ATLAS searches in the Higgs sector

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on behalf of the
ATLAS Collaboration

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Topics and references

All presented ATLAS searches use full Run2 LHC pp data: $\sqrt{s} = 13\,\text{TeV}$, $140\,\text{fb}^{-1}$

Search for additional scalars in the Higgs sector

- $X \to \gamma\gamma$ low-mass
- $X \to S(bb)H(\gamma\gamma)$
- $X \to S(VV)H(\gamma\gamma)$
- $X \to S(HH)H \to 6b$ with $126\,\text{fb}^{-1}$ New!
- $S \to Z_d Z_d \to 4\ell$

- DiHiggs combination (see talk by Marc)

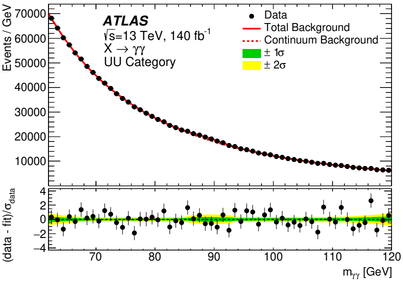
Seaches for $H^{\pm}$

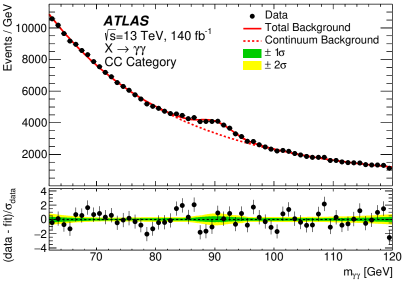
- $H^{\pm} \to Wh$ New!
- $H^{\pm} \to \tau\nu$ New!
- $H^{\pm} \to cs$

References in the links

$X \to \gamma\gamma$ low-mass

- Search for resonances in low-mass $m_{\gamma\gamma}$ (66, 110) GeV
- Excellent diphoton mass resolution
- Backgrounds
  - large irreducible $\gamma\gamma$ background
  - $Z \to ee$ background (difficult to model)
- Classify events by the number of photon conversions (different $e \to \gamma$ fake rate)
- Fit of the $m_{\gamma\gamma}$ distribution
- Improvements thanks to a new BDT to better separate electrons and photons

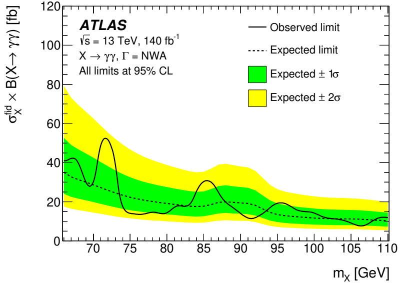


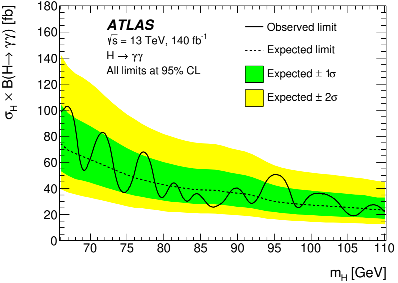


$X \to \gamma\gamma$ low-mass Results

arXiv:2407.07546

- Model independent = only ggF, generic spin-0 bosons X, in a fiducial region. Narrow width approximation or as a function of the width.
- Model dependent = additional H. Further categorization with a BDT, assuming main SM production modes.





2.9σ bump at 95 GeV seen by CMS [Phys. Lett. B 860 (2024) 139067] not confirmed
CMS exclusion for the model dependent: 15-73 fb in 70-110 GeV $\Rightarrow$ similar sensitivity

Additional scalars in the Higgs sector

Present data does not exclude that H has a small mixing with additional scalars

Model examples

- SM Higgs sector is extended with a complex singlet (csSM)
- Two real scalar singlets extensions (TRSM)
- Complex two-Higgs-doublet model (C2HDM)
- 2HDM extended by a real scalar singlet (N2HDM)
- Next-to-Minimal Supersymmetric Standard Model (NMSSM)

Can provide dark matter candidates, additional source of CP-violation, ν-masses, ...

