The Higgs Boson

Intrinsic Width

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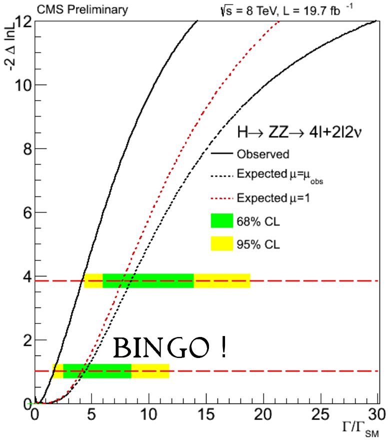
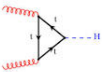
$d\sigma^{\text{off}} = \mu\, r\, d\sigma^{\text{peak}}$ $r = \frac{\Gamma_H}{\Gamma_H^{SM}}$ ↬ assume $\mu = 1$ ⇝ measure r

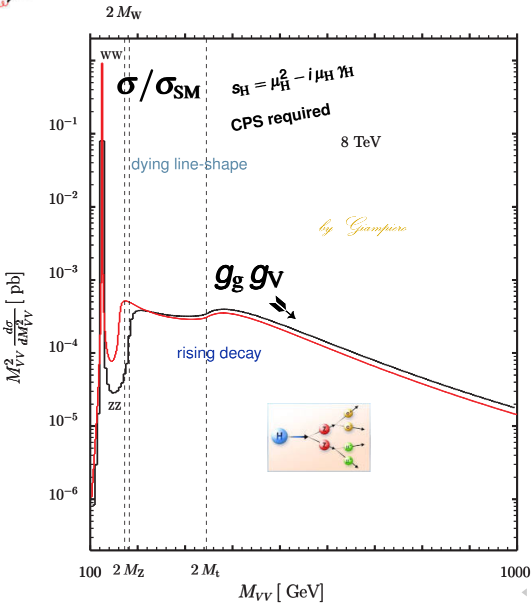
Combined limit

~ 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



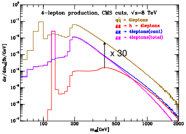


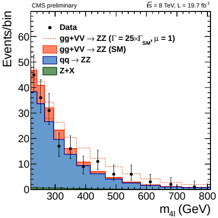
The big picture @ 8TeV

- 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.

$p_{T,\mu} > 5$ GeV, $|\eta_\mu| < 2.4$,
$p_{T,e} > 7$ GeV, $|\eta_e| < 2.5$,
$m_{ll} > 4$ GeV, $m_{4\ell} > 100$ GeV.

CMS cuts
CMS PAS HIG-13-002





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 ➥

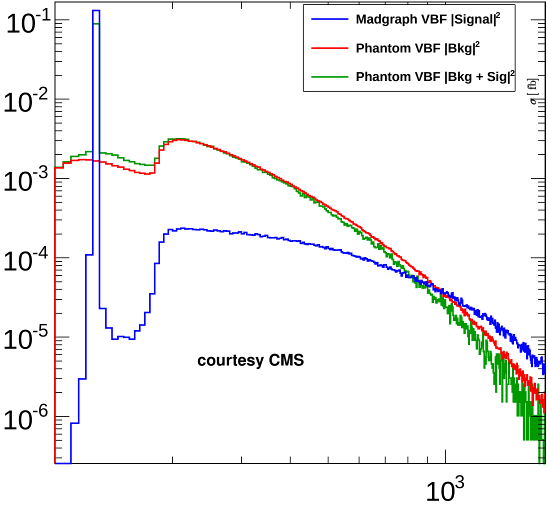
$$\Delta_{\mathrm{H}} \approx \frac{1}{\left(M^2_{\mathrm{VV}} - \mu^2_{\mathrm{H}}\right)^2}, \qquad ✔\frac{\Gamma_{\mathrm{H}\to\mathrm{VV}}\left(M_{\mathrm{VV}}\right)}{M_{\mathrm{VV}}} \sim G_{\mathrm{F}}\, M^2_{\mathrm{VV}}$$

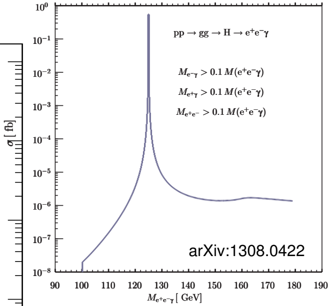
② Introduce the notion of **∞-degenerate** solutions for the Higgs couplings to SM particles **Dixon - Li (arXiv:1305.3854), Caola - Melnikov(arXiv:1307.4935)**

③ Observe that the enhanced tail is obviously γ_{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

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

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

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

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

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.

