New physics searches at the LHC
Where do we go with run II?

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On behalf of the ATLAS and CMS collaborations

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Introduction

• With the discovery of Higgs boson in 2012, the Standard Model has been completed
• However there are some short comings in the SM
  • hierarchy problem (Higgs mass divergence)
  • matter vs. anti–matter asymmetry
  • unification of the force
  • etc.
• Among all, the origin of the Dark Matter (DM) is one of the biggest mysteries
• In collider experiment, searches for weakly interacting particles (WIMP DM) use large imbalance of $p_T$ (or $E_T$), assuming they escape detection
• Hence Missing energy measurement is the key

N.B. there are other DM models which predict exotic signatures (e.g. displaced vertices)
ATLAS (A Toroidal LHC ApparatuS) and CMS (Compact Muon Solenoid) are general-purpose detectors with
- excellent tracking in the central region
- good calorimeter granularity with large coverage (|η| ≤ 5.0 ~0.8°)

make them good for missing transverse momentum measurements
LHC Run–1

Successful operations in both LHC and Experiments

- LHC was in good condition during Run–1 (2010–2012)
- ATLAS and CMS collected good fraction of data (>95%) throughout Run–1
- 8 (7) TeV proton–proton collisions ~20 (5) fb$^{-1}$ good data for physics
General strategy for the new physics

- Define the event selection based on signal and bkg characteristics (e.g. kinematics)
- Compare the data to bkg (MC or by data driven)
  - new physics would produce deviation from bkg prediction
  - If consistent → set the limits, typically on the cross-section x BR
- Then comparisons made for specific models

DM search approach with collider exp.

Specific models (e.g. SUSY)

Simplified Models

Effective Field Theory

PART 1:
Complete models (as targeted by SUSY searches)

PART 2:
Run-1 based more often on EFT, sliding to Simplified Models toward Run-2
PART 1
Complete SUSY models
SUSY overview for RUN1

- Searches based on R-parity conservation + neutral lightest SUSY particle
  → look for large Missing \( E_T \) final state

Productions
- Gluinos/Squarks strong productions
- Stop/sbottom productions
- Direct electro-weak productions

(searches for R-parity violating and long lived signatures are not covered in this talk. But I will briefly show the “disappearing track in the detector volume” search which is relevant for the pMSSM interpretation later on)

- Searches optimized and interpreted with simplified SUSY models
  (single production & decay mode)
- Results are also interpreted with more sophisticated models (mSUGRA, NUHM, GGM, …)

In this talk → pMSSM (19 parameters)
  consideration with DM relic density
Strong production (0/1/2 leptons + multi jets + $E_T^{\text{miss}}$)

- Dominant process at LHC, if squarks/gluinos are not too heavy
- Typical signature: high-pT multi-(b) jets, 0-1-2 leptons, $E_T^{\text{miss}}$ from LSP

### ATLAS searches

- 0-leptons + 2-6 jets + $E_T^{\text{miss}}$ JHEP 09 (2014), 176
- 0-leptons + 7-10 jets + $E_T^{\text{miss}}$ JHEP 10 (2013), 130
- 1-leptons + jets + $E_T^{\text{miss}}$ JHEP 04 (2015), 116
- 2-leptons + 2-6 jets + $E_T^{\text{miss}}$ EPJC 75 (2015), 318
- 2-leptons SS/3L+jets+EtMiss JHEP 06 (2014), 035
- 1-2 taus + jets + $E_T^{\text{miss}}$ JHEP 09 (2014), 103
- Photons + jets + $E_T^{\text{miss}}$ PRD 92 (2015) 072001
- Summary paper arXiv: 1507.05525

### CMS searches

- 3-5,6-7,>=8 jets + $E_T^{\text{miss}}$ JHEP 06 (2014) 055
- Multi-jets+b-jets+ $E_T^{\text{miss}}$ PLB 725 (2013) 243
- 1-leptons+jets+bjets+EtMiss PLB 733 (2014) 328
- 2-leptons SS+bjets+EtMiss JHEP 01 (2014), 163
- Multi-jets with MT2 variable JHEP 05 (2015), 078

Numerous analyses for different phase spaces
Strong production (0 leptons + ≥2–6jets + $E_T^{\text{miss}}$)

- define 15 orthogonal Signal Regions (SR) (each with 4 x Control Regions (CR: Bkg dominant))
- determine bkg expectations from fit

interpret with simplified model
Hint for the Run2?