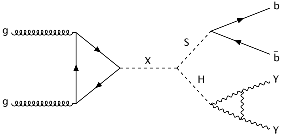
Present $X \to SH$ analyses

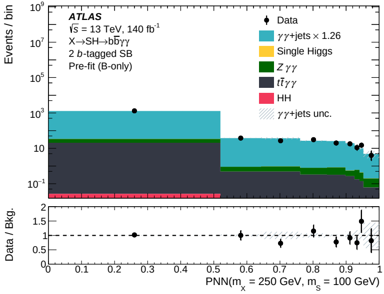
- Assuming $m_X > m_S + m_H$ to allow $X \to S + H$
- Prodution rate and BR very model dependent. If S is H-like $S \to b\bar{b}$ is dominant for $m_S < 130\,\text{GeV}$
- ATLAS searches in: $S(b\bar{b})H(\gamma\gamma)$, $S(VV)H(\gamma\gamma)$, $SH \to HHH \to 6b$, $S(VV)H(\tau\bar{\tau})$
- CMS searches in: $S(b\bar{b})H(\gamma\gamma)$, $S(b\bar{b})H(b\bar{b})$, $S(b\bar{b})H(\tau\tau)$

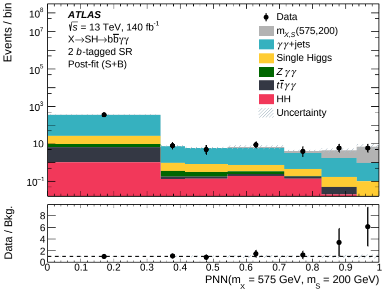
$X \to S(bb)H(\gamma\gamma)$

- Low BR($H \to \gamma\gamma$), excellent diphoton mass resolution: 1-2 GeV
- Use of parameterized neural networks (PNN) as final discriminant
  - provides optimal s/b separation for any fixed (m_X, m_S)
  - continuos sensitivity in the (m_X, m_S) plane
  - very different from $H/X \to \gamma\gamma$ approach: model based on histograms from MC

- resolved (2b) and boosted (1b, for $m_X \gg m_S$) topologies
- Main background $\gamma\gamma + j$ constrained by $m_{\gamma\gamma}$ sidebands region (SB)

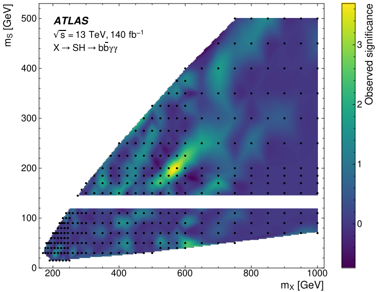


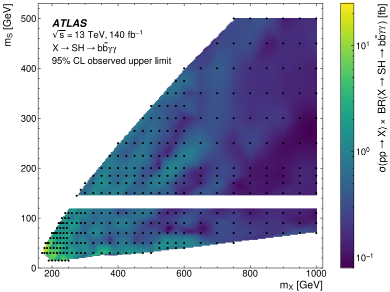




$X \to S(bb)H(\gamma\gamma)$ Results

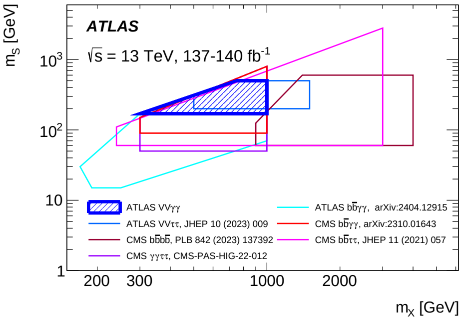
Largest deviation at $(m_X, m_S) = (575, 200)$ GeV, 3.5σ local significance, 2.0 global significance

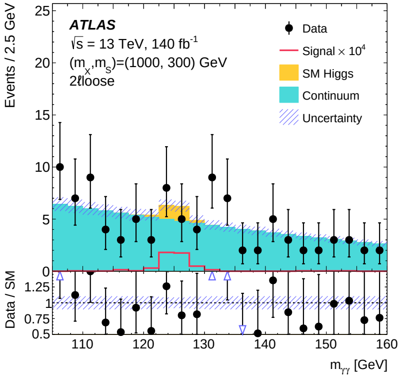




At $(m_X, m_S) = (650, 90)$ GeV (CMS reported [JHEP 05 (2024) 316] 3.8 local, 2.8 global): well agreement with background-only

- Complementing boosted $\gamma\gamma bb$ analysis
- Main background: $\gamma\gamma + j$, $V + \gamma\gamma$
- Categories: 1ℓ, $e\mu$, $2\ell(WW)$, $2\ell(ZZ)$
- Parametrized BDT to suppress background
- Fit of $m_{\gamma\gamma}$, background shape from control region with 0ℓ

