Vector Boson Scattering
Same Sign W Boson in CMS Experiment

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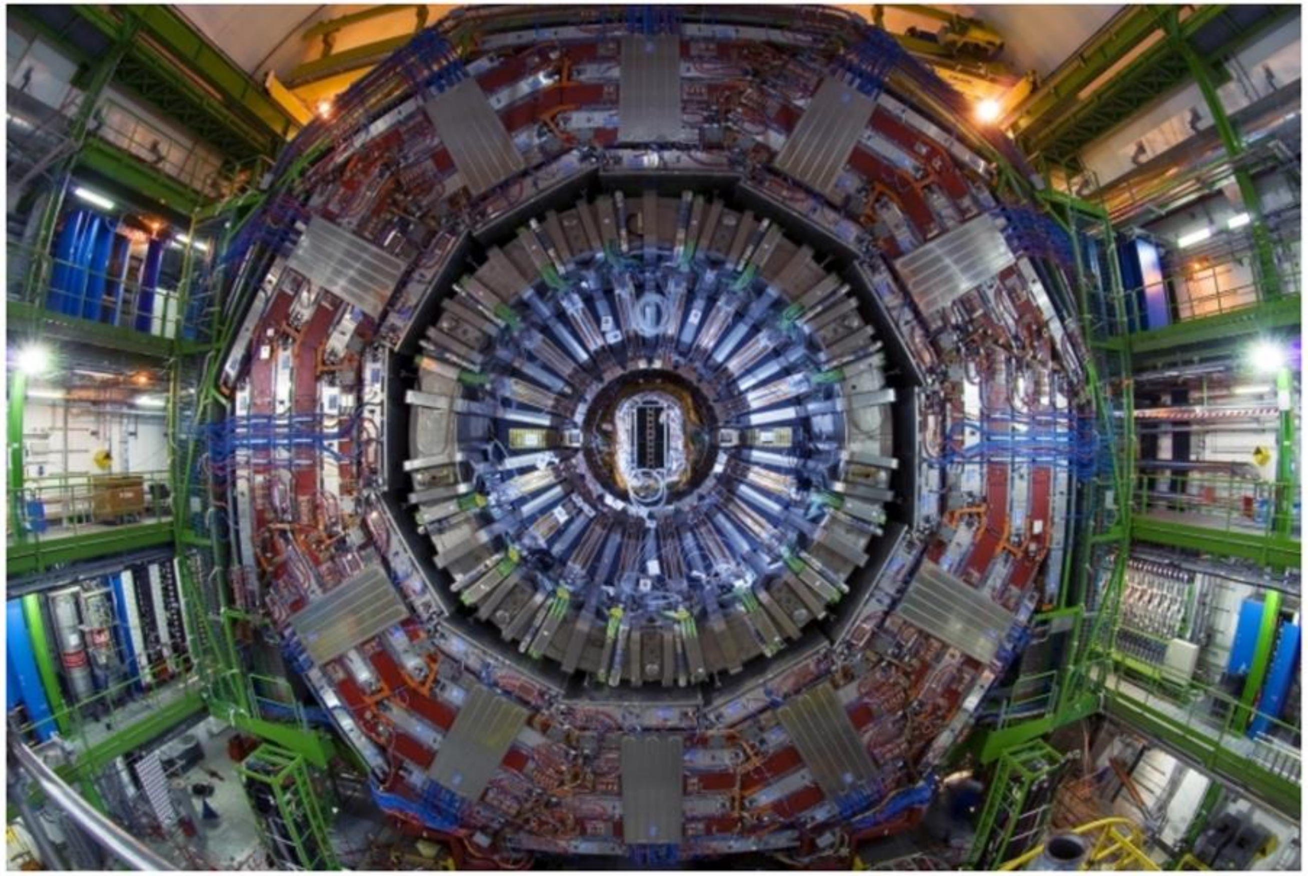
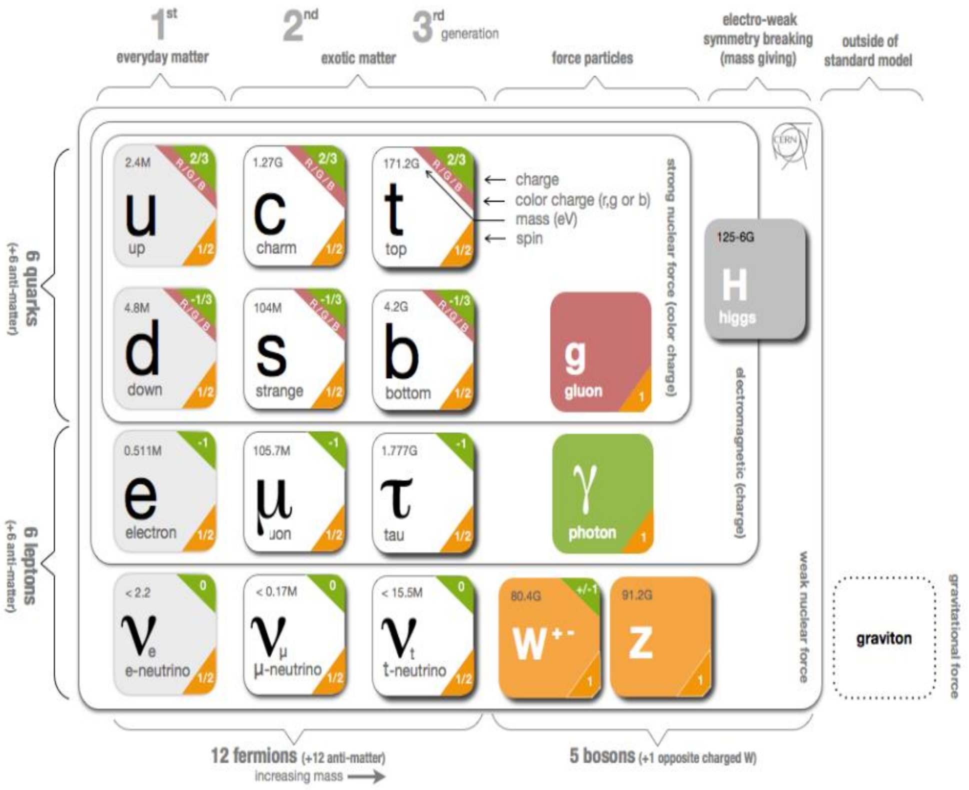


The Standard Model (SM)

What is the Standard Model?

All visible matter in the universe is made up of only a few fundamental particles



The SM is a model that describe these particles and three of the fundamental forces that mediate interactions among them

Beyond The Standard Model (SM)

Why we need beyond the SM?

