



中國科学院為能物現為完備 Institute of High Energy Physics Chinese Academy of Sciences



Search for vector-like quark and leptoquarks at CMS

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Search for Vector-like quark



Introduction



- The discovery of Higgs boson motivates search for new physics
- Possible extensions given by: little Higgs models, extra dimensions models, composite Higgs models
- These theories predict existence of heavy vector-like quarks (VLQ)
- We will search for single produced VLQ T decaying in top quark + Z boson in dineutrino channel





Signal region



- MET $p_T > 200GeV$ (to be in the trigger turn-on)
- $Min(\Delta \phi_{MET,jets}) > 0.6$ (to remove QCD events)
- Veto muons and electrons (to be closer to signal region)



≻6 categories in total

=0 or >=1 forward jets, resolved or partially merged or fully merged

Final discriminating variable: transverse mass M_T $M_T = \sqrt{2p_T^{top} \cdot p_T^{MET} (1 - cos\Delta\phi)}$ between top and MET



Background Estimation



- Main Background: Z+jets, W+jets, ttbar
- Using Data-driven method to get correction factors from control region in data

Control regions for the main backgrounds are defined as:

➢Resolved category

Variable	SR	Z+jets CR	W+jets CR	ttbar CR
lepton	veto	veto	>=1	>=1
Number of midum b jet	>=1	=0	=0	>=1

Partially merged category

Variable	SR	ttbar CR
minΦ(MET,jet)	> 0.6	< 0.6

Fully merged category

Variable	SR	W/Z+jets CR	ttbar CR
Leotpn	veto	veto	1 loose muon or electron
minΦ(MET,jet)	> 0.6	> 0.6	No cut
Top jet	1 b-subjet	0 b-subjet	1 b-subjet



M_T [GeV]

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Background estimation test





Comparison of data and the predicted background(resolved)



Systematics



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Source	Effect(%)	Туре	
Luminosity	1.8	rate	
Pileup	0.2-3	rate	
b-tagging	0.5-1.2	rate	
Top tagging	9-10	rate, shape	
W tagging	7-8	rate, shape	
Trigger efficiency	1-3	rate, shape	
Prefiring	0.2-3	rate, shape	
JES	2-18	rate, shape	
JER	2-5	rate, shape	
PDF	1-5	rate	
μ_F 和 μ_R	8-13	rate, shape	
Background scale factors	5-30	rate, shape	

The dominant systematics are: top tagging, W tagging, $\mu_{R},\,\mu_{F},\,background\,SF$



Results-Resolved topology





- Distribution of the transverse mass in the signal region (the boosted result see here)
- All background processes and the respective uncertainties are derived from the fit to data



Results-limit



95% confidence level(CL) exclusion limits on the production cross section of T' times BR



- Narrow width resonance: Cross section : greater than 602–15 fb. Masses: below 0.98TeV
- 10-30% width resonance : Cross section : greater than 836–16 fb Masses: below 1.4TeV
- 2D limit: The hashed red line indicates the boundary of the excluded region





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Search for leptoquark



Motivation



Several BSM ideas foresee new bosons that carry both lepton and baryon number

Can SU(3)×SU(2)×U(1) originate from a larger symmetry group? \rightarrow Grand Unified Theory

Can fermions be made of more fundamental objects?

 \rightarrow Compositeness

Can a symmetry exist between fermions and bosons?

 $\rightarrow \mathsf{Supersymmetry}$

Bound states of fundamental

 \rightarrow $% \left({{\rm constituents}} \right)$ constituents may decay to a quark and a lepton

Possible decay of sparticles to a quark \rightarrow and a lepton (see e.g. R-parity violation scenario)

- Searches for leptoquarks (LQ) are well-motivated at the LHC
- Recent enhanced interest for LQ as a possible candidate to explain some anomalies in B-physics precision measurements



LQ relevant experimental features

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- 2 production mechanisms considered(you can find them in paper here and here):



• Parameters determining the cross section(you can find paper <u>here</u> and <u>here</u>):

