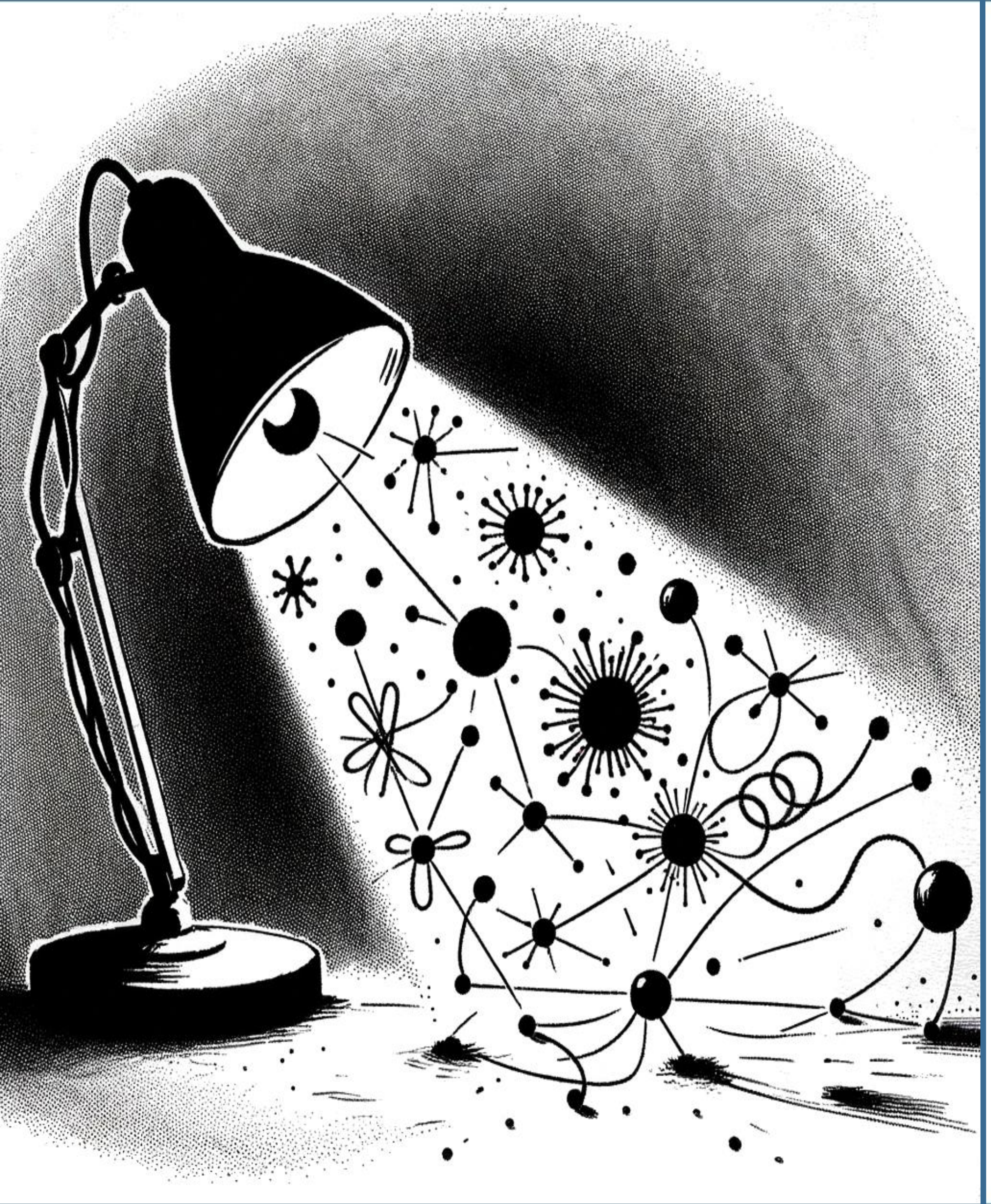


IoP HEPP Conference

Searching for Dark Matter in the Light of dark-Higgs Strahlung

Tim Brückler

Supervision: James Frost

Introduction

Dark-Matter:

-> Indirect evidence through gravitational effects

-> Standard Model: lack of valid candidate

-> BSM theories: postulating additional particles: e.g. WIMPs

Searches for Dark-Matter:

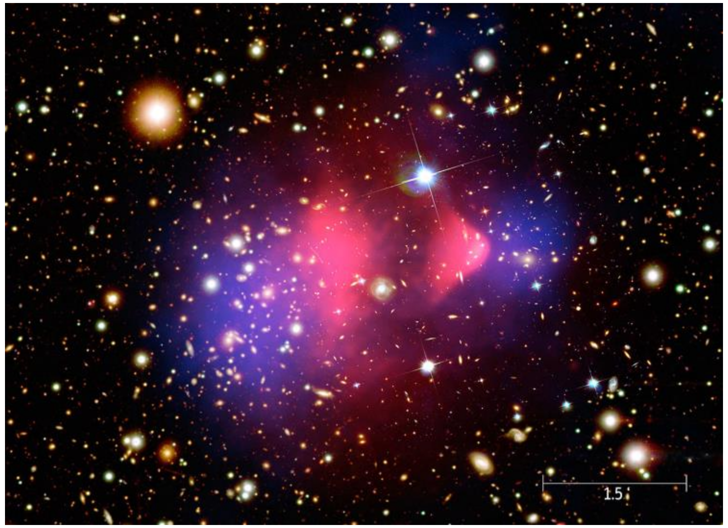
-> DM escapes detector

-> If visible radiation: Missing momentum

-> Search for X + E_T^{miss}

-> X = jets, photons, vector bosons

This talk: X = dark-Higgs $s \rightarrow hh \rightarrow 4b$

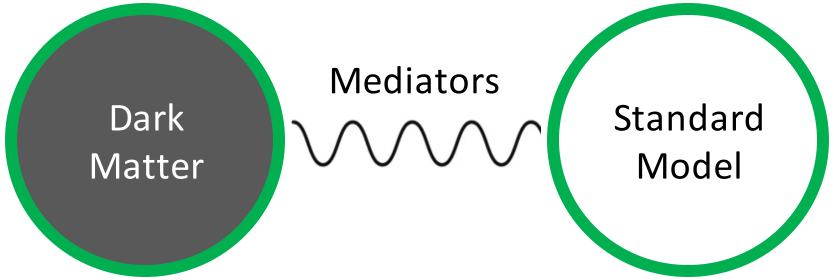


Evidence for dark matter: the *Bullet Cluster*.

Dark-Higgs Model - Introduction

Simplified Models:

-> Introduce single Z' between SM and DM
  -> Strong experimental constraints
    -> Small coupling to SM
      -> DM overproduction



Dark-Higgs Model:

-> Introduce U(1)' gauge group
  -> DM mass generated by Higgs mechanism in dark sector
  -> Two additional massive mediators: dark-Higgs and Z'
    -> Weaker experimental constraints
    -> Easier satisfaction of relic density constraints

Dark-Higgs Model

Interactions with Standard Model:

-> Z' couples to quarks

-> Dark-Higgs mixes with SM Higgs:

  -> Decay to SM Higgs, vector bosons or b-quarks

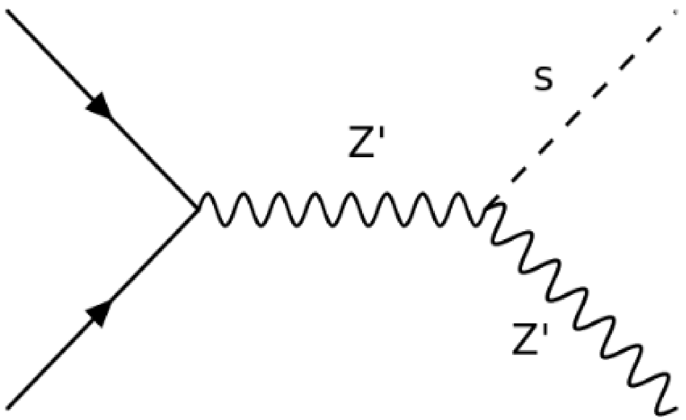
Interaction in dark sector:

