Search for Exclusive Hadronic W Decays with the ATLAS Experiment

Júlia Silva

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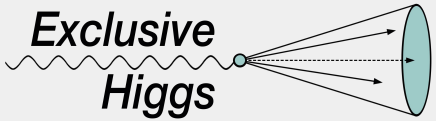
UNIVERSITY OF BIRMINGHAM



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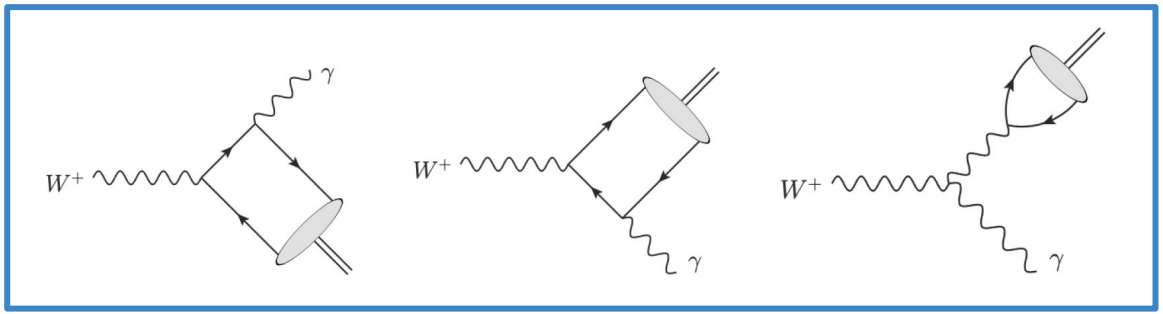
Exclusive W Decays

➔ **None of the exclusive hadronic W decays predicted by the Standard Model have been observed**

- These can offer novel precision studies of QCD factorisation (arXiv:1501.06569)
- Very small branching fractions predicted by SM (arXiv:1501.06569)

Channel	Branching fraction
$W^{\pm} \rightarrow \pi^{\pm}\gamma$	$(4.0 \pm 0.8) \times 10^{-9}$
$W^{\pm} \rightarrow K^{\pm}\gamma$	$(3.3 \pm 0.7) \times 10^{-10}$
$W^{\pm} \rightarrow \rho^{\pm}\gamma$	$(8.7 \pm 1.9) \times 10^{-9}$

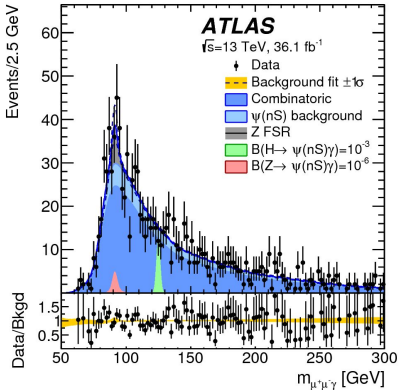


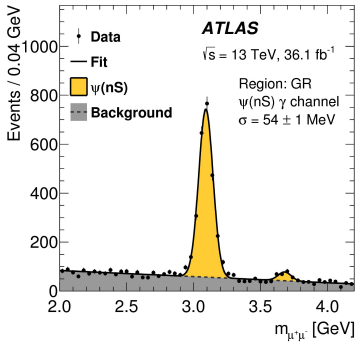
➔ **Searches currently underway for $W^{\pm} \rightarrow \pi^{\pm}\gamma$, $W^{\pm} \rightarrow \rho^{\pm}\gamma$ and $W^{\pm} \rightarrow K^{\pm}\gamma$ at ATLAS, using LHC Run-2 data**

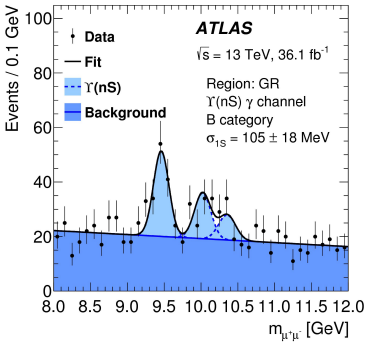
- World's best limit on $B(W^{\pm} \rightarrow \pi^{\pm}\gamma)$ of $< 7\times10^{-6}$ at 95 % CL by CDF (arXiv:1104.1585)
- Recent CMS result: $B(W^{\pm} \rightarrow \pi^{\pm}\gamma) < 1.5\times10^{-5}$ at 95 % CL (arXiv:2011.06028)
- No limits available on $B(W^{\pm} \rightarrow \rho^{\pm}\gamma)$ and $B(W^{\pm} \rightarrow K^{\pm}\gamma)$

