Overview of Higgs Physics In ATLAS

Partikeldagarna 2020

November 23, 2020

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Outline

- Overview of latest activities from ATLAS Higgs + "Higgs and Diboson Searches" (HDBS) groups, with a focus on analyses benefiting from Swedish contributions

  - Higgs precision measurements (*H->WW**)
  - Search for charged Higgs bosons (multi-lepton final states)
  - *HH* searches

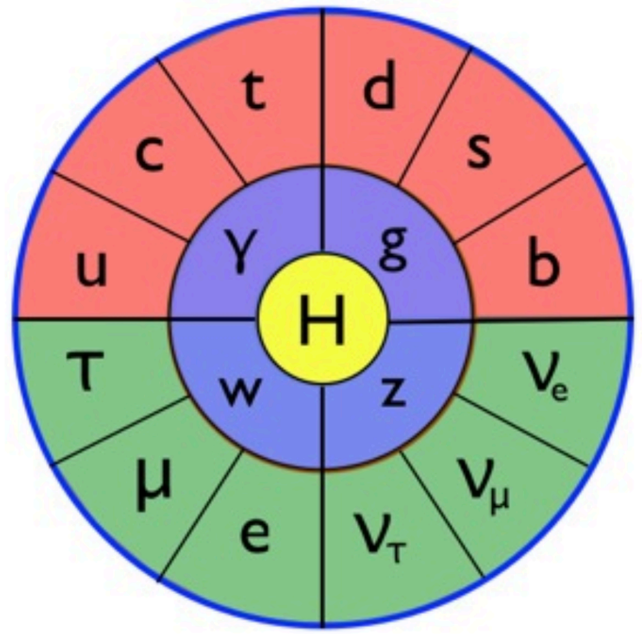
    - $bb\gamma\gamma$ - combination
    - $bb\tau\tau$ - future prospects

Introduction

- Higgs boson discovered in 2012 during Run 1 of the LHC

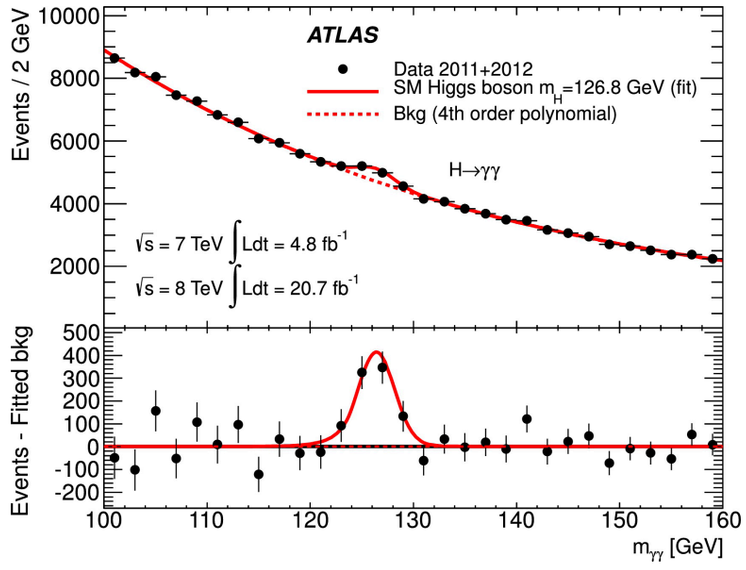
  Observation of a New Particle in the Search for the Standard Model Higgs Boson with the ATLAS Detector at the LHC

  - At the time, referred to simply as "a neutral boson with a measured mass of 126.0 ± 0.4 (stat) ± 0.4 (sys) GeV"



- More complete picture of the Higgs sector now possible with access to Run 2 dataset
  - Precision measurements of fermion/boson couplings and properties
  - Searches for rare processes predicted by the Standard Model (SM), including *HH* production
  - Searches for physics beyond the SM, e.g. charged Higgs boson
- Latest results shown last month at Higgs 2020 conference
- Even further scrutiny on offer with Run 3 and ultimately HL-LHC

H->γγ results from Run 1 ATLAS



arXiv:1307.1427

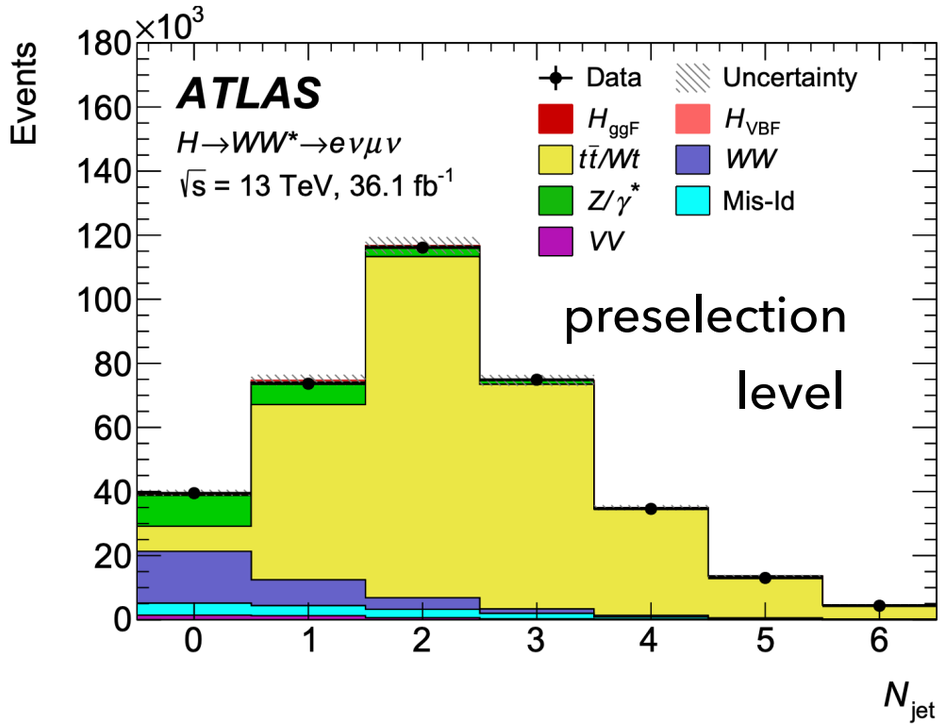
Phys. Lett. B 726 (2013) 88

SM H->*WW** Measurements

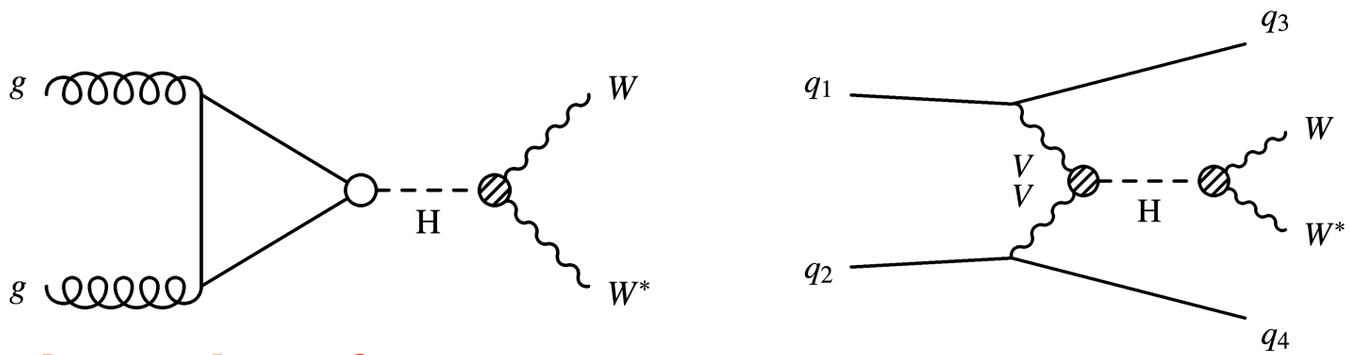
- *WW** second largest branching fraction behind *bb*
- All leading production modes can be probed
  - Clean final state, triggering on leptonic decay of *W*
- Simultaneously measure ggF+VBF channels
  - Two different flavour (*eμ*+*μe*), opposite sign leptons
  - Split into bins of number of jets

