Searches for vector-like quarks and leptoquarks at ATLAS and CMS

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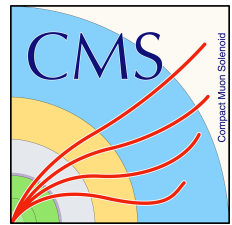
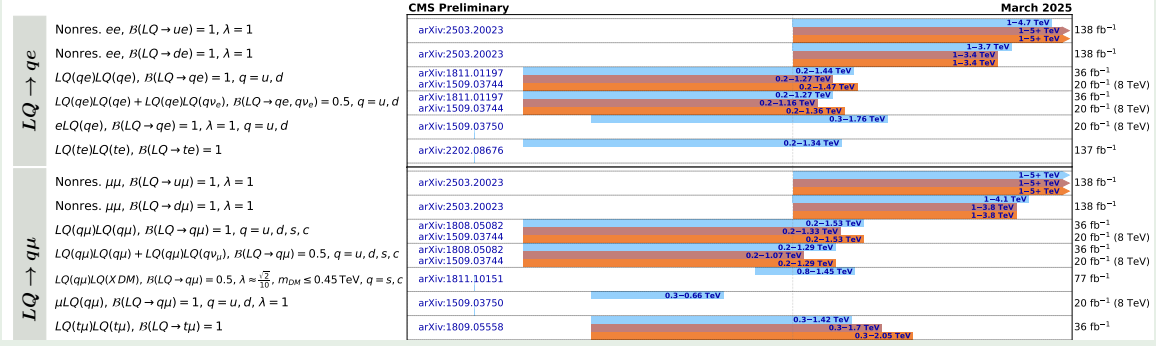
on behalf of
ATLAS and CMS Collaborations

MoriondEW2026 - La Thuile, Italy



Unexplained phenomena → Standard Model (SM) is not complete

- understand lepton and quark similarities, hierarchy problem, dark matter, ...



More ATLAS and CMS summary plots

Several beyond Standard Model (BSM) searches, focus here on ATLAS and CMS results for

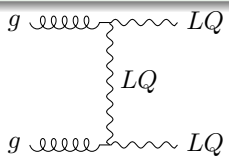
Leptoquarks (LQ), Vector-like quarks (VLQ) with $\mathscr{L} = 138$ fb^{-1} Run 2 pp@13 TeV data

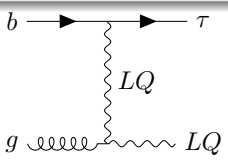
Leptoquarks

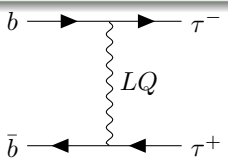
Explain similarities between lepton and quarks, predicted by several SM extensions:

- Composite models, GUT, technicolor, superstring, R-parity violating SUSY, ...

- Color-triplet scalar (spin-0) or vector (spin-1) bosons, fractional charge
- Carry both lepton and baryon number, decay in lepton and quark
- Single (qg fusion, ℓq collision) or pair production (gg fusion, $q\bar{q}$ annihilation), ...







Yukawa coupling at LQ-lepton-quark vertex: λ (using $\beta^{ij}_{L,R}$ to specify which involved q and ℓ)

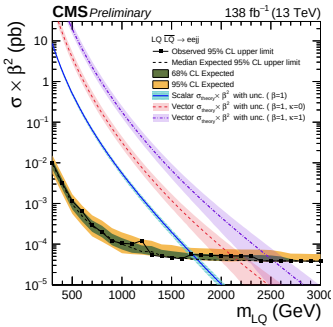
- Traditionally to a single lepton-quark generation; potential lepton universality violation
- Additional parameter κ, relating anomalous magnetic and electric quadrupole moment
- Considered coupling scenarios: minimal ($\kappa = 0$) and Yang-Mills ($\kappa = 1$)

