Z’ and leptoquark searches at the LHC

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Introduction to the LHC

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Introduction to $Z'$

- $Z'$ is a new gauge boson which is predicted in many models.
- Sequential Standard model ($Z'_{SSM}$), E6-motivated Grand Unification model ($Z'_{\psi}$ and $Z'_{\chi}$) and Dark-Matter Mediator model ($Z'_{DM}$).
- Include hadronic decay and leptonic decay.
- Leptonic decay with both same flavor and different flavor lepton pairs.
- Searches in different channels are performed.
List of Z’ searches

- ee and mumu channel:
  - CMS: 13 TeV 36 fb⁻¹ *JHEP06(2018)120*

- tautau channel:
  - ATLAS: 13 TeV 36.1 fb⁻¹ *JHEP01(2018)055*

- emu, etau and mutau channel:
  - ATLAS: 13 TeV 36.1 fb⁻¹ *PHYSICAL REVIEW D 98, 092008 (2018)*
  - CMS (only emu): 13 TeV 35.9 fb⁻¹ *JHEP04(2018)073*

- dijet:
  - ATLAS: 13 TeV 139 fb⁻¹ *JHEP03(2020)145*
  - CMS: 13 TeV 137fb⁻¹ *JHEP05(2020)033*
  - ATLAS: dijet+lepton 13 TeV 139fb⁻¹ *submitted to JHEP*

- other channels:
  - ATLAS: ttbar 13 TeV 139 fb⁻¹ *submitted to JHEP*
Several improvements compare with $36.1 \, fb^{-1}$:
- Higher luminosity
- The reconstruction software
- The first time of using data-driven fit.

Event selection:
- $M_{ll} > 225 \, GeV$
- ee channel: Two electrons.
- $\mu\mu$ channel: Two muons with opposite charge.

New background estimation method: data-driven fit

Fit function:

$$ f_{ll}(m_{ll}) = f_{llwZ}(m_{ll}) \cdot (1 - x^b) \cdot x^3 \sum_{i=0}^{3} p_i \log(x)^i $$

<table>
<thead>
<tr>
<th>Model</th>
<th>Lower limits on $m_{Z'}$ [TeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ee</td>
<td>exp</td>
</tr>
<tr>
<td>$Z'_e$</td>
<td>4.1</td>
</tr>
<tr>
<td>$Z'_\mu$</td>
<td>4.6</td>
</tr>
<tr>
<td>$Z'_{3SM}$</td>
<td>4.9</td>
</tr>
</tbody>
</table>

$\sqrt{s} = 13 \, TeV, 139 \, fb^{-1}$
Z’ to dielectron/dimuon @CMS

Dielectron Invariant Mass of CMS result

Dimuon Invariant Mass of CMS result

<table>
<thead>
<tr>
<th>Channel</th>
<th>$Z'_{SSM}$ Obs. [TeV]</th>
<th>$Z'_{SSM}$ Exp. [TeV]</th>
<th>$Z'_{\psi}$ Obs. [TeV]</th>
<th>$Z'_{\psi}$ Exp. [TeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$ee$</td>
<td>4.10</td>
<td>4.10</td>
<td>3.45</td>
<td>3.45</td>
</tr>
<tr>
<td>$\mu^+\mu^-$</td>
<td>4.25</td>
<td>4.25</td>
<td>3.70</td>
<td>3.70</td>
</tr>
<tr>
<td>$ee + \mu^+\mu^-$</td>
<td>4.50</td>
<td>4.50</td>
<td>3.90</td>
<td>3.90</td>
</tr>
</tbody>
</table>
Z’ to tautau @ATLAS 36.1 fb⁻¹

- Two channels:
  - $\tau_{\text{lep}}\tau_{\text{had}}$: At least one $\tau_{\text{had-vis}}$ and exactly one lepton, $m_T(\text{lep}, E_T^{\text{miss}}) < 40 \text{ GeV}$
  - $\tau_{\text{had}}\tau_{\text{had}}$: At least two $\tau_{\text{had-vis}}$, no electrons or muons, $|\Delta\Phi(\tau_1, \tau_2)| > 2.7$

- Mass definition:

$$m_T^{\text{tot}} = \sqrt{(p_T^1 + p_T^2 + E_T^{\text{miss}})^2 - (p_T^1 + p_T^2 + E_T^{\text{miss}})^2}$$

