STXS in Higgs decays: $H \to 4l$

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Goals

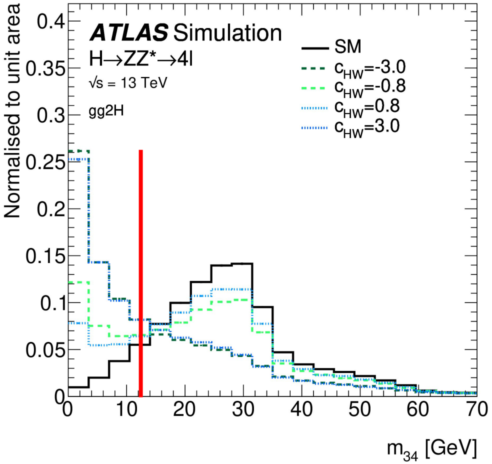
Make Higgs decay measurements that can be used as input to theory interpretations

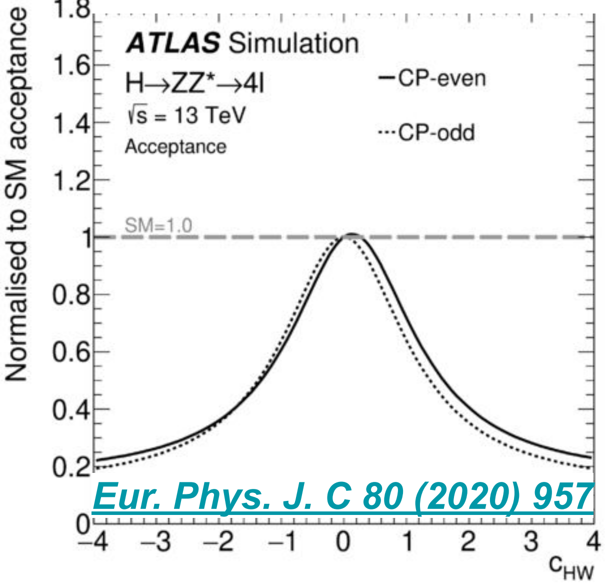
- **Stage 0**: current STXS measurements are done inclusive in the Higgs decay modes, although experiments don't necessarily measure inclusively
  ⇒ For each decay mode define a phase space region that approximates the experimental acceptance

- Stage 1: Measure properties within each decay mode
  ⇒ Allow decay properties to be used to constraint BSM effects in this decay

Why do we need a Stage 0?

- Experimental measurements are not inclusive
- Example: The acceptance of the ATLAS H→4l measurement shows a sizeable dependence on EFT parameters that is “resolved” by having EFT parameter dependent acceptance corrections
- Experiments apply a cut of m>10 GeV on the subleading lepton pair in H→4l that has a high acceptance for the SM, but the acceptance can be low for some BSM models





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Lorentz invariance

- When we measure a Higgs decay property, this measurement should be valid independent of the Higgs production mode or boost of the Higgs
- The measurement should be valid for LHC 7, 8, 13, 13.6 and 14 TeV
- It should be valid for pp and e^+e^- colliders
- Fortunately the Higgs is Spin 0, so production and decay completely decouple

- But all of the above is only possible, if our STXS decay selection is Lorentz invariant

➢ For each Higgs decay mode, we need a Lorentz invariant simple fiducial STXS decay selection
➢ This will also provide a clean definition of what $H \to ZZ^* \to 4l$, $H \to Z\gamma^* \to 4l$, $H \to \gamma^*\gamma^* \to 4l$, $H \to WW^* \to l\nu l\nu$ is beyond the Pythia decay mode selection

Not quite as complicated as it may sound

- $H \to 2$ body decays: decay objects are back-to-back in the Higgs rest frame.
  ⇒ No kinematic information in the decay!
  ⇒ We will still want some simple fiducial object definition. E.g. what is a “b”?

