

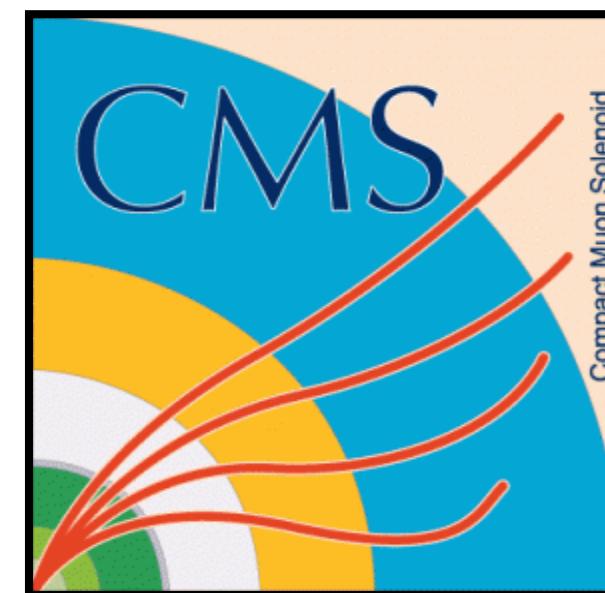
Vector Boson Scattering results at CMS

Raffaele Gerosa

University and INFN of Milano Bicocca

On behalf of the CMS Collaboration

The 30th International Conference on Supersymmetry and Unification of Fundamental Interactions



Vector Boson Scattering at the LHC

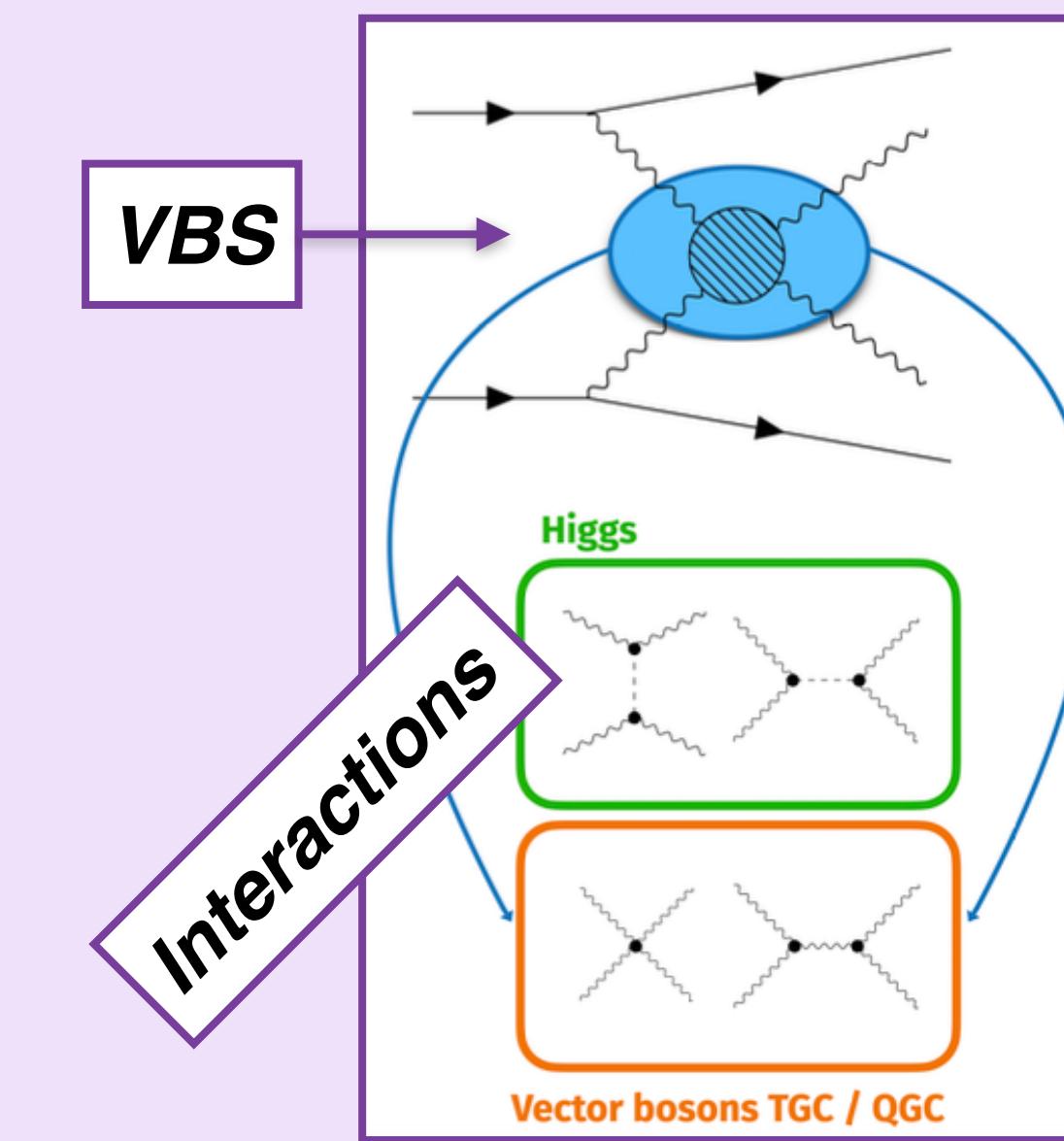
Vector Boson Scattering (VBS) realises at LHC when **two partons** from the interacting protons **radiate EW vector bosons** that **scatter** (interact) with each other

Theory p.o.v.

- **Pure EW** processes at the LO $O(\alpha_{EW}^6)$
- **Rare processes** with production x decay cross sections of $O(0.1\text{-}10 \text{ fb})$
- **Higher order corrections** known only for some final state topologies
 - **Small** impact from **NLO-QCD**
 - **Sizable** contributions from **NLO-EW** at high energy $O(10\%)$
- **Sensitive** to parton-shower models

Interaction p.o.v.

- **Several interactions** may happen when **two V-bosons scatters**



Experimental p.o.v

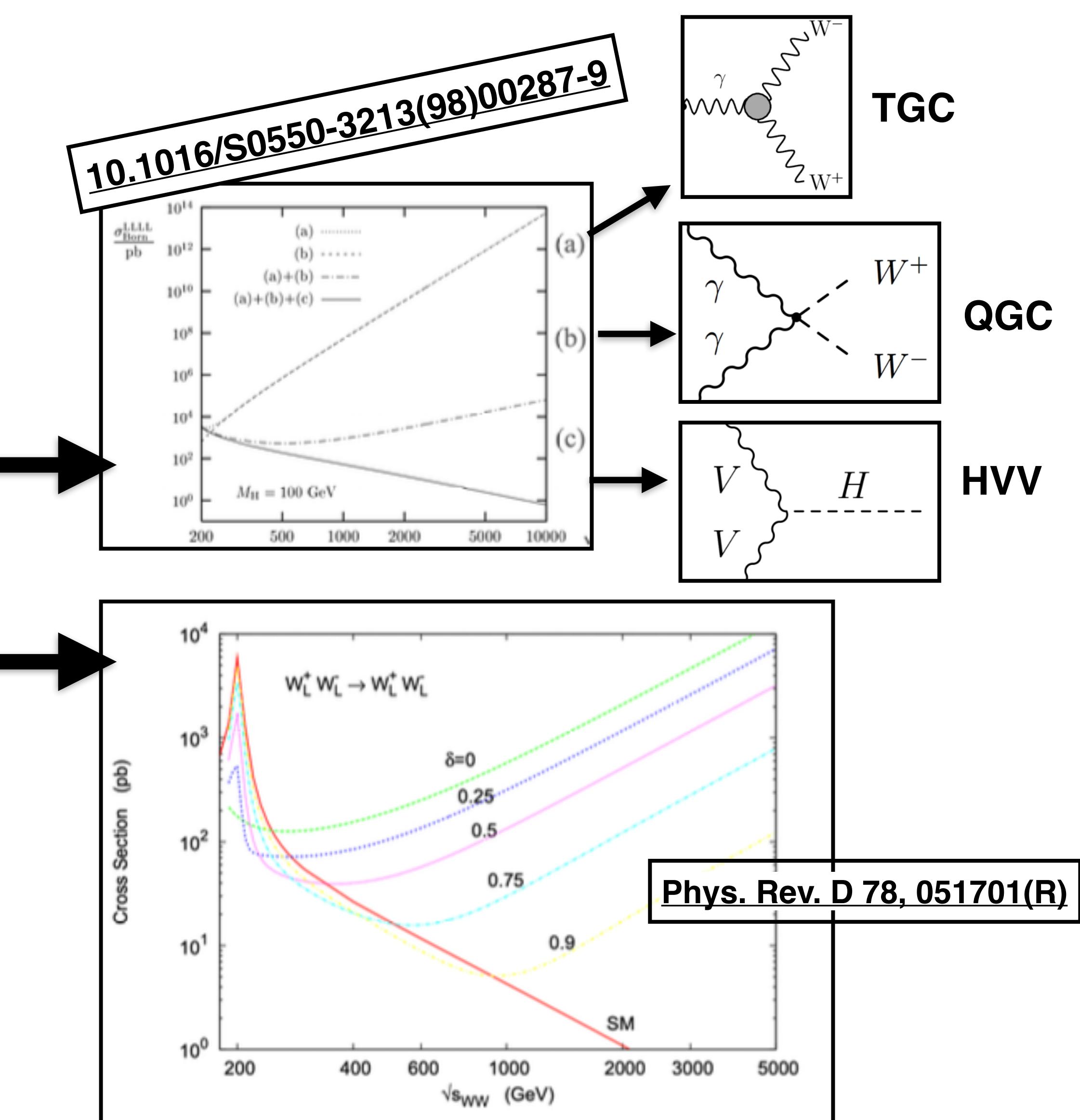
- **VV scattering**: six fermions in the final state → two from initial state, four from V-boson (W,Z) decay
- **Vγ scattering**: four fermions in the final state and a photon → two fermions from initial state, two from V decay
- **Main features**:
 - Jets from initial state partons have **high m_{jj} and $\Delta\eta_{jj}$ (VBS-jets)**
 - **No hadronic activity** in the VBS-jets **rapidity gap**

VBS role in the EWSB

VBS is an important and model independent *probe* of the **Electroweak Symmetry Breaking (EWSB)** mechanism

Why VBS is so important ?

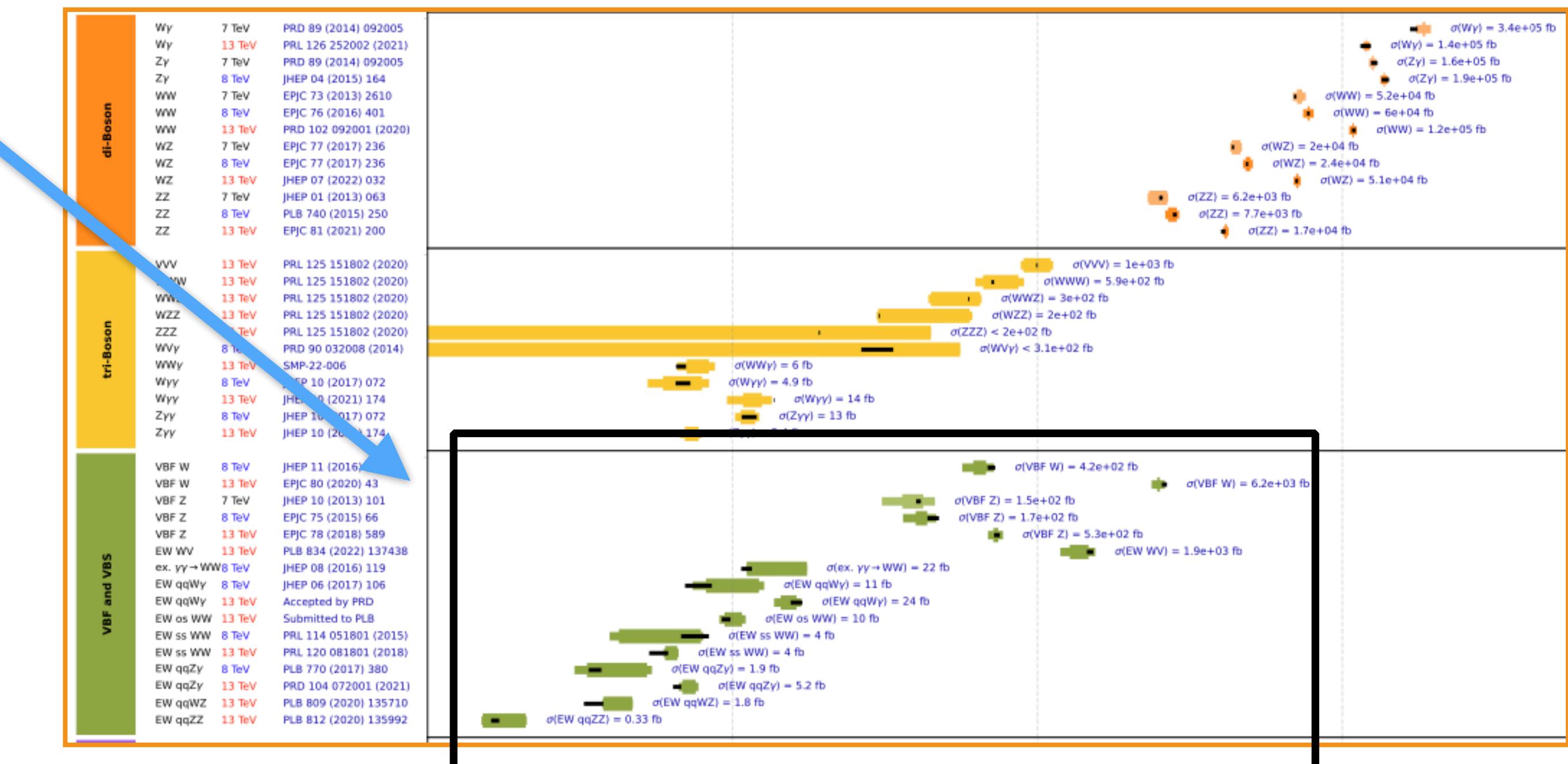
- **V-boson interactions** with the **Higgs field regularises** the **VBS cross section** at high energies cancelling diverging terms from bosonic couplings
- A **delicate equilibrium** between different *interactions* and their **interference** results in a **finite cross section prediction** along the VBS mass spectrum
- Presence of **new physics may distort** the **VBS scattering kinematics** and be detected as an **energy-growth** of the differential **VBS cross-section**
- This hypothetical behaviour is independent from the underlying new physics → **model-agnostic probe**



- CMS in Run2 recorded $\sim 140 \text{ fb}^{-1}$ of pp collisions

VBS results & measurements

- VBS observed in several final states**
- Measured fiducial cross-sections agree, within uncertainties, with SM predictions**
- First **differential cross section** measurements and 1D-2D **unfolded distributions**
- Indirect search for new physics** along the VBS spectrum
 - Effective field theory paradigm** introducing operators that can modify TGC, QGC, HVV, etc.
 - 95% CL upper limits** on strength of EFT dim-8 or dim-6 operators



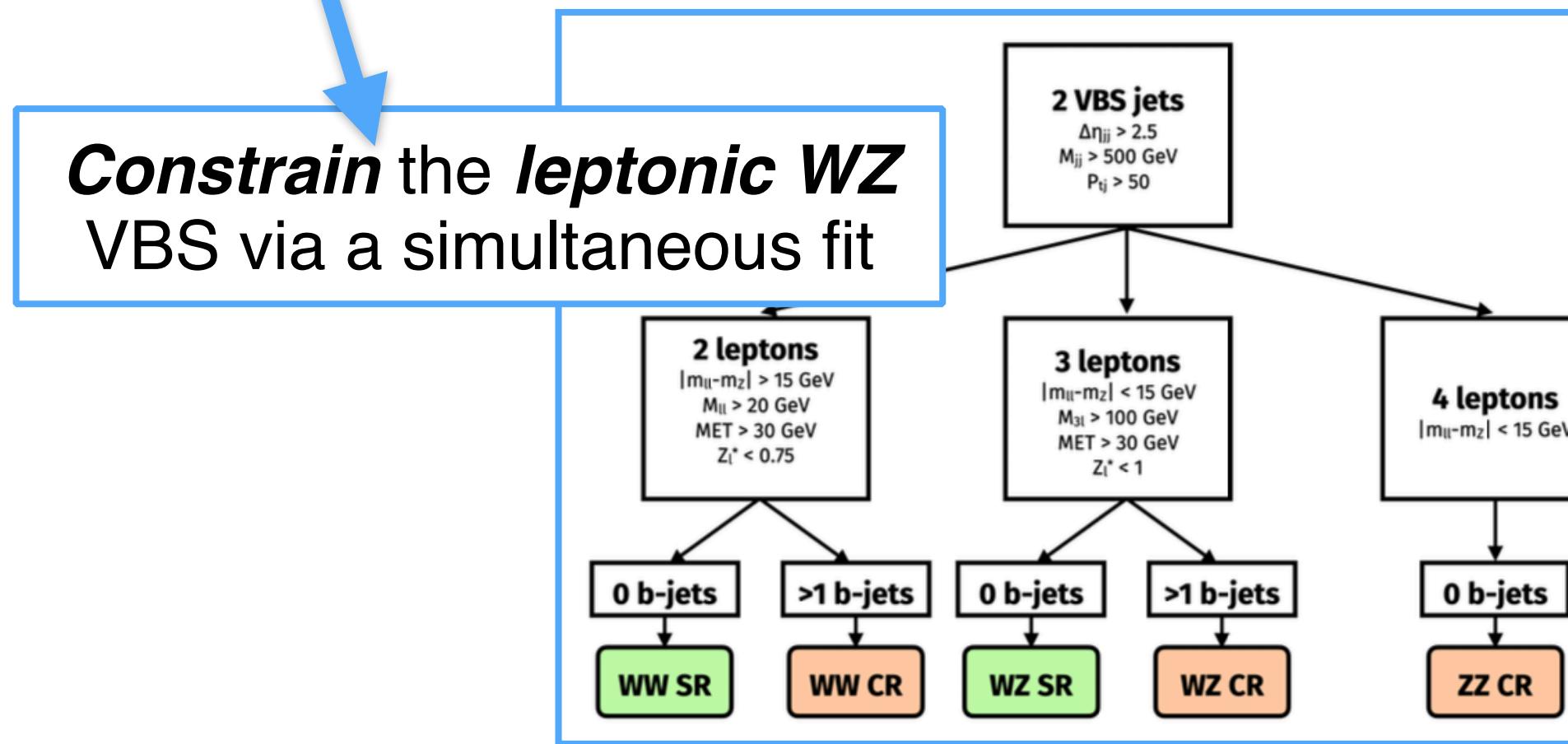
Leptonic VBS $W^\pm W^\pm \rightarrow 2l^\pm 2\nu$

- Final state:** 2 same-charged leptons (μ, e) + E_T^{miss}
- Golden channel:** among the VBS processes is that with **highest S/B** \rightarrow negligible QCD-induced bkg

Backgrounds:

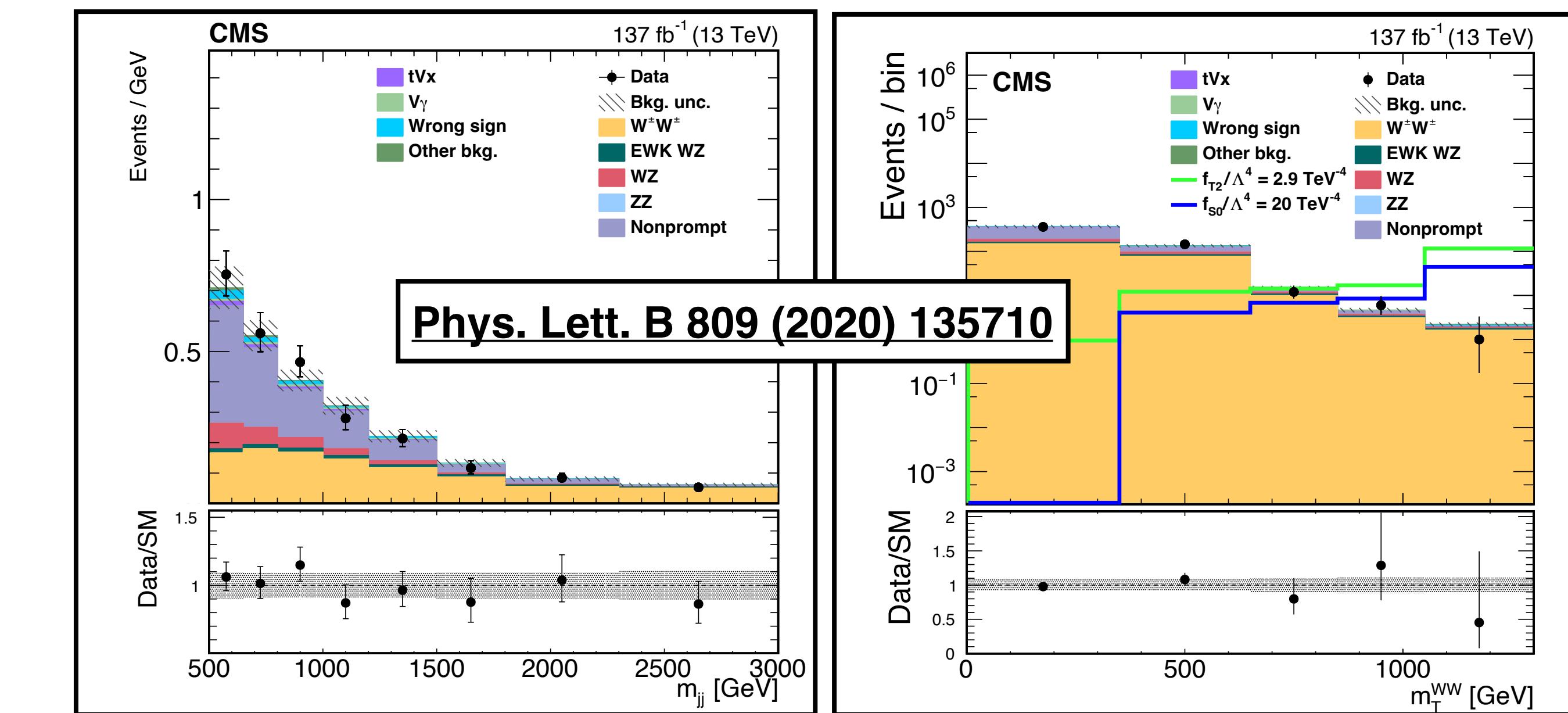
- Dominant non-prompt lepton bkg** estimated from data
- Leptonic VBS** $WZjj, ZZjj$ when at least one lepton is out of acceptance or not identified
- QCD-induced $W^\pm W^\pm, WZ, ZZ + \text{jets}$ **estimated** from **dedicated CRs**

Constrain the leptonic WZ VBS via a simultaneous fit



Measurements:

- Simultaneous ML fit across 5 regions. **NLO EW+QCD corrections** included for the $W^\pm W^\pm$ and WZ VBS processes
- Fiducial inclusive** and **differential cross section** in SR from a **2D fit** to $m(jj)$ - $ml(l\bar{l})$ distributions
- Search** for **aQGCs** in **dim-8 EFT** from a fit to the $m_T(WW)$ distribution. **Strong sensitivity** to $T0, T1, T2, S0, S1, M0, M1$

