Searches for vector-like quarks and leptons at CMS

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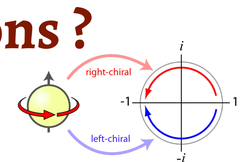
Vector-like fermions ?

- Nonchiral under SM gauge symmetries.
- Lagrangian mass terms not arising from Yukawa couplings to the Higgs.



SM fermions are "chiral". They pick-up a phase under rotation.

Image courtesy @quantumdiaries.org

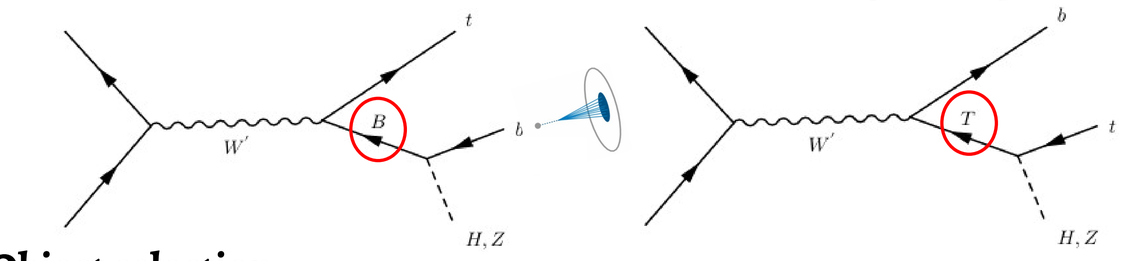
Theory & motivation

- Arise in wide variety of BSM scenarios including SUSY, ED, and GUTs. May provide a dark matter candidate, account for the mass hierarchy between SM generations & muon anomalous magnetic moment.
- Not constrained from electroweak precision measurements.

1-a) Vector-like quarks (VLQs)

CMS-PAS-B2G-20-002

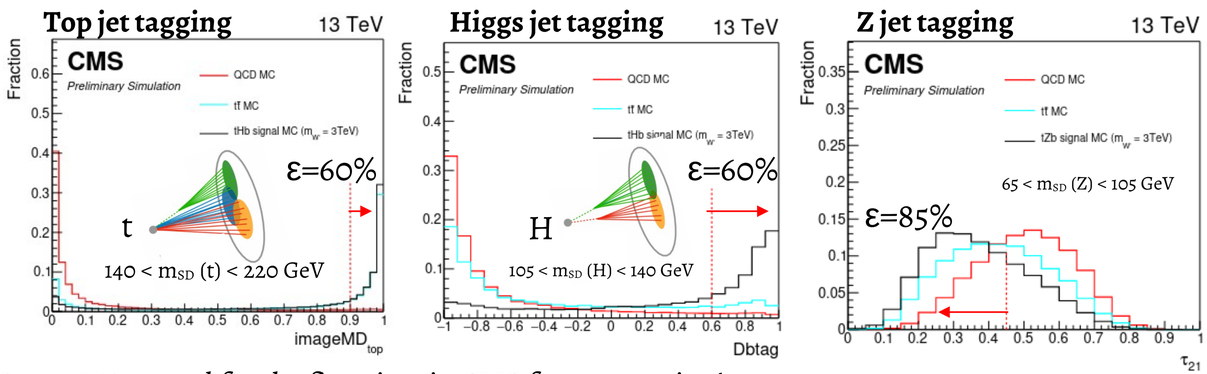
W' → B VLQ or T VLQ (s-channel)



Single VLQ production

Object selection:

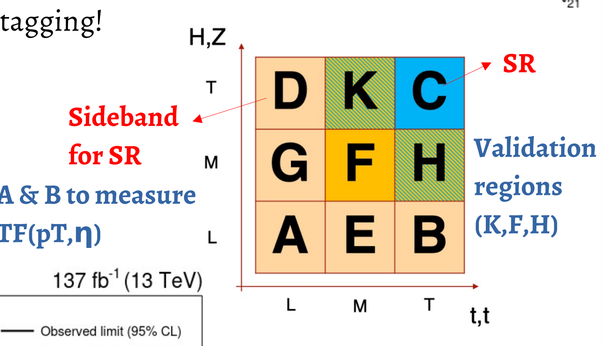
- Two AK8 jets (H/Z, t), pT>400 GeV. One AK4 jet (b), pT>200 GeV. |η|<2.4.
- ΔR(AK8 jet,AK8 jet)>1.6, ΔR(AK4 jet,AK8 jet)>1.2.



