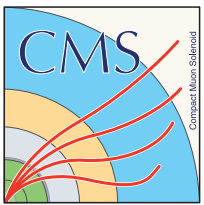
News from the Higgs boson

On behalf of the ATLAS and CMS collaborations

Cyril Becot

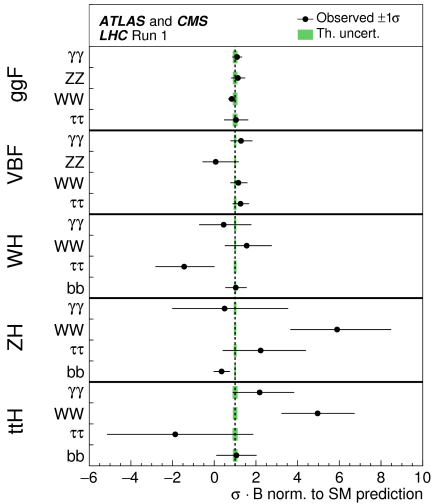
ALPS 2019, 27.04.2019



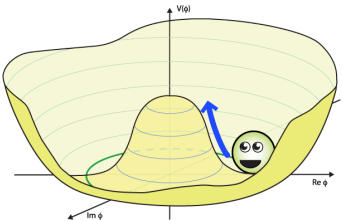
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

Run 1 legacy : from discovery to measurements



- Higgs boson discovery is the major LHC Run 1 legacy
- Already allowed some precise measurements : m_H, σ_{inc}
- But clearly missing pieces : associated productions...



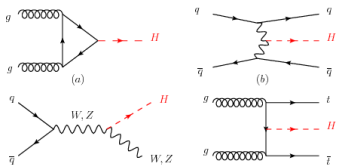
Current Run 2 status...

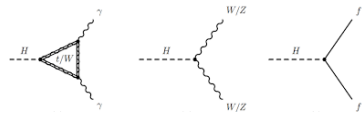
Throughout Run 2, combinations of channels have allowed to observe *ALL 5* expected production modes (ggF,VBF,VH,ttH) and decay modes ($\gamma\gamma$, ZZ, WW, $\tau\tau$,$b\bar{b}$)

Current emphasis on single-channel observations and precise measurements

	ggF	VBF	VH	$t\bar{t}H$
$b\bar{b}$	Searched for		Observed	Searched for
$\tau^+\tau^-$	Observed			Searched for
W^+W^-	Observed		Searched for	
Z^0Z^0	Observed			
$\gamma\gamma$	Observed			Strong evidence

Recent results for the channels in blue will be presented today





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<table>
<tr><th></th><th colspan="2">ggF</th><th>VBF</th><th>VH</th><th>$t\bar{t}H$</th></tr>
<tr><td>bb</td><td colspan="2">Searched for</td><td>Observed</td><td>Searched for</td></tr>
<tr><td>$\tau^+\tau^-$</td><td colspan="3">Observed</td><td rowspan="3">Searched for</td></tr>
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</table>

Recent results for the channels in blue will be presented today

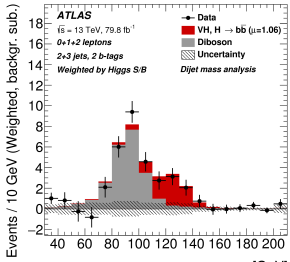
Completion of this measurement program, together with searches related to an extended Higgs sector, will put strong constrains on the Higgs potential

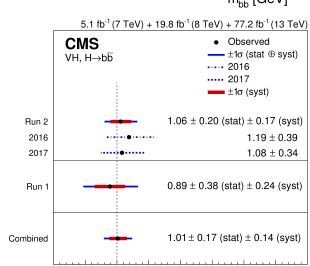
Outline of this talk

Pinning down the 125 GeV Higgs boson
- The Simplified Template Cross-sections framework (STXS)
- Cross-section measurements
- Toward single-channel observations
- (Too) rare decays

Searches for an extended Higgs sector
- Using the SM Higgs as a tool
- Searching for new heavy Higgs bosons

Evidence of $Vh,\ h \to b\bar{b}$





- Both experiments reported a strong evidence for $VH,\ H \to b\bar{b}$ last summer (ATLAS,CMS)
- The 3 channels are used ($WH \to l\nu b\bar{b}$, $ZH \to (ll/\nu\nu)b\bar{b}$
- Both experiments use MVAs to improve S/B (dominated by $m_{b\bar{b}}$, p_T^V, $\Delta R(b_1, b_2)$)
- Reported significances (Run1+2) :

  ATLAS 4.9σ(obs), 5.1σ(exp)

  CMS 4.8σ(obs), 4.9σ(exp)

- High single-channel significance makes it a great place for measurements !

