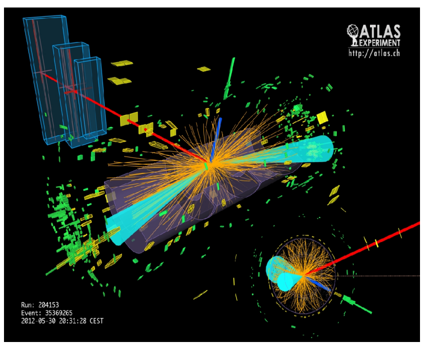

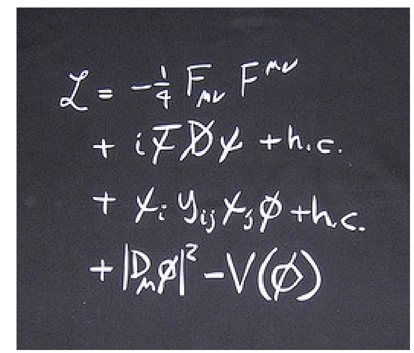

- The PO should be defined from kinematical properties of <u>on-shell processes</u> (*no problems of renormalization, scale dependence,…*)

- The theory corrections applied to extract them should be universally accepted as "NP-free" (*soft QCD and QED radiation*)

Pseudo Observables in Higgs physics

Example I: The mass of a particle is a PO

Not always obvious how to extract it from data (→ *debate on Z line-shape*) and how to make it in a way that is useful for theoreticians (→ *top mass*).

The M_Z, M_W, M_h, determined by experiments are 3 well-defined PO and not fundamental couplings of the SM Lagrangian (or BSM models)

Either we predict them (*at a certain order*) in terms of other couplings or we use them to extract the couplings (*at a given order and at a given scale...*). This does not affect their experimental determination, while the way they are defined from data affect the way we compute them.

Pseudo Observables in Higgs physics

Example II: The effective couplings of the Z boson

Parametrise the $Z\bar{f}f$ vertex as $\gamma_\mu \left(\mathcal{G}_V^f + \mathcal{G}_A^f \gamma_5\right)$

Radiators: final state radiation

$$\Gamma_f \equiv \Gamma\left(Z \to f\overline{f}\right) = 4\, c_f\, \Gamma_0 \left(|\mathcal{G}_V^f|^2\, R_V^f + |\mathcal{G}_A^f|^2\, R_A^f\right) + \Delta_{\rm EW/QCD}$$

Bardin, Grunewald, Passarino, '99

non-factorizable corrections, very small.

The pseudo-observables are defined as

$$g_V^f = \mathrm{Re}\, \mathcal{G}_V^f, \qquad g_A^f = \mathrm{Re}\, \mathcal{G}_A^f$$

To be model-independent it is important to work with on-shell initial and final states.

Then a theorist can take their model, or their EFT,
compute the contribution to these POs, and obtain the constraints on the model.

Pseudo Observables in Higgs physics

There are two main categories of PO:

A) "Ideal observables"

M_W, $\Gamma(Z \to ll)$, …

M_h, $\Gamma(h \to \gamma\gamma)$, $\Gamma(h \to 4\mu)$, …
but also $d\sigma(pp \to hZ)/dm_{hZ}$ ...

B) "Effective on-shell couplings"

g_Z^f, g_W^f, ...

- Both categories are useful, and we need to introduce them both in Higgs physics (*there is redundancy having both, but that's not an issue...*).
- For B) one can write an effective Feynman rule, not to be used beyond tree-level (its just a practical way to re-write, *and code in existing tools,* an on-shell amplitude).

Pseudo Observables in Higgs physics

Higgs decays

Multi-body modes
e.g. $h \rightarrow 4\ell,\ \ell\ell\gamma$, ...

There is more to extract from data other than the κ_i

Two-body (on-shell) decays
[*no polarization properties of the final state accessible*]
e.g. $h \rightarrow \gamma\gamma,\ \mu\mu,\ \tau\tau,\ bb$

The κ_i $(\leftrightarrow \Gamma_i)$ *is all what one can extract from data*

[+ *one more parameter if the polarization is accessible*]

Pseudo Observables in Higgs physics

Higgs decays

Multi-body modes
e.g. $h \to 4\ell$, $\ell\ell\gamma$, ...

↓

form factors $\to f_i(s)$ [E.g.: $s = m^2_{\ell\ell}$]

Two-body (on-shell) decays

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E.g.: $\mathcal{A}(h \to Z\,ee) \sim \varepsilon^Z_\mu J^{e_L}_\mu [f_1^{Ze_L}(q^2) g^{\mu\nu} + f_3^{Ze_L}(q^2)(pq\, g^{\mu\nu} - q^\mu p^\nu) + ...]$

N.B.: There is noting "wrong" or "dangerous" in using *f.f.*, provided

- they are defined from on-shell amplitudes
[*hill-defined for* $h \to WW^*$, ZZ^* *but perfectly ok for* $h \to 4\ell$]
- no model-dependent assumptions are made on their functional form

Pseudo Observables in Higgs physics

Higgs decays

↙ ↘

Multi-body modes

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Momentum expansion of the *f.f.* around leading poles, e.g.:

$$f_i^{\mathrm{SM+NP}}(s_1,s_2) = \frac{\kappa_i}{(s_1-m_Z^2+im_Z\Gamma_Z)(s_2-m_Z^2+im_Z\Gamma_Z)} + \frac{\varepsilon_i}{(s_1-m_Z^2+im_Z\Gamma_Z)} + \ldots$$

Two-body (on-shell) decays

[*no polarization properties of the final state accessible*]

e.g. $h \to \gamma\gamma,\ \mu\mu,\ \tau\tau,\ bb$

- No need to specify any detail about the underlying theory, but for the absence of light new particles → momentum exp. well justified by the Higgs kinematic
- The $\{\kappa_i, \varepsilon_i\}$ thus defined are well-defined PO → systematic inclusion of higher-order QED and QCD (soft) corrections possible (and necessary...)

Pseudo Observables in Higgs physics

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Momentum expansion of the *f.f.* around leading poles, e.g.:

$$f_i^{SM+NP}(s_1,s_2) = \frac{\kappa_i}{(s_1 - m_Z^2 + i m_Z \Gamma_Z)(s_2 - m_Z^2 + i m_Z \Gamma_Z)} + \frac{\varepsilon_i}{(s_1 - m_Z^2 + i m_Z \Gamma_Z)} + \ldots$$

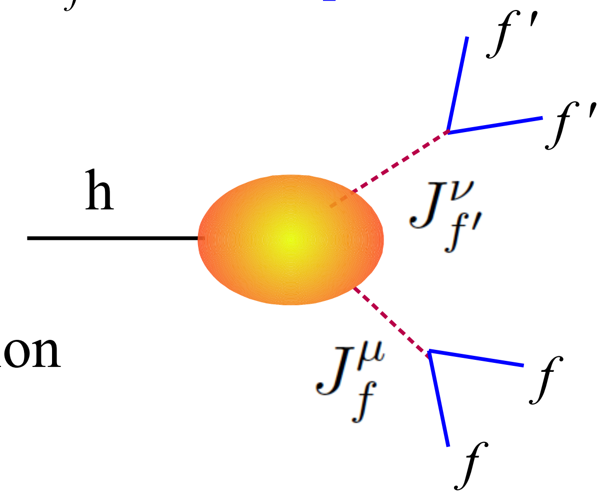
The PO thus defined are based on a minimal set of QFT assumptions: analiticity, unitarity, crossing-symmetry + no new light particles in the theory.

The $h \to 4f$ case

Two main hypotheses:

I. Fermion couples to the Higgs via helicity-conserving local currents
[↔ neglect helicity-violating interactions, naturally linked to m_f also BSM]

$$G_{[JJh]} = \langle 0|\mathcal{T}\left\{ J^\mu_f(x), J^\nu_{f'}(y), h(0) \right\}|0\rangle$$



The amplitude is fully determined by this Green function that contains long-distance modes (↔ non-local terms in x and y due to the exchange of EW gauge bosons) & short-distance modes (↔ contact terms for x or $y \to 0$)

Only 3 Lorentz structures allowed, e.g.:

$$\mathcal{A} = i\frac{2m_Z^2}{v_F}\sum_{e=e_L,e_R}\sum_{\mu=\mu_L,\mu_R}(\bar{e}\gamma_\alpha e)(\bar{\mu}\gamma_\beta\mu)\times$$
$$\left[F_1^{e\mu}(q_1^2,q_2^2)g^{\alpha\beta} + F_3^{e\mu}(q_1^2,q_2^2)\frac{q_1\cdot q_2\; g^{\alpha\beta} - q_2{}^\alpha q_1{}^\beta}{m_Z^2} + F_4^{e\mu}(q_1^2,q_2^2)\frac{\varepsilon^{\alpha\beta\rho\sigma}q_{2\rho}q_{1\sigma}}{m_Z^2}\right]$$

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↓

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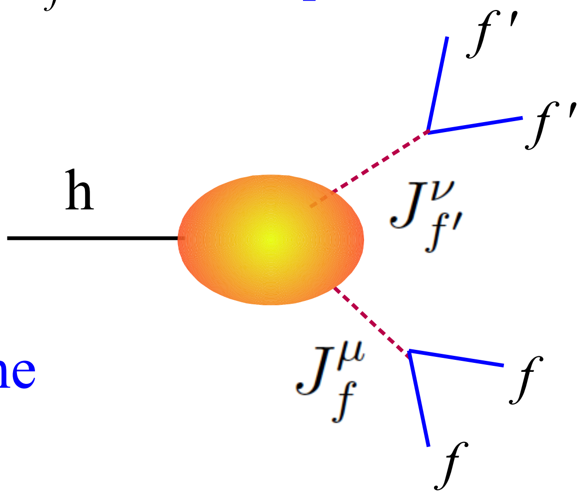
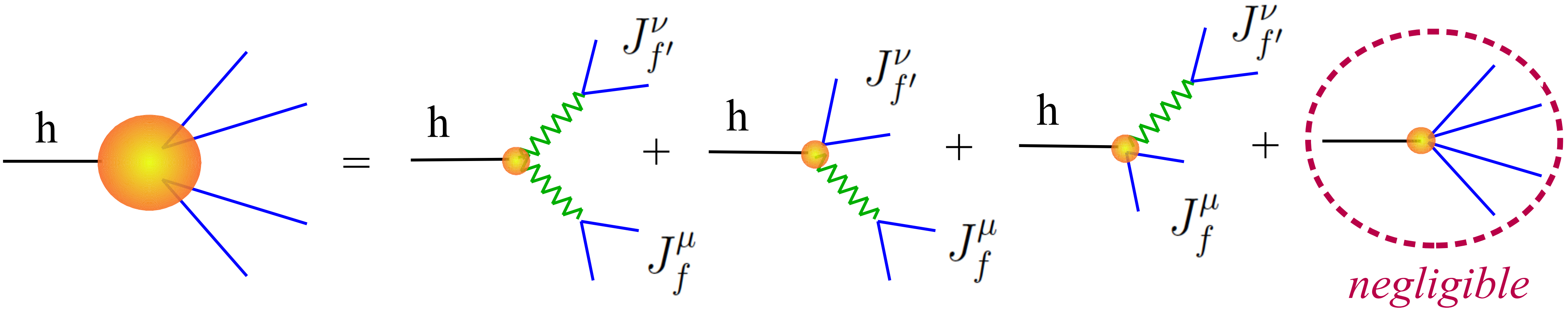


II. Kinematical (momentum) expansion of $G_{[JJh]}$ around the leading SM poles:

↓



The $h \to 4f$ case

Following these hypotheses we can expand the form factors around the physical poles and retain only the leading terms (in the momentum expansion), e.g.:

$$\epsilon_{\gamma\gamma}^{\text{SM-1L}} \simeq 3.8 \times 10^{-3} \qquad \epsilon_{Z\gamma}^{\text{SM-1L}} \simeq 6.7 \times 10^{-3}$$

$$\begin{aligned}\mathcal{A} =& i\frac{2m_Z^2}{v_F}\sum_{e=e_L,e_R}\sum_{\mu=\mu_L,\mu_R}(\bar{e}\gamma_\alpha e)(\bar{\mu}\gamma_\beta\mu)\times \\ &\left[\left(\kappa_{ZZ}\frac{g_Z^e g_Z^\mu}{P_Z(q_1^2)P_Z(q_2^2)} + \frac{\epsilon_{Ze}}{m_Z^2}\frac{g_Z^\mu}{P_Z(q_2^2)} + \frac{\epsilon_{Z\mu}}{m_Z^2}\frac{g_Z^e}{P_Z(q_1^2)}\right) g^{\alpha\beta} + \right. \\ &+\left(\epsilon_{ZZ}\frac{g_Z^e g_Z^\mu}{P_Z(q_1^2)P_Z(q_2^2)} + \kappa_{Z\gamma}\epsilon_{Z\gamma}^{\text{SM-1L}}\left(\frac{eQ_\mu g_Z^e}{q_2^2 P_Z(q_1^2)} + \frac{eQ_e g_Z^\mu}{q_1^2 P_Z(q_2^2)}\right) + \kappa_{\gamma\gamma}\epsilon_{\gamma\gamma}^{\text{SM-1L}}\frac{e^2 Q_e Q_\mu}{q_1^2 q_2^2}\right)\frac{q_1\cdot q_2\ g^{\alpha\beta} - q_2{}^\alpha q_1{}^\beta}{m_Z^2} + \\ &+\left.\left(\epsilon_{ZZ}^{\text{CP}}\frac{g_Z^e g_Z^\mu}{P_Z(q_1^2)P_Z(q_2^2)} + \epsilon_{Z\gamma}^{\text{CP}}\left(\frac{eQ_\mu g_Z^e}{q_2^2 P_Z(q_1^2)} + \frac{eQ_e g_Z^\mu}{q_1^2 P_Z(q_2^2)}\right) + \epsilon_{\gamma\gamma}^{\text{CP}}\frac{e^2 Q_e Q_\mu}{q_1^2 q_2^2}\right)\frac{\varepsilon^{\alpha\beta\rho\sigma}q_{2\rho}q_{1\sigma}}{m_Z^2}\right]\end{aligned}$$

$$P_Z(q^2) = q^2 - m_Z^2 + i m_Z \Gamma_Z$$

- The $\{\kappa_i, \varepsilon_i\}$ are defined from the residues of the amplitude on the physical poles $\to$ well-defined PO that can be extracted from data and computed to desired accuracy in a given BSM framework
- By construction, the g_Z^f are the PO from Z-pole measurements, while $\kappa_{\gamma\gamma}$ and $\kappa_{Z\gamma}$ are the standard "kappas" from on-shell $h \to \gamma\gamma$ and $h \to Z\gamma$

▸ *The h → 4f case*

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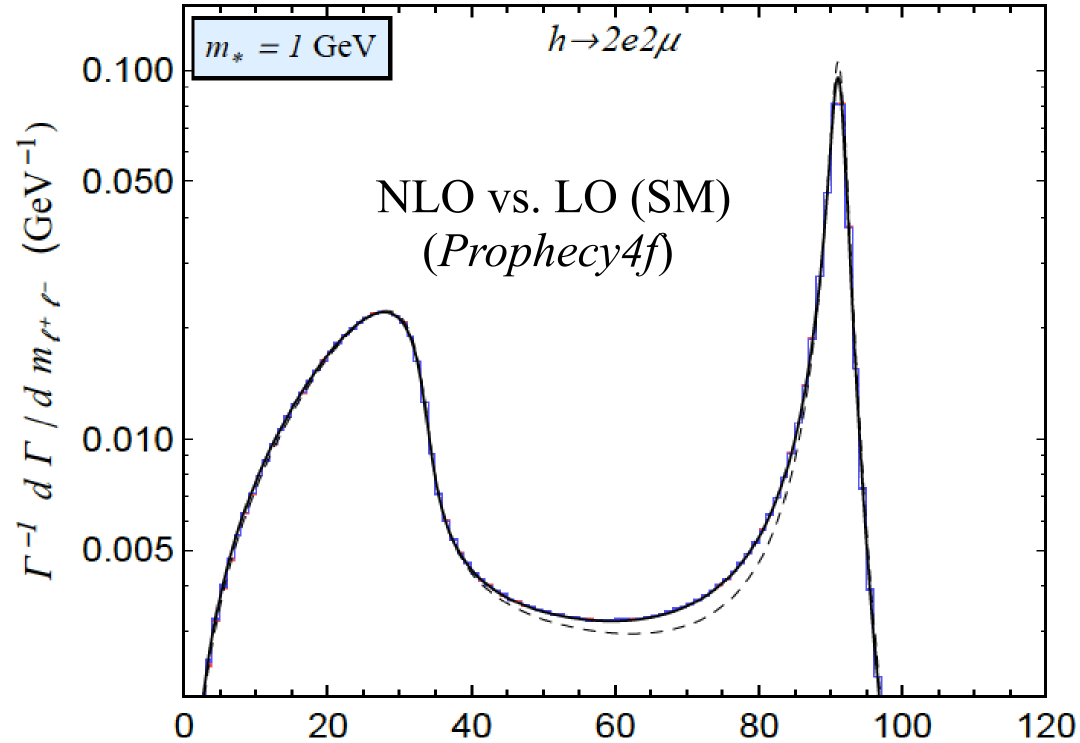
& + \left(\epsilon_{ZZ}^{\text{CP}} \frac{g_Z^e g_Z^\mu}{P_Z(q_1^2)P_Z(q_2^2)} + \epsilon_{Z\gamma}^{\text{CP}} \left(\frac{eQ_\mu g_Z^e}{q_2^2 P_Z(q_1^2)} + \frac{eQ_e g_Z^\mu}{q_1^2 P_Z(q_2^2)} \right) + \epsilon_{\gamma\gamma}^{\text{CP}} \frac{e^2 Q_e Q_\mu}{q_1^2 q_2^2} \right) \frac{\varepsilon^{\alpha\beta\rho\sigma} q_{2\rho} q_{1\sigma}}{m_Z^2} \Bigg]
\end{aligned}$$

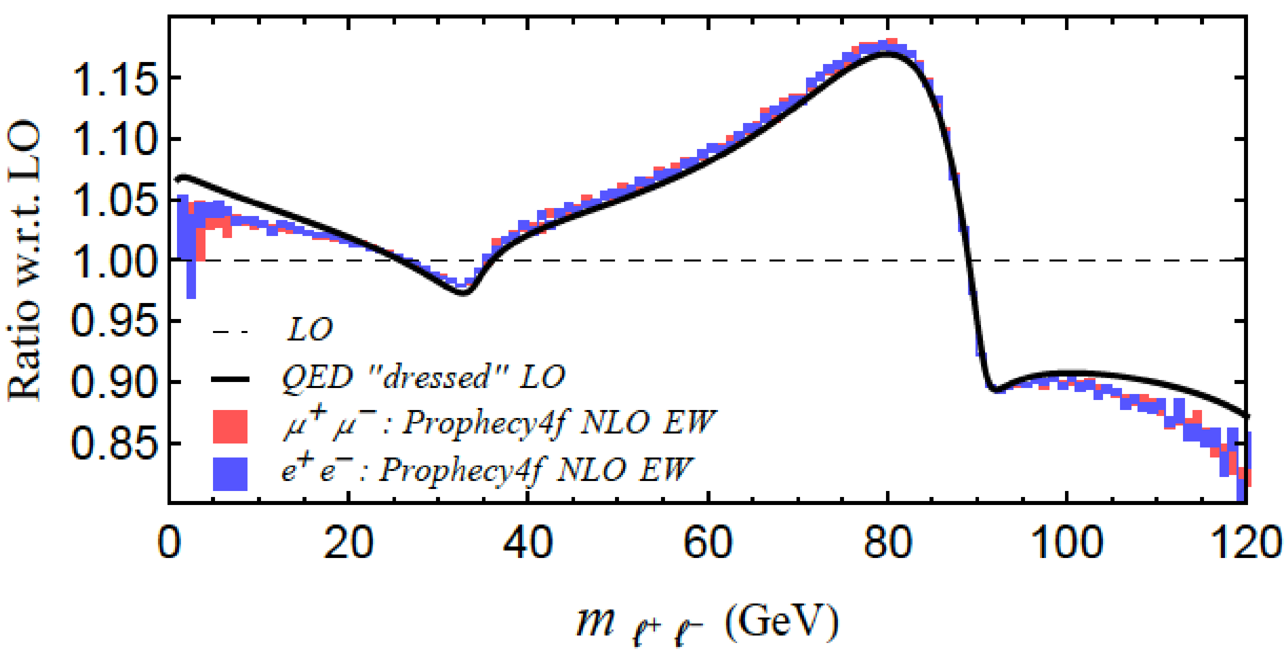
$$P_Z(q^2) = q^2 - m_Z^2 + i m_Z \Gamma_Z$$

- The κ_i are normalized such that the SM is recovered in the limit $\kappa_i \to 1$
- The ε_i describe terms not present in the SM at the tree level (*and always sub-leading*): SM recovered for $\varepsilon_i^{(SM)} = O(10^{-3}) \to 0$
- To this amplitude we can apply a "radiation function" to take into account QED radiation → excellent description of SM (and NP) beyond the tree level.

