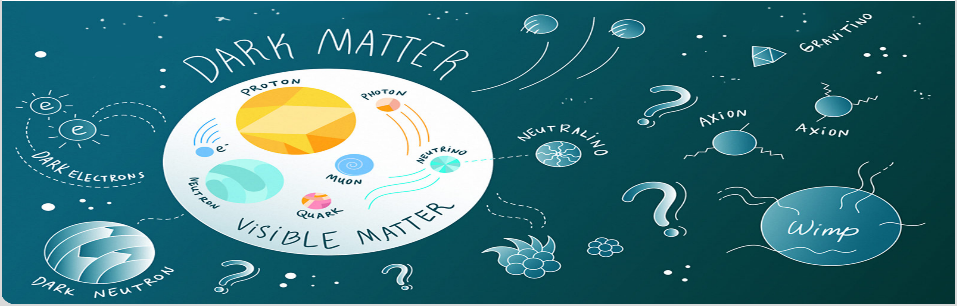
Karlsruhe Institute of Technology

DM Collider Searches

Introduction

Jonas Müller | 8.7.2019

INSTITUT FÜR THEORETISCHE PHYSIK (ITP)



Outline

1. Motivation/Expectation
2. Approaches
3. Top-Down
4. Bottom-Up

1. Motivation/Expectation
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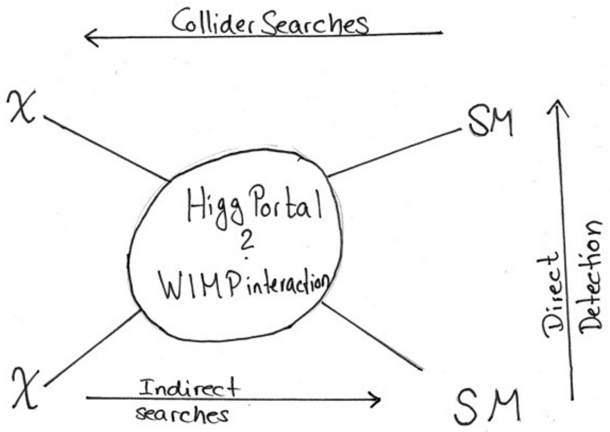
Motivation/Expectation

- *If* DM is a fundamental new particle *and* interacts with SM particles
  - Production in collider is possible
  - Decay chains into DM particles are possible



Motivation/Expectation

What can we expect?

- Suppose we have
  - $\dot{\mathcal{L}} = 5 \cdot 10^{33} cm^{-2} s^{-1}$
  - $m_\chi = 100\ \mathrm{GeV}$ and $\sigma_{LHC} = G_F^2 m_\chi^2$
  - Isotropic production in an distante $R = 10cm$
  - $\rho_{DM} = 0.3\ \mathrm{GeV}/cm^3$ and $v_{DM} = 220km/s$

$$\Phi_{LHC} = 4\pi R^2 \dot{\mathcal{L}} \sigma_{LHC} \sim 10^4 cm^2/s$$

$$\Phi_{halo} = \frac{\rho_{DM}}{m_\chi} \pi R^2 v_{DM} \sim 10^9 cm^2/s$$

$\Rightarrow$ The expected flux in the LHC collider is much smaller than the halo flux!

1. Motivation/Expectation
2. **Approaches**
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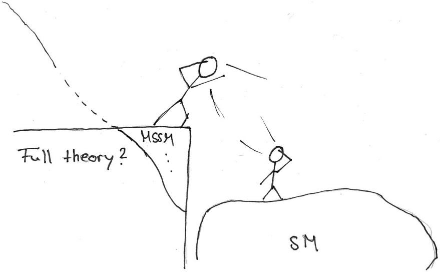
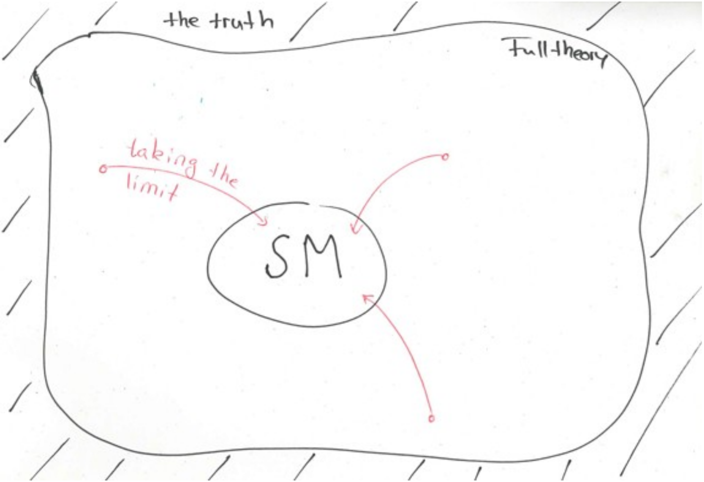
General Approaches

Extend the Standard Model

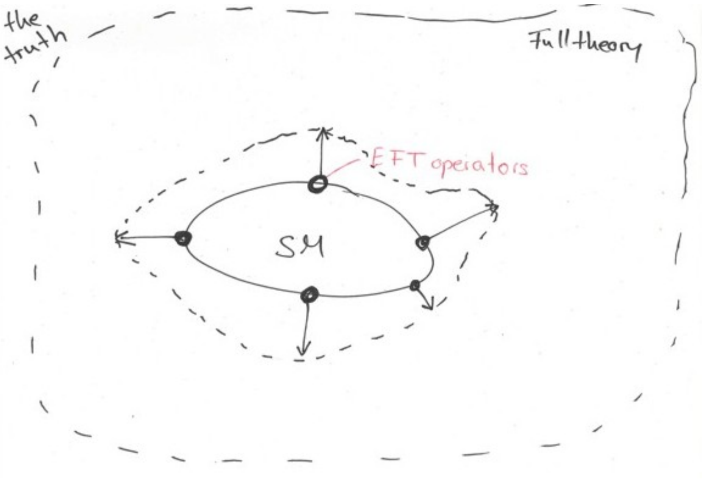
- top-down approach
- bottom-up approach



