Excited QCD 2016
Costa da Caparica, Lisbon, Portugal
6-12 March 2016

QCD at high temperatures & finite densities
- heavy-ion collisions, jets, diffraction, hadronisation
- quark-gluon plasma
- holography, colour-glass condensate
- compact stars, applications to astrophysics

QCD at low energies
- excited hadrons
- new resonances
- glueballs, multiquarks

Searches for Supersymmetry and Exotic phenomena with the ATLAS Detector

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Representing the ATLAS collaboration

More information
https://indico.cern.ch/event/453434/
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ATLAS Run-1 Recap

• No other clear indications of new physics beyond the SM
  – Need to cast wide a net as possible even with some theoretical guidance
  – Need to cover broad phase spaces: many different detector signatures, large range of masses, large span in production rates

• Run 1 results have been extremely useful to kill some models or narrow down their allowed phase spaces

- Many extensions of the SM have been developed over the past decades:
  - Supersymmetry
  - Extra-Dimensions
  - Technicolor(s)
  - Little Higgs
  - No Higgs
  - GUT
  - Hidden Valley
  - Leptoquarks
  - Compositeness
  - $4^{th}$ generation ($t', b'$)
  - LRSM, heavy neutrino
  - What else?

(for illustration only)
2015 data-taking

- 2015 dataset at 13 TeV:
  - 3.9 fb⁻¹ recorded
  - 3.3 fb⁻¹ "all good" for BSM searches
  - $L^{\text{inst}} = 5.1 \times 10^{33}$ cm² s⁻¹

- New 4th innermost layer of pixel in ATLAS: the IBL:
  at 3.3 cm vs 5.05 cm for the 2nd layer

- Improve $b$-tagging performance which is important for several BSM searches

**ATLAS performance close to or exceeding design specs in all compartments**
Strategy:

- Define selection based on signal signatures and background (bkg) kinematics.
- Compare data to Standard Model bkg (Monte Carlo (MC) + data driven) and MC signal predictions → data consistent with bkg+signal would be evidence for new physics.

No evidence for new physics:

- Limits typically set on cross-section x branching fraction ($\sigma \times BR$).
- Comparisons provided for specific models, but usually possible for reader to constrain additional models.
Global symmetry between fermions & bosons: all SM particles have SUSY partners

\[
Q | \text{fermion} \rangle = | \text{boson} \rangle
\]

\[
Q | \text{boson} \rangle = | \text{fermion} \rangle
\]

\[
S_{\text{SUSY}} = S_{\text{SM}}^{-1/2}
\]

\[
R = (-1)^{2s}(-1)^{3B}(-1)^L
\]

Why SUSY?

- Solves the hierarchy problem
- Provides the dark matter candidate: if R-parity is conserved, lightest SUSY particle (LSP, neutralino) is stable
- Extends the Poincare group, provides unification with gravity
- Required for the string theory
- ... and more others ...
Classification of SUSY searches

**Production modes**

- **Electroweak**
  - Gluinos/squarks
  - Third generation

- **Strong**
  - Inclusive searches for $\tilde{q}$ and $\tilde{g}$
    - Large cross-section
  - Dedicated searches for $\tilde{t}_1$ and $\tilde{b}_1$
    - Final state similar to the SM bkg
  - Searches for $\tilde{\chi}^0_1$ and $\tilde{\chi}^{\pm}_1$
    - Low cross-section
    - Multi-leptons final states with low SM bkg
  + Dedicated searches for long-lived particles and RPV SUSY
SUSY searches: from 8 TeV to 13 TeV

From http://inspirehep.net/record/1326406

- large increase of SUSY cross-section from 8 to 13 TeV:
  - $\sigma(\tilde{g}\tilde{g}) \times 30$ for $m(\tilde{g}) = 1.4$ TeV
  - $\sigma(\tilde{t}\tilde{t}) \times 8$ for $m(\tilde{t}) = 700$ GeV
  - $\sigma(\tilde{\chi}\tilde{\chi}) \times 4$ for $m(\tilde{\chi}) = 500$ GeV

- focus on gluino and third generation squarks searches with 2015 data, with a discovery potential beyond Run-1 limits even with 3 fb$^{-1}$ of 13 TeV data

- discovery potential of EW SUSY beyond Run-1 limits will be reached with 2016 data
Electrons:
- ID efficiencies measured in 2015 data to derive MC scale factors
- calibration based on run 1 with MC extrapolations

Muons:
- ID and reco efficiencies measured in 2015 data
- energy scale and resolution taken also from 2015 data

excellent agreement between data and MC

Electrons and Muons calibrated with Z events
Differences in efficiency and energy scale corrected
jets:
- Use Run-1 knowledge to extrapolate systematic uncertainties for run 2
- JES studies in 2015 data with photon-jet and multi-jets balance

b-tagging:
- improvements in algorithms and with new IBL
  - b-tagging efficiency increased by 10% for the same light jet rejection
- MC calibration validated in data with $t\bar{t}$ events
- new $E_T$ calculation with a track-based soft term (TST) combined with calorimeter-based measurements for hard objects

