Vector boson scattering and Triboson results from ATLAS and CMS

Junjie Zhu

University of Michigan

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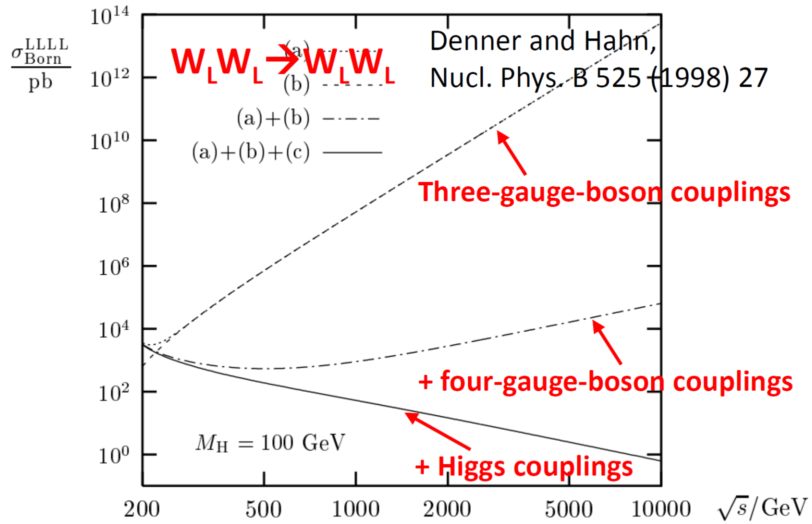
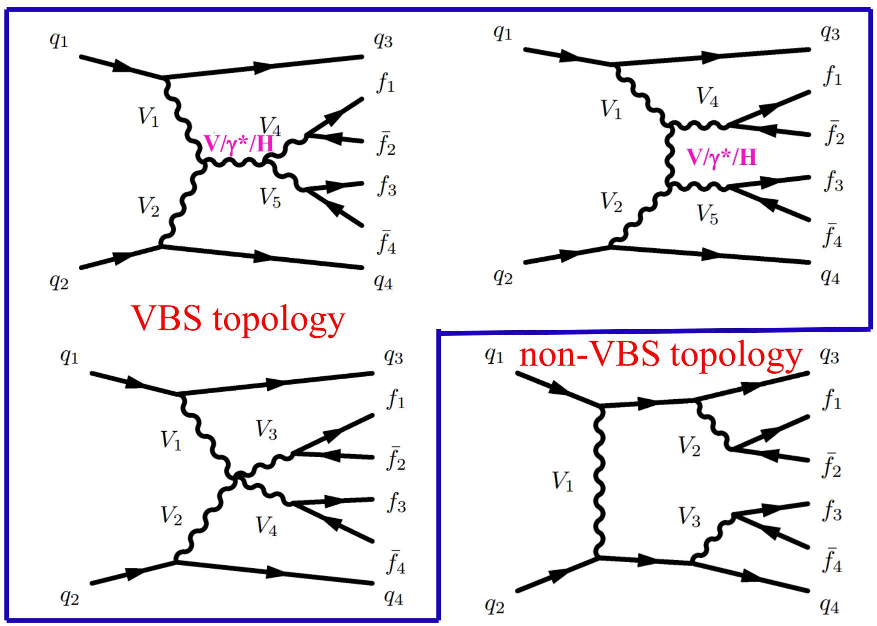
Introduction

- Higgs mechanism: Goldstone bosons resulting from EWSB are incorporated into the W and Z bosons and become their longitudinal components
- Critical to test EWSB and study its dynamics by studying the interactions of longitudinal modes of W or Z bosons (longitudinal VBS):

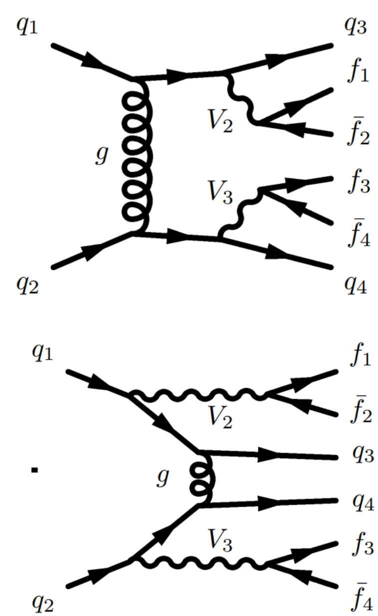
  $V_L V_L \rightarrow V_L V_L$ (V=W, Z)
- The SM Higgs boson is needed to unitarize the scattering amplitude



EW production: $O(\alpha^6)$



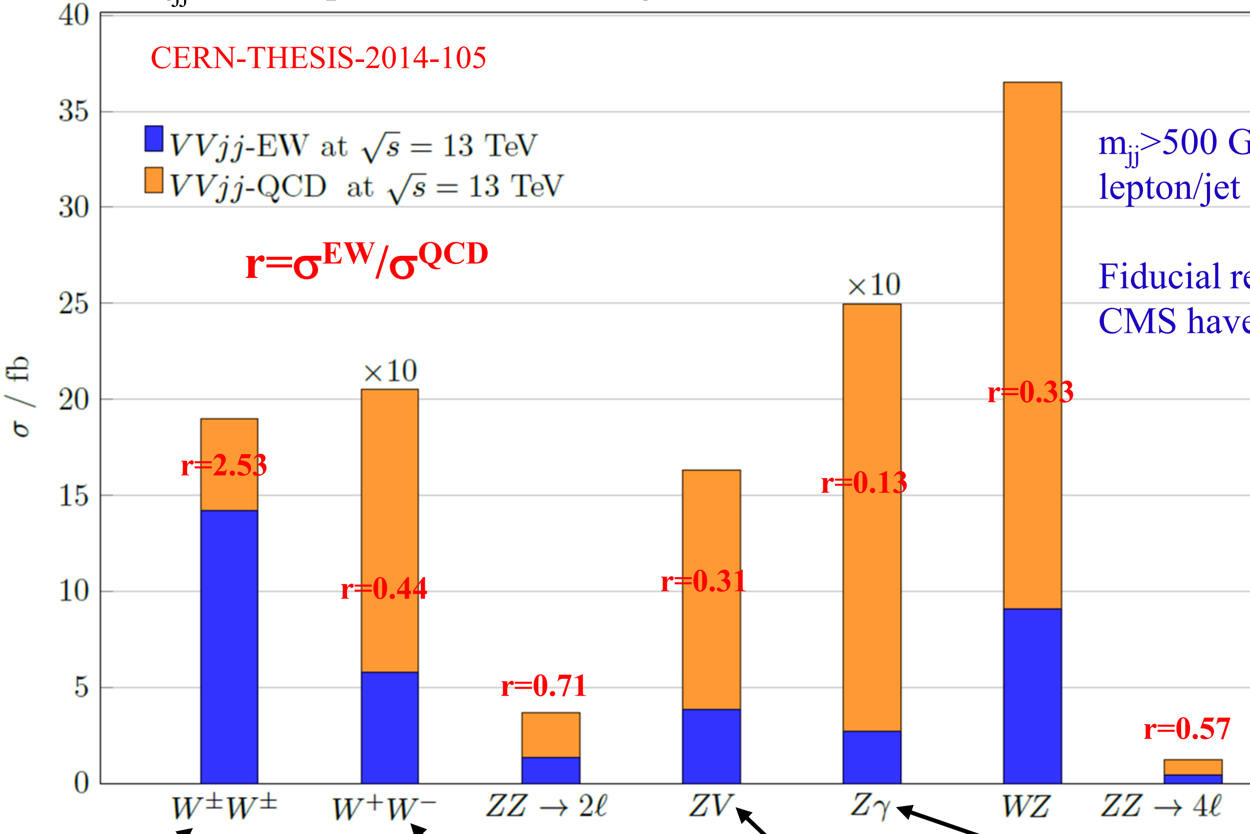
+ QCD production: $O(\alpha_S^2\alpha^4)$



+ Interference: $O(\alpha_S\alpha^5)$

VBS processes

Detector signatures for EW VBS topology: two jets with large m_{jj} and $\Delta\eta_{jj}$, central part of the scattering is free from QCD activities



m_{jj}>500 GeV and a few loose lepton/jet cuts applied

Fiducial regions used by ATLAS and CMS have cross sections ~ a few fb

- Charge conservation prevents gluon-initiated QCD processes
- Small bkgs due to ss dilepton
- Easier to calculate theoretically
- Golden channel for VBS

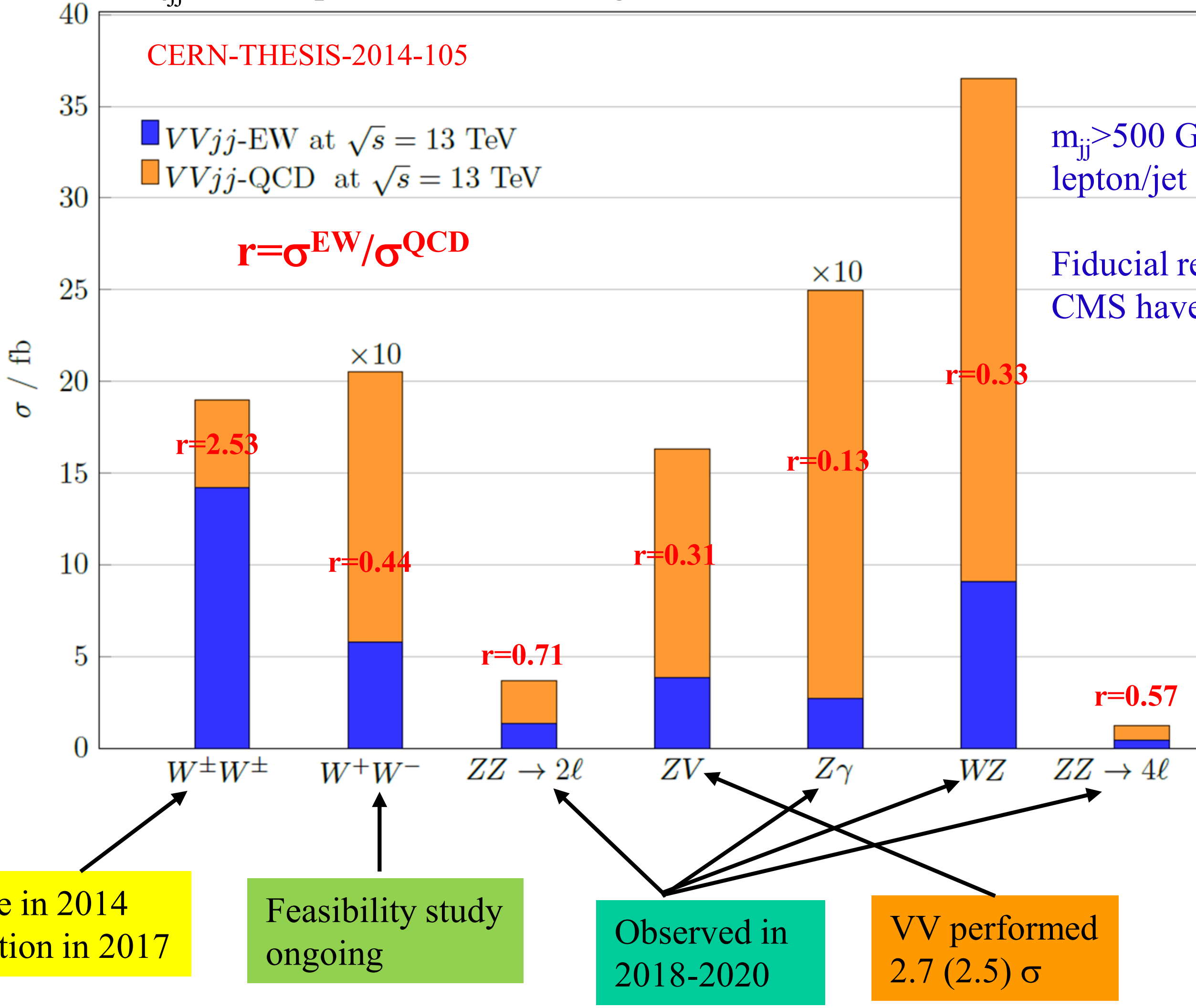
Large tt background

Large Z+jets and W+jets backgrounds

Large ISR and FSR backgrounds

VBS processes

Detector signatures for EW VBS topology: two jets with large m_{jj} and $\Delta\eta_{jj}$, central part of the scattering is free from QCD activities



