Measurement of k_{T} splitting scales in $W \to \ell\nu$ events at $\sqrt{s} = 7$ TeV with the ATLAS detector

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on behalf of the ATLAS collaboration

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k_{T} distance measures

- Distance between two momenta p_i, p_j:

$$d_{ij} = \min(p_{ti}^2, p_{tj}^2)\frac{\Delta R_{ij}^2}{R^2}$$

with transverse momenta p_t and angular distance ΔR

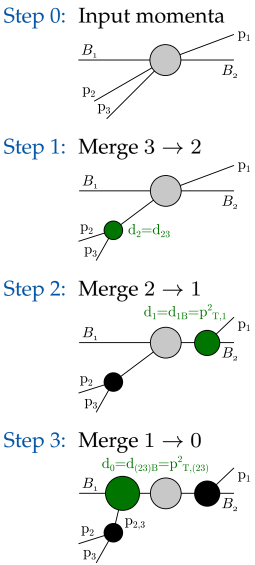
- Distance of p_i to the beams:

$$d_{iB} = p_{ti}^2$$

Cluster sequence of input momenta $\{p_i\}$

1. Calculate all d_{ij} and d_{iB}
2. Find their minimum, d_{min}
   2.1 If d_{min} is a d_{ij}, combine i and j
   2.2 If d_{min} is a d_{iB}, remove i from list → jet.
3. Return to step 1 or stop when no particle left

Example



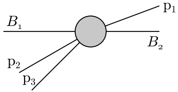
Definition of observables

- Input for cluster sequence in W+jets events:
  Everything except the W decay products
  (Use W only as clean but abundant signal)
- Define d_k as the $d_{\min}$ found at the step going from $k+1 \to k$
- First set of observables: k_T splitting scales
  - $\sqrt{d_k}$ [GeV]
  - Four observables: $0 \le k \le 3$
  - Clean separation of soft and hard regions
- Second set: ratios of subsequent scales
  - $\sqrt{\frac{d_{k+1}}{d_k}}$
  - Three observables: $0 \le k \le 2$
  - Cut on denominator $\sqrt{d_k} > 20$ GeV to avoid domination by non-perturb. effects
  - Systematics cancel to some extent
  - Motivated also from theory side

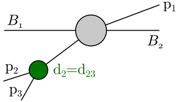
⇒ 7 observables in each decay channel

Example

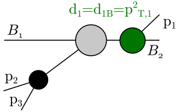
Step 0: Input momenta



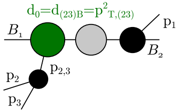
Step 1: Merge $3 \to 2$



Step 2: Merge $2 \to 1$



Step 3: Merge $1 \to 0$



Identification of QCD evolution with k_T cluster sequence

- Small-angle limit for k_T measure:

$$p_{ti}^2 \Delta R_{ij}^2 \simeq E_i^2 \theta_{ij}^2$$
$$p_{ti}^2 \simeq E_i^2 \theta_{iB}^2$$

- Small-angle limit for QCD splitting probability:

$$\frac{\mathrm{d}P_{ij\to i,j}}{\mathrm{d}E_i \mathrm{d}\theta_{ij}} \sim \frac{1}{\min(E_i, E_j)\theta_{ij}}$$

$\rightarrow k_\mathrm{T}$ measure identifies most singular pair in each step of the sequence

- Measurement can probe QCD evolution
- Provides useful test of LO and NLO QCD Monte-Carlo generators and analytical calculations

Data sample

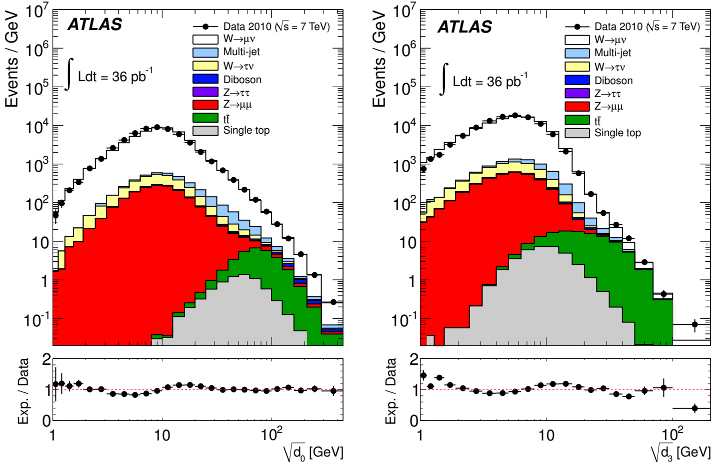
- 2010 data is used due to relatively low pileup conditions
- 36 pb^{-1} are investigated in two channels
  - $W \to e\nu$
  - $W \to \mu\nu$