-> Dark-Higgs strahlung: $Z'^* \rightarrow Z' + s$

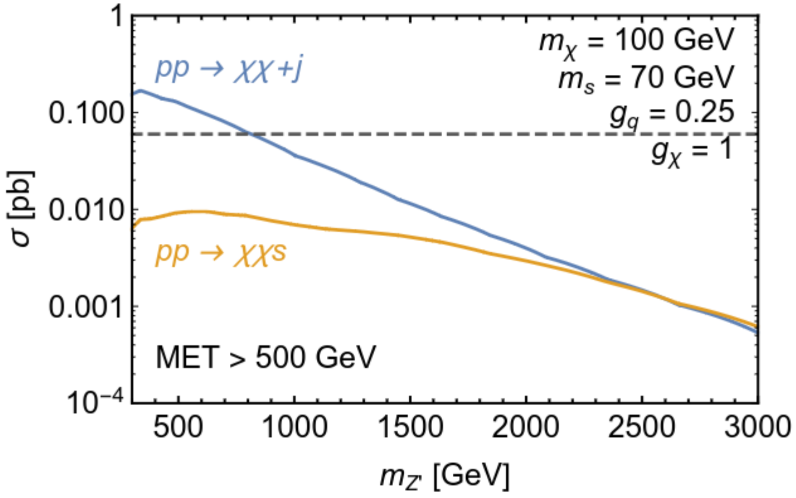
-> High chance of high E_T^{miss} at high $M_{Z'}$

  -> Only slowly declining cross-sections

  -> Expect sensitivity to high Z' masses



Dark-Higgs strahlung process.



Dark-Higgs strahlung cross-section.*

* https://arxiv.org/pdf/1701.08780.pdf

Dark-Higgs Model in ATLAS

Previous Searches:

-> Existing analyses for multiple channels:

-> s → bb: ATLAS-CONF-2024-004

-> s → WW/ZZ, DOI: 10.1103/PhysRevLett.126.121802

-> s → WW, DOI: 10.1007/JHEP07(2023)116

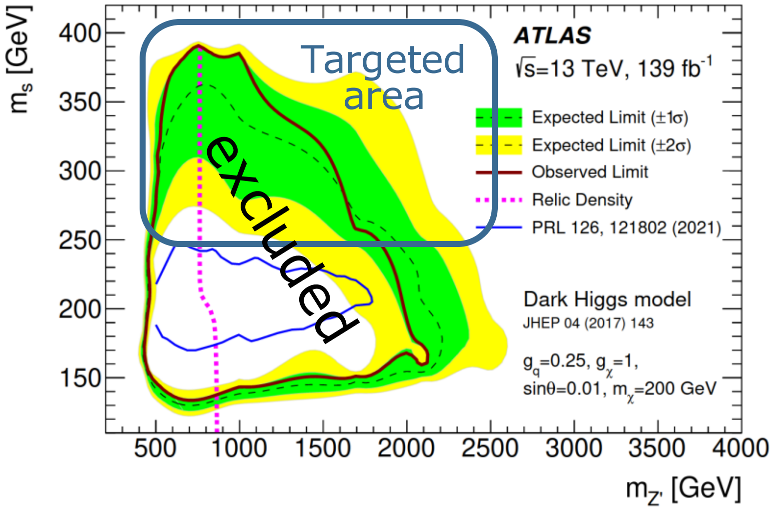
Target for this analysis:

-> Dark-Higgs → hh

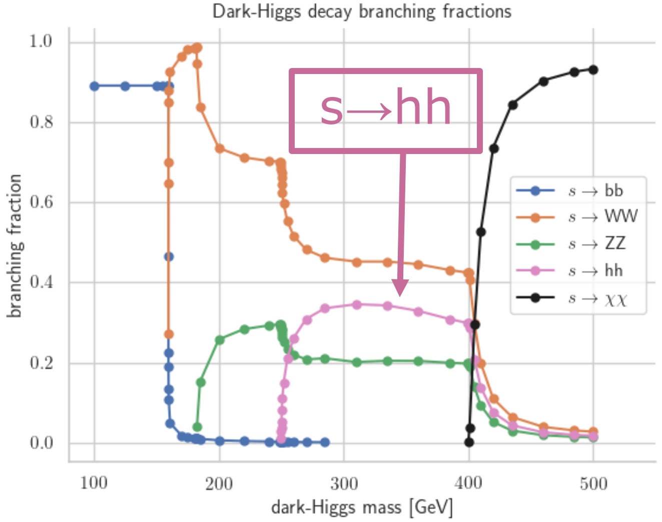
-> First search for resonant di-Higgs + E_T^{miss}

-> Four-b final state offers highest branching ratio

arXiv:2211.07175



Current best exclusion limits on dark-Higgs model with high M_s.



Dark-Higgs decay branching fractions.

Analysis Strategy

Kinematic Selection:

-> Reduce main backgrounds: semi-leptonic ttbar decays
-> Remove challenging multi-jet QCD background
-> Remaining main background: Z+jets, ttbar, single-top

Machine Learning:

-> Use full power of kinematic differences between signal and background
-> Generalisability: Only one network trained for all signal points
-> Physical Interpretability: Decouple output-score from M_{hh}

Fit di-Higgs mass distribution:

-> Background estimation in dedicated control regions
  -> Correct normalisation of SM processes in enriched regions
-> Compute exclusion limits

tim.lukas.bruckler@cern.ch

Kinematic Selection

E_T^{miss} Triggers:

-> Retain full efficiency: $E_T^{miss} \geq 200$ GeV

Kinematic preselection:

-> $N_{jets} \geq 4$ (≥ 3 b-tagged)

-> Select on S(E_T^{miss}) and Δφ of E_T^{miss} and b-jets

-> Remove QCD multi-jet background

-> Select on m_T (transverse mass) of b-jets

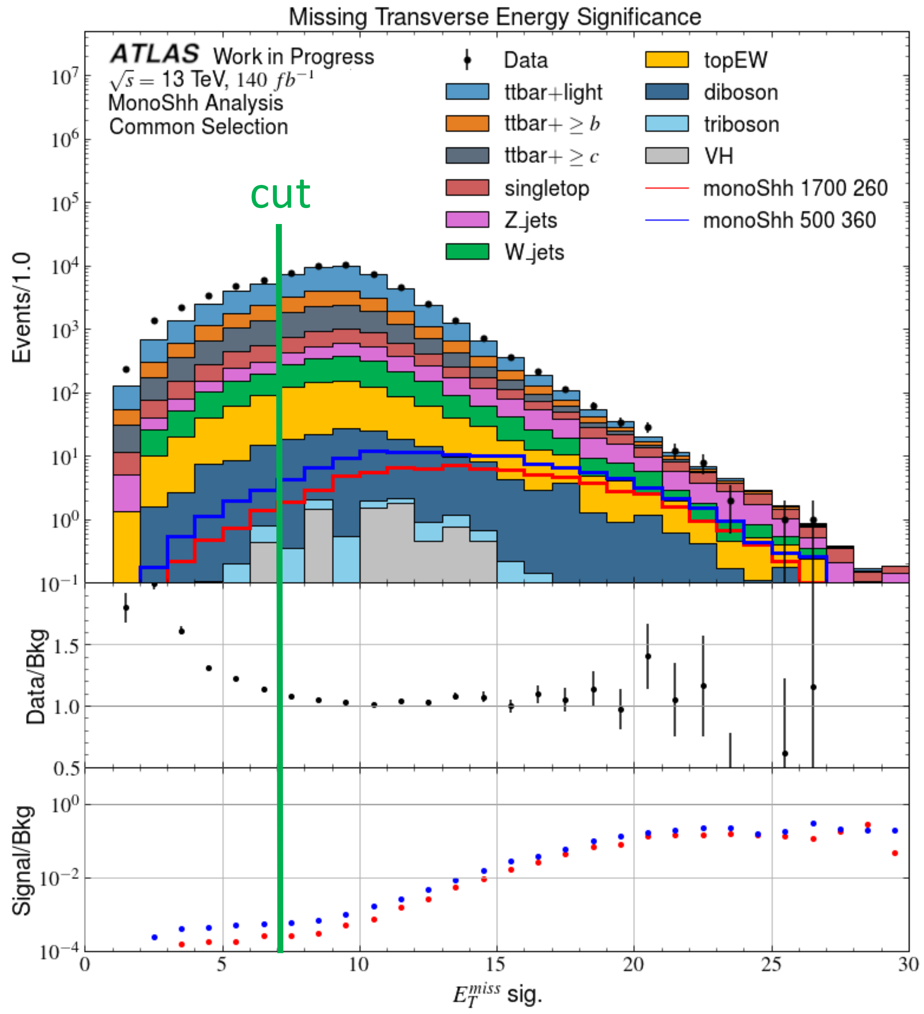
-> Reduction of ttbar background

Dominant Remaining backgrounds:

-> ttbar, Z+jets and single-top

-> Multi-jet background negligible

-> Fully MC based background estimation



Example of highly discriminating variable: E_T^{miss} significance.
Mis-modelling at low values due to QCD background.