The model does not include gravitation

Excess of matter over anti-matter that is observed in the universe

What is dark matter

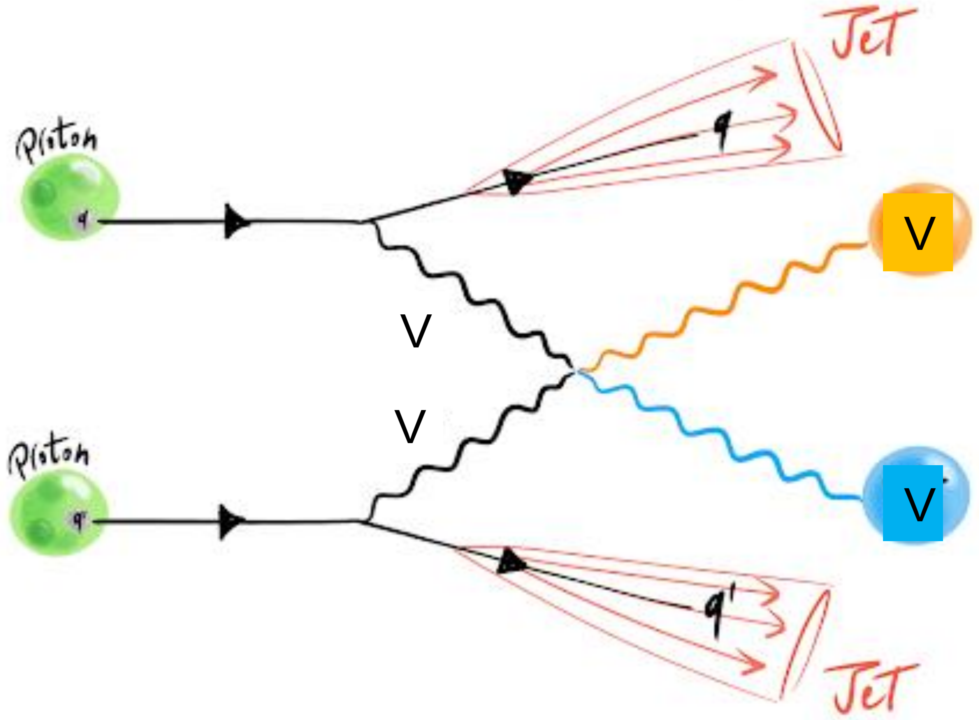
It is not a complete theory to explain our universe and we should go beyond it

Vector Boson Scattering (VBS) in the SM

By vector boson, I mean W, Z boson, and photon here

What is VBS?

When two vector bosons scatter each other

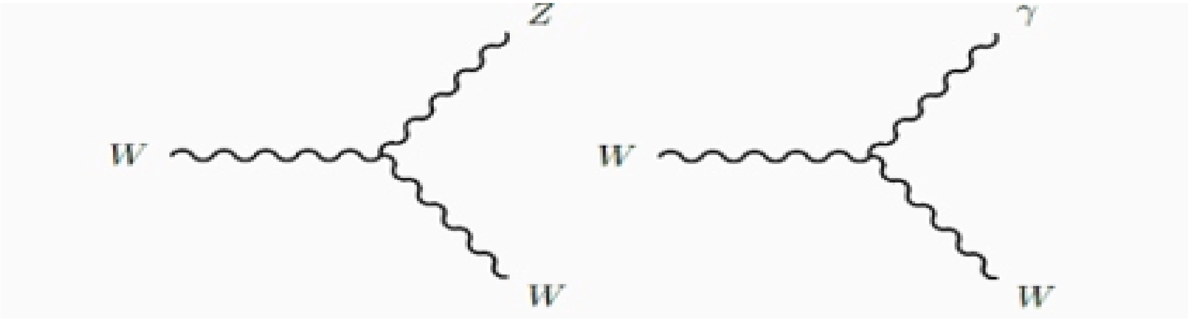


Vector Boson Scattering (VBS) in the SM

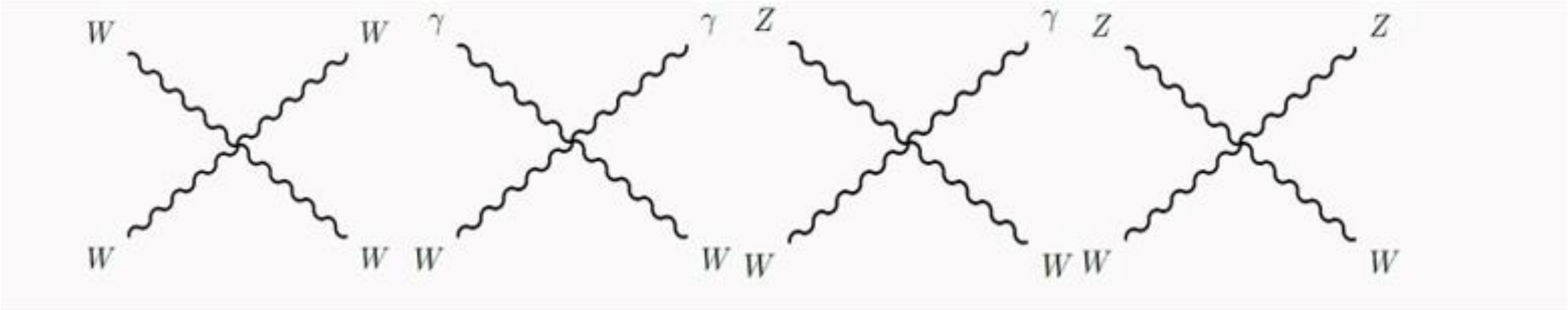
The SM explain Lagrangian for VBS

The VBS Lagrangian includes Triple and quartic gauge coupling constants

Triple



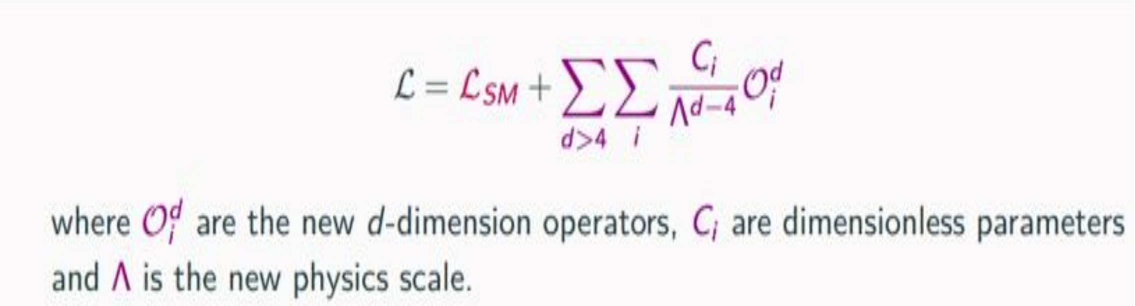
Quartic



Studying triple and quartic gauge couplings is important to test the SM

Beyond the SM and VBS

at low energy, one can extend the SM by adding higher dimension operators:

