The ATLAS jet trigger and the search for CP violation in WH production

A tale of (half of) a PhD

Ricardo Barrué, Patricia Muiño, Rui Santos, Valerio Dao

TÉCNICO LISBOA
LIP
ATLAS EXPERIMENT
FCT Fundação para a Ciência e a Tecnologia
SFRH/BD/150792/2020

Outline

1. Upgrades of the ATLAS jet trigger for Run 3 of the LHC
    1. Optimization of efficiency of Run 3 jet triggers
    2. Calorimeter jet preselections

2. Optimization of the search for CP violation in WH production
    1. CP violation and where to find it
    2. Fisher Information, ranking of observables and (linear) limits
    3. Full limits

1.
Upgrades of the ATLAS jet trigger for Run 3 of the LHC

Jets, trigger and the (Run 3) jet trigger

Jets: collimated sprays of hadrons, **essential to ATLAS physics programme**

Trigger: selects events in real time for storage and further analysis

- Jet trigger: fast jet reconstruction, selection based on number and properties

New for Run 3: full event track and vertex reconstruction (at the trigger), used to improve jet reconstruction (PFlow); Run 2: calorimeter-only jets

Jets, trigger and the (Run 3) jet trigger

Jets:

Trigg

- Je ies

New d to

impr

Challenge for the trigger !

Full event track and vertex reconstruction very CPU intensive - takes **~50%** of total CPU time / event

- **Needs to be < 1s** (trigger latency requirements)

Need to balance performance and CPU/time cost !

Optimization of performance of Run 3 jet triggers

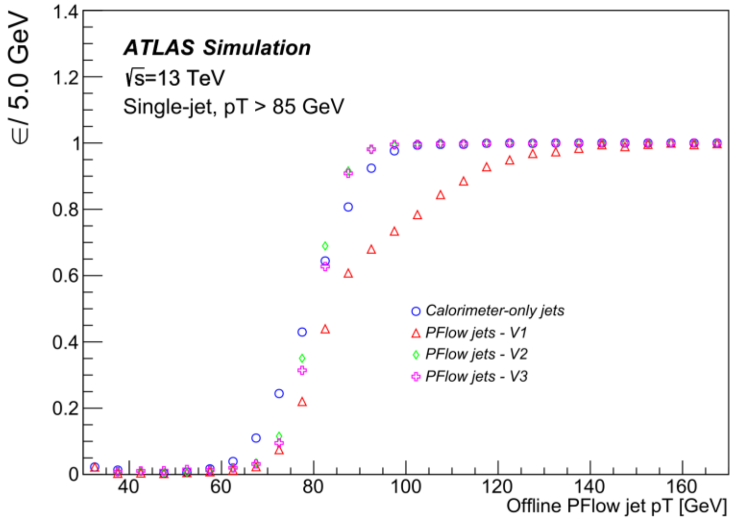


Figure 1: Efficiency curves for a trigger requiring a jet w/ pT > 85 GeV for calorimeter-only jets and Particle Flow jets

Selection of best track+vertex reconstruction, allowed optimization of the performance

PFlow jet triggers have **sharper turn-ons** and **higher acceptance** (~8%) than calorimeter-only jet (EMTopo) ones

Calorimeter-only jet preselections

Calorimeter+track jet reconstruction for every event is not possible

- calorimeter-only jet preselection can reduce average processing time/event
    - **Can these keep the same rates and efficiencies ?**

