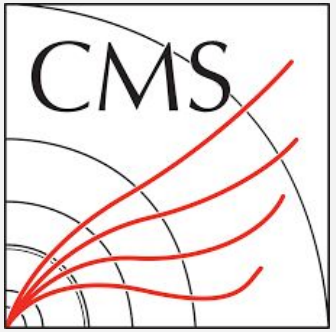
Vector-Like Leptons: Compact Analysis



Nadia Talbi

University of Wisconsin-Madison

Prof. Tulika Bose, Dr. Charis Koraka, & Elise Chavez

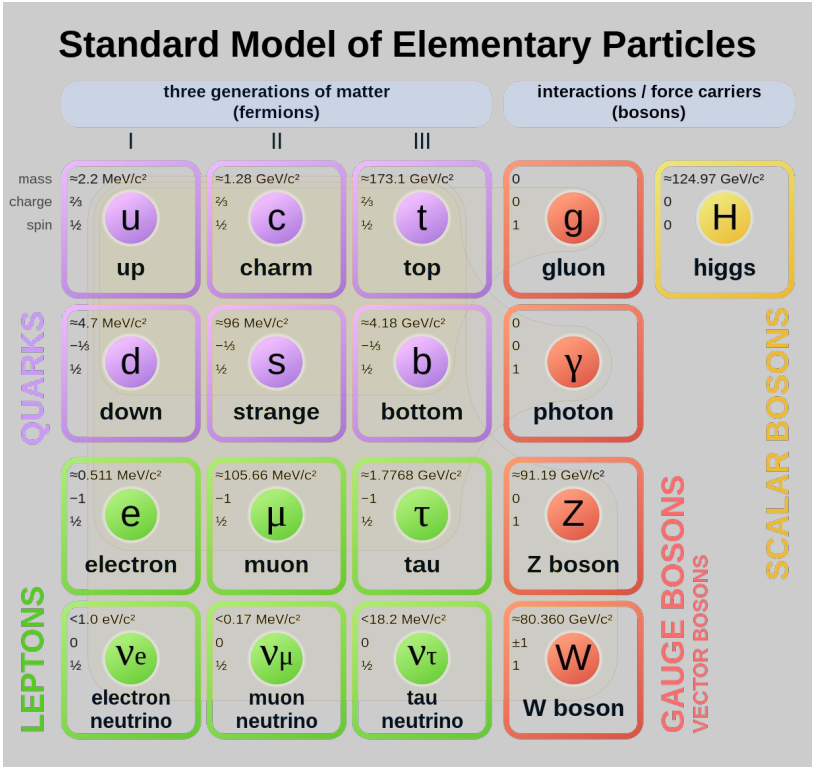
I. Introduction

The Standard Model

Depicts our understanding of the **fundamental composition** of all matter and interactions in the universe.

Unresolved questions remain: matter/antimatter, dark matter, gravity, origin of neutrino masses…

Vector-Like Leptons are one of the many potential resolutions.

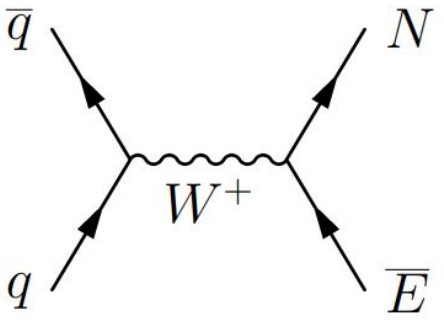


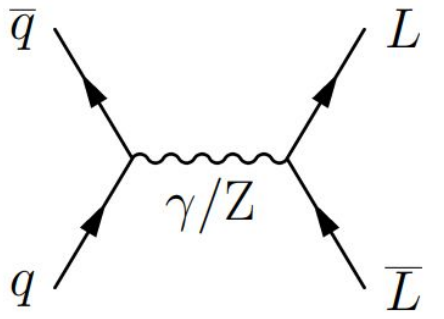
Vector-Like Leptons: An Introduction

L: general vector-like lepton
E: charged vector-like lepton
N: neutral vector-like lepton

A few characteristics:

- **Vector-like**
  - Non-chiral
  - **Left & right-handed** components have the same charge
- **Massive**
  - Search from 500 to 1000 GeV
  - Not directly related to the Higgs mechanism

