Same Sign WW Scattering

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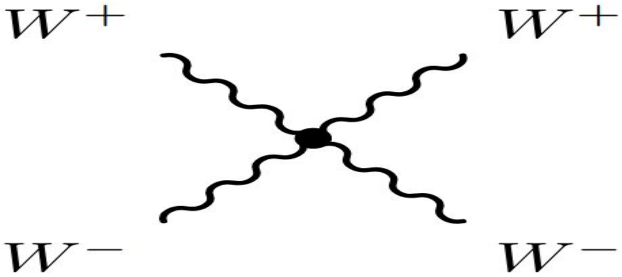
Overview

- Background and theory of vector boson scattering (VBS)
- Most recent ATLAS published results of same sign WW measurements

LHC and the "No Lose" Theorem

- Prior to Higgs discovery, it was known that at the LHC something would be found for EW interactions at a scale of ~1 TeV
- In SM Lagrangian, there exist terms that couple EW gauge bosons directly
- $$\mathcal{L} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{8}tr(\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}) + \ldots$$
- These terms lead to both WWZ type scattering terms, as well as WZ->WZ and WW -> WW terms
- These processes clearly probe the structure of the EW sector of the SM Lagrangian, but they also lead to ...

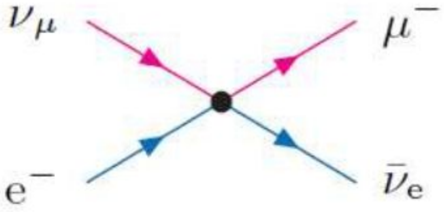
Divergences!



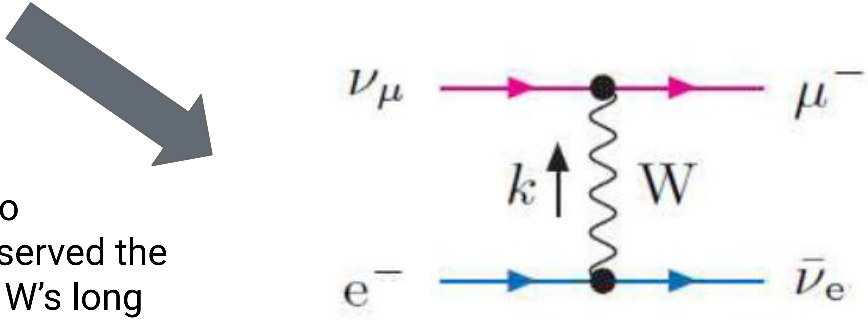
- When considering the cross section of longitudinal polarized scattering of W bosons, the cross section of this process alone is unbounded (ie $\sigma \sim s$)
- This is obviously unphysical, and thus to preserve unitarity and avoid a divergence, something must give at approximately 1 TeV

Historical Aside

- Analogous to the logic applied in 1933 to 4 fermion couplings observed in electron neutrino scattering