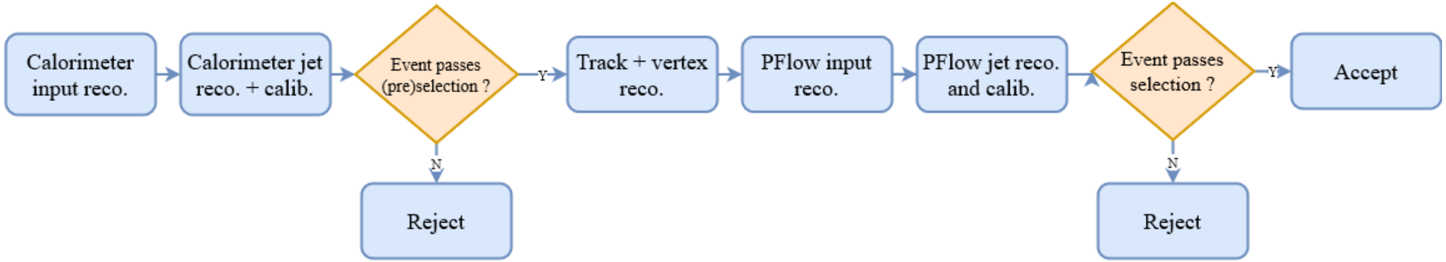


Figure 11: diagram of calorimeter jet preselection at the jet trigger

Calorimeter jet preselections

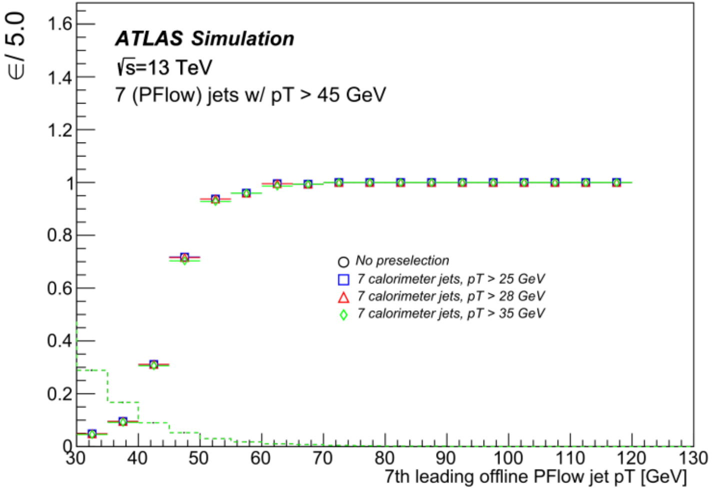


Figure 12: Efficiency curves for a trigger requiring 7 jets w/ pT > 45 GeV for the different tested preselections

Chain	Rate [Hz]	Relative reduction	Time per event [ms]	Relative reduction
No preselection	11.52	-	4.124E+03	-
7 jets, pT > 21 GeV	11.52	0.0%	3.152E+03	-24%
7 jets, pT > 28 GeV	11.50	0.0%	1.775E+03	-57%
7 jets, pT > 35 GeV	11.26	2.0%	878.7	-79%

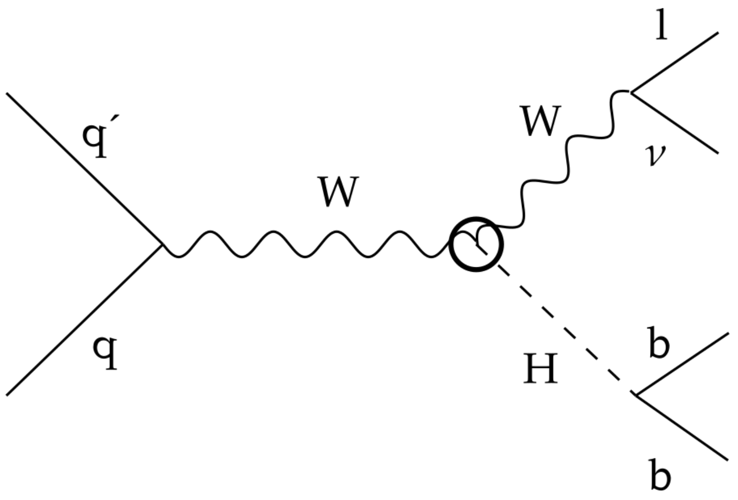
- Maintain rates and efficiencies w.r.t. no preselection
- Average of 70% reduction of the time per event for all chains tested

2.
Optimization of the search for CP violation in WH production

CP violation in HWW interaction

BSM CP violation required to explain observed matter-antimatter asymmetry

- EFT formalism, with a single dimension-6 operator, $c_{H\widetilde{W}}$



CP violation in HWW interaction

BSM CP violation required to explain observed matter-antimatter asymmetry

- **Challenge:** CP-violating terms come from SM-EFT interference, don't change the (total) cross-sections

