Vector-like leptons

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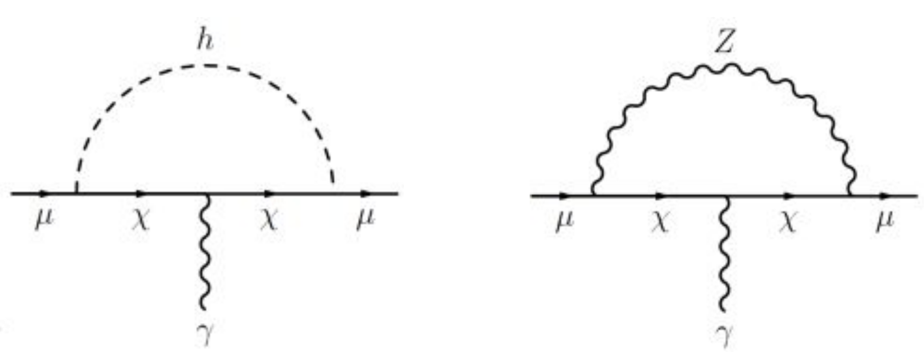
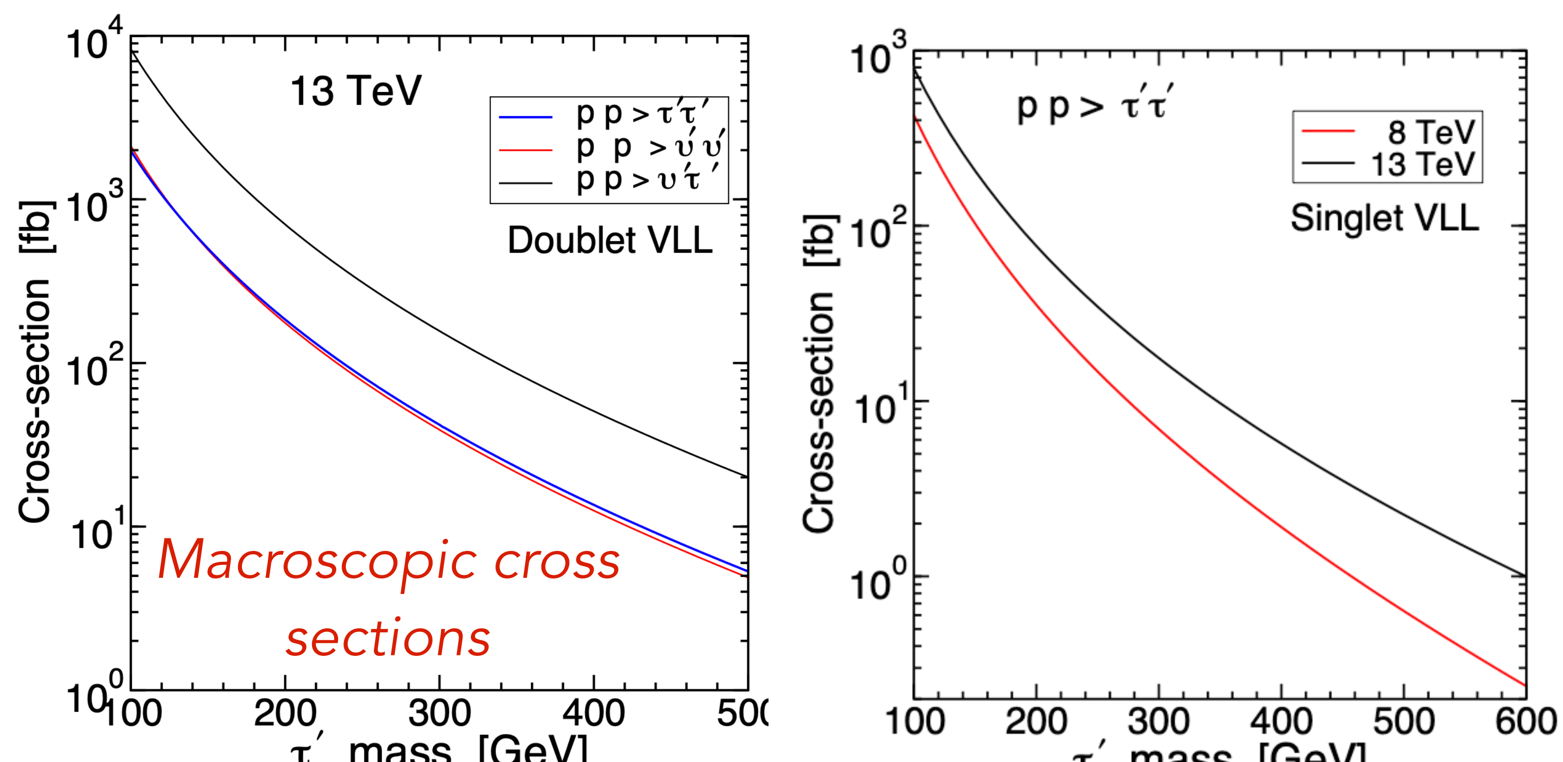
Vector-like leptons

* Vector-like fermions are simple and consistent candidate extension of the Standard Model
  * Non-chiral, i.e. their left- and right-handed components have the same charges
* Predicted in Composite Higgs models and other UV-complete constructions eg. 4321 Model
* Typical mass ≤1 TeV
* The mixing between the **muonphilic vector-like leptons** and the muon gives the main contribution to a_μ



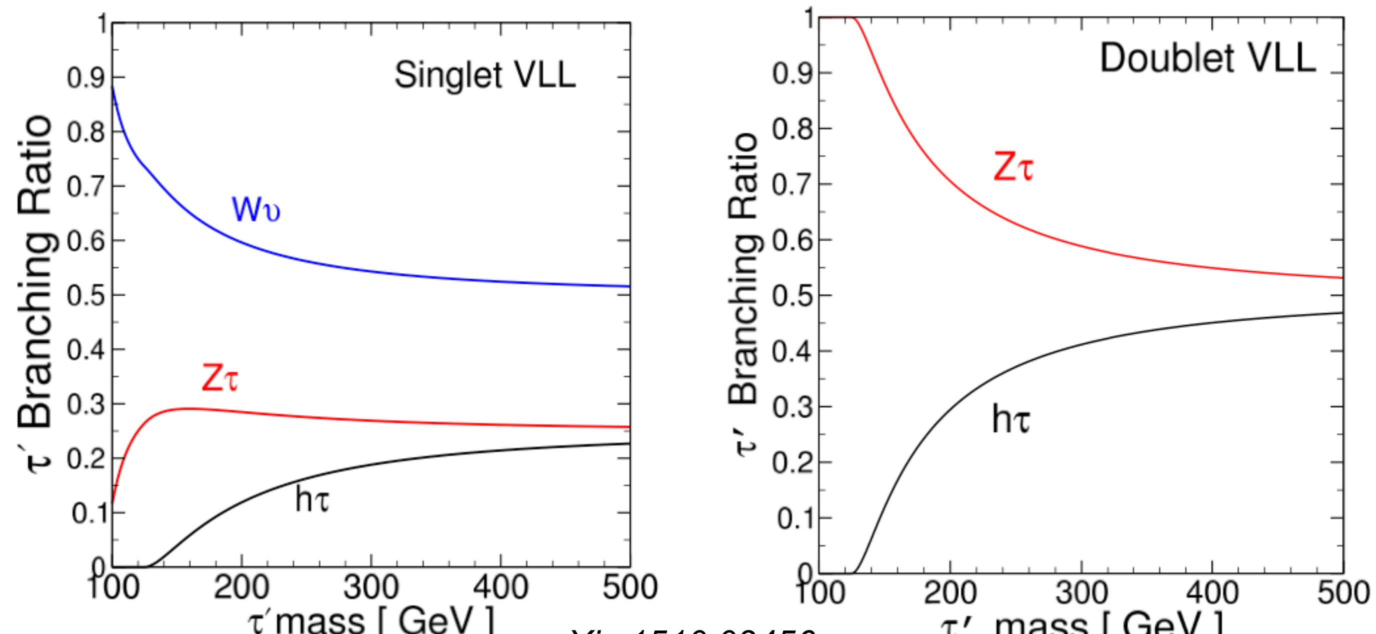
* Dominant production is in pairs, mediated by the EW interaction



