The long pending open question: How shall we make general measurements of Higgs decay properties

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0st edition: informal discussion, Les Houches 2017
1st edition: STXS/fiducial meeting, 17th May 2018
2nd edition: Les Houches, 12th June 2019
3rd edition: LHC Higgs XS WG workshop, 17th October 2019
4th edition: LHC Higgs XS WG2 STXS/fid meeting, 1st July 2020
5th edition: LHC Higgs XS WG workshop, 9th Nov 2020

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Long history of discussions

- After discussions over several years, no consensus was found so far for some form of continuous decay observable definition
- However, an STXS like approach defining simple kinematic bins, for example in H→ZZ→4l or in H → WW→lnln, could be a path forward
  - Such bins would match what is called "stage 1" in the production STXS bins
  - Before we can go to "stage 1", we have to go through the tiresome task to define “stage 0”:
    What is meant by “H→ZZ→4l” or
    “H → WW→lnln"? What is "H→bb" in terms of final state particles?
- Remember: Higgs decay is 4π symmetric, no preferred direction! Do everything in Higgs rest frame!

What is the question???

- Example: a generator produces a Higgs decay with a $b\bar{b}$-pair of 110 GeV and an e+e- pair of 5 GeV
- What process is this? If we want to define decay bins, we should be able to tell for each event where it belongs!
  - $H \rightarrow ZZ^* \rightarrow (Z \rightarrow bb)(Z \rightarrow ee)$?
  - $H \rightarrow Z\gamma^* \rightarrow (Z \rightarrow bb)(\gamma^* \rightarrow ee)$?
  - $H \rightarrow bb$+EW correction$\rightarrow bb\gamma^* \rightarrow bb(\gamma^* \rightarrow ee)$
- We don't need something extremely sophisticated. It needs to make sense and it needs to be a solid quantitative definition based on decay kinematics
- In the following: a first proposal, NOT backed by dedicated studies! Feedback and ideas absolutely needed!

Fiducial objects

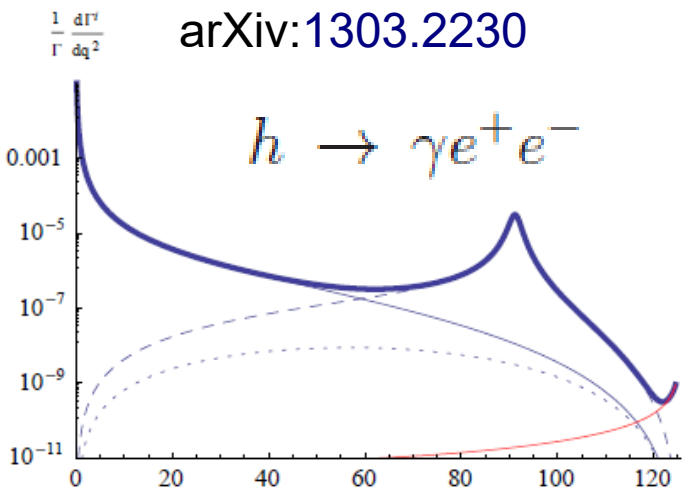
- **Consider only (prompt?) Higgs decay final state particles for all quantities.**
- **Leptons: use only dressed leptons**
  - **Dress bare electrons, muons (and taus?) with photons within dR<X (Rivet dressing)? X=0.1?**
- **Photons: use only isolated photons**
  - **Momentum sum of charged particles in dR<Y smaller than Z% of photon momentum? Y=0.2 and Z=5%?**
- **Quarks: use jets**
  - **Postpone for now, highly non-trivial how to define e.g. a b- or c-jet**
- **General issues:**
  - While a dR cone in a properly rotated Higgs rest frame could be seen as "Lorentz invariant", a truly Lorentz invariant definition would be much better. Using a (Lorentz invariant) jet-like clustering might be better?
  - Do we want/need kinematic cuts (on momentum?) in the Higgs rest frame?
  - Example: 600 MeV electron next to 20 GeV photon. Is this a dressed 20.6 GeV electron or a 20 GeV photon?

