Towards Observing $W_L^{\pm}W_L^{\pm} \rightarrow W_L^{\pm}W_L^{\pm}$ at the LHC (using hadronic decays)

OFFSHELL 2021

THE VIRTUAL HEP CONFERENCE

RUN 4 HL LHC

6-9 July 2021

Karolos Potamianos

July 6, 2021

UKRI Science and Technology Facilities Council

UNIVERSITY OF OXFORD

Probing VBS :: Motivation

- Important tests of Electroweak and Strong interaction
- They directly probe EW boson self-interactions
- They are a portal to
  - Understanding Electroweak Symmetry Breaking
  - Probing BSM physics

Measurements at the LHC:

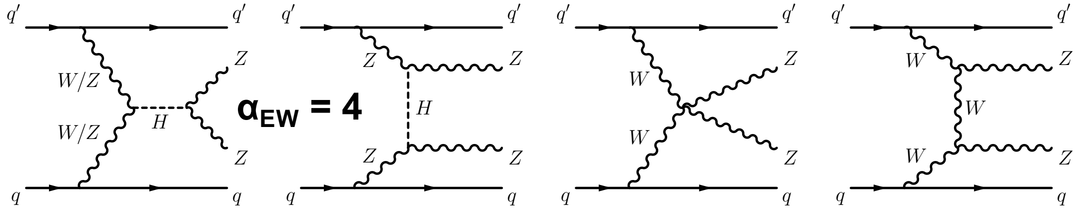
- Fiducial and differential cross-sections
- Looking for anomalous couplings (EFT)
- **Probing EW boson polarisation**

Probing VBS :: What we measure

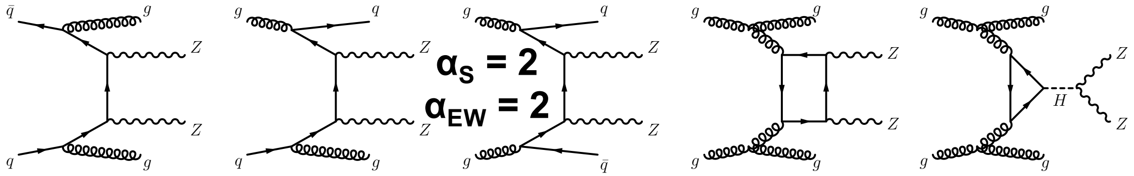
Cannot directly measure VBF/VBS

- **Significant interference with other diagrams with same order in**
- **Extracting** VBS component is **not gauge invariant**
- We can only **measure electroweak production** of VVjj (VBS)
- Moreover, QCD/strong production is much larger than EW (excl. $W^{\pm}W^{\pm}jj$)

EW

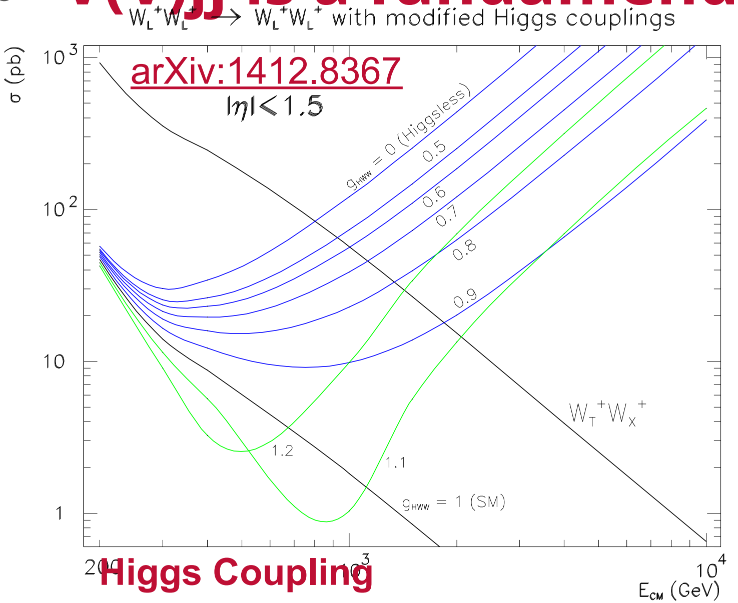


QCD

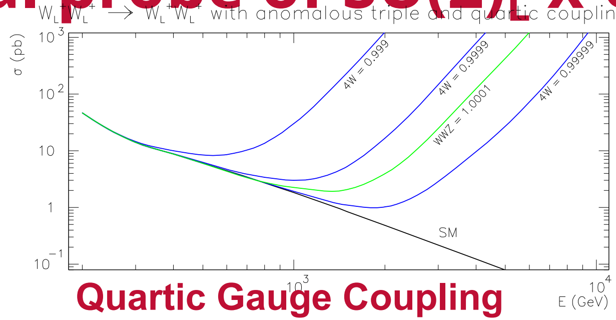


Probing Electroweak Symmetry Breaking

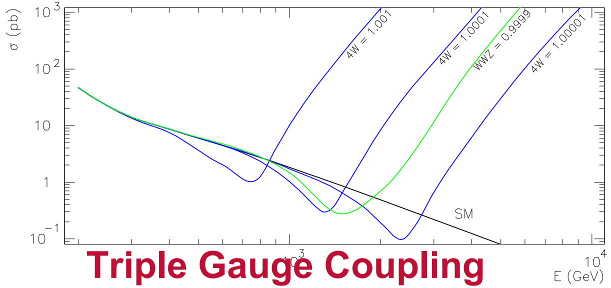
- VBS at high energy subject to **delicate cancellation between terms**
  - $\sigma(W_L W_L \rightarrow W_L W_L)$ grows with energy w/o Higgs boson
  - Very sensitive to shifts in the trilinear or quartic gauge coupling
- **V(V)jj is a fundamendal probe of $SU(2)_L \times U(1)_Y$**



