Recap: Dark Matter Searches

- Three main ways to search for evidence of particle DM via non-gravitational interactions
  - Indirect: Seek evidence for annihilation or decay products of DM particles trapped in galactic / solar / planetary potential wells
    - X-rays, gamma rays, neutrinos, anti-matter …
    - May prove DM but not identify particle
  - Direct: Seek evidence for DM particle interactions with targets in terrestrial detectors
    - Nucleons, nuclei, electrons, photons …
    - May prove DM but not identify particle
  - Accelerator/Collider: Seek evidence for invisible particle production in SM particle collisions
    - May identify particle but cannot prove DM
WIMP Searches at Colliders

- Pre-infl. QCD axion
- Post-infl. QCD axion
- Classical QCD axion
- General thermal WIMP
- Sterile neutrino
- ADM
- Non-thermal WIMP (FIMP)
- Standard thermal WIMP (e.g. SUSY neutralino)

Collider Kinematics

- Central to all DM searches at colliders is missing (transverse) energy
  - Negative vector sum of visible products
  - Lepton colliders (LEP, ILC, CepC, FCC-ee, muon collider): 3-vector $E_{\text{miss}}$
  - Hadron colliders (Tevatron, LHC, FCC-hh): 2-vector $E_T^{\text{miss}}$ (MET)
  - Care must be taken with soft particles / unclustered energy

- Lepton colliders further benefit from beam energy constraint:
  - ‘Missing mass’ / ‘recoil mass’

$$m_{\text{rec}}^2 = s + m_{\text{vis}}^2 - 2\sqrt{s} \sqrt{p_{\text{vis}}^2 + m_{\text{vis}}^2}$$
LHC Dark Matter Searches

- **Model-dependent searches (e.g. SUSY):**
  - Greater reach using (strongly coupled) decay chain → additional final state particles
  - Less inclusive
  - DM signal from $R_p$-conserving models
  - DM (neutralinos) pair-produced

- **Generic DM searches:**
  - DM couples to, and recoils against, specified visible final state
  - Simplified model with DM and mediator
  - Parameterisation: $m_\chi$, $m_A$, $g_\chi$, $g_q$, $J^{\text{CP}}(A)$, $J^{\text{CP}}(\chi)$
  - Coupling of mediator to pp enables complementary search for BSM mediator resonance
  - Usually assume DM pair production

See also: https://lpcc.web.cern.ch/content/lhc-dm-wg-dark-matter-searches-lhc
• Model-dependent SUSY searches exploit longer decay chains
• Introduces additional decay constraints on kinematics
• Event selection can exploit endpoints in
  - ‘Stransverse’ mass $m_{T2}$
    
    $$m_{T2} = \min_{p_T^{miss}=q_T(1)+q_T(2)} \left[ \max(m_T(p_T(1), q_T(1)), m_T(p_T(2), q_T(2))) \right]$$
  - ‘Contransverse’ mass $m_{CT}$
    
    $$m_{CT}^2 = (E_T(1) + E_T(2))^2 + (p_T(1) + p_T(2))^2$$
• Inclusive variables:
  - ‘Effective mass’
    
    $$m_{eff} = \sum_{i=1}^{N} p_T(i) + E_T^{miss}$$
Electroweak SUSY Searches

- \( \chi^0_1 \chi^0_1 \) pair production invisible
- Greatest sensitivity for \( \chi^0_2 \chi^\pm_1 \) production
  - Variety of decay modes, e.g. 3l/2l/0l+MET (WZ), lbb/0l+MET (Wh), slepton
  - Assume mass degenerate \( \chi^0_2, \chi^\pm_1 \)
  - Pure wino (AMSB) / higgsino: \( \chi^0_1 \) degenerate \( \rightarrow \chi^0_2, \chi^\pm_1 \) products soft
Wino/Higgsino Searches

- Small mass splitting creates meta-stable NLSP (phase-space)
  - Dedicated search for disappearing track signatures
  - Also soft lepton signatures (larger mass splitting)

See also https://atlas.cern/updates/briefing/new-higgsino-limits
3rd Generation Searches

- Greater reach using strongly produced states
- Stop must be light to solve hierarchy problem
- Mass limits ~ 500-700 GeV for high m(stop)
Gluino Searches