arXiv:1510.03456

VLL decays

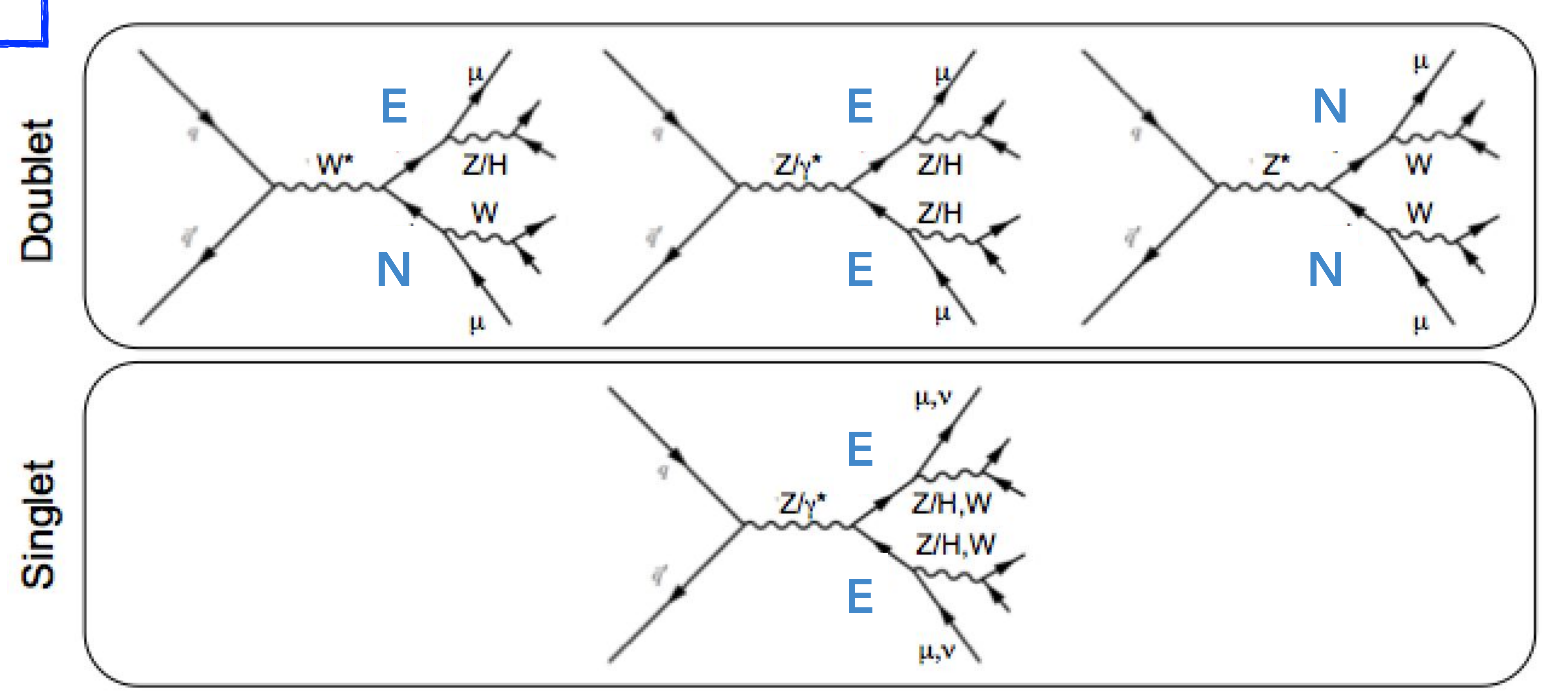
* VLLs come in *doublets/singlets*: one charged VLL, **E**, and one neutral VLL, **N**
* Rich phenomenology with multiple leptons, jets, b-jets and missing transverse momentum in the final state
    * 2ℓSS/OS, 3ℓ and $\geq 4\ell$
    * Jets/b-jets
    * MET …



arXiv:1510.03456

$$
\begin{aligned}
\Gamma(\tau' \to W\nu) &= 0, \\
\Gamma(\tau' \to Z\tau) &= \frac{M_{\tau'}}{32\pi}(1-r_Z)^2(2+1/r_Z)|g^Z_{\bar{\tau}^\dagger\bar{\tau}'}|^2, \\
\Gamma(\tau' \to h\tau) &= \frac{M_{\tau'}}{32\pi}(1-r_h)^2|y^h_{\tau'\bar{\tau}}|^2, \\
\Gamma(\nu' \to W\tau) &= \frac{M_{\nu'}}{32\pi}(1-r_W)^2(2+1/r_W)|g^{W^+}_{\bar{\tau}^\dagger\bar{\nu}'}|^2, \\
\Gamma(\nu' \to Z\nu) &= \Gamma(\nu' \to h\nu) = 0.
\end{aligned}
$$

$r_X = M_X^2/M_{\tau'}^2$ for $X = W, Z, h$.



Flavourful VLLs

- Flavourful BSM fermions and scalars (arXiv:2011.12964)
  - Presence of BSM scalars -- **can undergo LFV like decays**!
- **Singlet**: $\psi_{L,R\ i}(1, 1, -1)$, **doublet** $\psi_{L,R\ i}(1, 2, -1/2)$ they come in 3 generations, just like SM leptons; i = 1, 2, 3 lepton flavour generation
- **Scalar** singlets S_{ij} (1, 1, 0), i, j = 1, 2, 3; in total 9 flavourful scalars
- κ, κ' are BSM Yukawa couplings
- The free parameters are: M_S , M_F , κ, κ'
- Assume negligible mass splitting in multiplet, e.g. doublet $\psi = (\psi^-, \psi^0)$
- Strong constraints on κ from EWK data: $\kappa \nu_h/(2M_F) \leq O(10^{-2})$
  - κ couples leptons to the Higgs
- κ' can be O(1), and can then explain muon g – 2 at 1-loop for given M_S M_F

$$\mathcal{L}_Y^{\text{singlet}} = -\kappa \overline{L}_i H \psi_{Ri} - \kappa' \overline{E}_i (S^\dagger)_{ij} \psi_{Lj} - y\, \overline{\psi}_{Li} S_{ij} \psi_{Rj} + \text{h.c.}\,,$$

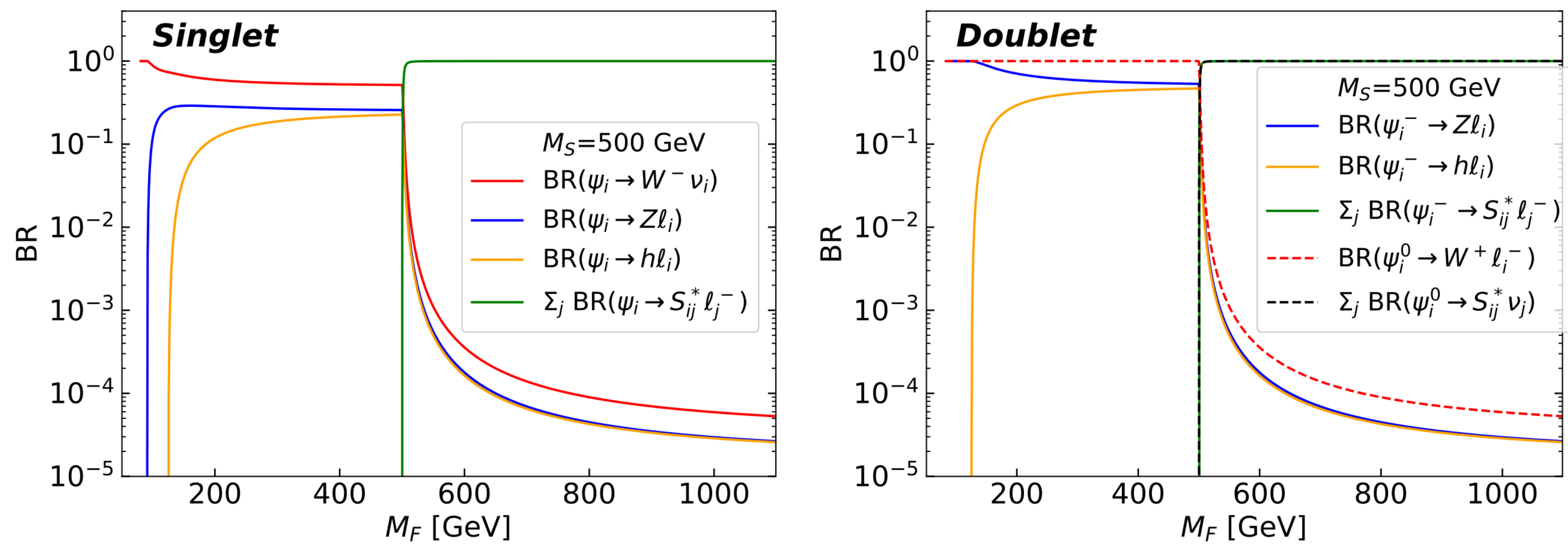
$$\mathcal{L}_Y^{\text{doublet}} = -\kappa \overline{E}_i H^\dagger \psi_{Li} - \kappa' \,\overline{L}_i S_{ij} \psi_{Rj} - y\, \overline{\psi}_{Li} S_{ij} \psi_{Rj} + \text{h.c.}\,,$$

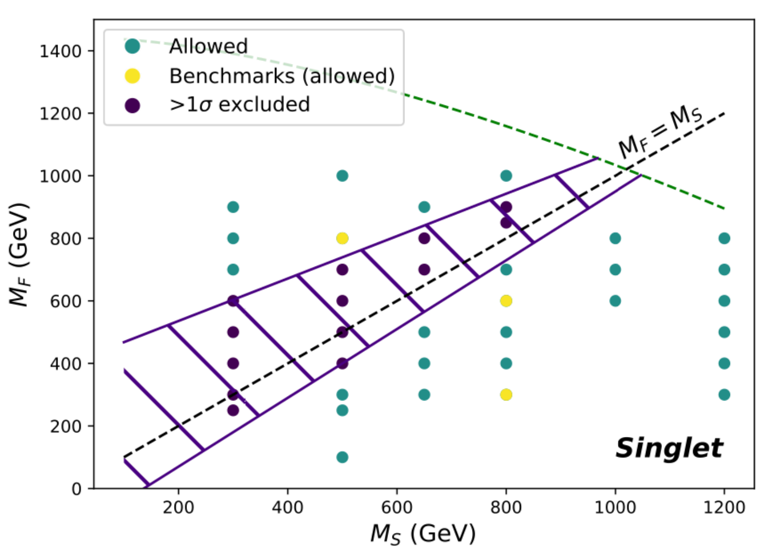
- Once kinematically allowed i.e., $M_F > M_S$, the ψ **decay predominantly** to S plus lepton, roughly for κ′& κ