	Pair		Single
Scalar: LQ_s	LQ mass	Lambda (λ)	(coupling of SM lepton-quark to LQ)
Vector: LQ_v	k dimensionless coupling		Lambda (λ) ,k
	k=0 minimal co	oupling	
	k=1 Yang-Mills		

Decay channel (you can find paper <u>here</u> and <u>here</u>):
 LQs->top tau or LQs->bottom nu
 LQv->bottom tau or LQv->top nu



Signal region



- (top tau nu bottom) + (top tau nu) selection
- P_T^{miss}>=200GeV, H_T^{miss}>=200GeV(= magnitude of the sum of pT of the AK4 jet)
- H_T >=300GeV ((H_T = scalar sum of the pT of all AK4 jets)
- 0 electron and muon
- 1 tauh
- massT(tau,P_T^{miss})>=300GeV
- >= 1 top candidate
 - Fully merged topology(1 merged top quark)
 - Partially merged topology(1 merged W boson + 1 b-jet)
 - Resolved topology(2 AK4 jets + 1 b-jet)

≻4 categories in total

>=2b or = 1b, boosted or resolved

AK4 jet: anti-kt jet with radius = 0.4



Data vs SM expectation in the signal region





Catagory	Boo	sted	Resolved		
Category	$N_{\text{b-jet}} = 1$	$N_{\text{b-jet}} \ge 2$	$N_{b-jet} = 1$	$N_{\text{b-jet}} \ge 2$	
Misidentified $ au$	20.5 ± 2.1	14.4 ± 1.8	199 ± 13	170 ± 12	
t production	7.8 ± 2.1	8.2 ± 1.9	59 ± 5	127 ± 9	
Others	5.3 ± 2.0	1.6 ± 0.8	56 ± 25	23 ± 11	
Total bkg	34 ± 4	24.2 ± 2.7	314 ± 29	320 ± 19	
Data	39	25	332	316	
$LQ_V LQ_V k=1, M=1.7 \text{ TeV}$	4.6 ± 0.7	8.0 ± 1.2	3.1 ± 0.3	7.7 ± 0.7	
$\tau LQ_V k=1 \lambda=1.5$, M=1.4 TeV	5.5 ± 0.4	4.8 ± 0.4	5.03 ± 0.22	6.6 ± 0.3	
$\tau LQ_V k=0 \lambda=1.5, M=1.1 \text{ TeV}$	10.1 ± 0.7	8.6 ± 0.7	13.4 ± 0.6	16.4 ± 0.8	
$\nu LQ_S \lambda$ =1.5, M=0.5 TeV	13.5 ± 0.8	11.0 ± 0.8	52.7 ± 2.7	58 ± 3	

- Misidentified tau main background →estimated from data
- top production relevant
 →estimated normalizing MC to data
- Others not dominant →taken from simulation



Systematic uncertainties



Uncertainty	Background	Signal
Pileup	1-6%	1%
PDF	-	5%
Trigger	1-2%	1-2%
JES/JER	1-35%	2.5%
b-tag	3-10%	8-23%
Tauh scale	1-5%	1%
Tauh ID	5-13%	13-20%
W jet tag	2-11%	1-4%
top jet tag	3-15%	7-14%
Misidentified taus bkg	9-56%	-
Misidentified tau closure	12%	-
Luminosity	2.3-2.5%	2.3-2.5%
Background cross-section	5-30%	-



Exclusions for scalar LQ





- Scalar Pair LQ production does not depend from λ .
- LQsLQs: LQs masses below 0.95 (1.03) TeV are excluded
- vLQs : LQs masses below 0.55 (0.56) TeV and 0.75(0.81) TeV for λ of 1.5 and 2.5 are excluded.
- LQsLQs+vLQs : LQs masses below 0.98 (1.06) TeV and 1.02 (1.10) TeV for **λ** of 1.5 and 2.5 are excluded.



