DARK SECTOR THEORY AT LHC

Felix Yu Johannes Gutenberg University, Mainz

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Goal of this overview

What underpins dark sector searches at LHC?

- Only nontrivial SM gauge quantum number for dark matter is an electrically neutral SU(2)xU(1) charge
 - Weakly interacting massive particle has correct parametric dependence to fit the measured relic abundance measured by Planck

$$\Omega h^2 \approx 8.76 \times 10^{-11} \text{GeV}^{-2} \left[\int_{T_0}^{T_F} g_*^{1/2} \langle \sigma v \rangle \frac{dT}{m_{\chi}} \right]^{-1}$$

Arcadi, et. al. [1703.07364]

$$\Omega h^2 = 0.1198 \pm 0.0026$$
 Planck [1502.01589]

 Separately, new physics at the weak scale strongly motivated by naturalness

- R-parity conserving MSSM (minimal supersymmetric SM) is a canonical example
 - Elegantly solves hierarchy problem and provides a dark matter candidate neutralino
 - Neutralino is fermionic superpartner of weak gauge bosons (cf. Cheung, Hall, Pinner, Ruderman [1211.4873])
 - DM gauge representations extended to consider beyond triplets of SU(2), other spins Cirelli, Fornengo, Strumia [0512090]

- R-parity conserving MSSM (minimal supersymmetric SM) is a canonical example
 - Spectacular cascade decay collider signals jets, leptons, and missing transverse energy (MET)



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 R-parity conserving MSSM (minimal supersymmetric SM) is a canonical example