The latest CMS Z’$\rightarrow$tautau:13 TeV 2.2 fb⁻¹, JHEP02(2017)048
Z’ to dilepton with different flavor @ATLAS $36.1 \text{ fb}^{-1}$

- Include $e\mu, e\tau, \mu\tau$ channels.
- Data-driven method for fake lepton background.
- Hadronic decay of $\tau$-leptons.
- Only events with exactly 2 different-flavor leptons.
- Only $\mu\mu$ channel
- Four events observed in the region $m_{\mu\mu} > 1.5$ TeV
- Lower limits for $Z'$: 4.4 TeV

Z’ to emu @CMS 35.9 fb⁻¹
Z’ to dijet @ATLAS \(139 \text{ fb}^{-1}\)

- Data-driven fit used in background estimation.
- New b-tagging algorithm: DL1r b-tagging
- Event selection category:

<table>
<thead>
<tr>
<th>Category</th>
<th>Inclusive</th>
<th>1b</th>
<th>2b</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jet (p_T)</td>
<td>(&gt; 150 \text{ GeV})</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jet (\phi)</td>
<td>(</td>
<td>\Delta\phi(jj)</td>
<td>&gt; 1.0)</td>
</tr>
<tr>
<td>Jet (</td>
<td>\eta</td>
<td>)</td>
<td>(&lt; 2.0)</td>
</tr>
<tr>
<td>(</td>
<td>y^*</td>
<td>)</td>
<td>(&lt; 0.6)</td>
</tr>
<tr>
<td>(m_{jj})</td>
<td>(&gt; 1100 \text{ GeV})</td>
<td>(&gt; 1717 \text{ GeV})</td>
<td>(&gt; 1133 \text{ GeV})</td>
</tr>
</tbody>
</table>

- 2.9 TeV

- DM mediator \(Z'\)
- \(W^*\)
- \(q^*\)
- QBII

Generic Gaussian

- \(b^*\)
- Generic Gaussian

DM mediator \(Z'\) (\(bb\))
SSM \(Z'\) (\(bb\))
Graviton (\(bb\))

Generic Gaussian
Z’ to dijet @CMS \[137 \text{ fb}^{-1}\]

Data-driven fit used in background estimation.

<table>
<thead>
<tr>
<th>Model</th>
<th>Final state</th>
<th>Observed (expected) mass limit [TeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>String</td>
<td>qg</td>
<td>7.9 (8.1)</td>
</tr>
<tr>
<td>Scalar diquark</td>
<td>qq</td>
<td>7.5 (7.9)</td>
</tr>
<tr>
<td>Axigloun/coloron</td>
<td>qq</td>
<td>6.6 (6.4)</td>
</tr>
<tr>
<td>Excited quark</td>
<td>qg</td>
<td>6.3 (6.2)</td>
</tr>
<tr>
<td>Color-octet scalar (k^2_s = 1/2)</td>
<td>gg</td>
<td>3.7 (3.9)</td>
</tr>
<tr>
<td>(W') SM-like</td>
<td>q(\bar{q})</td>
<td>3.6 (3.9)</td>
</tr>
<tr>
<td>(Z') SM-like</td>
<td>q(\bar{q})</td>
<td>2.9 (3.4)</td>
</tr>
<tr>
<td>RS graviton (k/M_{Pl} = 0.1)</td>
<td>q(\bar{q}), gg</td>
<td>2.6 (2.6)</td>
</tr>
<tr>
<td>DM mediator (m_{DM} = 1) GeV</td>
<td>q(\bar{q})</td>
<td>2.8 (3.2)</td>
</tr>
</tbody>
</table>
Event selection in signal region:

- At least one lepton (electron/muon)
- At least two jets
- $M_{jj} \geq 220$ GeV

Data-driven fit used in background estimation.
**Z’ to ttbar @ ATLAS**

139 fb$^{-1}$

- **ttbar events with fully hadronic decay:**
  - $>=2$ jets with $>=1$ large-R jet
  - $M_{jj}$ (2 large-R jets with highest-pT) $> 1.4$ TeV
  - $|\Delta\Phi_{jj}| > 1.6$.
  - **SR1b:** exactly 1 of the 2 top-tagged jets is a b-tagged jet
  - **SR2b:** both the 2 top-tagged jets are b-tagged jets

- **Background estimation:**
  - First using data-driven fit:
    
