Searching for Supersymmetry with the ATLAS Detector

Institute of Physics, Joint APP, HEPP, NP conference 2024

8-11 April 2024

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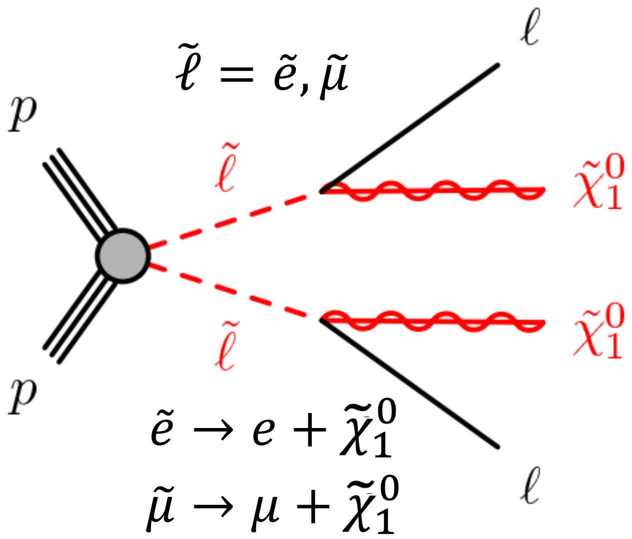
Supervisor: Alan Barr

Motivation

- Why are we still looking for SUSY?
- Still interesting places left to look!

Direct slepton decay



- Neutralino is a Dark Matter candidate
- Light smuons can provide extra loop corrections to explain the g-2 anomaly

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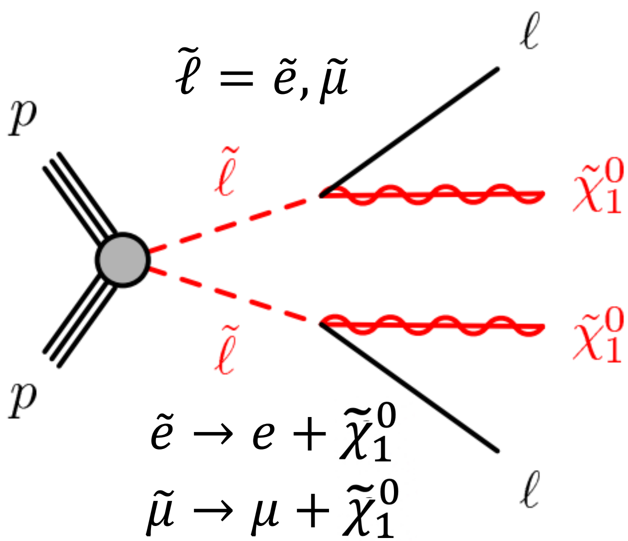

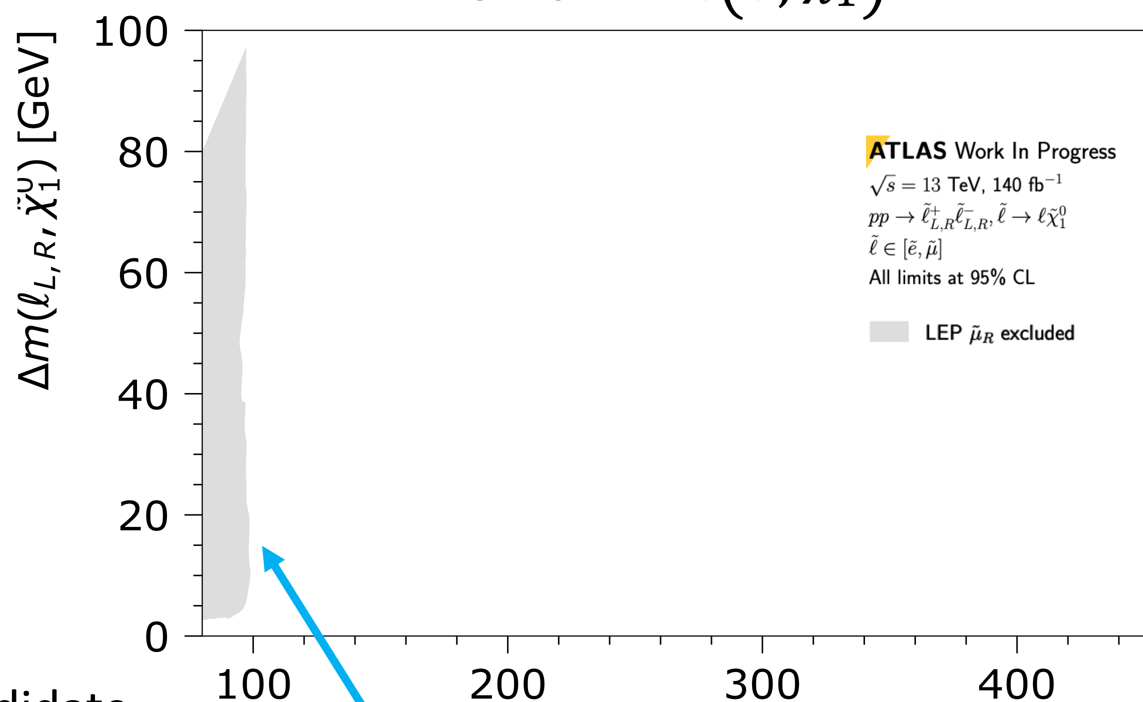

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<u>2008: ATLAS turns on</u>

Situation: LEP has set limits at low slepton mass

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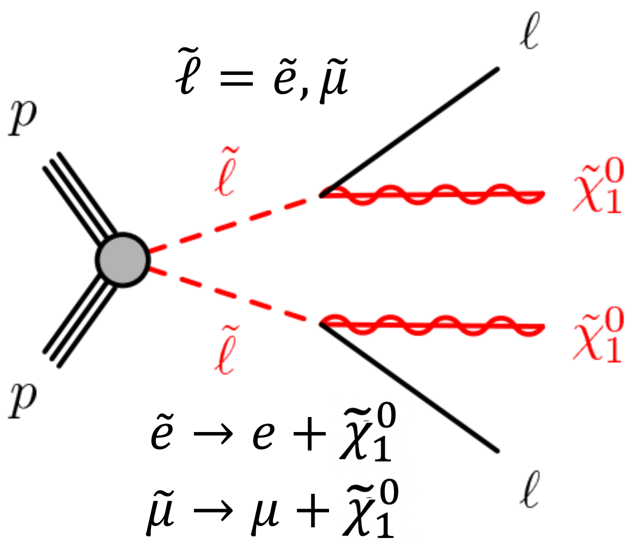

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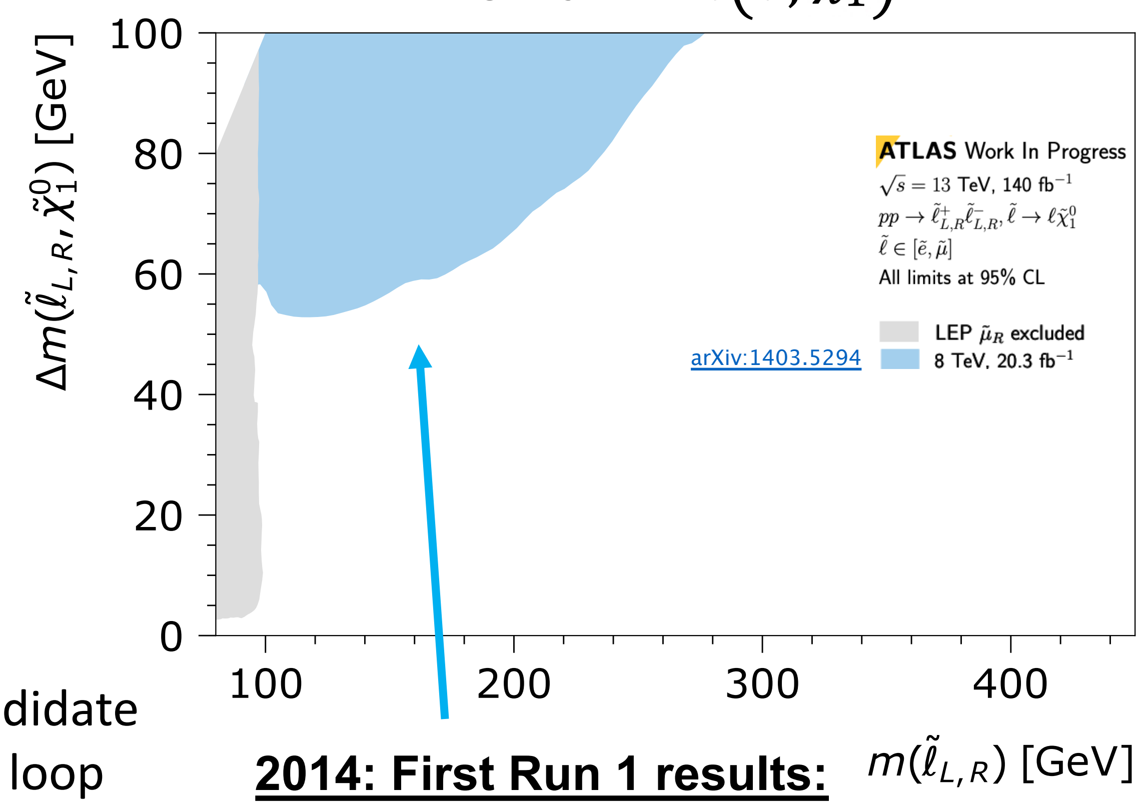

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2014: First Run 1 results:
Slepton search at 8TeV
arXiv:1403.5294

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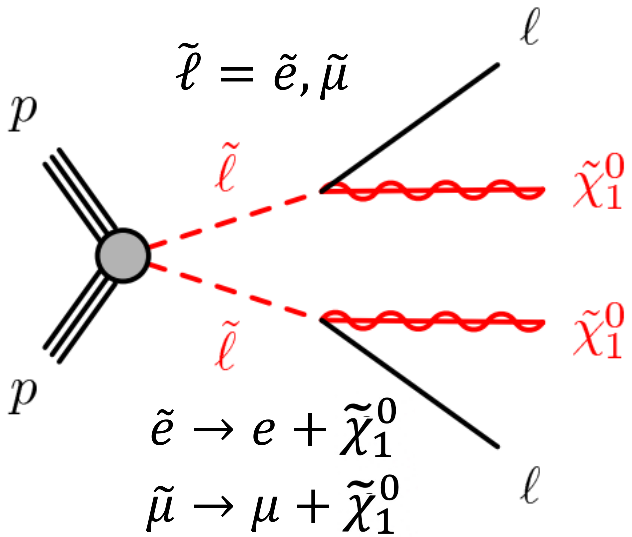

