Latest measurements of the electroweak cross-section for $W^{\pm}W^{\pm}jj$ production using 139 fb^{-1} of ATLAS data

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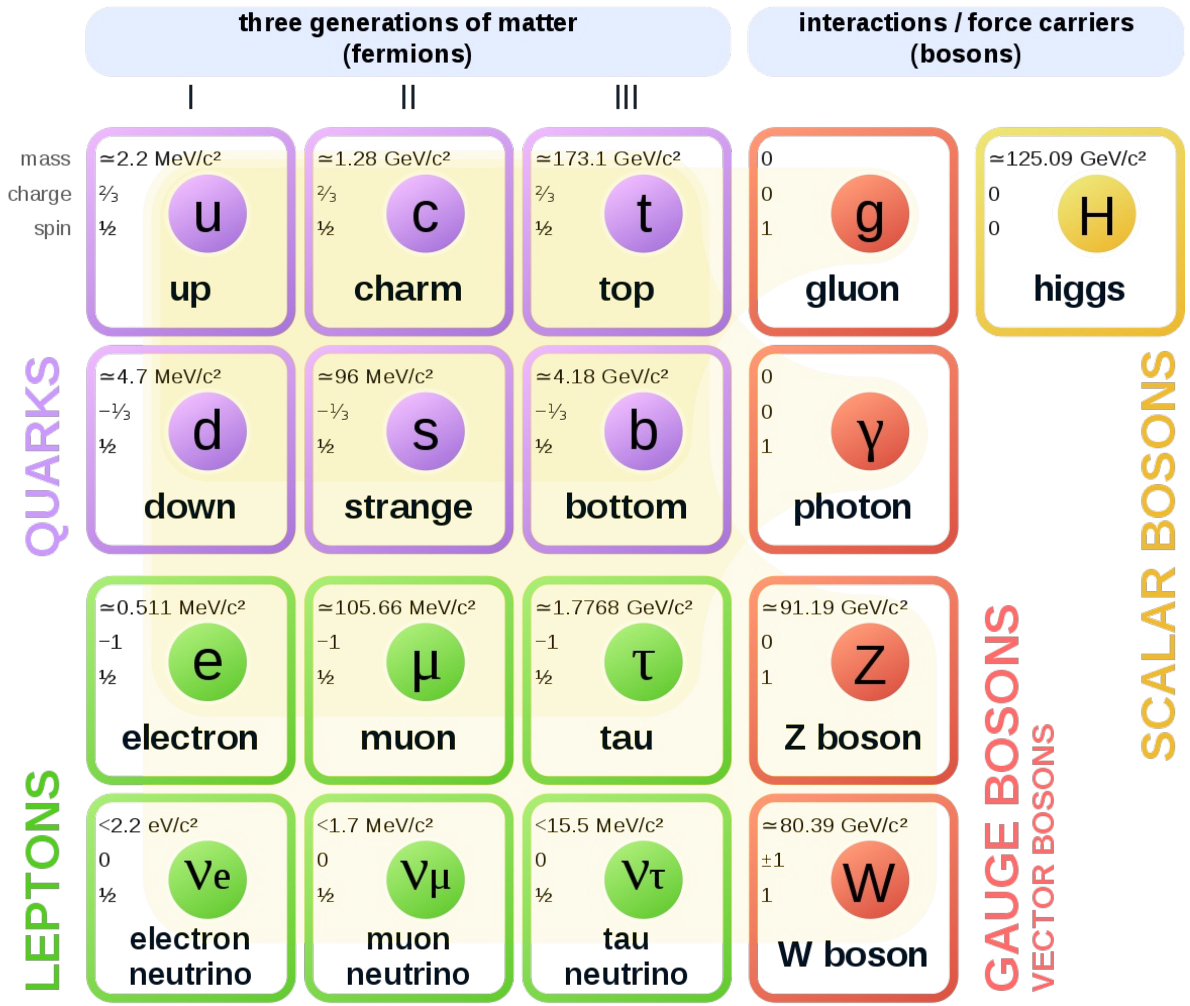
Outline

- **Why are we interested in this measurement?**
  - Electroweak interactions
  - Vector Boson Scattering (VBS)
  - Same-sign WW scattering ($W^{\pm}W^{\pm}jj$)
- **Measurement procedure and results**
  - Data accumulated by ATLAS during Run II of the LHC
  - Event selection and background estimation
  - Fiducial and differential cross-section measurements
  - Interpreting results for BSM searches
- **Summary**

Why are we interested in this measurement?

Electroweak interactions

The Standard Model (SM) of particle physics



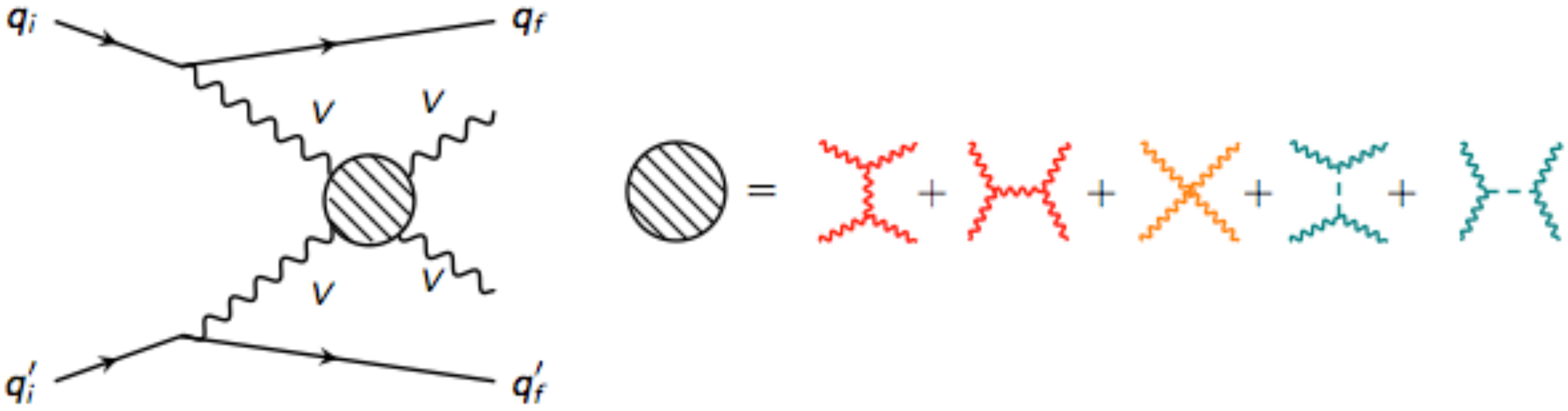
Source: https://en.wikipedia.org/wiki/Standard_Model

- **Electromagnetic force: mediated by photons**
- **Weak force: mediated by W and Z bosons**

- 1970’s: Glashow, Weinberg and Salam showed that electromagnetic and weak forces could be described as a single electroweak interaction (electroweak unification)
- The Higgs mechanism takes credit for the electroweak separation; W and Z bosons acquire mass while the photon remains massless when they interact with the Higgs field
  - ElectroWeak (EW) symmetry is broken
  - The exact nature of the EW symmetry breaking process is not very well understood
  - VBS processes can help us probe its nature

Vector Boson Scattering (VBS)

- **VBS measurements are important in our understanding of the nature of electroweak symmetry breaking**
  - If the Higgs potential has a different shape from what the SM predicts, we expect to see some deviations from SM predictions in these measurements



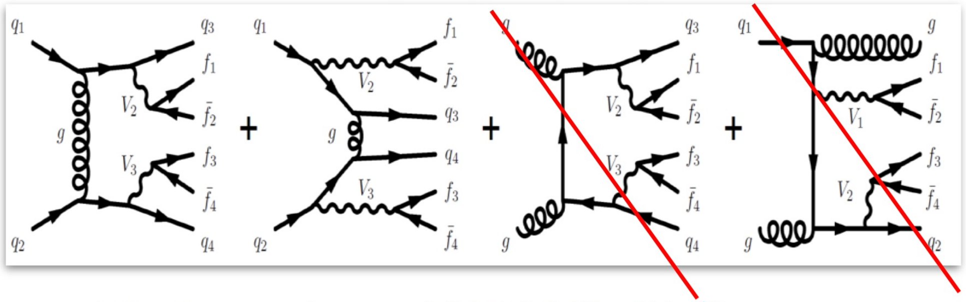
- VBS requires the presence of Higgs couplings for unitarity to be preserved at high energies
  - Unitarity: Probabilities of all diagrams contributing to a particular VBS process should add up to one
  - In the absence of Higgs diagrams, probability keeps growing with energy leading to probabilities > 1