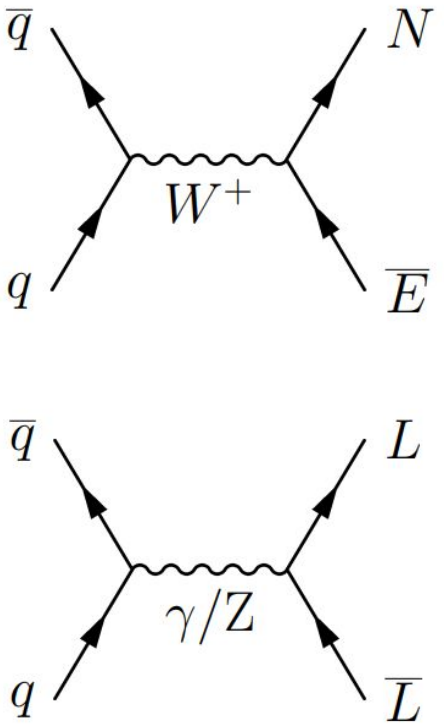




Vector-Like Leptons: An Introduction

L: general vector-like lepton
E: charged vector-like lepton
N: neutral vector-like lepton

- Vector-Like & Massive (≤ few TeV)
- **Hypothesized particles**
  - 4321 model[1]
    - Extends SM while preserving SM predictions
    - Predicts new particles:
      - Lightest fermions ≤ TeV



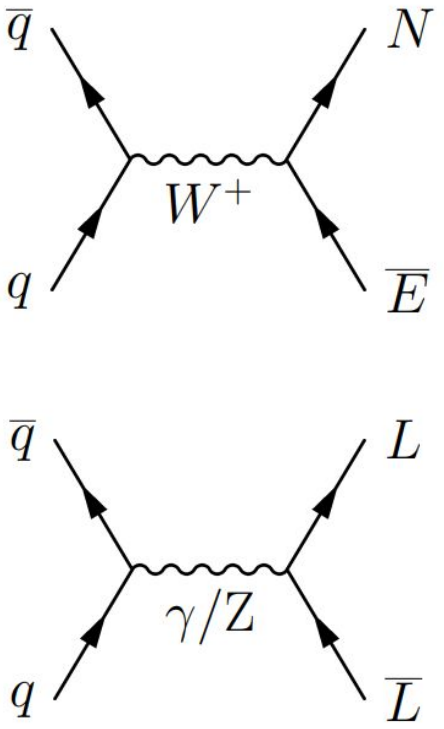
[1]B2G-21-004 *Search for vector-like leptons in the context of the "4321 model"*

Vector-Like Leptons: An Introduction

L: general vector-like lepton
E: charged vector-like lepton
N: neutral vector-like lepton

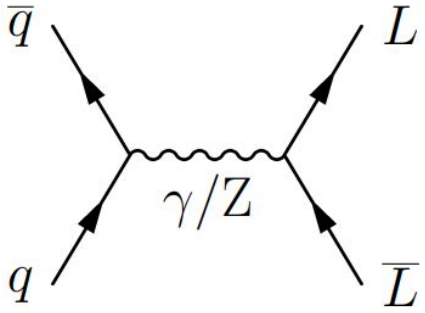
- Vector-Like & Massive (≤ few TeV)
- Hypothesized particles
  - 4321 model
- **Potential to answer**:
  - **Lepton-flavor non-universality**
    - B-anomalies
    - **Leptoquark** couplings could explain
  - Electron & Muon **anomalous magnetic moment**

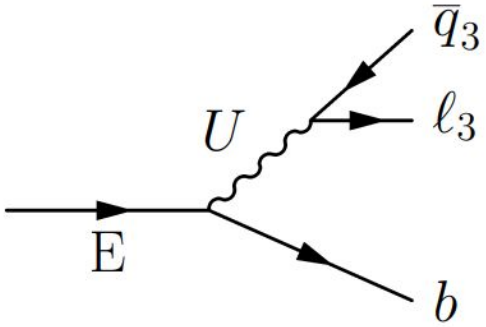
$$\Delta a_\mu = a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = 288(63)(49) \times 10^{-11}$$

