

### **DM Collider Searches**

Introduction

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# Outline





Motivation/Expectation

### 2 Approaches





Motivation/Expectation

Approaches

Top-Down

Bottom-Up

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### 2 Approaches





Motivation/Expectation

Approaches

Top-Down



- 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

Approaches



### What can we expect?

Suppose we have

• 
$$\dot{\mathcal{L}} = 5 \cdot 10^{33} cm^{-2} s^{-1}$$

- $m_{\chi} = 100 \text{ GeV}$  and  $\sigma_{LHC} = G_F^2 m_{\chi}^2$
- Isotropic production in an distante R = 10cm
- $\rho_{DM} = 0.3 \text{ GeV}/cm^3$  and  $v_{DM} = 220 km/s$

$$egin{aligned} \Phi_{LHC} &= 4\pi R^2 \dot{\mathcal{L}} \sigma_{LHC} \sim 10^4 \textit{cm}^2/\textit{s} \ \Phi_{halo} &= rac{
ho_{DM}}{m_\chi} \pi R^2 v_{DM} \sim 10^9 \textit{cm}^2/\textit{s} \end{aligned}$$

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

| Motivation/Expectation |
|------------------------|
|------------------------|

Approaches

Top-Down

Bottom-Up









Motivation/Expectation

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### **General Approaches**



### **Extend the Standard Model**

- top-down approach
- bottom-up approach



## top-down Approach





Motivation/Expectation

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## bottom-up Approach - EFT





### bottom-up Approach - Simplified Models







### 2 Approaches





Motivation/Expectation

Approaches

Top-Down

## **Top-Down Approach - SUSY**





Approaches

# **Top-Down Approach - SUSY**



# SUPERSYMMETRY



Motivation/Expectation

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### 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 ΔΓ<sub>inv</sub>

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

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

| ĸ | Acti | wati | ioni | EV | noot | nti | on  |
|---|------|------|------|----|------|-----|-----|
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Bottom-Up 13/37 **LEP-Results** 



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



Motivation/Expectation

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# **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 ∉<sub>T</sub>
  - Mono-X signatures
- The art of the parameter cuts
  - Boosted Decision Trees (BDTs)
  - Deep Learning (DL)

### **Example Search Process**





Approaches

# BDT/DL





Approaches

Top-Down

Bottom-Up

### What is used to select events?



- Event Topologies (0-jet,1-jet,...)
- *p<sub>T</sub>* cuts
- Invariant mass distributions





Motivation/Expectation

# **BDT/DL**





# Exclusion Limits for lightest neutralino and slepton masses







## **Exclusion Summary-ATLAS**



ATLAS Preliminary

 $\sqrt{s} = 13 \text{ TeV}$ B-4----

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

| Ма |     | 20    | 19   |
|----|-----|-------|------|
|    |     | lo di |      |
|    | - M | od    | - I. |

