Study of jets produced in association with a vector boson

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LPC Seminar

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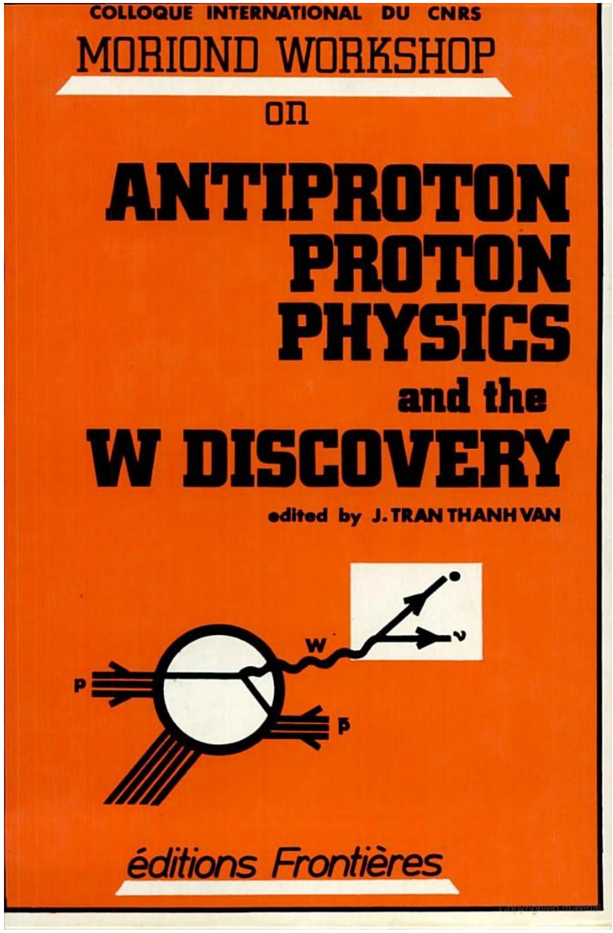
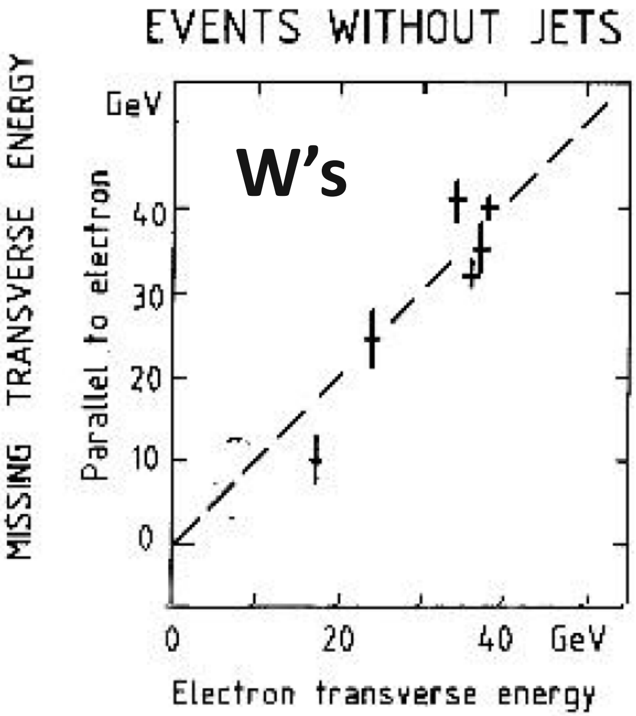
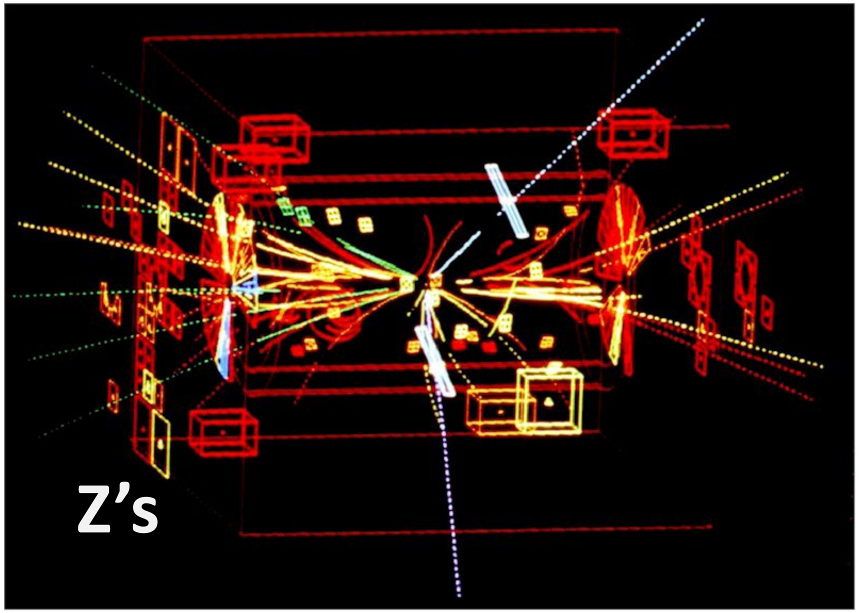
W- and Z- bosons 1983

- Discovered by UA1 and UA2 experiments at CERN in ppbar collisions







Quarks and Gluons 1968-1995

- Proposed in 1964 by Murray Gell-Mann and George Zweig
- 1968 @ SLAC
  - evidence of quarks in ep scattering
- 1979 @ DESY
  - Evidence of gluons in e+e- collisions

--Beginning of QCD era--

- …
- …
- 1995 @ Fermilab
  - Top quarks observed in ppbar collisions

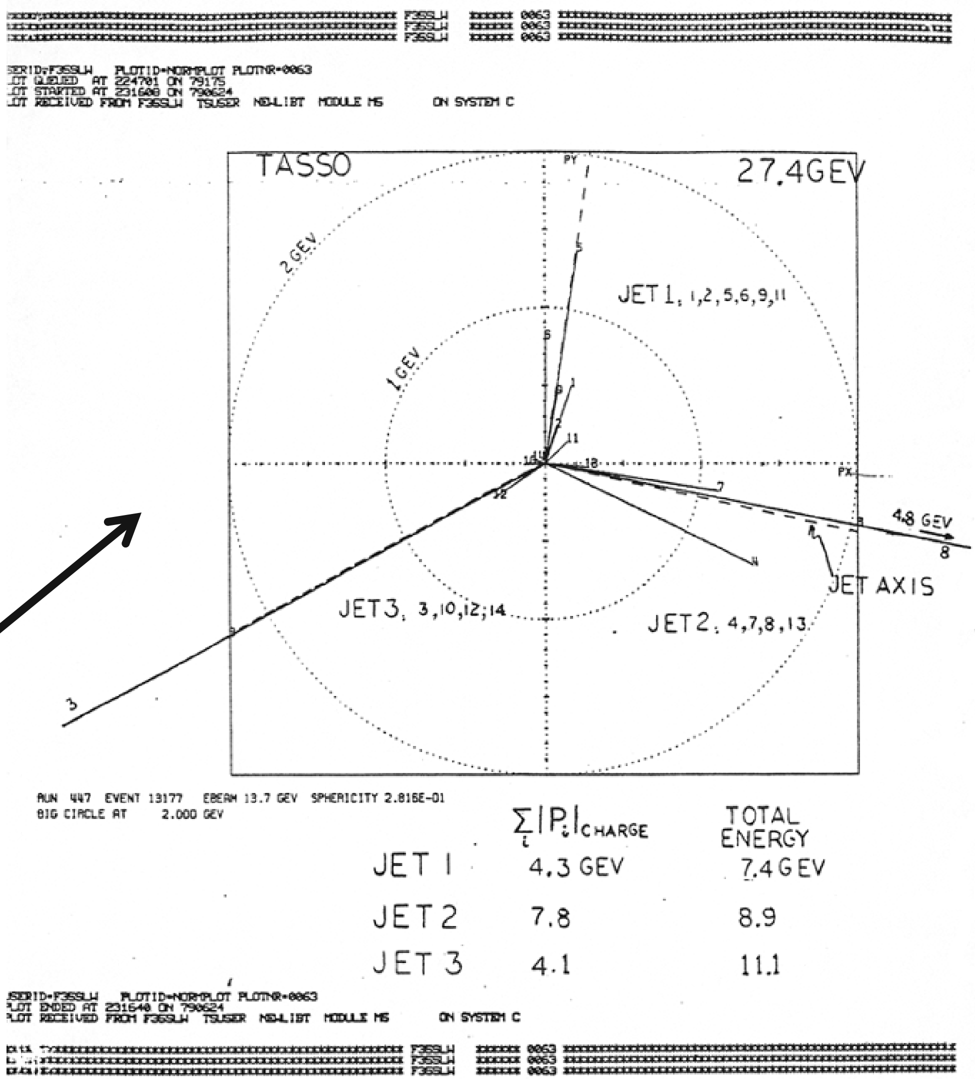
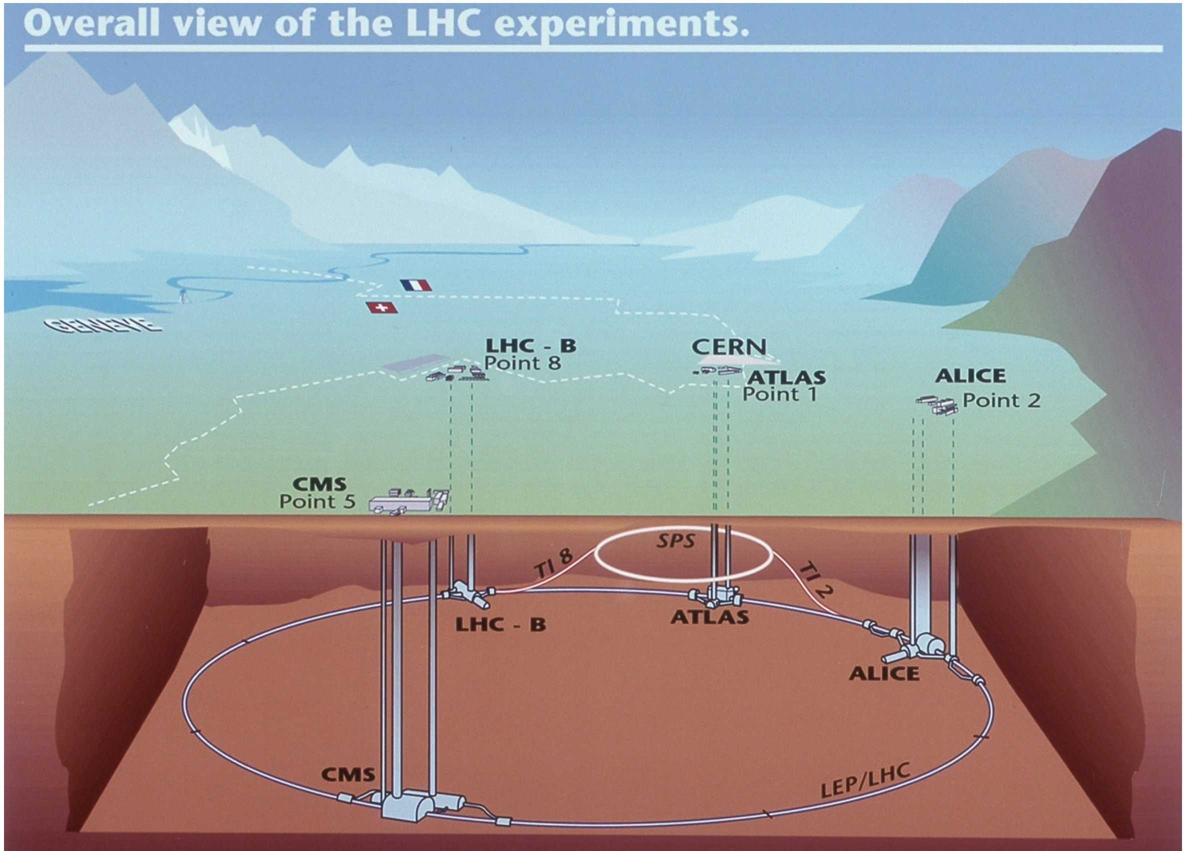


