



MAX-PLANCK-GESELLSCHAFT



Dark matter searches with Run 2 data

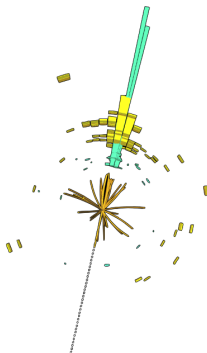
Patrick Rieck

on behalf of the Exotics,
Higgs and SUSY groups

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

ATLAS Week
Berlin

8 October 2019





- ▶ Landscape of models
- ▶ Overview of searches
- ▶ Combination of searches

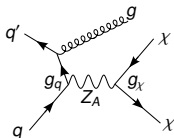


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BSM Mediator and Long Lived Particle searches covered in Exotics Working Group report by Nishu on Friday.

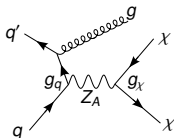
Simplified Models

- ▶ New mediators introduced *ad hoc* for SM-WIMP interaction
- ▶ Not UV-complete, also anomalies
- ▶ e.g. Z' resonance
⇒ Mono-Jet signature:



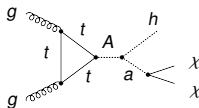
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Consistent Models

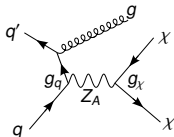
- ▶ UV-completeness, achieved with a larger particle content
- ▶ Hence more *complex phenomenology*
- ▶ Example:
2HDM+Pseudoscalar \Rightarrow Mono-h signature



- ▶ Includes SUSY, see also Will's talk

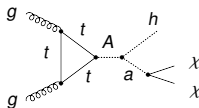
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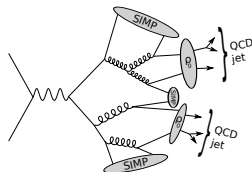
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More Exotic Models

- ▶ e.g. strongly interacting massive particles - SIMPs
- ▶ **QCD-like phenomenology in the dark sector**
- ▶ Example: dark showers \Rightarrow semi-visible jets



Signature

- ▶ $E_T^{\text{miss}} > 200 \text{ GeV}$ + up to 4 jets
⇒ sensitivity to several new phenomena
- ▶ Signal region (no leptons) + W, Z and top-quark control regions

Improvements

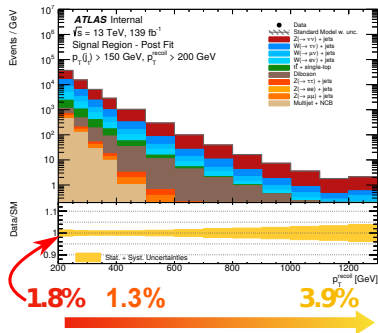
- ▶ More control regions ($W(e\nu)$, $Z(ee)$)
- ▶ MET threshold lowered to 200 GeV
- ▶ Lepton veto p_T thresholds lowered
- ▶ Overall approx. 20 % sensitivity increase due to analysis improvements only

Status

- ▶ Control Region fits being studied, then proceed to unblinding, circulate to ATLAS by the end of this year

Particularities

- ▶ W/Z+jets backgrounds including electroweak NLO corrections
- ▶ $Wt/t\bar{t}$ interference modelling affecting backgrounds in top control region



Signature

- ▶ Associated production of dark matter and a Higgs boson, $H \rightarrow bb \Rightarrow$ signal peak in di- b -jet mass distribution
- ▶ Target b -jet pairs in both resolved and merged topologies, for the latter use variable-radius track jets

Improvements

- ▶ Resolved event selection
- ▶ Background modelling uncertainties

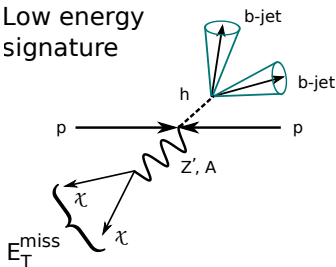
Status

- ▶ Finalised event selection, target Moriond 2020

Particularities

- ▶ Consider this analysis as a use case for a machine learning based boosted H -boson tagger (after this full Run 2 MET+H(bb) paper) – [link to slides](#)