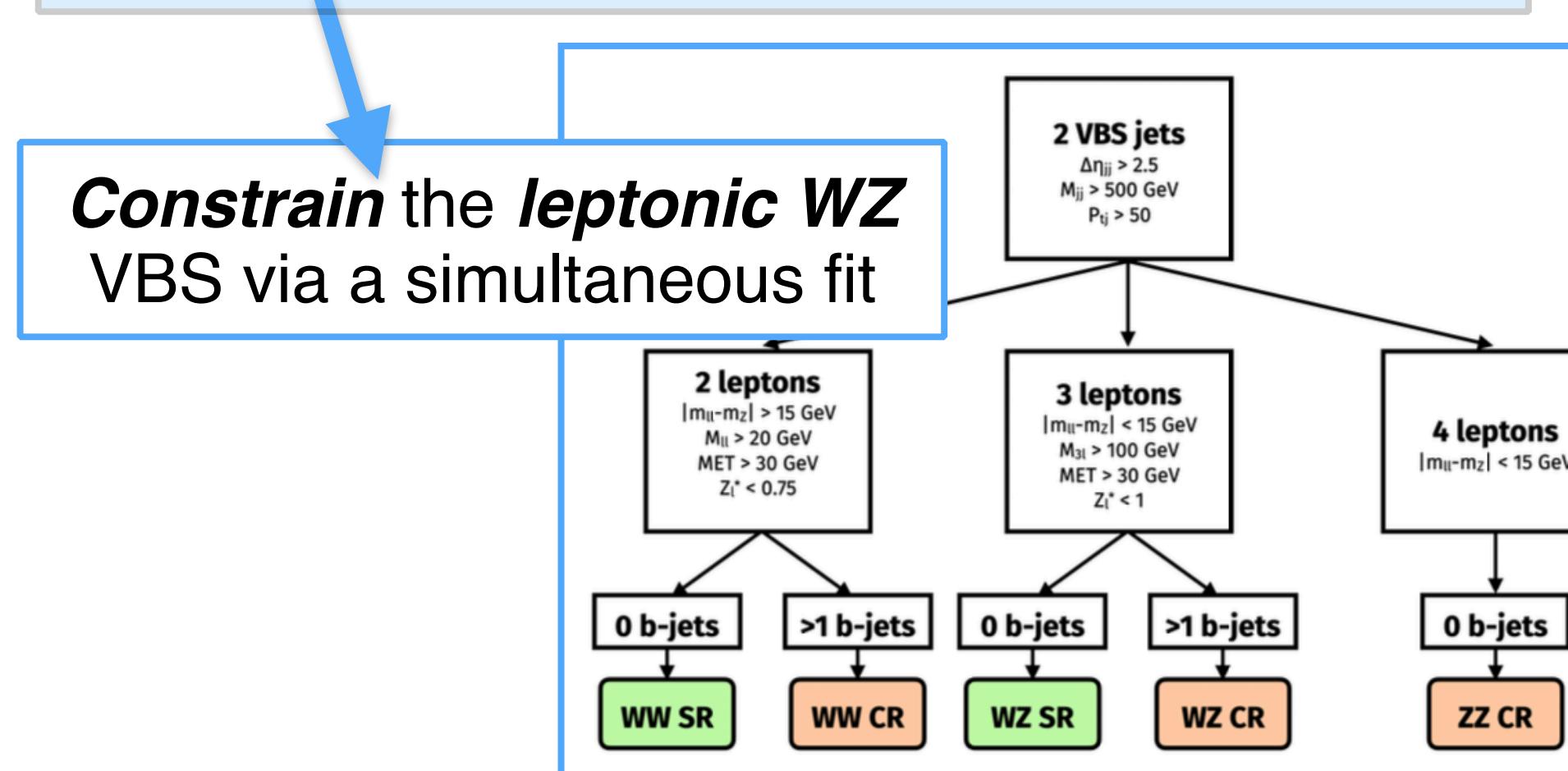


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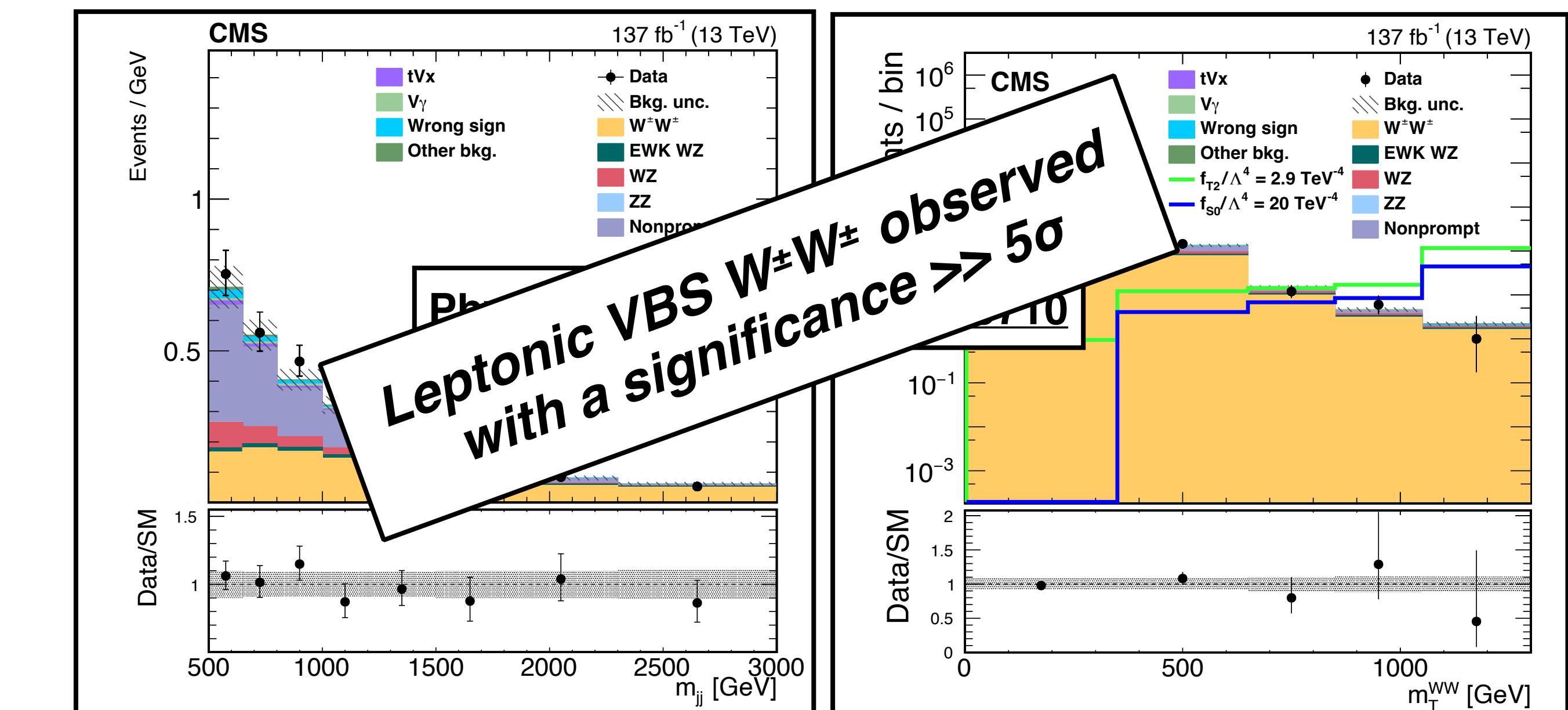
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Leptonic VBS $W^\pm Z \rightarrow 3l^\pm\nu$

- Final state:** 3 leptons (μ, e), two compatible with on-shell Z-boson decays, and E_T^{miss}
- Second best VBS** process studied at LHC after leptonic VBS $W^\pm W^\pm$

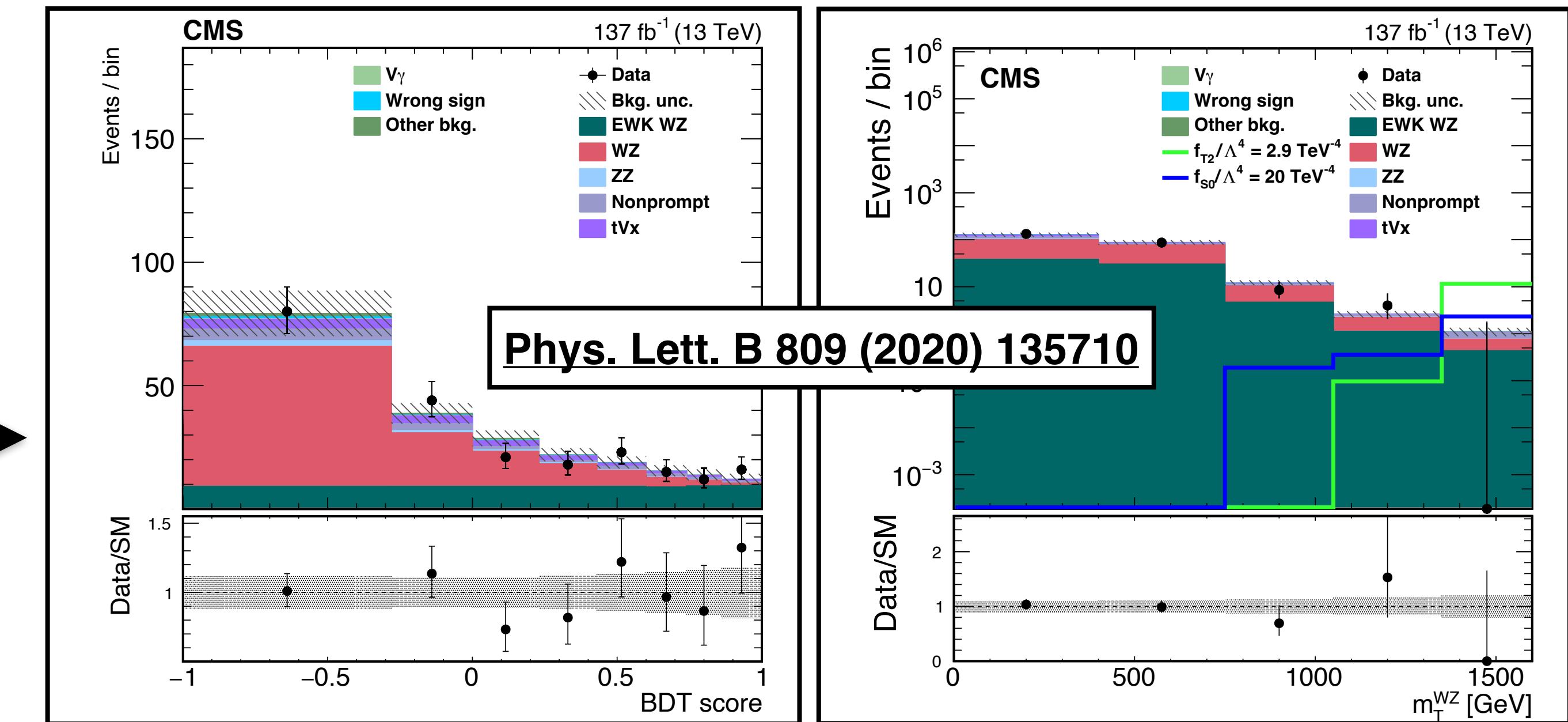
Backgrounds:

- Dominant QCD-induced** production of a WZ pair + 2-jets
- Non-prompt lepton bkg** estimated from data
- QCD and EW** induced ZZ + jets from a control region in data

Variable	Definition
m_{jj}	Mass of the leading and trailing jets system
$\Delta\eta_{jj}$	Absolute difference in rapidity of the leading and trailing jets
$\Delta\phi_{jj}$	Difference in azimuth angles of the leading and trailing jets
p_T^{j1}	p_T of the leading jet
p_T^{j2}	p_T of the trailing jet
η^{j1}	Pseudorapidity of the leading jet
$ \eta^W - \eta^Z $	Absolute difference between the rapidities of the Z boson and the lepton from the decay of the W boson
$z_{\ell_i}^*(i = 1, 2, 3)$	Zeppenfeld variable of the three selected leptons: $z_{\ell_i}^* = \eta_{\ell_i} - (\eta_{j1} + \eta_{j2})/2 / \Delta\eta_{jj}$
$z_{3\ell}^*$	Zeppenfeld variable of the triple-lepton system
$\Delta R_{j1,Z}$	The ΔR between the leading jet and the Z boson
$ p_T^{\text{tot}} / \sum_i p_T^i$	Transverse component of the vector sum of the bosons and tagging jets momenta, normalised to their scalar p_T sum

Measurements:

- Simultaneous ML fit across 5 regions as described in the previous slide
- Fiducial inclusive and differential cross section** from a **fit to a BDT discriminant** trained to enhance S/B
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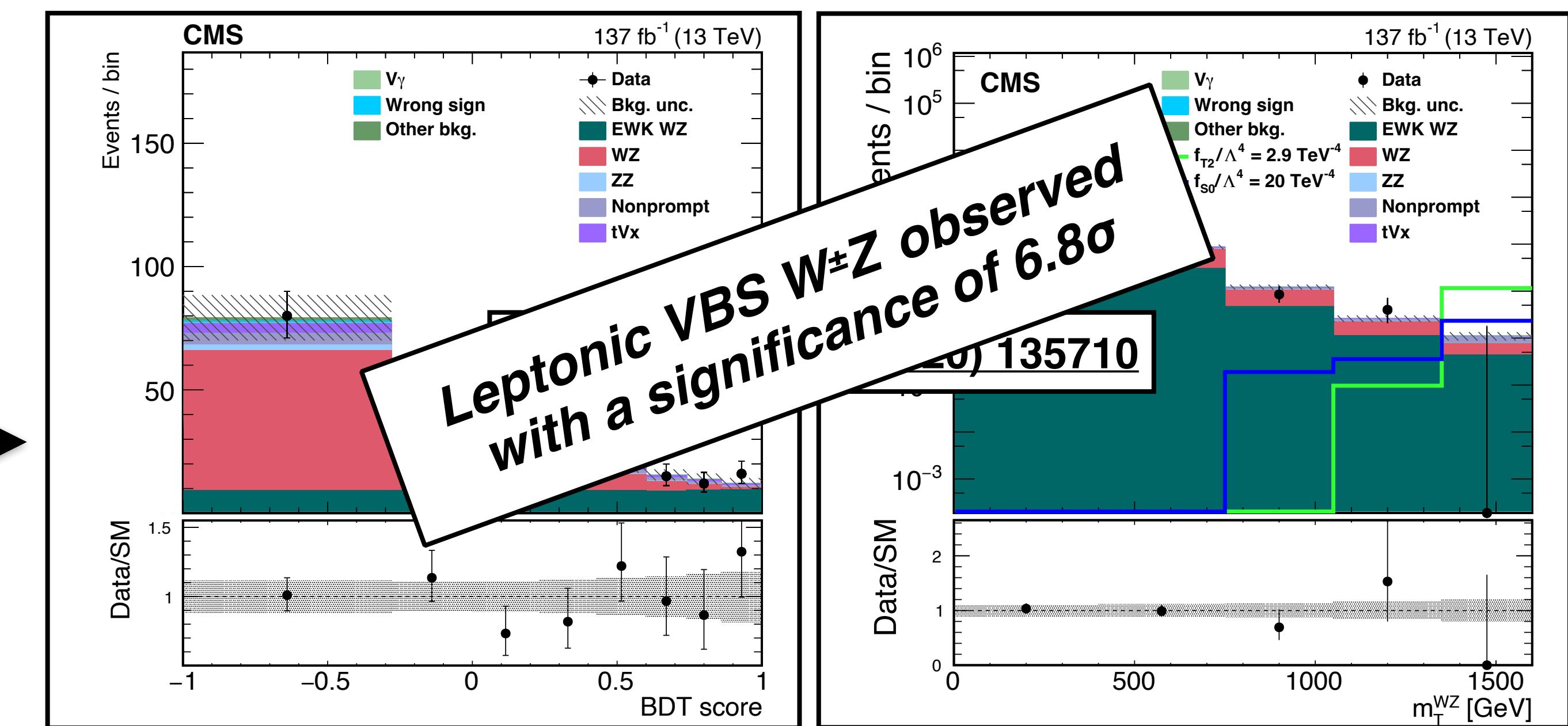
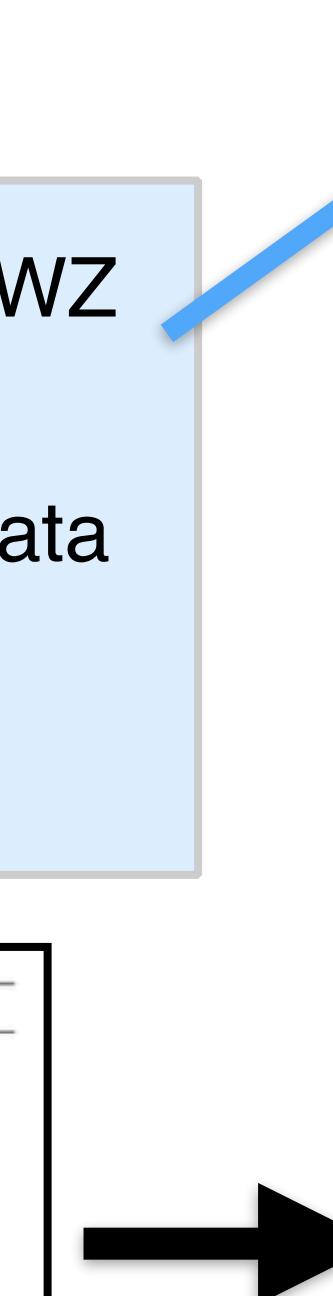
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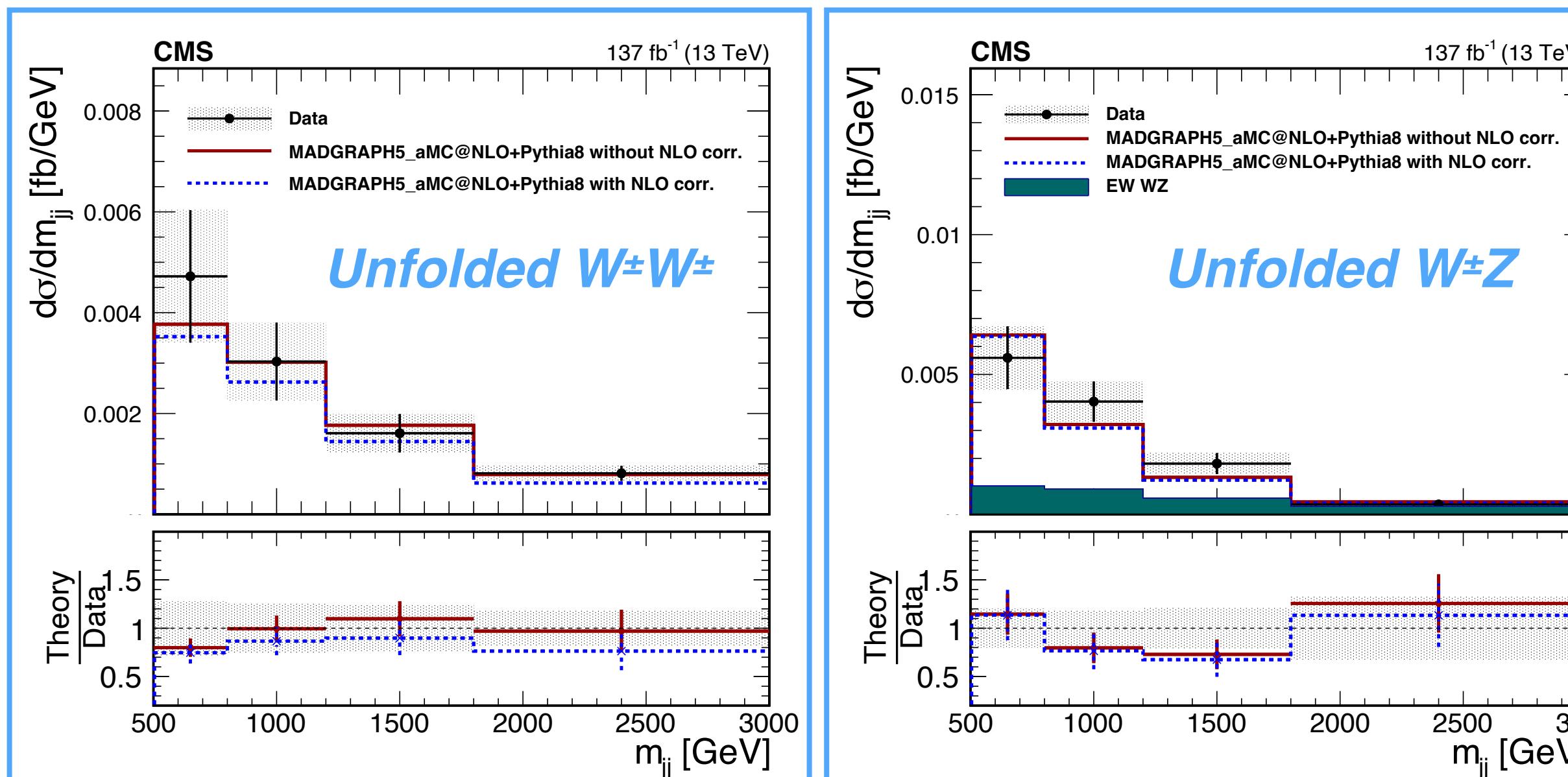


VBS $W^\pm W^\pm$ and $W^\pm Z$: results

- **Inclusive** and **differential** cross section measurements performed for both $W^\pm W^\pm$ and WZ VBS processes
- **Inclusive $W^\pm W^\pm$** sensitive to **systematic** uncertainties, while **WZ** one mostly limited by **statistics**

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 $0.39(\text{stat}) + 0.25(\text{syst})$	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

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Upper limits on dim-8 EFT operators

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{f_i^{(6)}}{\Lambda^2} O_i + \sum_j \frac{f_j^{(8)}}{\Lambda^4} O_j + \dots$$

	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]
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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]