→ However the best observables to measure need to be defined

The Simplified Template Cross-section framework (STXS)

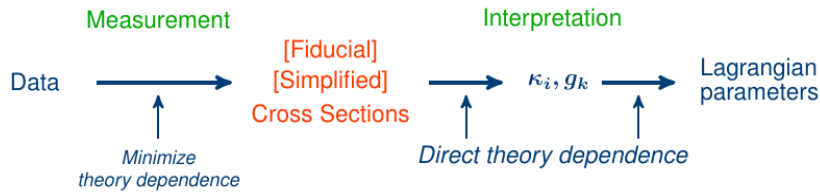
An optimal framework for Higgs measurements needs to :

> Allow to easily combine various decay channels and across exp.

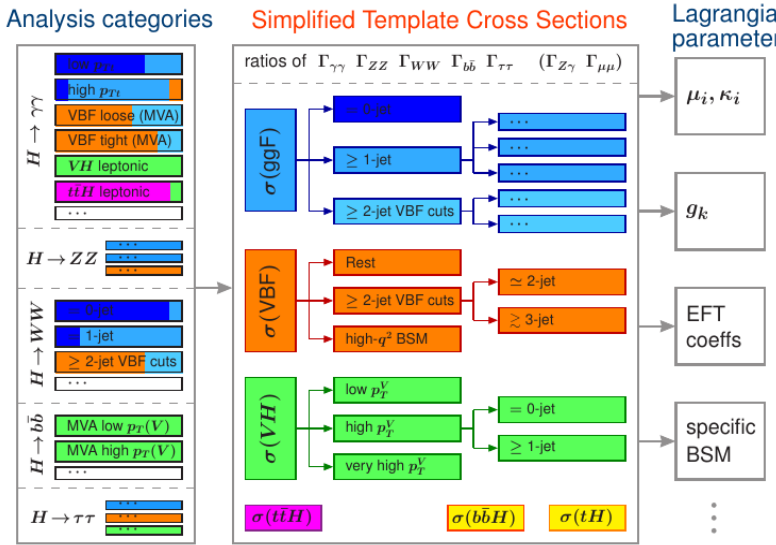
> Allow for easy re-interpretation

> Minimize theory dependence

→ Simplified template cross-section (STXS) : SM used to build templates for the different production modes in various kinematic regions, matching as close as possible the analysis categories

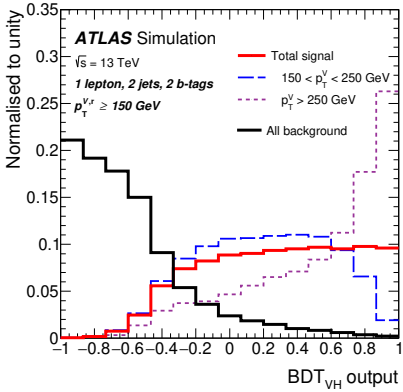


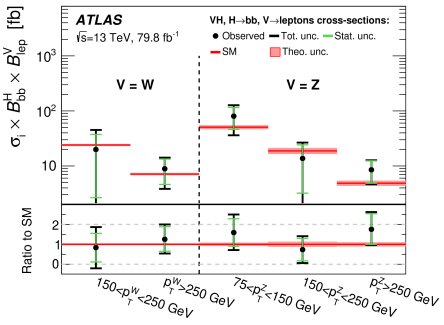
The Simplified Template Cross-section framework (STXS)



STXS measurement in $Vh,\ h \to b\bar{b}$ in ATLAS arXiv:1903.04618

The $Vh,\ h \to b\bar{b}$ analysis is then used to extract the VH STXS, where this channel brings strong constraints esp. on high-P_T^V bins. Allow to split in P_T^V and WH vs ZH

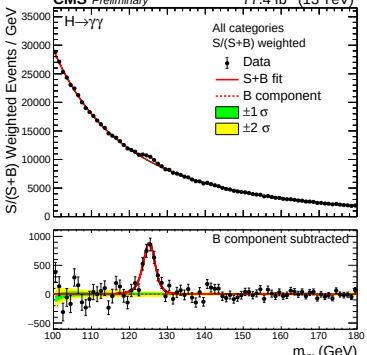


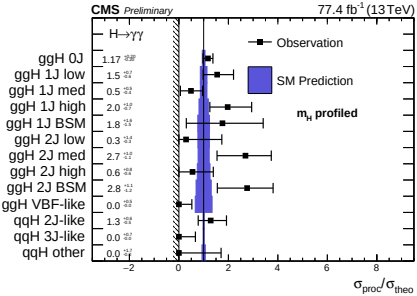


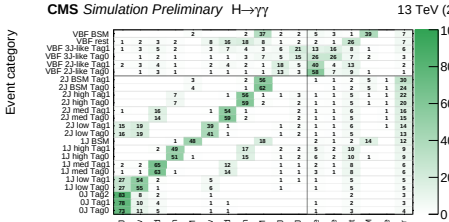
Different bin of $p_T^{V,\ truth}$ contribute to a given $p_T^{V,\ reco}$, but with a different BDT shape