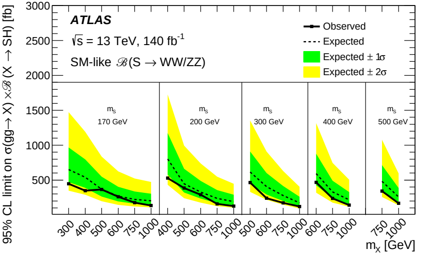


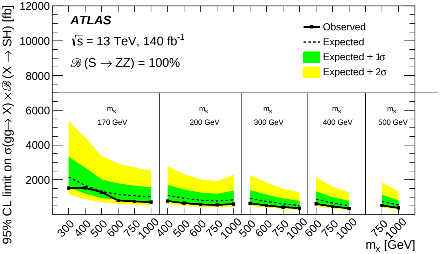


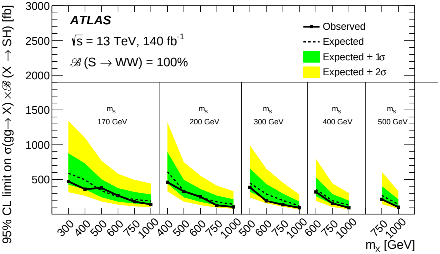
$X \to S(VV) + H(\gamma\gamma)$ Results

Limit on $\sigma(gg \to X) \times BR(X \to SH)$, assuming:

- SM-like: $BR(S \to VV)$
- $BR(S \to ZZ) = 1$
- $BR(S \to WW) = 1$

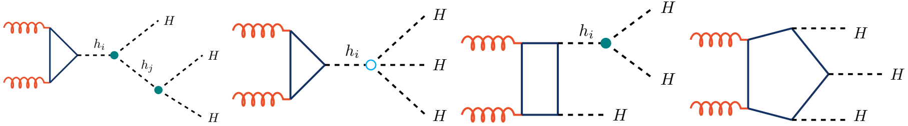






$X \to SH \to HHH \to 6b$

arXiv:2411.02040



Complicated final state, exploiting large $BR(H \to bb) = 58\%$

Three interpretations

- SM HHH ($0.079\,\text{fb} = 1/400 HH$ at NNLO, dominated by the pentagon)
- Two Real Singlet Scalars
- Generic heavy resonance

Three analysis, with different DNNs:

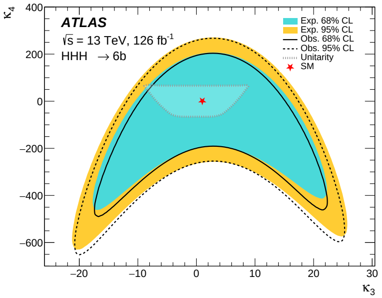
- Resonant $m_S > 2m_H = 250\,\text{GeV}$
- Non-resonant $m_S < 250\,\text{GeV}$ or SM
- Generic (narrow and wide) heavy resonance $m_S > 275\,\text{GeV}$, $m_X > 550\,\text{GeV}$

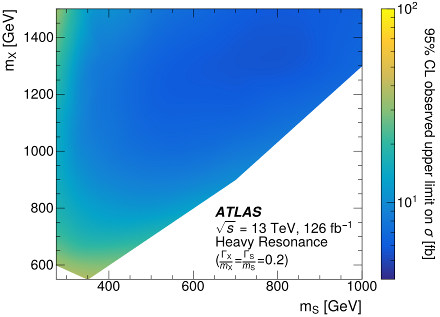
- Main background: multijet, data-driven estimated extrapolating $4b \to 5b \to 6b$ using low-DNN score region, assuming kinematic $5b/4b \sim 6b/5b$
- Combinatoric resolved minimizing $|m_{H1} - 120\,\text{GeV}| + |m_{H2} - 115\,\text{GeV}| + |m_{H3} - 110\,\text{GeV}|$ (right choice 60% for SM)
- Using DNN output as final discriminant, trained on 6b MC signal and 5b data

$X \to SH \to HHH \to 6b$ Results

First time $6b$ at LHC.