    $J(x; f, \mu, \sigma, \alpha_{CB}, n_{CB}, \mu_{CB}, \sigma_{CB}) = f \cdot g(x; \mu, \sigma) + (1 - f) h(x; \alpha_{CB}, n_{CB}, \mu_{CB}, \sigma_{CB})$

  - New top-tagging to improve the sensitivity
Introduction of leptoquark

- A common feature of many new physics models is the presence of a new class of bosons, called leptoquarks (LQs), that carry both lepton (L) and baryon numbers (B).
- Include pair production and single production.
- LQs has 3 generations like leptons and quarks.
- Fractional charge.
- Decays to lepton + quark in the same generation with LQs.
- Decays to lepton + quark in the different generation with LQs.
- LQs can provide an explanation of the flavour anomalies seen at B factories.

Pair production of LQs.

Single production of LQs.
List of leptoquark searches

- Leptonquark searches at the LHC:
  - First and second generations:
    - CMS: $eejj$ and $evjj$ @13 TeV 35.9 fb$^{-1}$ PHYSICAL REVIEW D 99, 052002 (2019)
    - CMS: $\mu\mu jj$ and $\mu\nu jj$ @13 TeV 35.9 fb$^{-1}$ PHYSICAL REVIEW D 99, 032014 (2019)
  - Third generation:
    - ATLAS: 5 channels @13 TeV 36.1 fb$^{-1}$ JHEP06(2019)144
    - CMS: $\tau\tau jj$ @13 TeV 35.9 fb$^{-1}$ JHEP03(2019)170
    - CMS: $t\tau\tau$ @13 TeV 35.9 fb$^{-1}$ Eur. Phys. J. C (2018) 78:707
    - CMS: $\tau b$ @13 TeV 35.9 fb$^{-1}$ JHEP07(2018)115
    - CMS: Quark+Neutrino @13 TeV 35.9 fb$^{-1}$ PHYSICAL REVIEW D 98, 032005 (2018)
  - Different/mixed generations:
    - CMS: $tt\mu\mu$ @13 TeV 35.9 fb$^{-1}$ PHYSICAL REVIEW LETTERS 121, 241802 (2018)
First and second generation LQ @ ATLAS

Event selection: $\text{eejj}, \mu\mu jj, \text{evjj}$ and $\mu\nu jj$.

- $\text{lljj}$: At least 2 jets and 2 same-flavor leptons
- $\text{lvjj}$: At least 2 jets, 1 lepton and a missing transverse energy (> 40 GeV)

Details shown in talk: “Search for LQs with the ATLAS detector”.

$\beta = 0.5$, Observed limits 1290 GeV

$\beta = 0.5$, Observed limits 1230 GeV
Two event selection criteria: eejj and evjj

The branching fractions for the LQ decay are expressed in terms of a free parameter $\beta$, where $\beta$ denotes the branching fraction to an electron and a quark, and $1 - \beta$ the branching fraction to a neutrino and a quark.

- $\beta = 1.0$: eejj limit 1435 GeV
- $\beta = 0.5$: evjj limit 1195 GeV
Second generation LQ @CMS

- Two event selection criteria: $\mu\mu jj$ and $\mu\nu jj$
- The branching fractions for the LQ decay are expressed in terms of a free parameter $\beta$, where $\beta$ denotes the branching fraction to an electron and a quark, and $1 - \beta$ the branching fraction to a neutrino and a quark.
  - $\beta = 1.0$: $\mu\mu jj$ limit 1530 GeV
  - $\beta = 0.5$: $\mu\nu jj$ limit 1150 GeV
## Third generation LQ @ ATLAS

