Vector boson scattering in CMS

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on behalf of the CMS collaboration

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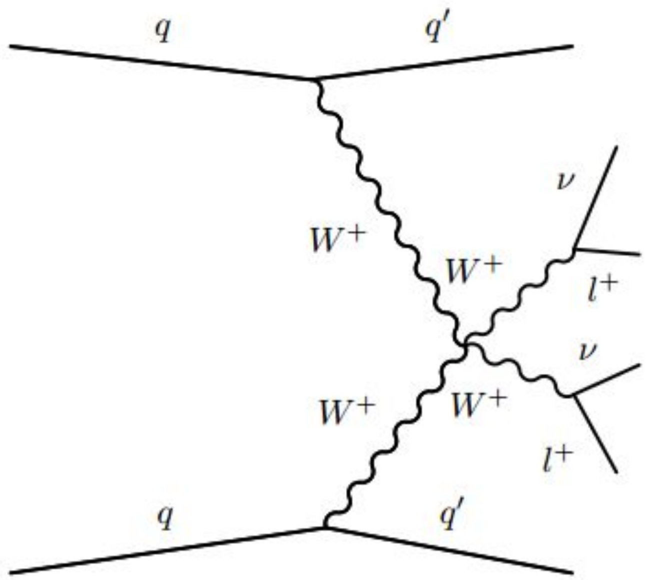
What is VBS and why study it

VBS: scattering between two vector bosons radiated from incoming partons.
Unique topologies:

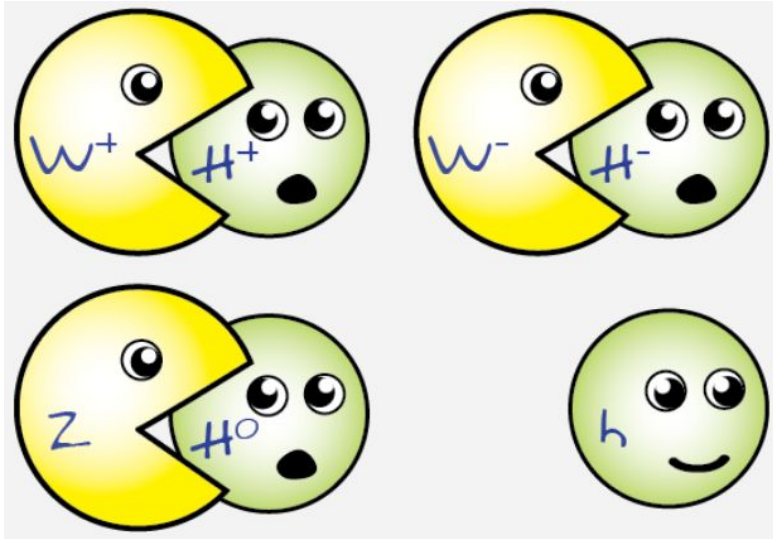
- Two very forward jets, with large eta separation and invariant mass
- Low hadronic activity in central region



Possible couplings: WWWW/WWZZ/WWZγ/WW$\gamma\gamma$ ...

Why VBS interesting?

- Very rare process (~ fbs), precision test of SM
- The longitudinal polarized part of massive vector boson is connected to the Higgs mechanism, help us have a better understanding on Higgs mechanism
- The SM could be extended with dimension-8 operators standing for anomalous couplings between vector bosons, model independent search of BSM



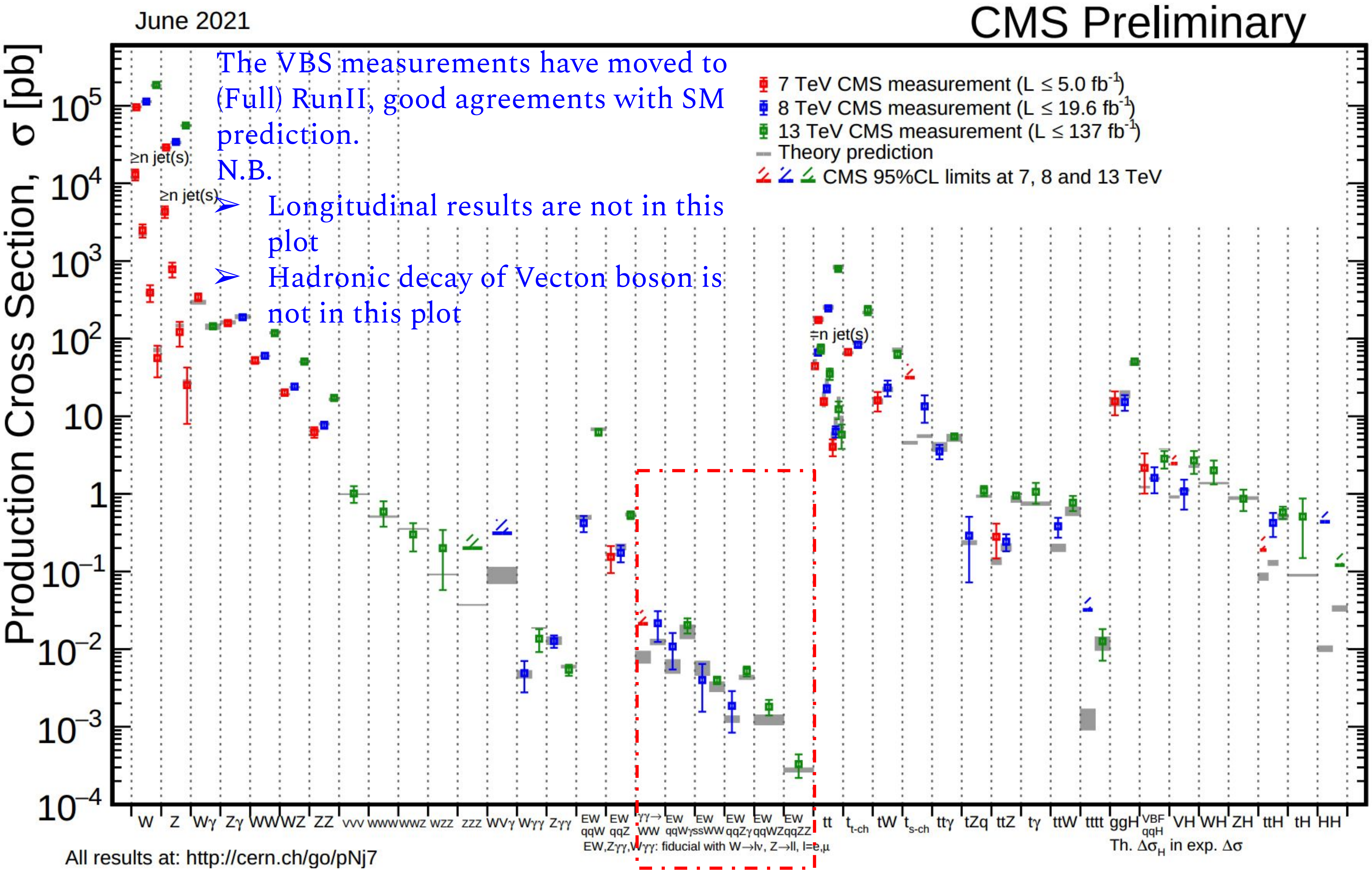
$$\mathcal{L}_{\mathrm{eff}} = \mathcal{L}_{\mathrm{SM}} + \sum_{n=5}^{\infty} \frac{f_n}{\Lambda^{n-4}} \mathcal{O}_n$$

Current results

The VBS measurements have moved to (Full) RunII, good agreements with SM prediction.

N.B.

- ➢ Longitudinal results are not in this plot
- ➢ Hadronic decay of Vecton boson is not in this plot



Topics in this talk

Recent VBS results:

- ➢ Longitudinally polarized scattering of same-sign WW: PLB 812(2021) 136018
- ➢ Semileptonic channel VBS WV: PAS **New**
- ➢ VBS WW+WZ: PLB 809(2020) 135710
- ➢ VBS Zgamma: PAS, submitted to PRD
- ➢ VBS Wgamma: PLB 811(2020) 135988

Poster
By Davide Valsecchi

First measurement of the polarized vector boson scattering.

Signal Region (SR)

Variable	Requirement
Leptons	Exactly 2 same-sign leptons, $p_T > 25/20$ GeV
p_T^j	>50 GeV
$\lvert m_{\ell\ell} - m_Z \rvert$	>15 GeV (ee)
$m_{\ell\ell}$	>20 GeV
p_T^{miss}	>30 GeV
b quark veto	Required
$\mathrm{Max}(z_\ell^*)$	<0.75
m_{jj}	>500 GeV
$\lvert\Delta\eta_{jj}\rvert$	>2.5

Two BDTs are used:

- BDT1 is used to separate inclusive ssWW from other bkg
- BDT2 is used to separate different polarized components of VBS

Several **Control Regions** (**CR**) are defined:

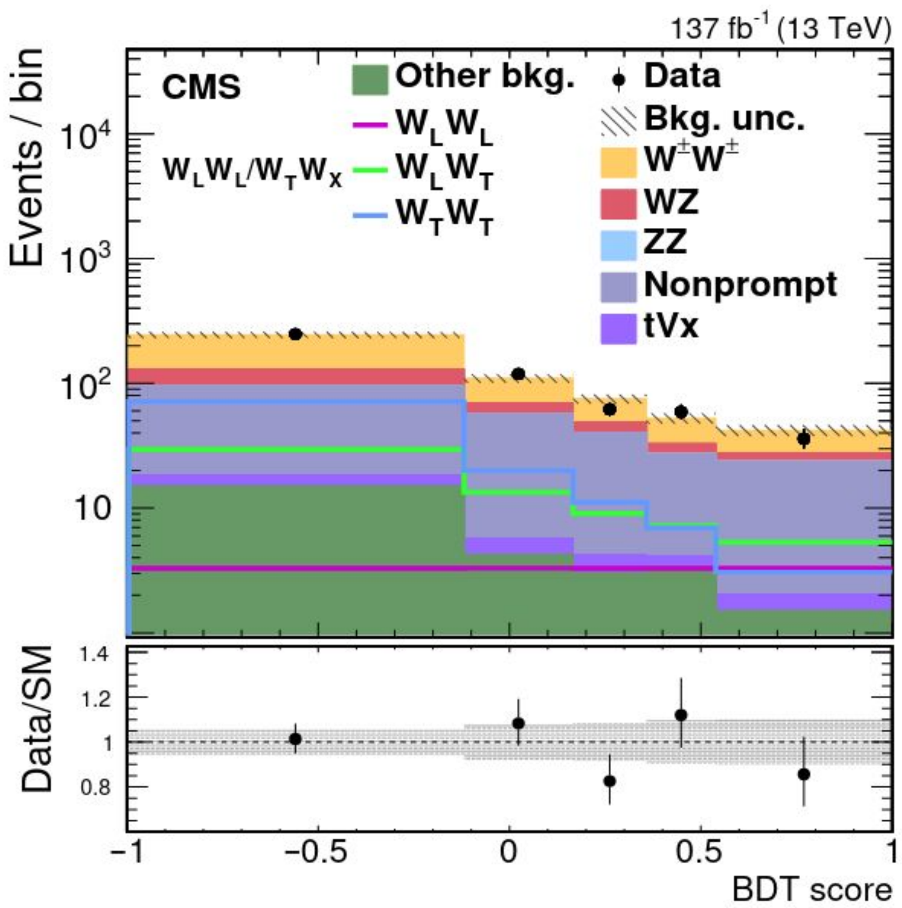
- Nonprompt CR: same with SR except b-veto inverted
- WZ CR: three leptons, two of them form a Z boson
- tZq CR: same as WZ CR except b-veto inverted
- ZZ CR: 4 leptons with VBS-like selection

Simultaneous fit is performed between SRs and CRs.

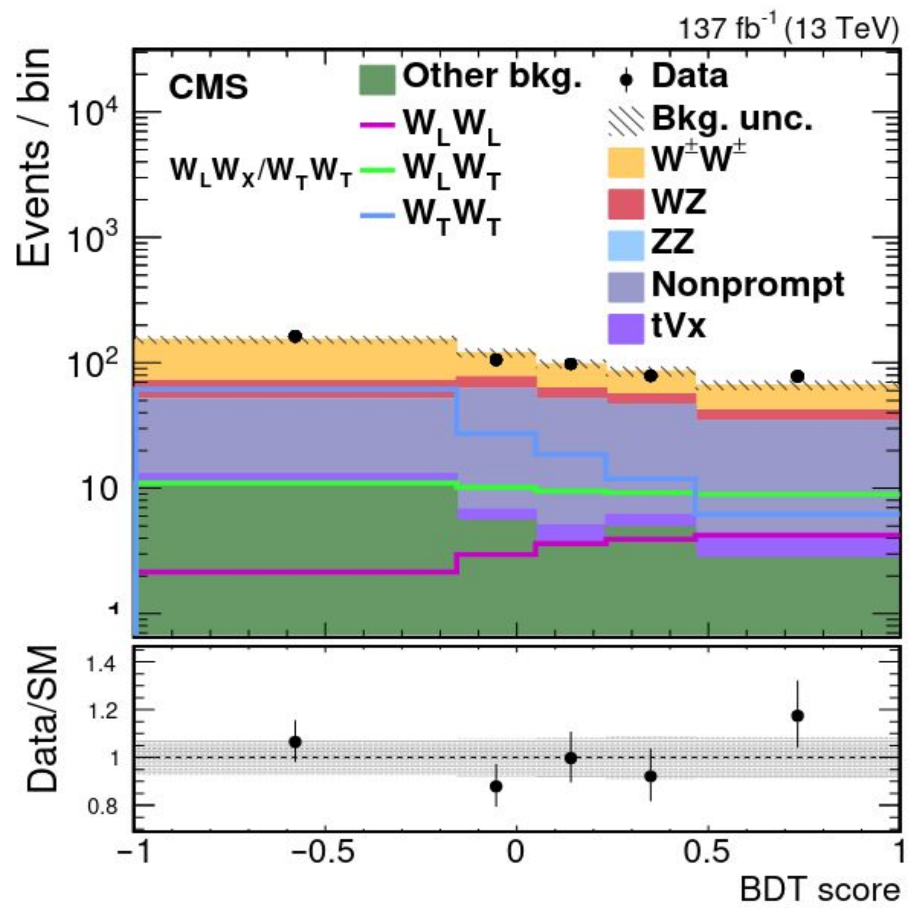
Longitudinally polarized scattering of same-sign WW

Simultaneous fit are performed between SR and CRs:

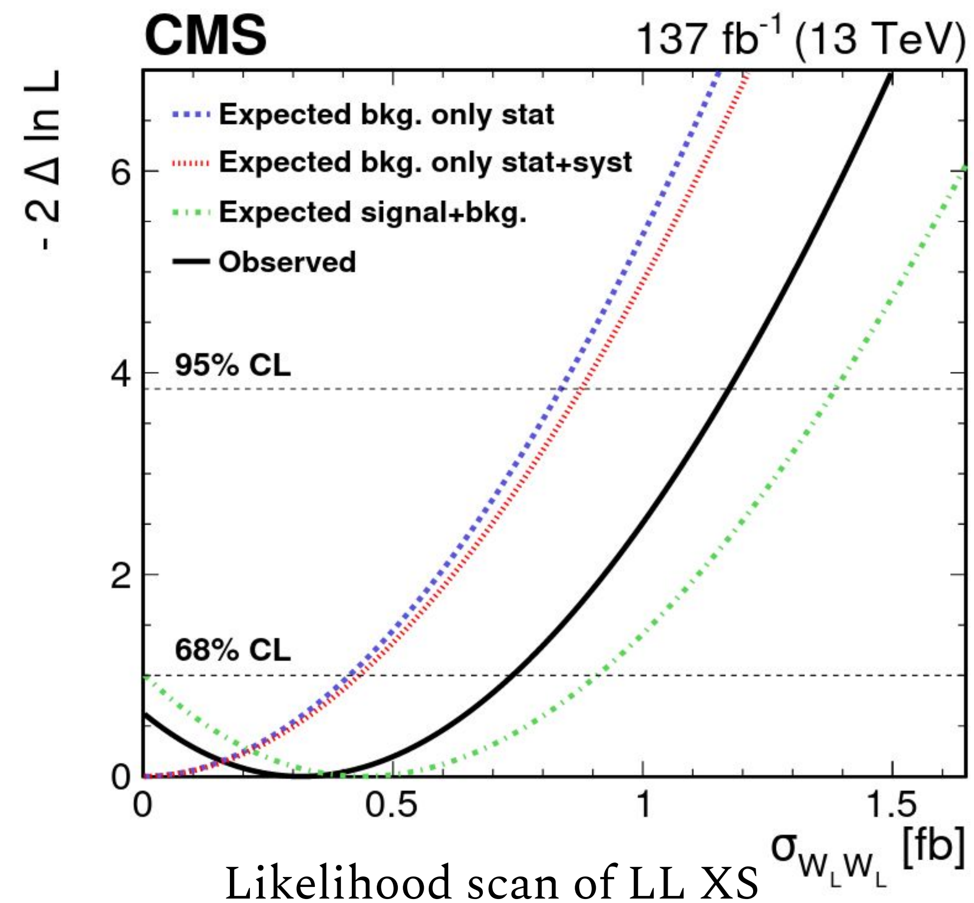
L: Longitudinally T: transversely
LX: LL + LT
XT: LT + TT



BDT2 score, separating LL and TX (also other bkgs)



BDT2 score, separating LX and TT (also other bkgs)



Likelihood scan of LL XS

results:

signal significance is extracted w.r.t LX signal:

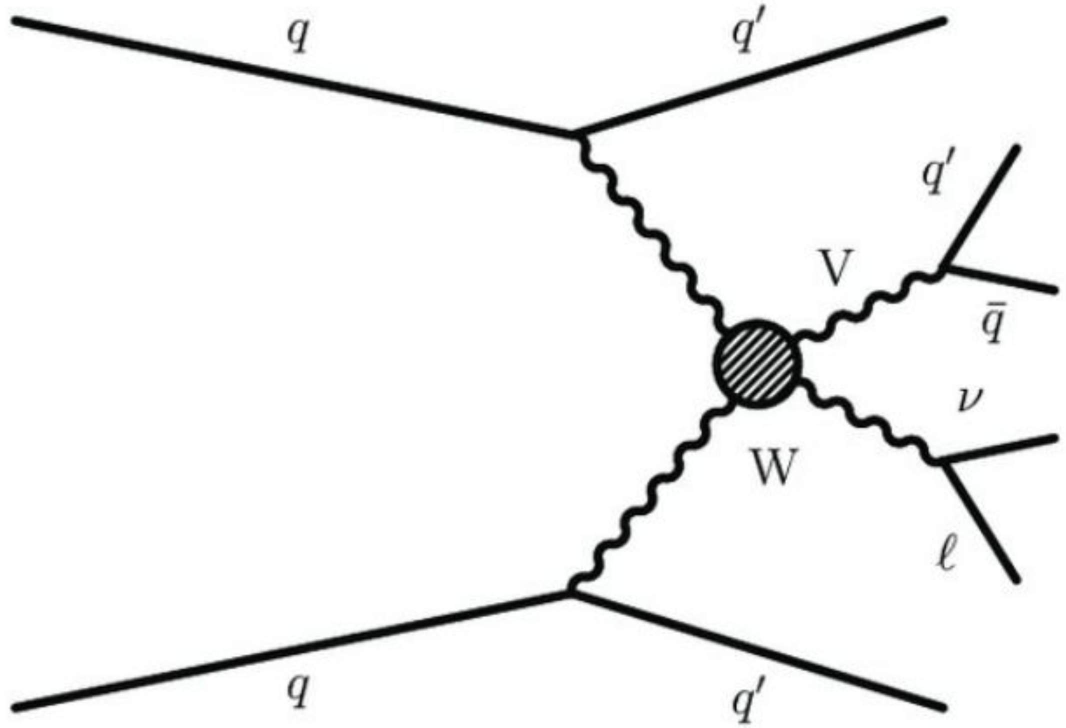
- ➢ LX In WW restframe: observed (expected) 2.3 (3.1) σ
- ➢ LX In pp restframe: observed (expected) 2.6 (2.9)σ

XS measurement:

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

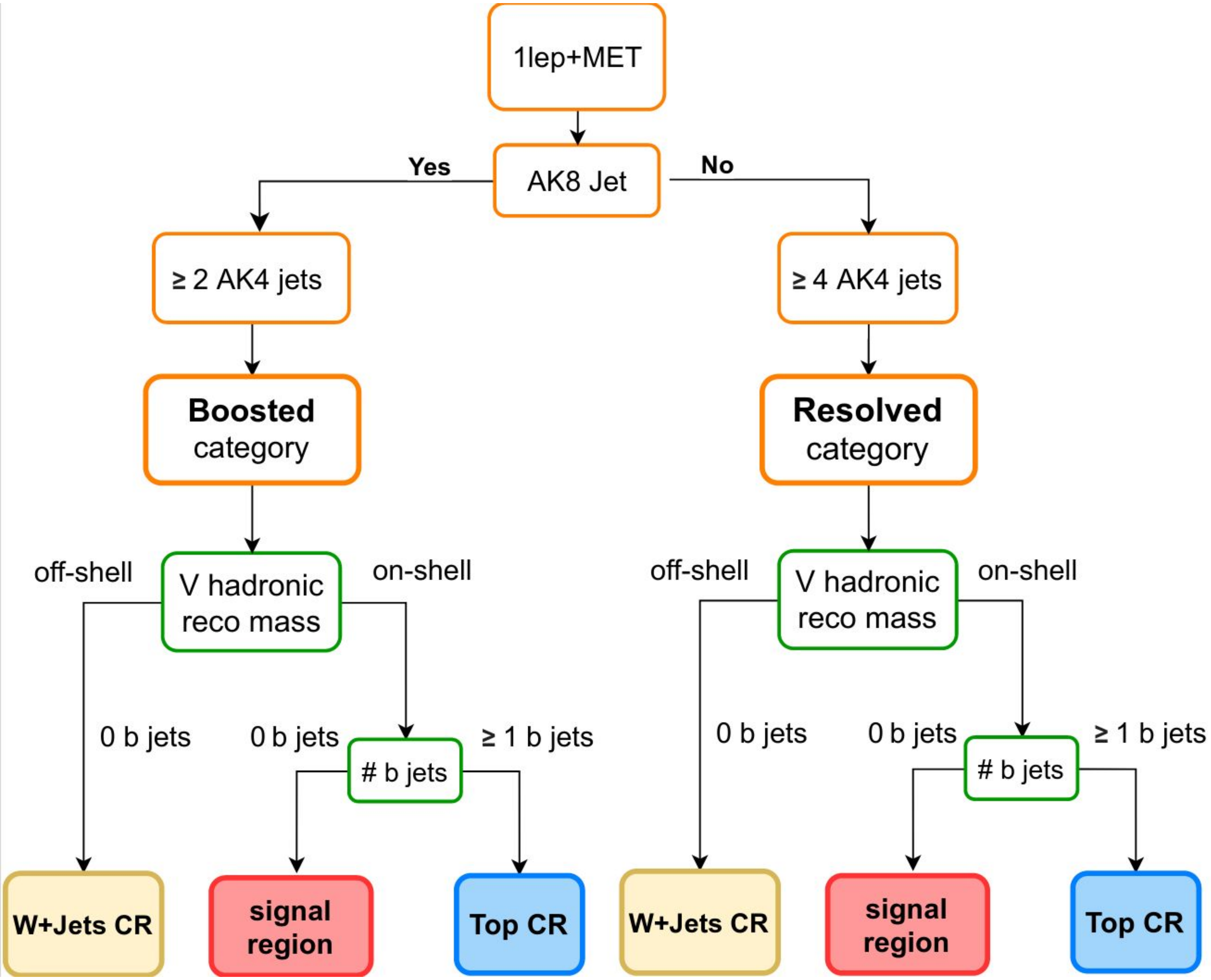
VBS WV

Signal: W is leptonic decay, and V (W, Z) is hadronic decay



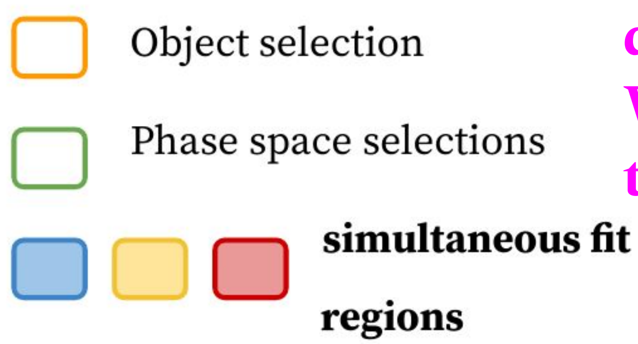
Good balance between:

- ➢ Larger XS than fully leptonic decay channel
- ➢ Smaller bkg than fully hadronic decay channel



Following objects/variables are used to separate signal and bkg, and also event topology:

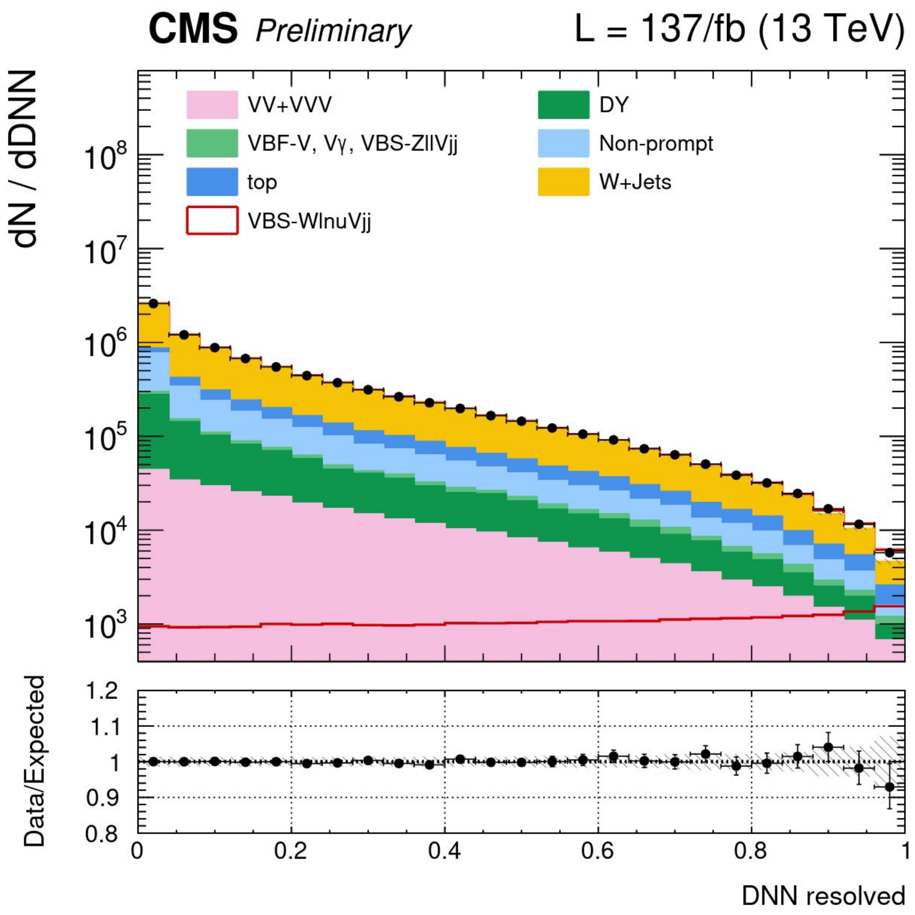
- ➢ AK8 jet: Boosted or Resolved
- ➢ V hadronic mass: signal or Wjets bkg
- ➢ B jets: signal or Top bkg

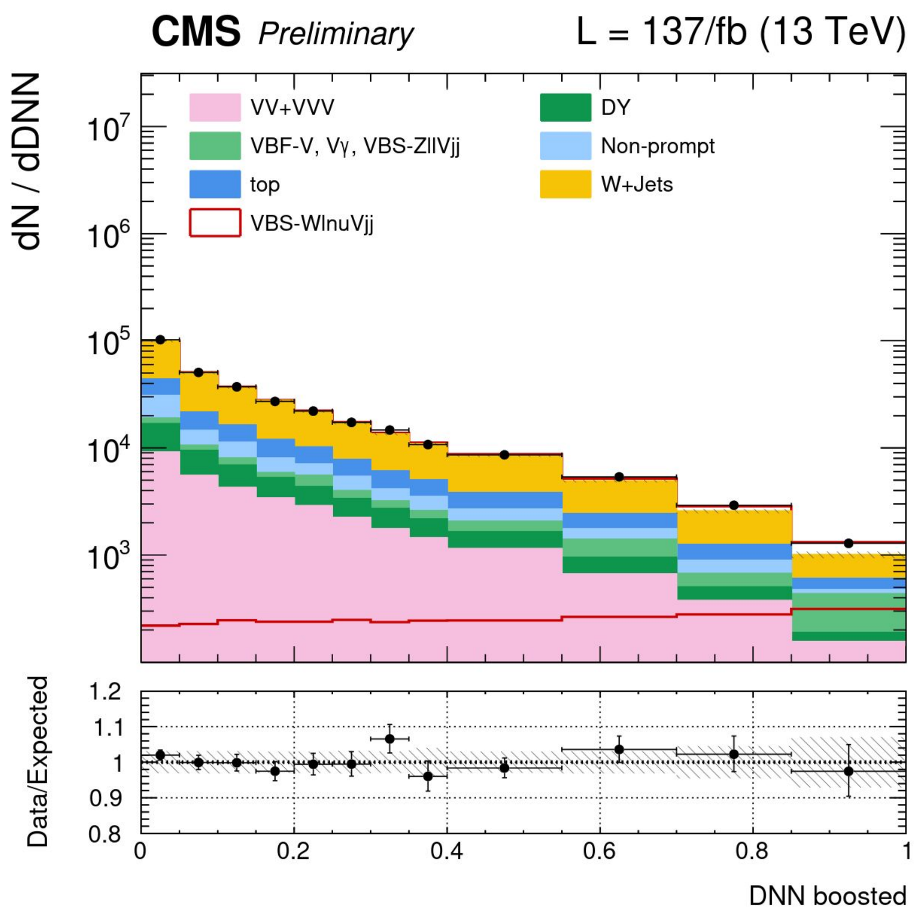


Wjet contribution is estimated using data-driven method in Wjets CR and propagated to SR.

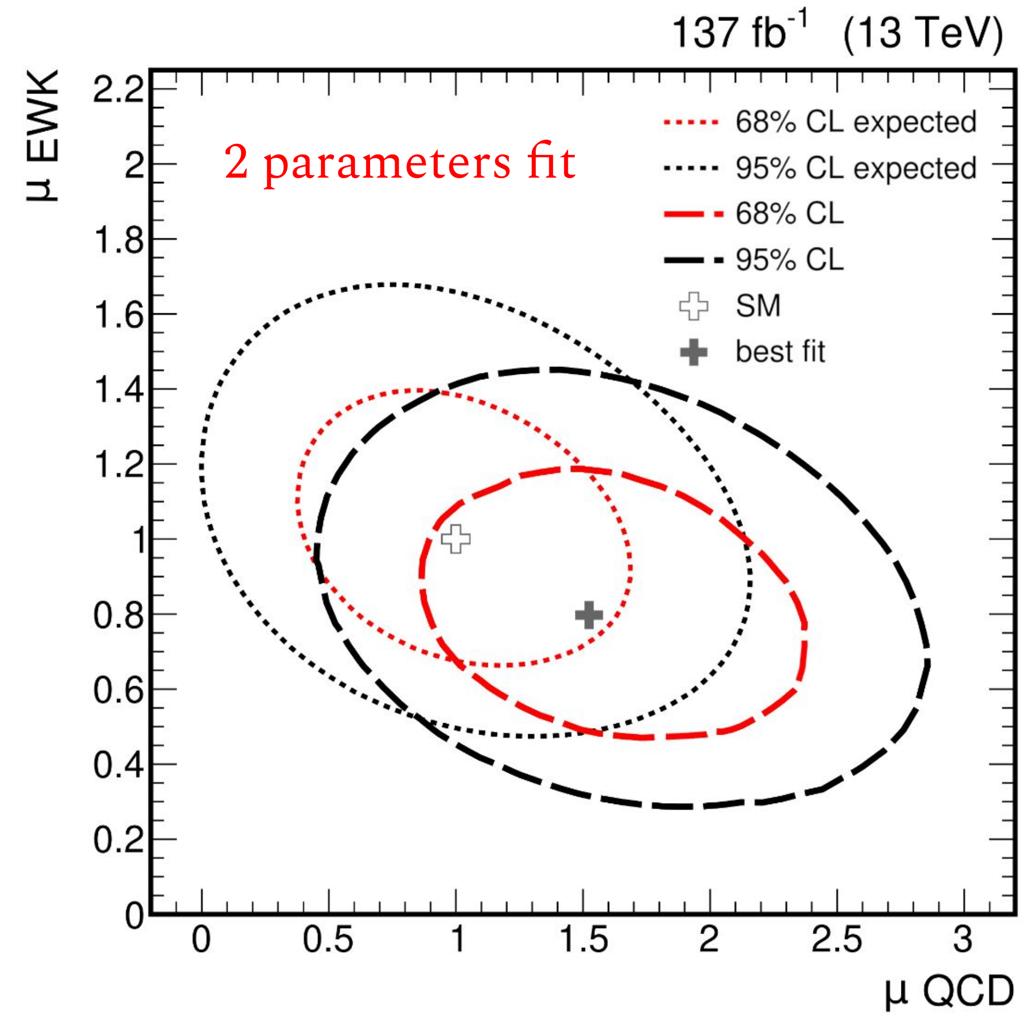
VBS WV

DNN is used to separate signal and all bkgs. Different DNNs are used for resolved and boosted case. DNN is trained in signal region.





Good agreements between data and MC prediction in both Boosted and Resolved signal regions. (EW as signal only)



Results:

- EW signal significance: 4.4 (5.1)**σ** observed (expected)

$$\mu_{EW} = \sigma^{obs}/\sigma^{SM} = 0.85^{+0.24}_{-0.20} = ^{+0.21}_{-0.17}\ (\text{syst.})\ ^{+0.12}_{-0.12}(\text{stat.})$$

$$\mu_{EW+QCD} = \sigma^{obs}/\sigma^{SM} = 0.98^{+0.20}_{-0.17} = ^{+0.19}_{-0.16}\ (\text{syst.})\ ^{+0.07}_{-0.07}(\text{stat.})$$

Combine ssWW and VBS WZ (both leptonically decay), using full Run2 data.

