Search for Exotic Physics Beyond the Standard Model with the ATLAS Detector

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Outline: ATLAS searches for Exotic physics

- Very extensive program: about 50 searches with full 2012 ($\sqrt{s} = 8$ TeV) dataset;

- Dibosons, multileptons, extra dimensions, heavy quarks, top, composite Higgs, jets + dark matter, unconventional signatures, exotic Higgs, $W'$, $Z'$, lepton flavor violation, …;

- Only the following searches are covered in this talk:

  - Photon+missing $E_T$
  - Heavy Majorana neutrino
    \[ Z' \rightarrow \tau^+ \tau^- \]
  - Long-lived neutral particles → displaced lepton jets
    \[ X \rightarrow t\bar{t} \rightarrow W^+bW^-\bar{b} \]
    \[ H \rightarrow Z_{\text{dark}}Z_{\text{dark}} \rightarrow 4l^\pm \]
  - High-mass diphoton resonances
    - Multi-charged particles
    - Low-scale gravity signatures

  | Searches with slight excesses in Run-I data: |
  | Events with b-jets and pair of same-sign leptons |
  | \[ X \rightarrow WW/WZ ZZ \rightarrow jj \] |

  | Several preliminary plots from early Run-II searches |
- General-purpose detector with near $4\pi$ coverage in solid angle;
- Inner tracking detector, calorimeters system, muon spectrometer;
- Physics with final states: $e^\pm$, $\mu^\pm$, jets, $\gamma$, missing transverse momentum ($E_T$), …
γ+MET search

- Search for events with a high-$p_T$ photon and large $E_T$ with no $e^\pm$ or $\mu^\pm$;
- Main background source is $Z(\to \nu\bar{\nu}) + \gamma_{ISR}$;
- Results are interpreted in terms of limits on the parameters of large extra dimension theories, WIMP dark matter and supersymmetric quarks.

\[ y \]

\begin{align*}
\text{ATLAS} & \\
\text{Data} & \\
\gamma + Z(\to \nu\bar{\nu}) & \\
\gamma + W(\to \ell\nu) & \\
W/Z + \text{jet}, \text{top}, \text{diboson} & \\
\gamma + Z(\to \ell\ell) & \\
\gamma + \text{jet} & \\
\text{uncertainty} & \\
\end{align*}

\begin{align*}
\text{ATLAS} & \\
\text{ADD model, 95\% CL limit} & \\
\text{observed limit (± 1 σ)} & \\
\text{expected ± 1σ} & \\
\text{expected ± 2σ} & \\
\end{align*}

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Heavy Majorana neutrino search

- $\nu \equiv \bar{\nu}$?
- Search for events with exactly two same-sign same-flavor leptons and at least two jets;
- Main background source is $WZ$ and $ZZ$ events; processes with two opposite-sign leptons with the charge of one of them incorrectly measured in the detector: $t\bar{t}$, $W^\pm W^\mp$, $Z$;
- Results are interpreted in terms of limits on mixing parameters between heavy neutrinos and SM neutrinos (mTISM model) and limits on heavy Majorana neutrino masses (LRSM model).
$Z' \to \tau^+ \tau^-$ search

- Two final state channels: $\tau^\pm \to l^\pm \nu \bar{\nu}$ (leptonic channel, $\tau_{lep}$) and hadronic channel ($\tau_{had}$);
- For both channels, the dominant background source is $Z/\gamma^* \to \tau\tau$, estimated from simulation and validated using $Z/\gamma^*$ decays to electrons and muons in data;
- Limits on the $Z'$ mass for the Sequential Standard Model and non-universal $G(221)$ model.

![Graph and diagram](image-url)
Search for long-lived neutral particles decaying into displaced lepton jets (LJs)

- Unstable hidden states → hidden particles ($\gamma_{dark}$) with non-negligible lifetime due to their weak interaction → visible final states (collimated jet-like structures containing pairs of $e^\pm$ or $\mu^\pm$ or $\pi^\pm$);

- Background:
  - SM processes w/ or w/o jets: $W +$ jets, $Z +$ jets, $t\bar{t}$, ... ⇒ data-driven matrix method;
  - Cosmic-ray muons + detector material → background to LJ TYPE1 and TYPE2 ⇒ empty bunches analysis;

- Limits on $\sigma \times BR$ for non-SM Higgs boson decays to dark photons and LJs (FRVZ model); limits on kinetic mixing parameter $\epsilon$ as $f(m_{\gamma_{dark}})$. 