|               | Model  | Signature  | ∫£ di [ſb'                                      | 1 Mass limit   |   | Reference   |
|---------------|--|--|---|--|---|---|
|               | $\tilde{q}\tilde{q}, \tilde{q} \rightarrow q \tilde{t}_{1}^{D}$  | 0 e. µ 2-6 jets P<br>mono-jet 1-3 jets P                                 | 57 <sup>tm</sup> 36.1                           |  | 0.9 1.55 m(t <sup>2</sup> )<100 GeV<br>0.71 mijm(t <sup>2</sup> )=5 GeV   | 1712.02332<br>1711.03301                          |
| archei        | $\tilde{g}\tilde{g},\;\tilde{g}{\rightarrow} q \tilde{g} \tilde{f}^0_1$  | 0 e, µ 2-6 jets I  | 57 36.1   | 2  | 2.0 m(t <sup>2</sup> )<200 GeV<br>Forbidden 0.95-1.6 m(t <sup>2</sup> )=500 GeV   | 1712.02332<br>1712.02332                          |
| ie Sei        | $\tilde{g}\tilde{g}, \tilde{g} \rightarrow q \tilde{g}(\ell \ell) \tilde{k}_{1}^{0}$   | 3 e.μ 4 jets<br>ee.μμ 2 jets į   | 36.1<br>7 35.1                                  | 8  | 1.85 m(ℓ <sub>1</sub> <sup>2</sup> )<500 GeV<br>1.2 m(ℓ)m(ℓ <sub>1</sub> <sup>2</sup> )=50 GeV  | 1706.03731<br>1805.11381                          |
| octural       | $\tilde{g}\tilde{g}, \tilde{g} \rightarrow qqWZ\tilde{t}_{1}^{0}$  | 0 ε,μ 7-11 jets <u>/</u><br>3 ε,μ 4 jets                                 | 57 36.1<br>36.1                                 | 2  | 1.8 m(t_1) <400 GeV<br>0.96 m(t_1)-200 GeV  | 1708.02794<br>1706.03731                          |
| -             | $gg, g \rightarrow n \overline{t}_1^0$   | 0-1 <i>e.μ</i> 3 <i>b</i> I<br>3 <i>e.μ</i> 4jets                        | 27 79.8<br>7 36.1                               | 2<br>2   | 2.25 m(t_1)+200 GeV<br>1.25 m(t_1)+300 GeV  | ATLAS-CONF-2018-041<br>1706.00731                 |
|               | $\tilde{b}_1 \tilde{b}_1, \tilde{b}_1 \rightarrow 6 \tilde{\xi}_1^0 / t \tilde{\xi}_1^\pm$   | Multiple<br>Multiple<br>Multiple   | 36.1<br>36.1<br>35.1                            | δ <sub>1</sub> Forbidden<br>δ <sub>1</sub> Forbidden<br>δ <sub>1</sub> Forbidden       | 0.9 m(t <sup>2</sup> )-300 GeV, BR(1k <sup>2</sup> )-1<br>0.58-0.82 m(t <sup>2</sup> )-300 GeV, BR(1k <sup>2</sup> )-1<br>0.7 m(t <sup>2</sup> )-300 GeV, BR(1k <sup>2</sup> )-1  | 1708.09266.1711.03301<br>1708.06266<br>1706.03731 |
| arks          | $b_1b_1, b_1 \rightarrow b\ell_2^0 \rightarrow bb\ell_1^0$   | 0 e, µ 6 b E   | 57 <sup>min</sup> 139                           | δ <sub>1</sub> Forbidden<br>δ <sub>1</sub> 0.23-0.44                                   | 0.23-1.35 Δm(t <sup>2</sup> <sub>1</sub> , t <sup>2</sup> <sub>1</sub> )=130 GeV, m(t <sup>2</sup> <sub>1</sub> )=100 GeV<br>Δm(t <sup>2</sup> <sub>2</sub> , t <sup>2</sup> <sub>1</sub> )=130 GeV, m(t <sup>2</sup> <sub>1</sub> )=10 GeV | SUSY2018-31<br>SUSY2018-31                        |
| pp of         | $\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow Wh\tilde{t}_1^0$ or $t\tilde{t}_1^0$  | 0-2 e, µ 0-2 jets/1-2 b I  | 97 36.1   | T <sub>1</sub>   | 1.0 m(t <sup>0</sup> <sub>1</sub> )=1 GeV   | 1505.08616, 1709.04183, 1711.11520                |
| d b           | i <sub>1</sub> i <sub>1</sub> , Well-Tempered LSP     i <sub>1</sub> i <sub>1</sub> , i <sub>1</sub> → i <sub>1</sub> i <sub>2</sub> i <sub>2</sub> → i <sup>2</sup> i <sub>1</sub> → i <sub>1</sub> i <sub>2</sub> → i <sub>2</sub> i <sub>2</sub> → i <sup>2</sup> i <sub>1</sub> → i <sub>2</sub> i <sub>2</sub> → i <sub>2</sub> → i <sub>2</sub> i <sub>2</sub> → i <sub>2</sub> i <sub>2</sub> → i <sub>2</sub> → i <sub>2</sub> → i <sub>2</sub> i <sub>2</sub> → i <sub>2</sub> i <sub>2</sub> → i <sub>2</sub> → i <sub>2</sub> i <sub>2</sub> i <sub>1</sub> i <sub>2</sub> i | Multiple   | 35.1<br>cmin 35.4                               | 7,<br>2.   | 0.48-0.84 m(l <sup>2</sup> )=150GeV, m(l <sup>2</sup> )=15 GeV, i <sub>1</sub> = i <sub>1</sub>   | 1709.04183, 1711.11520                            |
| 3.r           | $\tilde{i}_1\tilde{i}_1, \tilde{i}_1 \rightarrow c\tilde{k}_1^D / \tilde{i}\tilde{i}_1, \tilde{i} \rightarrow c\tilde{k}_1^D$  | 0 e, µ 2 c I   | 77 00.1   | 2  | 0.85 m(i)=0.6eV   | 1805.01649  |
|               |  | 0 c.v. mono-iet /  |   | ζ <sub>1</sub> 0.46<br>ζ. 0.43   | m(i, i) m(i <sup>2</sup> )=50 GeV   | 1805.01649  |
|               | $\tilde{t}_2\tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + h$  | 1-2 e.µ 4.b I  | 57 <sup>to</sup> 36.1                           | h  | 0.32-0.85 m(( <sup>2</sup> ))=0 GeV. m( <sup>2</sup> ))=180 GeV   | 1706.03886  |