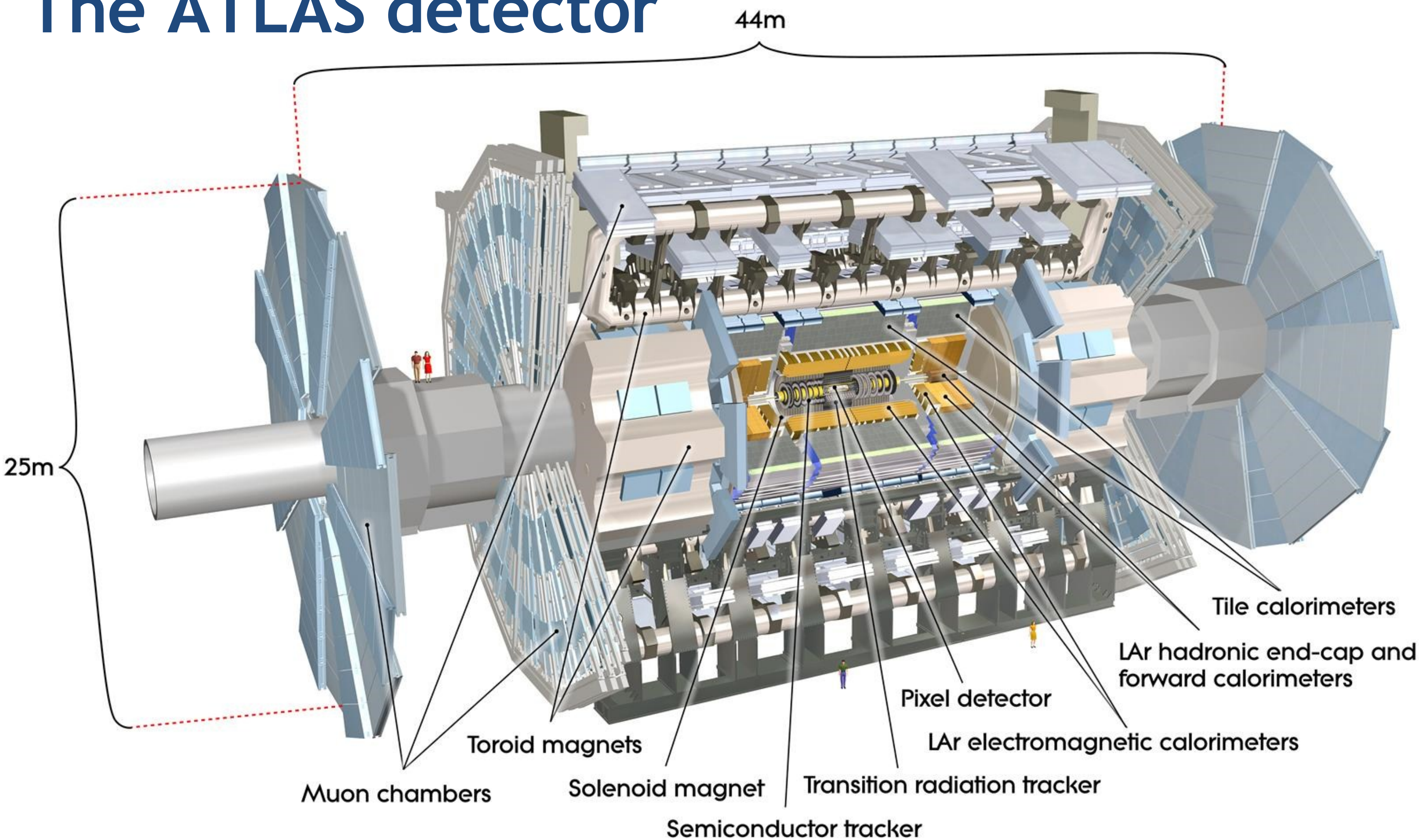
FIGURE 3

Strong and Weak interactions 2010-2011

- We put strong and weak interactions through more stringent tests than forty years ago by studying V+jets physics in **pp collisions at 7 TeV; V=W or Z (on-shell)**
- The LHC gives sensitivity to a different phase-space than the Tevatron:
  - pp instead of ppbar (better probe of sea quark and gluons)
  - 7 TeV instead of 1.96 TeV (wider reach in transferred momenta)

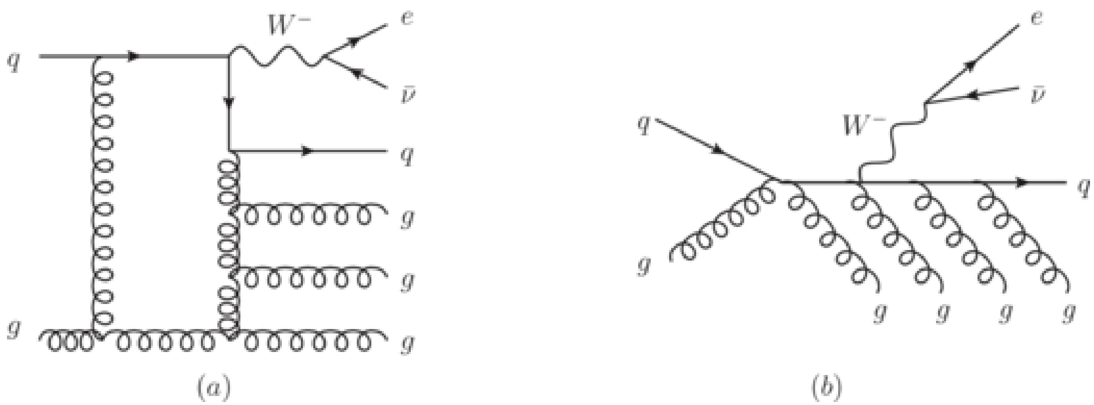


The ATLAS detector



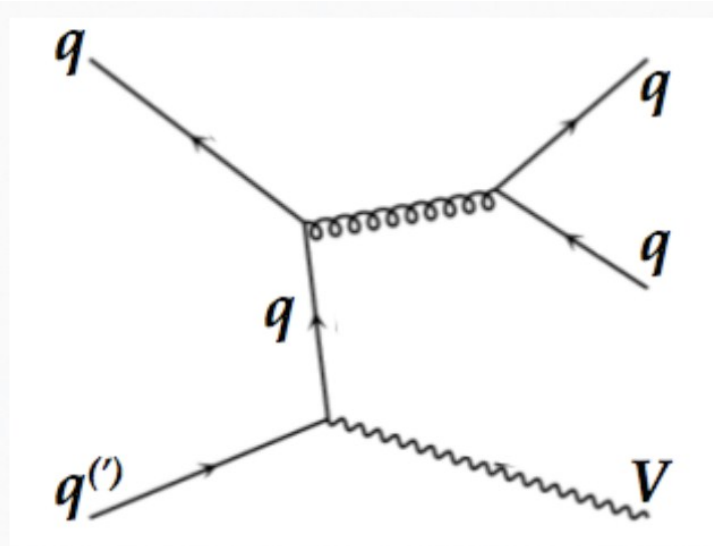
- Cylindrical coordinate system
- Almost all parts are involved in the measurement

Motivation for studies of jets produced with a *W* or *Z* boson



- "Standard Model Candle"; well-understood control region to test pQCD calculations; validation of detector performance
- An irreducible background to SM measurements (ttbar, single top, VBF, WW-scattering, H→WW) and new physics (eg SUSY)
- Foundation for development of novel pQCD calculations; choices of scales, jet-parton matching schemes, and parton showering
  - Alpgen, Sherpa, MCFM, BlackHat-Sherpa, Madgraph, etc.

Observables

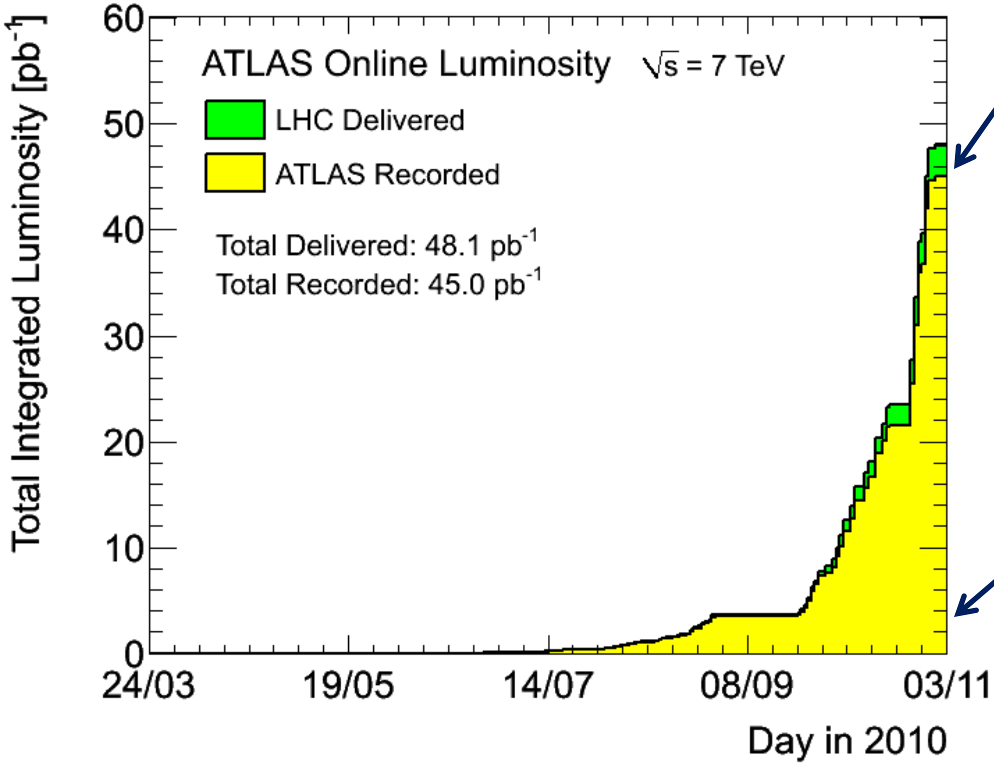


V = W- or Z-boson

- Cross sections and their ratios
  - **σ(V + ≥N jets) vs. jet multiplicity**
  - **Differential: $d\sigma/dp_T(N^{th}$ jet)**
  - **Ratio: σ(V + ≥N jets)/σ(V + ≥N-1 jets)**
- All cross sections are defined for:
  - Anti-k_T jets with R=0.4, and p_T^{jet}>20 or 30 GeV, $|y^{jet}|<4.4$, and dR(l,jet)>0.5
  - W/Z's are identified using electrons and muons with p_T>20 GeV
  - Leptons (QED radiation in cone R=0.1 is added to the four-vector of the lepton, http://arxiv.org/pdf/1003.1643)
  - $|\eta^{muon}|<$**2.4**; $|\eta^{electron}|<1.37$ or $1.52<|\eta^{electron}|<$**2.47**
  - $66<M_{inv}(l^+,l^-)<116$ GeV; $M_T(l,\text{mis-}E_T)>40$ GeV and mis-E_T>25 GeV

