Search for the exclusive W boson hadronic decays

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Maastricht – 09/05/2022

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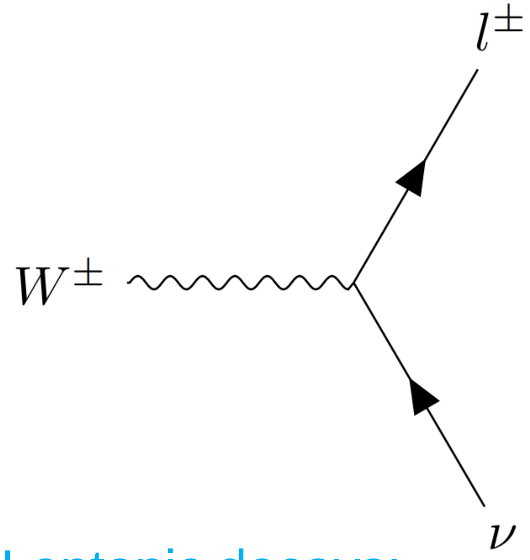
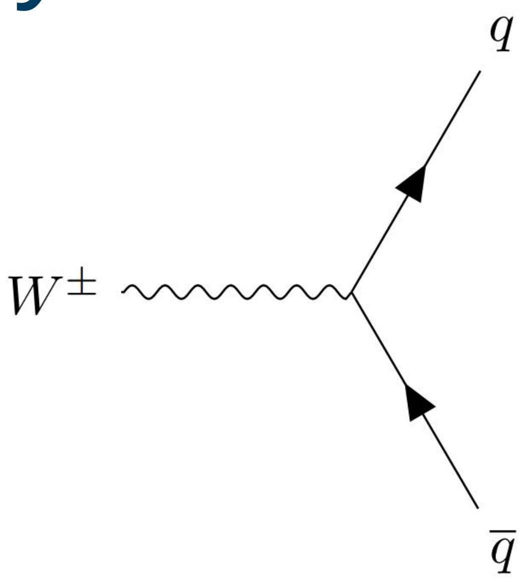
What and why?



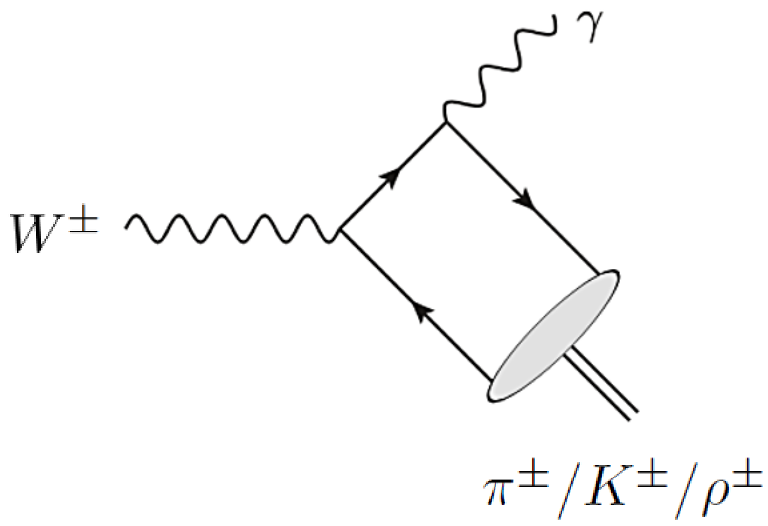
Leptonic decays:

10.86±0.09%



Hadronic decays:

67.41±0.27%



Exclusive hadronic decays:

$\pi^+\gamma$	< 7	$\times 10^{-6}$
$D_s^+\gamma$	< 1.3	$\times 10^{-3}$

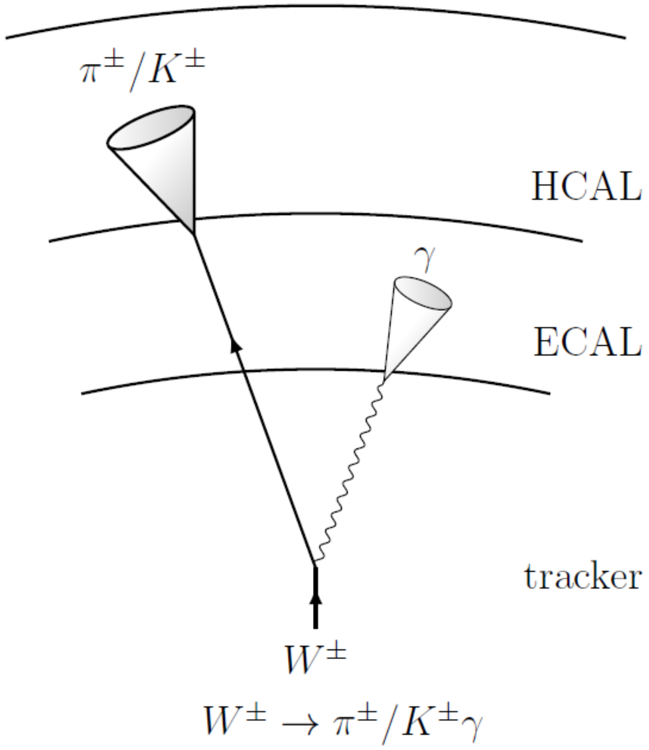
Standard model prediction: $\sim 10^{-9}$

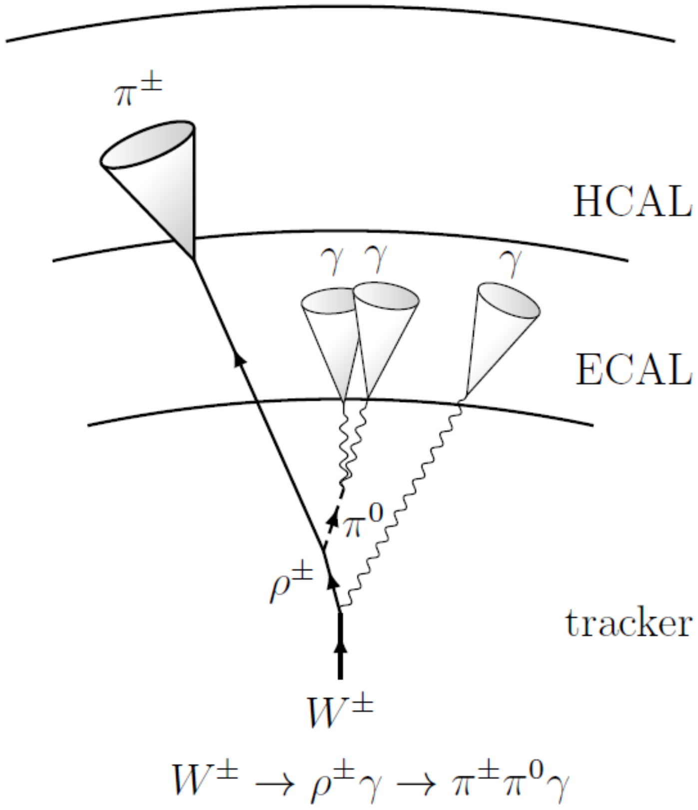
Expected amount of events using Run 2 data:

$N(W)$	$N(W \to \pi\gamma)$	$N(W \to K\gamma)$	$N(W \to \rho\gamma)$
$3 \cdot 10^{10}$	120	10	170

- Exclusive hadronic decay modes can offer novel precision studies of QCD factorisation (arXiv:1501.06569).
- Radiative decays are sensitive to the coupling of the W boson with the photon.

How?



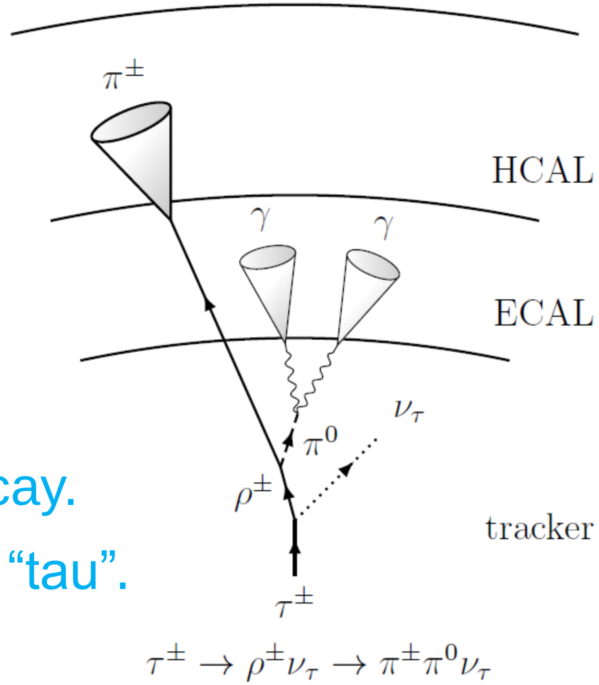


1. Track+Photon

- Sensitive to $W^\pm \to \pi^\pm/K^\pm/\rho^\pm + \gamma$ decays.
- π^0 from ρ decay is not reconstructed.

