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New Fermions

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On behalf of the EF09 editorial team

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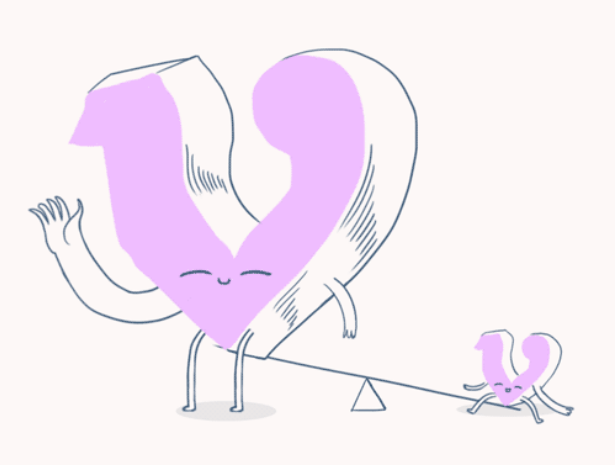
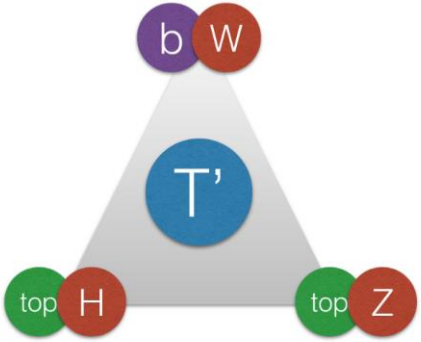
New Fermions

- The fermion sector revealed the first laboratory evidence for physics beyond the SM in the form of neutrino oscillations
- New fermions with masses from MeV -- TeV now appear in many possible extensions to the SM
- Seesaw models
  - Type-1: new neutral singlet
  - Type-3: new charged+neutral triplet
  - Could mix with SM neutrino flavors
  - Couplings will be small!
  - Can be connected to leptogenesis mechanisms
- Vector-like fermions
  - LH and RH components transform the same under SM
  - V-L leptons
  - V-L quarks

Symmetry

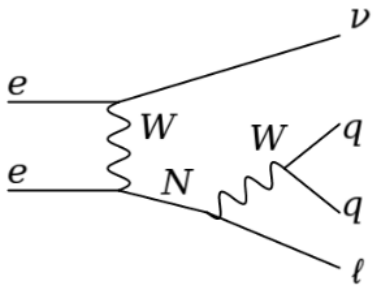


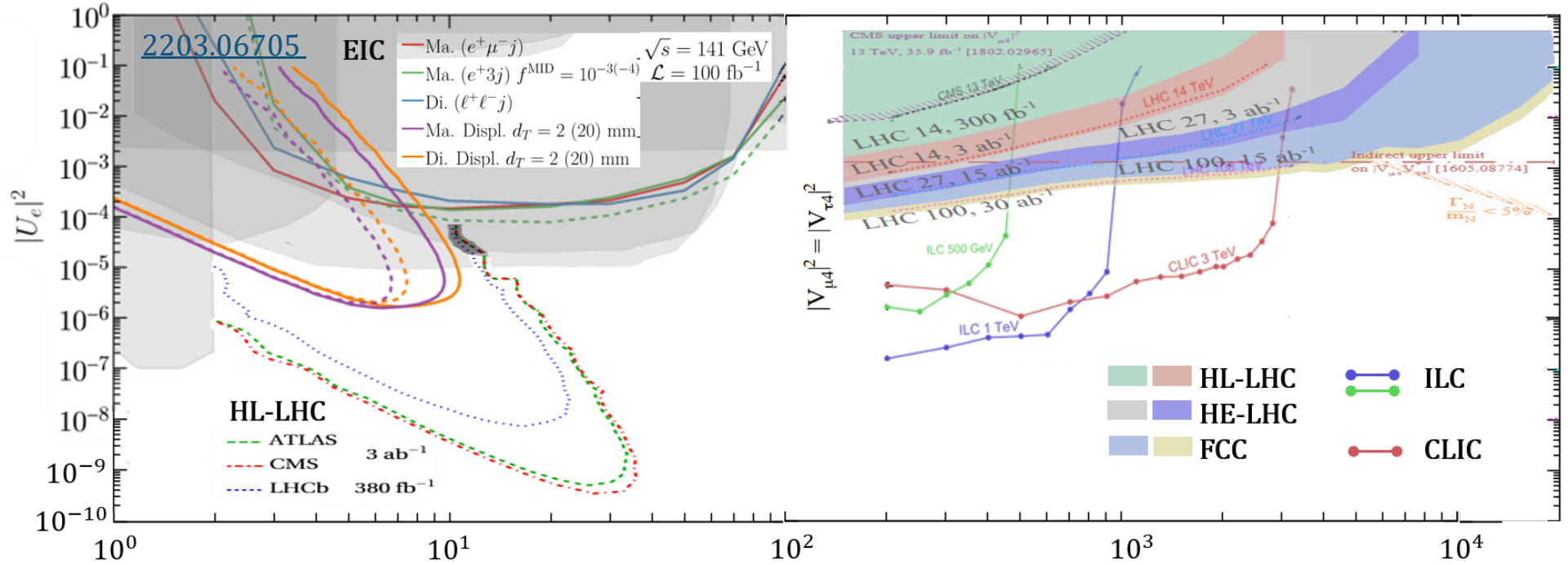


Heavy Neutral Leptons: Type-1

- N → V + lepton, decaying promptly or displaced into the detectors
- Multilepton or lepton + jets final states
- Low mass projections: single flavor mixing of N with SM
- High mass projections: 2 (pp) or 3 (ee) flavors with equal mixing

