Searches for supersymmetry in resonance production and R-parity violating prompt signatures with the ATLAS and CMS detectors

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On behalf of the ATLAS and CMS collaborations
Outline

- Introduction
- Multi-lepton searches
- Multi-lepton + b-jets
- 3rd generation scalar lepto-quarks and stops
- $e/\mu/\tau$ resonance search
- Muon + displaced vertex (see M. King’s talk, slide 6)

- Multi-jet searches
  - Resolved jets
  - Boosted jets
  - Light and heavy flavor three-jet resonances (see K. Terashi’s talk, slide 12)
Introduction - Supersymmetry

- Supersymmetric (SUSY) extensions of the Standard Model (SM) provide a mechanism for:
  - Solving the hierarchy problem.
  - Framework towards Grand Unification.
  - Impose conservation of R-parity, $R_p = (-1)^{3B + L + 2s}$, to protect the proton lifetime.
  - All SM particles have $R_p = +1$. All SUSY particles, $R_p = -1$.
  - Superpartners produced in pairs.
  - Lightest superpartner (LSP) is stable.

\[ \Delta m_H^2 = -\frac{\lambda_f}{8\pi^2} \Lambda_{UV}^2 + \ldots \]
Introduction - Why RPV?

• Experimental bounds on proton decay can be evaded in R-parity violating (RPV) scenarios, if the lagrangian conserves either \( L \) or \( B \).

• New terms are allowed to the SUSY lagrangian:

\[
\frac{1}{2} \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \kappa_i L_j H_2 + \frac{1}{2} \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k
\]

  Lepton number violation  \hspace{1cm}  Baryon number violation

• Results in large lepton and quark multiplicities.

• The value of \( \lambda \) determines the lifetime and therefore the decay length of the intermediate particle.

  • Upper limit set by constraints from CKM unitarity, \( \tau \)-decays, neutrino-mass values… [arXiv:0910.4980, arXiv:1005.3309]

  • Stringent limits to \( \lambda''_{11k} \) from neutron oscillation.

  • Only relatively weak constraints on third generation \( \lambda'' \) couplings.
Multi-lepton searches

- The focus of this analysis is the term $\frac{1}{2} \lambda_{ijk} L_i L_j \bar{E}_k$.

- If the RPV coupling is small RPC pair production of s-particles will dominate. RPV couplings will then decay the LSP.

- But sufficiently large so that the LSP decay is prompt.

- RPV decays via $\lambda_{ijk}$ give rise to high lepton multiplicities.

- Substantial $E_T^{\text{miss}}$ due to the presence of neutrinos.
Multi-lepton searches

• The signal regions require at least four leptons.

• Z-mass veto required to optimize for RPV searches.

• Background divided into:

**Irreducible background**

- Containing four real leptons (ZZ/γ*, ZWW, ZZZ, tWZ, Higgs boson decays…)
- Estimated using MC
- Validate in regions with different kinematic requirements such that these contributions are enhanced.

**Reducible background**

- Containing one or more “fake” leptons, either from semileptonic b or c decay, photon conversions or jet misidentified as leptons (WZ, WWW, Z/γ*+jets…)
- Estimated using data-driven “weighting method” in two control regions per signal region (with the same kinematics, only inverted lepton quality requirements).
Multi-lepton searches

- The signal regions require exactly four isolated leptons, containing at least one opposite sign, same flavor (OSSF) lepton pair.

- Nine regions defined according to conditions applied to the invariant masses of the pairs of leptons.

- The standard model processes entering the signal regions are:
  
  **Irreducible background**
  - Containing four prompt leptons.
  - ZZ from MC, normalized to the ZZ production $\sigma$ measured by CMS.
    - Assign systematic unc. of 25%.
  - WW, ttbar, WWZ, WZZ, ZZZ estimated using MC and normalized to theoretical $\sigma$.
    - Assign systematic unc. of 50%.

  **Reducible background**
  - Containing one or more “fake” leptons, either from semileptonic b or c decay, photon conversions or jet misidentified as leptons (WZ, WWW, Z/$\gamma^*$+jets…)
  - Contribution from non-prompt leptons is estimated using the “fake rate technique”.

CMS-PAS SUS-13-010
PRL 111, 221801 (2013)
Multi-lepton searches

Exclusion contour in terms of $m_{\text{NLSP}}$ vs $m_{\text{LSP}}$ for the different models considered.

- Strongest constraints when $\lambda_{121}, \lambda_{122} \neq 0$.
- Least stringent when $\lambda_{133}, \lambda_{233} \neq 0$.
- Nearly insensitive to the LSP mass.
Multi-lepton + b-jets

- This analysis focuses on the RPV terms $\frac{1}{2} \lambda_{ijk} L_i L_j \tilde{E}_k$ and $\lambda'_{ijk} L_i Q_j \bar{D}_k$.

- Require at least three isolated leptons (at most 1 hadronic $\tau$).

- Classify events in terms of opposite-sign same flavor dilepton pairs, b-tags, number of taus...

- Data-driven methods to estimate lepton fake contributions.

- Ttbar, diboson and rare processes estimation from simulations validated in validation regions.

- Interpret the results in context of
  - Light RPV stops.
  - Leptonic RPV
  - LQD RPV

Neutralino mass fixed to 300 GeV.
Multi-lepton + b-jets

- Exclusion contour in terms of $m_{\text{stop}}$ for the Stop RPV (left) and $m_{\text{squark}}$ vs $m_{\text{gluino}}$ for the different models considered.
- Stop masses up to 800 GeV are excluded for $\lambda_{122}$, $\lambda_{123}$ and $\lambda_{233}$ for $m_\chi$ fixed to 300 GeV.
- Squark masses up to about 1.4 TeV and gluino masses up to about 1 TeV are excluded for $\lambda_{231}'$ and $\lambda_{233}'$. 
3rd generation scalar lepto-quarks and stops

- 3rd generation scalar lepto-quarks.
  \[ \tilde{t}_1 \rightarrow \tau b \]
- Focuses in the $\lambda'_{333}$ term of the SUSY RPV lagrangian.
- Require 1 light lepton, 1 hadronic $\tau$ and at least 2 jets (1 b-tagged).

$S_T$ distribution used to extract the limits on both models

- Irreducible background from ttbar, estimated data-driven, from the observed $e\mu$ sample.
- Reducible background from hadronic $\tau$ misidentified as a jet (ttbar, W+jets, Z+jets) and multi-jet.
- Probability of misidentification and contribution from multi jet estimated data-driven.

Excluded $m_{LQ} < 740$ GeV at 95% CL

- Stop decay to a $\tilde{\chi}^\pm$ and a b.
  \[ \tilde{t}_1 \rightarrow \tilde{\chi}^\pm b, \quad \tilde{\chi}^\pm \rightarrow \tilde{\nu} + \tau^\pm \rightarrow jj + \tau^\pm \]
- Focuses in the $\lambda'_{3jk}$ term of the SUSY RPV lagrangian (j, k = 1, 2).
- Require 1 light lepton, 1 hadronic $\tau$ and at least 5 jets (1 b-tagged).

Exclude $m_{stop} < 576$ GeV at 95% CL
Neutrino oscillations show that lepton-flavour quantum numbers are not conserved in Nature.

Lepton flavor violation (LFV) has never been observed in the charged lepton sector.

Look for the production of a particle that decays to a pair of different flavour, opposite sign leptons.

