Searches for Vector Like Leptons in CMS

LHCP2024: 12th Edition of the Large Hadron Collider Physics Conference

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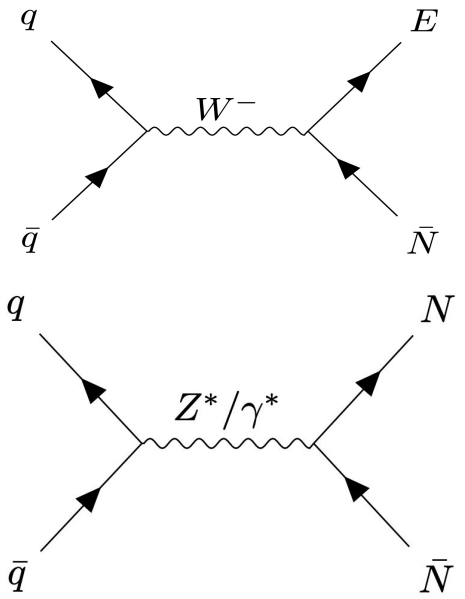
on behalf of the CMS collaboration

June 3rd - 7th 2024

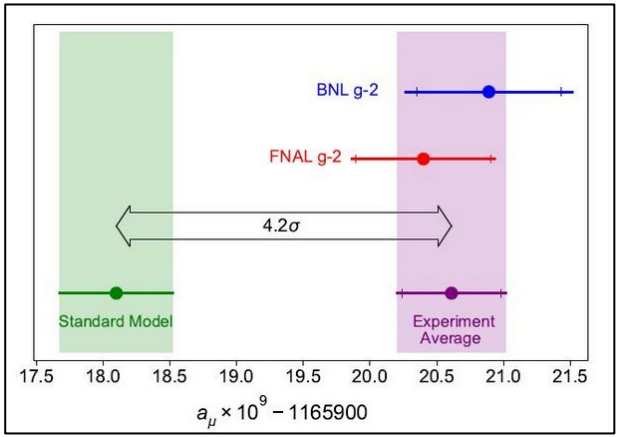
Vector-Like Leptons

- **SM incomplete → DM, hierarchy problem, neutrino oscillations …**
- **VLLs → Color-singlet counterparts of VLQs**
  - Non-chiral
  - Can be SU(2) doublets (E,N) or singlets (E)
  - Pair produced (pp → EE/NN) or produced in association (pp→ EN)



Vector-Like Leptons

- **Are predicted by many SM extensions**
  - Supersymmetric models
  - GUTs
  - Extra dimensional models
- **In BSM models VLLs :**
  - Provide dark matter candidates
  - Account for mass hierarchy via mixing with SM fermions
  - Explain tensions in muon g-2 measurements

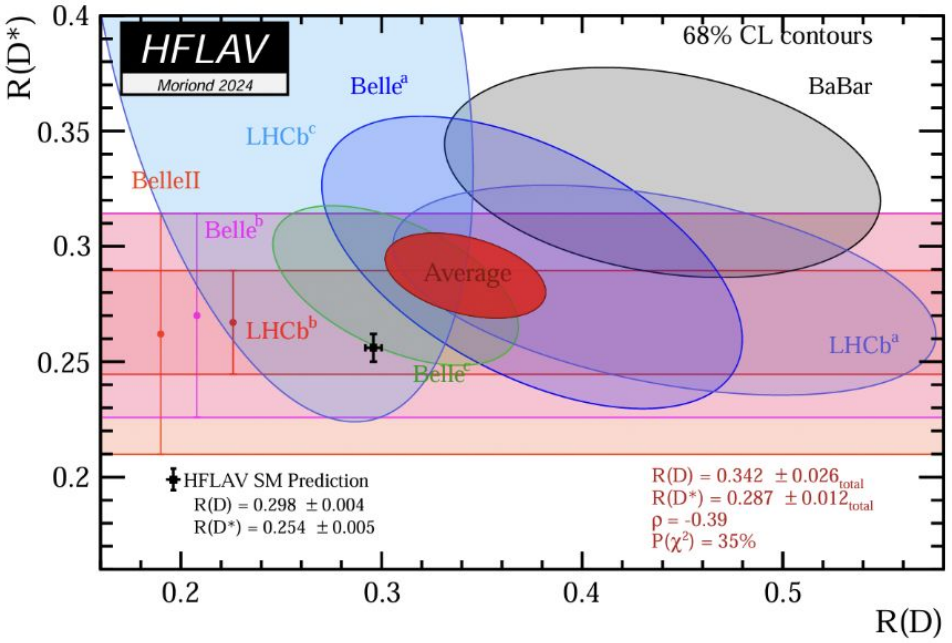


Motivation from B-physics anomalies

- Recent measurements show ~3σ deviation of $R(D^{(*)})$ from SM expectation

$$R(D^{(*)}) = \mathcal{B}_{B\to D^{(*)}\tau\nu}/\mathcal{B}_{B\to D^{(*)}\ell\nu}$$

- Strong motivation for VLLs searches @ CMS



Inclusive nonresonant multilepton probes of new phenomena

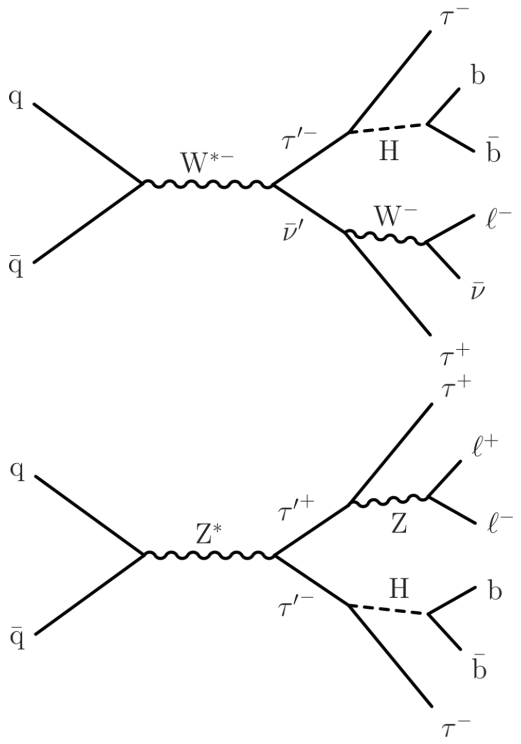
CMS-EXO-21-002 [arXiv:2202.08676]