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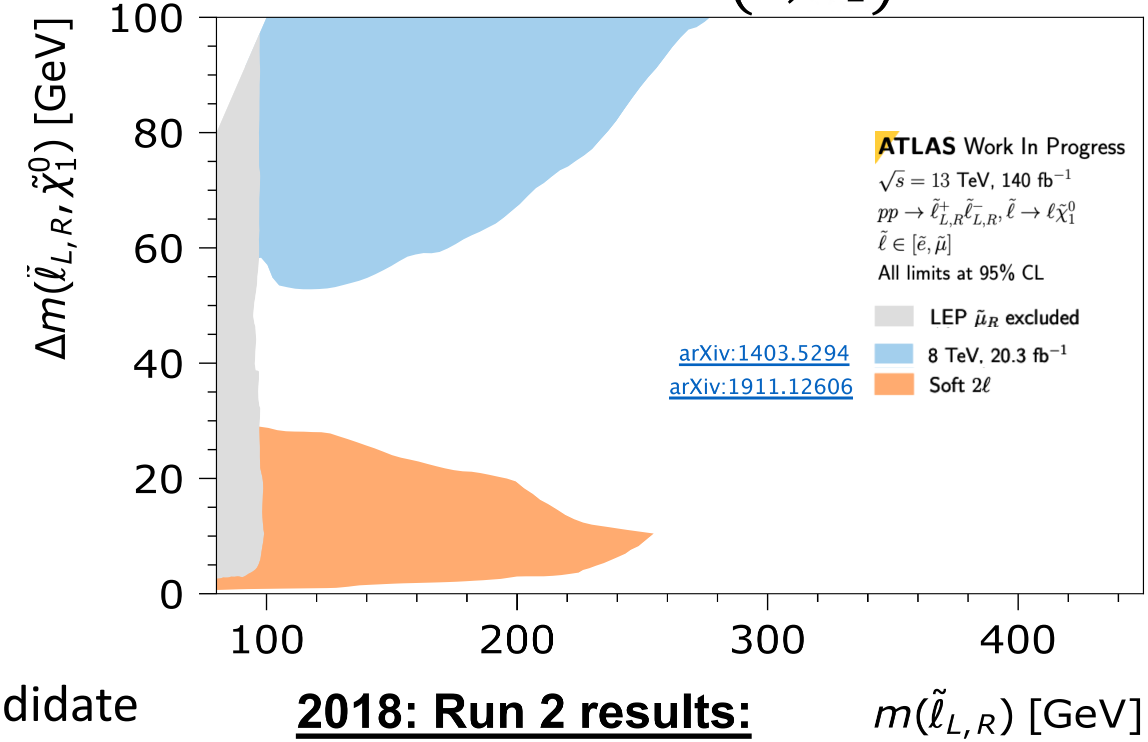

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<u>2018: Run 2 results:</u>

Soft 2 lepton search targeting very small Δm

arXiv:1911.12606

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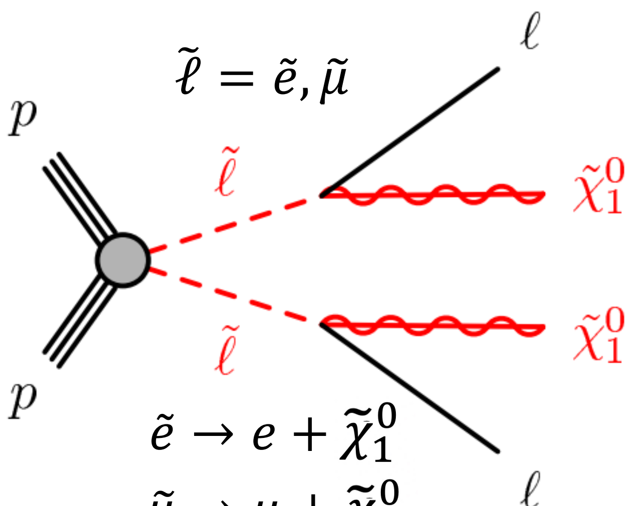
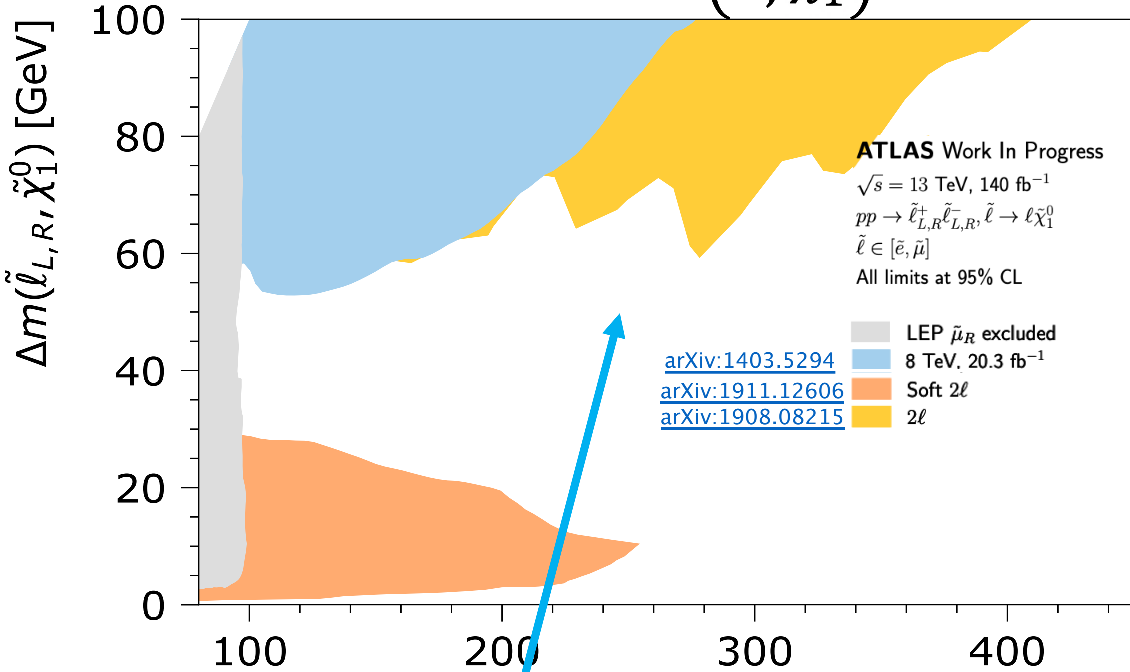


$\tilde{e} \rightarrow e + \tilde{\chi}_1^0$

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



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2019: Run 2 results:

Also: Analysis targeting final states with 2 leptons + 0,1,2 jets
arXiv:1908.08215

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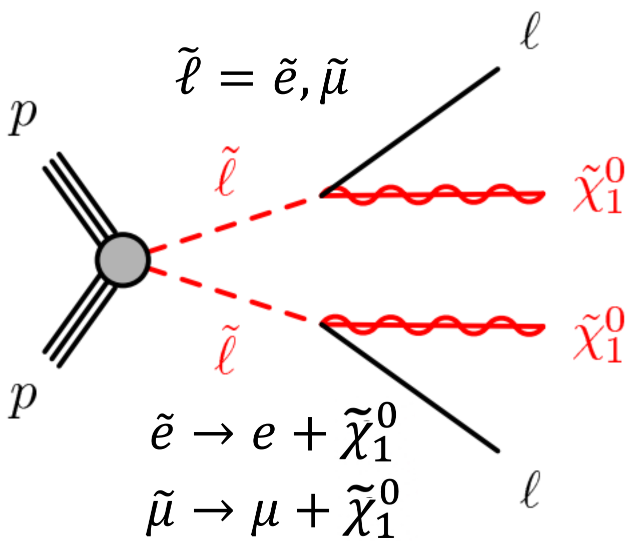

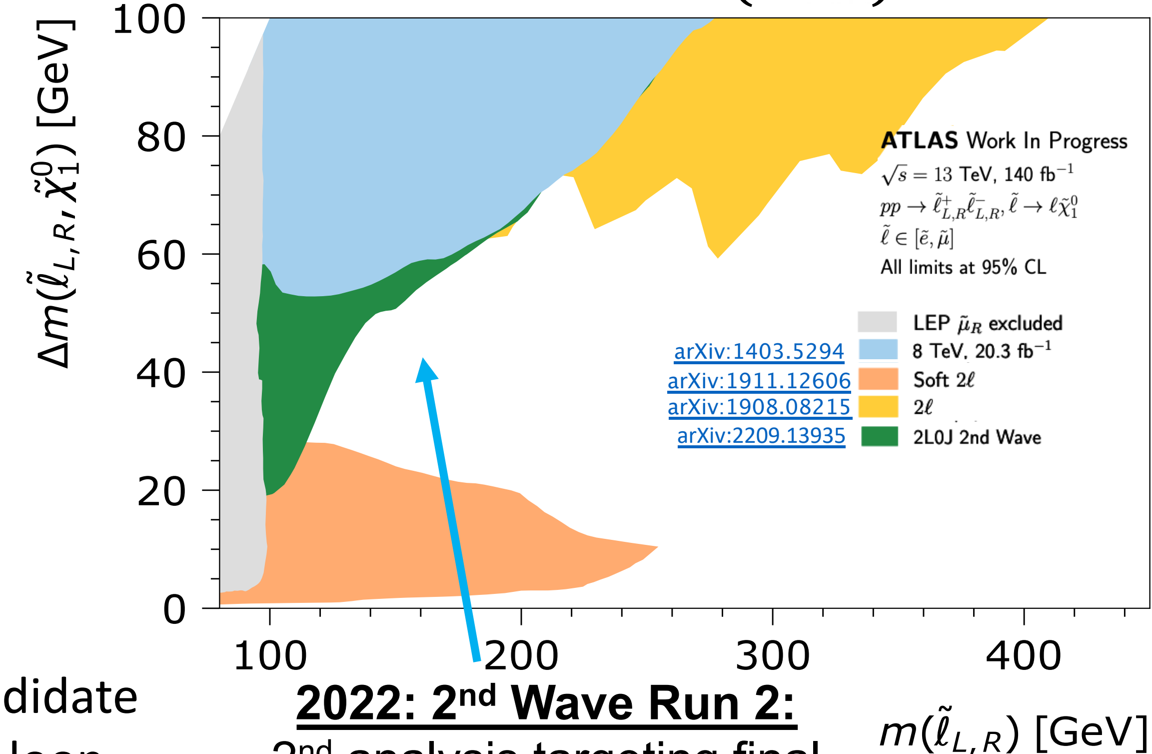

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2022: 2nd Wave Run 2:

2nd analysis targeting final states with 2 leptons + 0 jets

arXiv:2209.13935

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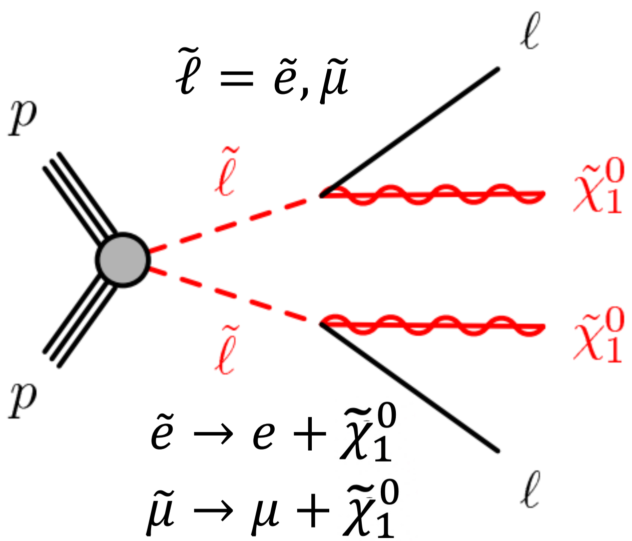