m_{jj}>500 GeV and a few loose lepton/jet cuts applied

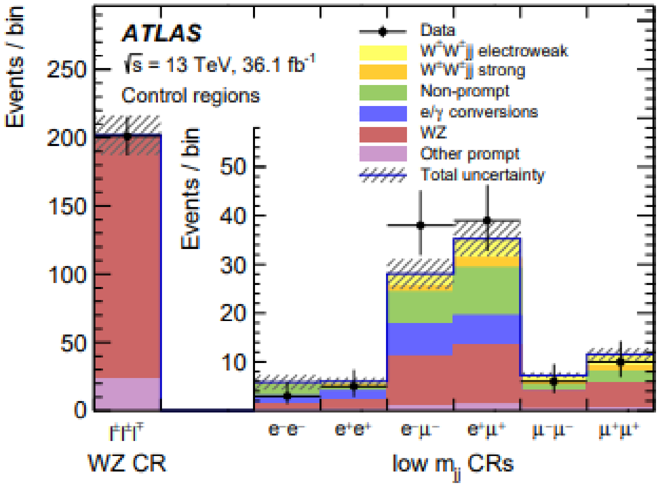
Fiducial regions used by ATLAS and CMS have cross sections ~ a few fb

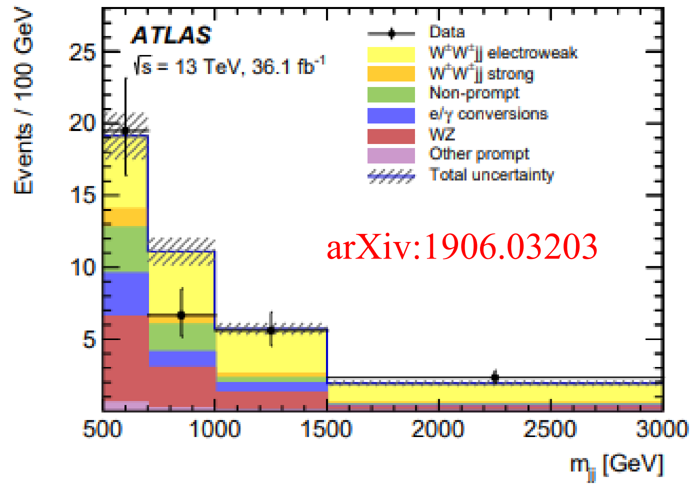
Wγ VBS observed with 5.3 σ (8 TeV and 13 TeV data combined)

Analysis strategies

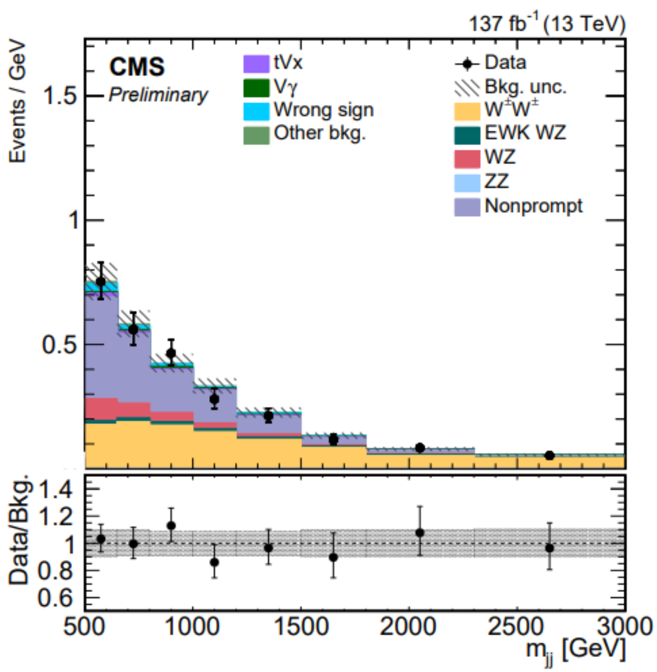
- Event selection:
  - Single-lepton or di-lepton triggers
  - Isolated electrons or muons (looser requirements applied for Z leptons to increase the signal acceptance)
  - Veto events with additional low p_T leptons to reduce prompt backgrounds
  - High p_T jets (use particle-flow jets or jet-vertex-fraction to reduce pileup jets)
  - Veto events with b jets to reduce the tt contribution
  - Signal regions are required to have large m_{jj} and $\Delta\eta_{jj}$
- Background estimation:
  - Backgrounds due to jet-faked leptons, photon-faked leptons or charge flip are often estimated using data-driven techniques
  - Dominant prompt background shapes are determined from MC, but normalizations are often derived from data
  - Data-driven or simulation-driven methods are validated in background validation regions that have similar cuts as used in the signal region
- Fiducial regions:
  - Defined by applying similar event selection cuts at the truth level
  - Often interference contributions are included as part of the signal
- Signal extraction:
  - Multivariate variables used in many analyses to reduce QCD VBS and other background contributions
  - A simultaneous fit is performed for both signal and background control regions

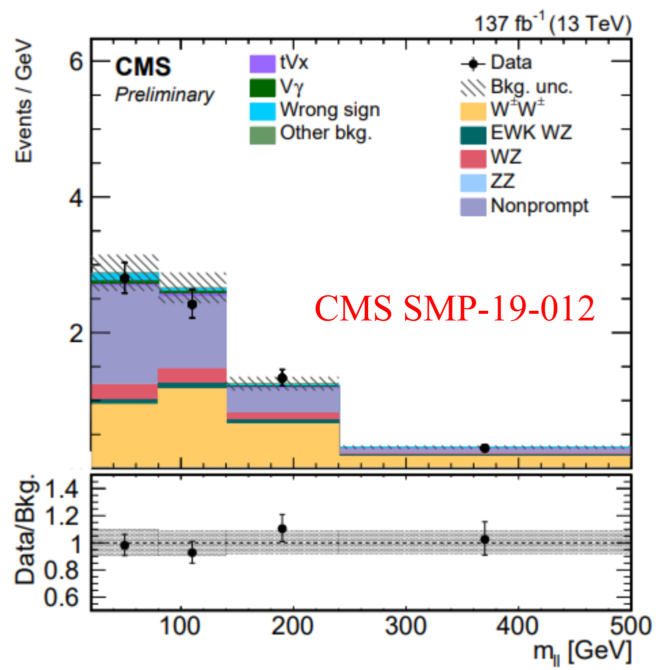
Same-sign WW VBS





- divided events into + + and – – final states to increase the sensitivity
- 60 signal + 69 bkgs
- 6.5σ observed
- σ = 2.89 ± 0.51 (stat) ± 0.29 (syst) fb
- 20% uncertainty (18% stat) on the cross section measurement



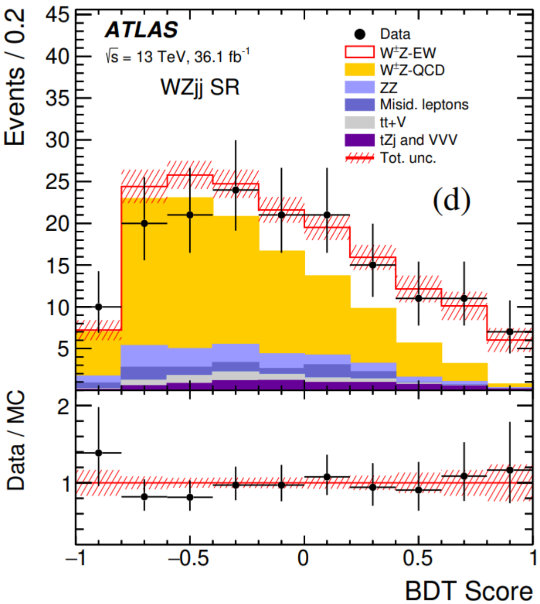


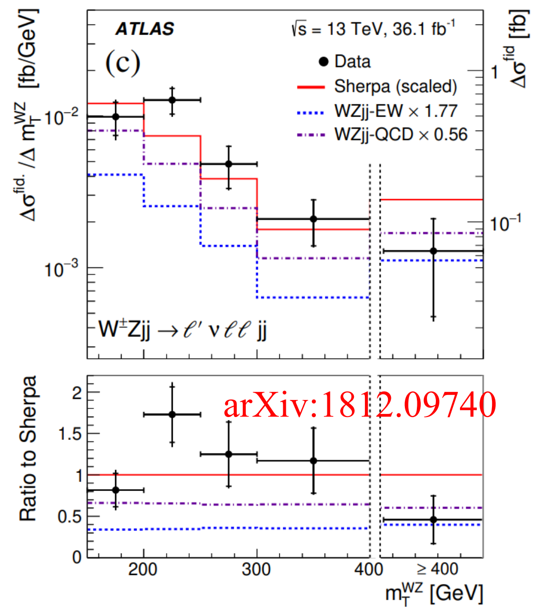
- max(z^*_1)<0.75 with

$$z^*_\ell = |\eta_\ell - \bar{\eta}_{(j_1,j_2)}|/\Delta\eta_{jj}$$

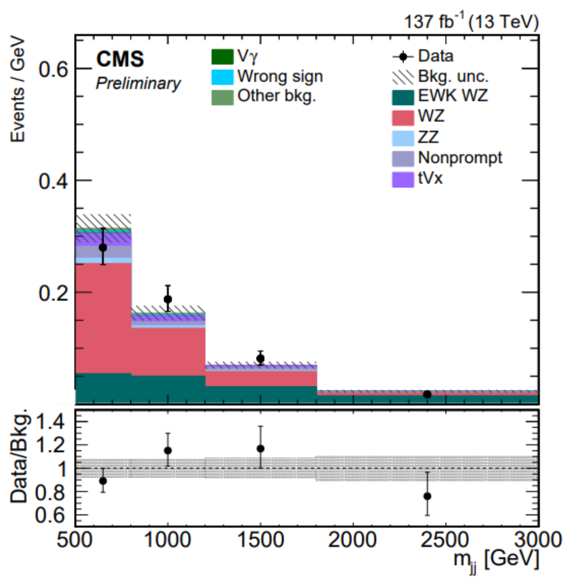
- 2-dimensional fit of m_{jj} and m_{ll} in the signal region
- 210 signal + 312 bkgs
- σ = 3.98 ± 0.37 (stat) ± 0.25 (syst) fb
- 11% uncertainty (9% stat) on the cross section measurement

