Search for mono-Z signature dark matter with the ATLAS detector at the LHC

WNPPC, February 13-16, 2020
Samantha Taylor
Supervisor: Michel Lefebvre
University of Victoria

Dark matter

Motivation

- Astronomical observations reveal the existence of dark matter
- The nature of dark matter is not explained by our current knowledge of physics

Detection methods

- Astronomical observations
  - Ex: galaxy rotation curves, velocity dispersion, gravitational lensing
- Direct detection
  - ie: DM - nuclei scattering
- Indirect detection
  - ie: products of DM decay/annihilation
- Production of dark matter
  - ie: DM as product from particle collisions

Dark matter production

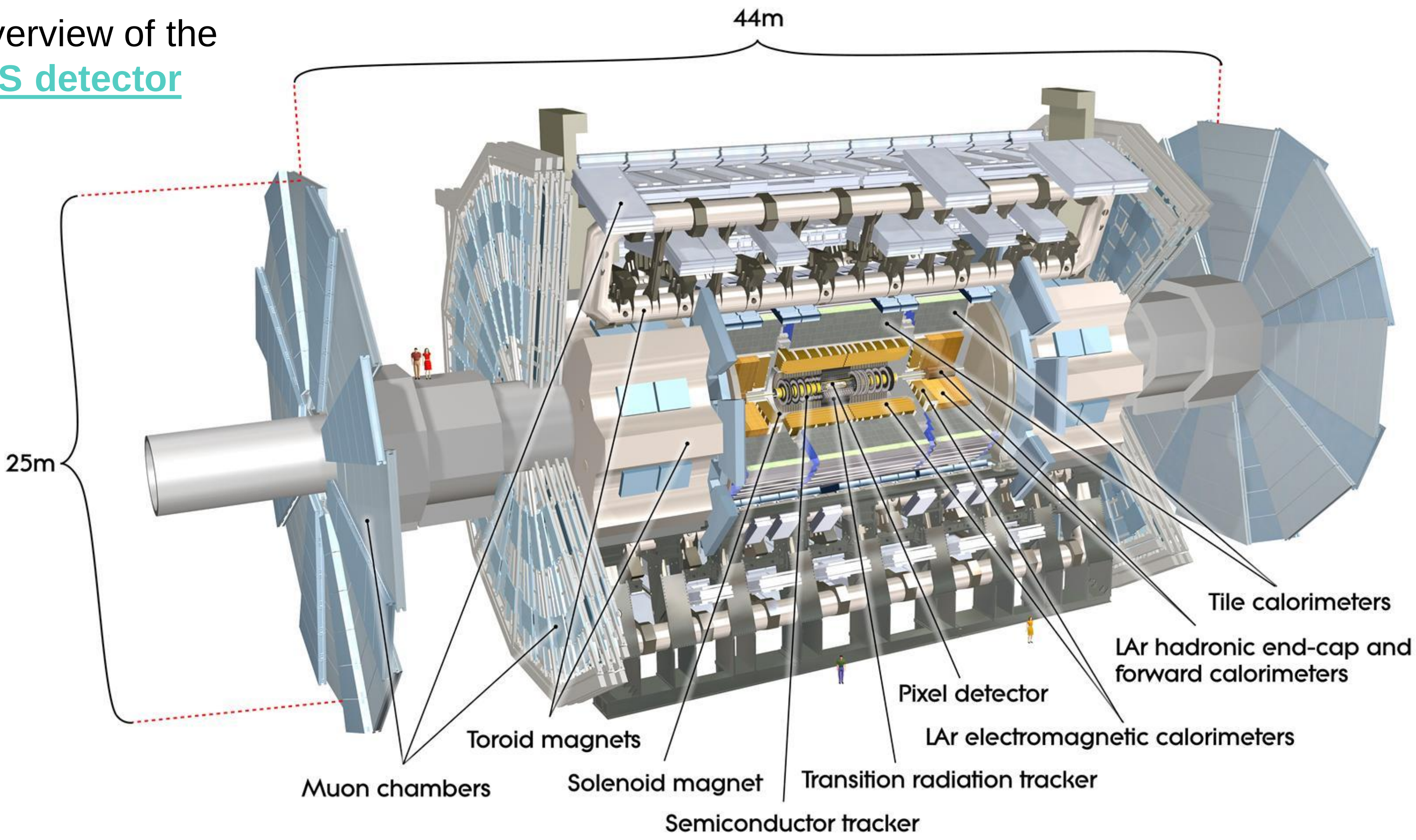
LHC

- *pp* beam collisions
- Most recent results from Run II (2015-2018) at 13 TeV
- Collection of 140 fb^{-1} of data so far
- Run III to operate 2021-2024 at 13-14 TeV

ATLAS

- Cylindrical detector with nearly 4π coverage
- Dark matter particle not yet detected
- Use data collected to make exclusion plots for parameters of interest
- *Missing transverse momentum* is usually the main discriminant

