Searches for Leptoquarks and Compositeness at CMS

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Introduction

Several CMS searches for leptoquarks and compositeness with pp data collected at 13 TeV at the LHC shown here:

- **First** and second generation leptoquarks (2.6, 2.7 fb$^{-1}$)
- Third generation leptoquarks (as part of $W_R$ search) in two channels, including $\tau_{\text{had}}\tau_{\text{had}}bb$ and $\tau_{\text{had}}\ell bb$ channel (2.1, 12.9 fb$^{-1}$)
- **Excited leptons** (2.7 fb$^{-1}$)

**Excited quarks** presented in separate talk on multijets (S. Bhattacharya)

Three new results for ICHEP2016 in this talk [green]

CMS Detector

- **Tracker**
- **ECAL**
- **HCAL**
- **Iron yoke**
- **Muon chambers**

**Specifications**

- **Weight**: 14,000 t
- **Diameter**: 15 m
- **Length**: 21.6 m
- **Magnetic field**: 3.8 T

**Diagram Details**

- 3.8 T solenoid
- Weight: 14,000 t
- Diameter: 15 m
- Length: 21.6 m
- Magnetic field: 3.8 T
Leptoquarks: Theory in brief

- New symmetry between quarks and leptons. Some beyond the SM models predict leptoquarks arising from this symmetry (Pati-Salam, GUTs, technicolor, etc.)

- Leptoquark (LQ): boson coupling to both quarks and leptons (carries baryon and lepton numbers) and fractional electric charge. Concentrating on scalar case.

- Consider pair-produced particles: Dominant gg production mode at LHC is virtually independent of the lepton/quark/LQ coupling strength.

- Separate analysis by lepton generation: FCNC constraints imply no intergenerational mixing

- Branching ratio $LQ \to \ell q$ is treated as free parameter $\beta$

- Final states covered in this talk:
  - $1^{st}/2^{nd}$ generation: $\ell j + \bar{\ell} j$, for $\ell = e, \mu$
  - $3^{rd}$ generation: $\tau_{had} b \ell b$ for $\ell = e, \mu$; $\tau_{had} b + \tau_{had} \bar{b}$
LQ 1\textsuperscript{st} and 2\textsuperscript{nd} generation analysis overview

2 high $p_T$ leptons and 2 high $p_T$ jets are a striking signature

Use single electron or muon trigger

- 2 isolated high-$p_T$ leptons ($p_T > 50$ GeV)
- 2+ high-$p_T$ jets ($p_T > 50$ GeV)
- Final selection variables:
  - $S_T = \Sigma p_T(\ell, j)$ for $\ell 1, \ell 2, j1, j2$
  - $M_{\text{min}}(\ell j)$
  - $M(\ell \ell)$
- Minimal $S_T$ requirement (300 GeV)
- Validate backgrounds vs. data at preselection
- Optimize final selections as a function of LQ mass

Backgrounds:
Z+Jets: MC shape, normalized in Z peak
TTbar+Jets: $e\mu jj$ data-driven shape/normalization (LQ2); MC normalized to $e\mu jj$ data (LQ1)
QCD Multijets (LQ1: data-driven fake rate)
Others: Diboson, single top, etc.: MC
Good data/MC agreement observed at preselection

CMS EXO-16-007

LQ $1^{\text{st}}/2^{\text{nd}}$ generation

CMS EXO-16-043

New for ICHEP2016

Preliminary $2.6 \, \text{fb}^{-1}$ (13 TeV)

Preliminary $2.7 \, \text{fb}^{-1}$ (13 TeV)

Systematic Uncertainties
LQ 1\textsuperscript{st} / 2\textsuperscript{nd} gen. results

1\textsuperscript{st} generation LQ mass limit is set at 1130 GeV for $\beta=1$

- Previous CMS: 1010 GeV (8 TeV, 19.7 fb$^{-1}$); ATLAS 1100 GeV (13 TeV, 3.2 fb$^{-1}$)

2\textsuperscript{nd} generation LQ mass limit is set at 1165 GeV for $\beta=1$

- Previous CMS: 1080 GeV (8 TeV, 19.7 fb$^{-1}$); ATLAS 1050 GeV (13 TeV, 3.2 fb$^{-1}$)
$W_R/LQ$ 3$^{rd}$ generation