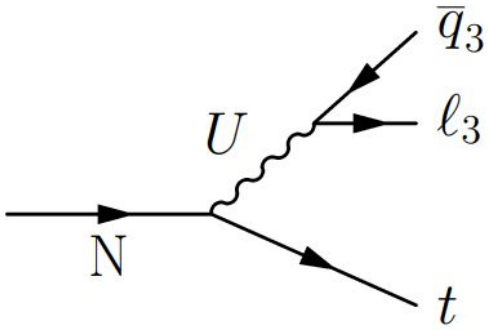


Vector-Like Leptons: **Production & Decay**

- Electroweak pair production
- Decay via **Leptoquark *U***
  - *U* couples strongly to **third gen.** could explain b-anomalies



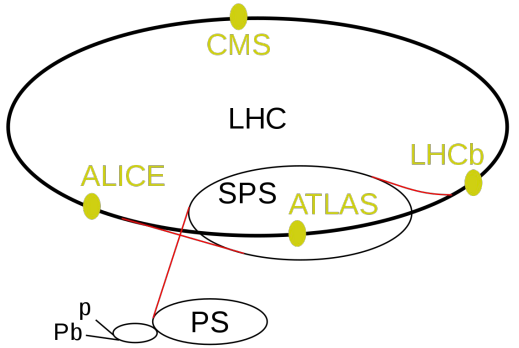


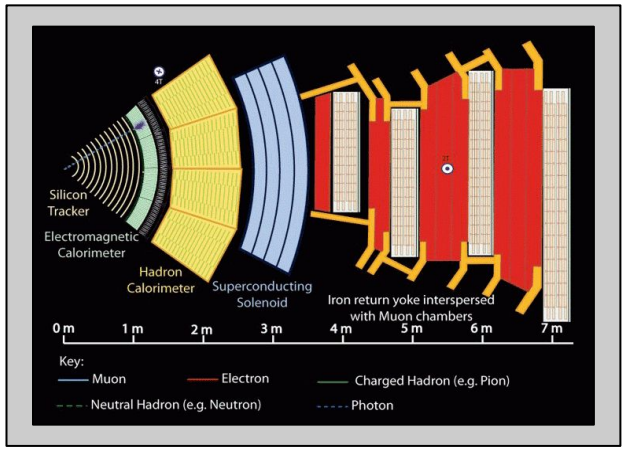


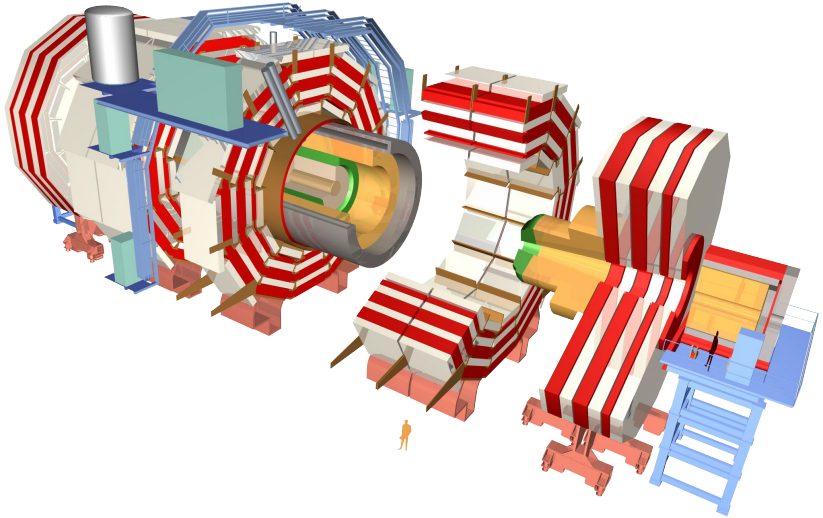
II. The Search Method

Vector-Like Leptons: **The Detector**

- Compact Muon Solenoid (**CMS**)
- Analyzes **proton-proton collisions** at LHC
  - ~ 4T Solenoid & 6.5 TeV per beam (Run II)







Vector-Like Leptons: **The Process of Analysis**

- The fundamental question: **Do vector-like leptons exist?**
- Current aim: Develop a strong method to determine signal from background
- **The Process**
  - Determine **signal**, **final states**, & **background**
  - Establish **S v. B expectations**
    - by employing Monte Carlo (MC) simulations
  - Develop **method** to help distinguish **S from B**
  - Employ method on **CMS Run II data**
  - Results: Analyze data for **vector-like lepton** presence

