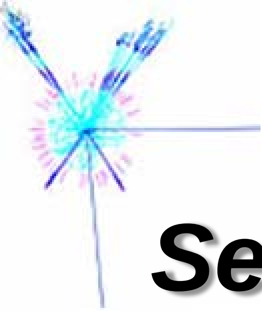

Search for Neutral Resonances in VBF at ATLAS

presented by
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analyses participated by
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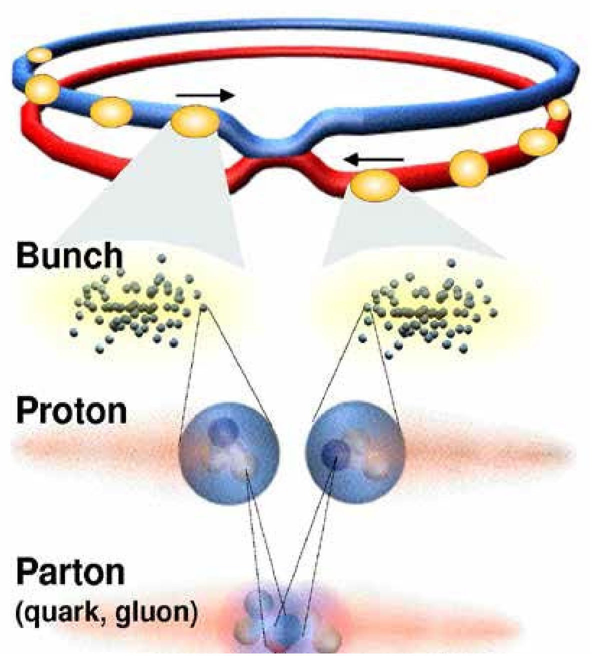
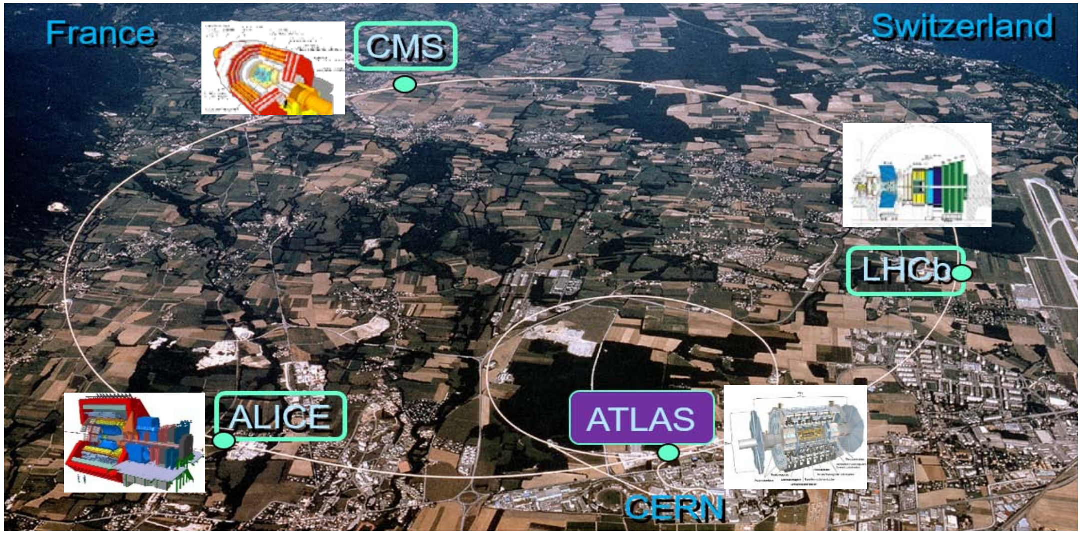
S. Hou,
Academia Sinica

05th-08th Dec. 2017
NCTS Annual Theory Meeting 2017

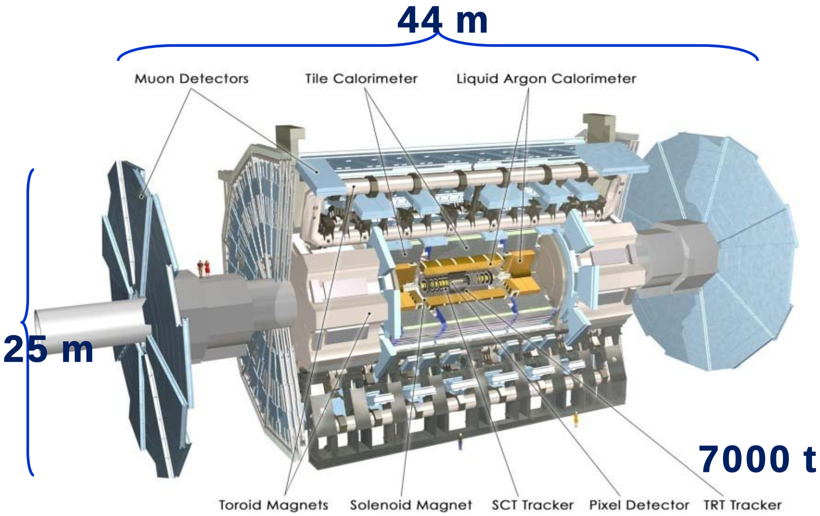
ATLAS at the LHC

proton-proton (*pp*) collisions





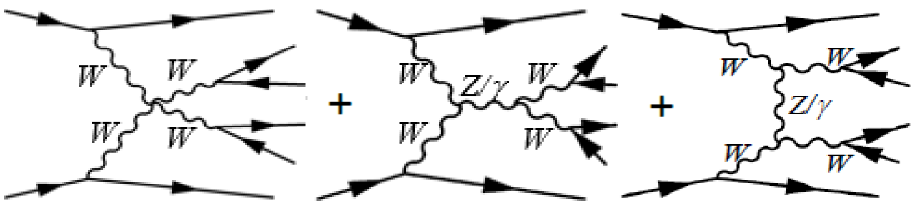
- LHC: large hadron collider
- Luminosity: $10^{34}/cm^2s$,
  bunch crossing: 25 ns
- Center of Mass energy:
  $\sqrt{s}$ = 13 TeV (2015-2018)



Vector Boson Fusion

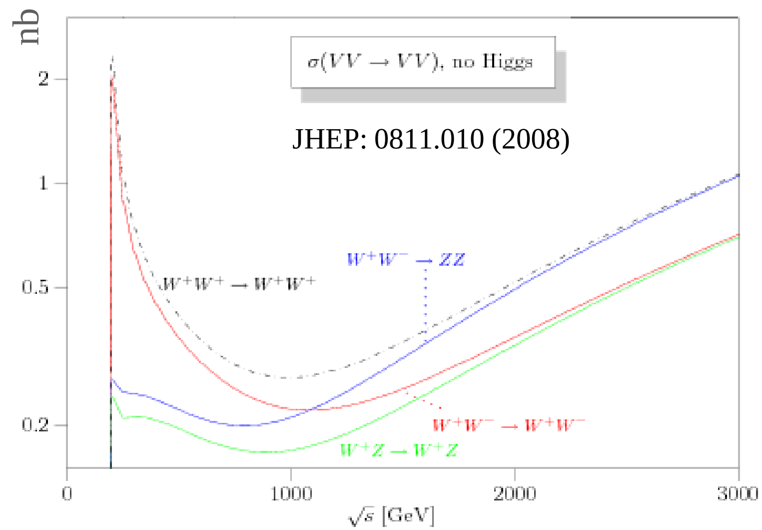
In the Standard Model , VBF (vector boson fusion)
provide a unique means to directly examine the EWSB mechanism