- Model-independent multi-lepton analysis performed with full Run-2 data
- Several BSM physics scenarios are probed that cover different corners of the multilepton phase-space:
  - **Minimal SM extension where VLLs couple to the SM τ**

Inclusive nonresonant multilepton probes of new phenomena

CMS-EXO-21-002 [arXiv:2202.08676]

- Minimal SM extension where VLLs couple to the SM τ
  - τ enriched final states
  - Signal masses from 100 GeV–1200 GeV
- **Two scenarios considered:**
  - Doublet scenario τ’ (charged) & ν’ (neutral) VLLs
    - Mass-degenerate
    - Pair & associated production
  - Singlet scenario only charged τ’ VLL



Inclusive nonresonant multilepton probes of new phenomena

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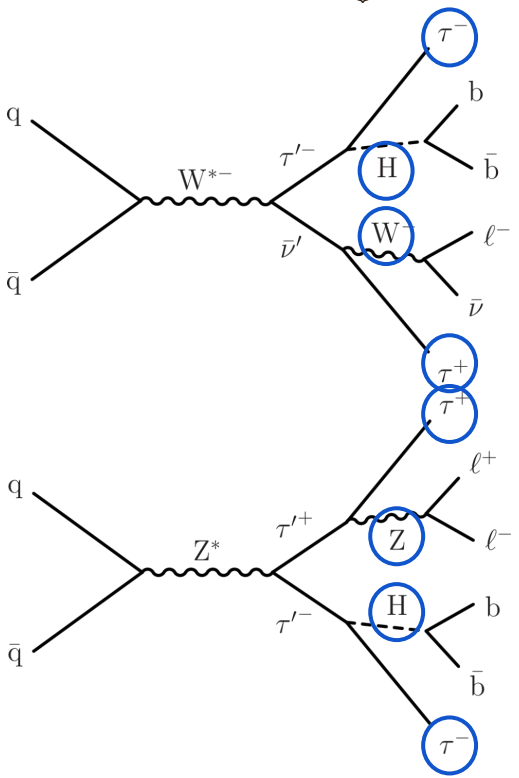
- Two scenarios considered:
  - Doublet scenario τ’ (charged) & ν’ (neutral) VLLs
    - Mass-degenerate
    - Pair & associated production
  - Singlet scenario only charged τ’ VLL
- **Assumed to mix through Yukawa interactions with SM leptons**
  - Decays are to SM boson-lepton pairs
  - Decay rates governed by $m_{\tau'}$



Inclusive nonresonant multilepton probes of new phenomena

CMS-EXO-21-002 [arXiv:2202.08676]

- Final states are categorized in seven orthogonal channels based on the number of light charged leptons and τ_h
- Categories are further split in 0, 1 and 2 or more b-jets categories (statistics permitting)

Trilepton channels	Quadlepton channels*
• **3L**: 3 light leptons, 0 had. taus	• **4L**: 4 light leptons, 0 had. tau
• **2L1T**: 2 light leptons, 1 had. tau	• **3L1T**: 3 light leptons, 1 had. tau
• **1L2T**: 1 light lepton, 2 had. taus	• **2L2T**: 2 light lepton, 2 had. taus
	• **1L3T**: 2 light lepton, 2 had. taus
	** No veto on additional leptons → only lead. four objects are considered*

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• **1L2T**: 1 light lepton, 2 had. taus	• **2L2T**: 2 lig
	• **1L3T**: 2 lig

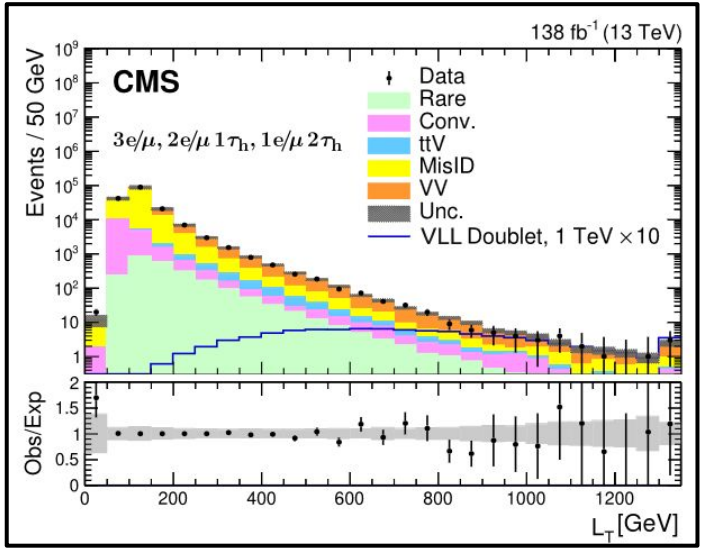
** No veto on additional leptons*
→ only lead. four objects are considered

- **Main background contributions** arise from :
  - SM processes WZ, ZZ, ttZ, and ttW
  - ISR/FSR
  - Lepton mis-ID (data-driven)
- Dedicated CRs defined for background estimation

Inclusive nonresonant multilepton probes of new phenomena

CMS-EXO-21-002 [arXiv:2202.08676]

- Two approaches utilized for defining the observables :
- **Model-Independent approach:**
  - Defining signal regions (SRs) based on kinematic properties.
  - Utilizing observables such as L_T (scalar sum of all charged leptons in the channel) to probe for VLL signal