    - N_{jets} = 0,1 => ggF; N_{jets} 2+ => VBF

- Associated production with W/Z measured as well in separate analysis: arXiv:1903.10052
  Phys. Lett. B 798 (2019) 134949



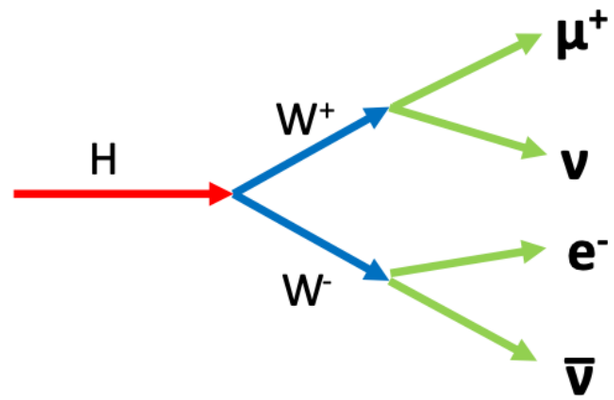
Production



gluon gluon fusion (ggF)
~ 88%

vector boson fusion (VBF)
~ 7%

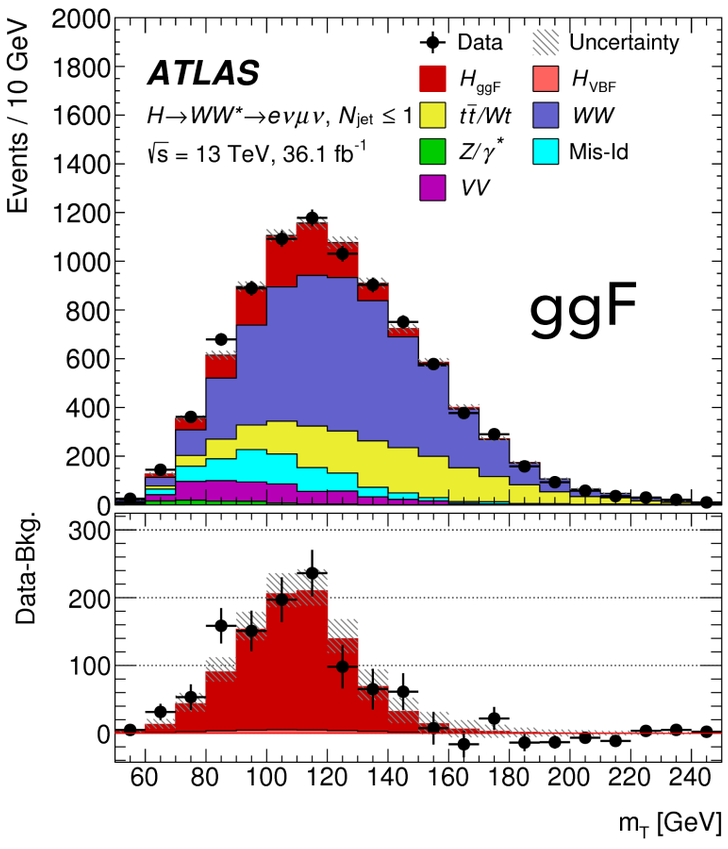
Decay

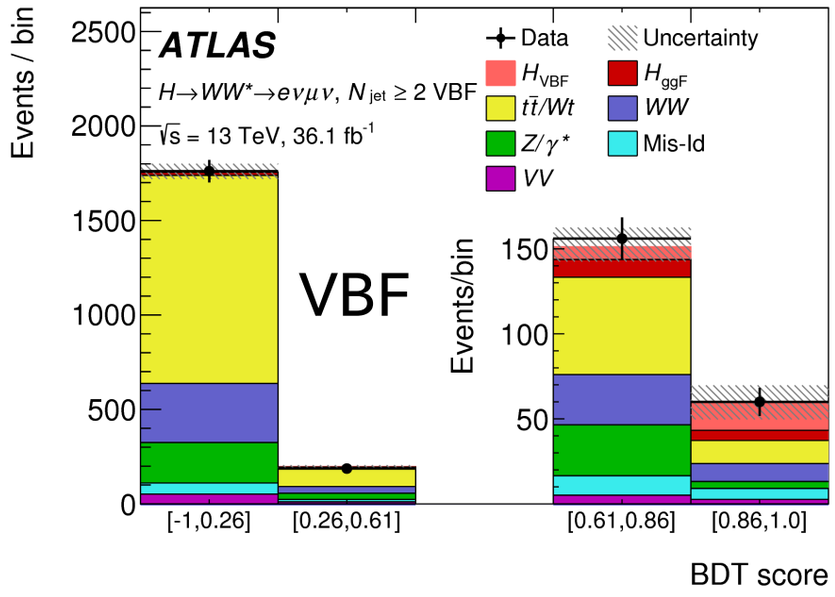


SM H->*WW** ggF+VBF Couplings

Partial Run 2 dataset (2015-2016), **36 fb^{-1}**

arXiv:1808.09054
Phys. Lett. B 789 (2019) 508

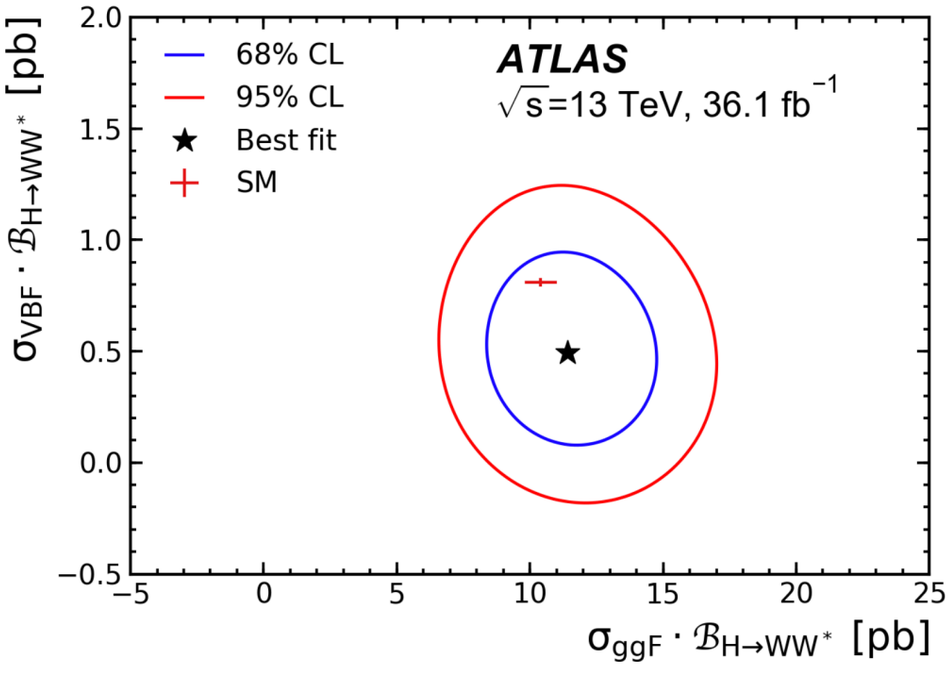




σ	Z_0^{obs}	Z_0^{exp}
ggF	6.0	5.3
VBF	1.8	2.6

$$\mu_{ggF} = 1.10^{+0.21}_{-0.20}$$

$$\mu_{VBF} = 0.62^{+0.36}_{-0.35}$$

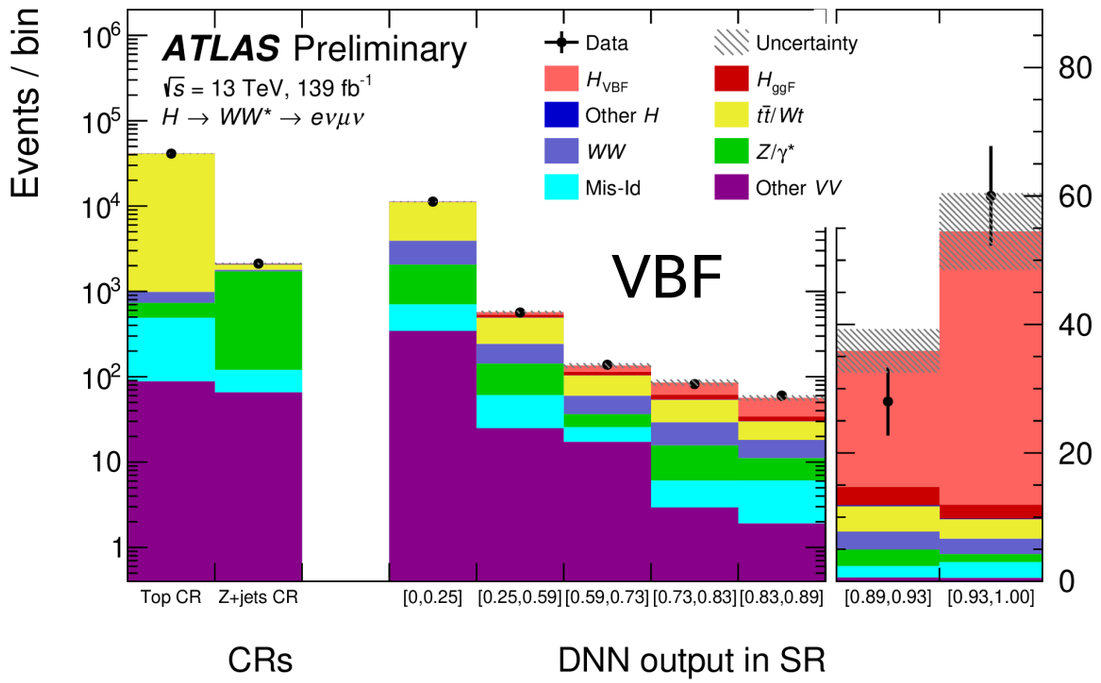


- Discriminating variable used in profile likelihood fit:
  - ggF: dilepton + E_T^{miss} transverse mass (m_T)
  - VBF: Boosted Decision Tree (BDT) trained on variables exploiting unique event topology of VBF
- VBF measurement limited by statistical uncertainty

SM H->*WW** ggF+VBF Couplings

Full Run 2 dataset (2015-2018), **139 fb^{-1}**