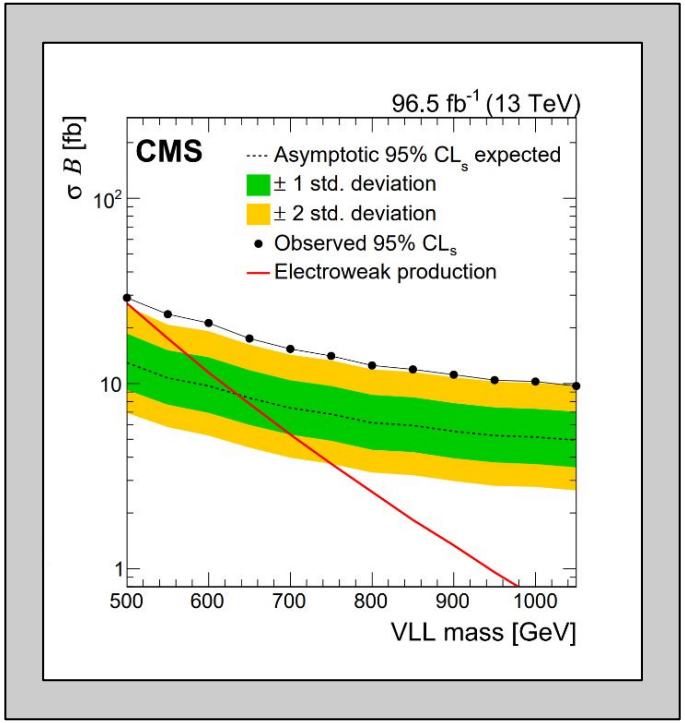
Vector-Like Leptons: **The Motivation**

Previous analysis, B2G-21-004, finds excess:

- Considers **hadronic** τ decay
  - Mainly QCD background

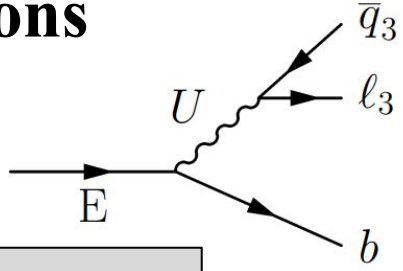
Vector-like lepton search in need of analysis in ⊥ phase space