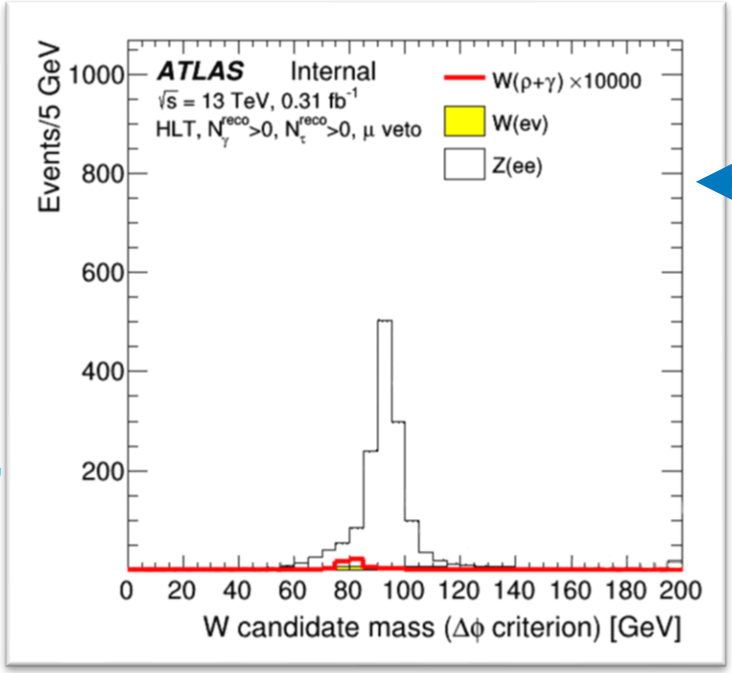
2. Tau+Photon

- Sensitive to $W^\pm \to \rho^\pm(\to \pi^\pm + \pi^0) + \gamma$ decay.
- ρ-candidate reconstructed as "tau".

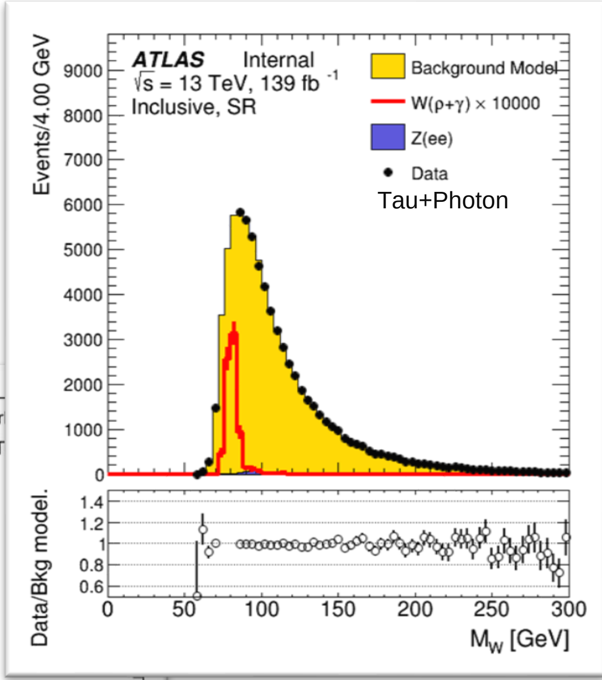


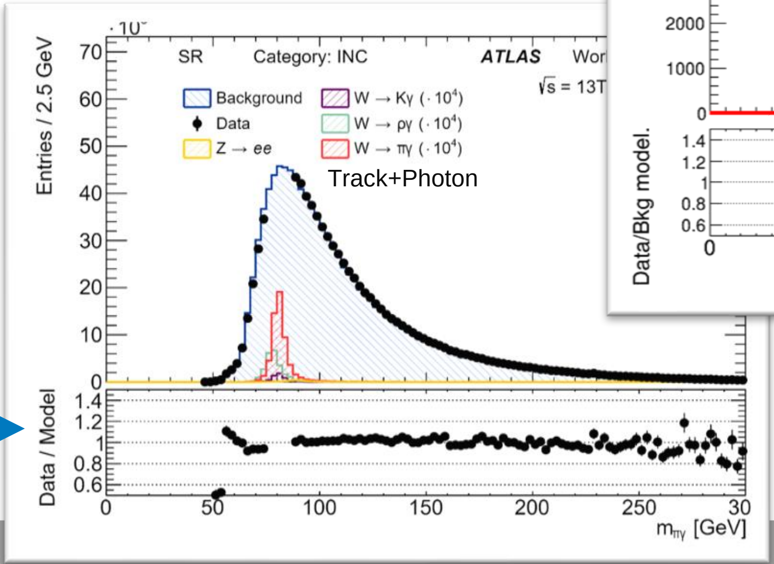
Why is it hard?

- Background processes:
  - $Z \rightarrow ee$ events:
    - One electron is reconstructed as photon, the other one as track or τ.
    - Modelled with Monte Carlo techniques.
    - Suppressed with selection criteria.
  - Multijet processes:
    - Not reliably modelled by Monte Carlo techniques.
    - Data-driven approach must be used (arXiv:2112.00650).



The peak shows the $Z \rightarrow ee$ background before the suppression, while the signal is displayed with red.





Background model in the signal region showed with blue in the track+photon and with yellow in the tau+photon final state.

Analysis is still blinded!

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Expected results

- Unbinned Maximum Likelihood Fit in track+photon and tau+photon mass with floating background normalisations and systematic uncertainties.

Track+Photon	Expected Upper Limit ($\cdot 10^{-6}$)
$W \to \pi\gamma$	1.30
$W \to K\gamma$	1.17
$W \to \rho\gamma$	9.64

Current limit: $7 \cdot 10^{-6}$

Tau+Photon	Expected Upper Limit ($\cdot 10^{-6}$)
$W \to \rho\gamma$	4.07

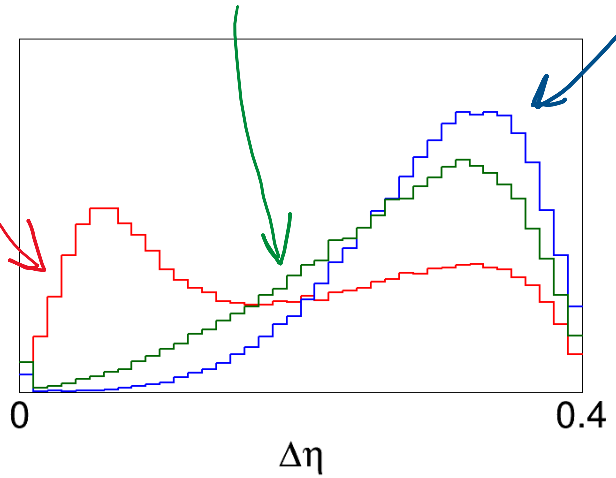
- Practically no overlap between events in the two final states.
  - The triggers used found to be ~orthogonal!
- Combined Fit in track + photon and tau + photon mass:

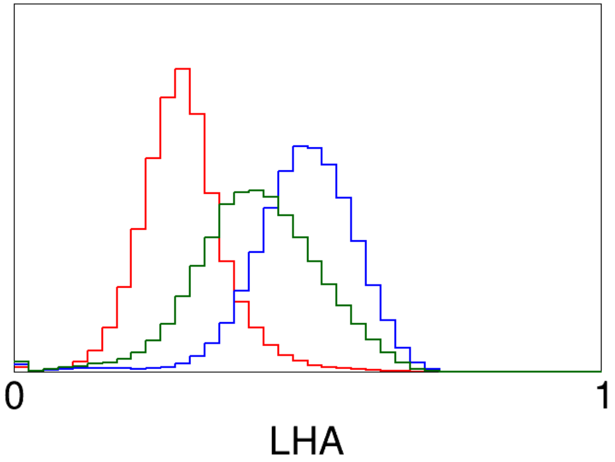
Combined	Expected Upper Limit ($\cdot 10^{-6}$)
$W \to \rho\gamma$	3.27