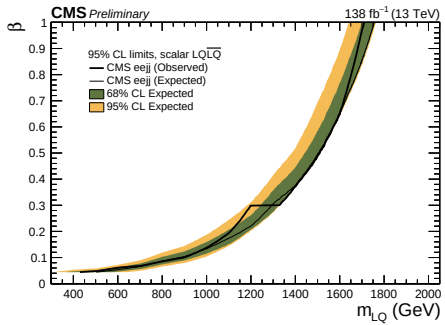
LQ pairs to electrons and jets - CMS-EXO-24-019

Pair production σ independent on λ value, dominating on single production for moderate λ

Event selection

- ≥ 2 e, ≥ 2 jets, $p_T > 50$ GeV, μ veto
- $m_{ee} > 50$ GeV, $p_T^{ee} > 70$ GeV
- $\Delta R(\ell j) > 0.3$, $S_T^{eejj} > 300$ GeV

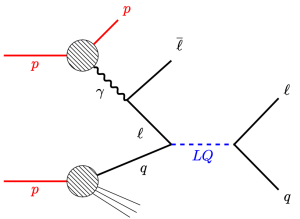




95% CL upper limits (constraining $LQ \to e^- q_{d,b}$ and $\overline{LQ} \to e^+ \bar{q}_{d,b}$, i.e., $\beta = 1$)

- Observed (Expected) limits on the $\sigma \times \beta^2$ vs LQ mass for several models
- $M_{LQ} < 1710$ (1755) GeV (decay to light quark), $M_{LQ} < 1700$ (1745) GeV (to b-quark)
- $M_{LQ} < 2110$ (2165) GeV (minimal scenario), $M_{LQ} < 2525$ (2525) GeV (Yang-Mills)

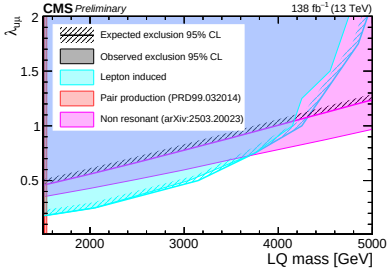
Scalar LQ via μ-scattering - CMS-PAS-EXO-24-005

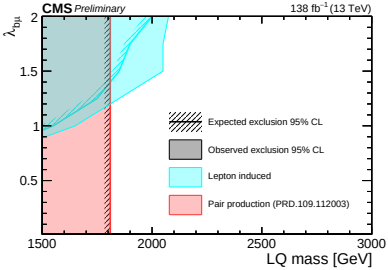


Event selection

- leading μ ($p_T > 55$ GeV) sub-lead μ ($p_T > 7$ GeV), e-veto
- leading jet or b-jet ($p_T > 100$ GeV), $0.6 < p_T^{\mu}/p_T^{j} < 1.6$
- $m_{\mu j} > 300$ GeV, $\Delta\phi(\mu, j) > 2.5$

Lepton-induced LQ production via photon PDF within proton





95% CL upper limits

- Explored muonic coupling w/ u and b quarks
- Limits on the coupling λ vs LQ mass
- Improved sensitivity for $M_{LQ} > 1.8$ TeV and $\lambda > 1$

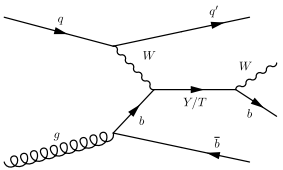
Vector-like quarks

- Cancel large fine-tuning corrections (2HDM, Little H, Composite H, extra dimensions)
- Appear in some SUSY models, stabilize electroweak vacuum, ...