Higgs Coupling



Quartic Gauge Coupling

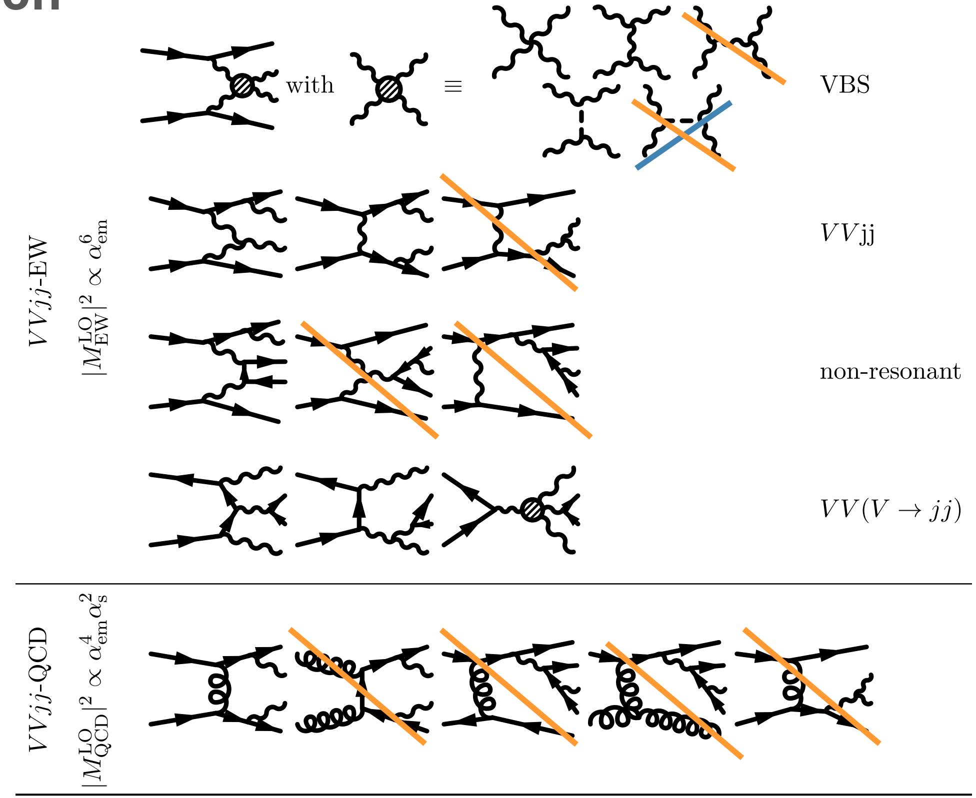


Triple Gauge Coupling

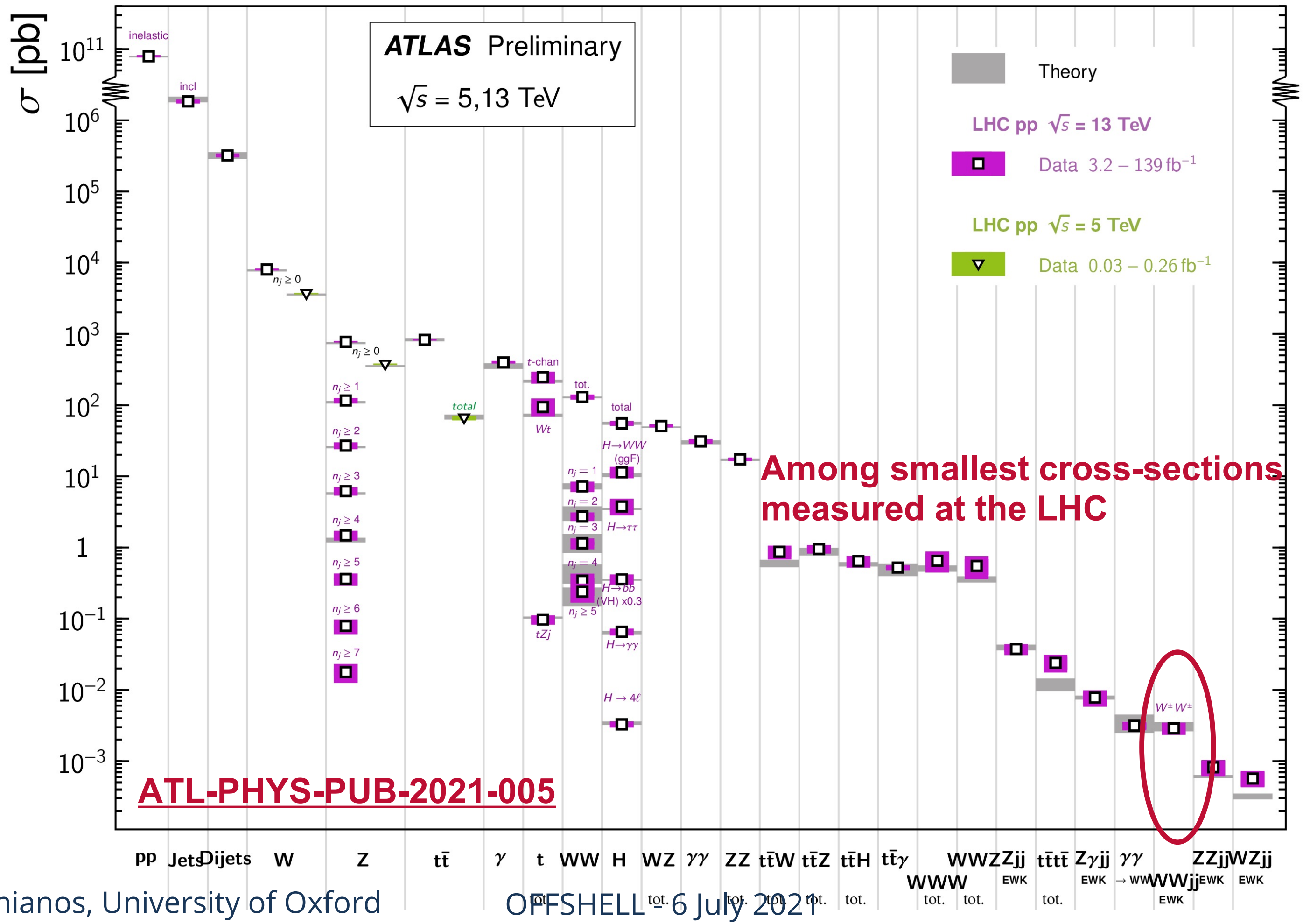
Advantages of probing $W^{\pm}W^{\pm}jj$

- **When VV = $W^{\pm}W^{\pm}$, some production modes are forbidden, yielding a large σ_{EW}/σ_{QCD} ratio**

- **Same-charge requirement helps reducing backgrounds (e.g. tt)**



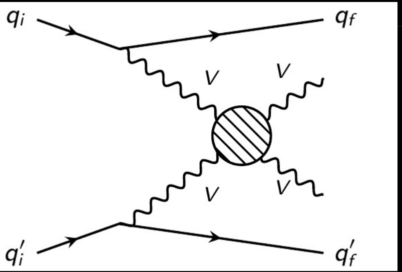
Standard Model Production Cross Section Measurements



Among smallest cross-sections measured at the LHC

ATL-PHYS-PUB-2021-005

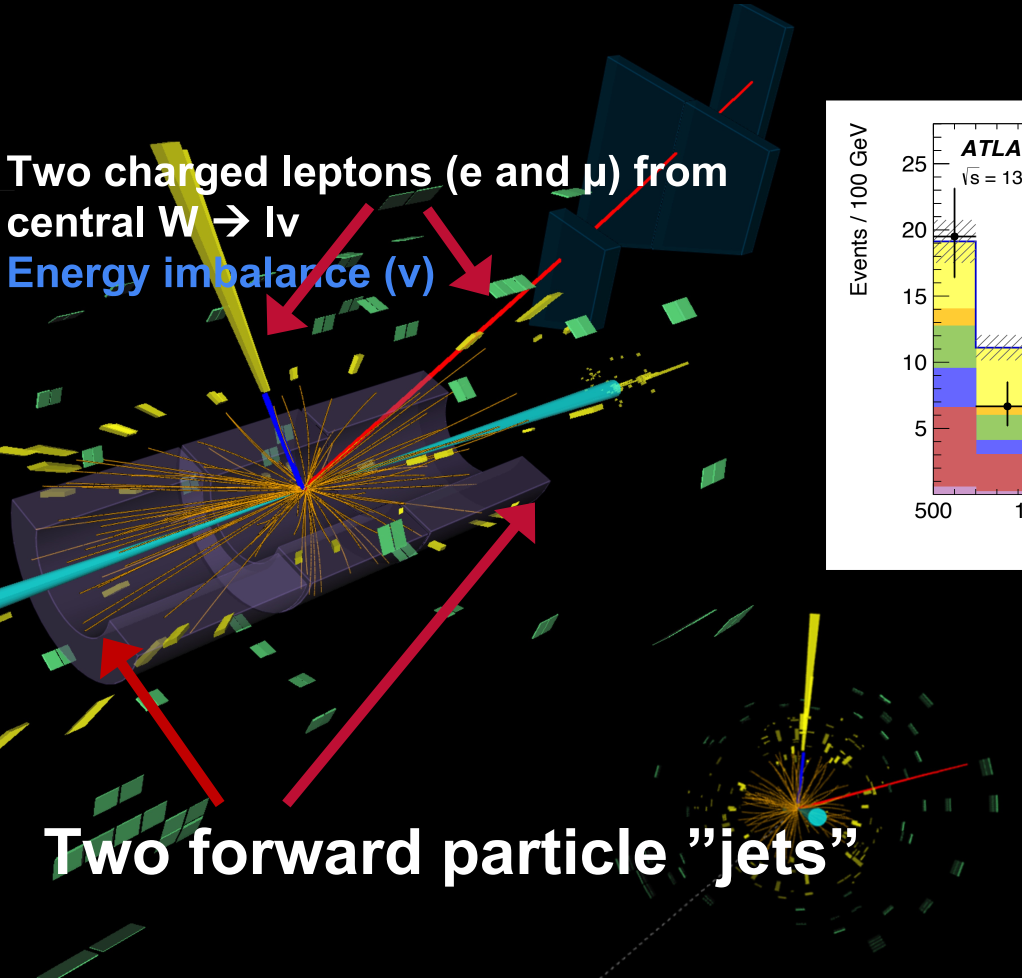
How does VBS look like ?

