Recent CMS Vector Boson Scattering (VBS) results

Miao Hu

on behalf of the CMS Collaboration

SUSY, Shanghai
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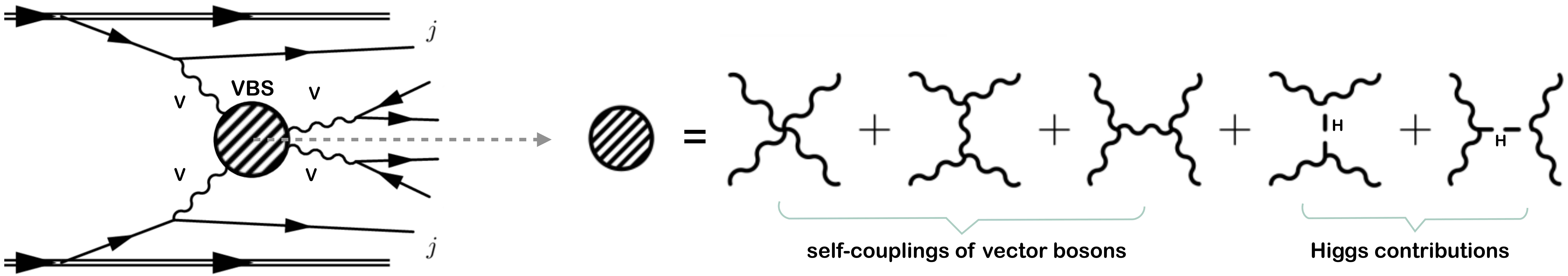
Introduction: What is VBS & Why of Interest?



- Sensitive to **Higgs boson couplings to gauge bosons** and the **triple and quartic vector boson self-couplings**
  - Precision **SM measurement**: test of the EW sector of SM at the TeV scale
  - Study the Anomalous Triple and Quartic Gauge Couplings (**aTGC/aQGC**)
  - Serve also for singly (WZ) and doubly ($W^{\pm}W^{\pm}$) **charged Higgs boson** searches

—> **VBS at the LHC is the measurable key process to experimentally probe the EWSB sector.**
Deviations of the VBS cross section from SM expectations point to new physics!

CMS RUN 2 VBS Analyses

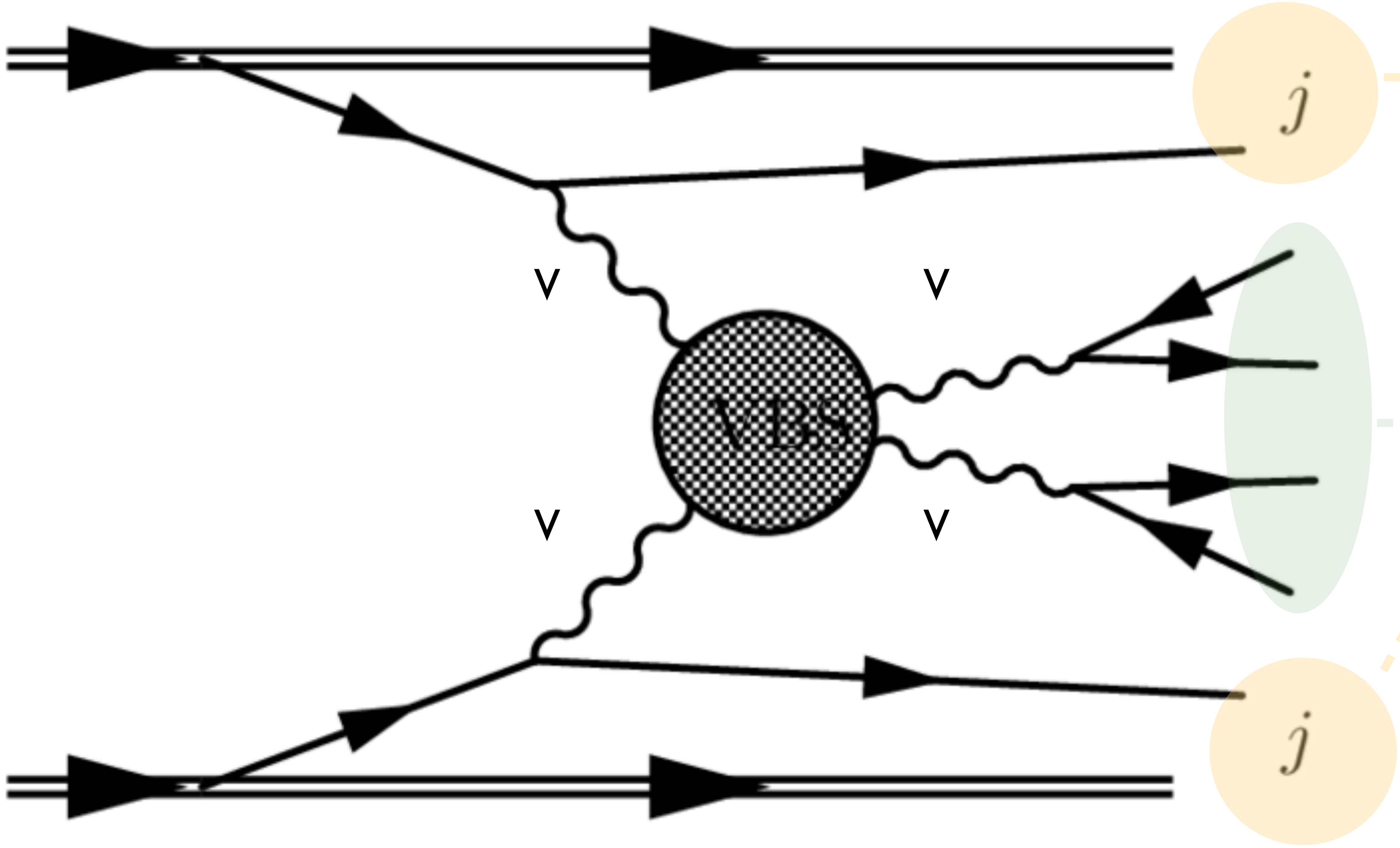
★ NEW AND FOCUS OF THIS TALK

Z→ ll | nn | qq

W→ ln | qq

Channel	Final State	Status	Publication	Features
Fully Leptonic	$W^{\pm}W^{\pm} \to \ell^{\pm}\nu\ell^{\pm}\nu$	Full Run2	*PLB 809 (2020) 135710 / ArXiv:2005.01173* *PLB 812(2021) 136018 / ArXiv:2009.09429* ★*EPJC 81, 723 (2021) / ArXiv:2104.04762*	• **clean** channel • $W^{\pm}W^{\mp}$: large top-quark background • $W^{\pm}Z$: larger QCD background • $ZZ \to 4\ell$: Final state can be fully reconstructed, but very limited number of events
	$W^{\pm}W^{\mp} \to \ell^{\pm}\nu\ell^{\mp}\nu$			
	$W^{\pm}Z \to 3\ell\nu$	Full Run2	*PLB 809 (2020) 135710 / ArXiv:2005.01173* ★*EPJC 81, 723 (2021) / ArXiv:2104.04762*	
	$ZZ \to 4\ell$	Full Run2	*PLB 812 (2020) 135992 / ArXiv:2008.07013*	
	$ZZ \to 2\ell 2\nu$			
Semi Leptonic	$ZW/ZZ \to 2\ell$ jj	2016	*PLB 798 (2019)134985 / ArXiv:1905.07445*	• more difficult due to **larger backgrounds** • powerful for aQGC searches
	$WW/WZ \to \ell\nu$ jj	Full Run2	★*CMS-PAS-SMP-20-013*	
Fully Hadronic	$WW/WZ/ZZ \to$ jjjj			
	$WZ/ZZ \to$ jj$\nu\nu$			
photonic	$Z\gamma \to \ell^{\pm}\ell^{\mp}\gamma$	Full Run2	★ *CMS-SMP-20-016 / ArXiv:2106.11082*	• relatively clean, except QCD background
	$W\gamma \to \ell\nu\gamma$	2016	*PLB 811(2020) 135988 / ArXiv: 2008.10521*	• larger signal, mostly experimental backgrounds

VBS Analyses Overview



VBS Signature

Two forward jets with

- **Large** rapidity separation $|\Delta\eta_{jj}|$
- **Large** dijet mass m_{jj}

VV Features

Two scattered bosons with specific selections of the corresponding final state

Background Estimation

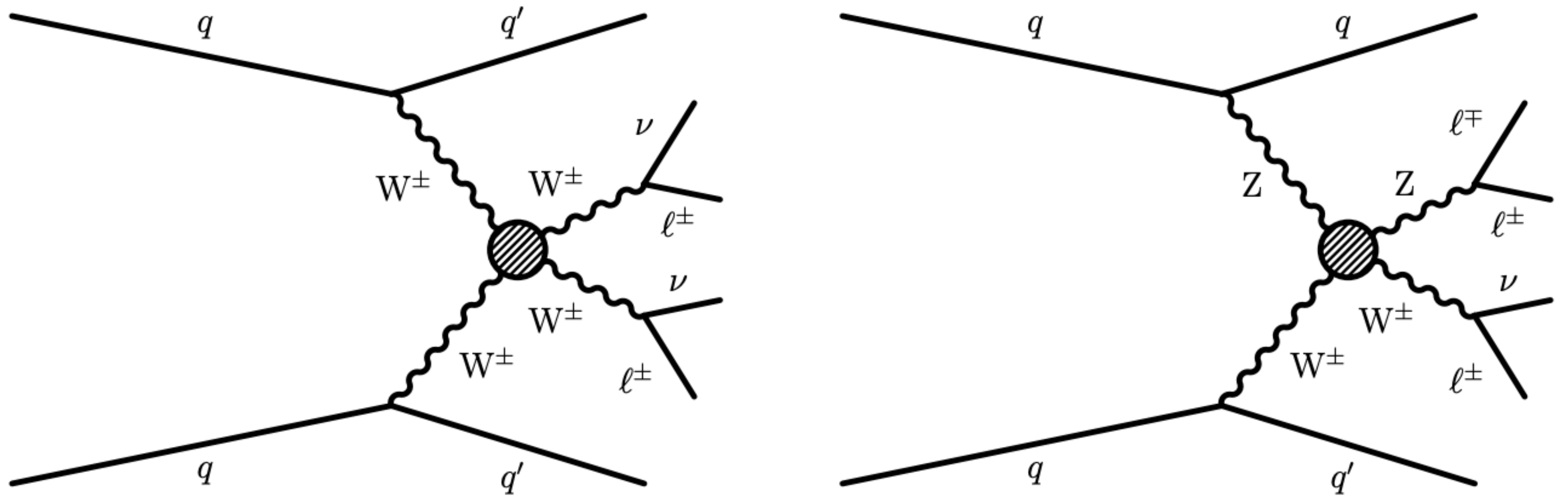
A combination of **data-driven** methods and **simulation** studies

Cross Section Measurements	New Physics Searches
A **cut-based** or **multivariate** analysis is applied to extract signals and perform measurements	• Anomalous couplings (EFT: effective field theory) • Heavy resonances like $H^{\pm}$ and $H^{\pm\pm}$

W±W± & WZ Fully Leptonic: Strategy

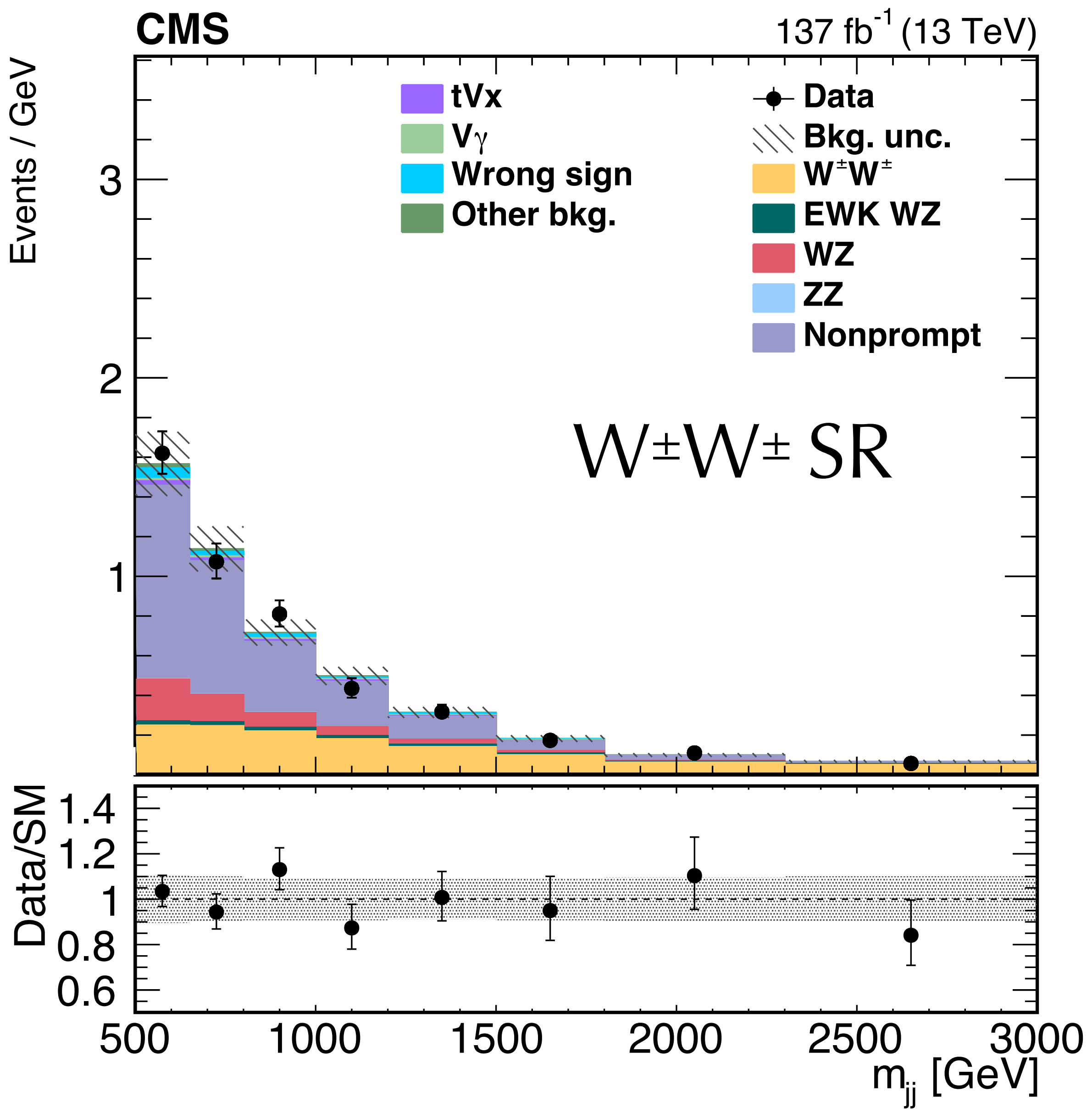
PLB 809 (2020) 135710 / ArXiv:2005.01173

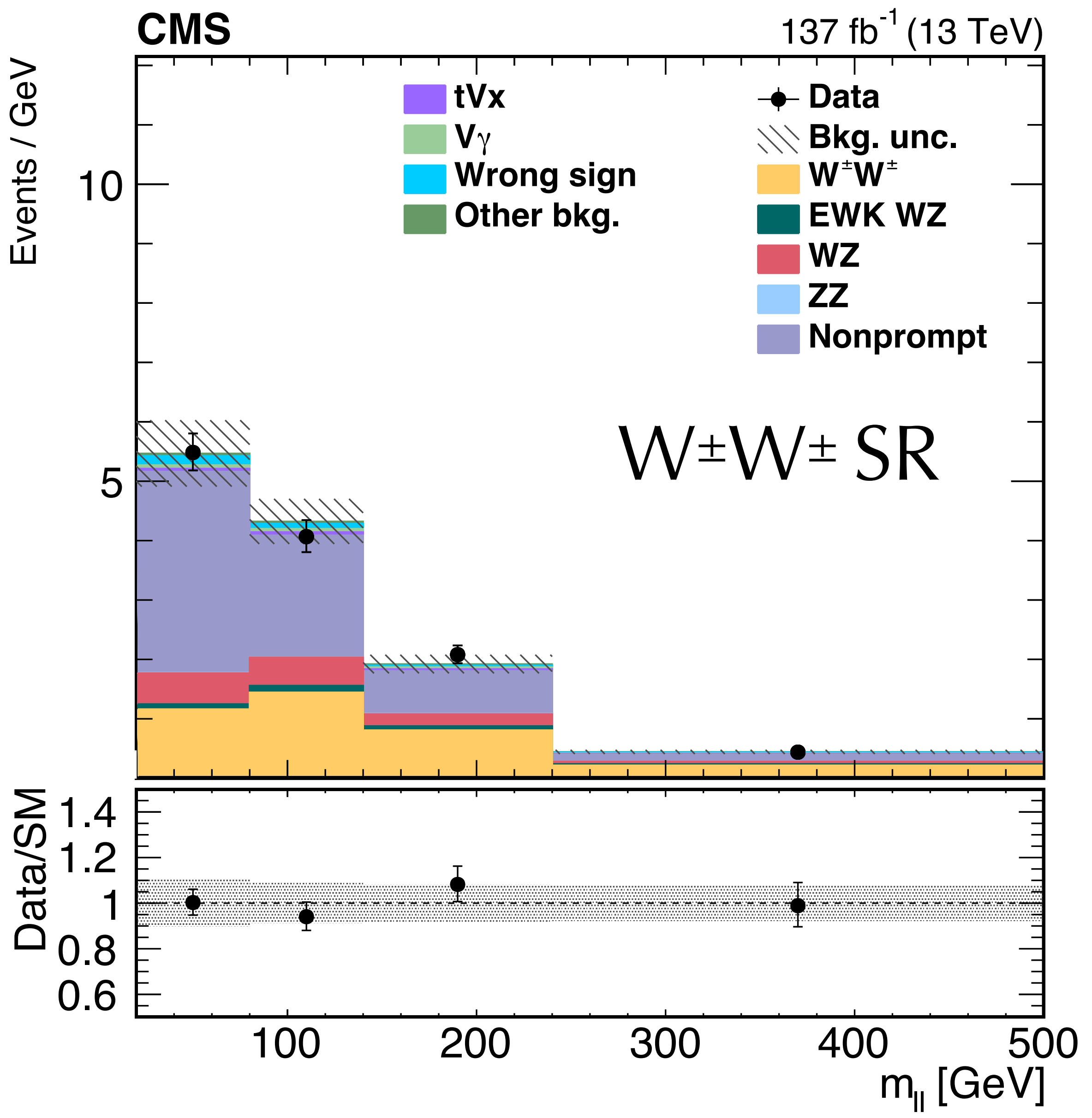
- VV Feature: fully **leptonic** decay $W^\pm W^\pm \rightarrow \ell^\pm\nu\ell'^\pm\nu$; $W^\pm Z \rightarrow \ell^\pm\nu\ell'^\pm\nu\ell'^\mp$
  - Cleanest final states hence lower backgrounds
  - Uniqueness of **Same Sign:** ◊Best σ_{EW}/σ_{QCD} ratio
    ◊A powerful shield against ttbar background
- Background estimation
  - Non prompt/fakes: from data
  - Prompt irreducible: from MC, with QCD WZ, ZZ, tZq normalization assessed from data

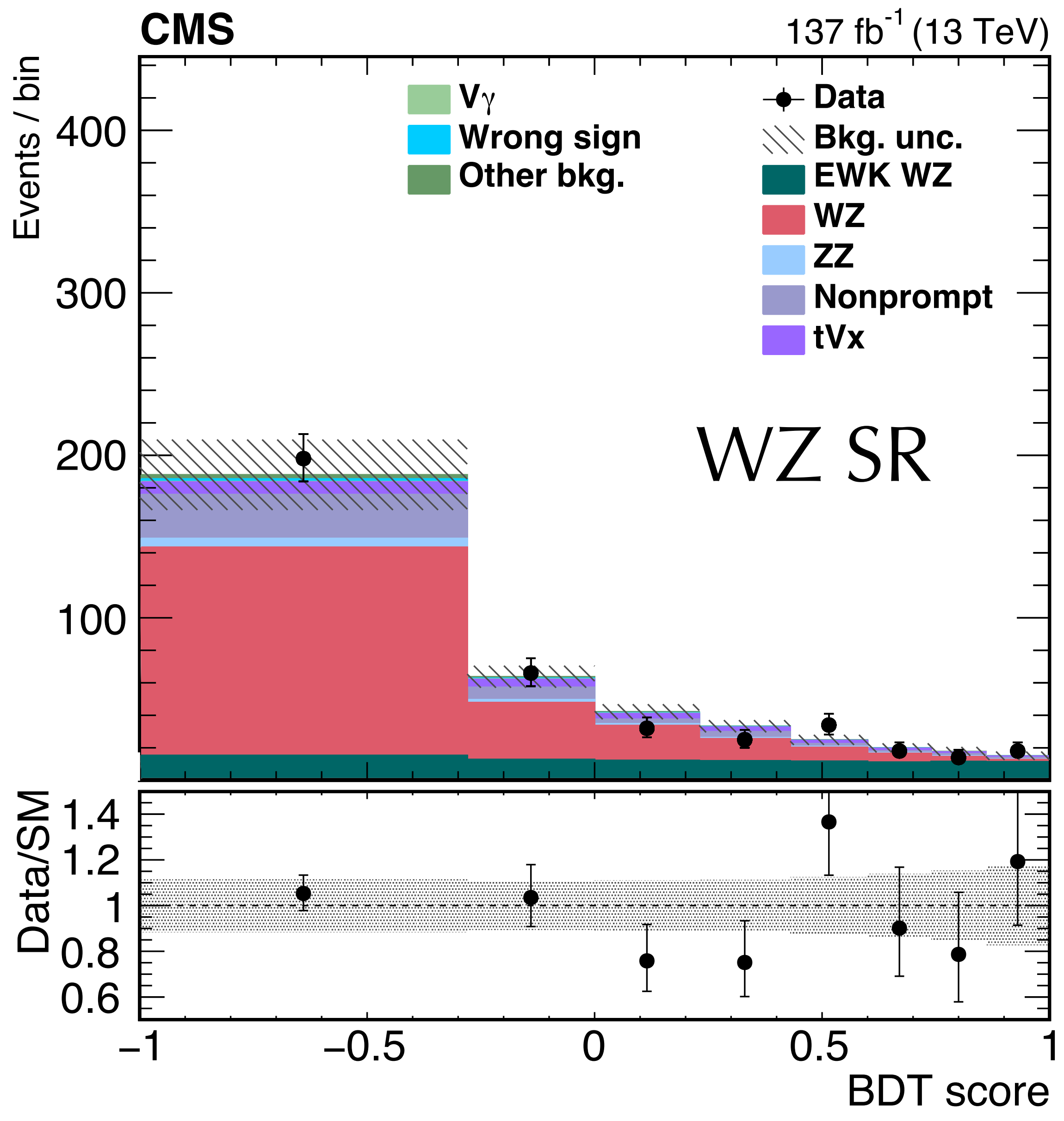


- A **multivariate analysis: BDT** is used to better discriminate EWK production from QCD for **WZ**

- **W±W±** and **WZ** production cross sections are measured by **simultaneously fitting** on several distributions across all SRs and CRs
  - W±W± SR: 2D — $m_{jj} \times m_{\ell\ell}$
  - WZ SR: BDT score
  - CR: m_{jj}







W±W± & WZ Fully Leptonic: Cross Section Measurements

First simultaneous measurements of W±W±jj & WZjj production

statistically limited !