- Studied in various processes; same-charge WW, opposite charge WW, WZ, ZZ …….
  - Next slides: Same-sign W boson scattering ($W^{\pm}W^{\pm}jj$)

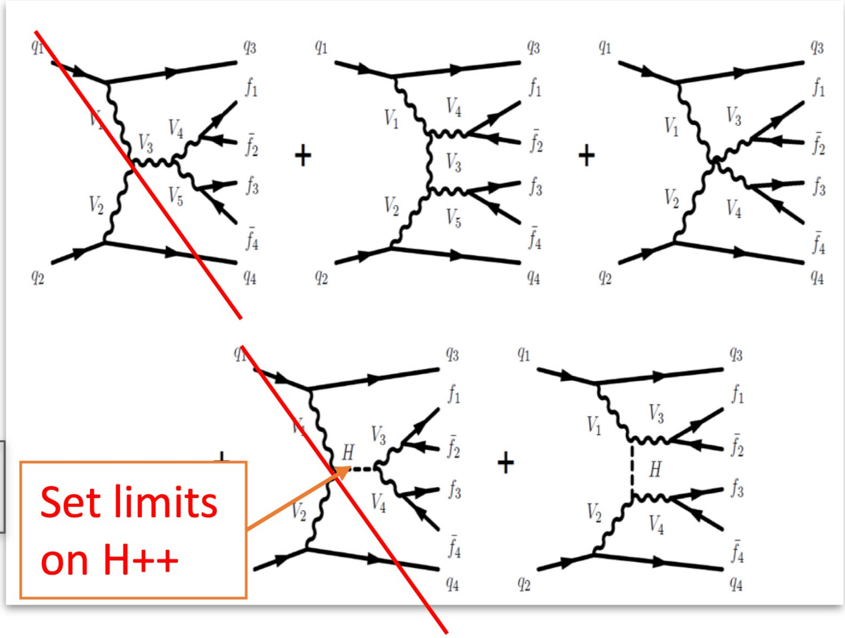
$W^{\pm}W^{\pm}jj$ production

- This process has the largest EW to strong production ratio among VBS processes, hence the QCD-induced background is suppressed.
  - Gluons in the initial state are not allowed

Strong VVjj, O($\alpha^4\alpha_s^2$)

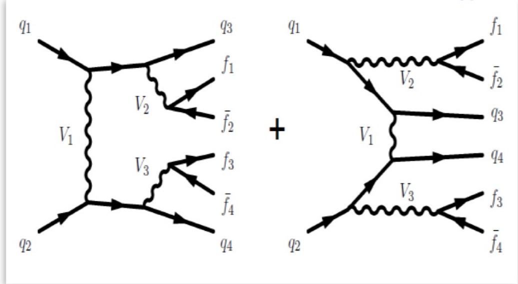


Electroweak VBS VVjj, O(α^6)



Set limits on H++

Electroweak non-VBS VVjj, O(α^6)

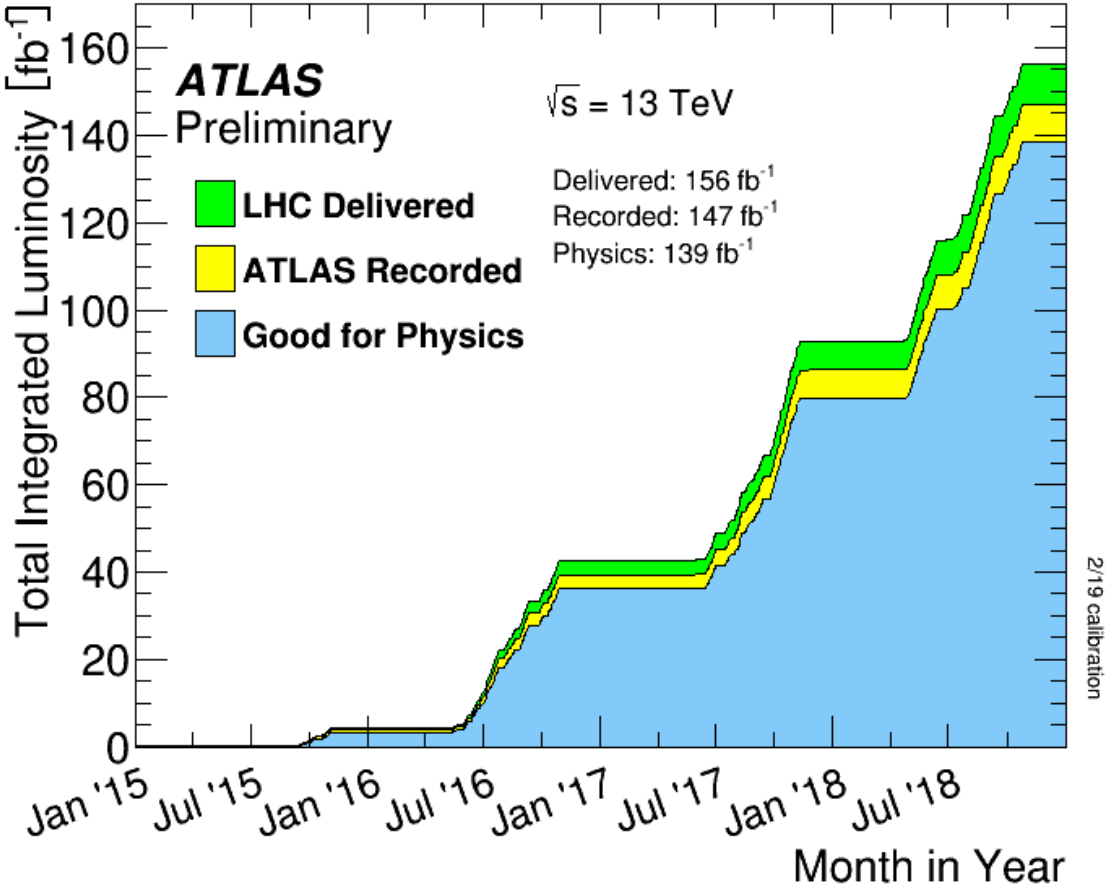


Not in SM W±W±

- EW VBS and EW non-VBS diagrams can not be separated in a gauge invariant way
  - EW measurement includes both
- This measurement is also sensitive to doubly charged Higgs production

Measurement procedure and results

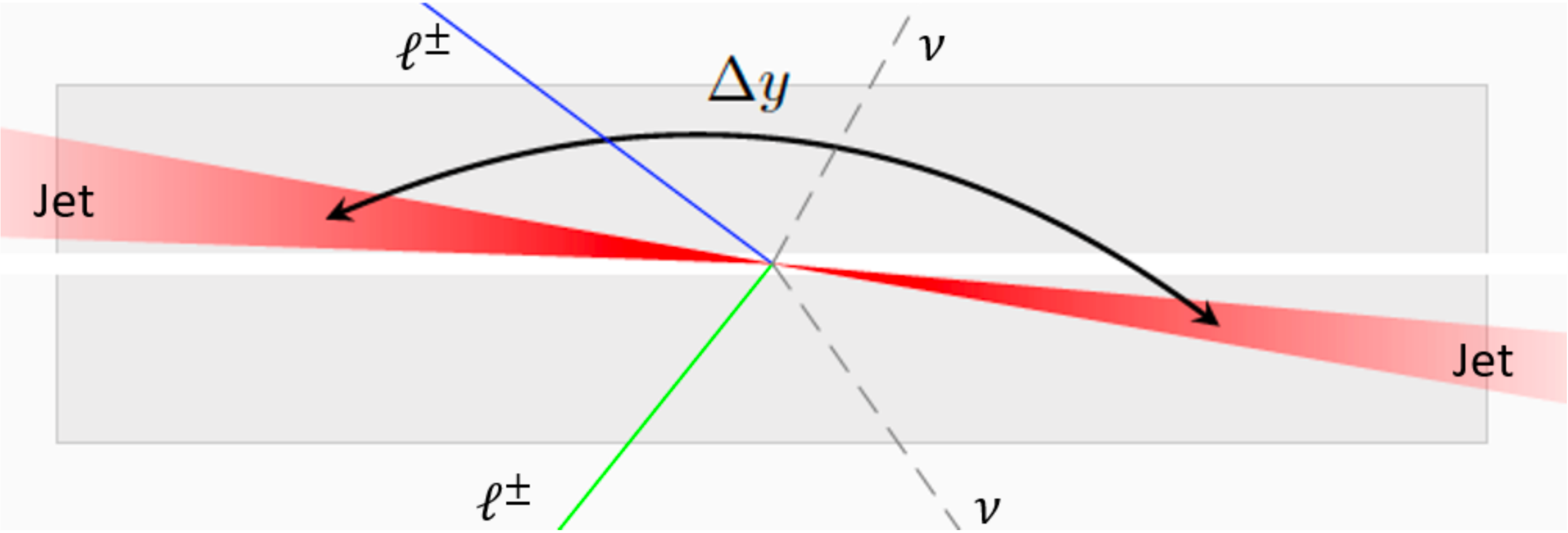
Run II ATLAS data (2015 - 2018)



