



Northeastern
University

VECTOR BOSON SCATTERING RESULTS IN CMS

ICHEP 2022, BOLOGNA

Yacine Haddad (*)
On behalf of CMS collaboration

(*) Supported by US NSF PHY-2011848 and PHY-1707666

THE STANDARD MODEL IN CMS

Electroweak

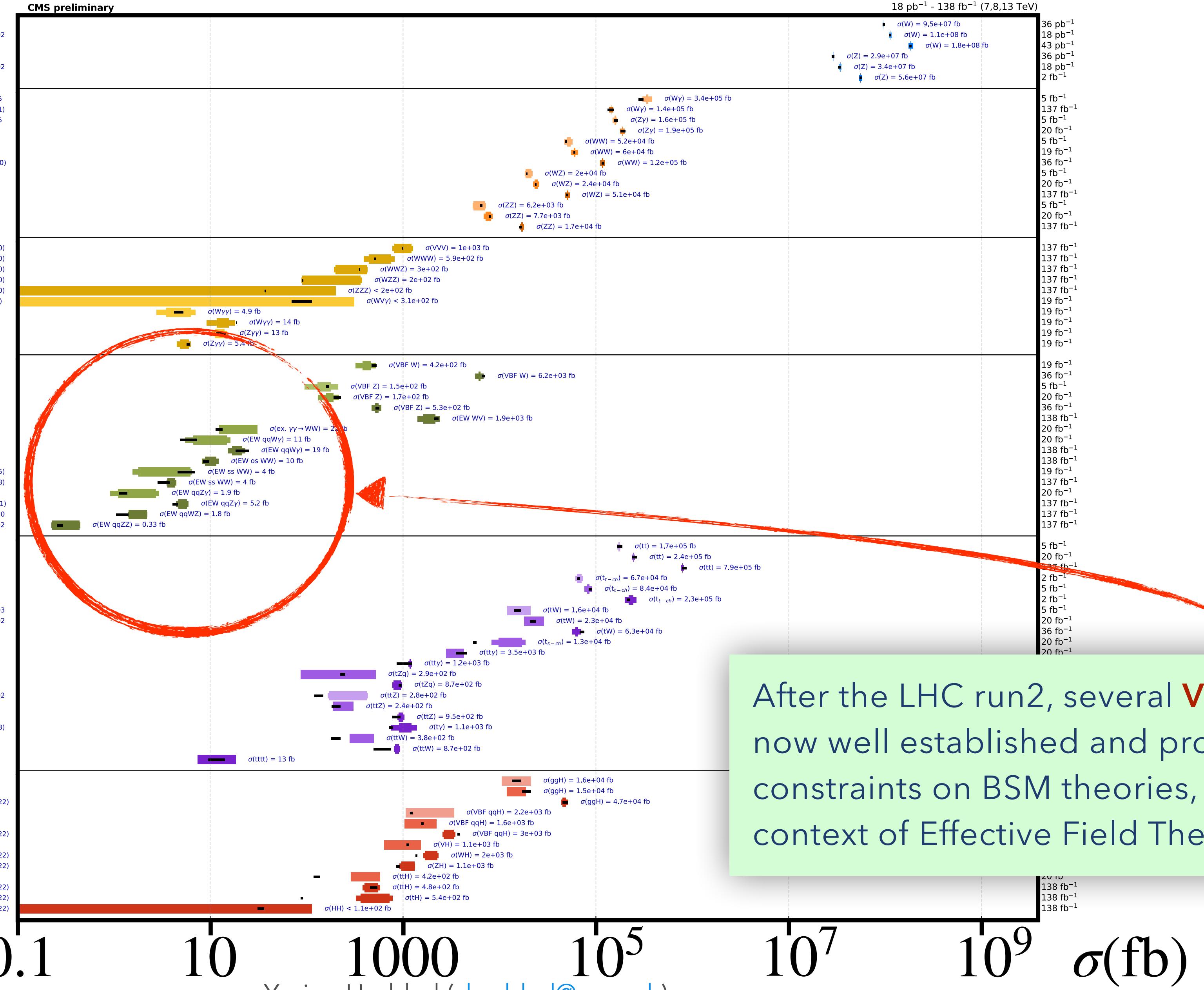
Diboson

Triboson

VBF & VBS

TOP

Higgs

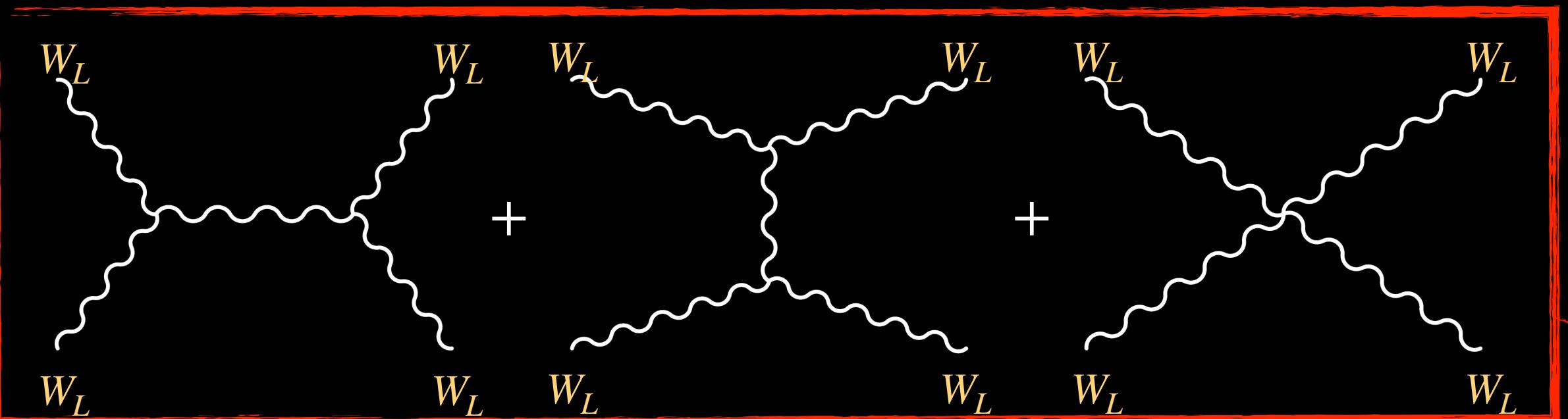


After the LHC run2, several **VBS channels** are now well established and provide stringent constraints on BSM theories, especially in the context of Effective Field Theory (EFT)

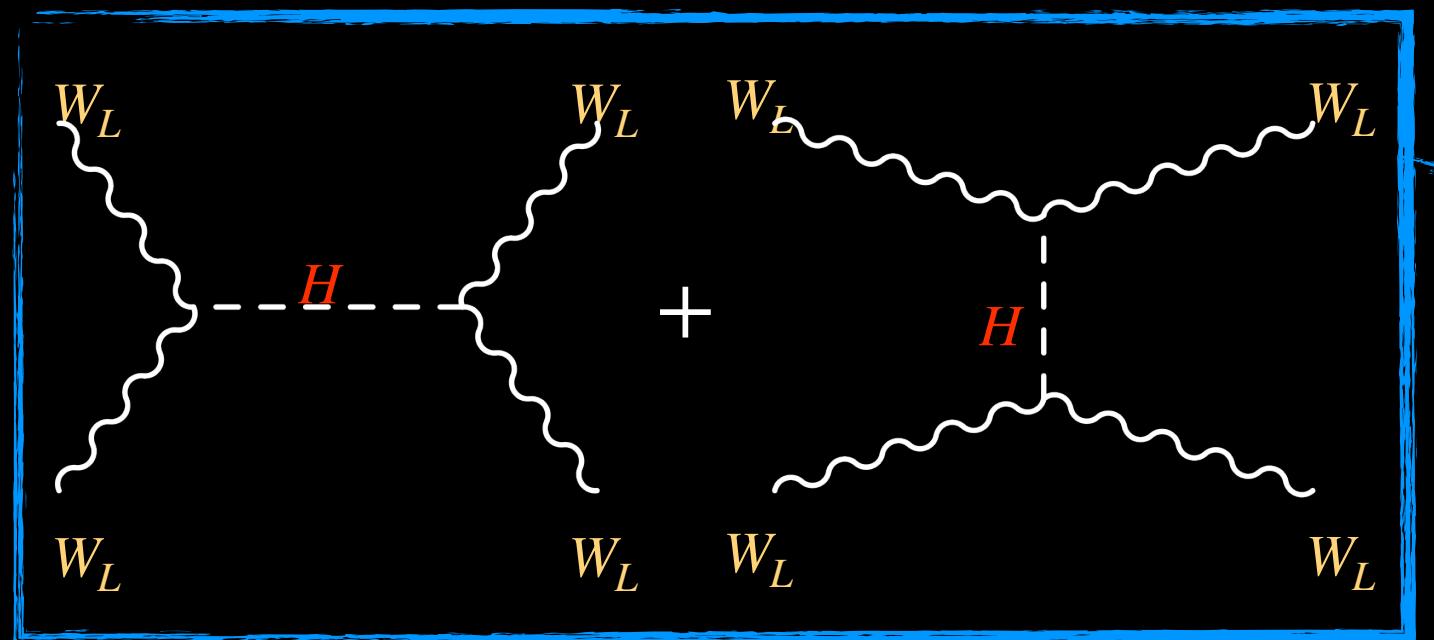
VBS MEASUREMENTS AT CMS

- Major effort undertaken to investigate VBS processes in CMS with full Run-II dataset
 - Inclusive cross-section measurements
 - Differential cross-section of various variables
 - Indirect search for New Physics within the EFT framework
- Plethora of results with full Run-II dataset are coming out
 - Observation of leptonic OS WW VBS (CMS-SMP-21-00, Submitted to PLB) ★
 - Evidence of semi-leptonic WV VBS (CMS-SMP-20-013, Submitted to Phys. Lett. B) ★
 - Observation of $Z\gamma$ scattering (PRD 104 (2021) 072001) ★
 - Observation and measurement of $W\gamma$ VBS (PLB 811 (2020) 135988, CMS-PAS-SMP-21-011) ★
 - PPS $\gamma\gamma$ to VV in hadronic decay (CMS-PAS-SMP-21-014, more details on A. Bellora's talk)
 - many results are already out and more are coming. [[click here](#)] to find out

WHAT IS VECTOR BOSON SCATTERING (VBS)

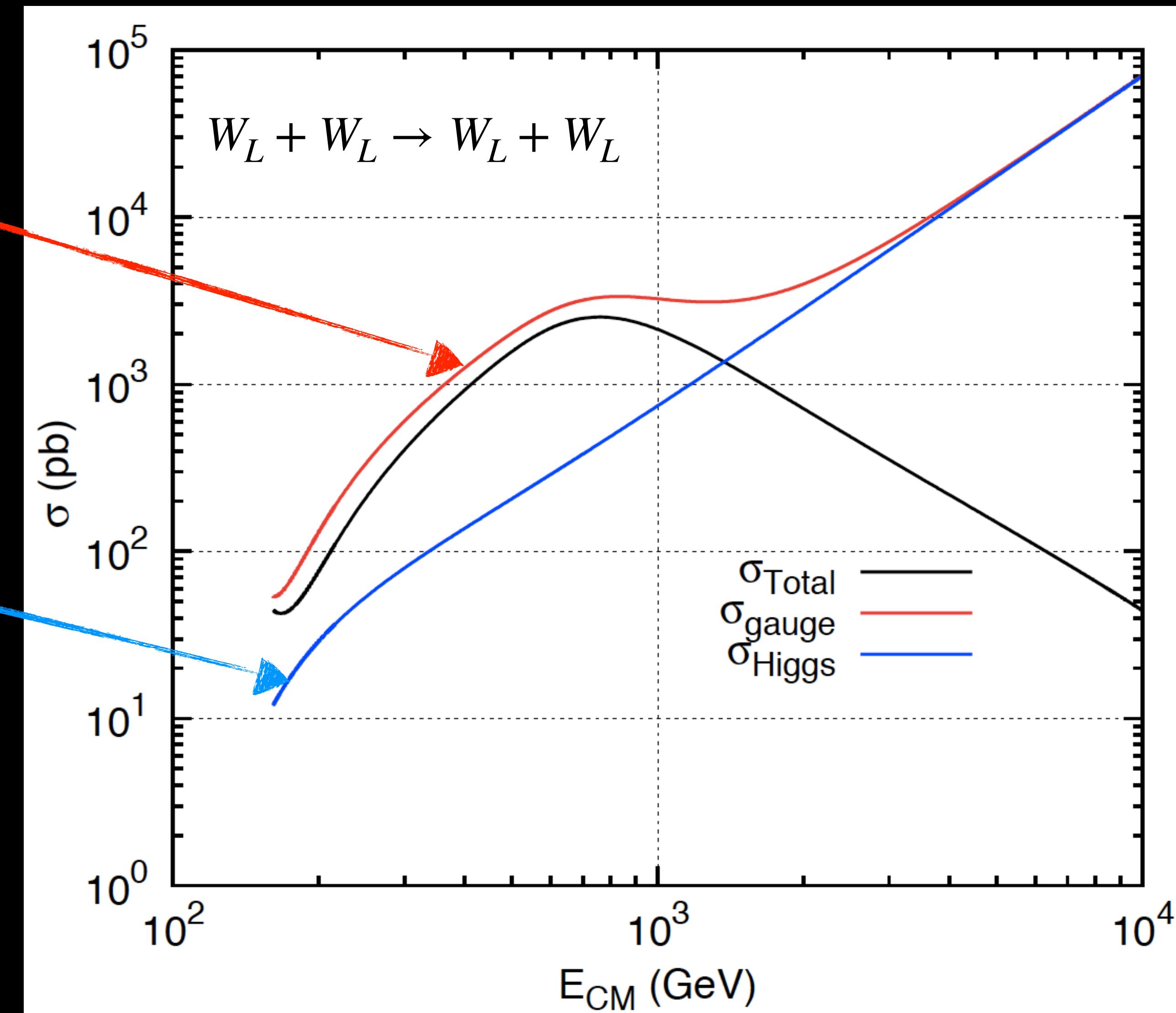


$$iM_{gauge} \simeq -i\frac{g^2}{4m_W^2}[s+t]$$



$$iM_{Higgs} \simeq i\frac{g^2}{4m_W^2}[s+t]$$

The Higgs boson contribution cancels exactly the E^2 dependance of the cross section at high energy



