Searches for BSM resonances in ATLAS

New Frontiers in Physics
ICNFP2023

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Kolymbary Crete

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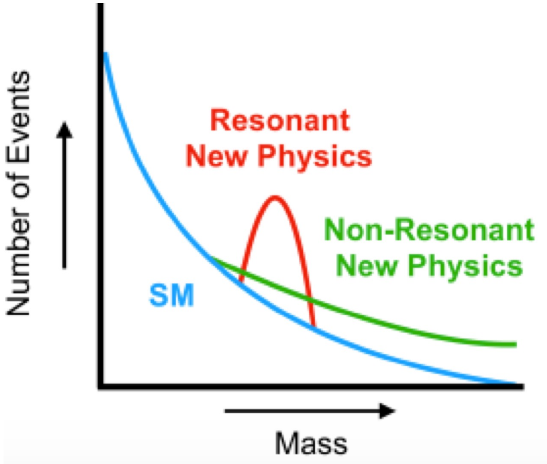
Outline

The Standard Model (SM) is currently the best description of the subatomic world, but it does not explain the complete picture!
Several BSM models have been introduced to explain the open questions, introducing new heavy particle resonances!

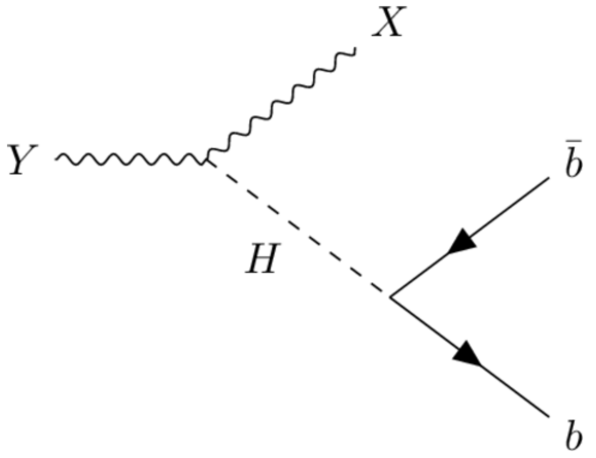
- Many public ATLAS papers and conference notes are available in ATLAS public results.
- Highlight more recent ATLAS searches for BSM resonances:
  - New Resonance $Y \rightarrow XH \rightarrow qqbb$ [2306.03637]
  - Heavy Higgs in multilepton and b-jets [ATLAS-CONF-2022-039]
  - Vector-like Top (VLT) partners [ATLAS-CONF-2023-020]
  - New Resonance $R \rightarrow W^+W^- \rightarrow e\nu\mu\nu$ [ATLAS-CONF-2022-066]



New Resonance $Y \rightarrow XH \rightarrow qqbb$

New heavy resonances Y decaying into a Standard Model Higgs boson H and a new boson X.

- Final states defined by a Higgs decays in to bb and the X to light quark resulting in a **fully hadronic final state.**
- Heavy Vector Triplet HVT model used as benchmark for **cross section upper limits**



Background estimation is fully data driven from regions which fail H tagging

Composition:

- ~97% QCD di-jet processes,
- ~3% *tt* and V+jets processes

Y Resonance Analysis Strategy

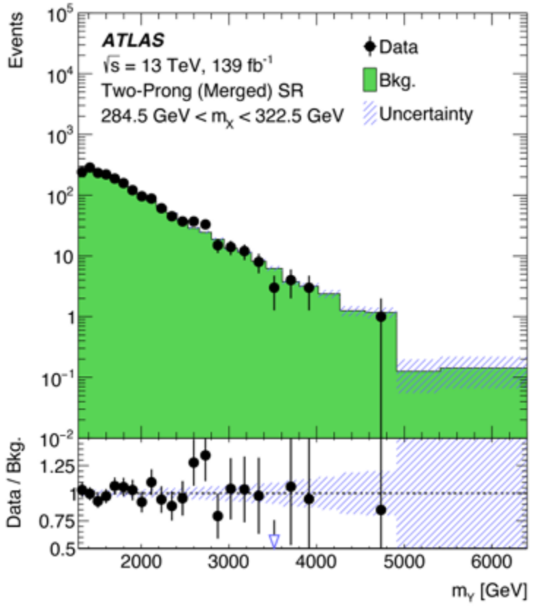
- The high mass of the Y results in both the H and the X are boosted.
- Three Signal Regions SR:
  - **SR (Merged):** X and H are reconstructed as a large radius jet.
  - **SR (Resolved):** an orthogonal resolved region where the X is reconstructed as two small radius jets.
  - **SR (Anomaly):** Additional anomaly detection, which selects the X particle based solely on its substructural incompatibility with background jets (not orthogonal to the other SRs).

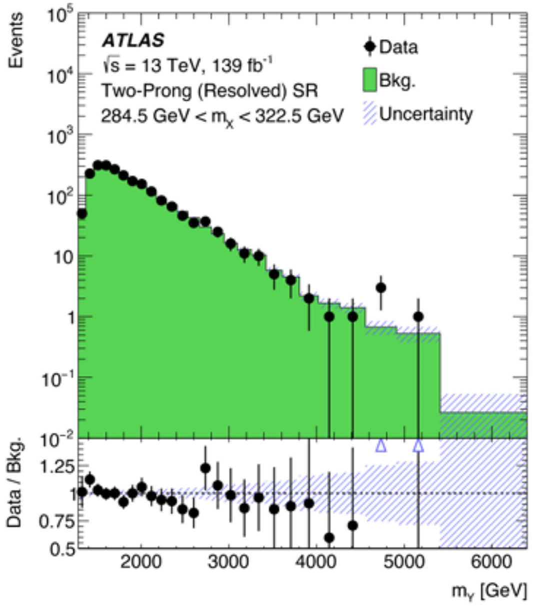
Neutral Network NN tagger

Parameter	Preselection requirements
m_{JJ} [GeV]	> 1300
$p_T(J_1)$ [GeV]	> 500
m_J [GeV]	$m_{J_1} > 50 \parallel m_{J_2} > 50$
$D_{H_{bb}}$	> −2

Parameter	Signal regions: Merged	Resolved	Anomaly
m_H [GeV]	(75, 145)	(75, 145)	(75, 145)
$D_{H_{bb}}$	> 2.44	> 2.44	> 2.44
D_2^{trk}	< 1.2	> 1.2	-
$\lvert\Delta y_{j_1,j_2}\rvert$	-	< 2.5	-
p_T^{bal}	-	< 0.8	-
Anomaly Score (S_A)	-	-	> 0.5

Parameter	Background estimation regions: CR0	HSB0	HSB1	LSB0	LSB1
m_H [GeV]	(75, 145)	(145, 200)		(65, 75)	
$D_{H_{bb}}$	< 2.44	< 2.44	> 2.44	< 2.44	> 2.44

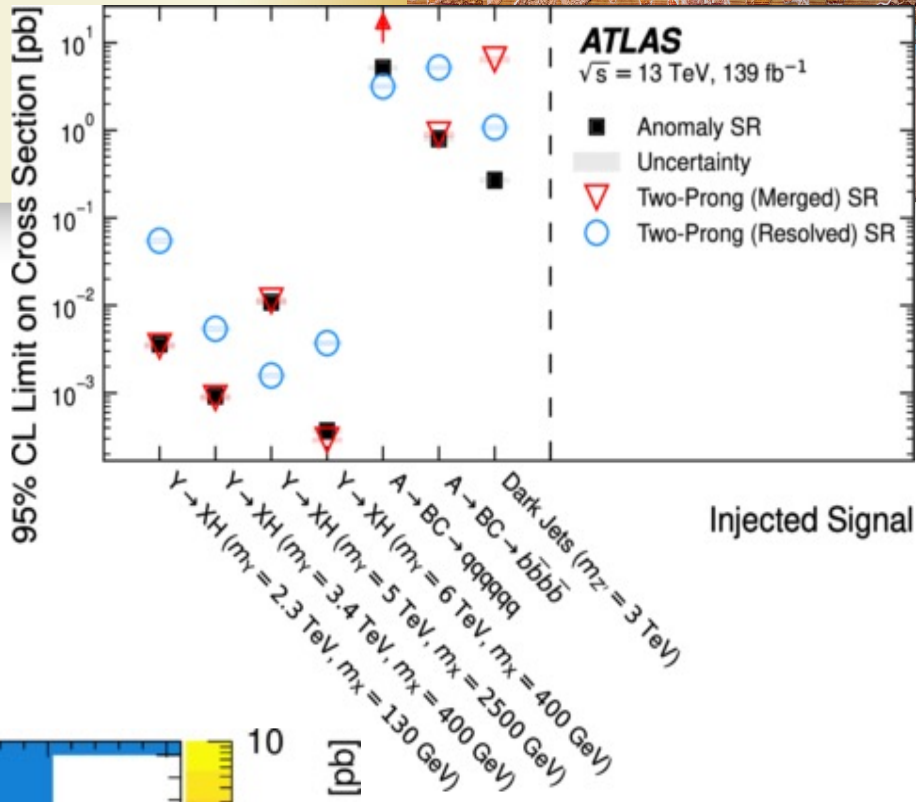


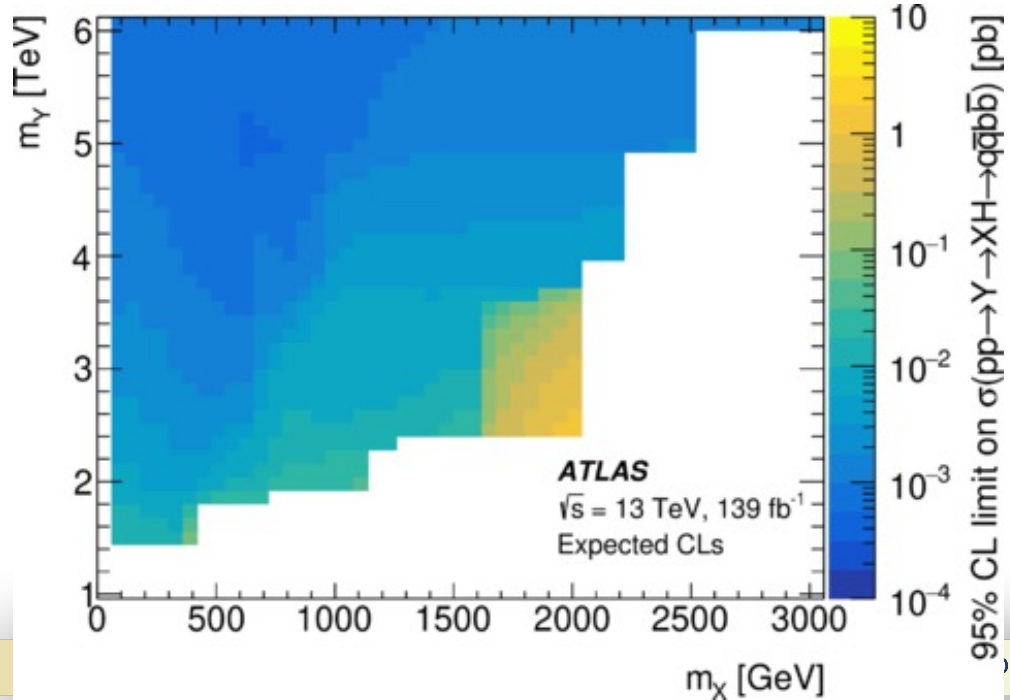


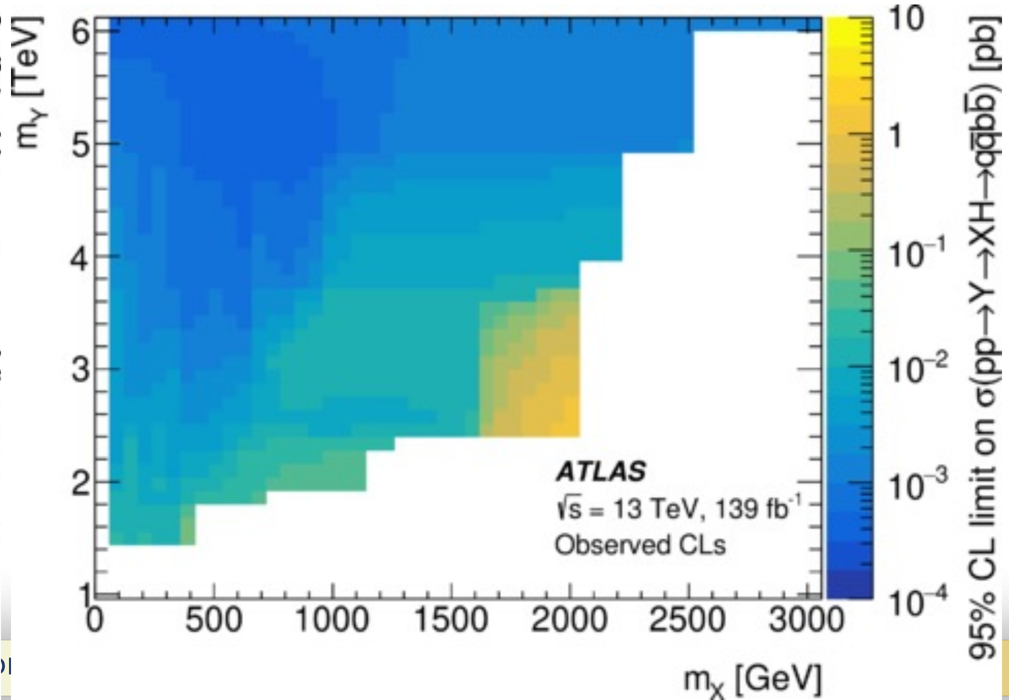
Results on Y→ XH→qqbb

No significant excess of data over the expected background is observed.