Low energy signature



Signature

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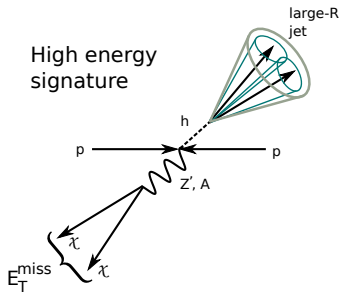
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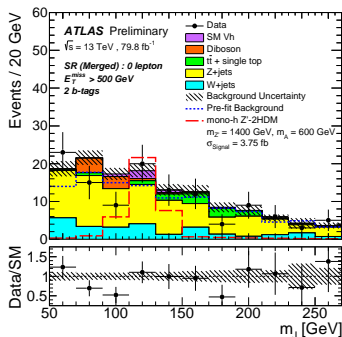
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Signature

- ▶ New mediator Z' acquiring a mass due to a **dark Higgs boson** $s \Rightarrow$ signal peak in invariant mass distribution at m_s
- ▶ Assuming $m_s > 2m_W \Rightarrow \text{MET}+WW(qqqq)$ final state dominating

Improvements

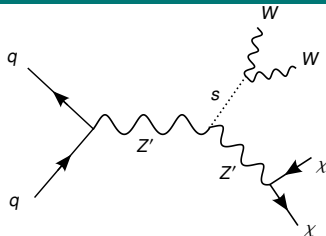
- ▶ **First analysis targeting this final state**

Status

- ▶ Finalising event selection, circulate to ATLAS this year

Particularities

- ▶ Use **track-assisted reclustered (TAR) jets** to identify merged $s \rightarrow WW \rightarrow qqqq$ decays \Rightarrow Flexibility for boosted jet reconstruction due to TAR jets
 - ▶ Choice of radius parameter
 - ▶ Track-based substructure (hence high granularity)
 - ▶ Bottom-up uncertainties



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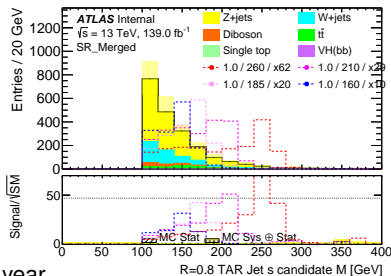
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Signature

- ▶ Pair of jets with $|\Delta\eta| > 3.8$, $\text{MET} > 150 \text{ GeV}$, signal excess at large MET and dijet-mass
- ▶ Primary channel to search for invisible Higgs boson decays

Improvements

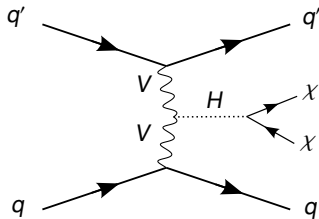
- ▶ Event selection and multi-region fitting
- ▶ Considering a Machine Learning approach
- ▶ Increased background MC statistics

Status

- ▶ Finalising Machine Learning studies and object selection, target Moriond 2020

Particularities

- ▶ Demanding W/Z +jets background MC generation (previously major uncertainty)
 - ▶ More efficient filters used in Sherpa 2.2.7
 - ▶ Ideally include electroweak NLO corrections and correlate W and Z +jets backgrounds in the statistical model (3 ACEs involved)
- ▶ Recently kicked-off a VBF+MET+Photon analysis targeting the same physics



Signature

- ▶ MET + leptons, which are used for triggering \Rightarrow **lower MET scenarios accessible**

Improvements

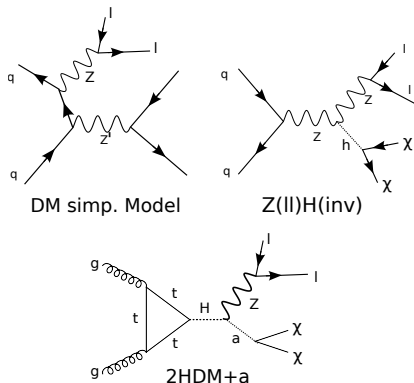
- ▶ Event selection optimised, including object based MET significance