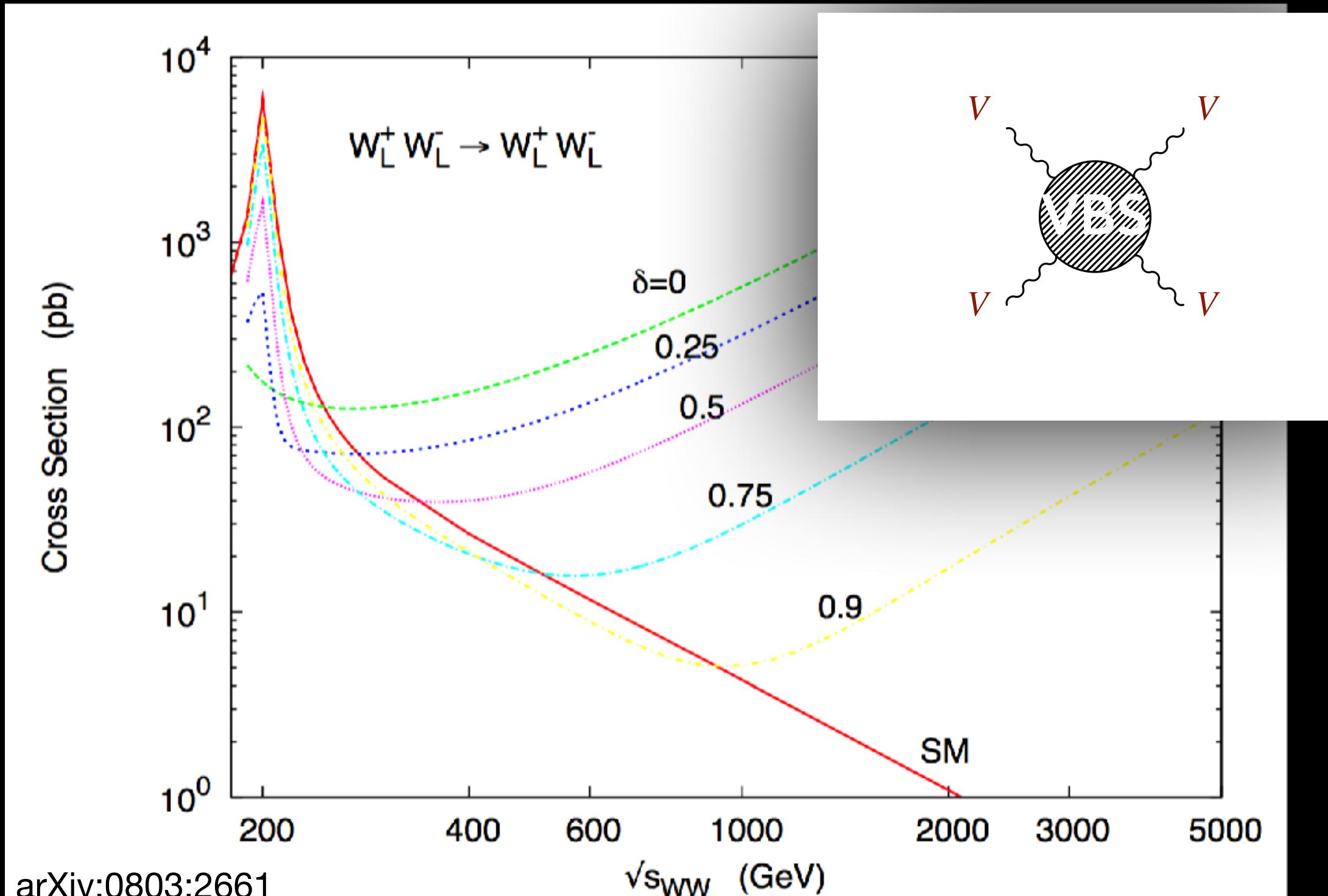
VBS IN CASE OF ANOMALIES

If the **delicate equilibrium** is perturbed ...

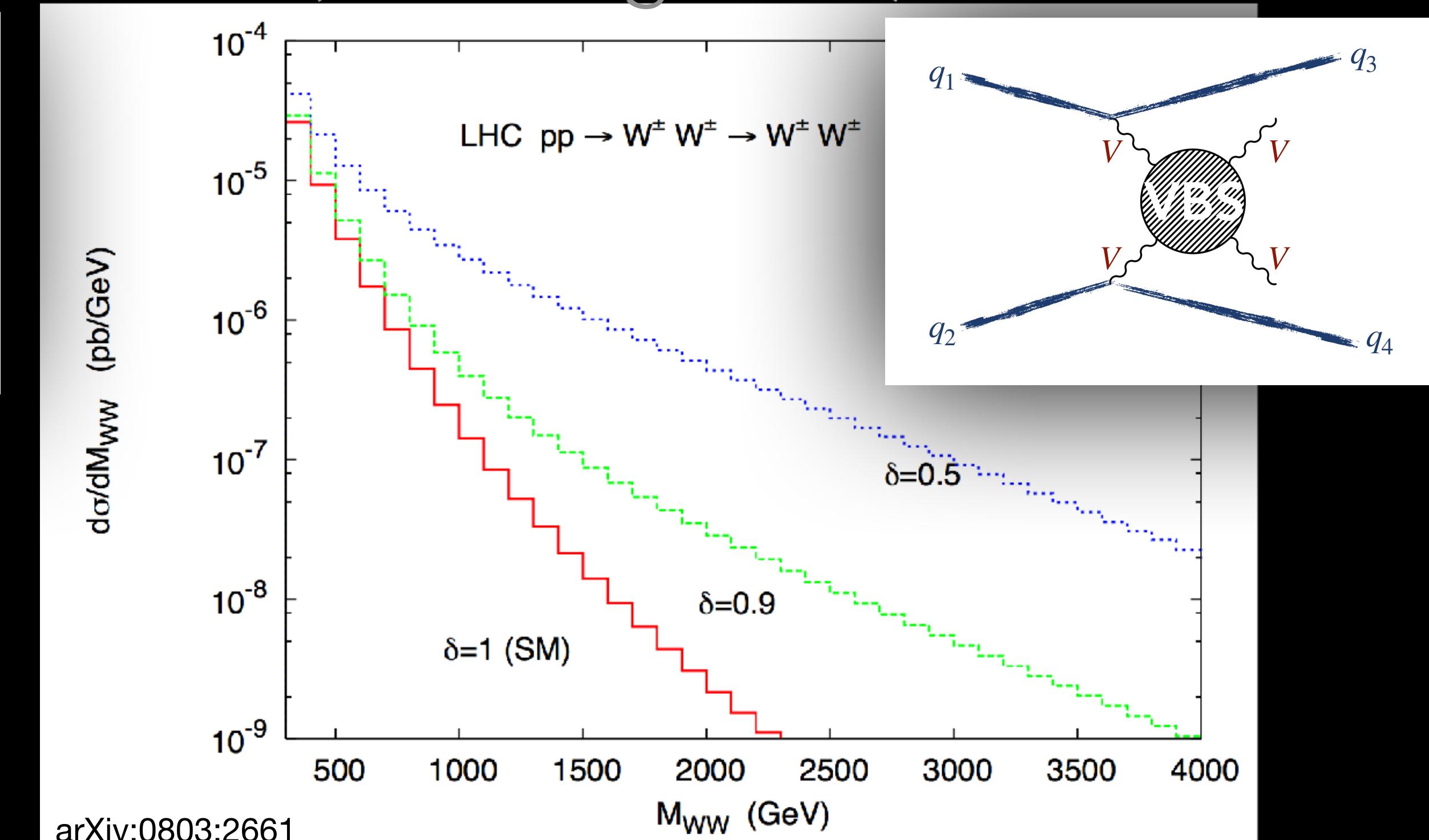
$$iM_{Higgs} \simeq i \frac{g^2}{4m_W^2} [s + t] (\delta)$$

any deviations signal **new physics independently of the theory considered**
(model-independent way) and hints on the scale of new physics

Parton level



@LHC (including PDFs)



arXiv:0803:2661

arXiv:0803:2661

VBS SIGNATURE @LHC

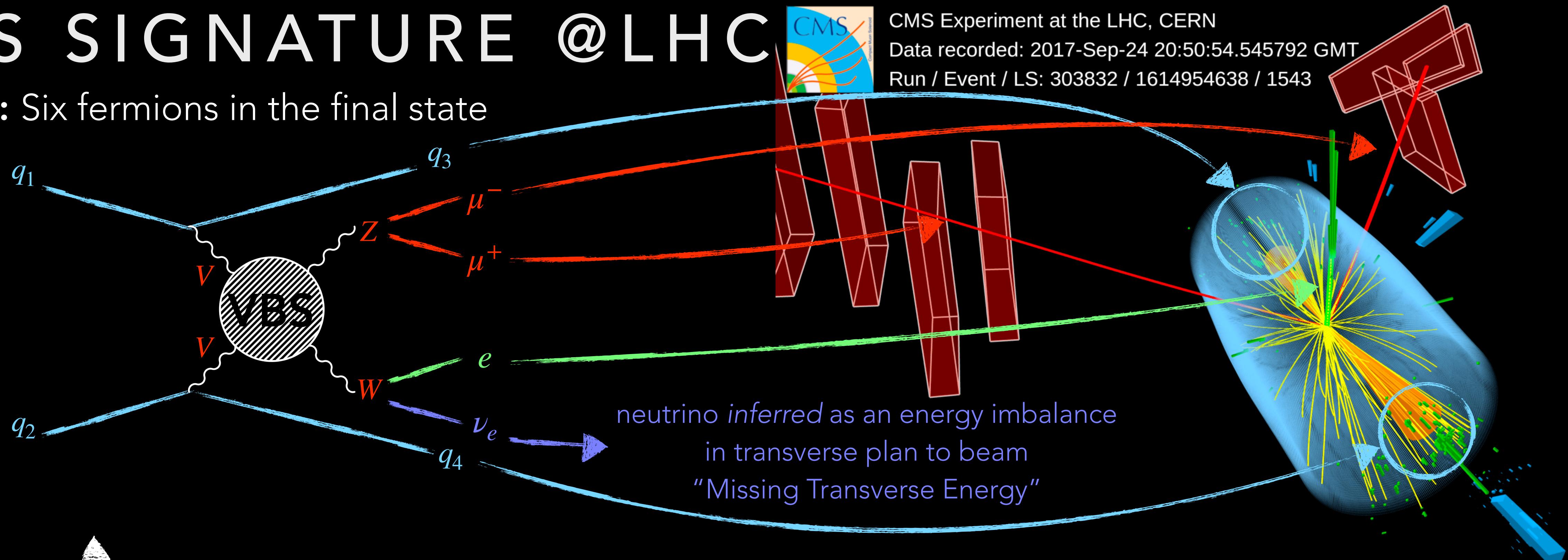


CMS Experiment at the LHC, CERN

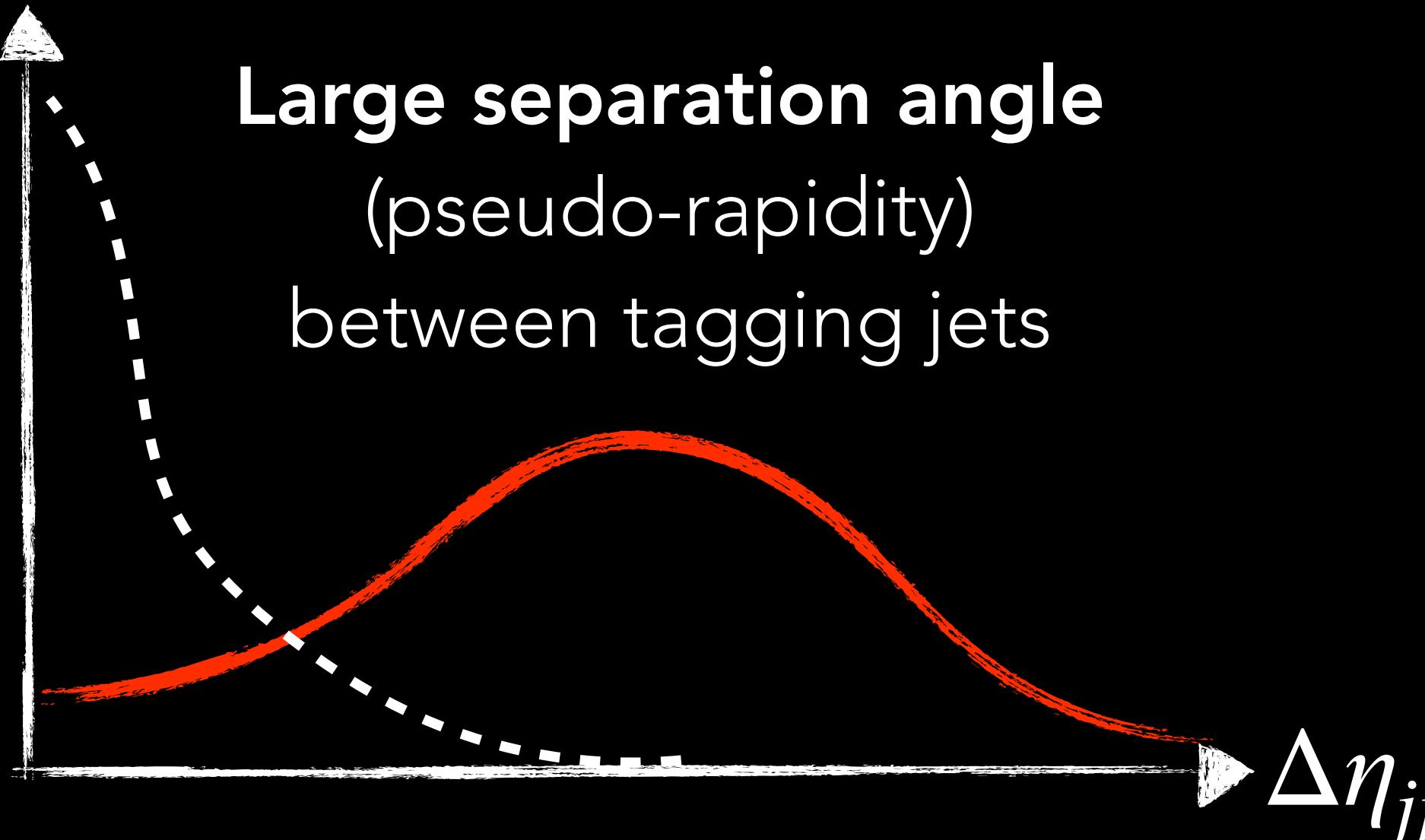
Data recorded: 2017-Sep-24 20:50:54.545792 GMT