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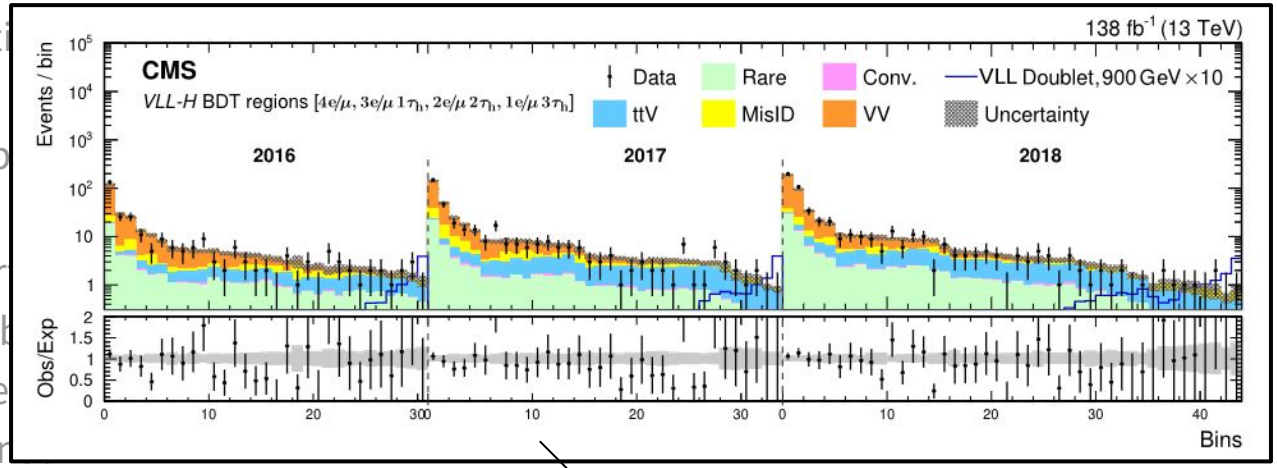

- **Model-Dependent approach:**
  - Signal specific BDT training for range of masses
  - Increase sensitivity for high signal masses

Bins correspond to variable-width regions of the BDT discriminant output defined for each of the combined three-lepton and four-lepton channels

Inclusive nonresonant multilepton probes of new phenomena

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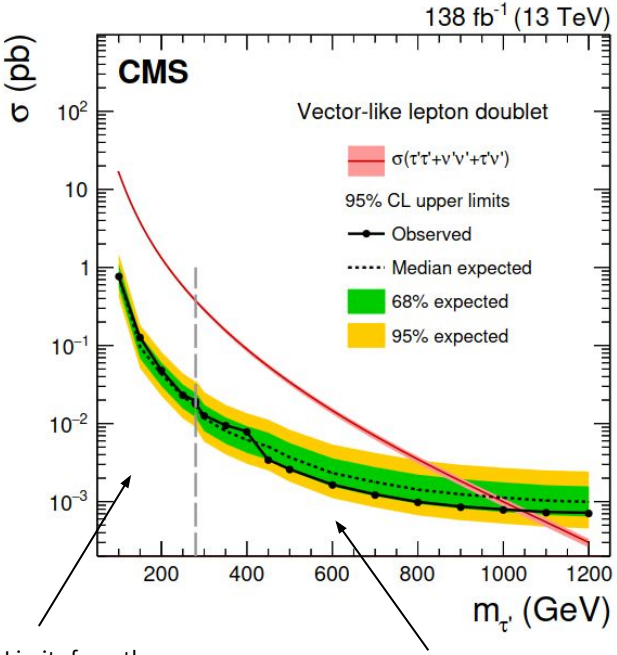
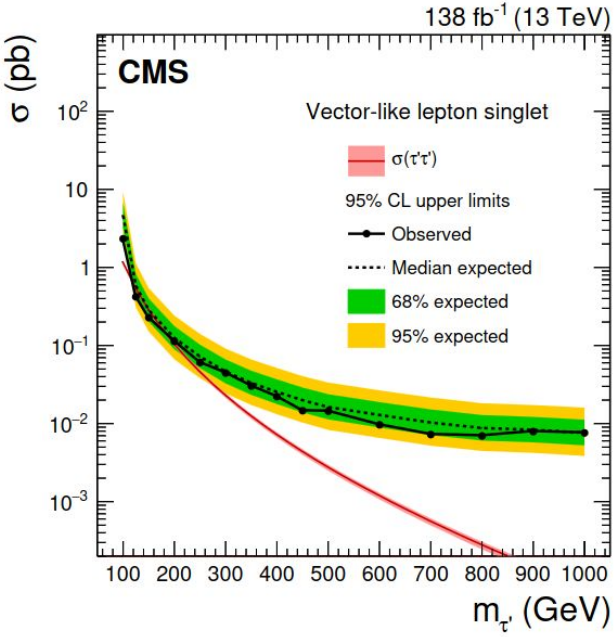


Limits from the model independent scheme.

Limits from the model dependent BDT regions.