- Non-trivial decays (today): $H \to Z^{(*)}\gamma \to ll\gamma$, $H \to WW^* \to l\nu l\nu$, $H \to ZZ^* \to 4l$

- Highest priority is $H \to ZZ^* \to 4l$ as current measurements are already affected by the tension of unfolding the experimental selection to the inclusive $H \to 4l$ decay

State of development

- Attached to the agenda is a (simple) writeup that gives more information on the current stage of development for decay selections
- This is NOT final and
  In many cases not well developed at all

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
$H \to f_1f_2f_3f_4$	$H \to f_1f_2f_3f_4 + X$	$f_1f_2f_3f_4!$ =modes above	Section 3.5

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

Goal for today: $H \to ZZ^* \to 4l$

- Present first candidates for a Lorentz invariant simple fiducial $H \to ZZ^* \to 4l$ selection

- The simple fiducial selection should
  - be "larger" than the experimental reconstruction selection, e.g. contain almost all events reconstructed as $H \to ZZ^* \to 4l$ in the experiments
  - have the same residual acceptance for SM and BSM models. Since we consider only Higgs decays Q^2 is fixed to 125 GeV and EFT models should span almost all BSM phase space. This makes the STXS decay measurement valid for BSM interpretations (<=> unfolding)
  - have the same residual acceptance for critical decay variables as function of BSM model parameters for SM and BSM models. This allows to use decay properties for BSM interpretation

- Ultimately we want to change what ATLAS and CMS quote as $H \to ZZ^*$.

  Instead of measuring the decay inclusive $H \to ZZ^*$: $\sigma_{ggH}(0jet, pT0\text{-}10) * BR(H \to ZZ^*)$

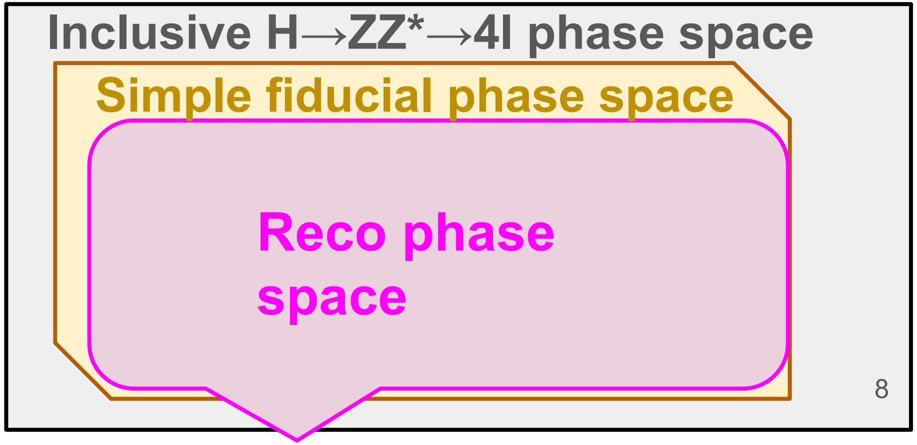
  Measure using a simple fiducial decay selection: $\sigma_{ggH}(0jet, pT0\text{-}10) * BR^{fid}(H \to 4l)$

From ATLAS experimental to simplified fiducial selection

Leptons and Jets	
Electrons	$E_T > 7$ GeV and $\lvert\eta\rvert < 2.47$
Muons	$p_T > 5$ GeV and $\lvert\eta\rvert < 2.7$, calorimeter-tagged: $p_T > 15$ GeV
Jets	$p_T > 30$ GeV and $\lvert\eta\rvert < 4.5$
Quadruplets	
All combinations of two same-flavour and opposite-charge lepton pairs	
- Leading lepton pair: lepton pair with invariant mass m_{12} closest to the Z boson mass m_Z	
- Subleading lepton pair: lepton pair with invariant mass m_{34} second closest to the Z boson mass m_Z	
Classification according to the decay final state: 4μ, $2e2\mu$, $2\mu2e$, $4e$	
Requirements on each quadruplet	
Lepton reconstruction	- Three highest-p_T leptons must have p_T greater than 20, 15 and 10 GeV - At most one calorimeter-tagged or stand-alone muon
Lepton pairs	- Leading lepton pair: $50 < m_{12} < 106$ GeV - Subleading lepton pair: $m_{min} < m_{34} < 115$ GeV - Alternative same-flavour opposite-charge lepton pair: $m_{\ell\ell} > 5$ GeV - $\Delta R(\ell, \ell') > 0.10$ for all lepton pairs
Lepton isolation	- The amount of isolation E_T after summing the track-based and 40% of the calorimeter-based contribution must be smaller than 16% of the lepton p_T
Impact parameter significance	- Electrons: $\lvert d_0\rvert/\sigma(d_0) < 5$ - Muons: $\lvert d_0\rvert/\sigma(d_0) < 3$
Common vertex	- χ^2-requirement on the fit of the four lepton tracks to their common vertex
Selection of the best quadruplet	
- Select quadruplet with m_{12} closest to m_Z from one decay final state in decreasing order of priority: 4μ, $2e2\mu$, $2\mu2e$ and $4e$	
- If at least one additional (fifth) lepton with $p_T > 12$ GeV meets the isolation, impact parameter and angular separation criteria, select the quadruplet with the highest matrix-element value	
Higgs boson mass window	
- Correction of the four-lepton invariant mass due to the FSR photons in Z boson decays	
- Four-lepton invariant mass window in the signal region: $115 < m_{4\ell} < 130$ GeV	
- Four-lepton invariant mass window in the sideband region: $105 < m_{4\ell} < 115$ GeV or $130 < m_{4\ell} < 160$ (350) GeV	