- less sensitivity to pile-up than with calorimeter-based soft term (CST)

- systematic uncertainties based on MC, and validated in data
Results and interpretations for 7 analyses

1-\(l\) + jets + \(E_T\) analysis  
ATLAS-CONF-2015-076

0-\(l\) + 2-6 jets + \(E_T\) analysis  
ATLAS-CONF-2015-062

0-\(l\) + 7-10 jets + \(E_T\) analysis  
ATLAS-CONF-2015-077

0-1-\(l\) + 3-4 \(b\)-jets + \(E_T\) analysis  
ATLAS-CONF-2015-067

2-\(l\) same-sign / 3-\(l\) analysis  
ATLAS-CONF-2015-078

\(Z \rightarrow ll + E_T\) analysis  
ATLAS-CONF-2015-082

0-\(l\) + 2 \(b\)-jets + \(E_T\) analysis  
ATLAS-CONF-2015-066
Search for gluino pair production in final states with 1 lepton, jets and $E_T$

**ATLAS-CONF-2015-076**

- **4 hard-ℓ SRs:**
  - $p_T > 35$ GeV lepton
  - No additional leptons with $p_T > 10$ GeV
  - 4-6 jets

- **2 soft-ℓ SRs:**
  - $p_T > 7(6)$ GeV for $e(\mu)$ and $p_T < 35$ GeV
  - No additional $e(\mu)$ with $p_T > 7(6)$ GeV
  - 2 or 5 jets

- Main backgrounds: $t\bar{t}$ and $W$ +jets events
- Suppressed with cuts on transverse mass
- Estimated by normalising the MC in CRs
  - Ex: soft $e+2j$: split CR with low $m_T$ and $E_T$:
    - $t\bar{t}$ CR: $\geq 1$ $b$-jet
    - $W$ +jets CR: $= 0$ $b$-jet

- Subdominant background from MC
Overall good agreement between expected background and observation

Largest deviation of $2\sigma$ observed in the SR with 1 hard lepton + 6 jets:

- 1 electron: $\text{exp} = 1.9 \pm 0.6$, $\text{obs} = 2$
- 1 muon: $\text{exp} = 2.5 \pm 0.8$, $\text{obs} = 8$
0-1 + 2-6 jets + $E_T$ analysis overview

- Search for gluino and squark pair production in final states with 0 lepton, jets and $E_T$

- Define 7 signal regions to probe all scenarios
- From 2 to $\geq 6$ jets to target different models
- Different $m_{\text{eff}}$ cuts to probe different mass splittings
7 SRs with 2-6 jets & different cuts
- Targeting different models

Veto leptons with $p_T > 10$ GeV

4 CRs for each SR, to obtain background from
- Multi-jet
- $Z(\rightarrow \nu\nu) +$jets
- $W(\rightarrow \ell\nu) +$jets
- $tt$, single-$t$

Background from MC
- Di-boson

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Signal Region</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_T^{\text{miss}}$ [GeV] &gt;</td>
<td>200</td>
</tr>
<tr>
<td>$p_T(j_1)$ [GeV] &gt;</td>
<td>200 300</td>
</tr>
<tr>
<td>$p_T(j_2)$ [GeV] &gt;</td>
<td>200 50 200</td>
</tr>
<tr>
<td>$p_T(j_3)$ [GeV] &gt;</td>
<td>100</td>
</tr>
<tr>
<td>$p_T(j_4)$ [GeV] &gt;</td>
<td>100</td>
</tr>
<tr>
<td>$p_T(j_5)$ [GeV] &gt;</td>
<td>100</td>
</tr>
<tr>
<td>$p_T(j_6)$ [GeV] &gt;</td>
<td>100</td>
</tr>
<tr>
<td>$\Delta \phi(j_{1,2,3}, E_T^{\text{miss}})_{\text{min}} &gt; 0.8$</td>
<td>0.4 0.4 0.8 0.4</td>
</tr>
<tr>
<td>$\Delta \phi(j_{i&gt;3}, E_T^{\text{miss}})_{\text{min}} &gt;$</td>
<td>0.2</td>
</tr>
<tr>
<td>$E_T^{\text{miss}}/\sqrt{H_T}$ [GeV$^{1/2}$] &gt;</td>
<td>15 20</td>
</tr>
<tr>
<td>Aplanarity &gt;</td>
<td>0.04</td>
</tr>
<tr>
<td>$E_T^{\text{miss}}/m_{\text{eff}}(N_j) &gt;$</td>
<td>0.2 0.25 0.2</td>
</tr>
<tr>
<td>$m_{\text{eff}}(\text{incl.})$ [GeV] &gt;</td>
<td>1200 1600 2000 2200 1600 1600 2000</td>
</tr>
</tbody>
</table>
Main backgrounds: \((Z \rightarrow \nu\nu)\)+jets, \(W\)+jets, \(tt\) and single top events with hadronic taus

