ATLAS and the search for VV Resonances

$[H, A, G^*, W', Z', X] \rightarrow VV$

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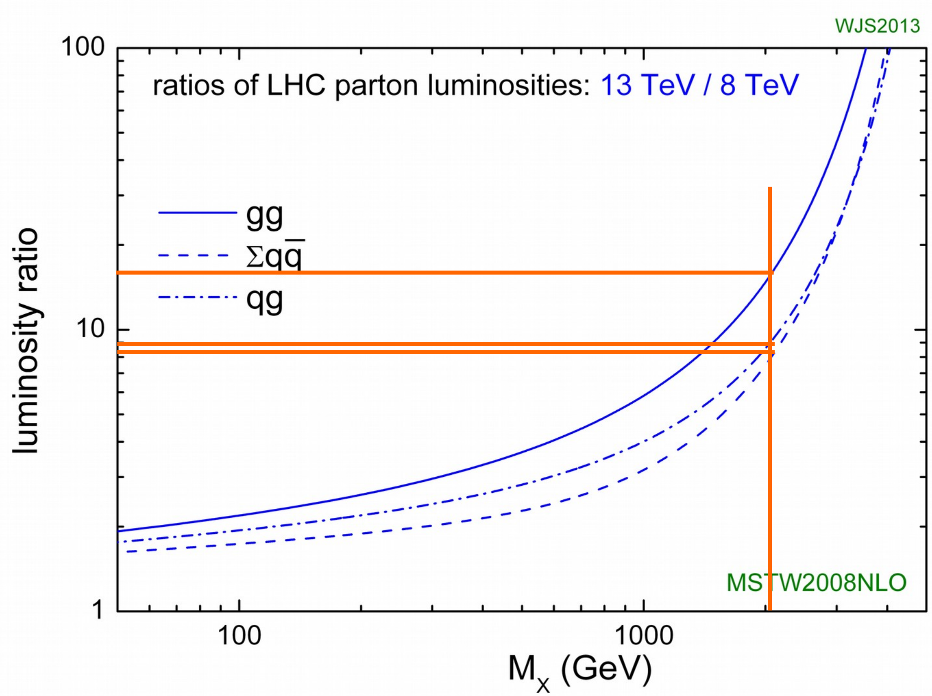
New Physics Interpretations @ the LHC
Argonne National Laboratory
May 2nd, 2016

Introduction

New opportunities for discovery at 13 TeV, especially at high mass

- *Cross sections increase by large factors with respect to Run 1*
- *Continue Run 1 searches for high-mass diboson (WW, WZ, ZZ) resonances*
  - **Large focus** on "merged"/boosted regime (high mass)
    - Use all hadronic + semi-leptonic channels: ***qqqq***, ***lvqq***, ***llqq***, ***vvqq***
      - *Hadronic W/Z reconstructed with single large-R jet*
  - ***At lower masses***
    - *Leptonic channels are more important/sensitive:*
      - *llll, vvll, lvlv, [lvll]*
  - **Where possible:** combine channels in a common likelihood to extend sensitivity

Focus today



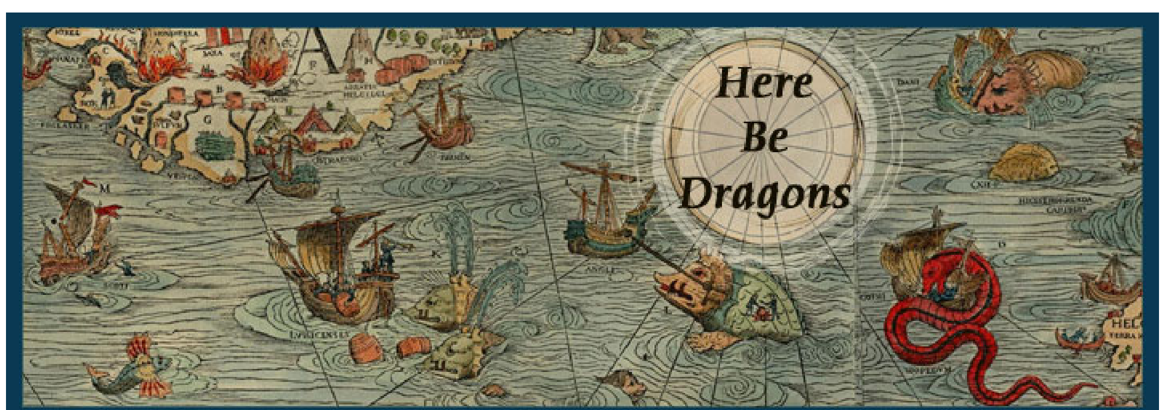
Outline

A) Run-1 recap (*Motivation?*)

B) Run-II

- *Signal Models*
- *Boosted Channels (semi-leptonic + hadronic)*
  - Boosted boson tagging interlude

C) Combination + Model dependence (*Discussion*)

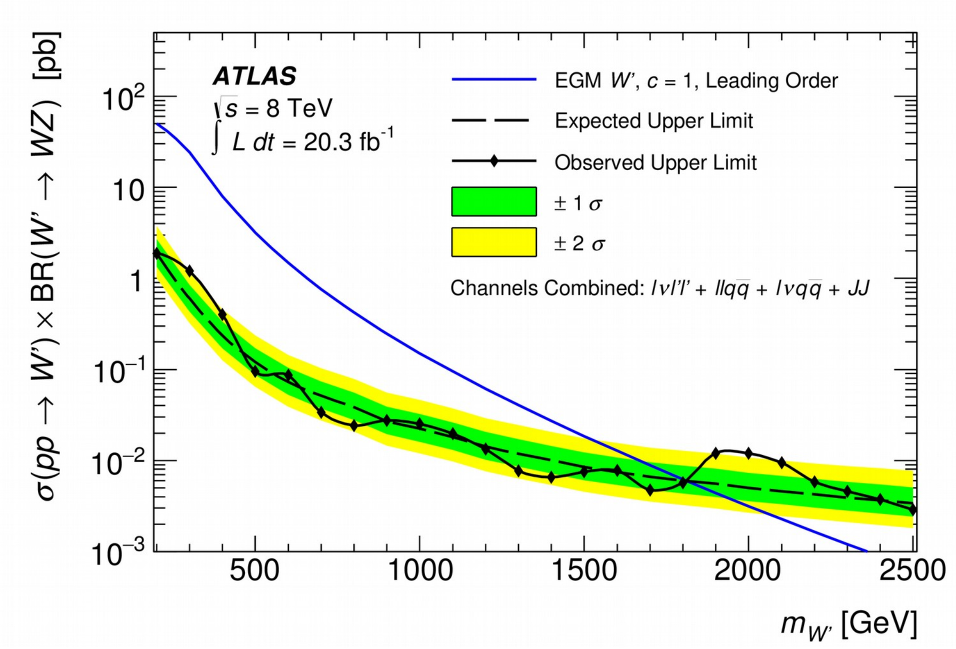


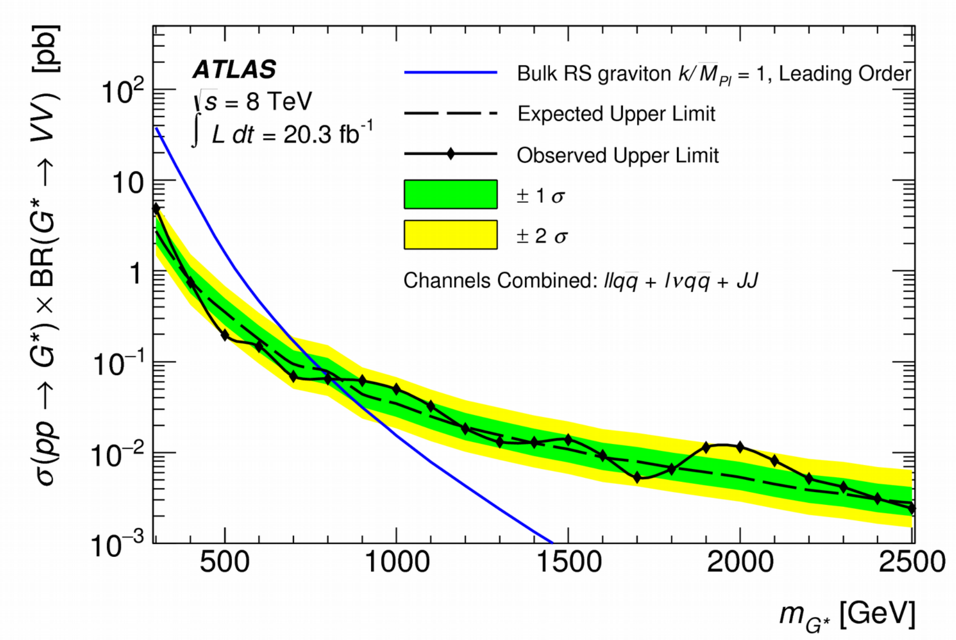
VH/HH searches (ATLAS) covered by Jie Yu

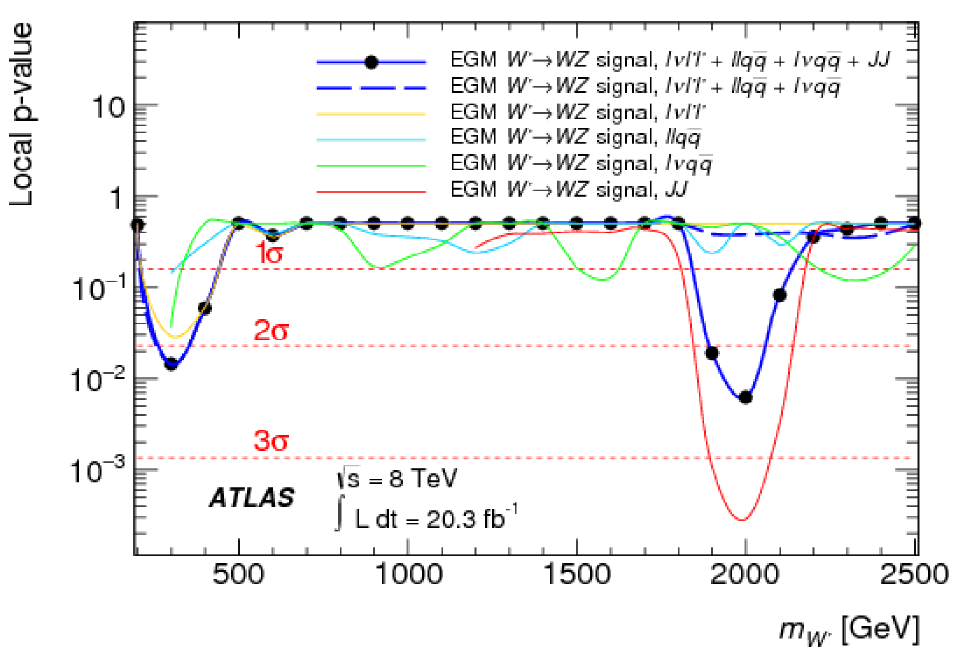
Run-I Recap

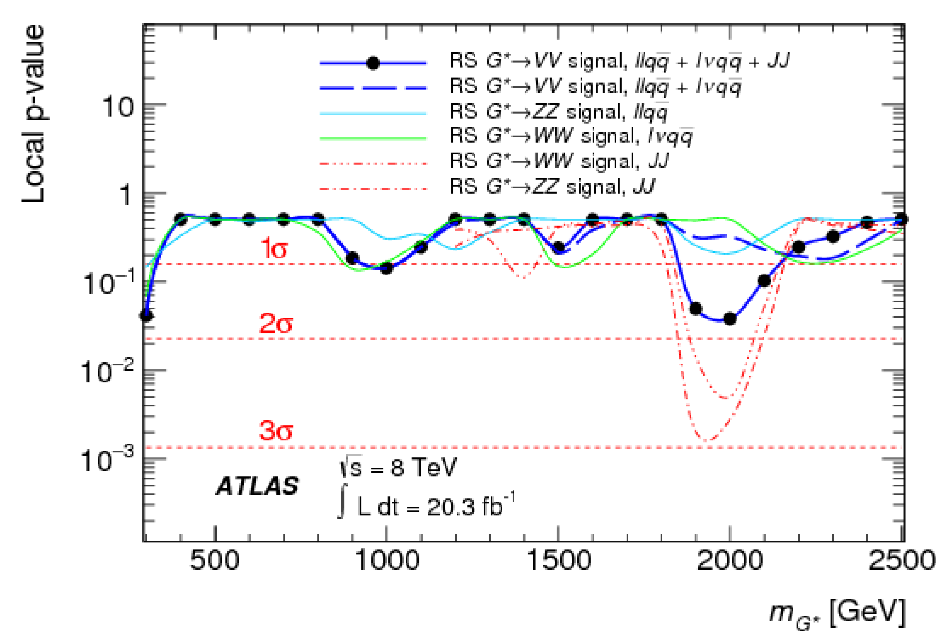
(This will be quick…)

Run-I Recap


ATLAS
√s = 8 TeV
∫ L dt = 20.3 fb-1
EGM W', c = 1, Leading Order
Expected Upper Limit
Observed Upper Limit
± 1 σ
± 2 σ
Channels Combined: lνl'l' + llqq̄ + lνqq̄ + JJ
σ(pp → W') × BR(W' → WZ) [pb]
m_W' [GeV]


ATLAS
√s = 8 TeV
∫ L dt = 20.3 fb-1
Bulk RS graviton k/M_Pl = 1, Leading Order
Expected Upper Limit
Observed Upper Limit
± 1 σ
± 2 σ
Channels Combined: llqq̄ + lνqq̄ + JJ
σ(pp → G*) × BR(G* → VV) [pb]
m_G* [GeV]


EGM W'→WZ signal, lνl'l' + llqq̄ + lνqq̄ + JJ
EGM W'→WZ signal, lνl'l' + llqq̄ + lνqq̄
EGM W'→WZ signal, lνl'l'
EGM W'→WZ signal, llqq̄
EGM W'→WZ signal, lνqq̄
EGM W'→WZ signal, JJ
1σ
2σ
3σ
ATLAS
√s = 8 TeV
∫ L dt = 20.3 fb-1
Local p-value
m_W' [GeV]


RS G*→VV signal, llqq̄ + lνqq̄ + JJ
RS G*→VV signal, llqq̄ + lνqq̄
RS G*→ZZ signal, llqq̄
RS G*→WW signal, lνqq̄
RS G*→WW signal, JJ
RS G*→ZZ signal, JJ
1σ
2σ
3σ
ATLAS
√s = 8 TeV
∫ L dt = 20.3 fb-1
Local p-value
m_G* [GeV]

Run-II

(Once more, with feeling)

Theory/Benchmark Models

S G* V'

Spin-0 H (Scalar/H → WW,ZZ)

- **NWA:** *Generation using NWA heavy Higgs*
  - *Interpretation using CP-even scalar singlet* http://arxiv.org/abs/1512.04933v1
    - Two free parameters: $\mathbf{c_H}$ $\mathbf{c_3}$
    - Constrain width to be always smaller than detector resolution (and interference effects)

c_H: scaling coupling to h(125)
c_3: scaling coupling to gluons

- **LWA:** *"Large Width Approximation" → generated with Γ/m = 15%*
  - Reweighted to *Γ/m* = 5%, 10%

Spin-1 V' (W'→WZ, Z'->WW)

- *Heavy Vector Triplet (HVT) phenomenological Lagrangian*
- **"Model A, g_V=1":** Stronger constraints from leptonic searches

Spin-2: "Bulk" Randall-Sundrum (RS) Graviton (G*→WW,ZZ)

- *Modification of original RS model that avoids constraints from electro-weak precision tests and FCNC's*
- *Features enhanced B.R.'s to VV relative to RS1*

Boosted Channels

(Semi-leptonic + hadronic)

Boosted Channel Searches

Four ~ orthogonal search channels/final states

- *llqq* } **X → WZ, ZZ final states**
- *ννqq* }
- *lνqq* } **X → WZ, WW final states**
- *qqqq* } **X → WZ, WW, ZZ final states**

Similar Object Reconstruction

- ***Electrons***
  - **Veto:** p_T > 7 GeV, loose ID, isolation requirements, $|\eta| < 2.47$
  - **Analysis:** p_T > 25 GeV, tighter ID + isolation, exclude $1.37 < |\eta| < 1.52$
- ***Muons***
  - **Veto:** p_T > 7 GeV, loose ID, isolation requirements, $|\eta| < 2.7$
  - **Analysis:** p_T > 25 GeV, tighter ID + isolation, $|\eta| < 2.5$
- $E_{T,miss}$
  - Calo-based w/ tracker soft term
- ***Jets:***
  - R = 0.4 (/0.2) → b-tagging (track-jet)
  - R = 1.0, Trimmed + ***R2D2*** tagged → V-tagging (→ next slide)

Leptons
High acceptance for **veto**
High purity for **signal** definition

Boosted Boson Tagging (/1)

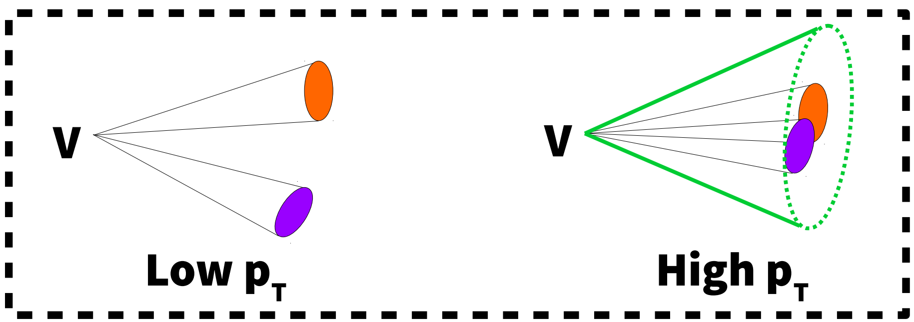
Why large-R jets?