- 95% CL upper limit on $\sigma_{HHH}^{SM} = 59.4\,\text{fb}$ (750× SM)
- First direct limits set on $\kappa_4 = \lambda_4/\lambda_4^{\text{SM}}$
- Limit on Two Real Singlet Model (TRSM) model and generic heavy resonance

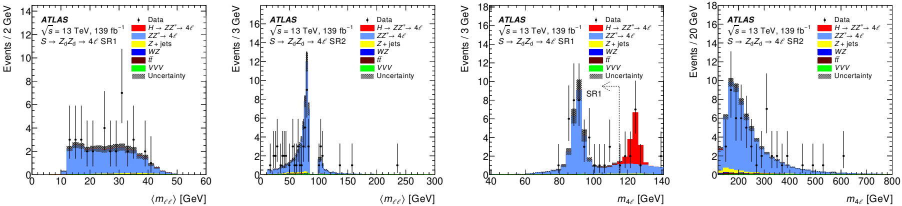




κ-framework should not be used outside the unitarity bound.

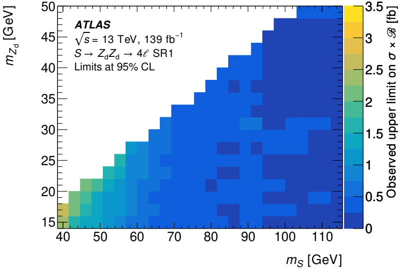
$S \to Z_d Z_d \to 4\ell$

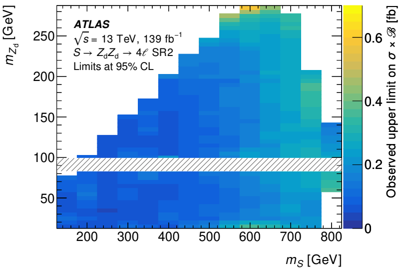
- Search for new scalar S ($[30, 115] \cup [130, 800]$ GeV) (dark matter model: Hidden Abelian Higgs Model (HAHM))
  - decaying to new spin-1 bosons Z_d (on-shell [15,300] GeV)
  - in the 4ℓ final states: $4e$, 4μ, $2e2\mu$
- Main background: $ZZ^* \to 4\ell$, from the simulation
- Reducible background ($t\bar{t}$, $Z + j$) estimated from control regions
- Two signal regions: $m_{4\ell} < 115$ GeV and $m_{4\ell} > 130$ GeV



Search for bump in the $\langle m_{\ell\ell} \rangle = \frac{m_{ab}+m_{cd}}{2}$ spectrum, in bins of $m_{4\ell}$, for different m_S, m_{Z_d} hypotheses

Exclusion limits on $\sigma(gg \to S) \times BR(S \to Z_d Z_d \to 4\ell)$



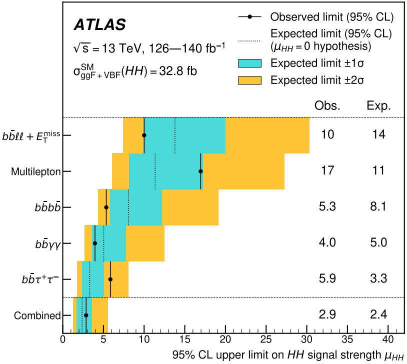


Z-veto cut in the analysis.

In the first signal region ($m_{4\ell} < 115$ GeV), the limits range from 0.14 fb to 3.1 fb and in the second ($m_{4\ell} > 130$ GeV), from 0.05 fb to 0.60 fb

DiHiggs combination → See Marc's talk

- $\gamma\gamma bb$ very clean, very sensitive to low-m_{HH}
- $bb\tau\tau$ good compromise between background and BR, very sensitive to medium-m_{HH}, best channel for SM
- ***bbbb*** highest cross section, complicated background, sensitive to boosted and VBF
- $bb\ell\ell$ and **multi-lepton**



$$\mu(HH) = 0.5^{+0.9}_{-0.8}(\text{stat.})^{+0.7}_{-0.6}(\text{syst.})$$

$$z = 0.4\sigma \text{ (1.0 expected)}$$

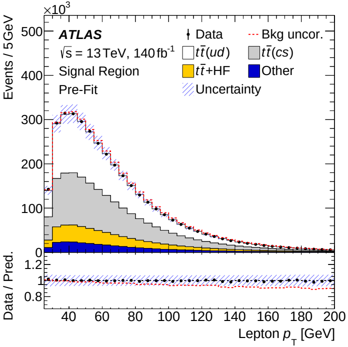
$$-1.2 < \kappa_\lambda < 7.2$$

$$0.6 < \kappa_{2V} < 1.5$$

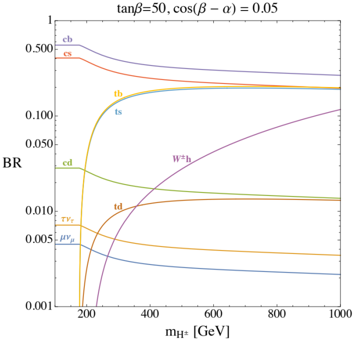
Limits improved by 17% with respect to previous combination.