$$\mathcal{M}(\nu_\mu e^- \to \nu_e \mu^-) = \frac{G_F s}{2\sqrt{2}\pi^2}$$

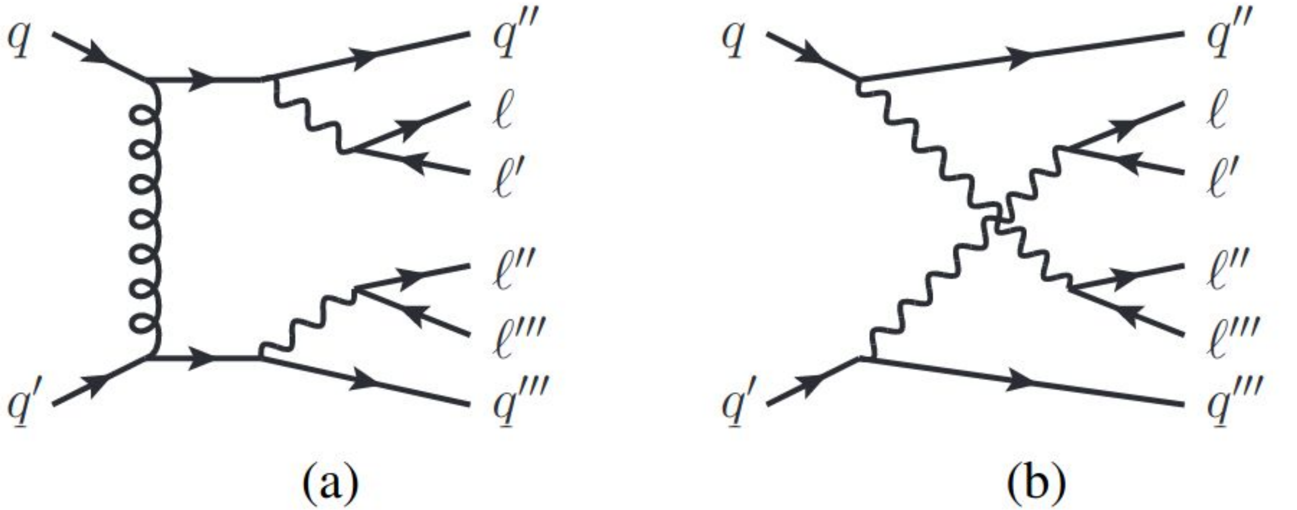


Transition from 4 fermion vertex, to exchange of a heavy mediator preserved the unitarity and provided evidence of W's long before they were observed experimentally

How Do We Preserve Unitarity?

- Many ideas pre LHC, the most popular of which today was the correct one, the Higgs Boson
- Addition of Higgs diagrams causes cancellation with the unbounded piece of the WWWW matrix element, leading to an implicit mass limit on the Higgs (< ~1 TeV) and restoration of unitarity
- Of course we found the Higgs in 2012, so this is moot right?
- Wrong, still interesting for many reasons
  - Self consistency of standard model
  - Potential for non cancellation / addition terms in the Lagrangian
  - Possible BSM physics in higher order terms

What processes can we look for at the LHC?



Two processes with same initial and final states

(a) Strong production
(b) Electroweak production

Why same sign WW?

- Largest ratio of EW production to strong production
  - As compared to WZ-> WZ, ZZ->ZZ, and opposite sign WW
  - At LO gluon initiated processes are absent
  - qqbar annihilation diagrams are suppressed
- Trilinear VBS reactions in the s channel are absent in this final state
- Same sign leptons are not common, relative to opposite sign leptons

Signal Selection

Selection	Cut
Trigger	Single lepton (e/mu)
m_{ll}	> 30 GeV
MET	> 30 GeV
Leading jet pT	> 60 GeV
Subleading jet pT	> 35 GeV
N bjets	== 0
m_{jj}	> 200 GeV
$\|\Delta y_{jj}\|$	> 2.0

Background Sources

- Backgrounds from SM originate from 3 main sources
  - SM processes with 2 same sign leptons
    - Modeled from MC simulation
    - Trilepton events (WZ) where the OS lepton is not reco’d
  - SM processes that lead to non-prompt or fake leptons
    - Estimated by data driven method
    - ttbar, W+jets, single top, QCD multijet events
  - SM processes with 2 opposite sign leptons where the charge on one is misIDed
    - Estimated by data driven method
    - ttbar, W+jets, Z/ɣ + jets

Background Estimation I

- WZ, V+ɣ, ZZ, ttbar + V are all estimated from MC simulation
  - WZ normalization is determined by events with 3 baseline leptons, two of which pass the signal selection, in the data
  - V + ɣ is corrected using Z - >μμɣ, in data, to account for photons faking electrons
    - The selection in data requires 75 GeV < m(μμe) < 100 GeV and an inverted MET cut, to enhance the Z contribution
    - Large systematic (44%) is assigned to interpolate from Z -> W

Background Estimation II

- Background contributions from non-prompt/fake leptons are estimated from a data control region via “fake factor” method
- Sources are heavy flavor and jets faking leptons (electrons)
- Method uses a region kinematically similar to signal, but enhanced in fake/non-prompt leptons
  - Leptons are divided into “loose” (inverted cuts) and “tight” (signal like)
- Background is generated by weighting control region events using fake factor, defined below
- Uncertainties vary from 40-90%

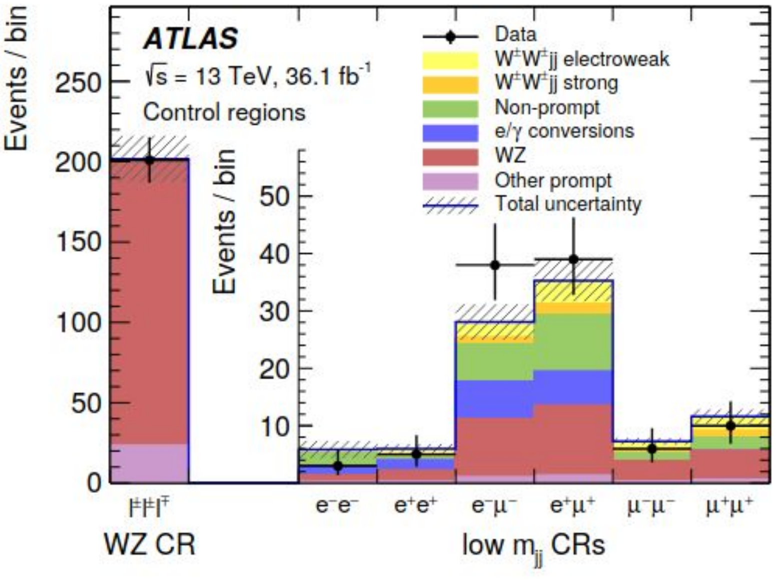
$$f_{\text{lepton, std}} \equiv \frac{N_{\text{nominal lepton ID}}}{N_{\text{loose lepton ID}}}$$