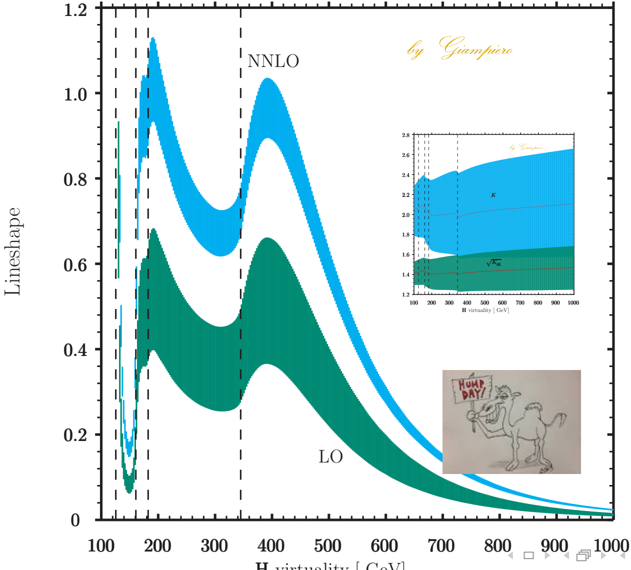
➤ Denoting by $\mathbf{S}$ the signal and by $\mathbf{I}$ the interference and assuming that $\mathbf{I}_{\text{peak}}$ is negligible we have

$$\frac{S_{\text{off}}}{S_{\text{peak}}} \kappa_H^2 + \frac{I_{\text{off}}}{S_{\text{peak}}} \frac{\kappa_H}{x_{if}}, \qquad x_{if} = \frac{\kappa_i \kappa_f}{\kappa_H}$$

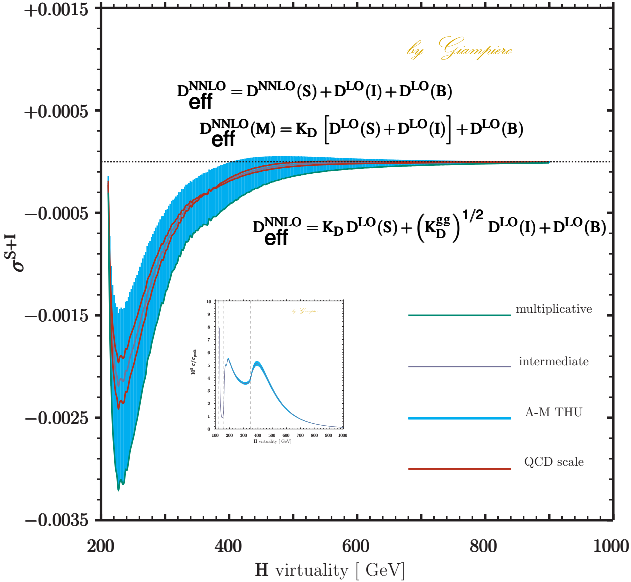
for the normalized $\mathbf{S} + \mathbf{I}$ off-shell cross section.

➢ The background, e.g. $gg \to 4l$, 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 $\mathbf{K} = \sigma^{\rm NNLO}_{\rm prod} / \sigma^{\rm LO}_{\rm prod}$, $\sigma_{\rm prod} = \sigma_{\rm gg \to H}$.



❶ The *zero-knowledge* scenario



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

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

- ☛ 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.

