Dark Matter at the LHC



LHC days in Split September 17th-22nd, Split

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Dark Matter searches in colliders



- [>] The nature of **Dark Matter** (DM) remains nowadays one of the misteries of the universe.
- [>] If DM interacts beyond gravity we should observe **new phenomena** in various experiments.
- > A very week interaction might require **all of them** to provide an observation or discovery.



Disclaimer: Showing just a selection/summary of results, use the links for more information.





The LHC: a marvellous machine



[>] The LHC has shown a superb performance since the beginning of the data taking in 2010.





Looking for DM at colliders





Direct production of DM

- > SM object back-to-back to the missing momentum.
- [>] Mono-X searches: DM + ISR gluons, photons, W, Z and H.
- [>] DM in association with heavy flavour (top, top-antitop, bb).
 - Mediator resonances and offshell.
- > A mediator decaying finally into SM products.
- Dijet resonances: low and high mass, narrow and broad.
- Dimuon mass spectra: dark photons.
 - Long decay chains: SUSY like
- \succ R-parity conserved → DM candidate with SM products.
- Strong production: gluinos, squarks, stops.
- > EWK production: chargino/neutralino, sleptons, staus.



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Monojet signatures: gluon, Z, and W



- > DM produced in association with one gluon, W, or Z decaying hadronically.
- > Jet back-to-back with missing momentum.
- > Typical backgrounds are $Z(\rightarrow UU)$ +jets and W+jets.
- [>] Use of AK4 and AK8 jets (for boosted W and Z).





Mono photon signatures



- > DM produced in association with one very energetic photon.
- Similar to previous search but with photon instead of jet.
- > Main backgrounds are Z(→ υ υ)+gamma and W(→ $l\upsilon$)+gamma.







Mono Z in the dilepton channel





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Mono Higgs signatures

- > DM produced in association with a Higgs boson.
- ≻ Several analysis according to decay: $H \rightarrow bb$, $\tau\tau$, $\gamma\gamma$, WW (soon).
- > Imposing constraint on the mass of the Higgs boson.
- ≻ Dominated by H → bb where backgrounds are Z(nunu) and W(lnu) + jets.
- > Interpreted in the 2HDM and Z' barionic models.





DM in association with 1(2) top(s)

QQQC

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 $\phi(a)$



 $\phi(a)$

- > DM produced in association with pairs of top or single top.
- > Exploring the different top decays: 0, 1, and 2 leptons.
- > Interpreted in terms of scalar and pseudoscalar mediators.
- > Exclusion of scalar mediators up to 250 GeV approximately.





Dijet resonances



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- > Dijet resonances provide a powerful handle to constrain DM interaction cross section.
- Background is SM QCD: fitting signal shapes over a background model.
- > Exploring low and high masses with narrow and broad resonances.
- > Low mass analysis using trigger objects to reduce pt thresholds.



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DM dark photons



Search for kinetic mixing with the offshell photon in the dimuon channels.





Putting all together



- > Dijet resonances dominates the exclusion for both vector and axial-vector mediators.
- > Both vector and axial-vector mediators excluded up to ~ 2.5 TeV.







Comparison with other experiments



> Fixing the limits on the couplings allows to translate xsections into DM production xsections.





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SUSY-like results



- > Assuming R-parity is conserved SUSY models provide candidates for DM (LSP).
- Experiments have a quite large program of SUSY searches in many different topologies.
- > MET is still a key ingredient but in these searches there are also many SM particles. .



