Hunting New Physics with ATLAS

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for the ATLAS Collaboration

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Why going beyond the Standard Model?

- SM provides an excellent description of the experimental data so far
  - QCD and hadronic structure
  - precision EW physics
  - top quark
  - flavour physics
- yet... it does not provide an answer to:
  - hierarchy / fine tuning problem
  - matter-antimatter asymmetry
  - dark matter & dark energy
  - neutrino masses
  - unification of EW interactions & QCD
  - gravitation
  - more than one fermion generation

An extension of the Standard Model is needed
(some) ideas beyond Standard Model

[Diagram showing a matrix of Big Ideas and Big Questions]

- Multiverse
- SUSY
- Compositeness, Extra dimensions
- Extended Higgs Sector
- Top Partner
- W/Z'
- Minimal Dark Matter
- Hidden Sector

Big Questions:
- Dark Matter
- Origin of EWSB
- Naturalness
- Unification
- Origin of Matter
- Origin of Flavor
- New Forces
- Elementary vs Composite

???
**ATLAS at the LHC**

- **Spectacular LHC performance**
- **Run 2: 2015 – ongoing**
  - $\sqrt{s} = 13$ TeV
  - 2015-2016: $\sim 40$ fb$^{-1}$ pp collisions recorded by ATLAS
  - 2017: $\sim 16$ fb$^{-1}$ recorded so far
Beyond-SM searches strategy

① Pursue signature-driven analyses:
   ▫ resonances: dileptons, jets, photons, ...
   ▫ non-resonant: tails in kinematic distributions
   ▫ special particles: slow-moving, long-lived, ...
   ▫ ...

② Search for excess of events over the expected SM background
   ▫ in one or more *Signal Regions (SRs)*

③ If no significant excess is observed
   ▫ set cross-section upper limits
   ▫ interpret in specific models to obtain limits on masses, couplings, ...

☞ Background estimate: data-driven techniques for main; MC for smaller
   ▫ measurement with data in *Control Regions (CRs)*, extrapolated to SRs
   ▫ method validated in *Validation Regions (VRs)*

☞ Blind analysis: first define and validate analysis, then open signal box
Signatures probing models

- **Resonances**
  - dileptons: $Z' \rightarrow \ell\ell$, ...
  - $W' \rightarrow \ell\nu$
  - dibosons: WW, WZ, γγ, ...
  - top/bottom: VLQs
  - BSM Higgs, ...
  - leptons+jets: leptoquarks, ...
  - dijets

- **Non-resonant final states**
  - dileptons
  - leptons+jets
  - mono-X + $E_T^{\text{miss}}$, dark matter, ...
  - ...

- **Long-lived particles**
  - high ionisation
  - disappearing tracks
  - displaced lepton jets, vertices

- **SUSY-specific signatures**: $E_T^{\text{miss}} + X$
  - strong production
  - 3rd-generation squarks
  - electroweak production
  - ...

**Emphasis on most recent results**

Signature-based searches cover multitude of theoretical scenarios

- Pawel Bruckman’s talk
- Yoram Rozen’s talk
- Cristiano Sebastiani’s poster

See talks by:
- André Sopczak
- Shunsuke Adachi
- Nicolas Koehler
- Athina Kourkoumeli
Looking for resonances & tails in distributions

- Non-SUSY searches only presented here
- Detailed reviews for SUSY in other talks
Dileptons (1/3)

- **Selection**
  - 2 opposite-sign (OS) isolated electrons OR muons with $p_T > 30$ GeV

- **Background**
  - Drell-Yan (DY), diboson, top (pair & single)
    - DY fitted to data at Z-peak
  - fakes (QCD jets & W+jets) → data-driven matrix method

- **Reconstruction of dilepton invariant mass $m_{\ell\ell}$**

- Looking for narrow resonances OR broad excesses in the invariant mass distribution
  - Data consistent with SM expectation

36.1 fb$^{-1}$ @ 13 TeV

arXiv:1707.02424
Dileptons (2/3)

- **Z’ resonances**: spin-1 neutral gauge bosons
  - Sequential SM (SSM): Z’ with same couplings as SM Z
  - GUT models based on $E_6$ gauge group predict two additional U(1) gauge fields: $Z'_\psi$, $Z'_\chi$
  - Observable as narrow resonances in dilepton invariant mass spectrum

