Probing Physics in the Standard Model and Beyond in gauge boson scattering with the CMS experiment at the LHC

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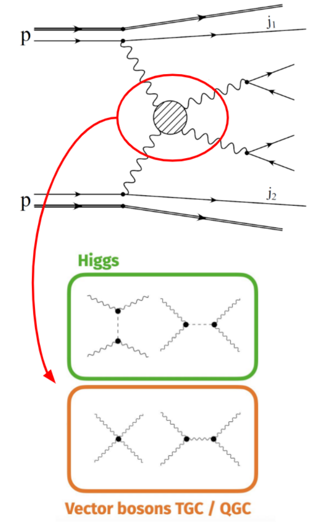
Vector Boson Scattering

Vector boson scattering (VBS) happens at the LHC when the two incoming partons radiate electroweak vector bosons that interact with each other.

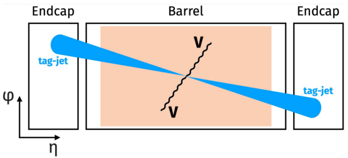
- Direct process probing the non-Abelian nature of SM

At LO there are three possible contributions:

- Pure EWK (α_{EWK}^{6}) - **signal**
- QCD-induced ($\alpha_{EWK}^{4}\alpha_{s}^{2}$) - **background**



Experimental signature:



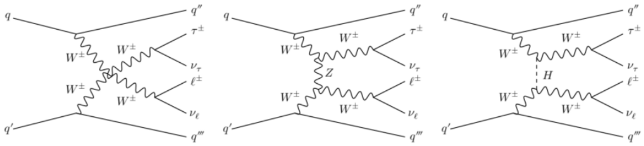
- 2 vector bosons produced centrally
- 2 forward energetic jets emitted back-to-back: high $\Delta\eta_{jj}$ and m_{jj}

Golden Channel $W^{\pm}W^{\pm}jj \to l^{\pm}l^{\pm}2\nu jj$

Thanks to the presence of two same-sign leptons, the QCD-induced background is drastically reduced. The first evidence dates back to Run I, and since then the light-lepton final state has mainly been studied.

With the advancement of Machine Learning techniques, the final state including a tau lepton has been studied.

Process that I am studying:



$$W^{\pm}W^{\pm}jj \to l^{\pm}\tau_h^{\pm}\nu_l\nu_\tau jj$$

Physics Analysis Pipeline

A complete and advanced analysis is very difficult and needs years of work, during my period here I've started this journey but I still have a lot of work to do.

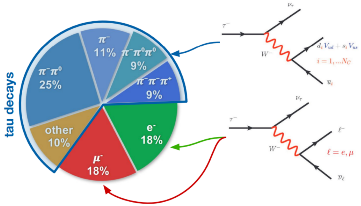
1. Study papers on this topic
2. Learn and implement existing analysis code
3. Physics process definition
4. Analysis framework setup
5. Physics object selection
6. Background estimation
7. ...

Physics process and objects selection

Process : $W^{\pm}W^{\pm}jj$ **with one** τ_h

L_{int} = 220.79 fb^{-1} RunIII dataset

- τ_h
- e/μ : same charge as τ
- two jets with highest p_T (VBS jets)



Selection Criteria	
τ_h	$p_T > 20$ GeV, $\lvert\eta\rvert < 2.3$, DeepTau ID
e	$p_T > 30$ GeV, $\lvert\eta\rvert < 2.5$, MVA iso ID
μ	$p_T > 30$ GeV, $\lvert\eta\rvert < 2.4$, cut-based ID
Jet	$p_T > 30$ GeV, $\lvert\eta\rvert < 5.1$
No additional loose leptons	
ΔR > 0.4 (object isolation)	
Same-sign ℓ-τ_h requirement	
B-jet veto UParTAK4B	
$n_{jets} \geq 2$	

Background

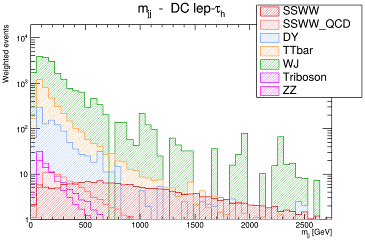
In order to carry out any study of a particular signal, the most important step is to understand the background, especially when the process under study is as rare as this one. The standard approach is to use Monte Carlo samples for every process that could mimic the signal final state.

