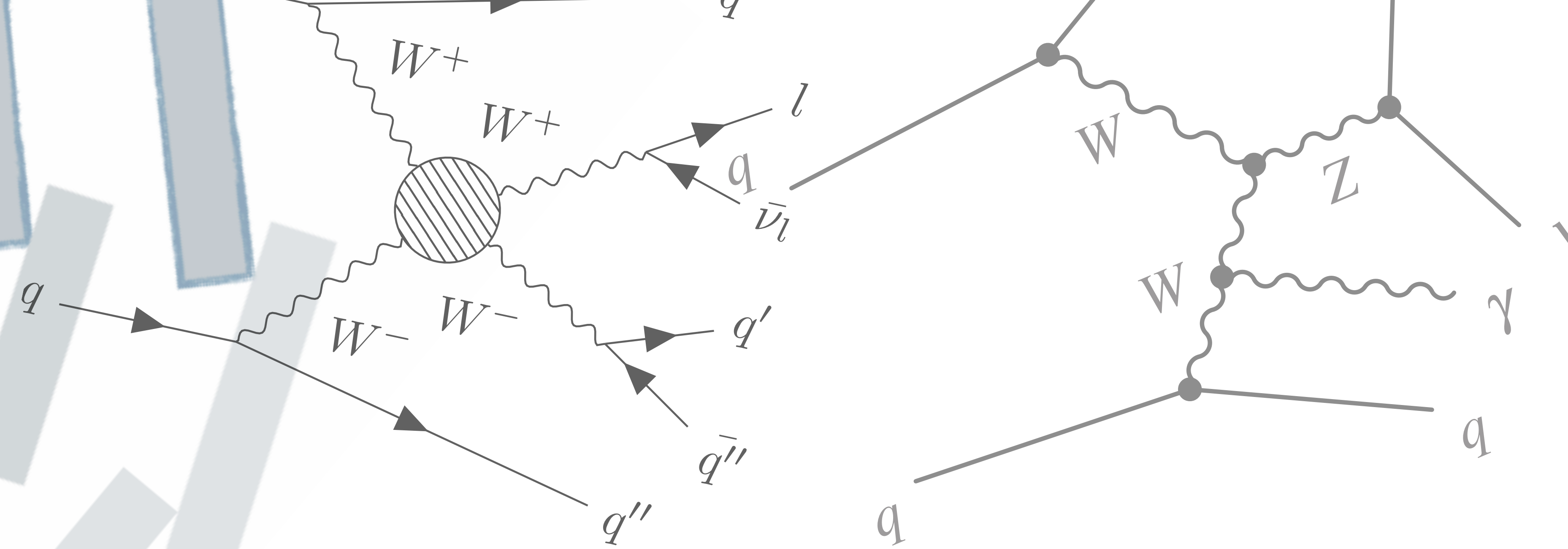


Electroweak VBS Measurements at the LHC

Shalu Solomon

on behalf of the ATLAS and CMS Collaborations

4th World Summit of EDSU

Brandeis UNIVERSITY

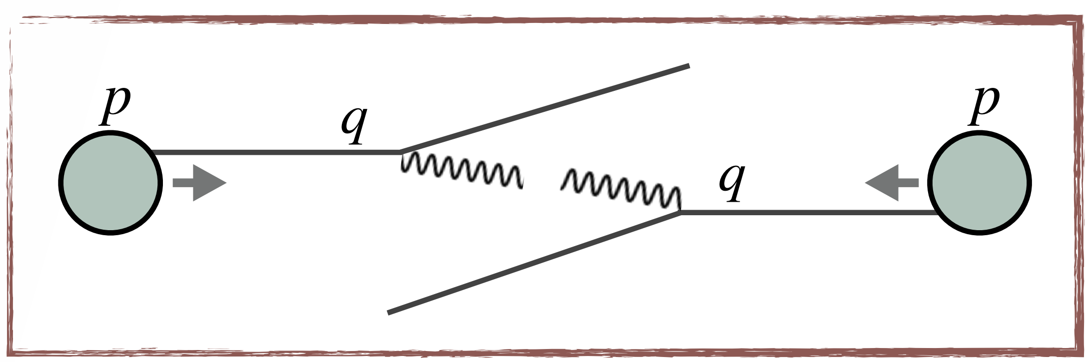
ATLAS EXPERIMENT

CMS

Vector Boson Scattering

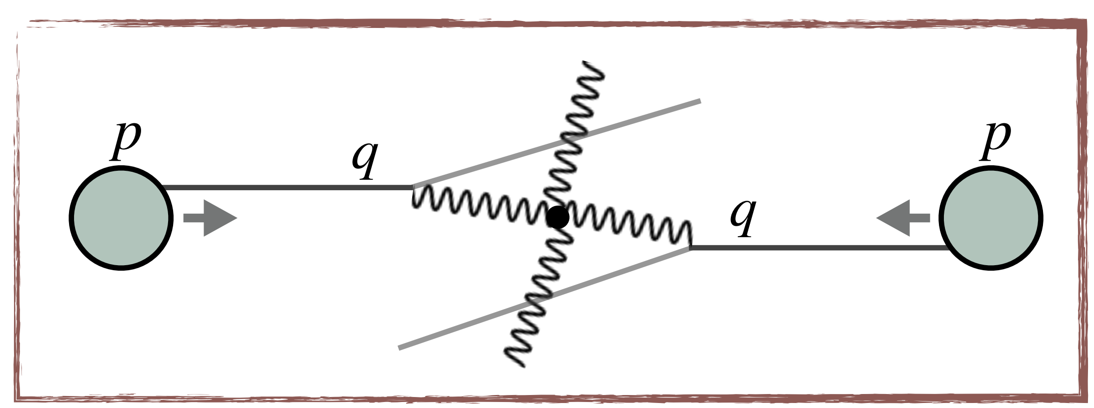
- Vector boson scattering (VBS) is one of the ideal phenomena at the LHC to probe the electroweak sector of the Standard Model
- At the LHC, VBS occurs when vector bosons are radiated from the incoming quarks and undergo subsequent self-interactions

Incoming quarks in the proton beams

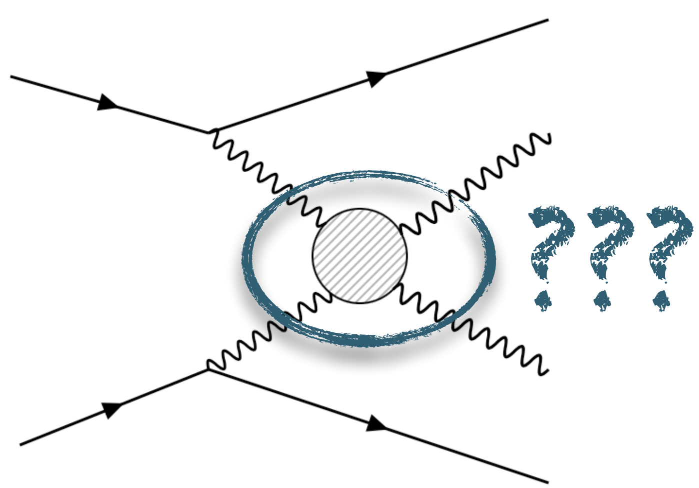


Vector bosons radiated from the quarks and the trajectory of the quarks altered

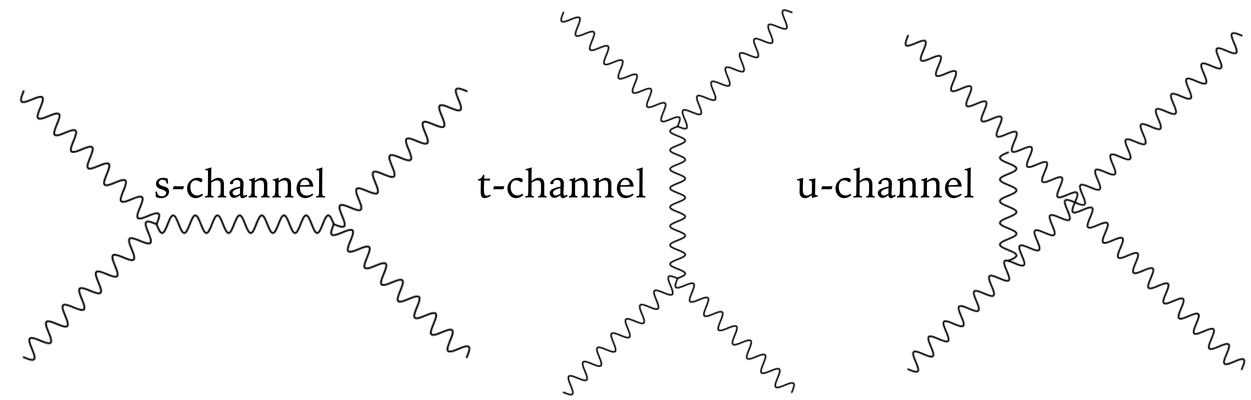
Vector bosons interact or scatter off each other