ATLAS-CONF-2020-045



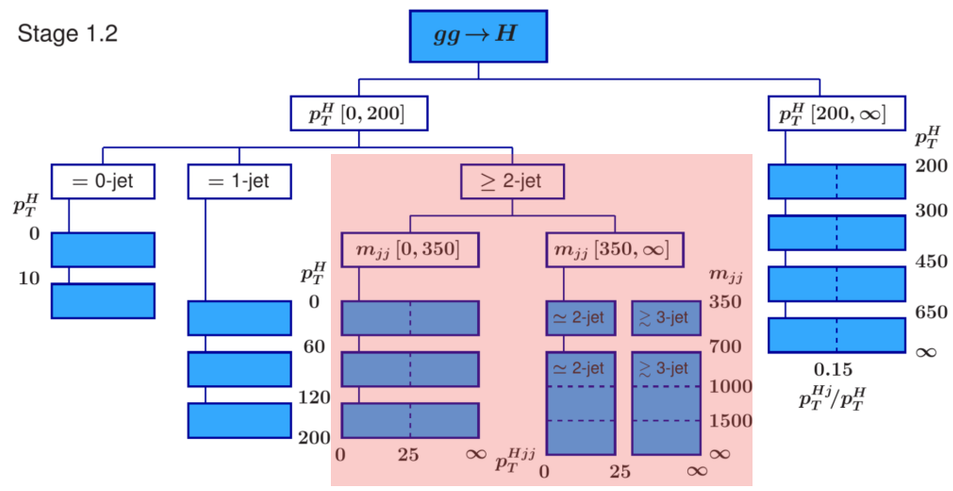
- VBF result presented in July as CONF note at ICHEP 2020
  - Final discriminant based on DNN
  - First observation for specific production and decay

    7.0 (6.2) σ obs (exp)
  - No longer statistically limited

$$\mu_{\mathrm{VBF}} = 1.04\ ^{+0.24}_{-0.20}$$

$$\sigma_{\mathrm{VBF}} \cdot \mathcal{B}_{H\to WW^*} = 0.85\ ^{+0.20}_{-0.17}\ \mathrm{pb}$$

- Ongoing effort to publish first full Run 2 paper
  - Include ggF ≥ 2 jets measurement for the first time in Run 2
  - Include measurement in "Simplified Template Cross-Section" (STXS) framework
  - Result to be included in combination with other Higgs boson decay channels



ggF ≥ 2 jets exclusive

Searches for Charged Higgs Bosons

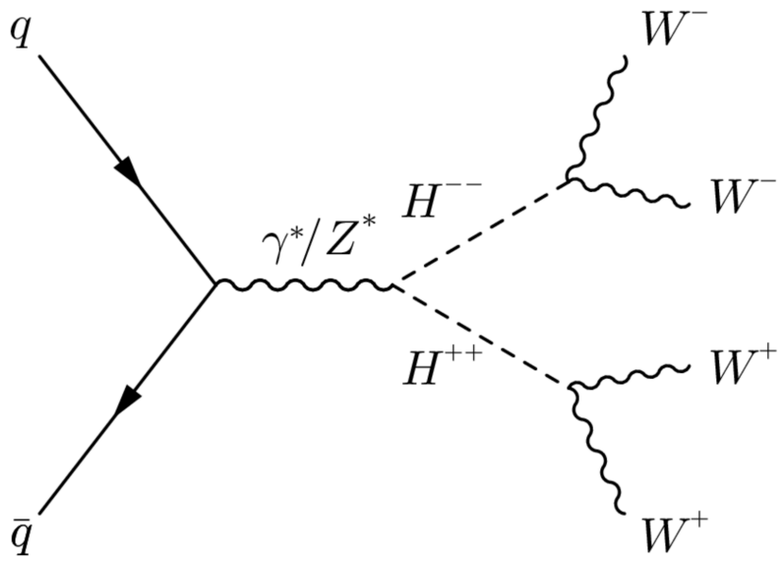
- Multiple analyses searching for pair production of double charged Higgs bosons
  - Here showing recent result using 3 channels based on number of leptons: two same-charge / three / four
  - Lund University involved in searches for similar signatures:

    - Direct leptonic decay of charged Higgs boson pair

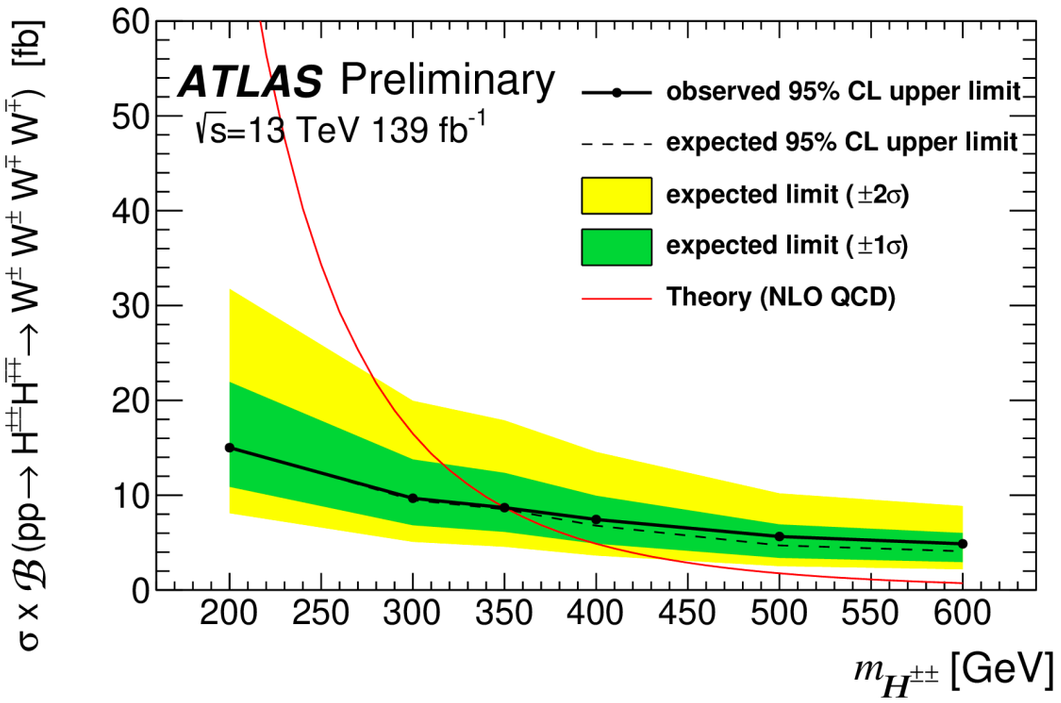
      pp -> $H^{++}H^{--}$ -> $\ell^+\ell^+\ell^-\ell^-$

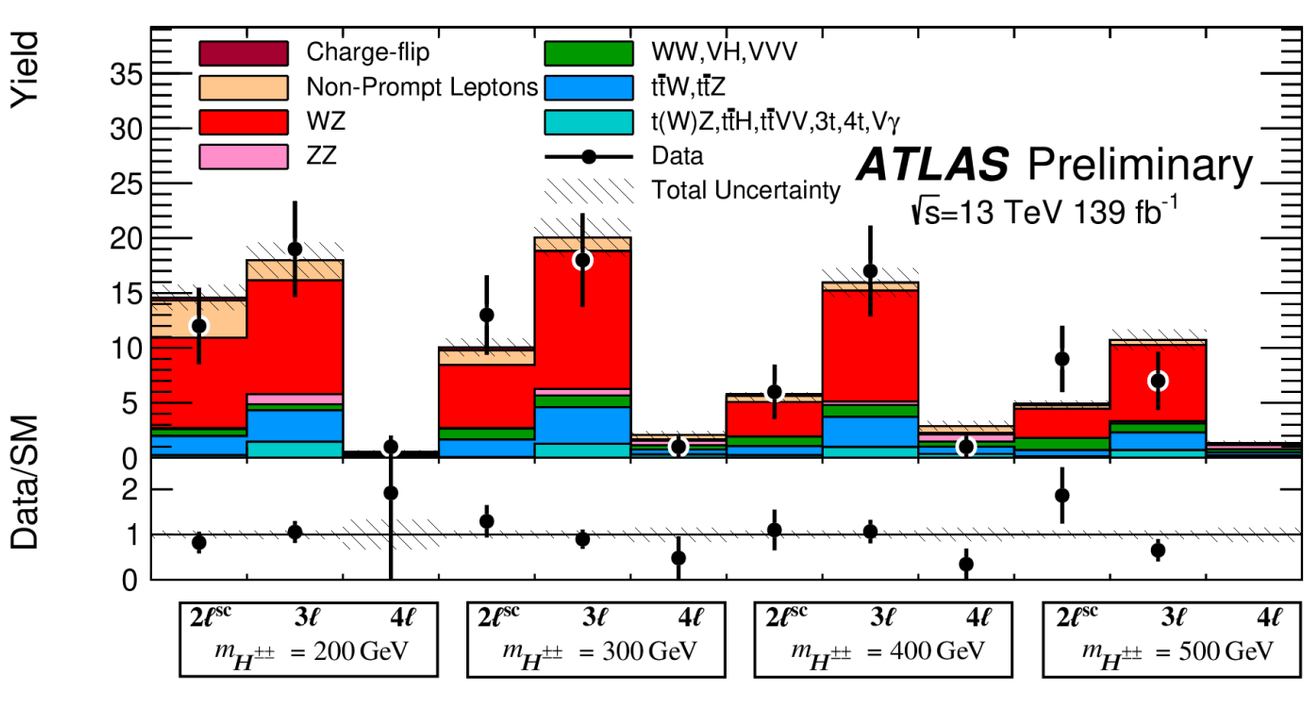
      arXiv:1710.09748
      Eur. Phys. J. C 78 (2018) 199 + CERN-THESIS-2019-352

ATLAS-CONF-2020-056



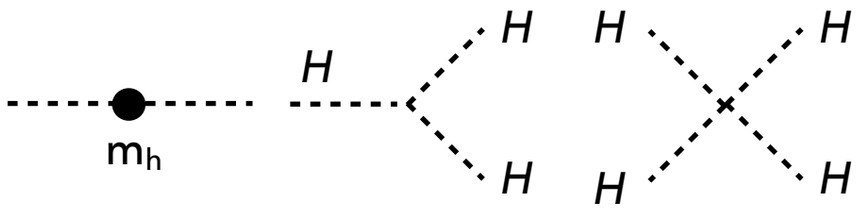
- Simple Higgs extension model with new scalar S produced together with a SM Higgs boson (pp -> *SH*)