Event selection

- Event selection follows the W analyses with 2010 ATLAS data:
  - Lepton $p_T > 20$ GeV
  - Second lepton veto
  - $E_{\mathrm{T}}^{\mathrm{miss}} > 25$ GeV
  - $m_T^W = \sqrt{2(p_T^\ell E_{\mathrm{T}}^{\mathrm{miss}} - \vec{p}_T^{\,\ell} \cdot \vec{E}_{\mathrm{T}}^{\mathrm{miss}})} > 40$ GeV
- There is no jet requirement applied.
- k_{T} cluster sequence built from cell pre-clusters within $|\eta| < 4.9$ calibrated to the hadronic energy scale
- Particle level defined in analogy, unfolding with Bayesian algorithm

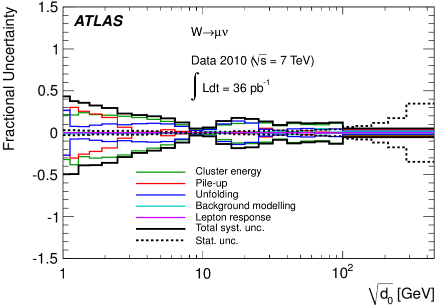
MC simulation and background subtraction

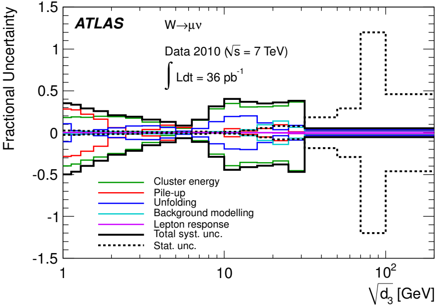
- Fully simulated signal samples
  - ALPGEN+HERWIG
  - SHERPA
- Most backgrounds subtracted using MC samples
  - $W \to \tau\nu$ (PYTHIA6)
  - $Z \to \ell\ell$ (PYTHIA6)
  - $t\bar{t}$ (MC@NLO, POWHEG)
  - single-top (MC@NLO)
  - Diboson WW, WZ, ZZ (HERWIG)
- Multi-jet background using data-driven methods (template fit, and extrapolating from control region)
- Total background contribution: 5% ($W \to e\nu$) and 9% ($W \to \mu\nu$)



Hardest and softest splitting scale in measurement

- Only muon results displayed here, electron channel basically identical
- Good Data/MC agreement (ALPGEN+HERWIG as signal MC)
- At high $\sqrt{d_3}$: sensitive to 4-jet production $\Rightarrow$ large $t\bar{t}$ background





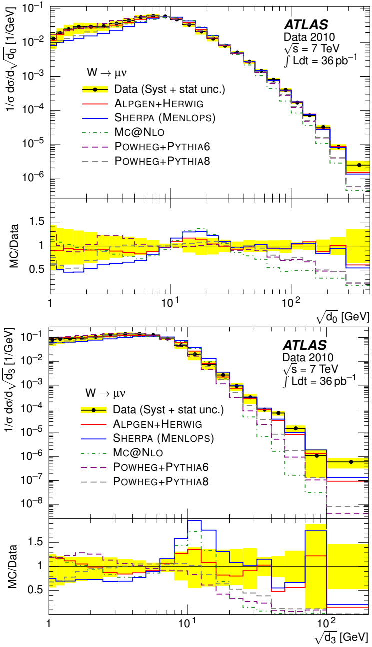
Dominant systematics

- Cluster energy scale
  - Variation of cluster energy based on MC studies/single pion response
- Pileup
  Low-pileup measurement ($N_{vtx} = 1$)
  - Comparison with and without bunch trains
  - Vertex selection variation

  High-pileup measurement ($N_{vtx} > 1$)
  - Uncertainty from comparison to measurement with $N_{vtx} = 1$

Both are evaluated separately for "Low-pileup" and "High-pileup", which are combined in weighted sum

