Hints of BSM physics at CMS

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On behalf of the CMS collaboration

New Physics Searches at CMS

LHC provides excellent opportunities to search for BSM physics and CMS has a wide range of new physics searches

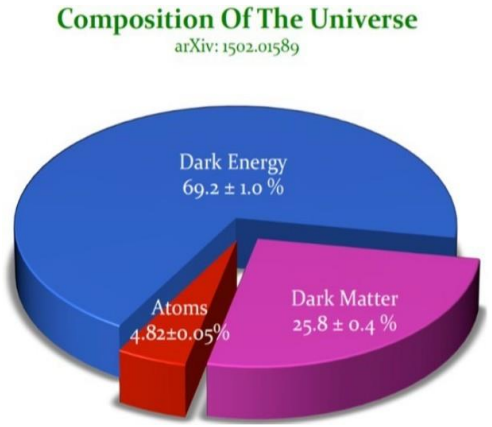
- SUSY, leptoquarks, heavy leptons, axions, new dynamics/couplings

Many of BSM scenarios considered explain unresolved mysteries in SM

- Hierarchy problem, dark matter, neutrino, mass, muon g-2, B anomalies, W mass

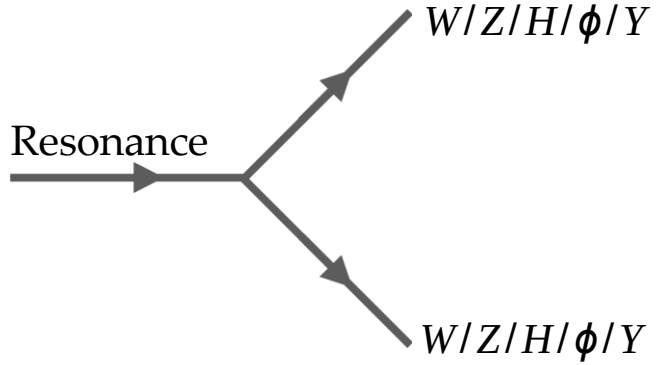
- Some of these BSM models produce mass resonance

- Some of them produce long-lived particles



This talk will focus only on a handful of recent results, with a critical eye on fluctuations present so far

Diboson searches



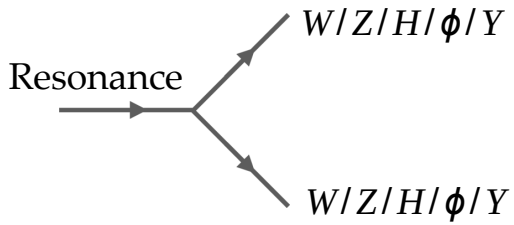
Cover a wide range of models

- Light scalars(φ/Y) and Radion
  - Extended Higgs sectors, 2HDM and Warped Extra dimensions
- Heavy Vector Triplet Models (HVT) and extensions of Minimal Warped ED
  - W'/Z'
  - WKK
- Warped extra dimensions
  - Bulk-Graviton

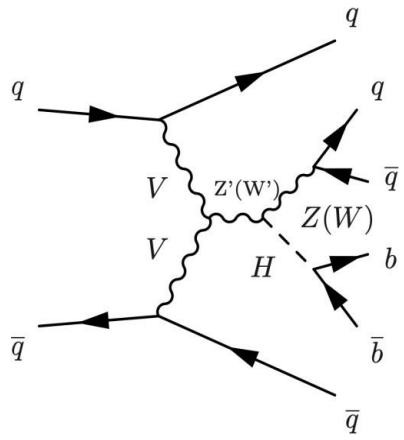
X → VV/VH → all-jets

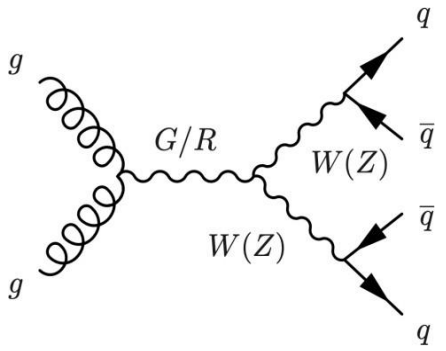
CMS-B2G-20-009

- **Resonances decaying to a VV pair with masses above 1.3 TeV**
  - Very sensitive full hadronic diboson search

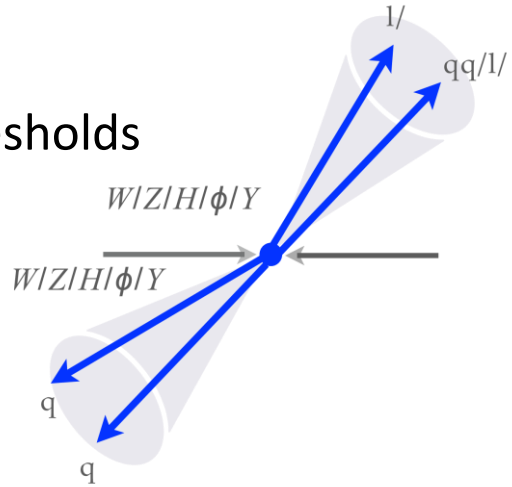


- **Produced via gluon fusion or vector boson fusion**
  - gg produced graviton or radion decaying to WW or ZZ
  - VBF produced Z' and W' decaying to WW and WZ, respectively





- **Final states and experimental signature**
  - Semi-leptonic and leptonic have smaller BR, smaller background and lower trigger thresholds
  - Hadronic have Largest BR but also large background and high jet pT trigger thresholds
  - High boosted 4 quarks final state
    - Because of the high boost, each boson decay is typically clustered as a single large-radius jet