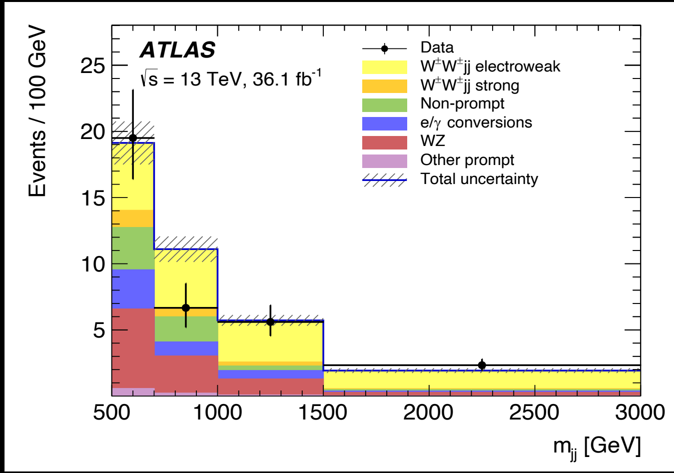


Two charged leptons (e and μ) from central W → lν

Energy imbalance (ν)

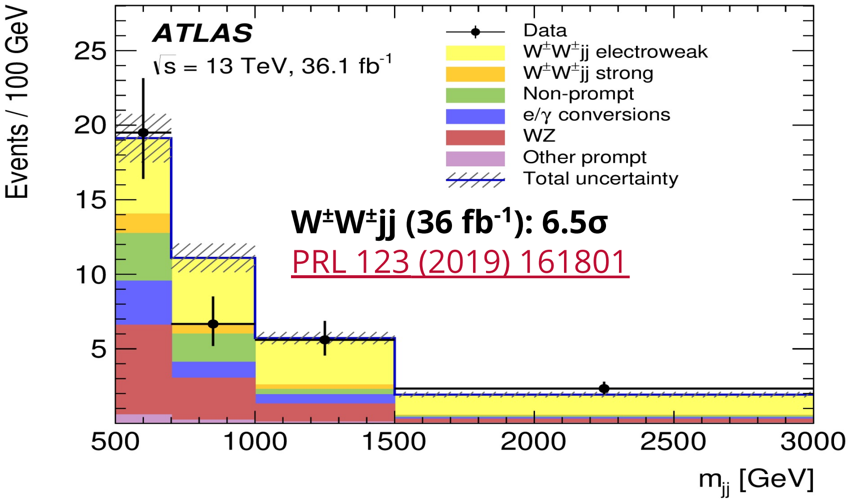
Two forward particle "jets"





Status of W±W±jj at the LHC

Observed using 36 fb-1 of LHC data by both ATLAS and CMS

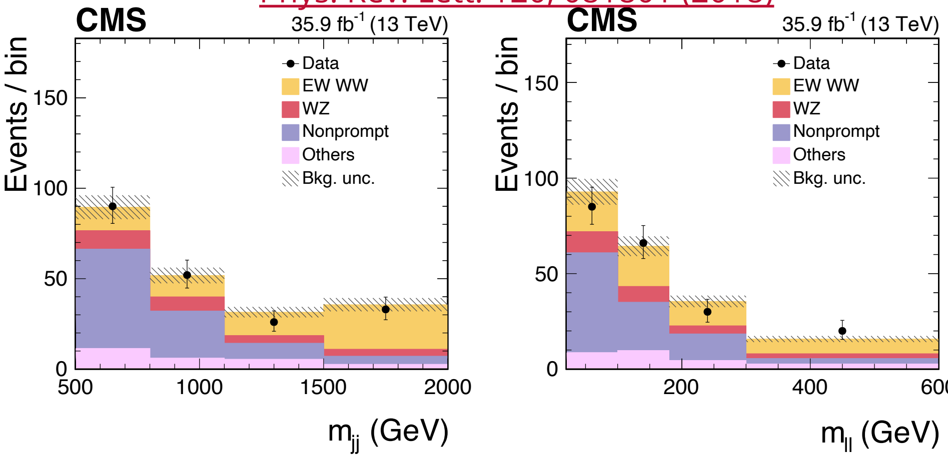


W±W±jj (36 fb^{-1}): 6.5σ

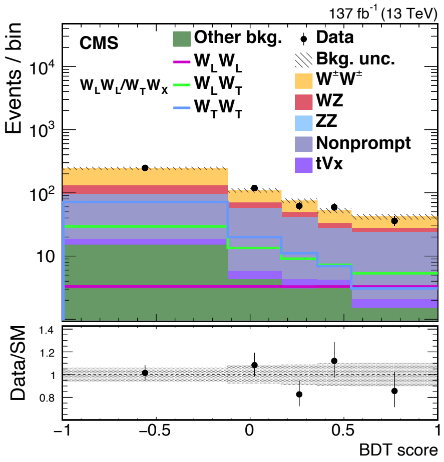
PRL 123 (2019) 161801

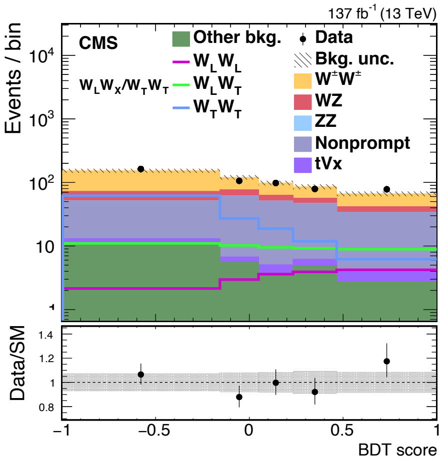
W±W±jj (36 fb^{-1}): 5.5σ

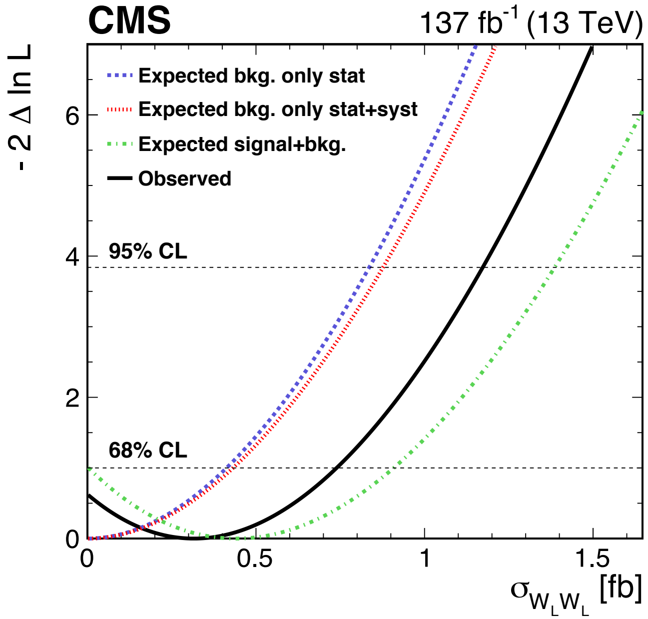
Phys. Rev. Lett. 120, 081801 (2018)



Status of $W_L^{\pm}W_L^{\pm}jj$ at the LHC

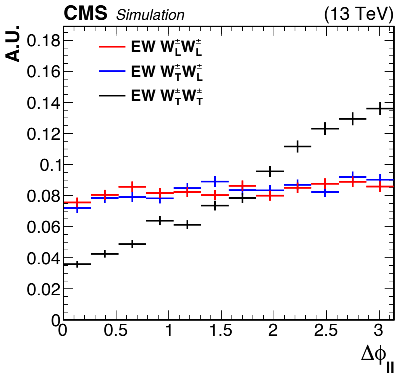






W±W± centre-of-mass frame

Process	$\sigma\mathcal{B}$ (fb)	Theoretical prediction (fb)
$W_L^{\pm}W_L^{\pm}$	$0.32^{+0.42}_{-0.40}$	0.44 ± 0.05
$W_X^{\pm}W_T^{\pm}$	$3.06^{+0.51}_{-0.48}$	3.13 ± 0.35
$W_L^{\pm}W_X^{\pm}$	$1.20^{+0.56}_{-0.53}$	1.63 ± 0.18
$W_T^{\pm}W_T^{\pm}$	$2.11^{+0.49}_{-0.47}$	1.94 ± 0.21