- 2015 - 2016: 36 fb^{-1} (Observation of $\boldsymbol{W^{\pm}W^{\pm}jj}$)
  - Cross-section: $2.91^{+0.51}_{-0.47}$ (stat) ± 0.23 (sys) fb
- 2015 – 2018: 139 fb^{-1} (precision measurement)
  - Cross-section: next slides

$W^{\pm}W^{\pm}jj$ signal event selection

- Two isolated same-sign leptons (electrons or muons) with high transverse momentum ($p_T > 27$ GeV)
- Large missing transverse energy ($E_{T,miss} > 30$ GeV)
- VBS topology:
  - ➢ Two forward jets with high transverse momentum ($p_T > 65\ [30]$ GeV)
  - ➢ Large di-jet invariant mass ($m_{jj} > 500$ GeV)
  - ➢ Large separation in rapidity ($|\Delta y_{jj} > 2|$)



$W^{\pm}W^{\pm}jj$ Background estimation

❖ WZ EW and WZ QCD background

- WZ QCD is the most dominant background
- Two same-charge leptons are picked up as signal
- WZ final states are modelled using Monte-Carlo (MC) simulations and are dominated by WZ QCD
- The normalization of the WZ QCD process is estimated from data in a dedicated WZ control region

❖ Charge flip and γ conversions background

- Main sources: $W^{\pm}\,W^{\mp}$ and $V\gamma$ processes
- One lepton is assigned the wrong charge or γ is mis-identified as an electron
- This is the third-largest background source
- Charge flip is estimated using a data-driven method
- $V\gamma$ processes are estimated from MC simulation

❖ Non-prompt background

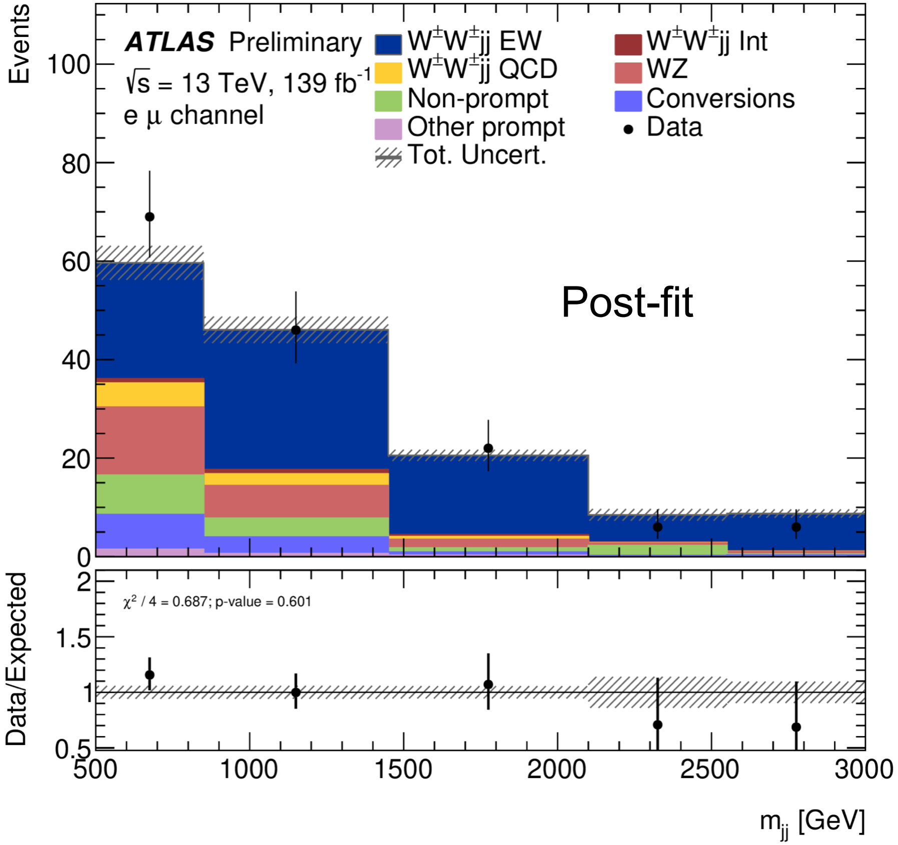
- Main sources: Semi-leptonic $t\bar{t}, W$+jets processes, single top processes
- $t \rightarrow W + bjet$, one lepton from W and the other from the $bjet$ are picked up
- This is the second-largest background
- Estimated using a data-driven method

❖ Other prompt background

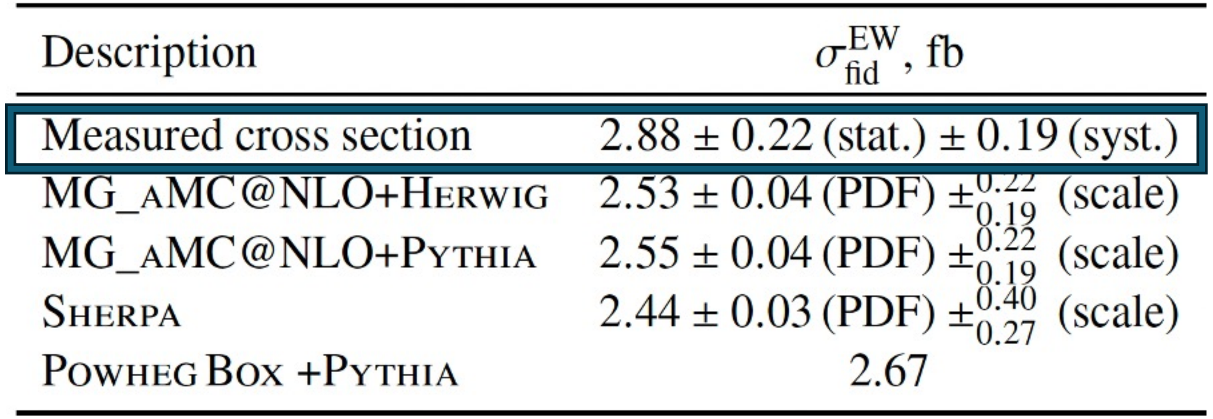
- Main sources: ZZ and VVV processes
- Two same-charge leptons are picked up as signal
- Smallest background contribution
- Estimated from simulation

$W^{\pm}W^{\pm}jj$ Fiducial cross section measurement

- Measured in a fiducial phase space which closely follows the signal region selection (see back-up)
- To extract the cross-section, a maximum likelihood fit is performed in bins of the di-jet invariant mass (m_{jj})
- The fit is done in four regions depending on lepton flavor ($e^{\pm}e^{\pm}, e^{\pm}\mu^{\pm}, \mu^{\pm}e^{\pm}, \mu^{\pm}\mu^{\pm}$)