Decay of a tau-sneutrino (produced via the $\lambda'_{311}$ coupling) to different-flavour leptons (via $\lambda_{i3k}$):

$$\tilde{\nu}_\tau \rightarrow e^\pm \mu^\mp, e^\pm \tau^\mp, \mu^\pm \tau^\mp$$

Therefore, the focus of this analysis are the terms $\frac{1}{2} \lambda_{ijk} L_i L_j \bar{E}_k$ and $\lambda'_{ijk} L_i Q_j \bar{D}_k$. 
**e/µ/τ resonance search**

- Electrons or muons required to be isolated. Tau candidates selected with a BDT discriminator.
- 2 leptons required to have different flavor, opposite charge and \(\Delta \phi(\text{leptons}) > 2.7\).
- Cut on \(m_{ll} \pm 3\sigma_m\): signal region*

> **mass resolution**

*If \(m_{ll} > 800\) GeV, signal region defined as \(m_{ll} > 800\) GeV

- "Prompt lepton backgrounds", e.g. ttbar, Z/γ*+l, Wt…
- Estimated using MC normalized to cross-sections.
- "Jet backgrounds": jet fakes lepton, e.g. W/Z+jets.
- Semi-data driven methods used to estimate them.

* \(m_{ll}\): signal region

**Data**

\(\text{ATLAS}\)

\(\int \text{Ldt} = 4.6\) fb\(^{-1}\)

\(\sqrt{s} = 7\) TeV

\(\tilde{\nu}_\tau\)

\(\Delta\phi(\text{leptons}) > 2.7\)

\(m_{\tilde{\nu}_\tau} \pm 3\sigma_m\)

\(m_{ll} > 800\) GeV
e/µ/τ resonance search

- 95% CL upper limit on the production cross section times branching ratio as a function of sneutrino mass. For the couplings $\lambda_{311}' = 0.10$ and $\lambda_{i3k} = 0.05$:

  - Contours of the limit on $\lambda_{311}'$ as a function of $m_{\tilde{\nu}}$ for various values of $\lambda_{i3k}$. Area above the curve is excluded.
Multi-jet searches

- The focus of this analysis is the term \( \frac{1}{2} \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k \).

- It is assumed that the \( \lambda''_{ijk} \) terms lead to short enough lifetimes, so that the displacement of the decay vertex of the NLSP is negligible.

- RPV decays via \( \lambda''_{ijk} \) give rise to high jet multiplicities.
  - Low \( E_T^{\text{miss}} \) due to the decay of the LSP into SM particles.
  - Huge number of possible jet combinations hinders the measurement of a resonance peak.
  - Instead, look for an excess of events with large number of high-\( p_T \) jets.

First time done!
Multi-jet searches: resolved jets

Search for high-mass gluino pairs assuming RPV SUSY.

• Final states with large number of high-\(p_T\) jets.

• Use \(b\)-tagging to estimate BR of RPV decays to different flavours.

• Optimize signal regions for different BR hypotheses and different gluino masses.
  • Vary \(N_{\text{jets}}\), minimum jet \(p_T\) cut…
  • 6-quark and 10-quark models.

• Main background coming from multi-jet production events.
  • Estimated by projecting from lower jet multiplicity bins.
Multi-jet searches: boosted jets

- If a low-mass gluino is highly boosted, all the decays can be recombined in a “fat” jet.

  - Use “N-subjettiness” substructure variables, $\tau_N$ to characterize how well a jet can be described as containing $N$ or fewer $k_t$ subjets

    $$\tau_N = \frac{1}{d_0} \sum_k p_{T k} \times \min(\delta R_{1k}, \delta R_{2k}, \ldots, \delta R_{Nk})$$, with $d_0 = \sum_k p_{T k} \times R$

  - $\tau_{32}$ ($= \tau_3 / \tau_2$) measures how well the “fat” jet can be as containing 3 ($\tau_{32} \approx 0$) or 2 ($\tau_{32} \approx 1$) jets. Require $\tau_{23} < 0.7$.

  - Use the mass of each fat jets to select gluino candidates.

- Main background: multi-jet, estimated data-driven.

  - Estimated using the “ABCD” method: event yields in orthogonal control regions in $m_{J1}$ and/or $m_{J2}$ are used to predict the total number of events expected in the signal region.

- Looking for a peak in the jet mass spectrum.
Multi-jet searches

**Resolved**

- Focus on two different mass ranges:
  - **High mass:** resolved analysis.
  - **Low mass:** boosted analysis.

**Resolved High mass:**
- Gluino decaying to light-flavor quarks: excludes $m_{\text{gluino}} < 917$ (853) GeV observed (expected).
- Gluino decaying to 1 b-jet and 2 light quarks: excludes $m_{\text{gluino}} < 929$ (921) GeV observed (expected).

**Resolved Low mass:**
- Gluinos produced with $p_T$ much greater than their mass.
  - Excludes $m_{\text{gluino}} < 255$ GeV.

**Boosted analysis establishes the use of boosted objects for future SUSY searches in ATLAS!**

**Boosted**

- Focus on two different mass ranges:
  - **High mass:** resolved analysis.
  - **Low mass:** boosted analysis.

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Boosted analysis establishes the use of boosted objects for future SUSY searches in ATLAS!
Multi-jet searches: three jet resonances

- Analysis **covered in detail in Koji’s talk** (Search for heavy resonances with the ATLAS and CMS detectors), slide 15.

- Search for **three-jet hadronic resonance production**.

- The signal models explored assume **RPV supersymmetric gluino pair production**, decaying to
  - Only light-flavour jets.
  - Both light- and heavy-flavour jets.

- High jet multiplicity final states are also covered by CMS black-hole analysis (EXO-12-009).
Conclusions

• Many searches in resonance production and R-parity violating SUSY have been presented by ATLAS and CMS.

• Limits on many RPV models have been extended.

  • Different final states with leptons and jets have been considered.

  • Interpretations on new models have been performed (e.g. 10-quark model).

• No sign of new physics yet… but a new era at 13 and 14 TeV will start soon.

  • Stay tuned!
Backup slides
References


• Multi-lepton + b-jets [CMS-PAS SUS-12-027 (CMS)]

• 3rd generation scalar lepto-quarks and stops [CMS-PAS EXO-12-032 (CMS)]

• $e/\mu/\tau$ resonance search [Physics Letters B 723 (2013) 15–32 (ATLAS)]

• Muon + displaced vertex [ATLAS-CONF-2013-092 (ATLAS)]

• Multi-jet searches
  • Resolved jets [ATLAS-CONF-2013-091 (ATLAS)]
  • Boosted jets [JHEP12(2012)086 (ATLAS)]
  • Light and heavy flavor three-jet resonances [CMS-EXO-12-049 (CMS)]
Multi-lepton searches

**Trigger**: single isolated or double electron/muon.

- **Data quality** requirements + PV with >5 tracks with $p_T > 400$ MeV.
- Baseline definitions:
  - **Electrons**: “medium” identification criteria. $|\eta| < 2.47$, $E_T > 10$ GeV.
  - **Muons**: combine tracks in ID and MS. $|\eta| < 2.5$, $E_T > 10$ GeV.
  - **Jets**: Anti-kt algorithm with $R = 0.4$. Electromagnetic and hadronic showers calibrated independently. $|\eta| < 4.5$, $p_T > 20$ GeV.
  - “B-tagging” using multivariate technique. 80% efficiency.
  - **Taus**: calorimeter seed jets with $|\eta| < 2.47$, $p_T > 10$ GeV.
- Signal definitions. Baseline plus:
  - **Electrons**: From the PV. “Tight” identification criteria. Isolated from hadronic activity (track and calorimeter isolation).
  - **Muons**: From the PV. Isolated from hadronic activity (track isolation).
  - **Jets**: $|\eta| < 2.5$ and jet vertex fraction requirement if $p_T < 50$ GeV.
  - **Taus**: “Medium” identification of a BDT.
  - $E_T^{\text{miss}}$: calculated from the transverse momenta of calibrated electrons, muons, photons, jets and topo clusters not associated.
Multi-lepton searches

- **Nine signal regions** optimized for different models.

