# Search for heavy resonances in vector boson scattering

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On behalf of the *ATLAS Collaboration*

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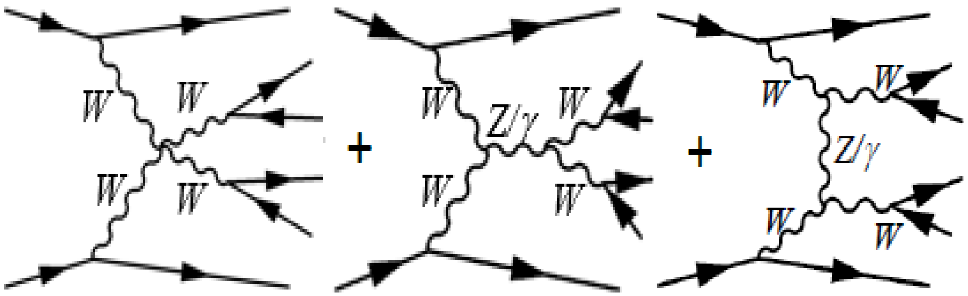
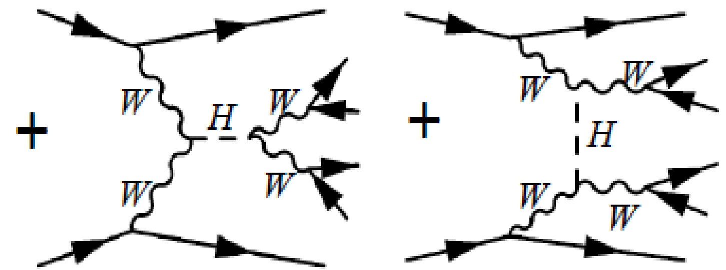
# Vector boson scattering

| $W^+W^-$ scattering/fusion without a SM Higgs | $W^+W^-$ scattering/fusion with a SM Higgs |
|---|---|



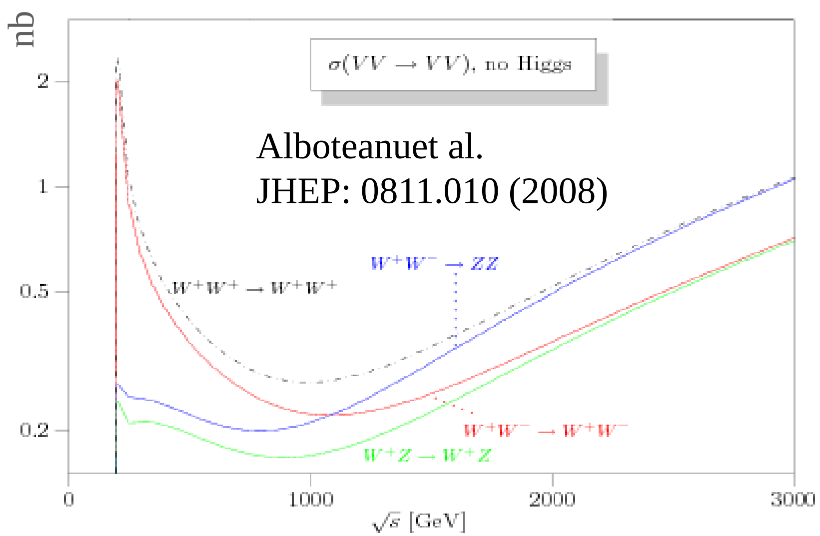



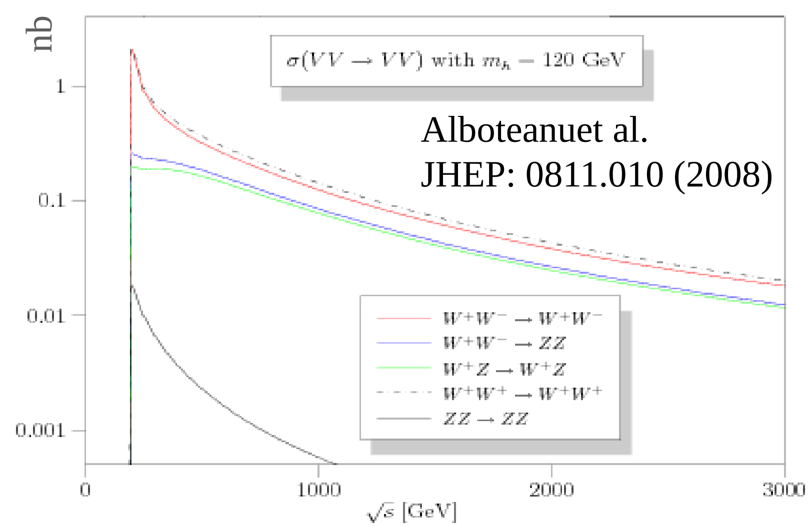

$M \propto s$, Unitarity violation

$M \propto M_H^2\left(\frac{s}{s-M_H^2}+\frac{t}{t-M_H^2}\right)$

Lee, Quigg, Thacker, PRD 16, 1519 (1977)

The unitarity can be restored by adding a Higgs scalar with exactly the SM HWW coupling

