The Higgs Boson

Intrinsic Width

Giampiero Passarino

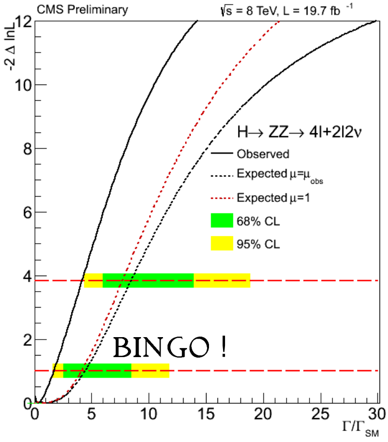
Dipartimento di Fisica Teorica, Università di Torino, Italy
INFN, Sezione di Torino, Italy

SM @ LHC, 9 April 2014 Madrid

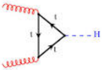
$d\sigma^{\rm off} = \mu\, r\, d\sigma^{\rm peak}$ $r = \frac{\Gamma_H}{\Gamma_H^{SM}}$ ↬ assume $\mu = 1$ ⇝ measure r

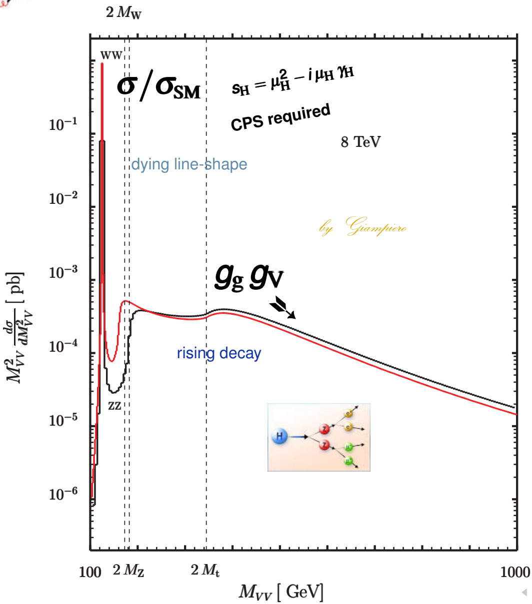
Combined limit

~ peak, exp resolution / SM width **2–3 *GeV*/4 *MeV***



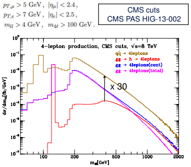
- Combined observed (expected) values
  - $r = \Gamma/\Gamma_{SM} < 4.2$ (8.5) @ 95% CL
    (p-value = 0.02)
  - $r = \Gamma/\Gamma_{SM} = 0.3^{+1.5}_{-0.3}$
- equivalent to:
  - $\Gamma < 17.4$ (35.3) MeV @ 95% CL
  - $\Gamma = (1.4^{+6.1}_{-1.4})$ MeV

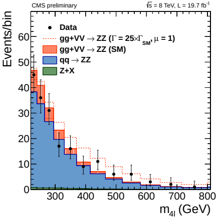




The big picture @ 8TeV

- Peak at Z mass due to singly resonant diagrams.
- Interference is an important effect.
- Destructive at large mass, as expected.
- With the standard model width, s_H, challenging to see enhancement/deficit due to Higgs channel.





dynamic QCD scales

A short History of beyond ZWA *(don't try fixing something that is already broken in the first place)*

① There is an enhanced Higgs tail **Kauer - Passarino (arXiv:1206.4803)**: away from the narrow peak the propagator and the off-shell H width behave like ➥