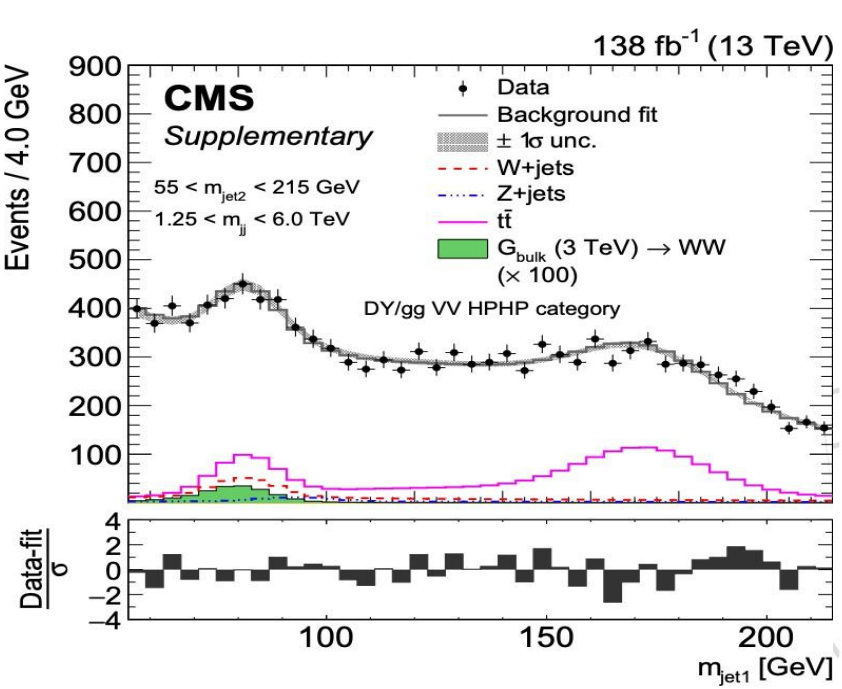


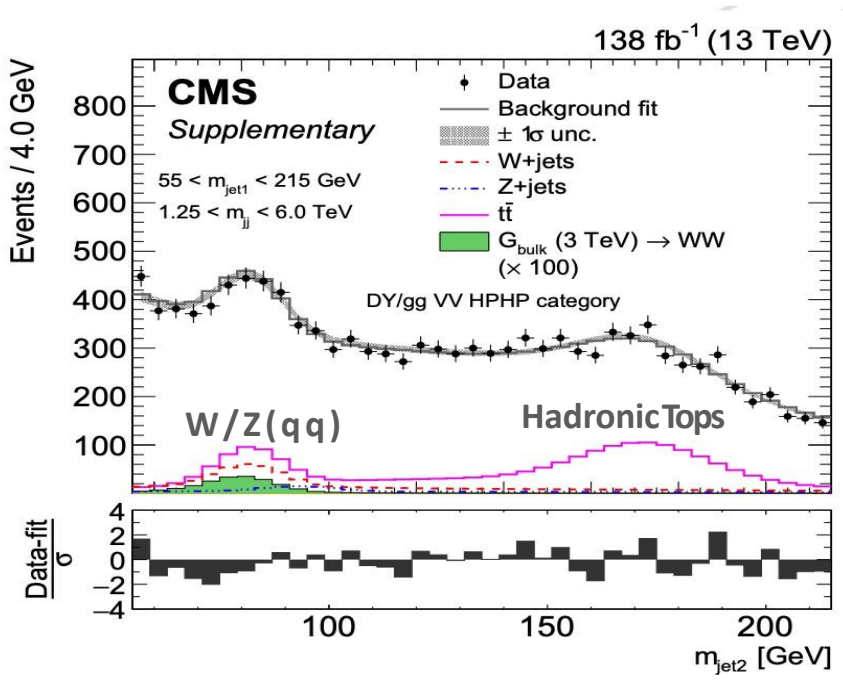
X → VV/VH → all-jets

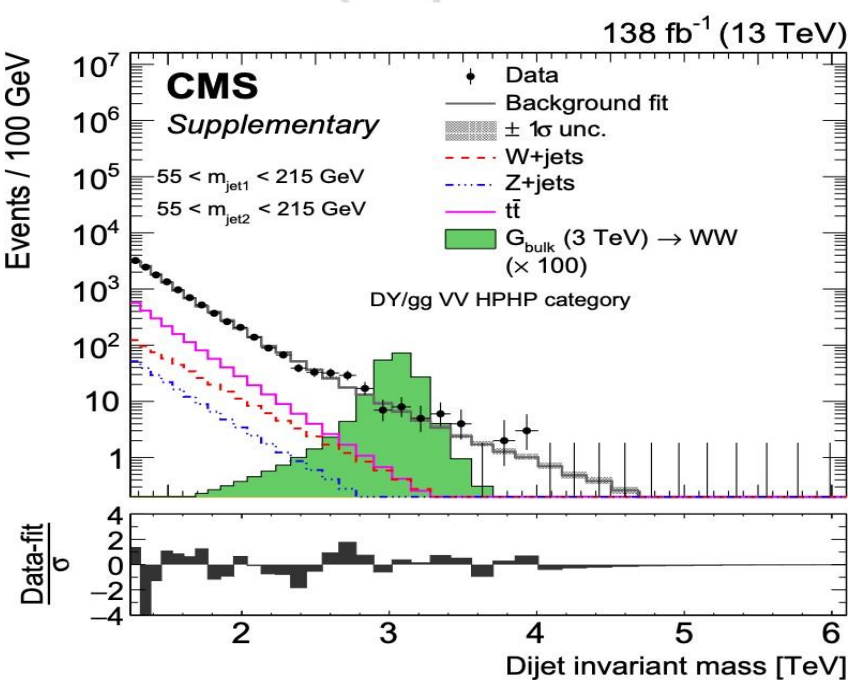
CMS-B2G-20-009

- **Jet tagging algorithms based categorization** → Improve sensitivity

- **3D-Fit: MJET 1 + MJET 2 + MJJ**
  - Fitting also each of the jets masses
  - QCD model adapts to data, uses MC-based gaussian kernel templates with increased statistics
  - Probing up to 4.8 TeV





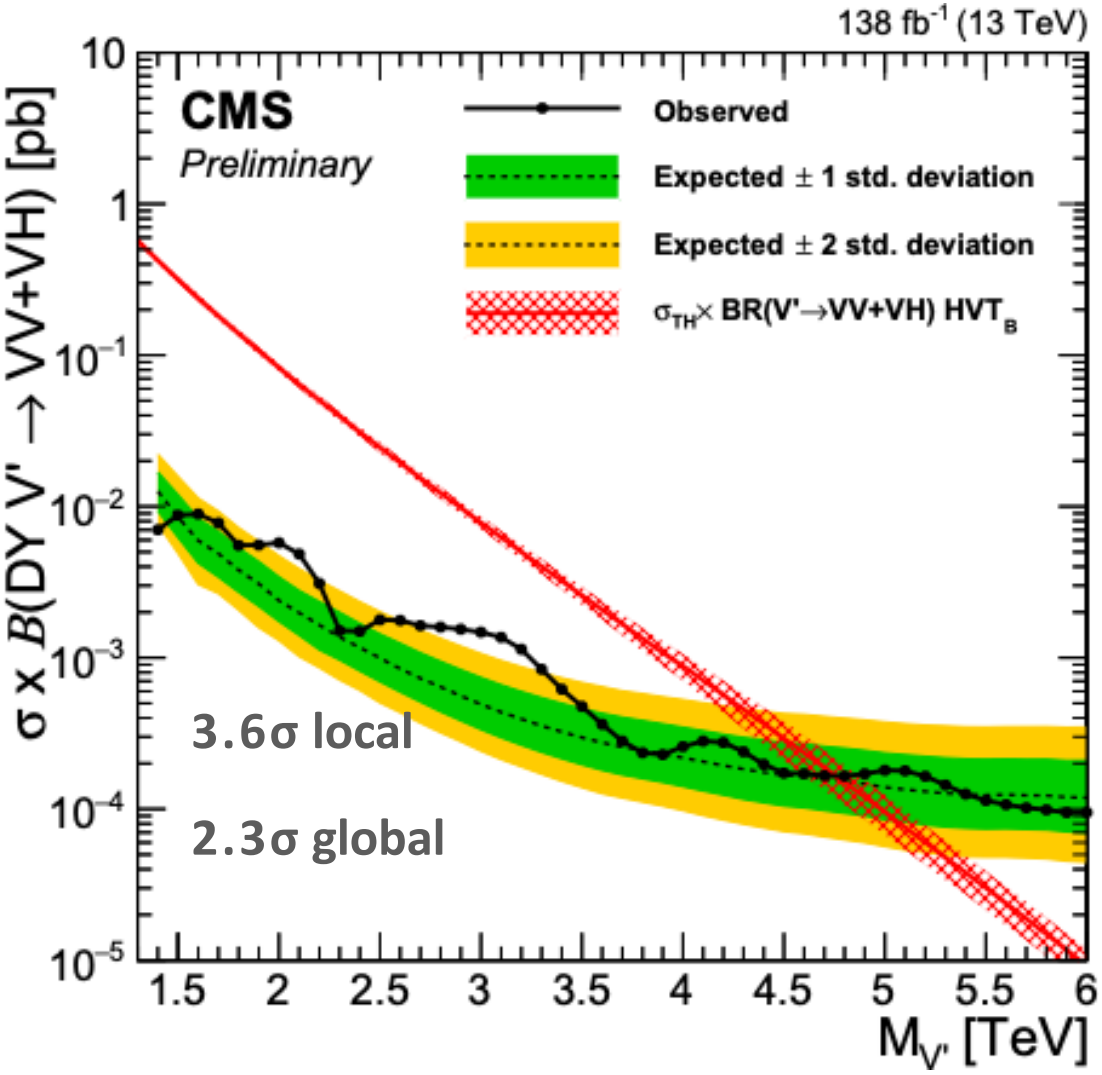


X → VV/VH → all-jets

CMS-B2G-20-009

Results for V’ → VV+VH, Heavy Vector Triplets model

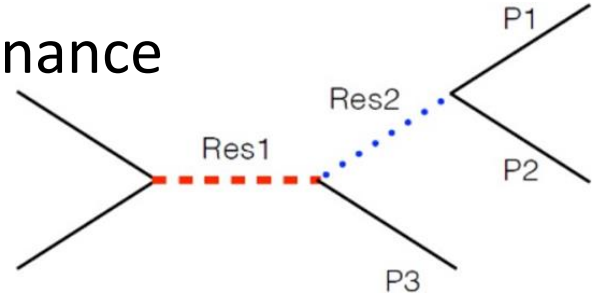
- Most stringent limits on V’ up to 4.8 TeV
- First VBF limits (no exclusion) on all-hadronic search
- **2.3 σ global (3.6 σ local) excess**



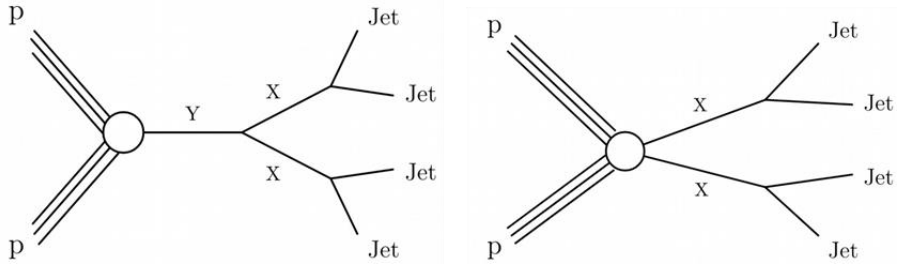
Searches in final states with jets

Many searches in CMS with jets in final states, recent Full Run 2 results:

