Simplified template cross sections for Higgs boson decays

Authorlist

Abstract
Definition of STXS Higgs decay modes and bins

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Higgs, decay, STXS

1 Introduction

For a STXS classification of Higgs boson decays, it is essential to be able to determine for each event, which decay mode it should be assigned to. The classification should be made based on the number and type of final state particles from the Higgs decay and their kinematic properties.

The aim of this document is to establish such a categorization with categories that capture the bulk of the decay events within a certain decay process. In analogy to the STXS scheme in the Higgs production modes [1–3], this categorization would be called Stage 0 STXS decay bins. As a secondary goal, additional kinematic Stage 1 sub-bins are proposed for the $H \to ZZ^* \to 4\ell$ and $H \to WW^* \to \ell\nu\ell\nu$ processes.

2 Fiducial particles

The following gives the fiducial particle definitions. It is understood that only particles coming from the Higgs decay are considered. Possible issues in the definitions:

- For practical purposes it would be much better to work only with Lorentz invariant definitions. While having a ΔR cone in the Higgs rest frame could be seen as such, some invariant mass related definition could be much better.
- No kinematic cuts are applied in section 3 on particles, only cuts on invariant masses of multi-particle systems are considered. This could cause issues with very low momentum particles. On the other hands, adding a momentum cut could cause issues with particles getting a large boost and then entering experimental acceptance.
- Difficult cases, like having a low momentum electron close to a high momentum photon, need a consistent approach to lepton and photon definitions. Should such a case be handled as high pT dressed lepton or high pT photon? Using a (Lorentz invariant?) jet like clustering and then labeling according to the leading momentum fraction might be an option.

2.1 Dressed leptons

In the following, all electrons and muons (TODO: decide on how to treat tau) are understood as dressed leptons. Bare leptons are dressed only with photons coming from the Higgs decay within a cone of dR=0.1 in the Higgs rest frame, following the Rivet [4] dressed lepton definition [5]. A photon within the dR=0.1 cone of several bare leptons is only added to the closest bare lepton in order to avoid double counting. Possible issues:

- How to treat the case of a high momentum photon and a very low momentum lepton?
- It needs to be checked if di-lepton invariant mass definitions are sufficiently large to avoid large logs in electroweak corrections of other decays that could lead to the same final state, e.g. $H \to ff + EW = H \to ff\mu\mu$ or similar.

2.2 Isolated photons

For each photon the scalar momentum sum (WARNING: usual scalar p_T sum is used!) of charged particles that also come from the Higgs decay within a cone of ΔR=0.2 around the photon in the Higgs rest frame is required to be less than 5% of the photon momentum. Possible issues:

- Should very low momentum charged particles enter the isolation?
- How to treat the case of a very low momentum photon? Are they counted in the decay classification?

2.3 Neutrinos

If needed, neutrinos from the Higgs decay are taken without any special treatment.

2.4 Quarks

Quarks cannot be used for the decay classification, as they are not final state particles. Hence, some form of jet algorithm needs to be run. Possible issues:

- How to define the jets and which particles from the Higgs decay enter into jets?
- How are leptons and photons included in jets?
- What is the minimum momentum for a jet?
- How is the flavour of a jet initiated by b- or c-quarks, light quarks or gluons defined?

3 Stage 0: Definition of final state

Table 1 gives an overview of the kinematic definition of Higgs decay modes. THE TABLE IS NOT COMPLETE, ESPECIALLY THERE WAS NO CARE YET HOW TO CORRECTLY TREAT CASES WITH AND WITHOUT SAME FLAVOUR, OPPOSITE CHARGE FERMION PAIRS. All numbers and definitions are first placeholders defined almost without any studies or plots to back them up!

