A Search for Vector-Like Leptons

On behalf of the CMS Collaboration

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Hubert Mack Thaxton Research Fellowship

I. Introduction

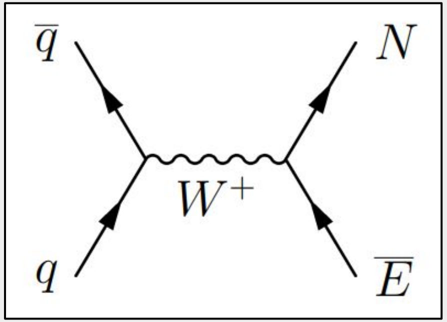
L: E or N vector-like lepton

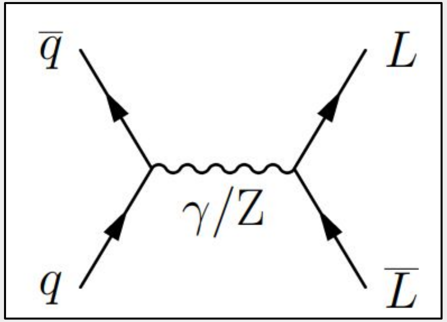
The Motivation for Vector-Like Leptons

- **Vector-like leptons (VLL) are hypothetical particles**
  - Predicted by many BSM models one of which is the 4321 model[1]

> The **4321 model** is an extension of the SM that resolves some tensions w/ experimental observations.
>
> This extension implies the existence of the **leptoquark** (*U*) and the **vector-like lepton** (*L/E/N*).

- Existence of vector-like leptons presents potential to explain:
  - **Lepton-flavor non-universality**
    - B-anomalies since couplings of **leptoquarks** to 3rd generation fermions are dominant
  - Electron & muon **anomalous magnetic moment**

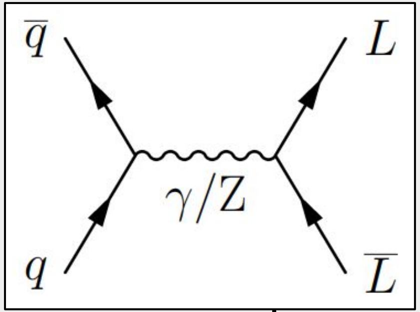


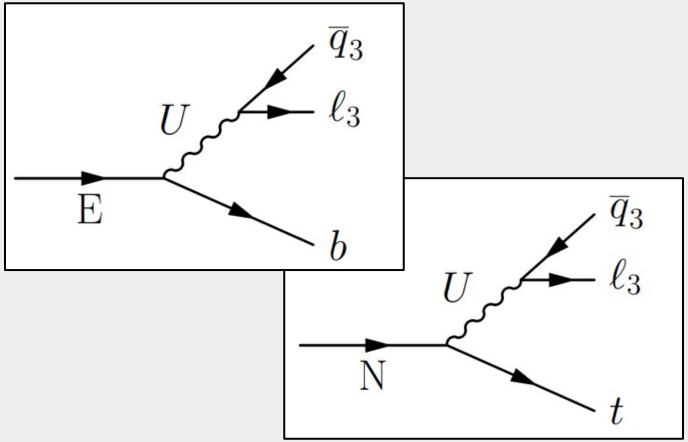


[1] *Gauge leptoquark as the origin of B-physics anomalies*

Vector-Like Leptons: Production & Decay Modes

- Vector-like & massive
  - Non-chiral (same charge in left and right-handed components)
  - ~ TeV
- Either charged (E) or neutral (N)