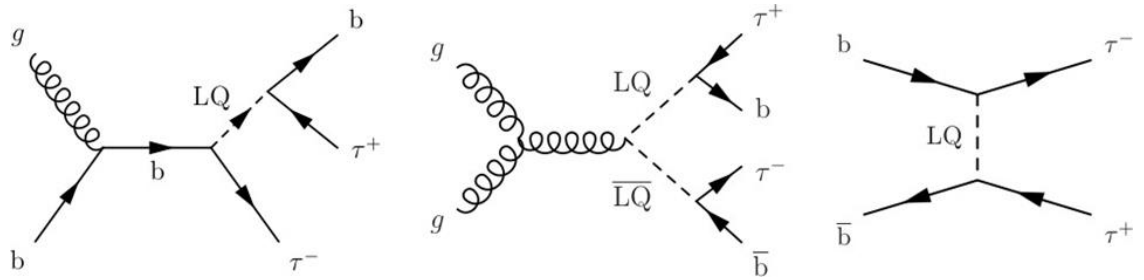
- High-mass resonances decaying to a jet and a Lorentz- boosted resonance



- Search for resonant and nonresonant production of pairs of dijet resonances



- Leptoquarks (LQs) decaying to tau and b

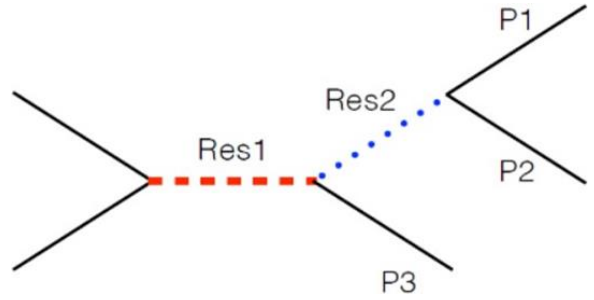


Di-tri-jets Search

CMS-EXO-20-007

Experimental Signature

Two large-radius (wide) resolved jets, one coming from R2 (R2-jet) and one coming from the third parton (P3-jet)



Main backgrounds

MultiJet QCD production estimated with a data-driven method

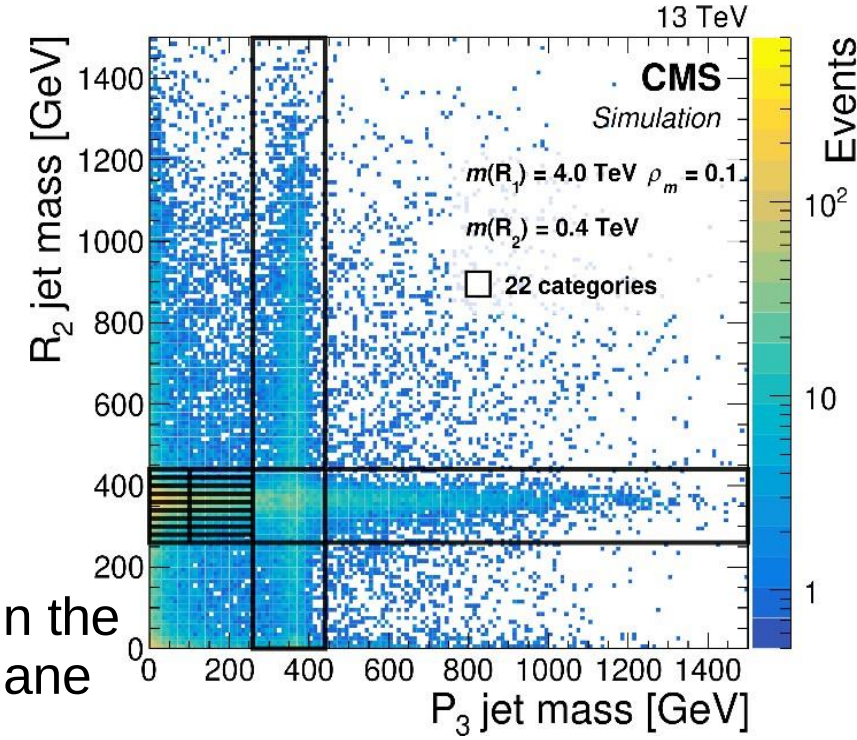
Signal Models

Warped extra dimensions where R1 is a KK gluon (GKK),

R2 is a radion (ϕ)

- GKK → ϕg → ggg (trijet)

Search largely model independent.

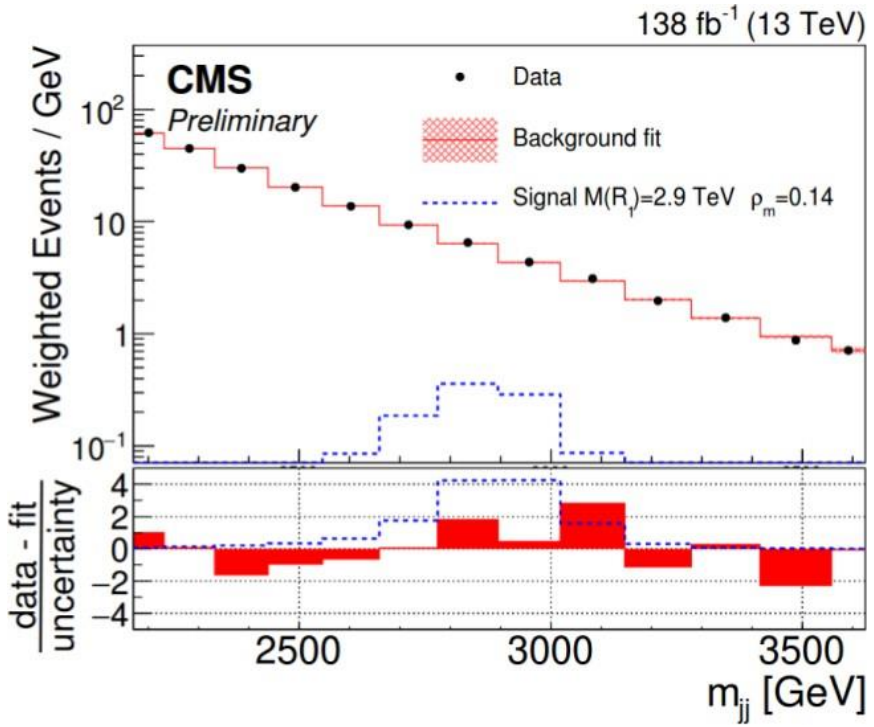


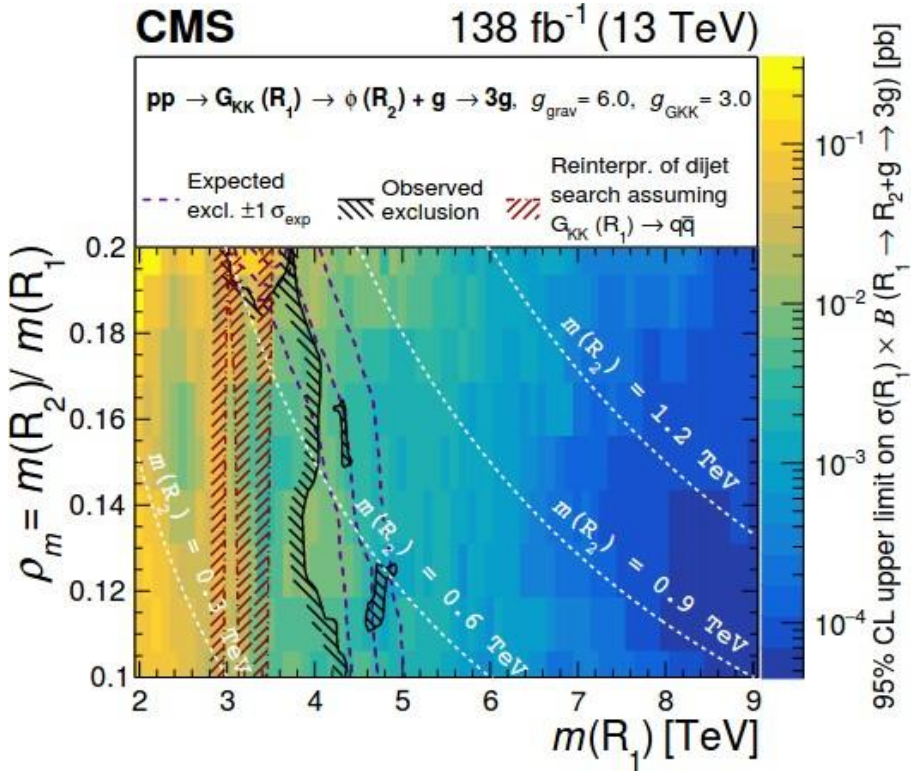
22 SRs defined in the m(R2)/m(P3) plane

Di-tri-jets Search

Maximum likelihood fit in the dijet mass performed in the SRs.