|               | $\hat{x}_1^* \hat{x}_2^0$ via WZ   | $2 \cdot 3 \epsilon, \mu$ $I$<br>$\epsilon \epsilon, \rho \mu \ge 1$ $I$ | 96.1<br>7 36.1                                  | $\frac{\hat{x}_{1}^{b}\hat{x}_{2}^{b}}{\hat{x}_{1}^{b}\hat{x}_{2}^{b}} = 0.17$         | 0.6 m(t <sup>2</sup> )=0 m(t <sup>2</sup> )=10 GeV  | 1403.5294, 1806.02293<br>1712.08119               |
|               | $\hat{\chi}_1^{\pm}\hat{\chi}_1^{\mp}$ via WW  | 2 e, µ 1   | 57 <sup>mint</sup> 139                          | x <sup>*</sup> <sub>1</sub> 0.42   | $m(\hat{v}_1^0) = 0$  | ATLAS-CONF-2019-008                               |
|               | $\hat{x}_1^* \hat{x}_2^0$ via Wh   | 0-1 e, µ 2 b l   | 7 36.1  | $\ddot{x}_{1}^{a} \beta \ddot{x}_{2}^{b}$  | 0.68 m(t <sup>*</sup> <sub>1</sub> )=0  | 1812.09432  |
| ≥ to          | $\chi_1^+\chi_1^- \operatorname{via} \ell_L/p$<br>$\chi_2^+\chi_1^- \chi_2^0  \chi^+  \text{and } \chi_1^0  \text{and } \chi_2^0$  | 21, μ 1  | (mko 36.1                                       | X1<br>01/09  | 1.0 m(/,i)=0.5(m(f_1)=m(f_1))<br>0.75 m(f_1)=0.5(m(f_1)=m(f_1))   | ATLAS CONF 2019 008<br>1709 07975                 |
| 5             | $x_1x_1/x_2, x_1 \rightarrow \tau_1v(\tau v), x_2 \rightarrow \tau_1\tau(vv)$  | 21   | -7 30.1   | x1/x2<br>x1/x2<br>0.22   | $m(\tilde{t}_1)m(\tilde{t}_1)m(\tilde{t}_1)m(\tilde{t}_1)m(\tilde{t}_1)m(\tilde{t}_1)m(\tilde{t}_1)$<br>$m(\tilde{t}_1)m(\tilde{t}_1)m(\tilde{t}_1)m(\tilde{t}_1)m(\tilde{t}_1)m(\tilde{t}_1)m(\tilde{t}_1)$                                | 1708.07070  |
|               | $\tilde{t}_{1,R}\tilde{t}_{1,R}, \tilde{t} \rightarrow \ell \tilde{t}_1^0$   | 2 e,μ 0 jets I<br>2 e,μ ≥ 1 I  | 139<br>57 36.1                                  | 7<br>7 0.18  | 0.7 m( $\tilde{t}^{+}_{1} =0$<br>m( $\tilde{t})$ -m( $\tilde{t}^{+}_{1} =5$ GeV   | ATLAS-CONF-2019-008<br>1712.08119                 |
|               | $\bar{H}\bar{H}, \bar{H} \rightarrow h\bar{G}/Z\bar{G}$  | $0 e, \mu \ge 3 b$ $I$<br>$4 e, \mu$ $0$ jets $I$                        | 57 <sup>4m</sup> 36.1<br>57 <sup>44m</sup> 36.1 | B 0.13-0.23<br>B 0.3   | 0.29-0.85 $BR(\tilde{t}_{1}^{0} \rightarrow k\tilde{G})=1$<br>$BR(\tilde{t}_{1}^{0} \rightarrow Z\tilde{G})=1$  | 1806.04030<br>1804.09802                          |
| lived         | $\operatorname{Direct} \hat{x}_1^* \hat{x}_1^- \operatorname{prod.}, \operatorname{long-lived} \hat{x}_1^+$  | Disapp. trk 1 jet /  | 57 <sup>min</sup> 36.1                          | x <sup>1</sup><br>x <sup>1</sup> <sub>1</sub> 0.15                                     | Pure Wito<br>Pure Higgsino  | 1712.02118<br>ATL-PHYS-PUB-2017-019               |
| pit           | Stable ¿ R-hadron  | Multiple   | 36.1  | 8  | 2.0   | 1902.01636,1808.04095                             |
| 20            | Metastable $\tilde{g}$ R-hadron, $\tilde{g} \rightarrow qq \tilde{\chi}_1^0$   | Muttiple   | 36.1  | g [r(g) =10 ms, 0.2 ms]  | 2.05 2.4 m(f_1)=103 GeV   | 1710.04901,1508.04095                             |
|               | LFV $pp \rightarrow \tilde{v}_{\tau} + X, \tilde{v}_{\tau} \rightarrow e\mu/e\tau/\mu\tau$   | ep,et,ot   | 3.2   | 5,   | 1.9 J <sub>11</sub> =0.11, J <sub>123330300</sub> =0.07   | 1607.08079  |
|               | $\hat{\chi}_{1}^{\pm}\hat{\chi}_{1}^{\mp}/\hat{\chi}_{2}^{0} \rightarrow WW/ZUUUrv$  | 4 e,μ 0 jets I   | Synton 36.1                                     | $\hat{\chi}_{1}^{*}[\hat{\chi}_{2}^{0} = [\lambda_{33} \neq 0, \lambda_{13} \neq 0]$   | 0.62 1.33 m(t <sup>2</sup> )=100 GeV  | 1604.00902  |
|               | $\tilde{g}\tilde{g}, \tilde{g} \rightarrow qg\tilde{\eta}_{1}^{0}, \tilde{\chi}_{1}^{0} \rightarrow qgq$   | 4-5 large- <i>R</i> jets   | 36.1  | 2 [m(£]]=200 GeV, 1100 GeV]  | 1.3 1.9 Large J <sub>112</sub>  | 1804.00568  |
| J.C.          | W Y  | Multiple   | 30.1  | 3 U" -2nd to 21  | 1.0 H(r)-200 Get, 505 He  | AT AS CONF 2018-003                               |
| -             | $n, r \rightarrow m_1, x_1 \rightarrow m_2$<br>$\tilde{h}\tilde{h}_1, \tilde{h}_1 \rightarrow b_2$   | 2 jets + 2 b   | 36.7  | h [es. b) 0.42   | 0.61  | 1710.07171  |
|               | $\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow q t$   | 2 ε.μ 2 b<br>1 μ DV  | 36.1<br>136                                     | $\vec{t}_1 = [10\cdot10< \vec{x}_{20} < 10\cdot0, 30\cdot10< \vec{x}_{20} < 30\cdot0]$ | 0.4+1.45         BR[i <sub>1</sub> →b <sub>7</sub> /h <sub>0</sub> )>29%           1.0         1.6         BR[i <sub>1</sub> →b <sub>7</sub> /h <sub>0</sub> )>20%  | 1710.06544<br>ATLAS CONF-2019-006                 |
|               |  |  |   |  |   |   |
| *Only<br>pher | a selection of the available mas<br>omena is shown. Many of the li   | s limits on new states o<br>mits are based on                            | or 1  | 0-1  | 1 Mass scale [TeV]  |   |