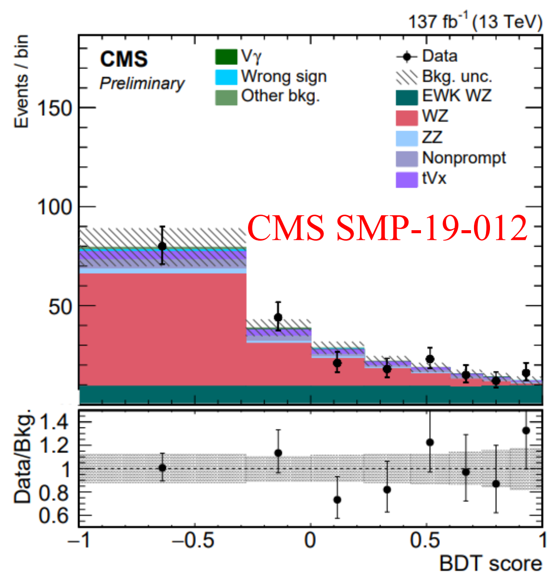
WZ VBS





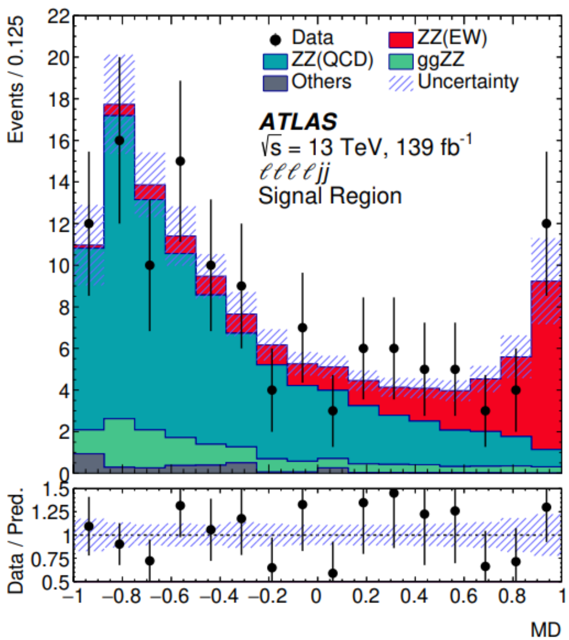
- 44 signal + 123 bkgs
- 5.3 σ observed
- $\sigma = 0.57 \pm 0.14$(stat) ± 0.08 (syst) fb for a single leptonic decay mode
- 28% uncertainty (25% stat) on the cross section measurement

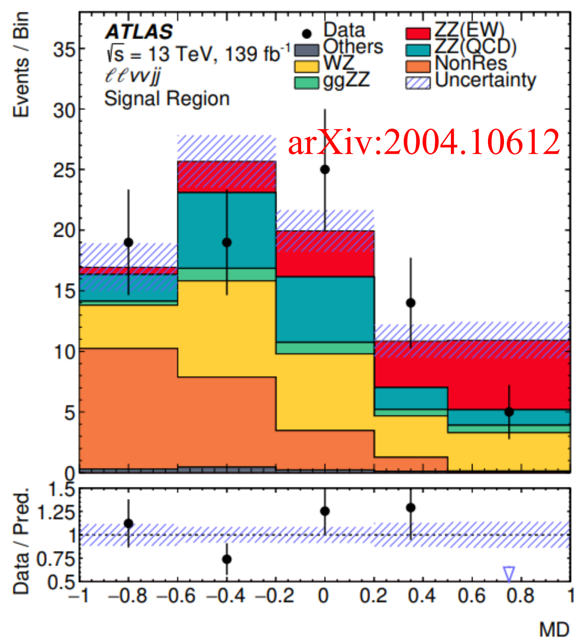




- 69 signal + 160 bkgs
- 6.8 σ observed
- $\sigma = 1.81 \pm 0.39$(stat) ± 0.14 (syst) fb
- 23% (21% stat) uncertainty on the cross section measurement

ZZ VBS

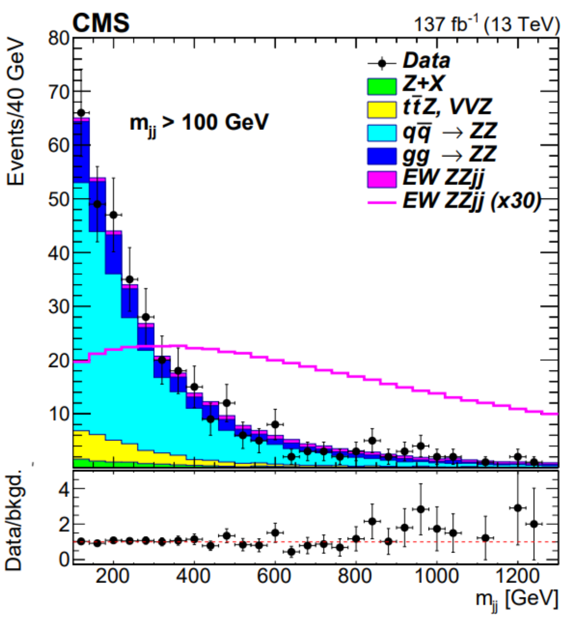


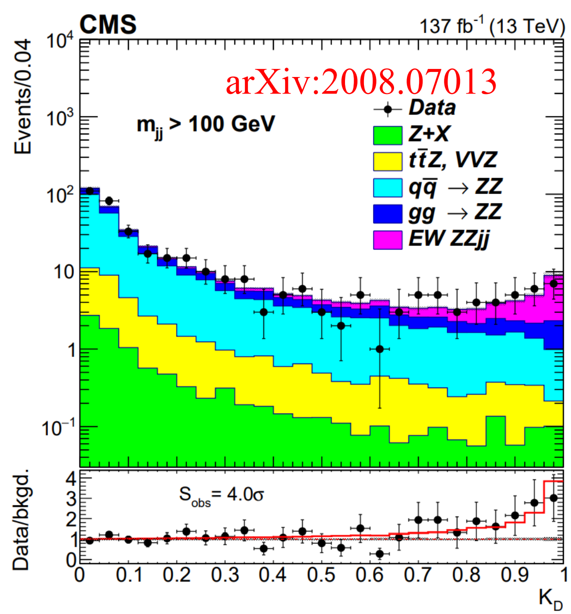


- 4l and 2l2ν channels included

- 4l: 21 signal + 93 bkgs, 5.5 σ
- σ = 1.27±0.12 (stat)±0.08 (syst) fb
- 11% uncertainty (10% stat) on the cross section measurement

- 2l2ν: 12 signal + 66 bkgs, 1.2 σ
- σ = 1.22±0.30 (stat)±0.18 (syst) fb
- 28% uncertainty (25% stat) on the cross section measurement

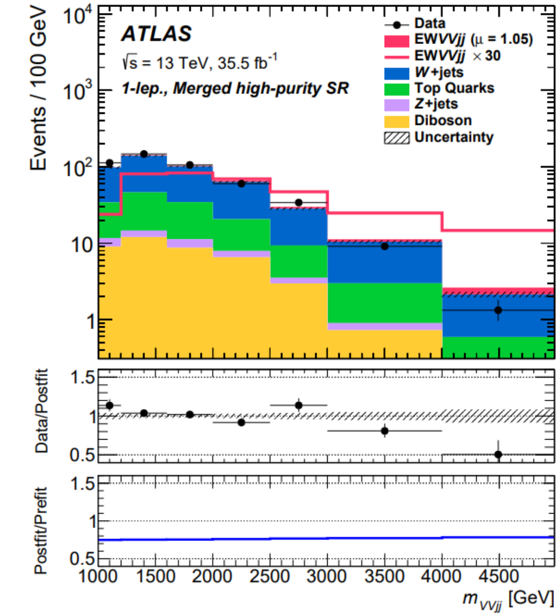


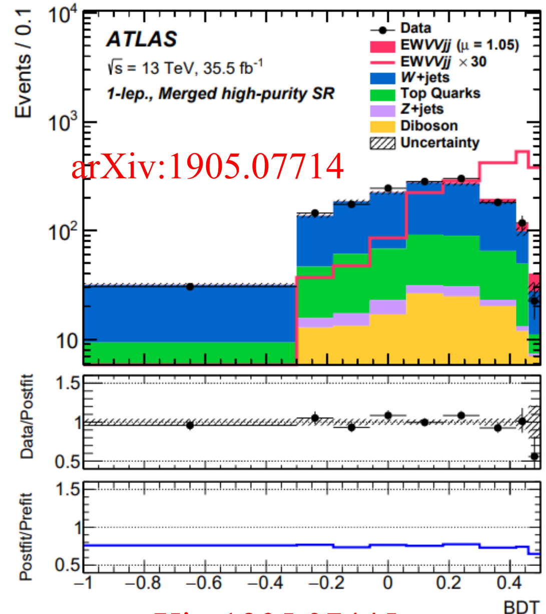


- 4l channel used
- Inclusive, loose (m_{jj}>400 GeV) and tight (m_{jj}>1 TeV) VBS regions defined
- 24 signal + 346 bkgs (inclusive), 4.0 σ
- σ = 0.33±0.11 (stat)±0.04 (syst) fb
- 35% uncertainty (33% stat) on the cross section measurement

Semi-leptonic VV VBS channels

- Stronger limits set by semi-leptonic channels on aQGCs and new physics models

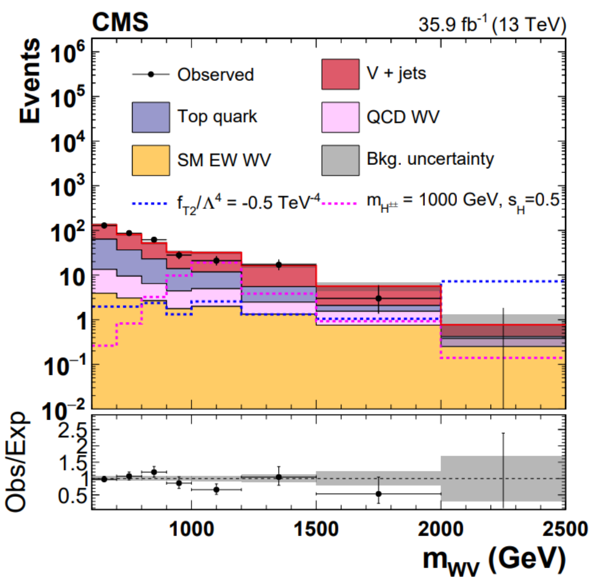


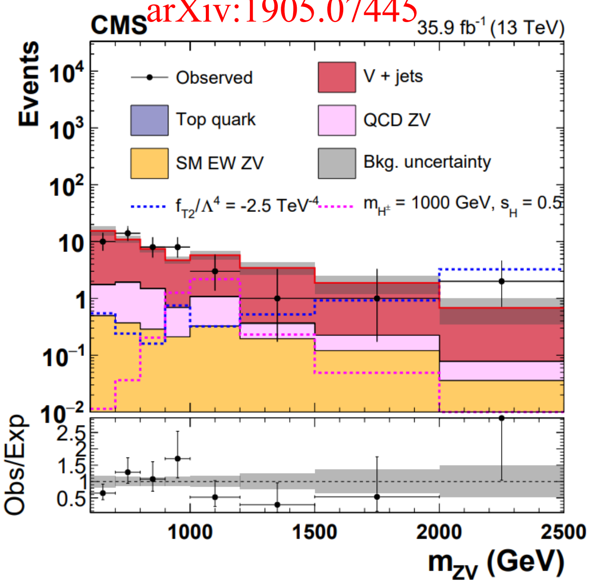


arXiv:1905.07714

- VV events with 0, 1 or 2 leptons and either 2 resolved jets or 1 merged jet as well as two tagging jets
- Main sensitivity comes from 1 lepton with 1 merged jet
- VVjj electroweak production: 2.7 σ
- σ = 45.1±8.6(stat)±15.9(syst) fb
- 40% uncertainty (20% stat) on the cross section measurement