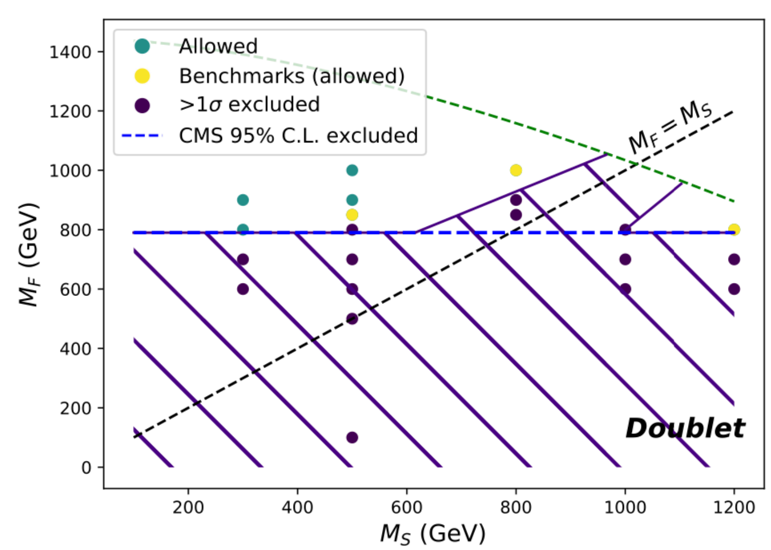
$$\psi_i^- \to S_{ji}\,\ell_j^- \to \ell_i^-\,\ell_j^+\,\ell_j^- \,, \quad \psi_i^0 \to S_{ji}\,\nu_j \to \ell_i^-\,\ell_j^+\,\nu_j \,.$$

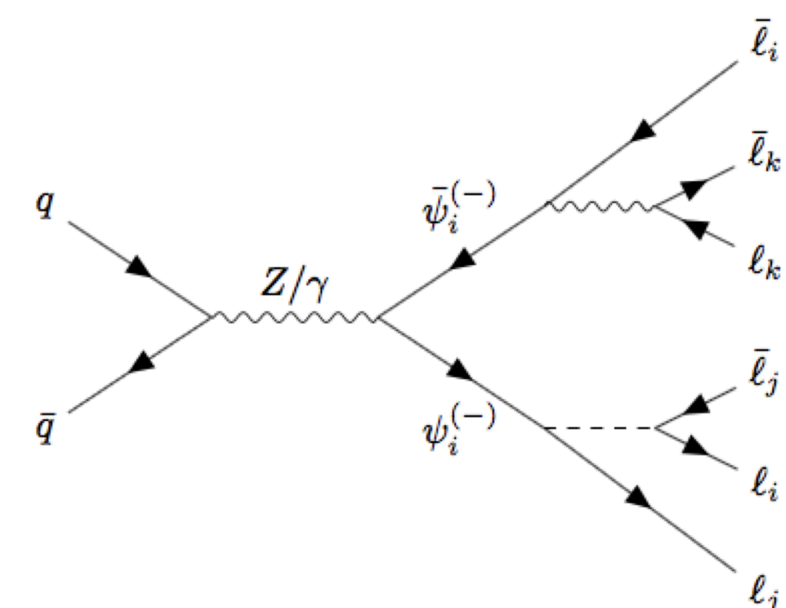
- κ′ fixed to explain g-2
  - κ = 10^{-2} κ′

arXiv:2011.12964





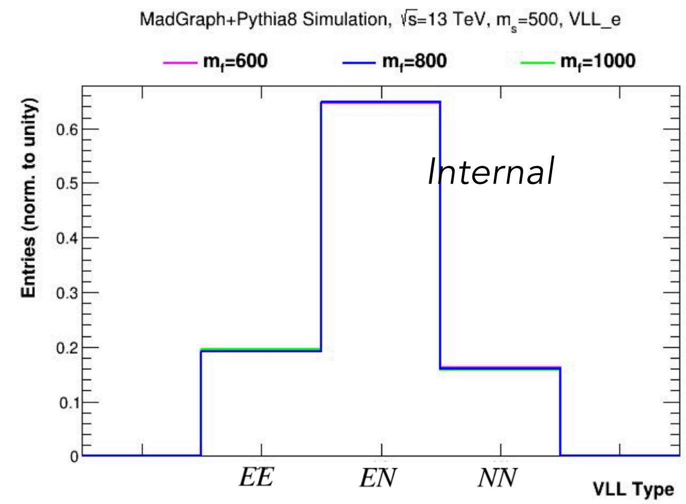


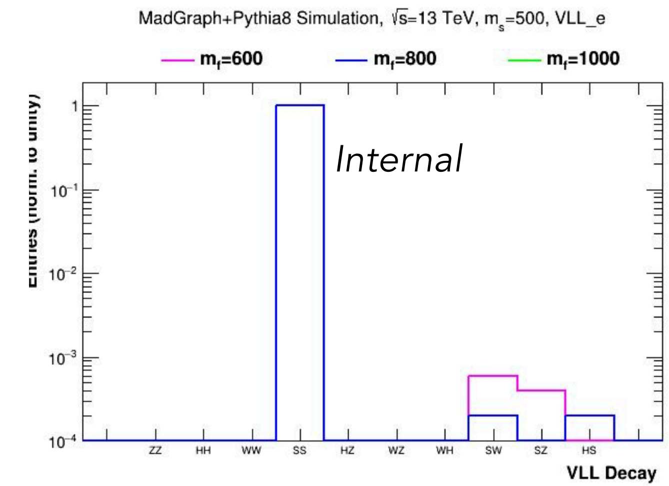


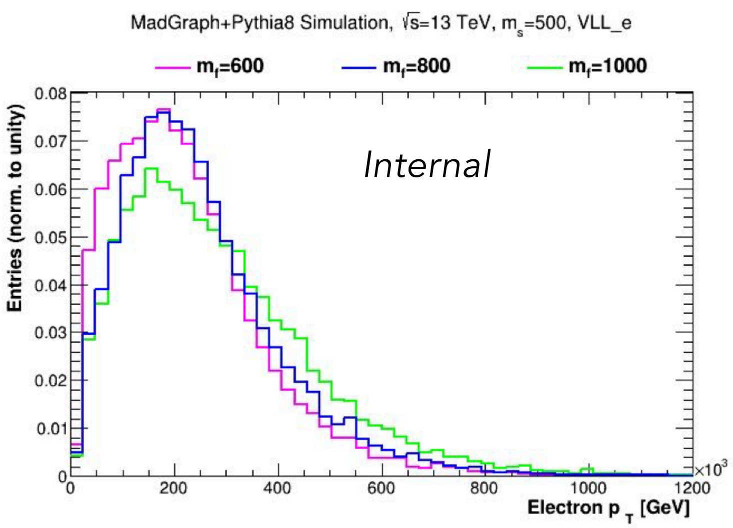
Excluded/allowed values of M_S M_F from CMS data

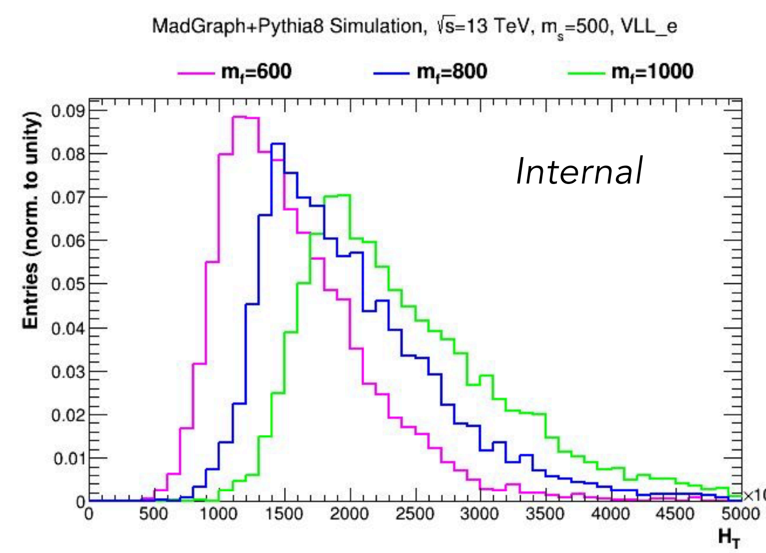
Flavourful VLLs

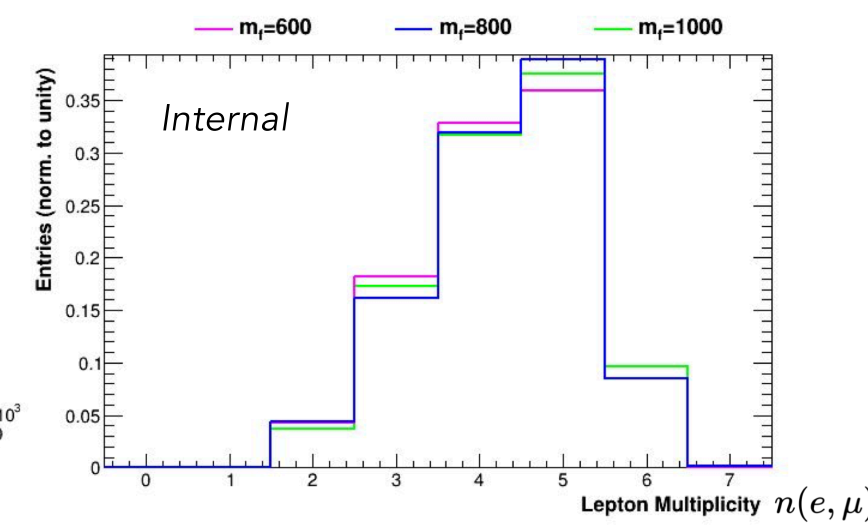
* Searches for "Flavourful VLLs" has started
* MadGraph + Pythia8