Datasets: 2010 → low pileup

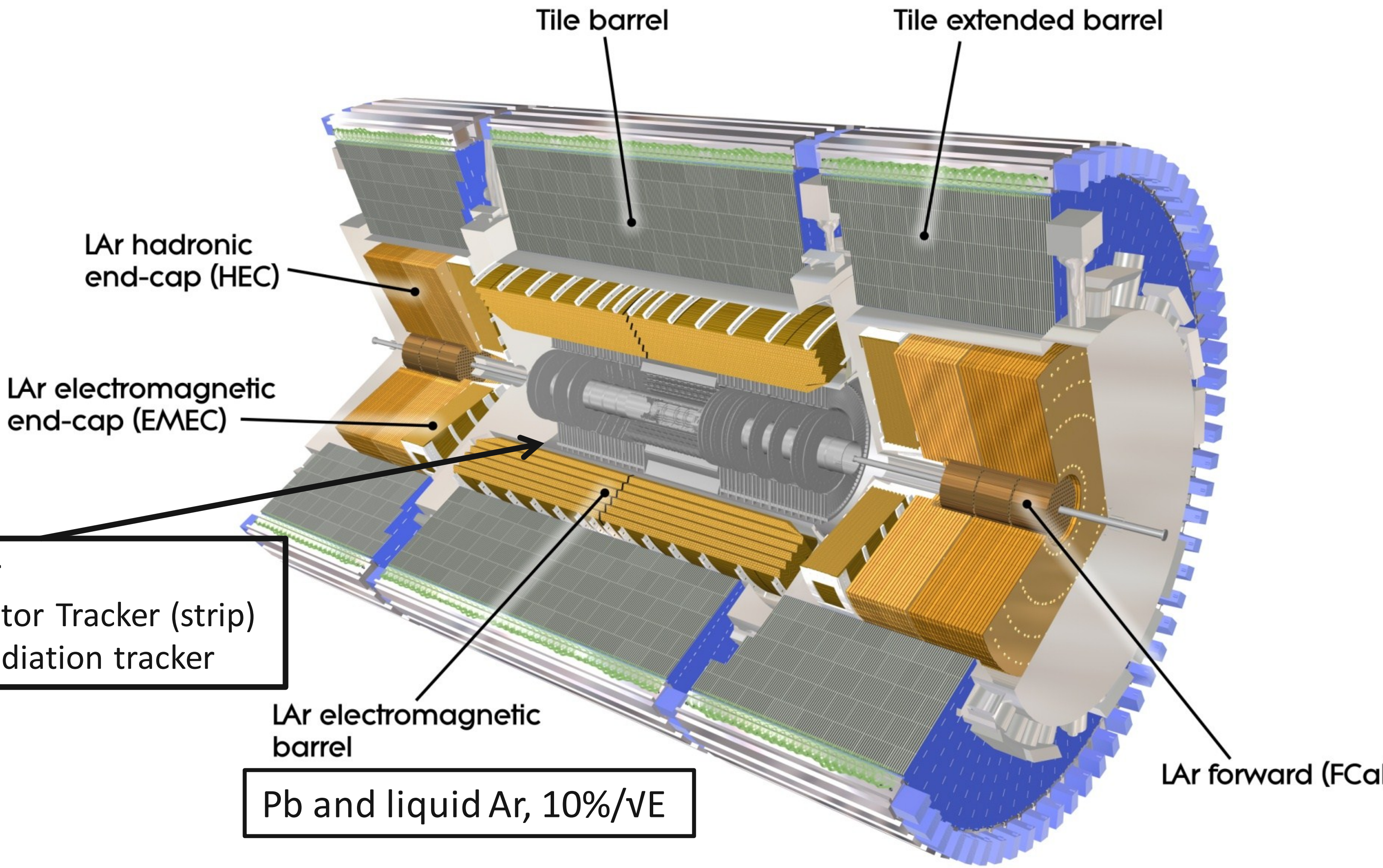
pp collisions at √s=7 TeV



- 36 pb^{-1} results:
  - W+jets→ arXiv:1201.127 [hep-ex] (published in PRD)
  - Z+jets→arXiv:1111.2690 [hep-ex] (published in PRD)
- Early 1.3 pb^{-1} results:
  - W+jets → arXiv:1012.5382 [hep-ex] (published in PLB)
  - Z+jets → ATLAS-CONF-2011-001

3.4% uncertainty on integrated luminosity!

Inner-detector Tracking and Calorimetry



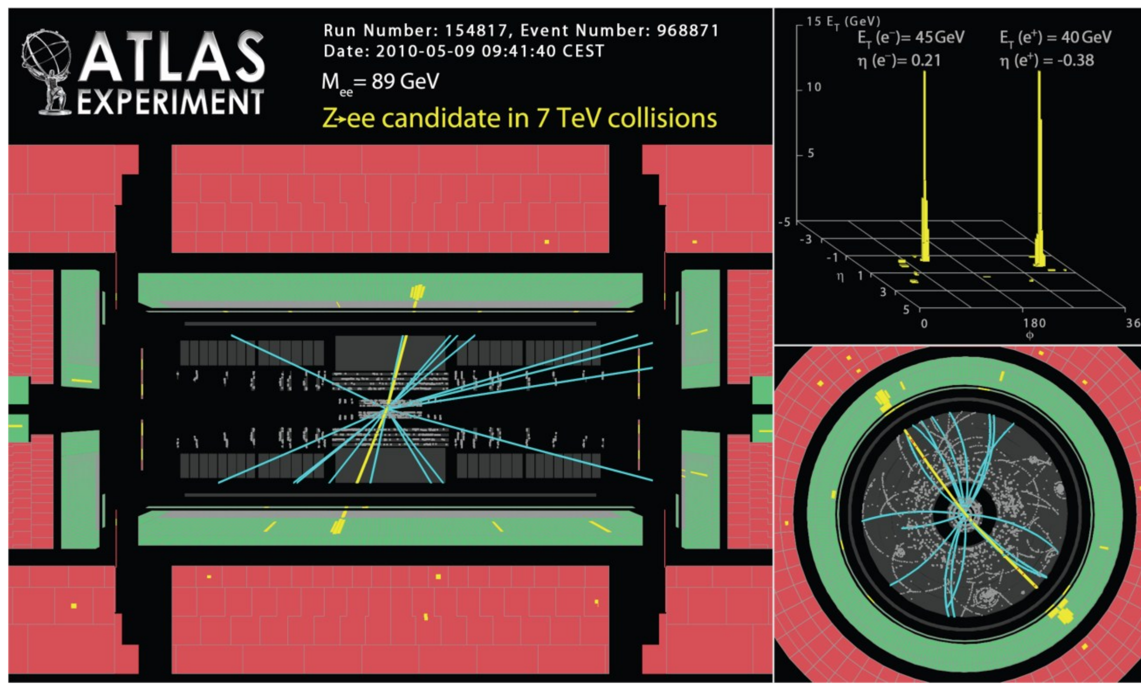
PIXEL tracker
Semi Conductor Tracker (strip)
Transition Radiation tracker

Pb and liquid Ar, 10%/√E

Tracking is up to |η|<2.5 . EM Calorimetry is up to |η|<3.2. Hadronic is up to |η|<4.9

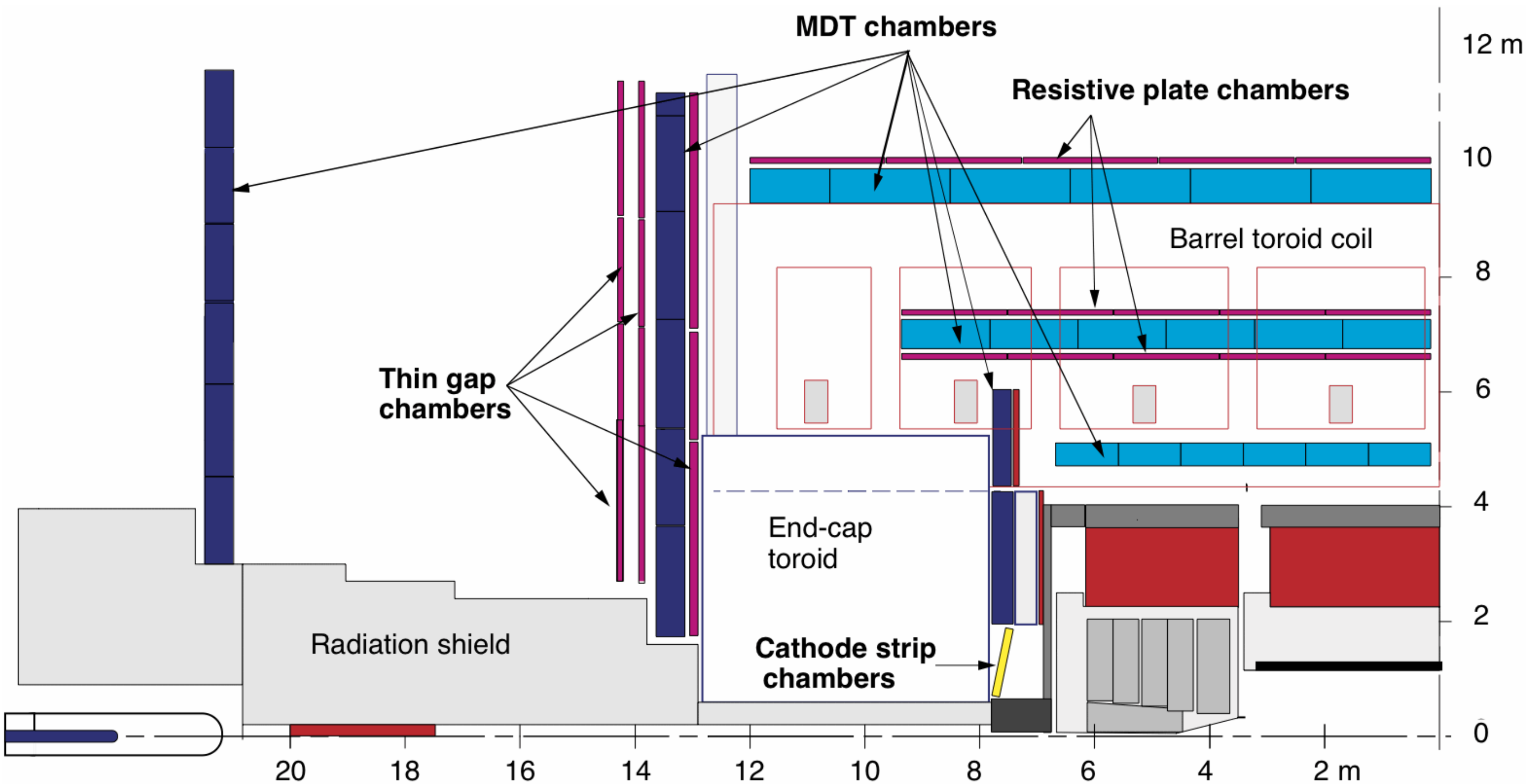
Identification of Electrons

- Shower shapes in the electromagnetic (EM) calorimeter
- No leakage into the hadronic compartment of the calorimeter
- Well-identified inner-detector track matched to the EM cluster
- Additional requirements for W→eν candidates:
  - The track has a hit in the 1st layer (closest to the beam) of the pixel detector
  - E/p consistent with electron and high transition radiation in the TRT
  - Isolated (calorimtere-based)

