

Multiboson measurements in CMS



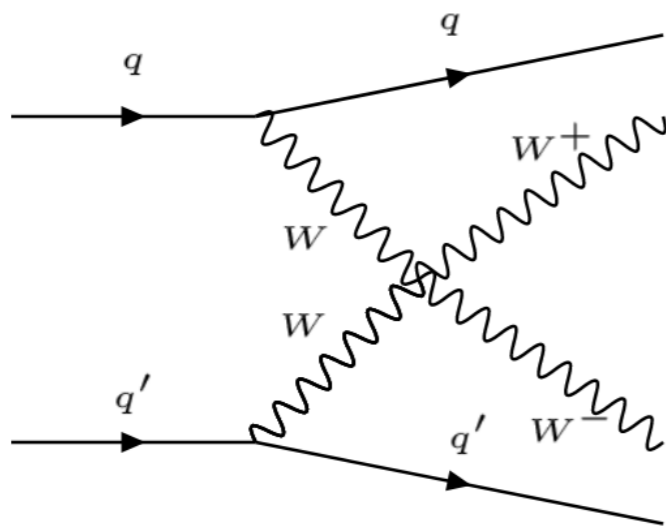
Saptaparna Bhattacharya

Pheno 2022

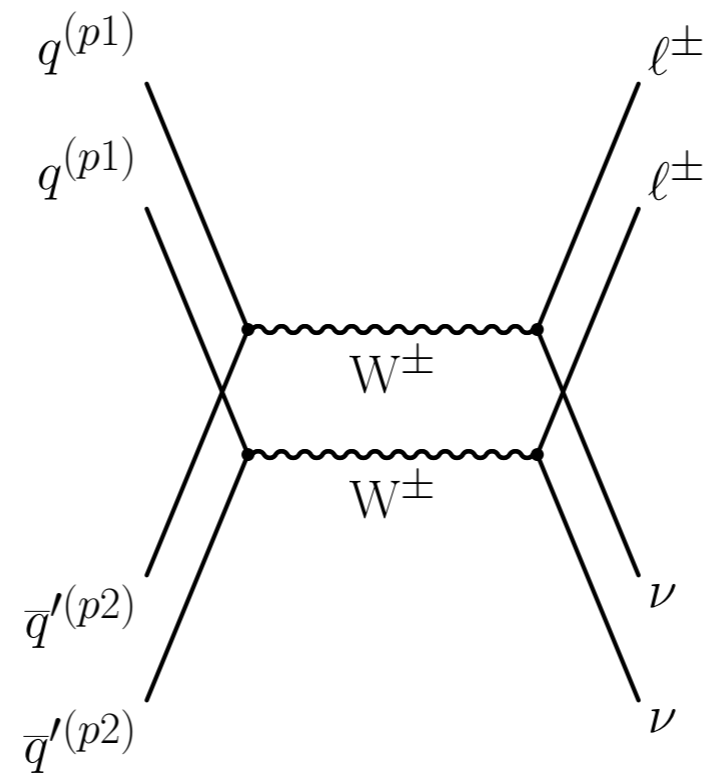
University of Pittsburgh

May 9th-11th, 2022

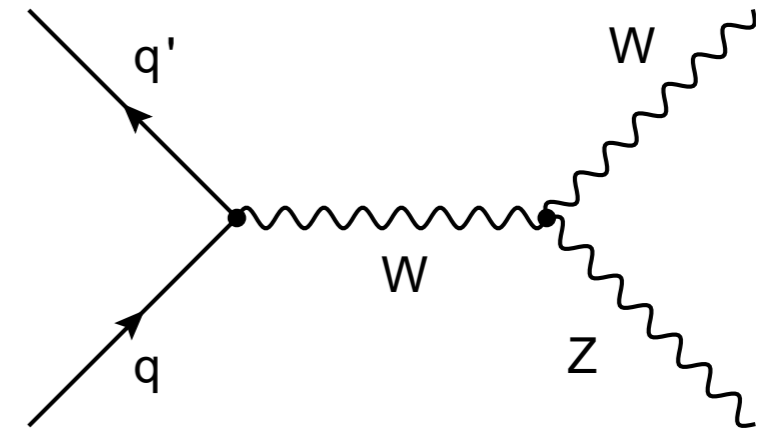
Multiboson measurements provide access to various processes



First observation of oppositely charge W-boson pairs with 2 jets

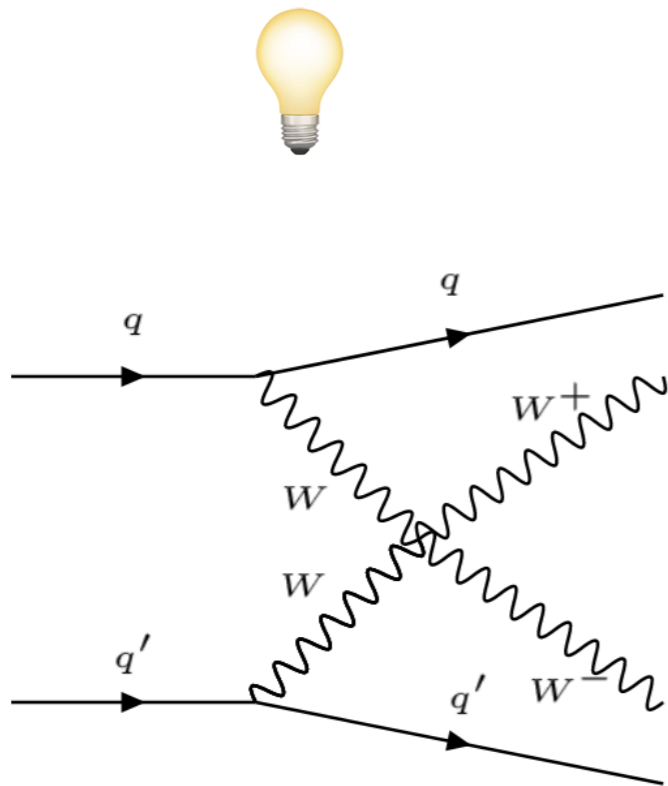


First observation of double parton scattering

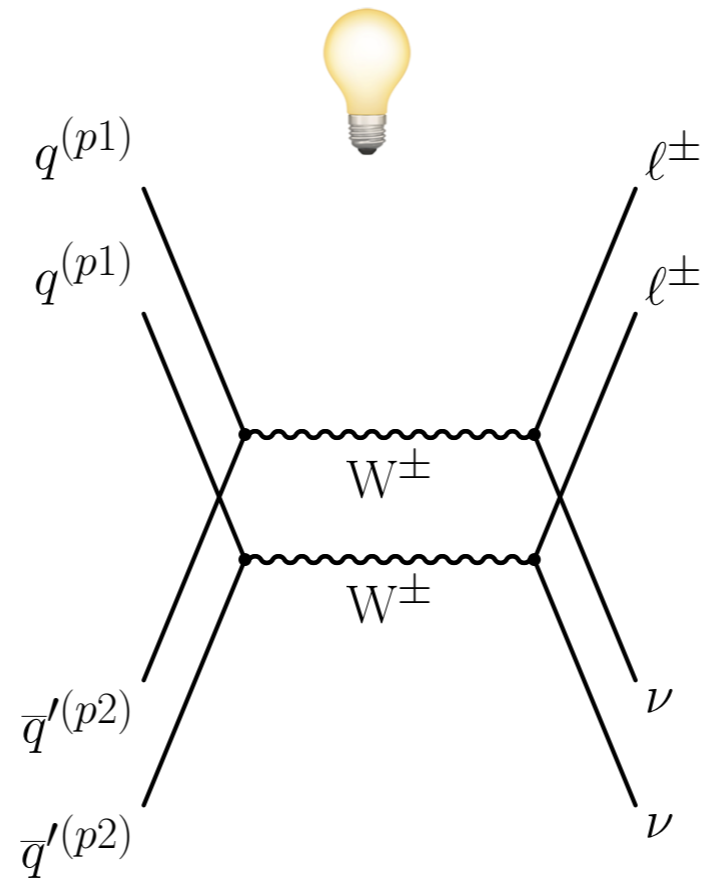


Precision measurements of WZ, **first observation** of longitudinally polarized W

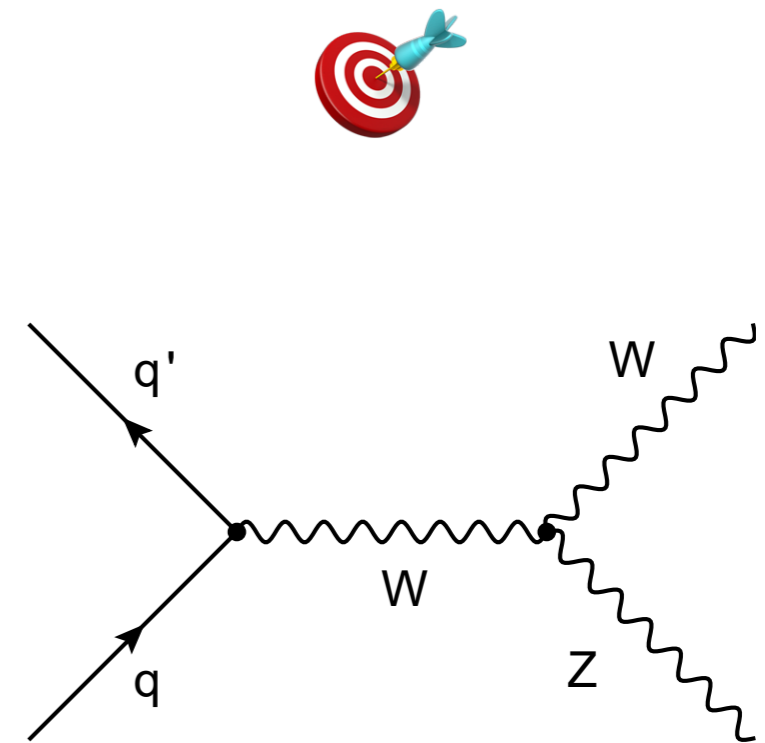
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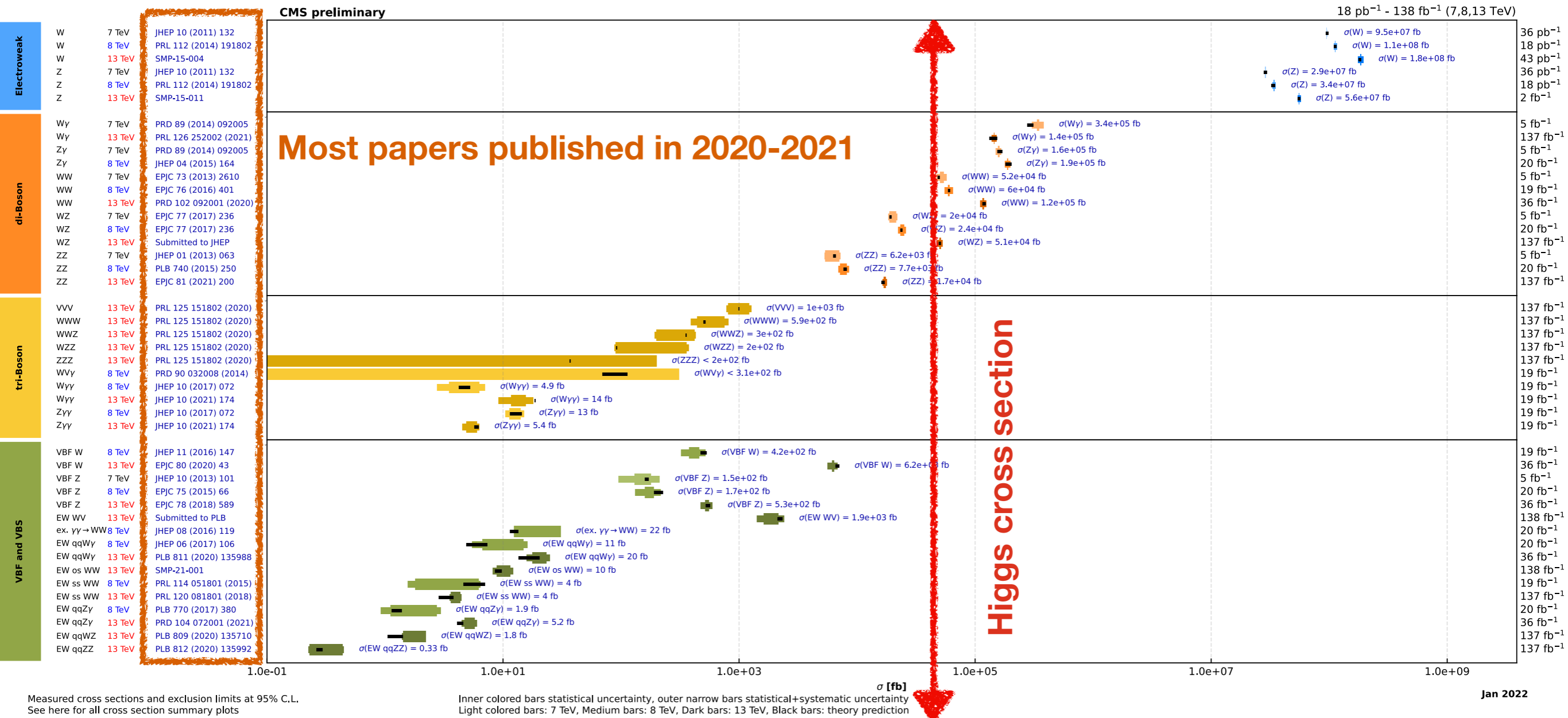
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Precision measurements of WZ, first observation of longitudinally polarized W