But no signals have been seen yet

	Model	e, μ, τ, γ	/ Jets	$E_{\rm T}^{\rm miss}$	∫ <i>L dt</i> [fb	Mass limit $\sqrt{s} = 7, 8 \text{ TeV}$	F = 13 TeV Reference
Inclusive Searches	$ \begin{array}{l} MSUGRA/CMSSM \\ \overline{q} \overline{q}, \overline{q}, -q \overline{q}_1^{D_1} \\ \overline{q} \overline{q}, \overline{q}, -q \overline{q}_1^{D_1} \\ \overline{q} \overline{q}, \overline{q}, -q \overline{q}_1^{D_1} \\ \overline{q} \overline{q}, \overline{q}, -q \overline{q} \overline{q}_1^{D_1} \\ \overline{q} \overline{q}, \overline{q}, -q \overline{q} \overline{q}_1^{D_1} \\ \overline{q} \overline{g}, \overline{g}, \overline{g}, -q \overline{q} \overline{Q} \\ \overline{g}, \overline{g}, \overline{g}, -q \overline{q} \overline{Q} \\ \overline{g}, \overline{g}, \overline{g}, -q \overline{q} \overline{Q} \\ \overline{g}, \overline{g}, \overline{g}, -q \overline{q} \\ \overline{g}, \overline{g}, \overline{g}, -q \overline{q} \\ \overline{g}, \overline$	$\begin{array}{c} 0\text{-}3 \ e, \mu/1\text{-}2 \ \tau \\ 0 \\ \text{mono-jet} \\ 0 \\ 3 \ e, \mu \\ 0 \\ 1\text{-}2 \ \tau + 0\text{-}1 \\ 2 \ \gamma \\ \gamma \\ 2 \ e, \mu \ (Z) \\ 0 \end{array}$	2-10 jets/3 / 2-6 jets 1-3 jets 2-6 jets 2-6 jets 2-6 jets 4 jets 7-11 jets ℓ 0-2 jets - 1 b 2 jets 2 jets prono-jet	Yes Yes Yes Yes Yes Yes Yes Yes Yes Yes	20.3 36.1 36.1 36.1 36.1 36.1 36.1 3.2 20.3 13.3 20.3 20.3	ἐ 1.85 TeV m(i)=m(i) 1.57 TeV m(i)?-200 GeV m(i)? 608 GeV 2.01 TeV m(i)?-200 GeV 2.01 TeV m(i)?-200 GeV m(i)?-200 GeV 1.85 TeV m(i)?-200 GeV m(i)?-200 GeV 1.825 TeV m(i)?-400 GeV m(i)?-400 GeV 1.85 TeV m(i)?-400 GeV 1.85 TeV m(i)?-400 GeV 1.37 TeV m(i)?-400 GeV 1.85 TeV m(i)?-400 GeV 1.37 TeV m(i)?-400 GeV m(i)?-540 GeV m(i)?-540 GeV	$\label{eq:constraints} \begin{array}{llllllllllllllllllllllllllllllllllll$
g med.	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow b \tilde{b} \tilde{\chi}_{1}^{0}$ $\tilde{g}\tilde{g}, \tilde{g} \rightarrow t \tilde{t} \tilde{\chi}_{1}^{0}$ $\tilde{g}\tilde{g}, \tilde{g} \rightarrow b \tilde{t} \tilde{\chi}_{1}^{+}$	0 0-1 e,μ 0-1 e,μ	3 b 3 b 3 b	Yes Yes Yes	36.1 36.1 20.1	1.92 TeV m(²),<800 G 1.97 TeV m(²),<800 G 1.97 TeV m(²),<800 G 1.37 TeV m(²),<800 G	eV ATLAS-CONF-2017-021 eV ATLAS-CONF-2017-021 eV 1407.0600
