Observation of VBS production in opposite-sign WW events @ CMS

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on behalf of the CMS collaboration

Standard Model at the LHC 2022

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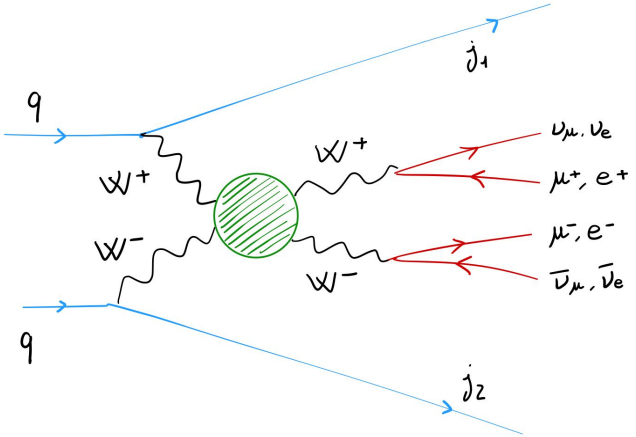
Introduction

"First observation of the electroweak production of a leptonically decaying W+W- pair in association with two jets in √s = 13 TeV pp collisions".

CDS

Why VBS → W+W-?

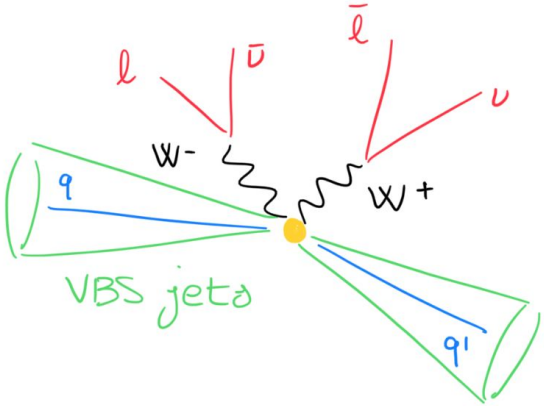
- A rare … :
  - ~ fb cross section
- … and challenging process due to bkgs:
  - ttbar + tW production
  - DY events (mostly in ee-μμ)
- Never been observed before
  →**First observation and first cross section measurement**



VBS → W^+W^-

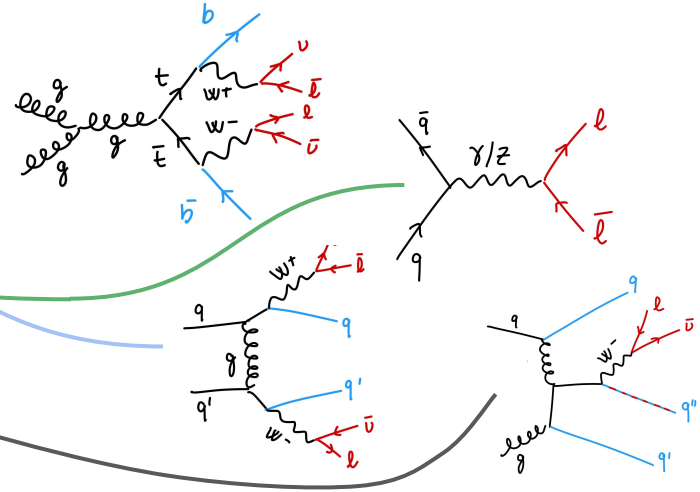
Typical leptonic signature

- 2 highly energetic jets (VBS jets) :
  - Large gap in **η** and high m_{jj}
  - No QCD activity between them
- 2 charged leptons and neutrinos p_T^{miss}
  - Central with respect to the VBS jets