Phys. Lett. B 812 (2020) 136018

Projections for the HL-LHC

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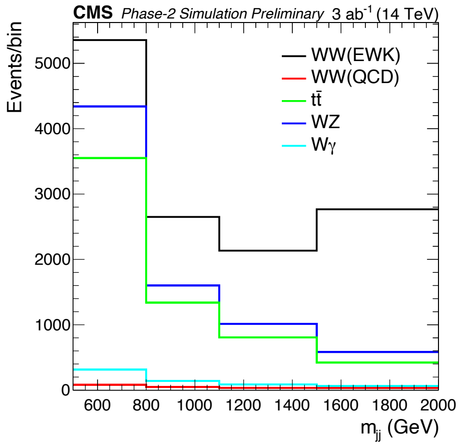
- **Large pool of events**
- Expecting **few percent precision** on σ(pp→W± W±jj)

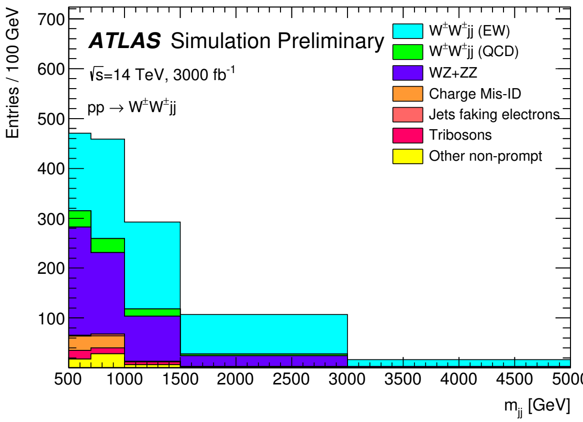
CMS

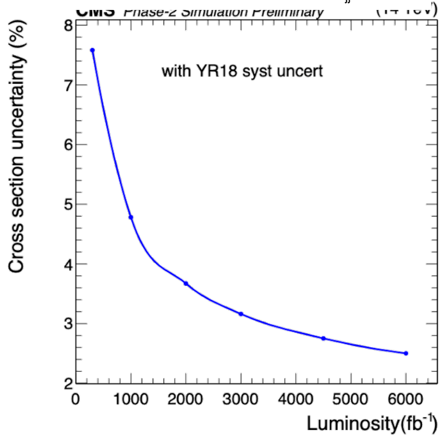
Process	Expected yield, $\mathcal{L} = 3000\,\text{fb}^{-1}$
$W^{\pm}W^{\pm}$ (QCD)	196
$t\bar{t}$	5515
WZ	1421
$W\gamma$	406
Total Background	7538
Signal $W^{\pm}W^{\pm}$ (EW)	5368

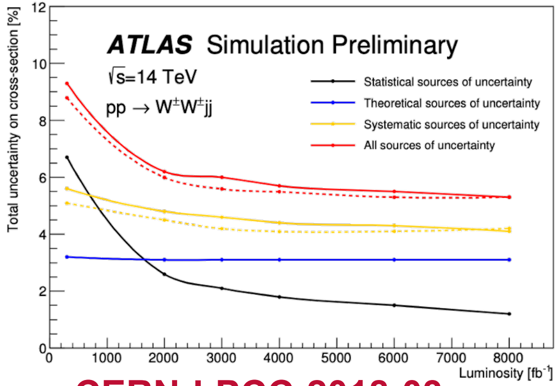
ATLAS

Process	All channels	$\mu^{\pm}\mu^{\pm}$	$e^{\pm}e^{\pm}$	$\mu^{\pm}e^{\pm}$	$e^{\pm}\mu^{\pm}$
$W^{\pm}W^{\pm}jj$(QCD)	168.7	74.6	19.7	32.2	42.2
Charge Misidentification	200	0.0	11	30	160
Jets faking electrons	460	0.0	130	260	70
$WZ + ZZ$	1286	322	289	271	404
Tribosons	76	30.1	9.6	15.1	21.6
Other non-prompt	120	29	16.6	50	19
Total Background	2310	455	480	660	710
Signal $W^{\pm}W^{\pm}jj$(EW)	2958	1228	380	589	761



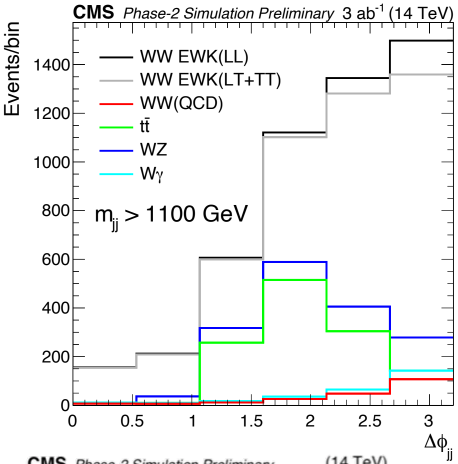


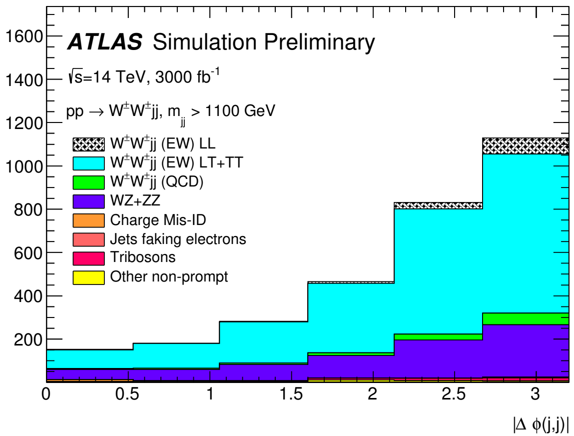


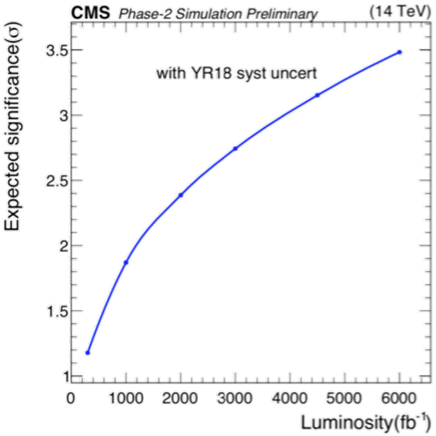


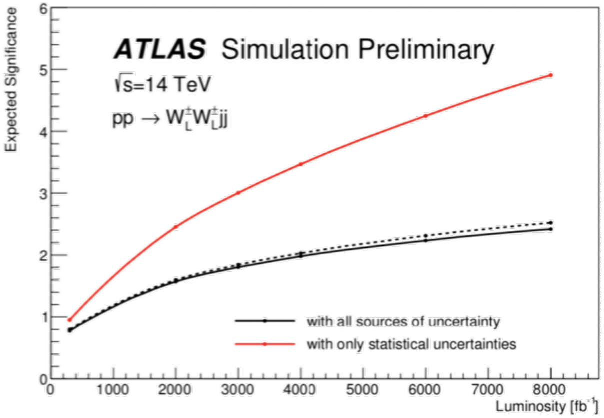
Projections for the HL-LHC for $W_L^{\pm}W_L^{\pm}jj$

- **Longitudinal polarisation can be probed at HL-LHC**
- ~3σ per experiment using leptonic decays (e, μ) and assuming limited analysis improvements
- Unfortunately, that’s **not enough**