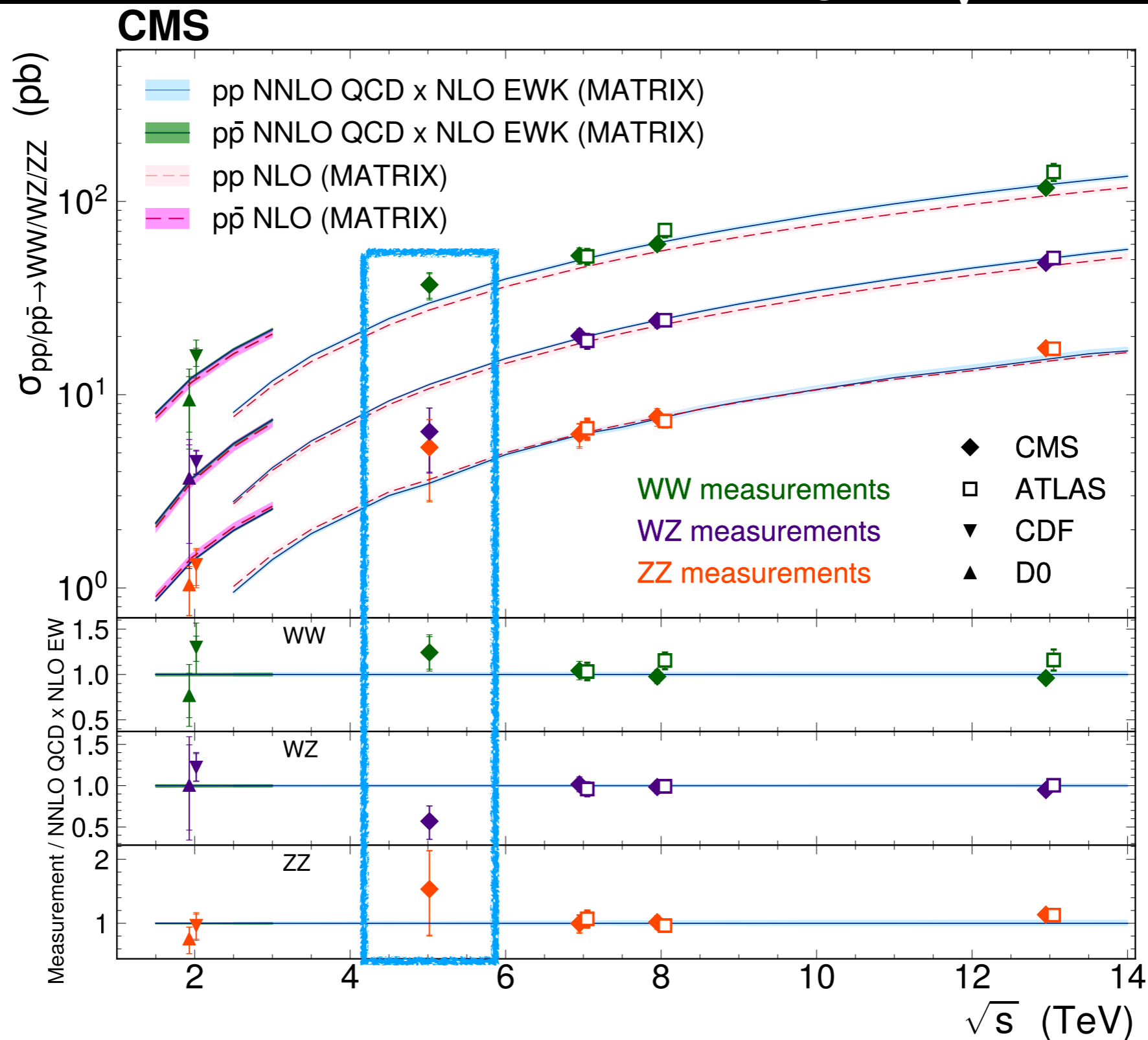
Multiboson cross section measurements

Overview of CMS cross section results



Span several orders of magnitude!

Diboson cross section measurements at several center of mass energies (\sqrt{s})



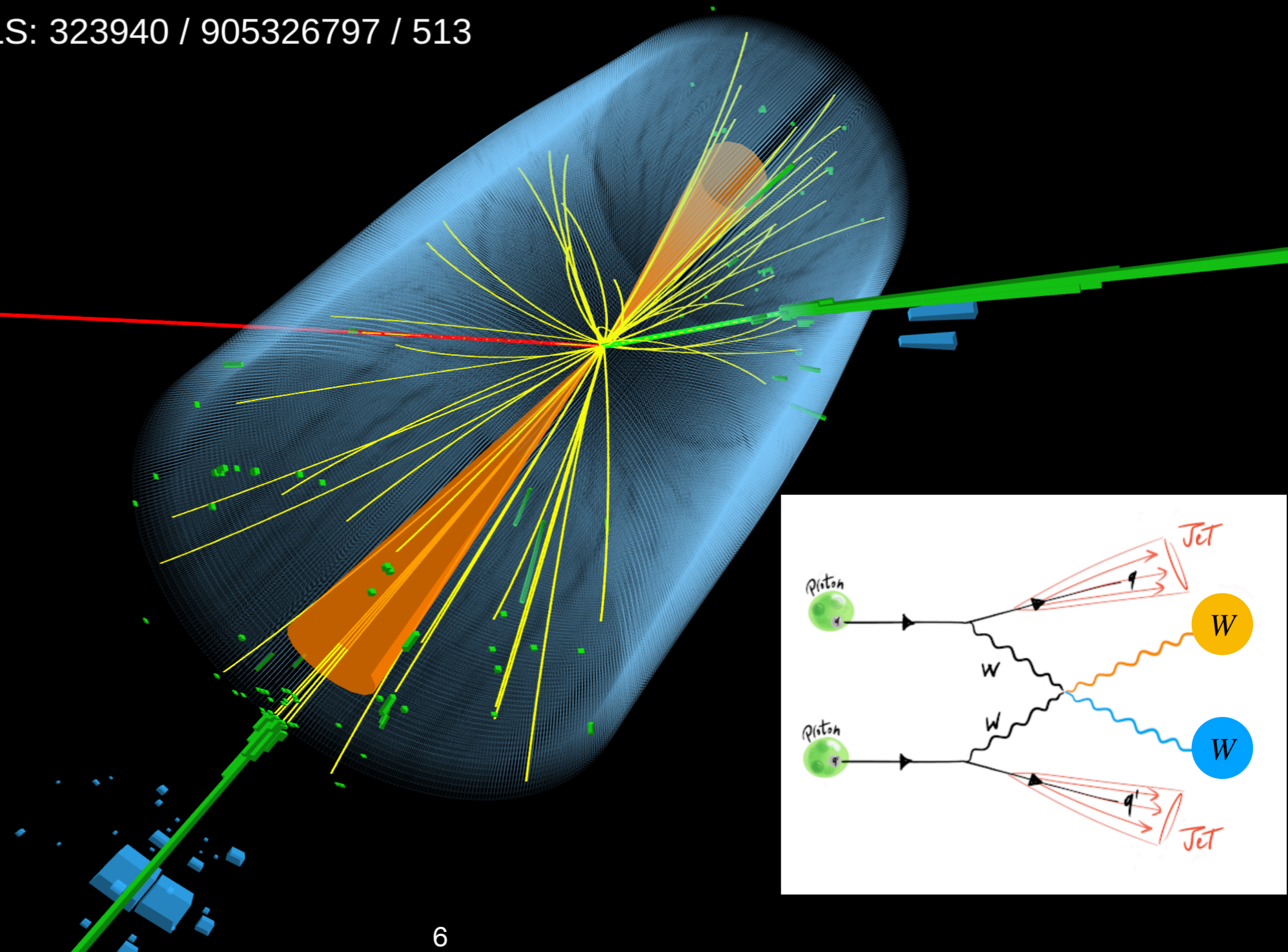
Vector Boson Scattering

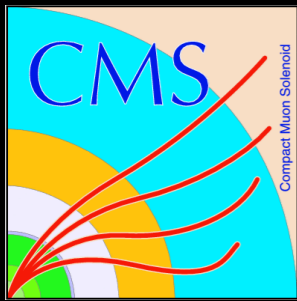


CMS Experiment at the LHC, CERN

Data recorded: 2018-Oct-03 04:13:04.188416 GMT

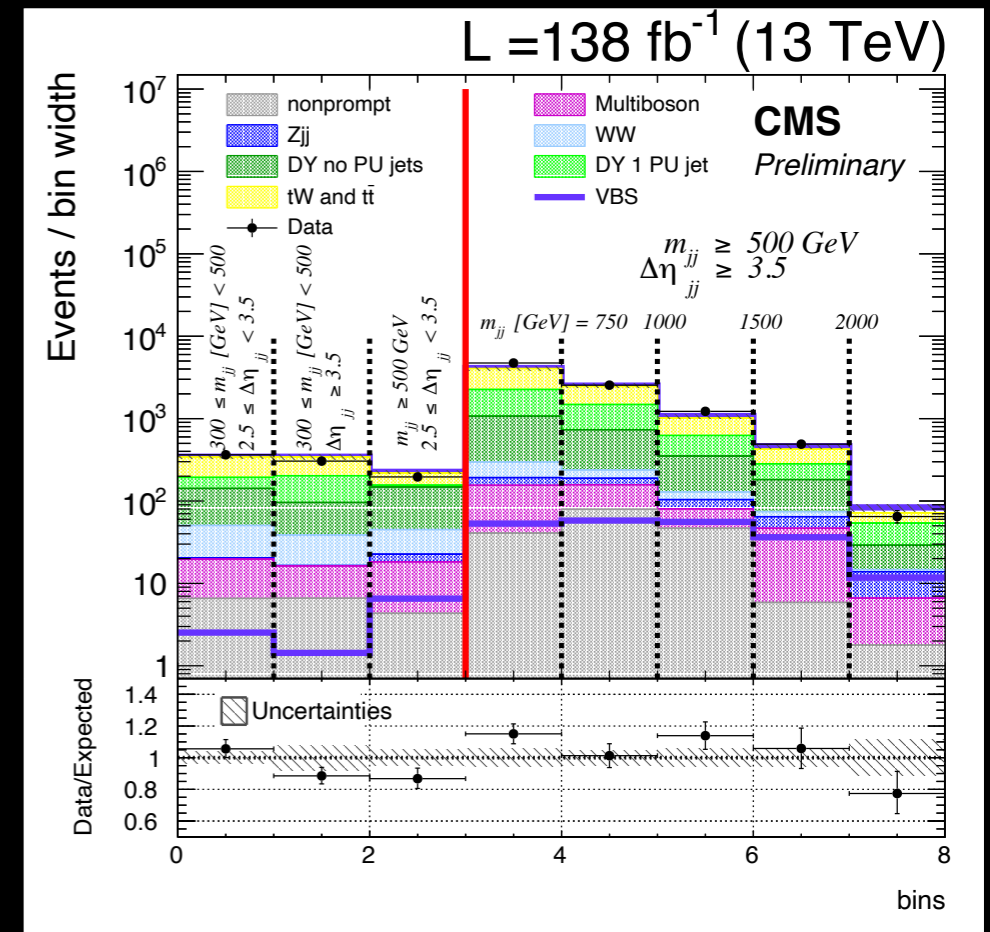
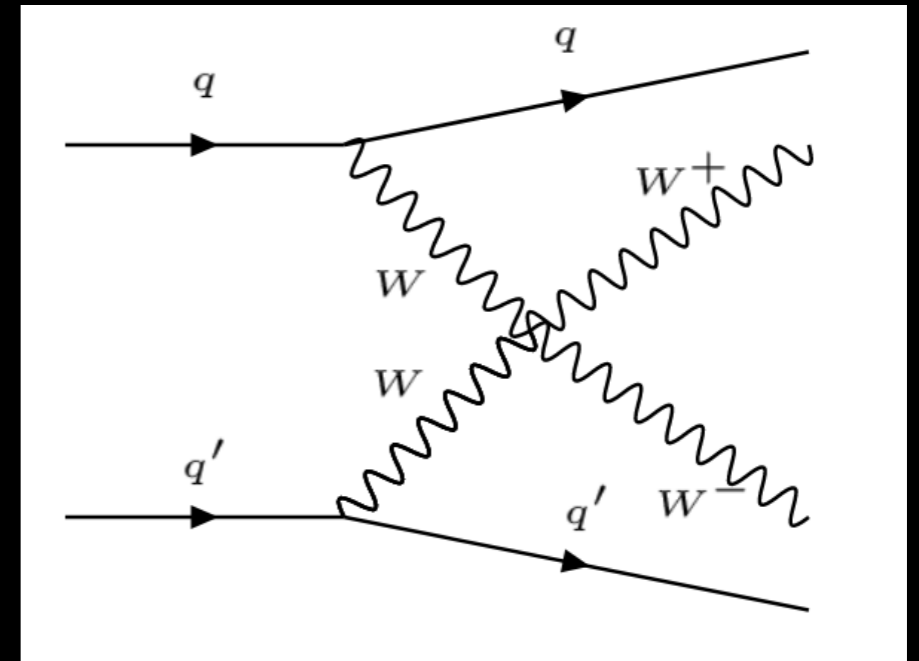
Run / Event / LS: 323940 / 905326797 / 513