- Only Lorentz invariant selections
- >99% of reco events also covered by the simple fiducial selection → no events "lost" !

Event selection (at most one quadruplet per event)	
Momentun of leptons	Leptons momentum in the Higgs rest frame $p > 4$ GeV
Mass requirements	$50\text{ GeV} < m_{12} < 106$ GeV and $12\text{ GeV} < m_{34} < 115$ GeV
Lepton separation	$Angle(\ell_i, \ell_j)$ in the Higgs rest frame $> 0.1(rad.)$
low-mass dilepton veto	$m(\ell_i, \ell_j) > 5$ GeV for all SFOC lepton pairs
Mass window	$115\text{ GeV} < m_{4\ell} < 130$ GeV

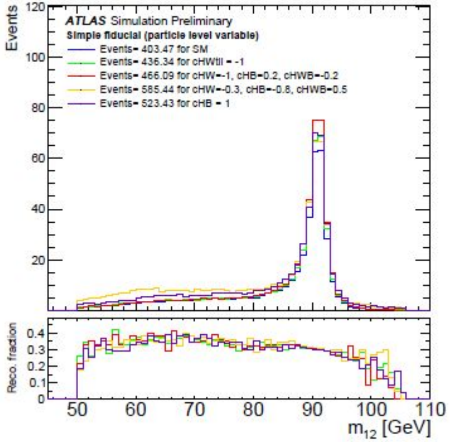


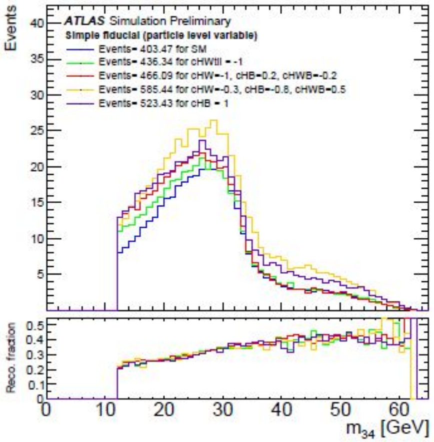
ATLAS: Check model dependence: compare SM to SMEFT

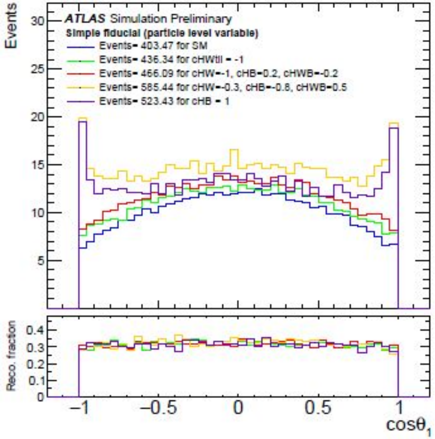
- Key quantity to study: residual effects of reconstruction

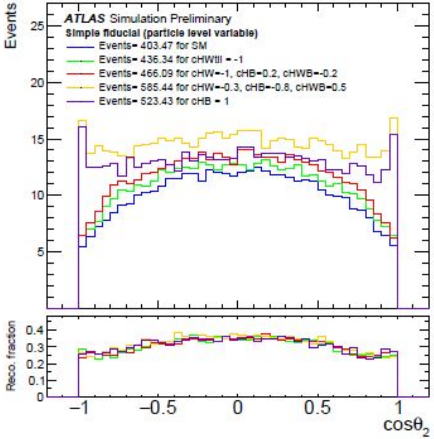
$$\text{reconstruction fraction} = \frac{\text{Reconstruction \& Fiducial}}{\text{Fiducial}}$$

