ATLAS searches for resonances decaying to boson pairs

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on behalf of the ATLAS collaboration

Analyses covered in this talk:

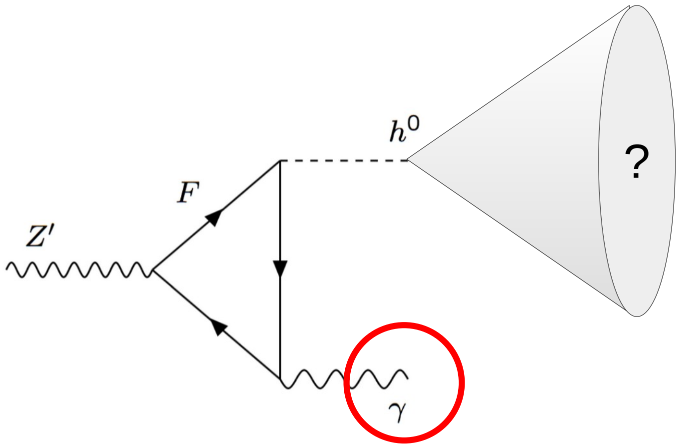
- $Z' \rightarrow H\gamma$ with $H \rightarrow bb$: *Phys. Rev. Lett. 125, 251802*
- $H^{\pm\pm}$ and $H^{\pm}$ into $2l^{SC}$, 3l, 4l: *CERN-EP-2020-240*
- Heavy diphoton resonances: *CERN-EP-2020-248*
- $HH \rightarrow \gamma\gamma bb$: ATLAS-CONF-2021-016

Data:

- 2015-2018
- 139 fb^{-1} @ 13 TeV
- Pileup = O(30-40) close to average for full dataset
- Different trigger settings

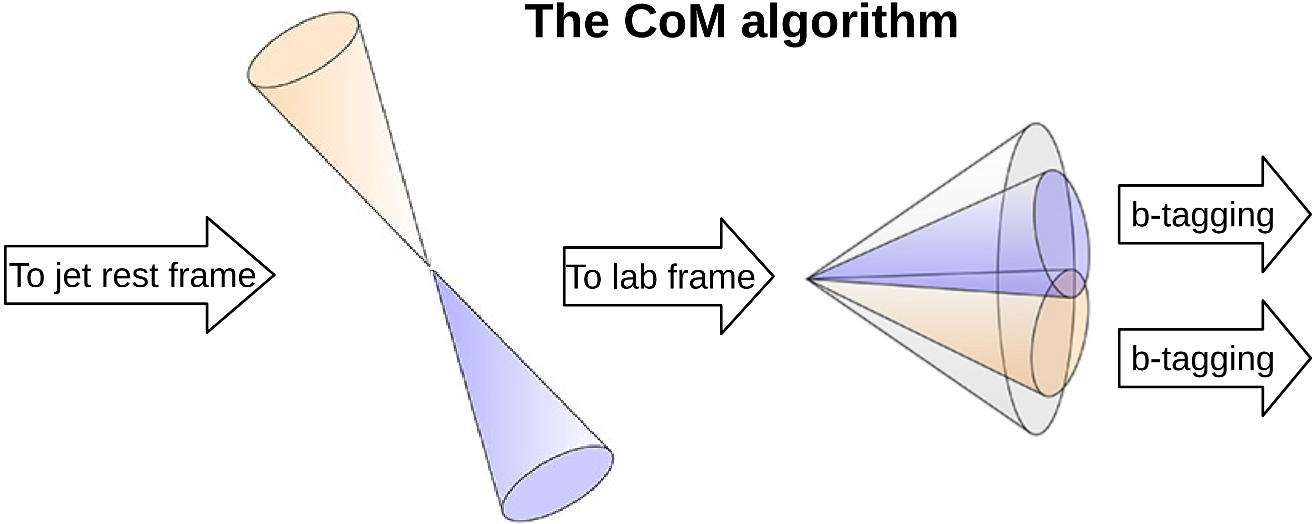
$Z' \rightarrow H\gamma$ with $H \rightarrow bb$

Novel b-jet identification technique

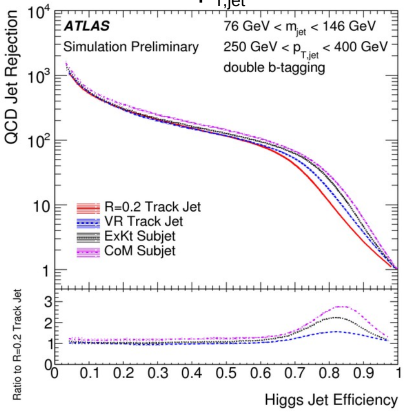


Photon p_T > 200 GeV

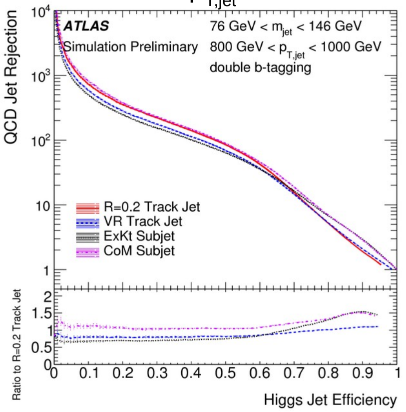
The CoM algorithm



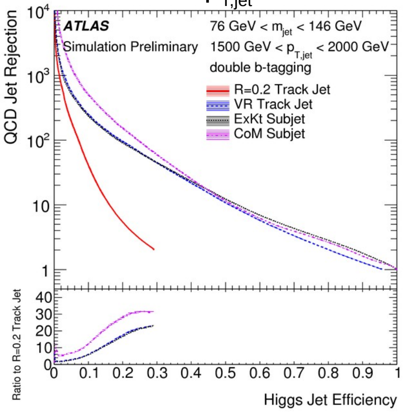
250 GeV < $p_{T,jet}$ < 400 GeV



800 GeV < $p_{T,jet}$ < 1000 GeV



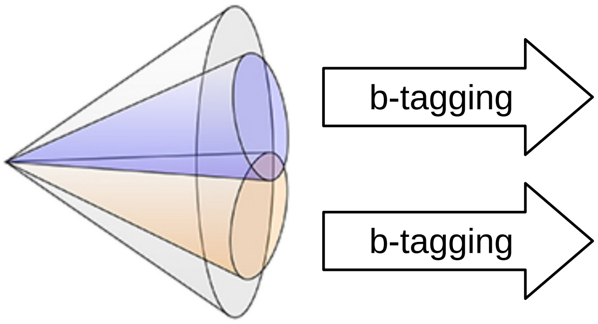
1500 GeV < $p_{T,jet}$ < 2000 GeV



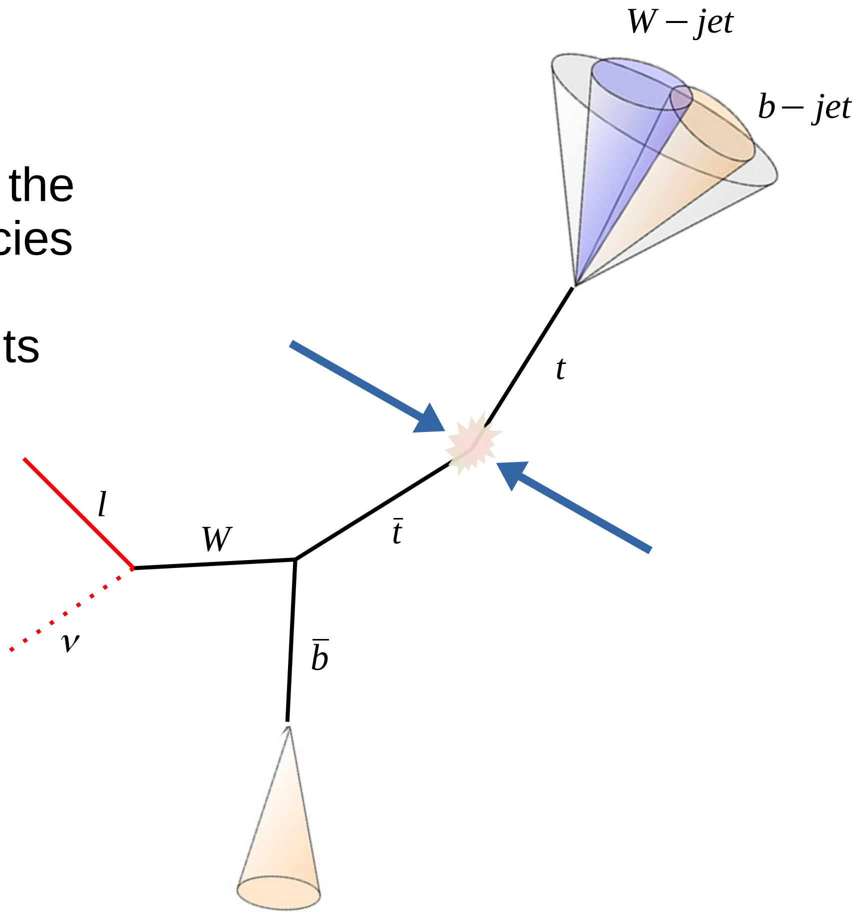
ATL-PHYS-PUB-2017-010

Z’ → Hγ with H → bb

Calibration of b-tagging efficiency



MC studies show that the two b-tagging efficiencies are **uncorrelated**
→ Can use ttbar events for calibration

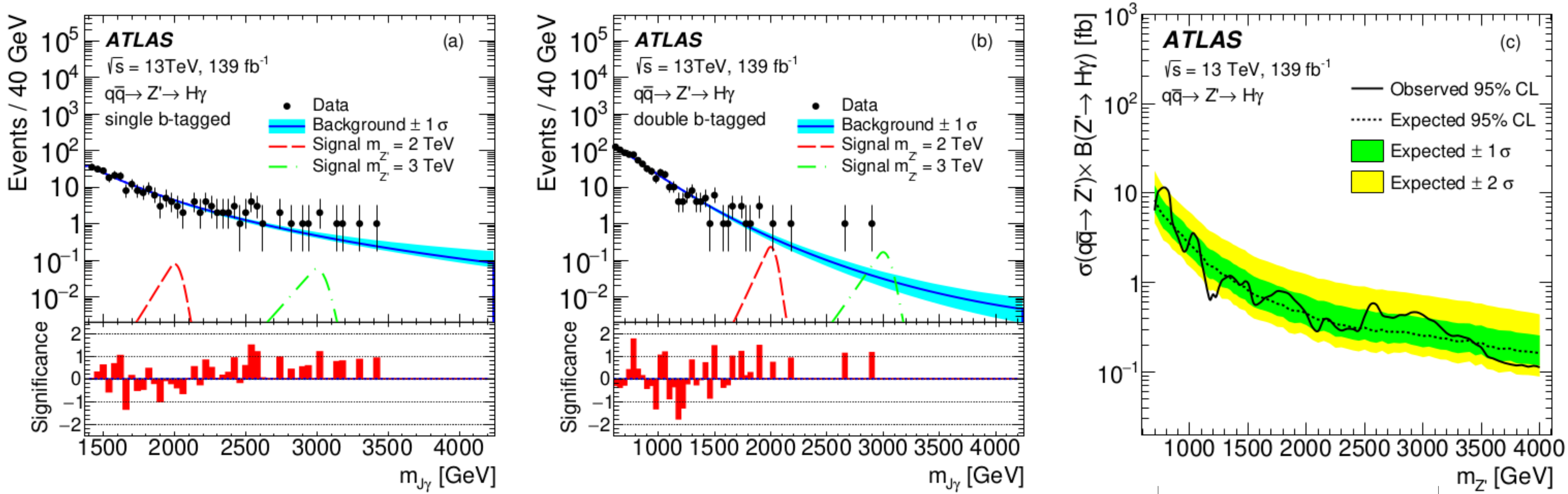


- MC studies show that the b-tagging efficiency is almost identical in top vs H → bb decays
- Estimated MC-to-data scale factor is consistent with 1 (within 5% syst)