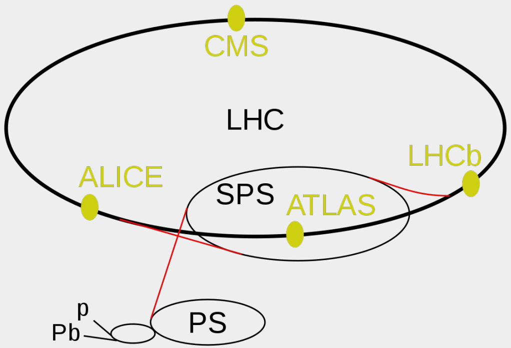


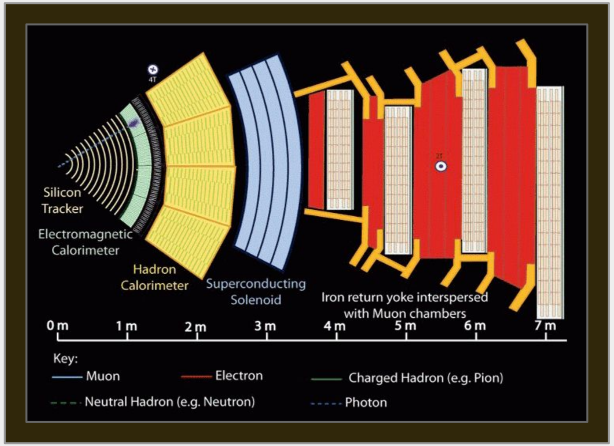
- Electroweak pair production
- Decay via **Leptoquark *U***
  - *U* couples strongly to **third generation fermions**
  - VLL decay chain is seen as 3-body decay

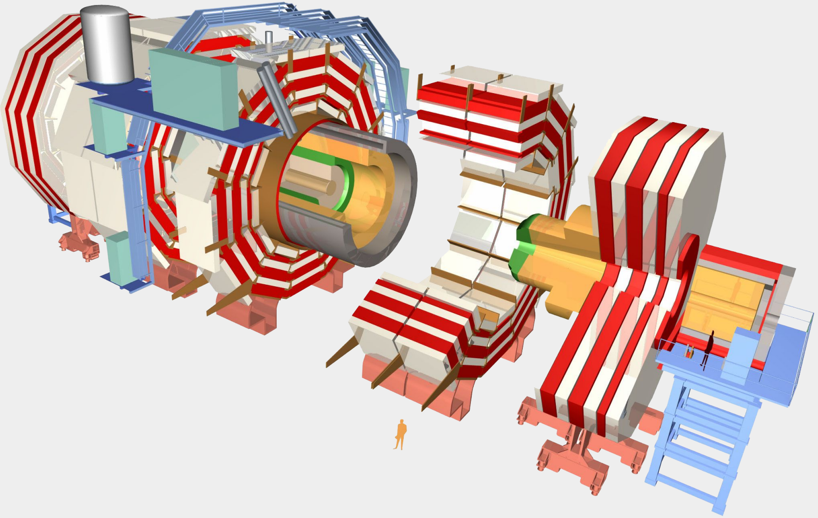
II. Analysis

The Detector

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







The Search for Vector-Like Leptons

- **Do vector-like leptons exist?**
- How do we **answer this question:**
  - Determine the signature of our **signal** (S)
  - Identify the **background** (B): SM processes that have similar signature
  - Optimize the **signal selection** ($\frac{S}{B}$ ratio)
    - For this, we utilize Monte Carlo (MC) simulations
    - Explore various **methods to help distinguish S from B**
  - Last, **analyze CMS data** in search of vector-like leptons

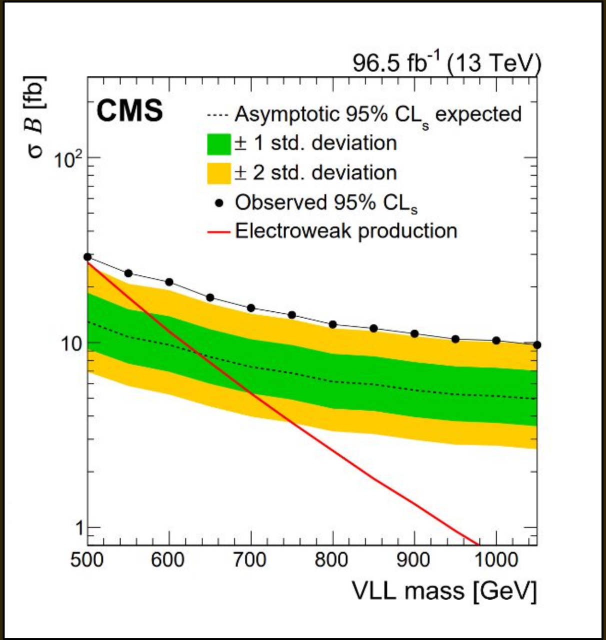
Defining the Signal Signature

Recent CMS search[2] for pair-produced VLLs found **an excess**:

- The search considered a **hadronic phase space**
  - **Jets + hadronic τ**
  - Dominated by QCD background

This analysis looks into an ⊥ phase-space:

- The **leptonic** phase space with final states of 2 SM leptons **(e or μ)**
- Additionally, we expect **jets, bjets, and missing energy**

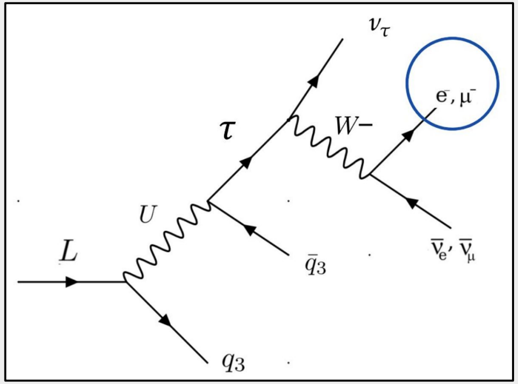


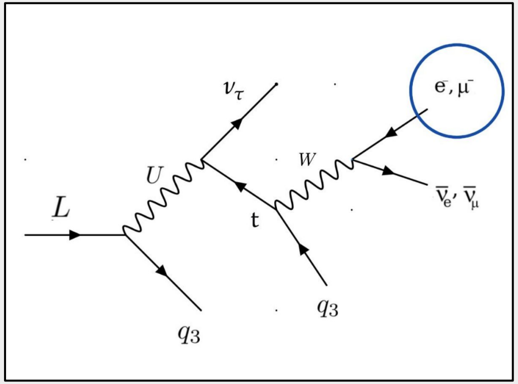
[2] CMS-B2G-21-004: *Search for pair-produced vector-like leptons*

Defining Search & Control Regions

- Decays resulting in 2ℓ from **t or τ**
  - **E+** → **t** $\nu\tau^{\sim}$ $\bar{b}$ 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** $\bar{\mathbf{t}}$ $\nu\tau^{\sim}$ or $\bar{\mathbf{t}}$ **τ**$^+$ b

VLL Pair	Final States
EE	**2l + 4b** + MET
EN	**2l + 4b** + 2j + MET
N$\bar{\text{N}}$	**2l + 4b** +4j + MET



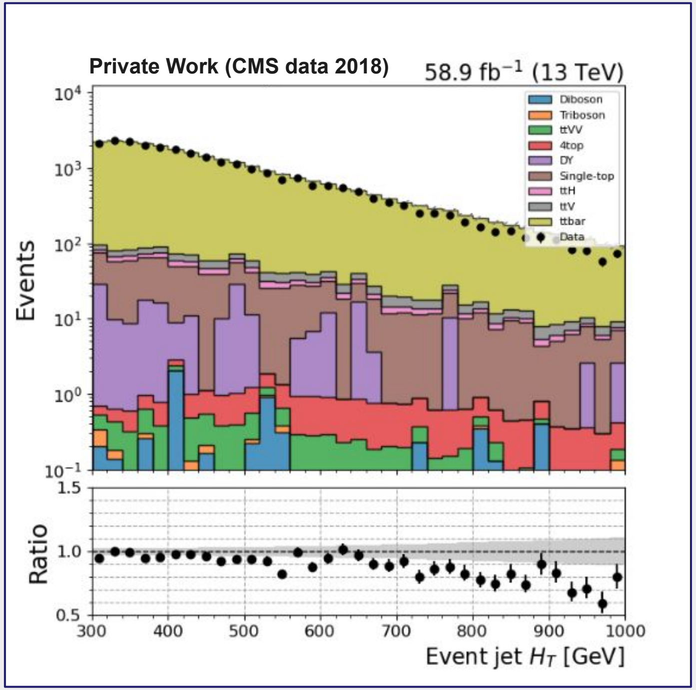


Signal Region (SR): 4b
Expect the greatest signal/background ratio.
Where to search.