The $h \to 4f$ case

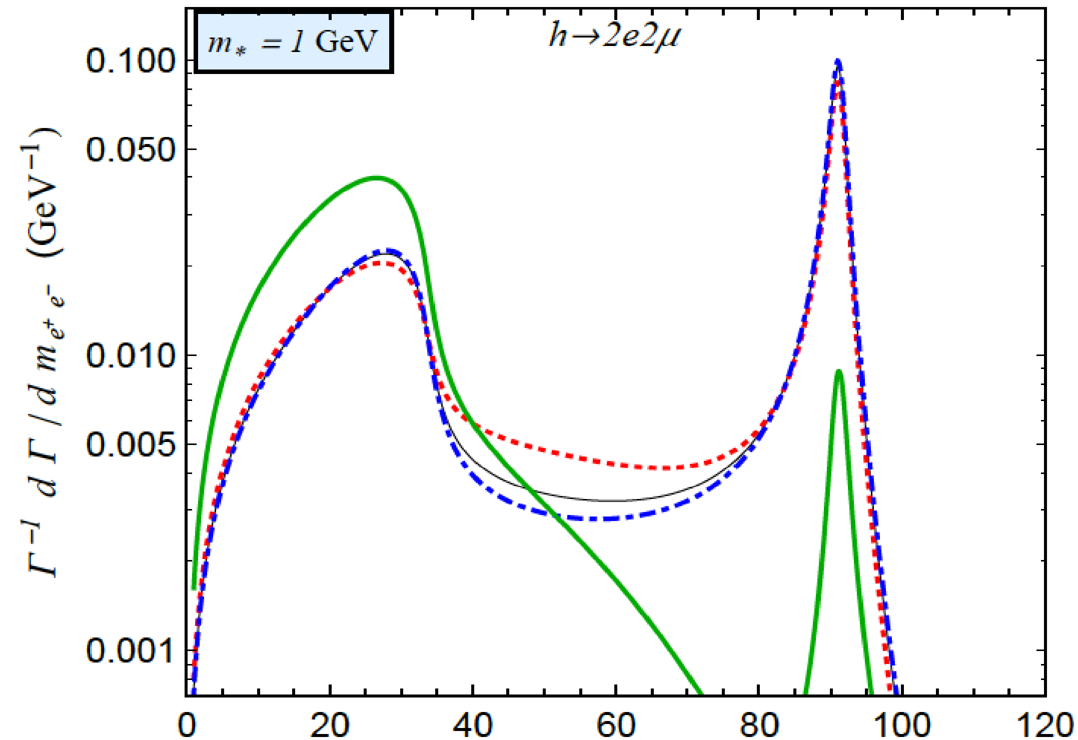


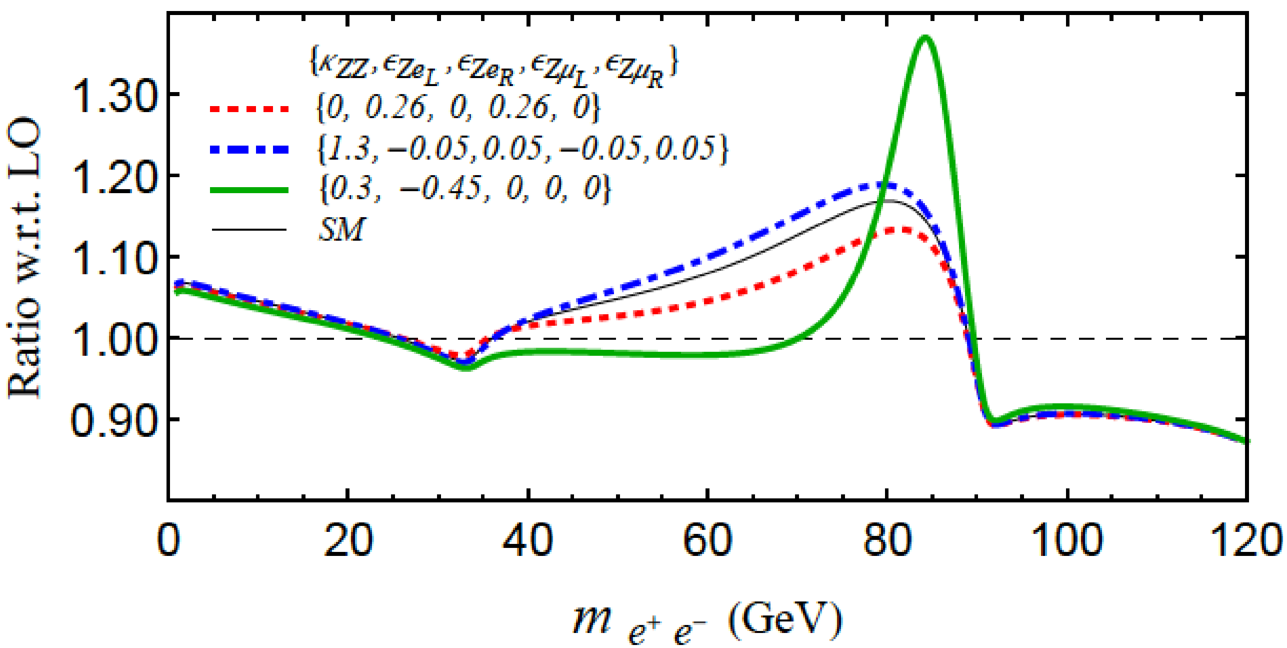
"Dressing" with QED radiation → excellent description of SM beyond the tree level



The $h \to 4f$ case

"Dressing" with QED radiation → excellent description of SM beyond the tree level & relevant impact for BSM @ NLO



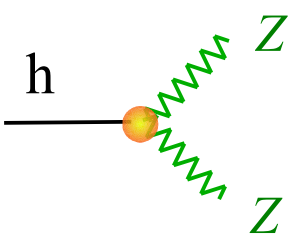


The $h \to 4f$ case

The "physical meaning" of the parameters appearing in this decomposition is not obvious at first sight, but it is actually quite simple [→ *physical PO*]:

$$\mathcal{A} = i\frac{2m_Z^2}{v_F}\sum_{e=e_L,e_R}\sum_{\mu=\mu_L,\mu_R}(\bar{e}\gamma_\alpha e)(\bar{\mu}\gamma_\beta \mu)\times$$
$$\left[\left(\kappa_{ZZ}\frac{g_Z^e g_Z^\mu}{P_Z(q_1^2)P_Z(q_2^2)} + \frac{\epsilon_{Ze}}{m_Z^2}\frac{g_Z^\mu}{P_Z(q_2^2)} + \frac{\epsilon_{Z\mu}}{m_Z^2}\frac{g_Z^e}{P_Z(q_1^2)}\right)g^{\alpha\beta} + \right.$$
$$+\left(\epsilon_{ZZ}\frac{g_Z^e g_Z^\mu}{P_Z(q_1^2)P_Z(q_2^2)} + \kappa_{Z\gamma}\epsilon_{Z\gamma}^{\text{SM-1L}}\left(\frac{eQ_\mu g_Z^e}{q_2^2 P_Z(q_1^2)} + \frac{eQ_e g_Z^\mu}{q_1^2 P_Z(q_2^2)}\right) + \kappa_{\gamma\gamma}\epsilon_{\gamma\gamma}^{\text{SM-1L}}\frac{e^2 Q_e Q_\mu}{q_1^2 q_2^2}\right)\frac{q_1\cdot q_2\, g^{\alpha\beta} - q_2{}^\alpha q_1{}^\beta}{m_Z^2} +$$
$$\left.+\left(\epsilon_{ZZ}^{\text{CP}}\frac{g_Z^e g_Z^\mu}{P_Z(q_1^2)P_Z(q_2^2)} + \epsilon_{Z\gamma}^{\text{CP}}\left(\frac{eQ_\mu g_Z^e}{q_2^2 P_Z(q_1^2)} + \frac{eQ_e g_Z^\mu}{q_1^2 P_Z(q_2^2)}\right) + \epsilon_{\gamma\gamma}^{\text{CP}}\frac{e^2 Q_e Q_\mu}{q_1^2 q_2^2}\right)\frac{\varepsilon^{\alpha\beta\rho\sigma}q_{2\rho}q_{1\sigma}}{m_Z^2}\right]$$

"double Z-pole"



$$\Gamma(h\to Z_L Z_L) \equiv \frac{\Gamma(h\to 2e2\mu)[\kappa_{ZZ}]}{\mathcal{B}(Z\to 2e)\mathcal{B}(Z\to 2\mu)} = 0.209\ |\kappa_{ZZ}|^2\ \text{MeV}$$

$$\Gamma(h\to Z_T Z_T) \equiv \frac{\Gamma(h\to 2e2\mu)[\epsilon_{ZZ}]}{\mathcal{B}(Z\to 2e)\mathcal{B}(Z\to 2\mu)} = 0.0189\ |\epsilon_{ZZ}|^2\ \text{MeV}$$

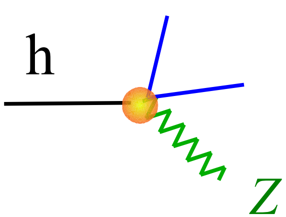
$$\Gamma^{\text{CPV}}(h\to Z_T Z_T) \equiv \frac{\Gamma(h\to 2e2\mu)[\epsilon_{ZZ}^{\text{CP}}]}{\mathcal{B}(Z\to 2e)\mathcal{B}(Z\to 2\mu)} = 0.00799\ |\epsilon_{ZZ}^{\text{CP}}|^2\ \text{MeV}$$

The $h \to 4f$ case

The "physical meaning" of the parameters appearing in this decomposition is not obvious at first sight, but it is actually quite simple [→ *physical PO*]:

$$
\begin{aligned}
\mathcal{A} = & \, i\frac{2m_Z^2}{v_F}\sum_{e=e_L,e_R}\sum_{\mu=\mu_L,\mu_R}(\bar{e}\gamma_\alpha e)(\bar{\mu}\gamma_\beta \mu)\times \\
& \left[\left(\kappa_{ZZ}\frac{g_Z^e g_Z^\mu}{P_Z(q_1^2)P_Z(q_2^2)} + \frac{\epsilon_{Ze}}{m_Z^2}\frac{g_Z^\mu}{P_Z(q_2^2)} + \frac{\epsilon_{Z\mu}}{m_Z^2}\frac{g_Z^e}{P_Z(q_1^2)}\right) g^{\alpha\beta} + \right. \\
& + \left(\epsilon_{ZZ}\frac{g_Z^e g_Z^\mu}{P_Z(q_1^2)P_Z(q_2^2)} + \kappa_{Z\gamma}\epsilon_{Z\gamma}^{\text{SM-1L}}\left(\frac{eQ_\mu g_Z^e}{q_2^2 P_Z(q_1^2)} + \frac{eQ_e g_Z^\mu}{q_1^2 P_Z(q_2^2)}\right) + \kappa_{\gamma\gamma}\epsilon_{\gamma\gamma}^{\text{SM-1L}}\frac{e^2 Q_e Q_\mu}{q_1^2 q_2^2}\right)\frac{q_1\cdot q_2\, g^{\alpha\beta} - q_2{}^\alpha q_1{}^\beta}{m_Z^2} + \\
& \left. + \left(\epsilon_{ZZ}^{\text{CP}}\frac{g_Z^e g_Z^\mu}{P_Z(q_1^2)P_Z(q_2^2)} + \epsilon_{Z\gamma}^{\text{CP}}\left(\frac{eQ_\mu g_Z^e}{q_2^2 P_Z(q_1^2)} + \frac{eQ_e g_Z^\mu}{q_1^2 P_Z(q_2^2)}\right) + \epsilon_{\gamma\gamma}^{\text{CP}}\frac{e^2 Q_e Q_\mu}{q_1^2 q_2^2}\right)\frac{\varepsilon^{\alpha\beta\rho\sigma} q_{2\rho} q_{1\sigma}}{m_Z^2}\right]
\end{aligned}
$$

"single Z-pole"



$$\Gamma(h \to Z\ell^+\ell^-) = 0.0366|\epsilon_{Z\ell}|^2 \text{ MeV}$$

▸ *The $h \to 4f$ case*

The "physical meaning" of the parameters appearing in this decomposition is not obvious at first sight, but it is actually quite simple [→ *physical PO*]:

PO	Physical PO	Relation to the eff. coupl.
$\kappa_f,\ \lambda_f^{\rm CP}$	$\Gamma(h\to f\bar f)$	$= \Gamma(h\to f\bar f)^{\rm (SM)}[(\kappa_f)^2+(\lambda_f^{\rm CP})^2]$
$\kappa_{\gamma\gamma},\ \lambda_{\gamma\gamma}^{\rm CP}$	$\Gamma(h\to\gamma\gamma)$	$= \Gamma(h\to\gamma\gamma)^{\rm (SM)}[(\kappa_{\gamma\gamma})^2+(\lambda_{\gamma\gamma}^{\rm CP})^2]$
$\kappa_{Z\gamma},\ \lambda_{Z\gamma}^{\rm CP}$	$\Gamma(h\to Z\gamma)$	$= \Gamma(h\to Z\gamma)^{\rm (SM)}[(\kappa_{Z\gamma})^2+(\lambda_{Z\gamma}^{\rm CP})^2]$
κ_{ZZ}	$\Gamma(h\to Z_L Z_L)$	$= (0.209~{\rm MeV})\times\lvert\kappa_{ZZ}\rvert^2$
ϵ_{ZZ}	$\Gamma(h\to Z_T Z_T)$	$= (1.9\times10^{-2}~{\rm MeV})\times\lvert\epsilon_{ZZ}\rvert^2$
$\epsilon_{ZZ}^{\rm CP}$	$\Gamma^{\rm CPV}(h\to Z_T Z_T)$	$= (8.0\times10^{-3}~{\rm MeV})\times\lvert\epsilon_{ZZ}^{\rm CP}\rvert^2$
ϵ_{Zf}	$\Gamma(h\to Zf\bar f)$	$= (3.7\times10^{-2}~{\rm MeV})\times N_c^f\ \lvert\epsilon_{Zf}\rvert^2$
κ_{WW}	$\Gamma(h\to W_L W_L)$	$= (0.84~{\rm MeV})\times\lvert\kappa_{WW}\rvert^2$
ϵ_{WW}	$\Gamma(h\to W_T W_T)$	$= (0.16~{\rm MeV})\times\lvert\epsilon_{WW}\rvert^2$
$\epsilon_{WW}^{\rm CP}$	$\Gamma^{\rm CPV}(h\to W_T W_T)$	$= (6.8\times10^{-2}~{\rm MeV})\times\lvert\epsilon_{WW}^{\rm CP}\rvert^2$
ϵ_{Wf}	$\Gamma(h\to Wf\bar f')$	$= (0.14~{\rm MeV})\times N_c^f\ \lvert\epsilon_{Wf}\rvert^2$

The $h \to 4f$ case

N. independent PO for a complete description of $h \to 4\ell$ (ℓ=e,μ,ν) + $\ell\ell\gamma$ + $\gamma\gamma$, with or without specific symmetry assumptions:

Decay modes	*flavor +CP symm.*	*flavor non univ.*	*CP violation*
$h \to \gamma\gamma, 2e\gamma, 2\mu\gamma$ $4e, 4\mu, 2e2\mu$	$\kappa_{ZZ}, \kappa_{Z\gamma}, \kappa_{\gamma\gamma}$ $\epsilon_{ZZ}, \epsilon_{Ze_L}, \epsilon_{Ze_R}$ (6)	$\epsilon_{Z\mu_L}, \epsilon_{Z\mu_R}$ (2)	$\epsilon^{CP}_{ZZ}, \epsilon^{CP}_{Z\gamma}, \epsilon^{CP}_{\gamma\gamma}$ (3)