<table>
<thead>
<tr>
<th>Channels</th>
<th>Event Selection</th>
<th>Covered Decay Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b\tau b\tau$</td>
<td>1. $1\ e/\mu, 1\ \text{had}, &gt;2(&gt;1\ b)\ \text{jets}$</td>
<td>LQLQ $\rightarrow b\tau b\tau$</td>
</tr>
<tr>
<td></td>
<td>2. $0\ e/\mu, 2\ \text{had}, &gt;2(&gt;1\ b)\ \text{jets}$</td>
<td>LQLQ $\rightarrow t\tau t\tau$</td>
</tr>
<tr>
<td></td>
<td>3. No loose lepton veto, $2\ \text{had}, &gt;2(&gt;1\ b)\ \text{jets}$</td>
<td></td>
</tr>
<tr>
<td>$t+\tau_1+\tau_2+E_T^{miss}(1\ \text{lepton})$</td>
<td>$&gt;= 4\ \text{jets with} &gt;1\ \text{b jet}, 1\ e/\mu, \text{high} E_T^{miss}$</td>
<td>LQLQ $\rightarrow \tau_1\tau_2\nu\tau_1\tau_2$</td>
</tr>
<tr>
<td>$t+\tau_1+\tau_2+E_T^{miss}(0\ \text{lepton})$</td>
<td>$&gt;= 4\ \text{jets with} &gt;1\ \text{b jet}, E_T^{miss} &gt; 250\ \text{GeV}$</td>
<td>LQLQ $\rightarrow \tau_1\tau_2\nu\tau_1\tau_2$</td>
</tr>
<tr>
<td>$\tau b+E_T^{miss}$</td>
<td>1. $1\ e/\mu, 1\ \text{had}, &gt;2 (=&gt;1\ b)\ \text{jets}$</td>
<td>LQLQ $\rightarrow \tau b\nu\tau b\nu$</td>
</tr>
<tr>
<td></td>
<td>2. $2\ \text{had}, &gt;2(&gt;1\ b)\ \text{jets}$</td>
<td></td>
</tr>
<tr>
<td>$b b+E_T^{miss}$</td>
<td>1. $2\ b\ \text{jets}, 0\ \text{leptons and large} E_T^{miss}$</td>
<td>LQLQ $\rightarrow b b\nu b b\nu$</td>
</tr>
<tr>
<td></td>
<td>2. $2\ b\ \text{jets}, 1\ \text{leptons and large} E_T^{miss}$</td>
<td></td>
</tr>
</tbody>
</table>

Details shown in talk: “Search for LQs with the ATLAS detector”.

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Event selection:
- At least 2 $\tau_h$ candidates.
- At least 2 jets.

\[
m_h = \sqrt{(E_{h1} + E_{h2} + E_{3} + E_{4} + P_T^{\text{miss}})^2 - (P_{h1} + P_{h2} + P_{3} + P_{4} + P_T^{\text{miss}})^2}
\]

LQs with a mass less than 1.02 TeV are excluded at 95% confidence level.
Event selection:

- Exactly one isolated muon or electron
- At least one \( \tau_h \) lepton
- \( p_T^{miss} > 50 \) GeV
- Category A: \( l\tau_h + \text{jets} \)
- Category B: \( l\tau_h \tau_h + \text{jets} \)

The scalar LQs are excluded with masses below 900 GeV, for \( B = 1 \)

Final event yield in category B in the muon and electron channels for different leptoquark mass hypotheses

<table>
<thead>
<tr>
<th>Process</th>
<th>( \tau_h \tau_h + \text{jets} )</th>
<th>( \mu\tau_h \tau_h + \text{jets} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>LQ3 (300 GeV)</td>
<td>97(^{+25}_{-24})</td>
<td>167(^{+26}_{-27})</td>
</tr>
<tr>
<td>LQ3 (400 GeV)</td>
<td>73(^{+11}_{-13})</td>
<td>98(^{+11}_{-15})</td>
</tr>
<tr>
<td>LQ3 (500 GeV)</td>
<td>34.1(^{+6.6}_{-6.2})</td>
<td>44.9(^{+8.5}_{-7.9})</td>
</tr>
<tr>
<td>LQ3 (600 GeV)</td>
<td>14.1(^{+2.8}_{-2.7})</td>
<td>21.1(^{+4.1}_{-3.8})</td>
</tr>
<tr>
<td>LQ3 (700 GeV)</td>
<td>7.3(^{+1.5}_{-1.4})</td>
<td>7.1(^{+1.4}_{-1.4})</td>
</tr>
<tr>
<td>LQ3 (800 GeV)</td>
<td>3.2(^{+0.7}_{-0.7})</td>
<td>4.4(^{+1.0}_{-0.9})</td>
</tr>
<tr>
<td>LQ3 (900 GeV)</td>
<td>1.5(^{+0.3}_{-0.2})</td>
<td>1.9(^{+0.4}_{-0.4})</td>
</tr>
<tr>
<td>LQ3 (1000 GeV)</td>
<td>0.8(^{+0.2}_{-0.2})</td>
<td>0.9(^{+0.2}_{-0.2})</td>
</tr>
<tr>
<td>( \bar{t}\tau_f )</td>
<td>2.5(^{+0.8}_{-0.2})</td>
<td>3.2(^{+1.5}_{-1.2})</td>
</tr>
<tr>
<td>( \bar{t}_p\tau_f )</td>
<td>1.5(^{+0.8}_{-0.8})</td>
<td>2.0(^{+0.8}_{-0.9})</td>
</tr>
<tr>
<td>Single t</td>
<td>0.3(^{+0.3}_{-0.3})</td>
<td>0.01(^{+0.2}_{-0.0})</td>
</tr>
<tr>
<td>W+jets</td>
<td>0.5(^{+1.2}_{-0.5})</td>
<td>0.4(^{+0.7}_{-0.4})</td>
</tr>
<tr>
<td>Z+jets</td>
<td>1.4(^{+0.5}_{-0.5})</td>
<td>1.0(^{+0.4}_{-0.4})</td>
</tr>
<tr>
<td>Diboson</td>
<td>1.6(^{+1.7}_{-1.6})</td>
<td>1.7(^{+1.8}_{-1.7})</td>
</tr>
<tr>
<td>Total background</td>
<td>( \tau_h^{2.4}_{-2.5})</td>
<td>( \tau_h^{2.6}_{-2.3})</td>
</tr>
<tr>
<td>Data</td>
<td>9</td>
<td>11</td>
</tr>
</tbody>
</table>
Single third generation LQ ($\tau b$) @ CMS