Exclusions for vector LQ(k=0)





- LQvLQv: LQv masses below 1.29 (1.39) TeV are excluded.
- *τ*LQv : LQv masses below 1.03 (1.12) TeV and 1.25(1.35) TeV for **λ** of 1.5 and 2.5 are excluded.
- LQvLQv+rLQv : LQv masses below 1.34 (1.46) TeV and 1.41 (1.54) TeV for λ of 1.5 and 2.5 are excluded.



Exclusions for vector LQ(k=1)



Single LQ

Pair + Single LQ



- LQvLQv: LQv masses below 1.65 (1.77) TeV are excluded.
- *τ*LQv : LQv masses below 1.20 (1.29) TeV and 1.41(1.53) TeV for **λ** of 1.5 and 2.5 are excluded.
- LQvLQv+rLQv: LQv masses below 1.69 (1.81) TeV and 1.73 (1.87) TeV for **λ** of 1.5 and 2.5 are excluded.



λ-Mass exclusion





- Values of λ up to 2.5 are constrained by electroweak precision measurements

• For LQv, the gray area(get from paper) shows the 95% CL band preferred by the B physics anomalies: $\lambda = \sqrt{0.7 \pm 0.2} \times m_{LQ}$ TeV. A relevant portion of this parameter space is excluded.



Summary



Study of single production of VLQ in tZ has been shown all Run2 data

	Cross section@95%CL	Mass@95%CL
Narrow width resonance	>602-15fb	<0.98TeV(5%)
10-30% width resonance	>836–16 fb	<1.4TeV(30%)

- This is first result of MET + jets final state in CMS
- This is the current best published result on single-VLQ T' in the tZ(vv) decay channel.
- The analysis has been published in PAS

>We have presented a search for for LQ produced singly and in pairs

	LQS		$LQ_V k = 0$		$LQ_V k = 1$	
Pair	0.95 (1.03)		1.29 (1.39)		1.65 (1.77)	
λ	1.5	2.5	1.5	2.5	1.5	2.5
Single	0.55 (0.56)	0.75 (0.81)	1.03 (1.12)	1.25 (1.35)	1.20 (1.29)	1.41 (1.53)
Pair+Single	0.98 (1.06)	1.02 (1.10)	1.34 (1.46)	1.41 (1.54)	1.69 (1.81)	1.73 (1.87)

- This is the first analysis consider the boosted topology.
- This is the first analysis study the single and pair production simultaneously to search leptoquark.
- This analysis has been published in PLB





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backup



Analysis strategy





Final discriminating variable: transverse mass ${\rm M_T}$ $M_T=\sqrt{2p_{\rm T}^{top}\cdot p_{\rm T}^{MET}\left(1-cos\Delta\phi\right)}$ between top and MET







≻Trigger

- HLT_PFMETNoMu120_PFMHTNoMu120_IDTight
- HLT_PFMET120_PFMHT120_IDTight

> Lepton

- Loose electron ID, pt > 30GeV
- Loose muon ID, pt >30GeV

> Jets

- CHS ak4 jets with jet pt > 30 GeV and passing the tight jet ID (2016 jet ID look here, 2017 look here and 2018 look here)
- PUPPI AK8 jets with pt > 200GeV
- DeepCSV b-tagger with medium WP for all Run2 data.
- $|\eta| < 2.4$ (or 2.4 < $|\eta| < 4.0$ for forward jets)

>MET

- MET pt > 200GeV
- 2016, 2017 and 2018 MET filters taken from here

≻W/top tagging

- W jet: PUPPI AK8 Jet, pt>200GeV, 65< SD mass < 105GeV, tau21DDT < 0.43
- Top jet: PUPPI AK8 Jet, pt > 400GeV, 105< SD mass< 220 GeV, tau32 < 0.65



Min DeltaPhi MET-jet





Remove QCD background



Scale factor







Background estimation test





Comparison of data and the predicted background(merged)

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Background estimation : SF extraction



We extract bin-by-bin SFs on backgrounds.

