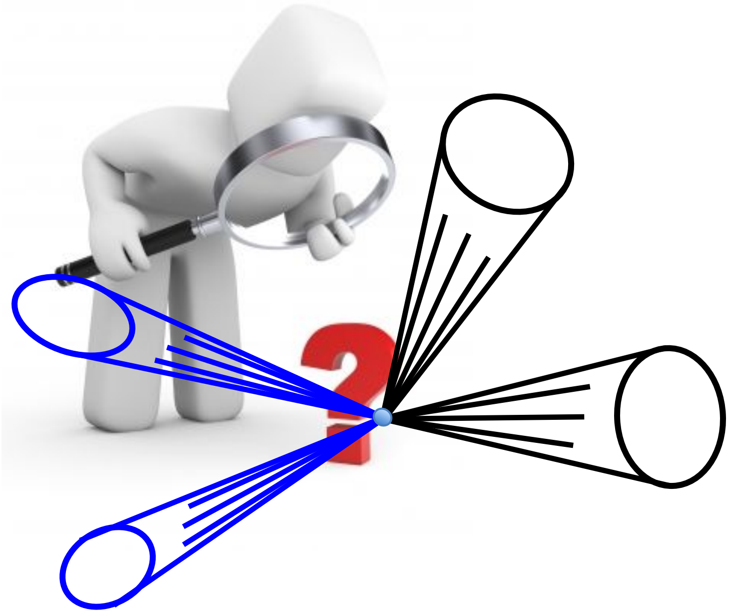
Searches for non-SM Higgs bosons + BSM decays of the Higgs boson at the ATLAS experiment



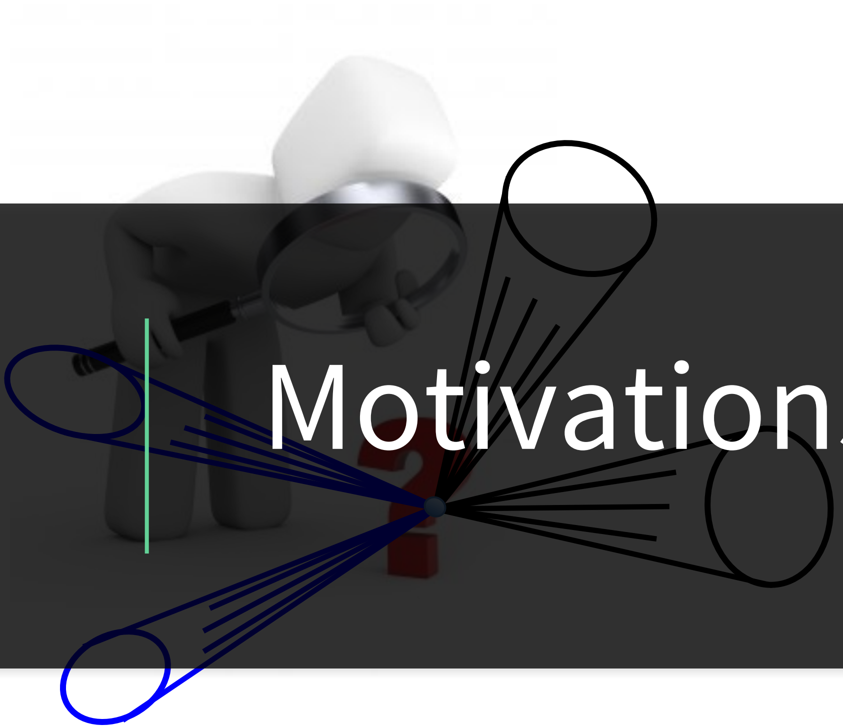
Arturo Sánchez, on behalf the ATLAS Collaboration

University of Udine, ICTP and INFN

November 27th, **SILAFAE 2018**. Lima, Peru

Outline

- Motivations
- Non-SM Higgs decays
  - Searches in decays
    - H → aa → 4b
    - H → XX → 4l (X = Z_d, a)
    - VBF H → aa → $\gamma\gamma gg$
- Non-SM Higgs(es)
  - More than one Higgs searches
    - Review of several channels
  - Mono-Higgs searches
    - H → $\tau\tau$
    - $H^{\pm}$ → tb
    - Reviews of “a Higgs + BSM”
- Summary
- Backup



Motivations

Motivations

The Standard Model (SM) measurements give a nice agreement with the theory predictions

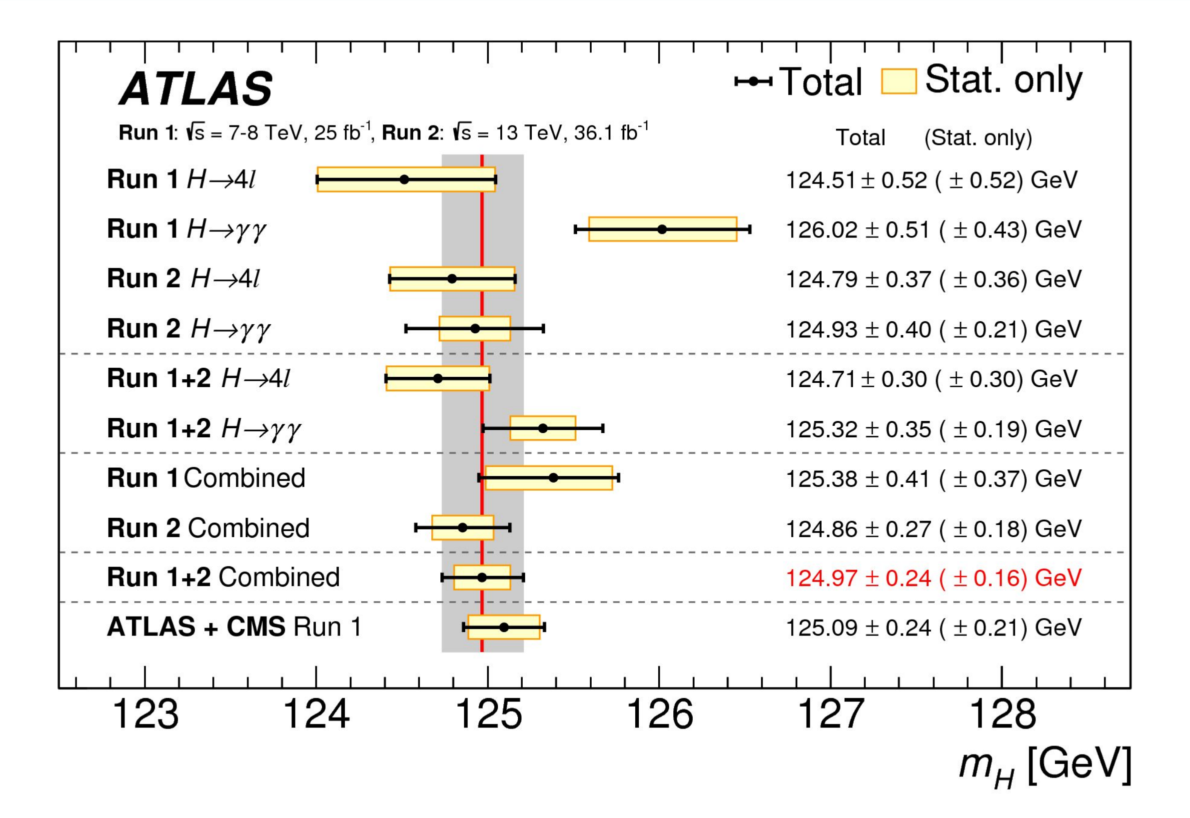
However, SM can not explain other important questions in physics, like:

- Hierarchy/naturalness/fine-tuning ?
- Dark matter ?
- Matter/antimatter asymmetry ?

… and the known observation of neutrino masses

For that reason, ATLAS, as many other experiments, has a very large program in BSM searches. Those relative to Higgs' searches are very promising!

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/HIGGS/



https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults

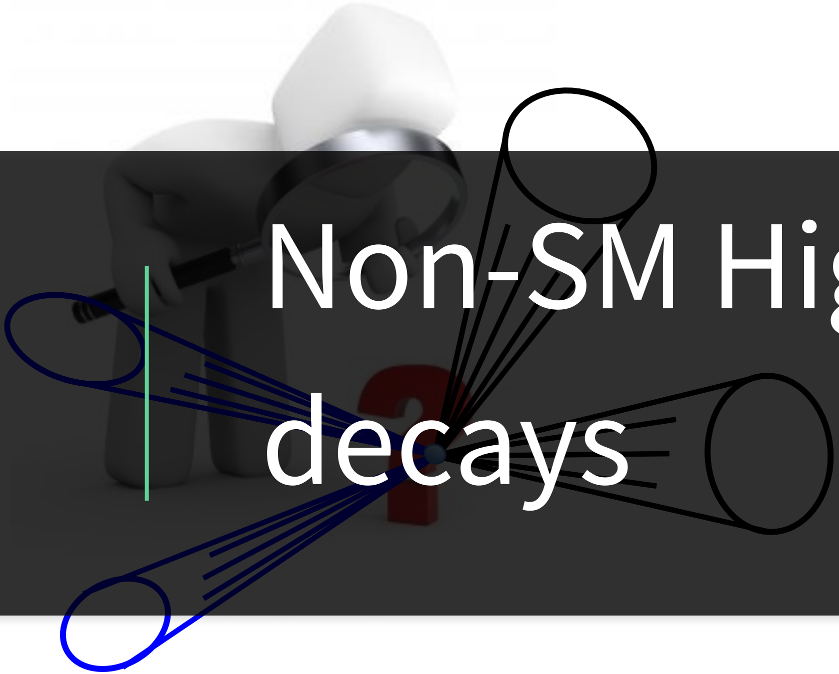
Looking for BSM physics *via* Higgs

BSM 125 GeV Higgs decays
Use of h→*xyz* to look for deviations and possible new physics

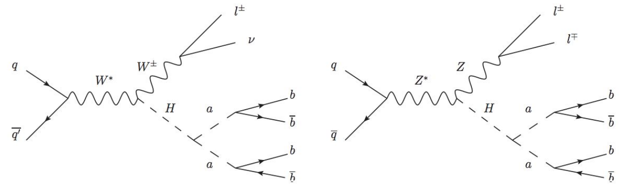
- Exotic Higgs boson decays are a powerful probe for BSM physics
- Very narrow Higgs decay width a sensitivity to small couplings to non-SM particles.
- Current measurements at the LHC constraints non-SM BR of the Higgs boson to less than 30% at 95% CL

BSM Higgs(es) searches
Search for particles defined as Higgs-kind or see if we have a non-SM higgs already

- Extend Standard Model additional Higgs field doublet (“2HDM”)
- 5 physical Higgs states (h,H,A,H±) , with “h” being the 125 GeV state
- Search for H→hh (heavy scalar decay)
- Alternative motivation: spin-2 graviton and Dark Matter candidates



Non-SM Higgs decays



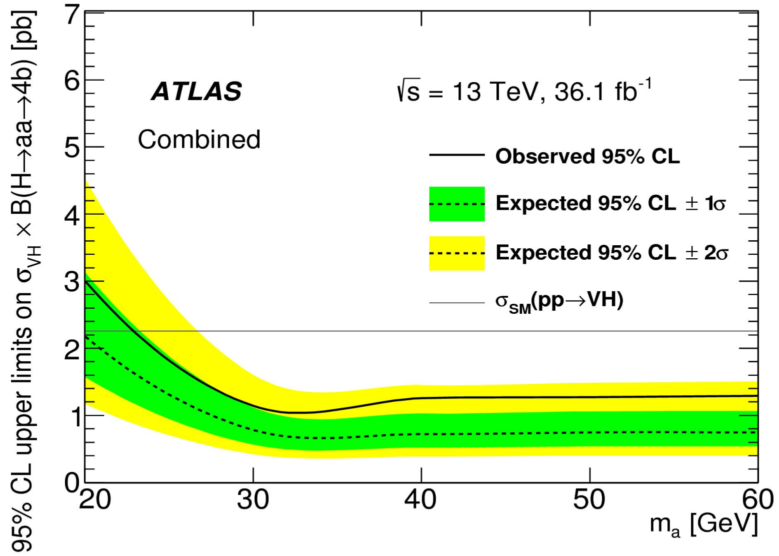
$H \to aa \to 4b$

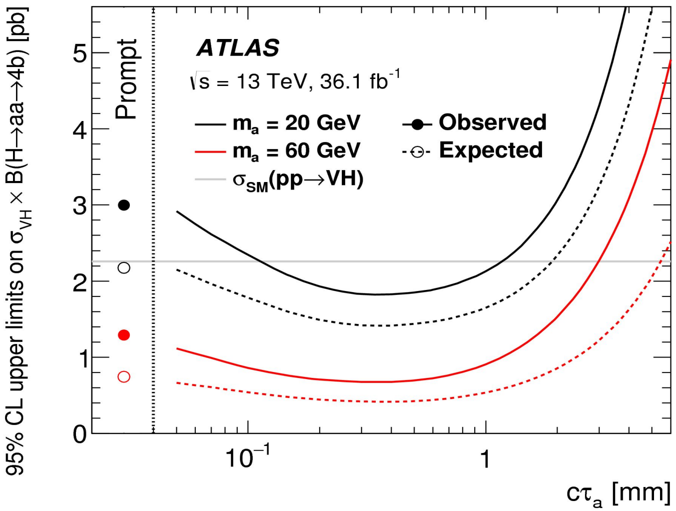
https://arxiv.org/abs/1806.07355 (arXiv:1806.07355)