2202.06703

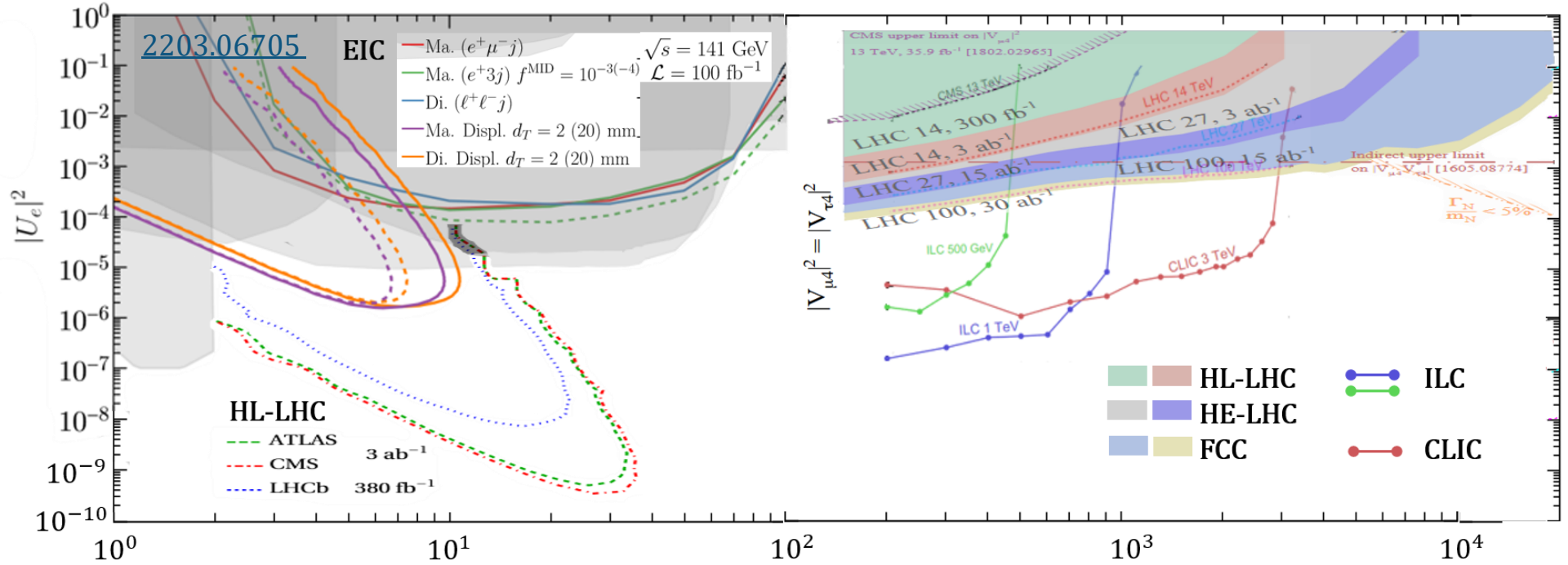




2203.08039, 2203.06705, 2203.07622

Heavy Neutral Leptons: Type-1

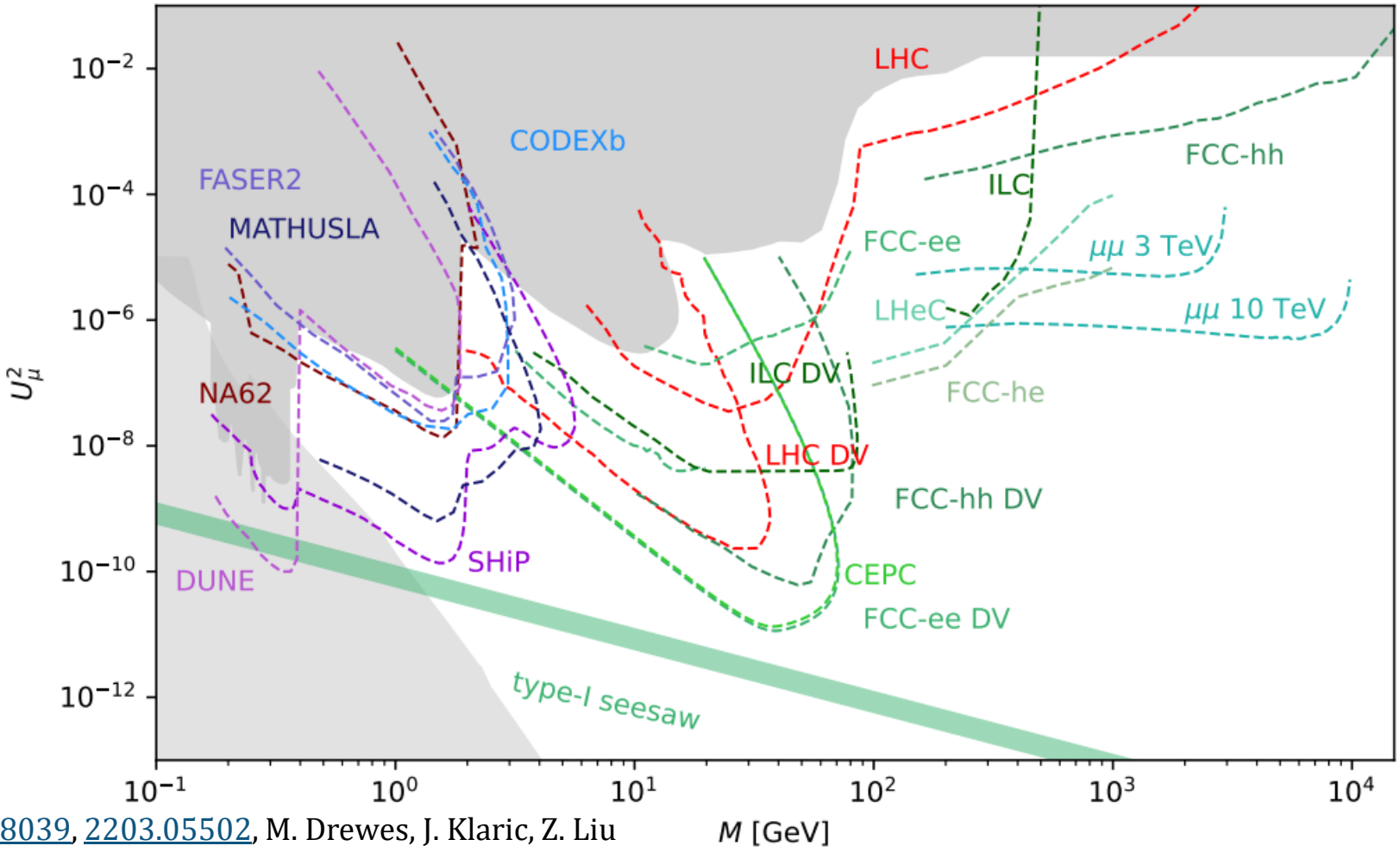
- **EIC**: sensitive at low and medium mass ranges, special LFV search possibility
- **LHC/FCC**: strong potential for low mass displaced searches, consistent coupling reach out to very high mass with increased lumi and energy
- **ILC/CLIC**: can dig more deeply into coupling space where energy allows.
  - Fast-sim study with machine learning