- ∴ search in the **leptonic** phase space

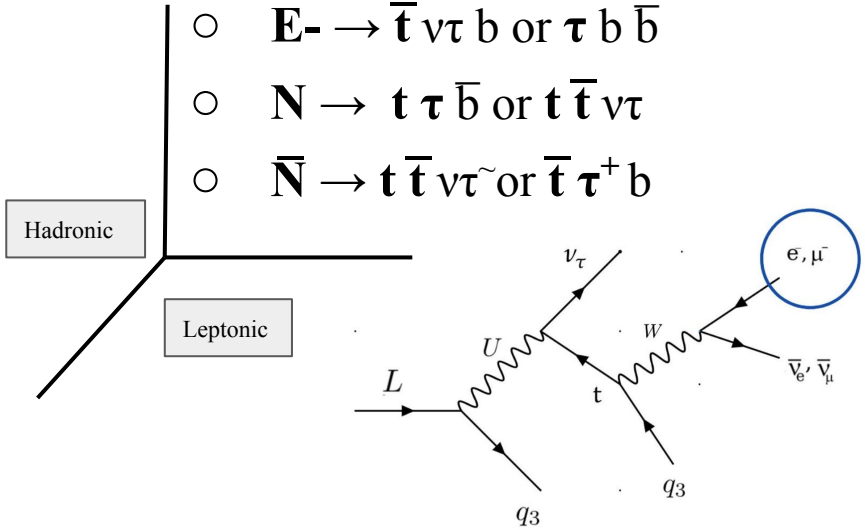


Vector-Like Leptons: Defining **Signal & Regions**

ℓ: electron or muon

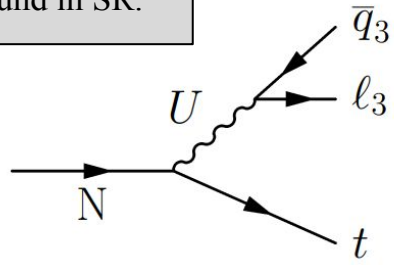


- **Leptonic phase space**
- Decays resulting in 2ℓ from **t or τ**
  - **E+** → **t** ντ~ $\bar{b}$ or **τ**$^+$ b $\bar{b}$
  - **E-** → $\bar{\mathbf{t}}$ ντ b or **τ** b $\bar{b}$
  - **N** → **t τ** $\bar{b}$ or **t** $\bar{\mathbf{t}}$ ντ
  - $\bar{\mathbf{N}}$ → **t** $\bar{\mathbf{t}}$ ντ~or $\bar{\mathbf{t}}$ **τ**$^+$ b



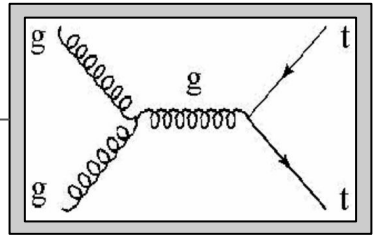
Signal Region (4b + jets)
Expect the greatest signal/background ratio.
Where to search.

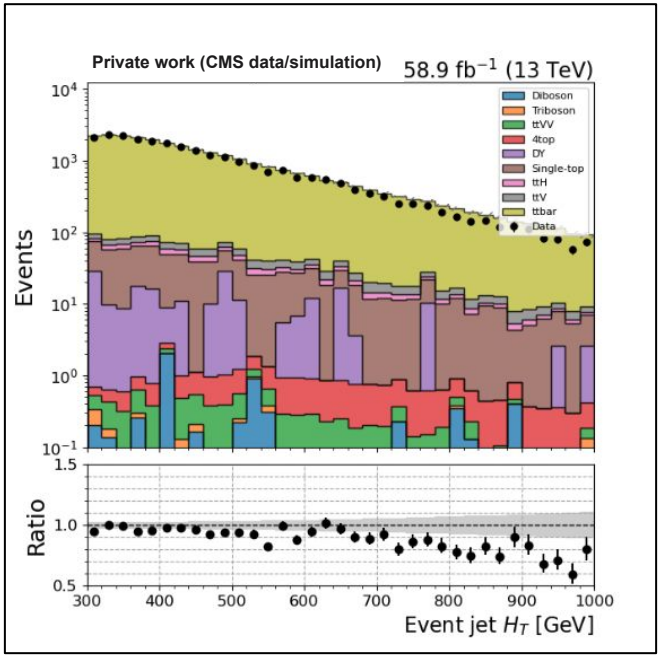
Control Region (3b or 2b + jets)
Expect negligible signal contribution
Aids in **understanding** background in SR.



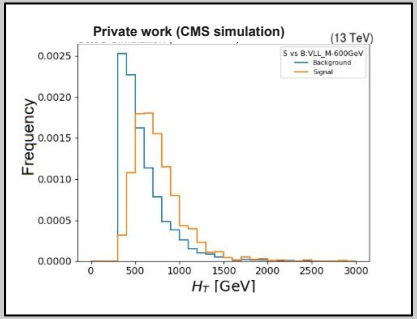
Vector-Like Leptons: **Signal & Background**

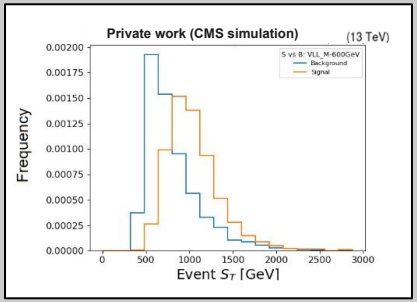
- Signal:
  - **2ℓ final states**
- Background:
  - **tt-bar**
  - DY+jets
  - Di-boson production
  - Tri-boson production
  - tt(V/H)+jets
  - tt+VV
  - 4-top