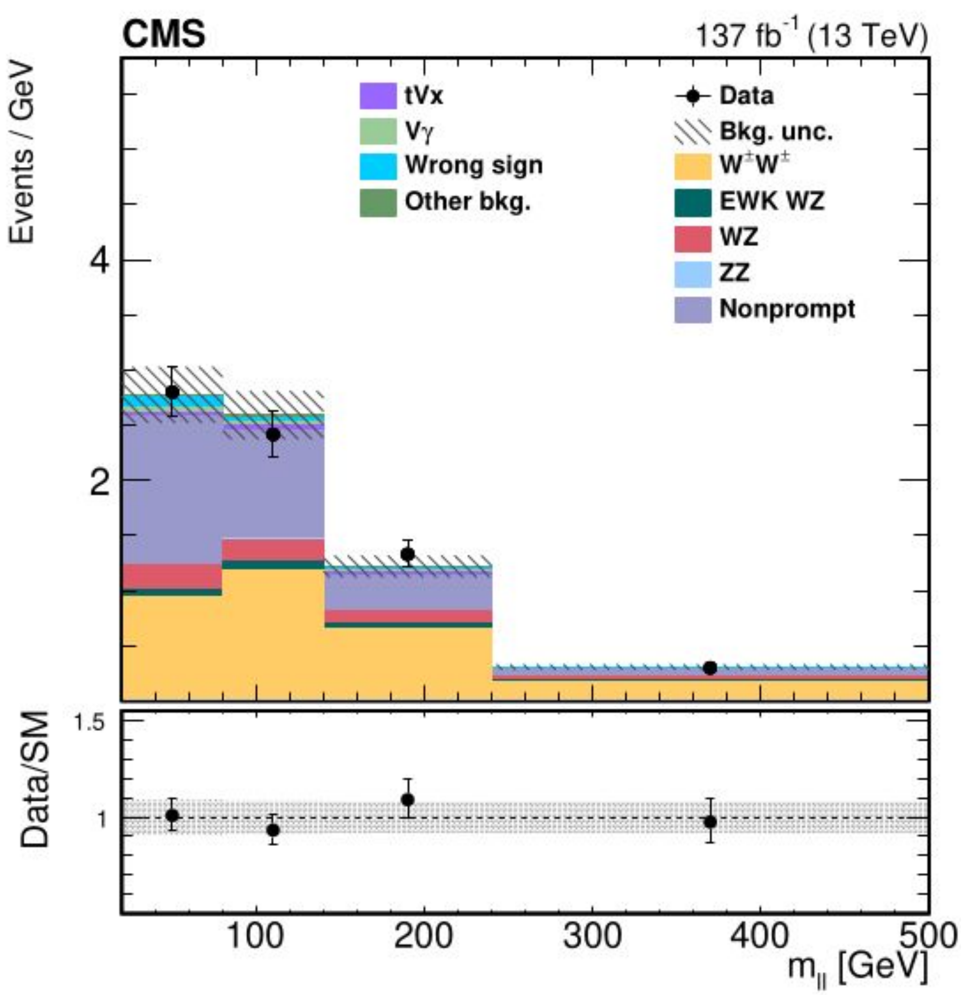
ssWW: very clean channel, EW dominant over QCD-induced in signal region

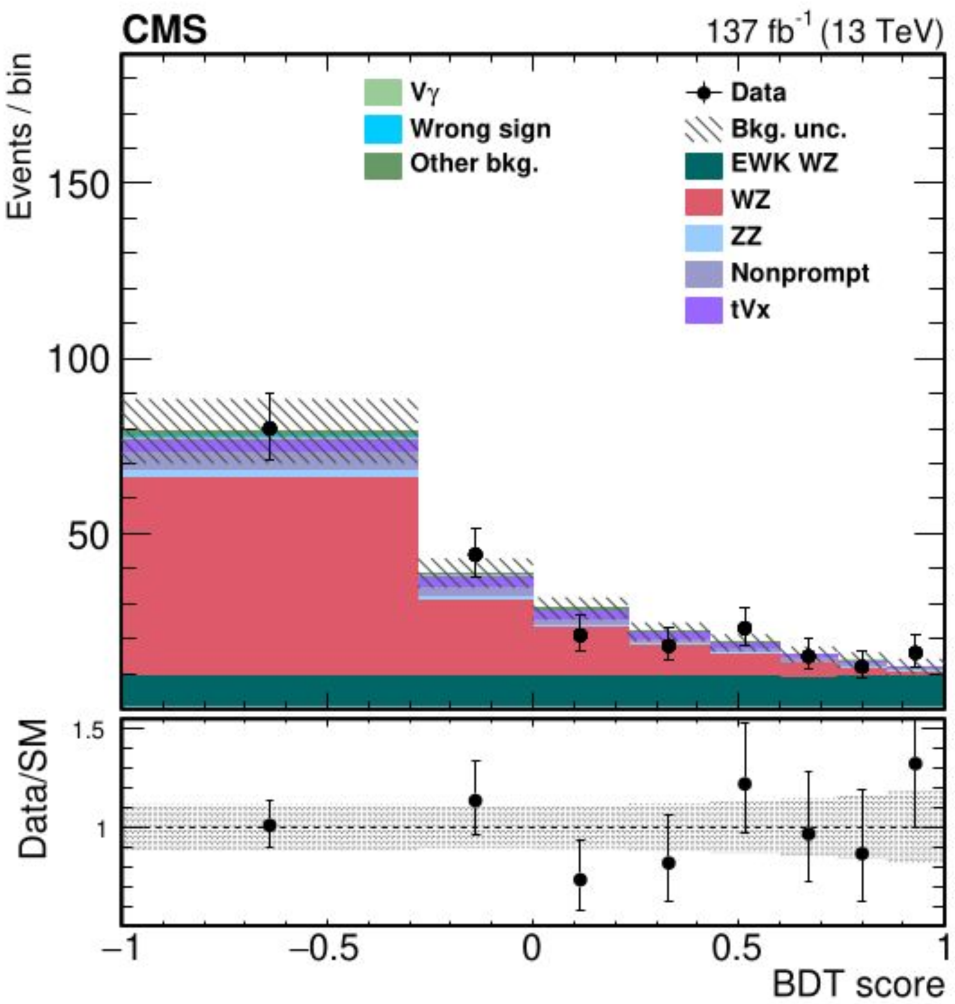
- ➢ Differential cross section are measured, w.r.t, m_jj, m_ll, pt of leading lepton
- ➢ Constraints are obtained on the aQGC

VBS WZ:

- ➢ EW signal extraction
- ➢ Differential cross section are measured, w.r.t, m_jj
- ➢ Constraints are obtained on the aQGC

SRs and CRs are similar to ssWW in slide5





BDT method is used to separate EW WZ and QCD WZ.

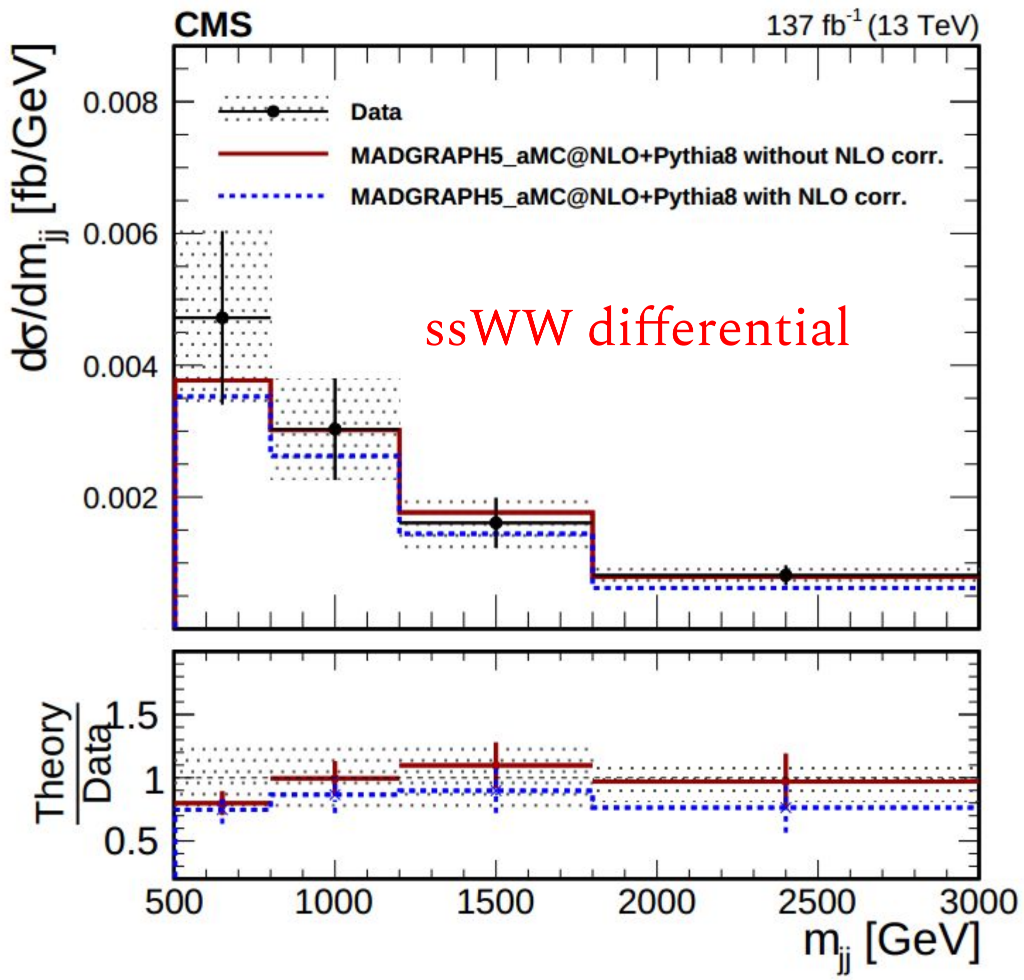
Left: m_ll in ssWW SR
Right: BDT score in VBS WZ SR

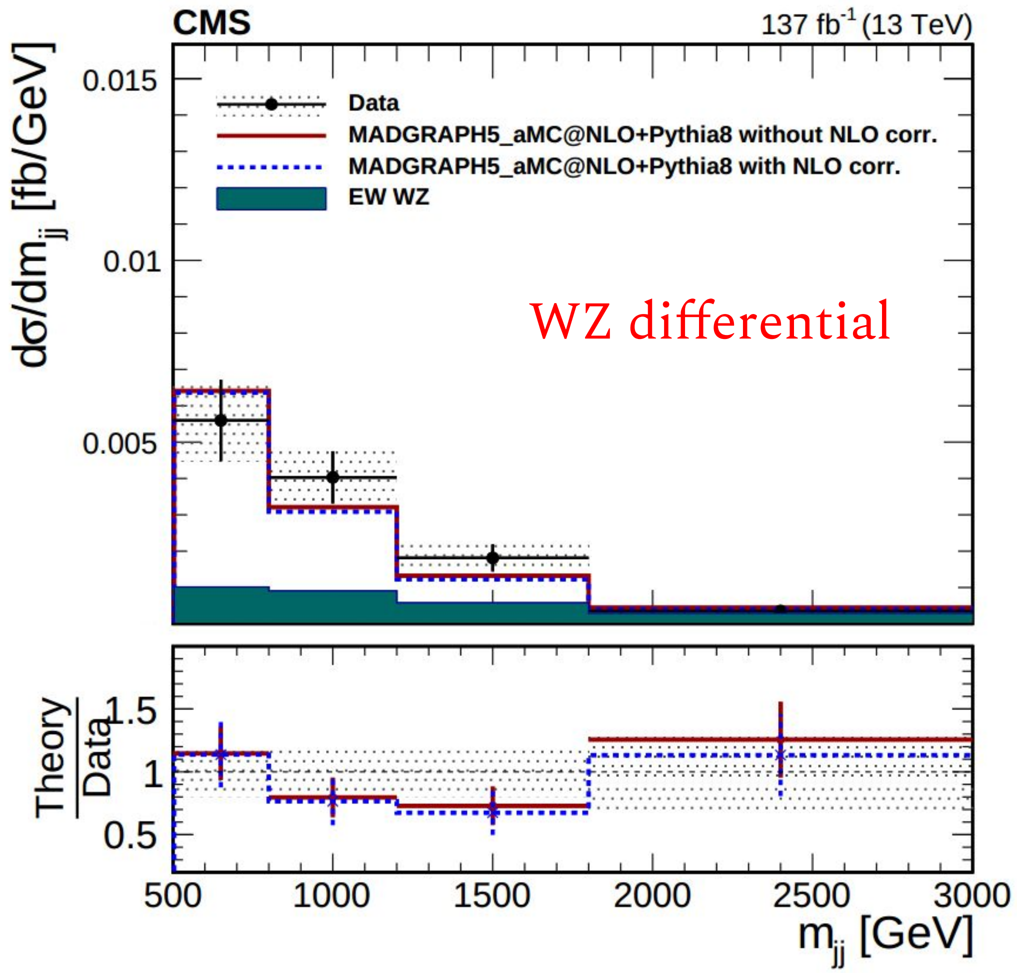
VBS ssWW+WZ

Significance Results:

- ssWW: 11.5 (11.3)σ for observed (expected)
- VBS WZ: 6.8 (5.3)σ for observed (expected)

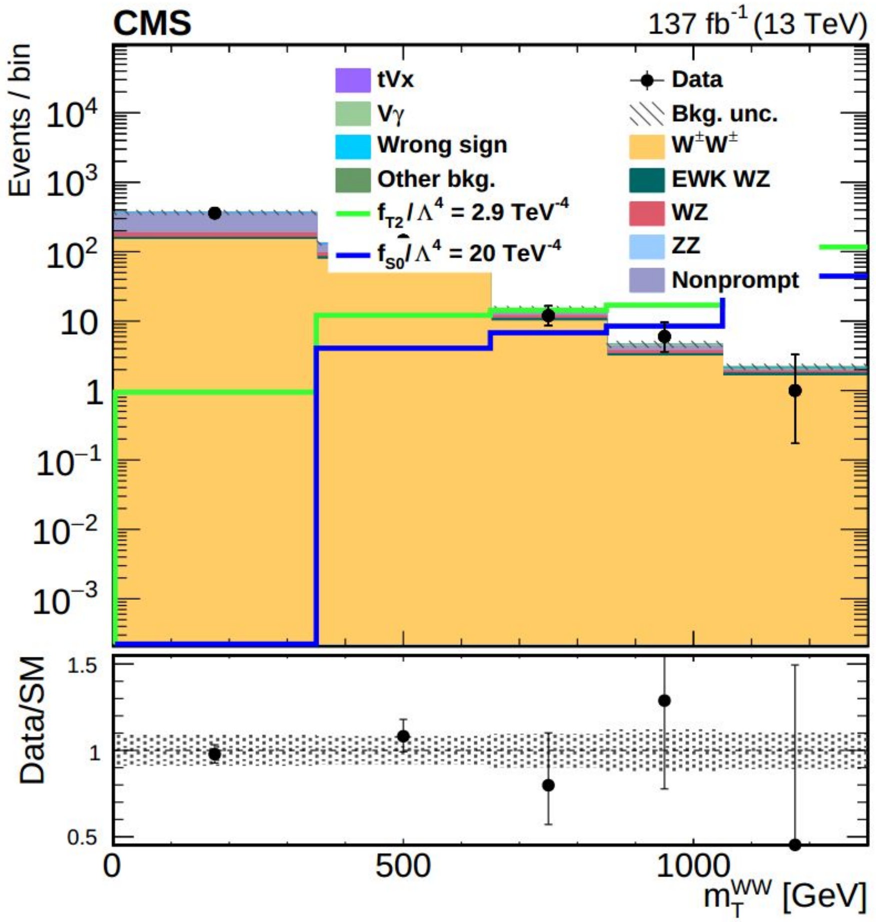
Process	$\sigma\mathcal{B}$ (fb)	Theoretical prediction without NLO corrections (fb)	Theoretical prediction with NLO corrections (fb)
EW $W^{\pm}W^{\pm}$	3.98 ± 0.45 $0.37\,(\text{stat}) \pm 0.25\,(\text{syst})$	3.93 ± 0.57	3.31 ± 0.47
EW+QCD $W^{\pm}W^{\pm}$	4.42 ± 0.47 $0.39\,(\text{stat}) \pm 0.25\,(\text{syst})$	4.34 ± 0.69	3.72 ± 0.59
EW WZ	1.81 ± 0.41 $0.39\,(\text{stat}) \pm 0.14\,(\text{syst})$	1.41 ± 0.21	1.24 ± 0.18
EW+QCD WZ	4.97 ± 0.46 $0.40\,(\text{stat}) \pm 0.23\,(\text{syst})$	4.54 ± 0.90	4.36 ± 0.88
QCD WZ	3.15 ± 0.49 $0.45\,(\text{stat}) \pm 0.18\,(\text{syst})$	3.12 ± 0.70	3.12 ± 0.70

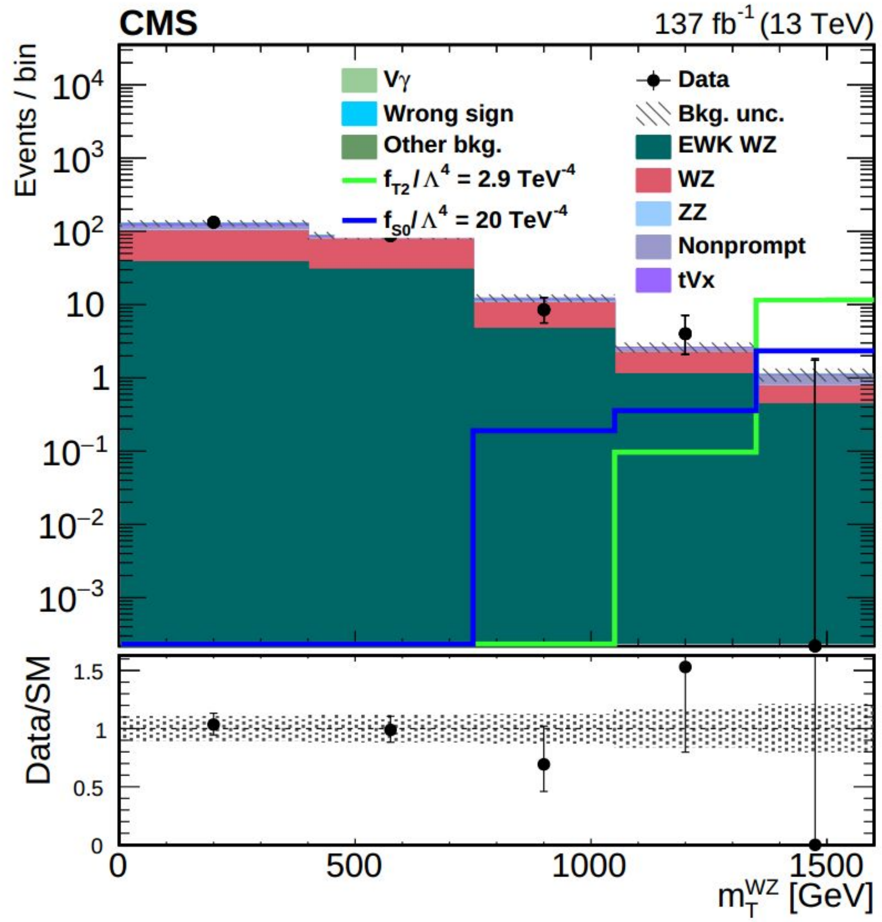




Generally good agreements between data and prediction.

VBS ssWW+WZ





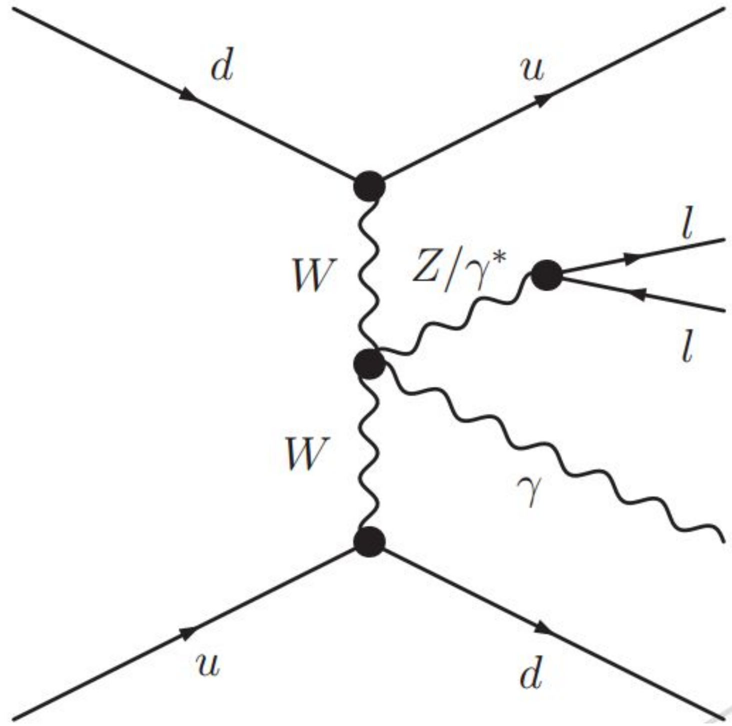
Diboson transverse mass is used for aQGC study, no deviation from SM is observed in either ssWW or WZ.