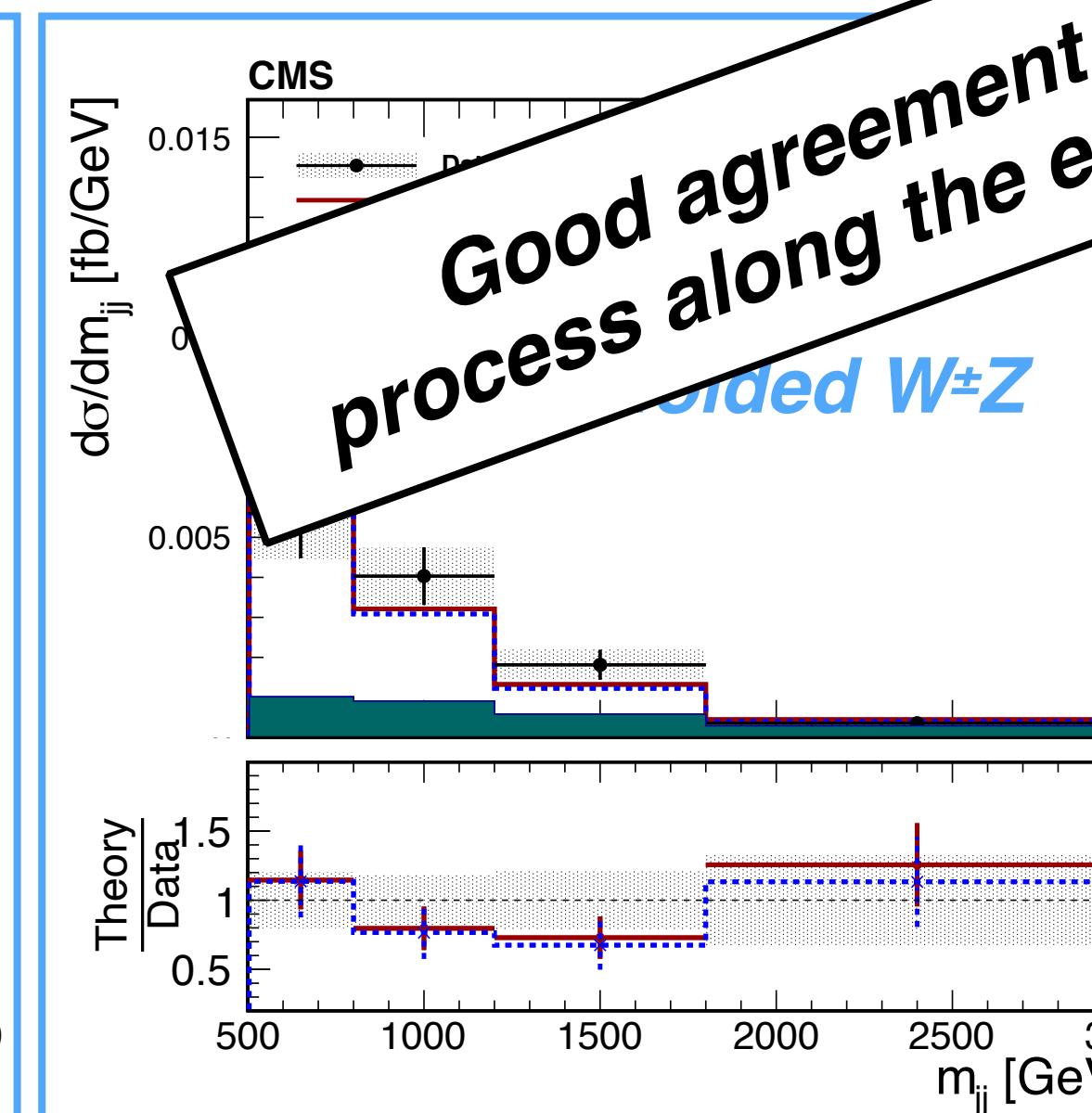
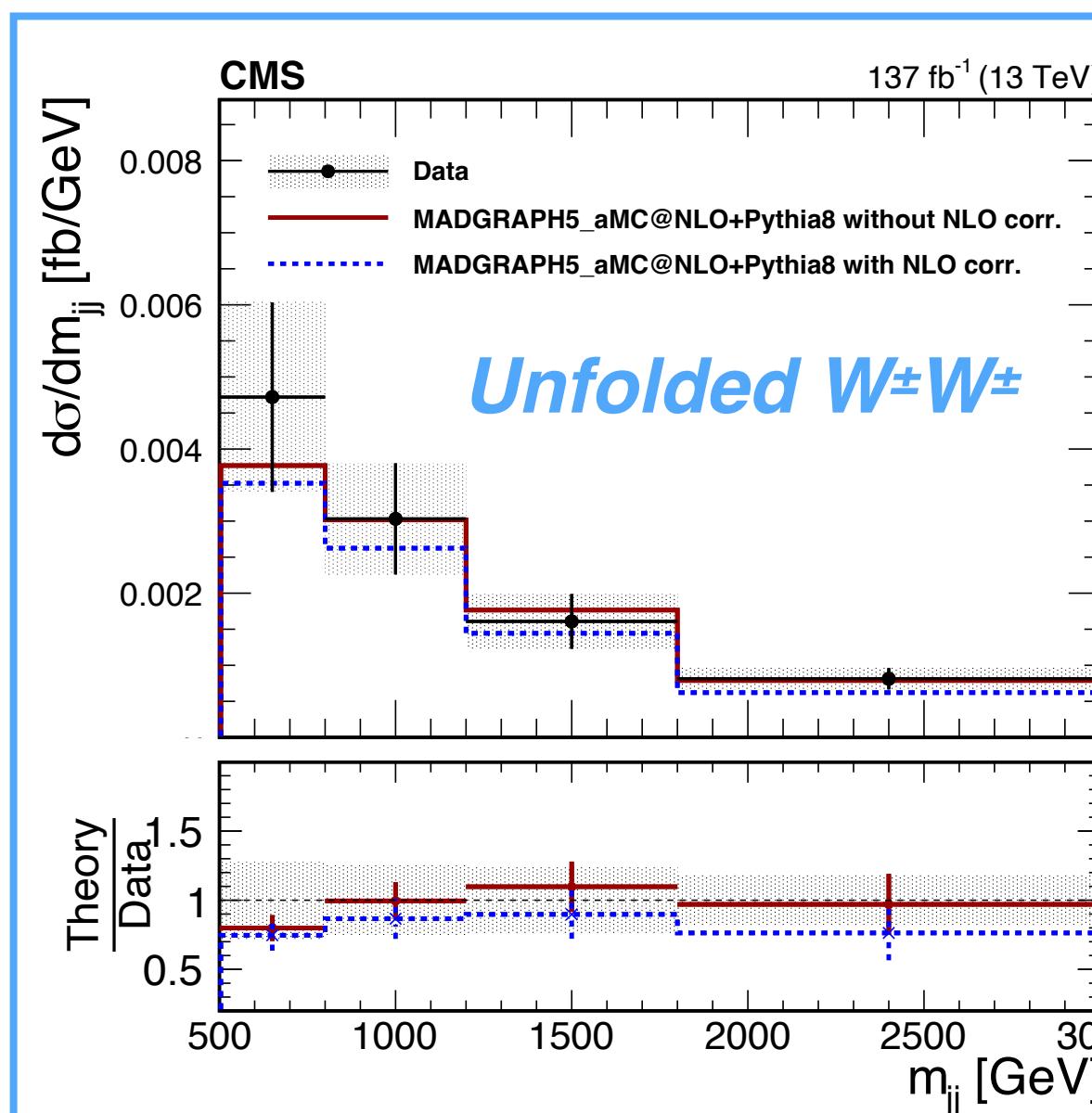
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Good agreement with SM for both process along the entire SR phase-space on dim-8 EFT operators

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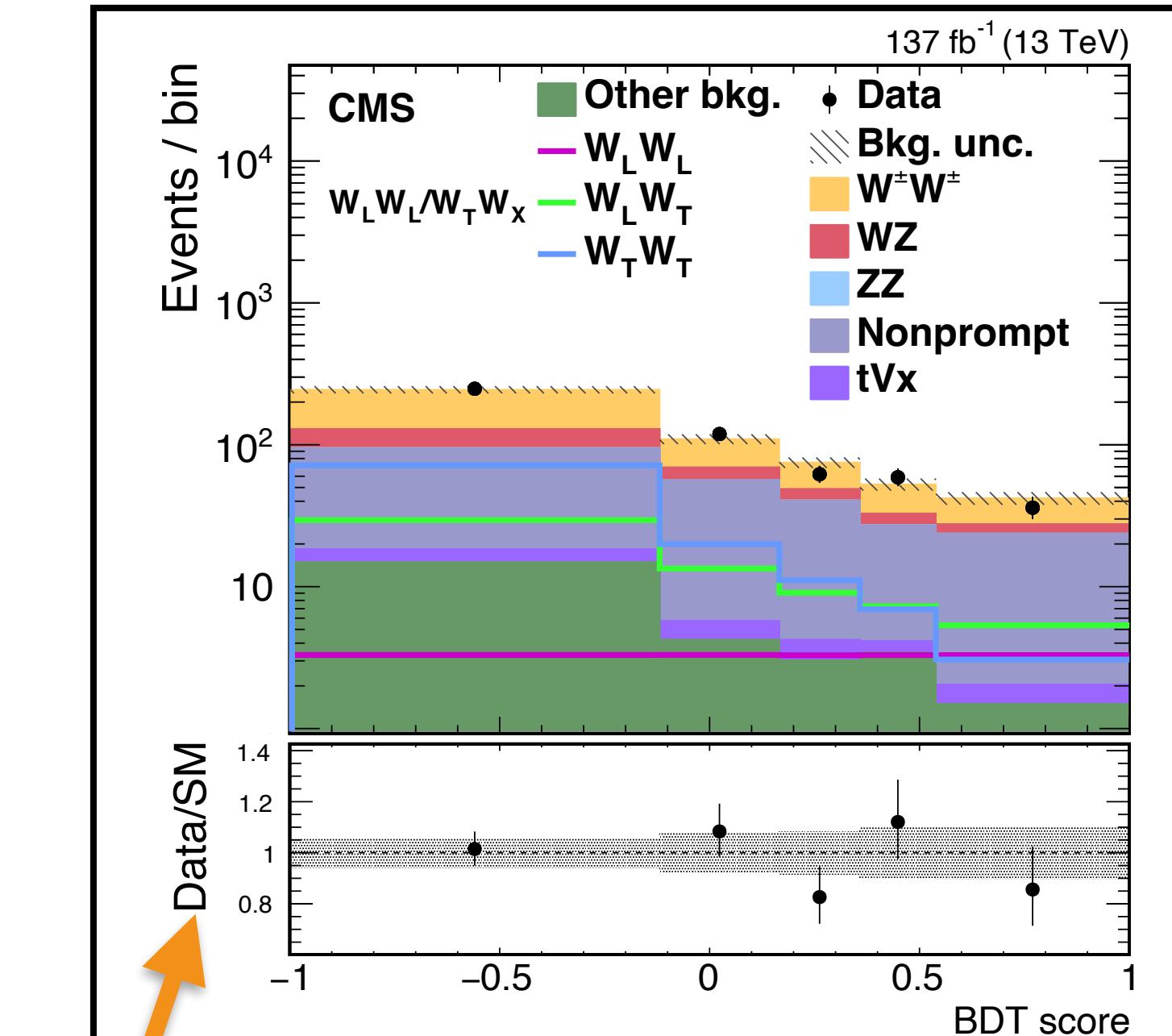
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Leptonic VBS $W^\pm W^\pm$: polarized cross-sections

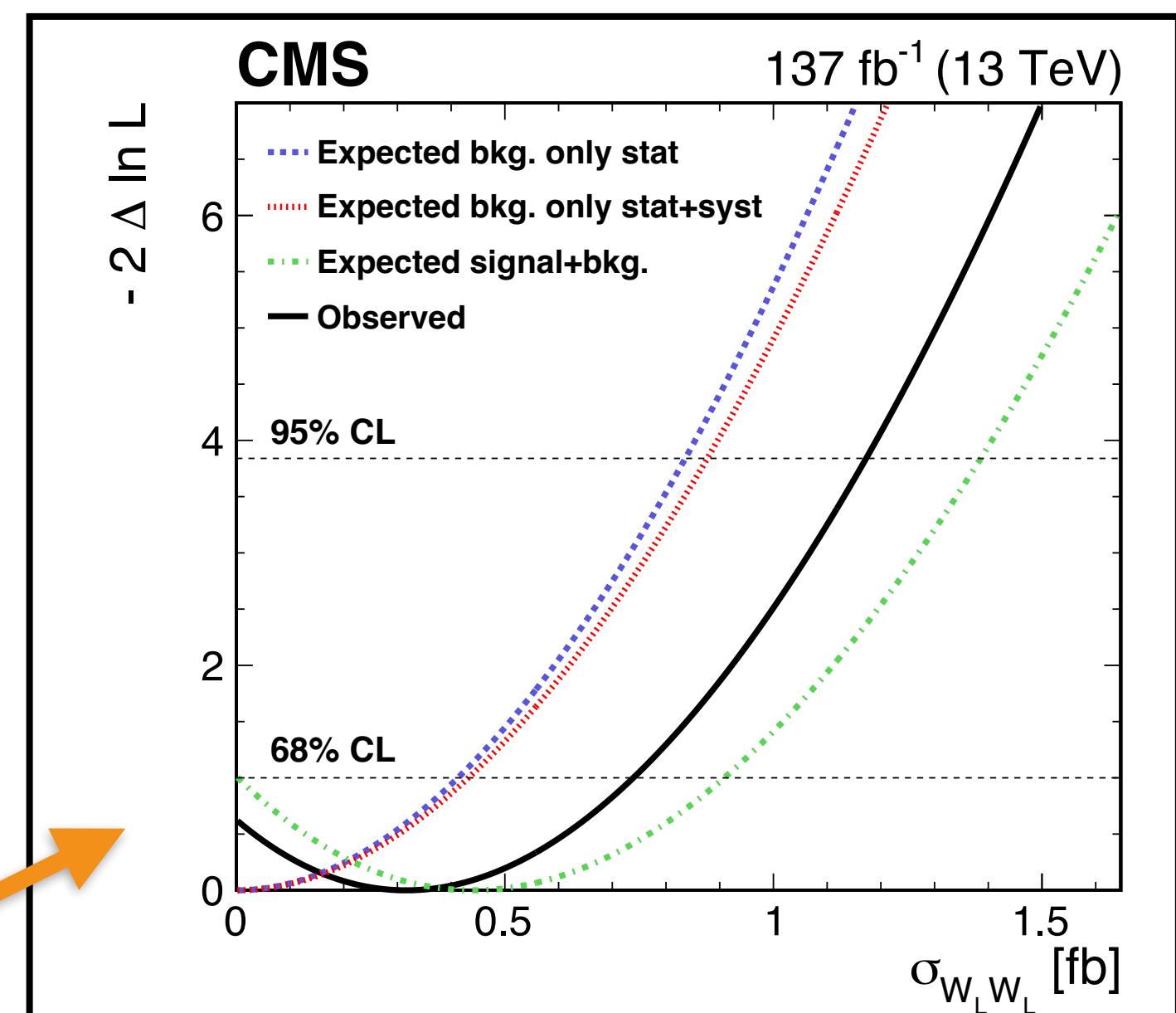
- **Final state:** 2 same-charged leptons (μ, e) + E_T^{miss}
- **Goal:** use the most sensitive VBS analysis to measured the polarized scattering components
- **Backgrounds:** already discussed in Slide 5
- **Helicity eigenstates** are frame dependent as the chirality and not the helicity is frame-invariant
 - **Frame 1:** initial parton reference frame
 - **Frame 2:** rest frame of the two W-bosons

Signal extraction

- **Inclusive BDT** trained to separate $W^\pm W^\pm$ from SM backgrounds
- **Signal BDT** trained to separate $W_T^\pm W_T^\pm$ from either $W_L^\pm W_L^\pm$ or $W_T^\pm W_L^\pm$
- In the **SR** a **simultaneous 2D fit** on the output of these BDTs is performed



[Phys. Lett. B812\(2020\)136018](#)



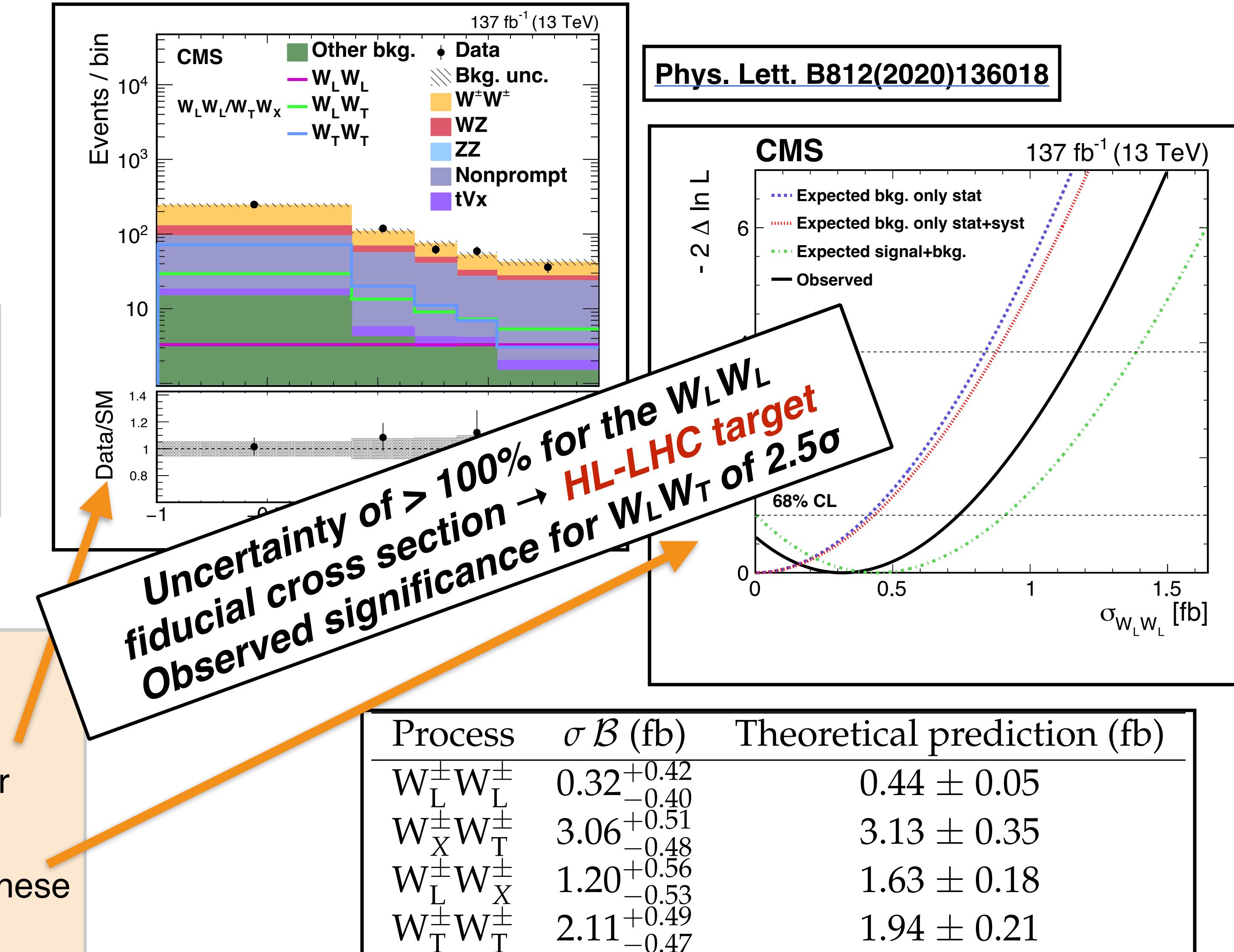
Process	$\sigma \mathcal{B}$ (fb)	Theoretical prediction (fb)
$W_L^\pm W_L^\pm$	$0.32^{+0.42}_{-0.40}$	0.44 ± 0.05
$W_X^\pm W_T^\pm$	$3.06^{+0.51}_{-0.48}$	3.13 ± 0.35
$W_L^\pm W_X^\pm$	$1.20^{+0.56}_{-0.53}$	1.63 ± 0.18
$W_T^\pm W_T^\pm$	$2.11^{+0.49}_{-0.47}$	1.94 ± 0.21

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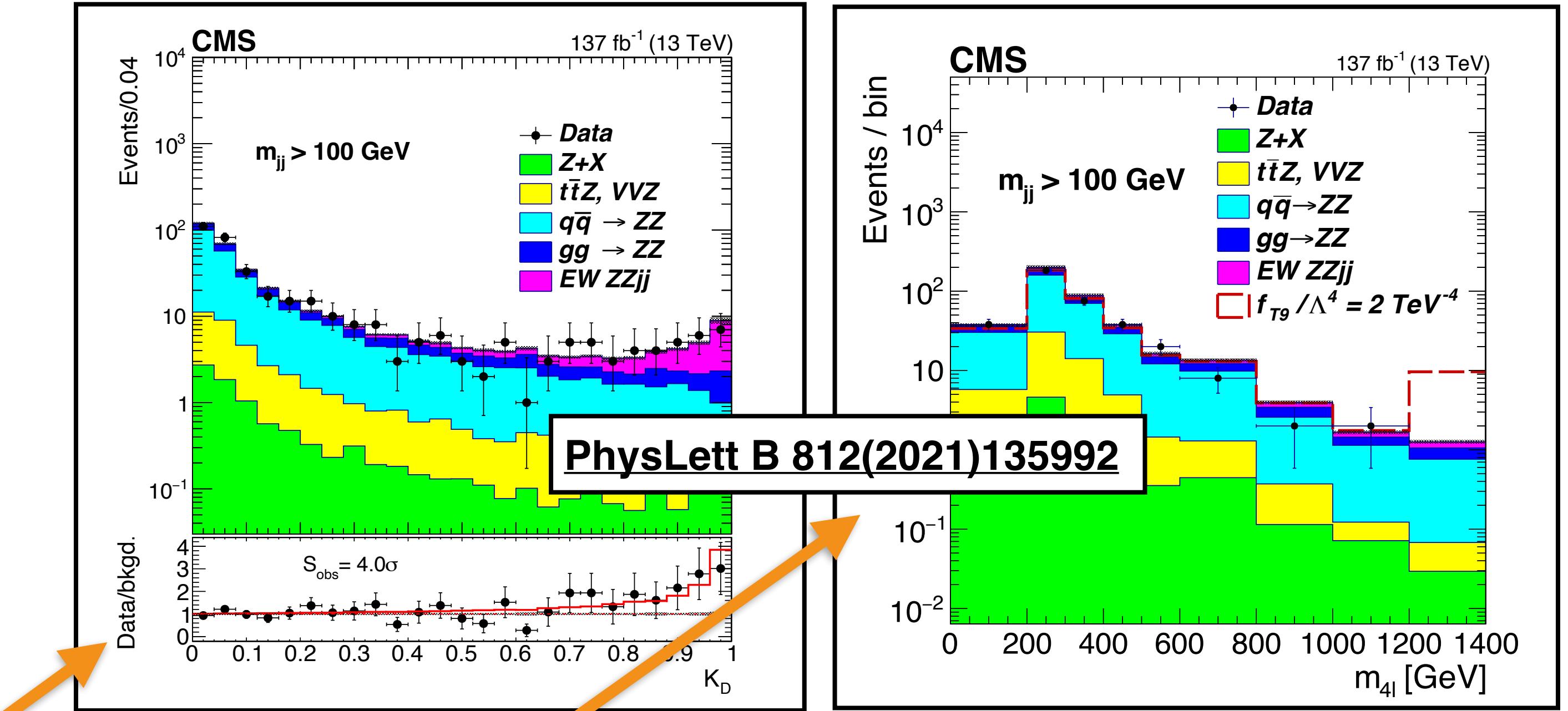


Leptonic VBS ZZ \rightarrow 4l

- **Final state:** 2 VBS-jets + two pairs of opposite charge same flavour leptons from on-shell Z-decay

Backgrounds:

- **QCD-induced ZZjj** production at $O(\alpha_{EW}^4 \alpha_{QCD}^2)$ from $q\bar{q}$ and gg
- **Irreducible** ttZ+jets and VVZ+jets
- **Reducible** non-prompt lepton background (Z+X) from DY, ttbar, etc