The observed limits range for the cross section from 0.34 fb for the signal point (m_Y = 5000 GeV, m_X = 600 GeV) to 1.22 pb for the signal point (m_Y = 2500 GeV, m_X = 2000 GeV).

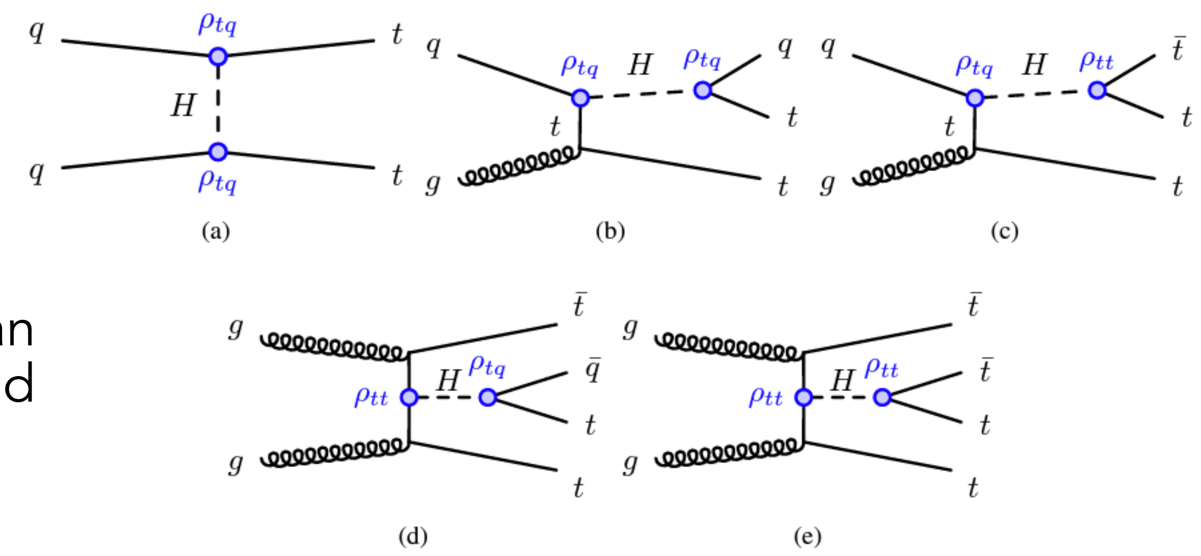




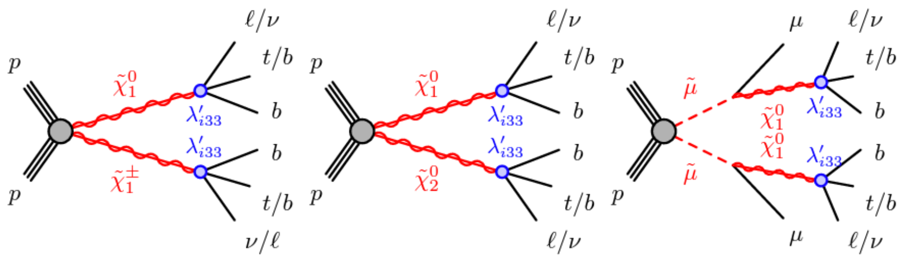


Heavy Higgs in multilepton and b-jets

- New heavy scalars with flavour-violating decays in final states with multiple leptons and b-tagged.
- Two benchmark models:
  - Two-Higgs-doublet-model (g2HDM) involving an additional scalar with couplings to top quark and the three up-type quarks (ρ_{tt}, ρ_{tc}, and ρ_{tu}).
  - R-parity violating supersymmetry.
- Target signal:
  - final states with either a same-sign top-quark pair, three top-quarks, or four top-quarks.

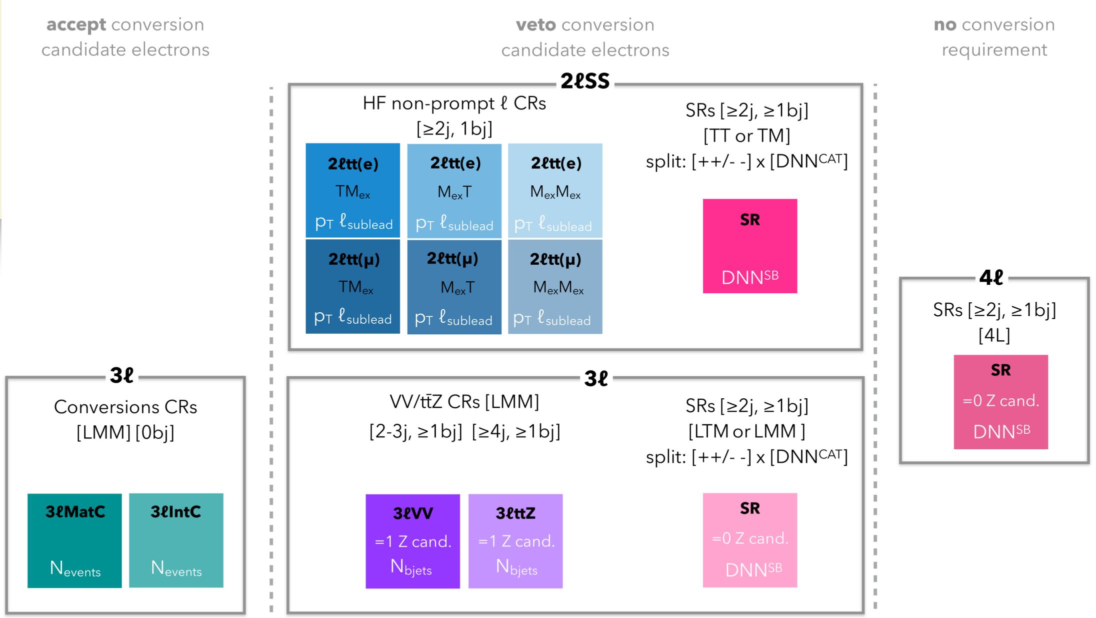


(a) (b) (c)
(d) (e)



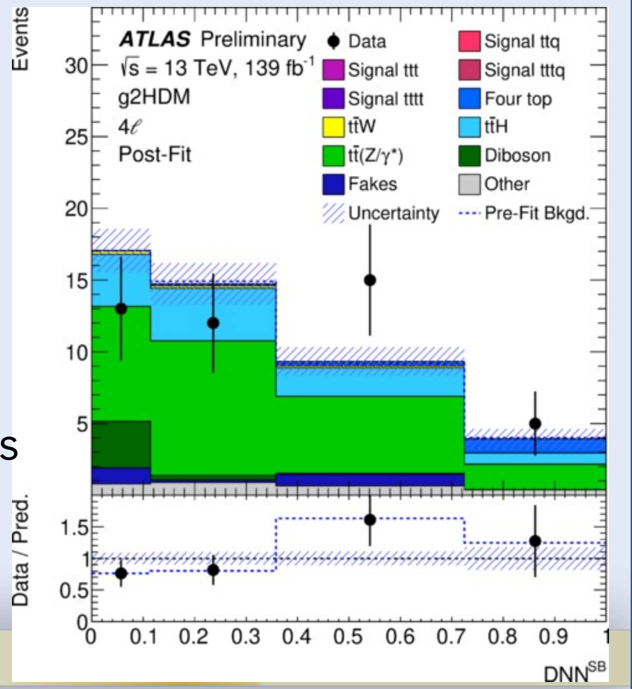
Event Categories

- **Events are categorised** depending on:
  - the multiplicity of light charged leptons (electrons or muons),
  - total lepton charge,
  - and a deep-neural-network to enhance the purity of each of the signals.



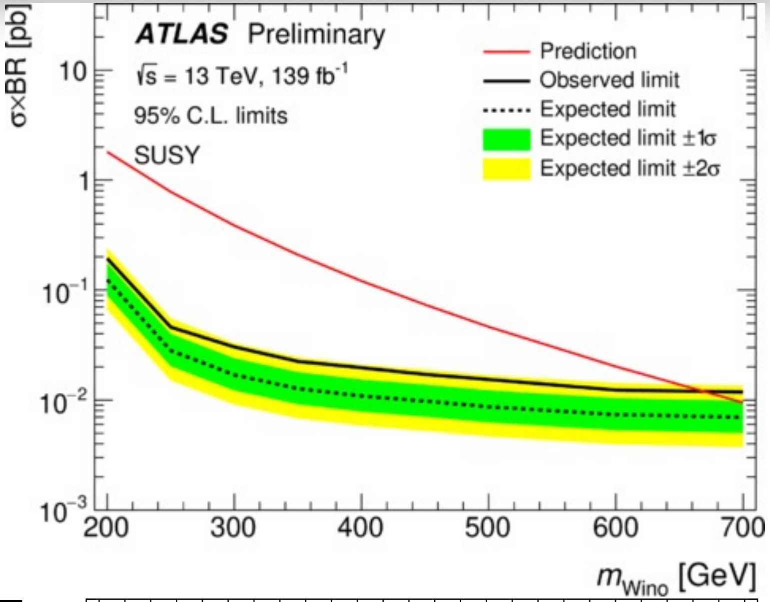
Lepton category	$2\ell SS$	3ℓ	4ℓ
Lepton definition	(T,T) with $\geq 1\ b^{60\%}$ || (T,M) with $\geq 2\ b^{77\%}$	(L,T,M) with $\geq 1\ b^{60\%}$ || (L,M,M) with $\geq 2\ b^{77\%}$	(L,L,L,L)
Lepton p_T [GeV]	(20, 20)	(10, 20, 20)	(10, 10, 10, 10)
$m^{OS-SF}_{\ell^+\ell^-}$ [GeV]	–	>12	
$\lvert m^{OS-SF}_{\ell^+\ell^-} - m_Z \rvert$ [GeV]	–	>10	
N_{jets}	≥ 2		
$N_{b\text{-jets}}$	$\geq 1\ b^{60\%}$ || $\geq 2\ b^{77\%}$		
Region split	(ssst, ttq, ttt, tttq, tttt) $\times (Q^{++}, Q^{--})$	(ttt, tttq, tttt) $\times (Q^{+}, Q^{-})$	–
Region naming	2ℓSS ++ CAT ssst	3ℓ ++ CAT ttt	4ℓ
	2ℓSS ++ CAT ttq	3ℓ ++ CAT tttq	
	2ℓSS ++ CAT ttt	3ℓ ++ CAT tttt	
	2ℓSS ++ CAT tttq	3ℓ −− CAT ttt	
	2ℓSS ++ CAT tttt	3ℓ −− CAT tttq	
	2ℓSS −− CAT ssst	3ℓ −− CAT tttt	
	2ℓSS −− CAT ttq		
	2ℓSS −− CAT ttt		
	2ℓSS −− CAT tttq		
	2ℓSS −− CAT tttt		

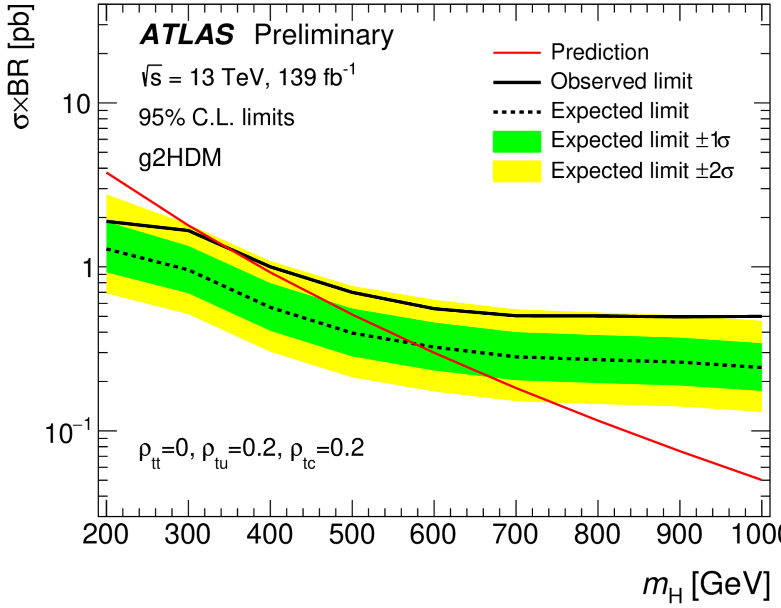
Comparison between data and prediction for the DNN^{SB} for 4leptons category