Run / Event / LS: 303832 / 1614954638 / 1543

Signal: Six fermions in the final state



Large separation angle
(pseudo-rapidity)
between tagging jets

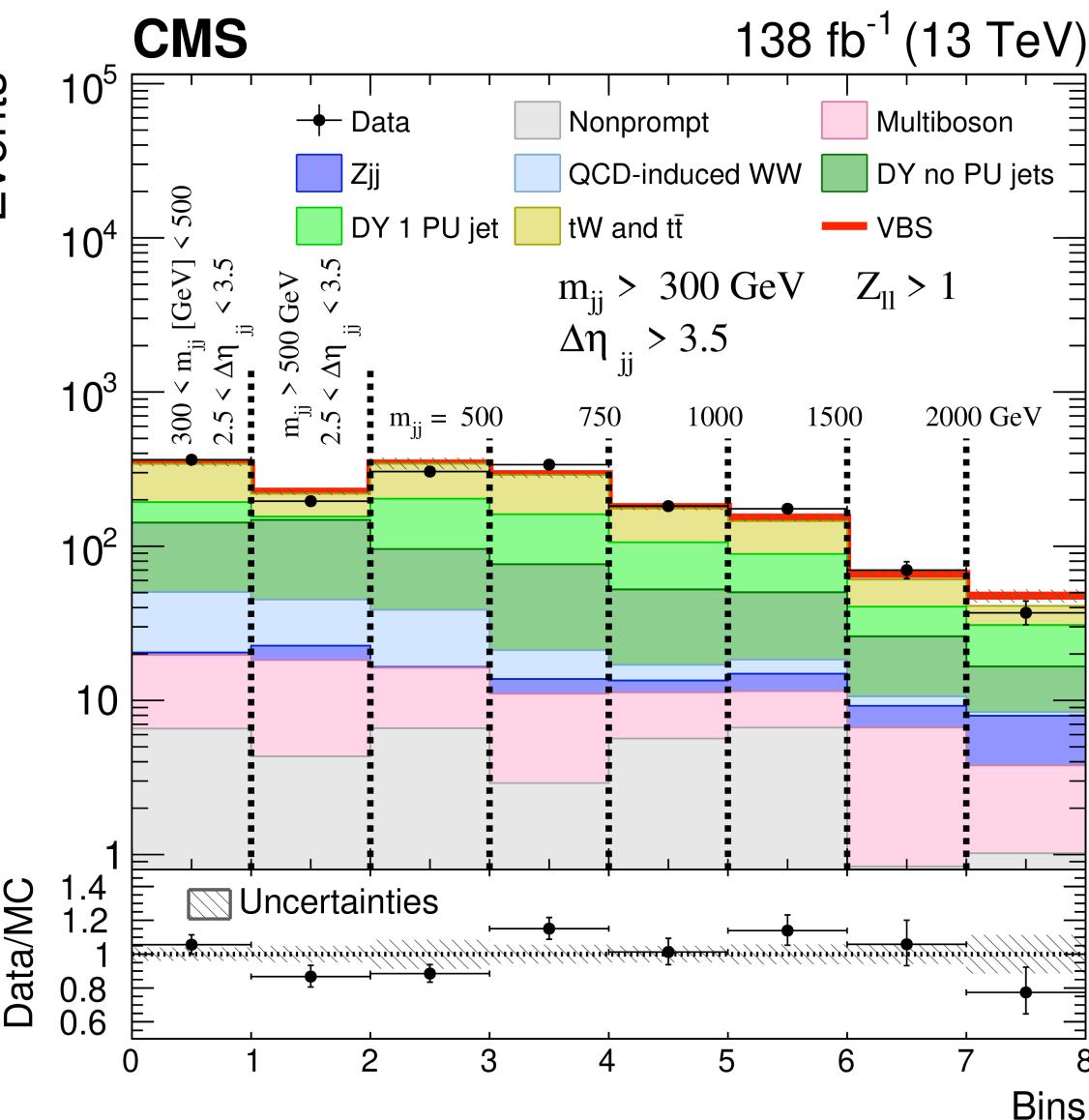
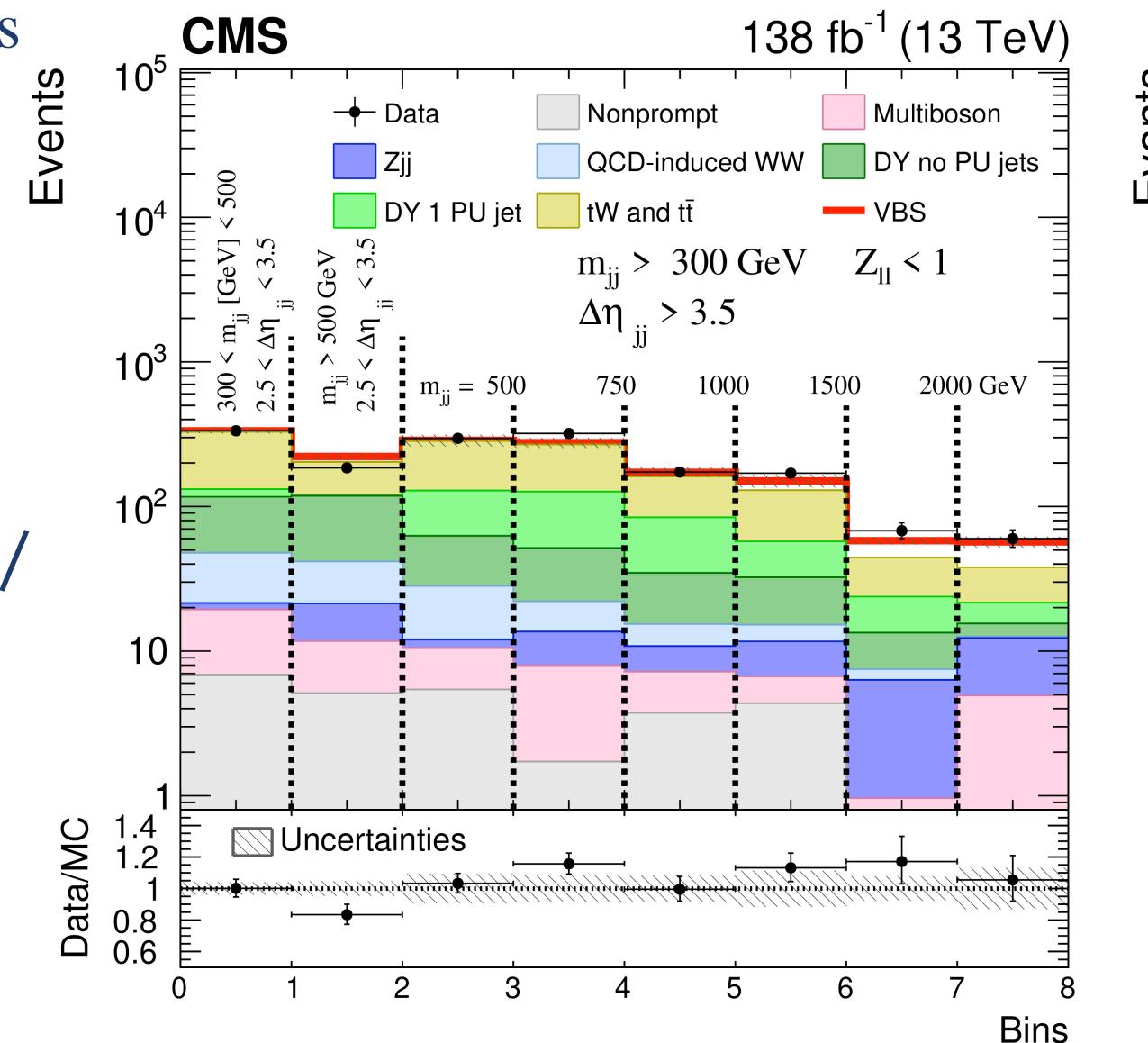


Low QCD activity
between tagging jets

OBSERVATION OF OPPOSITE-SIGN WW VBS

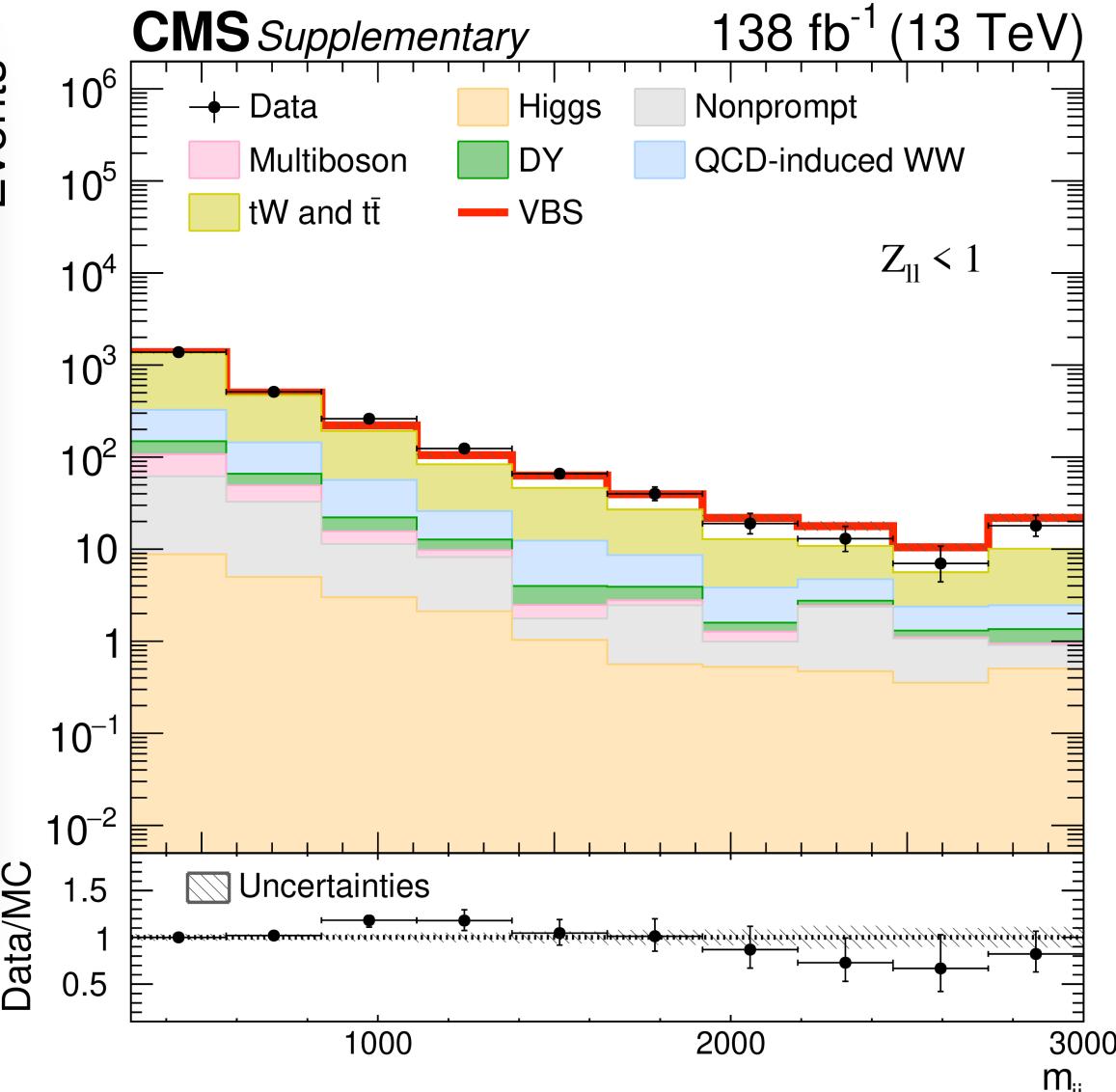
- 2 opposite-sign leptons, 2 jets and moderate missing p_T^{miss}
- Lepton-flavour-based event categories
 - $e\mu$: background dominated by $t\bar{t}$
 - $ee/\mu\mu$: background mostly dominated by DY
- Deep Neural-Network (DNN) selection based on 8 lepton/jets kinematic variables exploited in the $e\mu$ region
- Control Regions to estimate main backgrounds
 - $t\bar{t}$, tW and $Z \rightarrow ee/\mu\mu$ estimated with simulations
 - data-driven for non-prompt leptons and $Z \rightarrow \tau\tau \rightarrow \ell\ell$

