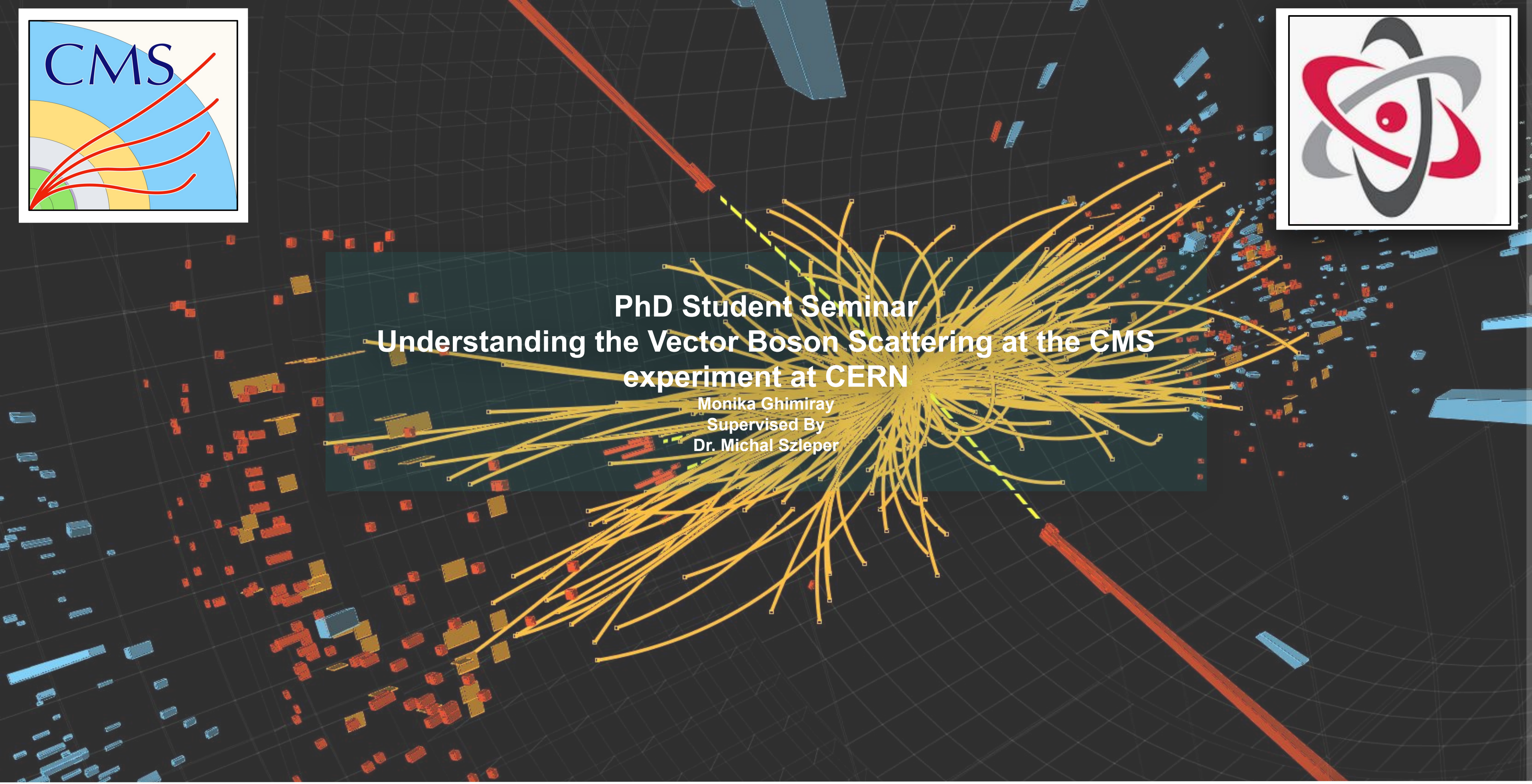


PhD Student Seminar
Understanding the Vector Boson Scattering at the CMS experiment at CERN

Monika Ghimiray
Supervised By
Dr. Michal Szleper

We are not at the end but at the beginning of a new physics. But whatever we find, there will always be new horizons continually awaiting us.
- Michio Kaku

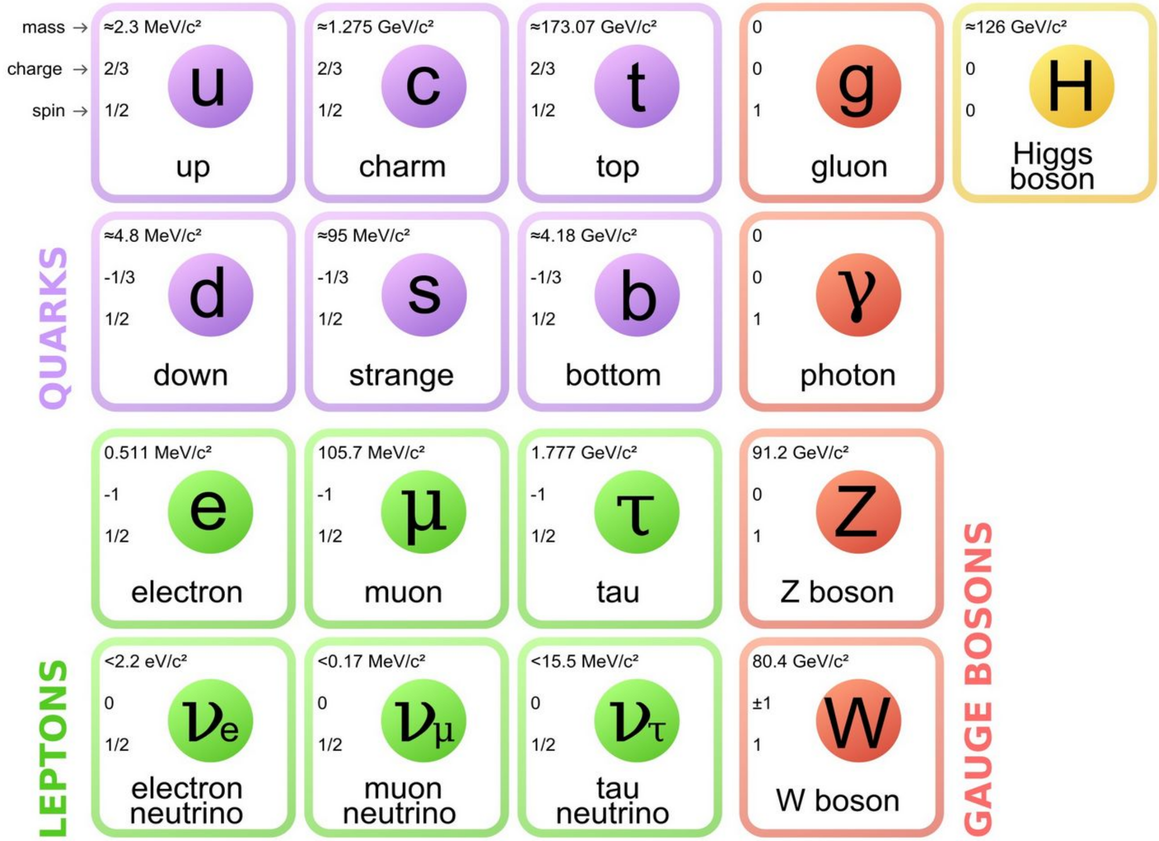
What to expect today!!

(Outline)

- Why do we need VBS?
- What is VBS?
- Different VBS processes
- Introduction to SMEFT
- Experimental overview
- What is CMS?
- My Analysis (Technical)
- Results from data analysis
- Results from SMEFT (phenomenological work)

Discovery of Higgs Boson

The Standard Model of particle physics



the Higgs: only one part of the full picture

going beyond the Higgs boson:

- Electroweak sector remains the least understood phenomena of the Standard Model

Beyond Standard Model

theoretical developments needed to explain the deficiencies of the Standard Model

Direct Searches for new Physics

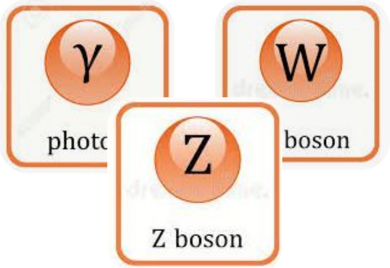
- Supersymmetry
- Long-lived particles
- Dark matter
- Heavy Resonances

Indirect Searches for new Physics

- Check for the standard model deviations.
- Measurement of the known quantities using High energy physics experiments.
  Ex: precise measurement of the properties of the Higgs boson
  study of the high-energy behaviour of W and Z bosons (VBS)

** **LHC ultimately plans to deliver an order of magnitude more collision data than ever but the center of mass energy of the collisions will not significantly increase anymore.**

Electroweak Sector

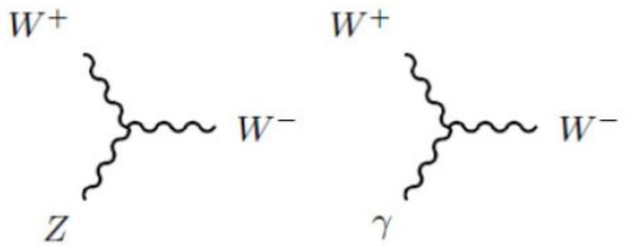


The electroweak gauge part of Standard Model

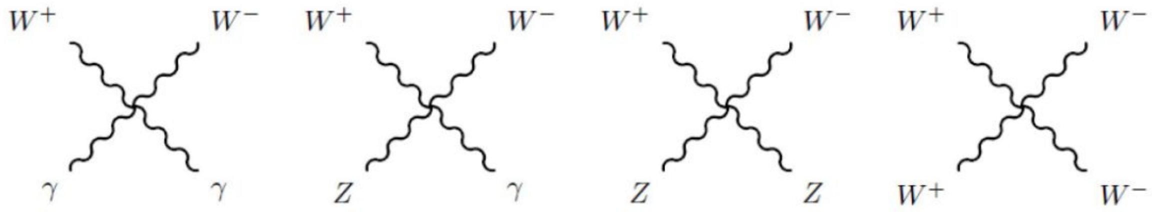
- 2 massive vector bosons: **$W^{\pm}$, Z**
- 1 massless vector boson: **γ**
- 2 triple gauge couplings: **WWγ**, **WWZ**
- 4 quartic gauge couplings: **WWWW**, **WWZZ**, **WWZγ**, **WWγγ**

All the above couplings, as well as W and Z masses, are completely determined by theory via the sole requirement of no tree-level divergences in any allowed processes.