Status

- ▶ Commitment increased recently; aiming to finalise in summer 2020

Particularities

- ▶ To be included in the $H \rightarrow \text{inv.}$ combination
- ▶ Main background $Z(\ell\ell)Z(\ell\nu)$ - investigating a data-driven estimate based on $Z(\ell\ell)+\gamma$ events – [link to slides](#)



Signature

- ▶ 2HMD+a model leading to single top-quark + Dark Matter production
 - ▶ Wt channel (single and di-lepton) dominating due to H^\pm resonance
 - ▶ Also consider t -channel production

Improvements

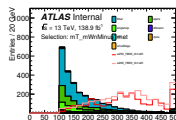
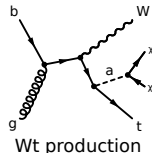
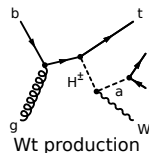
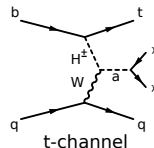
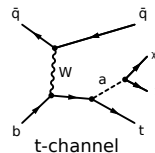
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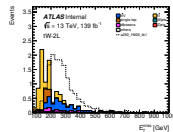
- ▶ Started EB review, circulate to ATLAS by the end of this year

Particularities

- ▶ Signal parameter scan using m_a , $\tan\beta$ and m_H^\pm
- ▶ Investigating BDT based signal separation for t -channel production



Wt 1 Lepton



Wt 2 Lepton

Dark Matter + Heavy Flavour pair production



[links to glance](#)

Signature

- ▶ Alternative interpretation to stop search: simplified model with dark matter + (pseudo)scalar, **essentially $t\bar{t}H$, $H \rightarrow \text{inv.}$**
- ▶ Covering all lepton multiplicities
- ▶ Also investigate $\text{MET} + b\bar{b}$ final state

Improvements

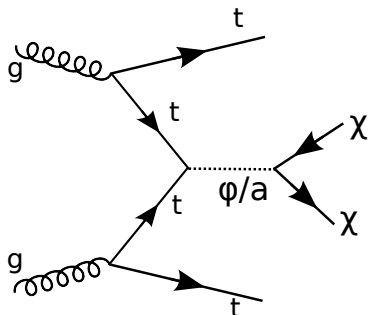
- ▶ Using a multi-bin approach

Status

- ▶ Finalise $\text{MET} + t\bar{t}$ with 0, 1, 2 leptons this fall
- ▶ $\text{MET} + b\bar{b}$ to follow until Moriond 2020 at the latest

Particularities

- ▶ **To be included in the $H \rightarrow \text{inv.}$ combination**
- ▶ $Wt/t\bar{t}$ interference modelling affecting backgrounds in top control region
- ▶ Possible future improvements: dedicated high- p_T b -tagging and DNN top-quark tagging with large-R jets



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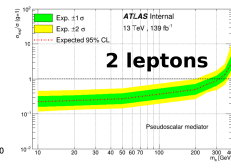
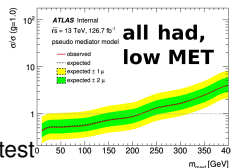
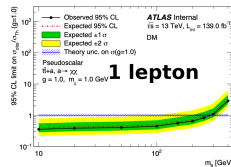
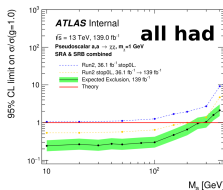
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More ongoing analyses