  Changes in (total) cross-sections come from EFT^2 terms (CP-conserving), which are very suppressed

CP violation and where to find it

Several possibilities (with increasing power/complexity):

1. Energy-related observables: directly interpretable
   - Only sensitive to EFT^2 terms (suppressed)
2. Angular observables: linearly sensitive to CP-violating (interference) term
   - Require full neutrino reconstruction
3. Multivariate method (SALLY): reconstructs (detector-level) optimal observables
   - Less interpretable

Caveat: taking only into account modifications to the **shape**, no systematics (ongoing)

Ranking observables and (linear) limits

Ranking different observables using the **Fisher Information** formalism

- allows defining optimal phase space cuts
- allows extraction of limits, mostly sensitive to linear (interference) terms

Observable	$c_{H\widetilde{W}}$ **S+B 95% CL (L= 300 fb^-1)**
1D: transverse momentum of W boson	[-1.62,1.62]
2D: W boson transverse momentum x transverse mass of WH system	[-1.4,1.4]
1D: $Q_\ell \times \cos\delta^+$	[-0.227,0.227]
2D: W boson transverse momentum x $Q_\ell \times \cos\delta^+$	[-0.088, 0.088]
MVA: SALLY, w/ final state particle 4 vectors	[-0.067, 0.067]
MVA: SALLY, w/ final state particle 4 vectors + 3 angular observables	[-0.062, 0.062]

Full limits

Next step: calculate limits w/ asymptotic approximation + likelihood ratio

- determine the effect of quadratic terms

Observable	$c_{H\widetilde{W}}$ **S+B 95% CL (L= 300 fb^-1)**
1D: transverse momentum of W boson	[-0.192, 0.216]
2D: W boson transverse momentum x transverse mass of WH system	[-0.36, 0.384]
1D: $Q_\ell \times \cos\delta^+$	[-0.264, 0.216]
2D: W boson transverse momentum x $Q_\ell \times \cos\delta^+$	[-0.096, 0.072]
MVA: SALLY, w/ final state particle 4 vectors	[-0.144, 0.12]
MVA: SALLY, w/ final state particle 4 vectors + 3 angular observables	[-0.168, 0.096]

Quadratic effects lead to worse limits w.r.t. Fisher Information (expected)

Conclusions

The calorimeter+track jet trigger is **ready for Run 3 !**

- several other upgrades have been implemented and validated

Several observables/methods studied to search for CP violation in WH production

- simple 2D analysis yields the best results in the presence of EFT^2 terms

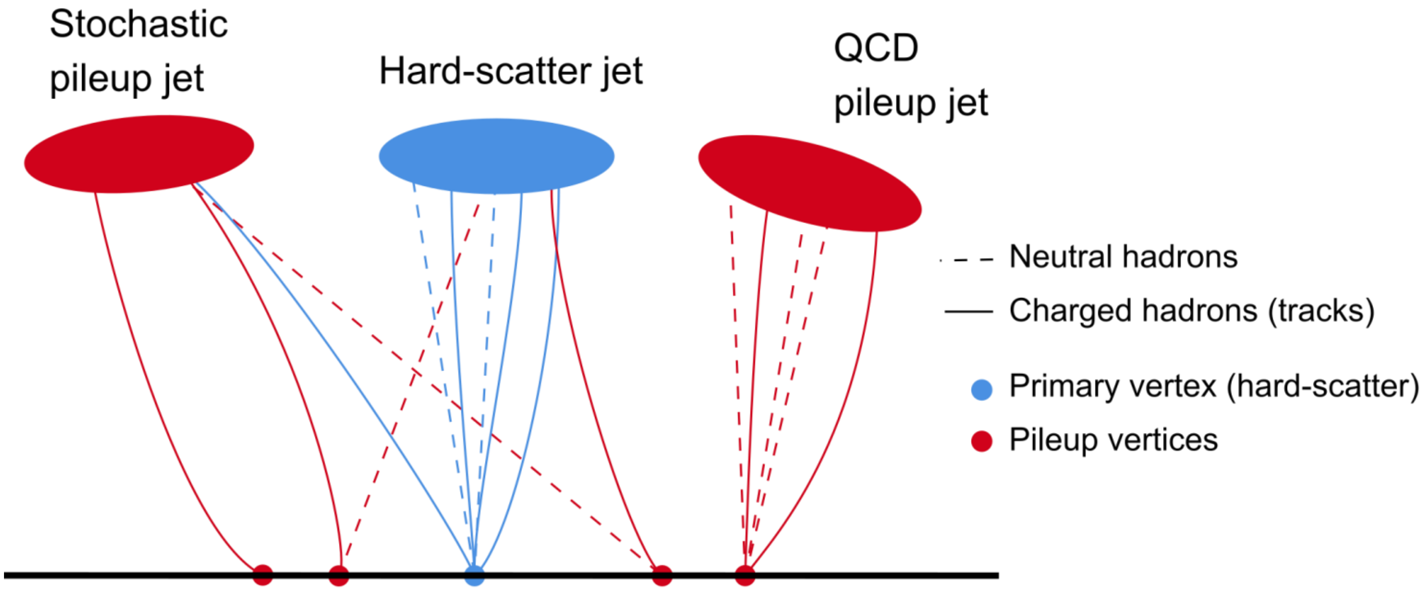
Next steps: study effect of extra jet emission (NLO) and experimental systematics