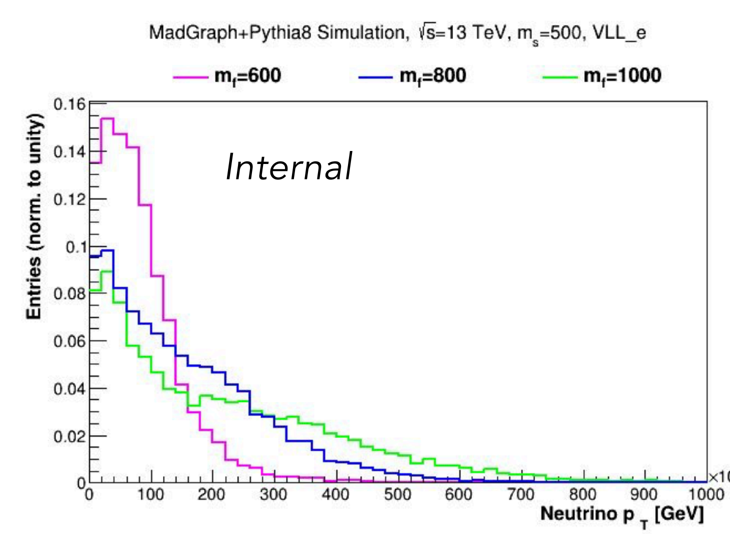






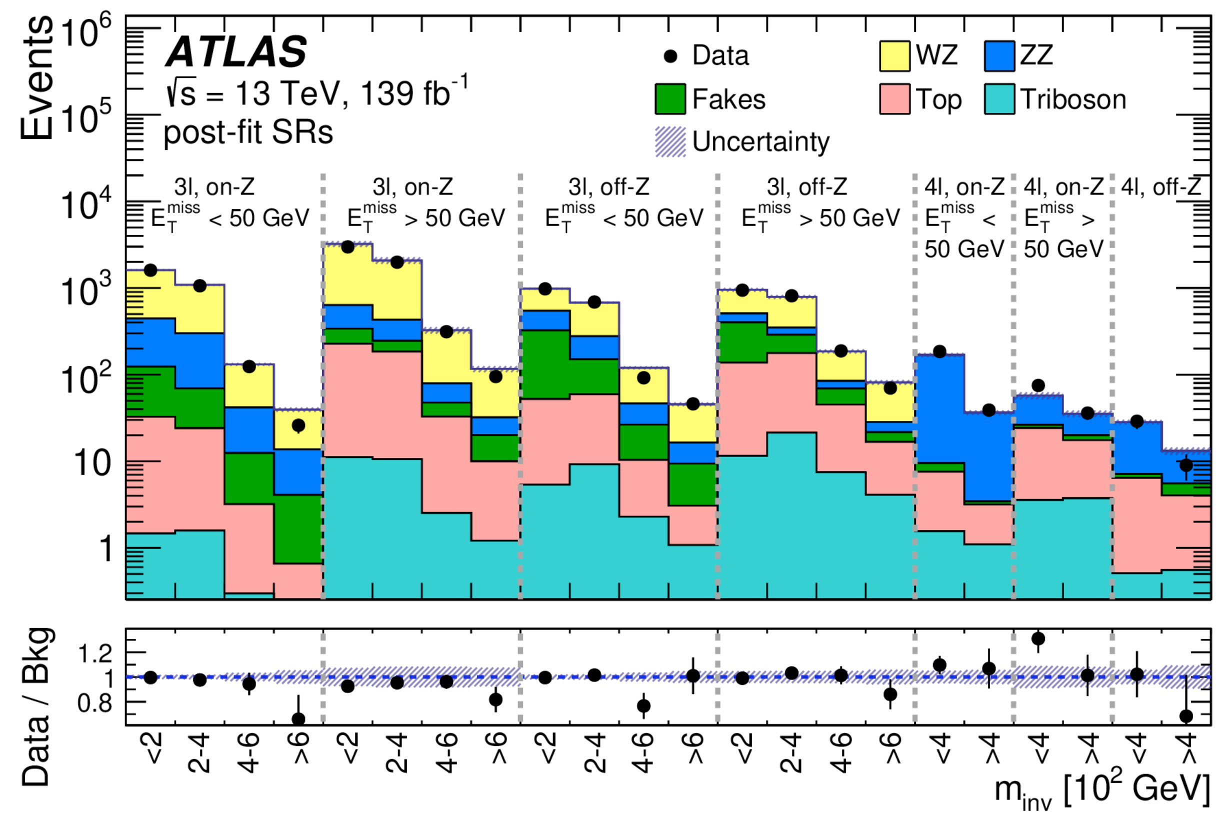


* EN production is dominant
* Decays with S is dominant (κ/κ')= 10^{-2}
* High lepton muliplicities with p_T< 600GeV
* Low MET
* High H_T (sum of transverse momentum)

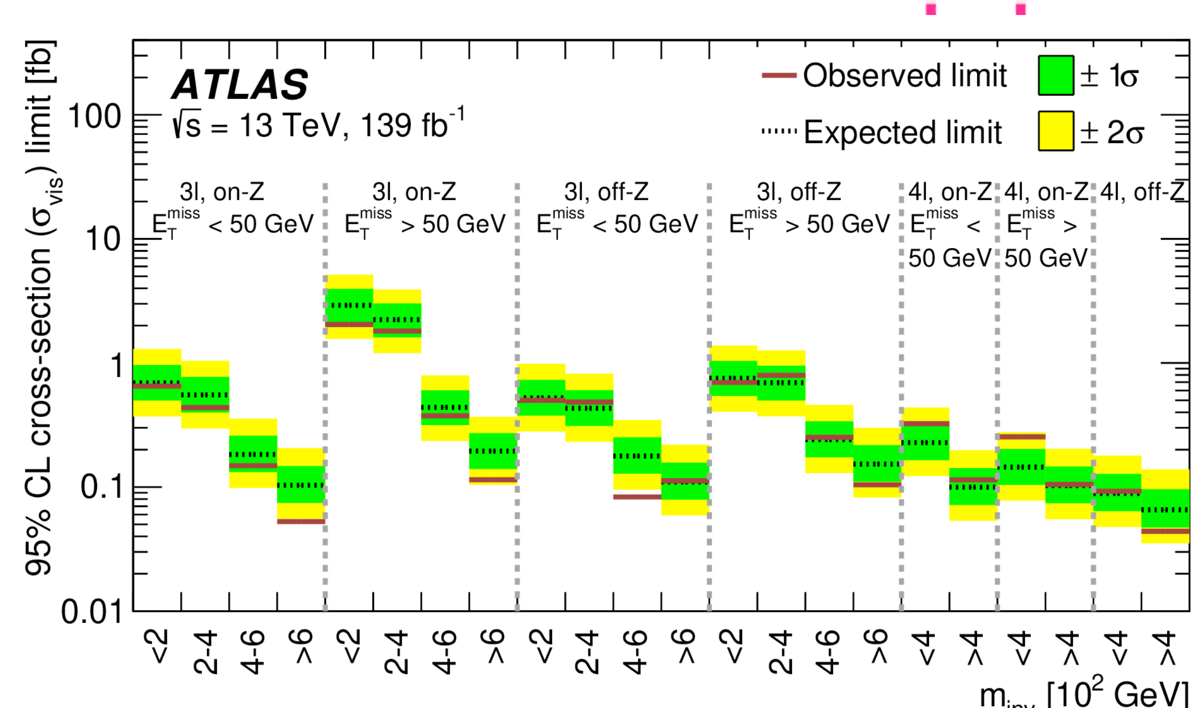


Excess in 4L channels

- Slight excess was seen in ATLAS analysis
- Phys. Lett. B 824 (2022) 136832
- Small excess in 4l signal regions found to be significantly larger when considering particular low-background sub-channels split by lepton flavour
- 4L, low MET and onZ peak and **eeem/emmm** final states
- Follow up on this analysis is ongoing
- Model-independent searches
- **VLL-flavorful** will be tested as model-dependent part!