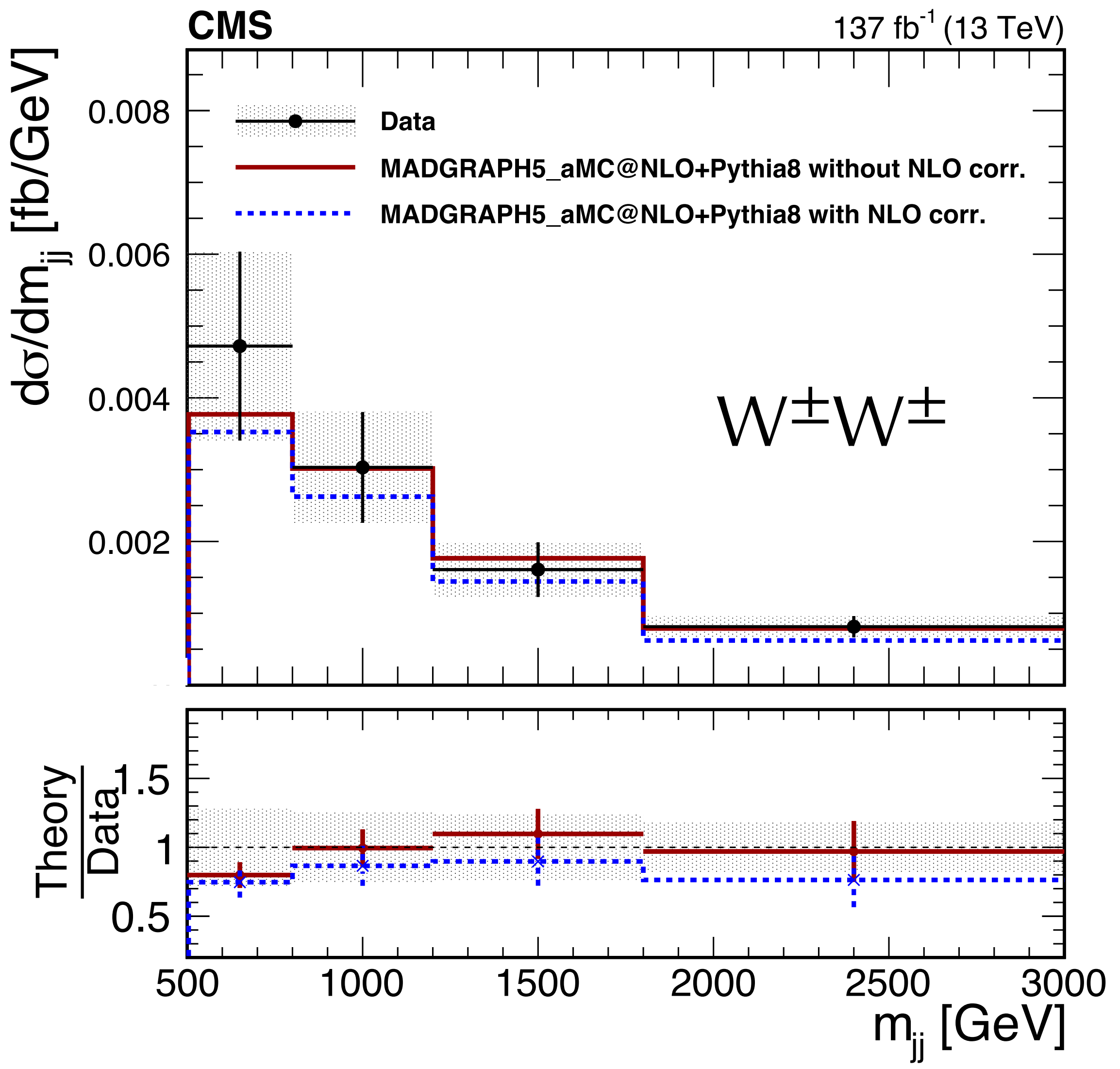
	W±W±(%)	WZ(%)
Systematic unc.	5.7	7.9
Statistical unc.	**8.9**	**22**
Total	11.0	23

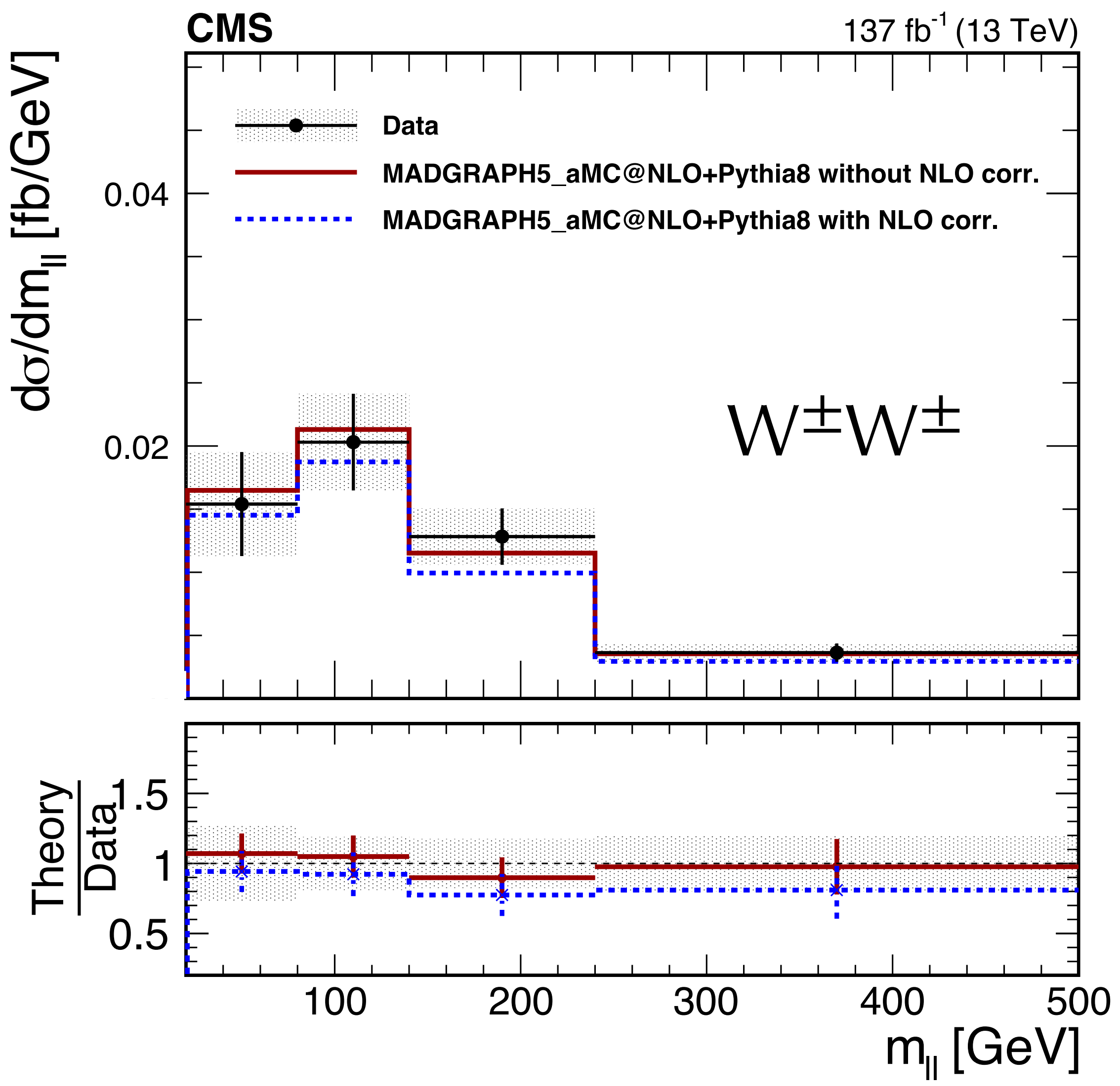
- Observed(Expected) **significance**
  - EWK WZ : 6.8 (5.3)σ
  - EWK WW : far above 5σ

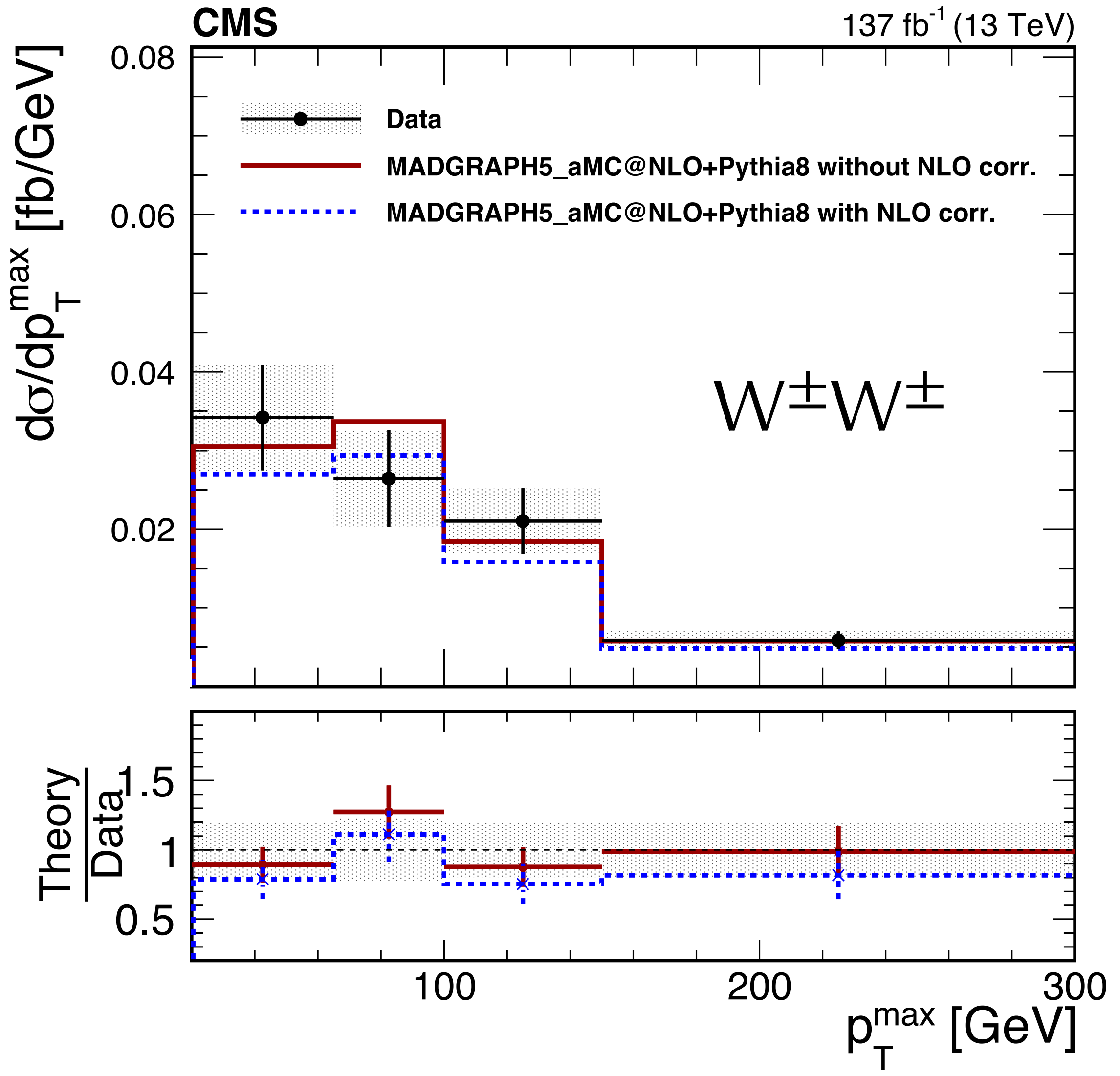
- **Inclusive cross section** measurements

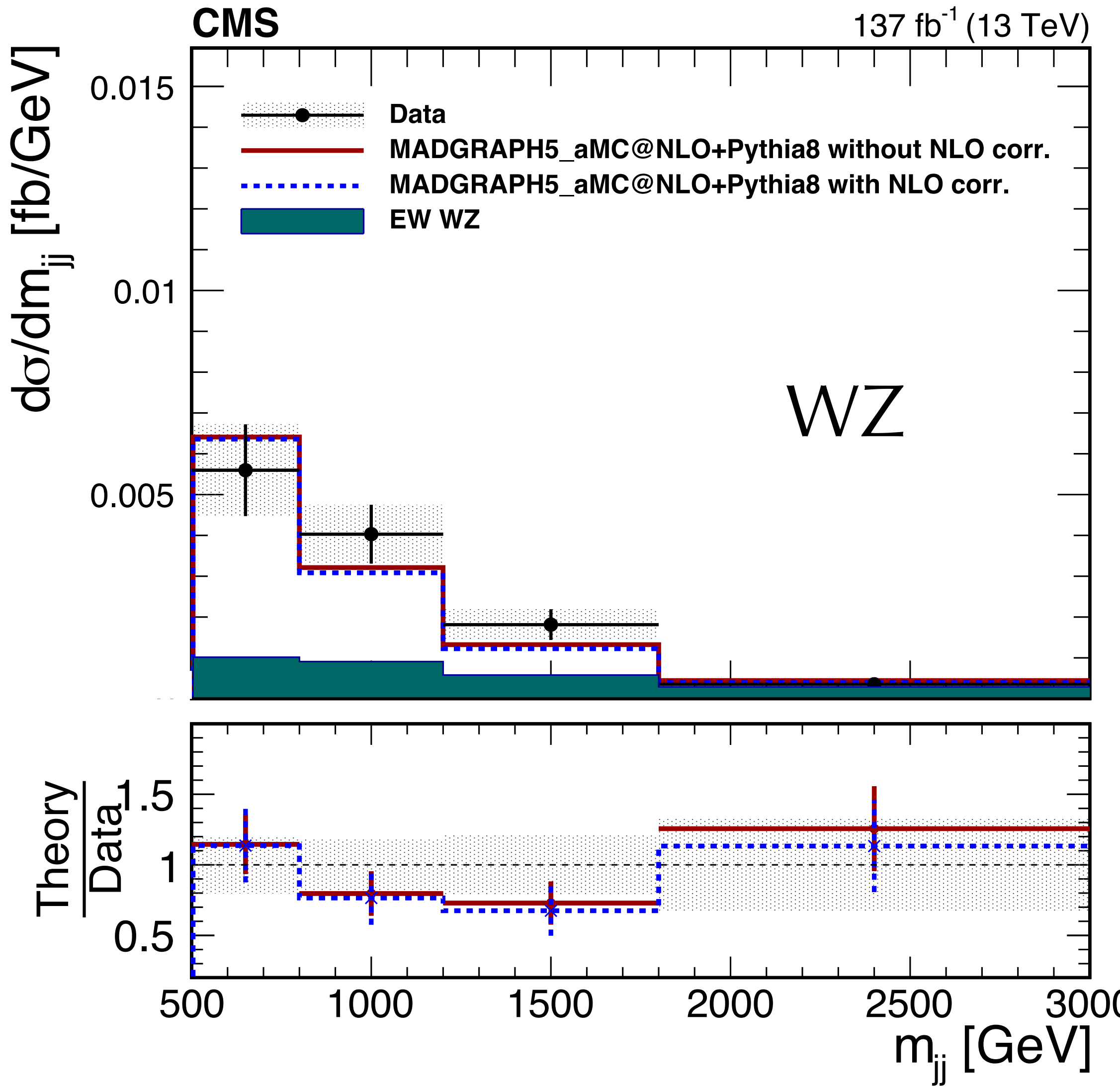
Process	$\sigma\,\mathcal{B}$ (fb)	Theoretical prediction without NLO corrections (fb)	Theoretical prediction with NLO corrections (fb)
EW $W^{\pm}W^{\pm}$	3.98 ± 0.45 $0.37\,(\text{stat}) \pm 0.25\,(\text{syst})$	3.93 ± 0.57	3.31 ± 0.47
EW+QCD $W^{\pm}W^{\pm}$	4.42 ± 0.47 $0.39\,(\text{stat}) \pm 0.25\,(\text{syst})$	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

- **First differential cross section** measurements on **m_{jj}, $m_{\ell\ell}$, p_T^{max}** for **W±W±** and **m_{jj}** for **WZ**









W±W± Fully Leptonic: Polarized

PLB 812(2021) 136018 / ArXiv:2009.09429

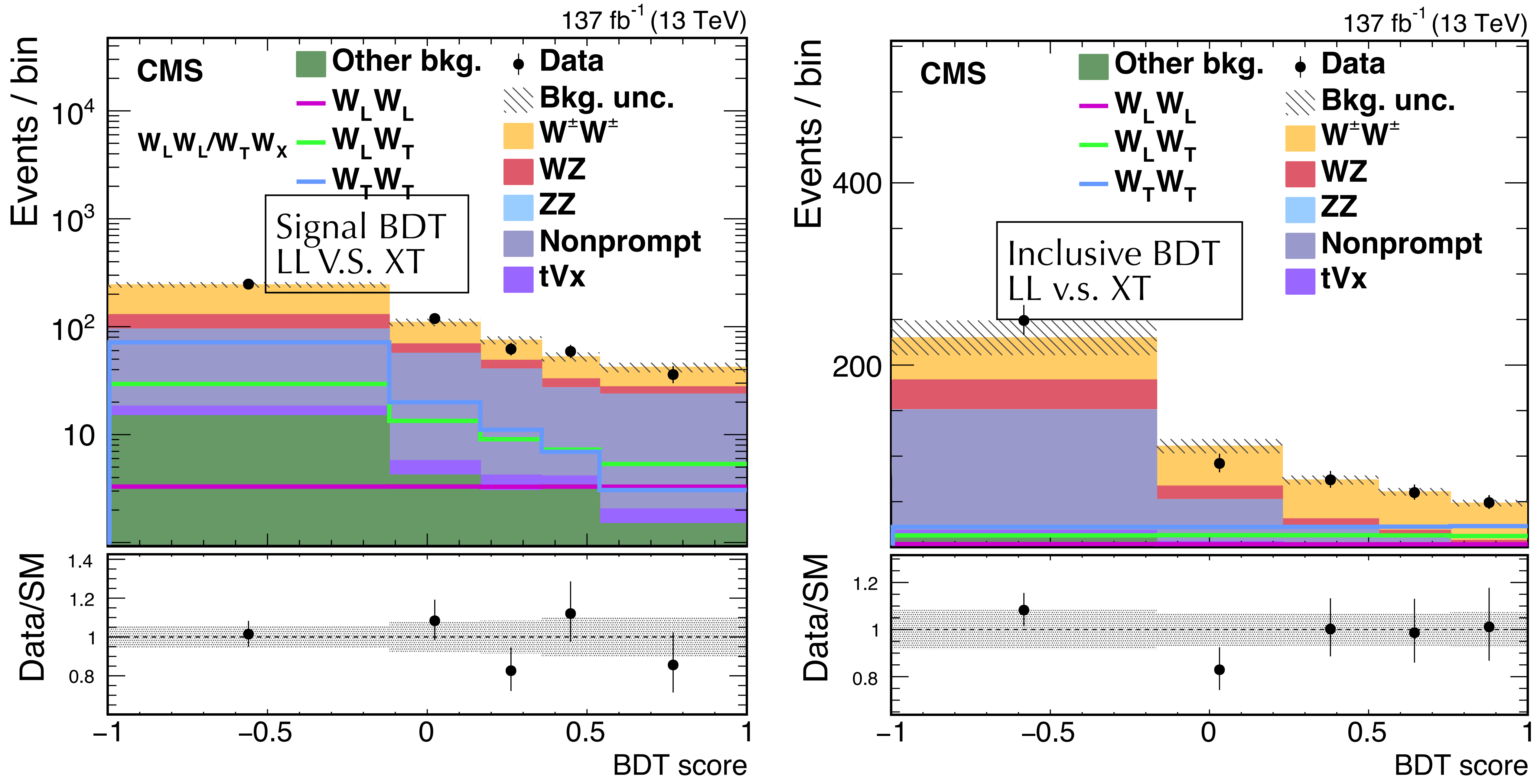
- Polarization of the massive vector boson
  - Three modes: one **L**ongitudinally and two **T**ransverse

$$\epsilon_L^\mu = \frac{1}{m}(k_3, 0, 0, E) \qquad \epsilon_{T_1,T_2}^\mu = \frac{1}{\sqrt{2}}(0, 1, \pm i, 0)$$

  - **Longitudinal polarization** is a consequence of the **EWSB**
- Uniqueness of **Same Sign** for **polarized VBS**
  - The only process for which the cross-talk amplitudes: $W_XW_T \rightarrow W_LW_L$ and $W_LW_L \rightarrow W_XW_T$ are completely negligible

- **Signal definition**
  - Polarization configurations
    - EW $W_L^\pm W_L^\pm$ (**LL**), $W_L^\pm W_T^\pm$(**LT**) and $W_T^\pm W_T^\pm$(**TT**)
  - Polarization vector is not Lorentz invariant for massive particles hence requires a **choice of reference frame**

- Analysis Strategy
  - Same object selection and background estimation as the W±W± & WZ SM analysis
  - Two sets of BDTs are used
    - **Signal BDTs** to separate different polarization configurations
    - **Inclusive BDT** to isolate EW W±W±jj from nonVBS backgrounds
    - SR: 2D fit — signal BDT X inclusive BDT



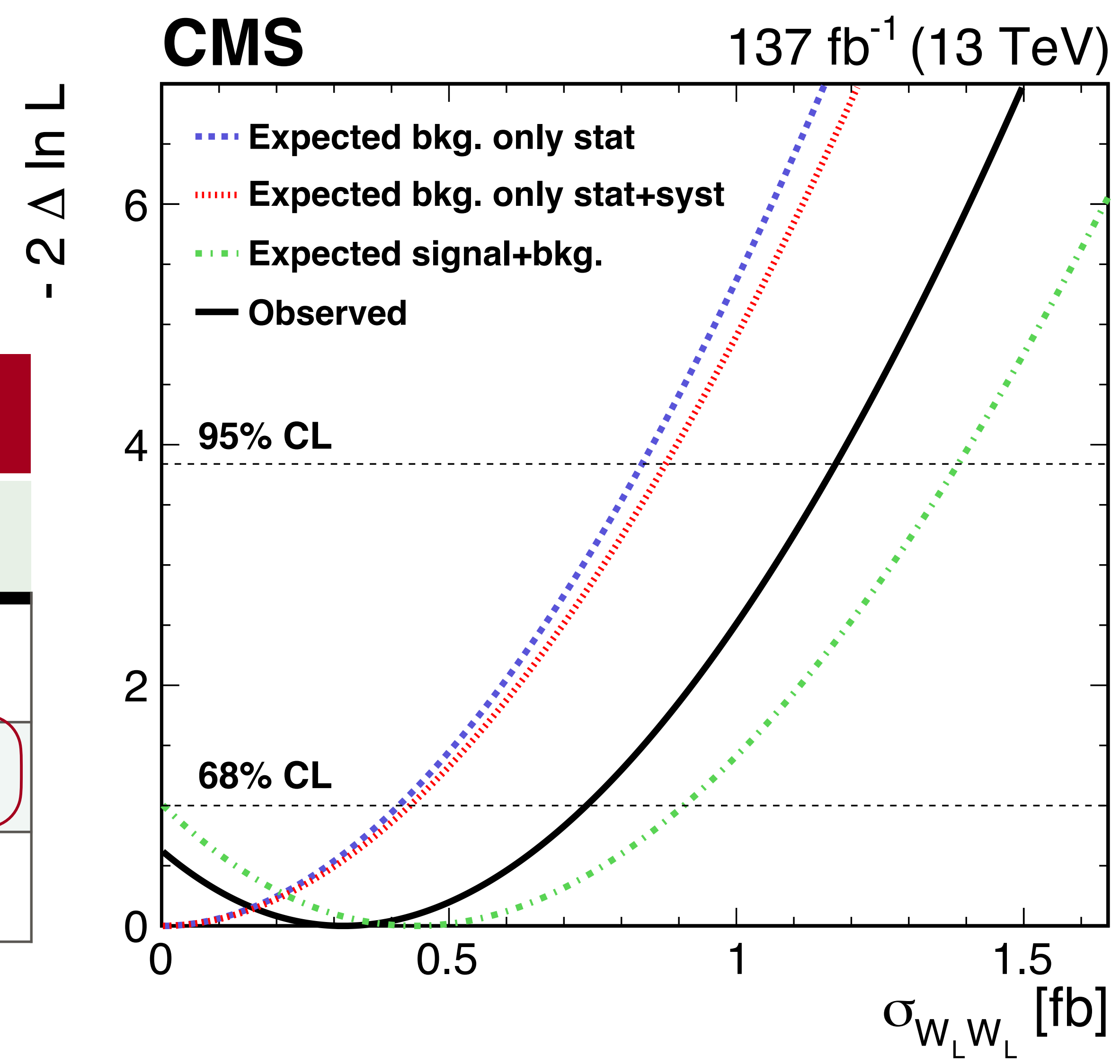
W±W± Fully Leptonic: Polarized

PLB 812(2021) 136018 / ArXiv:2009.09429

- Measurements Provided
  - Two sets of results are reported with the helicity eigenstates defined in
    - (i) the W±W± c.m. frame
    - (ii) the initial-state parton-parton c.m. frame
  - Provide two maximum-likelihood fits
    - (i) LL and XT (X = L or T)
    - (ii) LX and TT (X = L or T)

statistically limited !