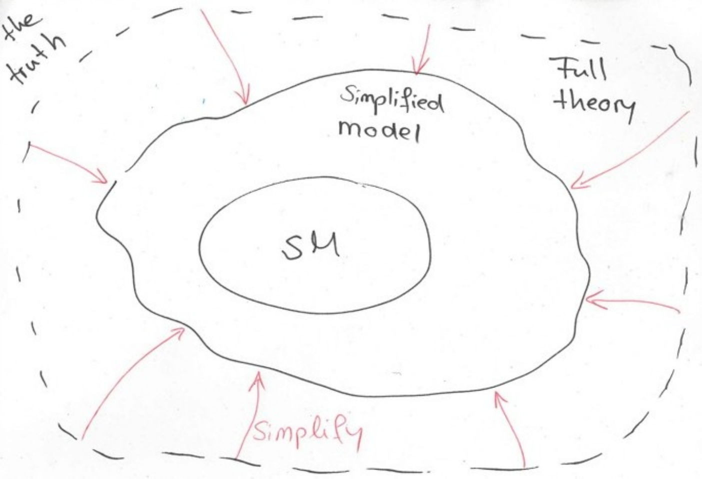
top-down Approach



bottom-up Approach - EFT



bottom-up Approach - Simplified Models



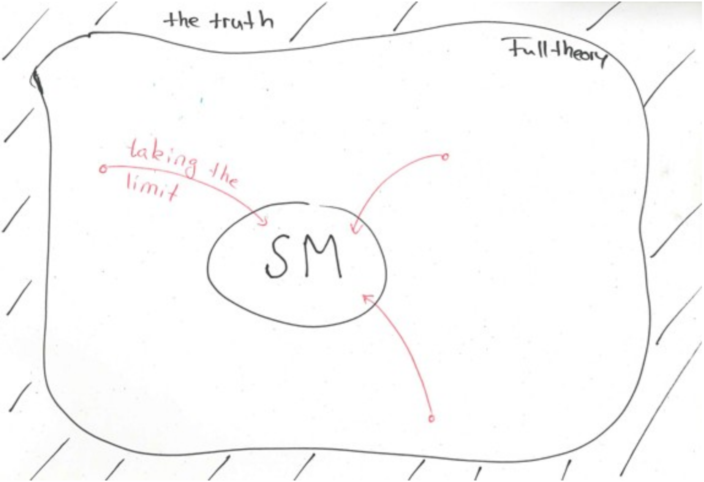
1 Motivation/Expectation

2 Approaches

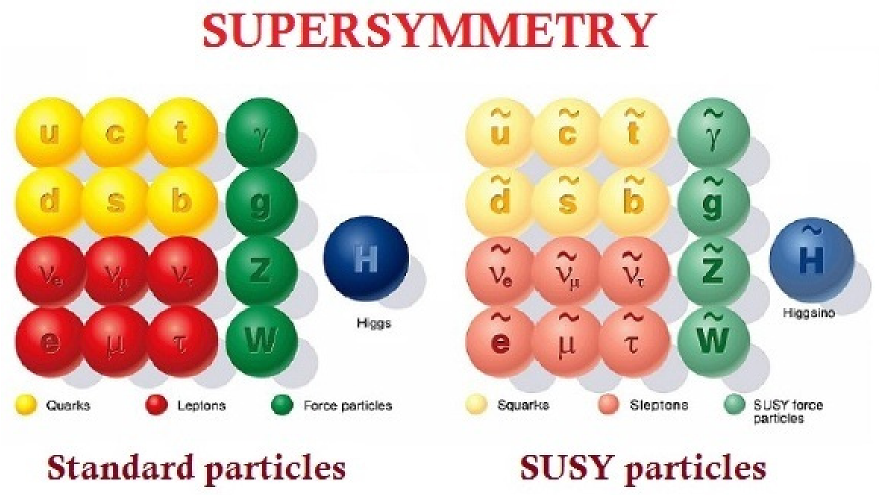
3 Top-Down

4 Bottom-Up

Top-Down Approach - SUSY



Top-Down Approach - SUSY



Neutralino - DM Candidate

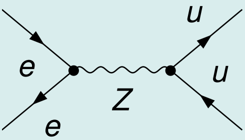
Neutralino is a mixing state of the gauge and Higgs boson superpartners

$$\begin{pmatrix} \tilde{\chi}_1^0 \\ \tilde{\chi}_2^0 \\ \tilde{\chi}_3^0 \\ \tilde{\chi}_4^0 \end{pmatrix} = N \cdot \begin{pmatrix} \tilde{W}^0 \\ \tilde{B}^0 \\ \tilde{H}_a^0 \\ \tilde{H}_b^0 \end{pmatrix}$$

the lightest neutralino $\tilde{\chi}_1^0$ is the stable DM candidate!

LEP - Searches

Z-Pole Measurement

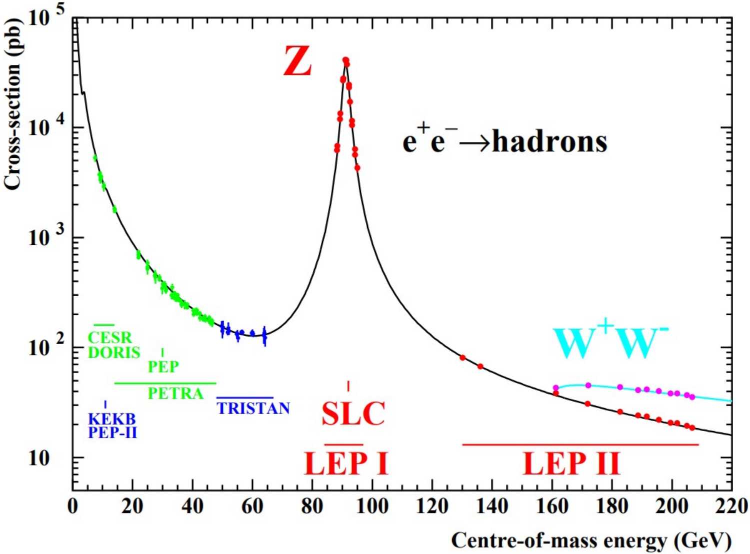


- $\sqrt{s} \sim m_Z$
- Measurement of the total width $\Delta\Gamma_Z$
- Looking for events with high missing transverse momentum/energy
- Allows for an upper bound of $\Delta\Gamma_{inv}$

$\Rightarrow$ Bound on $\Delta\Gamma_{inv}$ translates on an lower bound on m_χ!

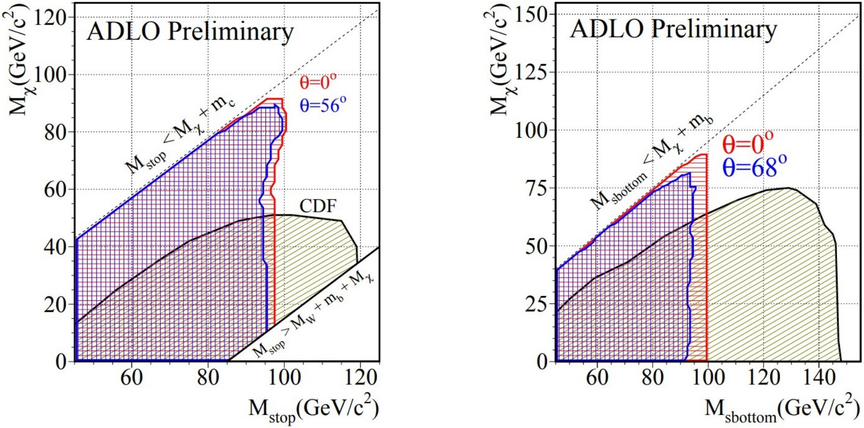
$$\tilde{f} \rightarrow f + \tilde{\chi}_1^0$$

LEP-Results


Cross-section (pb)
10^5
10^4
10^3
10^2
10
0
20
40
60
80
100
120
140
160
180
200
220
Centre-of-mass energy (GeV)
Z
$e^+e^- \rightarrow$ hadrons
W^+W^-
CESR
DORIS
PEP
PETRA
KEKB
PEP-II
TRISTAN
SLC
LEP I
LEP II

LEP-Results

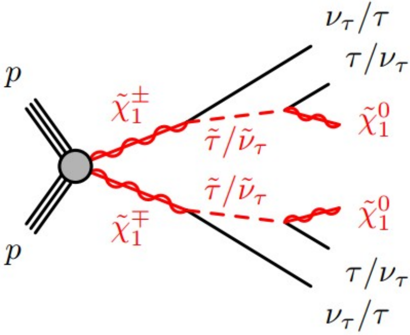
$$\tilde{f} \rightarrow f + \tilde{\chi}_1^0$$

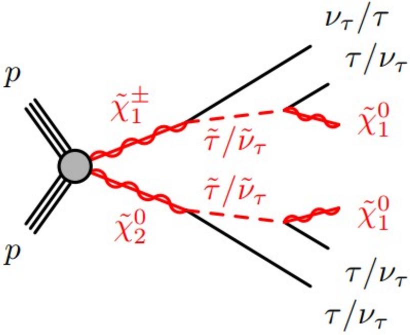


LHC - Searches

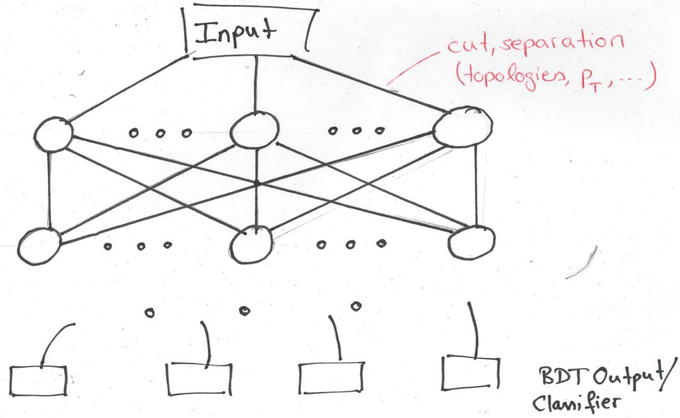
- More Energy, but more problems!
- General Idea of the searches:
  - Take your favorite model (e.g. MSSM,NMSSM...)
  - Calculate the production crosssection, branching ratios...
  - Generate an event simulation based on the model (and for the detector!)
  - Generate an event simulation with SM only (background)
  - Apply *smart* parameter cuts to maximise S/B
  - Hope for a detectable signal!
- Typical DM signatures:
  - High $\not{E}_T$
  - Mono-X signatures
- The *art* of the parameter cuts
  - Boosted Decision Trees (BDTs)
  - Deep Learning (DL)

Example Search Process



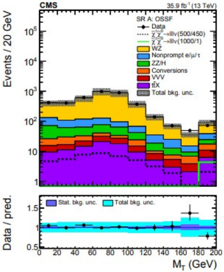


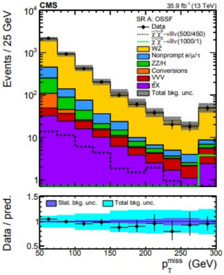
BDT/DL

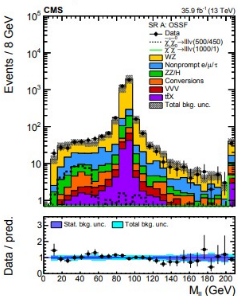


What is used to select events?