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Decay modes	*flavor +CP symm.*	*flavor non univ.*	*CP violation*
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$h \to 2e2\nu, 2\mu2\nu, e\nu\mu\nu$	κ_{WW} (4) $\epsilon_{WW}, \epsilon_{Z\nu_e}, \mathrm{Re}(\epsilon_{We_L})$	$\epsilon_{Z\nu_\mu}, \mathrm{Re}(\epsilon_{W\mu_L})$	$\epsilon^{CP}_{WW}, \mathrm{Im}(\epsilon_{We_L})$ $\mathrm{Im}(\epsilon_{W\mu_L})$ (5)

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$h \to 2e2\nu, 2\mu2\nu, e\nu\mu\nu$	κ_{WW} (4) $\epsilon_{WW}, \epsilon_{Z\nu_e}, \mathrm{Re}(\epsilon_{We_L})$	$\epsilon_{Z\nu_\mu}, \mathrm{Re}(\epsilon_{W\mu_L})$	$\epsilon^{CP}_{WW}, \mathrm{Im}(\epsilon_{We_L})$ $\mathrm{Im}(\epsilon_{W\mu_L})$ (5)
all modes *with custodial symmetry*	$\kappa_{ZZ}, \kappa_{Z\gamma}, \kappa_{\gamma\gamma}$ $\epsilon_{ZZ}, \epsilon_{Ze_L}, \epsilon_{Ze_R}$ $\mathrm{Re}(\epsilon_{We_L})$ (7)	$\epsilon_{Z\mu_L}, \epsilon_{Z\mu_R}$	$\epsilon^{CP}_{ZZ}, \epsilon^{CP}_{Z\gamma}, \epsilon^{CP}_{\gamma\gamma}$

20 (no symmetries) → 7 (CP + Lepton Univ + Custodial)

The $h \to 4f$ case

N. independent PO for a complete description of $h \to 4\ell$ (ℓ=e,μ,ν) + $\ell\ell\gamma$ + $\gamma\gamma$, with or without specific symmetry assumptions:

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$h \to 2e2\nu, 2\mu 2\nu, e\nu\mu\nu$	κ_{WW} $\epsilon_{WW}, \epsilon_{Z\nu_e}, \mathrm{Re}(\epsilon_{We_L})$ (4)	$\epsilon_{Z\nu_\mu}, \mathrm{Re}(\epsilon_{W\mu_L})$	$\epsilon^{CP}_{WW}, \mathrm{Im}(\epsilon_{We_L})$ $\mathrm{Im}(\epsilon_{W\mu_L})$ (5)
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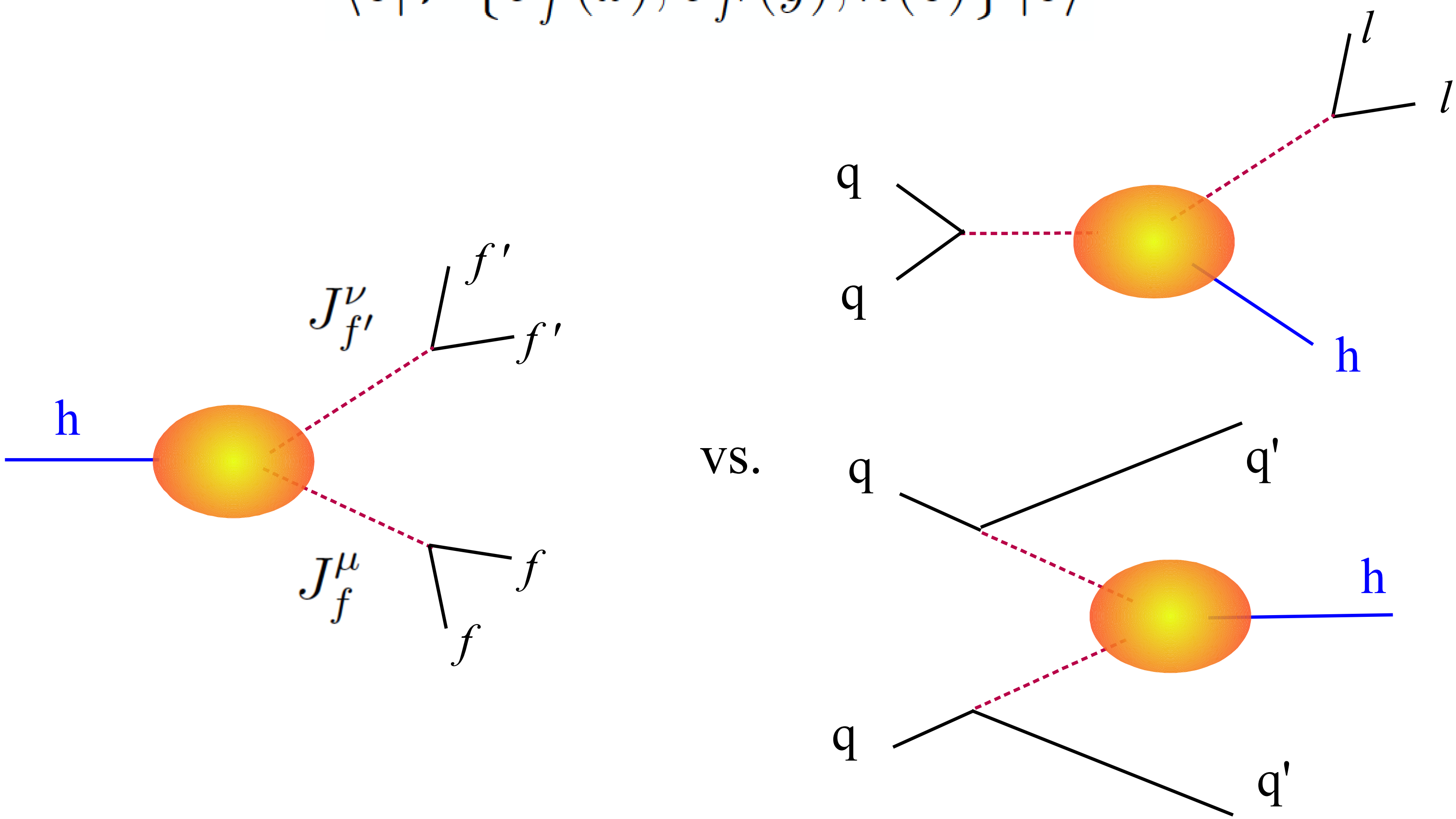
The symmetry assumptions can be directly tested from data, focusing on specific kinematical distributions sensitive to the relevant PO's [e.g. CPV-violating observables & LFU tests → key role played by the "contact terms" (ε_{Zl})]

▸ *PO in Higgs EW production*

The same Green Function controlling $h \to 4f$ decays is accessible also in $pp \to hV$ and $pp \to h$ via VBF, i.e. the two leading EW-type Higgs production processes (*N.B.: this follows from "plain QFT" no need to invoke any EFT...*)

$$\langle 0|\mathcal{T}\left\{J^{\mu}_{f}(x), J^{\nu}_{f'}(y), h(0)\right\}|0\rangle$$



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$$\langle 0|\mathcal{T}\left\{J^{\mu}_{f}(x), J^{\nu}_{f'}(y), h(0)\right\}|0\rangle$$

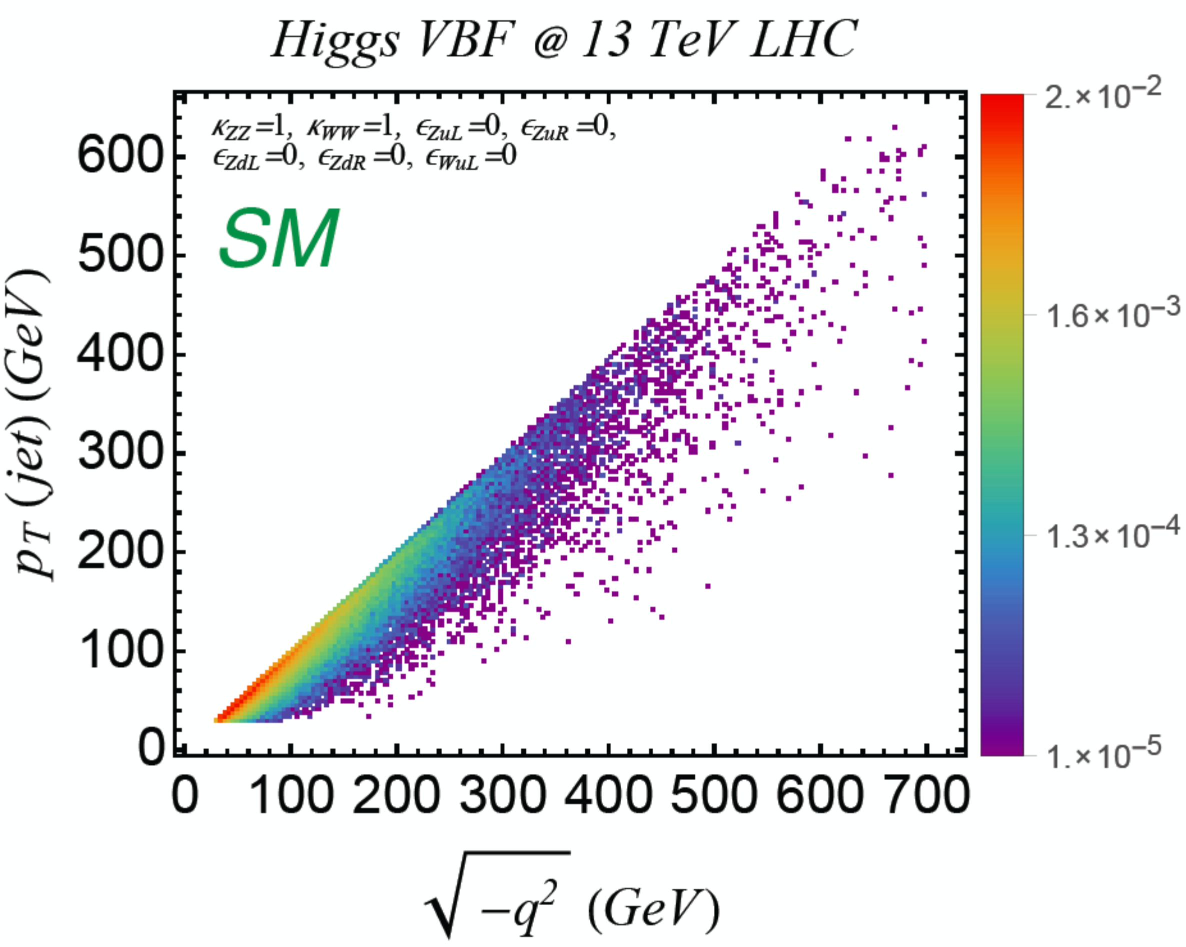
Same approach as in $h \to 4f$ (and, to some extent, same PO) but for three important differences:

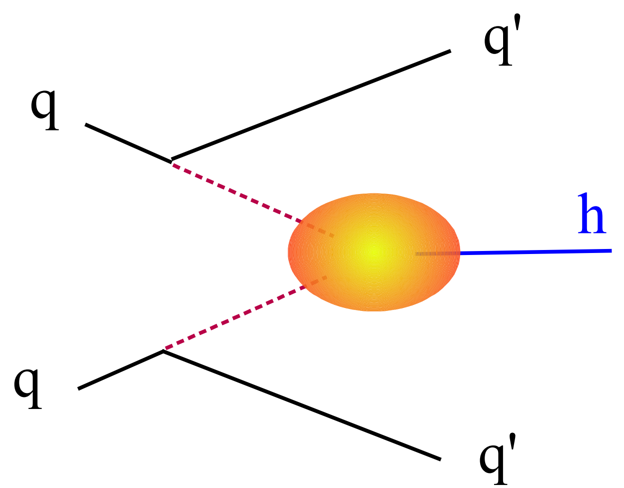
- different flavor composition ($q \leftrightarrow \ell$) $\to$ new param. associated to the physical PO $\Gamma(h \to Zqq)$ & $\Gamma(h \to Wud)$ — trivial
- large impact of (facotrizable) QCD corrections — conceptually easy
- different kinematical regime: momentum exp. not always justified (*large momentum transfer*) — delicate point

PO in Higgs EW production

Twofold problem:

I. identify which are the "dangerous" kinematical variables, and how to access them when not directly measurable → p_T^{jet} in VBF, p_T^Z in Zh





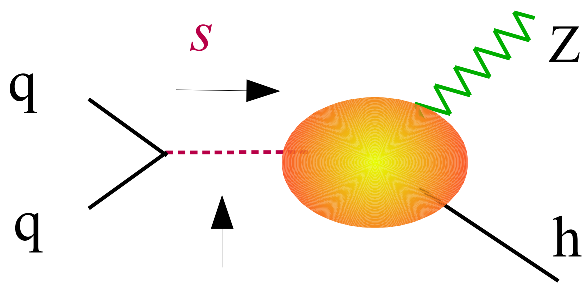
PO in Higgs EW production

Twofold problem:

I. identify which are the "dangerous" kinematical variables, and how to access them when not directly measurable → p_T^{jet} in VBF, p_T^Z in Zh

II. how to control the validity of the expansion

E.g.: $pp \to Zh$



$$s = (m_{hZ})^2$$

$$\frac{1}{s - m_Z^2} \left[g^Z_q \, \kappa_{ZZ} + \varepsilon_{Zq} (s - m_Z^2)/m_Z^2 + \ldots \right]$$

Key point: since we expand on a measurable kinematical variable, <u>the validity of the expansion can be directly checked/validated by data</u>

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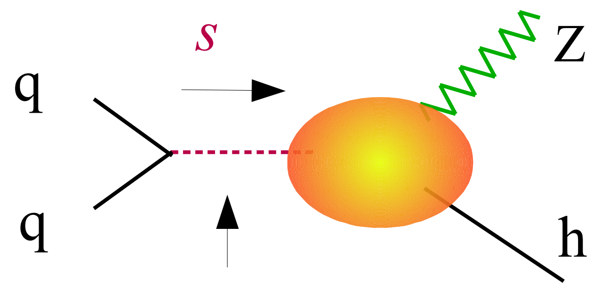

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$$\frac{1}{s - m_Z^2} \left[g^Z_q \, \kappa_{ZZ} + \epsilon_{Zq} (s - m_Z^2)/m_Z^2 + \ldots \right]$$

General procedure:

- Measure the PO setting close to the threshold region, setting a cut on the “dangerous” kinematical variable [→ a-posteriori data-driven check of the validity of the momentum expansion = definition of a “threshold region”]
- Report the cross-section as a function of the kinematical variable in the high-momentum region [→ natural link/merging with template cross-section method]

PO in Higgs EW production

Number of independent PO for EW Higgs decays + EW production + Yukawa modes (h → ff):

	PO with maximal symmetry [CP + Lepton Univ + Custodial]:
Production & decays	$\kappa_{ZZ}, \kappa_{Z\gamma}, \epsilon_{ZZ}$
EW decays only	$\kappa_{\gamma\gamma}, \epsilon_{Ze_L}, \epsilon_{Ze_R}, \mathrm{Re}(\epsilon_{We_L})$
EW productions only	$\epsilon_{Zu_L}, \epsilon_{Zu_R}, \epsilon_{Zd_L}, \epsilon_{Zd_R}$
	(11) [→ 32 with no symm.]
Yukawa modes	$\kappa_b, \kappa_c, \kappa_\tau, \kappa_\mu$ (4) [→ 8 with no symm.]
	(*as in the original κ-formalism*)

The EFT approach to Higgs physics vs. PO

PO and couplings in EFT Lagrangians are *intimately related but are not the same thing* (on-shell amplitudes vs. Lagrangians parameters) → full complementarity

When discussing EFT approaches to Higgs physics it is worth stressing there is not a unique way to proceed:

I. Nature of the "light fields"

II. Symmetries of the theory

III. Validity regime of the EFT

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- **Linear EFT**: h(125) embedded in the $SU(2)_L$ doublet ϕ (SM limit for $\Lambda \to \infty$)
- **Non-linear EFT**: h(125) is $SU(2)_L$ singlet + 3 Goldstones ($\Lambda \lesssim 4\pi v \sim 3$ TeV)

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II. Symmetries of the theory → Custodial symmetry, CP invariance, Flavor symmetries,... (all the accidental symmetries of the SM)

III. Validity regime of the EFT → Hopefully dictated by data, but so far unclear

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- The PO are calculable in any EFT approach (*linear, non-linear, LO, NLO...*)
  - In the limit where we work at the tree-level in the EFT there is a simple linear relation between PO and EFT couplings: each PO represent a unique linear combination of couplings of the most general Higgs EFT.
  - This does not hold beyond the tree-level (the PO do not change, but their relation to EFT couplings is more involved....)

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  - This does not hold beyond the tree-level (the PO do not change, but their relation to EFT couplings is more involved....)