For **background X** (e.g. yellow ZJets here) In control region **CR** vs signal region (**SR**):

1) subtract all non-X background

2) SF_CR= (Data-nonX)/X_CR

3) X_SR = X_MC_SR * SF_CR





Results – Partially merged topology







Results – Fully merged topology







Status of B-physics anomalies



Courtesy of Andreas Hoecker LHCP2020 Experimental highlights

Status of flavour anomalies:

$$R_{D^{(*)}} = \frac{B(B \to D^{(*)}\tau\nu)}{B(B \to D^{(*)}\ell\nu)}$$

Possible new physics in charged current in tree diagram

Tension reduced after 2019 Belle result ${\scriptstyle [1904.08794]}$ in agreement with SM

Remaining tension (HFLAV): 3.1 σ Corresponding $R_{J/\psi|\tau/\mu} \sim 2\sigma$ above SM [LHCb: 1711.05623]

 $R_{K^{(*)}} = \frac{B(B \to K^{(*)}\mu\mu)}{B(B \to K^{(*)}ee)} \stackrel{[SM]}{\cong} 1$

Experiments measure double ratio involving ${\rm J}/\psi$

 R_{K} : LHCb most precise, Run-2 ~SM, combination with Run-1: 2.5 σ < SM

 R_{K^*} : LHCb (most precise) low (2.3~2.5
ơ) at low q²

New results by LHCb:

$$R_{pK} = \frac{B(\Lambda_b^0 \to pK^-\mu\mu)}{B(\Lambda_b^0 \to pK^-ee)} \stackrel{[SM]}{\cong} 1$$

LHCb measures double ratios to ${\mathsf J}/\psi$

Result: $R_{pK} = 0.86^{+0.14}_{-0.11} \pm 0.05$ in agreement with SM (but also lower)



$B \rightarrow K^* \mu \mu$ angular analysis

New result from LHCb with 4.7 fb⁻¹ (Run 1 + 2016 data)



Full fit to all angular observables

Global fit by LHCb to SM model varying $Re(C_9)$ only gives 3.3σ discrepancy

- No firm conclusion, need more data!
- Possible to clarify anomalies within timescale of Phase 2((arXiv:1709.10308))



RK. RK*

B-physics anomalies and LQ





- Upper limit on new physics scale: 9 (80) TeV for $b \rightarrow clv$ ($b \rightarrow sll$) transition (arXiv:1706.01868)
- Couplings to 2nd, 3rd fermion generation favored
- LQ_s (LQ_v) \rightarrow t tau (t v), b nu (b tau) strong candidate to explain the anomalies arXiv:1808.02063 (arXiv:1706.07808)

Decay BR of 0.5 preferred case to explain the anomalies

 \rightarrow t tau nu b has x2 BR w.r.t. existing searches ttnunu (SUS-19-005) and bbtautau (EXO-17-016)



Leptoquark decay channel



• Decay branching ratio of 0.5 to each leptonquark





- Final states top tau nu bottom (pair LQ) and top tau nu (single LQ) \rightarrow 2 categories of events >= 2 b or = 1 b
- Fully hadronic decay of the top quark and tau lepton
- Top reconstruction



• ST = tauh p_T + top p_T + p_T^{miss} used for the signal extraction





jet->tau misidentification background estimation method

- **Tight-to-loose ratio** used to estimate **fake tau events** (QCD, ttbar, Wjets, etc, without genuine taus)
- FR is the probability that a VLoose tau has to pass the Medium ID

 $FR = \frac{N_{Medium}}{N_{VLoose}}$, measured in a control region

• From number of events passing VLoose but not the Medium ID, $N_{VL,!M}$, estimate number of predicted events in the signal region with fake tau:

 $N_{fake\,tau}^{SR} = \sum_{pt,eta} N_{VL,!M}(pt,eta) \cdot \frac{FR(pt,eta)}{[1 - FR(pt,eta)]}$

Top background

- Normalize MC to data in signal-free region
 - massT(tauh,p_T^{miss}) < 80 GeV
 - N b-jet >= 2
- MC Scaled by 10%