- **Lepton-flavour dependent signal extraction**
 - $ee/\mu\mu$: Fit bins in m_{jj} , $\Delta\eta_{jj}$, Zeppenfeld* variables
 - $e\mu$: fit DNN score distributions
 - Largest systematic uncertainties: theory, b-jet veto



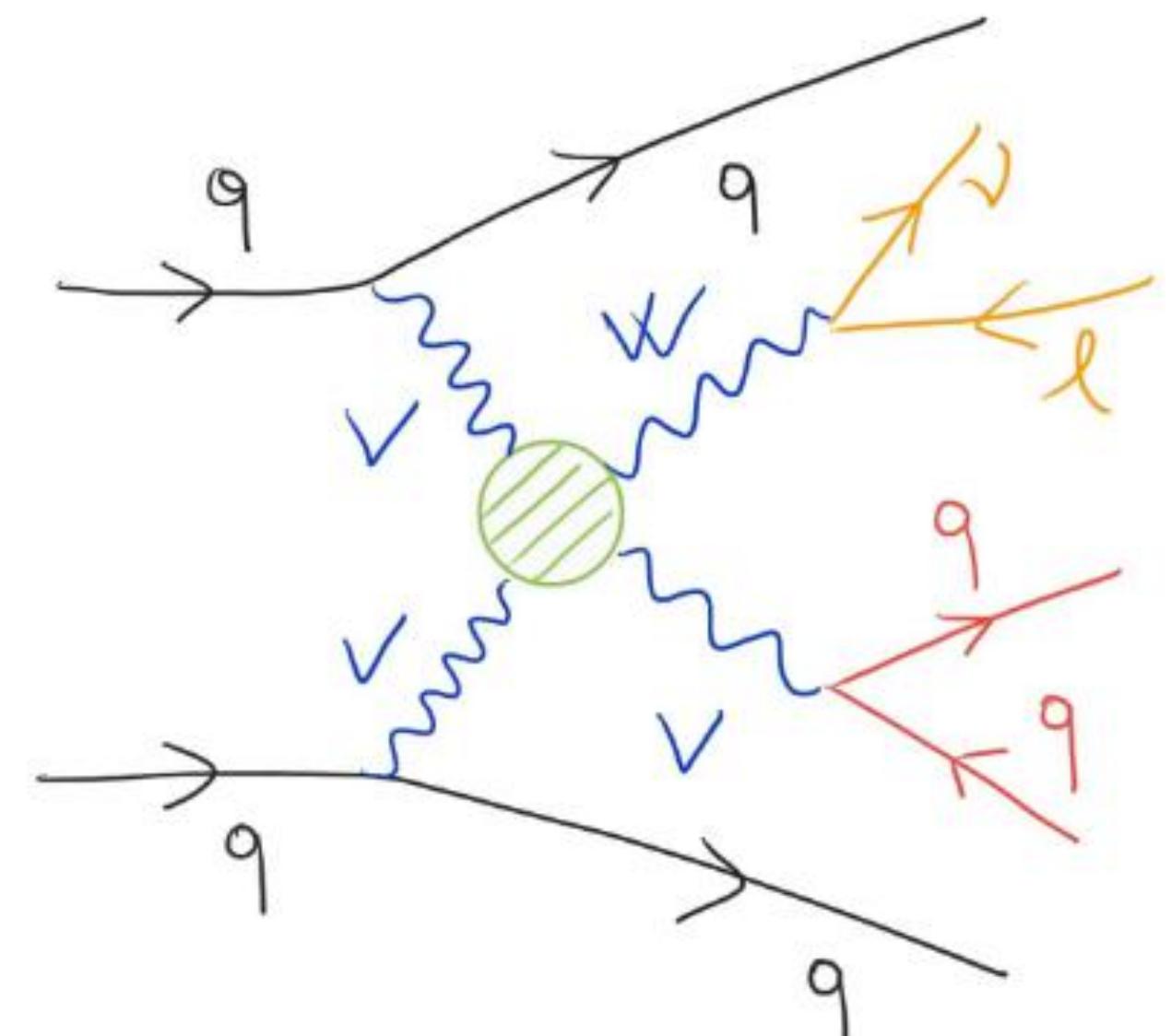
• Observed (expected) significance of 5.6 (5.2) First Observation ★
• Measured Fiducial cross-sections

- Inclusive: 99 ± 20 pb (theory: 89 ± 5 pb)
- Tight: 10.2 ± 2.0 fb (theory: 9.1 ± 0.6 pb)

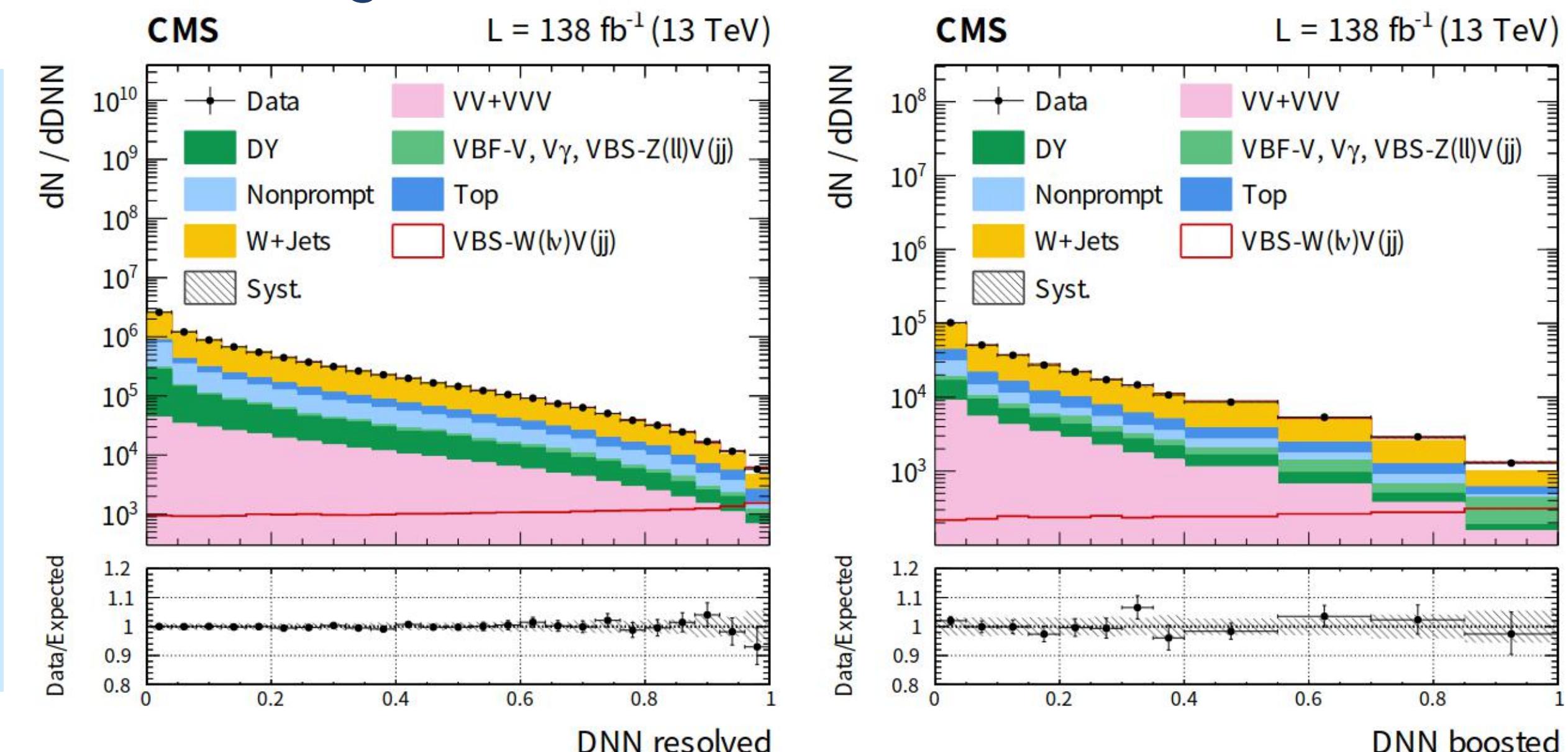


EVIDENCE OF SEMI-LEPTONIC WV VBS

- Signature:
 - A W boson decays **leptonically** and V boson **hadronically**.
 - Two decay regimes of the hadronic V boson: **Resolved** and **Merged**
- DNN model trained to separate signal and background
- Main background is **W+jets** estimated from a data-driven
- **Signal extraction**
 - Fit the DNN output distributions in boosted and resolved categories

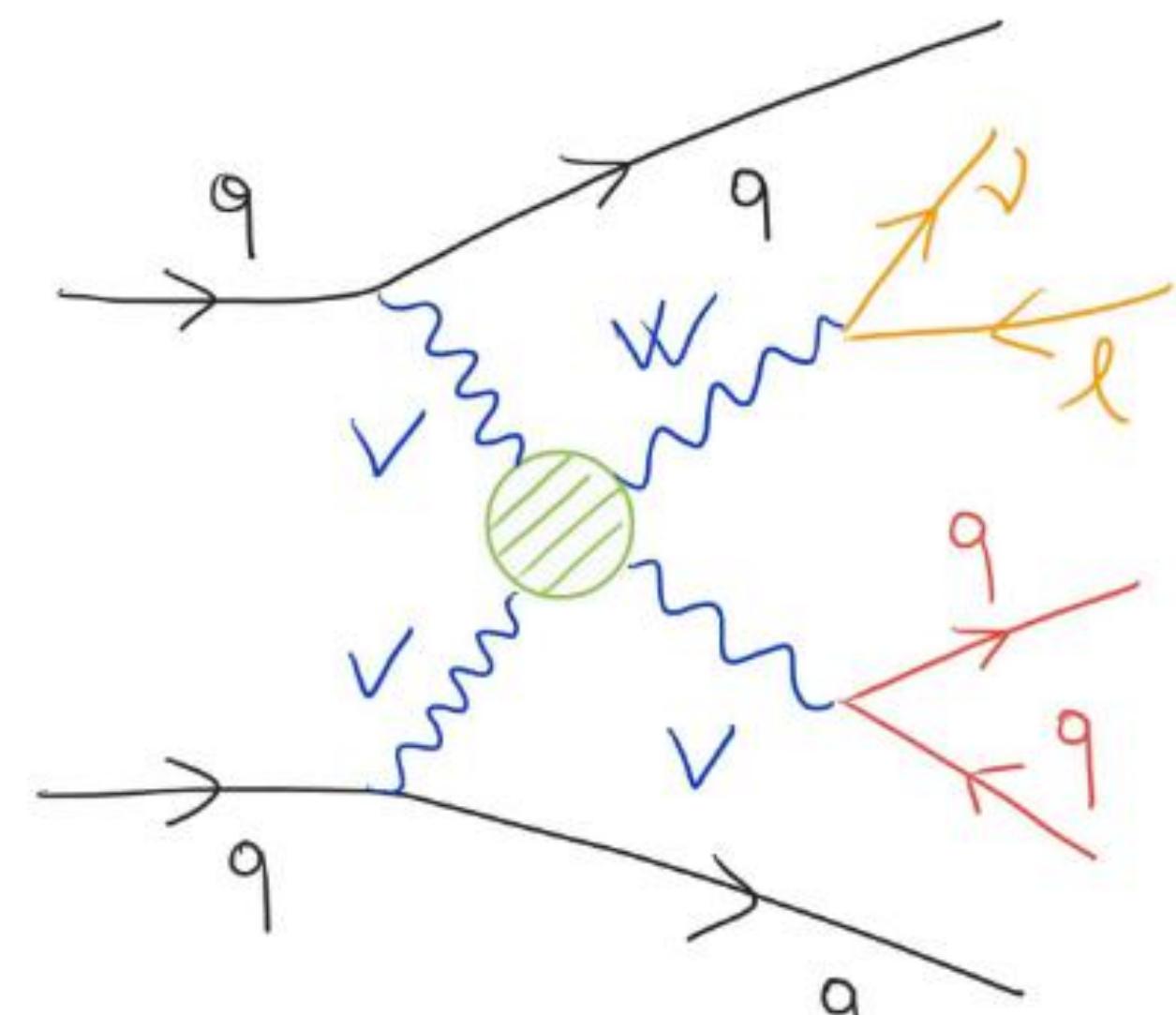


• **First evidence of this final state** ★
 • Combined signal significance: 4.4σ (5.1 exp)
 • Observed EW signal strength:
 $\mu_{\text{EW}} = \sigma^{\text{obs}}/\sigma^{\text{SM}} = 0.85 \pm 0.12 \text{ (stat)} {}^{+0.19}_{-0.17} \text{ (syst)}$
 • Measured fiducial cross-section :
 $1.9 \pm 0.5 \text{ pb}$ (expected 2.2 pb)