Combining two channels

	Observed ($W^\pm W^\pm$) (TeV^{-4})	Expected ($W^\pm W^\pm$) (TeV^{-4})	Observed (WZ) (TeV^{-4})	Expected (WZ) (TeV^{-4})	Observed (TeV^{-4})	Expected (TeV^{-4})
f_{T0}/Λ^4	[-0.28, 0.31]	[-0.36, 0.39]	[-0.62, 0.65]	[-0.82, 0.85]	[-0.25, 0.28]	[-0.35, 0.37]
f_{T1}/Λ^4	[-0.12, 0.15]	[-0.16, 0.19]	[-0.37, 0.41]	[-0.49, 0.55]	[-0.12, 0.14]	[-0.16, 0.19]
f_{T2}/Λ^4	[-0.38, 0.50]	[-0.50, 0.63]	[-1.0 , 1.3]	[-1.4, 1.7]	[-0.35, 0.48]	[-0.49, 0.63]
f_{M0}/Λ^4	[-3.0, 3.2]	[-3.7, 3.8]	[-5.8, 5.8]	[-7.6, 7.6]	[-2.7, 2.9]	[-3.6, 3.7]
f_{M1}/Λ^4	[-4.7, 4.7]	[-5.4, 5.8]	[-8.2, 8.3]	[-11, 11]	[-4.1, 4.2]	[-5.2, 5.5]
f_{M6}/Λ^4	[-6.0, 6.5]	[-7.5, 7.6]	[-12, 12]	[-15, 15]	[-5.4, 5.8]	[-7.2, 7.3]
f_{M7}/Λ^4	[-6.7, 7.0]	[-8.3, 8.1]	[-10, 10]	[-14, 14]	[-5.7, 6.0]	[-7.8, 7.6]
f_{S0}/Λ^4	[-6.0, 6.4]	[-6.0, 6.2]	[-19, 19]	[-24, 24]	[-5.7, 6.1]	[-5.9, 6.2]
f_{S1}/Λ^4	[-18, 19]	[-18, 19]	[-30, 30]	[-38, 39]	[-16, 17]	[-18, 18]

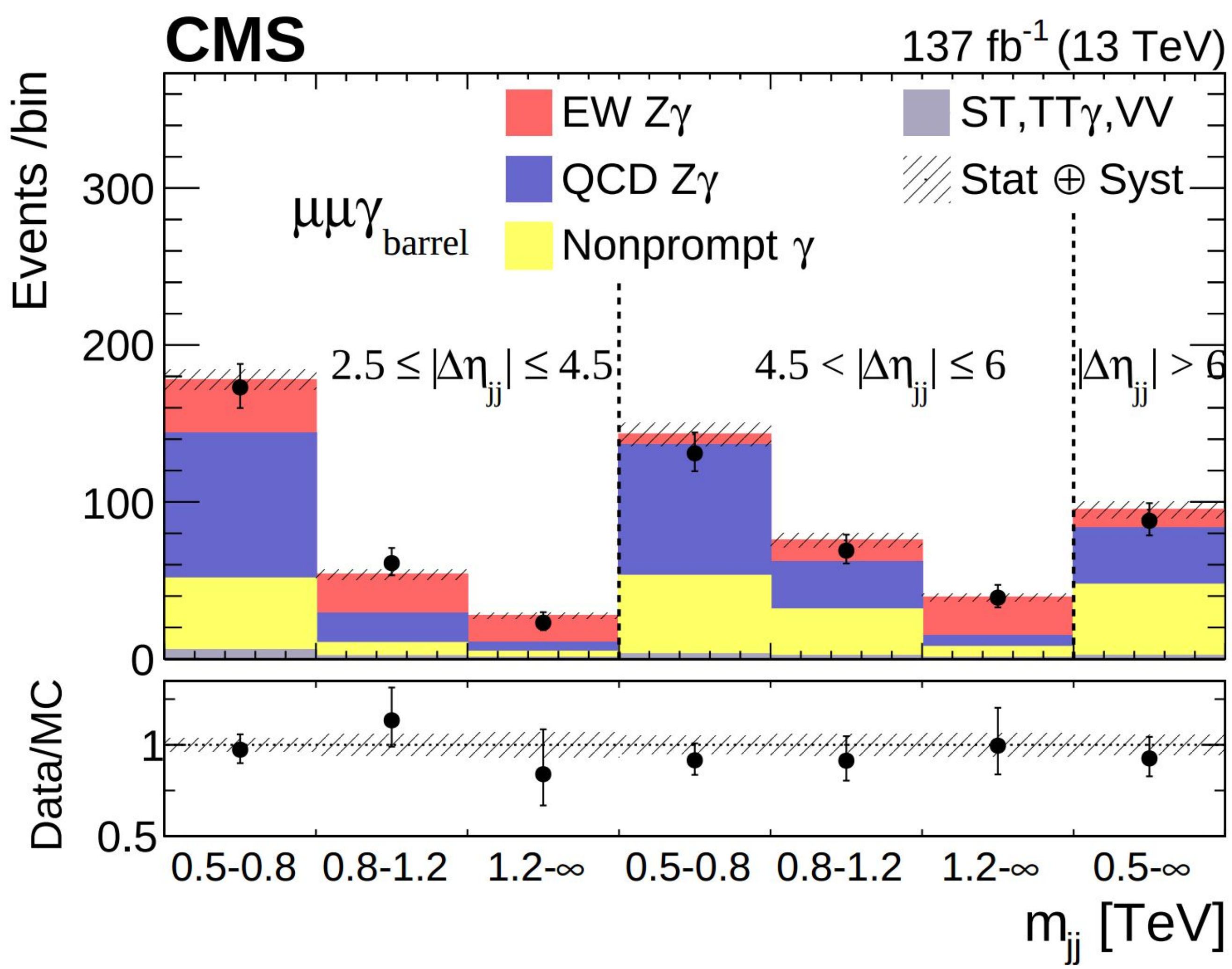
VBS Zγ

Because photon don't directly couple to Higgs boson, the interests of VBS Zγ is its sensitivity to pure neutral aQGC, i.e., ZZZγ/ZZ$\gamma\gamma$/Z$\gamma\gamma\gamma$



Using full Run2 data:

- ➢ m_jj and $\Delta\eta$_jj are used to extract EW signal
- ➢ Differential XS in pt of l1, j1, photon and mjj
- ➢ aQGC limits are set using m_Zγ



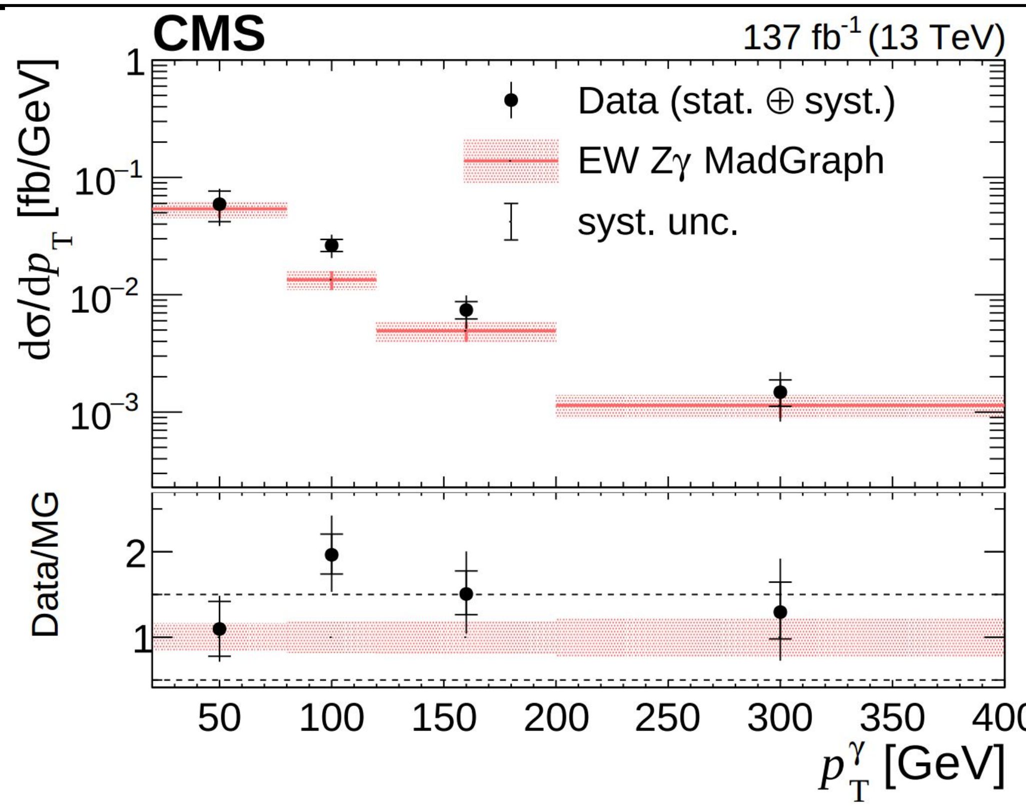
Main backgrounds:

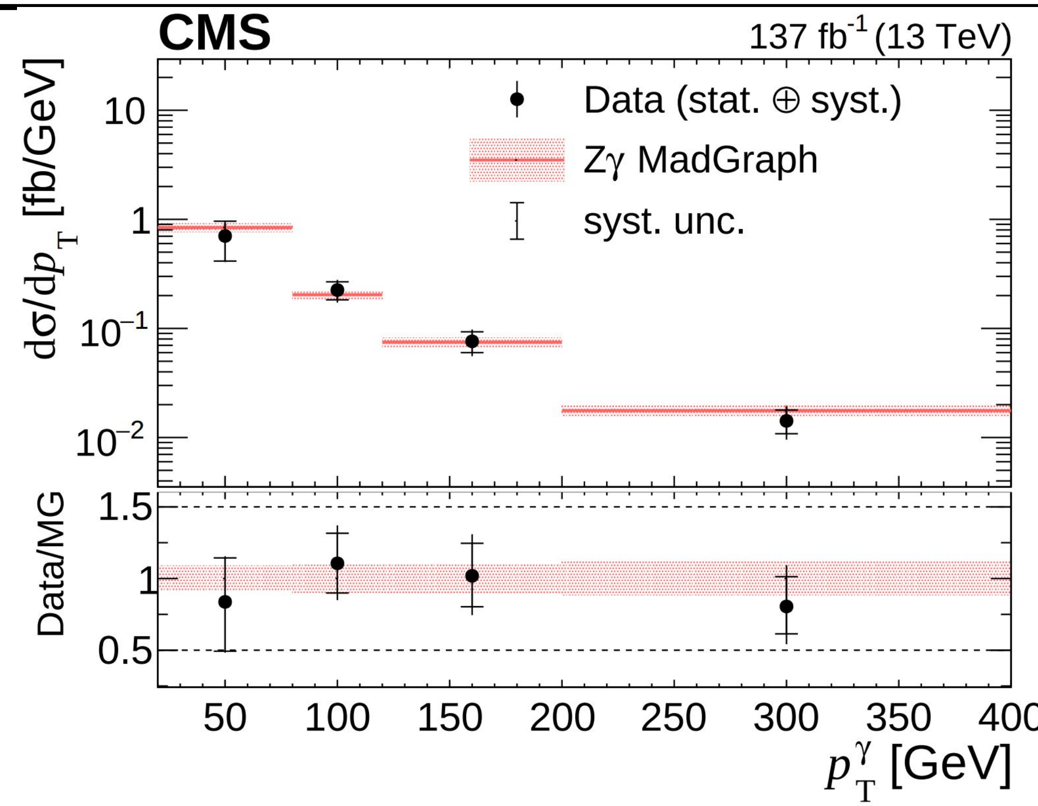
- ➢ QCD Zγ: estimated from MC, which is constrained by simultaneous fit
- ➢ Nonprompt photon: estimated using photon shape fit through data-driven method

Results:

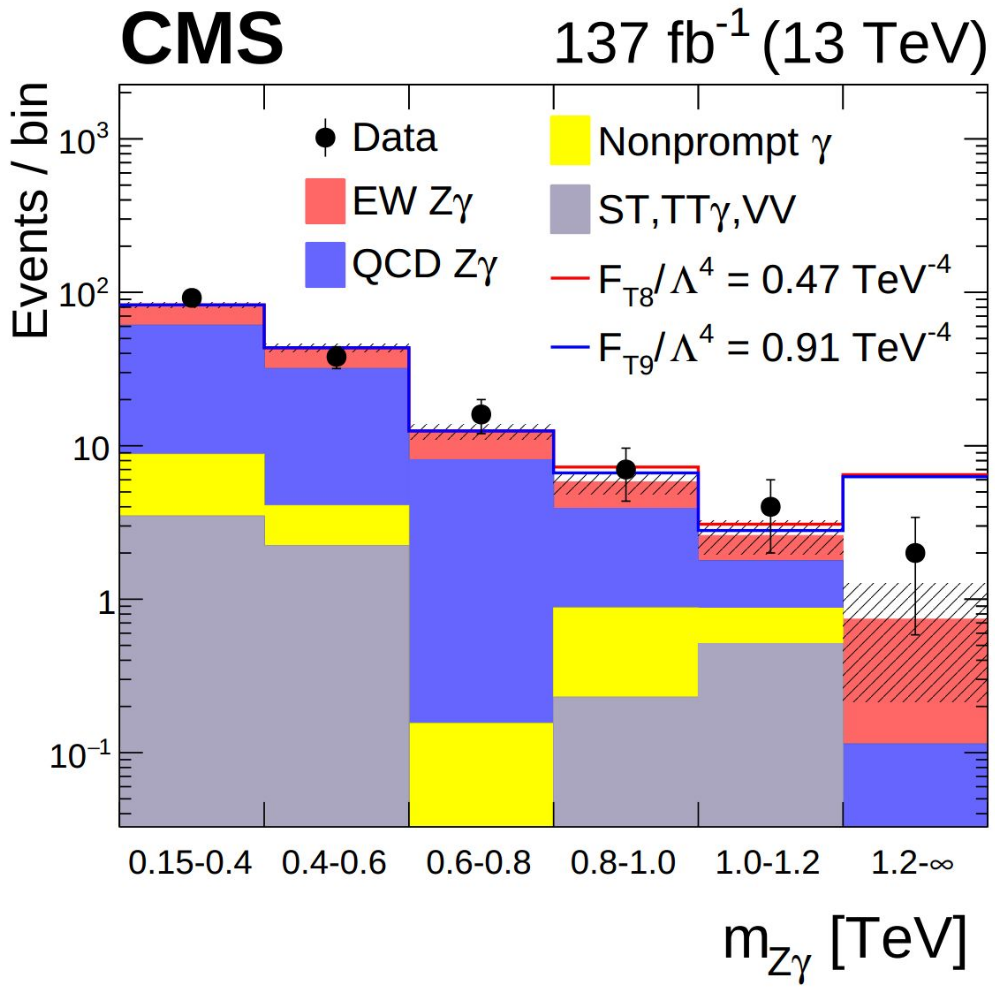
- ➢ observed significance much greater than 5σ
- ➢ EW signal strength: 1.25 +- 0.18
  XS: 5.43 +- 0.95 fb
- ➢ EW+QCD signal strength: 1.15 +- 0.12
  XS: 15.26 +- 1.75 fb

VBS Zγ





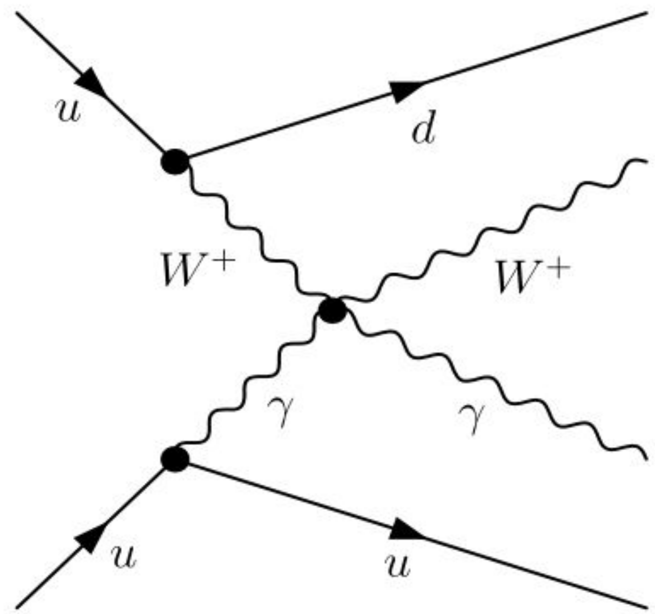
Generally good agreements between data and prediction.



Invariant mass of Z and photon is used for aQGC study. No obvious deviation from SM prediction is observed.

VBS Wγ

Similar to VBS Zγ, the main motivation of VBS Wγ is its sensitivity to aQGC.