2203.08039, 2203.06705, 2203.07622

Heavy Neutral Leptons: Type-1

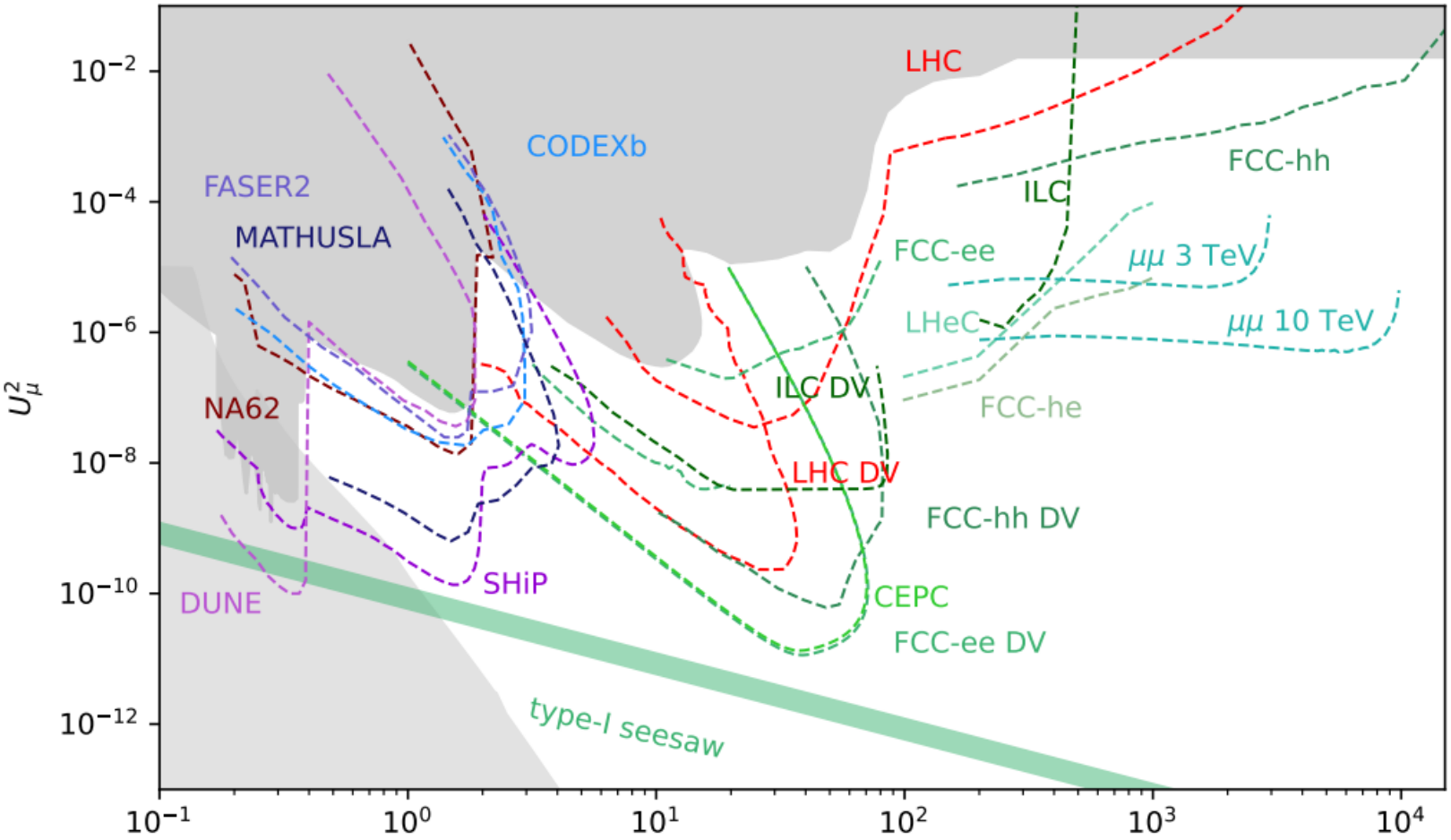
- **For displaced HNL signatures, more experiments can join the search**
- HL-LHC timescale: FASER2, MATHUSLA, CODEXb, DUNE can probe low masses



