Higgs Pseudo - Observables

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HEPTOOLS Network

Loops and Legs in Quantum Field Theory, 25 - 30 April 2010, Wörlitz, Germany

Based on work done in collaboration with
Christian Sturm and **Sandro Uccirati**

Thanks: **A. Denner, S. Dittmaier, M. Dührssen, M. Grünewald, S. Heinemeyer, C. Mariotti, R. Tanaka**

But I talk, so it's my responsibility

All that theories can tell us is how the world could be (van Fraassen 1991)

Outlines

(1, 2,)

1. *From signal and background at LHC to the definition of Pseudo - Obervables*
2. *and Feynman diagrams on the second Riemann sheet,*

what else, but the inevitable!
The suggestion that particles might be seen as aspects of pseudo-observability fits nicely with structural realism, even in the absence of further metaphysical explication (Higgs)

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$\pi\rho o\lambda o\gamma os$

Before the entry of the chorus

- **All the questions in this talk are not really urgent**, as nothing will be really measurable by LHC before 2013, 2014 or beyond
- **but they will be** if you consider as relevant to have results published in such a way that theorists can later enter their general model parameters, calculate resulting **POs** and see how well data constrains this model.
  - even if it will take 10 years to reach enough fb^{-1};
  - even if it is not LEP anymore

$\mapsto$ study tools that Exps can use in **future analysis to extract** Higgs **POs**

Oldies but Goldies

Experimenters

(should) extract (**unfold ?**) so-called *realistic observables* from raw data, e.g. $M(\gamma\gamma)$ in $\sigma(pp \to \gamma\gamma + X)$ and need

- to present results in a form that can be useful for comparing them with theoretical predictions, i.e. the results should be transformed into **POs**

Theorists

(should) compute **POs**

- using the best available technology and satisfying a list of demands from the self-consistency of the **underlying theory**

Prolegomena

The search for a mechanism explaining EWSB

has been a major goal for many years, in particular the search for a **SM Higgs boson**. *As a result of this an intense effort in the theoretical community has been made to produce the most accurate NLO and NNLO predictions*

However, there is a point

that has been ignored: the Higgs boson is an unstable particle and should be removed from the $|\,\mathrm{in}/\mathrm{out}\;>$ *bases in the* **H** *-space, without destroying* **unitarity** *of the theory. Therefore, concepts as the*

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Prolegomena II

Example

Combine $gg \to H$ with $H \to \gamma\gamma$. The full process is

$$\begin{aligned} pp &\to \gamma\gamma + X \\ &= \Big[\mathrm{Signal}\Big]\ \mathrm{pp} \to \mathrm{gg}(\to \mathrm{H} \to \gamma\gamma) + \mathrm{X}, \end{aligned}$$

and by a non-resonant background. The question is:

- how to extract from the data, without ambiguities, a PO H *partial decay width* into $\gamma\gamma$ which does not violate first principles?

Once again,

- Higgs boson $\notin |\,\mathrm{in}\, >$;
- $< \gamma\gamma\ \mathrm{out}|H\ \mathrm{in} >$ not definable in **QFT**.

Background: comment

Perhaps we have been too busy with polynomial 20 *gluons*,

but

The $\bar{q}q \rightarrow \gamma\gamma$ background was computed with NLO XX. However,

- XX is not an event Monte Carlos suitable for the detector simulation.

Hence LO YY is used to produce events and then σ, the $\mathbf{p_T}$ and the $\mathbf{M}_{\gamma\gamma}$ distributions are reweighted to XX.

- Theory issues exist independently of those experimental detector-related aspects and **must be tackled anyway** . . . . . .

The mother of all POs

resummed propagators

Skeleton expansion of the self-energy $S = 16\,\pi^4\, i\,\Sigma$ with propagators that are resummed up to $\mathcal{O}\,(n)$

$$\Delta_i^{(0)}(s) = \frac{1}{s - m_i^2},$$

$$\Delta_i^{(n)}(s) = -\Delta_i^{(0)}(s)\left[1 + \Delta_i^{(0)}(s)\,\Sigma_{ii}^{(n)}\left(s\,,\,\Delta_i^{(n-1)}(s)\right)\right]^{-1},$$

a dressed propagator is the formal limit

$$\overline{\Delta}_i(s) = \lim_{n\to\infty} \Delta_i^{(n)}(s),$$

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Complex pole

The Higgs boson complex pole

$\mathbf{s_H}$ is the solution of the equation

$$\mathbf{s_H} - M_H^2 + \Sigma_{HH}(\mathbf{s_H}, M_H^2, \xi) \quad = \quad 0,$$

where M_H^2 is the renormalized mass; all **local** CTs have been introduced to make the off-shell Σ UV finite.