Three channels:

- $\tau_h \tau_h$: 2 $\tau_h$ candidates in addition to a b-tagged jet
- $\mu \tau_h$: 1 muon, 1 $\tau_h$ candidate and 1 b-tagged jet
- $e \tau_h$: 1 electron, 1 $\tau_h$ candidate and 1 b-tagged jet

$\lambda = 1$: limit of mass $> 740$ GeV

$\lambda = 2.5$: limit of mass $> 1050$ GeV

<table>
<thead>
<tr>
<th>Process</th>
<th>$e \tau_h$</th>
<th>$\mu \tau_h$</th>
<th>$\tau_h \tau_h$</th>
</tr>
</thead>
<tbody>
<tr>
<td>tt</td>
<td>$114.8 \pm 2.9$</td>
<td>$194.6 \pm 4.4$</td>
<td>$6.7 \pm 1.0$</td>
</tr>
<tr>
<td>Single top quark</td>
<td>$23.2 \pm 2.2$</td>
<td>$36.6 \pm 2.6$</td>
<td>$1.5 \pm 0.5$</td>
</tr>
<tr>
<td>Electroweak</td>
<td>$9.1 \pm 2.3$</td>
<td>$10.9 \pm 3.1$</td>
<td>$2.2 \pm 1.0$</td>
</tr>
<tr>
<td>QCD multijet</td>
<td>$4.5 \pm 4.6$</td>
<td>$1.5 \pm 5.3$</td>
<td>$1.9 \pm 0.6$</td>
</tr>
<tr>
<td>Total expected background</td>
<td>$151.6 \pm 6.3$</td>
<td>$243.6 \pm 8.0$</td>
<td>$12.3 \pm 1.7$</td>
</tr>
<tr>
<td>LQ signal ($m_{LQ} = 700$ GeV, $\lambda = 1$, $\beta = 1$)</td>
<td>$8.8 \pm 0.3$</td>
<td>$12.9 \pm 0.4$</td>
<td>$9.5 \pm 1.2$</td>
</tr>
<tr>
<td>Observed data</td>
<td>143</td>
<td>225</td>
<td>14</td>
</tr>
</tbody>
</table>
Event selection:

- \( N_j \geq 2 \)
- \( M_{T2} > 200 \text{ GeV}(H_T < 1500 \text{ GeV}) \)
- \( M_{T2} > 400 \text{ GeV}(H_T > 1500 \text{ GeV}) \)
- Categorized according to \( H_T \) (scalar sum of jet pT), \( M_{T2} \) (computed from jets and the \( p_T^\text{miss} \)), \( N_j \) (number of jet) and \( N_b \) (number of b jet).

\( \kappa \) is a dimensionless coupling that is 1 in the Yang-Mills case and 0 in the minimal coupling case.
Decay mode: LQ $\rightarrow t\mu$

Event selection:
- At least two muons
- At least two jets
- At least one jet must be b-tagged.
- $M_{\mu\mu} - M_Z > 20$ GeV
- Category A: at least 3 leptons with at least 2 opposite charged muons (leptonic top quark)
- Category B: All the remaining events.