arXiv:1905.07445

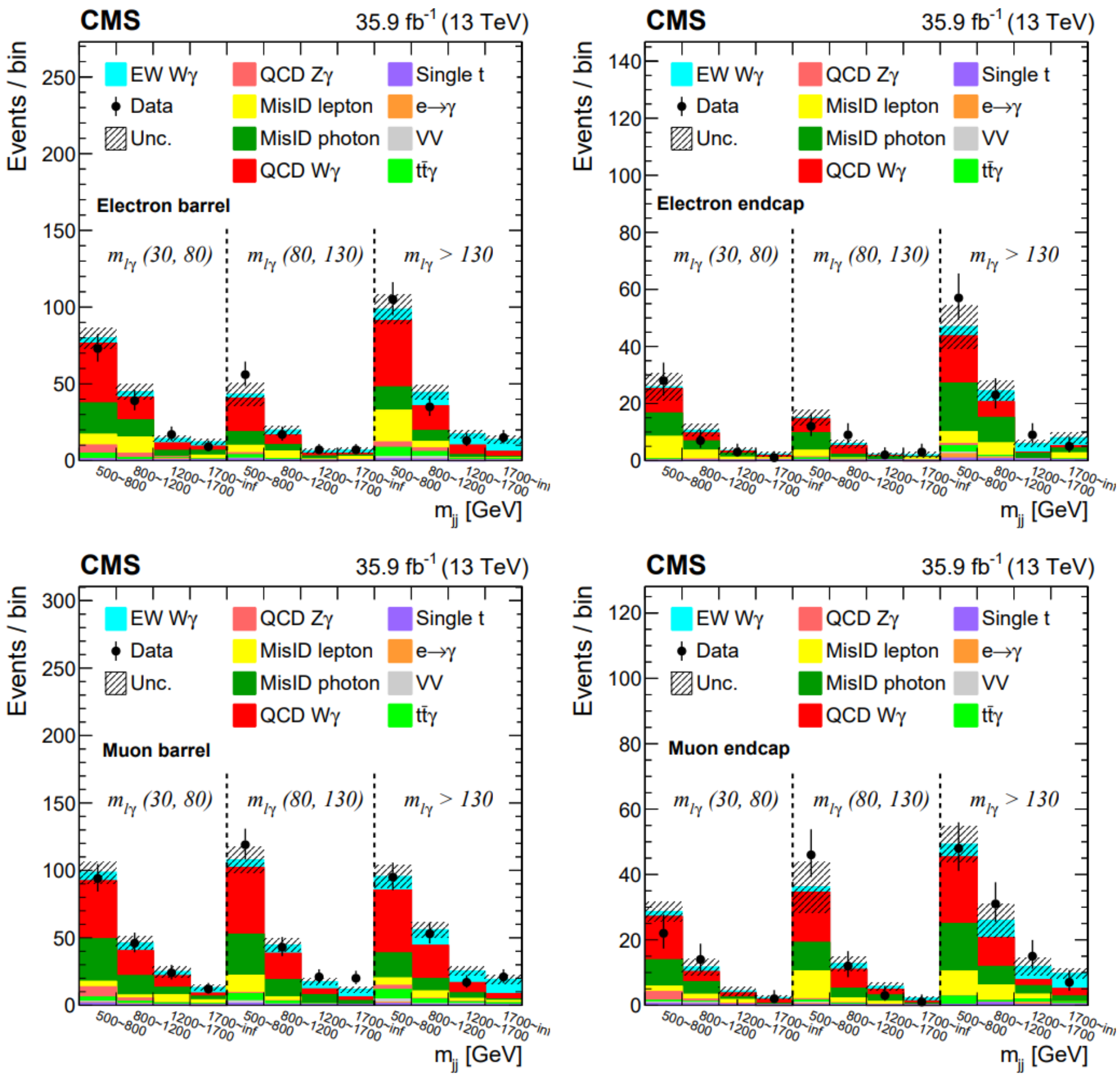




- VV events with 1 or 2 leptons and 1 merged jet together with two tagging jets
- Focused on aQGCs and new physics
- Limits set on aQGCs in the EFT framework and resonant charged Higgs boson production ($H^{\pm} \rightarrow W^{\pm}Z$ and $H^{\pm\pm} \rightarrow W^{\pm}W^{\pm}$)
- Comparable or better limits compared to limits obtained from leptonic $W^{\pm}W^{\pm}$ jj and WZjj channels with a dataset that is four times larger

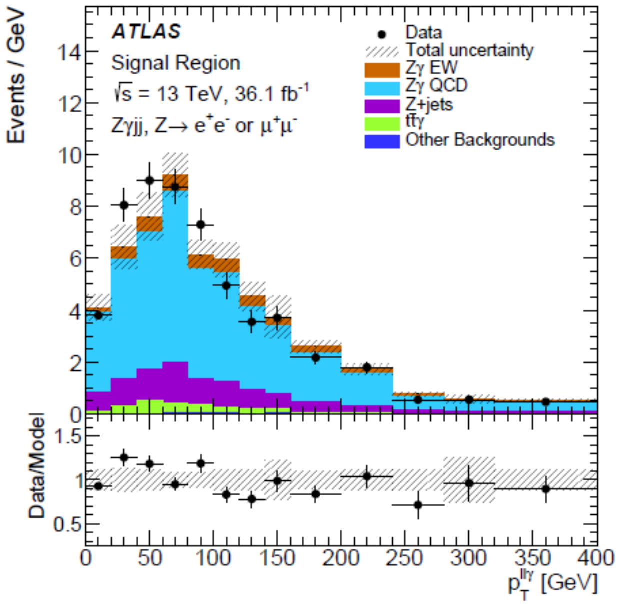
Wγ VBS

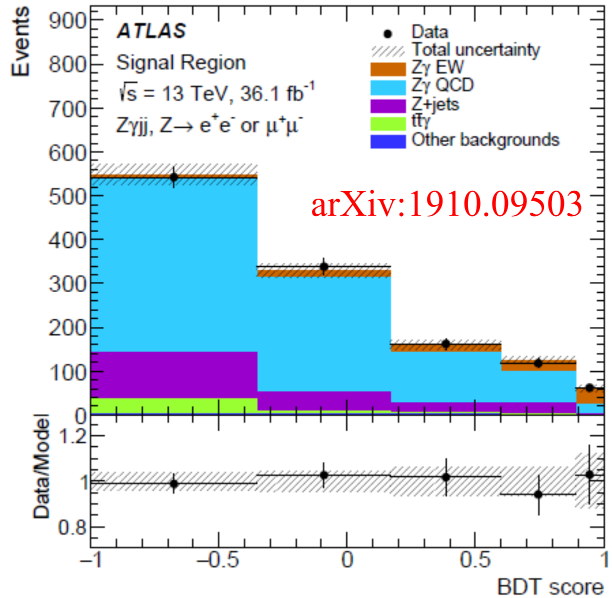
arXiv:2008.10521



- Require $\Delta R>0.5$ between any two selected objects (γ, lepton, jets)
- Cuts on $y_{W\gamma}$ and $\phi_{W\gamma}$ to ensure the momentum of the Wγ system is balanced by that of the dijet system
- 2-dimensional fit of m_{jj} and $m_{l\gamma}$ in the signal region
- 164 signal + 814 bkgs, 5.3 σ
- $\sigma = 20.4 \pm 2.8$ (stat) ± 3.5 (syst) fb
- 22% uncertainty (14% stat) on the cross section measurement

Zγ VBS

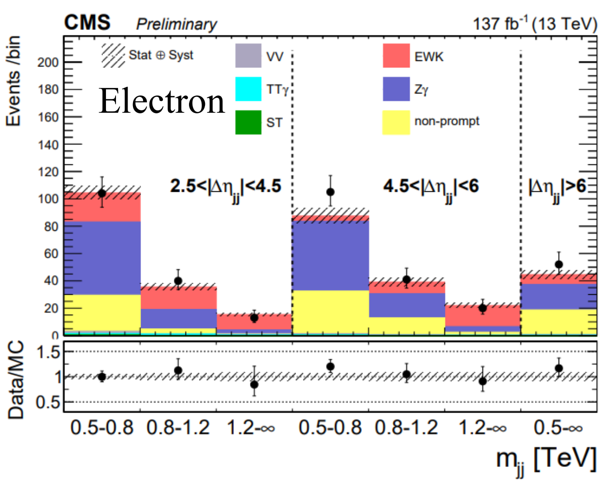


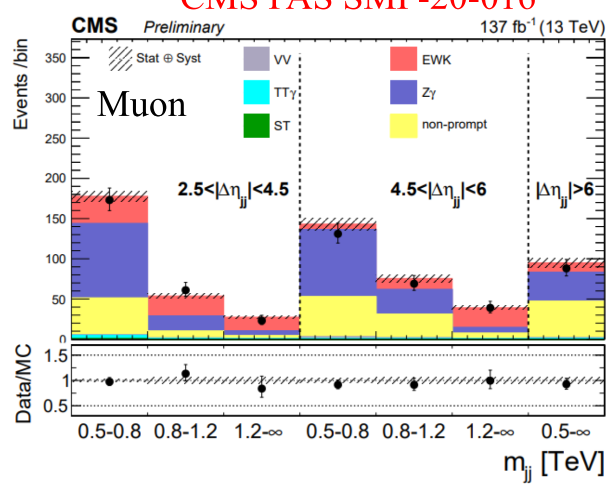


arXiv:1910.09503

- The centrality $\zeta(Z\gamma)<5$
- Require $\Delta R>0.4$ between a lepton and a photon
- $m_{ll}+m_{ll\gamma}>180$ GeV
- 104 signal + 1118 bkgs, 4.1 σ
- σ = 7.8±1.5 (stat)±1.0 (syst) fb
- 26% uncertainty (19% stat) on the cross section measurement