	LL(%)	XT(%)	LX(%)	TT(%)
Systematic unc.	44	6.6	18	7.0
Statistical unc.	**123**	**15**	**42**	**22**
Total	130	16	46	23



W±W± frame

- Observed (expected) significance of **2.3 (3.1) σ** for **$W_L^\pm W_X^\pm$**
- Observed (expected) limit of **1.17 (0.88) fb** for **$W_L^\pm W_L^\pm$**

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

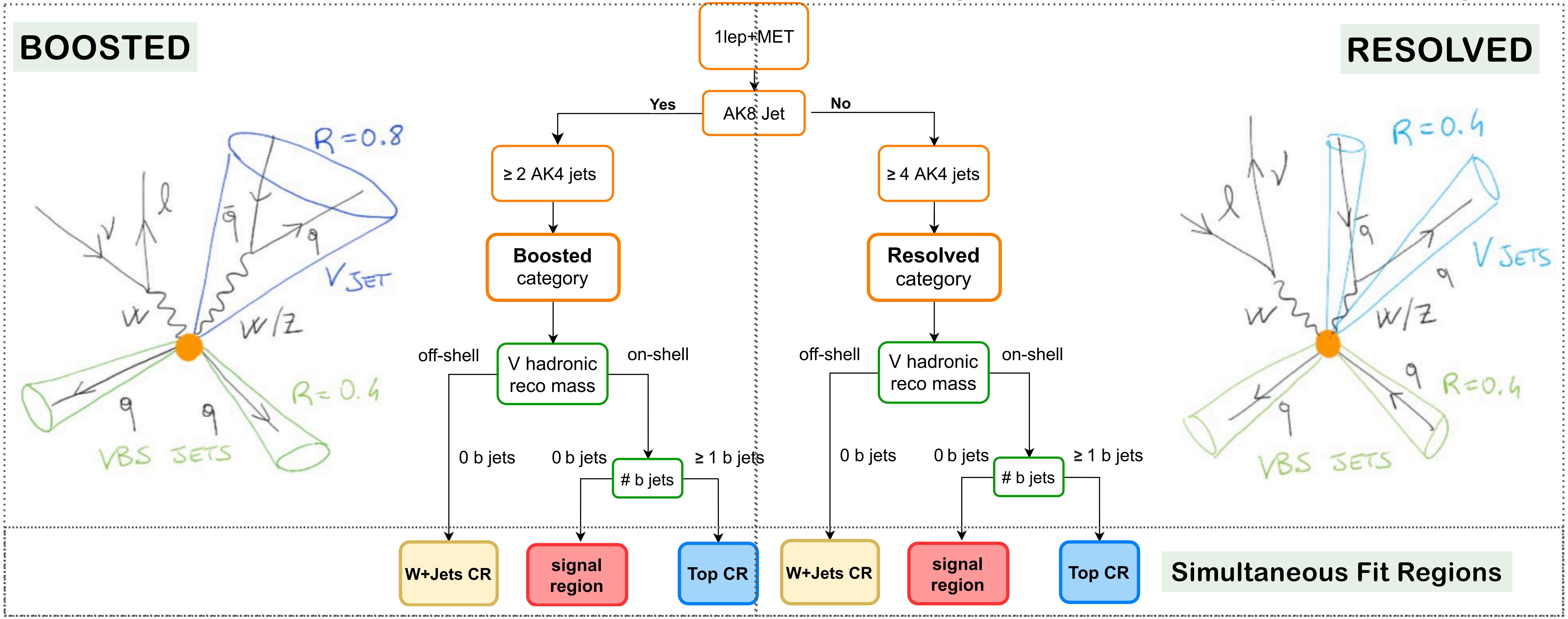
parton-parton frame

- Observed (expected) significance of **2.6 (2.9) σ** for **$W_L^\pm W_X^\pm$**
- Observed (expected) limit of **1.06 (0.85) fb** for **$W_L^\pm W_L^\pm$**

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

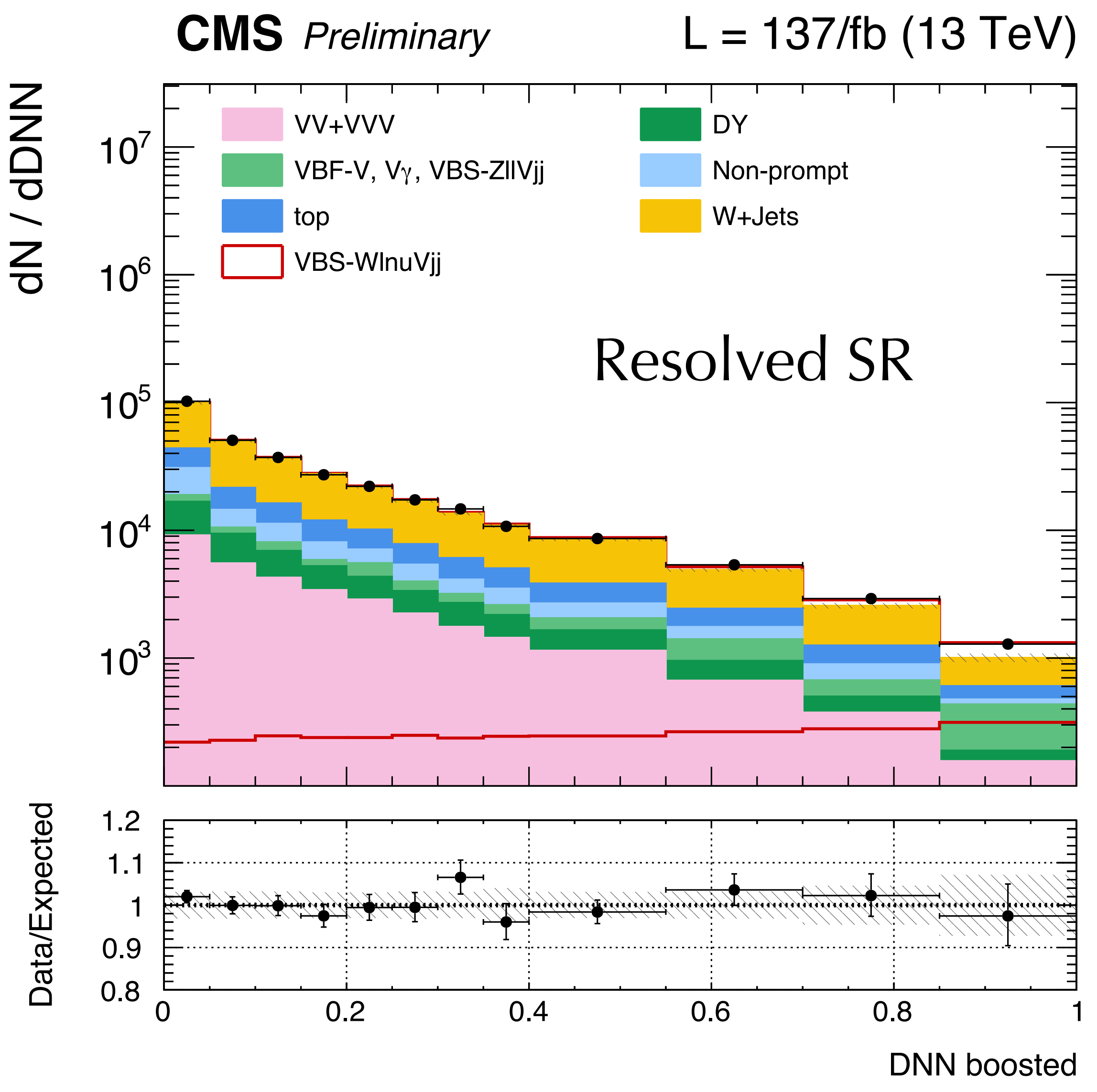
WV Semi-Leptonic: Strategy

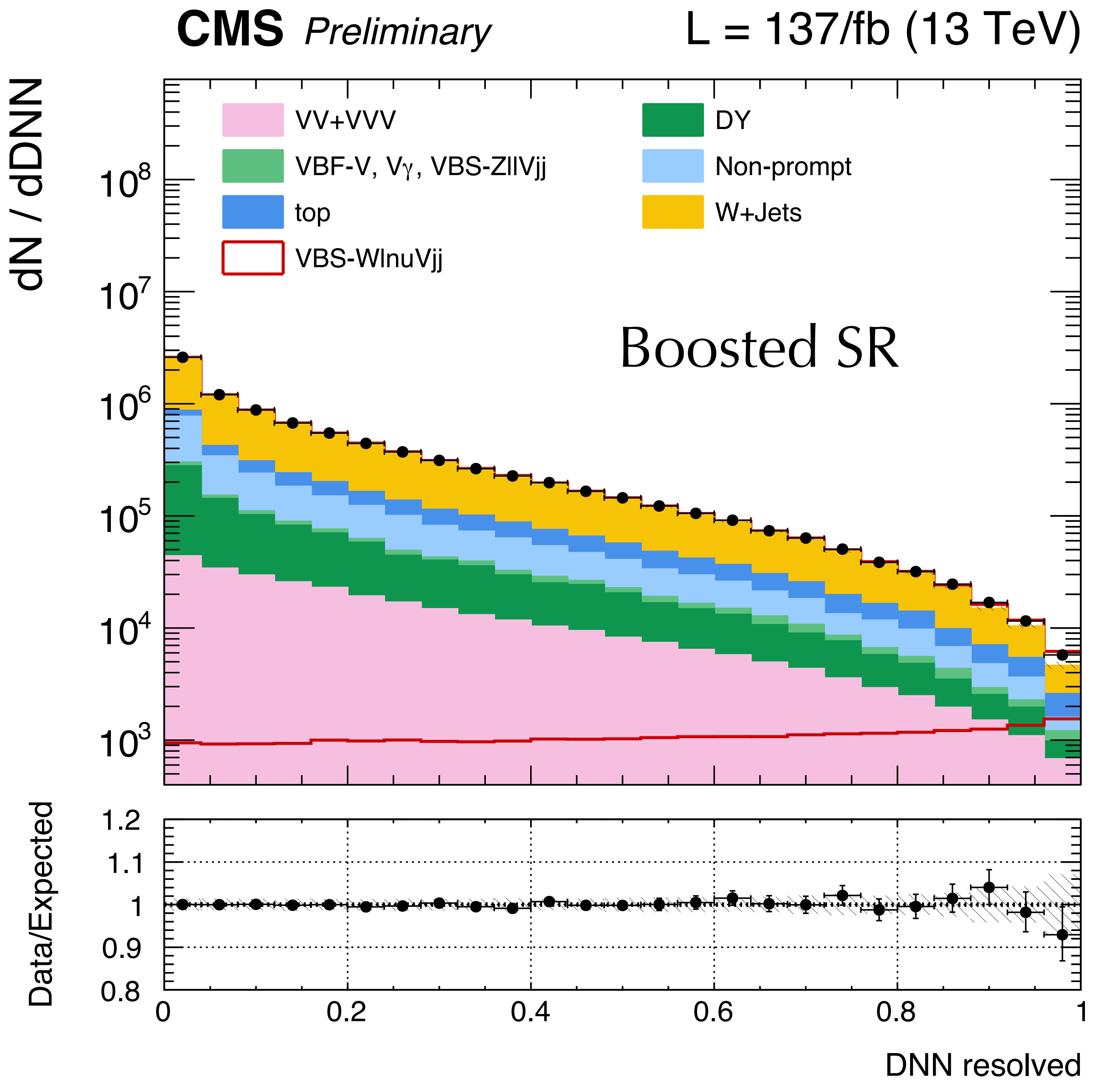
- VV Features: Semi-**leptonic** decay WV→$\ell\nu qq$
  - Larger cross section compared to fully leptonic and cleaner final states compared to fully hadronic
  - Powerful for aQGC searches
- Analysis Strategy
  - Target on both **resolved** and merged (**boosted**) decay regimes of the hadronic V
  - **Fully connected neural networks (DNN)** are trained in each category to better separate signal from background



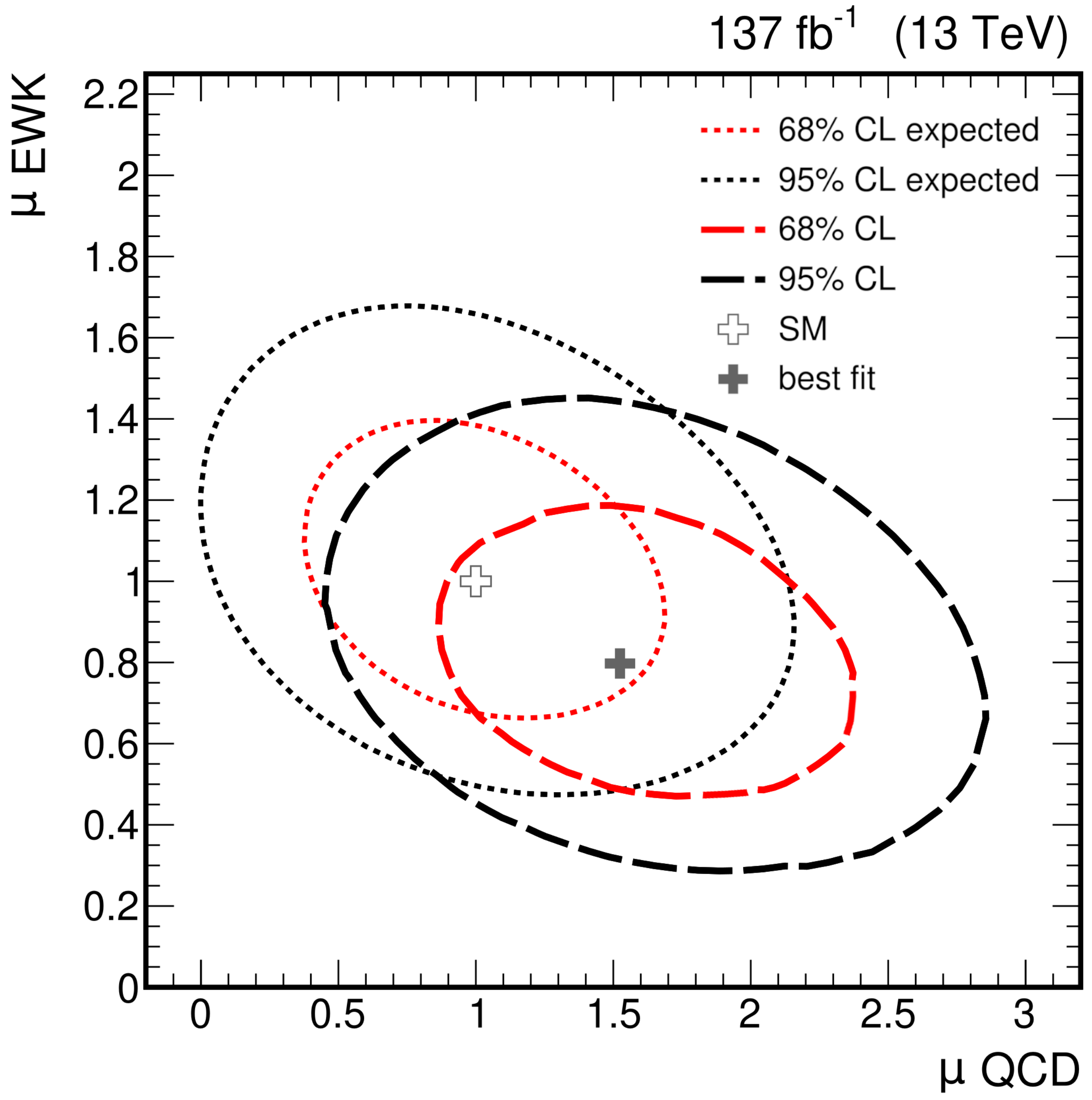
WV Semi-Leptonic: Cross Section Measurements

CMS-PAS-SMP-20-013





- A simultaneous fit is performed on **DNN score** across all regions
- Three separate likelihood ratio fits provided
  - EW WV
  - EW+QCD WV
  - 2D simultaneous measurement of free independent parameters μ_{EW} and μ_{QCD}

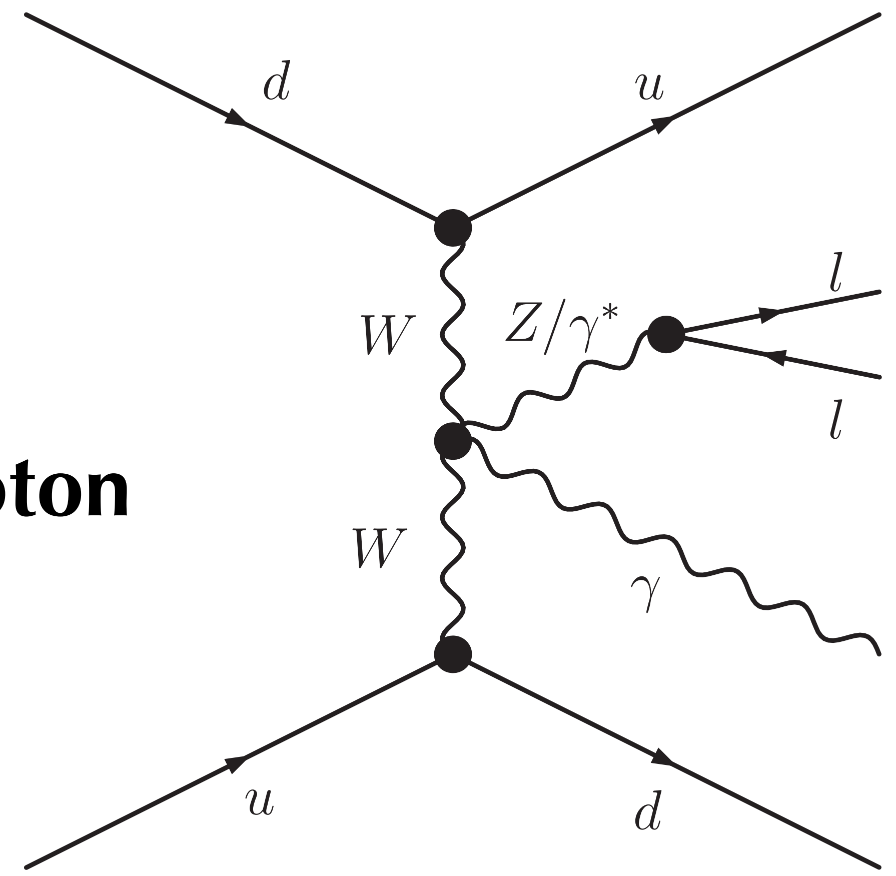


- **EW WV** : **First evidence** of semi-leptonic VBS at LHC!
  - observed (expected) significance of **4.5 σ** (5.3 σ)
  - $\mu_{EW} = \sigma^{obs}/\sigma^{SM} = 0.85^{+0.24}_{-0.20} = 0.85^{+0.21}_{-0.17}(\text{syst})\ ^{+0.12}_{-0.12}(\text{stat})$
  - Cross section: 1.9 ± 0.5 pb, $2.23^{+0.08}_{-0.11}(\text{scale})\ ^{+0.05}_{-0.05}(\text{pdf})$ pb expected
- **EW+QCD WV:**
  - $\mu_{EW+QCD} = \sigma^{obs}/\sigma^{SM} = 0.98^{+0.20}_{-0.17} = 0.98^{+0.19}_{-0.16}(\text{syst})\ ^{+0.07}_{-0.07}(\text{stat})$
  - Cross section: $16.6^{+3.4}_{-2.9}$ pb, $16.9^{+2.9}_{-2.1}(\text{scale})\ ^{+0.5}_{-0.5}(\text{pdf})$ expected

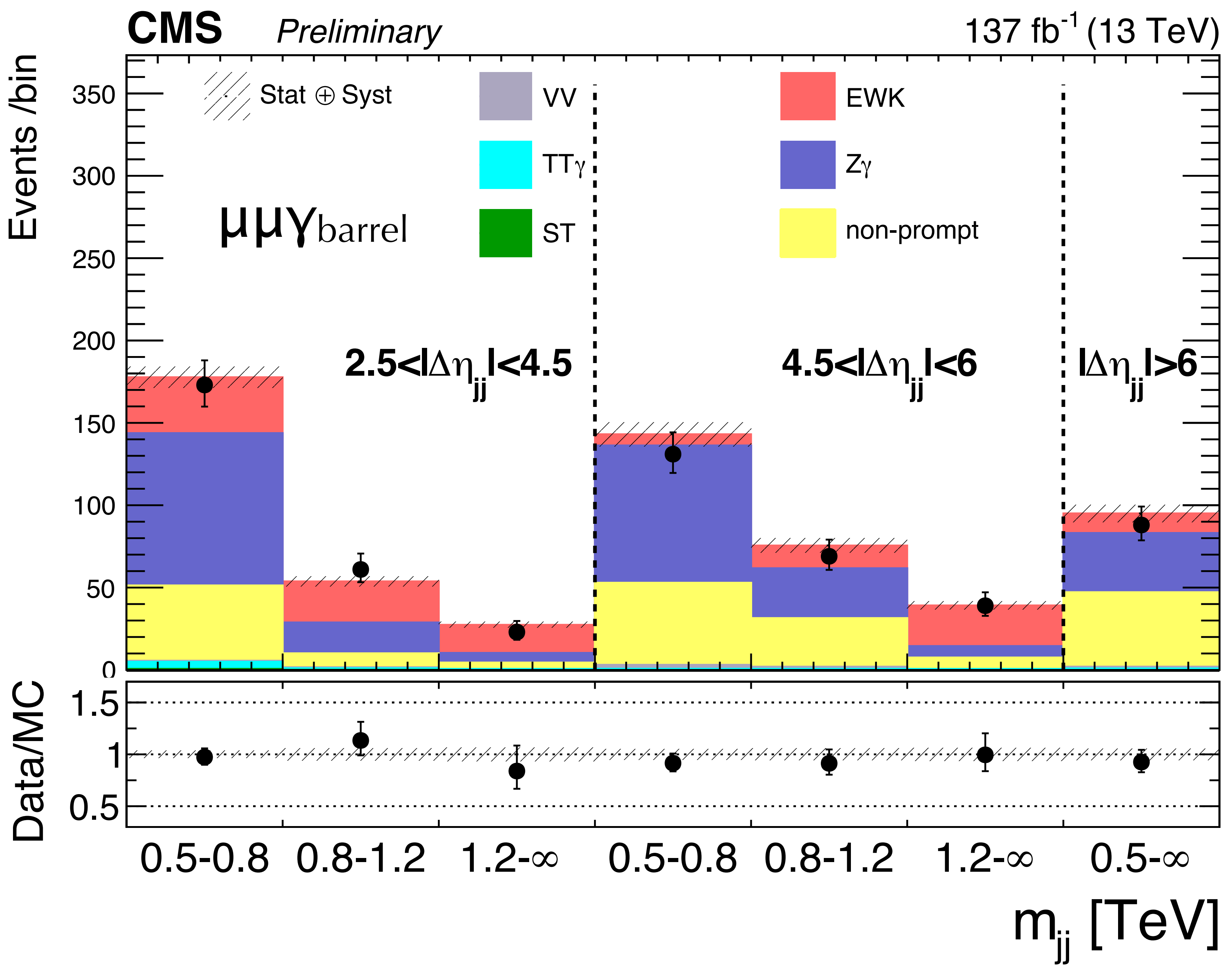
Zγ Leptonic: Strategy

CMS-SMP-20-016 / ArXiv:2106.11082

- VV Features: photonic-leptonic decay: $Z\gamma \to \ell^{\pm}\ell^{\mp}\gamma$
  - Relatively clean final states
  - Sensitive to neutral aQGC searches: $ZZZ\gamma/ZZ\gamma\gamma/Z\gamma\gamma\gamma$



- **Selections** based on **VBS signature** and exactly **one same-flavor os lepton pair** and **one good photon**
- **Categorization** based on lepton flavors and photons in the ECAL barrel/endcaps
  - $\mu\mu\gamma_{\text{barrel}}$, $ee\gamma_{\text{barrel}}$, $\mu\mu\gamma_{\text{endcap}}$, $ee\gamma_{\text{endcap}}$



- Background Estimation
  - Non-prompt photon: estimated from data using photon shape fit
  - QCD $Z\gamma$: estimated from simulation with normalization assessed from data
  - Other backgrounds: estimated from simulation