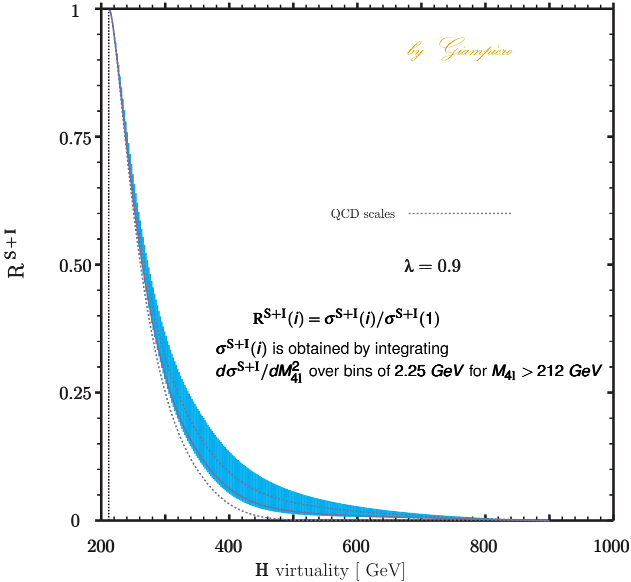
✶ The total systematic error is dominated by **theoretical** uncertainties, therefore one *should never accept theoretical predictions that cannot provide uncertainty in a systematic way* (i.e. providing an algorithm).

vertical morphing **Conway**

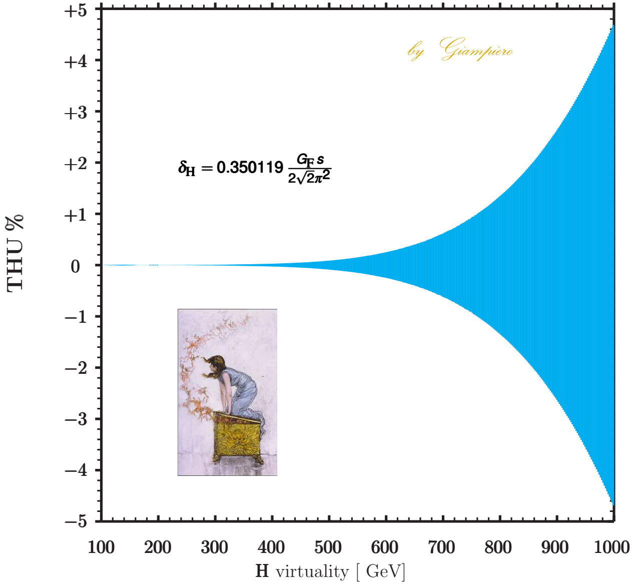
$$
\begin{aligned}
D_-\left(\lambda, M_{4l}\right) &= \lambda D_M\left(M_{4l}\right) + (1-\lambda)\, D_I\left(M_{4l}\right) \\
D_+\left(\lambda, M_{4l}\right) &= \lambda D_I\left(M_{4l}\right) + (1-\lambda)\, D_A\left(M_{4l}\right)
\end{aligned}
$$

☞ $\mathbf{1-\varepsilon \leq \lambda \leq 1}$, 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.



1
0.75
0.50
0.25
0
200
400
600
800
1000
H virtuality [GeV]
R S+I
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}/dM^2_{4l} over bins of 2.25 GeV for M_{4l} > 212 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;

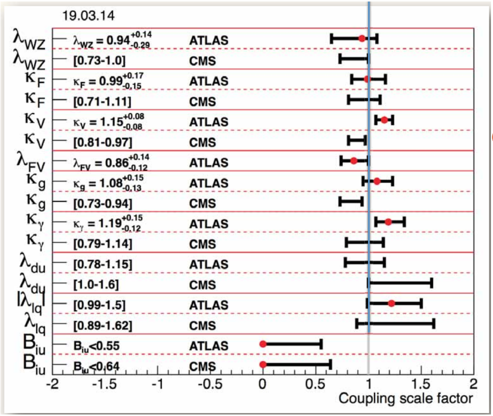
② ✓ μ_R, μ_F (renormalization and factorization QCD scales) variations; they are the standard substitute for missing higher order uncertainty (MHOU); MHOU are better treated in a Bayesian context with a flat prior;

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**)



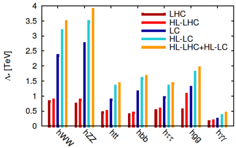


FIG. 2: Effective new physics scales Λ_* extracted from the Higgs coupling measurements collected in Table I. T
for the loop-induced couplings to gluons and photons contain only the contribution of the contact terms, as t
of the loop terms are already disentangled at the level of the input values Δ.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

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

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