- **Contact Interactions (CI)**
  - Probes quark and lepton compositeness, with binding energy scale $\Lambda$
  - Different chiral structures considered
  - Detectable as broad excess in dilepton invariant mass spectrum

arXiv:1707.02424

36.1 fb$^{-1}$ @ 13 TeV
**Dileptons (3/3)**

- **Minimal Z' models** are characterized by three parameters:
  - Z' boson mass
  - $\gamma'$: strength of Z' boson coupling relative to SM Z
  - $\theta_{\text{Min}}$: mixing angle between the generators of B-L (Baryon minus Lepton number) and the weak hypercharge gauge groups

<table>
<thead>
<tr>
<th>Model</th>
<th>$\gamma'$</th>
<th>$\tan\theta_{\text{Min}}$</th>
<th>Lower limits on $M_{Z'_{\text{Min}}}$ [TeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>$cc$</td>
</tr>
<tr>
<td>$Z'_{X}$</td>
<td>$\sqrt{\frac{11}{24}} \sin \theta_{\text{Min}}$</td>
<td>$-\frac{4}{5}$</td>
<td>3.7</td>
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<tr>
<td>$Z'_{3R}$</td>
<td>$\sqrt{\frac{3}{8}} \sin \theta_{\text{Min}}$</td>
<td>-2</td>
<td>4.0</td>
</tr>
<tr>
<td>$Z'_{B-L}$</td>
<td>$\sqrt{\frac{55}{12}} \sin \theta_{\text{Min}}$</td>
<td>0</td>
<td>4.0</td>
</tr>
</tbody>
</table>

- Also obtained generic upper limits on visible $\sigma$ in fiducial lepton $p_T$ & $\eta$ and mass-window for various widths *(not shown here)*

arXiv:1707.02424

36.1 fb\(^{-1}\) @ 13 TeV
Diphotons

- Search for heavy resonant and non-resonant BSM physics decaying into diphoton final states
- Event selection
  - $\geq 2$ isolated photons with $E_T > 40$ GeV & 30 GeV
  - different kinematic selections applied for spin-0 vs. spin-2
  - narrow-width approximation (NWA) bump in $m_{\gamma\gamma}$
  - non-resonant: counting experiment for $m_{\gamma\gamma} > 2240$ GeV

\[ \rightarrow \text{No significance excess observed up to diphoton masses of 2.7 TeV} \]

Limits set in various scenarios

- **Spin-0 resonance**: exclusion limits for NWA signal $\sigma \times \text{BR}(\gamma\gamma)$ range from 11.4 fb @200 GeV to about 0.1 fb @ 2.7 TeV
- **Spin-2 resonance**: Randall-Sundrum (RS) graviton with $k/M_{Pl}=0.1$ excluded below $m_{G^*}=4.1$ TeV
- **Spin-2 non-resonant**: lower limit on $M_S$ placed between 5.7 TeV and 8.6 TeV on ADD model depending on formalism used and number of extra dimension assumed
Dibosons: $V' \rightarrow VH \rightarrow q\bar{q}(\ell)bb$ (1/2)

- Search for boosted heavy resonances decaying to VH in all-hadronic channel
  - final state composed of two large-R jets, $J$
  - narrow-width bumps at di-jet ($m_{JJ}$) invariant mass for $m_{JJ} > 1$ TeV
- Event selection
  - lepton veto; $E_T^{miss}$ veto
  - $\geq 2$ large-R jets with $p_T > 250$ GeV; leading $p_T > 450$ GeV
  - larger mass is H-jet; smaller is V-jet
  - W/Z and H mass window
- Background estimated by side band and/or no-b-tag

Data compatible with SM hypothesis
Largest deviation in ZH channel at $m_{JJ} \approx 3$ TeV with local (global) significance of 3.3$\sigma$ (2.1$\sigma$)

arXiv:1707.06958
Dibosons: $V' \rightarrow VH \rightarrow q\bar{q}(\gamma)bb$

(2/2)

- Candidate signal models:
  - Heavy Vector Triplet (HVT) $W'$ and $Z'$
  - Model A: comparable BRs to fermions and gauge bosons
  - Model B: suppressed couplings to fermions