- ➢ Good agreement between data and MC
- ➢ Good EW signal purity

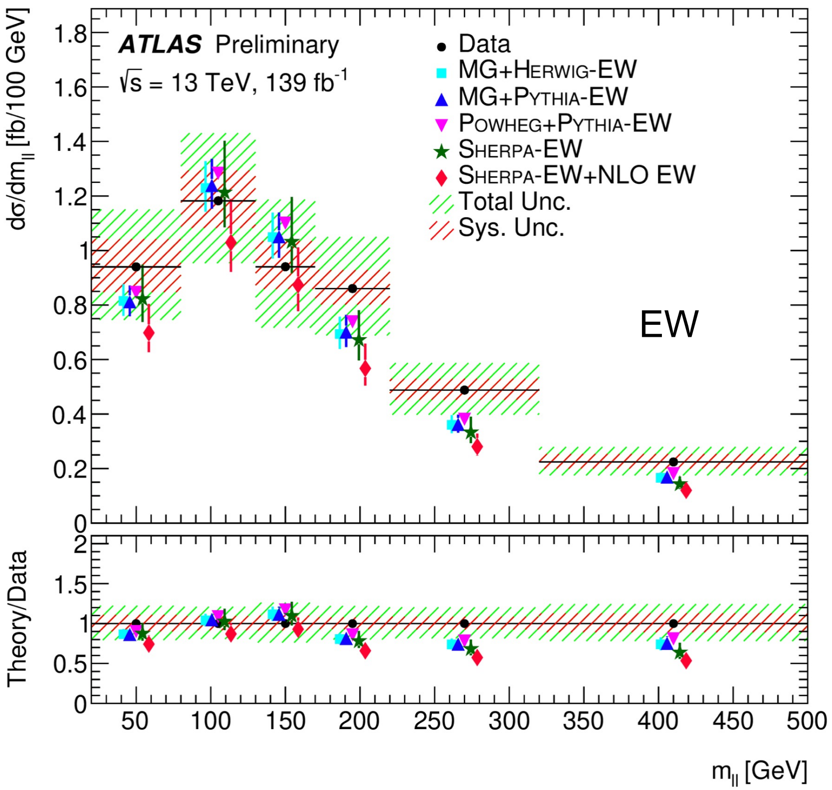


Description	$\sigma_{\text{fid}}^{\text{EW}}$, fb
Measured cross section	**$2.88 \pm 0.22\,(\text{stat.}) \pm 0.19\,(\text{syst.})$**
MG_aMC@NLO+Herwig	$2.53 \pm 0.04\,(\text{PDF}) \pm^{0.22}_{0.19}\,(\text{scale})$
MG_aMC@NLO+Pythia	$2.55 \pm 0.04\,(\text{PDF}) \pm^{0.22}_{0.19}\,(\text{scale})$
Sherpa	$2.44 \pm 0.03\,(\text{PDF}) \pm^{0.40}_{0.27}\,(\text{scale})$
Powheg Box +Pythia	2.67

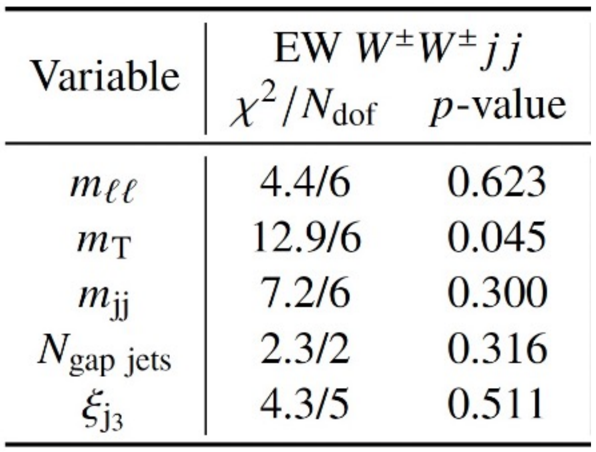
- ➢ The measured cross-section agrees with SM prediction within uncertainties
- ➢ This measurement is more precise than the previous one

$W^{\pm}W^{\pm}jj$ Differential cross section measurement

- Measured in the same fiducial phase space mentioned previously (no split in lepton flavor)



- Five observables measured
- χ^2 and p-values quantify data/MC compatibility

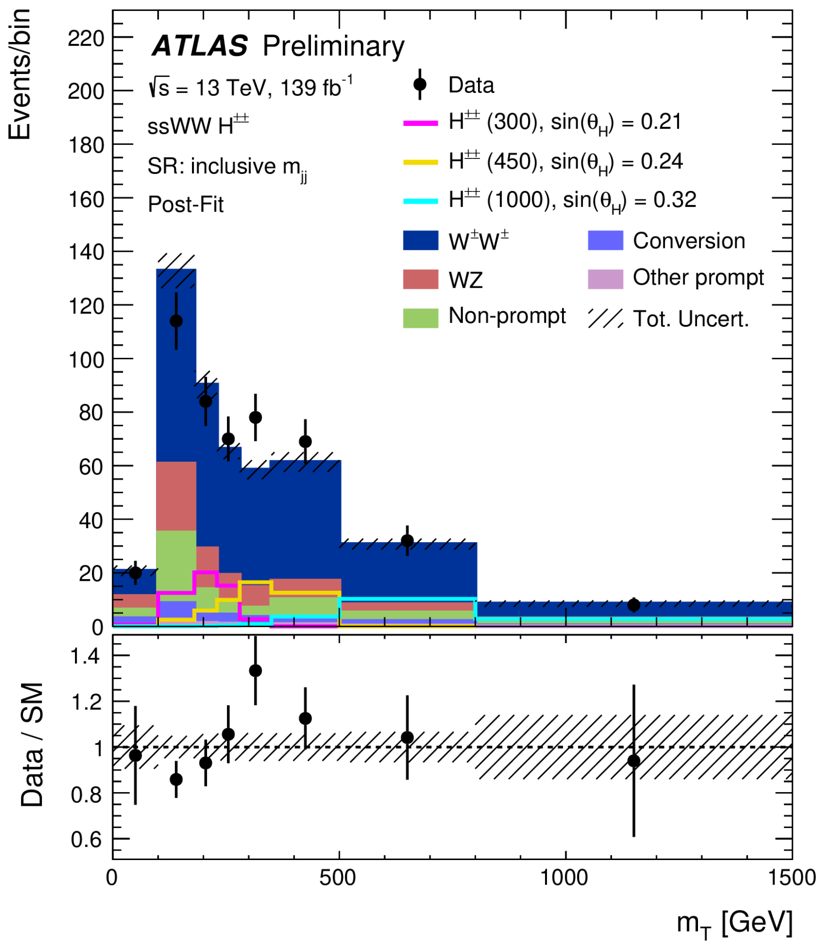


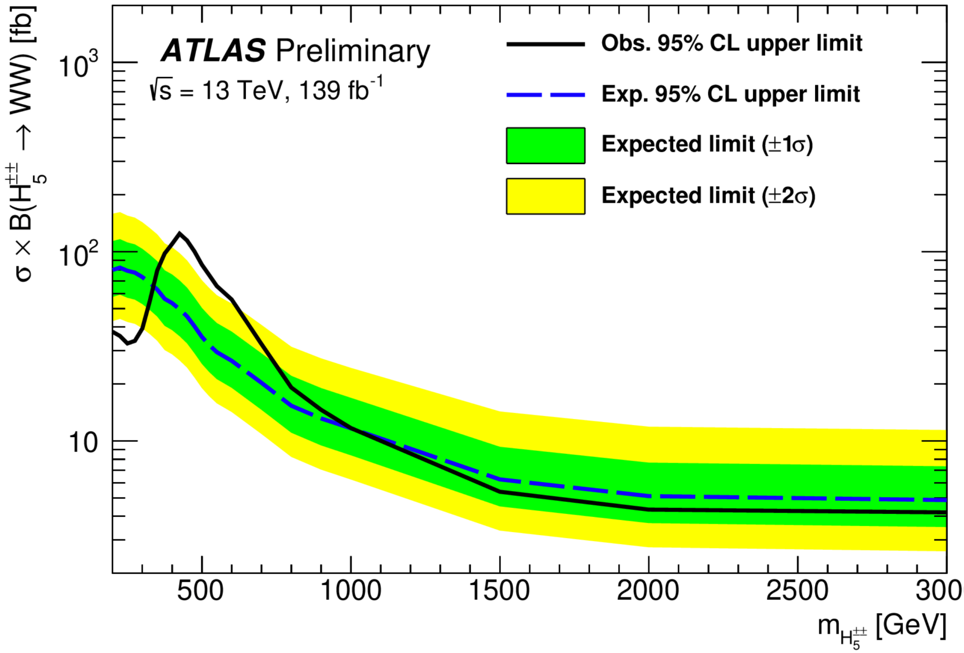
Variable	EW $W^{\pm}W^{\pm}jj$ χ^2/N_{dof}	p-value
$m_{\ell\ell}$	4.4/6	0.623
m_{T}	12.9/6	0.045
m_{jj}	7.2/6	0.300
$N_{\text{gap jets}}$	2.3/2	0.316
ξ_{j3}	4.3/5	0.511