<table>
<thead>
<tr>
<th>N(\ell)</th>
<th>N(\tau)</th>
<th>Z-veto</th>
<th>(E_T^{\text{miss}}) [GeV]</th>
<th>(m_{\text{eff}}) [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\geq 4)</td>
<td>(\geq 0)</td>
<td>SFOS, SFOS+\ell, SFOS+SFOS</td>
<td>(&gt; 50)</td>
<td>-</td>
</tr>
<tr>
<td>(= 3)</td>
<td>(\geq 1)</td>
<td>SFOS, SFOS+\ell</td>
<td>(&gt; 50)</td>
<td>-</td>
</tr>
<tr>
<td>(= 2)</td>
<td>(\geq 2)</td>
<td>SFOS</td>
<td>(&gt; 75)</td>
<td>-</td>
</tr>
<tr>
<td>(\geq 4)</td>
<td>(\geq 0)</td>
<td>SFOS, SFOS+\ell, SFOS+SFOS</td>
<td>(&gt; 75) or (&gt; 600)</td>
<td></td>
</tr>
<tr>
<td>(= 3)</td>
<td>(\geq 1)</td>
<td>SFOS, SFOS+\ell</td>
<td>(&gt; 100) or (&gt; 400)</td>
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</tr>
<tr>
<td>(= 2)</td>
<td>(\geq 2)</td>
<td>SFOS</td>
<td>(&gt; 100) or (&gt; 600)</td>
<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>N(\ell)</th>
<th>N(\tau)</th>
<th>Z-requirement</th>
<th>(E_T^{\text{miss}}) [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\geq 4)</td>
<td>(\geq 0)</td>
<td>SFOS</td>
<td>(&gt; 75)</td>
</tr>
<tr>
<td>(= 3)</td>
<td>(\geq 1)</td>
<td>SFOS</td>
<td>(&gt; 100)</td>
</tr>
<tr>
<td>(= 2)</td>
<td>(\geq 2)</td>
<td>SFOS</td>
<td>(&gt; 75)</td>
</tr>
</tbody>
</table>

- **Two control regions** per signal region to extract data-driven corrections to estimate the reducible background in each signal region.
  - Same cuts, only different lepton requirements.
  - CR1 (3 tight leptons, at least 1 loose) and CR2 (2 tight leptons, at least 2 loose).

\[
N_{\text{red}}^{\text{SR}} = [N_{\text{data}}^{\text{CR1}} - N_{\text{irr}}^{\text{CR1}}] \times F - [N_{\text{data}}^{\text{CR2}} - N_{\text{irr}}^{\text{CR2}}] \times F_1 \times F_2
\]
Multi-lepton searches

- The systematic uncertainties are:

<table>
<thead>
<tr>
<th>Experimental</th>
<th>Theoretical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jet energy scale</td>
<td>(\sigma: t\bar{t} + Z/WW) [75, 76] 30%</td>
</tr>
<tr>
<td>Jet energy resolution</td>
<td>(A\epsilon: t\bar{t} + Z) 30–40%</td>
</tr>
<tr>
<td></td>
<td>(\sigma: ZZ/\gamma^*) 5%</td>
</tr>
<tr>
<td>e efficiency</td>
<td>(A\epsilon: ZZ/\gamma^*) 5–20%</td>
</tr>
<tr>
<td>(\tau) efficiency</td>
<td>(\sigma: VVV/tWZ) 50%</td>
</tr>
<tr>
<td>(E_T^{\text{miss}}) energy scale</td>
<td>(\sigma A\epsilon: Vh/VBF) [72] 20%</td>
</tr>
<tr>
<td>(E_T^{\text{miss}}) resolution</td>
<td>(\sigma A\epsilon: ggF/t\bar{t}h) [72] 100%</td>
</tr>
<tr>
<td>Luminosity</td>
<td>Reducible</td>
</tr>
</tbody>
</table>
Multi-lepton searches

- The events observed in each signal region is:

<table>
<thead>
<tr>
<th>Region</th>
<th>$ZZ/\gamma^*$</th>
<th>$tWZ$</th>
<th>$tt + Z$</th>
<th>$VVV$</th>
<th>Higgs</th>
<th>Reducible</th>
<th>$\Sigma SM$</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>SR0noZa</td>
<td>0.29 $\pm$ 0.08</td>
<td>0.067 $\pm$ 0.033</td>
<td>0.8 $\pm$ 0.4</td>
<td>0.19 $\pm$ 0.09</td>
<td>0.27 $\pm$ 0.23</td>
<td>0.006$^{+0.164}_{-0.06}$</td>
<td>1.6 $\pm$ 0.5</td>
<td>3</td>
</tr>
<tr>
<td>SR1noZa</td>
<td>0.52 $\pm$ 0.07</td>
<td>0.054 $\pm$ 0.028</td>
<td>0.21 $\pm$ 0.08</td>
<td>0.14 $\pm$ 0.07</td>
<td>0.40 $\pm$ 0.33</td>
<td>3.3$^{+1.3}_{-1.1}$</td>
<td>4.6$^{+1.3}_{-1.2}$</td>
<td>4</td>
</tr>
<tr>
<td>SR2noZa</td>
<td>0.15 $\pm$ 0.04</td>
<td>0.023 $\pm$ 0.012</td>
<td>0.13 $\pm$ 0.10</td>
<td>0.051 $\pm$ 0.024</td>
<td>0.20 $\pm$ 0.16</td>
<td>3.4 $\pm$ 1.2</td>
<td>4.0$^{+1.3}_{-1.2}$</td>
<td>7</td>
</tr>
<tr>
<td>SR0noZb</td>
<td>0.19 $\pm$ 0.05</td>
<td>0.049 $\pm$ 0.024</td>
<td>0.68 $\pm$ 0.34</td>
<td>0.18 $\pm$ 0.07</td>
<td>0.22 $\pm$ 0.20</td>
<td>0.06$^{+0.15}_{-0.06}$</td>
<td>1.4 $\pm$ 0.4</td>
<td>1</td>
</tr>
<tr>
<td>SR1noZb</td>
<td>0.219$^{+0.036}_{-0.035}$</td>
<td>0.050 $\pm$ 0.026</td>
<td>0.17 $\pm$ 0.07</td>
<td>0.09 $\pm$ 0.04</td>
<td>0.30 $\pm$ 0.26</td>
<td>2.1$^{+1.0}_{-0.9}$</td>
<td>2.9$^{+1.0}_{-0.9}$</td>
<td>1</td>
</tr>
<tr>
<td>SR2noZb</td>
<td>0.112$^{+0.025}_{-0.024}$</td>
<td>0.016 $\pm$ 0.009</td>
<td>0.27$^{+0.28}_{-0.27}$</td>
<td>0.040 $\pm$ 0.018</td>
<td>0.13 $\pm$ 0.12</td>
<td>2.5$^{+0.9}_{-1.0}$</td>
<td>3.0 $\pm$ 1.0</td>
<td>6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Region</th>
<th>$\Sigma SM$</th>
<th>Data</th>
<th>$N_{BSM}^{obs}$</th>
<th>$N_{BSM}^{exp}$</th>
<th>$\sigma_{vis}^{obs}$ [fb] (asym.)</th>
<th>$\sigma_{vis}^{exp}$ [fb] (asym.)</th>
<th>$p_0$</th>
<th>$N_\alpha$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SR0Z</td>
<td>1.09$^{+0.26}_{-0.21}$</td>
<td>0.25 $\pm$ 0.13</td>
<td>2.6 $\pm$ 1.2</td>
<td>1.0 $\pm$ 0.5</td>
<td>0.60$^{+0.22}_{-0.21}$</td>
<td>0.00$^{+0.09}_{-0.09}$</td>
<td>5.6 $\pm$ 1.4</td>
<td>7</td>
</tr>
<tr>
<td>SR1Z</td>
<td>0.59$^{+0.11}_{-0.10}$</td>
<td>0.042 $\pm$ 0.022</td>
<td>0.41 $\pm$ 0.19</td>
<td>0.22 $\pm$ 0.11</td>
<td>0.14 $\pm$ 0.05</td>
<td>1.0 $\pm$ 0.5</td>
<td>2.5 $\pm$ 0.6</td>
<td>3</td>
</tr>
<tr>
<td>SR2Z</td>
<td>0.70$^{+0.12}_{-0.11}$</td>
<td>0.0018 $\pm$ 0.0015</td>
<td>0.035 $\pm$ 0.024</td>
<td>0.039 $\pm$ 0.014</td>
<td>0.14$^{+0.04}_{-0.05}$</td>
<td>0.9 $\pm$ 0.5</td>
<td>1.8 $\pm$ 0.5</td>
<td>1</td>
</tr>
</tbody>
</table>