STXS measurement in $h \to \gamma\gamma$ in CMS CMS-PAS-HIG-18-029

Narrow peak on a smooth background



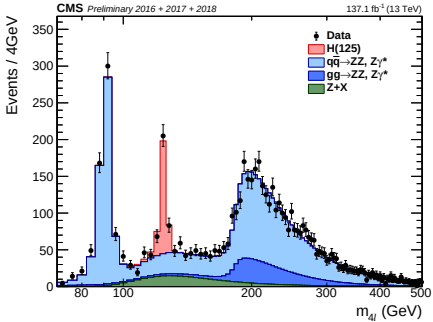




Signal extracted in different categories via S+B fit. Each category is populated by different fractions of STXS bins

STXS measurement in $h \to 4l$ in CMS - Full Run2 CMS-PAS-HIG-19-001

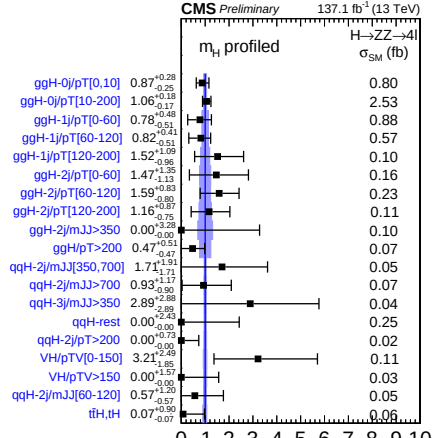
Early full Run 2 Result ! The statistics allows to further split ggF/VBF in N_{jets}, P_T^H



Clean and narrow peak on top of well-controlled background

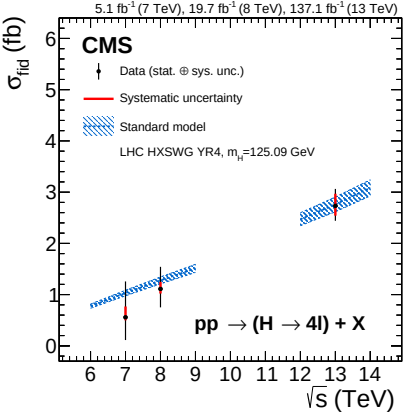
Corresponding ATLAS result ($36.1\ fb^{-1}$) :

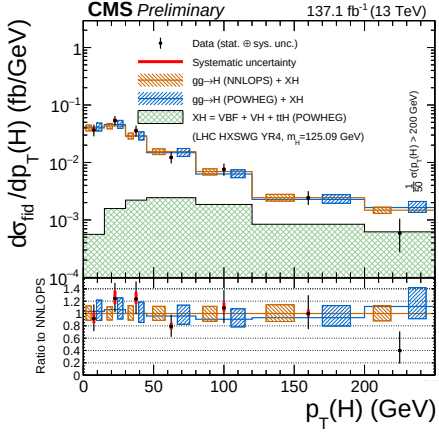
JHEP03(2018)095



σ_{Fid} measurement in $h \to 4l$ in CMS - Full Run2

As it doesn't involve any MVA, can be unfolded to truth-level directly
$\to$ measure fiducial and differential cross-section



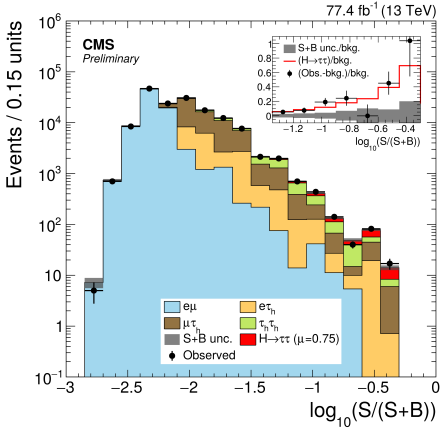


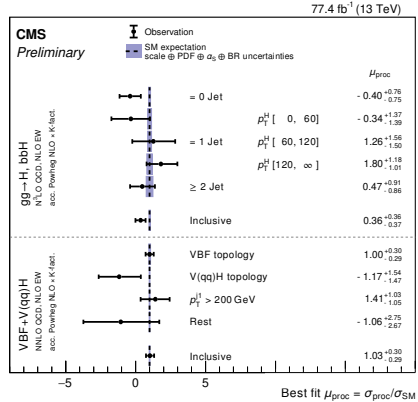
STXS measurement in $h \to \tau^+\tau^-$ in CMS CMS-PAS-HIG-18-032

Multi-class NN discriminates between ggF, VBF and main backgrounds.

Signal is extracted by fitting NN outputs.