Higgs Reconstruction

1) Selecting jets:

-> Select four leading b-jets
  -> If N_{jets} == 3:
    -> If heavy jet: assumed to be merged
    -> Otherwise add untagged jet

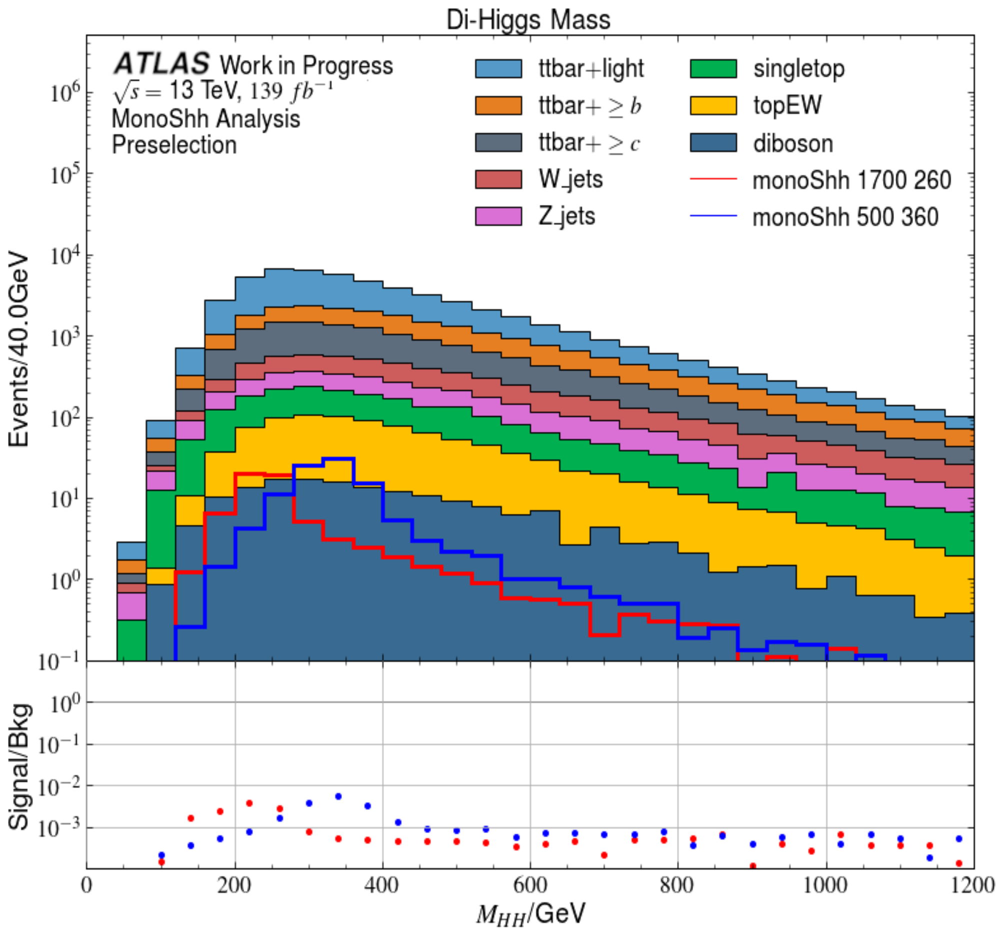
2) Higgs Candidates:

-> In case of heavy jet:
  -> Second candidate formed from other jets
-> Else:
  -> Pair jets by minimising max($\Delta R_{Higgs-1}$, $\Delta R_{Higgs-2}$)

ΔR = Lorentz inv. angular separation of decay products

3) Dark-Higgs:

-> Reconstructed from two Higgs candidates



Di-Higgs mass distribution after pre-selection.

Machine Learning

Further background reduction using neural net

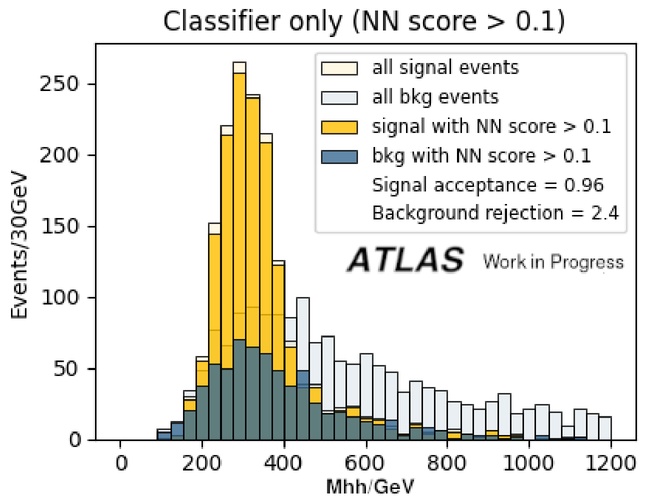
Little mass dependence on signal-point

-> Single neural net training using all events

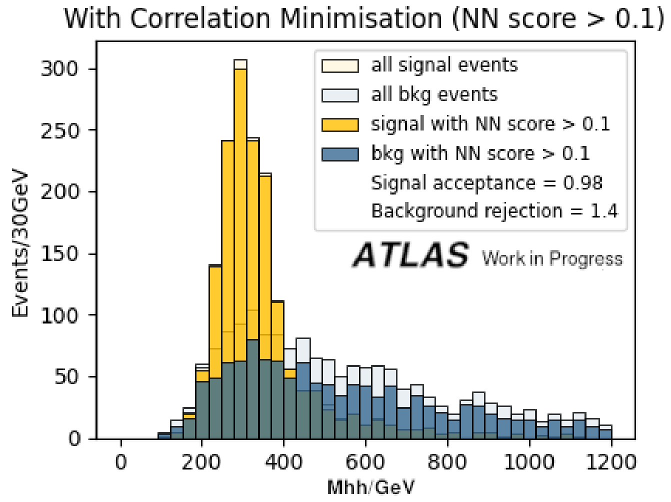
Di-Higgs distribution:

-> M_{hh} distributions of signal and bkg differ significantly
-> Observe strong sculpting when applying cut
-> Lose benefit of fitting physical variable
-> Solution: Add correlation term to loss-function:

$$\text{Total Loss} = \alpha * \underbrace{L_{BCE}(y, \hat{y})}_{\text{Binary cross-entropy for discrimination}} + (1-\alpha) * \underbrace{r_{X_{m_{HH}}, \hat{Y}}}_{\text{Distance-correlation}}$$



Di-Higgs mass distribution without decorrelation.



Di-Higgs mass distribution with decorrelation.