Control Regions (CR): 3b or 2b
Expect negligible signal contribution
Aids in **understanding** background in SR.

Standard Model Backgrounds

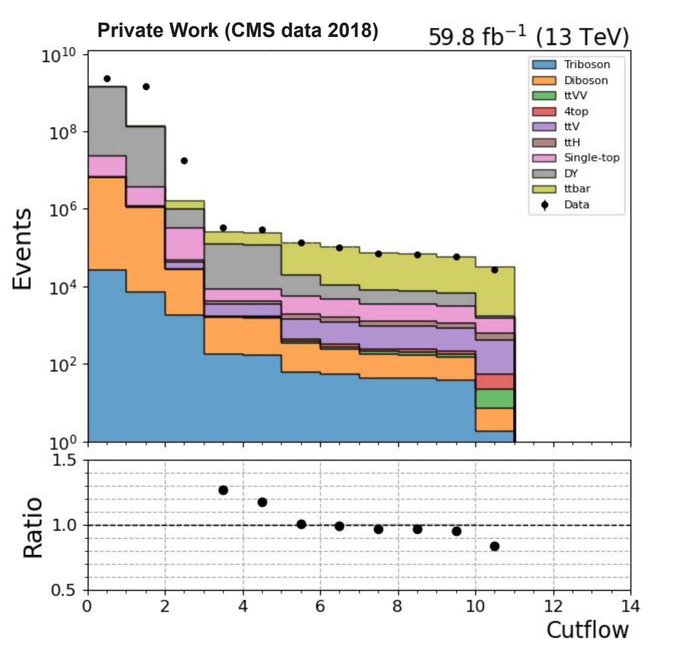
- **SM background** processes with similar signature:
  - **tt-bar**
  - DY+jets
  - Di-boson production
  - Tri-boson production
  - tt(V/H)+jets
  - tt+VV
  - 4-top
- The SM background:
  - **Scaled** to the expected cross-section
  - **Compared against the data** in the CR



Event Selection

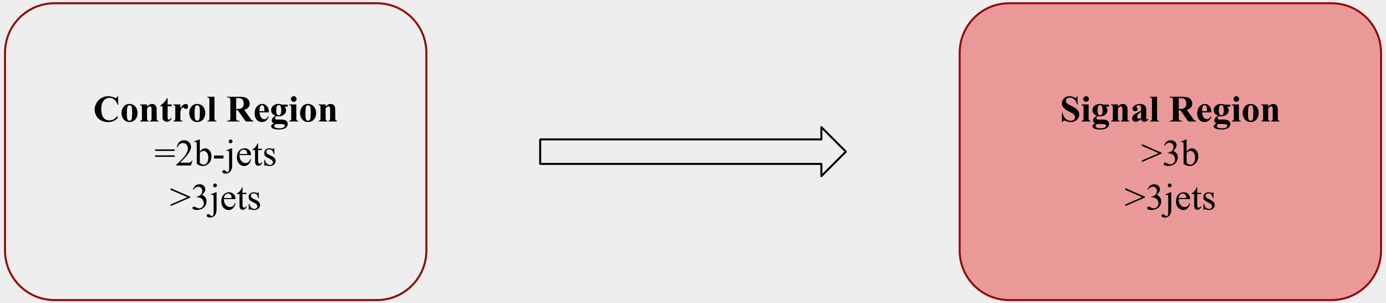
Bin	Variable	Criteria	Description
3	Jet #	> 3	Number of jets
4	Lepton #	2	Number of leptons
5	m_{ll}	> 20 GeV	Invariant mass of the two leptons
6	Z peak veto m_{ll}	< 76 & > 106 GeV	Veto events that the m_{ll} is in the mass range of the Z boson
7	MET	> 40 GeV	Missing transverse energy
8	$p_T^{\text{lead jet}}$	> 100 GeV	Transverse momentum of leading jet
9	$p_T^{\text{sub-lead jet}}$	> 50 GeV	p_T of sub-leading jet
10	H_T	> 300 GeV	Sum of all jet p_T
11	B-jet #	> 1	Number of b-tagged jets