- normalise the MC in 3 dedicated CRs with same jets \(p_T\) and \(m_{\text{eff}}\) cuts as the SRs:
  - \((Z \rightarrow \nu\nu)\)+jets CR
    - \(\gamma\)+jets
    - \(p_T(\gamma) > 130\) GeV
    - treat the photon as \(\nu\) in \(E_T\)
  - \(W\)+jets CR
    - 1-lepton treated as a jet
    - \(30 < m_T < 100\) GeV
    - \(b\)-jet veto
  - top CR
    - 1-lepton treated as a jet
    - \(30 < m_T < 100\) GeV
    - \(\geq b\)-jet

- sub-dominant diboson contribution estimated from MC
- residual contribution from multi-jets events with fake \(E_T\) estimated in a CR with reverted cuts on \(\Delta\phi_{\text{min}}(E_T, jets)\) and \(E_T / m_{\text{eff}}\)
$0-1+2-6$ jets $+E_T$: Results

Expected and observed event count in each SR:

- **ATLAS Preliminary**
- $s=13$ TeV, $3.2$ fb$^{-1}$

Data 2015
- SM Total
- Multi-jet
- W+jets
- $t\bar{t}$ ($t\bar{t}$EW) & single top
- Z+jets
- Diboson

Number of events

<table>
<thead>
<tr>
<th>Signal Region</th>
<th>Number of Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>2l</td>
<td>10$^7$</td>
</tr>
<tr>
<td>2j, 2m</td>
<td>10$^6$</td>
</tr>
<tr>
<td>2l</td>
<td>10$^5$</td>
</tr>
<tr>
<td>2j, 2m</td>
<td>10$^4$</td>
</tr>
<tr>
<td>2l</td>
<td>10$^3$</td>
</tr>
<tr>
<td>2j, 2m</td>
<td>10$^2$</td>
</tr>
</tbody>
</table>

**SR with 2 jets cover the whole plane**

exclude squark masses up to $\sim 1$ TeV

**interpretation with squarks**

$\tilde{q}\tilde{q} \rightarrow \tilde{q}q\tilde{\chi}_1^0$

0-lepton + 2-6 jets + $E_T^{miss}$

$s = 13$ TeV, $3.2$ fb$^{-1}$

**ATLAS Preliminary**

- Observed limit ($\pm 1\sigma_{SUSY}$)
- Expected limit ($\pm 1\sigma_{exp}$)

ATLAS 8 TeV, $20.3$ fb$^{-1}$

All limits at 95% CL

**ATLAS Preliminary**

- Observed limit ($\pm 1\sigma_{SUSY}$)
- Expected limit ($\pm 1\sigma_{exp}$)

ATLAS 8 TeV, $20.3$ fb$^{-1}$

All limits at 95% CL
Search for gluino pair production with complex decay chains

- 6 SRs with 7-8 $p_T > 80$ GeV jets, incl. 0-2 $b$-jets
  (trigger : 5 jets with $p_T > 70$ GeV)
- 9 SRs with 8-10 $p_T > 50$ GeV jets, incl. 0-2 $b$-jets
  (trigger : 6 jets with $p_T > 45$ GeV)
- No leptons with $p_T > 10$ GeV

- $tt$, $V$+jets background obtained from CRs containing a lepton with $p_T > 20$ GeV
- Multijet background from CRs with 1 jet less.
- Utilize near invariance of $E_T^{miss}/\sqrt{H_T}$ wrt. $N_{jets}$
  (shape is almost invariant wrt $N_{jets}$) when MET originates from calorimeter mismeasurement
  - Checked in VRs

**ATLAS-CONF-2015-077**
• SR: \( \frac{E_T^{miss}}{\sqrt{H_T}} > 4 \sqrt{\text{GeV}} \)

• Distribution normalization:
\( \frac{E_T^{miss}}{\sqrt{H_T}} < 1.5 \sqrt{\text{GeV}} \)

Overall good agreement between expected background and data in the 15 SR
Expected and observed event count in each SR:

<table>
<thead>
<tr>
<th>Signal region</th>
<th>Fitted background</th>
<th>Obs events</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Multijet</td>
<td>Leptonic</td>
</tr>
<tr>
<td>8j50</td>
<td>109.3 ± 6.8</td>
<td>79 ± 25</td>
</tr>
<tr>
<td>8j50-1b</td>
<td>76.7 ± 2.6</td>
<td>61 ± 21</td>
</tr>
<tr>
<td>8j50-2b</td>
<td>33.8 ± 2.1</td>
<td>33 ± 13</td>
</tr>
<tr>
<td>9j50</td>
<td>16.8 ± 1.2</td>
<td>12.8 ± 5.4</td>
</tr>
<tr>
<td>9j50-1b</td>
<td>13.5 ± 1.9</td>
<td>10.2 ± 4.9</td>
</tr>
<tr>
<td>9j50-2b</td>
<td>6.4 ± 1.6</td>
<td>5.8 ± 3.3</td>
</tr>
<tr>
<td>10j50</td>
<td>2.61 ± 0.60</td>
<td>1.99 ± 0.62</td>
</tr>
<tr>
<td>10j50-1b</td>
<td>2.42 ± 0.62</td>
<td>1.44 ± 0.49</td>
</tr>
<tr>
<td>10j50-2b</td>
<td>1.40 ± 0.87</td>
<td>0.83 ± 0.37</td>
</tr>
<tr>
<td>7j80</td>
<td>40.0 ± 5.1</td>
<td>30 ± 12</td>
</tr>
<tr>
<td>7j80-1b</td>
<td>29.1 ± 3.2</td>
<td>20.8 ± 10</td>
</tr>
<tr>
<td>7j80-2b</td>
<td>11.5 ± 1.6</td>
<td>11.0 ± 4.9</td>
</tr>
<tr>
<td>8j80</td>
<td>4.5 ± 1.9</td>
<td>4.9 ± 2.1</td>
</tr>
<tr>
<td>8j80-1b</td>
<td>3.9 ± 1.5</td>
<td>3.8 ± 2.1</td>
</tr>
<tr>
<td>8j80-2b</td>
<td>1.72 ± 0.92</td>
<td>2.3 ± 1.1</td>
</tr>
</tbody>
</table>

pMSSM model

- for $m(\tilde{\chi}^0_1) < 500$ GeV and $m(\tilde{g}) > 1200$ GeV: $\tilde{g} \to q\bar{q} \tilde{\chi}^0_1$ becomes dominant
- for $m(\tilde{\chi}^\pm_1) > 500$ GeV and $m(\tilde{g}) < 1200$ GeV: $\tilde{g} \to \tilde{\chi}^\pm_1$ becomes dominant

\[
m(\tilde{\chi}^\pm_1) = \frac{m(\tilde{g}) + m(\tilde{\chi}^0_1)}{2}
\]

\[
m(\tilde{\chi}^0_2) = \frac{m(\tilde{\chi}^\pm_1) + m(\tilde{\chi}^0_1)}{2}
\]
Searches with at least 3 or more b-jets

- Gluino-mediated stop pair production: **ATLAS-CONF-2015-067**
  - very rich final state
  - 2 channels with \( = 0 \) or \( \geq 1 \) lepton
    - require high jets and \( b \)-jets multiplicities
    - use jet substructure techniques to probe boosted topologies with large-R jets

- Gluino-mediated sbottom pair production:
  - 0-lepton channel only
  - require high \( b \)-jets multiplicity
  - Main discriminant variables to reject backgrounds are \( E_T \) and \( m_{\text{eff}} \)

8 SRs:
- \( \geq 3 \) \( b \)-jets
- 0 or 1 lepton
- 0 or \( \geq 1 \) top (\( R = 1 \) jet)

MET distributions in some SRs:
systematics dominated by $t\bar{t}$ modeling and $b$-tagging unc.

No significant excess in data
exclude gluino masses up to $\sim 1.7$ TeV

ATLAS-CONF-2015-067

No significant excess in data
exclude gluino masses up to $\sim 1.8$ TeV
very low SM bkg, broad sensitivity to many SUSY scenarios with leptons in the decay chain:

-Events selected with a logical OR combination of $E_T$ and di-lepton triggers
-4 signal regions defined according to the leptons, $b$-jets, jets, $E_T$ and $m_{eff}$:
  - 3 main sources of backgrounds:
    - fake+non-prompt leptons
    - electrons charge flip
    - irreducible bkg

<table>
<thead>
<tr>
<th>Signal region</th>
<th>$N_{signal\ lept}$</th>
<th>$N_{2\text{jets}}$</th>
<th>$N_{50\text{jets}}$</th>
<th>$E_{T\ miss}$ [GeV]</th>
<th>$m_{eff}$ [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SR0b3j</td>
<td>$\geq 3$</td>
<td>$=0$</td>
<td>$\geq 3$</td>
<td>$&gt;200$</td>
<td>$&gt;550$</td>
</tr>
<tr>
<td>SR0b5j</td>
<td>$\geq 2$</td>
<td>$=0$</td>
<td>$\geq 5$</td>
<td>$&gt;125$</td>
<td>$&gt;650$</td>
</tr>
<tr>
<td>SR1b</td>
<td>$\geq 2$</td>
<td>$\geq 1$</td>
<td>$\geq 4$</td>
<td>$&gt;150$</td>
<td>$&gt;550$</td>
</tr>
<tr>
<td>SR3b</td>
<td>$\geq 2$</td>
<td>$\geq 3$</td>
<td>-</td>
<td>$&gt;125$</td>
<td>$&gt;650$</td>
</tr>
</tbody>
</table>