Triple gauge couplings (TGC)



- **Quartic gauge couplings (QGC)**



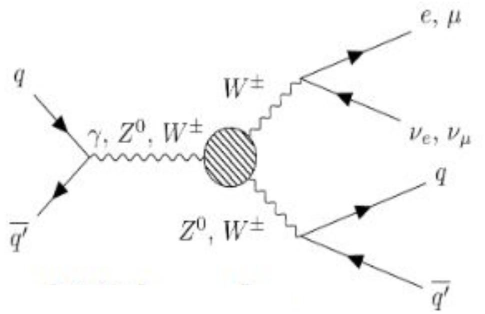
Anomalous (non-SM) couplings ⇔ **New (non-SM) particles**

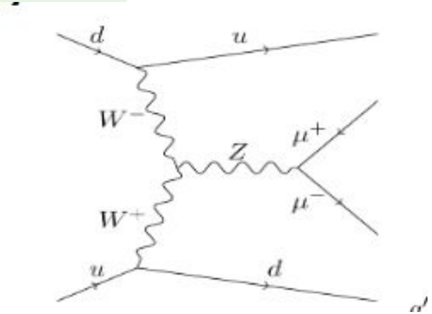
Presence of any new high-energy particle can significantly deviate the SM prediction of QGC.

Testing electroweak couplings at the LHC

Triple gauge couplings

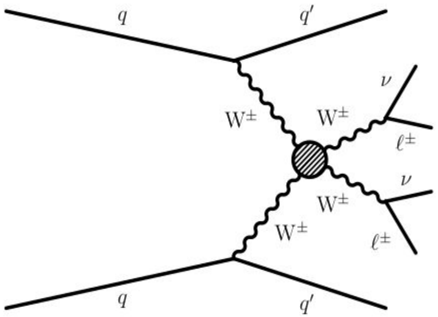
- Inclusive diboson production processes **(BEST)**
- Single boson production in Vector Boson Fusion (VBF) mode **(additional probe)**

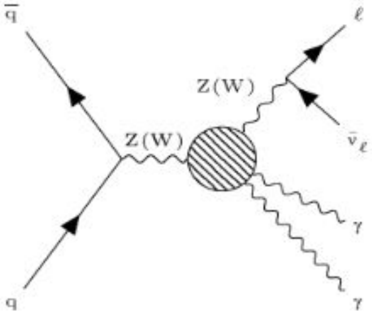




Quartic gauge couplings

- Vector Boson Scattering (VBS) **(BEST)**
- Inclusive triboson production processes **(additional probe)**

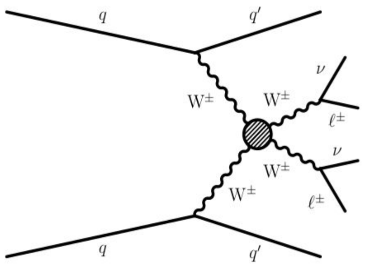




Vector Boson Scattering (VBS)

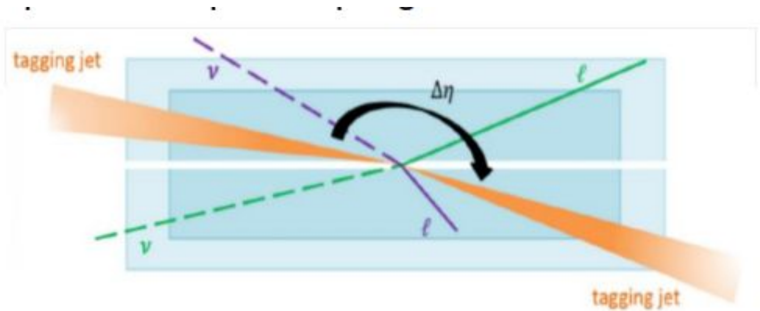
sensitive probe of quartic gauge couplings at the LHC

- VBS is a process of the type: $V\,V \rightarrow V\,V$ with vector-bosons $V = (W\pm, Z)$
- An event where two quarks from the high energy collision of protons, each radiates an electroweak vector-boson, which then scatter and decay.



General VBS topology

- purely electroweak
- 2 "tagging" jets with high mass and large separation



η is the pseudorapidity, a measure of angle along the beam axis

VBS Channels

Only listing the few important processes

V = W, Z

Channel	Fully Leptonic	Semi Leptonic	Fully Hadronic	Photonic
Final State	$W^\pm W^\pm \to \ell^\pm \nu \ell^\pm \nu$ $W^\pm W^\mp \to \ell^\pm \nu \ell^\mp \nu$ $WZ \to 3\ell\nu$ $WZ \to \ell 3\nu$ $ZZ \to 4\ell$ $ZZ \to 2\ell 2\nu$	$ZV \to 2\ell 2q$ $WV \to \ell\nu 2q$	$VV \to 4q$ $ZV \to 2\nu 2q$	$Z\gamma \to \ell^\pm \ell^\mp \gamma$ $Z\gamma \to 2\nu\gamma$ $W\gamma \to \ell\nu\gamma$ $V\gamma \to 2q\gamma$ $\gamma\gamma$

- Fully leptonic
  - **$W^\pm W^\pm \to l^\pm v l^\pm v$: best → This study**
  - $W^\pm Z \to$ 3lv: clean channel with three leptons
- Semi leptonic

  more difficult due to larger backgrounds
- Fully hadronic

  enormous multijet background produced
- Photonic

  Larger QCD background

the tool: **Standard Model Effective Field Theory**

theoretical framework used to study possible deviations from the SM in a model-independent way

Extension of the SM Lagrangian by introduction additional dimension-8 operators for QGCs

$$\mathcal{L}_{\rm Eff} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \frac{1}{\Lambda^3}\mathcal{L}_7 + \frac{1}{\Lambda^4}\mathcal{L}_8 + \cdots , \qquad \mathcal{L}_d = \sum_i c_i^{(d)} \mathcal{O}_i^{(d)}$$

Oi – higher-dimensional operators invariant under SM,
of dimensionalities d higher than 4,
suppressed by appropriate powers
of Λ – **the energy scale of new physics**,

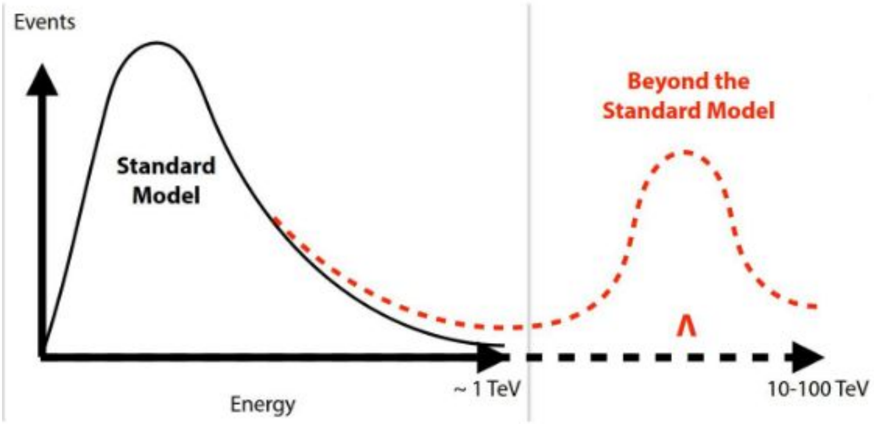
ci – dimensionless Wilson coefficients.

There are total 18 dimension-8 operators for aQGCs to parameterize hypothetical BSM interactions

18 dimension-8 operators S0-2, M0-7, T0-9 (18 in total) for aQGCs

Where is the problem!!

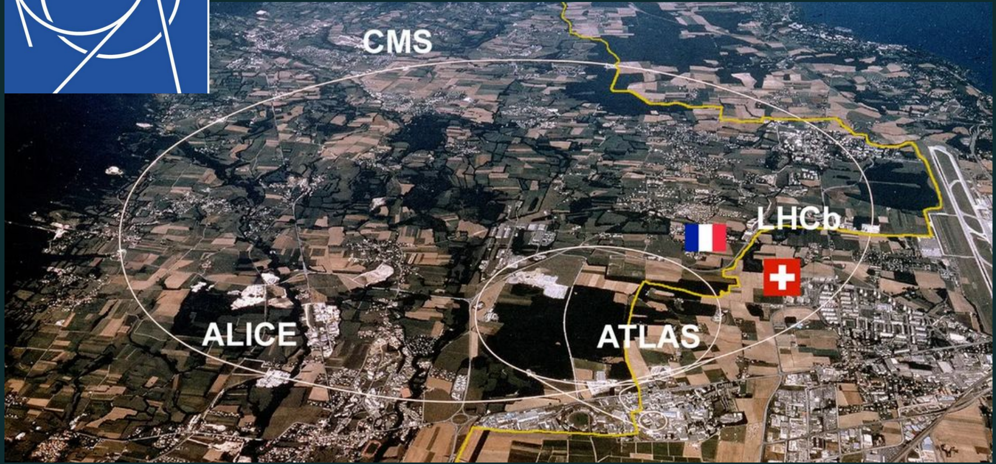
EFT validity issue
the value of parameter Λ(maximum range of validity) of the expansion, is not known in advance



Cutoff scale Λ

The Large Hadron Collider (LHC)