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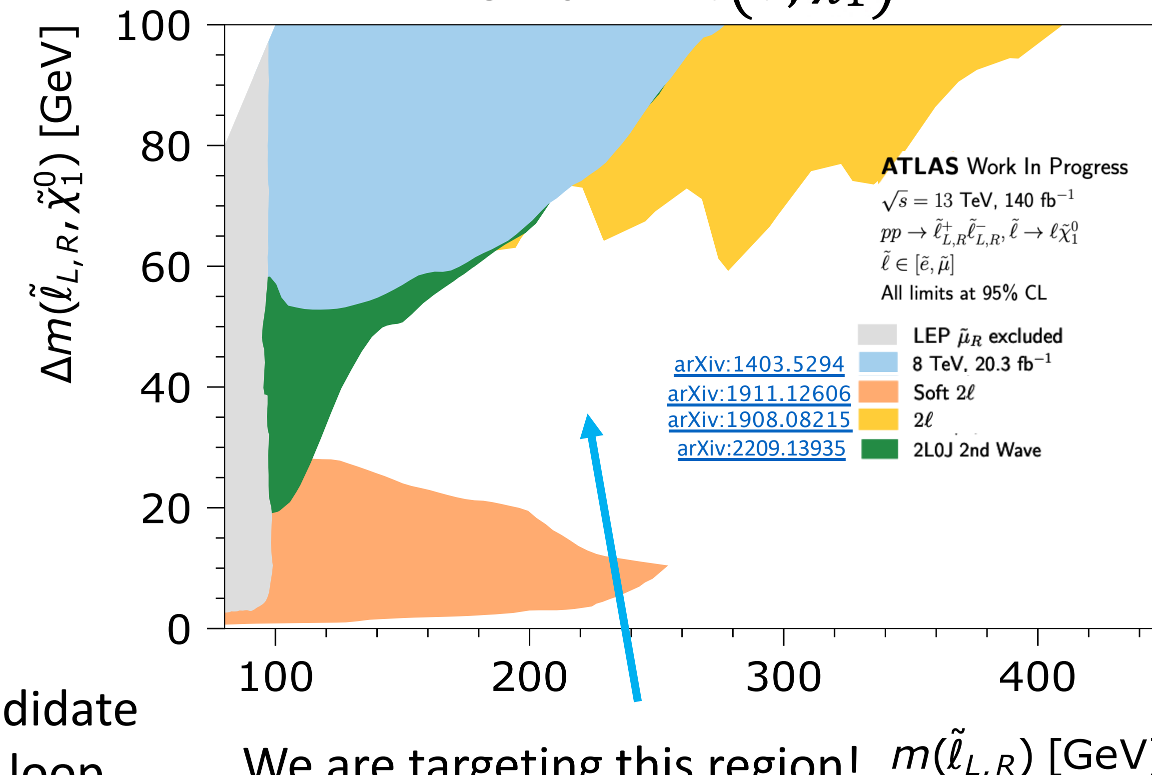

We are targeting this region!
Also not yet constrained by other experiments

Analysis Overview

Why is this region largely unexcluded?

- Low Pt leptons – large Fake/Non-Prompt lepton background
- Large $WW \rightarrow lvlv$ backgrounds
- Relatively low Missing transverse momentum (MET)

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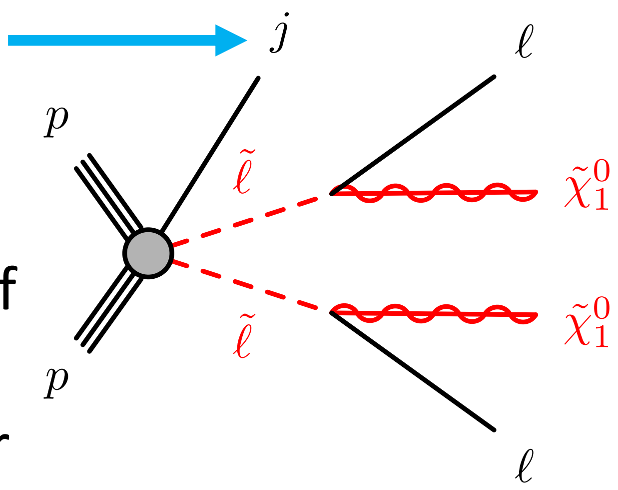
What do we do differently?

Require initial state radiation (ISR) Jet

Allows probing of lower Pt leptons as we can trigger on MET



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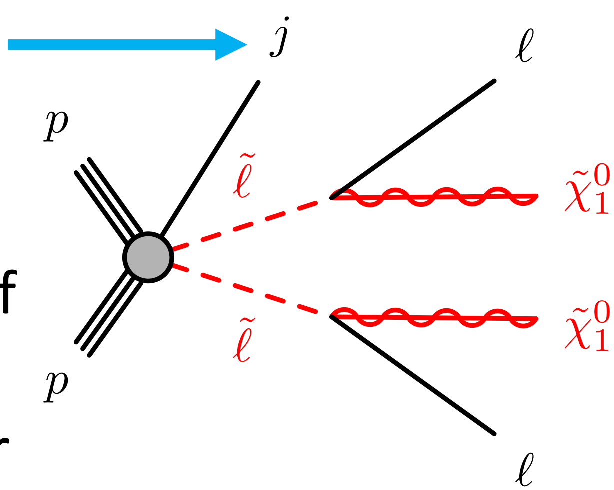
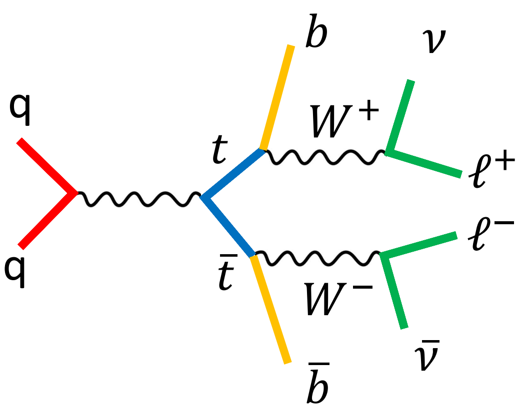
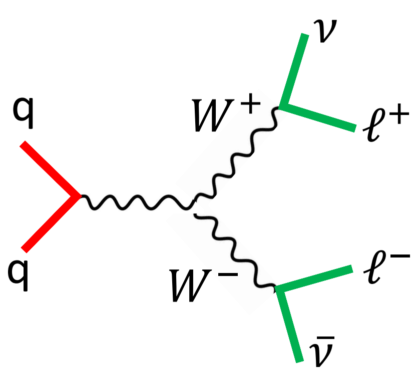


Allows probing of lower Pt leptons as we can trigger on MET

Strategy

- Cut based strategy: model independent limits + discovery SRs
- BDT strategy (me!): model dependent exclusion
- Will focus on my work
- Analysis is currently blinded

Major backgrounds and preselection

Dileptonic $t\bar{t}$	Diboson	Fake Non-Prompt (FNP) leptons
	 (majority WW)	Jets misidentified as leptons or leptons from secondary decays ↓ Estimated using data driven Fake Factor method

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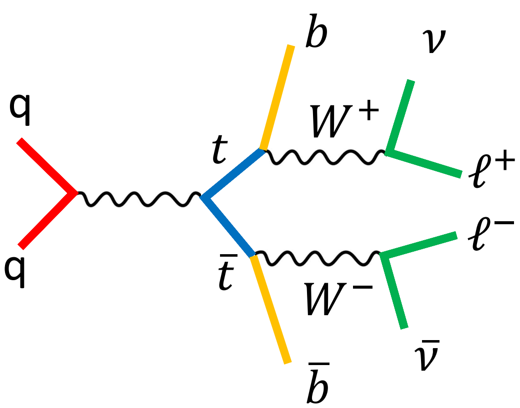
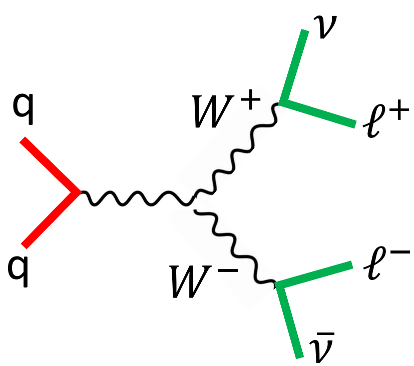


Diboson



(majority WW)

Fake Non-Prompt (FNP) leptons

Jets misidentified as leptons or leptons from secondary decays

↓

Estimated using data driven Fake Factor method

- Apply a loose preselection before BDT training – In words:
  - MET Trigger + MET cut to keep 100% efficiency in triggering
  - 2 Same Flavour Opposite Sign (SFOS) leptons
  - Cuts to reduce FNP lepton background
  - Cuts to enforce ISR topology
  - Veto Z boson decays, veto events with jets from B hadrons (bjets)

BDT Training

- Using the XGBoost package to train BDTs using binary classification
- Kinematics of signals change significantly across full range of Δm but similar for adjacent Δm

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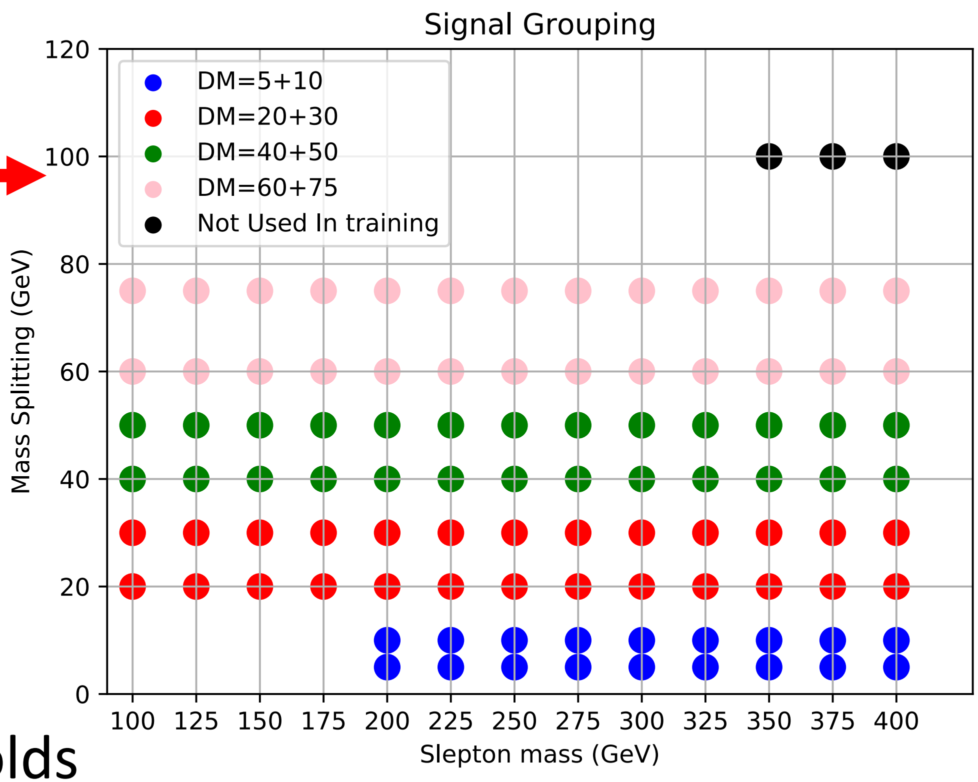
- Using the XGBoost package to train BDTs using binary classification
- Kinematics of signals change significantly across full range of Δm but similar for adjacent Δm
  - So, 5 BDTs are trained, signals grouped based on similar kinematics in key variables
    - Each BDT requires separate optimisation, validation and background estimation
  - Log loss as optimisation metric and used for early stopping to prevent overtraining
  - KFold cross-validation with 5 folds