- *Higher Higgs Mass → larger boost to W → ΔR of decay products gets smaller*

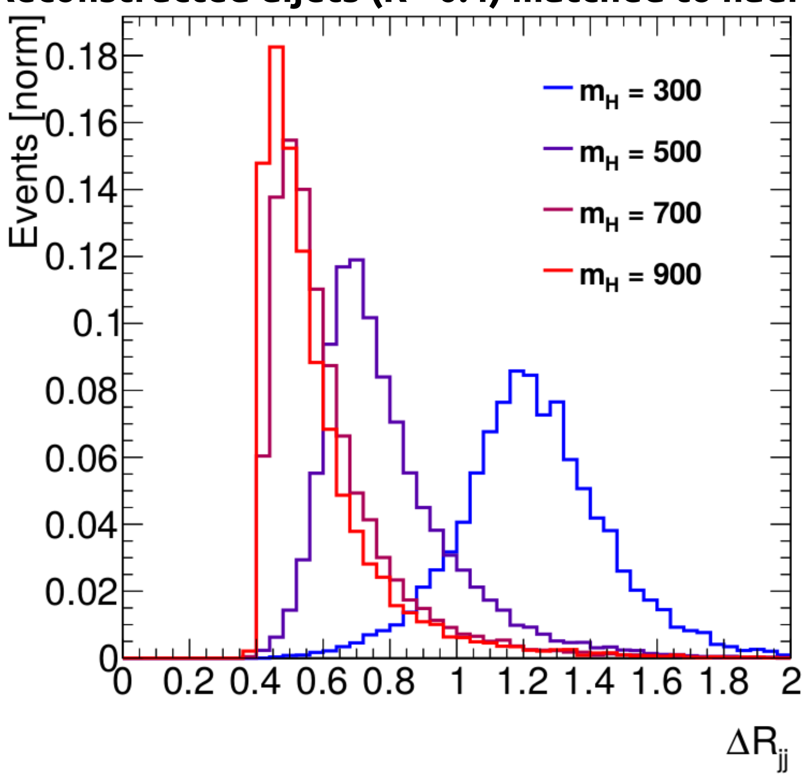
Back of the envelope calculation indicates that R=0.4 jets will begin to merge with resonant masses >~ 700 GeV

If only looking at dijets to reconstruct V, we lose efficiency as mass increases

$$\Delta R \sim \frac{2m}{p_T}$$



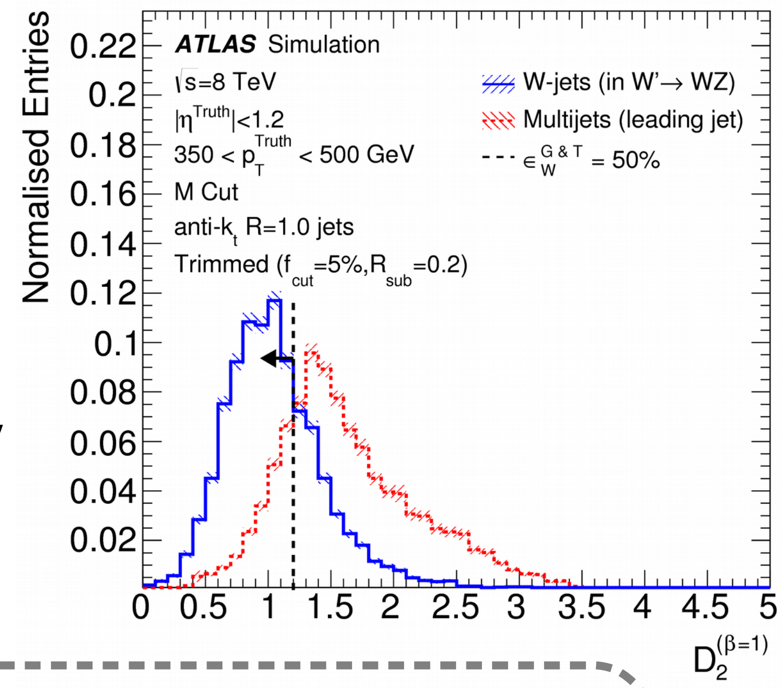
Reconstructed dijets (R= 0.4) matched to hadronic-W

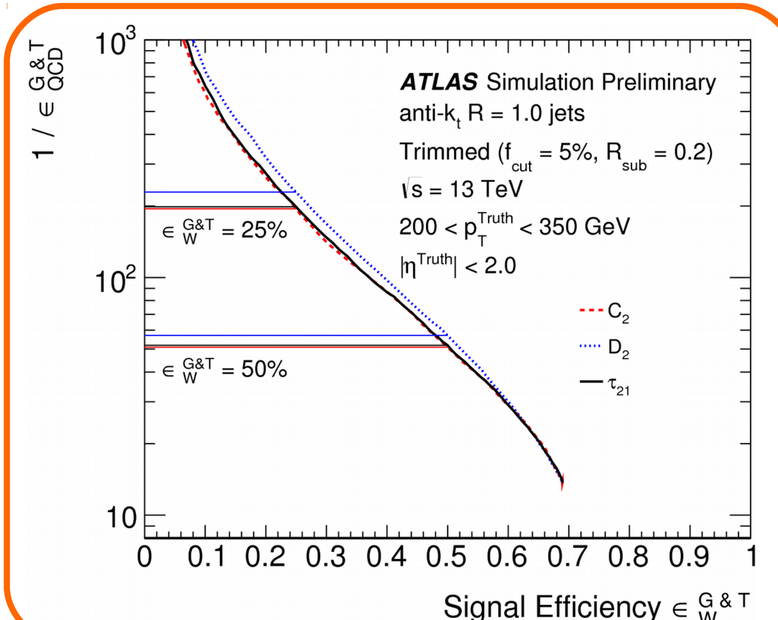


Boosted Boson Tagging (/2)

Use "R2D2" algo to tag our hadronic W/Z Jets

- *Start with anti-k_T, R = 1.0 jet*
- *Trimming: f_{cut} = 5%, R = 0.2 (k_T algorithm)*
- *D2 Variable: "loose" working point*
  - *50% efficiency → 40-50x bkg rejection*
- *W/Z differentiated by mass window cut + D2 cut*
  - **Mass window:** $|m_J - m_V| < 15$ GeV, $m_J > 50$ GeV
  - **D2:** Maximizes separation between two prong and one prong decays





$$D_2 = E_{CF3}\left(\frac{E_{CF1}}{E_{CF2}}\right)^3$$

E_{CF} (energy correlation functions)represent jet by combining the p_T and ΔR separation of:

- $\mathbf{E_{CF1}}$: All jet constituents
- $\mathbf{E_{CF2}}$: All pairs of jet constituents
- $\mathbf{E_{CF3}}$: All triplets of jet constituents

Fully Hadronic: *qqqq*

G* V'

Trigger

- *Large-R jet trigger (p_T > 360 GeV)*

Selection (jets):

- *N_{trk} > 30 GeV (p_T > 0.5 GeV, ghost associated)*
- *2 high p_T "R2D2" boson-tagged jets*
- *p_T (leading-jet) > 450 GeV*
- *Large mass, small angular separation, p_T balance*

Background: MJ background with analytic function

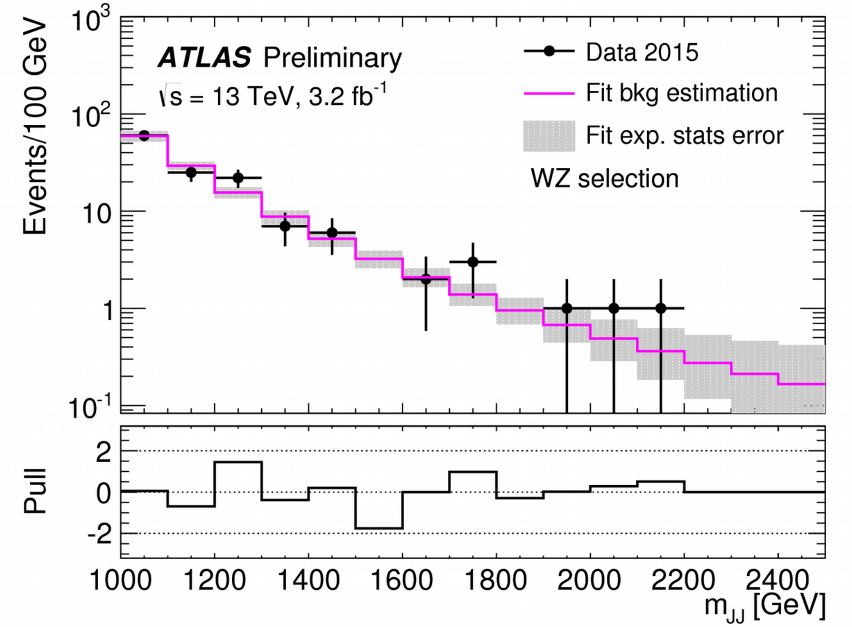
- *Validated in orthogonal validation region*
- *Final ML fit only to signal region*

Limited search range (1200 < m_X < 2500)

- *High MJ backgrounds at low mass*

Final discriminant: m_{JJ}

3 Signal regions: WW, ZZ, WZ (determined by boson-tagging)



$$f(x) = N(1-x)^{p_2+\xi p_3}\, x^{p_3}, \quad x = \frac{m_{JJ}}{\sqrt{s}}$$

Selection	Data	HVT W' simulation
$m_{JJ} > 1000$ GeV	972069	21.5 ± 0.1
Topological selections	285474	15.4 ± 0.1
Boson tagging	128	3.09 ± 0.05

Semi-leptonic: *ννqq*

S G* V'

Trigger

- *$E_{T,miss}$ (> 80 GeV, calo-only)*

Selection

- *$E_{T,miss}$ > 250 GeV*
- *Charged lepton veto*
- *$p_T(J)$ > 200 GeV*
- *$\Delta\varphi(E_{T,miss}, J) > 0.6$*

Final discriminating variable:

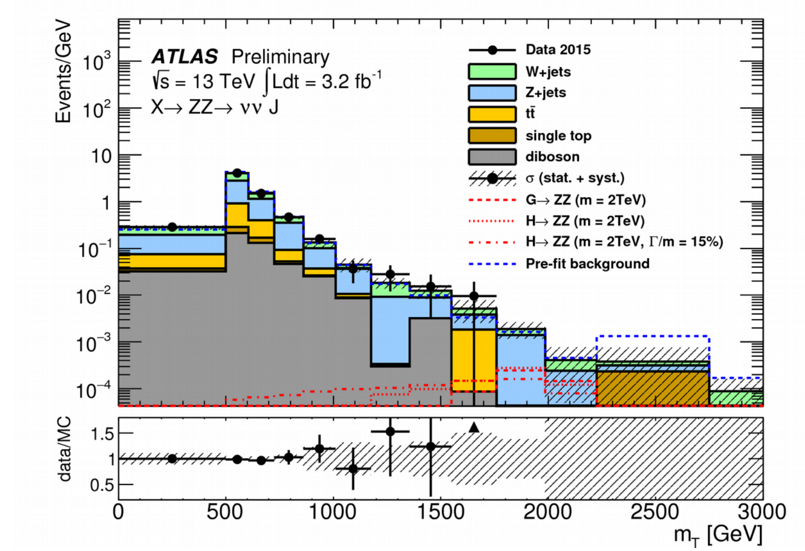
- *Transverse mass, m_T*

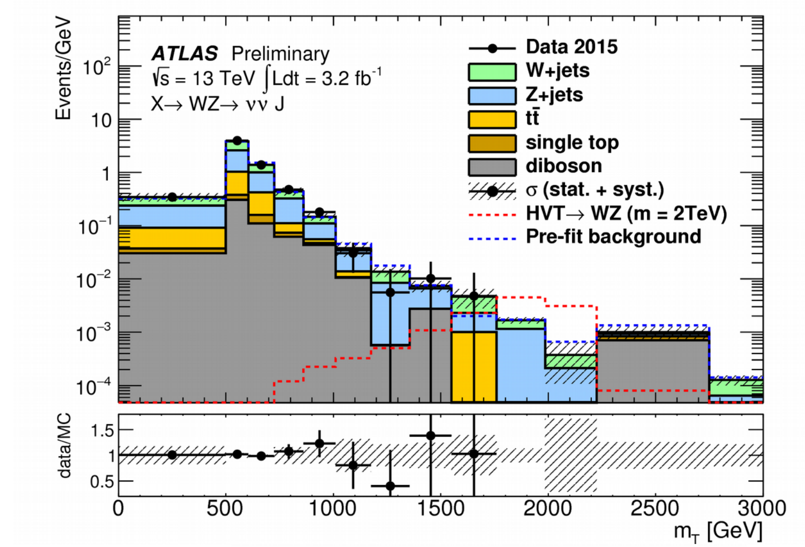
$$m_{\mathrm{T}} = \sqrt{(E_{\mathrm{T},J} + E_{\mathrm{T}}^{\mathrm{miss}})^2 - (\vec{p}_{\mathrm{T},J} + \vec{E}_{\mathrm{T}}^{\mathrm{miss}})^2}$$

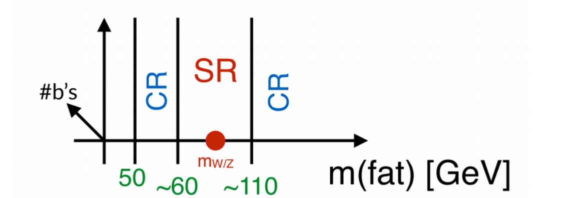
Background

- *ttbar, Z+jets (dominant)*
    - *MC with data-driven normalization*

Two Signal regions: WZ, ZZ (Determined by boson tagging)







Semi-leptonic: *lνqq*

S G* V'

Trigger

- *single-lepton (e, μ)*

Selection (Summary)

- *b-jet veto*
- *1 lepton + 1 boson-tagged jet + $E_{T,miss}$ > 100 GeV*
- *$p_T(V)$ > 200 GeV (both hadronic and leptonic)*
- *$p_T(V) > 0.4*m_{l\nu J}$*

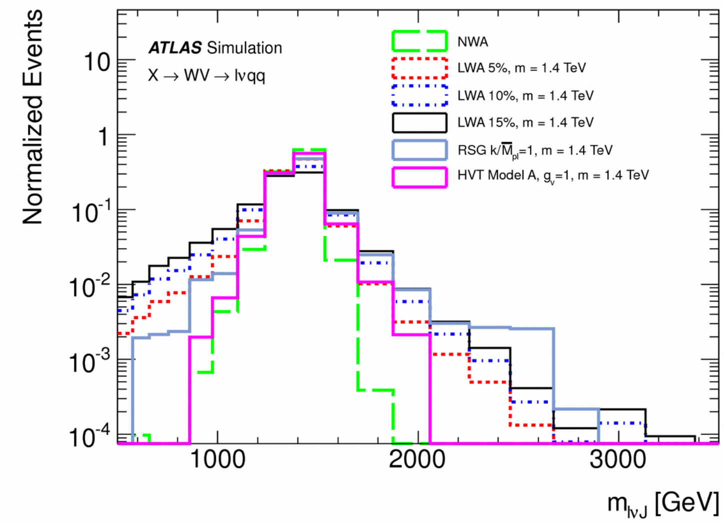
Background

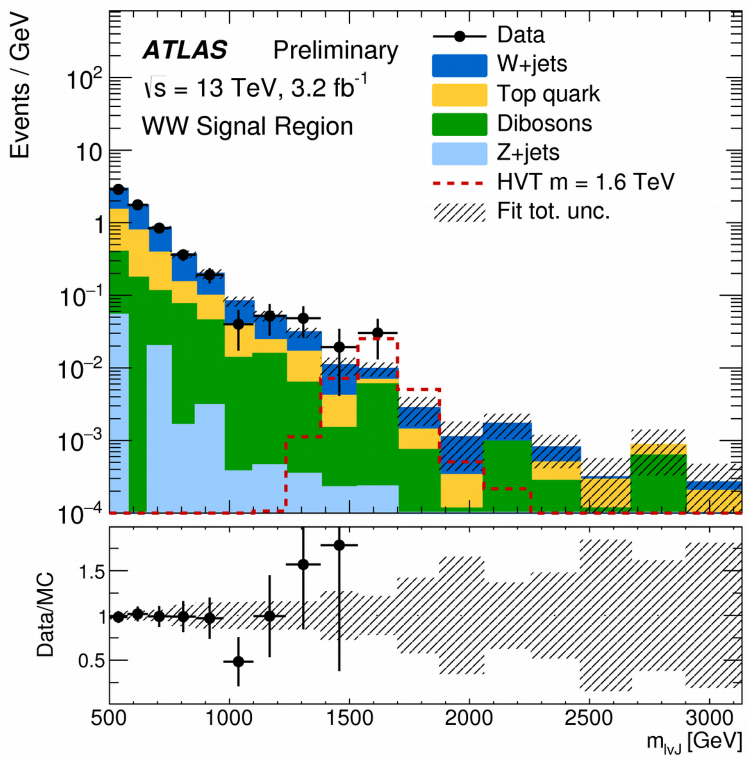
- *ttbar, W+jets (dominant)*
  - Shape from MC, data-driven normalization
- *Diboson/Z+jets*
  - MC (shape + normalization)

Final discriminant

- *Reconstructed mass: $m_{l\nu J}$*
  - $p_z(\nu)$ analytically solved for by constraining W to be on-shell

Two Signal Regions: WZ, WW





Semi-leptonic: *llqq*

S G* V'

Trigger

- *Single-lepton (e,μ)*

Selection

- *2 same flavor opposite sign leptons*
- *1 large-R jet (p_T>200 GeV), Z-tagged*
- *$p_T(V) > 0.4*m(llJ)$*
- *Veto on additional leptons*