Measurements:

- **Fiducial cross section** in $m(jj) > 400$ GeV or $m(jj) > 1$ TeV by extracting the signal from a fit to a **kinematic discriminant (K_D)**
- **Search** for **aQGCs** in **dim-8 EFT** from a fit to **$m(ZZ)$** distribution. Sensitive to neutral (T_0, T_1, T_2) and **charged operators (T_8, T_9)**

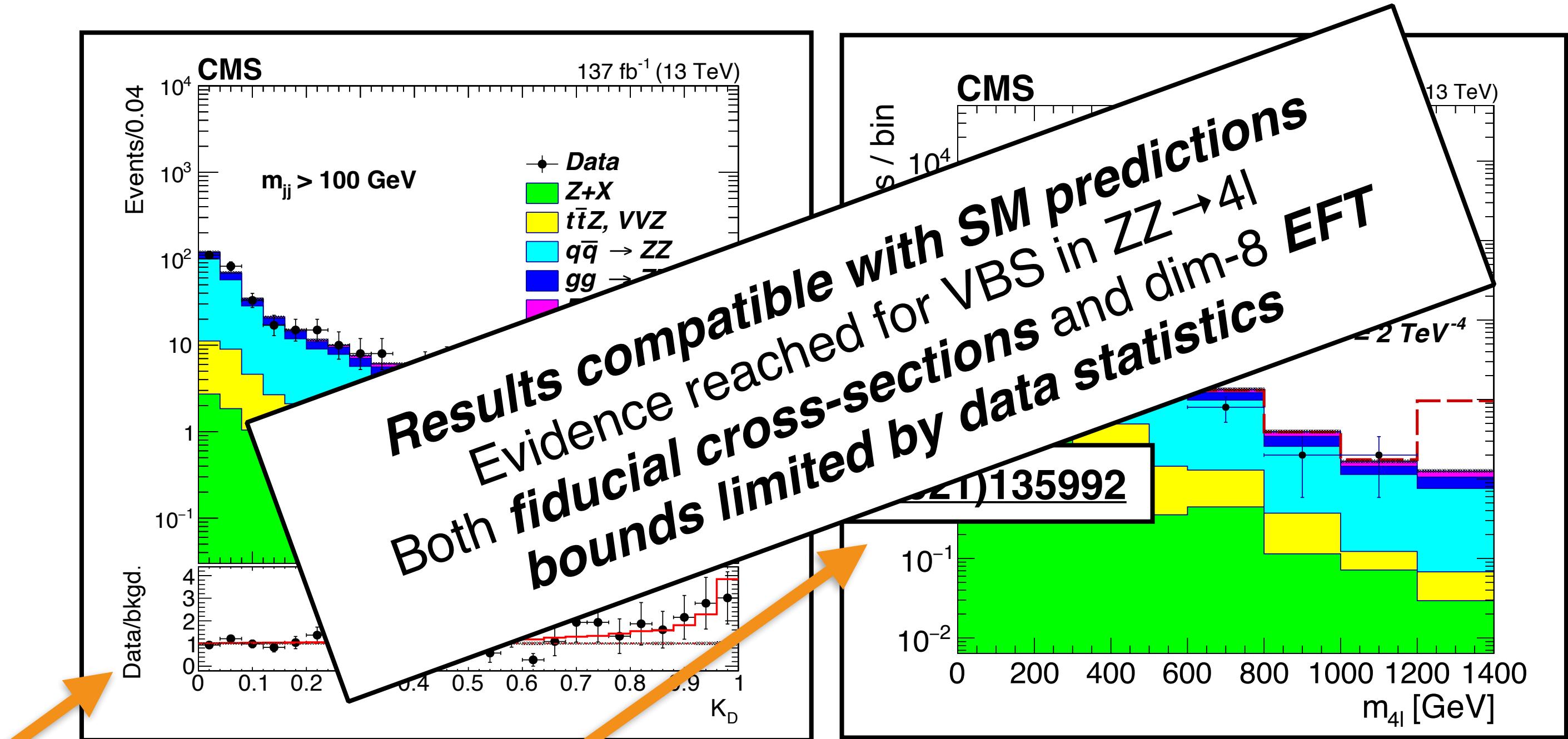
	Perturbative order	SM σ (fb)	Measured σ (fb)
EW	LO	ZZjj inclusive	0.275 ± 0.021
	NLO QCD	0.278 ± 0.017	$0.33^{+0.11}_{-0.10}$ (stat) $^{+0.04}_{-0.03}$ (syst)
EW+QCD	LO	5.35 ± 0.51	$5.29^{+0.31}_{-0.30}$ (stat) ± 0.46 (syst)
	NLO QCD	0.186 ± 0.015	$0.200^{+0.078}_{-0.067}$ (stat) $^{+0.023}_{-0.013}$ (syst)
EW	LO	0.197 ± 0.013	$1.00^{+0.12}_{-0.11}$ (stat) $^{+0.06}_{-0.05}$ (syst)
	NLO QCD	1.21 ± 0.09	
EW+QCD	LO	0.104 ± 0.008	$0.09^{+0.04}_{-0.03}$ (stat) ± 0.02 (syst)
	NLO QCD	0.108 ± 0.007	
EW	LO	0.221 ± 0.014	$0.20^{+0.05}_{-0.04}$ (stat) ± 0.02 (syst)
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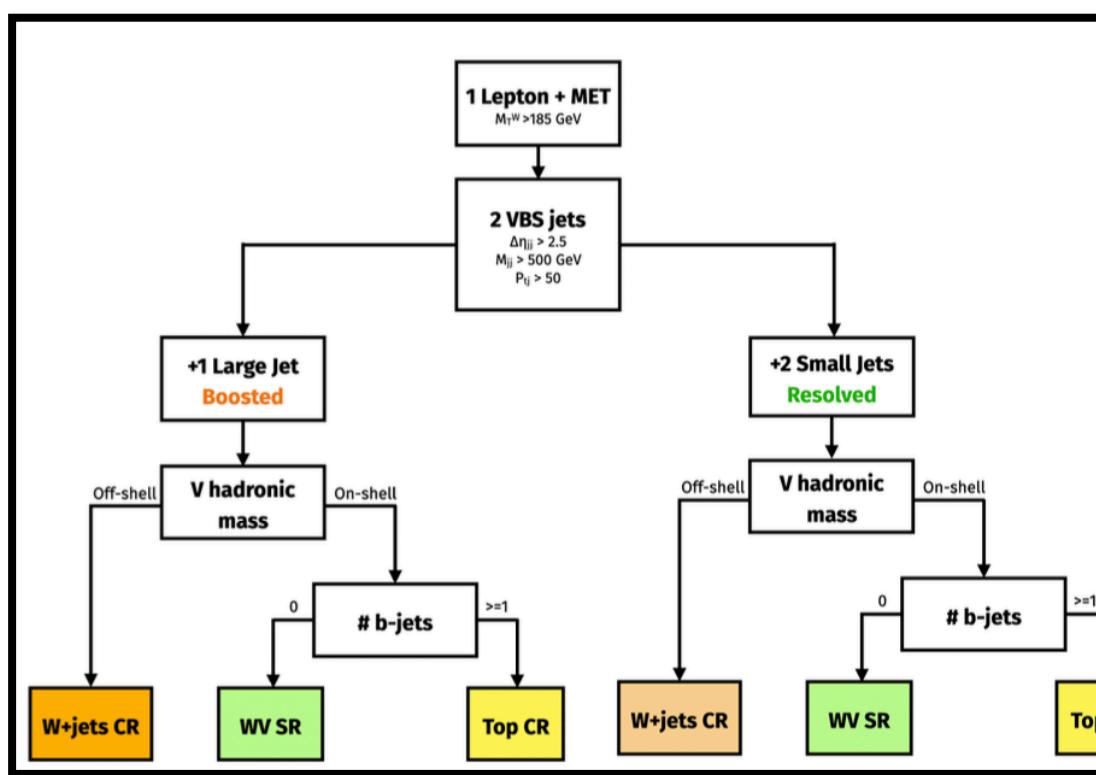
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EW+QCD		1.21 ± 0.09	$1.00^{+0.12}_{-0.11} (\text{stat})^{+0.06}_{-0.05} (\text{syst})$
		VBS-enriched (tight)	
EW	LO	0.104 ± 0.008	$0.09^{+0.04}_{-0.03} (\text{stat}) \pm 0.02 (\text{syst})$
	NLO QCD	0.108 ± 0.007	
EW+QCD		0.221 ± 0.014	$0.20^{+0.05}_{-0.04} (\text{stat}) \pm 0.02 (\text{syst})$

Semi-leptonic VBS $W^\pm V \rightarrow l\nu jj$

- **Final state:** 4-jets, one charged lepton (e, μ), E_T^{miss} .
Experimentally impossible to separate $W(\text{qq}')$ from $Z(\text{qq})$

Backgrounds:

- **Dominant $W+\text{jets}$** whose normalisation estimated from data vs $p_T(W)$
- Irreducible **$QCD\text{-induced } WVjj$** production
- **Non prompt lepton** estimated from data
- **Other contributions:** DY+jets, ttbar, etc
- **Analysis categories:** **boosted** (high $p_T(W)$) and **resolved**, plus $W+\text{jets}$ and ttbar control regions

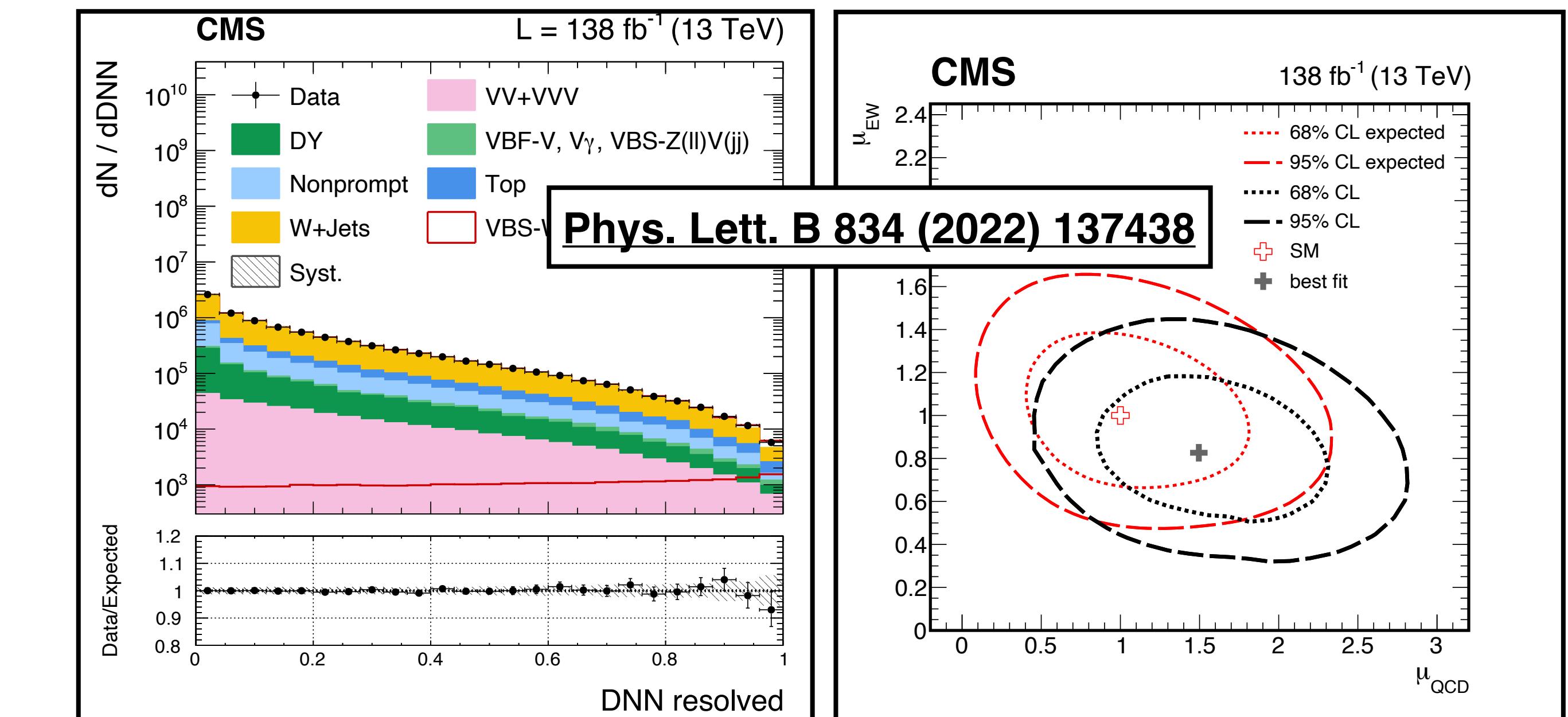


Measurements:

- **Signal extracted** from a fit to the ***output of a DNN***
- **Fiducial inclusive cross section** measurement for **pure EW** VBS and ***QCD-induced WV*** background

$$\begin{aligned}\mu_{EW} &= 0.85 \pm 0.12(\text{stat})^{+0.19}_{-0.17}(\text{syst}) = 0.85^{+0.23}_{-0.21} \\ \mu_{EW+QCD} &= 0.97 \pm 0.06(\text{stat})^{+0.19}_{-0.21}(\text{syst}) = 0.97^{+0.20}_{-0.22}\end{aligned}$$

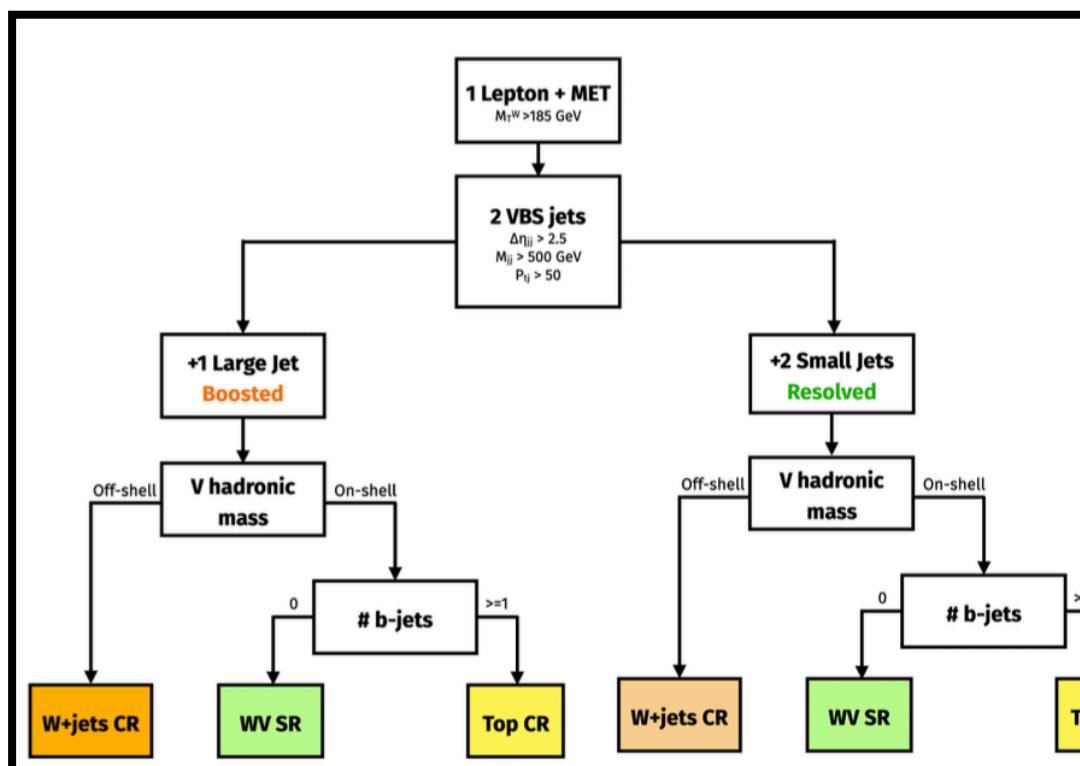
limited by systematics



- **Final state:** 4-jets, one charged lepton (e, μ), E_T^{miss} .
Experimentally impossible to separate $W(\text{qq}')$ from $Z(\text{qq})$

Backgrounds:

- **Dominant $W+\text{jets}$** whose normalisation estimated from data vs $p_T(W)$
- Irreducible **$QCD\text{-induced } WVjj$** production
- **Non prompt lepton** estimated from data
- **Other contributions:** DY+jets, ttbar, etc
- **Analysis categories:** **boosted** (high $p_T(W)$) and **resolved**, plus $W+\text{jets}$ and ttbar control regions

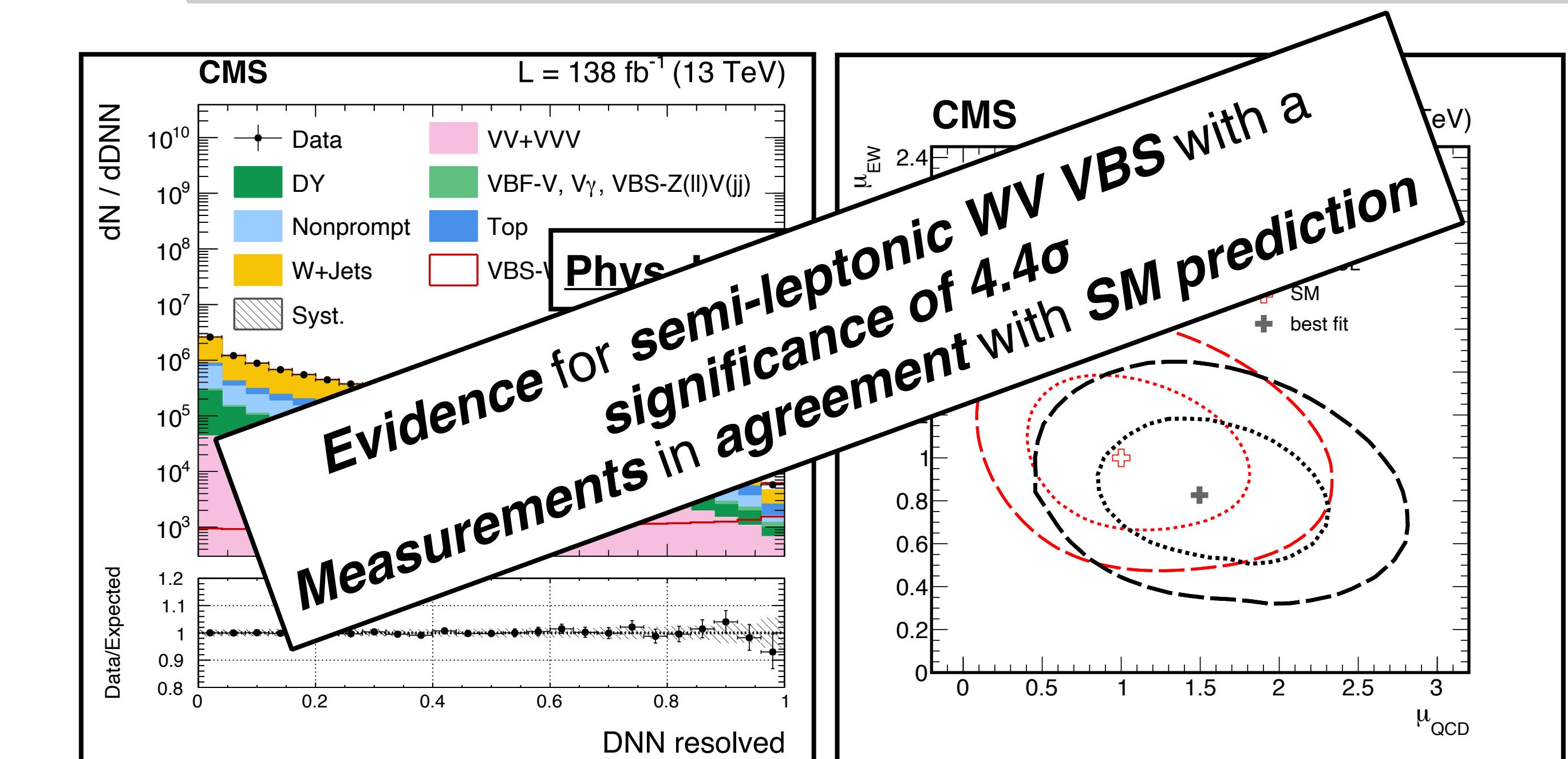


Measurements:

- **Signal extracted** from a fit to the ***output of a DNN***
- **Fiducial inclusive cross section** measurement for **pure EW VBS** and **$QCD\text{-induced } WV$ background**

$$\begin{aligned}\mu_{EW} &= 0.85 \pm 0.12(\text{stat})^{+0.19}_{-0.17}(\text{syst}) = 0.85^{+0.23}_{-0.21} \\ \mu_{EW+QCD} &= 0.97 \pm 0.06(\text{stat})^{+0.19}_{-0.21}(\text{syst}) = 0.97^{+0.20}_{-0.22}\end{aligned}$$

limited by systematics



Leptonic VBS $Z\gamma jj$ production

- **Final state:** two opposite charge same flavour leptons (μ, e), one isolated photon, and two VBS-jets
- **FSR contribution** reduced by $m(l\bar{l}\gamma) > 100$ GeV

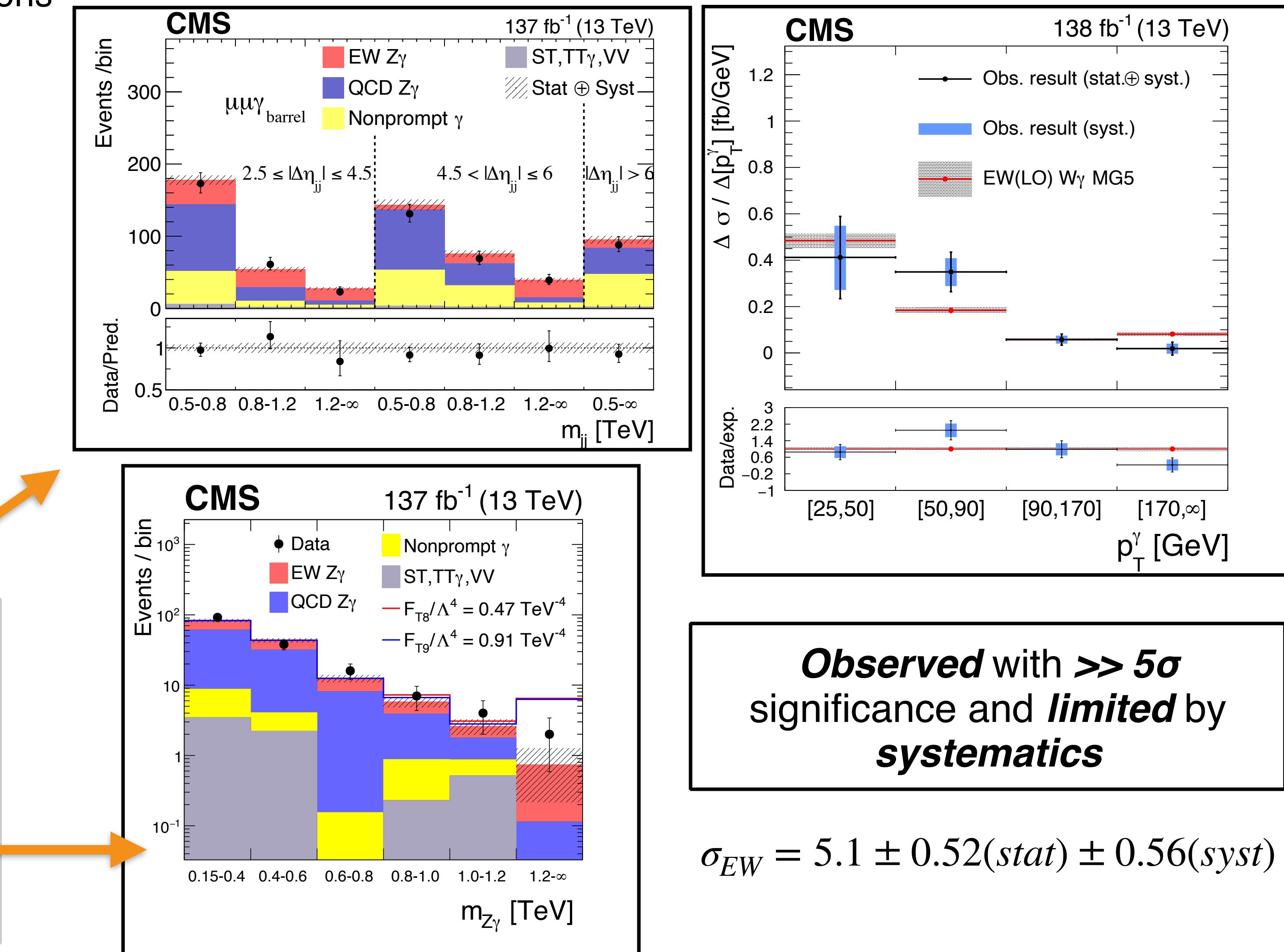
Backgrounds:

- **Dominant QCD-induced $Z\gamma jj$** background. **Normalisation** estimated from **data**
- **Non-prompt photons** estimated from data ($Z+jets$, etc)
- **Other contributions:** VV , $t\bar{t}+\gamma$, etc

Measurements

- **Fiducial cross section** measured for EW $Z\gamma jj$ and EW+QCD $Z\gamma jj$ by a fit to $m(jj)\text{-}\Delta n(jj)$
- **Differential cross section measurements** with unfolding of 1D and 2D distributions
- **Search for aQGCs in dim-8 EFT** fitting $m(Z\gamma)$ distribution. Complementary bounds to $W^\pm W^\pm$

Phys. Rev. D 104, 072001 (2021)



Observed with $>> 5\sigma$ significance and **limited** by **systematics**

$$\sigma_{EW} = 5.1 \pm 0.52(\text{stat}) \pm 0.56(\text{syst})$$

Leptonic VBS $W\gamma jj$ production

[arXiv:2212.12592](https://arxiv.org/abs/2212.12592)

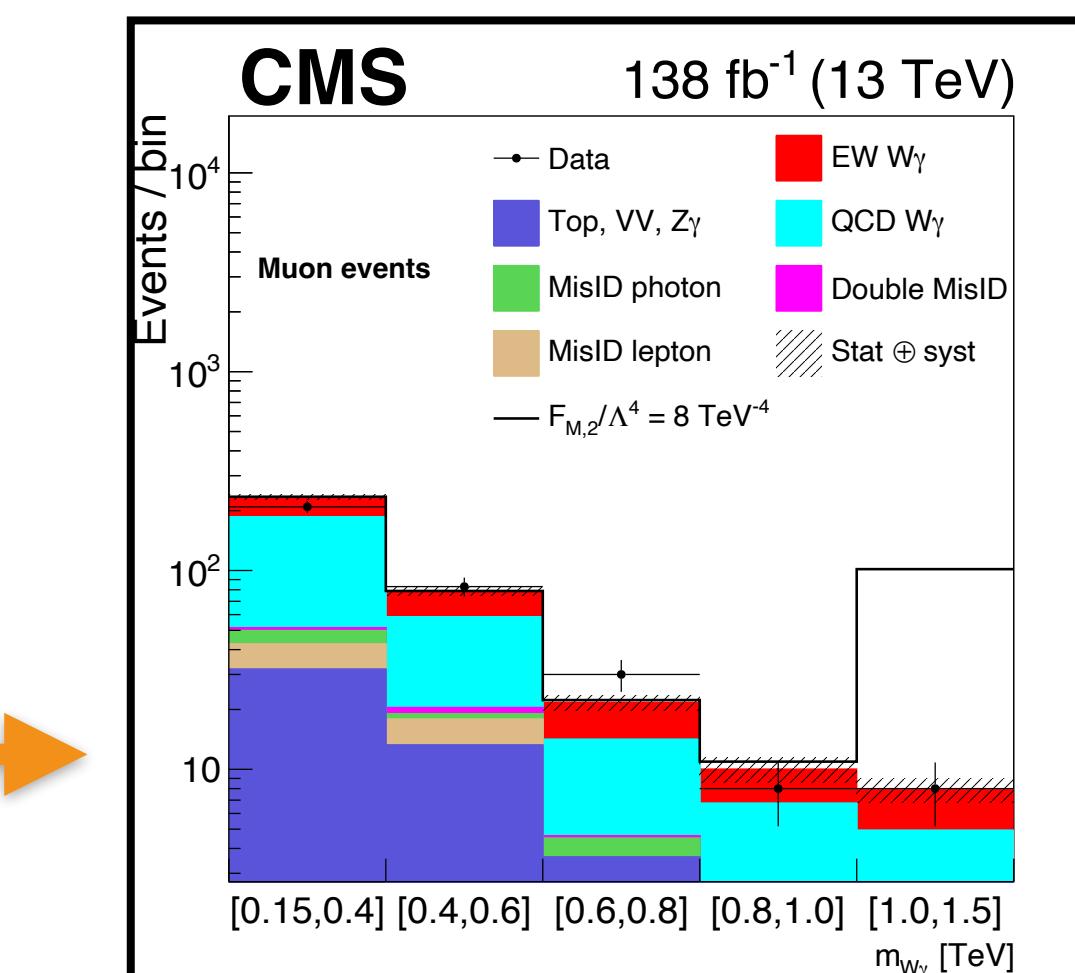
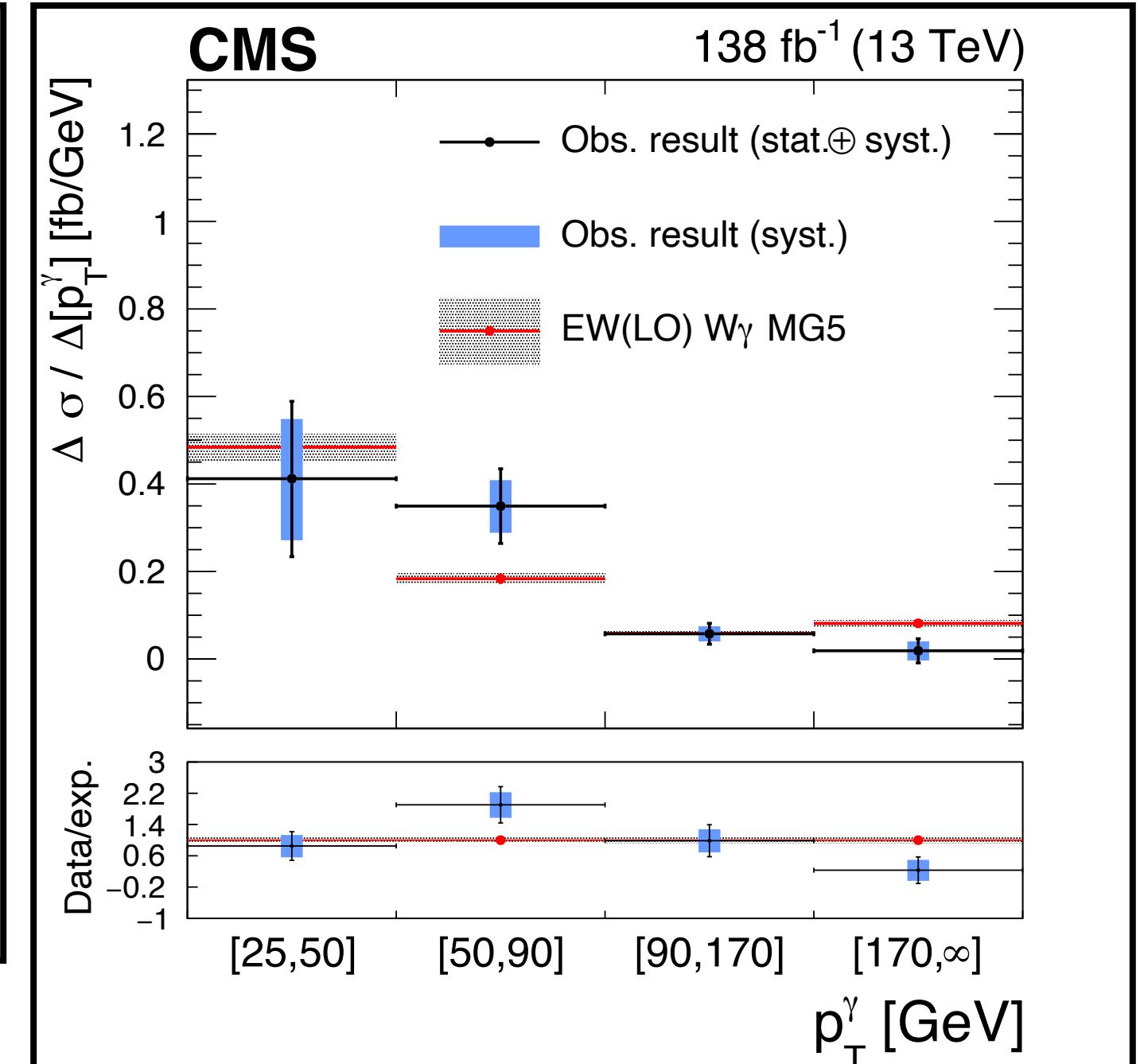
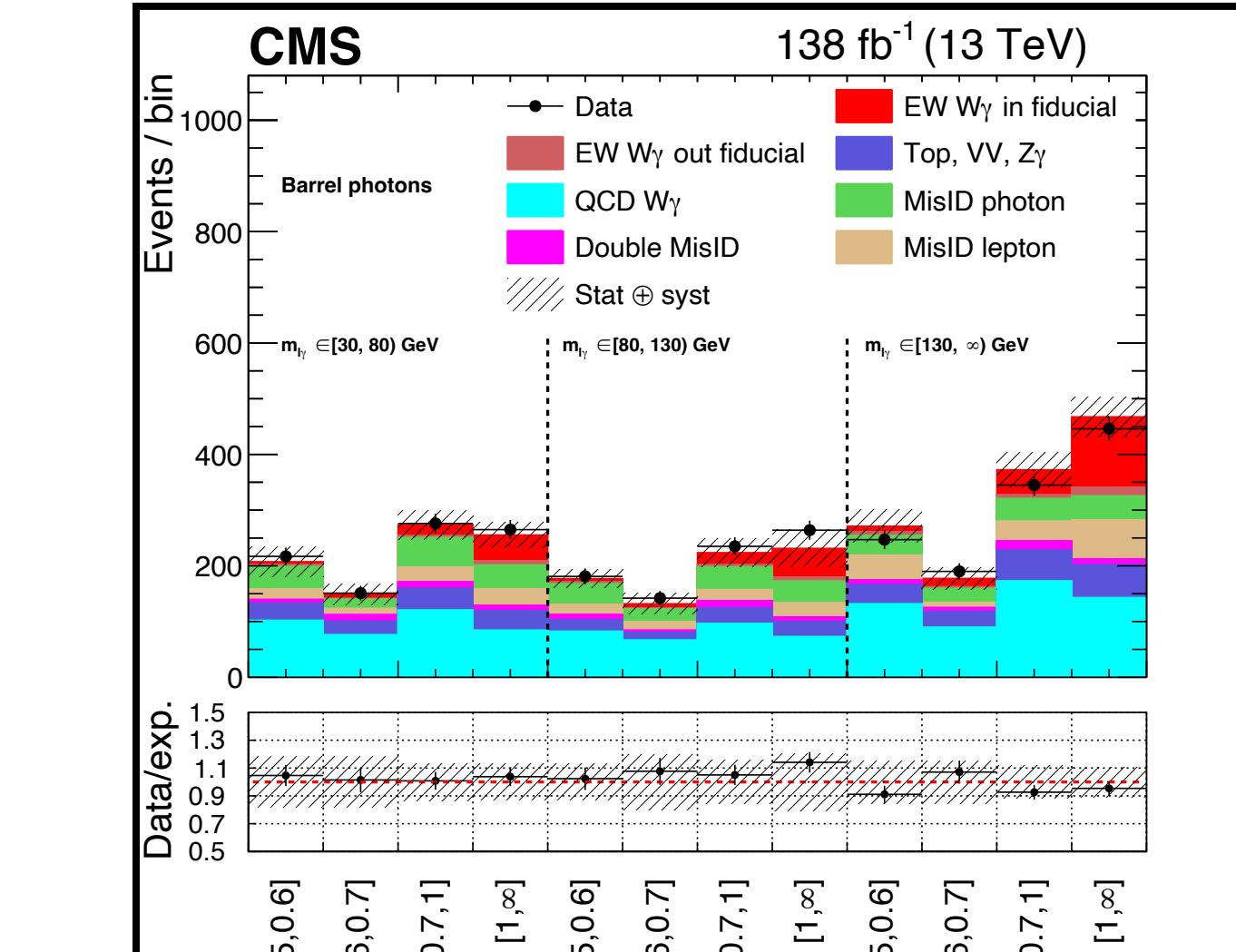
- **Final state:** one charged lepton (μ, e), E_T^{miss} , one isolated photon, and two VBS-jets
- **P_z neutrino** estimated via a W-mass constrain used **suppress reducible bkg**

Backgrounds:

- **Dominant QCD-induced $W\gamma jj$** background whose normalisation estimated from data
- **Non-prompt photons** (from $W+jets$, $t\bar{t}$ bar) estimated from data
- **Non-prompt leptons** (QCD multi-jet) also estimated from data

Measurements

- **Fiducial cross section** measured for EW $W\gamma jj$ and EW+QCD $W\gamma jj$ by a fit to $m(jj)-m(l\nu\gamma)$
- **Differential cross section measurements** with unfolding of 1D and 2D distributions
- **Search for aQGCs in dim-8 EFT** fitting $m(l\nu\gamma)$ distribution. Complementary bounds to $W^\pm W^\pm$



Observed with $>> 5\sigma$ significance
 Inclusive rate limited by sys

$$\sigma_{\text{EW}}^{\text{fid}} = 23.5^{+2.8}_{-2.8} (\text{stat})^{+1.9}_{-1.7} (\text{theo})^{+3.5}_{-3.4} (\text{syst})$$

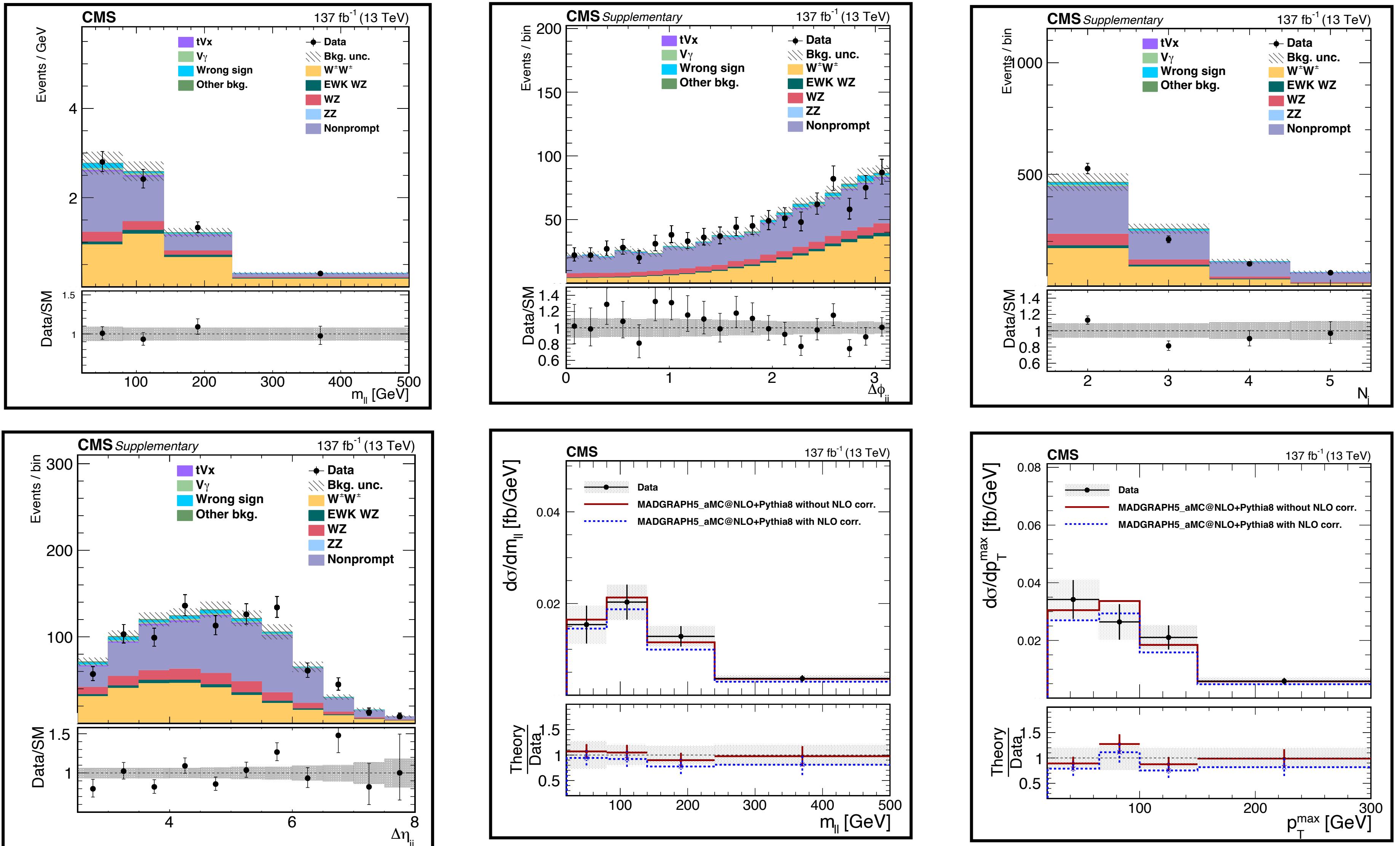
Conclusions

- With ***less than 10% of the total LHC expected luminosity***, CMS started to deliver precision measurements of EW VBS
- ***Differential unfolded measurements*** and ***EFT interpretations (dim-8 and dim-6)*** in VBS are the ***next milestones***
- ***Several challenges ahead:***
 - ***Improve event simulation*** including higher order QCD and EW corrections to VBS
 - ***Understand theory uncertainties*** from PDF, parton shower models, etc
 - ***Improve background modelling*** from data for non-prompt photon and lepton estimate and uncertainty
- Use ***VBS*** as ***indirect probe*** for ***BSM*** physics:
 - ***Global SM and EFT fits*** across VBS analyses and beyond
 - ***Publication of our results*** for EFT searches and unfolded distributions in formats that can be usable by a large scientific community

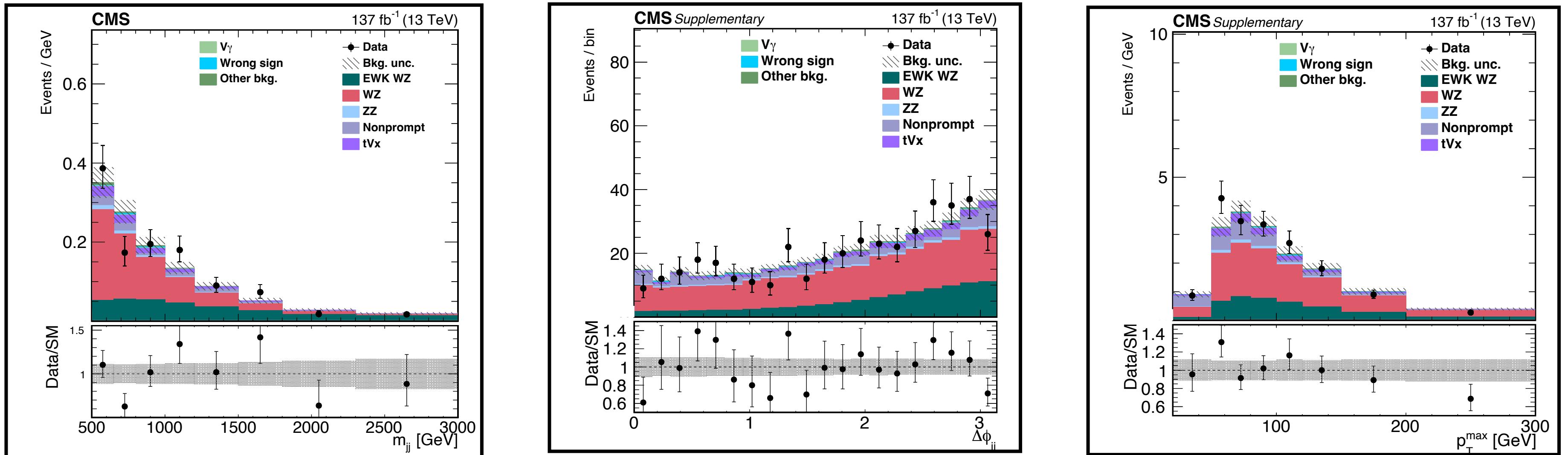


Backup slides

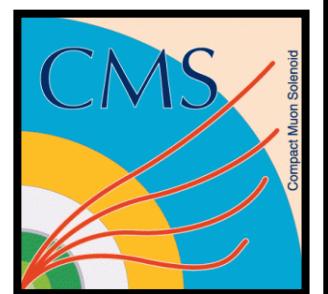
Leptonic VBS $W^\pm W^\pm \rightarrow 2l^\pm 2\nu$