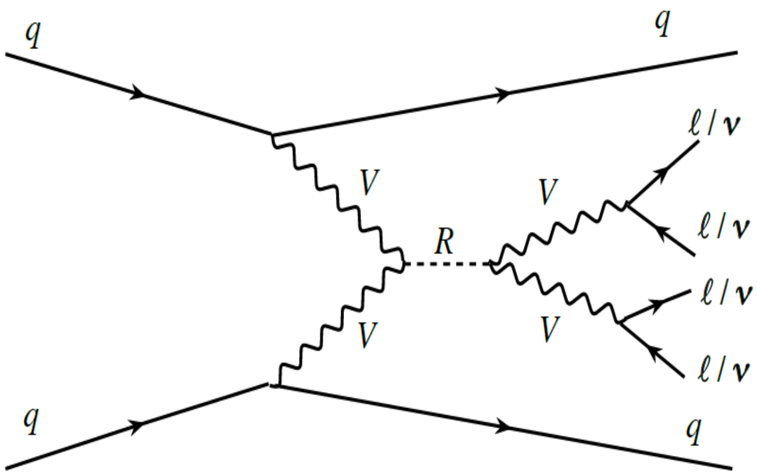


# Motivation

- If the Higgs discovered at the LHC is not exactly the one predicted by SM, vector boson scattering/fusion will violate unitarity in TeV range.
- New resonances may be needed to restore unitarity in the scattering amplitude of longitudinal gauge bosons
- Vector boson fusion (VBF) processes could provide the best sensitivity to these resonances if they have weak or no coupling to fermions

Signal Feynman diagram




- qq → Rqq → $\ell^+\nu\ell^-\bar{\nu}$qq ($\ell$ = e, μ)
- two charged leptons, $E_T^{miss}$, two forward jets
- large $\Delta\eta_{jj}$ & $m_{jj}$

# New resonances

## Resonance properties

- Benchmark Model: resonance with K-matrix unitarization using EWChL
- New resonance only couples to the longitudinal component of the vector boson, not to fermions, and thus can only be produced by VBF processes

$\Gamma_0 = g^2 m^3 / 64\pi v^2$

| Type | Spin $J$ | Isospin $I$ | Electric Charge | $\Gamma/\Gamma_0$ |
|---|---|---|---|---|
| $\sigma$ | 0 | 0 | 0 | 6 |
| $\phi$ | 0 | 2 | $--, -, 0, +, ++$ | 1 |
| $\rho$ | 1 | 1 | $-, 0, +$ | $\frac{4}{3}\left(\frac{v^2}{m^2}\right)$ |
| $f$ | 2 | 0 | 0 | $\frac{1}{5}$ |
| $t$ | 2 | 2 | $--, -, 0, +, ++$ | $\frac{1}{30}$ |

σ: scalar isoscalar
ϕ: scalar isotensor
ρ: vector isovector
f: tensor isoscalar
t: tensor isotensor

## Analysis status

- For Run1, no official results from both ATLAS and CMS
- For Run2, a search is performed for the first time for neutral resonances above the Higgs boson mass in VBF (CONF note: ATLAS-CONF-2016-053)



Guangyi Zhang (USTC / IPAS)

# Signal sample

- Signal definition:

| Signal sample | • New resonance<br>• SM EW $qq \to \ell^+ \nu \ell^- \bar{\nu} qq$<br>• Interference | **−** | SM continuum sample | • SM EW $qq \to \ell^+ \nu \ell^- \bar{\nu} qq$ |
|---|---|---|---|---|

**=** Signal (New resonance + interference)

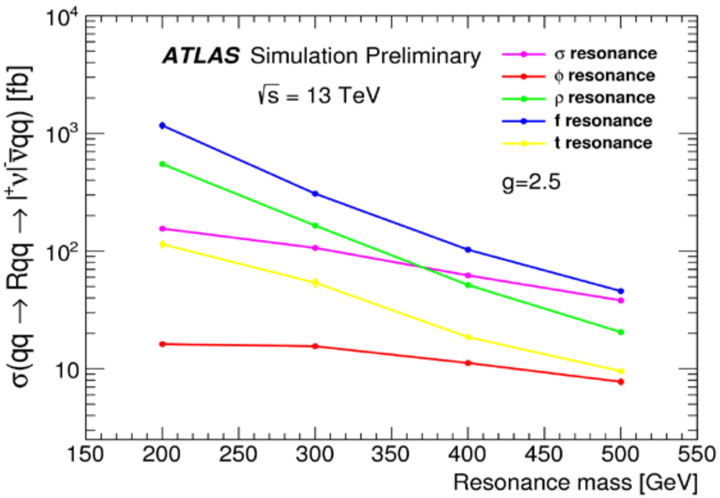
Using Whizard+Pythia8 to generate both samples

- EW samples are generated with g=2.5

  (g, coupling of new resonance to gauge bosons, the choice of g=2.5 is based on private discussions with theorists)

- 5 different resonance types (σ, φ, ρ, f and t) are generated with mass points from 200 to 500 GeV at 13 TeV