- from jet misID, HF decay, or $\gamma$ conversion
- data-driven estimate with the loose to tight matrix method
- from hard brem $\gamma$ conversion
- charge flip rate from data in $Z/\gamma^* \rightarrow e^+ e^-$ events
- apply this rate in 2L OS SR to get the 2L SS bkg in corresponding SR
- $tt+V, VV, VVV$ events with 2 SS or 3 real leptons:
  - estimated from MC and Validated with data in VRs
  - largest deviation of 1.3 $\sigma$ in the $tt+V$ VR

ATLAS-CONF-2015-078
2-/3-l same-sign / 3-/4-analysis Results

<table>
<thead>
<tr>
<th></th>
<th>SR0b3j</th>
<th>SR0b5j</th>
<th>SR1b</th>
<th>SR3b</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed events</td>
<td>3</td>
<td>3</td>
<td>7</td>
<td>1</td>
</tr>
<tr>
<td>Total bkg events</td>
<td>$2.4 \pm 0.7$</td>
<td>$0.98 \pm 0.32$</td>
<td>$4.3 \pm 1.0$</td>
<td>$0.78 \pm 0.24$</td>
</tr>
<tr>
<td>$p(s = 0)$</td>
<td>$0.33$</td>
<td>$0.06$</td>
<td>$0.12$</td>
<td>$0.36$</td>
</tr>
<tr>
<td>Fake/non-prompt leptons</td>
<td>$&lt; 0.2$</td>
<td>$0.04^{+0.17}_{-0.04}$</td>
<td>$0.8 \pm 0.8$</td>
<td>$0.12 \pm 0.16$</td>
</tr>
<tr>
<td>Charge flip</td>
<td>$0.02 \pm 0.01$</td>
<td>$0.60 \pm 0.12$</td>
<td>$0.19 \pm 0.06$</td>
<td>$0.21 \pm 0.09$</td>
</tr>
<tr>
<td>$t\bar{t}W, t\bar{t}Z$</td>
<td>$0.13 \pm 0.06$</td>
<td>$0.11 \pm 0.06$</td>
<td>$2.0 \pm 0.7$</td>
<td>$0.21 \pm 0.09$</td>
</tr>
<tr>
<td>$WZ$</td>
<td>$1.5 \pm 0.5$</td>
<td>$0.61 \pm 0.25$</td>
<td>$0.17 \pm 0.09$</td>
<td>$&lt; 0.02$</td>
</tr>
<tr>
<td>$W^\pm W^\pm jj$</td>
<td>$&lt; 0.14$</td>
<td>$&lt; 0.14$</td>
<td>$&lt; 0.03$</td>
<td>$&lt; 0.03$</td>
</tr>
<tr>
<td>$ZZ$</td>
<td>$0.6 \pm 0.4$</td>
<td>$0.6 \pm 0.4$</td>
<td>$0.02 \pm 0.01$</td>
<td>$&lt; 0.01$</td>
</tr>
<tr>
<td>Triboson</td>
<td>$0.09 \pm 0.05$</td>
<td>$0.05 \pm 0.04$</td>
<td>$0.7 \pm 0.4$</td>
<td>$0.26 \pm 0.14$</td>
</tr>
<tr>
<td>Rare</td>
<td>$0.05 \pm 0.04$</td>
<td>$0.05 \pm 0.04$</td>
<td>$0.7 \pm 0.4$</td>
<td>$0.26 \pm 0.14$</td>
</tr>
</tbody>
</table>

**ATLAS-CONF-2015-078**
Search for gluino (or squark) pair production with Z in the decay chains

**Dominant backgrounds:**

- $tt$, $t\bar{t}$:
  - Using CR with different-flavor leptons
- $Z/\gamma^* +$ jets:
  - Using CR with $\gamma +$ jets

- Check excess observed in the ATLAS
- Run-1 8 TeV analysis:
  - 3 (1.7) $\sigma$ excess in the $ee$ ($\mu\mu$) channel

- Reproduce the Run-1 signal region:
  - 2 $e$ ($e^+ e^-$ or $\mu^+ \mu^-$) with $p_T > 50.25$ GeV and $81 < m(ee) < 101$ GeV
  - $\geq 2$ jets with $\Delta\phi_{\text{min}}(E_T, \text{jets}) > 0.4$
  - $E_T > 225$ GeV and $H_T > 600$ GeV