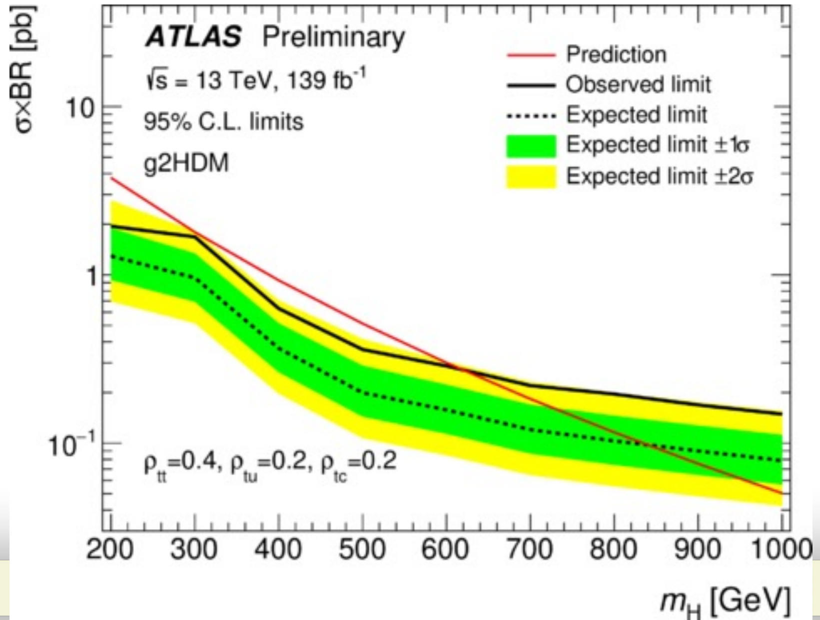


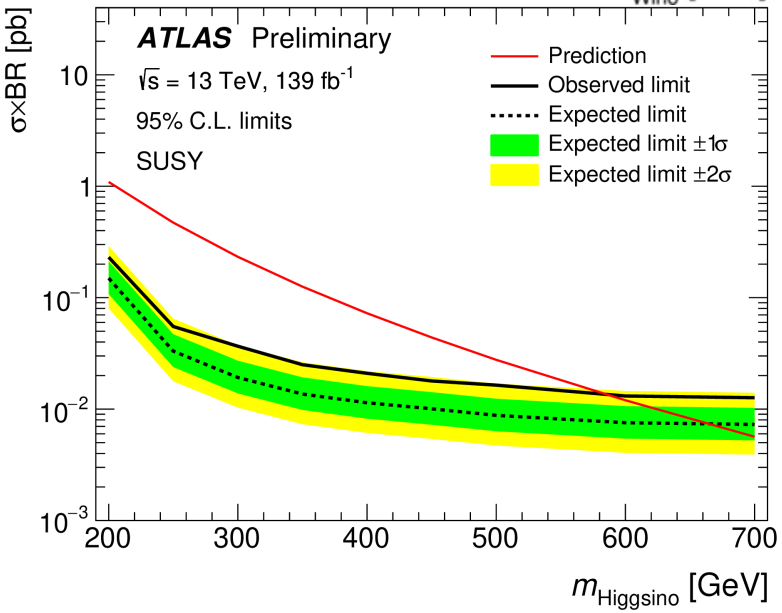
Limits on g2HDM and SUSY models

- Masses of an additional scalar boson m_H **between 200-630** (200-840) GeV with couplings **ρ_{tt}= 0.4, ρ_{tc}=0.2, and ρ_{tu}=0.2** are observed (expected) to be excluded at 95% confidence level.



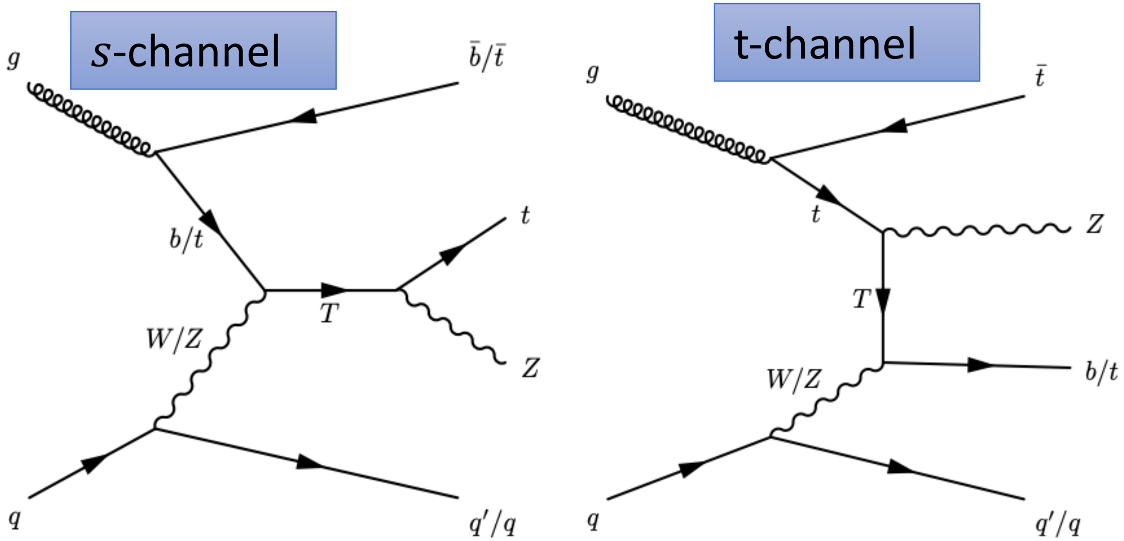






Vector-like Top (VLT)

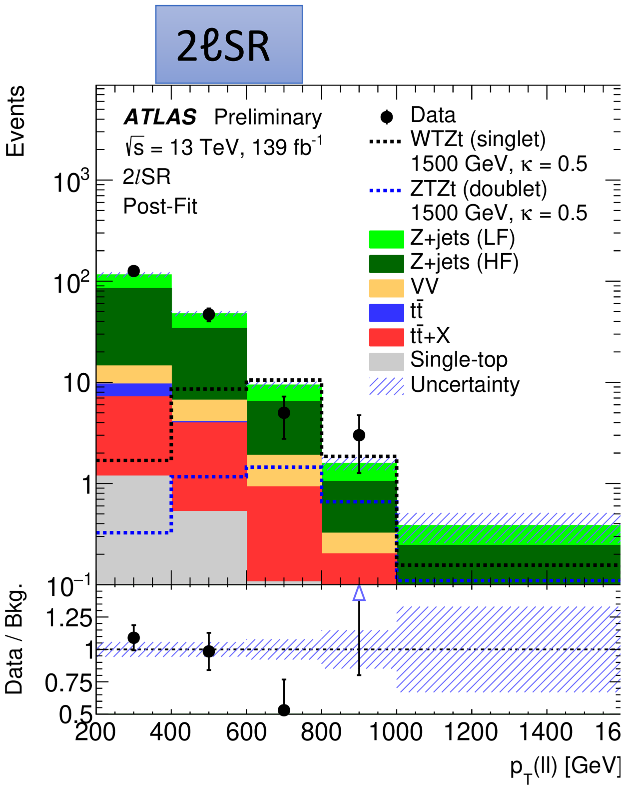
- A number of BSM models predict the existence of **Vector-Like Quarks (VLQs),** as singlets, doublets or triplets. VLQs usually couple to SM quarks - predominantly with the third generation - via an exchange of charged (*W*±) or neutral (*Z*, *H*) bosons
  - Single production of VLQs, unlike pair production, can have a larger cross-section at high masses and is dominated by electroweak processes.

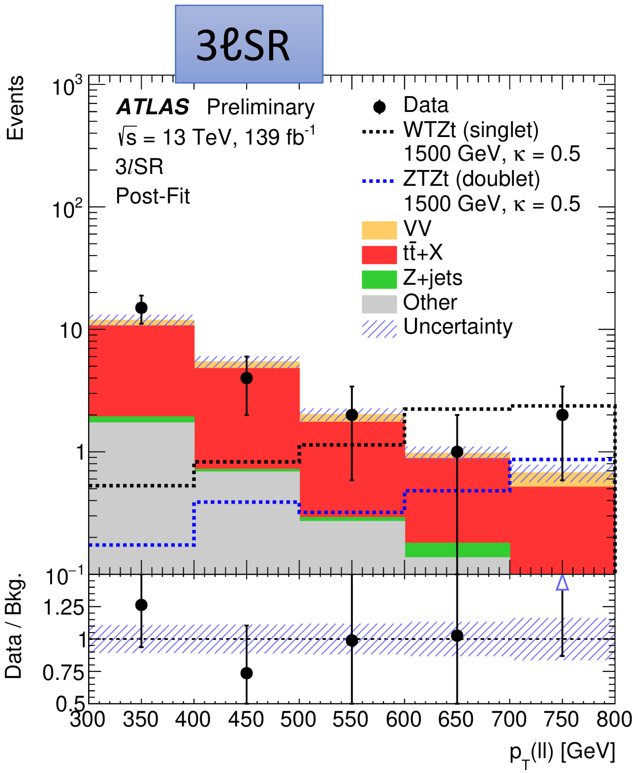


- Search for the **single production of vector-like top partners (T),** with final state containing an opposite-charge pair of electrons or muons (forming a Z boson candidate) and a b-tagged / forward jets.

Event Selection for VLT

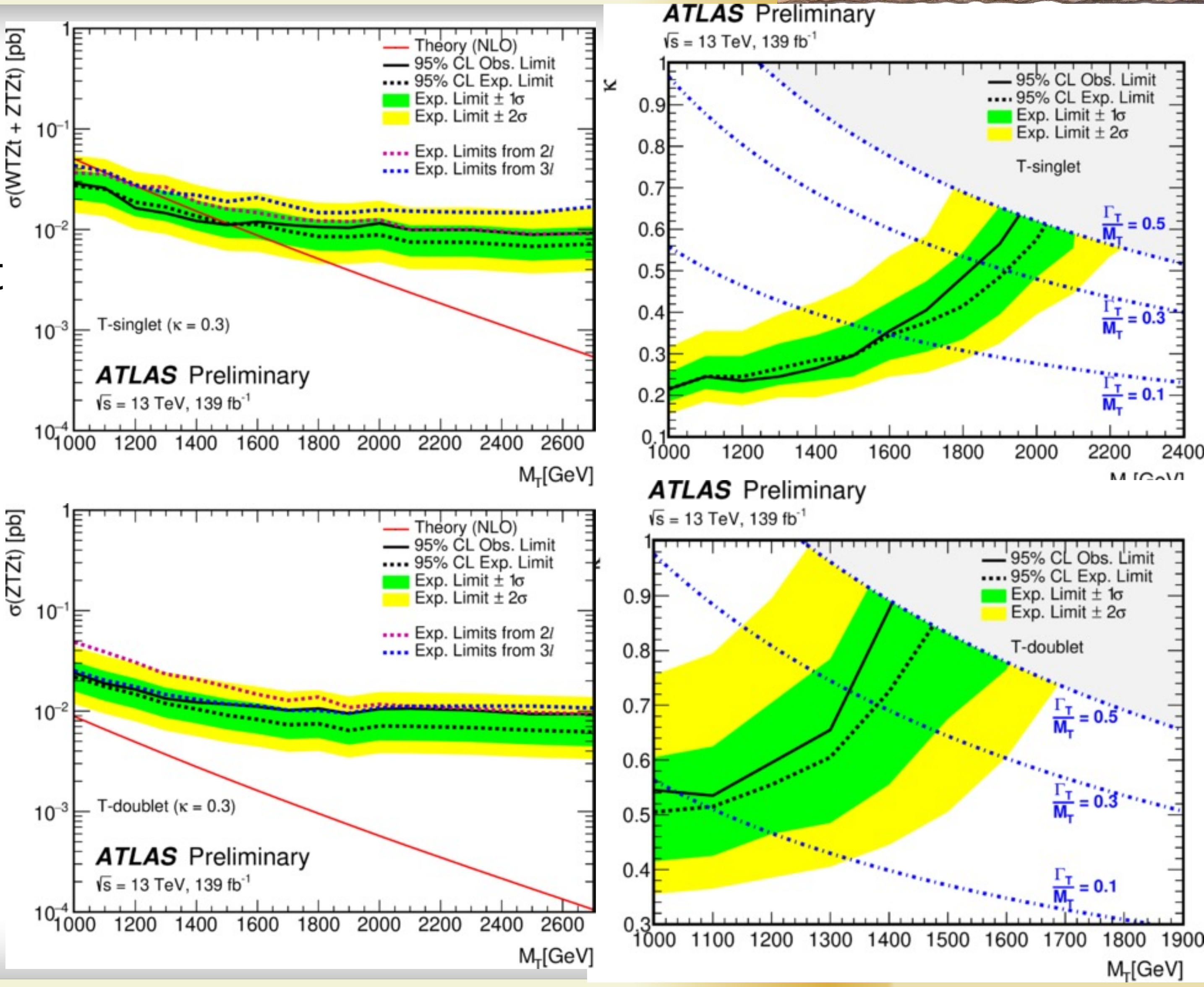
- Event selection
  - a single lepton trigger and OS-SF leptons with invariant mass $m(\ell\ell)$ closest to the mass of the Z.
- Events are categorized into two independently optimized analysis channels:
  - exactly two,
    - Main backgrounds: Z+jets, diboson, tt, $tt + X$
  - at least three leptons.
    - Main backgrounds: diboson, $tt + X$.
- Discriminating observable for both the categories is $p_T(ll)_Z$





Results on VLT

- No significant excess over the predicted background is observed.
- 95% CL limits on excluded masses and coupling strengths **κ** for singlet and doublet representations are provided:
- singlet: **κ** < 0.22 (0.64) for m(T) ~ 1000 (1975) GeV
- doublet: **κ** < 0.54 (0.88) for m(T) ~ 1000 (1425) GeV.



Heavy resonances (R) in $W^+W^- \rightarrow e\nu\mu\nu$

- A search for neutral heavy resonances (R), decaying into two W bosons ($WW \rightarrow e\nu\mu\nu$, either directly or through tau lepton), produced through either gluon-gluon fusion (ggF), quark-antiquark annihilation (qqA), or vector-boson fusion (VBF).