SUSY results





ATLAS Preliminary $\sqrt{s} = 7, 8, 13$ TeV

ATLAS SUSY Searches* - 95% CL Lower Limits

	Model	e, μ, τ, γ	Jets	$E_{ m T}^{ m miss}$	∫L dt[ft	-1]	Ma	ss limit		$\sqrt{s} =$	7, 8 TeV	$\sqrt{s} = 13 \text{ TeV}$	Reference
Inclusive Searches	$\tilde{q}\tilde{q},\tilde{q}{ ightarrow}q\tilde{\chi}_{1}^{0}$	0 mono-jet	2-6 jets 1-3 jets	Yes Yes	36.1 36.1	\tilde{q} [2x, 8x Degen.] \tilde{q} [1x, 8x Degen.]		0.43	0.9	1.55		$m(\tilde{\chi}_1^0) < 100 \text{ GeV}$ $m(\tilde{q}) \cdot m(\tilde{\chi}_1^0) = 5 \text{ GeV}$	1712.02332 1711.03301
	$\tilde{g}\tilde{g},\tilde{g}{\rightarrow}q\bar{q}\tilde{\chi}_{1}^{0}$	0	2-6 jets	Yes	36.1	ig ig			Forbidden	0.95-1.6	2.0	$m(\tilde{\chi}_{1}^{0}) < 200 \text{ GeV} \\ m(\tilde{\chi}_{1}^{0}) = 900 \text{ GeV}$	1712.02332 1712.02332
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}(\ell\ell)\tilde{\chi}_1^0$	3 e,μ ee,μμ	4 jets 2 jets	- Yes	36.1 36.1	ĩ g				1.85		$m(\tilde{\chi}_{1}^{0}) < 800 \text{ GeV}$ $m(\tilde{g})-m(\tilde{\chi}_{1}^{0}) = 50 \text{ GeV}$	1706.03731 1805.11381
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qqWZ\tilde{\chi}_1^0$	0 3 <i>e</i> , µ	7-11 jets 4 jets	Yes	36.1 36.1	ë ë			0.98	1.8		$m(\tilde{\chi}_1^0) <400 \text{GeV} \ m(\tilde{g}) \cdot m(\tilde{\chi}_1^0) =200 \text{GeV}$	1708.02794 1706.03731
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t t \tilde{\chi}_1^0$	0-1 <i>e</i> , μ 3 <i>e</i> , μ	3 b 4 jets	Yes -	36.1 36.1	196 196				1.25	2.0	m($\tilde{\chi}_1^0$)<200 GeV m(\tilde{g})-m($\tilde{\chi}_1^0$)=300 GeV	1711.01901 1706.03731
3 rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 {\rightarrow} b\tilde{\chi}_1^0/t\tilde{\chi}_1^\pm$		Multiple Multiple Multiple		36.1 36.1 36.1	$egin{array}{ccc} ilde{b}_1 & & & \ ilde{b}_1 &$	Forbidden	Forbidden Forbidden	0.9 0.58-0.82 0.7		$m(\tilde{\chi}_{1}^{0})=3$ $m(\tilde{\chi}_{1}^{0})=200$ G	$m(\tilde{\chi}_{1}^{0})$ =300 GeV, BR $(b\tilde{\chi}_{1}^{0})$ =1 300 GeV, BR $(b\tilde{\chi}_{1}^{0})$ =BR $(t\tilde{\chi}_{1}^{+})$ =0.5 eV, $m(\tilde{\chi}_{1}^{+})$ =300 GeV, BR $(t\tilde{\chi}_{1}^{+})$ =1	1708.09266, 1711.03301 1708.09266 1706.03731
	$\tilde{b}_1\tilde{b}_1,\tilde{\iota}_1\tilde{\iota}_1,M_2=2\times M_1$		Multiple Multiple		36.1 36.1				0.7			$m(\tilde{\chi}_{1}^{0})=60 \text{ GeV}$ $m(\tilde{\chi}_{1}^{0})=200 \text{ GeV}$	1709.04183, 1711.11520, 1708.03247 1709.04183, 1711.11520, 1708.03247
	$ \begin{split} \tilde{t}_1 \tilde{t}_1, \tilde{t}_1 &\rightarrow W b \tilde{\chi}_1^0 \text{ or } t \tilde{\chi}_1^0 \\ \tilde{t}_1 \tilde{t}_1, \tilde{H} \text{ LSP} \end{split} $	0-2 <i>e</i> , <i>µ</i> (0-2 jets/1-2 Multiple Multiple	b Yes	36.1 36.1 36.1	$egin{array}{ccc} ella_1 & & & \ ella_1 & & \ e$	Forbidden		1.0 0.4-0.9 0.6-0.8		$m(\tilde{\chi}_{\downarrow}^{0})=150 \text{ G}$ $m(\tilde{\chi}_{\downarrow}^{0})=300 \text{ G}$	$\begin{split} & m(\tilde{\chi}_{1}^{0}){=}1GeV\\ & ieV, m(\tilde{\chi}_{1}^{\pm}){-}m(\tilde{\chi}_{1}^{0}){=}5GeV, \tilde{t}_{1}\approx\tilde{t}_{L}\\ & ieV, m(\tilde{\chi}_{1}^{\pm}){-}m(\tilde{\chi}_{1}^{0}){=}5GeV, \tilde{t}_{1}\approx\tilde{t}_{L} \end{split}$	1506.08616, 1709.04183, 1711.11520 1709.04183, 1711.11520 1709.04183, 1711.11520