Upper observed mass limits:

Doublet scenario → 1045 GeV

Singlet scenario →125-170 GeV

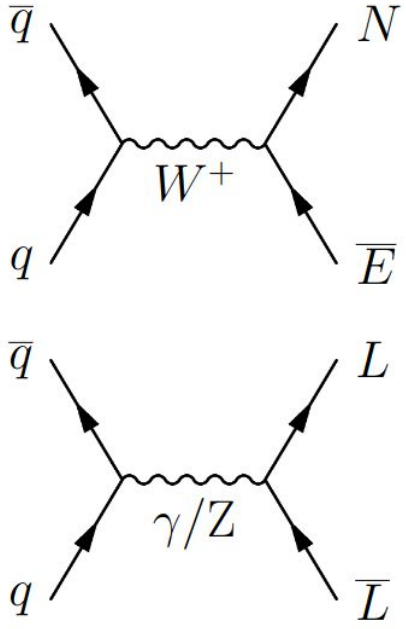
Search for pair-produced VLLs in final states with 3rd generation leptons

CMS-B2G-21-004 [arXiv:2208.09700v2]

- Performed in the context of the 4321 model [arXiv:1708.08450]

$$\mathrm{SU}(4) \times \mathrm{SU}(3)' \times \mathrm{SU}(2)_\mathrm{L} \times \mathrm{U}(1)'$$

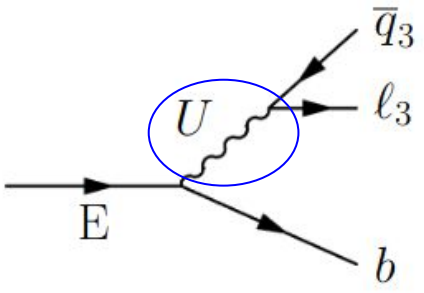
  - UV complete extension of SM gauge group
  - VLLs produced through Electroweak interactions
    - Doublet of charged (E) and neutral (N) VLL
    - E, N mass degenerate

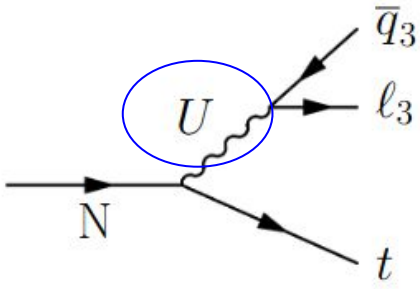


Search for pair-produced VLLs in final states with 3rd generation leptons

CMS-B2G-21-004 [arXiv:2208.09700v2]

- **Leptoquark predicted to exist as source of LFV explaining the B anomalies :**
  - U(3,1,2/3) → massive, spin-1
    - The R(D)$^{(*)}$ anomaly requires a leptoquark mass close to the TeV scale, in 4321 benchmark M_U = 1.6 TeV.
  - Search results in the 4321 model context also hold for other models with a Pati–Salam leptoquark

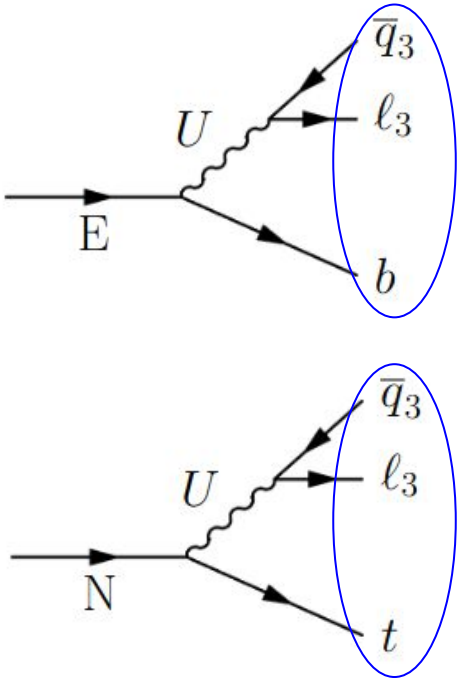




Search for pair-produced VLLs in final states with 3rd generation leptons

CMS-B2G-21-004 [arXiv:2208.09700v2]

- **Decays are expected to be almost entirely to third-generation fermions**
  - Branching fraction suppressed by at least an order of magnitude for 2nd and 1st generations



Search for pair-produced VLLs in final states with 3rd generation leptons

CMS-B2G-21-004 [arXiv:2208.09700v2]

- **Final states highly flavor asymmetrical**
  - At least two 3rd generation fermions expected in every VLL decay
  - All final states contain at least 4-b jets & a varying number of hadronic τ, ν_τ, and light jets from top decays

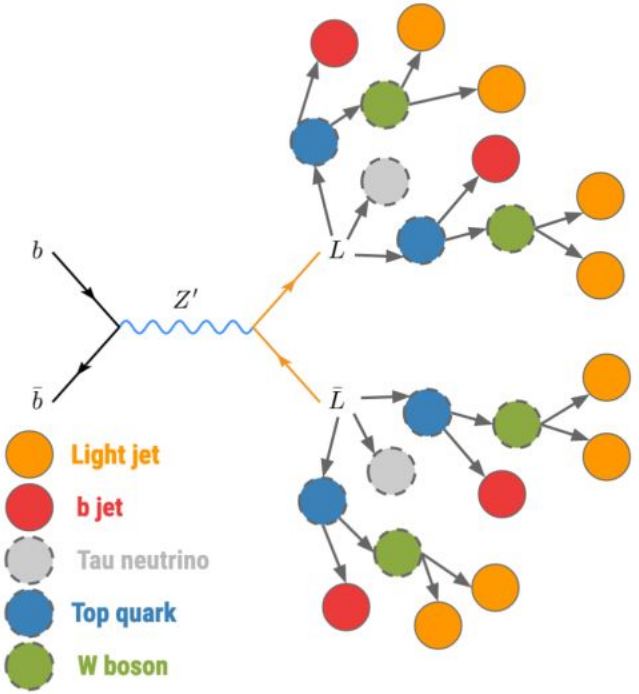
tau multiplicity	production + decay mode	final state
0 τ	EE $\rightarrow$ b(tν_τ)b(tν_τ)	4b + 4j + 2ν_τ
	EN $\rightarrow$ b(tν_τ)t(tν_τ)	4b + 6j + 2ν_τ
	NN $\rightarrow$ t(tν_τ)t(tν_τ)	4b + 8j + 2ν_τ
1 τ	EE $\rightarrow$ b(bτ)b(tν_τ)	4b + 2j + τ + ν_τ
	EN $\rightarrow$ b(tν_τ)t(bτ)	4b + 4j + τ + ν_τ
	EN $\rightarrow$ b(bτ)t(tν_τ)	4b + 4j + τ + ν_τ
	NN $\rightarrow$ t(bτ)t(tν_τ)	4b + 6j + τ + ν_τ
2 τ	EE $\rightarrow$ b(bτ)b(bτ)	4b + 2τ
	EN $\rightarrow$ b(bτ)t(bτ)	4b + 2j + 2τ
	NN $\rightarrow$ t(bτ)t(bτ)	4b + 4j + 2τ