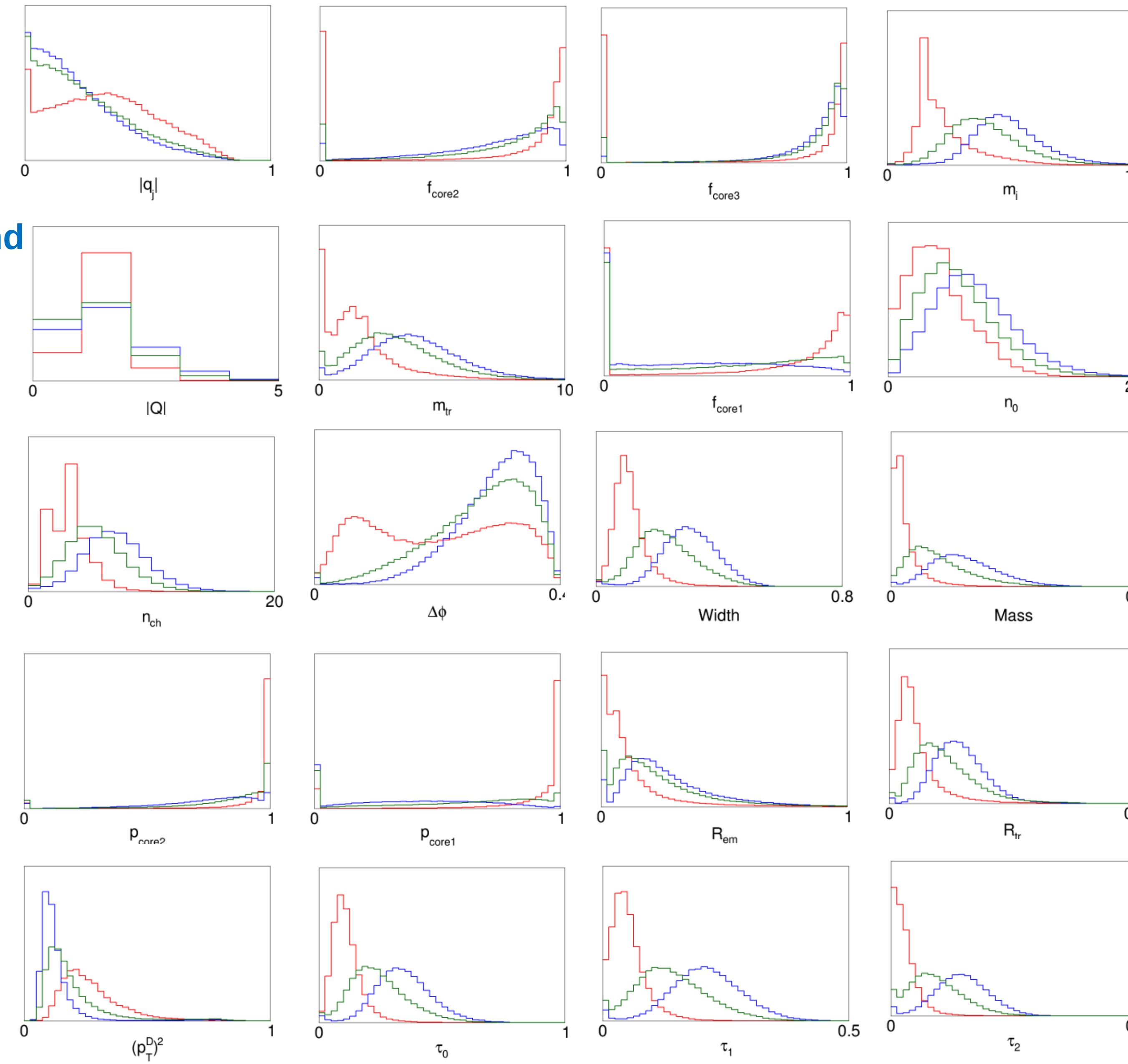
What more?

- Using MVA we can identify mesons!

Red – Signal, **Green – qq background**, **Blue – gg background**







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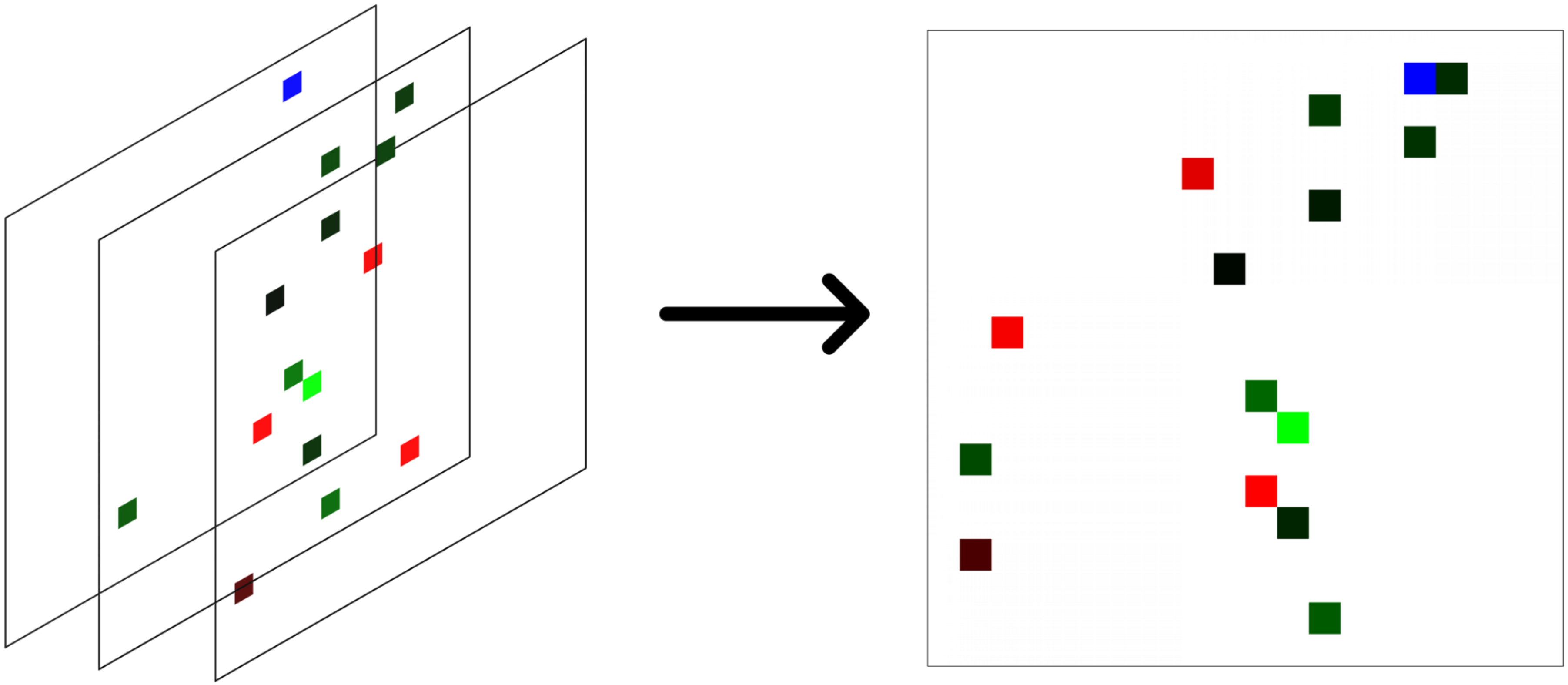
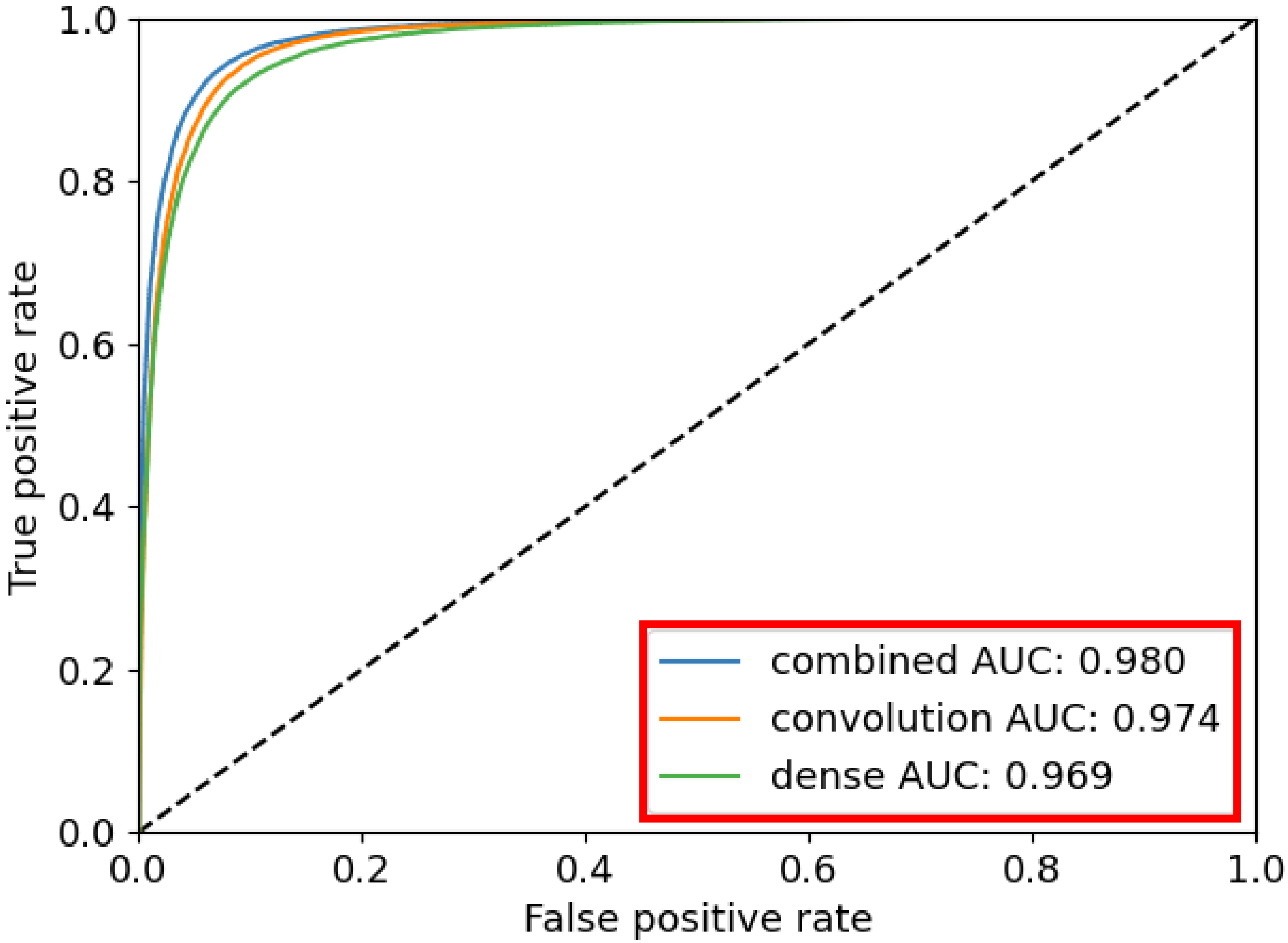
There is more!