- A 2D fit is performed on $m_{jj} \times |\Delta\eta_{jj}|$ across all regions

Zγ Leptonic: Cross Section Measurements

CMS-SMP-20-016 / ArXiv:2106.11082

- Observed(Expected) **significance**: far above 5σ

- **Inclusive cross section** measurements

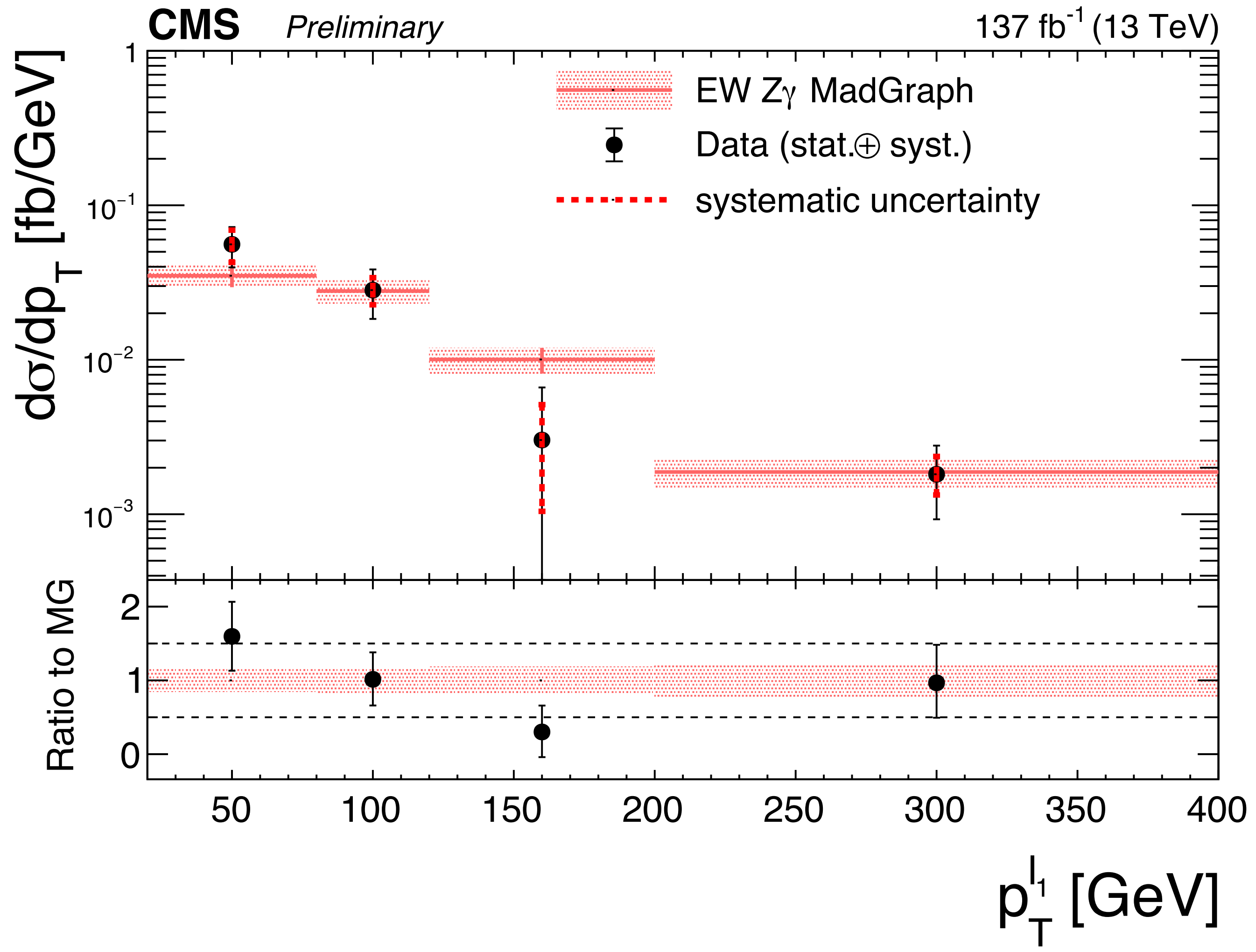
$$\mu_{\text{EW}} = 1.20^{+0.12}_{-0.12}\,(\text{stat})\,^{+0.14}_{-0.12}\,(\text{syst})$$

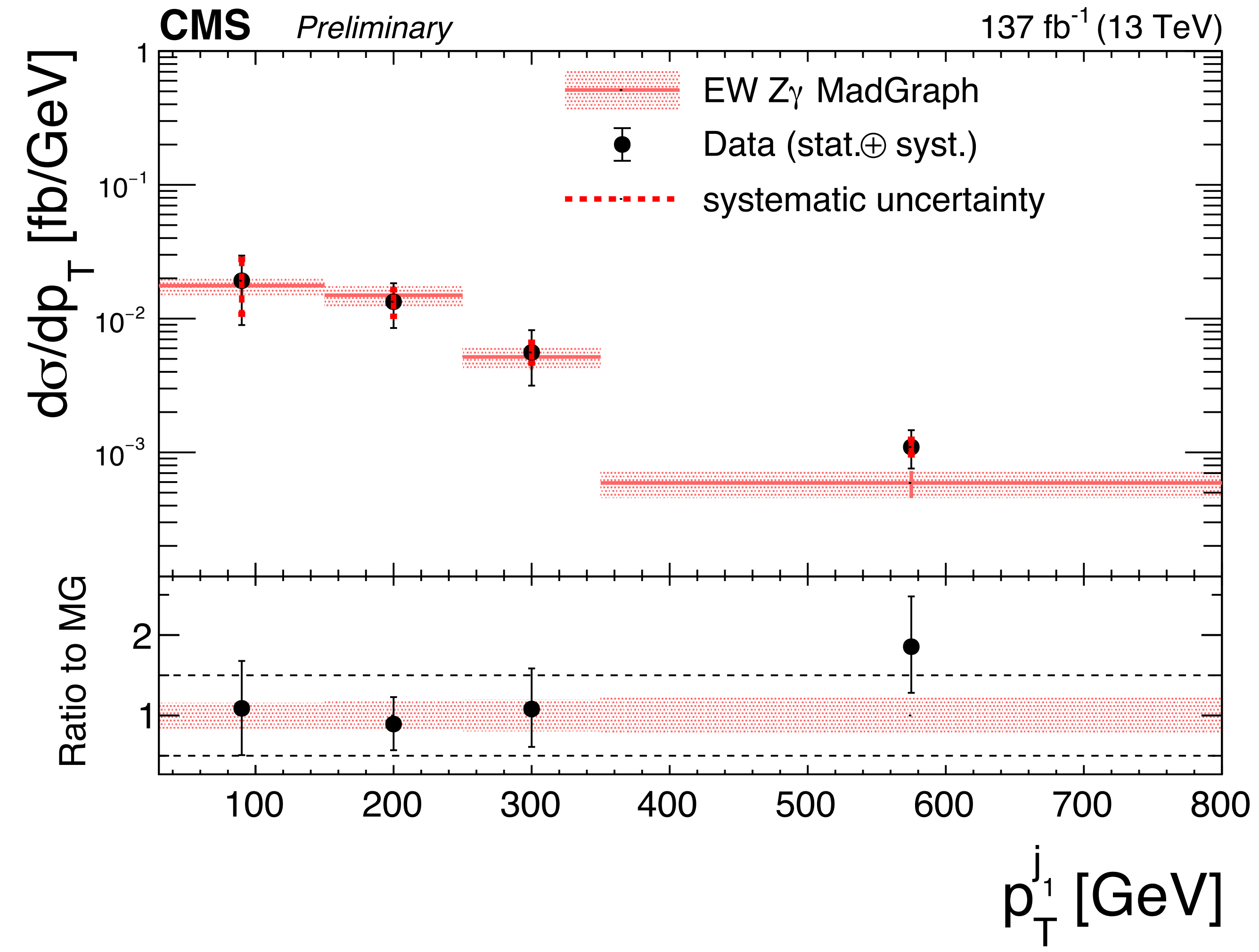
$$\sigma^{\text{fid}}_{\text{EW}} = 5.21 \pm 0.52\,(\text{stat}) \pm 0.56\,(\text{syst})\ \text{fb}$$

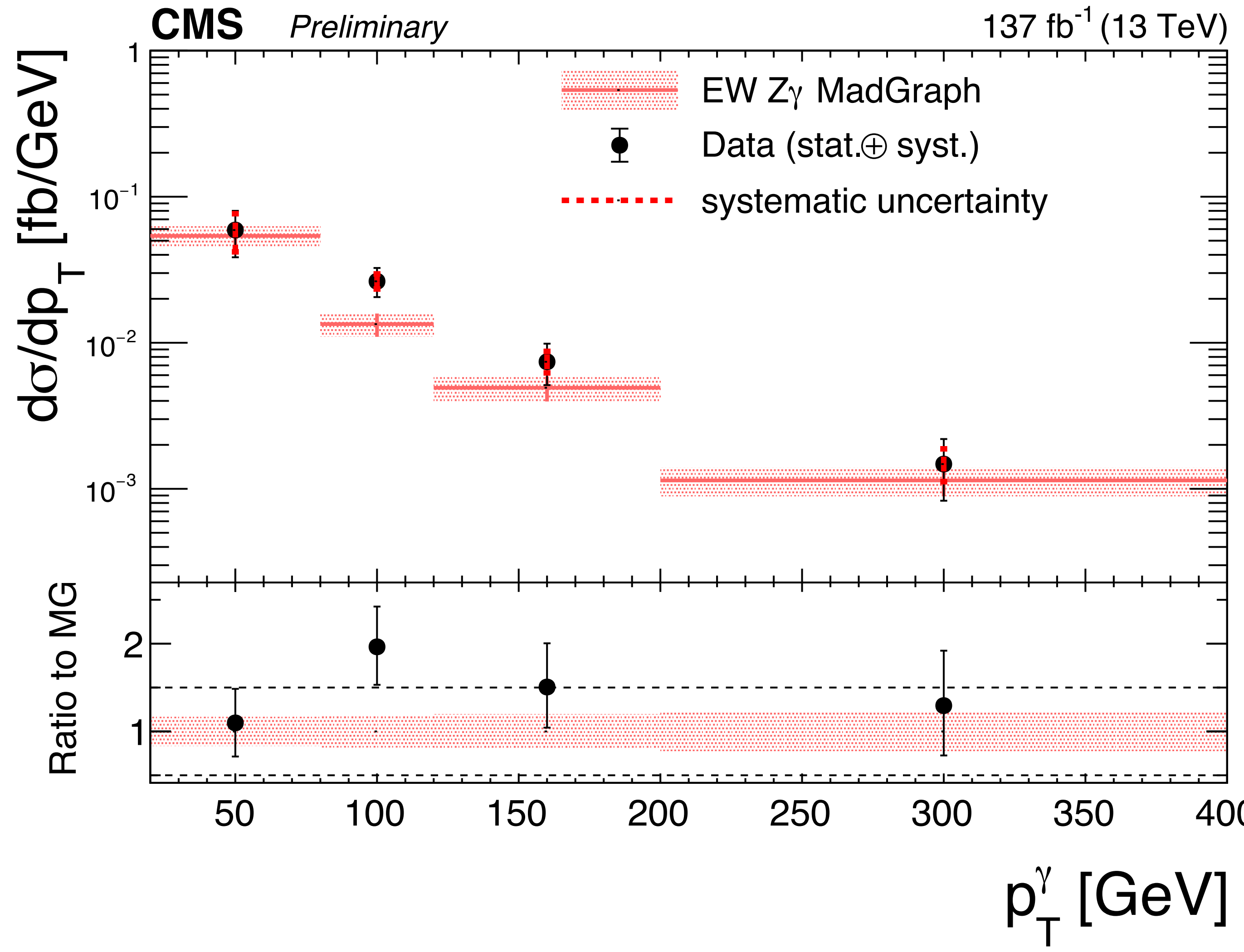
$$\mu_{\text{EW+QCD}} = 1.11^{+0.06}_{-0.06}\,(\text{stat})\,^{+0.10}_{-0.09}\,(\text{syst})$$

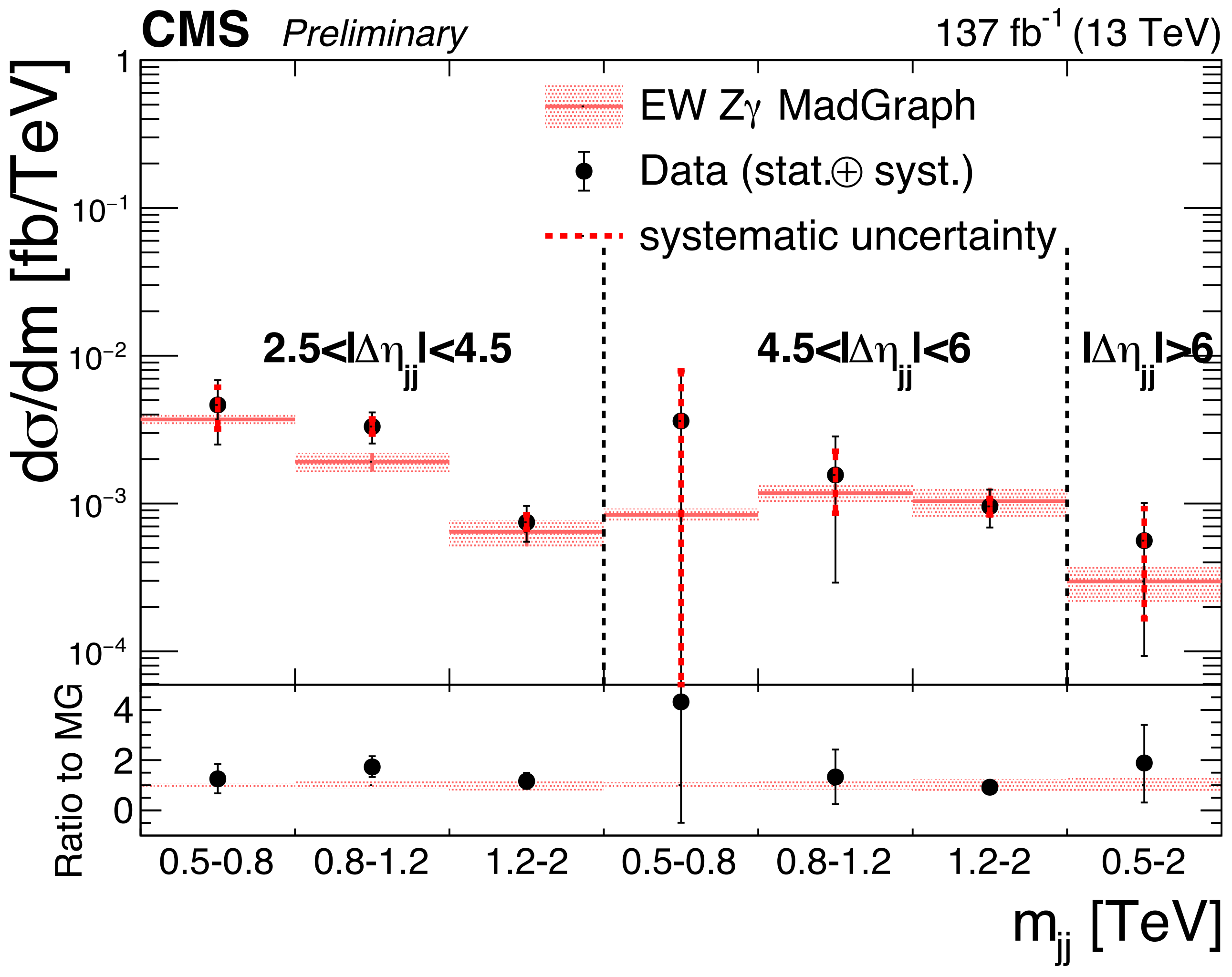
$$\sigma^{\text{fid}}_{\text{EW+QCD}} = 14.7 \pm 0.80\,(\text{stat}) \pm 1.26\,(\text{syst})\ \text{fb}$$

- **Differential cross section** measurements on $\mathbf{p_T^{l1}}$, $\mathbf{p_T^{j1}}$, $\mathbf{p_T^{\gamma}}$ and $\mathbf{m_{jj}}$-$|\Delta\eta_{jj}|$





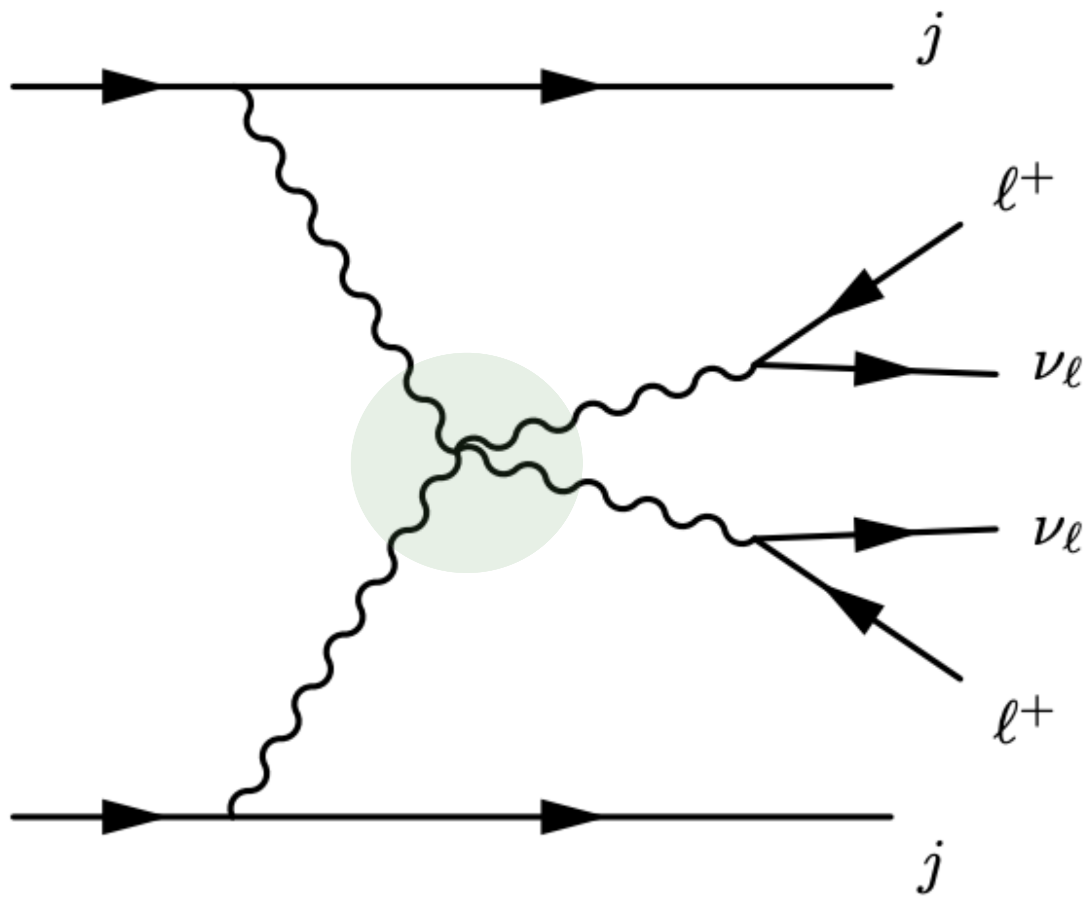




Anomalous Couplings Searches

- Extensions of the SM induce coupling modifications that can be parameterized in terms of an effective field theory (EFT) approach

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \left[\frac{a_i}{\Lambda} \mathcal{O}_i^{(5)} + \frac{c_i}{\Lambda^2} \mathcal{O}_i^{(6)} + \frac{e_i}{\Lambda^4} \mathcal{O}_i^{(8)} + \cdots \right]$$



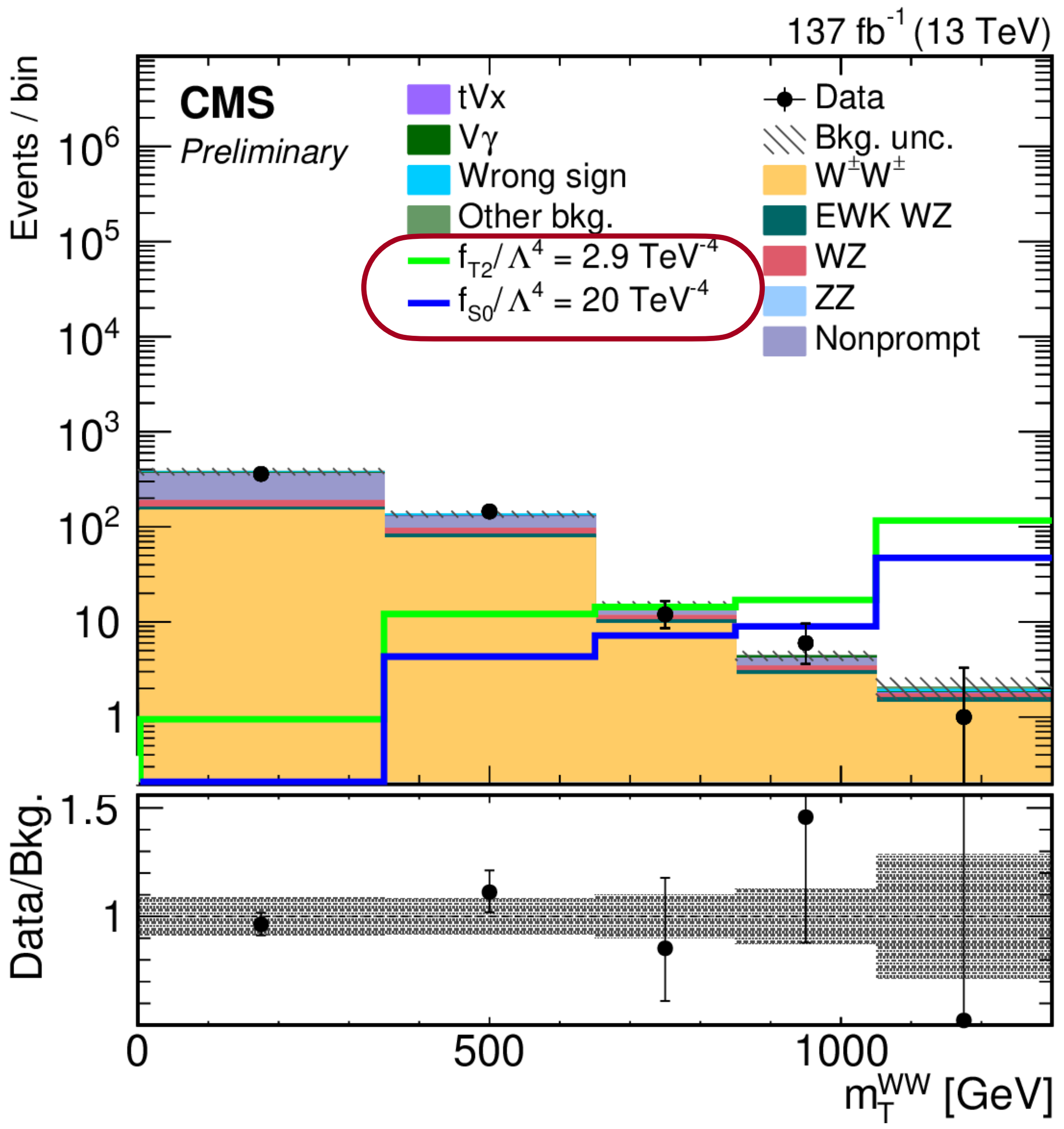
  - Each operator is scaled by a corresponding (Wilson) coefficient and new physics scale Λ
  - Dimension-8 operators can modify the VVjj production through anomalous quartic gauge couplings (aQGCs)

	WWWW	WWZZ	ZZZZ	WWAZ	WWAA	ZZZA	ZZAA	ZAAA	AAAA
$\mathcal{L}_{S,0}$, $\mathcal{L}_{S,1}$	X	X	X	O	O	O	O	O	O
$\mathcal{L}_{M,0}$, $\mathcal{L}_{M,1}$, $\mathcal{L}_{M,6}$, $\mathcal{L}_{M,7}$	X	X	X	X	X	X	X	O	O
$\mathcal{L}_{M,2}$, $\mathcal{L}_{M,3}$, $\mathcal{L}_{M,4}$, $\mathcal{L}_{M,5}$	O	X	X	X	X	X	X	O	O
$\mathcal{L}_{T,0}$, $\mathcal{L}_{T,1}$, $\mathcal{L}_{T,2}$	X	X	X	X	X	X	X	X	X
$\mathcal{L}_{T,5}$, $\mathcal{L}_{T,6}$, $\mathcal{L}_{T,7}$	O	X	X	X	X	X	X	X	X
$\mathcal{L}_{T,8}$, $\mathcal{L}_{T,9}$	O	O	X	O	O	X	X	X	X

