Search for Vector-Like Leptons
in multi-lepton final states with the ATLAS detector

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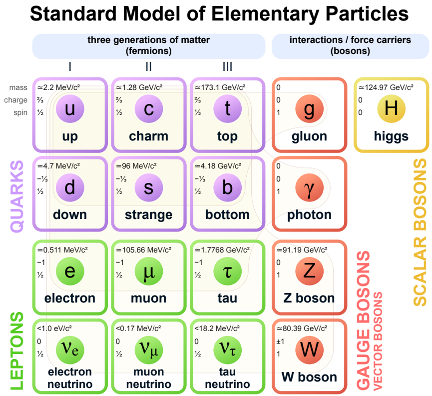
Background: Leptons in the Standard Model

- SM = best-tested theory to date
- Lepton: 1/2-integer spin, EM/Weak interactions
- Three flavours of lepton: e, μ, τ
- SM leptons are chiral (left- & right-handed components behave differently)
- Flavours identical except for mass: "Lepton Flavour Universality" (LFU)
- LFU Violation (LFUV): flavours not identical
- SM is very useful, but has problems: gravity, dark matter, ..., and the hierarchy problem



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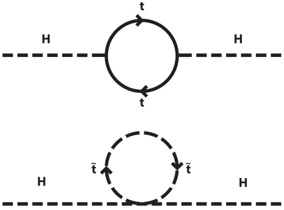
Motivation #1: The Hierarchy Problem

- Hierarchy Problem: The Higgs mass “should” diverge due to loop corrections, but it doesn't...Why?
- Maybe supersymmetry or extra dimensions, no evidence yet...
- Maybe something else helps cancel those loops?



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Vector-Like Quarks

- Composite Higgs Models could solve hierarchy, need more quarks for those
- Chiral 4th generation quarks are basically ruled out: <600 GeV are excluded, anything higher would increase the Higgs cross-section by 10x
- “Vector-Like” $=$ non-chiral quarks are one possible solution
- Vector-Like Leptons (VLLs) have been proposed as a similar solution

Motivation #2: VLLs in Particular

(Remember: VLL = non-chiral lepton)

Q: VLLs are one possible model, why study them vs. SUSY/VLQs?

A1: Some recent LFUV data could be explained by VLLs [2]

A2: There's lots of VLL parameter space that hasn't been explored (vs. say SUSY)

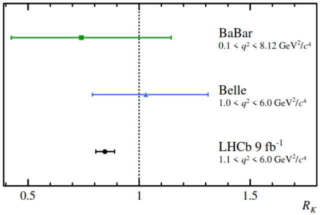
LHCb [1]: 3σ (+ more if combined) anomaly in B decays,

$$R(K) = \frac{B \to K\mu^+\mu^-}{B \to Ke^+e^-}$$

Muon $g-2$ [3]:

- 4.2σ anomaly in magnetic moment (a_μ)
- suggests different couplings of e and μ to photons

Other hints [4]: (irrelevant for VLLs)
Cabbibo Angle Anomaly (3σ),
$\tau \to \mu\nu\nu$ (2σ), $b \to c\tau\nu$ (3σ), $pp \to e^+e^-$ (3σ)



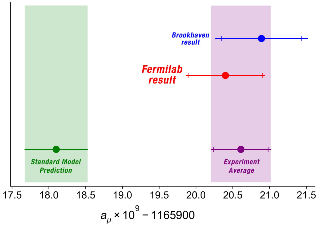
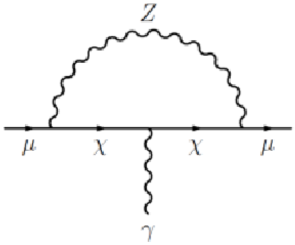


Image Sources: [1, 3]

How Can VLLs Explain The Data?