Event selection criteria are employed to reject background events while maintaining high signal acceptance

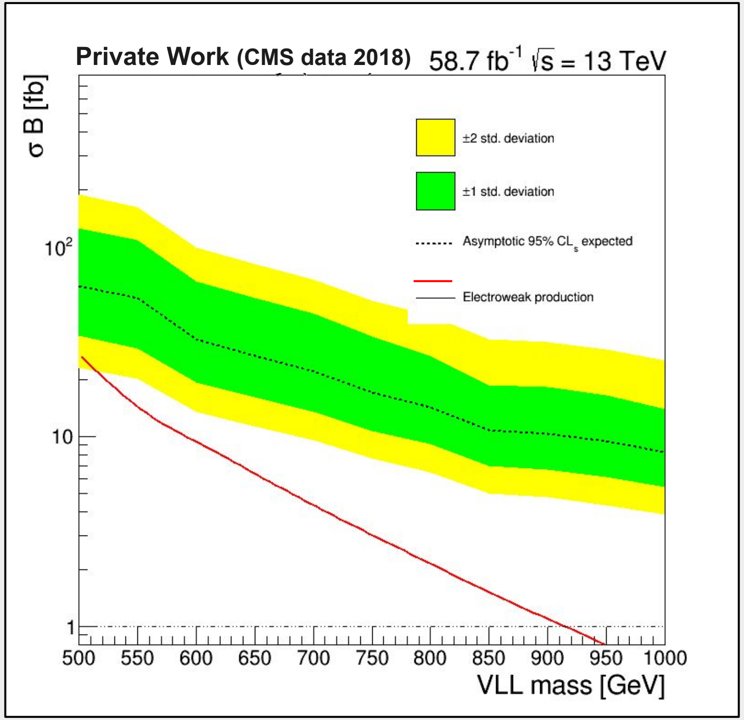


$t\bar{t}$ Background Estimation From Data

- The **dominant background comes from tt-bar**
  - Makes up to ~95% of all background in the signal region
- We plan to use a **ttbar enriched CR** to **estimate the tt-bar in our search region**
  - Events in the CR are used to constrain the number of tt-bar events expected in the SR



Expected Sensitivity



Sensitivity plots allow us to see how the data compares to the SM expectation

- A maximum likelihood method is utilized with the **signal strength as a parameter of interest**
- Here, the Asimov dataset is used to produce expected sensitivity
  - And, MC is used for all SM backgrounds

We expect the sensitivity to improve by **further improving the $\frac{S}{B}$ ratio**, applying the data-driven **tt-bar background estimation**, and using the **full Run II statistics**

Analysis Summary

- **Vector-like leptons are predicted** by many models that attempt to explain SM tensions
- **Excess observed** in hadronic phase space of previous search
  - Important to investigate the leptonic phase space (orthogonal)
- Designed **event selection criteria** (reduction of SM background)
- Developed a method to estimate the dominant ttbar background from data in a dedicated CR
- Calculated & showed the **expected sensitivity of this search** for 2018 CMS data
- **Improvements to come**:
  - Exploring **ML techniques**, the data-driven **background estimation**, & using full **Run-II** statistics

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

Thank you for your time

as well as **Prof. Tulika Bose, Dr. Charis Kleio Koraka, Elise Chavez, Victor Shang, & Andrea Maria Ola Mejicanos** for your vast wisdom and generous support