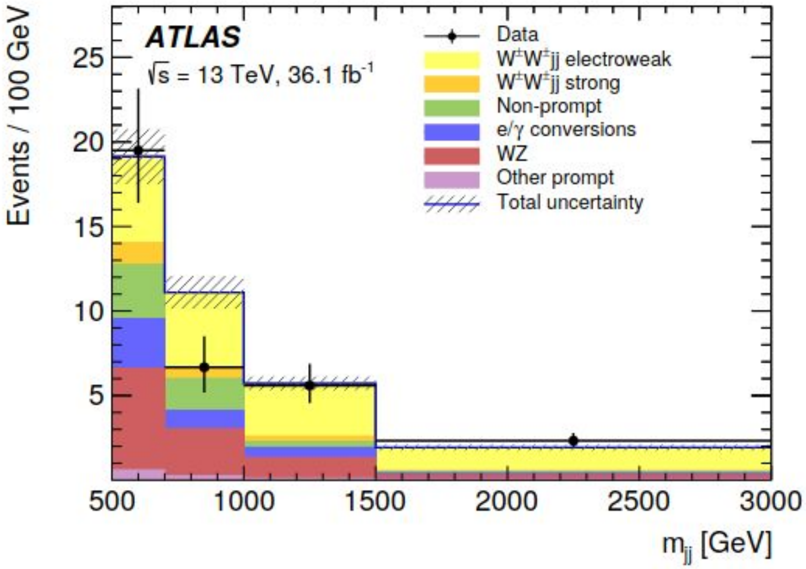
Background Estimation III

- Charge misID occurs when two opposite sign have one reconstructed with the incorrect charge
- The probability that a charge is misID'd, ϵ_{misrec}, is measured in Z -> ee events and varies from 0.1 - ~1%
- This is applied to the ssWW analysis by selecting dilepton pairs that satisfy all the electron selection criteria, except for the same sign requirement
- These events are then weighted by ϵ_{misrec} to estimate the background in the signal region
- Note muon charge misID is negligible