Red – Track p_T
Green – EM deposit
Blue – Hadronic deposit

- Addition of low level variables: Energy deposit and p_T of the tracks.
- Using combined model: Deep Neural Network and Convolutional Neural Network

Does it work?



The algorithm is able to identify hadronic $D_s\gamma$ decays with an efficiency of 67% while suppressing a background of quark and gluon jets by a factor 100.

Test sample	Training sample	AuC
S vs mixed B	S vs mixed B	0.980
S vs gluon B	S vs mixed B	0.994
S vs quark B	S vs mixed B	0.964
S vs gluon B	S vs gluon B	0.994
S vs quark B	S vs quark B	0.965

Conclusions

- No exclusive hadronic decay mode of the W boson has ever been observed.
  - Upper limit exist for $W \to \pi\gamma$ only and this is the first ever search of the $W \to \rho\gamma$ and $W \to K\gamma$.
- Expected upper limits on branching fractions still well above SM predictions.
- The results are limited by sample size.
  - With the statistics obtainable in the HL-LHC it will be possible to observe several of these decays.
- We can identify mesons using machine learning techniques.
  - Using both low level and high level variables.

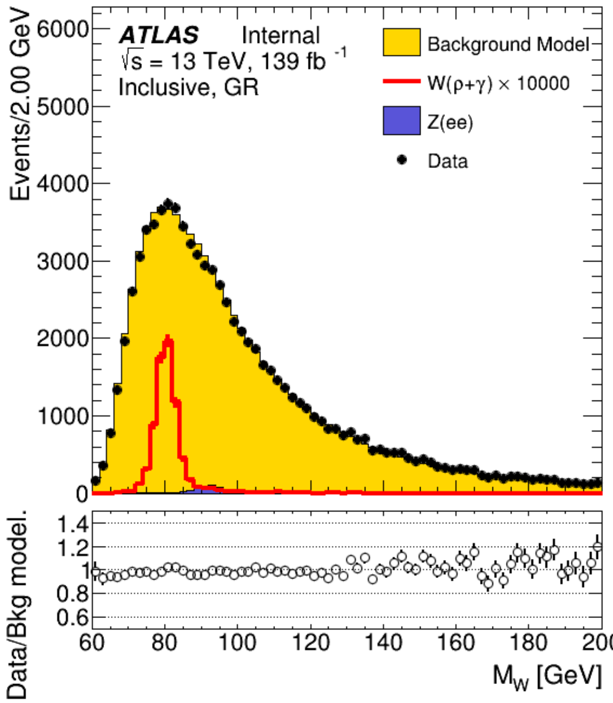
Thank you for your attention!

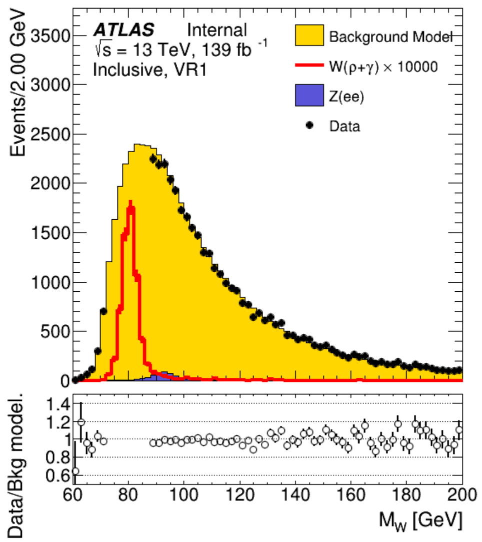
Backup

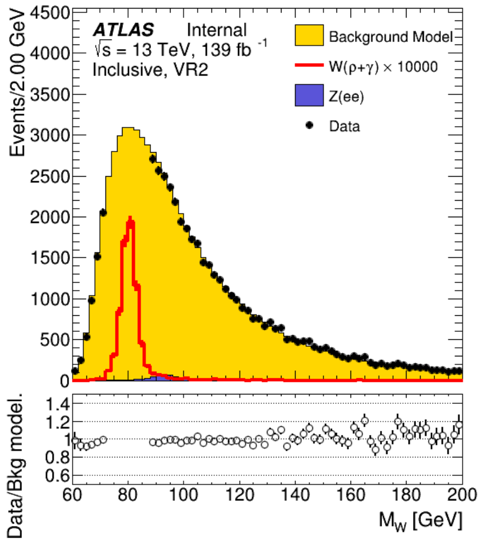
Rho+Photon model step-by-step

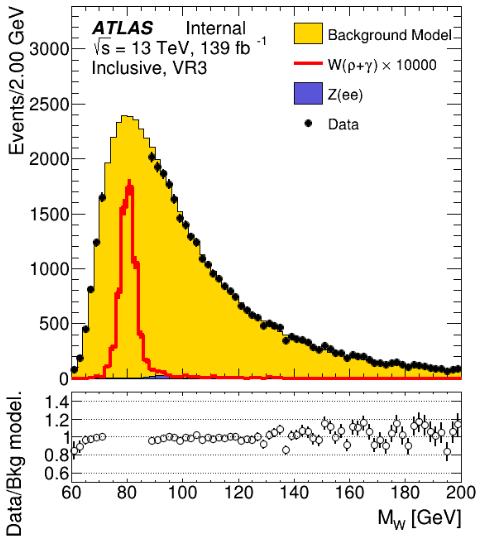
- Generate TauPt
- Model PhotonPt depending on TauPt
- Generate Tau dRmax depending on TauPt and PhotonPt
- TauTrackD0AbsLog is generated depending on TauPt and dRmax
- TauEta is generated depending both on TauTrackD0AbsLog and dRmax
- DeltaEta between Tau and Photon generated depending on TauEta
- DeltaPhi is generated depending on PhotonPt and TauPt
- TauPhi generated independently