Search

* A Higgs boson produced in association with a W or a Z boson
* a-boson decays into *b*-quarks promptly or with $c\tau_a$ up to 6mm

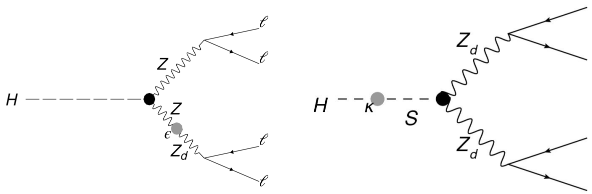
- BDT's trained in each SR and for three a-boson masses (20-30-50 GeV)
- *b*-jet pairs chosen to minimise m_{bb1} - m_{bb2}
- Dominant uncertainties: heavy flavour tagging, backgrounds and signal modeling
- Combined observed upper limits prompt decays: 3.0pb - 1.3pb
- Best limits for a-bosons with $c\tau_a$ ~0.4mm: 1.8pb - 068pb





$H \to XX \to 4l$ ($X = Z_d$, a)

https://arxiv.org/abs/1802.03388 (arXiv:1802.03388)



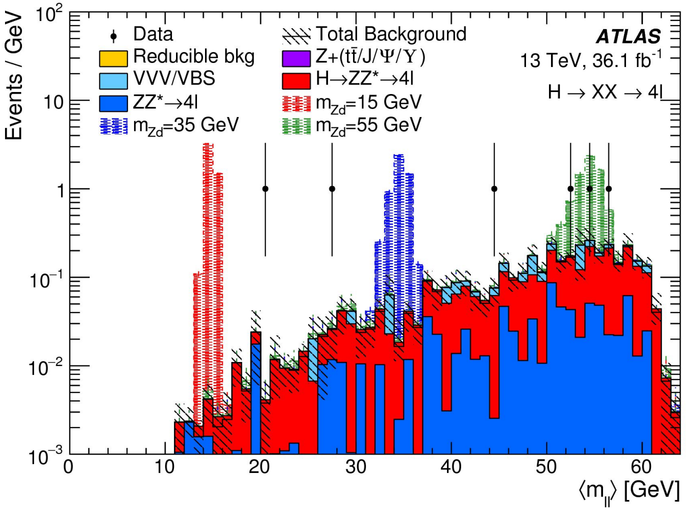
$\delta = | m_{12} - m_{34} |$

$(m_{34}/m_{12}) > 0.85$

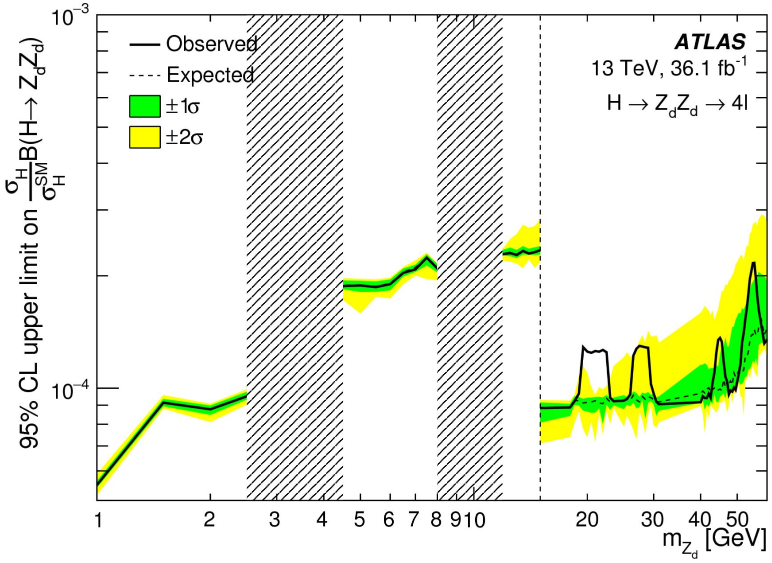
Benchmark models:

- Dark sector U(1)d → BSM vector boson Z_d: **$H \to Z_d Z_d \to 4l$**
- Two Higgs doublet model extended by one complex scalar singlet field (2HDM+S) → BSM pseudoscalar boson a: **$H \to aa \to 4\mu$**

$15 < m_X < 60$ GeV



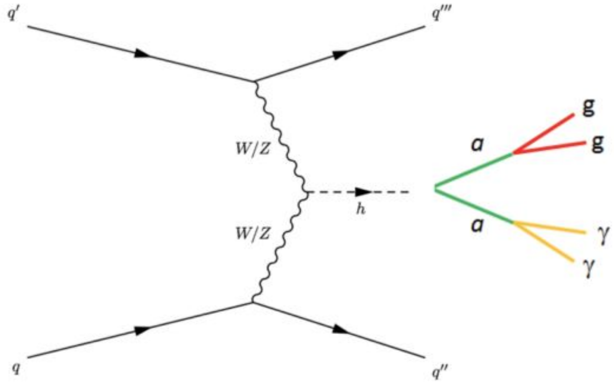
$115 < m_{4l} < 130$ GeV



$H \to Z_d Z_d \to 4l$

VBF H → aa → γγgg

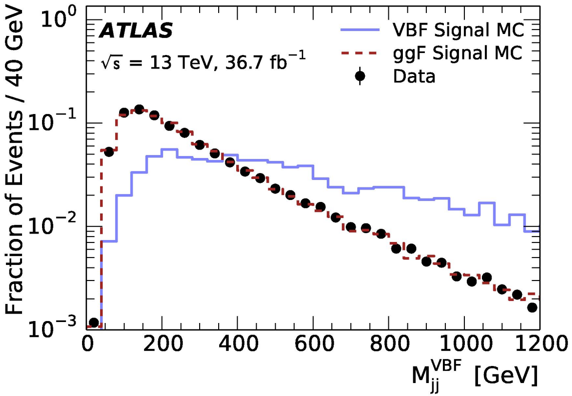
https://arxiv.org/abs/1803.11145 (arXiv:1803.11145)

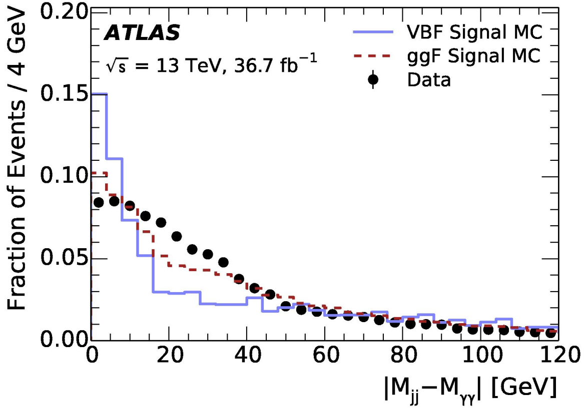


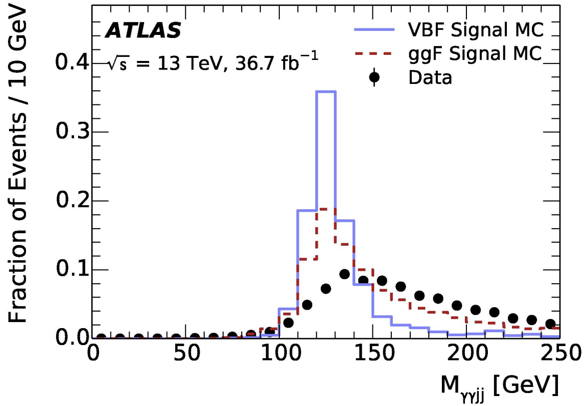
- Final state relevant in models where the **fermionic decays are suppressed** → the a-boson only decays to photons or gluons
- **VBF production mode** has higher cross section than VH and provides experimental handles to suppress backgrounds

* Di-photon trigger
* 4 or more jets, VBF jets selection:

- m^{VBF}_{jj} > 500 GeV
- Leading p_T > 60 GeV







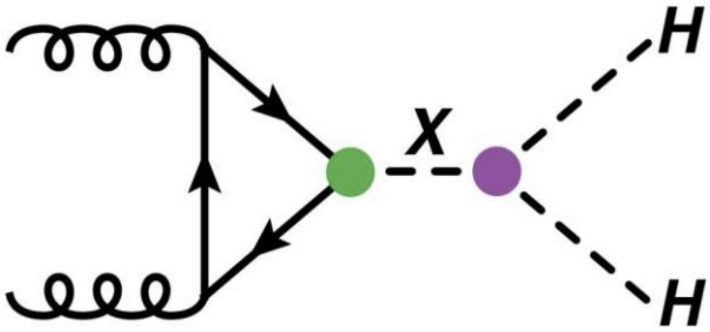
$100 < m_{\gamma\gamma jj} < 150$ GeV

$| m_{jj} - m_{\gamma\gamma} | < 12 - 24$ GeV

BSM Higgs(es) searches

Di-Higgs searches

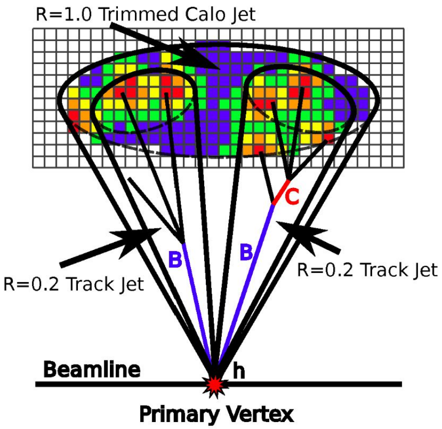
Resonant Higgs pair production



- Various models expect a new particle decaying into a Higgs boson pair
- Can reconstruct each Higgs boson and di-Higgs resonance
- Randall-Sundrum graviton (spin 2) $G \to HH$
- 2HDM CP-even heavy Higgs boson X $\to HH$

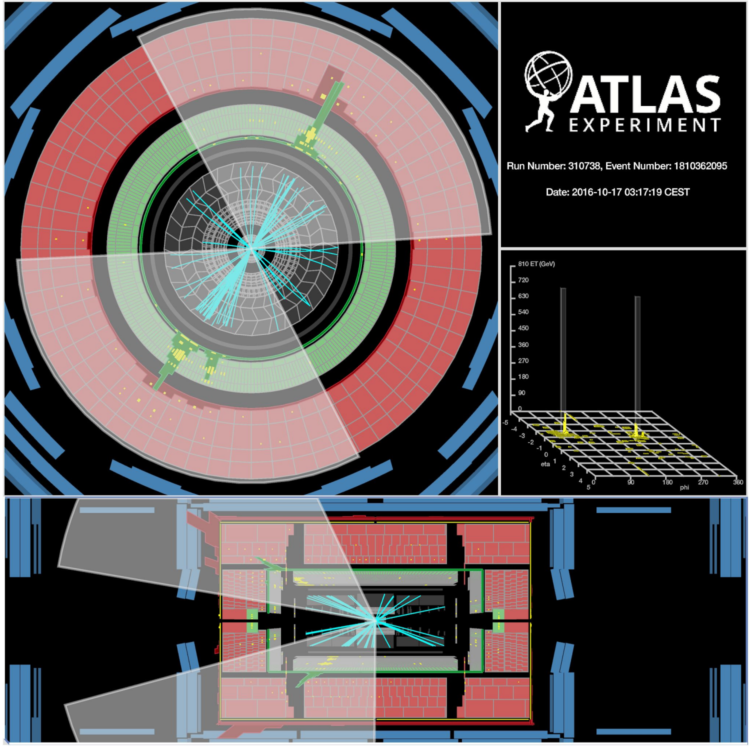
$HH \rightarrow 4b$

https://arxiv.org/abs/1804.06174 (arXiv:1804.06174)



- Data split into resolved and boosted regions
- *b* jet triggers for resolved and fat-jet trigger for boosted
- Resolved region (260 < M < 1400 GeV) has 4 clearly separated b tagged R=0.4 jets
- Boosted region (800 < M < 3000 GeV) has two R=1.0 fat-jets each containing one or two tagged R=0.2 track-jets

For Higgs-jet: b-hadron identification (R=0.2 b-tagged jet)