NI 1

$$\frac{\partial}{\partial \xi} s_H \quad = \quad 0$$

NI 2

$$\frac{\partial}{\partial \xi} \Sigma_{HH}(s_H, M_H^2, \xi) \quad = \quad 0,$$

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Corollary

From NIs it follows:

$$\frac{\partial}{\partial \xi} \Sigma^{(1)}_{HH}(s_H, s_H, \xi) \quad = \quad 0,$$

- at one-loop, the Higgs complex pole is **gauge parameter independent** if the self-energy is computed at $\mathbf{M_H^2 = s_H}$,
- the basis of the so-called complex-mass scheme
- higher than one-loop . . . no time . . .

S - matrix

At the parton level

the S -matrix for the process **i** $\rightarrow$ **f** can be written as

$$S_{fi} = V_i(s)\,\Delta_H(s)\,V_f(s) + B_{if}(s),$$

- V_i is the **production vertex** $i \rightarrow H$
- V_f is the **decay vertex** $H \rightarrow f$
- Δ_H the **H re-summed propagator**
- B_{if} is the **non-resonant background**

Modification of the LSZ reduction

Step 1

$$< f \text{ out} | H >< H | i \text{ in} > + \sum_{n \neq H} < f \text{ out} | n >< n | i \text{ in} >$$

$\{n\} \oplus H$ is a **complete set of states**

Step 2

$$\begin{aligned}
\Pi_{HH}(s) &= \frac{\Sigma_{HH}(s) - \Sigma_{HH}(s_H)}{s - s_H}, \\
\Delta_{HH}(s) &= (s - s_H)^{-1} \left[1 + \Pi_{HH}(s)\right]^{-1}, \\
Z_H &= 1 + \Pi_{HH}.
\end{aligned}$$

Modification of the LSZ reduction

Step 3

$$S_{fi} = \left[Z_H^{-1/2}(s)\, V_i(s)\right] \frac{1}{s - s_H} \left[Z_H^{-1/2}(s)\, V_f(s)\right] + B_{if}(s)$$

Step 4

$$S\,(H_c \to f) = Z_H^{-1/2}(s_H)\, V_f(s_H),$$

$$S_{fi} = \frac{S\,(i \to H_c)\; S\,(H_c \to f)}{s - s_H} + \text{non resonant terms.}$$

Main result

Example: $gg \to \gamma\gamma$

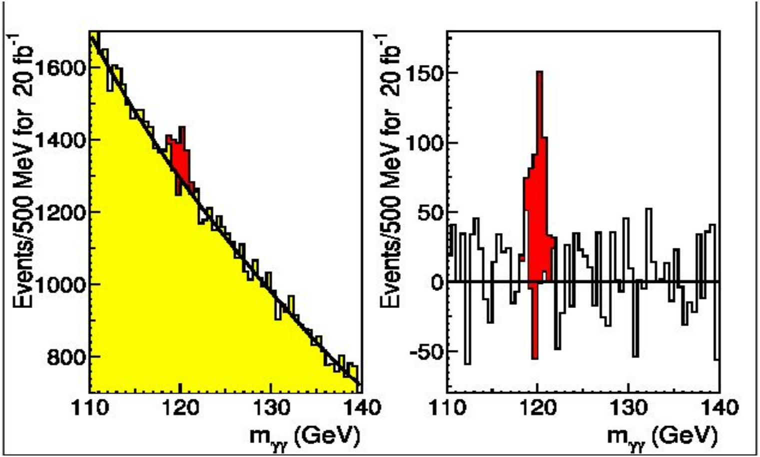
$$\frac{1}{s}\int d\Phi_f\,(P_H\,,\,\{p_f\}) \qquad \left|\frac{S_i(s_H)\,S_f(s_H)}{s-s_H}\right|^2 = \frac{\mu_H^5}{s\,\mid s-s_H\mid^2}$$

$$\times \quad \sigma(\mu_H)_{gg\to H} \otimes \Gamma(\mu_H)_{H\to\gamma\gamma}.$$