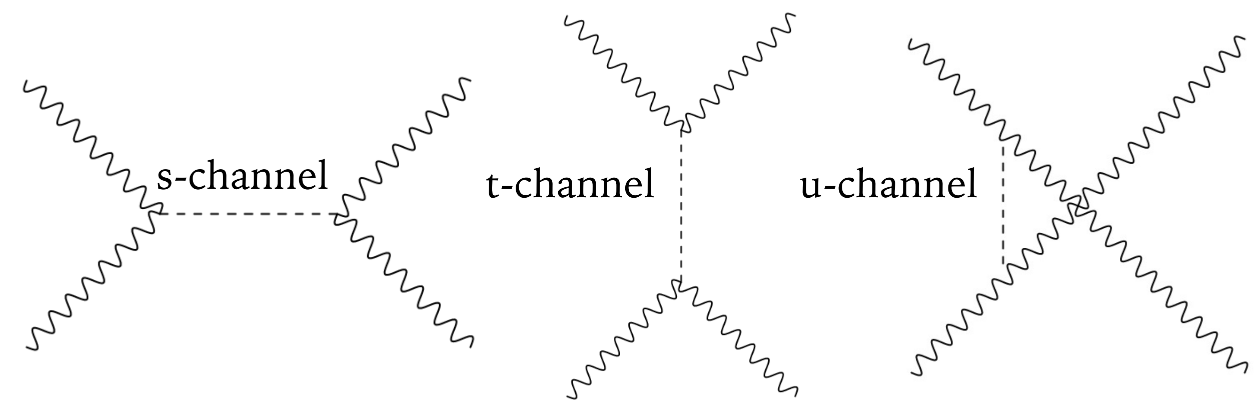
Interactions



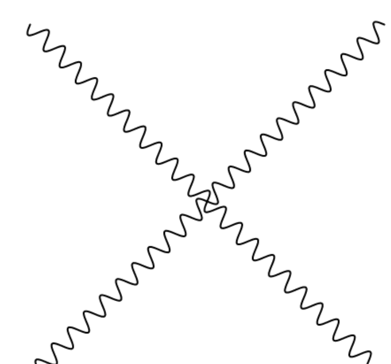
V exchange



Higgs exchange

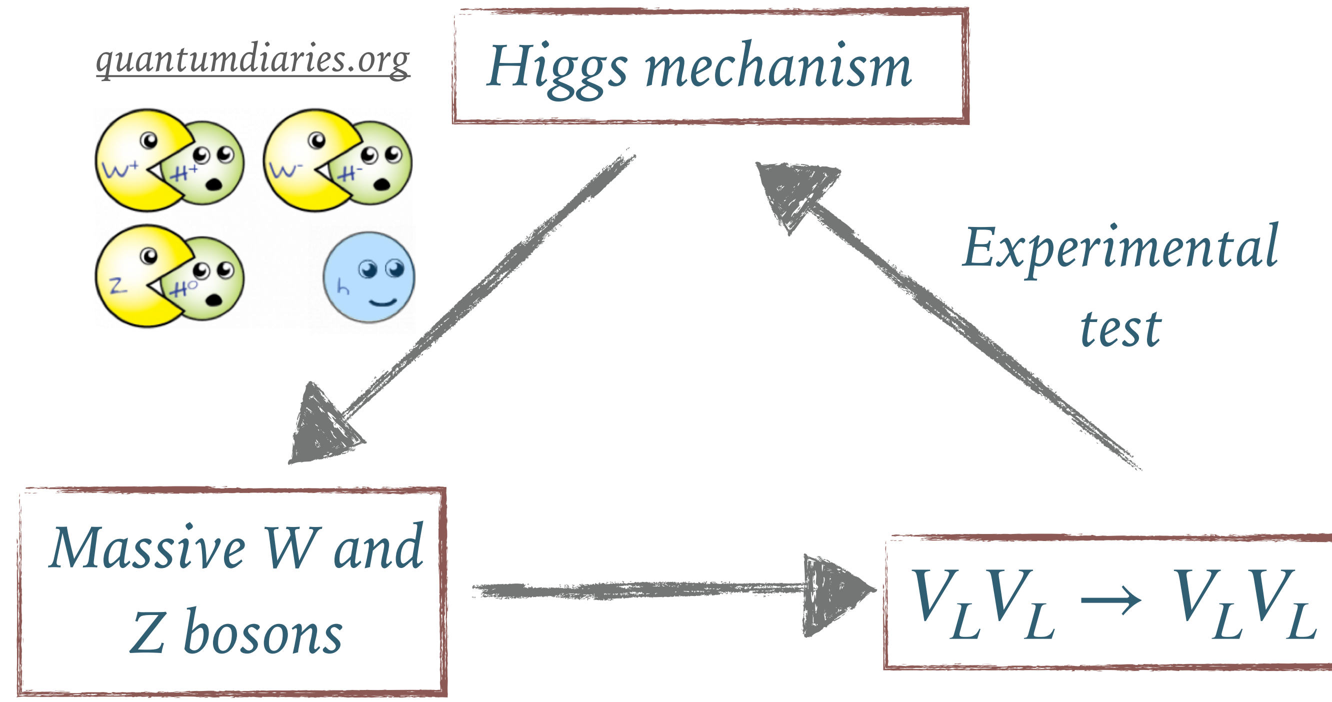


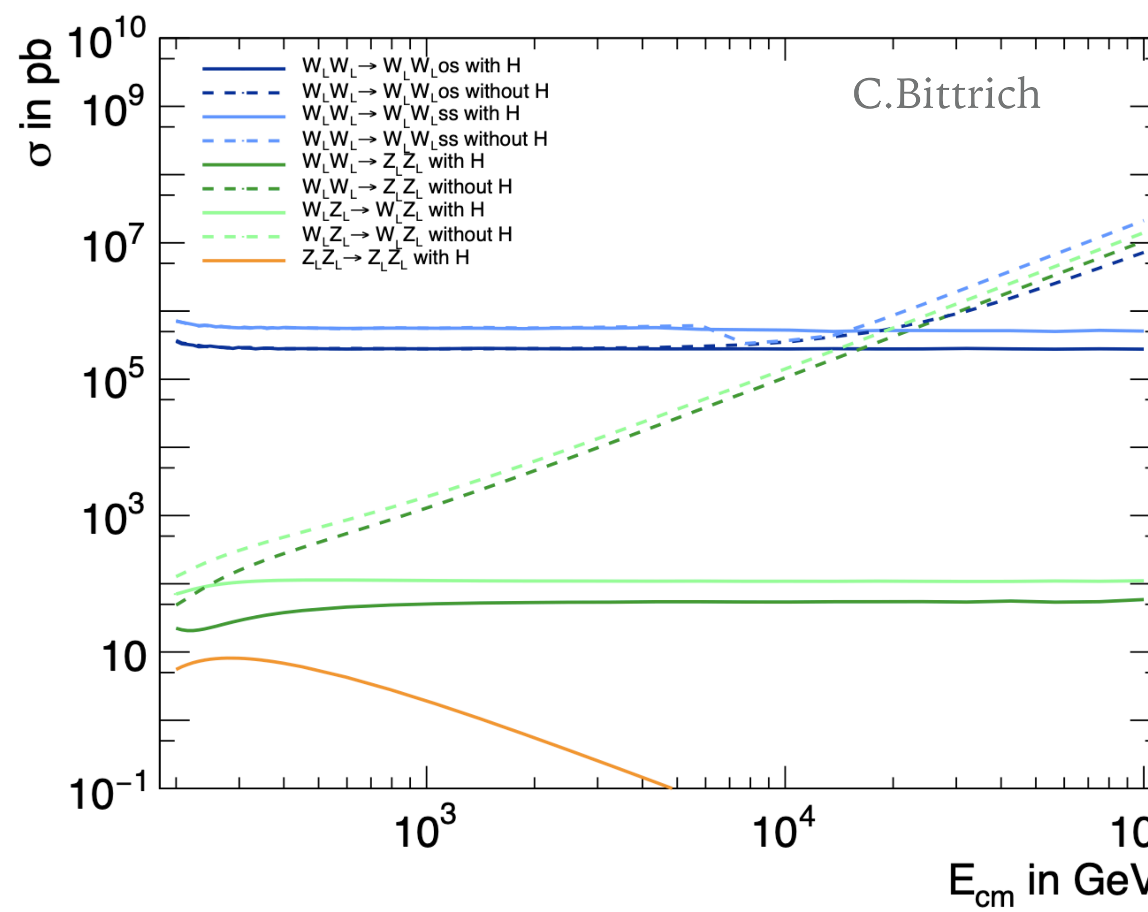
VVVV interaction



Why is VBS interesting?

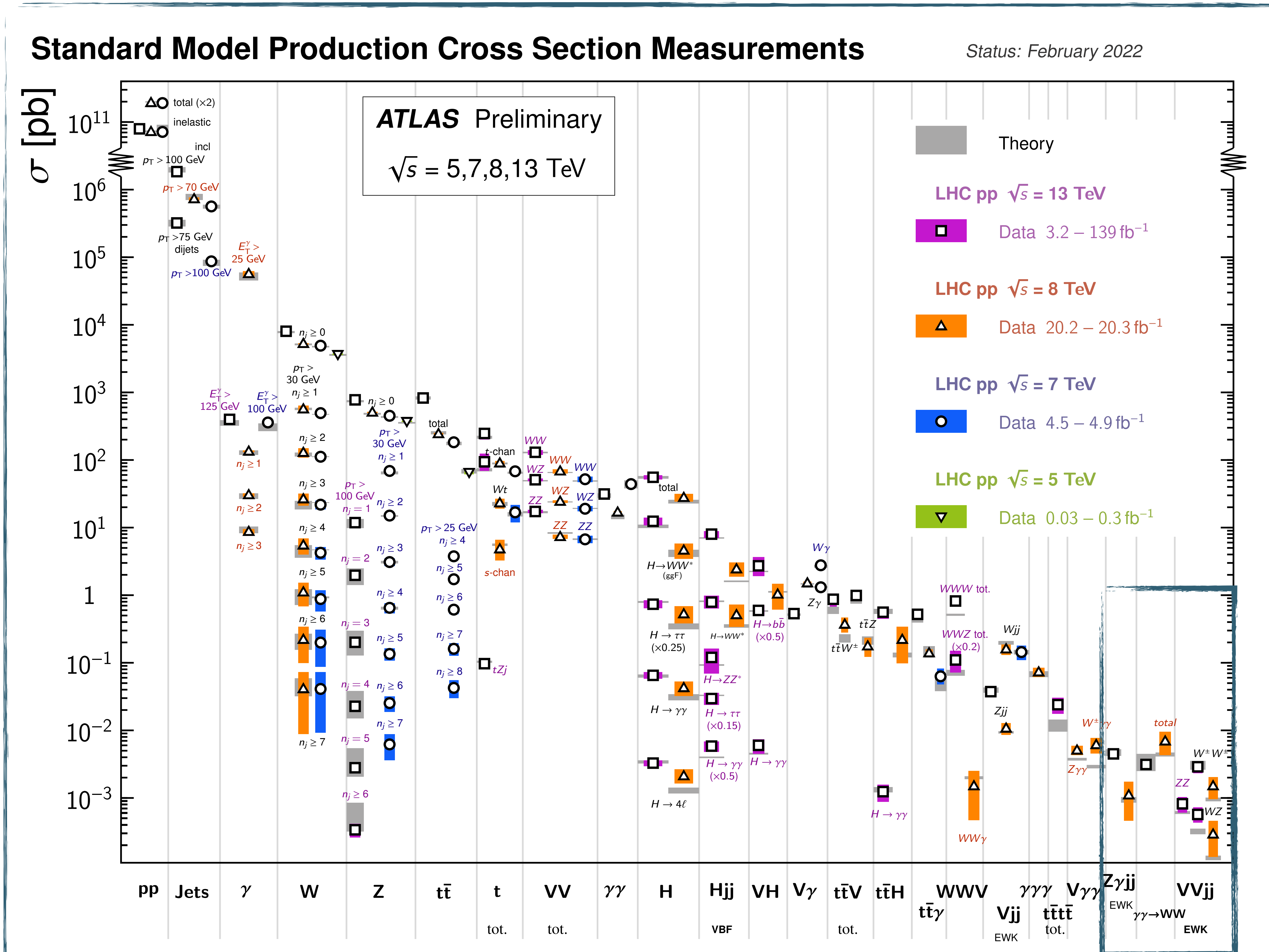
- The gauge bosons acquire mass through the Higgs mechanism
- The three Goldstone modes of the broken symmetry translate to the longitudinal polarization modes of W and Z bosons
- But in $V_L V_L \to V_L V_L$, unitarity is violated without Higgs interactions
- Contributions from SM Higgs *exactly* cancels the divergences and regularizes the scattering amplitude
- Sensitive to new physics:
  - direct searches for charged Higgs
  - indirect searches by parametrizing any deviations from the SM using the Effective Field Theory (EFT) such as anomalous triple/quartic gauge couplings