In parenthesis:
Originating from leptoquark decay

Search for pair-produced VLLs in final states with 3rd generation leptons

CMS-B2G-21-004 [arXiv:2208.09700v2]

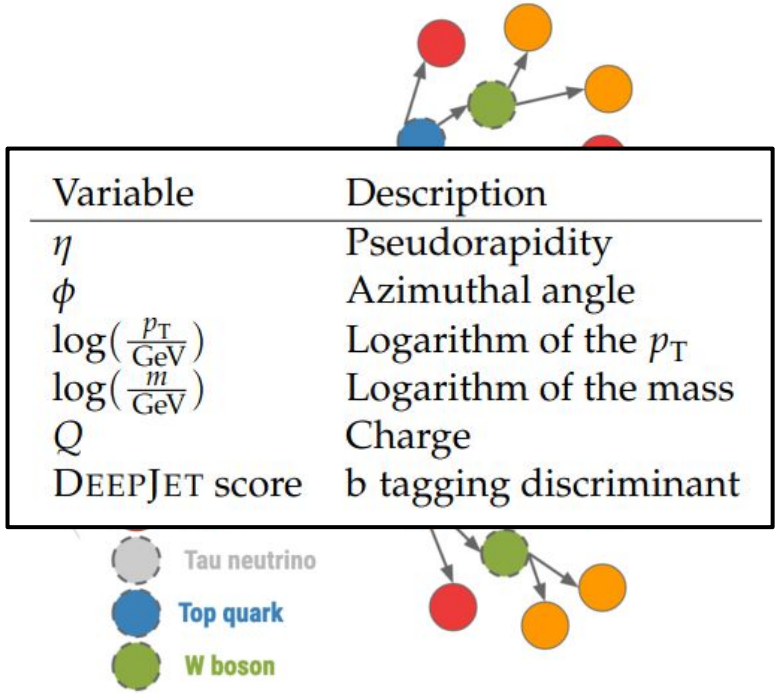
- **ML based strategy** to construct observable for signal vs background discrimination
- **Use of ABCNet**, a graph neural network [https://arxiv.org/abs/2001.05311] approach
  - Select up to 10 objects per event
    - Jets & hadronic τ's
  - Constructed using distances in η-ϕ space to connect jets using k-nearest neighbors (K = 8)



Search for pair-produced VLLs in final states with 3rd generation leptons

CMS-B2G-21-004 [arXiv:2208.09700v2]

- ML based strategy to construct observable
- **Two classifiers are trained with same underlying architecture**
  - Signal vs tt (>0-τ_h events)
  - Signal vs QCD (0-τ_h events)
- Several **kinematical features** are considered

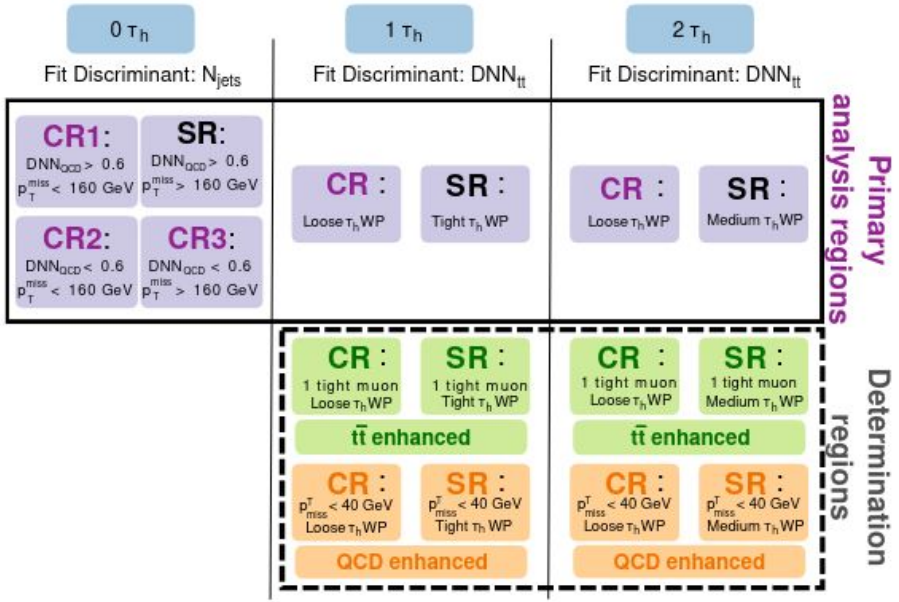


Search for pair-produced VLLs in final states with 3rd generation leptons

CMS-B2G-21-004 [arXiv:2208.09700v2]

- Different search and control regions defined **based on hadronic τ multiplicity :**

- $\tau_h = 0$, QCD dominated
- $\tau_h = 1$, fake τ and tt dominated
- $\tau_h = 2$, fake τ and tt dominated