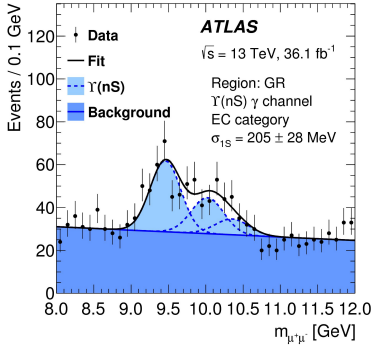
Exclusive Decays H/Z→Qγ

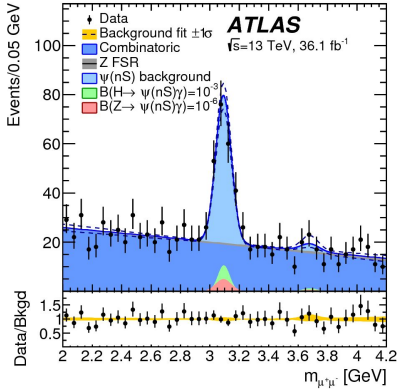
- **Several ATLAS publications on exclusive Higgs/Z decays**
  - Potential to probes light quark Yukawa couplings
- **Enabled by:**
  - Dedicated triggers
  - Non-parametric data-driven background modelling
- J/ψ+γ and Υ+γ (arXiv:1807.00802, arXiv:1501.03276), φ+γ and ρ+γ (arXiv:1712.02758, arXiv:1607.03400)







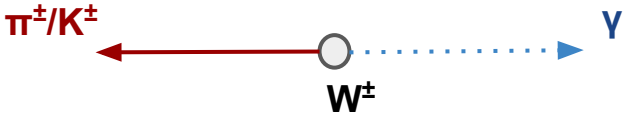




Analysis Final States

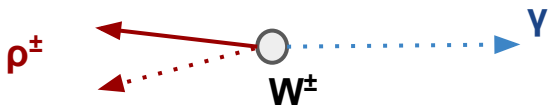
$W^{\pm} \rightarrow \pi^{\pm}/K^{\pm} + \gamma$

- **Isolated high p_T track** recoiling against **isolated high p_T photon**
- Angular distribution: $(1+ \cos^2\theta)$



$W^{\pm} \rightarrow \rho^{\pm}(\rightarrow \pi^{\pm}\pi^{0}) + \gamma$

- **High p_T track + electromagnetic deposition** recoiling against isolated **high p_T photon**
- Angular distribution: $\cos^2\theta$



➔ **$W^{\pm} \rightarrow \pi^{\pm}\gamma$ and $W^{\pm} \rightarrow K^{\pm}\gamma$ have the same experimental signature**
- Interpret the track+photon search as $W^{\pm} \rightarrow \pi^{\pm}\gamma$ and $W^{\pm} \rightarrow K^{\pm}\gamma$

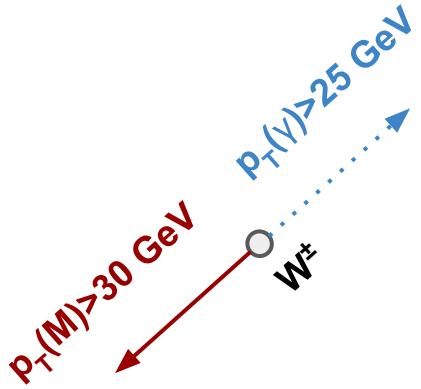
➔ During this presentation will refer to the **track + photon** and the **ρ+photon** final states:
- Different strategies employed

$W \rightarrow \pi/K + \gamma$
(track+photon)

Trigger

- **Dedicated triggers allow us to identify specific event topology**
  - Developed for exclusive Higgs/Z/W analyses
  - Using modified tau-lepton trigger algorithms:
    - Meson decay similar to hadronic tau decays

- **W→ M+γ trigger requiring single track + single photon**
  - Track p_T > 30 GeV
  - Photon p_T > 25 GeV
  - M(Meson + Photon) > 50 GeV
  - 0.4 < E_T/p_T(track) < 0.85

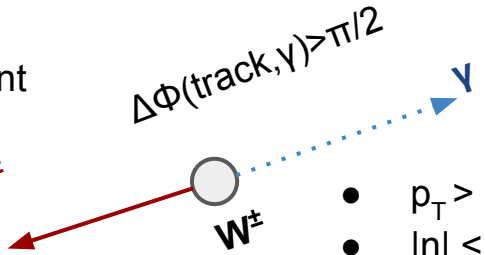


- **Collected 136 fb^{-1} from 2016 to 2018**
  - With around **50% efficiency** wrt offline selection