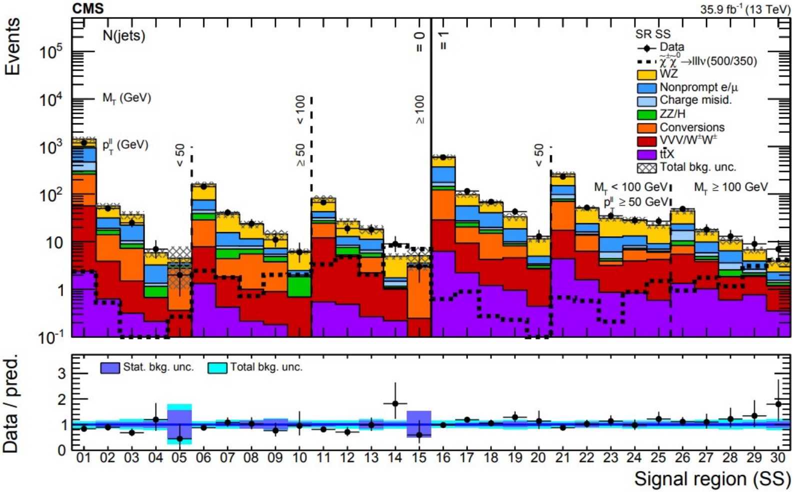
- Event Topologies (0-jet,1-jet,...)
- p_T cuts
- Invariant mass distributions
- Missing transverse energy $\not{E}_T$



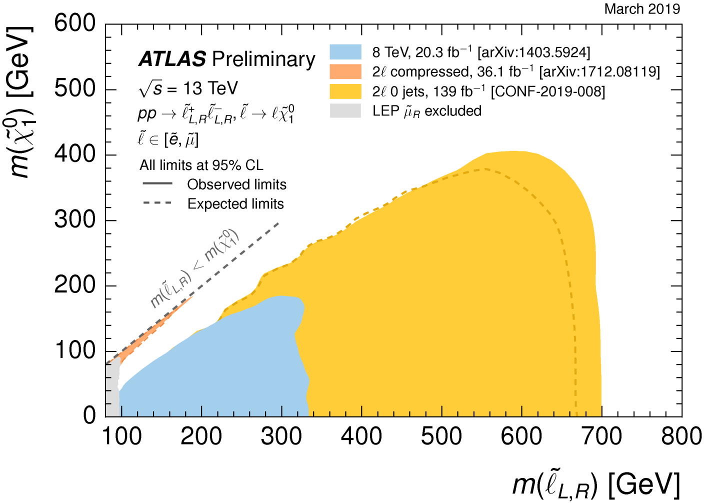




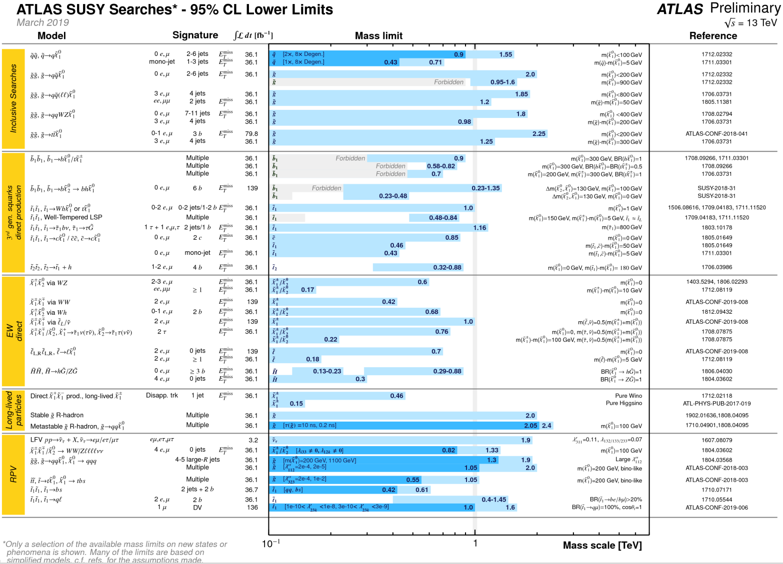
BDT/DL


CMS
35.9 fb^{-1} (13 TeV)
Events
N(jets)
= 0
= 1
M_T (GeV)
< 100
≥ 100
p_T^{ll} (GeV)
< 50
≥ 50
< 50
SR SS
Data
$\tilde{\chi}^{\pm}\tilde{\chi}^{0} \rightarrow lll\nu$(500/350)
WZ
Nonprompt e/μ
Charge misid.
ZZ/H
Conversions
VVV/W$^{\pm}$W$^{\pm}$
t$\bar{t}$X
Total bkg. unc.
M_T < 100 GeV
p_T^{ll} ≥ 50 GeV
M_T ≥ 100 GeV
10^5
10^4
10^3
10^2
10
1
10^{-1}
Data / pred.
Stat. bkg. unc.
Total bkg. unc.
3
2
1
0
01 02 03 04 05 06 07 08 09 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30
Signal region (SS)