- Novel experimental signature, experimental exclusion of this benchmark model of new physic significantly extended
- **1.8 σ global (3.2 σ local) excess**





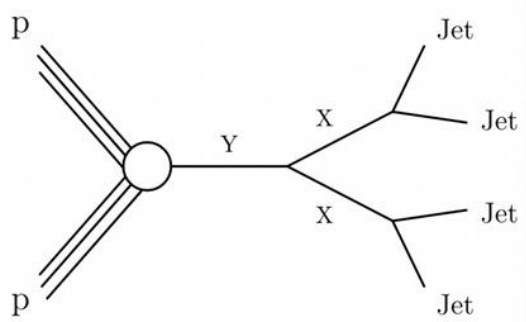
Paired Dijet Search

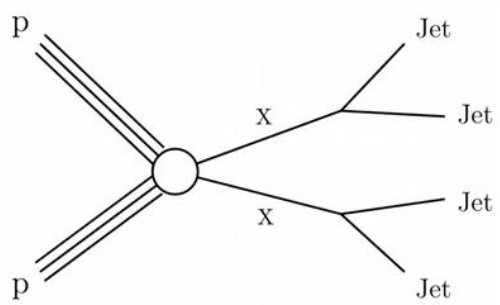
CMS-EXO-21-010

Dijet resonances produced in two modes

- **Resonant**

  Diquark decaying to vector-like quarks which decay to an up quark and gluon $\mathrm{uu} \to \mathrm{S} \to \chi\chi \to (\mathrm{ug})(\mathrm{ug})$





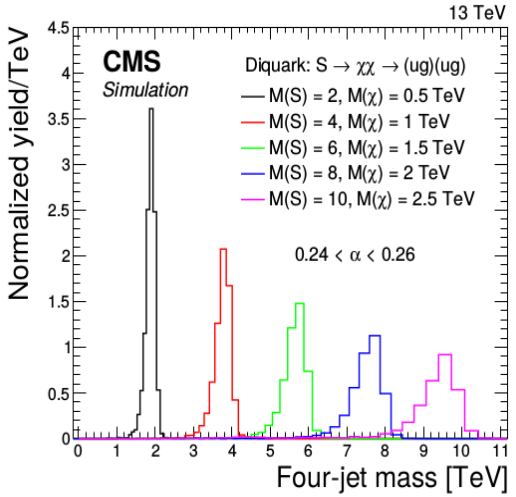
- **Non-resonant**

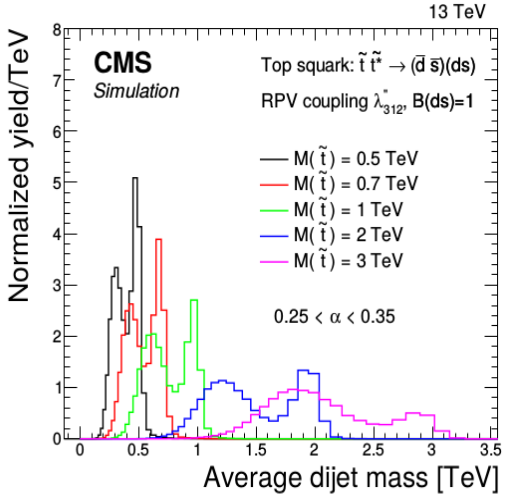
  R-parity violating stop pairs decaying to a d and s quark

$$\mathrm{pp} \to \widetilde{\mathrm{t}}\widetilde{\mathrm{t}}^{*} \to (\bar{\mathrm{d}}\bar{\mathrm{s}})(\mathrm{ds})$$

Experimental Signature

- Four or two resolved jets paired to same mass resonances.



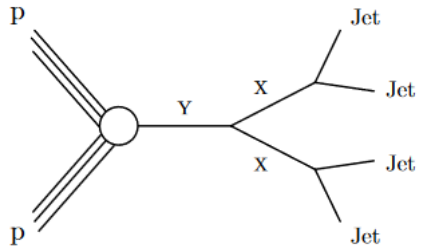


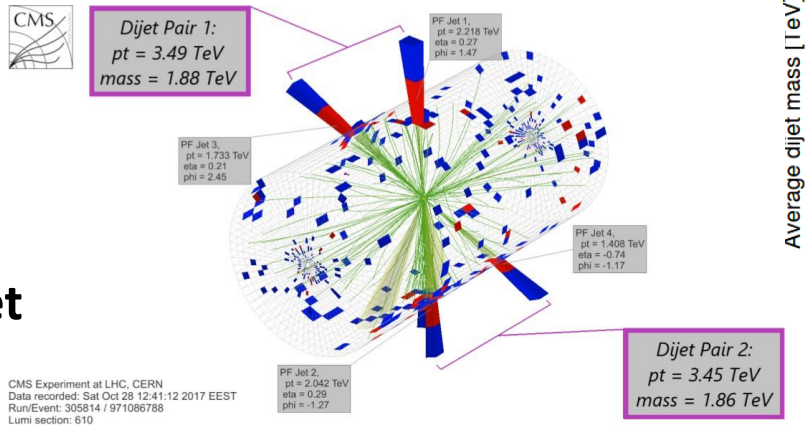
Paired Dijet Search – Resonant

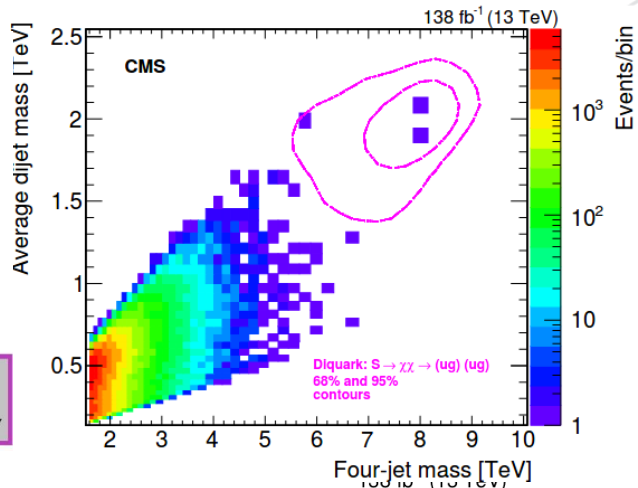
CMS-EXO-21-010

Initial motivation coming from previously recorded event containing four particle jets in the final state

- The invariant mass of all four jets was 8 TeV
- Jets could be divided into two pairs with a 1.9 TeV invariant mass each

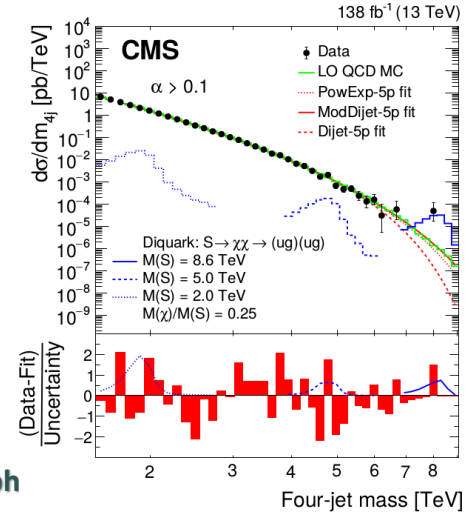


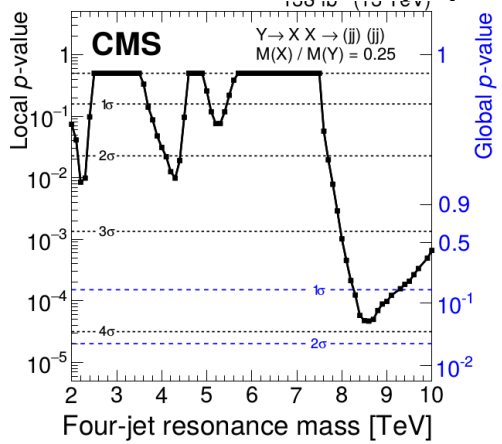




First LHC limits on resonant pair production of dijet resonances via high mass intermediate states

- Maximum likelihood fit in the four jet mass performed in the SRs.
- **1.6 σ global (3.9 σ local) excess**