Vector-Like Leptons: Signal **v.** Background



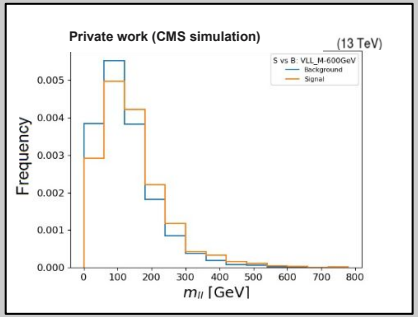


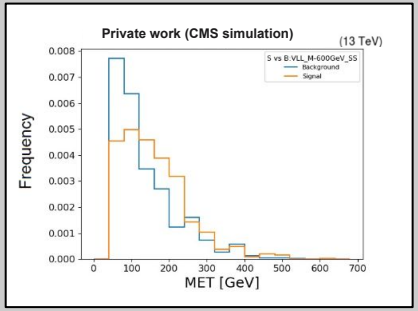
600-GeV Plots:

Normalized to the same arbitrary number

Challenging to distinguish as **signal resembles background**.

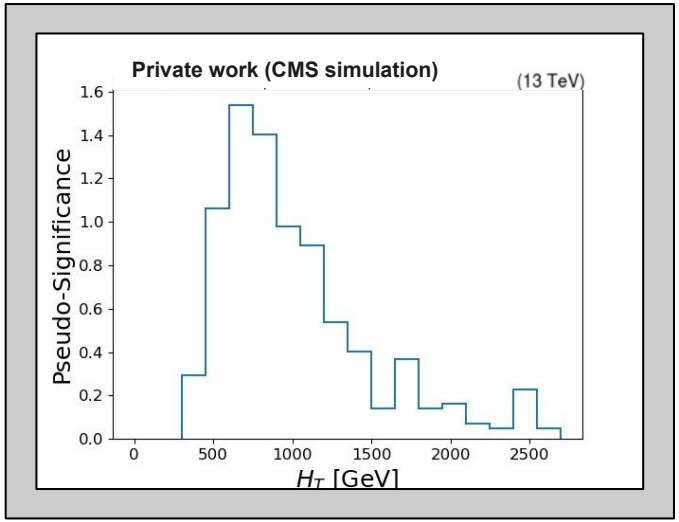
Shifted peaks give potential for signal-to-background **discrimination**





Vector-Like Leptons: Signal **v.** Background

Pseudo-Significance in Event H_T (600 GeV)



$$\frac{\int signal}{\sqrt{\int data}}$$

In need of:
increased sensitivity

Optimization of
kinematic cuts,
ML techniques, etc.

What does it signify?

Estimate how **significant** the **deviations** are between data and background.

$$S = \frac{N - n_b}{\sigma}$$

By taking $\sigma \approx \sqrt{N}$ …

$$S = \frac{n_s}{\sqrt{N}}$$

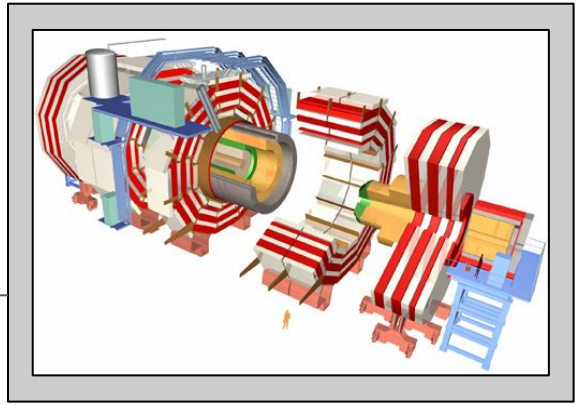
Often, **5σ** is the accepted value for the detection of **new particles**.

N: number of data events
n_b: number of background events
n_s: number of signal events
σ: standard deviation of N

Vector-Like Leptons: The Future

The Process

- ☑ Determine **signal**, **final states**, & **background**
- ☑ Establish **S v. B expectations** by employing MC simulations
- ❑ Develop **method** to further distinguish **S from B**
- ❑ Employ method on **CMS Run II data**
- ❑ Results: Analyze data for **vector-like lepton** presence

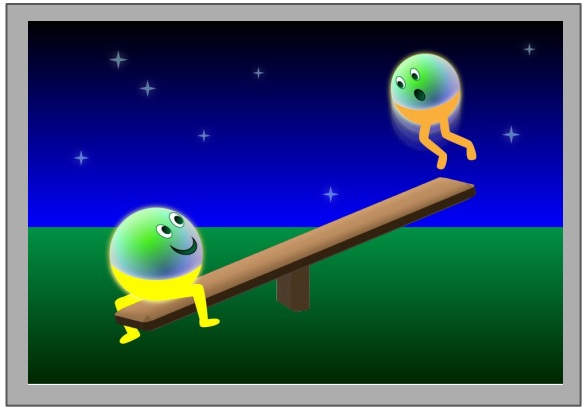


Will the existence of vector-like leptons be revealed or refuted?