- Upper limits on $\sigma \times \text{BR}$ set for $W'$ and $Z'$ resonances:
  - HVT Model B resonances excluded in mass range 1100 - 2500 GeV for WH, and 1100 - 2600 GeV for ZH
  - HVT Model A resonances excluded in mass range 1100 - 2400 GeV for WH, and 1100 - 1480 GeV and 1700 - 2350 for ZH

Note: there is a ~60% overlap of data between the WH and ZH selections, for both 1-tag and 2-tag regions

arXiv:1707.06958
Dibosons: $X \rightarrow WV \rightarrow \ell \nu q\bar{q}$

- Motivation:
  - Spin 0: Composite Higgs (ggF or VBF)
  - Spin 1: Heavy Vector Triplet (q\bar{q} or VBF)
  - Spin 2: RS graviton (ggF production)
- Consider both resolved (jj) and “merged” (J), if highly boosted, dijet system
- Events categorisation:
  - VBF or DY (includes ggF & q\bar{q})
  - (i) merged high purity (HP);
    (ii) merged low purity (LP); (iii) resolved
  - WW or WZ (overlap)
- Search for bump in $m(\ell vvjj)$ or $m(\ell vvJ)$ distributions

$\Rightarrow$ No significance excess observed
$\Rightarrow$ limits set in resonance masses for considered models

ATLAS-CONF-2017-051
Dibosons – summary

$\sigma \times BR$ upper limits for Heavy Vector Triplets decaying to dibosons for different final states

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/EXOTICS/
Vector-Like Quarks (VLQs): $T \rightarrow Wb$

- VLQs proposed to cancel quadratic divergences in Higgs mass
- Predicted in Little/Composite Higgs
- Production: pair (QCD) or single (EW)
- Decays:
  - $T \rightarrow Wb / Zt / Ht$
  - $B \rightarrow Wt / Zb / Hb$

$T \rightarrow Wb$ analysis
- 1 lepton, MET, $\geq 3$ jets, $\geq 1$ b-jet
- $\geq 1$ W-tagged large-R jet, no overlap with b-jet

Full event reconstruction by minimising $|\Delta m_T|$
- Profile likelihood fit to improve BG modelling
  - $\Delta R(\ell, \nu)$ & $S_T$ cut to define SR/CR
  - discriminating variable: $m_{T,\text{lep}}$

36.1 fb$^{-1}$ @ 13 TeV

No significant deviation from SM expectation is observed
VLQs: $T \rightarrow Wb$ results

- Uncertainties
  - dominated by low statistics
  - main systematics: $t$ & $t\bar{t}$ modelling

- Significantly improved limits w.r.t. Run I
  - $m_{T/Y} (BR_{Wb} = 100\%) > 1350 (782) \text{ GeV}$
  - $m_T$ (singlet) > 1170 GeV
  - $m_{B/X} (BR_{Wt} = 100\%) > 1250 \text{ GeV}$
  - $m_B$ (singlet) > 1180 GeV

![Graph showing experimental limits and expected limits for $m_T$ versus $B_T = \mathcal{B}(T \rightarrow Wb)$ with expected and observed limits on $\sigma(pp \rightarrow T \rightarrow Wb + X)$ for 36.1 fb$^{-1}$ at 13 TeV.](image-url)
VLQ summary

• All decays of vector-like T quark considered: $W_b / Z_t / H_t$
• Vector-like B decays not yet fully covered: only $W_t / H_b$ included
• Analyses make use of boosted decays at 13 TeV
... in a nutshell