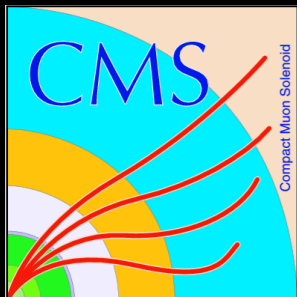




First observation of the electroweak production of a leptonically decaying W^+W^- pair in association with two jets

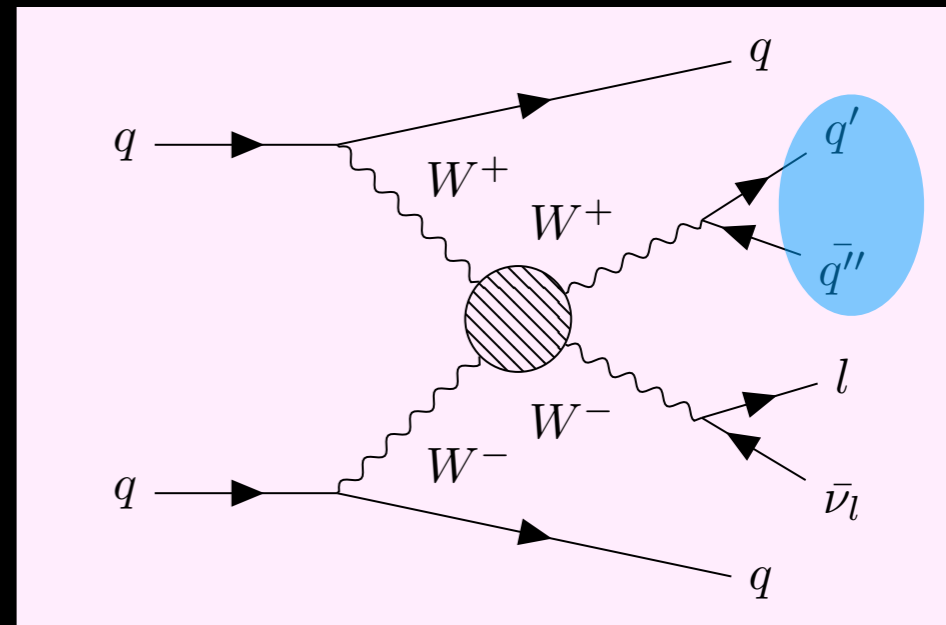
- First observation of $W^+W^- + 2$ jets with 5.6σ (5.2σ observed (expected) significance)
- Vector boson scattering characterized by the presence of two high p_T jets
 - $M_{jj} > 300$ GeV, $\Delta\eta_{jj} > |2.5|$ (rapidity gap)
- Require oppositely charged pair of leptons
- Major backgrounds: Drell-Yan, $t\bar{t}$
- Optimize signal significance: categorization based on the centrality of the dilepton system w.r.t. to the tagging jets
- Deep neural network (DNN) trained with (indicative):
 - M_{jj} and $\Delta\eta_{jj}$
 - $Z_{\ell_{1,2}} = n_{\ell_{1,2}} - \frac{1}{2} (n_{j_1} + n_{j_2})$
- Inclusive cross section: 99 ± 20 fb
- Largest uncertainty associated with QCD-induced W^+W^- normalization



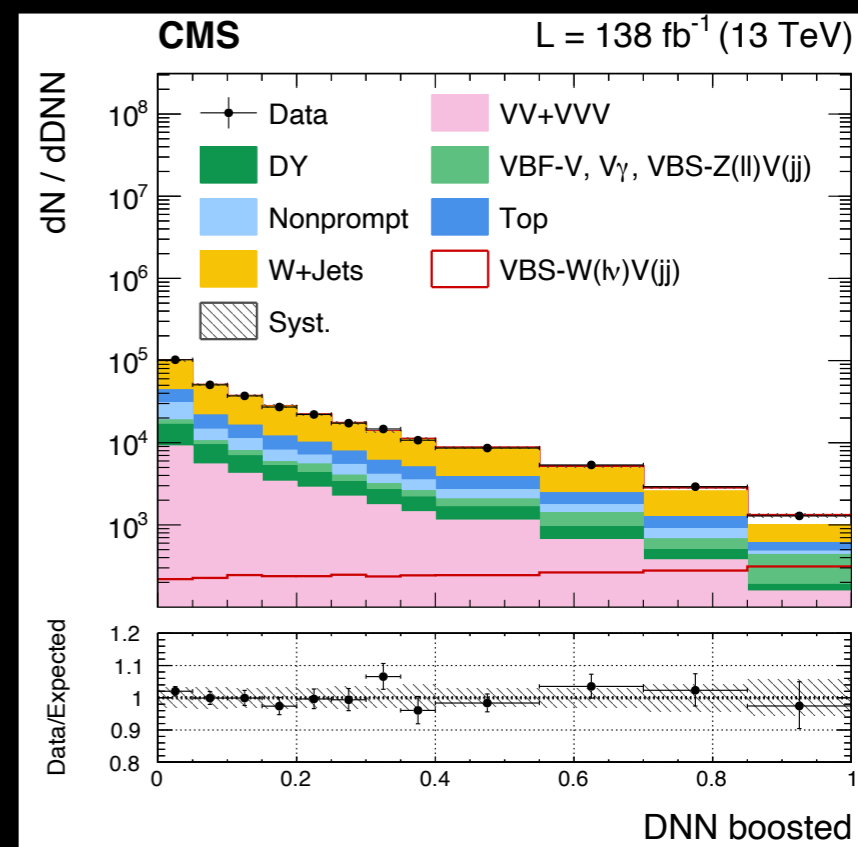
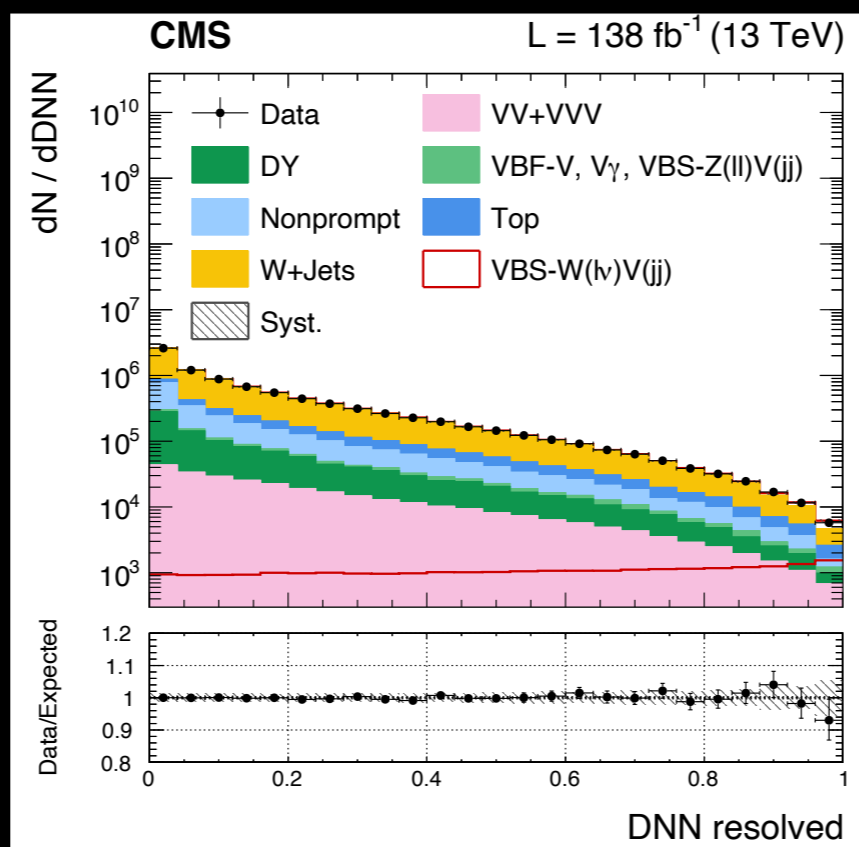


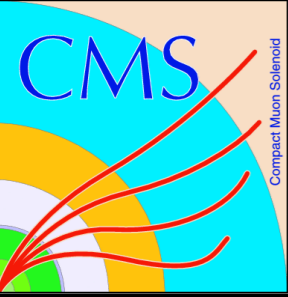
Search for vector boson scattering at the LHC Run 2 with CMS data in the semi-leptonic $\ell\nu qq$ final state

- First evidence of electroweak WW/WZ vector boson scattering ($\ell\nu qq$) with 4.4σ (5.1σ) **observed** (expected) significance
- DNN trained with (indicative):
 - Lepton η, p_T, M_{jj}