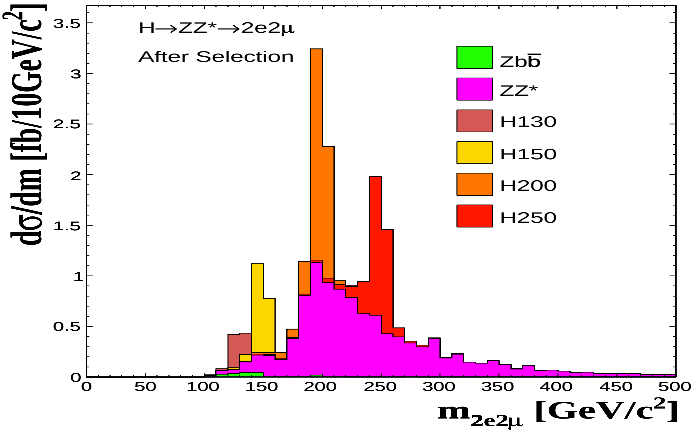
$$\mu_H\,\Gamma\,(H_c \to f) \;=\; \frac{(2\,\pi)^4}{2}\int d\Phi_f\,(P_H\,,\,\{p_f\})$$

$$\times \quad \sum_{\text{spins}}\Big|S\,(H_c \to f)\Big|^2,$$

real life: $\gamma\gamma$



real life: 4 leptons



Strategy

We have four parameters, all PO

$$s_H = \mu_H^2 - i\,\mu_H\,\gamma_H. \quad \sigma(\mu_H)_{ij\to H}, \quad \Gamma(\mu_H)_{H\to XX},$$

- to use in a fit to the (box-detector) experimental distribution (of course, after folding with PDFs);
- these quantities are **universal**, **uniquely defined**, and in **one-to-one correspondence** with *corrected* experimental data;
- after that one could start comparing the results of the fit with a **XM calculation**.

⇝ Proposed initial step: unfold **RO** into something with idealised cuts and then use the **PO** approach to fit that.

PO, once again

Why PO language?

- **POs** are the **the ‘moneta franca’ of LHC, creating an awful lot of wealth** . . . . There are reasons why the chain

  MCT $\longrightarrow$ detector simulation-selection cuts
  $\longrightarrow$ realistic distributions $\rightarrow$ unfolded distributions

  should be replaced by

  MCT $\longrightarrow$ box acceptance
  $\longrightarrow$ (unfolded particle-level) distributions

  Since detector-experimental issues are a moving target only PO are the *Frankish language* to understand LHC.

Why?

PO

- **POs** transform the **universal intuition** of a **QFT-non-existing** quantity into an **archetype**,
- **PO** $\equiv$ the archetypal model after which theoretical calculations are patterned without worries on generating and detector-simulating events for signal and background

Glossary

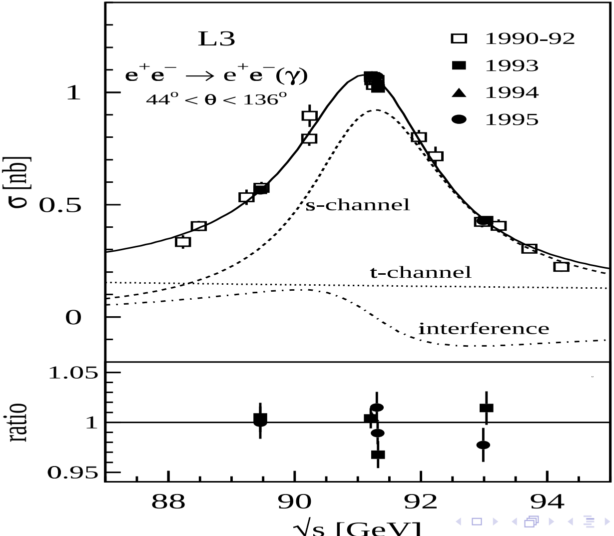
Example

- **RD** = real data
- **RO** = from *real data* $\longrightarrow$ distributions with cuts $\equiv$ **RO**
  - diphoton pairs $(E, p) \rightarrow M(\gamma\gamma)$;
- **PO** = transform the *universal intuition* of a *QFT-non-existing* quantity into an *archetype*, e.g. $\sigma(gg \rightarrow H), \Gamma(H \rightarrow \gamma\gamma)$,
  - $\mathrm{RO}_{\mathrm{th}}(m_H, \Gamma(H \rightarrow \gamma\gamma), \dots)$ fitted to $\mathrm{RO}_{\mathrm{exp}}$ (e.g. $\mathrm{RO} = M(\gamma\gamma)$) defines and extracts m_H etc.