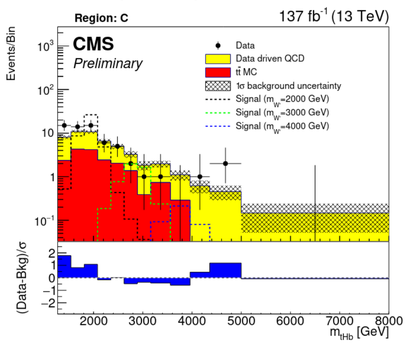
ImageMD$_{top}$ used for the first time in CMS for top-tagging!

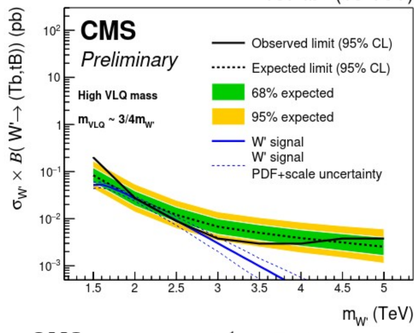
QCD multijet background estimation:

$$TF(p_T,\eta) \equiv (B_{data} - B_{t\bar{t}})/(A_{data} - A_{t\bar{t}})$$
$$C_{qcd} \simeq (D_{data} - D_{t\bar{t}}) \times TF(p_T,\eta)$$

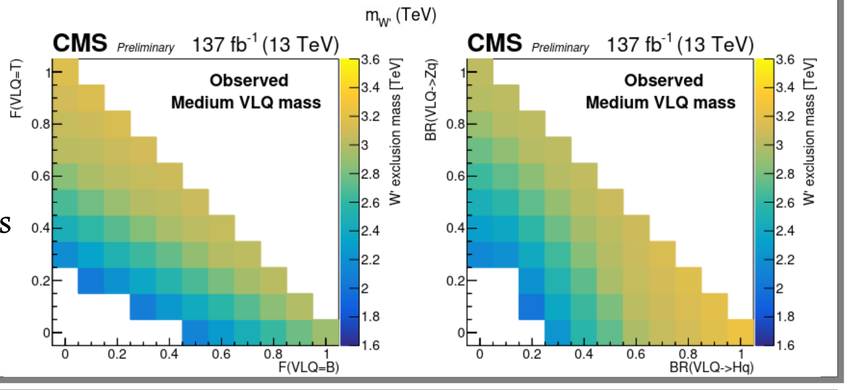


Reconstructed W′ boson mass (m_{tHb}) in the SR:





95% CL production cross section limit on W' for high-mass VLQ (~3/4$m_{W'}$).

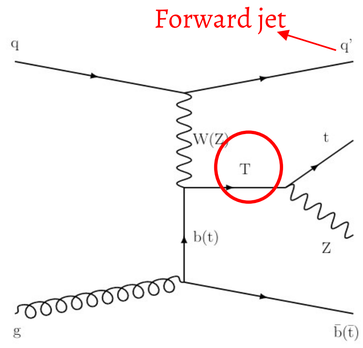


Generalized exclusion maps for hypotheses other than the benchmark model.

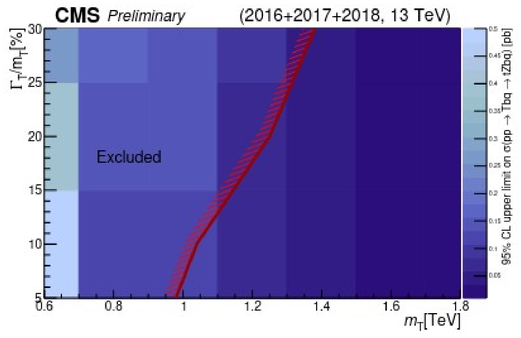
1-b) Vector-like quarks (VLQs)

CMS-PAS-B2G-19-004

T VLQ → tZ (→ νν)



Single VLQ production



M_T of top jet and pT^{miss} used as final discriminating variable.

Observed 95% CL upper limit on σ(single T)xB(T → tZ) shown for T mass widths of 10%, 20%, 30% of T mass.

Total **6 SR categories**: Single AK8 t jet **(merged)**, AK8 t jet from a W jet and a b jet **(partially merged)**, and three AK4 jets **(resolved) – with or without forward jet.**

1-c) Vector-like quarks (VLQs)