Event Selection

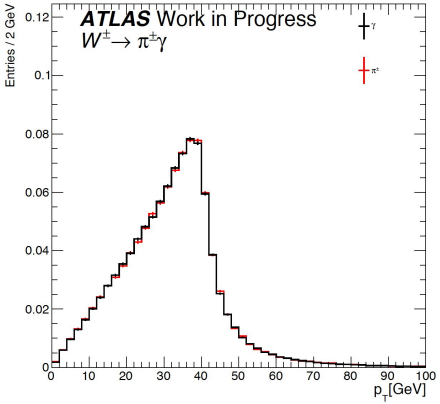
Track

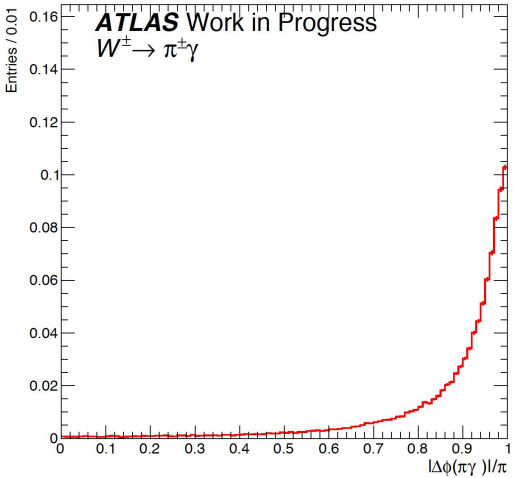
- $p_T > 33$ GeV
- $|\eta| < 2.5$
- Tight working point
- Track Isolation



Photon

- $p_T > 30$ GeV
- $|\eta| < 2.37$
- Exclude transition region
- Tight identification
- Tight isolation





W candidate = highest p_T track + highest p_T photon

Total Efficiency ~5%

Z → ee rejection

- **Resonant background arising from Z → ee events:**
  - One electron reconstructed as track and the other as photon
  - Corresponds to ~3% of the total background
- **Studied background rejection with simulated samples**
  - Look for closest reconstructed electron to the track in ΔR

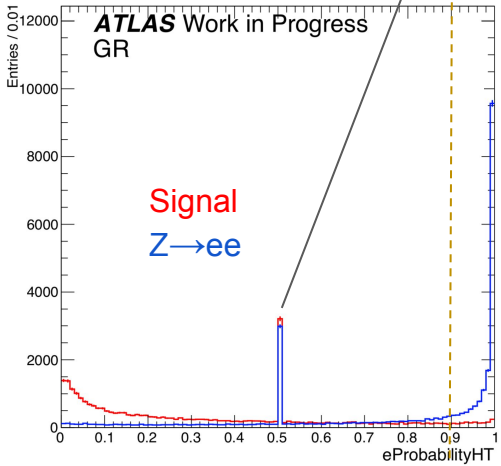
- **Efficiencies:**
  - Signal = 94%
  - Background = 15%

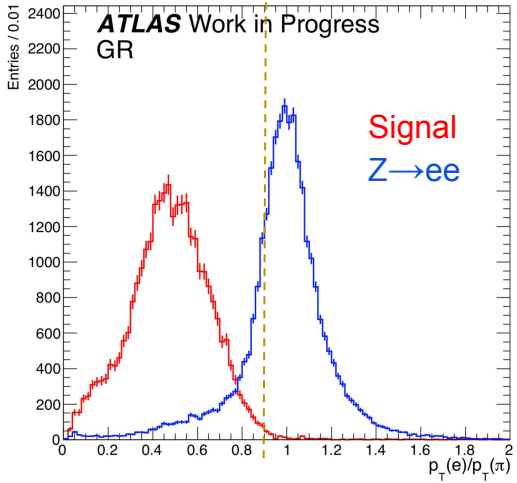
[eProbabilityHT - quantifies probability that track is in fact an electron, based on TRT]

