Search for Exotics Physics at ATLAS and CMS

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On Behalf of ATLAS and CMS Collaborations
Outline

- Motivation
- Resonances Search
- Dark Matter Search
- Long-lived Particles Search
- Summary
Why Exotics?

Finding new physics

- No one knows for sure where is the new physics
- Leave nothing untouched
- Go “exotic”!

How “exotic” can one go?

- New interactions and products: resonances
- Broad kinematic reach
  - Low to high masses
  - 28 GeV resonances not covered here, sorry!
- New signatures: long-lived particles, emerging jet
- Dark matter
- Model independent if possible

Not possible to cover all searches
- Only focus on recent results
- Personal taste
Resonances: Dijet Scan

Large kinematic range scan

- Limits on the universal coupling $g'_q$ between a leptophobic $Z'$ boson and quarks for various assumed $Z'$ width
- More beyond simple dijets: b-jets, top quark jets...

95% CL exclusions

- $\Gamma_{Z'}/M_{Z'} \leq 100\%$
- $\Gamma_{Z'}/M_{Z'} \leq 30\%$
- $\Gamma_{Z'}/M_{Z'} \leq 10\%$
- $\Gamma_{Z'}/M_{Z'} \leq 5\%$

arXiv:1611.03568
Select events with dedicated double-b tagger and constrain main QCD backgrounds with control region using “pass-fail ratio”

- Soft-drop jet mass $M_{SD}$ peaks at $\phi(bb)/A(bb)$ for signals (AK8/CK15)
- Background only fits show good agreement with data, with clear W and Z contributions
- No significant excess for signal masses between 50-350 GeV
- Exclusion limits: $\sigma X_{\phi(bb)}/A(bb) \sim 79(86)\text{pb}$, coupling $g_{q\phi}/g_{qA} \sim 3.9 (2.5)$
**Resonances: Double b-jets (Boosted)**

Select large-R jet for hadronically decaying resonance

- Data-driven estimation via fitting large-R jet mass distribution $m_J$ in SR, validated by data in CR$_{QCD}$
- Boosted $tt$ events constrained by MC template fitted to CR$_{tt}$ data
- Combined SM fit of $V$ + jets, $H$ + jets process and search for extra exotic signals in $m_J$ distribution with the range of 70 and 230 GeV
Resonances: Top Quark Jets

Select same-sign leptons with b-jet to look for vector-like quark, four-top-quark, and same-sign top-quark pair production

- Fake lepton background estimated by matrix method, mis-charge ID estimated by Z->ee enriched data sample
- Use validation region (VR) to verify background modelling in SR
Resonances: Top Quark Jets

- **Select single or opposite-sign dileptons with jets**
- **Major tt+jets backgrounds modelled by TRF method**
- **VR and SR divided by #jets, #b-jets, #large-R jets**
- **Signal + background fit**
  - $H_T^{\text{had}}$ distribution shows good agreement

Combined upper observed(expected) limit on $\mu$ (tttt): 5.3 (2.1)

Observed(expected) limit on BSM EFT (tttt) cross section: 21fb (15fb)
New Signatures: Long-lived Particles
New Signatures: Long-lived Particles

Long-lived particle signatures in a detector

- Neutral
- Charged
- Any charge

- HSCP
- Displaced dilepton
- Displaced lepton
- Displaced dijet
- Displaced vertex
- Displaced conversion
- Displaced photon
- Not pictured: stopped particles

J. Antonelli
New Signatures: Long-lived Particles

- Displaced objects: vertices, leptons, jets...
- Disappearing tracks, (Heavy/Multi-) Charged Particles...
New Signatures: Long-livedParticles