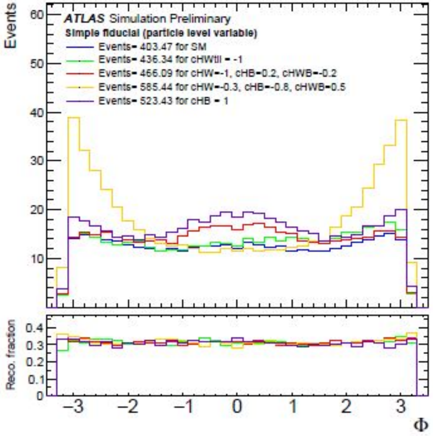
- Ideal: flat reco. Fraction
- Good enough: the same distribution for SM and BSM

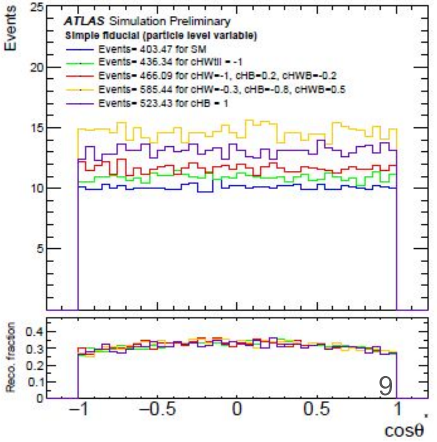












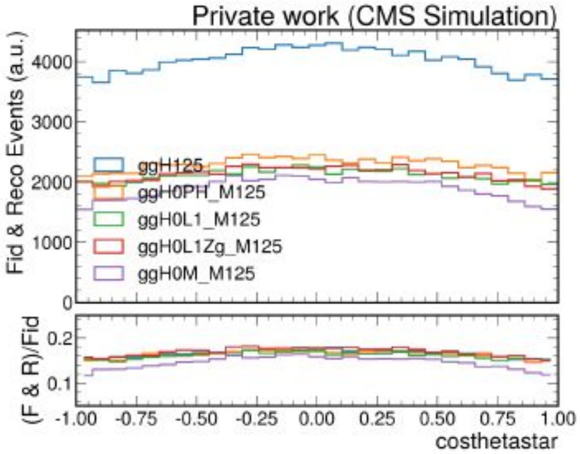
From CMS experimental to simplified fiducial selection

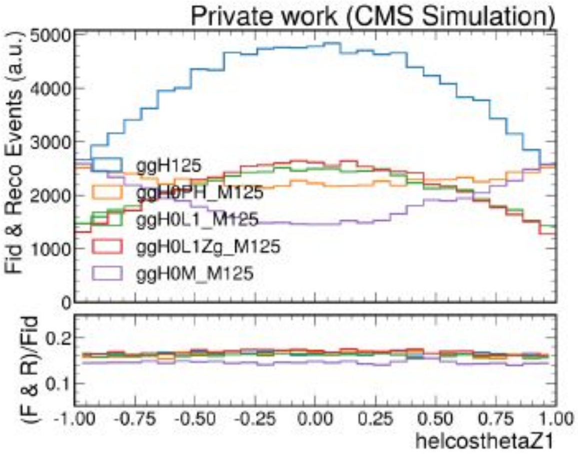
Selection	HIG-21-009	simplified*
Leading lepton	$p_T > 20$ GeV	$\boldsymbol{p > 4}$ **GeV**
Sub-leading lepton	$p_T > 10$ GeV	$\boldsymbol{p > 4}$ **GeV**
Additional electrons (muons)	$p_T > 7(5)$ GeV	$\boldsymbol{p > 4(4)}$ **GeV**
Pseudorapidity of electrons (muons)	$\|\eta\| < 2.5(2.4)$	no restrictions
Cone for dressing bare leptons with photons	$\Delta R = 0.3$	$\boldsymbol{\Delta R = 0.1}$
Inv. mass of the Z_1 candidate	$40 < m_{12} < 120$ GeV	$50 < m_{12} < 106$ GeV
Inv. mass of the Z_2 candidate	$12 < m_{34} < 120$ GeV	$12 < m_{34} < 115$ GeV
Distance between selected four leptons	$\Delta R_{ll} > 0.02$	$\boldsymbol{\Delta R_{ll} > 0.1}$
Inv. mass of any opposite sign lepton pair	$m_{ll} > 4$ GeV	$m_{ll} > 5$ GeV
Inv. mass of the selected four leptons	$105 < m_{4l} < 160$ GeV	not (yet) implemented

