Inclusive nonresonant multilepton probes of new phenomena using full Run 2 data at CMS

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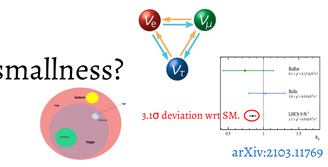
1) Why Beyond Standard Model phenomena ?

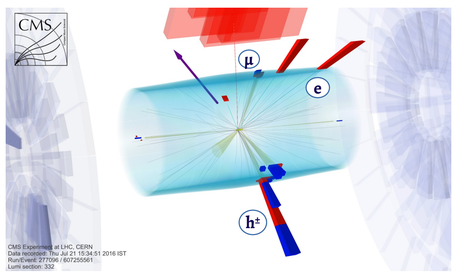
- **Dark Matter** Potential explanation in SM?
- **Neutrino oscillations** Mass of neutrinos and explanation for their smallness?
- **Flavor anomalies** in the heavy quark decays?
- **Hierarchy problem, Matter-Antimatter asymmetry etc.**



2) Probing BSM with Multileptons

Why multileptons?

- Leptons are clean isolated objects compared to jets.
- Better correspondence between true and experimentally determined values.
- At a hadron collider, lower rates for SM lepton production.



Multilepton channels

Exclusive channels

4ℓ	$3\ell+\geq1\tau$	3ℓ	$2\ell+\geq2\tau$	$2\ell+1\tau$	$1\ell+\geq3\tau$	$1\ell+2\tau$

Inclusive in light leptons and hadronically decaying taus

Inclusive in hadronically decaying taus

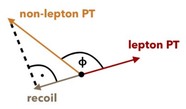
$\ell = e/\mu$
$\tau = \tau_h$

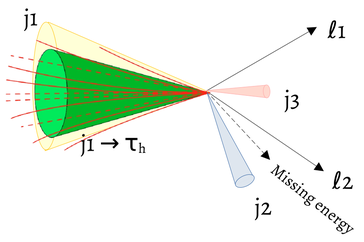
*Single isolated light lepton to trigger the events; ~ 27 GeV (μ) & ~30 GeV (e).

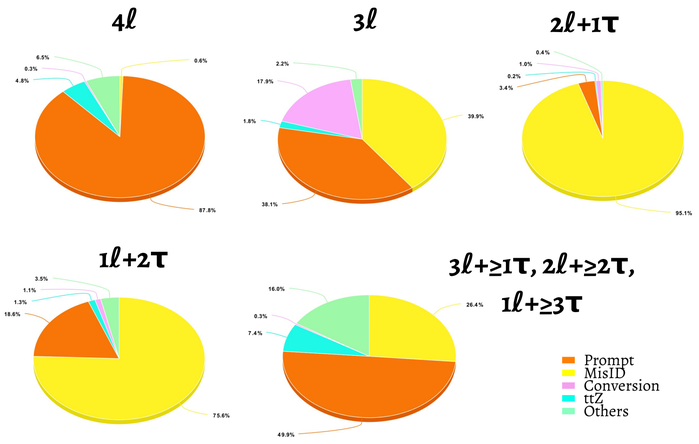
3) Standard Model Backgrounds

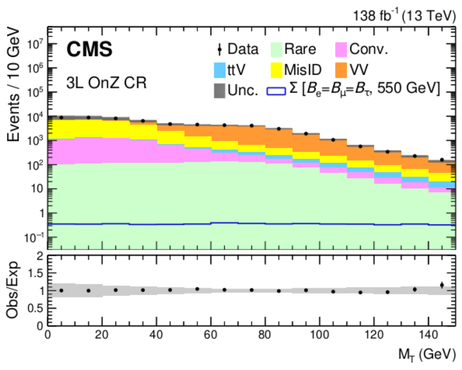
Background category	Leading processes	Estimated from	Notes
Irreducible	WZ, ZZ, ttZ, Zγ	Simulation	Normalized in 3L/4L CRs
Misidentified (jets → leptons)	ttbar, DY, WW, W+jets	Data	Developed in low p_T^{miss} 3L & 2L1T CRs
Rare	VVV, ttW, Higgs	Simulation	No normalization

- Data-driven 3D/4D matrix method for MisID background.
- Universal treatment for all leptons flavors.
- Fake rates parametrized in pT, η, and recoil.