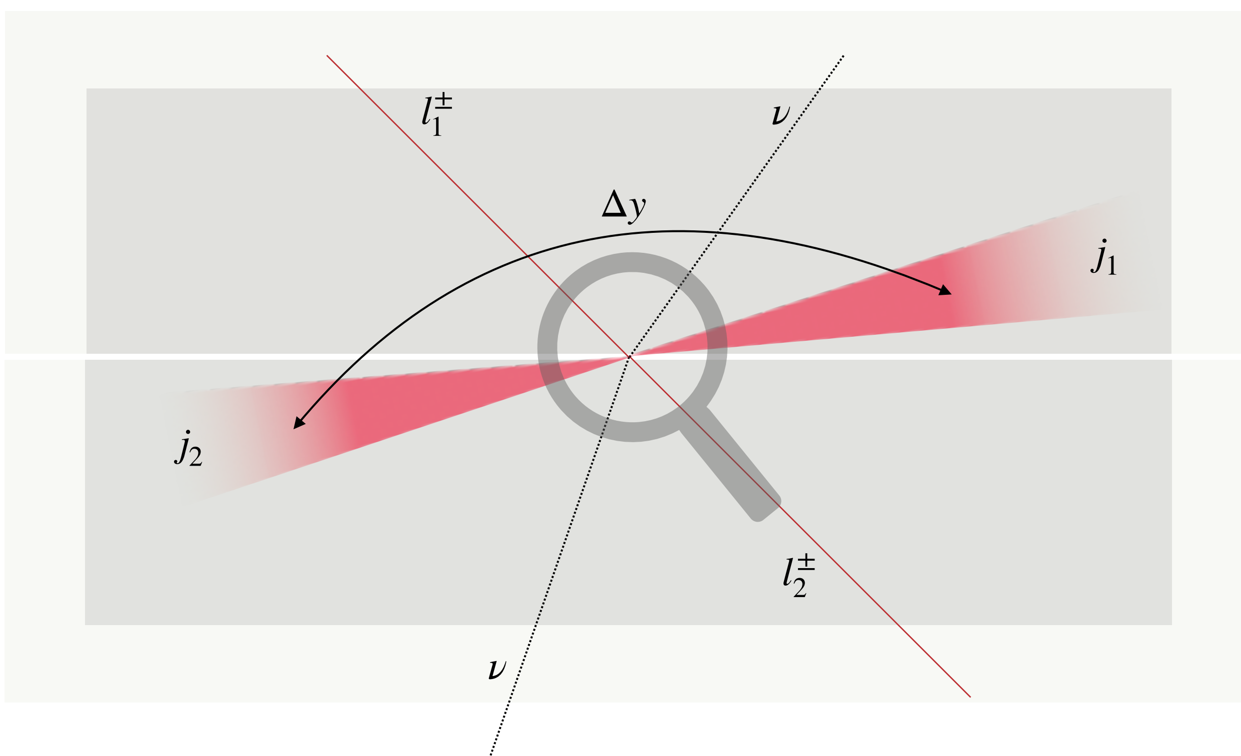


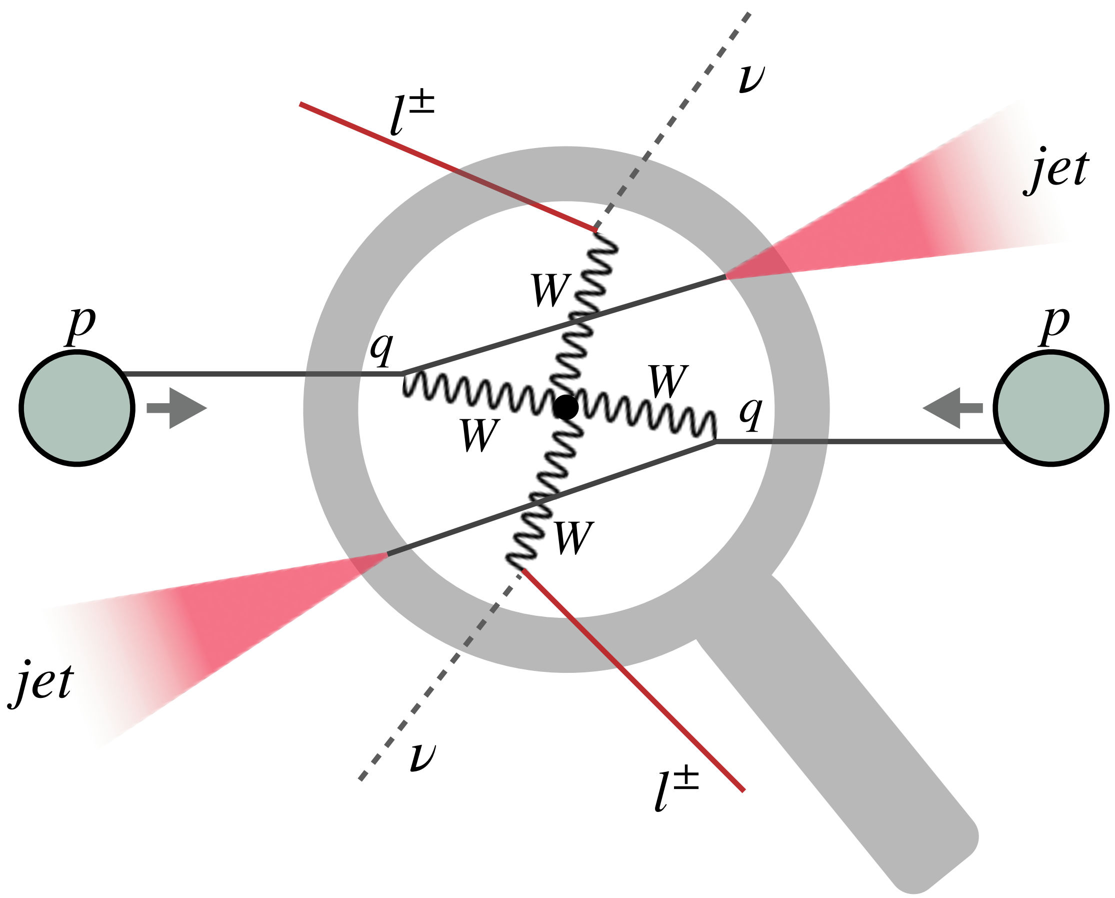
VBS among Other SM Measurements

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2022-009/fig_03a.png



VBS Topology



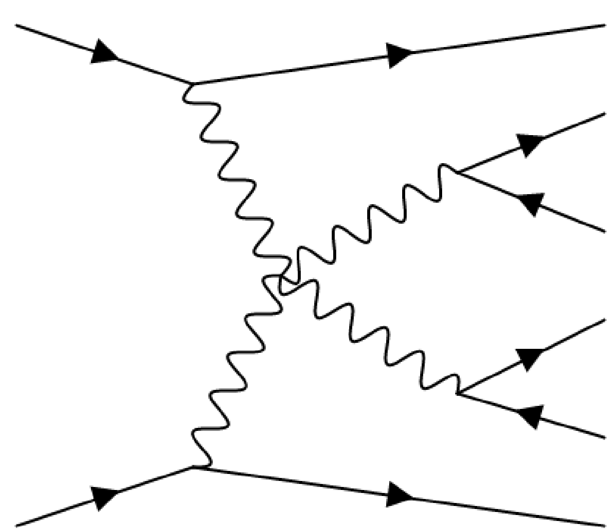


- Two energetic tagging jets (j_1 and j_2) with a large dijet invariant mass ($m_{j_1 j_2}$)
- Large rapidity gap between the tagging jets ($\Delta y_{j_1 j_2}$)
- Little hadronic activity in the rapidity gap
- V bosons between the tagging jets (centrality)

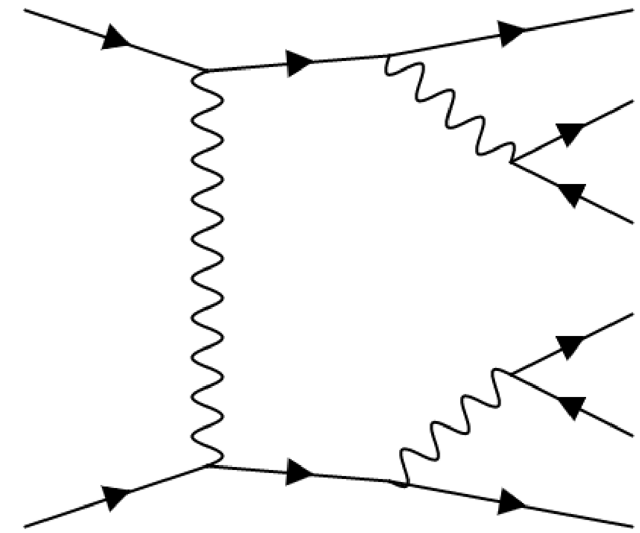
Production Modes (LO)

Electroweak

- Includes VBS and non-VBS
- VBS cannot be separated from non-VBS.
- VBS contributions enhanced with topological selections
- Measured is electroweak induced VVjj production



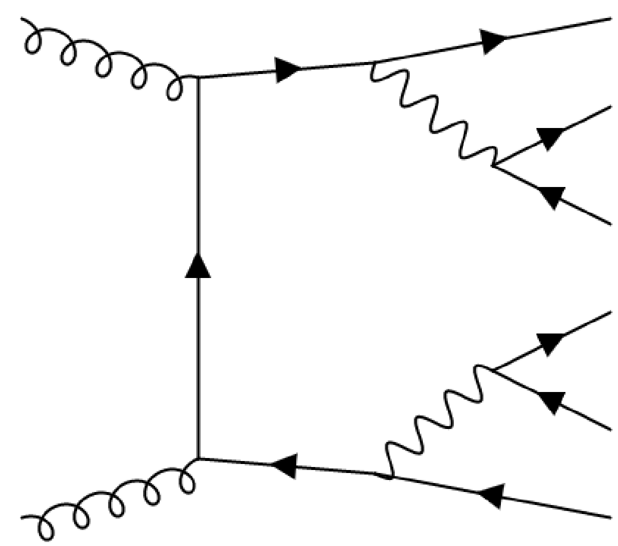
VBS



non-VBS

Strong

- Major background
- Experimental challenge



Strong

Interference

- Negligible (a few % w.r.t electroweak)

Channel	Final State	ATLAS	CMS
$W^{\pm}W^{\pm}jj$	$l^{\pm}\nu l^{\pm}\nu jj$	6.5σ (36.1 fb^{-1}, 13 TeV)	5.5σ (35.9 fb^{-1}, 13 TeV)
$WZjj$	$lll\nu jj$	5.3σ (36.1 fb^{-1}, 13 TeV)	6.8σ (137 fb^{-1}, 13 TeV)
$\gamma\gamma \to WW$	$l^{\pm}\nu l^{\mp}\nu$	8.4σ (139 fb^{-1}, 13 TeV)	3.2σ (19.7 fb^{-1}, 7 & 8 TeV)
$W\gamma jj$	$l\nu\gamma jj$	—	5.3σ (55.6 fb^{-1}, 8 & 13 TeV)
$Z\gamma jj$	$ll\gamma jj$	10σ (139 fb^{-1}, 13 TeV)	9.4σ (137 fb^{-1}, 13 TeV)
$Z\gamma jj$	$\nu\nu\gamma jj$	5.2σ	—
$ZZjj$	$llll jj$, $ll\nu\nu jj$	5.7σ (139 fb^{-1}, 13 TeV)	4.0σ (137 fb^{-1}, 13 TeV)
$W^{\pm}W^{\mp}jj$	$l^{\pm}\nu l^{\mp}\nu jj$	—	5.6σ (138 fb^{-1}, 13 TeV)
$WVjj$	$l\nu jjjj$	—	4.4σ (138 fb^{-1}, 13 TeV)
$VVjj$	$l\nu jjjj$, $\nu\nu jjjj$, $lljjjj$	2.7σ (35.5 fb^{-1}, 13 TeV)	—

VBS at the LHC

golden channel

Channel	Final State	ATLAS	CMS
$W^{\pm}W^{\pm}jj$	$l^{\pm}\nu l^{\pm}\nu jj$	6.5σ (36.1 fb-1, 13 TeV)	5.5σ (35.9 fb-1, 13 TeV)
$WZjj$	$lll\nu jj$	5.3σ (36.1 fb-1, 13 TeV)	6.8σ (137 fb-1, 13 TeV)
$\gamma\gamma \to WW$	$l^{\pm}\nu l^{\mp}\nu$	8.4σ (139 fb-1, 13 TeV)	3.2σ (19.7 fb-1, 7 & 8 TeV)
$W\gamma jj$	$l\nu\gamma jj$	—	5.3σ (55.6 fb-1, 8 & 13 TeV)
$Z\gamma jj$	$ll\gamma jj$	10σ (139 fb-1, 13 TeV)	9.4σ (137 fb-1, 13 TeV)
$Z\gamma jj$	$\nu\nu\gamma jj$	5.2σ	—
$ZZjj$	$llll jj, ll\nu\nu jj$	5.7σ (139 fb-1, 13 TeV)	4.0σ (137 fb-1, 13 TeV)
$W^{\pm}W^{\mp}jj$	$l^{\pm}\nu l^{\mp}\nu jj$	—	5.6σ (138 fb-1, 13 TeV)
$WVjj$	$l\nu jjjj$	—	4.4σ (138 fb-1, 13 TeV)
$VVjj$	$l\nu jjjj, \nu\nu jjjj, lljjjj$	2.7σ (35.5 fb-1, 13 TeV)	—

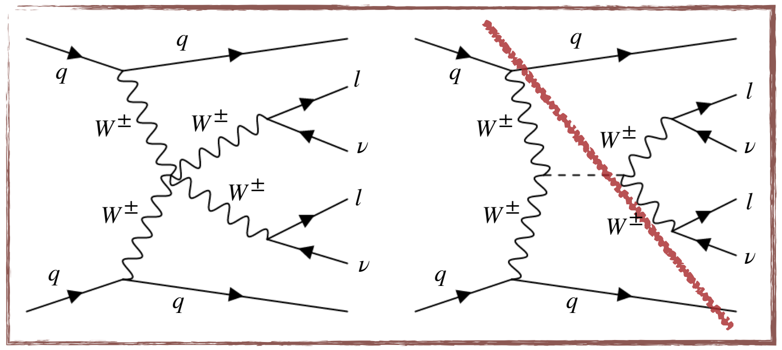
Recent

Phys. Rev. Lett 123 (2019) 161801
Phys. Lett B 809 (2020) 135710

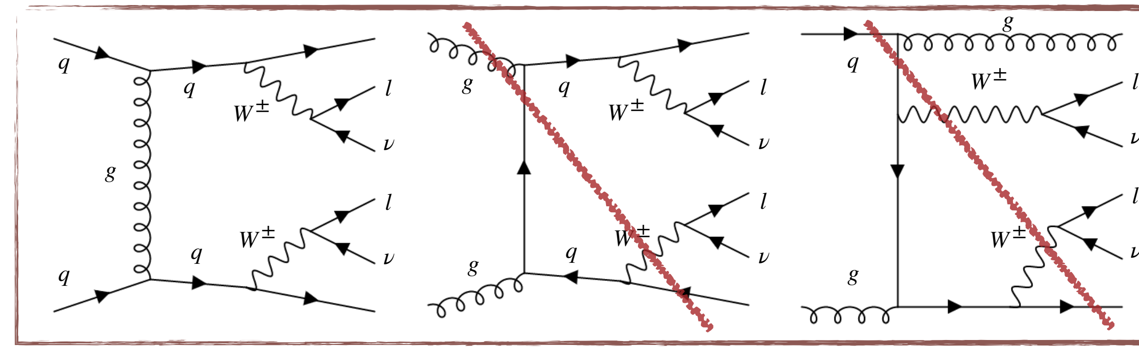
Electroweak $W^{\pm}W^{\pm}jj$ Production