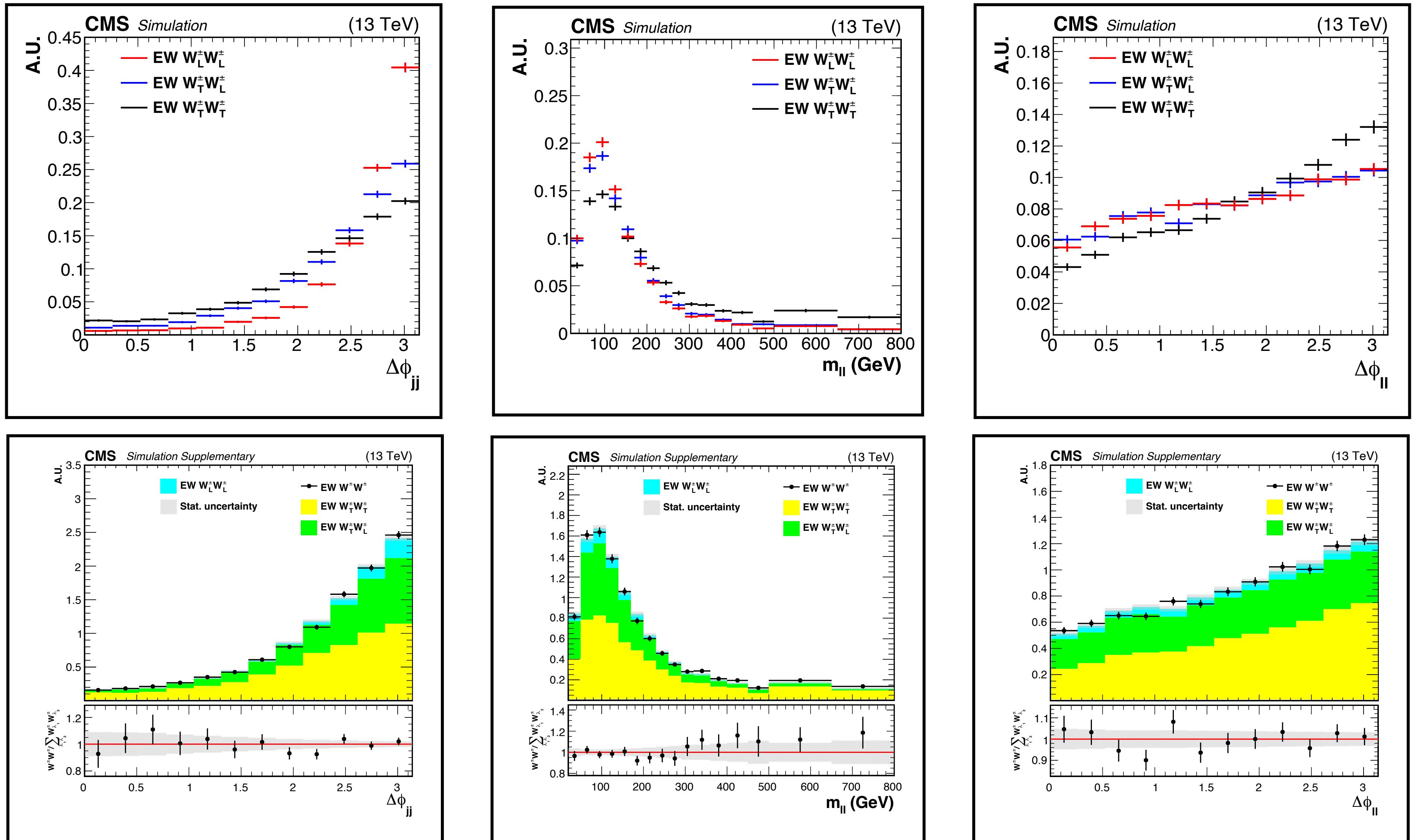
Leptonic VBS $W^\pm Z \rightarrow 3l^\pm\nu$



	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]

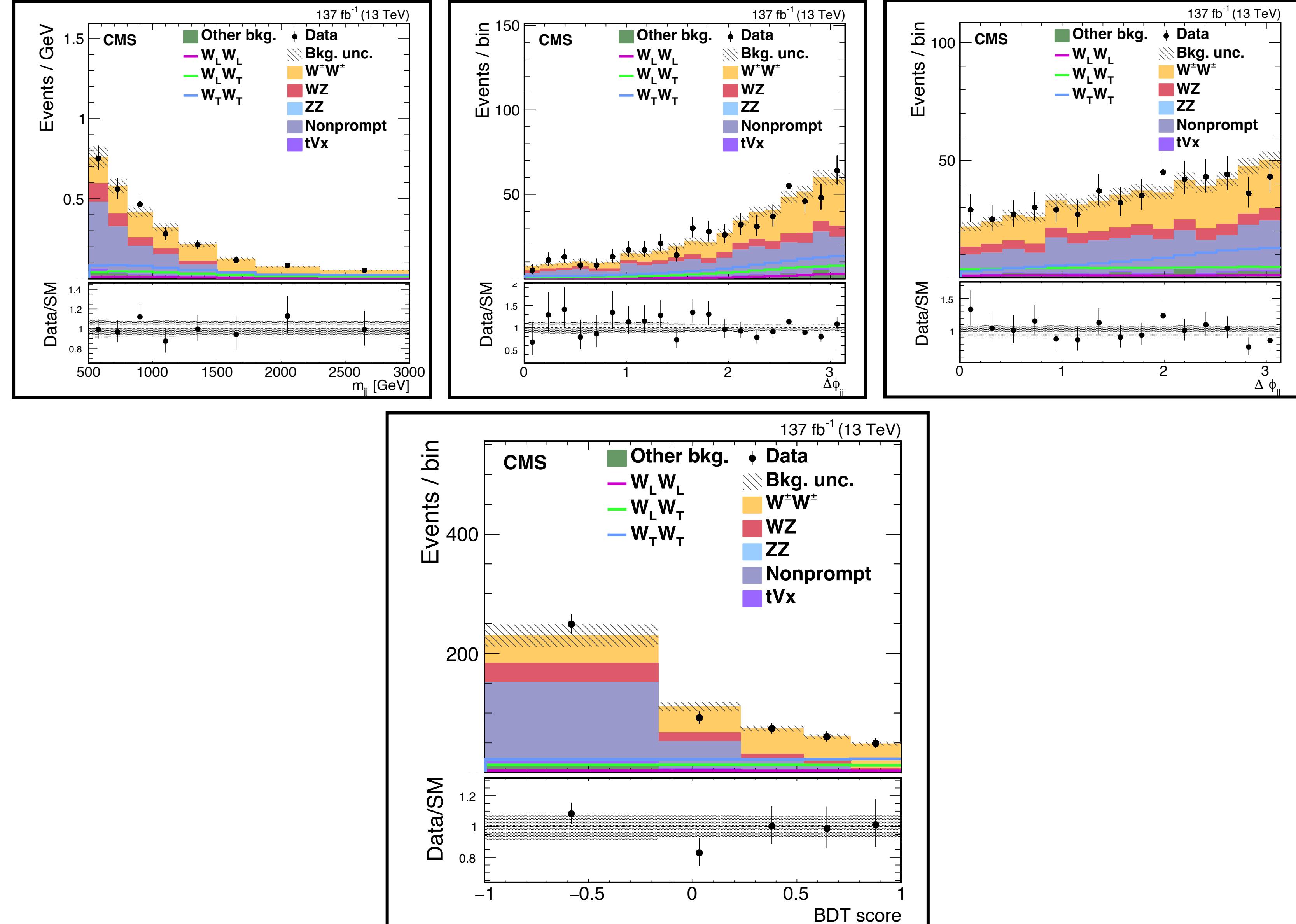


VBS $W^\pm W^\pm$: polarized cross sections

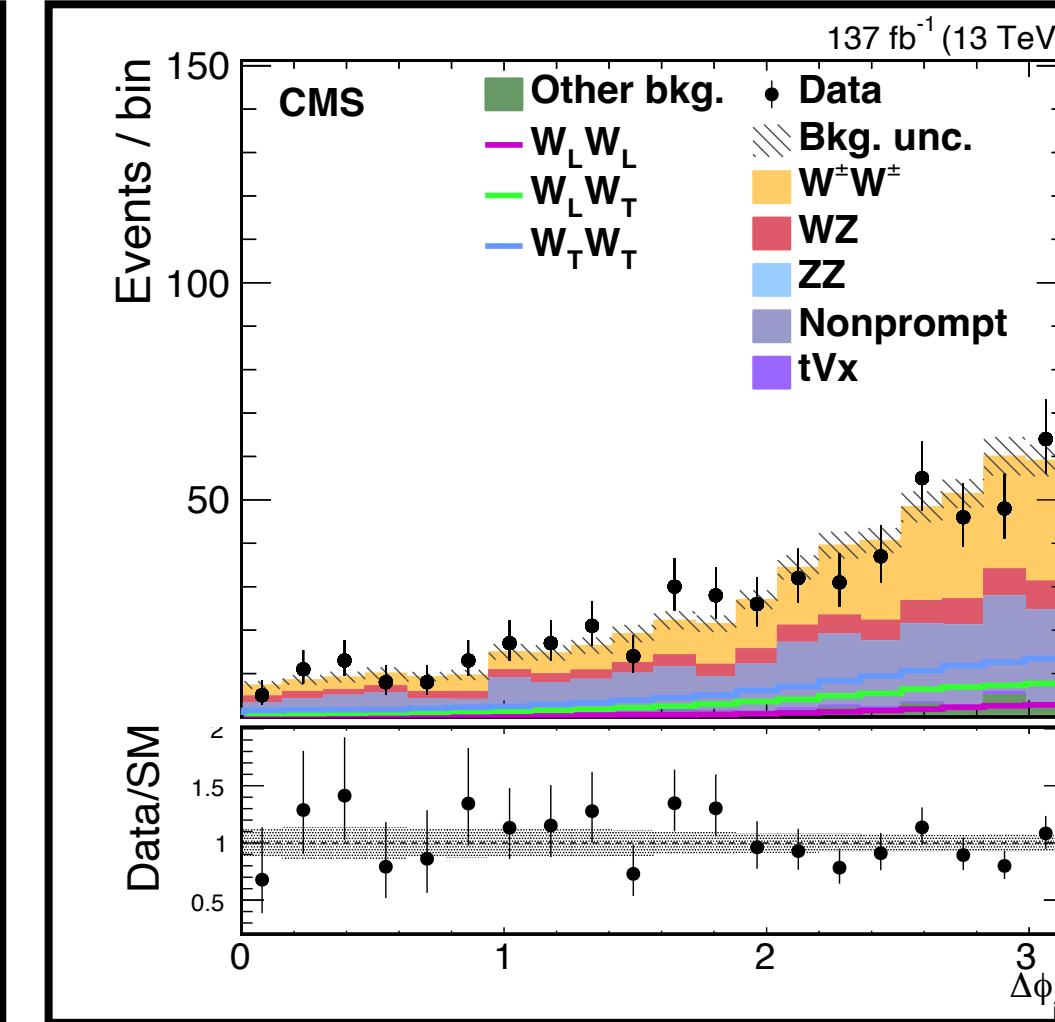
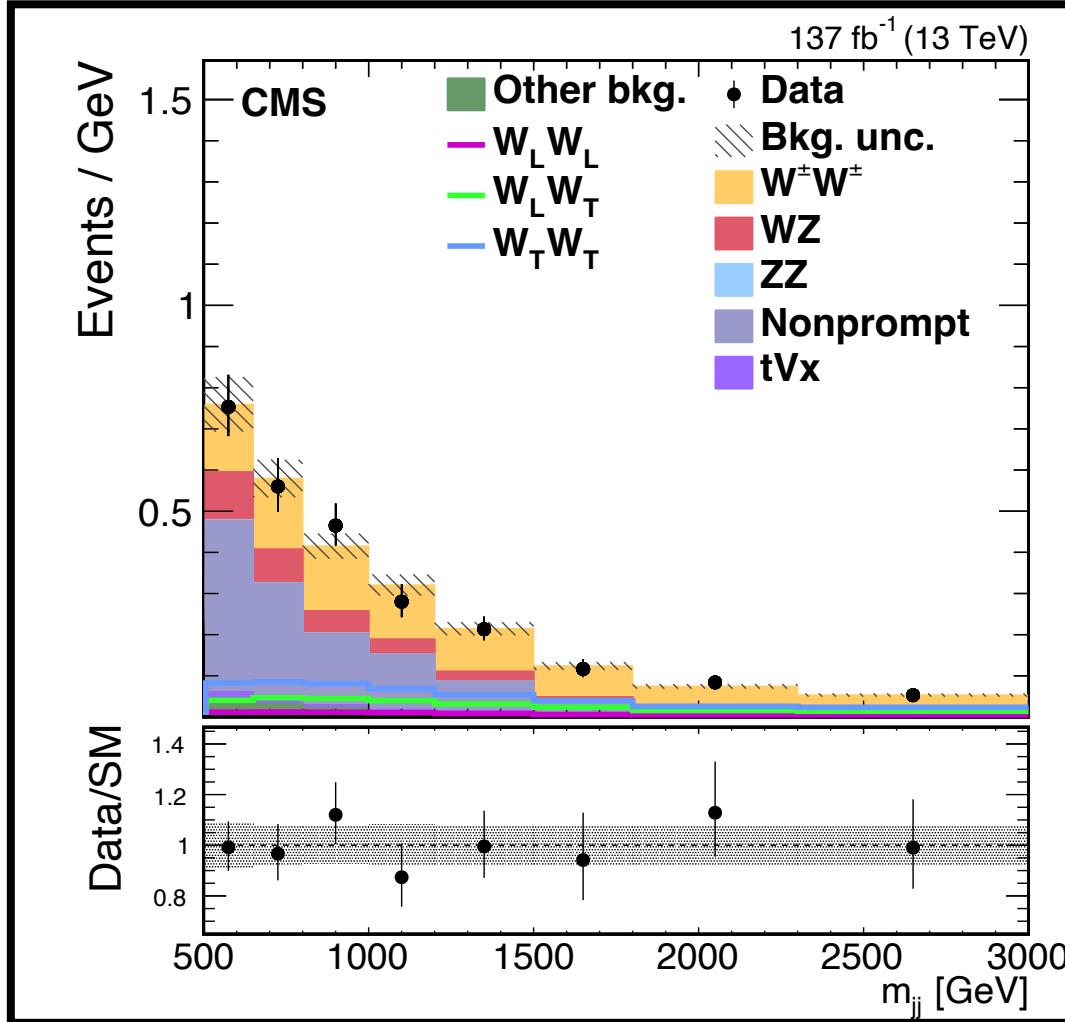




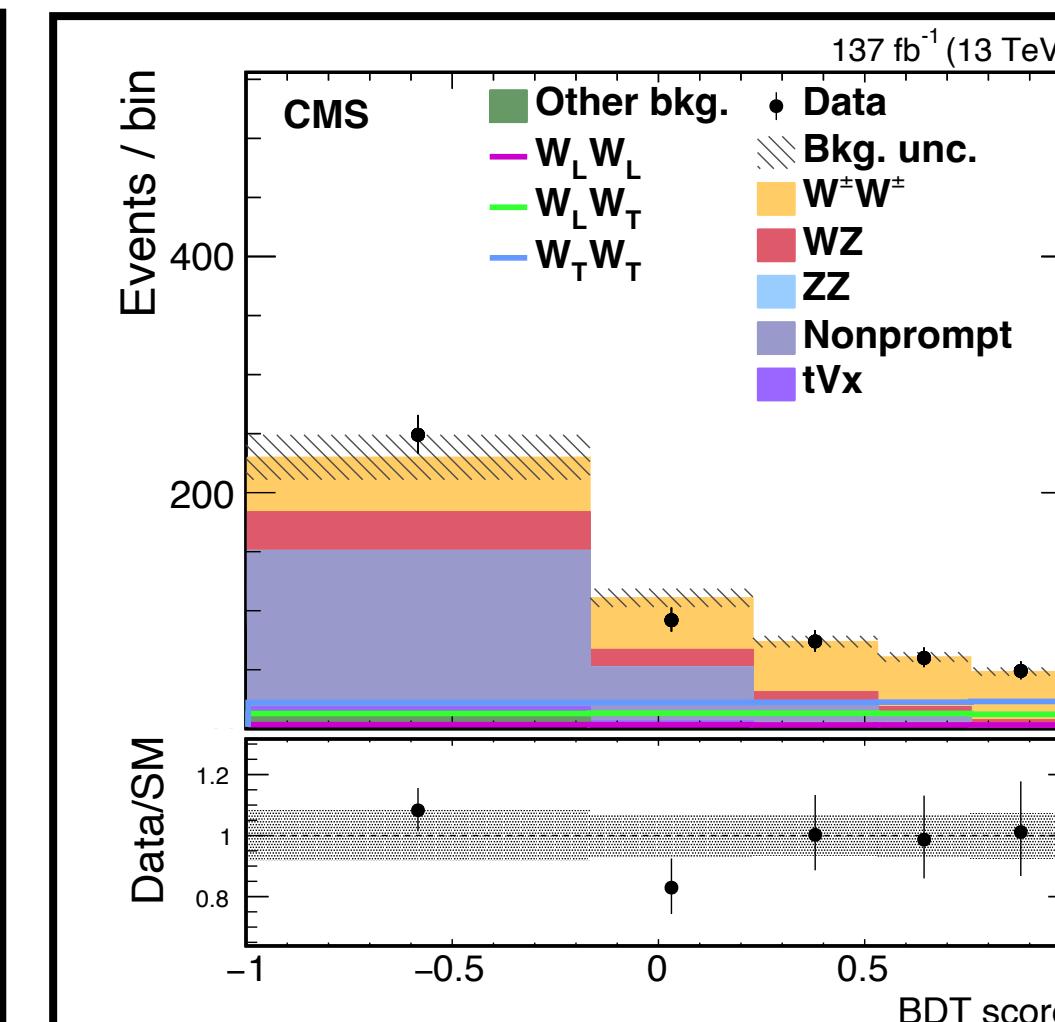
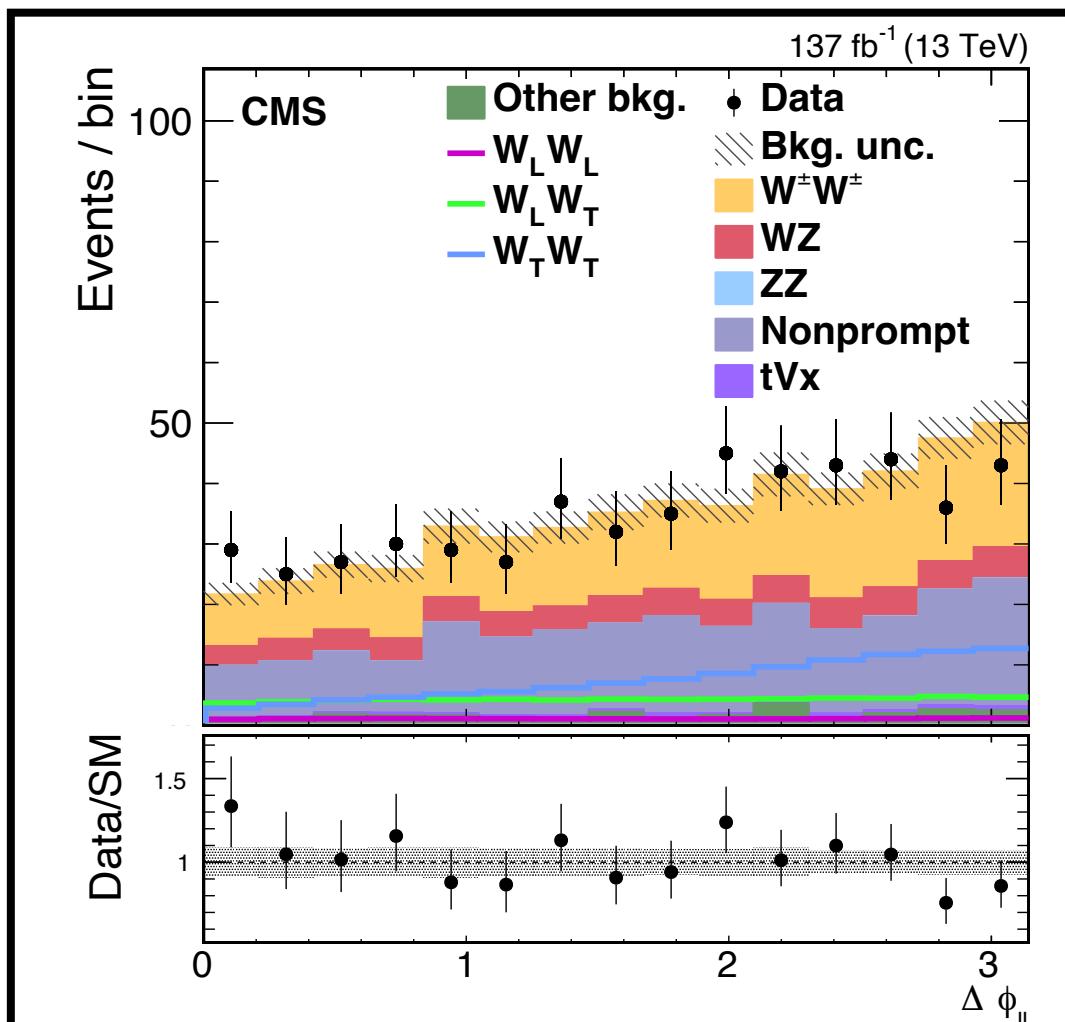
VBS $W^\pm W^\pm$: polarized cross sections



VBS $W^\pm W^\pm$: polarized cross sections



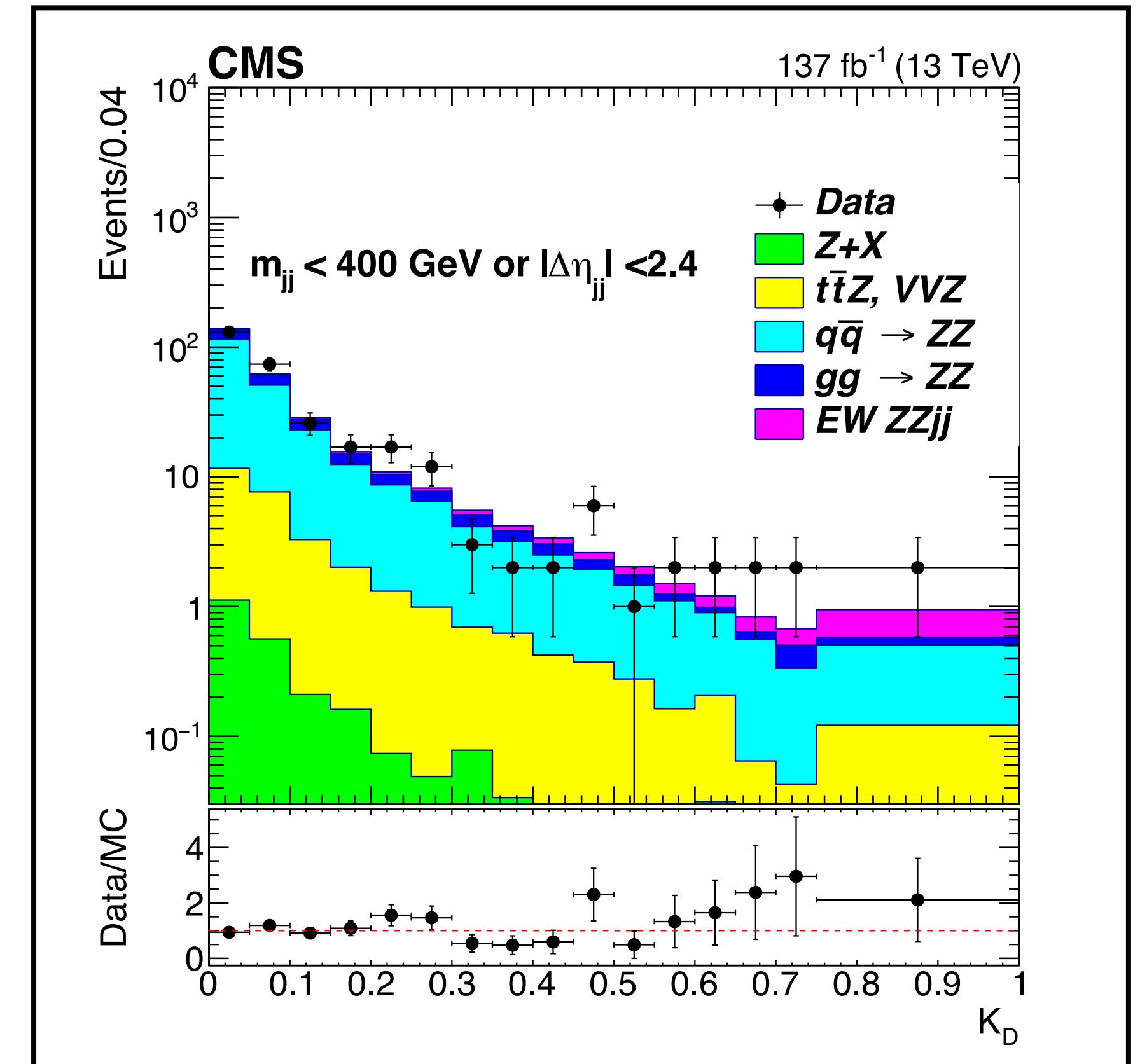
Source of uncertainty	$W_L^\pm W_L^\pm$ (%)	$W_X^\pm W_T^\pm$ (%)	$W_L^\pm W_X^\pm$ (%)	$W_T^\pm W_T^\pm$ (%)
Integrated luminosity	3.2	1.8	1.9	1.8
Lepton measurement	3.6	1.9	2.5	1.8
Jet energy scale and resolution	11	2.9	2.5	1.1
Pileup	0.9	0.1	1.0	0.3
b tagging	1.1	1.2	1.4	1.1
Nonprompt lepton rate	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