Backup

The jet trigger

Tracking+vertexing for jets

Using tracks and vertices in jets helps with (charged) pileup contamination



Simulation-based inference and Fisher Information in EFT constraints

The likelihood

The likelihood, p_{full}, is the central statistical object in any physics analysis

$$p_{\text{full}} = \text{Pois}(n|\mathcal{L}\sigma(\theta)) \prod_i p(x_i|\theta)$$

The latter can be factorized (but not calculated analitically…):

$$p(x|\theta) = \int \mathrm{d}z_d \int \mathrm{d}z_s \int \mathrm{d}z_p \, p(x|z_d)\, p(z_d|z_s)\, p(z_s|z_p)\, p(z_p|\theta)$$

Score, $t(x)|_\theta = \nabla_\theta \log p(x|\theta)|_\theta$, is the statistically optimal observable in the vicinity of a parameter point θ (generally the SM, $\theta = 0$)

Simulation-based inference, score and SALLY

Idea: use the joint score $t(x, z_p|\theta)$ to approximate the score (Type equation here.

- used in analyses, but neglecting PS, had. and detector simulation ($z_p \equiv x$)

$$t(x, z_p) = \nabla_\theta \log p(z_p|\theta) = \frac{\nabla_\theta p(z_p|\theta)}{p(z_p|\theta)}\Big|_\theta \approx \frac{\nabla_\theta |\mathcal{M}(z_p|\theta)|^2}{|\mathcal{M}(z_p|\theta)|^2} - \frac{\nabla_\theta \sigma(\theta)}{\sigma(\theta)}$$

Alternative: use a NN with detector-level observables as inputs to extract $t(x|\theta)$, using joint score $t(x, z|\theta)$ in the loss

- SALLY: Score Approximates Likelihood LocallY

Fisher Information

The Fisher Information matrix $I_{ij}(\theta)$ quantifies the sensitivity of a measurement

$$I_{ij}(\theta) \equiv -E\left[\frac{\partial^2 \log p_{\text{full}}(x|\theta)}{\partial\theta_i \partial\theta_j}\right]|\theta$$

- Can be used to benchmark observable by using $p_{full}(v|\theta)$
- Its differential distribution $dI_{ij}(x,\theta)/dv$ allows defining optimal phase space cuts

For small (linear) variations between θ_1 and θ_0 allows extraction of limits with I_{ij}

$$d(\theta_1,\theta_0)^2 = I_{ij}(\theta_0)(\theta_1-\theta_0)_i(\theta_1-\theta_0)_j$$