2203.08039, 2203.05502, M. Drewes, J. Klaric, Z. Liu

Heavy Neutral Leptons: Type-1

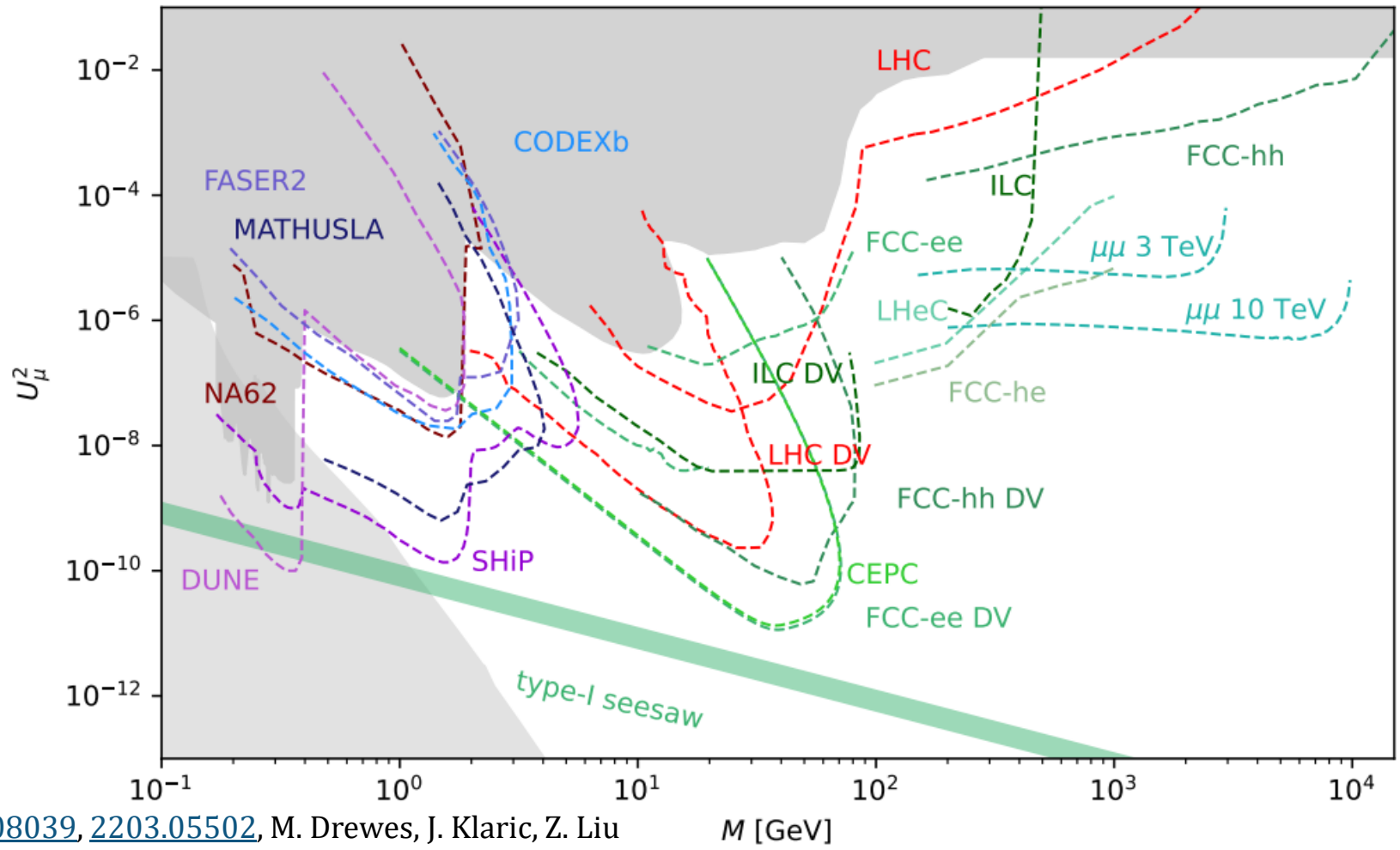
- **HL-LHC timescale**: LHC displaced searches advance in the 10 GeV region
- **Past HL-LHC**: FCC-ee offers the strongest sensitivity for GeV-scale HNLs