Z’ → Hγ with H → bb

Results

Previous results:
Phys. Rev. D 98 (2018) 032015 (ATLAS)
Phys. Rev. Lett. 122 (2019) 081804 (CMS)



Photon p_T > 200 GeV

$$B(m_{J\gamma}) = (1-x)^{p_1} x^{p_2+p_3 \log(x)} \quad x = m_{J\gamma}/\sqrt{s},\ \sqrt{s} = 13\ \text{TeV}$$

Old mass range:
0.72-3.25 TeV

New mass range:
0.7-4 TeV

<u>Data are compatible with background-only hypothesis</u>

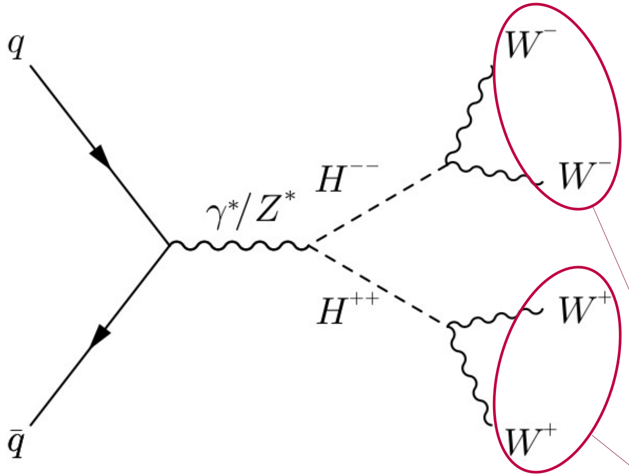
$H^{\pm\pm}$ and $H^{\pm}$ into $2l^{SC}$, $3l$, $4l$

Framework

Type-II seesaw model (J. Schechter and J. W. F. Valle, 1980)
Considering an additional Y=2 scalar triplet acquiring vev=100MeV at EWSB

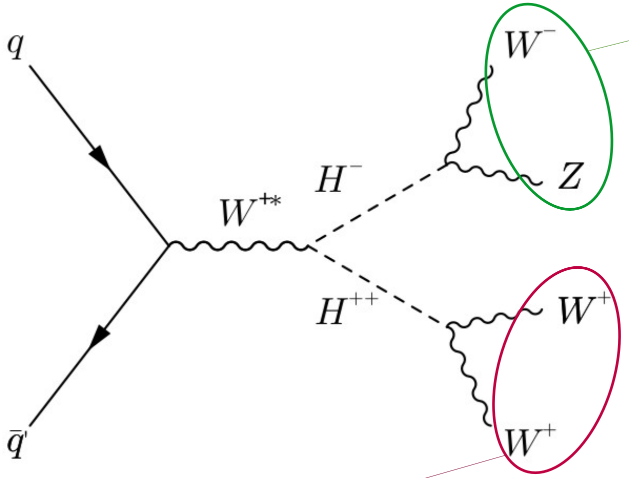
Scenario #1:

$m_{H^{\pm}} > 100\,GeV + m_{H^{\pm\pm}}$



Scenario #2 (new):

$m_{H^{\pm}} < 5\,GeV + m_{H^{\pm\pm}}$



BR = 40-60%
Other contributions are negligible after $2l^{SC}$ or $3l$ selection

BR = 100%

Considering only $m_{H^{\pm\pm}} > 200\,GeV$

$H^{\pm\pm}$ and $H^{\pm}$ into $2l^{SC}$, 3l, 4l
Lepton fake factors

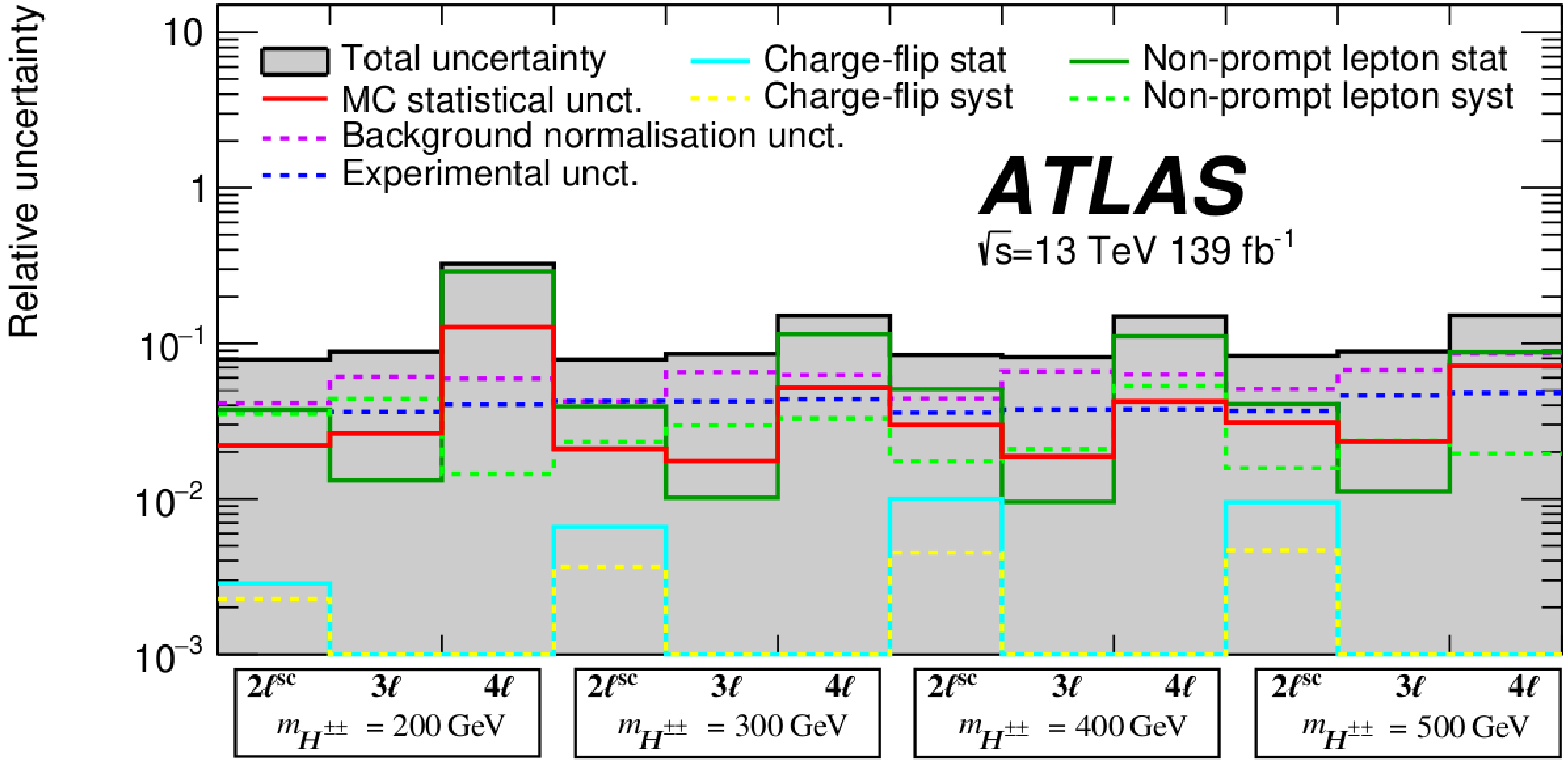
Increased statistics allowed for improvement in lepton fake factors (non-prompt lepton background) and their uncertainties

	electron			muon		
	fake factor	**stat. Uncertainty**	**total uncertainty**	**fake factor**	**stat. Uncertainty**	**total uncertainty**
2lSC	0.03 @ pT=40 GeV 0.16 @ pT>60 GeV (was 0.48)	0.01 @ pT=40 GeV 0.05 @ pT>60 GeV (was 0.07)	30% @ 20 GeV < pT < 60 GeV 55% @ pT > 60 GeV (was 35%)	0.03 @ pT=40 GeV 0.09 @ pT>60 GeV (was 0.14)	0.01 @ pT=40 GeV 0.02 @ pT>60 GeV (was 0.03)	20% @ 20 GeV < pT < 60 GeV 85% @ pT > 60 GeV (was 56%)
3l	0.021 (was 0.39)	0.009 (was 0.07)	60% (was 55%)	0.032 (was 0.17)	0.009 (was 0.07)	50% (was 81%)
4l	insufficient statistics					

Previous values from Eur. Phys. J. C (2019) 79:58

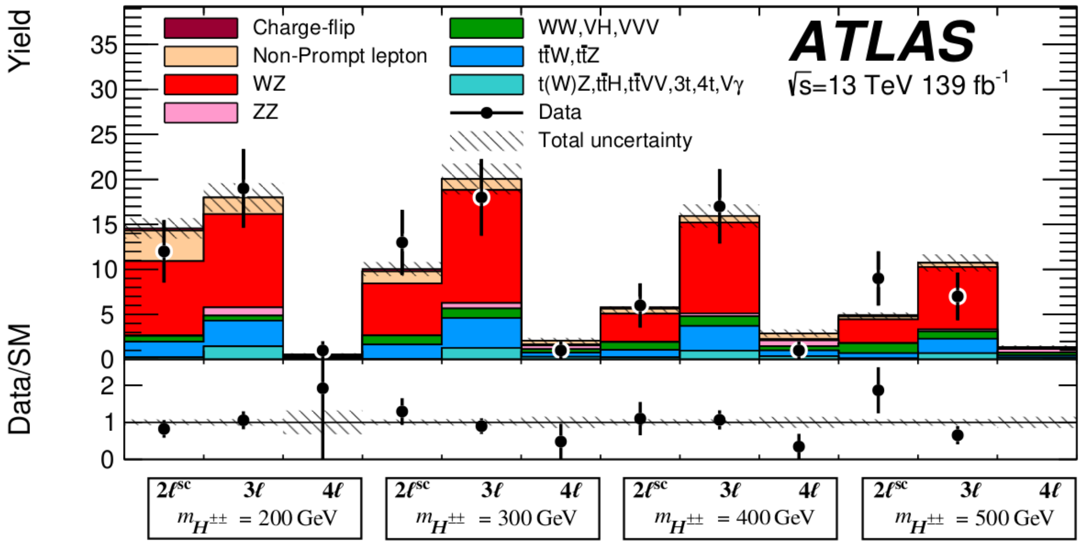
$H^{\pm\pm}$ and $H^{\pm}$ into $2l^{SC}$, 3l, 4l