excess mostly observed in: eeeμ or eμμμ events

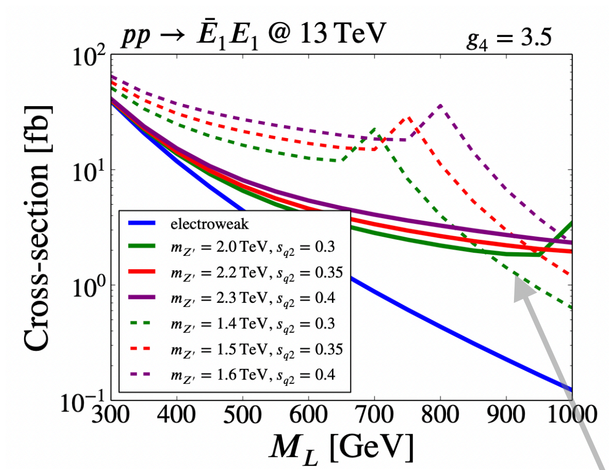


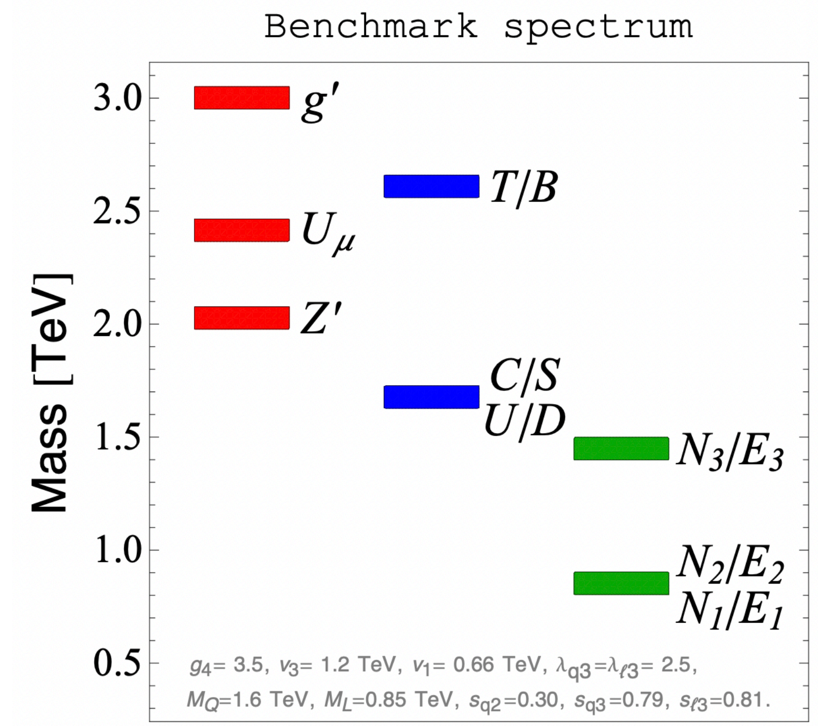
4321 model

- UV-complete model that extends the SM gauge groups to a larger group:

$$SU(4) \times SU(3)' \times SU(2)_L \times U(1)'$$

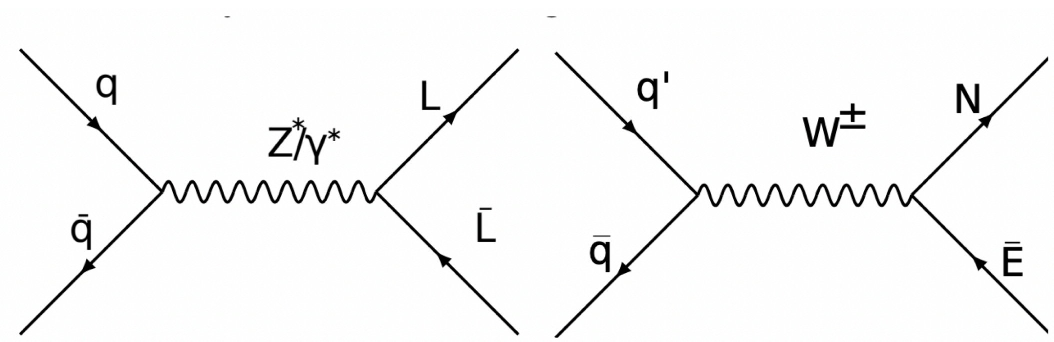
- Can accommodate B-physics anomalies (via a vector LQ).
- Consistent with all available constraints
- Three heavy gauge bosons:
  - Color octet (g')
  - Vector LQ (U_m)
  - Color singlet (Z')
- Three families of vector-like fermions:
  - VLQ doublets: U/D, C/S, T/B
  - VLL doublets: N_1/E_1, N_2/E_2, N_3/E_3

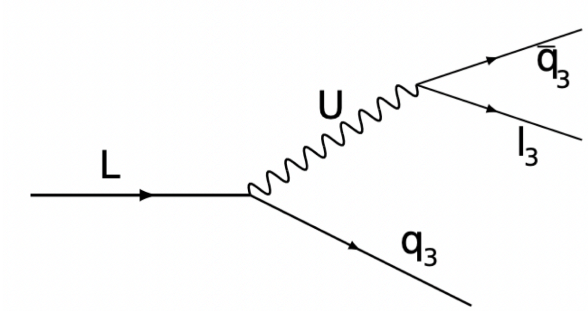




arXiv:1808.00942

- Search for **pair production** of the **lightest** new particles in this model: *vector-like leptons*
  - Produced via EWK production or through interactions with a Z' boson
  - Decay via intermediate leptoquark U, to two quarks and one lepton (mostly third generation fermions)





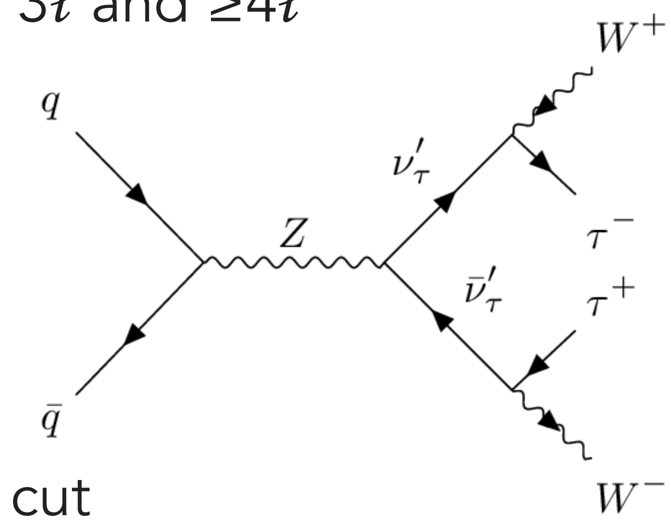
VLLs state of the art

	Type	Couple	Lumi	Exclusion	Excess
CMS	Doublet	3rd gen. leptons	77.4	120-790 GeV	-
	Doublet/singlet	3rd gen. leptons	138	<1045 GeV/ 125-170 GeV	-
	Doublet in 4321 model	3rd gen. leptons and quarks via LQ	96.5	500–1050 GeV	2.8σ
ATLAS	Singlet	Decaying to a Z boson and a 1st/2rd gen. leptons	20.3	114-176 GeV	-
	Doublet	3rd gen. leptons	139	130-900 GeV	-
	Doublet/singlet	1st/2rd gen. leptons	139	TBD	
	Doublet in 4321 model	3rd gen. leptons and quarks via LQ	139	TBD	

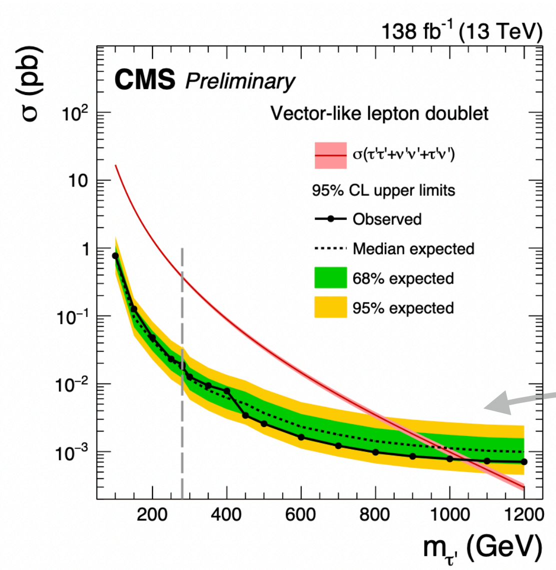
* **ATLAS** have two new VLL searches on the way!

VLL-taus in ATLAS

- SU(2) **doublet** VLLs coupling to third generation SM leptons in 2ℓ, 3ℓ and $\geq 4\ell$ w/ $\geq 0\tau$ channels using 139 fb^{-1}
- Mass points: 130-1000 GeV w/ 100 GeV steps
- Cross sections were normalised at NLO QCD
- CRs to normalize main backgrounds (top, WZ, ZZ)
- Fake factor for fake e/mu/taus, VRs defined by inverted BDT score cut
- SRs defined by cut on BDT score to discriminate the signal from background for all the regions
- No excess seen, limits sets for **900GeV**

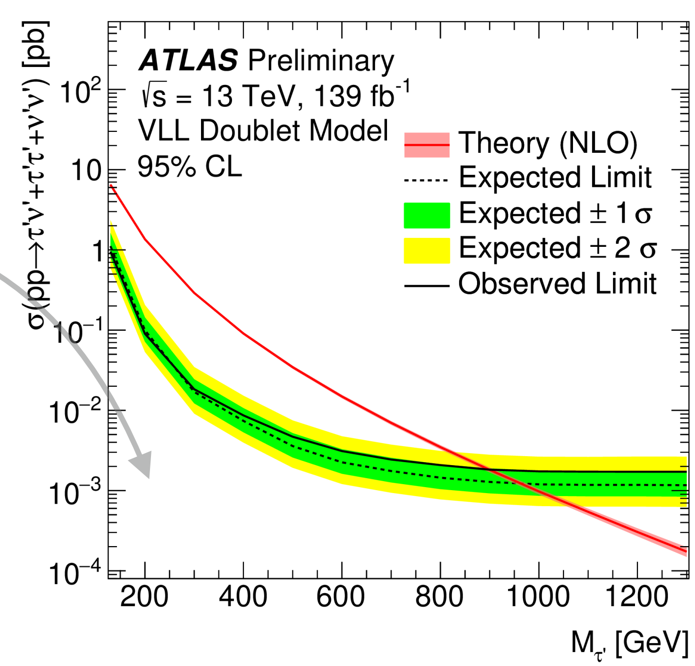


Signal Regions						
2ℓ SSSF, 1τ	2ℓ SSOF, 1τ	2ℓ OSSF, 1τ	2ℓ OSOF, 1τ	2ℓ, $\geq 2\tau$	3ℓ, $\geq 1\tau$	4ℓ, $\geq 0\tau$