Signal Xsec vs. resonance mass



# Data/MC samples

- Data samples:
  - 25 ns data in 2015, Luminosity = 3.2 $fb^{-1}$
- MC samples:
  - $t\bar{t}$: Powheg
  - Wt: Powheg
  - Z+jets: MadGraph (QCD) and Sherpa (EW)
  - diboson: Sherpa (QCD) and Whizard (EW)
  - Z$\gamma$: Sherpa
  - ttV: MadGraph
  - SM Higgs: Powheg (ggH and VBF)
- MC corrections:
  - Lepton energy/momemtum scale/resolution
  - Lepton Reco/ID/Iso/Trig effSF
  - Jet energy scale/resolution, b−tag effSF
  - Pile-up reweighting

# Object definitions

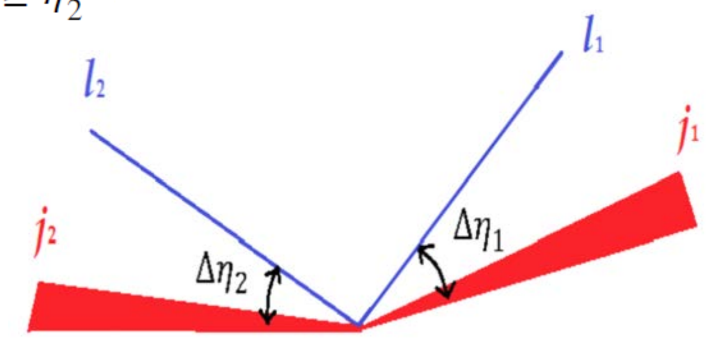
- Electron:
  - Kinematic cuts: $p_T$ > 25 GeV, $|\eta| < 2.47$ (veto on $1.37 < |\eta| < 1.52$)
  - Quality: track and parton shower shape requirements
  - Isolated electron
- Muon:
  - Kinematic cuts: $p_T$ > 25 GeV, $|\eta| < 2.5$
  - Quality: track and parton shower shape requirements
  - Isolated muon
- Jet:
  - Reconstructed using anti-$k_t$ algorithm with a radius parameter of R = 0.4
  - Kinematic cuts: $p_T$ > 30 GeV (> 50 GeV if $2.5<|\eta|<4.5$ ), $|\eta| < 4.5$
  - Pile-up removal
  - b-jets: BDT tagger with 85% efficiency working point
- $E_T^{miss}$:
  - Calculated using calibrated objects, track soft terms
  - $E_T^{miss}$ > 30 GeV

# Event selection

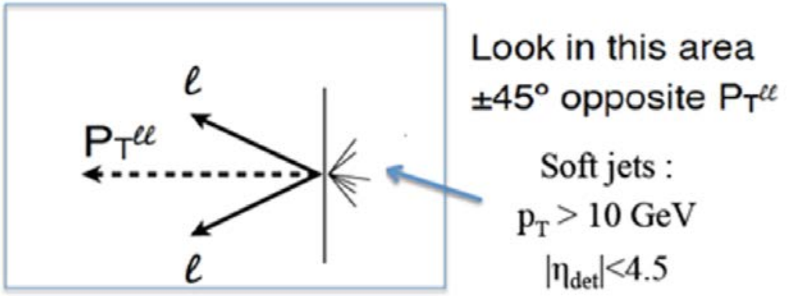
| # | Selection criteria |
|---|---|
| 1 | event preselection requirements, see text |
| 2 | exactly two leptons with $p_{\mathrm{T}} > 25$ GeV |
| 3 | pass single lepton trigger and trigger matching |
| 4 | third lepton veto |
| 5 | dilepton mass $m_{\ell\ell} > 40$ GeV |
| 6 | $q_{\ell_1} \times q_{\ell_2} < 0$ |
| 7 | $\|m_{\ell\ell} - m_Z\| > 25$ GeV in the $ee$ and $\mu\mu$ channels |
| 8 | at least two selected jets with $p_T > 30$ (50) GeV and $\|\eta\| < 2.5$ ($2.5 < \|\eta\| < 4.5$) |
| 9 | b-jet veto |
| 10 | $E_{\mathrm{T}}^{\mathrm{miss}} > 35$ GeV |
| 11 | $m_{jj} > 500$ GeV |
| 12 | $\|\Delta\eta_{jj}\| > 2.4$ |
| 13 | $\eta_{j_1} \times \eta_{j_2} < 0$ |
| 14 | lepton centrality $\zeta > -0.5$ |
| 15 | $f_{\mathrm{recoil}} < 2.0$ |

# Lepton centrality and $f_{recoil}$

- Lepton centrality $\zeta$ :
  - $\zeta = min\{\eta_1^{jet} - \eta_1^{\ell}, \eta_2^{\ell} - \eta_2^{jet}\}$ where $\eta_1^{\ell} \geq \eta_2^{\ell}$ and $\eta_1^{jet} \geq \eta_2^{jet}$
  - $\varsigma$ in VBF topology tends to be positive
  - To reduce the background from strong production of double vector boson processes ($\varsigma > -0.5$)