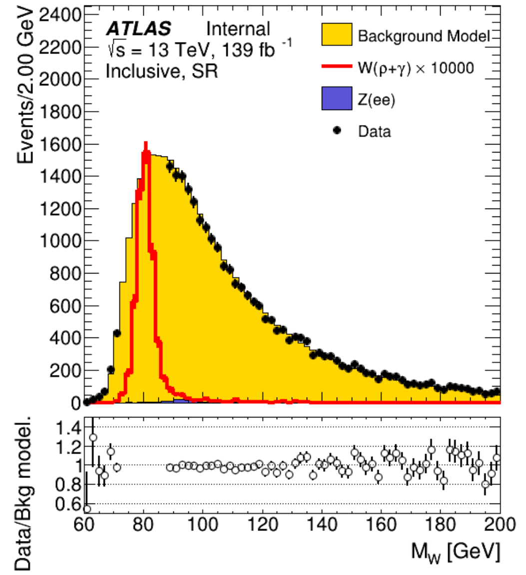
Control plots – Rho+Photon







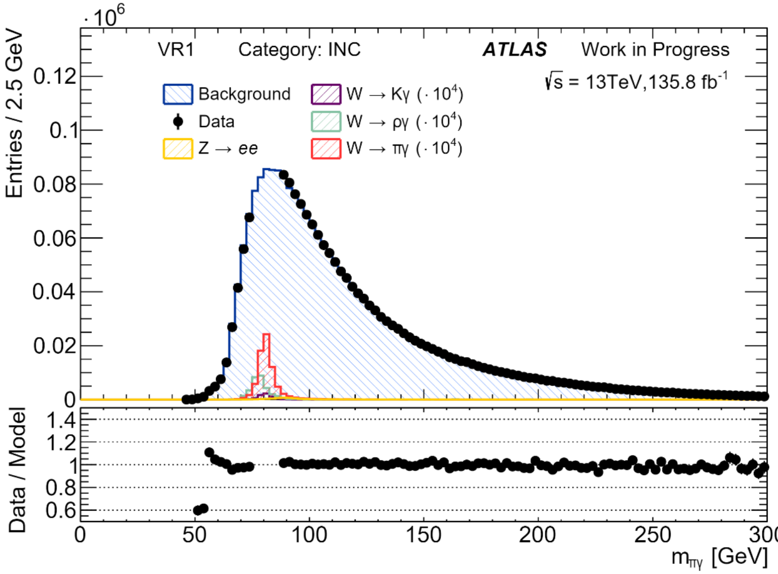


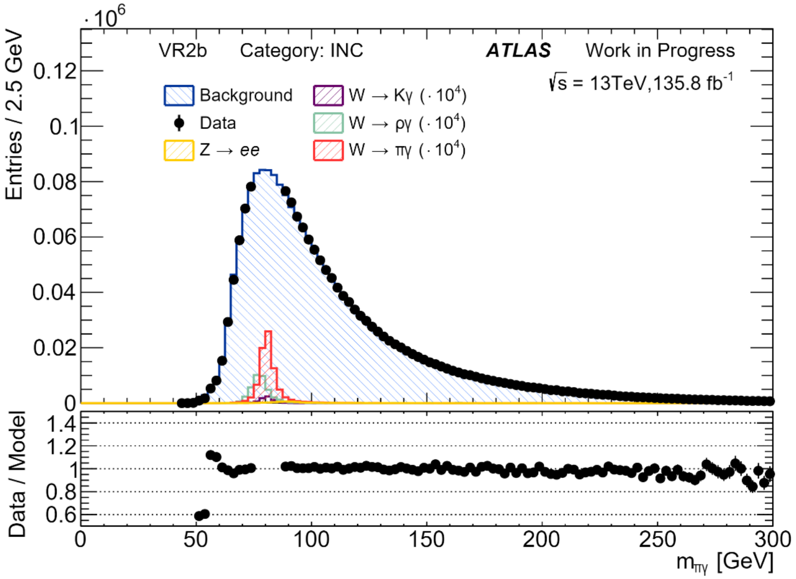


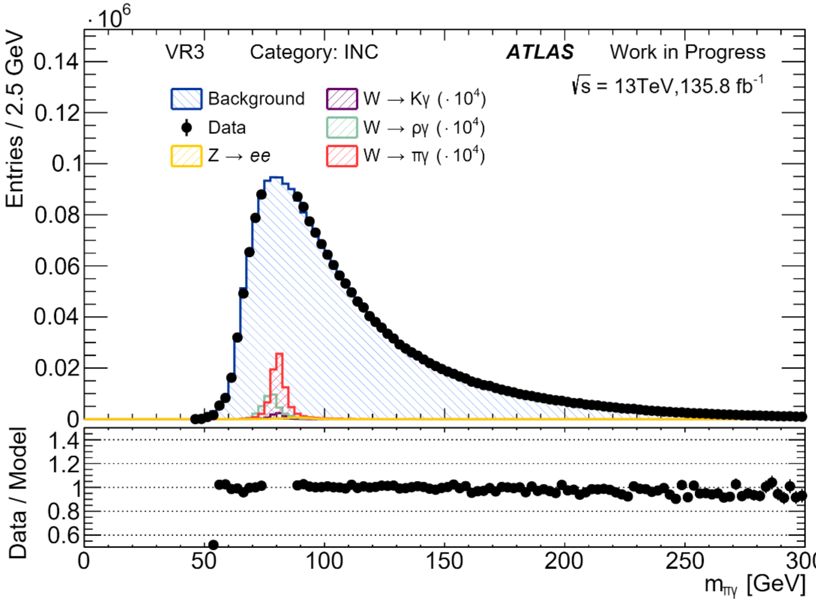
Track+Photon model step-by-step

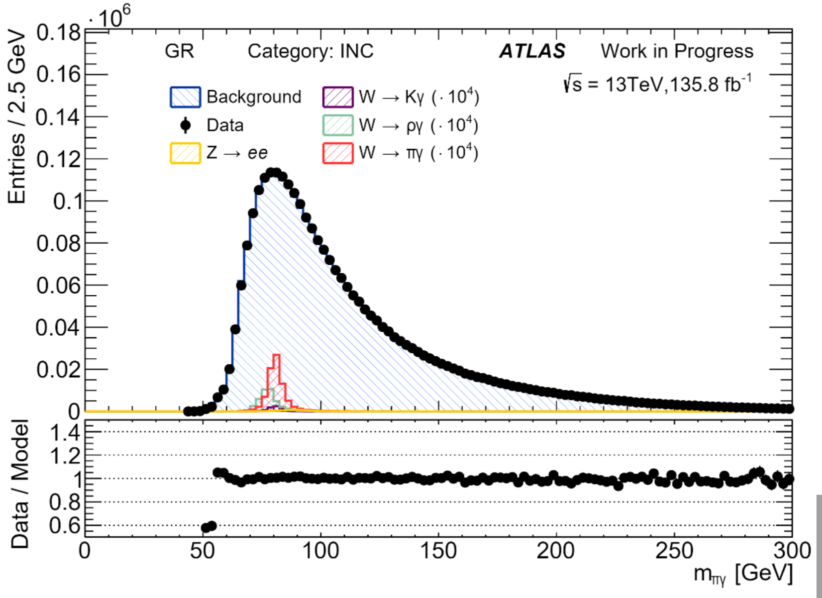
- Sample $p_T(\pi)$ from data $p_T(\pi)$ distribution
- $p_T(\gamma)$ described in bins of $p_T(\pi)$. Given the value picked previously, $p_T(\gamma)$ is sampled
- Track isolation in bins of $p_T(\gamma)$. Given the value of $p_T(\gamma)$ sampled, track isolation is sampled in the corresponding bin
- Values for $\Delta\eta(\pi,\gamma)$ and photon calorimeter isolation sampled simultaneously from a 2D distribution
  - 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
  - $\Delta\Phi(\pi,\gamma)$ 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
- Values of $\eta(\pi)$ and $\Phi(\pi)$ are sampled from the corresponding data distributions
- From previously obtained values for $\Delta\eta(\pi,\gamma)$ and $\Delta\Phi(\pi,\gamma)$, $\eta(\gamma)$ and $\Phi(\gamma)$ are calculated

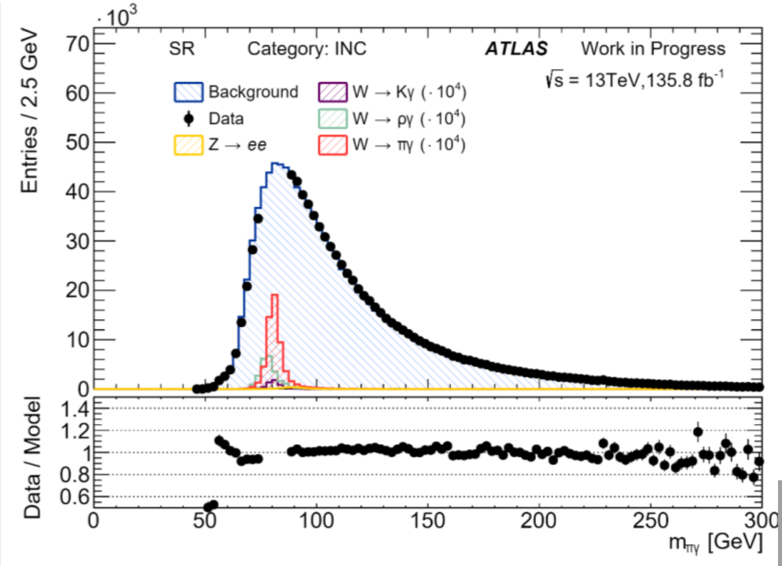
Control plots – Track+Photon











Region definitions

Track+Photon

Baseline selection
Trigger:
HLT_g35_medium_L1EM24VHI_tau25_singlepion_tracktwo_L1TAU12
HLT_g25_medium_tau25_singlepion_tracktwo_50mVis10000
Photon definition:
$p_T > 30$ GeV (or $p_T > 35$ GeV depending on trigger)
$\|\eta\| < 2.37$ + crack veto
Tight ID
Track definition:
$p_T > 30$ GeV, $\|\eta\| < 2.5$
Tight ID
Global requirements:
$\eta(\text{track}) \times \eta(\gamma) \geq 0$ if track and γ in endcap
At least one photon and one track with $\Delta\Phi(\pi, \gamma) > \pi/2$
Tracks are associated to the the primary vertex
$Z \to ee$ suppression requirement
If at least 1 electron is found with $\Delta R(\text{trk}, e) < 0.01$:
Rhad > 0.03 if also eProbabilityHT > 0.1
GR selection: baseline + $Z \to ee$ suppression requirement
VR1 selection: GR + $p_T(\pi) > 33$ GeV
VR2a selection: GR + Photon Calo Isolation
VR2b selection: GR + Photon Track Isolation
VR3 selection: GR + (ptcone20-p_T(track))/p_T(track) < 0.14
SR selection: union of all VR requirements

Tau+Photon

Triggers
HLT_g35_loose_g25_loose
HLT_g35_medium_g25_medium_L12EM20VH
Photon requirements
$p_T > 20$ GeV, $\|\eta\| < 2.37$ + crack veto
Tight ID, Tight isolation,
τ requirements
$h^{\pm}\pi^0$ decay mode
$p_T > 20$ GeV, $\|\eta\| < 2.5$ + crack veto
Medium τRNN score
$Z \to ee$ veto cuts:
Tight TauEleBDTScore
etOverPtLeadTrack > 2.4
$\Delta R_{\tau}^{\max} > 0.036$
eProbabilityHT (associated to the tau track) < 0.9
Global requirements
At least one primary vertex
At least one photon with $p_T > 36$ GeV (trigger threshold +1 GeV)
At least one τ with $p_T > 26$ GeV (trigger threshold +1 GeV)
At least a τ, γ pair with $\Delta\Phi(\tau_{\text{had}}, \gamma) > 2$