Recent $H^\pm$ searches

- Extension to the scalar sector: provide dark matter candidate, potential source of CP violation, . . .
- 2HDM, SUSY, Axions, . . . ,
- Use the associated production $pp \to tbH^\pm$, $t\bar{t}$ is the main background
- Several quantities are mis-modelled in $t\bar{t}$ due to missing higher-order QCD and electroweak corrections in MC
- Using a data-driven reweighting of the $t\bar{t}$ background



Example from $H^\pm \to cs$



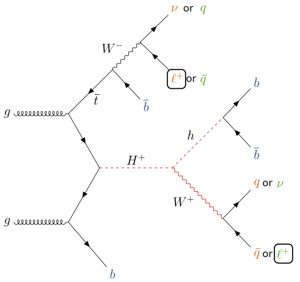
Specific model, Phys. Rev. D 94 115032 (2016)

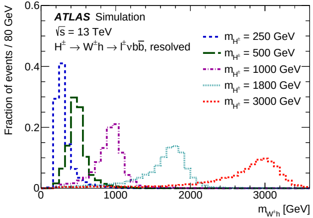
$H^{\pm} \to Wh$

arXiv:2411.03969

First search for $H^{\pm} \to Wh$, important decay in Georgi-Machacek, 3HDM Type-Z, N2HDM

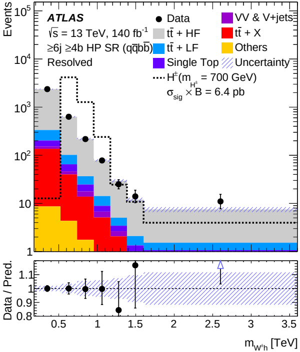
- Use $h \to b\bar{b}$ decay, two analyses: resolved (small $H^{\pm}$ mass) and merged ($W \to qq/h \to bb$ reconstructed using large-jets)
- Requiring one lepton (two channels: $H^{\pm} \to \ell\nu bb$ and $H^{\pm} \to qqbb$)
- In the resolved, BDTs to identify the decay products of $H^{\pm}$
- Split in many categories using BDTs/NN and (b-)jet multiplicity
- In $H^{\pm} \to \ell\nu bb$, m_{Wh} reconstructed using $p^{\text{miss}}_{x/y}$ and W-mass constrain
- $H^{\pm}$ mass resolution 6%-10%
- Main backgrounds: $t\bar{t}$ + jets (light/heavy flavor separately modeled)

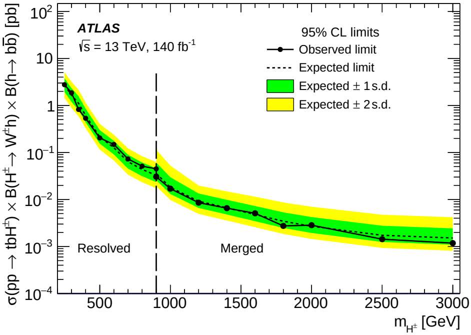


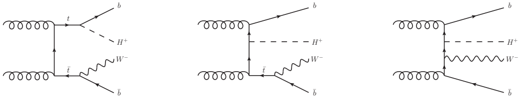


$H^\pm \to Wh$ Results

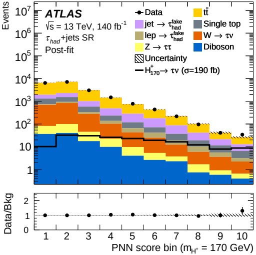
- Likelihood fit of the m_{Wh} distribution
- No significant excess (0.9σ at $m_{H^\pm} = 900$ GeV)
- Resolved and merged analysis not combined: use the most sensitive one (expected)
- $H^\pm \to \ell\nu b\bar{b}$ channel more sensitive

