Higgs Dalitz Decay
My Notes
and Something More

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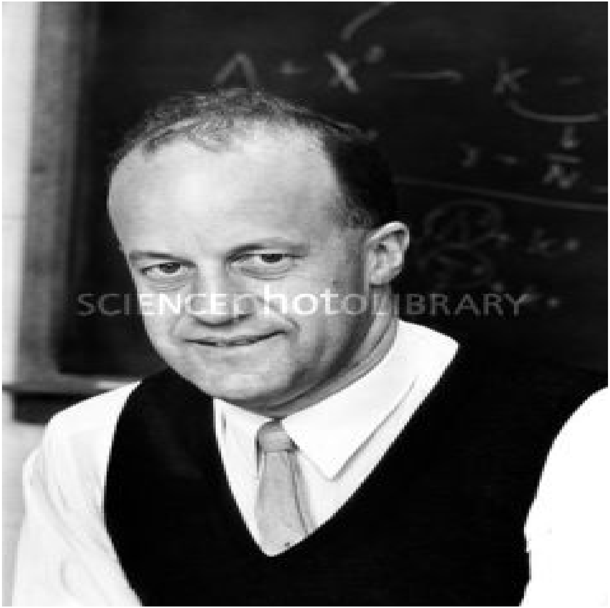
BR meeting, virtual, 7 May 2013

here we go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Prolegomena

From my Logbook:

The question of including Higgs Dalitz Decay

was introduced already during the Freiburg Meeting

Afterwards:

- **Material has been sent to several people,** *documentable*
- **Answers** converging around *Get lost*
- *Meanwhile, it came dangerously close to realizing a nightmare, of Physics done by sub-sets of diagrams instead of cuts.*

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Why Dalitz Decay?

$M_{\mathrm{H}} = 125.5\ GeV$ $\quad$ $\mathrm{BR}\left(\mathrm{H} \to \mathrm{e}^{+}\mathrm{e}^{-}\right) = 5.1 \times 10^{-9}$

while a *naive* estimate gives

$$\mathrm{BR}\left(\mathrm{H} \to \mathrm{Z}\gamma\right) \mathrm{BR}\left(\mathrm{Z} \to \mathrm{e}^{+}\mathrm{e}^{-}\right) = 5.31 \times 10^{-5}$$

4 **orders of magnitude larger**
How much is the corresponding PO extracted from full Dalitz Decay?
Recent estimates claim $\Gamma\left(\mathrm{H} \to \mathrm{e}^{+}\mathrm{e}^{-}\gamma\right) = 5.7\%\,\Gamma\left(\mathrm{H} \to \gamma\gamma\right)$ but photon isolation is not discussed.

Categories

Terminology:

The name **Dalitz Decay** *must be reserved for the full process*

$$\mathrm{H} \to \bar{\mathrm{f}}\mathrm{f}\gamma$$

Subcategories:

$$\begin{cases} \mathrm{H} \to \mathrm{Z}^* \left(\to \bar{\mathrm{f}}\mathrm{f}\right) + \gamma & \textbf{unphysical}^{1} \\ \mathrm{H} \to \gamma^* \left(\to \bar{\mathrm{f}}\mathrm{f}\right) + \gamma & \textbf{unphysical} \\ \mathrm{H} \to \mathrm{Z}_c \left(\to \bar{\mathrm{f}}\mathrm{f}\right) + \gamma & \textbf{PO}^{2} \end{cases}$$

---

[1] Z^* is the off-shell Z

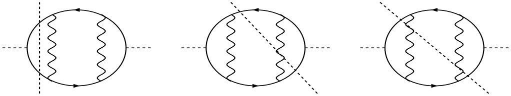
[2] Z_c is the Z at its complex pole

Understanding the problem

$$\mathrm{H} \to \bar{\mathrm{f}}\mathrm{f} \text{ or } \mathrm{H} \to \bar{\mathrm{f}}\mathrm{F} + n\gamma\,?$$

Go to two-loop, the process is considerably more complex than, say, $\mathrm{H} \to \gamma\gamma$ because of the role played by QED and QCD corrections.

The ingredients needed are better understood in terms of cuts of the three-loop H self-energy.



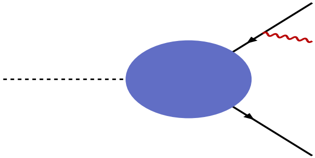
Moral: *Unless you* **Isolate photons** *you don't know which process you are talking about*

$\mathrm{H} \to \bar{\mathrm{f}}\mathrm{f}$ NNLO or $\mathrm{H} \to \bar{\mathrm{f}}\mathrm{f}\gamma$ NLO

The complete S-matrix element will read as follows:

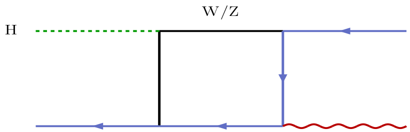
$$
\begin{aligned}
S &= \left| A^{(0)}\left(\mathrm{H} \to \bar{\mathrm{f}}\mathrm{f}\right)\right|^2 \\
&+ 2\,\mathrm{Re}\left[\mathrm{A}^{(0)}\left(\mathrm{H} \to \bar{\mathrm{f}}\mathrm{f}\right)\right]^{\dagger} \mathrm{A}^{(1)}\left(\mathrm{H} \to \bar{\mathrm{f}}\mathrm{f}\right) \\
&+ \left| A^{(0)}\left(\mathrm{H} \to \bar{\mathrm{f}}\mathrm{f}\gamma\right)\right|^2 \\
&+ 2\,\mathrm{Re}\left[\mathrm{A}^{(0)}\left(\mathrm{H} \to \bar{\mathrm{f}}\mathrm{f}\right)\right]^{\dagger} \mathrm{A}^{(2)}\left(\mathrm{H} \to \bar{\mathrm{f}}\mathrm{f}\right) \\
&+ 2\,\mathrm{Re}\left[\mathrm{A}^{(0)}\left(\mathrm{H} \to \bar{\mathrm{f}}\mathrm{f}\gamma\right)\right]^{\dagger} \mathrm{A}^{(1)}\left(\mathrm{H} \to \bar{\mathrm{f}}\mathrm{f}\gamma\right) \\
&+ \left| A^{(0)}\left(\mathrm{H} \to \bar{\mathrm{f}}\mathrm{f}\gamma\gamma\right)\right|^2 .
\end{aligned}
$$

Don't get trapped by your intuition, the **IR/collinear** stuff will not survive in the limit $m_{\rm f} \to 0$



There are **genuinely non-QED(QCD)** terms surviving the **zero-Yukawa** limit (a result known since the '80s)

Dalitz box



- **Collinear/Virtual** cancel in the total
- **Gram and Cayley** do not generate real singularities
- *Plenty* of hard stuff around

Only the total *Dalitz Decay* has a meaning and *can be differentiated through cuts*

- The most important is the definition of *visible photon* to distinguish between $\bar{f}f$ and $\bar{f}f\gamma$
- Next cuts are on $M(\bar{f}f)$ to *isolate* pseudo-observables
- One has to distinguish:
  - $H \to \bar{f}f +$ **soft(collinear)** photon(s) which is part of the real corrections to be added to the virtual ones in order to obtain $H \to \bar{f}f$ at (N)NLO
  - a **visible** photon and a soft $\bar{f}f$-pair where you probe the Coulomb pole and get large (logarithmic) corrections that nobody really knows how to exponentiate.

Unphysical $H \to Z\gamma \to \bar{f}f\gamma$ and $H \to \gamma\gamma \to \bar{f}f\gamma$

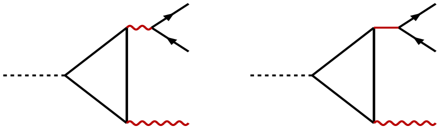
- None of these contributions exists by itself, each of them is **NOT even gauge invariant.** One can put cuts and
  - with a small window around the Z-peak the pseudo-observable $H \to Z_c\gamma$ can be enhanced, but there is a contamination due to many non-resonant backgrounds
  - Beware of generic statements *box contamination in* $H \to Z\gamma$ *is known to be small* and of *ad-hoc* definition of gauge-invariant **splittings**
  - at small di-lepton invariant masses γ^* dominates.

Partial Summary

- $\mathrm{H} \to \bar{\mathrm{f}}\mathrm{f}$ is well defined and $\mathrm{H} \to \bar{\mathrm{f}}\mathrm{F} + \gamma$ (γ **soft+collinear**) is part of the corresponding NLO corrections

- $\mathrm{H} \to \mathrm{Z}\gamma$ is not well defined being a gauge-variant part of $\mathrm{H} \to \bar{\mathrm{f}}\mathrm{F} + \gamma$ (γ **visible**) and can be *extracted* (in a PO sense) by *cutting the di-lepton invariant mass*.

Intuition



Facts of life with non-resonant

Discalimer

I am giving this talk with a twisted arm

Its is like asking **ATLAS** to present results before approval
(My) approval status not yet granted to my results

Structure of the calculation

- Process: $\mathrm{H} \to \bar{\mathrm{f}}\mathrm{f}\gamma$, $\mathrm{f} = \mathrm{l}, \mathrm{q}$,
  including b with non-zero m_{t}
- Setup: $m_{\mathrm{f}} = 0$ at NLO. Calculation based on helicity amplitudes
  LO and NLO do not interfere (with $m_{\mathrm{f}} = 0$)

Cuts available in the H rest-frame
Please complain but it took years to interface *POWHEG* and *Prophecy4f* ......
$\mathrm{gg} \to \bar{\mathrm{f}}\mathrm{f}\gamma$? Can be done, *But* ......