Explaining Further

The Standard Model

- **Matter/Antimatter Asymmetry**
- **Origin of Neutrino Masses**
- Gravitational Force
- Accounting for the 95%

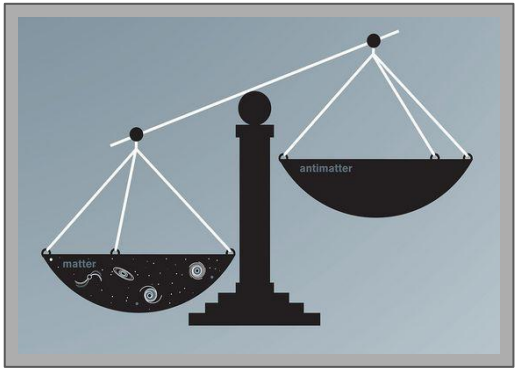


Matter/Antimatter Asymmetry:

Following the Big Bang there were inequivalent amounts of matter & antimatter

+1 matter particle per billion

Why?



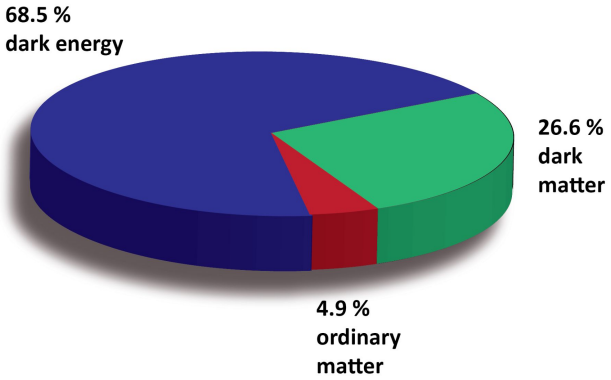
Neutrinos:

Standard Model explains neutrinos as massless observed to change flavor…

only possible with neutrino mass.

The Standard Model

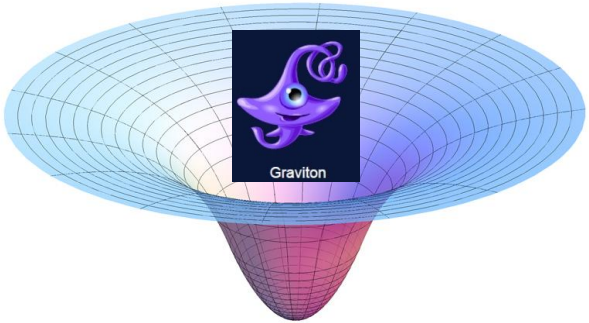
- Matter/Antimatter Asymmetry
- Origin of Neutrino Masses
- **Gravitational Force**
- **Accounting for the 95%**



Gravity:

currently not present in the Standard Model

QM must explain!



The 95%:

SM only accounts for baryonic matter

Dark Matter must be explained (galaxy rot. curves)

Dark Energy must be explained (accel. expansion)

Vector-Like Leptons: **Decay Probabilities**

E+N decay example

Branching Ratio: the probability that a particle decays a particular way

1) Possible decays:

a. E+ → b, bbar, τ+ or **bbar, t, vbarτ**

b. N → t, bbar, τ or **t, tbar, vτ**

2) **2ℓ Final States** from *this* decay

a. ℓ+ℓ+ b b bbar bbar vτ vτbar vℓ vℓ from [t,t]

b. ℓ+ ℓ- b b bbar bbar vτ vτbar vℓ vℓbar from 2x [t, tbar]