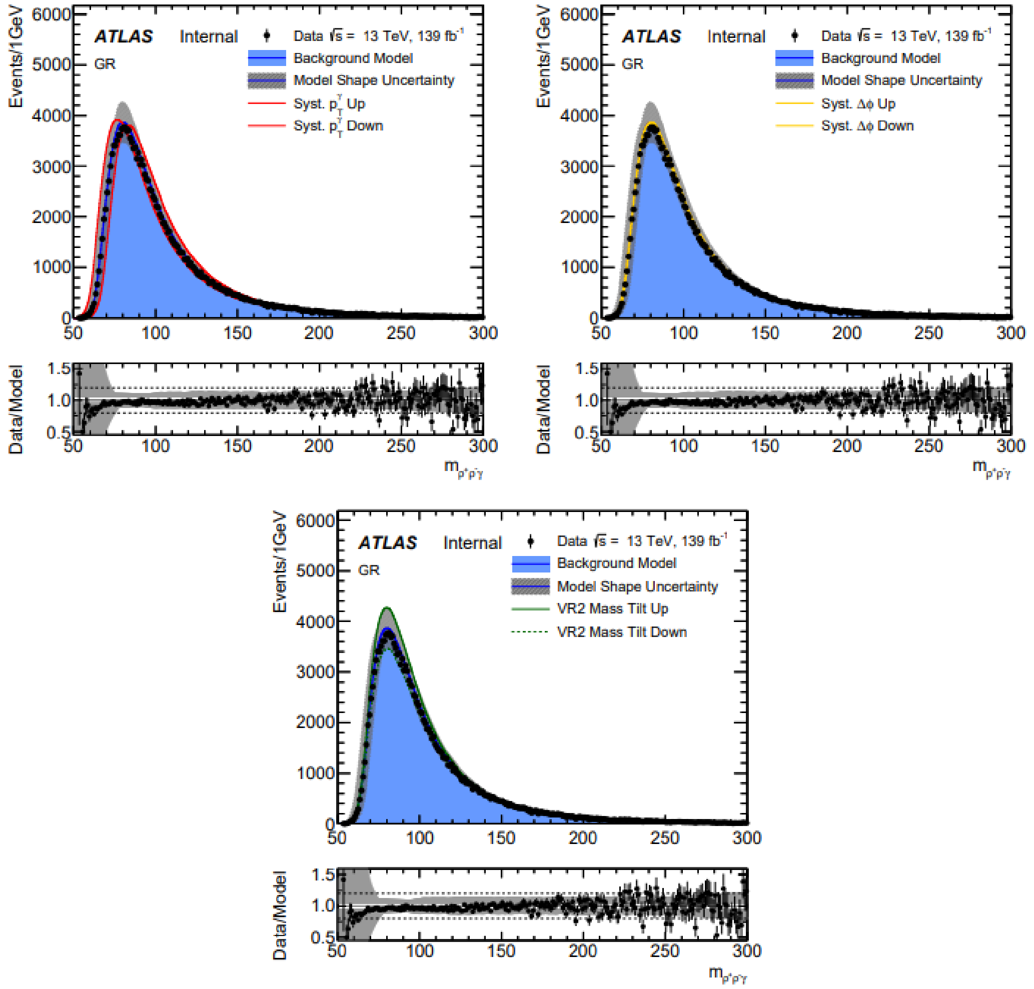
VR1	$p_T(\tau) > 30$ GeV
VR2	$\Delta R_{\tau}^{\max} < 0.065$
VR3	$\log(\|d_0(\tau)\|) < -1.2$
SR	All the requirements listed above: $p_T(\tau) > 30$ GeV, $\Delta R_{\tau}^{\max} < 0.065$, $\log(\|d_0(\tau)\|) < -1.2$

Background model uncertainties

1. $p_T(\tau)$ distributions are shifted by $\pm 3\ GeV$
2. $\Delta\phi(\rho,\gamma)$ distortion is implemented by scaling each bin by $1+10\cdot\ \delta\phi/\pi$ or $1+2(1-\ \delta\phi/\pi)$
3. $m_{\rho\gamma}$ distribution is tilted by re-weighting the model using a linear function.

$$\text{Up:}y = -0.0013\times \mathrm{m}(\text{track},\gamma)+1.16$$

$$\text{Down:}y = 0.0013\times \mathrm{m}(\text{track},\gamma)+0.84$$



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Signal uncertainties

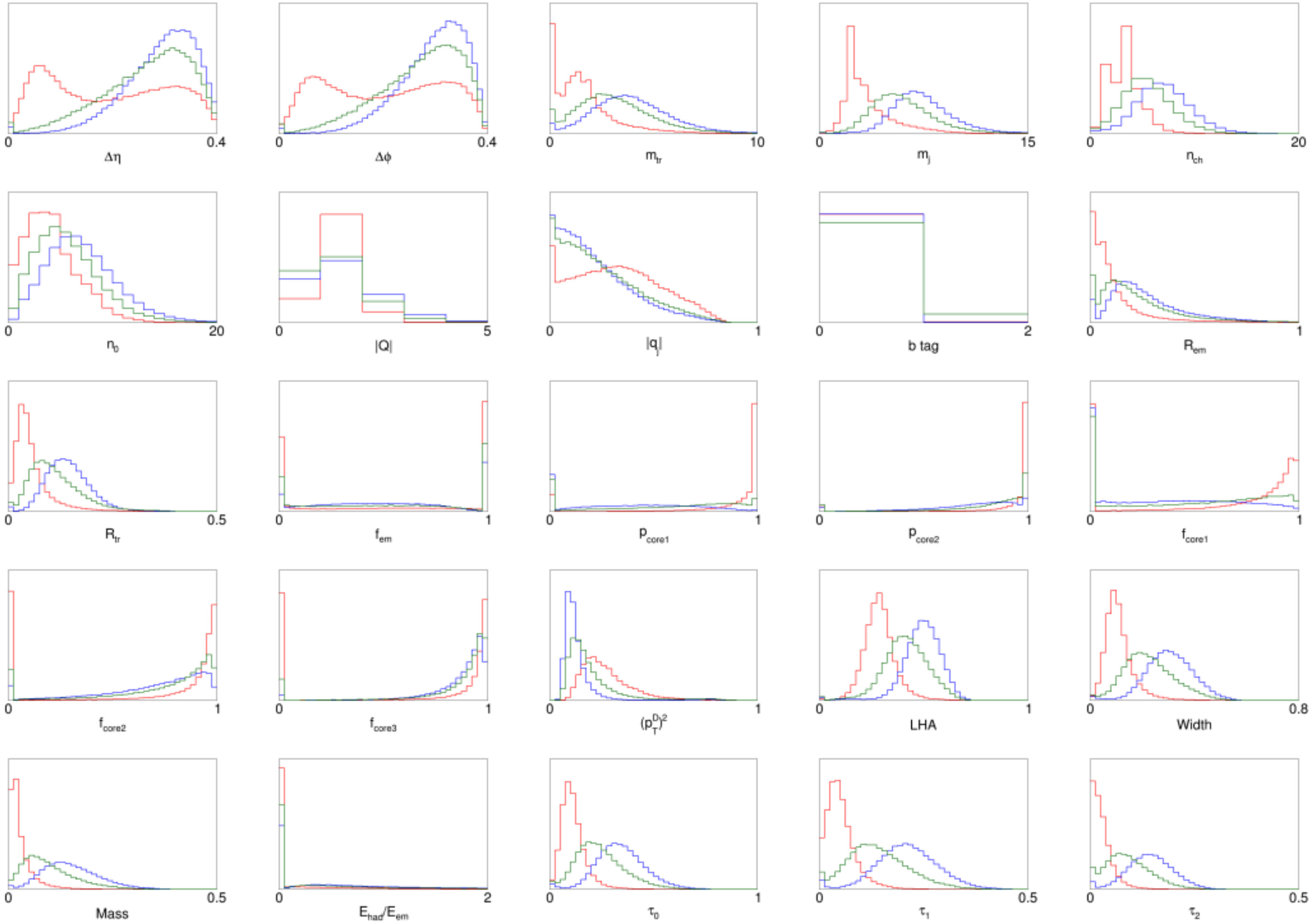
Track+Photon

Variation	Uncertainty (%)
Photon Efficiency	2.07
Track Efficiency	1.21
Luminosity	1.7
Cross Section	3.4

Tau+Photon

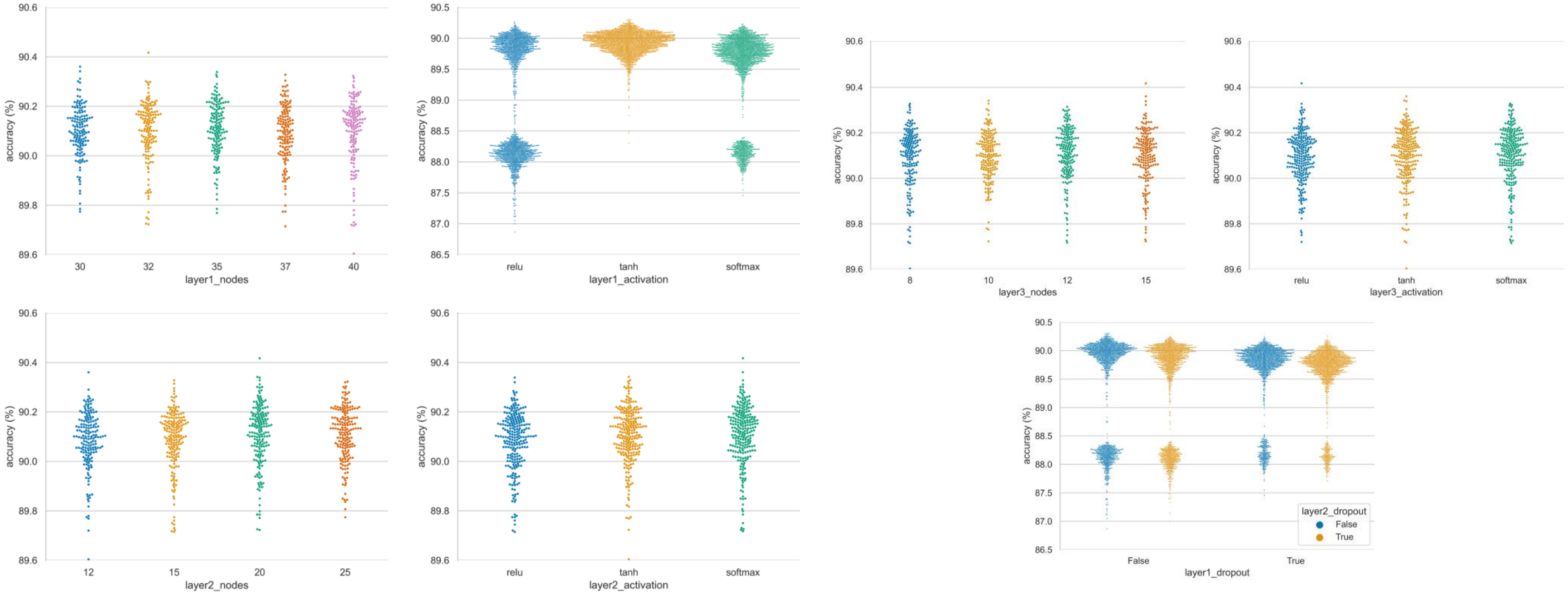
Uncertainty source	Variation (%)
Cross Section	3.4
Luminosity	1.7
Pileup	5.5
Photon Identification	1.1
Photon Isolation	1.6
EG scale	3.0
EG resolution	4.9
PH scale	1.7
TRUEHADTAU_EFF_RECO_TOTAL	1.2
TRUEHADTAU_EFF_RNNID_1PRONGSTATSYSTPT3040	0.3
TRUEHADTAU_EFF_RNNID_1PRONGSTATSYSTPTGE40	0.3
TAUS_TRUEHADTAU_EFF_RNNID_SYST	0.8
TAUS_TRUEHADTAU_EFF_ELEOLR_TOTAL	1.2
TAUS_TRUEELECTRON_EFF_ELEBDT_STAT	5.7
TAUS_TRUEELECTRON_EFF_ELEBDT_SYST	1.3
Trigger	10