**Table:**

<table>
<thead>
<tr>
<th>$E_T^{\text{miss}}$ [GeV]</th>
<th>$H_T$ [GeV]</th>
<th>$n_{\text{jets}}$</th>
<th>$m_{tt}$ [GeV]</th>
<th>SF/DF</th>
<th>$\Delta\phi(\text{jet}_{12}, p_T^{\text{miss}})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$&gt; 225$</td>
<td>$&gt; 600$</td>
<td>$\geq 2$</td>
<td>$81 &lt; m_{tt} &lt; 101$</td>
<td>SF</td>
<td>$&gt; 0.4$</td>
</tr>
</tbody>
</table>
10.3 ± 2.3 events expected
21 observed (10 ee + 11 µµ)
excess of 2.2 σ
CMS result: Exp = 12^{+4.0}_{-2.8}, obs = 12

ATLAS-CONF-2015-082
Search for direct sbottom squark production

\[ p \xrightarrow{\tilde{b}} \tilde{\chi}_1^0 \]

4 SRs:
- 3 “SRA” target pair production
- SRB target pair production with ISR jet

Main discriminator: contravese mass,
\[ m_{CT}^2(v_1, v_2) = [E_T(v_1) + E_T(v_2)]^2 - [p_T(v_1) - p_T(v_2)]^2 \]

Can be used to measure \( m_b \)
## Signal region channels

<table>
<thead>
<tr>
<th></th>
<th>SRA250</th>
<th>SRA350</th>
<th>SRA450</th>
<th>SRB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed events</td>
<td>22</td>
<td>6</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>Fitted bkg events</td>
<td>40 ± 8</td>
<td>9.5 ± 2.6</td>
<td>2.2 ± 0.6</td>
<td>13.1 ± 3.2</td>
</tr>
<tr>
<td>Fitted $t\bar{t}$ events</td>
<td>0.9 ± 0.4</td>
<td>0.37 ± 0.16</td>
<td>0.06 ± 0.03</td>
<td>5.9 ± 2.4</td>
</tr>
<tr>
<td>Fitted single top events</td>
<td>2.1 ± 1.3</td>
<td>0.54 ± 0.37</td>
<td>0.15 ± 0.10</td>
<td>1.2 ± 0.8</td>
</tr>
<tr>
<td>Fitted $W+$jets events</td>
<td>6.3 ± 2.4</td>
<td>1.3 ± 0.6</td>
<td>0.41 ± 0.23</td>
<td>1.2 ± 0.6</td>
</tr>
<tr>
<td>Fitted $Z+$jets events</td>
<td>30 ± 7</td>
<td>7.1 ± 2.4</td>
<td>1.5 ± 0.5</td>
<td>3.3 ± 1.4</td>
</tr>
<tr>
<td>(Alt. method $Z+$jets events)</td>
<td>(33 ± 7)</td>
<td>(7.2 ± 1.9)</td>
<td>(2.7 ± 0.9)</td>
<td>-</td>
</tr>
<tr>
<td>Fitted “Other” events</td>
<td>0.7 ± 0.6</td>
<td>0.1 ± 0.1</td>
<td>0.02 ± 0.02</td>
<td>1.4 ± 0.4</td>
</tr>
</tbody>
</table>

---

### ATLAS Preliminary

**Bottom squark pair production, $\tilde{b}_1 \rightarrow b \tilde{\chi}_1^0$**

**Observed limit (±1 $\sigma_{\text{theory}}$)**

**Expected limit (±1 $\sigma_{\exp}$)**

**All limits at 95% CL**

**Best SR**

---

**ATLAS-CONF-2015-066**
Leptonic final states:
- $e/\mu$ and missing energy [ATLAS-CONF-2015-063]
- $e^+e^-, \mu^+\mu^-$ [ATLAS-CONF-2015-070]
- $e^+\mu^-$ [ATLAS-CONF-2015-072]

Di-jet/photon mass spectra:
- jet-jet [arXiv:1512.01530v2]
- $\gamma$-jet [arXiv:1512.05910]
- $\gamma\gamma$ [ATLAS-CONF-2015-081]

“Exotics” means direct searches for particles/phenomena:
- beyond the Standard Model
- not supersymmetry or BSM Higgs

Leaves a huge range of hypotheses that explain one or more of the mysteries in the SM

These searches benefit greatly from the increased LHC energy
with ~3 fb-1 at 13 TeV, we have already exceeded Run-1 sensitivity in many cases
• Reconstruct exactly one isolated lepton with $p_T > 65\text{GeV}$.
• The missing transverse energy in the event must exceed $55\text{ GeV}$.
• Search in the transverse mass:

$$m_T = \sqrt{2p_T E_T^{\text{miss}}(1 - \cos \phi_{\ell\nu}),}$$

• Test for heavy spin-1 W' bosons.
  Event with one electron
• Select a pair of leptons
  – well isolated
  – matched to the primary vertex
  – $E_T$ or $p_T > 30$ GeV
• Main background from Drell-Yan $Z/\gamma$ production.
• Test di-lepton masses up to 5 TeV
• Search for heavy $Z'$ bosons or contact interactions.