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

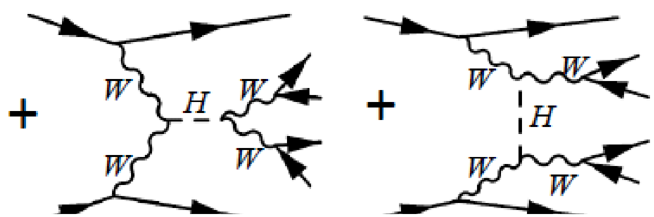


$$\mathcal{M}_{gauge} = -\frac{g^2}{4m_W^2}u + \mathcal{O}((\frac{E}{m_W})^0),$$

unitarity violated

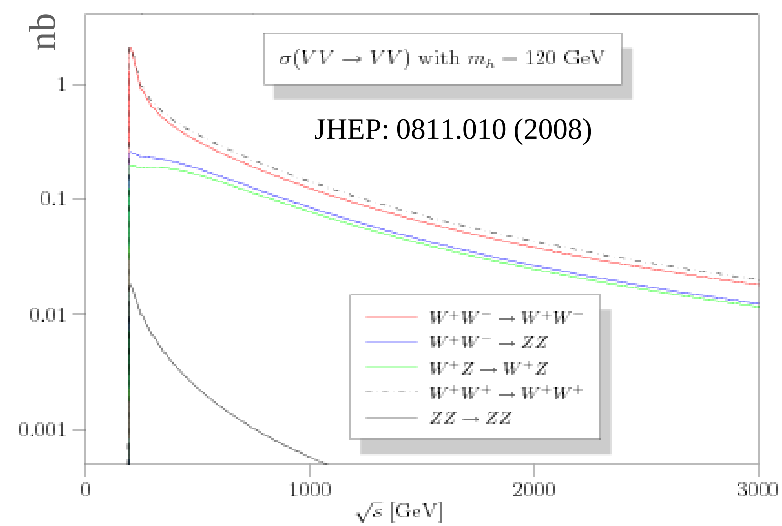


+ W^+W^- scattering/fusion with a SM Higgs



$$\mathcal{M}_{Higgs} = -\frac{g^2}{4m_W^2}\left[\frac{(s-m_W^2)^2}{s-m_H^2} + \frac{(t-m_W^2)^2}{t-m_H^2}\right] \approx \frac{g^2}{4m_W^2}u\,,$$

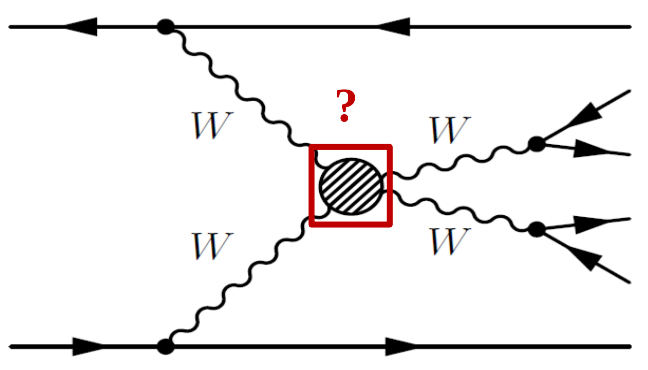
unitarity restored



Vector Boson Fusion, beyond SM

VBF is sensitive to phenomena beyond the SM

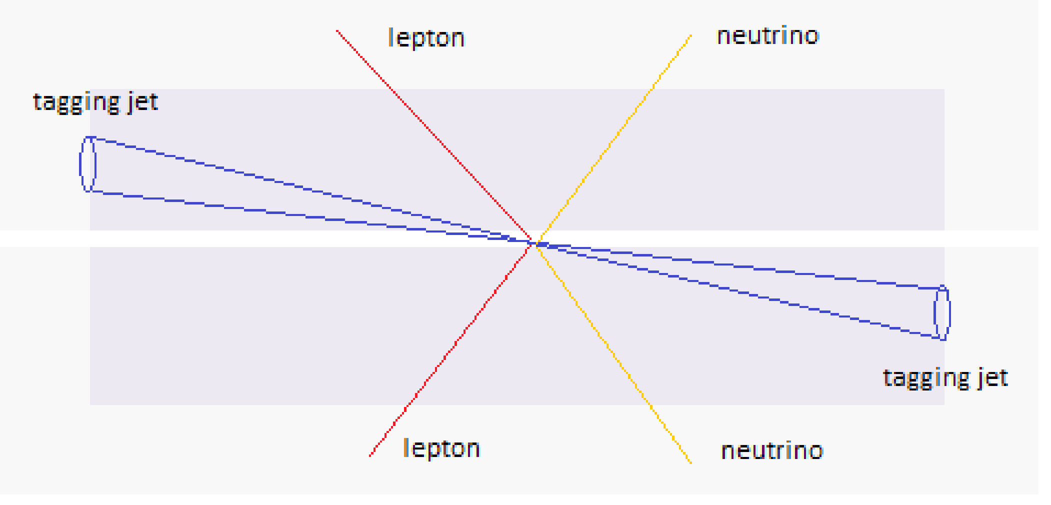
- Issues related to the Higgs boson :
  - ❑ fully or only partially unitarizes the VBF amplitude ?
  - ❑ is the coupling H→VV exactly the one that SM predicted ? (low measurement precision ~20 %)



- New resonance is needed:
  - ❑ Higgs partially unitarizes the VBF amplitude ➔ new resonances
  - ❑ Additional non-SM HVV coupling ➔ new physics
  - ❑ New resonance not coupling to fermions ➔VBF is a leading search channel

VBF characteristics

- Relatively small production cross sections
  ➔ Experimental studies of VBF are feasible only at the LHC so far
- Fully-leptonic channels have lower SM background
  ➔ Considered in the analyses
- VBF event topology at the LHC



VBF signal characteristics:

Large m_{jj} (>500 GeV)

Large $\Delta\eta_{jj}$ (>2.4)

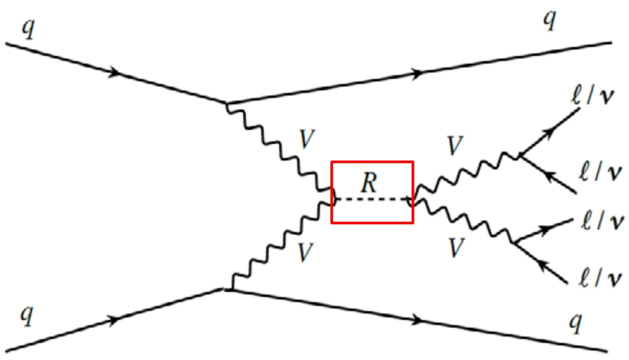
- ***Event Signature in search of Neutral resonance:***
  1. two charged leptons
  2. E_T^{miss}
  3. jet tagging, two forward jets

VBF resonance production

ATLAS-CONF-2016-053
EPJ Web of Conferences 137, 08016 (2017)

Initial study with 2015, 13 TeV, 3.2 fb^{-1}

Search for new resonances (R) in VBF qq → Rqq → $\ell^+\upsilon\ell^-\bar{\upsilon}$qq ($\ell$ = e, μ)
three decay channels: ee, μμ, eμ



Models:

- Benchmark model: EW chiral Lagrangian (EWChL) with K-matrix unitarization
- New resonances: only couples to vector boson, thus mainly produced via VBF
- Free parameters: coupling RVV (g=2.5) & mass [200, 500] GeV

	Type	Spin J	Isospin I	Electric Charge	Γ/Γ_0
scalar	σ	0	0	0	6
	ϕ	0	2	$--,-,0,+,++$	1
vector	ρ	1	1	$-,0,+$	$\frac{4}{3}(\frac{\upsilon^2}{m^2})$
tensor	f	2	0	0	$\frac{1}{5}$
	t	2	2	$--,-,0,+,++$	$\frac{1}{30}$

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

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

JHEP 0811 010 (2008)