- The model independent limits are:
Multi-lepton searches
Multi-lepton searches

- **Trigger**: at least two leptons.
- Events reconstructed off-line with the **Particle Flow (PF)** algorithm.
- Baseline definitions:
  - **Electrons**: Isolated, $|\eta| < 2.4$, $p_T > 20$ GeV.
  - **Muons**: Isolated, $|\eta| < 2.4$, $p_T > 10$ GeV.
- Select events with exactly 4 isolated leptons.
  - Containing at least one OSSF lepton pair.
- **$M_1$**: invariant mass of the lepton pair closest to the Z mass.
- **$M_2$**: invariant mass of the remaining lepton pair.
- Define 9 signal regions
Multi-lepton searches

• The background contributions are normalized:

  • **ZZ production**: normalized to the cross-section measured by CMS. Assign a 25% systematic.

  • **More rare processes** producing 4 and more prompt leptons: normalize to their cross-section and assign a 50% uncertainty.

  • Contributions from **non-prompt leptons** is estimated using the fake rate technique:
    • Define region with $E_{T}^{\text{miss}} < 30$ GeV, enriched with Drell-Yan production + 1 jet.
    • Define region with $E_{T}^{\text{miss}} < 30$ GeV and three isolated leptons.
    • Fake rate jet to electron extracted from comparing events in the Z peak in both regions.
Multi-lepton searches
Multi-lepton + b-jets

- Data collected with double-lepton trigger or e-μ trigger.
- Both 1-prong and 3-prong hadronic taus are selected with the hadrons plus strip CMS method.
- Use PF-reconstructed jets (|\(\eta\)| < 2.5, \(p_T\) > 30 GeV), separated \(\Delta R > 0.3\) from any other object.
  - B-tag using “Combined Secondary Vertex algorithm”: 70% efficiency, 13% misidentification.

- Require at least three leptons, where at most one of them is a hadronic tau.
- Define signal regions based on:
  - Maximum number of opposite-sign and same-flavor (OSSF) dilepton pairs.
  - Number of leptons.
  - At least one OSSF pair has a dilepton mass in the Z-mass window.
  - Cut on \(S_F\) (scalar sum of \(E_T^{\text{miss}}\), \(H_T\) and \(p_T\) of isolated leptons).
Multi-lepton + b-jets

- Estimate **lepton fake** contributions using data-driven methods:
  - Misidentified non-prompt leptons:
    - Mainly from Z+jets, with a third lepton from a jet or a photon.
    - From dilepton data, relate the rate for jets to produce isolated-lepton candidates to the rate for jets to produce isolated tracks.
  - Asymmetric **photon conversions**:
    - External conversion: create mainly $e^+e^-$ pair in the magnetic field or material of the detector.
    - Internal conversion: Virtual photon can produce both $e$ or $\mu$. If one lepton has very low $p_T$ (and is not reconstructed), Drell-Yan can lead to a big contribution.
    - Conversion factor measured in control regions: ratio between the number of $\ell^+\ell^\pm\ell^\pm$ on the Z peak to the number of $\ell^+\ell^-\gamma$ on the Z peak.
  - **ttbar production**:
    - From simulation, after validation in a single lepton control region.
  - **Irreducible** (WZ):
    - Obtained from theory and MC simulations.
Multi-lepton + b-jets

- Systematic uncertainties:

<table>
<thead>
<tr>
<th>Source of Uncertainty</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity</td>
<td>4.5% [27]</td>
</tr>
<tr>
<td>PDF</td>
<td>14% [28]</td>
</tr>
<tr>
<td>Renormalization Scale</td>
<td>10% [28]</td>
</tr>
<tr>
<td>$E_T^{miss} \text{ Res} (E_T^{miss})$: 0-50 GeV, 50-100 GeV, &gt; 100 GeV</td>
<td>(-3%, +4%, +4%)</td>
</tr>
<tr>
<td>Jet Energy Scale W$^{\pm}Z$</td>
<td>0.5% (WZ)</td>
</tr>
<tr>
<td>B-Tag Veto (CSVM)</td>
<td>0.1% (WZ), 6% (tt)</td>
</tr>
<tr>
<td>Muon ID/Isolation at 10 (100) GeV/c</td>
<td>11% (0.2%)</td>
</tr>
<tr>
<td>Electron ID/Isolation at 10 (100) GeV/c</td>
<td>14% (0.6%)</td>
</tr>
<tr>
<td>$t\bar{t}$ xsec/fake rate</td>
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</tr>
<tr>
<td>$WZ$ xsec</td>
<td>6%</td>
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<tr>
<td>$ZZ$ xsec</td>
<td>12%</td>
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</table>
Multi-lepton + b-jets

- Four lepton signal regions:

<table>
<thead>
<tr>
<th>N_{OSSF}</th>
<th>m_{b} (GeV)</th>
<th>S_{T} (GeV)</th>
<th>0-\tau, 0-b</th>
<th>1-\tau, 0-b</th>
<th>0-\tau, 1-b</th>
<th>1-\tau, 1-b</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>S_{T} &gt; 2000 GeV</td>
<td>0</td>
<td>0 ± 0.009</td>
<td>0</td>
<td>0 ± 0.009</td>
</tr>
<tr>
<td>0</td>
<td>1500 &lt; S_{T} &lt; 2000 GeV</td>
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<td>0 ± 0.009</td>
<td>0</td>
<td>0 ± 0.009</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>1000 &lt; S_{T} &lt; 1500 GeV</td>
<td>0</td>
<td>0 ± 0.009</td>
<td>0</td>
<td>0 ± 0.009</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>600 &lt; S_{T} &lt; 1000 GeV</td>
<td>0</td>
<td>0 ± 0.009</td>
<td>0</td>
<td>0 ± 0.009</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>300 &lt; S_{T} &lt; 600 GeV</td>
<td>0</td>
<td>0.009 ± 0.01</td>
<td>0</td>
<td>0.01 ± 0.01</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>0 &lt; S_{T} &lt; 300 GeV</td>
<td>0</td>
<td>0.009 ± 0.01</td>
<td>0</td>
<td>0.01 ± 0.01</td>
<td>0</td>
</tr>
</tbody>
</table>