CERN

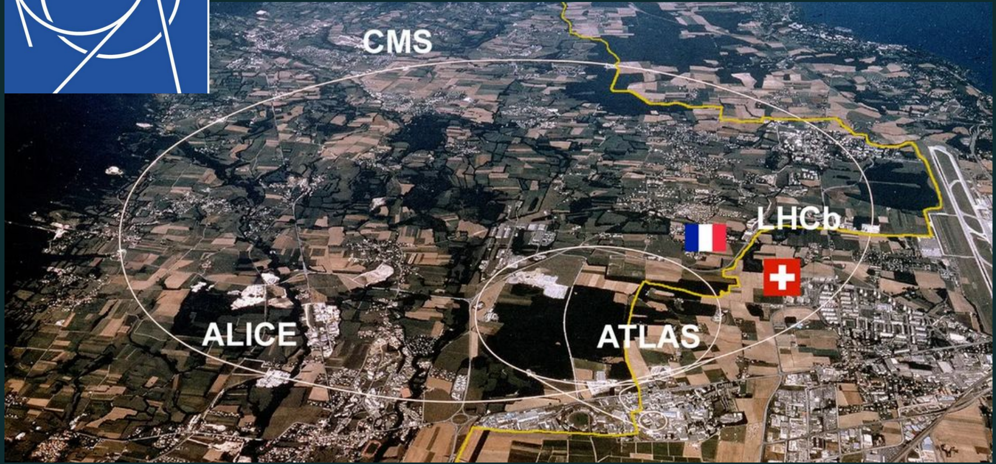


The four detectors of LHC

27-km Large Hadron Collider (LHC) is the largest and most powerful particle accelerator ever built

The Large Hadron Collider (LHC)

CERN

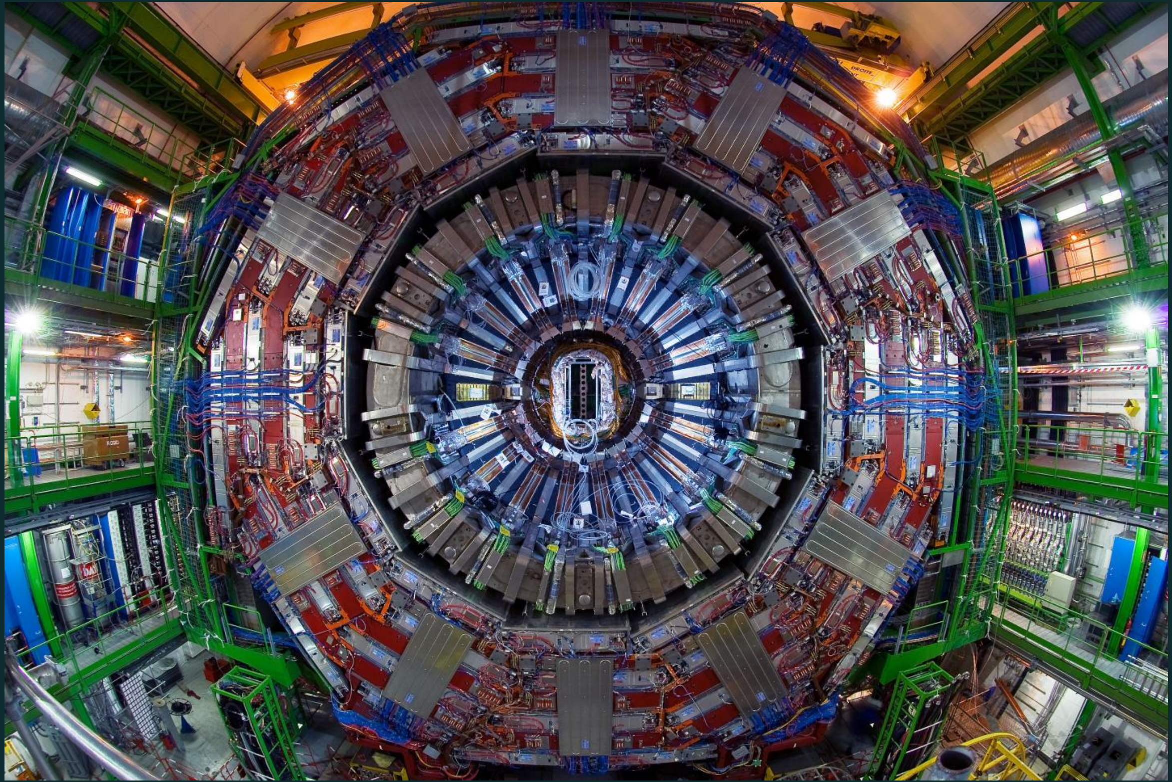


The four detectors of LHC

27-km Large Hadron Collider (LHC) is the largest and most powerful particle accelerator ever built

LHC luminosity plans

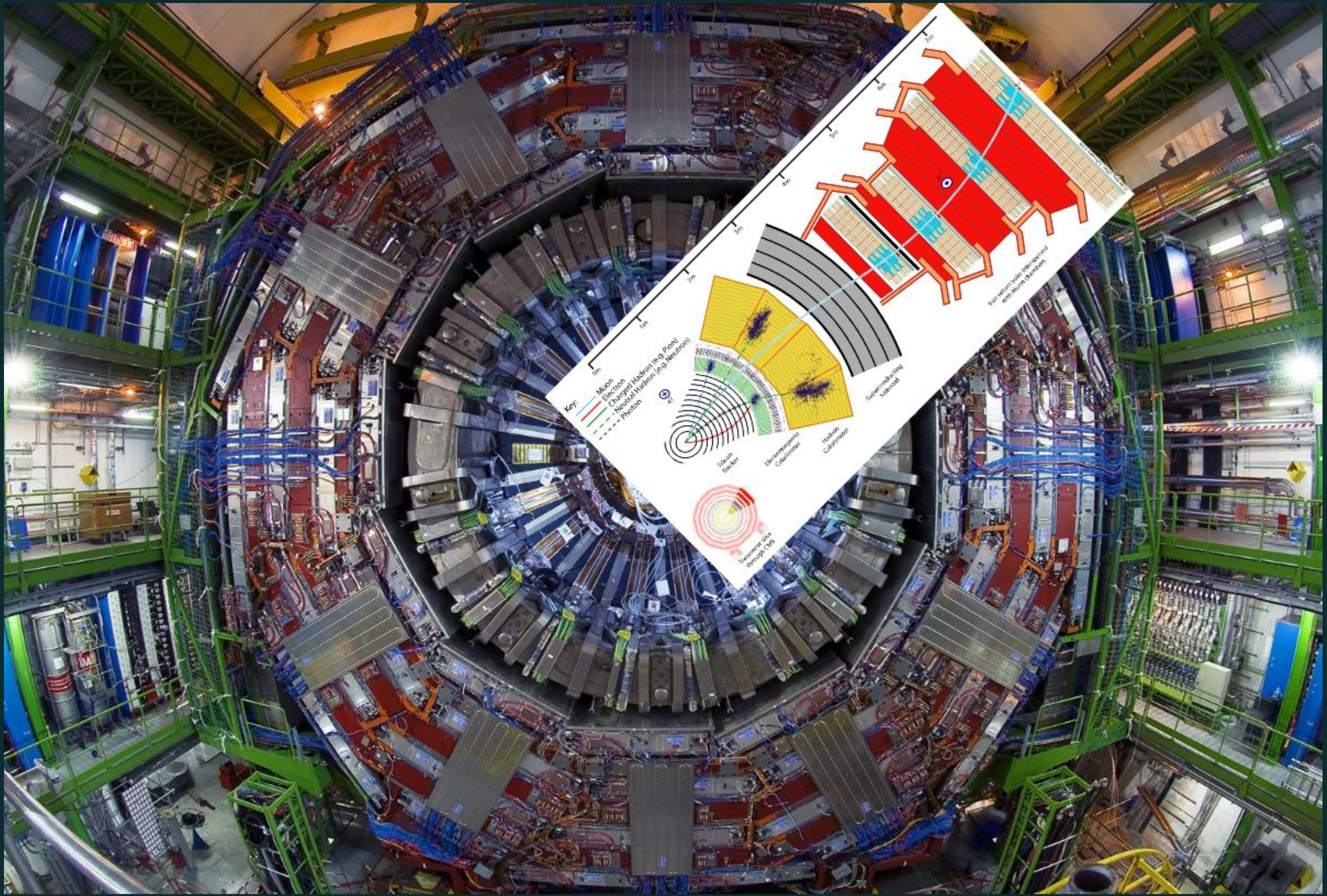
The Compact Muon Solenoid (CMS)



14,000-tonne detector
100 meters underground
Designed to detect particles known as **muons** very accurately; and it has the most powerful **solenoid** magnet ever made.

The Compact Muon Solenoid (CMS)

Detecting particles



Experimental Overview

What do we have??

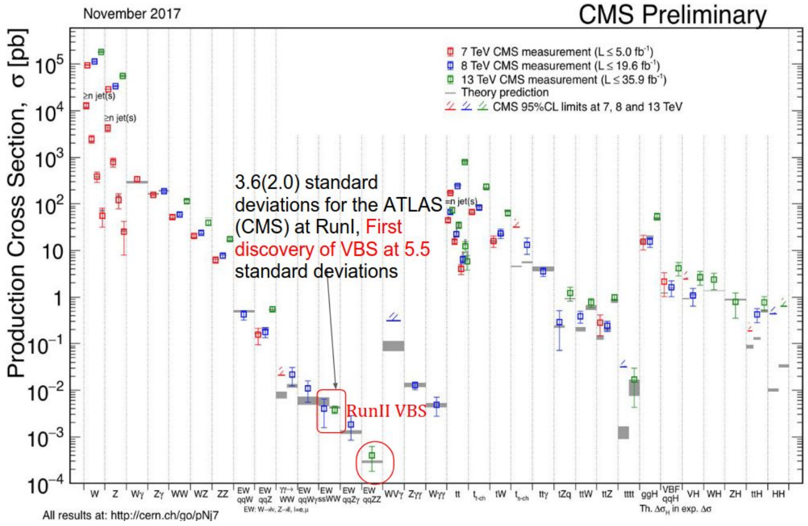
Results from Run 2 includes

- diboson production cross sections WW, WZ, ZZ, Wγ, Zγ, WV,
- electroweak diboson (VBS) cross sections ssWW, WZ, ZZ, Wγ, Zγ, WV+ZV, osWW
- study of quartic gauge couplings – limits have been put on all 18 relevant SMEFT dim-8 operators

Improvements from Run 2 !!