direct production	$ \begin{array}{l} \bar{b}_1 \bar{b}_1 , \bar{b}_1 \rightarrow b \bar{k}_1^0 \\ \bar{b}_1 \bar{b}_1 , \bar{b}_1 \rightarrow b \bar{k}_1^0 \\ \bar{r}_1 \bar{r}_1 , \bar{r}_1 \rightarrow c \bar{k}_1^0 \\ \bar{r}_1 \bar{r}_1 , \bar{r}_1 \rightarrow c \bar{k}_1^0 \\ \bar{r}_2 \bar{r}_2 , \bar{r}_2 \rightarrow \bar{r}_1 + Z \\ \bar{r}_2 \bar{r}_2 , \bar{r}_2 \rightarrow \bar{r}_1 + L \end{array} $	$\begin{array}{c} 0\\ 2\ e,\mu\ (\text{SS})\\ 0\text{-}2\ e,\mu\\ 0\text{-}2\ e,\mu\\ 0\\ 2\ e,\mu\ (Z)\\ 3\ e,\mu\ (Z)\\ 1\text{-}2\ e,\mu \end{array}$	2 b 1 b 1-2 b 0-2 jets/1-2 mono-jet 1 b 1 b 4 b	Yes Yes Yes Yes Yes Yes Yes Yes	36.1 36.1 4.7/13.3 20.3/36.1 3.2 20.3 36.1 36.1 36.1	950 GeV m(k ²)<420 G 117-170 GeV 2275-700 GeV m(k ²)<200	eV ATLAS-CONF-2017-038 eV, m(k1)=m(k1)+100 GeV ATLAS-CONF-2017-030 ATLAS-CONF-2017-030 ATLAS-CONF-2017-030 f1, m(k1)=56 GeV 1208-2102, ATLAS-CONF-2016-077 s GeV 1506-08616, ATLAS-CONF-2017-020 s GeV 1403-5222 eV 1403-5222 r ATLAS-CONF-2017-019
EW direct	$ \begin{array}{l} \tilde{\ell}_{1,\mathbf{R}}\tilde{\ell}_{1,\mathbf{R}},\tilde{\ell}\rightarrow\ell\tilde{K}_{1}^{0} \\ \tilde{\chi}[\tilde{\chi}_{1},\tilde{\chi}_{1}]\rightarrow\tilde{\chi}(\ell\tilde{r}) \\ \tilde{\chi}[\tilde{\chi}_{1},\tilde{\chi}_{1}]\rightarrow\tilde{\chi}(\ell\tilde{r}) \\ \tilde{\chi}[\tilde{\chi}_{1},\tilde{\chi}_{2}]\rightarrow\tilde{\chi}(\ell\tilde{r}),\tilde{\chi}_{2}]\rightarrow\tilde{\chi}(\tilde{r}) \\ \tilde{\chi}[\tilde{\chi}_{2}]\rightarrow\tilde{\chi}[\tilde{\chi}_{2}]\rightarrow\tilde{\chi}(\tilde{\chi}),\tilde{\chi}(\tilde{r}),\tilde{\chi}[\tilde{\chi}_{2}]\rightarrow\tilde{\chi}(\tilde{r}) \\ \tilde{\chi}[\tilde{\chi}_{2}]\rightarrow\tilde{\chi}[\tilde{\chi}_{2}]\rightarrow\tilde{\chi}(\tilde{r}),\tilde{\chi}($	$\begin{array}{c} 2 \ e, \mu \\ 2 \ e, \mu \\ 2 \ \tau \\ 3 \ e, \mu \\ 2 \ 3 \ e, \mu \\ 2 \ 3 \ e, \mu \\ e, \mu, \gamma \\ 4 \ e, \mu \\ \gamma \tilde{G} \ 1 \ e, \mu + \gamma \\ \gamma \tilde{G} \ 2 \ \gamma \end{array}$	0 0 - 0 0-2 jets 0-2 <i>b</i> 0 -	Yes Yes Yes Yes Yes Yes Yes Yes	36.1 36.1 36.1 36.1 20.3 20.3 20.3 20.3		$ \begin{array}{c c} ATLAS-CONF-2017-039 \\ \hline ATLAS-CONF-2017-039 \\ ATLAS-CONF-2017-039 \\ ATLAS-CONF-2017-039 \\ ATLAS-CONF-2017-039 \\ m(\tilde{\ell}_1^2) = O_2(m(\tilde{\ell}_1^2) + m(\tilde{\ell}_1^2)) \\ m(\tilde{\ell}_2^2) = O_2(cont) + m(\tilde{\ell}_1^2)) \\ m(\tilde{\ell}_2^2) = O_2(cont) + m(\tilde{\ell}_1^2) \\ m(\tilde{\ell}_2^2) = O_2(m(\tilde{\ell}_2^2) + m(\tilde{\ell}_1^2)) \\ m(\tilde{\ell}_2^2) = O_2(m(\tilde{\ell}_2^2) + m(\tilde{\ell}_1^2)) \\ m(\tilde{\ell}_2^2) = O_2(m(\tilde{\ell}_2^2) + m(\tilde{\ell}_1^2)) \\ hor(3.5086 \\ $