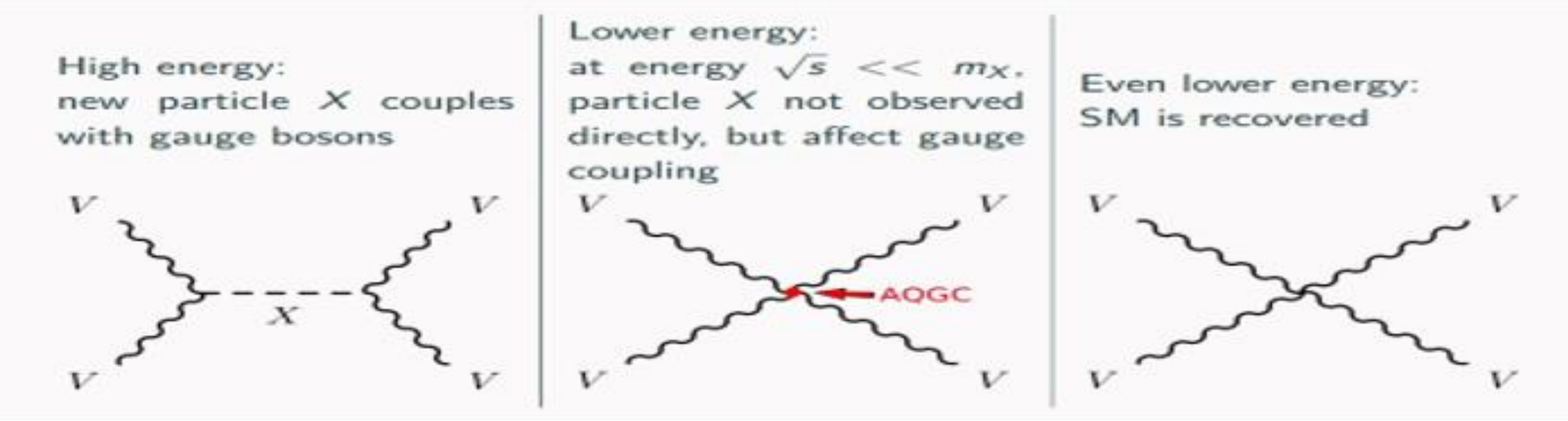


$$\mathcal{L} = \mathcal{L}_{SM} + \sum_{d>4}\sum_{i} \frac{C_i}{\Lambda^{d-4}} \mathcal{O}_i^d$$

where $\mathcal{O}_i^d$ are the new d-dimension operators, C_i are dimensionless parameters and Λ is the new physics scale.

By studying VBS, we can put limits on dimension-6 and dimension-8 parameters: vector boson fusion/scattering

Simple example to illustrate the idea:
Suppose there is a new particle X interacting with vector gauge bosons. Even if we do not have enough energy to produce it, its effect could be observed as an anomalous coupling.



High energy:
new particle X couples with gauge bosons

Lower energy:
at energy $\sqrt{s} << m_X$, particle X not observed directly, but affect gauge coupling

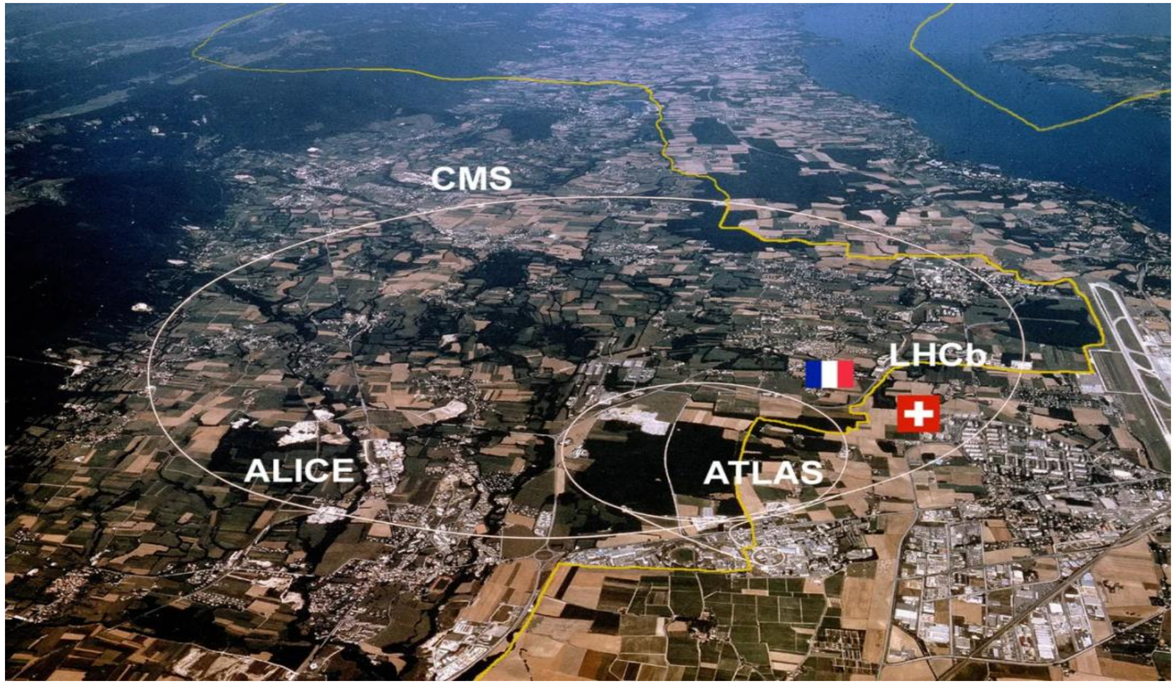
Even lower energy:
SM is recovered

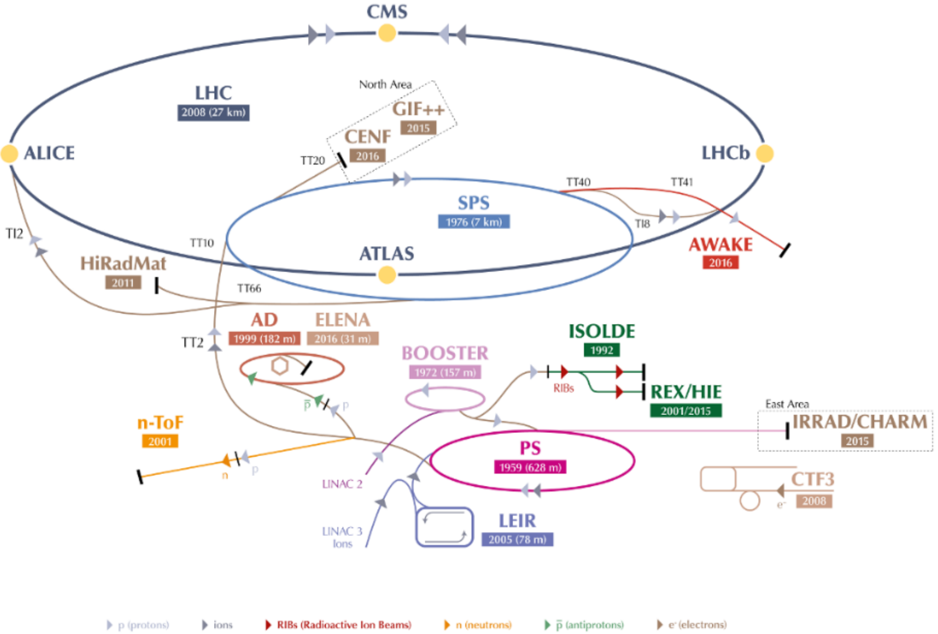
LHC and CMS detector

The Large Hadron Collider (LHC) is a complex scientific instrument designed to study the properties of matter and energy at the smallest scales