Fisher Information and the score

We can use Fisher Information and the score to extract detector-level information

$$I_{ij}(\theta) = \frac{\mathcal{L}}{\sigma} \frac{\partial \sigma}{\partial \theta_i} \frac{\partial \sigma}{\partial \theta_j} + \frac{\mathcal{L}\sigma}{N} \sum_{x \sim p(x|\theta)} t_i(x) t_j(x)$$

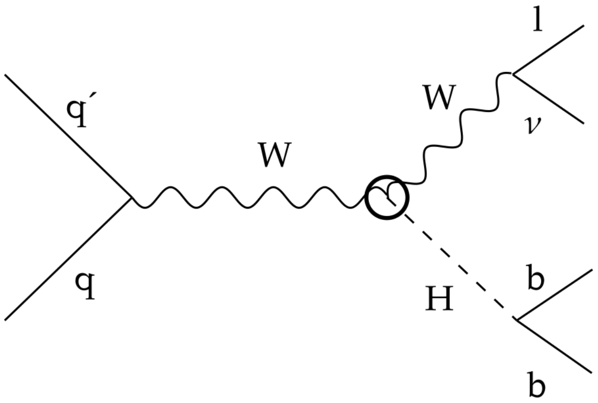
MadMiner software is a tool for the entire pipeline from automation of signal generation to statistical inference

State of the art: using MadMiner+ SALLY for optimizing CP-even EFT operator searches in WH

Analysis - signal

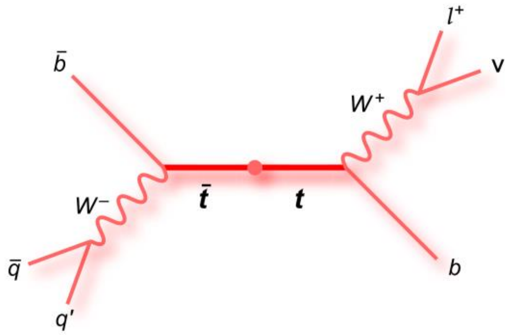
Signal: $p\, p \rightarrow WH \;\rightarrow \ell\, \nu\, b\, \bar{b}$

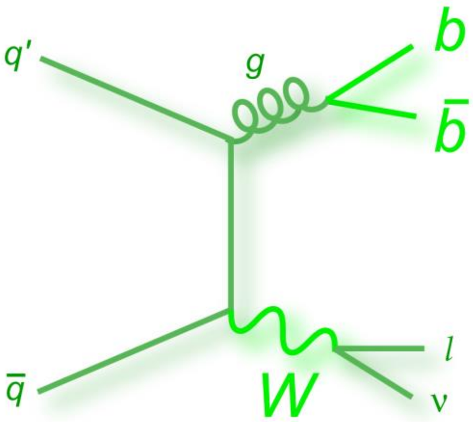
- Working in the context of the SMEFT w/ Warsaw basis
- $\tilde{O}_{HW} = \frac{c_{\widetilde{HW}}}{\Lambda^2} H^+ H\, \epsilon_{\mu\nu\rho\sigma} W^{I\mu\nu} W^{I\rho\sigma}, W^{I\mu\nu} = \partial_\mu W_\nu^I \; - \partial_\nu W_\mu^I + g_2 \epsilon_{IJK} W_\mu^J W_\nu^K$

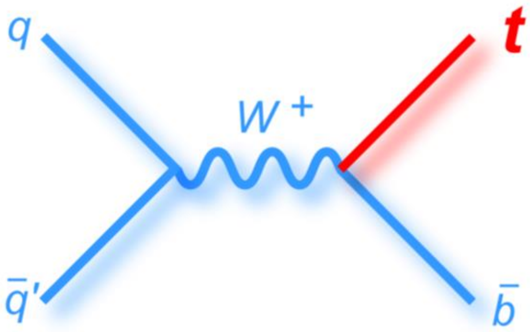


Analysis - backgrounds

Backgrounds: leptonic ttbar, W+(b)-jets, Wt single top







Setup + sample generation

Signals: Madgraph5_aMC@NLO (LO), SMEFTsim3

- $\Lambda = 1\ TeV$, default LO widths for unstable particles
- 2 sets of samples: SM+SM-EFT interference; **full matrix element (shown here)**