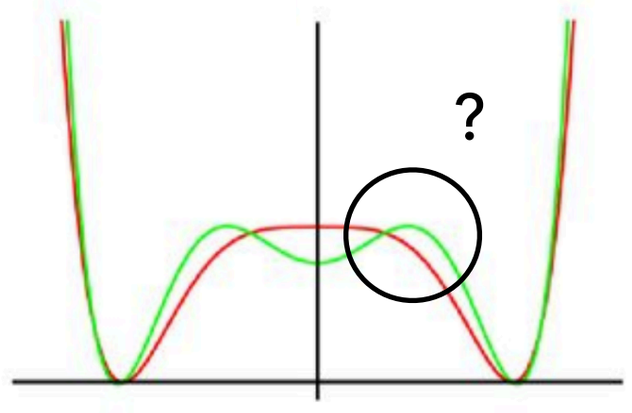




HH - Motivation

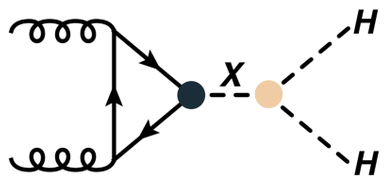
- Measure shape of global Higgs potential
  - $V(h) \sim \lambda v^2 h^2 + \lambda v h^3 + (\lambda/4) h^4 \ldots$

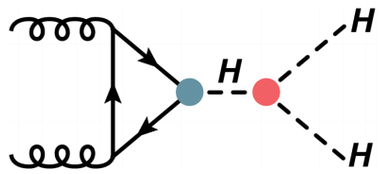


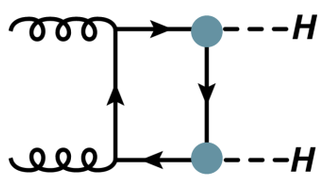


- *HH* cross-section depends strongly on e.g. value of Higgs self-coupling
  - Very small in SM -> destructive interference, maximal at $\kappa_\lambda \equiv \lambda_{HHH} / \lambda_{SM} = 2$

- Directly search for BSM resonances:

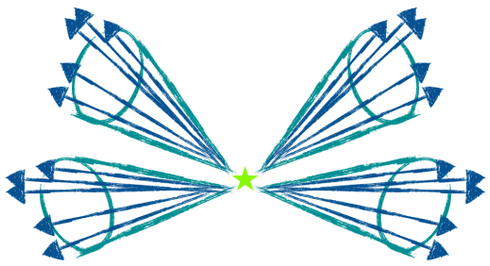




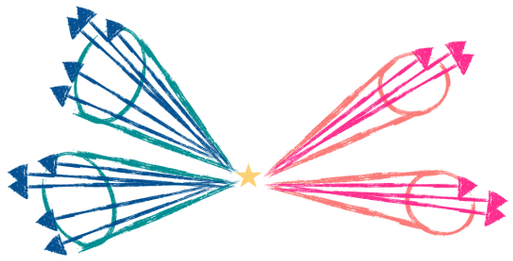


- Many decay modes to study, non-exhaustive list:

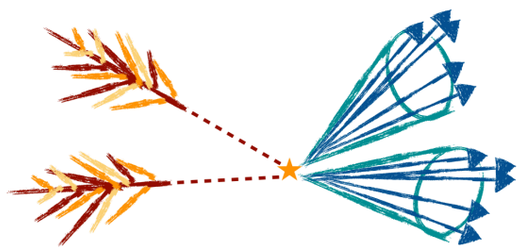
BR(HH->bbbb)
33%



BR(HH->bbττ)
7.4%



BR(HH->bbγγ)
0.26%



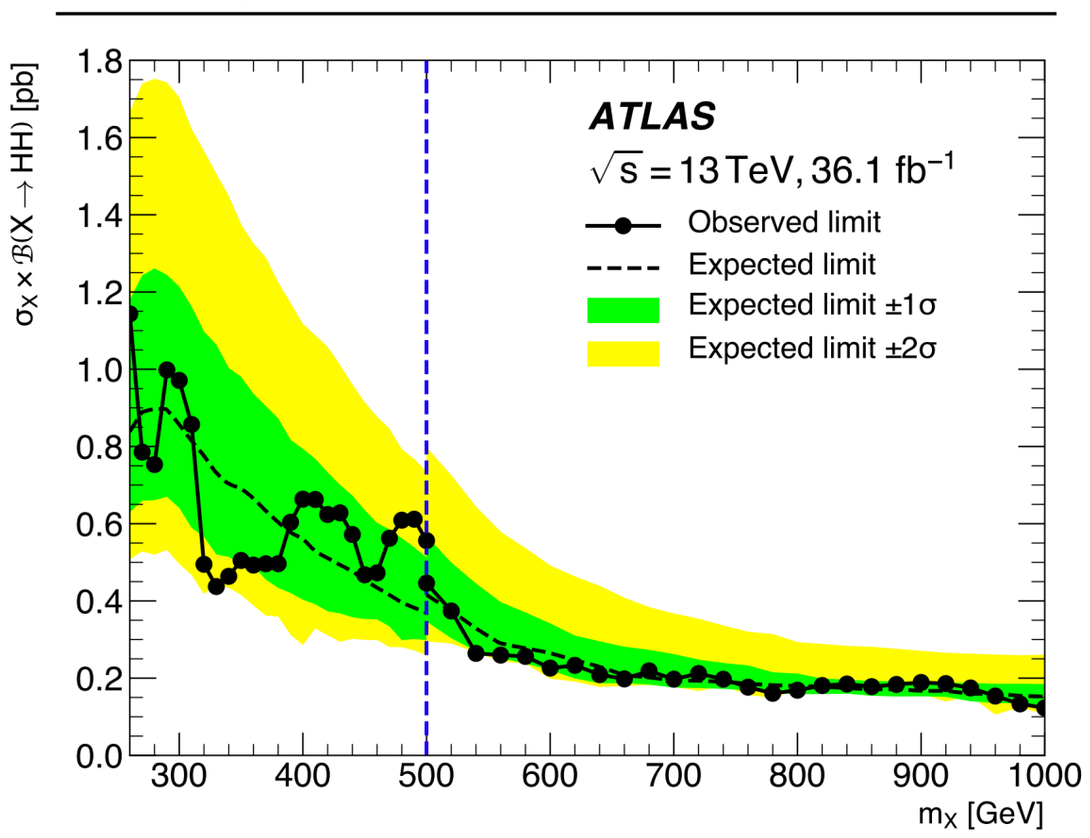
HH->bbγγ

- Trigger on γγ events, with two search categories defined by 1 or 2 *b*-jets and a 0 *b*-jet control category for data-driven γ+jet background shape estimation
- Fit $m_{\gamma\gamma}$ in non-resonant channel and $m_{\gamma\gamma jj}$ in resonant channel, which is sensitive to a generic scalar *X* decaying to *HH*
- Upper limits for the non-resonant *HH* cross-section obtained using tight selection
- Exclusion limits on resonant *HH* production obtained using both loose and tight selections
- Ongoing efforts to incorporate full Run 2 dataset, expected in early 2021
  - Recently public full Run 2 CMS result reaches 5.5x SM cross-section limit