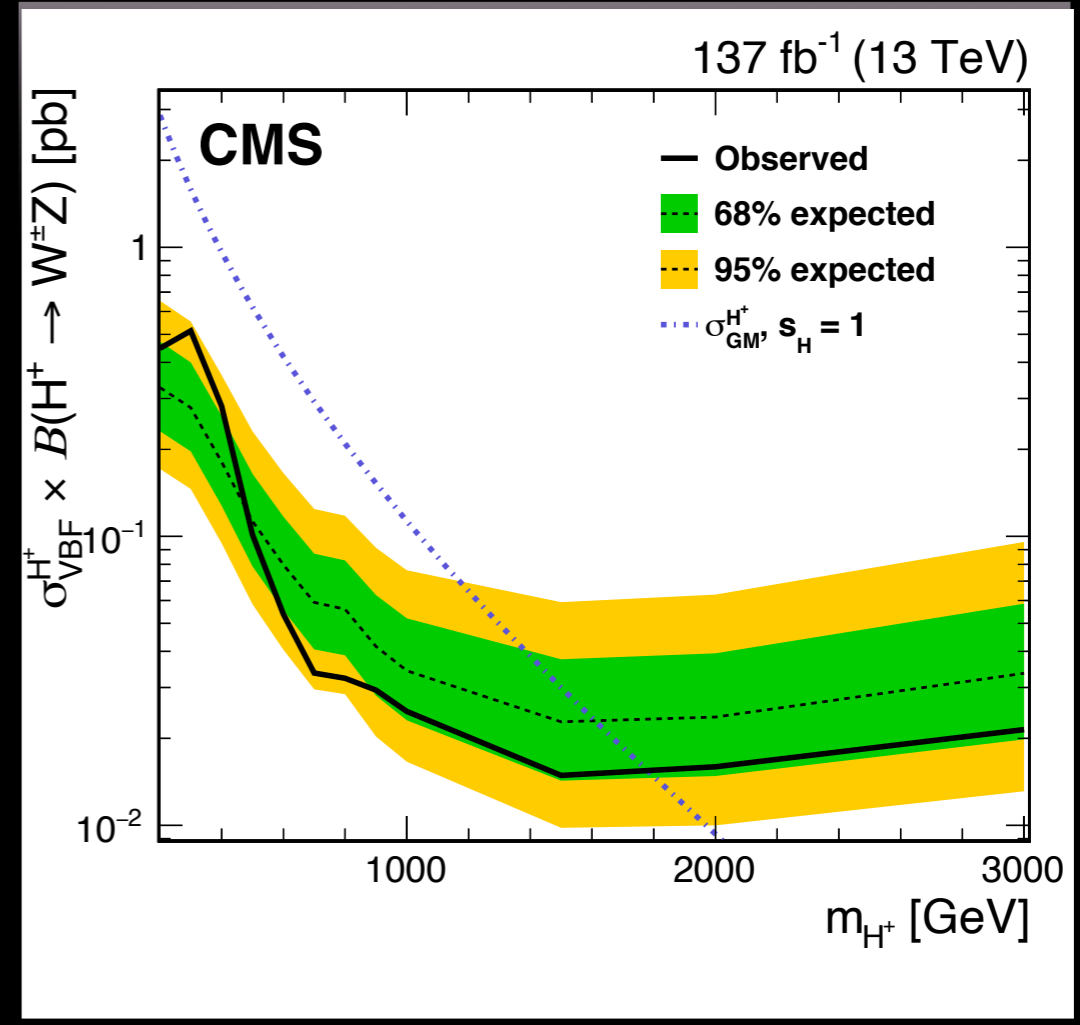
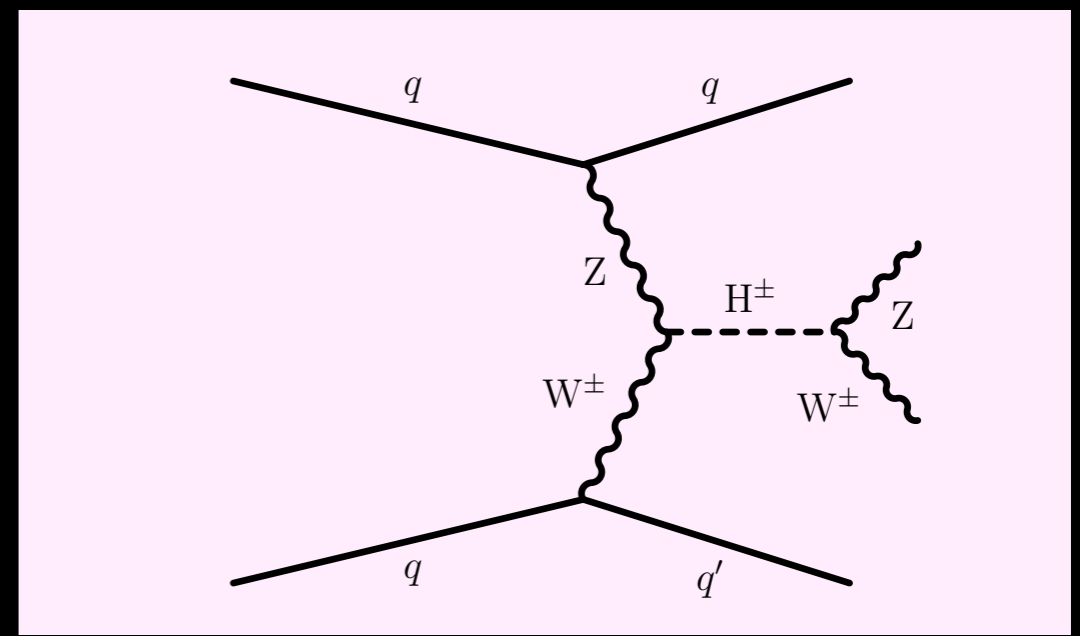
- Two different event categories:
 - based on reconstruction regime of hadronically decaying W
- Uncertainties arise from choice of renormalization and factorization scales

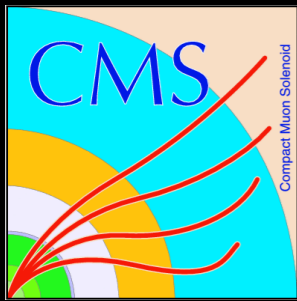




Looking for new physics with multi bosons

- Extended Higgs sectors → couplings of gauge bosons to (singly or doubly) charged Higgs bosons
- First search for charged Higgs bosons using vector boson fusion
 - $WWjj$ and $WZjj$ studied
- Variables of interest:
 - M_{jj} and m_T^{VV} ($m_T^{VV} = \sqrt{\left(\sum_i E_i\right)^2 - \left(\sum_i p_{z,i}\right)^2}$)
- Constraints on resonant charged Higgs boson derived
- Model independent limits for $\sigma \times \text{BF}$ set for charged Higgs mass [200, 3000] GeV





Double Parton Scattering

- First observation of double parton scattering with 6.2σ (6.7σ) **observed** (expected) significance

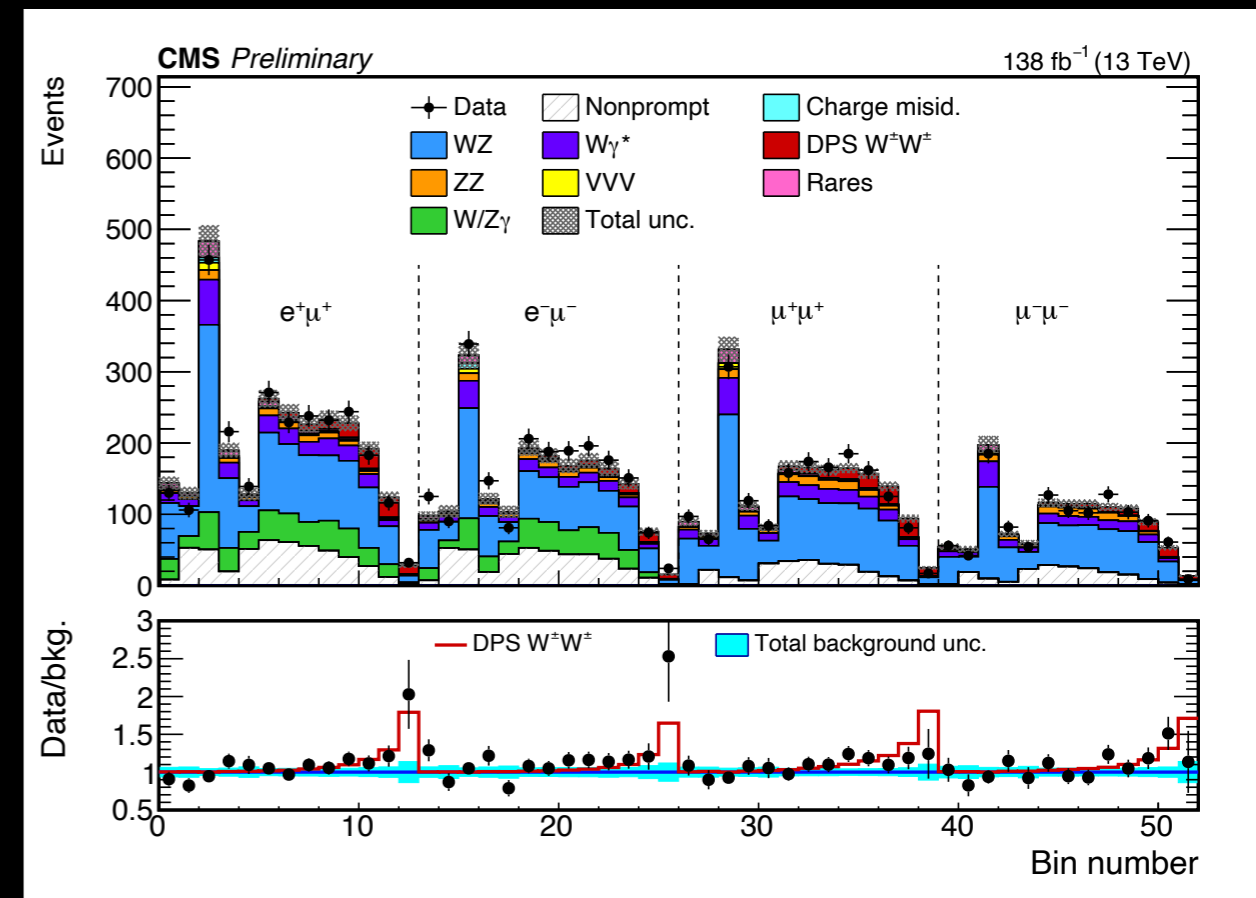
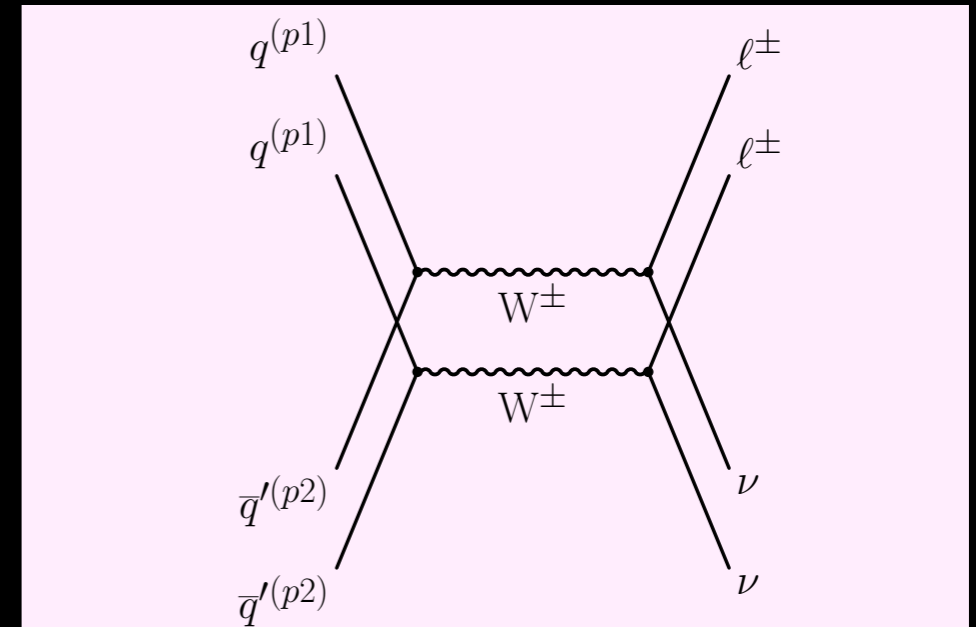
- Inclusive cross section:
$$\sigma_{AB}^{\text{DPS}} = \frac{n \sigma_A \sigma_B}{2 \sigma_{\text{eff}}}$$

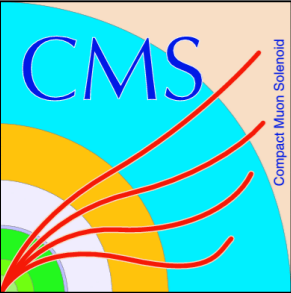
 0.16 ± 0.02 (stat.) ± 0.02 (syst.) ± 0.02 (model) pb

- Boosted decision tree (BDT) classifier trained against WZ and non prompt backgrounds