- Improve statistical precision by collecting more data
- Experimental improvements
- Introduction to new improved particle IDs for the leptons
- Methodological improvements: better understanding of backgrounds (new method)
- Improvements in SMEFT interpretations

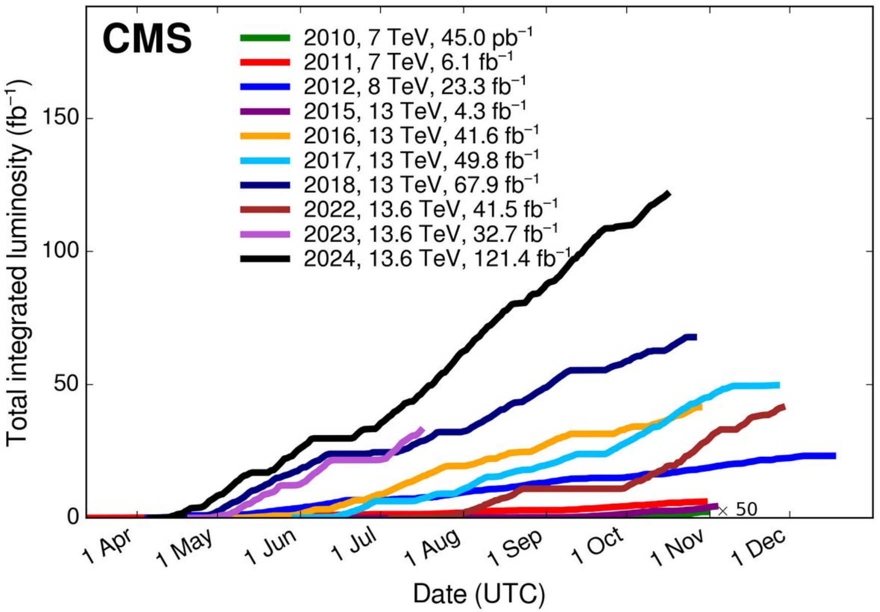
2012 was not just important for Higgs but!!



Experimental improvements

Data collected in Run 3 > Data collected in (Run 1 + Run 2)

- Increased Collision Energy
- Higher Luminosity
- LHC Injector Upgrade (LIU) Project
- CMS upgraded its tracking system and calorimeters
- Upgraded trigger systems to handle larger data
- larger volumes of data for analysis



Credit: twiki.cern.ch

Analysis Data formats in CMS today

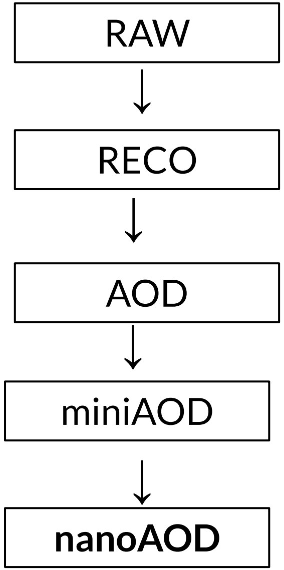
RAW → full event information, consists of detector info, nor used for Analysis

RECO → reconstructed data, contains physics objects with many details stored [hits, etc..]

AOD (Analysis Object Data) → a subset of RECO data tier. Used for physics analyses in Run 1, Run 2

miniAOD → default datatier for the Run 2 analyses

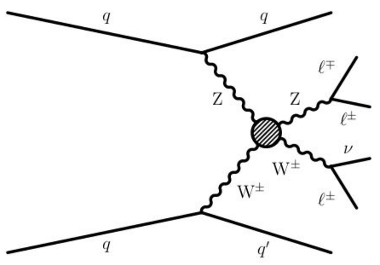
nanoAOD → light weight data tier introduced in 2017, Run 3 analyses



** Due to the change in the data format, to write and implement new version of codes is one of the major task for this analysis and also to determine the new most suitable cuts.

Backgrounds in ssWW processes

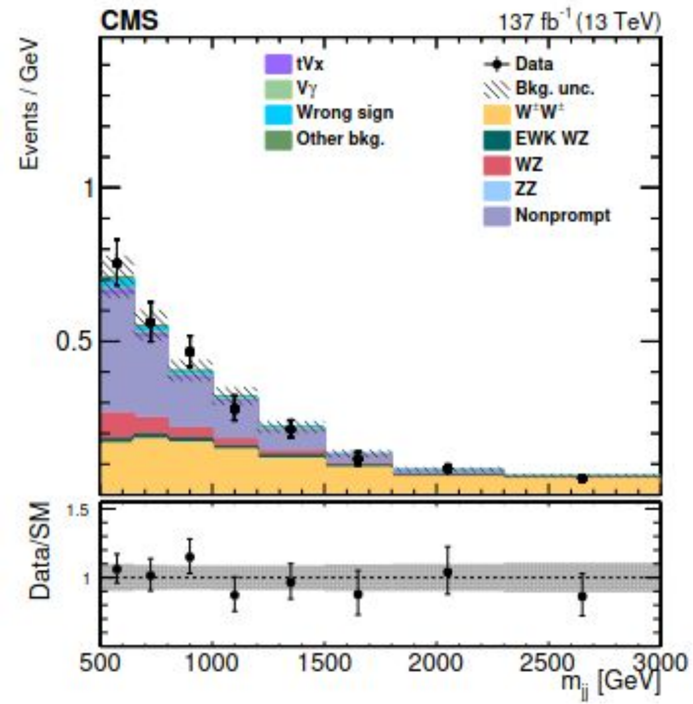
Reducible vs Irreducible backgrounds



Reducible Backgrounds

Non-prompt leptons (Improvements introduced)

- Signal → prompt leptons from W and Z decays
- Background → non-prompt leptons from Photon conversions or Hadron decays or any misidentified objects.

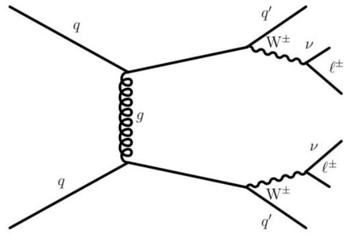


EW induced and QCD induced WZ processes

- One of the lepton from Z decay can be misidentified as from the decay of W boson.

Opposite sign leptons

- charge misidentification of one of the leptons, making an opposite-sign pair (OS) appear as a same-sign pair (detector reconstruction).



Irreducible Backgrounds

QCD induced ssWW processes

- Similar final states

Reducible Backgrounds

Non-prompt leptons (Improvements introduced)

- Signal → prompt leptons from W and Z decays
- Background → non-prompt leptons from Photon conversions or Hadron decays or any misidentified objects.
- Main Source of background in VBS studies.

Standard Method

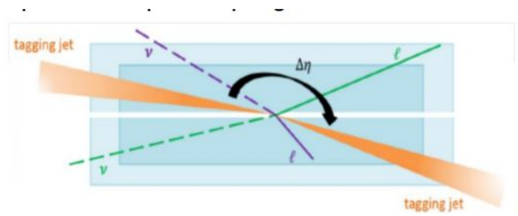
- Highly depended on MC simulations.
- Backgrounds were all generated from the MC samples
- Lepton isolation is a challenging process, and Monte Carlo simulations are not always adequate for handling such backgrounds.

New Method

- Less reliance of MC simulations
- we extract only one parameter from MC
- More effective results

Region of Interest (VBS Region ssWW)

- 2 leptons
- 2 neutrinos
- 2 jets



Jets:

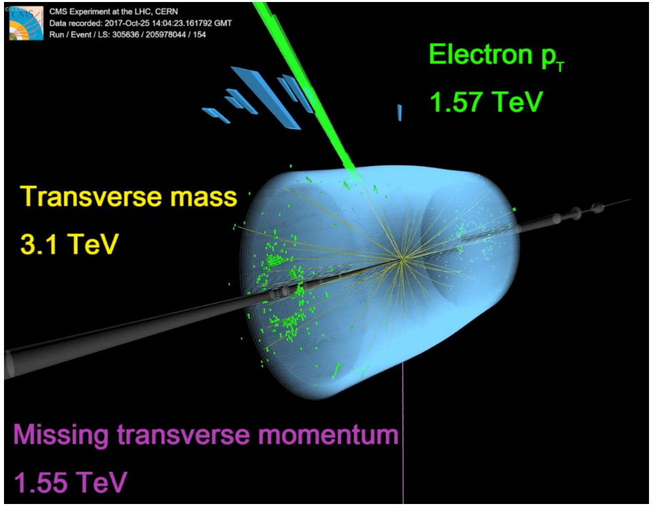
collimated streams of particles that result from the hadronization of quarks and gluons

VBS jets:

invariant mass of the two leading jets > 500 GeV (jets from high energy processes)
diff(jet_eta_1 - jet_eta_2) >2.5 (sufficient separation in rapidity)
Zeppenfeld variable < 1.0 (centrally located lepton)

Neutrinos:

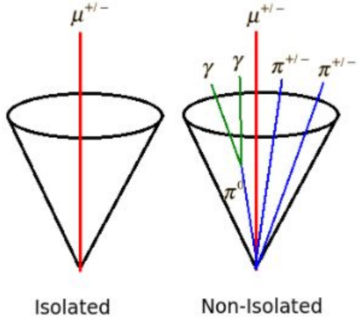
No direct detection
Missing transverse momentum
MET_pt > 30 GeV (significant amount of missing energy)



Credit: cds.cern.ch

Lepton identification

To distinguish between signal and non-prompt background
New physics phenomena can only be discovered when the interesting hard scatter events are properly identified.



Lepton Isolation (important)

To identify if a lepton is coming from a gauge boson

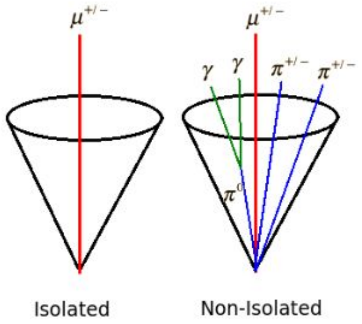
- Select a particle of interest (e.g., an electron or muon).
- Around this particle, we define a **cone** in **η-φ space**.
- Sum up the energies or transverse momenta of all the particles within this cone, excluding the particle of interest itself.

$$\text{Relative Isolation} = \frac{\sum_{\text{particles in cone}} p_T}{p_T^{\text{lepton}}} < \text{some threshold}$$

η is the pseudorapidity, a measure of angle along the beam axis, and
φ is the polar angle perpendicular to the beam axis

Lepton identification

To distinguish between signal and non-prompt background
New physics phenomena can only be discovered when the interesting hard scatter events are properly identified.