Systematic uncertainties

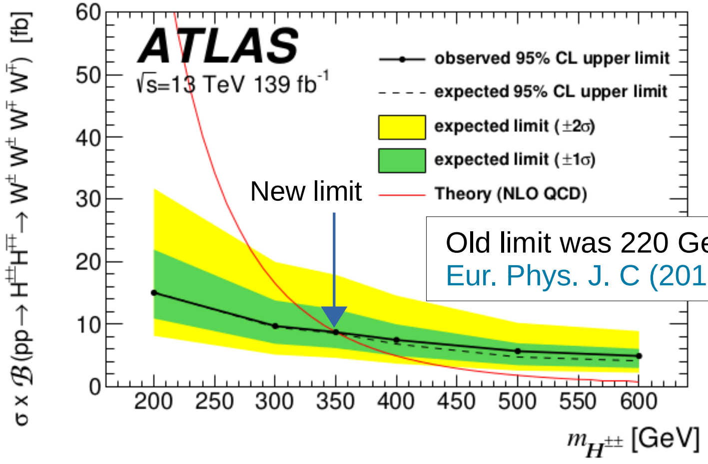


$H^{\pm\pm}$ and $H^{\pm}$ into $2l^{SC}$, 3l, 4l

Results

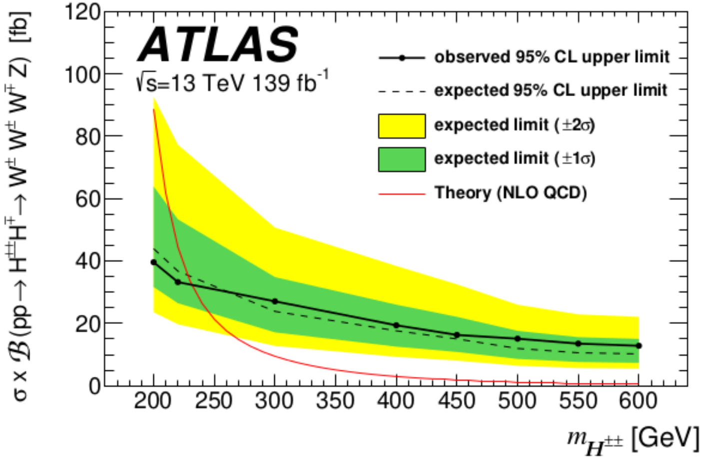


Pair production



Old limit was 220 GeV
Eur. Phys. J. C (2019) 79:58

Associated production **(new)**



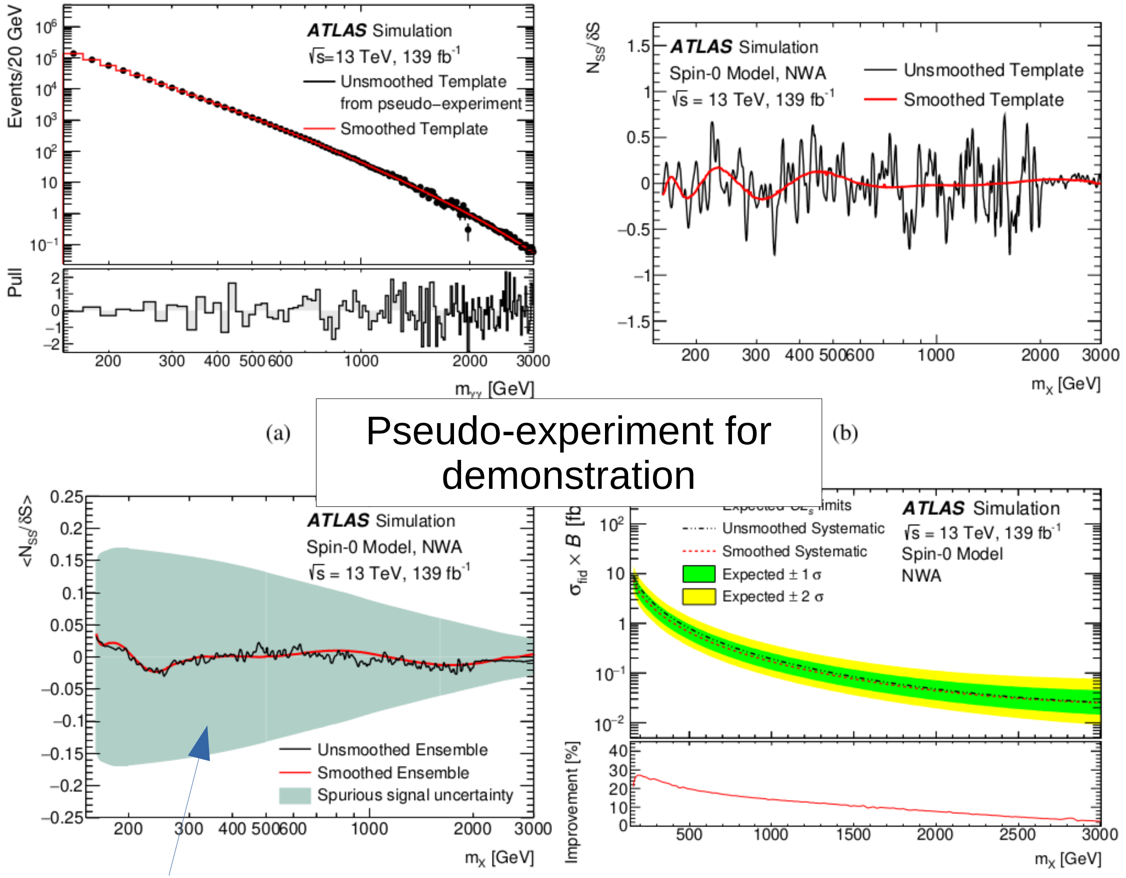
<u>Data agree with background-only hypothesis</u>

Heavy diphoton resonances
Framework

- Two benchmark models:
  - Spin 0 (generic resonance X) with m_X = 200 – 3000 GeV and Γ_X either 4 MeV (Narrow Width Approximation) or Γ_X = 0-10% m_X
  - Spin 2 (lowest KK graviton in RS1 model) with m_{G^*}>500GeV and k/M_{Pl} = 0.01 – 0.1
- Novelties of the analysis:
  - Common event selection for the two searches
  - **Functional decomposition** method (*arXiv:1805.04536*) to assess spurious signal uncertainty
  - Updated photon reconstruction, identification, isolation and energy calibration

Heavy diphoton resonances

Functional decomposition



Pseudo-experiment for demonstration

Repeated experiments: the bias is the same between unsmoothed and smoothed templates, and both are much smaller than the spurious signal uncertainty

Smallest (= fewest dof) function which maintains the flexibility to model all variations of background template:

$$f(x; b, a_0, a_1) = N(1 - x^{1/3})^b x^{a_0 + a_1 \log(x)}$$

$$x = m_{\gamma\gamma}/\sqrt{s}.$$

Fitted signal yields are considered **spurious signals**

Functional decomposition:

1) Fit the background template with orthonormal exponentials
2) Bin the smoothed template
3) Use it to determine the spurious signal via a sig+bkg model

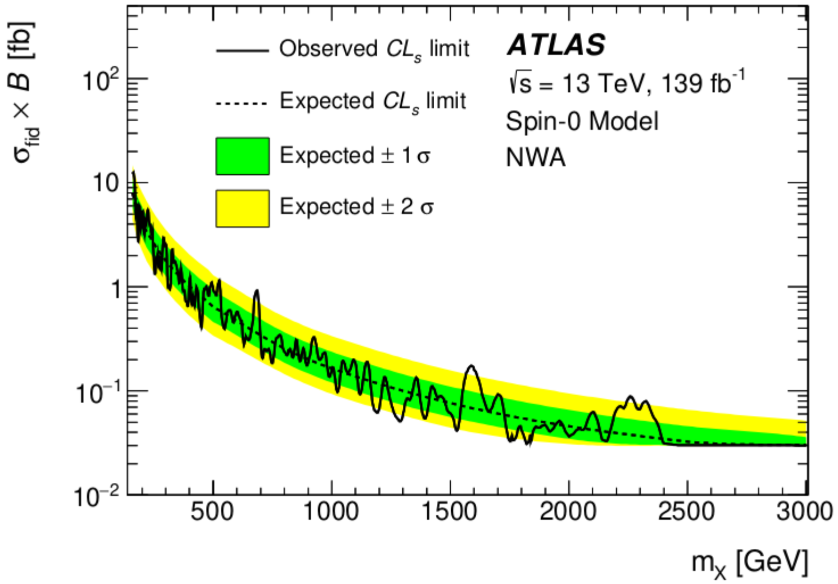
Sensitivity improves by 2-28 %

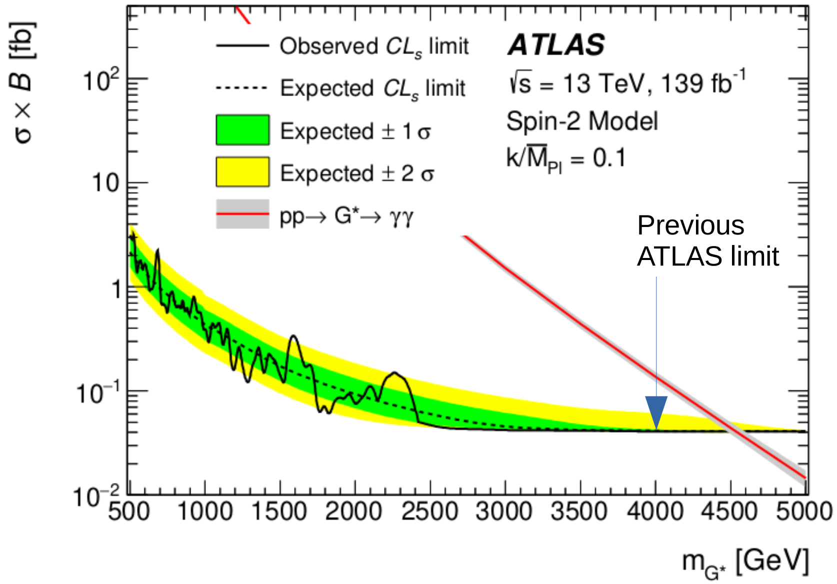
Heavy diphoton resonances

Result

Previous results:

- *Phys. Lett. B 775 (2017) 105 (ATLAS)*
- *Phys. Rev. D 98 (2018) 092001 (CMS)*



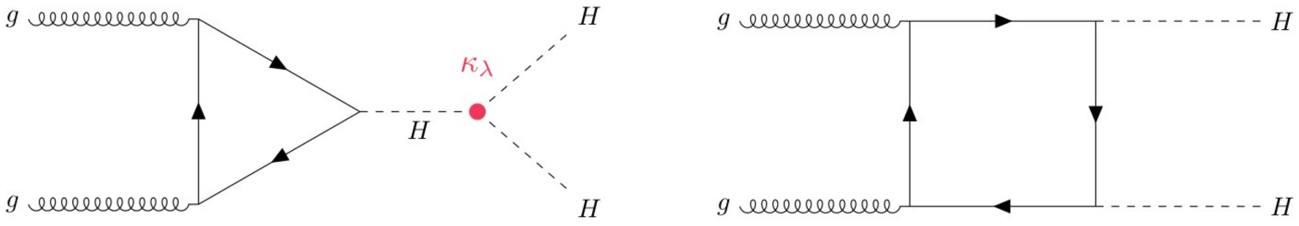


Most significant excess (m_X~684 GeV NWA and k/M_{Pl} = 0.01) has 3.29σ significance
Global significance is 1.30 (1.36) σ for spin-0 (spin-2) interpretations

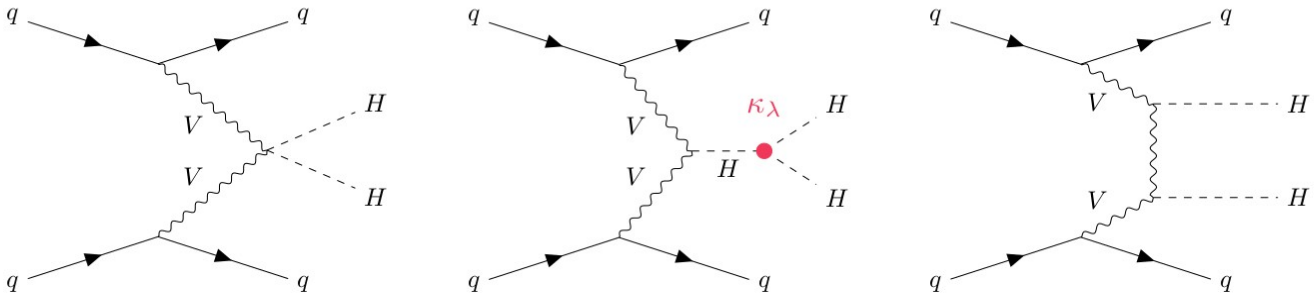
The RS1 model is excluded for m_{G^*}<2.2, 3.9, 4.5 TeV
k/M_{Pl} = 0.01, 0.05, 0.1

HH → γγbb

Framework



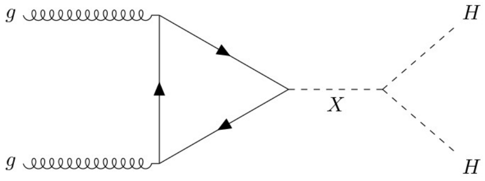
$$\sigma_{HH}(\text{ggF}) = 31.02^{+2.2\%}_{-5.0\%}\ (\text{Scale})\ \pm 3.0\%\ (\alpha_s\text{+PDF})\ \pm 2.6\%\ (m_{\text{top}})\ \text{fb}$$



$$\sigma_{HH}(\text{VBF}) = 1.72^{+0.03\%}_{-0.04\%}\ (\text{Scale})\ \pm 2.1\%\ (\alpha_s\text{+PDF})\ \text{fb}$$