Most powerful variables : $m_{\tau\tau}^{SV}, m_{vis}, p_T^{vis}, p_T^{\tau_{1,2}}, p_T^{j_{1,2}}$





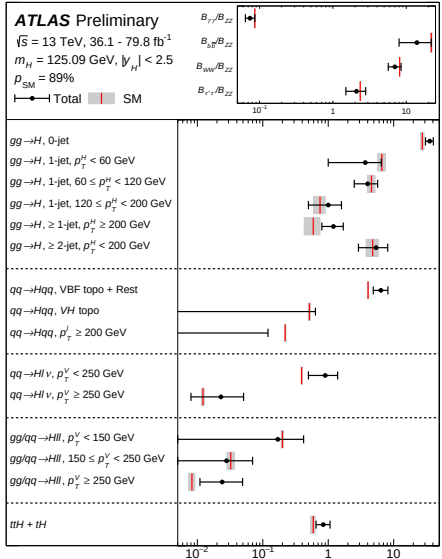
CMS also published a dedicated search for $VH(\tau\tau)$

arXiv:1809.03590 (2.3σ obs. significance)

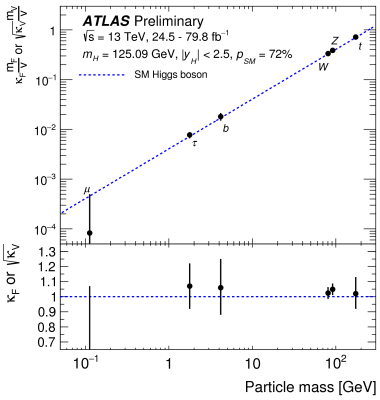
ATLAS ggF+VBF result : PhysRevD.99.072001

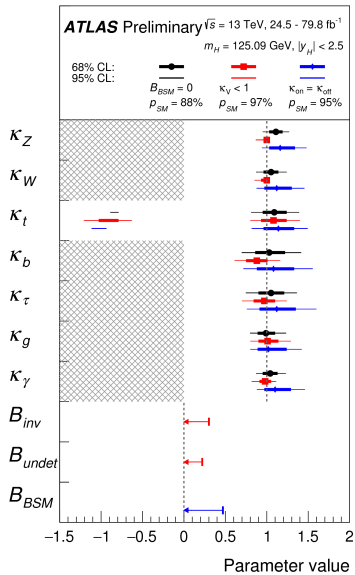
Higgs STXS combination in ATLAS ATLAS-CONF-2019-005

- Big interest in combining STXS among different decay channel
  - Framework uses production mode kinematic variables, not decay products
  - Different channels bring sensitivity to different phase spaces
- ATLAS combined results from the $\gamma\gamma$, ZZ, W^+W^-, $\tau^+\tau^-$, $b\bar{b}$ channels
- Results consistent with SM expectations
- Combination can also be done to measure couplings modifiers



Higgs STXS combination in ATLAS





Add offshell $H \to 4l$, $H \to inv$ searches here

Evolution vs mass as in SM

No deviations seen in couplings

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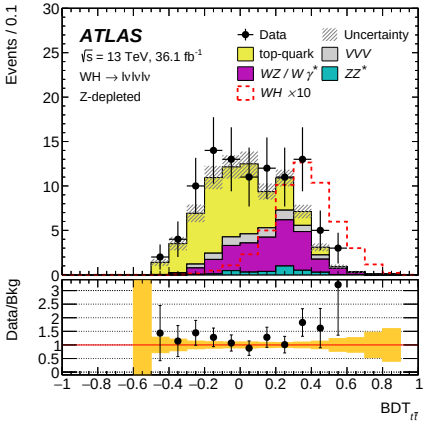
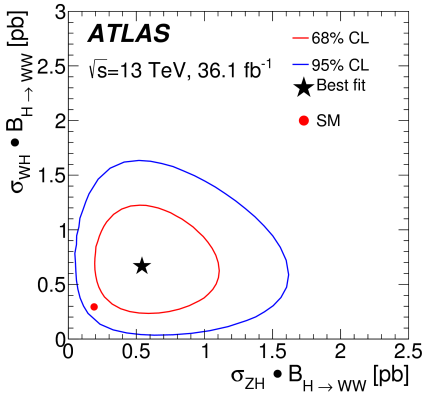
Analysis $Vh,\ h \to W^+W^-$ in ATLAS arXiv:1903.10052

Require 3 or 4 isolated leptons, with total charge matching WH/ZH events

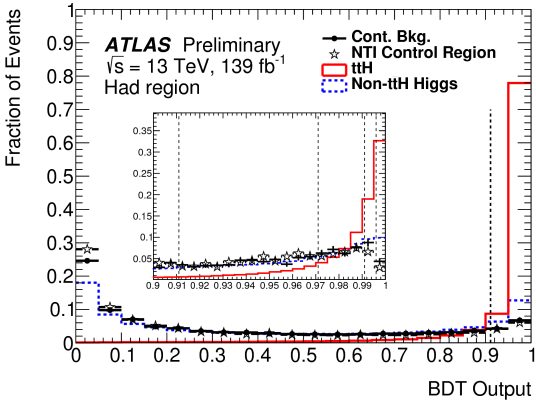
BDTs are used to select WH events, cut-based approach for ZH





Evidence for VH, H→ WW : 4.1σ observed, 1.9σ exp.