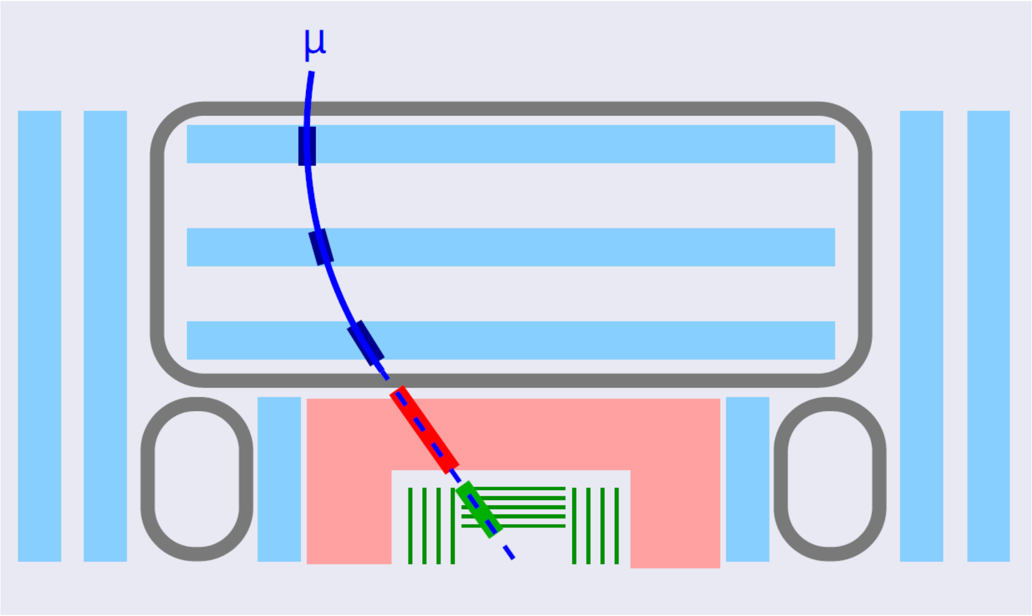


Muon Spectrometers

- RPC and TGC chambers provide L1 hardware-based, trigger for muons with |η|<2.4
- Monitored Drift Tubes → momentum and reconstruction for |η|<2.7



Identification of Muons

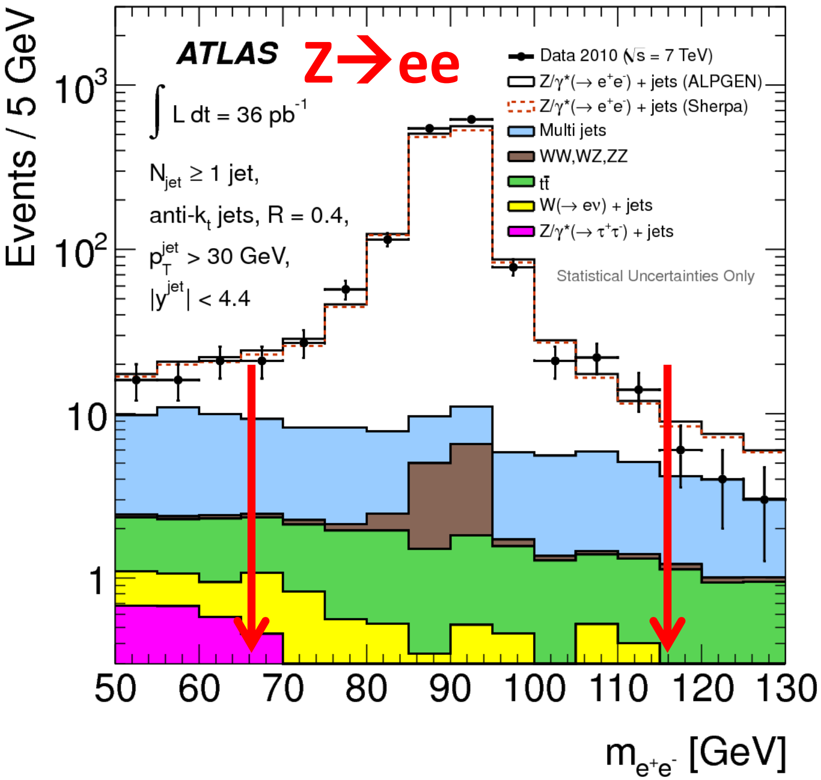


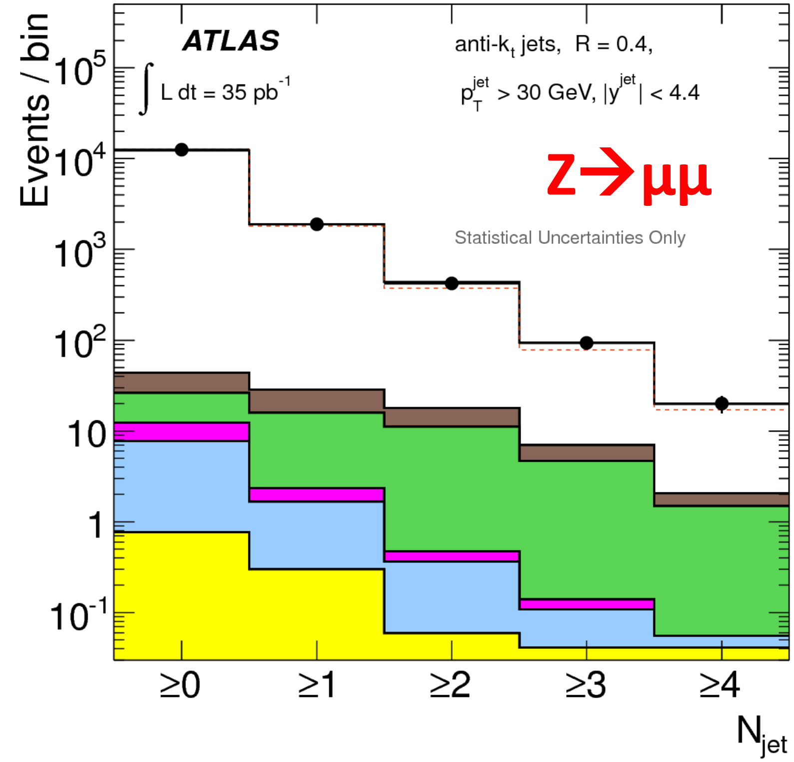
- Inner-detector track matched to a track in the muon spectrometer
- p_T>20 GeV, $|\eta|$<2.4
- Good quality of the inner-detector track, small impact parameter
- Track-based isolation in cone R=0.2; $\Sigma p_T^{tracks} < 0.1 * p_T$

Event selection

- Events are triggered using high-p_T electrons and muons
- At least 1 primary vertex with ≥3 tracks $|z_{PV}|<200$ mm
- $Z \to l^+l^-$ (l = electron or muon)
  - 66 GeV < M(Z) < 116 GeV
- $W \to l\nu$ (ν is measured as large missing p_T, mis-E_T)
  - $M_T(W) > 40$ GeV and mis-E_T>25 GeV
- Jet Identification
  - Reconstructed from calorimeter clusters using anti-k_T algorithm with distance parameter R=0.4
  - originate from the lepton vertex (removal of pileup jets)
  - Corrected to particle level p_T^{jet} >20/30 GeV (jet energy scale, JES)
  - The JES is a function of η^{jet} and p_T^{jet}

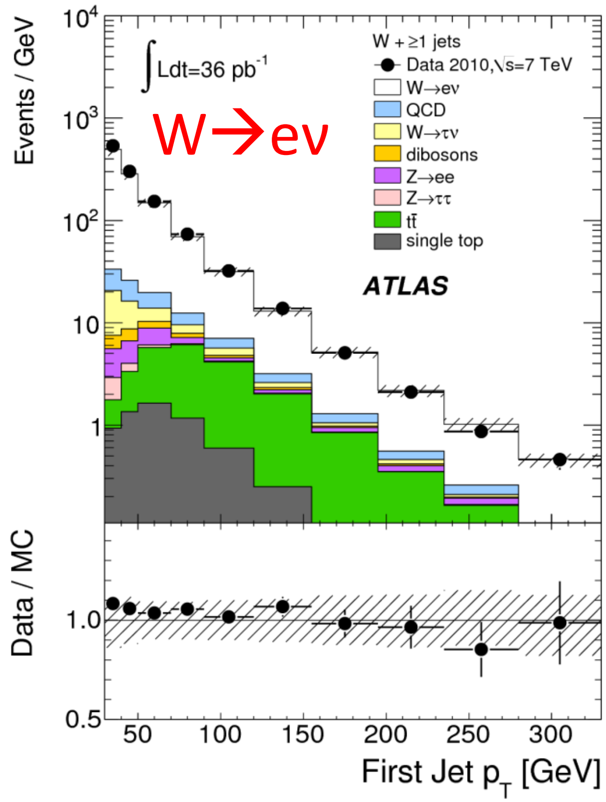
Backgrounds to Z+jets (Z→ee or Z→μμ)

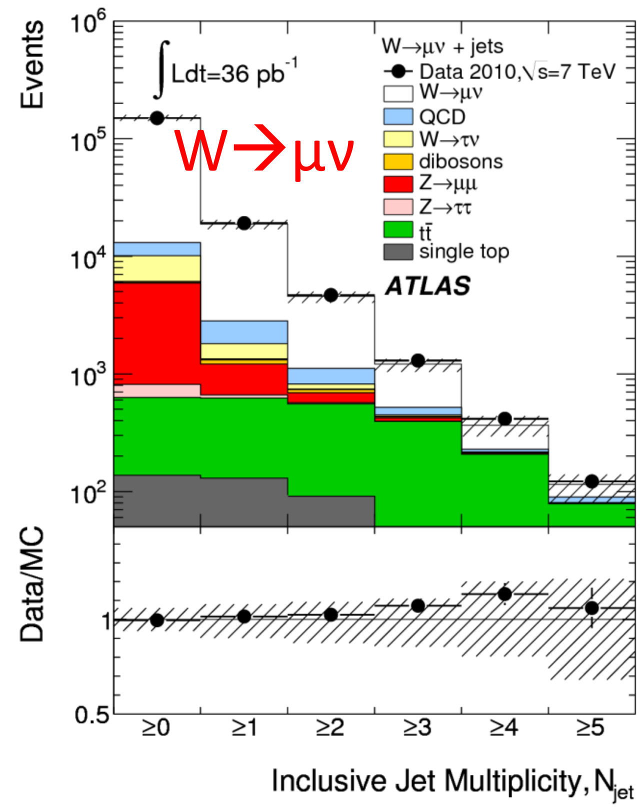




- Almost none.
- Irreducible backgrounds: the top pair production, Wt, WZ, ZZ, WW, and Z+γ; often estimated using simulations
- “fake” (non-prompt) leptons are from multi-jet and W+jet production are estimated using data

