Search for heavy neutral resonances in vector boson fusion qq -> lvlvqq with the ATLAS detector

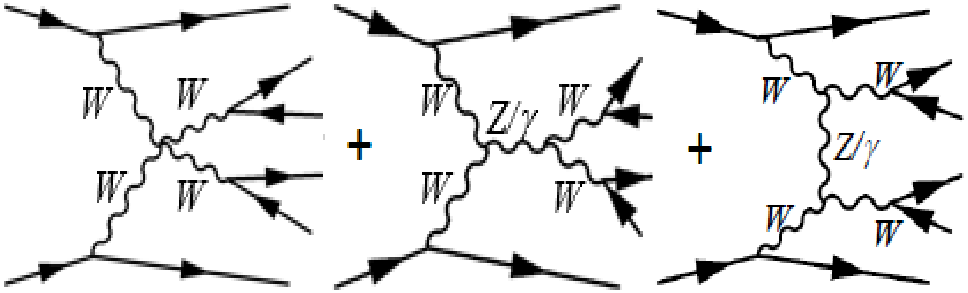
Liang Han, Minghui Liu, **Guangyi Zhang**

University of Science and Technology of China

Second China LHC Physics Workshop (CLHCP 2016)
Peking University, 16-19 December 2016

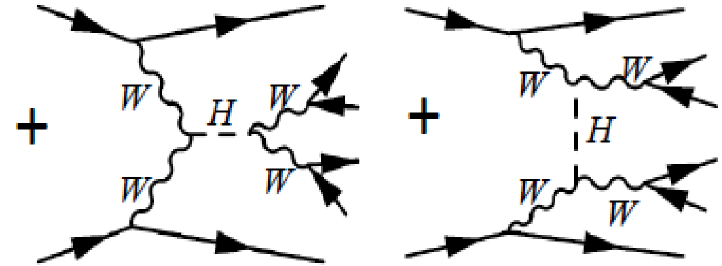
Vector boson fusion (VBF)

W^+W^- scattering/fusion without a SM Higgs



$\mathrm{M} \propto s$, Unitarity violation

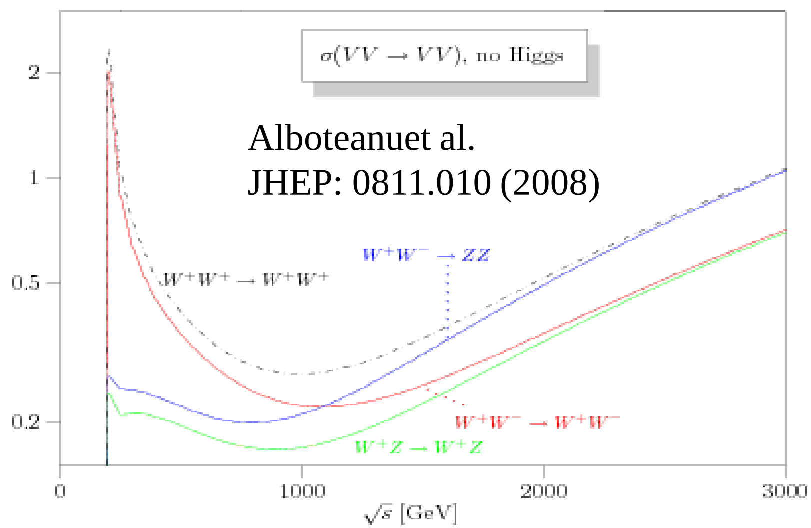
W^+W^- scattering/fusion with a SM Higgs