	$\tilde{t}_1 \tilde{t}_1$, Well-Tempered LSP $\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow c \tilde{\chi}_1^0 / \tilde{c} \tilde{c}, \tilde{c} \rightarrow c \tilde{\chi}_1^0$	0	Multiple 2c mono-iet	Yes	36.1 36.1 36.1	$\tilde{\iota}_1$ $\tilde{\iota}_1$ $\tilde{\iota}_1$ $\tilde{\iota}_2$		0.46	0.48-0.84 0.85		m($\tilde{\chi}_1^0$)=150 G	ieV, $m(\tilde{\chi}_{1}^{\pm})-m(\tilde{\chi}_{1}^{0})=5 \text{ GeV}, \tilde{r}_{1} \approx \tilde{r}_{L}$ $m(\tilde{\chi}_{1}^{0})=0 \text{ GeV}$ $m(\tilde{r}_{1},\tilde{c})-m(\tilde{\chi}_{1}^{0})=50 \text{ GeV}$ $m(\tilde{c},\tilde{c})-m(\tilde{v}_{1}^{0})=50 \text{ GeV}$	1709.04183, 1711.11520 1805.01649 1805.01649 1711.03301
	$\tilde{t}_2 \tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + h$	1-2 e,μ	4 b	Yes	36.1	τ ₂		0.10	0.32-0.88		$m(\tilde{\mathcal{X}}_1^0)$	$=0 \text{ GeV}, m(\tilde{t}_1)-m(\tilde{\chi}_1^0)=180 \text{ GeV}$	1706.03986
EW direct	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ via WZ	2-3 e,µ		Yes	36.1	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$			0.6			m($\tilde{\chi}_{1}^{0}$)=0	1403.5294, 1806.02293
	ũ±ũ ⁰ WI	ee, μμ fffsodfbb	≥ 1	Yes	36.1	$\tilde{\chi}_{1}^{\pm}/\tilde{\chi}_{2}^{0}$ 0.17 $\tilde{z}^{\pm}/\tilde{z}^{0}$	0.26					$m(\tilde{\chi}_1^{\pm})-m(\tilde{\chi}_1^{0})=10 \text{ GeV}$	1712.08119
	$\tilde{\chi}_{1}^{+}\tilde{\chi}_{2}^{\mp} \vee \tilde{\chi}_{2}^{0}, \tilde{\chi}_{1}^{+} \rightarrow \tilde{\tau}\nu(\tau\tilde{\nu}), \tilde{\chi}_{2}^{0} \rightarrow \tilde{\tau}\tau(\nu\tilde{\nu})$	2 τ	-	Yes	36.1		.22		0.76	$m(\tilde{\chi}_1^{\dagger})$	$m(\tilde{\chi}^{0})=100$	$ \begin{array}{l} \min\{\tilde{\tau}_{1}\}=0, \ m(\tilde{\tau},\tilde{\nu})=0.5(m(\tilde{\chi}_{1}^{0})+m(\tilde{\chi}_{1}^{0})) \\ \operatorname{GeV}, \ m(\tilde{\tau},\tilde{\nu})=0.5(m(\tilde{\chi}_{1}^{0})+m(\tilde{\chi}_{1}^{0})) \end{array} $	1708.07875 1708.07875
	$\tilde{\ell}_{\mathrm{L,R}}\tilde{\ell}_{\mathrm{L,R}},\tilde{\ell}{\rightarrow}\ell\tilde{\chi}^0_1$	2 e,μ 2 e,μ	0 ≥ 1	Yes Yes	36.1 36.1	ĩ ĩ 0.18		0.5				$m(\tilde{\ell}_1^0)=0$ $m(\tilde{\ell})$ - $m(\tilde{\chi}_1^0)=5~GeV$	1803.02762 1712.08119
	$\tilde{H}\tilde{H},\tilde{H}{ ightarrow}h\tilde{G}/Z\tilde{G}$	0 4 <i>e</i> , µ	$\geq 3b$ 0	Yes Yes	36.1 36.1	<u>Й</u> 0.13- <u>Й</u>	0.23		0.29-0.88			$ \begin{array}{l} BR(\tilde{\chi}^0_1 \to h\tilde{G}) = 1 \\ BR(\tilde{\chi}^0_1 \to Z\tilde{G}) = 1 \end{array} $	1806.04030 1804.03602
Long-lived particles	Direct $\tilde{\chi}_1^+ \tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	Yes	36.1			0.46				Pure Wino Pure Higgsino	1712.02118 ATL-PHYS-PUB-2017-019
	Stable g R-hadron	SMP		-	3.2	ĝ				1.6			1606.05129
	Metastable \tilde{g} R-hadron, $\tilde{g} \rightarrow qq \tilde{\chi}_1^0$	0	Multiple		32.8	$\tilde{g} = [\tau(\tilde{g}) = 100 \text{ ns}, 0.2]$! ns]			1.6	2.4	m($\tilde{\chi}_{1}^{0}$)=100 GeV	1710.04901, 1604.04520