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# **Exclusion Summary-ATLAS**



| A<br>M        | TLAS SUSY Sear<br>arch 2019<br>Model   | rches*                  | - 95%<br>Signatur                        | 6 Cl                             | _ Lo <sup>*</sup><br> | wer Limits  | lass limit                  |                         |                        |   | ATLAS Preliminary<br>$\sqrt{s} = 13 \text{ TeV}$<br>Reference              |
|---------------|--|-------------------------|--|----------------------------------|-----------------------|---|-----------------------------|-------------------------|------------------------|---|--|
| 10            | $\hat{q}\hat{q}, \hat{q} \rightarrow q \hat{t}_{1}^{0}$  | 0 e, μ<br>mono-jet      | 2-6 jets<br>1-3 jets                     | $E_T^{min}$<br>$E_T^{min}$       | 36.1<br>36.1          | ₽ [2x, 6x Degen.]<br>₽ [1x, 6x Degen.]  | 0.43                        | 0.9                     | 1.55                   | $\begin{array}{c} m(\tilde{x}_{\perp}^0){<}100~GeV\\ m(\tilde{x}_{\perp}^0){=}5~GeV \end{array}$  | 1712.02332<br>1711.03301   |
| arche         | $\tilde{g}\tilde{g}, \tilde{g} \rightarrow q \tilde{q} \tilde{t}_1^0$  | $0 \ e, \mu$            | 2-6 jets                                 | $E_T^{\min}$                     | 36.1                  | R<br>R  |                             | Forbidden               | 2.0<br>0.95-1.6        | m( $\tilde{k}_{1}^{0}$ )<200 GeV<br>m( $\tilde{k}_{1}^{0}$ )=900 GeV  | 1712.02332<br>1712.02332   |
| e Se          | $\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}(\ell\ell)\tilde{k}_{1}^{0}$  | 3 e, μ<br>ee, μμ        | 4 jets<br>2 jets                         | $E_T^{miso}$                     | 36.1<br>36.1          | 2<br>2  |                             |                         | 1.85                   | m(ℓ <sup>0</sup> <sub>1</sub> )<800 GeV<br>m(ℓ)-m(ℓ <sup>0</sup> <sub>1</sub> )=50 GeV  | 1706.03731<br>1805.11381   |
| clush         | $gg, g {\rightarrow} qq WZ \tilde{t}_1^0$  | 0 e.µ<br>3 e.µ          | 7-11 jots<br>4 jets                      | $E_T^{miss}$                     | 36.1<br>36.1          | it<br>it  |                             | 0.98                    | 1.0                    | m( $\tilde{t}_1^0$ ) <400 GeV<br>m( $\tilde{t}$ )=200 GeV   | 1708.02794<br>1706.03731   |
| ų.            | $\hat{g}\hat{g}, \hat{g} {\rightarrow} a \hat{t} \hat{t}_1^0$  | 0-1 e.μ<br>3 e.μ        | 3 b<br>4 jets                            | $E_7^{\rm miss}$                 | 79.8<br>36.1          | 2<br>2  |                             |                         | 1.25                   | 25 m( $\hat{r}_1^0$ )<200 GeV<br>m( $\hat{r}_1^0$ )=300 GeV   | ATLAS-CONF-2018-041<br>1706.03731  |
|               | $b_1b_1, b_1{\rightarrow} \delta \ell_1^0/\iota \ell_1^+$  |                         | Multiple<br>Multiple<br>Multiple         |                                  | 36.1<br>36.1<br>36.1  | kı Forbidde<br>kı<br>kı   | n<br>Forbidden<br>Forbidden | 0.9<br>0.58-0.82<br>0.7 | m)                     | $\begin{split} m(\tilde{t}^0_1) {=} 300 \ GeV, \ BR(k\tilde{t}^0_1) {=} 1 \\ m(\tilde{t}^0_1) {=} 300 \ GeV, \ BR(k\tilde{t}^0_1) {=} BR(\tilde{t}^0_1) {=} 0.5 \\ \tilde{t}^0_1) {=} 200 \ GeV, \ m(\tilde{t}^0_1) {=} 300 \ GeV, \ BR(\tilde{t}^0_1) {=} 1 \end{split}$ | 1766.09266, 1711.03301<br>1738.09266<br>1736.03731                         |
| unks          | $b_1 \bar{b}_1, \bar{b}_1 \rightarrow b \bar{\ell}_2^0 \rightarrow b b \bar{\ell}_1^0$   | $0 \ e, \mu$            | 6 6                                      | $E_T^{miss}$                     | 139                   | h Forbidden   | 0.23-0.48                   | 0                       | .23-1.35               | $\Delta m(\tilde{t}_{2}^{0}, \tilde{t}_{1}^{0}) = 130 \text{ GeV}, m(\tilde{t}_{1}^{0}) = 100 \text{ GeV}$<br>$\Delta m(\tilde{t}_{2}^{0}, \tilde{t}_{1}^{0}) = 130 \text{ GeV}, m(\tilde{t}_{1}^{0}) = 0 \text{ GeV}$  | SUSV2018-31<br>SUSV2018-31   |