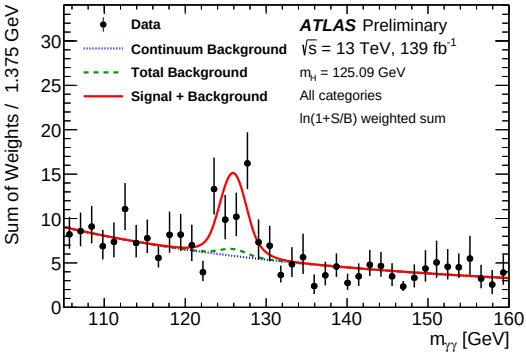
Search for $t\bar{t}h,\ h \to \gamma\gamma$ in ATLAS - Full Run2 ATLAS-CONF-2019-004

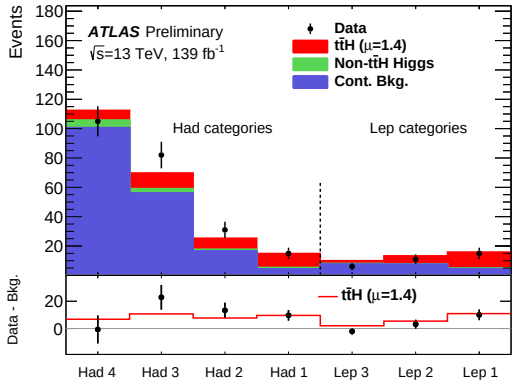


- Full Run 2 Result
- Uses 0lep and > 0lep categories
- Cut on BDT trained with low-level var. :
  - 4-vec of the photons
  - 4-vec of the leptons
  - 4-vec of the jets
- Defines 7 categories, where $m_{\gamma\gamma}$ is fitted using a functional form
- Signal extracted using combined likelihood fit over 7 categories

Search for $t\bar{t}h,\ h \to \gamma\gamma$ in ATLAS - Full Run2

Final significance : 4.9σ (obs), 4.2σ (exp)





$$\sigma_{t\bar{t}H} BR_{\gamma\gamma} = 1.59^{+0.38}_{-0.36}(stat.)^{+0.15}_{-0.12}(exp.)^{+0.15}_{-0.11}(theo).\ \text{fb}$$

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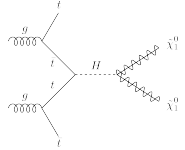
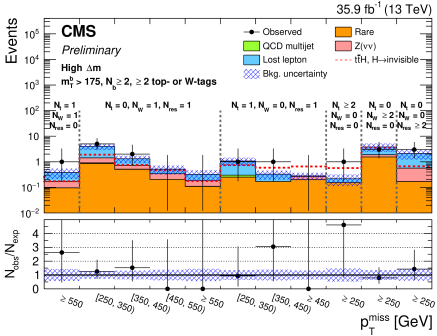
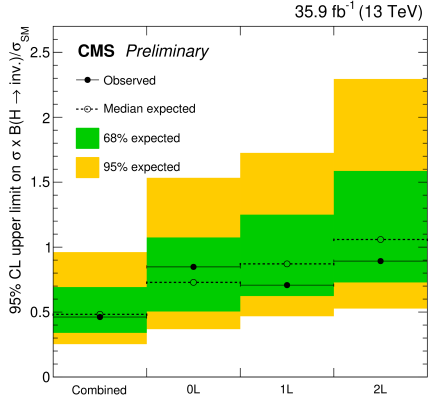
Searches for an extended Higgs sector
- Using the SM Higgs as a tool
- Searching for new heavy Higgs bosons

Search for invisible Higgs in $t\bar{t}h$ CMS-PAS-HIG-18-008





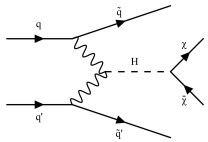
All full-had (merged+resolved), di-leptonic and semi-leptonic top decay channels considered

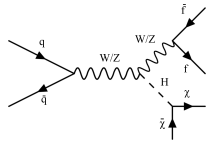


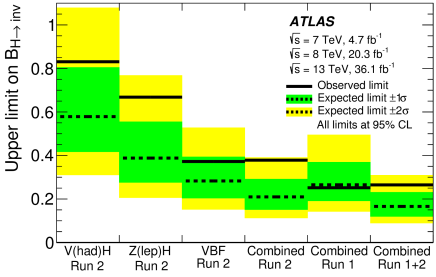
- $t\bar{t}H$ would be enhanced for large y_t and allows strong bkg suppression
- First search for invisible Higgs decays using $t\bar{t}H$ topology !