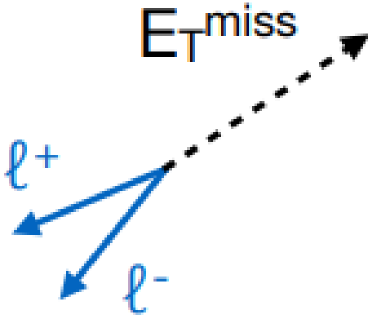
Quick overview of the
[ATLAS detector]



WN

Missing transverse momentum

- In principle, transverse momentum in particle collider final states should add to zero via conservation of momentum
- Certain processes give weakly-interacting/undetected particles in final state, giving the *illusion* of the violation of momentum conservation (missing transverse momentum, MET, or E_T^{miss})
  - Ex: invisible *Z* decay to two neutrinos, poor signal reconstruction
- Can search for the existence of DM by studying E_T^{miss}
  - Important observable!
- More info on E_T^{miss}: [Eur.Phys.J. C78 (2018) no.11, 903]



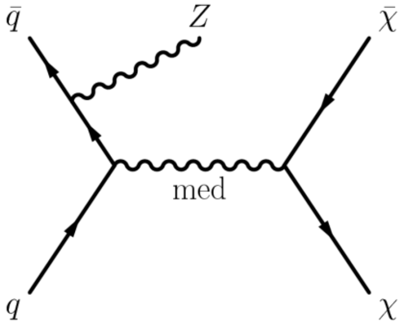
Models and signature

- *Mono-X* signature: large E_T^{miss} and one energetic particle
  - Ex: Mono-jet, Mono-Higgs
- Interested in *Mono-Z* signature in this analysis
- Final state is E_T^{miss} and *Z* boson
- *Z* decays to two same-flavour leptons (e^+e^- or $\mu^+\mu^-$)