• Still greater reach using gluino decays
  - High cross-section,
  - Long decay chains, high (b)-jet multiplicity → low background
  - Gluino mass correlated with stop mass → ‘gluino sucks’
  - Mass limits ~ 1000 – 1300 GeV for high m(gluino)

\[ \frac{\text{pp} \rightarrow \tilde{g} \tilde{g}, \tilde{g} \rightarrow t\tilde{t}_{10} \rightarrow t\tilde{\chi}^{0}_{1} \tilde{\chi}^{0}_{1}}{\text{CMS}} \]

\[ \text{ATLAS Preliminary} \]

\[ \begin{align*}
\tilde{g} \rightarrow q\tilde{q}_{L}^{0} & \quad \text{0 lep. [2010.14293]} \\
\tilde{g} \rightarrow b\tilde{b}_{L}^{0} & \quad \geq 3 \text{ b-jets [CONF-2018-041]} \\
\tilde{g} \rightarrow H_{L}^{0} & \quad \geq 3 \text{ b-jets + \geq 2 lep. SS [CONF-2018-041, 1706.03731]} \\
\tilde{g} \rightarrow q\tilde{q}_{L}^{0} & \quad \text{0 lep. + 1 lep. [2010.14293, 2101.01629]} \\
\tilde{g} \rightarrow q\tilde{q}_{L}^{0} & \quad \geq 7-12 \text{ jets + 1 lep. + \geq 2 lep. SS [2009.00302, 1708.02823, 1909.08457]} \\
\tilde{g} \rightarrow q\tilde{q}(\tilde{v}_{1}v_{2})^{0} & \quad \text{via} \ 2 \text{ lep. OS SF + \geq 3 lep. [1805.11381, 1706.03731]} \\
\tilde{g} \rightarrow q\tilde{q}(\tilde{v}_{1}v_{2})^{0} & \quad \text{via} \ \tilde{v} \geq 1 \text{ \geq 1 \gamma [1808.06358]} \\
\tilde{g} \rightarrow q\tilde{q}/Z\tilde{g} \quad \text{via} \ 2 \gamma & \quad \geq 1 \text{ \gamma [1802.03158]} \\
\end{align*} \]

Colours indicate different models
Observed limits at 95% CL

\[ \text{March 2021} \]

\[ \text{137 fb}^{-1} \text{ (13 TeV)} \]

\[ \text{CMS} \]

\[ \text{1909.08457, 1-lep (M_{\tilde{t}}) \quad 1909.03460, 0-lep (M_{\tilde{t}}) \quad 2103.01290, 0-lep (stop)} \]

\[ \text{1911.07556, 1-lep (M_{\tilde{t}}) \quad 2001.10086, 0-lep (same-sign)} \]

\[ \text{1710.11186, 0-lep (stop), 36 fb} \]
• Disappearing track signature gives possibility for 5σ observation of wino and higgsino DM production at FCC-hh

Saito et al., EPJC 79 (2019) 469
Generic DM Searches: mono-X

- To be produced, DM must couple (in-)directly to quarks/gluons
  - Tag invisible DM events with gluon (jet) + MET (a la LEP)
- Also consider $\gamma/W/Z/H/t/b+MET$
- Resonance searches give strong limits unless DM coupling v.large
  - Mediator must couple to qq due to production process
Generic DM Searches

- Within context of specific generic model, can reinterpret mono-X+MET and resonance limits in direct detection parameter space.
  - Highly model-dependent
  - Constraints most powerful for light DM, where direct searches lose kinematic sensitivity
Invisible Higgs Decays

- Direct search for invisible Higgs decays in VBF production mode
  - BR enhanced by decays to DM in higgs portal models
  - Relevant only for $m_\chi < m_H/2$
  - Results model-dependent. Most powerful for low $m_\chi$
- Higgs coupling combination further strengthens limit (with more assumptions)

29 Jun – 1 Jul 2021
CERN ATC Lectures: Dark Matter Searches
Search for Heavy Neutrino Dark Matter

- **10^{-21} eV**
- **peV**
- **neV**
- **μ eV**
- **meV**
- **eV**
- **keV**
- **MeV**
- **GeV**
- **TeV**
- **M_p**

- Fuzzy DM
- Pre-infl. QCD axion
- Post-infl. QCD axion
- "Classical" QCD axion
- QCD axion

- General thermal WIMP
- Sterile neutrino
- ADM
- Non-thermal WIMP (FIMP)

- Standard thermal WIMP (e.g. SUSY neutralino)