### ATLAS Long-lived Particle Searches\(^*\) - 95% CL Exclusion

**Status:** July 2018

<table>
<thead>
<tr>
<th>Model</th>
<th>Signature</th>
<th>( \mathcal{L} dt ) [fb(^{-1})]</th>
<th>Lifetime limit</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>RPV ( \chi_i^0 \to ee/\mu\mu/\tau\tau )</td>
<td>displaced lepton pair</td>
<td>20.3</td>
<td>( \chi_i^0 ) lifetime</td>
<td>( \sim 7.4 ) mm</td>
</tr>
<tr>
<td>GGM ( \chi_i^0 \to ZZ )</td>
<td>displaced vertex</td>
<td>20.3</td>
<td>( \chi_i^0 ) lifetime</td>
<td>( \sim 6.4 ) mm</td>
</tr>
<tr>
<td>GGM ( \chi_i^0 \to Z )</td>
<td>displaced dimuon</td>
<td>32.9</td>
<td>( \chi_i^0 ) lifetime</td>
<td>( \sim 0.02 ) mm</td>
</tr>
<tr>
<td>GMGSI ( \chi_i^0 \to \chi_i^0 \chi_i^0 )</td>
<td>non-pointing or delayed ( \gamma )</td>
<td>20.3</td>
<td>( \chi_i^0 ) lifetime</td>
<td>( \sim 0.05 ) mm</td>
</tr>
<tr>
<td>AMSIS ( pp \to \chi_i^0 \chi_i^0 \chi_i^0 )</td>
<td>disappearing track</td>
<td>36.1</td>
<td>( \chi_i^0 ) lifetime</td>
<td>( \sim 0.1 ) mm</td>
</tr>
<tr>
<td>AMSIS ( pp \to \chi_i^0 \chi_i^0 )</td>
<td>large pixel drift</td>
<td>18.4</td>
<td>( \chi_i^0 ) lifetime</td>
<td>( \sim 0.2 ) mm</td>
</tr>
<tr>
<td>Split SUSY</td>
<td>2 ID/MS vertices</td>
<td>19.5</td>
<td>( \chi_i^0 ) lifetime</td>
<td>( \sim 0.3 ) mm</td>
</tr>
<tr>
<td>Split SUSY</td>
<td>large pixel drift</td>
<td>36.1</td>
<td>( \chi_i^0 ) lifetime</td>
<td>( \sim 0.9 ) mm</td>
</tr>
<tr>
<td>Split SUSY</td>
<td>displaced vertex + ( E_{\text{T}}^{\text{miss}} )</td>
<td>32.8</td>
<td>( \chi_i^0 ) lifetime</td>
<td>( \sim 0.03 ) mm</td>
</tr>
<tr>
<td>Split SUSY</td>
<td>0 ( \ell ), 2 - 6 jets + ( E_{\text{T}}^{\text{miss}} )</td>
<td>36.1</td>
<td>( \chi_i^0 ) lifetime</td>
<td>( \sim 0.2 ) mm</td>
</tr>
</tbody>
</table>

#### Higgs + Four \( H \rightarrow gg \) 2 low-EMF trackless jets

| \( H \rightarrow gg \) | \( \sim 0 \) mm | \( \chi_i^0 \) lifetime | \( \sim 0.2 \) mm | 1501.04020 |
| \( H \rightarrow gg \) | \( \sim 0 \) mm | \( \chi_i^0 \) lifetime | \( \sim 0.3 \) mm | 1504.09634 |
| \( H \rightarrow gg \) | \( \sim 0 \) mm | \( \gamma \) lifetime | \( \sim 0.1 \) mm | 1511.02542 |
| \( H \rightarrow gg \) | \( \sim 0 \) mm | \( \chi_i^0 \) lifetime | \( \sim 0.02 \) mm | ATLAS-CONF-2016-342 |
| \( H \rightarrow gg \) | \( \sim 0 \) mm | \( \gamma \) lifetime | \( \sim 0.11 \) mm | ATLAS-CONF-2016-342 |