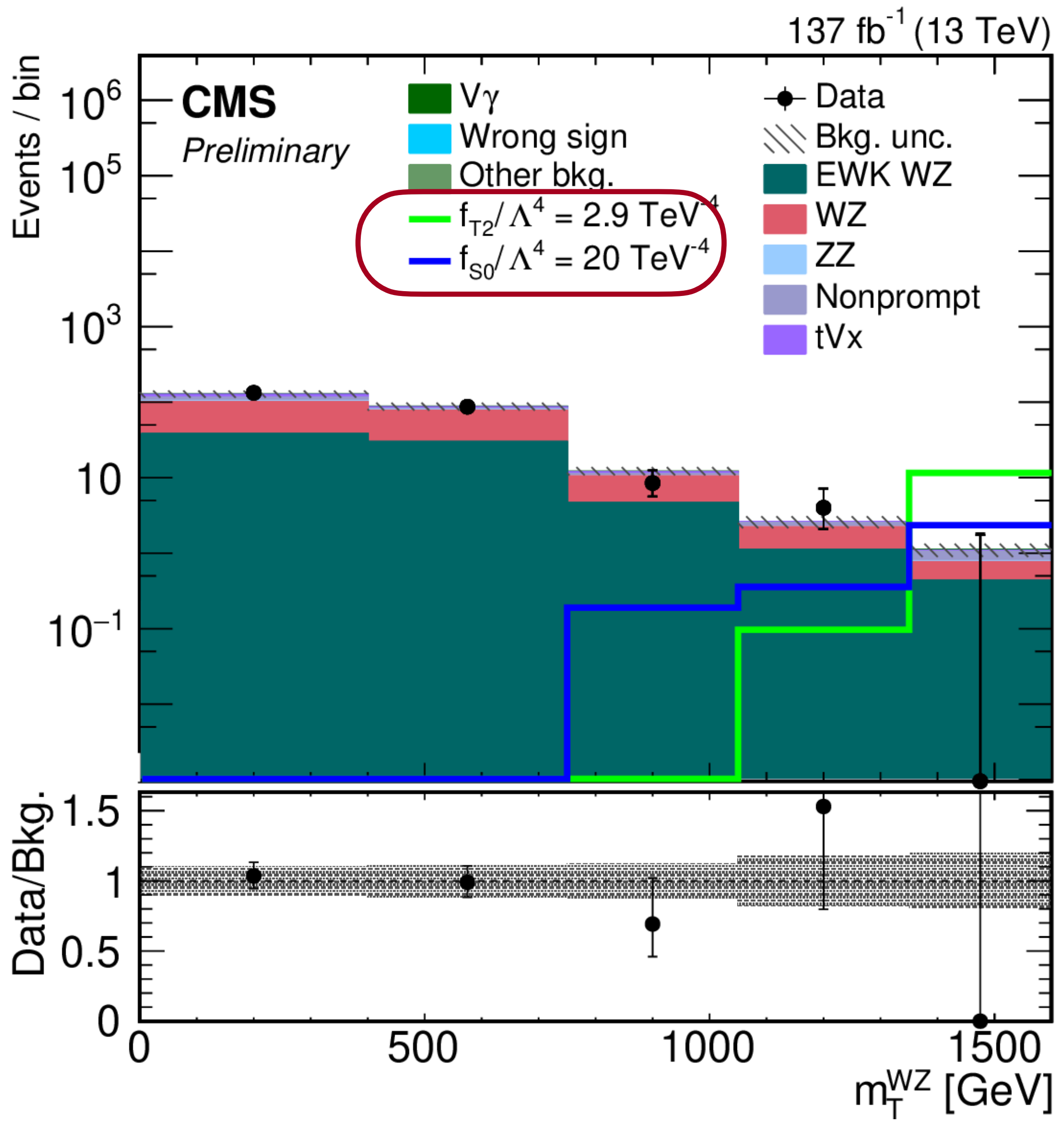
aQGC: Signal Extraction and Limits Obtainment

- Similar selections and analysis strategies as that in the corresponding analyses
- Variables sensitive to aQGC signals are added: VV mass $\mathbf{m_{VV}}$/transverse mass $\mathbf{m_T}$: $m_T^{VV} = \sqrt{\left(\sum_i E_i\right)^2 - \left(\sum_i p_{z,i}\right)^2}$
- Limits on f/Λ^4 obtained $$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \left[\frac{a_i}{\Lambda} \mathcal{O}_i^{(5)} + \frac{c_i}{\Lambda^2} \mathcal{O}_i^{(6)} + \frac{e_i}{\Lambda^4} \mathcal{O}_i^{(8)} + \cdots \right]$$
- Most stringent limits to date using semi-leptonic final states *PLB 798 (2019)134985 / ArXiv:1905.07445*

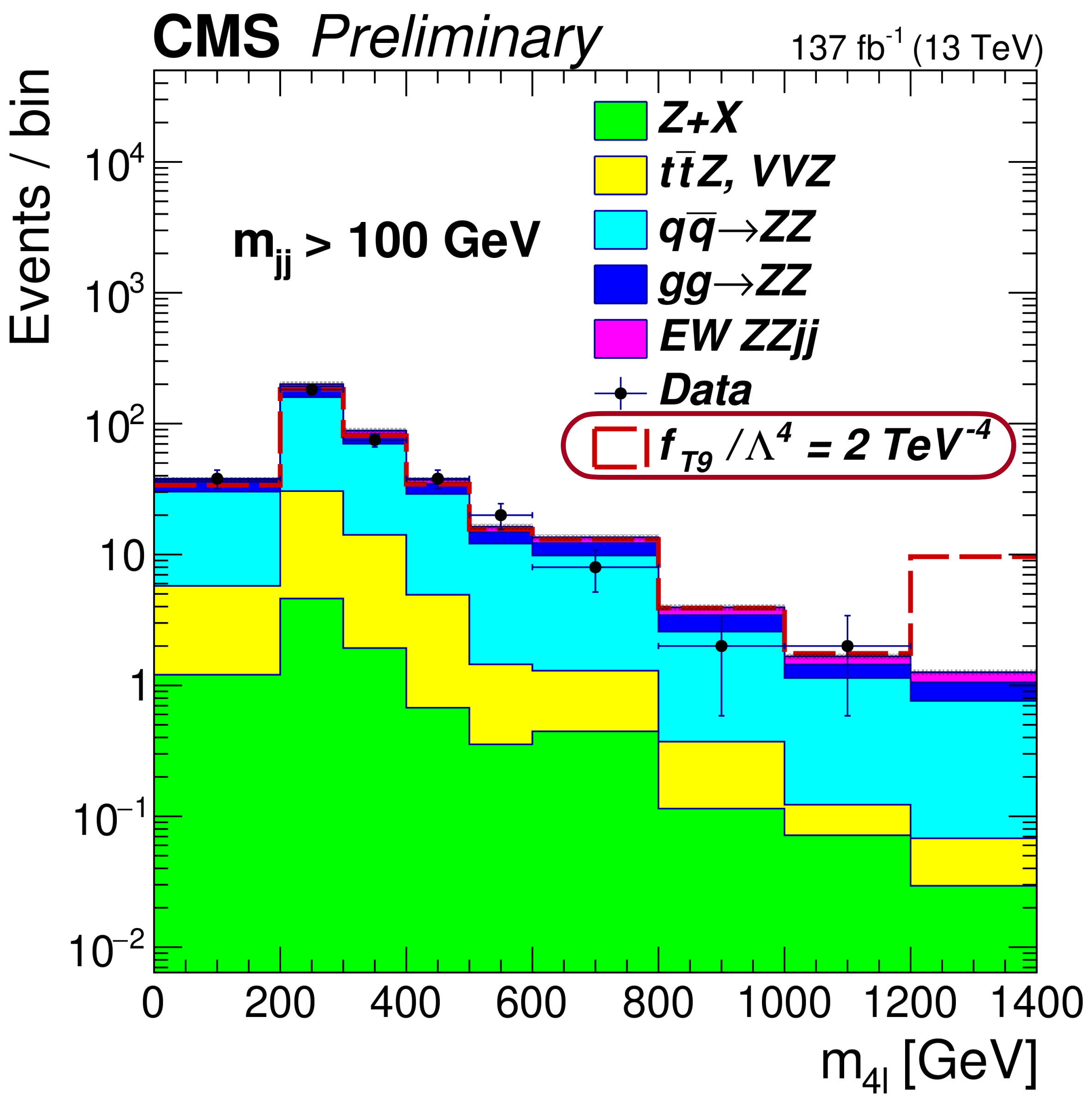
$W^{\pm}W^{\pm}$



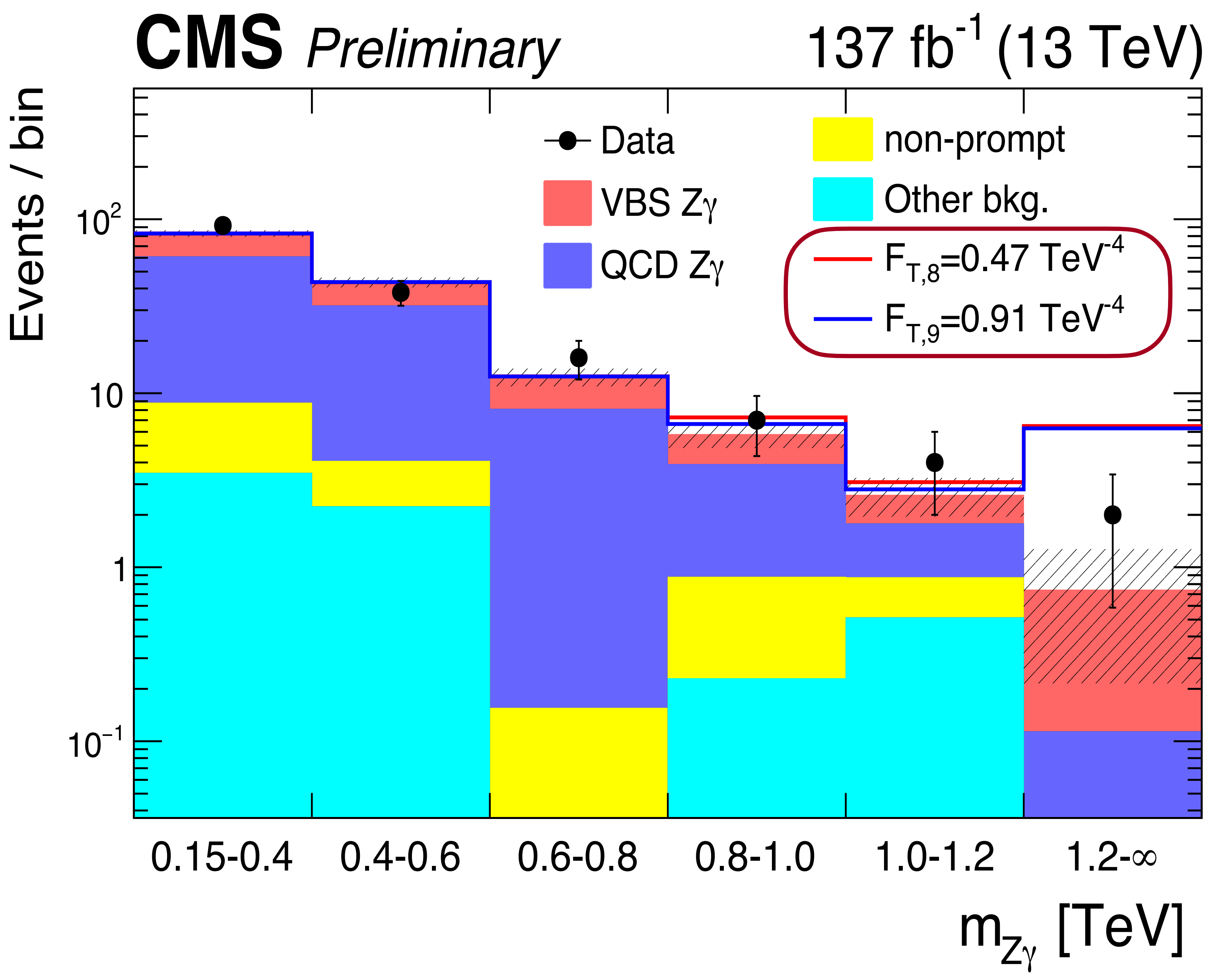
WZ



ZZ



Zγ

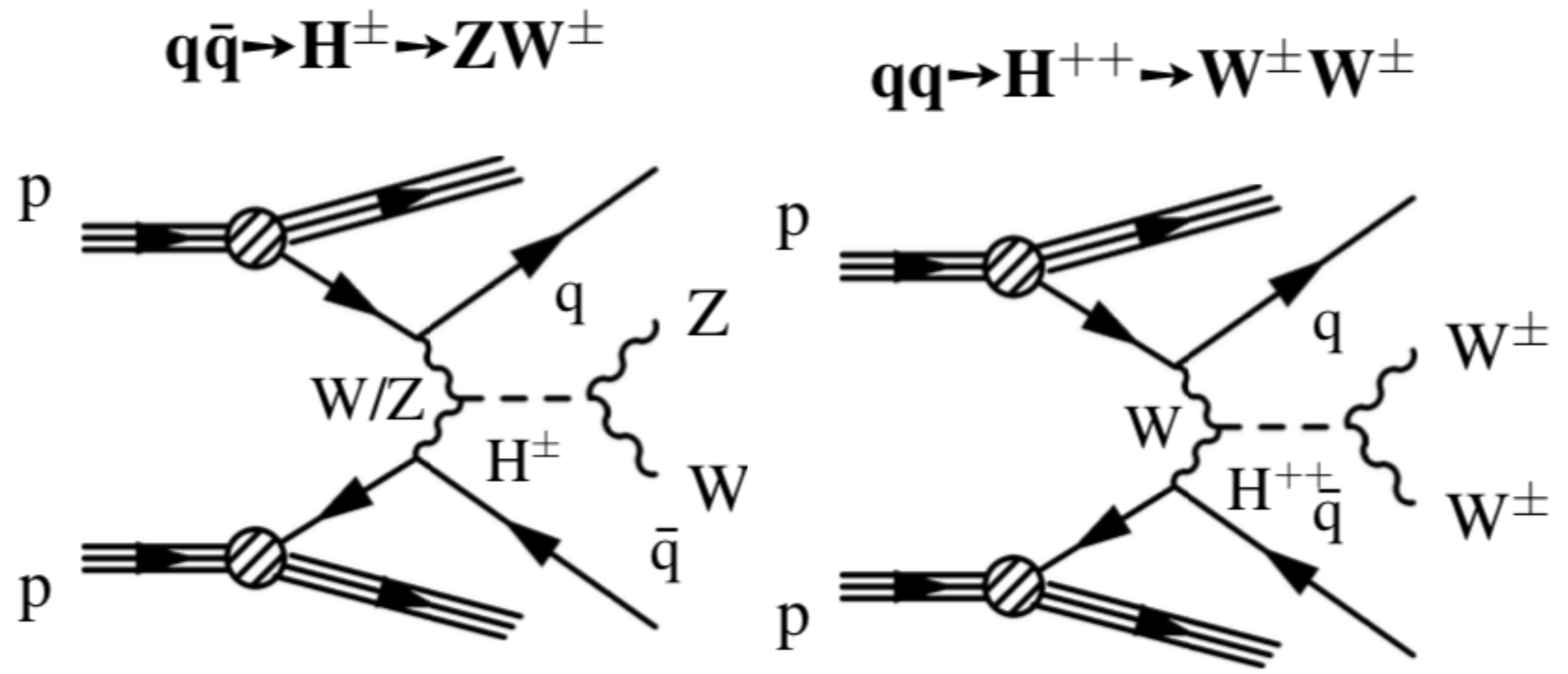


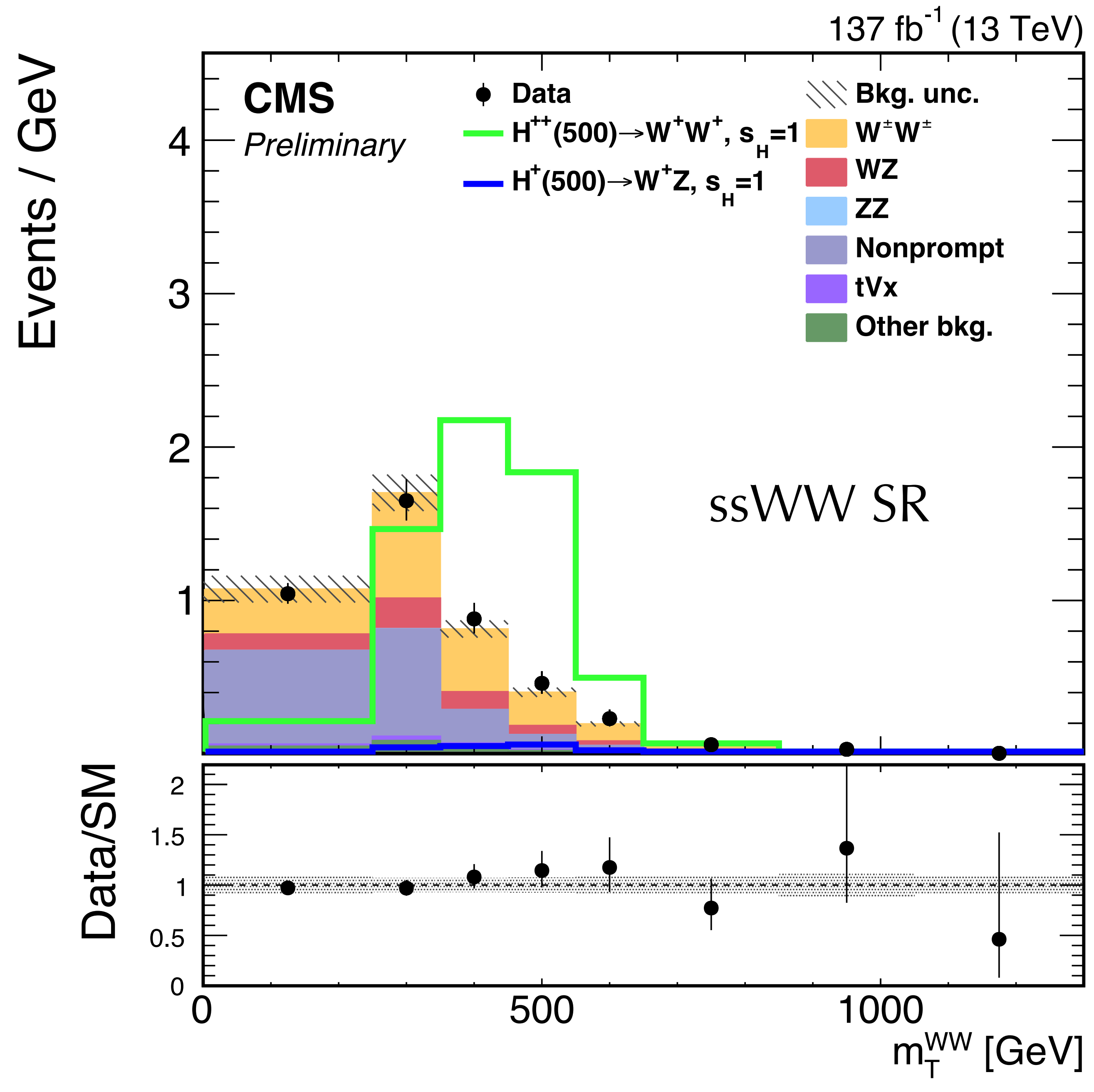
Charged Higgs Searches: W±W±(H±±)& WZ (H±) Fully Leptonic

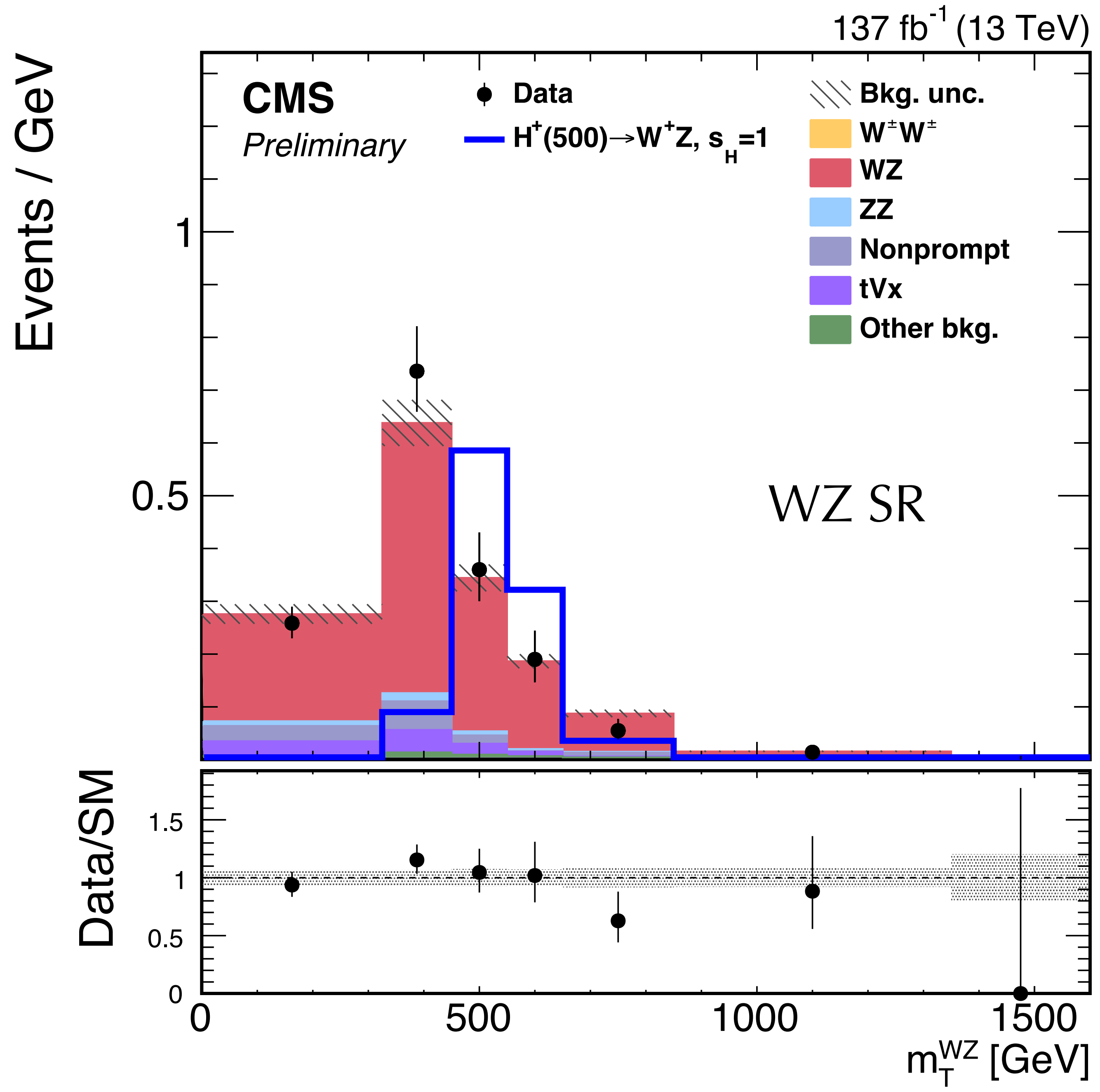
EPJC 81, 723 (2021) / ArXiv:2104.04762

Charged Higgs bosons are predicted in many SM extensions

- Higgs triplet models
  - Charged Higgs bosons appear in Higgs sectors extended by a scalar triplet Φ
  - Couplings to **W** and **Z** bosons at tree level
  - Georgi-Machacek (GM) model: one real and one complex SU(2) triplet
    - Preserve custodial SU(2) symmetry