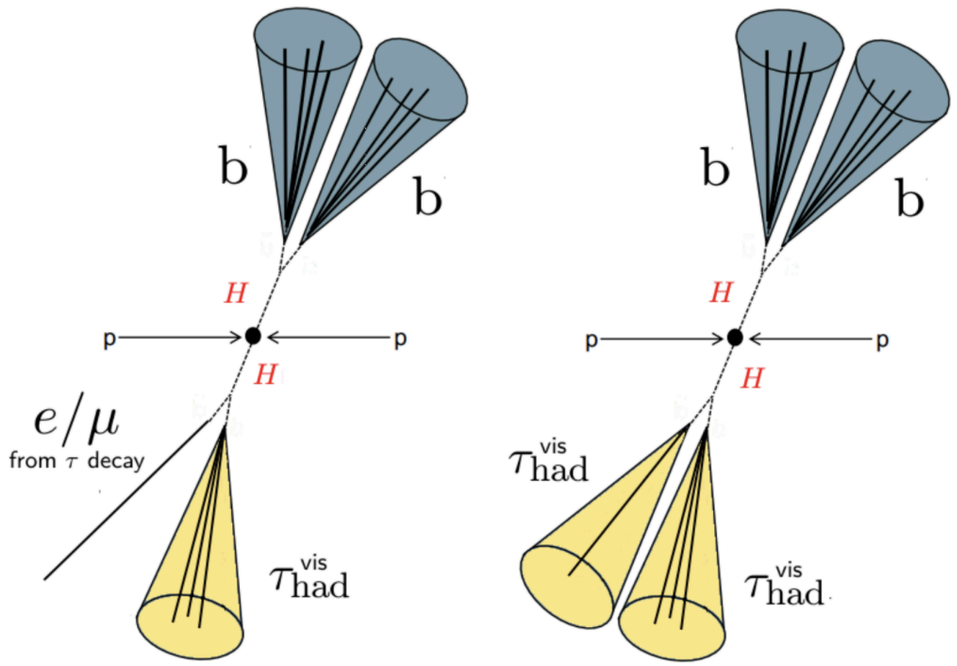
    -> improvements in analysis techniques offer additional sensitivity beyond the expected benefit from 36 fb^{-1} -> 139 fb^{-1}

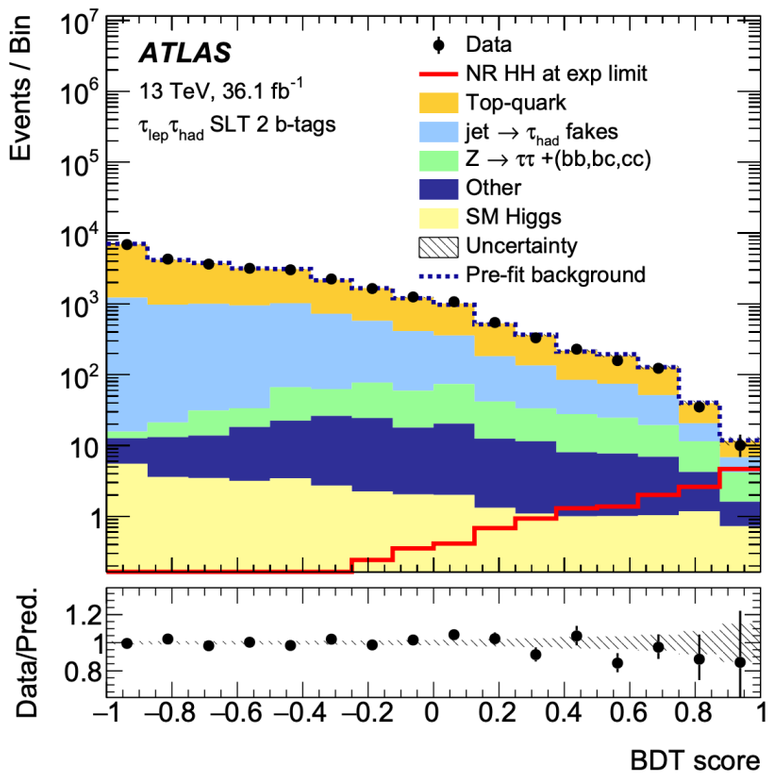
arXiv:1807.04873
JHEP 11 (2018) 040

	Observed	Expected	-1σ	$+1\sigma$
$\sigma_{gg\to HH}$ [pb]	0.73	0.93	0.66	1.3
As a multiple of σ_{SM}	22	28	20	40



HH->bbττ





arXiv:1808.00336

Phys. Rev. Lett. 121, 191801 (2018)

- Two final states, $\tau_{lep}\tau_{had}$ and $\tau_{had}\tau_{had}$, with three event categories accounting for different trigger strategies
- Require additionally 2 *b*-jets as well as a di-τ invariant mass $m_{\tau\tau}^{\text{MMC}}$ > 60 GeV
- BDT trained to separate signal from background used as discriminating variable in profile likelihood fit
- Constrain both resonant and non-resonant cross-sections

		Observed	-1σ	Expected	$+1\sigma$
$\tau_{\text{lep}}\tau_{\text{had}}$	$\sigma(HH \to bb\tau\tau)$ [fb]	57	49.9	69	96
	$\sigma/\sigma_{\text{SM}}$	23.5	20.5	28.4	39.5
$\tau_{\text{had}}\tau_{\text{had}}$	$\sigma(HH \to bb\tau\tau)$ [fb]	40.0	30.6	42.4	59
	$\sigma/\sigma_{\text{SM}}$	16.4	12.5	17.4	24.2
Combination	$\sigma(HH \to bb\tau\tau)$ [fb]	30.9	26.0	36.1	50
	$\sigma/\sigma_{\text{SM}}$	12.7	10.7	14.8	20.6