Model of VBF resonance signal

Resonance Signal

- New resonance
- SM EW qq→$\ell^+\nu\ell^-\bar{\nu}$qq
- Interference

−

SM continuum

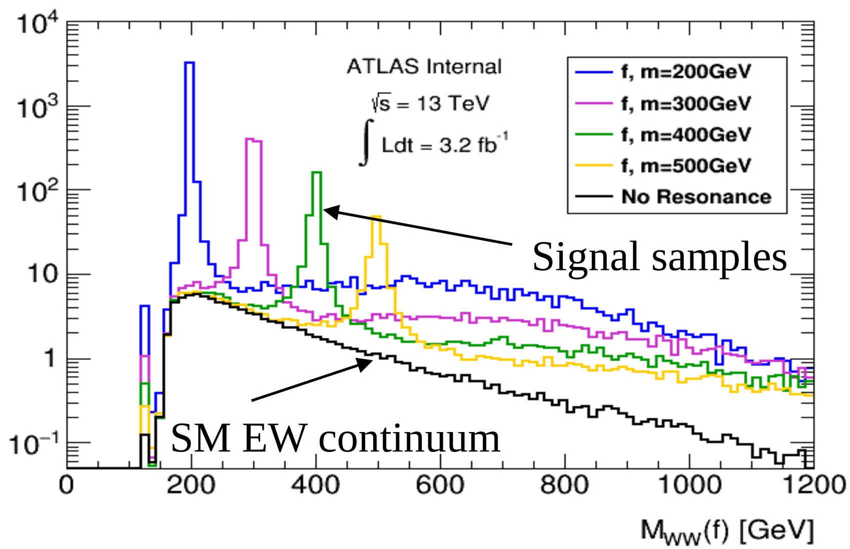
- SM EW qq→$\ell^+\nu\ell^-\bar{\nu}$qq

=

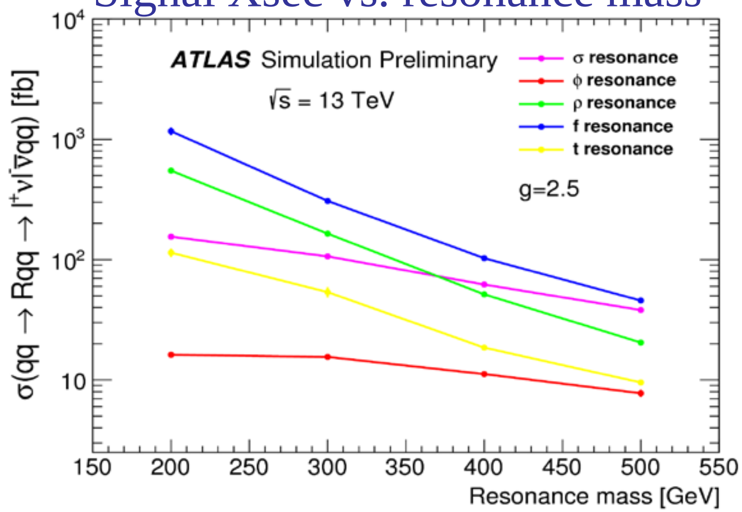
Signal

New resonance + interference

Simulation by Whizard + Pythia8 for both samples



Signal Xsec vs. resonance mass



Signal/Background for 13 TeV, 3.2 fb^{-1}

VBF $qq \rightarrow Rqq \rightarrow \ell^+ \nu \ell^- \bar{\nu} qq$ (ℓ = e, μ)

Analysis for $\ell\ell'$ + E_T^{miss} + 2jets

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

Background estimation

Processes yield two OS leptons

- Z+jets
- $t\bar{t}$
- Wt
- ttV
- Zγ+jets
- diboson (WW/WZ/ZZ)
- SM Higgs (ggH, VBF)

⇒ MC prediction

Processes with jets yield ≥1 lepton

- W+jets
- QCD

⇒ Data driven (Matrix method)

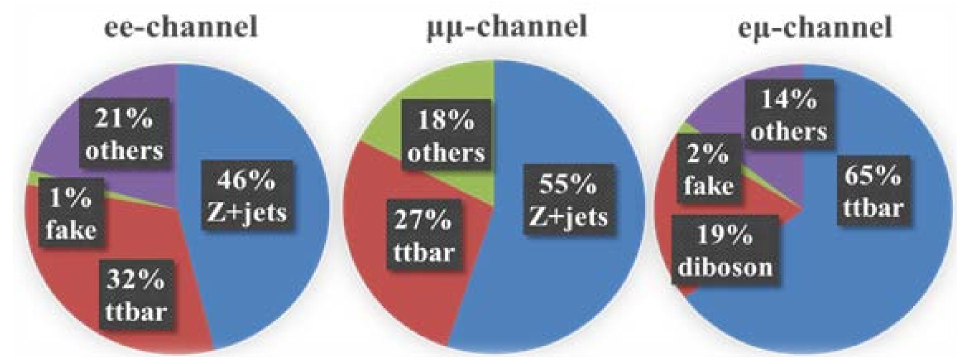
VBF resonance Signal, Background, Validation

➢ Signal Region (SR):

- two leptons of $P_T > 25$ GeV
- three-lepton veto
- di-lepton mass $m_{\ell\ell} > 40$ GeV
- $m_{\ell\ell} - m_Z > 25$ GeV (ee/μμ)
- Lepton centrality > −0.5
- ≥ two jets, $P_T > 30$ GeV, $|\eta| < 2.5$
- $m_{jj} > 500$ GeV, $|\Delta\eta_{jj}| > 2.4$
- b-jet veto
- $E_t^{miss} > 35$ GeV

➢ Dominant background sources :

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



➢ Validation regions (VRs) :

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

Validation for *Z+jets background*

***Z+jets* VR:** $|m_{\ell\ell}-m_Z| < 25$ GeV, no m_{jj} cut

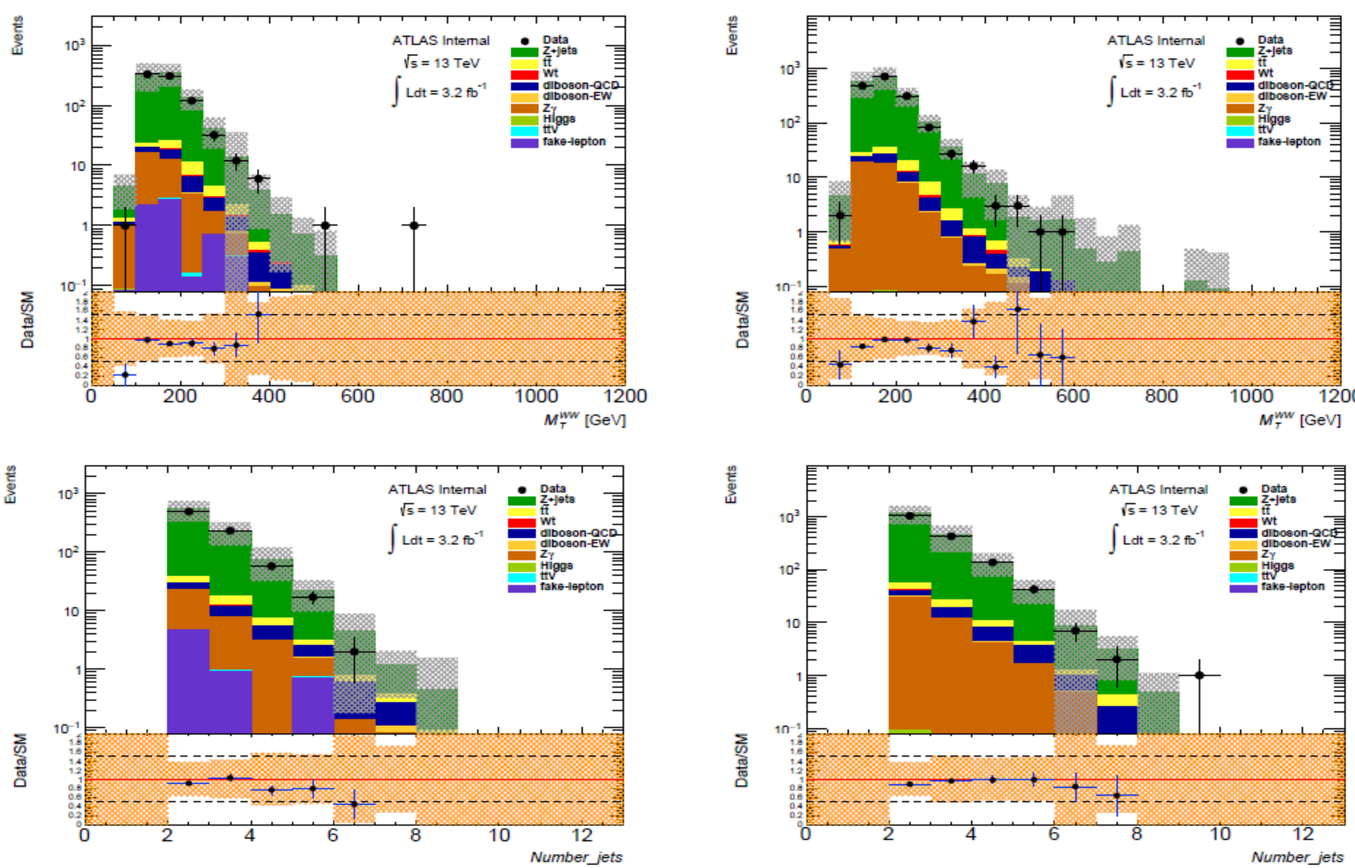
Agreement of data to the SM prediction

Discriminant on transverse mass: $(M_T^{WW})^2 = (P_{\ell_1} + P_{\ell_2} + P^{\text{miss}})(P_{\ell_1} + P_{\ell_2} + P^{\text{miss}})$