Steps

- go via idealised (model-independent?) **RO** distributions and from there then going to the **POs**.
    - Step 0) Use a (new) **MCT** – the **PO code** – to fit **ROs**
    - Step 1) Understand differences with a *standard* event generator plus detector simulation plus *calibrating* the method/event generator used (which differ from the PO-code in its theoretical content)
    - Step $\geq$ 2) Let's see . . . . . .

Lep example of RO



Plan

Example

$$\mathrm{RO}_{\mathrm{exp}} \quad \overrightarrow{\text{fit}} \quad \mathrm{RO}_{\mathrm{th}}(\mathrm{PO}_1 \ \ldots \ \mathrm{PO}_n)$$

$$\downarrow$$

$$\mathrm{PO}_1^{\mathrm{XM}} \ \ldots \ \mathrm{PO}_n^{\mathrm{XM}} \quad \overleftarrow{\text{comparison}} \quad \mathrm{PO}_1 \ \ldots \ \mathrm{PO}_n \quad (\mathrm{PO}_1 \otimes \mathrm{PO}_2 \ \ldots \ \mathrm{PO}_n)$$

- XM = any Model

Once again

on-shell $\rightarrow$ $|\mathbf{H}> \rightarrow |\mathbf{FS}>$ $\leftarrow$ **does not exist**

$\downarrow$

well defined $\leftarrow$ $\mathrm{RO}^{\mathrm{th}}_{\mathrm{FS}}(m_H\,\Gamma(H_c \rightarrow FS)\,,\,\dots)$

$\mathrm{RO}^{\mathrm{exp}}_{\mathrm{FS}}$ $\rightarrow$ $m_H,\ \Gamma(H_c \rightarrow FS) \leftarrow$ **extracted**

$\downarrow$

conventional but unique

Generalization

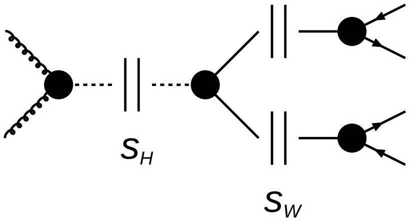


Figure: Gauge-invariant breakdown of the triply-resonant $gg \to 4\,\mathrm{f}$ signal into $gg \to H$ production, $H \to W^+W^-$ decay and subsequent $W \to \bar{f}f$ decays.

General setup

$\phi\,\sigma^2$ theory with $M_\phi > 2\,m_\sigma$; the ϕ propagator is

$$\Delta \;=\; \left[s - M_\phi^2 + \Sigma_{\phi\phi}(s)\right]^{-1},$$

The inverse function, $\Delta^{-1}(s)$

- is analytic in the entire s-plane except for a cut $[\,4\,m_\sigma^2 \;\rightarrow\; \infty\,]$;
- is defined above the cut, $\Delta^{-1}(s + i\,0)$ and the analytical continuation **downwards** is to the 2nd Riemann sheet

$$\Delta_2^{-1}(s - i\,0) \;=\; \Delta^{-1}(s + i\,0) = \Delta^{-1}(s - i\,0) + 2\,i\,\pi\,\rho(s),$$

$2\,i\,\pi\,\rho(s)$ is the discontinuity across the cut.

The logarithm

We need a few definitions which will help

the understanding of the procedure for the analytical continuation of functions defined through a **parametric integral representation**

Logarithm

- **Step 1** $\ln^{(k)} z = ln^{(0)} z + 2\,i\,\pi\,k,\ k = 0\,,\pm 1\,,\ldots$ where $\ln^{(0)} z$ denotes the principal branch ($-\pi < \arg(z) \leq +\pi$).
- **Step 2** Let $z_{\pm} = z_0 \pm i\,0$ and $z = z_R + i\,z_I$, define

$$\ln^{\pm}(z\,;\,z_{\pm}) = \begin{cases} \ln z \pm 2\,i\,\pi\,\theta\,(-z_0)\;\theta\,(\mp z_I) \\ \ln z \pm 2\,i\,\pi\,\theta\,(-z_R)\;\theta\,(\mp z_I)\,, \end{cases}$$

The logarithm II

first definition of the $\ln^{\pm}$ -functions

is most natural in defining analytical continuation of Feynman integrals with a smooth limit into the theory of stable particles; the reason is simple,

- in case some of the particles are taken to be **unstable** we have to perform analytical continuation only when the corresponding Feynman diagram, in the limit of all (internal) stable particles, develops an **imaginary part** (e.g. above some normal threshold);
- However, in all cases where the analytical expression for the diagram is known, one can easily see that the result does not change when replacing z_0 with z_R, the second variant.