Backgrounds to W+jets

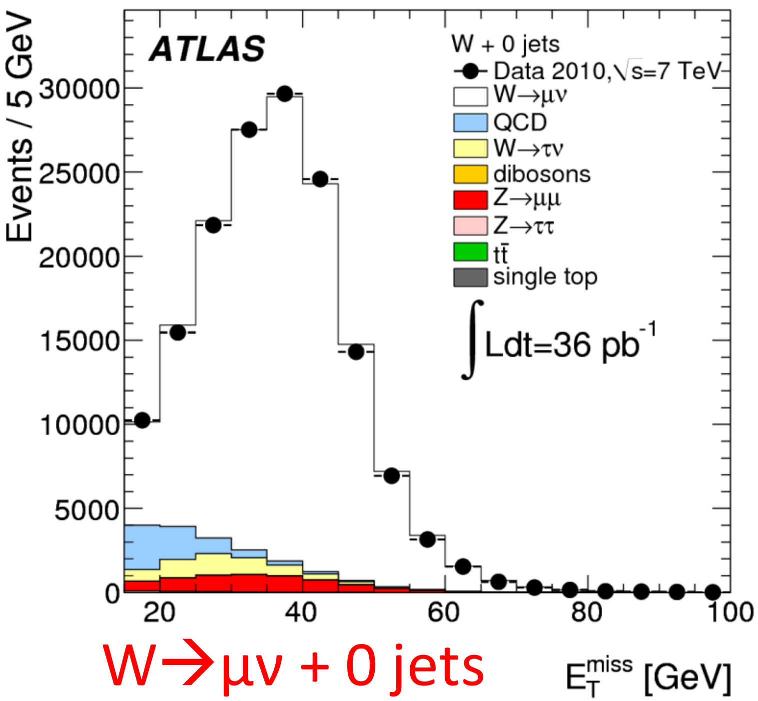




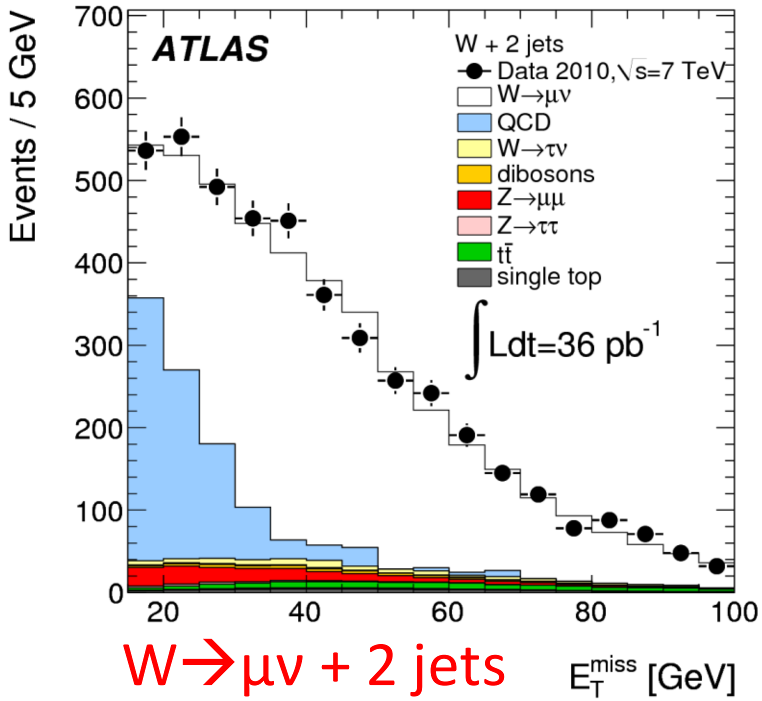
- Complements the Z+jets processes with higher statistics and different background composition
- Multi-jet events is a significant background at low jet multiplicities → **Important to do electron and muon channels simultaneously**
- The top pair production becomes the dominant background at high jet multiplicity (at 3-4) → Amplifies the systematic uncertainties

Evaluation of the multi-jet backgrounds in the *W*+jets sample

- Data-driven: Fit observed distributions in missing-p_T using templates for signal (W+jets, ttbar and Z+jets) and backgrounds (multi-jet events)
- The Fit is done for "control region" (looser cuts on missing-p_T and $M_T(W)$; the results are extrapolated to the full event selection
- The evaluation was done separately for each jet multiplicity sample



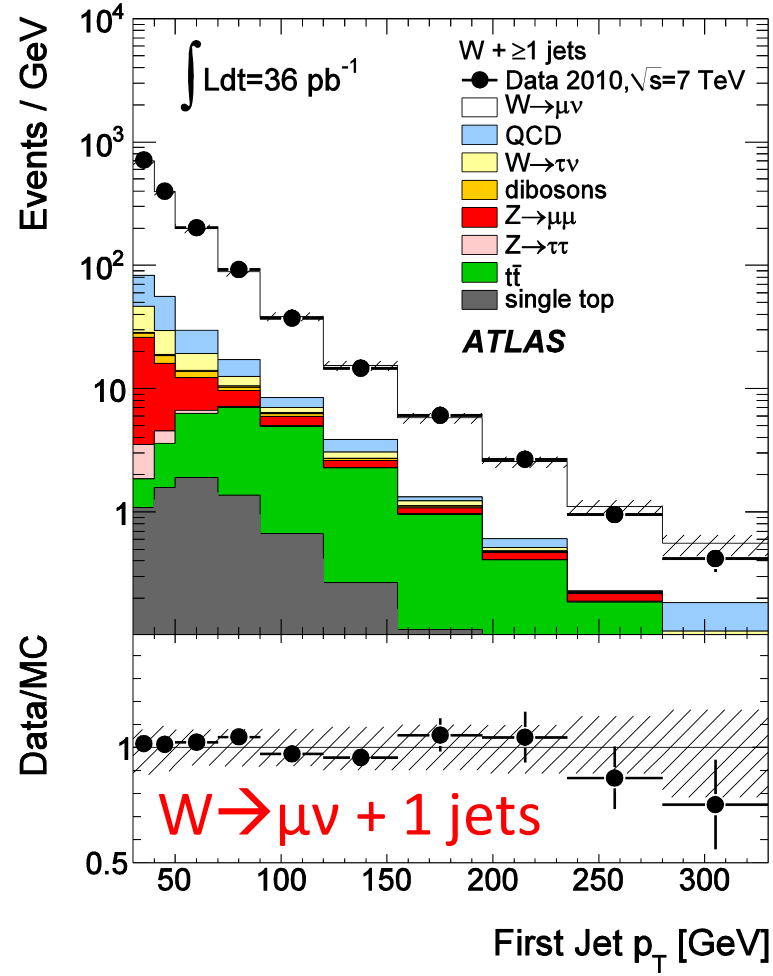
W→μν + 0 jets



W→μν + 2 jets

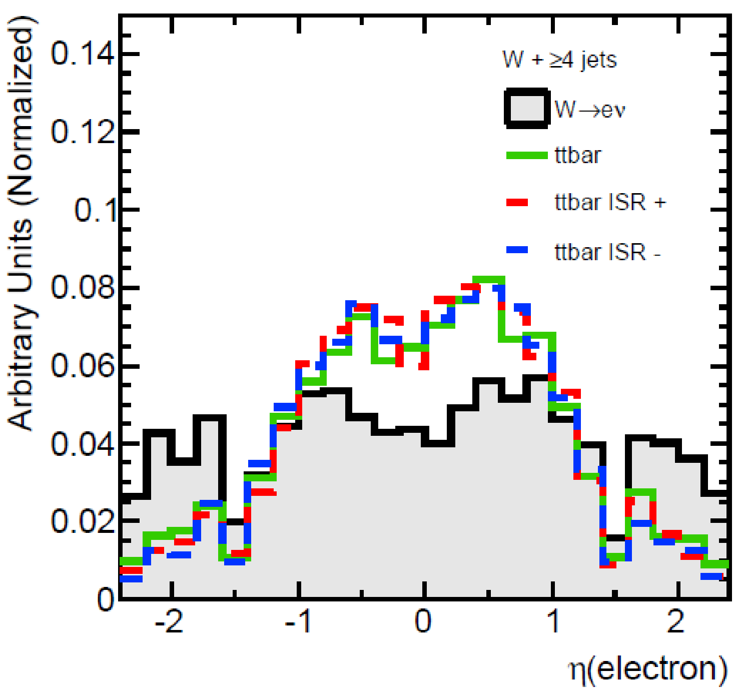
Evaluation of the multi-jet backgrounds in the *W*+jets sample

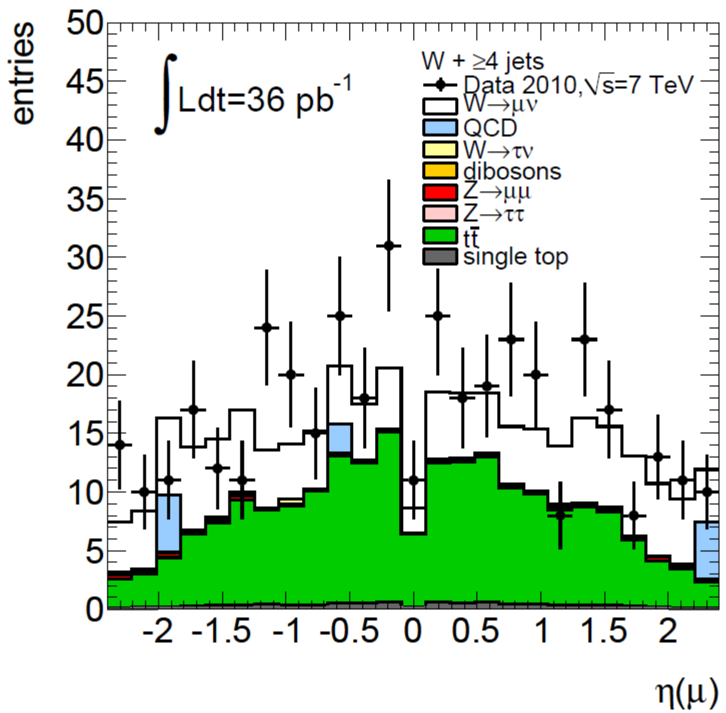
- Data-driven templates were obtained by
  - Reversal of d0-significance (significance of the transverse impact parameter in the muon sample
  - Reversal of the electron identification requirements and significance in the electron channel
- Naïve reversal of isolation leads to biases at high jet pT (negative measured cross-sections)



In situ validation of the top pair production rate

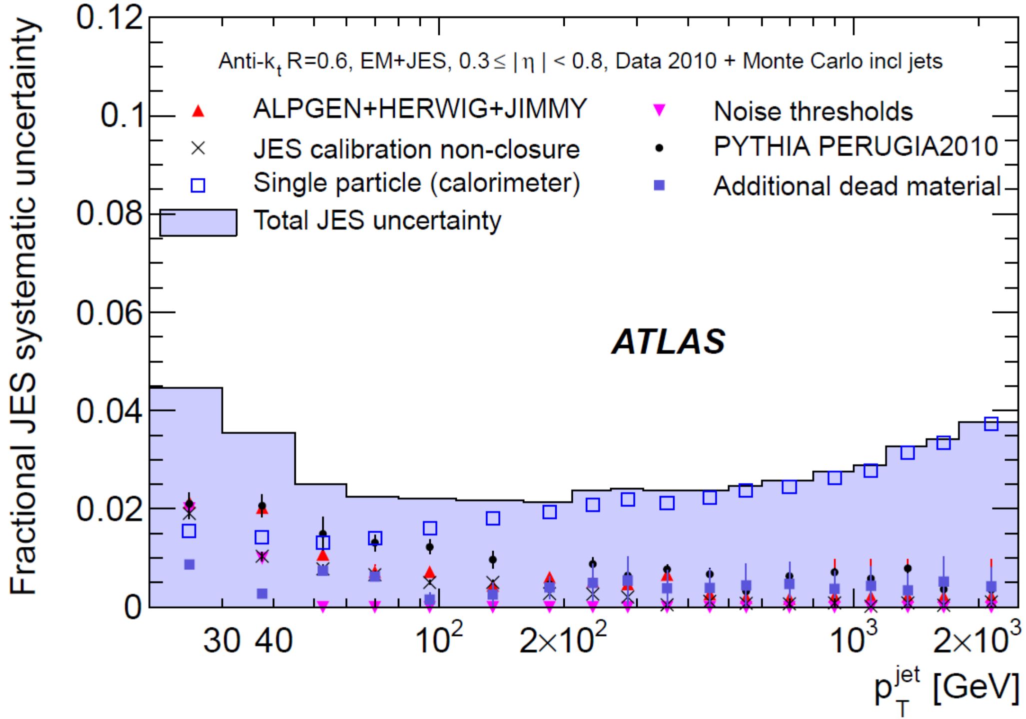
- The major background W+jets events when jet multiplicity above 3
  - 60% of W+4 jets (with pT>30 GeV)
  - Less significant when the jet threshold is 20 GeV instead of 30 GeV
- Amplifies the systematic uncertainties since the top pair rate is estimated using a NLO cross section → Limiting factor
- Used kinematic distribution to verify the predicted cross section