2203.08039, 2203.05502, M. Drewes, J. Klaric, Z. Liu

Heavy Neutral Leptons: Type-1

- **Muon collider**: offers access to smaller couplings for TeV-scale couplings, similar to ILC/CLIC projection for three flavor mixing



2203.08039, 2203.05502, M. Drewes, J. Klaric, Z. Liu

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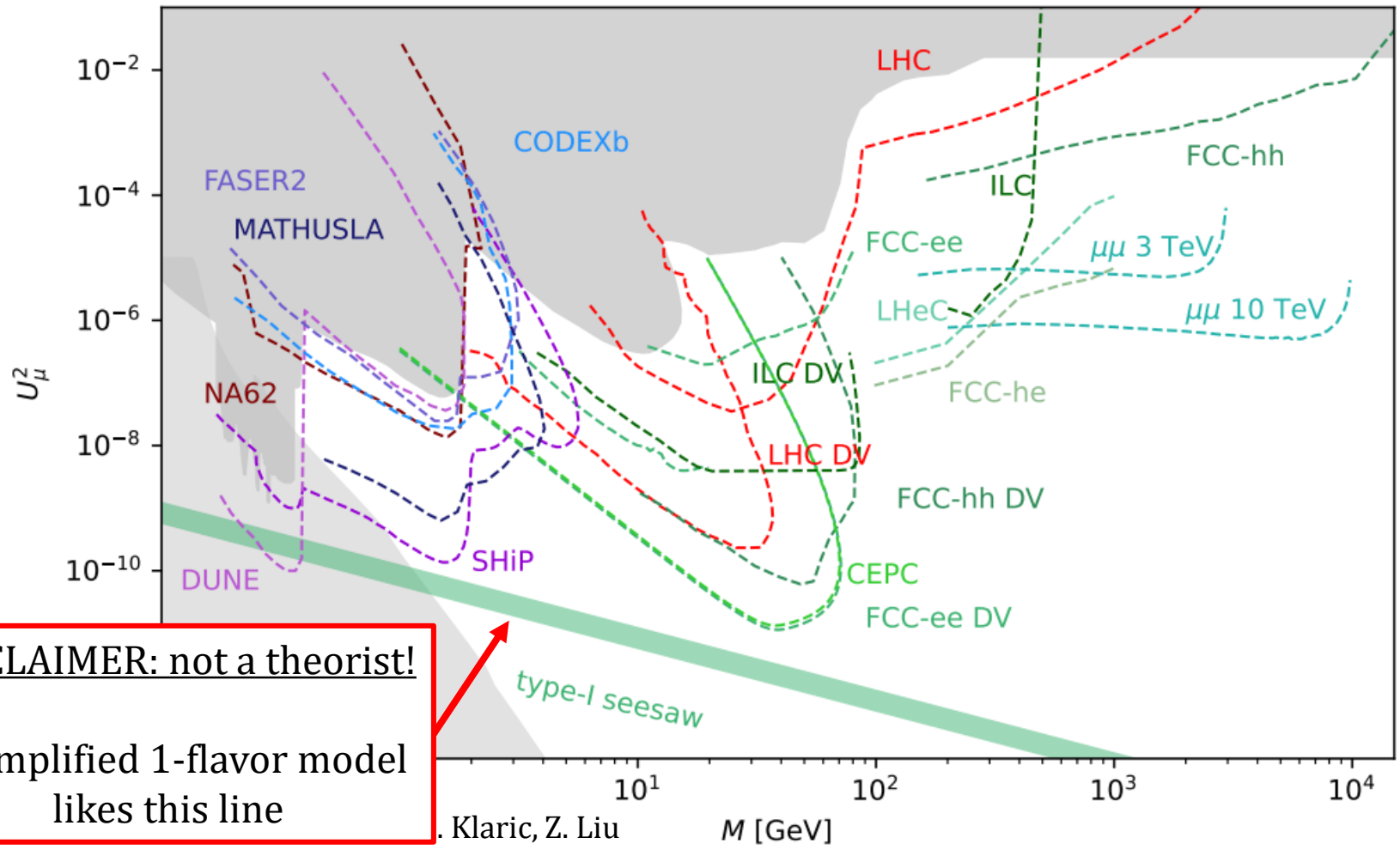