- The results have been compared to 5 different model predictions:

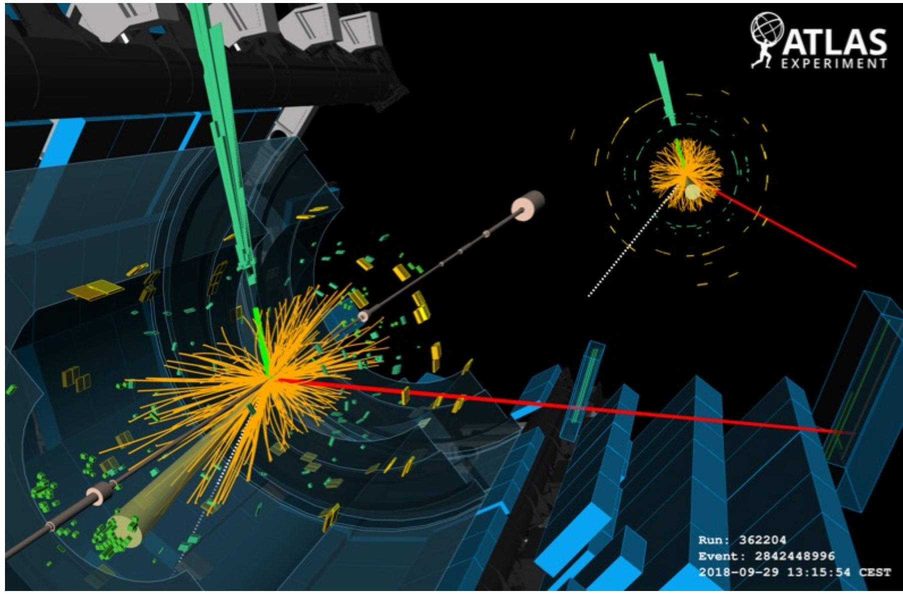
Scalar resonances:

- Higgs like narrow width scalar (NWA),
- Higgs boson in Georgi-Machacek model (GM),
- bulk Randall-Sundrum model

Non-scalar resonances:

- Heavy Vector Triplet (HVT),
- Graviton.

Model	Resonance spin	Production mode		
		ggF	qqA	VBF
NWA	Spin-0	x		x
GM				x
Radion		x		x
HVT	Spin-1		x	x
RS G^*_{KK}	Spin-2	x		x



Production of a heavy neutral particle via VBF. Electron (green), muon (red), jet (yellow cone), large MET (dashed white) with one jet out of the detector acceptance.

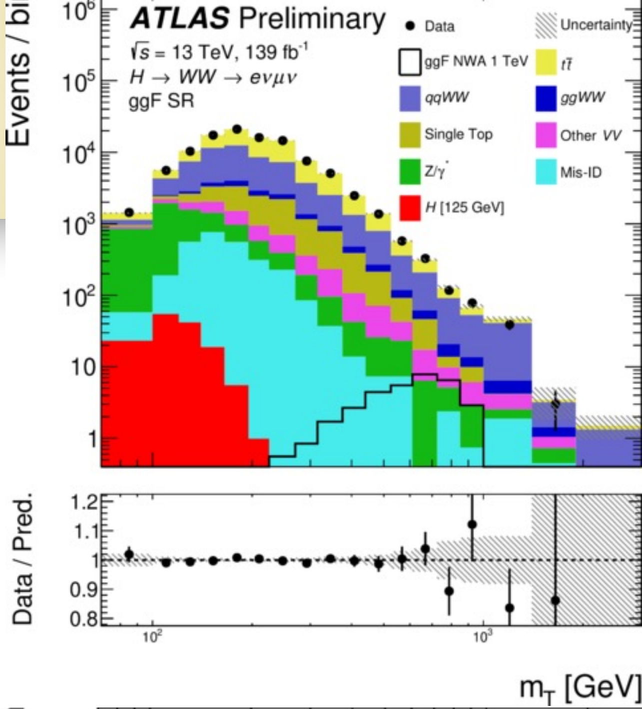
Selection of R → W+W- → eνμν

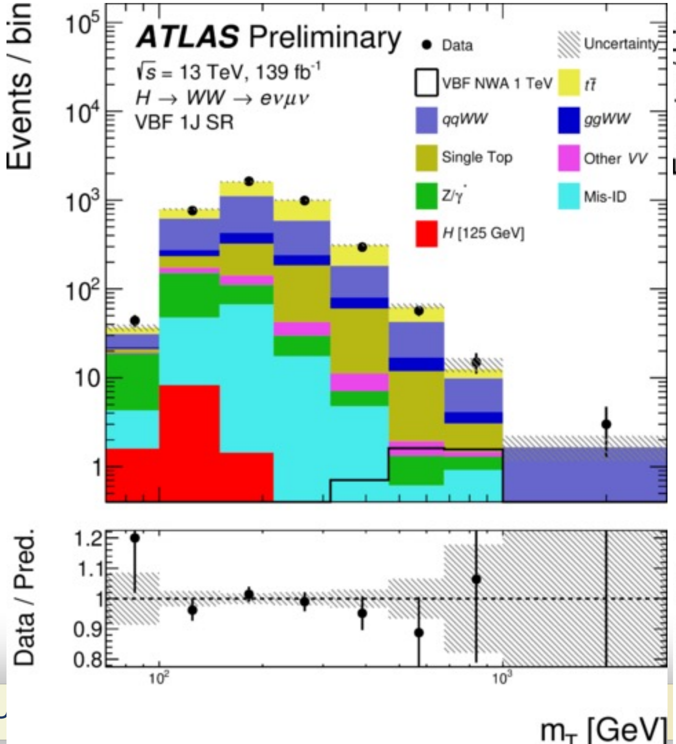
- Events selection:
  - two different flavour, opposite-sign leptons with each p_T > 25 GeV.
  - One lepton must match the lepton that fires the trigger.

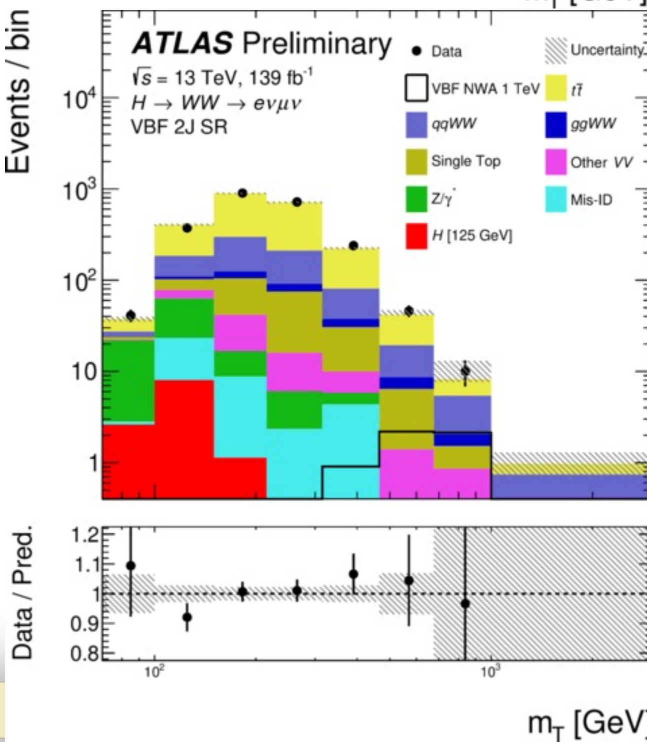
Three categories:
- ggF,
- VBF 1-jet,
- VBF 2-jet

- Backgrounds:
  - **top quarks** (vetoed b-tagged jet),
  - **non-resonant *WW* production.** (MC simulation + reweighing for *tt*),
  - ***W/Z*+jets ,multi-jets** (data driven),
  - **diboson, SM Higgs**
- Discriminating variable is the transverse mass

$$m_T = \sqrt{(E_T^{\ell\ell} + E_T^{\rm miss})^2 - |\vec{p}_T^{\,\ell\ell} + \vec{E}_T^{\rm miss}|^2}$$



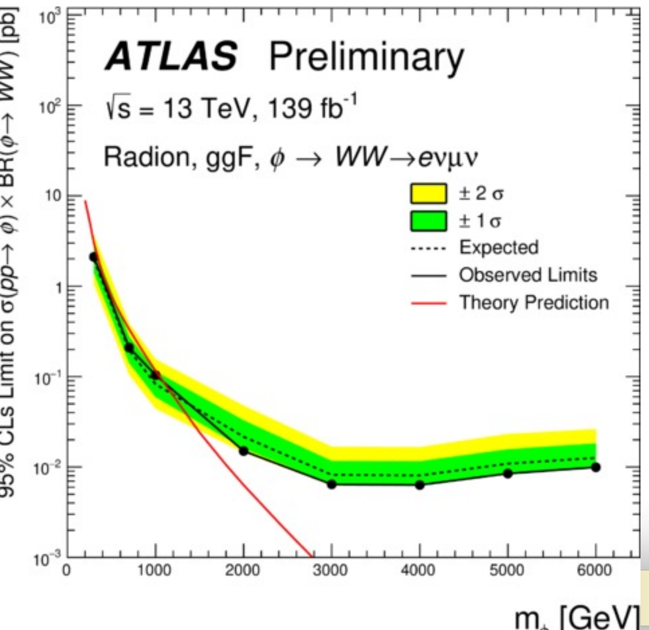


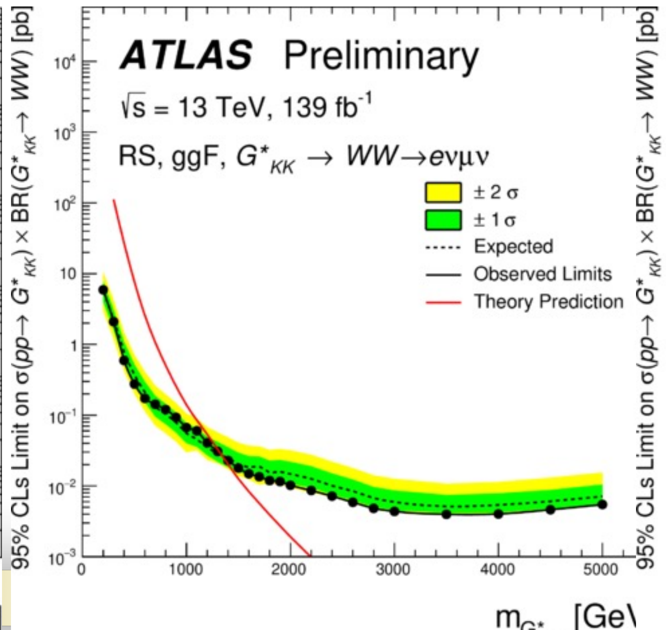


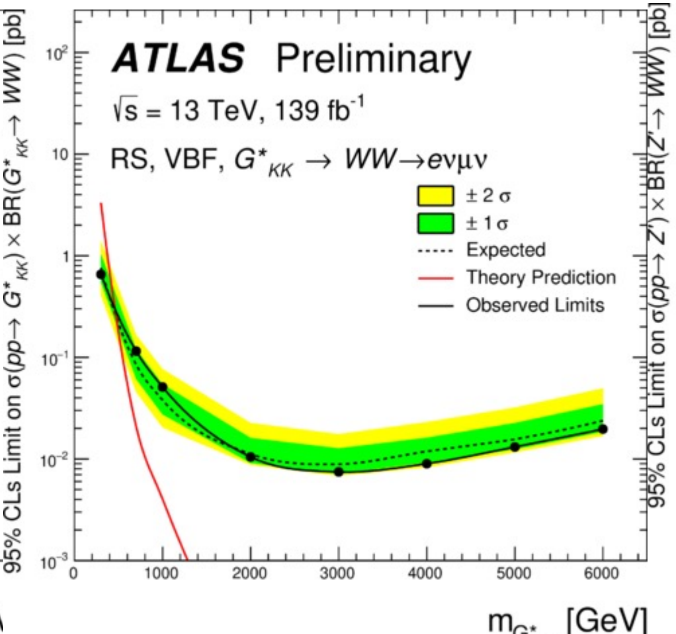
Results on Heavy Resonance R

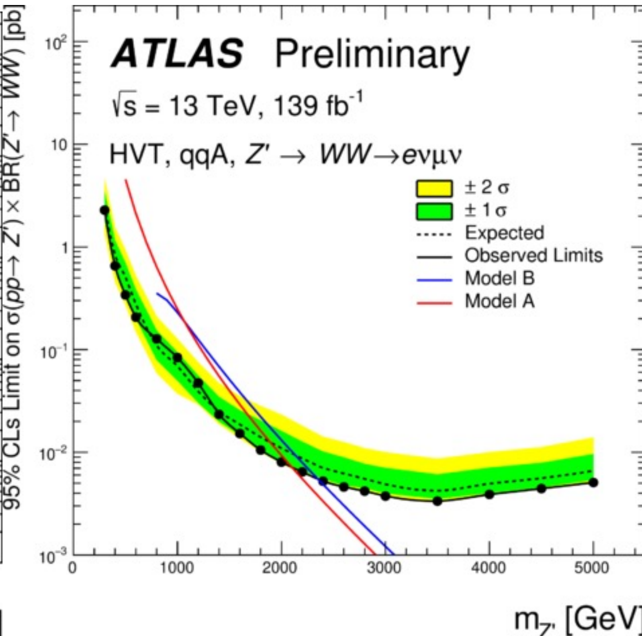
No significant excess is found in the mass range between 200 GeV and 6 TeV

Model	Obs. limit [GeV]	Exp. limit [GeV]
Radion, ggF	1090	1190
Kaluza-Klein graviton, ggF	1340	1340
Kaluza-Klein graviton, VBF	500	500
HVT scenario A, qqA	2100	1890
HVT scenario B, qqA	2350	2130