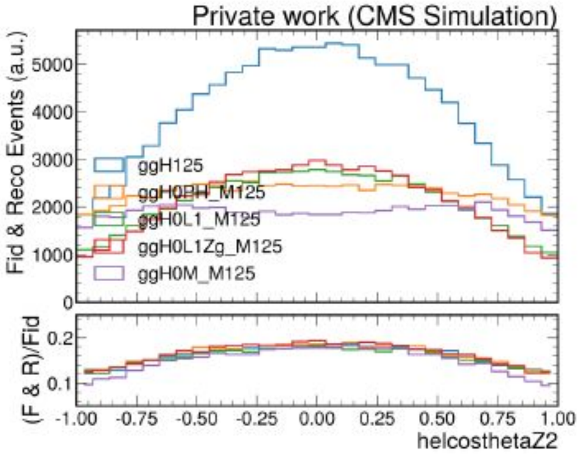
* Almost identical to ATLAS fiducial selection, exception: angle in ΔR place

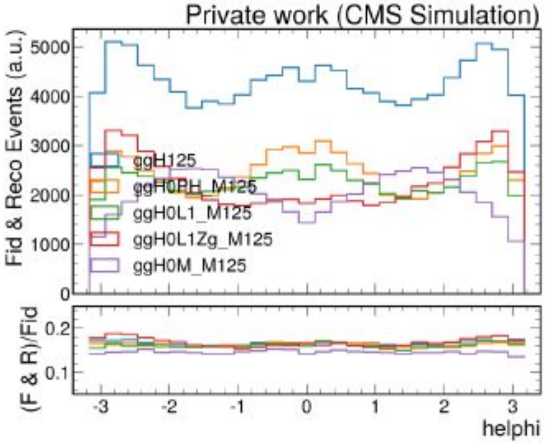
- Started with almost the same simple fiducial selection used by ATLAS
- Because selection matches less well, only ~98% of reco events also covered by the simple fiducial selection.

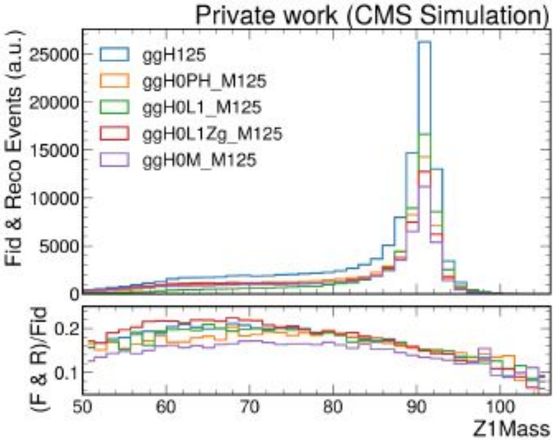
CMS: Check model dependence: compare SM to BSM

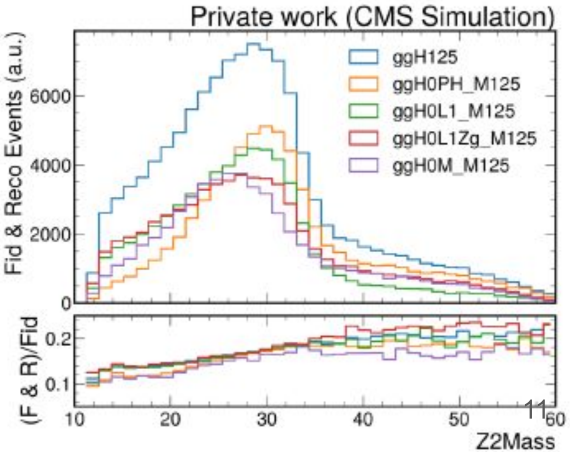












Summary

- A Lorentz invariant simple fiducial selection exists for H→ZZ*→4l that largely (hopefully fully) removes the need for acceptance corrections for BSM interpretations of STXS measurements
- The selection tuned to ATLAS works well for ATLAS and obviously less well for CMS, but still much better than extrapolating to the inclusive phase space
- TODO:
  - Find a compromise simple fiducial selection for H→ZZ*→4l that works equally well for ATLAS and CMS, then agree on it
  - Implement this selection into the LHC H XS WG STXS Rivet code (being worked on), and start using it in the experiments for future STXS measurements
  - Continue the same effort for H→WW*→2l2ν, H→Zγ, …
  - Find fiducial particle definition for gluon-jets, b-jets, c–jets to extend to all Higgs final states