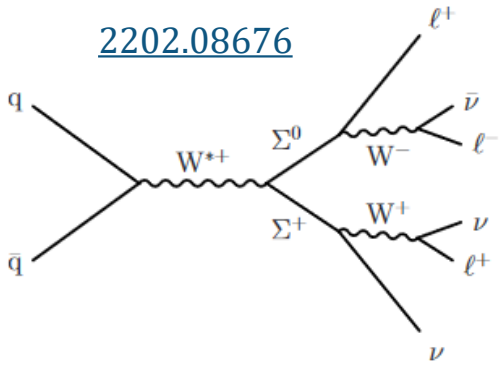
. Klaric, Z. Liu

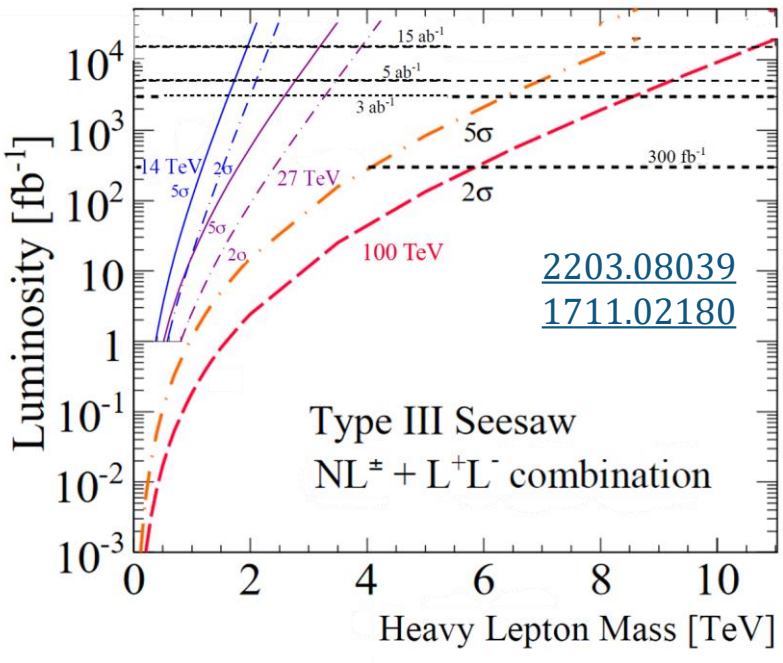
DISCLAIMER: not a theorist!

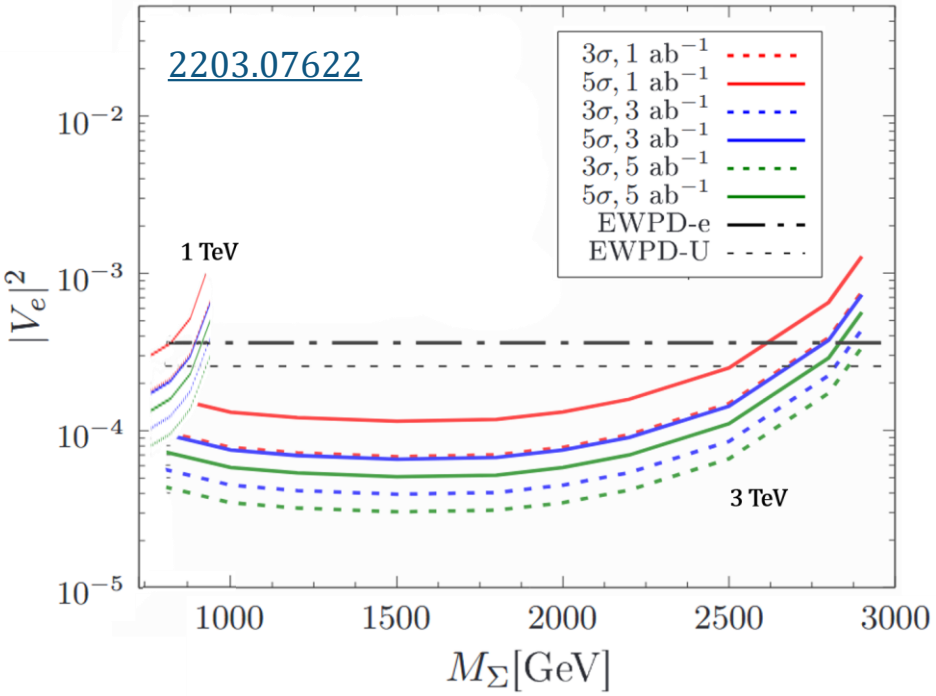
A simplified 1-flavor model likes this line

Heavy Neutral Leptons: Type-3

- N → Wℓ gives multilepton or boosted-jet final states
- **pp**: pair production of neutral + charged heavy leptons
  - HL-LHC will not reach far beyond ~1 TeV Run 2 bounds
  - 100 TeV could quickly out to 6 TeV, discover past 3 TeV
- **ee**: single production of neutral lepton
  - Below their thresholds, ee colliders can push couplings below EWPD bounds.