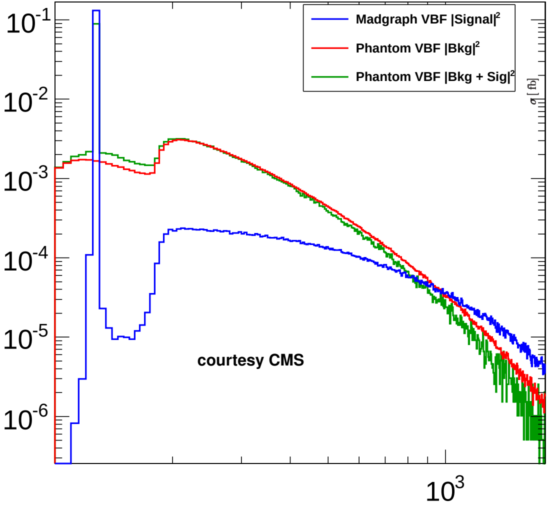
$$\Delta_{\rm H} \approx \frac{1}{\left(M^2_{\rm VV} - \mu^2_{\rm H}\right)^2}, \qquad ✔ \frac{\Gamma_{\rm H \to VV}\left(M_{\rm VV}\right)}{M_{\rm VV}} \sim G_{\rm F}\, M^2_{\rm VV}$$

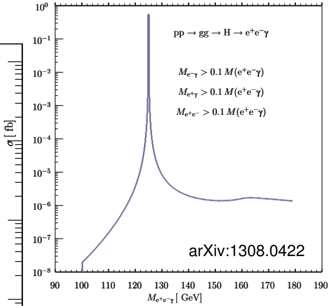
② Introduce the notion of **∞-degenerate** solutions for the Higgs couplings to SM particles **Dixon - Li (arXiv:1305.3854), Caola - Melnikov(arXiv:1307.4935)**

③ Observe that the enhanced tail is obviously $\gamma_{\rm H}$ -independent and that this could be exploited to constrain the Higgs width model-independently

④ Use a matrix element method (e.g. MELA) to construct a kinematic discriminant to sharpen the constraint **Campbell, Ellis and Williams (arXiv:1311.3589)**

Off-shellness forever





❶ On-shell ∞-**degeneracy**: allow for a scaling of the Higgs couplings and of the total Higgs width defined by

$$\sigma_{i\to \mathrm{H}\to f} = (\sigma\cdot \mathrm{BR}) = \frac{\sigma_i^{\mathrm{prod}}\Gamma_f}{\gamma_{\mathrm{H}}} \qquad \sigma_{i\to \mathrm{H}\to f} \propto \frac{g_i^2 g_f^2}{\gamma_{\mathrm{H}}} \qquad g_{i,f} = \xi\, g_{i,f}^{\mathrm{SM}} \;\; \gamma_{\mathrm{H}} = \xi^4\, \gamma_{\mathrm{H}}^{\mathrm{SM}}$$

Remark *Looking for ξ -dependent effects in the highly off-shell region is an approach that raises sharp questions on the nature of the underlying extension of the SM; furthermore it does not take into account variations in the SM background*

➢ The signal strength in **4l**, relative to the expectation for the SM Higgs boson, is measured to be

$$0.91^{+0.30}_{-0.24}\ \text{CMS} \qquad 1.43^{+0.40}_{-0.35}\ \text{ATLAS}$$

② Use κ-language, allowing for a consistent HEFT interpretation, Passarino:2012cb. Neglecting loop-induced vertices, we have

$$\frac{\Gamma_{gg}}{\Gamma_{gg}^{SM}(\mu_H)} = \frac{\kappa_t^2 \cdot \Gamma_{gg}^{tt}(\mu_H) + \kappa_b^2 \cdot \Gamma_{gg}^{bb}(\mu_H) + \kappa_t \kappa_b \cdot \Gamma_{gg}^{tb}(\mu_H)}{\Gamma_{gg}^{tt}(\mu_H) + \Gamma_{gg}^{bb}(\mu_H) + \Gamma_{gg}^{tb}(\mu_H)}$$

$$\sigma_{i\to H\to f} = \frac{\kappa_i^2 \kappa_f^2}{\kappa_H^2}\, \sigma_{i\to H\to f}^{SM}$$

Remark *The measure of off-shell effects can be interpreted as a constraint on γ_H only when we scale couplings and total width to keep σ_{peak} untouched, although its value is known with* **15–20%** *accuracy.*

THE GENERALIZATION IS AN ∞^2-**degeneracy**, $\kappa_i\kappa_f = \kappa_H$.