- For Higgs production also the PO involve an expansion in momenta; however, this is different that the operator expansion employed within the EFT
  - To define the PO we expand only on a measurable kinematical variables, this is why the validity of the *expansion can be checked directly by data* (on the same process used to determine the PO)

- In each process the PO are the maximum number of independent observables that can be extracted by that process only → naturally optimized for data analyses

The EFT approach to Higgs physics vs. PO

Computing the PO in specific EFT (e.g.: *the linear EFT*) we get additional dynamical constraints dictated by the specific extra dynamical assumption of the EFT employed (e.g.: *h belongs to the $SU(2)_L$ doublet breaking the EW symmetry*)

The most powerful of such constraints is the link between the contact terms and EW precision measurements performed at LEP:

EPWO + Linear EFT → small (tiny) & flavor-universal ε_{Zl}

↓

Excellent opportunity to test from data (via $h \to 4l$)
if h belongs to a pure $SU(2)_L$ doublet

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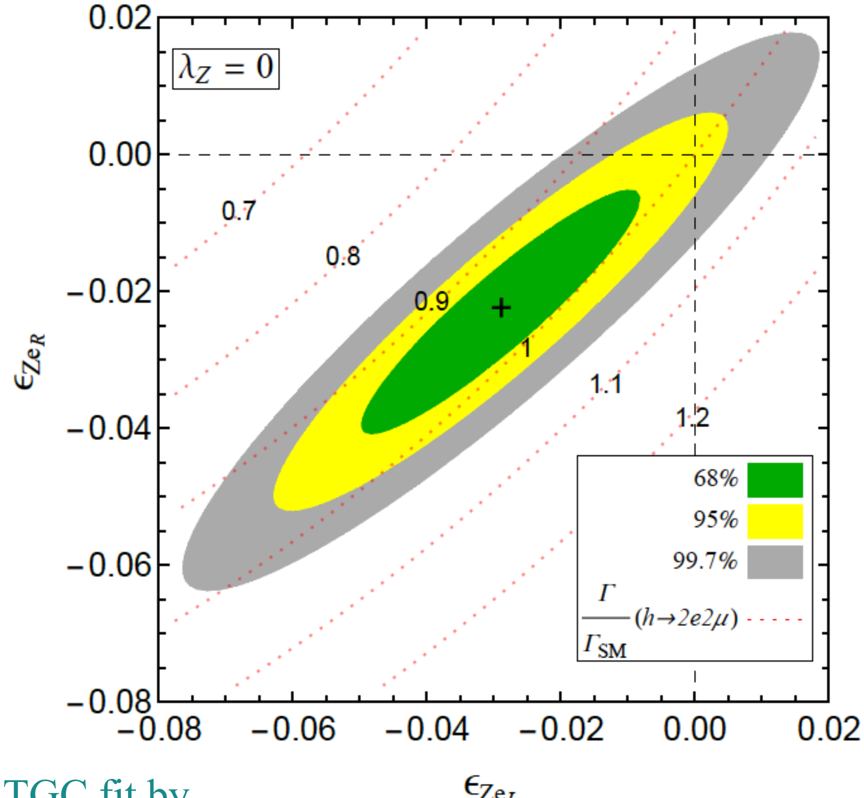
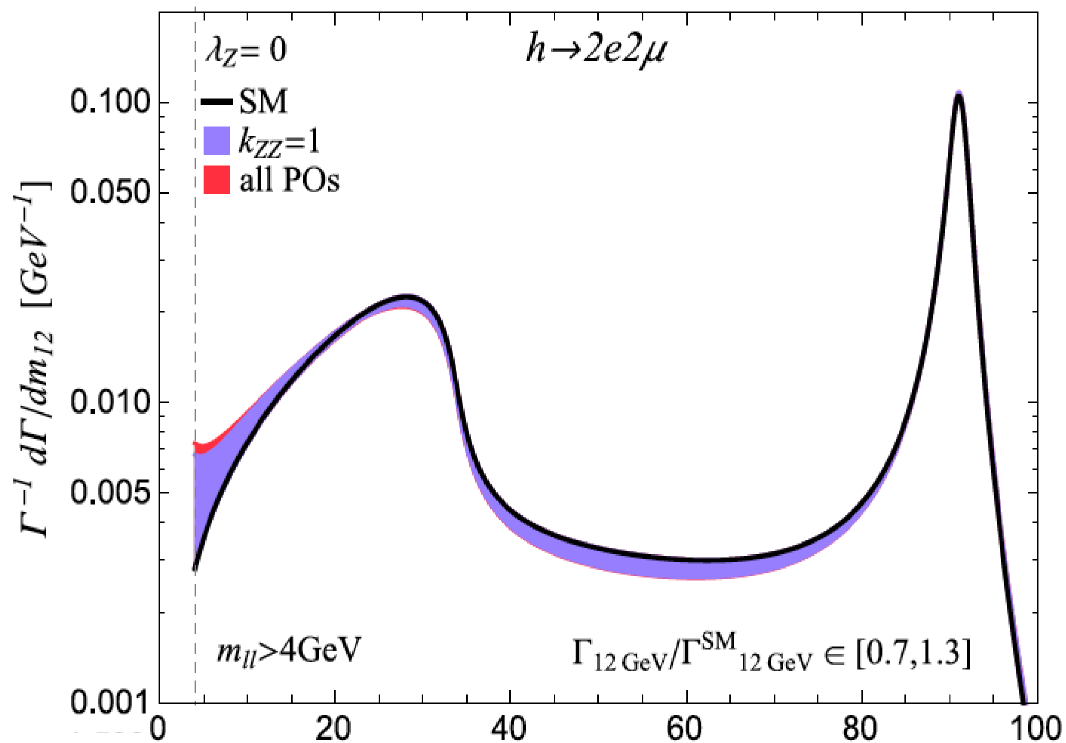


TGC fit by Falkowski & Riva, 1411.0669



Gonzales-Alonso et al. arXiv:1504.04018

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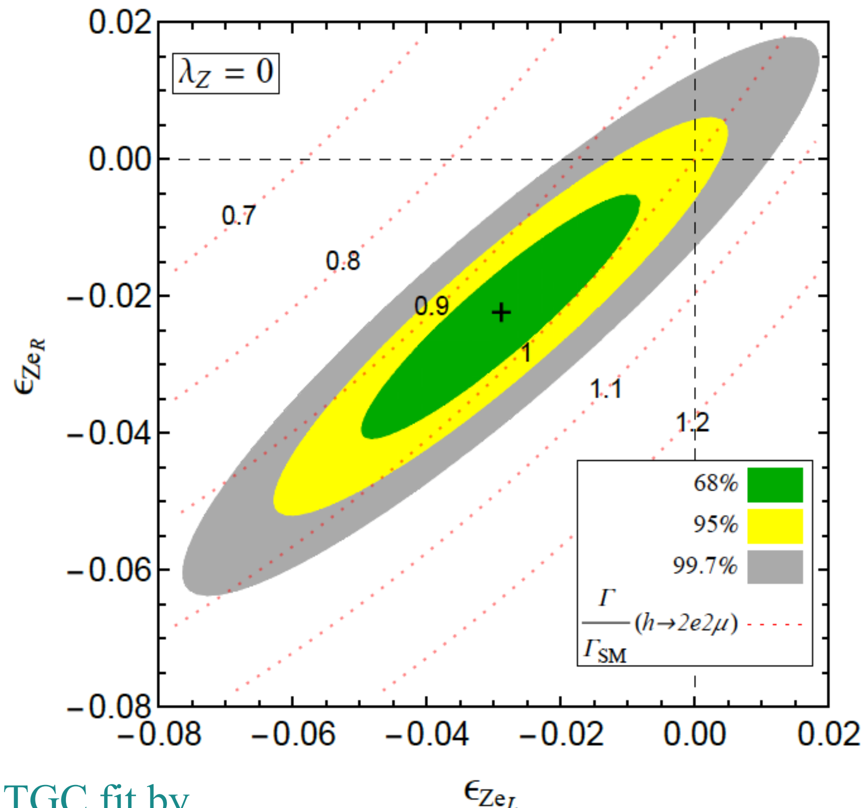

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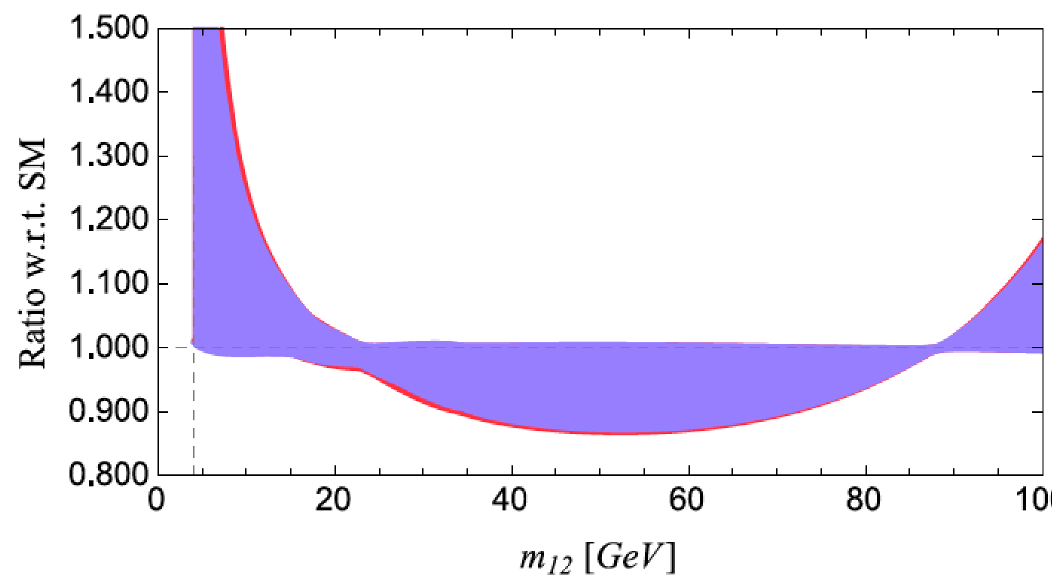

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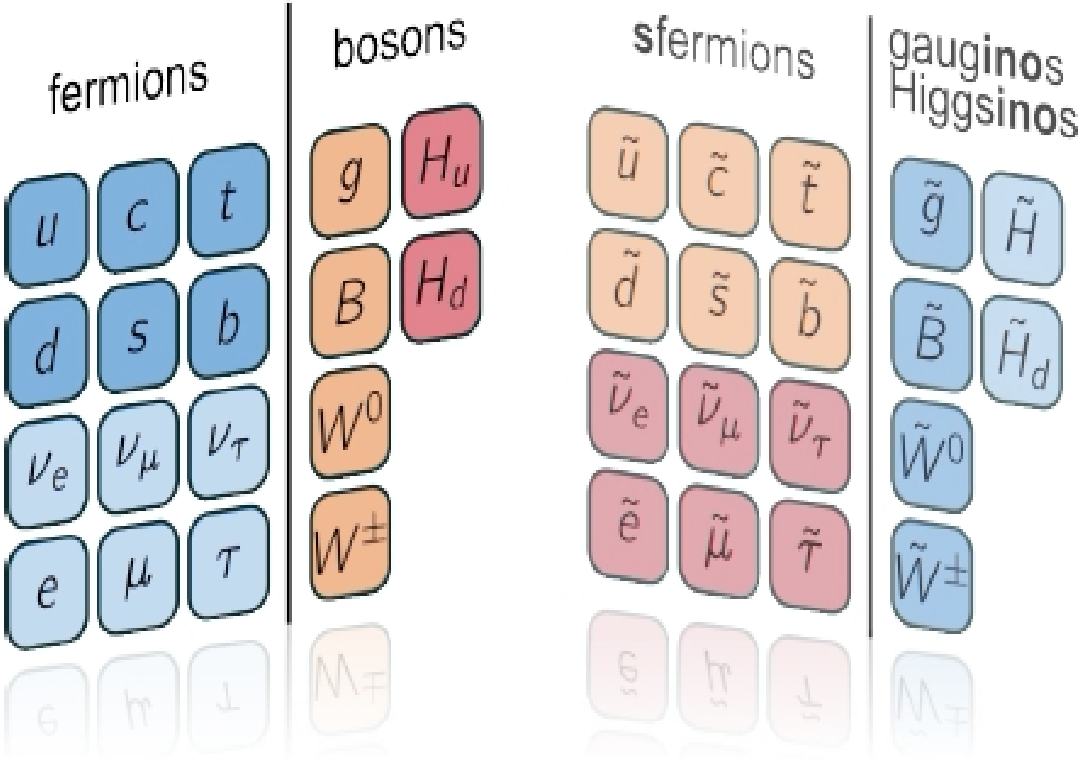
The most powerful of such constraints is the link between the contact terms and EW precision measurements performed at LEP.

Maim message: full complementary between PO approach and EFT.

- PO → inputs for EFT coupling fits
- EFT → predictions of relations between different PO sets (that can be tested)

SUSY


fermions
bosons
sfermions
gauginos
Higgsinos
u c t
d s b
ν_e ν_μ ν_τ
e μ τ
g H_u
B H_d
W^0
$W^\pm$
$\tilde{u}$ $\tilde{c}$ $\tilde{t}$
$\tilde{d}$ $\tilde{s}$ $\tilde{b}$
$\tilde{\nu}_e$ $\tilde{\nu}_\mu$ $\tilde{\nu}_\tau$
$\tilde{e}$ $\tilde{\mu}$ $\tilde{\tau}$
$\tilde{g}$ $\tilde{H}$
$\tilde{B}$ $\tilde{H}_d$
$\tilde{W}^0$
$\tilde{W}^\pm$

SUSY

Despite we have not seen any super-partner yet... low-energy SUSY remains one of the most interesting and more motivated extensions of the SM

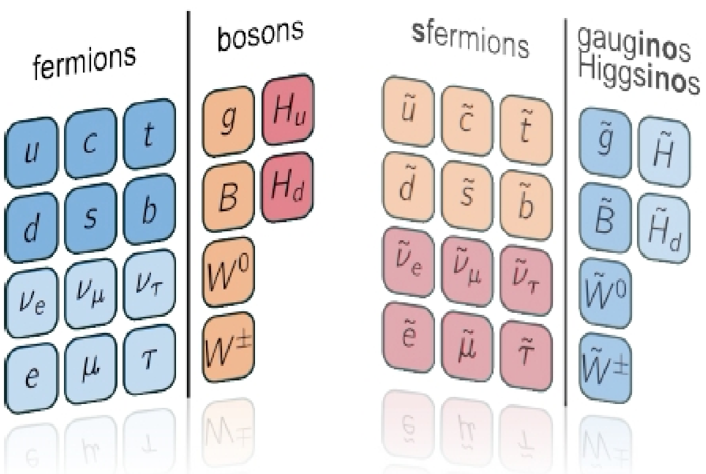
Basic principles of SUperSYmmetry:

$$Q|\text{fermion}\rangle = |\text{boson}\rangle$$
$$Q|\text{boson}\rangle = |\text{fermion}\rangle$$

$$\{Q, Q^+\} = P^\mu$$
$$\{Q, Q\} = \{Q^+, Q^+\} = 0$$
$$[Q, P^\mu] = [Q^+, P^\mu] = 0$$

~~The anthropic principle~~
~~"*Darwinism in physics...*"~~

New symmetries (& new dynamics)
"*The Galilean way...*"



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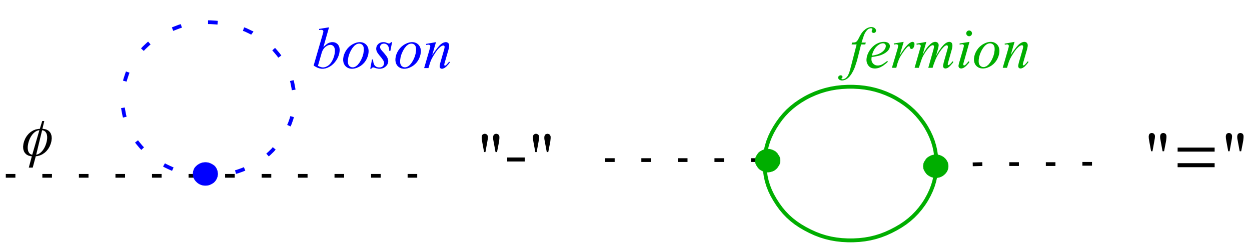
$$\{Q, Q^+\} = P^\mu$$
$$\{Q, Q\} = \{Q^+, Q^+\} = 0$$
$$[Q, P^\mu] = [Q^+, P^\mu] = 0$$

Very appealing idea from a pure theoretical point of view (*largest symmetry allowed in a QFT, connection with gravity*) with a very appealing phenomenological virtue:



no quadratic divergences
[natural solution for one of the main SM problems]

$$\Delta\mu^2 \sim \frac{g^2}{16\pi^2}[M_b^2 - M_f^2]$$

⇒ No (*or at least reduced...*) fine-tuning in m_h if SUSY breaking occurs not far from the e.w. scale [= low-energy SUSY]

SUSY

The price to pay for the *stabilization* of the hierarchy problem is non trivial (both in terms of particle content & in terms of free parameters)...

The Minimal Supersymmetric extension of the SM requires more than a doubling of the particle spectrum so far observed:

- scalar partners of the ordinary quarks and leptons [$\tilde{Q}_L$, $\tilde{u}_R$, ...]
- spin-1/2 partners of the ordinary gauge bosons [*gauginos*]
- Two Higgs doublets [H_U, H_D] with their corresponding spin-1/2 partners

The presence of (at least) two Higgs doublets is mandatory: cancellation of triangular gauge anomalies induced by the higgsinos ⊕ analiticity of the superpotential

... but to two very interesting feautres are obtained as by products:

- gauge coupling unification
- dark matter candidate [Lightest Supersymmetry Particle, assuming R-parity]

Higgs and SUSY

In the ideal limit of unbroken SUSY, all the non-gauge interactions of the MSSM are described by a single mass parameter + 3 Yukawa matrices (~SM):

$$W_{\mathrm{MSSM}} = \mu\, \Phi_{\mathrm{U}} \Phi_{\mathrm{D}} \quad + \quad \text{Yukawa terms}$$

With the inclusion of the (soft) SUSY breaking terms [not fixed a priori by symmetry/theory arguments other than "soft-breaking"] the number of free parameters increase drastically in the squark/slepton sector, while the pure Higgs sector maintains a rather simple structure:

$$V^{tree}_{Higgs} = m_1^2\, |H_U|^2 + m_2^2\, |H_D|^2 + B^2\, (H_D H_U + \text{h.c.}) + \tfrac{1}{8}\,(g_1^2+g_2^2)\,(|H_U|^2-|H_D|^2\,)^2 + \tfrac{1}{2}\, g_2^2\, |H_D H_U|^2$$

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$$+ \frac{1}{8}(g_1^2+g_2^2)\,(|H_U|^2-|H_D|^2)^2 + \frac{1}{2}\, g_2^2\, |H_D H_U|^2$$

3 unknown couplings

The Higgs quartic couplings are unambiguously fixed in terms of the gauge couplings [SUSY constraint]

$$v^2 = \langle H_U\rangle^2 + \langle H_D\rangle^2 = 246 \text{ GeV}$$
$$M_A, \quad \tan\beta = \langle H_U\rangle / \langle H_D\rangle$$

Higgs and SUSY

A light Higgs is one of the key predictions of the MSSM...