- Three lepton signal regions:

<table>
<thead>
<tr>
<th>N_{OSSF}</th>
<th>m_{b} (GeV)</th>
<th>S_{T} (GeV)</th>
<th>0-\tau, 0-b</th>
<th>1-\tau, 0-b</th>
<th>0-\tau, 1-b</th>
<th>1-\tau, 1-b</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>S_{T} &gt; 2000 GeV</td>
<td>0</td>
<td>0 ± 0.009</td>
<td>0</td>
<td>0 ± 0.009</td>
</tr>
<tr>
<td>0</td>
<td>1500 &lt; S_{T} &lt; 2000 GeV</td>
<td>0</td>
<td>0 ± 0.009</td>
<td>0</td>
<td>0 ± 0.009</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>1000 &lt; S_{T} &lt; 1500 GeV</td>
<td>0</td>
<td>0 ± 0.009</td>
<td>0</td>
<td>0 ± 0.009</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>600 &lt; S_{T} &lt; 1000 GeV</td>
<td>0</td>
<td>0 ± 0.009</td>
<td>0</td>
<td>0 ± 0.009</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>300 &lt; S_{T} &lt; 600 GeV</td>
<td>0</td>
<td>0.009 ± 0.01</td>
<td>0</td>
<td>0.01 ± 0.01</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>0 &lt; S_{T} &lt; 300 GeV</td>
<td>0</td>
<td>0.009 ± 0.01</td>
<td>0</td>
<td>0.01 ± 0.01</td>
<td>0</td>
</tr>
</tbody>
</table>

Total All

87 84.19 37 29.89 7 3.8 ± 1.1 3 2.5 ± 0.7
Multi-lepton + b-jets

Leptonic RPV couplings

LQD RPV couplings
3rd generation scalar lepto-quarks and stops

- **Trigger**: require the presence of either an electron or a muon.

- **Electrons**: $|\eta| < 2.1$, $p_T > 30$ GeV, electromagnetic shower shape compatible with that of an electron and energy deposition in ECAL consistent with tracks, required to be isolated.

- **Muons**: $|\eta| < 2.1$, $p_T > 30$ GeV, reconstructed by both tracker and muon spectrometer, required to be isolated.

- **Hadronic taus**: $|\eta| < 2.3$, $p_T > 50$ GeV, particle-flow (PF) technique used. Required to be isolated.

- **Jets**: $|\eta| < 2.4$, $p_T > 30$ GeV, reconstructed with anti-$k_t$ algorithm with $R = 0.5$.

- **Signal region definition**:
  - One light lepton and a hadronically decaying tau.
  - At least two jets (five jets), with at least one of the jets b-tagged in the scalar lepto-quarks (stop) models.
  - Invariant mass of the hadronic tau and a jet greater than 250 GeV (scalar lepto-quarks).
3rd generation scalar lepto-quarks and stops

- **Background composition:**
  - **Irreducible:**
    - $t\bar{t}$bar when both light lepton and hadronic tau are produced from decays of genuine tau leptons.
    - Estimated from observed events in $e\mu$ sample. Then scaled by the relative difference on the selection efficiencies between the $\ell\tau_h$ and the $e\mu$.
  - **Reducible:**
    - $t\bar{t}$bar, $W$+jets, $Z$+jets (jet misidentified as a hadronically decaying tau).
      - Probability of misidentification from data-driven. Use events $Z(\mu\mu)+$jets with at least a $\tau_h$ candidate. The probability is calculated as the fraction of $\tau_h$ candidates which pass the isolation requirements.
    - Multi-jet, contributes only in the $e\tau_h$ channel.
      - Estimated from a data sample satisfying the final selection criteria for the $e\tau_h$ channel except that the electron and the $\tau_h$ must have the same electric charge.
### 3\textsuperscript{rd} generation scalar lepto-quarks and stops

<table>
<thead>
<tr>
<th>$S_T$ bin (low edge) [GeV]</th>
<th>140</th>
<th>210</th>
<th>280</th>
<th>350</th>
<th>420</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Observed</strong></td>
<td>5</td>
<td>61</td>
<td>72</td>
<td>103</td>
<td>80</td>
</tr>
<tr>
<td>$Z(\ell\ell/\tau\tau)+\text{jets}$</td>
<td>$0.16 \pm 0.06 \pm 0.08$</td>
<td>$0.83 \pm 0.30 \pm 0.22$</td>
<td>$2.36 \pm 0.85 \pm 0.74$</td>
<td>$8.33 \pm 3.19 \pm 3.81$</td>
<td>$4.11 \pm 1.48 \pm 0.94$</td>
</tr>
<tr>
<td>Reducible</td>
<td>$2.92 \pm 0.34 \pm 1.05$</td>
<td>$30.51 \pm 3.48 \pm 4.52$</td>
<td>$49.13 \pm 5.68 \pm 4.25$</td>
<td>$54.60 \pm 6.27 \pm 4.25$</td>
<td>$42.31 \pm 4.84 \pm 3.77$</td>
</tr>
<tr>
<td>$t\bar{t}$ (irreducible)</td>
<td>$0.50 \pm 0.07 \pm 0.18$</td>
<td>$5.82 \pm 0.77 \pm 0.56$</td>
<td>$19.61 \pm 2.52 \pm 1.16$</td>
<td>$30.56 \pm 3.95 \pm 1.48$</td>
<td>$31.06 \pm 3.97 \pm 1.34$</td>
</tr>
<tr>
<td>VV</td>
<td>$0.13 \pm 0.03 \pm 0.13$</td>
<td>$0.42 \pm 0.09 \pm 0.19$</td>
<td>$1.18 \pm 0.25 \pm 0.33$</td>
<td>$1.67 \pm 0.35 \pm 0.37$</td>
<td>$1.51 \pm 0.32 \pm 0.37$</td>
</tr>
<tr>
<td>Single-t</td>
<td>$0.31 \pm 0.07 \pm 0.31$</td>
<td>$1.21 \pm 0.26 \pm 0.67$</td>
<td>$6.63 \pm 1.42 \pm 1.75$</td>
<td>$4.58 \pm 0.98 \pm 1.42$</td>
<td>$5.01 \pm 1.07 \pm 1.51$</td>
</tr>
<tr>
<td><strong>Total Bkg.</strong></td>
<td>$4.02 \pm 0.66 \pm 1.12$</td>
<td>$38.78 \pm 6.05 \pm 4.61$</td>
<td>$78.92 \pm 12.38 \pm 4.81$</td>
<td>$99.74 \pm 16.50 \pm 6.07$</td>
<td>$84.01 \pm 13.25 \pm 4.40$</td>
</tr>
</tbody>
</table>