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- **N-jets final discriminant**
  - **QCD estimated from data**
- DNN_{tt} final discriminant
  - Fake τ_h estimated from data
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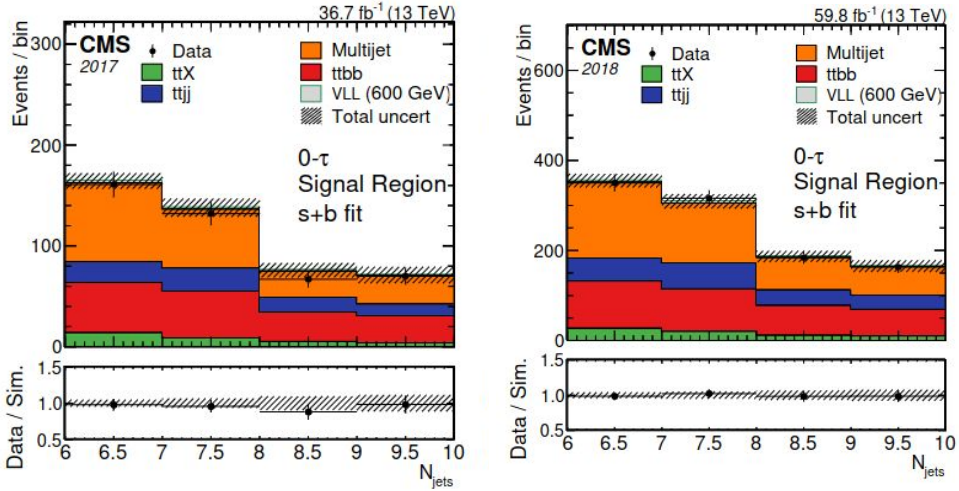

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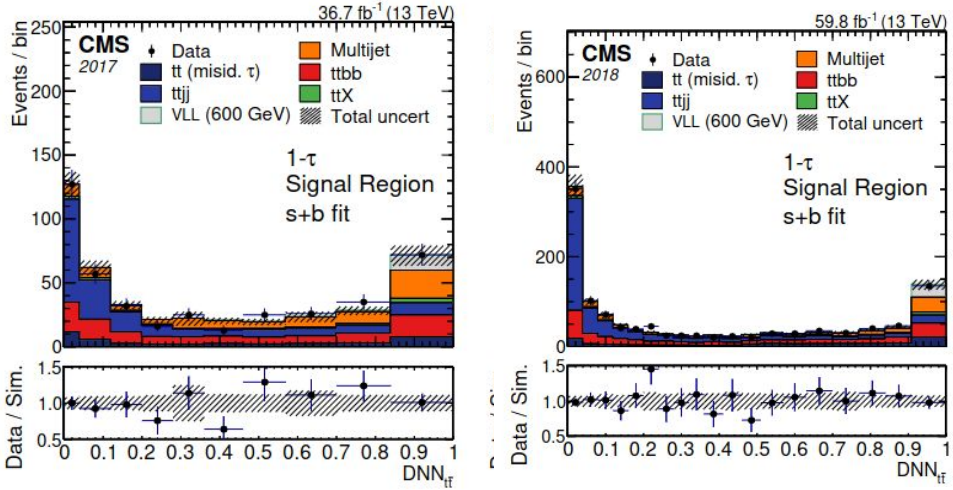

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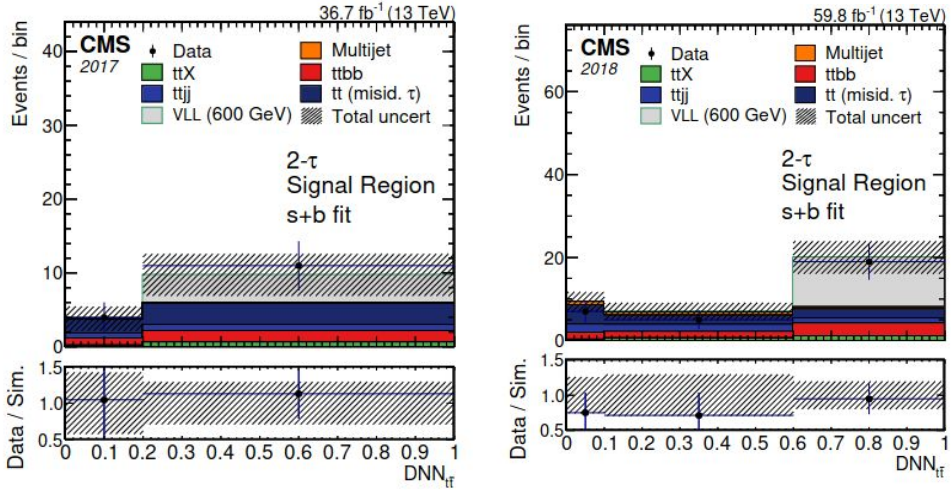

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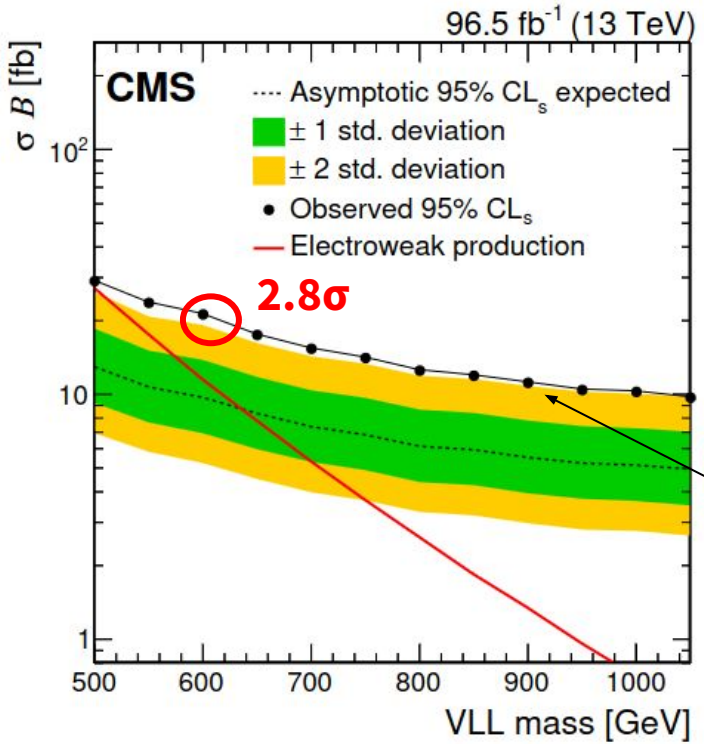

- Mild excess observed in data across VLL mass spectrum :
  - **~2.8 σ @ 600 GeV VLL mass**

Complicated final state → GNN observable has high discriminating power but low sensitivity to different mass hypotheses.