- $f_{recoil}$:
  - $$f_{\text{recoil}} = \frac{\left|\sum_{\text{soft jets}} \text{JVT}_j \cdot \vec{p}_{\text{T}}^{\,j}\right|}{p_{\text{T}}^{\ell\ell}}$$




  - Measures the strength of the recoil system relative to the dilepton system
  - Useful to reject the $Z/\gamma^* \to \ell\ell$ background
  - $f_{recoil} < 2$

# Background estimations

Backgrouds of ll'+$E_T^{miss}$+2jets

- SM processes that can produce events with two OS leptons
  - $t\bar{t}$
  - Z+jets
  - Wt
  - ttV
  - Zγ+jets
  - diboson (WW/WZ/ZZ)
  - SM Higgs (ggH, VBF)
  - → MC prediction
- SM processes that have one or two leptons from jets or photon (faked)
  - W+jets
  - QCD
  - → Data driven (Matrix method)

# Validation regions

➢ Dominant background sources :

- For ee/μμ channel: Z+jets & $t\bar{t}$
- For eμ channel: $t\bar{t}$

➢ Definitions of validation regions :

- The selection criteria listed on slide 8 is assumed unless otherwise specified

| Region | Purpose | Requirements |
|---|---|---|
| $Z$+jets VR | Validate $Z$+jets background modelling | no $m_{jj}$ cut,<br>$\lvert m_{\ell\ell} - m_Z \rvert < 25$ GeV (only $ee$ and $\mu\mu$ channels) |
| $t\bar{t}$ VR | Validate $t\bar{t}$ background modelling | no $m_{jj}$ cut,<br>at least one $b$-tagged jet |
| low-$m_{jj}$ VR | Validate low-mass background estimation | $m_{jj} < 500$ GeV |

➢ Z pT reweighting for the Z+jets prediction:

- Some discrepancy is found between data & MC prediction for the Z pT distribution
- A reweighting function is derived to correct the MC prediction
- This reweighting function used in both VRs and SR

# Data vs. predictions in the Z+jets VR

- Z+jets validation region:
  - No $m_{jj}$ > 500 GeV cut, $|m_{\ell\ell}-m_Z|$< 25 GeV, based on all selections on slide 8

| $Z$+jets VR | $ee$ | $\mu\mu$ |
|---|---|---|
| $Z$+jets | $808 \pm 13 \pm 337$ | $1686 \pm 20 \pm 721$ |
| $t\bar{t}$ | $17.2 \pm 0.7 \pm 4.5$ | $25.5 \pm 0.9 \pm 6.2$ |
| $Wt$ | $1.6 \pm 0.2 \pm 0.5$ | $2.5 \pm 0.2 \pm 0.5$ |
| diboson_QCD | $14.2 \pm 1.4 \pm 2.6$ | $20.9 \pm 1.7 \pm 5.4$ |
| diboson_EW | $0.7 \pm 0.0 \pm 0.1$ | $0.9 \pm 0.1 \pm 0.1$ |
| $Z\gamma$ | $29.0 \pm 0.9 \pm 8.4$ | $48.5 \pm 1.2 \pm 15.2$ |
| Higgs | $0.1 \pm 0.0 \pm 0.3$ | $0.1 \pm 0.0 \pm 0.0$ |
| $ttV$ | $0.1 \pm 0.0 \pm 0.0$ | $0.1 \pm 0.0 \pm 0.0$ |
| fake-lepton | $6.9 \pm 2.9 \pm 1.6$ | $0.0 \pm 0.0 \pm 0.0$ |
| Total background | $878 \pm 13 \pm 347$ | $1784 \pm 20 \pm 741$ |
| Data | 804 | 1630 |

Reasonable agreement of data and the SM prediction is observed.

# Data vs. predictions in the $t\bar{t}$ VR

- $t\bar{t}$ validation region:
  - No $m_{jj}$ > 500 GeV cut, at least one b-tagged jet, based on all selections on slide 8

| $t\bar{t}$ VR | $ee$ | $\mu\mu$ | $e\mu$ |
|---|---|---|---|
| $Z$+jets | $14.1 \pm 1.1 \pm 5.6$ | $24.6 \pm 2.0 \pm 8.7$ | $2.8 \pm 0.5 \pm 1.4$ |
| $t\bar{t}$ | $247 \pm 3 \pm 24$ | $364 \pm 3 \pm 35$ | $954 \pm 5 \pm 92$ |
| $Wt$ | $17.8 \pm 0.6 \pm 2.0$ | $26.7 \pm 0.8 \pm 2.7$ | $64.6 \pm 1.2 \pm 7.4$ |
| diboson_QCD | $1.6 \pm 0.2 \pm 0.4$ | $2.1 \pm 0.2 \pm 0.5$ | $4.6 \pm 0.2 \pm 1.0$ |
| diboson_EW | $0.2 \pm 0.0 \pm 0.0$ | $0.2 \pm 0.0 \pm 0.1$ | $0.7 \pm 0.0 \pm 0.2$ |
| $Z\gamma$ | $1.5 \pm 0.2 \pm 0.7$ | $1.8 \pm 0.2 \pm 1.0$ | $0.0 \pm 0.0 \pm 0.2$ |
| Higgs | $0.1 \pm 0.0 \pm 0.0$ | $0.1 \pm 0.0 \pm 0.0$ | $0.2 \pm 0.0 \pm 0.1$ |
| $ttV$ | $0.3 \pm 0.0 \pm 0.0$ | $0.4 \pm 0.0 \pm 0.1$ | $0.9 \pm 0.0 \pm 0.1$ |
| fake-lepton | $4.0 \pm 1.7 \pm 0.5$ | $0.0 \pm 0.0 \pm 0.0$ | $2.2 \pm 2.0 \pm 0.3$ |
| Total background | $287 \pm 3 \pm 29$ | $420 \pm 4 \pm 40$ | $1030 \pm 6 \pm 98$ |
| Data | 279 | 444 | 1042 |