peak at eProbabilityHT=0.5 from tracks with |η|>2 - out of TRT acceptance

reject

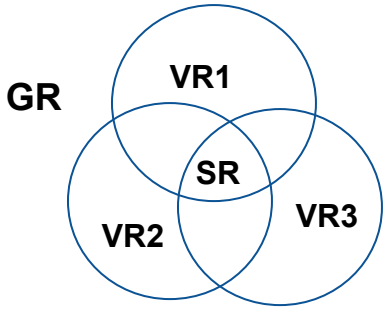
reject





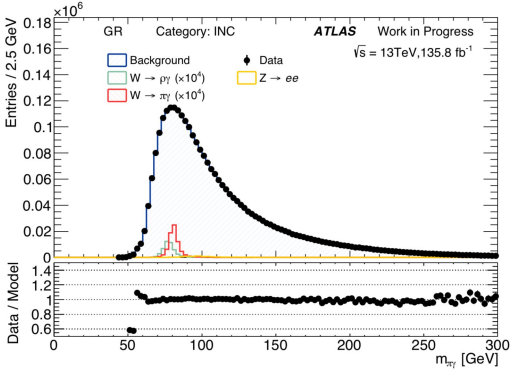
Background Modelling

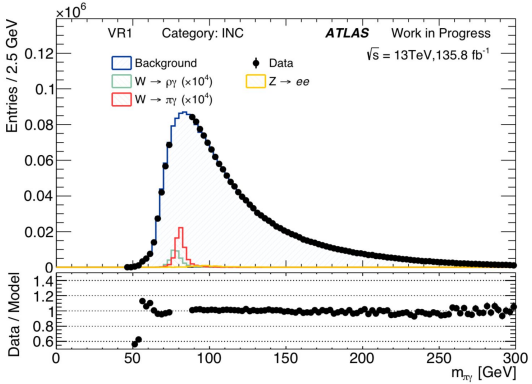
- **Main background arising from dijet and jet + photon processes**
  - Not reliably modelled by MC
- **A data-driven non-parametric method is applied**:
  - **Generation Region** (GR): Large sample of W candidates, with relaxed p_T(track) and isolation requirements
  - Model relevant kinematic/isolation distributions from data
  - Generate pseudo-candidates → reproduce correlations observed in data
  - Apply **Signal Region** requirements
  - **Validation Regions** (VR): control the model

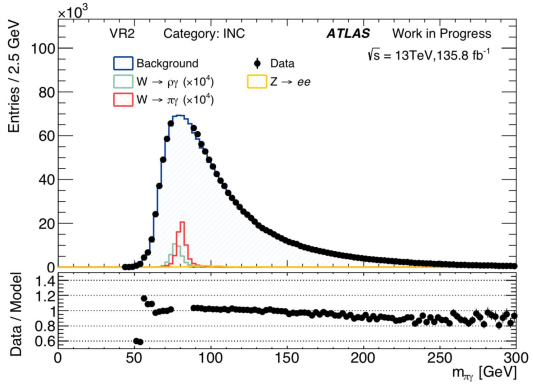


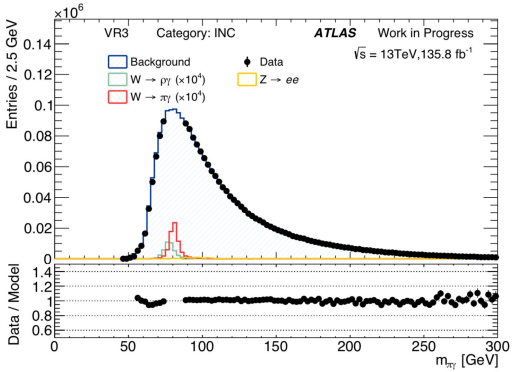
Region	Selection
VR1	GR + p_T(track) > 33 GeV
VR2	GR + Photon Isolation
VR3	GR + Track Isolation
SR	GR + all of the above