(3σ excess)

• ATLAS search for the jets + $E_T^{\text{miss}} + Z$ signature
  • At least 2 jets ($p_T > 35\text{GeV}$)
  • $H_T > 600\text{ GeV}$ (high jet activity) $H_T = \sum p_T(\text{jets}) + p_T(\text{leptons})$
  • $E_T^{\text{miss}} > 225\text{ GeV}$ then select SFOS lepton pair (ee, $\mu\mu$)
  • $M(\ell\ell) = M_Z \pm 10\text{ GeV}$

• Main Bkg: ‘flavour symmetric’, estimated from e$\mu$ data)

N.B. CMS (JHEP 04(2015),124) observes no such excess

\[ \begin{align*}
\text{ee channel 3.0 } \sigma \\
\text{\textit{ATLAS}} \\
\text{s = 8 TeV, 20.3 fb}^{-1} \\
\text{SR-Z ee}
\end{align*} \]

\[ \begin{align*}
\text{\textit{ATLAS}} \\
\text{s = 8 TeV, 20.3 fb}^{-1} \\
\text{SR-Z } \mu\mu
\end{align*} \]
3rd gen. squark production

- Searches for gluino mediated or direct stop/sbottom productions
- Natural (non–fine tuning) SUSY requires light stop/sbottom

Numerous channels covering different decay chains, mass splitting

\[ m_{stop} < 700 \ (750) \text{ GeV excluded for ATLAS (CMS)} \]

Summary Paper:
JHEP 06 (2015), 116

ATLAS 3rd gen summary
arXiv:1506.08616 (accepted by EPJC)
Electro-weak production

- If squarks/gluinos are all heavy, EW SUSY productions dominate
- Multi-lepton signatures with low hadronic activity
  - 2-leptons + EtMiss, 3-leptons + EtMiss, ≥ 4-leptons + EtMiss, ≥ 2-taus + EtMiss, 1-lepton+2 b-jets+EtMiss, etc

CMS Preliminary
s = 8 TeV
ICHEP 2014

2nd neutralino, or chargino mass [GeV]

- decay via W/Z
  - PRD 90, 092007 (2014)
- if decay via Higgs is allowed
  - PRD 90, 092007 (2014)
- with intermediate slepton decays
  - EPJC 74 (2014) 3036

ATLAS EW summary
arXiv:1509.07152 (submitted to PRD)
Long-lived $\tilde{\chi}_1^\pm$ search

Long lived chargino $\rightarrow \pi + \text{neutralino}$

- Backgrounds
  - hadrons interacting with material in ID
  - Leptons fails id criteria
  - $p_T$ mis-measured track
- ATLAS/CMS
  - Similar approach with different inner detector configuration

**ATLAS:** Phys. Rev. D 88, 112006 (2013)

Charginos mass <270 GeV is excluded (95% CL)

**CMS:** (JHEP01 (2015) 096)

has excluded up to 260GeV (95% CL)

cconstraints on chargino lifetime vs. mass is also obtained
pMSSM interpretation (ATLAS)

ATLAS arXiv:1508.06608 (accepted by JHEP)

• Evaluate the general pMSSM (19 parameters) limit from 22 Run1 searches
  • R–parity conserving
  • neutralino LSP

• Random sampling of the parameters 500 million model points (up to 4 TeV)

• Apply constraints from
  • Precision EW and flavor
  • DM abundance
  • LEP, Tevatron
  • Higgs mass

→ 310,327 models (Before Run–1)

• Generate/reconstructed 44,559 models 600 million simulated signal events

• Use 22 search results (200 signal regions), present in 2D the fraction of models excluded

Similar extensive analyses by CMS (SUS15010)
pMSSM interpretation (ATLAS)

• The plot shows the fraction of the models excluded by Run–1
  • Black : 100% excluded
  • White : no model points excluded at pre–selection
  • White line : 95% CL limit from a simplified model for comparison (not much different!)

• Compressed gluino–neutralino models are excluded up to 600GeV by mono–jet search
• Sensitivity for wino–like LSP model from disappearing track search ( $\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 + \pi$ )

arXiv:1508.06608
Impact of ATLAS Run1 searches on SUSY DM

- **Bino LSP models:**
  - 2/3 are excluded, sensitivity up to $m(\tilde{\chi}_1^{0}) \sim 800\text{GeV}$

- **Wino LSP models:**
  - Sensitivity up to 800GeV, especially below 200GeV (80% excluded)
  - Constraints from disappearing track analysis

- **Higgsino LSP models:**
  - Charged higgsino lifetime too short, not much constrained

arXiv:1508.06608
PART 2
Effective Field Theories and Simplified Models
Mono-X searches

• Effective Field Theory (EFT) approach

\[ \gamma, Z, W, h... \]

\[ \bar{q} \rightarrow \chi, q \]