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$$\downarrow$$

$$m_h^{tree} < |\cos(2\beta)|\, m_Z$$

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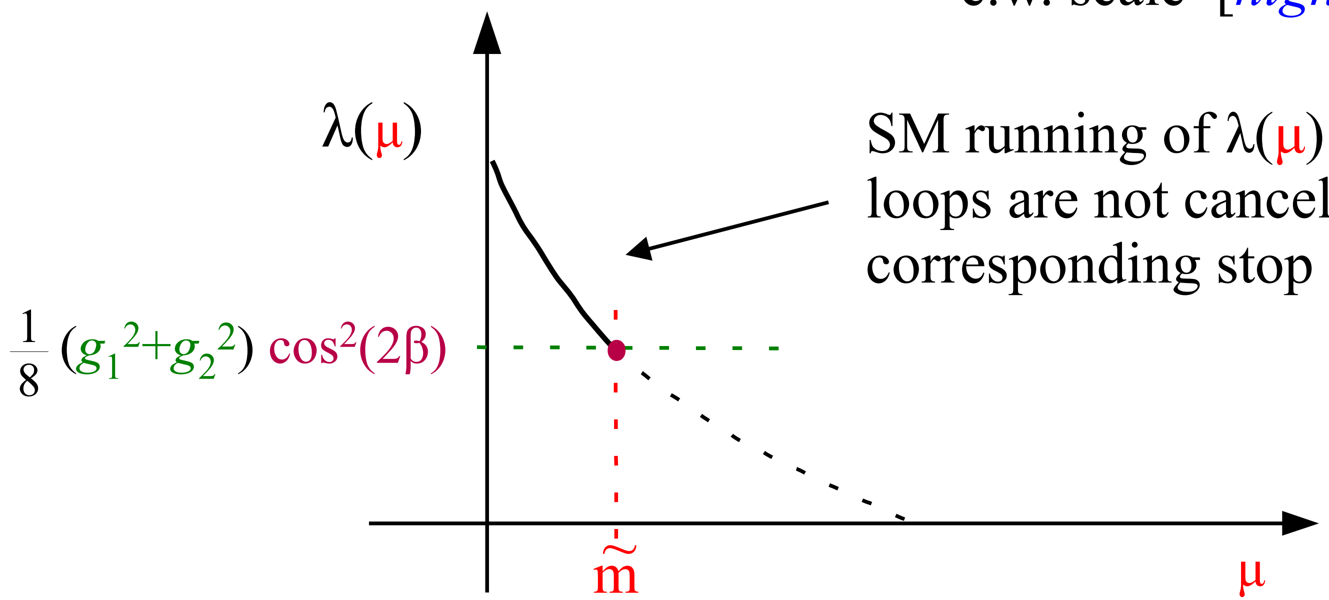
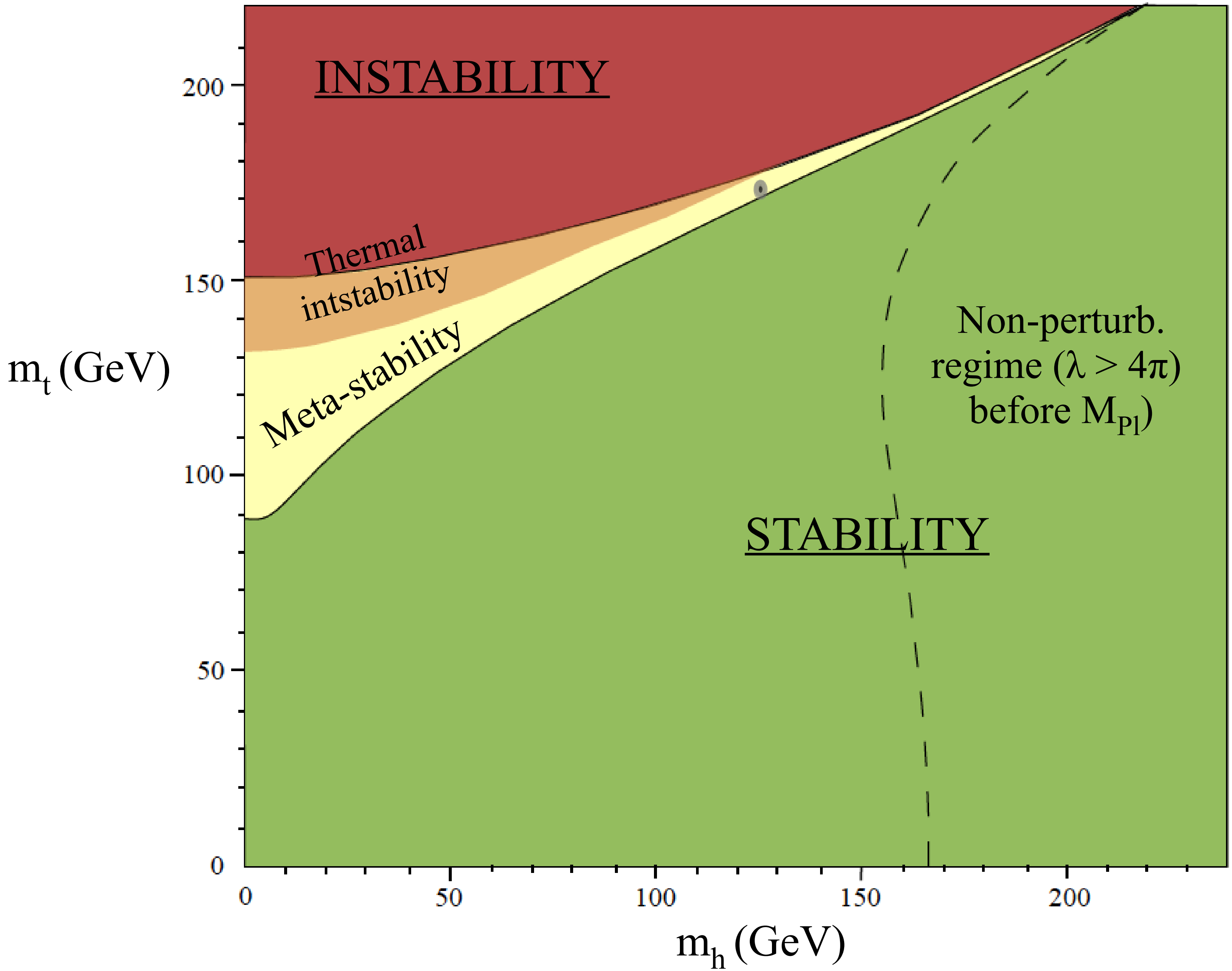
$$m_h^{tree} < |\cos(2\beta)|\, m_Z$$

This prediction is significantly modified if SUSY partners appear well above the e.w. scale [*high-scale*, *split*, *mini-split*...]

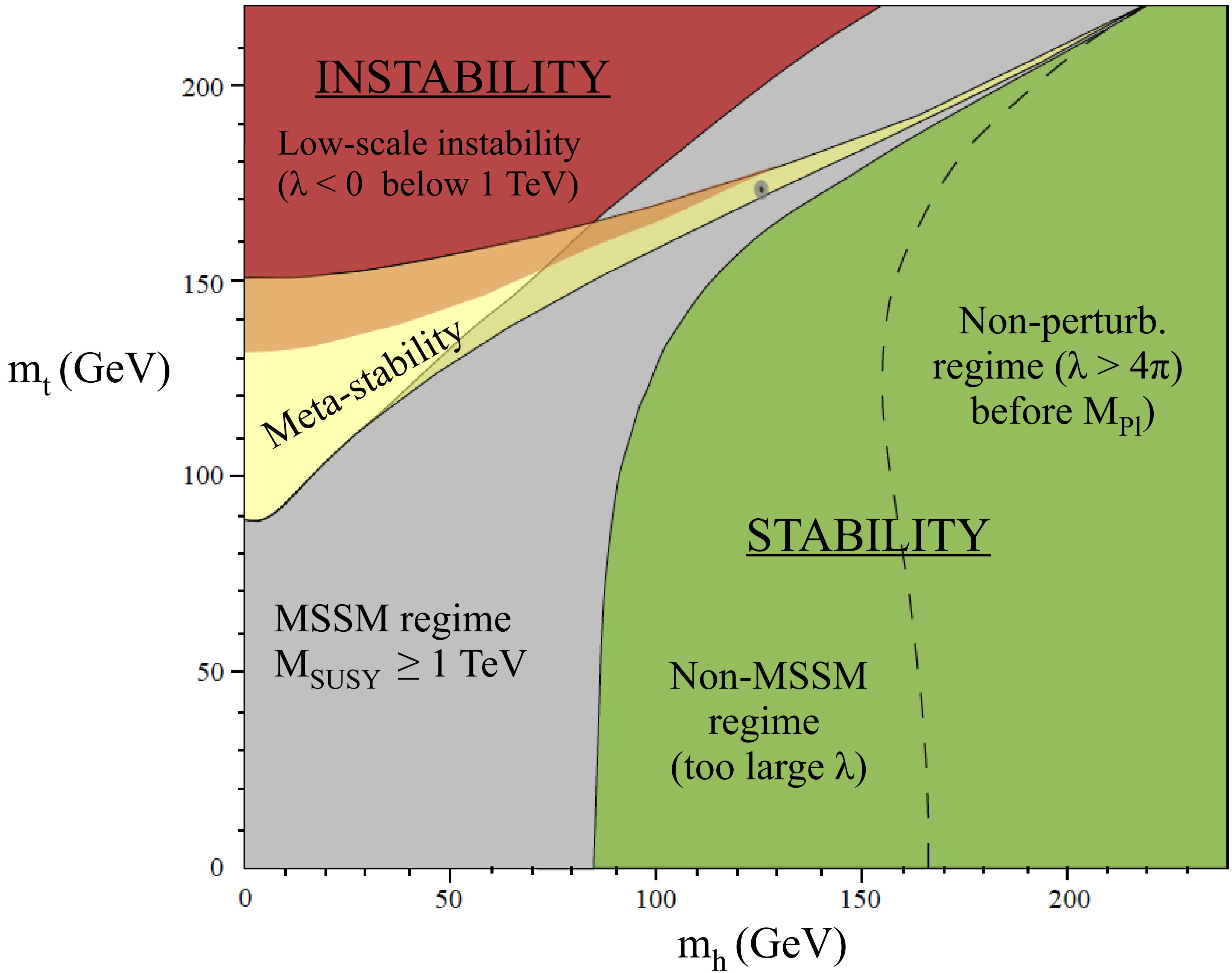


SM running of $\lambda(\mu)$ if top and Higgs loops are not canceled by corresponding stop and higgsino loops

Higgs and SUSY



Higgs and SUSY



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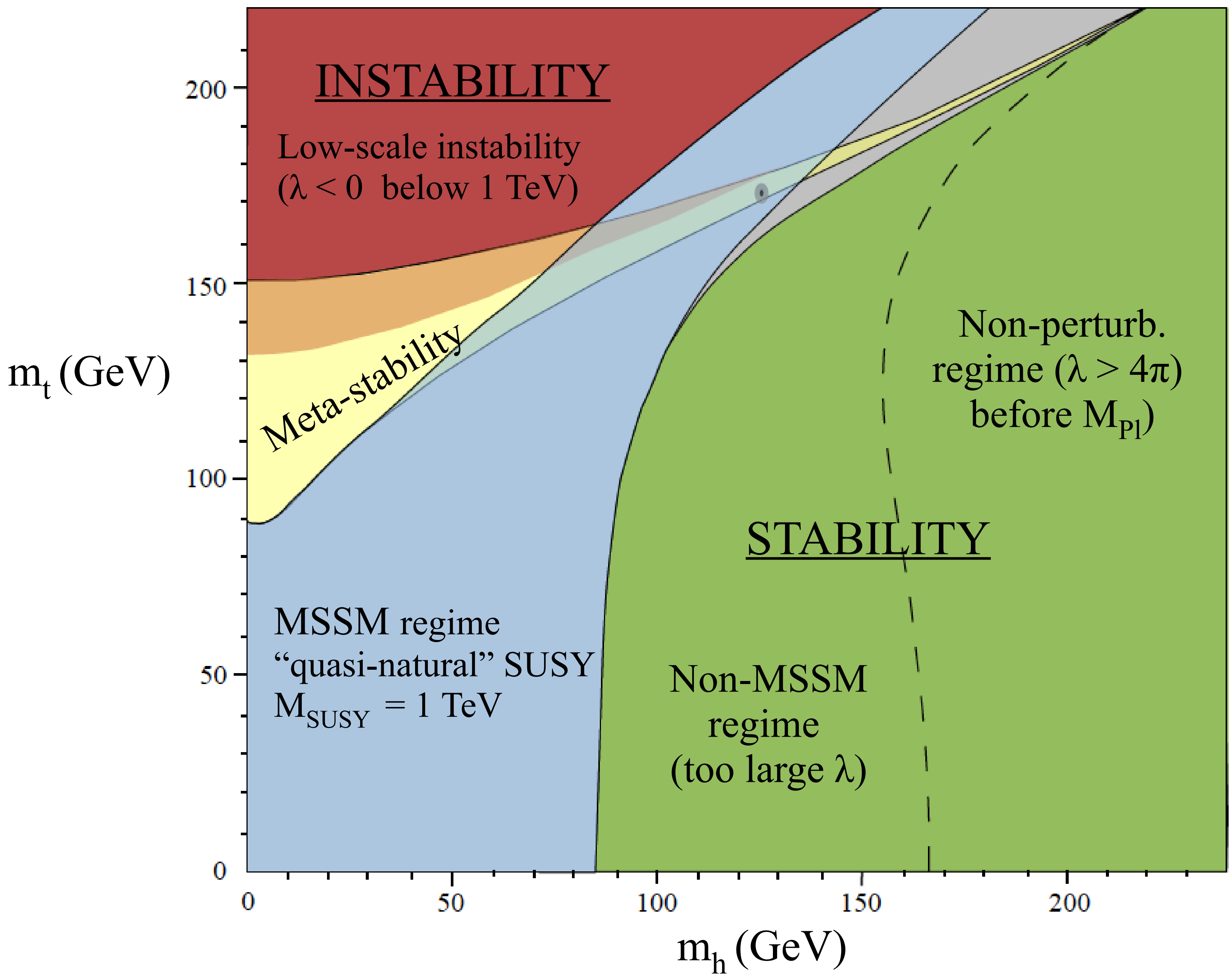
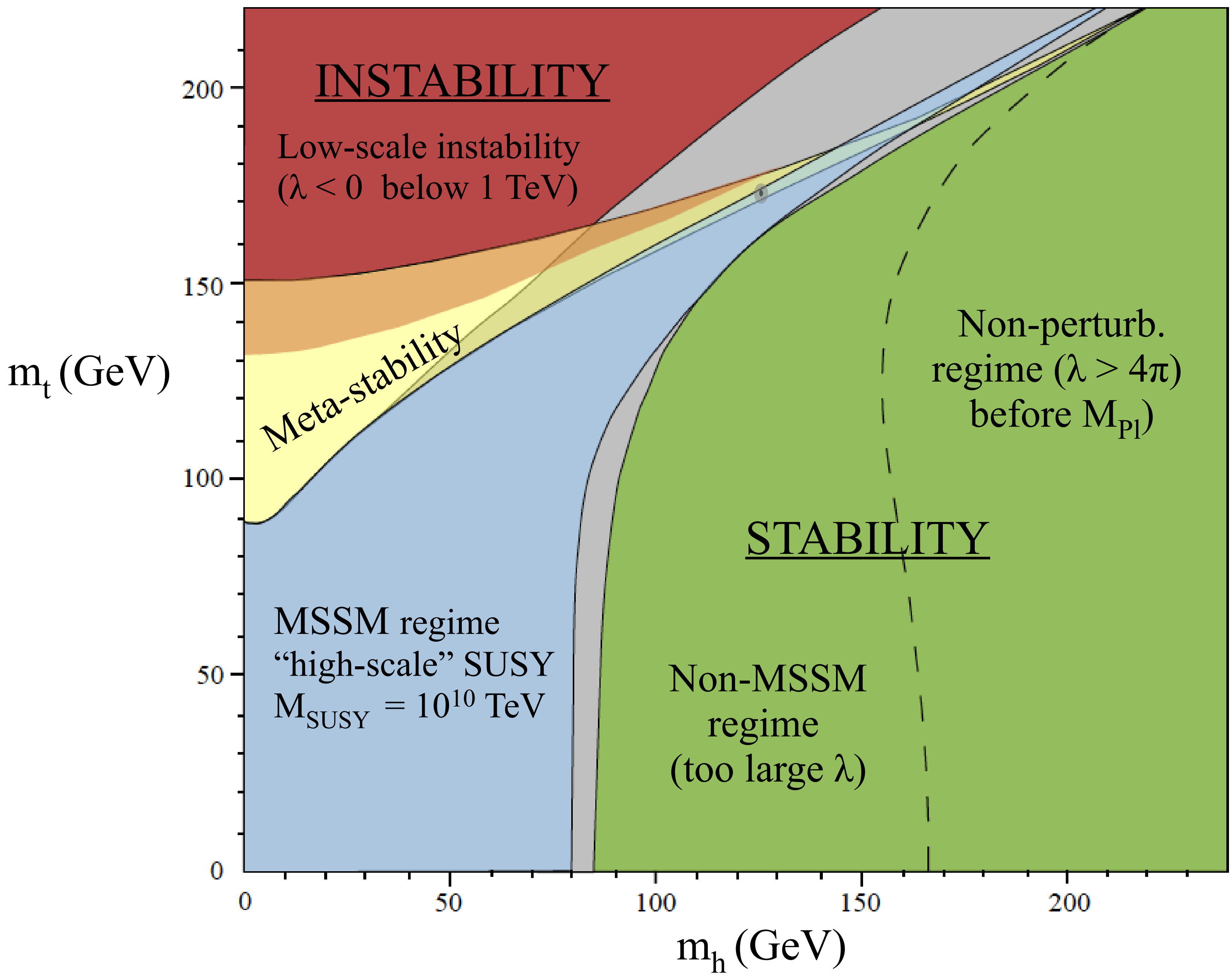
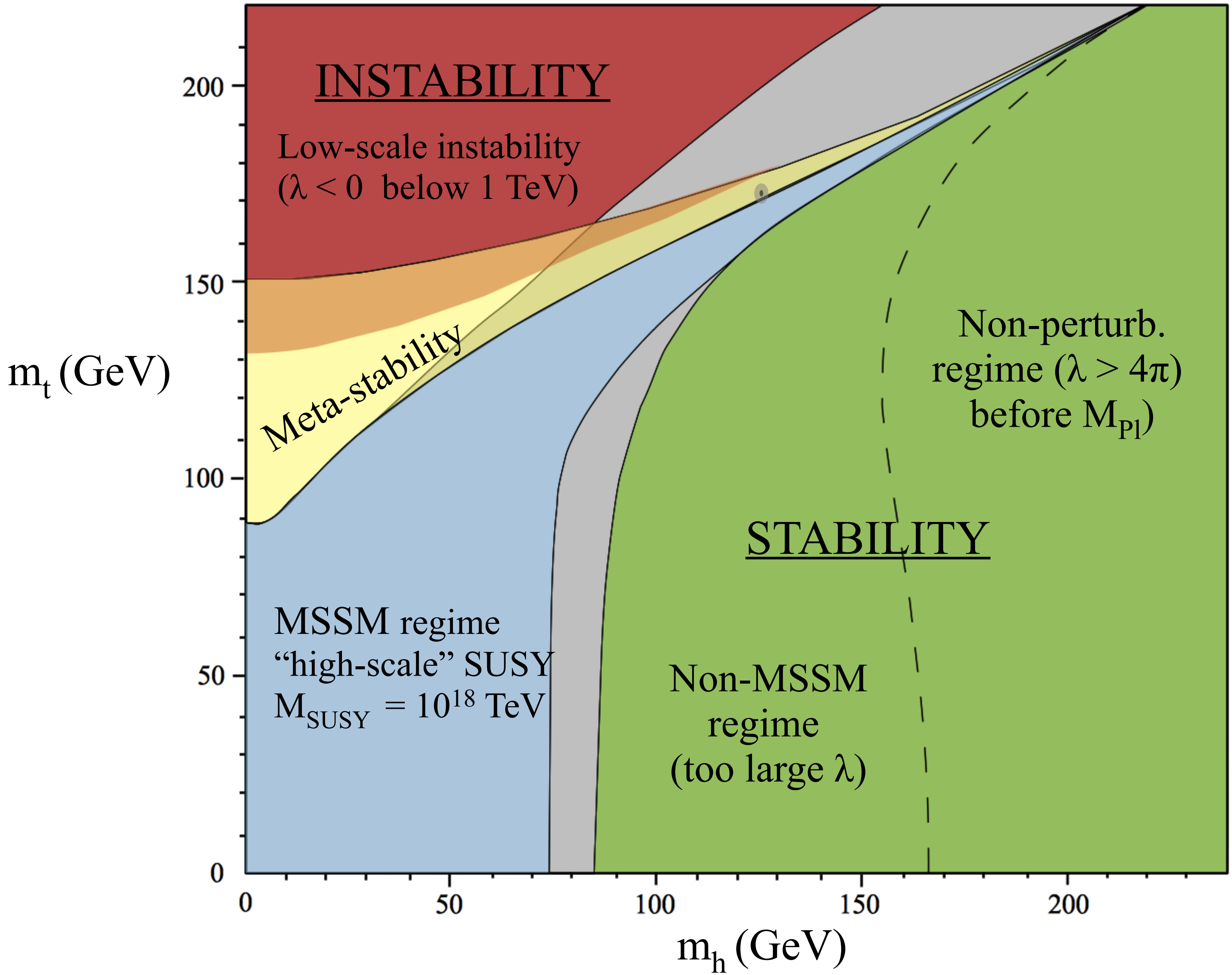