Sterile Neutrino DM

- Heavy LH neutrinos with SM couplings excluded (direct search with t-channel Z)
- RH singlet $\nu_R$ mixing with LH SM neutrinos $\nu_L$ allowed for small mixing angles $\theta$
- $\nu_R$ decays to $3\nu_L$ (invisible) and $\nu_L + \gamma \rightarrow$ mono-energetic photon signal $E_\gamma = m_{\nu_R}/2$
- Concrete model: $\nu$MSM

- Lightest SM $\nu_R$ is DM candidate ($N_1$)
- Explanation for baryogenesis, $\nu$ masses etc.
3.5 keV X-Ray Line

- Bulbul et al. (2014 and later) and others claim anomalous mono-energetic 3.5 keV X-ray line in stacked XMM observations of galaxy clusters, and galactic centre.
- Signal not observed in other studies of galaxies, dwarf galaxies (Draco etc.) and stacked XMM blank-sky observations of the MW halo.
- High-res calorimetry from XRISM (ex-HITOMI SXS) will be crucial test.


Dessert et al. Science 367 (2020) 1465
Future Accelerator Searches

- Accelerator searches for production and decay of N$_2$/N$_3$
  - SHiP (production in D-decays, displaced vertices)
  - FCC-ee (following earlier searches at LEP)
Searches for Axion and ALP Dark Matter

10^{-21} eV  peV  neV  \mu eV  meV  eV  keV  MeV  GeV  TeV  M_P

pre-infl. QCD axion
post-infl. QCD axion
``classical'' QCD axion
QCD axion
general thermal WIMP
sterile neutrino
ADM
non-thermal WIMP (FIMP)
standard thermal WIMP (e.g. SUSY neutralino)
fuzzy DM

Axions and ALPs

- QCD axion consequence of Peccei-Quinn mechanism dynamically explaining CP-conservation in strong interactions
  - PQ symmetry: spontaneously broken global U(1)
  - Axion: pseudo-NG boson from PQ symmetry breaking (a la Higgs mechanism)

- More generically, pseudoscalar boson coupling in similar way to SM fields - ALPs

- Couples at 1-loop to photon, modifying EM interactions

- Search for coupling to strong magnetic field (inverse Primakoff effect)

$$\mathcal{L} \supset -\frac{1}{4} g_{a\gamma\gamma} a \tilde{F}_{\mu\nu} F^{\mu\nu} = g_{a\gamma\gamma} a E \cdot B,$$
Axion Parameter Space

- Benchmark models:
  - KSVZ: SM quarks uncharged under PQ symmetry → no tree-level axion-quark couplings
  - DFSZ: SM quarks charged under PQ; 2 additional higgs doublets

- Relic density from axion CDM production:
  - PQ symmetry breaking post-inflation: axion formation from topological defects; $m_a \sim 25-5000 \mu eV$
  - PQ symmetry breaking pre-inflation: axion formation from vacuum realignment; masses smaller

$\theta_i = \text{vacuum misalignment angle}$

Ringwald, Rosenberg, Rybka, PDG 2020
Axion/ALP Searches (non-halo)

- Rich hunting ground – not solely reliant on cosmological production
- Stellar/solar axions:
  - Strong constraints from stellar cooling
  - Helioscope searches (CAST, IAXO…): photons convert to axions to solar B-field; keV X-rays detected in terrestrial magnet (inverse-Primakoff)
  - Axion-electron scattering in direct WIMP searches
- ‘Shining light through walls’ (OSQAR, ALPS….)
  - ~ Solar axion (Primakoff) production in lab
- Vacuum birefringence (PVLAS …)
Direct Axion DM Searches

• Main technology: cavity haloscope (Sikivie, 1983)
  - Strong solenoidal magnetic field
  - Dilution fridge
  - Cryogenic radio receiver and amplifier
  - Tunable high-Q microwave cavity
  - CDM axions convert to mono-energetic photons via inverse Primakoff effect

• Narrowband search:
  - Run-time required for scan
  - Easy rescan to confirm signal
• Longest running haloscope, U Washington
  - Previous experiments (1980s) at U Florida

• Apparatus:
  - 8T solenoid
  - Mechanically tuned cavity (1 m x 0.5 m φ)
  - Cryogenic quantum noise limited SQUID ($T_{\text{noise}} < 100$ mK) + HEMT and Josephson Parametric amplifiers
  - World’s lowest noise non-R&D microwave receiver