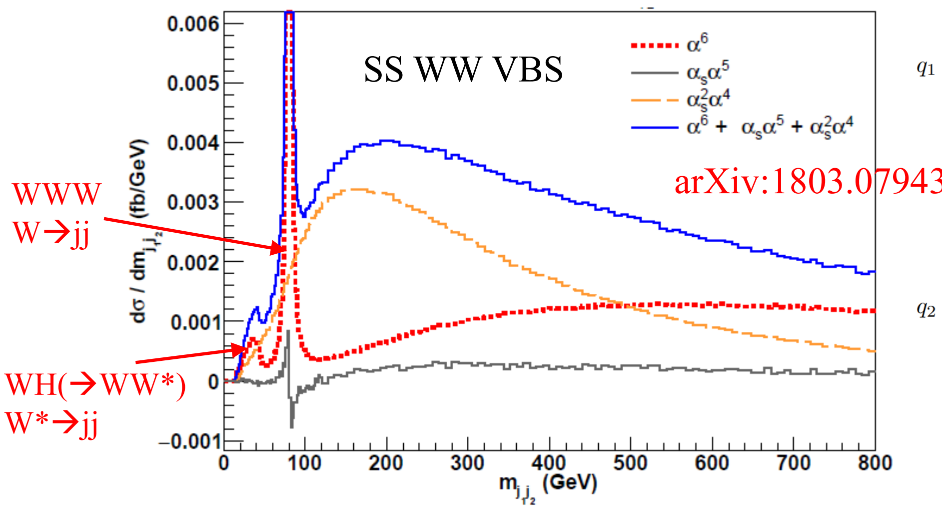
CMS PAS SMP-20-016

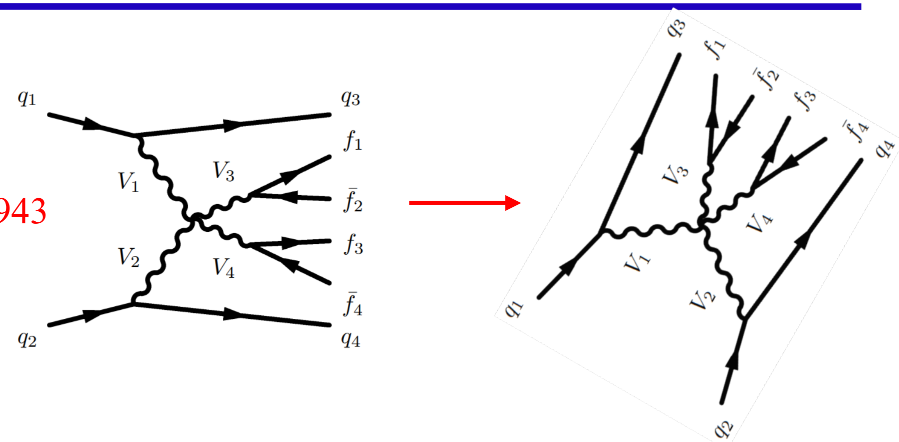




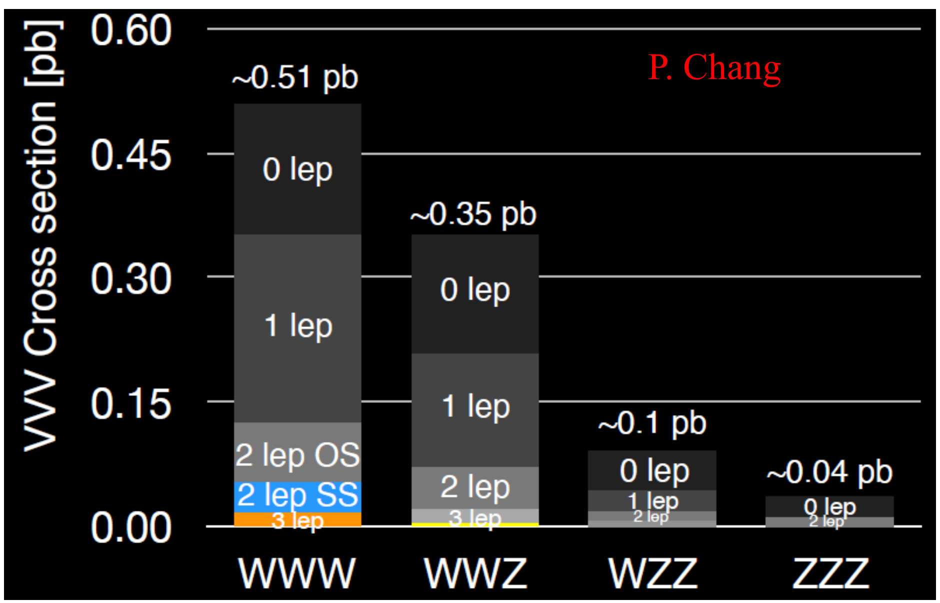
- Require $\Delta R>0.7$ between a lepton and a photon
- $m_{Z\gamma}>100$ GeV
- Cut on $\phi_{Z\gamma}$ to ensure the momentum of the Zγ system is balanced by that of the dijet system
- 292 signal + 1429 bkgs, 9.4 σ
- σ = 5.21±0.52 (stat)±0.56 (syst) fb
- 15% uncertainty (10% stat) on the cross section measurement
- A few unfolded differential distributions are measured

Triboson production





Similar Feynman diagrams as VBS: QGC vertex, Z/γ*/H-exchange, emission from a fermion



WWW:

3% BR to l±νl±νjj → 2500 evts expected

1% BR to 3l3ν → ~700 evts expected

WWZ:

1% to 3l1νjj → ~500 evts expected

0.3% to 4l2ν → ~150 evts expected

WZZ:

0.1% to 5l1ν → ~15 evts expected

ZZZ:

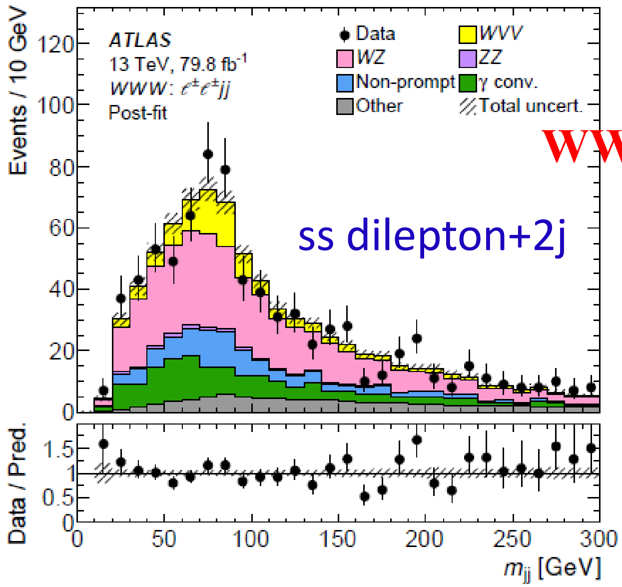
0.03% to 6l → ~1.5 evts expected

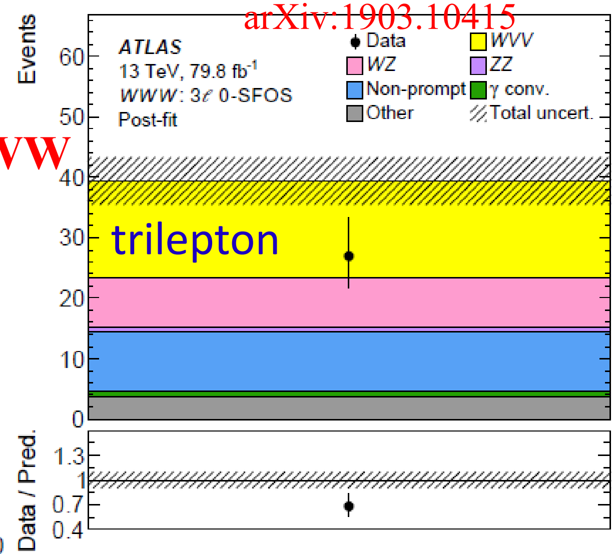
Smaller yields after taking into account kinematical and geometrical acceptances plus ~80% detection efficiency per lepton

Evidences of WWW and WWZ productions

arXiv:1903.10415

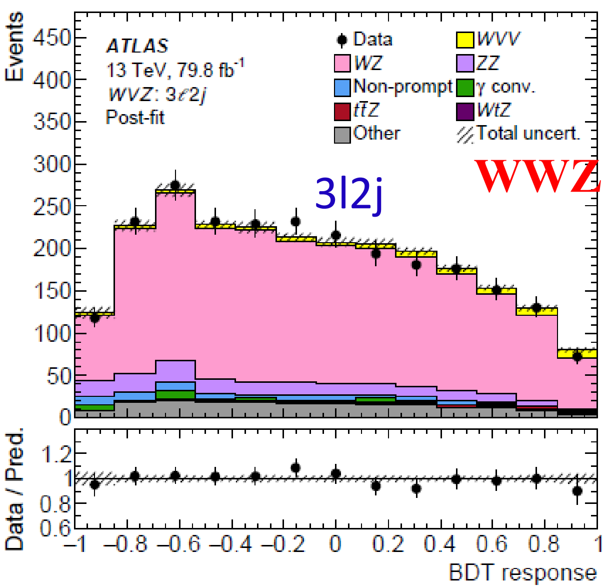
WWW

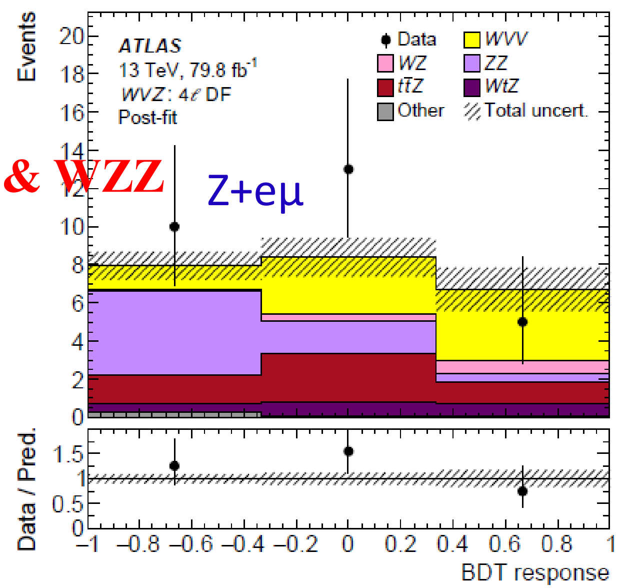




- Same-sign dilepton and trilepton with 0 SFOS lepton pair
- Dominant WZ backgrounds determined from data
- Fake backgrounds estimated using data-driven methods
- 3.2σ observed
- σ = 0.65±0.16(stat)±0.16(syst) pb
- 35% uncertainty (25% stat) on the cross section measurement

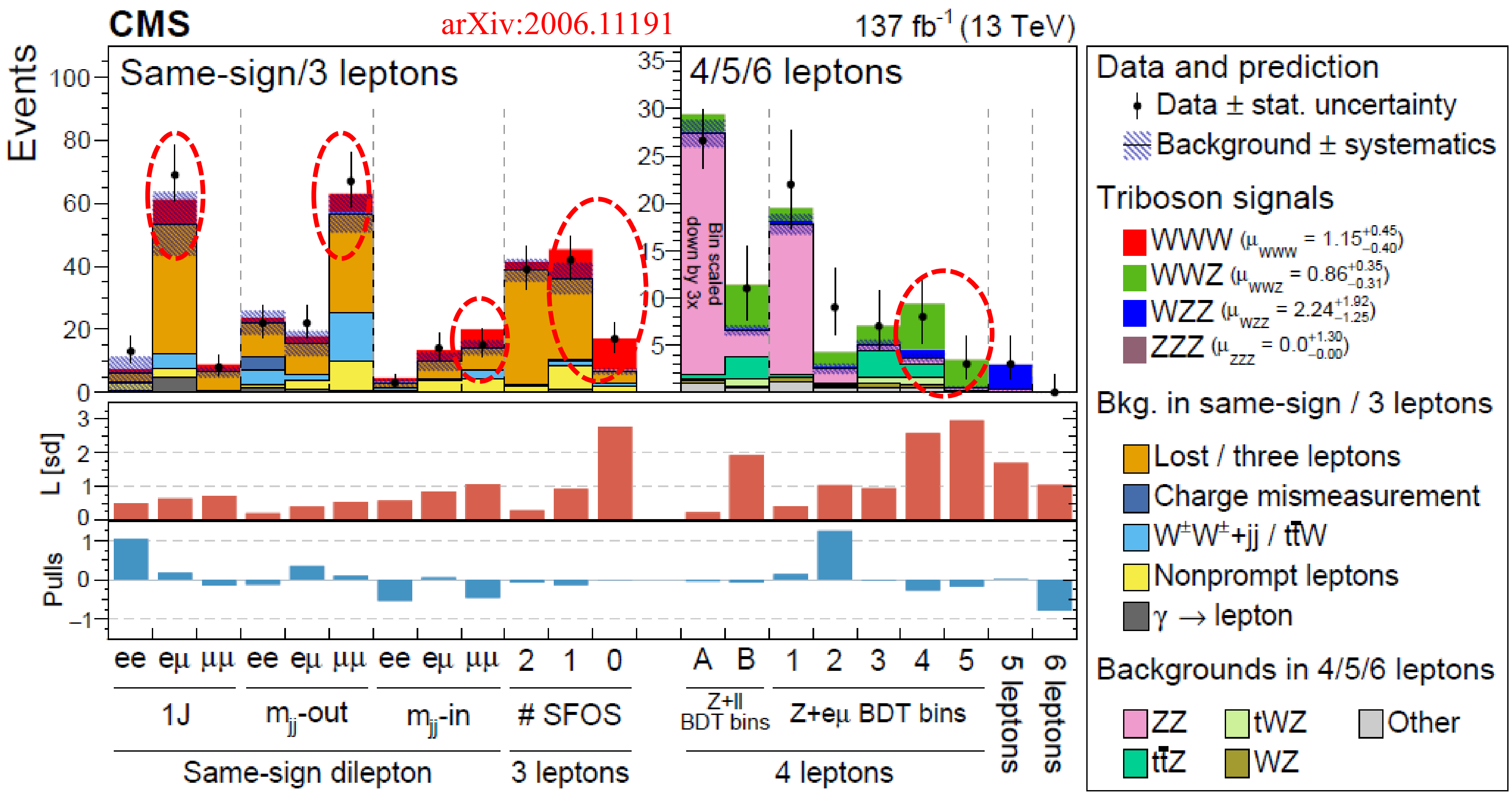
WWZ & WZZ





- WVZ(→lνjjll): 3l (1, 2, 3 jets) channels
- WWZ(→ lνlνll) + WZZ(jjllll): 4l (Z+eμ, Z+ll within and outside of the Z mass window) channels
- All backgrounds determined from simulation samples, modellings checked in data CRs
- BDT variables are used
- 3.2σ observed
- σ = 0.55±0.14(stat)±0.15(syst) pb
- 37% uncertainty (25% stat) on the cross section measurement