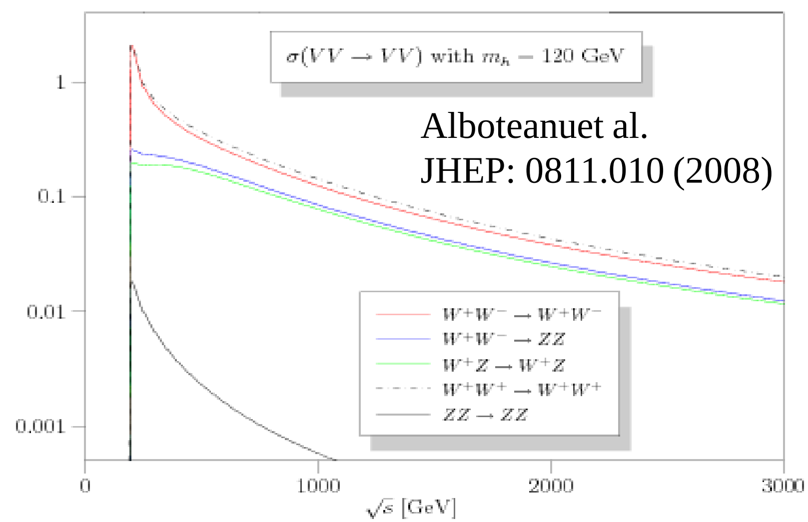


$$\mathrm{M} \propto M_H^2 \left(\frac{s}{s-M_H^2} + \frac{t}{t-M_H^2} \right)$$

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

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

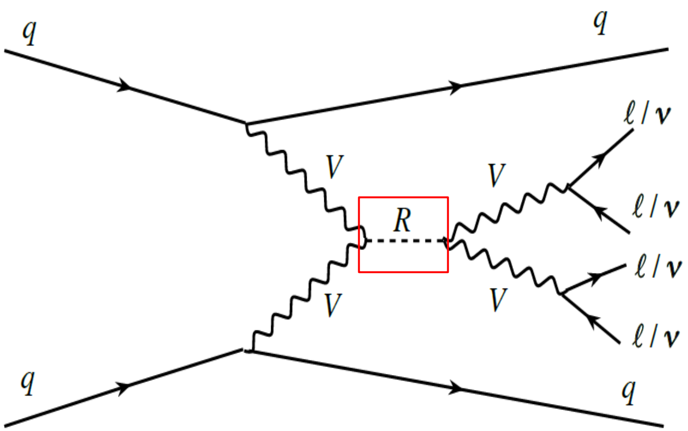




Motivation

- Sensitive to the new physics:
  - Unknown issues about Higgs discovered at the LHC:
    - ❑ fully or only partially unitarizes the VBF amplitude ?
    - ❑ the coupling $H \rightarrow VV$ is exactly the one that SM predicted ?
  - New resonances needed:
    - ❑ Any deviation of the coupling SM HVV would hint at new physics
    - ❑ New resonances will be needed to restore the unitarity

Signal Feynman diagram



If new resonance R has no/weak coupling to fermion, VBF will be a good channel

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

New resonances

Signal Model

- Benchmark Model: resonance with K-matrix unitarization using EWChL
- New resonances: 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	Γ/Γ_0
σ	0	0	0	6
ϕ	0	2	$--,-,0,+,++$	1
ρ	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

Free parameters: coupling & mass

Analysis status

- In 2016, a search is performed for the first time for neutral resonances above the Higgs boson mass in VBF (CONF note for ICHIP: ATLAS-CONF-2016-053)
- In 2017, aim to have a common paper with HWW analysis for Moriond

Signal sample

- Signal definition:

Signal sample	• New resonance • SM EW $qq \to \ell^+ \nu \ell^- \bar{\nu} qq$ • 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

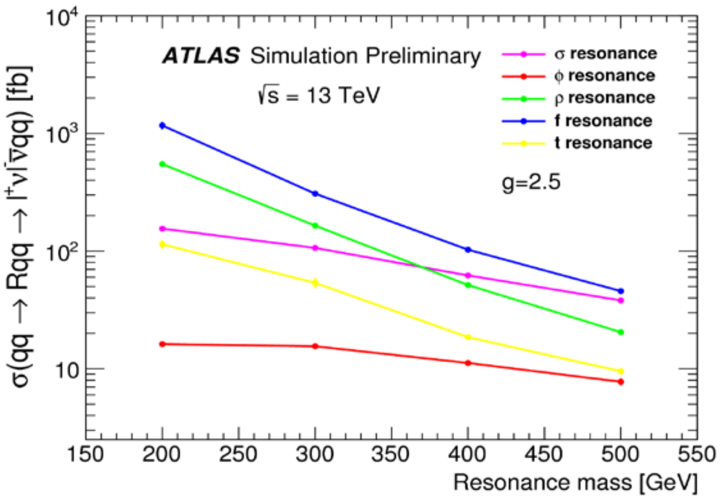
- EW samples are generated with fixed g=2.5

  (g, coupling of new resonance to gauge bosons)

- 5 different resonance types (σ, φ, ρ, f and t):

  m=200 -500 GeV

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)
  - Zγ: 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