ee-channel $\mu\mu$-channel

M_T^{WW}

N_{jets}



Validation for $t\bar{t}$ background

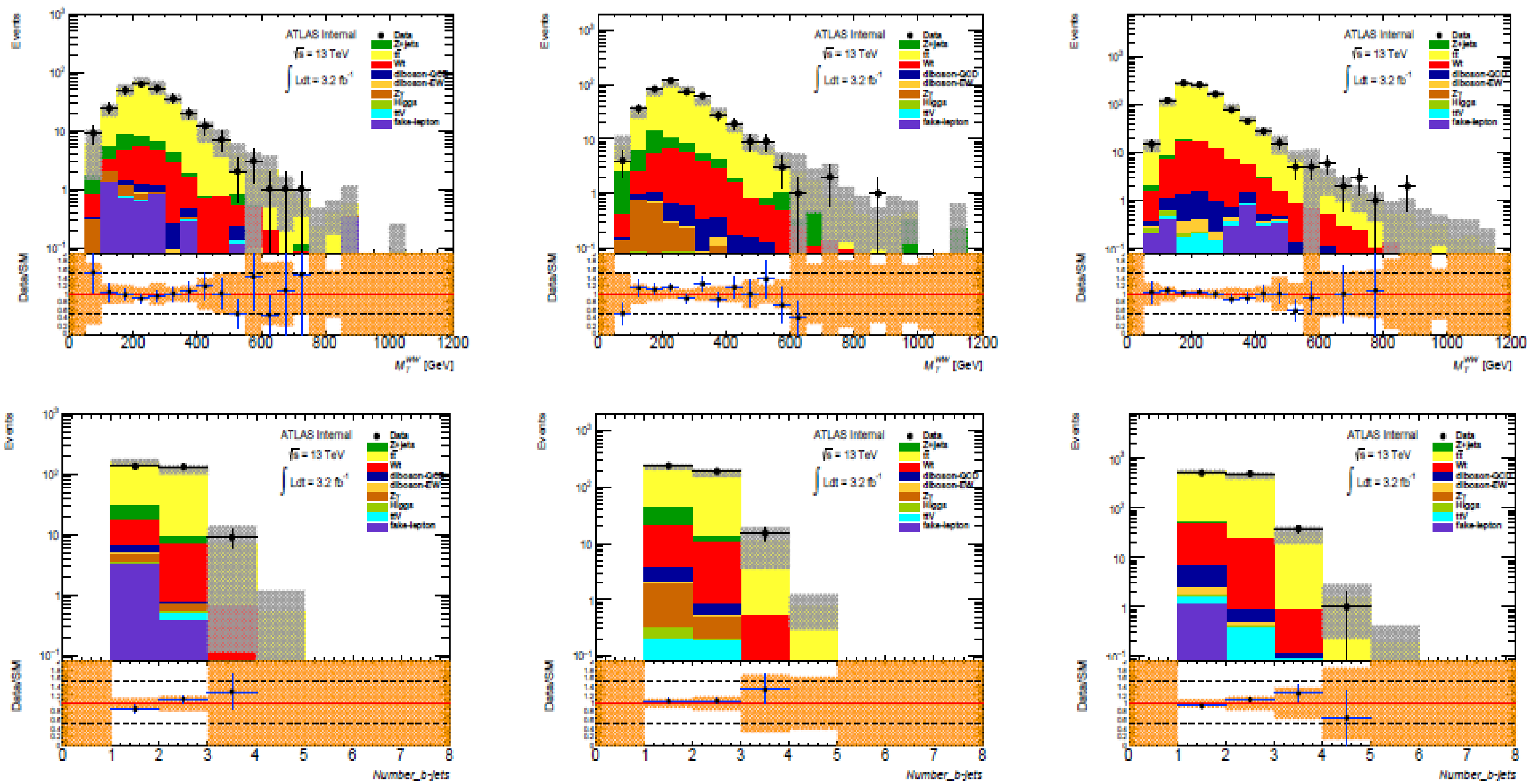
$t\bar{t}$ VR: $N_{b\text{-jet}} > 1$, no m_{jj} cut

Agreement of data to the SM prediction

ee-channel $\mu\mu$-channel $e\mu$-channel

M_T^{WW}

$N_{b\text{-jets}}$



Validation in m_{jj} region

***Low-m_{jj}* VR:** m_{jj} < 500 GeV,

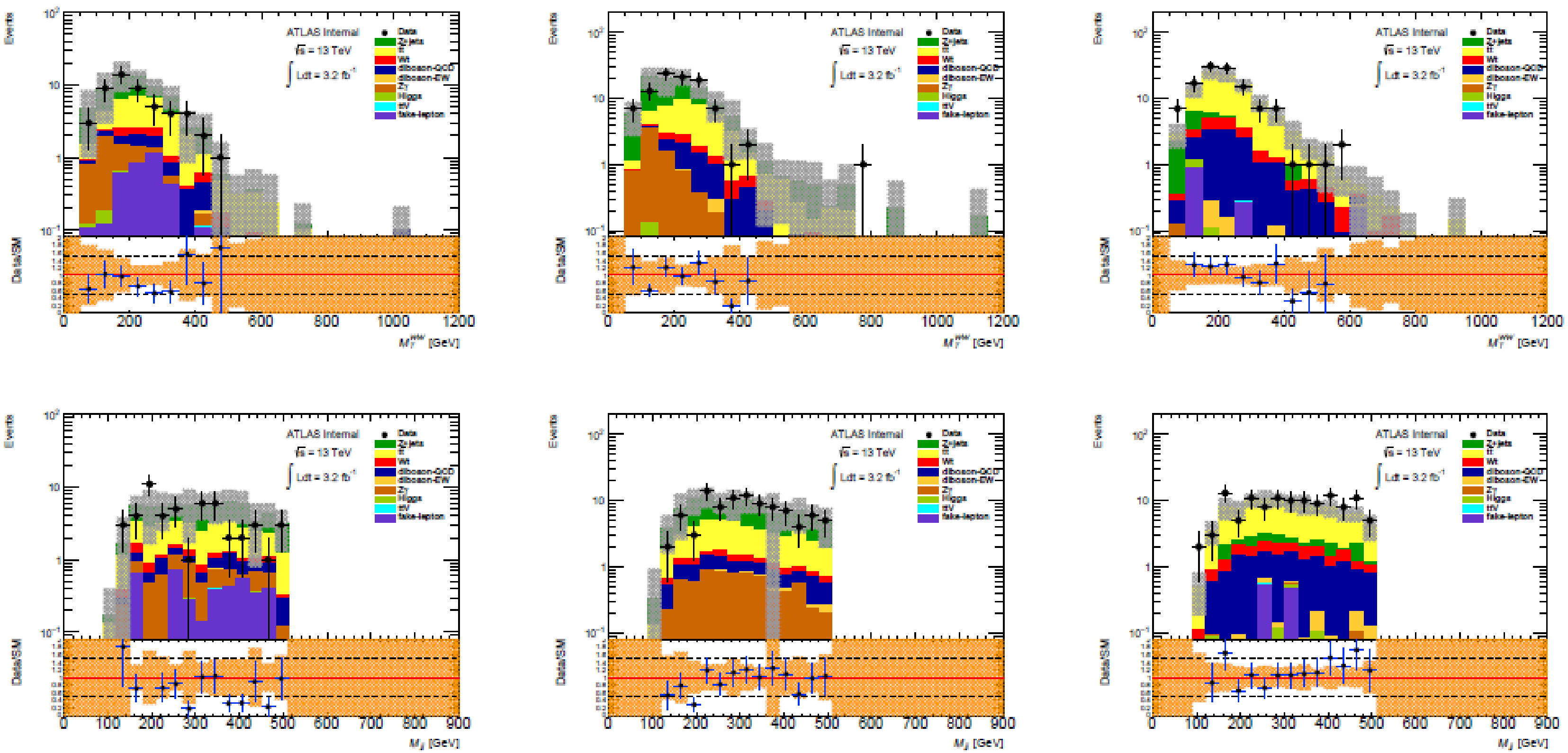
validating overall background estimation