Main backgrounds

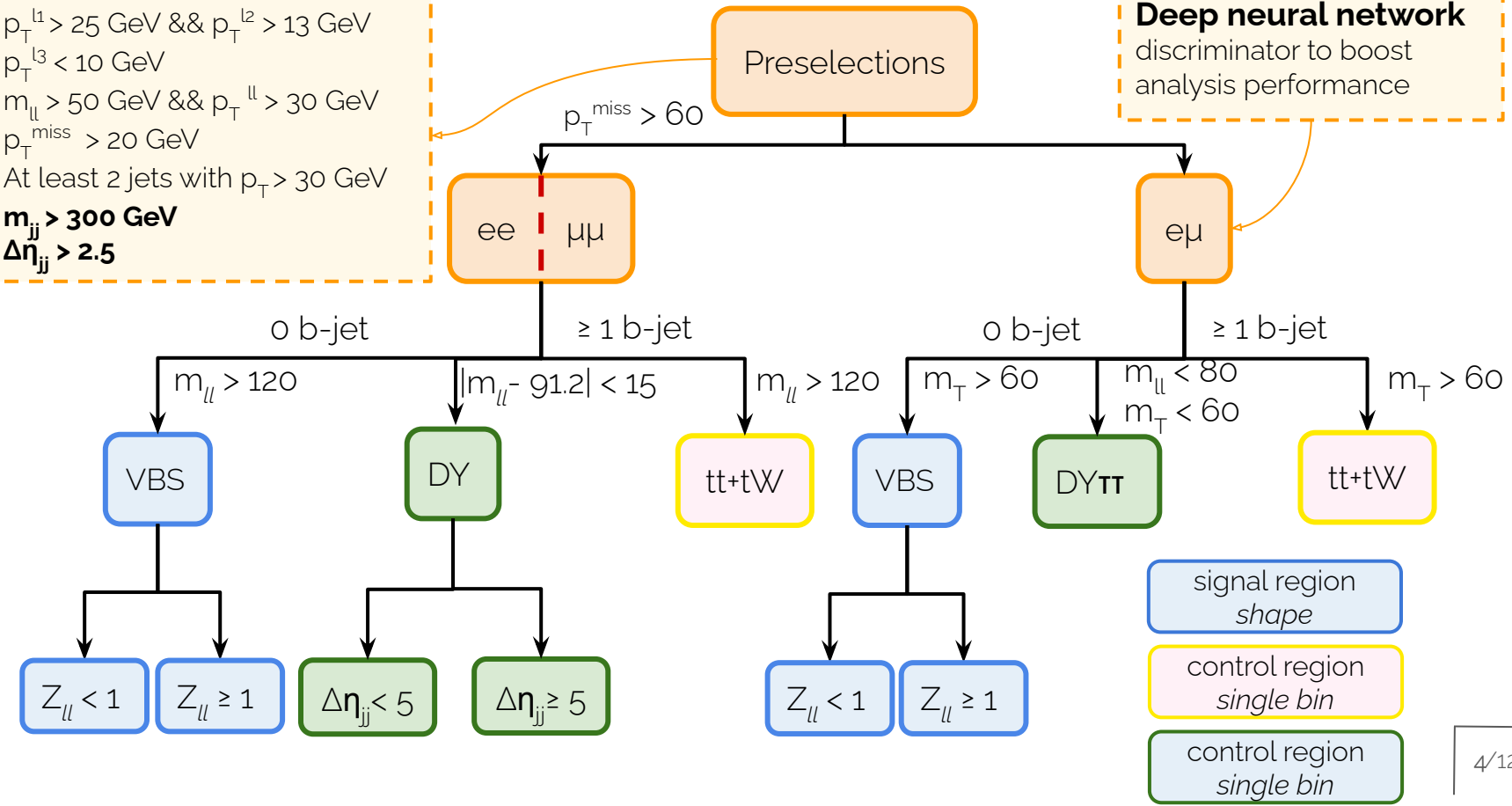
- ttbar - tW ~ 10^6 fb
- QCD WW ~ 10^5 fb
- Drell-Yan ~ 10^7 fb
- Nonprompt



Analysis strategy

- $p_T^{l1} > 25$ GeV && $p_T^{l2} > 13$ GeV
- $p_T^{l3} < 10$ GeV
- $m_{ll} > 50$ GeV && $p_T^{ll} > 30$ GeV
- $p_T^{miss} > 20$ GeV
- At least 2 jets with $p_T > 30$ GeV
- **$m_{jj} > 300$ GeV**
- **$\Delta\eta_{jj} > 2.5$**