\+

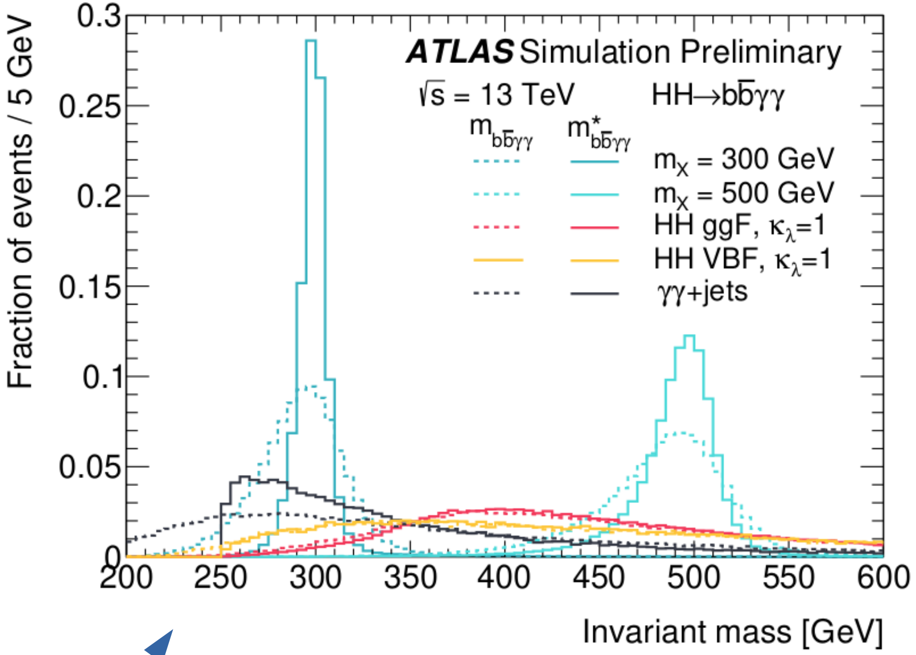
- Non-resonant enhancements, e.g. loop corrections, non-SM couplings, $k_\lambda=\lambda_{HHH}/\lambda^{SM}_{HHH}$
- Resonant enhancements, e.g.:



HH → γγbb

Common event preselection

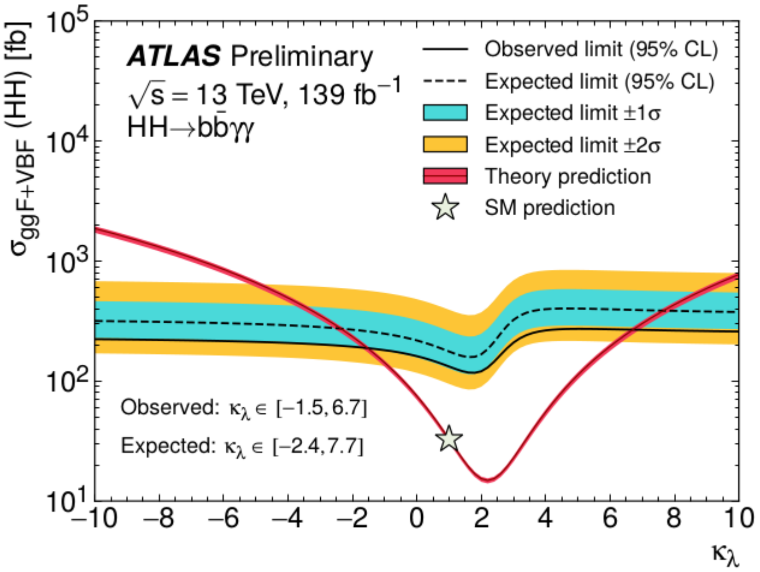
- Diphoton trigger with E_T>25,35 GeV
- Photon identification: loose (2015-16) + medium (2017-18)
- At least two photons passing the object selection criteria
- 105 GeV < $m_{\gamma\gamma}$ < 160 GeV
- (sub)leading p_T > (25%)35% $m_{\gamma\gamma}$
- Exactly two b-tagged jets (orthogonality wrt H→bbbb)
- No electrons, no electrons
- N_j < 6 @ |η|<2.5 (reject ttbarH events decaying hadronically)
- Object selection = tight ID, isolated photons
- **New categorization** based on $m^*_{b\bar{b}\gamma\gamma} = m_{b\bar{b}\gamma\gamma} - m_{b\bar{b}} - m_{\gamma\gamma} + 250\ \text{GeV}$



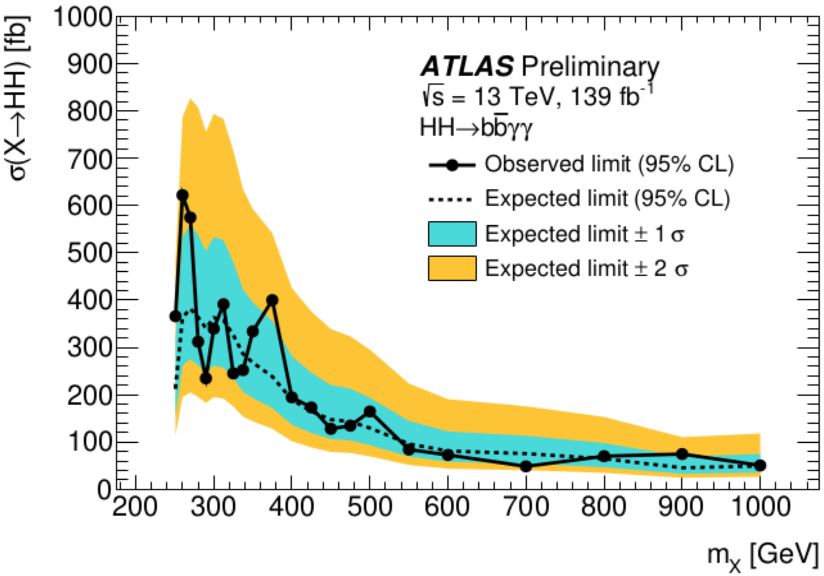
→ **improved resolution**

HH→γγbb
Results

Non-resonant search



Resonant search



Tighter constraint on k_λ

Old was k_λ = [-8.1,13.1] (CERN-EP-2019-099)

Extrapolated HL-LHC (15 TeV 3 ab^{-1}): k_λ = 1 with 3 (4.5) σ (stat + sys) per experiment (ATL-PHYS-PUB-2018-053, CMS PAS FTR-18-019)

Conclusions

Analysis updates on resonances decaying into boson pairs using 139 fb^{-1} @ 13 TeV collected in 2015-2018

Z’→Hγ with H→bb

- Enhanced sensitivity due to novel algorithm to identify b-jets in the large-R jet CoM frame

$H^{\pm\pm}$ and $H^{\pm}$ into $2l^{SC}$, 3l, 4l

- New channel: $H^{\pm\pm}H^{\pm}$ associated production
- Improved measurement of lepton fake factor and their uncertainties

Heavy diphoton resonances

- Common event selection for spin-0 and spin-2
- Spurious signal uncertainty assessed by Functional decomposition

HH→γγbb

- New categorization based on $m^{*}_{b\bar{b}\gamma\gamma}$ improves HH mass resolution

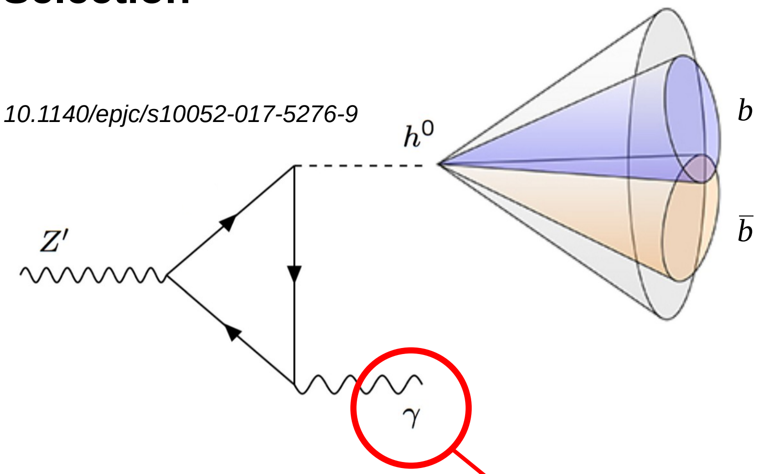
All searches are compatible with background-only hypotheses

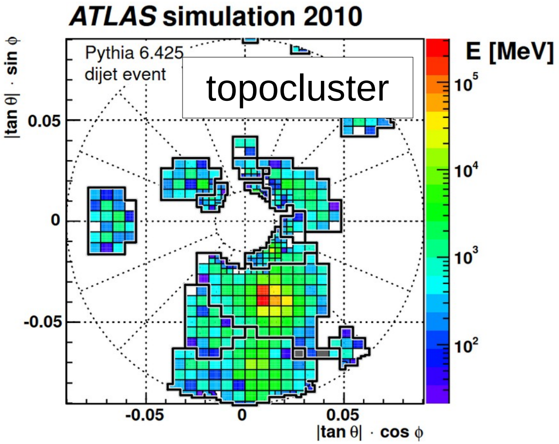
BACKUP

$Z' \to H\gamma$ with $H \to bb$

Selection

10.1140/epjc/s10052-017-5276-9





Eur. Phys. J. C 77 (2017) 490

- Large-R jet (R=1)
- Removed subjets (R=0.2) with <5%p_T
- m_J from calo+track
- 50 GeV < m_J < 200 GeV
- p_T > 200 GeV
- $|\eta|$ < 2.00

Single photon trigger
p_T > 200 GeV
$|\eta|$ < 1.37 (calo barrel)

- $\Delta R_{\gamma J}$ > 1.0
- At least 1γ+1J

Mass window optimization

$$m_H - \Delta_{m,D} < m_J < m_H - \Delta_{m,U}$$

- Calculated by maximizing search sensitivity
- $m_{Z'}$ dependent

Z'→Hγ with H→bb
Selection and fit

Selection

- Candidates are divided into single and double b-tagged
- Optimization of the p_T cuts:

$$p_T^{\gamma} > p_T^0 + a \times m_{J\gamma}$$
$$p_T^J > 0.8\left(p_T^0 + a \times m_{J\gamma}\right)$$

→ signal efficiency 10-20%

Fit

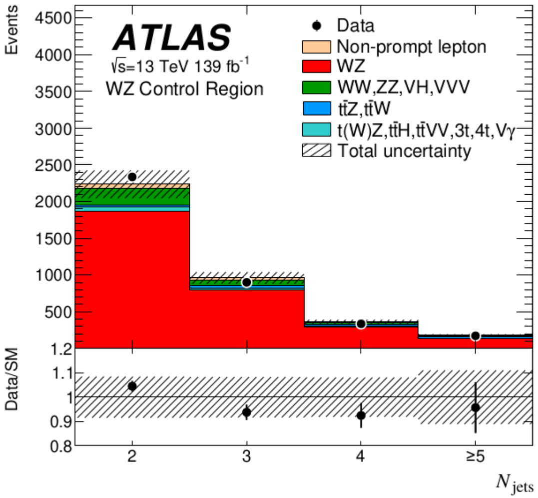
- Signal PDF:
  - Crystal ball + Gaussian
  - Parameters extracted from MC and interpolated in $m_{Z'}$ with polynomials
- Background PDF:
  - $B(x) = (1-x)^{p_1} x^{p_2 + p_3 \log(x)}$
  - validated in control regions
- Systematics as Gaussian nuisance parameters