Reasonable agreement of data and the SM prediction is observed.

# Data vs. predictions in the low-$m_{jj}$ VR

- low-$m_{jj}$ validation region:
  - $m_{jj}$<500 GeV, based on all selections on slide 8

| low-$m_{jj}$ VR | $ee$ | $\mu\mu$ | $e\mu$ |
|---|---|---|---|
| $Z$+jets | $30 \pm 2 \pm 13$ | $58 \pm 3 \pm 24$ | $7 \pm 1 \pm 2$ |
| $t\bar{t}$ | $21 \pm 1 \pm 5$ | $30 \pm 1 \pm 8$ | $73 \pm 1 \pm 19$ |
| $Wt$ | $2.4 \pm 0.2 \pm 0.6$ | $2.9 \pm 0.3 \pm 0.7$ | $6.8 \pm 0.4 \pm 1.6$ |
| diboson_QCD | $3.3 \pm 0.3 \pm 0.4$ | $5.2 \pm 0.3 \pm 0.5$ | $13.4 \pm 0.4 \pm 1.7$ |
| diboson_EW | $0.0 \pm 0.0 \pm 0.1$ | $0.3 \pm 0.0 \pm 0.1$ | $0.6 \pm 0.0 \pm 0.1$ |
| $Z\gamma$ | $4.3 \pm 0.4 \pm 1.4$ | $7.1 \pm 0.5 \pm 2.5$ | $0.1 \pm 0.1 \pm 0.1$ |
| Higgs | $0.1 \pm 0.0 \pm 0.0$ | $0.3 \pm 0.0 \pm 0.1$ | $0.5 \pm 0.0 \pm 0.0$ |
| $ttV$ | $0.0 \pm 0.0 \pm 0.0$ | $0.0 \pm 0.0 \pm 0.0$ | $0.1 \pm 0.0 \pm 0.0$ |
| fake-lepton | $3.2 \pm 1.0 \pm 0.1$ | $0.0 \pm 0.0 \pm 0.0$ | $1.2 \pm 0.7 \pm 0.1$ |
| Total background | $64 \pm 3 \pm 17$ | $103 \pm 3 \pm 29$ | $103 \pm 2 \pm 21$ |
| Data | 51 | 95 | 118 |

Reasonable agreement of data and the SM prediction is observed.

# Signal region

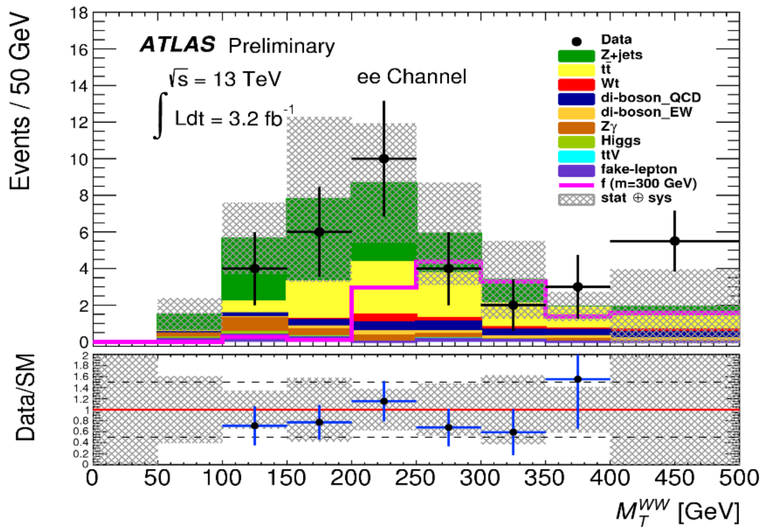
- Signal region:
  - Based on all selections on slide 8

