TECHNISCHE UNIVERSITÄT DRESDEN

BMBF-ErUM-Forschungsschwerpunkt ATLAS-EXPERIMENT

Ausbau von ATLAS am LHC: Physik mit dem ATLAS-Experiment

ErUM-FSP T02 ATLAS

GEFÖRDERT VOM Bundesministeri für Bildung und Forschung

ATLAS EXPERIMENT

Institute for Nuclear and Particle Physics - TU Dresden

Search for resonant WZ production with ATLAS detector at the LHC

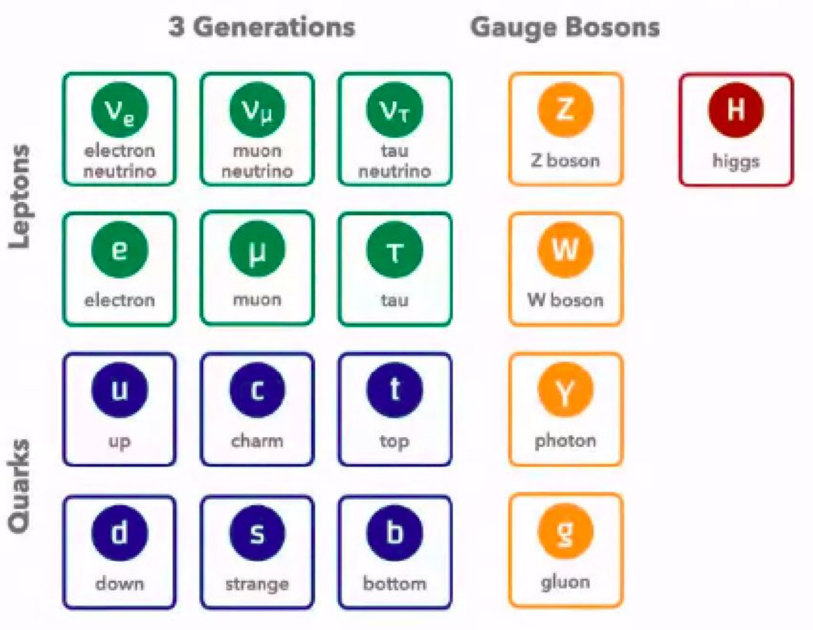
Abhishek Nag

INSTITUTE OF NUCLEAR AND PARTICLE PHYSICS

Physics at Terascale Meeting
November 23-24, 2021

Overview

Introduction: Standard Model



The Standard Model does not adequately explain:

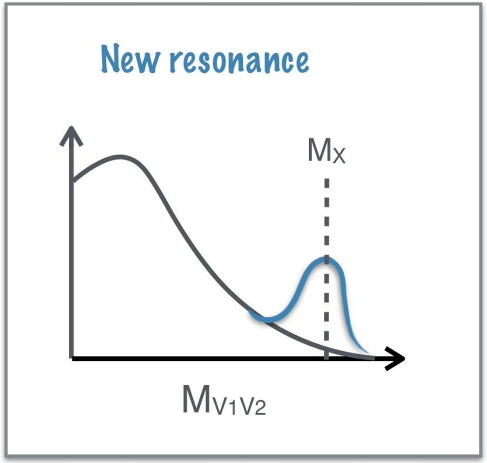
- Gravity
- Dark Matter
- Dark energy
- Neutrino Masses
- Matter- antimatter asymmetry

Problems:

- Hierarchy problem → couldn't explain the low mass of Higgs
- CP violation → weak interactions violate not only the charge-conjugation symmetry **C** between particles and antiparticles and the **P** or parity, but also their combination.

Need beyond SM physics to explain such problems.

Resonance Search: Looking for a bump



- Resonance searches: the simplest way to discover new particles.
- Observe a statistically significant bump above a smooth background in the invariant mass distribution
- Model-independent probe to new physics.

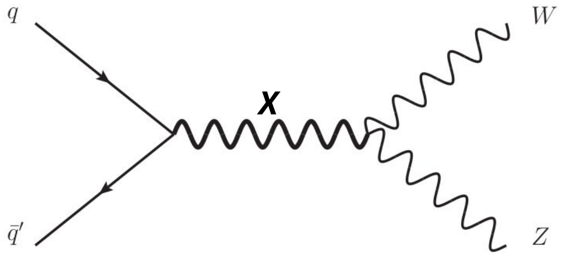


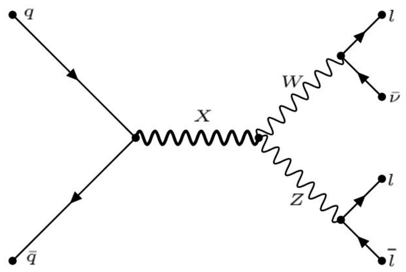
Fig: Feynman diagram for X -> WZ process at the LHC

- Resonance benchmark:
  - Heavy vector Triplets (simplified Lagrangian) produced either by qqF or VBF
  - Georgi - Machacek (GM) Higgs Triplet Model produced via VBF

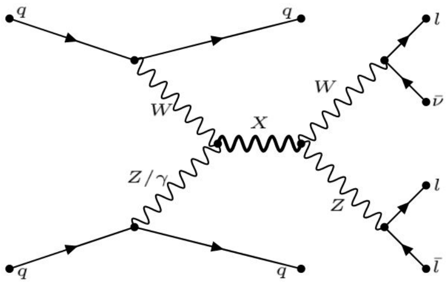
WZ Resonance search analysis strategy

- We look into fully leptonic decay mode:
  - Small branching fractions
  - Clean signature, low background
  - **Good sensitivity to low mass**
- Experimental signature:
  - 3 high p_T isolated leptons
  - Missing transverse energy (E_T^{miss})

Two signal regions are defined targeting 2 production modes:



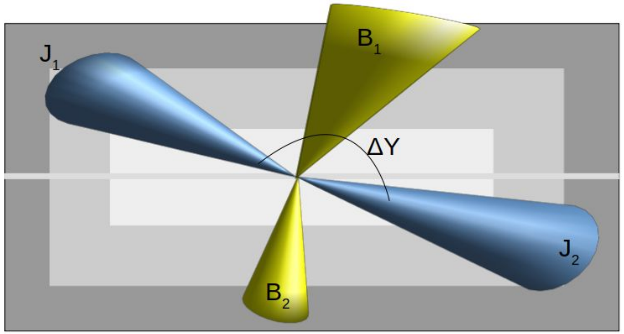
(a) $q\bar{q}$ fusion



(b) vector boson fusion

VBF category is defined exploiting the typical VBF topology:

- two "tagging" jets in forward region in opposite direction
- high invariant mass of tagging jets m_{jj}.
- vector bosons between tagging jets



WZ inclusive Selection

Designed to select good W and Z pairs decaying leptonically

		Motivation :
lepton selection	Single lepton trigger	High efficiency 3 leptons in final state
	High p_T leptons (p_T>25 GeV) in detector acceptance	
	Leptons must come from primary vertex. Impact parameter cuts $\lvert d0/\sigma_{d0} \rvert$	reduce background from jet, Z+jet, QCD, tt and single top
	Calorimeter and track isolation used	
	Only 3 good leptons (additional 7 GeV leptons)	Reduce ZZ background
Z selection	Pair of same flavor, opposite sign , high p_T isolated leptons. Consistent with a Z boson in a ±20 GeV window. If more than one pair, select the closest to Z mass	reduce non peaking backgrounds like tt and single top, WW+jets
W selection	Additional tight lepton requirement	reduce the Z+jets and Top background
	E_T^{miss}>25GeV	To account for the W and reduce Z+jets

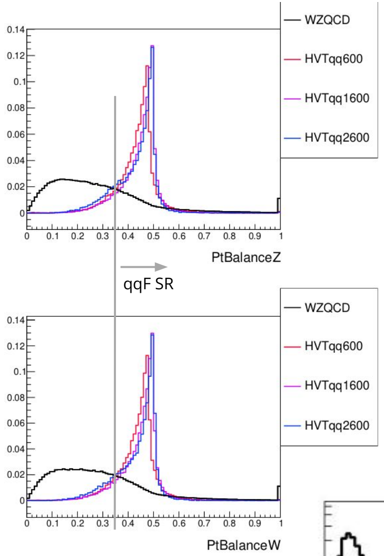
Signal Region definitions

- Starts from the inclusive WZ selection
- Events are defined into two → qq fusion and vector boson fusion
- Two types of Signal regions under study:

1. Cut based analysis:

qqF signal region:

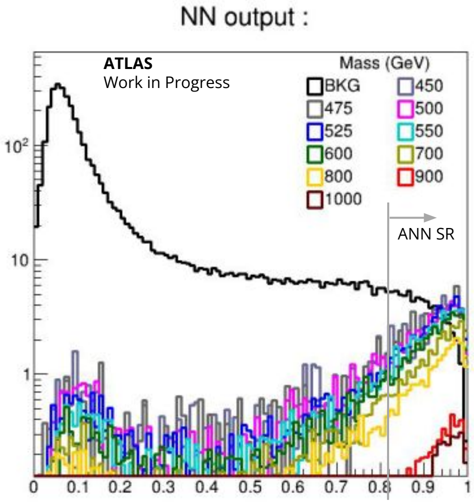
- $p^Z_T/m_{WZ} > 0.35$ and $p^W_T/m_{WZ} > 0.35$



2. Artificial Neural Network VBF analysis:

- Deep Neural Network trained using events at the inclusive selection level + Mjj>100 GeV + Njet>=2
- Training aiming to discriminate **VBF signals** from SM backgrounds
- Set of variables used for the training:
  - M_{jj}, ϕ_{jj}, η_W, η_Z, η_{j1}, Event centrality, E_T^{miss}, H_T
- The same ANN training is applied to HVT VBF and GM signal
- ANN VBF signal region optimised with a cut on the DNN output (ANN > 0.82) for the two models

NN output :



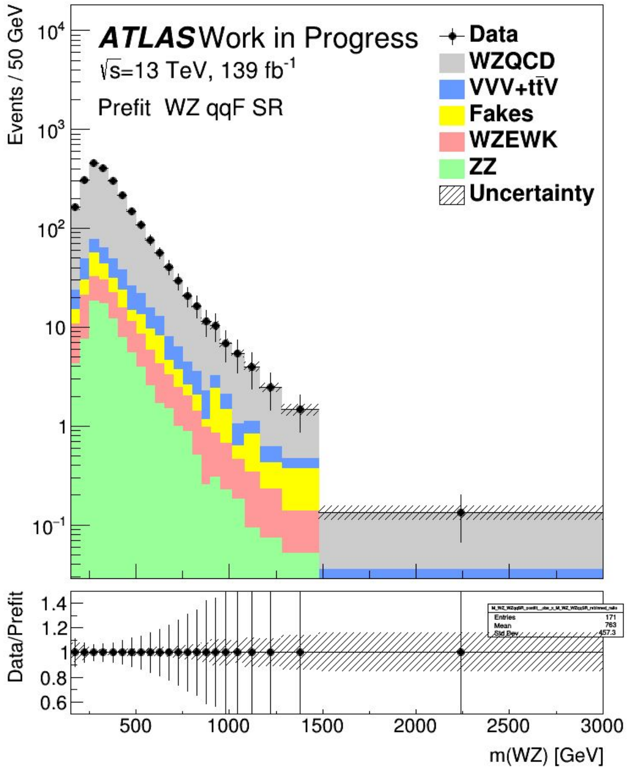
qqF: signal region yields (blinded)

- Yields in signal region

	$q\bar{q}$ SR
WZ EWK	90.4 ± 3.5
WZ QCD	1984 ± 72
Fakes	92.3 ± 51.5
$VVV + t\bar{t}V$	147.2 ± 29.9
ZZ	87.2 ± 4.6
Total Background	2401 ± 88
Observed	XX

- Main backgrounds:
  - WZ EWK: estimated from MC
  - WZ QCD and ZZ: Normalization will be extracted from data in respective control regions
  - Fakes: Normalization from the data driven and shape from MC
  - VVV+ ttV background from MC checked in validation region

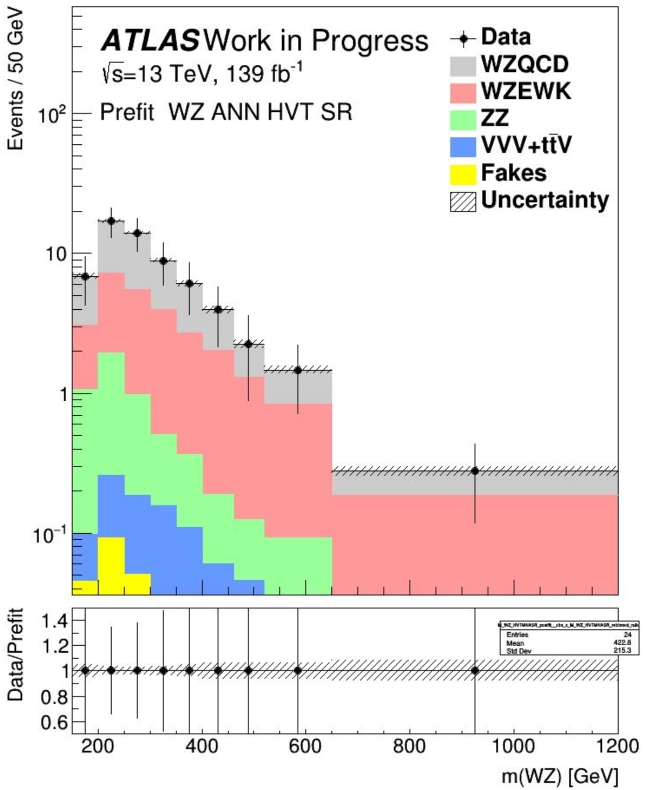
Data in the plot is **Asimov Data**



HVT VBF ANN: New signal region yields (blinded)

- Expected ~67 background events
- SM WZ QCD and EWK are the dominant background
  - WZ QCD and ZZ normalization will be extracted from data
  - WZ EWK has 6% uncertainty

	HVT VBF ANN SR
WZ EWK	25.11 ± 1.56
WZ QCD	36.51 ± 8.11
Fakes	0.245 ± 0.508
$VVV + t\bar{t}V$	0.818 ± 0.182
ZZ	4.56 ± 1.21
Total Background	67.24 ± 3.01
Observed	XX

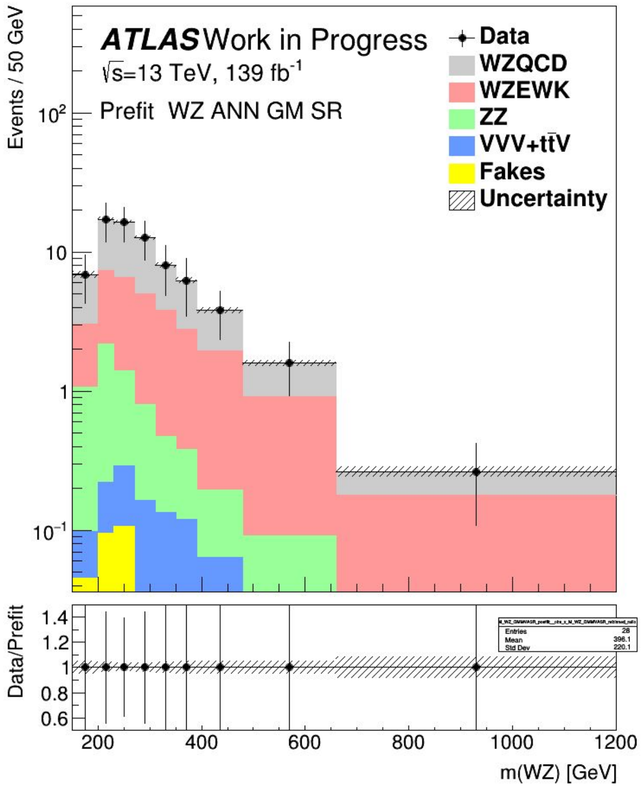


Data in the plot is **Asimov Data**

GM VBF ANN: signal region yields (blinded)

- Same region as HVT ANN, but slightly different binning
  - due to difference in the mass resolution of the two models
  - Optimized by having around 10 background events in each bins and at the most 30% uncertainty in MC