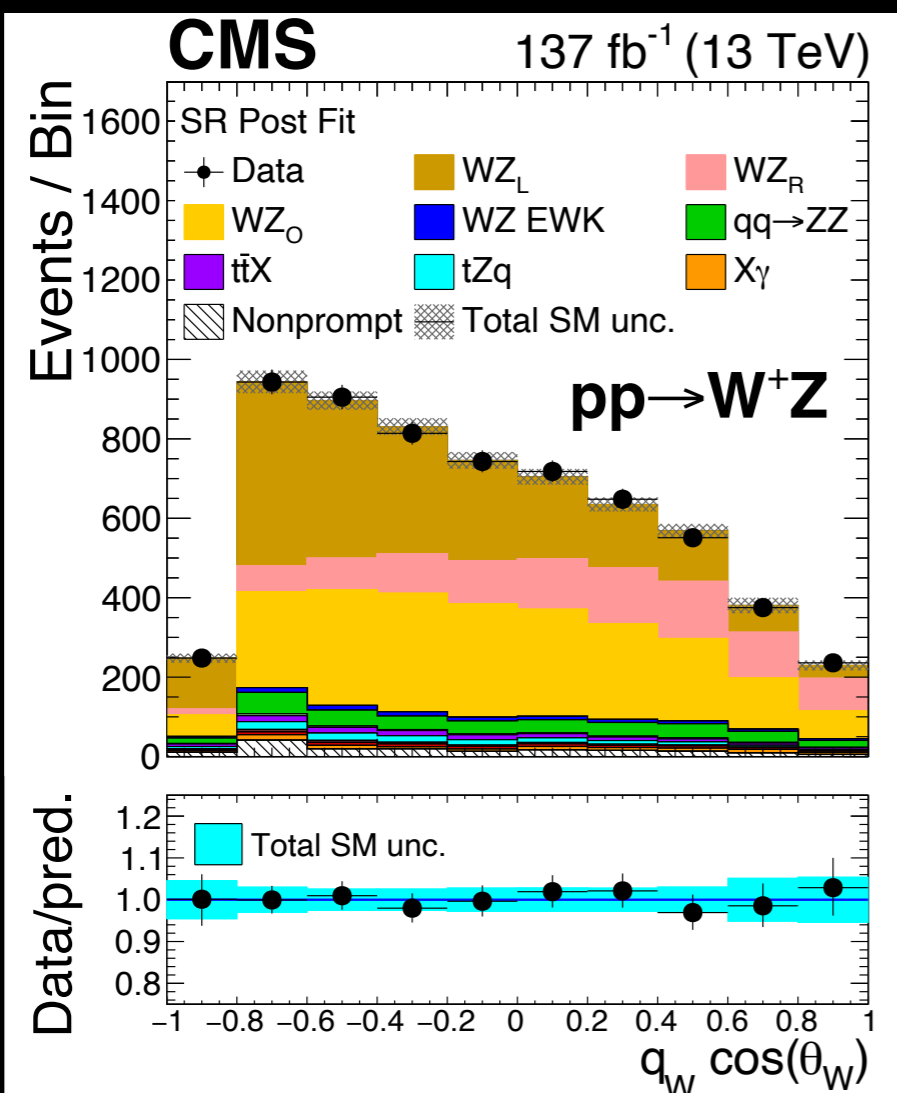
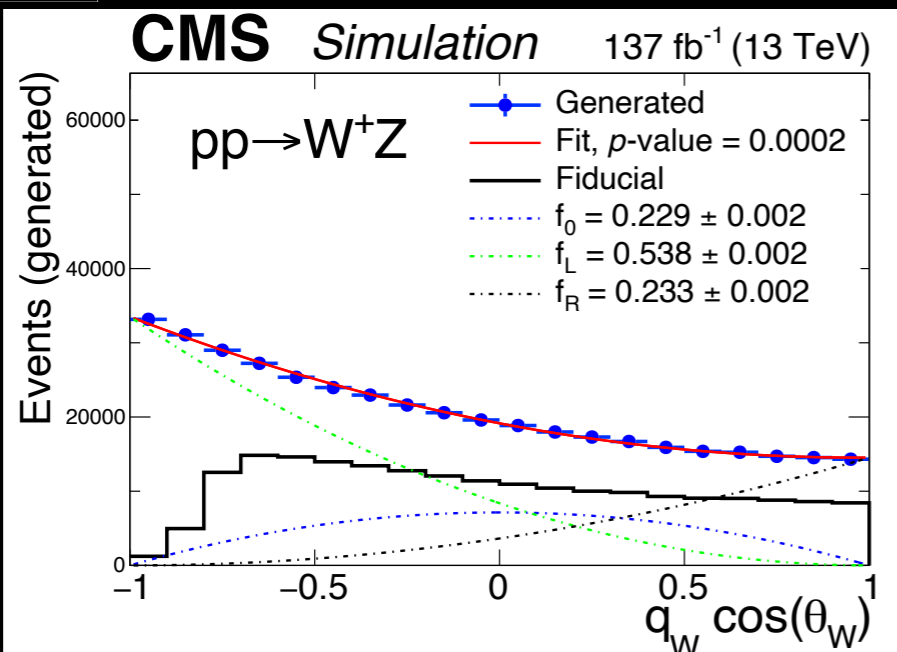
- Use p_T of the two leptons, p_T^{miss} , $|\eta^{\ell_1}| + |\eta^{\ell_2}|$, $\eta^{\ell_1} \times \eta^{\ell_2}$, azimuthal correlation between the leptons and p_T^{miss} as input variables

- BDT score mapped to 2D plane in both classifiers \rightarrow combined to map into 52 independent one dimensional bins





Measurement of the WZ process



- Electroweak process: sensitive to the PDFs of u and d quarks; relatively unaffected by the gluon
- High WZ cross section makes it the dominant process that can be studied in the trilepton final state
- Ratio of $\frac{W^+Z}{W^-Z}$ cross section is one of the most precisely measurable quantities
- Constitutes first measurement of longitudinally polarized W-bosons
- θ_W : angular distance between the momenta of the W boson and the charged lepton from its primary decay

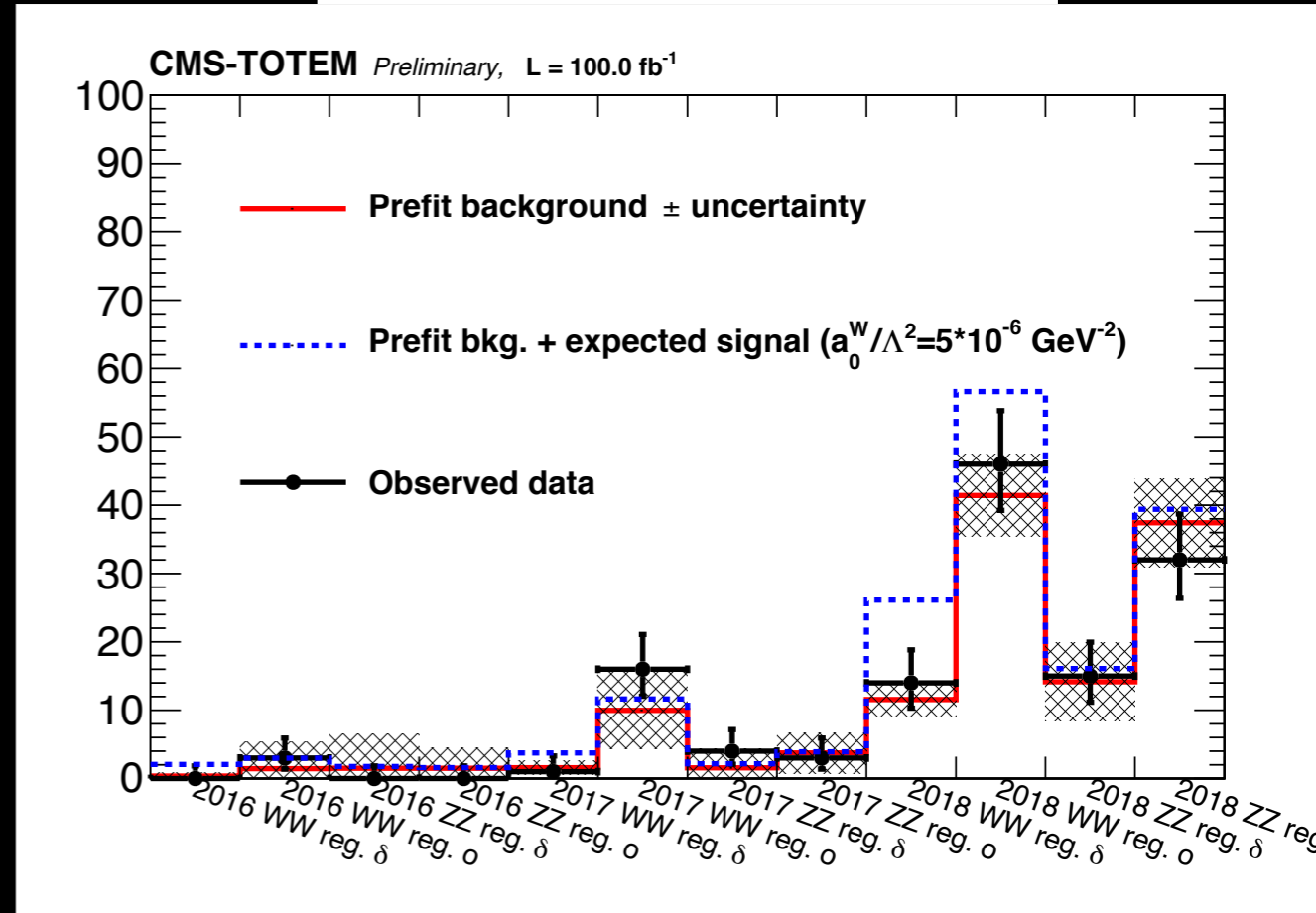
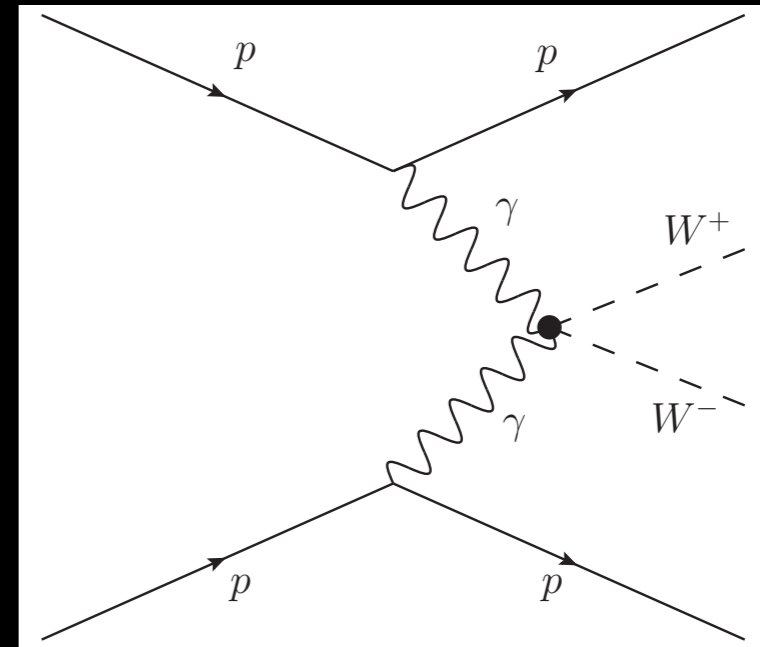
<https://arxiv.org/abs/2110.11231>

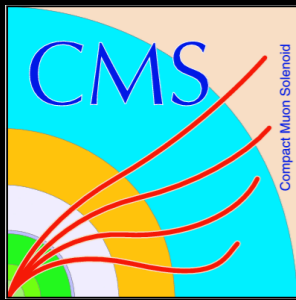


Search for exclusive $\gamma\gamma \rightarrow WW$ and $\gamma\gamma \rightarrow ZZ$ production in final states with jets and forward protons



- Both protons tagged by the precision proton spectrometer (PPS)
- The $\gamma\gamma \rightarrow WW$ process allows the study of the quartic coupling
- Events selected based on properties of jets, the protons and their correlation
- First search for anomalous high-mass $\gamma\gamma \rightarrow WW$ and $\gamma\gamma \rightarrow ZZ$ using reconstructed forward protons
 - Limits 15-20x more stringent than previous results