Unfolded results for $\sqrt{d_k}$

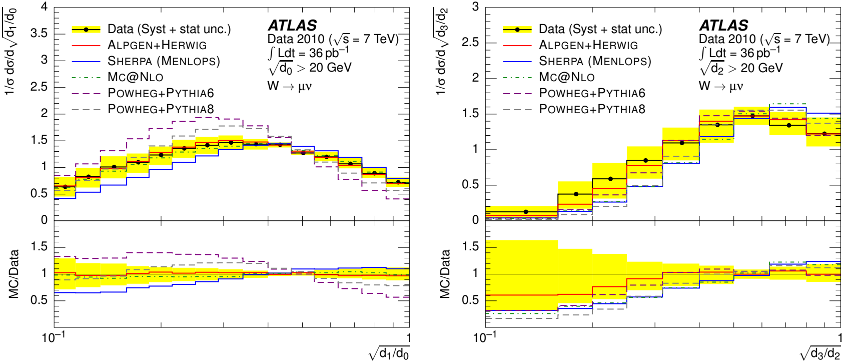


Particle level comparison with various MCs

Accuracy of MCs	W_{inc}	+1j	+2-5j	+≥6j
ALPGEN+HERWIG	LO	LO	LO	PS
SHERPA (MENLOPS)	NLO	LO	LO	PS
MC@NLO+HERWIG	NLO	LO	PS	PS
POWHEG+PYTHIA6	NLO	LO	PS	PS
POWHEG+PYTHIA8	NLO	LO	PS	PS

Examples: $\sqrt{d_0}$ and $\sqrt{d_3}$

- Hard tail of distributions:
  ME+PS generators work very well,
  NLO+PS generators are low (even in $\sqrt{d_0}$)
- HERWIG-based generators best in soft (resummation) region
- Excess of SHERPA and MC@NLO in intermediate region



- HERWIG-based generators provide good description of leading ratio
  Outlier POWHEG+PYTHIA6 – (α_s) matching issue?
- Higher ratios: Most generators just outside uncertainty

Conclusions

- First measurement of k_{T} splitting scales in $W \to \ell\nu$ events at a hadron-hadron collider has been performed
  - Electron and muon channels give consistent results
  - Distributions are corrected for detector effects
  - Dominant systematic uncertainties from cluster energy scale uncertainty and pileup mismodelling
- LO multi-leg predictions perform better than NLO+PS generators, especially in hard tails
- Differences even in perturbative region of hardest splitting scale, where all generators have same formal accuracy
- Significant differences also in soft region, probing QCD resummation

References

- Preprint arXiv:1302.1415
- Accepted for publication in EPJC
- Released with Rivet 1.8.3 as `ATLAS_2013_I1217867`

Backup material

Rationale for weighted average

Profit from low systematic uncertainty in a low-pileup measurement
and lower statistical uncertainty in full sample.

Two **unfolded** measurements for each distribution

Low pileup: Exactly one reconstructed vertex is required
- Suffers from lack of statistics

High pileup: At least two reconstructed vertices are required
- Suffers from pileup-mismodelling in simulation

Weighted average

- Best estimate N from the two distributions N_1, N_2 defined above:

$$N = \frac{N_1 \cdot W_1 + N_2 \cdot W_2}{W_1 + W_2}$$

- Weights W_i from inverse quadrature sum of statistical and pileup uncertainties
- Final statistical uncertainty calculated assuming no correlation between “Low pileup” and “High pileup”

Bayesian unfolding

- Three iterations of unfolding
- Particle level definition
  - $p_T^\ell > 20$ GeV ($\ell =$ electron e or muon μ)
  - $|\eta^e| < 2.47$ excluding $1.37 < |\eta^e| < 1.52$
  - $|\eta^\mu| < 2.4$
  - $p_{T,\text{lead}}^\nu > 25$ GeV ($\nu_{\text{lead}} =$ hardest neutrino in event)
  - $m_T^W > 40$ GeV
- Leptons defined including photon radiation within $\Delta R = 0.1$
- k_T cluster sequence built from four-momenta of all final state particles, excluding signal lepton and neutrino

Cluster energy scale uncertainty

- Change cluster energy by a factor

$$1 \pm a \times (1 + b/P_T^{\text{cl}})$$

- From MC studies and single pion response
  - $a = 0.03(0.1)$ when $|\eta^{\text{cl}}| < 3.2$ ($|\eta^{\text{cl}}| > 3.2$)
  - $b = 1.2$ GeV

Pileup uncertainty

- Low-pileup measurement ($N_{\text{vtx}} = 1$):
  - Comparison with and without bunch trains
  - Vertex selection variation
- High-pileup measurement ($N_{\text{vtx}} > 1$):
  - Uncertainty from comparison to measurement with $N_{\text{vtx}} = 1$

Both are evaluated separately for a “Low-pileup” and a “High-pileup” measurement, which are combined in weighted sum

Unfolding

Uncertainty from difference of unfolding with nominal Alpgen sample or:

- SHERPA
- Reweighted ALPGEN to match data at reco level

$\rightarrow$ Envelope of both as final uncertainty

Lepton scale resolution and efficiency

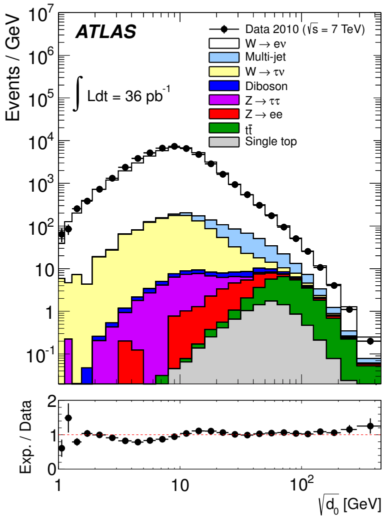
- Following recommendations derived using $Z \rightarrow \ell\ell$ tag/probe

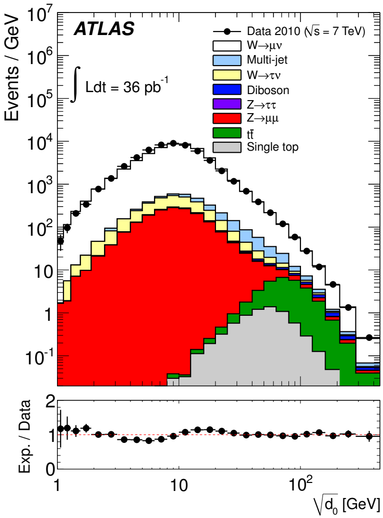
Physics backgrounds

- Variation of cross sections of background MC samples
- Separate estimation of uncertainties on multi-jet background

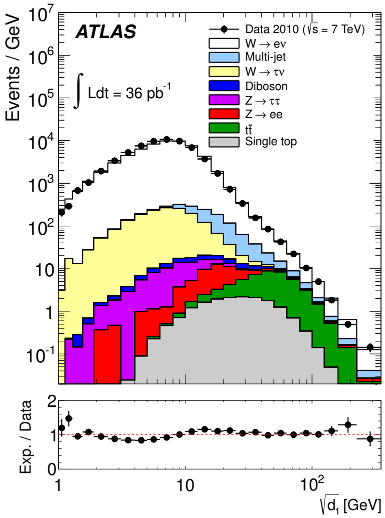
These are the sub-dominant uncertainties and they have been evaluated on the full sample (no requirement on N_{vtx})

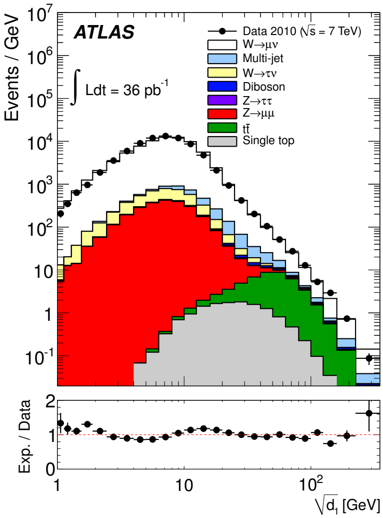
Splitting scale $\sqrt{d_0}$ in both channels