Signal Region

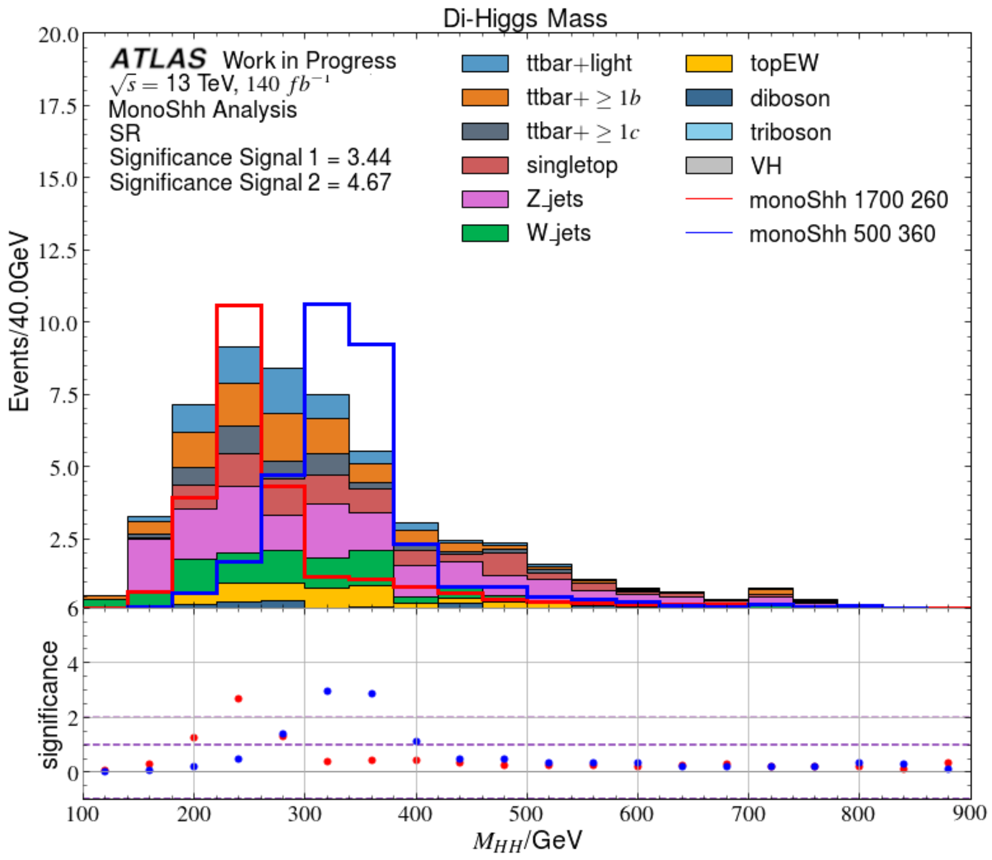
Multiple bins in di-Higgs mass

-> Events with high neural net score

-> Good resolution of dark-Higgs mass-peak

-> Single SR definition for all mass-points

-> Physical interpretability of results



Prefit di-Higgs mass distribution in signal region with two representative signal points shown.

Background Estimation

Analysis region definitions:

-> Based on neural network score

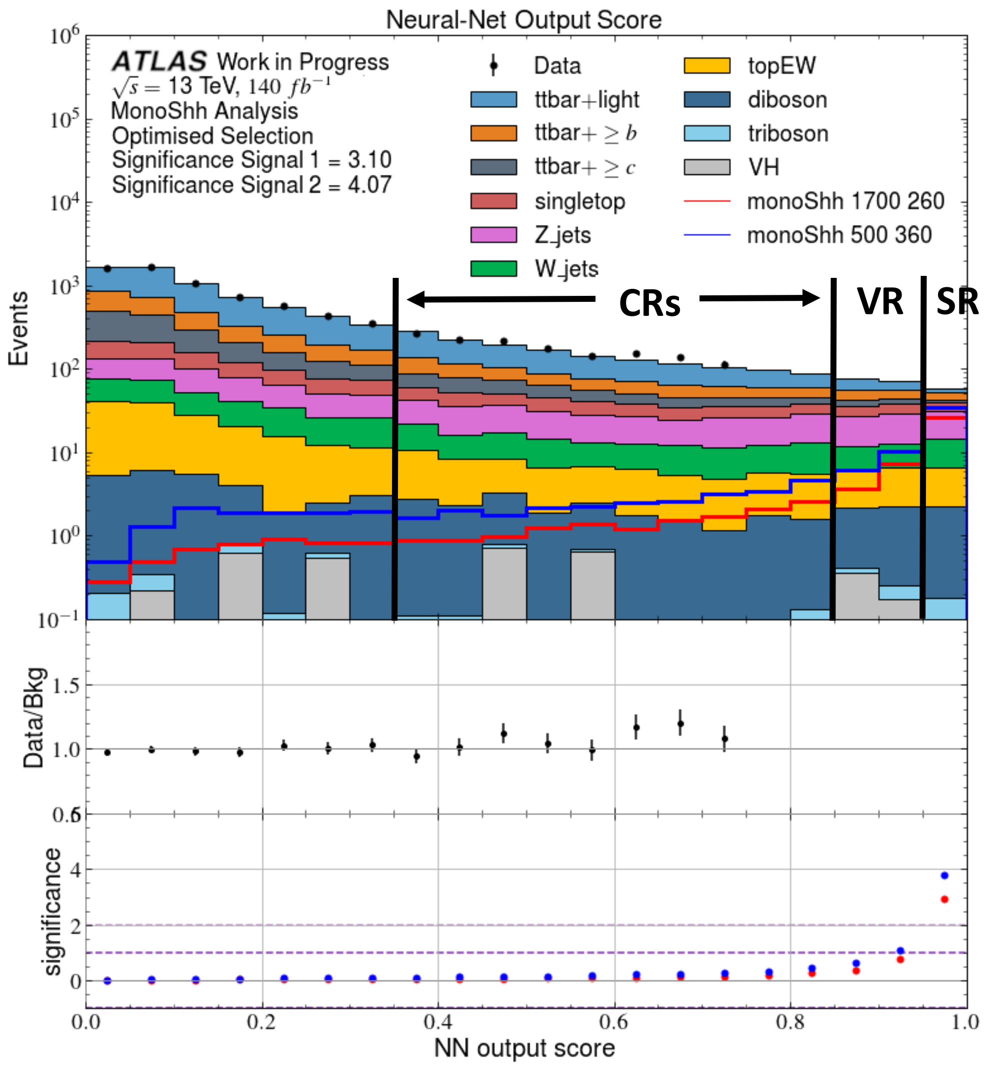
-> Control regions (CR)

  -> Correct normalisation

-> Validation region (VR)

  -> Validate background estimation

-> Adjacent to signal region (SR)



Neural network score after pre-selection.