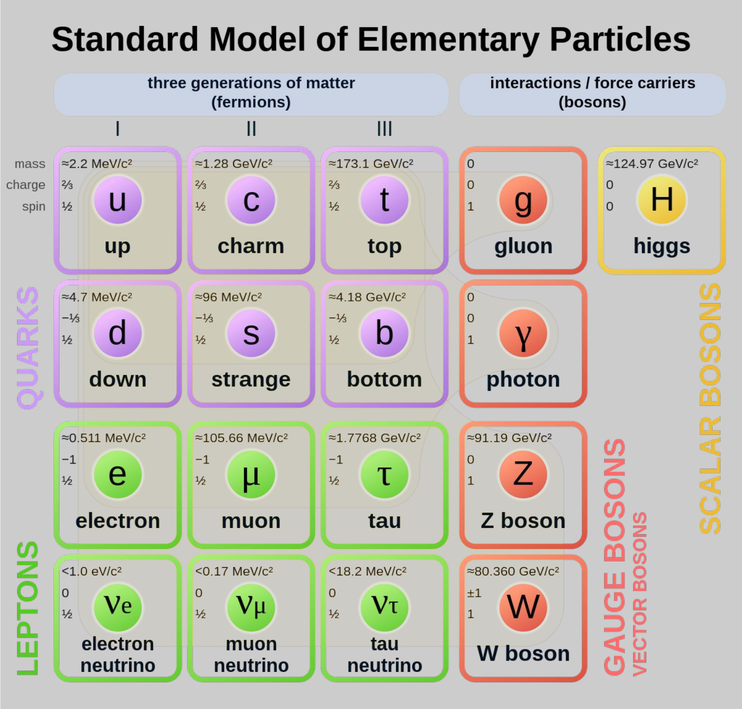
The Standard Model

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

Unresolved questions remain:

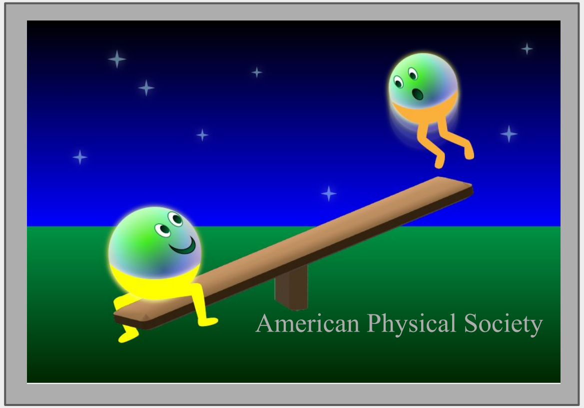
matter/antimatter, dark matter, gravity, origin of neutrino masses…

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



The Standard Model

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

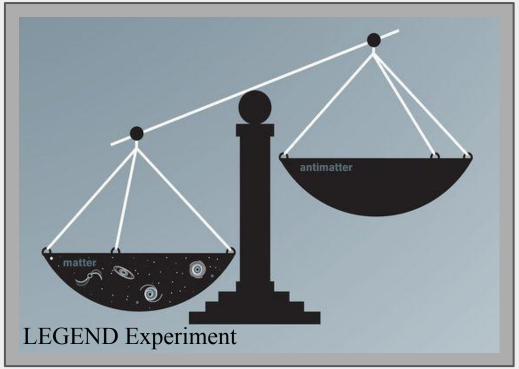


Matter/Antimatter Asymmetry:

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

+1 matter particle per billion

Why?



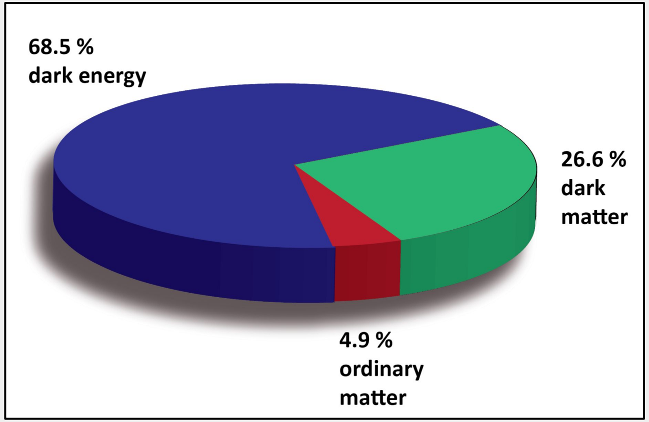
Neutrinos:

Standard Model explains neutrinos as massless observed to change flavor…

only possible with neutrino mass.