Deep neural network
discriminator to boost analysis performance

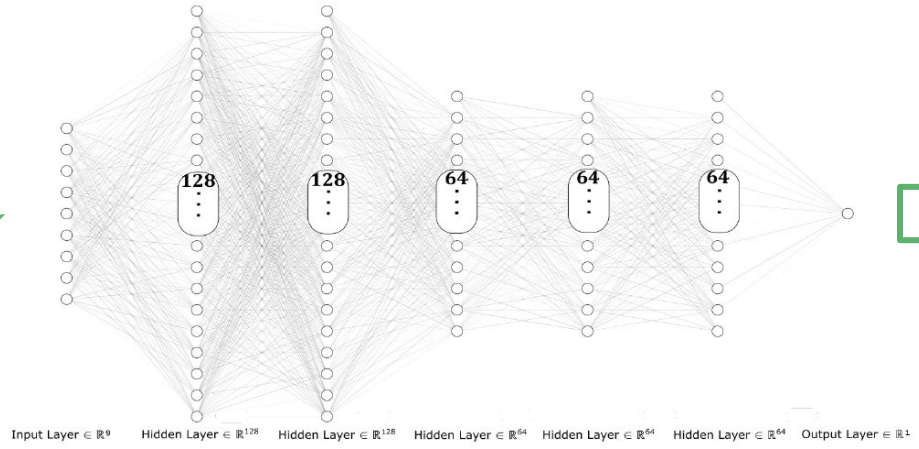


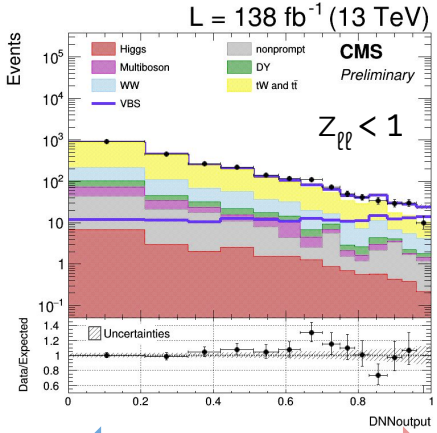
Deep Neural Network

Variable	Description
m_{jj}	Invariant mass of the two VBS jets pair
$\Delta\eta_{jj}$	Pseudorapidity gap between the two VBS jets
$p_{T j_1}$	p_T of the highest-p_T jet
$p_{T j_2}$	p_T of the second highest p_T jet
$p_{T\ell\ell}$	p_T of the lepton pair
$\Delta\phi_{\ell\ell}$	Azimuthal angle between the two leptons
Z_{ℓ_1}	Zeppenfeld variable of the highest-p_T lepton
Z_{ℓ_2}	Zeppenfeld variable of the second highest p_T lepton
m_{TW_1}	Transverse mass of the $(p_{T\ell_1}, p_T^{miss})$ system

Deep neural network to disentangle signal from top and QCD-WW background :

- Different flavour final state (**eμ**)
- **2 models** implemented:
  - $Z_{ll} < 1$ phase space
  - $Z_{ll} \geq 1$ phase space





background-like **signal-like**

Systematic and statistical uncertainties

Systematic uncertainties

- Nuisance parameters with log-normal distribution in the fit for signal extraction
- Could affect
  - Normalization of signal and backgrounds
  - Shape of the predictions across the distributions of the observables
- Correlations taken into account

Theoretical uncertainties

b tagging uncertainty

Uncertainty source	Impact
QCD-induced W^+W^- normalisation	5.3%
$t\bar{t}$ QCD scale	5.1%
QCD factorisation scale for VBS signal	5.0%
$t\bar{t}$ normalisation	4.9%
b tagging	3.5%
Prefiring corrections	3.3%
DY normalisation	2.9%
Jet energy scale + resolution	2.6%
p_T^{miss} energy scale	2.4%
QCD-induced W^+W^- QCD scale	2.1%
Luminosity	2.1%
Muon efficiency	2.0%
Pileup	1.8%
Electron efficiency	1.5%
Underlying event	1.3%
Parton shower	1.0%
Other	< 1%
Total systematic uncertainty	13.1%
Total statistical uncertainty	14.9%
Total uncertainty	**19.8%**

Dominated by **statistical** uncertainty

Signal extraction

- Combined binned maximum likelihood fit of the most discriminating variable distributions with signal and background templates

- Performed simultaneously in all signal region categories ($z_{\ell\ell} \gtrless 1$):
  - **SF** – divided into **4 m_{jj} - $\Delta\eta_{jj}$** bins:
    - $2.5 < \Delta\eta_{jj} < 3.5$ and $300 < m_{jj} < 500$
    - $2.5 < \Delta\eta_{jj} < 3.5$ and $m_{jj} > 500$ GeV
    - $\Delta\eta_{jj} > 3.5$ and $300\ \text{GeV} < m_{jj} < 500\ \text{GeV}$