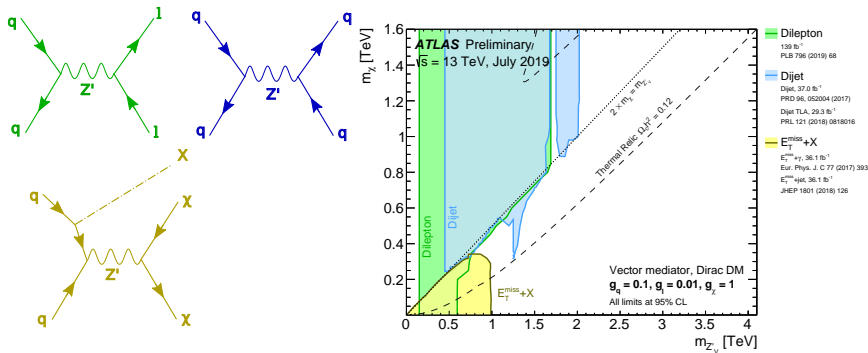
- ▶ Mono-Photon: EB requested
- ▶ MET+Jets/ $Z(\ell\ell)$ +Jets with unfolding: SM measurement, extends Mono-Jet sensitivity at low MET
- ▶ Mono- $W/Z(qq)$: ramping up efforts
- ▶ Mono- $H(\gamma\gamma)$: more sensitivity to lower MET compared to Mono- $H(bb)$, finalise by next summer
- ▶ Mono- $H(\tau\tau)$: finalise within this year
- ▶ Mono-Top: lack of person power
- ▶ Semi-visible jets: requesting signal MC (see Nishu's talk on Friday)

More signatures to be investigated

- ▶ Dark Matter simplified model with t -channel mediators - LHC Dark Matter Working Group effort started ([link to slides](#))
- ▶ SIMP models, e.g. as probed by semi-visible jets

Combinations of Dark Matter searches

Simplified Model Z' mediator



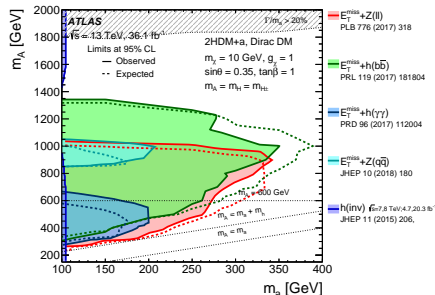
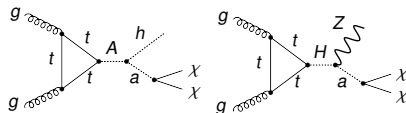
- ▶ Summary of exclusion limits of dark matter and resonance searches
- ▶ Complementarity: **large exclusion range achieved via overlay**
- ▶ Scanning parameter space of couplings and masses
- ▶ Compare with direct detection limits on WIMPs

Combinations of Dark Matter searches

2HDM+Pseudoscalar



- ▶ Scanning the space of 5 free parameters; new benchmarks under discussion to further highlight complementarity of different analyses
- ▶ Sensitivity provided by $\mathcal{O}(10)$ ongoing physics analyses, including MET+X and resonance searches
[link to slides](#)
- ▶ In particular: statistical combination of MET+ $H(bb)$ and MET+ $Z(\ell\ell)$ searches
- ▶ Coordinating efforts early on within the CDM group

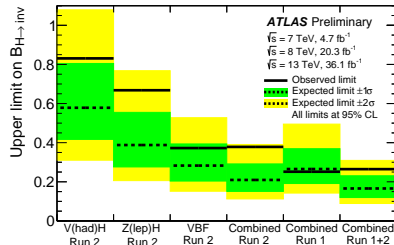
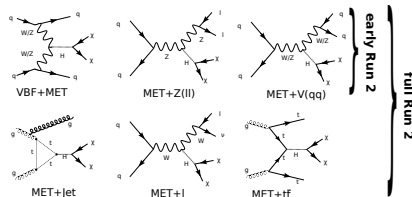


Combinations of Dark Matter searches

Higgs-boson decays to weakly interacting particles



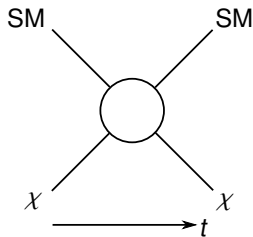
- ▶ 6 analyses to be statistically combined
- ▶ Coordinating efforts early on within the CDM and HComb groups in order to harmonize
 - ▶ Physics objects - PFlow!
 - ▶ Uncertainty schemes
 - ▶ Event selection - avoid overlaps
- ▶ Results will also enter the common Run 2 Higgs coupling combination



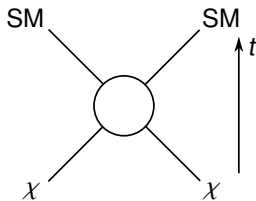
- ▶ Work in progress for a multitude of MET+X signatures
 - ▶ Extending early Run 2 results with gradual improvements
 - ▶ Exploring new final states and new CP techniques
- ▶ Combinations being prepared in parallel with efforts of contributing analyses
- ▶ More signatures to be explored in the future