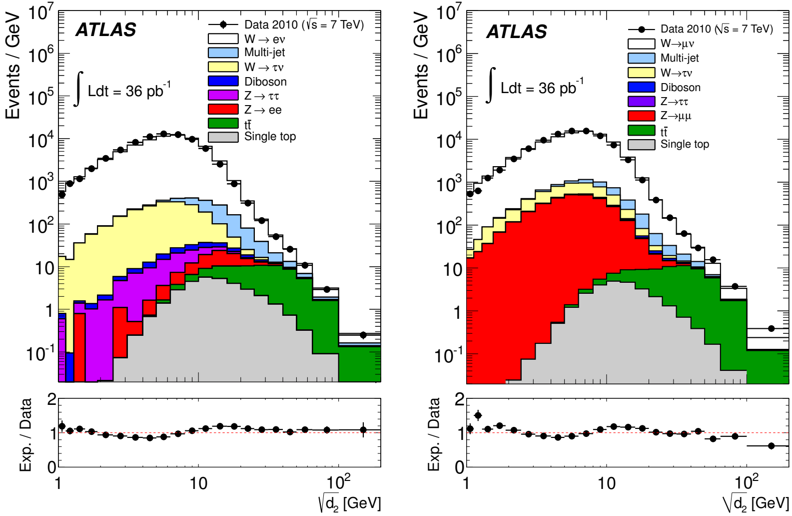


Splitting scale $\sqrt{d_1}$ in both channels

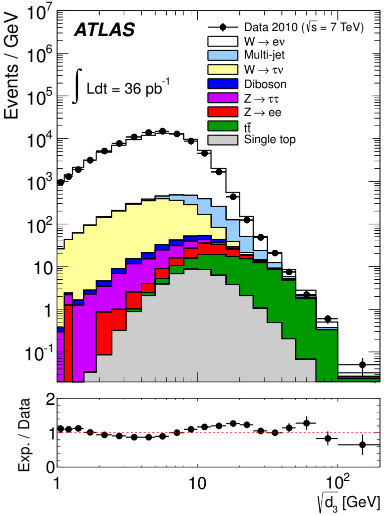


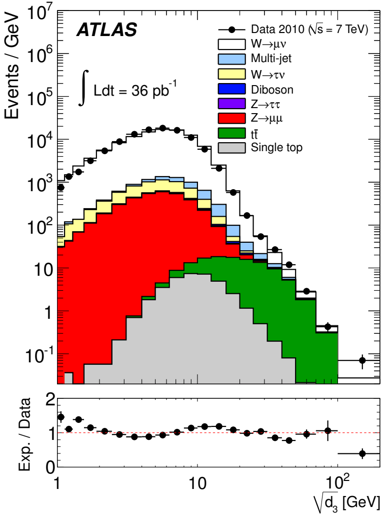


Splitting scale $\sqrt{d_2}$ in both channels

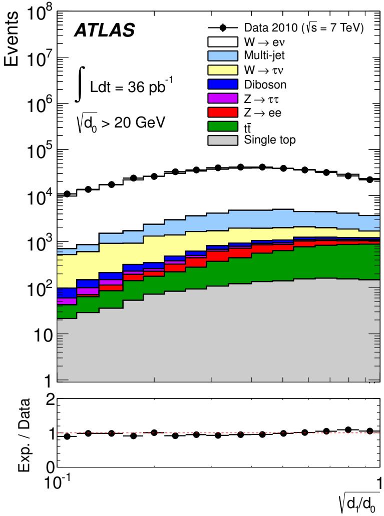


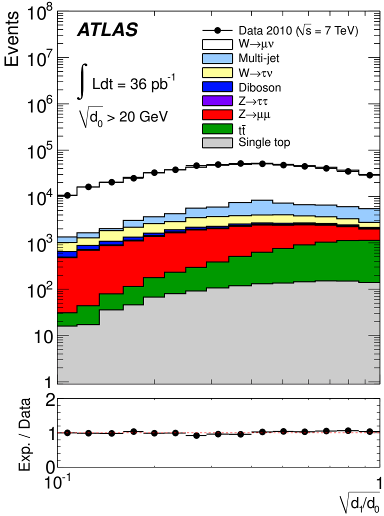
Splitting scale $\sqrt{d_3}$ in both channels



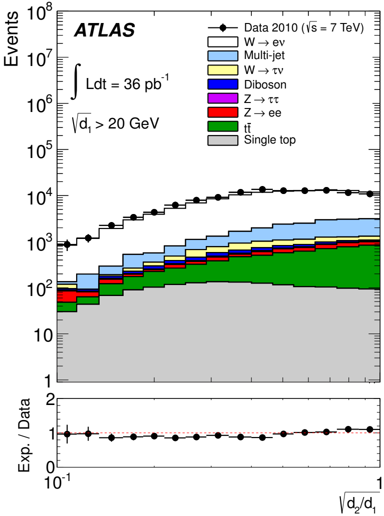


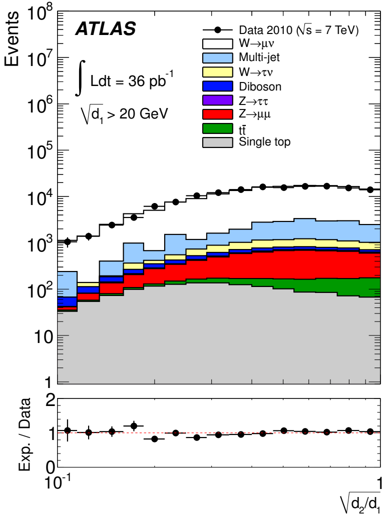
Ratio of splitting scales $\sqrt{\frac{d_1}{d_0}}$ in both channels