- Color-triplet, spin-1/2 fermions, mass term in $\mathscr{L}$ independent of Yukawa couplings to H
- Under $SU(2)_L \times U(1)_Y$, left- and right-handed components transform identically
- Pair (single) production via strong (weak) interaction
- Single production dominating for $m_{VLQ} > 1$ TeV
  - Electroweak coupling strenght to boson: κ depends on m_{VLQ}, Γ_{VLQ}, multiplet

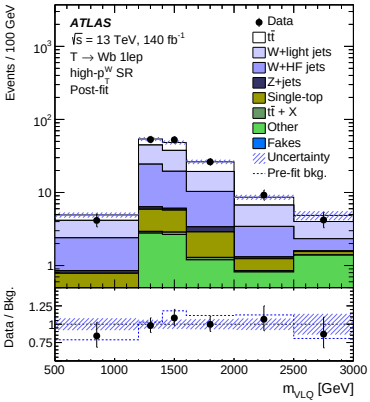
- Coupling predominantly to third-generation quarks to cancel H mass divergences
- $T(+2/3e)$, $B(-1/3e)$ in singlet, doublet or triplet w/ $X(5/3e)$, $Y(-4/3e)$
- Possible decays via charged and neutral current: $B \to bH$, bZ, tW, $T \to bW$, tH, tZ
  - $\mathscr{B}$ depends on multiplets, e.g. for high mass singlet T is $(bW : tH : tZ) = 2 : 1 : 1$

Single VLQ $T/Y \to Wb$ in 1-lepton channel - JHEP 12 (2025) 012



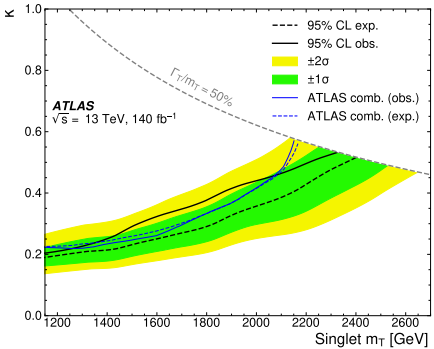
Requirement	Preselection
Leptons	1
Jets	≥ 2
Leading-jet p_{T} [GeV]	> 200
Leading-jet is central ($\lvert\eta\rvert < 2.5$)	Yes
Leading-jet is b-tagged	Yes
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	> 120
$\lvert\Delta\phi$(leading jet, $\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}})\rvert$	≥ 2

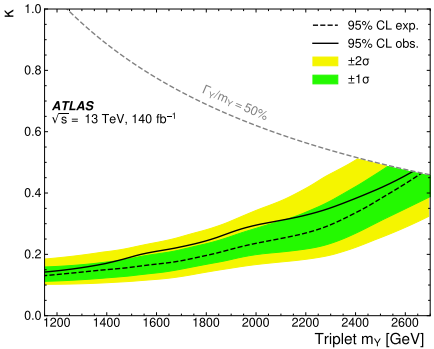
Requirement \ Region	SR	$t\bar{t}$ CR	$t\bar{t}$ VR	W+jets CR	W+jets VR1	W+jets VR2
b-tagged jets	≥ 1	≥ 2	≥ 1	1	1	1
Leading-jet p_{T} [GeV]	> 350	> 200	> 200	> 250	> 250	> 250
$\lvert\Delta\phi$(lepton, leading jet)$\rvert$	> 2.5	> 2.5	> 2.5	> 2.5	[1.5, 2.5]	[1.5, 2.5]
# additional hard central jets	0	0	≥ 1	-	-	-
# forward jets ($p_{\mathrm{T}} > 40$ GeV)	≥ 1	0	≥ 1	0	≥ 1	0



- Interference w/ SM background taken into account

Single VLQ $T/Y \to Wb$ in 1-lepton channel - JHEP 12 (2025) 012

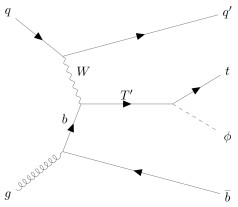




95% CL limit on coupling strength κ vs VLQ mass

- singlet: $\kappa \in [0.22, 0.52]$ for m_{VLQ} from 1150 to 2300 GeV
- triplet: $\kappa \in [0.14, 0.46]$ for m_{VLQ} from 1150 to 2600 GeV
- Complementary to the all-hadronic channel
- Extend mass coverage for ATLAS single-VLQ production limits