• First experiment sensitive to KSVZ and DFSZ axions
• Yale, previously ADMX-HF
• Targets higher masses / frequencies
  - Smaller cavity (25 cm x 10 cm $\phi$)
  - 9T field over smaller volume
  - Josephson Parametric Amplifier
• First run (2017-18) targeted post-inflationary PQ symmetry breaking models: masses $\sim$23-24 $\mu$eV
• Latest results (2021) uses squeezed microwave state to exceed quantum noise limit
  - Targets masses $\sim$ 17 $\mu$eV
Other Cavity Haloscopes

- New cavity haloscope experiments
  - CULTASK/CAPP (Korea): 8 T B-field with HEMT amplifier
  - ORGAN (Australia): 14 T B-field with JPA and array of thin cavities (c.f. ‘pipe organ’)
  - CAST-RADES (CERN): 8.8 T B-field with HEMT amplifier
  - KLASH proposal (Frascati): 0.6 T B-field, large volume – targets low mass ~0.2 µeV

CAST-RADES Collaboration, arXiv:2104.13798

CAST

ORGAN Collaboration, arXiv:1706.00209


CAST-RADES Collaboration, arXiv:2104.13798
Indirect Axion DM Searches

• Strongest B-fields in known universe generated by neutron stars / magnetars
  - Expect mono-chromatic line from axion-photon conversion (inverse-Primakoff effect as haloscopes)

• Foster et al. (2020): radio-spectroscopy search with Green Bank and Effelsberg telescopes
  - Not yet competitive with haloscopes but promising

Dielectric Haloscopes

- Cavity haloscope signal ~ volume ~ $1/m_a^3$
- Dielectric haloscope (MADMAX proposal):
  - Axion to photon conversion at permittivity boundary in B-field
  - Coherent enhancement of emission with multiple low loss disks (e.g. LaAlO$_3$) with tunable $\lambda/2$ separation
  - Mirror forms longitudinal cavity. Transverse dimension non-resonant. Signal scales with length.
Low Mass Axions: Time-Dependence

- Very low mass axions induce observable time-dependent fields
- ABRACADABRA:
  - Seek AC B-field induced inside static toroidal field cavity with tuned LC circuit
- Similar approach taken by DM-radio

Magnetic Resonant Signals

• For low mass axions/ALPs, oscillating field may give rise to observable signals
  
• ALP-photon coupling induces pseudo-magnetic field leading to spin-precession in hyper-polarised nuclei ($^{129}$Xe and $^3$He)
  - CASPEr-Wind: spin-precession with NMR

• Axion-gluon coupling induces oscillating nuclear EDM
  - CASPEr-Electric: apply static electric field in addition to magnetic field and perform NMR

• Coupling with electron spin induces magnetic resonance in ferromagnetic material in external B-field, with Larmor frequency tuned to axion mass
  - QUAX experiment

Axion Summary

![Axion Diagram]

- CAST limit
- transparency hint
- ALPs as dark matter
- QCD dark-matter axion pre-inflationary scenario
- QCD dark-matter axion post-inflationary scenario
- QCD axion in tension with astrophysics
• Compton wavelength of DM becomes macroscopic.

• Searches for time varying ‘fifth forces’ relevant
  - e.g. atom interferometers (MAGIS, AION etc.)
  - Huge potential for future innovation; connections with ‘quantum technologies’ initiatives
• Dark matter searches have grown rapidly over past 40 years from somewhat ‘niche’ area of astroparticle physics to major component of astrophysics, astroparticle and collider physics programmes.

• Range of candidates and interactions has expanded massively.

• No other area of particle physics has similar opportunities for innovation in detector design with potentially low barrier to realisation (e.g. ALPs searches)

• Scientific pay-off potentially immense

• Field has never been in better health
Backup
# ATLAS SUSY Summary

## June 2021

### ATLAS SUSY Searches - 95% CL Lower Limits

<table>
<thead>
<tr>
<th>Model</th>
<th>Signature</th>
<th>$\mathcal{L} \times \mathcal{E} \times (fb^{-1})$</th>
<th>Mass limit</th>
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<td>$\tilde{g} \rightarrow t\bar{t}$</td>
<td>0 jets</td>
<td>2-6 jets</td>
<td>139</td>
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<tr>
<td>$\tilde{b}_1 \rightarrow b\tilde{\chi}_1^0$</td>
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<td>139</td>
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<tr>
<td>$\tilde{\tau}_1 \rightarrow \tau\tilde{\chi}_1^0$</td>
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### EW direct