Exclusion Limits for lightest neutralino and slepton masses



Exclusion Summary-ATLAS



ATLAS SUSY Searches* - 95% CL Lower Limits

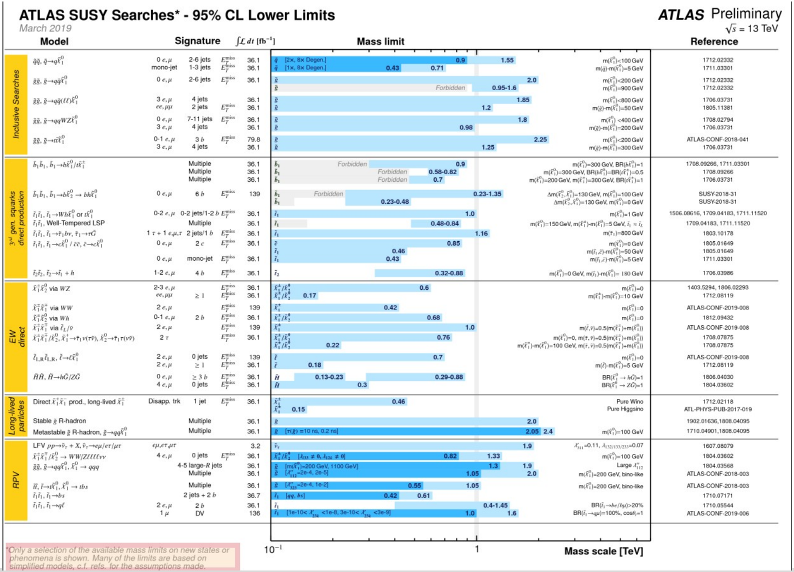
March 2019

ATLAS Preliminary
$\sqrt{s}$ = 13 TeV

	Model	Signature			$\int\mathcal{L}\,dt$ [fb^{-1}]	Mass limit			Reference
Inclusive Searches	$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}^0_1$	0 e,μ	2-6 jets	$E_T^{\rm miss}$	36.1	$\tilde{q}$ [2×, 8× Degen.]	0.9 1.55	m($\tilde{\chi}^0_1$)<100 GeV	1712.02332
		mono-jet	1-3 jets	$E_T^{\rm miss}$	36.1	$\tilde{q}$ [1×, 8× Degen.]	0.43 0.71	m($\tilde{q}$)-m($\tilde{\chi}^0_1$)=5 GeV	1711.03301
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}\tilde{\chi}^0_1$	0 e,μ	2-6 jets	$E_T^{\rm miss}$	36.1	$\tilde{g}$	2.0	m($\tilde{\chi}^0_1$)<200 GeV	1712.02332
						$\tilde{g}$	Forbidden 0.95-1.6	m($\tilde{\chi}^0_1$)=900 GeV	1712.02332
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}(\ell\ell)\tilde{\chi}^0_1$	3 e,μ	4 jets		36.1	$\tilde{g}$	1.85	m($\tilde{\chi}^0_1$)<800 GeV	1706.03731
		$ee,\mu\mu$	2 jets	$E_T^{\rm miss}$	36.1	$\tilde{g}$	1.2	m($\tilde{g}$)-m($\tilde{\chi}^0_1$)=50 GeV	1805.11381
	$\tilde{g}\tilde{g}, \tilde{g}\to qqWZ\tilde{\chi}^0_1$	0 e,μ	7-11 jets	$E_T^{\rm miss}$	36.1	$\tilde{g}$	1.8	m($\tilde{\chi}^0_1$) <400 GeV	1708.02794
		3 e,μ	4 jets		36.1	$\tilde{g}$	0.98	m($\tilde{g}$)-m($\tilde{\chi}^0_1$)=200 GeV	1706.03731
	$\tilde{g}\tilde{g}, \tilde{g}\to t\bar{t}\tilde{\chi}^0_1$	0-1 e,μ	3 b	$E_T^{\rm miss}$	79.8	$\tilde{g}$	2.25	m($\tilde{\chi}^0_1$)<200 GeV	ATLAS-CONF-2018-041
		3 e,μ	4 jets		36.1	$\tilde{g}$	1.25	m($\tilde{g}$)-m($\tilde{\chi}^0_1$)=300 GeV	1706.03731
3^{rd} gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to b\tilde{\chi}^0_1/t\tilde{\chi}^\pm_1$		Multiple		36.1	$\tilde{b}_1$	Forbidden 0.9	m($\tilde{\chi}^0_1$)=300 GeV, BR($b\tilde{\chi}^0_1$)=1	1708.09266, 1711.03301
			Multiple		36.1	$\tilde{b}_1$	Forbidden 0.58-0.82	m($\tilde{\chi}^0_1$)=300 GeV, BR($b\tilde{\chi}^0_1$)=BR($t\tilde{\chi}^\pm_1$)=0.5	1708.09266
			Multiple		36.1	$\tilde{b}_1$	Forbidden 0.7	m($\tilde{\chi}^0_1$)=200 GeV, m($\tilde{\chi}^\pm_1$)=300 GeV, BR($t\tilde{\chi}^\pm_1$)=1	1706.03731
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to b\tilde{\chi}^0_2\to bh\tilde{\chi}^0_1$	0 e,μ	6 b	$E_T^{\rm miss}$	139	$\tilde{b}_1$	Forbidden 0.23-1.35	Δm($\tilde{\chi}^0_2,\tilde{\chi}^0_1$)=130 GeV, m($\tilde{\chi}^0_1$)=100 GeV	SUSY-2018-31
						$\tilde{b}_1$	0.23-0.48	Δm($\tilde{\chi}^0_2,\tilde{\chi}^0_1$)=130 GeV, m($\tilde{\chi}^0_1$)=0 GeV	SUSY-2018-31
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to Wb\tilde{\chi}^0_1$ or $t\tilde{\chi}^0_1$	0-2 e,μ	0-2 jets/1-2 b	$E_T^{\rm miss}$	36.1	$\tilde{t}_1$	1.0	m($\tilde{\chi}^0_1$)=1 GeV	1506.08616, 1709.04183, 1711.11520
	$\tilde{t}_1\tilde{t}_1$, Well-Tempered LSP		Multiple		36.1	$\tilde{t}_1$	0.48-0.84	m($\tilde{\chi}^0_1$)=150 GeV, m($\tilde{\chi}^\pm_1$)-m($\tilde{\chi}^0_1$)=5 GeV, $\tilde{t}_1\approx\tilde{t}_L$	1709.04183, 1711.11520
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to\tilde{\tau}_1 b\nu, \tilde{\tau}_1\to\tau\tilde{G}$	1 τ + 1 e,μ,τ	2 jets/1 b	$E_T^{\rm miss}$	36.1	$\tilde{t}_1$	1.16	m($\tilde{\tau}_1$)=800 GeV	1803.10178
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to c\tilde{\chi}^0_1$ / $\tilde{c}\tilde{c}, \tilde{c}\to c\tilde{\chi}^0_1$	0 e,μ	2 c	$E_T^{\rm miss}$	36.1	$\tilde{c}$	0.85	m($\tilde{\chi}^0_1$)=0 GeV	1805.01649
						$\tilde{t}_1$	0.46	m($\tilde{t}_1,\tilde{c}$)-m($\tilde{\chi}^0_1$)=50 GeV	1805.01649
		0 e,μ	mono-jet	$E_T^{\rm miss}$	36.1	$\tilde{t}_1$	0.43	m($\tilde{t}_1,\tilde{c}$)-m($\tilde{\chi}^0_1$)=5 GeV	1711.03301
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1+h$	1-2 e,μ	4 b	$E_T^{\rm miss}$	36.1	$\tilde{t}_2$	0.32-0.88	m($\tilde{\chi}^0_1$)=0 GeV, m($\tilde{t}_1$)-m($\tilde{\chi}^0_1$)= 180 GeV	1706.03986