The di-logarithm

Example

$$
\begin{aligned}
\mathrm{Li}_2^{(0,0)}(z) & \qquad 0 < \arg(z-1) < 2\,\pi\,, \\
\mathrm{Li}_2^{(n,m)}(z) & = \mathrm{Li}_2^{(0,0)}(z) + 2\,n\,\pi\,i\,\ln^{(0)} z + 4\,m\,\pi^2
\end{aligned}
$$

Question: given

$$
\begin{aligned}
\mathrm{Li}_2(M^2 + i\,0) & = -\int_0^1 \frac{dx}{x}\,\ln\left(1 - M^2\,x - i\,0\right), \\
\mathrm{Im}\,\mathrm{Li}_2\left(M^2 + i\,0\right) & = \pi\,\ln M^2\,\theta\left(M^2 - 1\right),
\end{aligned}
$$

how do we understandbf analytical continuation in terms of an integral representation?

di-logarithm II

Let us consider the analytical continuation

- from $z^+ = M^2 + i\,0$ to $z = M^2 - i\,M\,\Gamma$ and define

$$
\begin{aligned}
I &= -\int_0^1 \frac{dx}{x} \ln^- \left(1 - z\,x\,;\,1 - z^+\,x\right), \\
\chi(x) &= 1 - z\,x = 1 - (M^2 - i\,M\Gamma)\,x
\end{aligned}
$$

- If $M^2 > 1$ χ **crosses** the positive imaginary axis

$$
I = \mathrm{Li}_2^{(0,0)}(z) + 2\,i\,\pi\,\ln M^2,
$$

which is not the expected result

di-logarithm III

The mismatch can be understood by observing that

- $\ln^{-} \chi$ has a cut $[0\,,\,+i\,\infty]$ and, in the process of continuation, with $x \in [0,1]$, we have been crossing the cut.
- The solution consists in **deforming the integration contour**, therefore defining a new integral,

$$I_C \quad = \quad \int_C \frac{dx}{x}\,\ln^{-}\left(1 - z\,x\,;\,1 - z^{+}\,x\right),$$

where $C = C_0 + C'$

- $C_0 = \{0 \leq x \leq 1/M^2 - \epsilon \oplus 1/M^2 + \epsilon \leq x \leq 1,$
- $C'(u)\ :\ \{x = u + i\,\frac{1-M^2\,u}{M\,\Gamma}\}\,,\ \frac{1}{M^2+\Gamma^2} \leq u \leq \frac{1}{M^2}$

di-logarithm IV

Result:

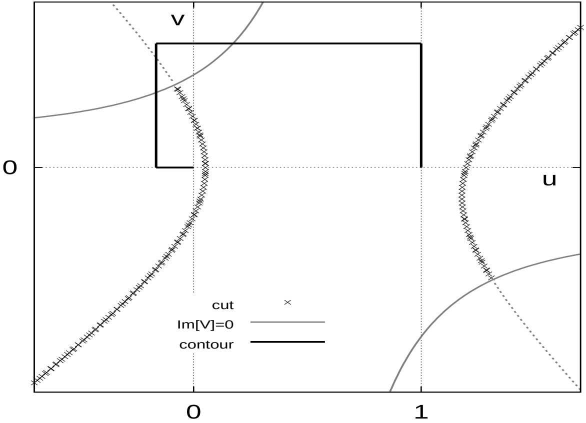
- The integral over C' is downwards on the first quadrant an upwards on the second (along the cut of $\ln^-$);
- Integration of $\ln^-$ over C' gives $-2\,i\,\pi\,(\ln M^2 - \ln z)$, showing that

$$\mathrm{Li}_2^{(1,0)}(z) \;=\; I_C\,,$$

- the correct analytical continuation. Therefore we can extend our integral, by **modifying the contour of integration**, to reproduce the right analytical continuation