Improvements in the leptonic channel

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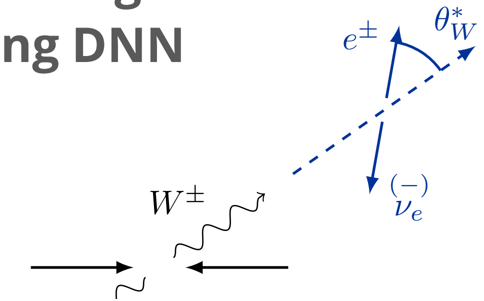
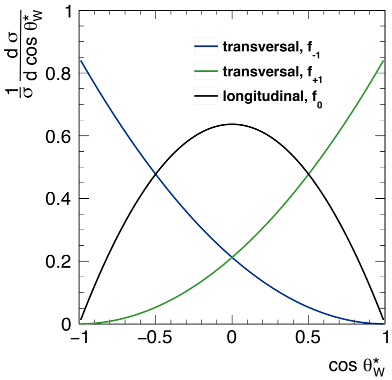
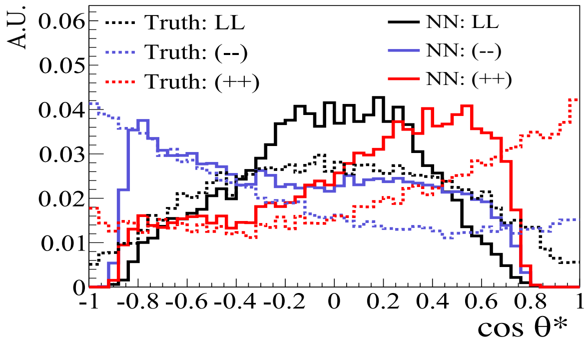
- **Inferring cos θW* using DNN**

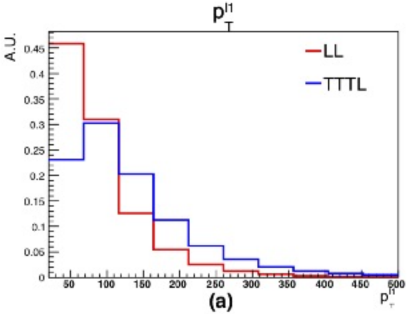


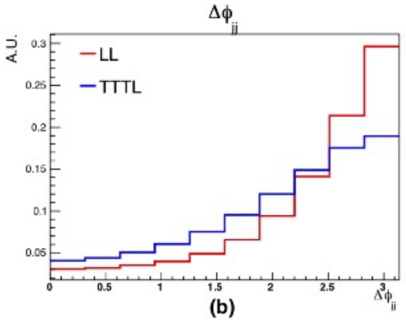


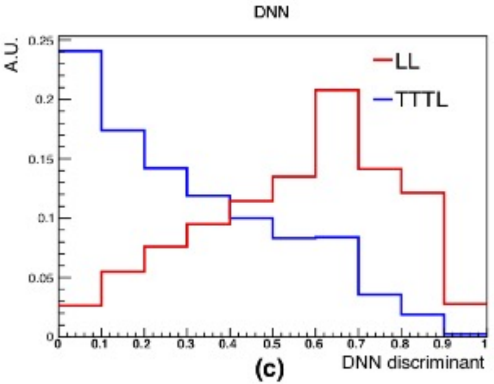
Phys. Rev. D 93, 094033 (2016)



- **Separating LL from TT, TL/LT using kinematic properties**







Phys. Rev. D 99, 033004 (2019)

W±W±jj at the (HL-)LHC :: Opportunities

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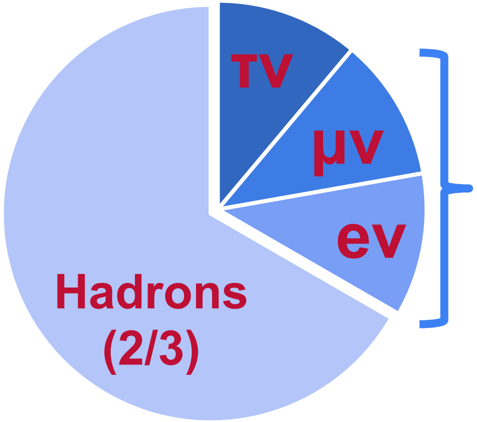
- Untapped potential: not leveraging **hadronic decays of the W bosons**
  - Access to **full event kinematics** (no neutrinos) to **extract W boson polarisation**
  - Usually used in BSM searches, but have also benefit for SM processes
- Increased luminosity provides large event pool

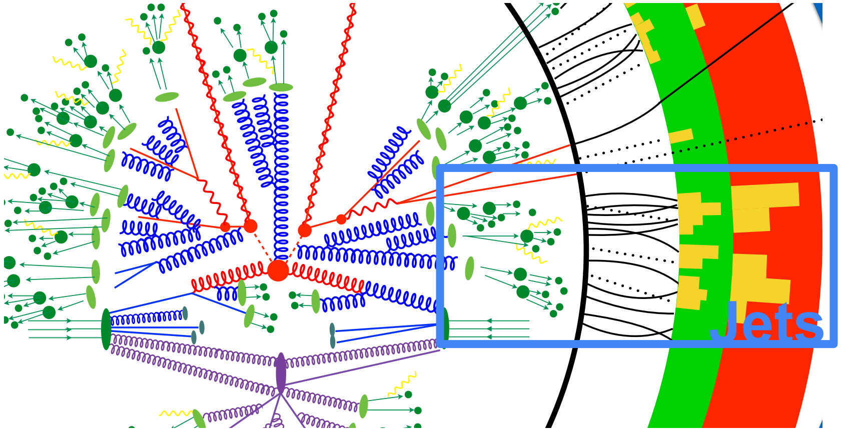
W Decay Fractions



EW $W^{\pm}W^{\pm}jj$ event yields	ATLAS Run-2 (2014-2018)	Run-3 (2021-2024*)	HL-LHC
Integrated Luminosity	140 fb^{-1}	250-300 fb^{-1}	2500-3000 fb^{-1}
Leptonic (l = e, μ)	232	420-500	4200-5000
Longitudinal (V_LV_L) (leptonic)	16	30-35	300-350
Hadronic (ε_{HAD} = 10% ε_{LEP})	**348**	**630-750**	**6300-7500**
V_LV_L (hadronic, ε_{HAD} = 10% ε_{LEP})	24	44-52	440-520

Challenges in probing VBS at HL-LHC

- Pile-up increase from 50 to 200 means **challenge to** maintain or improve signal acceptance
- Needs better pile-up mitigation, jet resolution and quark-gluon jet separation



Challenges

- **Jets are very complex:** detailed **jet substructure** studies and **deep learning** required to extract W boson charge and polarization
- **Huge backgrounds** from QCD processes: need quark-gluon jet discrimination, and use event properties (e.g., color flow)
- **Techniques to be used to improve measurements of other processes involving W bosons**