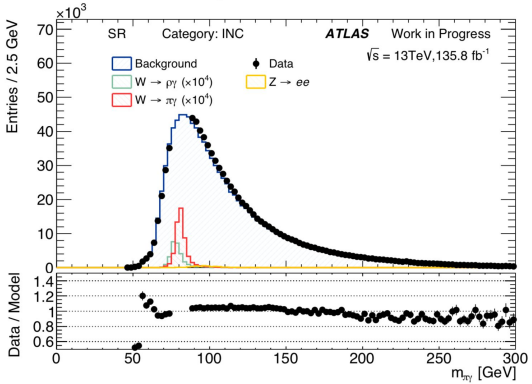
Control Plots - W Mass







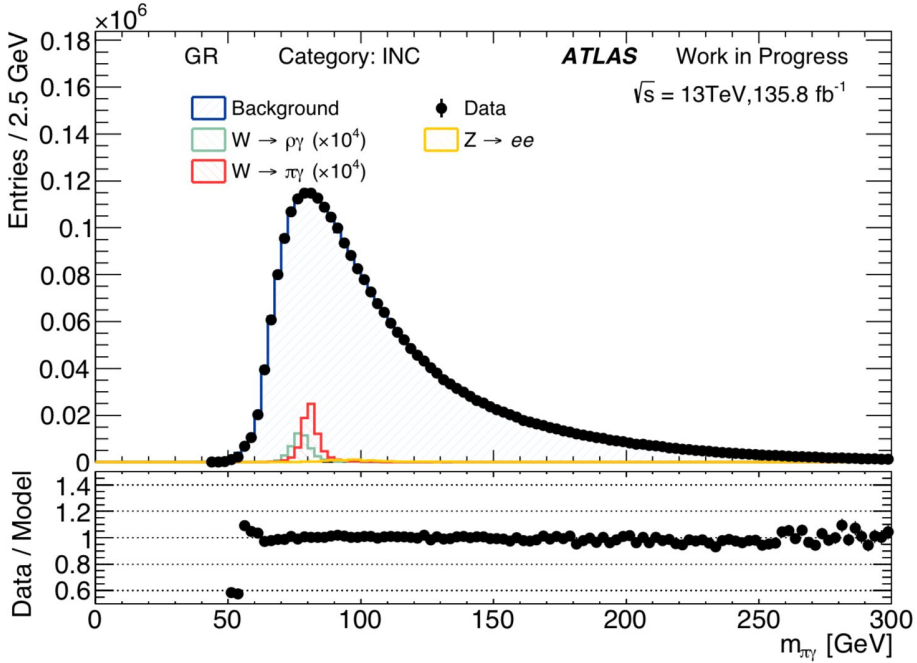




Data
Inclusive Background
Signal
Z→ee

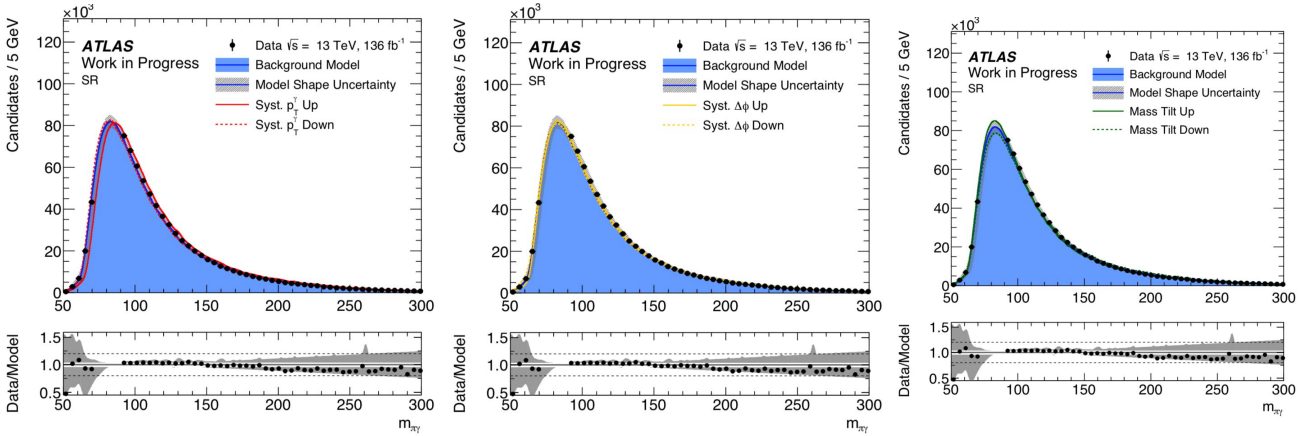
W→ργ Signal in track+photon Final State

- **Some W→ργ signal reconstructed in track+photon final state!**
  - ~ 2.5 events expected (efficiency = 1.1%)
  - Distinct signal shape to W→ π/K + γ
    - π^0 missed in reconstruction



Systematics

- **Background Systematics:**
  - 3 modifications to modelling implemented:
    - $p_T(\gamma)$ shifts
    - linear distortions to $\Delta\Phi$(track,γ)
    - global tilt to W invariant mass
- **Signal Systematics:**
  - Cross section - 3.4%
  - Photon ID and Isolation - 2%

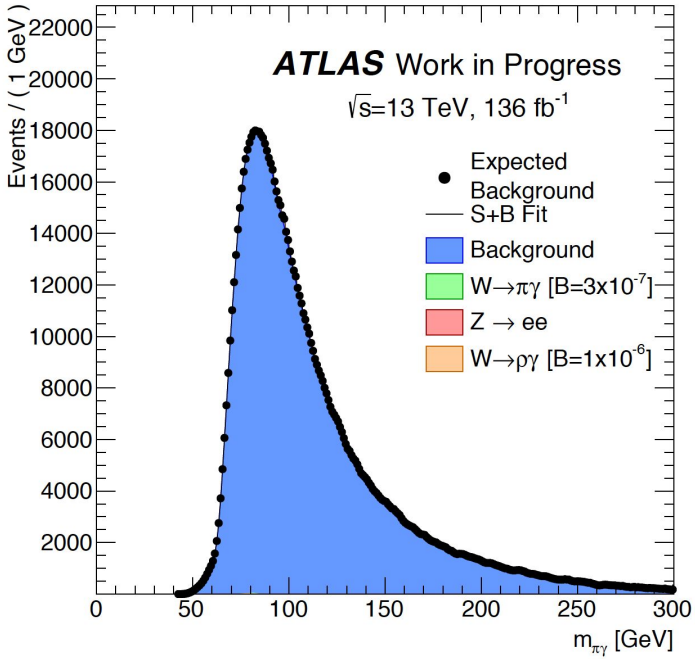


Results

Inclusive Background: Background model smoothed with KDE
Z→ ee: MC distribution
Signal: Sum of 2 voigtian functions with same mean
- Parameters fit to MC
- Width from PDG