EW direct	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2$ via WZ	2-3 e,μ		$E_T^{\rm miss}$	36.1	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$	0.6	m($\tilde{\chi}^0_1$)=0	1403.5294, 1806.02293
		$ee,\mu\mu$	≥ 1	$E_T^{\rm miss}$	36.1	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$	0.17	m($\tilde{\chi}^\pm_1$)-m($\tilde{\chi}^0_1$)=10 GeV	1712.08119
	$\tilde{\chi}^\pm_1\tilde{\chi}^\mp_1$ via WW	2 e,μ		$E_T^{\rm miss}$	139	$\tilde{\chi}^\pm_1$	0.42	m($\tilde{\chi}^0_1$)=0	ATLAS-CONF-2019-008
	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2$ via Wh	0-1 e,μ	2 b	$E_T^{\rm miss}$	36.1	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$	0.68	m($\tilde{\chi}^0_1$)=0	1812.09432
	$\tilde{\chi}^\pm_1\tilde{\chi}^\mp_1$ via $\tilde{\ell}_L/\tilde{\nu}$	2 e,μ		$E_T^{\rm miss}$	139	$\tilde{\chi}^\pm_1$	1.0	m($\tilde{\ell},\tilde{\nu}$)=0.5(m($\tilde{\chi}^\pm_1$)+m($\tilde{\chi}^0_1$))	ATLAS-CONF-2019-008
	$\tilde{\chi}^\pm_1\tilde{\chi}^\mp_1/\tilde{\chi}^0_2, \tilde{\chi}^+_1\to\tilde{\tau}_1\nu(\tau\tilde{\nu}), \tilde{\chi}^0_2\to\tilde{\tau}_1\tau(\nu\tilde{\nu})$	2 τ		$E_T^{\rm miss}$	36.1	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$	0.76	m($\tilde{\chi}^0_1$)=0, m($\tilde{\tau},\tilde{\nu}$)=0.5(m($\tilde{\chi}^\pm_1$)+m($\tilde{\chi}^0_1$))	1708.07875
						$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$	0.22	m($\tilde{\chi}^\pm_1$)-m($\tilde{\chi}^0_1$)=100 GeV, m($\tilde{\tau},\tilde{\nu}$)=0.5(m($\tilde{\chi}^\pm_1$)+m($\tilde{\chi}^0_1$))	1708.07875
	$\tilde{\ell}_{\rm L,R}\tilde{\ell}_{\rm L,R}, \tilde{\ell}\to\ell\tilde{\chi}^0_1$	2 e,μ	0 jets	$E_T^{\rm miss}$	139	$\tilde{\ell}$	0.7	m($\tilde{\chi}^0_1$)=0	ATLAS-CONF-2019-008
		2 e,μ	≥ 1	$E_T^{\rm miss}$	36.1	$\tilde{\ell}$	0.18	m($\tilde{\ell}$)-m($\tilde{\chi}^0_1$)=5 GeV	1712.08119
	$\tilde{H}\tilde{H}, \tilde{H}\to h\tilde{G}/Z\tilde{G}$	0 e,μ	≥ 3 b	$E_T^{\rm miss}$	36.1	$\tilde{H}$	0.13-0.23 0.29-0.88	BR($\tilde{\chi}^0_1\to h\tilde{G}$)=1	1806.04030
		4 e,μ	0 jets	$E_T^{\rm miss}$	36.1	$\tilde{H}$	0.3	BR($\tilde{\chi}^0_1\to Z\tilde{G}$)=1	1804.03602
Long-lived particles	Direct $\tilde{\chi}^+_1\tilde{\chi}^-_1$ prod., long-lived $\tilde{\chi}^\pm_1$	Disapp. trk	1 jet	$E_T^{\rm miss}$	36.1	$\tilde{\chi}^\pm_1$	0.46	Pure Wino	1712.02118
						$\tilde{\chi}^\pm_1$	0.15	Pure Higgsino	ATL-PHYS-PUB-2017-019
	Stable $\tilde{g}$ R-hadron		Multiple		36.1	$\tilde{g}$	2.0		1902.01636,1808.04095
	Metastable $\tilde{g}$ R-hadron, $\tilde{g}\to qq\tilde{\chi}^0_1$		Multiple		36.1	$\tilde{g}$ [$\tau(\tilde{g})$ =10 ns, 0.2 ns]	2.05 2.4	m($\tilde{\chi}^0_1$)=100 GeV	1710.04901,1808.04095
RPV	LFV $pp\to\tilde{\nu}_\tau+X, \tilde{\nu}_\tau\to e\mu/e\tau/\mu\tau$	$e\mu,e\tau,\mu\tau$			3.2	$\tilde{\nu}_\tau$	1.9	λ'_{311}=0.11, $\lambda_{132/133/233}$=0.07	1607.08079
	$\tilde{\chi}^\pm_1\tilde{\chi}^\mp_1/\tilde{\chi}^0_2\to WW/Z\ell\ell\ell\ell\nu\nu$	4 e,μ	0 jets	$E_T^{\rm miss}$	36.1	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$ [$\lambda_{i33}\neq 0, \lambda_{12k}\neq 0$]	0.82 1.33	m($\tilde{\chi}^0_1$)=100 GeV	1804.03602
	$\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}^0_1, \tilde{\chi}^0_1\to qqq$		4-5 large-R jets		36.1	$\tilde{g}$ [m($\tilde{\chi}^0_1$)=200 GeV, 1100 GeV]	1.3 1.9	Large λ''_{112}	1804.03568
			Multiple		36.1	$\tilde{g}$ [λ''_{112}=2e-4, 2e-5]	1.05 2.0	m($\tilde{\chi}^0_1$)=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}\tilde{t}, \tilde{t}\to t\tilde{\chi}^0_1, \tilde{\chi}^0_1\to tbs$		Multiple		36.1	$\tilde{g}$ [λ''_{323}=2e-4, 1e-2]	0.55 1.05	m($\tilde{\chi}^0_1$)=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to bs$		2 jets + 2 b		36.7	$\tilde{t}_1$ [qq, bs]	0.42 0.61		1710.07171
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to q\ell$	2 e,μ	2 b		36.1	$\tilde{t}_1$	0.4-1.45	BR($\tilde{t}_1\to be/b\mu$)>20%	1710.05544
		1 μ	DV		136	$\tilde{t}_1$ [1e-10< λ'_{23k} <1e-8, 3e-10< λ'_{23k} <3e-9]	1.0 1.6	BR($\tilde{t}_1\to q\mu$)=100%, cosθ_t=1	ATLAS-CONF-2019-006