- ➢ Prediction generally underestimates data but good agreement within uncertainties
- ➢ p-values range between 0.3 and 0.62 indicating reasonable agreement. p-value for m_T is 0.045

$H^{\pm\pm}$ Searches

- Model independent upper limits at 95% CL on $\sigma_{VBF}\times\mathcal{B}(H_5^{\pm\pm}\rightarrow W^{\pm}W^{\pm})$ were extracted
- Limit setting: maximum likelihood fit to the distribution for transverse mass (m_T) of the dilepton and $E_{T,miss}$ system





- ➢ Largest excess seen at $m_{H_5^{\pm\pm}}$ = 450 GeV
- ➢ Local significance: 3.2σ
- ➢ global significance: 2.5σ

Summary

- The scattering of two same-sign W bosons is an important VBS process to probe electroweak symmetry breaking
- The electroweak $W^{\pm}W^{\pm}jj$ fiducial cross section has been measured and found to be consistent with the SM
- $W^{\pm}W^{\pm}jj$ differential cross sections are also measured as a function of five observables sensitive to VBS
  - Also found to be consistent with the SM
- Results are also interpreted to set limits on doubly charged Higgs boson production
  - Model independent upper limits at 95% CL on $\sigma_{VBF}\times\mathcal{B}(H_5^{\pm\pm}\rightarrow W^{\pm}W^{\pm})$ are extracted for $m_{H_5^{\pm\pm}}$ between 200 GeV and 3 TeV
  - A local excess of events at 450 GeV is noted with a global significance of 2.5σ

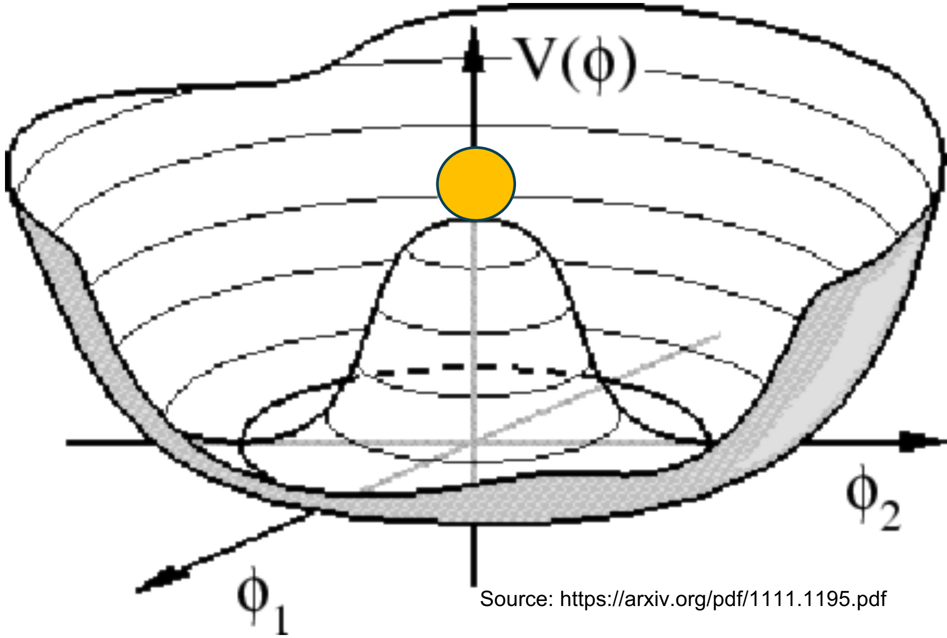
Link to $W^{\pm}W^{\pm}jj$ results

Back-up

Electroweak symmetry breaking

- The Standard Model (SM) is based on gauge theories
  - ➢ certain symmetries must be obeyed
- To write the SM Lagrangian in such a way that it obeys the underlying symmetry, mass terms for vector bosons are not allowed
  - ➢ Electroweak force carriers must have the same (or symmetric) zero mass, but W and Z bosons are massive
- To keep the Lagrangian invariant despite the massive W and Z bosons, a spontaneous symmetry breaking mechanism is introduced
- Higgs mechanism: Higgs boson interacts with W and Z bosons, making them massive, hence breaking electroweak symmetry
- The exact nature of this process is not very well understood

Higgs potential



Source: https://arxiv.org/pdf/1111.1195.pdf

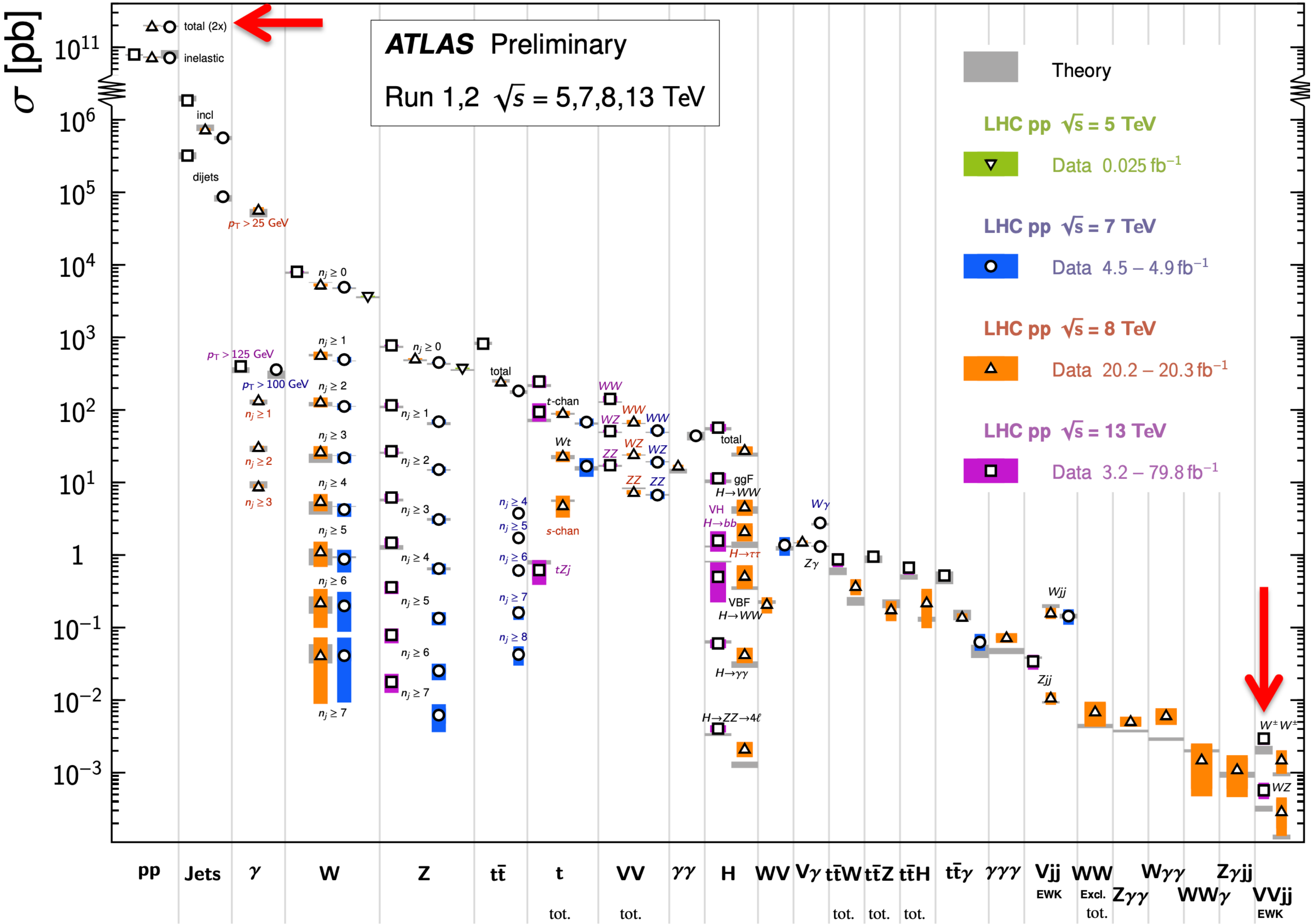
Spontaneous symmetry breaking happens when the Higgs rolls down to the circle of minimum potential