	GM VBF ANN SR
WZ EWK	25.11 ± 1.56
WZ QCD	36.51 ± 8.11
Fakes	0.245 ± 0.508
$VVV + t\bar{t}V$	0.818 ± 0.182
ZZ	4.56 ± 1.22
Total Background	67.24 ± 3.00
Observed	XX



Data in the plot is **Asimov Data**

Background overview

1. **SM WZ QCD background:**
   - Dominant background
   - Shape are estimated from MC simulation
   - Normalization fitted in dedicated control regions (orthogonal to SR)
     i. WZ VBF ANN control region
     ii. WZ $q\bar{q}$ control region
2. **SM WZ EWK:** estimated from MC simulation
3. **Other Prompt background**
   - ZZ production: normalization fitted in corresponding 4 lepton control region (ZZCR).
   - ttV background taken from MC checked in validation region
   - Triple boson production: Modeled using theory
4. **Fake/Non prompt background:**
   - Z+jets, $Z\gamma$, $W\gamma$, ttbar, single top or WW $\rightarrow$ where jets or photons were misidentified as leptons
   - Normalization estimated using data, shape from MC

qqF: Control region yields

- SM WZ QCD and ZZ are the dominant background in the SR
- Control Regions are designed for prompt background estimation
- Need to check if the theory prediction matches well with data
- Normalization factors are extracted from these control regions for the two backgrounds

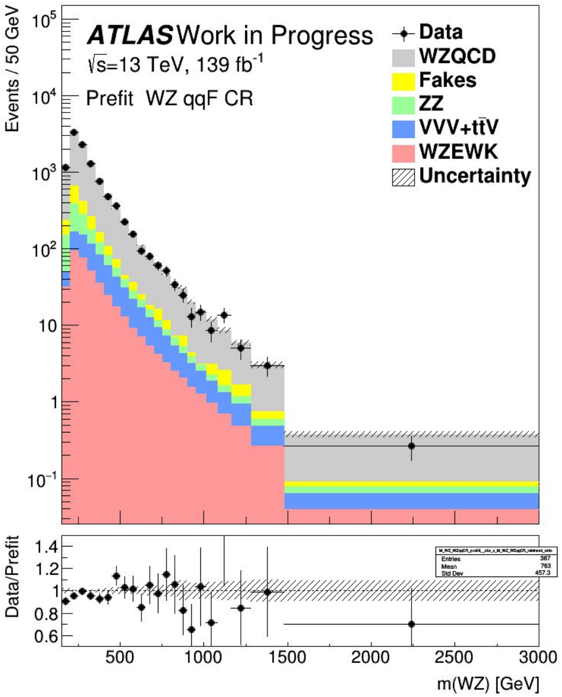
WZ QCD control region, defined by:

- $p^V_T / m_{WZ} > 0.1$
- $p^Z_T / m_{WZ} < 0.35$ or $p^W_T / m_{WZ} < 0.35$

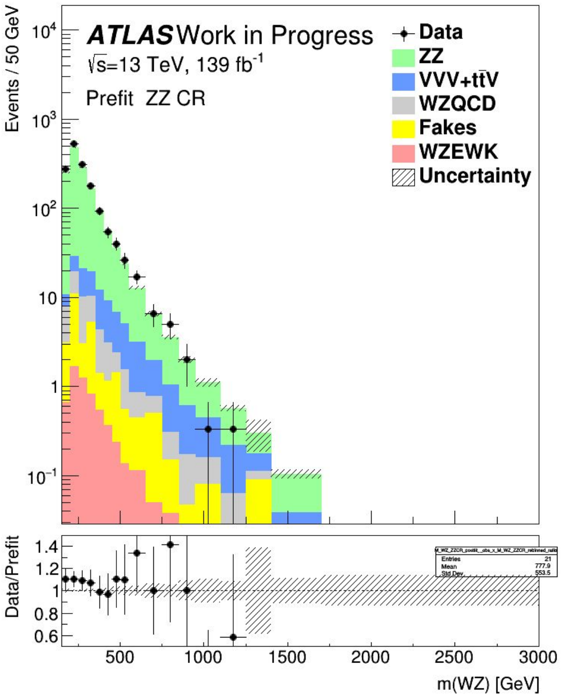
ZZ control region, defined by:

- 1 extra baseline lepton
- E_T^{miss} cut removed

WZ qqF QCD CR



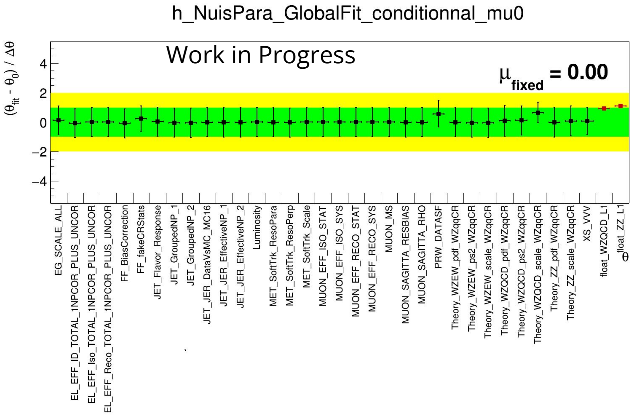
ZZ QCD CR



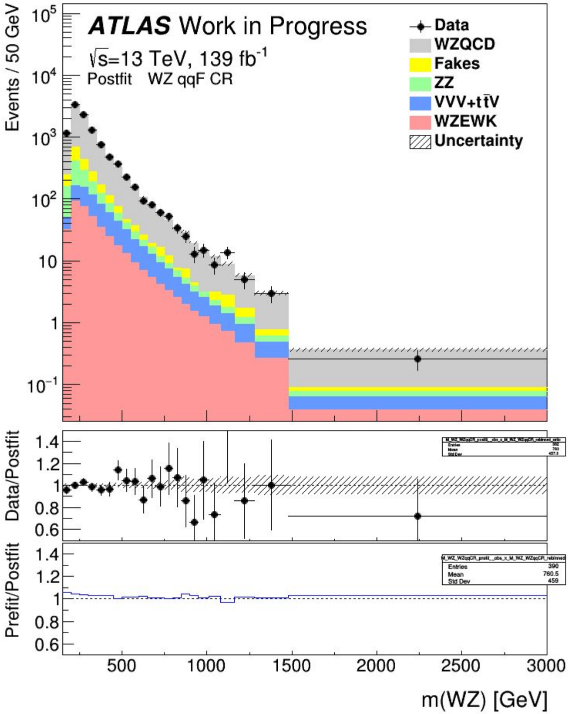
qqF Control region only fit

- Control region only fits also performed to extract normalization factors for WZ QCD and ZZ background
- Fitted factors are

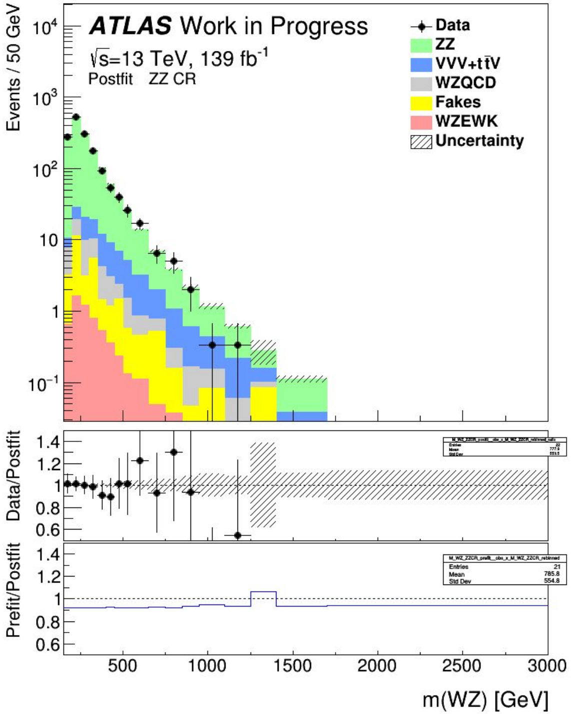
μ_{WZQCD}	0.942 ± 0.047
μ_{ZZ}	1.09 ± 0.05