Search for pair-produced VLLs in final states with 3rd generation leptons

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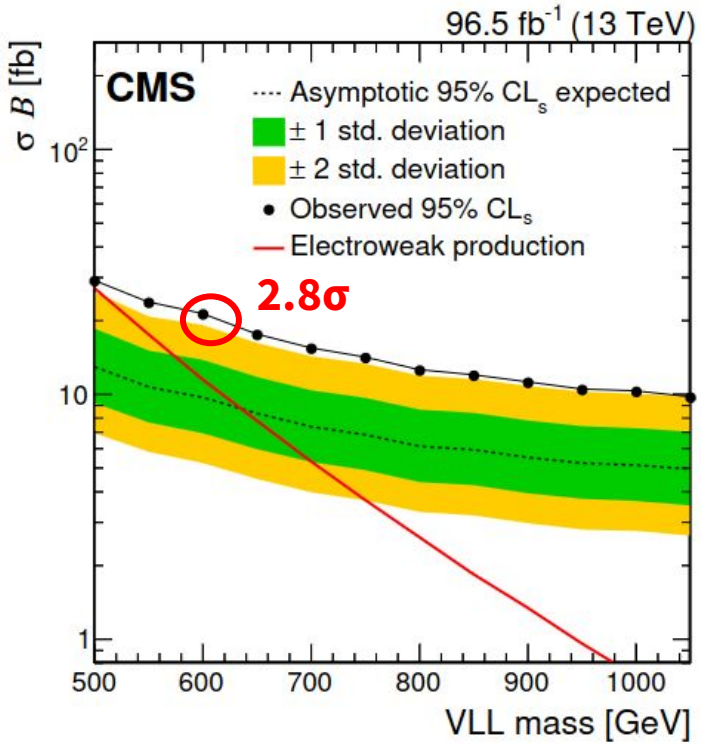


- Mild excess observed in data across VLL mass spectrum :
  - **~2.8 σ @ 600 GeV VLL mass**
- Ongoing CMS analyses studying final states with 1st and 2nd generation leptons to further scrutinise result

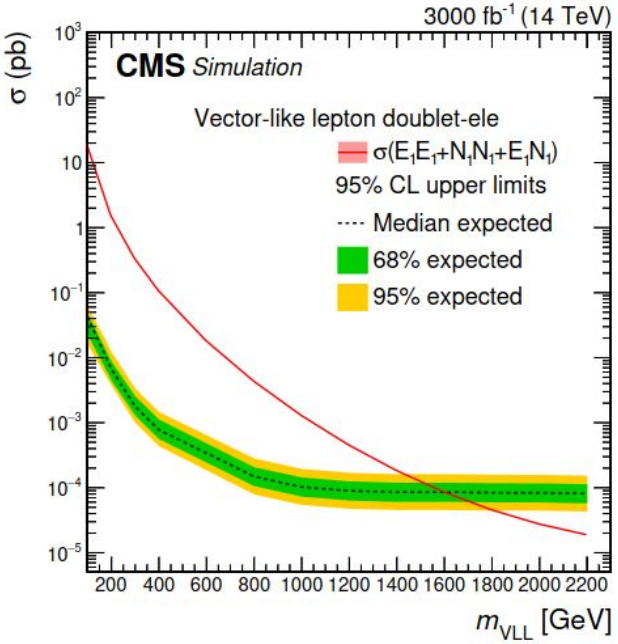
Future prospects for VLL searches

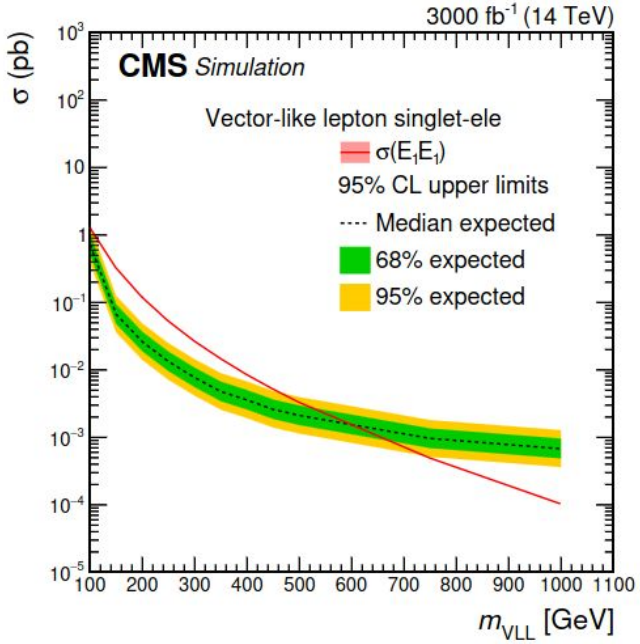
Review of VLQ/VLL/HNL searches [arXiv:2405.17605]

- Searches for VLL coupling to τ explored by CMS :
  - No search for VLLs coupling to electrons and muons in Run-1 or Run-2.
- Minimal VLL model is considered to extrapolate sensitivity to HL-LHC
  - Final states mix through Yukawa interactions with same generation SM leptons, decay into SM boson-lepton pairs
  - Singlet & doublet scenarios considered
- Similar strategy as described in [CMS-EXO-21-002]
  - Physics observable $L_T+p_T^{miss}$ in SR of all seven channels used to project sensitivity for these models
- Experimental uncertainties for signal and background yields were taken into consideration following the Yellow Report recommendations [CYRM-2019-007.585]

Future prospects for VLL searches

Review of VLQ/VLL/HNL searches [arXiv:2405.17605]





VLL-e expected exclusion limits:

Doublet scenario → 1600 GeV

Singlet scenario →600 GeV

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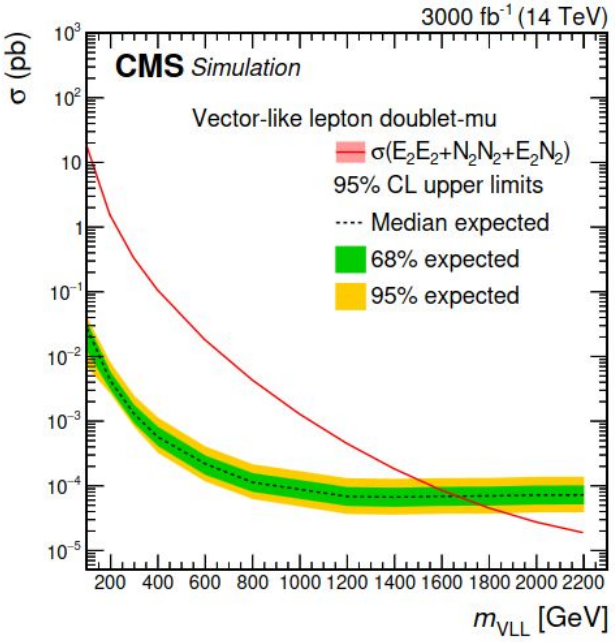

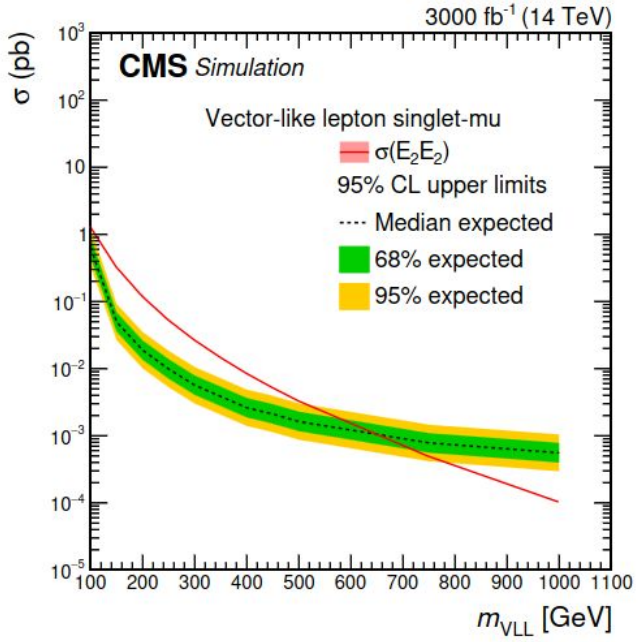

VLL-mu expected exclusion limits:

Doublet scenario → 1630 GeV

Singlet scenario →640 GeV

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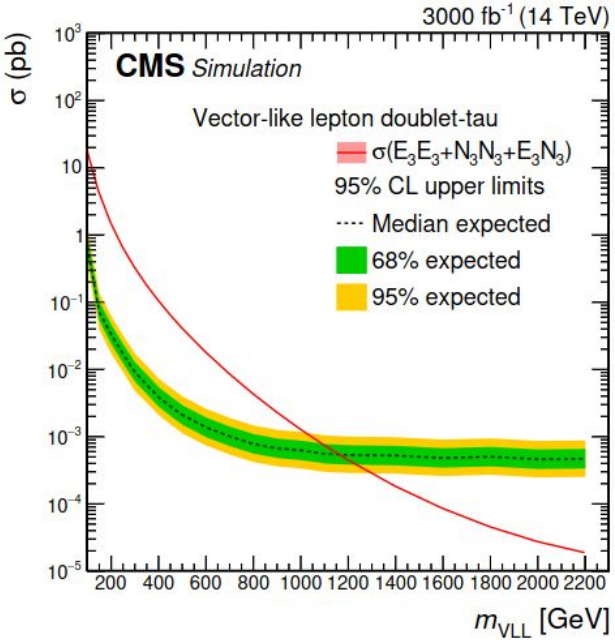

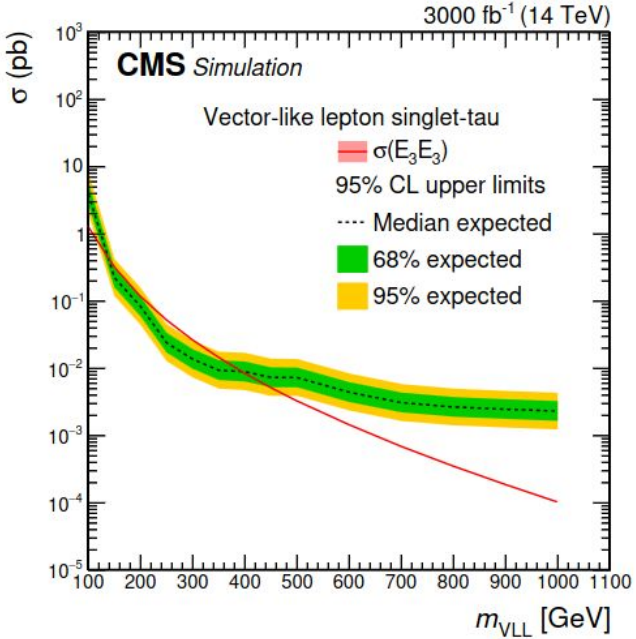

VLL-τ expected exclusion limits:

Doublet scenario → 1150 GeV

Singlet scenario →150-395 GeV

Summary & Outlook

- CMS has performed searches for Vector-like leptons with different model hypotheses
  - Minimal SM extensions & 4321 model
- Latest results have shown a 2.8σ mild excess in data
  - Complementary analyses are underway!
- Studies to explore the sensitivity of VLL searches in HL-LHC also shown

More interesting results expected in the future…

Stay tuned!