$$p + p \rightarrow Z + \chi\overline{\chi}$$
$$\hookrightarrow l^+l^-$$

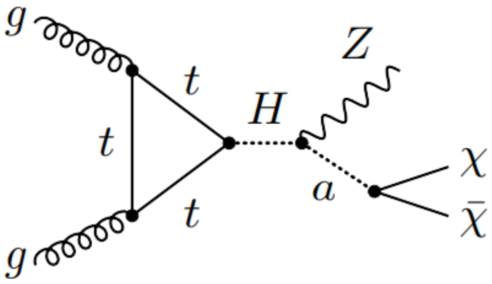
Simplified model

- Vector or axial-vector mediators

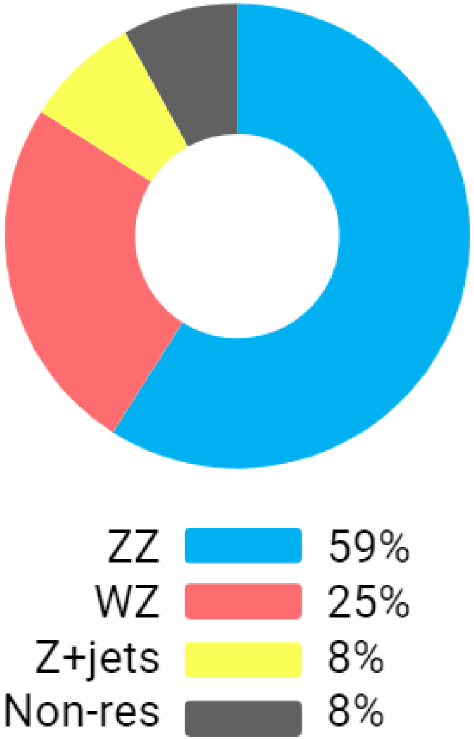


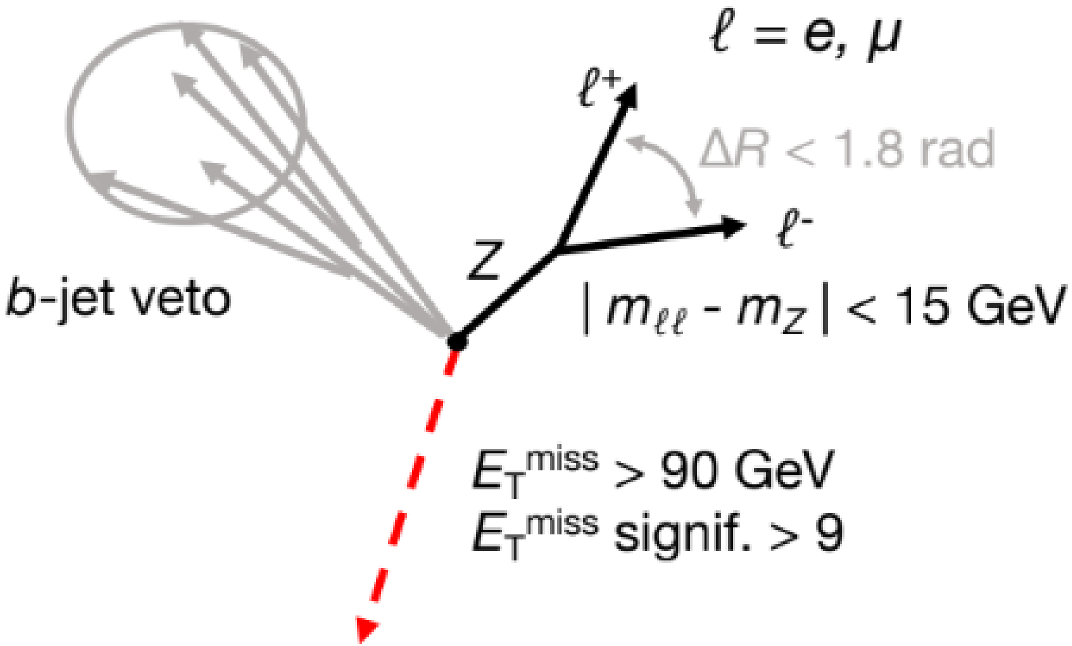
2HDMa

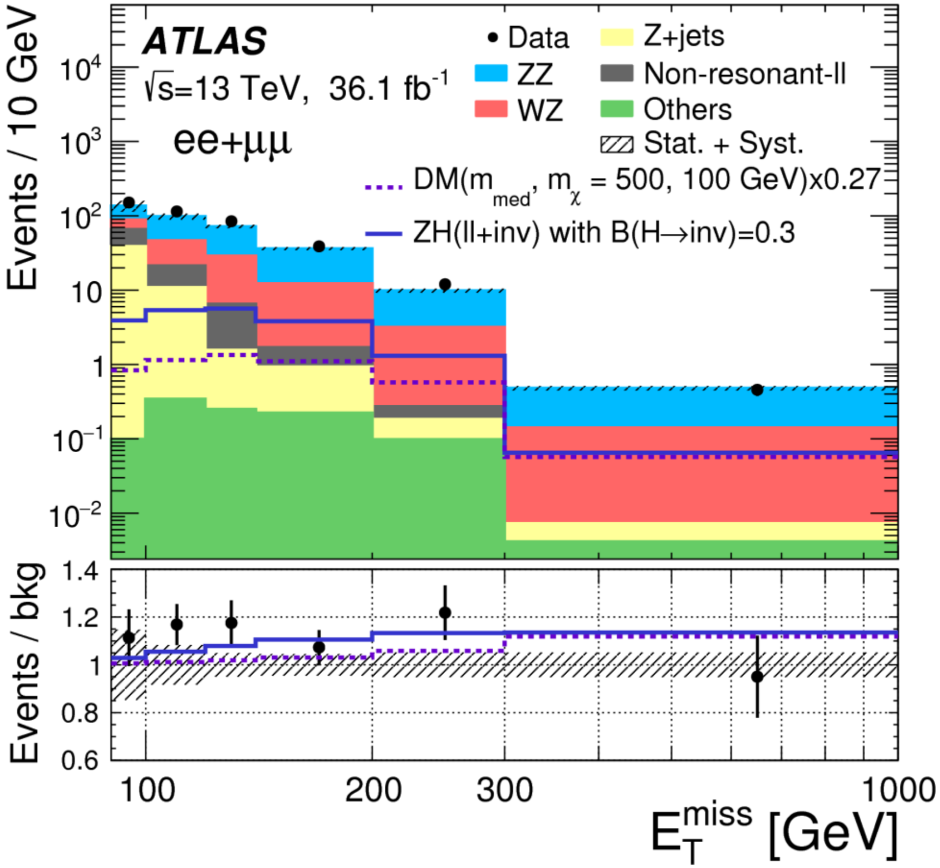
- Two Higgs doublet model plus pseudoscalar mediator



Event selection and main backgrounds







Published results in [Phys. Lett. B 776 (2017) 318]

Simplified model (V/AV) and 36 fb^{-1} result

- 6 free parameters:

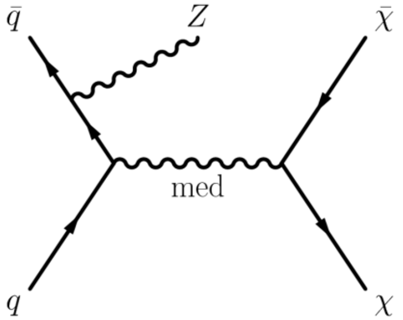
g_q, g_l, g_χ - Coupling to quarks, leptons, DM