*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.

Exclusion Summary-ATLAS



ATLAS SUSY Searches* - 95% CL Lower Limits

March 2019

ATLAS Preliminary

$\sqrt{s}$ = 13 TeV

	Model	Signature			$\int\mathcal{L}\,dt$ [fb^{-1}]	Mass limit		Reference
Inclusive Searches	$\tilde{q}\tilde{q}$, $\tilde{q}\rightarrow q\tilde{\chi}^0_1$	0 e,μ	2-6 jets	E_T^{miss}	36.1	$\tilde{q}$ [2×, 8× Degen.] 0.9 1.55	m($\tilde{\chi}^0_1$)<100 GeV	1712.02332
		mono-jet	1-3 jets	E_T^{miss}	36.1	$\tilde{q}$ [1×, 8× Degen.] 0.43 0.71	m($\tilde{q}$)-m($\tilde{\chi}^0_1$)=5 GeV	1711.03301
	$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow q\bar{q}\tilde{\chi}^0_1$	0 e,μ	2-6 jets	E_T^{miss}	36.1	$\tilde{g}$ 2.0	m($\tilde{\chi}^0_1$)<200 GeV	1712.02332
						$\tilde{g}$ Forbidden 0.95-1.6	m($\tilde{\chi}^0_1$)=900 GeV	1712.02332
	$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow q\bar{q}(\ell\ell)\tilde{\chi}^0_1$	3 e,μ	4 jets		36.1	$\tilde{g}$ 1.85	m($\tilde{\chi}^0_1$)<800 GeV	1706.03731
		$ee,\mu\mu$	2 jets	E_T^{miss}	36.1	$\tilde{g}$ 1.2	m($\tilde{g}$)-m($\tilde{\chi}^0_1$)=50 GeV	1805.11381
	$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow qqWZ\tilde{\chi}^0_1$	0 e,μ	7-11 jets	E_T^{miss}	36.1	$\tilde{g}$ 1.8	m($\tilde{\chi}^0_1$) <400 GeV	1708.02794
		3 e,μ	4 jets		36.1	$\tilde{g}$ 0.98	m($\tilde{g}$)-m($\tilde{\chi}^0_1$)=200 GeV	1706.03731
	$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow t\bar{t}\tilde{\chi}^0_1$	0-1 e,μ	3 b	E_T^{miss}	79.8	$\tilde{g}$ 2.25	m($\tilde{\chi}^0_1$)<200 GeV	ATLAS-CONF-2018-041
		3 e,μ	4 jets		36.1	$\tilde{g}$ 1.25	m($\tilde{g}$)-m($\tilde{\chi}^0_1$)=300 GeV	1706.03731
3rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\rightarrow b\tilde{\chi}^0_1/t\tilde{\chi}^{\pm}_1$		Multiple		36.1	$\tilde{b}_1$ Forbidden 0.9	m($\tilde{\chi}^0_1$)=300 GeV, BR($b\tilde{\chi}^0_1$)=1	1708.09266, 1711.03301
			Multiple		36.1	$\tilde{b}_1$ Forbidden 0.58-0.82	m($\tilde{\chi}^0_1$)=300 GeV, BR($b\tilde{\chi}^0_1$)=BR($t\tilde{\chi}^{\pm}_1$)=0.5	1708.09266
			Multiple		36.1	$\tilde{b}_1$ Forbidden 0.7	m($\tilde{\chi}^0_1$)=200 GeV, m($\tilde{\chi}^{\pm}_1$)=300 GeV, BR($t\tilde{\chi}^{\pm}_1$)=1	1706.03731
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\rightarrow b\tilde{\chi}^0_2\rightarrow bh\tilde{\chi}^0_1$	0 e,μ	6 b	E_T^{miss}	139	$\tilde{b}_1$ Forbidden 0.23-1.35	Δm($\tilde{\chi}^0_2,\tilde{\chi}^0_1$)=130 GeV, m($\tilde{\chi}^0_1$)=100 GeV	SUSY-2018-31
						$\tilde{b}_1$ 0.23-0.48	Δm($\tilde{\chi}^0_2,\tilde{\chi}^0_1$)=130 GeV, m($\tilde{\chi}^0_1$)=0 GeV	SUSY-2018-31
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\rightarrow Wb\tilde{\chi}^0_1$ or $t\tilde{\chi}^0_1$	0-2 e,μ	0-2 jets/1-2 b	E_T^{miss}	36.1	$\tilde{t}_1$ 1.0	m($\tilde{\chi}^0_1$)=1 GeV	1506.08616, 1709.04183, 1711.11520
	$\tilde{t}_1\tilde{t}_1$, Well-Tempered LSP		Multiple		36.1	$\tilde{t}_1$ 0.48-0.84	m($\tilde{\chi}^0_1$)=150 GeV, m($\tilde{\chi}^{\pm}_1$)-m($\tilde{\chi}^0_1$)=5 GeV, $\tilde{t}_1\approx\tilde{t}_L$	1709.04183, 1711.11520
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\rightarrow\tilde{\tau}_1b\nu$, $\tilde{\tau}_1\rightarrow\tau\tilde{G}$	1 τ + 1 e,μ,τ	2 jets/1 b	E_T^{miss}	36.1	$\tilde{t}_1$ 1.16	m($\tilde{\tau}_1$)=800 GeV	1803.10178
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\rightarrow c\tilde{\chi}^0_1$ / $\tilde{c}\tilde{c}$, $\tilde{c}\rightarrow c\tilde{\chi}^0_1$	0 e,μ	2 c	E_T^{miss}	36.1	$\tilde{c}$ 0.85	m($\tilde{\chi}^0_1$)=0 GeV	1805.01649
						$\tilde{t}_1$ 0.46	m($\tilde{t}_1,\tilde{c}$)-m($\tilde{\chi}^0_1$)=50 GeV	1805.01649
		0 e,μ	mono-jet	E_T^{miss}	36.1	$\tilde{t}_1$ 0.43	m($\tilde{t}_1,\tilde{c}$)-m($\tilde{\chi}^0_1$)=5 GeV	1711.03301
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\rightarrow\tilde{t}_1+h$	1-2 e,μ	4 b	E_T^{miss}	36.1	$\tilde{t}_2$ 0.32-0.88	m($\tilde{\chi}^0_1$)=0 GeV, m($\tilde{t}_1$)-m($\tilde{\chi}^0_1$)= 180 GeV	1706.03986
EW direct	$\tilde{\chi}^{\pm}_1\tilde{\chi}^0_2$ via WZ	2-3 e,μ		E_T^{miss}	36.1	$\tilde{\chi}^{\pm}_1/\tilde{\chi}^0_2$ 0.6	m($\tilde{\chi}^0_1$)=0	1403.5294, 1806.02293
		$ee,\mu\mu$	≥ 1	E_T^{miss}	36.1	$\tilde{\chi}^{\pm}_1/\tilde{\chi}^0_2$ 0.17	m($\tilde{\chi}^{\pm}_1$)-m($\tilde{\chi}^0_1$)=10 GeV	1712.08119
	$\tilde{\chi}^{\pm}_1\tilde{\chi}^{\mp}_1$ via WW	2 e,μ		E_T^{miss}	139	$\tilde{\chi}^{\pm}_1$ 0.42	m($\tilde{\chi}^0_1$)=0	ATLAS-CONF-2019-008
	$\tilde{\chi}^{\pm}_1\tilde{\chi}^0_2$ via Wh	0-1 e,μ	2 b	E_T^{miss}	36.1	$\tilde{\chi}^{\pm}_1/\tilde{\chi}^0_2$ 0.68	m($\tilde{\chi}^0_1$)=0	1812.09432
	$\tilde{\chi}^{\pm}_1\tilde{\chi}^{\mp}_1$ via $\tilde{\ell}_L/\tilde{\nu}$	2 e,μ		E_T^{miss}	139	$\tilde{\chi}^{\pm}_1$ 1.0	m($\tilde{\ell},\tilde{\nu}$)=0.5(m($\tilde{\chi}^{\pm}_1$)+m($\tilde{\chi}^0_1$))	ATLAS-CONF-2019-008
	$\tilde{\chi}^{\pm}_1\tilde{\chi}^{\mp}_1/\tilde{\chi}^0_2$, $\tilde{\chi}^{+}_1\rightarrow\tilde{\tau}_1\nu(\tau\tilde{\nu})$, $\tilde{\chi}^0_2\rightarrow\tilde{\tau}_1\tau(\nu\tilde{\nu})$	2 τ		E_T^{miss}	36.1	$\tilde{\chi}^{\pm}_1/\tilde{\chi}^0_2$ 0.76	m($\tilde{\chi}^0_1$)=0, m($\tilde{\tau},\tilde{\nu}$)=0.5(m($\tilde{\chi}^{\pm}_1$)+m($\tilde{\chi}^0_1$))	1708.07875
						$\tilde{\chi}^{\pm}_1/\tilde{\chi}^0_2$ 0.22	m($\tilde{\chi}^{\pm}_1$)-m($\tilde{\chi}^0_1$)=100 GeV, m($\tilde{\tau},\tilde{\nu}$)=0.5(m($\tilde{\chi}^{\pm}_1$)+m($\tilde{\chi}^0_1$))	1708.07875
	$\tilde{\ell}_{\mathrm{L,R}}\tilde{\ell}_{\mathrm{L,R}}$, $\tilde{\ell}\rightarrow\ell\tilde{\chi}^0_1$	2 e,μ	0 jets	E_T^{miss}	139	$\tilde{\ell}$ 0.7	m($\tilde{\chi}^0_1$)=0	ATLAS-CONF-2019-008
		2 e,μ	≥ 1	E_T^{miss}	36.1	$\tilde{\ell}$ 0.18	m($\tilde{\ell}$)-m($\tilde{\chi}^0_1$)=5 GeV	1712.08119
	$\tilde{H}\tilde{H}$, $\tilde{H}\rightarrow h\tilde{G}/Z\tilde{G}$	0 e,μ	≥ 3 b	E_T^{miss}	36.1	$\tilde{H}$ 0.13-0.23 0.29-0.88	BR($\tilde{\chi}^0_1\rightarrow h\tilde{G}$)=1	1806.04030
		4 e,μ	0 jets	E_T^{miss}	36.1	$\tilde{H}$ 0.3	BR($\tilde{\chi}^0_1\rightarrow Z\tilde{G}$)=1	1804.03602
Long-lived particles	Direct $\tilde{\chi}^{+}_1\tilde{\chi}^{-}_1$ prod., long-lived $\tilde{\chi}^{\pm}_1$	Disapp. trk	1 jet	E_T^{miss}	36.1	$\tilde{\chi}^{\pm}_1$ 0.46	Pure Wino	1712.02118
						$\tilde{\chi}^{\pm}_1$ 0.15	Pure Higgsino	ATL-PHYS-PUB-2017-019
	Stable $\tilde{g}$ R-hadron		Multiple		36.1	$\tilde{g}$ 2.0		1902.01636,1808.04095
	Metastable $\tilde{g}$ R-hadron, $\tilde{g}\rightarrow qq\tilde{\chi}^0_1$		Multiple		36.1	$\tilde{g}$ [$\tau(\tilde{g})$ =10 ns, 0.2 ns] 2.05 2.4	m($\tilde{\chi}^0_1$)=100 GeV	1710.04901,1808.04095
RPV	LFV $pp\rightarrow\tilde{\nu}_\tau+X$, $\tilde{\nu}_\tau\rightarrow e\mu/e\tau/\mu\tau$	$e\mu,e\tau,\mu\tau$			3.2	$\tilde{\nu}_\tau$ 1.9	λ'_{311}=0.11, $\lambda_{132/133/233}$=0.07	1607.08079
	$\tilde{\chi}^{\pm}_1\tilde{\chi}^{\mp}_1/\tilde{\chi}^0_2\rightarrow WW/Z\ell\ell\ell\ell\nu\nu$	4 e,μ	0 jets	E_T^{miss}	36.1	$\tilde{\chi}^{\pm}_1/\tilde{\chi}^0_2$ [$\lambda_{133}\neq 0$, $\lambda_{12k}\neq 0$] 0.82 1.33	m($\tilde{\chi}^0_1$)=100 GeV	1804.03602
	$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow qq\tilde{\chi}^0_1$, $\tilde{\chi}^0_1\rightarrow qqq$		4-5 large-R jets		36.1	$\tilde{g}$ [m($\tilde{\chi}^0_1$)=200 GeV, 1100 GeV] 1.3 1.9	Large λ''_{112}	1804.03568
			Multiple		36.1	$\tilde{g}$ [λ''_{112}=2e-4, 2e-5] 1.05 2.0	m($\tilde{\chi}^0_1$)=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}\tilde{t}$, $\tilde{t}\rightarrow t\tilde{\chi}^0_1$, $\tilde{\chi}^0_1\rightarrow tbs$		Multiple		36.1	$\tilde{g}$ [λ''_{323}=2e-4, 1e-2] 0.55 1.05	m($\tilde{\chi}^0_1$)=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\rightarrow bs$		2 jets + 2 b		36.7	$\tilde{t}_1$ [qq, bs] 0.42 0.61		1710.07171
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\rightarrow q\ell$	2 e,μ	2 b		36.1	$\tilde{t}_1$ 0.4-1.45	BR($\tilde{t}_1\rightarrow be/b\mu$)>20%	1710.05544
		1 μ	DV		136	$\tilde{t}_1$ [1e-10< λ'_{23k} <1e-8, 3e-10< λ'_{23k} <3e-9] 1.0 1.6	BR($\tilde{t}_1\rightarrow q\mu$)=100%, cos$\theta_t$=1	ATLAS-CONF-2019-006

*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.