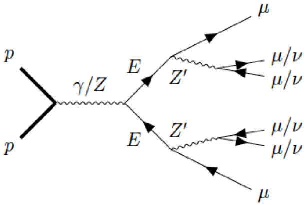
a_μ: different magnetic moment for μ vs. e

- To measure that moment, they used EM interactions
- Maybe new physics in the process $\mu \to \gamma + \mu$!
- Could be like top diagram, with χ = VLL



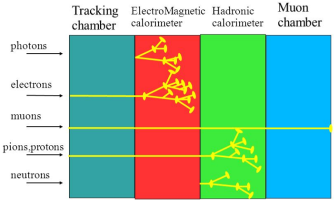
$R(K)$: similar idea, but $b \to s\mu^+\mu^-$ vs. $b \to se^+e^-$

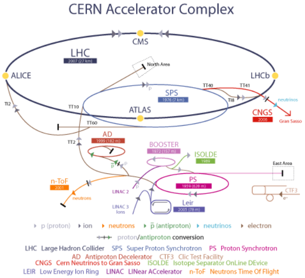
- Also requires Z', a heavier Z
- Like bottom diagram, with E = VLL



ATLAS Intro

- LHC: Large Hadron Collider
  - Large (27 km long)
  - Collides hadrons (protons)
  - $\sqrt{s} = 13\,\text{TeV}$
- ATLAS:
  - General-Purpose
  - Detects leptons and photons well
  - Over 200M readout channels
  - Using Run 2 dataset here (2015-2018), $L = 139\,\text{fb}^{-1}$





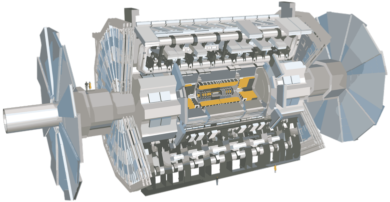
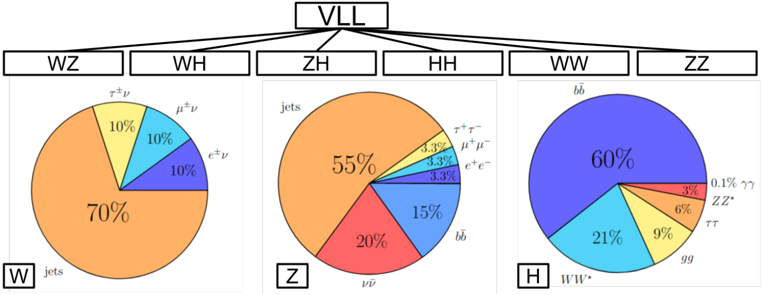


Image Sources: 1, 2, 3

Why Use ATLAS for a VLL Search?

- VLLs haven't been found yet, may have high mass
- LHC is on the high energy frontier, may have ability to produce VLLs directly
- ATLAS: LHC detector, so good tool for the job (hopefully)
- VLL models often decay to multi-lepton final states, and an ATLAS multi-lepton general analysis is being carried out now



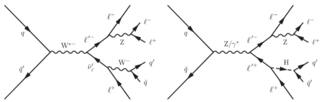
Pie chart source: [6]

Signal and Background Processes

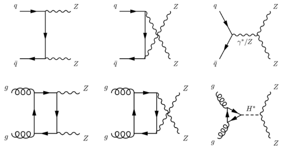
Must be able to separate VLL signal from noise.

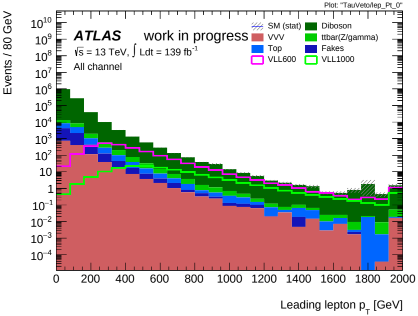
We have ≥ 3-lepton final states, so dominant backgrounds are VV, VH, $t\bar{t} + X$, ...