Best individual channel limit at the LHC based on 36 fb^{-1}

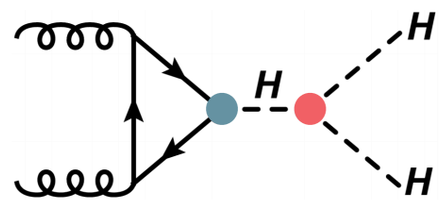
HH Combination

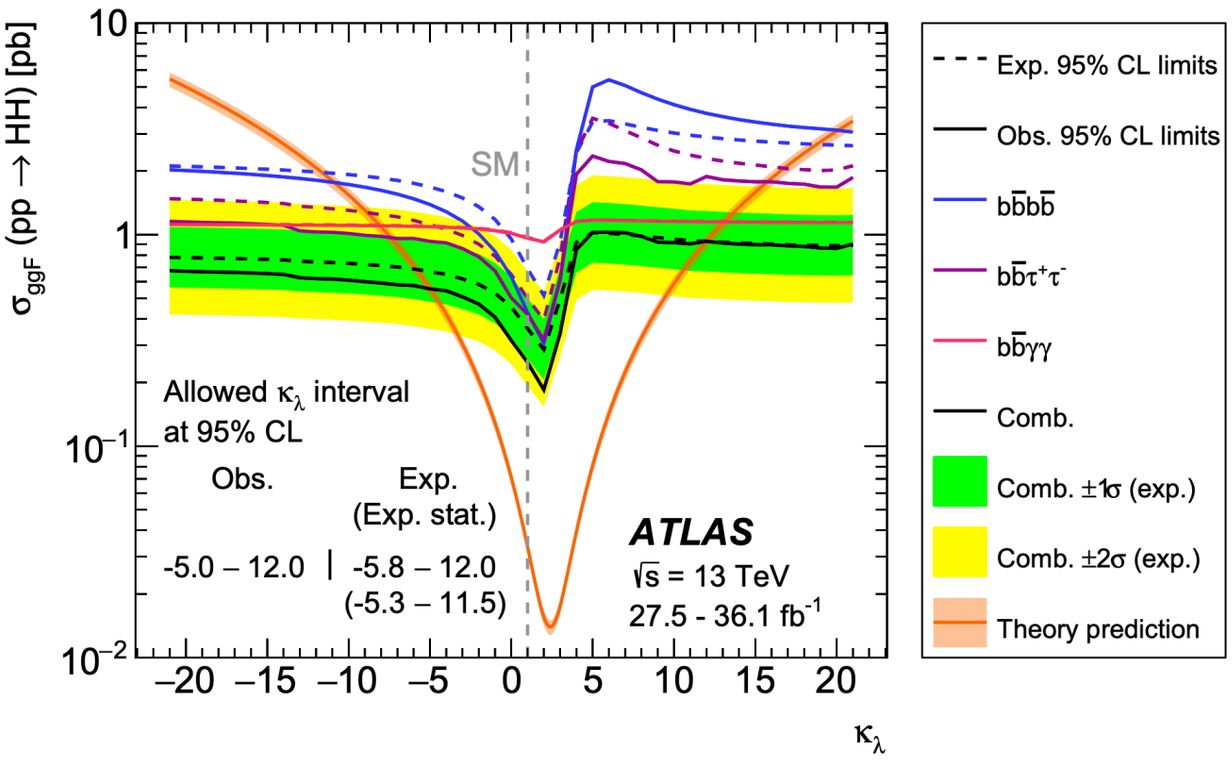
- Sensitivity of the Standard Model HH search is driven by the final states bbbb, bbττ, and bbγγ
- These three channels are used to set limits on κ_λ:

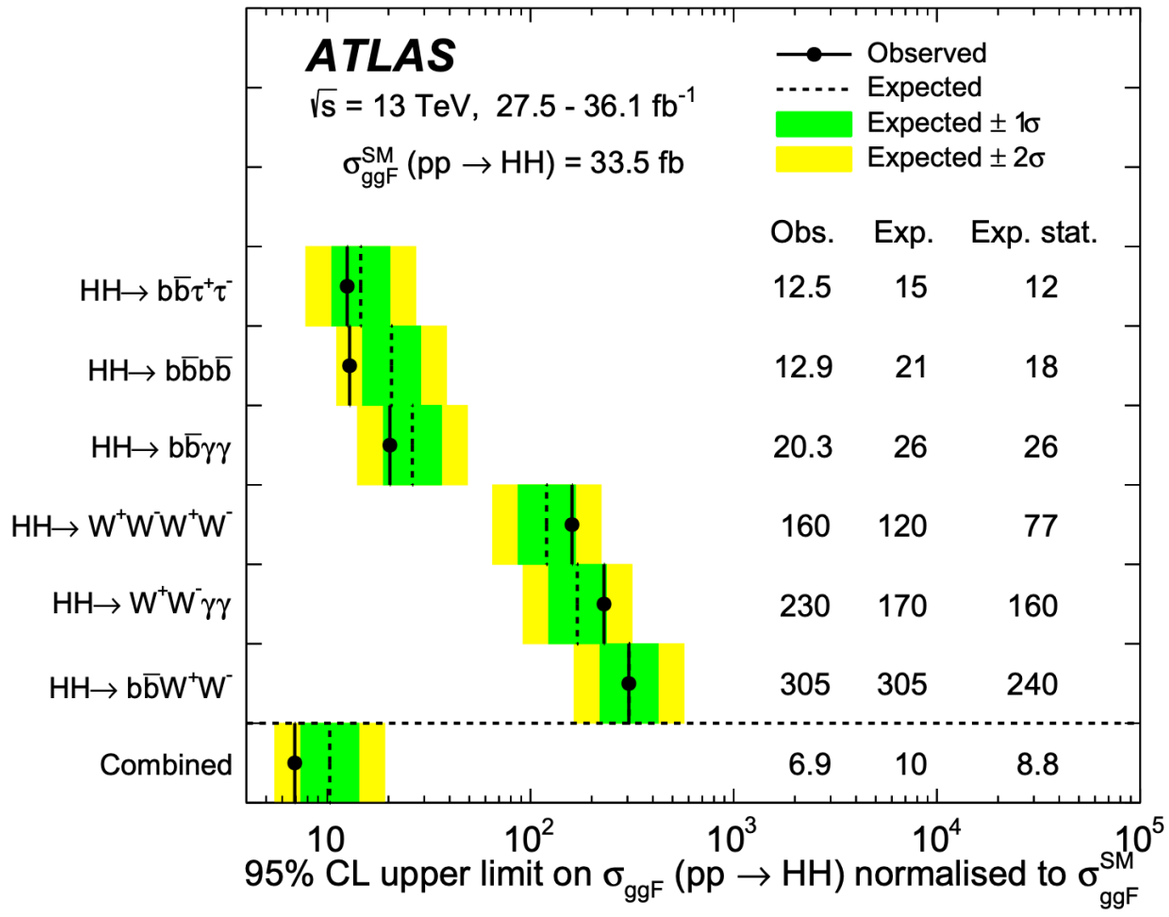
$$-5.0 < \kappa_\lambda < 12.0 \text{ @ 95\% CL}$$