### Lepto-quark signal regions yields

<table>
<thead>
<tr>
<th>$S_T$ bin (low edge) [GeV]</th>
<th>480</th>
<th>540</th>
<th>620</th>
<th>700</th>
<th>780</th>
<th>870</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Observed</strong></td>
<td>57</td>
<td>50</td>
<td>32</td>
<td>21</td>
<td>17</td>
<td>2</td>
</tr>
<tr>
<td>$6.53 \pm 2.48 \pm 3.07$</td>
<td>$2.50 \pm 0.90 \pm 0.43$</td>
<td>$0.87 \pm 0.31 \pm 0.25$</td>
<td>$0.99 \pm 0.36 \pm 0.27$</td>
<td>$0.27 \pm 0.10 \pm 0.13$</td>
<td>$1.76 \pm 0.66 \pm 1.05$</td>
<td></td>
</tr>
<tr>
<td>$33.61 \pm 3.83 \pm 3.31$</td>
<td>$22.66 \pm 2.62 \pm 2.22$</td>
<td>$14.30 \pm 1.65 \pm 2.02$</td>
<td>$7.34 \pm 0.84 \pm 1.22$</td>
<td>$3.23 \pm 0.38 \pm 0.91$</td>
<td>$2.98 \pm 0.41 \pm 0.89$</td>
<td></td>
</tr>
<tr>
<td>$25.97 \pm 3.34 \pm 1.21$</td>
<td>$24.19 \pm 3.11 \pm 1.19$</td>
<td>$15.90 \pm 2.03 \pm 1.07$</td>
<td>$7.87 \pm 1.03 \pm 0.69$</td>
<td>$5.44 \pm 0.70 \pm 0.89$</td>
<td>$2.97 \pm 0.40 \pm 0.42$</td>
<td></td>
</tr>
<tr>
<td>$0.47 \pm 0.10 \pm 0.17$</td>
<td>$0.38 \pm 0.08 \pm 0.17$</td>
<td>$0.22 \pm 0.05 \pm 0.14$</td>
<td>$0.14 \pm 0.03 \pm 0.11$</td>
<td>$0.25 \pm 0.05 \pm 0.15$</td>
<td>$0.16 \pm 0.03 \pm 0.14$</td>
<td></td>
</tr>
<tr>
<td>$3.40 \pm 0.72 \pm 1.26$</td>
<td>$3.31 \pm 0.71 \pm 1.25$</td>
<td>$3.07 \pm 0.66 \pm 1.16$</td>
<td>$2.81 \pm 0.60 \pm 1.30$</td>
<td>$0.45 \pm 0.10 \pm 0.45$</td>
<td>$1.08 \pm 0.23 \pm 0.77$</td>
<td></td>
</tr>
<tr>
<td>$69.98 \pm 11.65 \pm 4.84$</td>
<td>$53.03 \pm 8.46 \pm 2.85$</td>
<td>$34.37 \pm 5.37 \pm 2.57$</td>
<td>$19.15 \pm 3.14 \pm 1.93$</td>
<td>$9.65 \pm 1.54 \pm 1.37$</td>
<td>$8.95 \pm 1.81 \pm 1.64$</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$S_T$ bin (low edge) [GeV]</th>
<th>980</th>
<th>1100</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Observed</strong></td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>$0.07 \pm 0.03 \pm 0.07$</td>
<td>$0.16 \pm 0.06 \pm 0.08$</td>
<td></td>
</tr>
<tr>
<td>$0.93 \pm 0.11 \pm 0.39$</td>
<td>$0.53 \pm 0.09 \pm 0.27$</td>
<td></td>
</tr>
<tr>
<td>$1.20 \pm 0.15 \pm 0.25$</td>
<td>$1.14 \pm 0.16 \pm 0.23$</td>
<td></td>
</tr>
<tr>
<td>$0.12 \pm 0.02 \pm 0.12$</td>
<td>$0.02 \pm 0.01 \pm 0.02$</td>
<td></td>
</tr>
<tr>
<td>$0.93 \pm 0.20 \pm 0.65$</td>
<td>$0.43 \pm 0.09 \pm 0.00$</td>
<td></td>
</tr>
<tr>
<td>$3.25 \pm 0.54 \pm 0.81$</td>
<td>$2.29 \pm 0.45 \pm 0.37$</td>
<td></td>
</tr>
</tbody>
</table>
3rd generation scalar lepto-quarks and stops

<table>
<thead>
<tr>
<th>$S_T$ bin (low edge) [GeV]</th>
<th>Observed</th>
<th>200</th>
<th>280</th>
<th>350</th>
<th>420</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z(\ell\ell/\tau\tau)+$jets</td>
<td>0.00 ± 0.00 ± 0.00</td>
<td>0.00 ± 0.00 ± 0.00</td>
<td>0.14 ± 0.05 ± 0.14</td>
<td>1.76 ± 0.69 ± 1.17</td>
<td></td>
</tr>
<tr>
<td>Reducible</td>
<td>4.70 ± 0.80 ± 0.64</td>
<td>19.33 ± 3.23 ± 1.38</td>
<td>24.40 ± 4.08 ± 1.61</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$t\bar{t}$ (irreducible)</td>
<td>0.07 ± 0.49 ± 0.48</td>
<td>16.19 ± 1.92 ± 1.14</td>
<td>21.17 ± 2.53 ± 1.14</td>
<td></td>
<td></td>
</tr>
<tr>
<td>VV</td>
<td>0.03 ± 0.01 ± 0.03</td>
<td>0.23 ± 0.05 ± 0.17</td>
<td>0.16 ± 0.03 ± 0.10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Single-t</td>
<td>0.62 ± 0.13 ± 0.62</td>
<td>1.08 ± 0.23 ± 0.67</td>
<td>0.96 ± 0.20 ± 0.67</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Bkg.</td>
<td>9.41 ± 1.71 ± 1.02</td>
<td>36.97 ± 6.64 ± 1.93</td>
<td>48.45 ± 8.93 ± 2.39</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>480</th>
<th>540</th>
<th>610</th>
<th>680</th>
<th>770</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>37</td>
<td>41</td>
<td>24</td>
<td>24</td>
<td>13</td>
</tr>
<tr>
<td>4.00 ± 1.59 ± 3.08</td>
<td>2.42 ± 0.94 ± 1.56</td>
<td>3.30 ± 1.33 ± 3.01</td>
<td>1.38 ± 0.50 ± 0.47</td>
<td>0.32 ± 0.12 ± 0.23</td>
<td></td>
</tr>
<tr>
<td>21.28 ± 3.55 ± 1.37</td>
<td>17.63 ± 2.98 ± 1.29</td>
<td>14.07 ± 2.36 ± 1.32</td>
<td>11.01 ± 1.86 ± 1.05</td>
<td>6.41 ± 1.09 ± 0.76</td>
<td></td>
</tr>
<tr>
<td>22.99 ± 2.71 ± 1.31</td>
<td>23.58 ± 2.79 ± 1.33</td>
<td>16.11 ± 1.93 ± 0.98</td>
<td>15.38 ± 1.88 ± 1.18</td>
<td>9.95 ± 1.20 ± 0.78</td>
<td></td>
</tr>
<tr>
<td>0.01 ± 0.00 ± 0.01</td>
<td>0.09 ± 0.02 ± 0.06</td>
<td>0.20 ± 0.04 ± 0.12</td>
<td>0.25 ± 0.05 ± 0.15</td>
<td>0.02 ± 0.00 ± 0.02</td>
<td></td>
</tr>
<tr>
<td>0.38 ± 0.08 ± 0.38</td>
<td>1.56 ± 0.33 ± 0.91</td>
<td>0.00 ± 0.00 ± 0.00</td>
<td>1.25 ± 0.27 ± 0.70</td>
<td>0.00 ± 0.00 ± 0.00</td>
<td></td>
</tr>
<tr>
<td>48.66 ± 9.11 ± 3.63</td>
<td>45.28 ± 8.17 ± 2.59</td>
<td>33.68 ± 6.43 ± 3.43</td>
<td>29.27 ± 5.26 ± 1.80</td>
<td>16.69 ± 2.90 ± 1.11</td>
<td></td>
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</tbody>
</table>

