Recent Searches for *New Resonances* and *Contact Interactions with ATLAS*

**CERN LHC Seminar**
April 25th, 2017

*Arely Cortes-Gonzalez*
(CERN)
On behalf of the **ATLAS Collaboration**
Recent Searches for New Resonances and Contact Interactions with ATLAS

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Very **successful** theory.

* **Precise measurements** in great agreement with predictions.
Run I *legacy*: Higgs discovery
The discovery of a new particle also opened a new channel for searches.

Still left with many open questions....

e.g. High-levels of **fine tuning** needed to avoid divergences in Higgs mass corrections.

The **Higgs discovery** further validated the SM (*self-consistent theory*).
SM is a self-consistent theory, with predictions in agreement with measurements, but...

- **Hierarchy** problem (of mass scales).
  Large discrepancy between weak force and gravity: \( m_{\text{EW}} / m_{\text{Plank}} \sim 10^{-16} \).

- **Fine tuning** needed to avoid divergences in Higgs mass corrections.

- No **Dark matter** candidate.

- Baryon **asymmetry**.

- **Neutrino** masses.
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* **Neutrino** masses.

How to solve these?

* **SUSY**.

* **Extra Dimensions**.

* **Compositeness**.

* **Sequential Standard Model**.

* **Hidden Sectors**.

* **Top partners**,

* ... **New TeV scale interactions/particles**!
Why **BSM**?

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* **Neutrino** masses.

* **Excited** states of leptons and quarks ($q^*$) can be predicted from **composite models**.  
  Explains generational structure and mass hierarchy of quarks.

* **Composite Higgs**  
  Heavy Vector triplet model (**HVT**), with new $W'^\pm$, $Z'$ states.  
  o Model A: *Extended gauge symmetry*.  
  o Model B: *Minimal composite Higgs model*.  

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Arely Cortes Gonzalez  
CERN LHC Seminar  
25.04.17
**Why BSM?**

**SM** is a self-consistent theory, with predictions in agreement with measurements, but...

- **Hierarchy** problem (of mass scales).
  Large discrepancy between weak force and gravity: \( \frac{m_{EW}}{m_{Plank}} \approx 10^{-16} \).
- **Fine tuning** needed to avoid divergences in Higgs mass corrections.
- **No Dark matter** candidate.
- **Baryon asymmetry**.
- **Neutrino** masses.

Several extensions of the SM with extended gauge symmetries.

- **Sequential Standard Model.**
  SM + new spin-1 heavy gauge bosons with similar couplings as SM \( W^\pm \) and Z.

  *New bosons at the TeV scale.*
**Why BSM?**

**SM** is a self-consistent theory, with predictions in agreement with measurements, but...

- **Hierarchy** problem (of mass scales). Large discrepancy between weak force and gravity: $m_{EW}/m_{Plank}\sim 10^{-16}$.
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_Resonance searches can also be interpreted in terms of DM models._
We look for observations of new resonances in the *tails of the SM distributions*. These resonances could decay into e.g. vector bosons or fermions.

*SM background can be modeled in a data driven fashion.*

Different searches sensitive to **narrow** resonances *(wide variety of signatures to be explored!)*.

- **Fully hadronic**
  - di-jet, $V(qq)+H(qq)$

- **With leptons**
  - dileptons, lepton + $E_T^{\text{miss}}$

- **with Photons**
  - photon + $E_T^{\text{miss}}$
Searching…

We look for modifications in angular and mass distributions arising from **new contact interaction (CI) scales**.

New **mediating particle** with a mass much higher than the energy exchange modeled as contact interaction with new physics at **energy scale** $\Lambda$.

- **Dileptons**
  - Broad excess in invariant mass distributions.
- **Dijets**
  - CI is often more **isotropic** than QCD → use angular information.
Excellent **performance by the LHC** and high **data taking efficiency** by detectors in the **13 TeV pp** collisions period (2015, 2016).