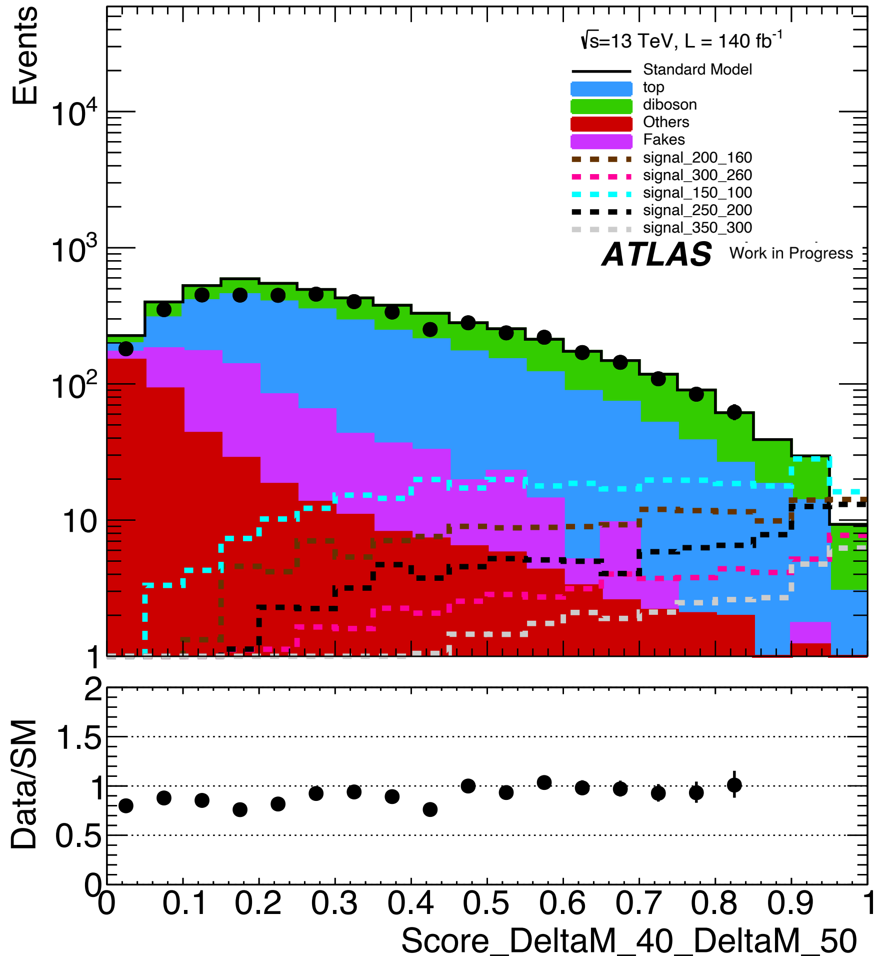


- Will focus on explaining Δm=40+50 BDT

Signal Regions

Signal format:
Smuon mass_neutralino mass

BDT Score distribution



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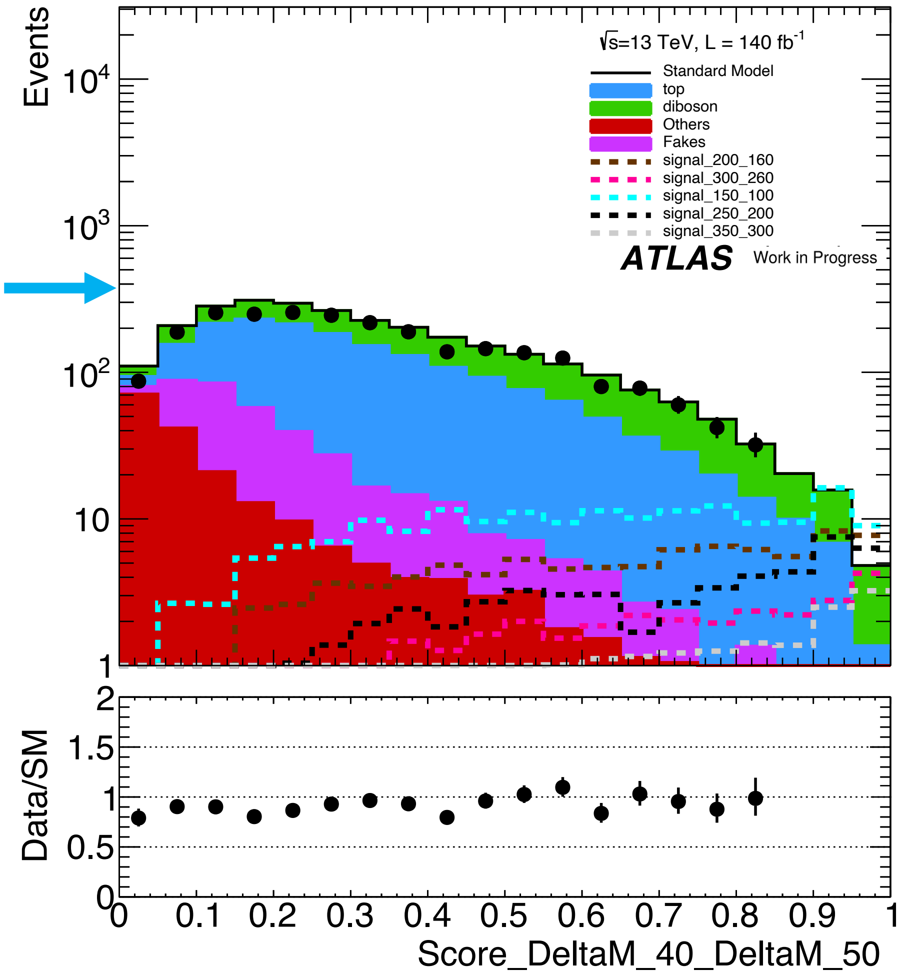
Signal Regions