ML variables



Name	Description
$\Delta\eta$	width of the jet in η
$\Delta\phi$	width of the jet in ϕ
m_{tr}	invariant mass of all charged tracks in the jet
m_j	invariant mass of all constituents of the jet
n_{ch}	charged particle multiplicity
n_0	neutral particle multiplicity
$\lvert Q \rvert$	absolute value of the total charge
$\lvert q_j \rvert$	jet charge
b-tag	output of the b-tagging algorithm
R_{em}	Average ΔR with respect to the jet axis weighted by electromagnetic energy
R_{track}	p_T weighted average ΔR for tracks
f_{em}	fraction of EM energy over total neutral energy of the jet
p_{core1}	ratio of sum p_T in a cone of ΔR <0.1 and the jet p_T
p_{core2}	ratio of sum p_T in a cone of ΔR <0.2 and the jet p_T
f_{core1}	ratio of sum ET in a cone of $\Delta R < 0.1$ and the jet total ET
f_{core2}	ratio of sum ET in a cone of $\Delta R < 0.2$ and the jet total ET
f_{core3}	ratio of sum ET in a cone of $\Delta R < 0.3$ and the jet total ET
$(p_T^D)^2$	λ_0^2
LHA	Les Houches Angularity; $\lambda_{0.5}^1$
Width	λ_1^1
Mass	λ_2^1
E_{had}/E_{em}	ratio of the hadronic versus electromagnetic energy deposited in the calorimeter
τ_0, τ_1, τ_2	N-Subjettiness

Optimisation of network - DNN



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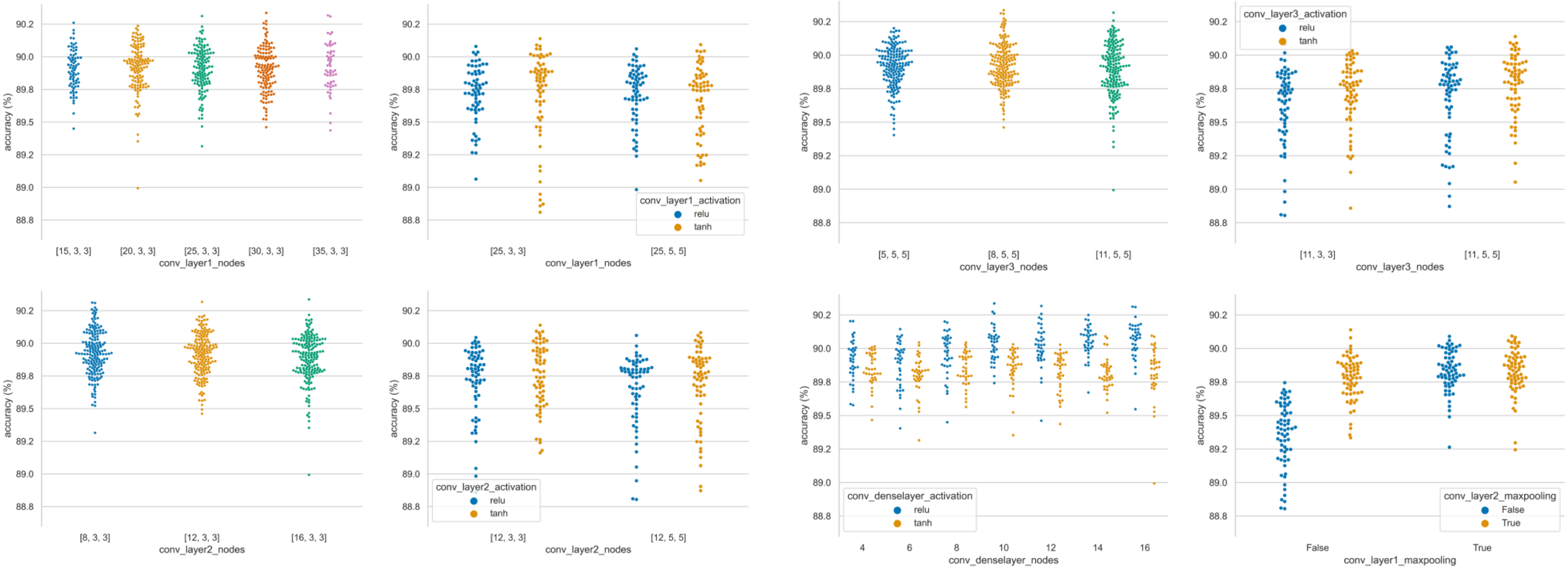
Optimisation of network - CNN

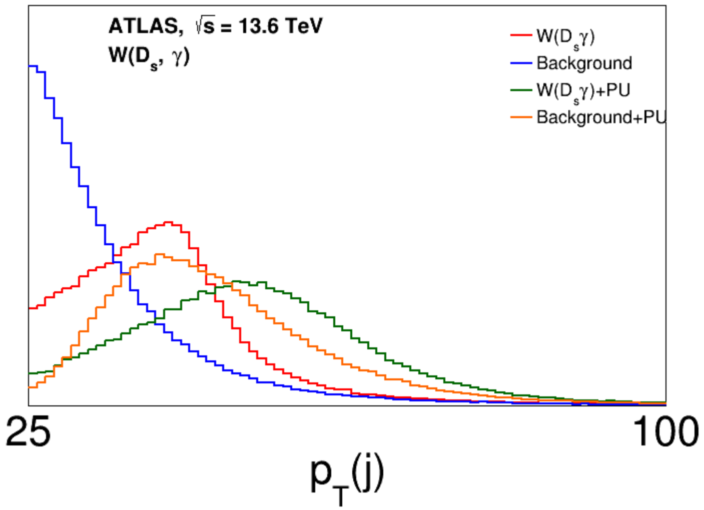


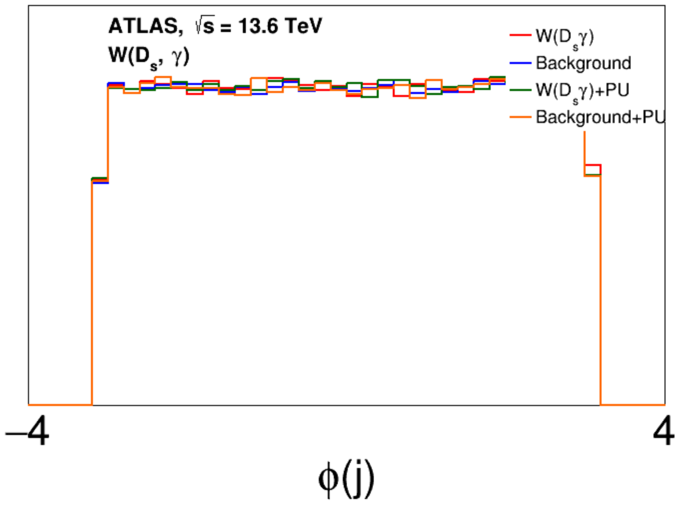
Network overview

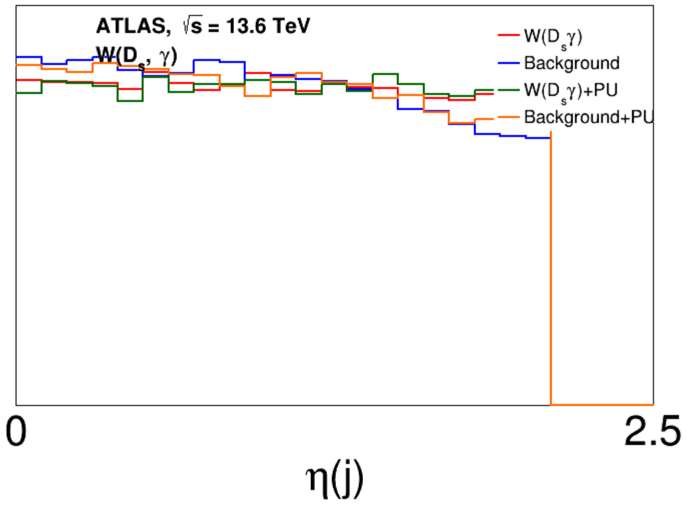
Parameter	DNN	CNN	Combined
Dense layer nodes	35 - 20 - 12 - 1	–	33 - 20 - 14
Dense layer activation	tanh - tanh - tanh - sigmoid	–	tanh - tanh - tanh
Convolutional layer nodes	–	30 - 8 - 8	30 - 8 - 8
Window size	–	[3×3], [3×3], [5×5]	[3×3], [3×3], [5×5]
Convolutional layer activation	–	tanh - tanh - tanh	tanh - tanh - tanh
Max pooling	–	After the 1^{st} convolutional layer	
Dense layers after convolution	–	10(relu) - 1(simoid)	–
Combined layer nodes	–	–	8 - 1
Combined layer activation	–	–	relu - sigmoid
Loss function	binary cross-entropy		
Optimizer	Adam		
Training epochs	40		
Batch size	1024		