| gen. sq.      | $\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow Wb \tilde{t}_1^0 \text{ or } s \tilde{t}_1^0$<br>$\tilde{t}_1 \tilde{t}_1, \text{ Well-Tempered LSP}$<br>$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow \tilde{t}_1 bv, \tilde{t}_1 \rightarrow \tau \tilde{G}$ | 0-2 e.μ<br>1 r + 1 e.μ. | 0-2 jets/1-2<br>Multiple<br>r 2 jets/1 6 | $b E_T^{min}$<br>$E_T^{min}$     | 36.1<br>36.1<br>36.1  | h<br>h<br>h   |                             | 0.48-0.84               | m)                     | $m(\tilde{t}_{1}^{0})=1 \text{ GeV}, m(\tilde{t}_{1}^{0})=m(\tilde{t}_{1}^{0})=5 \text{ GeV}, \tilde{t}_{1} \approx \tilde{t}_{2}$<br>$m(\tilde{t}_{1})=800 \text{ GeV}.$   | 1506.06616, 1709.04183, 1711.11520<br>1709.04183, 1711.11520<br>1803.10178 |
| 9.9           | $\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow e \tilde{k}_1^0 / \bar{e} \tilde{e}, \tilde{e} \rightarrow e \tilde{k}_1^0$  | 0 e.μ<br>0 e.μ          | 2 c<br>mono-jet                          | $E_7^{min}$<br>$E_7^{min}$       | 36.1<br>36.1          | ž<br>Ž <sub>1</sub><br>Ž <sub>1</sub>   | 0.46<br>0.43                | 0.85                    |                        | $m(\tilde{t}_{1}^{0})=0 \text{ GeV}$<br>$m(\tilde{t}_{1}, 2) \cdot m(\tilde{t}_{1}^{0})=50 \text{ GeV}$<br>$m(\tilde{t}_{1}, 2) \cdot m(\tilde{t}_{1}^{0})=5 \text{ GeV}$   | 1805.01649<br>1805.01649<br>1711.03301                                     |
|               | $\tilde{t}_2 \tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + h$   | $1\text{-}2~e,\mu$      | 4 b                                      | $E_T^{\rm miss}$                 | 36.1                  | l2  |                             | 0.32-0.88               |                        | $m(\hat{t}_1^0)=0$ GeV, $m(\hat{t}_1)-m(\hat{t}_1^0)=190$ GeV   | 1706.03986   |
|               | $\hat{\chi}_1^\pm \hat{\chi}_2^0$ via WZ   | 2-3 e, µ<br>ee, µµ      | 21                                       | $E_T^{min}$<br>$E_T^{min}$       | 36.1<br>36.1          | $\hat{\chi}_{1}^{+}/\hat{\chi}_{1}^{+}$<br>$\hat{\chi}_{1}^{+}/\hat{\chi}_{1}^{+}$ 0.17   |                             | 0.6                     |                        | m(t <sup>2</sup> )=0<br>m(t <sup>2</sup> )=n(t <sup>2</sup> )=10 GeV  | 1403.5294, 1806.02293<br>1712.05119  |
|               | $\hat{x}_1^*\hat{x}_1^*$ via WW  | $2 e, \mu$              |  | $E_T^{min}$                      | 139                   | $\hat{X}_{1}^{k}$   | 0.42                        |                         |                        | m(t <sup>2</sup> )=0  | ATLAS-CONF-2019-008  |
|               | X1X2 via Wh  | 0-1 e.µ                 | 2.6                                      | Erria                            | 36.1                  | $\hat{\chi}_{1}^{*} \hat{\chi}_{1}^{*}$   |                             | 0.68                    |                        | n(î';)+0  | 1812.09432   |
| EW            | $\begin{array}{l} \hat{x}_1 \hat{x}_1 \ \text{via} \ \hat{t}_2 / \nu \\ \hat{x}_1^* \hat{x}_1^\top / \hat{x}_2^0 , \hat{x}_1^+ {\rightarrow} \hat{\tau}_1 \nu (r \hat{v}), \hat{x}_2^0 {\rightarrow} \hat{\tau}_1 r (\nu \hat{v}) \end{array}$                       | 27                      |  | $E_7^{min}$                      | 36.1                  | $\frac{\dot{x}_{1}}{\dot{x}_{1}^{*}/\dot{x}_{1}^{*}}$<br>$\frac{\dot{x}_{1}^{*}/\dot{x}_{1}^{*}}{\dot{x}_{1}^{*}/\dot{x}_{1}^{*}}$ 0.22 |                             | 0.76                    | m(t <sup>*</sup> _1)-n | $m(t, r)=0.5[m(t_1)+m(t_1)]$<br>$m(\tilde{t}_1^0)=0, m(t, r)=0.5[m(\tilde{t}_1^0)+m(\tilde{t}_1^0)]$<br>$n(\tilde{t}_1^0)=100$ GeV, $m(t, r)=0.5[m(\tilde{t}_1^0)+m(\tilde{t}_1^0)]$  | 1708.07875<br>1708.07875   |
|               | $\tilde{\ell}_{L,R}\tilde{\ell}_{L,R},\tilde{\ell}{\rightarrow}\ell\tilde{\chi}_1^0$   | 2 e, µ<br>2 e, µ        | 0 jets<br>≥ 1                            | $E_T^{miss}$<br>$E_T^{miss}$     | 139<br>36.1           | 7<br>7 0.18   |                             | 0.7                     |                        | m(ž <sup>0</sup> )=0<br>m(ž)-m(ž <sup>0</sup> )=5 GeV   | ATLAS-CONF-2019-008<br>1712.08119  |