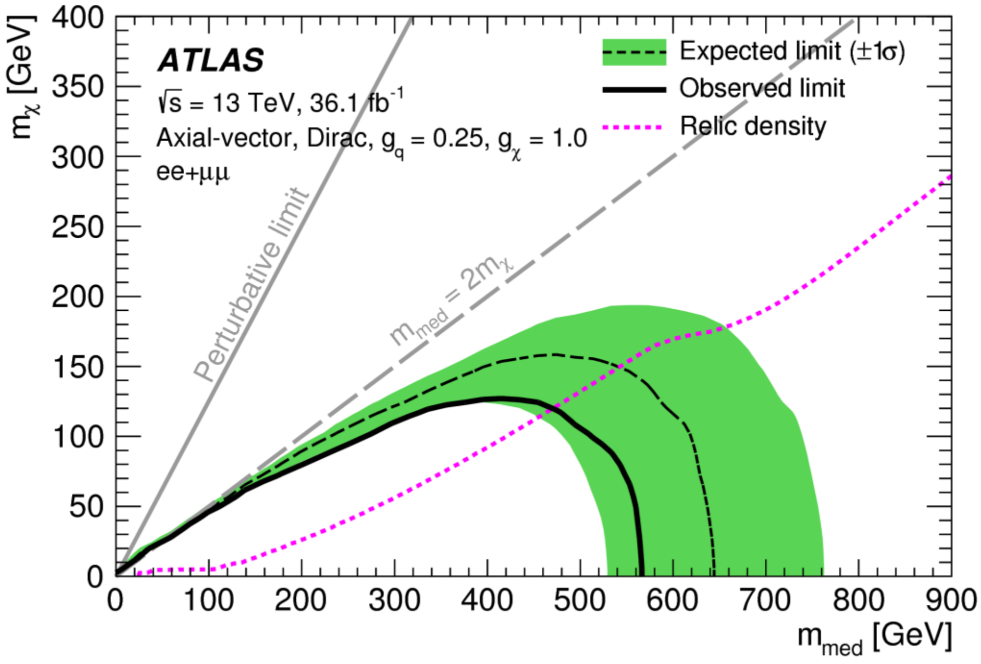
- $g_q = 0.25$, $g_l = 0.00$, $g_\chi = 1.00$

m_χ - Dark matter mass

m_{med} - Mediator mass

Γ_{med} - Mediator width





Published results in [Phys. Lett. B 776 (2017) 318]
140fb^{-1} result coming soon with Run II data

2HDMa

- *gg*-induced leading order diagrams
- 5 free parameters:

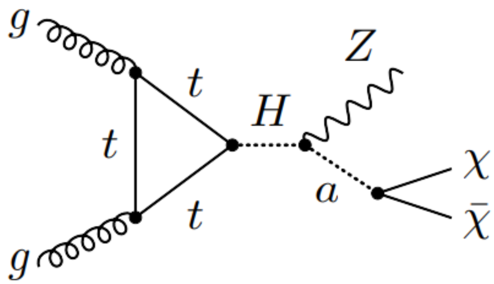
$m_A = m_H = m_{H^\pm}$ - Mass of *A, H, H+/-*

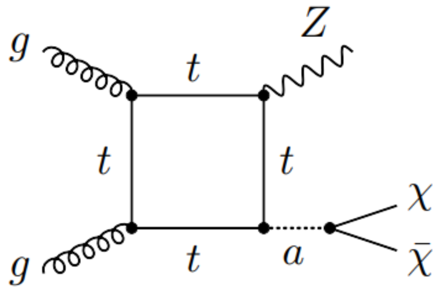
m_a - Mass of pseudoscalar *a*

$\sin\theta$ - Mixing angle between *A, a*

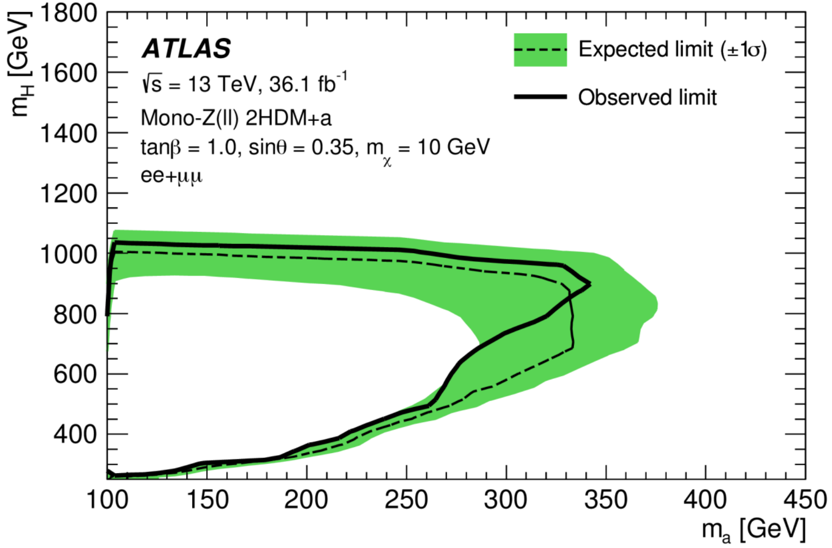
$\tan\beta$ - Ratio of VEVs of Higgs doublets