Uncertainties

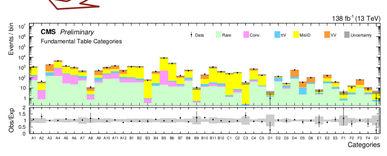
- Largely dominated by the WZ, ZZ, ttZ, and Zγ normalization factors (5-25%) as well as the misidentified lepton contributions (40-60%).
- Subdominant contributions from rare processes (50%), energy-scale corrections (<20%), and those due to scale factors & electron charge misidentification (1-10%) have a negligible impact.

4) Model-Independent Search

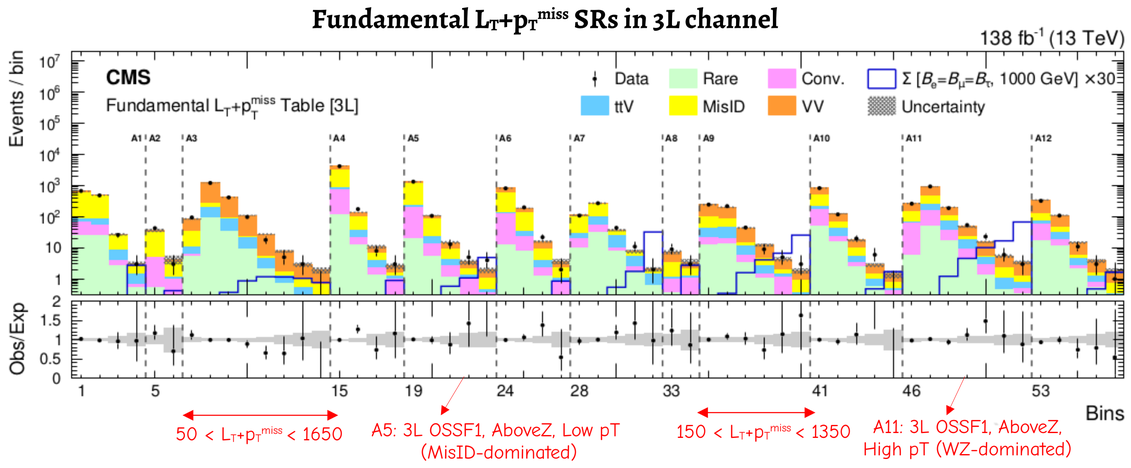
"Fundamental" 43 categories, binned in $L_T+p_T^{miss}$ or S_T distributions.

		OSSF0 BelowZ	OSSF0 AboveZ	OSSF0 SS	OSSF1 OnZ	OSSF1 BelowZ	OSSF1 AboveZ	OSSF1 MixedZ	OSSF2 Single-OnZ	OSSF2 Double-OnZ	OSSF2 OffZ
3L	Low p_T/M_T	A1	A1	A2	A3	A4	A5	A6	–	–	–
	High p_T/M_T	A7	A7	A8	A9	A10	A11	A12	–	–	–
2L1T	Low p_T	B1	B2	B3	B4	B5	B6	–	–	–	–
	High p_T	B7	B8	B9	B10	B11	B12	–	–	–	–
1L2T		C1	C2	C3	–	C4	C5	–	–	–	–
4L		D1	D1	D1	D2	D3	D3	D3	D4	D5	D6
3L1T		E1	E1	E1	E2	E3	E3	E3	–	–	–
2L2T		F1	F1	F1	F2	F2	F2	–	F3	–	F4
1L3T		G1	G1	G1	–	G1	G1	–	–	–	–

L = e/μ; T = τ_h



Fundamental $L_T+p_T^{miss}$ SRs in 3L channel



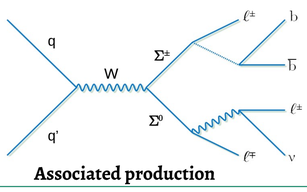
Additional categorization in b tag multiplicity, p_T^{miss} and H_T → **"Advanced"** scheme (204 categories).

- Total **468** signal regions in **Fundamental $L_T+p_T^{miss}$** table scheme.
- Total **771** signal regions in **Fundamental S_T** table scheme.
- Total **2415** signal regions in **Advanced S_T** table scheme.

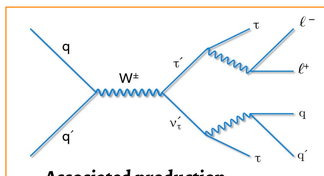
5) Model specific search

Type-III Seesaw Mechanism

- Predicts three mass-degenerate fermions : Dirac $\Sigma^\pm$ and a Majorana Σ°.
- **Assumes SM neutrinos as Majorana, describe their small masses through coupling with Σ°.**
- Pair-production ($\Sigma^\pm\Sigma$) or associated-production ($\Sigma^\circ\Sigma^\pm$) via electroweak interaction.
- Σ° decays: $W\ell/Z\nu/h\nu$. $\Sigma^\pm$ decays: $W\nu/Z\ell/h\ell$.