Observation of $W^{\pm}W^{\pm}jj$ in ATLAS and Measurement in CMS

Not a recent measurement but the golden channel for VBS



electroweak



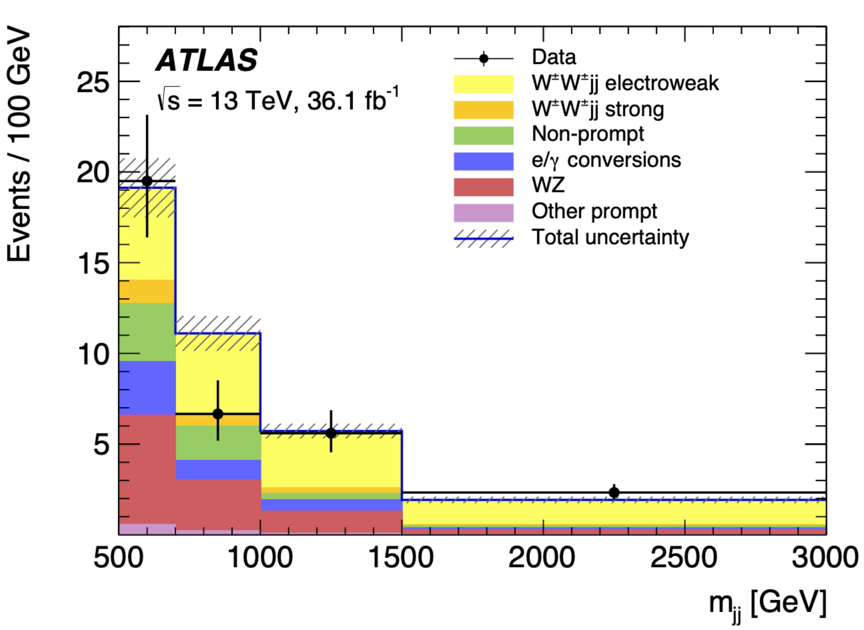
strong

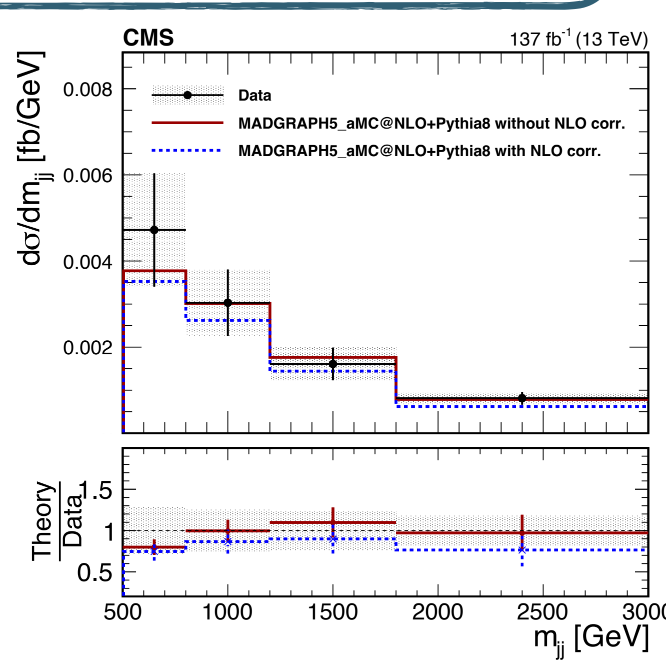
the golden channel of VBS

- No gg or qg initiating diagrams
- Largest electroweak to strong production ratio among other VV
- Final state with 2 same-sign leptons
- Small background rates due to the same-sign leptons in the final state

ATLAS: *Observed with 5.3σ*
(Partial Run 2 data)

CMS: *Observed with 5.5σ*
(Partial Run 2 data)
Differential cross-section measurement
(Full Run 2 data)





In both ATLAS & CMS:

- Dominant backgrounds from WZ and mis-identified leptons
- Signal extracted from a simulaneous maximum likelihood 2D fit in SR and CR
- Leading uncertainty is data statistics

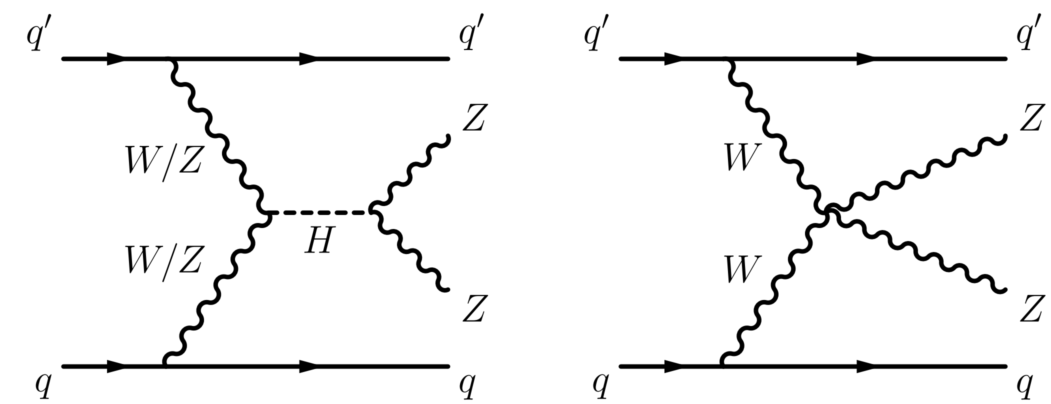
arXiv:2004.10612 (Accepted by Nature Physics)
Phys. Lett B 812 (2020) 135992

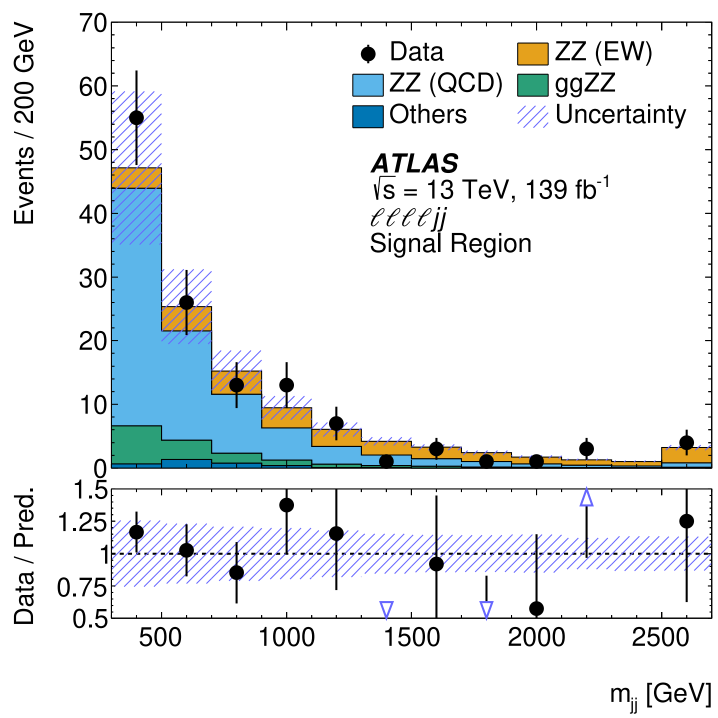
Electroweak *ZZjj* Production

Observation of *ZZjj* in ATLAS and Evidence in CMS

ATLAS: Two final states used and combined

- 4ljj: Two Z bosons decaying leptonically
- 2l2νjj: One Z boson decaying leptonically and the other invisibly





BDT for signal separation

ATLAS: Observation in 4l and combined 4l+2l2ν

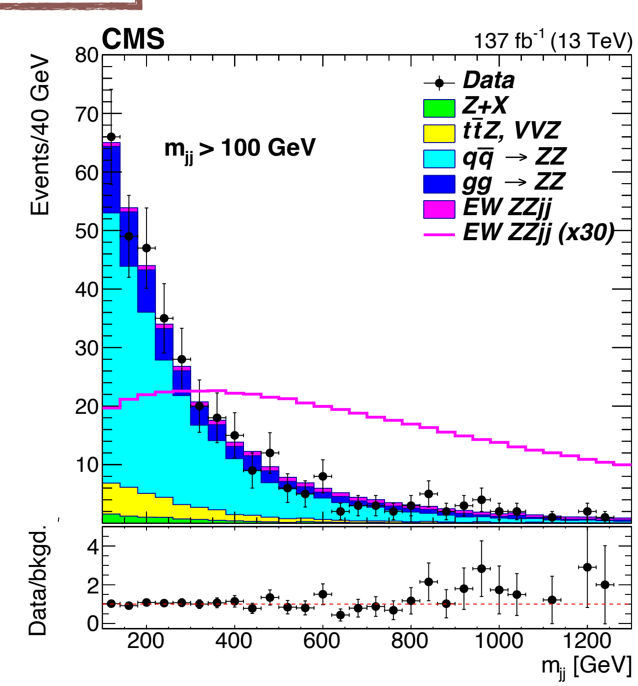
	μ_{EW}	$\mu_{\mathrm{QCD}}^{\ell\ell\ell\ell jj}$	Significance Obs. (Exp.)
$\ell\ell\ell\ell jj$	1.4 ± 0.4	0.98 ± 0.22	5.5 (4.4) σ
$\ell\ell\nu\nu jj$	0.8 ± 0.6	–	1.3 (2.0) σ
Combined	1.21 ± 0.31	0.99 ± 0.22	5.7 (4.8) σ

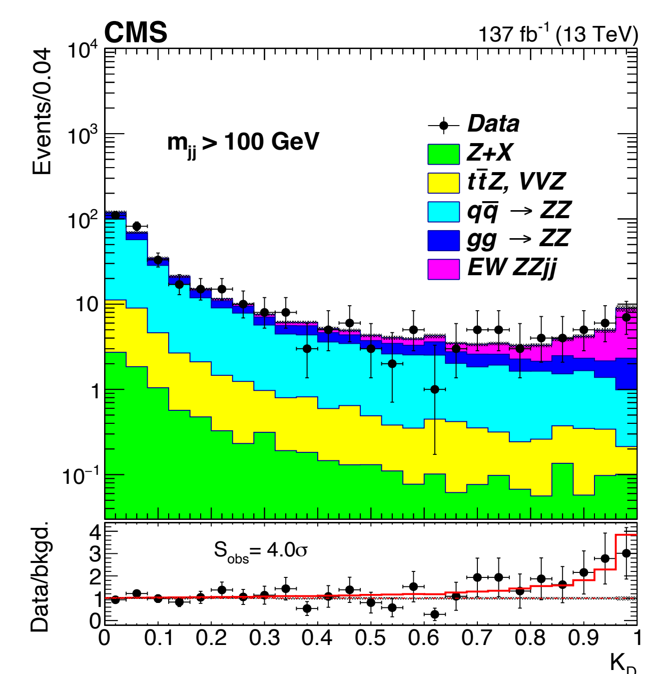
$$\sigma_{fid} = 0.75 \pm 0.19 \text{ fb}$$

Very small cross-section!

CMS: Evidence in 4l with 4σ

- Matrix element discriminant for signal separation
- Cross-checked with BDT

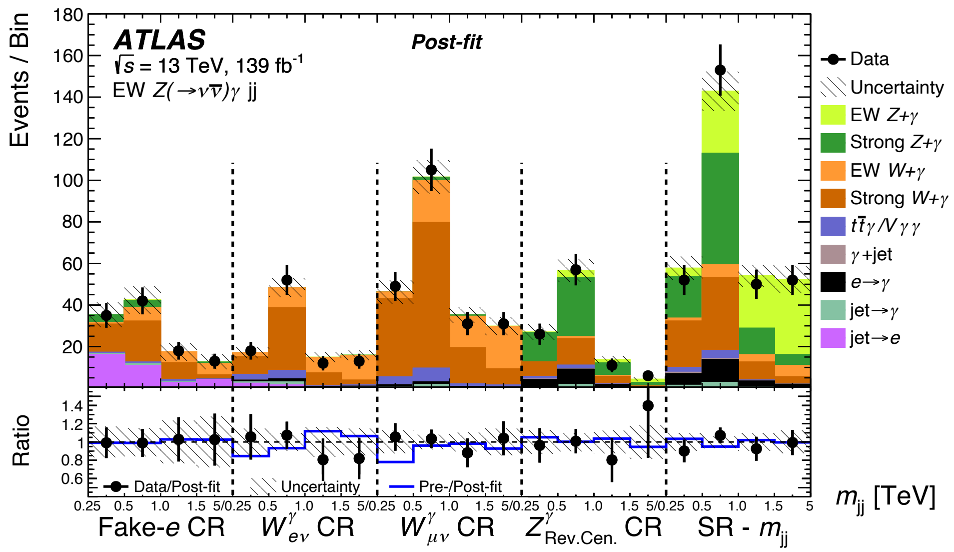




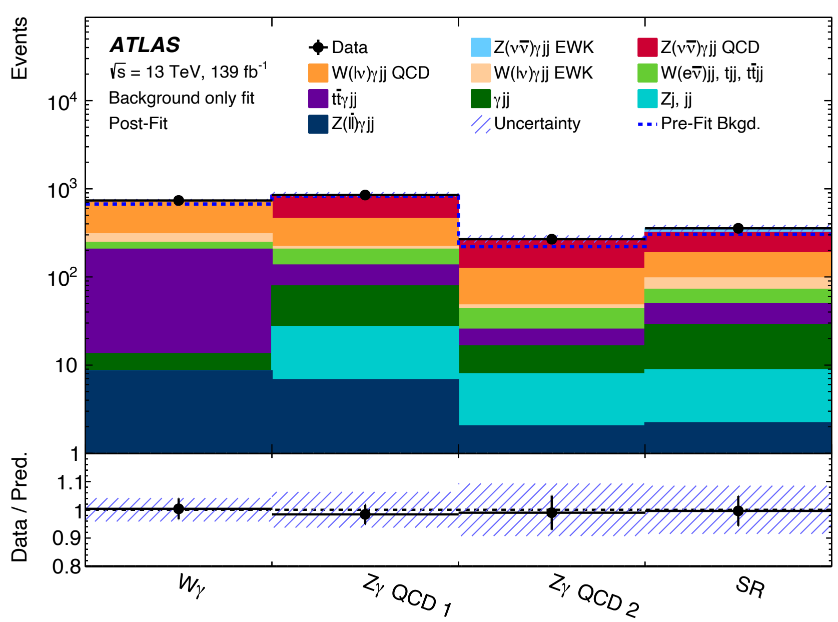
Eur. Phys. J. C 82 (2022) 105
arXiv:2208.12741 (Submitted to JHEP)