Backup

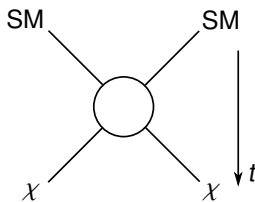
- Direct detection: nuclear recoil from elastic scattering



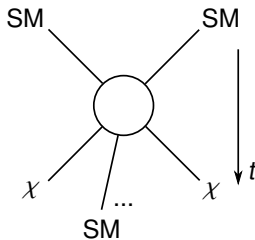
- ▶ Direct detection: nuclear recoil from elastic scattering
- ▶ Indirect detection: dark matter annihilation



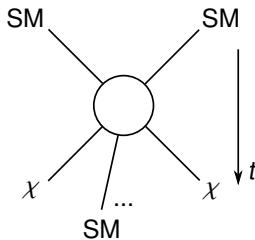
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- ▶ Collider searches: associated production of dark matter and SM particles



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Comparison of search strategies:

	Direct	Indirect	Collider - LHC
Typical mass range	$10 \text{ GeV} < m_\chi < 1 \text{ TeV}$	$10 \text{ GeV} < m_\chi < 100 \text{ TeV}$	$m_\chi \lesssim 1 \text{ TeV}$
Observables beyond m_χ	$\sigma_{\chi N \rightarrow \chi N}$	$\sigma_{\chi\chi \rightarrow NN}$	many
Model dependence	DM on Earth	DM in space	particle physics

- ▶ Aim to maximize the physics output of BSM searches \Rightarrow analysis preservation
- ▶ Exotics and SUSY groups: for this purpose implemented RECAST as a requirement
- ▶ Growing number of published results using RECAST. Examples in MET+X context: Mono- $H(bb)$
 - ▶ 2HDM+Pseudoscalar reinterpretation: Dark Matter Summary paper, 36 fb^{-1}
 - ▶ Dark Higgs boson Mono- $s(bb)$: complementary to Mono- $s(WW)$, dedicated PUB note, 80 fb^{-1}



ATLAS PUB Note
ATL-PHYS-PUB-2019-032
11th August 2019




RECAST framework reinterpretation of an ATLAS Dark Matter Search constraining a model of a dark Higgs boson decaying to two b-quarks

The ATLAS Collaboration

The reinterpretation of a search for dark matter produced in association with a Higgs boson decaying to b-quarks performed with RECAST, a software framework designed to facilitate the reinterpretation of existing searches for new physics, is presented. Reinterpretation using RECAST is enabled through the sustainable preservation of the original data analysis as re-executable declarative workflows using modern cloud technologies and integrated with the wider CERN Analysis Preservation efforts. The reinterpretation targets a model predicting dark matter production in association with a hypothetical dark Higgs boson decaying into b-quarks where the mass of the dark Higgs boson m_h is a free parameter, necessitating a faithful reinterpretation of the analysis. The dataset has an integrated luminosity of 79.8 fb^{-1} and was recorded with the ATLAS detector at the Large Hadron Collider at a centre-of-mass energy of $\sqrt{s} = 13 \text{ TeV}$. Constraints on the parameter space of the dark Higgs model for a fixed choice of dark matter mass $m_\chi = 200 \text{ GeV}$ exclude model configurations with a mediator mass up to 3.2 TeV .

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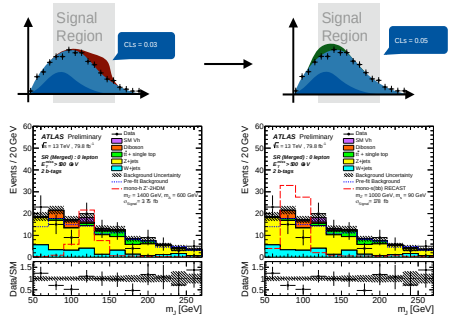
ATL-PHYS-PUB-2019-032
11 August 2019



RECAST



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