③ On the whole, we have a constraint in the multidimensional κ-space, since $\kappa_g^2 = \kappa_g^2(\kappa_t, \kappa_b)$ and $\kappa_H^2 = \kappa_H^2(\kappa_j, \forall j)$.

- Only on the assumption of degeneracy one can prove that off-shell effects measure κ_H; a combination of on-shell effects (measuring $\kappa_i\kappa_f/\kappa_H$) and off-shell effects (measuring $\kappa_i\kappa_f$) gives information on κ_H without prejudices.

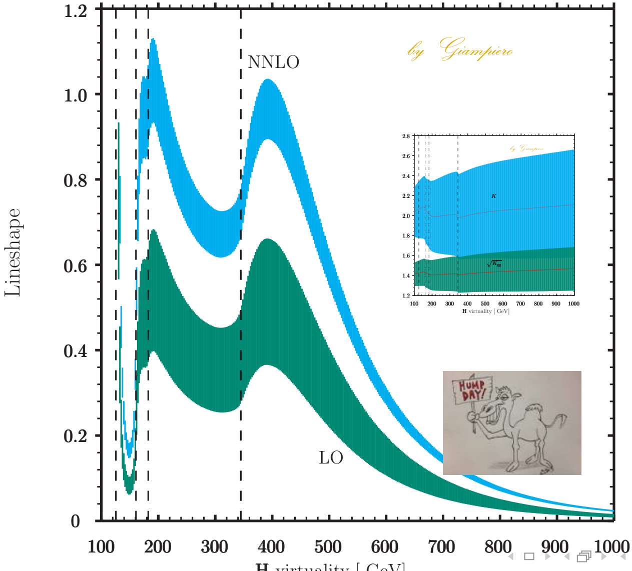
- Denoting by $\mathbf{S}$ the signal and by $\mathbf{I}$ the interference and assuming that $\mathbf{I}_{\text{peak}}$ is negligible we have

$$\frac{\mathrm{S}_{\text{off}}}{\mathrm{S}_{\text{peak}}}\,\kappa_{\mathrm{H}}^2 + \frac{\mathrm{I}_{\text{off}}}{\mathrm{S}_{\text{peak}}}\,\frac{\kappa_{\mathrm{H}}}{x_{if}}, \qquad x_{if} = \frac{\kappa_i\kappa_f}{\kappa_{\mathrm{H}}}$$

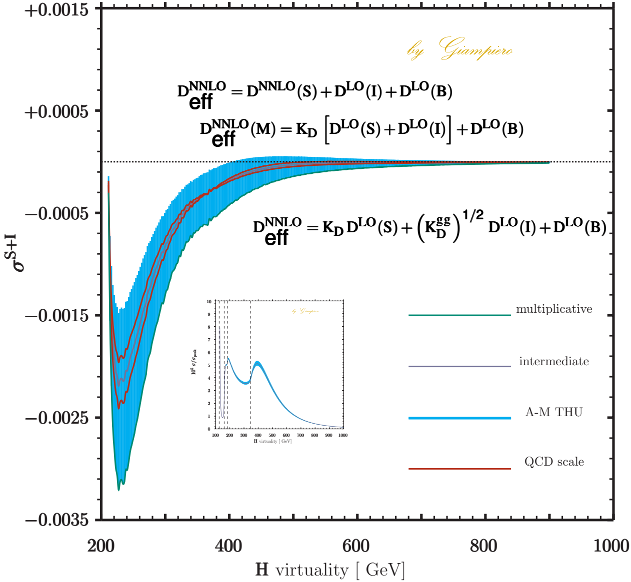
for the normalized $\mathbf{S}+\mathbf{I}$ off-shell cross section.