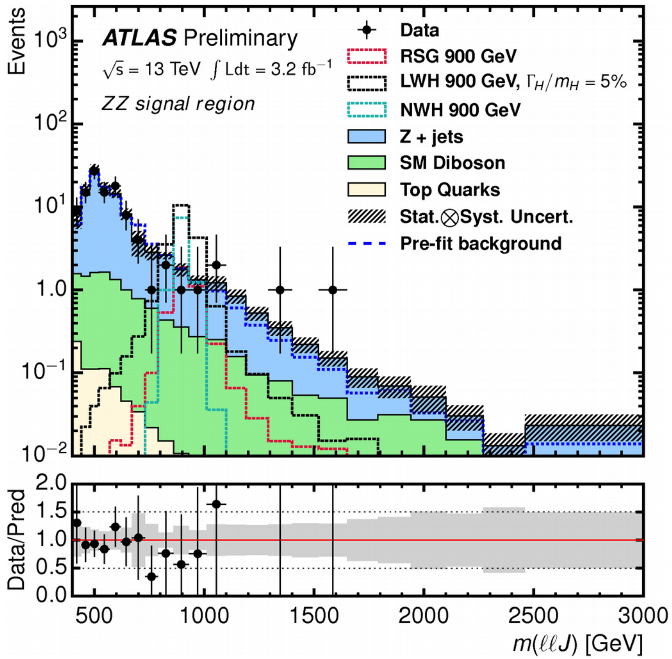
Final Discriminating variable:

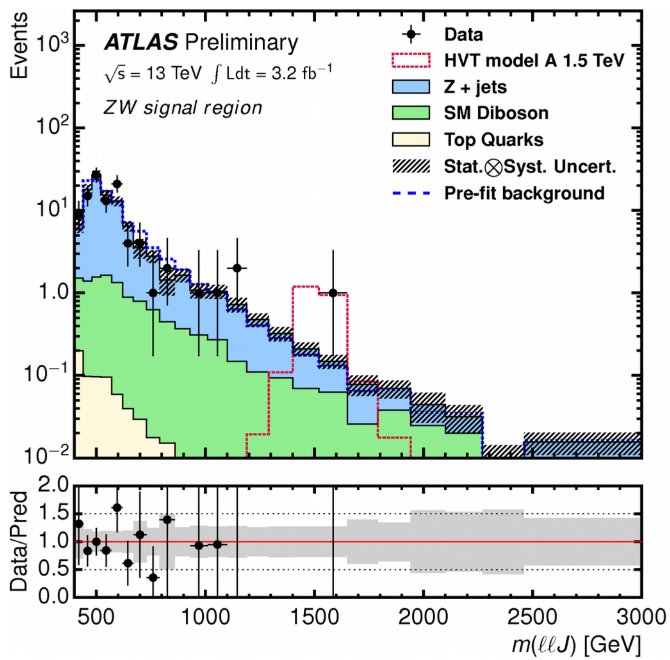
- *Reconstructed mass: m_{llJ}*

Backgrounds:

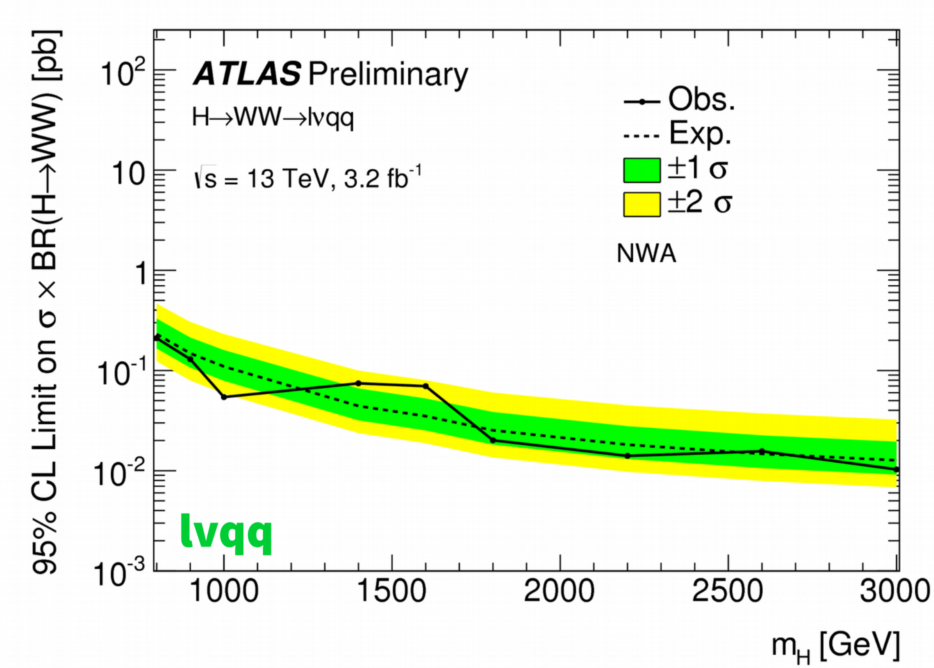
- *V + jets (dominant)*
  - MC with data-driven normalization (extrapolated from m(J) sidebands)

Two signal regions: WZ, ZZ (separated by boson tagging)





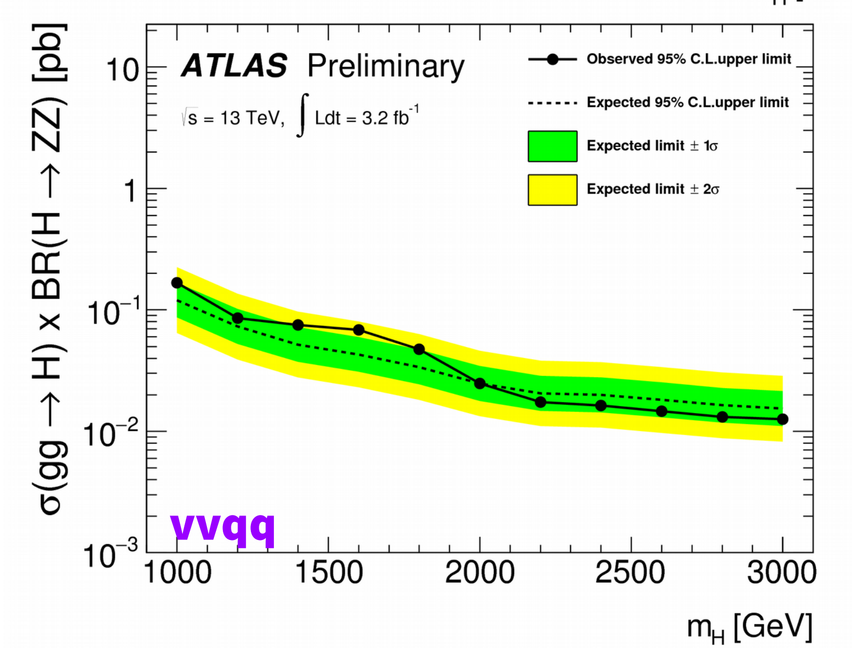
H/Scalar → VV [NWA]

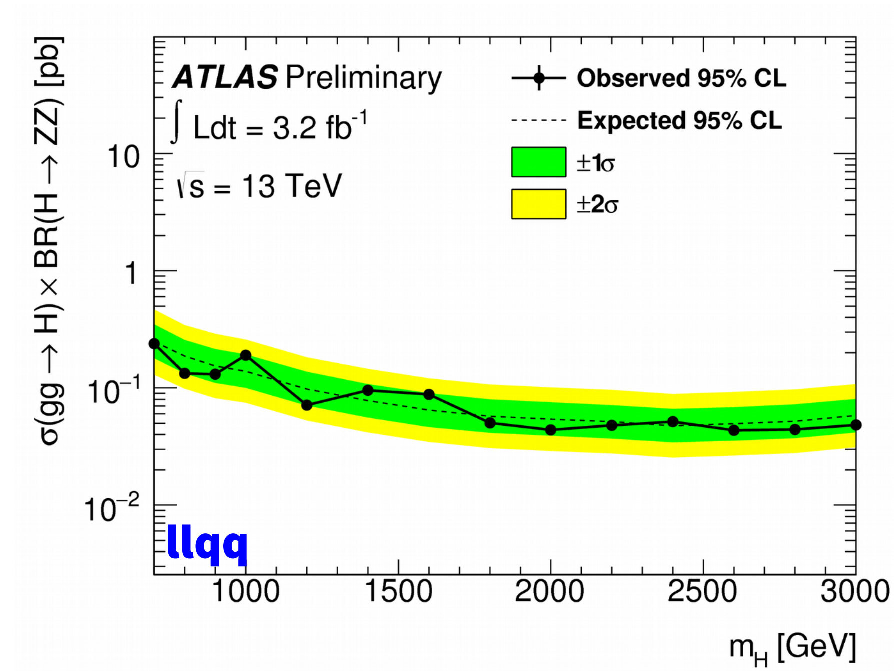


Limits set for:

- *NWA resonance (shown here)*
- *Γ/m = 5, 10, 15% (backup)*

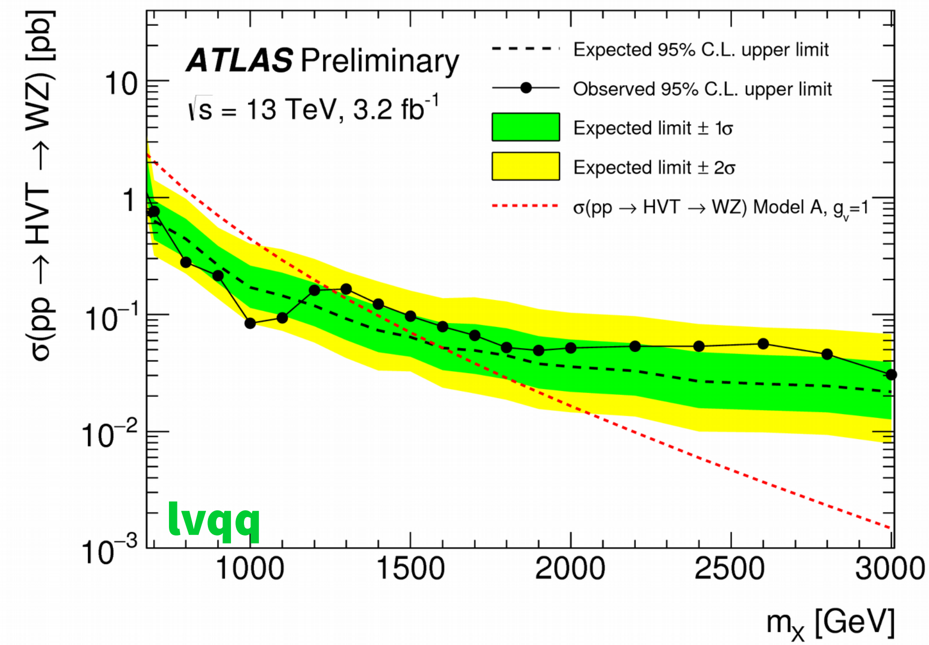
Stay tuned for further results in these channels!

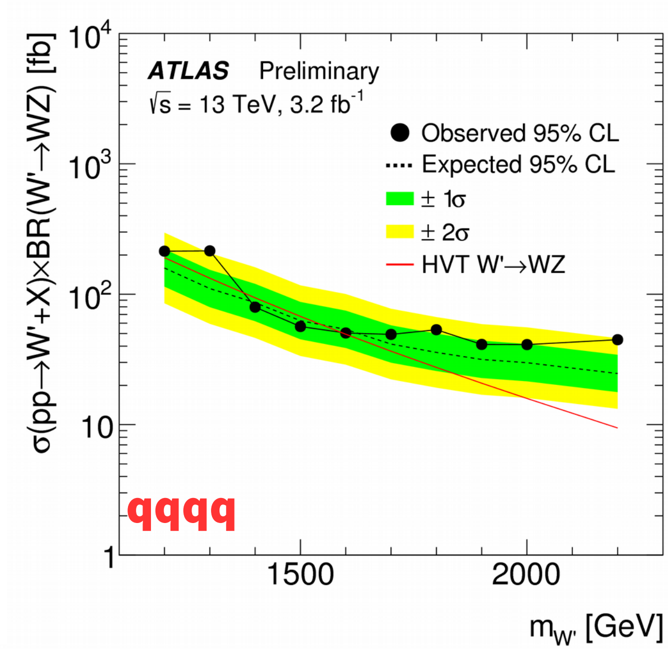


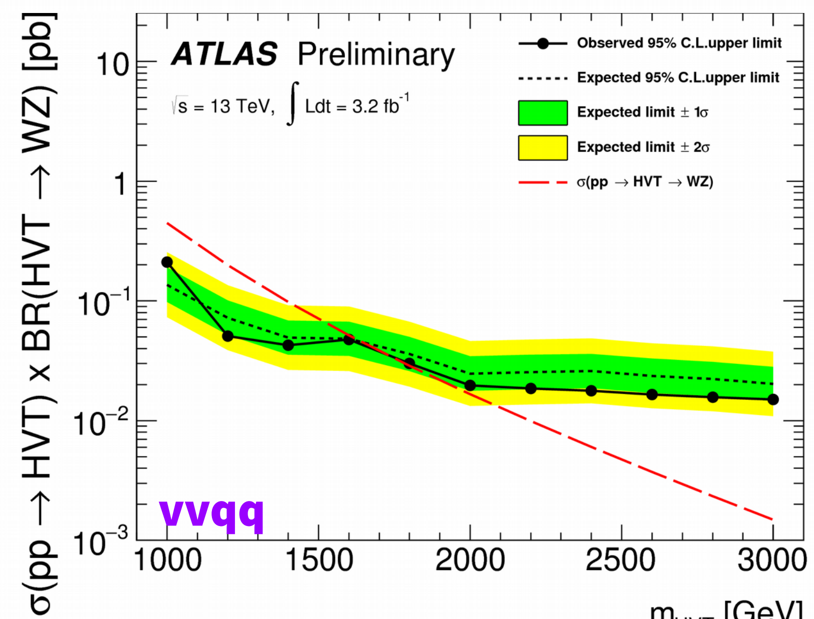


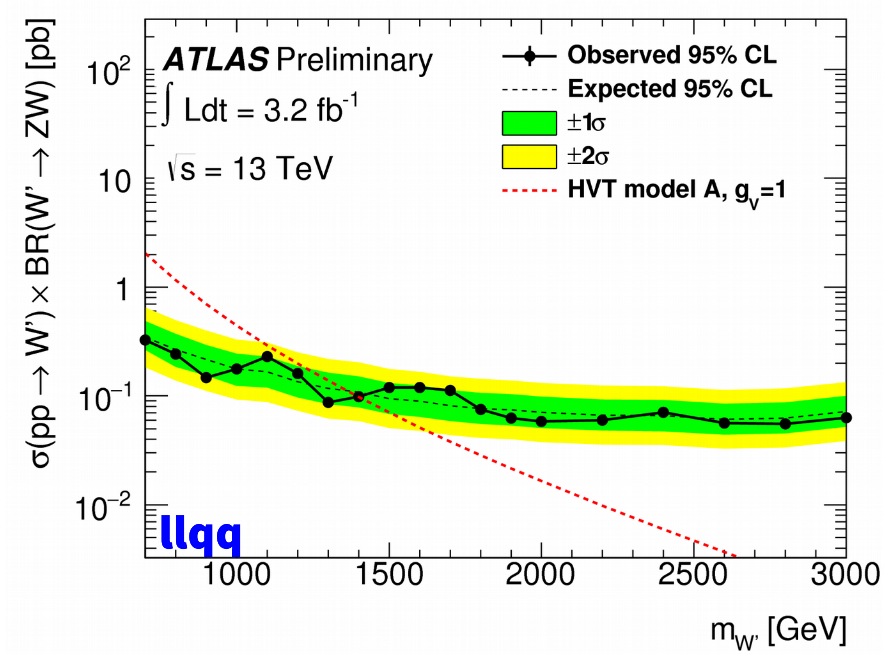
ATLAS-CONF-2015-068
ATLAS-CONF-2015-071
ATLAS-CONF-2015-075
ATLAS-CONF-2015-073

W' → WZ [limits]