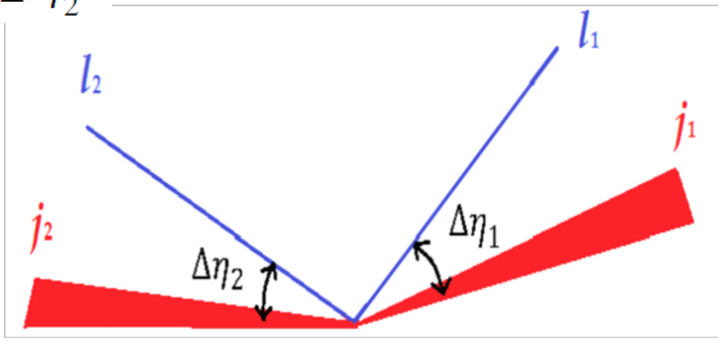
- Electron:
  - Kinematic cuts: p_T > 25 GeV, $|\eta|$ < 2.47 (veto on 1.37 < $|\eta|$ < 1.52)
  - Quality: track and calorimeter requirements
  - Isolated electron
- Muon:
  - Kinematic cuts: p_T > 25 GeV, $|\eta|$ < 2.5
  - Quality: track requirements
  - Isolated muon
- Jet:
  - Reconstructed using 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

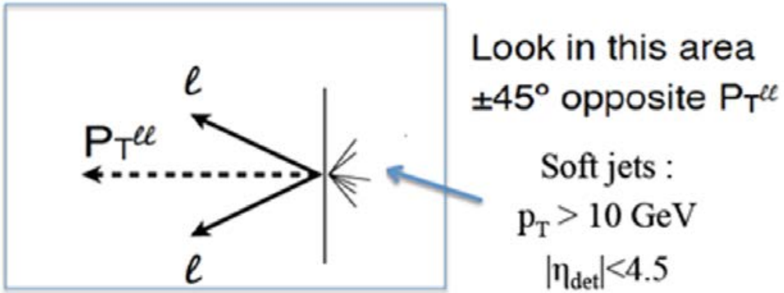
#	Selection criteria
1	event preselection requirements, see text
2	exactly two leptons with $p_{\mathrm{T}} > 25$ GeV
3	pass single lepton trigger and trigger matching
4	third lepton veto
5	dilepton mass $m_{\ell\ell} > 40$ GeV
6	$q_{\ell_1} \times q_{\ell_2} < 0$
7	$\lvert m_{\ell\ell} - m_Z \rvert > 25$ GeV in the ee and $\mu\mu$ channels
8	at least two selected jets with $p_T > 30$ (50) GeV and $\lvert\eta\rvert < 2.5$ $(2.5 < \lvert\eta\rvert < 4.5)$
9	b-jet veto
10	$E_{\mathrm{T}}^{\mathrm{miss}} > 35$ GeV
11	$m_{jj} > 500$ GeV
12	$\lvert\Delta\eta_{jj}\rvert > 2.4$
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 ζ :
  - $\zeta = min\{\eta_1^{jet} - \eta_1^{\ell}, \eta_2^{\ell} - \eta_2^{jet}\}$ where $\eta_1^{\ell} \geq \eta_2^{\ell}$ and $\eta_1^{jet} \geq \eta_2^{jet}$
  - ς in VBF topology tends to be positive
  - To reduce the background from strong production of double vector boson processes (ς > -0.5)



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



  - Measures the strength of the recoil system relative to the dilepton system
  - Useful to reject the $Z/\gamma^* \rightarrow \ell\ell$ 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 :

- 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, $\lvert m_{\ell\ell} - m_Z \rvert < 25$ GeV (only ee and $\mu\mu$ channels)
$t\bar{t}$ VR	Validate $t\bar{t}$ background modelling	no m_{jj} cut, 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 for 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/$t\bar{t}$ VRs

- Z+jets validation region:

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

- $t\bar{t}$ validation region: Reasonable agreement of data and the SM prediction observed.