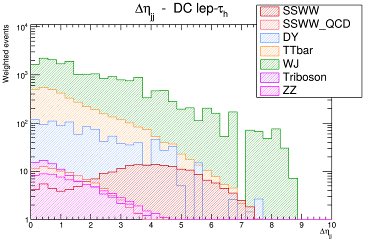
In this case, many previous analyses have already identified the most relevant background sources.

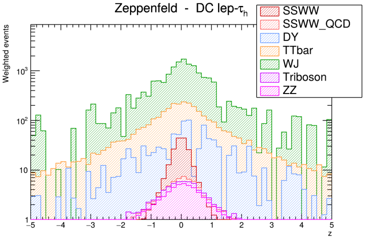
- Drell-Yan + jets
- $t\bar{t}$
- ttV
- Opposite-sign
- W+jets
- WZ
- ZZ
- Triboson

Background visualization

Preliminary study on MC background for key VBS variables:







Invariant mass of two VBS jets

Difference in pseudorapidity between the two VBS jets

$$z_{ev} = \frac{\eta_l + \eta_\tau - |\eta_{j_1} + \eta_{j_2}|}{2(\eta_{j_1} - \eta_{j_2})}$$

These are three powerful variables widely used to create the VBS signal region and as features for a machine learning discriminator.

Yields and Selection Efficiency

After object selection

Process	Events
Signal	208 ± 14
ssWW QCD	91 ± 9
Drell-Yan	5002 ± 71
W + Jets	19717 ± 141
$t\bar{t}$	3845 ± 62
Triboson	98 ± 10
ZZ	78 ± 9
Total Bkg	24898 ± 157

$\Rightarrow$

$m_{jj} > 500$ GeV
$\Delta\eta_{jj} > 2.5$
$|z_{ev}| < 1$

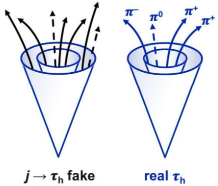
After kinematic cuts

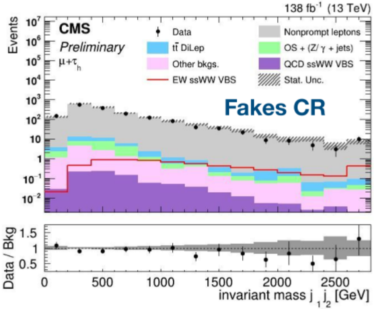
Events	Efficency
139 ± 10	67%
7 ± 3	8%
612 ± 8	25%
1778 ± 42	9%
287 ± 17	7%
6 ± 2	6%
5 ± 2	6%
2694 ± 48	11%

Estimation of non-prompt l/τ_h background

Jet-induced fake leptons, also referred to as ”non-prompt” leptons, are the dominant source of background in this analysis, where either e/μ or τ_h are mimicked by misreconstructed hadronic jets.

Fake leptons are mainly produced by QCD-mediated multijet processes: W+jets, Drell-Yan, and $t\bar{t}$.
$\Rightarrow$ MC simulation is not reliable for properly modeling non-prompt leptons; data-driven methods are therefore preferred.





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Data-driven "fakeable object" method (for $e/\mu/\tau$)

QCD-enriched sample:

- JetMET samples: CMS primary dataset containing real collision events selected by jet- and MET-based triggers
- Set of prescaled trigger paths (HLT_PFJet)

The first step is to find the fake rate, which is a measure of the probability that a real jet can be misidentified as a tight lepton.

Fake Rate Definition

$$\epsilon_{fake}(p_T, \eta) = \frac{N_{tight}}{N_{loose}}$$

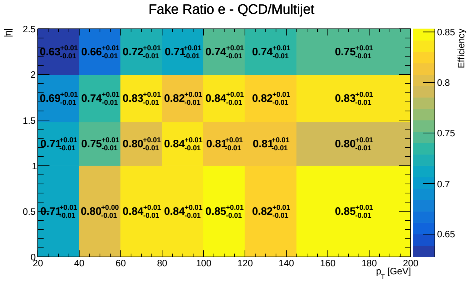
- N_{tight} = Number of leptons passing tight criteria
- N_{loose} = Number of leptons passing loose criteria

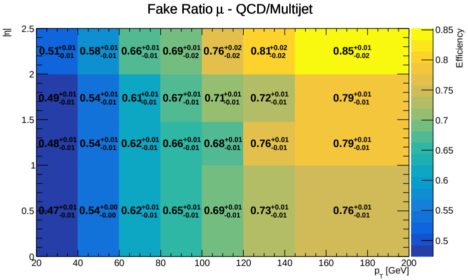
This ratio is measured from data and applied event-by-event to estimate fake lepton contributions in the signal region.