$S_T^{lep}$ is the scalar $p_T$ sum of all selected muons and electrons and $S_T$ is defined as the scalar sum of $S_T^{lep}$, $p_T^{miss}$, and the $p_T$ of all selected jets.
No evidence for New Physics yet.

Limits are set for different theory models.

New searches are being performed to look for Z’ and LQs with LHC full run II data.

ATLAS publication list

Thanks!

CMS publication list
Backup: summary of ATLAS Z’(jet) result

$g_{\tilde{A}}$ vs $m_{Z'}$ [GeV]

1. ATLAS Preliminary
2. $\sqrt{s} = 13$ TeV, 3.6-139 fb$^{-1}$
3. May 2020
4. 95% CL upper limits
   - Observed
   - Expected

- Boosted dijet + ISR
  - 36.1 fb
- Boosted di-b-jet + ISR
  - 60.3 fb
  - ATLAS-CONF-2018-052
- Resolved dijet + ISR
  - 79.8 & 76.6 fb
- Resolved di-b-jet + ISR
  - 79.8 & 76.6 fb
- Dijet TL
  - 5.6 & 5.7 fb
- Di-b-jet
  - 24.3 & 13.9 fb$^{-1}$
  - Phys. Rev. D 96 (2017) 032016
  - JHEP 02 (2020) 145
- Dijet
  - 13.9 fb$^{-1}$
  - JHEP 03 (2020) 145
- Dijet angular
  - 37.0 fb$^{-1}$
- $t\bar{t}$ resonance
  - 36.1 fb

Axial-vector mediator
Dirac DM
$m_{\tilde{A}} = 10$ TeV, $g_{\tilde{A}} = 1.0$

Single $\gamma$ trigger
$\gamma +$ jets trigger
Z’ to ditau @ CMS

- Four channels:
  - $\tau_e \tau_\mu$: DY+ttbar 75%
  - $\tau_\mu \tau_\tau$: DY+Wjet 90%
  - $\tau_e \tau_\tau$: DY+Wjet 70%
  - $\tau_\tau \tau_\tau$: QCD 80%

- Mass definition and signal region: 
  \[ m(\tau_1, \tau_2, \vec{p}_T^{\text{miss}}) > 300 \text{ GeV} \]
  \[ m(\tau_1, \tau_2, \vec{p}_T^{\text{miss}}) = \sqrt{(E_{\tau_1} + E_{\tau_2} + E_{\text{miss}})^2 - (\vec{p}_{\tau_1} + \vec{p}_{\tau_2} + \vec{p}_T^{\text{miss}})^2}. \]
Z’ to dijet @ATLAS

**ATLAS**

\( \sqrt{s} = 13 \text{ TeV}, 139 \text{ fb}^{-1} \)

**Inclusive**

- Data
- Background fit
- BumpHunter interval
- \( q'^*, m_{q'} = 4 \text{ TeV} \)
- \( q'^*, m_{q'} = 6 \text{ TeV} \)

\( q'^*, \sigma \times 10 \)

\( p\text{-value} = 0.89 \)

**ATLAS**

\( \sqrt{s} = 13 \text{ TeV}, 139 \text{ fb}^{-1} \)

**2 b-tag**

- Data
- Background fit
- BumpHunter interval
- DM \( Z' \), \( m_{Z'} = 2 \text{ TeV} \)
- DM \( Z' \), \( m_{Z'} = 3 \text{ TeV} \)

DM \( Z' \), \( \sigma_{\delta} = 0.25, \sigma \times 10 \)

\( p\text{-value} = 0.83 \)
Third generation LQ @ ATLAS

\( b\tau\tau: 1030 \text{ GeV for } LQ^u_3 \text{ and } 930 \text{ GeV for } LQ^d_3 \)

\( tt+E_T^{miss} (1 \text{ lepton}): 930 \text{ GeV} \)

\( bb+E_T^{miss}: 970 \text{ GeV} \)

\( tt+E_T^{miss} (0 \text{ lepton}): 1000 \text{ GeV for } LQ^u_3 \text{ and } 860 \text{ GeV for } LQ^d_3 \)

\( \tau b+E_T^{miss}: 780 \text{ GeV for } LQ^u_3 \text{ and } 800 \text{ GeV for } LQ^d_3 \)