Example VLL processes:



Example background processes with ZZ:





Background will wash out signal, need to make event selections to deal with that.

Selections To Improve Signal Strength

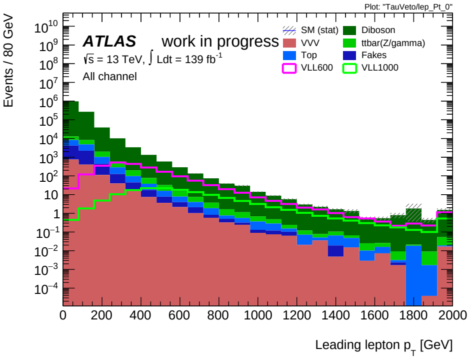
We want to:

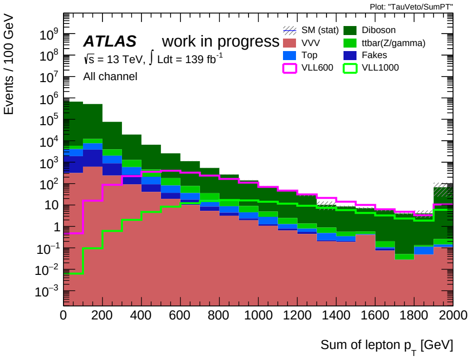
- Improve signal-to-noise ratio
- Avoid reducing number of signal events too much,
  i.e. keep signal efficiency (signal/background) high
- Enhance sensitivity for discovery $\propto \frac{\text{signal}}{\sqrt{\text{background}}}$

The next few plots:

- Sum of p_T of all leptons, and p_T of the leading lepton
- (p_T = "transverse" momentum, i.e. not in the direction of the beam)
- Subsequent plots include previous selections too
- Plots are normalized using $N_{\text{events}} = L * \sigma$ ($L = 139\,\text{fb}^{-1}$), for comparison with data

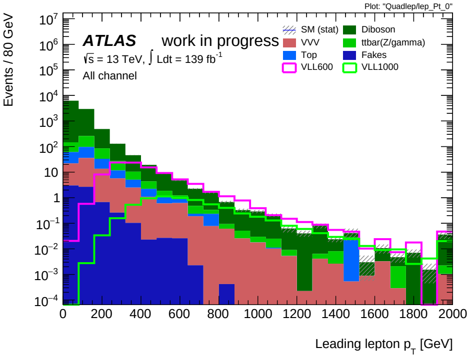
Selections: No Taus (yet)

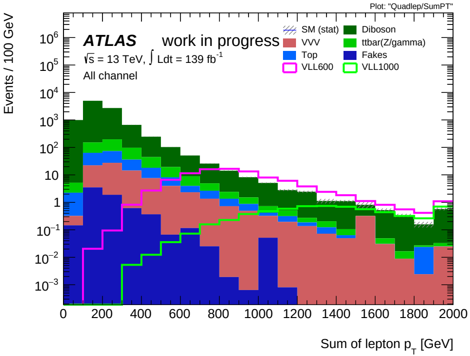




- For simplicity / comparison with another search
- Will add them later

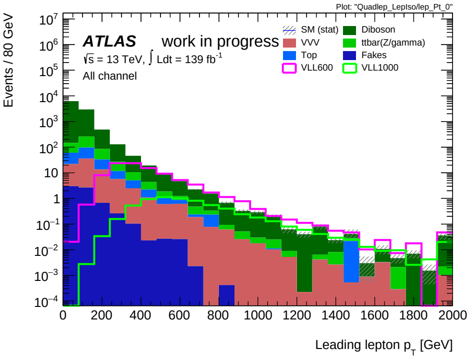
Selections: 4 Leptons (also looked at 3)