❖ **VBS measurements are important in our understanding of the nature of electroweak symmetry breaking**

- ➢ If the Higgs potential has a different shape from what the SM predicts, we expect to see some deviations from SM predictions in these measurements

$W^{\pm}W^{\pm}jj$ electroweak cross-section

- Cross-section for same-charge WW boson ($W^{\pm}W^{\pm}jj$) production is small ⟹ precision measurements require lots of data



Source:https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2019-010/

Same-sign WW object and event selection

Signal electrons:

- LHTight
- Gradient isolation
- ECIDS (charge ID selector)
- $p_T > 27$ GeV
- $|\eta_e| < 2.47$ excluding $1.37 < |\eta_e| < 1.52$

Jets:

- AntiKt4EMPFlowJets
- $p_T > 25$ GeV
- $|\eta_j| < 4.5$
- JVT

Signal muons:

- Medium ID
- FixedCutPflowTight isolation
- $p_T > 27$ GeV
- $|\eta_\mu| < 2.5$

b-jets (for b-veto):

- AntiKt4EMPFlowJets
- $p_T > 20$ GeV
- $|\eta_j| < 2.5$
- DL1r @ 85% efficiency WP

Analysis objects are after passing overlap removal (OR)

Event selection:

- Two same-sign signal leptons; 3rd lepton veto
- $m_{ll} >= 20$ GeV
- $|m_{ee} - m_Z| > 15$ GeV, $|\eta_e| < 1.37$ in the ee channel
- $E_{T,miss} > 30$ GeV
- $p_{T,jet,1(2)} > 65$ (35) GeV
- $m_{jj} > 500$ GeV
- $|\Delta y_{jj}| > 2$

3rd lepton veto:

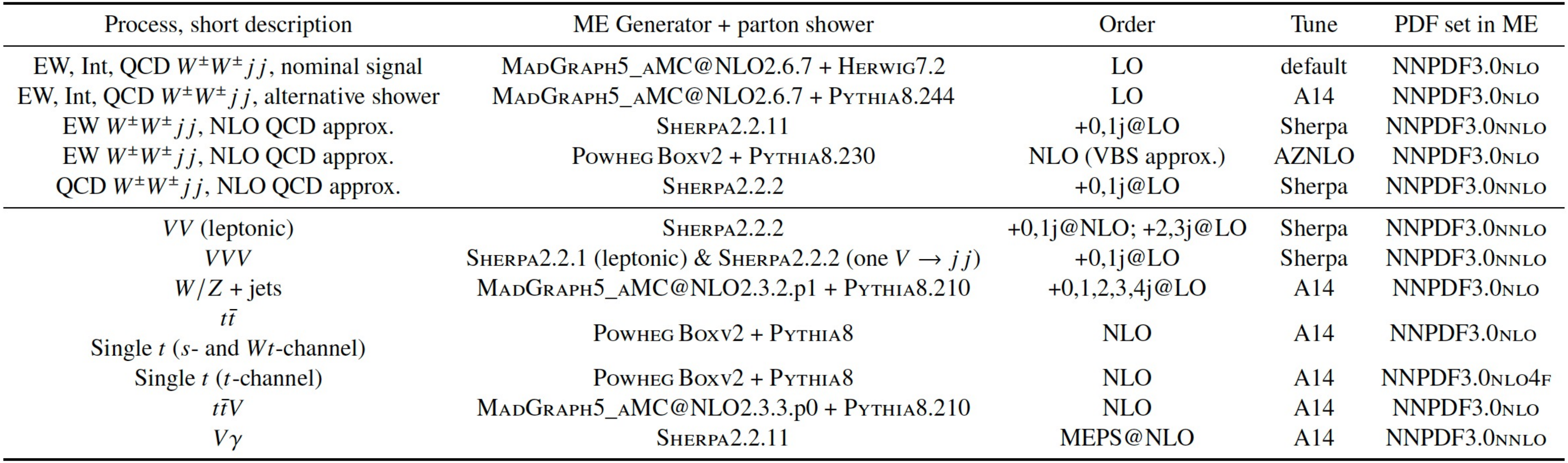
Reject event if there is a 3rd lepton surviving the OR, with:

- $p_{T,e} > 4.5$ GeV
- $p_{T,\mu} > 3$ GeV

or if there is a lepton not surviving the OR and is forming a dilepton with one of the signal leptons, with