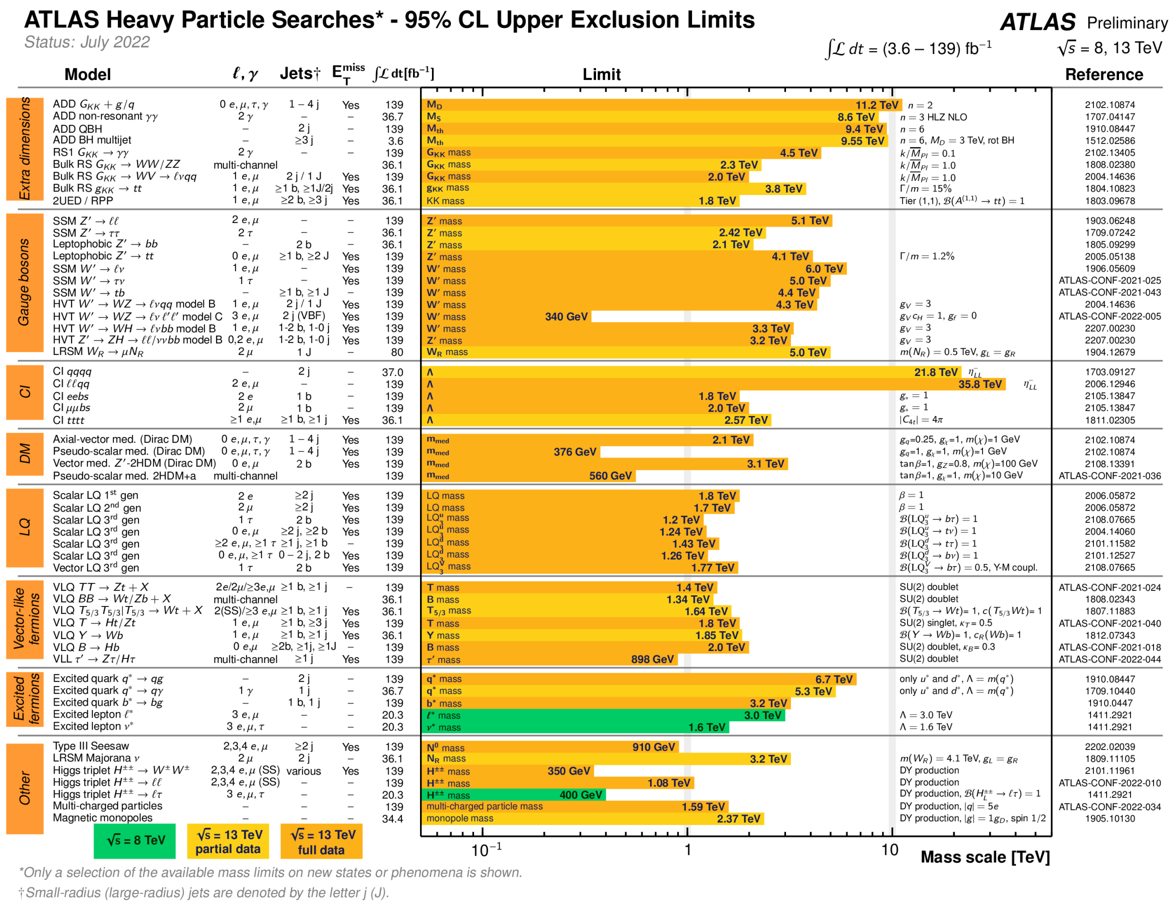






Conclusions

- ATLAS is searching for many final states which would arise from new BSM resonances: no evidence of new physics yet.
- The analyses performed on full Run2 data improved the previous lower/upper limits:
  - new analysis techniques are developed
  - explored new models
- Run 3 is ongoing!



THANKS!

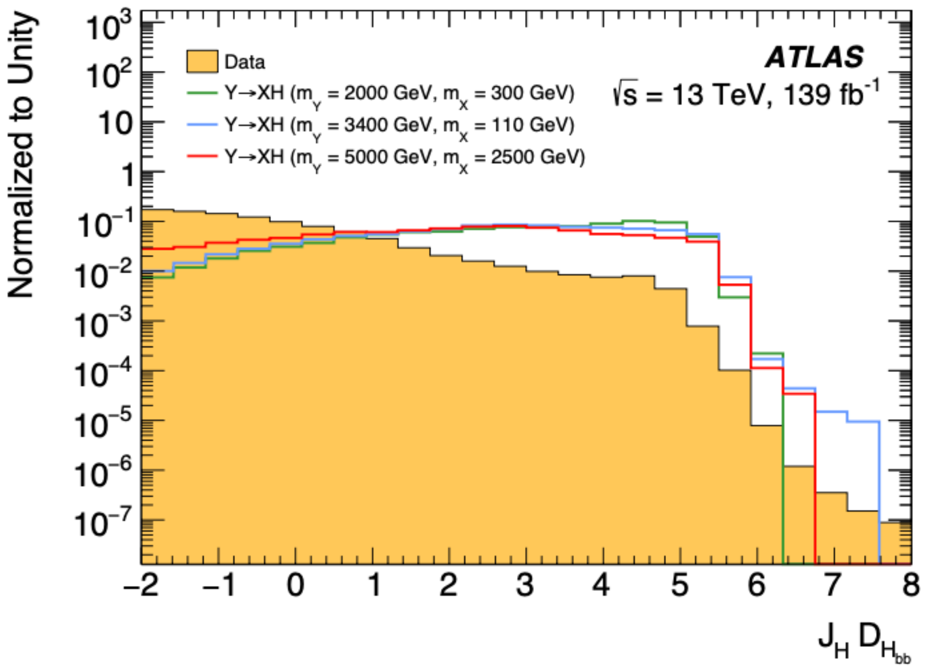
New Resonance Y → XH→qqbb

Distributions of the J_H candidate D_{Hbb} score in data after preselection requirement. Requiring $D_{Hbb} > 2.44$ defines a working point that is 60% efficient for the selection of the boosted $H \to bb$ topology across the full p_T range.

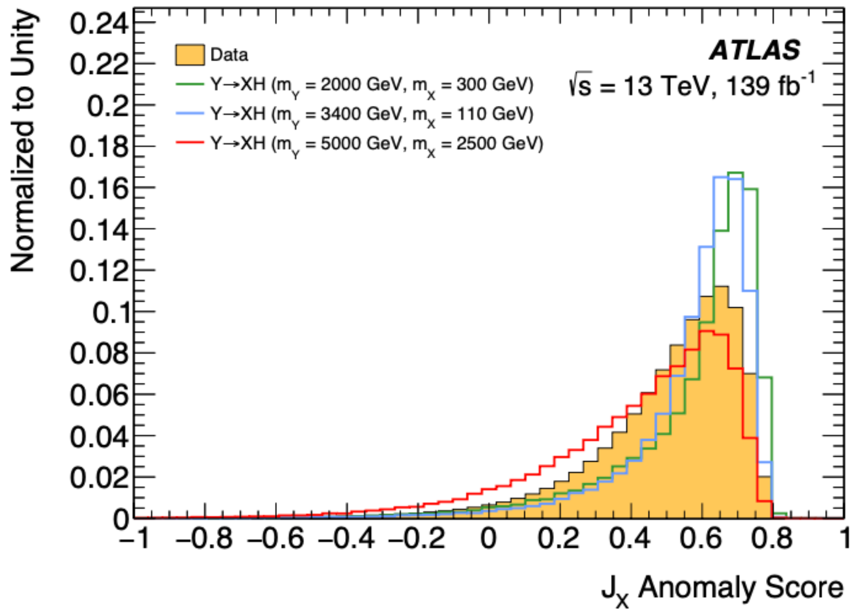
$$D_{H_{bb}} = \ln \frac{P_{\text{Higgs}}}{f_{\text{top}} \cdot P_{\text{top}} + (1 - f_{\text{top}}) \cdot P_{\text{multijet}}},$$

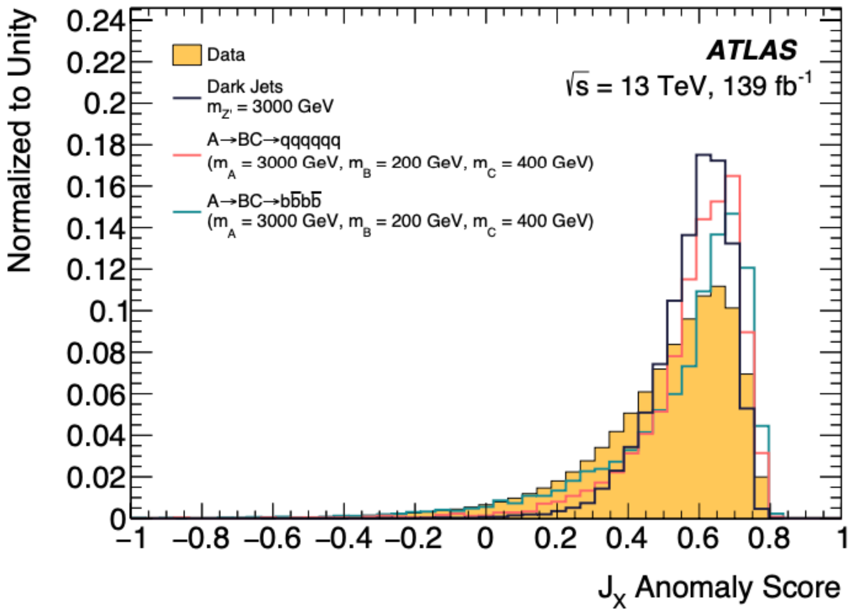
NN weight

P_X = probability of being originated by top, Higgs or multileptons



New Resonance Y → XH→qqbb





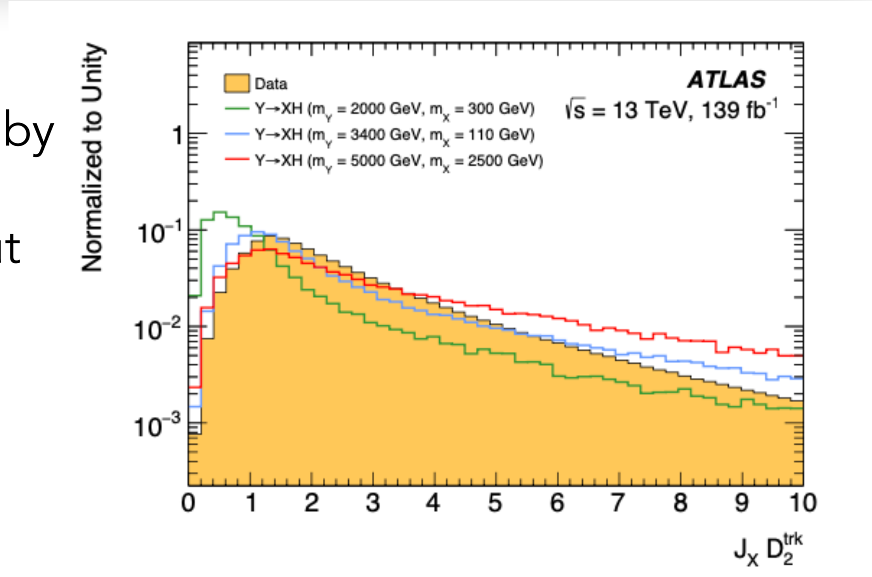
Distributions of the J_X candidate Anomaly Score (S_A) in data after preselection.
A selection $S_A > 0.5$ applied to J_X defines the anomaly analysis category

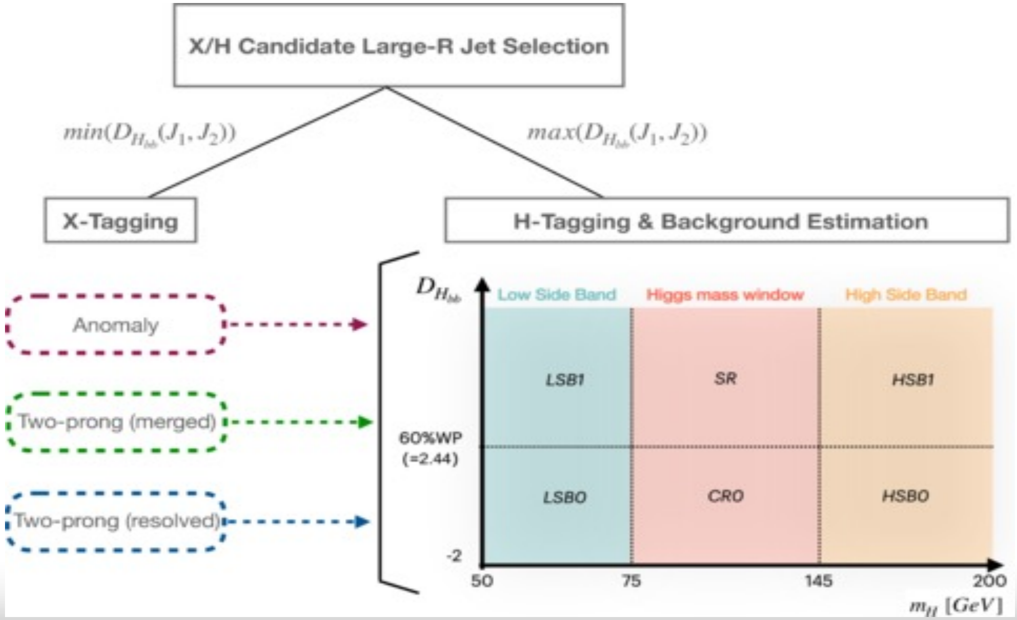
Input consists solely of jets from data, no labeling scheme is used in training, distinguishing this method of unsupervised learning from traditional supervised machine learning, where the input is labeled in signal or background categories.