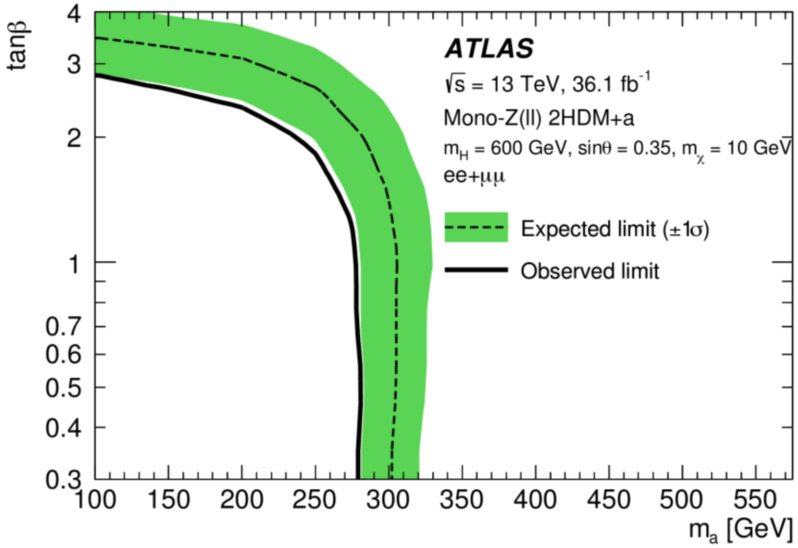
m_χ - Dark matter mass





36 fb^{-1} result (2HDMa)





Published results from [JHEP 05 (2019) 142]

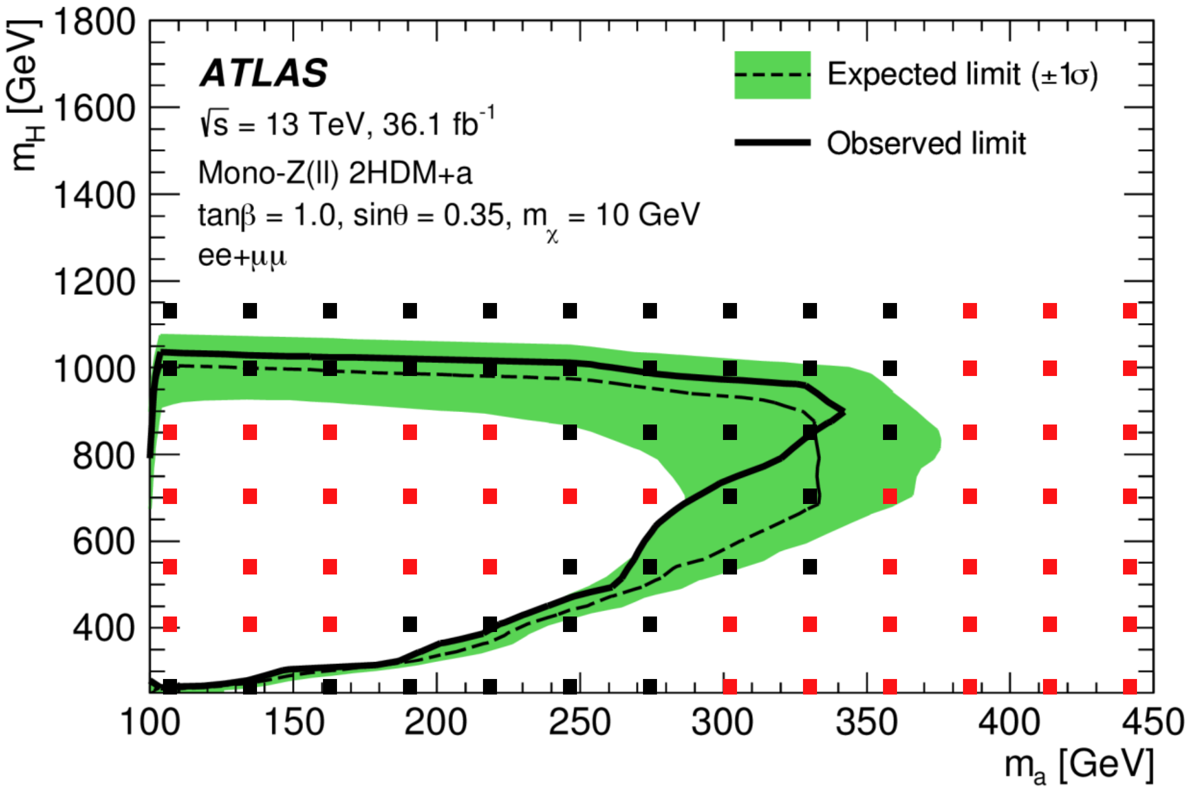
Reweighting techniques

MadGraph reweighting

- Many model parameter points are needed for limit scans
  - Full ATLAS simulation CPU intensive
- Instead, only need to fully simulate a few model parameter points using MadGraph
- Produce distributions using event reweighting to other target points
- Based on matrix element ratios

Histogram reweighting

- 2D histograms of two kinematic variables, $p_T(\chi\chi)$ and $p_T(ll)$, characterizing the event
- Take ratio of target parameter point histogram to fully simulated histogram for a given model parameter point
- Use these ratios to obtain an event weight to emulate distributions to target point