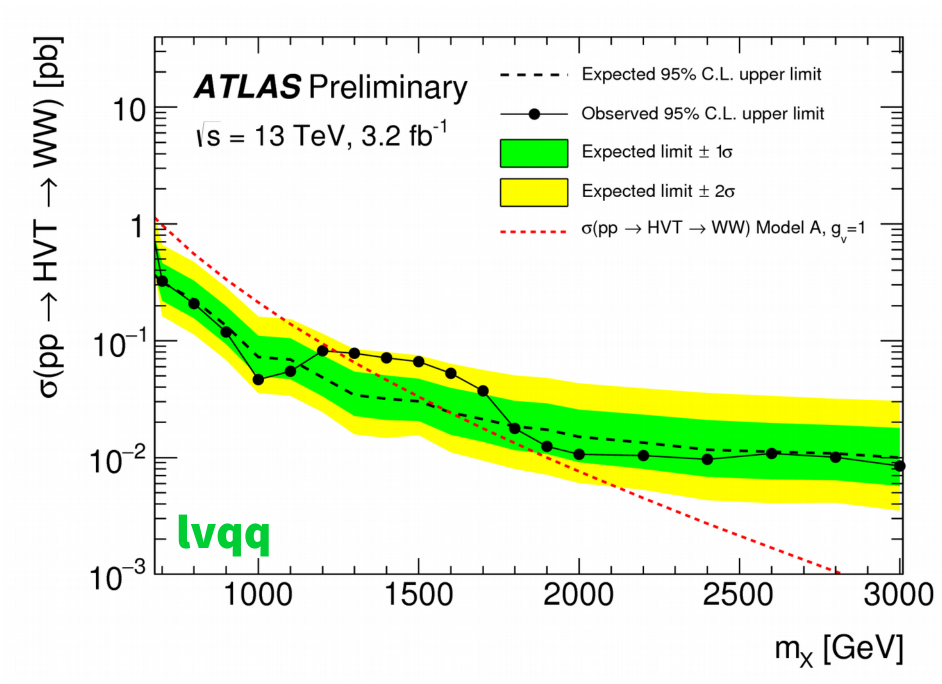


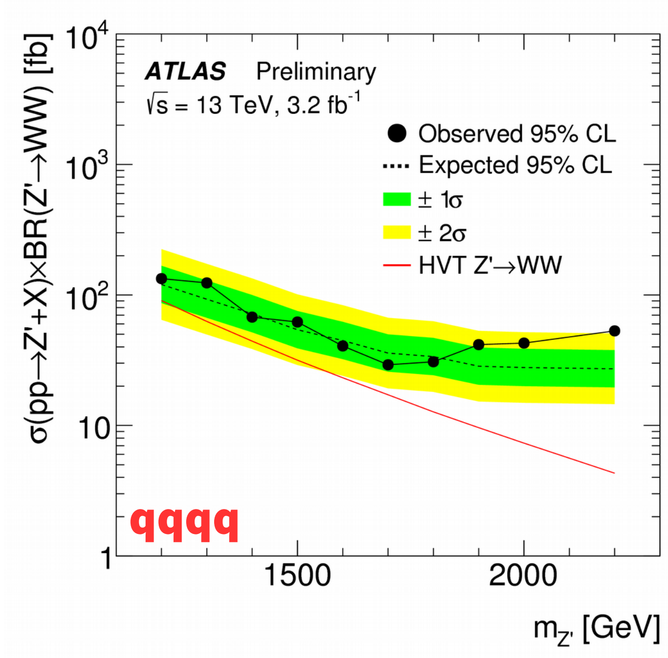




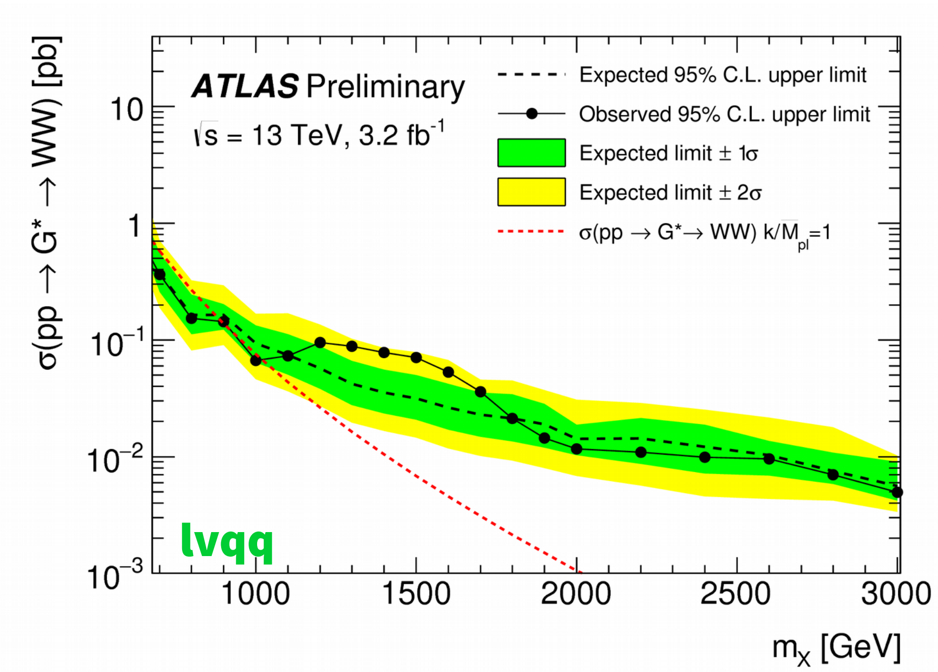


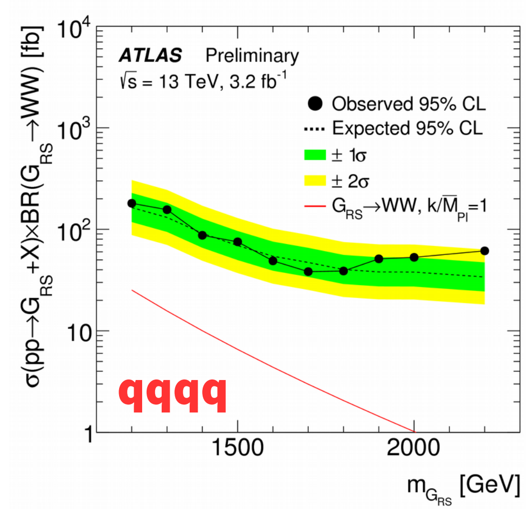
Z' → WW [limits]

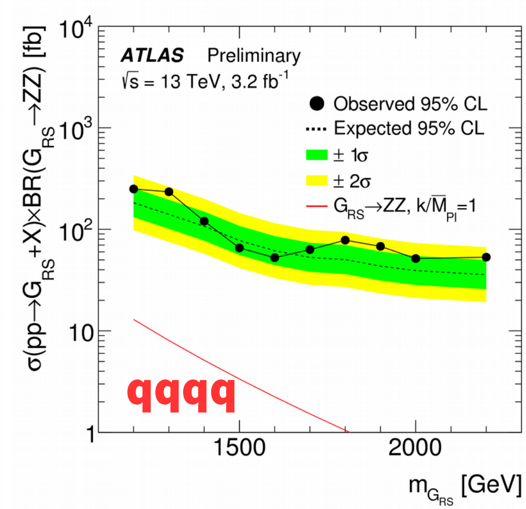

ATLAS Preliminary
√s = 13 TeV, 3.2 fb-1
Expected 95% C.L. upper limit
Observed 95% C.L. upper limit
Expected limit ± 1σ
Expected limit ± 2σ
σ(pp → HVT → WW) Model A, gv=1
σ(pp → HVT → WW) [pb]
mX [GeV]
lvqq

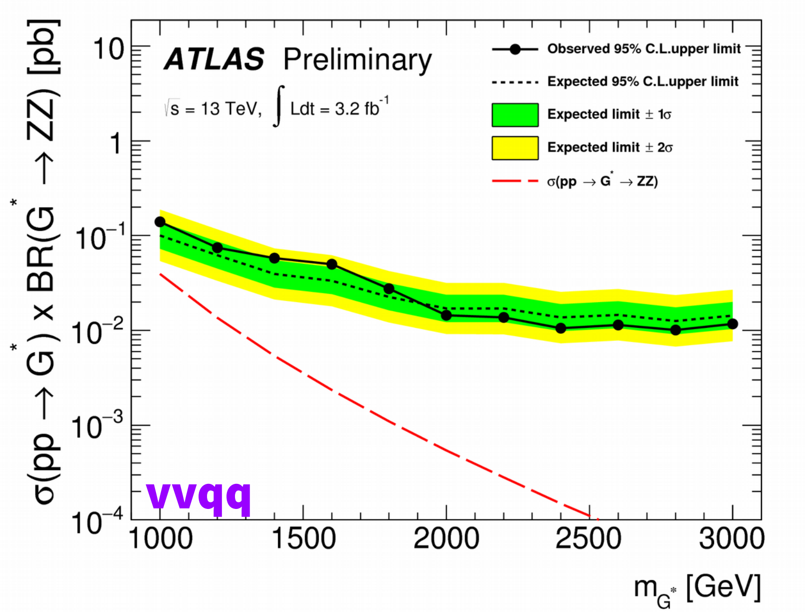

ATLAS Preliminary
√s = 13 TeV, 3.2 fb-1
Observed 95% CL
Expected 95% CL
± 1σ
± 2σ
HVT Z'→WW
σ(pp→Z'+X)×BR(Z'→WW) [fb]
mZ' [GeV]
qqqq

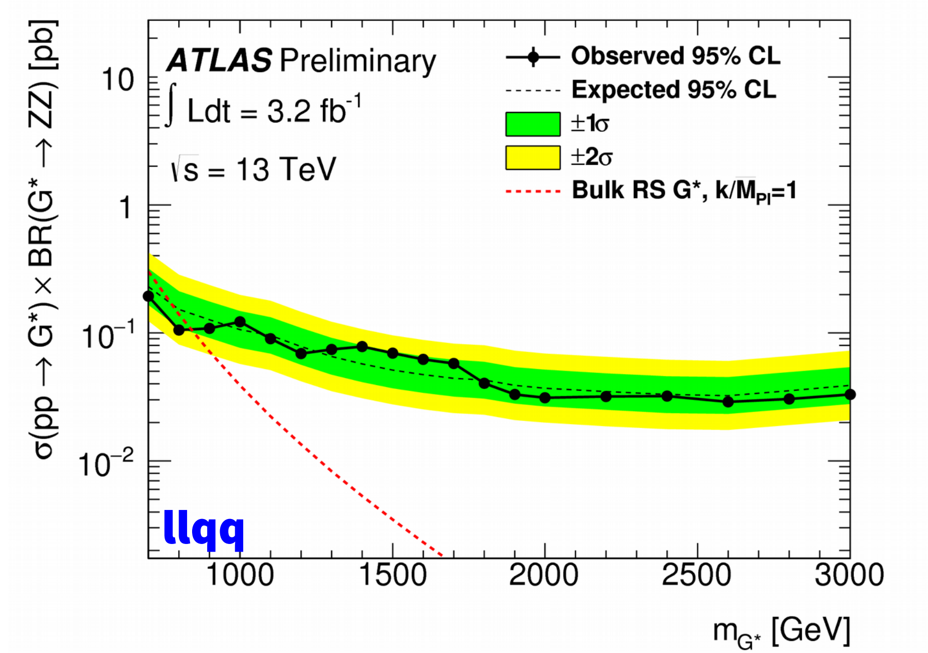
$G^* \rightarrow VV$ [limits]











H → ZZ → llqq (A glimpse of the future)

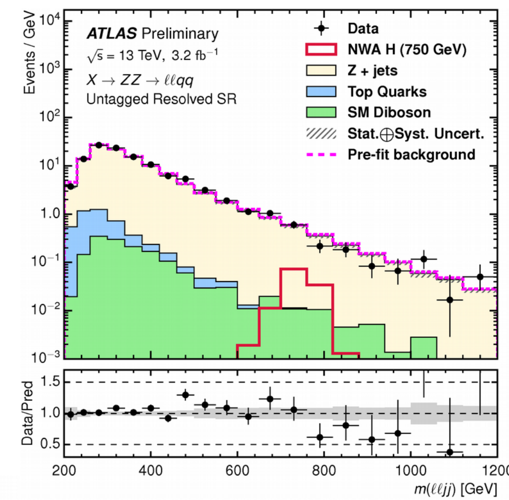
Analysis Strategy

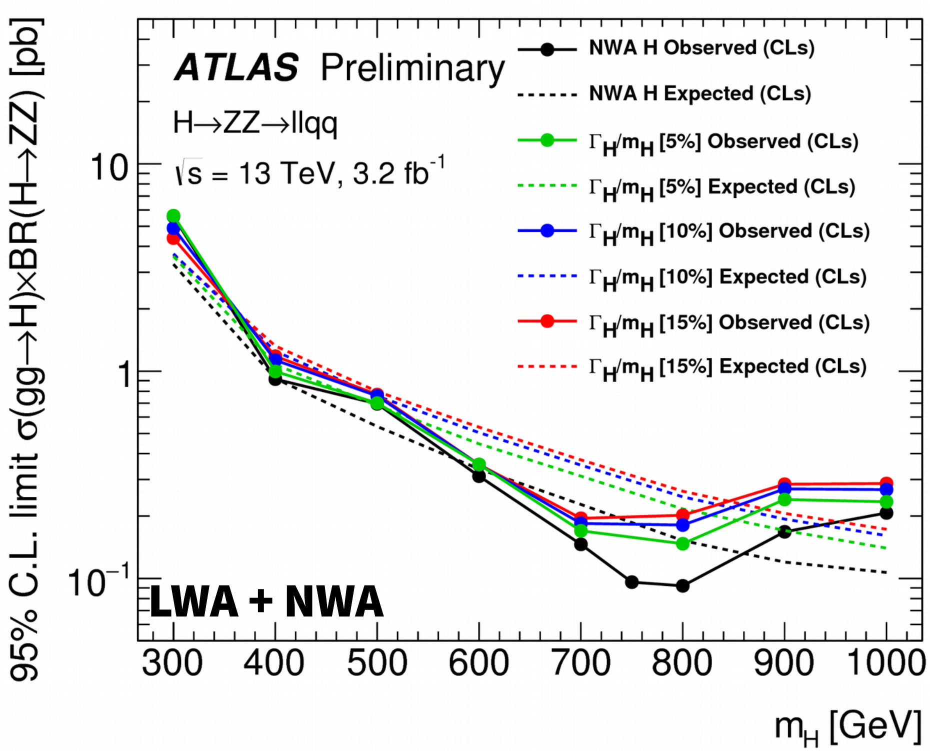
Merged Analysis
2 same flavor opposite sign leptons
1 large-R jet (p_T>200 GeV), Z-tagged
p_T(ll) > 0.3m(ll)

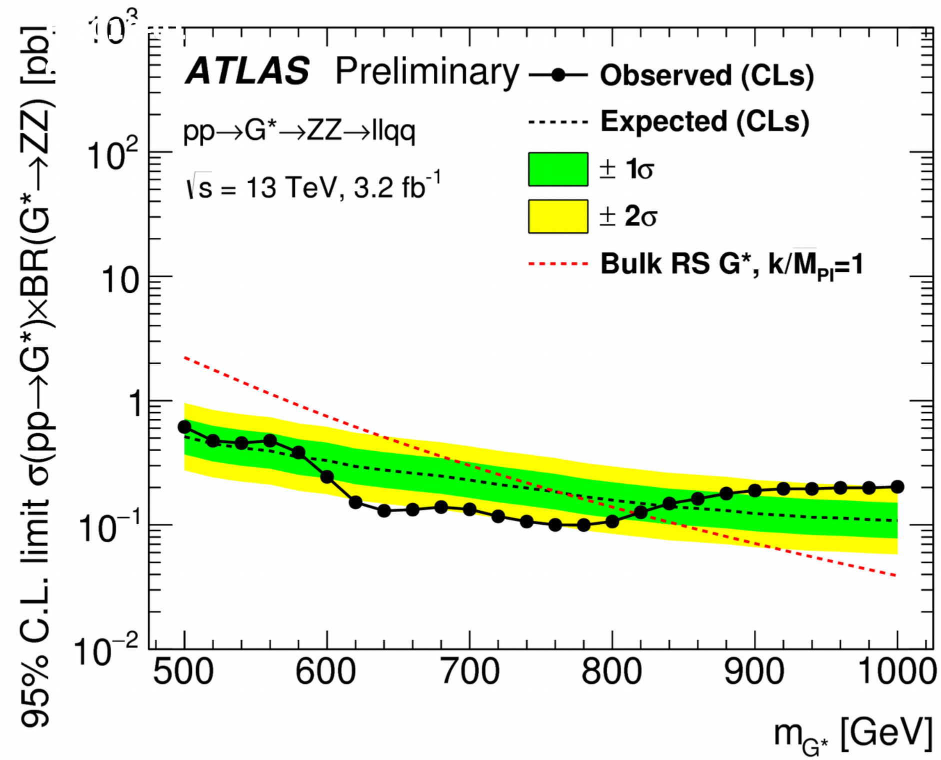
Resolved Analysis
2 same flavour opposite sign leptons
2 small-R jets, Z-tagged

Two Signal Regions (Resolved analysis)
0/2 b-tagged

Final Discriminant: m_{llqq}





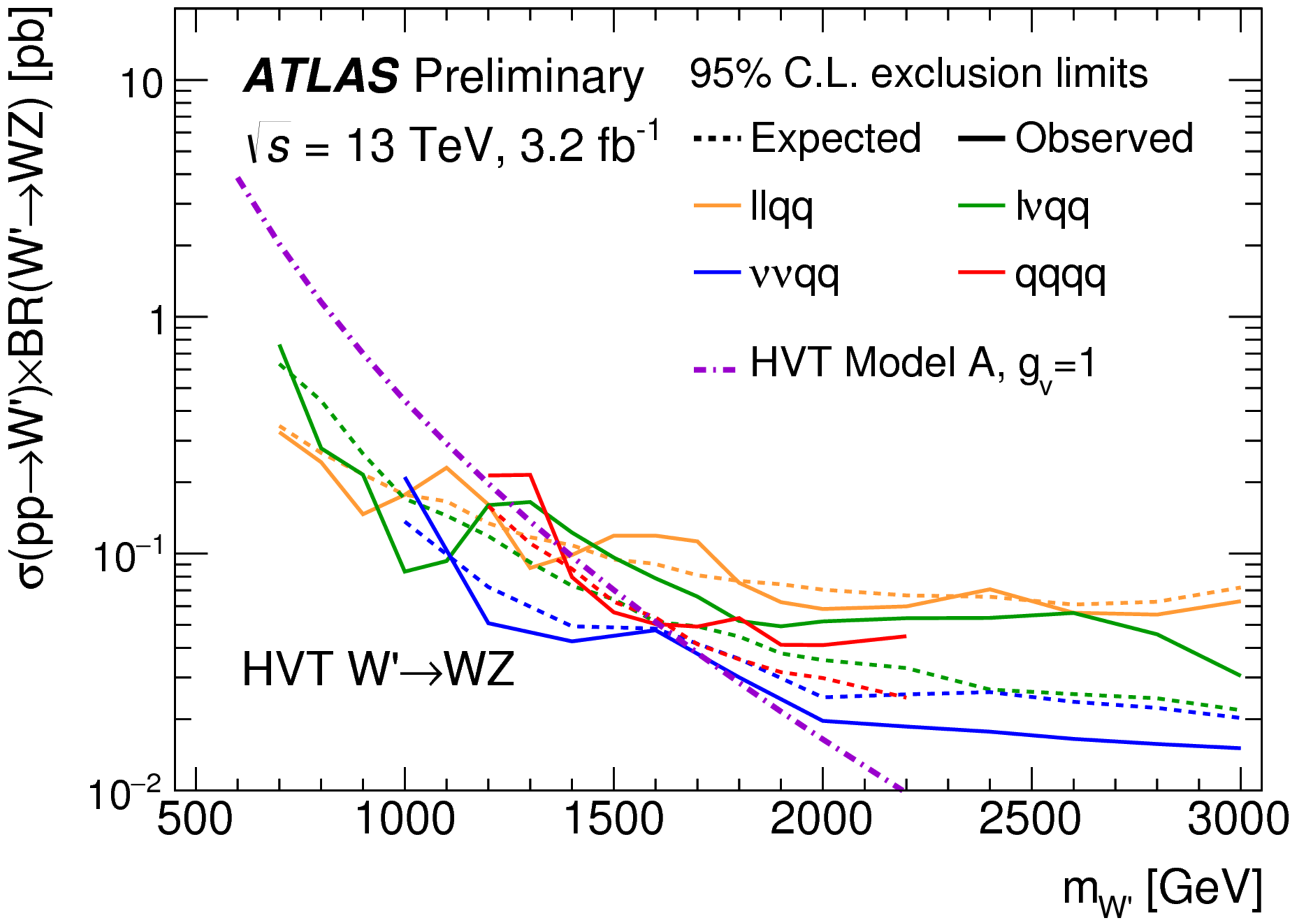


Resolved + Merged analyses combined
Event recycling: Priority given to merged analysis

Combination
(+ Model Dependencies)

Preliminary Superposition (Boosted)

Stay tuned for further results in these channels!