Statistical Analysis
- ➔ Unbinned Maximum Likelihood Fit in track + photon mass
- ➔ Nuisance parameters for systematic uncertainties
  - Background shape systematics as “morphing” NPs
- ➔ Asymptotic CL_s with profile likelihood as test statistic

Expected 95% CL Upper Limits
Br(W→ πγ) < 3x10^{-7} (70 x SM value)
Br(W→ργ) < 1x10^{-6} (124 x SM value)



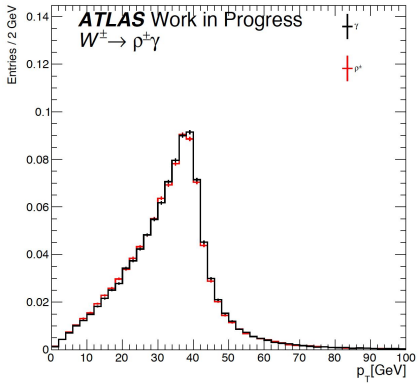
$W \rightarrow \rho + \gamma$
(ρ+photon)

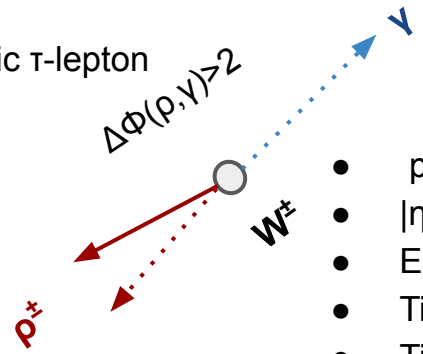
Event Selection

Trigger: Di-photon triggers requiring 2 photons with $p_T > 35$ GeV and $p_T > 25$ GeV (~10% efficiency)

ρ candidate

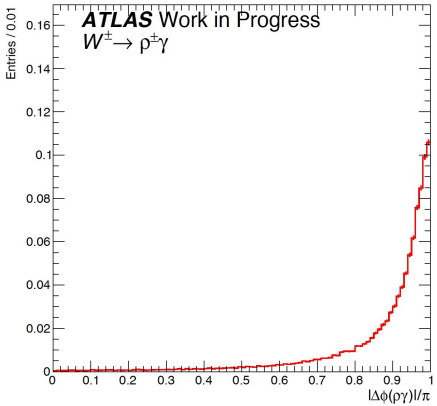
- Reconstructed as hadronic τ-lepton
- $p_T > 26$ GeV
- $|\eta| < 2.5$
- Exclude transition region
- Medium TauRNNScore
- $h^{\pm}\pi^0$ decay mode





Photon

- $p_T > 36$ GeV
- $|\eta| < 2.37$
- Exclude transition region
- Tight identification
- Tight Isolation



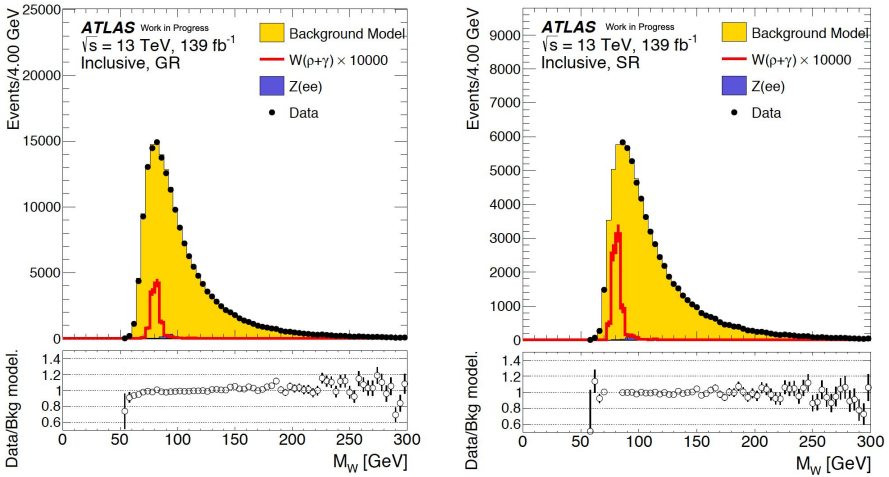
W candidate = candidate with maximum ΔΦ(ρ,γ)

