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Discovery of ZZ Vector Boson Scattering at Compact Muon Solenoid experiment

PhD project

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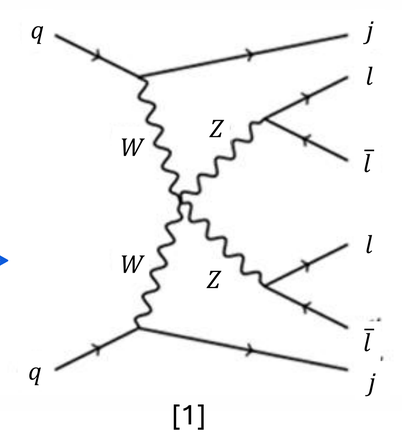
1 ZZ Vector Boson Scattering (VBS)

At the Large Hadron Collider (LHC) at CERN, VBS is initiated by quarks (q) from the colliding protons, each radiating a vector boson (V = W,Z), which then interact to produce a variety of final states.

This analysis focuses on the ZZ channel, in specifically on the **fully leptonic final state**, where both Z bosons decay into a lepton–antilepton pair.

One of the Feymann diagrams:
$qq \rightarrow ZZ + jj \rightarrow 4l + jj$



[1]

The final jets are the result of quarks hadronization and they are emitted back-to-back.

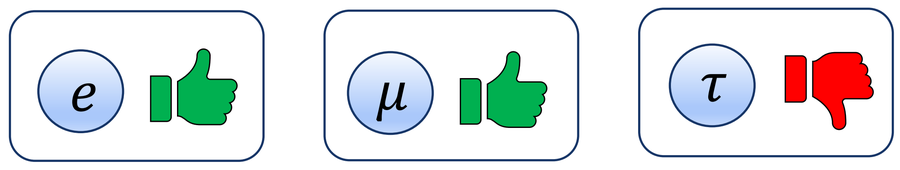
- Probe the innermost structure of electroweak interaction in the Standard Model (SM).

2 Strategy

The analysis consists in **identifying the leptons and jets in the final state** by applying cuts on their invariant mass and momentum.
Aim to reconstruct the invariant mass of the scattering ZZ pairs.

Cut examples:
- $p_T(l) > 20\ GeV$
- $m(4l) > 180\ GeV$
- $\Delta\eta_{jj} \gg 4.7$
- $m_{jj} \simeq 150 - 300\ GeV$

Not all leptons are selected for the analysis



Selected final states:

- $4e$ • $2e2\mu$ • 4μ

Varying the selection cuts, different estimates of the number of VBS signal events (S) and background events (B) are obtained. The **goal is to maximize the significance**.

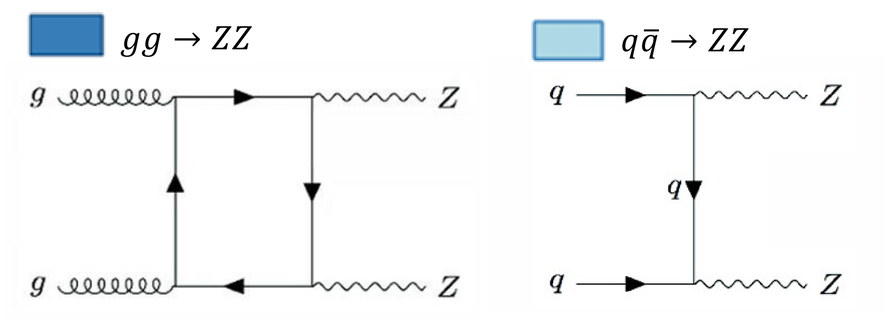
$$Significance = \frac{S}{\sqrt{B}}$$

A significance larger than 5σ is considered evidence for a discovery!

3 Challenges

The study of the fully leptonic channel presents several challenges:
- The decay of the boson into a lepton–antilepton pair has a branching ratio of only about 6%, and, since the τ channel is excluded, this results in **an extremely rare event**!
- The **cross section is very small:**
  - It is $\simeq 10^7$ times smaller than that one for single Z production.
  - Dominated by statistical uncertainty.
- The background represents a significant obstacle for this channel.

Types of background:
- **Irreducible** background component arising from processes that produce the same fully leptonic final state.

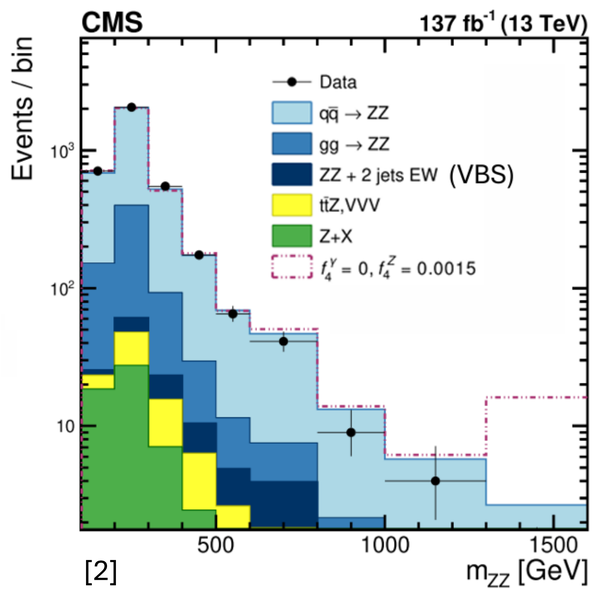


- **Reducible** background associated with particles that are misidentified by the detectors.

4 State of the art

A 2021 analysis using the full Run 2 dataset found evidence of this process with **a significance of 4σ**.

Run 2 LHC and CMS parameters:
- Energy of proton-proton collision: $\sqrt{S} = 13\ TeV$
- Luminosity: $L_{int} = 137 fb^{-1}$



[2]

The dark blue histogram corresponds to the VBS signal. The others correspond to processes that lead to the same final state as the ZZ VBS channel but do not involve boson scattering.

A lot of background!

Cross section obtained:

$$\sigma_{EW} = 0.33^{+0.11}_{-0.10}(stat)^{+0.04}_{-0.03}(syst)\ fb$$

5 Goals and expected results

In 2026, Run 3 at the LHC will conclude, providing an integrated luminosity $\simeq 300 fb^{-1}$. Since the number of observed events is directly proportional to the integrated luminosity, according to the formula $\boldsymbol{N = \sigma L \varepsilon}$, where σ is the cross section and ε is the detector efficiency, it is possible to estimate the expected significance achievable.

	Time	$\sqrt{S}\ (TeV)$	$L_{int}\ (fb^{-1})$
Run 2	2016 - 2018	13	137
Run 3	2022 - 2026	13.6	$\simeq$ 300

Run2 + Run3 expectations:
- **Improving cross section** measurements reducing statistical uncertainty by 40%
- **Expected significance** $\simeq 6\sigma$

6 Bibliography

[1] The CMS Collaboration, "Measurement of vector boson scattering and constraints on anomalous quartic couplings from events with four leptons and two jets in proton-proton collision at $\sqrt{S} = 13\ TeV$ Physics Letters B 774 (2017) 682-705

[2] CMS Collaboration, 'Measurements of $pp \rightarrow ZZ$ production cross section and constraints on anomalous triple gauge couplings at $\sqrt{S} = 13\ TeV$'. The European Physical Journal C (2021) 81:200