Electroweak $Z\gamma jj$ Production

Observation of $Z(\rightarrow \nu\nu)\gamma jj$ in ATLAS



$15 < E_T^{\gamma} < 110$ GeV



$E_T^{\gamma} > 150$ GeV

- Final state with an energetic photon and large E_T^{miss}
- Dominant backgrounds from $W\gamma$ and QCD induced $Z\gamma$
- Two separate phase spaces (analyses):

Observed with 6.3σ

Rare example of a search resulting in an observation

*$15 < E_T^{\gamma} < 110$ GeV ***Obs sig of 5.2σ***

$E_T^{\gamma} > 150$ GeV ***Obs sig of 3.2σ***

*started as a search for BSM Higgs decays

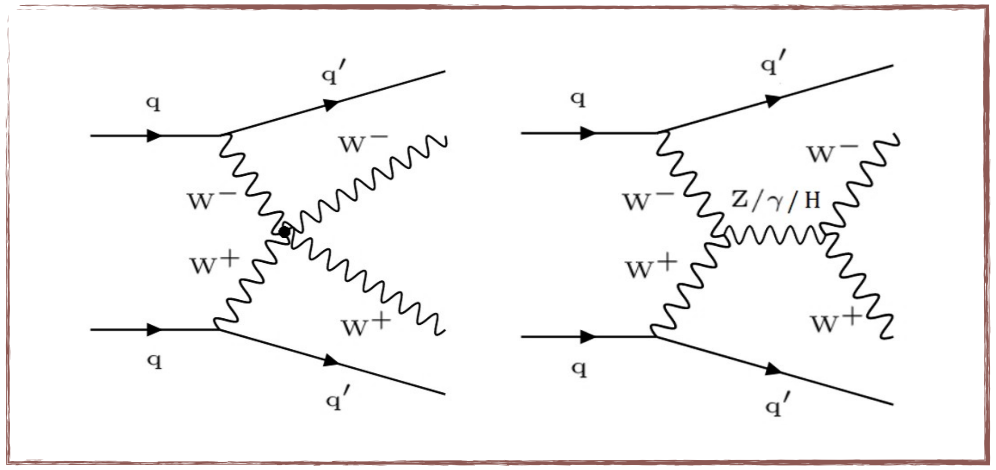
- Signal obtained from a binned maximum likelihood fit of CR and SR

POI	$15 < E_T^{\gamma} < 110$ GeV	$E_T^{\gamma} > 150$ GeV	Combination
$\mu_{Z\gamma\text{EWK}}$	0.78 ± 0.33	1.04 ± 0.23	0.96 ± 0.18
$\mu_{Z\gamma\text{QCD}}$	1.21 ± 0.37	1.02 ± 0.41	1.17 ± 0.27
$\mu_{W\gamma}$	1.02 ± 0.22	1.01 ± 0.20	1.01 ± 0.13

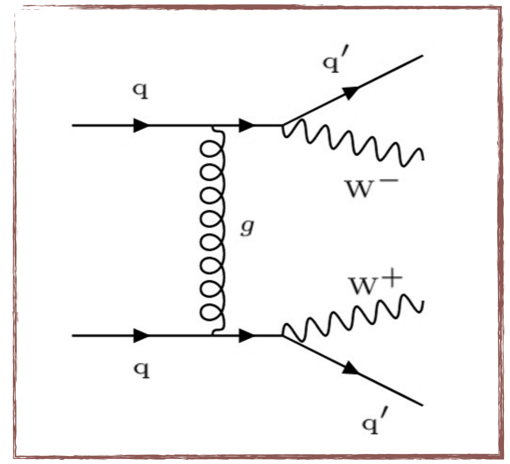
arXiv:2205.05711
(Accepted by Phys. Lett B)

Electroweak $W^{\pm}W^{\mp}jj$ Production

Observation of $W^{\pm}W^{\mp}jj$ in CMS



electroweak



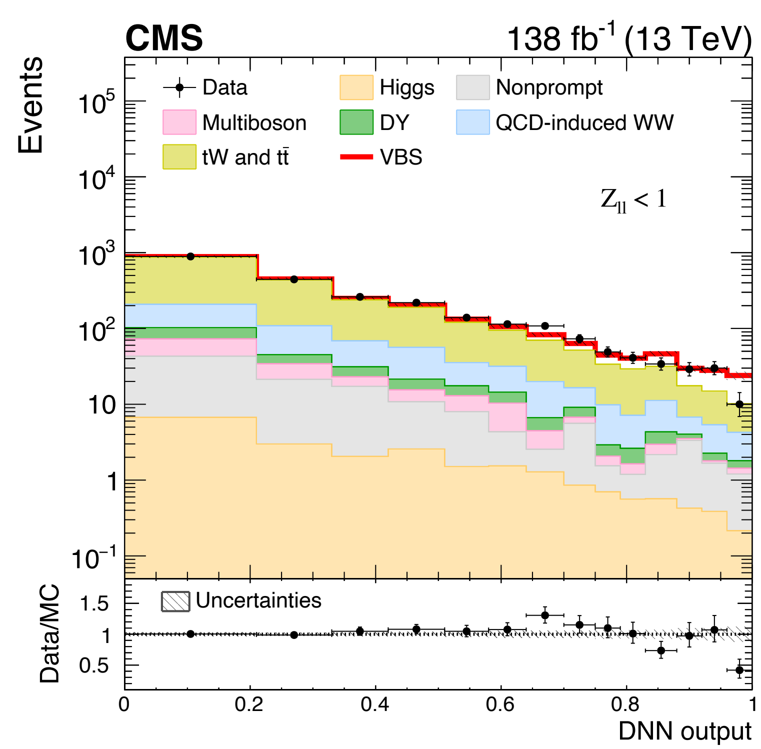
strong

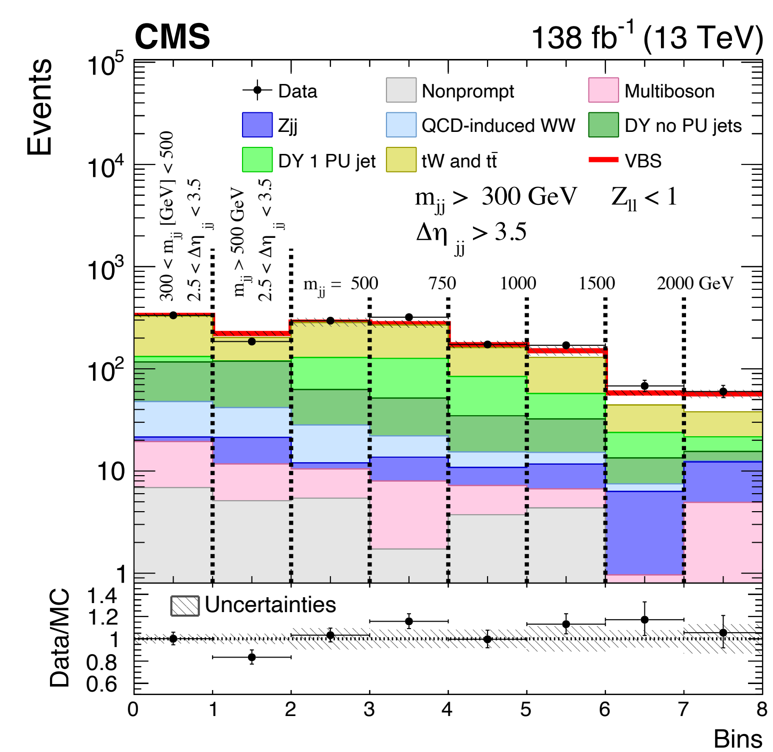
- Dilepton final state with opposite charges
- Experimentally challenging due to the enormous backgrounds from top, $W^{\pm}W^{\mp}jj$-QCD, and Drell-Yan

Process	SR eμ $Z_{\ell\ell} < 1$	SR e$\mu Z_{\ell\ell} > 1$	SR ee - $\mu\mu$ $Z_{\ell\ell} < 1$	SR ee - $\mu\mu$ $Z_{\ell\ell} > 1$
DATA	2441	2192	1606	1667
Signal + background	2396.8 ± 98.5	2239.6 ± 106.0	1590.4 ± 49.4	1660.5 ± 43.6
Signal	169.1 ± 20.2	69.9 ± 8.4	98.0 ± 6.5	38.3 ± 2.5
Background	2227.7 ± 96.4	2169.7 ± 105.6	1492.4 ± 48.9	1622.1 ± 43.5

- Signal extracted from a binned maximum likelihood fit of the most discriminating variable (DNN score for $e\mu$ or m_{jj} for $ee/\mu\mu$)