Components of LHC:

- **Beam pipe:** Large vacuum chamber surrounding the proton beams as they circulate inside the LHC
- **Accelerating cavities:** To boost the energy of the proton beams
- **Magnets:** To guide the proton beams through the accelerator.
- **Detectors:** ATLAS, CMS, LHCb, ALICE

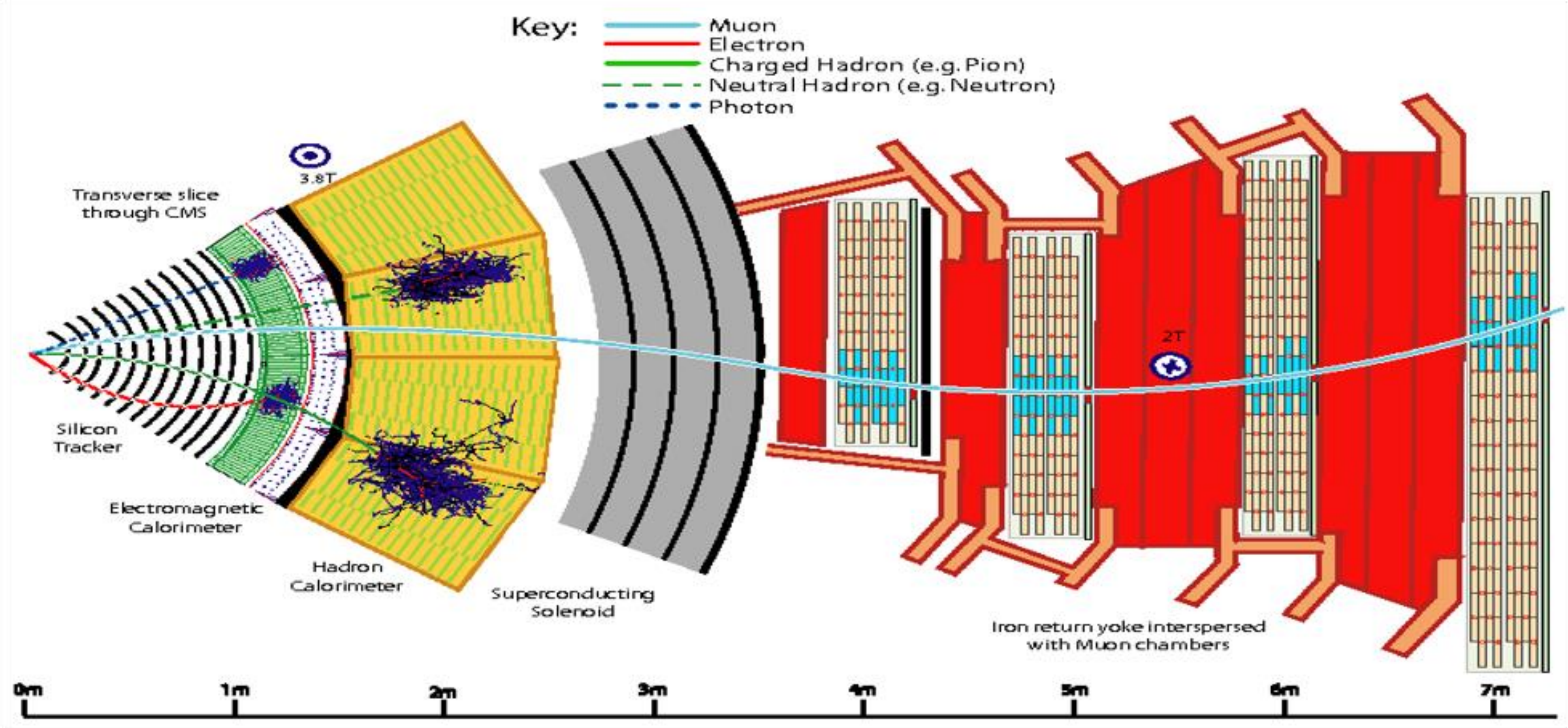




The CMS Detector

A sketch of the specific particle interactions in a transverse slice of the CMS detector, from the beam interaction region to the muon detector. The muon and the charged pion are positively charged, and the electron is negatively charged

Fig. 4

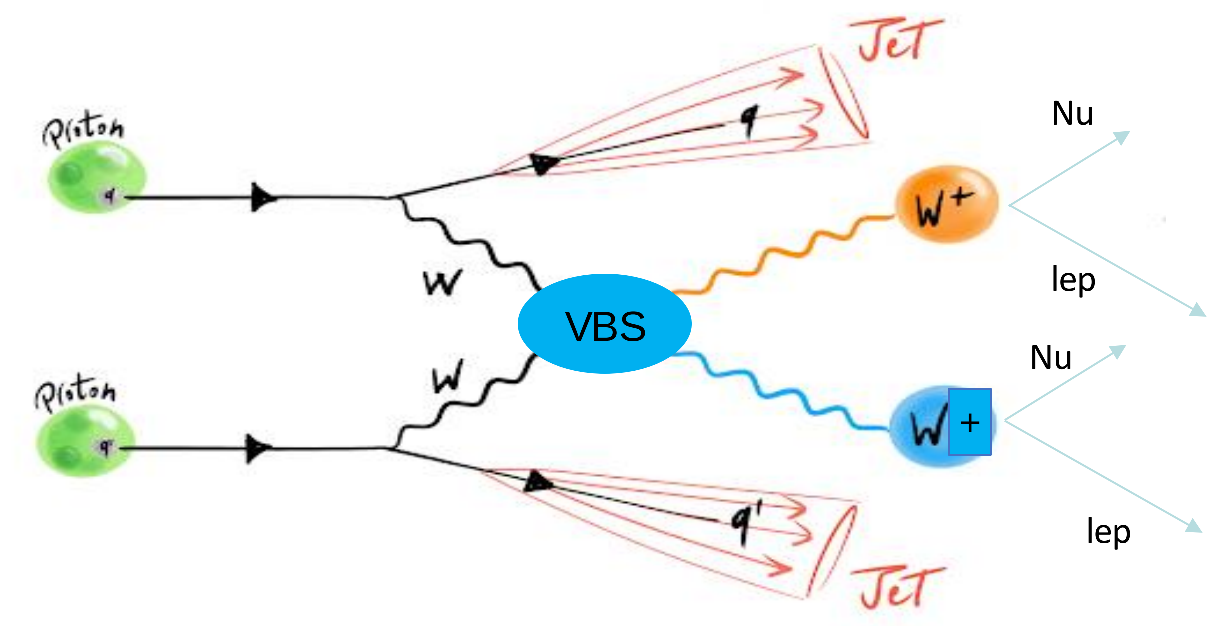


My Analysis:
Same sign W Boson Electroweak Scattering

Signal:

The electroweak production of same-sign W boson pairs in the two jets and two same-sign leptons final state

$$q\,q \rightarrow W^+W^+ q\,q \rightarrow \ell^+\nu\;\ell^+\nu\;q\,q$$



Same sign W Boson Scattering

Background:

The background events can be split in two categories:

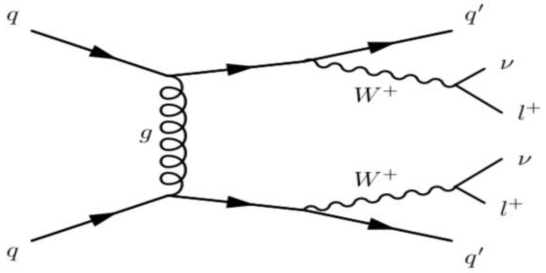


Fig. 7

- **Irreducible backgrounds:**

- have the same final state particles as the signal process and cannot be distinguished from VBS on an event-by-event basis.

- **Reducible backgrounds:**

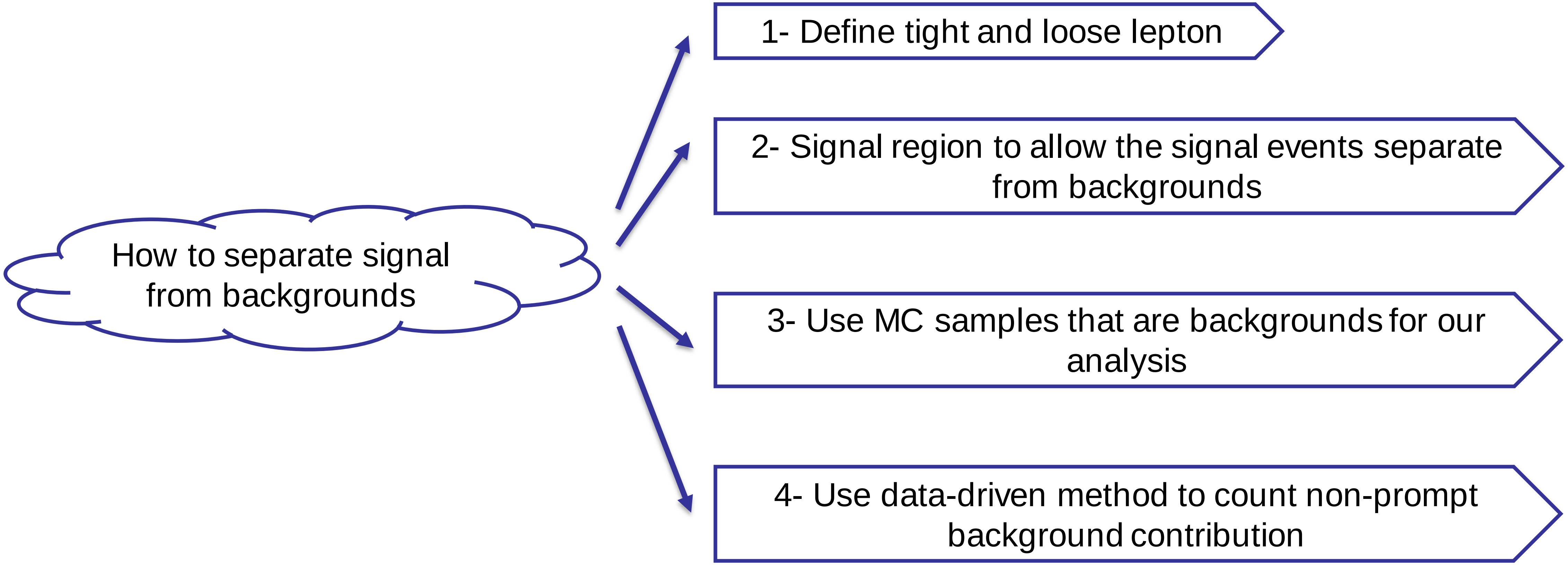
-are processes with a final state different from VBS, but can enter the signal region.
One example is when objects are not correctly reconstructed (e. g. a jet that is misreconstructed as a lepton) or are not within the detector acceptance. (Like ttbar->L+2Q and W+Jet -> L+Nu+Jet)

The main reducible backgrounds:

- Where one of the reconstructed leptons is a mis reconstructed jet (this kind of leptons are Fake Lepton and we consider them for counting non-prompt background)

- WZ production in the fully leptonic decay channel with one of the 3 final state leptons outside of the tracker acceptance or not passing the lepton selection
- In same-sign WW the non-prompt background is the largest background of all, so we have to know it precisely

Identification



How to separate signal from backgrounds

1- Define tight and loose lepton

2- Signal region to allow the signal events separate from backgrounds

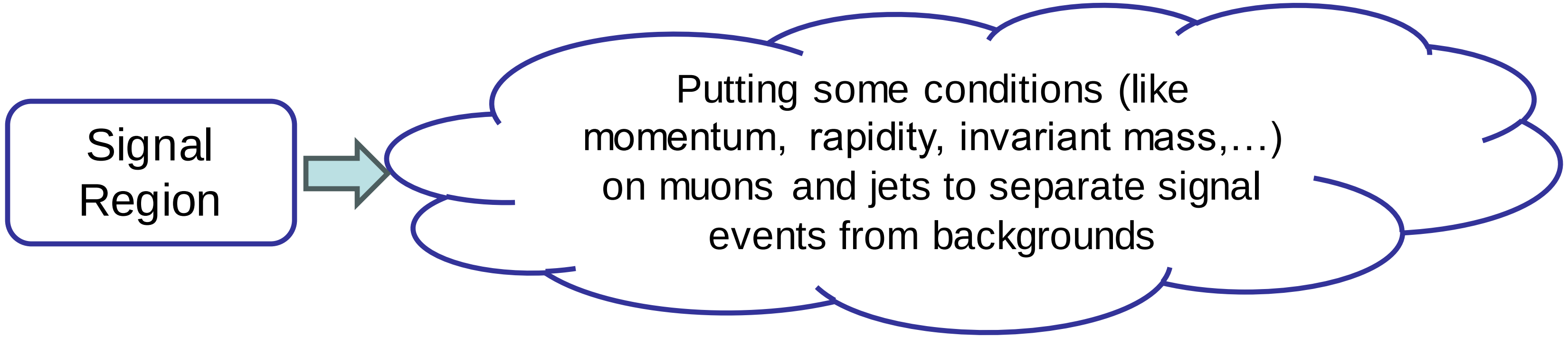
3- Use MC samples that are backgrounds for our analysis