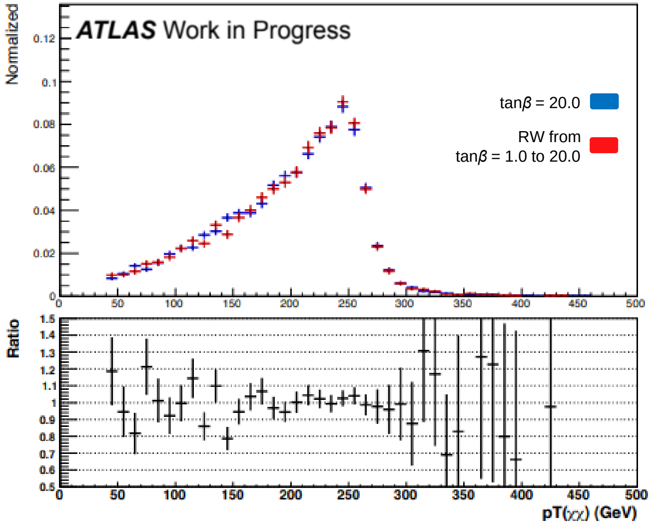
Published results from [JHEP 05 (2019) 142]

- Full reconstruction
- Emulation using RW techniques

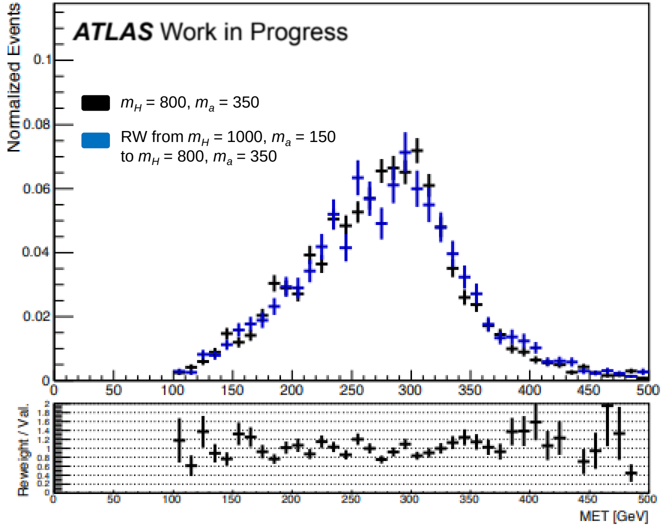
The black and red dots are added on the published figure to illustrate the concept of emulation in model parameter space

Closure tests of reweighting techniques

MadGraph reweighting
$p_T(\chi\chi)$ distribution
Reweight parameter: tanβ
Nominal value: 1.0
Target value: 20.0



Histogram reweighting
MET distribution
Reweight parameter: m_H, m_a
Nominal value: 1000, 150
Target value: 800, 350



2HDMa dark matter mass scan

Analysis method for parameter limits

1. Dark matter signal simulation with MadGraph
2. 'Fast' ATLAS detector simulation (Delphes)
3. Use SM background MET distribution from full analysis
4. Use data MET distribution from full analysis

   - 36 fb^{-1} and/or 140 fb^{-1} (currently blinded)

5. Extract parameter limits

   - frequentist profiled likelihood method

m_χ = [1, 500] GeV mass scan

DELPHES
fast simulation

Conclusion

- Lots of evidence for the existence of dark matter
- LHC, ATLAS use *pp* collisions to try to produce and detect dark matter
- Interested in Simplified V/AV and 2HDMa models
  - Mono-Z signature
- Know what main backgrounds are, and what selection criteria are needed to reduce them
- If no discovery is made, can use data to create exclusion ranges for model parameters
- Different reweighting techniques to efficiently simulate DM models
  - Validated
- Can then do 'fast analysis' to simulate data and create distributions to extend model parameter scans
  - Must be validated
- Can then extract parameter limits to create exclusion contour plots

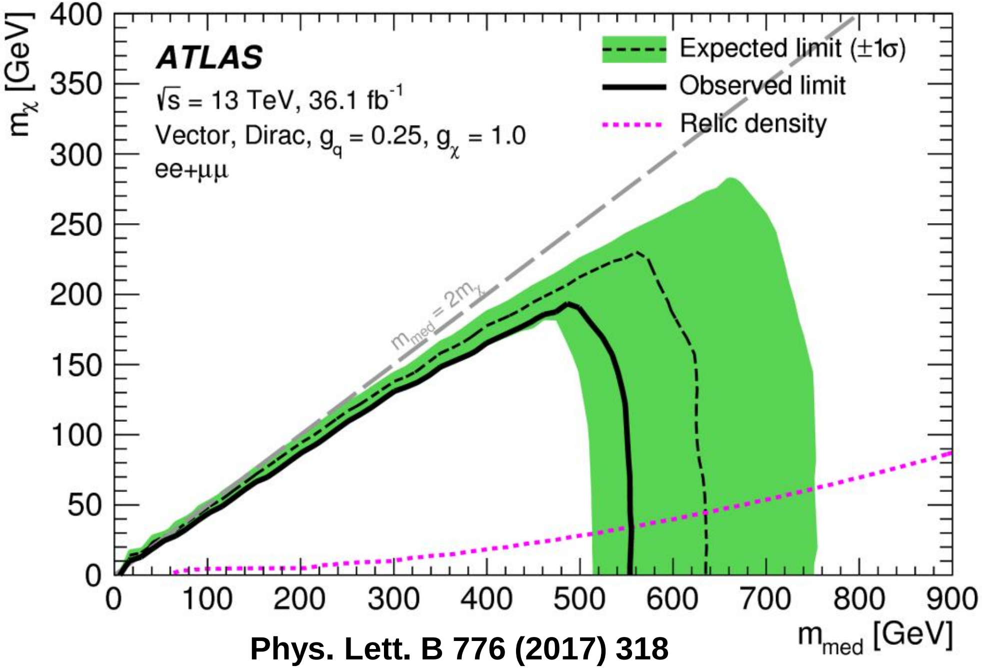
Questions?