|               | ĤĤ, Ĥ→hĜ/ZĜ  | 0 e, μ<br>4 e, μ        | ≥ 3 b<br>0 jets                          | $E_T^{\rm min} \\ E_T^{\rm min}$ | 36.1<br>36.1          | H 0.13-0.23<br>H 0.   | 3                           | 0.29-0.88               |                        | $BR(\hat{t}_1^0 \rightarrow hG) = 1$<br>$BR(\hat{t}_1^0 \rightarrow ZG) = 1$  | 1806.04030<br>1804.03602   |
| lived<br>cles | $\operatorname{Direct} \widehat{x}_1^* \widehat{x}_1^- \operatorname{prod}_{\sim} \operatorname{long-lived} \widehat{x}_1^+$   | Disapp. trk             | i 1 jet                                  | $E_T^{miss}$                     | 36.1                  | $\frac{\hat{k}^{4}}{\hat{k}_{1}^{4}} = 0.15$  | 0.46                        |                         |                        | Pure Wino<br>Pure Higgsino  | 1712.02118<br>ATL-PHYS-PUB-2017-019  |
| Long-         | Stable ∦ R-hadron<br>Metastable # R-hadron, #→wa <sup>0</sup>  |                         | Multiple<br>Multiple                     |                                  | 38.1<br>38.1          | ≩<br>≩ [r(ĝ) =10 ns, 0.2 ns]  |                             |                         | 2.0                    | 2.4 m(v_1)=100 GeV  | 1902.01638.1808.04095<br>1710.04901.1808.04095                             |
|               | LEV $pp \rightarrow P_{a} + X, P_{a} \rightarrow eu/et/ut$   | ener ar                 |  |                                  | 3.2                   | B.  |                             |                         | 1.9                    | X., +0.11, Augustum=0.07  | 1607.08079   |
|               | $\hat{\chi}_1^{\pm} \hat{\chi}_1^{\pm} / \hat{\chi}_2^0 \rightarrow WW/Z\ell\ell\ell\ell \nu\nu$   | 4 e. µ                  | 0 jets                                   | $E_T^{min}$                      | 36.1                  | $\hat{X}_{1}^{\pm}/\hat{X}_{2}^{\pm} = [\hat{X}_{00} \neq 0, \hat{X}_{121} \neq 0]$   |                             | 0.82                    | 1.33                   | m(\$ <sup>0</sup> )=100 GeV   | 1804.03602   |
| ~             | $\tilde{g}\tilde{g}, \tilde{g} \rightarrow qq\tilde{q}_{1}^{0}, \tilde{\chi}_{1}^{0} \rightarrow qqq$  |                         | 4-5 large-R ja                           | ets                              | 36.1                  | E [m(X <sup>0</sup> )=200 GeV, 1100 GeV]     E [X <sup>0</sup> = 2e,4, 2e,5]  |                             |                         | 1.3 1.9                | Large A <sup>*</sup> <sub>112</sub>   | 1004.03568   |
| de            |  |                         | Multiple                                 |                                  | 30.1                  | B (F =20.4 to.2)  |                             | 1.0                     | 2.0                    | m(r) (=200 GeV, bino-like   | AT AS COMP 2018-003  |
| -             | $\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow bx$  |                         | 2 jots + 2 /                             |                                  | 36.7                  | 71 [qq. bx]   | 0.42                        | 0.61                    |                        | ways 11/4/2010 CaleV, Disch-deal  | 1710.07171   |
|               | $\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow q\ell$  | 2 e,μ<br>1 μ            | 2 b<br>DV                                |                                  | 38.1<br>136           | $\vec{t}_1 = \vec{t}_1 = [1e-10 < d_{100}^2 < 1e-8, 3e-10 < d_{100}^2]$   | 24 <30-9]                   | 1.0                     | 0.4-1.45<br>1.6        | $\begin{array}{c} {\sf BR}(\hat{r}_{1} {\rightarrow} b_{\ell}/\hat{r}_{3} {\rm d}) {\rm >} 20\% \\ {\sf BR}(\hat{r}_{1} {\rightarrow} {\rm sgr}) {=} 100\%, \ {\rm cos} {\rm d} {\rm =} 1 \end{array}$  | 1710.05544<br>ATLAS-CONF-2019-006  |
|               |  |                         |  |                                  |                       |   |                             |                         |                        |   |  |
| Calu          |  |                         | new state                                |                                  |                       | 0-1   |                             |                         | 1                      | Mass scale [TeV]  |  |