Stop signal regions yields

<table>
<thead>
<tr>
<th></th>
<th>860</th>
<th>960</th>
<th>1100</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>8</td>
<td>9</td>
<td>6</td>
</tr>
<tr>
<td>2.84 ± 1.16 ± 2.84</td>
<td>0.08 ± 0.03 ± 0.08</td>
<td>0.15 ± 0.05 ± 0.00</td>
<td></td>
</tr>
<tr>
<td>3.61 ± 0.61 ± 0.68</td>
<td>1.50 ± 0.25 ± 0.37</td>
<td>1.59 ± 0.27 ± 0.34</td>
<td></td>
</tr>
<tr>
<td>7.46 ± 0.88 ± 0.66</td>
<td>3.57 ± 0.43 ± 0.47</td>
<td>2.68 ± 0.32 ± 0.30</td>
<td></td>
</tr>
<tr>
<td>0.00 ± 0.00 ± 0.00</td>
<td>0.00 ± 0.00 ± 0.00</td>
<td>0.00 ± 0.00 ± 0.00</td>
<td></td>
</tr>
<tr>
<td>1.54 ± 0.33 ± 1.04</td>
<td>0.00 ± 0.00 ± 0.00</td>
<td>0.00 ± 0.00 ± 0.00</td>
<td></td>
</tr>
<tr>
<td>15.44 ± 3.17 ± 3.17</td>
<td>5.15 ± 0.87 ± 0.60</td>
<td>4.43 ± 0.77 ± 0.46</td>
<td></td>
</tr>
</tbody>
</table>
e/µ/τ resonance search

• Events satisfy single-electron trigger for eµ and eτ_{had} and single-muon trigger for the µτ_{had} search.

• **Electron**: “tight” identification (calo shower shape, track matching with calo energy deposition, track quality…). |η| < 2.47, p_{T} > 25 GeV.

• **Muon**: Reconstructed tracks in both ID and MS. |η| < 2.5, p_{T} > 25 GeV.

• **Tau** (hadronic): Seeded by anti-k_{t} jets with cone ∆R = 0.4. 0.03 < |η| < 2.5, E_{T} > 20 GeV.

• **Jets**: from calorimeter energy depositions using the anti-k_{t} jet algorithm. |η| < 2.5, p_{T} > 20 GeV.
e/µ/τ resonance search

- The SM processes that can produce a $\ell \ell'$ signature are classified into:
  
  - **Irreducible backgrounds** (ttbar, $Z/\gamma^* (\rightarrow \ell\ell)$, diboson, Wt...) are estimated using MC samples and normalized to cross sections with higher-order corrections applied.
  
  - **Reducible backgrounds**: jet backgrounds where one or both of the $\ell$ come from a misidentified jet.

- Estimated using data in sub-regions of the signal regions (same cuts, extra cut in $E_T^{\text{miss}} < 30$ GeV). Then extrapolated to full region.
e/µ/τ resonance search

Event yields in the different regions:

<table>
<thead>
<tr>
<th>Process</th>
<th>$m_{E\tau} &lt; 200$ GeV</th>
<th>$m_{E\tau} &gt; 200$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$N_{e\mu}$</td>
<td>$N_{e\tau\text{had}}$</td>
</tr>
<tr>
<td>$Z/\gamma^* \rightarrow \tau\tau$</td>
<td>1880 ± 150</td>
<td>4300 ± 600</td>
</tr>
<tr>
<td>$Z/\gamma^* \rightarrow ee$</td>
<td>1050 ± 80</td>
<td></td>
</tr>
<tr>
<td>$Z/\gamma^* \rightarrow \mu\mu$</td>
<td>3030 ± 290</td>
<td></td>
</tr>
<tr>
<td>tt</td>
<td>760 ± 110</td>
<td>96 ± 14</td>
</tr>
<tr>
<td>Diboson</td>
<td>260 ± 27</td>
<td>57 ± 8</td>
</tr>
<tr>
<td>Single top quark</td>
<td>87 ± 8</td>
<td>11 ± 2</td>
</tr>
<tr>
<td>W + jets</td>
<td>420 ± 260</td>
<td>3500 ± 700</td>
</tr>
<tr>
<td>Multijet</td>
<td>37 ± 13</td>
<td>2200 ± 700</td>
</tr>
<tr>
<td>Total background</td>
<td>3440 ± 300</td>
<td>11200 ± 900</td>
</tr>
<tr>
<td>Data</td>
<td>3345</td>
<td>11212</td>
</tr>
</tbody>
</table>

**Systematic uncertainties:**

- Extrapolation from the subsample to the full sample for the W+jets background: 10%
- Theoretical uncertainties of the prompt-lepton processes: 5-10%
- Integrated luminosity: 3.9%
- Others: lepton trigger (1%), reconstruction and identification efficiencies (1-5%), energy/momentum scale/reconstruction (1-3%)...
e/\mu/\tau resonance search
e/μ/τ resonance search

\[ \lambda'_{311} \]

\[ \int L \, dt = 4.6 \, \text{fb}^{-1} \]
\[ \sqrt{s} = 7 \, \text{TeV} \]

\[ \lambda'_{311} = \begin{cases} 0.07, \quad \lambda_{132} = 0.07(1 \, \text{fb}^{-1} 7 \, \text{TeV}) \\
0.05, \quad \lambda_{132} = 0.05 \\
0.01, \quad \lambda_{132} = 0.01 \\
0.07, \quad \lambda_{132} = 0.07(1 \, \text{fb}^{-1} 7 \, \text{TeV}) \end{cases} \]

\[ m_{\tilde{\nu}_e}, m_{\tilde{\nu}_\mu}, m_{\tilde{\nu}_\tau} \quad [\text{GeV}] \]

\[ \lambda'_{311} \]

\[ \int L \, dt = 4.6 \, \text{fb}^{-1} \]
\[ \sqrt{s} = 7 \, \text{TeV} \]

\[ \lambda'_{311} = \begin{cases} 0.07, \quad \lambda_{233} = 0.07 \\
0.05, \quad \lambda_{233} = 0.05 \end{cases} \]

\[ m_{\tilde{\nu}_e}, m_{\tilde{\nu}_\tau} \quad [\text{GeV}] \]

\[ \lambda'_{311} \]

\[ \int L \, dt = 4.6 \, \text{fb}^{-1} \]
\[ \sqrt{s} = 7 \, \text{TeV} \]

\[ \lambda'_{311} = \begin{cases} 0.07, \quad \lambda_{133} = 0.07 \\
0.05, \quad \lambda_{133} = 0.05 \end{cases} \]

\[ m_{\tilde{\nu}_e}, m_{\tilde{\nu}_\tau} \quad [\text{GeV}] \]
Muon plus displaced vertex

- The focus of this analysis is the term $\lambda'_{2ij}$ in $\chi'_{ijk} L_i Q_j D_k$

- Look for a muon and many charged tracks originating from a single displaced vertex (DV).

  - Values of $\lambda'_{2ij}$ that allow the neutralino to decay in the detector volume.

- Events in muon-triggered sample required to contain at least one reconstructed DV identified using the Inner Detector, and a high-$p_T$ reconstructed muon.

