## Dark Matter searches with the ATLAS detector at the LHC

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Astrophysics

Bridge between astrophysics and the laboratory

**Experimentally elusive** 

 Sparked a diverse and ingenious search programme

**Particle physics** 

## **DM Scale: Experimental reach**



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## **Dark Matter Models**



Need to balance between generality and completeness

- Simplified Models are used as guidance
- Few free parameters:
  - Masses
  - Couplings / lifetimes
  - Nature of BSM particles
- Visualisation of results is easier
- Easy comparisons between experiments

Most models provide some kind of Weakly interacting massive particles (WIMPs)



## **Dark matter in Colliders**



## **Dark matter in Colliders**



## **Recent ATLAS searches for DM**

#### **Exploiting the full Run 2 dataset**

#### • ATLAS has a broad program of searches for Dark Matter candidates

ATLAS-CONF-2020-052

#### Individual searches

- E<sub>T</sub><sup>miss</sup>+Jet Phys. Rev. D 103, 112006 (2021)
- E<sub>T</sub><sup>miss</sup>+s(WW) Phys. Rev. Lett. 126 (2021) 121802
- $E_{T}^{miss}+Z(ll)$ arXiv:2111.08372
- VBF+ $E_{T}$ <sup>miss</sup>+Y arXiv:2109.00925
- Emmiss+tW Eur. Phys. J. C 81 (2021) 860

- Emmiss+V
- $E_{T}^{miss}+h(bb)$
- E<sub>T</sub><sup>miss</sup>+bjets
- $E_{\pi^{miss}+2L+jets}$

- JHEP 02 (2021) 226
- JHEP 11 (2021) 209
- JHEP 05 (2021) 093
- E<sub>T</sub><sup>miss</sup>+1L+jets JHEP 04 (2021) 174
  - JHEP 04 (2021) 165

#### **Combinations and summaries**

- Simplified models ATL-PHY8-PUB-2021-045
- Higgs portal
- 2HDM+a ATL-PHYS-PUB-2021-045





## Search for $E_T^{miss}$ + jet

#### <u>JHEP 11 (2021) 153</u> Phys. Rev. D 103, 112006





Main backgrounds: Z(vv)+jet, W(lv) +jet

 Extreme accuracy of SM predictions (Eur. Phys. J. C 77 (2017) 829)

No significant excess or deficit

- Results from 2017-2018 data combined with earlier dataset
- Simplified models with vector, axialvector, scalar, or pseudoscalar mediators
- Fermion portal model

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#### <u>2111.08372</u> EPJC 81 (2021) 13

## Search for $E_T^{miss}$ +Z(II)

Sensitivity to a range of beyond-SM processes (not only DM)

Main backgrounds: ZZ, WZ, Z+jets

Discriminators depend on target model:

- BDT output (ATLAS:  $H \rightarrow inv$ )
- Transverse mass (2HDM+a)



Complementary, model-dependent, constraints to direct detection



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## **Higgs portal models**

Higgs boson as a mediator between SM and DM sectors

- Invisible Higgs decay would increase  $BR(h \rightarrow inv)$  w-r-t SM predictions
- SM BR(h $\rightarrow$ inv) = 0.1% from h  $\rightarrow$  ZZ \* $\rightarrow$ 4v



## **Constraining H**→invisible

Preliminary combination of Run 2 results VBF and tth (0L and 2L channels)

- Statistical combination with additional results obtained at  $\sqrt{s}$  = 7 and 8 TeV
- Final results will include more,

e.g. E<sub>τ</sub><sup>miss</sup>+Z(II) [<u>2111.08372</u>], VBF+γ+E<sub>τ</sub><sup>miss</sup> [<u>2109.00925</u>]

BR(h→inv) < 0.11 (0.11<sup>+0.04-0.03</sup>) at 95% CL Complementary sensitivity to DD experiments for both scalar and Majorana WIMPs at low masses



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## **Mediator searches**



## Search for resonances with four top quarks

#### **Probing the rarest final states**



Search built with minimal model dependence

• Selects events with two large-R jets

Main background: top pairs with extra jets

Scan of m(JJ) in 6 categories based on the number of additional jets and additional b-jets

Limits set on top-philic Z' models

 65 fb to 12 fb for Z' masses between 1.0 TeV and 3.0 TeV



## "Classic" bump-hunts



Dijet searches limited by trigger thresholds.

Less sensitive to mediator masses
< 900 GeV than SPS/Tevatron</li>

Substantial effort is being put in extending the reach to lower masses.

- Trigger-level searches
- Additional ISR

## Simplified model summary

Mediator searches probe mass range from O(10) GeV to above 3 TeV

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E_{_{\rm T}}^{_{\rm miss}} searches probe mass range up to ~2 TeV
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Note: the actual reach depends on the coupling choices

## Leptophilic vector mediator

## Leptophobic axial-vector mediator



## **Simplified model summary**

Upper limits on scattering cross-section can be set to compare with direct detection results (note: collider sensitivity is model dependent!)



# Beyond simplified models



## $E_T^{miss}$ + Higgs(bb)



Targets both resolved and merged topologies of  $H \rightarrow bb$  decays

 Larger E<sub>T</sub><sup>miss</sup> → more collimated Higgs decays

Main backgrounds: V+heavy flavours, top pairs

Shape fit of  $E_{\tau}^{miss}$  distribution and m(bb)

 Two categories for exactly 2 b-jets, or three or more

23/03/2022

## $E_T^{miss}$ + Higgs(bb) interpretation

Limits set on a variety of models.

For example, 2HDM+Z'





## Search for $E_T^{miss}$ + single top





Target all dominant  $E_{T}^{miss}$ +single-top diagrams in 2HDM+a<sup>T</sup>

Main backgrounds: top pairs, single top, tt+Z

Discriminators depend on target signature:

- $m_{T} and am_{T^2}$  (Wt 1L)  $m_{T^2}$  (Wt 2L)
- BDT output (tj)

## $E_T^{miss}$ + single top interpretation

The results were interpreted in the context of 2HDM+a models, and used to set upper limits on the visible cross section of generic BSM contributions.



## **Summary of 2HDM+a searches**

Various updates compared to partial Run 2 results JHEP 05 (2019) 142

- Additional signatures:  $H^{\pm}(tb)$  and  $E_{-}^{miss}$  + single top
- Statistical combination of  $E_{\perp}^{\text{miss}} + Z(II)$  and  $E_{\perp}^{\text{miss}} + H(bb)$



#### Eur. Phys. J. C 81 (2021) 1118 2201.02472

## **Higgsino dark matter**

Great effort in constraining the most viable supersymmetric dark matter candidates

• Example: statistical combination of two and three-leptons searches



## **Beyond the WIMP**



## **DM at HL-LHC**

- High Luminosity Large Hadron Collider (HL-LHC) will reach an instantaneous luminosity by a factor of 5 larger than the LHC nominal value
- $E_T^{miss}$  + Jet could be a key channel for the search for dark matter
- Extrapolation from current results to 300 fb<sup>-1</sup> (Run2+Run3) and 3000 fb<sup>-1</sup> (HL-LHC) show the reach in DM searches
- Impact of different systematic uncertainties scenarios were investigated





Vibrant programme of searches for Dark Matter at colliders beyond

• Complementarity between searches for dark matter and mediator searches

Productive collaborations between theory and experiment

- Benchmark models to compare results from different experiments
- Models inspire new searches

The LHC Run 3 is just around the corner. Expecting ~350 fb<sup>-1</sup>

Full HL-LHC program will extend significantly the reach (one order of magnitude more data!)

## Thank you!