Combination of searches for invisible Higgs in ATLAS

arXiv:1904.05105





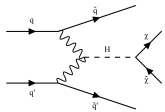


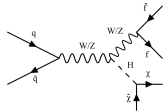
- ATLAS performed other $H \rightarrow$ inv. searches earlier
  - VBF, VH signatures (no ggF)
  - Also combined with Run 1 results

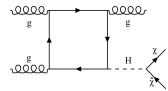
- $BR(H \rightarrow inv.) < 0.26$ obs (0.17 exp.)
  - Full Run1+Run2 combination for these signatures, 95% C.L. exclusion
  - Remember : $BR_{SM}(H \rightarrow inv.) = 0.1\%$

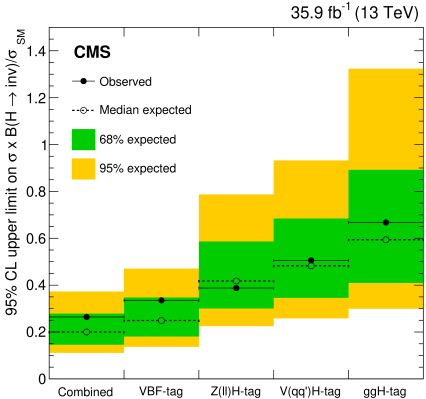
Combination of searches for invisible Higgs in CMS

arXiv:1809.05937





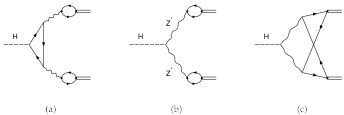




- CMS performed a similar combination
  - VBF, VH and ggF signatures
  - These signatures were combined !
  - Also combined with Run 1 results

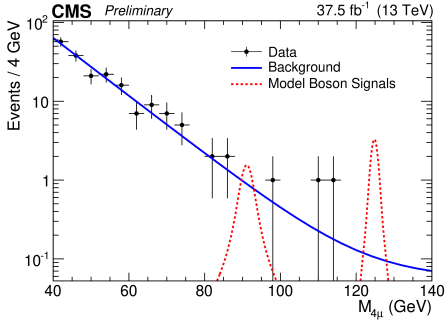
- $BR(H \to inv.) < 0.19$ obs (0.15 exp.)
  - Strongest limit on $BR(H \to inv.)$ so far
  - Full Run1+Run2 combination for these signatures, 95% C.L. exclusion

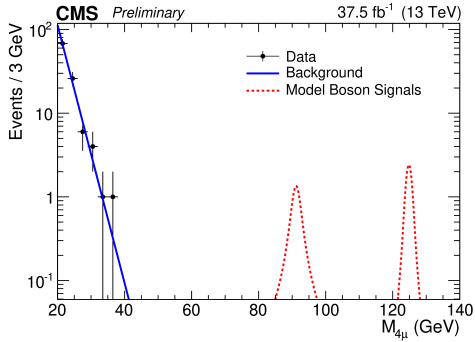
Searches for rare decay of the Higgs boson CMS-PAS-HIG-18-025



	observed	expected
$\mathcal{B}(\mathrm{H} \to \mathrm{J/\psi J/\psi}) \times 10^3$	1.8	$1.8^{+0.2}_{-0.1}$
$\mathcal{B}(\mathrm{H} \to \mathrm{YY}) \times 10^3$	1.4	1.4 ± 0.1
$\mathcal{B}(\mathrm{Z} \to \mathrm{J/\psi J/\psi}) \times 10^6$	2.2	$2.8^{+1.2}_{-0.7}$
$\mathcal{B}(\mathrm{Z} \to \mathrm{YY}) \times 10^6$	1.5	1.5 ± 0.1

$H \to J/\Psi J/\Psi$, $H \to \Upsilon\Upsilon$ suppressed in the SM but could be enhanced (large y_c...). Clean signature ($M_{4\mu}$ peak)





Very small background → limit scales as luminosity

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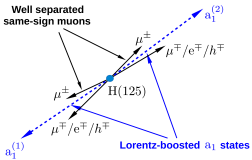
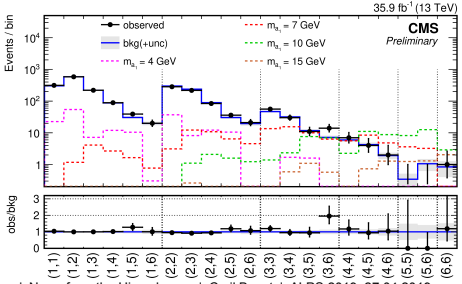
Searches for an extended Higgs sector
- Using the SM Higgs as a tool
- Searching for new heavy Higgs bosons