The Standard Model

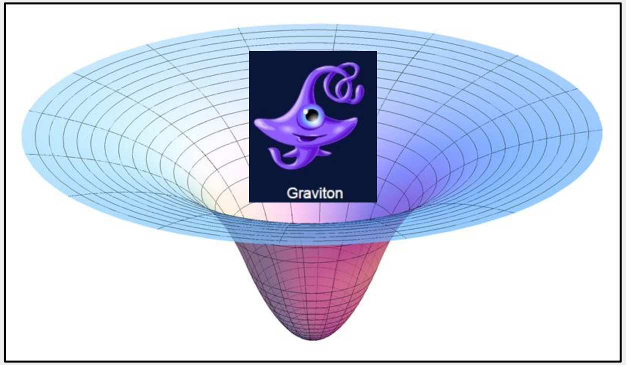
- Matter/Antimatter Asymmetry
- Origin of Neutrino Masses
- **Gravitational Force**
- **Accounting for the 95%**



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)

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**

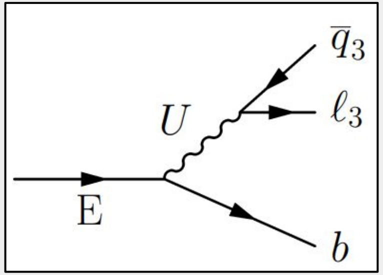
2) **2ℓ Final States** from *this* decay

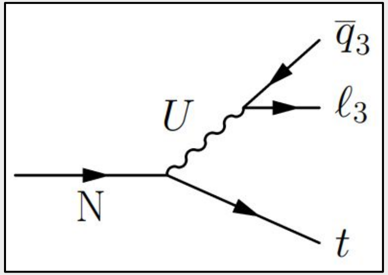
a. ℓ+ℓ+ b b bbar bbar vτ vτbar vℓ vℓ from [t,t]
b. ℓ+ ℓ- b b bbar bbar vτ vτbar vℓ vℓbar from 2x [t, tbar]

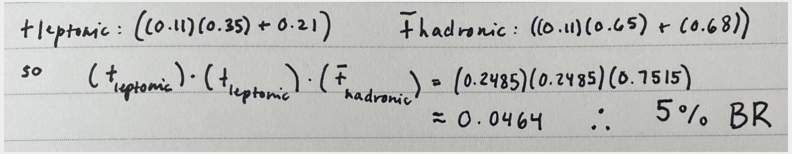
3) BR Calculation considering all **t's and τ's**

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!

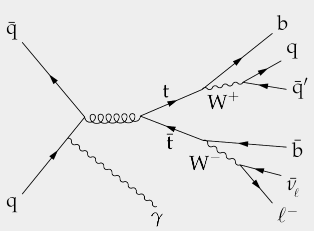


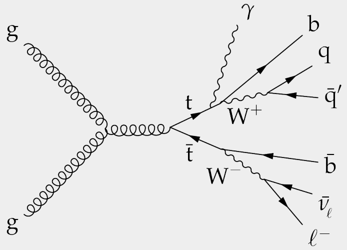



$t_{leptonic}$: ((0.11)(0.35) + 0.21) $\bar{t}_{hadronic}$: ((0.11)(0.65) + (0.68))
so $(t_{leptonic}) \cdot (t_{leptonic}) \cdot (\bar{t}_{hadronic}) = (0.2485)(0.2485)(0.7515)$
≈ 0.0464 ∴ 5% BR

Background Processes

- **ttbar**





- **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
- Gauge leptoquark as the origin of B-physics anomalies
- 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