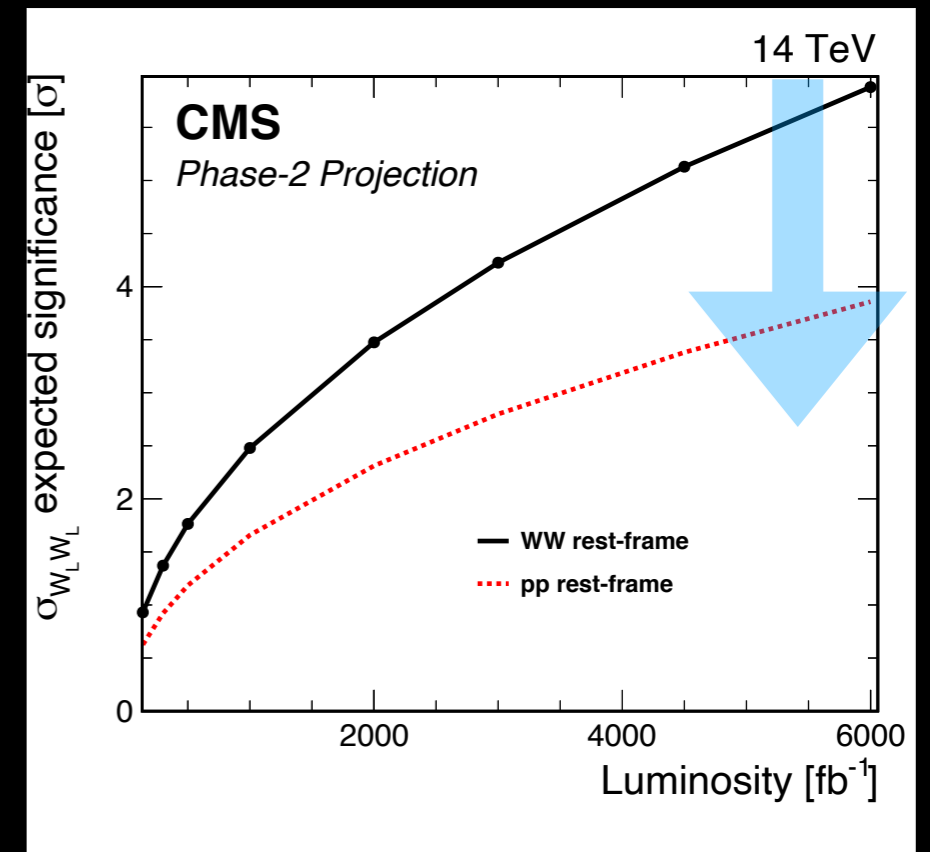
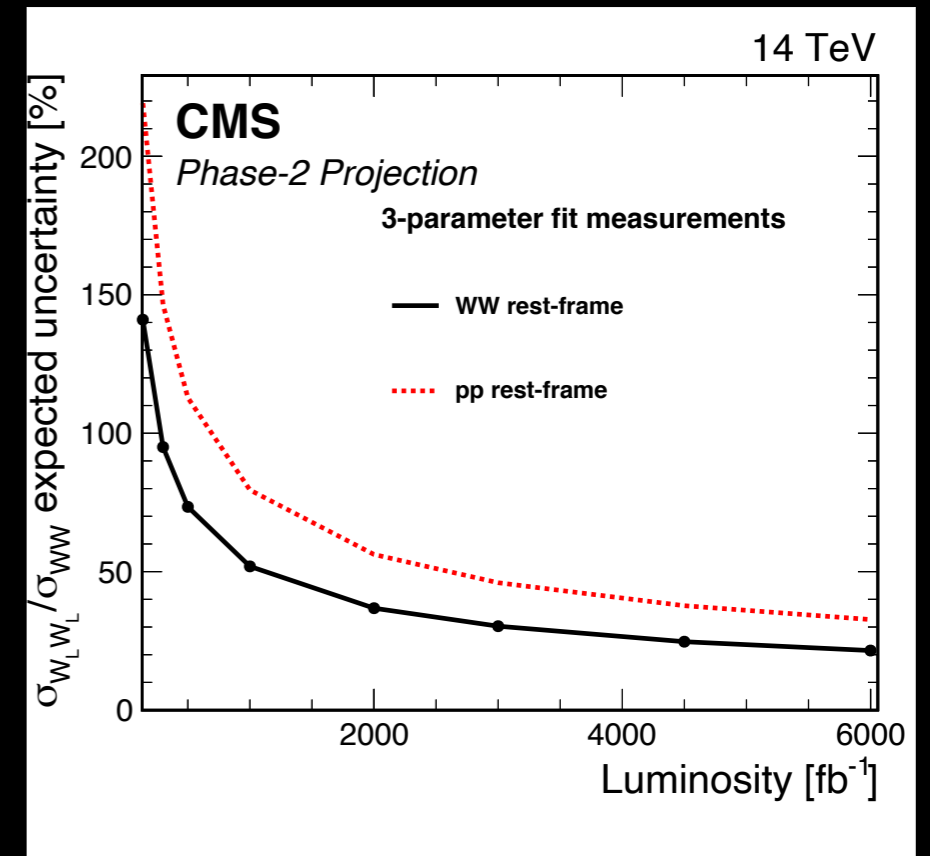
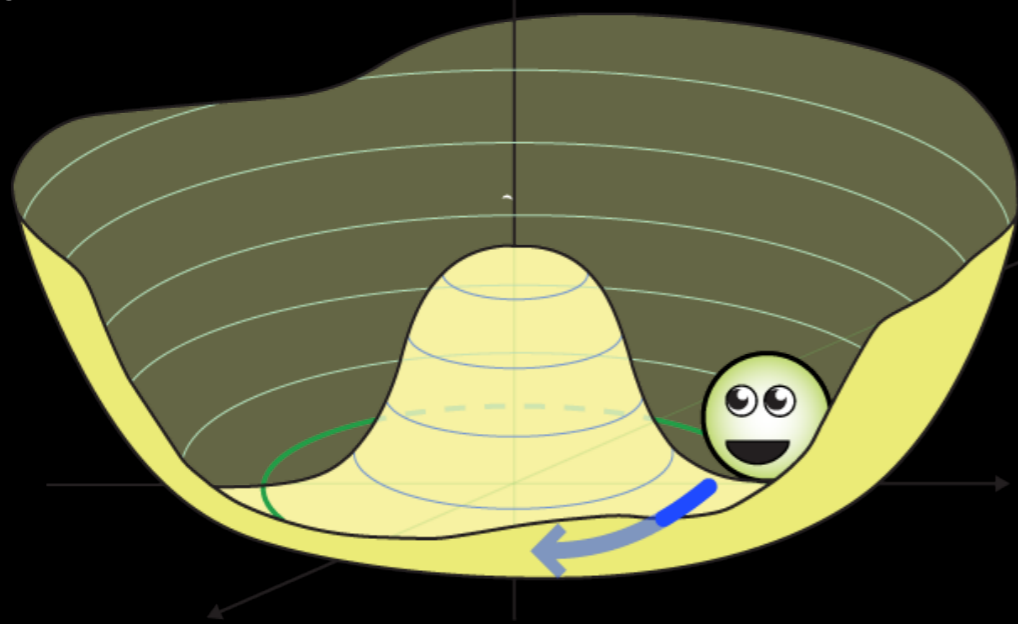






Future multiboson measurements



- Higgs boson will turn 10 years old in July 2022!
- 10 years of the LHC = 8 million Higgs bosons!
- Understanding electroweak symmetry breaking → crucial part of LHC physics program
- Longitudinally polarized scattering of W and Z complementary to direct measurements of the Higgs coupling to gauge bosons
- Analysis projected from Run II to 3000 fb⁻¹



Outlook

- Presented several multiboson analyses with full Run II dataset
- Many rare processes predicted by the Standard Model becoming accessible at the LHC
- Ubiquitous use of advanced deep learning techniques 
- These novel topologies used to look for new physics
- Precision studies of diboson processes possible 

The future is bright and precise!

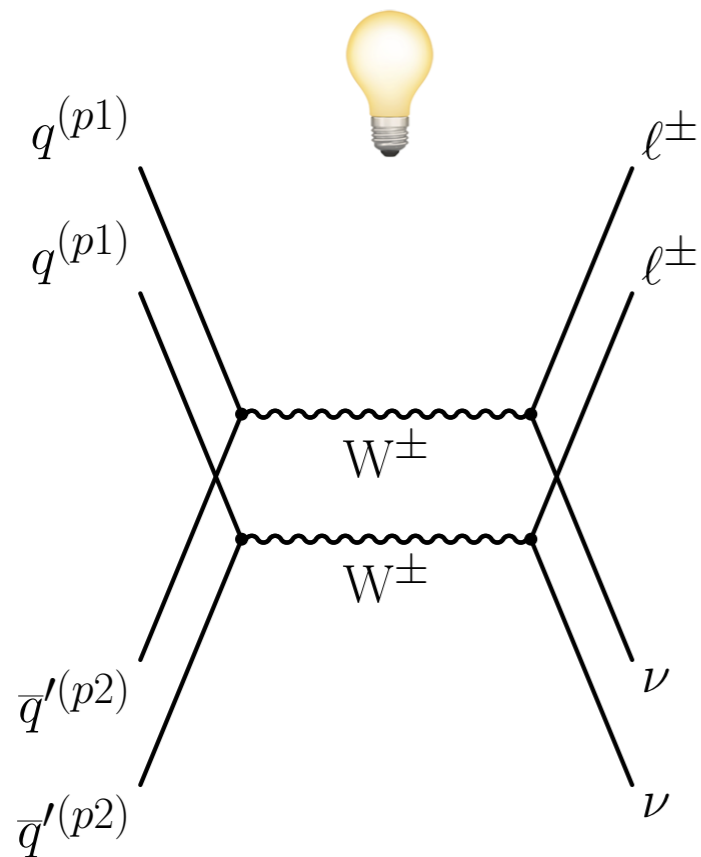
Additional Material



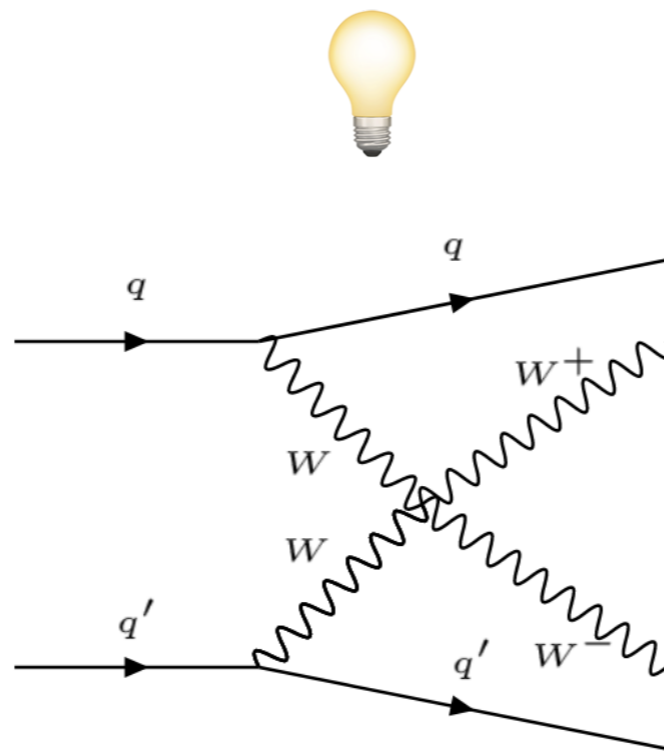
Outline of the talk

- CMS-PAS-SMP-21-014: Search for exclusive $\gamma\gamma \rightarrow WW$ and $\gamma\gamma \rightarrow ZZ$ production in final states with jets and forward protons
- CMS-PAS-SMP-21-013: Observation of WW from double parton scattering in proton-proton collisions at $\sqrt{S} = 13$ TeV
- CMS-PAS-SMP-21-001: First observation of the electroweak production of a leptonically decaying W^+W^- pair in association with two jets in $\sqrt{S} = 13$ TeV pp collisions
- CMS-PAS-SMP-20-013: Search for vector boson scattering at the LHC Run 2 with CMS data in the semi-leptonic $\ell\nu qq$ final state
- CMS-PAS-SMP-19-012: Measurements of production cross sections of same-sign WW and WZ boson pairs in association with two jets in proton-proton collisions at $\sqrt{S} = 13$ TeV (HIG-20-017 and EXO-21-003)

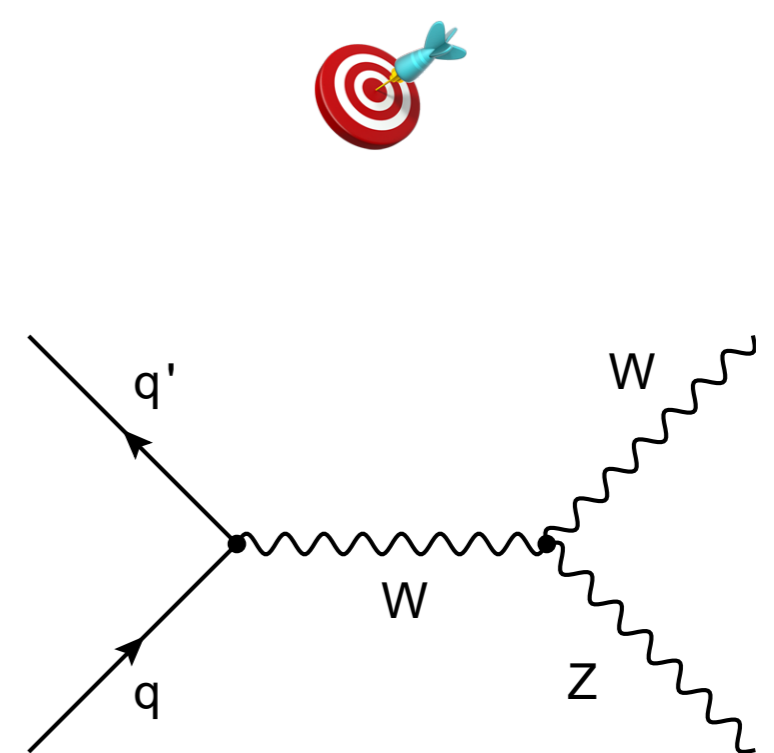
Multiboson measurements provide access to various processes