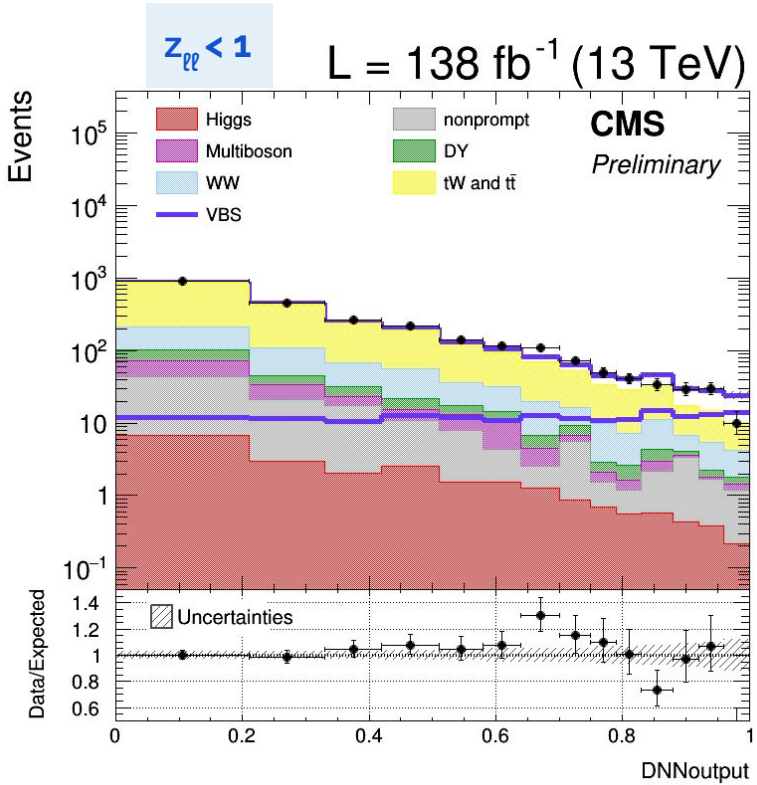
    } **Number of events**

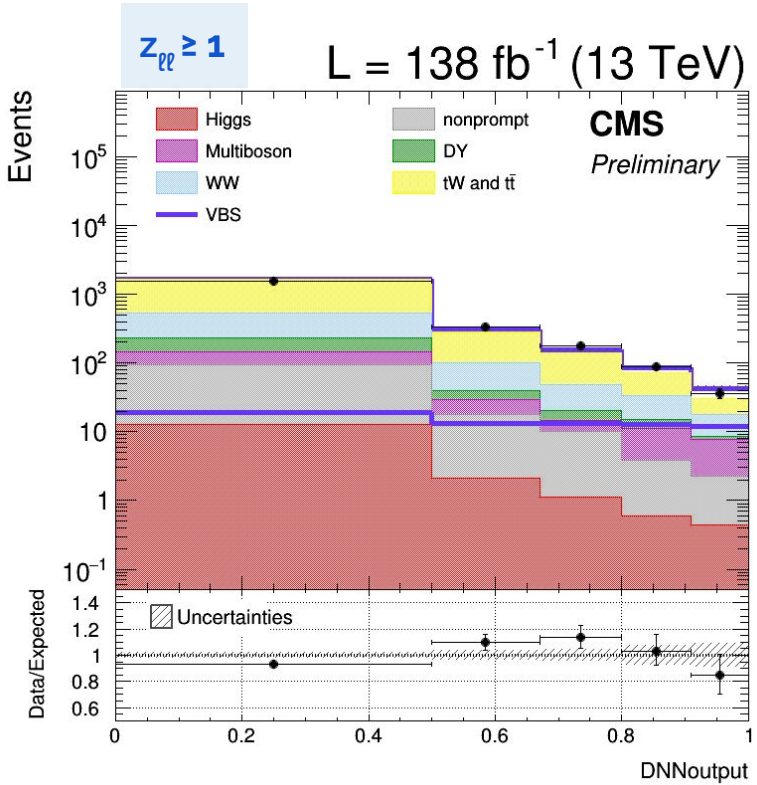
    - $\Delta\eta_{jj} > 3.5$ and $m_{jj} > 500$ GeV → purest region → **m_{jj} distribution**
  - **DF** – ***DNN score***

All categories are included simultaneously in the fit

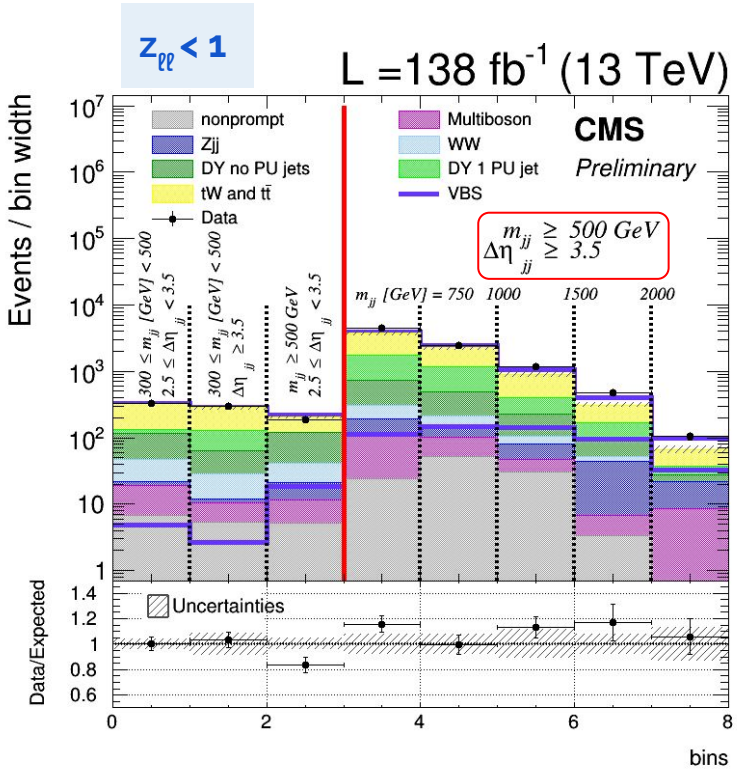
- Control regions: **single bin** categories → To constraint **DY and top normalizations**