New physics could alter the $ee$ and $\mu\mu$ mass distributions in two ways:

- a new resonance ($Z'$) would create a bump
- non-resonant effects could change the shape

[ATLAS-CONF-2015-070]
Opposite-sign dileptons

}\textit{p} values:

\begin{itemize}
  \item \textbf{ATLAS} Preliminary $\sqrt{s} = 13 \text{ TeV}, \int L dt = 3.2 \text{ fb}^{-1}$
  \item Observed $p_{\text{e}0}'$, $Z'\rightarrow \ell\ell$
  \item Global significance for largest excess
\end{itemize}

$Z'$ and contact interaction limits:

\begin{itemize}
  \item $\text{ATLAS}$ Preliminary $\sqrt{s} = 13 \text{ TeV}, 3.2 \text{ fb}^{-1}$
  \item $Z' \rightarrow \ell\ell$
  \item Expected limit
  \item Observed limit
  \item $\tilde{Z}'_{\text{SSM}}$
  \item $Z'_{\chi}$
  \item $Z'_{\nu}$
\end{itemize}
Highly sensitive channel for new neutral resonance with lepton-flavor violating decays

- Require different flavor leptons
- Main background from $t\bar{t} \rightarrow W^+W^-$
- Test for LFV in $Z'$ models and quantum black holes in RS and ADD models.
- No excess observed.
di-jet, $\gamma\gamma$, $\gamma$-jet mass spectra

Tests for $q^*$, quantum black holes, $Z'/W'$, heavy Higgs models
Searches for di-jet resonances

- Sensitive to new particles in s- and t-channels, respectively
  - any new particle produced at the LHC must couple to quarks/gluons
  - dijet search is sensitive to all such particles

- Jet selections:
  - $p_T(j_1) > 440$ GeV, $p_T(j_2) > 50$ GeV
  - compatibility with primary vertex

- Multi-jet background reduced with requirement on rapidity difference $|y^*| = |(y_1-y_2)/2| < 0.6$

- Di-jet mass resolution $\sim 2\%$ over full mass range
- Background modeled with a power law function.
- Look for a narrow resonance or an excess.
Searches for di-jet resonances

ATLAS

- Data
- SM
- $\Delta m, \eta_L = +1, \Lambda = 12 \text{ TeV}$
- $\Delta m, \eta_L = -1, \Lambda = 17 \text{ TeV}$
- QBH (QBH), $M_{\text{qb}} = 8.0 \text{ TeV}$

Theoretical uncertainties
Total uncertainties

4.6 < $m_{jj}$ < 5.4 TeV
4.0 < $m_{jj}$ < 4.6 TeV
3.4 < $m_{jj}$ < 4.0 TeV
3.1 < $m_{jj}$ < 3.4 TeV
2.8 < $m_{jj}$ < 3.1 TeV
2.5 < $m_{jj}$ < 2.8 TeV

Limits on benchmark Gaussian signals:
- The m(jj) region above 5.4 TeV was previously unexplored.
- Large improvements in the exclusion limits over Run I.

<table>
<thead>
<tr>
<th>Model</th>
<th>95% CL Exclusion limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quantum black holes, ADD (BLACKMAX generator)</td>
<td>5.6 TeV  8.1 TeV  8.1 TeV</td>
</tr>
<tr>
<td>Quantum black holes, ADD (QBH generator)</td>
<td>5.7 TeV  8.3 TeV  8.3 TeV</td>
</tr>
<tr>
<td>Quantum black holes, RS (QBH generator)</td>
<td>--        5.3 TeV  5.1 TeV</td>
</tr>
<tr>
<td>Excited quark</td>
<td>4.1 TeV  5.2 TeV  4.9 TeV</td>
</tr>
<tr>
<td>$W^*$</td>
<td>2.5 TeV  2.6 TeV  2.6 TeV</td>
</tr>
<tr>
<td>Contact interactions ($\eta_{LL} = +1$)</td>
<td>8.1 TeV  12.0 TeV  12.0 TeV</td>
</tr>
<tr>
<td>Contact interactions ($\eta_{LL} = -1$)</td>
<td>12.0 TeV 17.5 TeV  18.1 TeV</td>
</tr>
</tbody>
</table>

\[ \text{di-jet results} \]