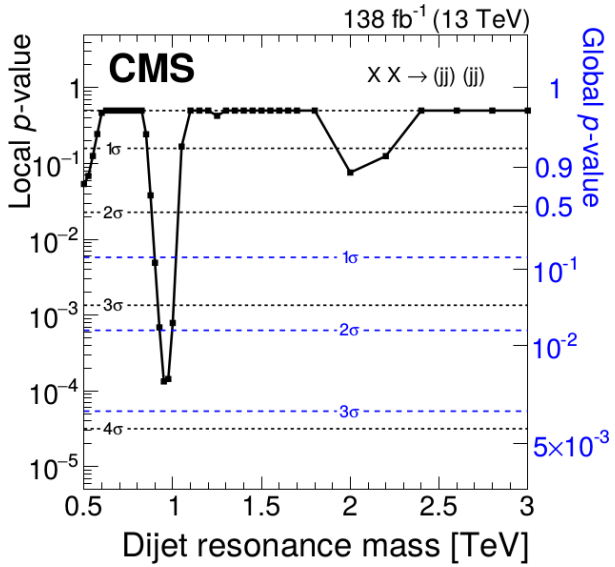


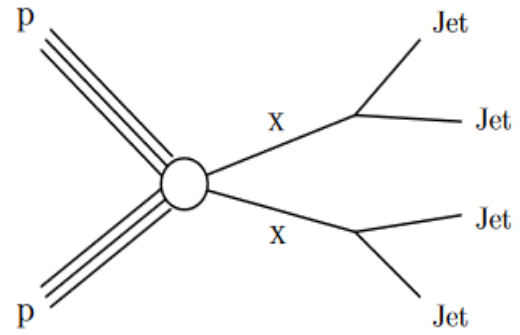
Paired Dijet Search – Nonresonant

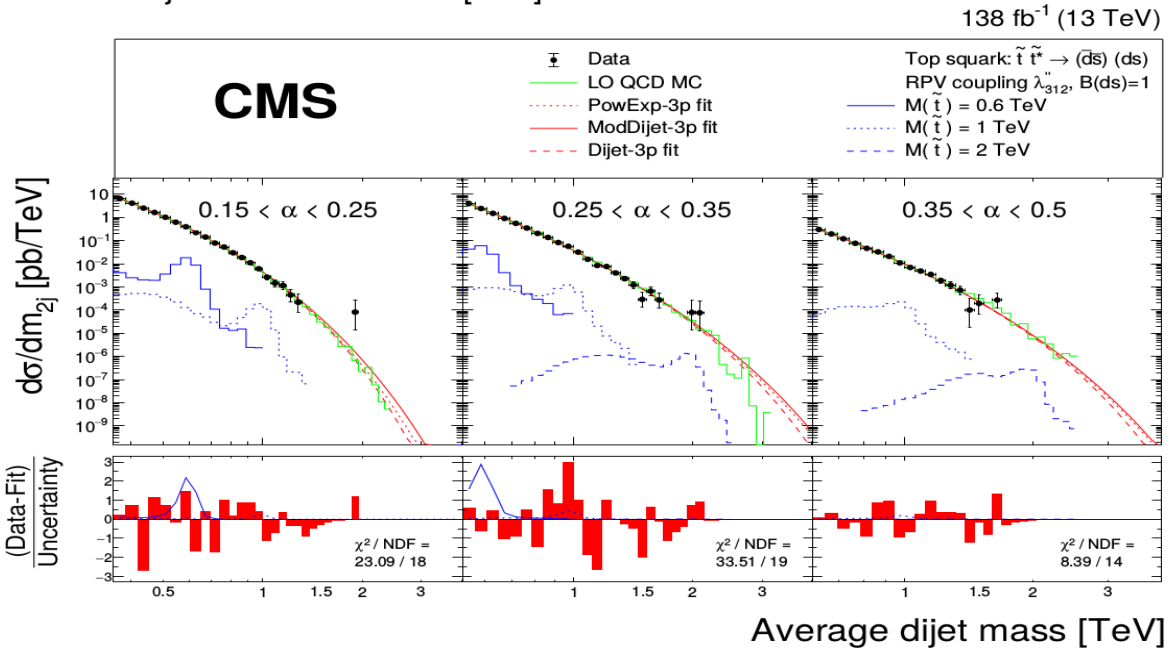
CMS-EXO-21-010

Maximum likelihood fit in the average dijet mass performed in the SRs

- Significantly extend the previous limits
- **2.5 σ global (3.6 σ local) excess**

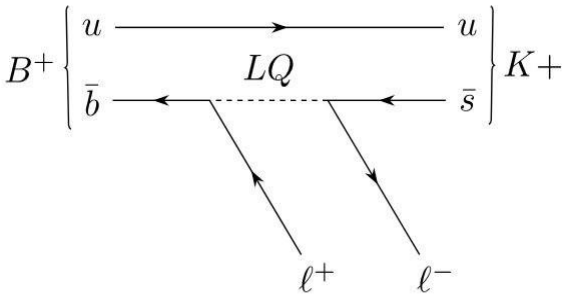




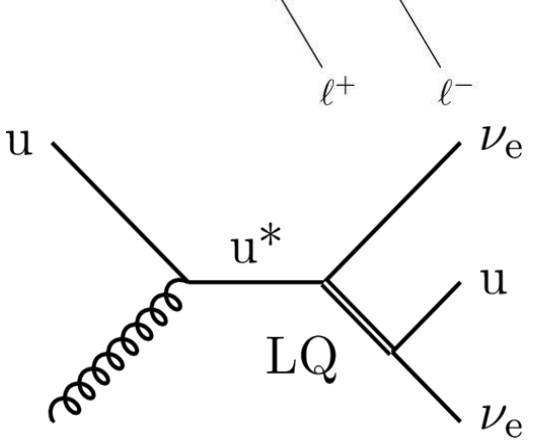


Leptoquarks (LQs)

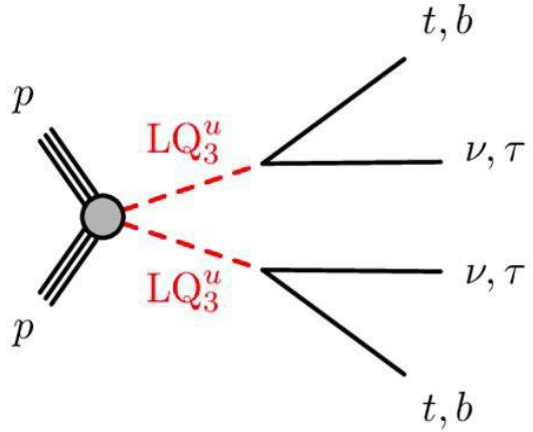
- LQs can couple to both leptons and quarks
  - Both scalar and vector bosons are possible
  - Carry fractional electric charge



- Processes can violate lepton flavor universality



- Strongly couple to 3rd generation SM fermions

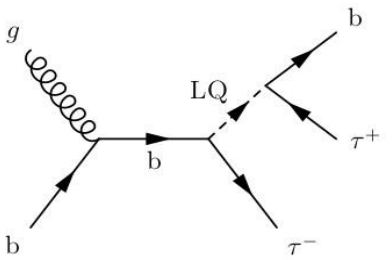


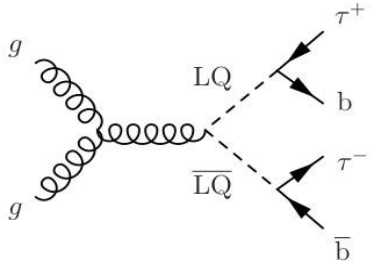
- Possible explanation for B anomalies
  - B → Dτν and B → D*τν decay rates by the BaBar, Belle and LHCb collectively deviate from the SM predictions by about 4 σ

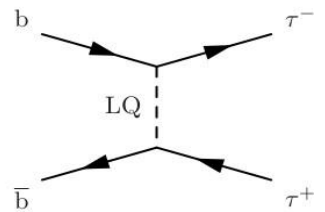
Search for LQs → τb

CMS-EXO-19-016

Search for a third-generation leptoquark (LQ) coupling to a τ lepton and a b quark

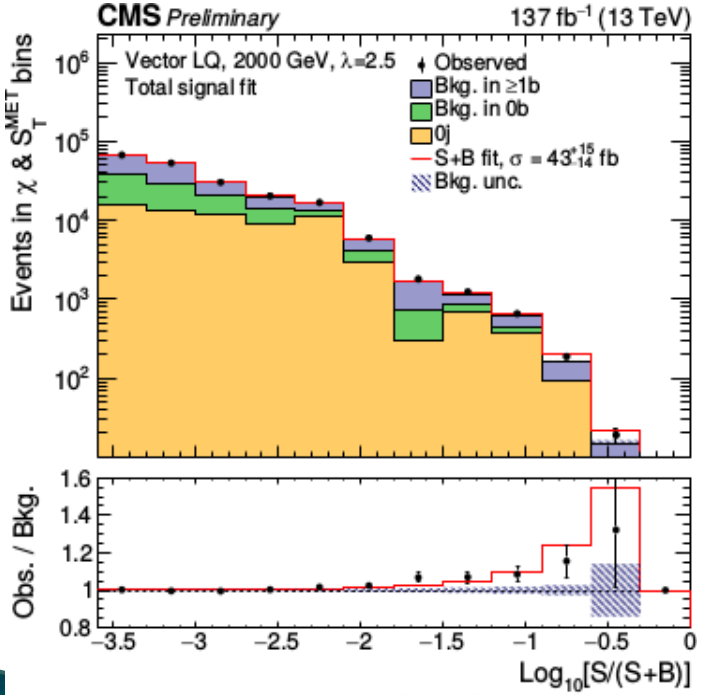






Resonant production as single LQ or in pair
- two high-pT τ leptons, and one or two high-pT b quarks