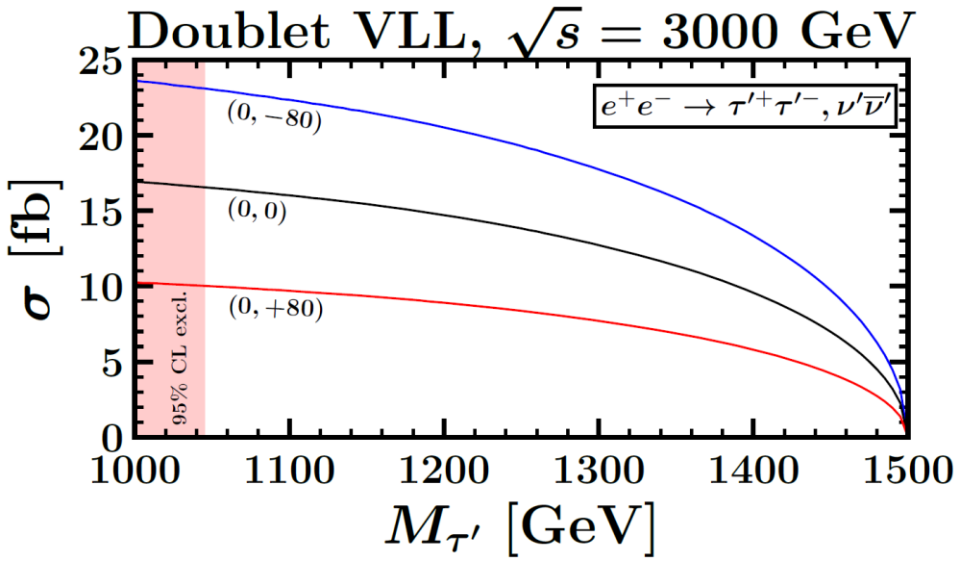


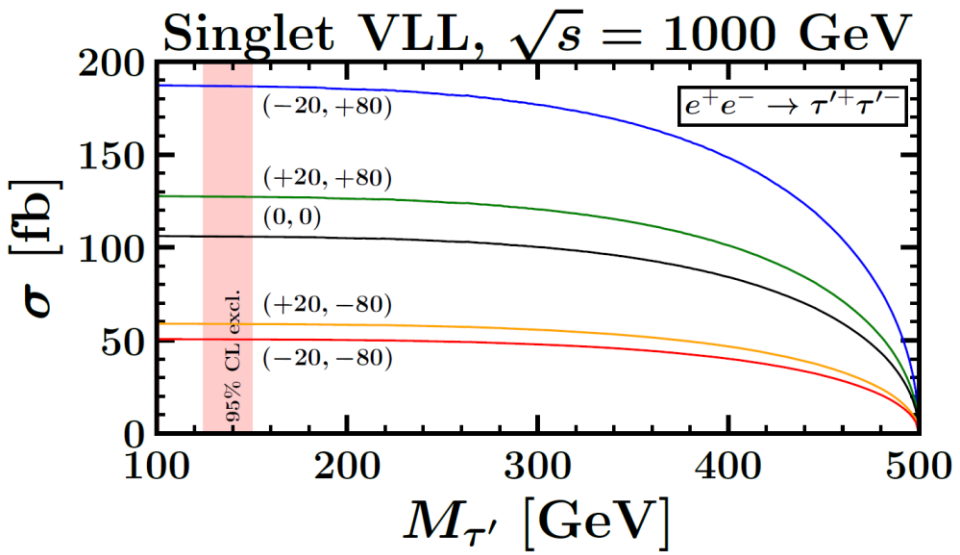
Vector-like leptons

- EW singlet τ' or doublet of (τ', ν')
- Many final states with various numbers of light leptons and hadronic τ decays
- Doublet VLL excluded to 1 TeV at LHC
  - Discovery potential up to 4 TeV at FCC-hh
- **Singlet VLL will be tough for pp colliders!**
  - But could be discovered with < 200/fb at ee!