~40 fb$^{-1}$ @ 13 TeV recorded in 2015 and 2016

Data quality efficiency 93-95%
**Performance: Leptons**

**Electrons**

ATLAS Preliminary
\( \sqrt{s} = 13 \text{ TeV}, L = 3.1 \text{ (2015)} + 33.9 \text{ (2016)} \text{ fb}^{-1} \)
\( |\eta| < 2.47, p_T > 27 \text{ GeV} \)

Electron energy scale correction \( \sim 0.02\% \)

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**Muons**

ATLAS Preliminary
\( \sqrt{s} = 13 \text{ TeV}, 33.3 \text{ fb}^{-1} \)

Muon \( p_T \) resolution \( \sim 2 \text{ GeV} \)

22 GeV \( < p_T(\mu) < 300 \text{ GeV} \)
Analyses rely on a good understanding of jet calibration up to multi-TeV scale.

Jet mass improvements

Optimizes large-R jet mass computed using combination of calorimeter and tracking information

\[ m_J = w_{\text{calo}} \times m_{J}^{\text{calo}} + w_{\text{track}} \times \left( m_{J}^{\text{track}} \frac{p_{T}^{\text{calo}}}{p_{T}^{\text{track}}} \right) \]
Performance: Boson Tagging

Energy depositions in calorimeter used to form topological clusters: reconstruct **large R-jets**: \textit{Anti-}k_t, R=1.0 jets.

Trimming

Remove softer components (mainly from UE and pileup).

Improved **mass resolution**.

Re-cluster with \( R_{\text{sub}} = 0.2 \).
Remove sub-jets with \( f_{\text{cut}} < 0.05 \).
**Performance: Boson Tagging**

**Discriminating** against background: boson tagging. Use differences in the jet characteristics between signal and background jets.

Jet mass is consistent with $m_W$ or $m_Z$.

Mass windows for $W/Z$ bosons are $p_T$-dependent.
**Performance: Boson Tagging**

**Discriminating** against background: boson tagging.

Use differences in the jet characteristics between signal and background jets.

**Substructure variable $D_2^{\beta=1}$** consistent with two prong decays.

$D_2^{\beta=1}$ exploits energy correlations functions to tag boosted objects with two-prong structures.

Constant $\sim 50\%$ efficiency in $V$-jet $p_T$ for $\sim 2\%$ fake rate.
Highest-mass dijet event: $m_{jj} = 8.12$ TeV, $|y^*| = 0.38$
High Mass **Di-Jet** Search

**Strategy:** Resonance

$$f(z) = p_1(1-z)^{p_2}z^{p_3}z^{p_4} \log z$$

*With increasing luminosity and corresponding $m_{jj}$ range extension, a single global fit may not necessarily work.*

**Selection**

Events selected with lowest un-prescaled single jet trigger ($p_T > 380$ GeV).

| $p_T^{\text{leading}}$ | $p_T^{\text{subleading}}$ | $|y^*|$ | $|y_B|$ | $m_{jj}$ |
|------------------------|--------------------------|-------|--------|---------|
| Resonance              | > 0.44 TeV               | > 0.06 TeV | < 0.6 | -       | > 1.1 TeV |
| $W^*$                  | > 0.44 TeV               | > 0.06 TeV | < 1.2 | -       | > 1.7 TeV |
| Angular                | > 0.44 TeV               | > 0.06 TeV | < 1.7 | < 1.1   | > 2.5 TeV |

$$|y^*| = |y_1 - y_2|/2$$

*Rejects forward peaking $t$-channel QCD processes.*

**Sliding Window Fit**

- Perform the $f(z)$ fit in restricted (sliding) ranges (**more flexible**!).
- The limited range allows to use a 3-parameter function.
- Excellent linearity between injected and extracted signal.
Resonance Search

- **BumpHunter** algorithm compares the binned $m_{jj}$ of data to the fitted bkg estimate.

- Global significance is computed with pseudo-experiments.

**Most discrepant region:**
(global $p=0.63$) 4326–4595 GeV

No evidence of a localized contribution from BSM observed.
Resonance Limits

95% CL upper observed (expected) limits on the cross section times acceptance for different signal models.