Here: Need relative X → WW/WZ BRs

Note: Limits down to 700 GeV (excl. ννqq/*qqqq*)

H → WW → lνlν

Analysis Strategy

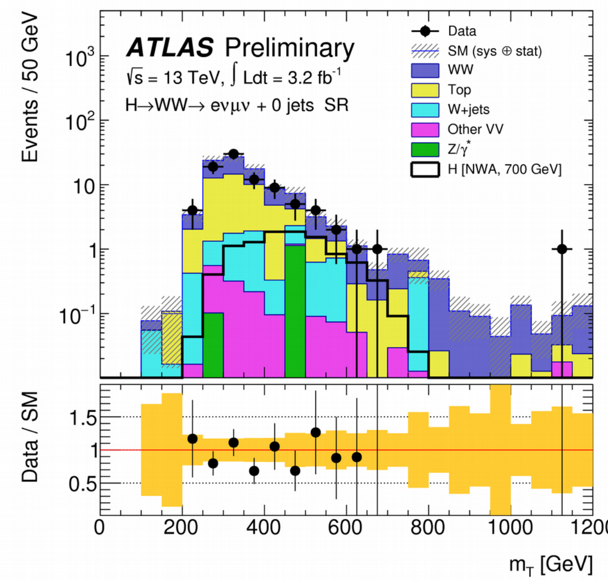
Selection

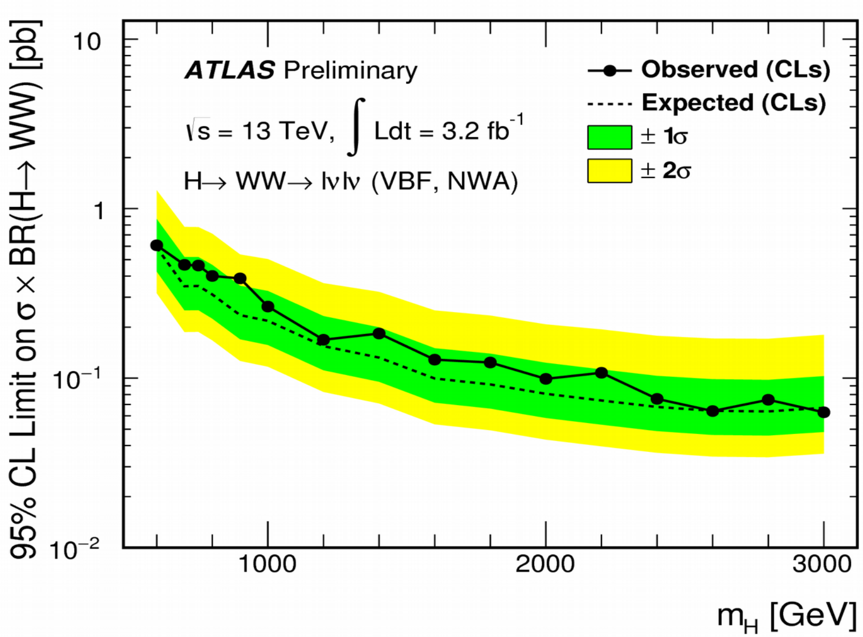
2 opposite flavor opposite charged leptons
Veto additional charged leptons
p_T (leading lepton) > 120 GeV
b-jet veto
$p_{T,miss}$ > 40 GeV (track based missing energy)

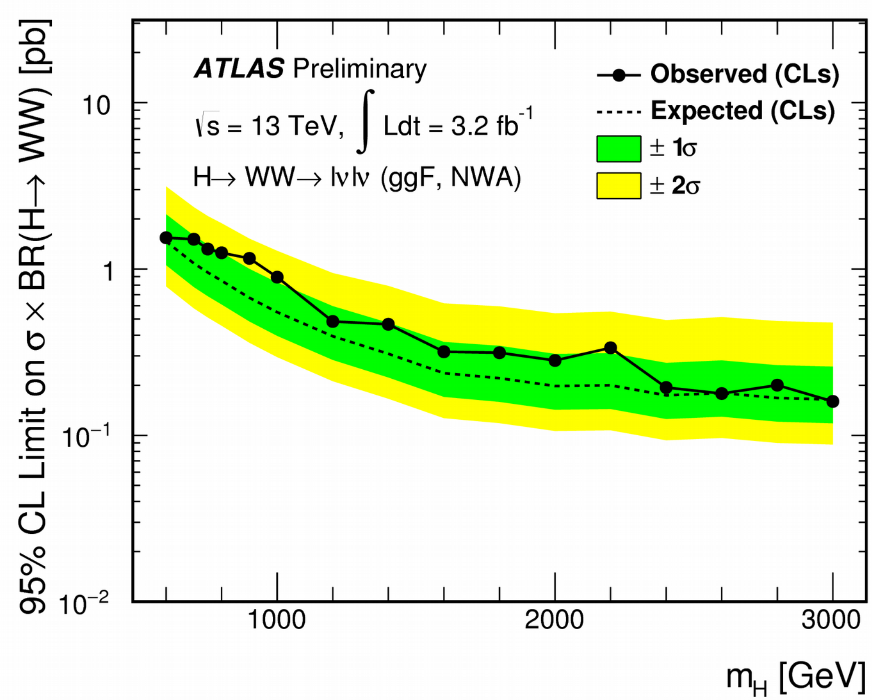
Three Signal Regions

0/1 (ggF) and 2 jet (VBF)

Discriminating variable: m_T

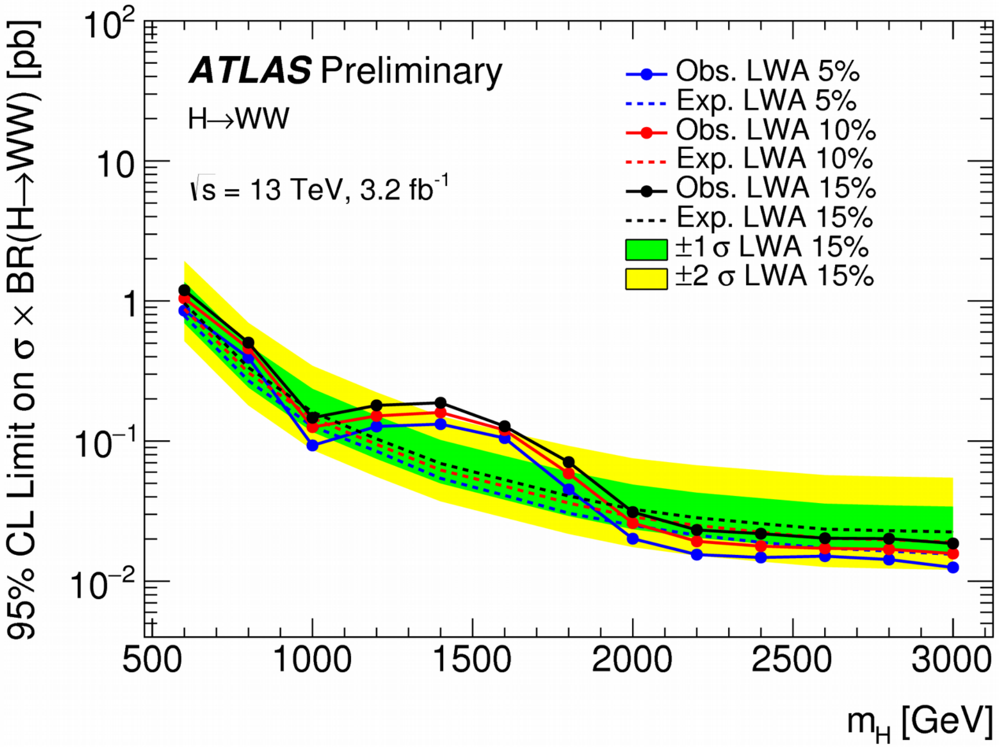


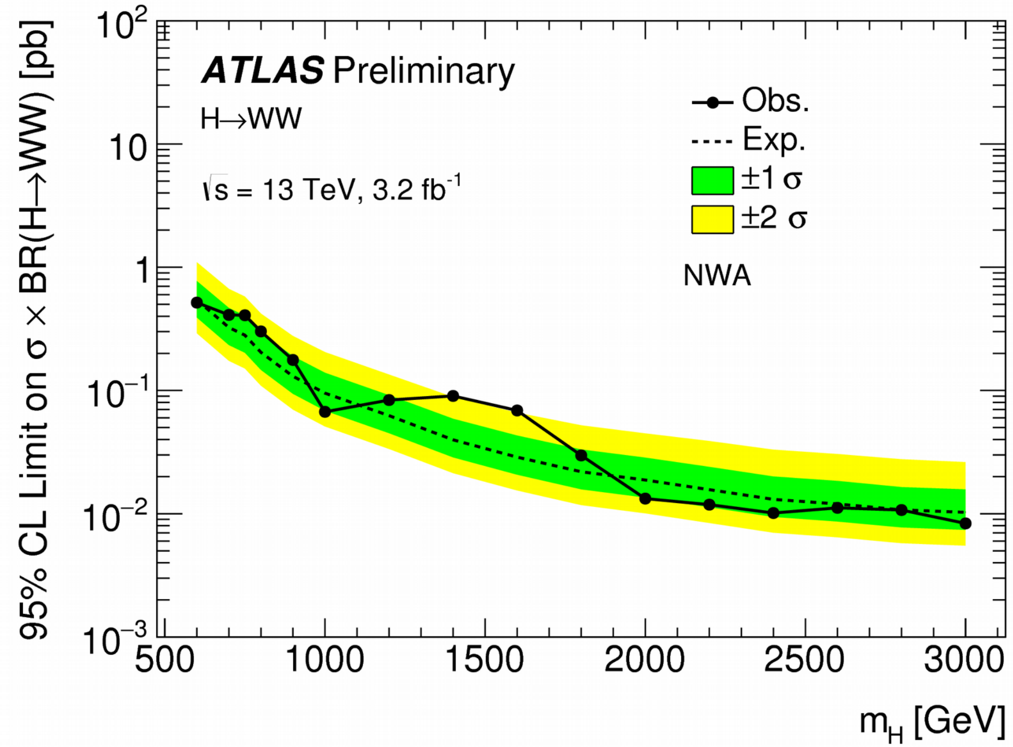




Combination of lvlv + lvqq

ggF Production Only!





NWA: *Narrow* width approximation (Γ = 4.07 MeV)
LWA: *Large* width approximation

Adding lvlv adds ~ 10% to sensitivity at ~700 GeV

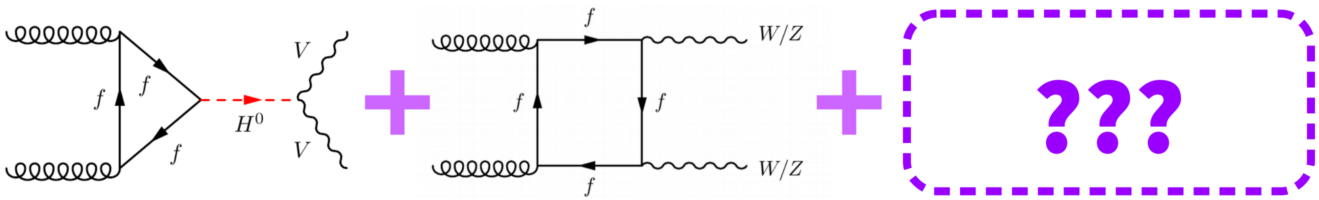
Model Dependents/Dependence

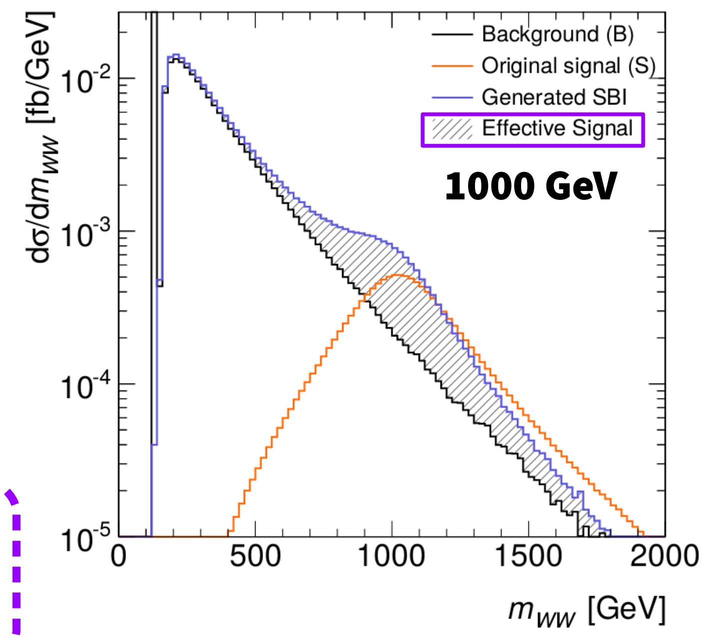
GGF/VBF Ratios

Combination of which final state channels

Narrow resonances

- *Covers widths < detector resolution*
- *+Interference for wider resonances*





- *For scalar searches: Γ/m = 15% is as wide as we can go w/o considering interference*

There is a trade off between model dependence and increased sensitivity (where is the line?)

Conclusion(s)

No sign of new physics...yet!

Sensitivity increases through

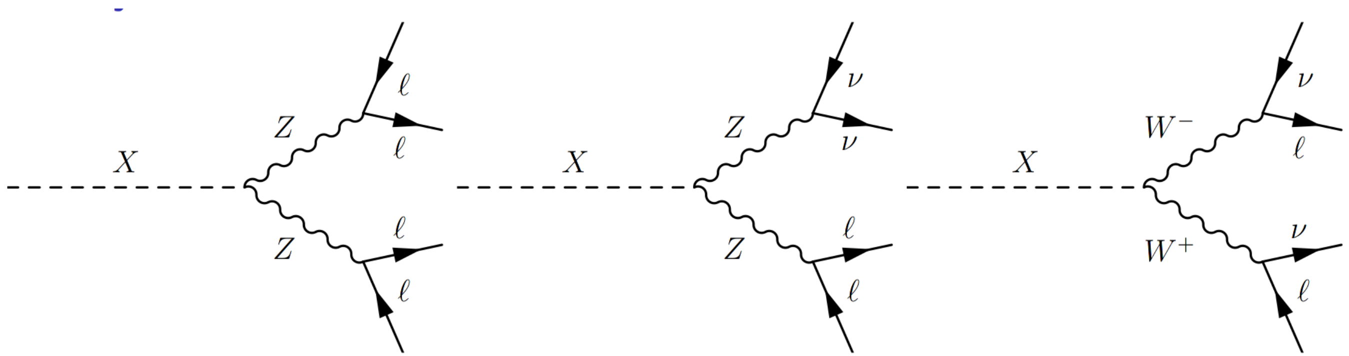
- *More data*
- ***Combinations among channels***
- *Analysis optimizations*

STAY TUNED!

Run-II continues…

- *Already getting first physics collisions*
- *~ 10 fb^{-1} for summer conferences (exp.)*

Thank-you!