Single vector-like T' in final state w/ scalar - CMS-PAS-B2G-22-001

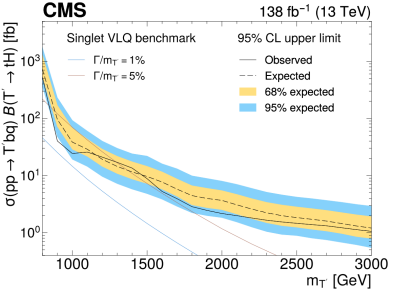


Event selection: $T' \to t\phi$, scalar $\phi \to b\bar{b}$, and $t \to Wb$ highly boosted

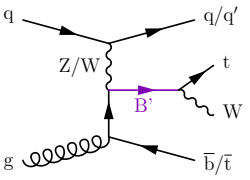
- Trigger on scalar $\sum p_T$ of all jets or single high-p_T jet
- ≥ 2 AK8 jets, large radius, high $p_T > 350$ GeV, back-to-back
- soft jet, $p_T > 50$ GeV, separated $|\Delta\phi| > \pi/2$, lepton-veto
- dynamic graph convolutional neural network tagger

95% CL upper limits on $\sigma \times \mathscr{B}(T' \to t(bq\bar{q}')\phi(b\bar{b}))$

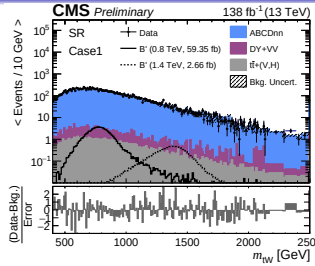
- Global combination with semileptonic channel
- for $\phi = H$:
  - for $1 < m_{T'} < 3$ TeV: 10-0.4 fb
  - for singlet T', $\Gamma/m_{T'} = 5\%$: excluded $0.85 < m_{T'} < 1.3$ TeV, most stringent for $m_{T'} > 2$ TeV
- for other m_ϕ: as low as 0.1 fb

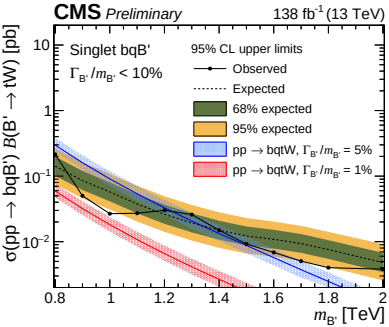


Single narrow vector-like $B' \to tW$ in 1-lepton - CMS-PAS-B2G-24-013



- ≥ 1, $p_T > 200$ GeV large-radius jet
- ≥ 1 small-radius jet, $\sum p_T > 250$ GeV
- $= 1e, \mu$ $p_T > 55$ GeV, $|\Delta R(\ell, j)| > \pi/2$
- $E_T^{\text{miss}} > 60$ GeV, $m_T^W < 200$ GeV