Nonresonat production with two τ in final states
- τ lepton pair decay can be fully hadronic (τh τh), semileptonic (eτh, μτh), and two fully leptonic channels (eμ, μμ)



Event selection

Resonant

$$S_{\mathrm{T}}^{\mathrm{MET}} \equiv p_{\mathrm{T}}^{1} + p_{\mathrm{T}}^{2} + p_{\mathrm{T}}^{j_1} + p_{\mathrm{T}}^{\mathrm{miss}}$$

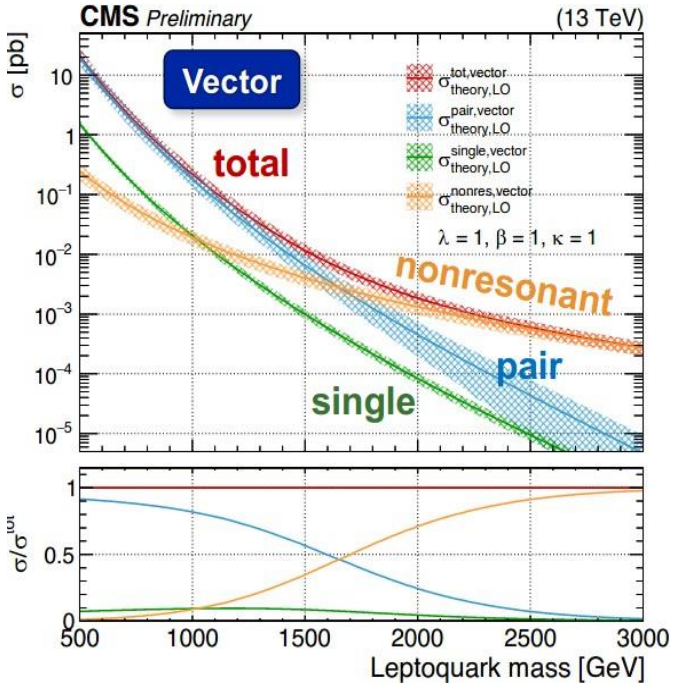
≥ 1 jet (0 or 1 b tag)

Nonresonant

$$\chi = e^{\Delta\eta}$$

0 jet

Simultaneous maximum likelihood fit of χ and S_T^{MET}



Search for LQs → τb

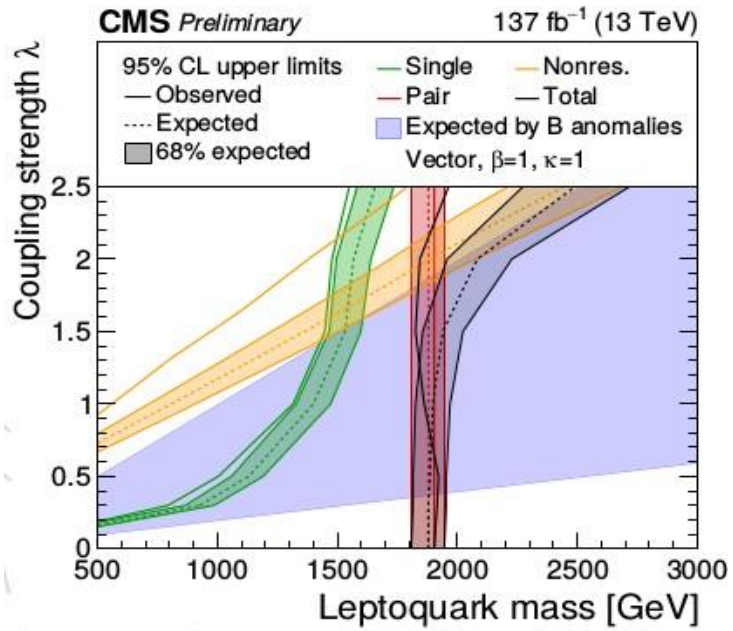
CMS-EXO-19-016

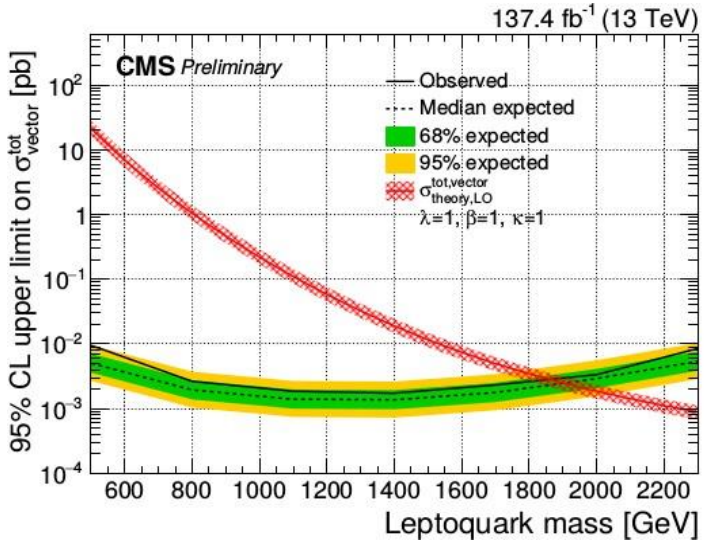
All three production modes treated as one signal

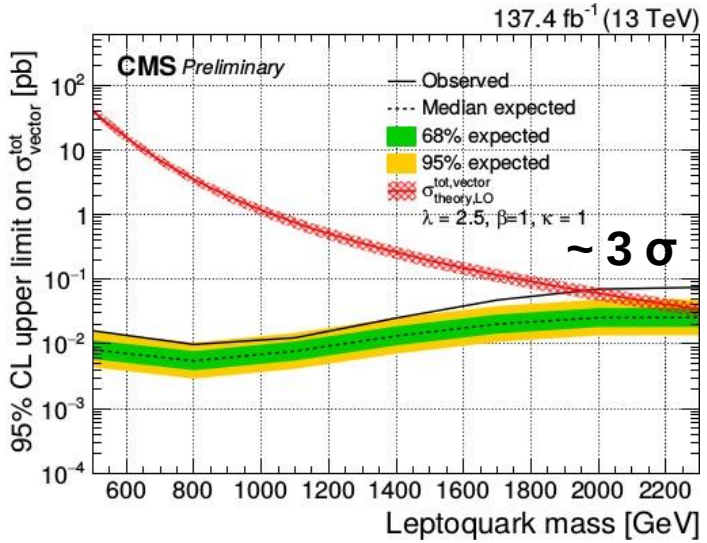
- Maximal sensitivity and exclusion power
- Upper limits placed on scalar and vector LQ

For a Vector LQ, ~ 3 σ excess for LQ mass > 1.8 TeV

- Driven by nonresonant mode





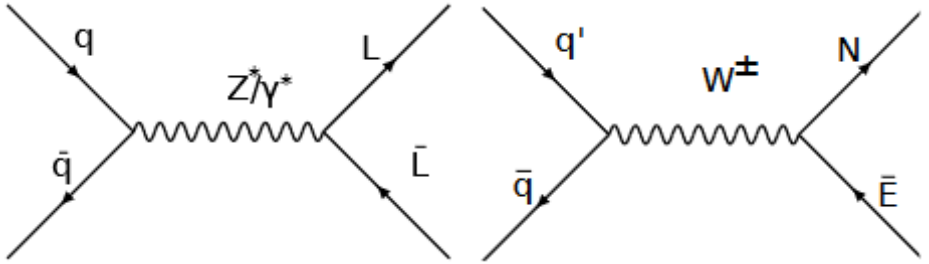


Vector Like Leptons (VLL)

The model consists of a SM extension with an SU(4) × SU(3)′ × SU(2)L × U(1)′ gauge sector

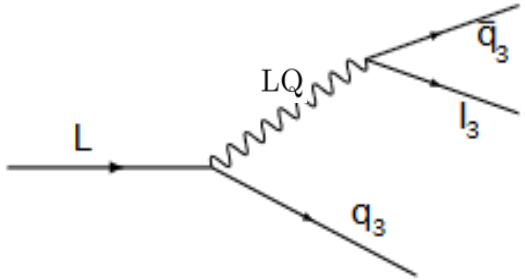
- Motivations from B-Physics Anomalies
- Points to lepton flavor nonuniversality