Event-based DNN

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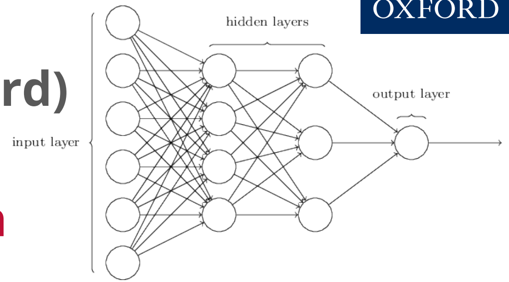
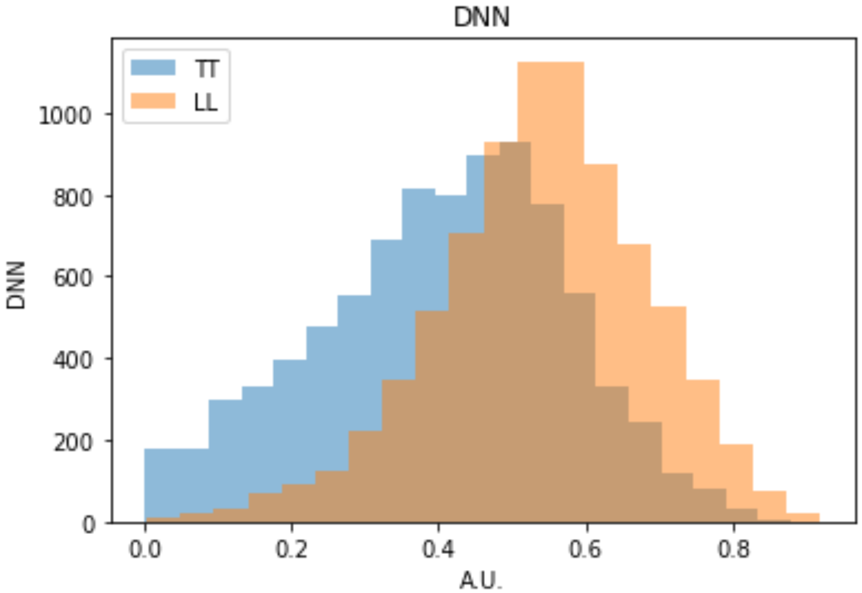
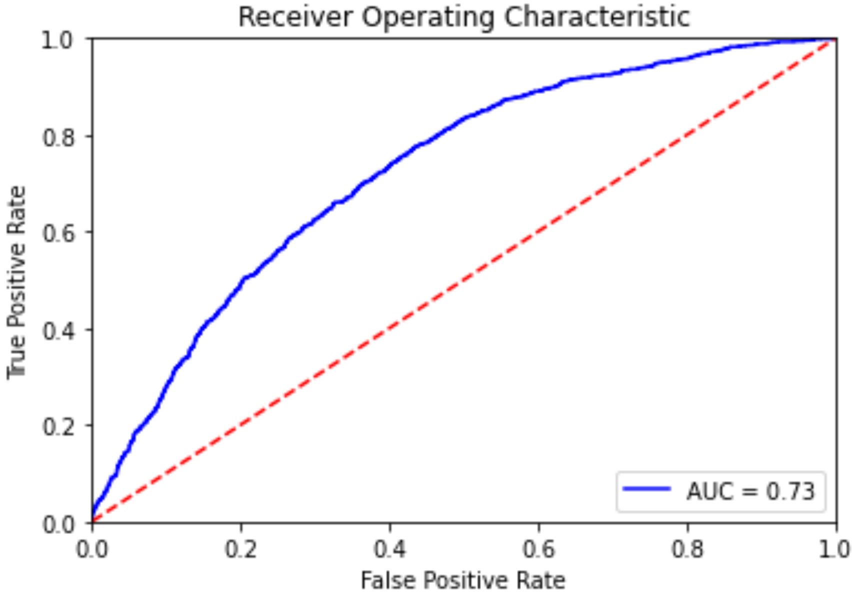
- **MG3.1 + Herwig (Dipole Shower) + Delphes (HL-LHC card)**
- Does not take pile-up into account
- Using only jet {pT, Eta, Phi, Area} :: **Good but not enough**







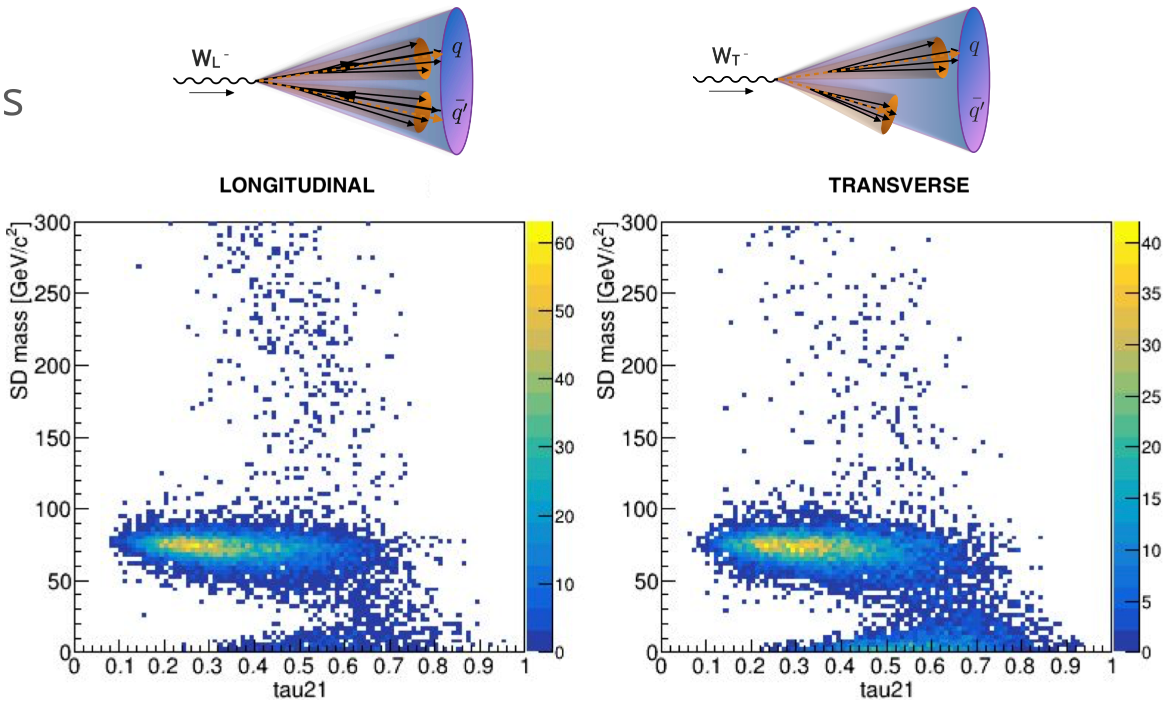
Differentiating W_L from W_T

- Jet substructure can be used to study the hardonic W decays

- However, grooming reduces the detection efficiency of hadronic W_T decays (yiels more often 1-prong)

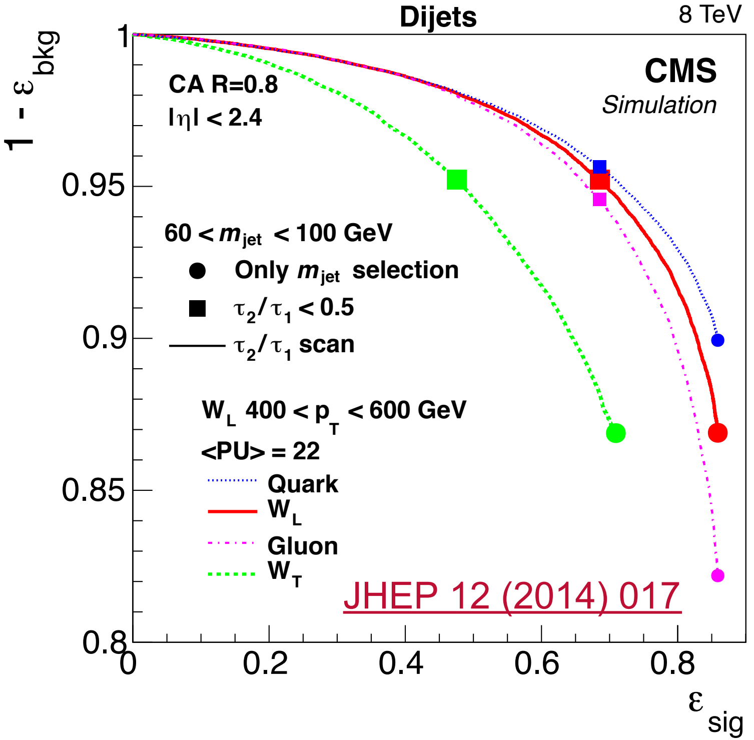
VBSCAN-PUB-04-21

CERN-STUDENTS-Note- 2018-220 (2018)



W Tagging Techniques

- Jet substructure algorithms can be used to identify W_L, but more work is needed to improve the efficiency for W_T (to measure all polarisation components)
- Promising avenues include particle-based Deep/Graph Neural Networks (e.g., JEDI-net, or ParticleNet)



The Start of a Long Journey

- $W^{\pm}W^{\pm}jj$ observed during Run-2

Learned to model signal and bkg., increasing presicion [O(10%)]

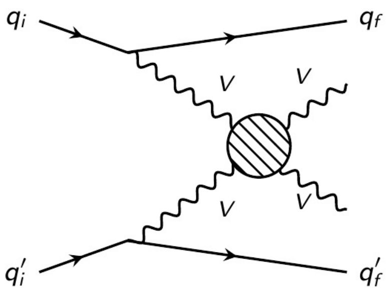
- Run-3 will yield additional data (x2-3)
- Will it be enough to observe $W_L^{\pm}W_L^{\pm}jj$?
- Need to use ALL data
  (incl. semi-leptonic and hadronic)
- HL-LHC will again increase data (x10)
- Allow measuring $W^{\pm}W^{\pm}jj$ and $W_L^{\pm}W_L^{\pm}jj$ to high precision

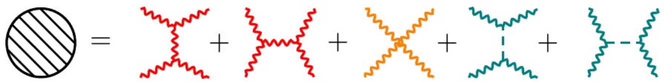
Meanwhile, we have to get ready for the challenge and prepare new techniques to get the most out of our data.