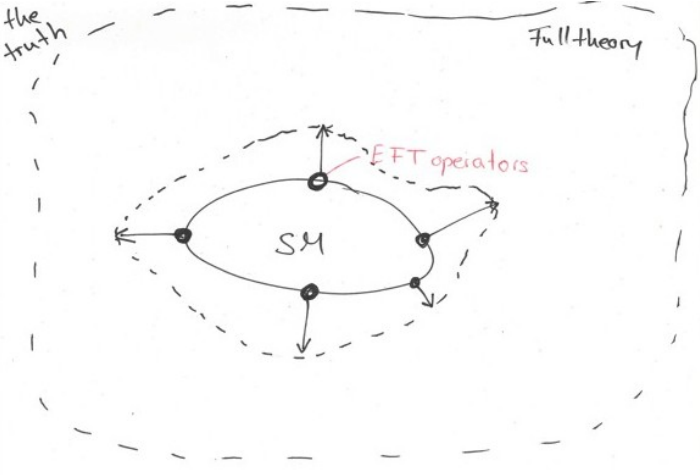
1 Motivation/Expectation

2 Approaches

3 Top-Down

4 Bottom-Up

Bottom-Up Approach - EFT



General Idea

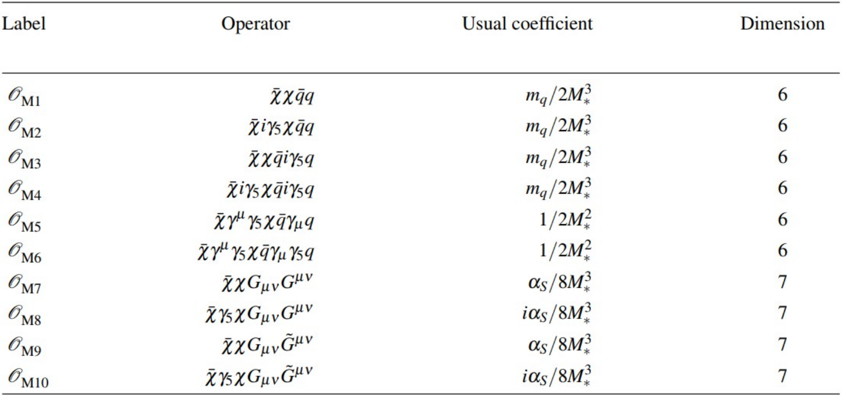
- We want to extend the SM with minimal additional assumptions:
  - Additional fundamental DM particles → fermionic/scalar
  - $\mathbb{Z}_2$ symmetry to ensure stability of the DM candidate
  - DM interaction with the SM particles (e.g. with quarks)

$$\mathcal{L} = \mathcal{L}_{SM} + \underbrace{i\overline{\chi}\gamma_\mu\partial^\mu\chi - m_\chi\overline{\chi}\chi}_{DM-kinetic\ \ terms} + \underbrace{\sum_q \sum_{i,j} \frac{G_{qij}}{\sqrt{2}} \left[\overline{\chi}\Gamma_i^\chi \chi\right] \left[\overline{q}\Gamma_q^j q\right]}_{DM-SM\ \ interaction}$$

- To be general

$$\mathcal{L}_{int.} = \sum_i C_i \mathcal{O}_i$$

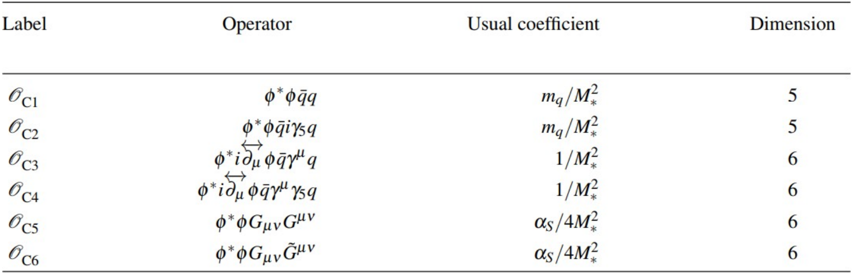
Lowest Dimensional Operators



Label	Operator	Usual coefficient	Dimension
$\mathcal{O}_{\mathrm{M1}}$	$\bar{\chi}\chi\bar{q}q$	$m_q/2M_*^3$	6
$\mathcal{O}_{\mathrm{M2}}$	$\bar{\chi}i\gamma_5\chi\bar{q}q$	$m_q/2M_*^3$	6
$\mathcal{O}_{\mathrm{M3}}$	$\bar{\chi}\chi\bar{q}i\gamma_5 q$	$m_q/2M_*^3$	6
$\mathcal{O}_{\mathrm{M4}}$	$\bar{\chi}i\gamma_5\chi\bar{q}i\gamma_5 q$	$m_q/2M_*^3$	6
$\mathcal{O}_{\mathrm{M5}}$	$\bar{\chi}\gamma^\mu\gamma_5\chi\bar{q}\gamma_\mu q$	$1/2M_*^2$	6
$\mathcal{O}_{\mathrm{M6}}$	$\bar{\chi}\gamma^\mu\gamma_5\chi\bar{q}\gamma_\mu\gamma_5 q$	$1/2M_*^2$	6
$\mathcal{O}_{\mathrm{M7}}$	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_S/8M_*^3$	7
$\mathcal{O}_{\mathrm{M8}}$	$\bar{\chi}\gamma_5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_S/8M_*^3$	7
$\mathcal{O}_{\mathrm{M9}}$	$\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_S/8M_*^3$	7
$\mathcal{O}_{\mathrm{M10}}$	$\bar{\chi}\gamma_5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_S/8M_*^3$	7

Table 2: Operators for Majorana DM.

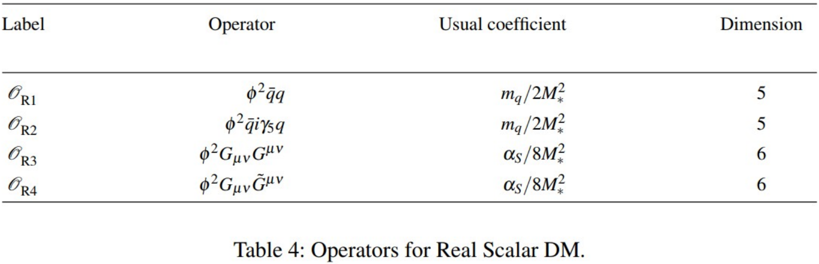
Lowest Dimensional Operators



Label	Operator	Usual coefficient	Dimension
$\mathcal{O}_{\mathrm{C1}}$	$\phi^*\phi\bar{q}q$	m_q/M_*^2	5
$\mathcal{O}_{\mathrm{C2}}$	$\phi^*\phi\bar{q}i\gamma_5 q$	m_q/M_*^2	5
$\mathcal{O}_{\mathrm{C3}}$	$\phi^* i\overleftrightarrow{\partial_\mu}\phi\bar{q}\gamma^\mu q$	$1/M_*^2$	6
$\mathcal{O}_{\mathrm{C4}}$	$\phi^* i\overleftrightarrow{\partial_\mu}\phi\bar{q}\gamma^\mu\gamma_5 q$	$1/M_*^2$	6
$\mathcal{O}_{\mathrm{C5}}$	$\phi^*\phi G_{\mu\nu}G^{\mu\nu}$	$\alpha_S/4M_*^2$	6
$\mathcal{O}_{\mathrm{C6}}$	$\phi^*\phi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_S/4M_*^2$	6

Table 3: Operators for Complex Scalar DM.

Lowest Dimensional Operators



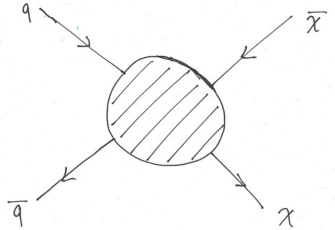
Label	Operator	Usual coefficient	Dimension
$\mathcal{O}_{\mathrm{R1}}$	$\phi^2\bar{q}q$	$m_q/2M_*^2$	5
$\mathcal{O}_{\mathrm{R2}}$	$\phi^2\bar{q}i\gamma_5 q$	$m_q/2M_*^2$	5
$\mathcal{O}_{\mathrm{R3}}$	$\phi^2 G_{\mu\nu}G^{\mu\nu}$	$\alpha_S/8M_*^2$	6
$\mathcal{O}_{\mathrm{R4}}$	$\phi^2 G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_S/8M_*^2$	6

Table 4: Operators for Real Scalar DM.