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Top quarks: the most massive SM fundamental particles, can have large coupling to heavy Higgs bosons;

General search; composite Higgs and topcolour-assisted technicolor scenarios propose mechanisms for EWSB, incorporating $X$ with large coupling to $t\bar{t}$ (w.r.t. lighter quarks);

One $W$ boson decays leptonically, the other one decays hadronically $\Rightarrow$ “lepton-plus-jets events”;

Events signature: 1 isolated $e^\pm/\mu^\pm$, $E_T$, hadronic jets consistent with having originated from a b-quark;

Background to the $m_{t\bar{t}}$ spectrum: $W +$ jets and $t\bar{t}$ processes $\Rightarrow$ data- and MC-driven estimations;

Results are interpreted as mass limits on the $Z'$, heavy Kaluza-Klein gluons, Kaluza-Klein excitations of the graviton, and color-singlet scalar particles.
Search for new light gauge bosons

in $H \rightarrow Z_{dark}Z_{[dark]} \rightarrow 4l^\pm (e^\pm$ or $\mu^\pm$)

- $H \rightarrow Z_{dark}Z$ search: test for excess an invariant mass spectrum of two leptons, not associated with $Z$; backgrounds are $ZZ^*$, $t\bar{t}$ and $Z +$ jets ⇒ data-driven methods;

- $H \rightarrow Z_{dark}Z_{dark}$ search: look for a small difference in invariant masses of pairs of two same-flavor opposite-charge leptons; backgrounds are $H \rightarrow ZZ^* \rightarrow 4l$, $ZZ^* \rightarrow 4l$, $WW$, $WZ$, $t\bar{t}$ and $Z +$ jets processes ⇒ estimated from simulation;

- Interpretation in terms of limits on $\frac{BR(H \rightarrow Z_{dark}Z \rightarrow 4l^\pm)}{BR(H \rightarrow ZZ^* \rightarrow 4l^\pm)}$ vs. $m_{Z_d}$ and 95% CL upper bound on the branching ratio of $H \rightarrow Z_{dark}Z_{dark}$ in the combined $4e + 2e2\mu + 4\mu$ final state;

- $H \rightarrow Z_{dark}Z_{dark}$ search: no significant excess, but two events did pass tight requirements.
Search for high-mass diphoton resonances

- Randall-Sundrum model: solving the SM hierarchy problem assuming an extra spatial dimension; its compactification leads to a Kaluza-Klein tower of gravitons excitations $G^*$.
- Model phenomenology: the mass of the lightest KK graviton excitation $m_{G^*}$ and the dimensionless coupling to the SM fields $k/M_{Pl}$.
- Diphoton trigger and two isolated high-$E_T$ photons.
- Dominant background is SM processes with prompt $\gamma\gamma$ production: events with $\gamma +$ jet or jet+jet, where one or two jets are reconstructed as photons. Irreducible bkg contribution is obtained from MC, a reducible one – from data.

- Limits on $\sigma \times BR(G^* \rightarrow \gamma\gamma)$ and $m_{G^*}$. 

“Blue-sky” search for heavy long-lived particles with $2 \leq |q|/e \leq 6$;

Events with at least one muon-like particle with high ionization loss along its trajectory;

Main background: high-$p_T$ muons $\Rightarrow$ estimated with data-driven matrix method;

Limits on $\sigma$ and mass as a function of charge.
Search for low-scale gravity signatures

- Quantum gravity $\rightarrow$ hierarchy problem $\rightarrow$ existence of non-perturbative gravitational states: micro black holes, string balls, higher-dimensional branes;

- Events with multiple high-$p_T$ jets: scalar sum of $p_T$ of the jets in the event $H_T > 1.5$ TeV & $N_{jet} \geq 3$;

- Background: small contribution from SM QCD processes like $t\bar{t}$, $\gamma/W/Z$+jets $\Rightarrow$ fit-based data-driven technique;

- Upper limits on visible cross-section for different jet multiplicities and lower mass limits on black holes and string balls masses.
Analysis of events with b-jets and pair of same-sign leptons

- Sensitive to models postulating vector-like quarks existence, enhancement of $t\bar{t}t\bar{t}$ production cross-section, chiral 4\textsuperscript{th} generation quarks existence, $tt$ production;

- $t\bar{t}t\bar{t}$ cross-section enhancement: via sgluon pair production & pair production of Kaluza-Klein excitations of the photon decaying to $t\bar{t}$;

- $\geq 2$ same-sign leptons, $\geq 2$ jets (at least one should originate from a b-quark) and large $\not{E}_T$;

- Background: small SM yields from $W^\pm W^\pm jj$, $t\bar{t}W/Z$, $t\bar{t}W^+W^-$, $t\bar{t}H$, $W/ZH$, ... + instrumental ⇒ data-driven methods.
Search for $X \rightarrow WW/WZ/ZZ \rightarrow jj$

- Two specific benchmark models:
  - Extended Gauge Model (similar to the Sequential Standard Model) $W' \rightarrow WZ$;
  - Kaluza-Klein mode of the bulk Randall-Sundrum graviton $G_{RS} \rightarrow WW/ZZ$;

- Analysis feature: boson jet tagging;

- Analysis signature: two typically $p_T$-balanced large-radius jets with large momentum & $m_{jj} > 1.05$ TeV;

- Purely data-driven background estimation;

- Results: data excess in all three channels at around 2 TeV; global significance of the discrepancy in the $WZ$ channel (largest deviation) is $2.5\sigma$.