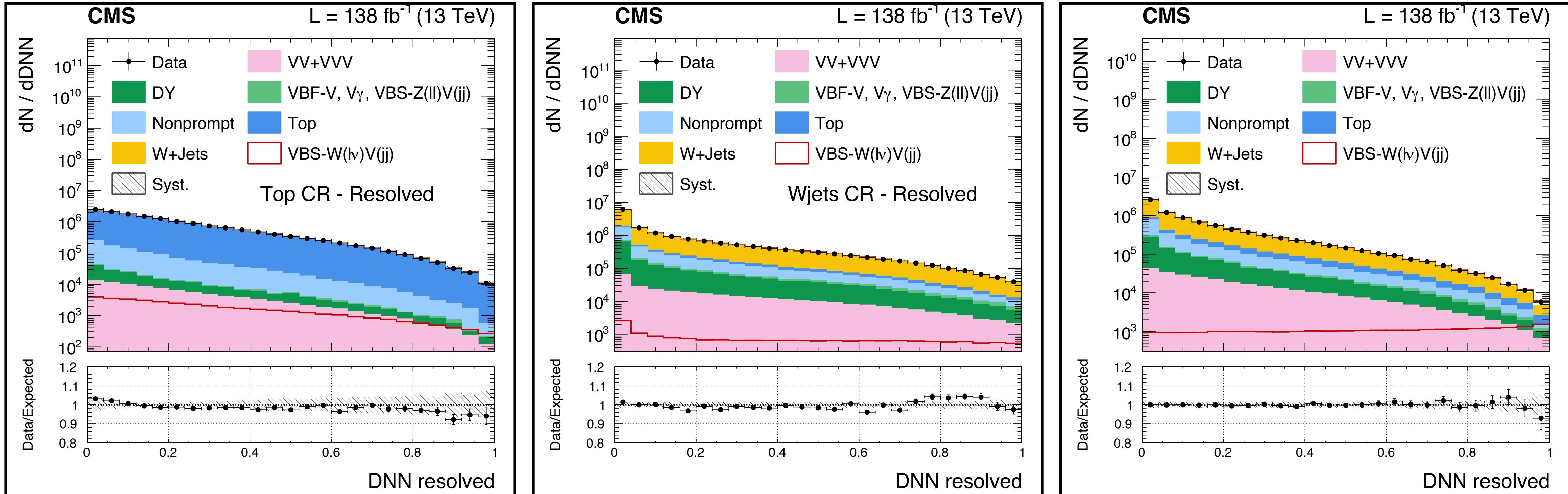
Leptonic VBS ZZ \rightarrow 4l

	Perturbative order	SM σ (fb)	Measured σ (fb)
ZZjj inclusive			
EW	LO	0.275 ± 0.021	
	NLO QCD	0.278 ± 0.017	$0.33^{+0.11}_{-0.10}$ (stat) $^{+0.04}_{-0.03}$ (syst)
VBS-enriched (loose)			
EW	LO	0.186 ± 0.015	
	NLO QCD	0.197 ± 0.013	$0.200^{+0.078}_{-0.067}$ (stat) $^{+0.023}_{-0.013}$ (syst)
VBS-enriched (tight)			
EW	LO	0.104 ± 0.008	
	NLO QCD	0.108 ± 0.007	$0.09^{+0.04}_{-0.03}$ (stat) ± 0.02 (syst)
EW+QCD			
EW	LO	0.221 ± 0.014	$0.20^{+0.05}_{-0.04}$ (stat) ± 0.02 (syst)

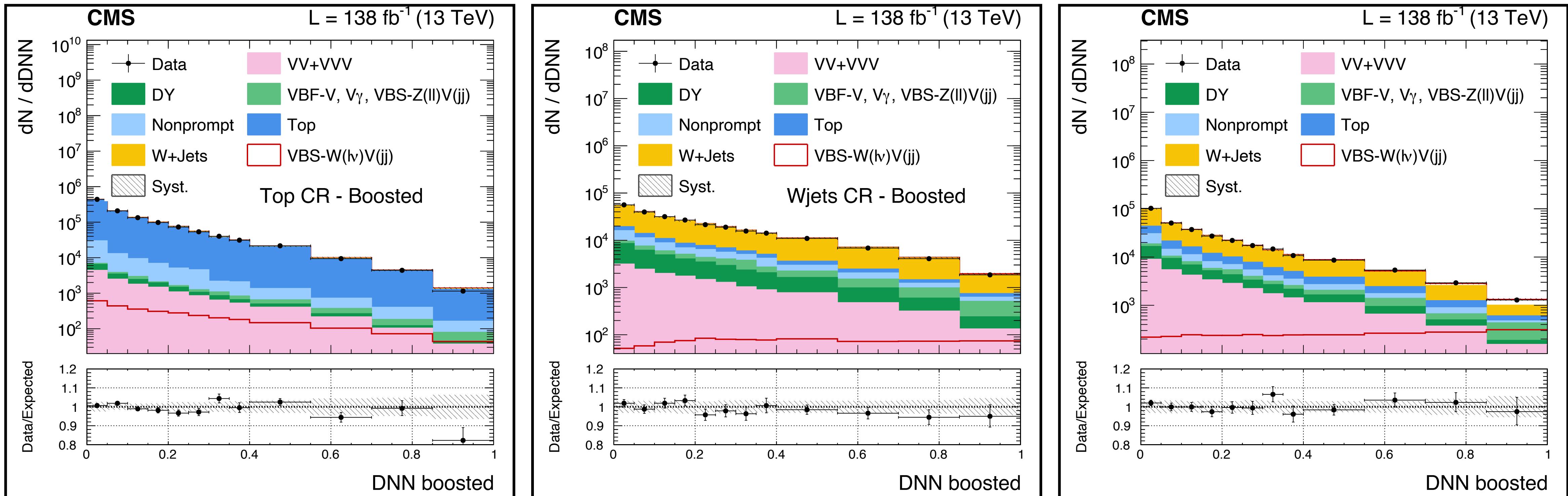
Coupling	Exp. lower	Exp. upper	Obs. lower	Obs. upper	Unitarity bound
f_{T0}/Λ^4	-0.37	0.35	-0.24	0.22	2.4
f_{T1}/Λ^4	-0.49	0.49	-0.31	0.31	2.6
f_{T2}/Λ^4	-0.98	0.95	-0.63	0.59	2.5
f_{T8}/Λ^4	-0.68	0.68	-0.43	0.43	1.8
f_{T9}/Λ^4	-1.5	1.5	-0.92	0.92	1.8



Semi-leptonic VBS $W^\pm V \rightarrow l\nu jj$

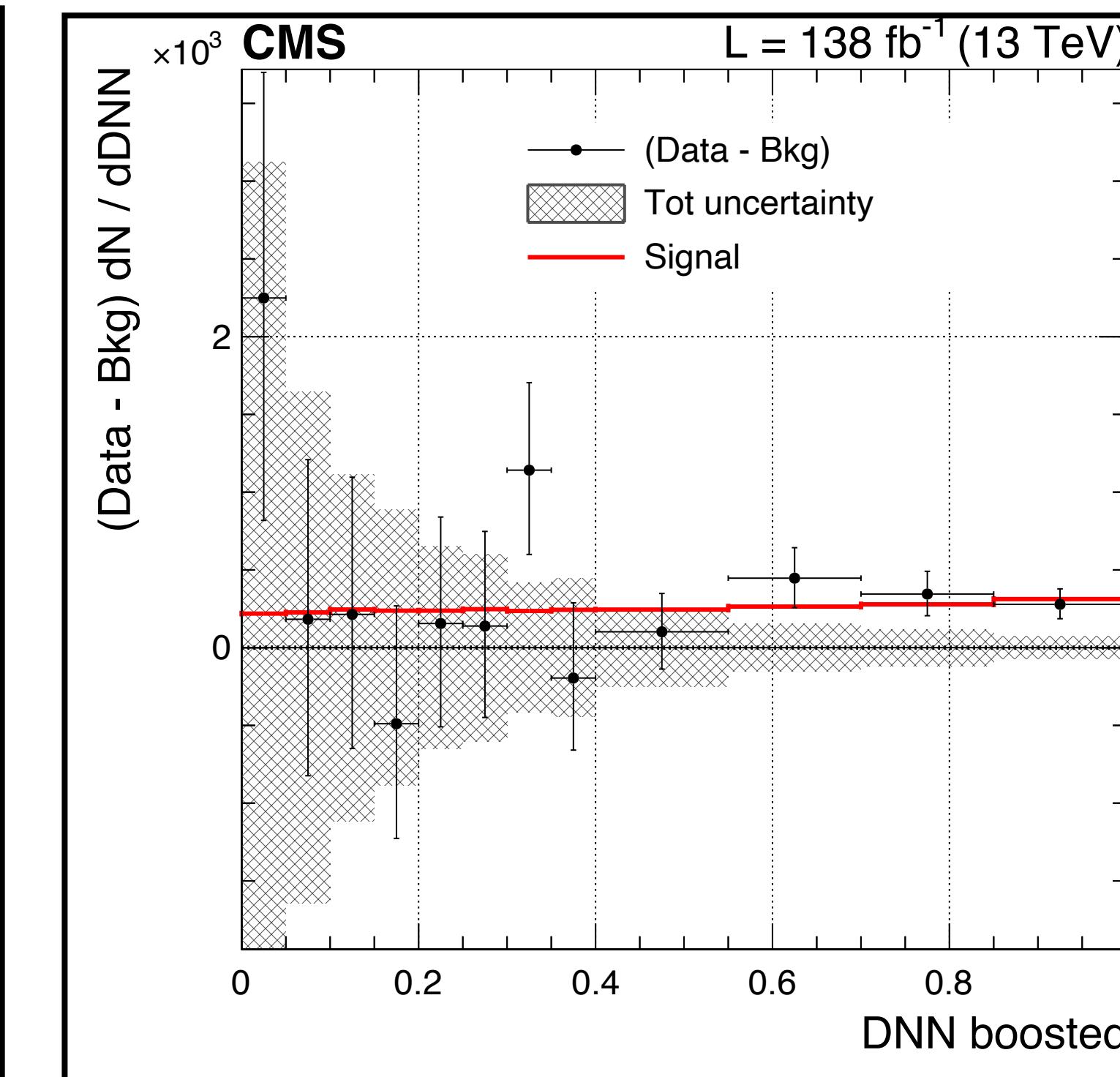
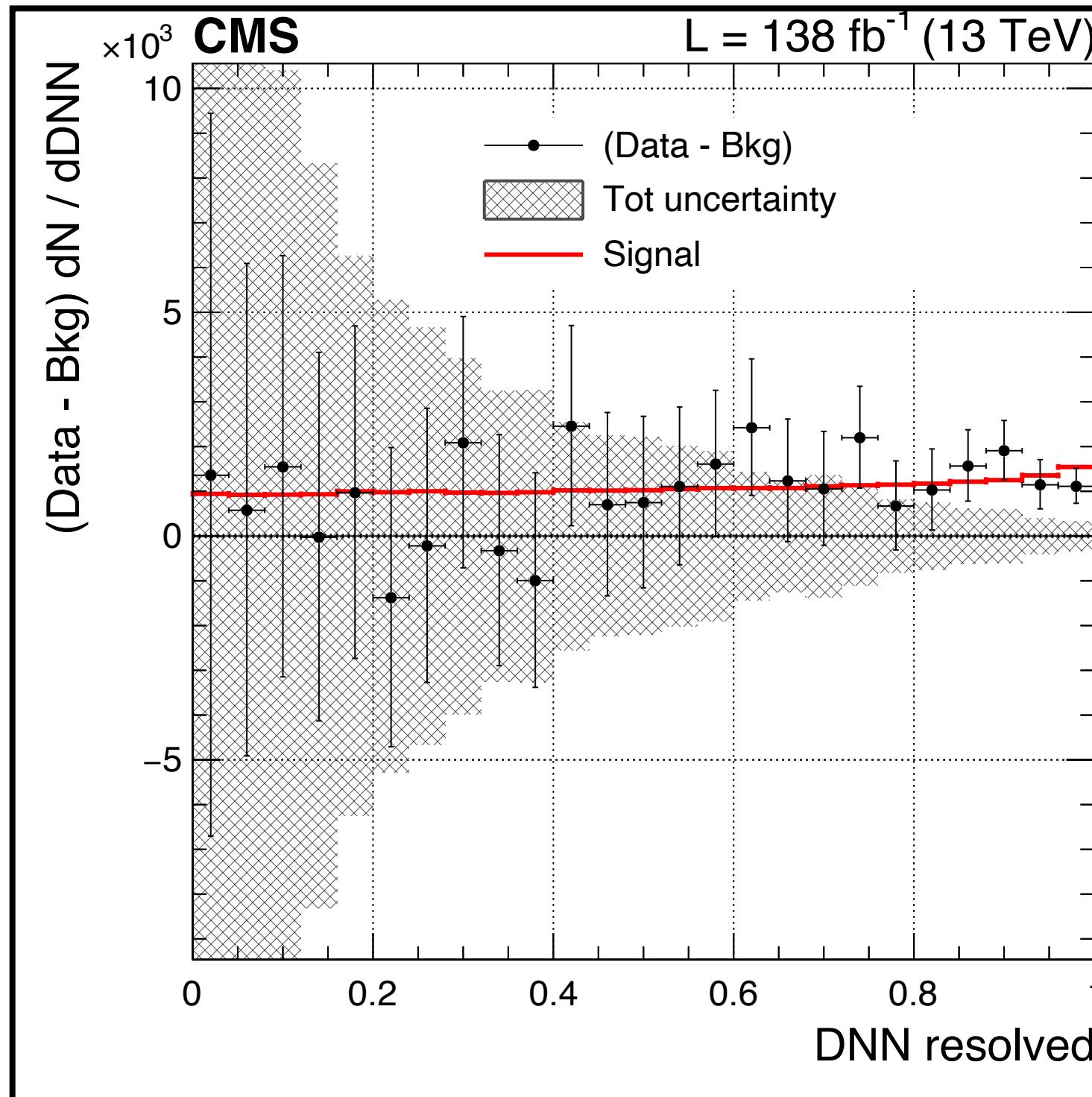


Semi-leptonic VBS $W^\pm V \rightarrow l\nu jj$





Semi-leptonic VBS $W^\pm V \rightarrow l\nu jj$

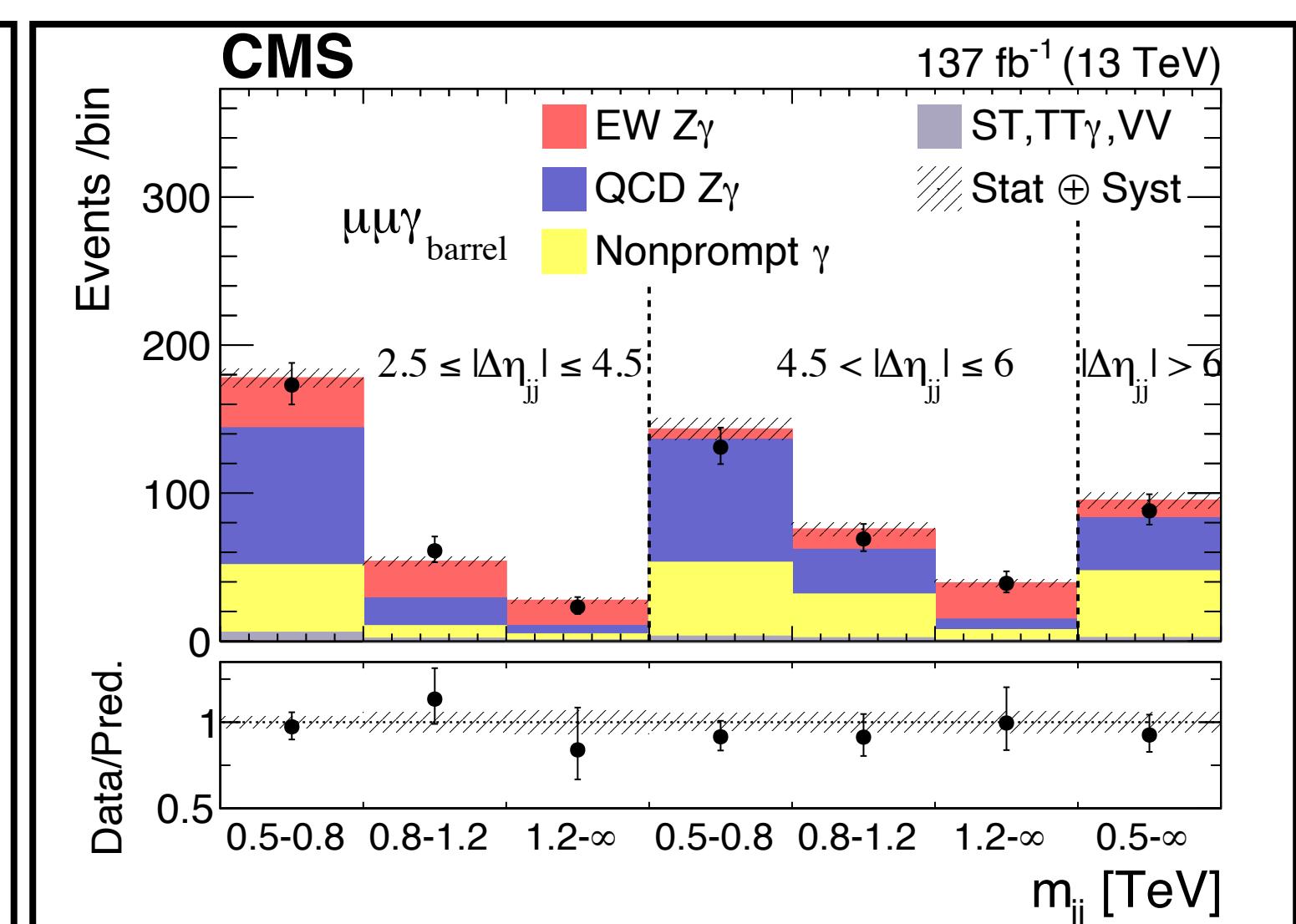
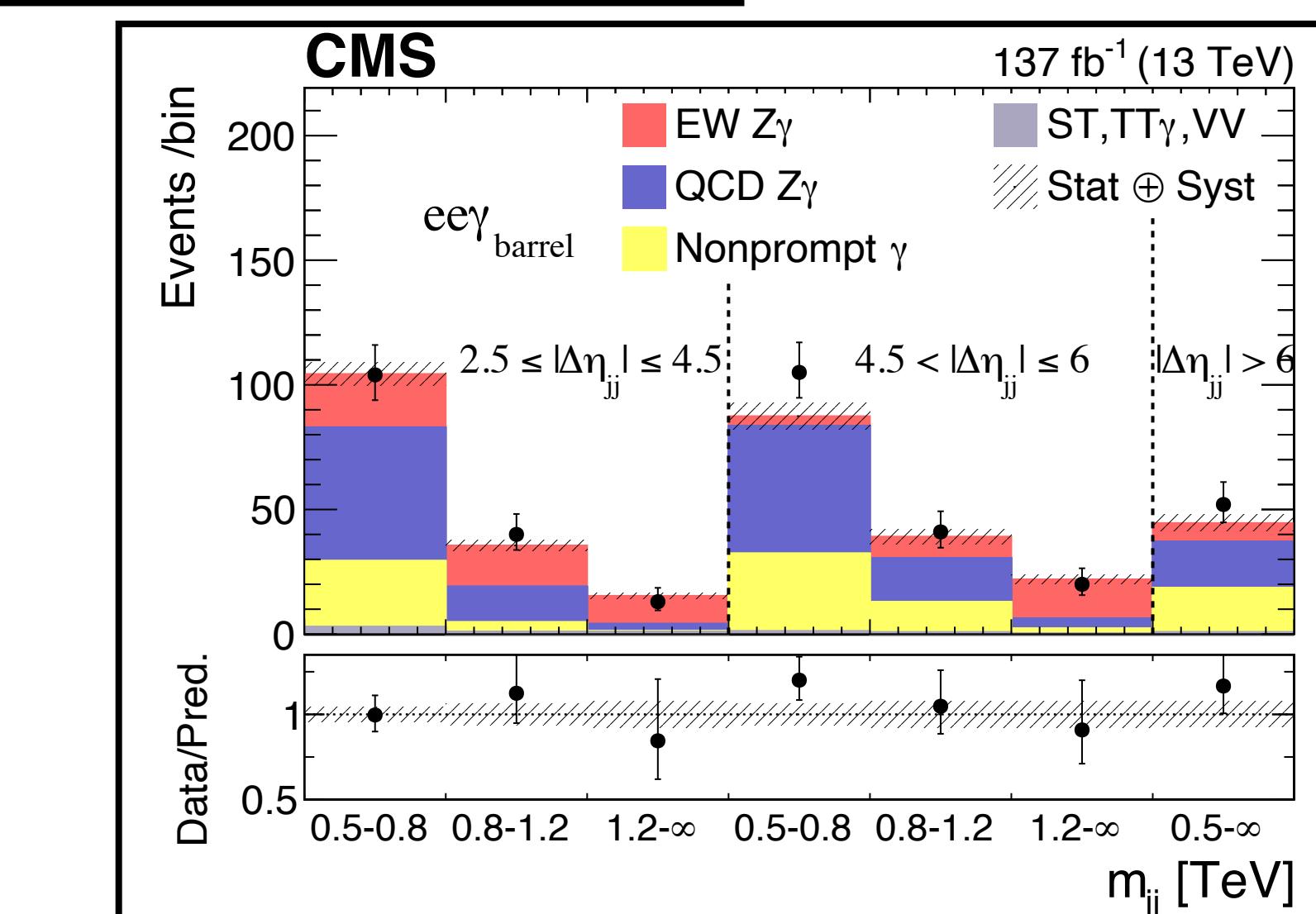
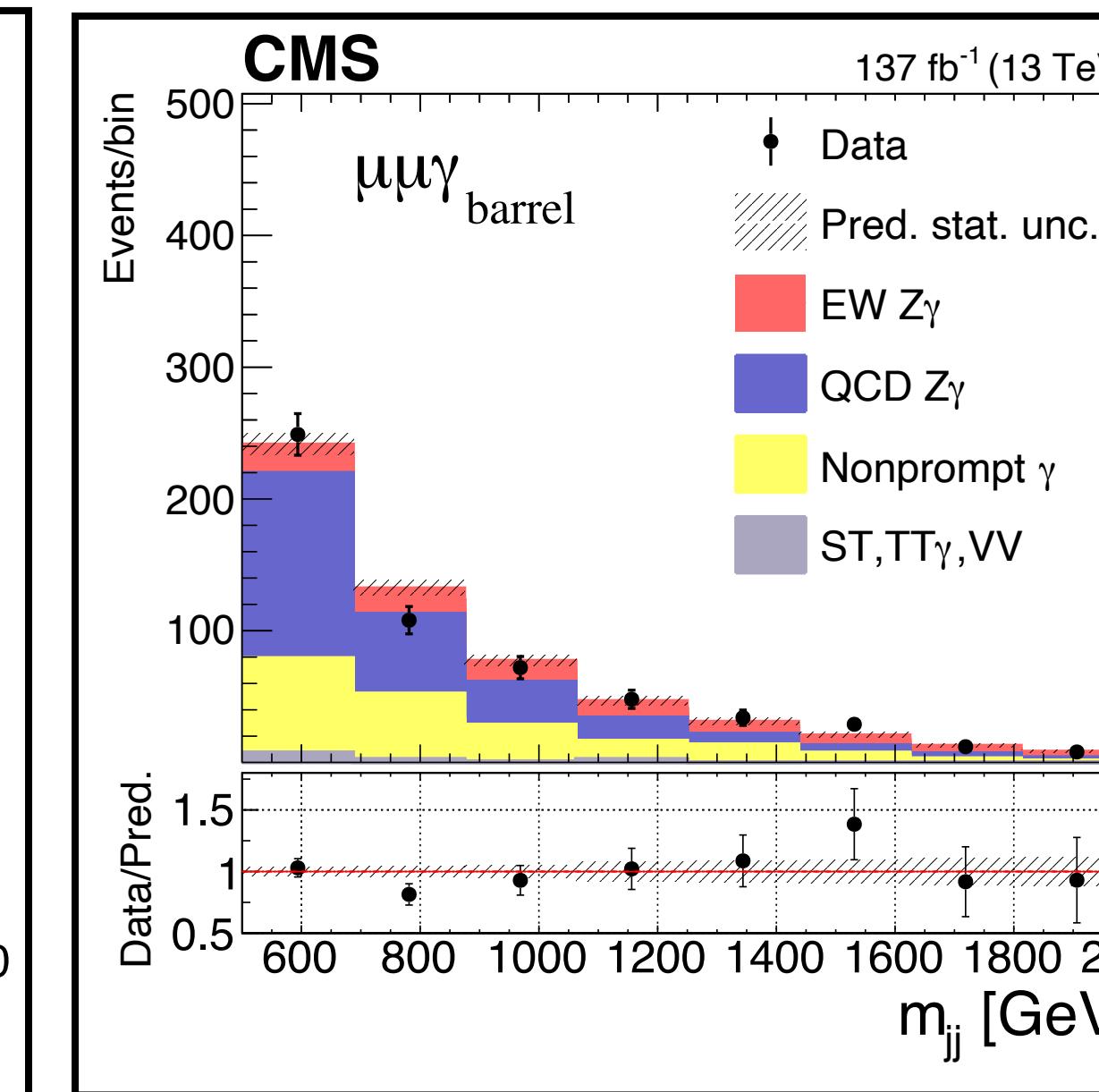
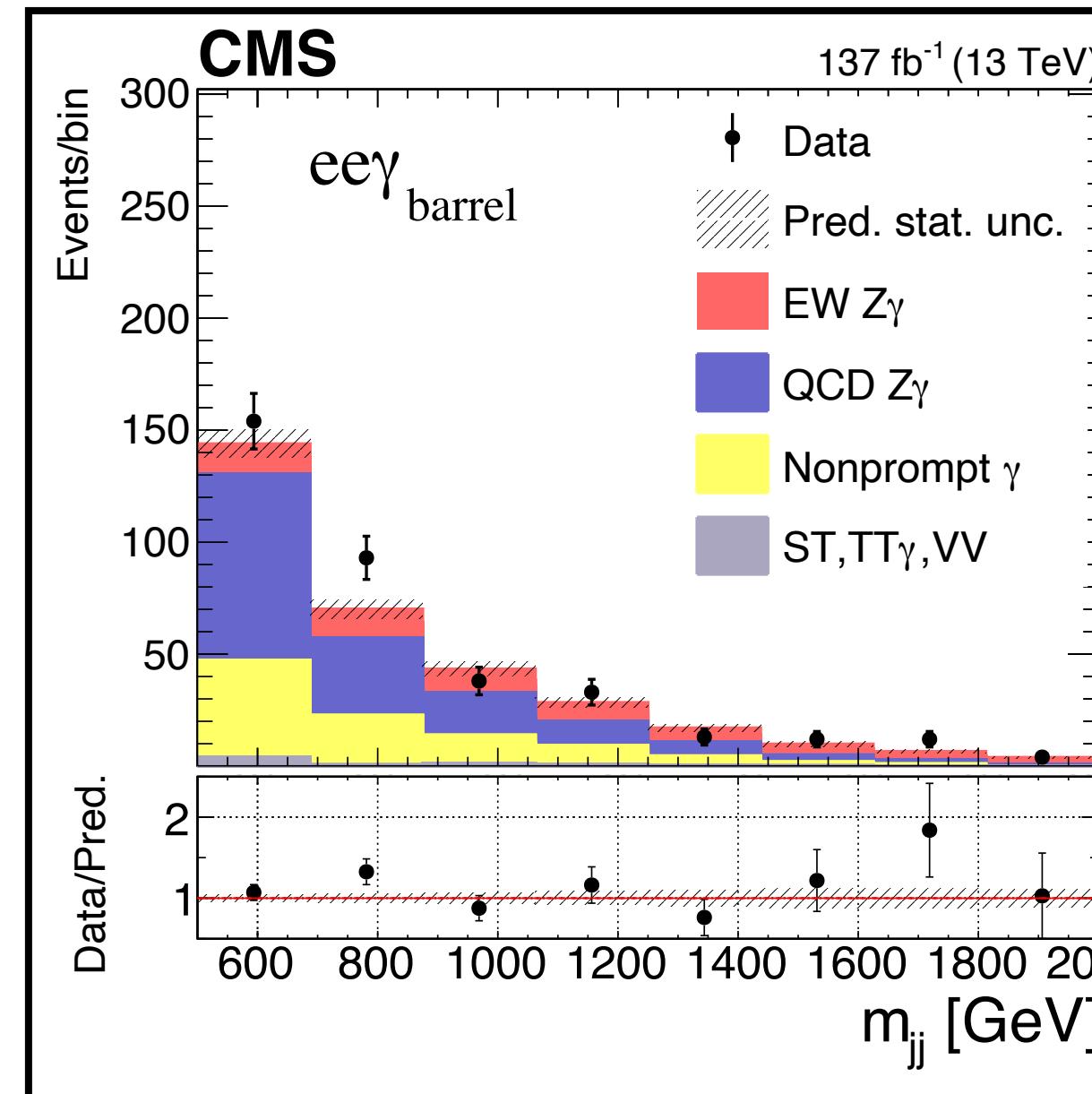