WZ qqF QCD CR



ZZ QCD CR



ANN: Control region yields

- SM WZ and ZZ are the dominant background in the SR

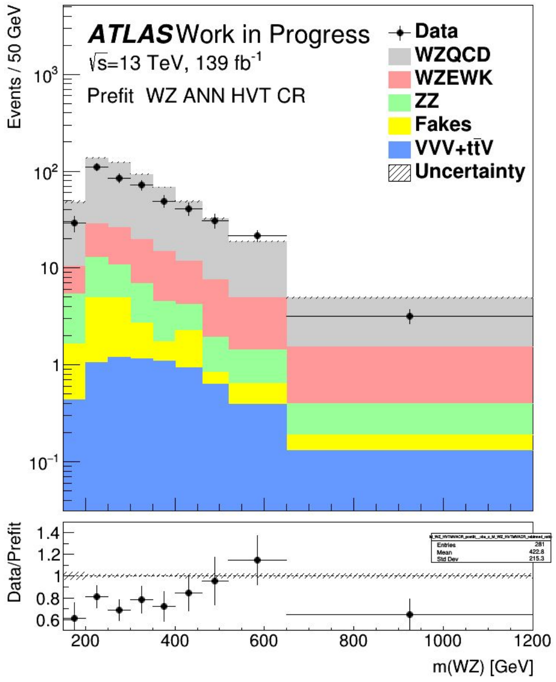
WZ QCD VBF control regions

- The WZ QCD background is the dominant one in the VBF ANN signal regions
- To constrain it, control regions are defined by:
  - Inverting the ANN SR requirement
  - Applying Mjj> 500 GeV (included since most of SR events are expected to have high Mjj)

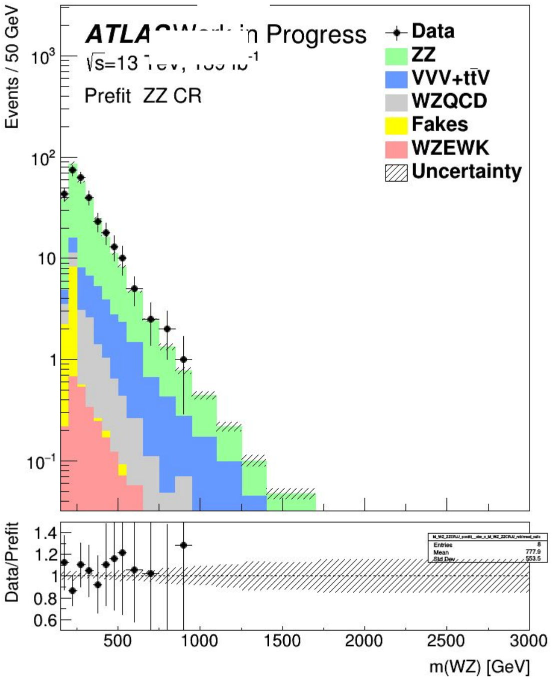
ZZ +2jets CR, defined by:

- 1 extra baseline lepton
- No E_T^{miss} cut
- 2 VBS jets

WZ ANN QCD CR



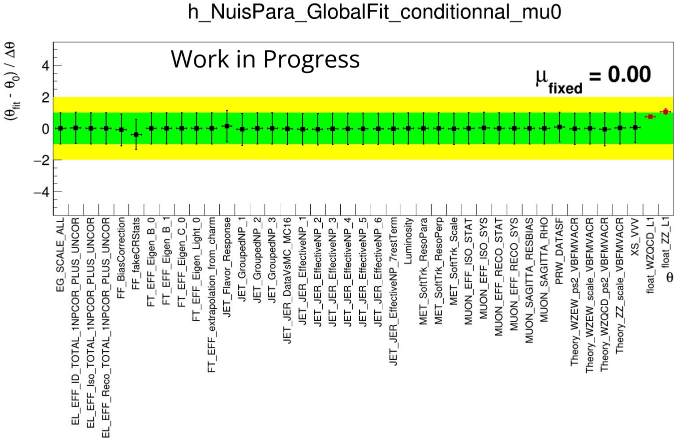
ZZ JJ QCD CR



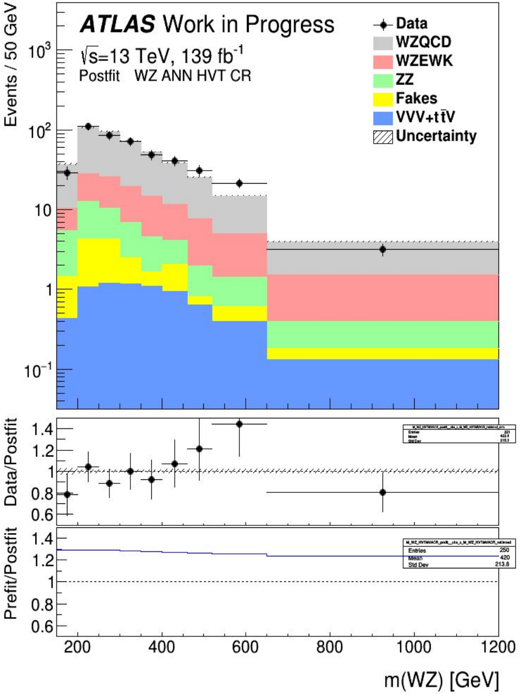
HVT MVA Control Region only fit

- Control region only fits are performed
- Fitted factors are

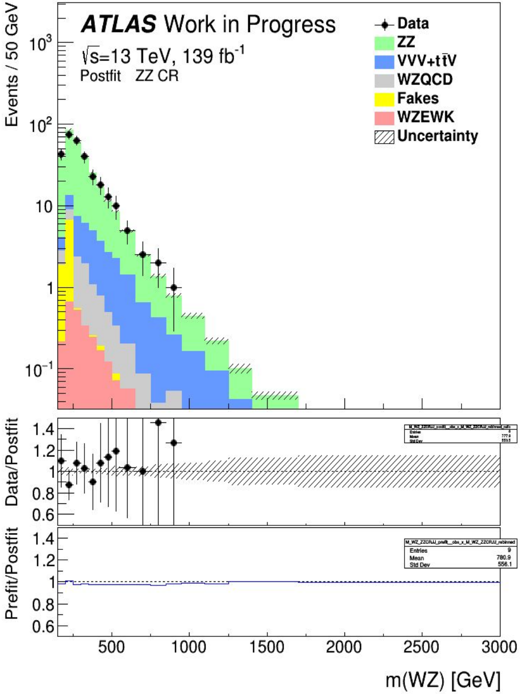
μ_{WZQCD}	0.726 ± 0.078
μ_{ZZJJ}	1.07 ± 0.19



WZ ANN QCD CR



ZZ JJ QCD CR

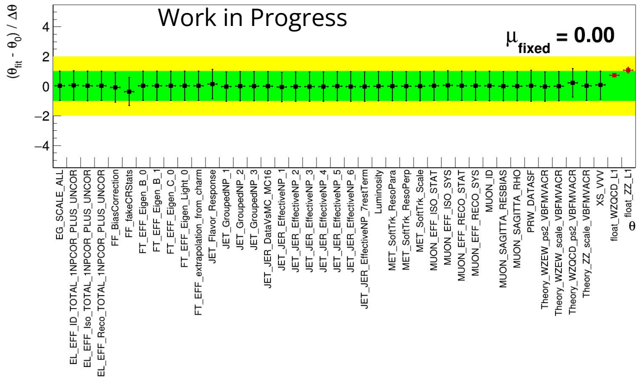


GM MVA Control Region only fit

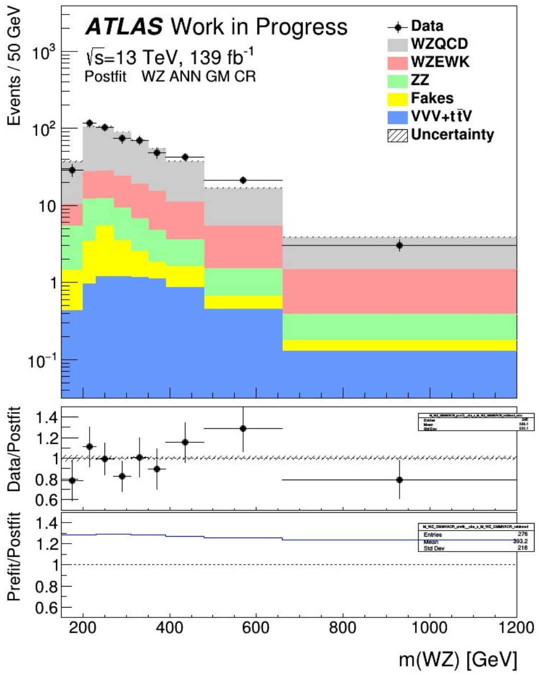
- Same region as the HVT MVA CR
- Showing postfit distributions after CR only background fit
- Fitted factor slightly different due to different binning