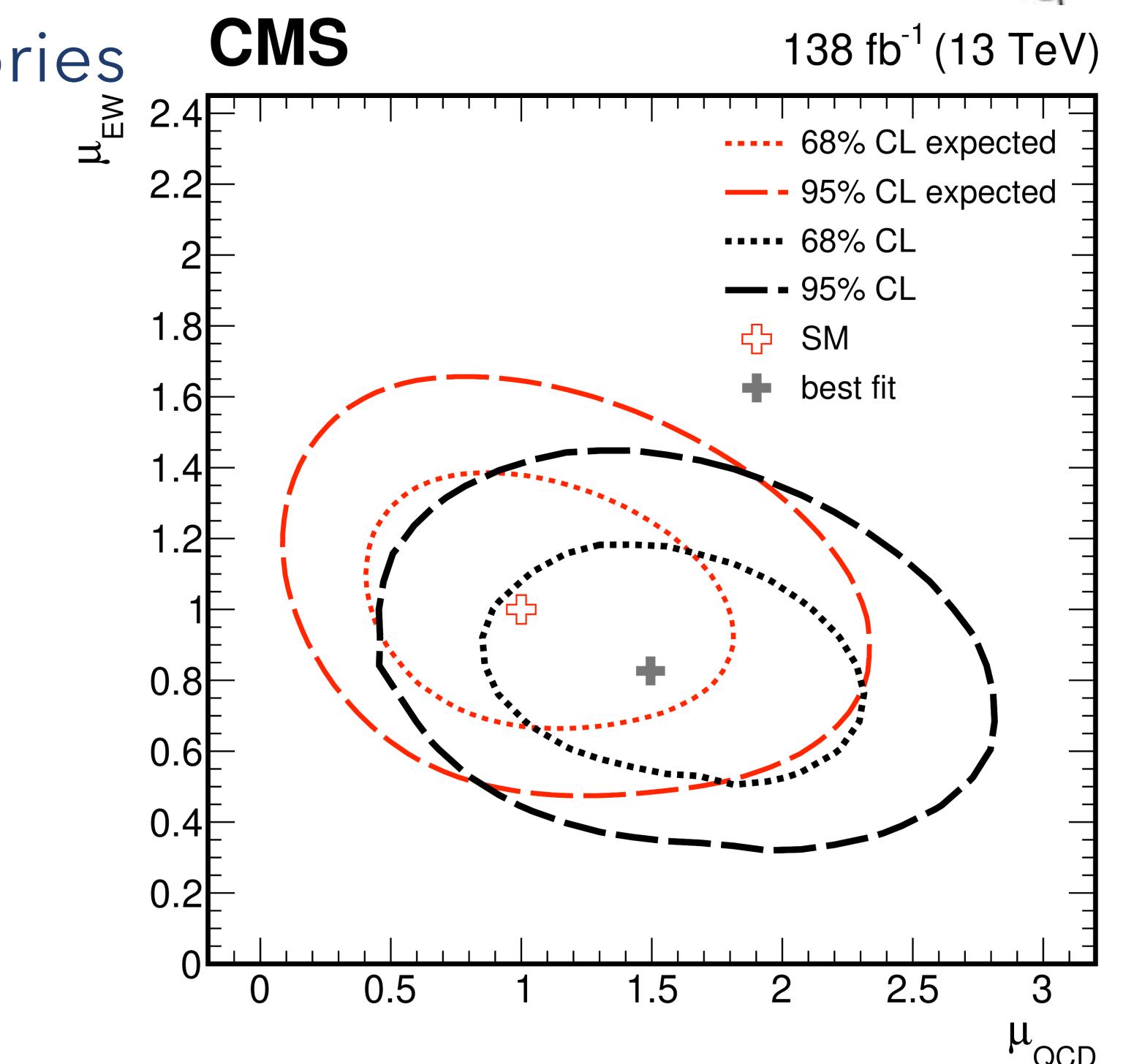
EVIDENCE OF SEMI-LEPTONIC WV VBS

- Signature:
 - A W boson decays **leptonically** and V boson **hadronically**.
 - Two decay regimes of the hadronic V boson: **Resolved** and **Merged**
- DNN model trained to separate signal and background
- Main background is **W+jets** estimated from a data-driven



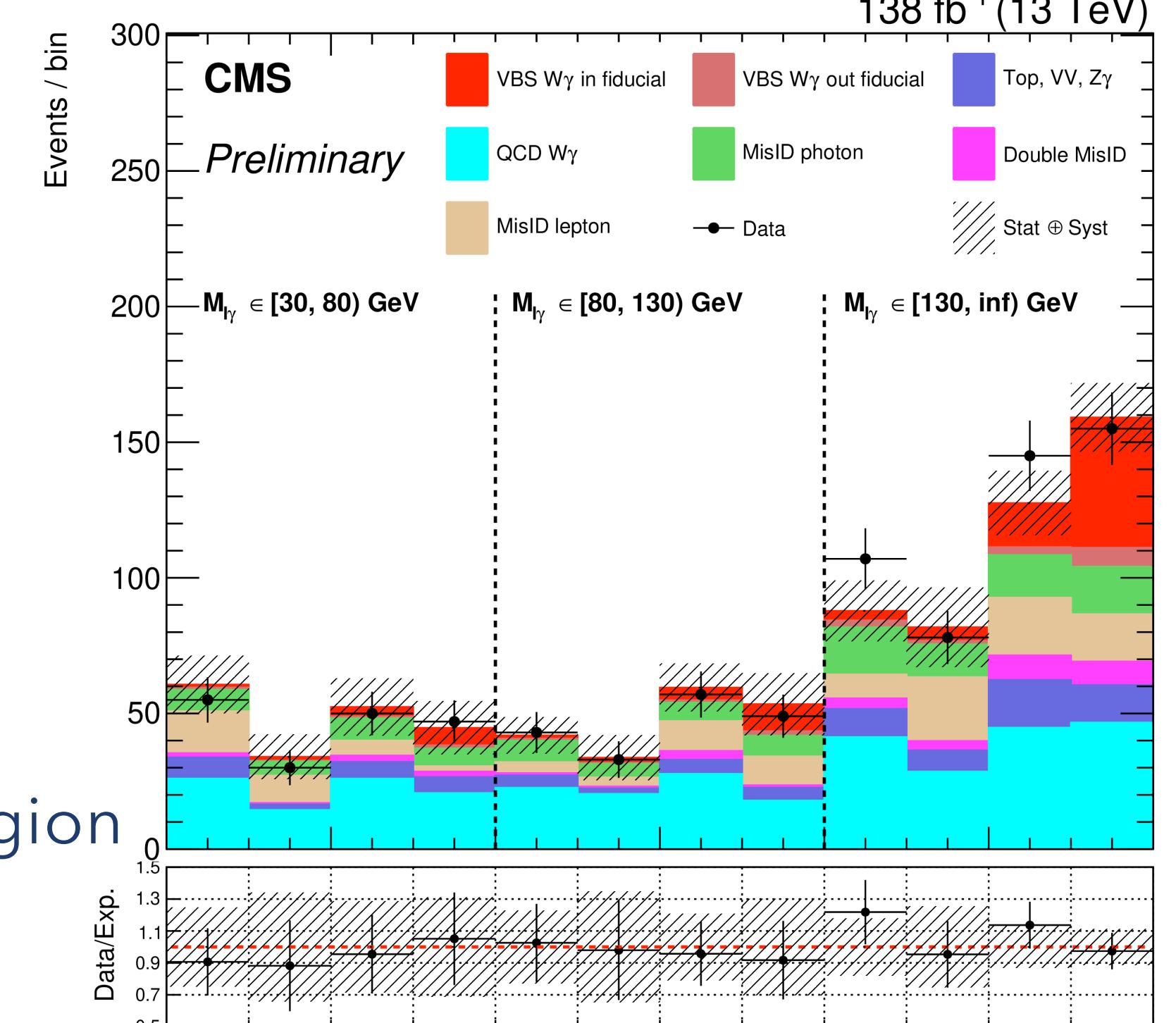
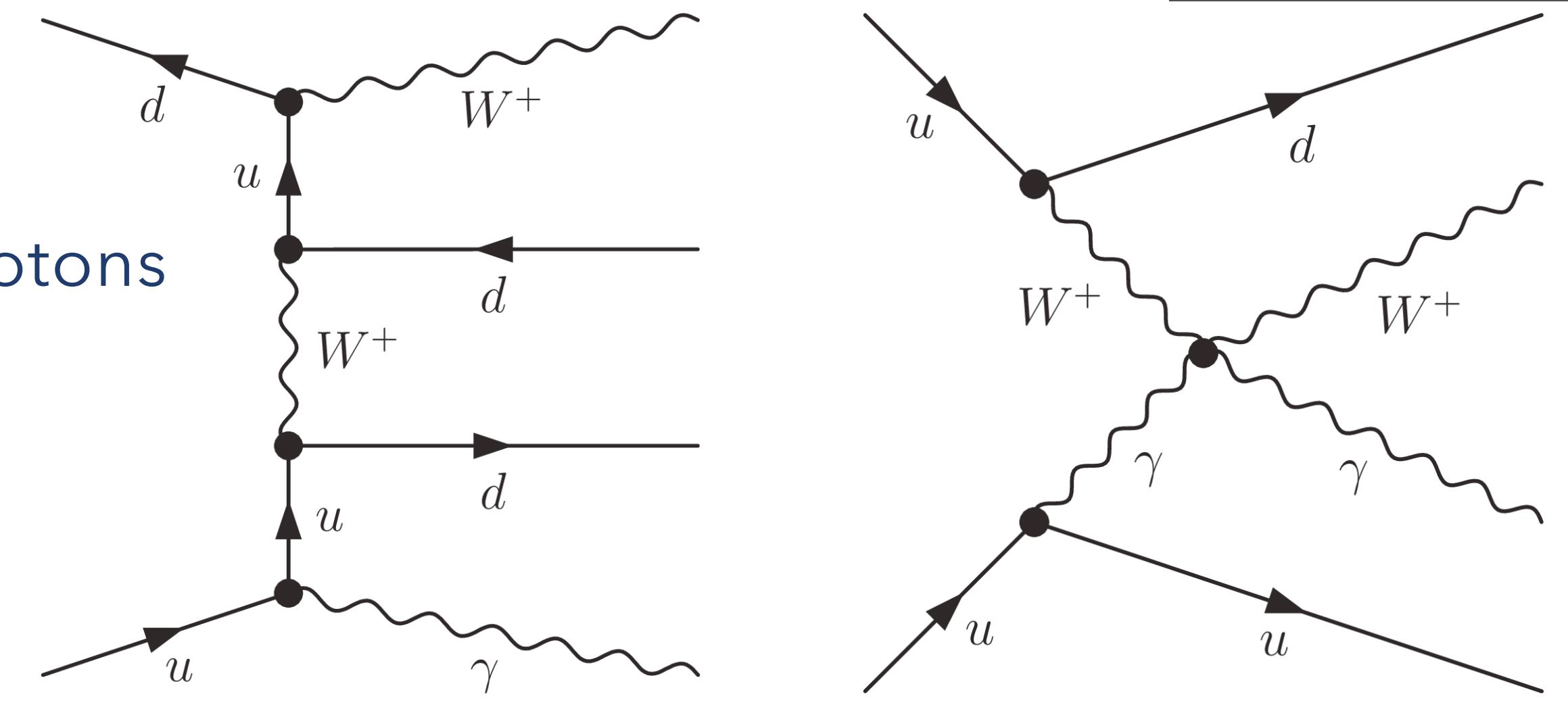
- **Signal extraction**
 - Fit the DNN output distributions in boosted and resolved categories

• EWK+QCD WV fit on the same observables
 • **Fiducial region at parton level:**
 • $\sigma_{\text{EW+QCD}} = 16.4 \text{ pb} (\text{Obs}) = 16.9 \text{ pb} (\text{Exp})$
 • **Signal strength**
 • $\mu_{\text{EW+QCD}} = 0.97^{+0.20}_{-0.22} (\text{Obs}) = 1.0^{+0.20}_{-0.22} (\text{Exp})$



OBSERVATION $W\gamma$ VBS

- Leptonic V-boson decays combined with isolated photons
 - Final states: $e\nu\gamma + 2\text{jets}$ and $\mu\nu\gamma + 2\text{jets}$
- Signature: large di-jet mass and large η_{jj} separation between the VBS tagging jets
- Data-driven method for background estimate:
 - Template fit: **non-prompt photon**
 - Tight-loose method: **non-prompt lepton**
- **Signal extraction**
 - Simultaneous 2D ($m_{jj} - m_{\ell\gamma}$) fit in signal region and 1D (m_{jj}) in control region
 - Limits on EFT dim-8 operators + Fiducial and differential cross section