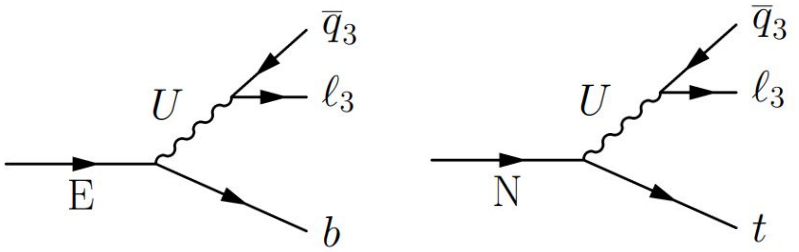
3) BR Calculation considering all **t's and τ's**

E: **t** → b W+ → either vτ τ+ → **ℓ+** vℓ vτ or W+ → **ℓ+** vℓ

N: **t** → b W+ → vτ τ+ → **ℓ+** vℓ vτ or W+ → **ℓ+** vℓ

N: tbar → bbar W- → vτbar τ- → hadronic! or W- → hadronic!

4) BR found!



$t_{leptonic}$: $(0.11)(0.35) + 0.21$ $\quad$ $\bar{t}_{hadronic}$: $((0.11)(0.65) + (0.68))$

so $(t_{leptonic}) \cdot (t_{leptonic}) \cdot (\bar{t}_{hadronic}) = (0.2485)(0.2485)(0.7515)$

≈ 0.0464 $\quad \therefore$ 5% BR

Vector-Like Leptons: **Background Prediction**

CR:
4j**2b**
5j**2b**
6j**2b**
4j**3b**
5j**3b**
6j**3b**

In order to determine the presence of vector-like leptons in data…

Develop a function which predicts background so as to isolate signal contribution

Tag Rate Function

Data-driven background predictor

Utilizes data in **CR** to predict background in **SR**

Advantage of minimized simulation uncertainties

Process:

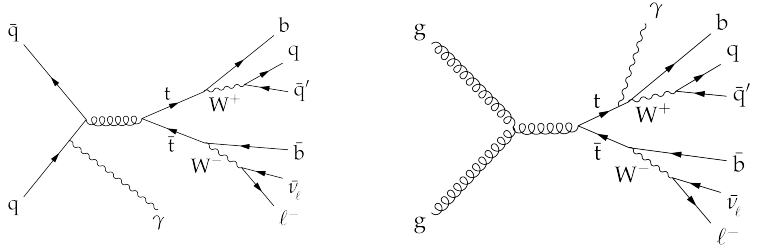
1. Estimate probability that a jet in an event is b-tagged.
2. Determine probability that an event contains certain number of b-tagged jets.
3. Create probability map to predict if a background jet is b-tagged
4. Determine the formula to predict the background.

Vector-Like Leptons: Selection Criteria

Electrons	$p_T > 10$ GeV	$\|\eta\| < 2.4$	CutBasedIdTight	eleEtaGapVeto
Muons	$p_T > 10$ GeV	$\|\eta\| < 2.4$	tightId	pfRelIso04_all < 0.25
MET	$p_T > 40$ GeV			
Jets	$p_T > 30$ GeV	$\|\eta\| < 2.4$	mediumJetIDbit	mediumJetIDbit

Explaining Further: **Background**

- **tt-bar**



- **DY+jets (Drell-Yan)**
  - Originates from ℓ & ℓbar, virtual photon or Z boson.
  - Fewer jets than signal.
- **Di-boson production** (ZZ, WW, ZW)
  - The production of weak bosons (W, Z, gamma).
  - Lower x-section than signal.
- **Tri-boson production** (WWW, ZZZ, WWZ)
  - The production of weak bosons.
  - Rarer & more complex final states..
- **tt(V/H)+jets** (ttZ, ttW, ttH)
  - The production of t pairs with bosons
  - 10x greater x-section than signal.
- **tt+VV** (ttHH, ttZZ)
  - The production of t pair, vector & scalar bosons.
  - X-sections often smaller than ttbar
- ***4-top*** *(tttt)*
  - The production of 4 top quarks.
  - X-section much smaller than ttbar.

References

- B2G-21-004
- Why should we search for vector-like leptons?
- CMS Search for vector-like leptons in the 4321 model (Kyle Cormier)
- Review+(partial) combination of VLQ+VLL+HNL (short and long-lived)
- Hunting leptoquarks with the CMS experiment
- Search for vector-like leptons in multilepton final states