#### Scalar \( H \rightarrow Z^0 \ Z^0 \)

| \( (300 \text{ GeV}) \) \( \rightarrow \chi_i^0 \chi_i^0 \) | \( \sim 0 \) mm | \( \chi_i^0 \) lifetime | \( \sim 0.03 \) mm | CERN-EP-2018-173 |
| \( (300 \text{ GeV}) \) \( \rightarrow \chi_i^0 \chi_i^0 \) | \( \sim 0 \) mm | \( \chi_i^0 \) lifetime | \( \sim 0.09 \) mm | 1806.07255 |
| \( (300 \text{ GeV}) \) \( \rightarrow \chi_i^0 \chi_i^0 \) | \( \sim 0 \) mm | \( \chi_i^0 \) lifetime | \( \sim 0.1 \) mm | 1501.04020 |
| \( (300 \text{ GeV}) \) \( \rightarrow \chi_i^0 \chi_i^0 \) | \( \sim 0 \) mm | \( \chi_i^0 \) lifetime | \( \sim 0.15 \) mm | 1504.09634 |
| \( (300 \text{ GeV}) \) \( \rightarrow \chi_i^0 \chi_i^0 \) | \( \sim 0 \) mm | \( \chi_i^0 \) lifetime | \( \sim 0.2 \) mm | ATLAS-CONF-2015-163 |
| \( (300 \text{ GeV}) \) \( \rightarrow \chi_i^0 \chi_i^0 \) | \( \sim 0 \) mm | \( \chi_i^0 \) lifetime | \( \sim 0.4 \) mm | 1504.09634 |
| \( (300 \text{ GeV}) \) \( \rightarrow \chi_i^0 \chi_i^0 \) | \( \sim 0 \) mm | \( \chi_i^0 \) lifetime | \( \sim 0.6 \) mm | 1504.09634 |

#### Color

- \( V \rightarrow (1 \text{ TeV}) \rightarrow q\bar{q} \)
- \( V \rightarrow (2 \text{ TeV}) \rightarrow q\bar{q} \)

\[ \chi_i^0 \text{ lifetime} \]

\[ \gamma \beta = 1 \]

### Notes

- *Only a selection of the available lifetime limits on new states is shown.*

- **Validated:**
  - Displaced objects: vertices, leptons, jets...
  - Disappearing tracks, (Heavy/Multi-) Charged Particles...
Long-lived Particles: Displaced Jets

- Displaced vertex associated with dijet, build discriminant from vertex track multiplicity, vertex $L_{xy}$ significance and Cluster RMS
- Limits obtained for pair-produced LLPs, gluino and squark masses
Event signature: $Z_d$ decaying within the TileCal and no charged tracks point to the primary vertex

- Define calorimeter-ratio jet (CRjet) with $\log_{10}(E_{\text{Tile}}/E_{\text{LAr}})>1.2$
- Data-driven method to estimate background using $W+$jets sample
Long-lived Particles: Multi-charged Particles

The significance variable of $S(dE/dx)$ is a powerful discriminator

- Use 2D $S(\text{TRT} \ dE/dx) \ S(\text{MDT} \ dE/dx)$ to define signal and control region, background estimation using ABCD method and sideband
- No observed events (<1 background expected)
- Multi-charged particles mass lower limit: 980–1220 GeV

arXiv:1812.03673
Dark Matter Searches

✓ (Mono-)X + MET
• X=jet, photon, W, Z, H, t…
• jet: most general and powerful
• photon: less powerful
• W/Z hadronic: large background
• W/Z leptonic: clean signature, small signal
• Higgs: Higgs portal
• Top: Yukawa-like coupling, more complex signature

✓ Di-X Resonance
• X=jet, photon, W, Z, H, t…
• Resonance scan

✓ Searches comparison
• Collider vs. direct/indirect searches
Dark Matter Searches

**ATLAS-CONF-2018-051**

- Use MET distribution to extract signal
- Different shape, although overwhelming background
- Background modelling important
Dark Matter Searches: Vector or Axial Vector Mediator