Stay tuned on this exciting area!

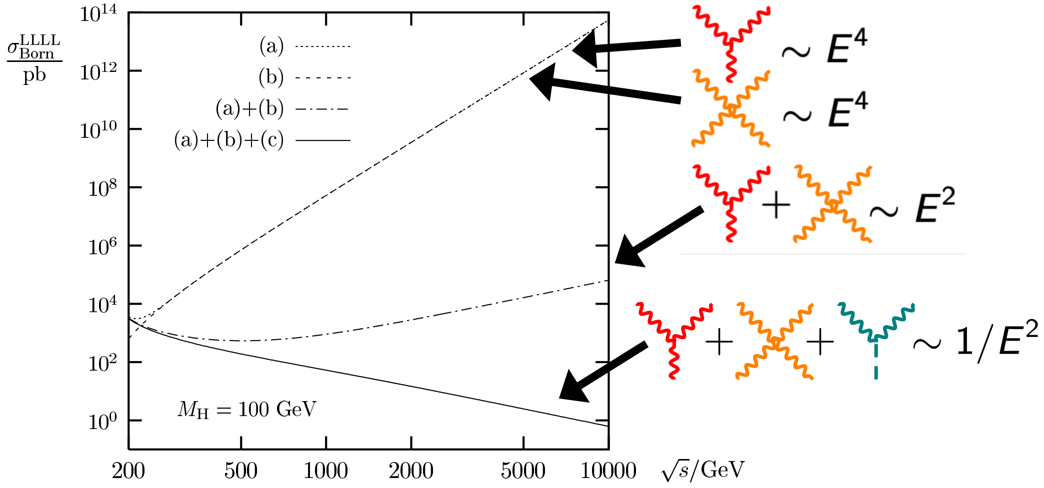
ADDITIONAL MATERIAL

Unraveling Electroweak Symmetry Breaking



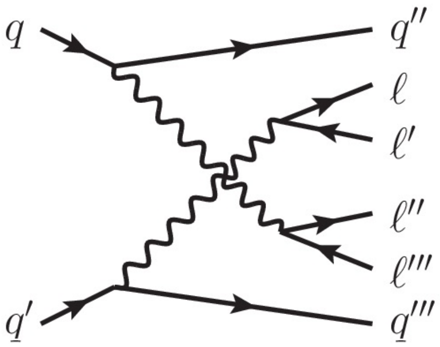


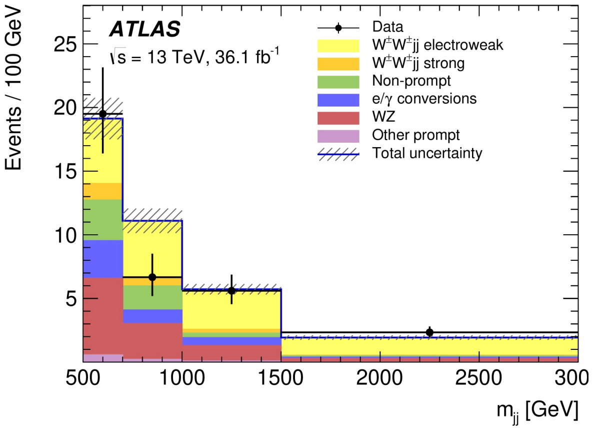
Denner, Hahn, Nucl.Phys.B525:27-50,1998

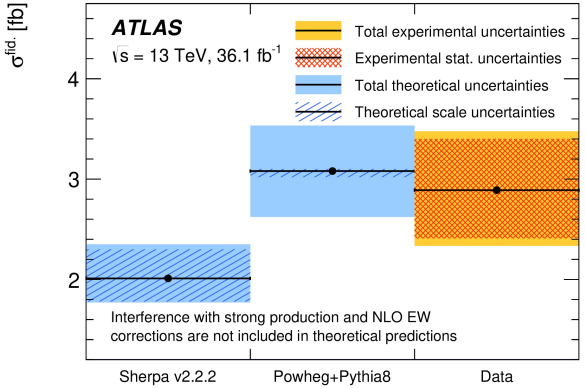


EW W±W±jj Production

W±W±jj (36 fb^{-1}): 6.5σ
PRL 123 (2019) 161801







Source	Impact [%]
Experimental	
Electrons	0.6
Muons	1.3
Jets and $E_{\mathrm{T}}^{\mathrm{miss}}$	3.2
b-tagging	2.1
Pileup	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

Observation using 36 fb^{-1}

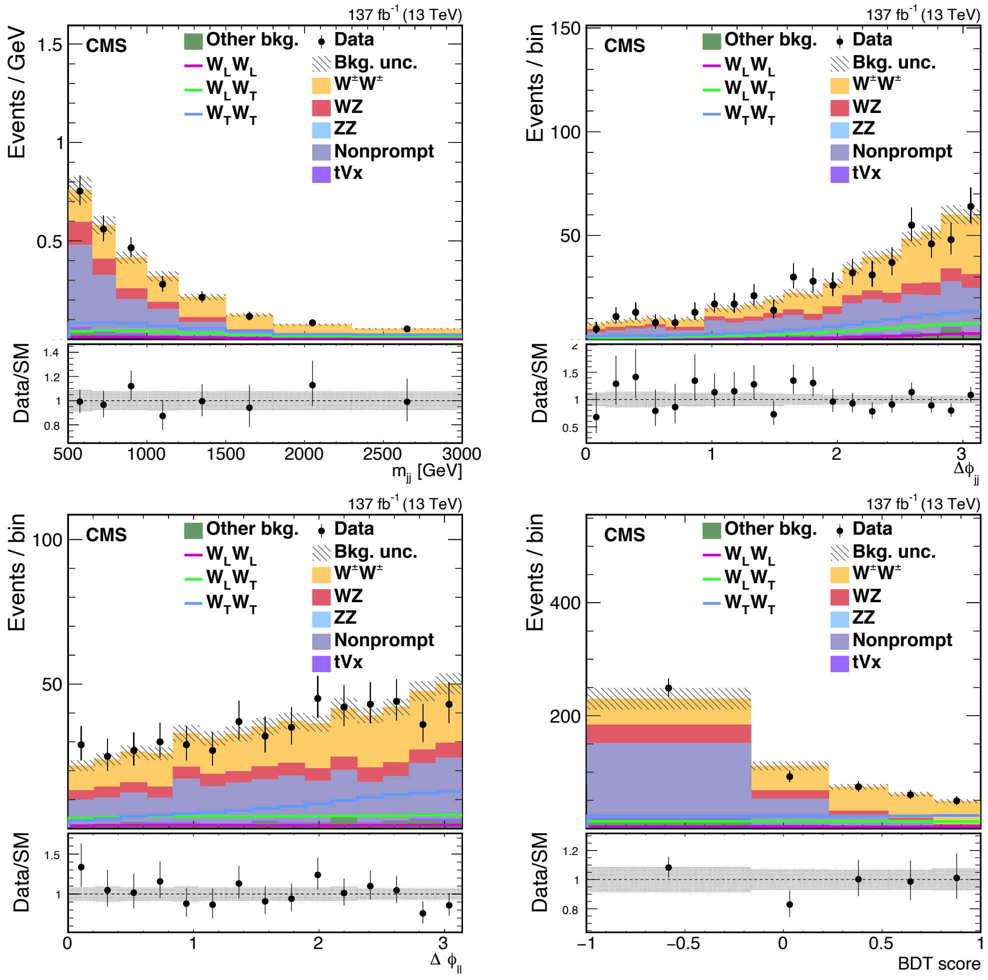
	e^+e^+	e^-e^-	$e^+\mu^+$	$e^-\mu^-$	$\mu^+\mu^+$	$\mu^-\mu^-$	Combined
WZ	1.48 ± 0.32	1.09 ± 0.27	11.6 ± 1.9	7.9 ± 1.4	5.0 ± 0.7	3.4 ± 0.6	30 ± 4
Non-prompt	2.2 ± 1.1	1.2 ± 0.6	5.9 ± 2.5	4.7 ± 1.6	0.56 ± 0.05	0.68 ± 0.13	15 ± 5
e/γ conversions	1.6 ± 0.4	1.6 ± 0.4	6.3 ± 1.6	4.3 ± 1.1	—	—	13.9 ± 2.9
Other prompt	0.16 ± 0.04	0.14 ± 0.04	0.90 ± 0.20	0.63 ± 0.14	0.39 ± 0.09	0.22 ± 0.05	2.4 ± 0.5
$W^\pm W^\pm jj$ strong	0.35 ± 0.13	0.15 ± 0.05	2.9 ± 1.0	1.2 ± 0.4	1.8 ± 0.6	0.76 ± 0.25	7.2 ± 2.3
Expected background	5.8 ± 1.4	4.1 ± 1.1	28 ± 4	18.8 ± 2.6	7.7 ± 0.9	5.1 ± 0.6	69 ± 7
$W^\pm W^\pm jj$ electroweak	5.6 ± 1.0	2.2 ± 0.4	24 ± 5	9.4 ± 1.8	13.4 ± 2.5	5.1 ± 1.0	60 ± 11
Data	10	4	44	28	25	11	122