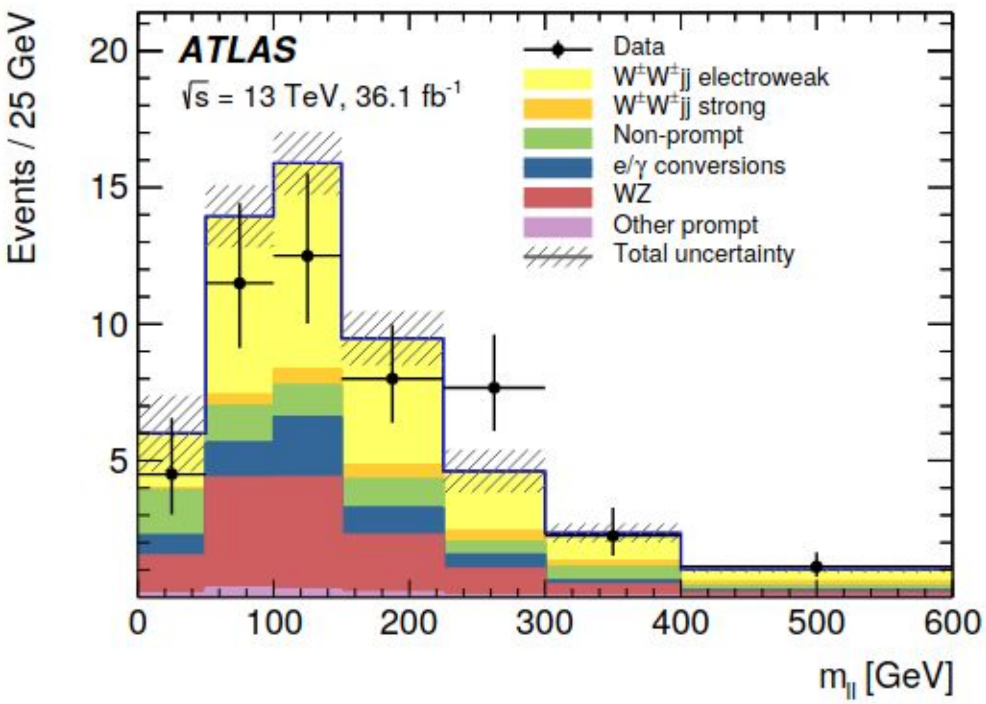
Results

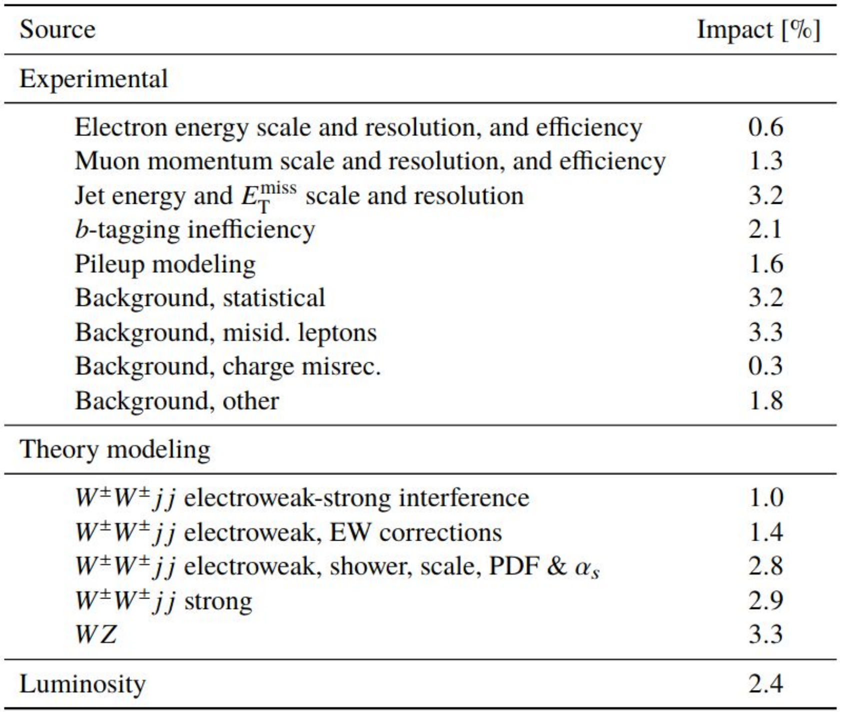
- Six channels are made in all flavor/charge combinations
- Four bins are made in m_{jj} > 500 GeV plus additional control regions at lower m_{jj} values
- All regions are combined into a profile likelihood fit





Results II





Source	Impact [%]
Experimental	
Electron energy scale and resolution, and efficiency	0.6
Muon momentum scale and resolution, and efficiency	1.3
Jet energy and E_T^{miss} scale and resolution	3.2
b-tagging inefficiency	2.1
Pileup modeling	1.6
Background, statistical	3.2
Background, misid. leptons	3.3
Background, charge misrec.	0.3
Background, other	1.8
Theory modeling	
$W^{\pm}W^{\pm}jj$ electroweak-strong interference	1.0
$W^{\pm}W^{\pm}jj$ electroweak, EW corrections	1.4
$W^{\pm}W^{\pm}jj$ electroweak, shower, scale, PDF & α_s	2.8
$W^{\pm}W^{\pm}jj$ strong	2.9
WZ	3.3
Luminosity	2.4

Conclusion

- Final measurement: $\sigma^{\text{fid.}} = 2.89^{+0.51}_{-0.48}\,(\text{stat.})\,^{+0.24}_{-0.22}\,(\text{exp. syst.})\,^{+0.14}_{-0.16}\,(\text{mod. syst.})\,^{+0.08}_{-0.06}\,(\text{lumi.})\text{ fb.}$
- Background only rejected by 6.5 sigma (4.4 exp)
- Extensions possible here though not explored in the 13 TeV ATLAS result
    - Higher level operators in the Lagrangian
    - Specifically, O(6) operators can produce small effects at EW scale, depending on the new physics scale
    - As precision improves for such processes, it is worth improving precision to look for anomalous couplings in ssWW in particular

References

[1] arxiv:1906.03203
[2] arxiv: hep-ph/9504426
[3] B. Jager. “Vector Boson Scattering: A phenomenological Perspective” HiggsTools Summer School. Online Talk. https://conference.ippp.dur.ac.uk/event/447/contributions/2227/attachments/1838/2047/Jaeger1.pdf