Backup

Selection criteria for event analysis

	Selection criteria
Two leptons	Two opposite-sign leptons, leading (subleading) $p_T > 30$ (20) GeV
Third lepton veto	Veto events if any additional lepton with $p_T > 7$ GeV
m_{ll}	$76 < m_{ll} < 106$ GeV
E_T^{miss} and E_T^{miss} significance	$E_T^{miss} > 90$ GeV and E_T^{miss} sig > 9
ΔR_{ll}	$\Delta R_{ll} < 1.8$
b-jets veto	$N(b\text{-jets}) = 0$ with b-jet $p_T > 20$ GeV and $\lvert\eta\rvert < 2.5$

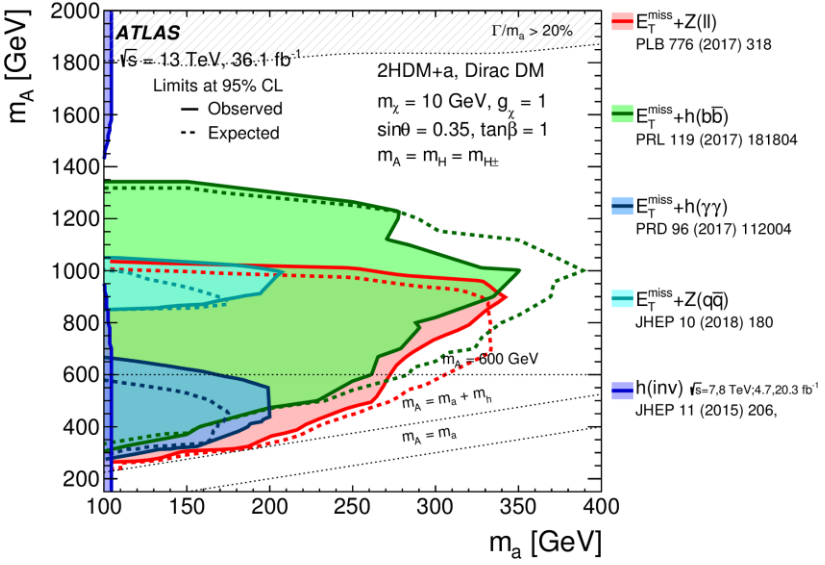
m_χ-m_{med} contour plot for vector mediator ($ee+\mu\mu$)

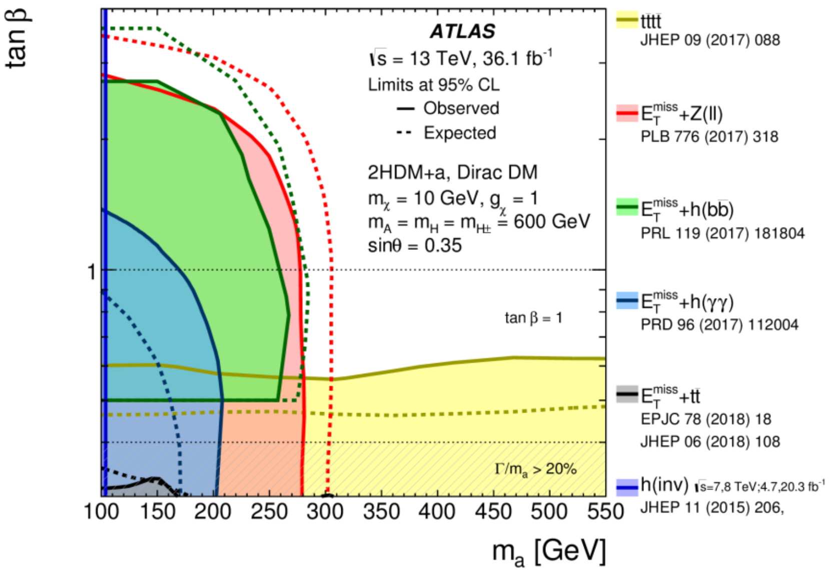


Phys. Lett. B 776 (2017) 318

Auxiliary material:
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HIGG-2016-28/