BR	Singlet τ'	Doublet τ'	Doublet ν'
Wν Wτ	50%		100%
Zτ	25%	50%	
Hτ	25%	50%	

2202.08676, Shang et al, S. Martin, P. Bhattiprolu

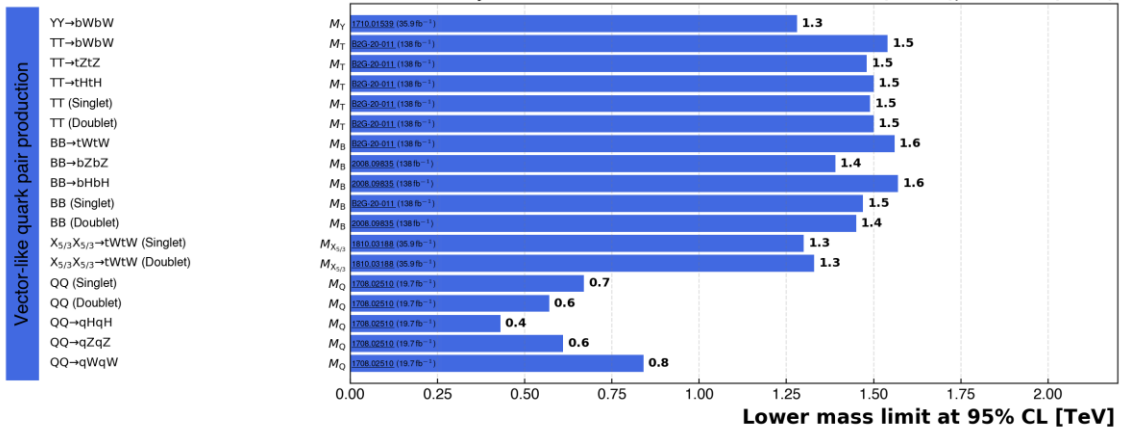


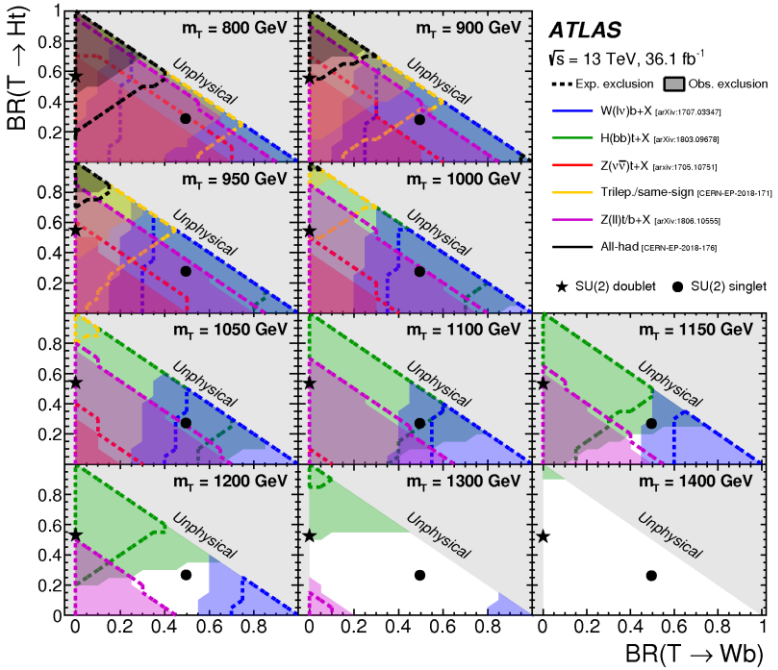


Vector-like Quarks

- Fermionic top quark partners, T (+2/3) and X (+5/3), also B (-1/3) and Y (-4/3)
- Exciting detector signatures featuring many massive SM particles
- **LHC:** comprehensive search programs exclude pair T and B below ~1.5 TeV
- **HL-LHC**: not much more mass reach for pair searches!
- **FCC-ee: sensitive to single production of T, X with G/M < 30% up to 14 TeV!**

[1710.06353](1710.06353)





Vector-like Quarks

- **Exotic VLQ decays** are very important to consider in the future
- **2HDM:** heavy CP-even H or charged H
  - H decays could produce VLQ or VLL
  - **HL-LHC:** sensitive to VLQs up to 2.4 TeV, or up to 1.8 TeV when produced from H decays

$$T \to tH,\ T \to bH^{\pm}$$
$$B \to bH,\ B \to tH^{\pm},$$

2203.03852, 1907.07188

- **Composite Higgs:** scalar S
  - Ψ = any VLQ X, T, or B
  - **HL-LHC:** reach VLQ masses 1-1.5 TeV for ~500 GeV scalars

$$\bar{\Psi}\Psi \to t\bar{t}SS,\ b\bar{b}SS$$

2203.07270

- **EFTs:** T/B couple to t/b through (chromo-)magnetic effective interaction
  - Single production via a gluon, decay with gluon/photon
  - **HL-LHC**: reach for gluon or photon decays up to 1.4 TeV

2107.12402, 1808.03649

$$pp \to Tt \qquad T \to tg/t\gamma$$

Summary

- Many options for new fermions – **and all the colliders have something to offer!**
- HNLs: lepton colliders offer the best sensitivity for masses below their thresholds
- Vector-like leptons: sensitivity is strongest at lepton colliders given the expected decay modes and backgrounds.
- Vector-like quarks: Expanding search program to single production and exotic signals is key!