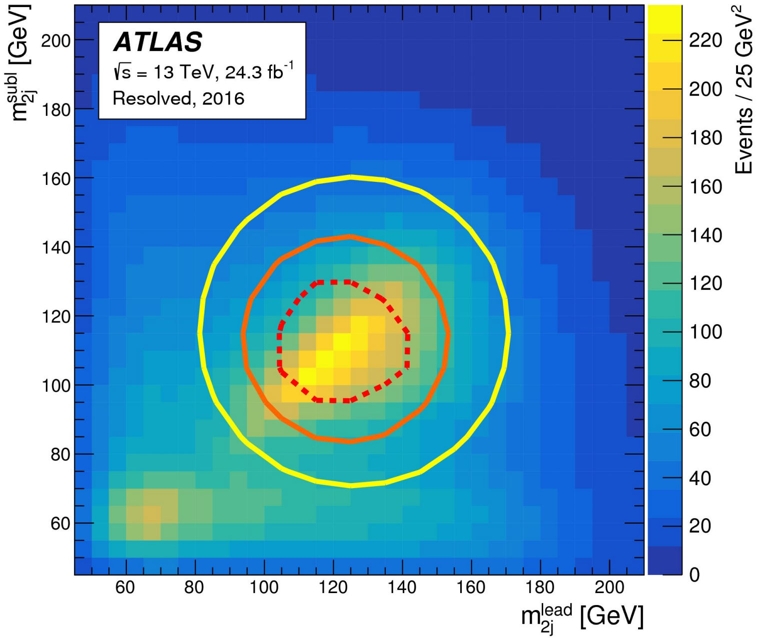


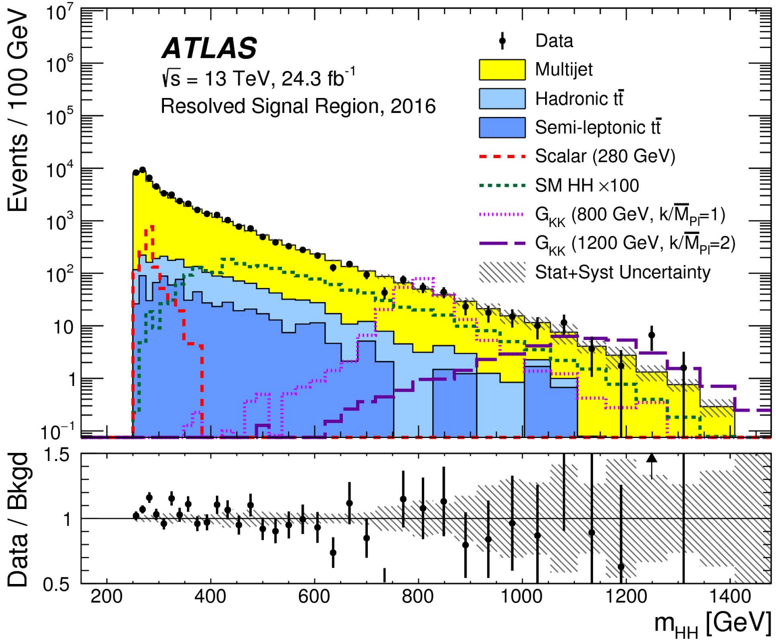
The event shown passes the boosted signal region in the two-tag sample, i.e. it contains two large-R jets with one b-tagged track jet associated to each

$HH \rightarrow 4b$: resolved analysis

https://arxiv.org/abs/1804.06174 (arXiv:1804.06174)

- **Main multijet background taken from data using 4 jets, 2 tag events**
- **Weights applied by comparing 2 tag to 4 tag events in the sideband to account for different jet multiplicities and b-tagging efficiency**
- **Validation region used for checking background modelling**

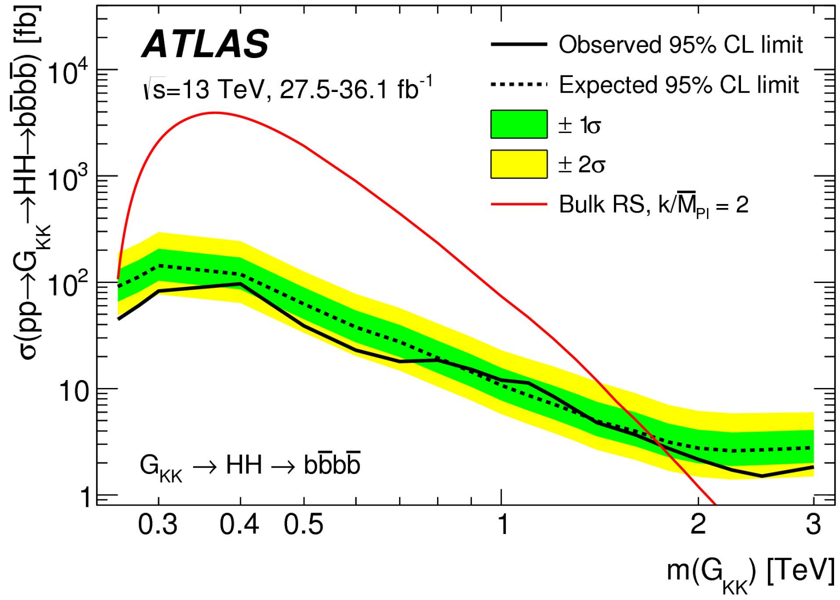




HH → 4*b*

https://arxiv.org/abs/1804.06174 (arXiv:1804.06174)

- **No clear excess observed**
- **Largest deviation for resonant search is 3.6σ local significance at M=280 GeV (2.3σ global)**
- **Slightly tighter limits on non-resonant limits than expected**



Non-resonant 95% CL limits as ratio to SM

Observed	-2σ	-1σ	Expected	$+1\sigma$	$+2\sigma$
13.0	11.1	14.9	20.7	30.0	43.5

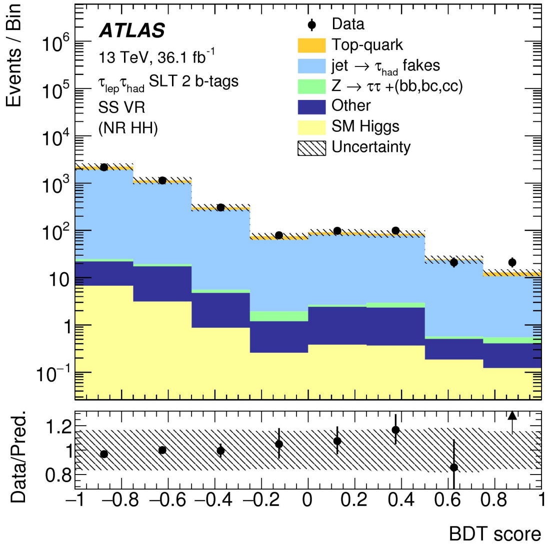
$\tau_{lep}\tau_{had}$ and $\tau_{had}\tau_{had}$ channels analysed

HH → $bb\tau\tau$ (1)

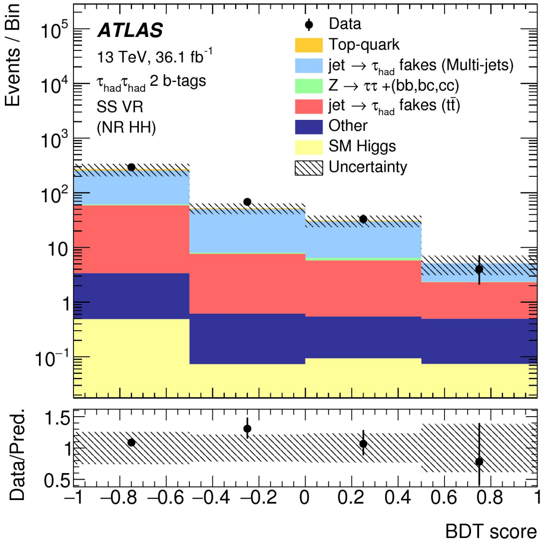
https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.121.191801 (Phys. Rev. Lett. 121 (2018) 191801)

- Major background from $ttbar \rightarrow b\tau\nu b\tau\nu$ taken from Monte Carlo
- $ttbar$ background with jets faking τ's taken from data ($\tau_{lep}\tau_{had}$) or from MC corrected for jet to τ fake rate as measured from data ($\tau_{had}\tau_{had}$)
- Validate fake τ treatment by looking at same sign control regions
- $Z \rightarrow \tau\tau$+heavy flavour MC normalised on $Z \rightarrow \mu\mu$+heavy flavour control region
- Combine kinematic information using boosted decision trees

Same Sign $\tau_{lep}\tau_{had}$



Same Sign $\tau_{had}\tau_{had}$

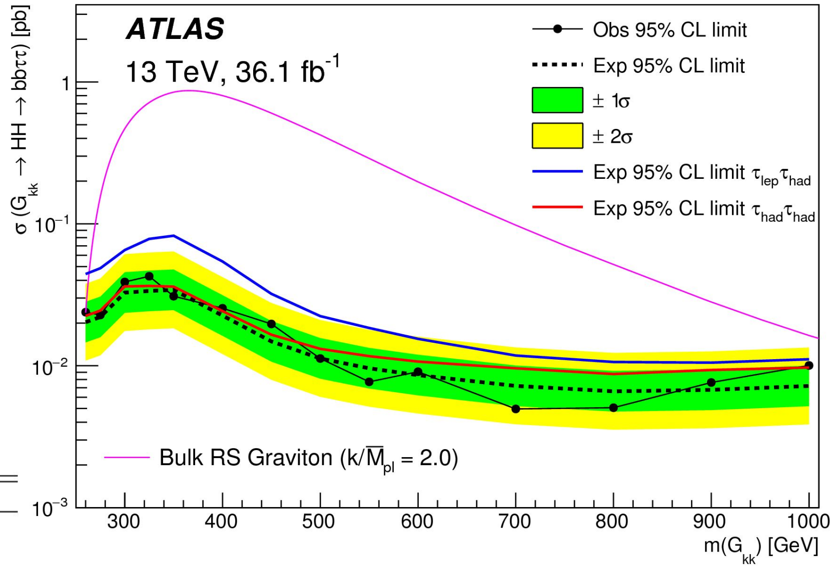


$\tau_{lep}\tau_{had}$ and $\tau_{had}\tau_{had}$ channels analysed

$HH \rightarrow bb\tau\tau$ (2)

https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.121.191801 (Phys. Rev. Lett. 121 (2018) 191801)

- **No excess seen in either channel**
- **Rules out a wide parameter space in BSM models**
- **Non-resonant limit is the best individual channel to date**

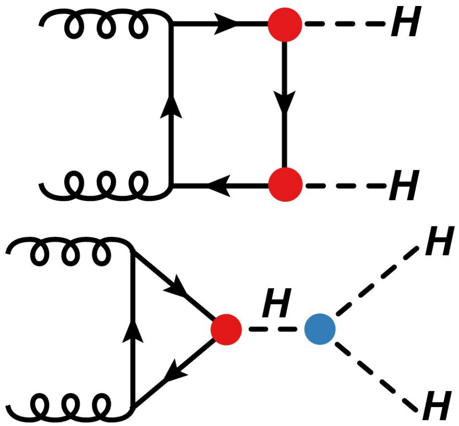


		Observed	-2σ	-1σ	Expected	$+1\sigma$	$+2\sigma$
$\tau_{lep}\tau_{had}$ (SLT)	$\sigma(HH \rightarrow bb\tau\tau)$ [fb]	52	38.4	52	72	100	134
	σ/σ_{SM}	21.3	15.7	21.1	29.3	40.8	55
$\tau_{lep}\tau_{had}$ (LTT)	$\sigma(HH \rightarrow bb\tau\tau)$ [fb]	326	123	165	229	319	428
	σ/σ_{SM}	134	50	68	94	131	175
$\tau_{lep}\tau_{had}$ Combined	$\sigma(HH \rightarrow bb\tau\tau)$ [fb]	57	37.2	49.9	69	96	129
	σ/σ_{SM}	23.5	15.2	20.5	28.4	39.5	53
$\tau_{had}\tau_{had}$	$\sigma(HH \rightarrow bb\tau\tau)$ [fb]	40.0	22.8	30.6	42.4	59	79
	σ/σ_{SM}	16.4	9.33	12.5	17.4	24.2	32.4
All channels combined	$\sigma(HH \rightarrow bb\tau\tau)$ [fb]	30.9	19.4	26.0	36.1	50	67
	σ/σ_{SM}	12.7	7.93	10.7	14.8	20.6	27.6