Long-Ilved particles	$\begin{array}{l} \label{eq:constraints} & \operatorname{Direct} \hat{x}_1^+ \hat{x}_1^- \operatorname{prod.}, \log_1 \operatorname{long-lived} \hat{x}_1^+ \\ & \operatorname{Direct} \hat{x}_1^+ \hat{x}_1^- \operatorname{prod.}, \log_1 \operatorname{long-lived} \hat{x}_1^- \\ & \operatorname{Stable}, \operatorname{stoped} \mathbb{R} \operatorname{R-hadron} \\ & \operatorname{Stable} \mathbb{R} \operatorname{R-hadron} \\ & Sta$	Disapp. trk dE/dx trk 0 trk dE/dx trk $1-2 \mu$ 2γ displ. $ee/e\mu/$ / displ. vtx + je	k 1 jet - 1-5 jets - - - - - μμ - ets -	Yes Yes - - Yes - Yes	36.1 18.4 27.9 3.2 3.2 19.1 20.3 20.3 20.3	430 GeV m(k1)-m(k1)- m(k1)-m(k1) 495 GeV m(k1)-m(k1)- m(k1)-m(k1) 850 GeV m(k1)-m(k1)- m(k1)-m(k1) 1.50 TeV m(k1)-m(k1)- m(k1)-m(k1) 537 GeV 1.57 TeV 440 GeV 1-ctr(k1)-3 m 1-ctr(k1)-3 1.0 TeV 6 < cr(k1)-x	Hol MeV, r(ξ ⁺ ₁)=0.2 ns ATLAS-CONF-2017-017 -160 MeV, r(ξ ⁺ ₁)=1.5 ns 1506.05332 eV, 10 µs <rr(ỹ)<1000 s<="" td=""> 1310.6584 ieV, 10 ns 1606.05129 ieV, r>10 ns 1604.04520 1411.6725 1411.6725 3, SPS8 model 1400.5542 40 mm, m(ž)=1.3 TeV 1504.05162 0 mm, m(ž)=1.1 TeV 1504.05162</rr(ỹ)<1000>
RPV	$ \begin{array}{l} LFV pp {\rightarrow} \bar{v}_\tau + X, \bar{v}_\tau {\rightarrow} \epsilon \mu / e \tau / \mu \tau \\ Bilinear RPV CMSSM \\ \bar{X}_1^{(\tau)}, \bar{X}_1^{-1} {\rightarrow} W_1^{(0)} \bar{X}_1^{-1} {\rightarrow} erv, \mu \mu \tau \\ \bar{X}_1^{(\tau)}, \bar{X}_1^{-1} {\rightarrow} W_1^{(0)} \bar{X}_1^{-1} {\rightarrow} erv_\tau \\ \bar{g} \bar{g}, \bar{g} {-} a q q \\ \bar{g} \bar{g}, \bar{g} {-} a \bar{\chi}_1^{(\tau)}, \bar{\chi}_1^{(1)} {\rightarrow} q q q \\ \bar{g} \bar{g}, \bar{g} {-} a \bar{\chi}_1^{(\tau)}, \bar{\chi}_1^{-1} {\rightarrow} g q \\ \bar{\eta} \bar{\eta}, \bar{\eta} {-} b \bar{g} \\ \bar{\eta}, \bar{\eta}, \bar{\eta} {-} b \bar{g} \end{array} $	$e\mu, e\tau, \mu\tau \\ 2 e, \mu (SS) \\ 4 e, \mu \\ 3 e, \mu + \tau \\ 0 \\ 4 e, \mu \\ 1 e, \mu \\ 1 e, \mu \\ 0 \\ 2 e, \mu \\ e, \mu \\ 0 \\ 2 e, \mu \\ e, \mu \\ 0 \\ 2 e, \mu \\ e, \mu \\ 0 \\ 2 e, \mu \\ 0 \\ 2 e, \mu \\ 0 \\ 0 \\ 2 e, \mu \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\$	- - 4-5 large- <i>R</i> je 4-5 large- <i>R</i> je 8-10 jets/0-4 8-10 jets/0-4 2 jets + 2 b 2 b	- Yes Yes ts - ts - b - b - -	3.2 20.3 13.3 20.3 14.8 14.8 36.1 36.1 15.4 36.1	1.9 TeV 4 ₃₁₁ =0.11, A 2 1.45 TeV m(k)=m(k), c; (A) 1.14 TeV m(k²)=0.00C 450 GeV m(k²)=0.00C 1.08 TeV BR(n=0,-BR(n)) 1.55 TeV m(k²)=0.00C 1.55 TeV m(k²)=1.00 1.55 TeV m(k²)=1.00 1.55 TeV m(k²)=1.00 1.55 TeV m(k²)=1.00 410 GeV 450-510 GeV 0.4-1.45 TeV BR(n=-be/ab) BR(n=-be/ab)	1µ21(3)/213=0.07 1607.08079 1µ21×10/210 1404.2500 1µ21×11 1404.2500 1µ21×11 1404.2500 1µ21×11 1405.5086 8R(c)=0% 1405.5086 1µ21×11 1405.5086 1µ21×11 1405.5086 1µ21×11 1405.5086 1µ21×11 1405.5086 1µ21×11 1405.508
)ther	Scalar charm. $\tilde{c} \rightarrow c \tilde{\chi}_1^0$	0	2 c	Yes	20.3	510 GeV m(2 ⁰)<200 G	ieV 1501.01325