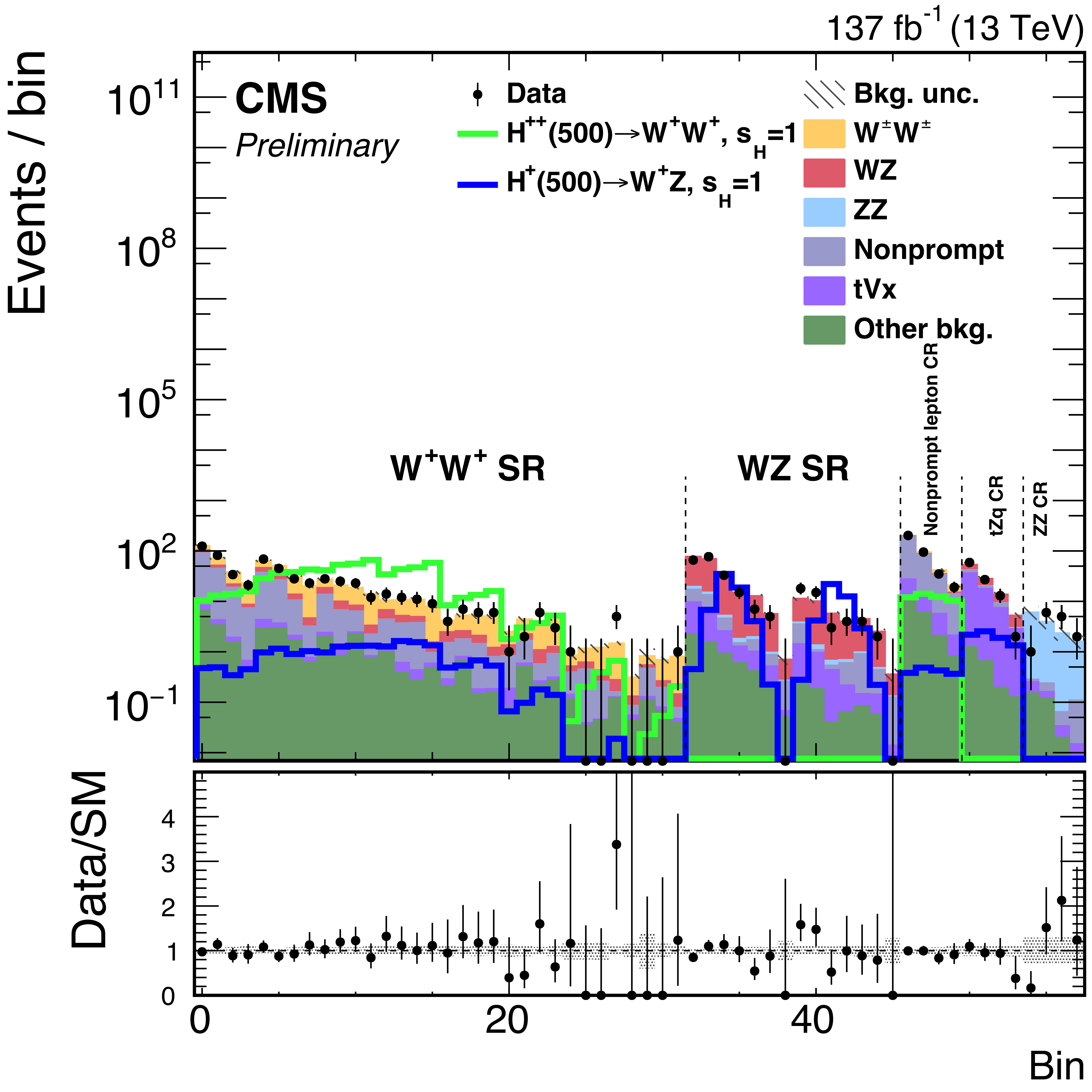






- Analysis Strategy
  - Same object selection and background estimation as the W±W± & WZ SM analysis
  - Making us of the full $\mathbf{m_T}$ variable (same as in aQGC)

- Signal and control regions are fit to **simultaneously for H± and H±± searches**
  - W±W± & WZ SR: 2D — $m_{jj} \times m_T$
  - CR: m_{jj}
- **No excess** of events w.r.t. the SM background predictions is observed



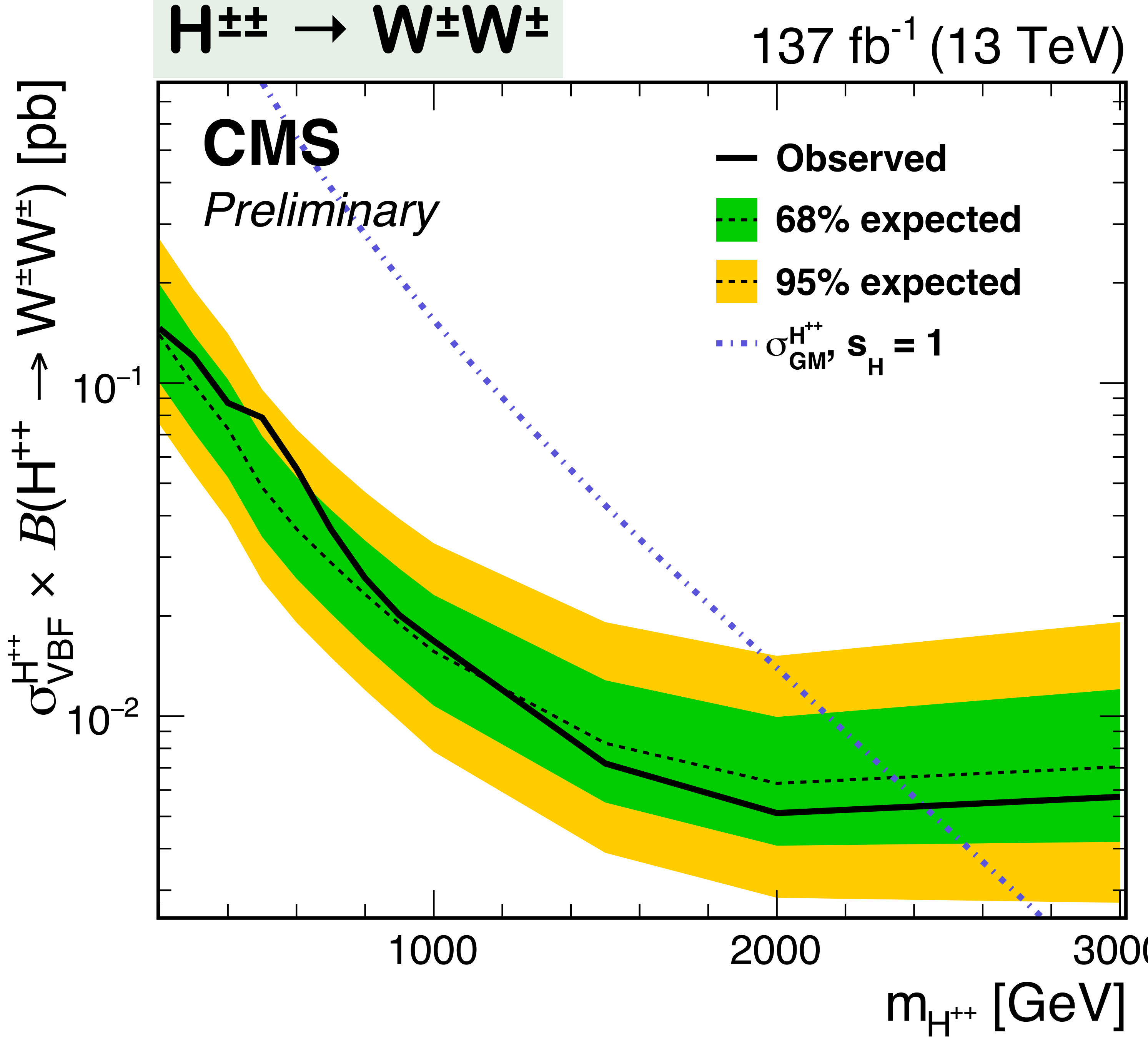
Charged Higgs Searches: W±W±(H±±)& WZ (H±) Fully Leptonic

EPJC 81, 723 (2021) / ArXiv:2104.04762

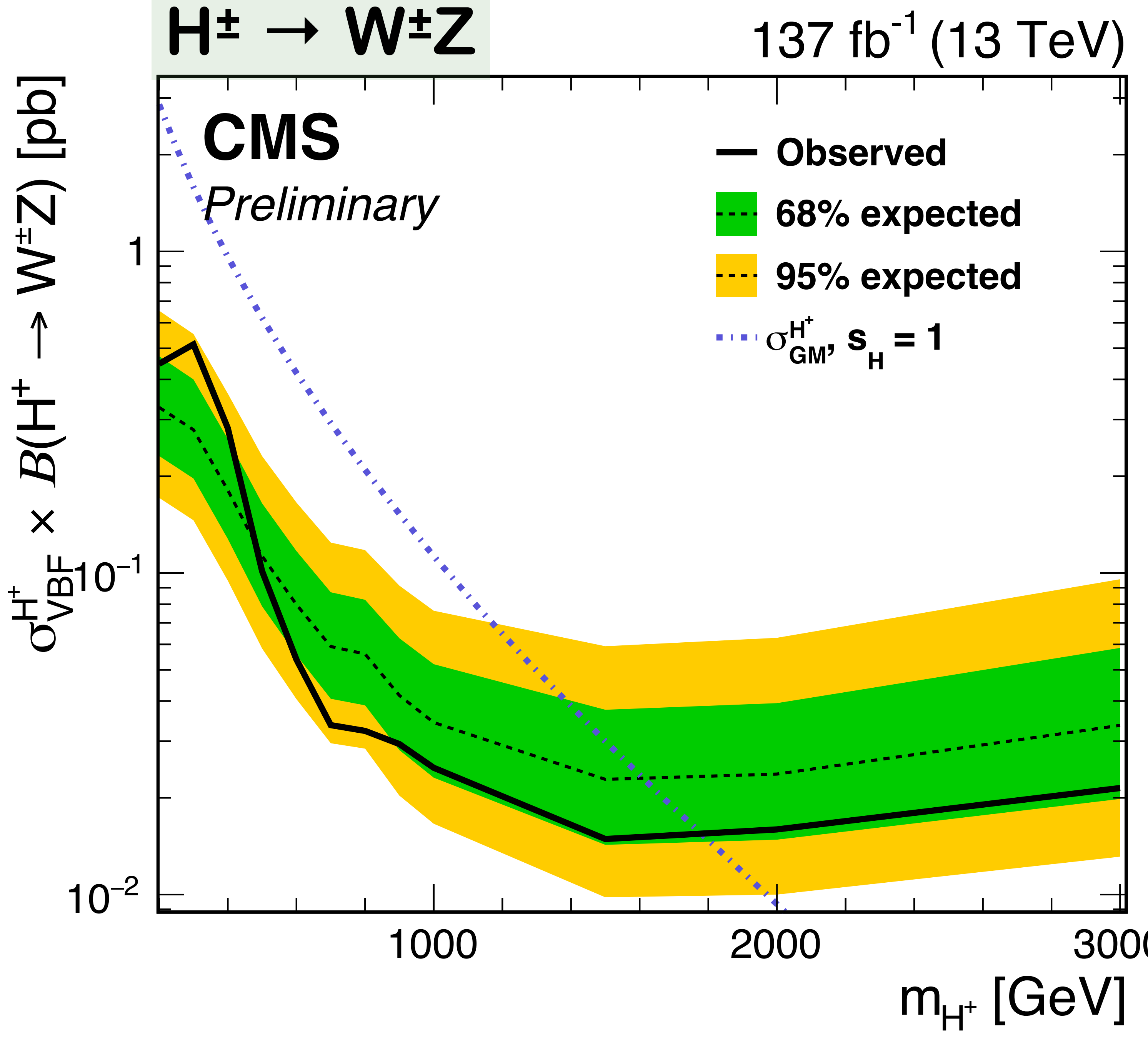
- Limits extended to high masses
- **Most stringent limits** to date are derived in the GM model

Model Independent Limits

H±± → W±W±

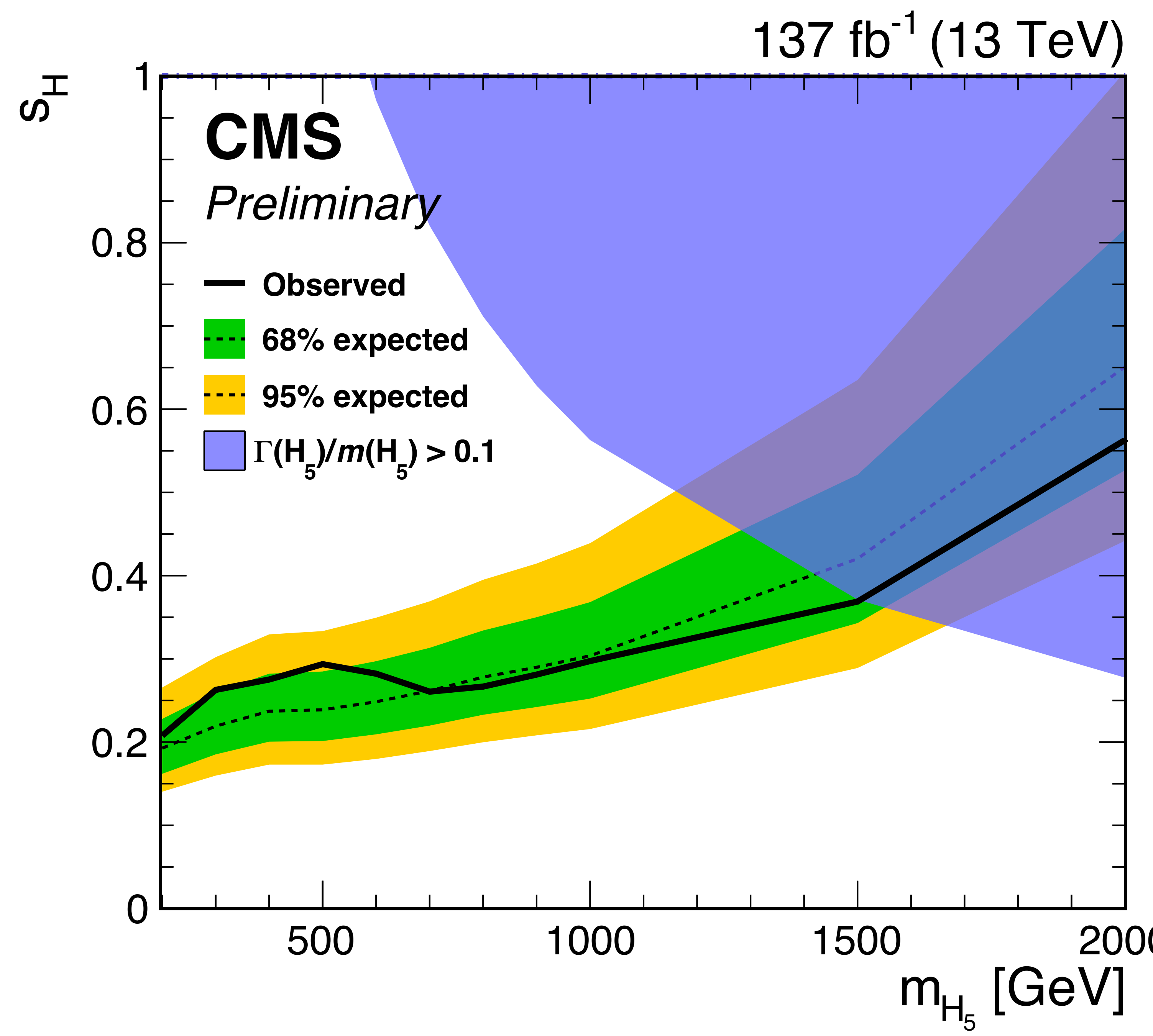


H± → W±Z

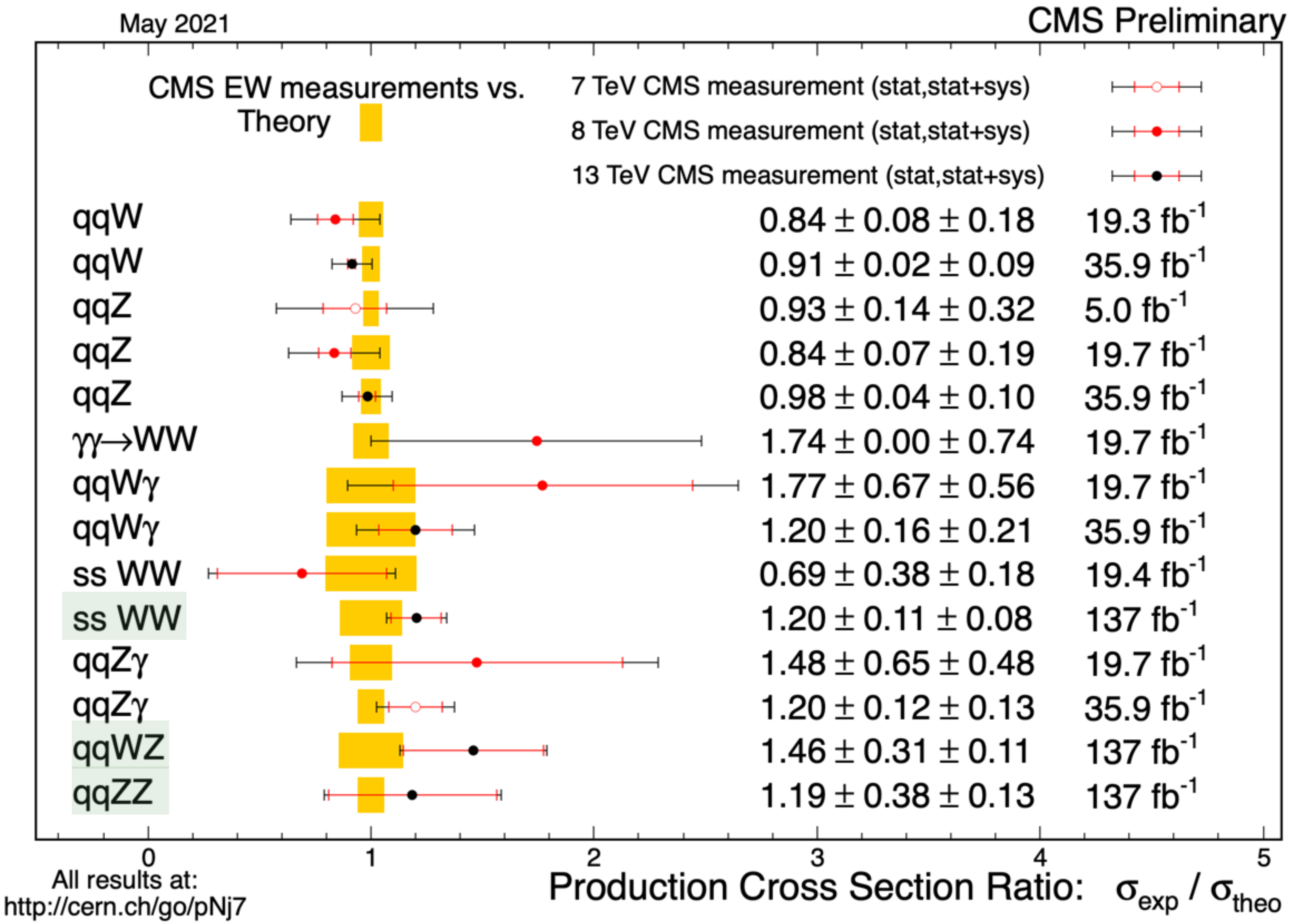


Limits in GM Model

- $H^{\pm}$ and $H^{\pm\pm}$ in the GM model are degenerate in mass: $\mathbf{m_{H5}}$
- $\mathbf{s_H}$ parameter: fraction of vev generated by the triplet field



Summary of Cross Section Measurements



CMS has a comprehensive VBS Analysis program

- Presented recent CMS results of the cross section measurements of **VBS W±W±** and **WZ** in fully leptonic, **WV** in semi-leptonic and **Zγ** in leptonic final states
  - **Observation** of **EW WZjj** production
  - **First differential** cross sections measurements of **W±W± jj** & **WZjj** production
  - **First** cross section measurement of the **polarized VBS**
  - **First evidence** on **WV semi-leptonic**
  - **Latest** results and **Zγ** leptonic **with full Run II dataset** are shown

- Measurements agree with SM predictions

Summary of New Physics Searches and Prospects

- **CMS has a comprehensive VBS Analysis program**
  - Results on new physics searches are also shown
    - Heavy resonance: charged Higgs boson to vector bosons: $H^{\pm} \rightarrow W^{\pm}Z$ and $H^{\pm\pm} \rightarrow W^{\pm}W^{\pm}$
      - No excesses observed
      - Most stringent limits to date are derived in the GM model
    - aQGCs
      - Limits on dim-8 operators are set with analysis sensitive to them correspondingly

  - Prospects
    - Additional final states to be studied
    - More precise measurements could be performed
      - Finer differential measurements
      - Increase scope of polarization measurements
    - Expand searches using these final states

  - More to expected with higher luminosity

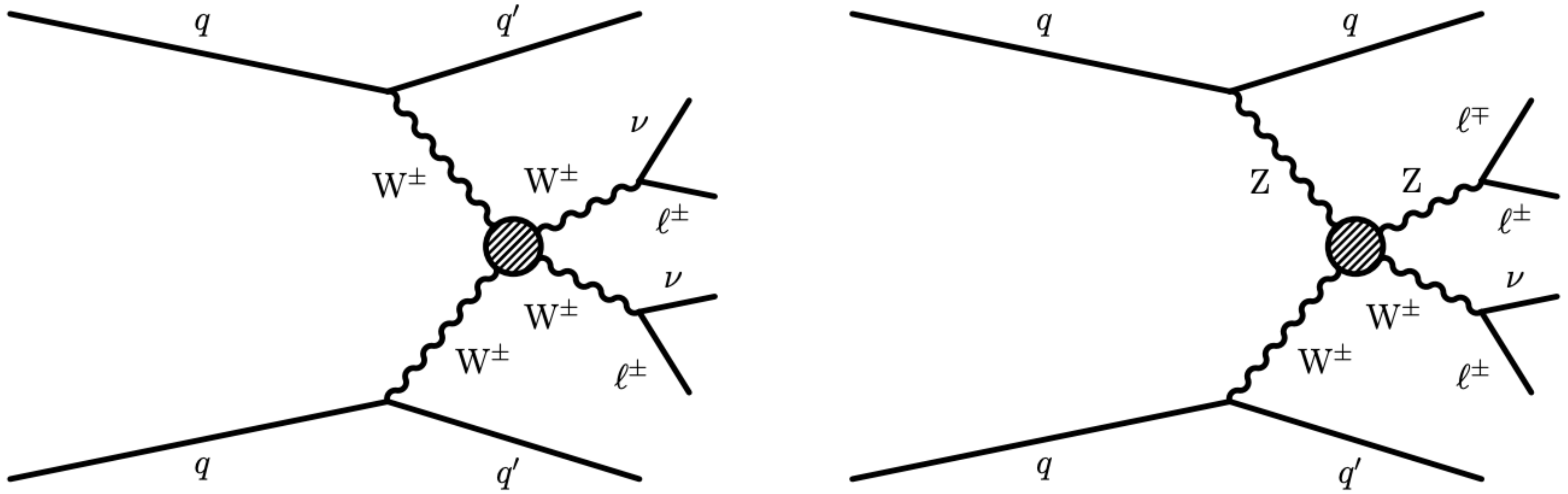
Thanks!