Observed with 5.6σ



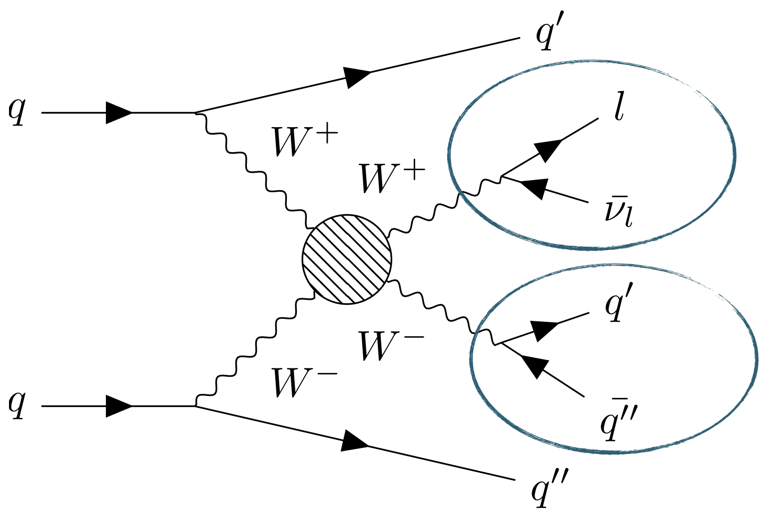


 Phys. Lett B 834 (2022) 137438

Electroweak *WVjj* Production

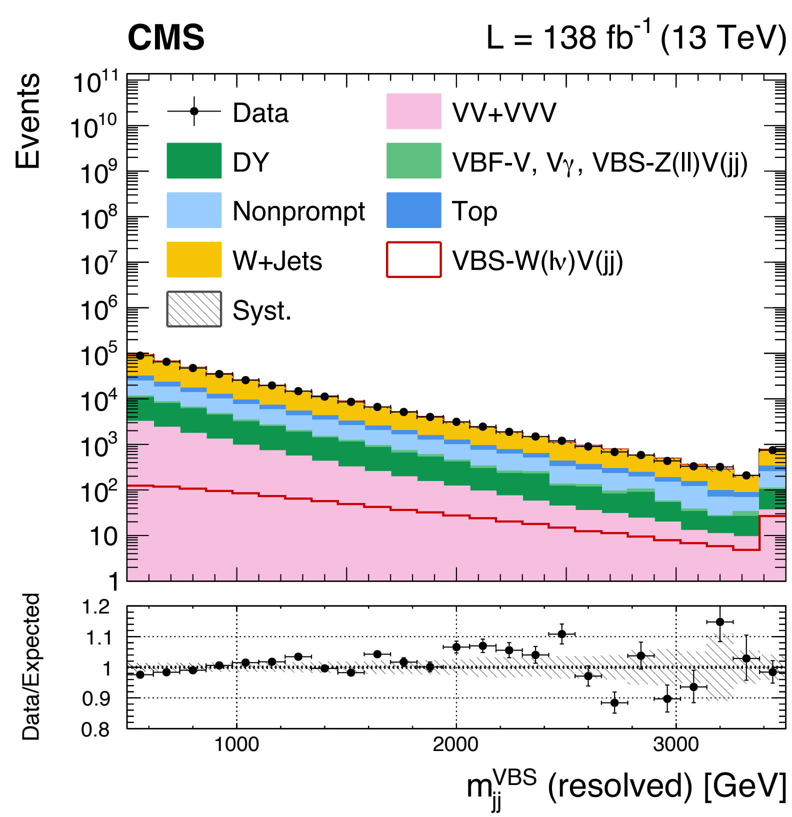
To more complex final states…

Evidence for WWjj/WZjj (semi-leptonic) in CMS

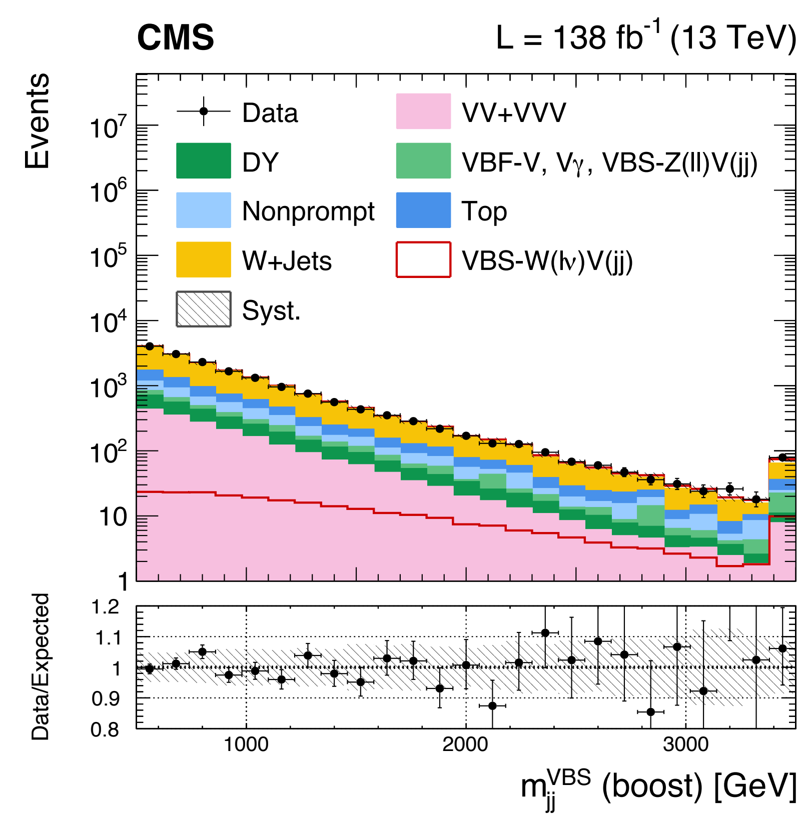


- Larger cross-sections than fully leptonic V decays.
- Final state with lνqq in addition to the tagging jets

- Dominant backgrounds: W+jets and $t\bar{t}$
- Events categorized as boosted (merged) and resolved (separate) based on the topology of the non-tagging jets
- DNN trained for signal and background separation.
- Different DNNs are used for resolved and boosted categories



$\mu_{resolved} = 1.09 \pm 0.32$



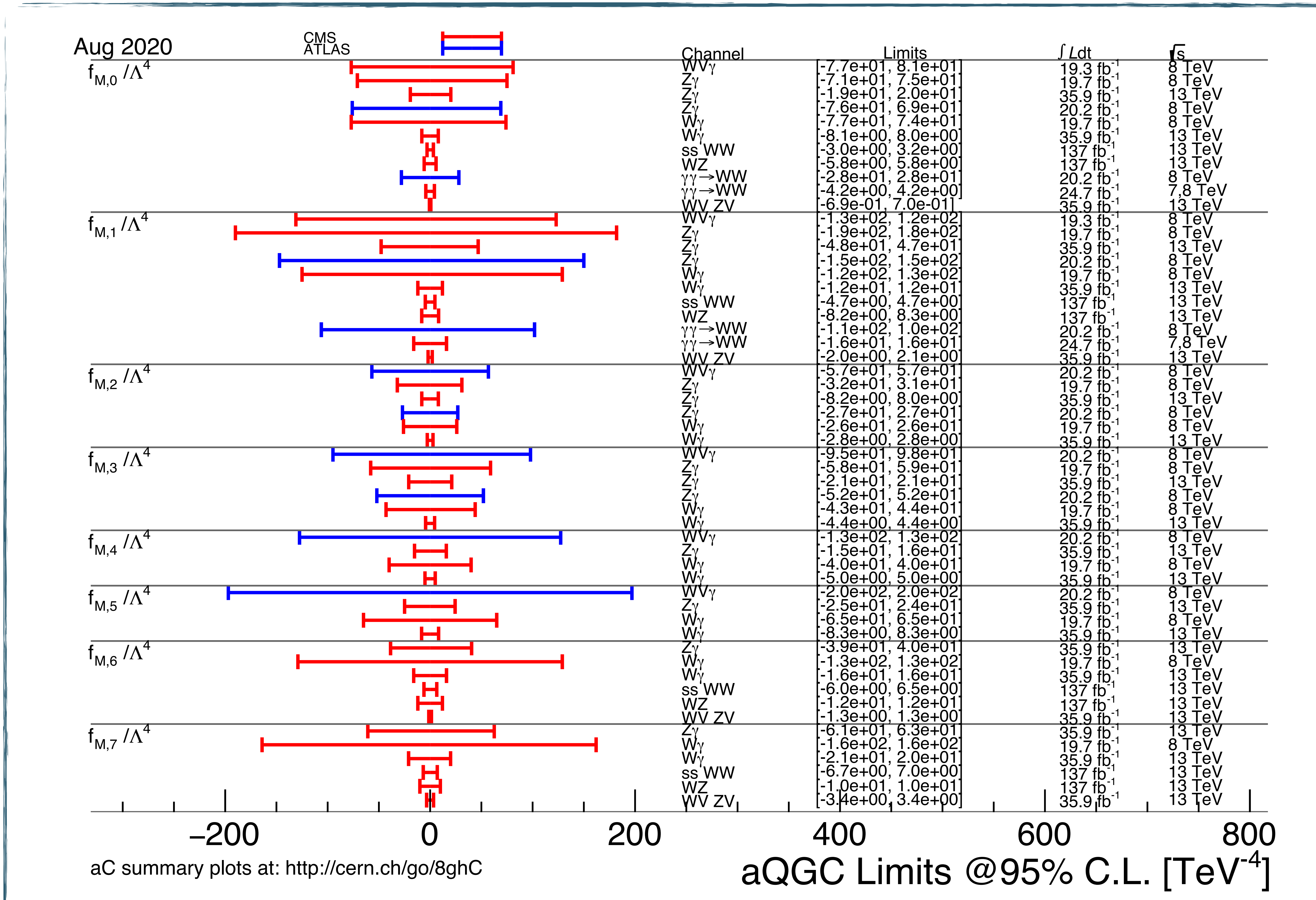
$\mu_{boosted} = 0.85 \pm 0.26$

Combined observed significance is 4.4σ (5.1σ exp)

First evidence

aQGC Limits

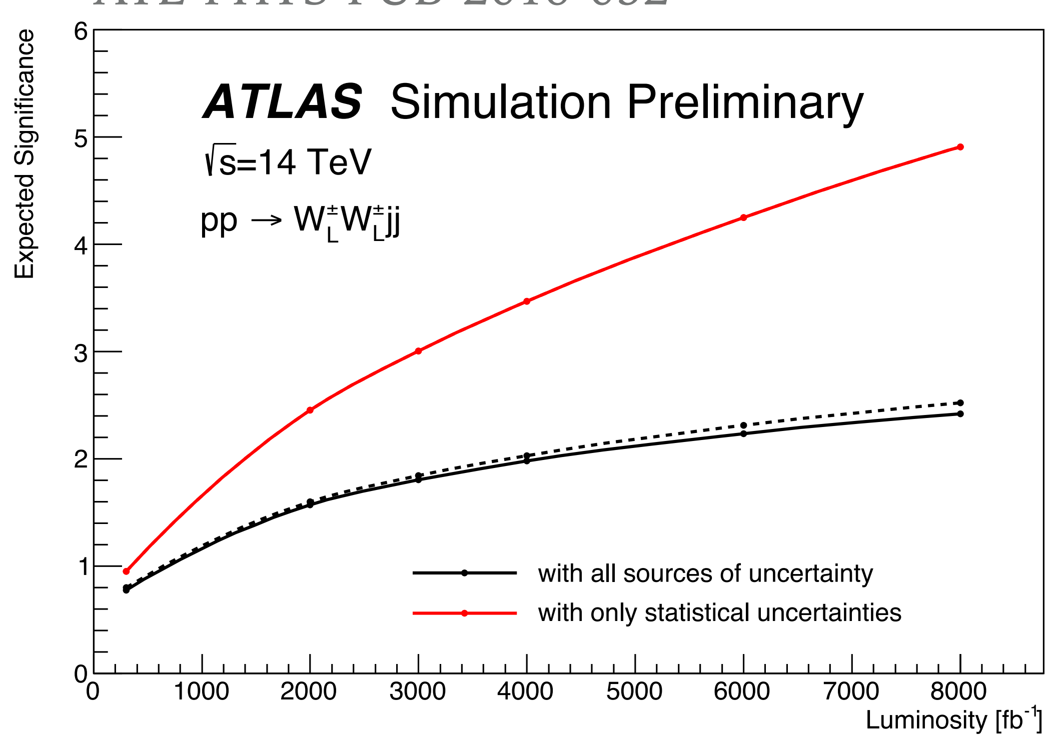
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC



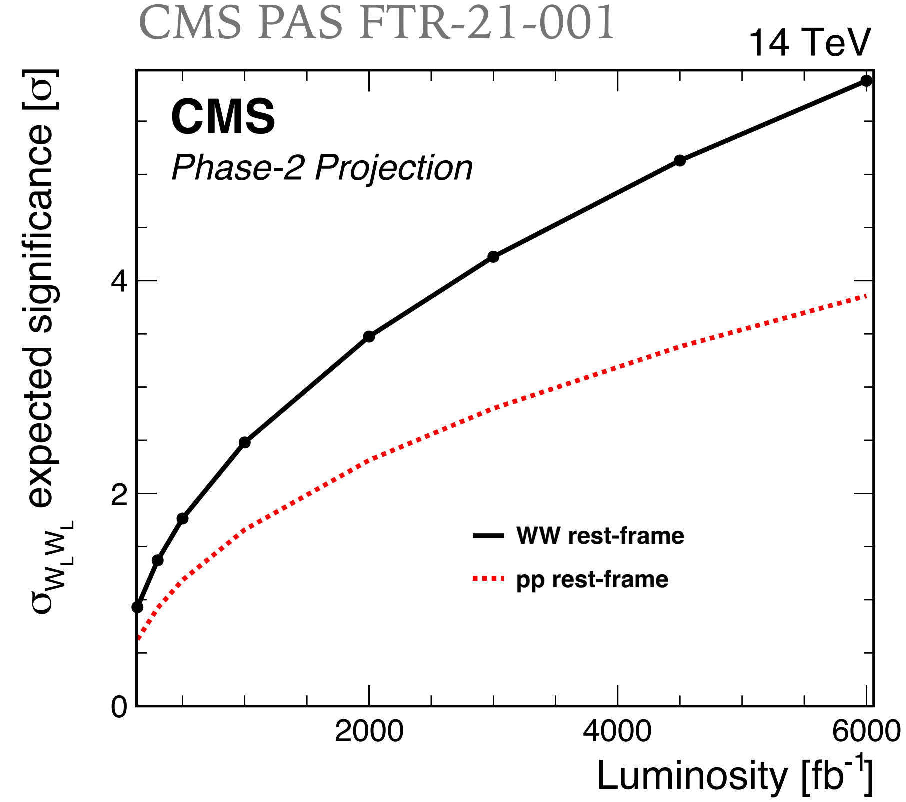
What to expect in Run 3 and beyond?

- Current Run 2 measurements suffer from limited statistics
- In Run 3, higher centre of mass energy and two times more data than in Run 2 expected
- Era of precision electroweak studies with many differential cross-section measurements
- Improved sensitivity for new physics from direct and indirect searches
- Extraction of polarization fractions
- With the future LHC upgrade, potential for evidence of $V_L V_L \rightarrow V_L V_L$

ATL-PHYS-PUB-2018-052



CMS PAS FTR-21-001



Extrapolated from Run 2 measurements
Latest results compared to ATLAS

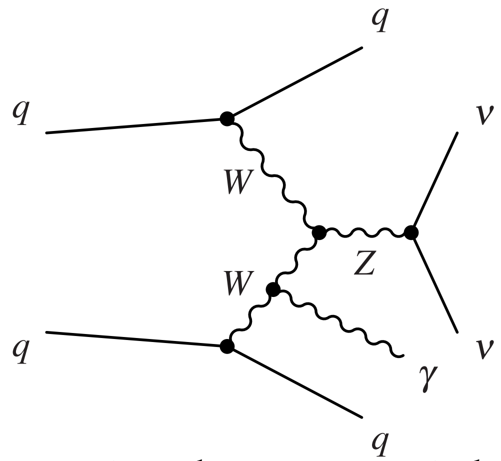
Summary

- VBS enables a stringent test of the Standard Model
- Tree level sensitivity to quartic gauge couplings
- Probes extreme phase spaces which became experimentally accessible for the first time in LHC Run 2
- Most of the VBS processes have been observed in Run 2 with some already in the measurement phase
- Understanding the electroweak sector has only begun
- Wealth of interesting results from the LHC awaiting us in Run 3 and beyond!