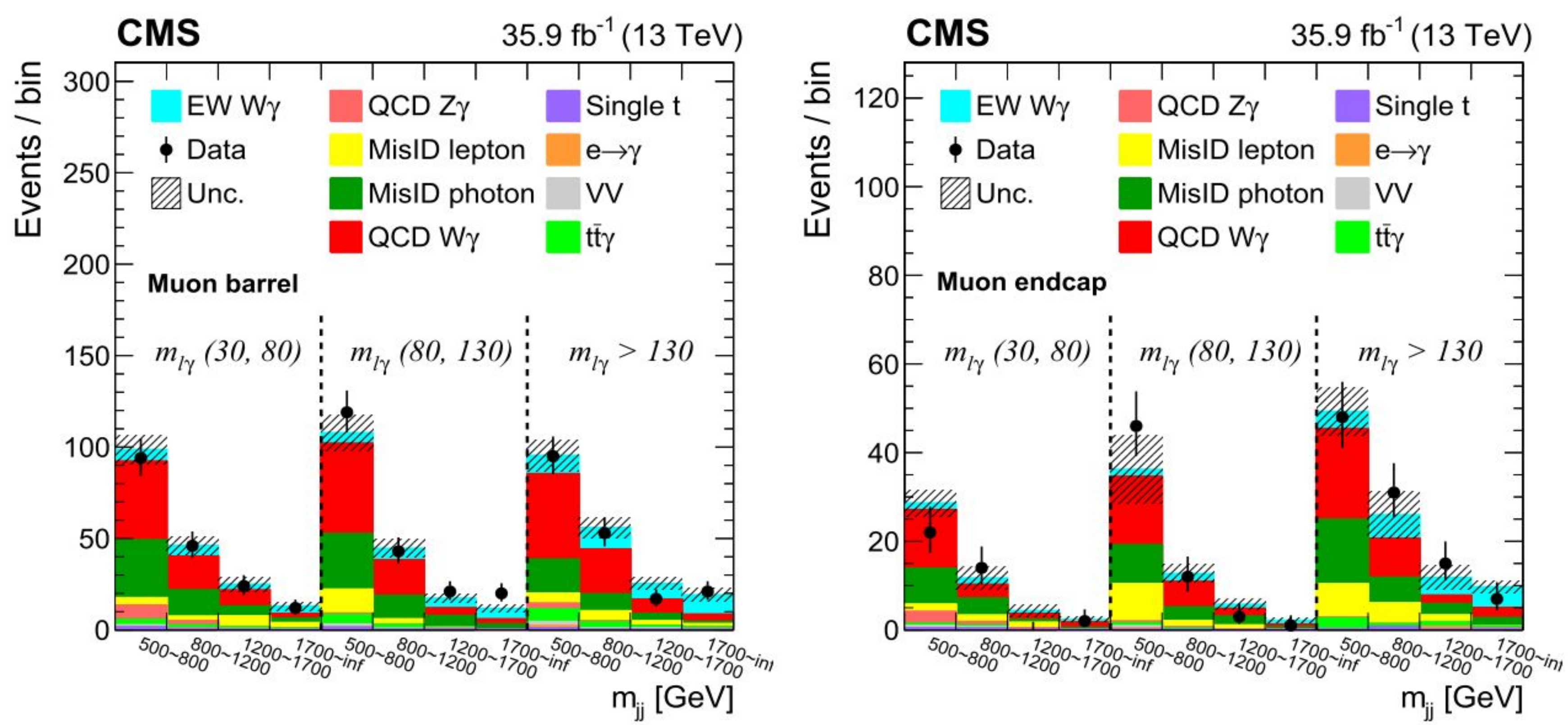


Using 2016 data:

- m_jj and mlγ are used to extract EW signal
- aQGC limits are set using m_Wγ

Main backgrounds:

- QCD Wγ: estimated from MC, which is constrained by simultaneous fit
- Nonprompt photon: estimated using photon shape fit through data-driven method
- Nonprompt lepton: estimated through data-driven method

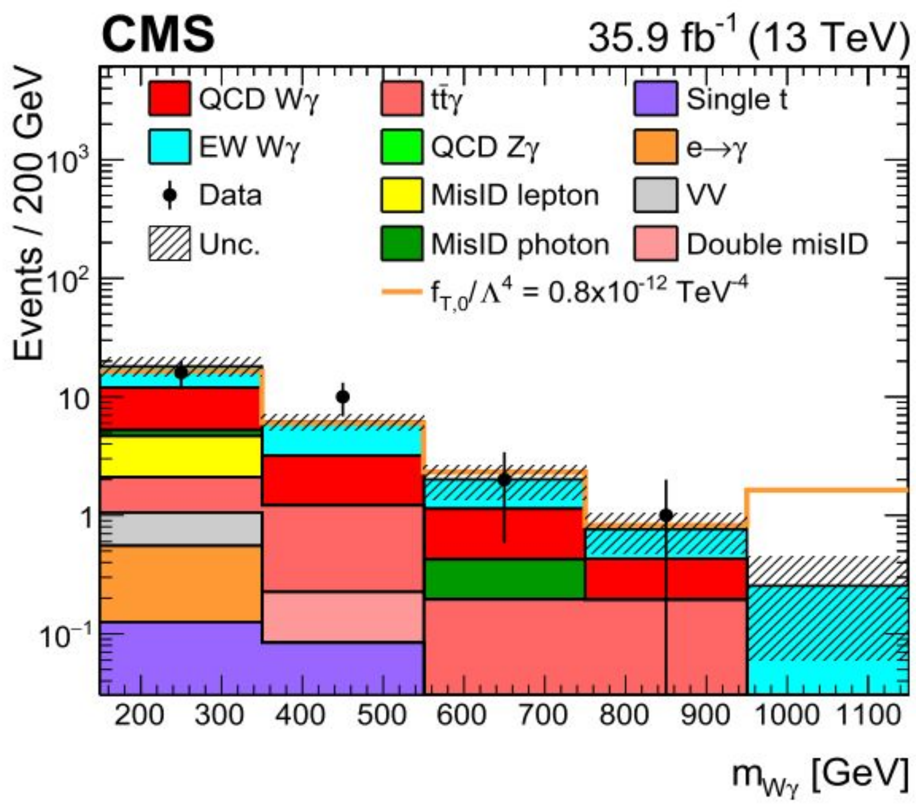


VBS Wγ

Results:

- ➢ Observed (expected) significance: 4.9σ (4.6σ) for 2016 data, 5.3σ (4.8σ) after combing with Run I data
- ➢ EW signal cross section: 20.4 ± 4.5 fb (corresponding signal strength: 1.20 +0.26-0.24)
- ➢ EW+QCD cross section: 108 ± 16 fb (corresponding signal strength: 1.21 +0.17-0.16)

Invariant mass of W and photon is used for aQGC study. No obvious deviation from SM prediction is observed.



Most stringent limits on fM2-5, fT6-7

Parameters	Obs. limit	Exp. limit	U_{bound}
$f_{M,0}/\Lambda^4$	[−8.1, 8.0]	[−7.7, 7.6]	1.0
$f_{M,1}/\Lambda^4$	[−12, 12]	[−11, 11]	1.2
$f_{M,2}/\Lambda^4$	[−2.8, 2.8]	[−2.7, 2.7]	1.3
$f_{M,3}/\Lambda^4$	[−4.4, 4.4]	[−4.0, 4.1]	1.5
$f_{M,4}/\Lambda^4$	[−5.0, 5.0]	[−4.7, 4.7]	1.5
$f_{M,5}/\Lambda^4$	[−8.3, 8.3]	[−7.9, 7.7]	1.8
$f_{M,6}/\Lambda^4$	[−16, 16]	[−15, 15]	1.0
$f_{M,7}/\Lambda^4$	[−21, 20]	[−19, 19]	1.3
$f_{T,0}/\Lambda^4$	[−0.6, 0.6]	[−0.6, 0.6]	1.4
$f_{T,1}/\Lambda^4$	[−0.4, 0.4]	[−0.3, 0.4]	1.5
$f_{T,2}/\Lambda^4$	[−1.0, 1.2]	[−1.0, 1.2]	1.5
$f_{T,5}/\Lambda^4$	[−0.5, 0.5]	[−0.4, 0.4]	1.8
$f_{T,6}/\Lambda^4$	[−0.4, 0.4]	[−0.3, 0.4]	1.7
$f_{T,7}/\Lambda^4$	[−0.9, 0.9]	[−0.8, 0.9]	1.8

Unitarity bound

Summary

- CMS has performed quite comprehensive studies of the VBS process, and many of them have moved to full Run2 data analysis
- Longitudinally polarized VBS process has been measured for the first time in ssWW channel at CMS
- Semileptonic VBS analysis is shown for the first time
- No obvious deviation has been observed in EFT measurement through VBS processes

Outlook:

- More Run2 analyses to come
- Run3 is coming (and HL-LHC), it's expected that it will give us more interesting VBS results with more data

Additional slides

Table 2: List and description of all the input variables for the signal BDT trainings.

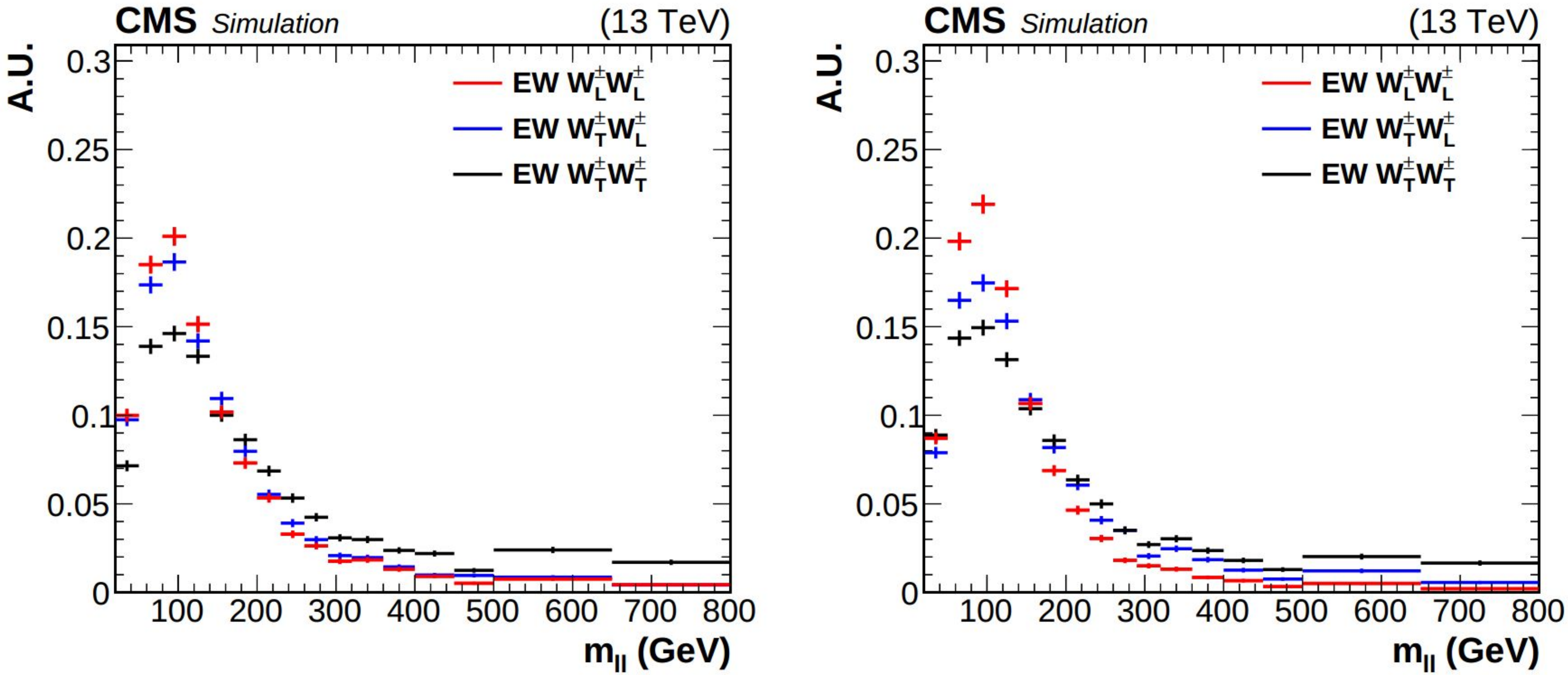
Variables	Definitions
$\Delta\phi_{jj}$	Difference in azimuthal angle between the leading and subleading jets
p_T^{j1}	p_T of the leading jet
p_T^{j2}	p_T of the subleading jet
$p_T^{\ell_1}$	Leading lepton p_T
$p_T^{\ell_2}$	Subleading lepton p_T
$\Delta\phi_{\ell\ell}$	Difference in azimuthal angle between the two leptons
$m_{\ell\ell}$	Dilepton mass
$p_T^{\ell\ell}$	Dilepton p_T
m_T^{WW}	Transverse WW diboson mass
$z^*_{\ell_1}$	Zeppenfeld variable of the leading lepton
$z^*_{\ell_2}$	Zeppenfeld variable of the subleading lepton
$\Delta R_{j1,\ell\ell}$	ΔR between the leading jet and the dilepton system
$\Delta R_{j2,\ell\ell}$	ΔR between the subleading jet and the dilepton system
$(p_T^{\ell_1} p_T^{\ell_2})/(p_T^{j1} p_T^{j2})$	Ratio of p_T products between leptons and jets
p_T^{miss}	Missing transverse momentum

$$z^*_\ell = \left|\eta^\ell - \frac{\eta^{j_1} + \eta^{j_2}}{2}\right| / |\Delta\eta_{jj}|$$

Table 3: List and description of the input variables for the inclusive BDT training.

Variables	Definitions
m_{jj}	Dijet mass
$\lvert\Delta\eta_{\mathrm{jj}}\rvert$	Difference in pseudorapidity between the leading and subleading jets
$\Delta\phi_{\mathrm{jj}}$	Difference in azimuth angles between the leading and subleading jets
$p_{\mathrm{T}}^{\mathrm{j1}}$	p_{T} of the leading jet
$p_{\mathrm{T}}^{\mathrm{j2}}$	p_{T} of the subleading jet
$p_{\mathrm{T}}^{\ell_1}$	Leading lepton p_{T}
$p_{\mathrm{T}}^{\ell\ell}$	Dilepton p_{T}
$z^*_{\ell_1}$	Zeppenfeld variable of the leading lepton
$z^*_{\ell_2}$	Zeppenfeld variable of the subleading lepton
$p_{\mathrm{T}}^{\mathrm{miss}}$	Missing transverse momentum

Longitudinal ssWW



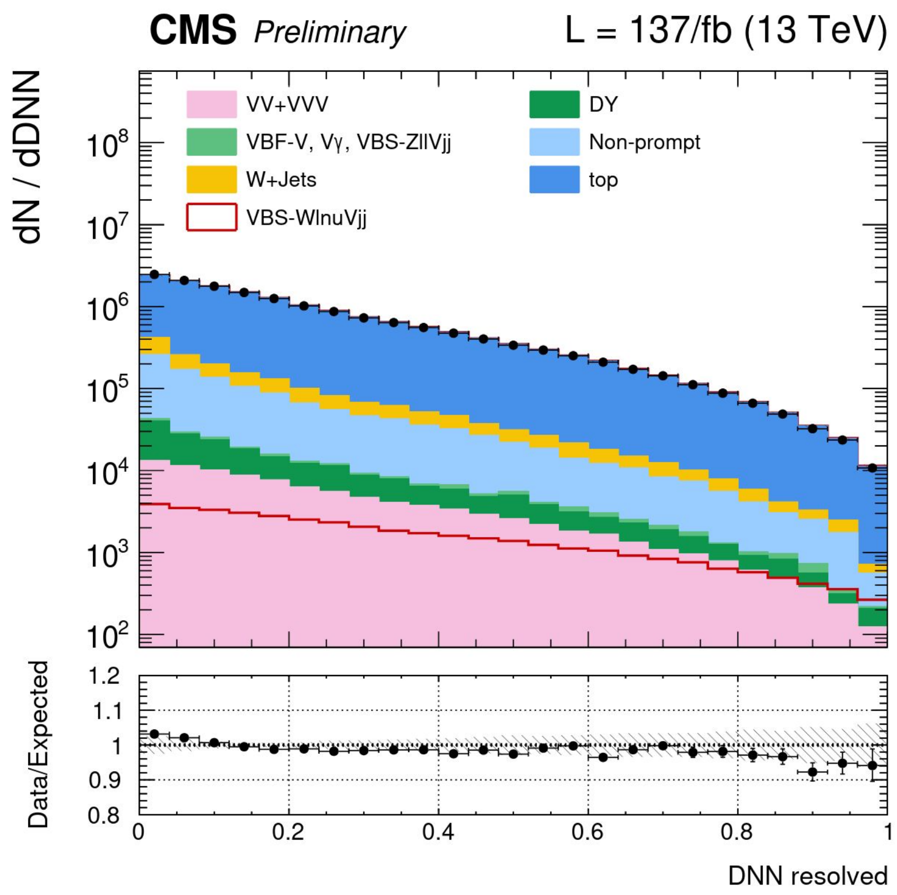
XS results in pp restframe

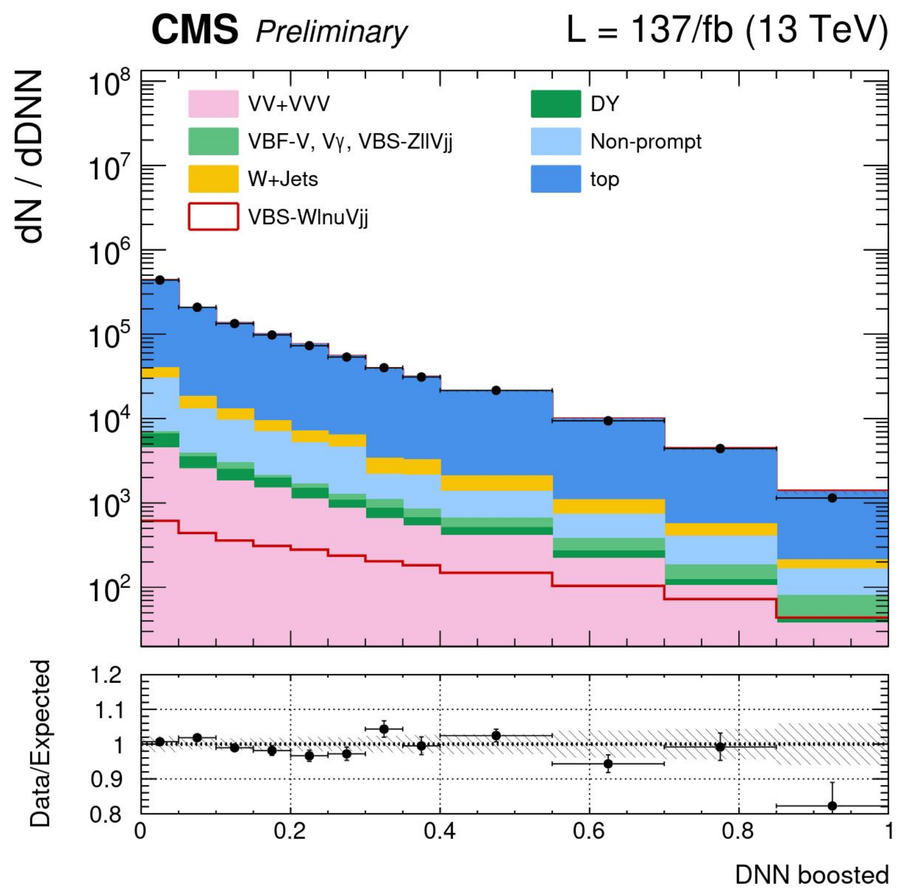
Process	$\sigma\mathcal{B}$ (fb)	Theoretical prediction (fb)
$W^{\pm}_{L}W^{\pm}_{L}$	$0.24^{+0.40}_{-0.37}$	0.28 ± 0.03
$W^{\pm}_{X}W^{\pm}_{T}$	$3.25^{+0.50}_{-0.48}$	3.32 ± 0.37
$W^{\pm}_{L}W^{\pm}_{X}$	$1.40^{+0.60}_{-0.57}$	1.71 ± 0.19
$W^{\pm}_{T}W^{\pm}_{T}$	$2.03^{+0.51}_{-0.50}$	1.89 ± 0.21