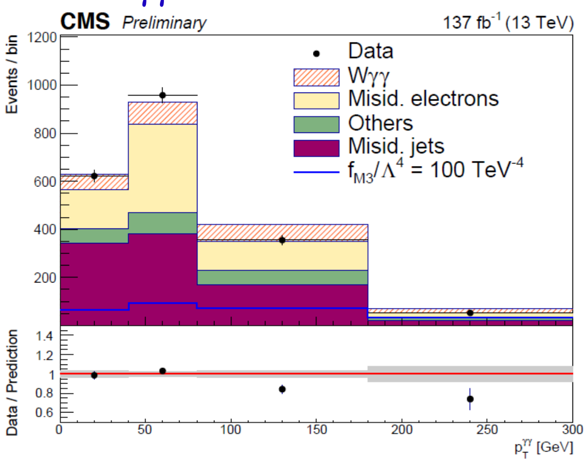
Observation of combined VVV production



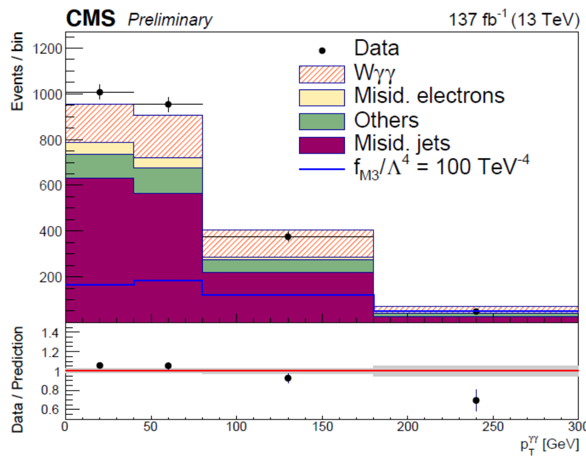
- WWW: same-sign dilepton (separated into 1 and ≥2 jet categories) and trilepton channels included (0, 1, and 2 SFOS channels included), cuts made on two BDT variables trained to separate the signal from non-prompt and other backgrounds
- WWZ: only considered 4-lepton channels, main sensitivity comes from the Z+eμ channel, BDT used
- 2.5σ for WWW, 3.5σ for WWZ, 1.6σ for WZZ, 0σ for ZZZ → 5.7σ for combined VVV production

Wγγ and Zγγ production

Wγγ e channel



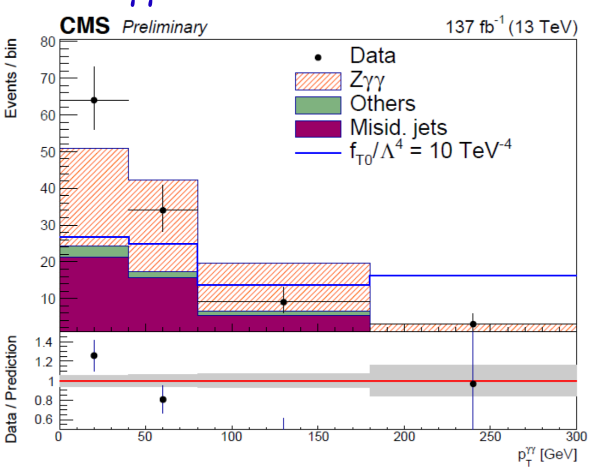
Wγγ μ channel



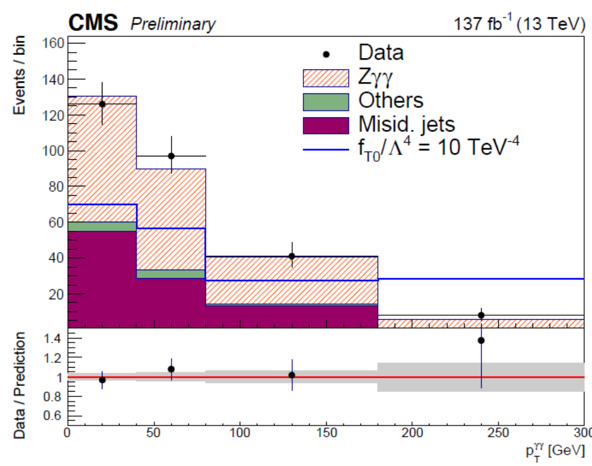
CMS PAS SMP-19-013

- Require ΔR>0.4 between a lepton and a photon
- Remove photons if $m_{e\gamma}$ or $m_{e\gamma\gamma}$ is close to the Z pole mass
- “Misid electrons” important for the e channel due to Zγ → eeγ with e→γ
- 748 signal + 3638 bkgs, 3.1σ
- σ = 13.6±1.9(stat)±4.0(syst) pb
- 33% uncertainty (14% stat) on the cross section measurement

Zγγ e channel



Zγγ μ channel



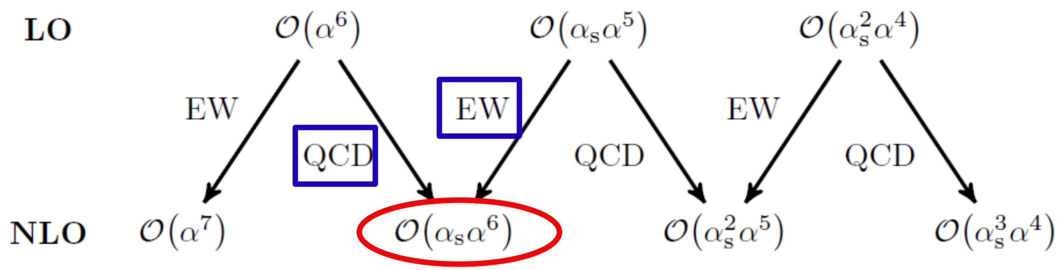
- Require ΔR>0.4 between a lepton and a photon
- Remove photons if $m_{e\gamma}$ or $m_{e\gamma\gamma}$ is close to the Z pole mass
- Background due to “Misid. Electrons” is small due to the requirement on the Z boson
- 225 signal + 157 bkgs, 4.8σ
- σ = 5.41±0.58(stat)±0.70(syst) pb
- 17% uncertainty (11% stat) on the cross section measurement

Personal opinions about Run 3 analyses

- Promising VBS and triboson studies in Run 3:
  - Most analyses are still dominated by statistical uncertainty
  - The improvement should be better than the naïve $\sqrt{2}$ improvement (normalizations for dominant prompt WZ/ZZ backgrounds, and fake backgrounds were determined from data)
  - VBS analyses: expect $\delta\sigma/\sigma \sim 10\%$ or better for most processes; expect polarized VBS studies and differential cross section measurements; expect to see more efforts spent on semileptonic channels
  - Triboson analyses: expect to observe individual WWW and WWZ production; improve search sensitivities for WZZ and ZZZ production
- Theoretical:
  - Further developments on higher-order corrections and event generators: larger theoretical uncertainties assigned due to differences coming from different assumptions/approximations used in the calculations and some inconsistency/bugs found in different generators; more accurate modelling of 3rd jet for VBS analyses
  - Further developments on calculations of polarized VBS processes
  - EFT framework
- Experimental:
  - Improvements on lepton and jet reconstruction and identification
  - Lower p_T cuts and looser IDs on leptons to increase the signal acceptance and reject (often dominant) prompt backgrounds (5 GeV at ATLAS)
  - Multivariate techniques
  - VBS studies: quark-like and gluon-like jet separation, dijet selection using two leading p_T jets or jets with the largest m_{jj} or $\Delta\eta_{jj}$
  - Semileptonic VBS studies: large-R jet reconstruction and identification
  - Polarized VBS studies in fully-leptonic and semileptonic channels: neutrino p_z calculation
  - …

Theoretical predictions

- Various generators available: MadGraph, Powheg, Sherpa, VBFNLO, PHANTOM, EONSAY, MoCaNLO+RECOLA
- Different approximations used and higher-order corrections implemented



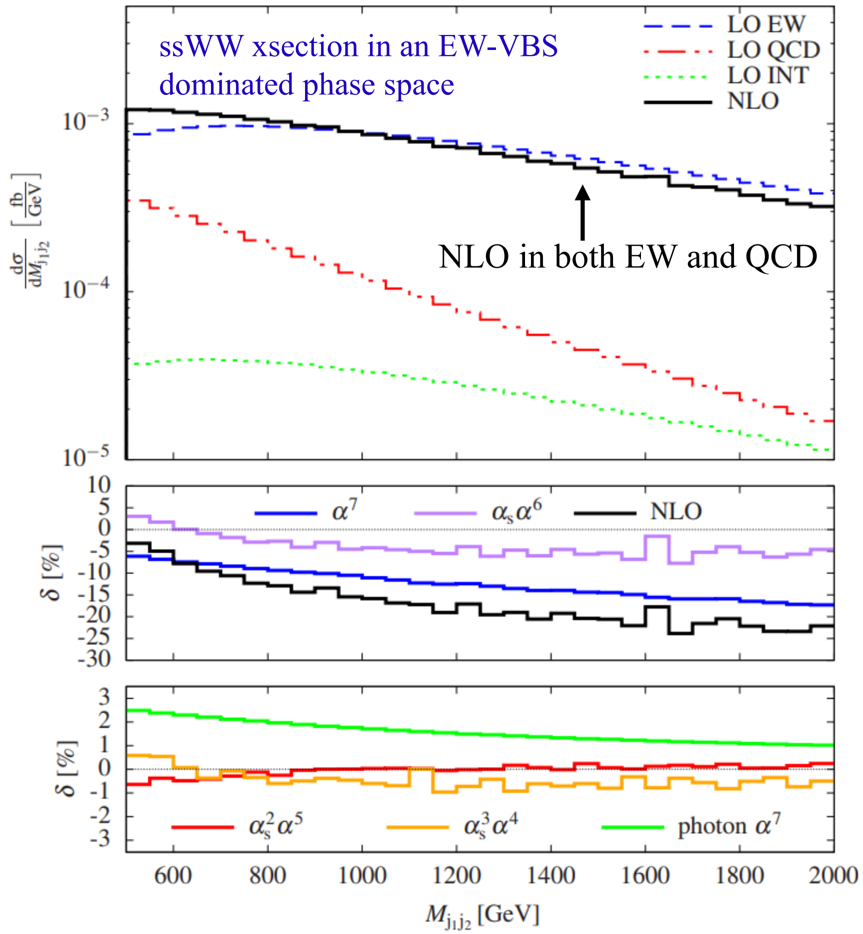
arXiv:2102.10991

- LO: arbitrary choice to include interference contribution to either the EW signal or the QCD background
- NLO: some of these corrections are of mixed types
- Important to measure fiducial cross sections of the EW and QCD production separately as well as their sum
- To reduce computational complexity, some approximations are made, small differences in typical VBS phase spaces, but could be >5% in inclusive phase spaces