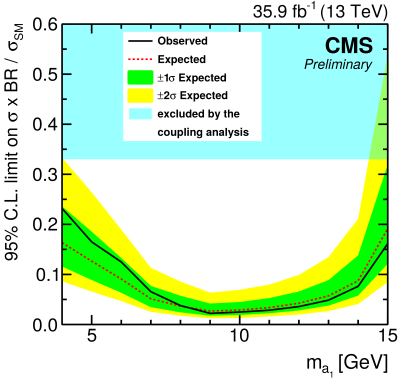
Decays of the Higgs to light pseudo-scalars CMS-PAS-HIG-18-006

Targets models with light pseudoscalar (2HD+1S) in $H \to a_1 a_1 \to 2\tau 2\mu / 4\tau$



Reconstruct 1μ with nearby OS charged track for each a_1

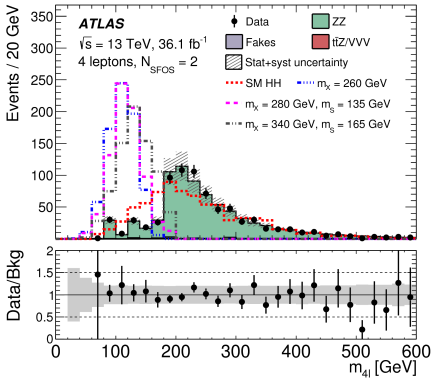


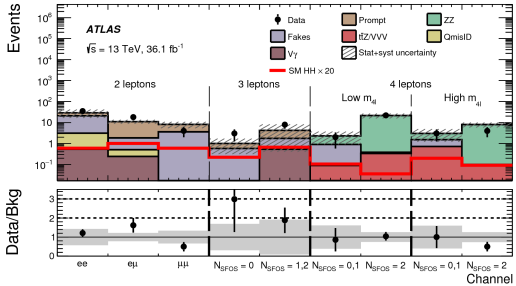


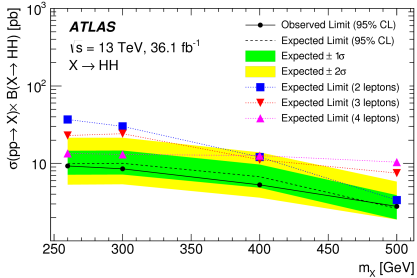
- Performs especially well for overlapping a_1 decay products (lower mass)
- However at very low mass background becomes important (mainly b-jets)

Searching new Higgs decaying in SM Higgs ATLAS-HIGG-2016-24

- Search for additional heavy scalar (MSSM)
  - $X \to 2\ H_{SM} \to 4W$ or $2\ S \to 4W$
  - $X \to t\bar{t}$ dominates $m_X > 2\ m_{Top}$
- Tag the H_{SM} to search for the new sector

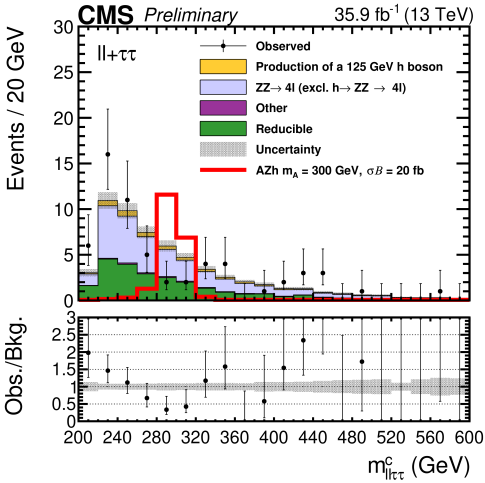




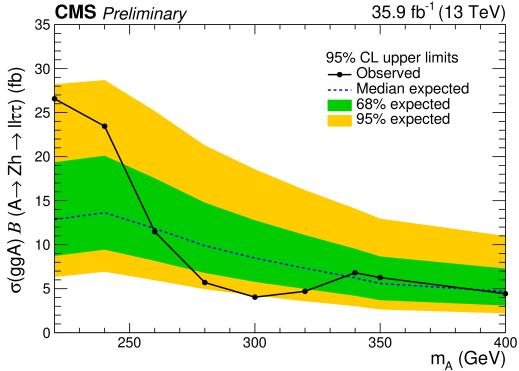


New Higgs searches tagging SM Higgs CMS-PAS-HIG-18-023

Search for an additional pseudo-scalar (MSSM) in $A \to (Z^0 \to ee/\mu\mu)(H_{SM} \to \tau\tau)$



- In particular low $tan\beta(= \frac{v_1}{v_2})$
- Constrain $m_{\tau\tau} = m_{H_{SM}}$ to improve the sensitivity (SVFIT)



Outline

Pinning down the 125 GeV Higgs boson
- The Simplified Template Cross-sections framework (STXS)
- Cross-section measurements
- Toward single-channel observations
- (Too) rare decays