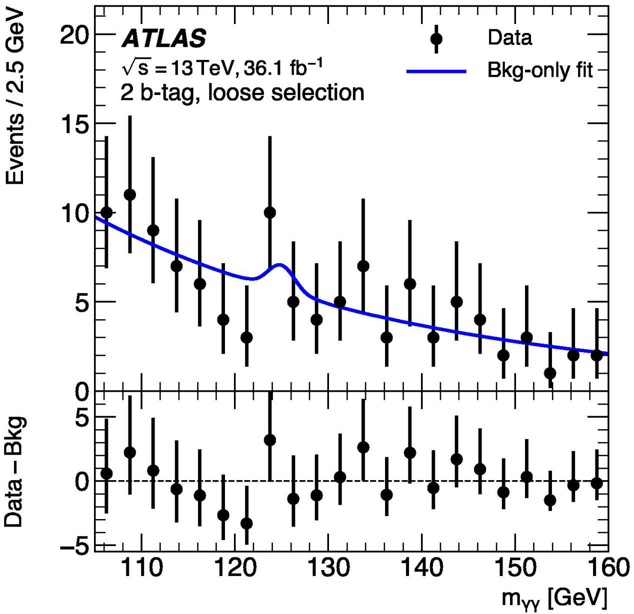
Non-resonant limit

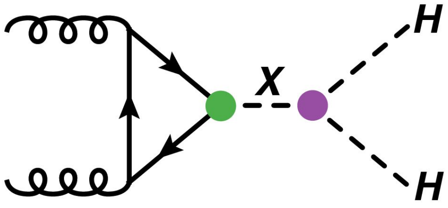
HH → $bb\gamma\gamma$

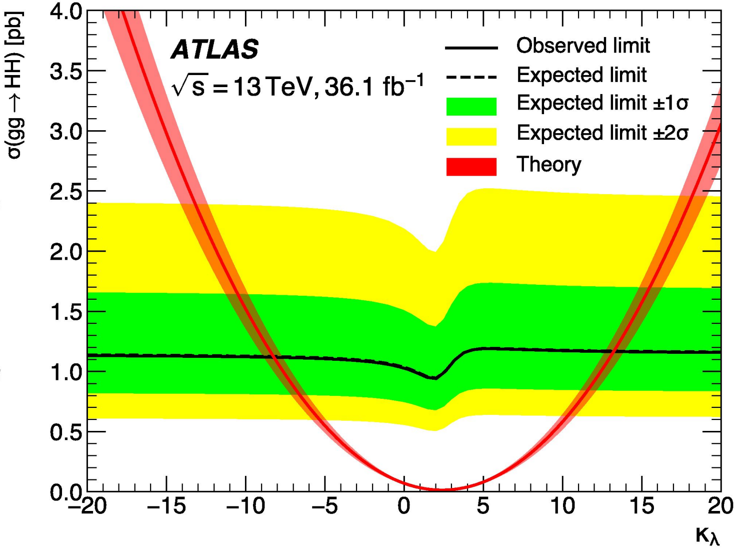
https://link.springer.com/article/10.1007/JHEP11(2018)040 (JHEP 11 (2018) 040)



- 2 photons +2 jets (1 or 2 b-tags)
- Parameterised fit to data distribution to obtain limits
- Set limits on resonant + non-resonant production
- Set limits on Higgs self coupling
- No significant excess seen
- Observed non-resonant limit 22× SM (28 expected)





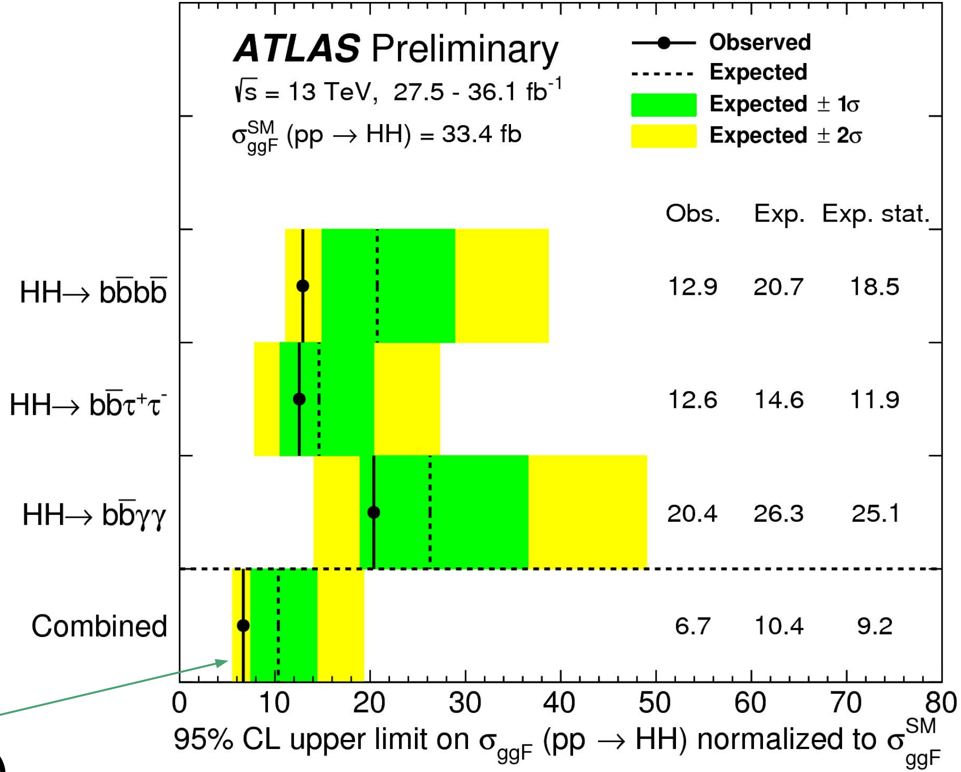


HH → Combination

http://cdsweb.cern.ch/record/2638212 (ATLAS-CONF-2018-043)

A combination of nono-resonants searches for Higgs boson pairs using up to 36.1 fb^{-1} of proton-proton collision data at √s=13 TeV.

The **combination is performed using three analyses searching for the HH→bb¯bb¯, HH→bb¯τ+τ− and HH→bb¯γγ** decay channels.

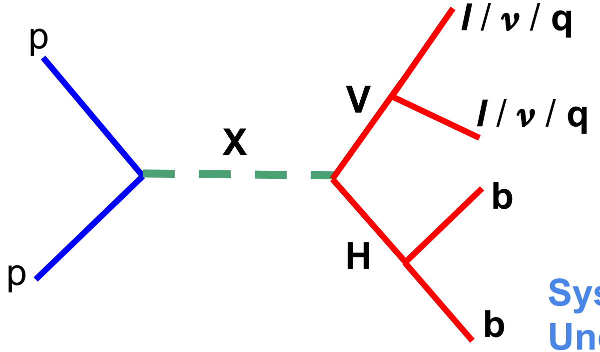


6.7 (10.4)

Diboson Searches

$X \rightarrow V(ll, l\nu, \nu\nu, qq)H(bb)$

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/EXOT-2016-12/ (Phys. Lett. B 774)(2017) 494)
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/EXOT-2016-10/ (arXiv:1712.06518)



Signature
Use of H→bb as a tag (bbH)

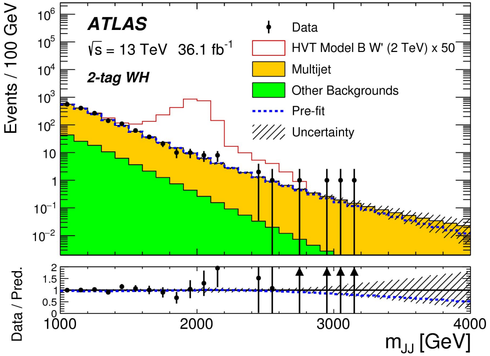
Backgrounds

- ttbar (V→ℓν, **νν**), and Z+jets (V→ℓℓ), shape is MC estimated, normalisation is constrained from CRs
- Multi-jet (V→qq), both shape and normalisation are data-driven.

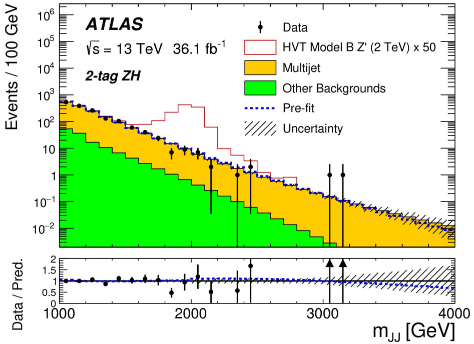
No evidence of heavy resonance is observed

Systematics Uncertainties
jet energy scale/resolution, b-tagging, Bkgs' normalisations

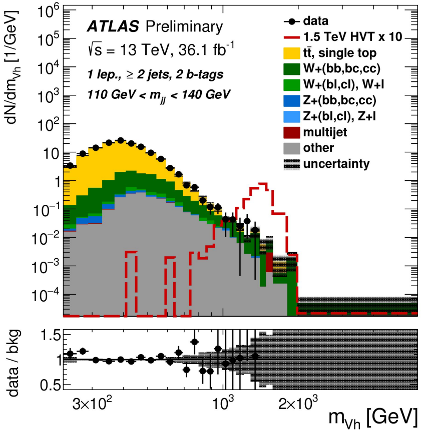
X → WH → J(qq)J(bb)



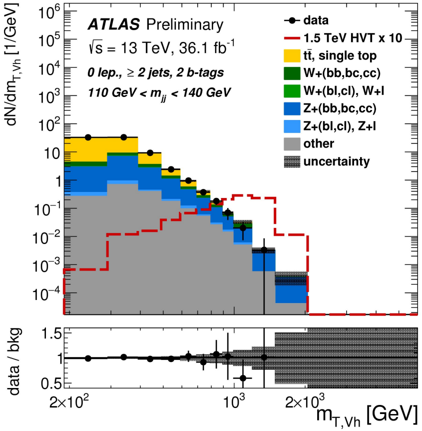
X → ZH → J(qq)J(bb)



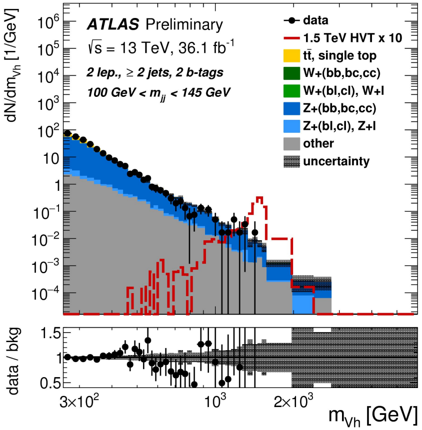
X → WH → lνbb



X → ZH → ννbb



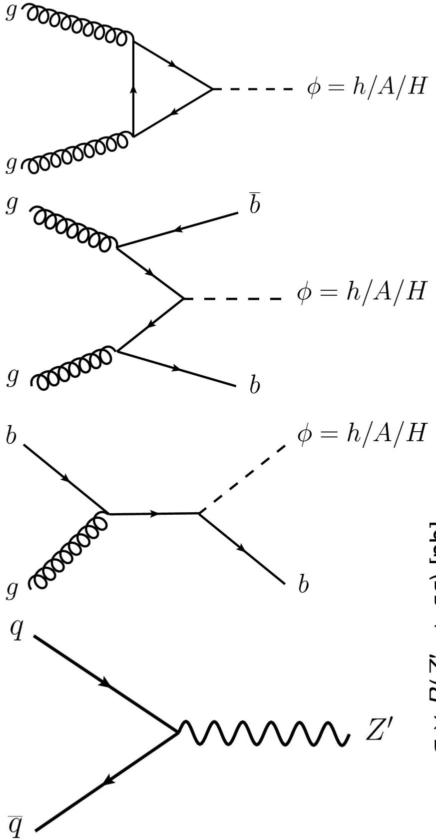
X → ZH → llbb



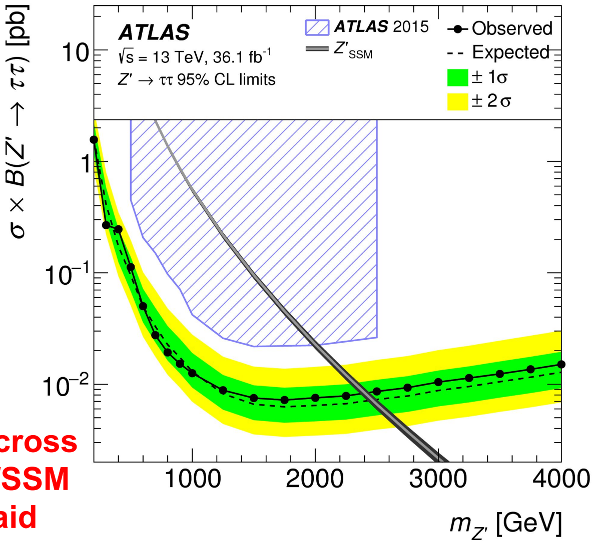
Mono-Higgs & DM searches

h/A/H → $\tau\tau$

https://link.springer.com/article/10.1007/JHEP01(2018)055 (JHEP 01 (2018) 055)

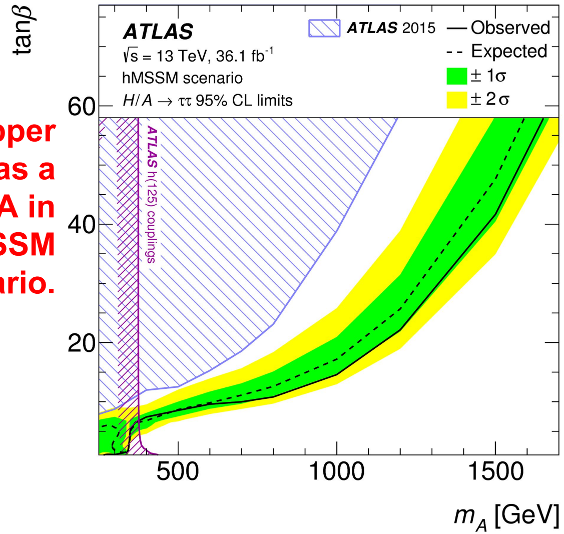


- The heavy resonance is assumed to decay to τ+τ- with at least one tau lepton decaying to final states with hadrons and a neutrino.
- Search in mass 0.2–2.25 TeV for Higgs and 0.2–4.0 TeV for Z' bosons.
- In hMSSM, the data exclude tanβ > 1.0 for m_A= 0.25 TeV & tanβ > 42 for m_A= 1.5 TeV at the 95% CL.
- For the Z'_{SSM} with $m_{Z'}$ < 2.42 TeV is excluded @95%.