$$\sigma^{\text{fid.}} = 2.89^{+0.51}_{-0.48}\,(\text{stat.})\,^{+0.24}_{-0.22}\,(\text{exp. syst.})\,^{+0.14}_{-0.16}\,(\text{mod. syst.})\,^{+0.08}_{-0.06}\,(\text{lumi.})\ \text{fb}$$

Process	Yields in $W^{\pm}W^{\pm}$ SR
$W^{\pm}_{L}W^{\pm}_{L}$	16.0 ± 18.3
$W^{\pm}_{L}W^{\pm}_{T}$	63.1 ± 10.7
$W^{\pm}_{T}W^{\pm}_{T}$	110.1 ± 18.1
QCD $W^{\pm}W^{\pm}$	13.8 ± 1.6
Interference $W^{\pm}W^{\pm}$	8.4 ± 0.6
WZ	63.3 ± 7.8
ZZ	0.7 ± 0.2
Nonprompt	213.7 ± 52.3
tVx	7.1 ± 2.2
Other background	26.9 ± 9.9
Total SM	522.9 ± 60.7
Data	524

Source of uncertainty	$W^{\pm}_{L}W^{\pm}_{L}$ (%)	$W^{\pm}_{X}W^{\pm}_{T}$ (%)	$W^{\pm}_{L}W^{\pm}_{X}$ (%)	$W^{\pm}_{T}W^{\pm}_{T}$ (%)
Integrated luminosity	3.2	1.8	1.9	1.8
Lepton measurement	3.6	1.9	2.5	1.8
Jet energy scale and resolution	11	2.9	2.5	1.1
Pileup	0.9	0.1	1.0	0.3
b tagging	1.1	1.2	1.4	1.1
Nonprompt lepton rate	17	2.7	9.3	1.6
Trigger	1.9	1.1	1.6	0.9
Limited sample size	38	3.9	14	5.7
Theory	6.8	2.3	4.0	2.3
Total systematic uncertainty	44	6.6	18	7.0
Statistical uncertainty	123	15	42	22
Total uncertainty	130	16	46	23

Phys. Lett. B 812 (2020) 136018



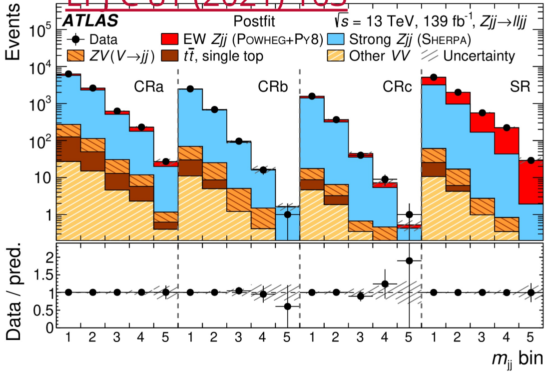
Phys. Lett. B 812 (2020) 136018

Overview of Run-2 ATLAS VBS/VBF Analyses

UNIVERSITY OF OXFORD

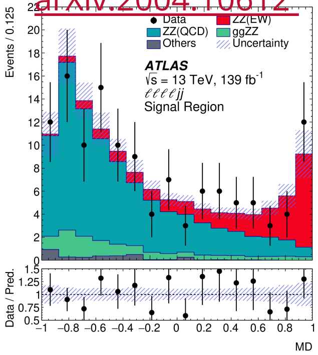
Zjj (139 fb^{-1})

EPJ C 81 (2021) 163



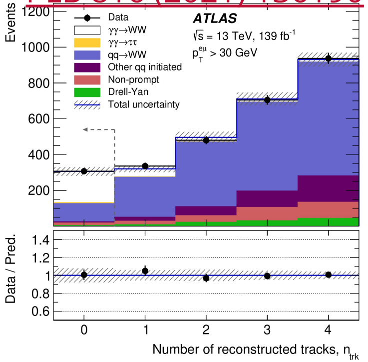
ZZjj (139 fb^{-1}): 5.5σ

arXiv:2004.10612



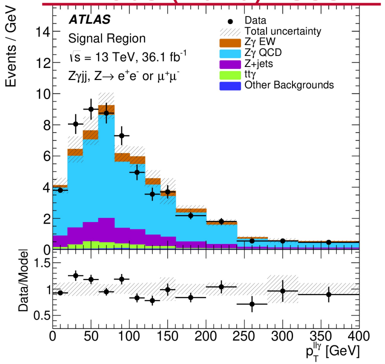
γγ → WW (139 fb^{-1}): 8.4σ

PLB 816 (2021) 136190



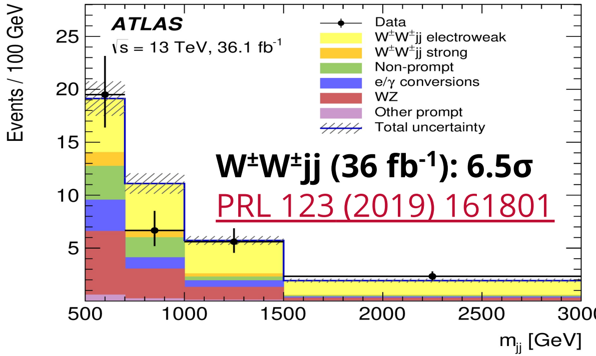
Zγjj (36 fb^{-1}): 4.1σ

PLB 803 (2020) 135341



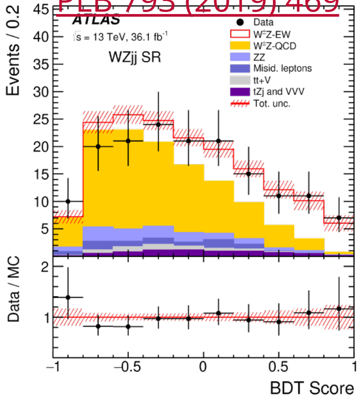
W±W±jj (36 fb^{-1}): 6.5σ

PRL 123 (2019) 161801



WZjj (36 fb^{-1}): 5.3σ

PLB 793 (2019) 469



VVjj (36 fb^{-1}): 2.7σ

PRD 100 (2019) 032007