QBH Limits:

- $m_{Th} > 8.9$ TeV (8 TeV)

High Mass Di-Jet Search

2015 limit $m_{W'} > 2.6$ TeV

- $m_{W'} > 3.4$ TeV, $3.77$ TeV - $3.85$ TeV ($3.6$ TeV)

2015 limit $m_{q'} > 5.2$ TeV

- $m_{q'} > 6$ TeV ($5.8$ TeV)

Axial vector mediator

For $g_q = 0.6$ the intrinsic width of the $Z'$ in the mass range of interest increases to 15%.

Results limited to $g_q < 0.5$
Gaussian Limits

- Limits on *generic Gaussian signals* used to recast results for new signal models.
- Folding method using MC based transfer matrix used to factorized out physics and detector effects.
- The predicted signals can now be compared at *particle level* (assuming Gaussian signal shape).
Other Di-Jet Searches

Di-Jet searches covering the low and high mass regime!

Di-jet + ISR ($\gamma$/jet)
Triggering on ISR $\gamma$/jet, we can also reach lower $m_{jj}$.
Last results with 15.5 fb$^{-1}$.

Trigger level analysis
Strategy: reduce data size/complexity to increase rate of recorded data.
Last results with 3.4 fb$^{-1}$.

High mass di-jets
Reach at low masses limited by trigger bandwidth and storage.
Background prediction based onPythia (used as template) corrected for NLO and EW effects.

- Correction factors are mass and angle dependent.

Uncertainties:
- Jet Energy Scale is the dominant experimental uncertainty.
- Main theoretical uncertainties: renormalization and factorization scales, PDFs.
Angular Limits

- Limits on CI with non-zero left-chiral color coupling.
  - Resulting angular distribution is representative of other BSM models (e.g. Z').

\[ L_{qq} = \frac{2\pi}{\Lambda^2} [ \eta_{LL}(\bar{q}_L \gamma^\mu q_L)(\bar{q}_L \gamma_\mu q_L) + \eta_{RR}(\bar{q}_R \gamma^\mu q_R)(\bar{q}_R \gamma_\mu q_R) + 2\eta_{RL}(\bar{q}_R \gamma^\mu q_R)(\bar{q}_L \gamma_\mu q_L)] \]

- Both destructive and constructive interference are considered (\( \eta_{LL} = \pm 1 \)).
**V(qq)H(bb) Search**

**Selection**

- **Large BRs:** \( W/Z \rightarrow qq \) (67\%), \( H \rightarrow bb \) (~70\%).
- Select events with large-R jets consistent with highly boosted \( V \rightarrow qq \) and \( H \rightarrow bb \).

  - Use **boson tagging**:
    - \( V \)-tagging: mass + \( D_2^{β=1} \).
    - \( H \)-tagging: mass + b-tagging.

- Leading jet \( p_T > 450 \) GeV, sub-leading jet \( p_T > 250 \) GeV.
- Larger mass jet assigned as Higgs candidate.
- Events categorized in 1-tag and ≥2-tag.

**WH and ZH SRs not orthogonal** (~60\% overlap).
Strategy

Main background from **multijet** events.

\(~10\%\) contributions from t-tbar, \(~1\%\) from V+jets (taken from MC),

0-tag region in **data** is used to extract a template of the multijet background.

**High mass side-bands** used to extract normalization and re-weighting corrections.

\[ \frac{N^{1(2)-\text{tag}}_{\text{Multijet}}}{N^{0-\text{tag}}_{\text{Multijet}}} = \frac{N^{1(2)-\text{tag}}_{\text{data}} - N^{1(2)-\text{tag}}_{t\bar{t}} - N^{1(2)-\text{tag}}_{V+\text{jets}}}{N^{0-\text{tag}}_{\text{data}} - N^{0-\text{tag}}_{t\bar{t}} - N^{0-\text{tag}}_{V+\text{jets}}} \]