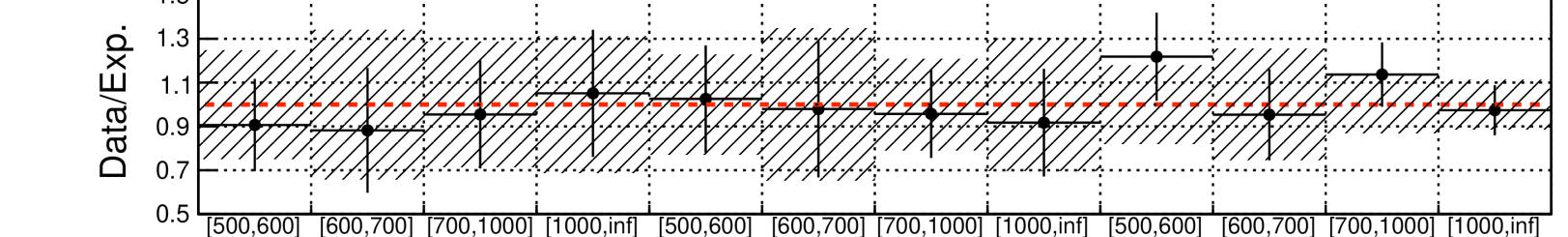
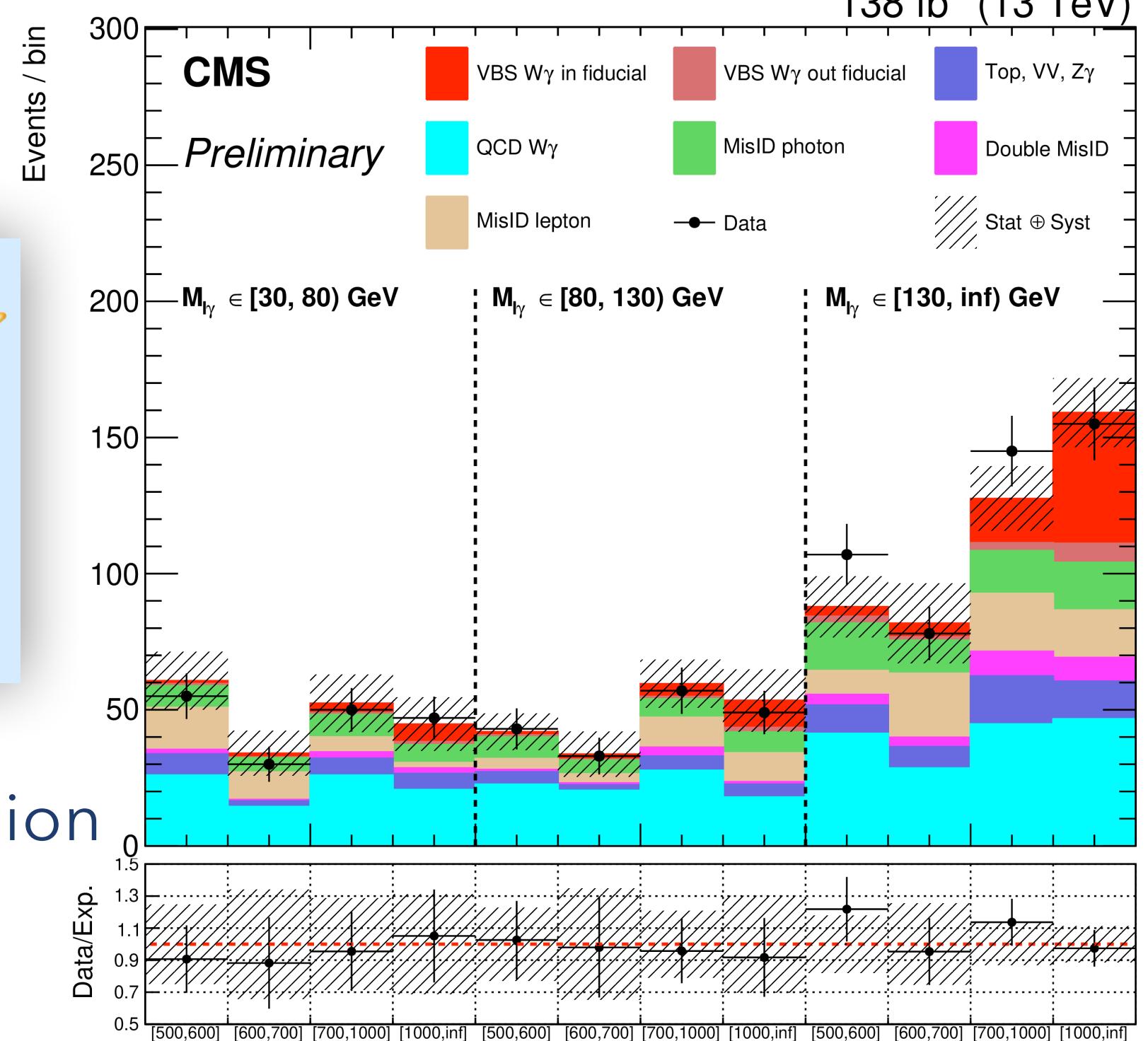
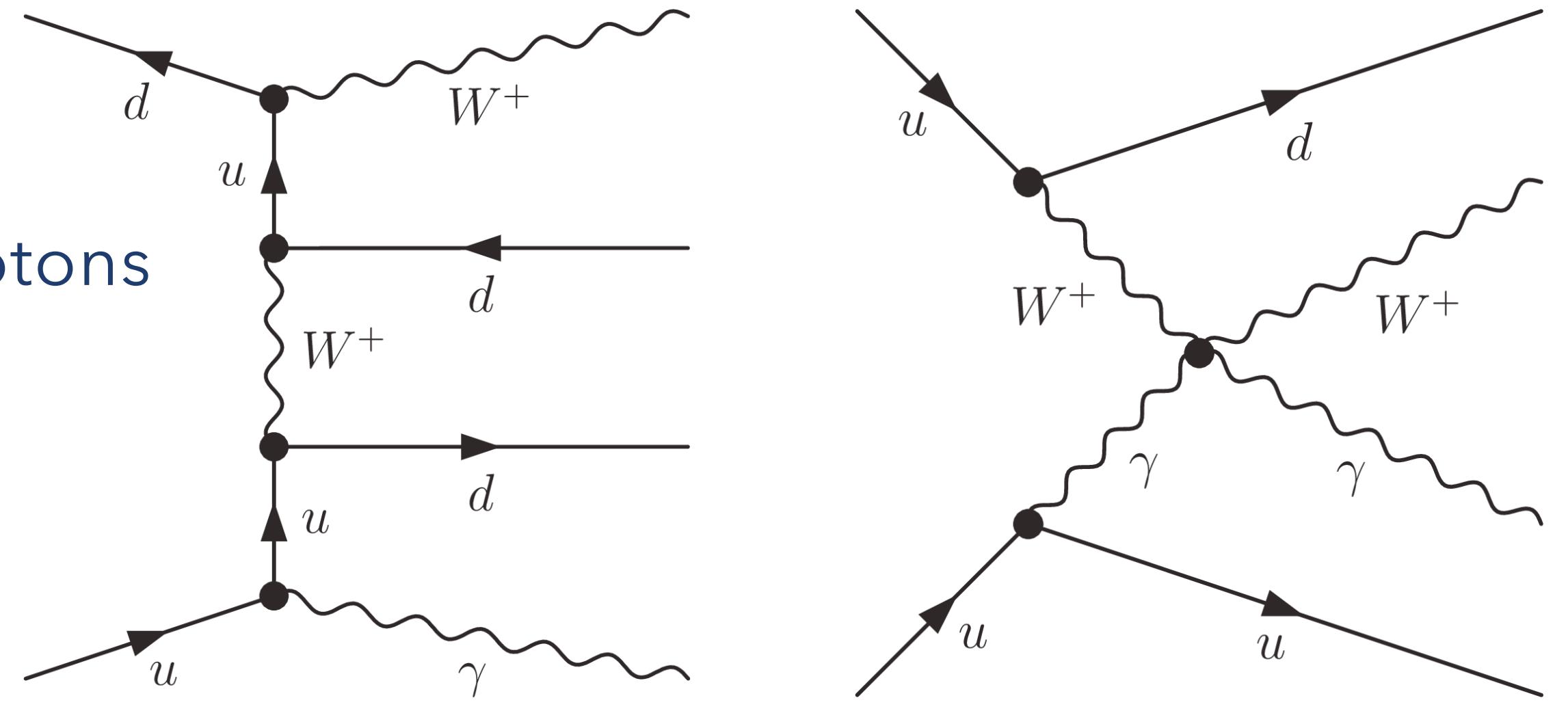
OBSERVATION $W\gamma$ VBS

- Leptonic V-boson decays combined with isolated photons
 - Final states: $e\nu\gamma + 2\text{jets}$ and $\mu\nu\gamma + 2\text{jets}$
- Signature: large di-jet mass and large η_{jj} separation between the VBS tagging jets
- Data-driven method for background estimate:
 - Template fit: **non-prompt photon**
 - Tight-loose method: **non-prompt lepton**

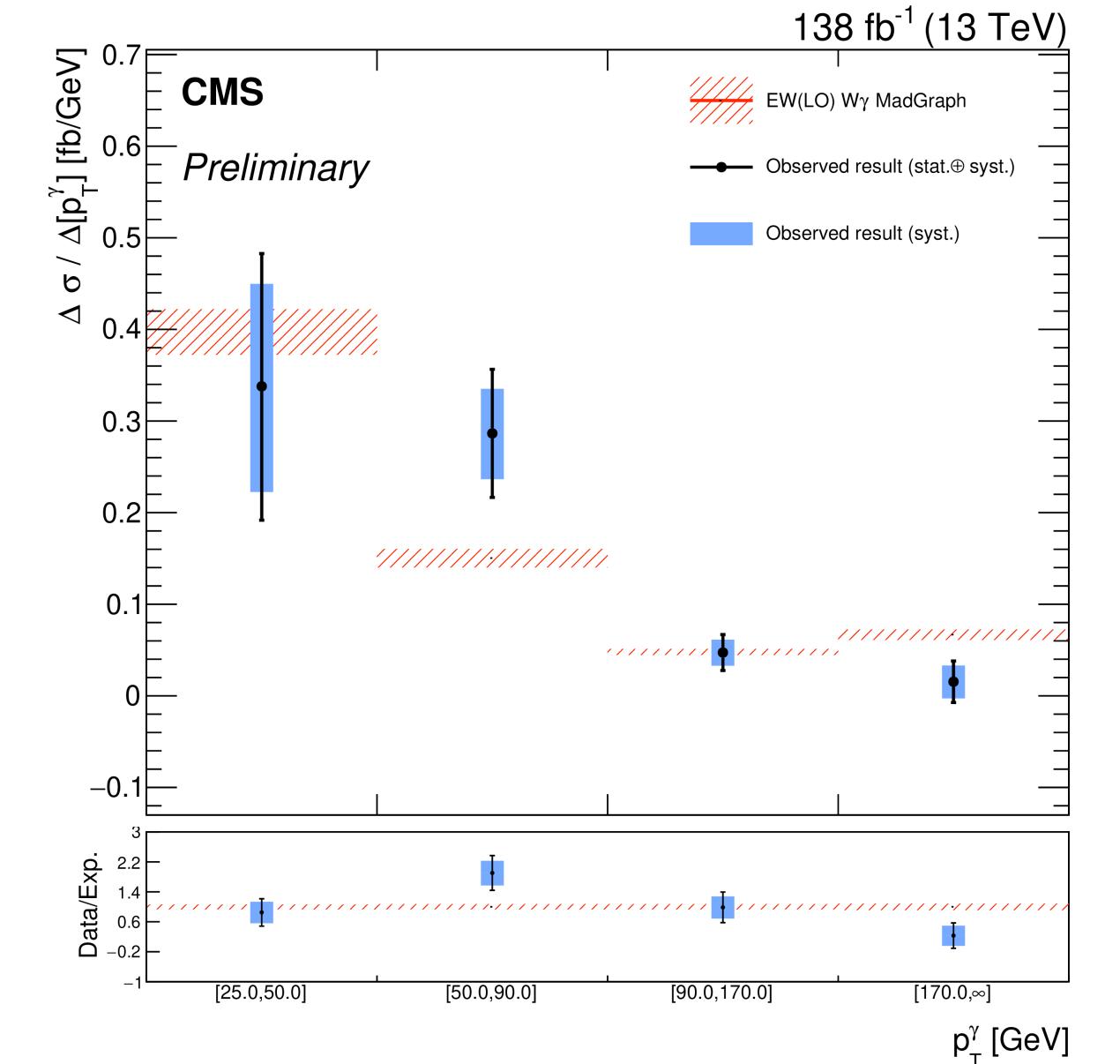
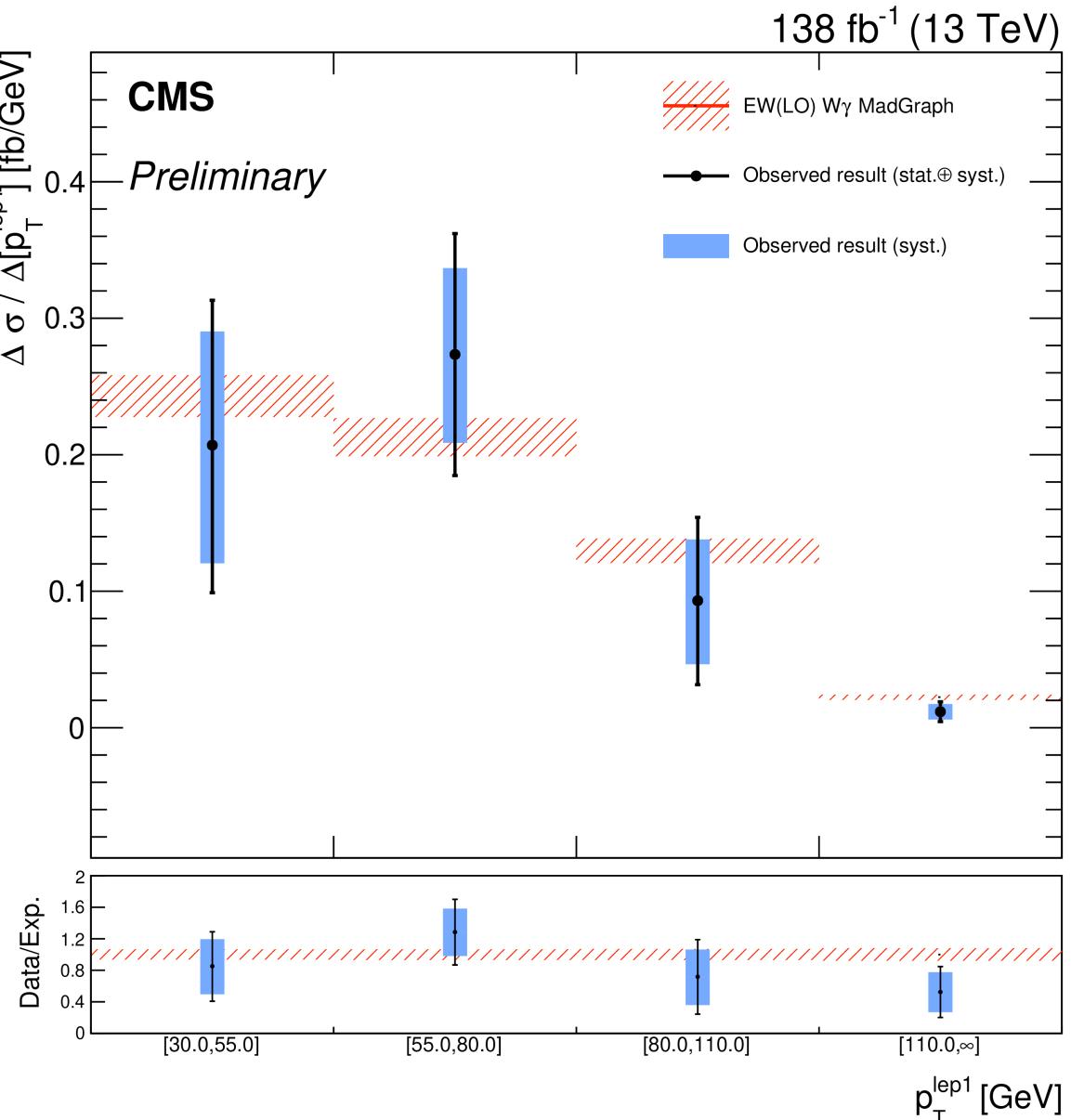
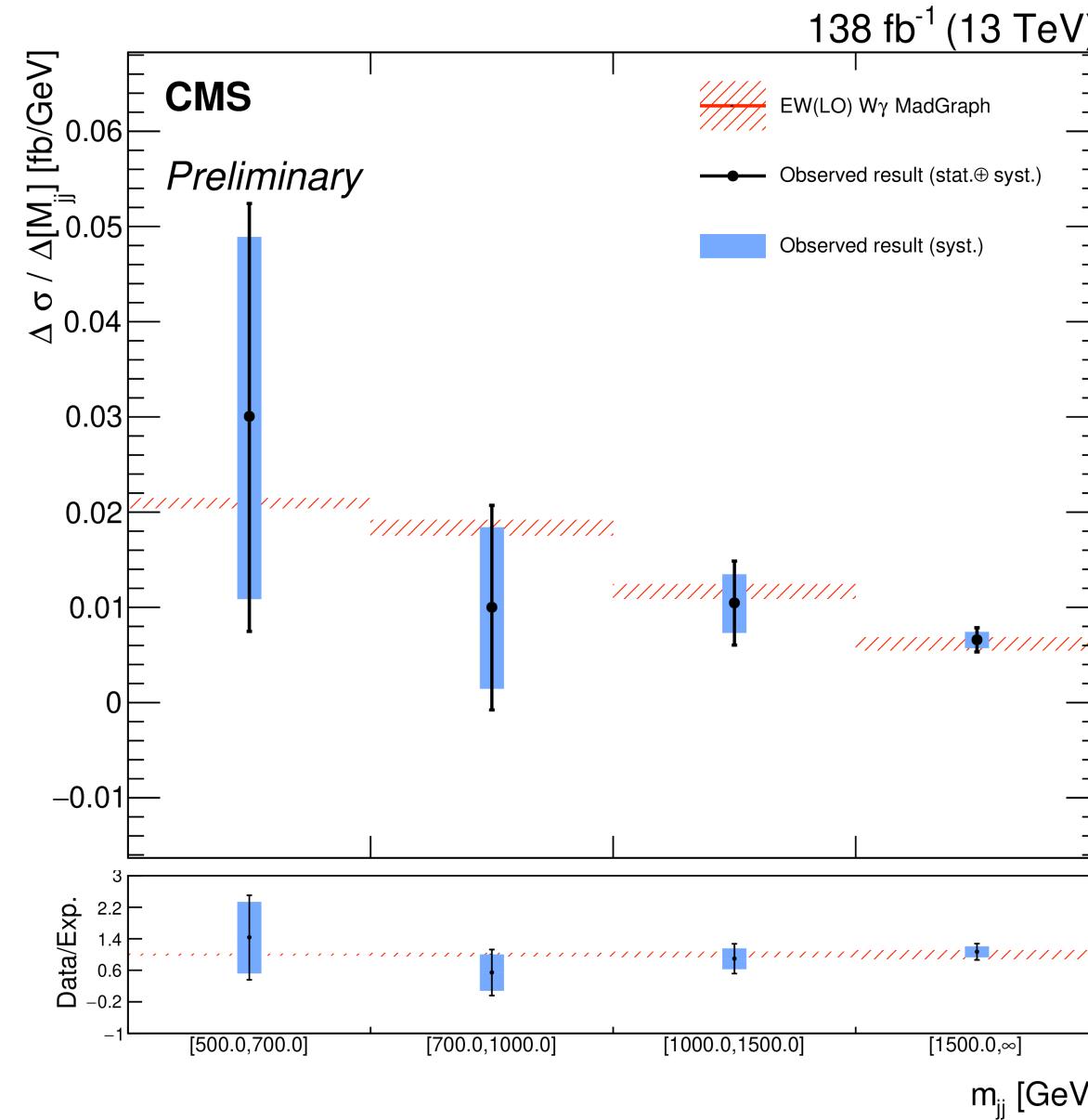
• **Observed (exp) significance of 6.0 (6.8) ⭐**
 • **Measured Fiducial cross-sections**