Higgs and SUSY

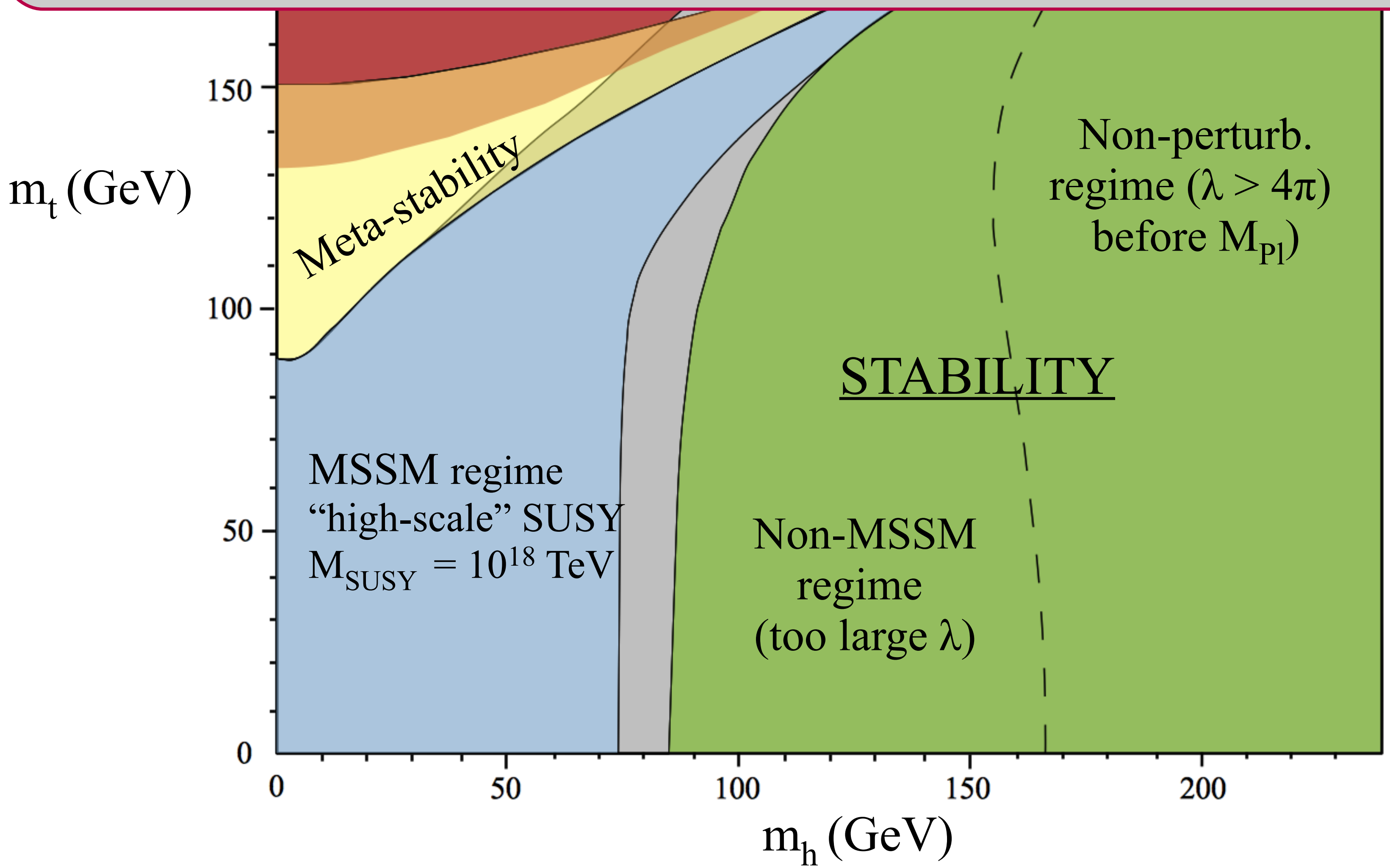


Higgs and SUSY

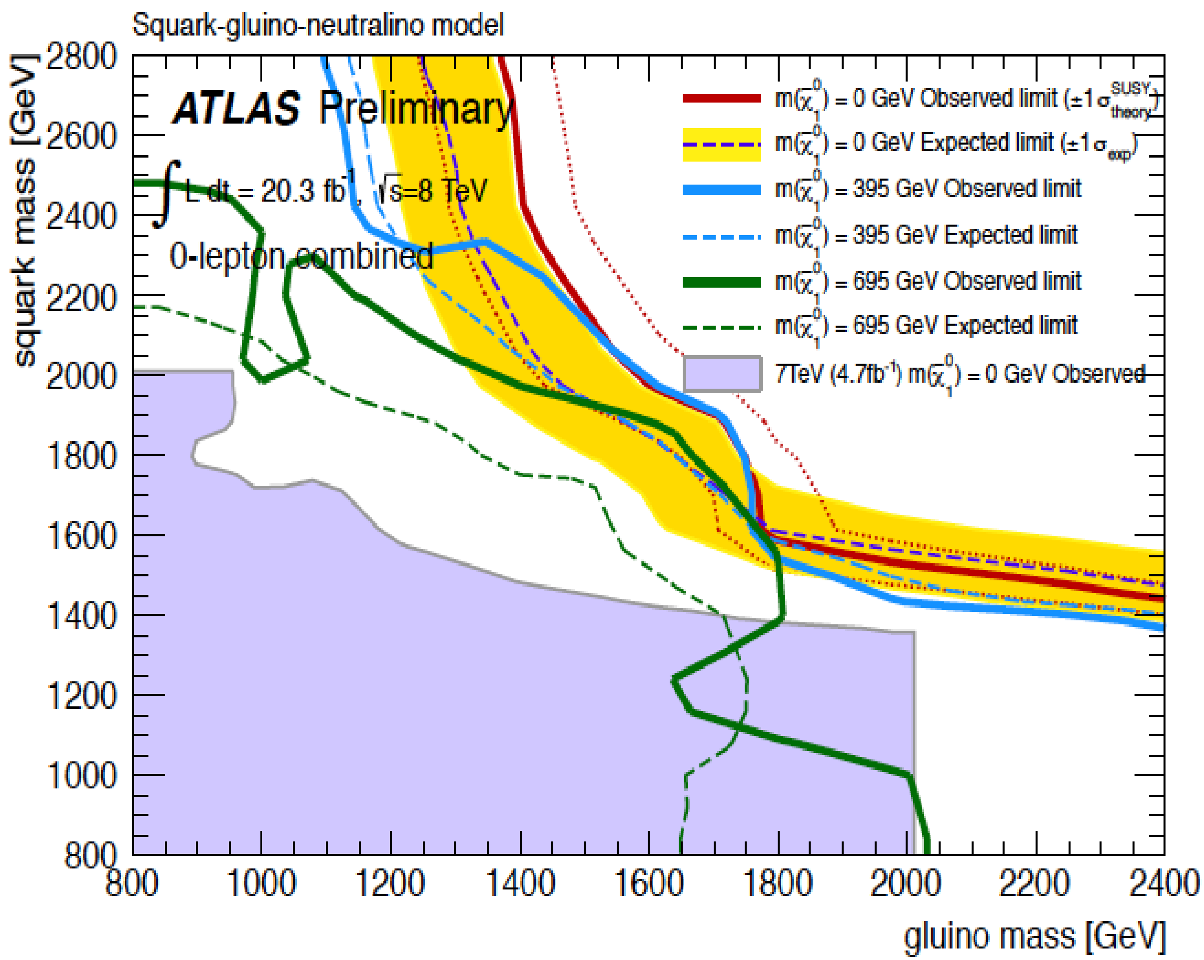


Higgs and SUSY

Main message: A light SM-like Higgs with $m_h \approx$ 125-126 GeV fits very well with SUSY, but it gives no clear clues about the SUSY breaking scale (beside excluding a too-light SUSY spectrum, in agreement with direct searches)



Few comments on direct SUSY searches



Present bounds in the SUSY context:

- Gluinos and 1st -2nd generation squarks above ~ 1.5 TeV

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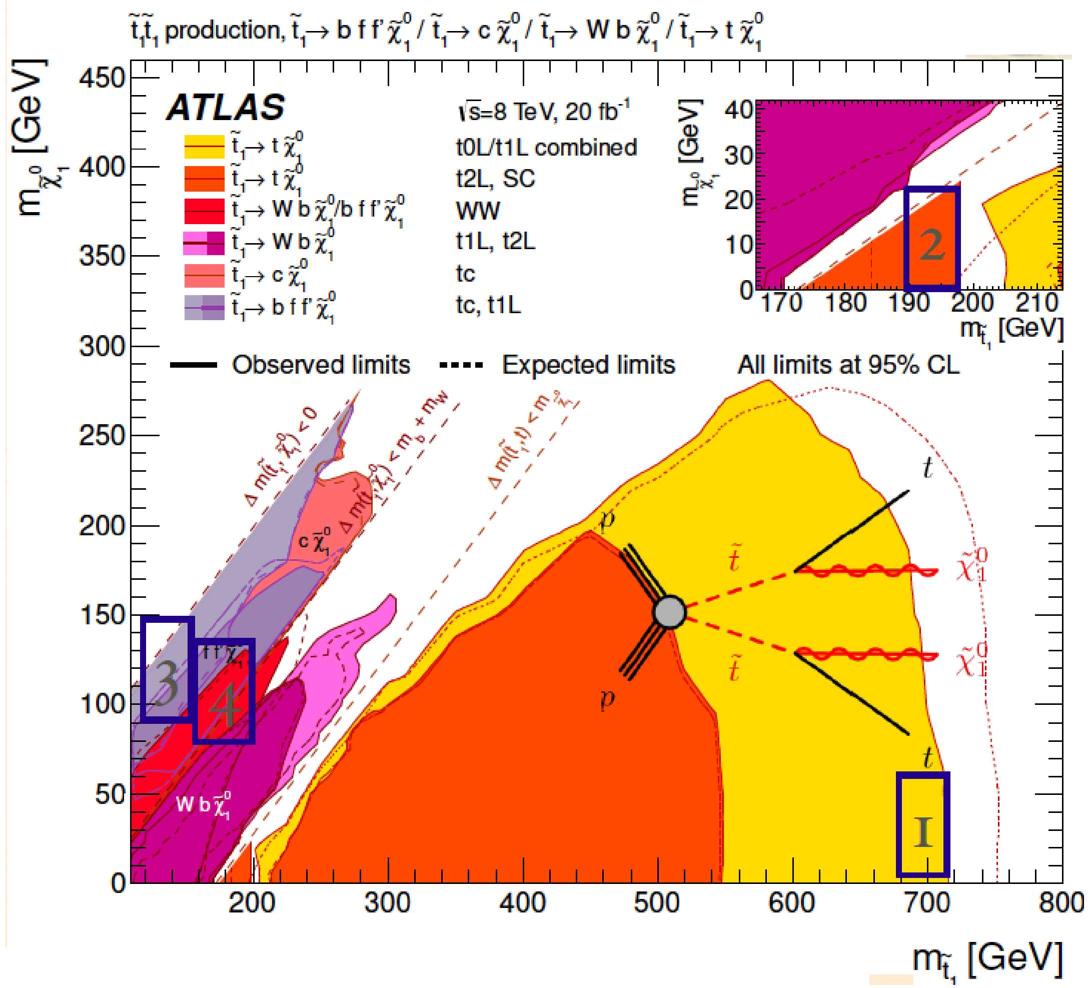

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- Gluinos and 1st -2nd generation squarks above ~ 1.5 TeV
- Colored new states coupled only to 3rd gen. quarks still allowed below 1 TeV

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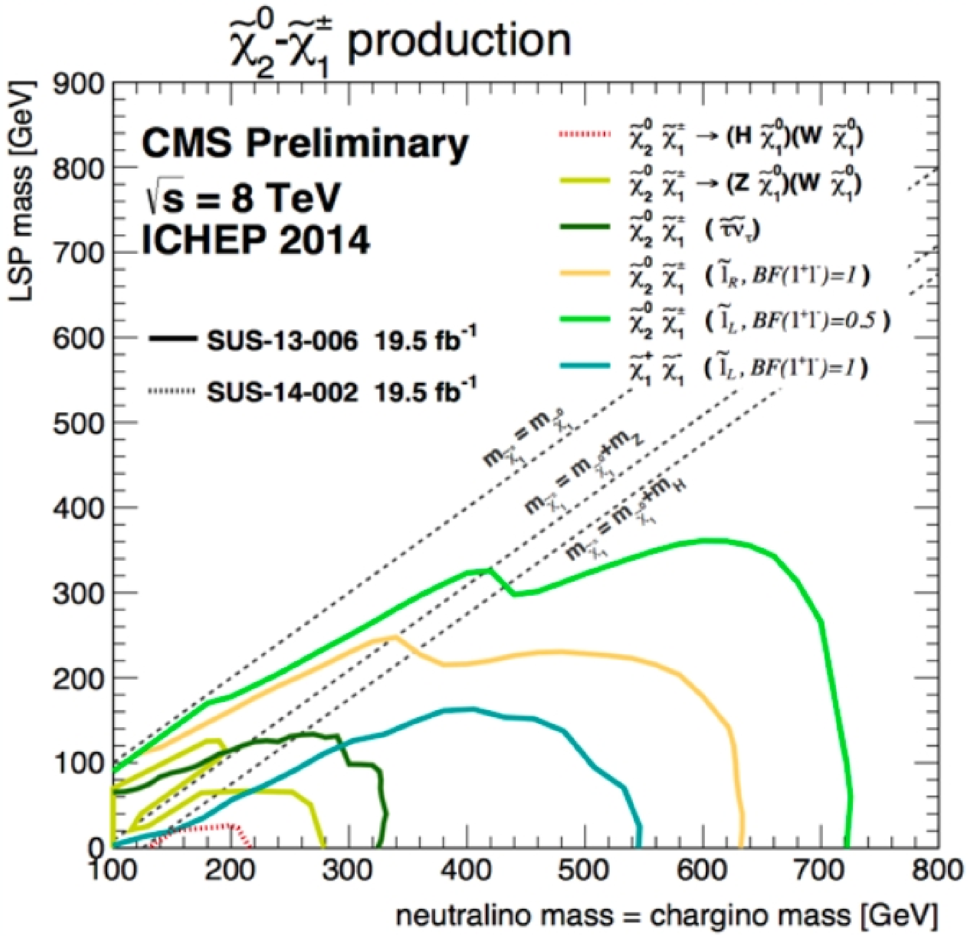
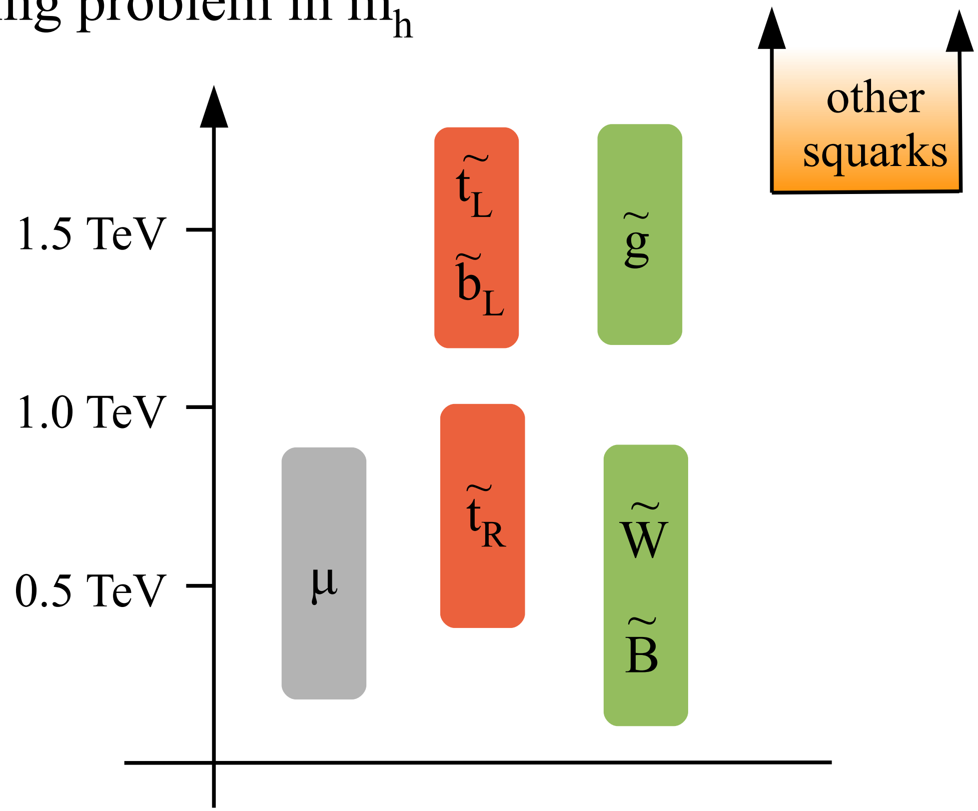