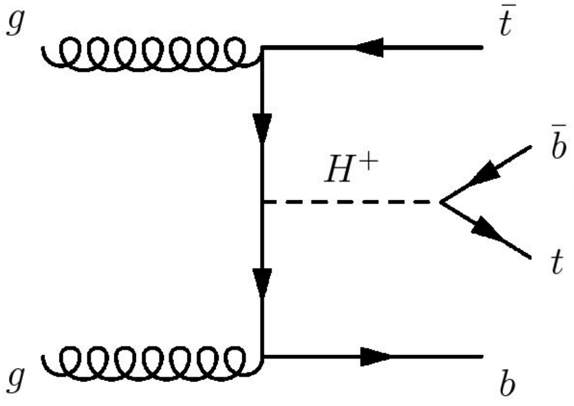
The predicted cross section for a Z′SSM boson is overlaid

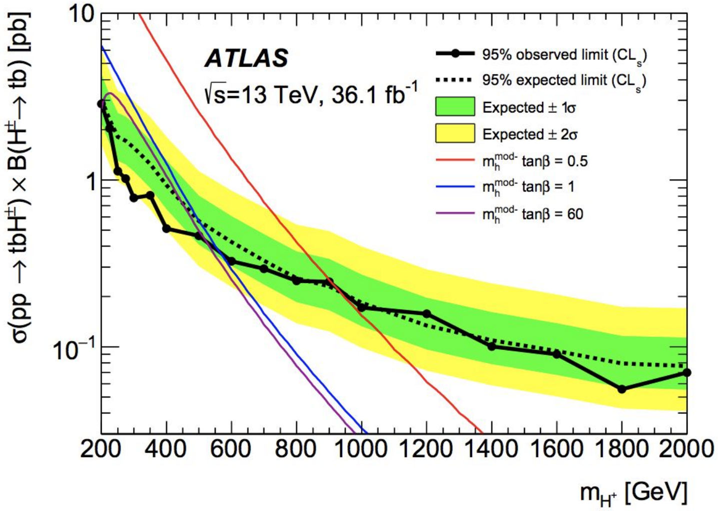
95% CL upper limits on tanβ as a function of mA in the hMSSM scenario.

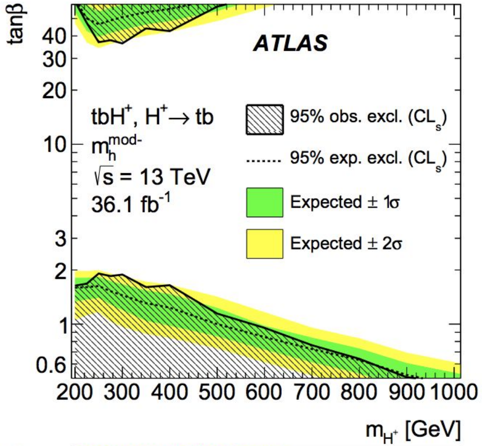


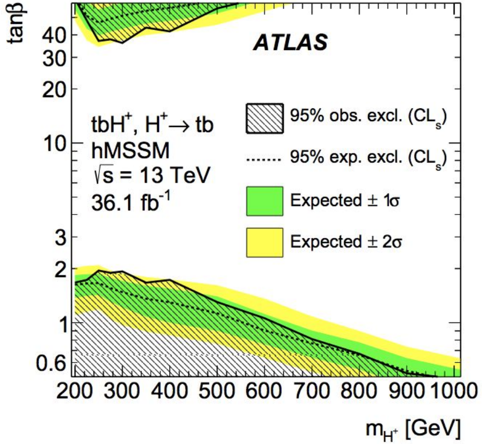
$H^{\pm} \to tb$

https://arxiv.org/abs/1808.03599 (arXiv:1808.03599)



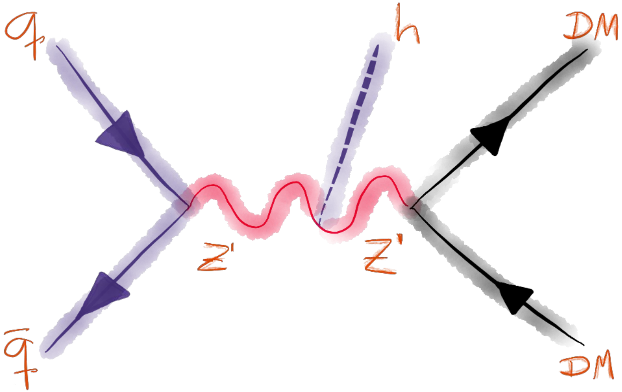






- $H^{\pm} \to tb$ produced in association with *tb*
- Considers 200 GeV ≤ $m_{H\pm}$ ≤ 2000 GeV
- ℓℓ and ℓ + jets final states, single lepton triggers

- Model independent limit
- Exclusion for m_h^{mod-} and hMSSM interpretations

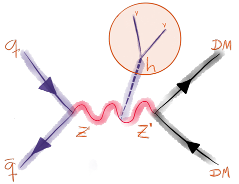


Mono-Higgs + X

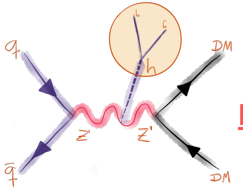
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/EXOT-2015-08/ (Phys. Lett. B 763 (2016) 251)

Models in which the higgs couples to dark sector particles, e.g. higgs couplings to the mediator

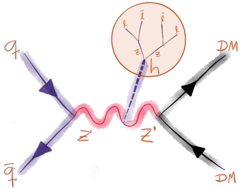
Multiple mono-H final states



H → $\gamma\gamma$
Phys. Rev. D 96 (2017) 112004



H → *bb*
Phys. Rev. Lett. 119 (2017) 181804

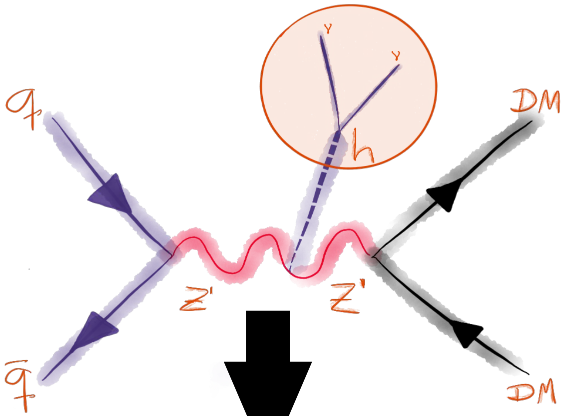


H → ZZ* → 4*l*
JHEP 10 (2017) 132

- **Not ISR** (small coupling)
- **Mainly Simplified Models:**
  - s-channel vector mediator radiating Higgs
- **Other models considered:**
  - s-channel scalar mediator radiating Higgs
  - Z'-2HD simplified model
  - scalar 2HD simplified model
- **Additional parameters as: $g_{Z'Z'h}$, mixing angles...**

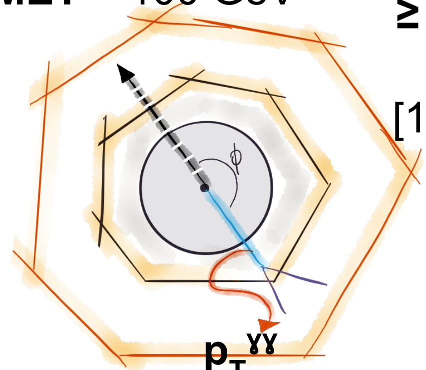
Mono-Higgs($\gamma\gamma$) + X

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HIGG-2016-18/ (Phys. Rev. D 96 (2017) 112004)



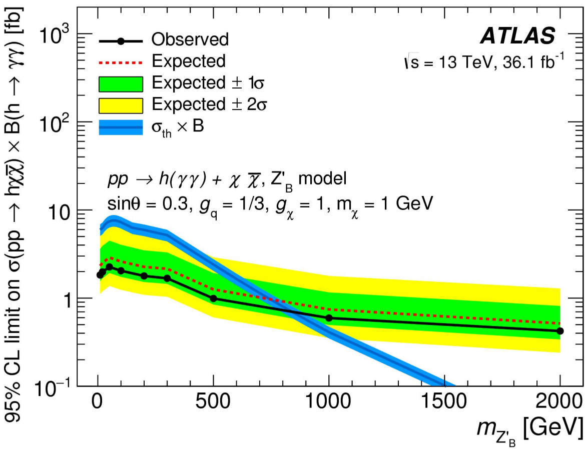
Signature
Two γ + MET

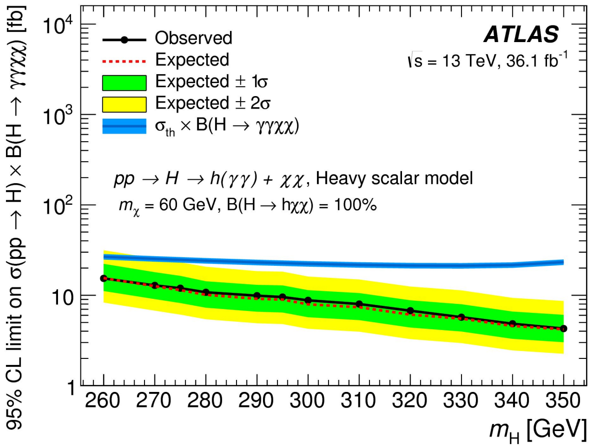
MET > 100 GeV



$p_T^{\gamma\gamma}$ > 100 GeV

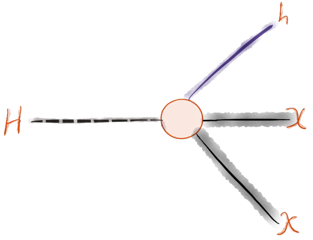
≥ 2γ with $m_{\gamma\gamma}$ [105,160] GeV





Simplified Model: Vector mediator
4 categories: cuts on MET, $p_T^{\gamma\gamma}$, p_T [γ's , jets]
Largest uncertainties: vertex selection and MET estimation
95% CL exclusion limit on m_{med}

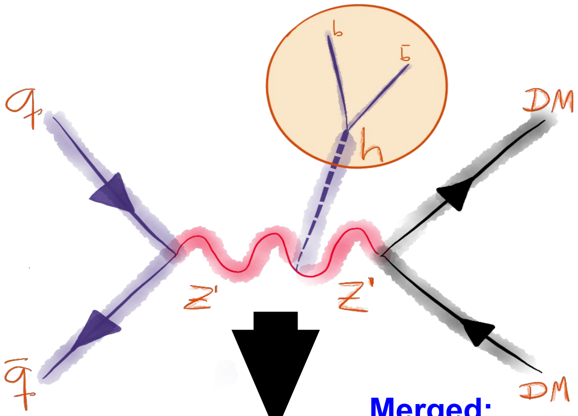
EFT model:
In both model cases a simultaneous fit to all regions was applied



No excess found in data

Mono-Higgs(bb) + X

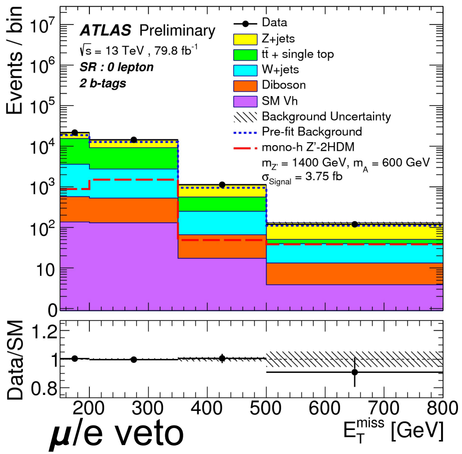
http://cdsweb.cern.ch/record/2632344 (ATLAS-CONF-2018-039)