Agreement of data to the SM prediction

ee-channel $\mu\mu$-channel $e\mu$-channel

M_T^{WW}

m_{jj}



Data vs. prediction in *Signal Region*

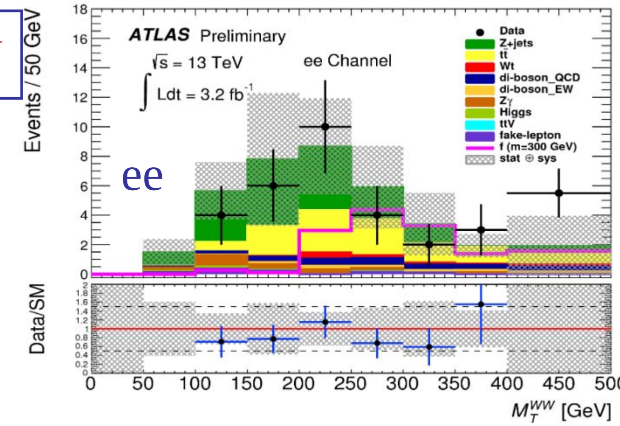
M_T^{WW}

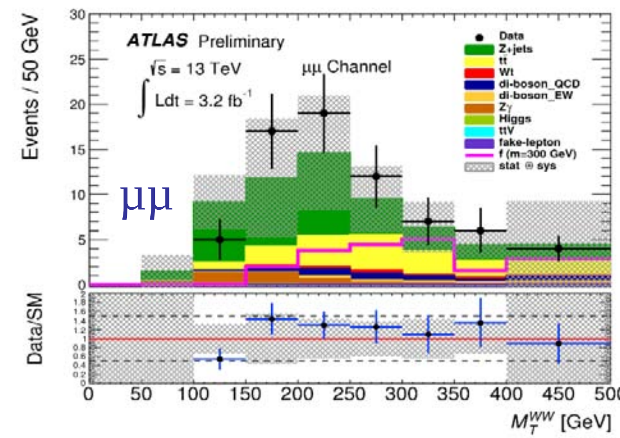
Discriminant :transverse mass

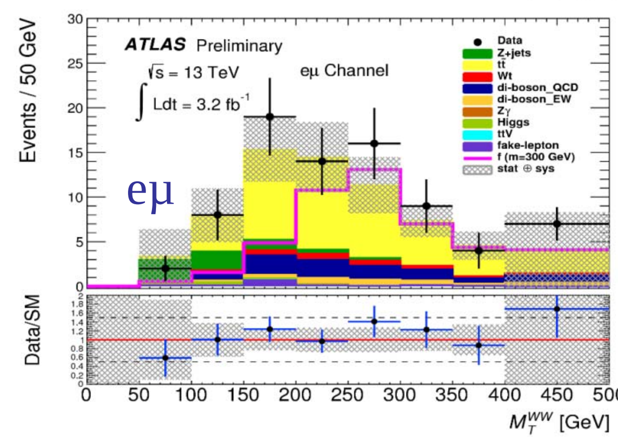
$$(M_T^{WW})^2 = (P_{\ell_1} + P_{\ell_2} + P^{\text{miss}})(P_{\ell_1} + P_{\ell_2} + P^{\text{miss}})$$

Data agrees with prediction

	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



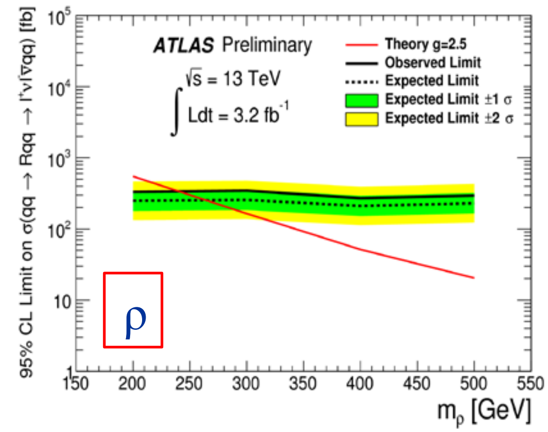


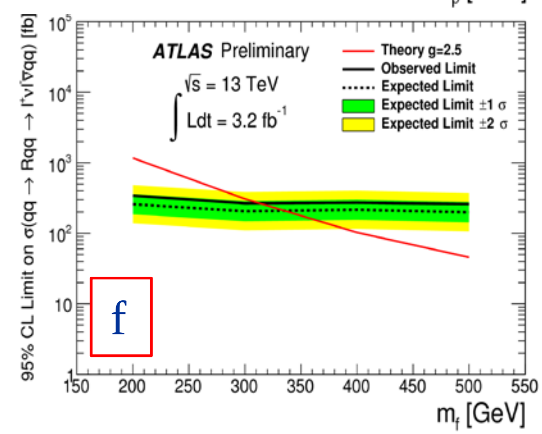


VBF qq→Rqq→ℓνℓ'$\bar{\nu}$qq   95% CL upper limit

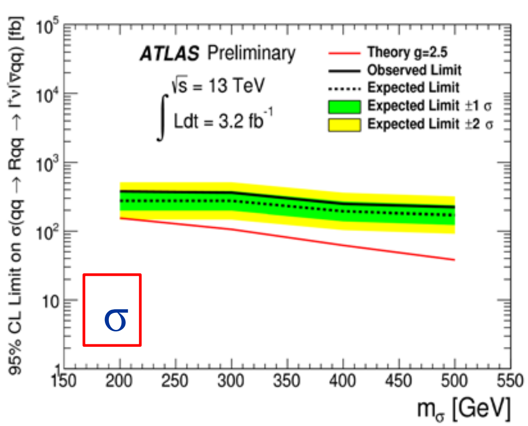
- No excess above to SM background
- 95% CL upper limits derived by frequentist method for $\sigma \times Br$ of resonances (σ, φ, ρ, f and t)

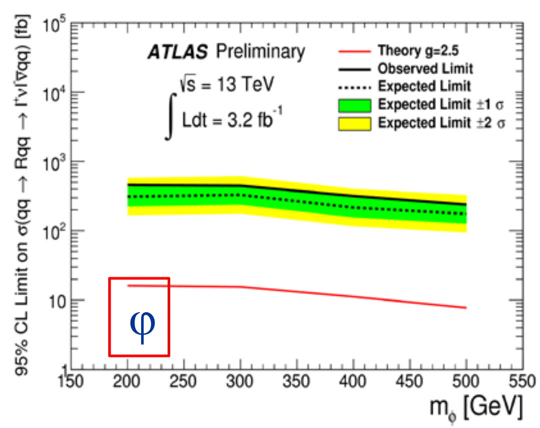
m_R < 230 (300) GeV for ρ (f) excluded

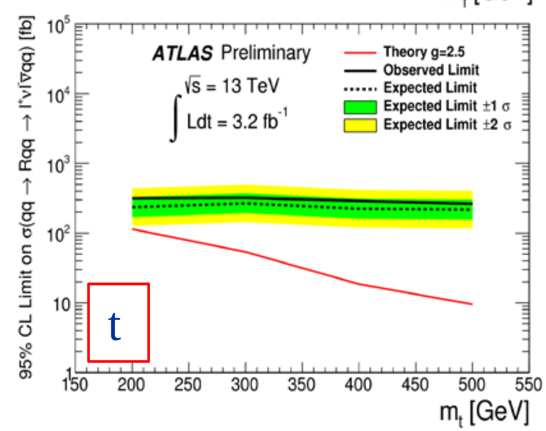




Source	ee	$\mu\mu$	$e\mu$
JES and JER	33%	29%	12%
b-tagging	8%	7%	16%
E_T^{miss} modelling	7%	6%	1%
Lepton	3.1%	2.2%	1.5%
Trigger	0.1%	0.5%	0.5%
Matrix method	0.2%	0.0%	0.1%
Z boson p_T reweighting	0.5%	0.4%	0.0%
MC statistics	4.1%	3.7%	2.6%
Luminosity	2.1%	2.1%	2.1%
Total experimental uncertainty	35%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