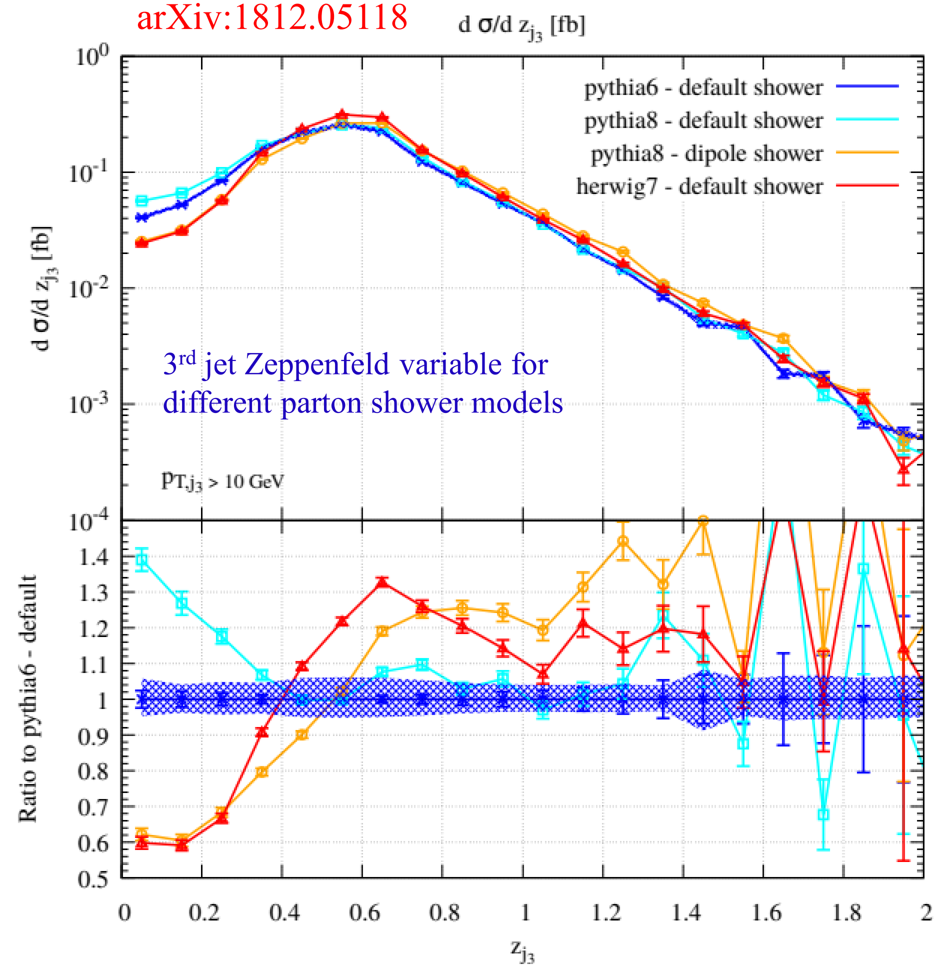
	Order	$O(\alpha^7)$	$O(\alpha_s\alpha^6)$	$O(\alpha^2_s\alpha^5)$	$O(\alpha^3_s\alpha^4)$
ss WW VBS	NLO	√	√	√	√
	NLO+PS	√	√*	x	√
WZ VBS	NLO	√	√	x	√
	NLO+PS	x	√*	x	√
ZZ VBS	NLO	√	√	x	√
	NLO+PS	x	√*	x	√
os WW VBS	NLO	x	√*	x	√
	NLO+PS	x	√*	x	√
Wγ VBS	NLO	√	x	x	√
Zγ VBS	NLO	√	x	x	√

Theoretical predictions

arXiv:1708.00268



arXiv:1812.05118

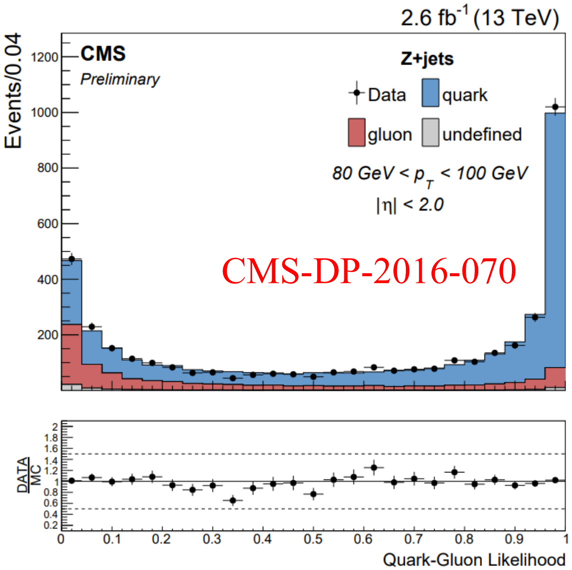


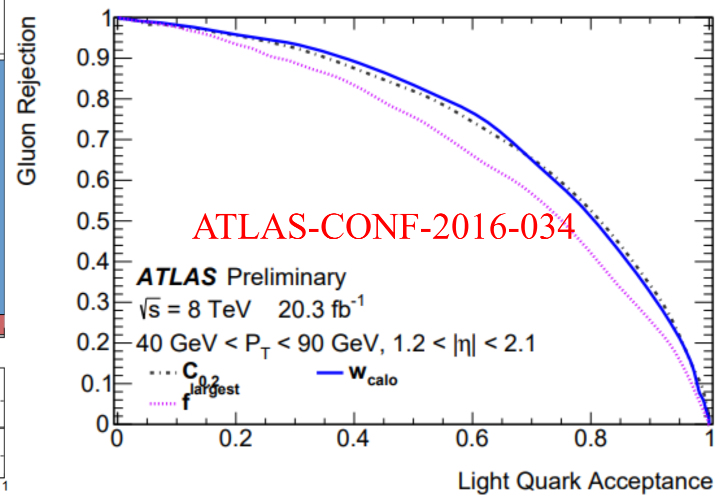
- σ_{NLO}/σ_{LO}~83% for ssWW, mainly due to large negative EW corrections (similar size for other VBS processes) in the high-energy limit
- The scale dependence is reduced by a factor of 5

- Different parton-shower models affect the 3rd jet
- 3rd jet information is often used in the event selection or included in the multivariate technique

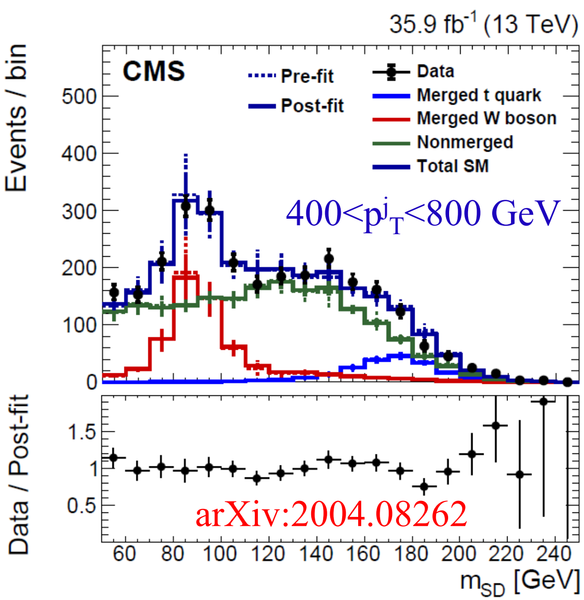
Quark-gluon jet tagging and merged jets

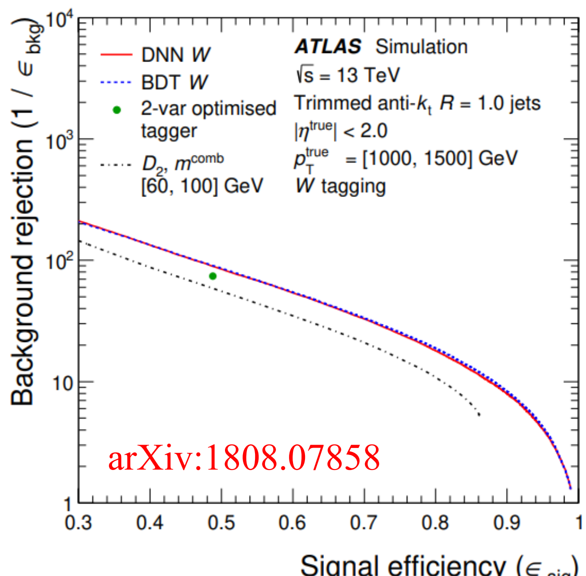
- Large experimental uncertainties come from jets





- VBF jets are quark-like jets
- Quark-gluon jet discriminant built from variables such as # of tracks, jet width, fraction of energy carried by the largest energy constituent
- Discriminant shapes obtained from MC simulation and validated using Z+jets and dijet events





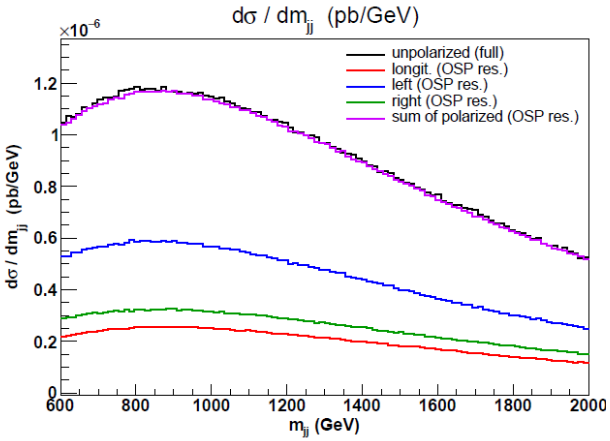
- Expect more efforts spent on semileptonic channels in Run 3
- Most sensitive channels have a merged jet from a hadronically-decayed vector boson
- Intensive development of algorithms to identify jets from highly-boosted W/Z/H/t
- Machine-learning techniques for jet tagging shows strong improvement compared to cutoff-based methods

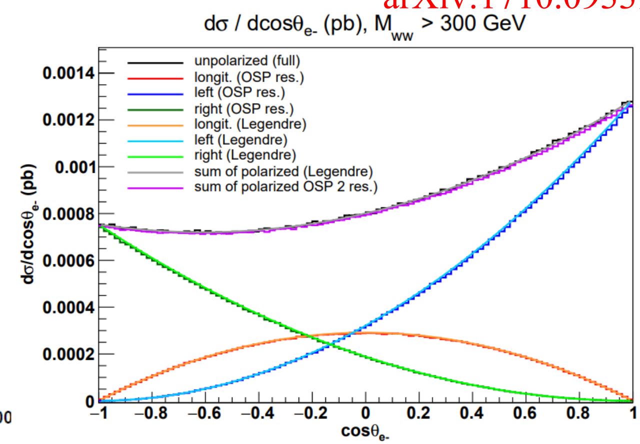
Polarized VBS

- Expect that we will include polarization measurements for all VBS processes
- Vector bosons are not external particles and their polarization states interfere with each other, the interference terms integrate to 0 over the whole range of the decay azimuthal angle
- Polarization fractions depend on the reference frame used

os WW VBS

arXiv:1710.09339

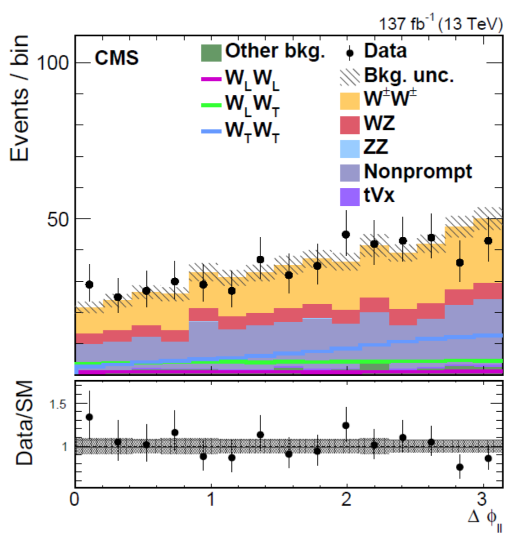


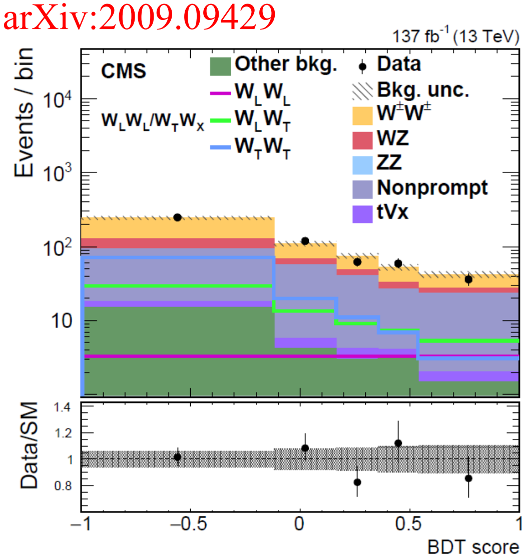


- Exploit kinematic differences with machine learning to separate different polarized scattering processes
- Fitted signal yields: W_LW_L= 16.0±18.3, W_LW_T=63.1±10.7, W_TW_T=110.1±18.1