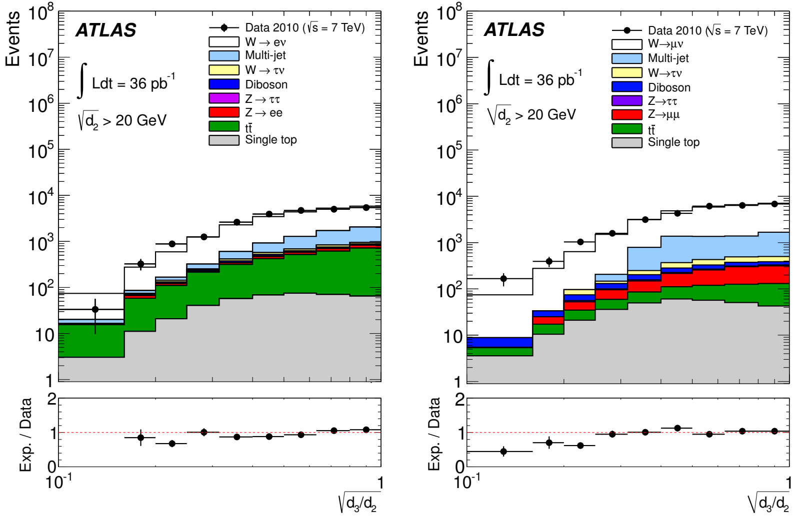


Ratio of splitting scales $\sqrt{\frac{d_2}{d_1}}$ in both channels

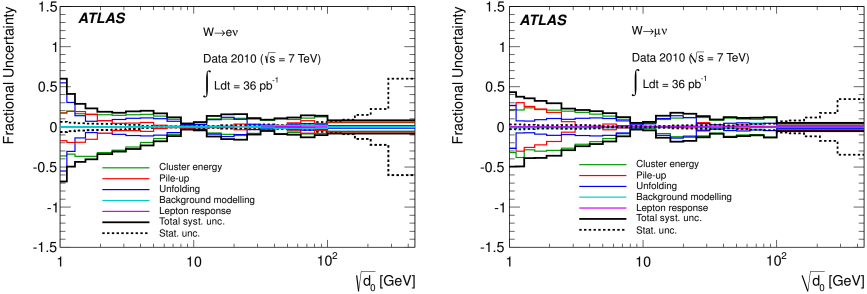




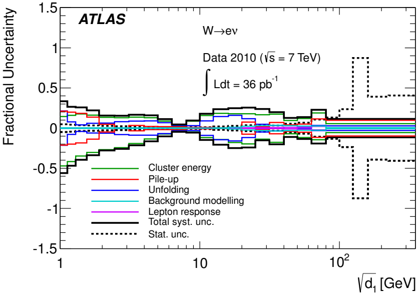
Ratio of splitting scales $\sqrt{\frac{d_3}{d_2}}$ in both channels

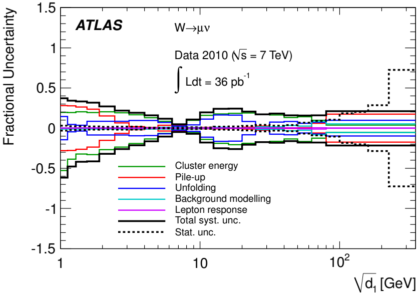


Splitting scale $\sqrt{d_0}$ in both channels

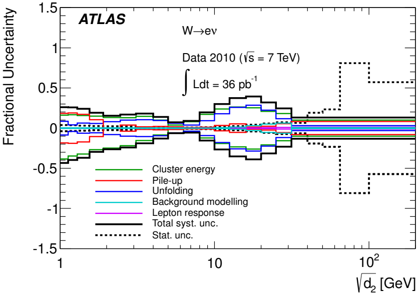


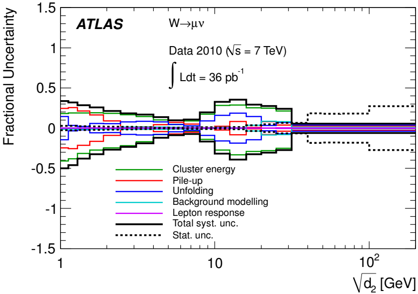
Splitting scale $\sqrt{d_1}$ in both channels