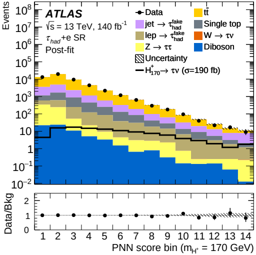


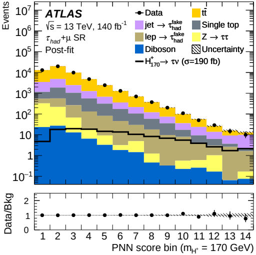




- New result, with extended mass range: 80-3000 GeV.
- $H^{\pm} \to \tau\nu$ dominant in 2HDM for $m_H^{+} < m_t$
- Three channels:
  - $\tau_{\text{had}} + j$: most sensitive at high-mass, thanks to large $W \to q\bar{q}$
  - $\tau_{\text{had}} + \mu/e$: most sensitive at low-mass, thanks to single lepton triggers
- Using recurrent NN to identify τ_{had} and BDT to separate electrons.
- Main background from $t\bar{t}$, $W + j$
- Likelihood fit to parameterized neural networks (PNN) output



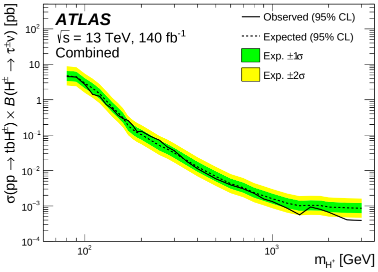


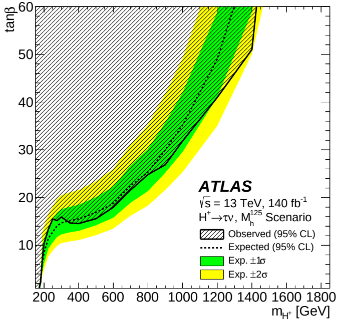


$H^{\pm} \to \tau\nu$ Results

Limits on

- $\sigma(pp \to tbH^{\pm}) \times BR(H^{\pm} \to \tau\nu)$
- $BR(t \to bH^{\pm}) \times BR(H^{\pm} \to \tau\nu)$ in the low-mass range, assuming SM $t\bar{t}$
- $\tan\beta$ vs $m_{H^{\pm}}$ in the hMSSM and MSSM with M_h^{125} scenario



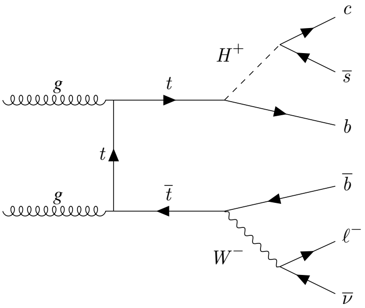


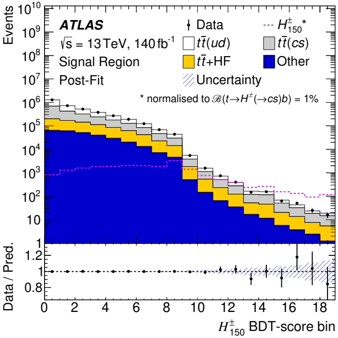
Improvement by factor 2-4 with respect to previous analysis: better τ_{had} identification, fake τ_{had} background estimation

$H^\pm \to cs$

arXiv:2407.10096

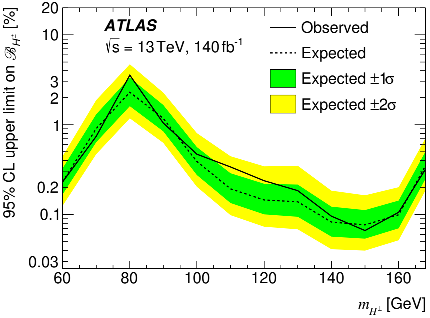
- Requiring 1ℓ from $W \to \ell\nu$, 2 bjets, 4 jets. Using b and c-tagging
- Usually $BR(H^\pm \to cs) > BR(H^\pm \to cb)$ due to $V_{cs} \gg V_{cb}$
- First analysis in ATLAS at 13 TeV
- Resolve combinatorics using top-mass reconstruction
- BDT trained to separate signal from $t\bar{t}$, using top kinematic ($H^\pm$ vs W), event, flavour tagging variables
- Likelihood fit to BDT output