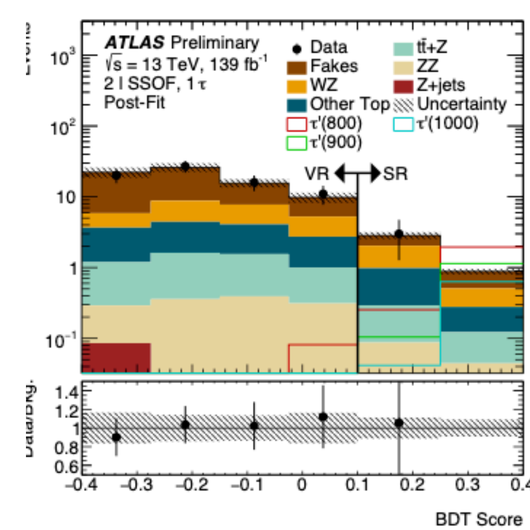


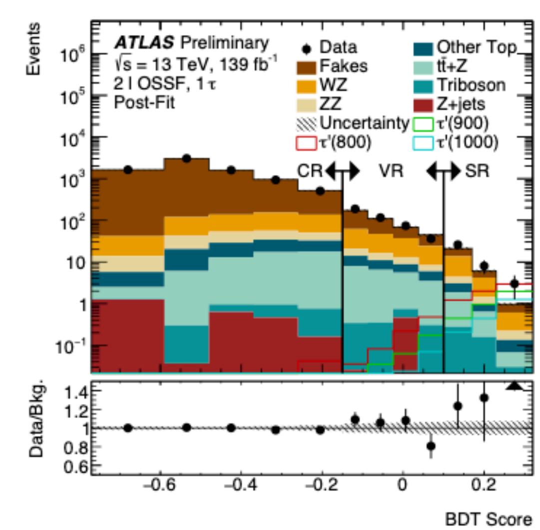
CMS PAS EXO-21-002

Similar results to CMS



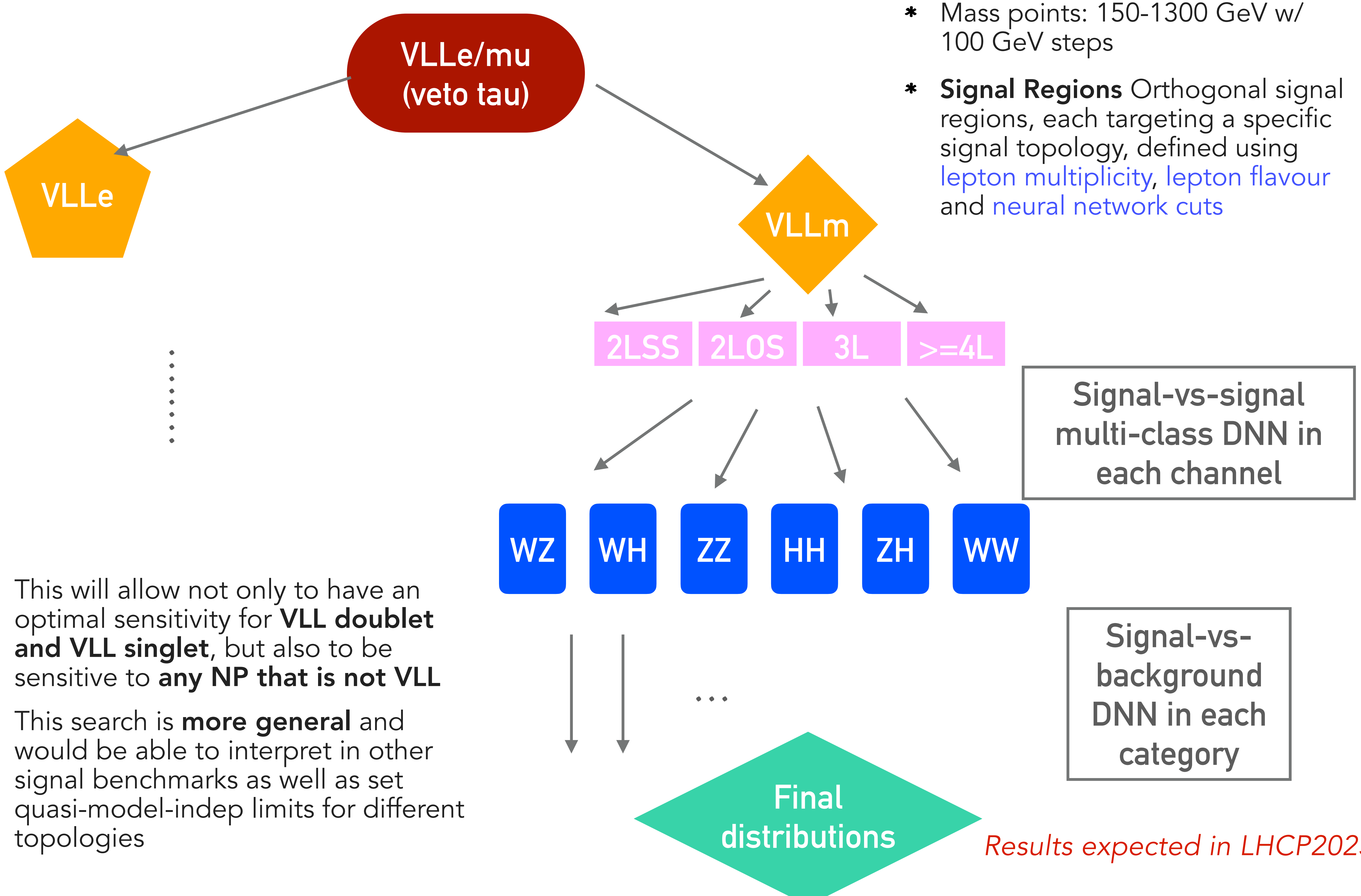
ATLAS-CONF-2022-044





VLLe/mu in ATLAS

* Mass points: 150-1300 GeV w/ 100 GeV steps
* **Signal Regions** Orthogonal signal regions, each targeting a specific signal topology, defined using lepton multiplicity, lepton flavour and neural network cuts

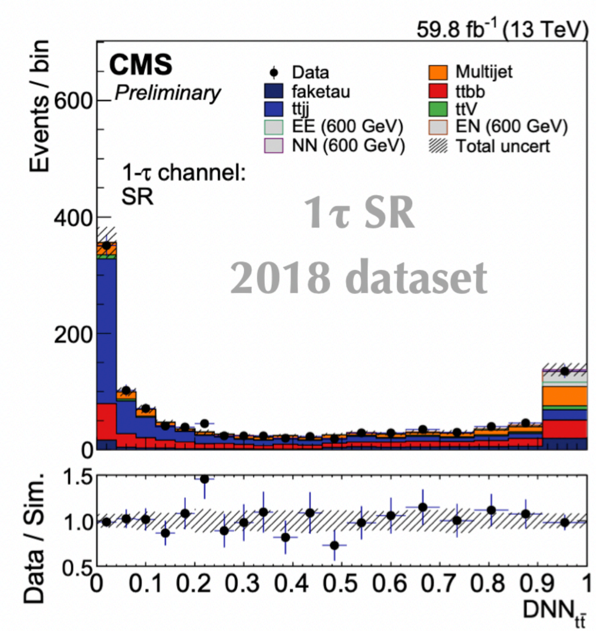


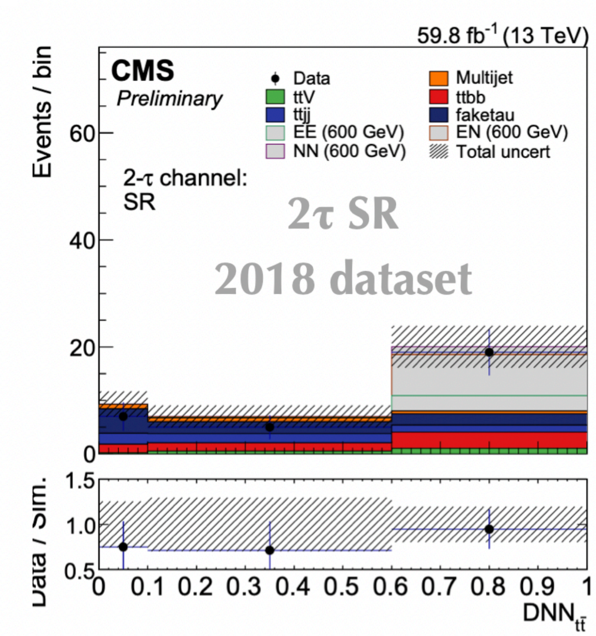
* This will allow not only to have an optimal sensitivity for **VLL doublet and VLL singlet**, but also to be sensitive to **any NP that is not VLL**
* This search is **more general** and would be able to interpret in other signal benchmarks as well as set quasi-model-indep limits for different topologies