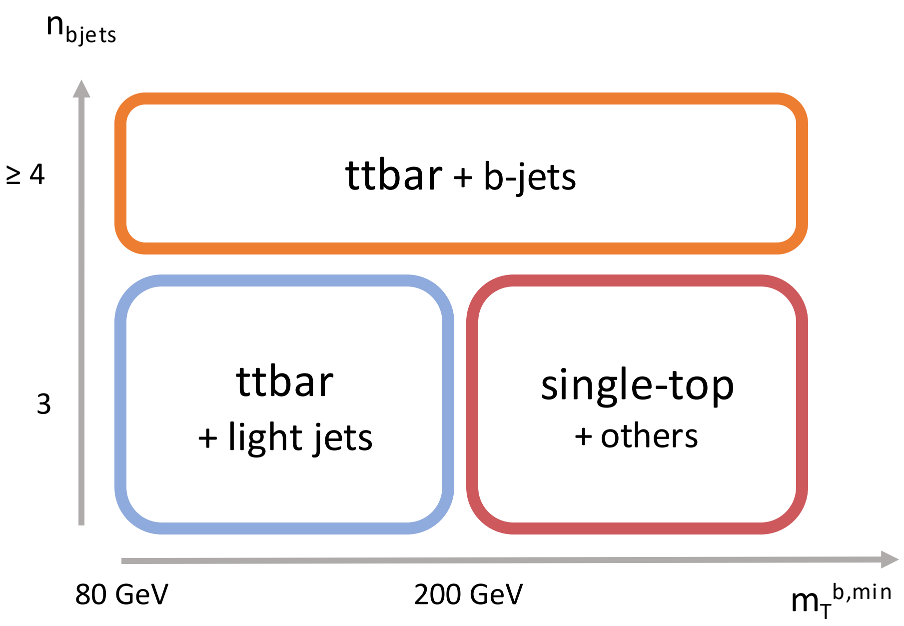
Control Regions

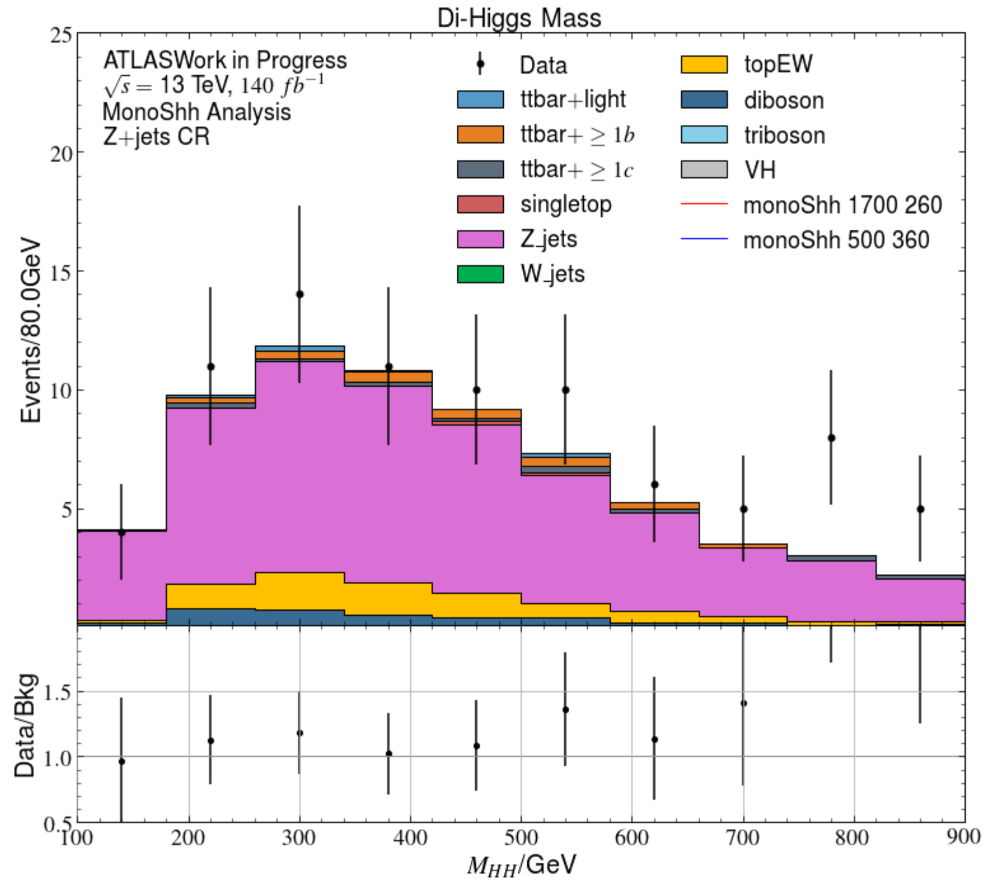
-> Dedicated CR for Z+jets:

-> Replace neutrinos by OS leptons

-> Two opposite-sign leptons + low E_T^{miss}

-> Three CRs for top related processes





Di-Higgs mass distribution in Z+jets CR.

Background-Only Fit

Simultaneous fit in all CRs:

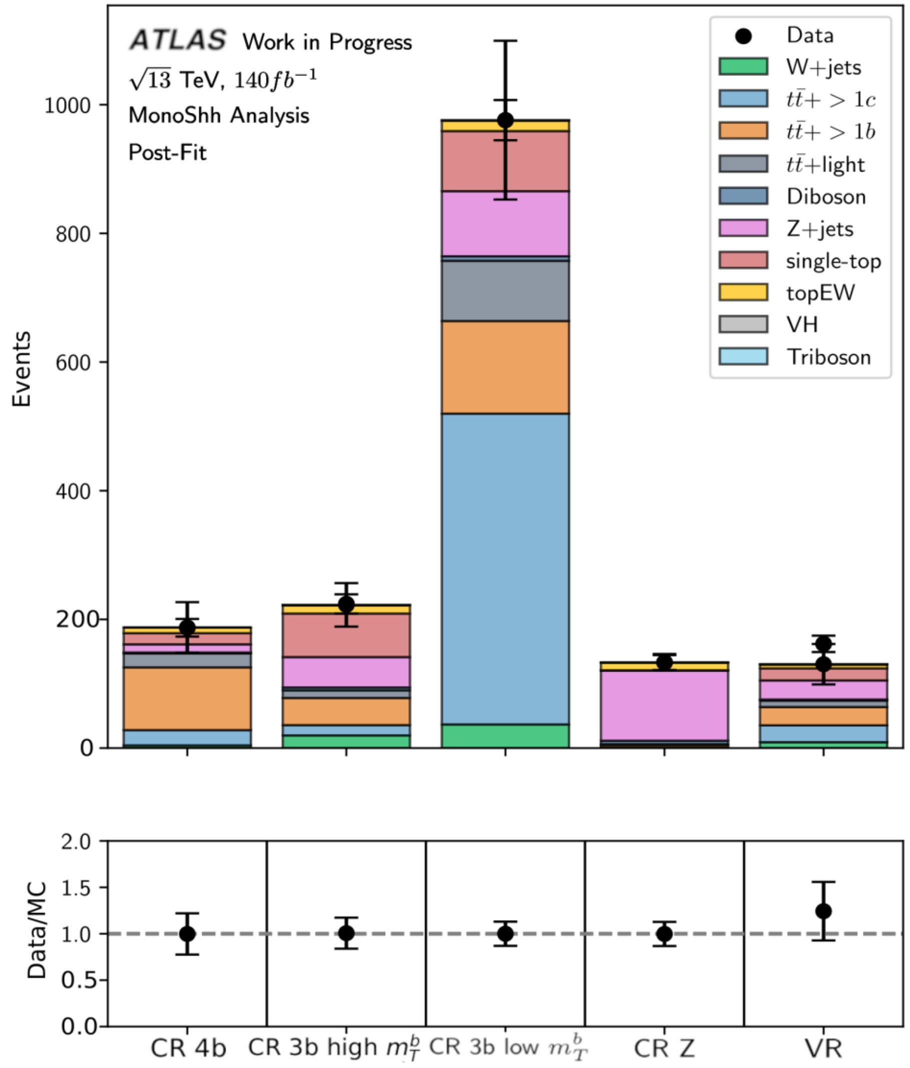
-> Signal contamination neglected

-> Normalisation parameters

-> Correct for main backgrounds

-> Good post-fit agreement observed

Post-fit Results



Exclusion Fit

Preliminary expected exclusion limits:

-> Important systematics included

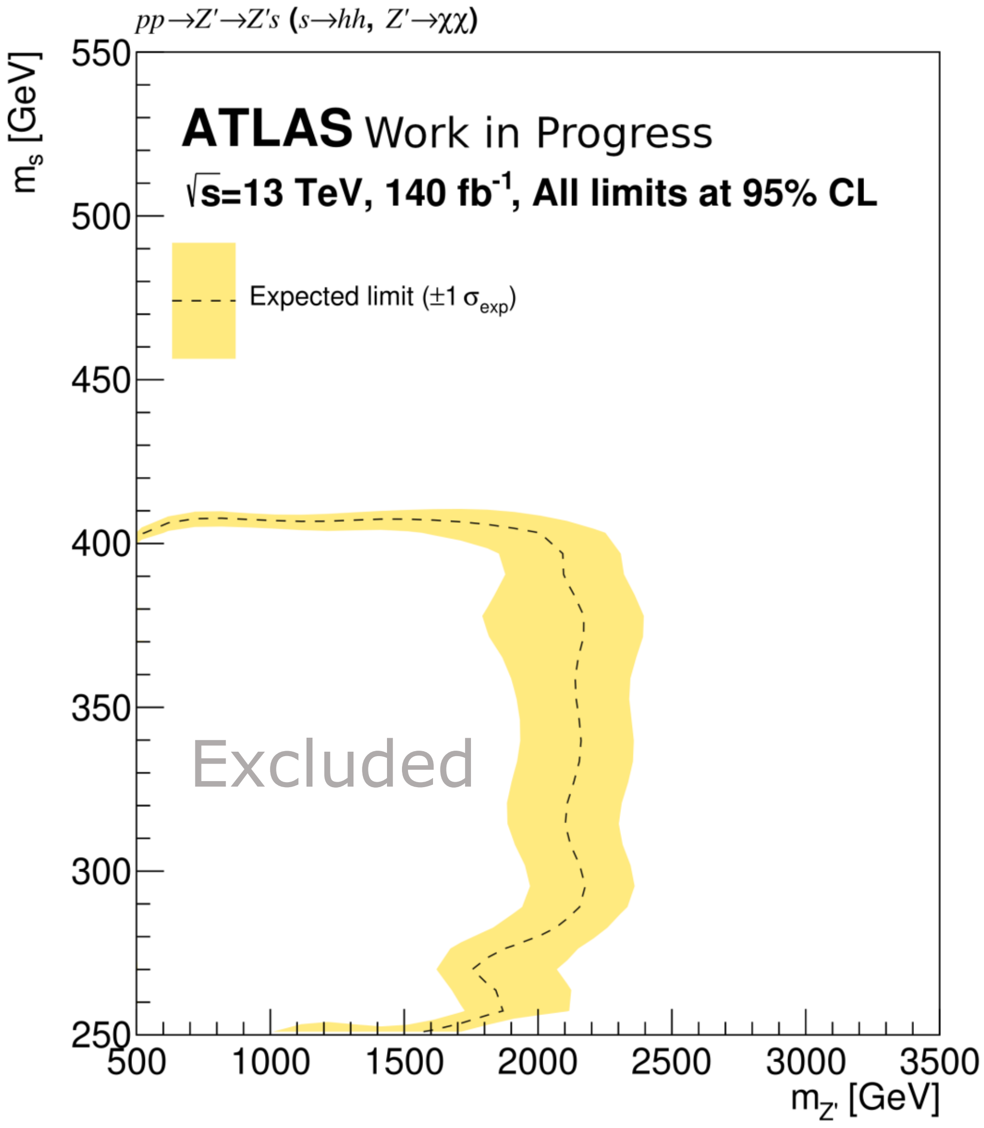
-> Competitive sensitivity up to

-> 2200 GeV in $M_{Z'}$

-> 410 GeV in M_s

-> Further optimisations still to be added

-> e.g. SR binning



Summary

A first search for a resonant di-Higgs + E_T^{miss} signature was presented

-> Unique kinematics allow to reduce SM backgrounds

-> Machine learning is used to avoid sculpting of di-Higgs mass

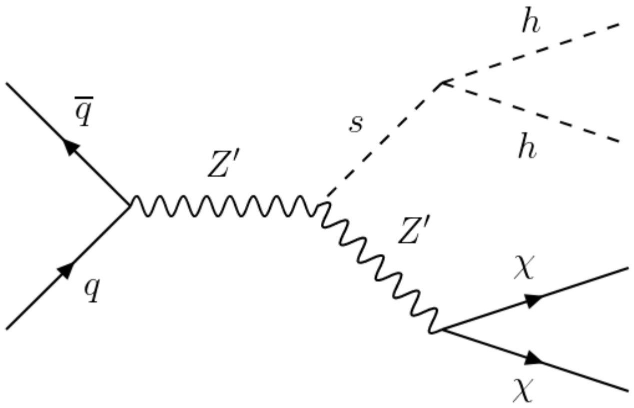
-> Background estimation in dedicated control regions

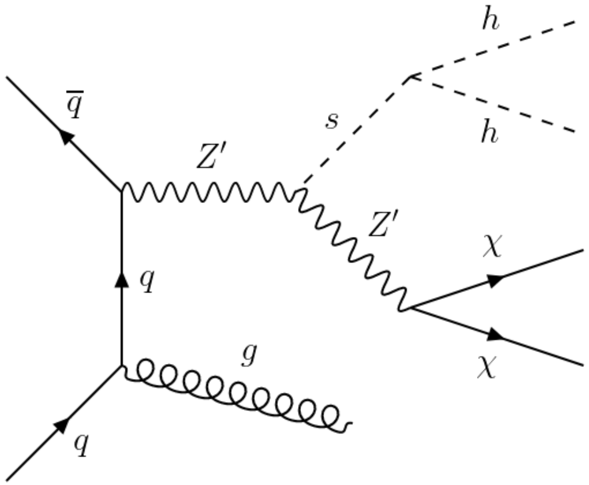
-> Interpretation in terms of the dark-Higgs model

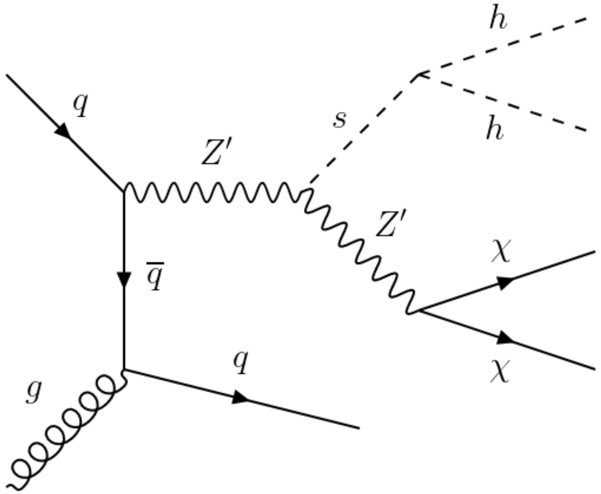
-> Stay tuned for unblinded results!

Backup

Main signal processes

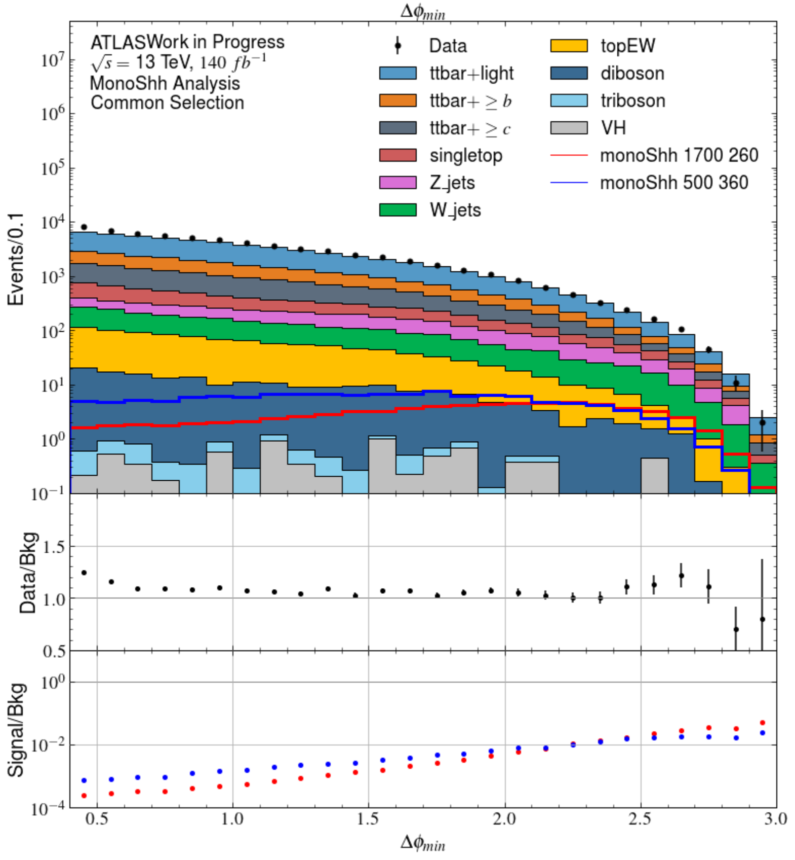




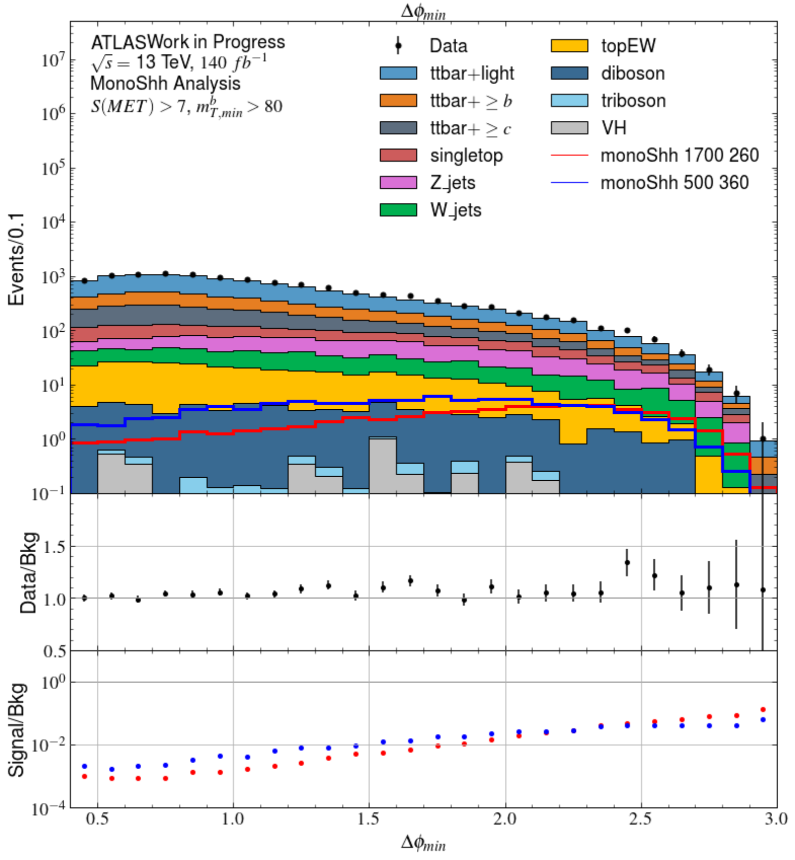


QCD background: $\Delta\varphi_{min}$(b-jets, E_T^{miss})