**Extract** \( \mu_{\text{multijets}} \) from high mass sideband, different for each SR: 1- and 2-tag, and WH, ZH.
Probing $\text{ZH}$ and $\text{WH}$ not orthogonal
- **Normalization and shape of multijet bkg**: estimated from largest deviation between data and prediction yields in validation region.
  - Normalization: 2-tag: 13% (sys), 3% (stat); 1-tag: 5% (sys), 1% (stat).
  - Shape (split for <2TeV and >2TeV).
- Fit **WH** and **ZH** signal regions separately.
  - Combining 1-tag and 2-tag regions in each case.
Largest excess found at 3.0 TeV in ZH channel, with global significance of 2.2σ.

**Heavy Vector Triplet (HVT) W’ and Z’**.

- **Model A**: comparable BR to fermions and gauge bosons.
- **Model B**: Suppressed couplings to fermions.
$m_{\mu\mu} = 1.98$ TeV invariant mass di-muon event observed with ATLAS
Highest-\( m_T \) event in the electron channel observed with ATLAS: \( m_T = 2.26 \) TeV
\( (p_T^e = 1.11 \) TeV, \( E_T^{\text{miss}} = 1.16 \) TeV)
Searches with \textbf{Leptons}

- Single electron triggers.
  - $E_T^{\text{electron}} > 65$ GeV.
  - \textit{Tight} ID.
  - $m_T > 130$ GeV.
  - $E_T^{\text{miss}} > 65$ GeV.

- Single muon triggers.
  - $p_T^{\text{muon}} > 55$ GeV.
  - $m_T > 110$ GeV.
  - $E_T^{\text{miss}} > 55$ GeV.

\textit{Veto on additional leptons}

- Di-electron triggers.
  - $E_T^{\text{electrons}} > 30$ GeV.

- Single muon triggers.
  - $p_T^{\text{muons}} > 30$ GeV.

Highest $m_{ll}$ pair ($>80$ GeV).

- Reduced acceptance in the muon channels:
  - Lower \textit{muon identification efficiency},
  - \textit{tighter selection criteria} (to improve muon resolution).

- Opposite charge required for \textit{di-muons}.
  - Charge mis-identification does not affect energy measurement for electrons.

\textbf{Medium Electrons}

Loose isolation

\textbf{High $p_T$ WP Muons}

(Trk-based) Loose isolation

\textbf{ATLAS Simulation}

$\sqrt{s} = 13$ TeV

$W^+ \rightarrow e\nu$

$W^\pm \rightarrow \mu\nu$

---

\textbf{e channel eff. up to $\sim$80%}

\textbf{\mu channel eff. up to $\sim$50%}
Searches with **Leptons**

**Strategy**

**Main background** from **Drell-Yan production.**
Additional contributions from processes with **real leptons** in the final state (t-tbar, single top quark, diboson). *Estimated using MC samples.*

**DY** events are simulated with **NLO Powheg** generator.  
Events yields are corrected with **mass dependent rescaling from NLO to NNLO QCD.**  
**Mass-dependent EW-corrections at NLO are also applied.**

- **Fakes** background: e.g. from multijet events, where one or more jets satisfies the lepton selection.
  - Negligible in muon channels. Minor background in the electron channels.
  - Using data-driven approach: **matrix method.** Measure fake and real rates: probabilities of a jet or an electron **to be identified as an electron.**

*Background estimates may suffer from low statistics in the high mass tails (e.g. multijets). Extrapolation performed by fitting the lower mass distribution and using the fitted function to predict the background at higher mass.*
## Background and signal systematic uncertainties at dilepton masses of 2 TeV (4 TeV)