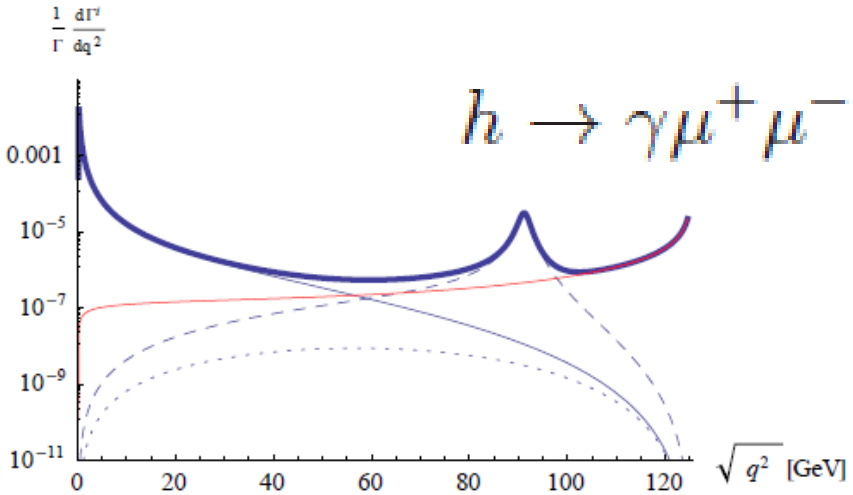
H→ff̄, H→Zγ, H→γ*γ

Label	Final state	Kinematic selection
$H \to ee$	$H \to ee + X$	$m_{ee} \geq 120$ GeV
$H \to ff$	$H \to f\bar{f} + X$	$m_{ff} \geq 105$ GeV
$H \to Z\gamma$	$H \to ee + \gamma + X$	$50 \leq m_{ff} < 120$ GeV, $m_{ff\gamma} \geq 120$ GeV
$H \to Z\gamma$	$H \to ff + \gamma + X$	$50 \leq m_{ff} < 105$ GeV, $m_{ff\gamma} \geq 120$ GeV
$H \to \gamma^*\gamma$	$H \to ff + \gamma + X$	$m_{ff} < 50$ GeV, $m_{ff\gamma} > 120$ GeV

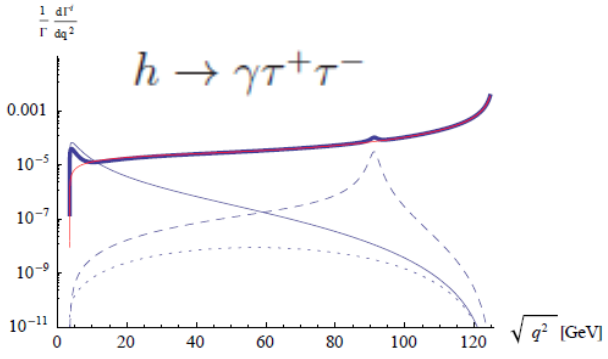
Needed?

arXiv:1303.2230





Some very interesting discussions in the
BR subgroup meeting May 2013 and
BR subgroup meeting Sep 2019: E_γ>X GeV?



H→γ*γ, H→γγ

$H \to \gamma^*\gamma$	$H \to ff + \gamma + X$	$m_{ff} < 50$ GeV, $m_{ff\gamma} > 120$ GeV
$H \to \gamma\gamma$	$H \to \gamma\gamma$	$m_{\gamma\gamma} = 125$ GeV

Needed?

- What are the best values for the transitions between bins?
- Is the $m_{ff\gamma}$ cut needed for H→Zγ and H → γ*γ?
- What is the distinction between H → γ*γ and H → γγ with converted photons?
- How to treat ττ decays? Figure on previous slide would indicate that the tree level H→ττ decay is dominating for almost the whole mass range
- How should final state QCD radiation be handled for processes like H→bb for a kinematic separation from 4-fermion processes?

H→4l, H→2l2f

$H \to 4\ell$	$H \to 4\ell + X$	$m_{34} \geq 10$ GeV, $m_{34} \leq m_{12} < 105$ GeV
$H \to 2e2\mu$	$H \to 2e2\mu + X$	$m_{34} \geq 10$ GeV, $m_{34} \leq m_{12} < 105$ GeV
$H \to 2\ell 2\nu$	$H \to \ell\ell\nu\nu + X$	$80 \leq m_{2\ell} < 105$ GeV
$H \to 2\ell 2f$	$H \to \ell\ell ff + X$	$80 \leq m_{2\ell} < 105$ GeV, $ff! = ee, \mu\mu, \nu\nu$

- **What are the best values for the transitions between bins?**
- **Which lepton pairing choice to make if all four leptons have the same flavor**
- **How to treat ττ decays?**
- **Is a cut of m_{34}>10 GeV safe with respect to large logarithms that might appear in H→ff+EW corrections?**
- **Possible stage 1:**

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

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

- **Note: once m_{34} is fixed inside some bin, the q^2 is essentially fixed and one could bin/expand further in the future**

H→2l2n, H→lnln

$H \to \ell\nu\ell\nu$	$H \to \ell\nu\ell\nu + X$	$10 < m_{\ell\ell} < 80$ GeV
$H \to e\nu\mu\nu$	$H \to e\nu\mu\nu + X$	$10 < m_{e\mu} < 105$ GeV
$H \to \ell\nu f f'$	$H \to \ell\nu f f' + X$	$10 < m_{\ell\nu} <?$ GeV

- **What are the best values for the transitions between bins? Especially for the kinematic separation of H→ZZ*→2l2n from H→WW*→lnln**
- **How to treat ττ decays?**

Stage 1:

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

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

H→4f

$H \to ffff'f'$	$H \to ffff'f' + X$	$10 < m_{12} < 105$ GeV, $ffff'f'!$ =modes above
$H \to f_1f_2f_3f_4$	$H \to f_1f_2f_3f_4 + X$	$f_1f_2f_3f_4!$ =modes above

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?

Summary

- **Coming up with a good first proposal for STXS-like bins for Higgs decays is less trivial then it might seem**
- **Next step: stop talking, start coding**
- **Ideas and help are very welcome**