Associated production



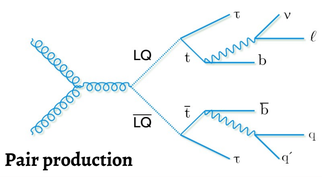
Associated production

Vector-Like Lepton (VLL)

- Two scenarios: Doublet (τ',ν') and Singlet (τ'). Non-chiral, mass-degenerate fermions.
- **Fourth generation of fermions, arise in SUSY, ED etc. Account for the mass hierarchy.**
- Pair-production (τ'τ',ν'ν') or associated-production (τ',ν') via electroweak interaction.
- Singlet τ' decays: Wν/Zτ/hτ. Doublet τ' decays: Zτ/hτ and ν' decays: Wτ.

Third-generation Leptoquarks

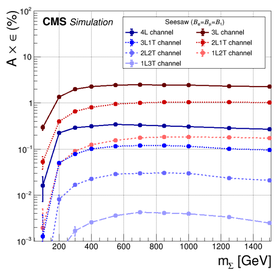
- Color-triplet scalar bosons, nonzero baryon & lepton numbers, and charge -1/3e.
- **Could provide an explanation for the observed b-anomalies.**
- Strong production. Decay to a top quark and a SM lepton of any one flavor (β=1).
- Three coupling scenarios: top-e, top-μ, and top-τ.



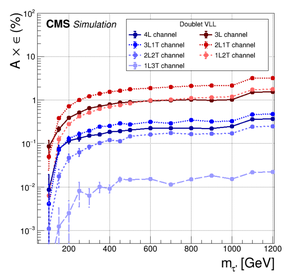
Pair production

Challenges... → BDTs to the rescue!

1) **Three** years of data-taking period.
2) **Three** different models with diverse physics properties.
3) **Large** mass range being simultaneously probed.
4) Different **couplings**:
   - **Seesaw:** $B_e + B_\mu + B_\tau = 1$
   - **VLL:** Always coupled to τ's.
   - **LQ:** $B_e = 1$ or $B_\mu = 1$ or $B_\tau = 1$
5) **Seven** multilepton channels with different relative importance for different signals.



Type-III Seesaw
"3L is the golden channel"



Doublet VLL
"2L1T & 1L2T are the golden channels"

6) Changing **background composition** in the channels needs to be considered as well while designing SRs.

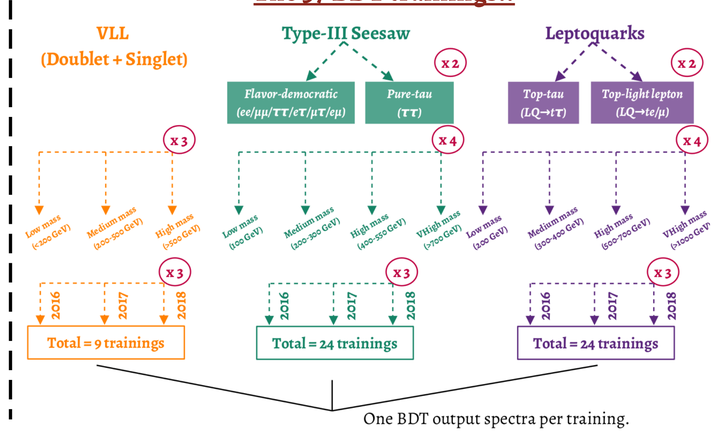
1) **One** BDT training per year, using samples from other two years.
2) **One** BDT per signal model.
3) **One** BDT per mass (3-4 mass ranges per model). For example:

BDT	Trained using masses (GeV)	Applied for masses (GeV)
Type-III seesaw		
SS-L	200, 300	200, 300
SS-M	400, 550, 700, 850	400, 550
SS-H	1000, 1250	700 and higher

4) **Flavor-splitting**: light leptons vs taus (for Seesaw & LQ).
5) **One** channel-inclusive training.
6) Novel **input variables** for the BDT training.