**ATLAS Exotics Searches** - 95% CL Upper Exclusion Limits

**Status:** July 2017

<table>
<thead>
<tr>
<th>Model</th>
<th>(\ell, \gamma)</th>
<th>Jets(^\dagger)</th>
<th>(E_{\text{miss}}^\ell)</th>
<th>Limit</th>
<th>Reference</th>
</tr>
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<tbody>
<tr>
<td>ADD G(\chi) (q/q)</td>
<td>0, 1, (q)</td>
<td>1 - 4 (</td>
<td>\geq 2</td>
<td>)</td>
<td>2 - 3</td>
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<tr>
<td>ADD non-resonant (\gamma\gamma)</td>
<td>2, 1</td>
<td>1 - 4</td>
<td>3.4 TeV</td>
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<tr>
<td>ADD DBH</td>
<td>2, 2 (</td>
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<td>)</td>
<td>2 - 3</td>
<td>5.9 TeV</td>
</tr>
<tr>
<td>ADD BH</td>
<td>2, 3 (</td>
<td>\geq 2</td>
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<td>2 - 3</td>
<td>5.9 TeV</td>
</tr>
<tr>
<td>ADD BH multi Jet</td>
<td>2, 3, 4 (</td>
<td>\geq 2</td>
<td>)</td>
<td>2 - 3</td>
<td>5.9 TeV</td>
</tr>
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<td>RS1 G(\chi)</td>
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<td>Bulk RS G(\chi) (\rightarrow) WW (\rightarrow) (\ell\ell) (\gamma\gamma)</td>
<td>2, 1</td>
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<td>3.4 TeV</td>
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<td>2UED / RPP</td>
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<td>2 - 3</td>
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<tr>
<td>Extra dimensions</td>
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<td>3.4 TeV</td>
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<td></td>
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<tr>
<td>SSM Z(\rightarrow) (\ell\ell)</td>
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<td>1 - 4</td>
<td>3.4 TeV</td>
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<td></td>
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<tr>
<td>SSM Z(\rightarrow) (\tau\tau)</td>
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<td>1 - 4</td>
<td>3.4 TeV</td>
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<td></td>
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<td>Leptophotic Z(\rightarrow) bb</td>
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<td>1 - 4</td>
<td>3.4 TeV</td>
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<tr>
<td>Leptophotic Z(\rightarrow) (\ell\ell)</td>
<td>1, 2 (</td>
<td>\geq 2</td>
<td>)</td>
<td>2 - 3</td>
<td>5.9 TeV</td>
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<tr>
<td>SSM WW (\rightarrow) (\ell\ell) (\gamma\gamma)</td>
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<td>2 - 3</td>
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<tr>
<td>HVT V(\rightarrow) WW (\rightarrow) (\ell\ell) model B</td>
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<td>HVT V(\rightarrow) WH/ZH model B multi-channel</td>
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<td>LRSM W(\rightarrow) (\ell\ell)</td>
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<td>)</td>
<td>2 - 3</td>
<td>5.9 TeV</td>
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<tr>
<td>LRSM W(\rightarrow) (\ell\ell)</td>
<td>1, 2 (</td>
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<td>)</td>
<td>2 - 3</td>
<td>5.9 TeV</td>
</tr>
<tr>
<td>DM</td>
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<tr>
<td>Scalar DM 1(^{\text{st}}) gen</td>
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<td>)</td>
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<td>5.9 TeV</td>
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<tr>
<td>Scalar DM 2(^{\text{nd}}) gen</td>
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<tr>
<td>Scalar DM 3(^{\text{rd}}) gen</td>
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<td>LO</td>
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<tr>
<td>Heavy quarks</td>
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<tr>
<td>VLO TT (\rightarrow) Ht+X</td>
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<td>1 - 4</td>
<td>3.4 TeV</td>
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<tr>
<td>VLO TT (\rightarrow) Zt+X</td>
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<td>3.4 TeV</td>
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<td></td>
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<tr>
<td>VLO TT (\rightarrow) Wb+X</td>
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<td>1 - 4</td>
<td>3.4 TeV</td>
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<td></td>
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<tr>
<td>VLO BB (\rightarrow) Hb+X</td>
<td>2, 1</td>
<td>1 - 4</td>
<td>3.4 TeV</td>
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<td></td>
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<tr>
<td>VLO BB (\rightarrow) Wb+X</td>
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<td>1 - 4</td>
<td>3.4 TeV</td>
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<tr>
<td>VLO QQ (\rightarrow) WgWg</td>
<td>1, 2 (</td>
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<td>)</td>
<td>2 - 3</td>
<td>5.9 TeV</td>
</tr>
<tr>
<td>Excited fermions</td>
<td></td>
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<td>3.4 TeV</td>
<td></td>
<td></td>
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<tr>
<td>LRSM Majorana v</td>
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<td>1 - 4</td>
<td>3.4 TeV</td>
<td></td>
<td></td>
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<tr>
<td>Higgs triplet H(\rightarrow) (\ell\ell)</td>
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<td>3.4 TeV</td>
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<tr>
<td>Magnetic monopoles</td>
<td></td>
<td>1 - 4</td>
<td>3.4 TeV</td>
<td></td>
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</tbody>
</table>

*Only a selection of the available mass limits on new states or phenomena is shown.