EW production and their couplings to the SM W and Z bosons, or through interactions with a new Z'



Decays proceed through their interactions with the vector leptoquark LQ

- L represents either the neutral, N, or the charged, E VLL
- Final state with two quarks and one lepton

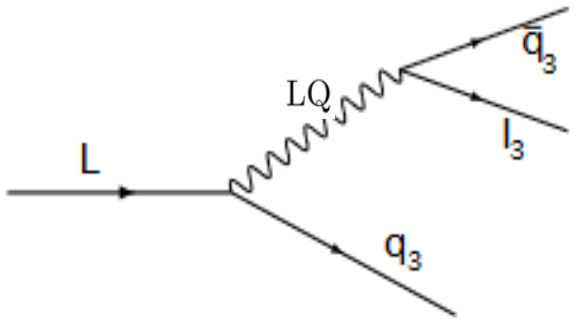


Pair-produced VLL in ≥ 3b + Nτ final states

B2G-21-004-PAS

Pair-Produced VLL

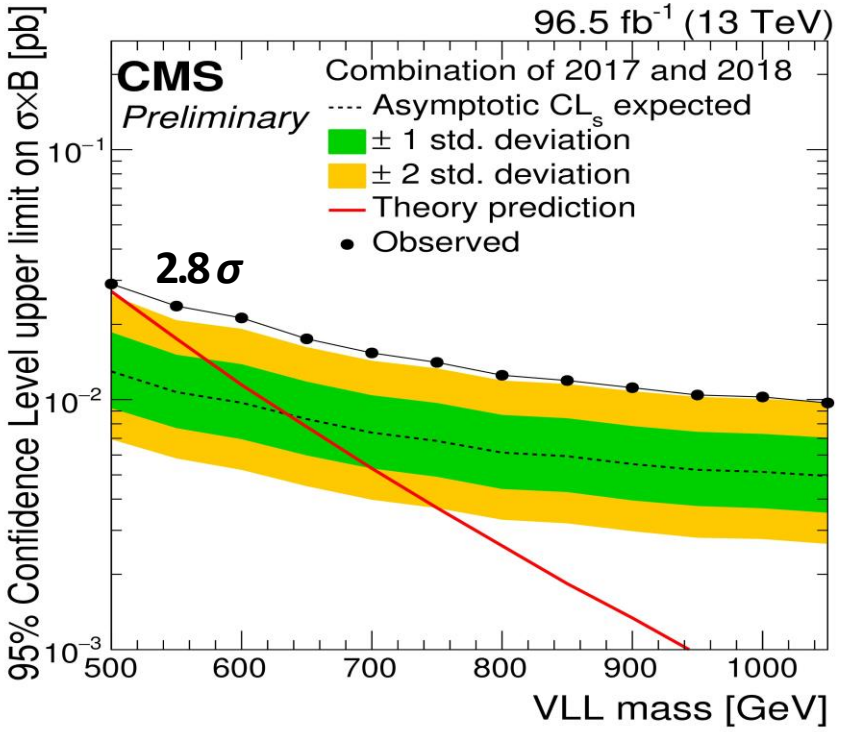
- $L \rightarrow tt^{-}(\tau/\nu\tau)$
- $t \rightarrow bW$, $W \rightarrow qq$



Categorization based on Nτ

- Nτ=0, QCD dominated
- Nτ=1, QCD and t
- Nτ=2, t dominated

Mild excess ~ 2.8 σ around a VLL mass of 600 GeV



Conclusions

- **CMS performed many searches beyond Standard Model**
  - No clear evidence for BSM yet
- **Run-3 just started in July**
  - More data, improvements in data collection and analysis techniques
- **CMS is entering into a new era that will shed light on BSM physics**
  - Stay tuned for Run 3!

Thank you

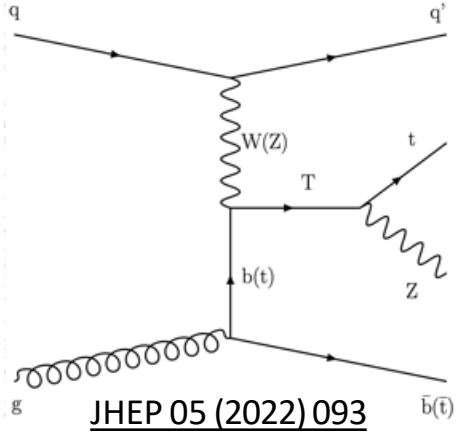
Vector Like Quarks (VLQ)

Many extensions of SM have VLQs

- Can be singlets, doublets, triplets, …
- Mass from mixing, not Higgs (Yukawa)
- Mechanism to stabilize Higgs mass

Single-Production

- EW, In association w/ t/b + quark



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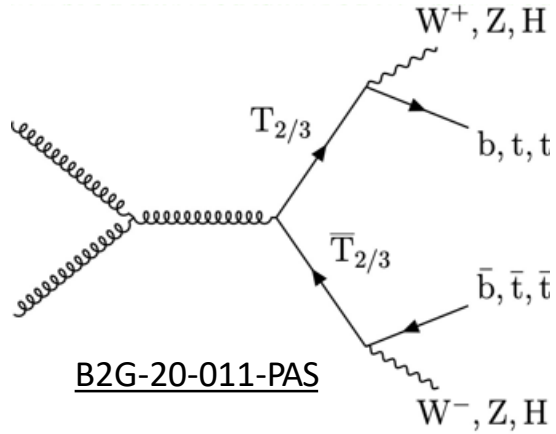
Pair-Production

- Strong, 4 massive (boosted) bosons and 3rd generation quarks



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Motivation from experiments

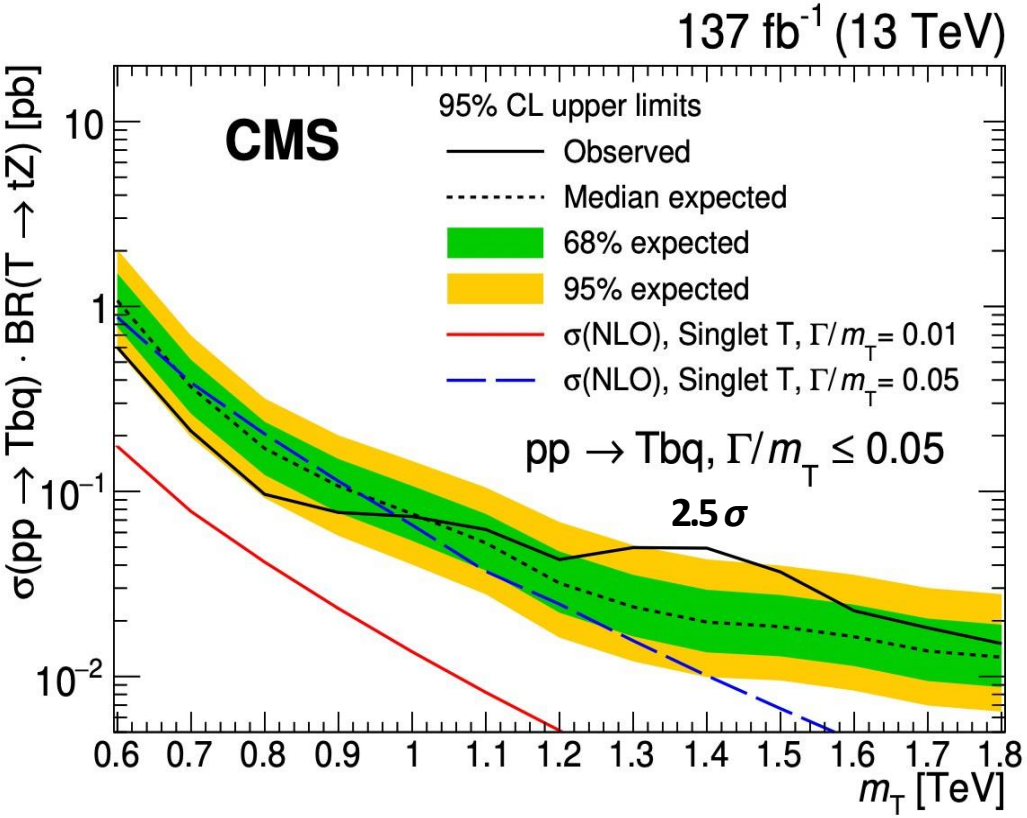
- Higgs properties align with SM
  - VLQs compatible w/ constraints
- Possible explanation for BSM phenomena