Let's keep things easy

- Assuming fermionic DM and only vector-like DM-quark interactions

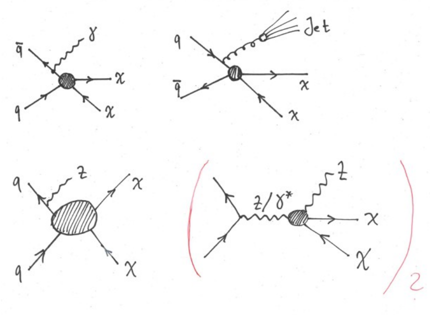
$$\Rightarrow \mathcal{O}_5 = \frac{1}{M_*}\left(\overline{\chi}\gamma_\mu\chi\right)\left(\overline{q}\gamma^\mu q\right)$$



- Pro: Only two open parameters: m_χ, M_*

Mono-X Searches

- Looking for events with high missing tranverse energy (DM-particles are lost in the detection)
- Mono-X events have one particle/jet with high transverse momentum "*without*" anything to *recoil* against



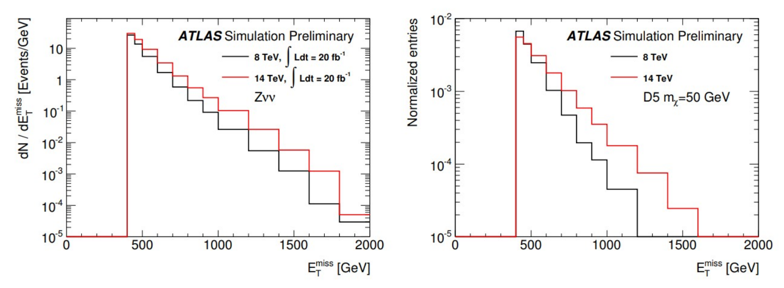
- irreducible background

$$\bar{q}q \rightarrow Z \rightarrow \bar{\nu}\nu$$

Atlas Note-2014

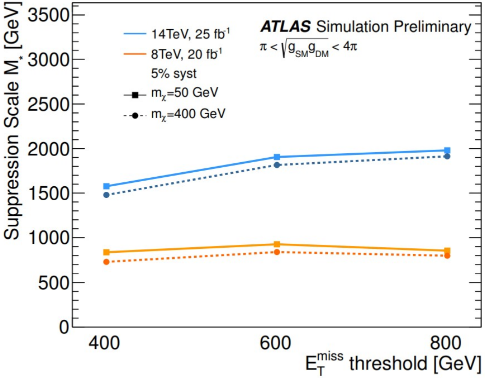
Sensitivity to WIMP Dark Matter in the Final States Containing Jets and Missing Transverse Momentum

- Atlas mono-jet search to pair production of WIMP DM
- $\sqrt{s} = 14\mathrm{TeV}$
- Sensitivity projection
- Monte Carlo of the background (left) and signal (right):



Sensitivity of the Atlas Analysis

- 95% CL lower limit on the suppression scale M_*
- Assumed 5% systematic unvertainty on the SM background
- EFT approach is assumed to be valid



Validity of the EFT

What is the range of validity of the effective theory?

- The suppression scale M_* can be *mapped* to the ”UV” theory with a mediator of a mass M_{med} and two couplings g_{SM}, g_χ describing the coupling of the mediator to DM and SM

$$\frac{g_{SM} g_\chi}{Q^2 - {M_{med}}^2} = -\frac{g_{SM} g_\chi}{{M_{med}}^2} \left(1 + \frac{Q^2}{{M_{med}}^2} + \mathcal{O}\left(\frac{Q^4}{{M_{med}}^4} \right) \right) \approx -\frac{1}{M_*^2}$$

$$\Rightarrow M_* \sim M_{med} / \sqrt{g_{SM} g_\chi}$$

- Pair-annihilation requires

$$M_{med} > 2 m_\chi$$

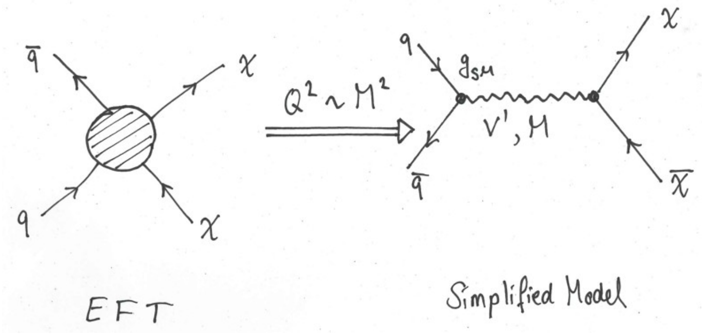
- Perturbativity requires

$$g_{SM} g_\chi \lesssim (4\pi)^2$$

- Validity for

$$m_\chi \lesssim 2\pi M_* \qquad \text{and} \qquad Q^2 \ll M_{med}$$

Bottom-Up Approach - Simplified Model



Simplified Models

- Extend the SM with additional minimal field content
  - DM: majorana/dirac fermions, real/complex scalars
  - Mediator: Scalar, Pseudoscalar, Vector ...
- Write down your favorit effective Lagrangian (renormalizable!)
  - 0s0 model: Mediator spin → 0 ; DM spin → 0

$$\mathcal{L}_{0s0} = \underbrace{\frac{1}{2}(\partial_\mu \phi)^2 - \frac{1}{2} m_\phi^2 \phi^2}_{Kinetic\ terms} - \underbrace{\frac{\lambda_\phi}{4} \phi^2 H^\dagger H}_{Higgs\ portal}$$

  - 0s1/2 model: Mediator spin → 0 ; DM spin → 1/2

$$\mathcal{L}_{0_S s_{\frac{1}{2}}} = \frac{1}{2}(\partial_\mu S)^2 - \frac{m_S^2}{2} S^2 + \overline{\chi}(i\partial\!\!\!/ - m_\chi)\chi - g_\chi S \overline{\chi}\chi - g_{SM} S \sum_f \frac{y_f}{\sqrt{2}} \bar{f} f$$

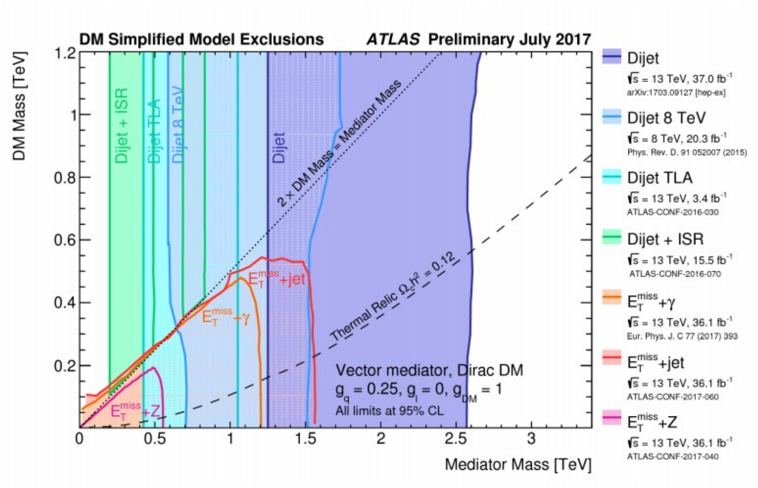
  - Vector Mediator: Mediator spin → 1; DM spin → $1/2$

$$\mathcal{L}_{vec} \supset \frac{1}{2} M_{med}^2 V_\mu V^\mu - g_{DM} V_\mu \overline{\chi}\gamma^\mu \chi - \sum_q g_{SM}^q V_\mu \bar{q}\gamma^\mu q$$

- Start calculating...

Simplified Model Results

V1



Conclusion

- DM collider searches are *challenging* (small fluxes, small production rates,...)
- Two general approaches for model building/searches
  - Top-down
    - \+ Particle Content is *known*
    - +/- Direct limits on model parameters
    - \- Each model needs a detailed and involved analysis
  - Bottom up
    - \+ *Model-independent* searches **and** limits!
    - \- Huge amount of free parameters in the EFT operators (most of the time only a subset of operators)
    - \+ Simplified models can handle single problems without (*unnecessary*) huge amount of workload
    - \- At the most shows only the direction; not the end of the story!

Thank you for your attention!

Conclusion

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Thank you for your attention!

Ref.

- Title Picture
  `https://www.symmetrymagazine.org/article/december-2013/four-things-you-might-not-know-about-dark-matter`
- SUSY searches:
  - ArXiv: hep-ex/9809031 (OPAL search)
  - ArXiv:1709.05406v2 (LEP search)
- Simplified/EFT:
  - ArXiv: 1603.08002v2
  - ATL-PHYS-PUB-2014-007