VBS WV

	Signal region	Top control region	W+jets control region
Resolved category	Ele $p_T >$ 30 GeV (2016), 35 GeV (2017, 2018) Muon $p_T >$ 30 GeV PuppiMET > 30 GeV Leading VBS jet $p_T >$ 50 GeV trailing VBS jet and Vjets $p_T >$ 30 GeV $\Delta\eta_{VBS} > 2.5$, $M_{jj\ VBS} >$ 500 GeV Leptonic $M^T_W <$ 185 GeV **bVeto with Loose** DeepCSV WP **V had p_T < 200 GeV** **65 GeV < Mjj Vhad < 105 GeV**	Ele $p_T >$ 30 GeV (2016), 35 GeV (2017, 2018) Muon $p_T >$ 30 GeV PuppiMET > 30 GeV Leading VBS jet $p_T >$ 50 GeV trailing VBS jet and Vjets $p_T >$ 30 GeV $\Delta\eta_{VBS} > 2.5$, $M_{jj\ VBS} >$ 500 GeV Leptonic $M^T_W <$ 185 GeV **bTag with Tight** DeepCSV WP **V had p_T < 200 GeV** **65 GeV < Mjj Vhad < 105 GeV**	Ele $p_T >$ 30 GeV (2016), 35 GeV (2017, 2018) Muon $p_T >$ 30 GeV PuppiMET > 30 GeV Leading VBS jet $p_T >$ 50 GeV trailing VBS jet and Vjets $p_T >$ 30 GeV $\Delta\eta_{VBS} > 2.5$, $M_{jj\ VBS} >$ 500 GeV Leptonic $M^T_W <$ 185 GeV **bVeto with Loose** DeepCSV WP **V had p_T < 200 GeV** **40 < Mjj Vhad < 65 GeV, Mjj Vhad > 105 GeV**
Boosted category	Ele $p_T >$ 30 GeV (2016), 35 GeV (2017, 2018) Muon $p_T >$ 30 GeV PuppiMET > 30 GeV Leading VBS jet $p_T >$ 50 GeV trailing VBS jet $p_T >$ 30 GeV $\Delta\eta_{VBS} > 2.5$, $M_{jj\ VBS} >$ 500 GeV Leptonic $M^T_W <$ 185 GeV **bVeto with Loose** DeepCSV WP **V had p_T > 200 GeV** **70 GeV < Mjj Vhad < 115 GeV**	Ele $p_T >$ 30 GeV (2016), 35 GeV (2017, 2018) Muon $p_T >$ 30 GeV PuppiMET > 30 GeV Leading VBS jet $p_T >$ 50 GeV trailing VBS jet $p_T >$ 30 GeV $\Delta\eta_{VBS} > 2.5$, $M_{jj\ VBS} >$ 500 GeV Leptonic $M^T_W <$ 185 GeV **bTag with Tight** DeepCSV WP **V had p_T > 200 GeV** **70 GeV < Mjj Vhad < 115 GeV**	Ele $p_T >$ 30 GeV (2016), 35 GeV (2017, 2018) Muon $p_T >$ 30 GeV PuppiMET > 30 GeV Leading VBS jet $p_T >$ 50 GeV trailing VBS jet $p_T >$ 30 GeV $\Delta\eta_{VBS} > 2.5$, $M_{jj\ VBS} >$ 500 GeV Leptonic $M^T_W <$ 185 GeV **bVeto with Loose** DeepCSV WP **V had p_T > 200 GeV** **40 GeV < Mjj Vhad < 70 GeV** **115 GeV < Mjj Vhad < 250 GeV**

VBS WV



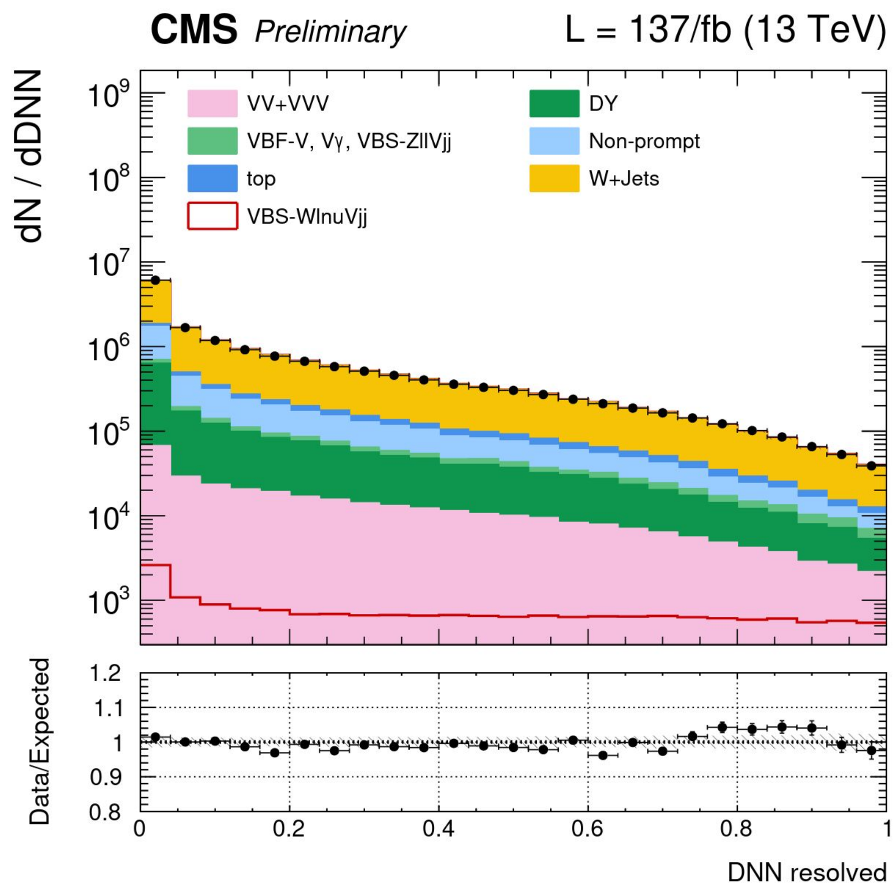


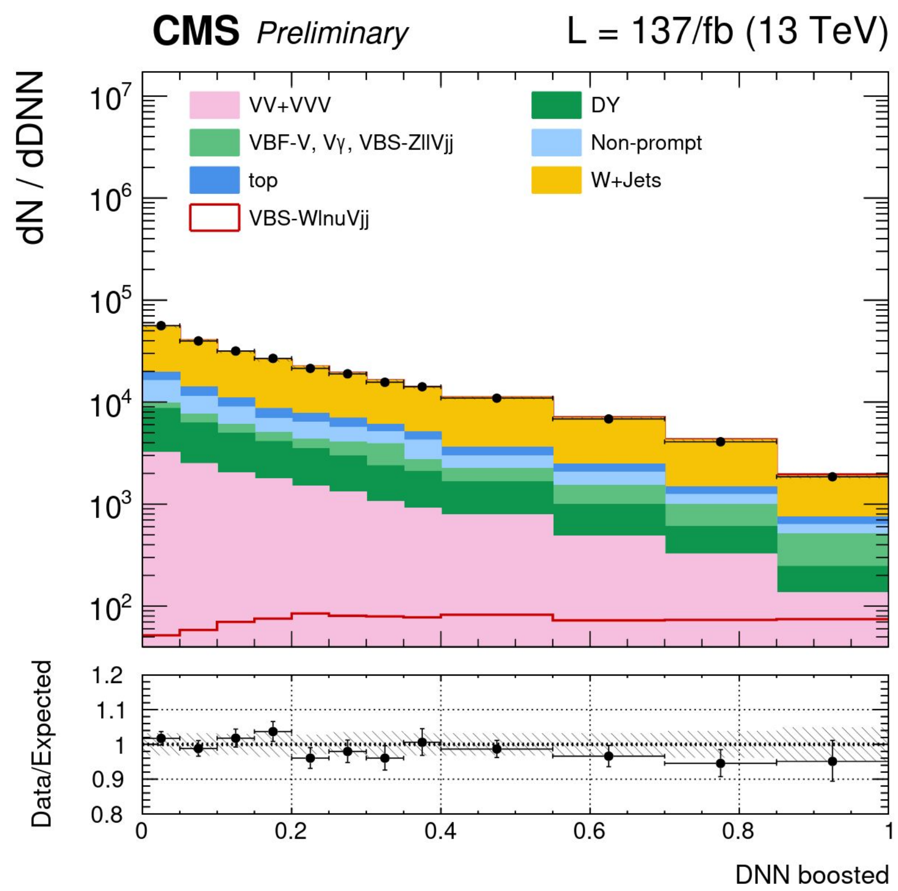
Top:

Top control region

Bottom:

W+jets region



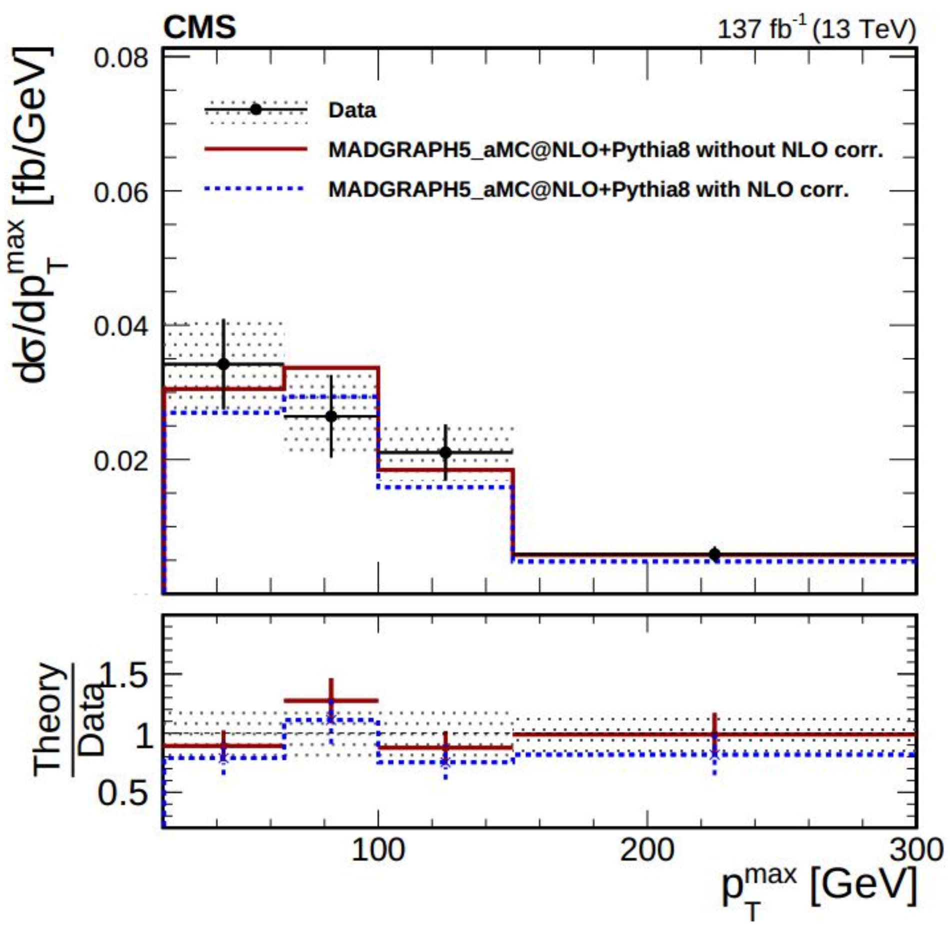


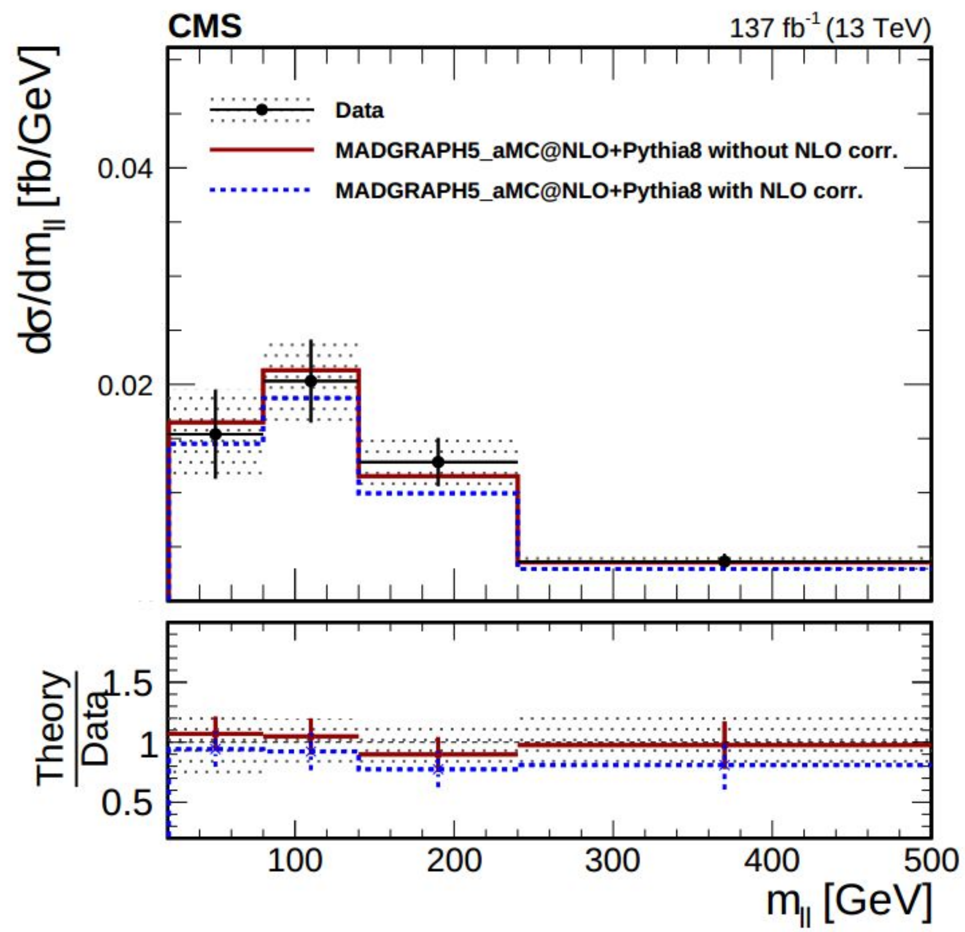
- ➢ Fit DNN shape in the signal regions
- ➢ Fit W+jets subcategories normalizations in W+jets control regions
- ➢ Fit only normalization in top-quark control regions

ssWW+WZ

BDT inputs for separation between EW WZ and QCD WZ.