First observation of double parton scattering

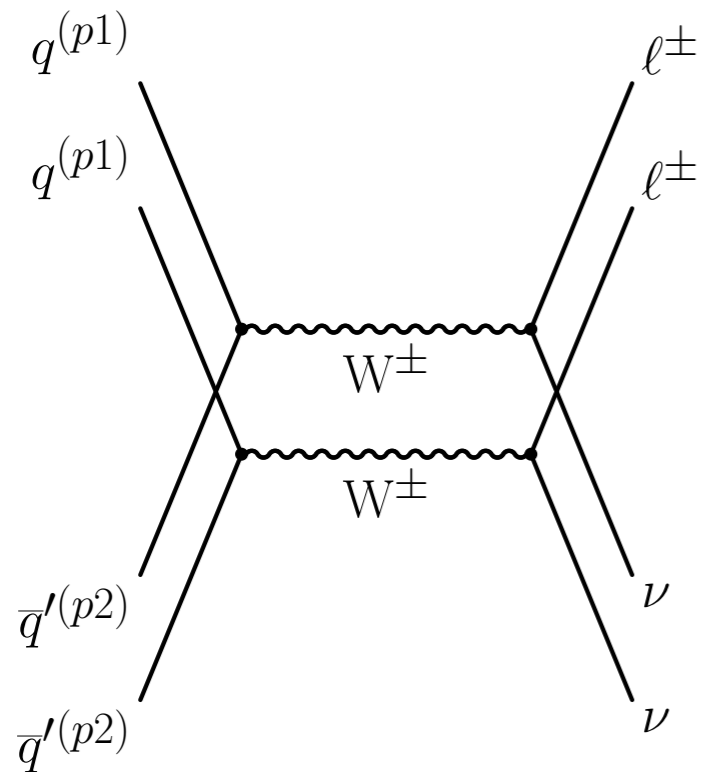


First observation of oppositely charge W -boson pairs with 2 jets

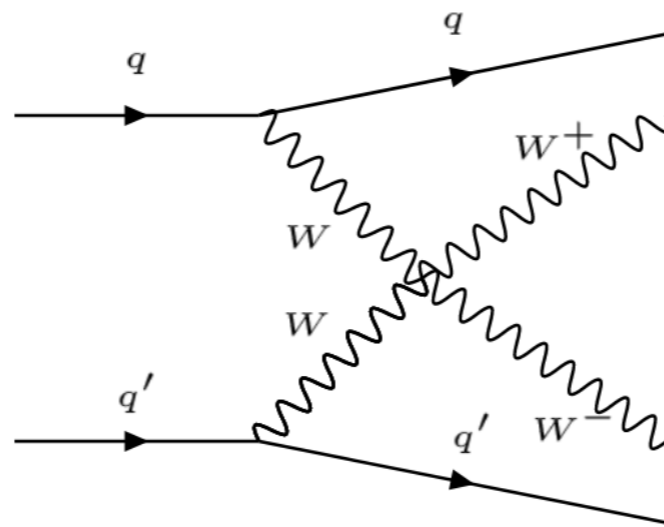


Precision measurements of WZ , first observation of longitudinally polarized W

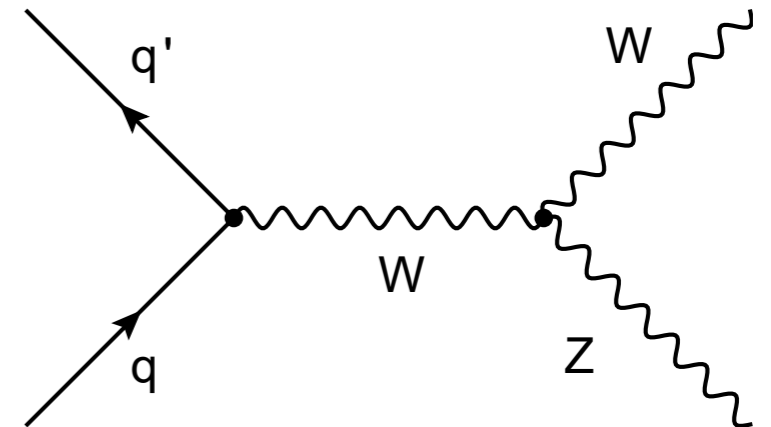
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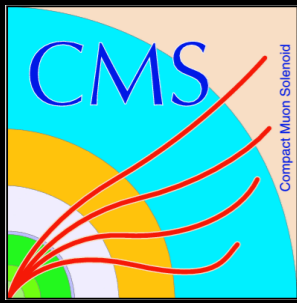
First observation of double parton scattering



First observation of oppositely charge W -boson pairs with 2 jets

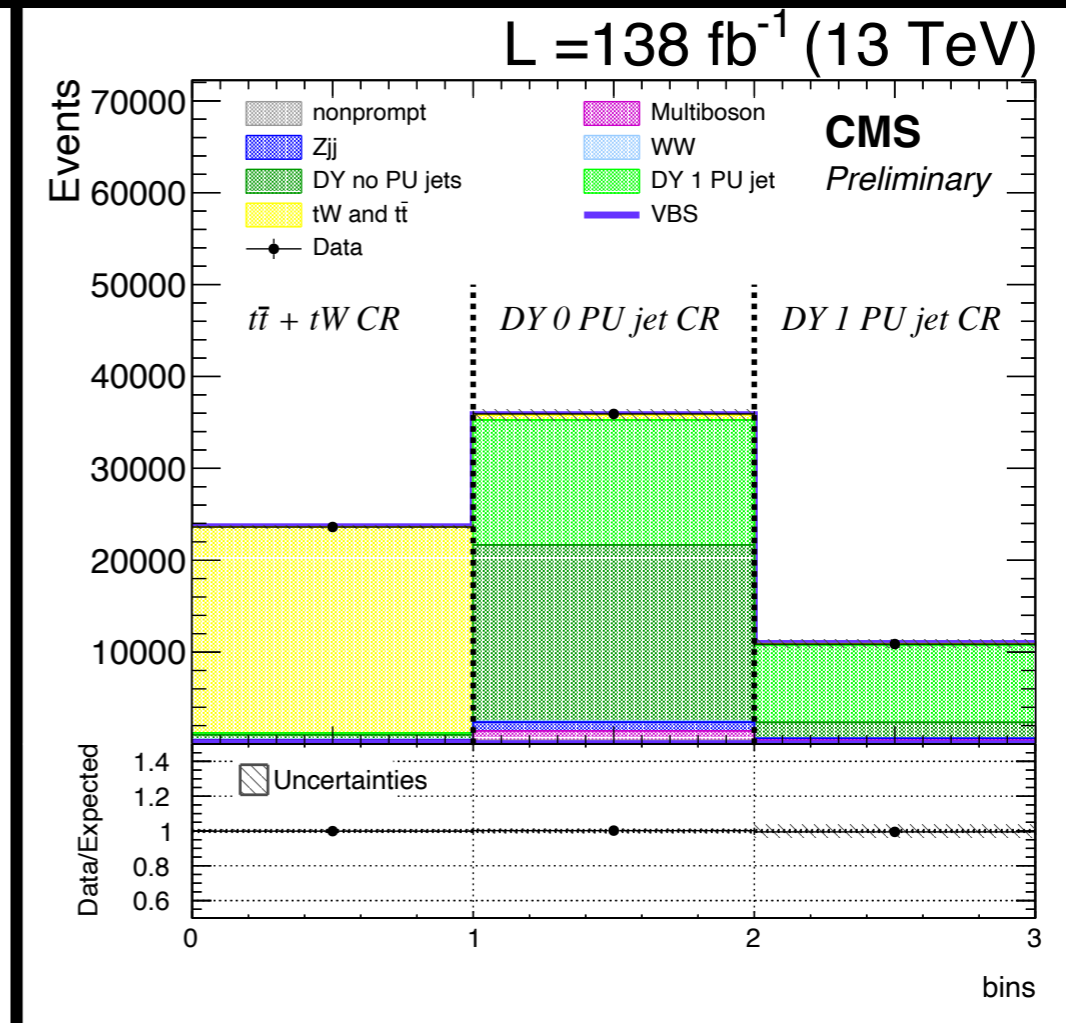
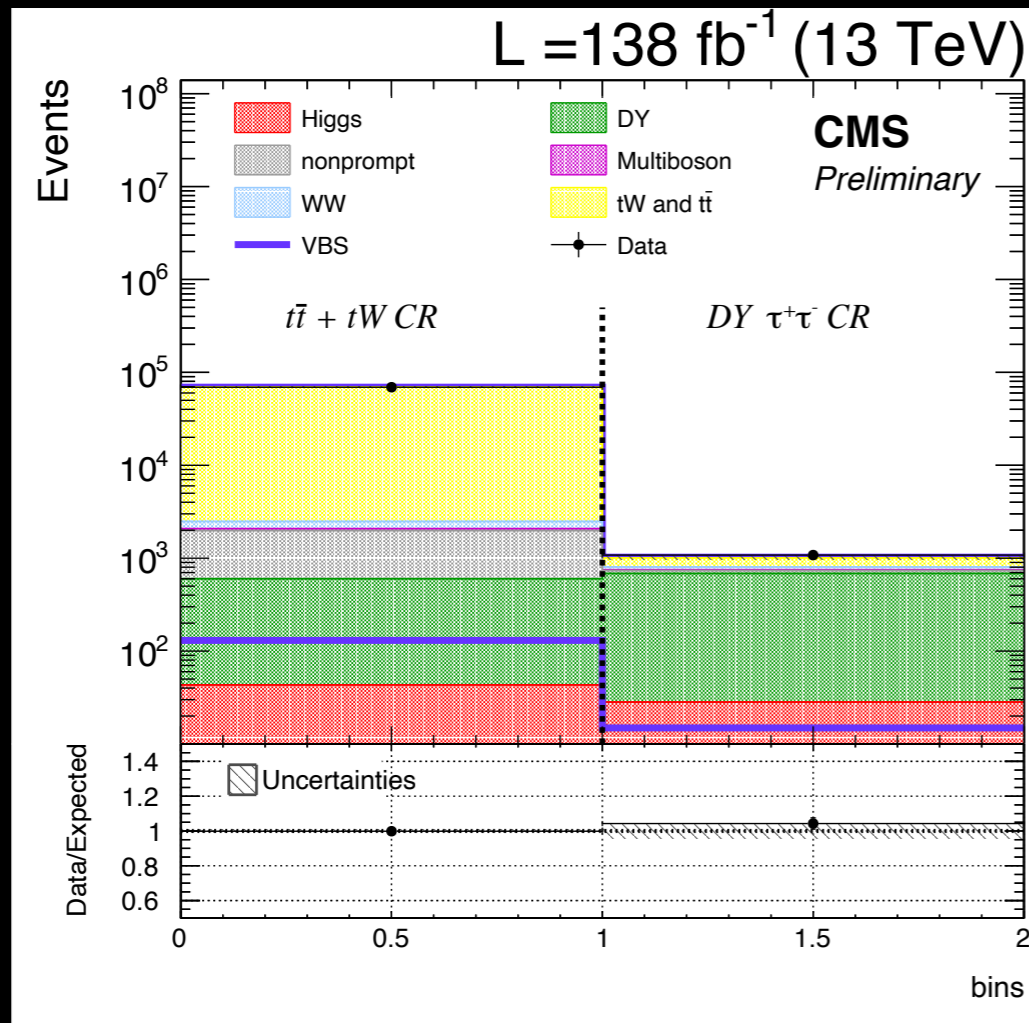


Precision measurements of WZ , **first observation** of longitudinally polarized W



First observation of the electroweak production of a leptonically decaying W^+W^- pair in association with two jets