<table>
<thead>
<tr>
<th>Source</th>
<th>Dieelectron channel</th>
<th>Dimuon channel</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Signal (Background)</td>
<td>Signal (Background)</td>
</tr>
<tr>
<td>Luminosity</td>
<td>3.2% (3.2%)</td>
<td>3.2% (3.2%)</td>
</tr>
<tr>
<td>MC statistical</td>
<td>&lt;1.0% (&lt;1.0%)</td>
<td>&lt;1.0% (&lt;1.0%)</td>
</tr>
<tr>
<td>Beam energy</td>
<td>2.0% (4.1%)</td>
<td>1.9% (3.1%)</td>
</tr>
<tr>
<td>Pile-Up effects</td>
<td>&lt;1.0% (&lt;1.0%)</td>
<td>&lt;1.0% (&lt;1.0%)</td>
</tr>
<tr>
<td>DY PDF choice</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>DY PDF variation</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>DY PDF scale</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>DY $\alpha_s$</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>DY EW corrections</td>
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<td>N/A</td>
</tr>
<tr>
<td>DY $\gamma$-induced corrections</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Top Quarks theoretical</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Dibosons theoretical</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Reconstruction efficiency</td>
<td>&lt;1.0% (&lt;1.0%)</td>
<td>10% (17%)</td>
</tr>
<tr>
<td>Isolation efficiency</td>
<td>9.1% (9.7%)</td>
<td>1.8% (2.0%)</td>
</tr>
<tr>
<td>Trigger efficiency</td>
<td>&lt;1.0% (&lt;1.0%)</td>
<td>&lt;1.0% (&lt;1.0%)</td>
</tr>
<tr>
<td>Identification efficiency</td>
<td>2.6% (2.4%)</td>
<td>N/A</td>
</tr>
<tr>
<td>Lepton energy scale</td>
<td>&lt;1.0% (&lt;1.0%)</td>
<td>&lt;1.0% (&lt;1.0%)</td>
</tr>
<tr>
<td>Lepton energy resolution</td>
<td>&lt;1.0% (&lt;1.0%)</td>
<td>2.7% (2.7%)</td>
</tr>
<tr>
<td>Multi-jet &amp; W+jets</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Total</td>
<td>10% (11%)</td>
<td>11% (18%)</td>
</tr>
</tbody>
</table>

Largest theory uncertainty.

Largest experimental uncertainty.

Large uncertainty at high masses due to extrapolation.
Most significant excess in di-electron mass spectrum is observed at 2.37 TeV, global significance of -0.2σ.
Upper limits are set for $Z'$ cross sections times BR wrt $m_{Z'}$, for various $Z'$ scenarios.

**Limits weaken above $3.5$ TeV:**
Rapidly falling signal x-sections and off-shell low mass signal tail.

Limits for minimal $Z'$ models are also discussed in the paper.
Generic Z' limits

Aim to provide more general limits. Applying fiducial cuts ($p_T > 30$ GeV, $|\eta| < 2.5$) on signal templates and a mass window of $x^2$ the signal width (Breit-Wigner).

Other models can be interpreted with these cross-sections!

\[
\mathcal{L} = \frac{g^2}{\Lambda^2} \left[ \eta_{LL} (\bar{q}_L \gamma_\mu q_L) (\ell_L \gamma^\mu \ell_L) + \eta_{RR}(\bar{q}_R \gamma_\mu q_R) (\ell_R \gamma^\mu \ell_R) \\
+ \eta_{LR}(\bar{q}_L \gamma_\mu q_R) (\ell_R \gamma^\mu \ell_R) + \eta_{RL}(\bar{q}_R \gamma_\mu q_L) (\ell_L \gamma^\mu \ell_L) \right]
\]

Different chiral structures are studied; with the left-right (right-left) model obtained by setting $\eta_{LR} = \pm 1$ ($\eta_{RL} = \pm 1$) and all other parameters to zero.
○ Most significant excess in electron channel is at \( m_{W'} = 1.1 \) TeV, global significance of 0.6\( \sigma \).

○ Most significant excess in muon channel is at \( m_{W'} \sim 5 \) TeV, global significance of 0.1\( \sigma \).
Upper limits on cross section times BR for the electron and muon channels.