Lepton Isolation (important)

To identify if a lepton is coming from a gauge boson

- Select a particle of interest (e.g., an electron or muon).
- Around this particle, we define a **cone** in **η-φ space**.
- Sum up the energies or transverse momenta of all the particles within this cone, excluding the particle of interest itself.

$$\text{Relative Isolation} = \frac{\sum_{\text{particles in cone}} p_T}{p_T^{\text{lepton}}} \quad < \quad \text{some threshold}$$

Lepton Identification cuts in CMS

Traditional Flags

cutBased

Applying cuts on
Diff variables e.x, Transverse moementum, isolation etc

New Flags

Machine Learning (MVA)

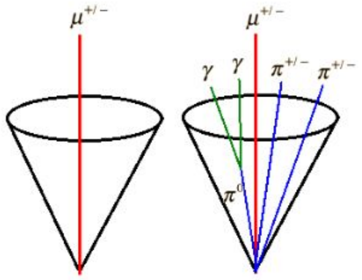
for better background rejection
Additional variables e.x, shower shape etc

η is the pseudorapidity, a measure of angle along the beam axis, and
φ is the polar angle perpendicular to the beam axis

**Every possible combinations of cuts were used to find the best cut suited for the study of VBS

Lepton identification

To distinguish between signal and non-prompt background
New physics phenomena can only be discovered when the interesting hard scatter events are properly identified.

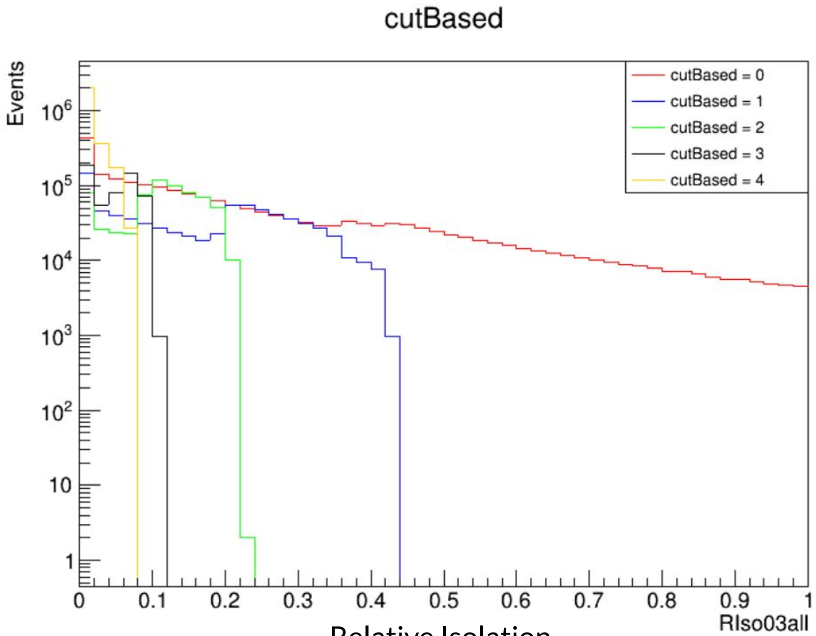


Lepton Isolation (important)

To identify if a lepton is coming from a gauge boson

- Select a particle of interest (e.g., an electron or muon).
- Around this particle, we define a **cone** in **η-φ space**.
- Sum up the energies or transverse momenta of all the particles within this cone, excluding the particle of interest itself.

$$\text{Relative Isolation} = \frac{\sum_{\text{particles in cone}} p_T}{p_T^{\text{lepton}}} < \text{some threshold}$$



Relative Isolation
Where R = 0.3

Lepton Identification cuts in CMS

Traditional Flags

cutBased

Applying cuts on
Diff variables e.x, Transverse momentum, isolation etc

New Flags

Machine Learning (MVA)

for better background rejection
Additional variables e.x, shower shape etc

η is the pseudorapidity, a measure of angle along the beam axis, and
φ is the polar angle perpendicular to the beam axis

**Every possible combinations of cuts were used to find the best cut suited for the study of VBS

Rejection of Non-prompt background

Loose leptons: Electron_cutbased >= 1
Loose muon ID

Tight leptons: loose selections +
Electron_cutBased >= 2
Cuts from MultiVariate Analysis

Loose = pass && tight = pass → Tight lepton
Loose = pass && tight = fail → Fail lepton

Three types of events:

1) Tight+Tight (TT)
2) Tight+Fail (TF)
3) Fail+Fail (FF)

**Every possible combinations of cuts were used to find the best cut suited for the study of VBS
**Only mentioning the important cuts

Rejection of Non-prompt background

Loose leptons: Electron_cutbased >= 1
Loose muon ID

Tight leptons: loose selections +
Electron_cutBased >= 2
Cuts from MultiVariate Analysis

Loose = pass && tight = pass → Tight lepton
Loose = pass && tight = fail → Fail lepton

Three types of events:

1) Tight+Tight (TT)
2) Tight+Fail (TF)
3) Fail+Fail (FF)

ϵ = fakerate (probability for a non-prompt lepton to pass the tight criteria)

δ = promptrate (probability for a prompt lepton to fail the tight criteria)

New Method (background rejection)

The observed and true numbers of events in each category relate to each other like:

$$\begin{pmatrix} TT \\ TF \\ FT \\ FF \end{pmatrix} = \begin{pmatrix} (1-\delta_1)(1-\delta_2) & (1-\delta_1)\varepsilon_2 & \varepsilon_1(1-\delta_2) & \varepsilon_1\varepsilon_2 \\ (1-\delta_1)\delta_2 & (1-\delta_1)(1-\varepsilon_2) & \varepsilon_1\delta_2 & \varepsilon_1(1-\varepsilon_2) \\ \delta_1(1-\delta_2) & \delta_1\varepsilon_2 & (1-\varepsilon_1)(1-\delta_2) & (1-\varepsilon_1)\varepsilon_2 \\ \delta_1\delta_2 & \delta_1(1-\varepsilon_2) & (1-\varepsilon_1)\delta_2 & (1-\varepsilon_1)(1-\varepsilon_2) \end{pmatrix} \begin{pmatrix} PP \\ PN \\ NP \\ NN \end{pmatrix}$$

from which we find

$$PP = \sum_{TT} \frac{(1-\varepsilon_1)(1-\varepsilon_2)}{(1-\varepsilon_1-\delta_1)(1-\varepsilon_2-\delta_2)} - \sum_{TF+FT} \frac{(1-\varepsilon_T)\varepsilon_F}{(1-\varepsilon_T-\delta_T)(1-\varepsilon_F-\delta_F)} + \sum_{FF} \frac{\varepsilon_1\varepsilon_2}{(1-\varepsilon_1-\delta_1)(1-\varepsilon_2-\delta_2)},$$

The summation runs over the TT, TF+FT and FF events
PP: prompt-prompt leptons

After calculating PP, the signal can be estimated as:
Nsignal = (1-δ)2PP

**Every possible combinations of cuts were used to find the best cut suited for the study of VBS
**Only mentioning the important cuts

Computing fakerate (Data Driven Method)

Data-driven method relies heavily on the use of real experimental data, rather than solely on theoretical simulations (Monte Carlo).

Non prompt leptons passing the tight criteria

Leptons from Photon conversions or Hadron decays or any misidentified objects

Dedicated Dijet Selection (Non VBS region)

- Missing transverse momentum < 30 GeV
- No. of jets in an event >= 1

Apply lepton “loose” criteria, same as that of VBS selection to create a new sample of loose lepton in this region (Events with single “loose” lepton).

To the events with single loose lepton, following filters are applied;

- Transverse mass (loose lepton and missing Et_vector) < 20 GeV
- If electron is not associated with the jet, no of jets present in the event >= 1
- If electron is associated with the jet, no of jets present in the event >= 2

Implementation of Tight criteria; Same as the VBS selection.

Here, the leptons that pass the tight criteria are not real prompt leptons.

Backgrounds in dijet selection (MC Samples)

W+jets

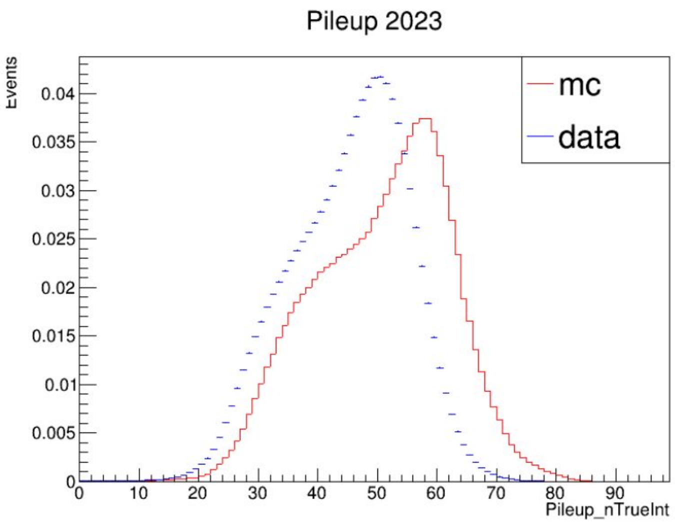
Drell-Yan processes

Comparing data with monte carlo simulations

Luminosity Normalization

- Luminosity normalization adjusts the **event yield** from simulations to match the actual number of events expected based on the collected data in CMS.

$$N' = \frac{\mathcal{L}_{\text{int}} \times \sigma_{\text{process}}}{N_{\text{total}}}$$



Pileup Reweighting

- In **luminosity operations**, we use "pileup" to refer to the total number of pp interactions in same bunch crossing.
- In **MC generation**, "pileup" refers to the number of additional interactions added to the primary hard-scatter process.