- $\sigma_{EW} = 19.0^{+2.3}_{-3.9} = 19^{+2.3}_{-2.3}$ (stat) $^{+1.6}_{-1.4}$ (theo) $^{+2.9}_{-2.8}$ (syst) fb
- $\sigma_{EW+QCD} = 90^{+11}_{-10} = 90^{+1.6}_{-1.6}$ (stat) $^{+2.0}_{-1.8}$ (theo) $^{+10}_{-10}$ (syst) fb

- **Signal extraction**
 - Simultaneous 2D ($m_{jj} - m_{\ell\gamma}$) fit in signal region and 1D (m_{jj}) in control region
 - Limits on EFT dim-8 operators + Fiducial and differential cross section



OBSERVATION $W\gamma$ VBS

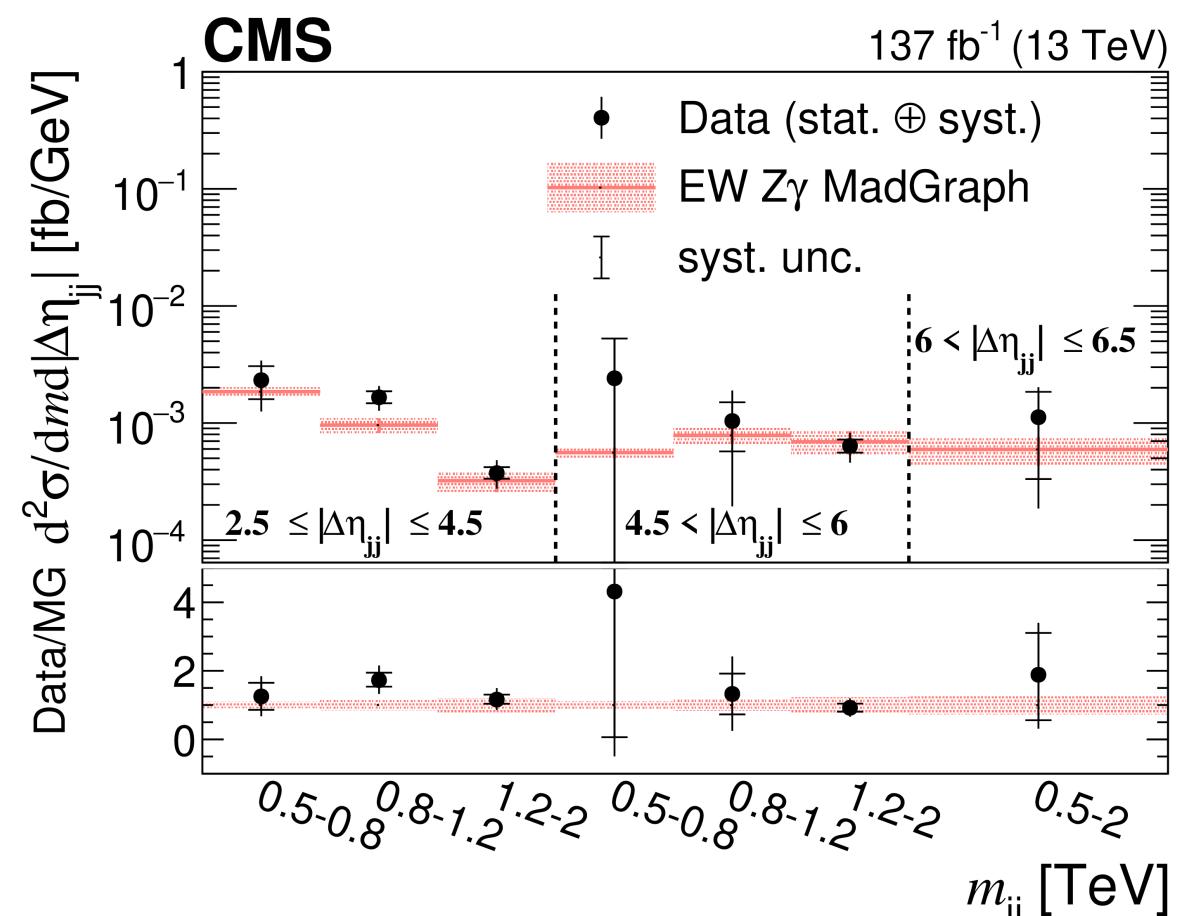
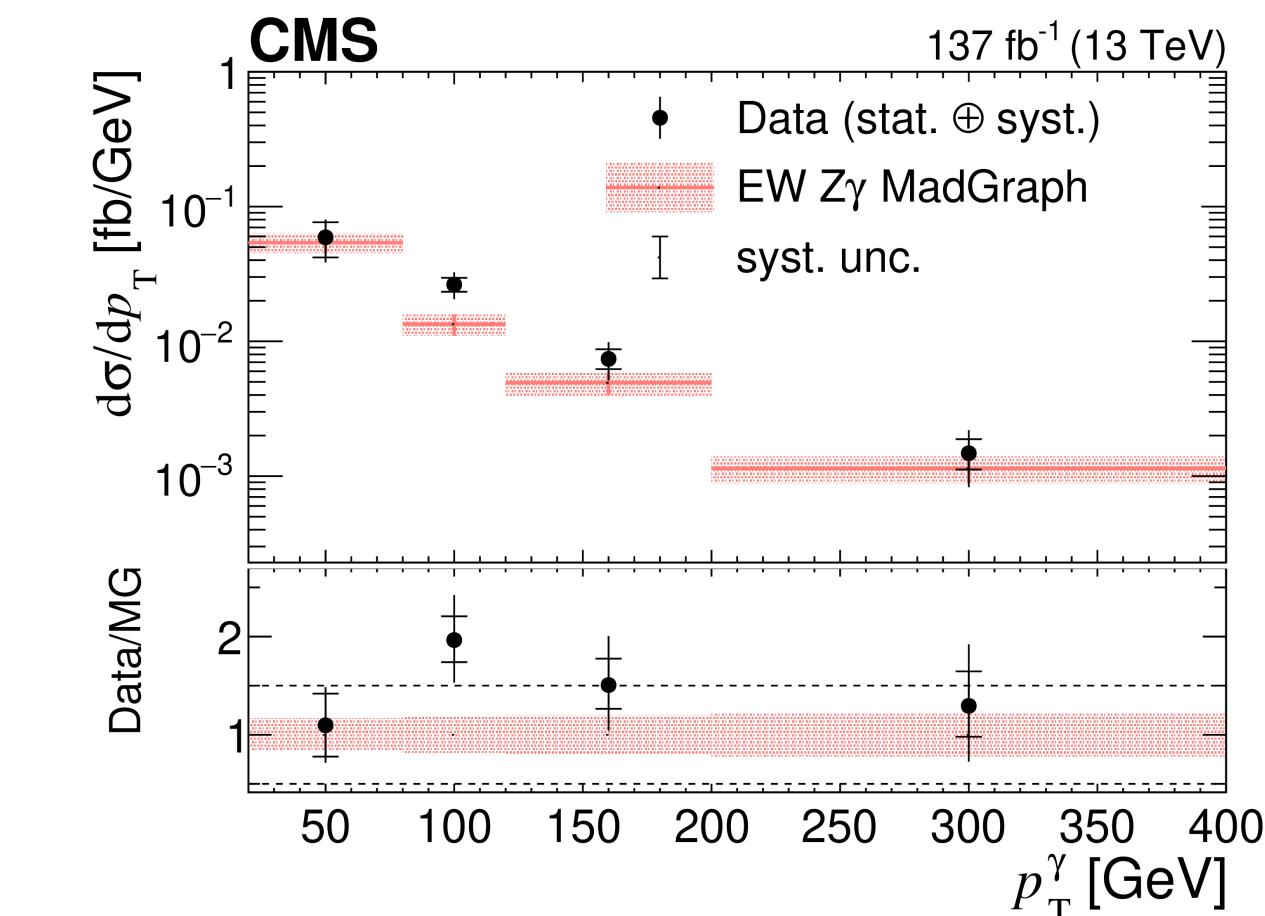
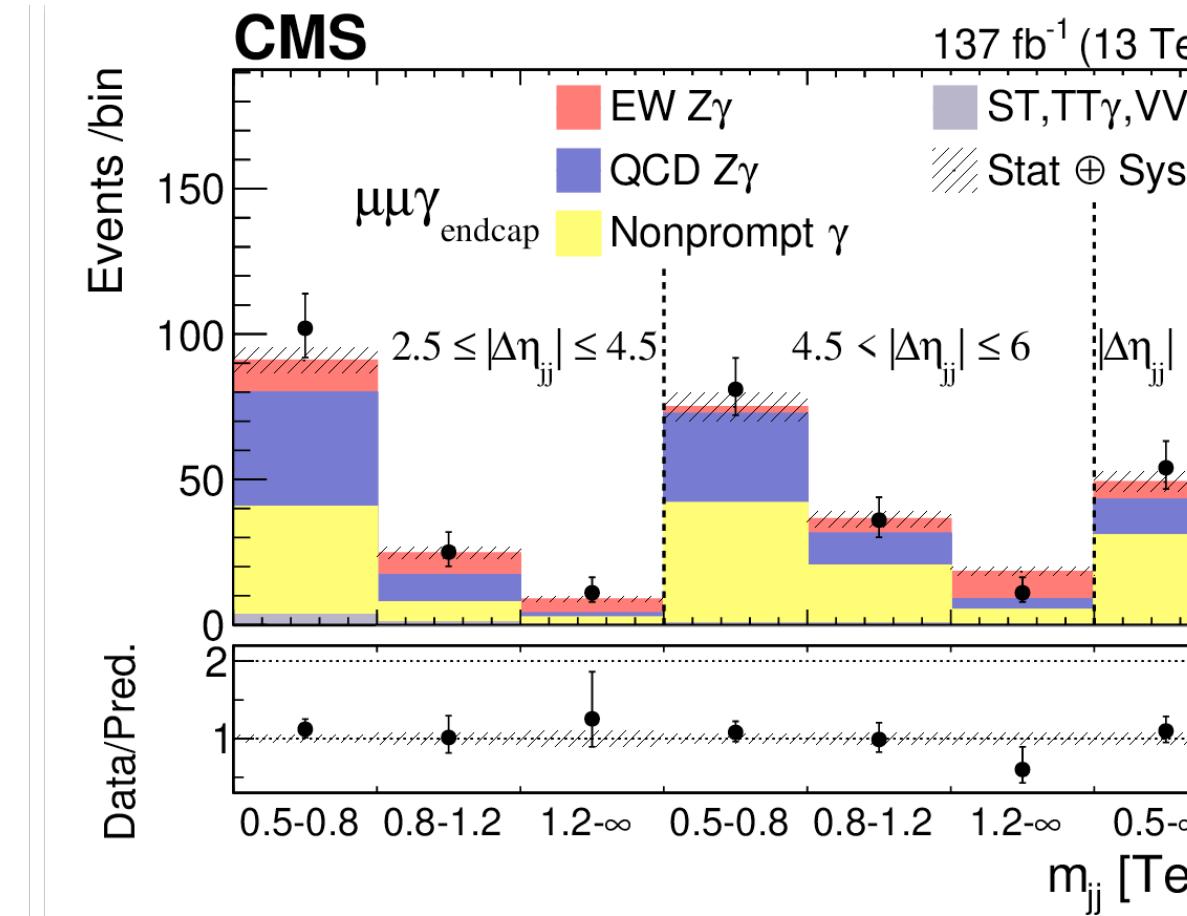
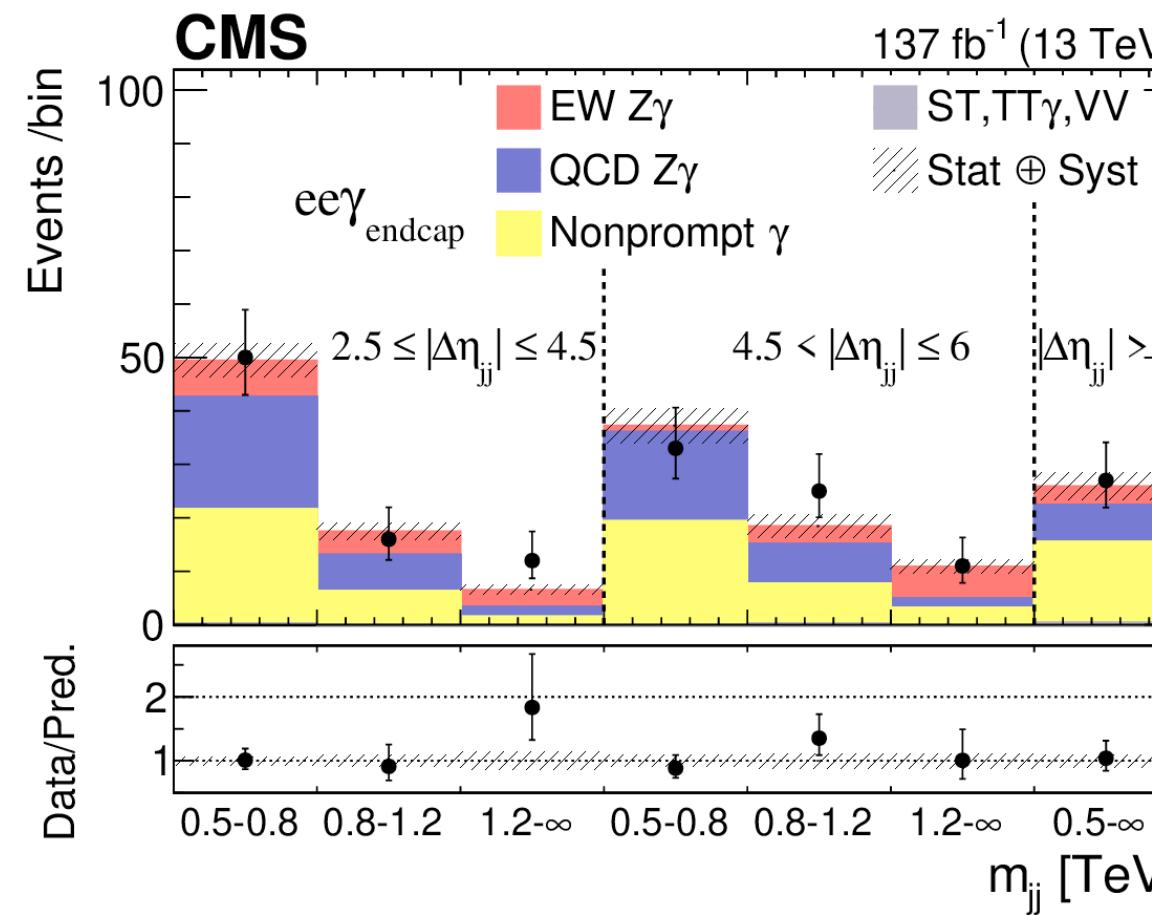