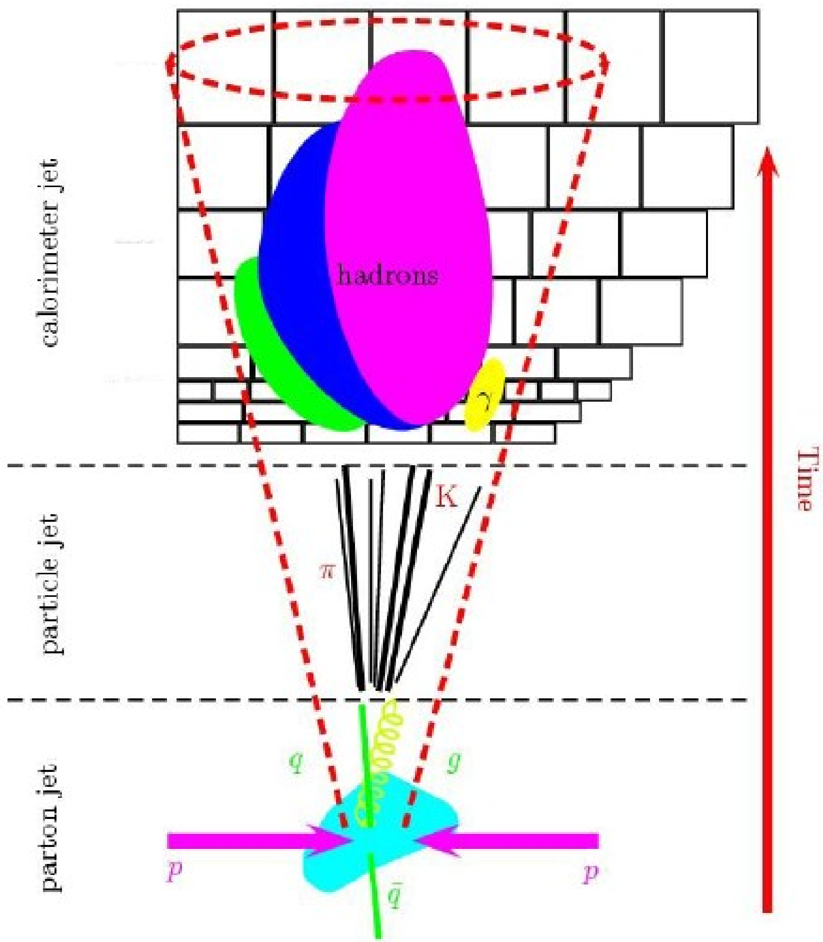




Jet Energy Scale

- p_T- and η- dependent function which turns uncorrected (EM-scale) jet momentum into momentum of a particle-jet
- Derived from simulations and verified using experimental data





Naïve calculation of cross-sections

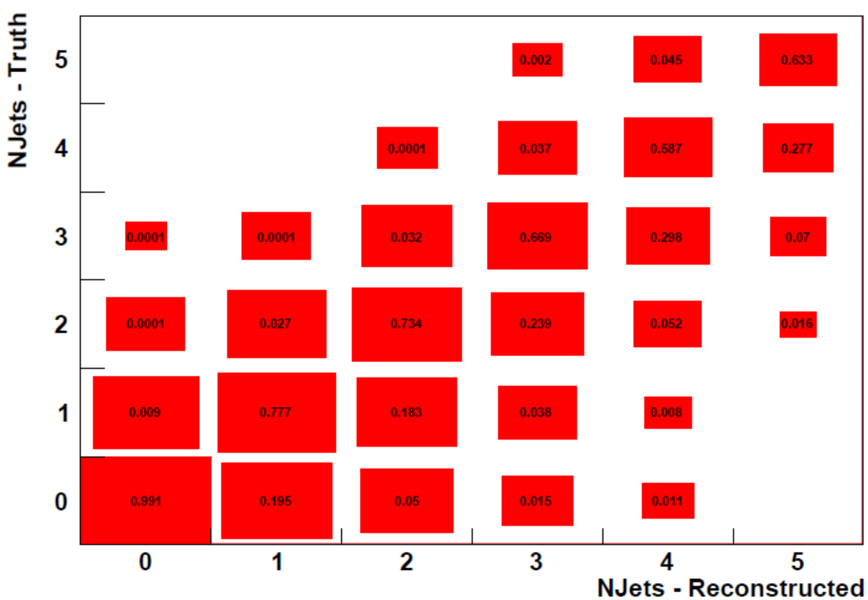
- We measure cross-section, σ_i, for each inclusive final state, *i*, (e.g. *W*+≥2 jets), or histogram bin (we use the Bayesian unfolding):

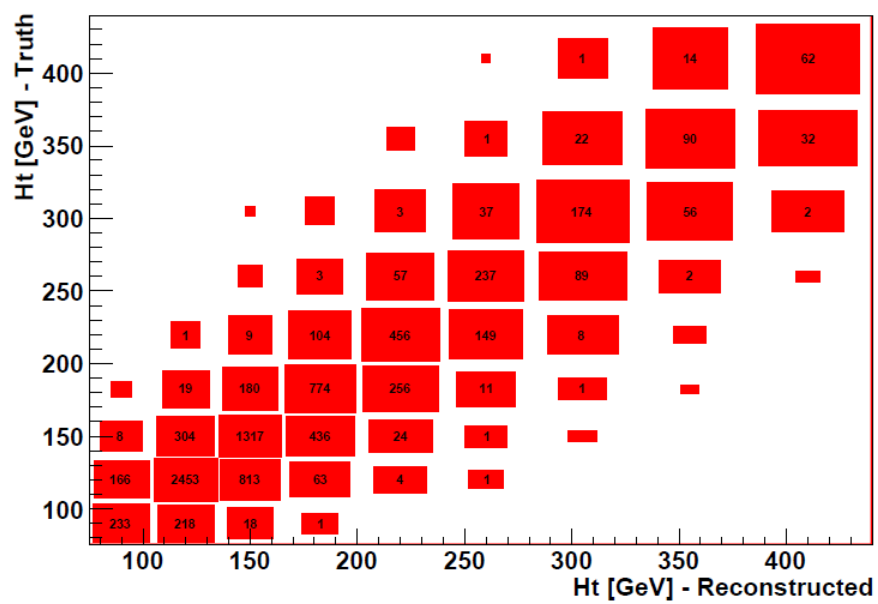
$$\sigma_i = \frac{N_i - B_i}{L \cdot \varepsilon_i} \qquad B_i = \sum_j \sigma_j \varepsilon_{i,j} L + QCD_i$$

  - N - number of observed events; L – integrated luminosity
  - B - number of background events (QCD, $W \to \tau\nu$, $Z \to \mu\mu$, and ttbar)
- Electroweak backgrounds are normalized using NNLO cross-sections (σ_j), efficiencies ($\varepsilon_{i,j}$), and luminosity
- Normalization of QCD (multi-jet) is determined in situ by fitting distribution in mis-E_T for each jet multiplicity bin
- Efficiencies (trigger and reconstruction) are derived from MC and corrected using data-derived scale factors

Unfolding of the observed distributions

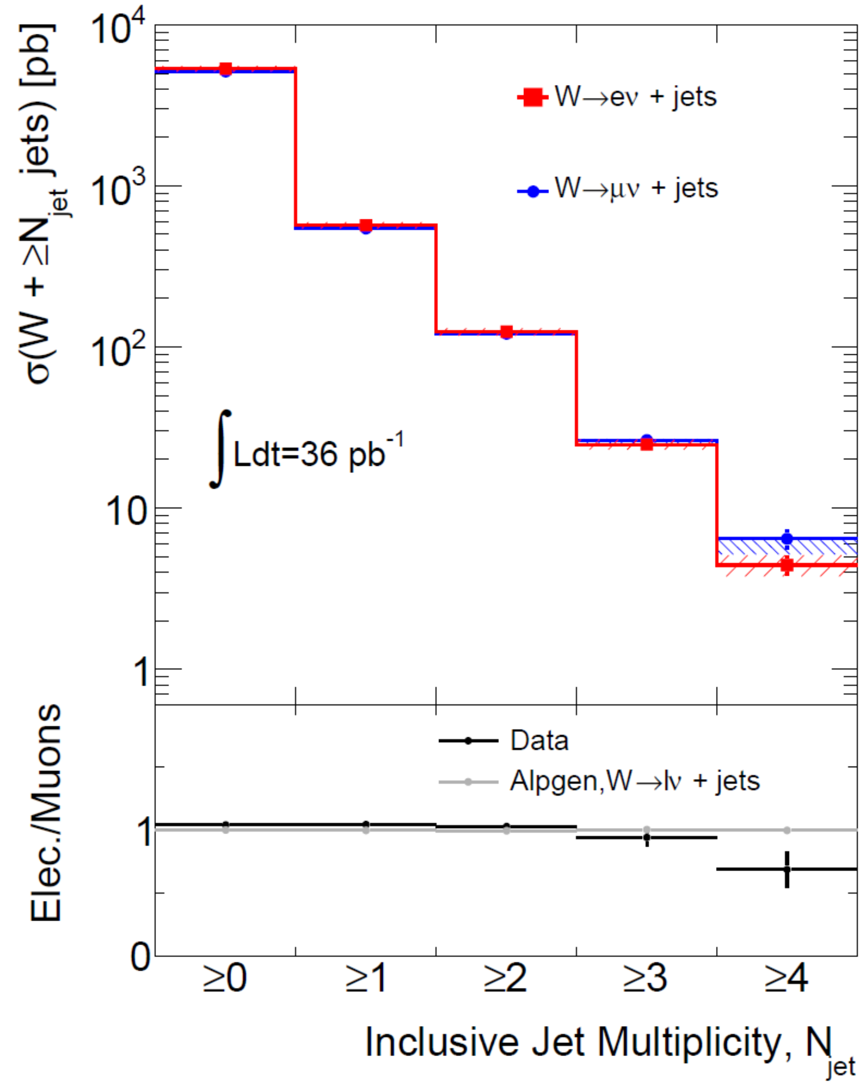
- Bayesian, iterative, unfolding
  - Vector of “Observed minus background”, $\{N_i\text{-}B_i\}$, is an input.
  - Handles bin-to-bin migrations.
  - Returns cross-sections
  - Repeated for each variation of a systematic uncertainty (JES, luminosity, background estimates)
  - Done for the electron and muon channels separately