Cross section depends on:
\[ M_* = \frac{m_\gamma}{\sqrt{g fg_\chi}} \]
Suppression mass
\[ m_\gamma: \text{mediator mass} \]
\[ g fg_\chi: \text{coupling strength} \]

• Search for particle X (=\gamma, jet, Z/W, etc) recoiling against DM (=Missing E_T)

• Result interpretation:
  • Cross section
  • Effective operators

<table>
<thead>
<tr>
<th>Name</th>
<th>Operator</th>
<th>Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1</td>
<td>\bar{\chi} \gamma \bar{q} q</td>
<td>\frac{m_q}{M_*^3}</td>
</tr>
<tr>
<td>D2</td>
<td>\bar{\chi} \gamma^5 \bar{q} \gamma q</td>
<td>\frac{i m_q}{M_*^3}</td>
</tr>
<tr>
<td>D3</td>
<td>\bar{\chi} \gamma^5 \bar{q} q</td>
<td>\frac{i m_q}{M_*^3}</td>
</tr>
<tr>
<td>D4</td>
<td>\bar{\chi} \gamma^5 \bar{q} \gamma^5 q</td>
<td>\frac{m_q}{M_*^3}</td>
</tr>
<tr>
<td>D5</td>
<td>\bar{\chi} \gamma^5 \bar{\gamma} \gamma^5 \gamma q</td>
<td>1/M_*^2</td>
</tr>
<tr>
<td>D6</td>
<td>\bar{\chi} \gamma^5 \bar{q} \gamma^5 \gamma q</td>
<td>1/M_*^2</td>
</tr>
<tr>
<td>D7</td>
<td>\bar{\gamma} \gamma^5 \bar{q} \gamma^5 \gamma q</td>
<td>1/M_*^2</td>
</tr>
<tr>
<td>D8</td>
<td>\bar{\chi} \gamma^5 \bar{\gamma} \gamma^5 \gamma q</td>
<td>1/M_*^2</td>
</tr>
<tr>
<td>D9</td>
<td>\bar{\chi} \gamma^5 \bar{\gamma} \gamma^5 \gamma q</td>
<td>1/M_*^2</td>
</tr>
<tr>
<td>D10</td>
<td>\bar{\chi} \gamma^5 \bar{\gamma} \gamma^5 \gamma q</td>
<td>\frac{i m_q}{M_*^2}</td>
</tr>
<tr>
<td>D11</td>
<td>\bar{\chi} \gamma^5 \bar{\gamma} \gamma^5 \gamma q</td>
<td>\frac{\alpha_s}{4 M_*^3}</td>
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<tr>
<td>D12</td>
<td>\bar{\chi} \gamma^5 \bar{\gamma} \gamma^5 \gamma q</td>
<td>\frac{i \alpha_s}{4 M_*^3}</td>
</tr>
<tr>
<td>D13</td>
<td>\bar{\chi} \gamma^5 \bar{\gamma} \gamma^5 \gamma q</td>
<td>\frac{\alpha_s}{4 M_*^3}</td>
</tr>
<tr>
<td>D14</td>
<td>\bar{\chi} \gamma^5 \bar{\gamma} \gamma^5 \gamma q</td>
<td>\frac{\alpha_s}{4 M_*^3}</td>
</tr>
</tbody>
</table>

Mono-photon search

- $E_T^{\text{miss}} > 140$ GeV
- $p_T > 145$ GeV (central) accept up to 1jet
- Bkg estimation with simulation corrected for data/MC differences
- Similar analysis from ATLAS (Phys. Rev. D 91, 012008 (2015))

630 events for $614 \pm 63$ expected
**Mono–Jet search**

- $p_T^{\text{jet}}>125$ GeV (central)
- $p_T^{\text{jet}}/E_T^{\text{miss}}>0.5$
- at least 1 jet, lepton and isolated track vetoes
- Bkg estimation in CRs, Cross check in VRs
- $E_T^{\text{miss}}$: SR1 (>150 GeV)– SR9 (>700 GeV)

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**ATLAS**

$1s=8$ TeV, 20.3 fb$^{-1}$

$E_T^{\text{miss}}>150$ GeV

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**Expected**

- **Expected limit ($\pm 1\sigma/2\sigma$)**
- **Observed limit**
- **Thermal relic**
- **Truncated, coupling=1**
- **Truncated, max coupling**

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**ET^{miss}>700 GeV**

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**WIMP mass m_χ [GeV]**

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**ET^{miss}>700 GeV**
Comparison plots