4- Use data-driven method to count non-prompt background contribution

Identification:
Signal region, Tight and Loose lepton

- Tight lepton: Used to select signal events
- Loose lepton: To veto events with extra leptons and used in the non-prompt background estimation

The conditions to define tight and loose muons are backup slides



Signal Region

Putting some conditions (like momentum, rapidity, invariant mass,…) on muons and jets to separate signal events from backgrounds

The conditions for signal region are backup slides

Counting Number of Signal and Background Events

The purpose is to count the number of signal and background events.
For that, we make signal (Tight-Tight) events, we also need to make Tight-Loose (TL) and Loose-Loose (LL) samples for counting non-prompt backgrounds

Definition used in TT, TL, and LL to compute signal and background:

- Denoted as NT or Tight: A muon that passes both loose and tight selection

- Denoted as NL or Loose: A muon that passes loose but fails to pass tight selection

Data	Tight-Tight (number of events)	Tight-Loose(number of events)	Loose-Loose(number of events)
Run3- 2022 Era EFG	25	204	336

Data-Driven Method to Compute Non-Prompt Background

The data-driven (dijet) method that is used to estimate the non-prompt background

The measurement is performed in a data region that is enhanced in non-prompt and fake leptons, and will be called the dijet region which has very loose set of single lepton triggers

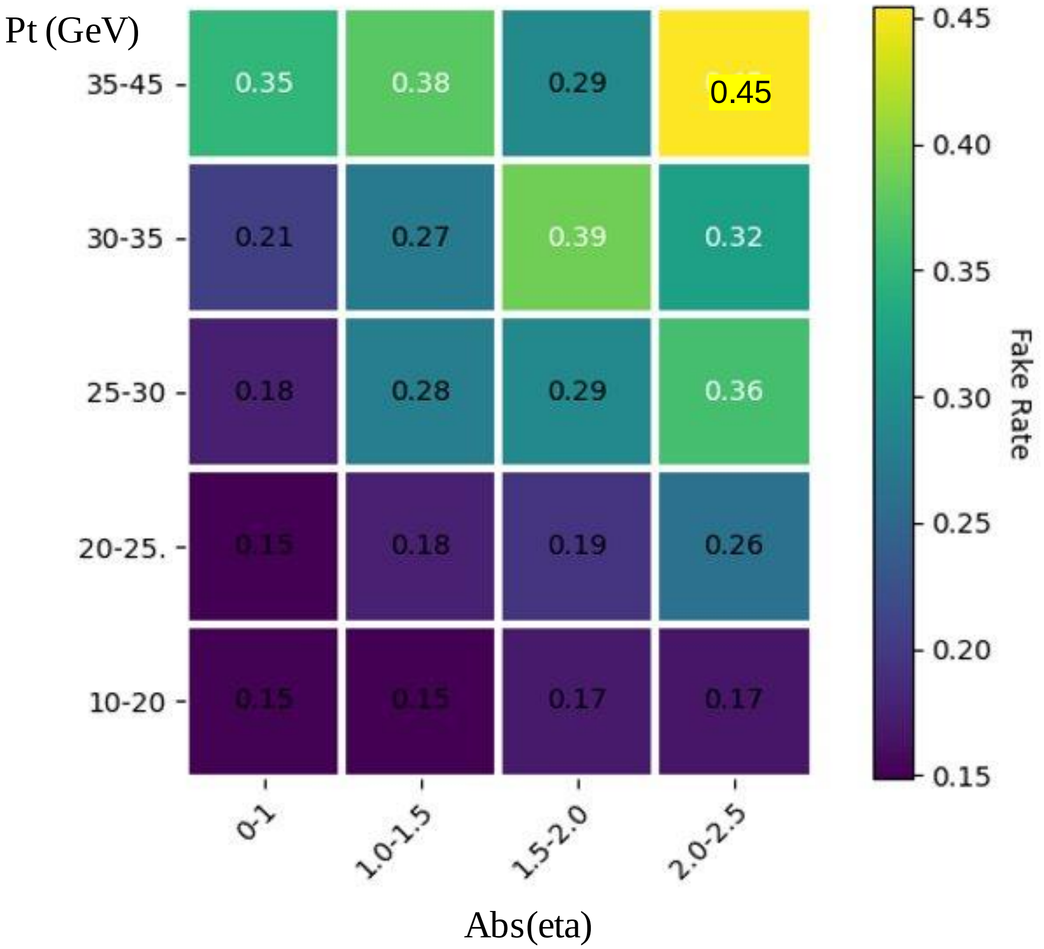
In this method, we compute the probability for a lepton passing a loose lepton selection to also pass a tighter lepton selection which is called fake rate

The fake rate is computed from this formula:

$$\mathcal{E}(\text{fake rate}) = NT/(NT+NL)$$

The fake rate is a function of pt and eta of the lepton

Data-Driven Method to Compute Non-Prompt Background



Pt (GeV)	0-1	1.0-1.5	1.5-2.0	2.0-2.5
35-45	0.35	0.38	0.29	0.45
30-35	0.21	0.27	0.39	0.32
25-30	0.18	0.28	0.29	0.36
20-25.	0.15	0.18	0.19	0.26
10-20	0.15	0.15	0.17	0.17

Fig. 10: Fake rate as a function of pt and eta of lepton

Data-Driven Method to Compute Non-Prompt Background

After computing fake rate, we need to use it to reweight the Tight-Loose and Loose-Loose events so that we can count the Non-Prompt background. Weight is computed as follow:

$$w_i = \frac{\epsilon_{\text{fake}}(p_{\text{Ti}}, \eta_i)}{1 - \epsilon_{\text{fake}}(p_{\text{Ti}}, \eta_i)},$$

$$w_{ij} = \frac{\epsilon_{\text{fake}}(p_{\text{Ti}}, \eta_i)}{1 - \epsilon_{\text{fake}}(p_{\text{Ti}}, \eta_i)} \times \frac{\epsilon_{\text{fake}}(p_{\text{Tj}}, \eta_j)}{1 - \epsilon_{\text{fake}}(p_{\text{Tj}}, \eta_j)},$$

Where W_i and W_ij go over all TL and LL events, respectively

The formula to count Non-Prompt backgrounds is as below which has two parts of data and MC section. I will investigate both sections se

$$N^{Nonprompt} = \sum_i w_i^{data} - \sum_i w_i^{MC} - (\sum_{i,j} w_{ij}^{data} - \sum_{i,j} w_{ij}^{MC})$$

Compute Non-Prompt Background for Data

For Data section, we have:

Non-Prompt Background (For Data) = $\sum_{i}^{data} w_i - \sum_{i,j}^{data} w_{ij}$

Now, by using table 3, Equ 2, and Fig 8 we calculate the equation 4 as following:

Non-Prompt Background (For Data) = 124.7 - 106.92 = 17.78

Compute Non-Prompt Background for MC

For muons, the non-prompt backgrounds is dominated by non-prompt muons from $t\bar{t}$ events in the semi-leptonic decay channel

An example Feyn- man diagram is shown below:

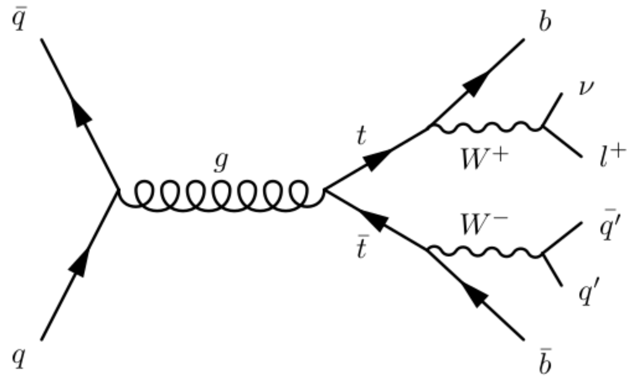


Fig. 11

There is one prompt lepton from the W decay, while a second, non-prompt lepton can be produced in the b-quark decay

TL Events	Cros-section of ttbar->L+2Q	Luminosity of Data	Normalization Scale
20	405.7 (pb)	27 (1/fb)	0.16

Table 6

Non-Prompt Background (For MC) = $\sum_{i}^{MC} w_i$ = 28.87 * 0.16 = 4.62

Compute Non-Prompt Background

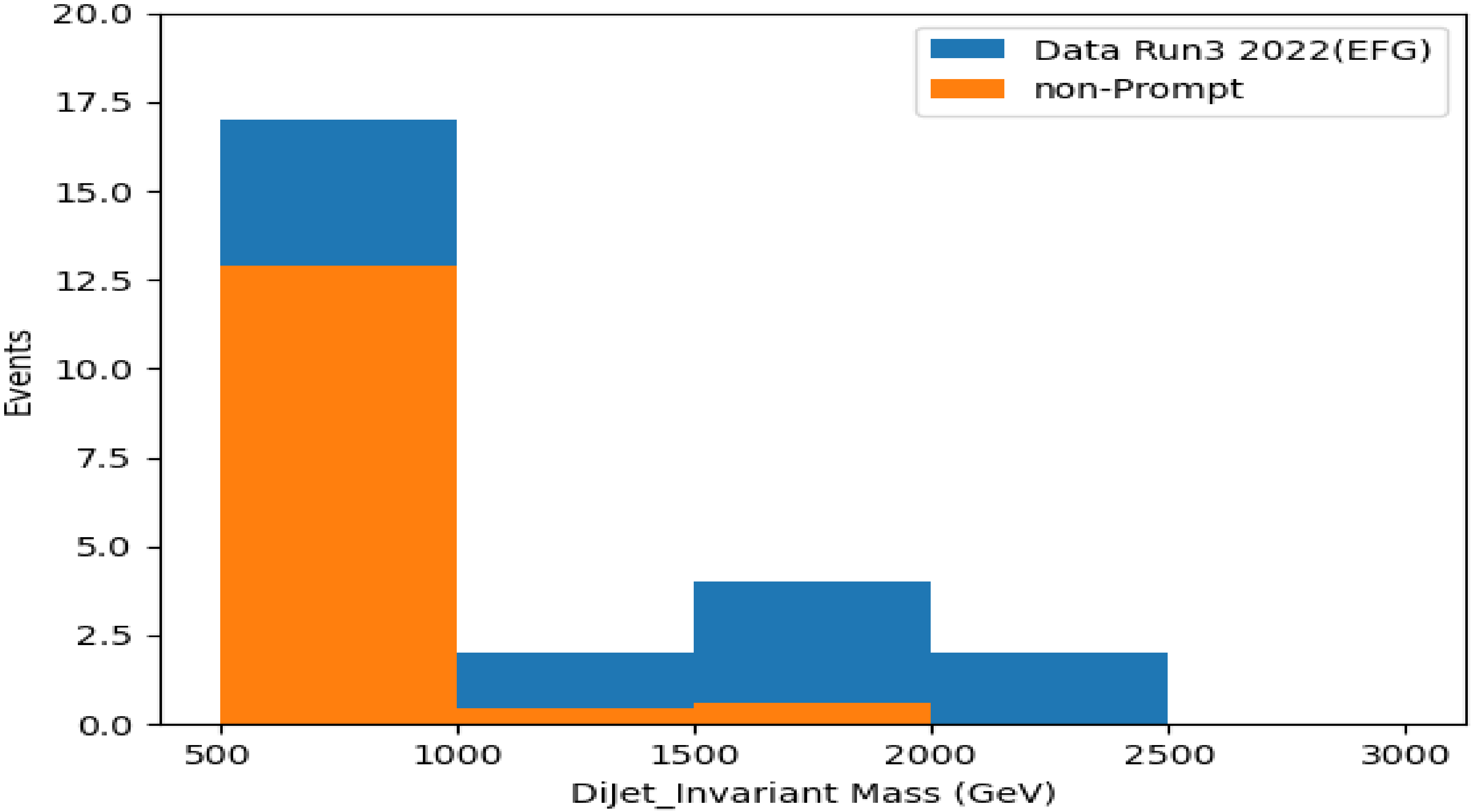
Now, we can count the whole non-prompt background using equ 3

Non-Prompt Background = Non-Prompt Background (For Data) - Non-Prompt Background (For MC)