Left-Right Symmetric standard model

- Heavy right-handed neutrinos and right-handed $W_R$

Also sensitive to scalar leptoquarks decaying to $\tau\tau bb$

Require:

- 1 (or 2) isolated $\tau_{\text{had}}$, high $p_T$ (50-70 GeV)
- 2 high $p_T$ jets (50 GeV)
- $\tau$, jet $\ell$, jet $\tau, \ell$ spatial separation

Calculate $S_T(\tau, \tau,j,j,\text{MET})$
**Trigger:** double $\tau$

$M(\tau\tau) > 100$ GeV

$\text{MET} > 50$ GeV

Examine $S_T$, $m(\tau,\tau,j,j,MET)$

QCD multijet background dominates

- Data-driven ABCD method (MET, isolation of $\tau$)

Others (ttbar+jets, DY+jets, etc., via MC)
$W_R/$LQ 3$^\text{rd}$ generation: $\tau_{\text{had}}\tau_{\text{had}}bb$

Limit $M(LQ_3) > 740$ GeV

Limit $M(W_R) > 2.31$ TeV [$m(N\tau) = 0.5 \times m(W_R)$]
**W_R/LQ 3\textsuperscript{rd} generation: \(\tau_{\text{had}}\ell bb\)**

2016 pp data

\(\tau_{\text{had}}\ell bb\) channel

Trigger: single e/\(\mu\)

Require 1 b-tagged jet (LQ)

\(M(\tau_{\text{had}}j) > 250\) GeV (LQ)

MET > 50 GeV (\(W_R\))

\(M(\tau_{\text{had}},\ell) > 150\) GeV (\(W_R\))

**ttbar background dominates**

- MC, checked with e\(\mu\) data

Others (\(W+jets\), \(DY+jets\), QCD, etc., via MC)
Limit $M(LQ_3) > 900$ GeV

Limit $M(W_R) > 3.2$ TeV [$m(N\tau) = 0.5$ $m(W_R)$]
Compositeness: theory overview

As far as we know, quarks and leptons are elementary particles.

But if they in fact have substructure, it could help answer some open questions in the standard model, such as the mass hierarchy of quarks and leptons.

Constituents known as preons, bounded by a new strong gauge interaction of scale $\Lambda$ (Pati and Salam)

Can lead to production of excited quarks and leptons

- Direct evidence of compositeness

Known $\ell$, $q$: ground states

Flavor shared with SM particle

Look in $\ell\ell\gamma$ final state

\[ \mathcal{L}_{CI} = \frac{g^*2}{2\Lambda^2} j^\mu j_\mu \]

where $g^*2$ is chosen to be $4\pi$, $\Lambda$ is the compositeness scale, and $j^\mu$ is the fermion current.
Excited leptons: analysis overview

CMS EXO-16-009
New for ICHEP2016

- Use double electron or double muon trigger
- Select photon
- Impose photon/lepton separation $\Delta R > 0.7$
- Veto Z peak: $M(\ell\ell) > 116$ GeV
- Two highest-$p_T$ leptons paired with photon: $M_{\ell\gamma}$ min, max

- Background: DY, diboson, ttbar+jets
  - Data-driven QCD jet background, misidentified photon from MC (checked with data)
Excited leptons: analysis overview

CMS EXO-16-009
New for ICHEP2016

Signal forms an “L” shape in $M_{\ell\gamma}$ min vs. max

- Create signal region from 2-D regions
Excited leptons: results

Search windows defined in $M_\gamma \text{ min, max}$

Limits on cross-section($\times$)branching ratio for excited leptons

$M(e^*) > 2.8 \text{ TeV}$ (electron)

$M(\mu^*) > 3.0 \text{ TeV}$ (muon)

(8 TeV CMS mass limit: 2.5 TeV)

Also limits on $\Lambda$ itself:

$\Lambda > 15 \text{ TeV}$
Summary

Wide range of CMS results on 2015 and 2016 data from leptoquark and compositeness searches

• Leptoquark searches extend previous LHC Run I limits with 2015 data (1st gen., 2nd gen.)
• LQ3 in two channels also extend previous limits, with the \( \tau_{\text{had}} \ell bb \) channel results using 2016 data
• Excited lepton results extend limits on the compositeness scale to \(~15\) TeV

Overall, 3 new results for ICHEP2016 [green] presented here

Expect results with 2016 data from all analyses
Backup
Optimized Thresholds (LQ2)

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