Motivation/Expectation

Approaches

Top-Down



### 2 Approaches





Motivation/Expectation

Approaches

Top-Down

Bottom-Up

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### **Bottom-Up Approach - EFT**





### **General Idea**



• We want to extend the SM with minimal additional assumptions:

- Additional fundamental DM particles  $\rightarrow$  fermionic/scalar
- $\mathbb{Z}_2$  symmetry to ensure stability of the DM candidate
- DM interaction with the SM particles (e.g. with quarks)

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

$$\mathcal{L}_{int.} = \sum_{i} C_{i} \mathcal{O}_{i}$$

Approaches

Top-Down

Bottom-Up

# **Lowest Dimensional Operators**



| Label                   | Operator   | Usual coefficient  | Dimension |
|-------------------------|--|--------------------|-----------|
| 0 <sub>M1</sub>         | ΧXq̄q  | $m_q/2M_*^3$       | 6         |
| 0 <sub>M2</sub>         | $\bar{\chi}i\gamma_5\chi\bar{q}q$                                | $m_q/2M_*^3$       | 6         |
| $\mathcal{O}_{M3}$      | $\bar{\chi}\chi\bar{q}i\gamma_5q$                                | $m_q/2M_*^3$       | 6         |
| $\mathcal{O}_{M4}$      | $\bar{\chi}i\gamma_5\chi\bar{q}i\gamma_5q$                       | $m_q/2M_*^3$       | 6         |
| $\mathcal{O}_{M5}$      | $\bar{\chi}\gamma^{\mu}\gamma_{5}\chi\bar{q}\gamma_{\mu}q$       | $1/2M_{*}^{2}$     | 6         |
| $\mathcal{O}_{M6}$      | $\bar{\chi}\gamma^{\mu}\gamma_5\chi\bar{q}\gamma_{\mu}\gamma_5q$ | $1/2M_{*}^{2}$     | 6         |
| 0 <sub>M7</sub>         | $ar{\chi}\chi G_{\mu u}G^{\mu u}$                                | $\alpha_S/8M_*^3$  | 7         |
| 0 <sub>M8</sub>         | $ar{\chi}\gamma_5\chi G_{\mu u}G^{\mu u}$                        | $i\alpha_S/8M_*^3$ | 7         |
| 0 <sub>M9</sub>         | $ar{\chi}\chi G_{\mu u}	ilde{G}^{\mu u}$                         | $lpha_S/8M_*^3$    | 7         |
| $\mathcal{O}_{\rm M10}$ | $\bar{\chi}\gamma_5\chi G_{\mu u}\tilde{G}^{\mu u}$              | $i\alpha_S/8M_*^3$ | 7         |