BACK UP

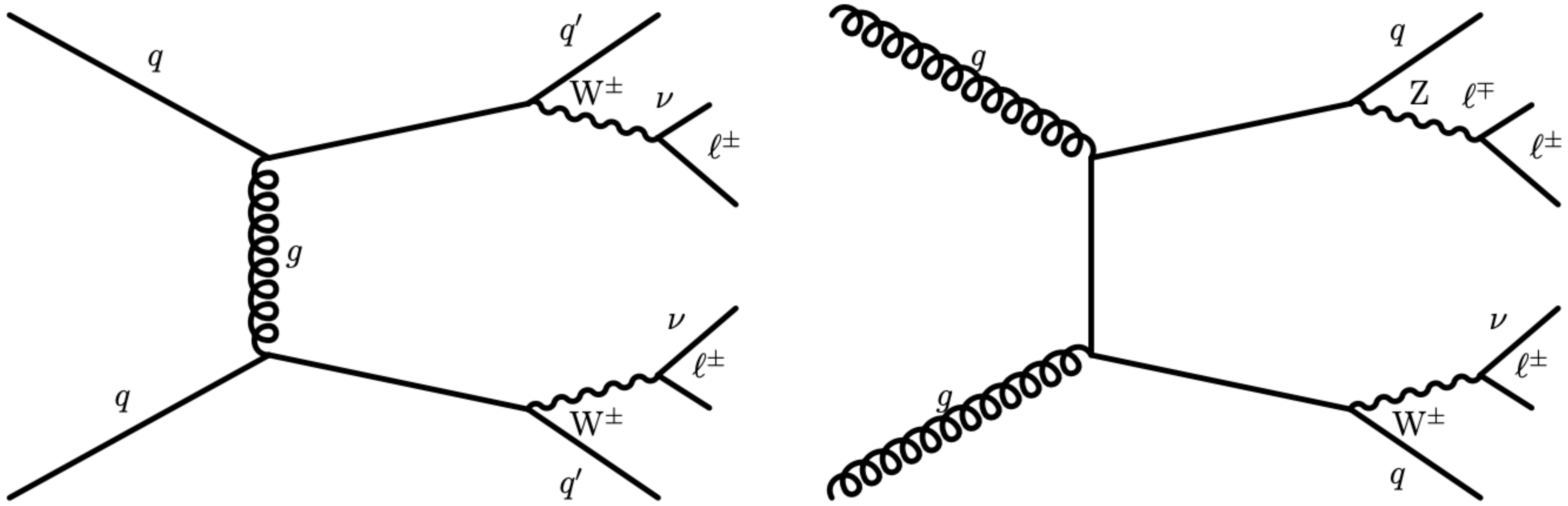
$W^\pm W^\pm$ & WZ Fully Leptonic: Signal Definition

- Representative Feynman Diagrams of **EW-induced (Signal)** contribution @ $O(\alpha^6)$ and **QCD-induced (Background)** contribution @ $O(\alpha^4\alpha_s^2)$ are shown
- EW-QCD interference at $O(\alpha^5\alpha_s)$ negligible

EW-induced $W^\pm W^\pm$jj and WZjj production

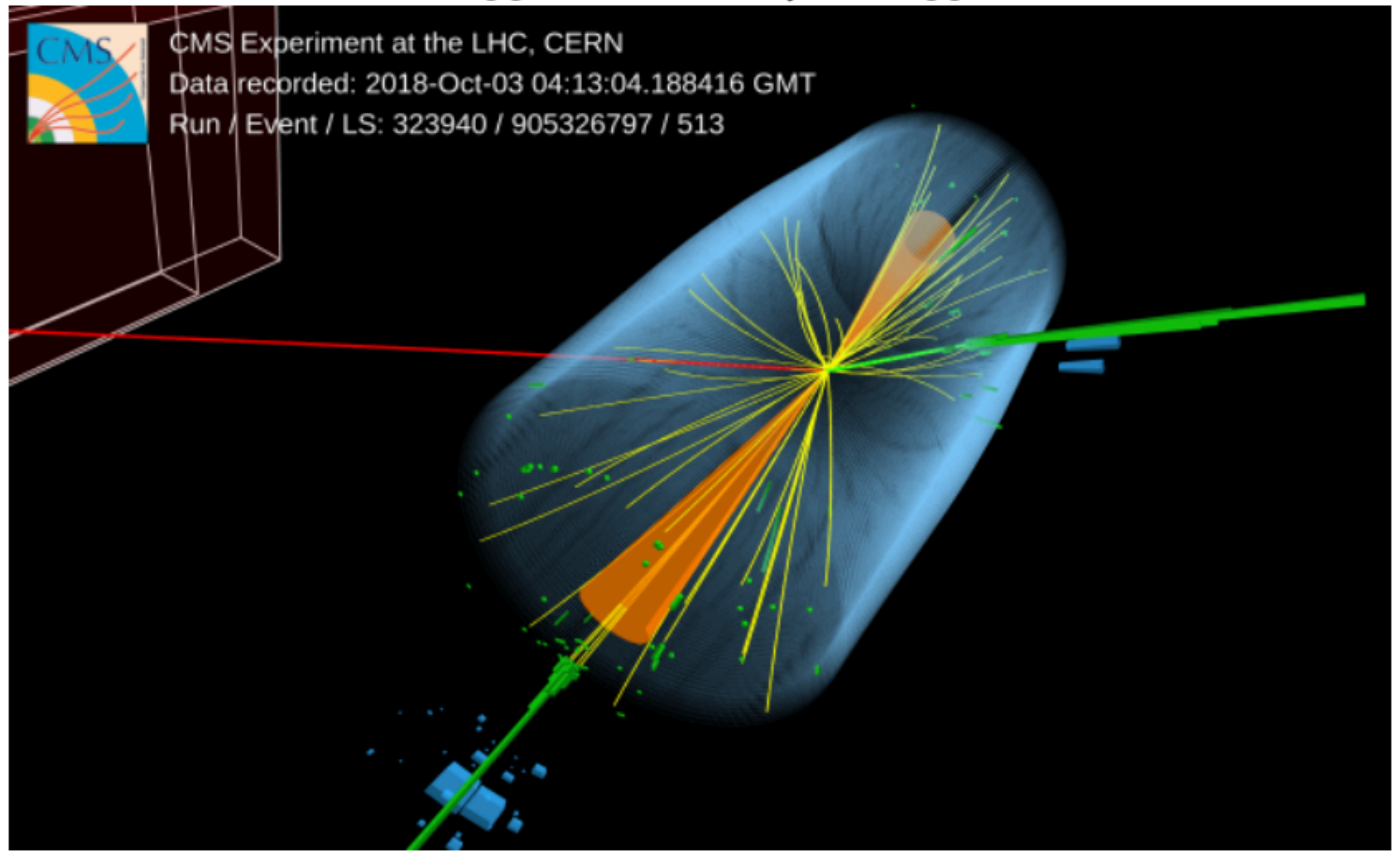


QCD-induced $W^\pm W^\pm$jj and WZjj production

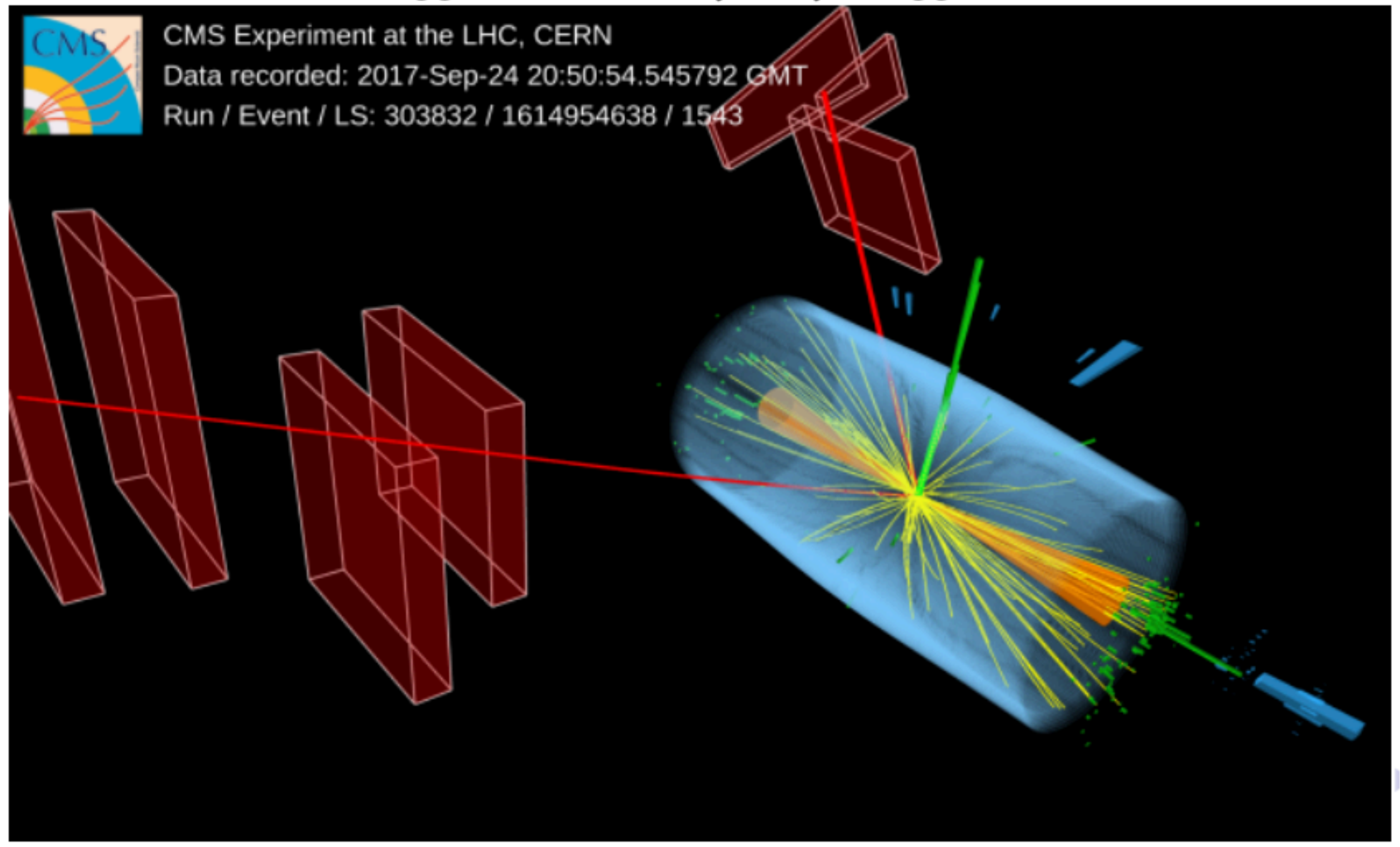


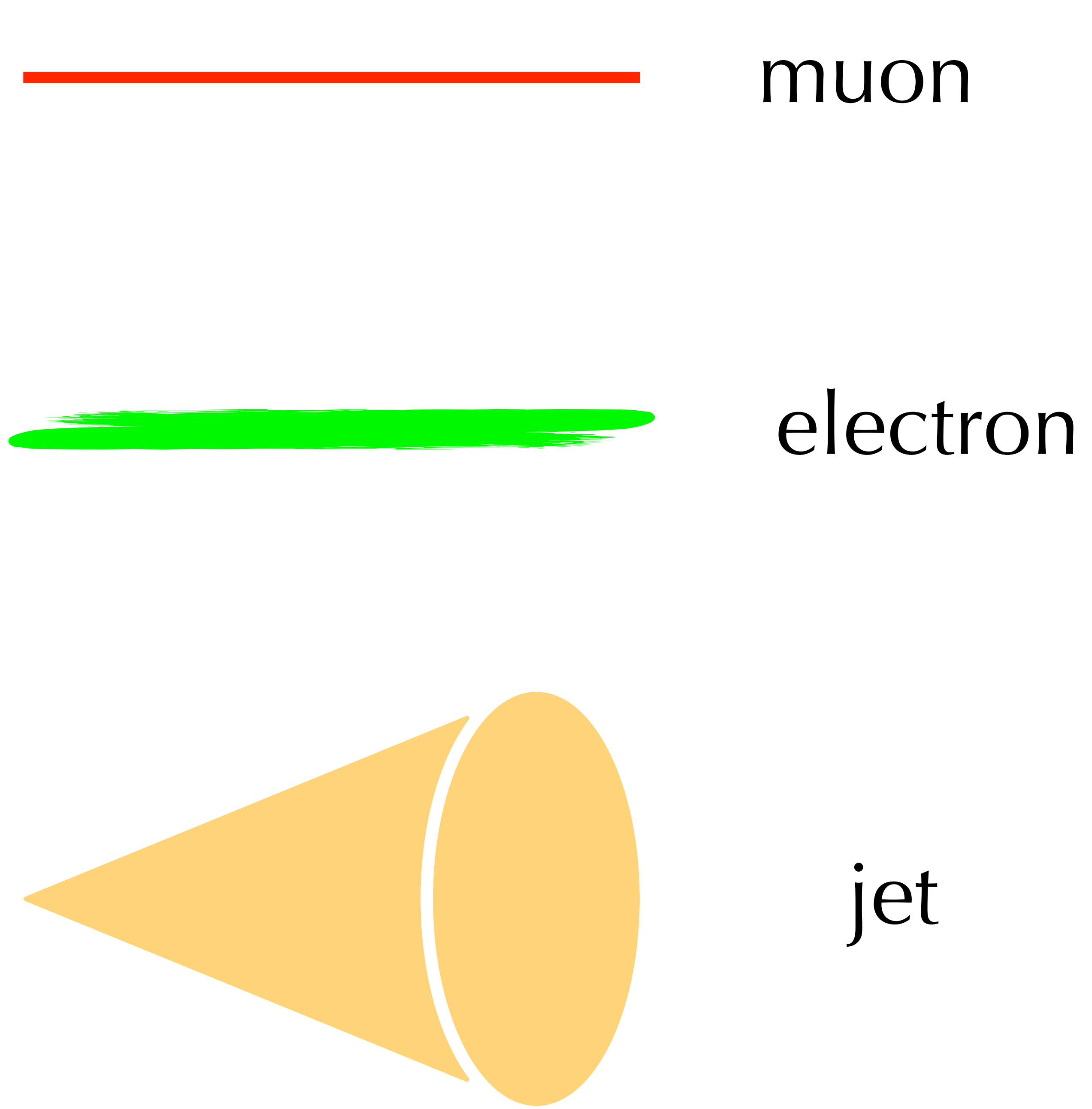
$W^{\pm}W^{\pm}$ & WZ Fully Leptonic: Event Display

$W^+W^+jj \rightarrow e^+\nu\mu^+\nu jj$ event



$W^+Zjj \rightarrow e^+\nu\mu^+\mu^-jj$ event





$W^\pm W^\pm$ & WZ Fully Leptonic: MVA for WZ

- A BDT is trained to better discriminate EWK production from QCD for WZ
- Improved sensitivity by ~20% compared with an analysis using 2D: m_{jj} X $|\Delta\eta_{jj}|$

	Variables	Definitions
jj variables (6)	m_{jj}	The mass of the leading and trailing jets
	$\Delta\eta_{jj}$	Difference in rapidity of the leading and trailing jets
	$\Delta\Phi_{jj}$	Difference in Φ 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}	Rapidity of the leading jet
VV variables(1)	$\|\eta^W-\eta^Z\|$	Difference in rapidity of the two bosons
V-j mix variables(6)	$z^*_{\ell_i}$	$z^*_{\ell_i}=\|\eta_{\ell i}-(\eta_{j1}+\eta_{j2})/2\|/\|\Delta\eta_{jj}\|$ (i=1,2,3)
	z^*_{trilep}	$z^*_{trilep}=\|\eta_{trilep}-(\eta_{j1}+\eta_{j1})/2\|/\|\Delta\eta_{jj}\|$ (trilep=$\ell 1+\ell 2+\ell 3$)
	$\Delta R_{j1,Z}$	Separation between the leading jet and the Z boson
	$\|\vec{p}_T^{\,tot}\|/\sum p_T$	Normalized transverse momentum of the disbon and tagging jets

$W^{\pm}W^{\pm}$ & WZ Fully Leptonic: Selections of Regions

Variable	SSWW SR	Nonprompt CR	WZ CR	WZb CR	ZZ CR
leptons	2 SS, P_T > 25/20 GeV	2 SS, P_T > 25/20 GeV	1 OS pair + 1, P_T > 25/10/20 GeV	1 OS pair + 1, P_T > 25/10/20 GeV	2 OS pairs, P_T > 25/20/10/10GeV
$\lvert m_{\ell\ell} - m_Z \rvert$	> 15 GeV (ee)	> 15 GeV (ee)	< 15 GeV	< 15 GeV	< 15 GeV(both pairs)
$m_{\ell\ell}$	> 20 GeV	> 20 GeV	-	-	-
$m_{\ell\ell\ell}$	-	-	>100GeV	>100GeV	-
p_T^j	> 50GeV	> 50GeV	> 50GeV	> 50GeV	-
p_T^{miss}	> 30 GeV	> 30 GeV	> 30 GeV	> 30 GeV	-
Anti b-tagging	applied	Inverted	applied	Inverted	-
tau veto	applied	applied	applied	applied	-
$\max(z^*_\ell)$	<0.75	<0.75	<1.0	<1.0	<0.75
m_{jj}	> 500GeV	> 500GeV	> 500GeV	> 500GeV	> 500GeV
$\lvert \Delta\eta_{jj} \rvert$	> 2.5	> 2.5	> 2.5	>2.5	> 2.5

W±W± & WZ Fully Leptonic: Nonprompt Leptons

- Fake rate ε_{fake}
  - Defined as the efficiency for fakeable objects to pass full lepton selection
  - Measured in a QCD-enriched sample
  - η and p_T dependence (2D e/μ fake rate for each year in backup slide 35)

- Extrapolate the background yields
  - from "tight+loose" and "loose+loose" data events in "SR"
  - by weighted

"tight+loose": $$w_i = \frac{\epsilon_{\text{fake}}(p_{\text{T}i}, \eta_i)}{1 - \epsilon_{\text{fake}}(p_{\text{T}i}, \eta_i)}$$

"loose+loose": $$\left(w_{ij} = \frac{\epsilon_{\text{fake}}(p_{\text{T}i}, \eta_i)}{1 - \epsilon_{\text{fake}}(p_{\text{T}i}, \eta_i)} \times \frac{\epsilon_{\text{fake}}(p_{\text{T}j}, \eta_j)}{1 - \epsilon_{\text{fake}}(p_{\text{T}j}, \eta_j)}\right)$$

  - and with real lepton from simulation subtraction

$$N^{non-prompt} = \sum_i w_i^{data} - \sum_i w_i^{MC} - \sum_{i,j} w_{ij}^{data} + \sum_{i,j} w_{ij}^{MC}$$

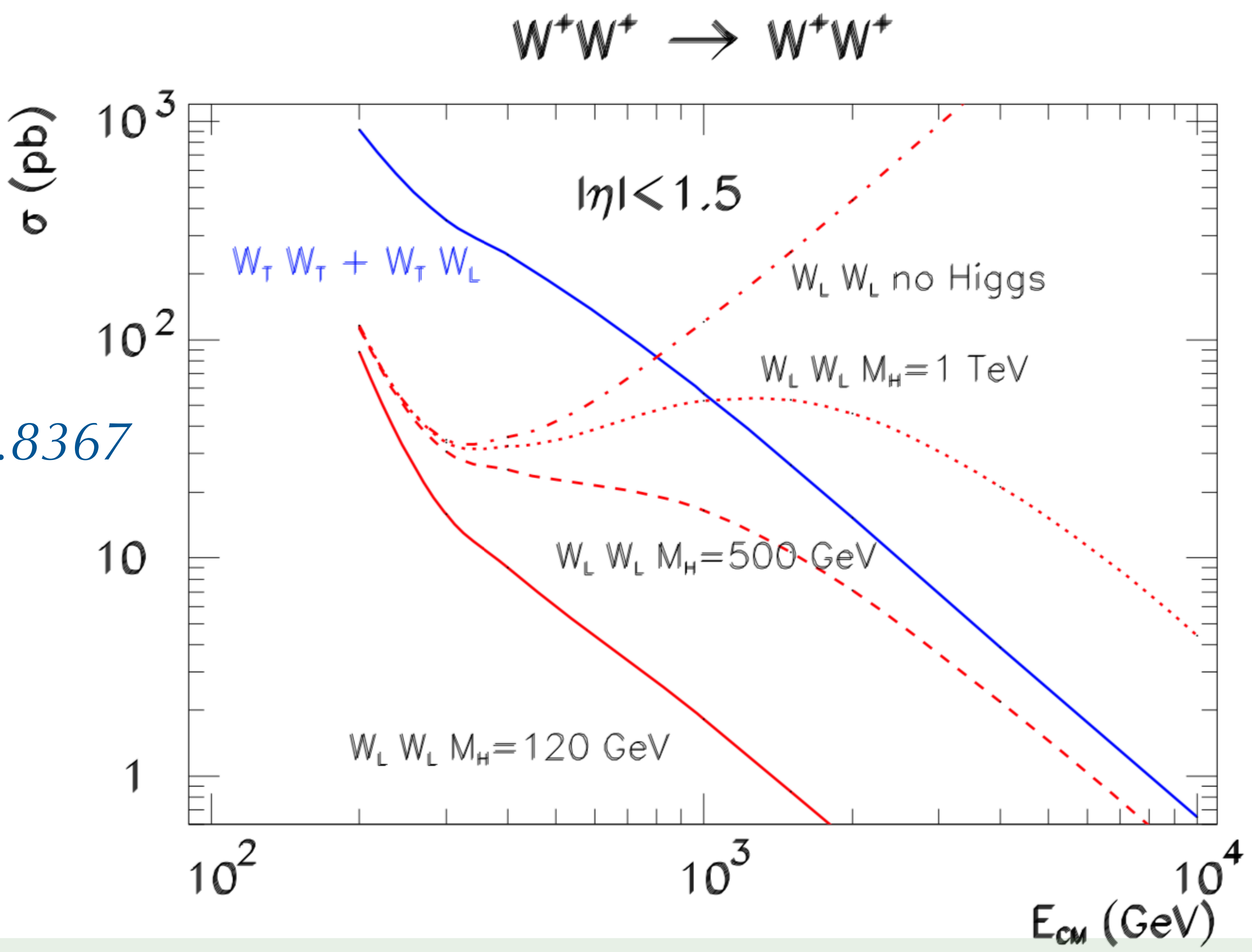
Polarized W±W±: Theory

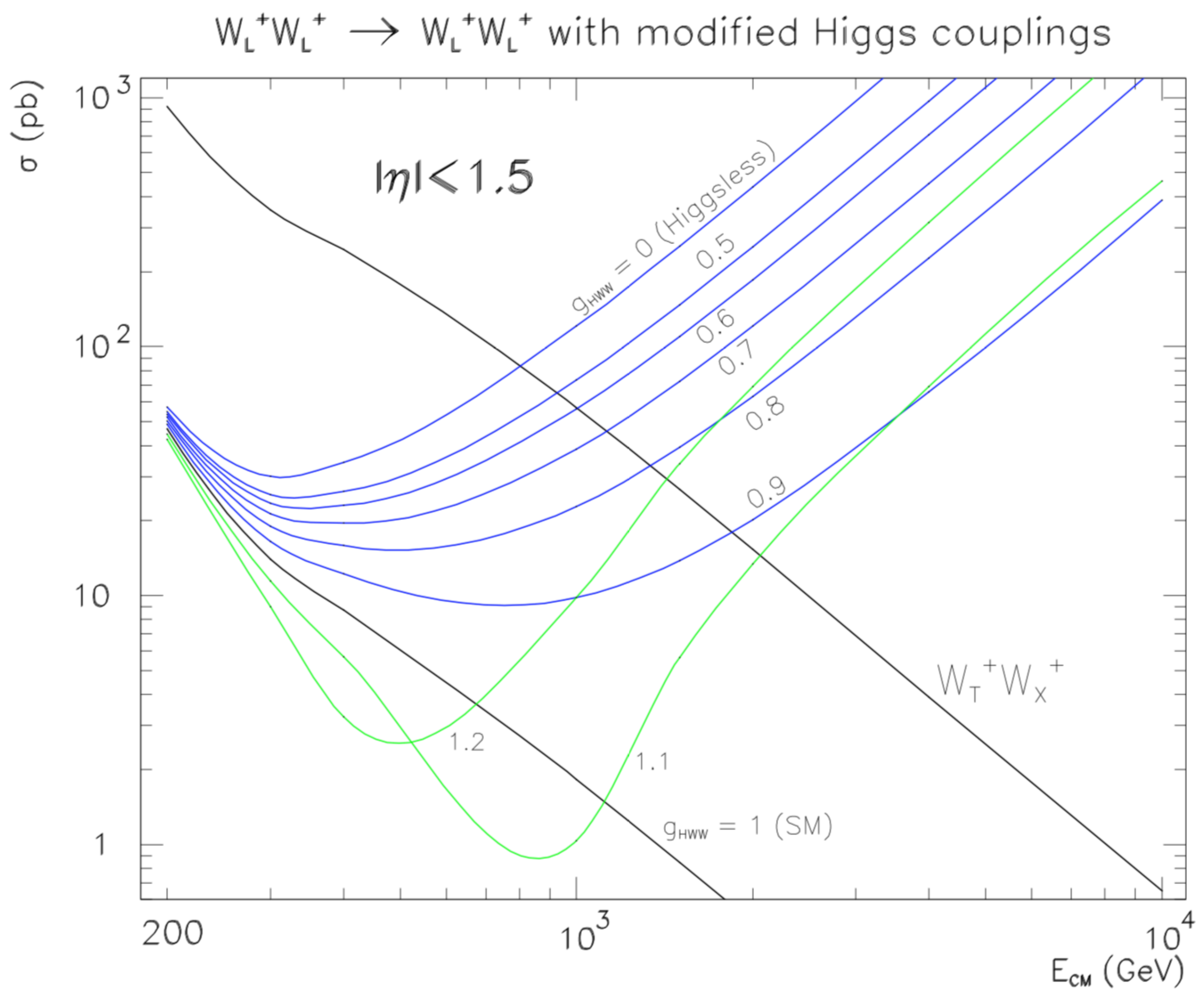
- **Polarization** of the massive vector boson
  - Three modes: one longitudinally and two transverse

$$\epsilon^{\mu}_{T_1,T_2} = \frac{1}{\sqrt{2}}(0,1,\pm i,0) \qquad \epsilon^{\mu}_{L} = \frac{1}{m}(k_3,0,0,E)$$