Leptonic Search Channels

(Lower Mass searches)

$H \rightarrow ZZ \rightarrow 4l$ (/1)

S

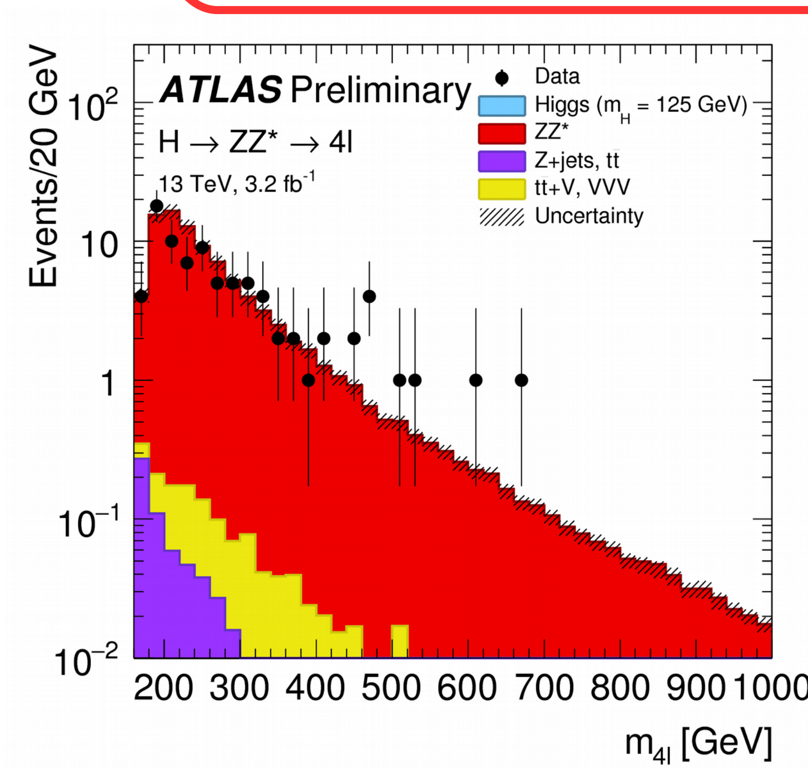
Selection/Strategy based on the h(125) → 4l analysis

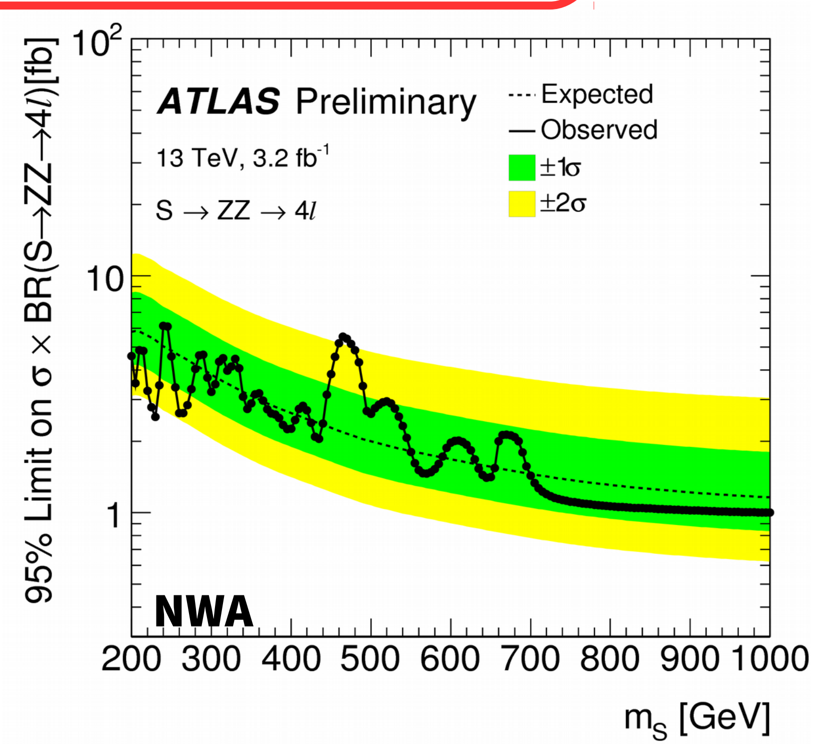
Analysis Strategy

Selection
2-pairs of same flavour, opposite sign leptons
Lepton pairs matched to Z-mass
Lepton isolation requirement (ΔR)
m_{ll} > 5 GeV (J/Ψ veto)

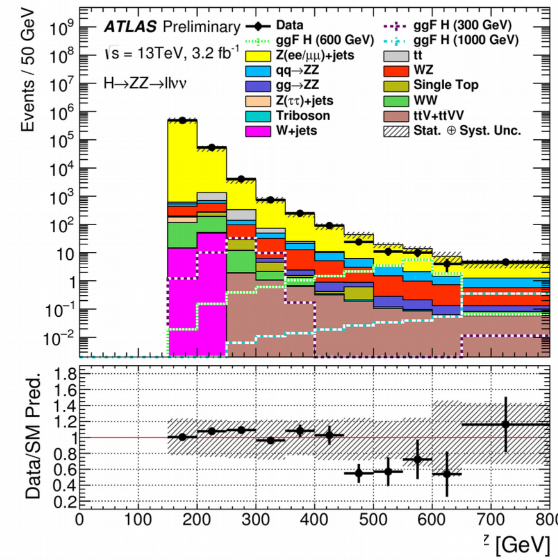
Channels separated by charged lepton flavours (4e, 4μ, 2e2μ, 2μ2)e

Discriminating variable: m_{4l}





$H \to ZZ \to ll\nu\nu$



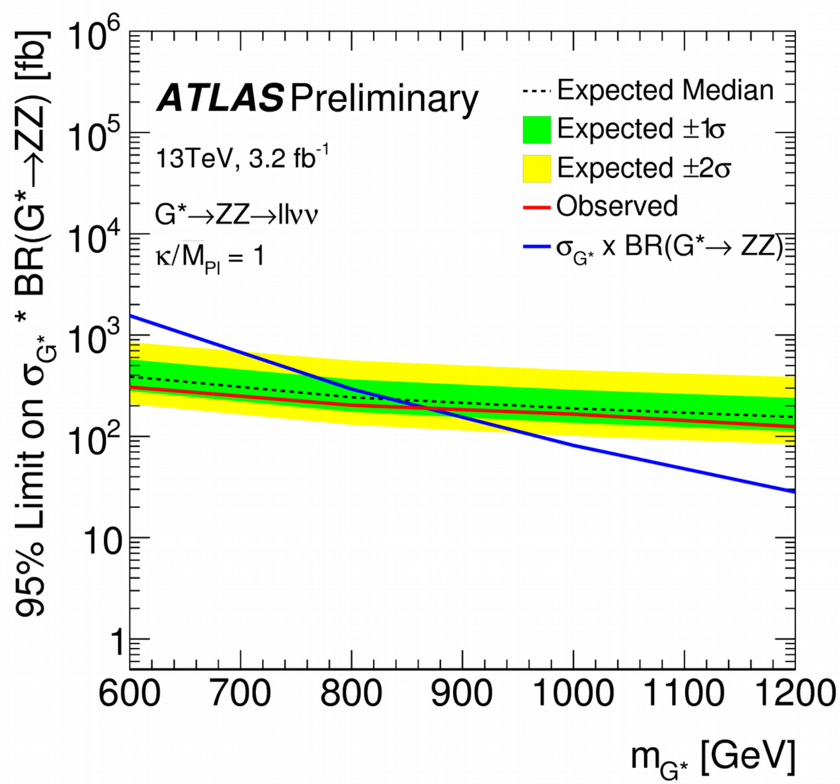
Analysis Strategy

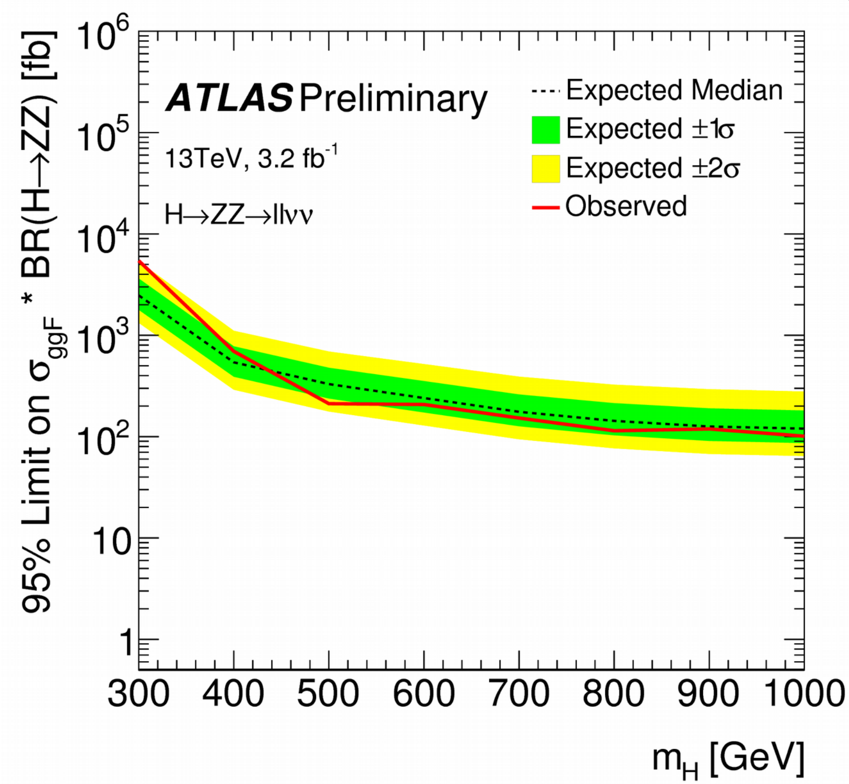
Selection

2 same flavour, opposite sign leptons
Missing energy > 120 GeV
$p_T(Z)/m_T < 0.7$
$\Delta\phi(E_{T,miss}, ll) > 2.7$
b-jet veto

Channels separated by charged lepton flavour

Discriminating variable: m_T





H → ZZ → 4l (Back)

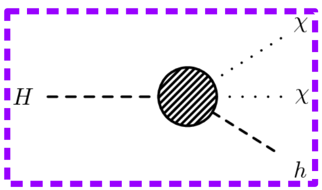
Can use Higgs physics as new probe for DM

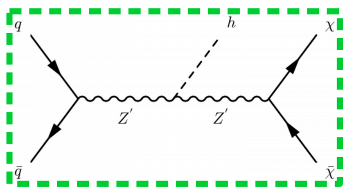
- Other results: γγ/bb + $E_{T,miss}$

Two models considered:

- Scalar mediator model
- Vector mediator model

BR(h → invis) = 0 for simplicity

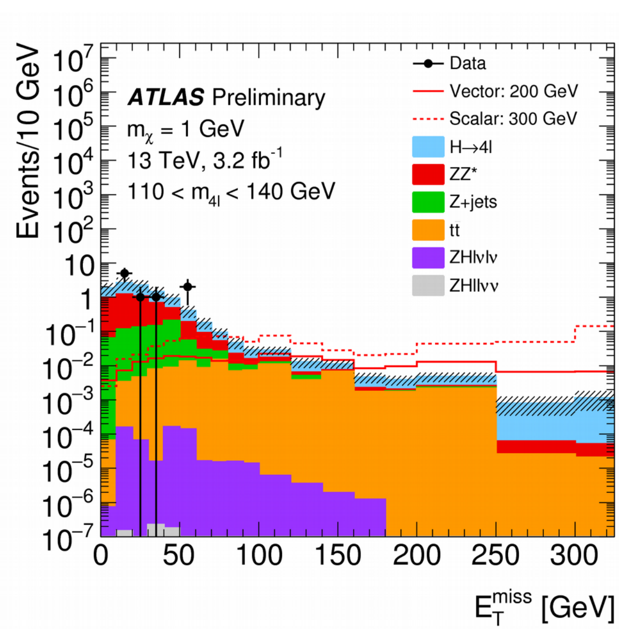


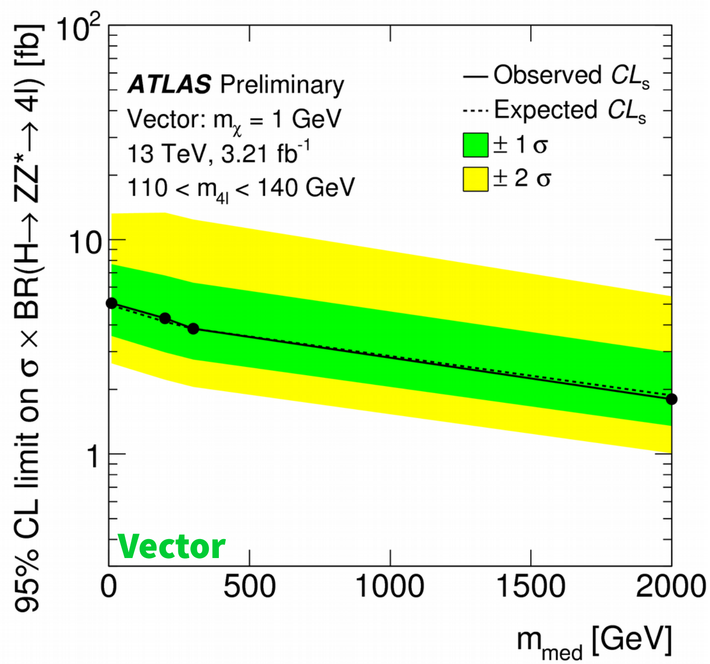


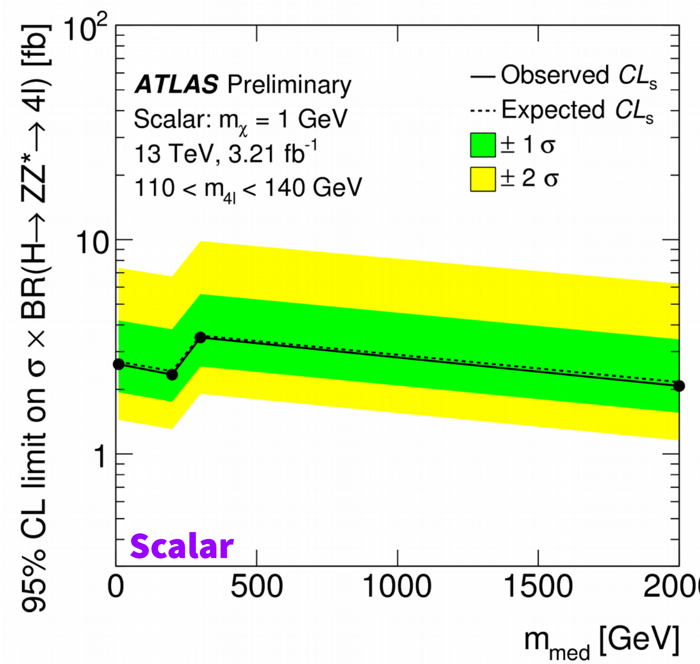
m_x = 1 GeV

Additional backgrounds from:
ZH → ll + lvlv and **ZH → ll + llvv**

Fit done on missing transverse energy for 4l events in mass window:
110 < m_{4l} < 140 GeV







D2 [Back]

D_2 [1] is a jet substructure variable optimised to discriminate between jets initiated by 1 or 2 hard (LO) objects. Unlike similar variables (such as n-subjettiness) It does not require any reclustering into smaller subjets, instead it uses a ratio of a jet's energy correlation functions (ECFs) which describe the angular distribution of energy within a jet.

$$D_2^{\beta} = \frac{\mathrm{ECF}(3,\beta) \times \mathrm{ECF}(1,\beta)^3}{\mathrm{ECF}(2,\beta)^3}$$

$$\mathrm{ECF}(N,\beta) = \sum_{i_1 < i_2 < \ldots < i_N \in J} \left(\prod_{a=1}^{N} p_{T,i_a} \right) \left(\prod_{b=1}^{N-1} \prod_{c=b+1}^{N} \Delta R_{i_b i_c} \right)^{\beta}$$

For a jet containing N hard subjet, $\mathrm{ECF}(\beta, N+1) \ll \mathrm{ECF}(\beta, N)$ so for a two-prong jet (such as those from a vector boson) D_2 will be small.

---

[1] See *Power Counting to Better Jet Observables, A. Larkoski et. al., 10.1007/JHEP12(2014)009*

VV Interference (WW @ 8 TeV shown here)

Crucial to take interference into account for broad resonances→ modifies both effective lineshape and cross-section

SM continuum process pp → WW will interference quantum mechanically diagrams with the Higgs processes pp → H → WW

Break-up components of invariant-mass WW spectrum as

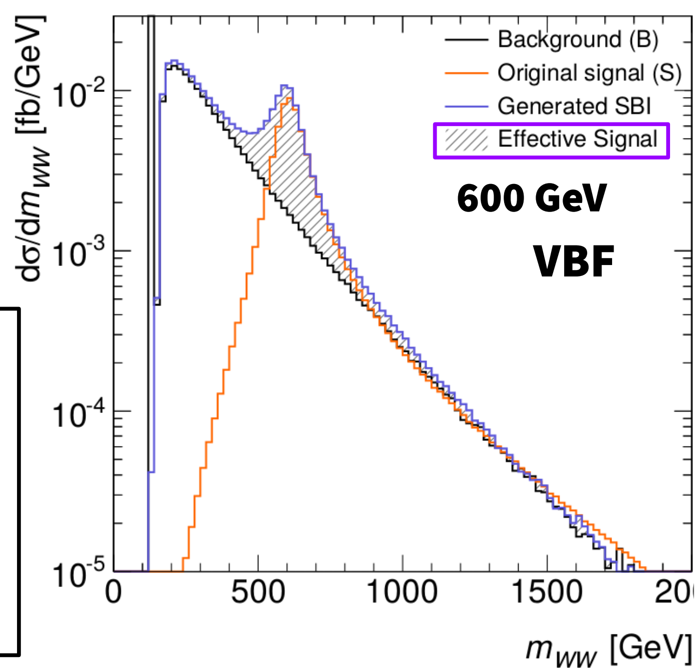
- *Signal only ($\mathcal{S}$)*
- *Background only ($\mathcal{B}$)*
- *Signal + Background ($\mathcal{SBI}$) → Includes interference*
- *We are interested in $\mathcal{SI}$ as our signal*

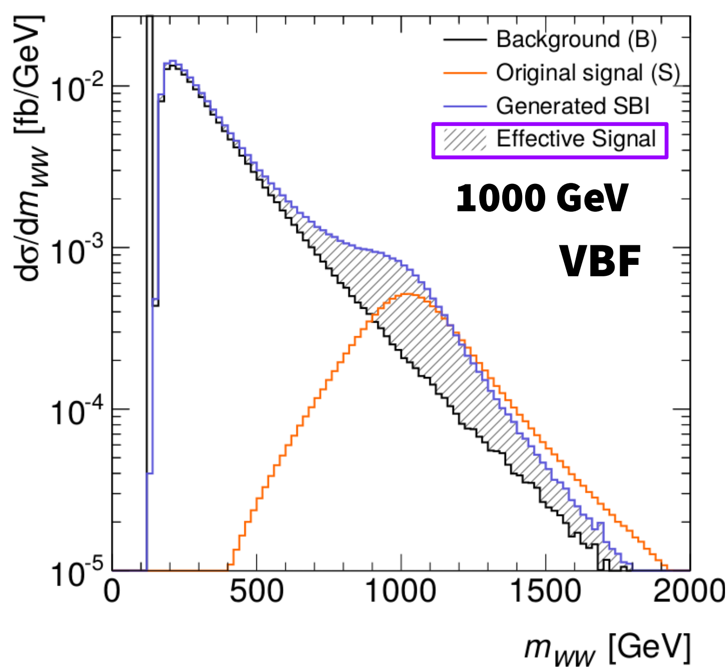
Different diagrams for ggF/VBF → must evaluate effect on lineshape separately