To set limits on selectrons and smuons separately

BDT Score distribution

Require e^+e^-

Require $\mu^+\mu^-$



Signal Regions

Signal format:
Smuon mass_neutralino mass

To set limits on selectrons and smuons separately

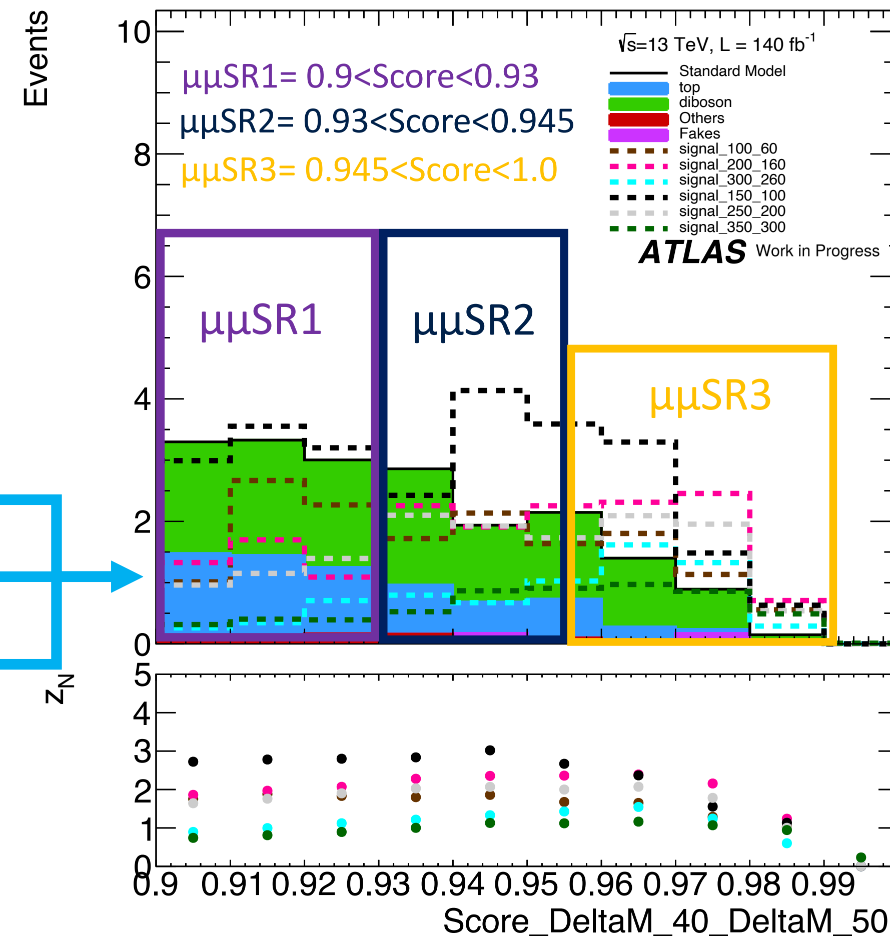
3 SRs per lepton flavour

BDT Score distribution

Require e^+e^-	Require $\mu^+\mu^-$
eeSR1	μμSR1
eeSR2	μμSR2
eeSR3	μμSR3

So overall 6 SRs

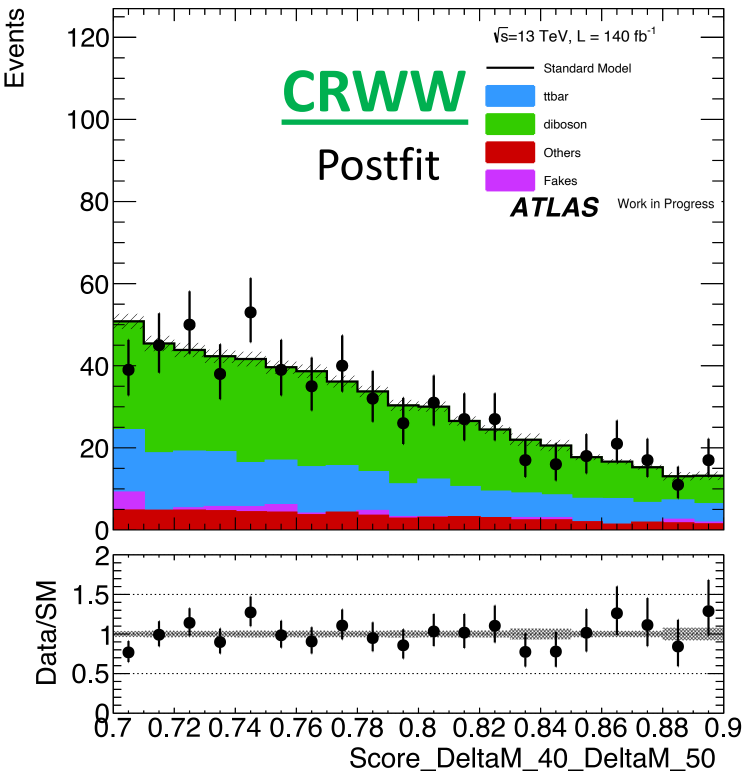
μμSR example



Background estimation

Bold cuts provide orthogonality with SR

- Background only fit: define control regions targeting: WW



0.7 < BDT Score <0.9
Require 2 Opposite sign leptons
Bjet veto, Z Decay Veto

Along with training cuts

Background estimation

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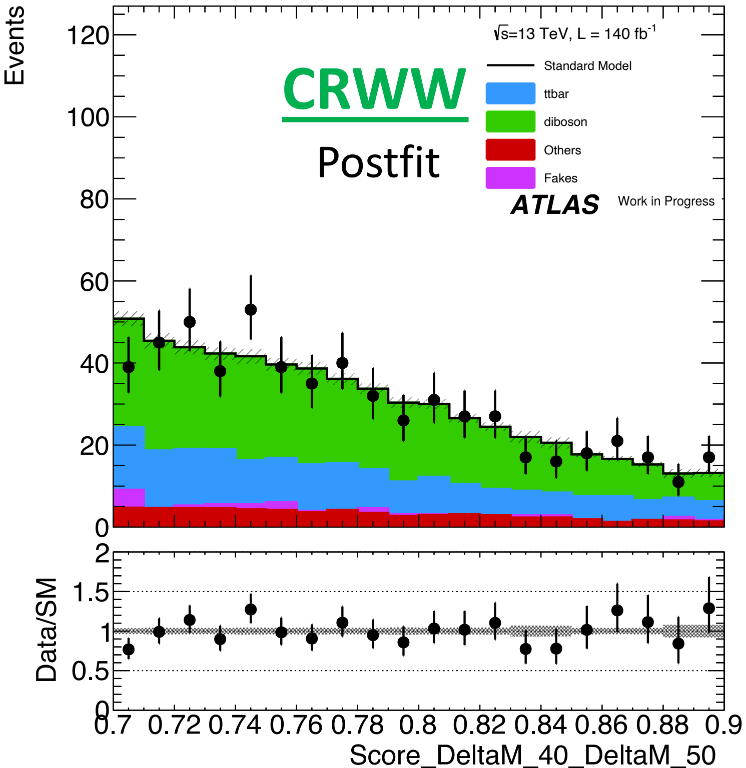

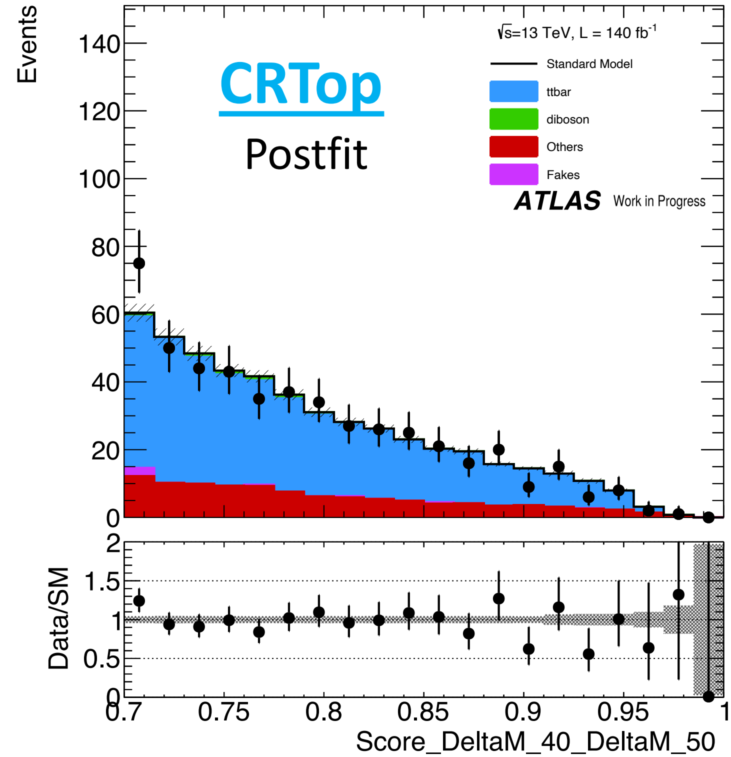

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Along with training cuts

BDT Score > 0.7
Require e^+e^- or $\mu^+\mu^-$
Bjets > 0 , Z Decay Veto

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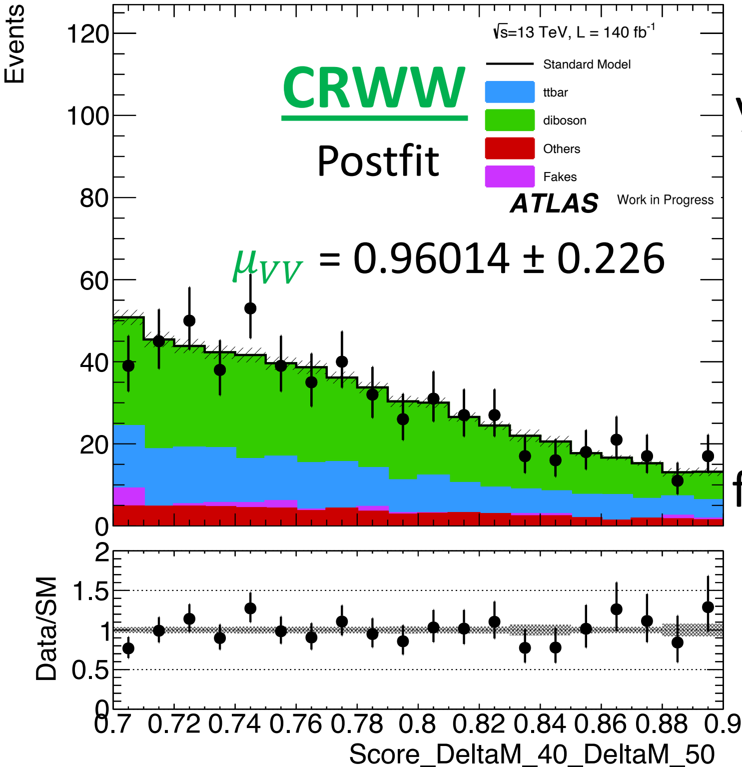
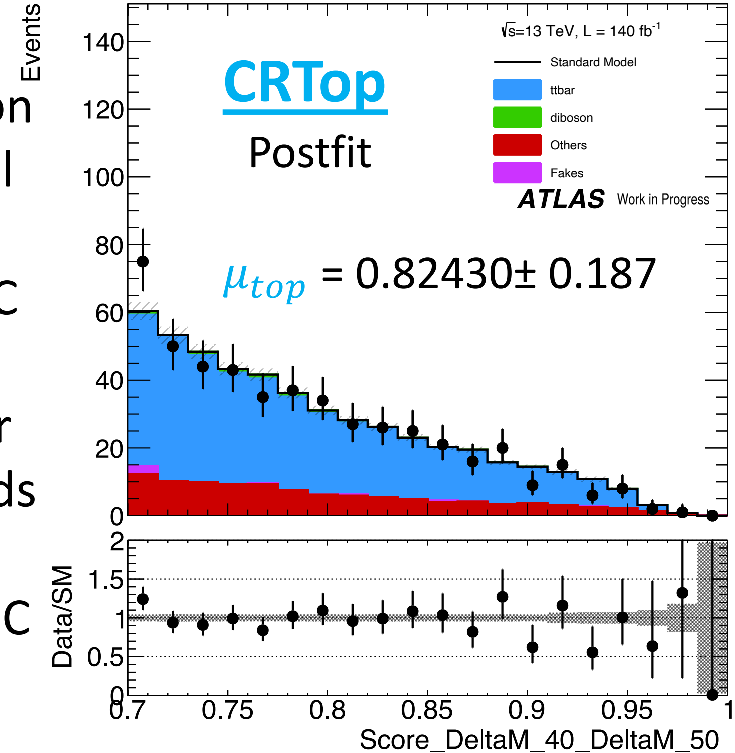


Compare Data/MC yields in similar region to SRs but low signal

Keep shape from MC but extract normalisation factor for major backgrounds

Helps to constrain MC uncertainties



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Along with training cuts

BDT Score > 0.7
Require e^+e^- or $\mu^+\mu^-$
Bjets > 0 , Z Decay Veto

Validation Regions

- Only cuts orthogonal to the training preselection are shown

Cuts

Postfit VRs for Δm=40+50 BDT

DFVR

BDTScore > 0.9
Require $e^+\mu^-$ or μ^+e^-
Bjet Veto, Z veto

DFVR Bjet

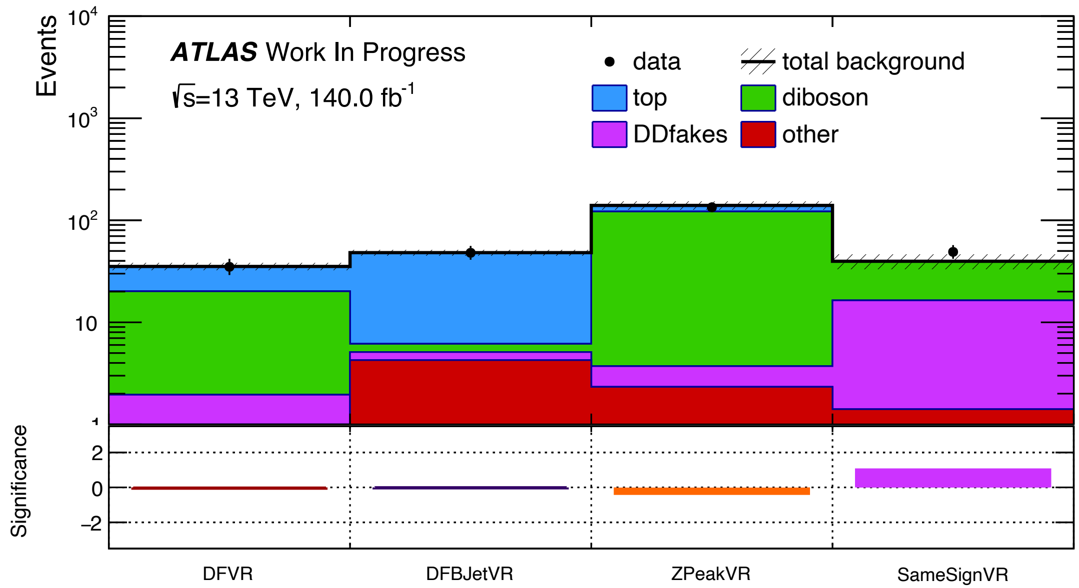
BDTScore > 0.9
Require $e^+\mu^-$ or μ^+e^-
Bjets > 0, Z veto