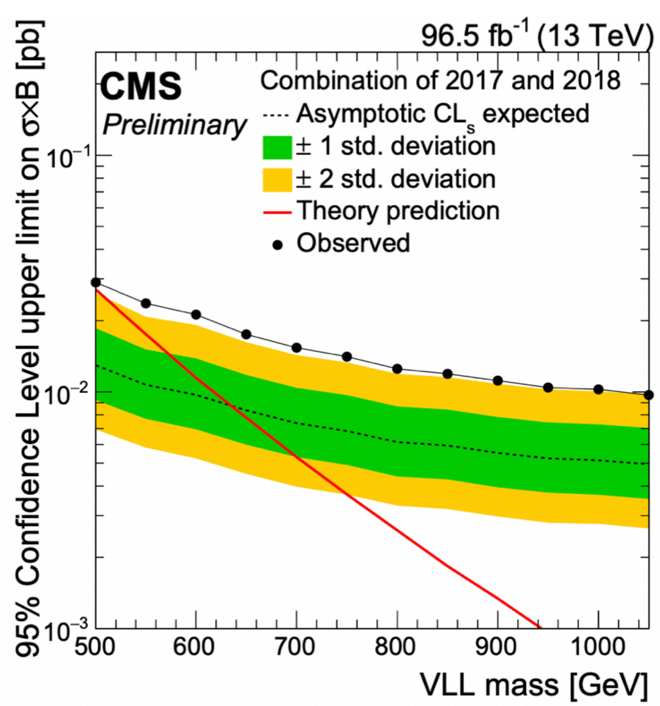
Results expected in LHCP2023

4321 model - CMS analysis

- CMS analysis selection driven by the **highly flavour-asymmetric** final states produced in the VLL decays
  - high b-jet multiplicity (Nbjet>3)
  - categorised by the number of *(hadronically-decaying)* **τ** leptons
- B-jet triggers
- Graph neural network called ABC- Net to discriminate signal from QCD multijet/tt backgrounds
- No exclusions, overall **2.8σ** excess (more pronounced in tau channels)





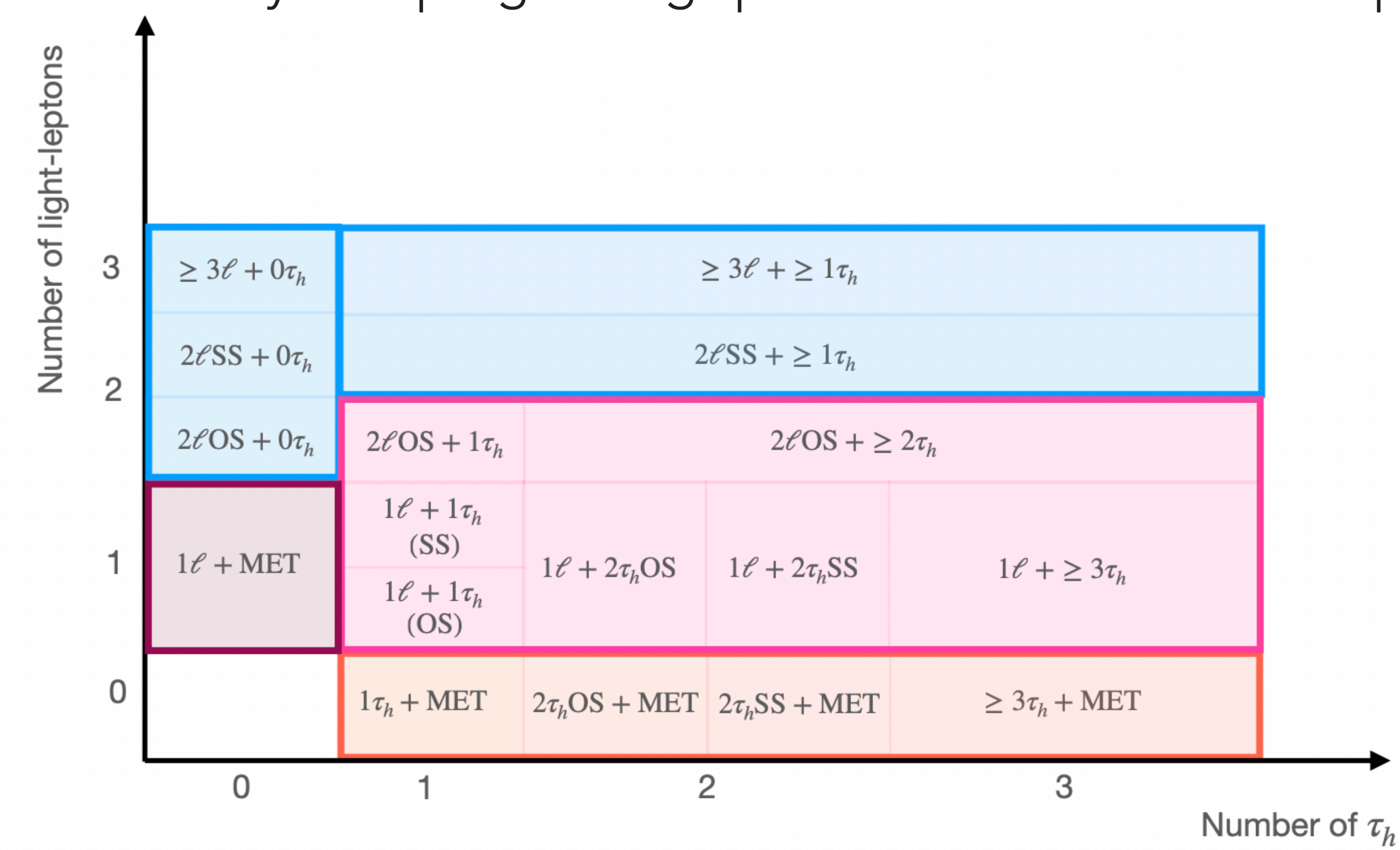


tau multiplicity	production + decay mode	final state
0 τ	$EE \to b(t\nu_\tau)b(t\nu_\tau)$	$4b + 4j + 2\nu_\tau$
	$EN \to b(t\nu_\tau)t(t\nu_\tau)$	$4b + 6j + 2\nu_\tau$
	$NN \to t(t\nu_\tau)t(t\nu_\tau)$	$4b + 8j + 2\nu_\tau$
1 τ	$EE \to b(b\tau)b(t\nu_\tau)$	$4b + 2j + \tau + \nu_\tau$
	$EN \to b(t\nu_\tau)t(b\tau)$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

B2G-21-004-pas

4321 model - New ATLAS analysis

- New ATLAS analysis will exploit all possible leptonic final states including **light leptons* (Nbjet>2)** in the final state
- Latest Rel21 analysis, will share expertise from VLLe/mu, LQ analyses etc..
- Make use of **trigger buckets*** (single/di-tau, bjet and MET) to increase the signal efficiency
- Sophisticated **MVA** analysis with many SRs
- Possibility to set limits with **Z' production***
- Also possible **SUSY interpretations*** (e.g. RPV w/λ'_{333})
- Analysis is progressing quite fast for the first EB request!



	% of surviving events			
	VLL 400 GeV		VLL 1000 GeV	
	1 tau	2 tau	1 tau	2 tau
MET (MET > 150 GeV)	18.63	14.45	76.04	65.54
MET + STT	25.18	25.31	85.69	86.38
MET + DTT	18.63	54.72	76.04	72.23
MET + STT + DTT (w/o 4J12)	25.18	45.29	85.69	88.99
MET + STT + DTT	25.18	65.58	85.69	93.07

Results expected in LHCP2023

** extending the scope of CMS*

Summary

* VLLs are well-motivated by a number of theories that seek for explaining the deficiencies of the Standard Model
* Broad program probing many VLL production/decay modes in both ATLAS and CMS
* ATLAS is building new analyses targeting not covered areas
* Many more signatures with VLLs to be probed!