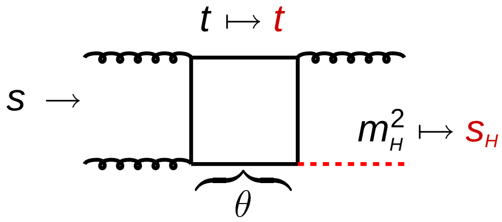
$$\mathrm{Li}_n \overset{\text{Analyt.Cont.}}{\longmapsto} \mathrm{Li}_n^-\,, \qquad \mathrm{Li}_{n+1}^-(z) \neq \int_0^z \frac{dx}{x}\,\mathrm{Li}_n^-(x),$$

Deformation: example



$$x \to u + iv \text{ in } \int_0^1 dx\, ln^{-} V.$$

Complexification: example



natural choice: real kin → complex inv

$$\begin{aligned}
\text{PO} &= \sigma\left(gg \to Hj\right)\left(s_H, s, t\right) \\
t &= -\frac{s}{2}\left[1 - \frac{s_H}{s} - \left(1 - 4\,\frac{s_H}{s}\right)^{1/2}\cos\theta\right] \\
u &= -\frac{s}{2}\left[1 - \frac{s_H}{s} + \left(1 - 4\,\frac{s_H}{s}\right)^{1/2}\cos\theta\right]
\end{aligned}$$

Schemes

Schemes

RMRP the usual **on-shell** scheme where all masses and all Mandelstam invariants are real;

CMRP the **complex mass** scheme with complex internal W and Z poles (extendable to top complex pole) but with real, external, on-shell Higgs, W, Z, etc. legs and with the standard LSZ wave-function renormalization;

CMCP the (complete) **complex mass** scheme with complex, external, Higgs (W, Z, etc.) where the LSZ procedure is carried out at the **Higgs complex pole** (on the second Riemann sheet).

No theoretical uncertainty; only the CMCP scheme is fully consistent.

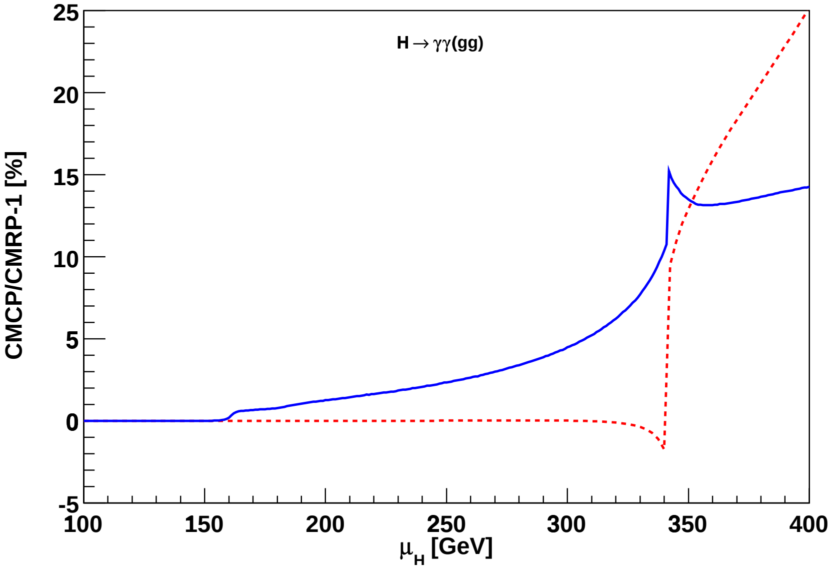


Figure: $H \to \gamma\gamma$ (blue), $H \to gg$ (red)