Variable	Definition
m_{jj}	Mass of the leading and trailing jets system
$\lvert\Delta\eta_{\mathrm{jj}}\rvert$	Absolute difference in rapidity of the leading and trailing jets
$\Delta\phi_{\mathrm{jj}}$	Absolute difference in azimuthal angles of the leading and trailing jets
$p_{\mathrm{T}}^{\mathrm{j1}}$	p_{T} of the leading jet
$p_{\mathrm{T}}^{\mathrm{j2}}$	p_{T} of the trailing jet
η^{j1}	Pseudorapidity of the leading jet
$\lvert\eta^{\mathrm{W}} - \eta^{\mathrm{Z}}\rvert$	Absolute difference between the rapidities of the Z boson and the charged lepton from the decay of the W boson
$z^*_{\ell_i} (i = 1-3)$	Zeppenfeld variable of the three selected leptons
$z^*_{3\ell}$	Zeppenfeld variable of the vector sum of the three leptons
$\Delta R_{\mathrm{j1,Z}}$	ΔR between the leading jet and the Z boson
$\lvert\vec{p}_{\mathrm{T}}^{\,\mathrm{tot}}\rvert / \sum_i p_{\mathrm{T}}^i$	Transverse component of the vector sum of the bosons and tagging jets momenta, normalized to their scalar p_{T} sum





In ssWW:
Left: leading lepton pt
Right: invariant mass of two leptons

ssWW+WZ

	Observed ($W^\pm W^\pm$) (TeV^{-4})	Expected ($W^\pm W^\pm$) (TeV^{-4})	Observed (WZ) (TeV^{-4})	Expected (WZ) (TeV^{-4})	Observed (TeV^{-4})	Expected (TeV^{-4})
f_{T0}/Λ^4	[-0.28, 0.31]	[-0.36, 0.39]	[-0.62, 0.65]	[-0.82, 0.85]	[-0.25, 0.28]	[-0.35, 0.37]
f_{T1}/Λ^4	[-0.12, 0.15]	[-0.16, 0.19]	[-0.37, 0.41]	[-0.49, 0.55]	[-0.12, 0.14]	[-0.16, 0.19]
f_{T2}/Λ^4	[-0.38, 0.50]	[-0.50, 0.63]	[-1.0 , 1.3]	[-1.4, 1.7]	[-0.35, 0.48]	[-0.49, 0.63]
f_{M0}/Λ^4	[-3.0, 3.2]	[-3.7, 3.8]	[-5.8, 5.8]	[-7.6, 7.6]	[-2.7, 2.9]	[-3.6, 3.7]
f_{M1}/Λ^4	[-4.7, 4.7]	[-5.4, 5.8]	[-8.2, 8.3]	[-11, 11]	[-4.1, 4.2]	[-5.2, 5.5]
f_{M6}/Λ^4	[-6.0, 6.5]	[-7.5, 7.6]	[-12, 12]	[-15, 15]	[-5.4, 5.8]	[-7.2, 7.3]
f_{M7}/Λ^4	[-6.7, 7.0]	[-8.3, 8.1]	[-10, 10]	[-14, 14]	[-5.7, 6.0]	[-7.8, 7.6]
f_{S0}/Λ^4	[-6.0, 6.4]	[-6.0, 6.2]	[-19, 19]	[-24, 24]	[-5.7, 6.1]	[-5.9, 6.2]
f_{S1}/Λ^4	[-18, 19]	[-18, 19]	[-30, 30]	[-38, 39]	[-16, 17]	[-18, 18]

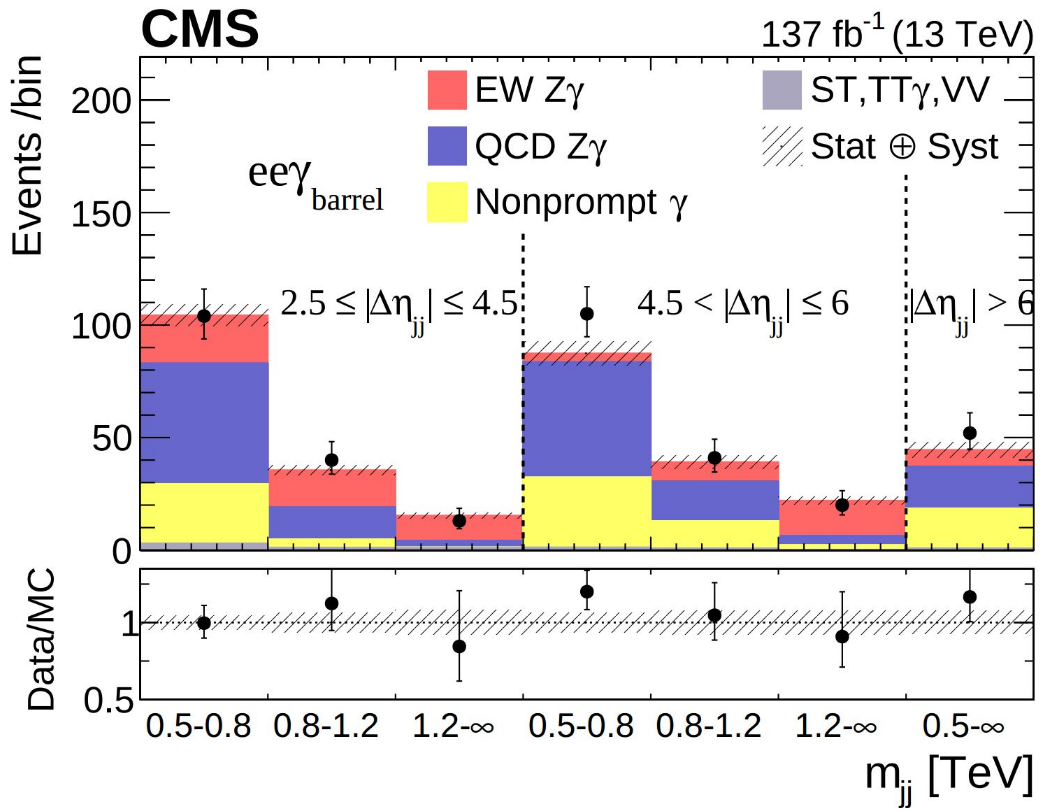
Bottom: cutting the EFT expansion at the unitarity limit

	Observed ($W^\pm W^\pm$) (TeV^{-4})	Expected ($W^\pm W^\pm$) (TeV^{-4})	Observed (WZ) (TeV^{-4})	Expected (WZ) (TeV^{-4})	Observed (TeV^{-4})	Expected (TeV^{-4})
f_{T0}/Λ^4	[-1.5, 2.3]	[-2.1, 2.7]	[-1.6, 1.9]	[-2.0, 2.2]	[-1.1, 1.6]	[-1.6, 2.0]
f_{T1}/Λ^4	[-0.81, 1.2]	[-0.98, 1.4]	[-1.3, 1.5]	[-1.6, 1.8]	[-0.69, 0.97]	[-0.94, 1.3]
f_{T2}/Λ^4	[-2.1, 4.4]	[-2.7, 5.3]	[-2.7, 3.4]	[-4.4, 5.5]	[-1.6, 3.1]	[-2.3, 3.8]
f_{M0}/Λ^4	[-13, 16]	[-19, 18]	[-16, 16]	[-19, 19]	[-11, 12]	[-15, 15]
f_{M1}/Λ^4	[-20, 19]	[-22, 25]	[-19, 20]	[-23, 24]	[-15, 14]	[-18, 20]
f_{M6}/Λ^4	[-27, 32]	[-37, 37]	[-34, 33]	[-39, 39]	[-22, 25]	[-31, 30]
f_{M7}/Λ^4	[-22, 24]	[-27, 25]	[-22, 22]	[-28, 28]	[-16, 18]	[-22, 21]
f_{S0}/Λ^4	[-35, 36]	[-31, 31]	[-83, 85]	[-88, 91]	[-34, 35]	[-31, 31]
f_{S1}/Λ^4	[-100, 120]	[-100, 110]	[-110, 110]	[-120, 130]	[-86, 99]	[-91, 97]

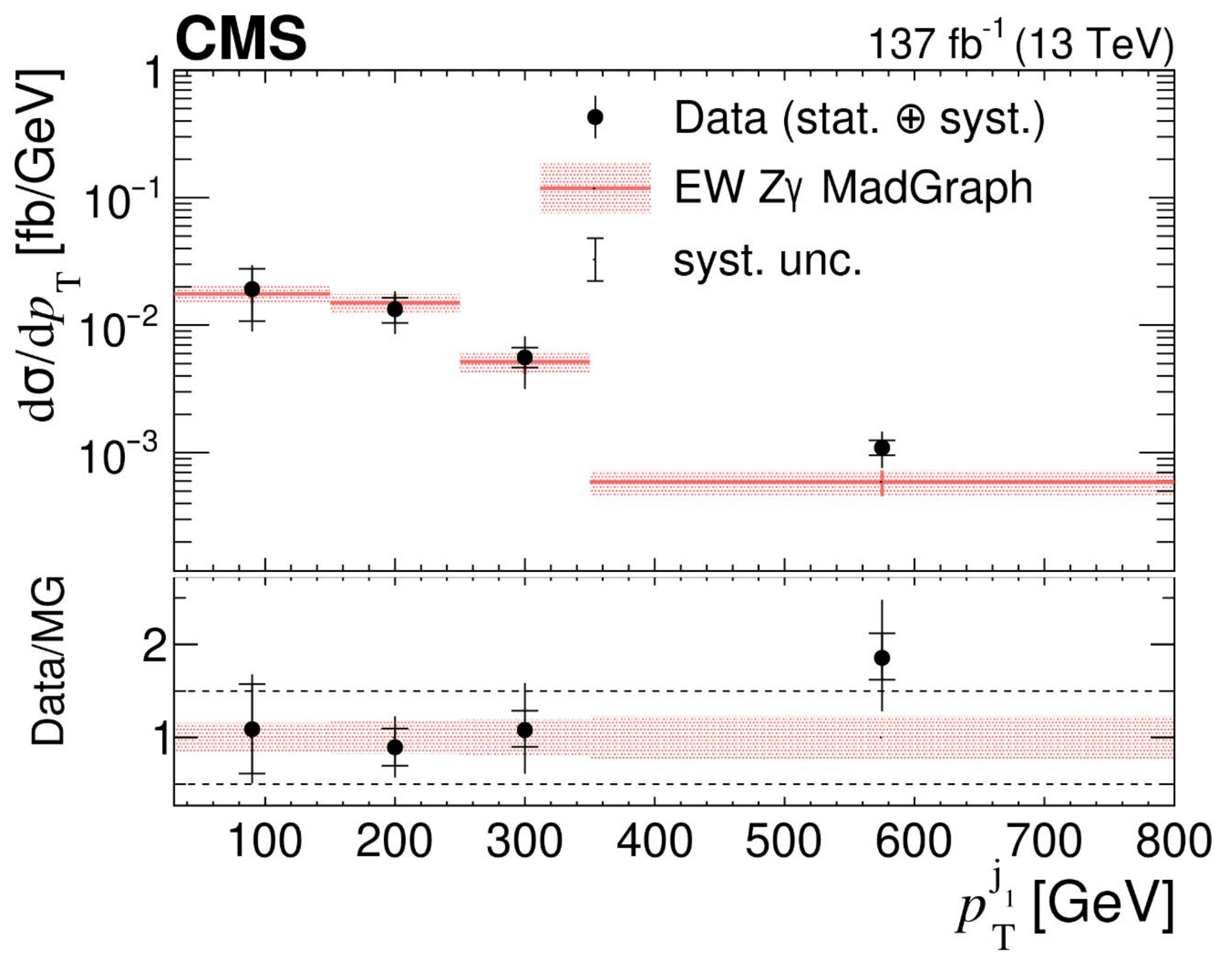
VBS $Z\gamma$

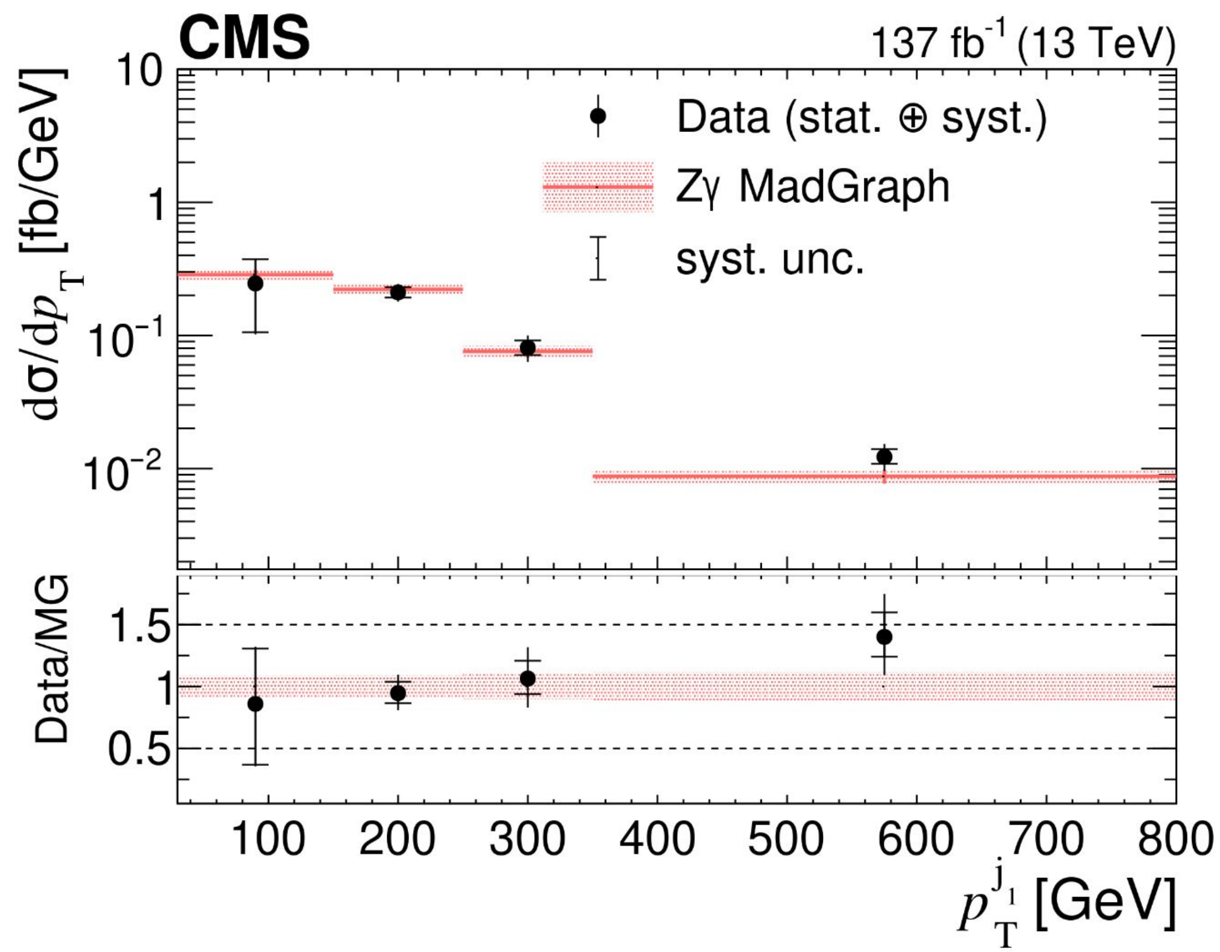
Common selection	$p_T^{\ell1,\ell2} > 25\,\mathrm{GeV}$, $\lvert\eta^{\ell1,\ell2}\rvert < 2.5$ for electron channel $p_T^{\ell1,\ell2} > 20\,\mathrm{GeV}$, $\lvert\eta^{\ell1,\ell2}\rvert < 2.4$ for muon channel $p_T^{\gamma} > 20\,\mathrm{GeV}$, $\lvert\eta^{\gamma}\rvert < 1.444$ or $1.566 < \lvert\eta^{\gamma}\rvert < 2.500$ $p_T^{j1,j2} > 30\,\mathrm{GeV}$, $\lvert\eta^{j1,j2}\rvert < 4.7$ $70 < m_{\ell\ell} < 110\,\mathrm{GeV}$, $m_{Z\gamma} > 100\,\mathrm{GeV}$ ΔR_{jj}, $\Delta R_{j\gamma}$, $\Delta R_{j\ell} > 0.5$, $\Delta R_{\ell\gamma} > 0.7$
Control region	$150 < m_{jj} < 500\,\mathrm{GeV}$, Common selection
EW signal region	$m_{jj} > 500\,\mathrm{GeV}$, $\lvert\Delta\eta_{jj}\rvert > 2.5$, Common selection $\eta^* < 2.4$, $\Delta\phi_{Z\gamma,jj} > 1.9$
Fiducial volume	$m_{jj} > 500\,\mathrm{GeV}$, $\lvert\Delta\eta_{jj}\rvert > 2.5$, Common selection
aQGC search region	$m_{jj} > 500\,\mathrm{GeV}$, $\lvert\Delta\eta_{jj}\rvert > 2.5$, $p_T^{\gamma} > 120\,\mathrm{GeV}$, Common selection, without requirement on $m_{Z\gamma}$

VBS Zγ

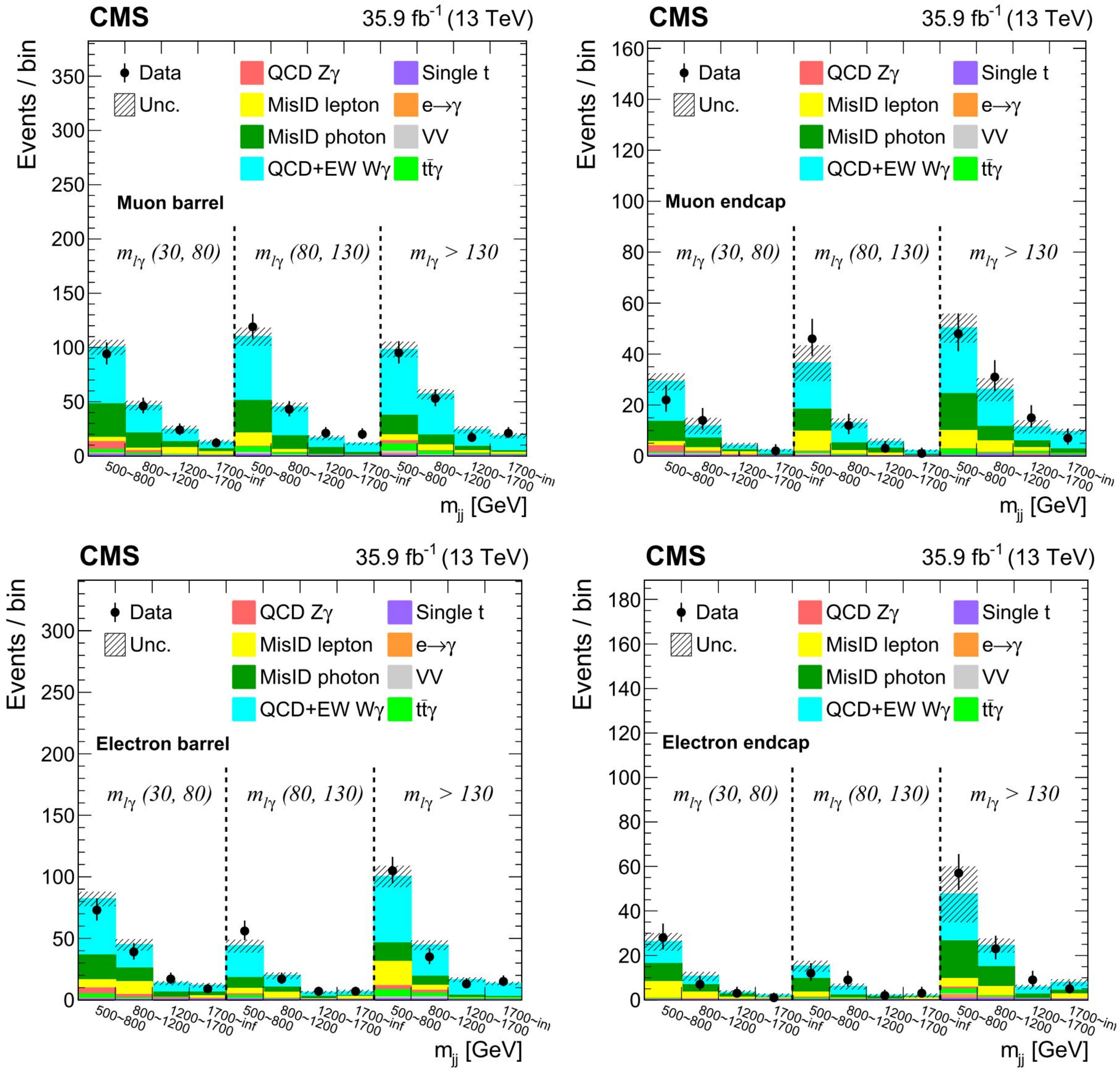


Left: differential XS of leading jet pt in EW only signal strategy
Right: differential XS of leading jet pt in EW+QCD signal strategy