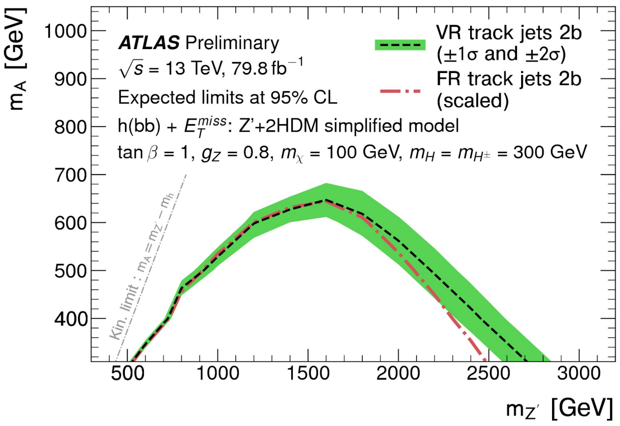
Resolved:
2 small-R (0.4) jets

Merged:
1 large-R (1.0) jet
+ 2 track jets

MET > 150 GeV , $\mathbf{p_T}$ > 30 GeV

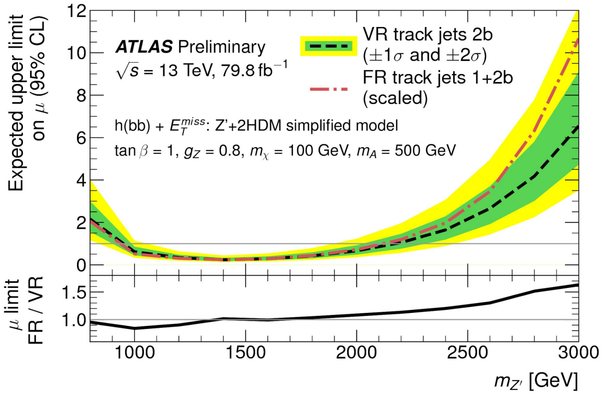


μ/e veto



Exclusion contours for

- The Z′-2HDM exclusion contour in the ($m_{Z'}$,m_A) plane for tanβ = 1, $g_{Z'}$=0.8 and m_χ = 100,GeV

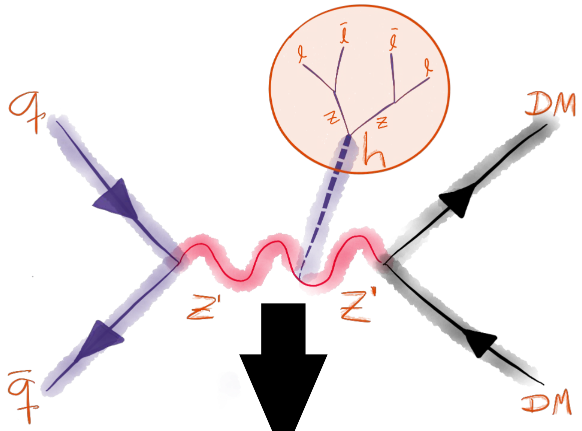


Upper limits at 95% CL , for fixed mA = 500 GeV and different values of $m_{Z'}$ of the Z'-2HDM benchmark model

No excess found in data

Mono-Higgs(4*l*) + X

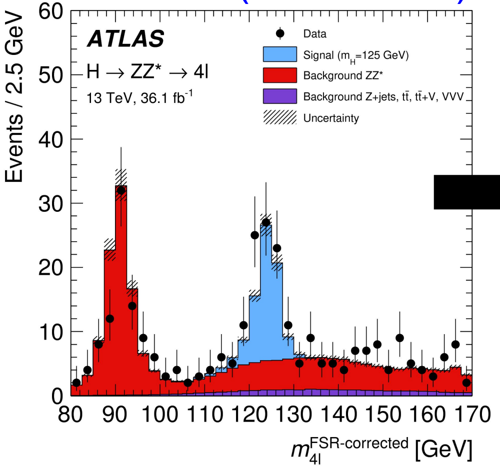
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HIGG-2016-25/ (JHEP 10 (2017) 132)

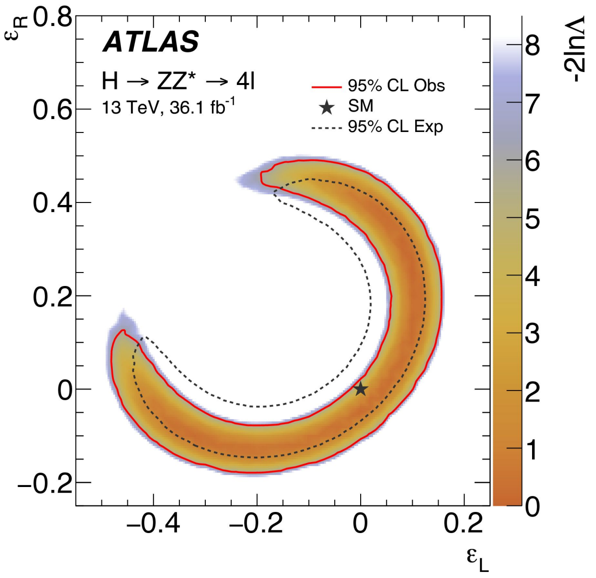


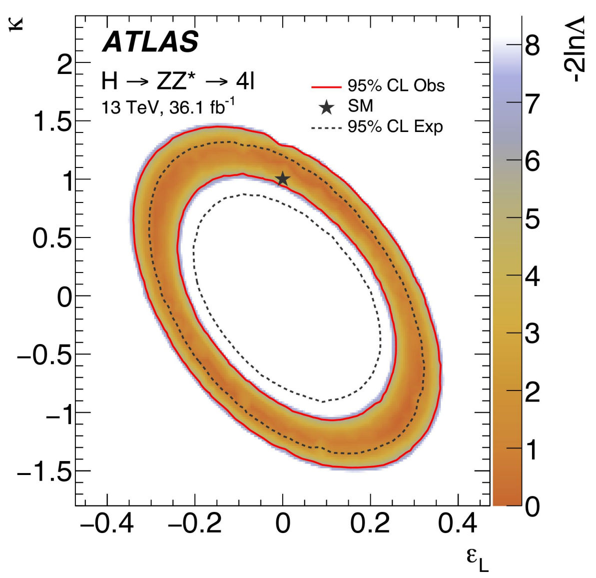
Signature

Four leptons (μ/e)

+ **MET** (> 100 GeV)

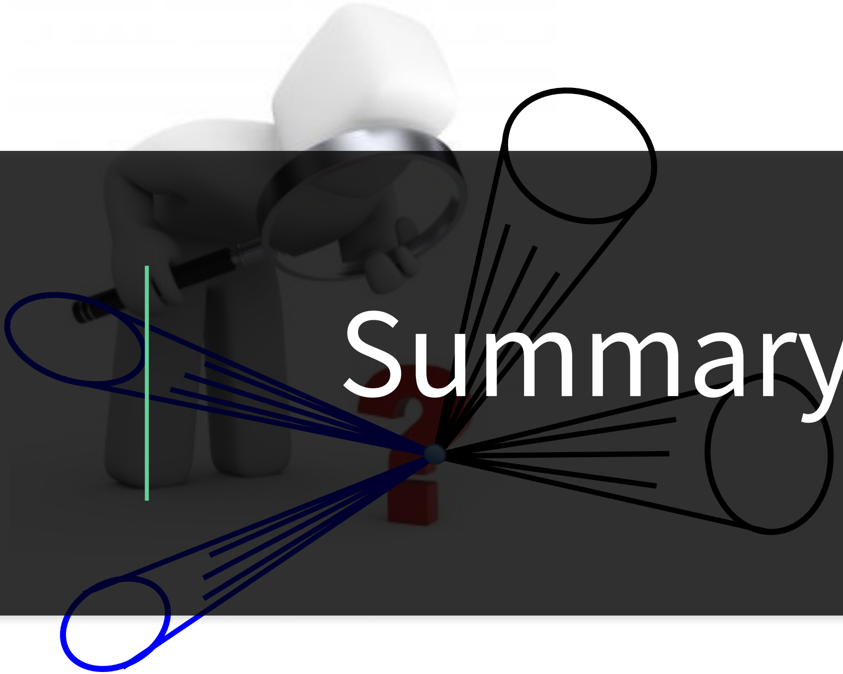






Limits on modified Higgs boson decays

- The limits are extracted in the plane of ϵ_L and ϵ_R
- The limits with tested parameters are εL and κ. The latter modifies the coupling of the Higgs boson to Z bosons.



Summary

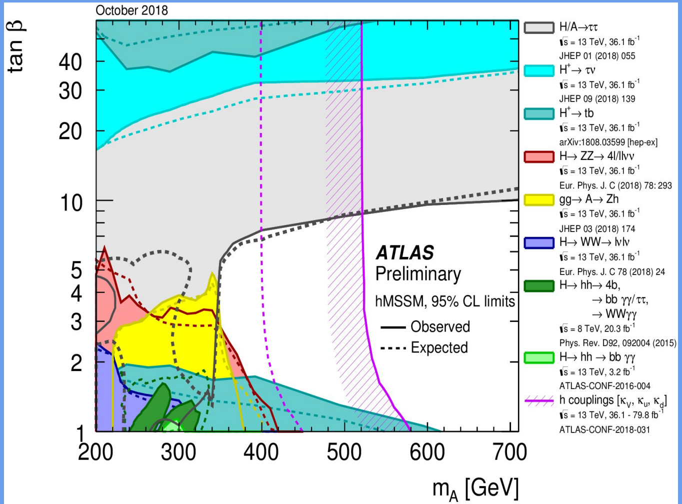
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults

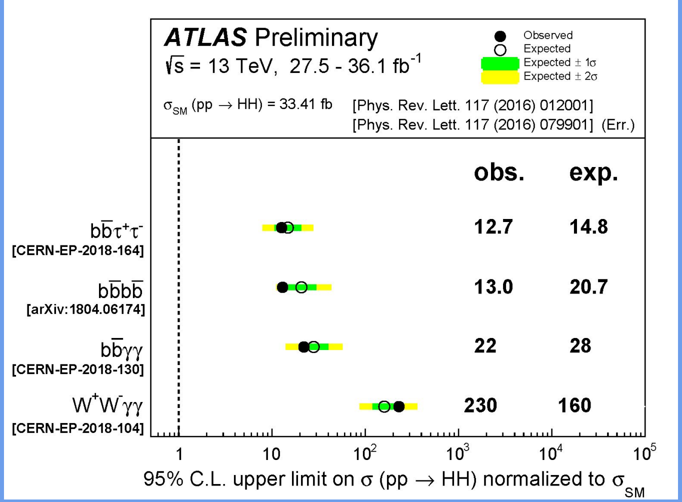
Summary

The discovery of the Higgs has provided a new tool for BSM Higgs searches

- The ATLAS di-Higgs program is active and has a broad scope
- Recent results on many different decay modes
- Dedicated efforts in the combination of channels
- The scope and number of these searches have multiplied since Run 1, thanks to the expansion of data statistics but also approaches and methodologies

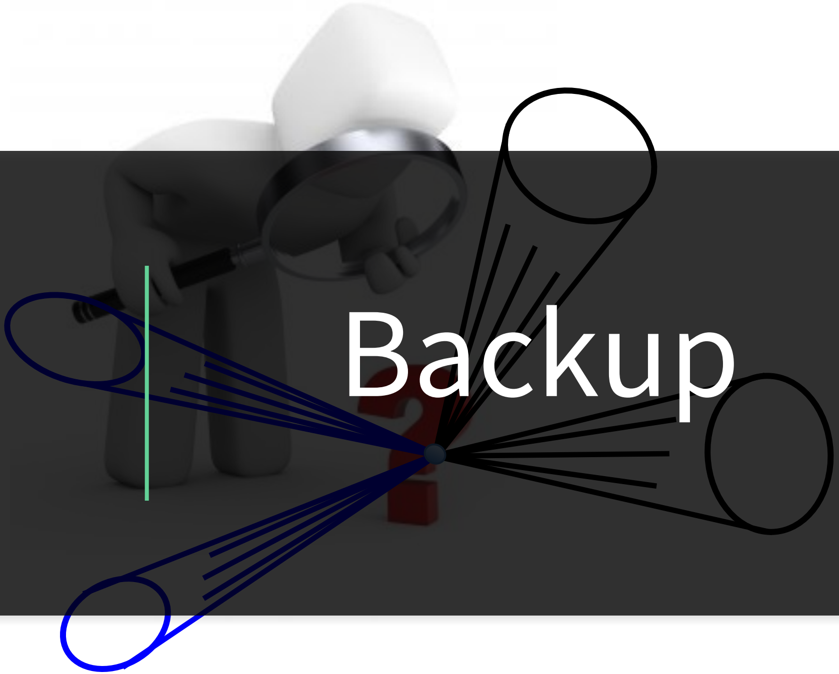
ATLAS will continue to push the sensitivity of the searches presented today, update other searches not mentioned here, including more data recorded during 2018, looking for possible BSM physics.





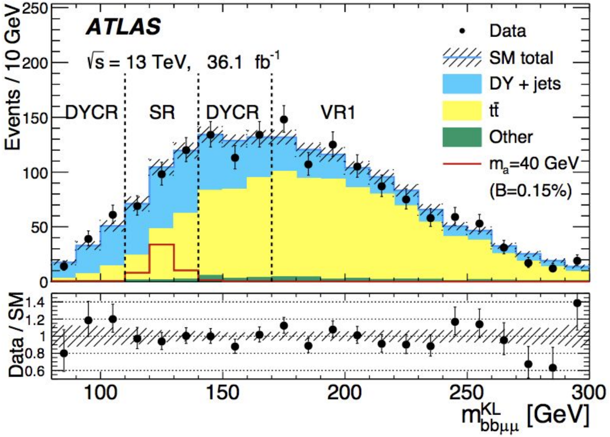
Thank You!