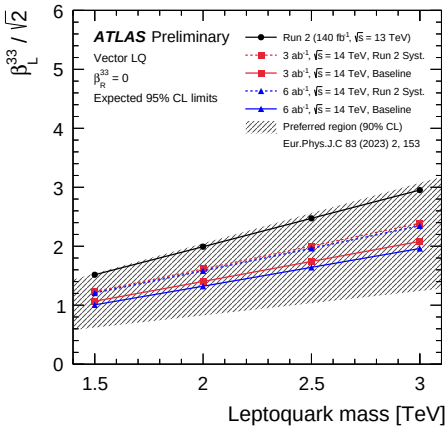


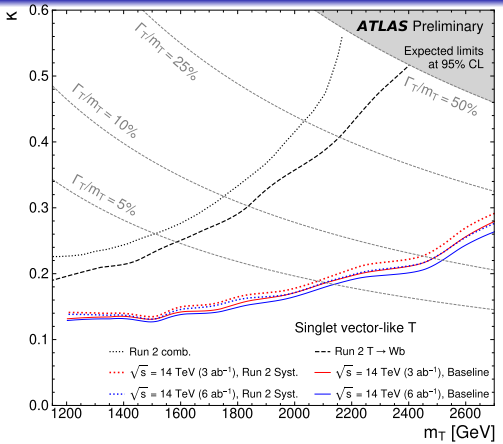


95% CL limits

- for bqB', singlet, $\Gamma/m_{B'} = 5\%$:
  - excl. $m_{B'} < 1.23$ TeV
  - for $m_{B'} \in [0.8 - 1.8]$TeV, excl. $\kappa > 0.30$
- for tqB', singlet (doublet), $\Gamma/m_{B'} = 5\%$ (1%):
  - excl. $m_{B'} < 1$ TeV
  - for singlet $m_{B'} \in [0.8 - 1.2]$TeV, excl. $\kappa > 0.41$
  - for doublet $m_{B'} \in [0.8 - 2.0]$TeV, excl. $\kappa > 0.29$

HL-LHC extrapolation of LQ and VLQ searches - ATL-PHYS-PUB-2025-040





Projected limit sensitivities for 3 ab^{-1} (ATLAS only) and 6 ab^{-1} (ATLAS and CMS comb)

- LQ β_L^{33} improves by 30% (20%), 40% (20%) in baseline (Run 2 syst.) scenario
- VLQ κ improves by 30% at 1.2 TeV and 60% at 2.3 TeV

ATLAS and CMS searches in Run 2 data ($\sim$ 140 fb^{-1}): LQ, VLQ

95% CL limit on LQ pair and single production

- Observed (Expected) limits on the $\sigma \times \beta^2$ vs LQ mass for several models
  - $M_{LQ} < 1710$ (1755) GeV (light), $M_{LQ} < 1700$ (1745) GeV (b)
  - $M_{LQ} < 2110$ (2165) GeV (minimal), $M_{LQ} < 2525$ (2525) GeV Yang-Mills scenario
- Upper limits on coupling λ vs LQ mass, probed high β_L^{23} region
- Explored μ coupling w/ u and b quarks, improved for $M_{LQ} > 1.8$ TeV and $\lambda > 1$

95% CL limit on VLQ single production

- singlet (triplet): $\kappa \in [0.22, 0.52]$ ([0.14, 0.46]) for m_{VLQ} from 1150 to 2300 (2600) GeV
- limits on $\sigma \times \mathscr{B}(T' \to t\phi)$ and on narrow vector-like $B' \to tW$ mass and coupling
- limits on $m_T < 1.40$ (1.56) TeV singlet (doublet), < 1.66 TeV ($\mathscr{B}(T \to Ht) = 100\%$)

Conclusion and perspectives

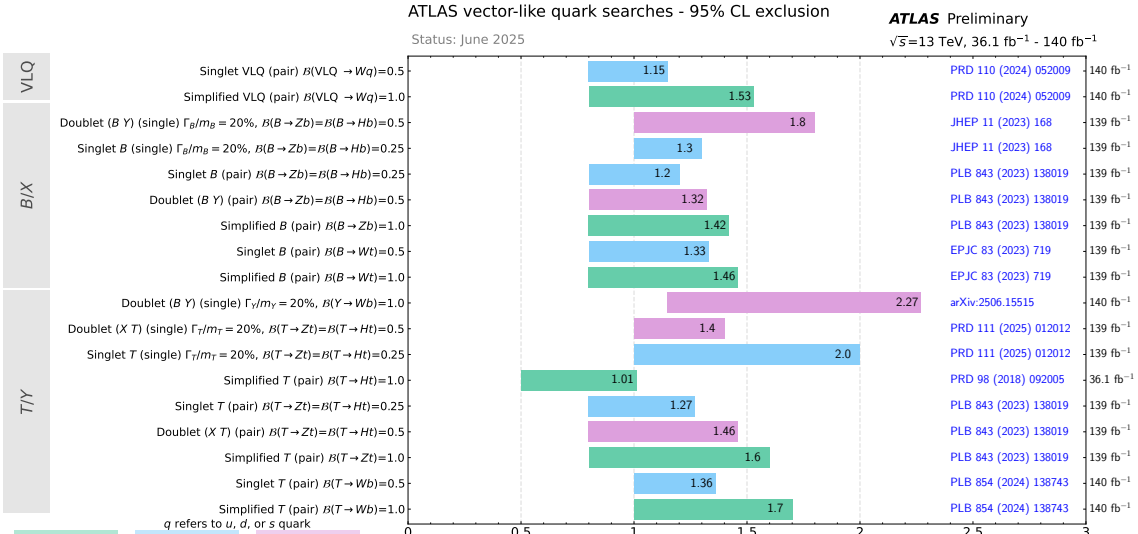
Projected limit sensitivities for 3 ab^{-1} (ATLAS only) and 6 ab^{-1} (ATLAS and CMS comb)