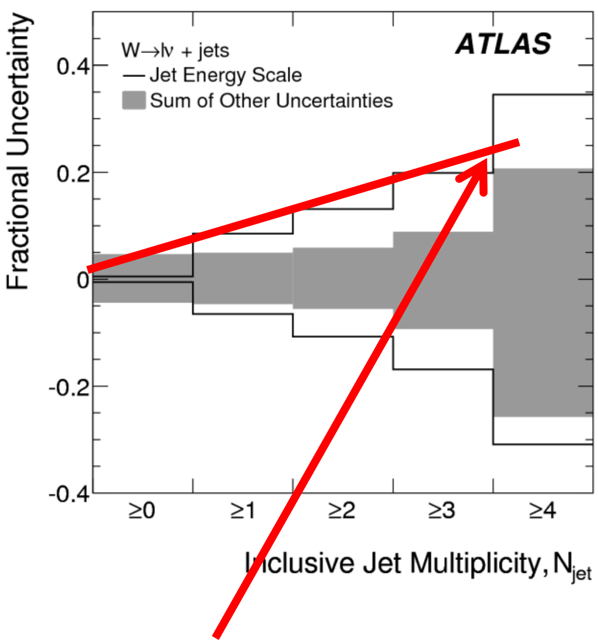
Combination of the results for electron and muon channels

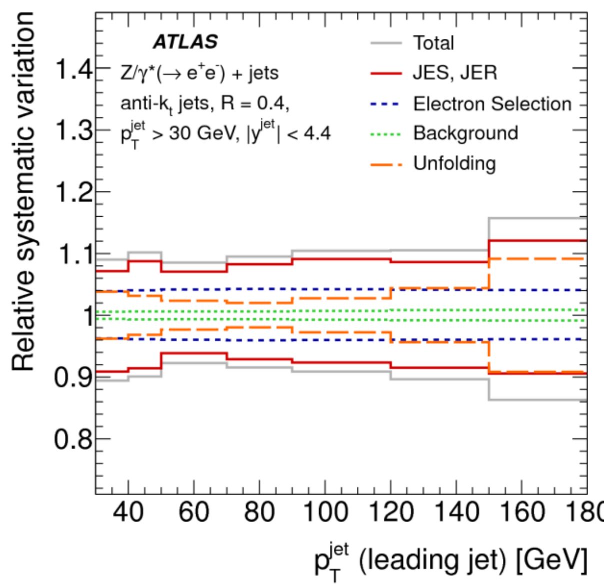
- The electron and muon cross-sections (e.g. for Z→ee and Z→μμ) were compared using the uncorrelated uncertainties
  - They were found in agreement
  - Safeguard from poorly understood backgrounds and detector effects
- Then they were combined using the BLUE (Best Linear Uncertainty Estimate) that finds a linear combination of the individual measurements that gives the minimum uncertainty for the combined number

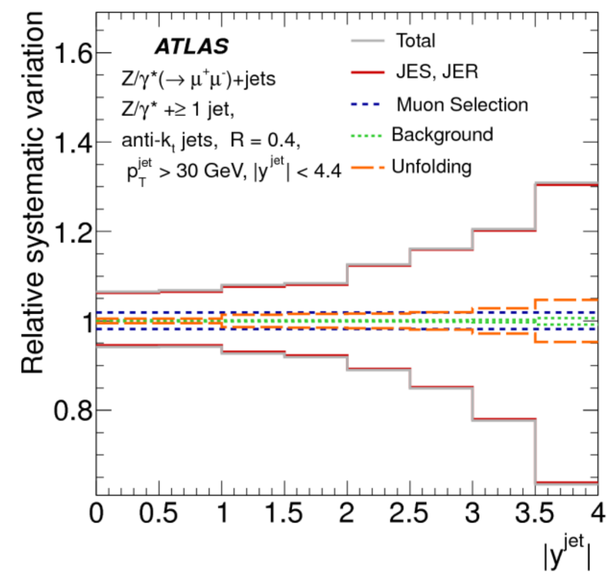


Systematic Uncertainties

- Dominated by the uncertainty on the jet response (JES)
  - Increases for forward jets and decreased with jet p_T
- The top pair production amplifies the systematic uncertainties for W+4jets and W+5jets
- Z+jets events are "immune" to the top quark background



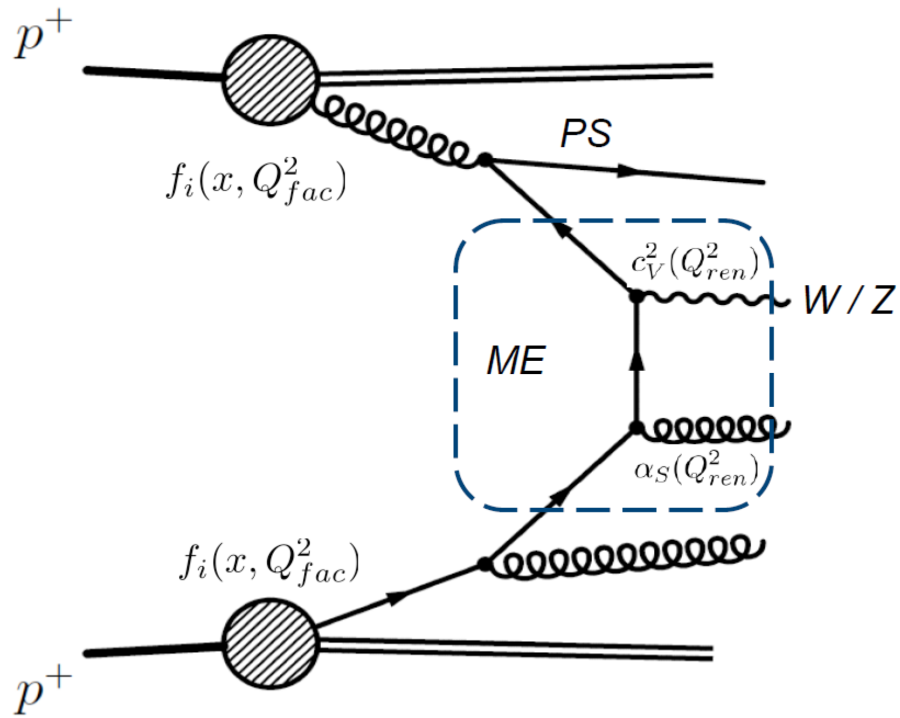


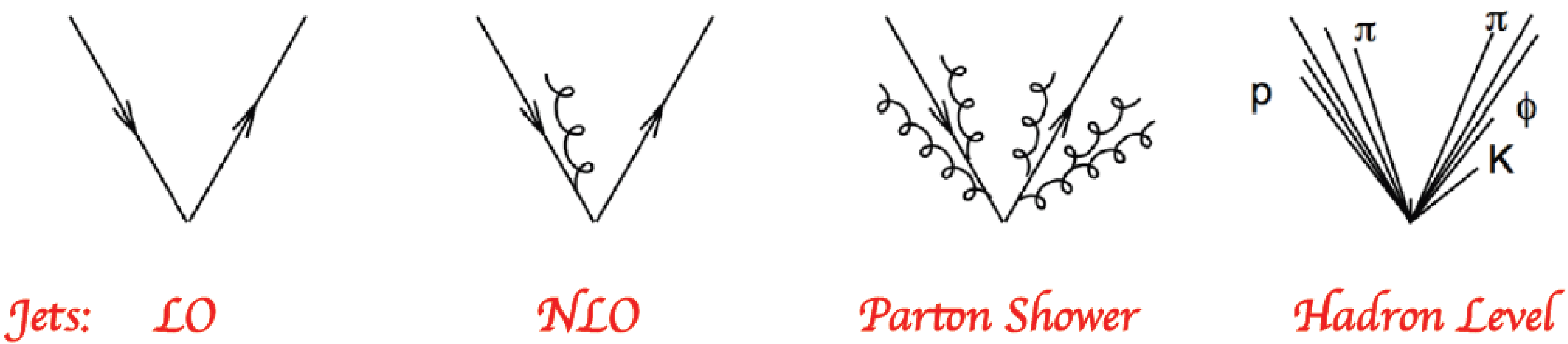


Amplified by the top pair background

Theory view of pp collisions

- Parton Density Functions (PDF)
- Matrix Element (ME)
- Parton showering
  - Fragmentation
  - Hadronization
- Underlying event and color reconnection





Details of W/Z+jet predictions

- BlackHat-Sherpa:
  - NLO for W + up to 4 jets
  - Parton-level jets are corrected for non-pQCD effects (hadronization and parton showering) and Underlying Event
  - QED correction for the radiation of the leptons (1-2% effect)
- Sherpa → p_T-ordered parton shower (PS)
  - Matrix-element + Partion Shower matched using CKKW matching; used a NLO PDF CTEQ6.6 → low strong coupling
- Alpgen+Herwig → Angular-ordered PS
  - Matrix-element + Partion Shower matched using MLM matching; used a LO PDF CTEQ6L1
- Pythia
  - LO ME for W/Z+0p and a correction to the 1st ISR PS emission

BlackHat-Sherpa NLO calculation

- Novel revolutionary calculation for the high number of parton emissions ("legs") → takes 1 week at MSU computer farm (~10 TB)
- Five "samples" to cover all the multiplicities from ≥0, to ≥4 at NLO
  - e.g. W+ ≥ 0jet samples contain ME's with W+0p and W+1p
  - e.g. W+ ≥ 1jet samples contain ME's with W+1p and W+2p …

$$\sigma_n^{NLO} = \int_n \sigma_n^{tree} + \int_n \sigma_n^{virt} + \int_{n+1} \sigma_{n+1}^{real}$$

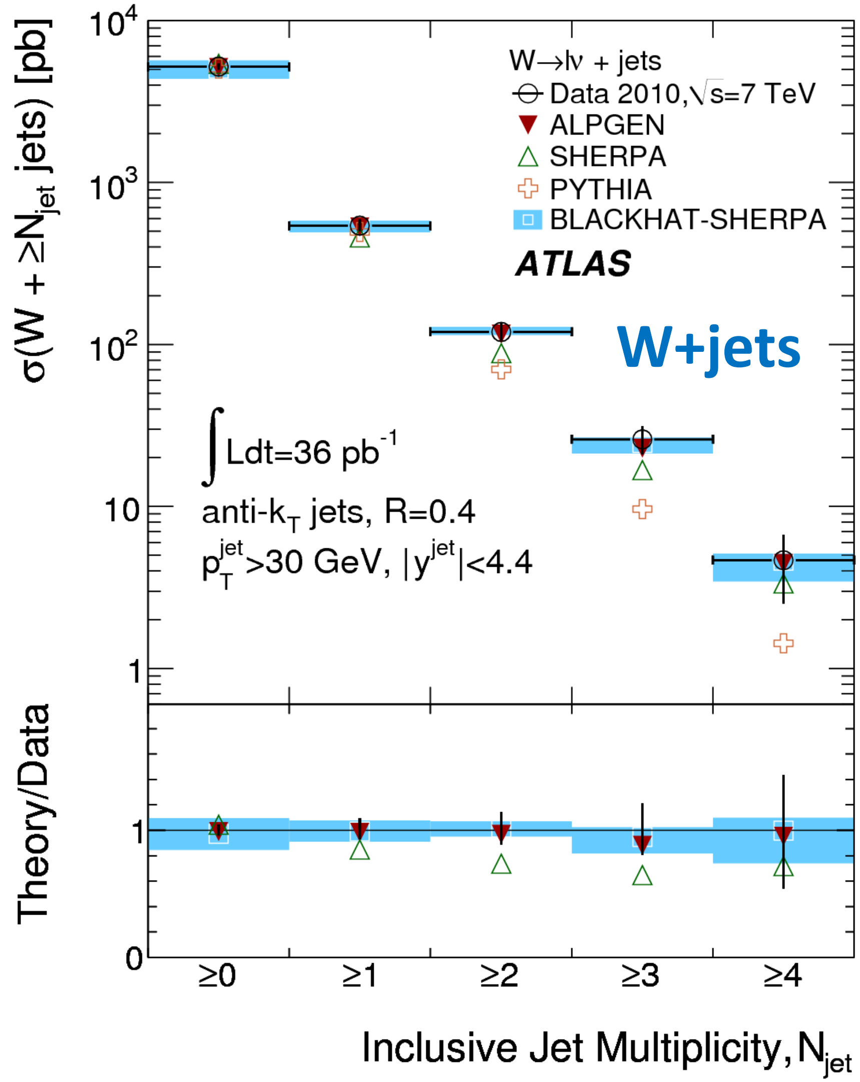
- Cross-checked against MCFM (conventional tool) for 0,1, and 2 jets
- Systematic uncertainties
  - PDF's
  - Choice of scale; varied the renormalization scale ($H_T/2$) and factorization scale ($H_T/2$) independently by a factor of 2
  - Included non-pQCD effects: fragmentation, hadronization, and the underlying effect