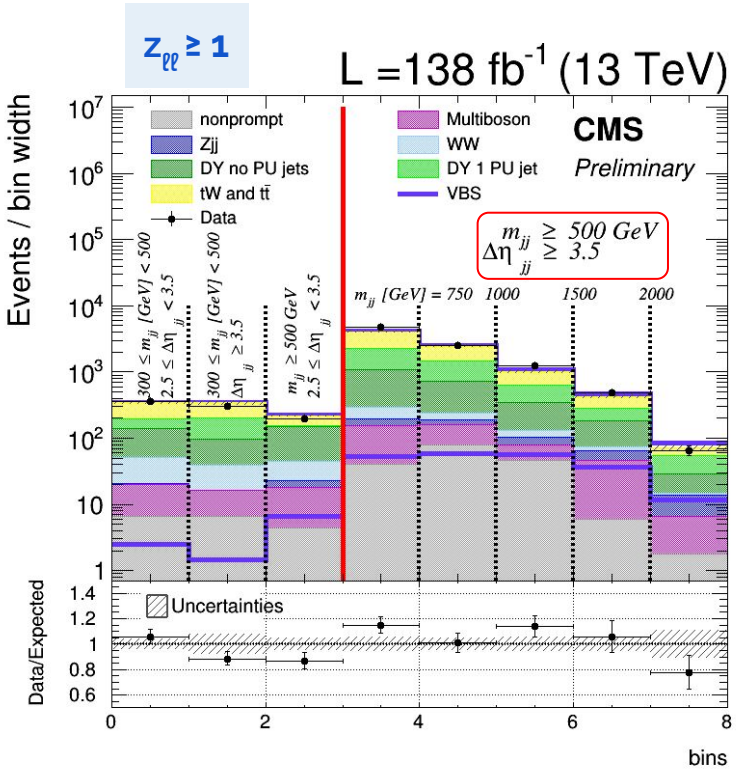
Signal regions eμ





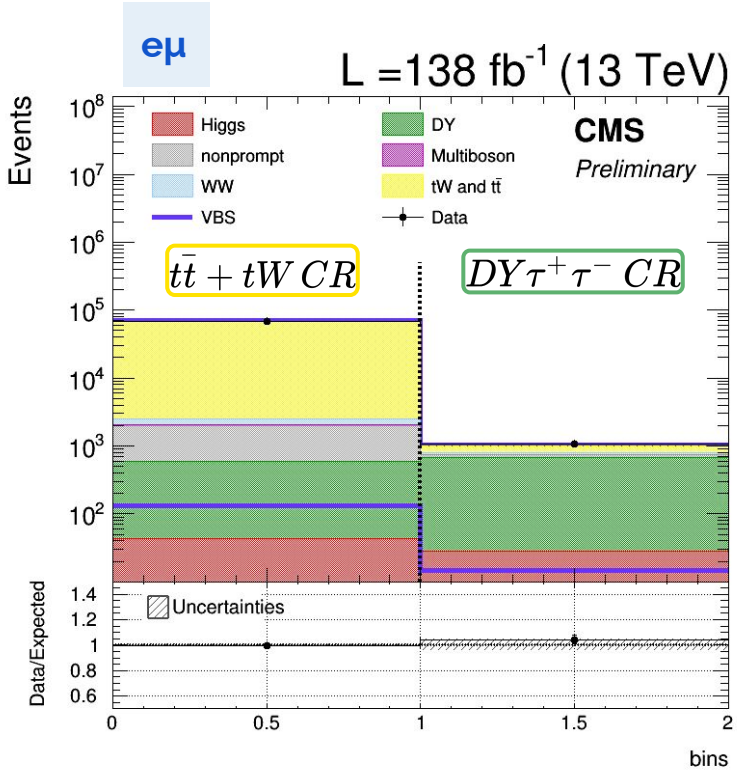
Signal regions ee-μμ



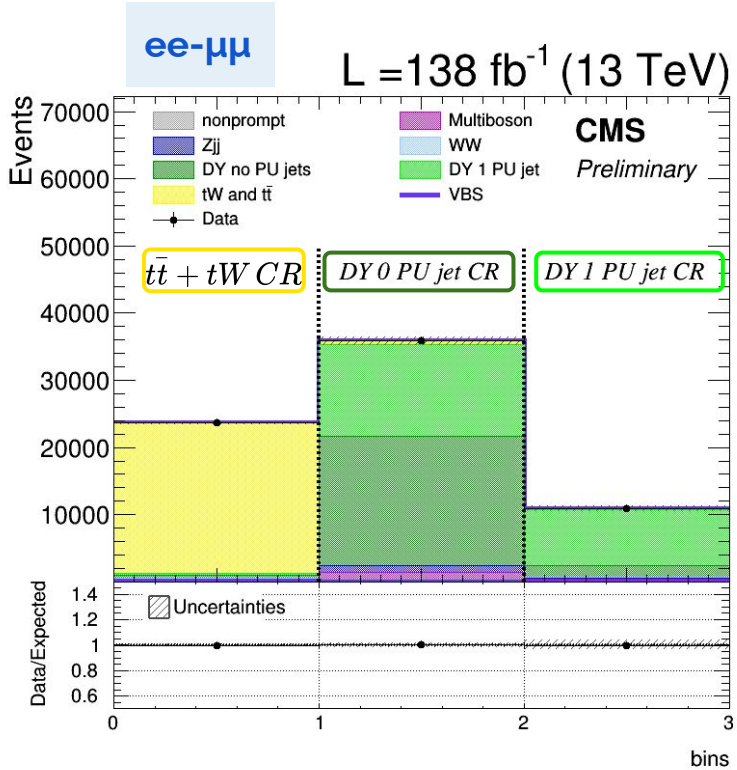


Control regions

eμ



ee-μμ



Results

- Observed (expected) significance w.r.t. the background-only hypothesis is **5.6 σ** (5.2 σ)
- The cross section measurement of the W^+W^- EW production is performed in two fiducial volumes:

Inclusive phase space

Measured: 99 ± 20 fb
LO prediction: 89 ± 5 fb

Parton-level observables:
$m_{qq} > 100$ GeV
$p_T > 10$ GeV

Good agreement with SM predictions!

Exclusive phase space

Measured: 10.2 ± 2.0 fb
LO prediction: 9.1 ± 0.6 fb

Objects	Requirements
Leptons	$e^+e^-, \mu^+\mu^-, e^+\mu^-, e^-\mu^+$ $p_T^\ell = p_T^{bare\,\ell} + \sum_i p_T^{\gamma_i}$ if $\Delta R(\ell,\gamma_i) < 0.1$ $p_T^{\ell_1} > 25$ GeV, $p_T^{\ell_2} > 13$ GeV, $p_T^{\ell_3} < 10$ GeV $\lvert\eta\rvert < 2.5$ $p_T^{\ell\ell} > 30$ GeV, $m_{\ell\ell} > 50$ GeV
Jets	$p_T^j > 30$ GeV, $\lvert\eta\rvert < 4.7$ $\Delta R(j,\ell) > 0.4$ At least 2 jets, no b jets $m_{jj} > 300$ GeV, $\Delta\eta_{jj} > 2.5$
p_T^{miss}	$p_T^{miss} > 20$ GeV

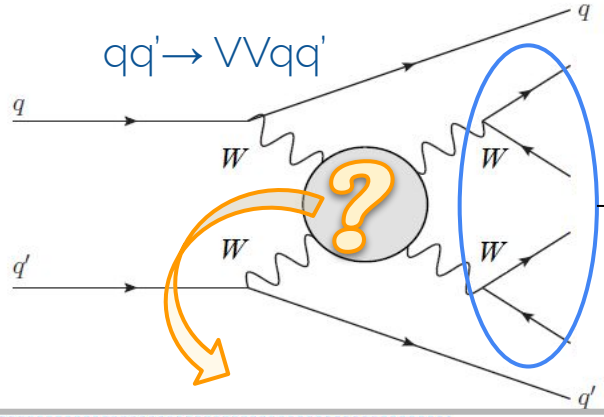
More similar to the signal region

Future developments

- Analysis statistically limited → expected to benefit from the larger RUN III dataset
- Global fit of relevant EFT operators of dimensions 6 and dimension 8 @ reco-level, to get a more complete understanding of the SM validity range
    - EFT dim6 study @ lhe-level arXiv: 2108.03199 [hep-ph]
- Polarization studies to investigate the EWSB mechanism and test models of physics BSM