$H^{\pm\pm}$ and $H^{\pm}$ into $2l^{SC}$, 3l, 4l

Backgrounds

Type 1: WZ production ($2l^{SC}$, 3l)

- Jet multiplicity distribution corrected by normalisation factor from WZ CR (ortogonal to 3l CR)



Type 2: electron charge flip ($2l^{SC}$)

- Due to electron interaction in the ID
- Misidentification rate estimated from $Z \rightarrow ee$ (*JINST 14 (2019) P12006*)

Type 3: non-prompt leptons (all)

- Main sources: b- and c-hadron decays
- Fake-factor method (*Eur. Phys. J. C 79 (2019) 58*) for $2l^{SC}$ and 3l
- Scale factors measured in data for 4l

$H^{\pm\pm}$ and $H^{\pm}$ into $2l^{SC}$, 3l, 4l

$m_{H^{\pm\pm}}$ [GeV]	200	300	350	400	500	600
$m_{H^{\pm}}$ [GeV]	400	400	700	700	700	700
$\mathcal{B}(H^{\pm\pm} \to W^{\pm}W^{\pm})$ [%]	100	100	100	100	100	100
Cross section [fb] ($H^{\pm\pm}$ pair production)	81.0	16.5	8.7	4.9	1.8	0.7

QCD NLO cross sections for **signal**

$m_{H^{\pm\pm}}$ [GeV]	200	220	300	400	450	500	550	600
$m_{H^{\pm}}$ [GeV]	196	215	295	395	445	496	545	602
$\mathcal{B}(H^{\pm\pm} \to W^{\pm}W^{\pm})$ [%]	100	100	100	100	100	100	100	100
$\mathcal{B}(H^{\pm} \to W^{\pm}Z)$ [%]	58.8	44.3	37.3	44.7	45.9	45.7	48.4	50.8
Cross section [fb] ($H^{\pm\pm}H^{\mp}$ associated production)	88.7	44.5	9.5	3.0	1.9	1.2	0.8	0.5

Mass hypotheses produced in MC

Backgrounds

Process	Generator	ME accuracy	PDF	Parton shower and hadronisation	Parameter set
VV, $V\gamma$	SHERPA	NLO (0-1j) + LO (2-3j)	NNPDF3.0nnlo	SHERPA	default
VV-EW jj	SHERPA	LO	NNPDF3.0nnlo	SHERPA	default
VVV	SHERPA	NLO(0j) + LO (1-2j)	NNPDF3.0nnlo	SHERPA	default
V+jets	SHERPA	NLO (0-2j) + LO (3-4j)	NNPDF3.0nnlo	SHERPA	default
VH	PYTHIA 8	LO	NNPDF2.3lo	PYTHIA 8	A14
$t\bar{t}H$	POWHEG-BOX v2	NLO	NNPDF3.0nlo	PYTHIA 8	A14
$t\bar{t}V$, tWZ, tZ	MADGRAPH5_aMC@NLO	NLO	NNPDF3.0nlo	PYTHIA 8	A14
$t\bar{t}$, tW	POWHEG-BOX v2	NLO	NNPDF3.0nnlo	PYTHIA 8	A14
$t\bar{t}t\bar{t}$, $t\bar{t}t$ $t\bar{t}WW$, $t\bar{t}WZ$	MADGRAPH5_aMC@NLO	NLO	NNPDF3.1nlo	PYTHIA 8	A14

$H^{\pm\pm}$ and $H^{\pm}$ into $2l^{SC}$, 3l, 4l

Event reconstruction

Primary vertices:

- From ID tracks with p_T>500 MeV

Jets:

- Particle flow, anti-k_t (R=0.4) with p_T > 20 GeV and $|\eta| < 2$
- Removed calo noise and non-collision background
- Jet-vertex tagging discriminant to remove pile-up

b-tagging

- RNN-based algorithm at $|\eta| < 2.5$
- 70% efficiency measured on ttbar

Electrons

- ID tracks matched to EM-cal clusters at $|\eta| < 2.47$ (excluding barrel-endcap transition)
- p_T > 10 GeV
- Loose identification for candidates (85-95% efficiency), tight identification for signal (65-88% efficiency)
- Reduced photon conversion background + Non-prompt-lepton veto
- Isolation requirements
- Suppressing charge flip using a BDT discriminant

$H^{\pm\pm}$ and $H^{\pm}$ into $2l^{SC}$, 3l, 4l
Event reconstruction

Muons:

- MS tracks matching ID tracks at $|\eta| < 2.5$
- $p_T > 10$ GeV and “Medium quality” requirement
- 98% efficiency in $Z \rightarrow$ mumu
- Constraints on impact parameters and isolation
- Non-prompt-lepton veto

Overlap removal

- To remove cases in which the detector response to a single physical object produces two final state objects

$H^{\pm\pm}$ and $H^{\pm}$ into $2l^{SC}$, 3l, 4l

Event reconstruction

Loose

Loose and minimal isolated

Tight

	Electrons				Muons			
	Candidate	L	L*	T	Candidate	L	L*	T
$\lvert z_0 \sin\theta \rvert$	< 0.5 mm	< 0.5 mm	< 0.5 mm	< 0.5 mm	< 0.5 mm	< 0.5 mm	< 0.5 mm	< 0.5 mm
$\lvert d_0 \rvert / \sigma(d_0)$	< 5	< 5	< 5	< 5	< 3	< 3	< 3	< 3
Identification	Loose	Loose	Loose	Tight	Medium	Medium	Medium	Medium
Isolation	No	No	Loose	Yes	No	No	FixedCutLoose	Yes
Non-prompt-lepton veto	No	No	No	Yes	No	No	No	Yes
Electron charge-flip veto	No	Yes	Yes	Yes	N/A	N/A	N/A	N/A

$H^{\pm\pm}$ and $H^{\pm}$ into $2l^{SC}$, 3l, 4l

Signal regions

Charged Higgs boson mass	$m_{H^{\pm\pm}}$ = 200 GeV	$m_{H^{\pm\pm}}$ = 300 GeV	$m_{H^{\pm\pm}}$ = 400 GeV	$m_{H^{\pm\pm}}$ = 500 GeV
Selection criteria	$2\ell^{sc}$ channel			
m_{jets} [GeV]	[100, 450]	[100, 500]	[300, 700]	[400, 1000]
S	<0.3	<0.6	<0.6	<0.9
$\Delta R_{\ell^\pm\ell^\pm}$	<1.9	<2.1	<2.2	<2.4
$\Delta\phi_{\ell\ell,E_T^{\text{miss}}}$	<0.7	<0.9	<1.0	<1.0
$m_{x\ell}$ [GeV]	[40, 150]	[90, 240]	[130, 340]	[130, 400]
E_T^{miss} [GeV]	>100	>130	>170	>200
Selection criteria	3ℓ channel			
$\Delta R_{\ell^\pm\ell^\pm}$	[0.2, 1.7]	[0.0, 2.1]	[0.2, 2.5]	[0.3, 2.8]
$m_{x\ell}$ [GeV]	>160	>190	>240	>310
E_T^{miss} [GeV]	>30	>55	>80	>90
$\Delta R_{\ell\text{jet}}$	[0.1, 1.5]	[0.1, 2.0]	[0.1,2.3]	[0.5, 2.3]
$p_T^{\text{leading jet}}$ [GeV]	>40	>70	>100	>95
Selection criteria	4ℓ channel			
$m_{x\ell}$ [GeV]	>230	>270	>360	>440
E_T^{miss} [GeV]	>60	>60	>60	>60
$p_T^{\ell_1}$ [GeV]	>65	>80	>110	>130
$\Delta R_{\ell^\pm\ell^\pm}^{\min}$	[0.2, 1.2]	[0.2, 2.0]	[0.5, 2.4]	[0.6, 2.4]
$\Delta R_{\ell^\pm\ell^\pm}^{\max}$	[0.3, 2.0]	[0.5, 2.6]	[0.4, 3.1]	[0.6, 3.1]

$$S = \frac{\mathcal{R}(\phi_{\ell_1}, \phi_{\ell_2}, \phi_{E_T^{\text{miss}}}) \cdot \mathcal{R}(\phi_{j1}, \phi_{j2}, \cdots)}{\mathcal{R}(\phi_{\ell_1},, \phi_{\ell_2}, \phi_{E_T^{\text{miss}}}, \phi_{j1}, \phi_{j2}, \cdots)}$$

$$\mathcal{R}(\phi_1, \cdots, \phi_n) = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(\phi_i - \overline{\phi})^2}.$$

- SR's are optimized to maximize sensitivity for $H^{\pm\pm}$ pair production
- Same SR's used for $H^{\pm\pm}$ associated production
- Increased statistics improves **lepton fake factors** (*10.1140/epjc/s10052-018-6500-y*) from previous analysis

$H^{\pm\pm}$ and $H^{\pm}$ into $2l^{SC}$, 3l, 4l

Event preselection

Selection criteria	$2\ell^{sc}$	3ℓ	4ℓ
At least one offline tight lepton with $p_T^{\ell} > 30$ GeV that triggered the event			
N_ℓ (type L)	=2	=3	=4
N_ℓ (type L*)	–	–	=4
N_ℓ (type T)	=2	≥2 ($\ell_{1,2}$)	≥1
$\lvert\sum Q_\ell\rvert$	=2	=1	≠4
Lepton p_T	$p_T^{\ell_1,\ell_2} > 30, 20$ GeV	$p_T^{\ell_0,\ell_1,\ell_2} > 10, 20, 20$ GeV	$p_T^{\ell_1,\ell_2,\ell_3,\ell_4} > 10$ GeV
E_T^{miss}	> 70 GeV	> 30 GeV	> 30 GeV
N_{jets}	≥ 3	≥ 2	–
$N_{b\text{-jets}}$	=0		
Low SFOC $m_{\ell\ell}$ veto	–	$m_{\ell\ell}^{oc} > 15$ GeV	
Z boson decay veto	$\lvert m_{ee}^{sc} - m_Z\rvert > 10$ GeV	$\lvert m_{\ell\ell}^{oc} - m_Z\rvert > 10$ GeV	

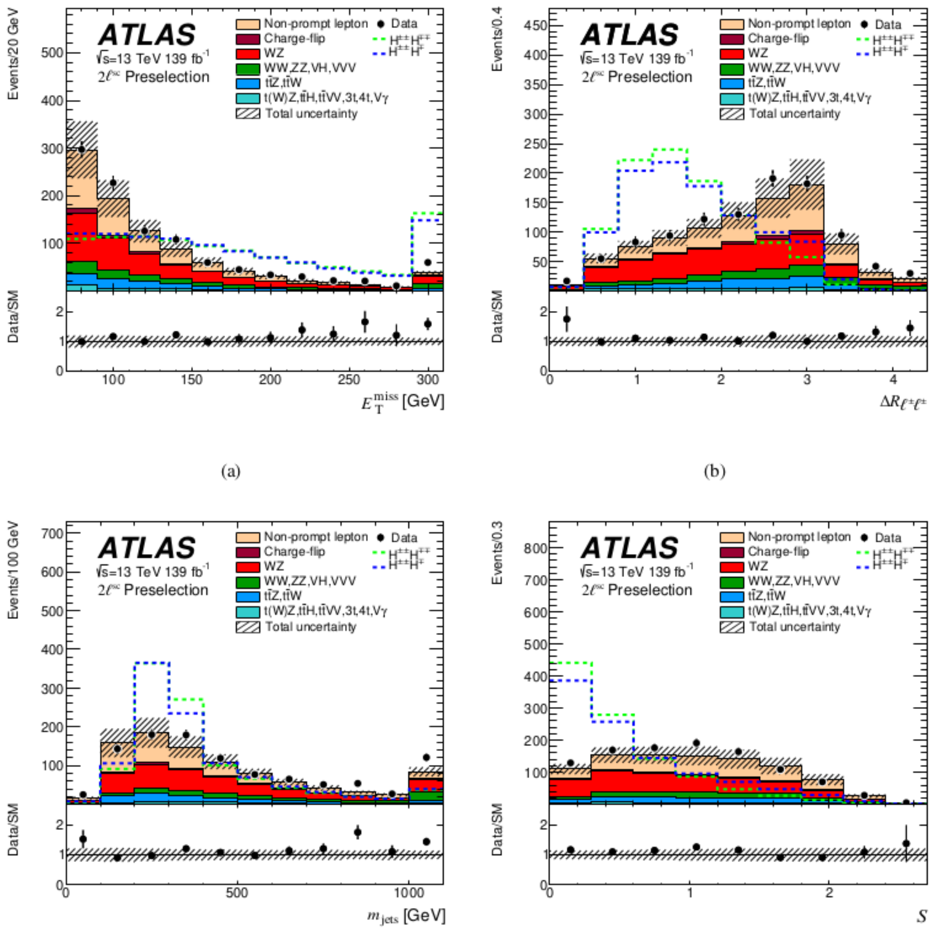
Reduce
- Non-prompt lepton
- Electron charge-flip
- VV background
- t-production background