Present bounds in the SUSY context:

- Gluinos and 1st -2nd generation squarks above ~ 1.5 TeV
- Colored new states coupled only to 3rd gen. quarks still allowed below 1 TeV
- Bounds on colorless new states still in the few 100 GeV domain

Few comments on direct SUSY searches

Possible SUSY spectrum still compatible with present data that minimizes the fine-tuning problem in m_h



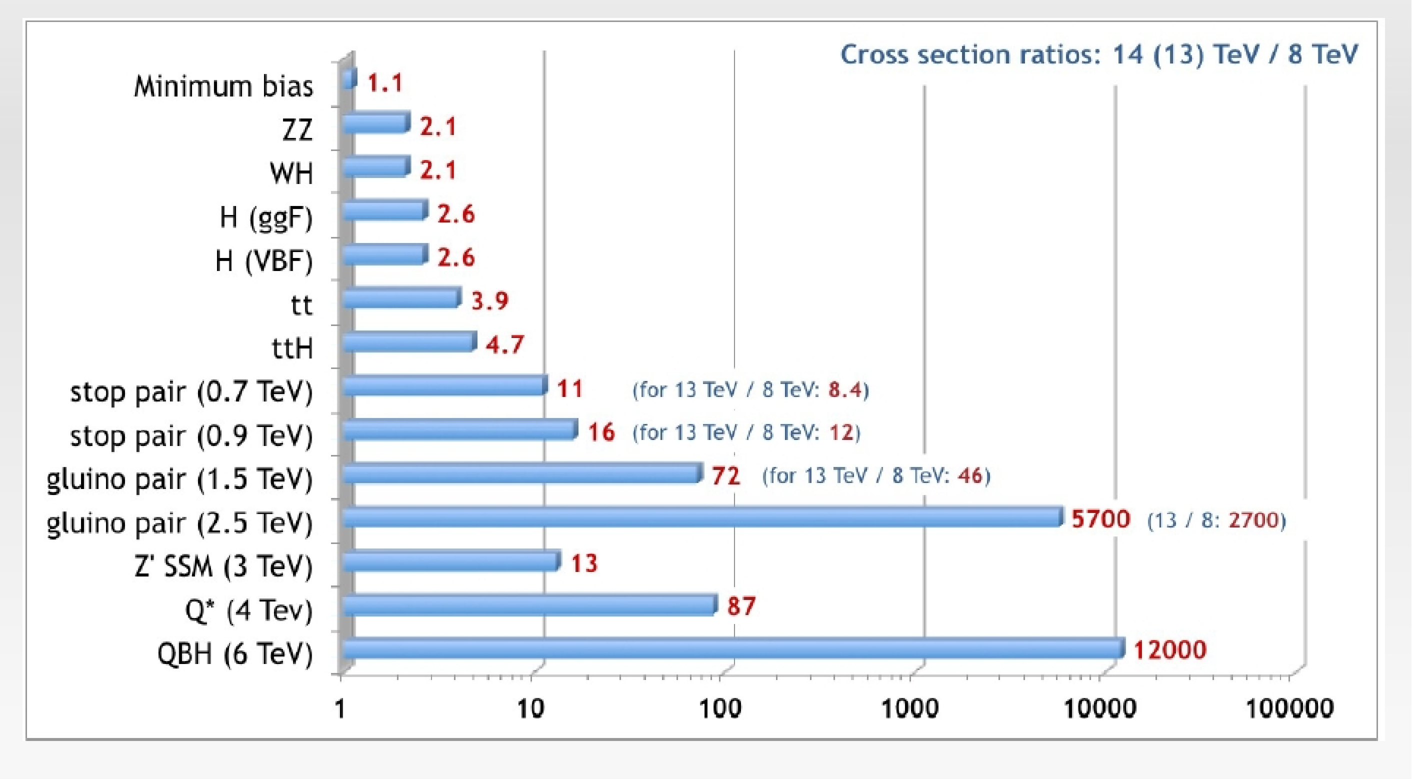
"Split-family" SUSY

Dimopulos, Giudice, '95
Cohen, Kaplan, Nelson '96
+ many others...

- Only 3rd gen. squarks + Higgsinos need to be "light" to minimize the tuning in m_h
- A large stop-mixing term is needed to explain $m_h \sim 125$ GeV → large splitting among the stops → one of the two mass eigenstates (*an almost RH stop*) could be below 1 TeV, with all other colored states above 1 TeV

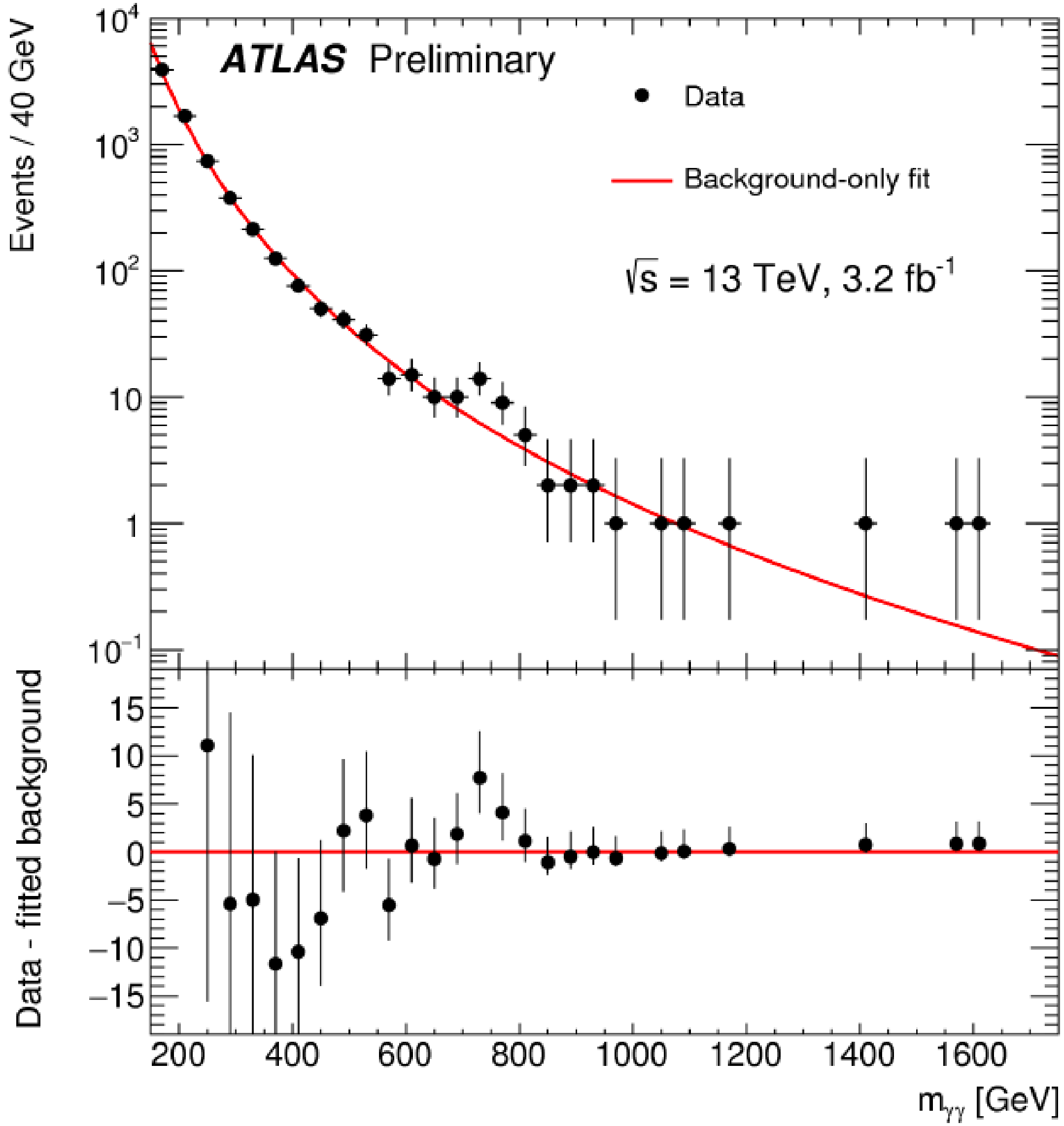
Few comments on direct SUSY searches

Well-motivated scenarios such as *"split-family SUSY"* could be well within the reach of the 14TeV run



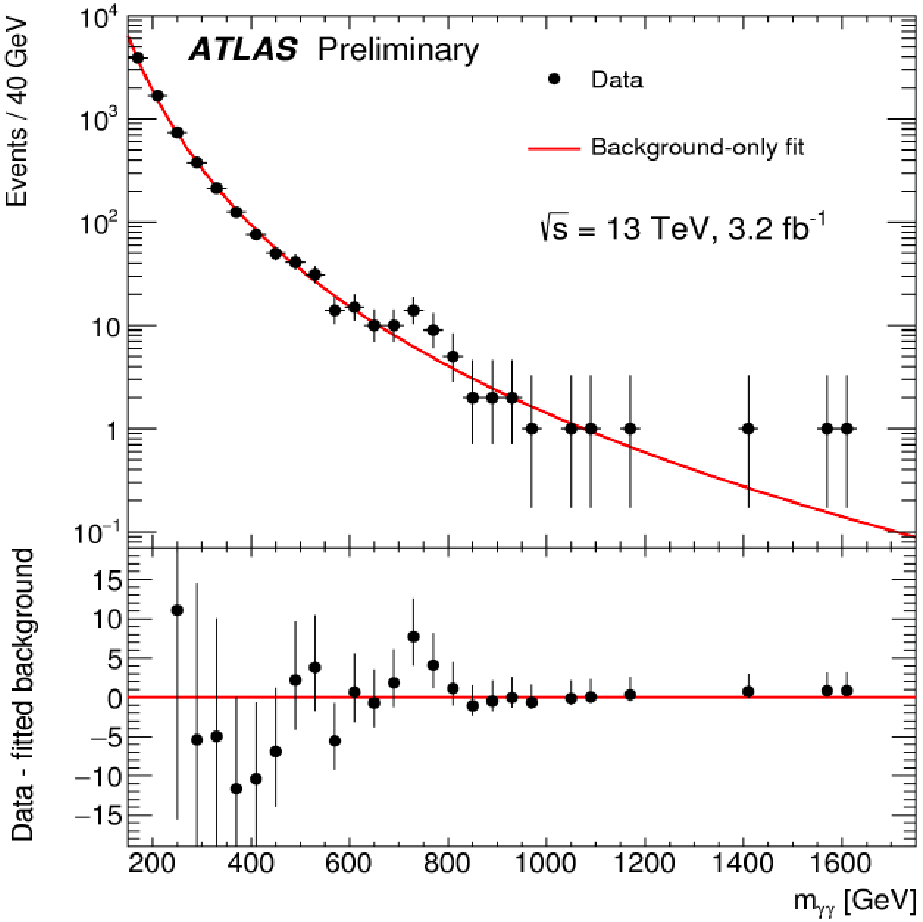
- If something is discovered "soon" → strong interest also in a complementary searches at a 0.5TeV ILC (*complementary reach on color-less states*) and of course also in improved measurements at HL-LHC
- If nothing is found also at 13/14TeV with 300 fb^{-1} → small chances of major discoveries at ILC & HL-LHC (*although the case still needs to be clarified*)

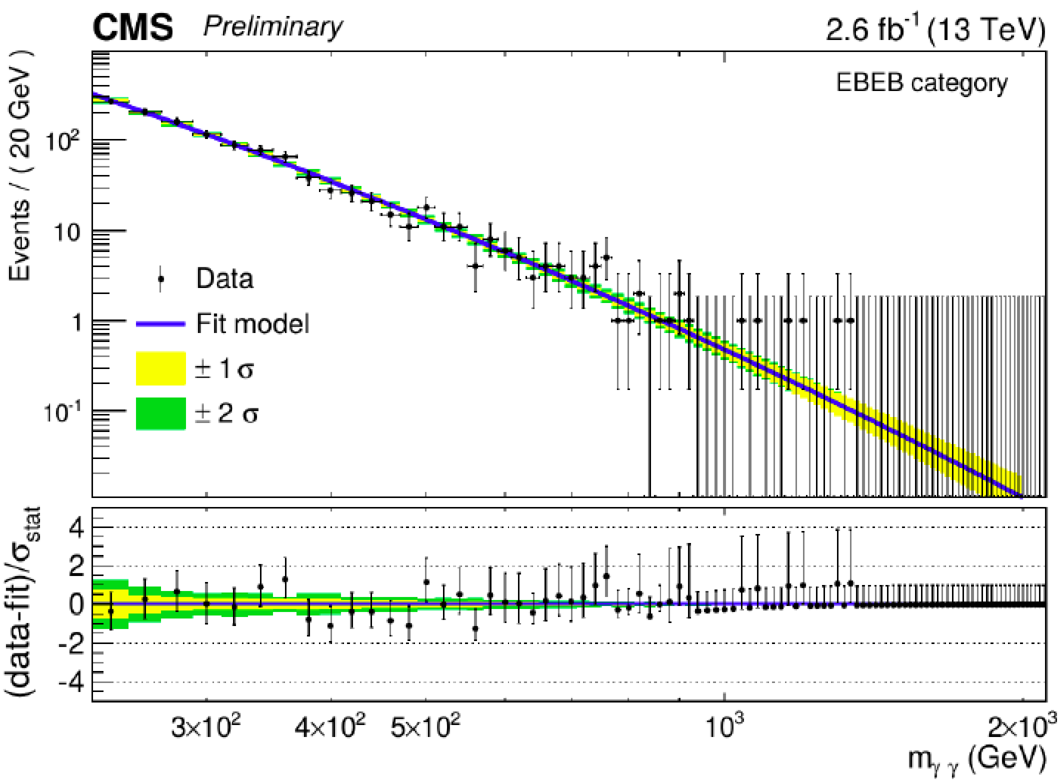
Some comments on the "750 GeV di-photon excess"



Some comments on the "750 GeV di-photon excess"

The excess in the di-photon distribution, peaked around 750 GeV, observed by ATLAS (~3.6σ local signif.) and, to a minor extent, also by CMS (~2.2σ local), has triggered a lot of discussion [~ about 200 pheno papers till today !]





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The most interesting phenomenological messages (in my opinion) have been presented in the very first pheno papers (*& Adam's blog !*). It is definitely premature to discuss "models"...

Before starting to discuss these phenomenological messages, a few general considerations:

- Nobody predicted a particle of this type (*before the observation..*)
  → if it will be confirmed, it will be a BIG revolution

- The statistical evidence is still very week, given the large LEE (*much larger with respect to the SM Higgs case*)

Some comments on the "750 GeV di-photon excess"

A very natural/easy interpretation is in terms of a scalar resonance (S) produced mainly via gluon fusion and decaying (*at least in...*) two photons

$$\mathcal{L}^{\rm eff} = c_{gg}\frac{\alpha_s}{12\pi m_S} S G^a_{\mu\nu} G^{a,\mu\nu} + c_{\gamma\gamma}\frac{\alpha}{4\pi m_S} S F_{\mu\nu} F^{\mu\nu}$$

Buttazzo, Greljo, Marzocca (& many others)

$$\sigma_{pp\to S}(8\,\mathrm{TeV}) = c_{gg}^2 \times (12 \pm 1)\,\mathrm{fb}$$
$$\sigma_{pp\to S}(13\,\mathrm{TeV}) = c_{gg}^2 \times (55 \pm 6)\,\mathrm{fb}$$

The large 13TeV/8TeV ratio in $\sigma(gg \to S)$ allow a good (reasonable?) compatibility with the lack of anomalies in 8 TeV data

The normalization of c_{gg} & $c_{\gamma\gamma}$ is such that they are expected to be O(1) if generated at 1-loop by the exchange of a few (new) particles with O(1) charges

$$\mu_{pp\to S\to\gamma\gamma} = \sigma_{pp\to S} \times \mathcal{B}_{S\to\gamma\gamma}\Big|_{\rm data} \approx (4\pm1)\,\mathrm{fb}$$

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$$\Gamma_{S\to\gamma\gamma} = \frac{m_S}{4\pi}\left(\frac{\alpha\, c_{\gamma\gamma}}{4\pi}\right)^2 \simeq 2.3\times 10^{-5}\, c_{\gamma\gamma}^2\ \mathrm{GeV},$$
$$\Gamma_{S\to gg} = \frac{2m_S}{\pi}\left(\frac{\alpha_s c_{gg}}{12\pi}\right)^2 \left(1+\frac{67\alpha_s}{4\pi}\right) \simeq 4.1\times 10^{-3}\, c_{gg}^2\ \mathrm{GeV}$$

$$\mu_{pp\to S\to\gamma\gamma} = \sigma_{pp\to S}\times \mathcal{B}_{S\to\gamma\gamma} \approx (4\pm 1)\ \mathrm{fb}$$

data

O(1) values of c_{gg} & $c_{\gamma\gamma}$ OK <u>if the width is small</u>

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$$\sigma_{pp\to S}(8\,\mathrm{TeV}) = c^2_{gg} \times (12 \pm 1)\,\mathrm{fb},$$
$$\sigma_{pp\to S}(13\,\mathrm{TeV}) = c^2_{gg} \times (55 \pm 6)\,\mathrm{fb}.$$

$$\sigma_{pp\to S} \times \mathcal{B}_{S\to\gamma\gamma} \simeq 6.3 \times 10^{-5} \left(\frac{20\,\mathrm{GeV}}{\Gamma_S}\right) c^2_G c^2_{\gamma\gamma}\,\mathrm{fb}$$

Much larger (*unnatural?*) values of c_{gg} & $c_{\gamma\gamma}$ needed if the width is "large"

$$\mu_{pp\to S\to\gamma\gamma} = \sigma_{pp\to S} \times \mathcal{B}_{S\to\gamma\gamma} \approx (4\pm 1)\,\mathrm{fb}$$