| | $ee$ | $\mu\mu$ | $e\mu$ |
|---|---|---|---|
| $Z$+jets | $17.6 \pm 1.2 \pm 11.6$ | $36.6 \pm 2.3 \pm 19.0$ | $6.7 \pm 1.2 \pm 1.7$ |
| $t\bar{t}$ | $12.1 \pm 0.6 \pm 3.2$ | $18.2 \pm 0.7 \pm 4.6$ | $46.9 \pm 1.2 \pm 12.1$ |
| $Wt$ | $1.2 \pm 0.2 \pm 0.3$ | $1.5 \pm 0.2 \pm 0.5$ | $3.1 \pm 0.3 \pm 0.8$ |
| diboson_QCD | $3.1 \pm 0.3 \pm 0.5$ | $4.2 \pm 0.3 \pm 0.7$ | $10.2 \pm 0.3 \pm 1.6$ |
| diboson_EW | $1.2 \pm 0.1 \pm 0.1$ | $1.7 \pm 0.1 \pm 0.2$ | $3.6 \pm 0.1 \pm 0.4$ |
| $Z\gamma$ | $2.1 \pm 0.3 \pm 0.6$ | $3.8 \pm 0.3 \pm 0.7$ | $0.1 \pm 0.0 \pm 0.1$ |
| Higgs | $0.3 \pm 0.0 \pm 0.1$ | $0.4 \pm 0.0 \pm 0.1$ | $0.8 \pm 0.0 \pm 0.1$ |
| $ttV$ | $0.0 \pm 0.0 \pm 0.0$ | $0.0 \pm 0.0 \pm 0.0$ | $0.1 \pm 0.0 \pm 0.0$ |
| fake-lepton | $0.6 \pm 0.6 \pm 0.1$ | $0.0 \pm 0.0 \pm 0.0$ | $1.3 \pm 0.7 \pm 0.1$ |
| $\sigma$ ($m = 300$ GeV) | $5.1 \pm 0.3 \pm 0.6$ | $7.5 \pm 0.3 \pm 0.9$ | $14.4 \pm 0.4 \pm 1.9$ |
| $\phi$ ($m = 300$ GeV) | $0.3 \pm 0.1 \pm 0.2$ | $1.0 \pm 0.1 \pm 0.4$ | $1.6 \pm 0.2 \pm 0.4$ |
| $\rho$ ($m = 300$ GeV) | $8.0 \pm 0.4 \pm 1.6$ | $11.7 \pm 0.4 \pm 1.4$ | $24.1 \pm 0.6 \pm 3.1$ |
| $f$ ($m = 300$ GeV) | $15.6 \pm 0.6 \pm 1.9$ | $22.6 \pm 0.8 \pm 1.9$ | $50.4 \pm 1.2 \pm 3.8$ |
| $t$ ($m = 300$ GeV) | $3.3 \pm 0.2 \pm 0.4$ | $4.7 \pm 0.2 \pm 0.6$ | $6.9 \pm 0.3 \pm 1.1$ |
| Total background | $38.2 \pm 1.6 \pm 13.9$ | $66.4 \pm 2.5 \pm 21.6$ | $72.6 \pm 1.9 \pm 14.8$ |
| Data | 40 | 74 | 86 |

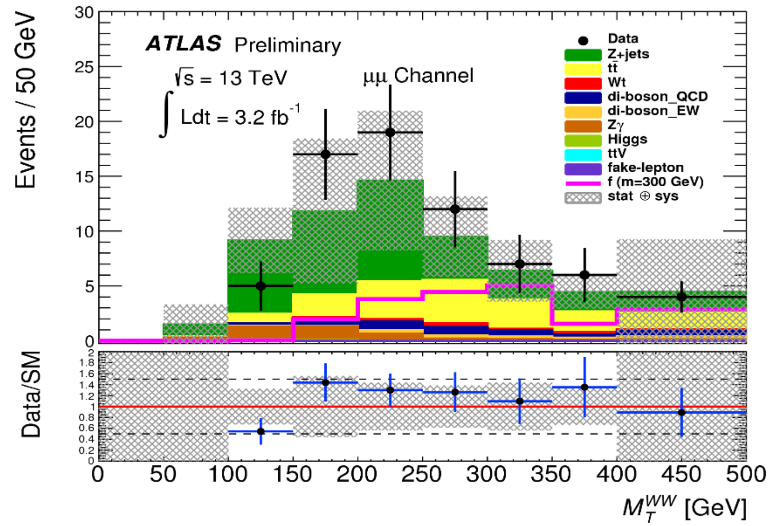
No significant excess above the SM background expectation is observed.

# Data vs. predictions in the signal region

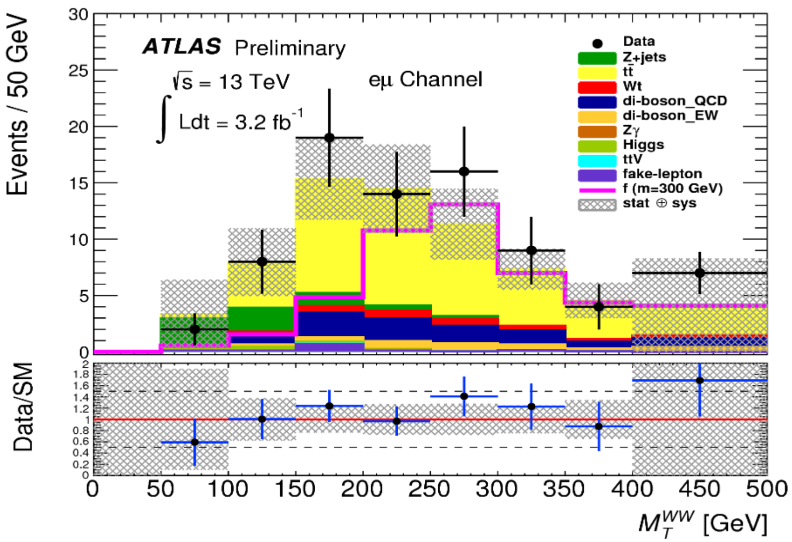
ee-channel




μμ-channel




eμ-channel




-- Due to two neutrinos in the final state, $M_T^{WW}$ is a useful discriminating variable:

$$(M_T^{WW})^2 = (P_{\ell_1} + P_{\ell_2} + P^{miss})(P_{\ell_1} + P_{\ell_2} + P^{miss})$$