Label	Final state	Kinematic selection	Comment
$H \to ee$	$H \to ee + X$	$m_{ee} \geq 120$ GeV	Section 3.1
$H \to ff$	$H \to f\bar{f} + X$	$m_{ff} \geq 105$ GeV	Section 3.1
$H \to Z\gamma$	$H \to ee + \gamma + X$	$50 \leq m_{ff} < 120$ GeV, $m_{ff\gamma} \geq 120$ GeV	Section 3.1
$H \to Z\gamma$	$H \to ff + \gamma + X$	$50 \leq m_{ff} < 105$ GeV, $m_{ff\gamma} \geq 120$ GeV	Section 3.1
$H \to \gamma^*\gamma$	$H \to ff + \gamma + X$	$m_{ff} < 50$ GeV, $m_{ff\gamma} > 120$ GeV	Section 3.1
$H \to \gamma\gamma$	$H \to \gamma\gamma$	$m_{\gamma\gamma} = 125$ GeV	Section 3.1
$H \to 4\ell$	$H \to 4\ell + X$	$m_{34} \geq 10$ GeV, $m_{34} \leq m_{12} < 105$ GeV	Section 3.2
$H \to 2e2\mu$	$H \to 2e2\mu + X$	$m_{34} \geq 10$ GeV, $m_{34} \leq m_{12} < 105$ GeV	Section 3.2
$H \to 2\ell 2\nu$	$H \to \ell\ell\nu\nu + X$	$80 \leq m_{2\ell} < 105$ GeV	Section 3.3
$H \to 2\ell 2f$	$H \to \ell\ell ff + X$	$80 \leq m_{2\ell} < 105$ GeV, $ff! = ee, \mu\mu, \nu\nu$	Section 3.4
$H \to \ell\nu\ell\nu$	$H \to \ell\nu\ell\nu + X$	$10 < m_{\ell\ell} < 80$ GeV	Section 3.3
$H \to e\nu\mu\nu$	$H \to e\nu\mu\nu + X$	$10 < m_{e\mu} < 105$ GeV	Section 3.3
$H \to \ell\nu ff'$	$H \to \ell\nu ff' + X$	$10 < m_{\ell\nu} <?$ GeV	Section 3.4
$H \to fff'f'$	$H \to fff'f' + X$	$10 < m_{12} < 105$ GeV, $fff'f'! =$modes above	Section 3.5
$H \to f_1 f_2 f_3 f_4$	$H \to f_1 f_2 f_3 f_4 + X$	$f_1 f_2 f_3 f_4! =$modes above	Section 3.5

Table 1: Kinematic definition of Higgs decay modes. Only particles originating from the Higgs decay are considered. Definitions: $4\ell = 4e, 4\mu$; $2\ell = ee, \mu\mu$

3.1 $H \to ff$, $H \to Z\gamma$, $H \to \gamma^*\gamma$ and $H \to \gamma\gamma$

Figure 4 in Ref. [6] show the transition between $H \to ee$ and $H \to Z(\to ee)\gamma$ around 120 GeV. The transition for $\mu\mu$ is around 105 GeV (Figure 5 in Ref. [6]). The transition between the $H \to \gamma^*\gamma$ and $H \to Z\gamma$ process is around 50 GeV in both cases. Open questions:

- Exact value of transitions
- Is the $m_{ff\gamma}$ cut needed for $H \to Z\gamma$ and $H \to \gamma^*\gamma$?
- What is the distinction between $H \to \gamma^*\gamma$ and $H \to \gamma\gamma$ with converted photons?
- How to treat $\tau\tau$ decays. Figure 6 in Ref. [6] would indicate that the tree level $H \to \tau\tau$ decay is dominating for almost the whole mass range
- How should final state QCD radiation be handled for processes like $H \to bb$ for a kinematic separation from 4-fermion processes?
- More in general: if f is a quark, will the binning be done according to the quarks or according to some final state jets?

3.2 $H \to 4\ell$

Open questions:

- Exact value of transitions
- Which lepton pairing choice to make if all four leptons have the same flavour
- How to treat $\tau\tau$ decays

3.2.1 Lepton pairing definition in $H \to 4\ell$

To be worked out by ATLAS and CMS

3.2.2 Stage 1: Definition of additional bins in m_{34}

To be worked out by ATLAS and CMS. Starting point of discussion: Bin boundaries at

m_{34}	[10,20)	[20,35)	[35,m_{12})

Table 2: Bin definitions for $H \to 4\ell$

3.3 $H \to \ell\ell\nu\nu$, $H \to \ell\nu\ell\nu$ and $H \to e\nu\mu\nu$

Open questions:

- Exact value of transitions, especially for the kinematic separation of $H \to ZZ^* \to \ell\ell\nu\nu$ from $H \to WW^* \to \ell\nu\ell\nu$
- How to treat $\tau\tau$ decays

3.3.1 Stage 1: Definition of additional bins in $m_{\ell\ell}$

To be worked out by ATLAS and CMS. Starting point of discussion: Bin boundaries at

$m_{\ell\ell}$	[10,30)	[30,50)	[50,80)
$m_{e\mu}$	[10,30)	[30,50)	[50,105)

Table 3: Bin definitions for $H \to \ell\nu\ell\nu$

3.4 Semileptonic 4-fermion decays

Semileptonic Higgs decays of the type $H \to ZZ^* \to \ell\ell ff$ or $H \to WW^* \to \ell\nu ff$ are currently not well constrained experimentally. The ttH multi-lepton channel and the $VH, H \to WW^*$ measurements likely have the largest signal components. Open questions:

- How to treat $\tau\tau$ decays
- How to best treat the large number of possible fermion combinations
- What to do about $H \to ZZ^* \to \nu\nu ff$?

3.5 Hadronic 4-fermion decays

Hadronic Higgs decays of the type $H \to ZZ^* \to ffff$ or $H \to WW^* \to ffff$ are currently not constrained experimentally. Open questions:

- How to treat $\tau\tau$ decays
- How to best treat the large number of possible fermion combinations
- If jets are used, how to treat 3-jet or 5-jet events?

Acknowledgements

Bibliography

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