Why Pileup Correction!!

- To correct for the difference between the actual pileup in data and the pileup modeled in Monte Carlo (MC) simulations.
- Without reweighting, MC predictions may not accurately reflect the conditions in the actual CMS detector, leading to biases in physics measurements.

** The weights are calculated as data/mc and the weights are applied to the respective mc samples as a function of Pileup_nTrueInt (True number of the interactions).

Dedicated dijet selection

Backgrounds in dijet selection (MC Samples)

- W+jets
- Drell-Yan processes

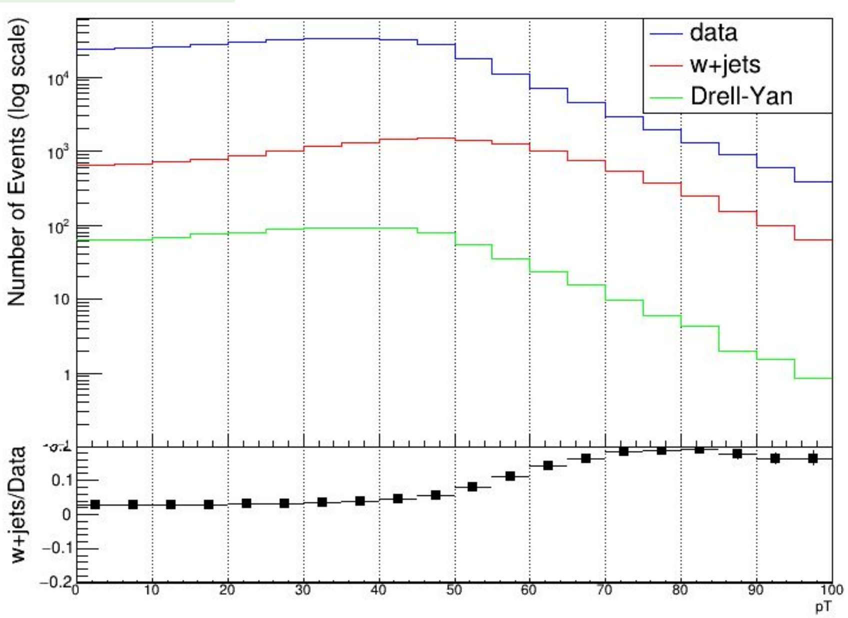


Fig: Backgrounds in Dijet Selection

Dedicated dijet selection

Backgrounds in dijet selection (MC Samples)

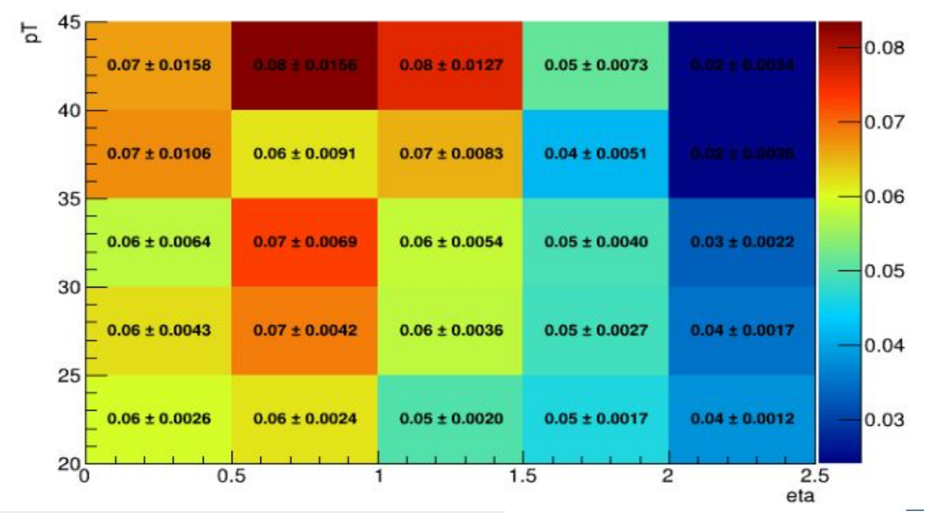
W+jets

Drell-Yan processes

Fakerate

Probability for a non-prompt lepton to pass tight selection criteria

$$\epsilon = \frac{Tight_{electrons} - Wjets\,Tight_{electrons} - DY\ Tight_{electrons}}{Loose_{electrons} - Wjets\ Loose_{electrons} - DY\ Loose_{electrons}}$$



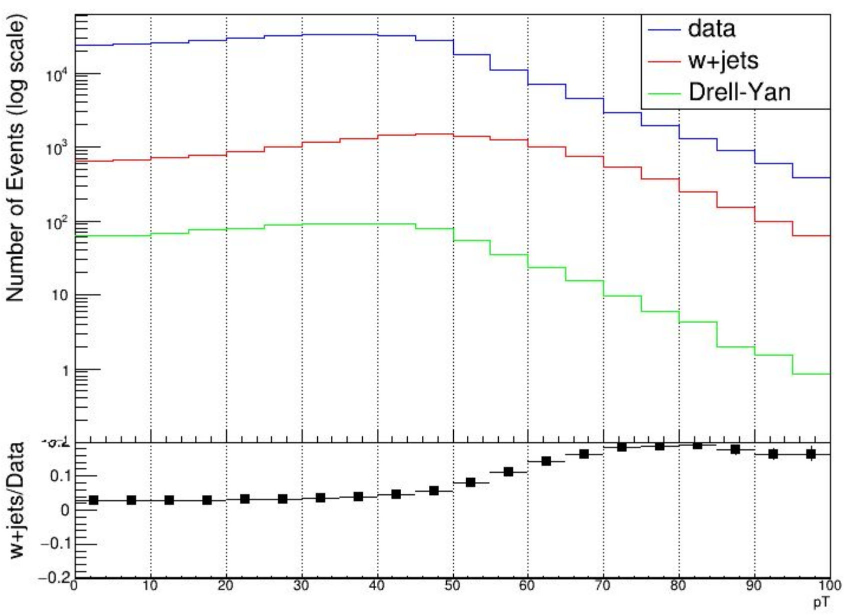
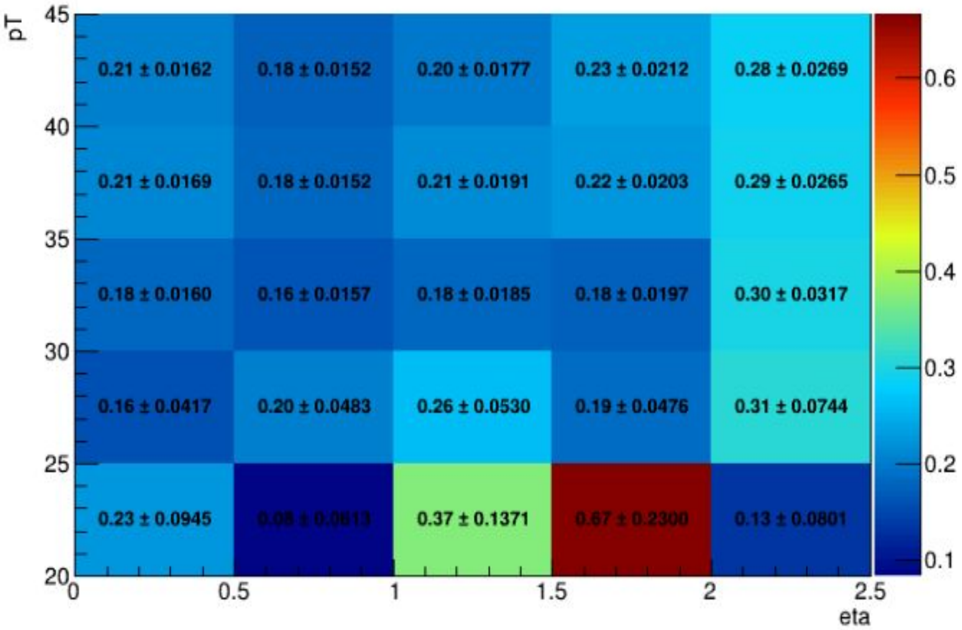


Fig: Backgrounds in Dijet Selection

Prompt rate

Probability for a prompt lepton to fail tight selection criteria

VBS cuts are used in a clean **signal Monte Carlo** sample to check if a real (good) prompt lepton is failing the tight criteria.



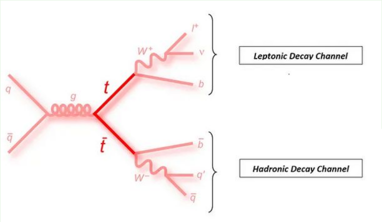
Selecting Events:

- All the VBS cut previously used are used here
- The loose, tight and fail leptons are selected as before
- For each event with 1 electron: Select the events passing loose criteria

Select the events passing the fail criteria
Final division: Fail/Loose

$$\delta = \text{fail lepton / loose lepton}$$

Correctness of the New Method



Monte Carlo Samples

Sample similar to experimental data

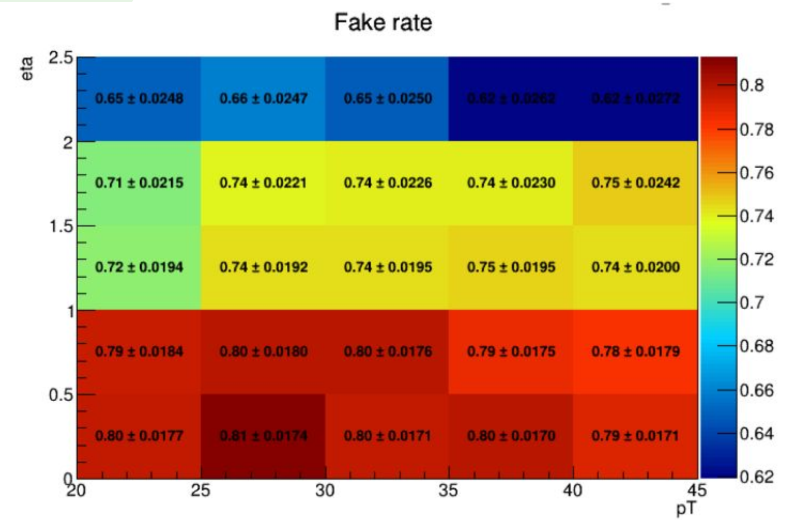
- ssWW sample (signal)
- ttbar sample (background)