- LQ β_L^{33} improves by 30% (20%), 40% (20%) in baseline (Run 2 syst.) scenario
- VLQ κ improves by 30% at 1.2 TeV and 60% at 2.3 TeV

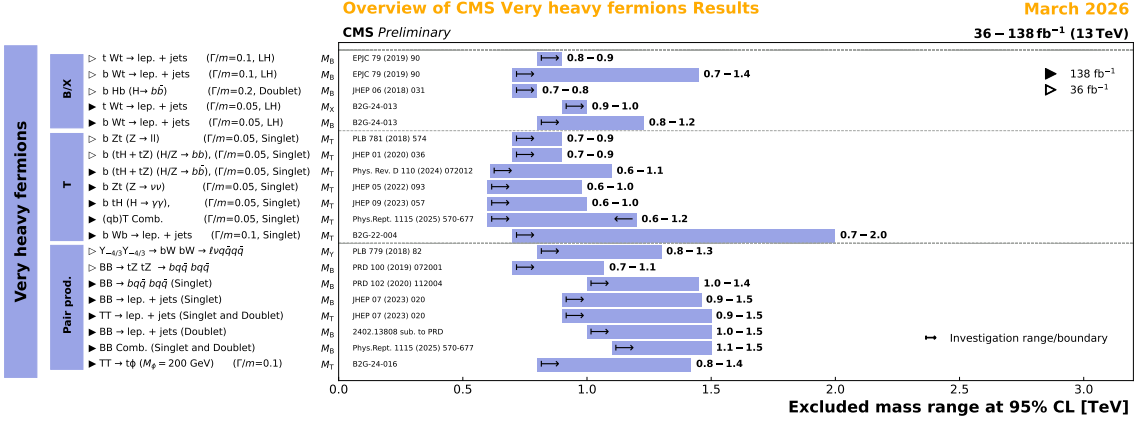
- Large Run 3 dataset provides ample opportunities for VLQ searches
- Impressive amount of new results produced by ATLAS and CMS on this topic
- Several LQ/VLQ analyses are currently in preparation