\[ \text{• Large improvements in the exclusion limits over Run I.} \]
• Test quantum black holes (QBH) and excited quark models
• Events are selected with a well isolated photon. Both the photon and jet must have $E_T > 150$ GeV
• $\gamma$+jet mass resolution is $\sim 2.5\%$ up to 6 TeV
• Exclusion limits surpass Run I analysis.
- Select two isolated photons
- Photon energy calibrated using $Z \rightarrow ee$ events
- Energy selections relative to the signal mass
- Signal efficiencies range between 20-45% depending on the mass and production mechanism
- Main background is from non-resonant di-photon (90%) and jet (10%) production
• Run II shows some excess at \( m(\gamma\gamma) \sim 750 \) GeV
• Significance: local \( \sim 3.6\sigma \), global \( \sim 2.0 \) sigma, estimated using a narrow width signal model.
• Using width \( \Gamma \sim 45 \) GeV gives larger significances: 3.9\( \sigma \) local (2.3\( \sigma \) global)
• Run I analysis did not see excess, but is still compatible within 2.3\( \sigma \) of the current result assuming gluon fusion production.

**Exclusion Limits**

```latex
\begin{align*}
& \text{ATLAS Preliminary} \\
& \gamma\gamma = 13 \text{ TeV, } 3.2 \text{ fb}^{-1} \\
& 95\% \text{ CL Upper Limit on } \sigma_{el} \times \text{BR (fb)}
\end{align*}
```

**Local p-value in NWA**

```latex
\begin{align*}
& \text{ATLAS Preliminary} \\
& \gamma\gamma = 13 \text{ TeV, } 3.2 \text{ fb}^{-1} \\
& \text{Local p-value}
\end{align*}
```
• successful commissioning of the ATLAS detector upgrade for Run-2
• early SUSY searches performed with 3.3 fb\(^{-1}\) at 13 TeV
  - exclude \(m(\tilde{g})\) up to 1.8 TeV
  - exclude \(m(\tilde{q}_{1,2})\) up to \(\sim 1\) TeV
  - exclude \(m(\tilde{b}_1)\) up to \(\sim 840\) GeV

  ⇒ significantly improves exclusion limits from Run-1

- Excess of 2.2 \(\sigma\) in the \(Z+E_T\) analysis, after 3 \(\sigma\) in Run-1
ATLAS is pursuing a broad search for exotic phenomena

Some searches have already been updated using the 2015 data
- thanks to the increased LHC energy, Run 1 sensitivity to many signals has already been exceeded with $\sim 3 \text{ fb}^{-1}$

Unfortunately, few surprises so far but there is the diphoton excess

Still to come:
- updated searches for many other new phenomena
- including follow up on some of the most interesting results from Run 1
BACK UP SLIDES
Physics Object Selection

• Jets:
  – Reconstructed from calorimeter energy clusters using the anti-$k_T$ algorithm with radius parameter $R = 0.4$
  – Jets are reclustered with $R = 1$ to search for boosted top quarks
  – Corrected for avg. energy deposition from pile-up (= multiple collisions, averaging 14 in 2015)
  – Jet energy scale calibrated with detector response from MC and 8 TeV data
  – Event rejected if contains jet identified as due to noise or non-collision

• b-jets:
  – Tagged by multivariate algorithm using the impact parameters of tracks in the jet, and the presence and flight paths of displaced vertices from b/c hadrons

• Electrons:
  – Matching EM calorimeter clusters to inner-detector tracks & TRT threshold

• Muons:
  – Matching tracks in the muon spectrometer and inner detector
• **Physics-object overlap removal:**
  - If 2 objects \((e, \mu, \text{jet}, \text{or } b\text{-jet})\) are nearby, indicating mis-identification, one of them is discarded according to an optimized algorithm.

• **Missing transverse energy:**
  
  \[
  \vec{p}_T^{\text{miss}} = -\left( \sum_{\text{physics objects}} \vec{p}_T + \sum_{\text{other PV tracks}} \vec{p}_T \right)
  \]

  \[
  \text{MET} \equiv E_T^{\text{miss}} = \left| \vec{p}_T^{\text{miss}} \right|
  \]

• **Scalar \(p_T\) sum**

  \[
  H_T = \sum_{\text{physics objects}} p_T
  \]

• **Effective mass:**

  \[
  m_{\text{eff}} = \sum_{\text{physics objects}} p_T + E_T^{\text{miss}}
  \]
Common Analysis procedures

• Define signal regions (SRs)
  – Based on \( N_{\text{leptons}}, N_{\text{jets}}, N_{b-jets} \) with \( T \) cuts, \( H_T \), MET, \( m_{\text{eff}} \), etc.
  – Targeting different regions in SUSY parameter space

• Estimate background for each SR in control regions (CRs)
  – Usually using Monte Carlo distributions to relate CR yields to SR yields
  – Background estimate from CRs validated using validation regions (VRs)
  – Smaller backgrounds often obtained from MC

• If no excess, set limits using the CLs prescription, accounting for systematic uncertainties:
  – Finite MC statistics
  – Theory, e.g., models used for background shapes
  – Jet energy scale and resolution
  – Lepton / b-jet ID efficiencies and purities