Excess in data!
First look at Run-II data

- Run-II ($\sqrt{s} = 13$ TeV data) is here!
- No complete analyses available yet, some representative plots instead.

Dimuon invariant mass (more info)


Diphoton invariant mass (more info)

Corresponding Run-I result: [arXiv:1504.05511](https://arxiv.org/abs/1504.05511)
First look at Run-II data

- Monojets: $E_T$ in the $W \rightarrow \mu \nu$ CR (more info)
- e-u invariant mass ($Z' \rightarrow e\mu$) (more info)
- Transverse mass ($W' \rightarrow e\nu$) (more info)
- Mono-$b$: $E_T$ in the $1\mu 0e$ CR (more info)

Corresponding Run-I result: arXiv:1503.04430
Corresponding Run-I result: arXiv:1407.0608
Corresponding Run-I result: arXiv:1407.7494
Corresponding Run-I result: arXiv:1410.4031
... and much more
Exotics “mass reach” summary plot (as of July 2015), …
... the vector-like B quarks search summary and the lifetime limits plots

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/EXOTICS/
THANKS!

And stay tuned for upcoming Run-II ATLAS Exotics results!
The vector-like T quarks search summary

ATLAS Preliminary
Status: March 2015
\[ \sqrt{s} = 8 \text{ TeV}, \quad L = 20.3 \text{ fb}^{-1} \]

- 95% CL exp. excl.
- 95% CL obs. excl.

SU(2) (T, B) doub.  \quad SU(2) singlet

\begin{align*}
\text{BR} & \rightarrow \text{Ht} \\
\text{m}_T &= 350 \text{ GeV} \\
\text{Unphysical} \\
\text{BR} & \rightarrow \text{Wb} \\
\text{m}_T &= 350 \text{ GeV} \\
\text{Unphysical} \\
\text{BR} & \rightarrow \text{Ht} \\
\text{m}_T &= 400 \text{ GeV} \\
\text{Unphysical} \\
\text{BR} & \rightarrow \text{Wb} \\
\text{m}_T &= 400 \text{ GeV} \\
\text{Unphysical} \\
\text{BR} & \rightarrow \text{Ht} \\
\text{m}_T &= 450 \text{ GeV} \\
\text{Unphysical} \\
\text{BR} & \rightarrow \text{Wb} \\
\text{m}_T &= 450 \text{ GeV} \\
\text{Unphysical} \\
\text{BR} & \rightarrow \text{Ht} \\
\text{m}_T &= 500 \text{ GeV} \\
\text{Unphysical} \\
\text{BR} & \rightarrow \text{Wb} \\
\text{m}_T &= 500 \text{ GeV} \\
\text{Unphysical} \\
\text{BR} & \rightarrow \text{Ht} \\
\text{m}_T &= 550 \text{ GeV} \\
\text{Unphysical} \\
\text{BR} & \rightarrow \text{Wb} \\
\text{m}_T &= 550 \text{ GeV} \\
\text{Unphysical} \\
\text{BR} & \rightarrow \text{Ht} \\
\text{m}_T &= 600 \text{ GeV} \\
\text{Unphysical} \\
\text{BR} & \rightarrow \text{Wb} \\
\text{m}_T &= 600 \text{ GeV} \\
\text{Unphysical} \\
\text{BR} & \rightarrow \text{Ht} \\
\text{m}_T &= 650 \text{ GeV} \\
\text{Unphysical} \\
\text{BR} & \rightarrow \text{Wb} \\
\text{m}_T &= 650 \text{ GeV} \\
\text{Unphysical} \\
\text{BR} & \rightarrow \text{Ht} \\
\text{m}_T &= 700 \text{ GeV} \\
\text{Unphysical} \\
\text{BR} & \rightarrow \text{Wb} \\
\text{m}_T &= 700 \text{ GeV} \\
\text{Unphysical} \\
\text{BR} & \rightarrow \text{Ht} \\
\text{m}_T &= 750 \text{ GeV} \\
\text{Unphysical} \\
\text{BR} & \rightarrow \text{Wb} \\
\text{m}_T &= 750 \text{ GeV} \\
\text{Unphysical} \\
\text{BR} & \rightarrow \text{Ht} \\
\text{m}_T &= 800 \text{ GeV} \\
\text{Unphysical} \\
\text{BR} & \rightarrow \text{Wb} \\
\text{m}_T &= 800 \text{ GeV} \\
\text{Unphysical} \\
\text{BR} & \rightarrow \text{Ht} \\
\text{m}_T &= 850 \text{ GeV} \\
\text{Unphysical} \\
\text{BR} & \rightarrow \text{Wb} \\
\text{m}_T &= 850 \text{ GeV} \\
\text{Unphysical} \
\end{align*}