$\rightarrow$ **Stay tuned!**

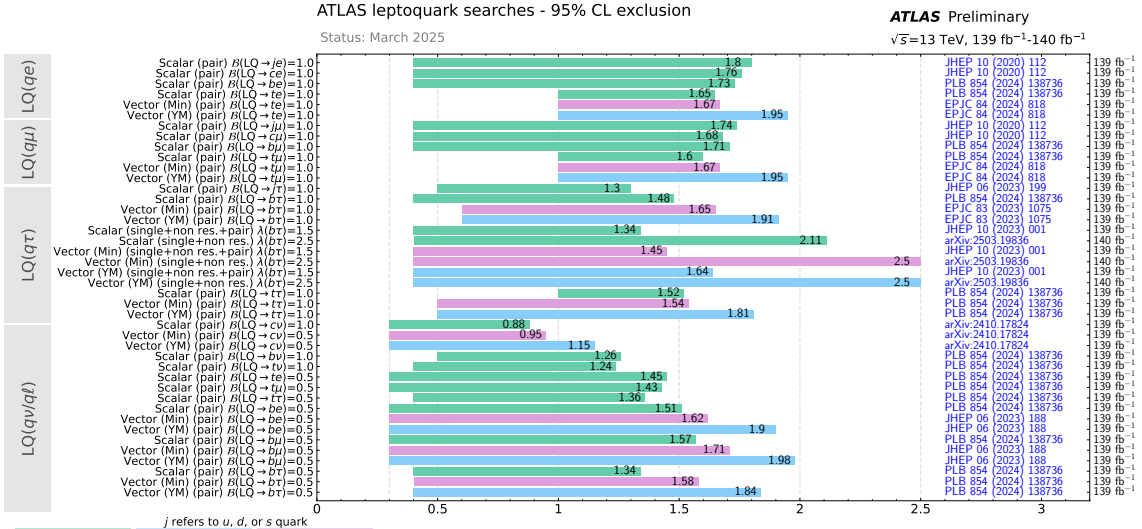
Vector-like quarks ATLAS results summary



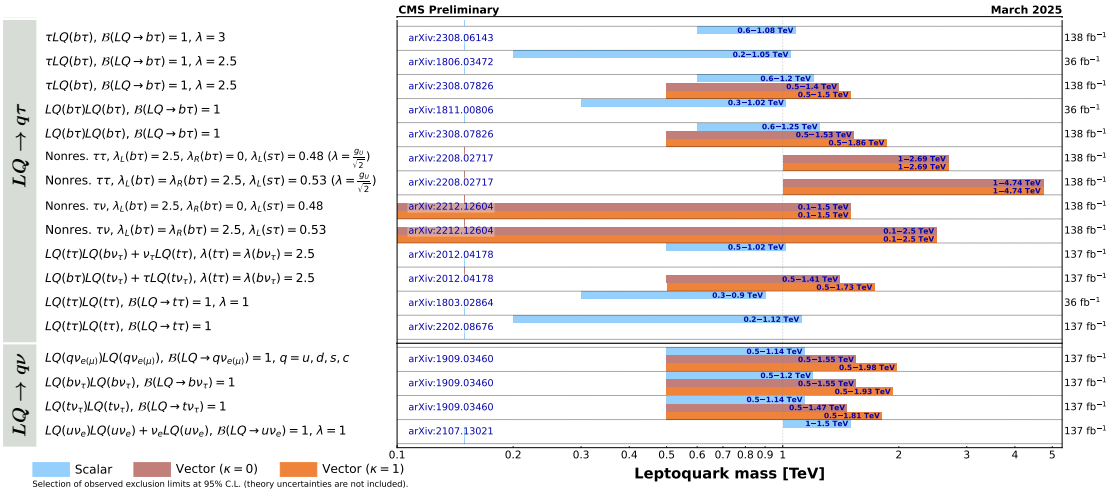
Vector-like quarks CMS results summary



Leptoquarks ATLAS results summary



Leptoquarks CMS results summary



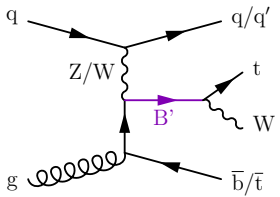
Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included).