Backup

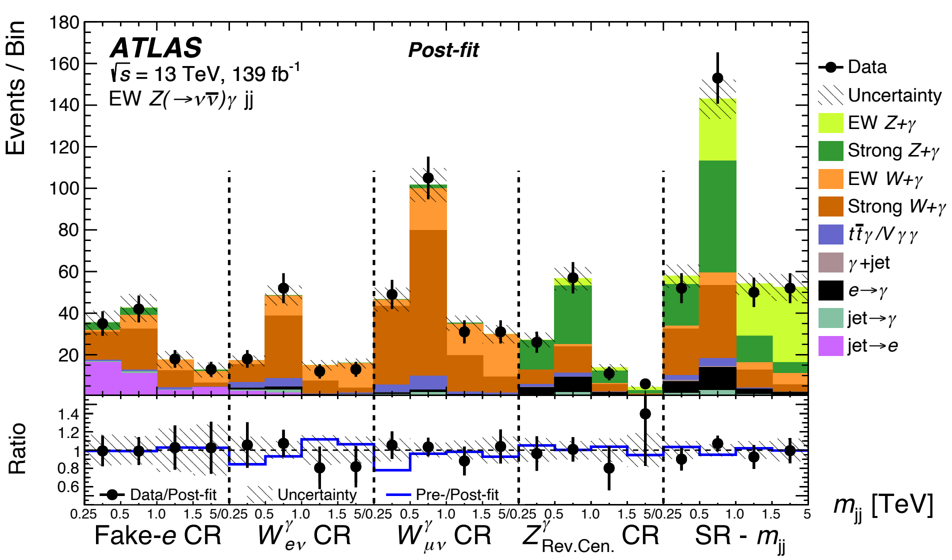
Electroweak $Z\gamma jj$ Production

Observation of $Z(\rightarrow \nu\nu)\gamma jj$, and search for Higgs boson decaying into invisible particles in ATLAS



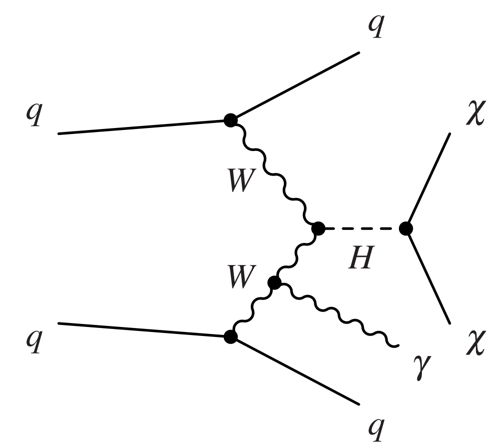
Observed with 5.2σ

- Final state with an energetic photon and large E_T^{miss}
- Dominant backgrounds from $W\gamma$ and QCD induced $Z\gamma$
- Signal obtained from a binned maximum likelihood fit of CR and SR



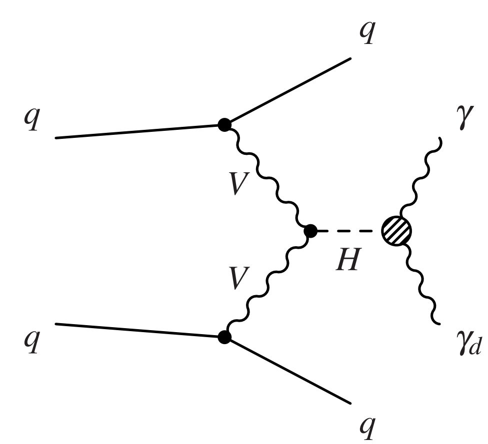
$\mu_{Z\gamma_{\text{EW}}}$	$\beta_{Z\gamma_{\text{strong}}}$	$\beta_{W\gamma}$
1.03 ± 0.25	1.02 ± 0.41	1.01 ± 0.20

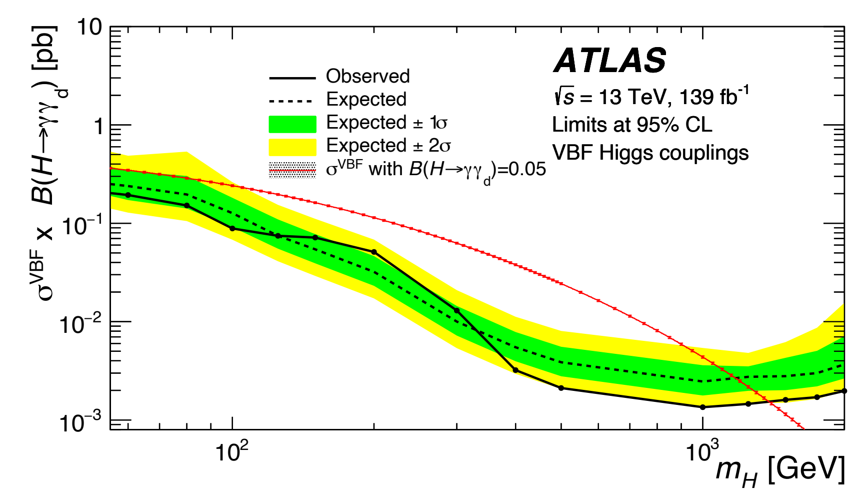
- Setting constraints on invisible and partially invisible decays of Higgs



- VBF $H(\rightarrow \chi\chi)\gamma$
  Obs(exp) upper limits on BR of $0.37(0.34^{+0.15}_{-0.10})$ at 95% CL

- VBF $H \rightarrow \gamma\gamma_d$
  Obs(exp) upper limits on BR of $0.018(0.017^{+0.007}_{-0.005})$ at 95% CL





Electroweak $Z\gamma jj$ Production

EFT Limits in ATLAS

Coefficient	E_c [TeV]	Observed limit [TeV^{-4}]	Expected limit [TeV^{-4}]
f_{T0}/Λ^4	1.7	$[-8.7, 7.1] \times 10^{-1}$	$[-8.9, 7.3] \times 10^{-1}$
f_{T5}/Λ^4	2.4	$[-3.4, 4.2] \times 10^{-1}$	$[-3.5, 4.3] \times 10^{-1}$
f_{T8}/Λ^4	1.7	$[-5.2, 5.2] \times 10^{-1}$	$[-5.3, 5.3] \times 10^{-1}$
f_{T9}/Λ^4	1.9	$[-7.9, 7.9] \times 10^{-1}$	$[-8.1, 8.1] \times 10^{-1}$
f_{M0}/Λ^4	0.7	$[-1.6, 1.6] \times 10^{2}$	$[-1.5, 1.5] \times 10^{2}$
f_{M1}/Λ^4	1.0	$[-1.6, 1.5] \times 10^{2}$	$[-1.4, 1.4] \times 10^{2}$
f_{M2}/Λ^4	1.0	$[-3.3, 3.2] \times 10^{1}$	$[-3.0, 3.0] \times 10^{1}$

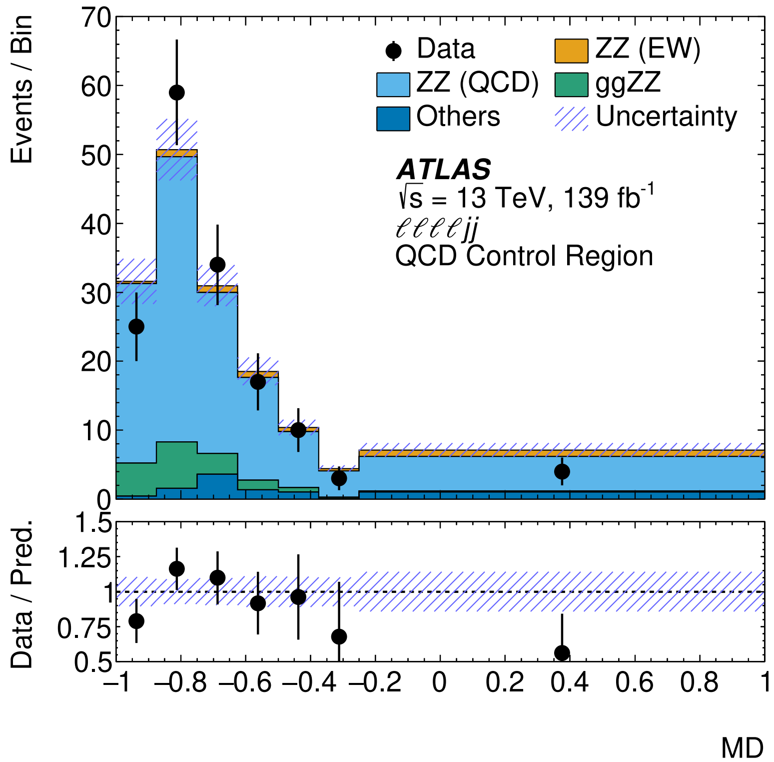
Unitarity preserved

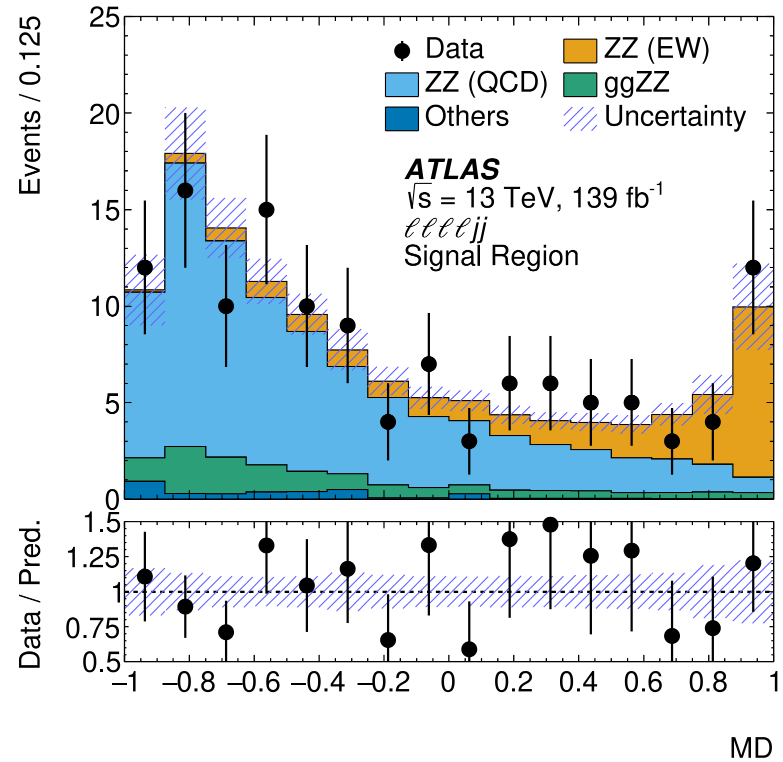
Coefficient	Observed limit [TeV^{-4}]	Expected limit [TeV^{-4}]
f_{T0}/Λ^4	$[-9.4, 8.4] \times 10^{-2}$	$[-1.3, 1.2] \times 10^{-1}$
f_{T5}/Λ^4	$[-8.8, 9.9] \times 10^{-2}$	$[-1.2, 1.3] \times 10^{-1}$
f_{T8}/Λ^4	$[-5.9, 5.9] \times 10^{-2}$	$[-8.1, 8.0] \times 10^{-2}$
f_{T9}/Λ^4	$[-1.3, 1.3] \times 10^{-1}$	$[-1.7, 1.7] \times 10^{-1}$
f_{M0}/Λ^4	$[-4.6, 4.6]$	$[-6.2, 6.2]$
f_{M1}/Λ^4	$[-7.7, 7.7]$	$[-1.0, 1.0] \times 10^{1}$
f_{M2}/Λ^4	$[-1.9, 1.9]$	$[-2.6, 2.6]$