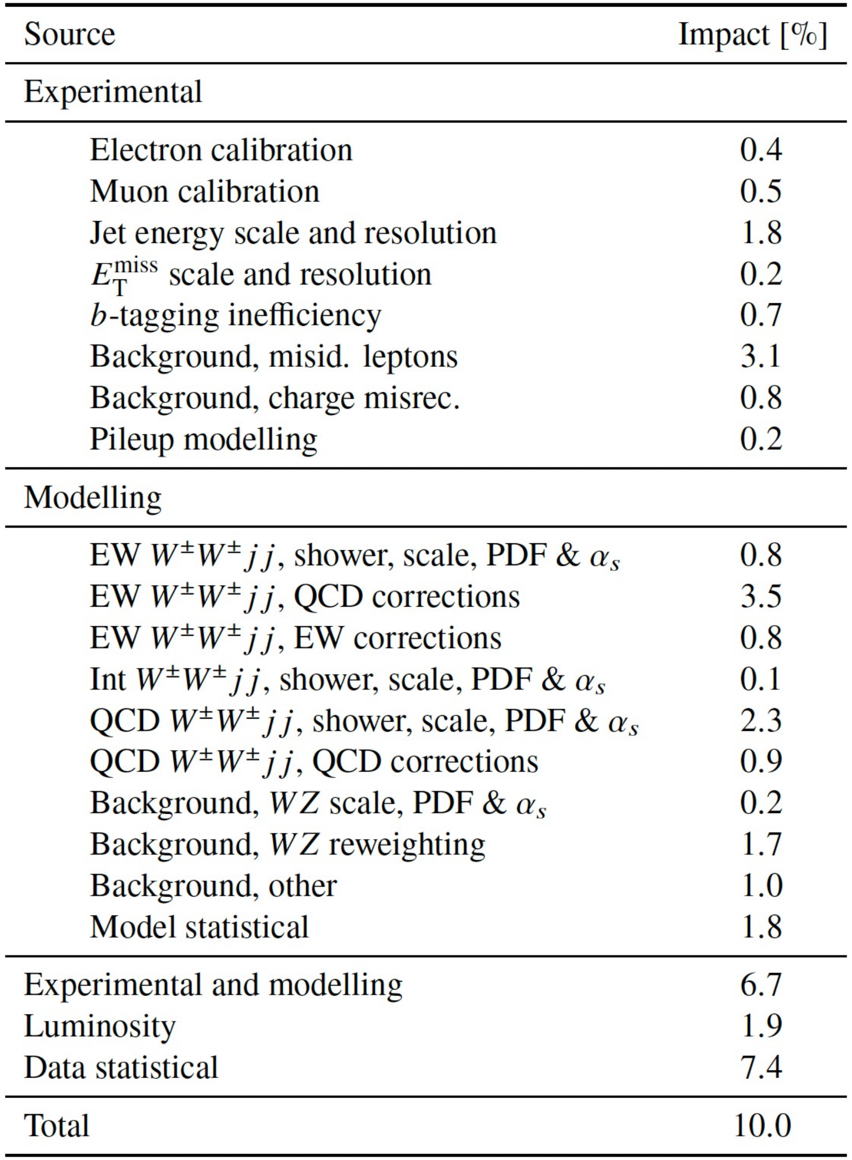
- $|m_{ll} - m_Z| < 15$ GeV

Same-sign WW samples

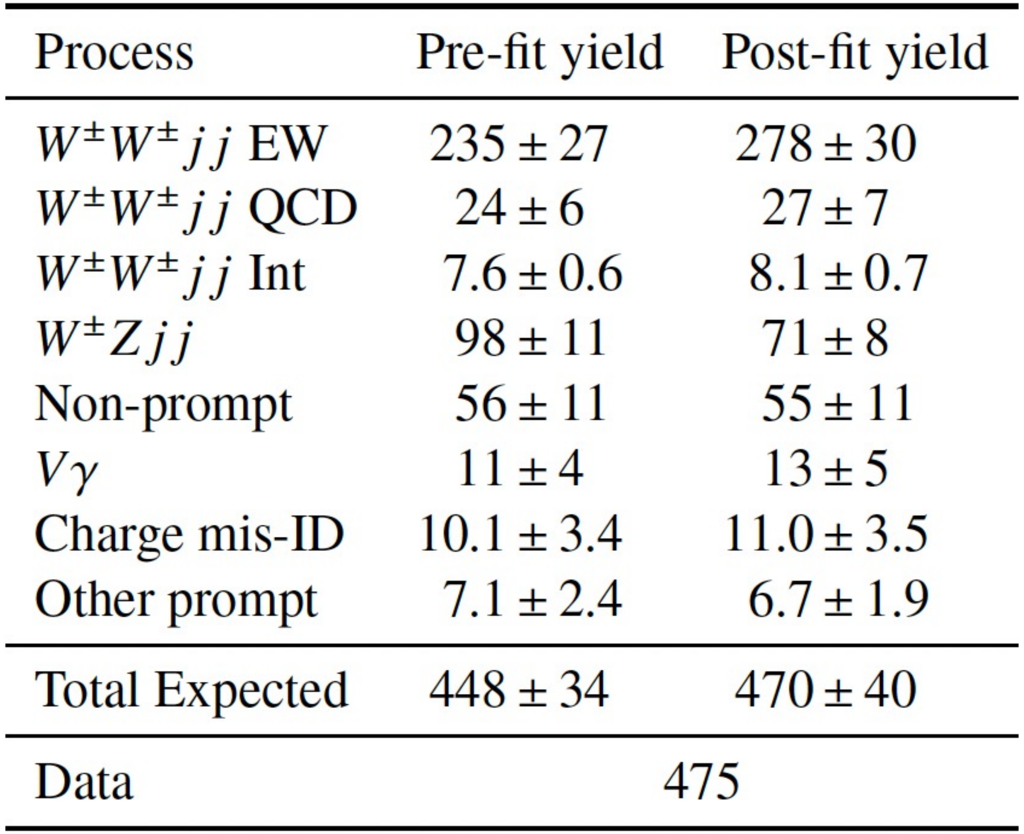


Process, short description	ME Generator + parton shower	Order	Tune	PDF set in ME
EW, Int, QCD $W^\pm W^\pm jj$, nominal signal	MadGraph5_aMC@NLO2.6.7 + Herwig7.2	LO	default	NNPDF3.0nlo
EW, Int, QCD $W^\pm W^\pm jj$, alternative shower	MadGraph5_aMC@NLO2.6.7 + Pythia8.244	LO	A14	NNPDF3.0nlo
EW $W^\pm W^\pm jj$, NLO QCD approx.	Sherpa2.2.11	+0,1j@LO	Sherpa	NNPDF3.0nnlo
EW $W^\pm W^\pm jj$, NLO QCD approx.	Powheg Boxv2 + Pythia8.230	NLO (VBS approx.)	AZNLO	NNPDF3.0nlo
QCD $W^\pm W^\pm jj$, NLO QCD approx.	Sherpa2.2.2	+0,1j@LO	Sherpa	NNPDF3.0nnlo
VV (leptonic)	Sherpa2.2.2	+0,1j@NLO; +2,3j@LO	Sherpa	NNPDF3.0nnlo
VVV	Sherpa2.2.1 (leptonic) & Sherpa2.2.2 (one $V \rightarrow jj$)	+0,1j@LO	Sherpa	NNPDF3.0nnlo
W/Z + jets	MadGraph5_aMC@NLO2.3.2.p1 + Pythia8.210	+0,1,2,3,4j@LO	A14	NNPDF3.0nlo
$t\bar{t}$	Powheg Boxv2 + Pythia8	NLO	A14	NNPDF3.0nlo
Single t (s- and Wt-channel)				
Single t (t-channel)	Powheg Boxv2 + Pythia8	NLO	A14	NNPDF3.0nlo4f
$t\bar{t}V$	MadGraph5_aMC@NLO2.3.3.p0 + Pythia8.210	NLO	A14	NNPDF3.0nlo
$V\gamma$	Sherpa2.2.11	MEPS@NLO	A14	NNPDF3.0nnlo

Same-sign yields and systematics



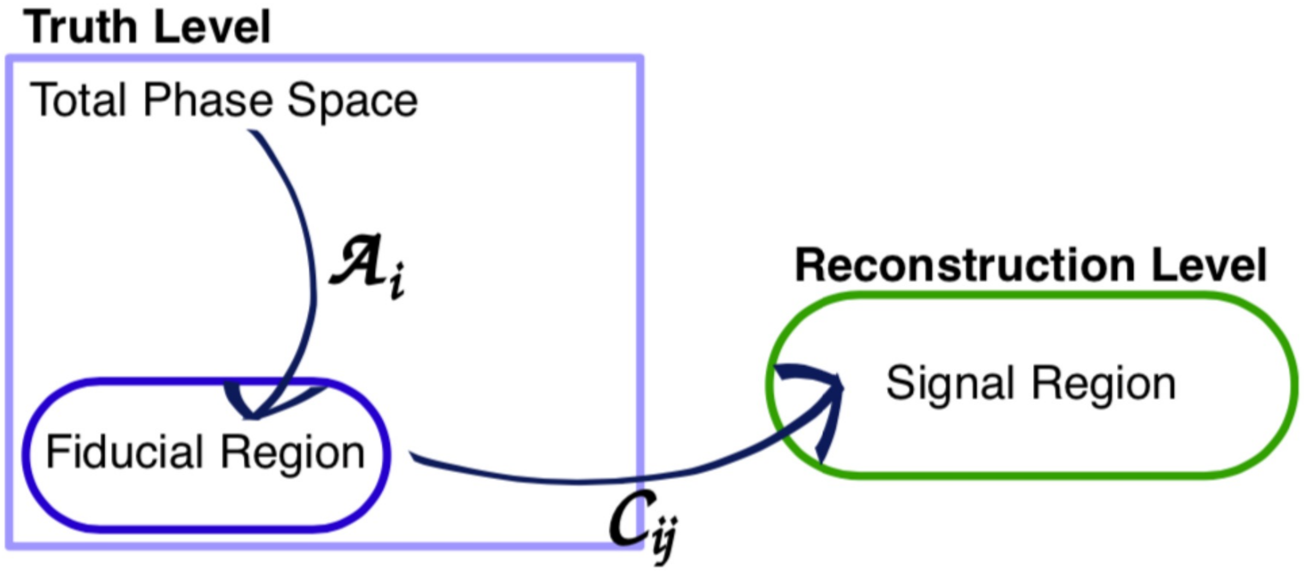
Source	Impact [%]
Experimental	
Electron calibration	0.4
Muon calibration	0.5
Jet energy scale and resolution	1.8
E_T^{miss} scale and resolution	0.2
b-tagging inefficiency	0.7
Background, misid. leptons	3.1
Background, charge misrec.	0.8
Pileup modelling	0.2
Modelling	
EW $W^\pm W^\pm jj$, shower, scale, PDF & α_s	0.8
EW $W^\pm W^\pm jj$, QCD corrections	3.5
EW $W^\pm W^\pm jj$, EW corrections	0.8
Int $W^\pm W^\pm jj$, shower, scale, PDF & α_s	0.1
QCD $W^\pm W^\pm jj$, shower, scale, PDF & α_s	2.3
QCD $W^\pm W^\pm jj$, QCD corrections	0.9
Background, WZ scale, PDF & α_s	0.2
Background, WZ reweighting	1.7
Background, other	1.0
Model statistical	1.8
Experimental and modelling	6.7
Luminosity	1.9
Data statistical	7.4
Total	10.0