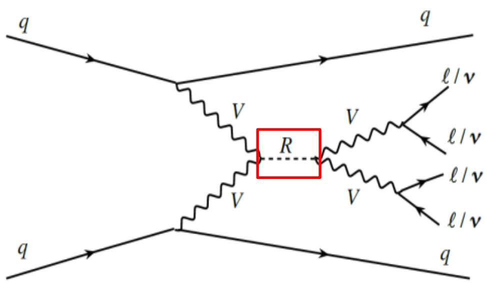


VBF resonance production

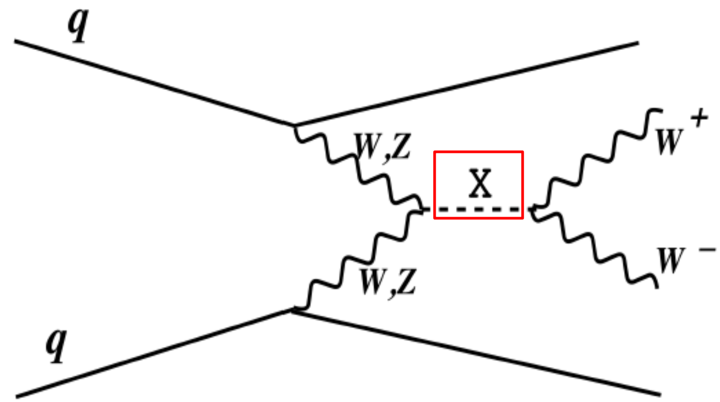
arXiv:1710.01123

2015+2016, 13 TeV, 36.1 fb^{-1}

- Search for new resonances (X) in VBF qq → Xqq → WWqq → eυμυqq



➔



Changes from 3.2 fb^{-1} analysis :

- signal of EWChL model ➔ models of scalar, vector and tensor resonances
- mass range from 500 GeV ➔ up to 3000 GeV
- Final lepton of ee, μμ, eμ ➔ eμ most sensitive from SM background
- Selection of VBF $N_{jet} \geq 2$ ➔ VBF $N_{jet} \geq 2$ + VBF $N_{jet} = 1$ sensitivities

Resonance of VBF qq → Xqq → WWqq

1. **Heavy Higgs with a Narrow Width Approximation (NWA, scalar)**
   - ✓ width = 4 MeV (same widths for different heavy Higgs masses)
   - ✓ mass = [200, 3000] GeV
2. **Heavy Higgs with a Large Width Assumption (LWA, scalar)**
   - ✓ width = 5%, 10% and 15% of heavy Higgs mass
   - ✓ mass = [200, 3000] GeV
3. **Georgi-Machacek model (GM, scalar)**
   - ✓ new scalar resonance: H_5^0 not coupling to fermions to suppress non-VBF contribution
   - ✓ H_5^0VV coupling proportional to $sin\theta_H$ (=0.4)
   - ✓ mass = [200, 1000] GeV
4. **Heavy Vector Triplet model (HVT, vector)**
   - ✓ new ***vector*** resonance: *Z'*, not coupling to fermions
   - ✓ *Z'VV* coupling g_V=1
   - ✓ mass = [200, 1000] GeV
5. **Effective Lagrangian model (ELM, tensor)**
   - ✓ new ***tensor*** resonance: *T*, not coupling to fermions
   - ✓ *TVV* coupling f_i=1
   - ✓ mass = [200, 1000] GeV

Resonance Spin	Signal Model
Spin-0	NWA, LWA, GM
Spin-1	HVT
Spin-2	ELM

VBF qq → Xqq → WWqq signal selection

➢ *Signal Regions event selection*

VBF $N_{\text{jet}} = 1$ SR	VBF $N_{\text{jet}} \geq 2$ SR
Preselection cuts	
pass single-lepton triggers	
$N_\ell = 2$ ($\ell = e, \mu$)	
$p_T^\ell > 25$ GeV	
veto if $p_T^{\ell,\text{other}} > 15$ GeV	
$m_{\ell\ell} > 10$ GeV	
Common selections	
$N_{b\text{-jet}} = 0$	
$\lvert\Delta\eta_{\ell\ell}\rvert < 1.8$	
$m_{\ell\ell} > 55$ GeV	
$p_T^{\ell,\text{lead}} > 45$ GeV	
$p_T^{\ell,\text{sublead}} > 30$ GeV	
$max(m_T^W) > 50$ GeV	
VBF1J phase space	VBF2J phase space
$N_{\text{jet}} = 1$	$N_{\text{jet}} \geq 2$
$\lvert\eta_j\rvert > 2.4$	$m_{jj} > 500$ GeV
$min(\lvert\Delta\eta_{j\ell}\rvert) > 1.75$	$\lvert\Delta y_{jj}\rvert > 4$

➢ *discriminant*

$$m_T^W = \sqrt{2 p_T^\ell E_T^{\text{miss}} \left(1 - \cos(\phi^\ell - \phi^{E_T^{\text{miss}}})\right)}$$

➢ *Control Regions on bkgrnd*

WW CR$_{\text{VBF1J}}$	Top CR$_{\text{VBF}}$
Preselection cuts	Preselection cuts
$N_{b\text{-jet}} = 0$	$N_{b\text{-jet}} \geq 1$
($\lvert\Delta\eta_{\ell\ell}\rvert > 1.8$ or	–
10 GeV$<m_{\ell\ell}<$55 GeV)	$m_{\ell\ell} > 10$ GeV
$p_T^{\ell,\text{lead}} > 25$ GeV	$p_T^{\ell,\text{lead}} > 25$ GeV
$p_T^{\ell,\text{sublead}} > 25$ GeV	$p_T^{\ell,\text{sublead}} > 25$ GeV
VBF1J phase space	VBF1J and VBF2J phase space

cuts inverted, removed or loosened for statistics and higher purity

WW background:

- VBF N_{jet} = 1: WW CR
- VBF $N_{\text{jet}} \geq 2$: WW MC simulation

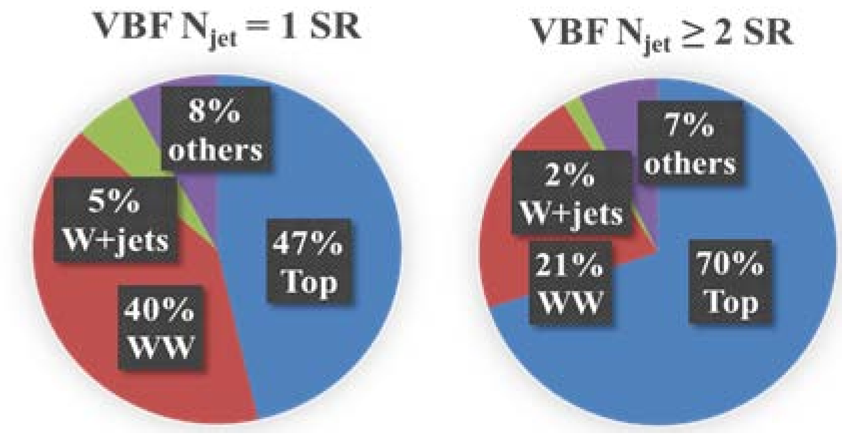
Top background:

- Top CR: combined VBF N_{jet} = 1 and VBF $N_{\text{jet}} \geq 2$ to gain more statistics

VBF qq → Xqq → WWqq background

Background processes:

- Top,
- WW,
- non-WW diboson,
- Z+jets, W+jets,
- Higgs production



Top and WW are dominant :