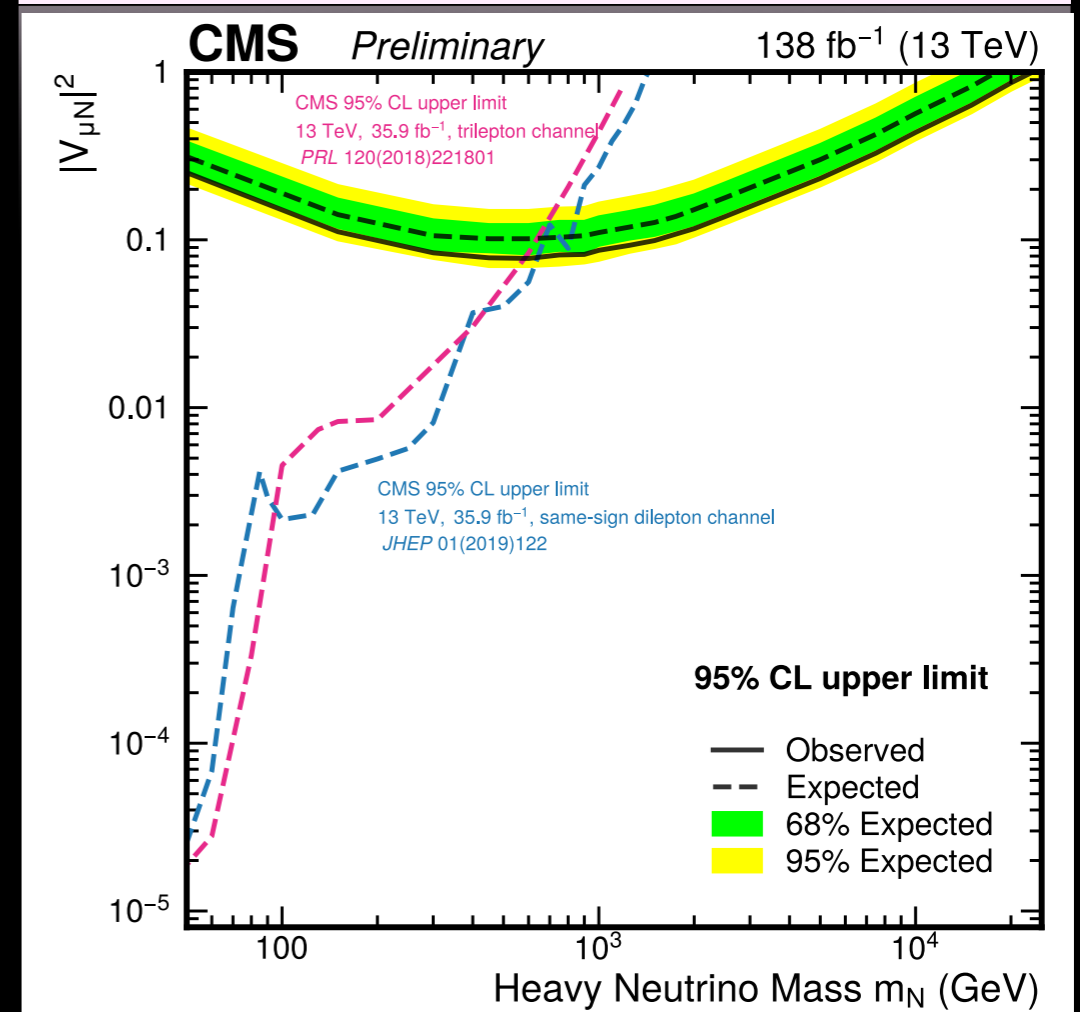
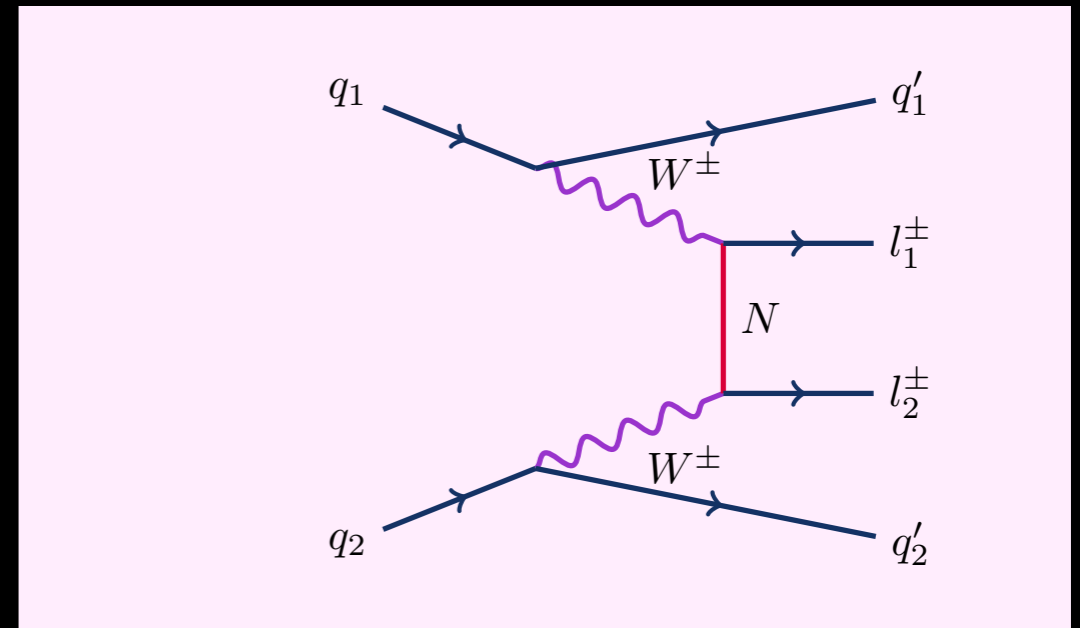
• $Z_{\ell\ell} = \frac{1}{2} \left| Z_{\ell_1} + Z_{\ell_2} \right|$, where $Z_{\ell} = \eta_{\ell} - \frac{1}{2} \left(\eta_{j_1} + \eta_{j_2} \right)$

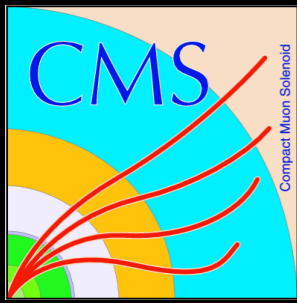


Looking for new physics with VBS topology

- Neutrino mass arises in the SM \rightarrow Weinberg operator:

$$\mathcal{L} = C_5^{ll'} / \Lambda [\Phi \cdot \bar{L}_\ell^c] [L_{\ell'} \cdot \Phi]$$

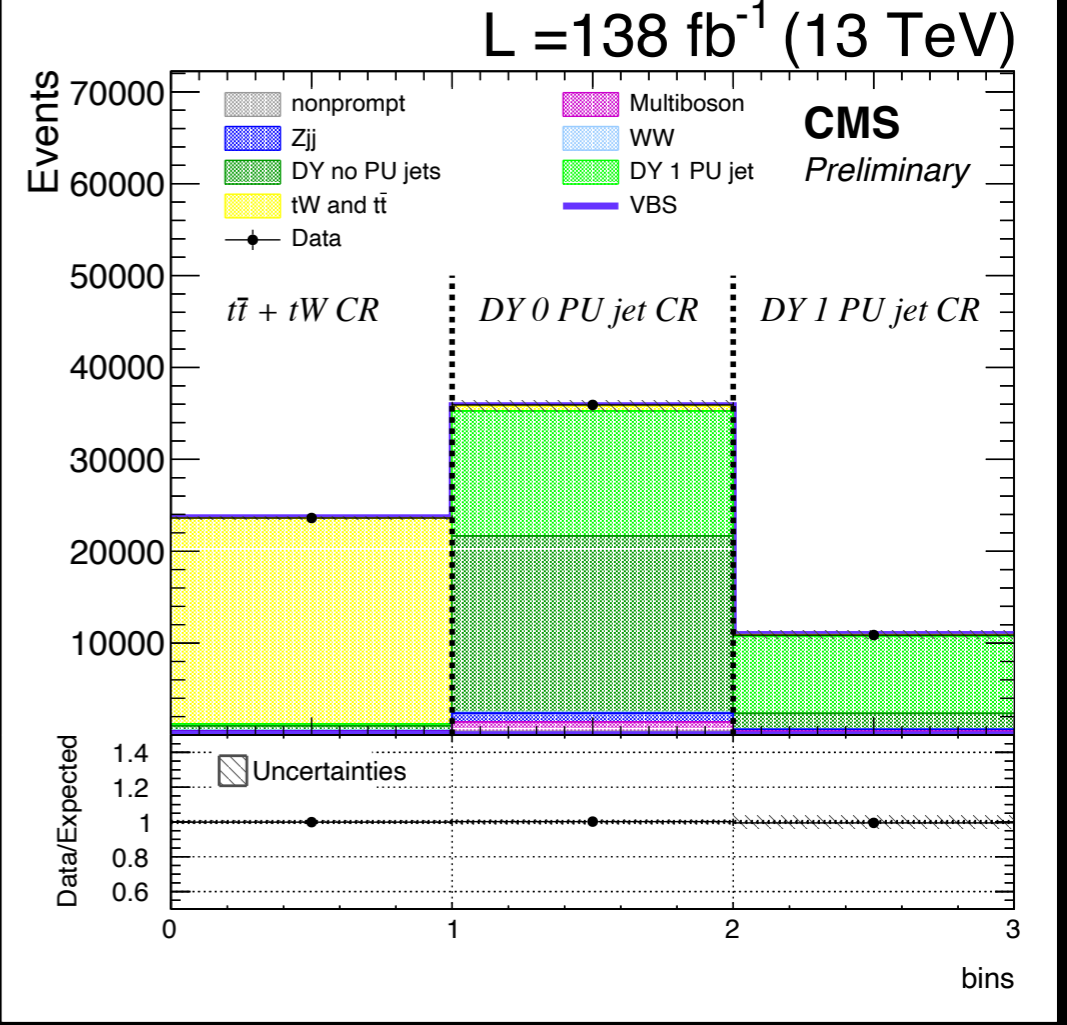
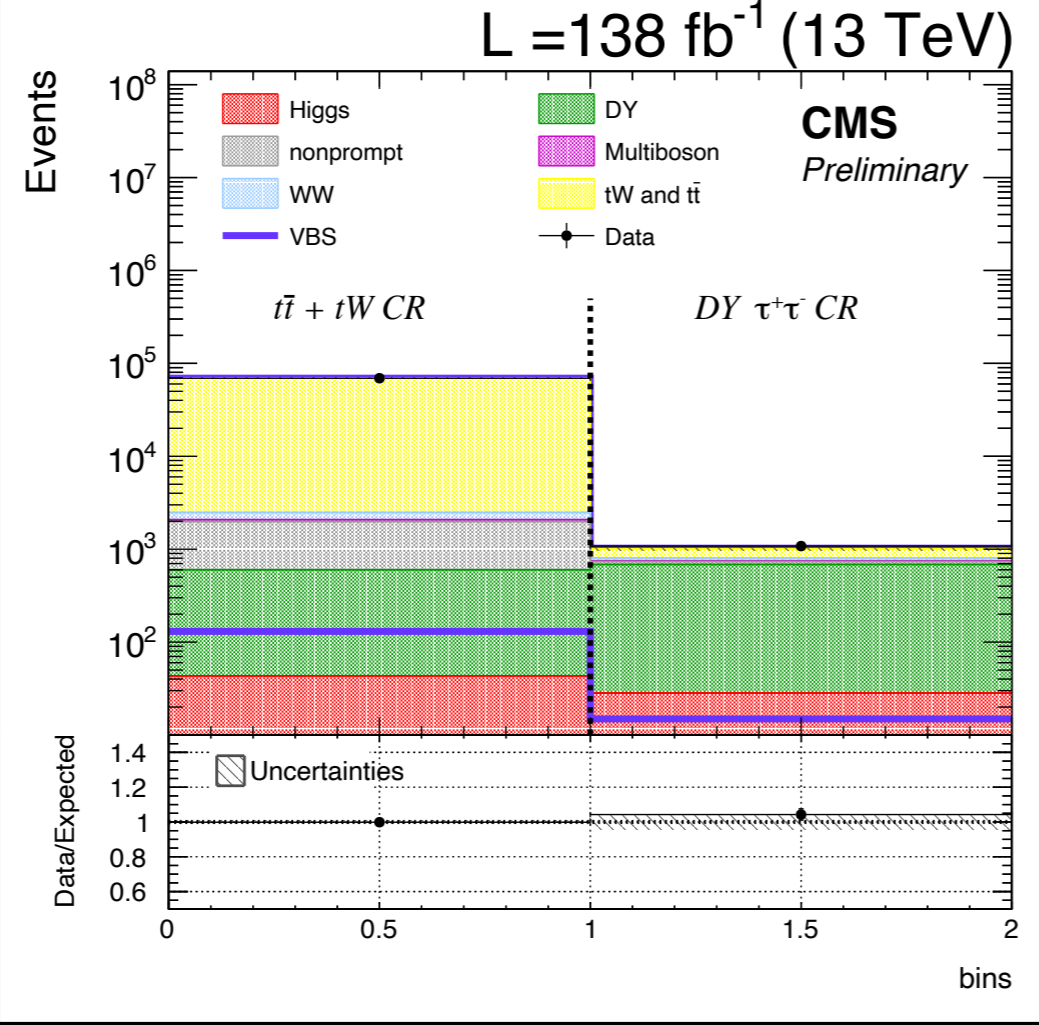


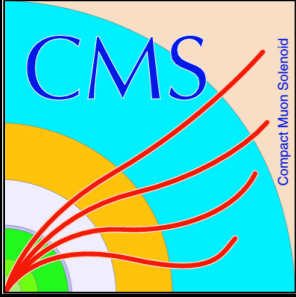


First observation of the electroweak production of a leptonically decaying W^+W^- pair in association with two jets

- Backgrounds from Drell-Yan and $t\bar{t}$ studied in dedicated control regions
 - Z-peak used to study Drell-Yan
 - b-veto inverted to study $t\bar{t}$ background
- Drell-Yan contributes when lepton pair is reconstructed with high $p_T^{\text{miss}} \rightarrow$ instrumental effects

Two separate regions defined by $\Delta\eta_{jj} < 5$ and > 5 for pileup mitigation





Looking for new physics with VBS topology

- First search probing Majorana neutrinos and the Weinberg operator in vector boson fusion topology at the LHC
- Major backgrounds to mitigate: WZ , $t\bar{t}$
- Discriminating variable: $H_T/p_T^{\mu_1} \rightarrow$ measure of the ratio of hadronic to leptonic activity
 - Sensitive to color structure
 - Lower values for signal events
- For Majorana neutrinos, upper limits set in the mass (m_N) range [75 GeV, 250 TeV]