arXiv:1906.02025
Phys. Lett. B 800 (2020) 135103

$$\kappa_\lambda \equiv \lambda_{HHH} / \lambda_{SM}$$



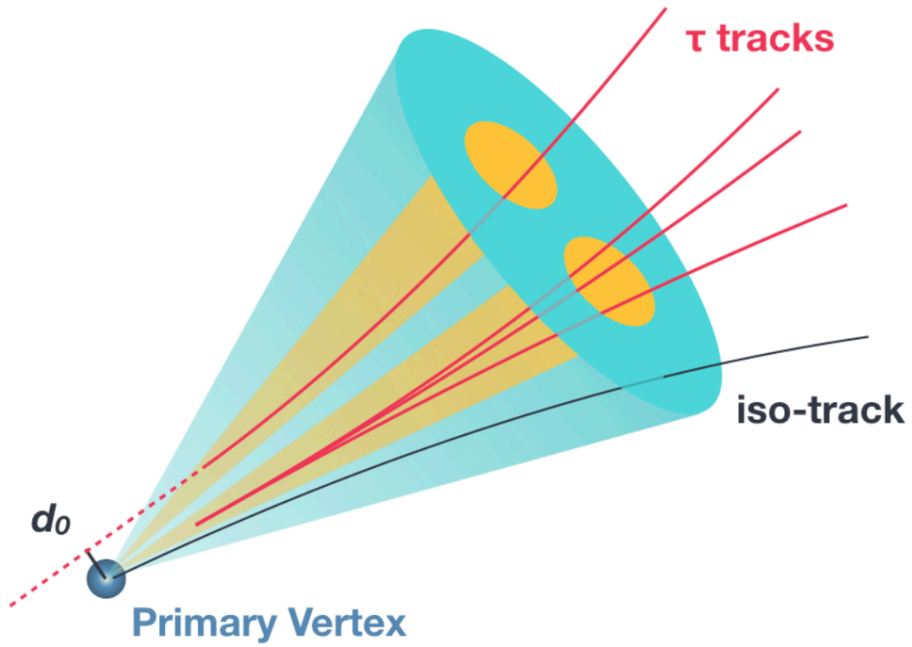




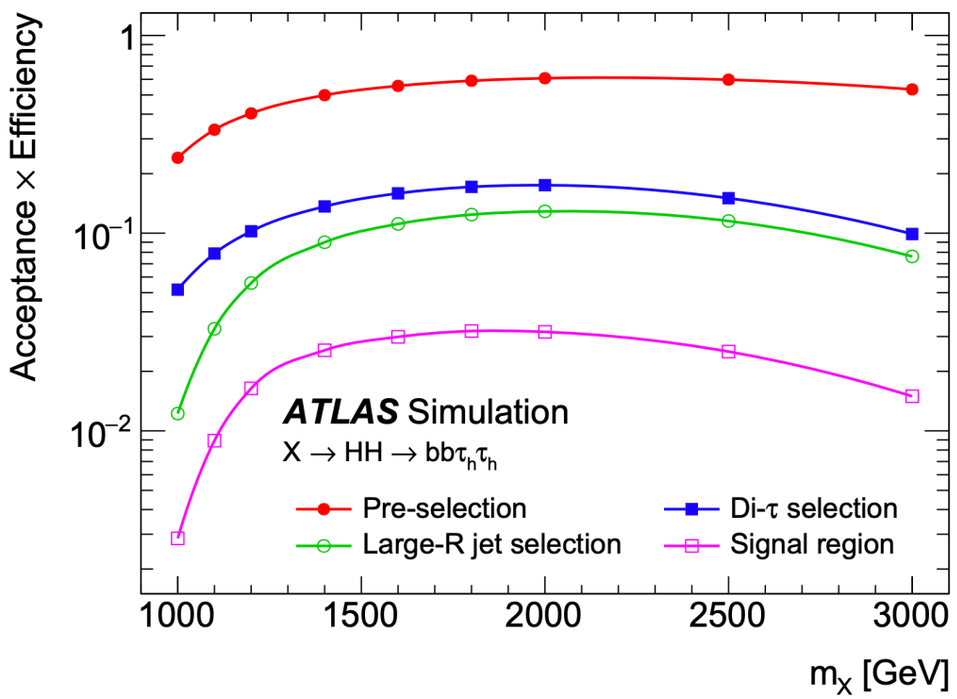
Boosted Resonant *HH->bbττ*

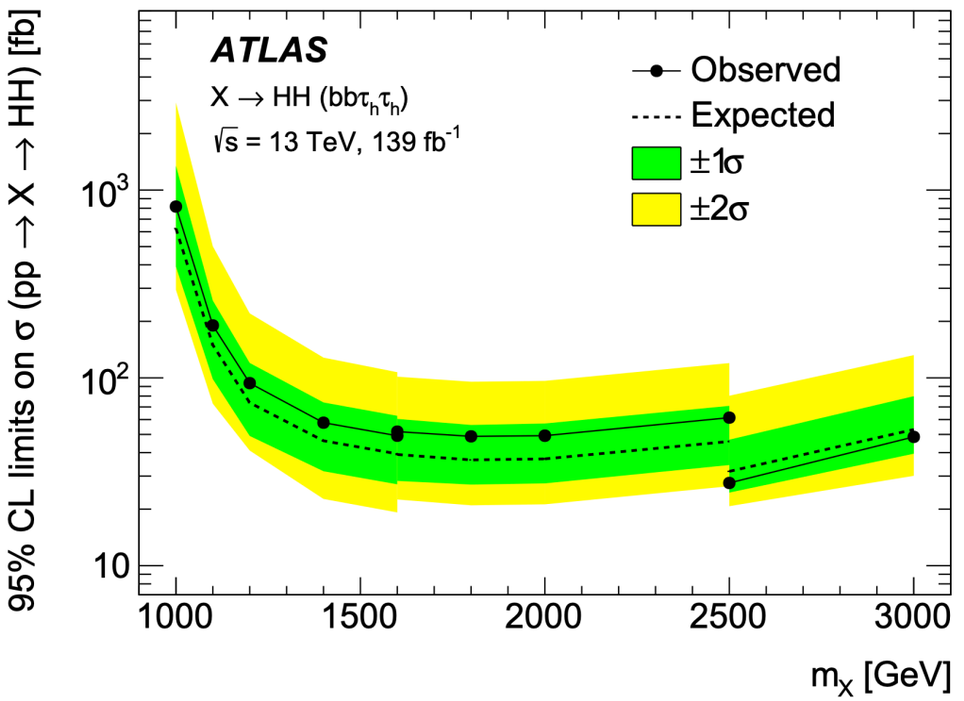
- Novel analysis technique developed: di-τ tagger
  - Reconstruct and identify hadronically decaying $\tau^+\tau^-$ pairs with large Lorentz boost
  - Taus appear as "subjets" inside a single large-R jet
  - Designed benchmark with 60% ID efficiency

arXiv:2007.14811
submitted to JHEP



- Search performed as single-bin counting experiment for each mass point





HH - Future Prospects

Run 2
139 fb^{-1}

- Update all public results with full Run 2 statistics, while including improvements to the current analysis techniques
- Design methods to interpret *HH* searches in terms of Effective Field Theory (EFT) parameters

Run 3
~350 fb^{-1}

- Possibility to observe *ZH* -> bbγγ / bbττ as an intermediate step towards measuring *HH* production (see Christina's talk tomorrow)
  - e.g. *ZH* (*Z*->*bb*, H->γγ) has cross-section 3.7x that of corresponding *HH*

HL-LHC
3000 fb^{-1}

Channel	bbbb	bb$\tau\tau$	bbWW($\ell\nu\ell\nu$)	bb$\gamma\gamma$	bbZZ($\ell\ell\ell\ell$)
$\mathcal{B}$ [%]	33.9	7.3	1.7	0.26	0.015
Number of events	37000	8000	1830	290	17

- Arrive at statistics sufficient for *HH* evidence/observation

Channel	Statistical-only	Statistical + Systematic
$HH \to b\bar{b}b\bar{b}$	1.4	0.61
$HH \to b\bar{b}\tau^+\tau^-$	2.5	2.1
$HH \to b\bar{b}\gamma\gamma$	2.1	2.0
Combined	3.5	3.0

σ

ATL-PHYS-PUB-2018-053

Summary

- Analyses targeting properties of the Higgs sector continue to be a vital component of the ATLAS physics program, with a lifetime of another decade and beyond
- Sweden's ATLAS groups provide critical expertise and person-power across many of the ongoing areas of Higgs activities
- Di-Higgs production remains one key component to a better understanding of the Higgs sector, offering (among other things) the ability to probe the Higgs self-coupling
  - Swedish Di-Higgs Working Group established to pool resources and facilitates collaboration between experimentalists and theorists

ATLAS EXPERIMENT

BACKUP