-- No significant excess beyond the SM background predication is found

# Systematic uncertainties

- Experimental uncertainties(%) on the backgrounds in the signal region:

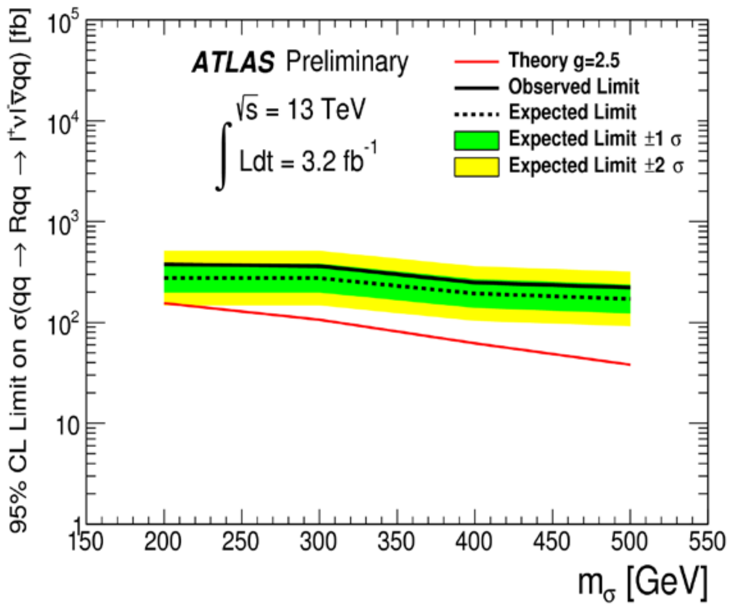
| Source | $ee$ | $\mu\mu$ | $e\mu$ |
|---|---|---|---|
| JES and JER | 33% | 29% | 12% |
| $b$-tagging | 8% | 7% | 16% |
| $E_T^{miss}$ modelling | 7% | 6% | 1% |
| Lepton | 3.1% | 2.2% | 1.5% |
| Trigger | 0.1% | 0.5% | 0.5% |
| Matrix method | 0.2% | 0.0% | 0.1% |
| $Z$ boson $p_{\mathrm{T}}$ reweighting | 0.5% | 0.4% | 0.0% |
| MC statistics | 4.1% | 3.7% | 2.6% |
| Luminosity | 2.1% | 2.1% | 2.1% |
| Total experimental uncertainty | 35% | 31% | 20% |

- Experimental uncertainties on the signal are considered (JES/JER, b-tagging, $E_T^{miss}$ modelling, Lepton, Trigger, Luminosity)
- Theoretical uncertainties on the production Xsec of the backgrounds and additional shape systematic uncertainties for the two dominant background (Z+jets, $t\bar{t}$) are included.

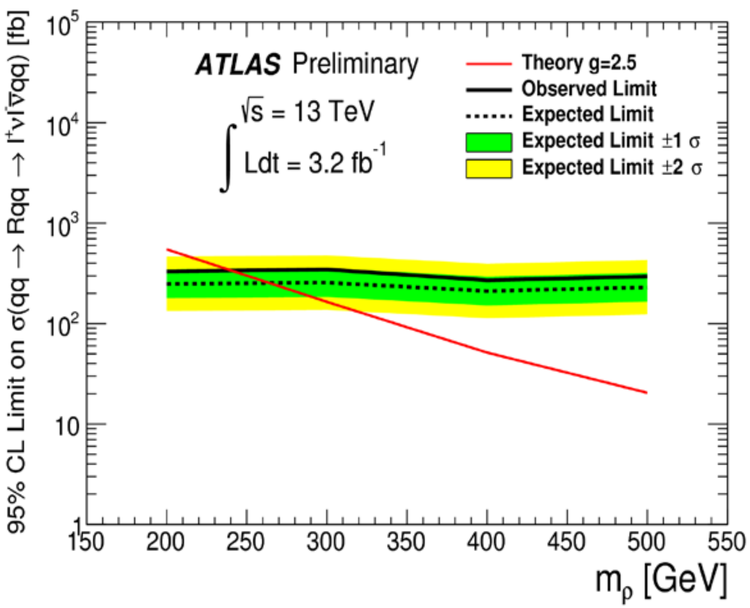
# 95% CL upper limits I

- No significant excess above the SM background expectation is observed.
- 95% CL upper limits are derived on the production cross section times branching ratio for five new resonances (σ, φ, ρ, f and t).
- The asymptotic approximation is used to compute 95% CL upper limits based on a common statistical framework “Resonance Finder”.
- Number counting (1 bin) as inputs to set limit due to limited signal statistics.