ZPeak VR

BDTScore > 0.7
Require $e^+\mu^-$ or μ^+e^-
Bjet Veto, **Z selection**

Same Sign VR

BDTScore > 0.9
Require 2 Same sign leptons
Bjets > 0, Z veto



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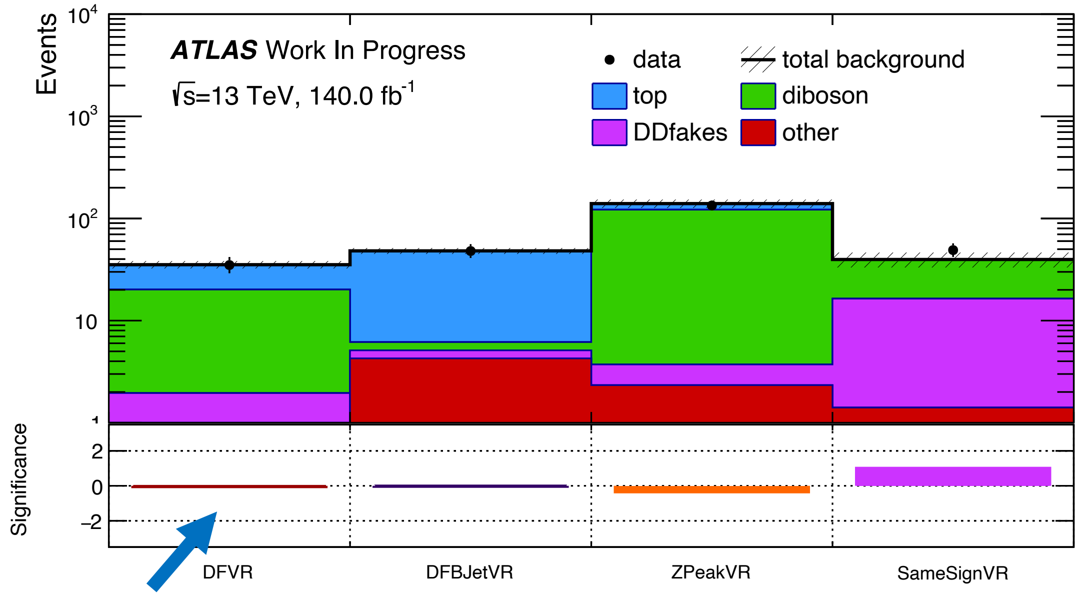
Cuts

Region	Cuts
DFVR	BDTScore > 0.9 **Require $e^+\mu^-$ or μ^+e^-** Bjet Veto, Z veto
DFVR Bjet	BDTScore > 0.9 **Require $e^+\mu^-$ or μ^+e^-** **Bjets > 0,** Z veto
ZPeak VR	BDTScore > 0.7 **Require $e^+\mu^-$ or μ^+e^-** Bjet Veto, **Z selection**
Same Sign VR	BDTScore > 0.9 Require 2 Same sign leptons **Bjets > 0,** Z veto

Postfit VRs for ∆m=40+50 BDT



Main VR - should be kinematically very similar to SR due to flavour universality

Good Data/MC agreement in VRs shows that the background estimation is accurate and can be used in the SRs

Exclusion Fit

- Carry out 3 shape fits: electron SRs only, muon SRs only, and using both sets of SRs together.
- Compare the background only prediction and the signal + background prediction to data and extract a CLs value.
- For each signal and each BDT: If CL_s > 95% we ‘exclude’ the signal

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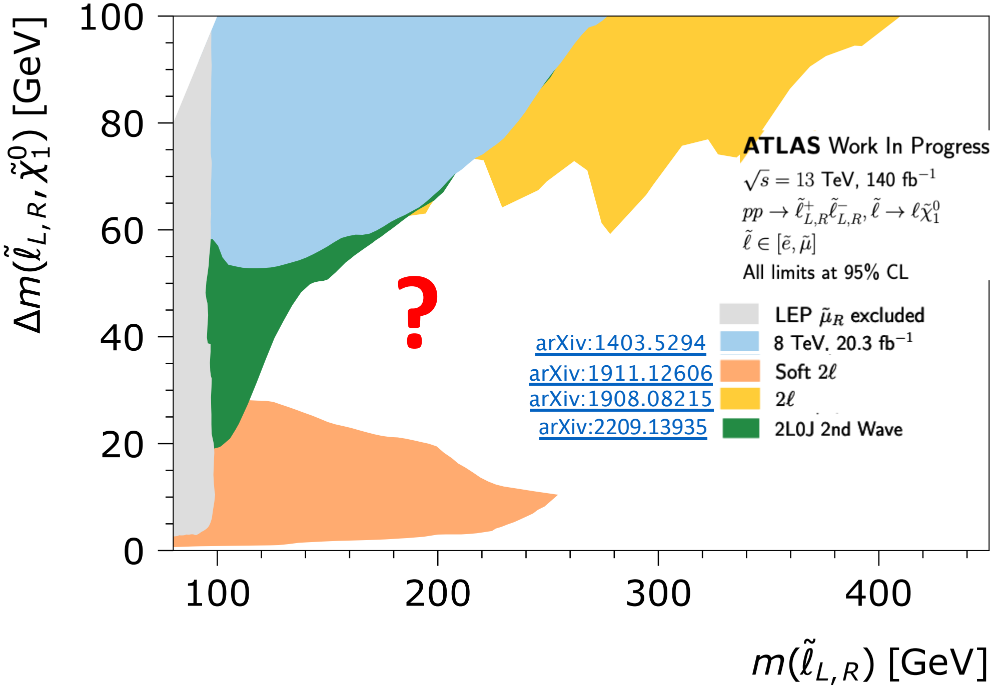
- Draw an exclusion contour:



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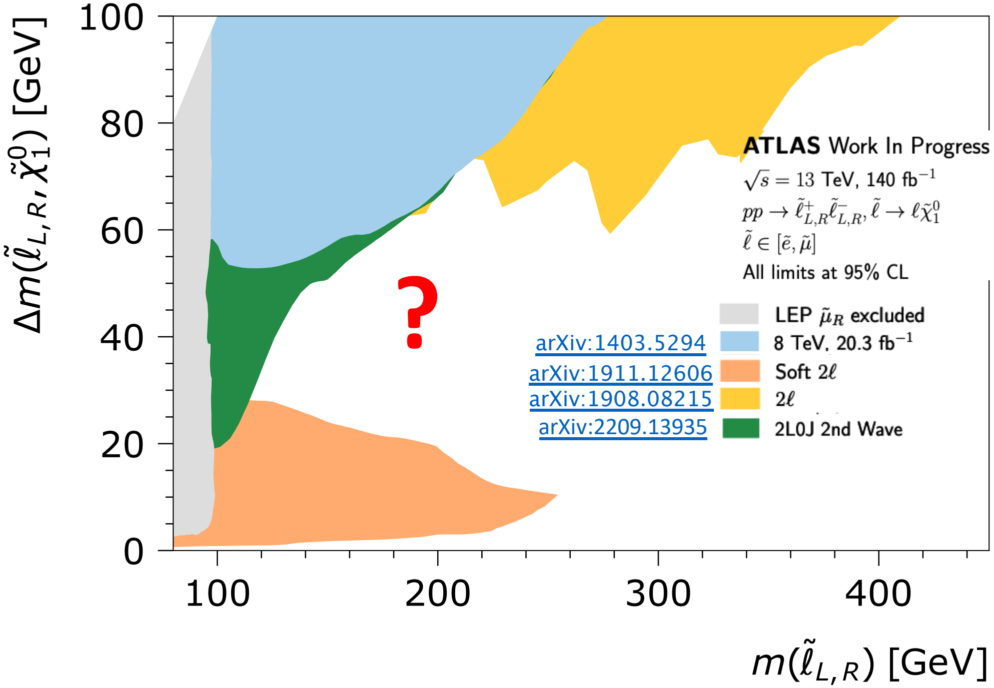
- For each signal and each BDT: If CL_s > 95% we 'exclude' the signal
- Draw an exclusion contour:
- Leading systematics are:
    - For all BDTs: uncertainty on resolution of jet energy
    - At low ΔM: FNP lepton uncertainties
    - At high ΔM: MET uncertainties



Summary and conclusion

- This talk summarised an ongoing ATLAS effort to search for Supersymmetry
  - Targeting small $\Delta m\left(\tilde{\ell}, \tilde{\chi}_1^0\right)$ signals with an ISR jet
- The analysis utilises Machine Learning (BDTs) to carry out binary classification and from score distributions:
  - Define control and validation regions – to carry out the background estimation
  - Define signal regions - which are then used in a shape fit to provide exclusion limits
- Projects to give a significant improvement on current ATLAS limits in this very interesting region where SUSY can explain the g-2 anomaly and provide a Dark Matter candidate

Backup

Preselection Cuts → Reasoning

Preselection Cuts	Reasoning
2 Same Flavour Opposite Sign leptons No B jets	Signal model
MET trigger passed Offline MET>200 GeV	MET Trigger + turnon efficiency
m_{ll}> 101.2 GeV, m_{ll} <81.2. GeV	Z Veto
Lepton pt >6 GeV	Lowest Pt for reliable fakes + isolation
R_{ll}>0.75	To deal with isolation + fakes modelling
$\Delta\phi_{J1,MET}$ >2.0 min($\Delta\phi_{CentralJets,MET}$) >0.4 At least 1 Jet, Leading Jet Pt>100 GeV	ISR Selection
$N_{J30} < 3$	Only for cut based analysis

Main Backgrounds

- Main Backgrounds are:
  - Diboson -> Sherpa (mix of 2.2.12 and 2.2.2)
  - Leptonic tt ->PowHegPythia8
  - Fakes (at low Pt) -> using Data Driven Fakes estimate

With BDT preselection cuts applied →

Background	Percentage
tt	40%
VV	30%
Fakes (Data Driven estimate)	15%
$Z\tau\tau$	5%
Single Top	5%
Other	5%

ATLAS EXPERIMENT

Data Driven Fakes method explanation

- MC Fakes do not model the fake background well at low pt so lots of work put into the Data Driven Fakes estimate
- Define Control sample (Dijet events passing prescaled single lepton triggers) and extract a fake factor using:

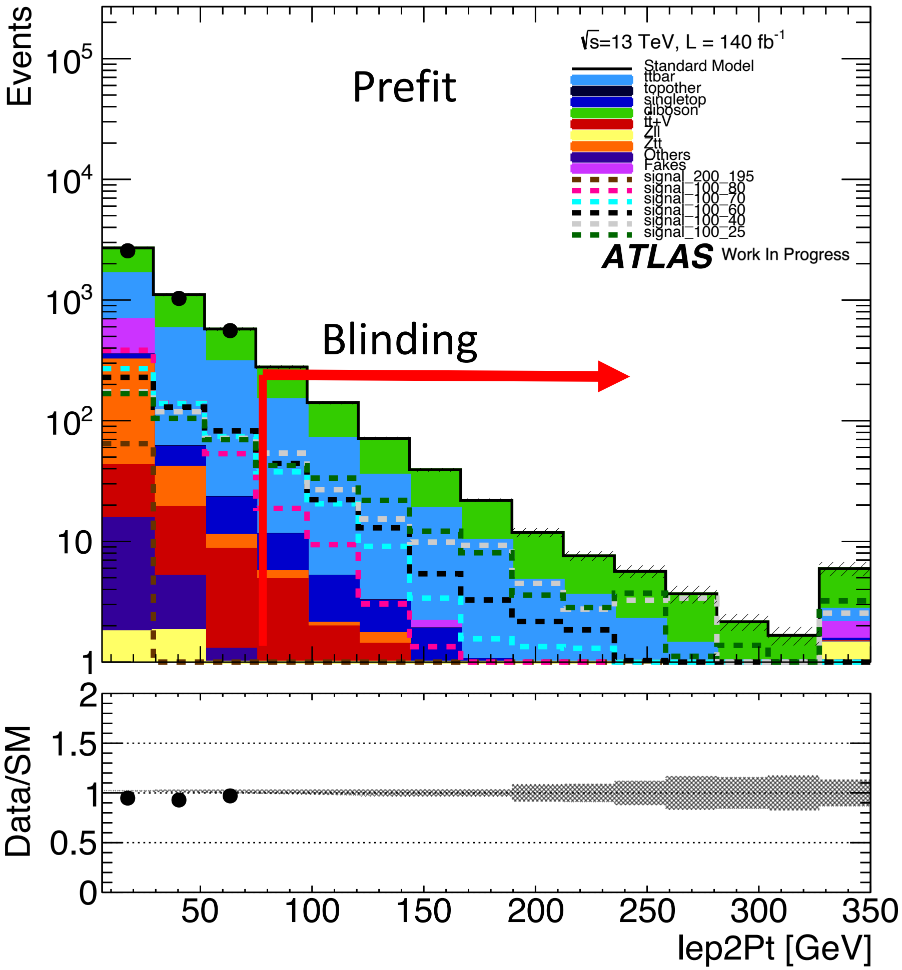
Where i is a correlated variable (pt, nbjet for us)

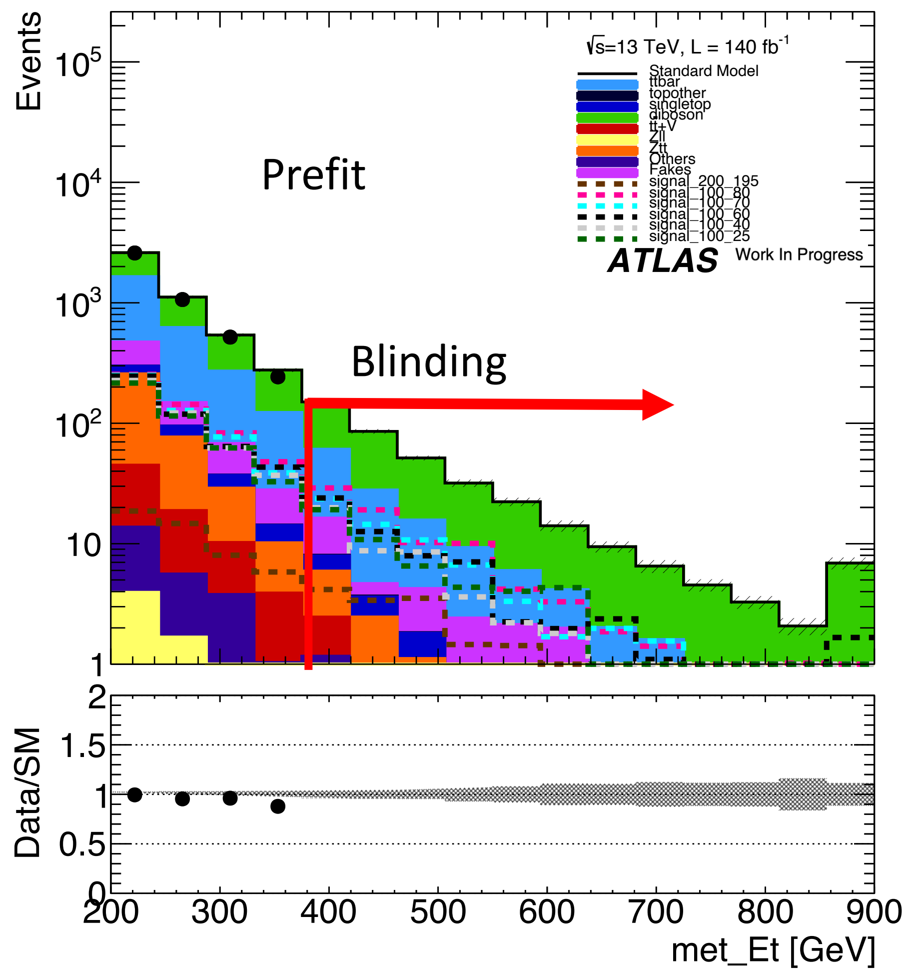
$$F(i) = \frac{N_{\mathrm{ID}}(i) - N_{\mathrm{ID}}^{\mathrm{Prompt\ MC}}(i)}{N_{\mathrm{anti-ID}}(i) - N_{\mathrm{anti-ID}}^{\mathrm{Prompt\ MC}}(i)}$$

- Then apply F to anti ID leptons in the data
- And verify with (one or more) Same Sign VRs
- Work on systematic uncertainty underway
- Everything shown will use the Data Driven Fakes

Training Preselection distributions

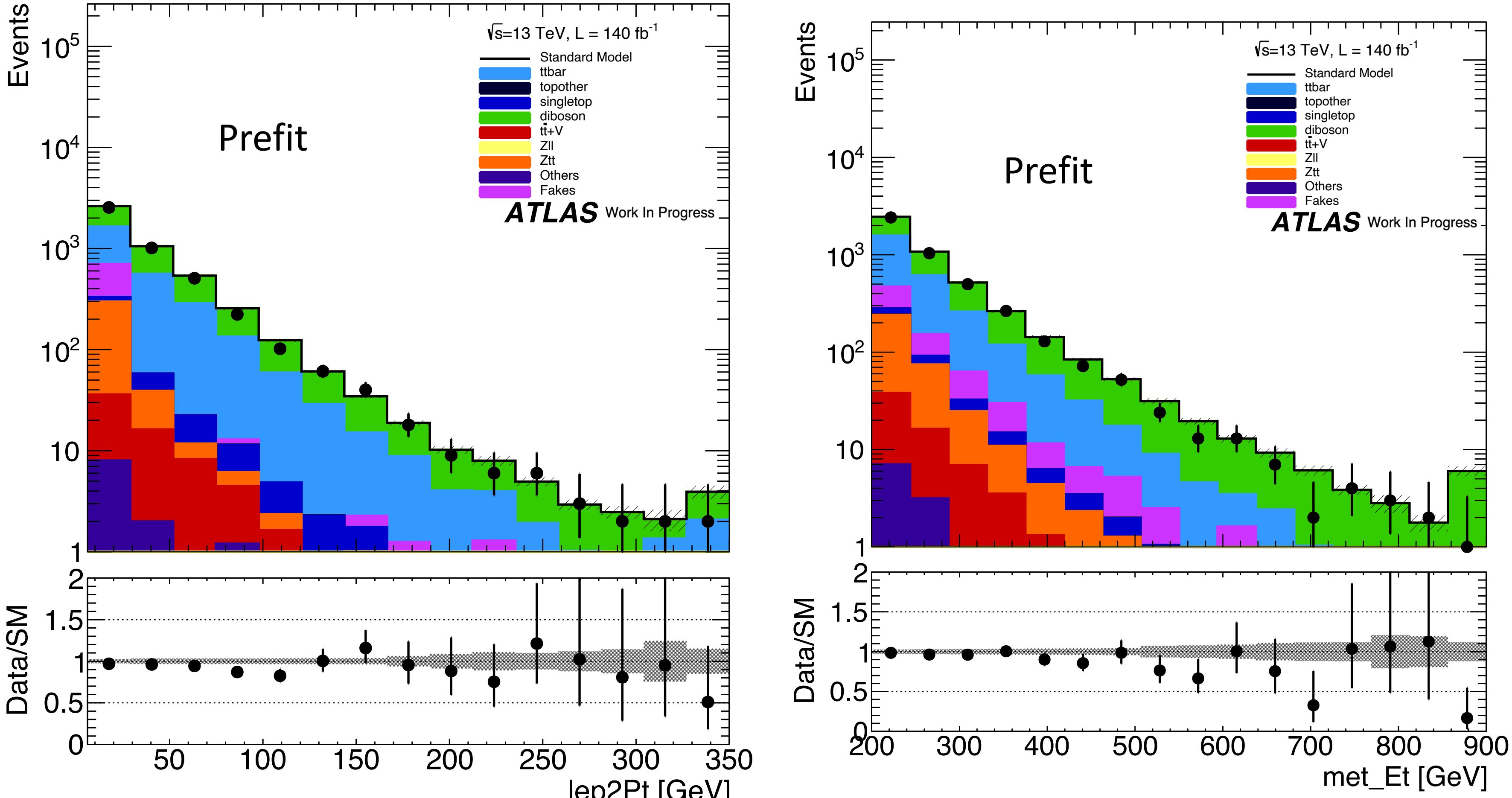
- Same Flavour with preselection + Bjet, Z peak veto, no BDT score cut





Data/MC for Different flavour

- Can unblind fully and get an idea of modelling in the regions the BDT uses



Different Flavour with preselection + Bjet, Z peak veto, no BDT score cut

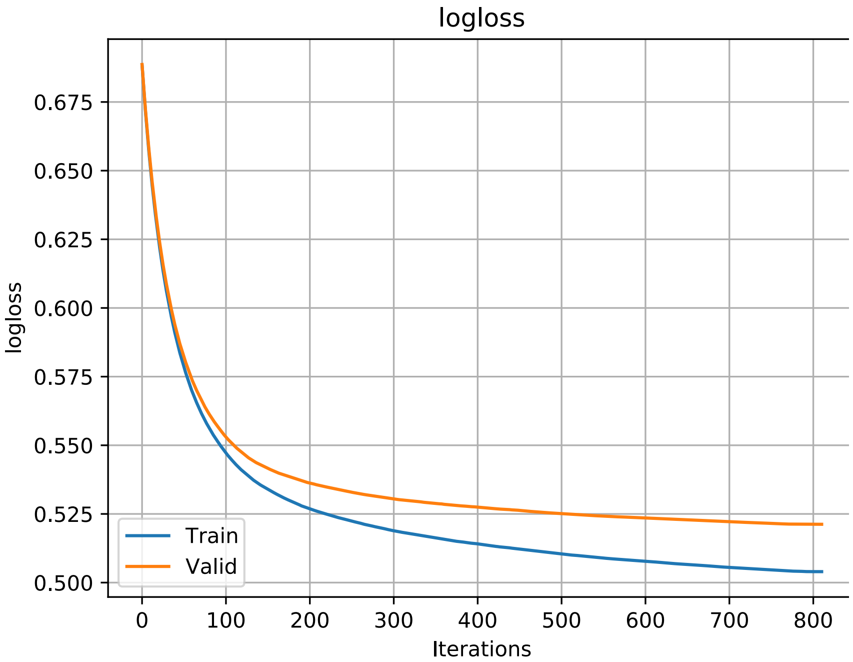
Training Variables

Variable
$p_{\mathrm{T}}^{\ell_1}$ and $p_{\mathrm{T}}^{\ell_2}$
$p_{\mathrm{T}}^{\ell\ell}$
$m_{\ell\ell}$
$m_T^{\ell_1}$ and $m_T^{\ell_2}$
$E_{\mathrm{T}}^{\mathrm{miss}}$
$E_{\mathrm{T}}^{\mathrm{miss}}$ significance
$\Delta\phi(\ell_1, E_{\mathrm{T}}^{\mathrm{miss}})$ and $\Delta\phi(\ell_2, E_{\mathrm{T}}^{\mathrm{miss}})$
$\Delta\phi(j_1, E_{\mathrm{T}}^{\mathrm{miss}})$
$p_{\mathrm{T}}^{j_1}$ and $p_{\mathrm{T}}^{\mathrm{2nd}}$
ΔR
$M_{\tau\tau}$
$\cos\theta_{\ell\ell}^{*}$ and $\cos\theta_{\ell\ell}^{V}$
m_{T2}, with invisible mass $0, 50, 100, 150, 200$ and 300 GeV