- Differential cross-section in various kinematic variables
 - full set available [[here](#)]
- aQGC dim-8 limits for $f_{M,0-7}/\Lambda^4$, $f_{T,0-2}/\Lambda^4$ and $f_{T,5-7}/\Lambda^4$
 - World best limits for $f_{M,2-5}/\Lambda^4$, $f_{T,5-7}/\Lambda^4$**

Expected. limit	Observed. limit	U_{bound}
$-5.1 < f_{M0}/\Lambda^4 < 5.1$	$-5.6 < f_{M0}/\Lambda^4 < 5.5$	1.7
$-7.1 < f_{M1}/\Lambda^4 < 7.4$	$-7.8 < f_{M1}/\Lambda^4 < 8.1$	2.1
$-1.8 < f_{M2}/\Lambda^4 < 1.8$	$-1.9 < f_{M2}/\Lambda^4 < 1.9$	2.0
$-2.5 < f_{M3}/\Lambda^4 < 2.5$	$-2.7 < f_{M3}/\Lambda^4 < 2.7$	2.7
$-3.3 < f_{M4}/\Lambda^4 < 3.3$	$-3.7 < f_{M4}/\Lambda^4 < 3.6$	2.3
$-3.4 < f_{M5}/\Lambda^4 < 3.6$	$-3.9 < f_{M5}/\Lambda^4 < 3.9$	2.7
$-13 < f_{M7}/\Lambda^4 < 13$	$-14 < f_{M7}/\Lambda^4 < 14$	2.2
$-0.43 < f_{T0}/\Lambda^4 < 0.51$	$-0.47 < f_{T0}/\Lambda^4 < 0.51$	1.9
$-0.27 < f_{T1}/\Lambda^4 < 0.31$	$-0.31 < f_{T1}/\Lambda^4 < 0.34$	2.5
$-0.72 < f_{T2}/\Lambda^4 < 0.92$	$-0.85 < f_{T2}/\Lambda^4 < 1.0$	2.3
$-0.29 < f_{T5}/\Lambda^4 < 0.31$	$-0.31 < f_{T5}/\Lambda^4 < 0.33$	2.6
$-0.23 < f_{T6}/\Lambda^4 < 0.25$	$-0.25 < f_{T6}/\Lambda^4 < 0.27$	2.9
$-0.60 < f_{T7}/\Lambda^4 < 0.68$	$-0.67 < f_{T7}/\Lambda^4 < 0.73$	3.1

OBSERVATION $Z\gamma$ VBS

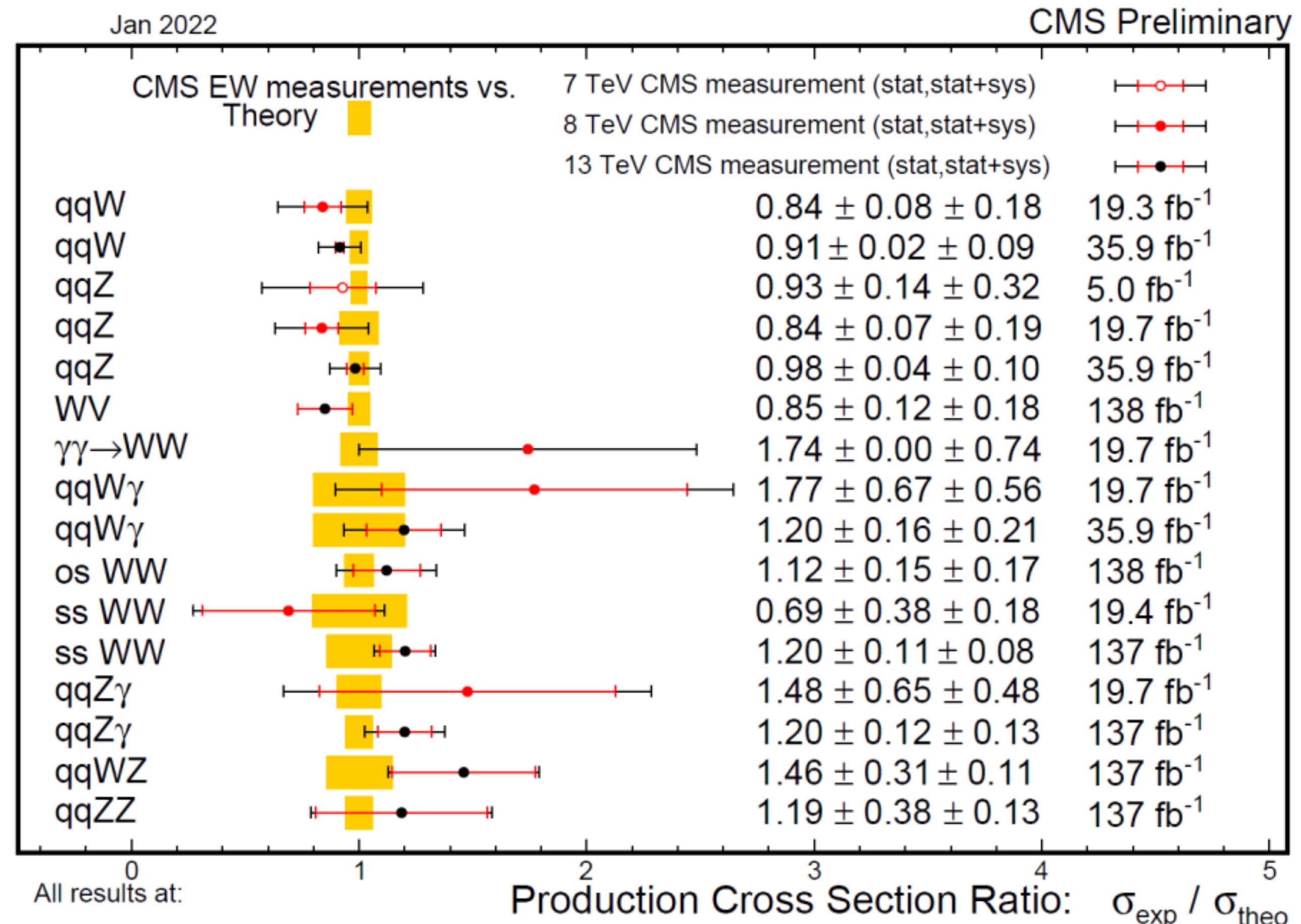
- Leptonic heavy-boson decays combined with isolated photons
- Final state: $\ell\ell\gamma + 2\text{jets}$
- Data-driven estimation non-prompt background
- **Signal extraction:**
 - 2D fit in $(m_{jj} - m_{\ell\ell})$ distributions
 - **First Observation 9.4 sigma (8.5 exp) and strongest constraints on dim-8 EFT operators (T8,T9)**
- Inclusive and differential fiducial cross section measurements of $Z\gamma$ VBS (EW and EW+QCD contributions)



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

CROSS-SECTIONS SUMMARY

- **Good agreement with SM so far** 
- **A $\sigma_{\text{exp}} \geq \sigma_{\text{theo}}$ trend (not yet significant) seen in the VBS measurements**
 - Underlines the importance of modelling all diboson+2 jet QCD contributions with the best possible accuracy
 - A very challenging task but theory literature on the subject has increased in recent years



VBS MEASUREMENTS AT CMS

- **VBS are challenging processes to study**
 - Low yields and in most cases large irreducible backgrounds advanced ML techniques are a must
 - A growing need for modelling QCD diboson processes (*with extra 2 jets*) with best possible accuracy
- **VBS measurements at LHC**
 - **Among the rarest SM processes ever measured**
 - **Evidence/Observation** and first cross-section measurements made possible with the full LHC 13-TeV data
 - **Access to the elusive quartic gauge couplings**
- **Full set of Run 2 results + LHC Run3 data essential to clarify global picture**