- Combination of the two channels
  - Uncertainties treated as correlated.
- Stronger expected limits from electron channel.
  - Larger acceptance times efficiency,
  - better momentum resolution.
Significant improvement wrt previous ATLAS searches!

Observed limits to the $Z'_{SSM}$ cross section from the combination of di-electron and di-muon channels.

Observed limits to the $W'_{SSM}$ cross section from the combination of electron and muon channels.
A photon with $E_T = 265$ GeV is balanced by $E_T^{\text{miss}}$ of 268 GeV.
Photon + $E_T^{miss}$ Search

Multiple CRs defined to constrain SM bkg

Selection

- $\gamma$: $p_T^{\gamma} > 150$ GeV,
- jet: up to 1 $p_T^{\text{jet}} > 30$ GeV
- $\mu/e$ veto
- $\phi > 0.4$
- MET $> 150$ GeV

Data/Bkg

- $\gamma + \text{jets CR}$
- $W(\to \nu\nu)\gamma$ CR
- $Z(\to \nu\nu)\gamma$ CR
- $Z(\to \mu\mu)\gamma$ CR

Events / 75 GeV

$\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$
Main uncertainties: Statistical from CRs: 9%.

This analysis places limits on simplified DM models (photon from ISR) and EFT DM models (probing the $\gamma\gamma\chi\chi$ coupling).

- Dominant: $Z(\nu\nu) + \gamma$ (ISR), followed by $W\gamma$ and fake $\gamma$.
- $V\gamma +jets$ normalized in dedicated CRs.
- $3 E_{T}^{\text{miss}}$ dependent scale factors: $k_Z$, $k_W$, $k_{\gamma\text{jet}}$.
- $Z(\nu\nu)$ normalized in $2\mu + 2e$ CRs.
- $\gamma + jets$ bkg from $\gamma + jet$ CR.
New results for $Z(\nu\nu)\gamma$ resonance as a function of its mass.

Limits from $Z(qq)\gamma$ with $3.2 \text{ fb}^{-1}$ are shown for comparison.
BONUS!

Connection to **Dark Matter**

Di-jet and dilepton resonance searches interpreted in terms of DM mediators limits.

However, note that the **choice of couplings** is very relevant to study the complementarity of these and other mono-X searches.
Conclusions

- Searches for new physics have been performed with the full 2015+2016 dataset.
  - *Not possible to achieve without the amazing performance of the LHC machine and injector chain. Thanks to all involved!*
- New resonances and contact interactions are a strong components of the LHC physics program.
  - New techniques are being developed and new models are studied.
  - *So far, no significant deviations from Standard Model observed.*
  
- Improved limits on multiple signal models!
  - Di-jet searches now exclude excited quarks up to 6 TeV.
  - Upper limits on $\sigma x BR$ to the qq(γ)bb final state are set for masses between 1.1-3.8 TeV.
  - $W_{SSM}$ excluded for $m_W > 5.1$ TeV from the lepton+$E_T^{miss}$ search,
  - $Z_{SSM}$ excluded for $m_Z > 4.5$ TeV from di-lepton searches.
  - Upper limits on $\sigma x BR$ for a $Z(\nu\nu)gamma$ resonance set for masses between 2-5 TeV.

<table>
<thead>
<tr>
<th>Di-Jet</th>
<th>arXiv:1703.09127</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V(qq)H(bb)$</td>
<td>ATLAS-CONF-2017-018</td>
</tr>
<tr>
<td>Dilepton</td>
<td>ATLAS-CONF-2017-027</td>
</tr>
<tr>
<td>Lepton + $E_T^{miss}$</td>
<td>ATLAS-CONF-2017-016</td>
</tr>
<tr>
<td>Photon + $E_T^{miss}$</td>
<td>arXiv:1704.03848</td>
</tr>
</tbody>
</table>
Many thanks!
**Muons Spectrometer**
MS includes precision tracking chambers ($|\eta|<2.7$) and fast detectors for triggering ($|\eta|<2.4$).