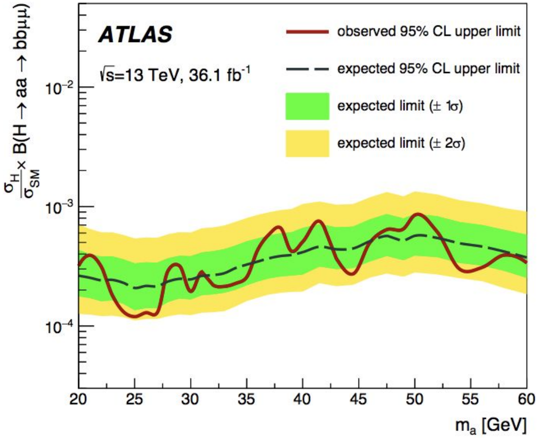
Backup



$H \rightarrow aa \rightarrow bb\mu\mu$

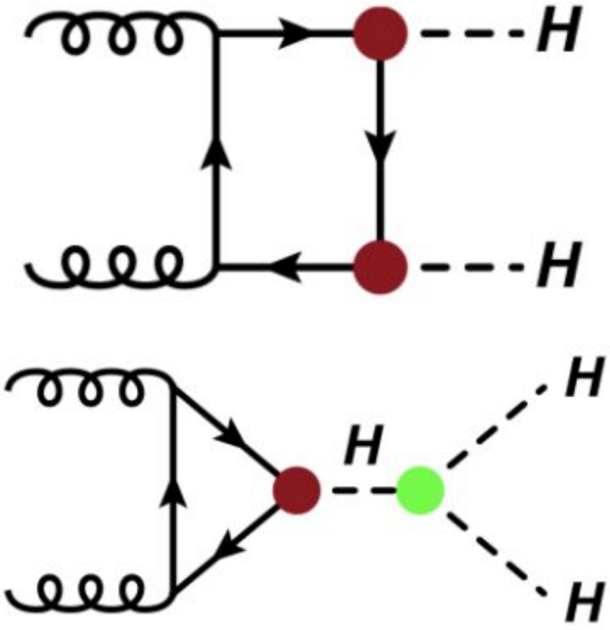
- **Dimuon signature**
  - Triggering and mass reconstruction
  - models with enhanced lepton Couplings
- **$m_{\mu\mu}$ invariant mass resolution is 10x better than m_{bb} → use a kinematic fit exploiting the symmetry of *H → aa* decays:**
  - 2x improvement in $m_{\mu\mu bb}$ resolution
  - Require $|m_{\mu\mu bb} - m_H| < 15$ GeV





- Top background, modeled using simulation, and Drell-Yan, estimated from 0-tag data templates are normalized in a profile likelihood fit to the data over the control and signal regions
- Dominant uncertainties: jet energy scale and resolution, signal and background modeling, and DY template
- Upper limits on $(\sigma_H/\sigma_{SM}) \times B\ (H \rightarrow aa \rightarrow bb\mu\mu)$ range between 10^{-4} and 10^{-3}

Higgs self coupling

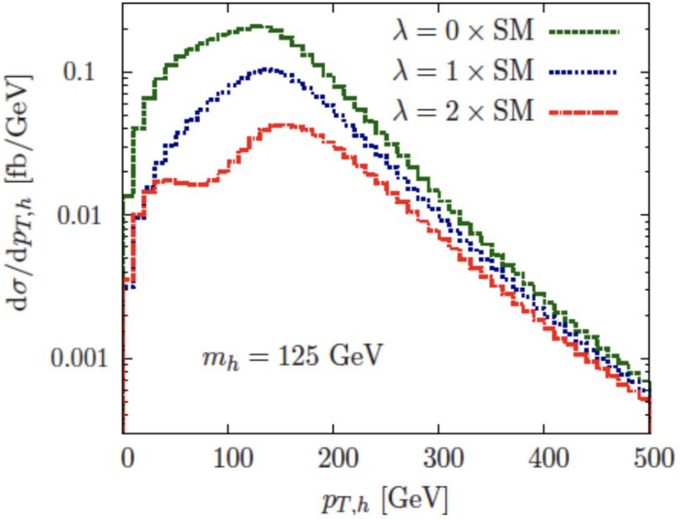


Di-Higgs makes possible measurement of Higgs self coupling and hence fully reconstruct Higgs potential $\phi \rightarrow v + h$

$$V(\phi) = \frac{1}{2}\mu^2\phi^2 + \frac{1}{4}\lambda\phi^4 = \lambda v^2 h^2 + \lambda v h^3 + \frac{1}{4}\lambda h^4$$

mass term self coupling terms

- Destructive interference between diagrams reduces cross section
- Measurements of $p_T(H)$ can enhance sensitivity to λ
- Rare process: 33.4 fb^{-1} at 13 TeV

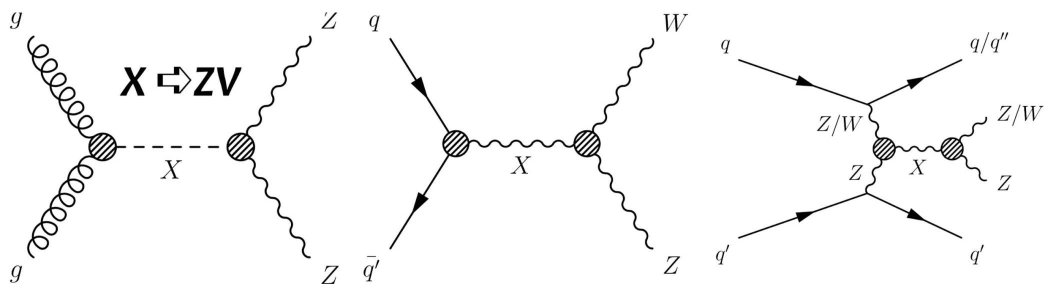


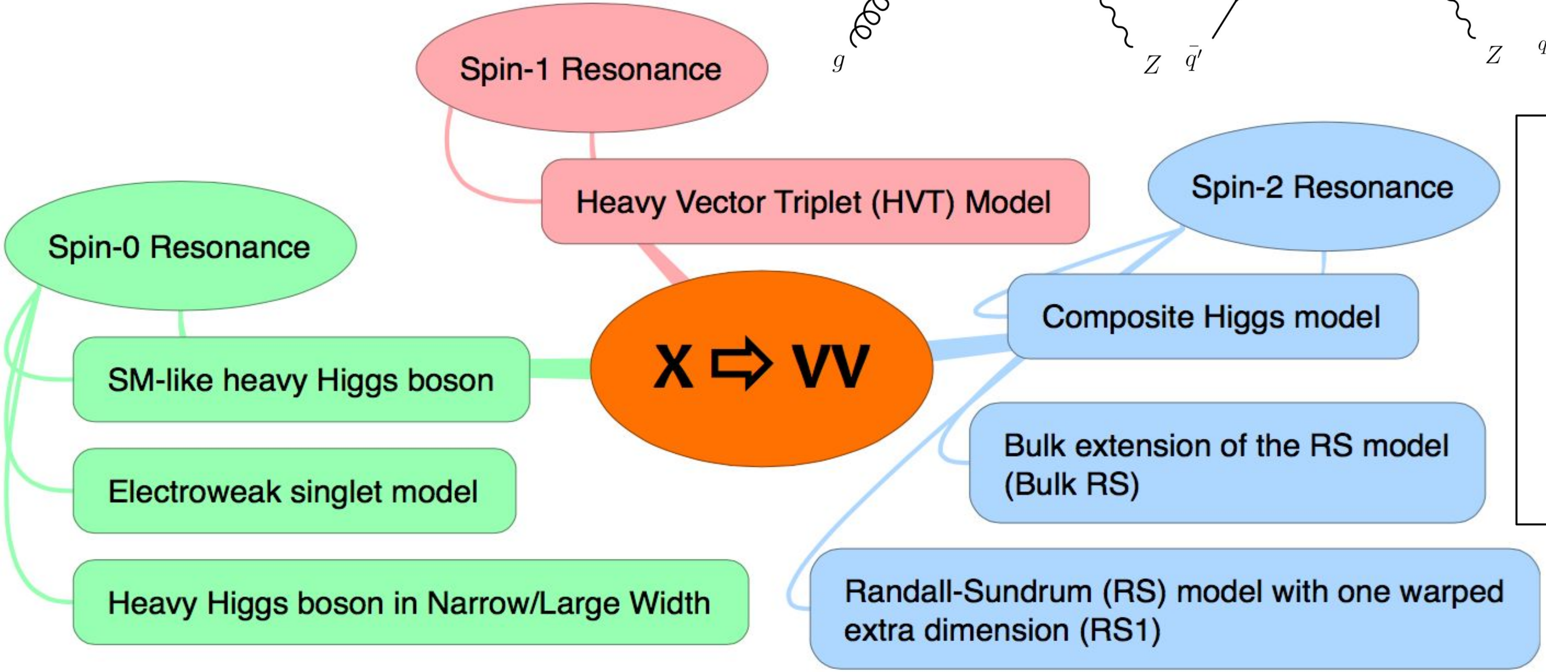
Motivations

The existence of new heavy resonance will be able to help to

- **resolve Hierarchy problem**
- **understand the mechanism of EWSB**
- **understand flavour structure of the SM**

3 types of productions



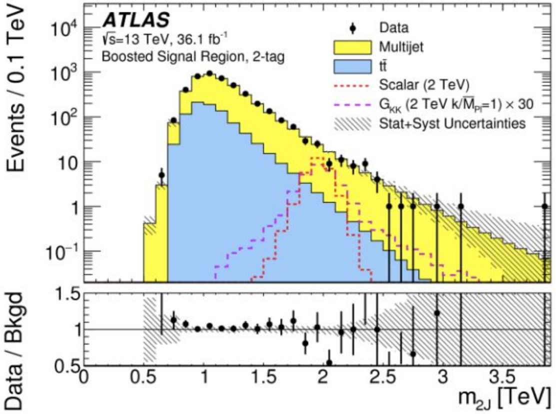


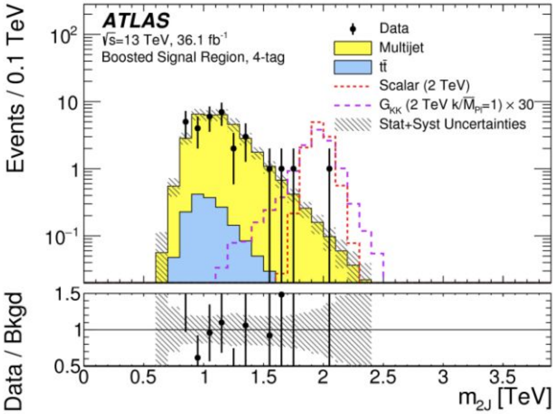
Many models predict the existence of new heavy resonances decaying into diboson!

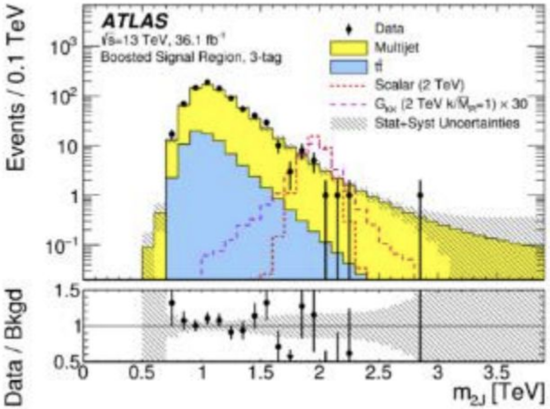
HH → 4*b* : boosted analysis

https://arxiv.org/abs/1804.06174 (arXiv:1804.06174)

- **Multijet background taken from lower tagged samples in sideband**
- **Background modelling checked in the validation region**
- **2,3,4 tagged signal regions**







Non-resonant Searches

Vector-Like Quarks (1)

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2016-104/ (Phys. Lett. B 774)(2017) 494)
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/EXOT-2016-15/ (ATLAS-CONF-2017-055)

Vector-Like quarks (VLQ)

- Color-triplet spin-½ fermions, left-handed and right-handed components transform in a same way under the SM gauge group

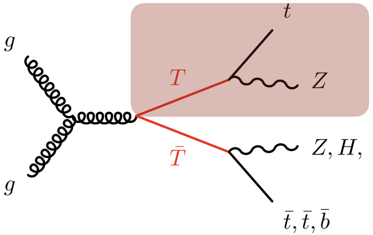
Composite Higgs models | Little Higgs models | Warped or universal extra-dimensions

- Masses of the VLQ are not generated by a Yukawa coupling, not excluded by existing Higgs measurements
- The VLQs couple preferentially to 3rd-generation quarks, they have both **charged-current decays (T → W*b*; B → Wt)** and **neutral current decays (T → Zt; B → Z*b*; H*b*)**
- Contrary to sequential fourth generation

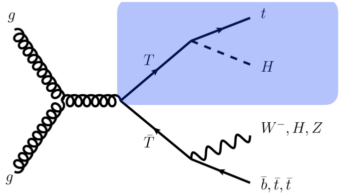
Vector-Like Quarks (2)