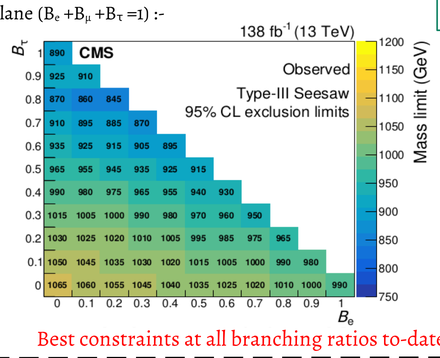
Variable type	Used for: All signals	Vector-like lepton	Seesaw and leptoquarks
Event	H_T, p_T^{miss}, N_b, M_ℓ	Q_ℓ	L_T, p_T^ℓ/L_T, L_T/S_T, H_T/S_T, p_T^{miss}/S_T
Lepton	p_T^ℓ, p_T^{OSSF}		
Angular	ΔR_{min}	Max, Min: $\Delta\phi^{\ell j}$, Max, Min: $\Delta\phi^{\ell j}$	Max: $\Delta\eta^{\ell j}$
Mass	M_T^ℓ	$M^{\ell j}$, M_T^{12}, M_T^{13}, M_T^{23}	

The 57 BDT trainings!!



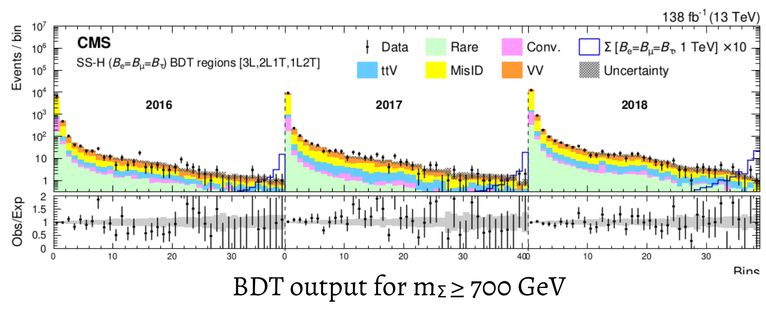
6) Interpreting the results

Exclusion limits on m_Σ in the B_e B_τ plane ($B_e + B_\mu + B_\tau = 1$) :-



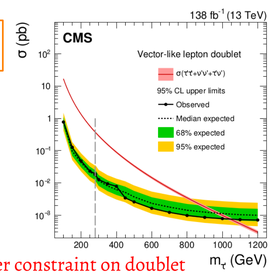
Best constraints at all branching ratios to-date.

Type-III Seesaw

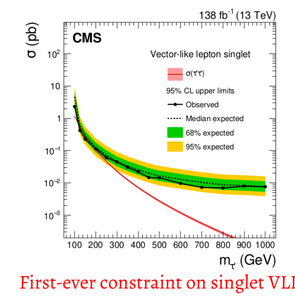


BDT output for $m_\Sigma \geq 700$ GeV

VLL

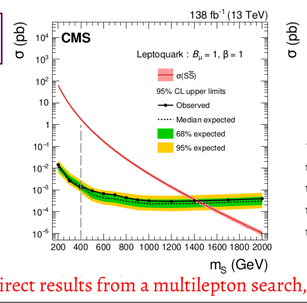


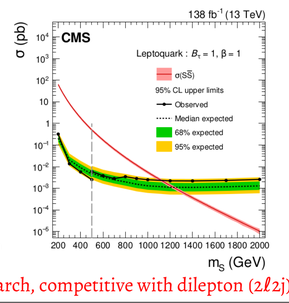
First-ever constraint on doublet VLLs at low mass!



First-ever constraint on singlet VLL!

LQ



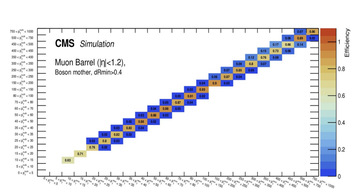


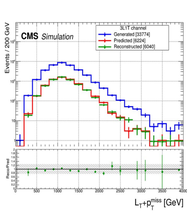
First direct results from a multilepton search, competitive with dilepton (2ℓ2j).

7) Ensuring longevity of results

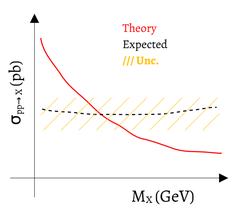
To enable reinterpretation of other BSM models, we are releasing on HEPDATA :

- 2D gen-to-reco efficiency maps for each lepton flavor (e/μ/1-prong τ_h/3-prong τ_h).
- Parameterized as a function of lepton pT, η, lepton mother, and global event properties (N_j or DRmin).
- Recipe to recreate reconstructed-level event from the generated event; produce $L_T+p_T^{miss}$, and S_T.





Using this with background yields from our model-independent tables to ROOFit etc.



- Simplified likelihoods of the backgrounds in our model-independent signal regions also provided.

References

CMS-PAS-EXO-21-002 (2021), PRD in prep.
J. High Energ. Phys. 2020, 51 (2020)
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