μ_{WZQCD}	0.725 ± 0.077
μ_{ZZJJ}	1.06 ± 0.19

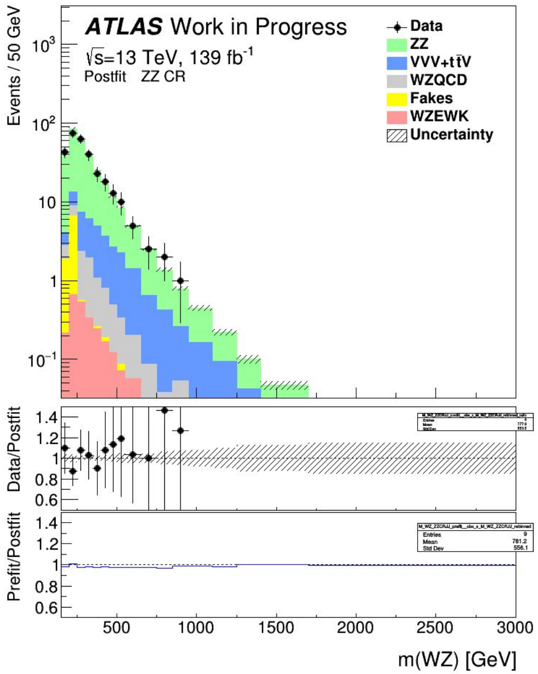
h_NuisPara_GlobalFit_conditionnal_mu0



WZ ANN QCD CR



ZZ JJ QCD CR

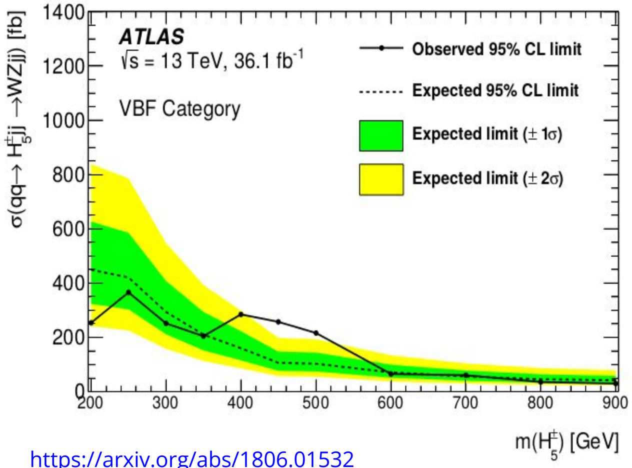


Fit Strategy

- Binning optimized considering
  - The signal resolution.
  - The Background Statistics: At least 5 expected background events in the last couple of bins
  - The Background Uncertainties: At the most 30% stat uncertainty in MC
- All theory and experimental uncertainties included
  - We have shape uncertainties comparing different MC for the main backgrounds (WZ EWK, WZ QCD and ZZ)
  - Cross section uncertainties for minor backgrounds
- Free parameters of the fit:
  - Normalization factor of WZ QCD
  - Normalization factor of ZZ
  - Signal normalization
- Simultaneous fit of SR and CRs