**Calorimeters**
LAr and scintillator calorimeters provide EM and hadronic energy measurements up to $|\eta|<4.9$.

**Tracking**
Inner tracking detectors cover up to $|\eta|=2.5$.

**Trigger**
Hardware based L1 ~100kHz
Software based HLT ~1kHz
Performance: Boson Tagging

**ATLAS** Simulation Preliminary
- Fitted mean
- $\mu \pm \sigma$
- $\mu \pm 2\sigma$
- Linear fit

Trimmed ($f_{\text{cut}} = 5\%$, $R_{\text{sub}} = 0.2$)

- $|\eta| < 2.0$, Z-jets
- $|\eta| < 2.0$, W-jets

Jet $p_T$ [GeV]
Performance: Electrons

\begin{center}
\begin{tikzpicture}
\begin{axis}[
    title={ATLAS Preliminary},
    xlabel={\(E_T\) [GeV]},
    ylabel={Reco + ID efficiency},
    legend style={at={(0.5,0.25)},anchor=north},
]
\addplot[blue,mark=diamond] coordinates { (10,0.8) (20,0.85) (30,0.9) (40,0.95) (50,1) (60,0.95) (70,0.9) (80,0.85) };
\addplot[red,mark=square] coordinates { (10,0.75) (20,0.8) (30,0.85) (40,0.9) (50,0.95) (60,1) (70,0.95) (80,0.9) };
\addplot[black,mark=triangle] coordinates { (10,0.7) (20,0.75) (30,0.8) (40,0.85) (50,0.9) (60,0.95) (70,1) (80,0.95) };
\legend{Loose, Medium, Tight}
\end{axis}
\end{tikzpicture}
\end{center}

\begin{center}
\begin{tikzpicture}
\begin{axis}[
    title={ATLAS Preliminary},
    xlabel={\(\eta\)},
    ylabel={Data / MC},
    legend style={at={(0.5,0.25)},anchor=north},
]
\addplot[blue,mark=diamond] coordinates { (-2.5,0.95) (-2,0.98) (-1.5,0.97) (-1,0.96) (-0.5,0.95) (0,0.94) (0.5,0.93) (1,0.92) (1.5,0.91) (2,0.9) (2.5,0.89) };
\addplot[red,mark=square] coordinates { (-2.5,0.92) (-2,0.91) (-1.5,0.9) (-1,0.89) (-0.5,0.88) (0,0.87) (0.5,0.86) (1,0.85) (1.5,0.84) (2,0.83) (2.5,0.82) };
\addplot[black,mark=triangle] coordinates { (-2.5,0.89) (-2,0.88) (-1.5,0.87) (-1,0.86) (-0.5,0.85) (0,0.84) (0.5,0.83) (1,0.82) (1.5,0.81) (2,0.8) (2.5,0.79) };
\legend{Loose, Medium, Tight}
\end{axis}
\end{tikzpicture}
\end{center}

\text{\(\sqrt{s} = 13\) TeV, 3.2 fb\(^{-1}\)}

\text{\(-2.47 < \eta < 2.47\)}

\text{Data: full, MC: open}
Photon + $E_T^{\text{miss}}$ Search

- **High $p_T$ photon.**
  - $p_T > 150$ GeV, $|\eta| < 2.37$, tight, isolated.
- **$E_T^{\text{miss}} > 150$ GeV.**
  - $\Delta\phi(\gamma, E_T^{\text{miss}}) > 0.4$
- **$N_{\text{jets}}$** ($p_T > 30$ GeV, $|\eta| < 4.5$) $\leq 1$
- **$\Delta\phi(E_T^{\text{miss}}, \text{jet}) > 0.4$.**
- **SR:** veto on muons ($p_T > 6$ GeV) and electrons ($p_T > 7$ GeV).