- Background estimation:
  - Vertices from real hadronic interactions with gas molecules outside the beam pipe: control regions to extract contamination data-driven.
  - Purely random combinations of tracks (real or fake): estimated from the distance between two vertices in different events from control samples.
Muon plus displaced vertex

- No data events found in the signal region.
- Upper limits at 95% CL on $\sigma$ vs. the neutralino lifetime for different combinations of squark and neutralino masses

<table>
<thead>
<tr>
<th>Sample</th>
<th>$m_{\tilde{q}}$ [GeV]</th>
<th>$m_{\chi^0_1}$ [GeV]</th>
<th>$\sigma$ [fb]</th>
<th>$\langle y\beta\rangle_{\chi^0_1}$</th>
<th>$c_{\text{MC}}$ [mm]</th>
<th>$\lambda'_{211}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>MH</td>
<td>700</td>
<td>494</td>
<td>124.3</td>
<td>1.0</td>
<td>175</td>
<td>$0.2 \times 10^{-5}$</td>
</tr>
<tr>
<td>ML</td>
<td>700</td>
<td>108</td>
<td>124.3</td>
<td>3.1</td>
<td>101</td>
<td>$1.5 \times 10^{-5}$</td>
</tr>
<tr>
<td>HL</td>
<td>1000</td>
<td>108</td>
<td>11.9</td>
<td>5.5</td>
<td>220</td>
<td>$20.0 \times 10^{-5}$</td>
</tr>
</tbody>
</table>

\[ \text{700 GeV squark pair production (NLO+NLL)} \]
\[ \text{1.0 TeV squark pair production (NLO+NLL)} \]

$\text{BR}(\chi^0_1 \rightarrow \mu jj) = 100\%$

$\text{BR}(\chi^0_1 \rightarrow \mu jj) = 50\%$
Multi-jet searches: resolved jets

- **Jets** reconstructed using anti-$k_t$ algorithm with $R = 0.4$.
  - Energy deposits in the calorimeter weighted in the electromagnetic and the hadronic calorimeters separately.
  - B-tagging uses multivariate algorithms. 70% efficiency.

- **Triggers**
  - Signal regions: more than 6 jets with $p_T > 45$ GeV.
  - Control regions: prescaled triggers.

- Largest **background**: multijet production.
  - Estimated from data-driven techniques.
  - Start with a signal-depleted control region in data and project it into the signal region using a factor that is determined from a multi-jet simulation.
  - Correct for other minor background processes.
Multi-jet searches: resolved jets

- The **signal** and the **control regions** differ in the number of jets required:
  - \( \leq 5 \) jets: background \( \gg \) signal. Validate the background model for assigning systematic uncertainties.
  - \( > 5 \) jets: signal becomes significant. Candidate signal region.

- The formula used for the projections is:

\[
N_{\text{data}}^{n\text{-jet}} = \left( N_{\text{data}}^{m\text{-jet}} - N_{\text{MC}}^{m\text{-jet, OtherBGs}} \right) \times \left( \frac{N_{\text{MC}}^{n\text{-jet}}}{N_{\text{MC}}^{m\text{-jet}}} \right) + N_{\text{MC}}^{n\text{-jet, OtherBGs}}
\]
Multi-jet searches: resolved jets

• Final systematic uncertainties on the background chosen to cover the worst observed discrepancies of all projections from different jet multiplicities.
Multi-jet searches: resolved jets

- Each RPV decay produces two down-type quarks (different flavor) and one up-type quark.

- Cross-sections for gluino production don’t depend on $\lambda''_{ijk}$, so it’s not possible to set limits directly on individual $\lambda$ parameters.

- Results categorized based on the probability for an RPV decay to produce a t-quark, a b-quark or a c-quark.
  - Only one c-quark or t-quark per event, so $\text{BR}(t) + \text{BR}(c) \leq 1$.
  - Signal regions optimized for each of these hypotheses.
Multi-jet searches: resolved jets

6-quark model
Multi-jet searches: resolved jets

10-quark model
Multi-jet searches: boosted jets

- In a boosted scenario, the three quarks are collimated in a single fat jet.
  - Jet candidates are based on anti-\(k_t\) with \(R = 1.0\).
  - Use “\(N\)-subjettiness” variables, \(\tau_N\) to characterize how well a jet can be described as containing \(N\) or fewer \(k_t\) subjets.
    \[
    \tau_N = \frac{1}{d_0} \sum_k p_{T_k} \times \min(\delta R_{1k}, \delta R_{2k}, \ldots, \delta R_{N_k}) , \quad \text{with} \quad d_0 \equiv \sum_k p_{T_k} \times R
    \]
  - \(\tau_{32} = \tau_3 / \tau_2\) used.

- Also the multiplicity of \(R = 0.4\) jets provide some discriminating power.

<table>
<thead>
<tr>
<th>Selection</th>
<th>Baseline Selection</th>
<th>SR1</th>
<th>SR2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small-(R) ((R = 0.4)) jet (p_T^{\text{jet}})</td>
<td>(p_T^{\text{jet}} &gt; 30) GeV</td>
<td>(p_T^{\text{jet}} &gt; 30) GeV</td>
<td>(p_T^{\text{jet}} &gt; 30) GeV</td>
</tr>
<tr>
<td>Large-(R) ((R = 1.0)) jet (p_T^{\text{jet}})</td>
<td>(p_T^{\text{jet}} &gt; 200) GeV</td>
<td>(p_T^{\text{jet}} &gt; 200) GeV</td>
<td>(p_T^{\text{jet}} &gt; 350) GeV</td>
</tr>
<tr>
<td>Scalar sum (\sum_{i=1}^{N_{\text{jet}}^{R=4}} p_T^{\text{jet}})</td>
<td>(—)</td>
<td>600 GeV</td>
<td>(—)</td>
</tr>
<tr>
<td>Small-(R) jet multiplicity</td>
<td>(—)</td>
<td>(N_{\text{jet}}^{R=4} \geq 4)</td>
<td>(N_{\text{jet}}^{R=4} \geq 4)</td>
</tr>
<tr>
<td>Large-(R) jet multiplicity</td>
<td>(N_{\text{jet}} \geq 2)</td>
<td>(N_{\text{jet}} \geq 2)</td>
<td>(N_{\text{jet}} \geq 2)</td>
</tr>
<tr>
<td>Large-(R) jet mass</td>
<td>(—)</td>
<td>(m_{J_1,J_2}^{\text{jet}} &gt; 60) GeV</td>
<td>(m_{J_1,J_2}^{\text{jet}} &gt; 140) GeV</td>
</tr>
<tr>
<td>Large-(R) jet (\tau_{32})</td>
<td>(—)</td>
<td>(\tau_{32} &lt; 0.7)</td>
<td>(\tau_{32} &lt; 0.7)</td>
</tr>
</tbody>
</table>
Multi-jet searches: boosted jets
Multi-jet searches: boosted jets

• Standard model multijet production is the dominant background.

• Estimated using the “ABCD” method.

• Event yields in orthogonal control regions are used to predict the total number of events expected in the signal region.

• Rely on the inversion of some of the signal region selection criteria.

<table>
<thead>
<tr>
<th>Region</th>
<th>Jet ($J_1$) selections</th>
<th>Jet ($J_2$) selections</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CR-A</td>
<td>$m_{\text{jet}} &lt; M_{\text{threshold}}$</td>
<td>$m_{\text{jet}} &lt; M_{\text{threshold}}$</td>
<td>Low-mass jets, to validate $\tau_{32}$ shape</td>
</tr>
<tr>
<td>CR-B</td>
<td>$m_{\text{jet}} &gt; M_{\text{threshold}}$</td>
<td>$m_{\text{jet}} &lt; M_{\text{threshold}}$</td>
<td>Signal-like leading jet, to validate $m_{\text{jet}}$</td>
</tr>
<tr>
<td>CR-C</td>
<td>$m_{\text{jet}} &lt; M_{\text{threshold}}$</td>
<td>$m_{\text{jet}} &gt; M_{\text{threshold}}$</td>
<td>Signal-like subleading jet, to validate $m_{\text{jet}}$</td>
</tr>
</tbody>
</table>

$N_{SR} = N_{CR-C} \times \left( \frac{N_{CR-B}}{N_{CR-A}} \right) \times \alpha$

$\alpha = \left( \frac{N_{SR}/N_{CR-C}}{N_{CR-B}/N_{CR-A}} \right)_{MC}$