$t\bar{t}$ 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

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

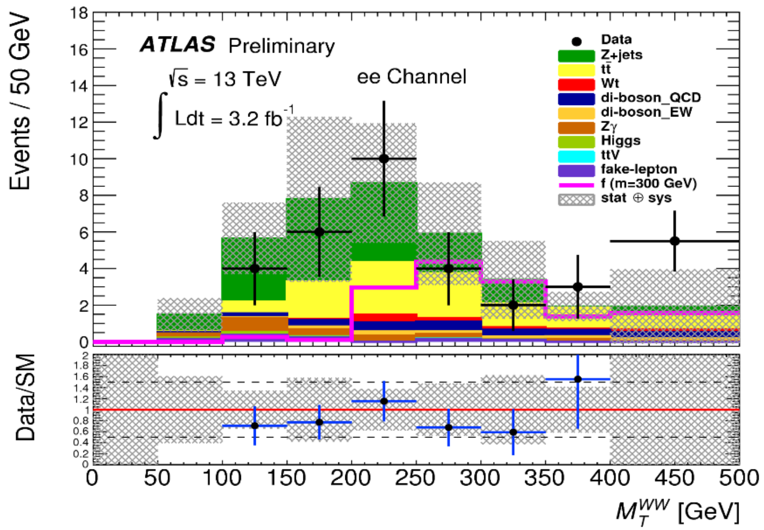
- Signal region:
  - Based on all selections on slide 8

	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
σ ($m = 300$ GeV)	5.1 $\pm 0.3 \pm 0.6$	7.5 $\pm 0.3 \pm 0.9$	14.4 $\pm 0.4 \pm 1.9$
ϕ ($m = 300$ GeV)	0.3 $\pm 0.1 \pm 0.2$	1.0 $\pm 0.1 \pm 0.4$	1.6 $\pm 0.2 \pm 0.4$
ρ ($m = 300$ 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

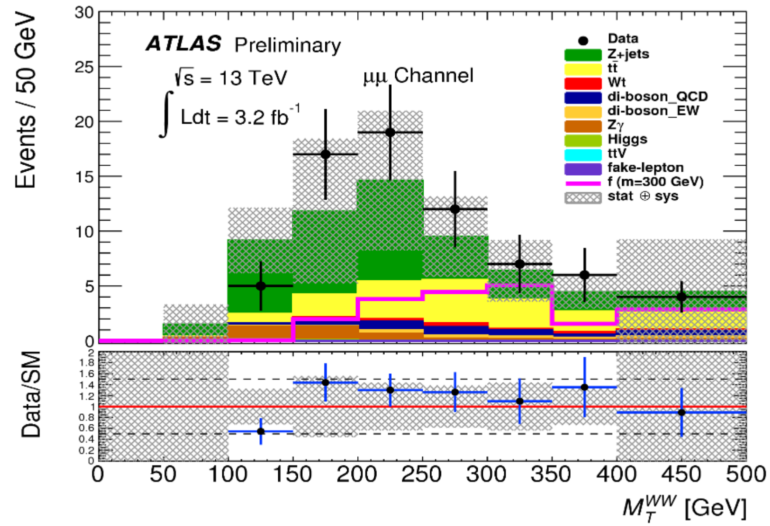
No significant excess above the SM background expectation is observed.

Data vs. predictions in the signal region

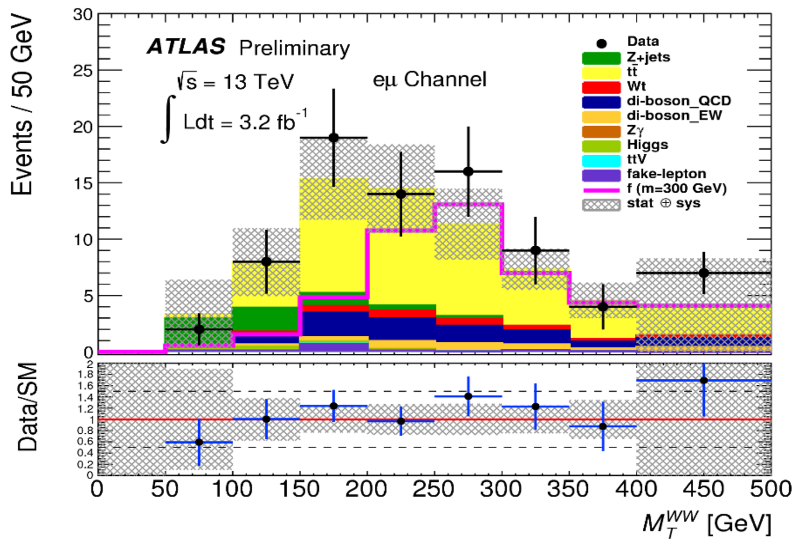
ee-channel



μμ-channel



eμ-channel



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

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

-- 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_{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%