Generating signal samples at benchmark points + morphing to interpolate:

- SM+SM-EFT interference: SM ($c_{H\widetilde{W}} = 0$) (1M), $c_{H\widetilde{W}} = -1.155$ (200k)
- Full matrix element: SM (1M), $c_{H\widetilde{W}} = 1.15$ (200k) , $c_{H\widetilde{W}} = -1.035$ (200k)

Backgrounds: Madgraph5_aMC@NLO (LO), ‘sm’ model, 1M events

Detector approximation + selection cuts

Selection cuts applied at generator level:

- $p_{T,\ell} > 10\ GeV$
- $E_T^{miss} > 25\ GeV$
- $p_{T,b} > 35\ GeV$
- $|\eta_{\ell,b}| < 2.5\ GeV$
- $\Delta R_{bb,\ell b} > 10\ GeV$
- $80\ GeV < m_{bb} < 160\ GeV$
- $p_{T,l} < 30\ GeV$
- $\Delta R_{bj,\ell j} > 10\ GeV$

Pythia + Delphes shown to lead to a large mismodelling of E_T^{miss} and m_{bb}, detector is approximated by Gaussian transfer function smearing

- Neutrino energy/ E_T^{miss}: $\sigma_E = 12.5\ GeV$
- b-quark energies: $\sigma_E/E = 0.1$

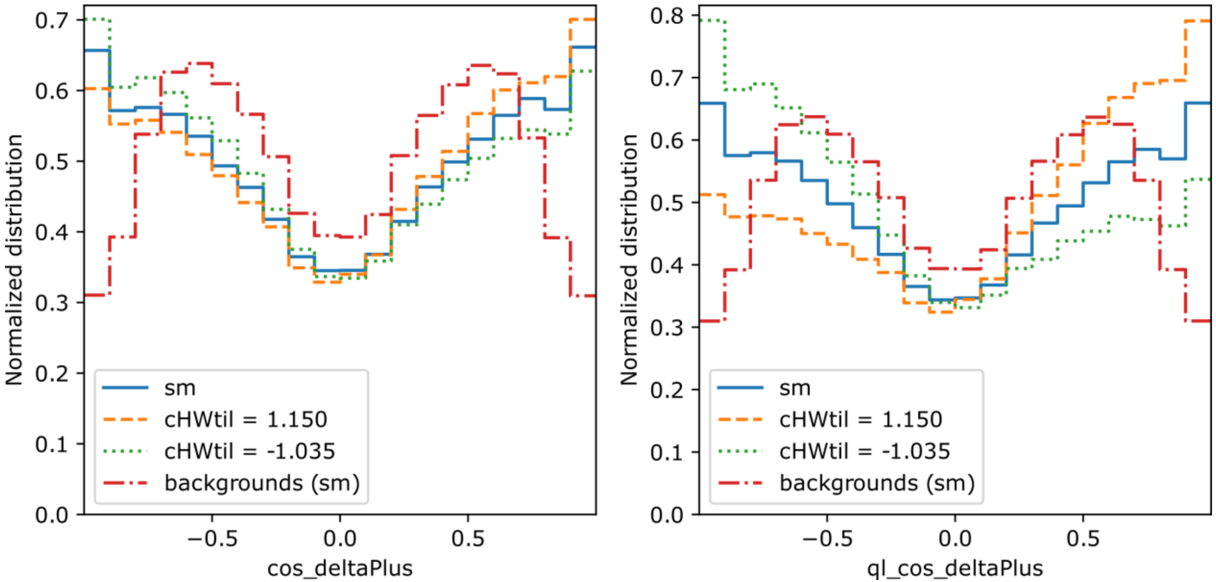
Observables

Studied a large set of kinematic and angular observables:

- 4-vector of two b-quarks, lepton
- p_T, θ, η, ϕ of two b-quarks + Higgs cand.
- m_{bb}
- $\Delta\phi_{bb,b_1\ell,b_2\ell}, \Delta R_{bb,b_1\ell,b_2\ell}$
- $E_T^{miss}{}_x, E_T^{miss}{}_y$
- $|E_T^{miss}|$
- $\Delta\phi_{b_1 E_T^{miss}, b_2 E_T^{miss}, \ell E_T^{miss}}$
- $m_{T_{\ell\nu}}, m_{T_{\ell\nu bb}}$ (total transverse mass)
- $\cos\delta^+ = \frac{p_\ell^{(W)} . (p_H \backslash\text{x}\, p_W)}{\left|p_\ell^{(W)}\right| |p_H \backslash\text{x}\, p_W|}, \mathrm{Q}_\ell \cos\delta^+$
- $\cos\delta^- = \frac{p_W . (p_{\ell(H-)} \backslash\text{x}\, p_{\nu(H-)})}{|p_W| |p_{\ell(H-)} \backslash\text{x}\, p_{\nu(H-)}|}, \mathrm{Q}_\ell \cos\delta^-$

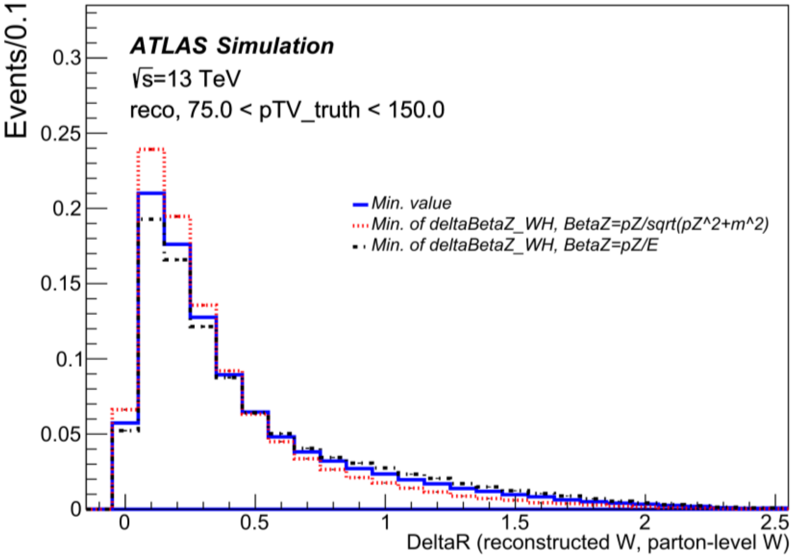
Angular observable distributions

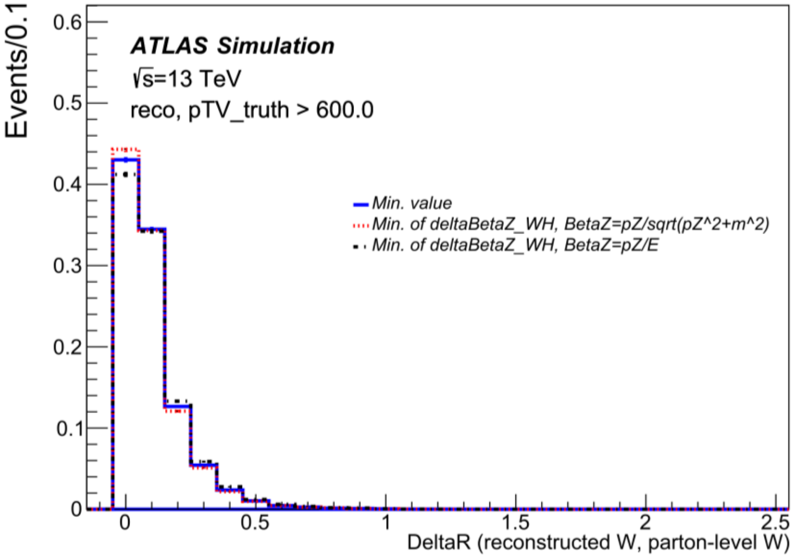
Showing shape-only distributions of the main angular observable



Implementation in ATLAS analysis frameworks + NLO samples

Neutrino reconstruction in NLO signal samples





Solution with $\min.|\beta_z^W - \beta_z^H|, \beta_z = p_z/\sqrt{p_z^2 + m^2}$ appears the best.