- Comparison with other experiments
- Complementary with direct searches, esp. LHC has sensitivities for low DM mass
- LHC mono-X searches also have similar sensitivity for spin-dependent operators, where direct searches are weaker (backup slide)

**mono-photon**

CMS, arXiv:1410.8812

**mono-jet**


\[\chi\text{-Nucleon Cross Section} \left[ \text{cm}^2 \right] \]

\[\chi\text{-Nucleon Cross Section} \left[ \text{cm}^2 \right] \]

\[\text{WIMP-nucleon cross section} \left[ \text{cm}^2 \right] \]

\[\text{WIMP mass } m_\chi \left[ \text{GeV} \right] \]

\[\text{Spin Independent, Vector Operator} \left( \chi Y_q, \chi Y_q \right) \left( q Y_q \right) \]

\[\Lambda^2 \]

\[\text{LUX} \]

\[\text{COUPP 2012} \]

\[\text{CDMS II} \]

\[\text{XENON100} \]

\[\text{SIMPLe} 2012 \]

\[\text{CMS Monolepton } \xi = +1 \]

\[\text{CMS Monophoton, 7 TeV, 5.1 fb}^{-1} \]

\[\text{CMS Monophoton, 8 TeV, 19.6 fb}^{-1} \]

\[\text{CoGeNT 2011} \]

\[\text{DAMa/LIBRA, 3} \sigma \]

\[\text{CRESST II, 2} \sigma \]

\[\text{CoGeNT, 99} \% \text{ CL} \]

\[\text{CDMS, 1} \sigma \]

\[\text{CDMS, 2} \sigma \]

\[\text{LUX 2013 90} \% \text{ CL} \]

\[\text{LUX 2015 90} \% \text{ CL} \]

\[\text{Xenon100 90} \% \text{ CL} \]

\[\text{CMS 8TeV D5} \]

\[\text{CMS 8TeV D11} \]
Mono–W or Z searches

- Search for DM signature with gauge boson
- Lower background, complementary to mono–jet search
- Both hadronic, leptonic decays covered (hadronic channel has stronger sensitivity)

- a large radius jet ($p_T > 250$ GeV)
- $m_{\text{jet}} = [50, 120]$ GeV
- lepton, photon vetoes
- Data driven background estimation

ATLAS 20.3 fb$^{-1}$ $\sqrt{s} = 8$ TeV
SR: $E_T^{\text{miss}} > 500$ GeV

- Data
- $Z(\nu\nu)+\text{jet}$
- $W/Z(e/\mu/\tau)+\text{jet}$
- Top
- Diboson
- uncertainty

$\chi$-N cross-section [cm$^2$]

PRL 112 (2014) 041802

CMS DM+Z search EXO12054
Searches with Simplified Models

- Less simple and versatile as it is more model-dependent. However, it overcomes the problems of EFT (validity, comparisons with the direct detection experiments).
- Additional parameters are needed (e.g. mediator mass, couplings...)
- already in use by ATLAS and CMS during Run-1

**Signatures:**
- Jet + $E_T^{\text{miss}}$
- Boson + $E_T^{\text{miss}}$
- Higgs + $E_T^{\text{miss}}$
- HeavyFlavor $q + E_T^{\text{miss}}$

**Free parameters**
- $g (= g_{\text{SM}} = g_{\text{DM}})$
- $m_{\text{DM}}$, $m_{\text{med}}$
Other DM searches + mini-summary

- There are other searches based on rich phenomenology (interpreted by simplified models)
  - DM + heavy flavours: enhanced coupling
  - DM + Higgs
  - Higgs portal model:
    - [invisible decays] ATLAS:
      - CMS: CMS-HIG-14-038
  - Broad variety of mono-X searches carried out, so far consistent with SM
  - Large range of parameter space was scanned, complementary to direct and indirect DM search experiments
PART 3
Beginning of new era: LHC RUN–2
LHC Run2 (2015~2018) started

- Center of mass energy becomes 13TeV (about twice)
- Data taking since June 2015, already used for physics
- Run2 this year ~ a few fb$^{-1}$
  by the end of Run2 ~ 100fb$^{-1}$

Sensitivity for High scale BSM will be boosted by O (10-1000)

Ratios of LHC parton luminosities: 13 TeV / 8 TeV

- gg
- $\Sigma q\bar{q}$
- qg

Higgs physics factor $\sim$2 gain

Z' SSM (3TeV) x 13

Gluino pair prod. (1.5 TeV) x 72
High-mass events

5.4 TeV di-jet

We are at the Experimental Energy Frontier

3.0 TeV di-electron
13 TeV analysis in ATLAS

- First control region plots for measurements and searches already available
- Run-1 limits on black hole production has already been surpassed by Run-2 data set (80pb$^{-1}$ ATLAS-CONF-2015-043, ATLAS-CONF-2015-045)
- Whole list of analyses (SUSY, Exotics) found here
  
  https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults
  https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults

Di-jet mass search

**ATLAS** Preliminary
\( \sqrt{s} = 13 \text{ TeV}, 80 \text{ pb}^{-1} \)

- Data
- Background fit
- BumpHunter interval
- BlackMax, \( m = 4.0 \text{ TeV} \)
- BlackMax, \( m = 5.0 \text{ TeV} \)

\( p \)-value = 0.79
Fit Range: 1.1 - 5.3 TeV
\(|y^*| < 0.6 \)

**ATLAS-CONF-2015-042**

Data 2015 (\( \sqrt{s} = 13 \text{ TeV} \))
- SM Total
- W+jets
- Top
- Z+jets
- Diboson

CRW selection

ATL-PHYS-PUB-2015-028
13 TeV analysis in CMS

- Preliminary control region plots based on 42pb$^{-1}$ data
- whole list of analyses (SUSY, Exotics) found here

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO

$\alpha_T$ distribution for $H_T > 225$GeV

Di-jet mass search

DP-2015-035

EXO-15-001
Run-2 expectations for DM searches

- Run-1 sensitivity will be surpassed by the first 5 fb\(^{-1}\) of Run-2 data

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**ATL-PHYS-PUB-2014-007**

**ATLAS** Simulation Preliminary

D5, \(m_\chi = 50\) GeV

5% syst

\[ \pi < g_{SM} g_{DM} < 4\pi \]

**mono-Jet analysis Control Region** in early 13TeV Run-2 data

\[ p_T^{\ell} > 80\text{GeV} \]
\[ E_T^{\text{miss}} > 100\text{ GeV} \]

one muon (\(p_T > 30\text{GeV}, |\eta| < 2.5\))

**ATLAS** Preliminary

\[ L dt = 68 \text{pb}^{-1}, \, \sqrt{s} = 13 \text{ TeV} \]
Conclusion and outlook

• **From Run1**
  • DM Searches from both directions i.e.
    • Complete models (SUSY)
    • Effective Field Theory and Simplified Models
  • no evidences were found (except for some hints)
  • strong limits made in the parameter space

• **For Run2 and beyond**
  • Higher energy regime ($\sqrt{s} = 13\text{TeV}$): expected much higher sensitivities for large scale physics
  • Many new schemes, new implementations, even new detector (!) installed: smooth start of the Run–2 owing to the accumulations of knowledge, experiences during Run–1

New surprise can happen anytime – stay tuned
EXTRA SLIDES
spin-dependent interaction limit

- **ATLAS mono-jet search**

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![Graph showing WIMP-nucleon cross section vs. WIMP mass](image-url)
pMSSM mass limits

light squarks

EW gauginos

ATLAS

pMSSM: $\tilde{\chi}^0_1$ LSP

$\tilde{q} \rightarrow q \tilde{\chi}^0_1$ [1405.7875]

$\tilde{q}/4 \rightarrow q \tilde{\chi}^0_1$ [1405.7875]

$s=8$ TeV, 20.3 fb$^{-1}$

Electroweak searches

$\tilde{\chi}^+_1 \tilde{\chi}^0_2 \rightarrow W^{(*)} \tilde{\chi}^0_1 \tilde{\chi}^0_1$ [1403.5294]
pMSSM mass limit

use 3rd gen searches

use all searches

$\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0 \quad \tilde{t}_1 \rightarrow Wb\tilde{\chi}_1^0$

$\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0 \quad \tilde{t}_1 \rightarrow bff\tilde{\chi}_1^0$

$\{s=8 \text{ TeV}, 20.3 \text{ fb}^{-1} \}$

LHC/ATLAS/CMS
pMSSM mass limit

EW Sleptons

ATLAS

pMSSM: \( \tilde{\chi}_1^0 \) LSP

\( \sqrt{s} = 8 \) TeV, 20.3 fb\(^{-1} \)

\( \tilde{l}_L \rightarrow l\tilde{\chi}_1^0 [1403.5294] \)

Electroweak searches

LH

RH

ATLAS

pMSSM: \( \tilde{\chi}_1^0 \) LSP

\( \sqrt{s} = 8 \) TeV, 20.3 fb\(^{-1} \)

\( \tilde{l}_R \rightarrow l\tilde{\chi}_1^0 [1403.5294] \)

Electroweak searches

Fraction of Models Excluded