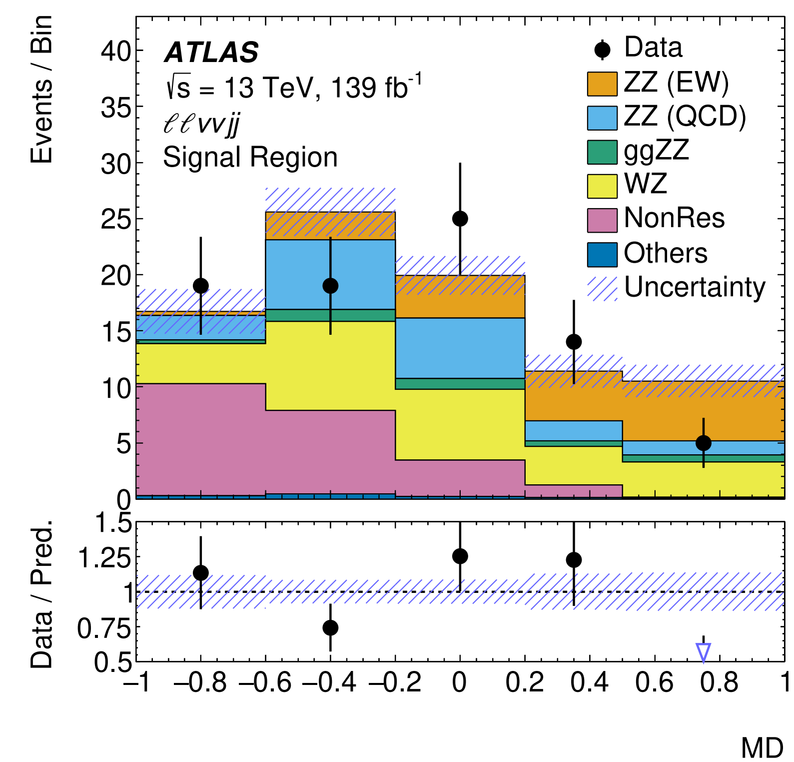
Unitarity not preserved

Electroweak *ZZjj* Production

Observation of *ZZjj* in ATLAS





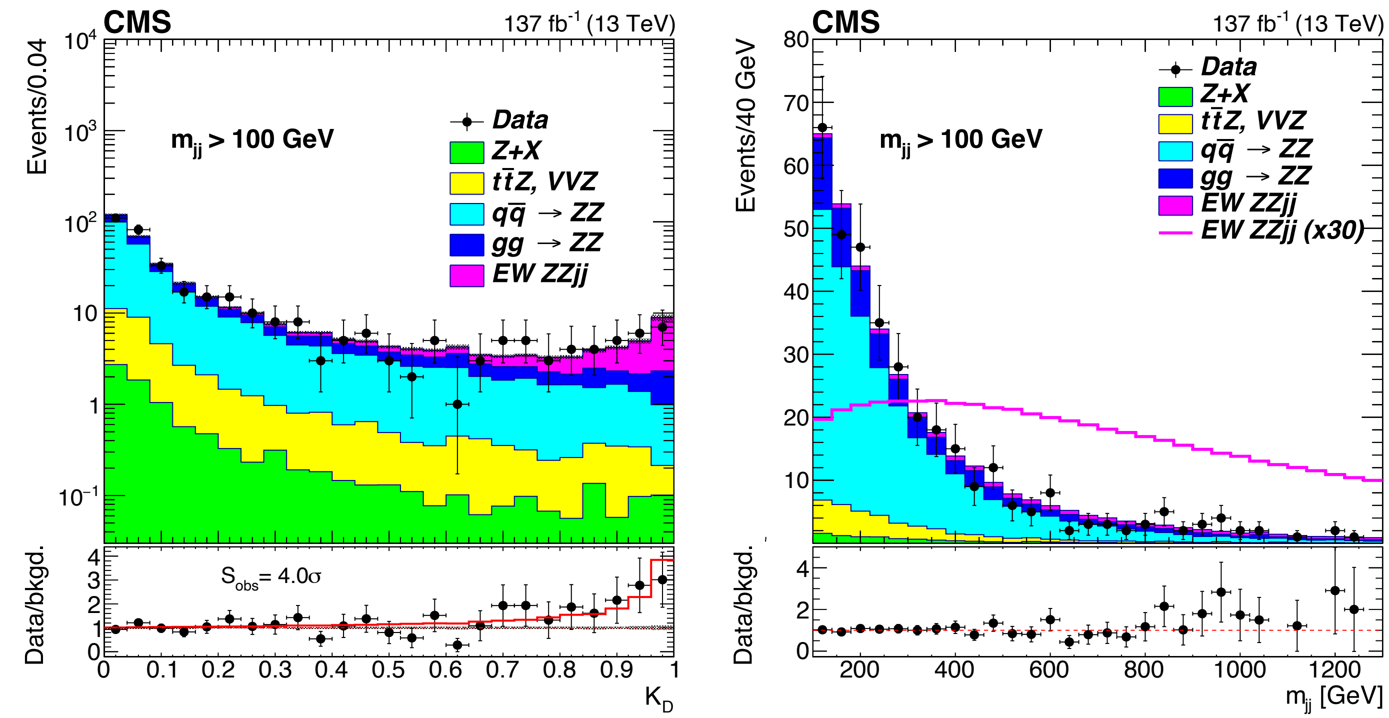


- MD based on Gradient BDT for signal separation from background
- 12 input variables in the 4ljj channel and 13 in the 2l2νjj channel
- Jet related variables provides the greatest sensitivity in 4ljj, while both jet and di-lepton related variables in 2l2νjj
- MD distributions in CR and SR used in the fit for 4ljj channel while only the MD distribution in the SR used for the 2l2νjj channel

Electroweak *ZZjj* Production

Evidence of *ZZjj* in ATLAS

- Matrix element discriminant (K_D) to separate signal from the QCD background
- Utilizes matrix element calculations and employs kinematical distributions of leptons and jets for signal separation
- Cross-checked with MD based on a BDT but no significant gain obtained
- The most stringent limits on the neutral current operators T8 and T9 so far



$$\sigma_{fid} = 0.33^{+0.11}_{-0.10}\,(stat)^{+0.04}_{-0.03}\,(syst)\ \text{fb}$$

$$-0.24 < f_{T0}/\Lambda^4 < 0.22$$

$$-0.31 < f_{T1}/\Lambda^4 < 0.31$$

$$-0.63 < f_{T2}/\Lambda^4 < 0.59$$

$$-0.43 < f_{T8}/\Lambda^4 < 0.43$$

$$-0.92 < f_{T9}/\Lambda^4 < 0.92$$

Electroweak *WVjj* Production

Evidence for WWjj/WZjj (semi-leptonic) in CMS

Pileup treatment

- Pileup-per-partile identification (PUPPI) algorithm applied to AK8 jets to remove pileup tracks
- Soft drop (SD) removes soft, wide-angle radiation from AK8 jets
- AK4 jets overlapping with AK8 jets are removed

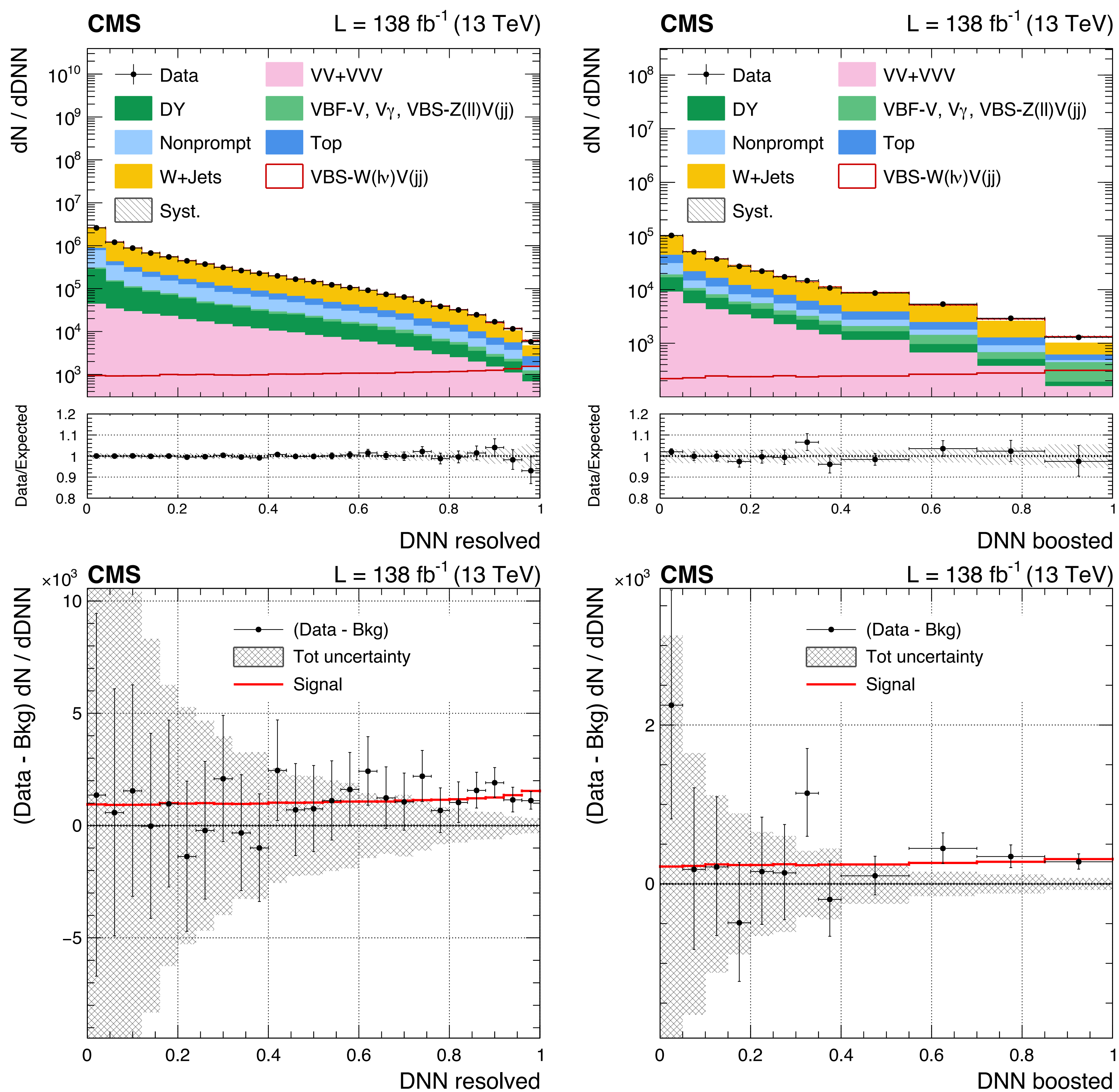
Event selections

- Exactly one isolated tight lepton. Second lepton veto
- MET > 30 GeV
- One AK8 jet, with pT > 200 GeV, together with at least two AK4 jets (boosted category). If not, four AK4 jets with pT > 30 GeV (resolved category)
- In both the categories, two AK4 jets with the largest invariant mass are the tagging jets
- $m_{jj} > 500$ GeV and $|\Delta\eta_{jj}| > 2.5$
- $m_T^W < 185$ GeV and m_V window consistent with W and Z mass windows

Electroweak *WVjj* Production

Evidence for WWjj/WZjj (semi-leptonic) in CMS

- ttbar and W+jets control regions
- Signal discriminator built with DNN
- Sensitive variables: mjj, Zeppenfeld, quark/gluon discriminator of the leading jet from V



Electroweak $W^{\pm}W^{\pm}jj$ Production

EFT Limits in CMS

- Without unitarization
- Limits are two times more restrictive than the previous analyses of the leptonic decay modes
- Less restrictive than the analysis using semi-leptonic decay modes

	Observed ($W^{\pm}W^{\pm}$) (TeV^{-4})	Expected ($W^{\pm}W^{\pm}$) (TeV^{-4})
f_{T0}/Λ^4	[-0.28, 0.31]	[-0.36, 0.39]
f_{T1}/Λ^4	[-0.12, 0.15]	[-0.16, 0.19]
f_{T2}/Λ^4	[-0.38, 0.50]	[-0.50, 0.63]
f_{M0}/Λ^4	[-3.0, 3.2]	[-3.7, 3.8]
f_{M1}/Λ^4	[-4.7, 4.7]	[-5.4, 5.8]
f_{M6}/Λ^4	[-6.0, 6.5]	[-7.5, 7.6]
f_{M7}/Λ^4	[-6.7, 7.0]	[-8.3, 8.1]
f_{S0}/Λ^4	[-6.0, 6.4]	[-6.0, 6.2]
f_{S1}/Λ^4	[-18, 19]	[-18, 19]

Electroweak $W^{\pm}W^{\mp}jj$ Production

Observation of $W^{\pm}W^{\mp}jj$ in CMS

- SR divided as: $Z_{ll} < 1$ and $Z_{ll} > 1$ where,

$$Z_{ll} = \frac{1}{2}|Z_{l1} + Z_{l2}| \text{ and } Z_l = \eta_l - \frac{1}{2}(\eta_{j1} + \eta_{j2})$$

- Dedicated CR for ttbar and Drell-Yan backgrounds

Drell-Yan

- In $ee/\mu\mu$ channels, DY is the largest background (high MET in the event due to instrumental effects)
- Two main sources:
  - at least one jet from pileup vertex: CR with $\Delta\eta_{jj} > 5$
  - jets radiated by initial state quarks (QCD radiation): CR with $\Delta\eta_{jj} < 5$
- DY background of $\tau^+\tau^-$ determined from $e\mu$ events ($\tau^+\tau^- \to e\mu$)

Electroweak $W^{\pm}W^{\mp}jj$ Production

Observation of $W^{\pm}W^{\mp}jj$ in CMS