σ

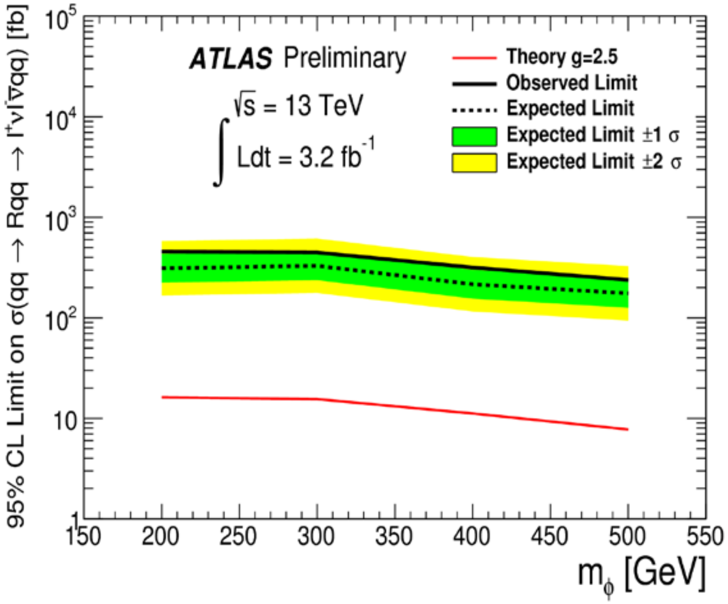



ρ

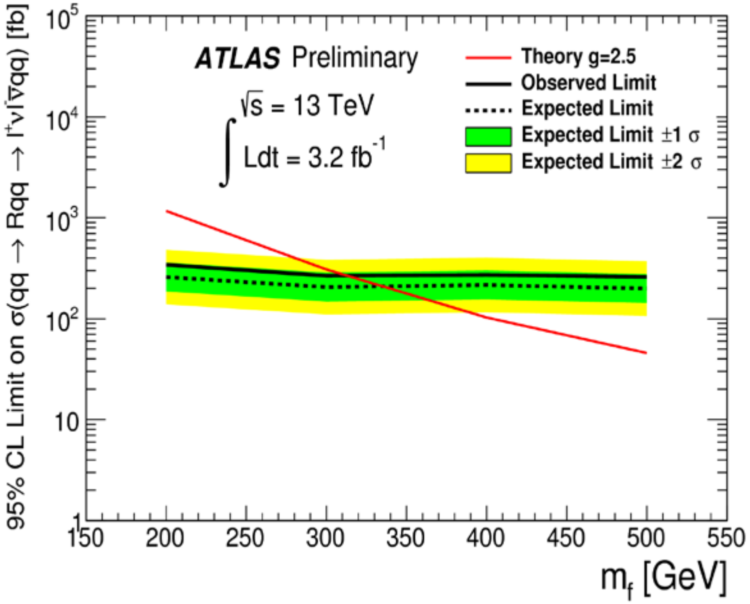


# 95% CL upper limits II

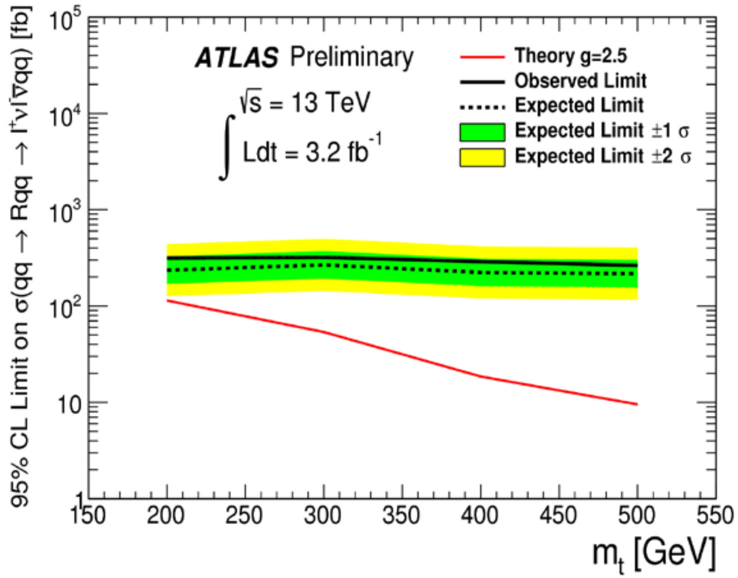
φ




f




t



# Summary

- A search for a heavy neutral resonance in vector boson fusion using 3.2 $fb^{-1}$ of data at $\sqrt{s}$ = 13 TeV recorded by the ATLAS detector was presented:
  - Presented Z+jets, $t\bar{t}$ and low-$m_{jj}$ validation regions, and reasonable agreement of data and SM prediction observed.
  - No significant excess above the SM background expectation is observed in signal region.
  - First sets of limits are obtained on the production cross section times branching ratio of five types of new resonances (σ, φ, ρ, f, t).
  - CONF note: ATLAS-CONF-2016-053