Pre-selection without QCD cuts



Pre-selection with QCD cuts



Selections

Variable	Cut Value
Pre-Selection	
n_{jets}	$(4, 7)$
$n_{b-\text{jets}}$	≥ 3
$\Delta\phi^{4j}_{\text{min}}$	> 0.4
n_{leptons}	$== 0$
Optimised selection	
$E_{\text{T}}^{\text{miss}}$ [GeV]	> 200
$m^{b}_{\text{T},min}$ [GeV]	> 80
$S(E_{\text{T}}^{\text{miss}})$	> 7

Variable	Cut Value
$Z+$jets CR	
Preselection	Pass (except n_{leptons} veto)
n_{μ}	2
$E_{\text{T}}^{\text{miss}}$ [GeV]	< 75
$E_{\text{T}}^{\text{miss}-\mu}$ [GeV]	> 200
$E_{\text{T}}^{\text{miss}-\mu}/\sqrt{H_{\text{T}}}$	> 7
$m^{b,min}_{\text{T,ZCR}}$ [GeV]	> 80
$\lvert m_{\mu\mu} - m_Z \rvert$ [GeV]	< 15

Selections

Variable	Cut Value		
	3b low-$m^{b}_{\mathrm{T},min}$ CR	3b high-$m^{b}_{\mathrm{T},min}$ CR	4b CR
Preselection	Pass		
$S(E_{\mathrm{T}}^{\mathrm{miss}})$	$(7, 18)$		
m_{T}^{4b} [GeV]	$(350, 800)$		
$\Delta R_{\mathrm{min}}(b,b)/E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV^{-1}]	> 0.001		
NN output-score	$(0.35, 0.85)$		
$n_{b\mathrm{-jets}}$	$== 3$	$== 3$	$== 4$
$m^{b}_{\mathrm{T},min}$ [GeV]	$(100, 200)$	$(200, 350)$	$(80, 280)$

tim.lukas.bruckler@cern.ch

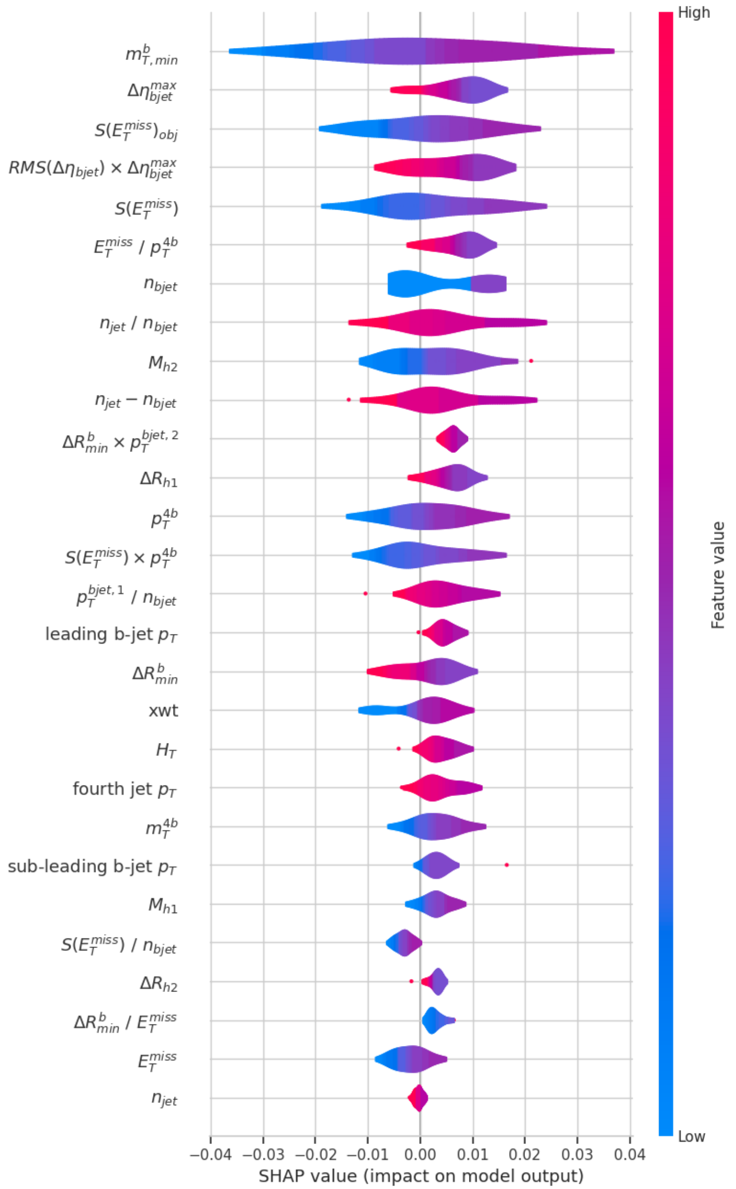
Selections

Variable	Cut Value
Validation Region Selection	
Preselection	Pass
$n_{b-\text{jets}}$	≥ 3
$m^{b}_{\mathrm{T},min}$ [GeV]	$(125, 350)$
$S(E_{\mathrm{T}}^{\mathrm{miss}})$	$(7, 18)$
m^{4b}_{T} [GeV]	$(350, 800)$
$\Delta R_{\min}(b, b)/E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV^{-1}]	$(0.001, 0.012)$
NN output-score	$(0.85, 0.95)$