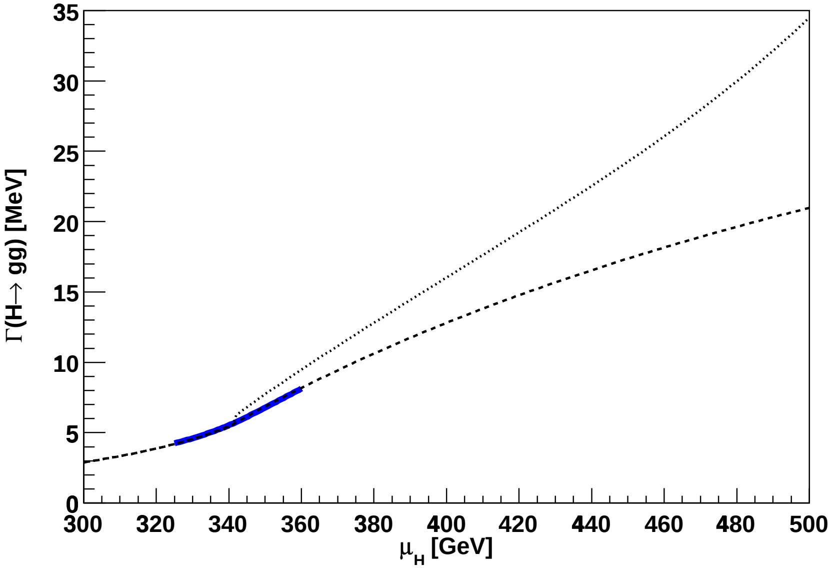


Figure: $\Gamma(H \to gg)$ CMRP (dashed), CMCP (dotted)

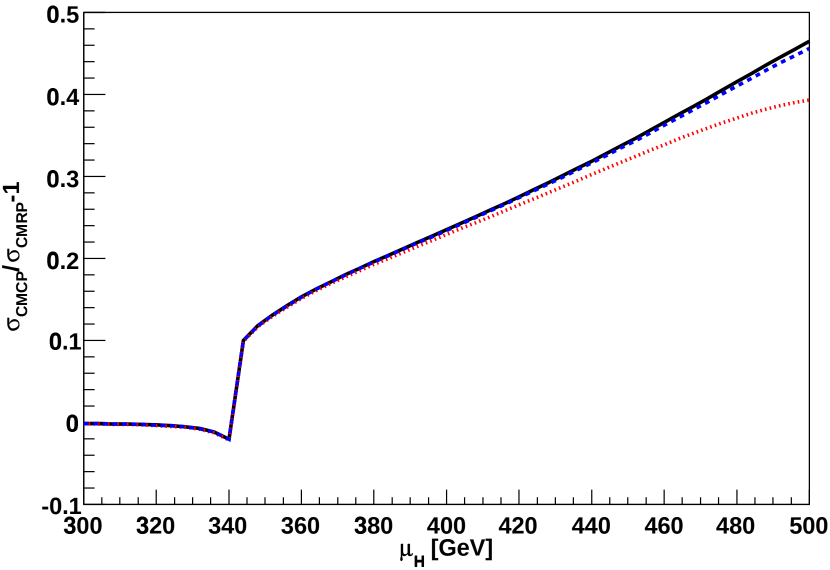


Figure: $\sigma_{\rm CMCP}/\sigma_{\rm CMRP}\,(pp \to H)$ $\sqrt{s} = 3$ TeV (red), $\sqrt{s} = 10$ TeV (blue) and $\sqrt{s} = 14$ TeV (black)

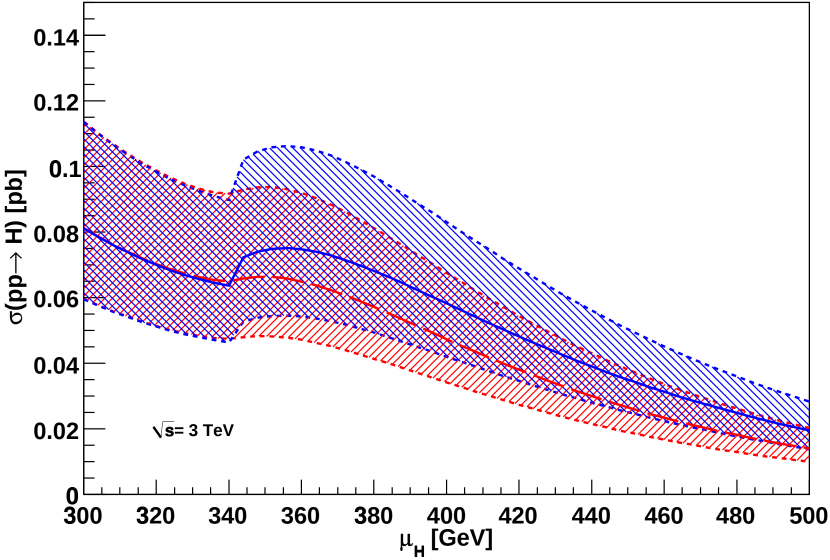


Figure: $\sigma(pp \to H)$ at $\sqrt{s} = 3\,\text{TeV}$ for CMRP (red) and CMCP (blue). Dashed lines give the scale uncertainty