Consideration of pileup

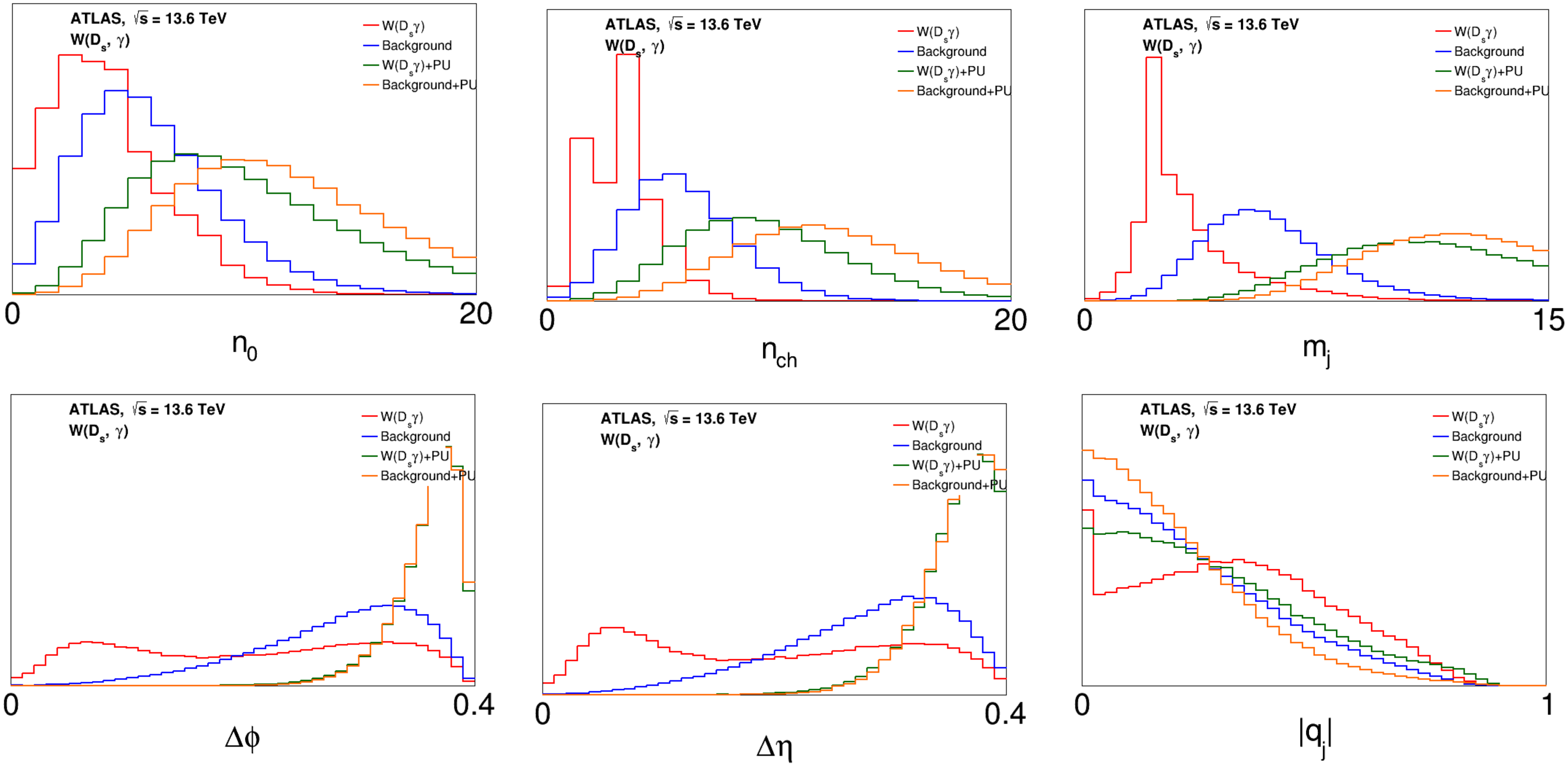
	Accuracy	Loss	Accuracy w Pileup	Loss w Pileup
Dense only	91.24%	0.2223	81.07%	0.4235
Convolutional only	92.26%	0.2050	81.10%	0.4209
Combined model	93.21%	0.1773	82.73%	0.3902



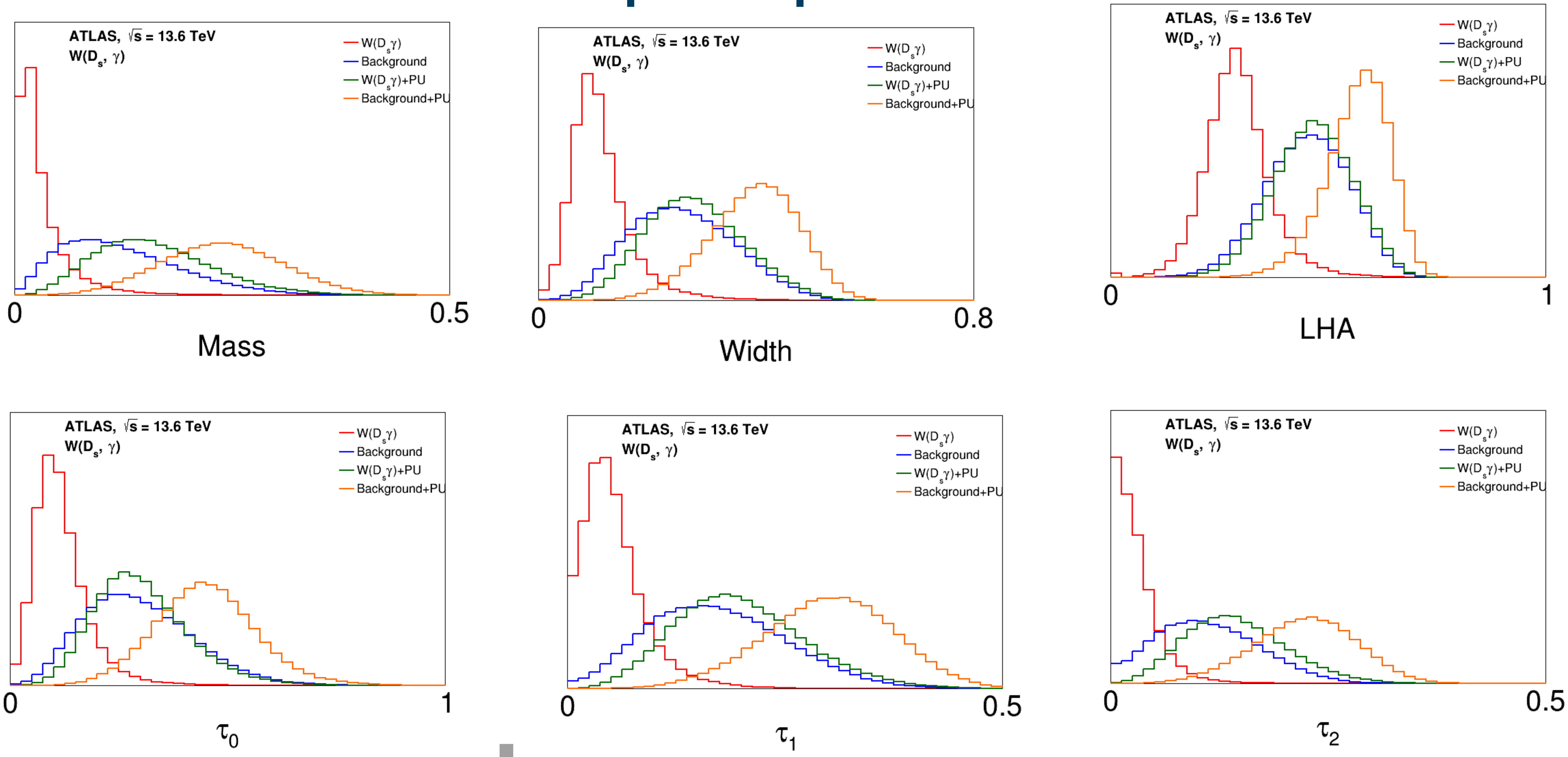




Consideration of pileup



Consideration of pileup



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