VBS Wγ



QCD+EW: comparison between data and prediction

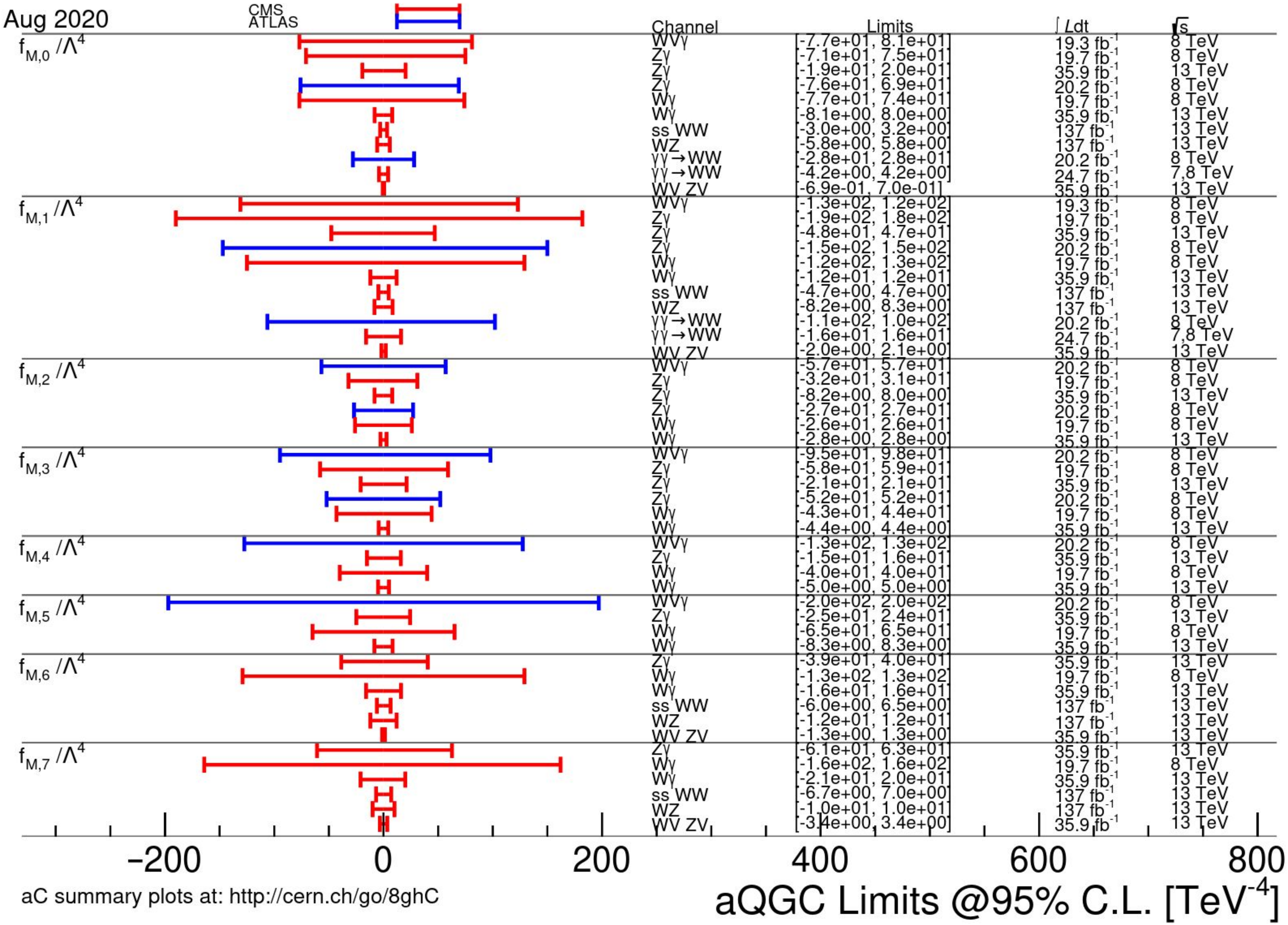
aQGC operators

$$\mathcal{L}_{M,0} = \frac{f_{M0}}{\Lambda^4} \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right],$$
$$\mathcal{L}_{M,1} = \frac{f_{M1}}{\Lambda^4} \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right],$$
$$\mathcal{L}_{M,2} = \frac{f_{M2}}{\Lambda^4} \left[B_{\mu\nu}B^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right],$$
$$\mathcal{L}_{M,3} = \frac{f_{M3}}{\Lambda^4} \left[B_{\mu\nu}B^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right],$$
$$\mathcal{L}_{M,4} = \frac{f_{M4}}{\Lambda^4} \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu} D^\mu\Phi\right] \times B^{\beta\nu},$$
$$\mathcal{L}_{M,5} = \frac{f_{M5}}{\Lambda^4} \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu} D^\nu\Phi\right] \times B^{\beta\mu},$$
$$\mathcal{L}_{M,6} = \frac{f_{M6}}{\Lambda^4} \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\nu} D^\mu\Phi\right],$$
$$\mathcal{L}_{M,7} = \frac{f_{M7}}{\Lambda^4} \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\mu} D^\nu\Phi\right].$$

$$\mathcal{L}_{T,0} = \frac{f_{T0}}{\Lambda^4} Tr[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}] \times Tr[\hat{W}_{\alpha\beta}\hat{W}^{\alpha\beta}],$$
$$\mathcal{L}_{T,1} = \frac{f_{T1}}{\Lambda^4} Tr[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}] \times Tr[\hat{W}_{\mu\beta}\hat{W}^{\alpha\nu}],$$
$$\mathcal{L}_{T,2} = \frac{f_{T2}}{\Lambda^4} Tr[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}] \times Tr[\hat{W}_{\beta\nu}\hat{W}^{\nu\alpha}],$$
$$\mathcal{L}_{T,5} = \frac{f_{T5}}{\Lambda^4} Tr[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}] \times B_{\alpha\beta}B^{\alpha\beta},$$
$$\mathcal{L}_{T,6} = \frac{f_{T6}}{\Lambda^4} Tr[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}] \times B_{\mu\beta}B^{\alpha\nu},$$
$$\mathcal{L}_{T,7} = \frac{f_{T7}}{\Lambda^4} Tr[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}] \times B_{\beta\nu}B^{\nu\alpha},$$
$$\mathcal{L}_{T,8} = \frac{f_{T8}}{\Lambda^4} B_{\mu\nu}B^{\mu\nu}B_{\alpha\beta}B^{\alpha\beta},$$
$$\mathcal{L}_{T,9} = \frac{f_{T9}}{\Lambda^4} B_{\alpha\mu}B^{\mu\beta}B_{\beta\nu}B^{\nu\alpha}.$$

Φ is Higgs doublet, W$\mu\nu$ and B$\mu\nu$ are field-strength tensors of SU(2) and U(1)

fM* limits



Aug 2020
CMS
ATLAS
Channel
Limits
∫Ldt
√s
$f_{M,0}/\Lambda^4$
WVγ [-7.7e+01, 8.1e+01] 19.3 fb^{-1} 8 TeV
Zγ [-7.1e+01, 7.5e+01] 19.7 fb^{-1} 8 TeV
Zγ [-1.9e+01, 2.0e+01] 35.9 fb^{-1} 13 TeV
Zγ [-7.6e+01, 6.9e+01] 20.2 fb^{-1} 8 TeV
Wγ [-7.7e+01, 7.4e+01] 19.7 fb^{-1} 8 TeV
Wγ [-8.1e+00, 8.0e+00] 35.9 fb^{-1} 13 TeV
ss WW [-3.0e+00, 3.2e+00] 137 fb^{-1} 13 TeV
WZ [-5.8e+00, 5.8e+00] 137 fb^{-1} 13 TeV
γγ→WW [-2.8e+01, 2.8e+01] 20.2 fb^{-1} 8 TeV
γγ→WW [-4.2e+00, 4.2e+00] 24.7 fb^{-1} 7,8 TeV
WV ZV [-6.9e-01, 7.0e-01] 35.9 fb^{-1} 13 TeV
$f_{M,1}/\Lambda^4$
WVγ [-1.3e+02, 1.2e+02] 19.3 fb^{-1} 8 TeV
Zγ [-1.9e+02, 1.8e+02] 19.7 fb^{-1} 8 TeV
Zγ [-4.8e+01, 4.7e+01] 35.9 fb^{-1} 13 TeV
Zγ [-1.5e+02, 1.5e+02] 20.2 fb^{-1} 8 TeV
Wγ [-1.2e+02, 1.3e+02] 19.7 fb^{-1} 8 TeV
Wγ [-1.2e+01, 1.2e+01] 35.9 fb^{-1} 13 TeV
ss WW [-4.7e+00, 4.7e+00] 137 fb^{-1} 13 TeV
WZ [-8.2e+00, 8.3e+00] 137 fb^{-1} 13 TeV
γγ→WW [-1.1e+02, 1.0e+02] 20.2 fb^{-1} 8 TeV
γγ→WW [-1.6e+01, 1.6e+01] 24.7 fb^{-1} 7,8 TeV
WV ZV [-2.0e+00, 2.1e+00] 35.9 fb^{-1} 13 TeV
$f_{M,2}/\Lambda^4$
WVγ [-5.7e+01, 5.7e+01] 20.2 fb^{-1} 8 TeV
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Wγ [-4.0e+01, 4.0e+01] 19.7 fb^{-1} 8 TeV
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$f_{M,6}/\Lambda^4$
Zγ [-3.9e+01, 4.0e+01] 35.9 fb^{-1} 13 TeV
Wγ [-1.3e+02, 1.3e+02] 19.7 fb^{-1} 8 TeV
Wγ [-1.6e+01, 1.6e+01] 35.9 fb^{-1} 13 TeV
ss WW [-6.0e+00, 6.5e+00] 137 fb^{-1} 13 TeV
WZ [-1.2e+01, 1.2e+01] 137 fb^{-1} 13 TeV
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$f_{M,7}/\Lambda^4$
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ss WW [-6.7e+00, 7.0e+00] 137 fb^{-1} 13 TeV
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-200
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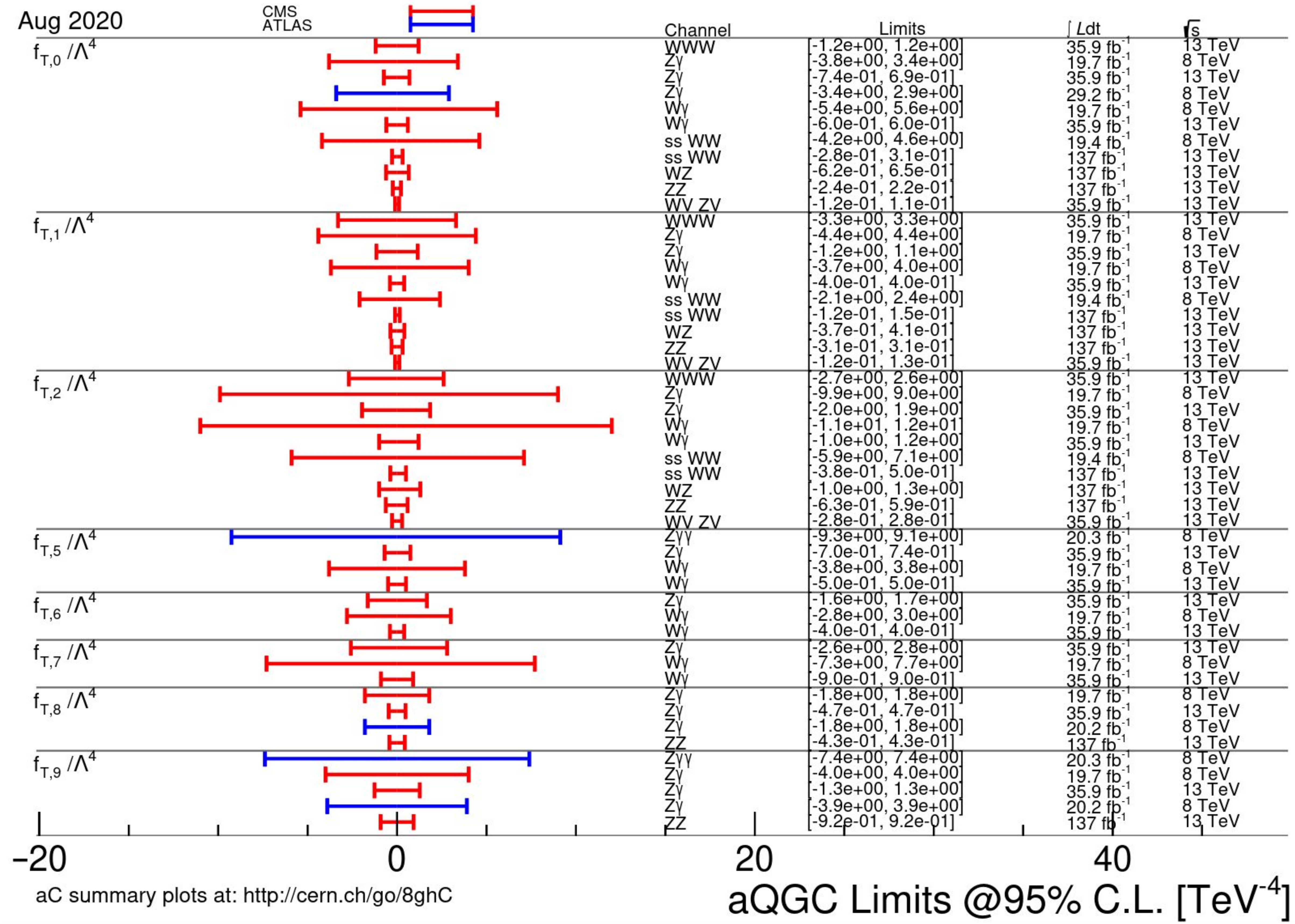
aC summary plots at: http://cern.ch/go/8ghC
aQGC Limits @95% C.L. [TeV^{-4}]

fT* limits


Aug 2020
CMS
ATLAS
Channel Limits ∫Ldt √s
$f_{T,0}/\Lambda^4$
WWW [-1.2e+00, 1.2e+00] 35.9 fb-1 13 TeV
Zγ [-3.8e+00, 3.4e+00] 19.7 fb-1 8 TeV
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Wγ [-5.4e+00, 5.6e+00] 19.7 fb-1 8 TeV
Wγ [-6.0e-01, 6.0e-01] 35.9 fb-1 13 TeV
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WZ [-6.2e-01, 6.5e-01] 137 fb-1 13 TeV
ZZ [-2.4e-01, 2.2e-01] 137 fb-1 13 TeV
WV ZV [-1.2e-01, 1.1e-01] 35.9 fb-1 13 TeV
$f_{T,1}/\Lambda^4$
WWW [-3.3e+00, 3.3e+00] 35.9 fb-1 13 TeV
Zγ [-4.4e+00, 4.4e+00] 19.7 fb-1 8 TeV
Zγ [-1.2e+00, 1.1e+00] 35.9 fb-1 13 TeV
Wγ [-3.7e+00, 4.0e+00] 19.7 fb-1 8 TeV
Wγ [-4.0e-01, 4.0e-01] 35.9 fb-1 13 TeV
ss WW [-2.1e+00, 2.4e+00] 19.4 fb-1 8 TeV
ss WW [-1.2e-01, 1.5e-01] 137 fb-1 13 TeV
WZ [-3.7e-01, 4.1e-01] 137 fb-1 13 TeV
ZZ [-3.1e-01, 3.1e-01] 137 fb-1 13 TeV
WV ZV [-1.2e-01, 1.3e-01] 35.9 fb-1 13 TeV
$f_{T,2}/\Lambda^4$
WWW [-2.7e+00, 2.6e+00] 35.9 fb-1 13 TeV
Zγ [-9.9e+00, 9.0e+00] 19.7 fb-1 8 TeV
Zγ [-2.0e+00, 1.9e+00] 35.9 fb-1 13 TeV
Wγ [-1.1e+01, 1.2e+01] 19.7 fb-1 8 TeV
Wγ [-1.0e+00, 1.2e+00] 35.9 fb-1 13 TeV
ss WW [-5.9e+00, 7.1e+00] 19.4 fb-1 8 TeV
ss WW [-3.8e-01, 5.0e-01] 137 fb-1 13 TeV
WZ [-1.0e+00, 1.3e+00] 137 fb-1 13 TeV
ZZ [-6.3e-01, 5.9e-01] 137 fb-1 13 TeV
WV ZV [-2.8e-01, 2.8e-01] 35.9 fb-1 13 TeV
$f_{T,5}/\Lambda^4$
Zγγ [-9.3e+00, 9.1e+00] 20.3 fb-1 8 TeV
Zγ [-7.0e-01, 7.4e-01] 35.9 fb-1 13 TeV
Wγ [-3.8e+00, 3.8e+00] 19.7 fb-1 8 TeV
Wγ [-5.0e-01, 5.0e-01] 35.9 fb-1 13 TeV
$f_{T,6}/\Lambda^4$
Zγ [-1.6e+00, 1.7e+00] 35.9 fb-1 13 TeV
Wγ [-2.8e+00, 3.0e+00] 19.7 fb-1 8 TeV
Wγ [-4.0e-01, 4.0e-01] 35.9 fb-1 13 TeV
$f_{T,7}/\Lambda^4$
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Wγ [-7.3e+00, 7.7e+00] 19.7 fb-1 8 TeV
Wγ [-9.0e-01, 9.0e-01] 35.9 fb-1 13 TeV
$f_{T,8}/\Lambda^4$
Zγ [-1.8e+00, 1.8e+00] 19.7 fb-1 8 TeV
Zγ [-4.7e-01, 4.7e-01] 35.9 fb-1 13 TeV
Zγ [-1.8e+00, 1.8e+00] 20.2 fb-1 8 TeV
ZZ [-4.3e-01, 4.3e-01] 137 fb-1 13 TeV
$f_{T,9}/\Lambda^4$
Zγγ [-7.4e+00, 7.4e+00] 20.3 fb-1 8 TeV
Zγ [-4.0e+00, 4.0e+00] 19.7 fb-1 8 TeV
Zγ [-1.3e+00, 1.3e+00] 35.9 fb-1 13 TeV
Zγ [-3.9e+00, 3.9e+00] 20.2 fb-1 8 TeV
ZZ [-9.2e-01, 9.2e-01] 137 fb-1 13 TeV
−20 0 20 40
aC summary plots at: http://cern.ch/go/8ghC
aQGC Limits @95% C.L. [TeV-4]