Reduces background from DY and neutral mesons

** SFOC = same flavor opposite charge*

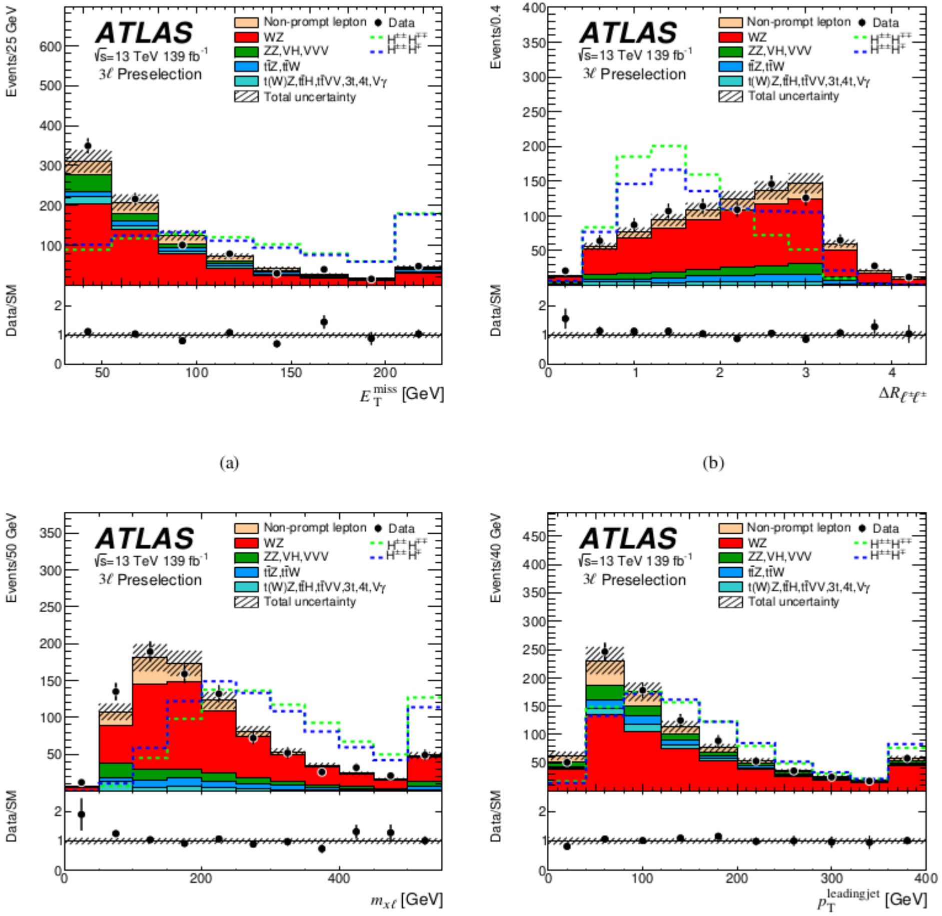
$H^{\pm\pm}$ and $H^{\pm}$ into $2l^{SC}$, 3l, 4l

Distribution of selected variables used to define the $2l^{SC}$ SRs



$H^{\pm\pm}$ and $H^{\pm}$ into $2l^{SC}$, 3l, 4l

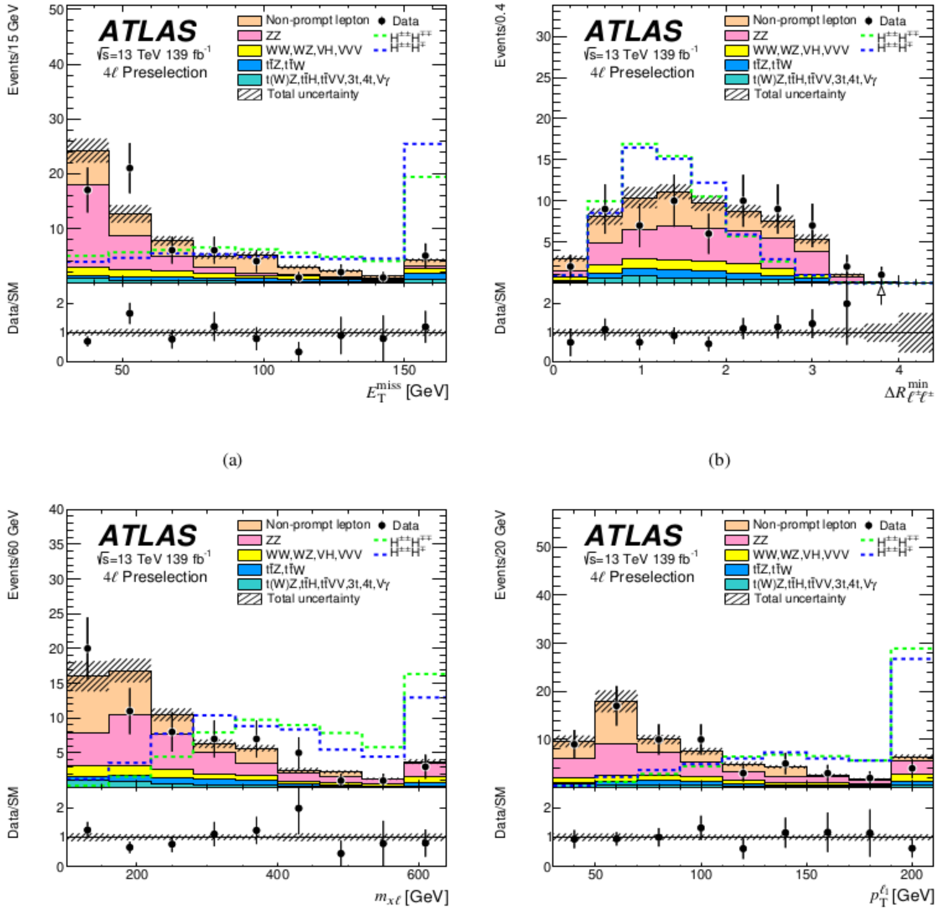
Distribution of selected variables used to define the 3l SRs



(a) (b)

$H^{\pm\pm}$ and $H^{\pm}$ into $2l^{SC}$, 3l, 4l

Distribution of selected variables used to define the 4l SRs



$H^{\pm\pm}$ and $H^{\pm}$ into $2l^{SC}$, 3l, 4l

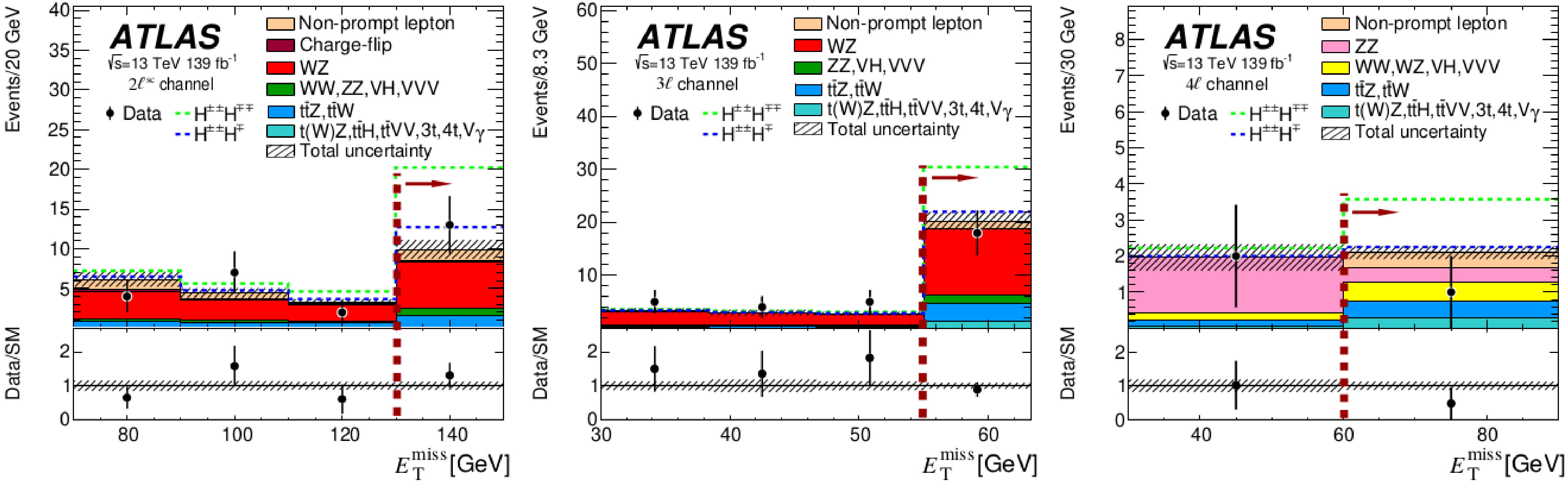
Results

SR	$2\ell^{sc}$			3ℓ		4ℓ
				Number of same-flavour opposite-charge pairs		
	ee	$e\mu$	$\mu\mu$	0	> 0	
Prompt lepton	1.66±0.28	4.3±0.5	2.30±0.26	1.62±0.20	17.2±1.6	1.69±0.19
Charge-flip	0.17±0.07	0.102±0.034	–	–	–	–
Non-prompt lepton	0.3±0.25	0.65±0.33	0.39±0.19	0.36±0.23	0.9±0.6	0.41±0.25
Total background	2.1±0.4	5.1±0.6	2.69±0.32	1.98±0.29	18.1±1.6	2.10±0.30
Data	4	8	1	1	17	1
$H^{\pm\pm}H^{\mp\mp}$	1.99±0.24	5.3±0.6	3.03±0.35	2.63±0.30	7.6±0.9	1.50±0.17
A_{PP} [%]	0.087	0.233	0.132	0.115	0.333	0.065
$H^{\pm\pm}H^{\mp}$	0.57±0.07	1.43±0.16	0.81±0.09	0.43±0.05	1.35±0.16	0.156±0.020
A_{AP} [%]	0.043	0.109	0.062	0.033	0.103	0.012
n_{95}	6.72	9.21	3.24	3.27	9.52	3.31

- The expected background and the observed data event yields in the signal region defined for the m $H^{\pm\pm}$ = 300 GeV mass hypothesis
- No significant excess over the expected yields is observed in any of the SRs

$H^{\pm\pm}$ and $H^{\pm}$ into $2l^{SC}$, $3l$, $4l$

Results



- The E^{T}_{miss} distribution for the SRs of the m $H^{\pm\pm}$ = 300 GeV signal mass hypothesis

Heavy diphoton resonances
Framework

Data:

- Diphoton trigger with E_T>25,35 GeV

MC signal:

- Spin-0:
  - m_X in 200-3000 GeV
  - Γ_X = 4 MeV
- Spin-2:
  - RS1 model
  - m_{G^*} in 500-5000 GeV
  - Coupling k/M_{Pl} in 0.01-0.1

MC background:

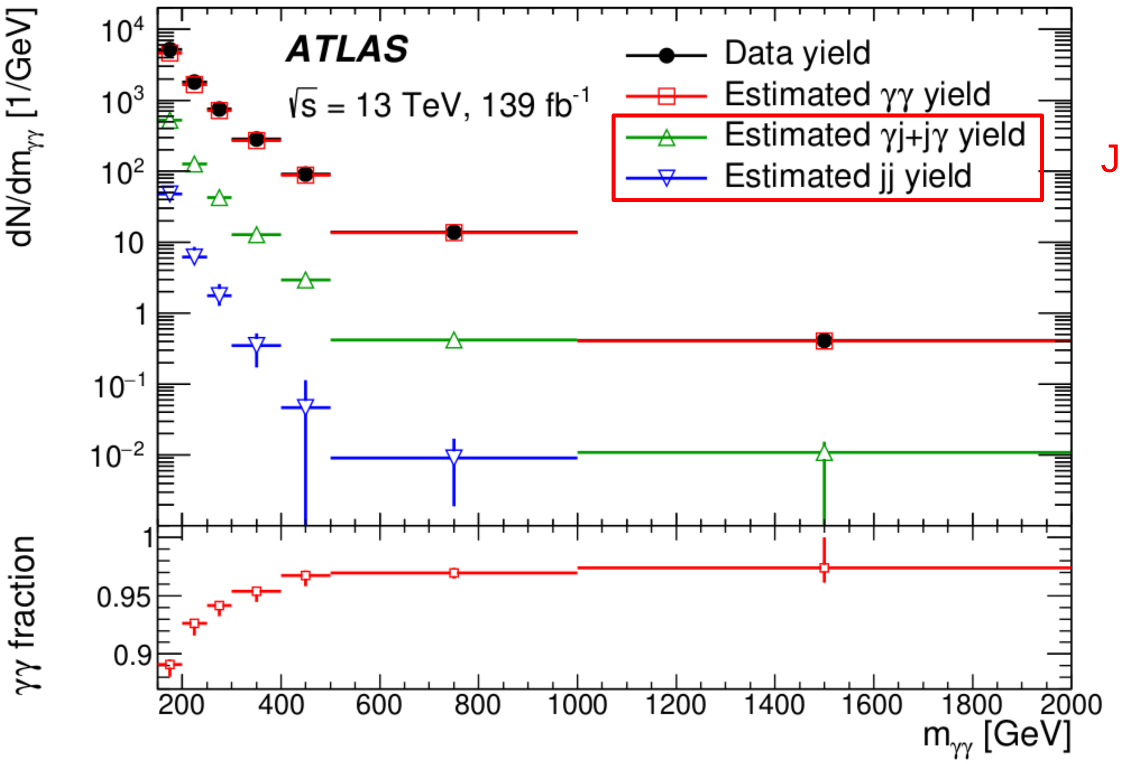
- Events with 2 prompt photons

Heavy diphoton resonances
Object and event selection

Event selection
- At least two photons with E_T>22 GeV and $|\eta| < 2.37$ (excluding transition between barrel and endcap calo)
- Identification of the diphoton vertex using tracking information
- Tight identification of photons (jet bkg reduction)
- Calculation of $m_{\gamma\gamma}$:
  - Optimized kinematic selection: $E_T/m_{\gamma\gamma}>0.3,0.25$
  - Improved significance
  - **Unified selection** for the two spin models
  - In most of the mass range, the expected limits improve

Heavy diphoton resonances
Background estimates

As the search selections for the two models are unified, a **common background modeling** is used



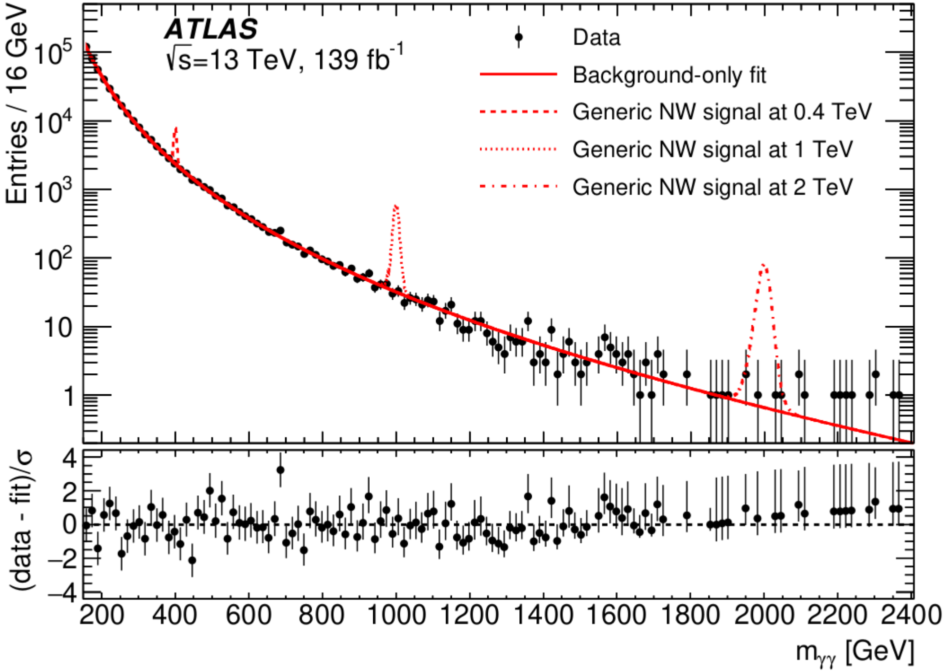
Jets misidentified as photons

Heavy diphoton resonances
Fit

Systematic uncertainties

Signal yield			
Luminosity	±1.7%	Trigger	±0.5%
Photon identification	±0.5%	Photon isolation	±1.5%
Photon energy scale/resolution	negligible	Pile-up reweighting*	±(2–0.2)%
Spin-0 production process*	±(7–3)%		
*Signal modelling**			
Photon energy resolution	$^{+14\%}_{-9.3\%} - ^{+51\%}_{-29\%}$		
Photon energy scale	±(0.5–0.6)%		
Pile-up reweighting	negligible		
*Spurious signal, Spin-0**			
NWA	114–0.04 events (m_X = 160–2800 GeV)		
$\Gamma_X/m_X = 2\%$	107–0.14 events (m_X = 400–2800 GeV)		
$\Gamma_X/m_X = 6\%$	223–0.38 events (m_X = 400–2800 GeV)		
$\Gamma_X/m_X = 10\%$	437–0.50 events (m_X = 400–2800 GeV)		
*Spurious signal, Spin-2**			
$k/\overline{M}_{Pl} = 0.01$	4.71–0.04 events (m_{G^*} = 500–2800 GeV)		
$k/\overline{M}_{Pl} = 0.05$	19.0–0.09 events (m_{G^*} = 500–2800 GeV)		
$k/\overline{M}_{Pl} = 0.1$	31.2–0.20 events (m_{G^*} = 500–2800 GeV)		

* mass-dependent



The RS1 model is excluded for
m_{G*}<2.2, 3.9, 4.5 TeV
k/M_{Pl} = 0.01, 0.05, 0.1

HH→γγbb
Backgrounds

Main contributions:
- γγ+jets
- H→γγ
- Reducible: jets wrongly identified as photons

Process	Generator	PDF set	Showering	Tune
ggF	NNLOPS [65–67] [68, 69]	PDFLHC [42]	Pythia 8.2 [70]	AZNLO [71]
VBF	Powheg Box v2 [39, 66, 72–78]	PDFLHC	Pythia 8.2	AZNLO
WH	Powheg Box v2	PDFLHC	Pythia 8.2	AZNLO
$qq \to ZH$	Powheg Box v2	PDFLHC	Pythia 8.2	AZNLO
$gg \to ZH$	Powheg Box v2	PDFLHC	Pythia 8.2	AZNLO
$t\bar{t}H$	Powheg Box v2 [73–75, 78, 79]	NNPDF3.0nlo [80]	Pythia 8.2	A14 [81]
bbH	Powheg Box v2	NNPDF3.0nlo	Pythia 8.2	A14
$tHqj$	MadGraph5_aMC@NLO	NNPDF3.0nlo	Pythia 8.2	A14
tHW	MadGraph5_aMC@NLO	NNPDF3.0nlo	Pythia 8.2	A14
$\gamma\gamma$+jets	Sherpa v2.2.4 [56]	NNPDF3.0nnlo	Sherpa v2.2.4	–
$t\bar{t}\gamma\gamma$	MadGraph5_aMC@NLO	NNPDF2.3lo	Pythia 8.2	–

HH→γγbb
Object selection

Photons:

- Connected EM clusters in $|\eta|<2.37$ (excluding endcap-barrel transition)
- Converted-unconverted classification
- Calibrated photon energy with MV regression
- Direction from calo segmentation
- Lateral shower profile + hcal leakage → reduce π^0 background
- Tight identification + two isolation variables

Vertex:

- At least one primary (at least two tracks with $p_T>0.5$ GeV)
- Selection from collision vertices using a NN algorithm

Electron:

- EM-cal deposits matched to ID tracks in $|\eta|<2.37$ (excluding endcap-barrel transition)
- $p_T > 10$GeV
- Medium identification criterion: calo + track + TRT

HH→γγbb
Object selection

Muons:

- High quality MS tracks in |η|<2.7 (|η|<2.5 to match ID track)
- p_T > 10GeV
- Medium identification criterion

Jets:

- Particle flow reconstruction (calo + track)
- Anti-k_T with R=0.4
- |y| < 4.4
- p_T > 25 GeV
- If in tracking acceptance (|η|<2.4) and p_T < 60 GeV→ tight jet vertex tagger

Flavor tagging:

- NN DL1r
- Inputs to DL1r are generated by a RNN (RNNIP)
- Energy corrected for bhad→μ and neutrinos

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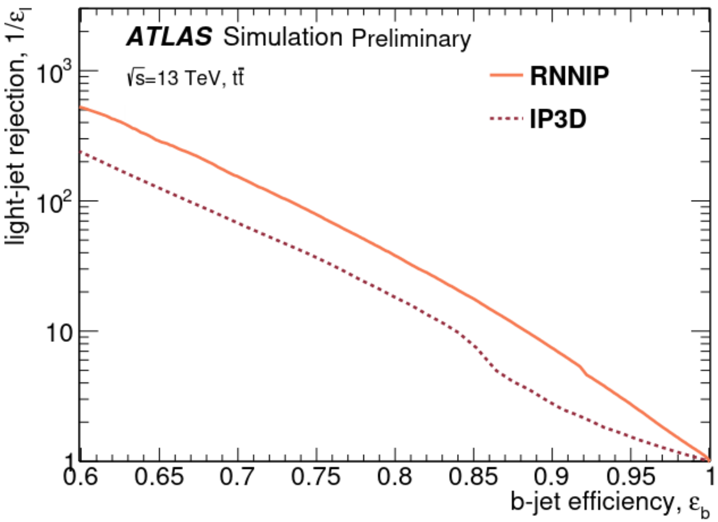
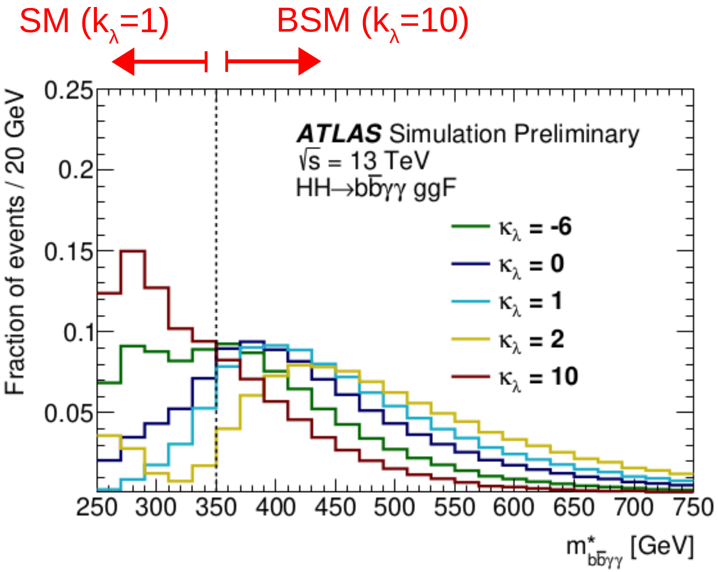
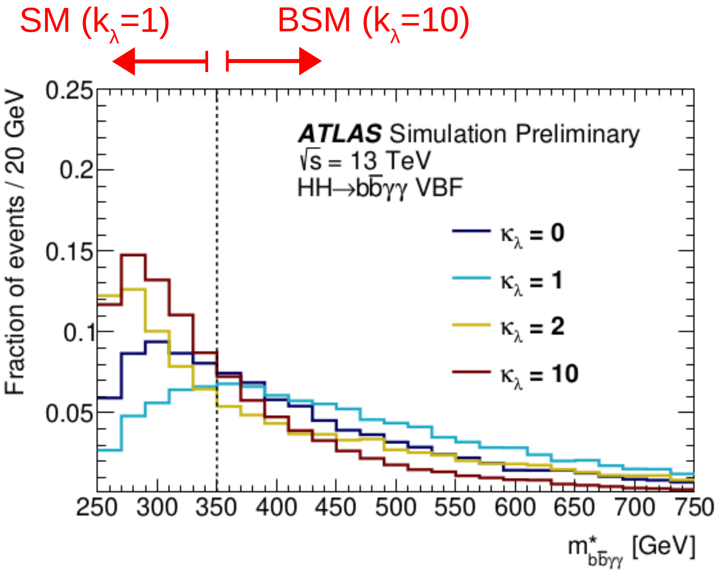