$H^{\pm} \rightarrow cs$ Results

- Assuming $m_{H^{\pm}} < m_t$: large BR at small masses
- Dominated by $t\bar{t}$ modeling systematic
- Limit on $BR(t \rightarrow H^{\pm}b)$ assuming $BR(t \rightarrow Wb) + BR(t \rightarrow H^{\pm}(cs)b) = 1$



- Least stringent close to the W-boson mass
- Close to m_t the limits weaken due to low p_T of b-jet

Summary

- Many results in searches in the Higgs sector and extensions
- Exploiting the full Run2 dataset ($140\,\text{fb}^{-1}$, $\sqrt{s} = 13\,\text{TeV}$)
- No excess found, many limits have been shown
- First analysis looking for quartic Higgs coupling (HHH)
- First analysis looking for $H^{\pm} \to Wh$
- First analysis looking for $H^{\pm} \to cs$
- Analysis will benefit from Run3 statistics at $\sqrt{s} = 13.6\,\text{TeV}$, (now: $\sim 180\,\text{fb}^{-1}$, target: $\sim 300\,\text{fb}^{-1}$), but also from performance improvements.


Thanks for your
attention

Section 1

Backup

$S \to Z_d Z_d \to 4\ell$ Selection

		$S \to \mathrm{Z_d Z_d} \to 4\ell$ ($\ell = e, \mu$)	
Mass range		SR1 $15\,\mathrm{GeV} < m_{Z_\mathrm{d}} < 50\,\mathrm{GeV}$ $30\,\mathrm{GeV} < m_S < 115\,\mathrm{GeV}$	SR2 $15\,\mathrm{GeV} < m_{Z_\mathrm{d}} < 300\,\mathrm{GeV}$ $130\,\mathrm{GeV} < m_S < 800\,\mathrm{GeV}$
Baseline electrons		$p_\mathrm{T} > 7\,\mathrm{GeV}$ and $\lvert\eta\rvert < 2.47$; Loose identification with an IBL hit $\lvert z_0 \sin\theta\rvert < 0.5\,\mathrm{mm}$	
Baseline muons		$p_\mathrm{T} > 5\,\mathrm{GeV}$ ($15\,\mathrm{GeV}$ if calo-tagged) and $\lvert\eta\rvert < 2.7$; Loose identification $\lvert z_0 \sin\theta\rvert < 0.5\,\mathrm{mm}$ and $\lvert d_0\rvert < 1\,\mathrm{mm}$ (except for stand-alone muons)	
Quadruplet selection		Trigger-matched $e^+e^-e^+e^-$, $e^+e^-\mu^+\mu^-$, or $\mu^+\mu^-\mu^+\mu^-$; ≤ 1 SA+CT μ Three leading-p_T leptons satisfying $p_\mathrm{T} > 20\,\mathrm{GeV}$, $15\,\mathrm{GeV}$, $10\,\mathrm{GeV}$ Define pairs m_{ab} and m_{cd} such that $m_{ab} > m_{cd}$	
		$\Delta R(\ell, \ell') > 0.10$ (0.20) for same-flavour (different-flavour) ℓ, ℓ'	
Quadruplet ranking		Select quadruplet with smallest $\Delta m_{\ell\ell} = \lvert m_{ab} - m_{cd}\rvert$	
Event selection	Isolation & impact parameter	Track and calorimeter isolation, excluding tracks/clusters from other leptons in the quadruplet $\lvert d_0\rvert/\sigma_{d_0} < 5$ for electrons and $\lvert d_0\rvert/\sigma_{d_0} < 3$ for muons	
	$m_{4\ell}$	$m_{4\ell} < 115\,\mathrm{GeV}$	$m_{4\ell} > 130\,\mathrm{GeV}$
	Low mass veto	$m_{ab,cd,ad,cb} > 5\,\mathrm{GeV}$	
	Z boson veto	$m_{ab} < 50\,\mathrm{GeV}$ or $m_{ab} > 106\,\mathrm{GeV}$	$\lvert m_{ab,cd} - m_Z\rvert > 8\,\mathrm{GeV}$ For $4e$ and 4μ channels: $\lvert m_{ad,cb} - m_Z\rvert > 4\,\mathrm{GeV}$
	Heavy-flavour veto / ZZ^* alt. pairing veto	Reject event unless $m_{ab,cd,ad,cb} >$: $(m_{\Upsilon(3S)} + 0.75\,\mathrm{GeV}) = 11.105\,\mathrm{GeV}$	
	Signal region	$m_{cd} > 0.85 m_{ab} - 0.1125 f(m_{ab}) m_{ab}$ $\lvert E'_{ab}/m_{4\ell} - 0.5\rvert < 0.008$	