- fitting top and WW contributions to data simultaneously in CR, SR
  → normalization factors
- MC prediction for WW in VBF 2J, small fraction, diffcult to be isolated

W+jets:

- data driven method - “fake-factor” method

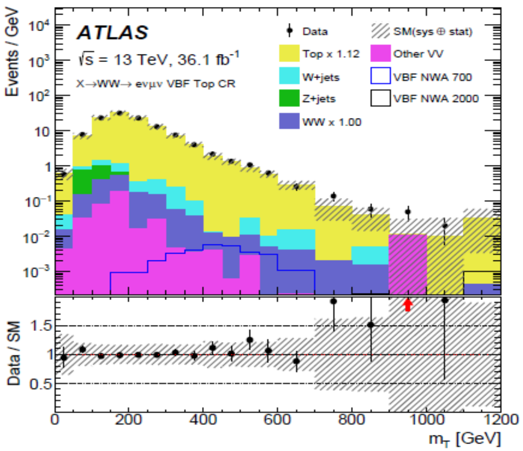
Z+jets, non-WW diboson, Higgs production:

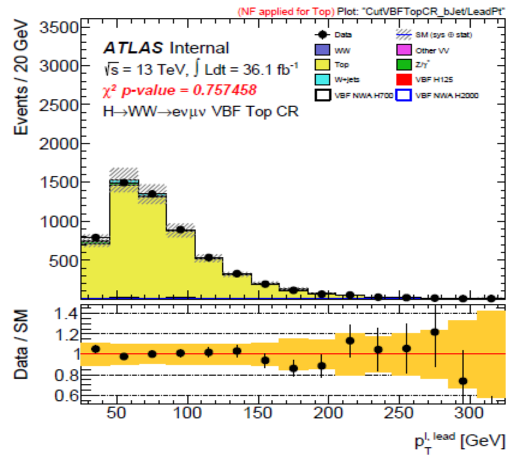
- small contribution by MC simulation

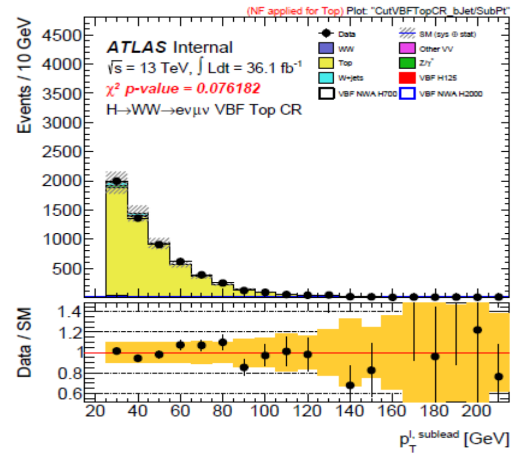
VBF qq → Xqq → WWqq, in control regions

Top control region:

$$NF\_Top\_VBF = 1.12^{+0.13}_{-0.12}$$

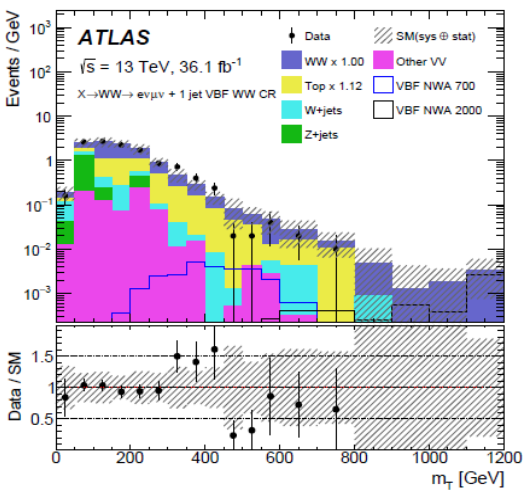


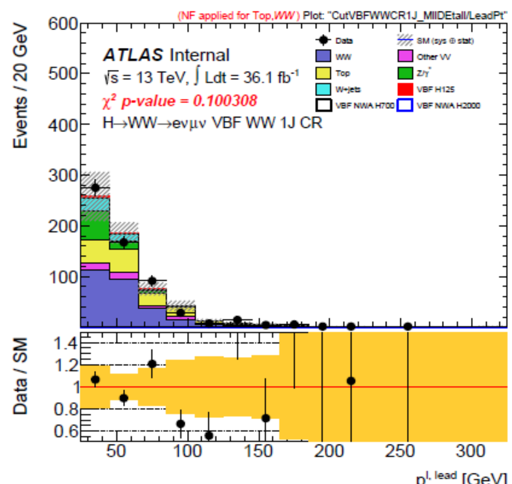


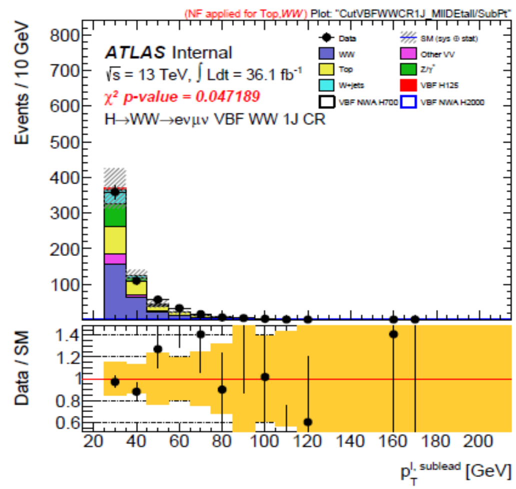


WW control region:

$$NF\_WW\_VBF1J = 1.0 \pm 0.2$$







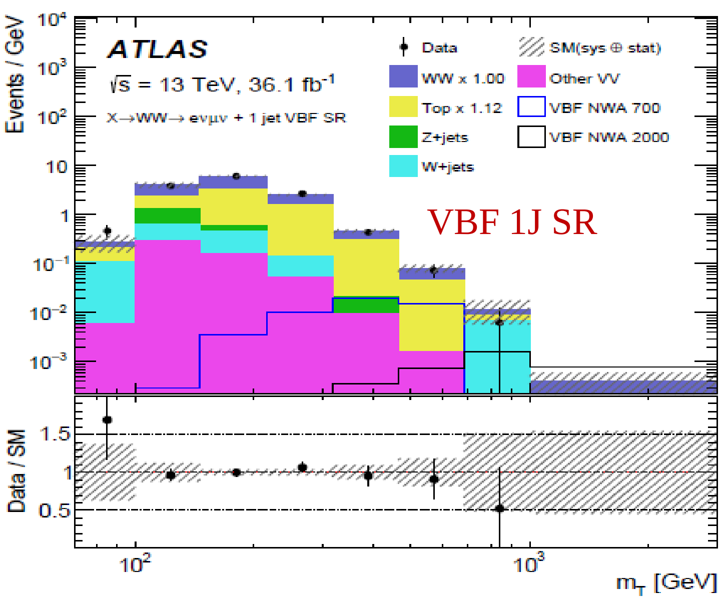
VBF qq → Xqq → WWqq, in signal region

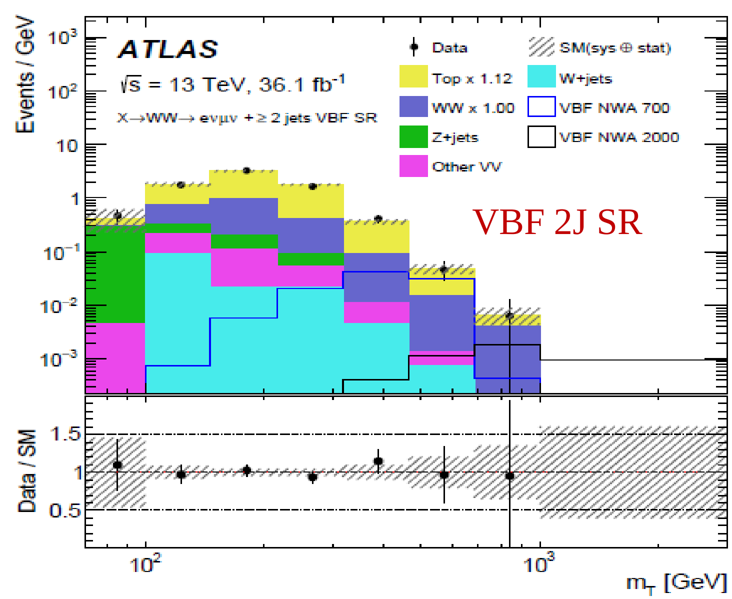
No excess to the SM background prediction