	GMSB, $\chi_1^{\circ} \rightarrow \gamma G$, long-lived χ_1° $\tilde{g}g, \tilde{\chi}_1^{0} \rightarrow eev/e\mu v/\mu\mu v$	2γ displ. ee/eµ/μ	μ-	Yes -	20.3	$\frac{\chi_1}{\tilde{g}}$		0.44		1.3	6 <	$1 < \tau(\tilde{\chi}_1) < 3$ ns, SPS8 model $c\tau(\tilde{\chi}_1^0) < 1000$ mm, m $(\tilde{\chi}_1^0) = 1$ TeV	1409.5542 1504.05162
RPV	LFV $pp \rightarrow \tilde{v}_{\tau} + X, \tilde{v}_{\tau} \rightarrow e\mu/e\tau/\mu\tau$	еµ,ет,µт	-	-	3.2	ν̃,				1.3	9	$\lambda'_{211} = 0.11, \lambda_{132/133/233} = 0.07$	1607.08079
	$\tilde{\chi}_1^{\pm} \tilde{\chi}_1^{\mp} / \tilde{\chi}_2^0 \to WW/Z\ell\ell\ell\ell\nu\nu$	4 e, µ	0	Yes	36.1	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0 [\lambda_{i33} \neq 0, \lambda_{12}]$	$k \neq 0$]		0.82	1.33		$m(\tilde{\chi}_1^0)=100 \text{ GeV}$	1804.03602
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qq\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow qqq$	0 4	5 large-R je Multiple	ets -	36.1 36.1	$\tilde{g} = [m(\tilde{\chi}_1^0) = 200 \text{ GeV}, \\ \tilde{g} = [\chi_{112}^{\prime\prime\prime} = 2e-4, 2e-5]$	1100 GeV]		1.0	1.3 1.9	9 2.0	Large λ_{112}'' m $(\tilde{\chi}_{1}^{0})$ =200 GeV bino-like	1804.03568 ATLAS-CONF-2018-003
	$\tilde{g}\tilde{g}, \tilde{g} \to tbs / \tilde{g} \to t\tilde{k}_1^0, \tilde{\chi}_1^0 \to tbs$		Multiple Multiple		36.1	$\tilde{g} = [\lambda''_{323} = 1, 1e-2]$ $\tilde{g} = [\lambda''_{323} = 2e-4, 1e-2]$		0.5	5 1.0	1.8	2.1	$m(\tilde{x}_1^0)$ =200 GeV, bino like $m(\tilde{x}_1^0)$ =200 GeV, bino like	ATLAS-CONF-2018-003
	$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow bs$	0	2 jets + 2 l	, -	36.7	$\tilde{t}_1 [qq, bs]$		0.42	0.61			m(1)=200 Gev, bin0-like	1710.07171
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow b\ell$	2 e, µ	2 b	-	36.1	ĩ ₁				0.4-1.45		$BR(\tilde{t}_1 \rightarrow be/b\mu) > 20\%$	1710.05544
*Onlv	a selection of the available ma	uss limits on r	new state	s or	1	0 ⁻¹				1			





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Conclusions



- > The experiments at the LHC have very broad and ambitious DM search program.
- [>] This is possible thanks to the superb performance of the LHC machine.
 - > Run 2 will end up with up to 150 fb⁻¹ most of it still to be analyzed.
- > Unfortunately no evidence of a signal found so far.
- [>] But increasing luminosity will allow better limits in the time to come (or discovery!).
 - Specially for vector and axial-vector mediator models.
- > Interest is also turning now on searches for long-lived particles.
 - > This kind of tolopologies require dedicated reconstruction techniques.
- > A lot of new results will come in the next months. Stay tuned!



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Backup





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Putting all together



- > Dijet resonances dominates the exclusion for both vector and axial-vector mediators.
- > Both vector and axial-vector mediators excluded up to ~ 2.5 TeV.







Comparison with other experiments



[>] Fixing the limits on the couplings allows to translate xsections into DM production xsections.







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