- The background, e.g. $\mathrm{gg} \to 4\mathrm{l}$, is also changed by the inclusion of $d = 6$ operators and one cannot claim that New Physics is modifying only the signal

The higher-order correction in gluon-gluon fusion have shown a huge $\mathbf{K}$-factor $\mathbf{K} = \sigma^{\mathrm{NNLO}}_{\mathrm{prod}} / \sigma^{\mathrm{LO}}_{\mathrm{prod}}$, $\sigma_{\mathrm{prod}} = \sigma_{\mathrm{gg}\to\mathrm{H}}$.



❶ The *zero-knowledge* scenario



The *soft-knowledge* scenario: in a nutshell, one can ✎

$$\sigma \;=\; \sigma^{\rm LO} + \sigma^{\rm LO}\,\frac{\alpha_s}{2\pi}\,[\text{universal} + \text{process dependent} + \text{reg}]$$

- where *universal* (the " + " distribution) gives the bulk of the result
- while *process dependent* (the δ function) is known up to two loops for the signal but not for the background
- and *reg* is the regular part.

A possible strategy (Bonvini et al. arXiv:1304.3053) would be to use for background the same *process dependent* coefficients and allow for their variation within some ad hoc factor.

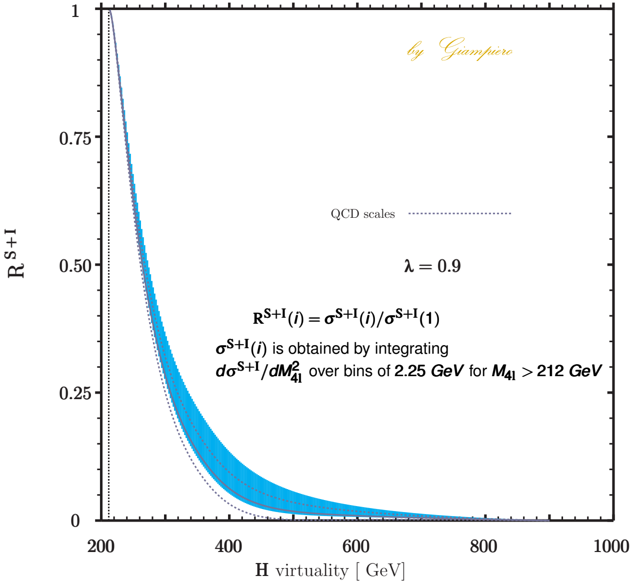
✳ The total systematic error is dominated by theoretical uncertainties, therefore one *should never accept theoretical predictions that cannot provide uncertainty in a systematic way* (i.e. providing an algorithm).

vertical morphing **Conway**

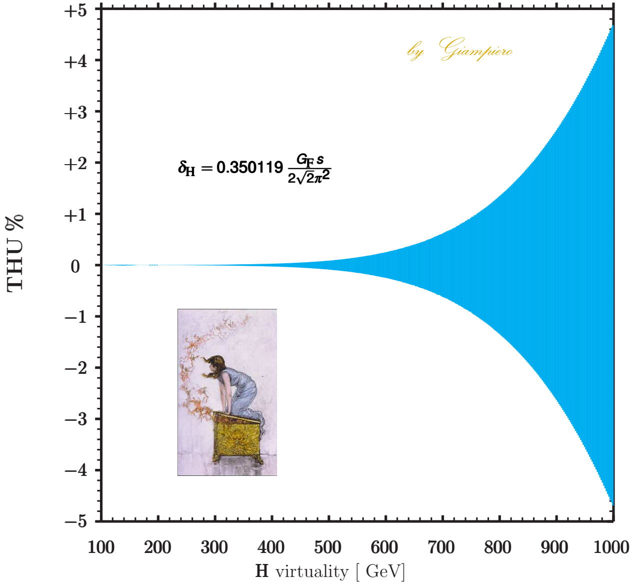
$$
\begin{aligned}
D_{-}\left(\lambda, M_{4l}\right) &= \lambda D_{M}\left(M_{4l}\right) + (1-\lambda)\, D_{I}\left(M_{4l}\right) \\
D_{+}\left(\lambda, M_{4l}\right) &= \lambda D_{I}\left(M_{4l}\right) + (1-\lambda)\, D_{A}\left(M_{4l}\right)
\end{aligned}
$$