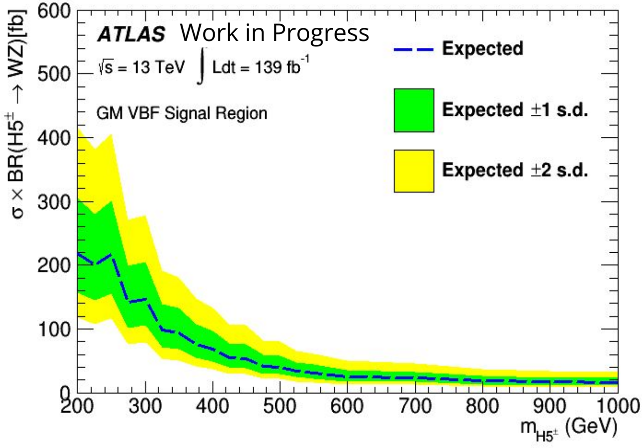
Limits Evolution: GM

Cut-based 36.1 fb^{-1}

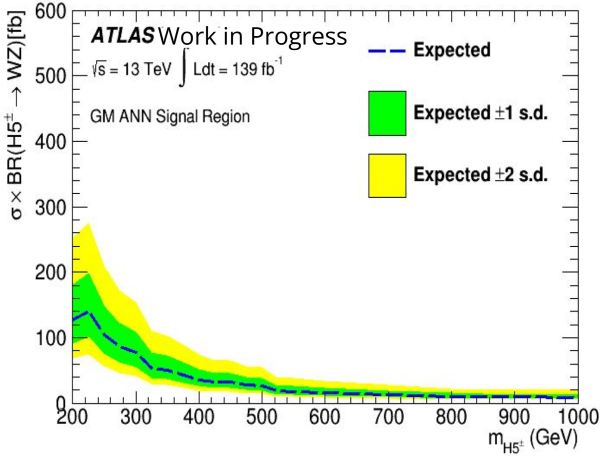


https://arxiv.org/abs/1806.01532

Cut-based 139 fb^{-1}



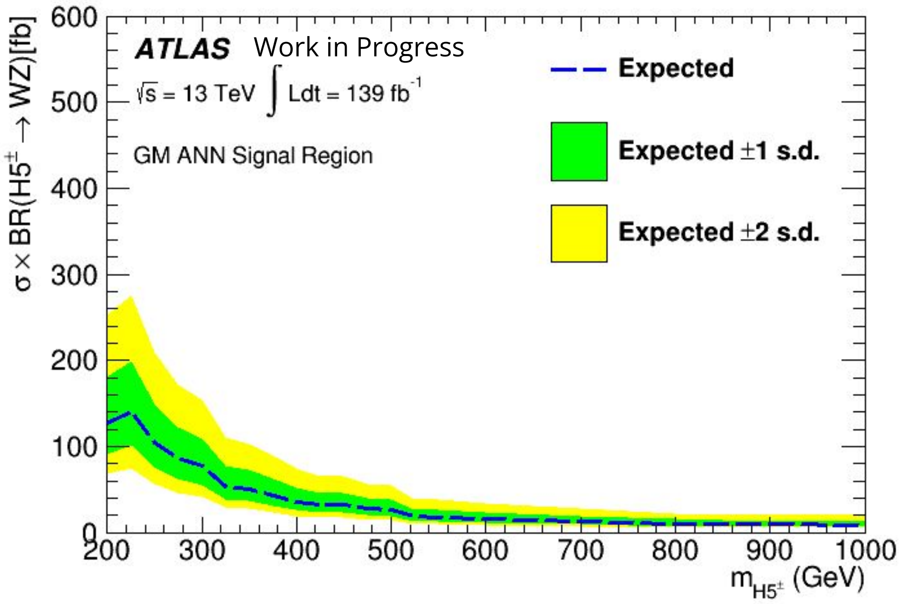
ANN 139 fb^{-1}

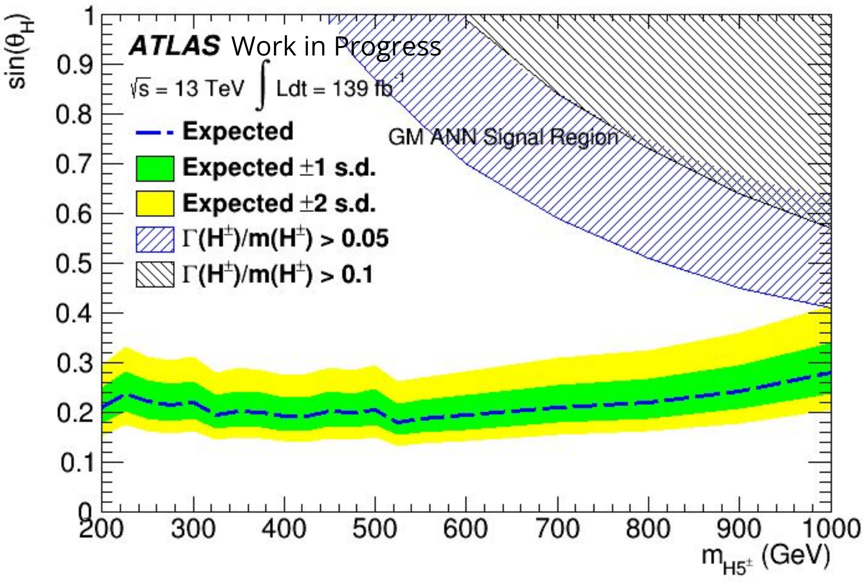


Luminosity increases 4 times, limit improves by 50%

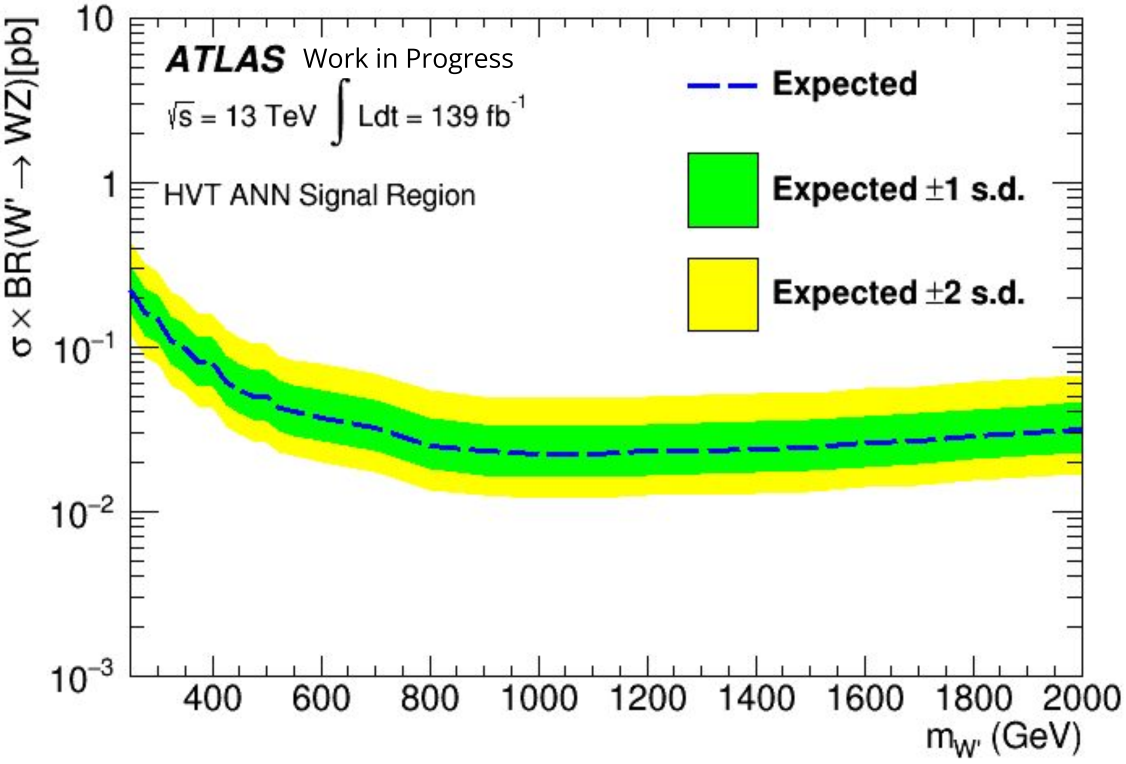
Using ANN further improves the limit by 40%

GM ANN expected limits

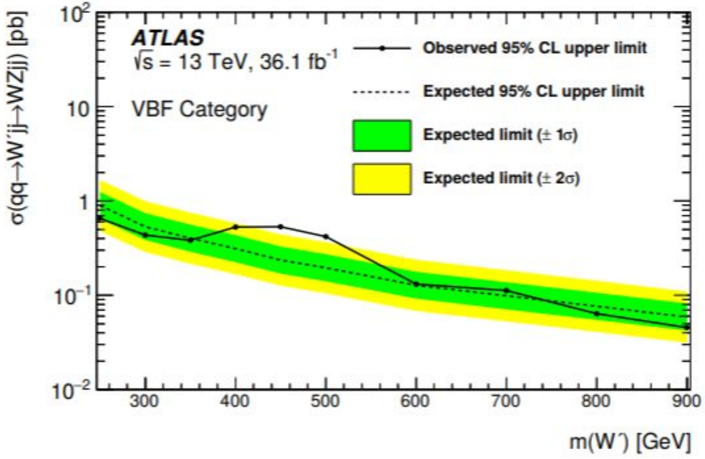




HVT VBF ANN expected limits

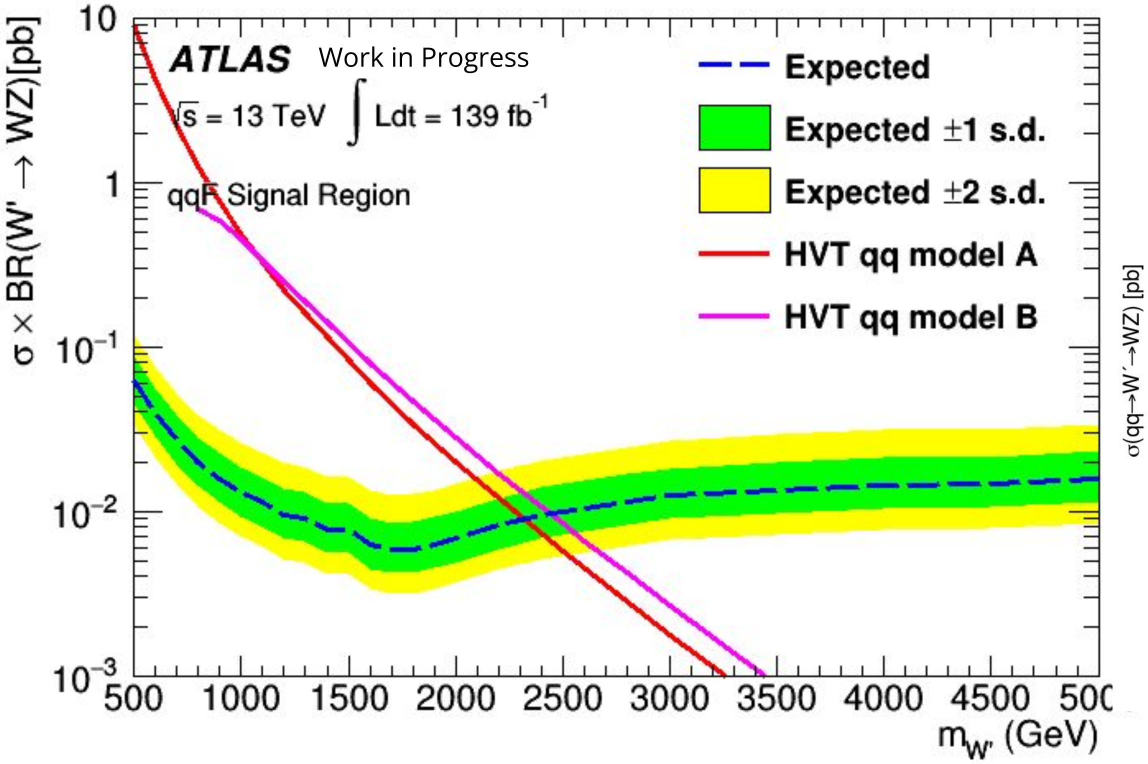


https://arxiv.org/abs/1806.01532



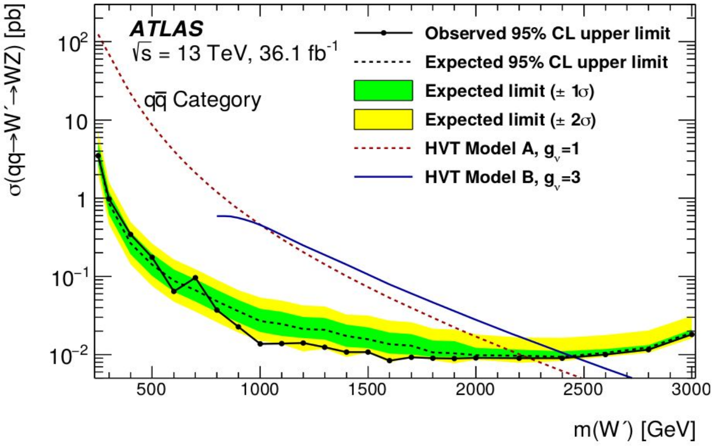
published 36 fb^{-1} limits

qqF expected limits



- Limits on the figure start now at 500 GeV while new samples from 250-500 GeV are produced