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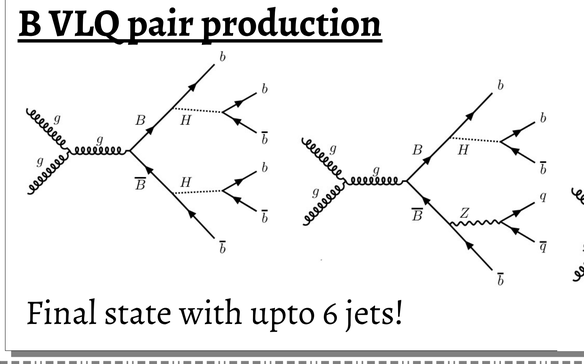
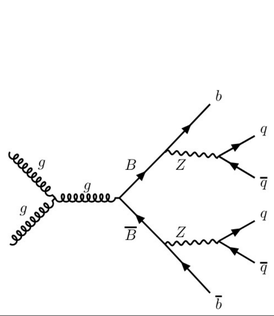
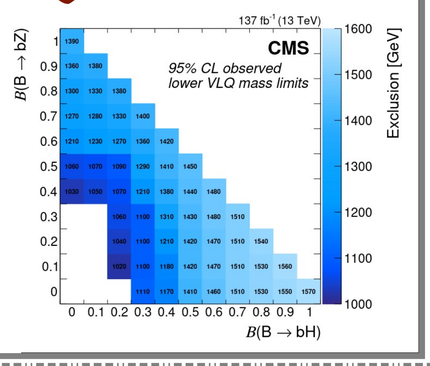
B VLQ pair production





Final state with upto 6 jets!

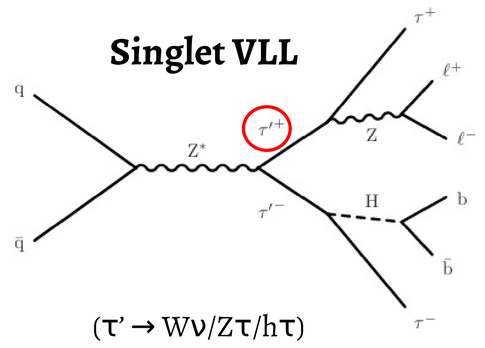


2) Vector-like leptons (VLLs)

CMS-PAS-EXO-21-002

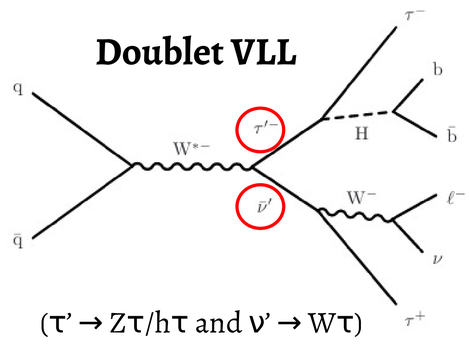
Pair-production (τ'τ',ν'ν') or associated-production (τ',ν') via electroweak interaction.

Singlet VLL



(τ' → Wν/Zτ/hτ)

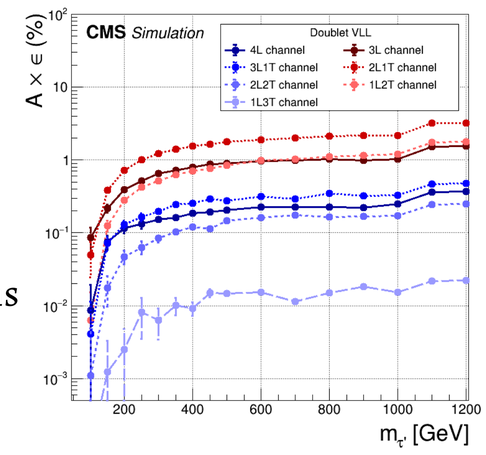
Doublet VLL



(τ' → Zτ/hτ and ν' → Wτ)

Multilepton analysis

- **Final states:** 4ℓ, 3ℓ1τ$_h$, 3ℓ, 2ℓ2τ$_h$, 2ℓ1τ$_h$, 1ℓ3τ$_h$, and 1ℓ2τ$_h$.
- **Primary irreducible backgrounds:** WZ, ZZ, ttZ, Zγ. Estimated using simulation.
- **Reducible background:** Misidentified leptons from jets, and/or heavy flavor decays. Data-driven 3D/4D matrix method.

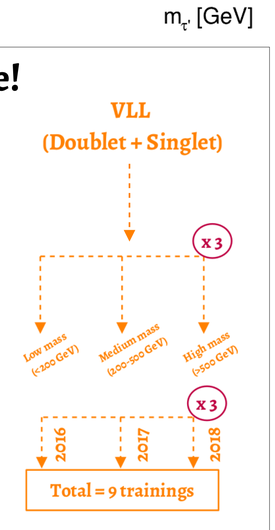


Low signal acceptance → BDTs to the rescue!