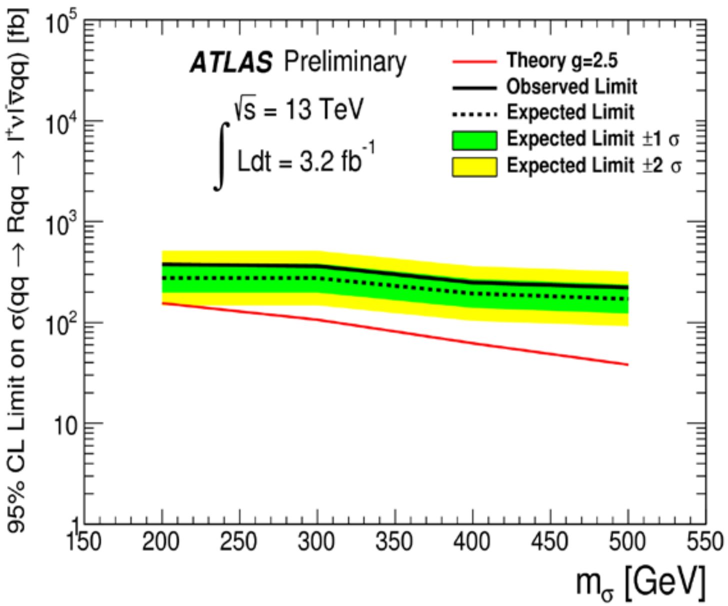
- Experimental uncertainties on signal considered (JES/JER, b-tagging, E_T^{miss}etc.)
- Theoretical uncertainties on the production Xsec of the backgrounds
- Additional shape systematic uncertainties for two dominant backgrounds (Z+jets, $t\bar{t}$) are included.

95% CL upper limits I

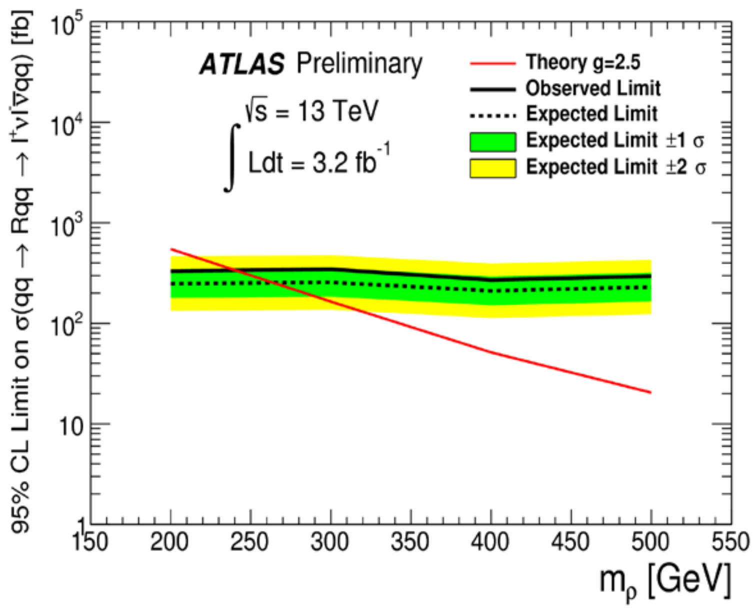
- No significant excess above the SM background expectation is observed.
- 95% CL upper limits are derived on σ x Br for new resonances (σ, φ, ρ, f and t)
- Number counting as inputs to set limit due to limited signal statistics
- The frequentist method (CLs), is used to compute 95% CL upper limits

$$L(\mu, \vec{\alpha}) = \prod_{i \in \{ee, \mu\mu, e\mu\}} \text{Pois}\left(N_i^{\text{obs}} | N_i^{\text{exp}}(\mu, \vec{\alpha})\right) \prod_{j \in \text{syst}} g(\alpha'_j | \alpha_j).$$