https://arxiv.org/abs/1806.01532



published 36 fb^{-1} limits

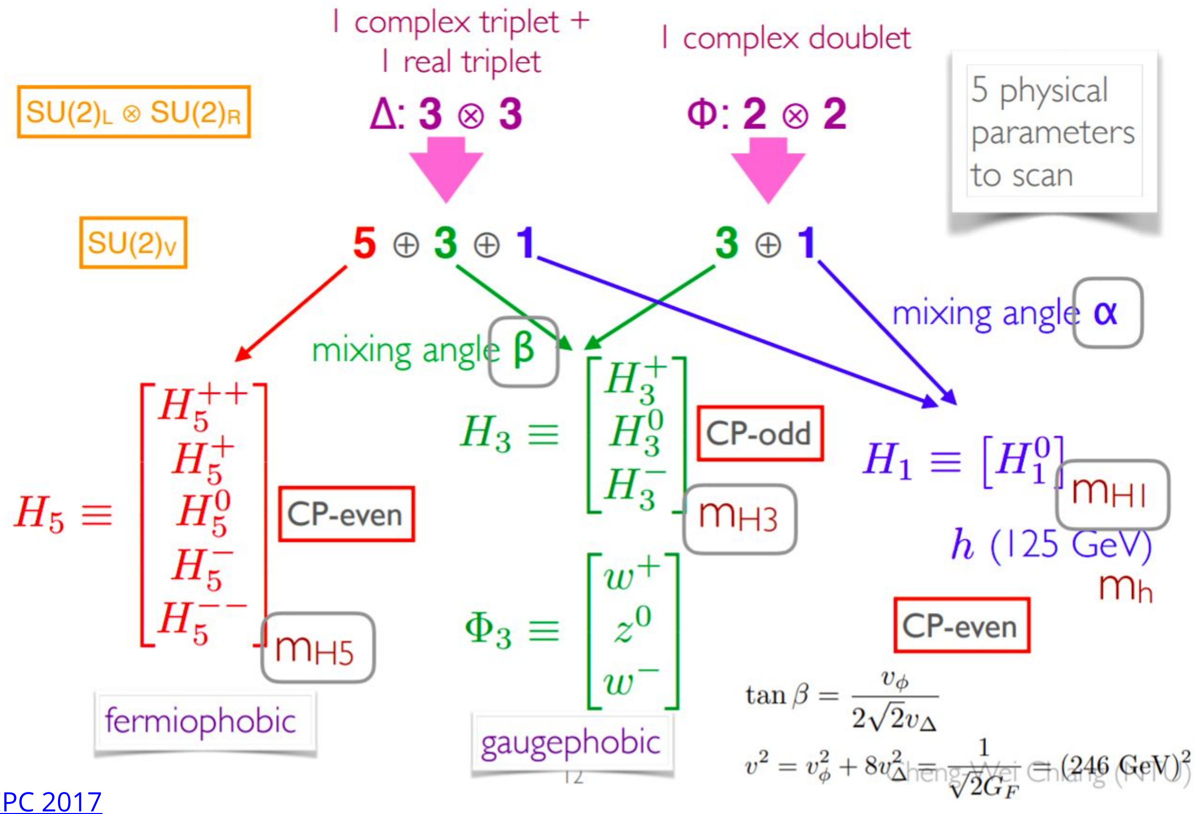
Take home message

- Resonances offer an easy way to look for new physics
- Leptonically decaying W and Z bosons give low statistics but cleaner signature
- Fully leptonic decay channel offer best limits for low mass resonances
- We see improvements with the expected full RunII limits
  - ANN improves the limits significantly

We are actively looking for physics beyond SM and there is room for **surprises**

BACKUP

GM Higgs Spectrum



[Cheng-Wei Chiang, CEPC 2017]

Heavy Vector Triplets

- Parameterized Lagrangians incorporating heavy vector triplet (**HVT**) permit interpretation of searches for vector resonances.
- Simplified phenomenological Lagrangian used.
- Two benchmark models used:
    - **Model A**: heavy vectors emerging from an underlying weakly-coupled extensions of the SM gauge group (g_v=1)
    - **Model B**: strongly coupled Composite Higgs scenario (g_v=3)

Variables used for the ANN training

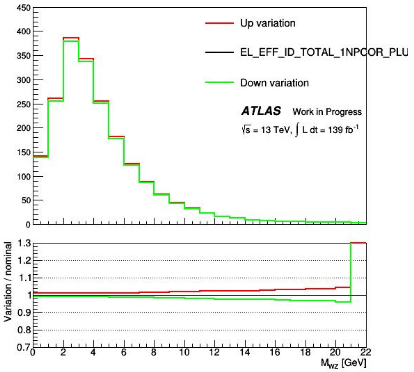
Parameter	Definition
M_{jj}	Invariant mass of two leading-p_{T} jets
$\Delta\phi_{jj}$	Difference in ϕ of the leading-p_{T} jets
η_W, η_Z	Pseudorapidities of the reconstructed gauge bosons
$\eta(j_1)$	Leading jet pseudorapidity
ζ_{Lep}	Event centrality (defined in Eqn. 2)
$E_{\mathrm{T}}^{\mathrm{miss}}$	Missing transverse energy
H_T	Scalar sum of the transverse momenta of visible objects (jets and leptons)

$$\text{centrality} = \min\left\{\left[\min(\eta_{\ell_1}, \eta_{\ell_2}, \eta_{\ell_3}) - \min(\eta_{j_1}, \eta_{j_2})\right], \left[\max(\eta_{j_1}, \eta_{j_2}) - \max(\eta_{\ell_1}, \eta_{\ell_2}, \eta_{\ell_3})\right]\right\}$$

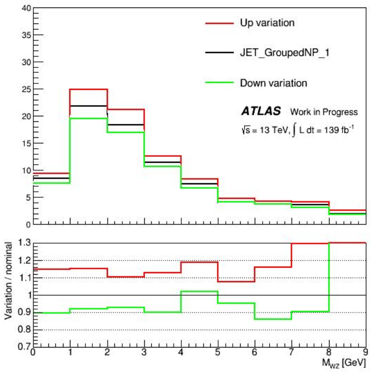
Systematic Uncertainties

- Complete set of objects uncertainties included :
  - Electron systematics (important in qqF)
  - Muon systematics (important in qqF)
  - Missing Et systematics
  - PRW systematics (important in qqF and VBF fits)
  - Jet systematics (using R4_SR_Scenario1_SimpleJER → will update to GlobalReduction_SimpleJER)
  - Flavor tagging systematics
  - Matrix method systematics
- Shapes are smoothed in resonance finder for the fit

qqF: Electron ID efficiency



VBF HVT: JET calibration uncertainties



electron systematics

EG_RESOLUTION_ALL	0.01074%
EG_SCALE_AF2	0.00000%
EG_SCALE_ALL	0.17909%
EL_EFF_ID_TOTAL_1NPCOR_PLUS_UNCOR	1.03462%
EL_EFF_Iso_TOTAL_1NPCOR_PLUS_UNCOR	0.13293%
EL_EFF_Reco_TOTAL_1NPCOR_PLUS_UNCOR	0.17624%

missing Et systematics

MET_SoftTrk_ResoPara	0.36243%
MET_SoftTrk_ResoPerp	0.29816%
MET_SoftTrk_ScaleDown	0.36701%