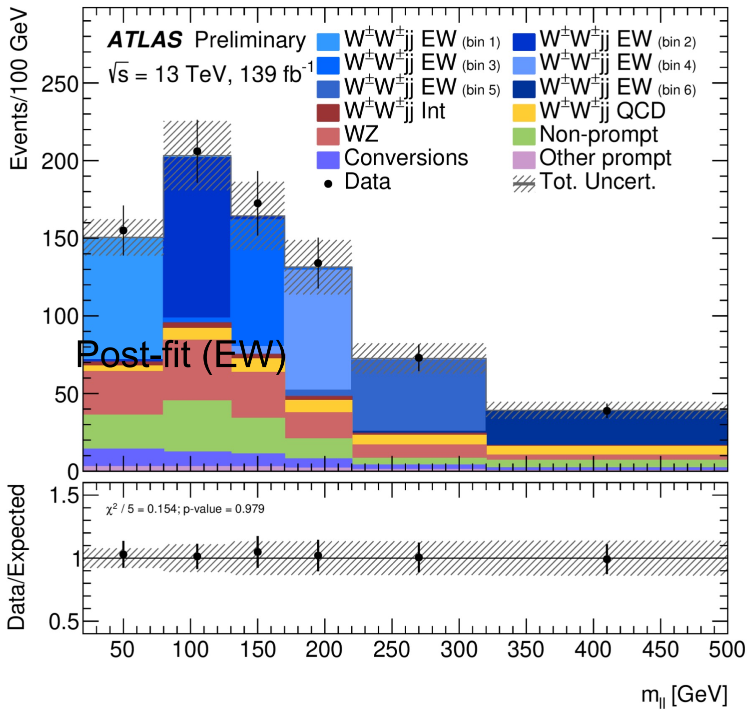
Process	Pre-fit yield	Post-fit yield
$W^\pm W^\pm jj$ EW	235 ± 27	278 ± 30
$W^\pm W^\pm jj$ QCD	24 ± 6	27 ± 7
$W^\pm W^\pm jj$ Int	7.6 ± 0.6	8.1 ± 0.7
$W^\pm Zjj$	98 ± 11	71 ± 8
Non-prompt	56 ± 11	55 ± 11
$V\gamma$	11 ± 4	13 ± 5
Charge mis-ID	10.1 ± 3.4	11.0 ± 3.5
Other prompt	7.1 ± 2.4	6.7 ± 1.9
Total Expected	448 ± 34	470 ± 40
Data	475	

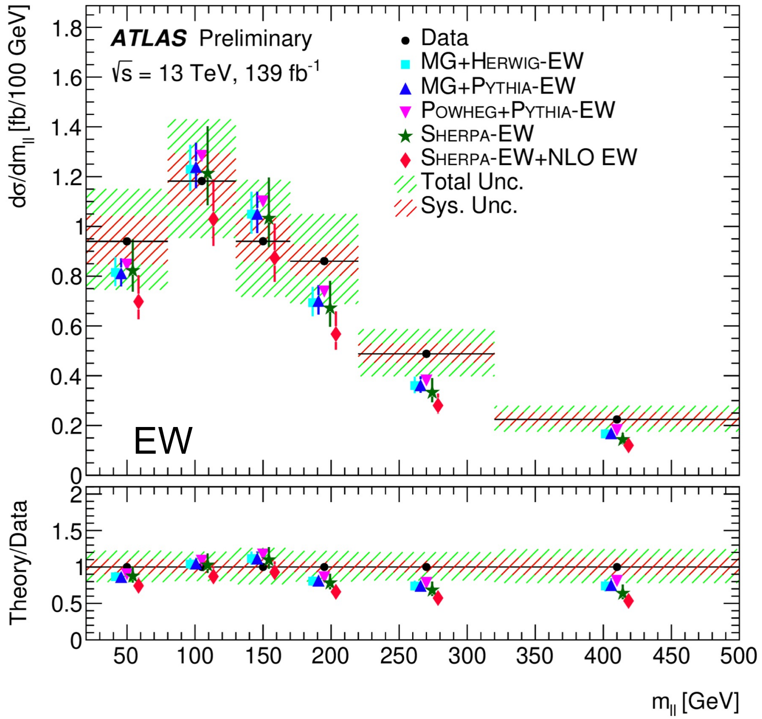
Same-sign fiducial region definition

- Two same-sign leptons (e or μ), dressed
- e or μ from tau lepton decays are excluded
- $p_{T,\text{lep}1,2} > 27$ GeV, $|\eta_{\text{lep}1,2}| < 2.5$
- $m_{ll} >= 20$ GeV
- $|m_{ee} - m_Z| > 15$ GeV
- $E_{T,\text{miss}} > 30$ GeV
- Two jets from AntiKt4TruthJets
- Overlap removal between electrons and jets
- $p_{T,\text{jet},1(2)} > 65\ (35)$ GeV, $|\eta_j| < 4.5$
- $m_{jj} > 500$ GeV
- $|\Delta y_{jj}| > 2$



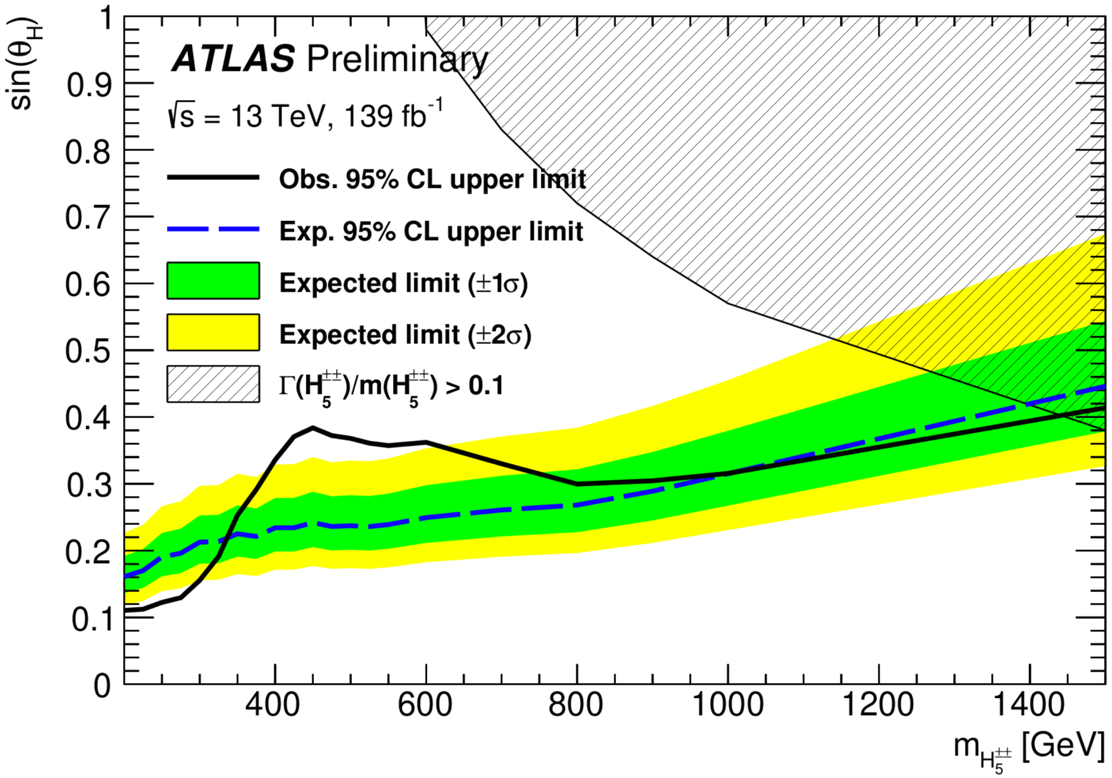
$W^\pm W^\pm jj$ Differential cross section measurement





$H^{\pm\pm}$ Searches

- Results are also interpreted to search for a doubly charged Higgs boson produced in VBF processes within the Georgi-Machacek model using $m_{H_5^{\pm\pm}}$ and $\sin\theta_H$ as model parameters
- Limit setting: maximum likelihood fit to the distribution for transverse mass (m_T) of the dilepton and $E_{T,miss}$ system



➢ $\sin\theta_H$ > 0.11-0.41 for $200 < m_{H_5^{\pm\pm}} < 1500$ are excluded