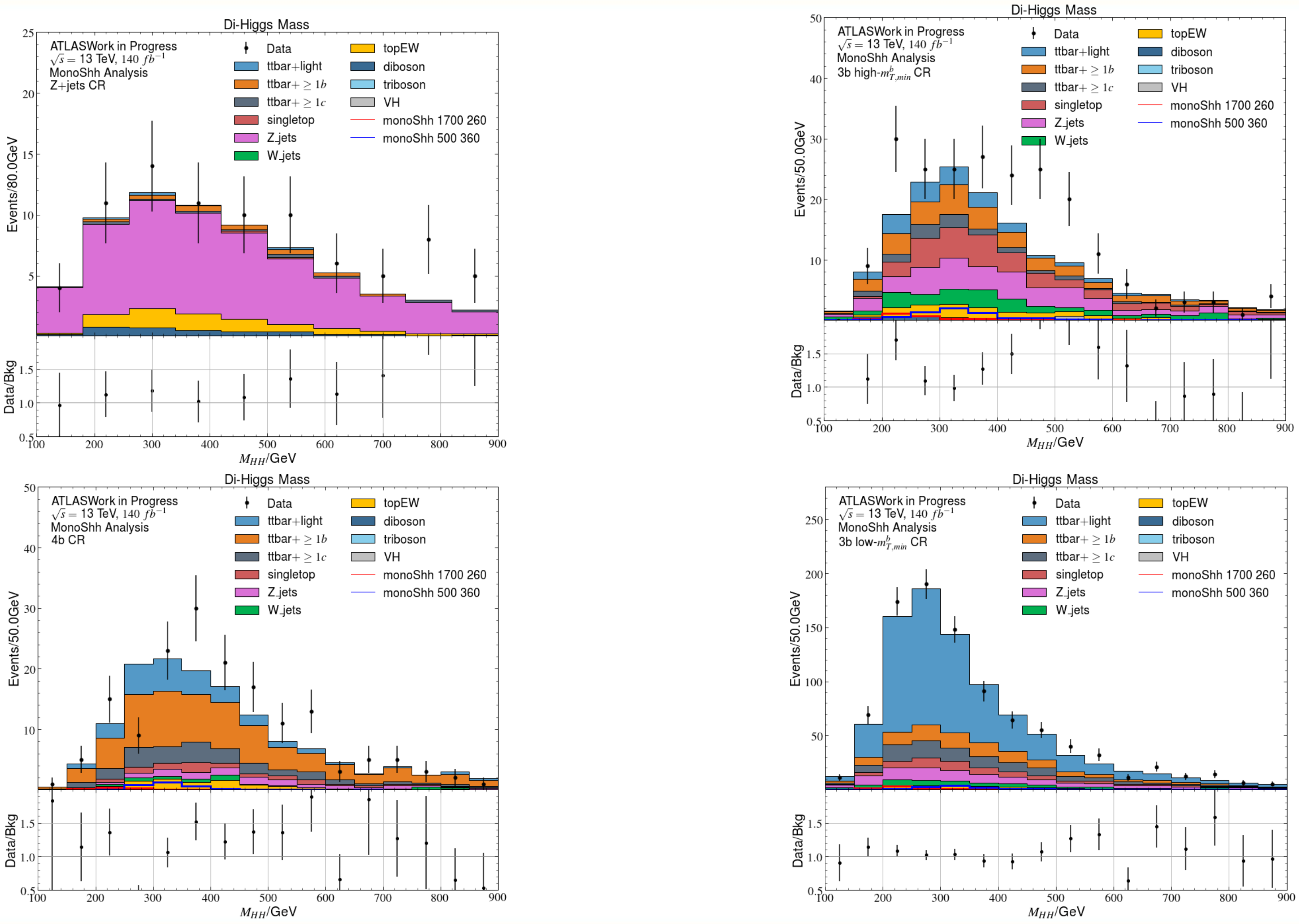
Variable	Cut Value
Signal Region Selection	
Preselection	Pass
$m^{b}_{\mathrm{T},min}$ [GeV]	> 125
$S(E_{\mathrm{T}}^{\mathrm{miss}})$	> 7
m^{4b}_{T} [GeV]	> 300
$\Delta R_{\min}(b, b)/E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV^{-1}]	< 0.01
NN output-score	> 0.95

Neural Net Training Variables

- Additional "constructed" features enhance the discrimination power due to limited size of training set

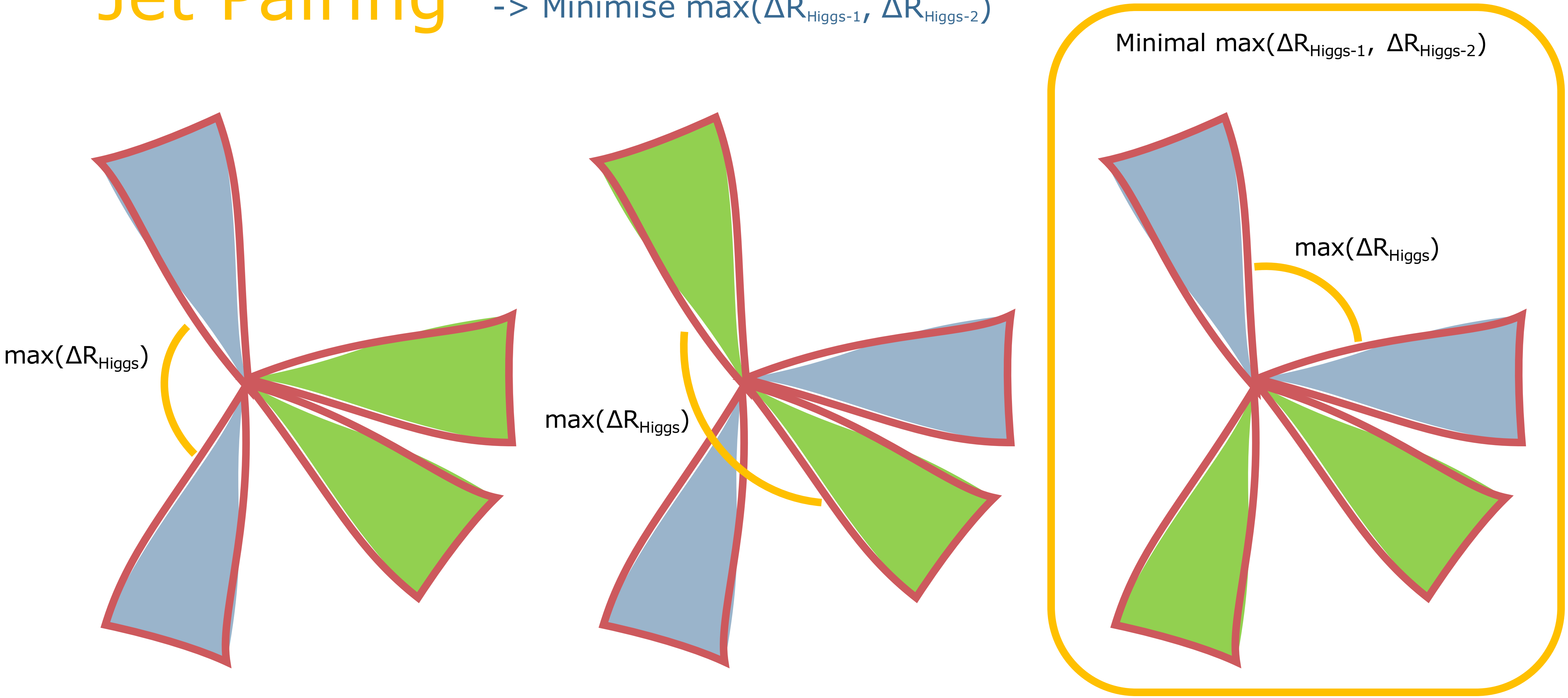


Pre-fit Control Regions



Jet Pairing

-> Four jets ->Three possible pairings
-> Minimise $\max(\Delta R_{\text{Higgs-1}}, \Delta R_{\text{Higgs-2}})$



Signal region composition

Process	Number of Selected Events
signal ($M_{Z'} = 1700, M_s = 260$ GeV)	25.5
data yield	blinded
total background yield	55.4
$t\bar{t}$ + light	6.0
$t\bar{t} + \geq 1$ b-jet	8.2
$t\bar{t} + \geq 1$ c-jet	3.9
Z + jets	15.8
W+ jets	7.6
single-top	7.6
top+EW	4.3
di-boson	1.9
tri-boson	0.2
VH	0.0

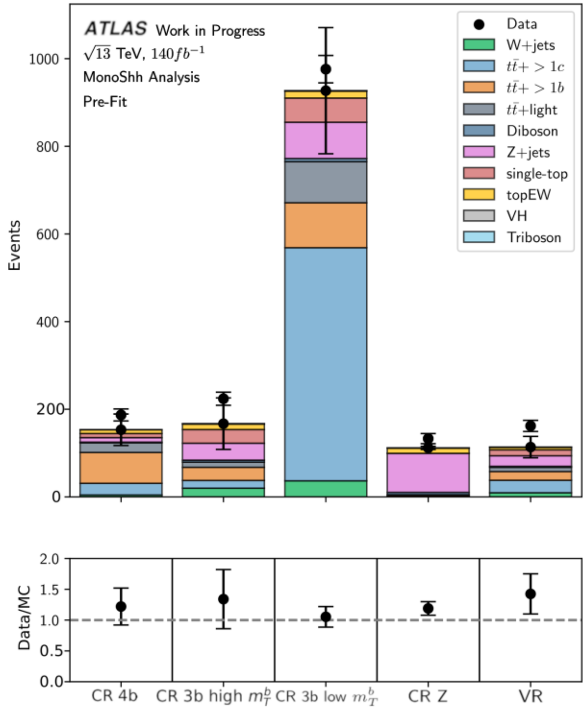
tim.lukas.bruckler@cern.ch

Background-Only Fit

Run likelihood fit simultaneously in all CRs

-> Signal contamination neglected
-> Normalisation parameters to correct for main backgrounds
-> Good post-fit agreement observed

Pre-fit



Background-only Fit

Post-fit