T → tZ → νν All-Hadronic

JHEP 05 (2022) 093

Z → ν (invisible): Missing pT

- Top Reconstruction: b+W

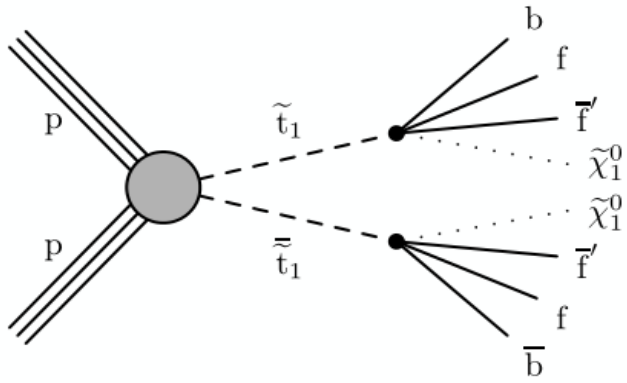


Search for top squarks decaying via the four-body mode in single-lepton final states

SUS-21-003

Analysis targets top squark pair production

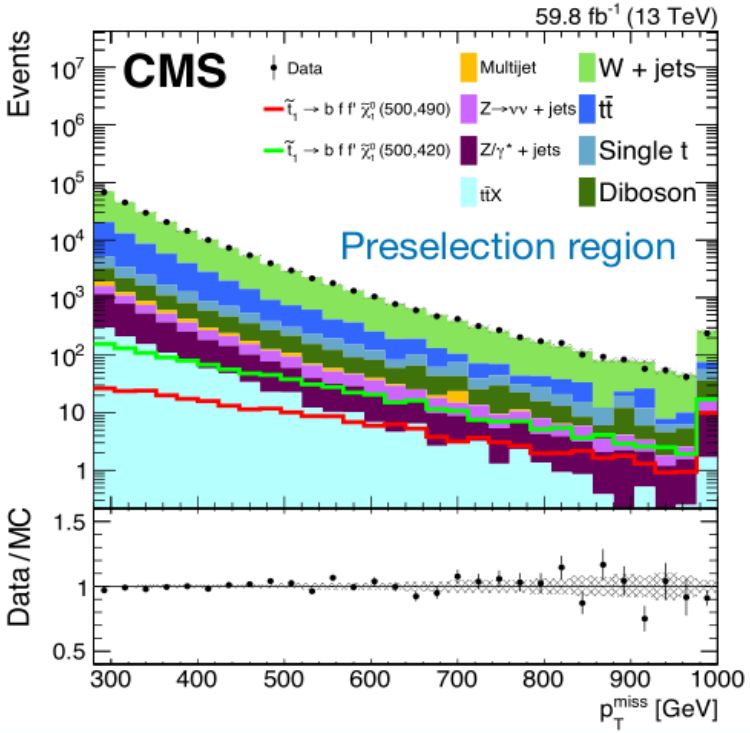
- compressed scenario ($\Delta m = m_{\tilde{t}} - m_{\tilde{\chi}} < m_W$)
- 4-body decays



Search strategy

- 1 lepton final state with use of soft leptons
  - pT(μ) > 3.5 GeV, pT(e) > 5 GeV
- Require p_T(jet1) > 110 GeV for ISR boost
- Trigger based on p_T^{miss} and H_T^{miss}
- S vs bkg discrimination via set of 8 BDTs trained for different Δm scenarios
- Counting experiment in 8 (overlapping) signal regions

(after cut on BDT output)



Preselection

- Exactly 1 soft lepton with pT < 30 GeV
- HT > 200 GeV
- pTmiss > 280 GeV
- Δϕ (jet1, jet2) < 2.5

Search for top squarks decaying via the four-body mode in single-lepton final states

SUS-21-003

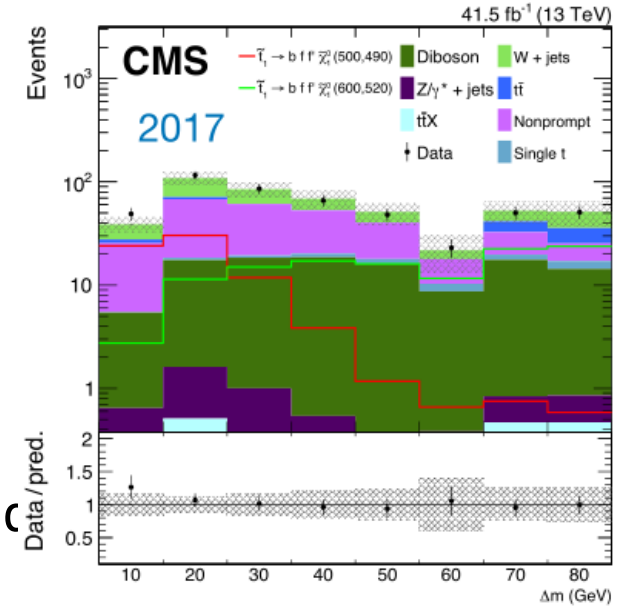
Non-prompt background prediction

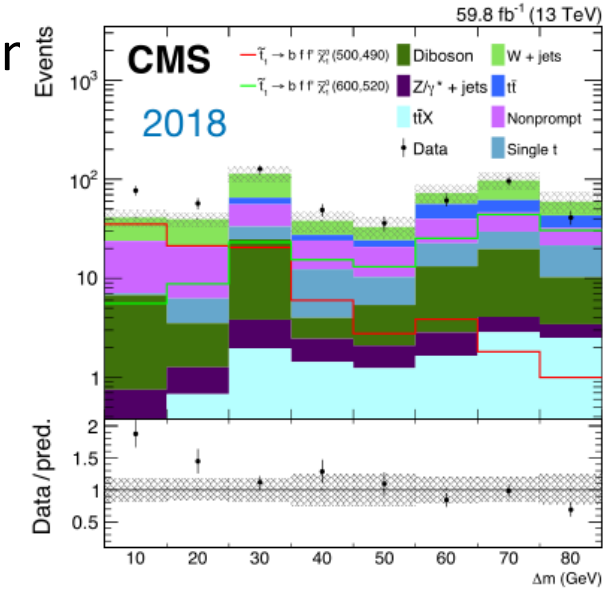
- Estimated via tight-to-loose method
- Includes systematic uncertainty for flavor composition in CR vs SR

Prompt background prediction

- Control regions at low BDT score, enhanced in W (0 loose b) or $t\bar{t}$ (≥1 tight b)
- Estimated using MC-derived transfer factor, after subtracting other backgrounc from yield in control region
- Validation regions (lower pTmiss or higher lepton pT) used to derive syster

~ 2.5 σ deviation for $\Delta m = 10\ GeV$





Di-& Multi-jets, W_R and Wgamma

CADI	Final state	X mass [TeV]	Local (global) significance	Publication
EXO-19-012	High mass dijets	8 TeV	Prob from QCD 10^{-4}	JHEP05(2020)33
EXO-21-010	Paired dijets	8.6/1	3.9(1.6)/ 3.6(2.5)	Submitted to JHEP
EXO-20-008	B-tagged dijet	-	-	Submitted PRD
EXO-20-007	Trijet resonances	2.9	3.2(1.8)	PLB 832 (2022) 137263
EXO-21-004	Multijet scouting	0.75		Pre-app/unblinded
EXO-20-001	W(had) + gamma	1.6(nar-bro)	2.8(1.1)-3.1(1.7)	PLB 826 (2022) 136888
EXO-20-002	Right-handed W & heavy neutrino→llqq	6 (mN =0.8)	2.95(2.78)	JHEP 2204 (2022) 047

High pT dileptons

CADI	Final state	X mass [TeV]	Local (global) significance	Publication
EXO-19-019	Z' to dileptons	0.5 & 0.7	2.4 & 3.1(1.4)	JHEP 2107 (2021) 208
SMP-21-002	Forward-backward asymmetry	discrepancy between ee/$\mu\mu$	2.4sigma	JHEP08(2022)063

B2G VLQ/VLL & DIB/RES

CADI	Final state	X mass [TeV]	Local (global) significance	Publication
B2G-21-004	VL leptons: 4b+Ntau	0.6 (0.5-1)	2.8	Submitted PLB
B2G-19-004	T->tZ(vv)	1.4	2.5	JHEP 2205 (2022) 093
B2G-21-003	X→ YH→ 4b	1.6 (M_Y = 90 GeV)	3.1 (0.7)	Submitted PLB
B2G-20-009	X→ VV/VH (had)	2.1, 2.9(broad)	3.6 (2.3)	CMS-PAS-B2G-20-009

Susy

CADI	Final state	X mass [TeV]	Local (global) significance	Publication
SUS-19-004	**stealth/RPV stops→t + jets**	0.4	2.8	PRD 104 (2021) 032006
SUS-18-004	**2 or 3 soft leptons + p_T^{miss}**	0.125 (Δm 40 GeV)	2.4	JHEP 04 (2022) 091
SUS-20-004	**HH(4b)+ME**	Bin 11 (in 22 bins)	3.3 (2.1)	JHEP 2205 (2022) 014