Backup

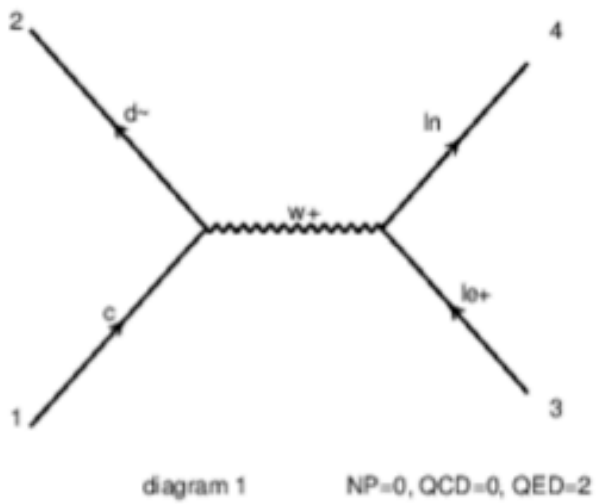
ATLAS

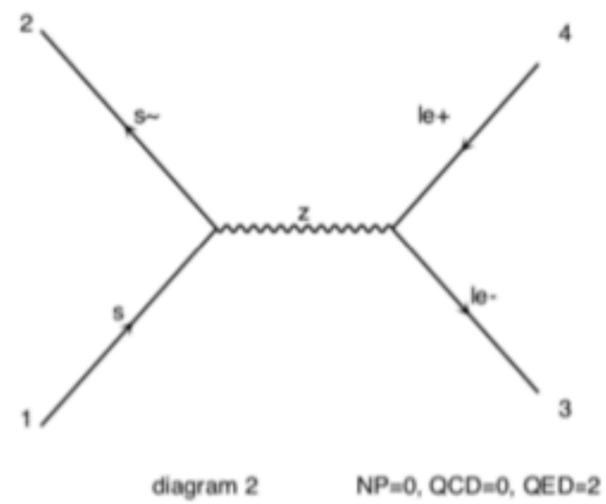
Variable	2ℓ SSSF, 1τ	2ℓ SSOF, 1τ	2ℓ OSSF, 1τ	2ℓ OSOF, 1τ	2ℓ, $\geq 2\tau$	3ℓ, $\geq 1\tau$	4ℓ, $\geq 0\tau$
$p_T(\tau_1)$	1	1	1	1	2	2	
$M_{l\tau}$	2	2	5	3	1	1	
$L_T + E_T^{\text{miss}}$	3	3	2	2	23	4	1
E_T^{miss}	4	7	4	21	5	8	5
$\Delta\phi(\tau_1 E_T^{\text{miss}})$	5	6	6	13	3	3	
$\Delta R(l_1 l_2)$	6	24	7	7	15		17
M_{jj}	7	21	24	15	1	12	19
M_{lj}	8	11	26	11	27	14	2
$\Delta\phi(l_1 E_T^{\text{miss}})$	9	16	20	8	20	10	15
$\Delta R(l_1 \tau_1)$	10	8	12	6	16	15	
$\Delta R(j_1 \tau_1)$	11	9	17	25	25	23	
$\Delta R(l_1 E_T^{\text{miss}})$	12	29	11	19	17	11	10
$\Delta\phi(l_1 l_2)$	13	13	18	16	28	13	9
$\Delta R(\tau_1 E_T^{\text{miss}})$	14	27	9	5	12	9	
$p_T(j_1)$	15	19	10	12	22	19	11
M_T	16	23	16	18	8	17	7
$\Delta\phi(j_1 \tau_1)$	17	20	27	29	24		
M_{ll}	18	10	25	20	10	22	4
$p_T(l_1)$	19	4			30	5	16
$\mathbb{S}(E_T^{\text{miss}})$	20	5	14	24	9	24	8
N_j	21	14	28	23	26		22
$L_T + p_T(\tau)$	22	22		26			
$p_T(l_2)$	23	15			18		
$\Delta R(j_1 E_T^{\text{miss}})$	24	18	23	10	31		21
$\Delta\phi(l_1 j_1)$	25	17	13	17	13	25	13
N_b	26	26	21	22	29	20	14
L_T	27	32			32		3
$M_{j\tau}$	28	31	15	9	6	18	
$\Delta R(l_1 j_1)$	29		8	4	11		18
$L_T + H_T$		12	3	14			
M_{OSSF}			22		7	6	12
$\Delta\phi(l_1 \tau_1)$		25	19		19	16	
$\Delta\phi(j_1 E_T^{\text{miss}})$				27	21		6
H_T		28		28	33	21	20

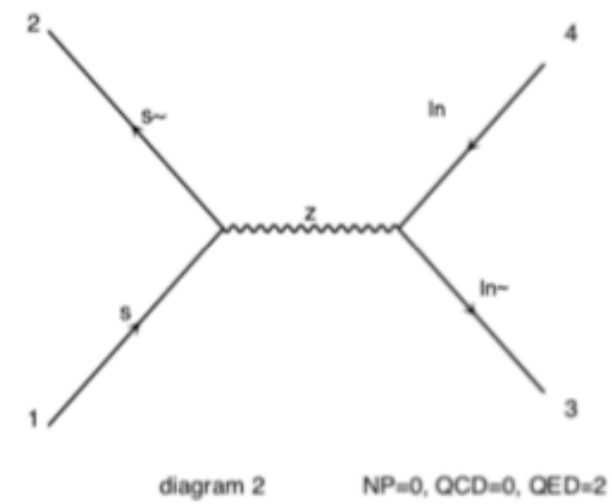
CMS

Variable type	Used for		
	All signals	Vector-like lepton	Seesaw and leptoquarks
Event	H_{T}, $p_{\mathrm{T}}^{\text{miss}}$, N_{b}, M_ℓ	Q_ℓ	L_{T}, $p_{\mathrm{T}}^i/L_{\mathrm{T}}$, $L_{\mathrm{T}}/S_{\mathrm{T}}$, $H_{\mathrm{T}}/S_{\mathrm{T}}$, $p_{\mathrm{T}}^{\text{miss}}/S_{\mathrm{T}}$
Lepton	p_{T}^i, $p_{\mathrm{T}}^{\text{OSSF}}$		
Angular	ΔR_{min}	Max, Min: $\Delta\phi^i$, Max, Min: $\Delta\phi^{ij}$	Max: $\Delta\eta^{ij}$
Mass	M_{T}^i	M^{ij}, M_{T}^{12}, M_{T}^{13}, M_{T}^{23}	

Backup







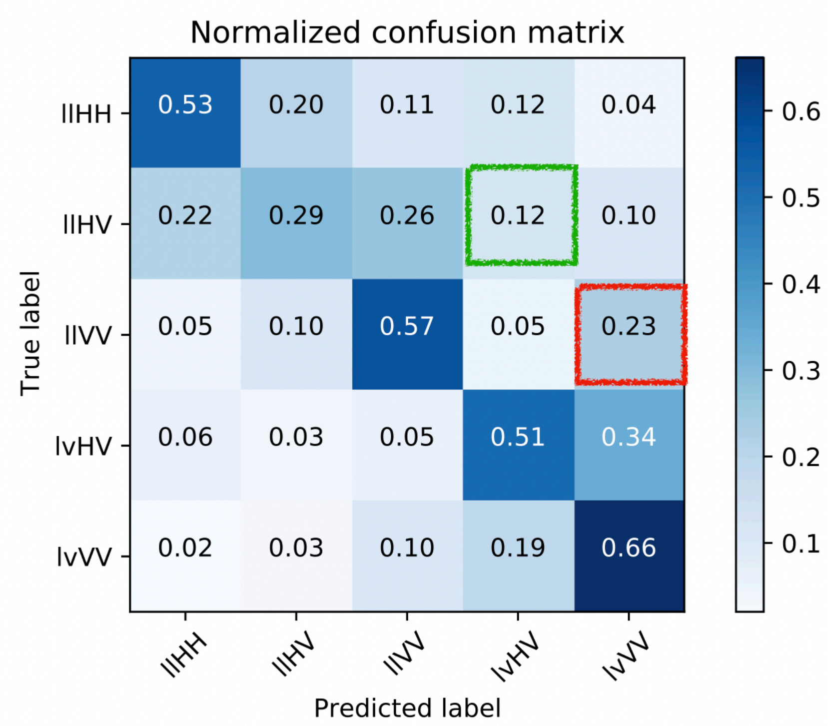
$$E^+N \rightarrow t(\bar{b}\bar{\nu}_\tau)\ t(\bar{t}\nu_\tau)$$
$$E^+N \rightarrow b(\bar{b}\tau^+)\ t(\bar{t}\nu_\tau)$$
$$E^+N \rightarrow t(\bar{b}\bar{\nu}_\tau)\ t(\bar{b}\tau^-)$$
$$E^+N \rightarrow b(\bar{b}\tau^+)\ t(\bar{b}\tau^-)$$
$$E^-\bar{N} \rightarrow \bar{t}(b\nu_\tau)\ \bar{t}(t\bar{\nu}_\tau)$$
$$E^-\bar{N} \rightarrow \bar{b}(b\tau^-)\ \bar{t}(t\bar{\nu}_\tau)$$
$$E^-\bar{N} \rightarrow \bar{t}(b\nu_\tau)\ \bar{t}(b\tau^+)$$
$$E^-\bar{N} \rightarrow \bar{b}(b\tau^-)\ \bar{t}(b\tau^+)$$

$$E^+E^- \rightarrow \bar{t}(\nu_\tau b)\ t(\bar{\nu}_\tau\bar{b})$$
$$E^+E^- \rightarrow \bar{b}(b\tau^-)\ t(\bar{\nu}_\tau\bar{b})$$
$$E^+E^- \rightarrow \bar{t}(\nu_\tau b)\ b(\tau^+\bar{b})$$
$$E^+E^- \rightarrow \bar{b}(b\tau^-)\ b(\tau^+\bar{b})$$

$$N\bar{N} \rightarrow t(\bar{t}\nu_\tau)\ \bar{t}(t\bar{\nu}_\tau)$$
$$N\bar{N} \rightarrow t(\bar{t}\nu_\tau)\ \bar{t}(b\tau^+)$$
$$N\bar{N} \rightarrow t(\bar{b}\tau^-)\bar{t}(b\tau^+)$$

$$E^+ \rightarrow U_1 b$$
$$N \rightarrow U_1 t$$
$$U_1 \rightarrow b\tau^+ /\ t\bar{\nu}$$

Backup


Normalized confusion matrix
True label
Predicted label
llHH
llHV
llVV
lvHV
lvVV
0.53 0.20 0.11 0.12 0.04
0.22 0.29 0.26 0.12 0.10
0.05 0.10 0.57 0.05 0.23
0.06 0.03 0.05 0.51 0.34
0.02 0.03 0.10 0.19 0.66
0.6
0.5
0.4
0.3
0.2
0.1