References

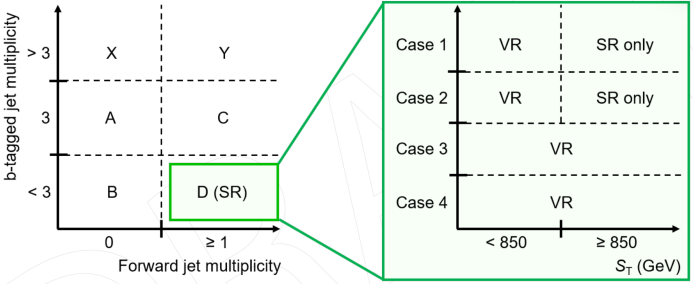
- "Search for single production of vector-like quarks decaying into $W(\ell\nu)b$ in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector" - JHEP 12 (2025) 012
- "Projected sensitivity for non-resonant production of vector leptoquarks and single production of vector-like T quarks in final states with b-jets with the ATLAS experiment at the HL-LHC " - ATL-PHYS-PUB-2025-040
- Search for pair production of leptoquarks decaying to electrons and quarks in proton-proton collisions a $\sqrt{s} = 13$ TeV - CMS-EXO-24-019
- Search for scalar leptoquarks produced via muon-quark scattering in pp collisions at $\sqrt{s} = 13$ TeV - CMS-PAS-EXO-24-005
- A search for a heavy resonance decaying to a top quark and a new scalar in the boosted all-hadronic final state at $\sqrt{s} = 13$ TeV - CMS-PAS-B2G-22-001
- Search for single production of a vector-like B' quark decaying to tW in the single-lepton final state - CMS-PAS-B2G-24-013

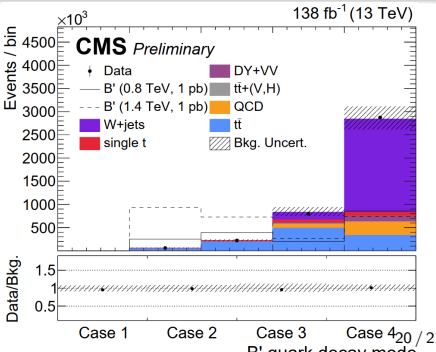
Backup

Single narrow vector-like $B' \to tW$ in 1-lepton - CMS-PAS-B2G-24-013

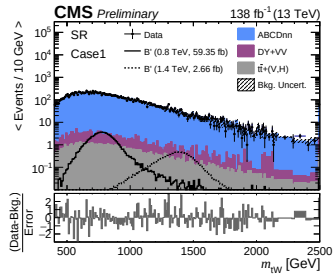


- ≥ 1 small-radius jet, $\sum p_T > 250$ GeV, b-tag 98% w.p.
- $= 1e, \mu$ $p_T > 55$ GeV, $|\Delta R(\ell, j)| > 0.4$
- ≥ 1, $p_T > 200$ GeV large-radius jet, $|\Delta R(\ell, j)| > \pi/2$
  - Case 1: t-tagged, Case 2: W-tagged, Case 3-4: not tagged
- $p_T^{\text{miss}} > 60$ GeV, $m_T^W < 200$ GeV, $S_T = \sum(p_T^j, p_T^\ell, p_T^{\text{miss}})$

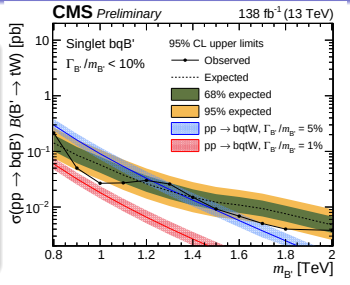




Single narrow vector-like $B' \to tW$ in 1-lepton - CMS-PAS-B2G-24-013



- Neural network ABCDnn method
- Learn transfer factor from 5 CR
- Apply to SR to get bkgd prediction



95% CL limits

- for bqB', singlet, $\Gamma/m_{B'} = 5\%$:
  - excl. $m_{B'} < 1.23$ TeV
  - for $m_{B'} \in [0.8 - 1.8]$TeV, excl. $\kappa > 0.30$
- for tqB', singlet (doublet), $\Gamma/m_{B'} = 5\%$ (1%):
  - excl. $m_{B'} < 1$ TeV
  - for singlet $m_{B'} \in [0.8 - 1.2]$TeV, excl. $\kappa > 0.41$
  - for doublet $m_{B'} \in [0.8 - 2.0]$TeV, excl. $\kappa > 0.29$