Features

- Internal cross-check, loops are evaluated both *analytically* and *numerically* (using BST-algorithm)
- The code makes extensive use of *In-House* abbreviation algorithms (if $a+b$ appears twice or more it receives an abbreviarion and it is pre-computed only once).
- All functions are **collinear-free**
- High performances thanks to gcc-4.8.0
- *Open MPI* version under construction, *GPU* version in a preliminar phase
- Returns the full result and also the unphysical components

Man at work

- Extensions: as it was done during Lep times, there are diagrams where both the Z and the γ propagators should be Dyson-improved, i.e.

$$\alpha_{\mathrm{QED}}(0) \to \alpha_{\mathrm{QED}}(\mathrm{virtuality}) \qquad \rho_{\mathrm{f}} - \text{parameter included}$$

- However, the interested sub-sets are not gauge invariant, therefore appropriate subtractions must be performed (at virtuality $= 0$, s_{Z}, the latter being the Z complex-pole).

In the meantime rely on

Ali Abbasabadi, David Bowser-Chao, Duane A. Dicus), Wayne W. Repko. Nov 1996. 18 pp.
Phys.Rev. D55 (1997) 5647-5656 Yi Sun, Hao-Ran Chang,

Dao-Neng Gao. Mar 9, 2013. 16 pp.
e-Print: arXiv:1303.2230

- *Warning* photon isolation is not discussed

Old plot, Abbasabadi et al. parameters unknown, no isolation

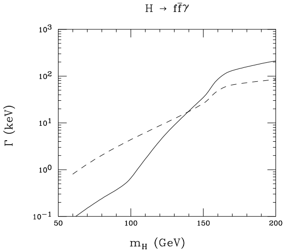


FIG. 5. The partial width $\Gamma(H \to f\bar{f}\gamma)$, obtained by summing the neutrino, electron, muon, up quark, down quark and strange quark contributions is shown as the solid line. For comparison, the dashed line is the partial width $\Gamma(H \to \gamma\gamma)$.

Finally, cuts at 125 GeV

Duane A. Dicus, Wayne W. Repko. Feb 8, 2013
e-Print: arXiv:1302.2159 [hep-ph]

- $E_\gamma > 5\ GeV$, $E_{l_1} > 25\ GeV$ and $E_{l_2} > 7\ GeV$
- s-cut, $M\left(\bar{f}f\right) > x\,M_H$
- t-cut, $M\left(\bar{f}\gamma\right) > x\,M_H$, $M\left(f\gamma\right) > x\,M_H$

Untuned, *face-value* comparison,
CPS implemented in DHTO

$s - \mathrm{cut} = 0.1$	$t - \mathrm{cut} = 0.1$
DR	DHTO(preliminar)
$\Gamma = 0.243\ keV$	$\Gamma = 0.229\ keV$

DHTO preliminar

$$\Gamma_{\mathrm{NLO}} = 0.229\ keV \quad \oplus \quad \begin{cases} \Gamma_{\mathrm{LO}} = 0.29 \times 10^{-6}\ keV & \mathrm{e} \\ \Gamma_{\mathrm{LO}} = 0.012\ keV & \mu \\ \Gamma_{\mathrm{LO}} = 3.504\ keV & \tau \end{cases}$$

LO and NLO **do not interfere**, they belong to different helicity sets

DHTO preliminar

$0.1\,M_{\mathrm{H}}$-cut

e	$\mathrm{d-}$quark
$\Gamma_{\mathrm{tot}} = 0.229\ keV$	$\Gamma_{\mathrm{tot}} = 0.567\ keV$
$\Gamma_{\gamma^*} = 0.025\ keV$	$\Gamma_{\gamma^*} = 0.008\ keV$
$\Gamma_{\mathrm{Z}^*} = 0.025\ keV$	$\Gamma_{\mathrm{Z}^*} = 0.112\ keV$

$M_{\mathrm{Z}} - 2\Gamma_{\mathrm{Z}} < M\left(\bar{\mathrm{f}}\mathrm{f}\right) < M_{\mathrm{Z}} + 2\Gamma_{\mathrm{Z}}$

$\Gamma_{\mathrm{tot}} = 0.092\ keV$	$\Gamma_{\mathrm{tot}} = 0.392\ keV$
$\Gamma_{\mathrm{Z}^*} = 0.022\ keV$	$\Gamma_{\mathrm{Z}^*} = 0.097\ keV$

Misunderstandings

- use $M(\bar{f}f\gamma)$ and require $|M - M_Z| < n\Gamma_Z$. *This is not the photon we are discussing*
  Photons are collinear to leptons only if emitted by leptons but those are Yukawa-suppressed.
  In any case $M(\bar{f}f\gamma) = M_H$ or it is *Not* Dalitz decay
- Requiring a cut on the opening angle between leptons and the photon to define *isolated photons* is highly recommended, *But* at the moment we are still in the Higgs rest-frame (*Miracles take a bit longer*)

Conclusions

If you are *throat thirsty* for numbers
contact Dicus and Repko