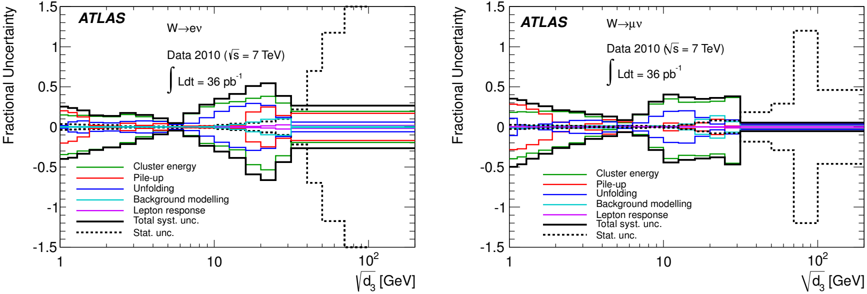


Splitting scale $\sqrt{d_2}$ in both channels

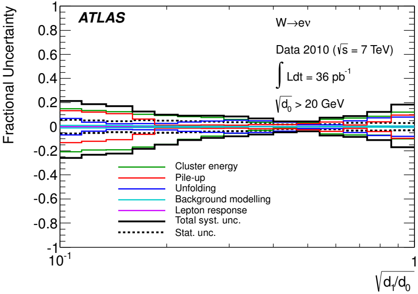


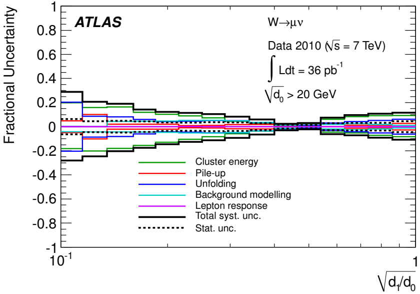


Splitting scale $\sqrt{d_3}$ in both channels

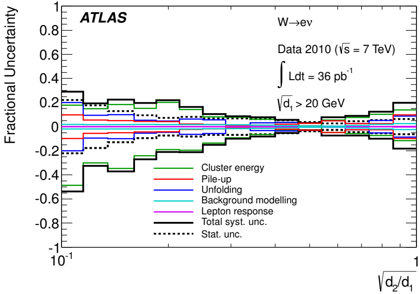


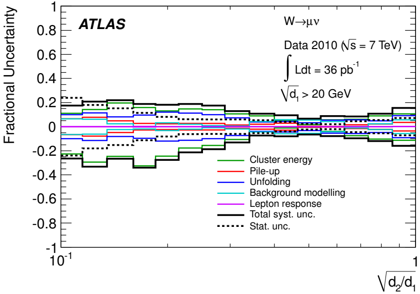
Ratio of splitting scales $\sqrt{\frac{d_1}{d_0}}$ in both channels



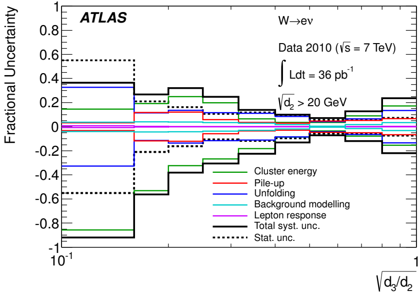


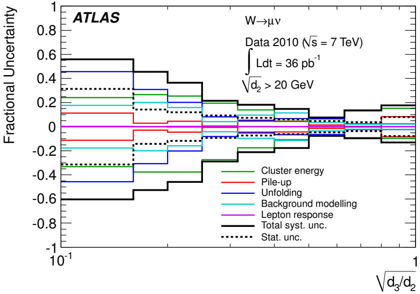
Ratio of splitting scales $\sqrt{\frac{d_2}{d_1}}$ in both channels