Dijet Selection applied on the ttbar sample

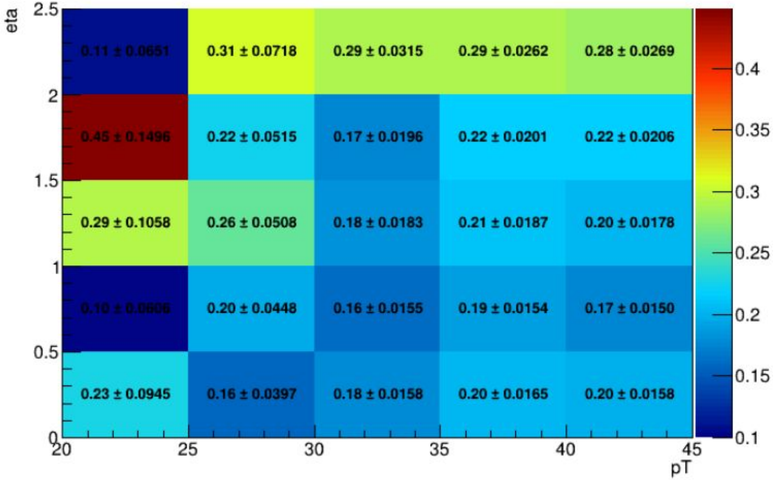
- Calculating the fake rate

Purely Signal Sample (ssWW)

- Calculating the prompt rate



Prompt rate



Expectation:

Since the signal and the background is known the observed and the N_{signal} events should be same.

Result:

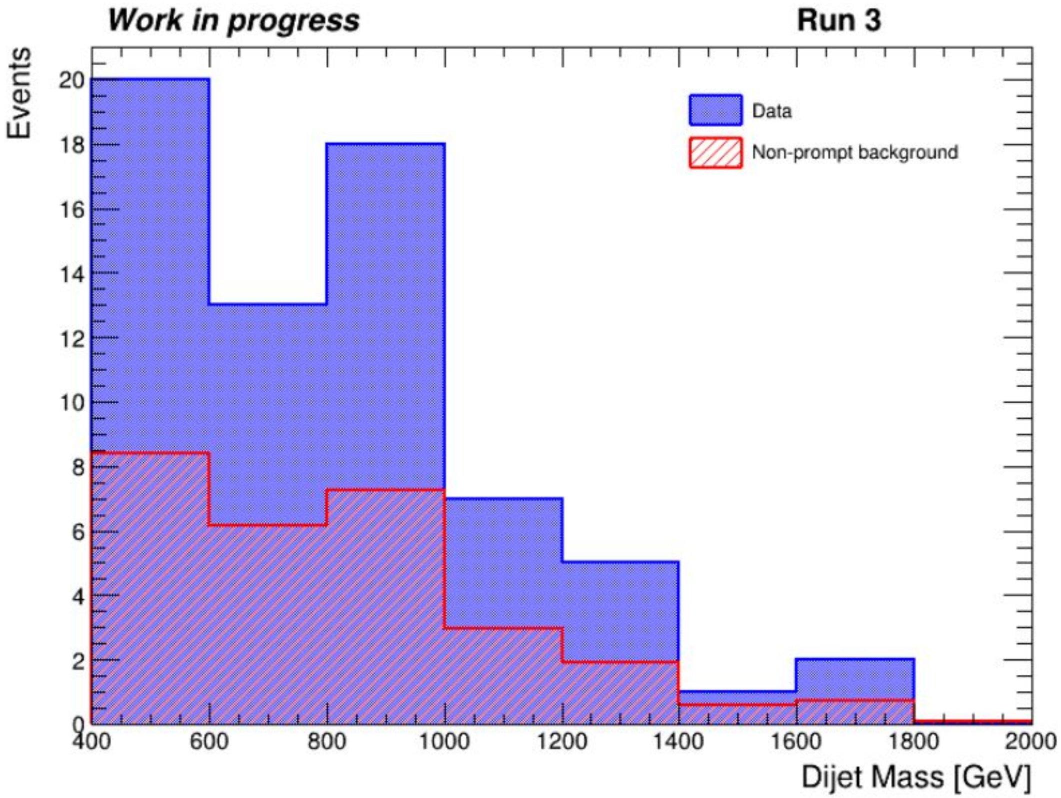
TT = 8775

N_{signal} = 8704.27

Non-prompt background

Data Used: Only half a portion of the data from 2023
Reason: to check the correctness of the method

Only electron-electron events are considered
The background is only from the non-prompt electrons



Standard Model Effective Field Theory

total cross section of a process in the EFT framework can be written down as a coherent sum of three terms

$$\sigma \propto |\mathcal{A}_{\text{full}}|^2 = |\mathcal{A}_{\text{SM}}|^2 + 2\Re(\mathcal{A}_{\text{SM}}\mathcal{A}^*_{\text{dim-8}}) + |\mathcal{A}_{\text{dim-8}}|^2$$

We expect BSM effects be dominated by the interference term, otherwise it is not justified to truncate the expansion at this order.

$\sim \frac{c^2}{\Lambda^4}$ $\sim \frac{c^2}{\Lambda^8}$

Interference issue

interference may dominate only in a restricted kinematic range

Goal of this study

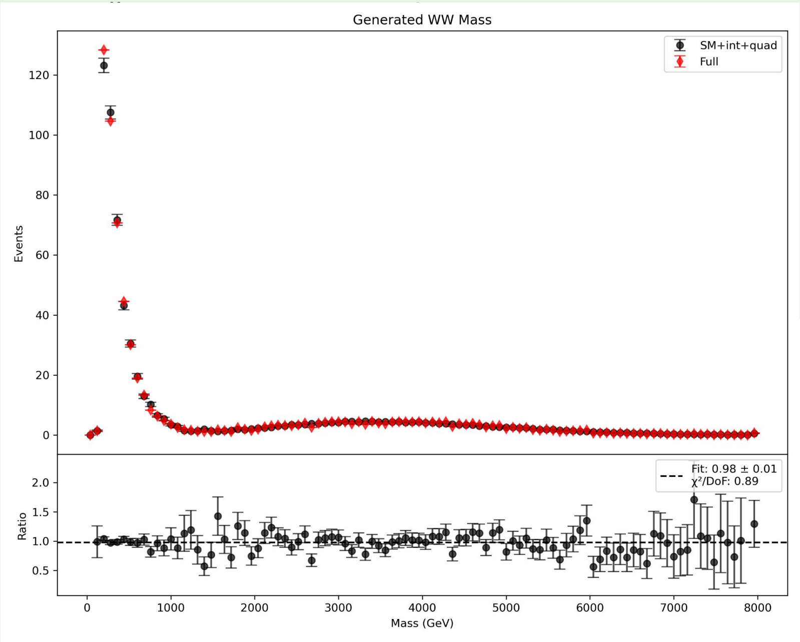
- Compare relative contributions from interference and quadratic terms
- Study interference term in details
- Enhance our sensitivity to interference term

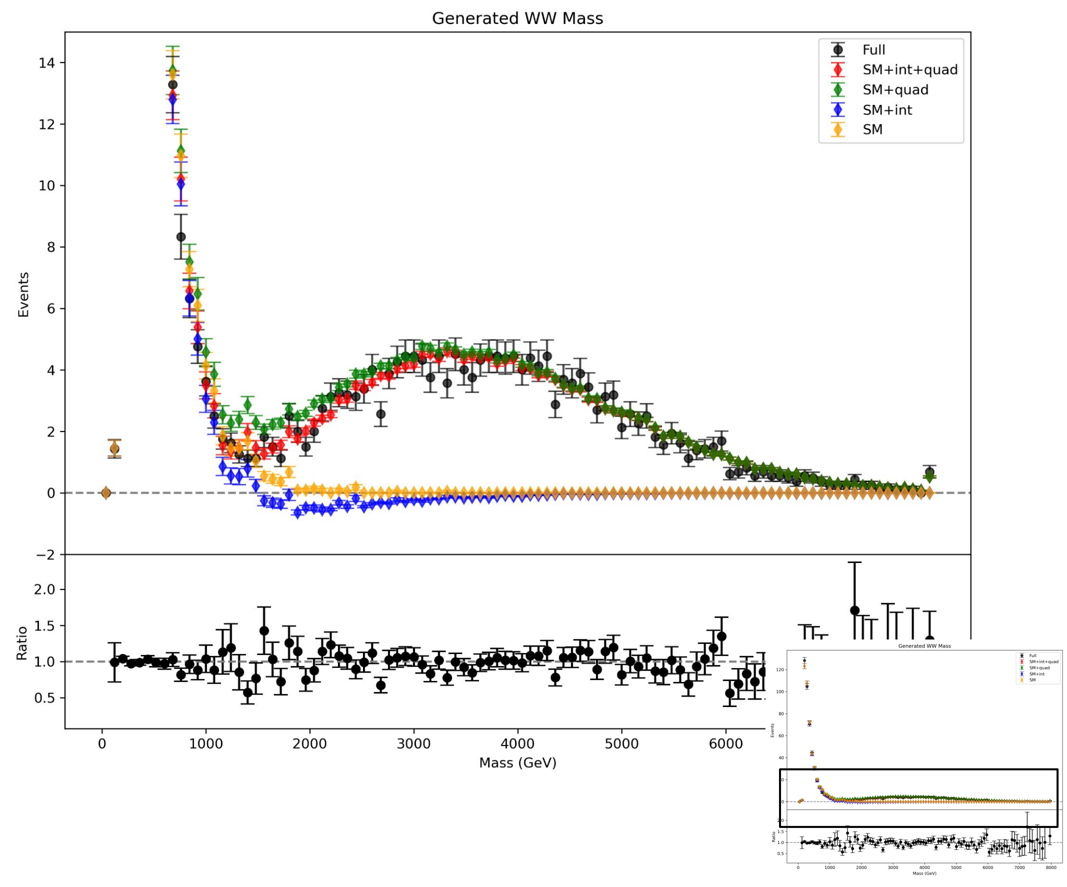
Gap in CMS Analysis:

Partially studied for aTGCs
Never for aQGCs

Standard Model Effective Field Theory

Monte Carlo Samples: MadGraph 2.9.7(Simulation tool)
Separate samples for : SM, quadratic term, interference term
And full sample.
Analyse: ssWW events
Samples with consistent value of T2 operator : 2.0 TeV-4





Higher contribution from quadratic term in higher Invariant mass region.