σ

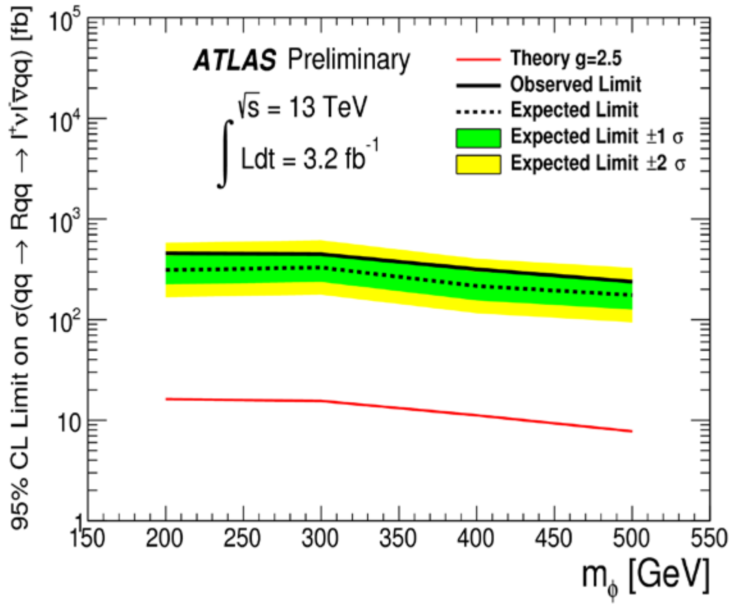


ρ

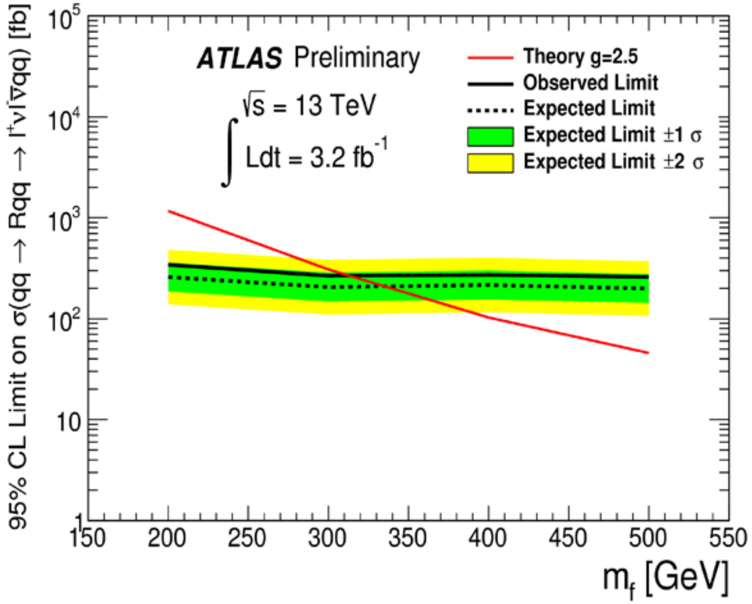


95% CL upper limits II

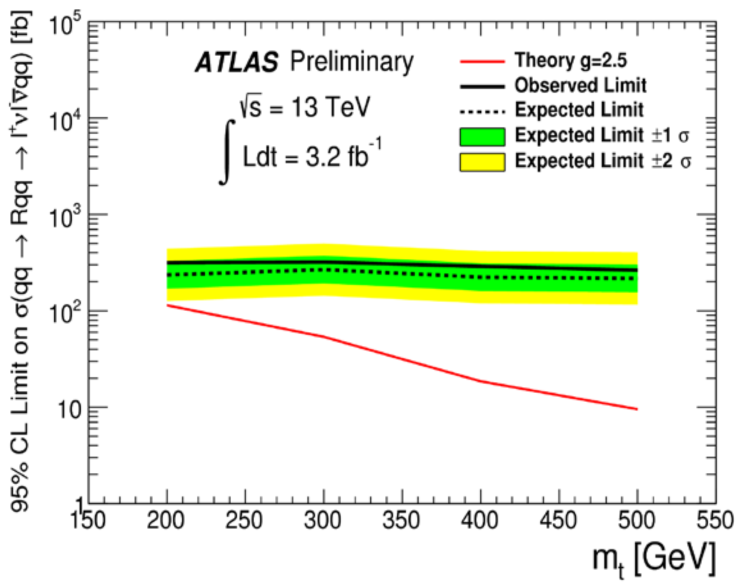
φ



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 for ICHIP: ATLAS-CONF-2016-053
  - Aim to have a common paper with HWW analysis for Moriond 2017