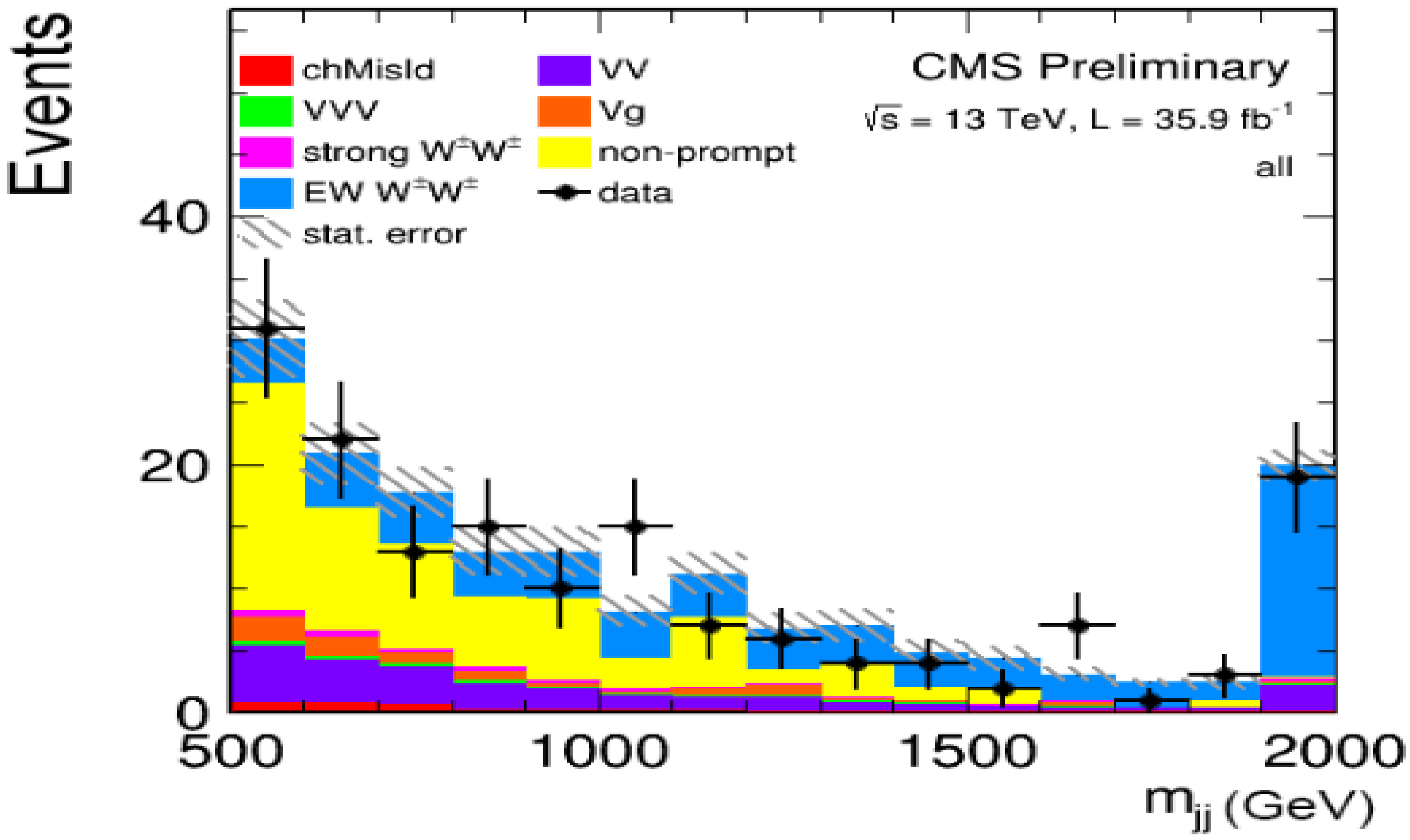
= 17.78 = 4.62 = 13.16

The percentage of no-prompt background in obvserved events (Tight-Tight from table 1) = 13.16/25 = 53%

Signal and Non-prompt Background



Signal and All Backgrounds



Thanks for your attention

Backup

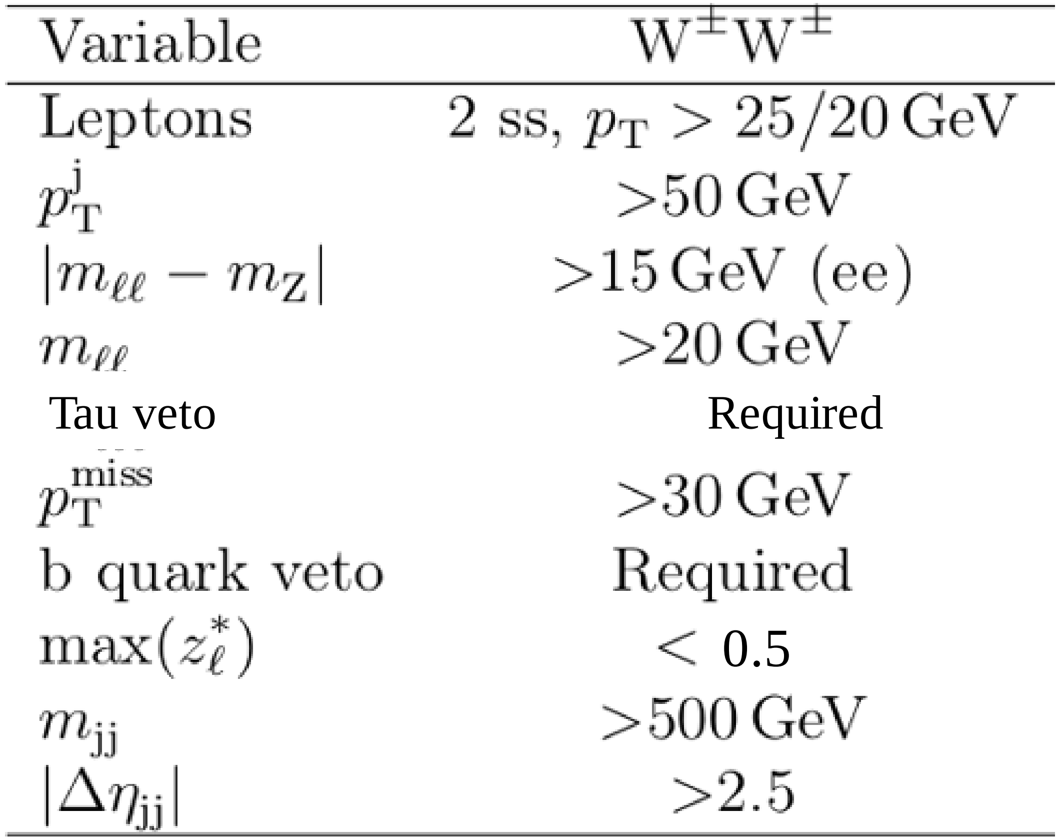
Identification:
Tight and Loose Lepton

Now, after knowing some objects used to define tight and loose muon, I can define tight and loose identification for my analysis:

	Muon (|η|<2.4)
Tight	Muon_MiniPFRelIso_all < 0.05, Muon_PuppiIsoID >= 3 , Muon_MediumPromptID == True, Muon_MVAMuID_WP >= 2, Muon_TightCharge == 2
Loose	Muon_MiniIsoId >= 2 and Muon_PuppiIsoID >= 2

Table 2

VBS Selections
Signal Region (SR)



Variable	$W^{\pm}W^{\pm}$
Leptons	2 ss, $p_T > 25/20$ GeV
p_T^j	>50 GeV
$\lvert m_{\ell\ell} - m_Z \rvert$	>15 GeV (ee)
$m_{\ell\ell}$	>20 GeV
Tau veto	Required
p_T^{miss}	>30 GeV
b quark veto	Required
$\max(z_\ell^*)$	< 0.5
m_{jj}	>500 GeV
$\lvert \Delta\eta_{jj} \rvert$	>2.5

Table 3

DiJet Region

Selection	Threshold
Number of Jet	>= 1
Transverse Momentum of Jet	>35 GeV
Transverse Momentum of Neutrino	< 30 GeV
Transverse Mass of Neutrino and lepton	< 20 GeV
Delta R between lepton and jet ΔR = sqrt((Δη) ^2 + (Δϕ) ^2)	>1