### Table 2: Operators for Majorana DM.

| Motivation/Expectation              | Approaches | Top-Down |          | Bottom-Up |
|-------------------------------------|------------|----------|----------|-----------|
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# **Lowest Dimensional Operators**



| Label           | Operator  | Usual coefficient | Dimension |
|-----------------|---|-------------------|-----------|
| 0 <sub>C1</sub> | $\phi^*\phiar q q$  | $m_q/M_*^2$       | 5         |
| 0 <sub>C2</sub> | $\phi^*\phiar q i\gamma_5 q$  | $m_q/M_*^2$       | 5         |
| 0 <sub>C3</sub> | $\phi^* i\overleftrightarrow{\partial_\mu} \phi \bar q \gamma^\mu q$            | $1/M_{*}^{2}$     | 6         |
| 0 <sub>C4</sub> | $\phi^* i \overleftrightarrow{\partial_\mu} \phi \bar{q} \gamma^\mu \gamma_5 q$ | $1/M_{*}^{2}$     | 6         |
| 0 <sub>C5</sub> | $\phi^*\phi G_{\mu u}G^{\mu u}$   | $\alpha_S/4M_*^2$ | 6         |
| O <sub>C6</sub> | $\phi^*\phi G_{\mu u}	ilde{G}^{\mu u}$  | $lpha_S/4M_*^2$   | 6         |

Table 3: Operators for Complex Scalar DM.

# **Lowest Dimensional Operators**



| Label                       | Operator                             | Usual coefficient | Dimension |
|-----------------------------|--------------------------------------|-------------------|-----------|
|                             |                                      |                   |           |
| $\mathcal{O}_{R1}$          | $\phi^2 \bar{q} q$                   | $m_q/2M_*^2$      | 5         |
| $\mathcal{O}_{R2}$          | $\phi^2 \bar{q} i \gamma_5 q$        | $m_q/2M_*^2$      | 5         |
| 0 <sub>R3</sub>             | $\phi^2 G_{\mu u}G^{\mu u}$          | $\alpha_S/8M_*^2$ | 6         |
| $\mathcal{O}_{\mathrm{R4}}$ | $\phi^2 G_{\mu u} \tilde{G}^{\mu u}$ | $\alpha_S/8M_*^2$ | 6         |

Table 4: Operators for Real Scalar DM.

## Let's keep things easy



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

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

• Pro: Only two open parameters:  $m_{\chi}, M_*$ 

Motivation/Expectation

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# **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

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

# 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
- √*s* = 14TeV
- Sensitivity projection
- Monte Carlo of the background (left) and signal (right):



Motivation/Expectation

Approache

Top-Down

Bottom-Up

# Sensitivity of the Atlas Analysis



- 95% CL lower limit on the suppression scale M<sub>\*</sub>
- 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<sub>\*</sub> can be mapped to the "UV" theory with a mediator of a mass M<sub>med</sub> and two couplings g<sub>SM</sub>, g<sub>\chi</sub> 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

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

Perturbativity requires

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

Validity for

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

Approaches

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## **Bottom-Up Approach - Simplified Model**





Motivation/Expectation

Approaches

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Jonas Müller - DM Collider Searches

# **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 ightarrow 0 ; DM spin ightarrow 0

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

• 0s1/2 model: Mediator spin  $\rightarrow$  0 ; DM spin  $\rightarrow$  1/2

$$\mathcal{L}_{0_{\mathcal{S}}Srac{1}{2}} = rac{1}{2} \left(\partial_{\mu}S
ight)^2 - rac{m_{\mathcal{S}}^2}{2}S^2 + \overline{\chi}(i\partial \!\!\!/ - m_{\chi})\chi - g_{\chi}S\overline{\chi}\chi - g_{SM}S\sum_{f}rac{y_f}{\sqrt{2}}\overline{f}h$$

• Vector Mediator: Mediator spin  $\rightarrow$  1; DM spin  $\rightarrow$  1/2

$$\mathcal{L}_{\textit{vec}} \supset rac{1}{2} \textit{M}_{\textit{med}}^2 \textit{V}_{\mu} \textit{V}^{\mu} - \textit{g}_{\textit{DM}} \textit{V}_{\mu} \overline{\chi} \gamma^{\mu} \chi - \sum_{q} \textit{g}_{\textit{SM}}^q \textit{V}_{\mu} \overline{q} \gamma^{\mu} q$$

Start calculating...

Motivation/Expectation

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### **Simplified Model Results**







Motivation/Expectation

Approaches

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# 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!

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# Conclusion



- DM collider searches are *challenging* (small fluxes, small production rates,...)
- Two general approaches for model building/searches
  - Top-down
    - + Particle Content is known
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      - Each model needs a detailed and involved analysis
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### Thank you for your attention!

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### 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