$H^{\pm} \to cs$ cutflow

Selection steps	Fraction of events passing selection [%]		
	$H^{\pm}_{80}$	$H^{\pm}_{130}$	$H^{\pm}_{160}$
Initial	100.0	100.0	100.0
Trigger	37.8	37.5	37.5
At least 1 medium ID e/μ with $p_{\mathrm{T}} > 10\,\mathrm{GeV}$	35.3	35.2	35.0
Exactly 1 medium ID e/μ with $p_{\mathrm{T}} > 10\,\mathrm{GeV}$	34.8	34.7	34.7
No medium ID μ/e with $p_{\mathrm{T}} > 10\,\mathrm{GeV}$	33.8	33.7	33.9
Exactly 1 medium ID e/μ with $p_{\mathrm{T}} > 27\,\mathrm{GeV}$	32.9	32.7	33.0
Lepton matches Trigger lepton	32.6	32.5	32.8
Jet Cleaning	32.5	32.4	32.7
At least 1 Jet with $p_{\mathrm{T}} > 25\,\mathrm{GeV}$	32.4	32.3	32.6
At least 2 Jets with $p_{\mathrm{T}} > 25\,\mathrm{GeV}$	31.7	31.5	31.5
At least 3 Jets with $p_{\mathrm{T}} > 25\,\mathrm{GeV}$	28.0	27.8	26.5
At least 4 Jets with $p_{\mathrm{T}} > 25\,\mathrm{GeV}$	19.1	19.2	15.8
At least 1 b-tagged Jet	16.6	15.8	11.1
Lepton is Medium Isolated	15.5	14.7	10.3
Lepton is Tight Identified	14.9	14.2	9.9
Lepton is Tight Isolated	13.6	12.9	9.1
At least 2 b-tagged Jets	6.6	5.4	1.7

$H^{\pm} \to cs$ BDT

Variable type	Variable name	Definition
Top-quark kinematic variables		
t_{had}	j_1 p_{T}	p_{T} of j_1-labelled jet
	j_2 p_{T}	p_{T} of j_2-labelled jet
	b_{had} p_{T}	p_{T} of b_{had}-jet
	$b_{\mathrm{had}}^{t_{\mathrm{had}}-\mathrm{rest}}$ p	Momentum of b_{had}-jet in t_{had} rest frame
	dijet mass	Invariant mass of j_1+j_2 jets
	(j_1+b_{had}) mass	Invariant mass of j_1+b_{had} jets
	(j_2+b_{had}) mass	Invariant mass of j_2+b_{had} jets
	$\cos\theta$	Boson spin sensitive variable
t_{lep}	b_{lep} p_{T}	p_{T} of b_{lep}-jet
	Lepton p_{T}	p_{T} of reconstructed lepton
	W mass	Invariant mass of reconstructed W boson
	t_{lep} mass	Invariant mass of reconstructed t_{lep}
	t_{lep} p_{T}	p_{T} of reconstructed t_{lep}
$t\bar{t}$-system	ΔR(b_{lep},b_{had})	ΔR between the b_{lep}-jet and b_{had}-jet
	$t\bar{t}$ mass	Invariant mass of t_{had}+t_{lep}
Event variables		
Event level	N_{jets}	Number of jets in the event
	S_{T}	Scalar p_{T} sum of all calibrated objects
	$\overline{P}_{t\bar{t}}$	Normalised probability of correct jet labelling
Flavour-tagging variables		
Flavour-tagging score	j_1 PCFT	PCFT score of j_1
	j_2 PCFT	PCFT score of j_2
	b_{had} PCFT	PCFT score of b_{had}-jet
	b_{lep} PCFT	PCFT score of b_{lep}-jet
Number of tags	$N_{c\text{-tagLo}}$	Number of jets passing loose c-tag WP (b-veto)
	$N_{c\text{-tagTi}}$	Number of jets passing tight c-tag WP (b-veto)
	$N_{b\text{-tag70}}$	Number of jets passing 70 % b-tag WP
	$N_{b\text{-tag60}}$	Number of jets passing 60 % b-tag WP