**Selection**

- **$W(\to \mu\nu)\gamma$ CR**
- **$\gamma + \text{jets}$ CR**
- **$Z(\to ll)\gamma$ CR**
- **$Z(\to ee)\gamma$ CR**
- **$Z(\to \mu\mu)\gamma$ CR**

Multiple CRs defined to constrain SM backgrounds (inverting lepton vetoes, or in different $E_T^{\text{miss}}$ regions).
Performance: Leptons
**Dilepton Search**

**Strategy**

- **Main background** from Drell-Yan production. Additional contributions from processes including 2 real leptons in the final state (t-tbar, single top quark, diboson).
  - Estimated using MC samples.

**DY events are simulated with NLO Powheg generator.**

Events yields are corrected with mass dependent rescaling from NLO to NNLO QCD. Mass-dependent EW-corrections at NLO are also applied.

- **Fakes** background: multijet and W+jets events, where one or more jets satisfies the lepton selection.
  - Negligible in di-muon channel.
  - Using data-driven approach: *matrix method*. Measure fake (f) and real (r) rates: probabilities of a jet or an electron to be identified as an electron.

\[
\begin{pmatrix}
N_{TT} \\
N_{TL} \\
N_{LT} \\
N_{LL}
\end{pmatrix} = \begin{pmatrix}
r^2 & rf & fr & f^2 \\
(r-1-r) & r(1-f) & f(1-r) & f(1-f) \\
(1-r)r & (1-r)f & (1-f)r & (1-f)f \\
(1-r)^2 & (1-r)(1-f) & (1-f)(1-r) & (1-f)^2
\end{pmatrix} \begin{pmatrix}
N_{RR} \\
N_{RF} \\
N_{FR} \\
N_{FF}
\end{pmatrix}
\]

\[
N_{Multi-jet & W+jets}^{TT} = rf(N_{RF} + N_{FR}) + f^2 N_{FF}
\]

- \(N_{RF}, N_{FR}, \) and \(N_{FF}\) obtained through matrix inversion
  - expressed in terms of measurable quantities: \(N_{TT}, N_{TL}, N_{LT}, N_{LL}\)
Motivation

CI in **mass** distributions:
- Observable as broad excess in dilepton invariant mass spectrum.
  - Observation in $m_{ll}$ distribution requires precise understanding of QCD cross section.

CI in **angular** distributions:
- CI is often more isotropic than QCD.
  - As function of $\cos\theta^*$. 
- Angular distributions have much smaller systematic uncertainties than cross section vs $m_{jj}$.
- Some sensitivity to resonant signals too.

\[ \chi = \frac{1 + \cos \theta^*}{1 - \cos \theta^*} \]
Performance: Boson Tagging

**ATLAS** Preliminary

\[ \sqrt{s} = 13 \text{ TeV}, 36.5 \text{ fb}^{-1} \]

Trimmed anti-\( k_t \), \( R=1.0 \)

Dijet Selection
\[ p_T > 450 \text{ GeV} \]

- Data 2015+2016
- Pythia8 dijet (\( \times 0.71 \))
- Herwig++ dijet (\( \times 1.43 \))
- W+jets (\( \times 25 \))
- Z+jets (\( \times 25 \))
- all-had \( t\bar{t} \) (\( \times 25 \))

Stat. uncert.
Stat. + syst. uncert.

**ATLAS** Preliminary

\[ \sqrt{s} = 13 \text{ TeV}, 36.5 \text{ fb}^{-1} \]

Trimmed anti-\( k_t \), \( R=1.0 \)

Dijet Selection
\[ p_T > 450 \text{ GeV} \]
\[ m^{\text{comb}} > 50 \text{ GeV} \]

- Data 2015+2016
- Pythia8 dijet (\( \times 0.70 \))
- Herwig++ dijet (\( \times 1.36 \))
- W+jets (\( \times 50 \))
- Z+jets (\( \times 50 \))
- all-had \( t\bar{t} \) (\( \times 50 \))

Stat. uncert.
Stat. + syst. uncert.
The **Higgs discovery** further validated the SM (self-consistent theory).

Run I legacy: Higgs discovery
The discovery of a new particle also opened a new channel for searches.

Still left with many open questions....

* e.g. High-levels of **fine tuning** needed to avoid divergences in Higgs mass corrections.