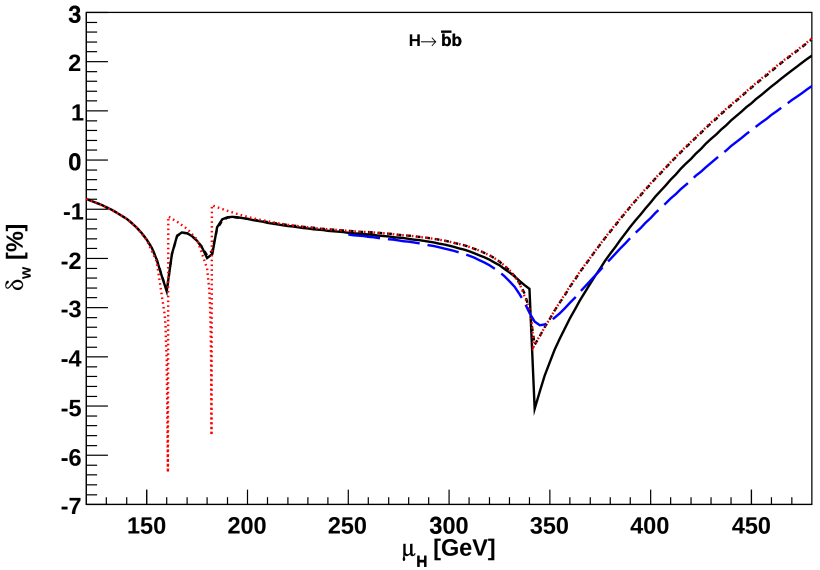


Figure: Weak one-loop radiative corrections to $H \to \overline{b}b$; RMRP (red), CMRP (black dotted) and CMCP scheme (black)

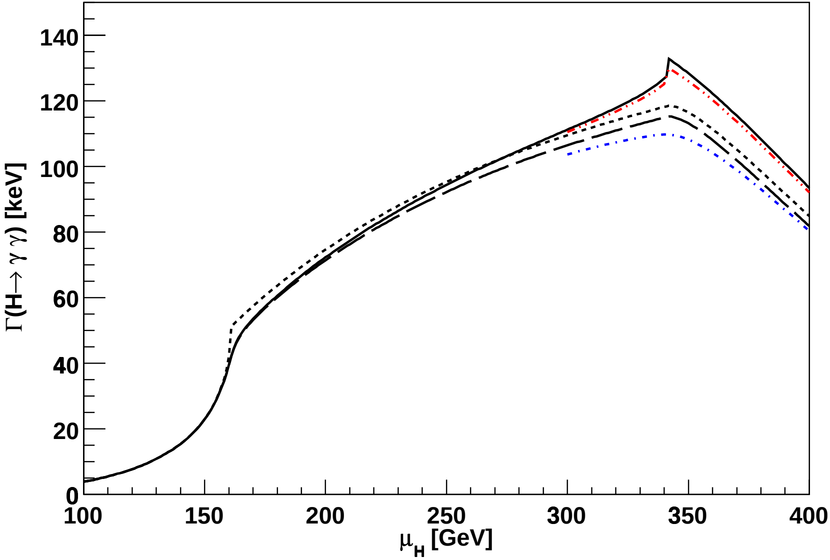


Figure: $\Gamma(H \to \gamma\gamma)$; RMRP (dotted line), CMRP (dashed line) and the CMCP (solid line)

$\epsilon\pi\iota\lambda o\gamma$os

(1, 2)

1. *We get a consistent PO definition of mass, width, couplings, meaning we can write $\sigma\,(pp \to H) \otimes BR(H \to X)$ as product of* **POs**
2. *This is needed if we want published results in such a way that theorists can later enter their general model parameters, calculate resulting* **POs** *and see how well data constrains this model*

Happening at Higgs Cross Section Working Group
https://twiki.cern.ch/twiki/bin/view/LHCPhysics

$\epsilon\pi\iota\lambda o\gamma os$

(1, 2,)

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Happening at Higgs Cross Section Working Group
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