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

arXiv:2009.09429



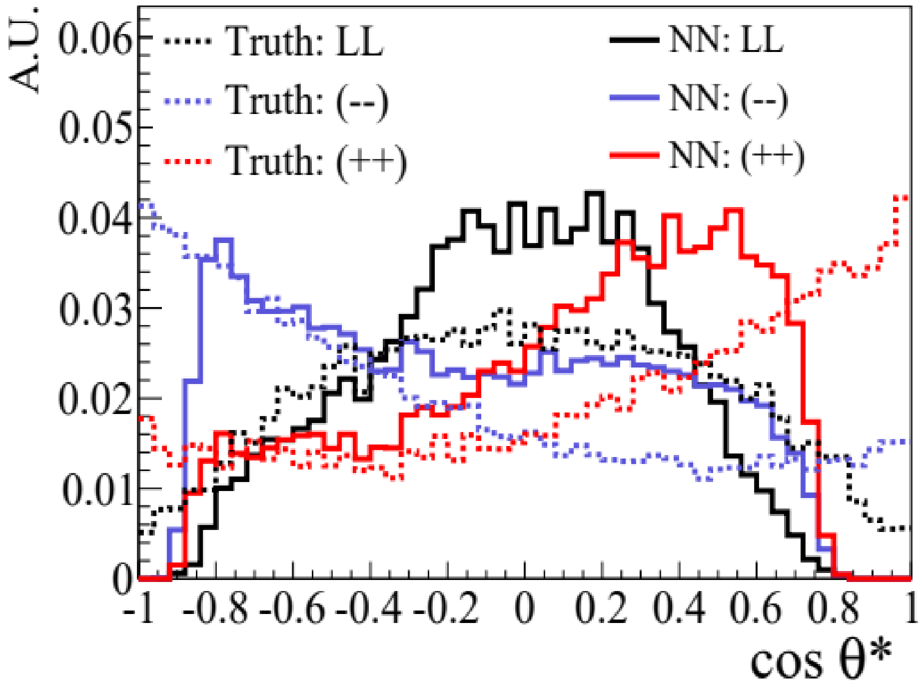


- Exclude ~2×SM production at 95% CL for W_LW_L production
- Observed (expected) significance of 2.3 (3.1)σ for W_LW_X production

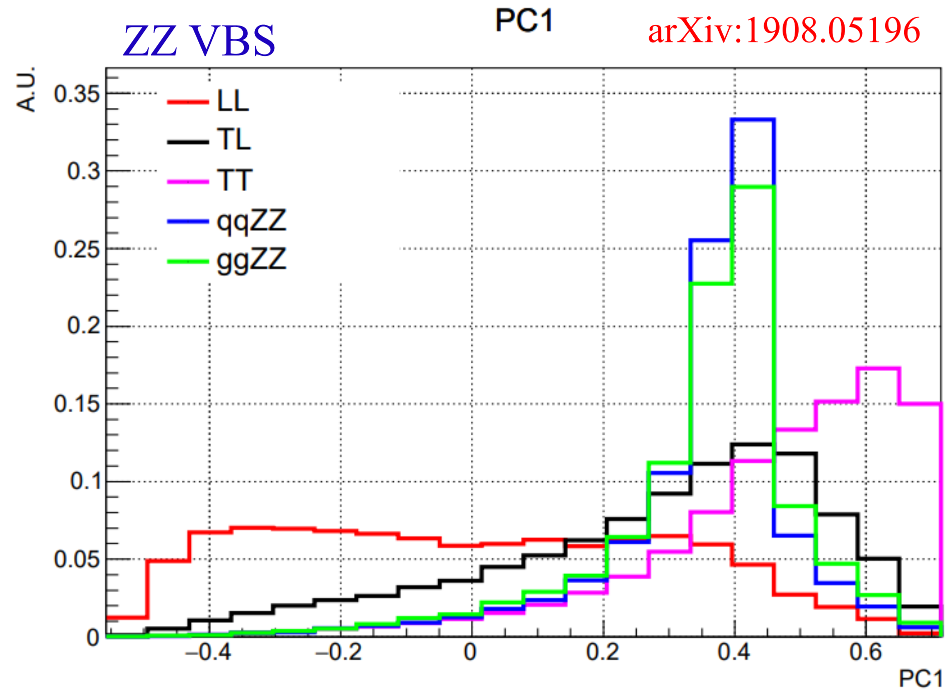
Machine learning for polarized measurements

- Need to develop more powerful discriminators to separate LL polarization from others

ss WW fully-leptonic arXiv:1510.01691



ZZ VBS arXiv:1908.05196

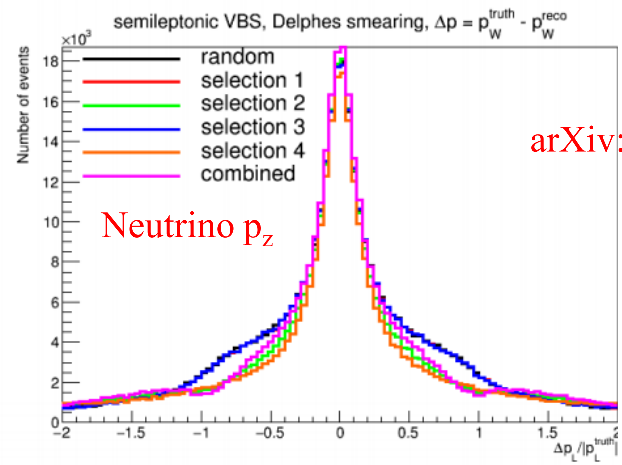


- Not easy to reconstruct the W rest frames due to two neutrinos in the final state
- Use a deep NN with regression to map measurable quantities to the truth cosθ* values for ss WW VBS events (charged lepton direction in the W rest frame wrt the W boson direction, need to fully reconstruct neutrinos)
- Double the sensitivity with variables studied before

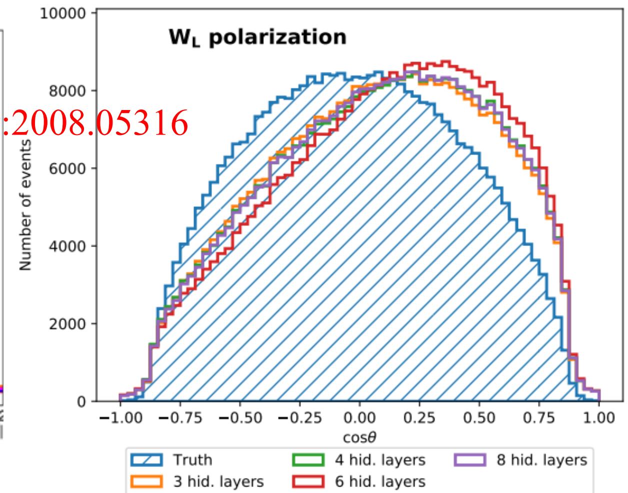
- Deep NN used, standardization and Yeo-Johnson power transformation used to each input variable, principle component analysis (PCA) applied to the 5-dimensional outputs of the DNN, and then 2-3 dimensional fits are performed
- 40% improvement compared to a previous study using BDTs

Neutrino p_z calculations

- Important to be able to reconstruct all kinematical variables for VBS studies
- Difficult to reconstruct neutrino p_z in semi-leptonic and fully-leptonic channels

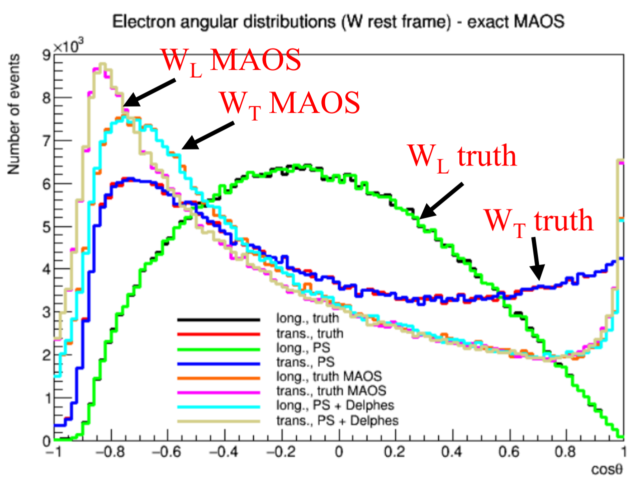


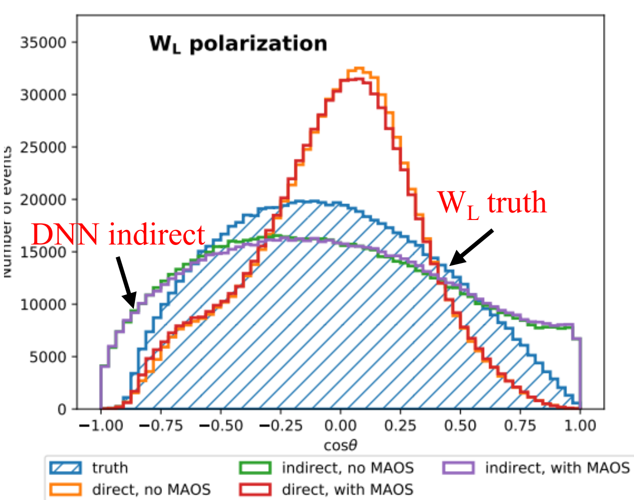
arXiv:2008.05316



ssWW VBS semi-leptonic:

- Use the W mass constraint to find neutrino p_z, sometimes two solutions found, often pick up a smaller value, which may not be correct
- Use a DNN with binary classification technique to find the correct solution





ssWW VBS fully-leptonic:

- Use the M_T2-Assisted On-Shell (MAOS) algorithm to reconstruct p_z of the two neutrinos
- Use a DNN with regression technique
- Direct: reconstruct cosθ using DNN
- Indirect: first use the regression method to derive two neutrino momenta, and then calculate cosθ

Conclusions

- VBS studies:
  - Important for validate the Higgs mechanism and study the dynamics of EWSB
  - Almost all VBS processes have been observed by ATLAS and CMS
  - 10-30% uncertainty on fiducial cross section measurements, dominated by statistical uncertainty
  - Aim to reduce the uncertainty to ~10% or lower for most processes in Run 3
  - Focus more on differential and polarized VBS studies
  - More efforts will be spent on semi-leptonic channels
- Triboson studies:
  - Among least-studied SM processes and important to search for aQGCs/aTGCs
  - Evidences for WWW, WWZ, W$\gamma\gamma$, Z$\gamma\gamma$ processes obtained
  - Aim to observe all triboson processes except WZZ and ZZZ in Run 3
- Very active experimental and theoretical research areas
- Annual VBScan and MBI workshops to discuss these topics