**ATLAS-CONF-2018-051**

**ATLAS Preliminary**

95% CL upper limits

- **Observed**
- **Expected**

- **Dijet 8 TeV**
  - ATL-PHYS-PUB-2016-070
- **Boosted dijet + ISR**
  - ATL-PHYS-PUB-2016-070
- **Resolved dijet + ISR (γ)**
  - ATL-PHYS-PUB-2016-070
- **Resolved dijet + ISR (γ)**
  - ATL-PHYS-PUB-2016-070
- **Dibjet**
  - Phys. Rev. D 95 (2017) 052006
- **Dijet TLA**
- **Higgs boson resonances**
  - ATL-PHYS-PUB-2016-070
- **Dijet angular**
  - Phys. Rev. D 95, 052004 (2017)

**CMS Preliminary**

Axial-vector mediator
Dirac DM
\( m_D = 1079 \text{ GeV/} c^2, g_1 = 1.0 \)

- \( |y_D| < 0.3 \)
- \( |y_D| < 0.6 \)

**ICHEP 2018**

- **DM + VVV** (5.9 fb⁻¹)
  - [arXiv:1711.02045]
- **DM + TV** (5.9 fb⁻¹)
- **DM + TV** (5.9 fb⁻¹)
  - [arXiv:1711.02045]

**g_q = coupling to SM**
**g_{DM} = coupling to DM**
**\( M = \) mediator mass**
**\( \Gamma_{med} = \) mediator width**

**Legend**

- **Dijet**
  - \( g_1 = 1.3 \text{ TeV} \), 36.1 fb⁻¹
  - Phy. Rev. D 96 (2017) 032001
- **Di-bjet trigger**
- **Jet trigger**
- **Di-jet angular**

**ATLAS-CONF-2018-051**

**Dijet**
- \( p_T > 30 \text{ GeV} \)
- **MET > 200 GeV**
- **Higgs boson resonances**
- ATL-PHYS-PUB-2016-070
Dark Matter Searches: Scalar or Pseudo-Scalar

**ATLAS Preliminary**

- \( \sqrt{s} = 13 \text{ TeV}, 36.1 \text{ fb}^{-1} \)
- All limits at 95% C.L.
- Scalar \( \phi, \phi \rightarrow \chi \chi \)
- \( g = g_\chi = g_\chi = 1 \)
- \( m_\chi = 1 \text{ GeV}, \) Dirac DM

**CMS Preliminary**

- \( \sigma / \sigma_{\text{theory}} \)
- **Scalar Mediator**
- Dirac DM
- \( g_\chi = 1.0 \)
- \( g_\chi = 1.0 \)
- \( m_{\text{DM}} = 1 \text{ GeV} \)

**ATLAS Preliminary**

- \( \sqrt{s} = 13 \text{ TeV}, 36.1 \text{ fb}^{-1} \)
- All limits at 95% C.L.
- Pseudo-scalar \( a, a \rightarrow \chi \chi \)
- \( g = g_\chi = g_\chi = 1 \)
- \( m_\chi = 1 \text{ GeV}, \) Dirac DM

**CMS Preliminary**

- \( \sigma / \sigma_{\text{theory}} \)
- **Pseudoscalar Mediator**
- Dirac DM
- \( g_\chi = 1.0 \)
- \( g_\chi = 1.0 \)
- \( m_{\text{DM}} = 1 \text{ GeV} \)
Dark Matter Searches Comparison: Spin Dependent
Dark Matter Searches Comparison: Spin Dependent

CMS Preliminary

ICHEP 2018

CMS observed exclusion 90% CL
- Axial-vector med., Dirac DM; $g_a = 0.25$, $g_{DM} = 1.0$

- Boosted dijet (35.9 fb$^{-1}$)
  [arXiv:1710.00159]

- Dijet (35.9 fb$^{-1}$)
  [arXiv:1806.00843]

- DM + $J/\psi(qq)$ (35.9 fb$^{-1}$)
  [arXiv:1712.02345]