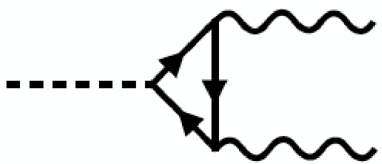
data

Some comments on the "750 GeV di-photon excess"

Two basic categories of models:

Only Loop-induced decays

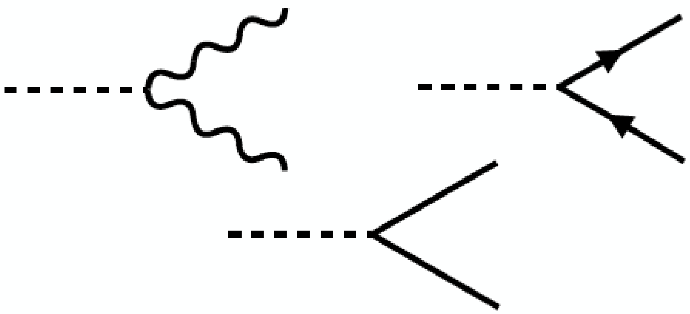
Decays only via loop diagrams



- Small total decay width
- Sizable $\mathrm{Br}(\gamma\gamma)$ even with weaker couplings

Extra decay channels

Allowed tree-level decays to lighter states



- Sizable total decay width
- $\mathrm{Br}(\gamma\gamma)$ is very small
- Need stronger couplings to increase signal rate
- Bounds from other channels

Some comments on the "750 GeV di-photon excess"

On the "loop-type" models:

$$\mathcal{L}^{\rm eff} = c_{gg} \frac{\alpha_s}{12\pi m_S} S G^a_{\mu\nu} G^{a,\mu\nu} + c_{\gamma\gamma} \frac{\alpha}{4\pi m_S} S F_{\mu\nu} F^{\mu\nu}$$

$$\frac{\alpha}{4\pi m_S} S \left(c_W W^i_{\mu\nu} W^{i,\mu\nu} + c_B B_{\mu\nu} B^{\mu\nu} \right)$$

We have 2 gauge-invariant operators at d=5 that controls 4 accessible final states: γγ, Zγ, ZZ, WW → we should see comparable signals (σ×B) in all of them (at most one eff. coupling can be tuned to 0)

Right now OK (other channels less constraining than γγ), but this will be a key test for the near future

$$\frac{\mu_{Z\gamma}}{\mu_{\gamma\gamma}} = \frac{2(1-R_{WB})^2 \tan^2\theta_W}{(1+R_{WB}\tan^2\theta_W)^2}$$

$$\frac{\mu_{ZZ}}{\mu_{\gamma\gamma}} = \frac{(\tan^2\theta_W + R_{WB})^2}{(1+R_{WB}\tan^2\theta_W)^2}$$

$$\frac{\mu_{WW}}{\mu_{\gamma\gamma}} = \frac{2R_{WB}^2}{(\cos^2\theta_W + R_{WB}\sin^2\theta_W)^2}$$

$$(R_{WB} = c_W / c_B)$$

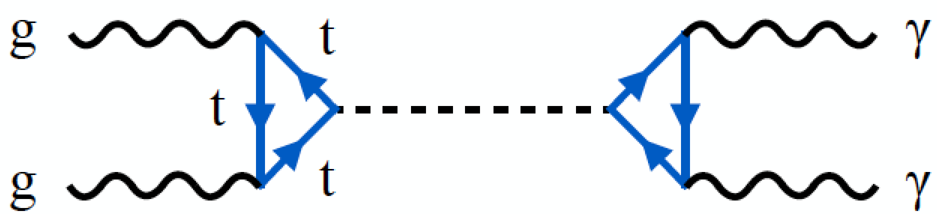
▸ *Some comments on the "750 GeV di-photon excess"*

On the "loop-type" models:

$$\mathcal{L}^{\rm eff} = c_{gg}\frac{\alpha_s}{12\pi m_S} S G^a_{\mu\nu} G^{a,\mu\nu} + c_{\gamma\gamma}\frac{\alpha}{4\pi m_S} S F_{\mu\nu} F^{\mu\nu}$$

Can we generate the required eff. coupl. from SM particles only inside the loops (e.g. top-quarks) ?

No: large S-t-tbar coupling (c_t) needed → too large width



$\mu \sim c_t^4 / \Gamma_{tot}$

$\Gamma_{tot} \propto c_t^2$

$\sigma(pp \to S) \times Br(\gamma\gamma) \propto c_t^2$

Need

$c_t \sim 50$

$\Gamma_{(S \to t\bar{t})} \sim 8$ TeV

Some comments on the "750 GeV di-photon excess"

On the "loop-type" models:

$$\mathcal{L}^{\text{eff}} = c_{gg} \frac{\alpha_s}{12\pi m_S} S G^a_{\mu\nu} G^{a,\mu\nu} + c_{\gamma\gamma} \frac{\alpha}{4\pi m_S} S F_{\mu\nu} F^{\mu\nu}$$

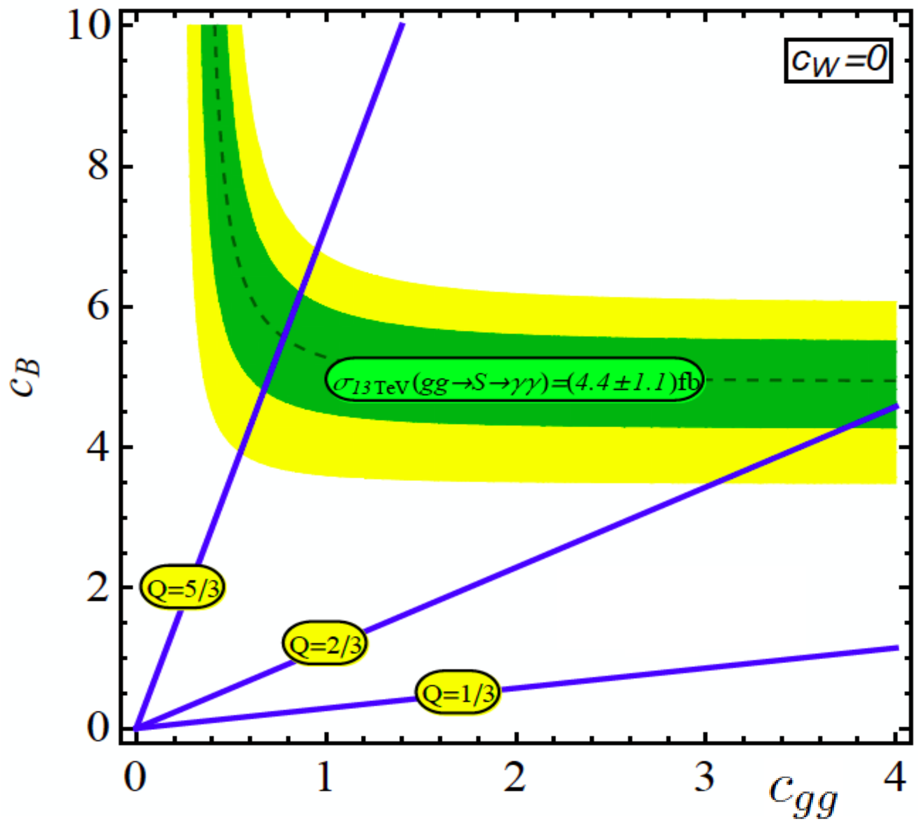
On the other hand, the required eff. coupl . can easily accounted for by vector-like fermions (*L & R components of the fields with same quantum numbers*):

Buttazzo, Greljo, Marzocca

$$\mathcal{L}_{\text{eff}} \supset -g_i^* S \bar{\Psi}_i \Psi_i - M_i \bar{\Psi}_i \Psi_i$$

$$c_{gg} = \sum_{i \in \text{triplets}} g_i^* \frac{m_S}{M_i} \,,$$

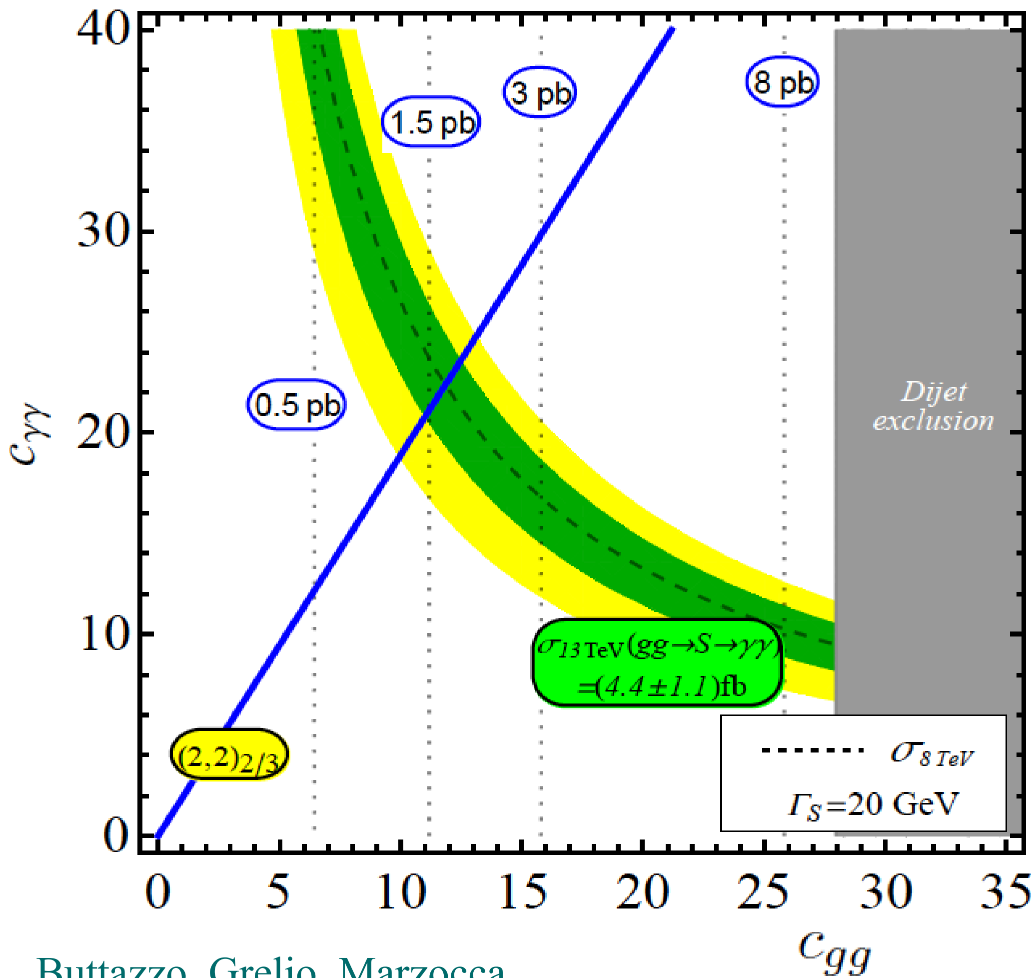
$$c_{\gamma\gamma} = \frac{2}{3} \sum_i g_i^* \frac{m_S}{M_i} N_i^c Q_i^2$$



These new states cannot be too far..

Some comments on the "750 GeV di-photon excess"

On the "large-width" models:



Buttazzo, Greljo, Marzocca

- Higher multiplicity & stronger couplings required for the "mediators" to enhance the ($S \to \gamma\gamma$)
- Model-independent bound on c_{gg} dictated by consistency with di-jet searches
- Model-dependent bounds on possible other decay channels of S

Some comments on the "750 GeV di-photon excess"

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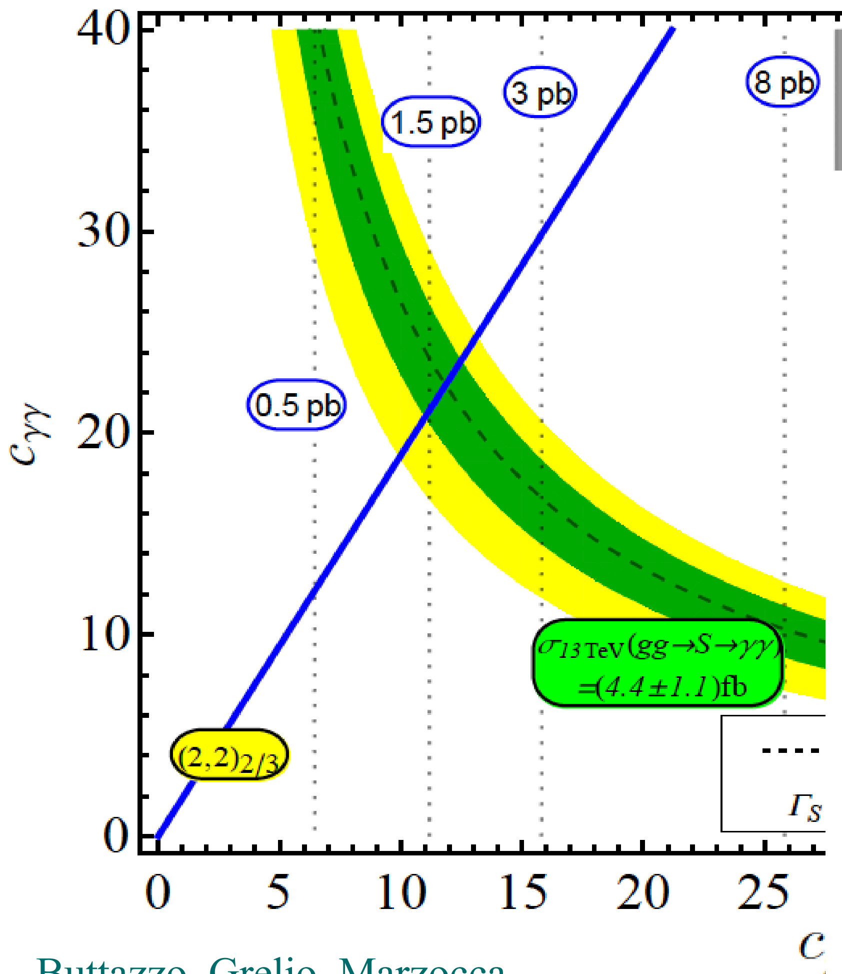
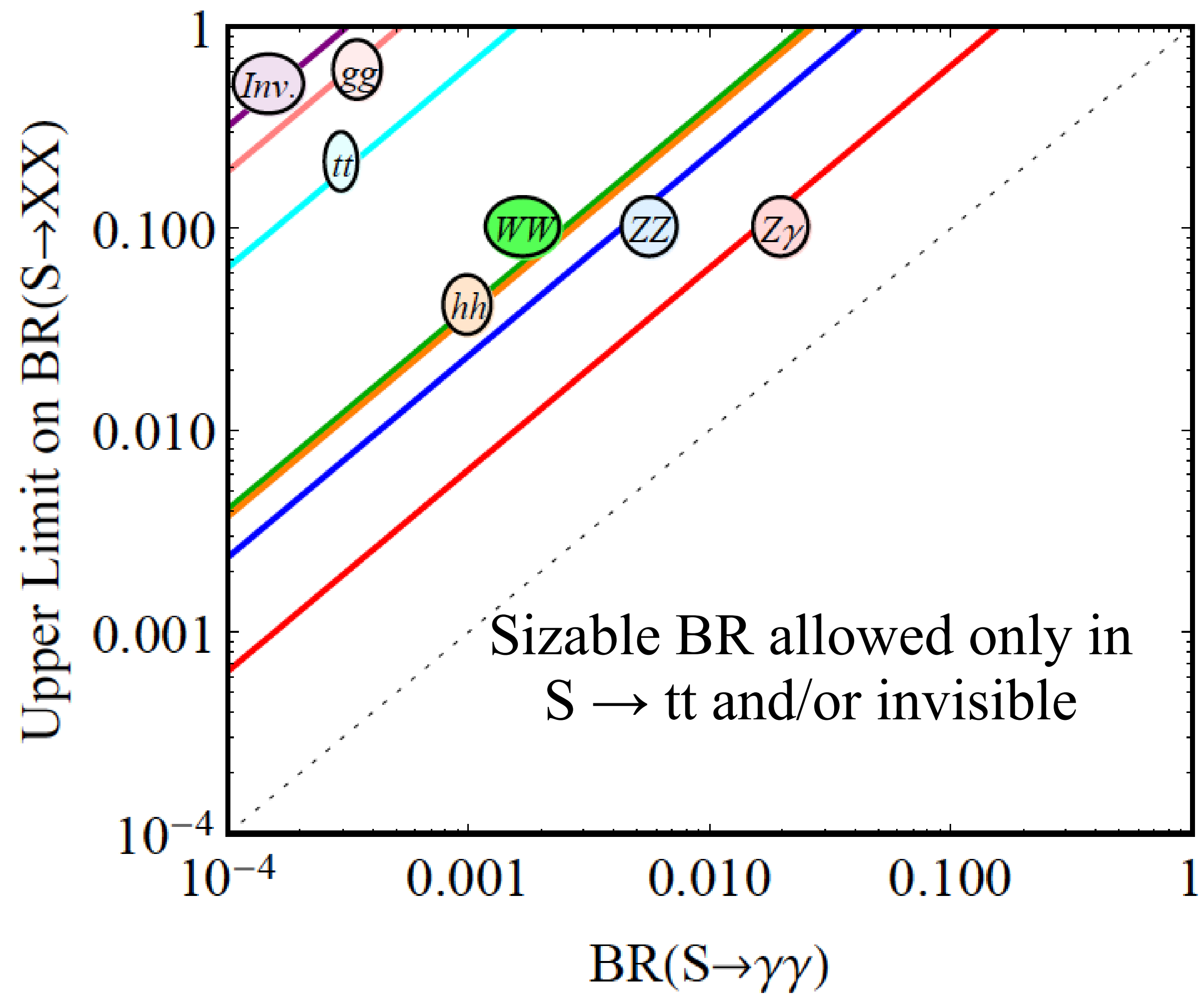


Buttazzo, Greljo, Marzocca

- Model-dependent bounds on possible other decay channels of S:



Some comments on the "750 GeV di-photon excess"

The literature is full of more explicit models, but I think it is premature to discuss them at this stage.

The key messages cane be summarized as follows:

- If confirmed as a new state, it cannot be "alone"...
- Very important to search for a similar bump in $Z\gamma$, ZZ, WW (always) and tt/jj (if the width is large)
- The info on the width is crucial

And let's not forget (*this is a message mainly for my th. colleagues...*) that "big discoveries" require a "very strong evidence"...