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### Dark Matter Searches

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### Reference

- ATLAS Preliminary $\sqrt{s} = 13$ TeV
- June 2021
- ATLAS CONF-2021-001
- ATLAS CONF-2021-015
- ATLAS CONF-2021-026
- ATLAS CONF-2021-028
- ATLAS CONF-2021-031
- ATLAS CONF-2021-033
- ATLAS CONF-2021-035
- ATLAS CONF-2021-040
- ATLAS CONF-2021-042

Note: Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.
# SUSY Summary

## Overview of SUSY results: electroweak production

<table>
<thead>
<tr>
<th>Process</th>
<th>Observed</th>
<th>Mass Scale [GeV]</th>
</tr>
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<tr>
<td>$pp \rightarrow \tilde{\chi}^0 \tilde{\chi}^\pm \rightarrow \ell^+ \ell^- \rightarrow \ell \nu \ell \tilde{\chi}^0 \tilde{\chi}^0$</td>
<td>2 or same-sign and ≥ 3ℓ: SUS-19-012</td>
<td>137 fb⁻¹ (13 TeV)</td>
</tr>
<tr>
<td>$pp \rightarrow \tilde{\chi}^0 \tilde{\chi}^0 \rightarrow 2\ell$</td>
<td>flavour democratic, $x = 0.5$</td>
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<tr>
<td>$pp \rightarrow \tilde{\chi}^0 \tilde{\chi}^0 \rightarrow 2\ell$</td>
<td>flavour democratic, $x = 0.05$</td>
<td>2 or same-sign and ≥ 3ℓ/ηₚ: SUS-19-012</td>
</tr>
<tr>
<td>$pp \rightarrow \tilde{\chi}^0 \tilde{\chi}^0 \rightarrow \tau \nu \ell \rightarrow \tau \nu \ell \tilde{\chi}^0 \tilde{\chi}^0$</td>
<td>1ℓ+jets: SUS-20-003</td>
<td>≥ 3ℓ/ηₚ: SUS-19-012</td>
</tr>
<tr>
<td>$pp \rightarrow \tilde{\chi}^0 \tilde{\chi}^0 \rightarrow W \tilde{\chi}^0 \tilde{\chi}^0$</td>
<td>2ℓ and 3ℓ/soft: SUS-18-004 $\Delta M = 5-10$ GeV</td>
<td>2ℓ and opposite-sign: arXiv:2012.08600</td>
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<td>$pp \rightarrow \tilde{\chi}^0 \tilde{\chi}^0 \rightarrow (W^<em>/Z^</em>) \tilde{\chi}^0$</td>
<td>2ℓ and 3ℓ/soft: SUS-18-004 higgsino simplified model, $\Delta M = 5-10$ GeV</td>
<td>2ℓ and opposite-sign: arXiv:1807.07799 $M_{\tilde{\chi}} = 1$ GeV</td>
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<tr>
<td>$pp \rightarrow \tilde{\chi}^0 \tilde{\chi}^0 \rightarrow W \tilde{\chi}^0$</td>
<td>2ℓ opposite-sign: arXiv:1807.07799 $M_{\tilde{\chi}} = 1$ GeV</td>
<td></td>
</tr>
<tr>
<td>$pp \rightarrow \tilde{\ell} \tilde{\ell}$</td>
<td>$B(\ell \nu) = 50%$, $x = 0.5$</td>
<td>2ℓ opposite-sign: arXiv:1807.07799</td>
</tr>
<tr>
<td>$pp \rightarrow \tilde{\ell}_L/R \tilde{\ell}_L/R \tilde{\ell}$</td>
<td>$\ell \nu$, $\mu$, $\tau$: arXiv:2012.08600</td>
<td>2ℓ opposite-sign: arXiv:1807.07799</td>
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</table>

Selection of observed limits at 95% C.L. (theory uncertainties are not included). Probes up to the quoted mass limit for light LSPs unless stated otherwise. The quantities $\Delta M$ and $x$ represent the absolute mass difference between the primary sparticle and the LSP, and the difference between the intermediate sparticle and the LSP relative to $\Delta M$, respectively, unless indicated otherwise.
Limits on generic DM models with mediators coupling preferentially to top or bottom quarks can be obtained by modifying 3rd generation SUSY searches.