m_A-m_a and tanβ-m_a full contour plot for 2HDMa

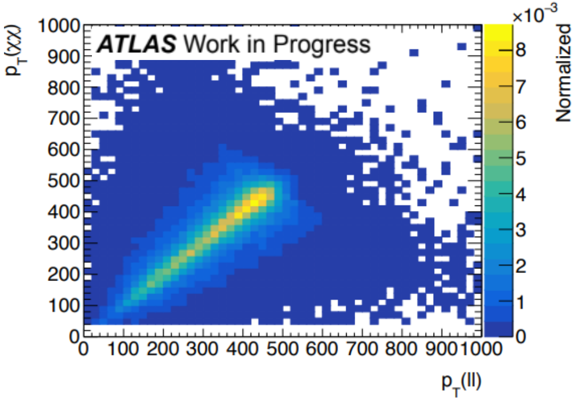




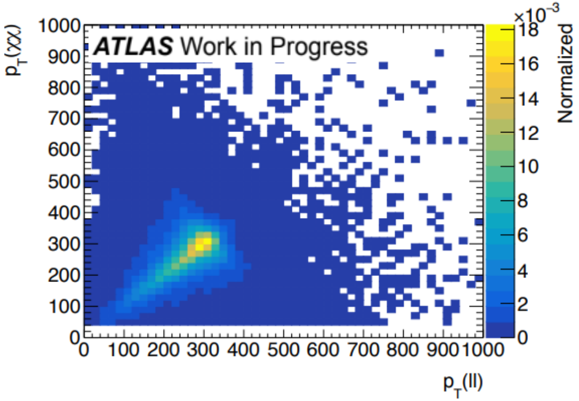
JHEP 05 (2019) 142

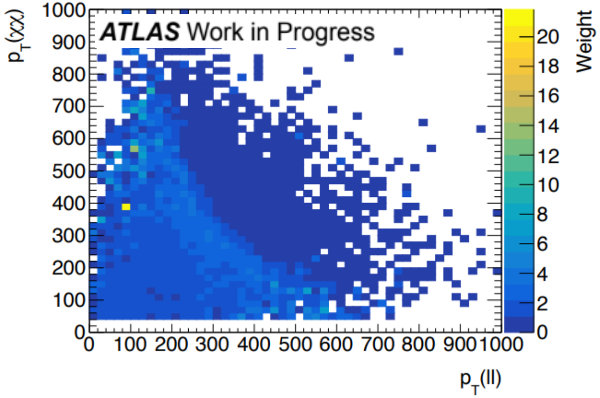
Histogram reweighting ratios

(mH=1000 GeV, ma =150 GeV)



(mH = 800 GeV, ma=350 GeV)





Definitions and values of parameters in the 2HDM+a model		
Symbol	Definition	Value
α	Mixing angle of the two neutral CP-even weak eigenstates	$\cos(\beta-\alpha)=0$
θ	Mixing angle of the two neutral CP-odd weak eigenstates	varied
$\tan\beta$	Ratio of the vacuum expectation values of the two Higgs doublets	varied
v	Electroweak vacuum expectation value	246 GeV
λ_{P1}	Quartic coupling between the scalar doublet H_1 and the pseudo-scalar a	$=\lambda_3$
λ_{P2}	Quartic coupling between the scalar doublet H_2 and the pseudo-scalar a	$=\lambda_3$
λ_3	The quartic coupling between the scalar doublets H_1 and H_2	3
y_χ	Coupling between the DM and the pseudo-scalar a	1
m_h	Mass of the light CP-even mass eigenstate	125 GeV
m_H	Mass of the heavy CP-even mass eigenstate	$=m_A$
m_A	Mass of the heavy CP-odd mass eigenstate	varied
m_a	Mass of the light CP-odd mass eigenstate	varied
$m_{H^\pm}$	Mass of the charged Higgs eigenstate	$=m_A$
m_χ	Mass of the DM particle	10 GeV

JHEP 05 (2019) 142

Observed data yield for signal and background

Final State	ee	$\mu\mu$
Observed Data	437	497
Signal		
$ZH \rightarrow \ell\ell + \text{inv}$ ($B_{H\rightarrow\text{inv}} = 30\%$)	$32 \pm 1 \pm 3$	$34 \pm 1 \pm 3$
DM ($m_{\text{med}} = 500$ GeV, $m_{\chi} = 100$ GeV) $\times$ 0.27	$10.8 \pm 0.3 \pm 0.8$	$11.1 \pm 0.3 \pm 0.8$
Backgrounds		
$qqZZ$	$212 \pm 3 \pm 15$	$221 \pm 3 \pm 17$
$ggZZ$	$18.9 \pm 0.3 \pm 11.2$	$19.3 \pm 0.3 \pm 11.4$
WZ	$106 \pm 2 \pm 6$	$113 \pm 3 \pm 5$
Z + jets	$30 \pm 1 \pm 28$	$37 \pm 1 \pm 19$
Non-resonant-$\ell\ell$	$30 \pm 4 \pm 2$	$33 \pm 4 \pm 2$
Others	$1.4 \pm 0.1 \pm 0.2$	$2.5 \pm 2.0 \pm 0.8$
Total Background	$399 \pm 6 \pm 34$	$426 \pm 6 \pm 28$

PLB 776 (2017) 318