X-Tagging

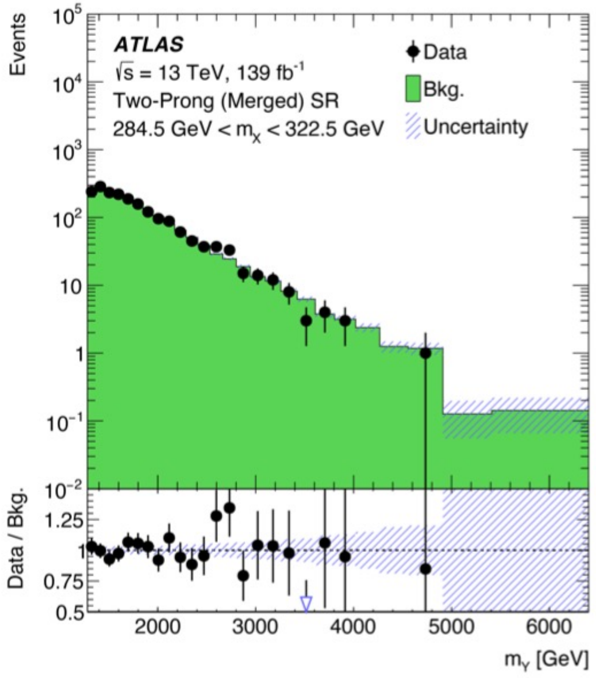
- Sensitivity over the dominant multijet background is enhanced by additional machine-learning applications, namely a NN-based $H \to bb$ tagger and a DNN-based reweighting to ensure good modeling

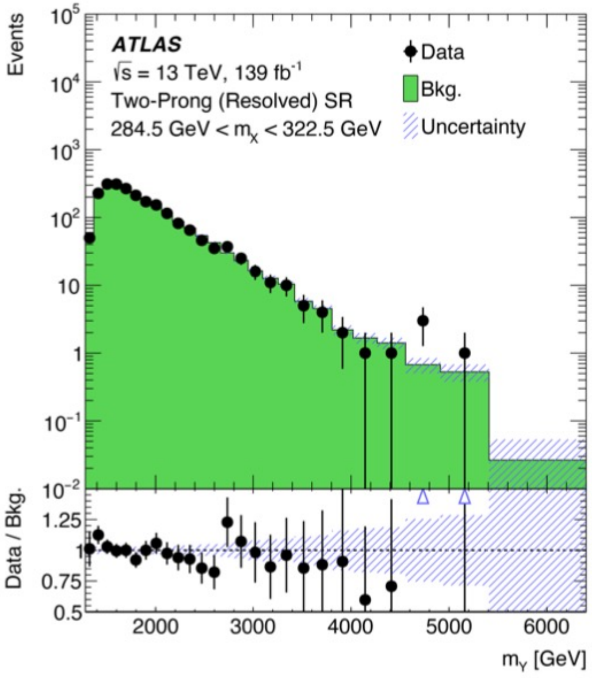
The merged region is defined by applying a selection $D_{\mathrm{trk}} < 1.2$, where D_{trk} is the same as D_2 but computed using only tracks associated with the jet.

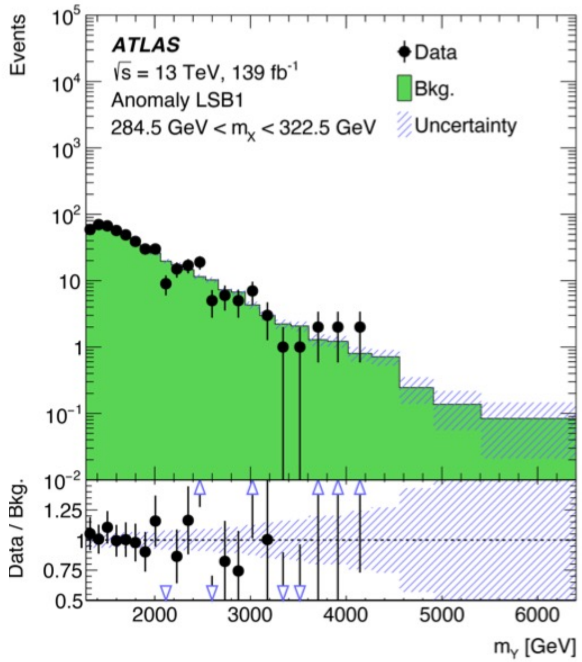


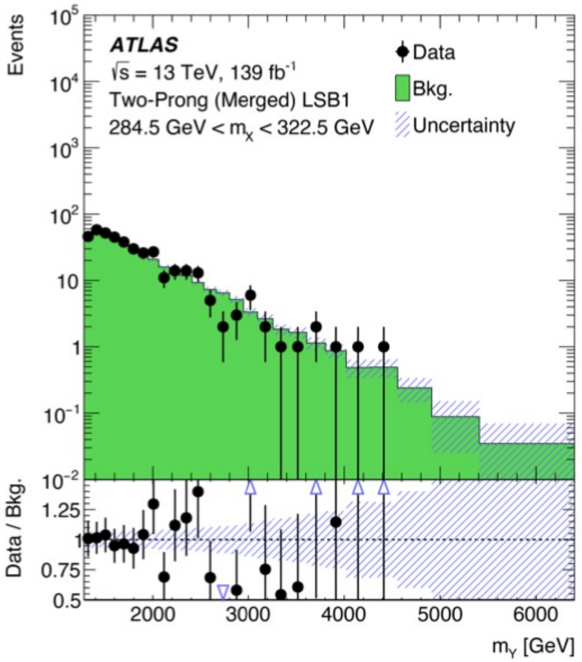


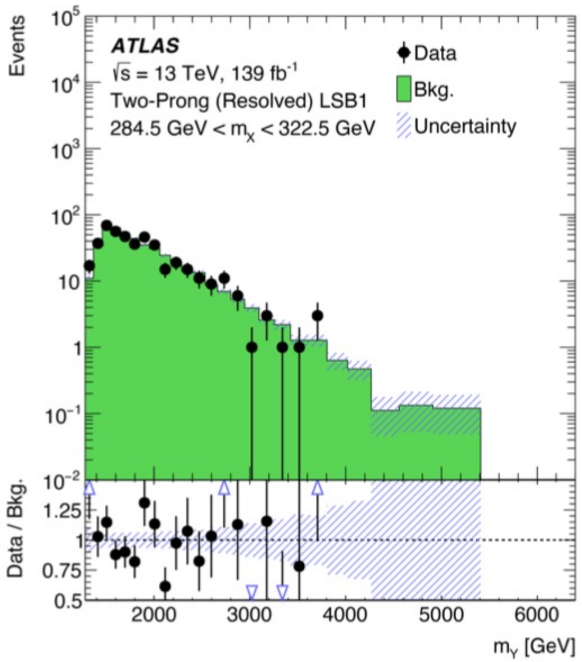
Bump-Hunter


ATLAS
√s = 13 TeV, 139 fb⁻¹
Two-Prong (Merged) SR
284.5 GeV < m_X < 322.5 GeV
Data
Bkg.
Uncertainty
Events
Data / Bkg.
m_Y [GeV]


ATLAS
√s = 13 TeV, 139 fb⁻¹
Two-Prong (Resolved) SR
284.5 GeV < m_X < 322.5 GeV
Data
Bkg.
Uncertainty
Events
Data / Bkg.
m_Y [GeV]

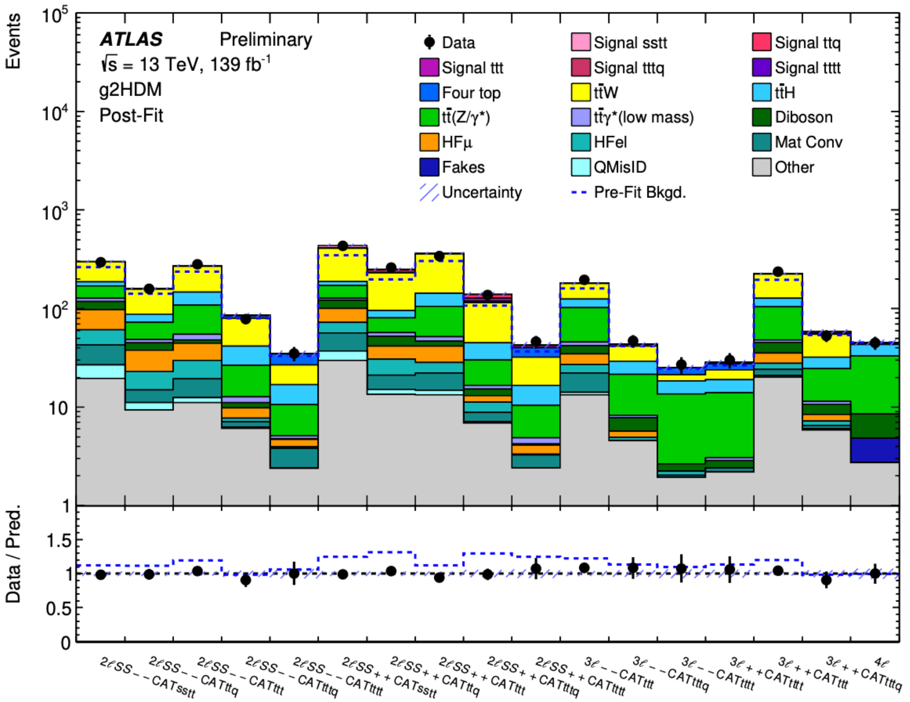

ATLAS
√s = 13 TeV, 139 fb⁻¹
Anomaly LSB1
284.5 GeV < m_X < 322.5 GeV
Data
Bkg.
Uncertainty
Events
Data / Bkg.
m_Y [GeV]

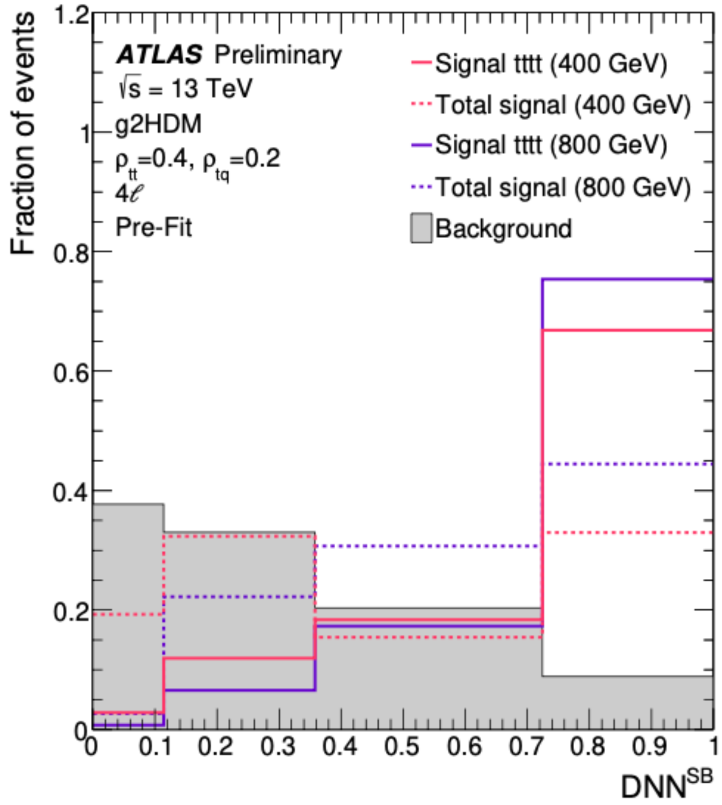

ATLAS
√s = 13 TeV, 139 fb⁻¹
Two-Prong (Merged) LSB1
284.5 GeV < m_X < 322.5 GeV
Data
Bkg.
Uncertainty
Events
Data / Bkg.
m_Y [GeV]


ATLAS
√s = 13 TeV, 139 fb⁻¹
Two-Prong (Resolved) LSB1
284.5 GeV < m_X < 322.5 GeV
Data
Bkg.
Uncertainty
Events
Data / Bkg.
m_Y [GeV]

g2HDM

Variable	DNN^{cat}	DNN^{SB}
Number of jets (N_{jets})	✓	✓
Sum of pseudo-continuous b-tagging scores of jets	✓	✓
Pseudo-continuous b-tagging score of 1st, 2nd, 3rd leading jet in p_T	✓	✓
Sum of p_T of the jets and leptons ($H_{T,jets}$, $H_{T,lep}$)	✓	✓
Angular distance of leptons (sum in the case of 3ℓ and 4ℓ)	✓	✓
Missing transverse energy	✓	✓
Leading transverse momentum of jet	-	✓
Invariant mass of leading lepton and missing transverse energy	-	✓
Di/tri/quad-lepton type variable (associated to the number of electrons/muons in event)	-	✓





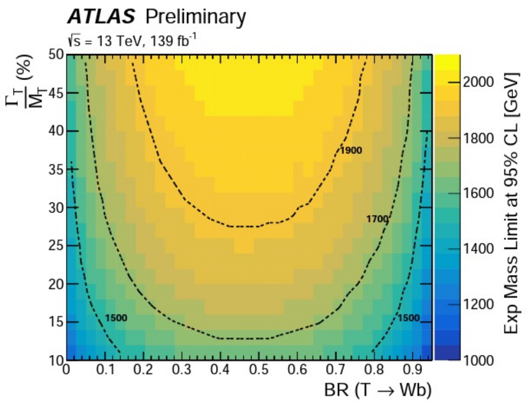
VLT

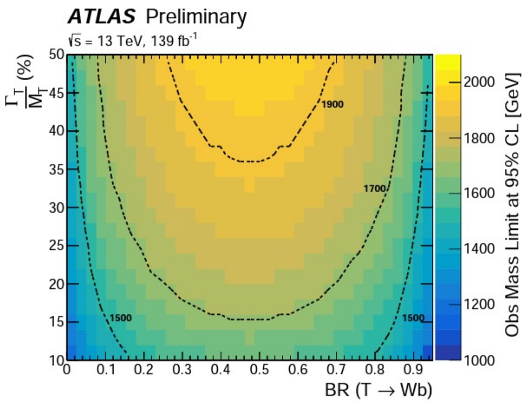
- Selection Criteria for the different SR and CR, VR