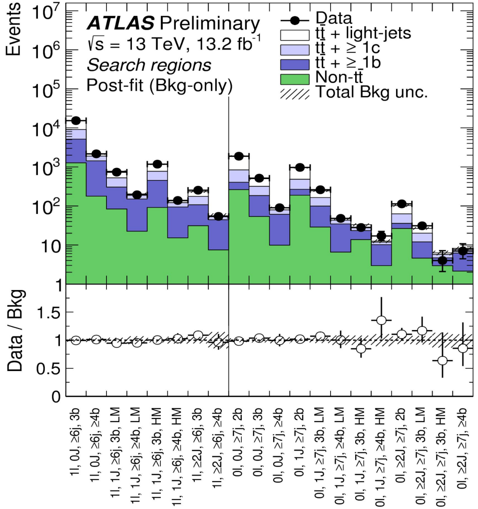
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2016-104/ (Phys. Lett. B 774)(2017) 494)
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/EXOT-2016-15/ (ATLAS-CONF-2017-055)

TT → **Z(νν)t** + X: 1 lepton, jets, MET

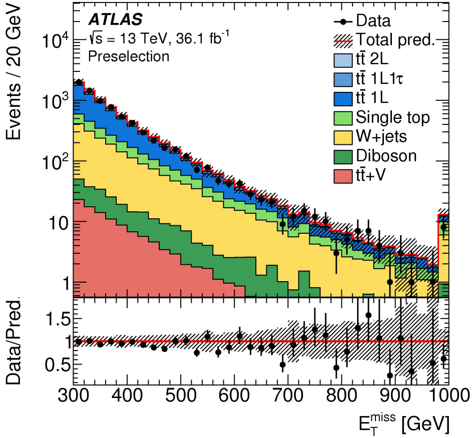


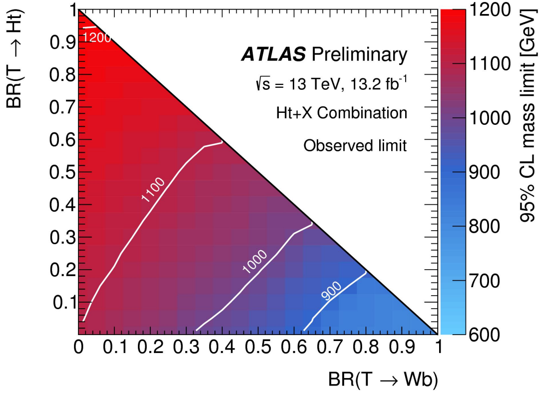
TT → **H(*bb*)t** + X: 0/1 lepton, jets, *b*-jets



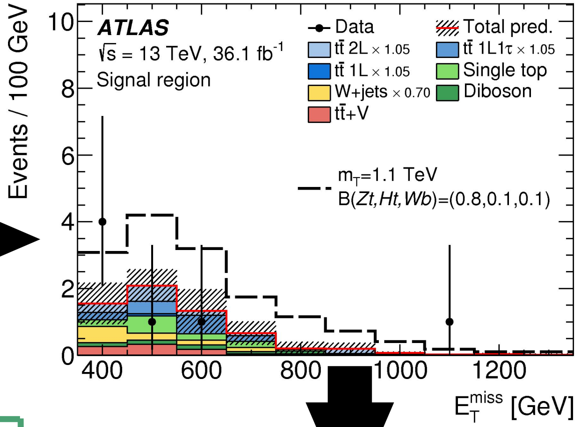


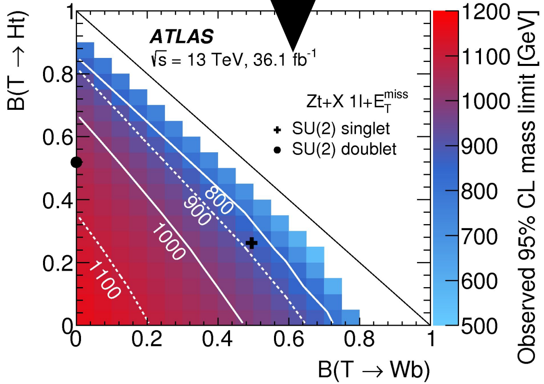
Analysis with 20 Signal regions and 15 Validation regions combined Fit!





No excess found in data

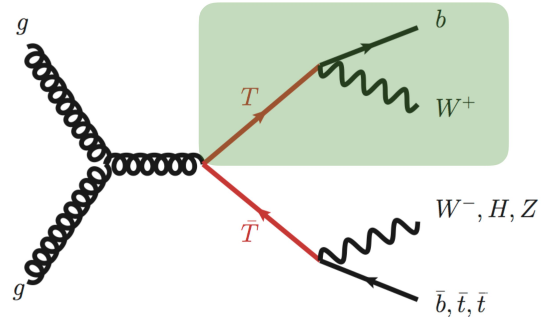




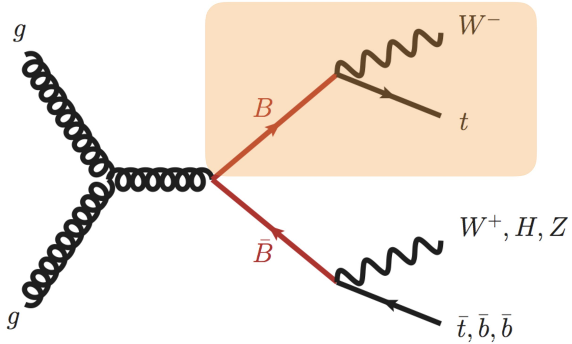
Vector-Like Quarks (3)

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2016-104/ (Phys. Lett. B 774)(2017) 494)
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/EXOT-2016-15/ (ATLAS-CONF-2017-055)

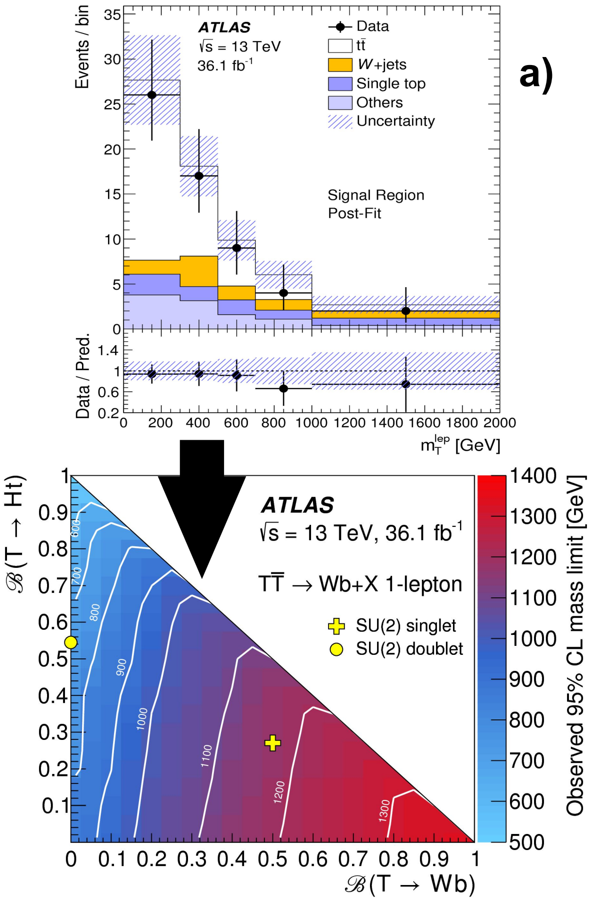
a) TT → **W(qq)*b*** + X: 1 lepton, 1 large-R W tagged jet, >1 b-tagged Small-R jets, MET

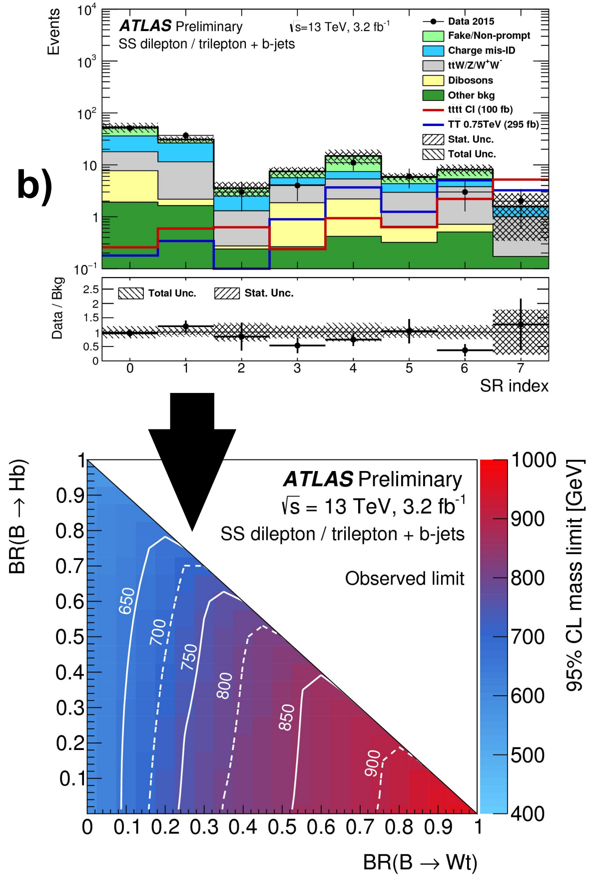


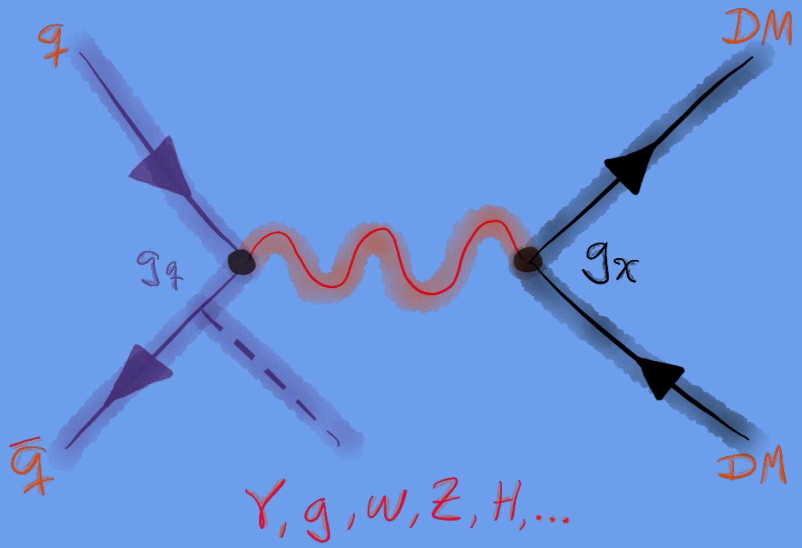
b) BB → **W⁻tW⁺t / W⁻tZ*b***: > 1 same-sign leptons, > 1 jets, >0 b-tagged Small-R jets



No excess found in data







ATLAS-CMS (LHC) Dark Matter (DM) Forum
arXiv:1507.00966
define benchmark models for kinematically distinct signals for the so-called Run-2 searches:

LHC Run-1: “traditional" Effective Field Theory (**EFT**) approach ***(some searches on Run-2)***

- Assume mediator too heavy to be produced
- 2 parameters: WIMP mass (**m_χ**) & suppression scale (M*)
- Some comparisons to simplified models

For Run-2: benchmark **Simplified Models***

- Provide basis for re-interpretations (distinct kinematics)
- Collected by **LHC DM** forum
- Dirac-fermionic WIMPs

Mostly 4 parameters:

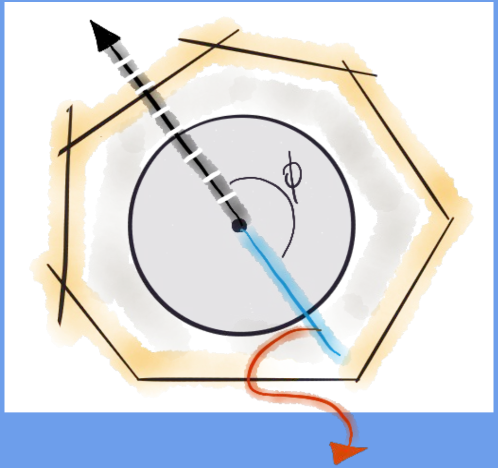
- mediator mass (M_{Med})
- WIMP mass (m_χ)
- 2 couplings (g_q,g_χ), typically (1, 0.25)

Different types of mediators, minimal width

*(where possible)

General Analyses Remarks

Non-interacting **DM** particles →
Missing transverse energy **(MET)**



X (ɣ, jet, $W^{\pm}$, Z, h)

Similar strategy in all the mono-X searches:

- Event Selection
  - High MET, compatible with $\chi\chi$ production
  - If X=ɣ, jet → high pT(X) with quality criteria
  - If X=W, Z, h → reconstruct mass within a windows
  - Large $\Delta\phi$(X,MET)
  - Veto events with other "good" physics objects, like leptons

Finally, the search focus in look for excess in different regions of high MET, and in case of absence of excess, exclusion limits are extracted for the model