Backup

VBS processes @LHC

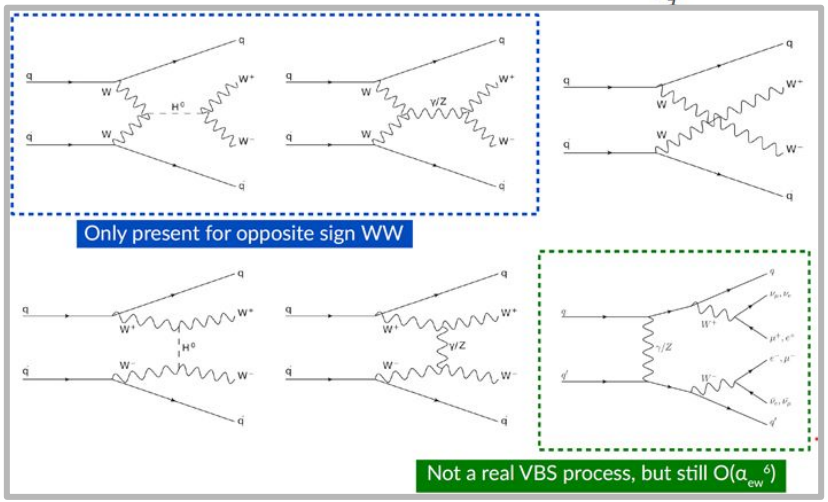


The two massive bosons may decay hadronically or leptonically, leading to 3 possible final states:

1. leptonic VV→ lν lν (this talk)
2. semileptonic VV → lν q'q''
3. hadronic VV → qq' q''q'''

+purity

+statistics



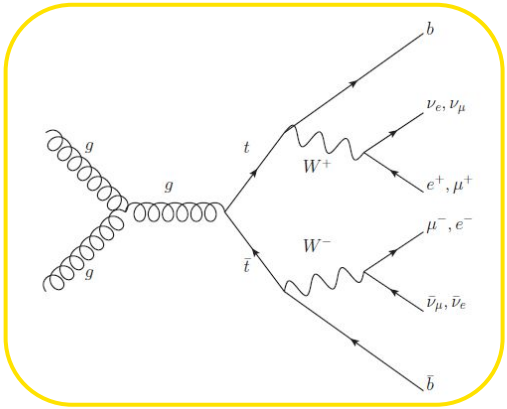
- Production of a pair of W+W- bosons from a purely electroweak process @LO $O(\alpha^6_{EWK}\,\alpha^0_S)$
- Diagrams where an on-shell Higgs boson is exchanged (VBF) are considered as backgrounds and modeled with dedicated MC samples
- The interference with the QCD-induced WW background $O(\alpha^4_{EWK}\,\alpha^2_S)$ is negligible

Main backgrounds

ttbar - tW

σ_{tt} ~ 1 nb – Main background of the analysis.

Strategy: b jets veto

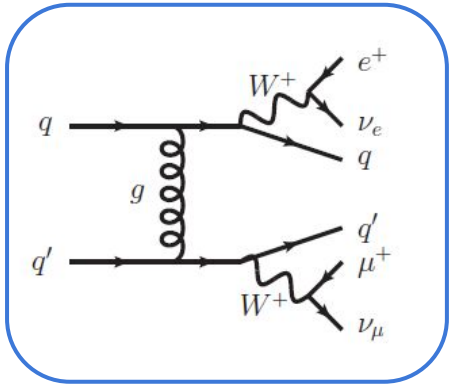


QCD WW

Strong interaction between the initial state quarks

Same final state, but different kinematic.

Strategy: VBS selections.

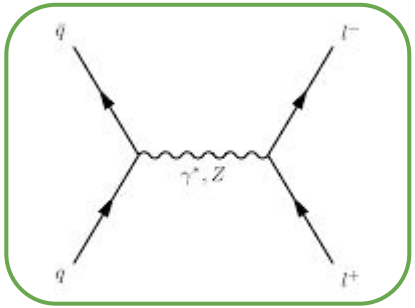


Drell-Yan

Mainly affecting the ee-μμ final state.

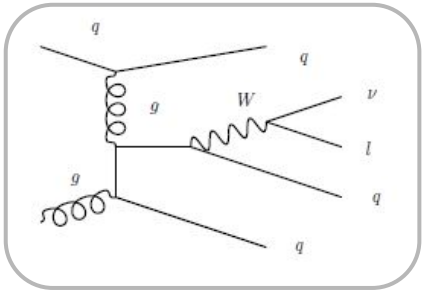
Strategy:

- selections on *m* and p_T of lepton pair
- tighter selections on p_T^{miss}



Nonprompt

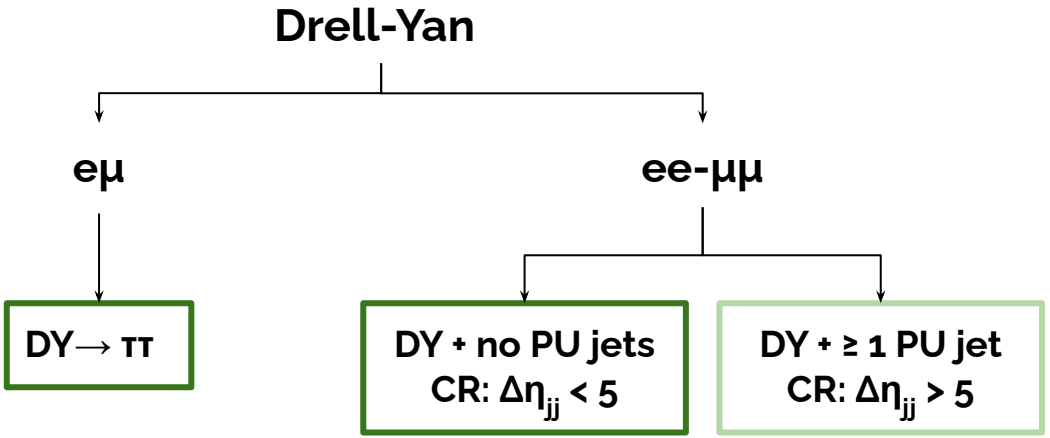
Mainly W+Jet :
jet misidentified as lepton *(fake lepton)*



DY→ℓℓ treatment

- In DY CRs 2 different contributions are clearly visible and much sensitive to the $\Delta\eta_{jj}$ distribution:
  - "Hard" DY events populate the low $\Delta\eta_{jj}$ region
  - DY process + at least 1 PU jet peaks around $\Delta\eta_{jj} \sim 5$
- 3 contributions in total with different control regions
- Their normalisations are free to float in the fit and mainly driven by dedicated CRs $\Delta\eta_{jj} \gtrless 5$

PU jet = Reco jet not matched to any $p_T > 25\ GeV$ gen jet



Post-fit (pre-fit) yields table

Process	VBS $e\mu$	VBS $ee - \mu\mu$
WWewk	238.9 ± 21.9 (209.0 ± 5.4)	132.6 ± 6.9 (115.5 ± 2.2)
top	3081.9 ± 99.7 (2998.0 ± 189.3)	1152.3 ± 18.3 (1073.7 ± 33.7)
WW	736.3 ± 98.8 (1086.8 ± 89.0)	201.1 ± 22.6 (405.6 ± 22.0)
DY no PU jets	–	594.7 ± 19.9 (417.6 ± 25.9)
DY + 1 PU jet	–	436.1 ± 43.5 (370.4 ± 120.4)
DY$\tau\tau$	171.2 ± 7.4 (195.9 ± 6.2)	–
Non-prompt leptons	216.8 ± 24.6 (242.5 ± 31.7)	51.8 ± 6.1 (58.0 ± 7.8)
Multiboson	143.3 ± 9.8 (141.0 ± 15.9)	96.0 ± 6.0 (89.2 ± 7.8)
Higgs	46.6 ± 1.8 (43.2 ± 2.9)	–
Zjj	1.3 ± 0.2 (1.3 ± 0.3)	59.1 ± 4.3 (50.4 ± 6.5)

Selections

Preselections

$p_T^{l1} > 25$ GeV && $p_T^{l2} > 13$ GeV
$p_T^{l3} < 10$ GeV
$m_{ll} > 50$ GeV && $p_T^{ll} > 30$ GeV
At least 2 jets with pT > 30 GeV
mjj > 300 GeV && $\Delta\eta_{jj} > 2.5$

Categories selections

VBS	$e\mu/\mu e$	$Z_{\ell\ell} < 1$	$m_T > 60$ GeV $m_{\ell\ell} > 50$ GeV no bjet with $p_T > 20$ GeV
		$Z_{\ell\ell} \geq 1$	
	ee	$Z_{\ell\ell} < 1$	$m_{\ell\ell} > 120$ GeV $p_T^{miss} > 60$ GeV no bjet with $p_T > 20$ GeV
		$Z_{\ell\ell} \geq 1$	
	$\mu\mu$	$Z_{\ell\ell} < 1$	
		$Z_{\ell\ell} \geq 1$	
$t\bar{t}$ and tW	$e\mu/\mu e$		$m_{\ell\ell} > 50$ GeV no b-jet with $p_T > 20$ GeV
	ee		$m_{\ell\ell} > 120$ GeV $p_T^{miss} > 60$ GeV at least one b-jet with $p_T > 20$ GeV
	$\mu\mu$		
DY	$e\mu/\mu e$		$m^T < 60$ GeV 50 GeV$< m_{\ell\ell} <$ 80 GeV no b-jet with $p_T > 20$ GeV
	ee	$\Delta\eta_{jj} < 5$	$\lvert m_{\ell\ell} - m_Z \rvert < 15$ GeV $p_T^{miss} > 60$ GeV no b-jet with $p_T > 20$ GeV
		$\Delta\eta_{jj} \geq 5$	
	$\mu\mu$	$\Delta\eta_{jj} < 5$	
		$\Delta\eta_{jj} \geq 5$	