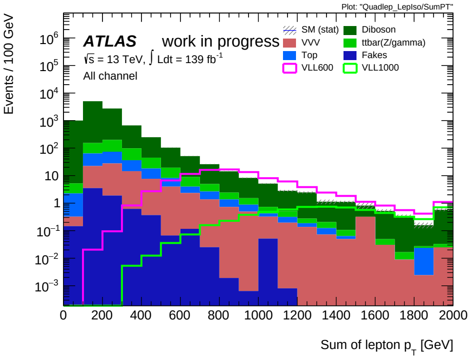




- VLLs decay (a lot of the time) into 4-lepton final states
- Background processes tend to have other numbers as well, cut those out

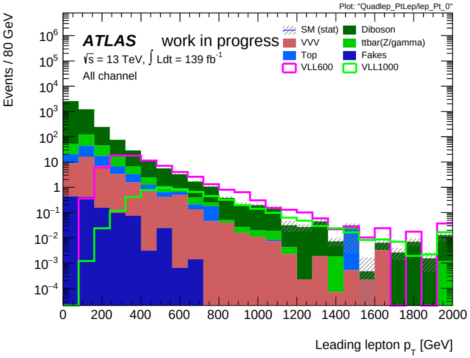
Selections: Leptons Must be Well-Isolated

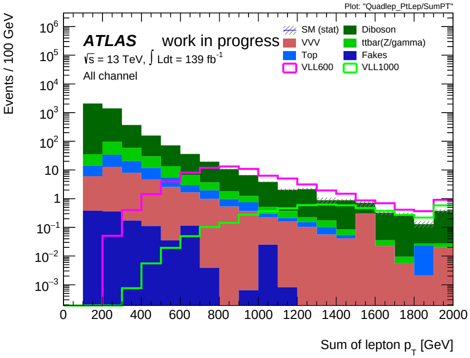




- Well-isolated = no nearby "junk" in detector
- Cleans up events for later

Selections: All Leptons Must Have p_T > 25 GeV

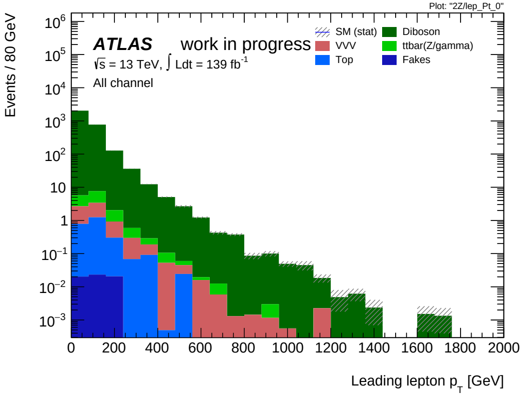




- Signals are more noticeable now
- Work in progress, this will likely get better!

Signal / Control Regions

- Signal Region = VLL signal expected
- Control Region = no signal expected, used to constrain backgrounds
- Possible CR (in plot): 4 leptons, ZZ
- Regions need to be formally defined by the group before looking at data



What's Next?

Typical ATLAS analysis workflow:

- Define/optimize SR&CR, blind SR
- Use CR to constrain backgrounds
- Create framework to detect VLLs, test on simulated SR
- Unblind SR and use framework
- Ideally discover VLLs! Exclude some parameter space if no discovery

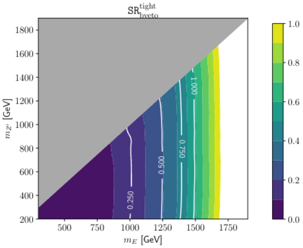


Image Source: [5]

Example exclusion plot for a theoretical VLL model with a Z', at the HL-LHC. Their VLL is "E."

Colours represent exclusion limits ($p_{excl} < 0.05$) for the branching ratio $BR(E \to Z'\mu)$.

White lines show the projected 5σ exclusion regions ($p_{disc} < 2.867 \times 10^{-7}$) for each BR.

Thanks for listening!

Also many thanks to the ATLAS Multi-Lepton Analysis Team
for guidance while doing this work and making this talk!

References I

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