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

	VBF $N_{\mathrm{jet}} = 1$ SR	VBF $N_{\mathrm{jet}} \geq 2$ SR	Top CR$_{\mathrm{VBF}}$	WW CR$_{\mathrm{VBF1J}}$
WW	390 ± 50	120 ± 26	61 ± 11	265 ± 32
Top quark	450 ± 50	391 ± 24	$5\,650 \pm 90$	167 ± 18
Z/γ^*	45 ± 11	24 ± 6	68 ± 19	74 ± 12
W+jets	52 ± 13	8.9 ± 2.5	91 ± 24	43 ± 11
VV	32 ± 7	16.6 ± 1.9	20 ± 9	38 ± 4
Background	972 ± 29	563 ± 22	$5\,890 \pm 80$	596 ± 22
Data	978	560	5 889	594

$\boxed{M_T}$





VBF qq → Xqq → WWqq, systematics

Uncertainties of

Top background (%):

- dominant items listed
- Single top: of theoretical

Uncertainties from top background (%)

Source	Jet	b-tag	ME+PS	Scale	Single top	PDF	Total
VBF $N_{\mathrm{jet}} = 1$ SR	9.6	7.8	1.0	1.6	5.9	3.5	15
VBF $N_{\mathrm{jet}} \geq 2$ SR	9.7	14	9.5	5.0	2.1	3.6	21
Top CR$_{\mathrm{VBF}}$	8.2	3.5	10	1.5	1.3	3.6	14
WW CR$_{\mathrm{VBF1J}}$	9.9	8.3	9.4	3.9	5.3	3.4	18

WW background (%):

- dominant items listed

Uncertainties from WW background (%)

Source	Jet	Pile-up	ME+PS	μ_{R}	Resummation	PDF	Total
VBF $N_{\mathrm{jet}} = 1$ SR	17	2.8	11	7.3	5.0	1.0	23
VBF $N_{\mathrm{jet}} \geq 2$ SR	18	3.1	38	18	1.4	1.3	47
WW CR$_{\mathrm{VBF1J}}$	16	4.5	12	11	2.3	1.6	23

Shapes of Top and WW:

- m_T shape on PDF in the SRs are considered

W+jets background:

- from jet flavor composition, EW subtraction, statistics
- VBF 1J SR: 32%, VBF 2J SR: 35%

Other background:

- smaller contributions, normalized to cross sections

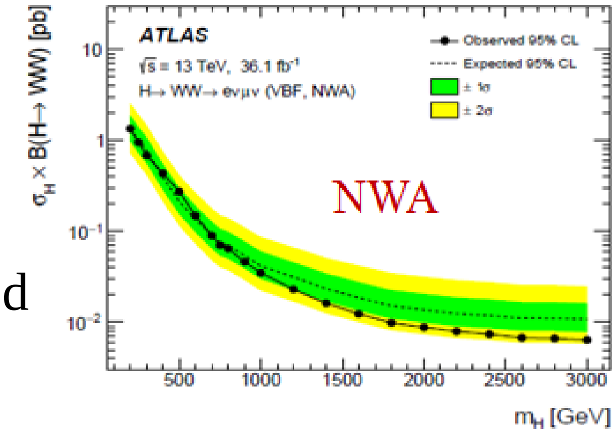
Signal (NWA):

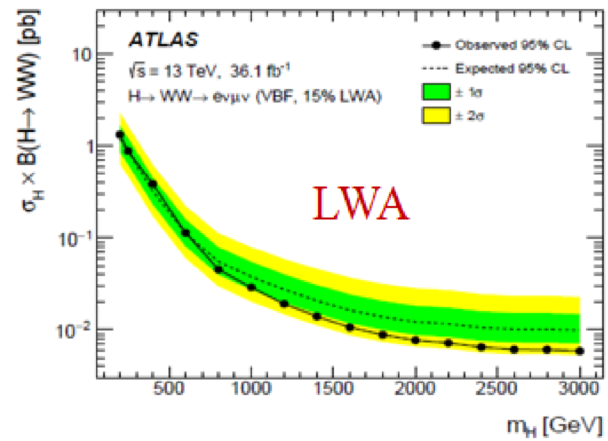
- arise from parton shower, PDF, QCD scales
- VBF 1J SR: 5.1% - 9.0%, VBF 2J SR: 3.3% - 8%

VBF qq → Xqq → WWqq, 95% CL upper limits

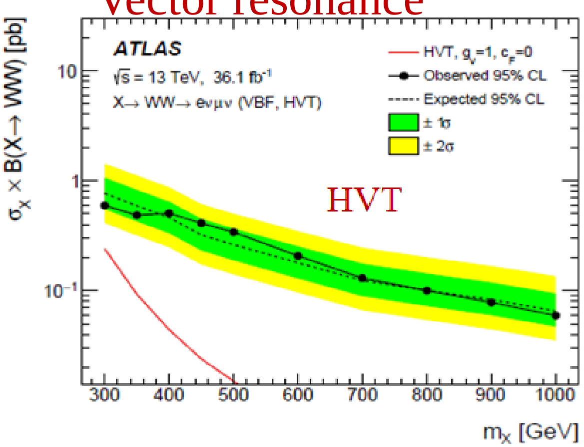
No excess to the SM prediction
95% CL upper limits derived by the frequentist method
for $\sigma_X \times Br(X \rightarrow WW)$

- Values above 1.3 pb at 200 GeV and above 0.006 pb at 3 TeV for NWA and 15% LWA are excluded
- sensitivity not sufficient to exclude GM, HVT and ELM models

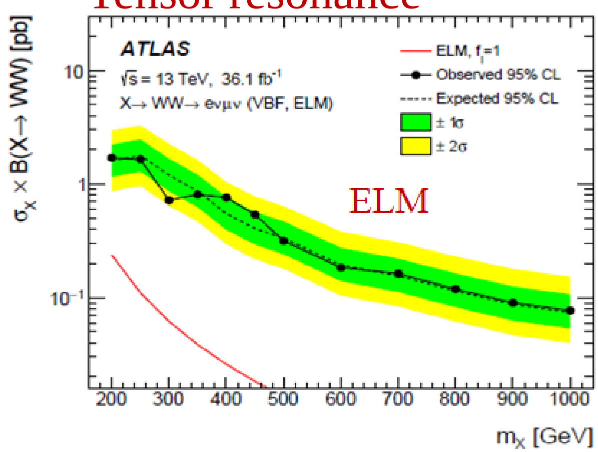


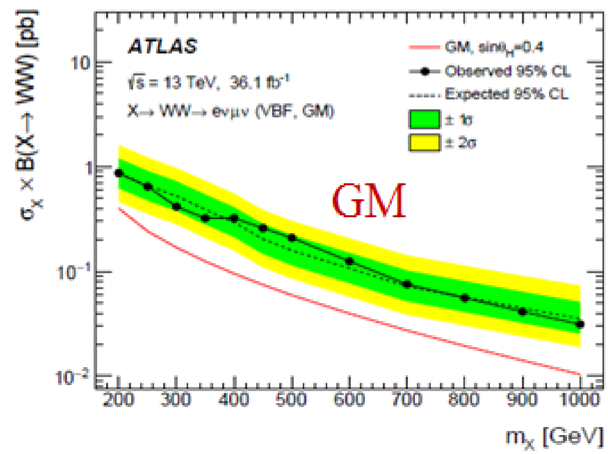


Vector resonance



Tensor resonance





Summary

- Vector Boson Fusion to heavy neutral resonances searched for $qq \rightarrow Xqq \rightarrow WWqq$ in $e\upsilon\mu\bar{\upsilon}qq$ final state
- No excess to SM background prediction
- Limits on $\sigma_X \times Br(X \rightarrow WW)$ set to
  3 TeV for NWA, LWA scalar
  1 TeV for GM and vector, tensor resonances