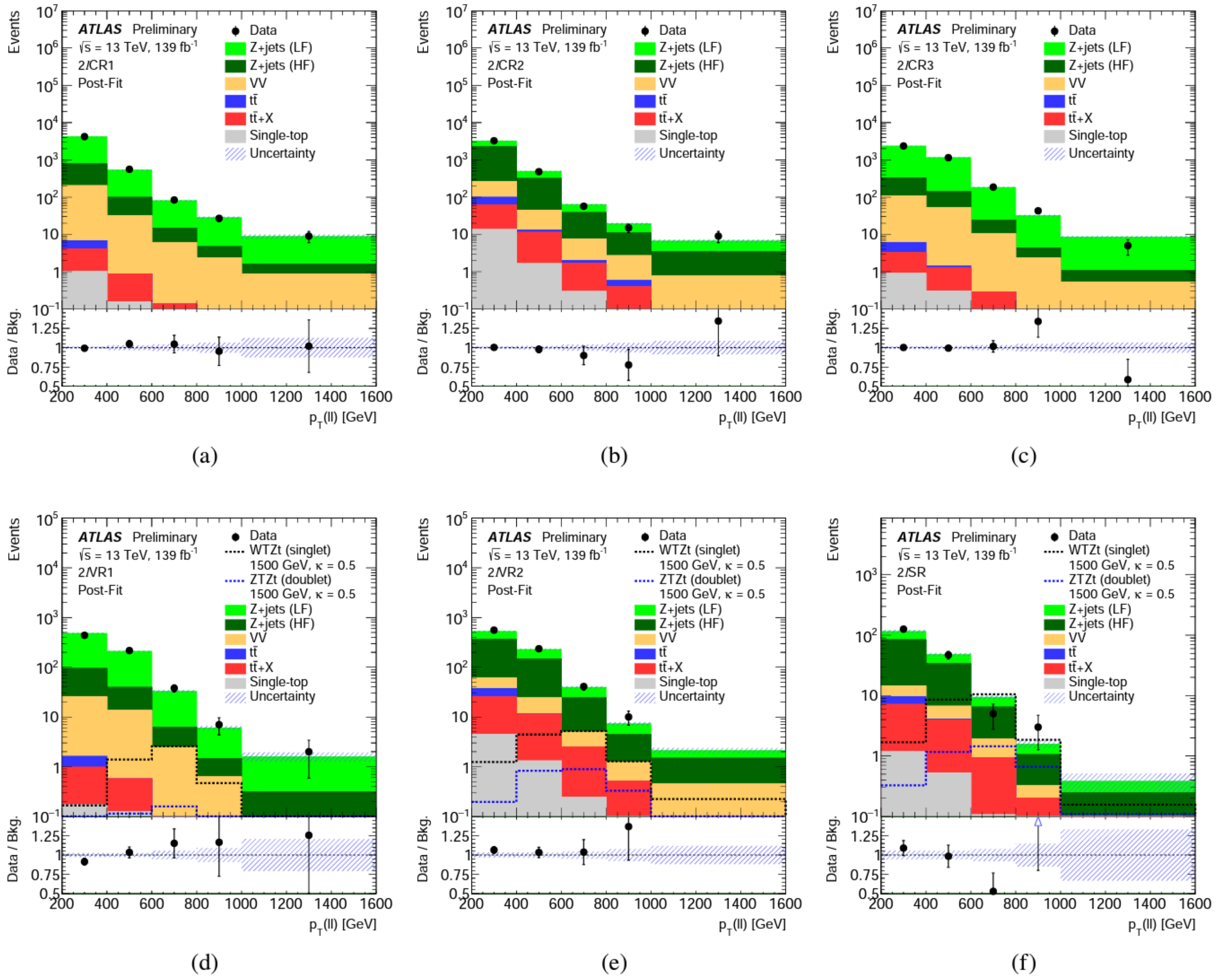
	2ℓCR1	2ℓCR2	2ℓCR3	2ℓVR1	2ℓVR2	2ℓSR
Preselection	1 pair of OS-SF leptons with $\lvert m(\ell\ell) - m_Z \rvert < 10$ GeV $p_{\mathrm{T}}(\ell\ell) > 200$ GeV, $H_{\mathrm{T}} > 300$ GeV ≥ 1 vRC jet $H_{\mathrm{T}} + E_{\mathrm{T}}^{\mathrm{miss}} < m_{\ell\ell J}$					
forward jets	≥ 1	0	0	≥ 1	0	≥ 1
b-tagged jets	0	≥ 1	0	0	≥ 1	≥ 1
top-tagged jets	-	-	≥ 1	≥ 1	≥ 1	≥ 1
top-vetoed jets	≥ 1	≥ 1	-	-	-	-

	3ℓVV	3ℓMixed	3ℓttX	3ℓVR	3ℓSR
Preselection	≥ 3 leptons ≥ 1 pair of OS-SF leptons with $\lvert m(\ell\ell) - m_Z \rvert < 10$ GeV				
b-tagged jets	0	1	≥ 2	≥ 1	≥ 1
forward jets	-	0	0	≥ 1	≥ 1
$\Delta\phi$ selections	-	$\Delta\phi(Z, \ell_3) < 2.6$	$\Delta\phi(Z, \ell_3) < 2.6$	$\Delta\phi(Z, \ell_3) < \frac{\pi}{2}$ **OR** $\Delta\phi(Z, b_{\mathrm{lead}}) < \frac{\pi}{2}$	$\Delta\phi(Z, \ell_3) > \frac{\pi}{2}$ **AND** $\Delta\phi(Z, b_{\mathrm{lead}}) > \frac{\pi}{2}$
other selections	-	-	-	-	$\max(p_{\mathrm{T}}(\ell)) > 200$ GeV $p_{\mathrm{T}}(\ell\ell) > 300$ GeV $H_{\mathrm{T}} \cdot n(\mathrm{jets}) < 6$ TeV

VLT







Excluded top partner mass as a function of its relative decay width and branching ratio to the W channel

$W^+W^- \to e\nu\mu\nu$

- Event Selection

Pre-Selection		
Two Different Flavour, Opposite Sign Leptons, $p_T^\ell > 25$ GeV Third lepton veto, $p_T^\ell > 15$ GeV		
Common Selection		
$N_{b-\text{tag}} = 0$ $\lvert\Delta\eta_{\ell\ell}\rvert < 1.8$ $m_{\ell\ell} > 55$ GeV $p_T^{\ell,\text{lead}} > 45$ GeV $p_T^{\ell,\text{sublead}} > 30$ GeV $\max(m_T^W) > 50$ GeV		
SC_{ggF}	SC_{VBF1J}	SC_{VBF2J}
Inclusive in N_{jet} but excluding SC_{VBF1J} and SC_{VBF2J}	$N_{\text{jet}} = 1$ and $\lvert\eta_j\rvert > 2.4$, $\min(\lvert\Delta\eta_{j\ell}\rvert) > 1.75$	$N_{\text{jet}} \geq 2$ and $m_{jj} > 500$ GeV, $\lvert\Delta y_{jj}\rvert > 4$

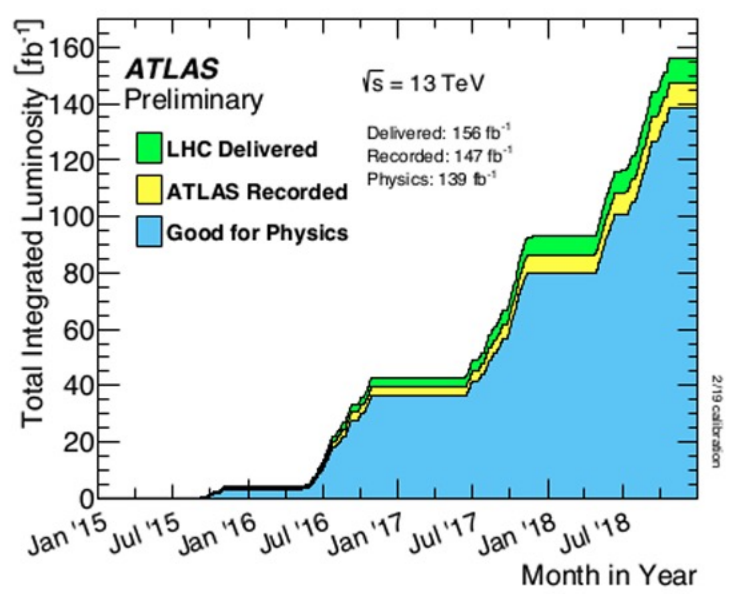
Pre-Selection			
Two Different Flavour, Opposite Sign Leptons, $p_T^\ell > 25$ GeV Third lepton veto, $p_T^\ell > 15$ GeV			
WW CR_{ggF}	Top CR_{ggF}	WW CR_{VBF1J}	Top CR_{VBF}
$N_{b-\text{tag}} = 0$	$N_{b-\text{tag}} = 1$	$N_{b-\text{tag}} = 0$	$N_{b-\text{tag}} \geq 1$
$\lvert\Delta\eta_{\ell\ell}\rvert > 1.8$	$\lvert\Delta\eta_{\ell\ell}\rvert < 1.8$	$(\lvert\Delta\eta_{\ell\ell}\rvert > 1.8$ or	$\lvert\Delta\eta_{\ell\ell}\rvert < 1.8$
$m_{\ell\ell} > 55$ GeV		10 GeV $< m_{\ell\ell} < 55$ GeV$)$	$m_{\ell\ell} > 55$ GeV
$p_T^{\ell,\text{lead}} > 45$ GeV		–	$p_T^{\ell,\text{lead}} > 45$ GeV
$p_T^{\ell,\text{sublead}} > 30$ GeV		–	$p_T^{\ell,\text{sublead}} > 30$ GeV
$\max(m_T^W) > 50$ GeV		–	$\max(m_T^W) > 50$ GeV
METSigRatio > 0.8 GeV^{-1}	–	–	
Excluding VBF1/2J phase space		VBF1J phase space	VBF1/2J phase space

Table 3: Summary of all the selections used in the ggF and VBF WW and top-quark control regions.

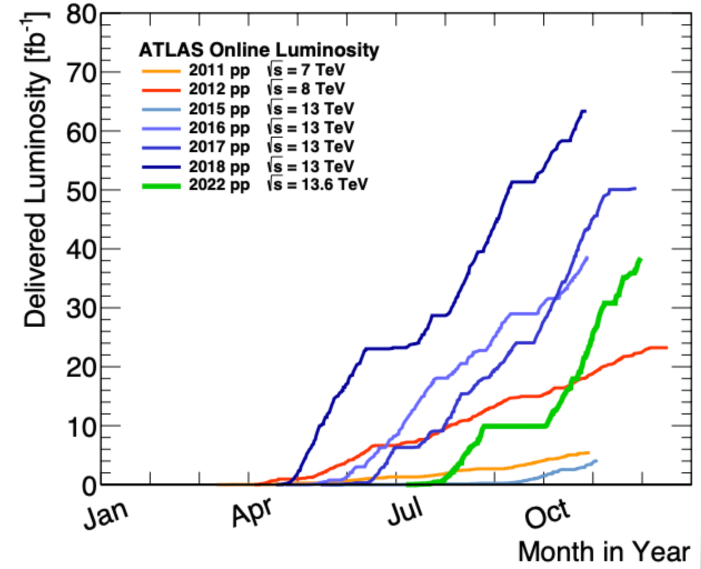
Systematics

ggF Production		VBF Production	
Systematic Source	Impact (%)	Systematic Source	Impact (%)
$m_H = 300$ GeV			
Flavour tagging: b-jets	11	WW QCD Scale	14
WW QCD Scale	10	Wt Shower	12
JES: b-jets	9	Wt Matrix Element	10
Floating Normalizations: WW	8.77	JES: Pile-up μ Offset	7.97
Data stat. uncertainty	9	Data stat. uncertainty	16
Total Syst. uncertainty	33	Total Syst. uncertainty	40
$m_H = 1000$ GeV			
WW Shower: Recoil	6	WW Scale	4
e fake factor stat. uncertainty	5	Wt Shower	3.4
Wt Interference	5	WW Shower: CKKW	3.4
WW QCD Scale	4	$t\bar{t}$ Final-state Rad.	2.9
Data stat. uncertainty	17	Data stat. uncertainty	25
Total Syst. uncertainty	20	Total Syst. uncertainty	10
$m_H = 3000$ GeV			
WW Shower: Recoil	20	WW Scale: QSF	7
WW Scale: QSF	19	WW Shower: Recoil	6
WW Shower: CKKW	16	WW Shower: CKKW	5
Wt Interference	7	Floating Normalizations: WW	1
Data stat. uncertainty	22	Data stat. uncertainty	18
Total Syst. uncertainty	21	Total Syst. uncertainty	15