MC signal generators do not take $\mathcal{I}$ into account → must reweight signal to take into account interference (separately for ggF and VBF)

Constructive interference for $m_{WW} < m_H$
Destructive interference for $m_{WW} > m_H$

Effect grows with m_H
For ggF: dependent on Γ
For VBF: ~ independent of Γ (modest perturbations)



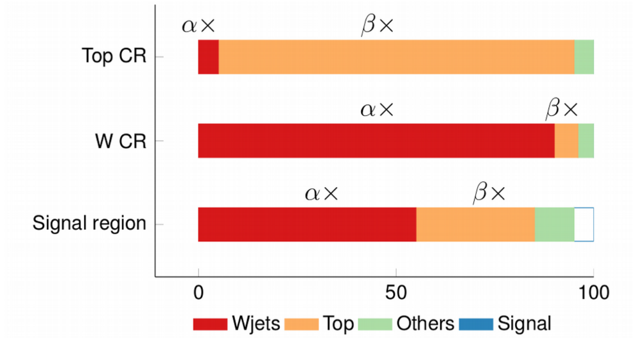


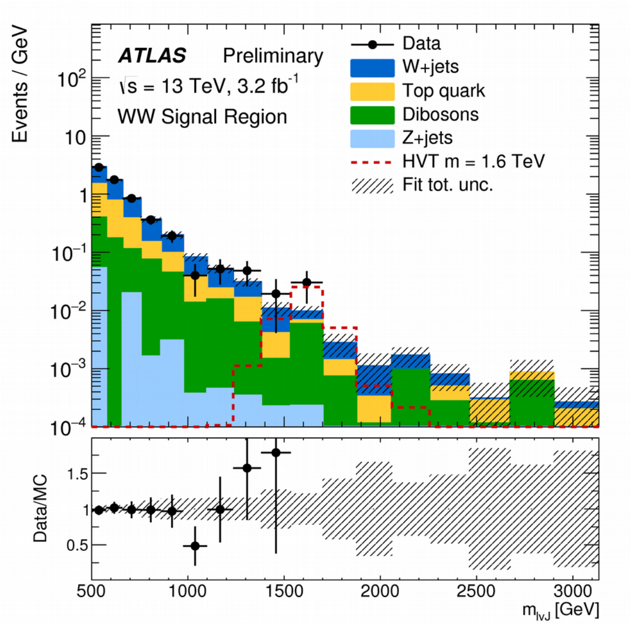
Statistical Treatment (example)

Perform *simultaneous fit* to mass spectra across SR and CRs (→ Top CR, W CR for lvJ channel)

- *Simultaneous fit applies common normalization factors across CRs and SRs*
  - *Strength parameters for the signal, Top, and W + jet backgrounds (shared strength common across all regions)*

Binning and fit range of final m_{lvJ} spectrum is varied for each mass hypothesis





Single bin likelihood

$$L(\mu, \mu_b) = \underbrace{P(N|\mu s + \mu_b b_{\text{SR}}^{exp})}_{\text{Signal bin}} \times \underbrace{P(M|\mu_b b_{\text{CR}}^{exp})}_{\text{Control bin}}$$

Multi-bin likelihood

$$L(\mu, \boldsymbol{\theta}) = \left\{ \underbrace{\prod_{i=\substack{e^+,e^- \\ \mu^+,\mu^-}} \prod_{j=\substack{\text{ggF} \\ \text{VBF}}} \prod_{k=1}^{k=N_{bins}}}_{\text{All flavours, production modes and bins}} P\left(N_{ijk} \middle| \mu s_{ijk} + \sum_{Nbkg} b_{ijk}\right) \right\} \times \underbrace{\prod_{i=1}^{N_\theta} N(\tilde{\theta}_i|\theta_i)}_{\text{Nuisance parameters*}}$$

*One nuisance parameter for each background and source of uncertainty

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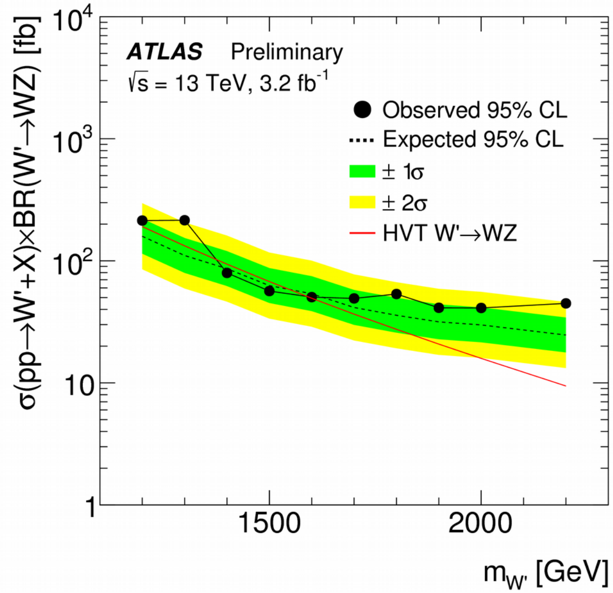
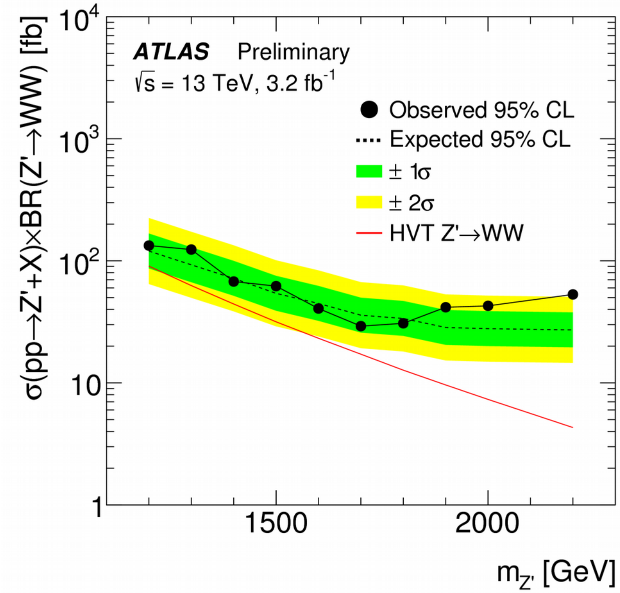
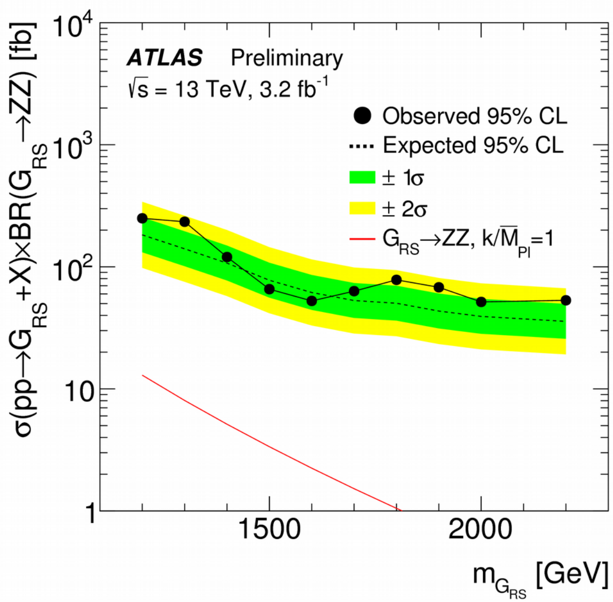
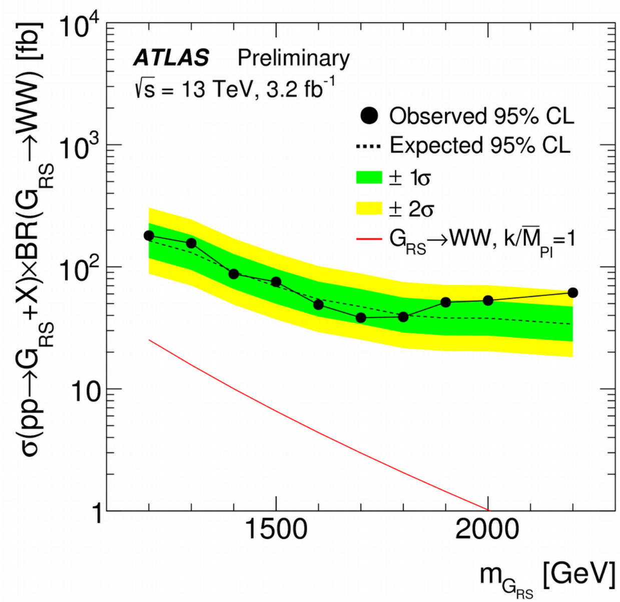
Fully Hadronic: *qqqq*

G* V'