PRW systematics

PRW_DATASF	1.48271%

muon systematics

MUON_EFF_ISO_STAT	0.03322%
MUON_EFF_ISO_SYS	0.42996%
MUON_EFF_RECO_STAT	0.14751%
MUON_EFF_RECO_STAT_LOWPT	0.00000%
MUON_EFF_RECO_SYS	0.56604%
MUON_EFF_RECO_SYS_LOWPT	0.00000%
MUON_EFF_TTVA_STAT	0.04483%
MUON_EFF_TTVA_SYS	0.05624%
MUON_ID	0.02327%
MUON_MS	0.01655%
MUON_SAGITTA_RESBIAS	0.00642%
MUON_SAGITTA_RHO	0.00662%
MUON_SCALE	0.24776%

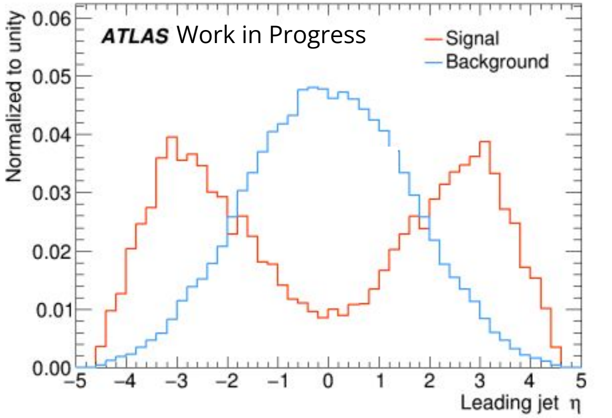
jet systematics

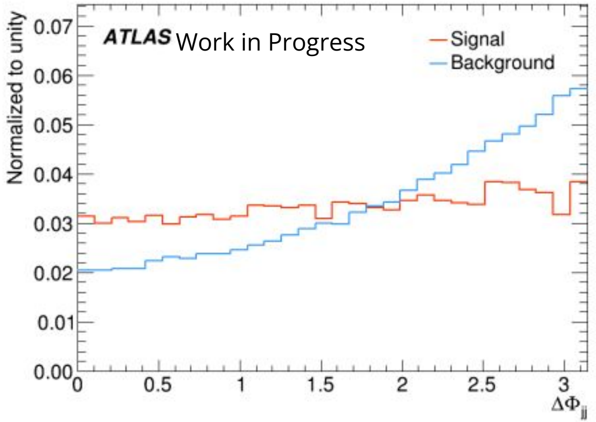
JET_EtaIntercalibration_NonClosure_highE	0.00001%
JET_EtaIntercalibration_NonClosure_negEta	0.00631%
JET_EtaIntercalibration_NonClosure_posEta	0.00319%
JET_Flavor_Response	0.13921%
JET_GroupedNP_1	0.23703%
JET_GroupedNP_2	0.22260%
JET_GroupedNP_3	0.01573%
JET_JER_EffectiveNP_1	0.00001%
JET_JER_EffectiveNP_2	0.00000%
JET_JER_EffectiveNP_3	0.00001%
JET_JER_EffectiveNP_4	0.00000%
JET_JER_EffectiveNP_5	0.00000%
JET_JER_EffectiveNP_6	0.00000%
JET_JER_EffectiveNP_7restTerm	0.00001%
JET_JvtEfficiency	0.07487%
JET_fJvtEfficiency	0.31240%

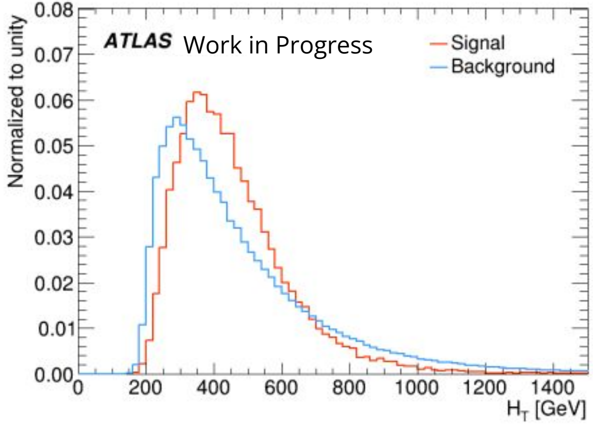
(results here are at the level of the WZ inclusive Validation region)

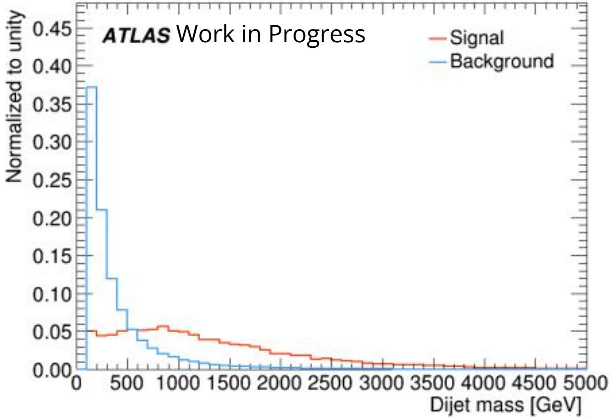
flavor tagging systematics

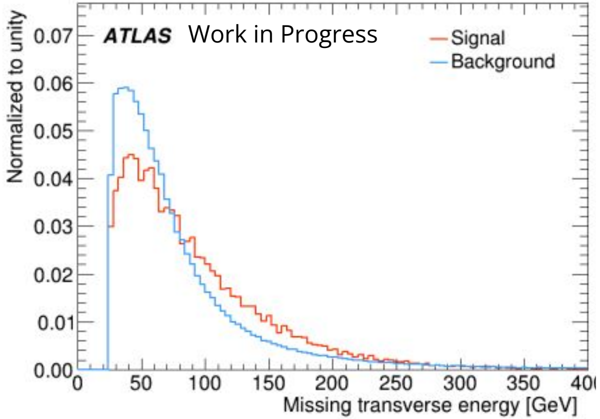
FT_EFF_Eigen_B_0	0.02674%
FT_EFF_Eigen_B_1	0.00604%
FT_EFF_Eigen_B_2	0.00434%
FT_EFF_Eigen_B_3	0.00158%
FT_EFF_Eigen_B_4	0.00014%
FT_EFF_Eigen_B_5	0.00002%
FT_EFF_Eigen_B_6	0.00002%
FT_EFF_Eigen_B_7	0.00000%
FT_EFF_Eigen_B_8	0.00000%
FT_EFF_Eigen_C_0	0.04878%
FT_EFF_Eigen_C_1	0.00381%
FT_EFF_Eigen_C_2	0.00318%
FT_EFF_Eigen_C_3	0.00048%
FT_EFF_Eigen_Light_0	0.04676%
FT_EFF_Eigen_Light_1	0.00179%
FT_EFF_Eigen_Light_2	0.00492%
FT_EFF_Eigen_Light_3	0.00036%
FT_EFF_extrapolation	0.00336%
FT_EFF_extrapolation_from_charm	0.01013%

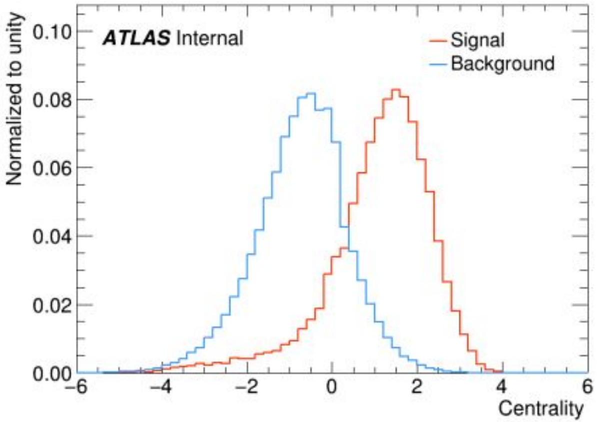

ATLAS Work in Progress
Signal
Background
Normalized to unity
Leading jet η


ATLAS Work in Progress
Signal
Background
Normalized to unity
ΔΦjj


ATLAS Work in Progress
Signal
Background
Normalized to unity
HT [GeV]


ATLAS Work in Progress
Signal
Background
Normalized to unity
Dijet mass [GeV]


ATLAS Work in Progress
Signal
Background
Normalized to unity
Missing transverse energy [GeV]


ATLAS Internal
Signal
Background
Normalized to unity
Centrality