Beyond WIMPs at and beyond LHC

- Thermal vs. non-thermal mechanism
 - Simplified model
 - Coannihilation
- Dark sector vs. dark matter
 - Cascade decays
 - Probe mediators directly
- Effective operators for new, invisible particles
 - Complete parametric ignorance
- Symmetry mechanism
- Mass generation
- (Self-interactions)

LHC most powerful when dark sector particles charged under SM color

Next jumps in reach for SM weak interactions

Mediators searched as resonances

Marginal operators more difficult

Beyond WIMPs \rightarrow effective operators

- Give up on Ωh² connection, simply characterize gauge-invariant fermion bilinears with SM operators at lowest order
- Use initial state radiation (jet, photon, etc.) to generate mono-X + MET signal ("mono-mania")

At LHC, must control jet mismeasurement and neutrino MET tail

$$\mathcal{L} = G_{\chi} \left[\bar{\chi} \Gamma^{\chi} \chi \right] \times \left[\bar{q} \Gamma^{q} q \right]$$

Goodman, et. al. [1005.1286, 1008.1783], Bai, Fox, Harnik [1005.3797]

Name	Type	G_{χ}	Γ^{χ}	Γ^q
M1	qq	$m_q/2M_*^3$	1	1
M2	qq	$im_q/2M_*^3$	γ_5	1
M3	qq	$im_q/2M_*^3$	1	γ_5
M4	qq	$m_q/2M_*^3$	γ_5	γ_5
M5	qq	$1/2M_{*}^{2}$	$\gamma_5\gamma_\mu$	γ^{μ}
M6	qq	$1/2M_{*}^{2}$	$\gamma_5\gamma_\mu$	$\gamma_5\gamma^\mu$
M7	GG	$\alpha_s/8M_*^3$	1	-
M8	GG	$i\alpha_s/8M_*^3$	γ_5	-
M9	$G\tilde{G}$	$\alpha_s/8M_*^3$	1	-
M10	$G\tilde{G}$	$i\alpha_s/8M_*^3$	γ_5	-

- operators \rightarrow simplified models
- Divorce dark matter from weak interactions
 - Ωh² from weak-like (i.e. perturbative) couplings and
 O(100) GeV masses
- Easiest situation: mediator is leptophobic Z'_B



operators \rightarrow simplified models

Straightforward, tree-level mediator leads to a dijet



ATLAS [1611.03568]

operators \rightarrow simplified models

Straightforward, tree-level mediator leads to a dijet resonance



CMS [1611.03568]

operators \rightarrow simplified models

 Translating LHC limits to, *e.g.*, direct detection plane requires complete model specification and astrophysical assumptions



CMS [1611.03568]

Even further \rightarrow coannihilating simplified models

 Tree-level mediator for DM coannihilation instead of DM pair annihilation



- Mediator strongly produced, leads to resonance + MET signatures
 - Identified leptoquark + MET and diquark + MET signatures as new channels for LHC searches

The Coannihilation Codex (Baker, [FY] et. al.) [1510.03434], [1605.0805]

Even further \rightarrow coannihilating simplified

models The Coannihilation Codex (Baker, [FY] et. al.) [1510.03434], [1605.0805] Complementary reach from LHC in mediator and dark sector searches, overlay preferred region from Ωh²



Even further \rightarrow coannihilating simplified models

• Tag soft decays from coannihilation partner



Beyond WIMPs → marginal operators

- Divorce dark sector from all SM gauge interactions
 - Ωh² from weak-like (i.e. perturbative) couplings and O(100) GeV masses
- Leading interactions at dim-4
 - Scalar Higgs portal
 - Neutrino portal
 - Kinetic mixing portal
- Dimension-5
 - Axion portal

 $(\mu\phi + \lambda\phi^2)H^{\dagger}H$ $y_n LHN$ $-\frac{\epsilon}{2\cos\theta_W}B_{\mu\nu}F'^{\mu\nu}$ $\frac{a}{f_a}F_{\mu\nu}\tilde{F}^{\mu\nu}$

Beyond LHC

 Study dark scalar Higgs and dark U(1)' gauge boson prospects at future e⁺e⁻ collider

Emphasizes *complementary reach* from direct detection, indirect detection, Planck, and colliders





Summary: collider dark matter

- LHC has special opportunity to test relic density mechanism via direct production of mediators
 - Many classes of models (within kinematic reach of LHC) with new particles charged under SM gauge symmetries
- Combination of production and decay rates will measure underlying Lagrangian parameters

Powerful post-discovery possibilities

- Must keep in mind
 - Timescale for collider stability ≠ cosmological stability
 - Dark matter stability ≠ parity
 - Model dependent and astrophysical assumptions to translate constraints to, *e.g.* nucleon cross section