Z→ee background rejection using eProbabilityHT and tau variables

Total Efficiency ~0.3%

Background Modelling

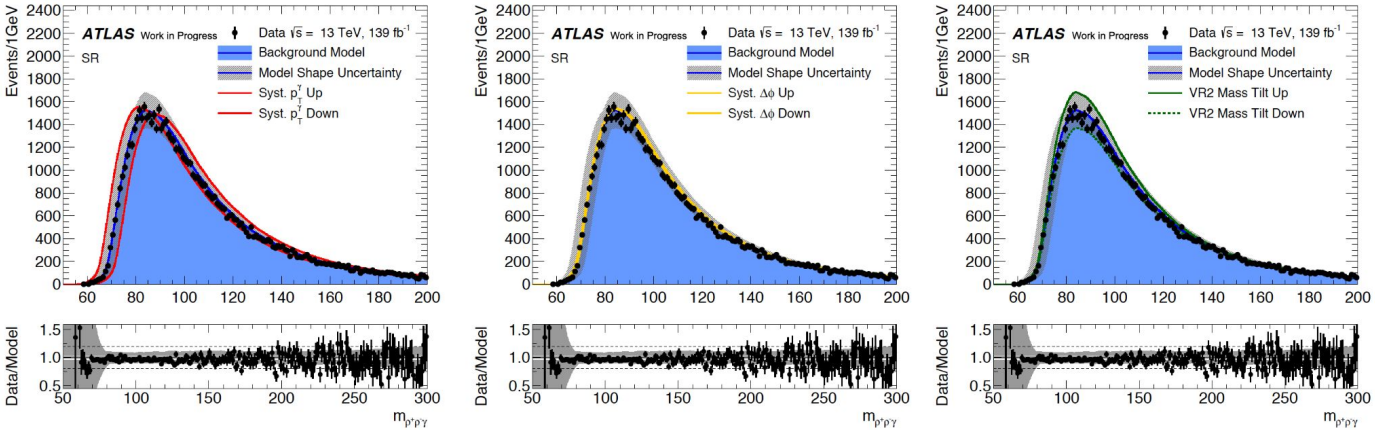
- ➔ **Main background arising from dijet and jet + photon processes**
- ➔ **The same non-parametric data-driven background modelling method used**
  - ◆ γ and τ variables used in the modelling



Region	Selection
VR1	GR + $\mathbf{p_T(\tau) > 32\ GeV}$
VR2	GR + $\mathbf{\Delta R_T^{max} < 0.067}$
VR3	GR + $\mathbf{\log(\lvert d_0(\tau_W)\rvert) < -1}$
SR	GR + all of the above

Systematics

- **Background Systematics:**
  - Background shape allowed to vary around nominal shape using same variations as described for track+photon final state
- **Signal Systematics:**
  - EG scale - 4.8%
  - Cross Section - 3.4%
  - EG Resolution - 3%

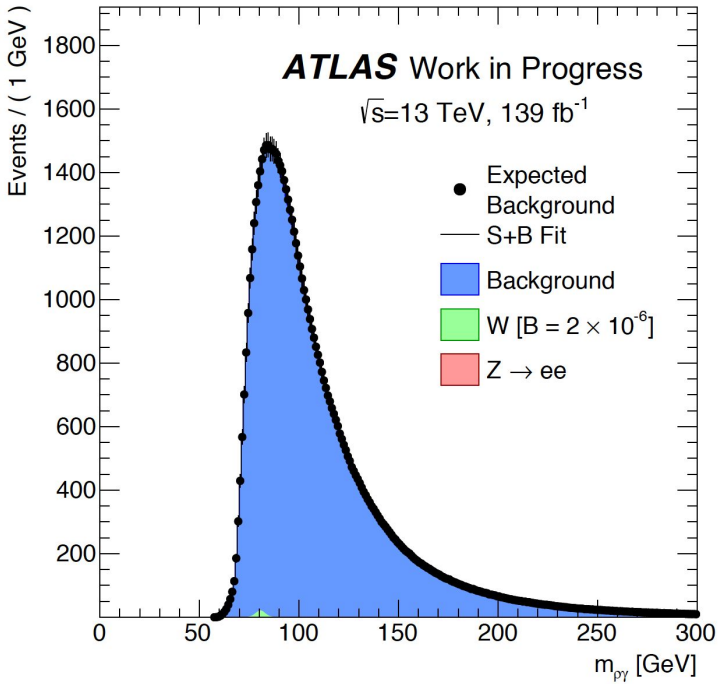


Results

Inclusive Background: Background model
Z→ ee: MC distribution
Signal: Sum of 2 voigtian functions with same mean
- Parameters fit to MC
- Width from PDG