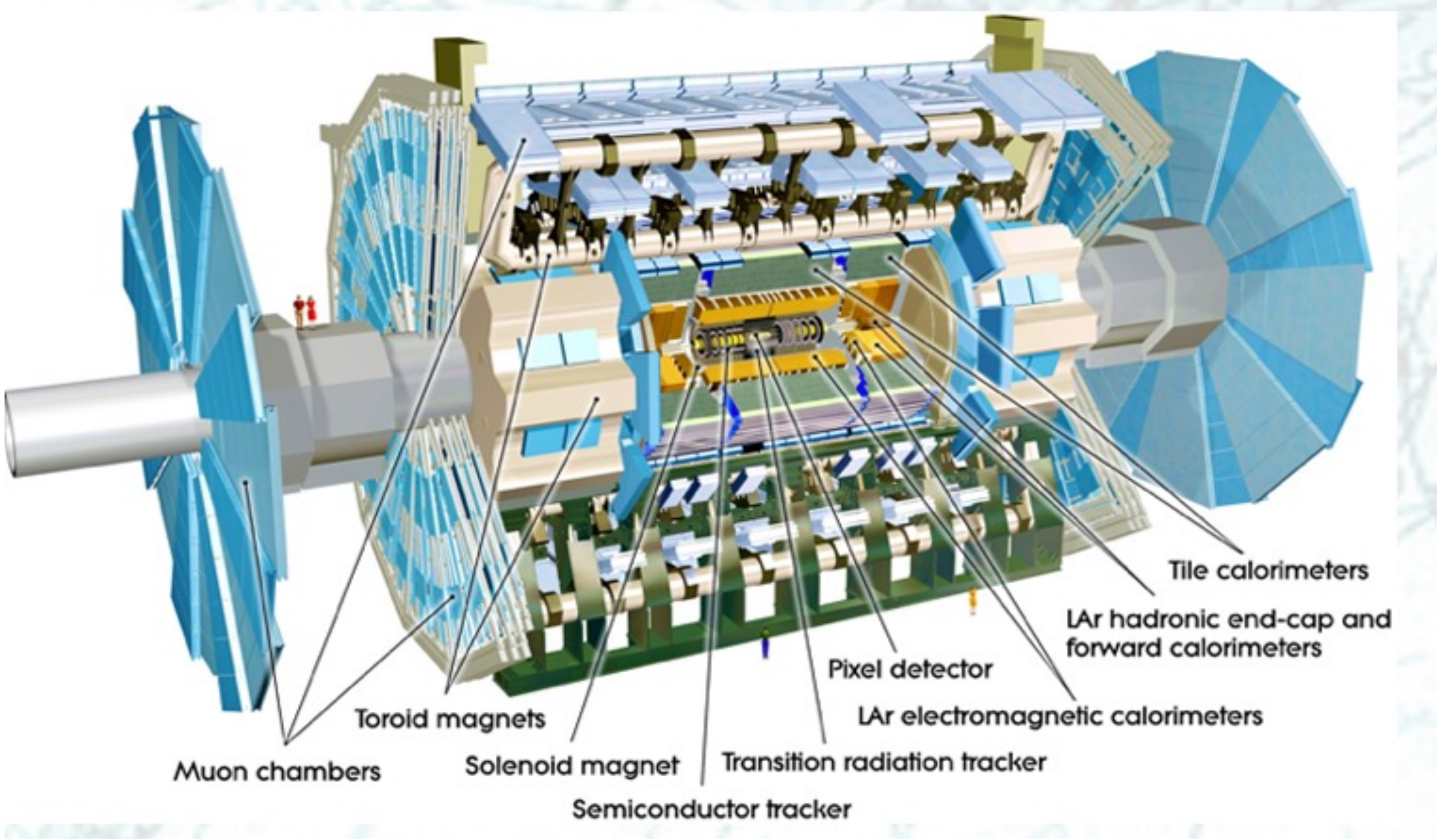
ATLAS



ATLAS
Preliminary
√s = 13 TeV
LHC Delivered
ATLAS Recorded
Good for Physics
Delivered: 156 fb^{-1}
Recorded: 147 fb^{-1}
Physics: 139 fb^{-1}
Total Integrated Luminosity [fb^{-1}]
Jan '15 Jul '15 Jan '16 Jul '16 Jan '17 Jul '17 Jan '18 Jul '18
Month in Year
2/19 calibration

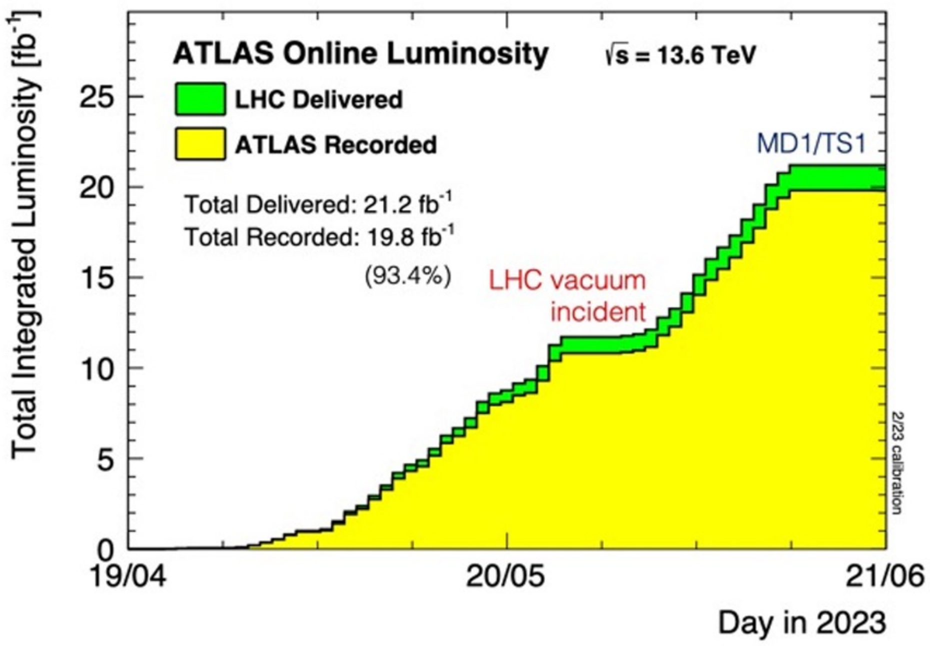


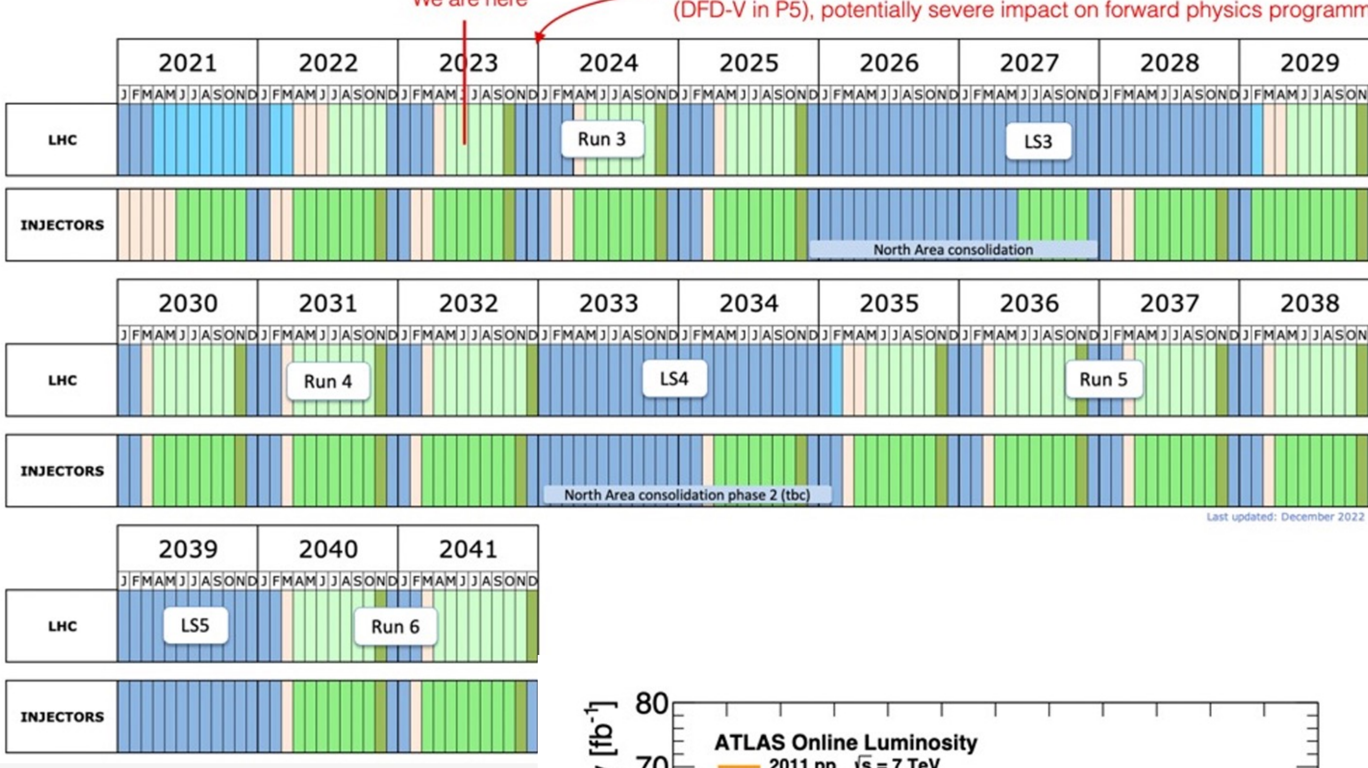
ATLAS Online Luminosity
2011 pp √s = 7 TeV
2012 pp √s = 8 TeV
2015 pp √s = 13 TeV
2016 pp √s = 13 TeV
2017 pp √s = 13 TeV
2018 pp √s = 13 TeV
2022 pp √s = 13.6 TeV
Delivered Luminosity [fb^{-1}]
Jan Apr Jul Oct
Month in Year

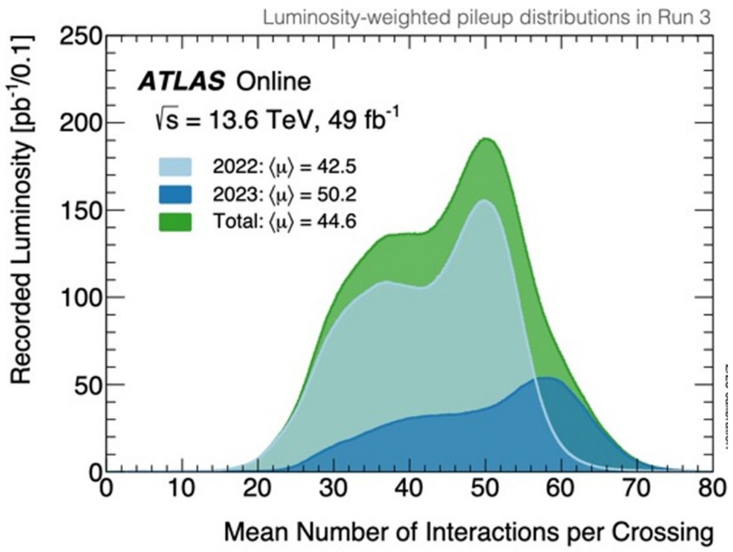


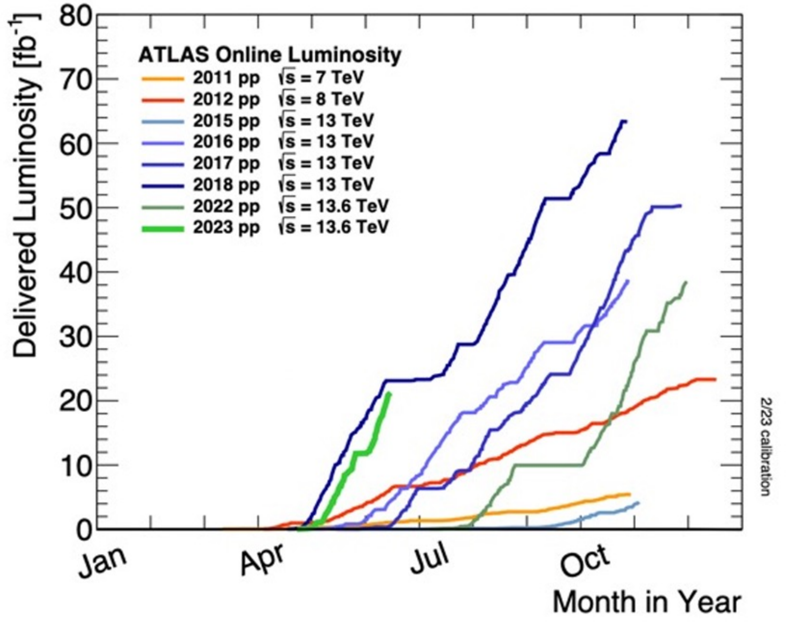
Tile calorimeters
LAr hadronic end-cap and forward calorimeters
Pixel detector
LAr electromagnetic calorimeters
Toroid magnets
Muon chambers
Solenoid magnet
Transition radiation tracker
Semiconductor tracker

Run3


ATLAS Online Luminosity
√s = 13.6 TeV
LHC Delivered
ATLAS Recorded
Total Delivered: 21.2 fb^{-1}
Total Recorded: 19.8 fb^{-1}
(93.4%)
LHC vacuum incident
MD1/TS1
2/23 calibration
Total Integrated Luminosity [fb^{-1}]
19/04
20/05
21/06
Day in 2023


(DFD-V in P5), potentially severe impact on forward physics
2021 2022 2023 2024 2025 2026 2027 2028 2029
LHC
INJECTORS
Run 3
LS3
North Area consolidation
2030 2031 2032 2033 2034 2035 2036 2037 2038
Run 4
LS4
Run 5
North Area consolidation phase 2 (tbc)
Last updated: December 2022
2039 2040 2041
LS5
Run 6


Luminosity-weighted pileup distributions in Run 3
ATLAS Online
√s = 13.6 TeV, 49 fb^{-1}
2022: ⟨μ⟩ = 42.5
2023: ⟨μ⟩ = 50.2
Total: ⟨μ⟩ = 44.6
Recorded Luminosity [pb^{-1}/0.1]
Mean Number of Interactions per Crossing


ATLAS Online Luminosity
2011 pp √s = 7 TeV
2012 pp √s = 8 TeV
2015 pp √s = 13 TeV
2016 pp √s = 13 TeV
2017 pp √s = 13 TeV
2018 pp √s = 13 TeV
2022 pp √s = 13.6 TeV
2023 pp √s = 13.6 TeV
Delivered Luminosity [fb^{-1}]
Jan
Apr
Jul
Oct
Month in Year
2/23 calibration