☞ $\mathbf{1 - \varepsilon \leq \lambda \leq 1}$, has a flat distribution

☞ We will have $\mathbf{D_{-} < D_{I} < D_{+}}$ and a value for $\boldsymbol{\lambda}$ close to one (e.g. **0.9**) gives less weight to the additive option, highly disfavored by the eikonal approximation.



by Giampiero
QCD scales
λ = 0.9
R^{S+I}(i) = σ^{S+I}(i)/σ^{S+I}(1)
σ^{S+I}(i) is obtained by integrating
dσ^{S+I}/dM²_{4l} over bins of 2.25 GeV for M_{4l} > 212 GeV
R^{S+I}
1
0.75
0.50
0.25
0
200
400
600
800
1000
H virtuality [GeV]



by Giampiero
$\delta_{\rm H} = 0.350119 \, \frac{G_F \, s}{2\sqrt{2}\pi^2}$
THU %
+5
+4
+3
+2
+1
0
−1
−2
−3
−4
−5
100
200
300
400
500
600
700
800
900
1000
H virtuality [GeV]

THU summary

① PDF $+ \alpha_s$; these have a Gaussian distribution;

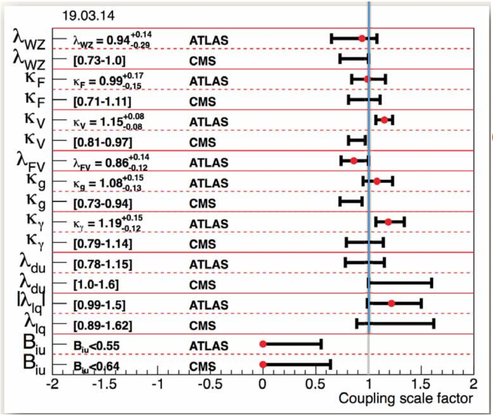
② ✓ μ_R, μ_F (renormalization and factorization QCD scales) variations; they are the standard substitute for missing higher order uncertainty (MHOU); MHOU are better treated in a Bayesian context with a flat prior;

③ uncertainty on γ_H due to missing higher orders, negligible for a light Higgs;

④ ✓ uncertainty for $\Gamma_{H \to F}(M_f)$ due to missing higher orders (mostly EW), especially for high values of the Higgs virtuality M_f (i.e. the invariant mass in $pp \to H \to f + X$);

⑤ ✓ uncertainty due to missing higher orders (mostly QCD) for the background

FUTURE (Moriod EW **2014**)



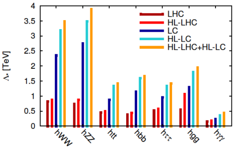


FIG. 2: Effective new physics scales Λ_* extracted from the Higgs coupling measurements collected in Table I. T for the loop-induced couplings to gluons and photons contain only the contribution of the contact terms, as t of the loop terms are already disentangled at the level of the input values Δ. (The ordering of the columns fro right corresponds to the legend from up to down.)

$$\mathcal{L} = \mathcal{L}_4 + \sum_{n>4} \sum_{i=1}^{N_n} \frac{a_i^n}{\Lambda^{n-4}} \mathcal{O}_i^{(d=n)}$$

TH has to improve
with NLO κ-language

CONCLUSIONS

- The successful search for the on-shell Higgs-like boson did put little emphasis on the potential of the off-shell events. *Wind of change is blowing* (CMS-PAS-HIG-14-002), thanks Chiara.
- The associated THU is (almost) dominating the total systematic error and *precision Higgs physics* requires control of both systematics, not only the experimental one
- Very often THU is nothing more than educated guesswork but a workable falsehood is more useful than a complex incomprehensible truth. In other words, *closeness to the whole truth is in part a matter of degree of informativeness of a proposition*

What can be said at all can be said clearly and whereof one cannot speak thereof one must be silent **Ludwig Wittgenstein**

Thanks for your attention