HH → γγbb

Non-resonant selection





BDT to discriminate signal from background

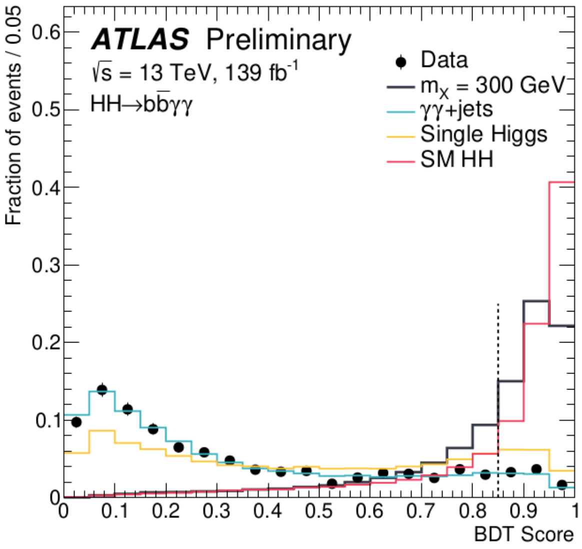
Category	Selection criteria
High mass BDT tight	$m^*_{b\bar{b}\gamma\gamma} \geq 350$ GeV, BDT score $\in [0.967, 1]$
High mass BDT loose	$m^*_{b\bar{b}\gamma\gamma} \geq 350$ GeV, BDT score $\in [0.857, 0.967]$
Low mass BDT tight	$m^*_{b\bar{b}\gamma\gamma} < 350$ GeV, BDT score $\in [0.966, 1]$
Low mass BDT loose	$m^*_{b\bar{b}\gamma\gamma} < 350$ GeV, BDT score $\in [0.881, 0.966]$

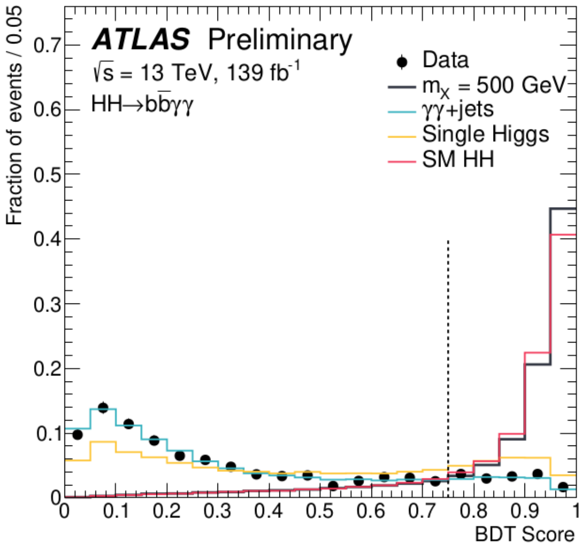
HH → γγbb
Resonant selection

- Trained two different BDT's:
  - One for ttbar+γγ background
  - One for single-H background

$$\mathrm{BDT_{tot}} = \frac{1}{\sqrt{C_1^2 + C_2^2}} \sqrt{C_1^2 \left(\frac{\mathrm{BDT}_{\gamma\gamma} + 1}{2}\right)^2 + C_2^2 \left(\frac{\mathrm{BDT}_{\mathrm{Single}H} + 1}{2}\right)^2}$$

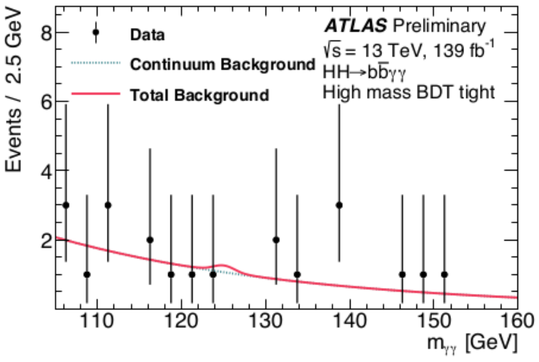
Optimized coefficients to maximize sensitivity



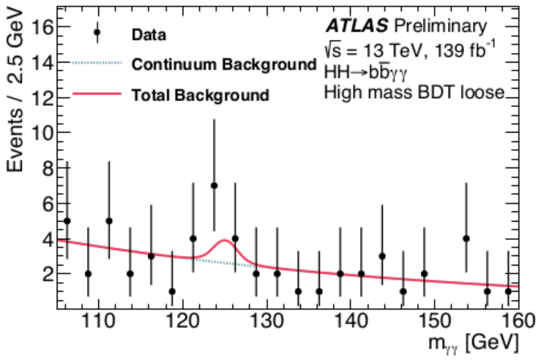


HH → γγbb

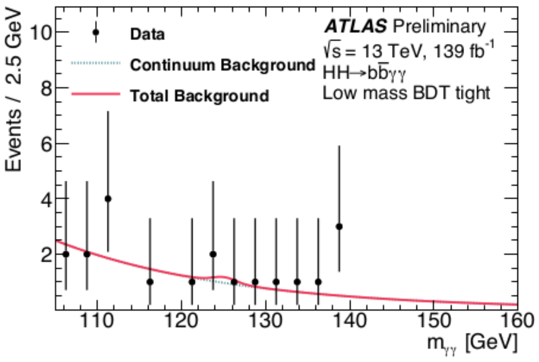
Fit in non-resonant search



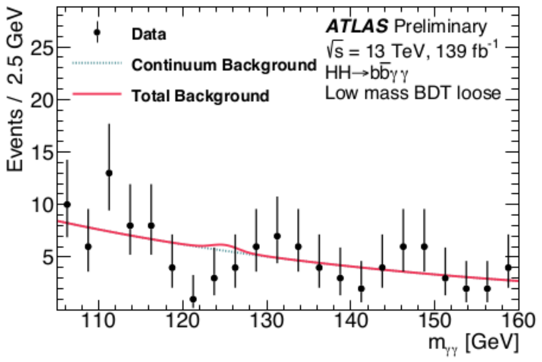
(a) High mass BDT tight



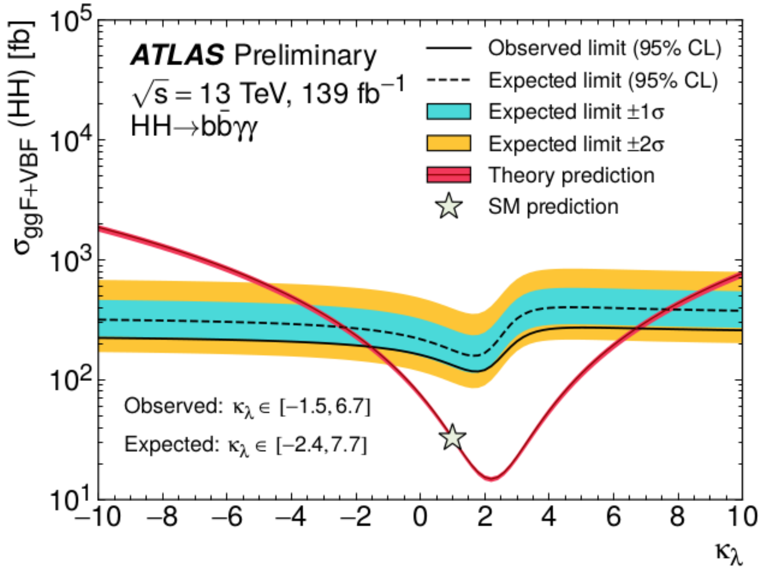
(b) High mass BDT loose



(c) Low mass BDT tight

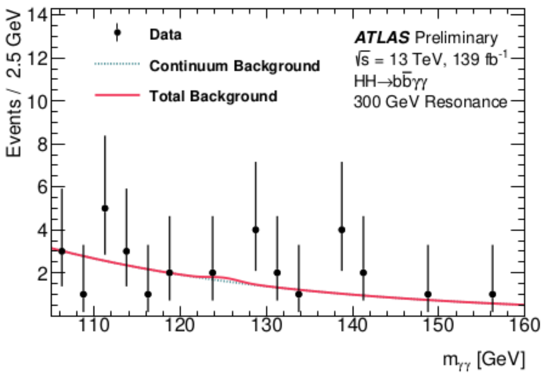


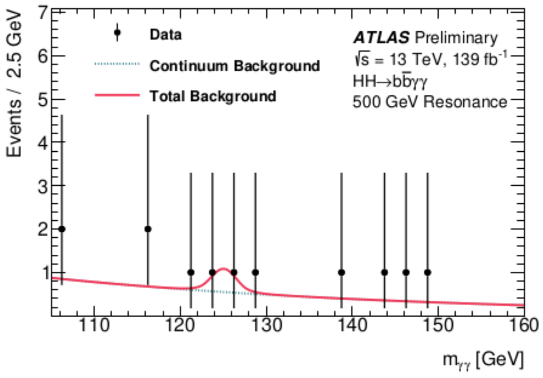
(d) Low mass BDT loose

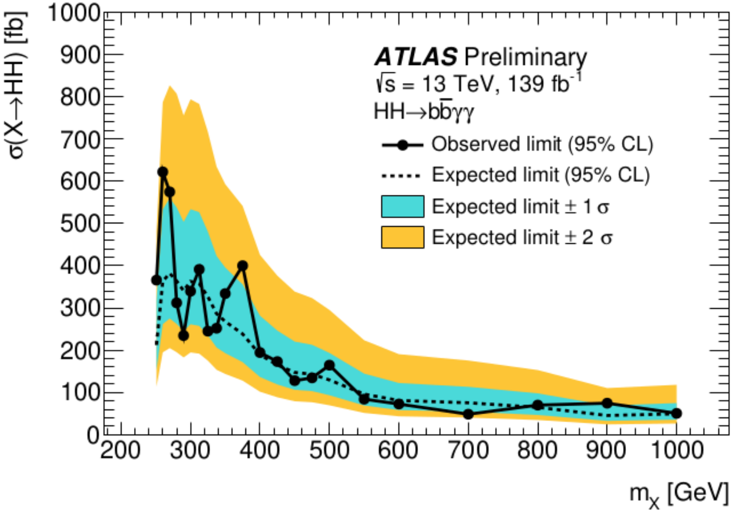


Tighter constraint on k_λ

HH → γγbb
Fit in resonant search







Narrow Width Approximation (NWA)