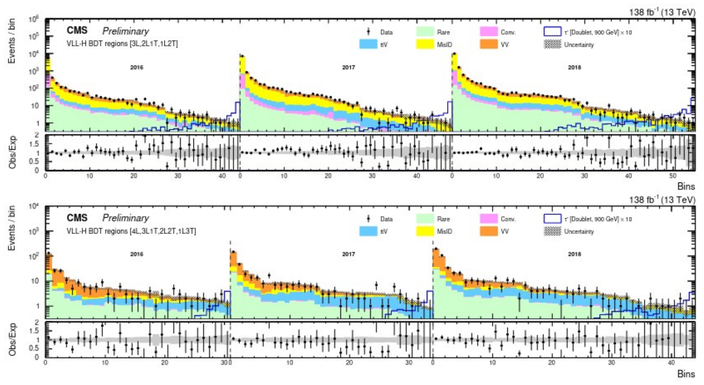
1) **One** BDT training per year, using samples from other two years.
2) **One** combined training for singlet and doublet VLL.
3) **One** BDT per mass (total 3 mass ranges).
4) **One** channel-inclusive training.
5) Novel **input variables** for the BDT training.

Variable type	All signals	Vector-like lepton	Used for
Event	H_T, p_T^{miss}, N_b, M_ℓ	Q_ℓ	
Lepton	p_T^i, p_T^{OSSF}		
Angular	ΔR_{min}	Max, Min: $\Delta\phi^i$,	Max, Min: $\Delta\phi^{ij}$
Mass	M_T^i	M^{ij}, M_T^{12}, M_T^{13}, M_T^{23}	

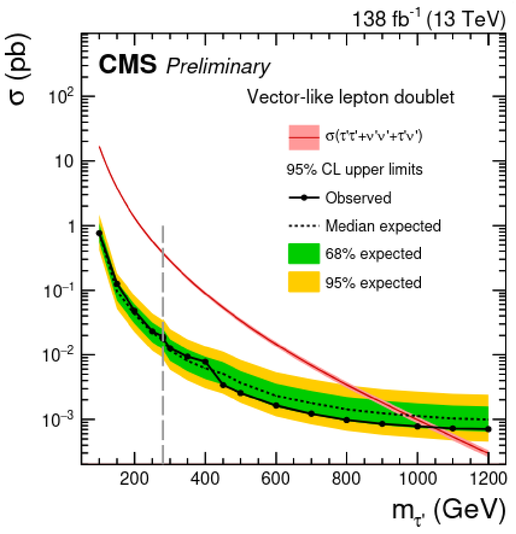
6) **Adaptive-binning** for BDT output spectra for maximum gains.



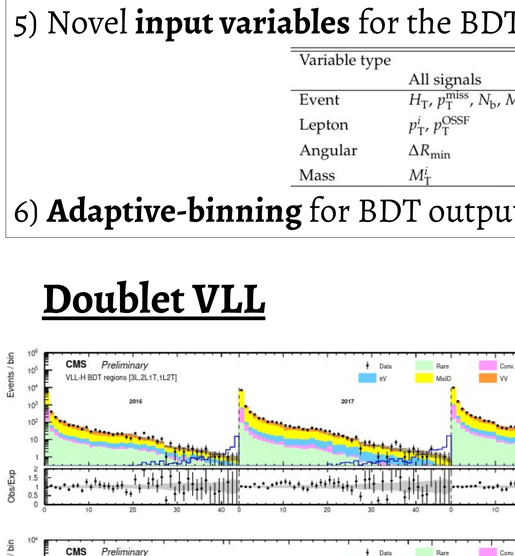
Doublet VLL

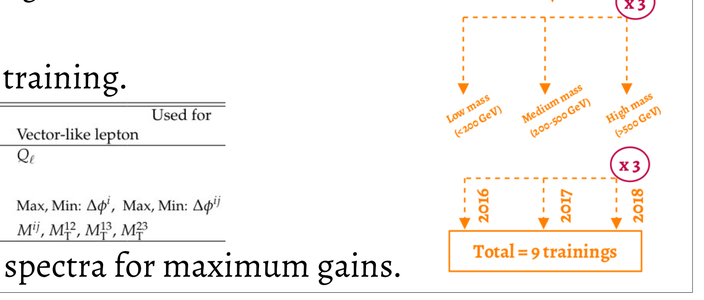


VLL-H BDT signal regions in full Run 2.



Singlet VLL





Limits are derived from the model-independent categories in bins of S_T distribution.

Singlet VLL model challenging due to lower acceptance and smaller production cross section.

References

CMS-PAS-EXO-21-002 (2021)
Vector-like leptons singlet & doublet

CMS-PAS-B2G-20-002
W' → B/T VLQ single production

CMS-PAS-B2G-19-004
T VLQ → tZ (→ νν) single production

Phys. Rev. D 102, 112004 (2020)
VLQ pair production

Poster Session at the 30th International Symposium on Lepton Photon Interactions at High Energies (LP2021)