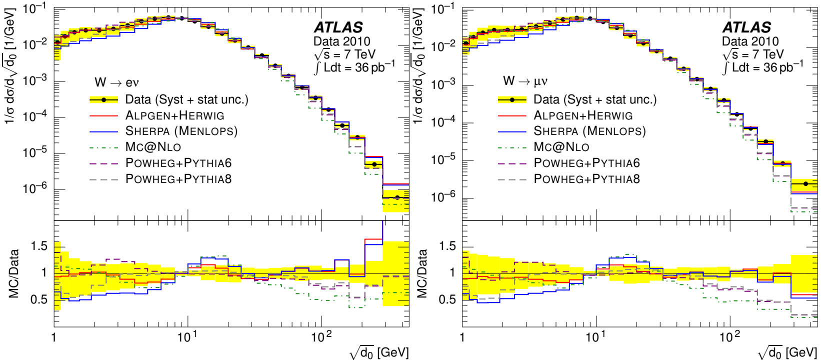


Ratio of splitting scales $\sqrt{\frac{d_3}{d_2}}$ in both channels

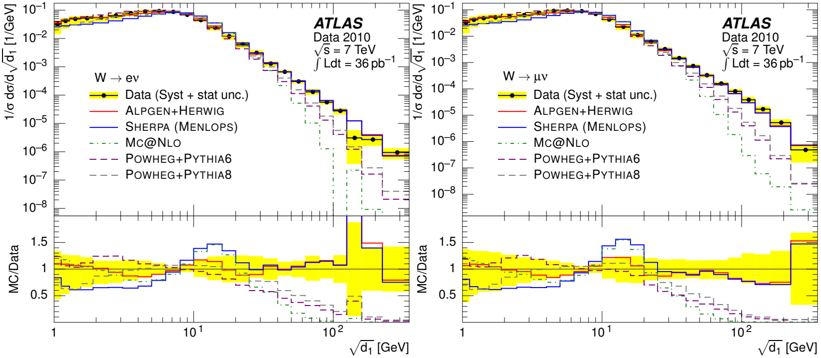




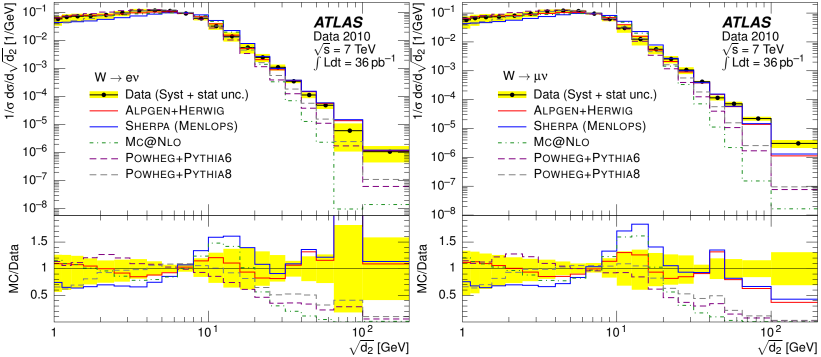
Splitting scale $\sqrt{d_0}$ in both channels



Splitting scale $\sqrt{d_1}$ in both channels

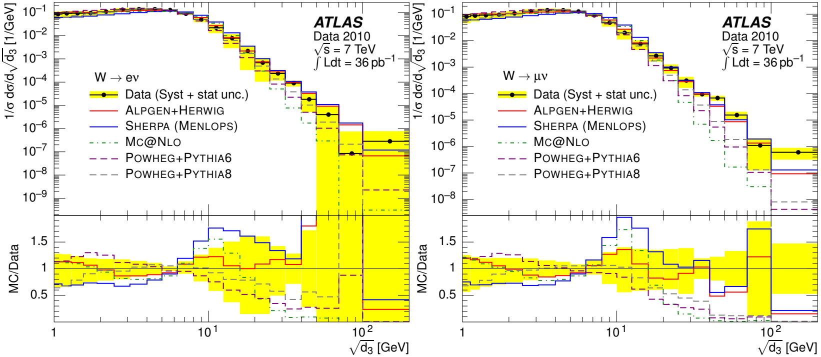


Splitting scale $\sqrt{d_2}$ in both channels

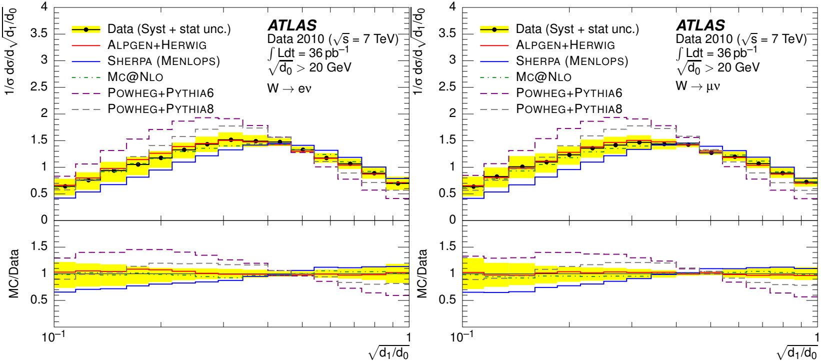


Unfolded results

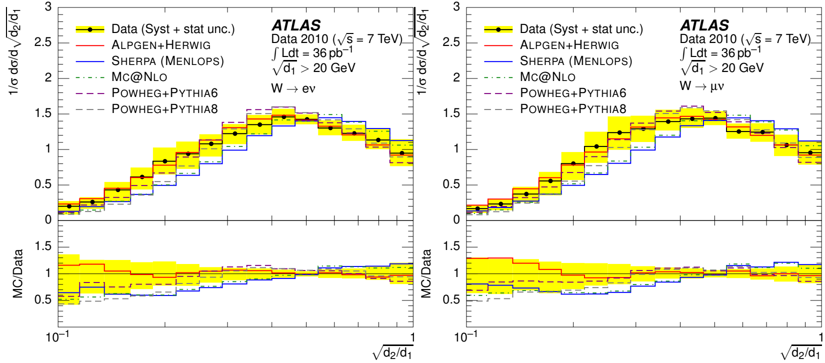
Splitting scale $\sqrt{d_3}$ in both channels



Ratio of splitting scales $\sqrt{\frac{d_1}{d_0}}$ in both channels



Ratio of splitting scales $\sqrt{\frac{d_2}{d_1}}$ in both channels



Ratio of splitting scales $\sqrt{\frac{d_3}{d_2}}$ in both channels