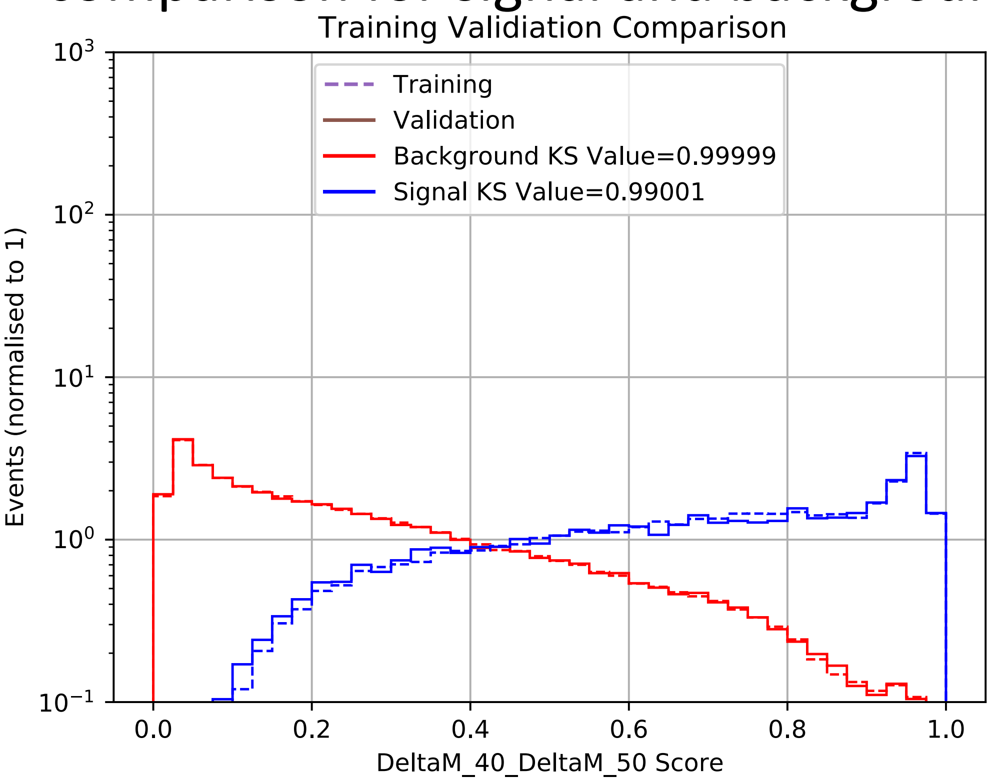
BDT Diagnostic Plots

For first Fold of ∆m=40+50 BDT

Logloss for training and validation



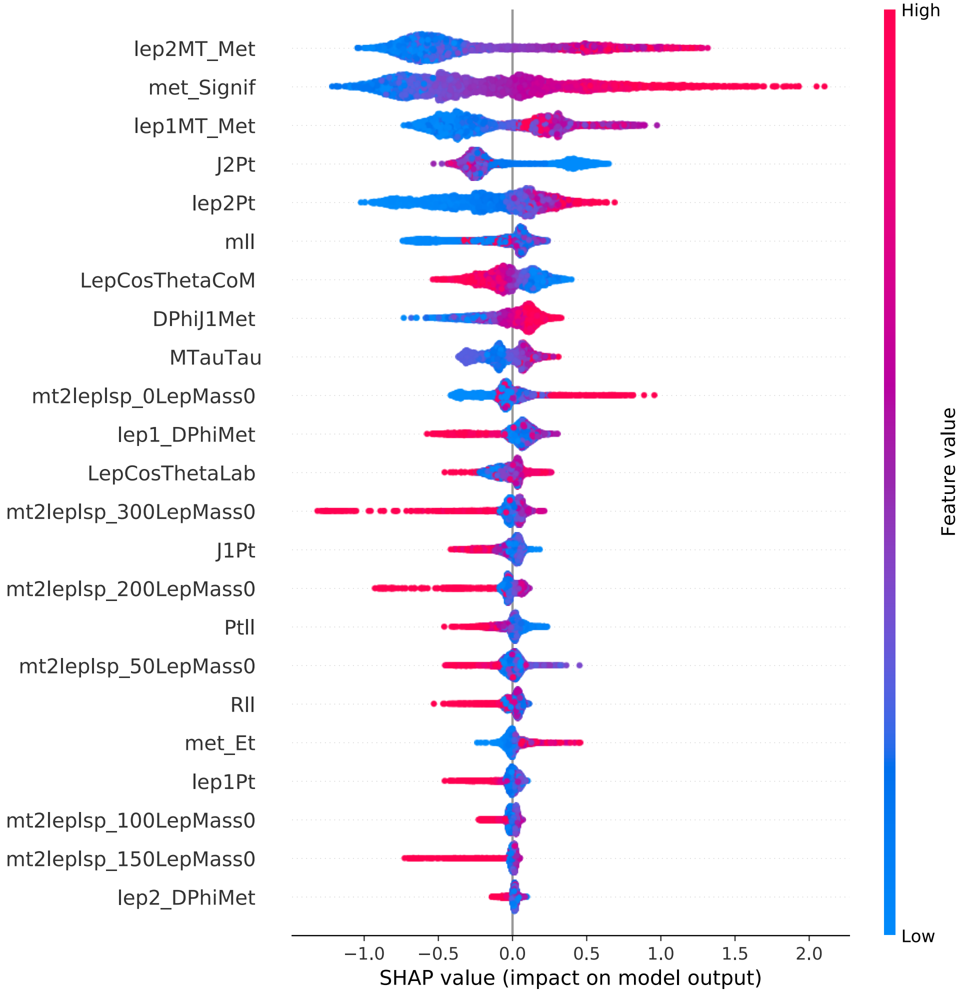
Training, validation distribution comparison for signal and background



Calculate Kolmogorov–Smirnov(KS) score – closer to 1 more similar the distributions

Important variables

- Explain BDT models using SHAP scores



More signal-like

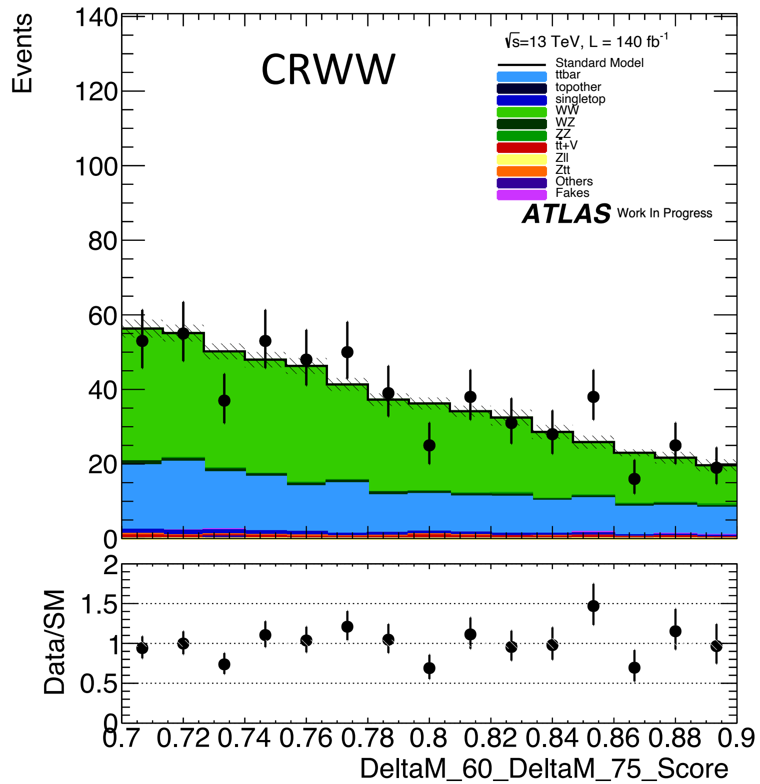
High values of Transverse mass
High MET significance

More background-like

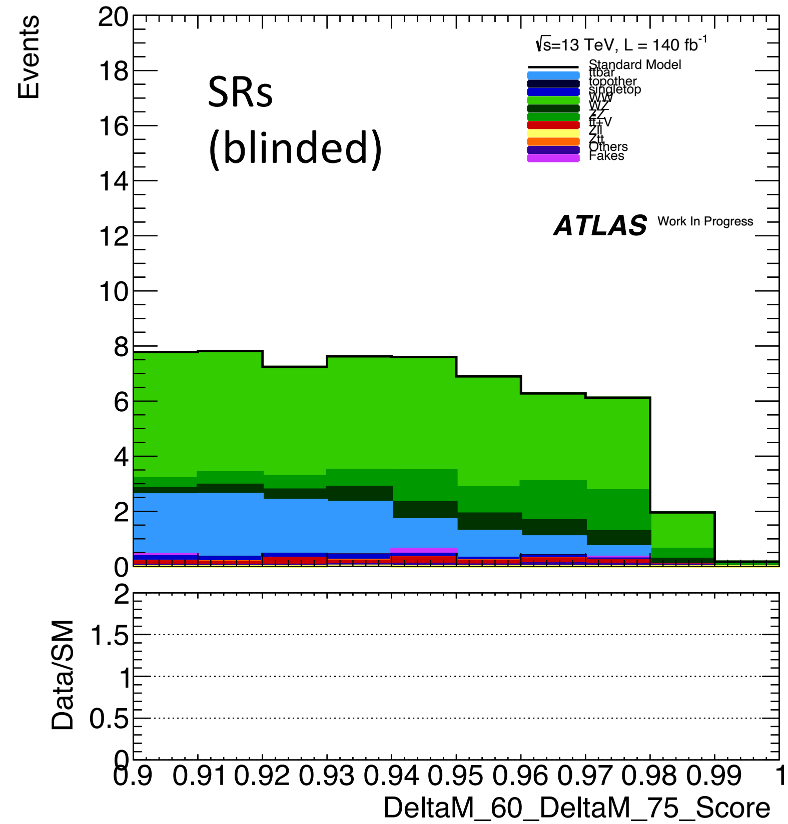
High values of MT2
Low subleading lepton Pt

Diboson Breakdown

Using powheg to split diboson into, WW,ZZ,WZ



Can clearly see the CR is almost entirely WW.



The SR is not however, hence the need for the ZPeakVR