Uncertainty source	$\Delta\mu_{\text{EW}}$
Statistical	0.12
Limited sample size	0.10
Normalization of backgrounds	0.08
Experimental	
b-tagging	0.05
Jet energy scale and resolution	0.04
Integrated luminosity	0.01
Lepton identification	0.01
Boosted V boson identification	0.01
Total	0.06
Theory	
Signal modeling	0.09
Background modeling	0.08
Total	0.12
Total	0.22

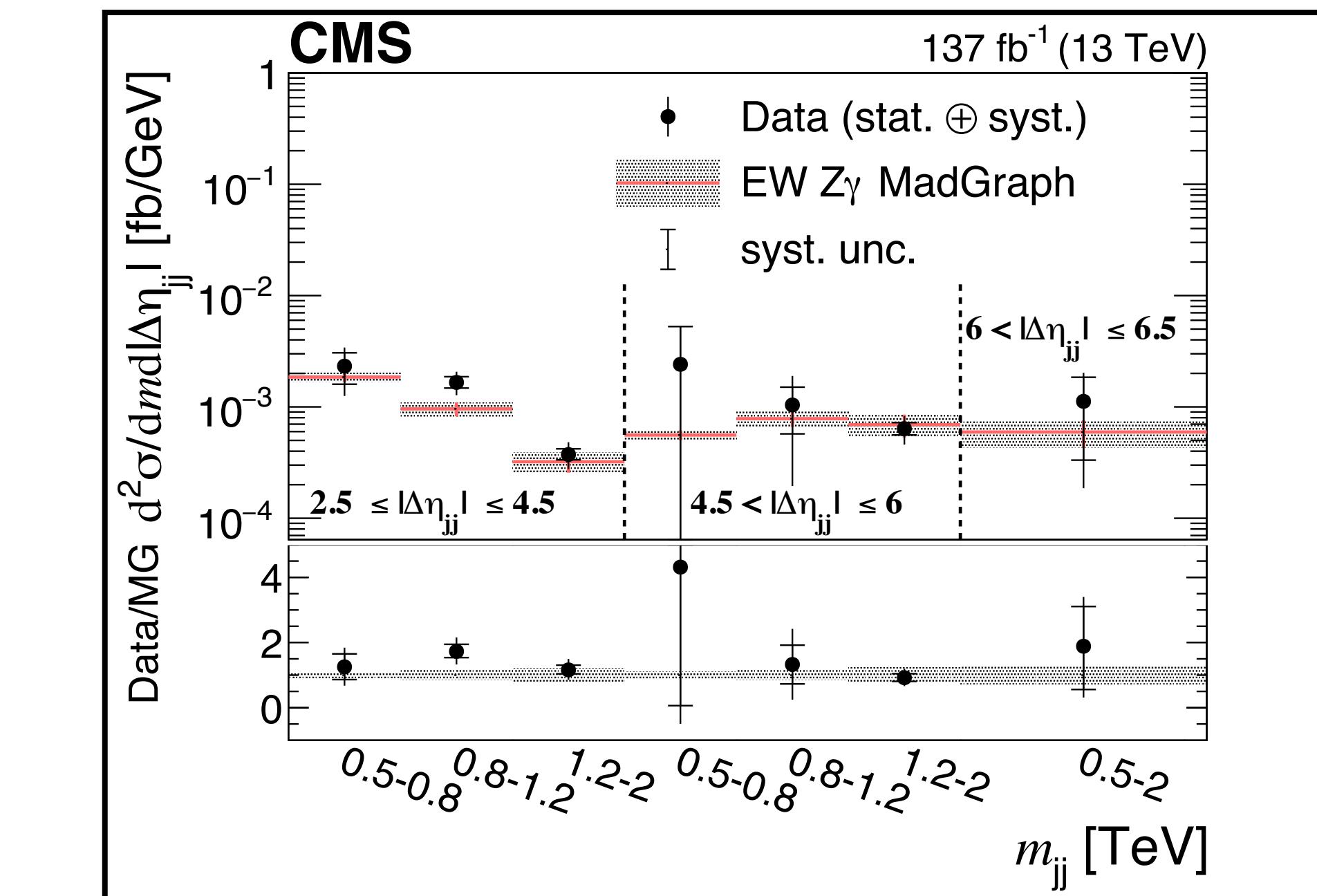
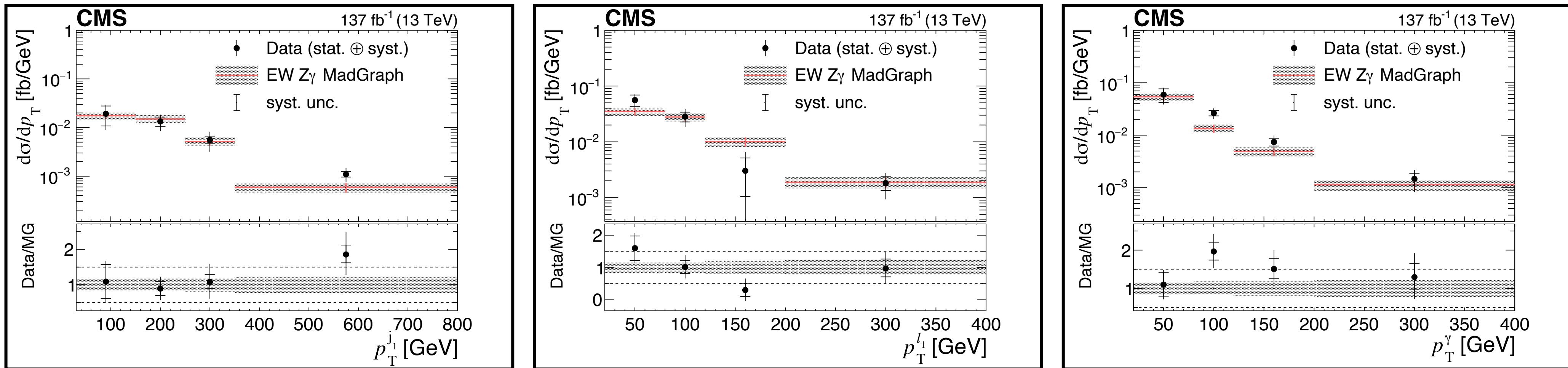


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VBS production of $Z\gamma$



VBS production of $Z\gamma$

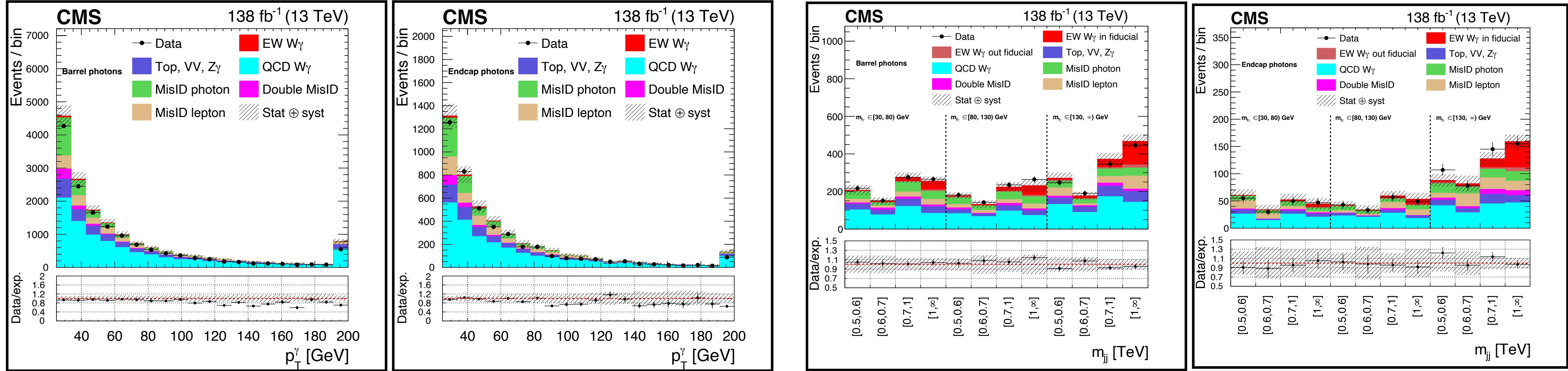


VBS production of Z γ

Variables	Bin [GeV]	$\mu \pm \Delta\mu$	Predicted $d\sigma/dp_T$ [fb/GeV]	Observed $d\sigma/dp_T$ [fb/GeV]
p_T^γ	20–80	$1.10^{+0.39}_{-0.38}$	0.0539 ± 0.0089	0.059 ± 0.021
	80–120	$1.96^{+0.46}_{-0.43}$	0.0134 ± 0.0024	0.0264 ± 0.0060
	120–200	$1.51^{+0.50}_{-0.46}$	0.0049 ± 0.0010	0.0074 ± 0.0024
	200–400	$1.29^{+0.63}_{-0.57}$	0.00114 ± 0.00025	0.00147 ± 0.00068
	30–150	$1.09^{+0.59}_{-0.58}$	0.0176 ± 0.0028	0.019 ± 0.010
$p_T^{j_1}$	150–250	$0.89^{+0.34}_{-0.33}$	0.0149 ± 0.0026	0.0133 ± 0.0050
	250–350	$1.08^{+0.50}_{-0.47}$	0.0052 ± 0.0010	0.0056 ± 0.0025
	350–800	$1.86^{+0.63}_{-0.57}$	0.00059 ± 0.00014	0.00109 ± 0.0036
	20–80	$1.60^{+0.47}_{-0.47}$	0.0350 ± 0.0055	0.056 ± 0.016
	80–120	$1.01^{+0.37}_{-0.35}$	0.0278 ± 0.0048	0.028 ± 0.010
$p_T^{\ell_1}$	120–200	$0.30^{+0.36}_{-0.34}$	0.0100 ± 0.0019	0.0030 ± 0.00035
	200–400	$0.97^{+0.52}_{-0.47}$	0.00187 ± 0.00041	0.00188 ± 0.00092

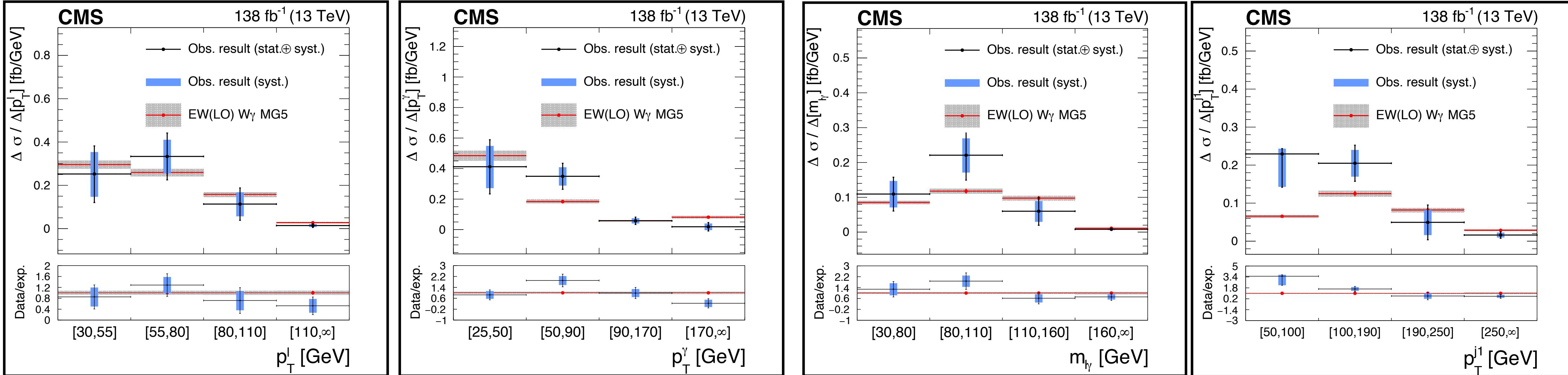
Systematic uncertainty	Impact [%]
Jet energy correction	+7.9 -6.7
Theoretical uncertainties	+5.5 -4.7
MC statistical uncertainties	+4.7 -4.5
PU	+4.7 -4.1
Related to e, γ	+4.5 -3.6
PU jet ID	+3.7 -3.4
ECAL timing shift at L1	+3.5 -2.8
Nonprompt- γ bkg. estimate	+2.0 -1.6
Related to μ	+1.7 -1.4
Integrated luminosity	+0.8 -0.6
Total systematic uncertainty	+14 -12

Coupling	Exp. lower	Exp. upper	Obs. lower	Obs. upper	Unitarity bound
F_{M0}/Λ^4	-12.5	12.8	-15.8	16.0	1.3
F_{M1}/Λ^4	-28.1	27.0	-35.0	34.7	1.5
F_{M2}/Λ^4	-5.21	5.12	-6.55	6.49	1.5
F_{M3}/Λ^4	-10.2	10.3	-13.0	13.0	1.8
F_{M4}/Λ^4	-10.2	10.2	-13.0	12.7	1.7
F_{M5}/Λ^4	-17.6	16.8	-22.2	21.3	1.7
F_{M7}/Λ^4	-44.7	45.0	-56.6	55.9	1.6
F_{T0}/Λ^4	-0.52	0.44	-0.64	0.57	1.9
F_{T1}/Λ^4	-0.65	0.63	-0.81	0.90	2.0
F_{T2}/Λ^4	-1.36	1.21	-1.68	1.54	1.9
F_{T5}/Λ^4	-0.45	0.52	-0.58	0.64	2.2
F_{T6}/Λ^4	-1.02	1.07	-1.30	1.33	2.0
F_{T7}/Λ^4	-1.67	1.97	-2.15	2.43	2.2
F_{T8}/Λ^4	-0.36	0.36	-0.47	0.47	1.8
F_{T9}/Λ^4	-0.72	0.72	-0.91	0.91	1.9





Leptonic VBS $W\gamma$



Expected limit	Observed limit	U_{bound}
$-5.1 < f_{M,0}/\Lambda^4 < 5.1$	$-5.6 < f_{M,0}/\Lambda^4 < 5.5$	1.7
$-7.1 < f_{M,1}/\Lambda^4 < 7.4$	$-7.8 < f_{M,1}/\Lambda^4 < 8.1$	2.1
$-1.8 < f_{M,2}/\Lambda^4 < 1.8$	$-1.9 < f_{M,2}/\Lambda^4 < 1.9$	2.0
$-2.5 < f_{M,3}/\Lambda^4 < 2.5$	$-2.7 < f_{M,3}/\Lambda^4 < 2.7$	2.7
$-3.3 < f_{M,4}/\Lambda^4 < 3.3$	$-3.7 < f_{M,4}/\Lambda^4 < 3.6$	2.3
$-3.4 < f_{M,5}/\Lambda^4 < 3.6$	$-3.9 < f_{M,5}/\Lambda^4 < 3.9$	2.7
$-13 < f_{M,7}/\Lambda^4 < 13$	$-14 < f_{M7}/\Lambda^4 < 14$	2.2
$-0.43 < f_{T,0}/\Lambda^4 < 0.51$	$-0.47 < f_{T,0}/\Lambda^4 < 0.51$	1.9
$-0.27 < f_{T,1}/\Lambda^4 < 0.31$	$-0.31 < f_{T,1}/\Lambda^4 < 0.34$	2.5
$-0.72 < f_{T,2}/\Lambda^4 < 0.92$	$-0.85 < f_{T,2}/\Lambda^4 < 1.0$	2.3
$-0.29 < f_{T,5}/\Lambda^4 < 0.31$	$-0.31 < f_{T,5}/\Lambda^4 < 0.33$	2.6
$-0.23 < f_{T,6}/\Lambda^4 < 0.25$	$-0.25 < f_{T,6}/\Lambda^4 < 0.27$	2.9
$-0.60 < f_{T,7}/\Lambda^4 < 0.68$	$-0.67 < f_{T,7}/\Lambda^4 < 0.73$	3.1