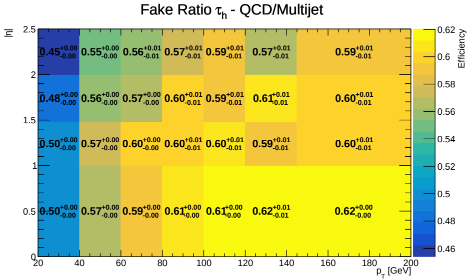
Fake Ratio Measurements

These 2D maps show the fake ratio as function of:

- Trasverse momentum
- Pseudorapidity







Summary

- ✓ Study of the process
- ✓ Learn the analysis framework
- ✓ Event selection
- ✓ Distributions of signal and background processes

Work in progress:

- ○ Data-driven non-prompt background estimation
- ○ Validation in control region
- ○ ML discriminator for signal extraction

Thank you for your attention

References

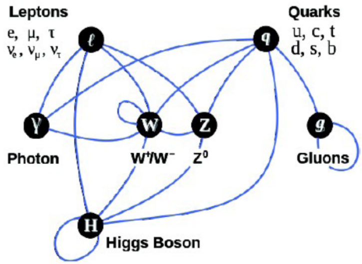
- **Vector Boson Scattering Processes:** Franzosi et al., arXiv:2106.01393 (2021)
- **Vector-Boson Scattering at the LHC:** Covarelli et al., arXiv:2102.10991v2 (2021)
- **First VBS evidence:** CMS Collaboration, arXiv:submit/1096090 (2015)
- **Study of same-sign W boson scattering and anomalous couplings in events with one tau lepton:** CMS Collaboration, arXiv:2410.04210v2 (2024)
- **Fake Rates for dilepton Analyses:** CMS Collaboration, CMS AN-2010/257 (2010)

Additional material

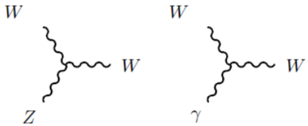
Why is VBS so important?

- Test of the non-Abelian structure of the Electroweak theory of the Standard Model
- Validation of the perturbative calculations
- Test of standard model couplings
  - In vector boson scattering processes, the unitarity is preserved via Higgs contributions
  - Test the gauge structure of the EW interactions
  - Test the couplings between the Higgs and gauge bosons
- Search for new physics
  - Through resonances
  - Through deviations

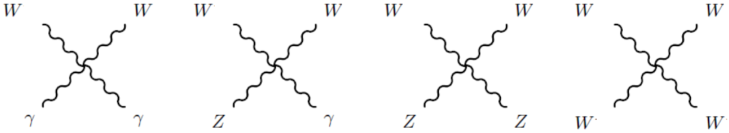
Triple and Quartic Gauge Couplings



- **Triple gauge couplings (TGC)**



- **Quartic gauge couplings (QGC)**



Complete event selection

Electron

- p_T > 30 GeV
- $|\eta|$ < 2.5
- |dxy| < 0.1 cm
- |dz| < 0.2 cm
- pass conversion veto
- TIGHT $\rightarrow$ MVA Iso ID WP80
- LOOSE $\rightarrow$ MVA Iso ID WP90

Muon

- p_T > 30 GeV
- $|\eta|$ < 2.4
- |dxy| < 0.1 cm
- |dz| < 0.2 cm
- TIGHT $\rightarrow$ cut-based ID WP medium $\&\&$ PF relative isolation < 0.15
- LOOSE $\rightarrow$ cut-based ID WP loose $\&\&$ PF relative isolation < 0.4

Complete event selection

Tau

- p_T > 20 GeV
- $|\eta|$ < 2.3
- |dz| < 0.2 cm
- DM 2, 5, and 6 excluded
- DeepTau2018v2p5VSe WP Tight
- DeepTau2018v2p5VSmu WP Tight
- TIGHT $\rightarrow$ DeepTau2018v2p5VSjet WP Medium
- LOOSE $\rightarrow$ DeepTau2018v2p5VSjet WP Loose

Jet

- p_T > 30 GeV
- $|\eta|$ < 5.1
- due to spikes, in 2.5 < $|\eta|$ < 3.0 region p_T is required > 50 GeV
- Jet ID Tight