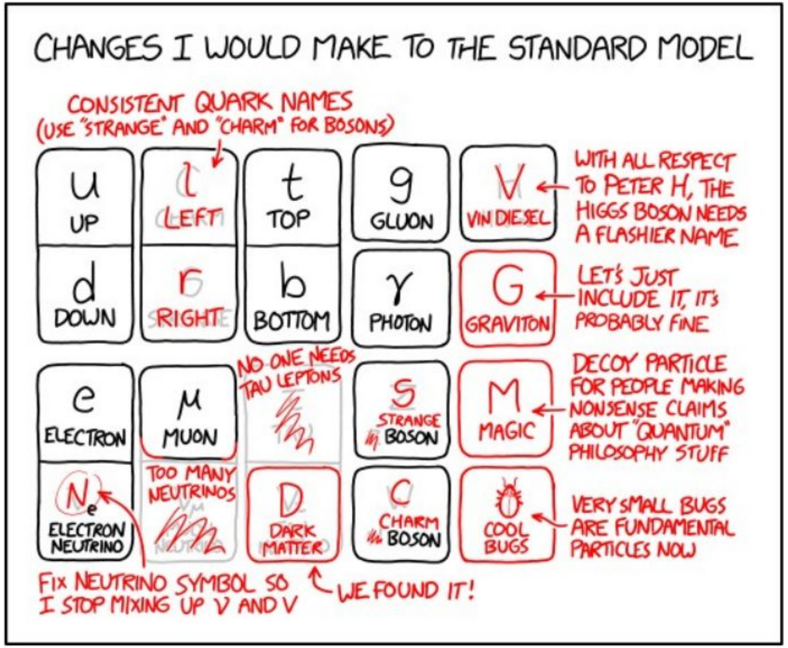
Conclusion

- Study of VBS processes using ssWW channels
- Implemented a new method for correcting non-prompt backgrounds
- Used MCs to check the correctness of the new method
- Produced some of the initial results from SMEFT

What's Next!! (Work in progress)

- Interference may dominate only in a restricted kinematic range
- Study interference: where is it positive, where is it negative?
- Adding muons to the experimental analysis
- Taking WZ processes into account

Thank you



Backup

Variables on NanoAOD v12

that can be used to define tight and loose (fake) leptons

- **For muons:**

Muon_looseId	muon is loose muon
Muon_mediumId	cut-based ID, medium WP
Muon_tightId	cut-based ID, tight WP
Muon_mvaMuID	MVA-based ID score
Muon_mvaMuID_WP	MVA-based ID selector Wps (1=MVAIDwpMedium,2=MVAIDwpTight)
Muon_pfIsoId	PFIso ID from miniAOD selector (1-6)
Muon_pfRelIso03_all	PF relative isolation dR=0.3, total (deltaBeta corrections)
Muon_pfRelIso03_chg	PF relative isolation dR=0.3, charged component
Muon_pfRelIso04_all	PF relative isolation dR=0.4, total (deltaBeta corrections)
Muon_dxy	dxy (with sign) wrt first PV, in cm
Muon_dz	dz (with sign) wrt first PV, in cm
Muon_tightCharge	Tight charge criterion using pterr/pt of muonBestTrack (0:fail, 2:pass)

- **For electrons:**

Electron_cutBased	cut-based ID RunIII Winter22 (0:fail, 1:veto, 2:loose, 3:medium, 4:tight)
Electron_mvaIso	MVA Iso ID score, Winter22V1
Electron_mvaIso_WP80	MVA Iso ID WP80, Winter22V1
Electron_mvaIso_WP90	MVA Iso ID WP90, Winter22V1
Electron_pfRelIso03_all	PF relative isolation dR=0.3, total (with rho*EA PU Winter22V1 corrections)
Electron_pfRelIso03_chg	PF relative isolation dR=0.3, charged component
Electron_dxy	dxy (with sign) wrt first PV, in cm
Electron_dz	dz (with sign) wrt first PV, in cm
Electron_tightCharge	Tight charge criteria (0:none, 1:isGsfScPixChargeConsistent, 2:isGsfCtfScPixChargeConsistent)
Electron_convVeto	pass conversion veto

SMEFT dimension-8 operators for aQGCs

Eboli, Gonzalez-Garcia, *arXiv:1604.03555*

S (scalar) operators,
affect longitudinal polarizations

$$\mathcal{O}_{S,0} = \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D^\mu\Phi)^\dagger D^\nu\Phi\right]$$

$$\mathcal{O}_{S,1} = \left[(D_\mu\Phi)^\dagger D^\mu\Phi\right] \times \left[(D_\nu\Phi)^\dagger D^\nu\Phi\right]$$

$$\mathcal{O}_{S,2} = \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D^\nu\Phi)^\dagger D^\mu\Phi\right]$$

T operators, affect
transverse polarizations (dominant)

$$\mathcal{O}_{T,0} = \text{Tr}\left[\widehat{W}_{\mu\nu}\widehat{W}^{\mu\nu}\right] \times \text{Tr}\left[\widehat{W}_{\alpha\beta}\widehat{W}^{\alpha\beta}\right]$$

$$\mathcal{O}_{T,1} = \text{Tr}\left[\widehat{W}_{\alpha\nu}\widehat{W}^{\mu\beta}\right] \times \text{Tr}\left[\widehat{W}_{\mu\beta}\widehat{W}^{\alpha\nu}\right]$$

$$\mathcal{O}_{T,2} = \text{Tr}\left[\widehat{W}_{\alpha\mu}\widehat{W}^{\mu\beta}\right] \times \text{Tr}\left[\widehat{W}_{\beta\nu}\widehat{W}^{\nu\alpha}\right]$$

$$\mathcal{O}_{T,5} = \text{Tr}\left[\widehat{W}_{\mu\nu}\widehat{W}^{\mu\nu}\right] \times \widehat{B}_{\alpha\beta}\widehat{B}^{\alpha\beta}$$

$$\mathcal{O}_{T,6} = \text{Tr}\left[\widehat{W}_{\alpha\nu}\widehat{W}^{\mu\beta}\right] \times \widehat{B}_{\mu\beta}\widehat{B}^{\alpha\nu}$$

$$\mathcal{O}_{T,7} = \text{Tr}\left[\widehat{W}_{\alpha\mu}\widehat{W}^{\mu\beta}\right] \times \widehat{B}_{\beta\nu}\widehat{B}^{\nu\alpha}$$

$$\mathcal{O}_{T,8} = \widehat{B}_{\mu\nu}\widehat{B}^{\mu\nu}\widehat{B}_{\alpha\beta}\widehat{B}^{\alpha\beta}$$

$$\mathcal{O}_{T,9} = \widehat{B}_{\alpha\mu}\widehat{B}^{\mu\beta}\widehat{B}_{\beta\nu}\widehat{B}^{\nu\alpha}$$

M operators, affect mixed polarizations

$$\mathcal{O}_{M,0} = \text{Tr}\left[\widehat{W}_{\mu\nu}\widehat{W}^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right]$$

$$\mathcal{O}_{M,1} = \text{Tr}\left[\widehat{W}_{\mu\nu}\widehat{W}^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right]$$

$$\mathcal{O}_{M,2} = \left[\widehat{B}_{\mu\nu}\widehat{B}^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right]$$

$$\mathcal{O}_{M,3} = \left[\widehat{B}_{\mu\nu}\widehat{B}^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right]$$

$$\mathcal{O}_{M,4} = \left[(D_\mu\Phi)^\dagger \widehat{W}_{\beta\nu} D^\mu\Phi\right] \times \widehat{B}^{\beta\nu}$$

$$\mathcal{O}_{M,5} = \left[(D_\mu\Phi)^\dagger \widehat{W}_{\beta\nu} D^\nu\Phi\right] \times \widehat{B}^{\beta\mu}$$

$$\mathcal{O}_{M,7} = \left[(D_\mu\Phi)^\dagger \widehat{W}_{\beta\nu}\widehat{W}^{\beta\mu} D^\nu\Phi\right]$$

Contribution to the different vertices:

	$\mathcal{O}_{S,0}$, $\mathcal{O}_{S,1}$, $\mathcal{O}_{S,2}$	$\mathcal{O}_{M,0}$, $\mathcal{O}_{M,1}$, $\mathcal{O}_{M,7}$	$\mathcal{O}_{M,2}$, $\mathcal{O}_{M,3}$, $\mathcal{O}_{M,4}$, $\mathcal{O}_{M,5}$	$\mathcal{O}_{T,0}$, $\mathcal{O}_{T,1}$, $\mathcal{O}_{T,2}$	$\mathcal{O}_{T,5}$, $\mathcal{O}_{T,6}$, $\mathcal{O}_{T,7}$	$\mathcal{O}_{T,8}$, $\mathcal{O}_{T,9}$
$WWWW$	X	X		X		
$WWZZ$	X	X	X	X	X	
$ZZZZ$	X	X	X	X	X	X
$WWZ\gamma$		X	X	X	X	
$WW\gamma\gamma$		X	X	X	X	
$ZZZ\gamma$		X	X	X	X	X
$ZZ\gamma\gamma$		X	X	X	X	X
$Z\gamma\gamma\gamma$				X	X	X
$\gamma\gamma\gamma\gamma$				X	X	X

← forbidden at tree level in the SM ($ZZZ\gamma$, $ZZ\gamma\gamma$, $Z\gamma\gamma\gamma$, $\gamma\gamma\gamma\gamma$)

Various parts of CMS detector