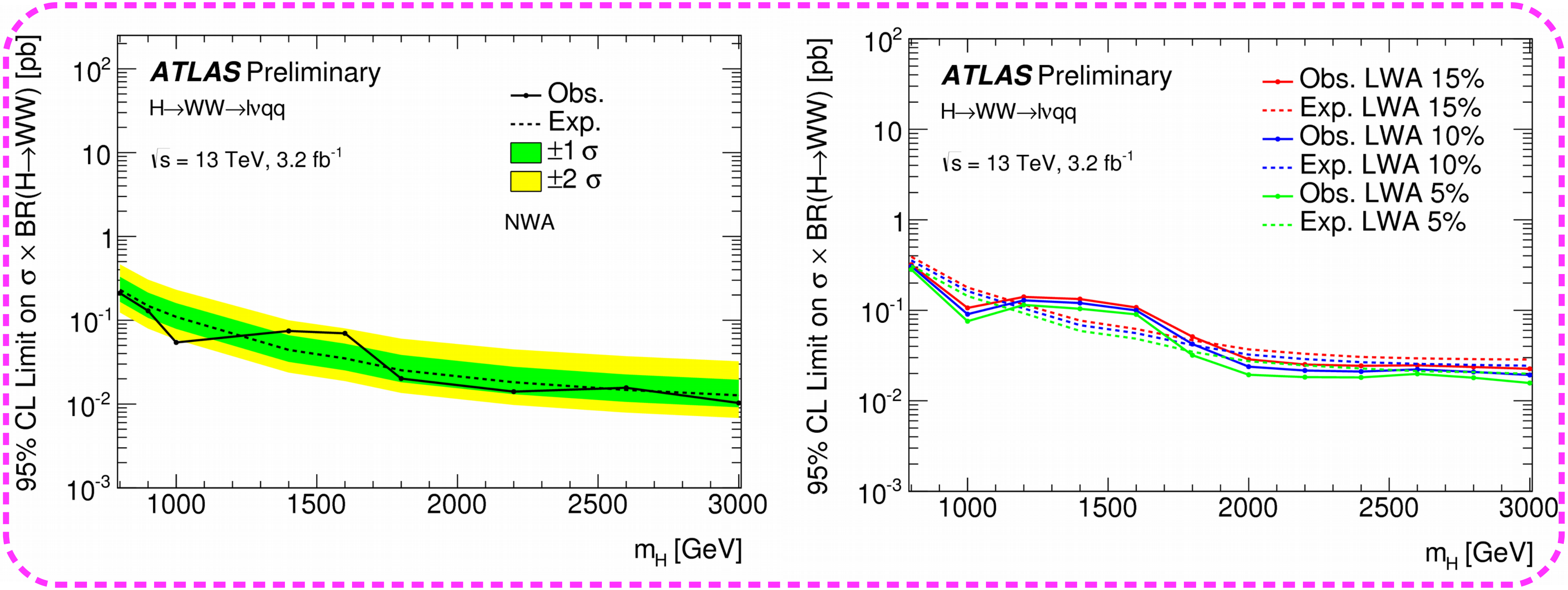




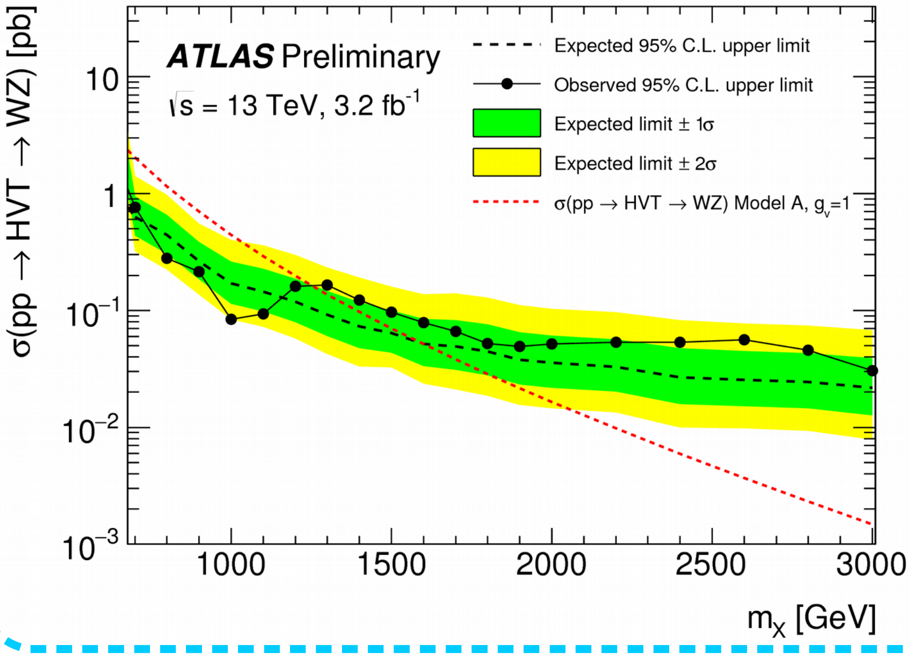


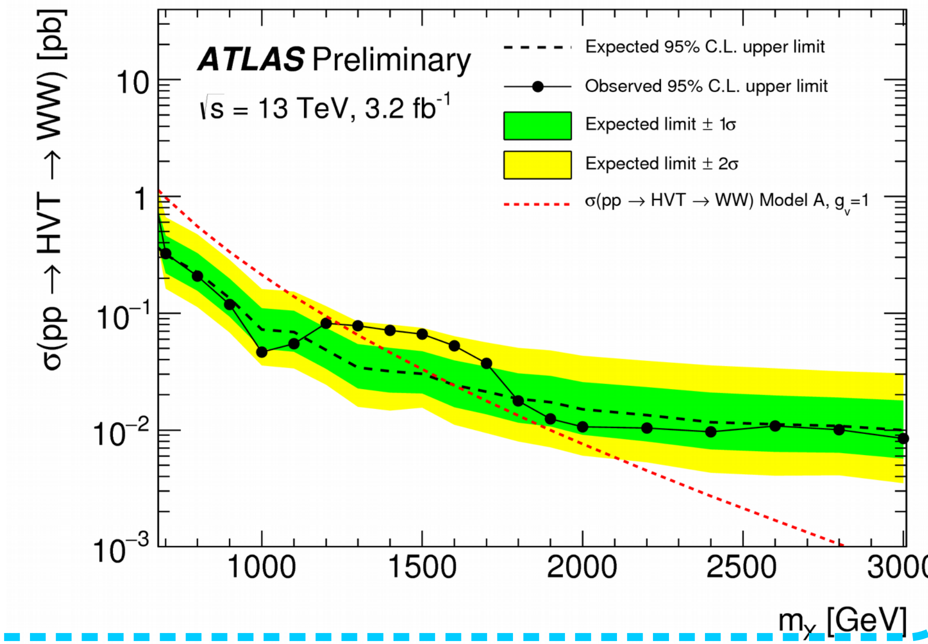


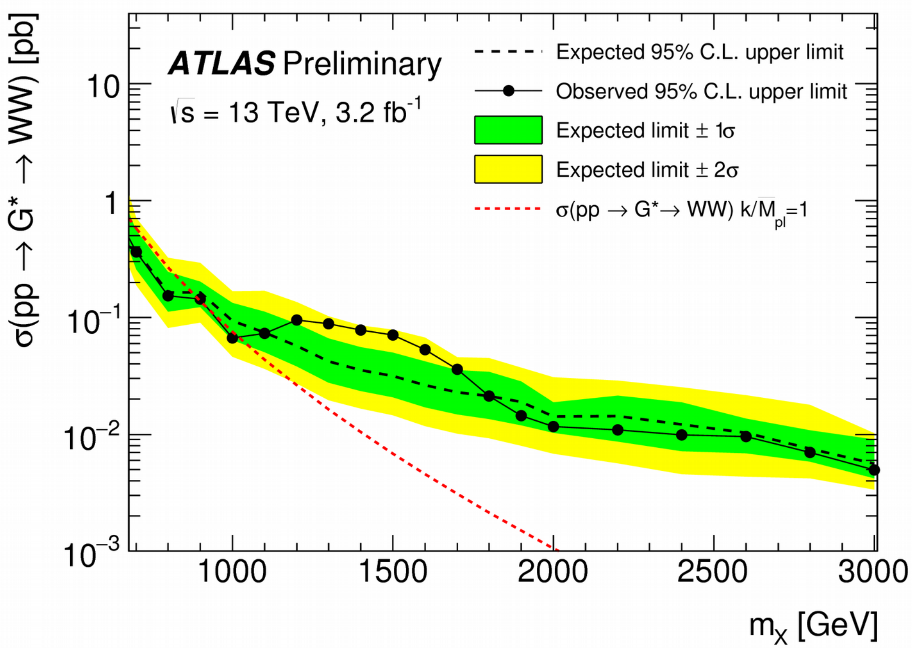
Semi-leptonic: *lvqq*



Semi-leptonic: *lvqq*

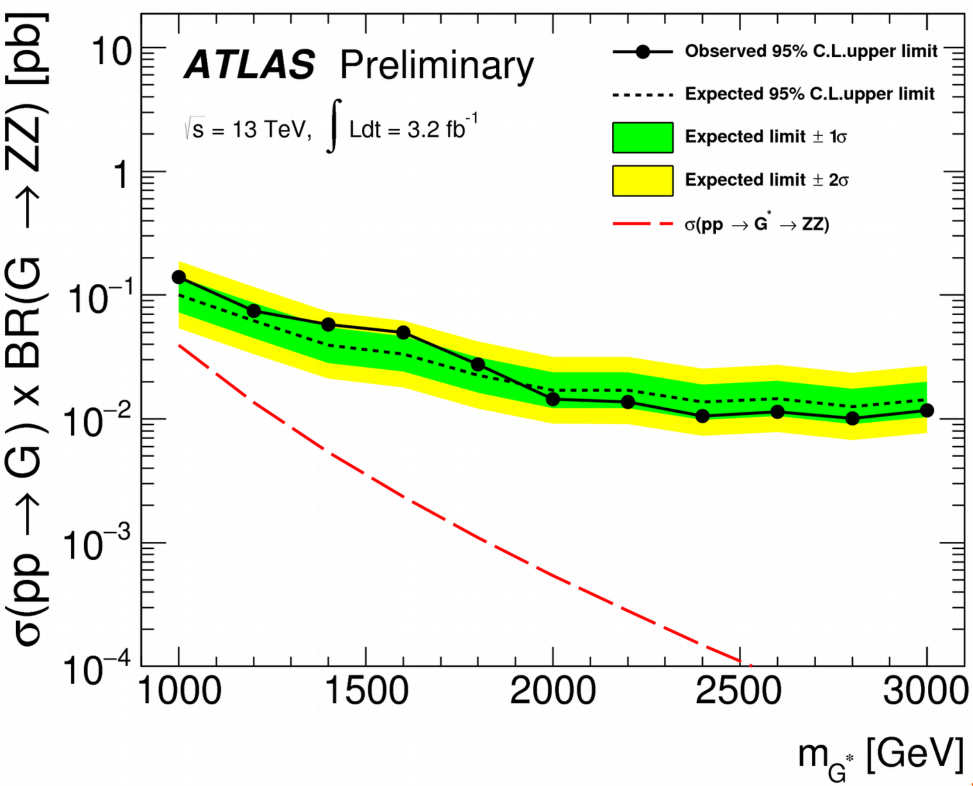


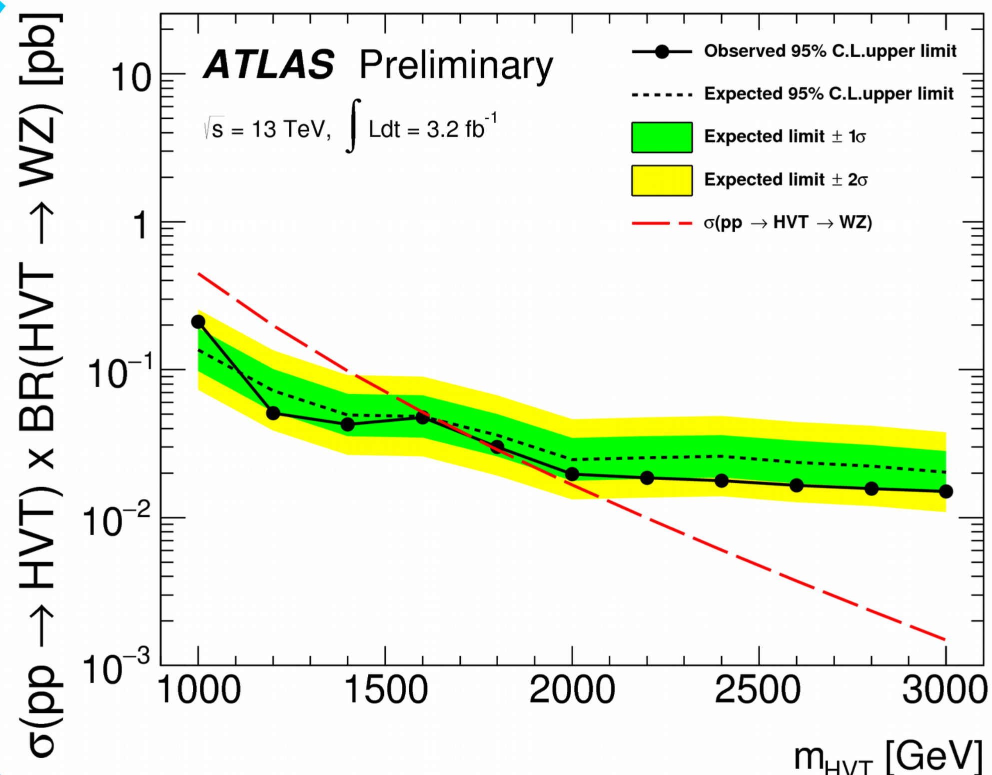




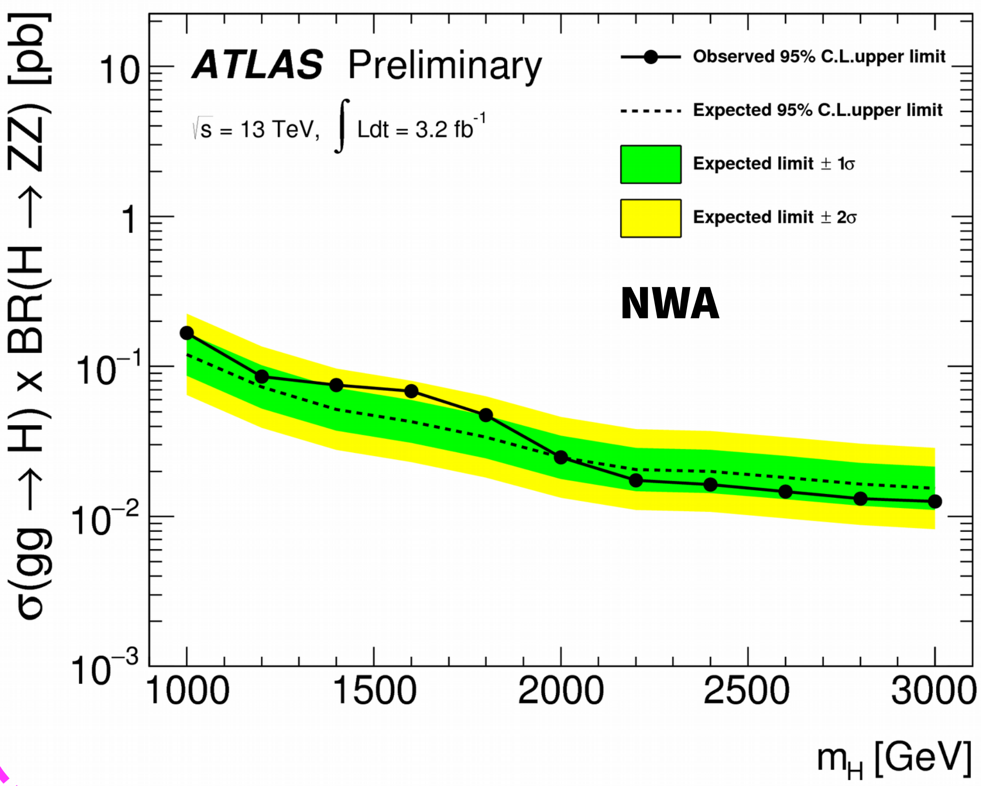
Semi-leptonic: *vvqq*

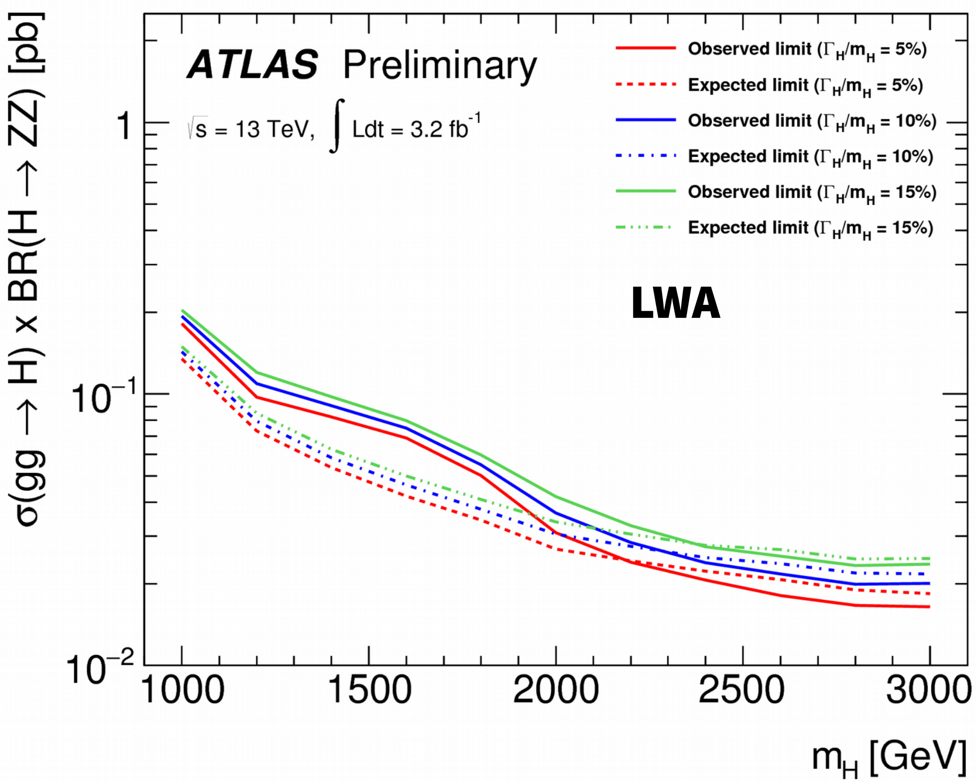
G* V'





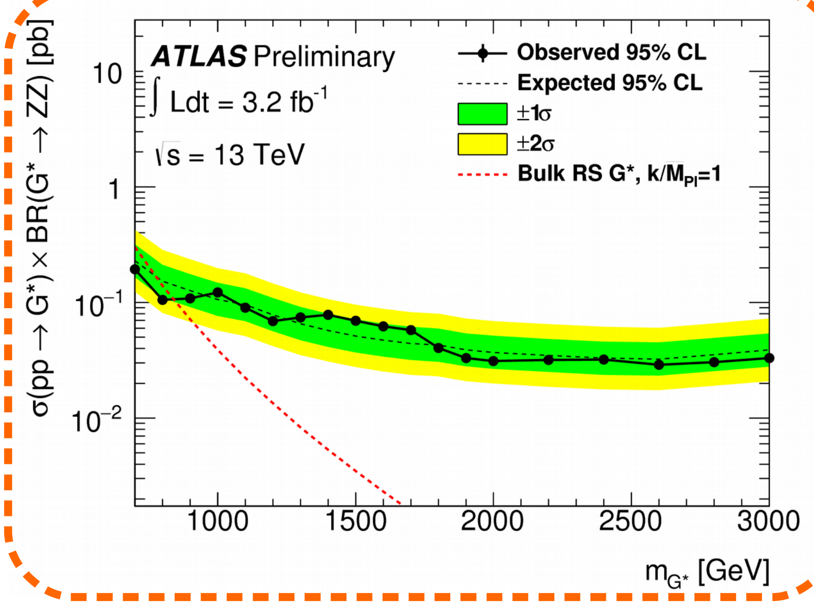
Semi-leptonic: *ννqq*

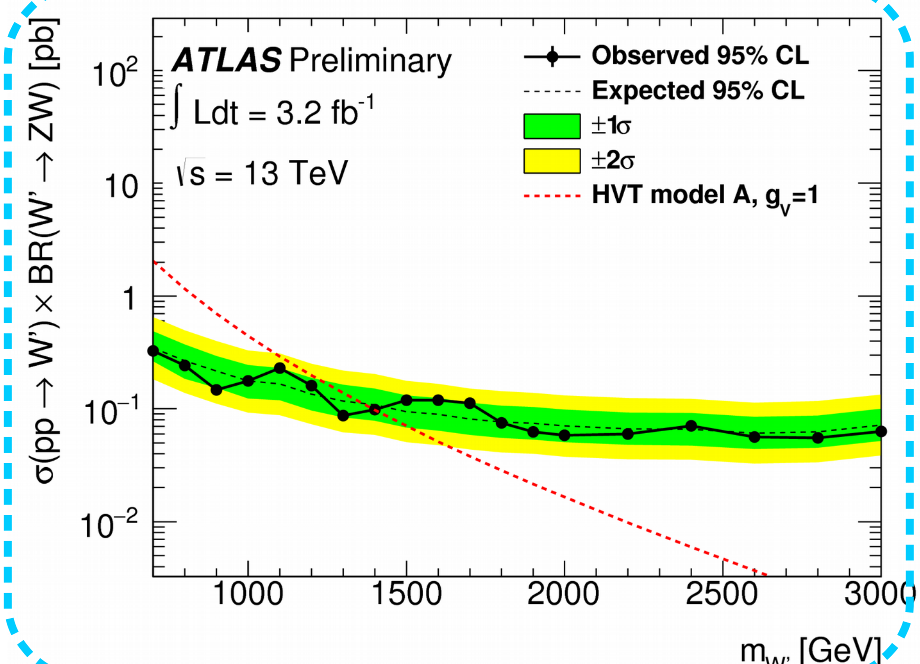


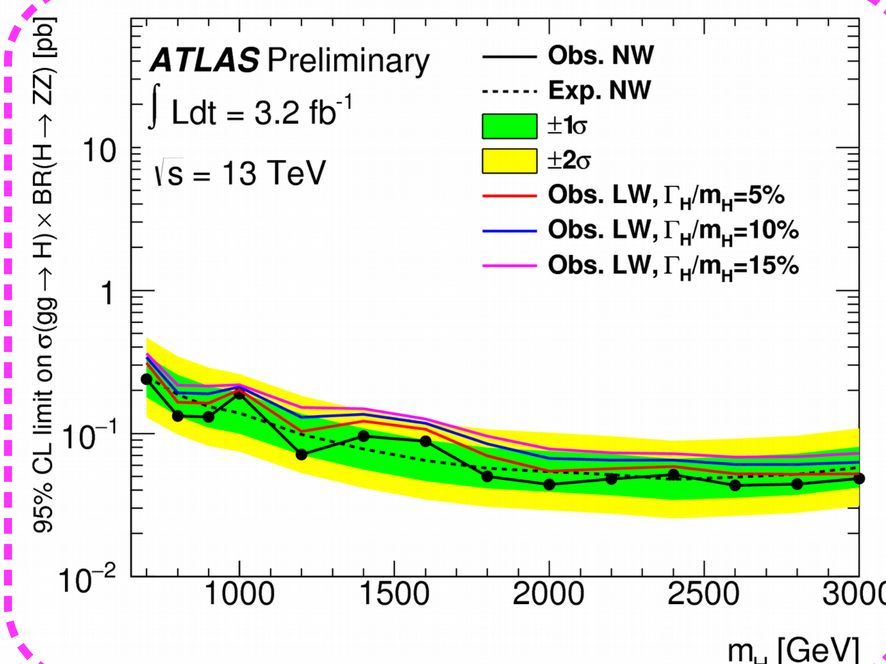


Semi-leptonic: *llqq*

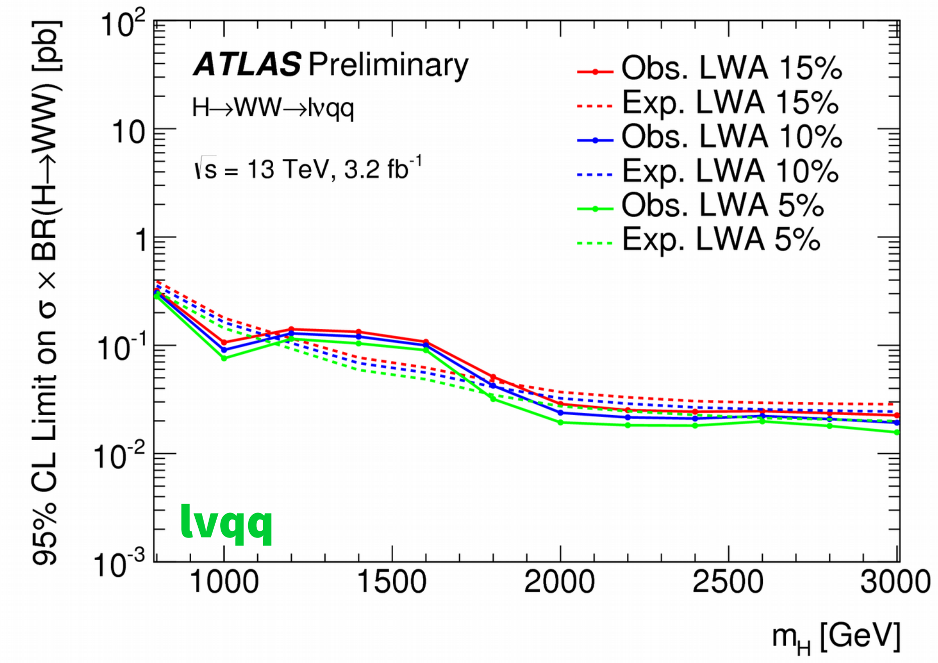
S G* V'







H/Scalar → VV [LWA]



Limits set for:

- *NWA resonance (shown previous)*
- *Γ/m = 5, 10, 15% (shown here)*