\(^\dagger\)Small-radius (large-radius) jets are denoted by the letter \(\ell\) (\(J\)).

**Reference**

- ATLAS-PB-2016-04
- ATLAS-CONF-2017-051
- ICNFP 2017
- V.A. Mitsou
Long-lived particles

- Most recent results @ 13 TeV presented here
- Searches for supersymmetric particles
- Many more searches for non-SUSY are underway with 13 TeV data
Stable or metastable particles

- Long-lived decays of sparticles possible in several frameworks, including:
  - nearly conserved symmetry
    - e.g. long lived gluinos or squarks that hadronise before decaying → R-hadrons in Split SUSY
  - low coupling between the particle and the final state
    - e.g. weak R-parity violating (RPV) couplings in SUSY
  - mass degeneracy between the particle and the final state

- Depending on the lifetime, different detection techniques involving various objects: tracks, photons, leptons, ...

![Diagram showing different types of tracks and their lifetimes:](image)
**Displaced vertices** (1/2)

- Metastable particles decaying in the Inner Detector
  - predicted in models of RPV SUSY or split-SUSY
  - benchmark signal: gluino hadronising into an R-hadron

32.7 fb⁻¹ @ 13 TeV

- **Large-radius tracking**: re-running standard track and vertex reconstruction improves signal efficiency at large radii
- **Backgrounds**: instrumental and estimated from data
  - high track multiplicity hadronic interactions
    - DV in regions with high material density vetoed
  - merged DV extrapolated from low-n_{trk} region
- Background estimate validated in signal-depleted regions
Displaced vertices (2/2)

- SR defined as a DV with mass > 10 GeV and high track multiplicity (> 5 tracks)
- No event is observed in the SR, compatible with a bkg. expectation of 0.2±0.2 events

Limits are set on gluino R-hadrons as a function of masses and lifetime
- For a lifetime of 1 ns, gluino masses up to 2.2 TeV are excluded

32.7 fb⁻¹ @ 13 TeV
Disappearing track (1/2)

- Decays to invisible products in the Inner Detector
  - chargino and neutralino nearly degenerate, the soft pions in the decay are not reconstructed
  - for wino LSP generic prediction of ~160 MeV splittings, or lifetimes of ~0.2 ns ➤ 6 cm

- **Pixel tracklets (≡ pixel-only tracks):** 10× increase in acceptance over standard tracks for low lifetimes

- Backgrounds estimated by a simultaneous fit to the tracklet $p_T$ distribution

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36.1 fb$^{-1}$ @ 13 TeV

ATLAS-CONF-2017-017
Disappearing track (2/2)

• No significant excess is observed
• EWK production limits significantly improved at low lifetimes ($c\tau \lesssim 12$ cm)
  □ thanks to new insertable pixel B-layer (IBL) installed during long shutdown ($r \sim 3$ cm)
• Strong production: reaching $1.4\ (1.1)$ TeV in chargino mass for lifetimes of $1.0\ (0.2)$ ns

36.1 fb$^{-1}$ @ 13 TeV
Long-lived particles in SUSY - summary

8-TeV results on R-hadrons
Split SUSY with metastable $\tilde{g} \rightarrow g/qq \tilde{x}_1^0$

Summary 8-TeV & 13 TeV on disappearing track
Long lived chargino, $\tilde{x}_1^\pm \rightarrow \pi^\pm \tilde{x}_1^0$

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/SUSY/
Summary

• Standard Model limitations imperatively call for Physics beyond it, extending and complementing it
• ATLAS has searched for physics BSM at TeV scale in a variety of signatures inspired by a multitude of theoretical scenarios
• No significant deviation from SM expectations observed so far
• LHC Run 2 new data may reveal hints of New Physics
  ▫ ATLAS is well-prepared to make the most of them
  ▫ analysis continuously improved with new trigger and/or reconstruction techniques

Continuously updated public results:
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults
Thank you for your attention!