- DM + $\gamma$ (35.9 fb$^{-1}$)
  [EXO-16-053]

- DM + $Z(II)$ (35.9 fb$^{-1}$)
  [arXiv:1711.00431]

DD/MD observed exclusion 90% CL
- PICASSO
  [arXiv:1611.01499]

- PICO-60
  [arXiv:1702.07668]

- Super-K (b$\bar{b}$)
  [arXiv:1503.04858]

- IceCube (b$\bar{b}$)
  [arXiv:1612.05949]

- IceCube ($t\bar{t}$)
  [arXiv:1601.00653]
Dark Matter Searches Comparison:
Spin Dependent

ATLAS Preliminary

$\sigma_{\text{SD}}(\chi\text{-neutron})$ [cm$^2$]

$m_\chi$ [GeV]

Dijet

Dijet $\sqrt{s} = 13$ TeV, 37.0 fb$^{-1}$
PRD 96, 052004 (2017)
Dijet TLA $\sqrt{s} = 13$ TeV, 29.3 fb$^{-1}$
PRL 121 (2018) 0818016
Dijet + ISR $\sqrt{s} = 13$ TeV, 15.5 fb$^{-1}$
ATLAS-CONF-2016-070

tt resonance

$\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$
EPJC 78 (2018) 565

Dibjet

$\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$
PRD 98 (2018) 032016

$E_T^{\text{miss}} + X$

Axial-vector mediator, Dirac DM
$g_q = 0.25, g_l = 0, g_\chi = 1$
ATLAS limits at 95% CL, direct detection limits at 90% CL

LUX

$\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$
PRL 116, 021303 (2017)
Dark Matter Searches Comparison: Spin Independent
Dark Matter Searches Comparison: Spin Independent

CMS Preliminary

ICHEP 2018

CMS exclusion 90% CL
Vector med., Dirac DM; $g_q = 0.25$, $g_{\text{DM}} = 1.0$

- $\text{DM + tt (35.9 fb}^{-1})$: Observed
  [EXO-16-049]
- $\text{DM + tt (35.9 fb}^{-1})$: Expected
  [EXO-16-049]

DD observed exclusion 90% CL
- CRESST-II
  [arXiv:1509.01515]
- CDMSlite
  [arXiv:1509.02448]
- PandaX-II
  [arXiv:1708.06917]
- LUX
  [arXiv:1608.07648]
- XENON1T
  [arXiv:1805.12562]
- CDEX-10
  [arXiv:1802.09016]
Dark Matter Searches Comparison: Spin Independent

\[ \sigma_{SI}(\chi-nucleon) \text{ [cm}^2\text{]} \]

\[ \sqrt{s} = 13 \text{ TeV, 29.3-37.0 fb}^{-1} \]

ATLAS Vector Z'
Vector mediator, Dirac DM
\[ g_q = 0.25, g_1 = 0, g_\chi = 1 \]
[ATLAS-CONF-2015-070]
[JHEP 01 (2018) 126]
[PLB 775 (2017) 319]
[arXiv:1807.11471 [hep-ex]]

ATLAS Z' baryonic
Z' baryonic, Dirac DM
\[ \sin \theta = 0.3, g_q = 1/3, g_\chi = 1 \]

ATLAS Scalar
Scalar mediator, Dirac DM
\[ g_q = 1, g_\chi = 1 \]

DarkSide-50
[arXiv:1802.06994]

CRESST III
[arXiv:1711.07692]

XENON1T
[arXiv:1805.12562]

PandaX

LUX
Extensive exotics searches done at LHC

- Most searches analyzed 36$\text{fb}^{-1}$ data
  - Resonances scan
  - New signatures
  - Long-lived particles
  - Dark matter
- 150$\text{fb}^{-1}$ already collected
- No new (exotic) physics found so far
- Continue the effort to search for all possible final states and signatures
  - Many more interesting ideas to test and search
  - No one knows when or where the new physics will appear