  - **Longitudinal polarization** is a consequence of the **EWSB**
- The polarized VBS amplitudes at high energies is sensitive to the **Higgs mass**, **Higgs-to-Vector-Boson couplings**, and **self-couplings of vector boson**
  - The unitarity of the longitudinally polarized VBS at high energies is restored in the SM by a Higgs boson with a mass < 1 TeV
  - Key process linked with EWSB sector

arXiv:1412.8367





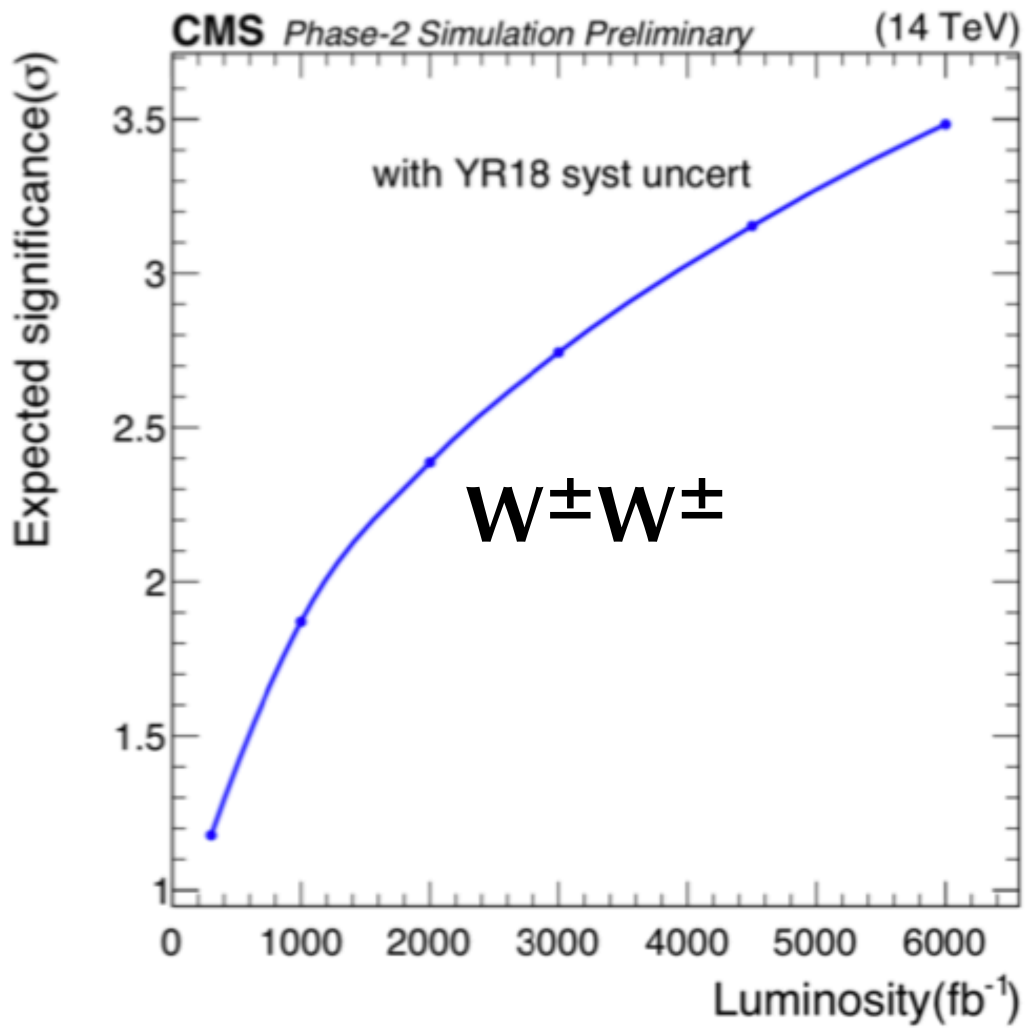
Polarized W±W±: Experiment

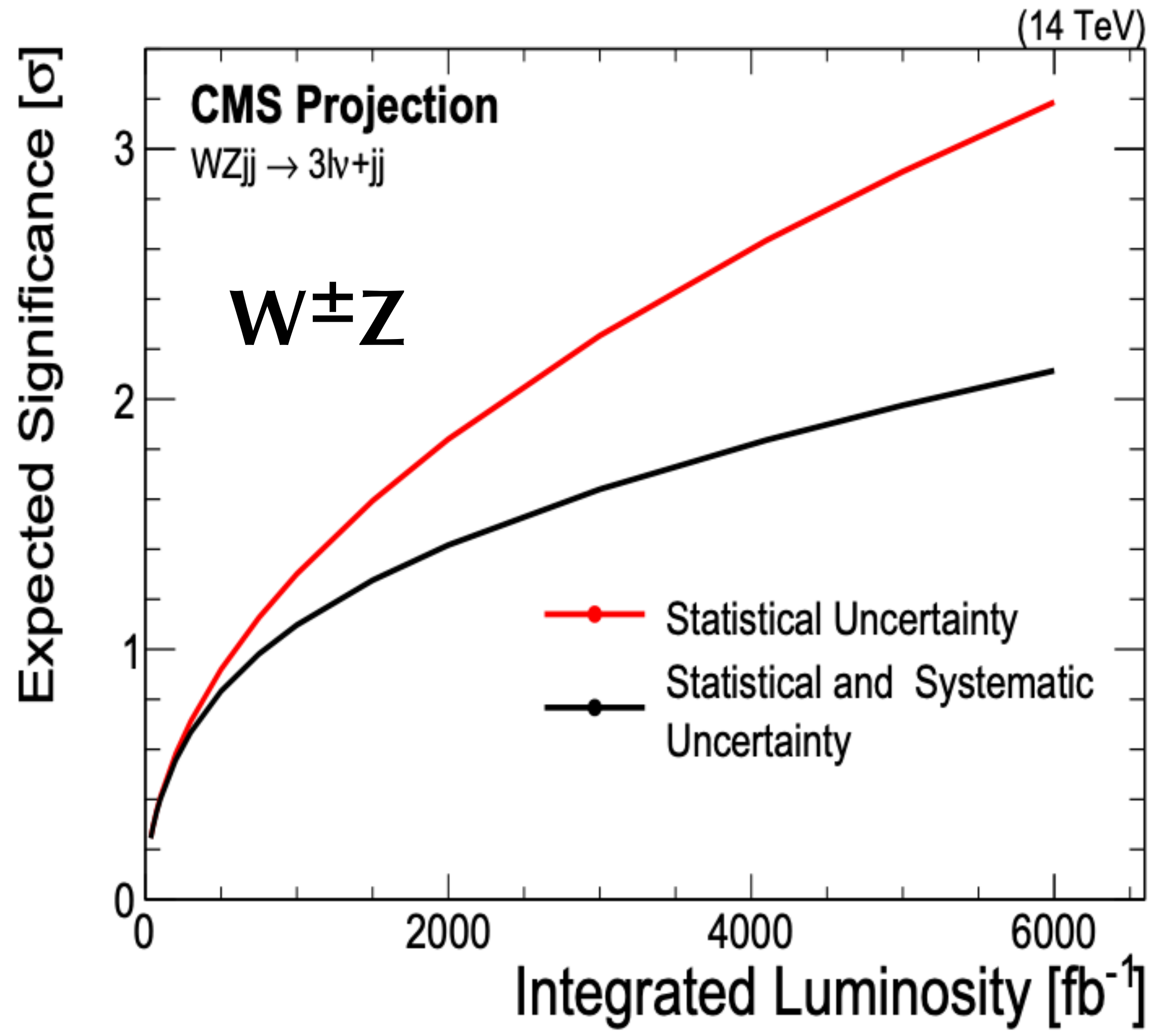
- Challenge: low production rate
  - The longitudinal scattering contributes to about ~10% of the overall EW production
- Now, what can we say already with Run-II data?
  - LHC Full Run 2 integrated luminosity opens up possibilities for polarized VBS study
  - Equipped with the most precise measurement of EW W±W± cross section to date
    - Follow the same strategies

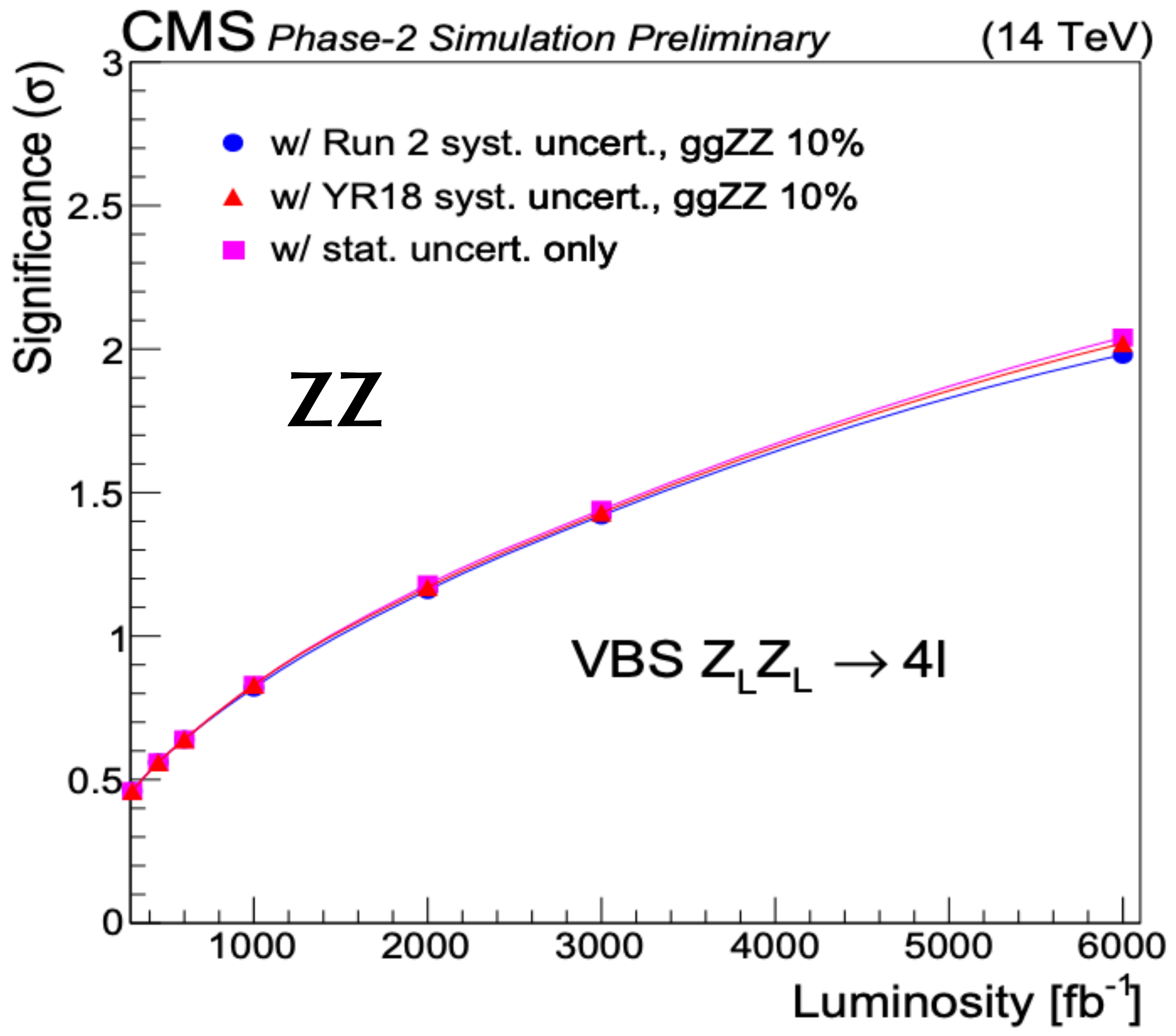
phys.lett.b.2020.135710

—> **First measurement** of the EW production cross sections of the **polarized VBS**!

Also one of the high profile analyses for HL-LHC

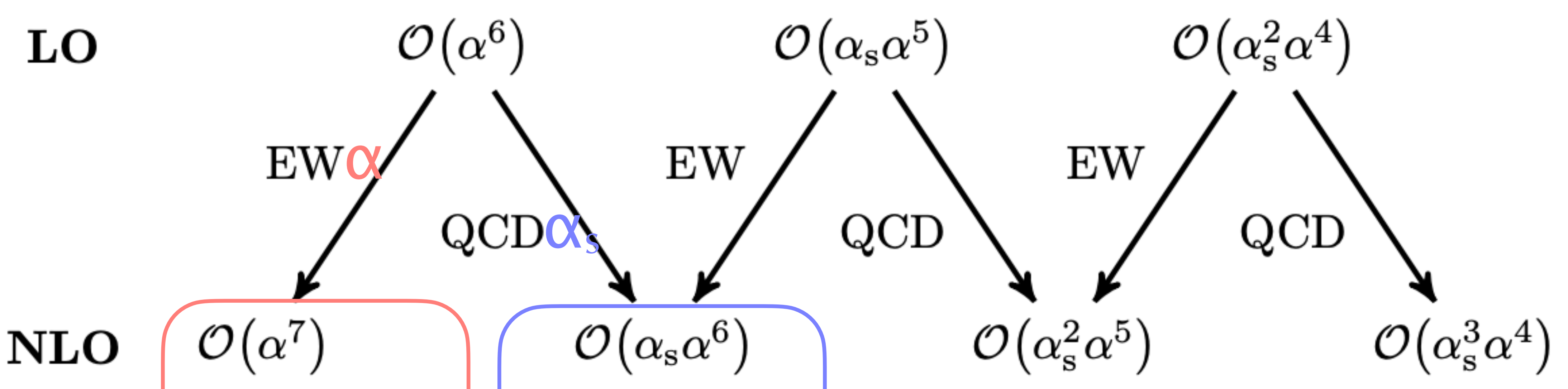






Polarized $W^{\pm}W^{\pm}$: NLO corrections

- The full NLO QCD and EW corrections for the leptonic unpolarized $W^{\pm}W^{\pm}$ scattering have been computed *B.Biedermann, A.Denner, and M.Pellen arXiv:1611.02951 arXiv:1708.00268*
- Reduce the LO cross section for the EW $W^{\pm}W^{\pm}$ process by approximately 10–15%
- Unknown for LL, LT, TT processes
  - α_s corrections expected to be the **same for all the 3** polarization modes
  - α corrections expected to be **small for the L** mode
  - Take the NLO corrections for the unpolarized EW $W^{\pm}W^{\pm}$ and apply
    - $\mathcal{O}(\alpha_s\alpha^6)$ and $\mathcal{O}(\alpha^7)$ to **TT**
    - Only $\mathcal{O}(\alpha_s\alpha^6)$ to **LL** and **LT**
    - $\mathcal{O}(\alpha^7)$ on the shapes of **LL** and **LT** considered as a systematic uncertainty



Order	$\mathcal{O}(\alpha^7)$	$\mathcal{O}(\alpha_s\alpha^6)$	$\mathcal{O}(\alpha_s^2\alpha^5)$	$\mathcal{O}(\alpha_s^3\alpha^4)$	Sum
$\delta\sigma_{NLO}$ [fb]	−0.2169(3)	−0.0568(5)	−0.00032(13)	−0.0063(4)	−0.2804(7)
$\delta\sigma_{NLO}/\sigma_{LO}$ [%]	−13.2	−3.5	0.0	−0.4	−17.1

Polarized $W^{\pm}W^{\pm}$: Signal BDTs

- Signal BDTs to separate different polarization configurations
  - Same input variables for two settings (i) LL against (LT+TT) and (ii) (LL+LT) against TT

	Variables	Definitions
jj variables (3)	$\Delta\Phi_{jj}$	Difference in Φ between the leading and trailing jets
	p_T^{j1}	P_T of the leading jet
	p_T^{j2}	P_T of the trailing jet
V(l) variables(6)	p_T^{l1}	P_T of the leading lepton
	p_T^{l2}	P_T of the trailing lepton
	$\Delta\Phi_{ll}$	Difference in Φ between the two leptons
	m_{ll}	Dilepton mass
	p_T^{ll}	Dilepton P_T
	m_T^{WW}	Transverse WW diboson mass
V-j mix variables(6)	$z^*_{\ell_1}$	Zeppenfeld variable of the leading lepton
	$z^*_{\ell_2}$	Zeppenfeld variable of the trailing lepton
	p_T^{miss}	Missing transverse momentum
	$\Delta R_{j1,ll}$	ΔR between the leading jet and the dilepton system
	$\Delta R_{j2,ll}$	ΔR between the trailinging jet and the dilepton system
	$(p_T^{l1}p_T^{l2})/(p_T^{j1}p_T^{j2})$	Ratio of P_T products between leptons and jets

Polarized $W^{\pm}W^{\pm}$: Inclusive BDTs

- Inclusive BDT to isolate EW $W^{\pm}W^{\pm}$ signal from nonVBS backgrounds
  - 10 Input variables for training

	Variables	Definitions
jj variables (5)	m_{jj}	The mass of the leading and trailing jets
	$\lvert\Delta\eta_{jj}\rvert$	Absolute difference in rapidity of the leading and trailing jets
	$\Delta\Phi_{jj}$	Difference in Φ of the leading and trailing jets
	p_T^{j1}	P_T of the leading jet
	p_T^{j2}	P_T of the trailing jet
V(l) variables(2)	p_T^{l1}	Leading lepton pT
	p_T^{ll}	Dilepton pT
V-j mix variables(3)	$z^*_{\ell_1}$	Zeppenfeld variable of the leading lepton
	$z^*_{\ell_2}$	Zeppenfeld variable of the trailing lepton
	p_T^{miss}	Missing transverse momentum

aQGC Searches

- Limits on aQGCs are set via an effective field theory (EFT) approach
  - A series of operators with mass dimensions larger than four are added to the SM Lagrangian LSM , each is scaled by a corresponding coefficient (Wilson coef) and New Physics scale Λ $\mathcal{L} = \mathcal{L}_{SM} + \sum_i \left[\frac{a_i}{\Lambda} \mathcal{O}_i^{(5)} + \frac{c_i}{\Lambda^2} \mathcal{O}_i^{(6)} + \frac{e_i}{\Lambda^4} \mathcal{O}_i^{(8)} + \cdots \right]$

	WWWW	WWZZ	ZZZZ	WWAZ	WWAA	ZZZA	ZZAA	ZAAA	AAAA
$\mathcal{L}_{S,0}$, $\mathcal{L}_{S,1}$	X	X	X	O	O	O	O	O	O
$\mathcal{L}_{M,0}$, $\mathcal{L}_{M,1}$,$\mathcal{L}_{M,6}$,$\mathcal{L}_{M,7}$	X	X	X	X	X	X	X	O	O
$\mathcal{L}_{M,2}$,$\mathcal{L}_{M,3}$, $\mathcal{L}_{M,4}$,$\mathcal{L}_{M,5}$	O	X	X	X	X	X	X	O	O
$\mathcal{L}_{T,0}$,$\mathcal{L}_{T,1}$,$\mathcal{L}_{T,2}$	X	X	X	X	X	X	X	X	X
$\mathcal{L}_{T,5}$,$\mathcal{L}_{T,6}$,$\mathcal{L}_{T,7}$	O	X	X	X	X	X	X	X	X
$\mathcal{L}_{T,9}$,$\mathcal{L}_{T,9}$	O	O	X	O	O	X	X	X	X

$$L_{S,0} = \left[(D_\mu \Phi)^\dagger D_\nu \Phi \right] \times \left[(D_\mu \Phi)^\dagger D_\nu \Phi \right]$$
$$L_{S,1} = \left[(D_\mu \Phi)^\dagger D^\mu \Phi \right] \times \left[(D_\nu \Phi)^\dagger D_\nu \Phi \right]$$

covariant derivatives of Higgs doublets — scalar/longitudinal

$$L_{M,0} = Tr[\hat{W}_{\mu\nu} \hat{W}^{\mu\nu}] \times \left[(D_\beta \Phi)^\dagger D^\beta \Phi \right]$$
$$L_{M,1} = Tr[\hat{W}_{\mu\nu} \hat{W}^{\nu\beta}] \times \left[(D_\beta \Phi)^\dagger D^\mu \Phi \right]$$
$$L_{M,6} = \left[(D_\mu \Phi)^\dagger \hat{W}_{\beta\nu} \hat{W}^{\beta\nu} D^\mu \Phi \right]$$
$$L_{M,7} = \left[(D_\mu \Phi)^\dagger \hat{W}_{\beta\nu} \hat{W}^{\beta\mu} D^\nu \Phi \right]$$

$SU_L(2)$ gauge fields — transverse

$$L_{T,0} = Tr \left[W_{\mu\nu} W^{\mu\nu} \right] \times Tr \left[W_{\alpha\beta} W^{\alpha\beta} \right]$$
$$L_{T,1} = Tr \left[W_{\alpha\nu} W^{\mu\beta} \right] \times Tr \left[W_{\mu\beta} W^{\alpha\nu} \right]$$
$$L_{T,2} = Tr \left[W_{\alpha\mu} W^{\mu\beta} \right] \times Tr \left[W_{\beta\nu} W^{\nu\alpha} \right]$$

mixed transverse and longitudinal parameters

aQGC Searches

	Observed	Expected	Observed	Expected	Observed	Expected	Observed	Expected
	$W^{\pm}W^{\pm} + WZ$ (TeV^{-4})		ZZ (TeV^{-4})		$W\gamma$ (TeV^{-4})		$Z\gamma$ (TeV^{-4})	
f_{T0}/Λ^4	[-0.25, 0.28]	[-0.35, 0.37]	[-0.24, 0.22]	[-0.37, 0.35]	[-0.6, 0.6]	[-0.6, 0.6]	[-0.52,0.44]	[-0.64,0.57]
f_{T1}/Λ^4	[-0.12, 0.14]	[-0.16, 0.19]	[-0.31, 0.31]	[-0.49, 0.49]	[-0.4, 0.4]	[-0.3, 0.4]	[-0.65,0.63]	[-0.81,0.90]
f_{T2}/Λ^4	[-0.35, 0.48]	[-0.49, 0.63]	[-0.63, 0.59]	[-0.98, 0.95]	[-1.0, 1.2]	[-1.0, 1.2]	[-1.36,1.21]	[-1.68,1.54]
f_{T5}/Λ^4	—	—	—	—	[-0.5, 0.5]	[-0.4, 0.4]	[-0.45,0.52]	[-0.58,0.64]
f_{T6}/Λ^4	—	—	—	—	[-0.4, 0.4]	[-0.3, 0.4]	[-1.02,1.07]	[-1.30,1.33]
f_{T7}/Λ^4	—	—	—	—	[-0.9, 0.9]	[-0.8, 0.9]	[-1.67,1.97]	[-2.15,2.43]
f_{T8}/Λ^4	—	—	[-0.43, 0.43]	[-0.68, 0.68]	—	—	[-0.36,0.36]	[-0.47,0.47]
f_{T9}/Λ^4	—	—	[-0.92, 0.92]	[-1.50, 1.50]	—	—	[-0.72,0.72]	[-0.91,0.91]
f_{M0}/Λ^4	[-2.7, 2.9]	[-3.6, 3.7]	—	—	[-8.1, 8.0]	[-7.7, 7.6]	[-12.5,12.8]	[-15.8,16.0]
f_{M1}/Λ^4	[-4.1, 4.2]	[-5.2, 5.5]	—	—	[-12, 12]	[-11, 11]	[-28.1,27.0]	[-35.0,34.7]
f_{M2}/Λ^4	—	—	—	—	[-2.8, 2.8]	[-2.7, 2.7]	[-5.21,5.12]	[-6.55,6.49]
f_{M3}/Λ^4	—	—	—	—	[-4.4, 4.4]	[-4.0, 4.1]	[-10.2,10.3]	[-13.0,13.0]
f_{M4}/Λ^4	—	—	—	—	[-5.0, 5.0]	[-4.7, 4.7]	[-10.2,10.2]	[-13.0,12.7]
f_{M5}/Λ^4	—	—	—	—	[-8.3, 8.3]	[-7.9, 7.7]	[-17.6,16.8]	[-22.2,21.3]
f_{M6}/Λ^4	[-5.4, 5.8]	[-7.2, 7.3]	—	—	[-16, 16]	[-15, 15]	—	—
f_{M7}/Λ^4	[-5.7, 6.0]	[-7.8, 7.6]	—	—	[-21, 20]	[-19, 19]	[-44.7,45.0]	[-56.6,55.9]
f_{S0}/Λ^4	[-5.7, 6.1]	[-5.9, 6.2]	—	—	—	—	—	—
f_{S1}/Λ^4	[-16, 17]	[-18, 18]	—	—	—	—	—	—