Statistical Analysis
- ➔ Unbinned Maximum Likelihood Fit in rho + photon mass
- ➔ Not including systematic uncertainties
- ➔ Asymptotic CLs with profile likelihood as test statistic

Expected 95% CL Upper Limits
Br (W→ργ) < 2x10^{-6} (184 x SM value)

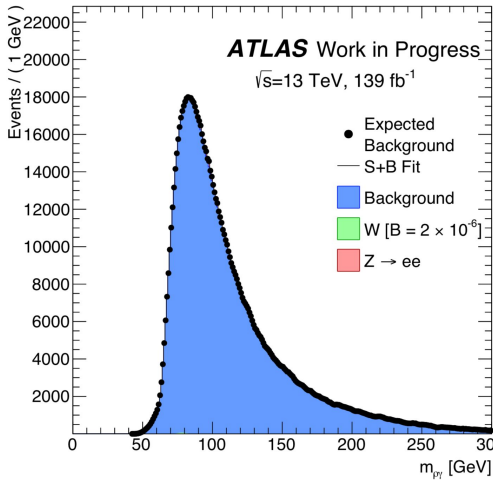


Combined Fit Result

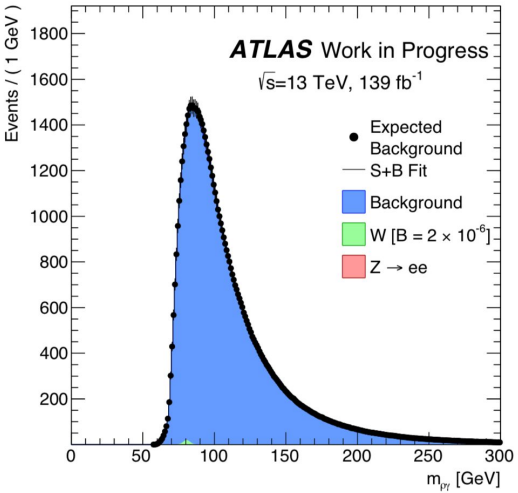
- **No overlap between events in the two final channels**
  - Dedicated triggers and diphoton triggers used found to be practically orthogonal
- **Improve limit on Br(W→ργ) with 2 category fit using both final states**

Expected 95% CL upper limit:
Br (W→ργ) < 7x10^{-7} (79 x SM value)

track+ γ SR

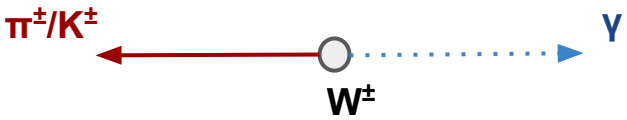


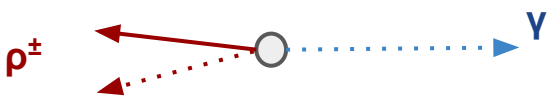
ρ+γ SR



Summary

- ➔ **None of the exclusive hadronic decays of the W boson have been observed**
  - Weak or no experimental constraints available
- ➔ **Searches for these decays currently underway at ATLAS!**
  - Enabled by:
    - Dedicated meson + photon triggers
    - Data-driven non-parametric background modelling method
  - Estimated expected upper limits at 95% CL:
    - $B(W^{\pm} \rightarrow \pi^{\pm}\gamma) < 3 \times 10^{-7}$
    - $B(W^{\pm} \rightarrow \rho^{\pm}\gamma) < 7 \times 10^{-7}$
  - Same analysis strategy used for $W^{\pm} \rightarrow \pi^{\pm}\gamma$ to be used for $W^{\pm} \rightarrow K^{\pm}\gamma$ search





BACK-UP

Background Model

1. Sample $\mathbf{p_T(\pi)}$ and $\mathbf{p_T(\pi)}$ from data 2D distribution

2. Track isolation in bins of $p_T(\gamma)$. Given the value of $p_T(\gamma)$ sampled in 1, track isolation is sampled in the corresponding bin

3. Photon calorimeter isolation described in bins of $p_T(\gamma)$. Given the value of $p_T(\gamma)$ sampled in 1, photon calorimeter isolation is sampled in the corresponding bin

4. **$\Delta\eta(\pi,\gamma)$** and described in bins of photon calorimeter isolation. GIven previously sampled value of photon calorimeter isolation, a value of $\Delta\eta(\pi,\gamma)$ is sampled

5. **$\Delta\Phi(\pi,\gamma)$** described in bins of $\Delta\eta(\pi,\gamma)$. Given the selected value of $\Delta\eta(\pi,\gamma)$, a $\Delta\Phi(\pi,\gamma)$ value is chosen

6. Photon track isolation described in bins of photon calorimeter isolation. Given selected value of photon calorimeter isolation, a value of photon track isolation is sampled for the distribution of the data