Searches for an extended Higgs sector
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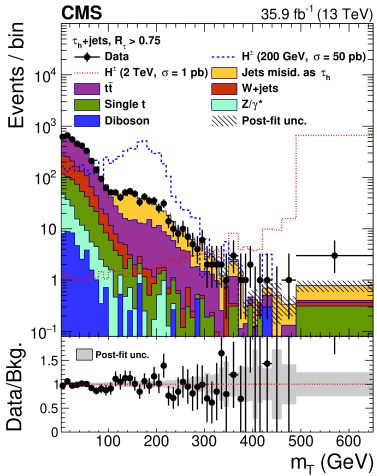
Searches for charged Higgs decaying in $\tau\nu$ arXiv:1903.04560

2HDMs predict charged scalar, with sizeable $BR(H^{\pm} \to \tau^{\pm}\nu)$ at high $tan\beta$ (in type-2)



> Produced in association with top and b-quarks

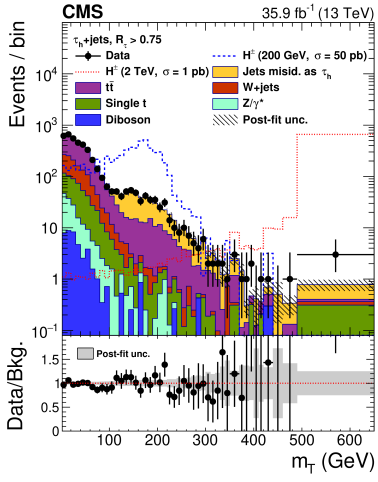
> Split into 3 final states
- τ_{Had}+jets, τ_{Had}+leptons, no-τ_{Had}+leptons

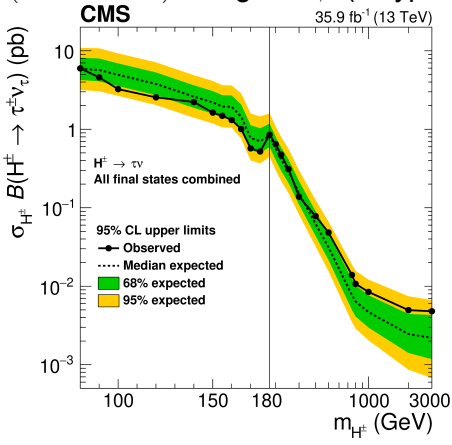
> Further categorize these FS
- Esp. wrt number of jets, b-jets

> Extract the signal from a combined fit of m_T over all 36 categories

Searches for charged Higgs decaying in $\tau\nu$ arXiv:1903.04560

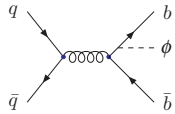
2HDMs predict charged scalar, with sizeable $BR(H^{\pm} \to \tau^{\pm}\nu)$ at high $tan\beta$ (in type-2)

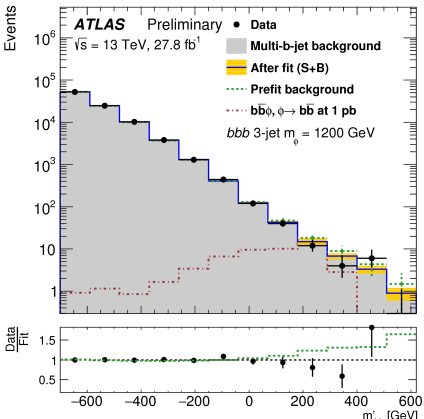


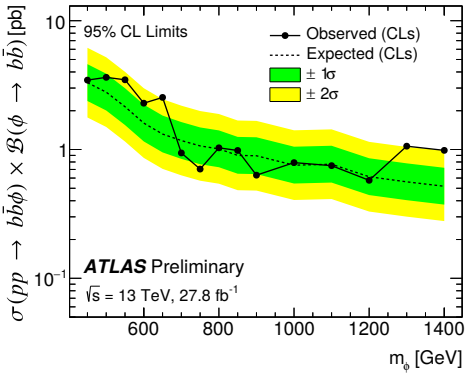


Up to $m_{H^{\pm}} = 165$ GeV, production is $t \to H^{\pm}b$.
No assumption made after

bH production of a new Heavy neutral boson ATLAS-CONF-2019-010







- Targets flipped 2HDM at high-$tan\beta$ where new scalar could mainly couple to $b-quarks$
- Challenging b-jet trigger ($\epsilon_{2016} = 80-90\%$)
- Sensitivity enhanced by transforming m_{bb},$p_T^{1,2}$ to isolate signal from FSR $g^* \to b\bar{b}$

Conclusion

> Large effort is being carried out to pinpoint the nature of the Higgs boson in detail

→ So far no deviation from SM observed, but a large increase in stat. expected : most analyses only use $\frac{1}{4}$ of the dataset - stay tuned !

> Potential additional content of the Higgs sector being studied as well

→ Only scratched a few of searches available already (eg $H \to t\bar{t}$)

→ And many more will be performed !

> Complex and precise legacy analyses take time

→ Stay tune for new strong results throughout LS 2 !