Availability of V+jets results to theorists

- W+jets →The Durham HepData
  - http://hepdata.cedar.ac.uk/view/irn9326537
  - 100 tables (that includes non-pQCD corrections and other reference distributions)
  - Rivet; a framework to compare the data to theory predictions (event selection)
  - Results for $p_T^{JET} > 20$ GeV and $p_T^{JET} > 30$ GeV
- Z+jets → in the paper itself
  - Results for $p_T^{JET} > 30$ GeV

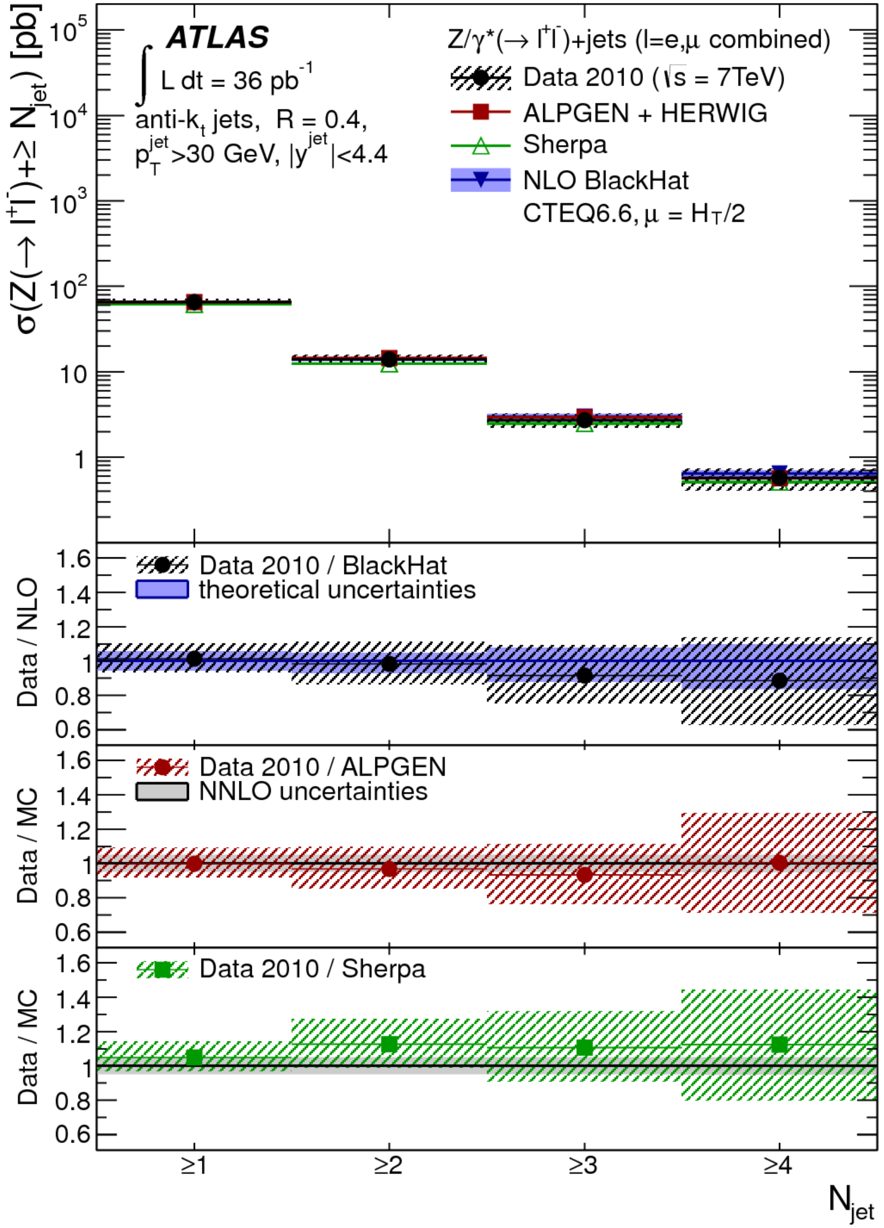
W+jets: Inclusive jet multiplicity

- Accurate predictions require ME+PS approach (Alpgen, MadGraph, & Sherpa)
  - Alpgen shows better agreement because of the LO PDF
- PS-only simulations (Pythia) fail at high jet multiplicity, >1 jet, as expected
- Key for measurements and searches (e.g. separation between H→WW and ttbar; BSM searches involving high jet multiplicities)
- NLO calculation (BlackHat-Sherpa) are superbly accurate.

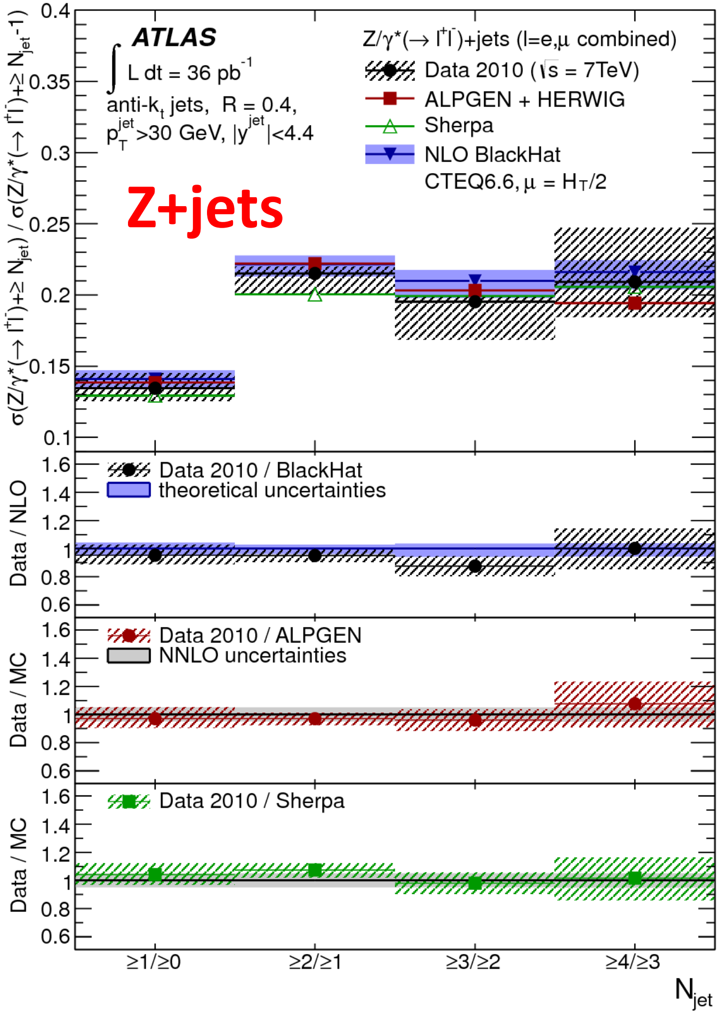


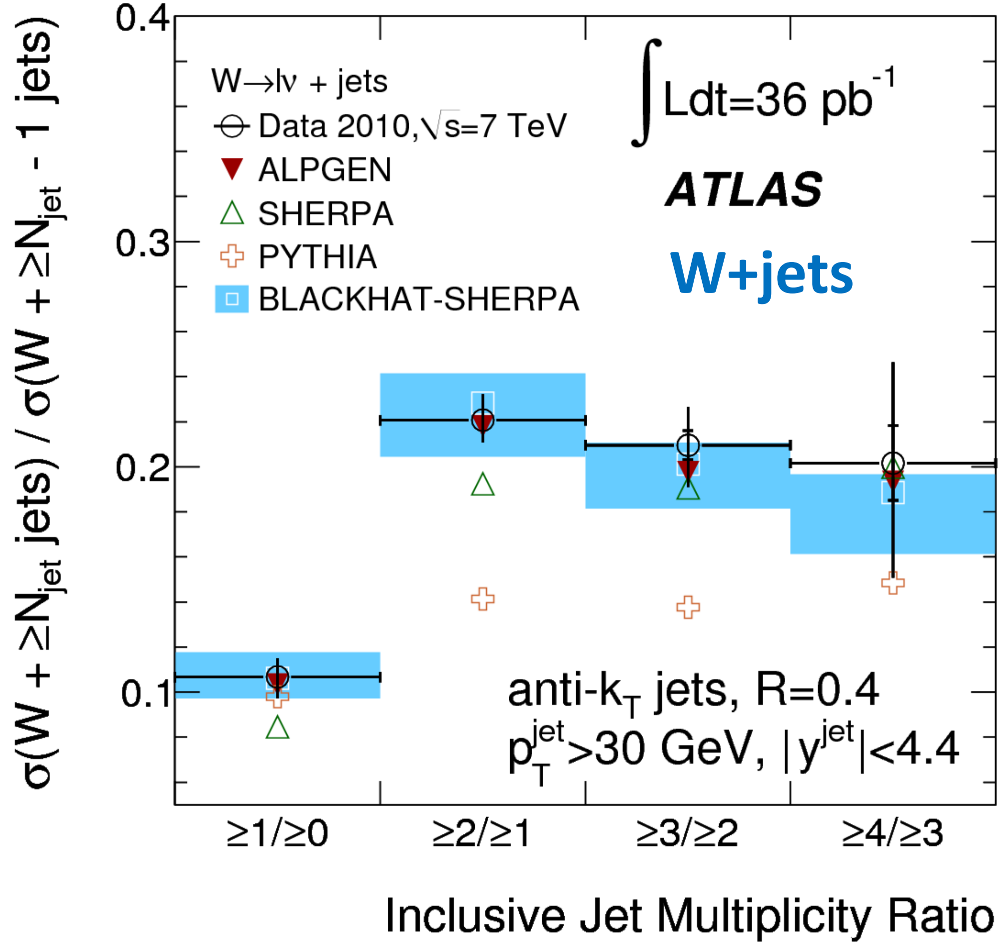
Z+jets: Multiplicity

- Complements the W+jets results;
  - different backgrounds and colliding partons
  - Different detector effects
- Good agreement with NLO and ME+PS predictions (within statistics)



Ratios of cross sections: $\sigma(V+N_{jet})/\sigma(V+N_{jet}-1)$

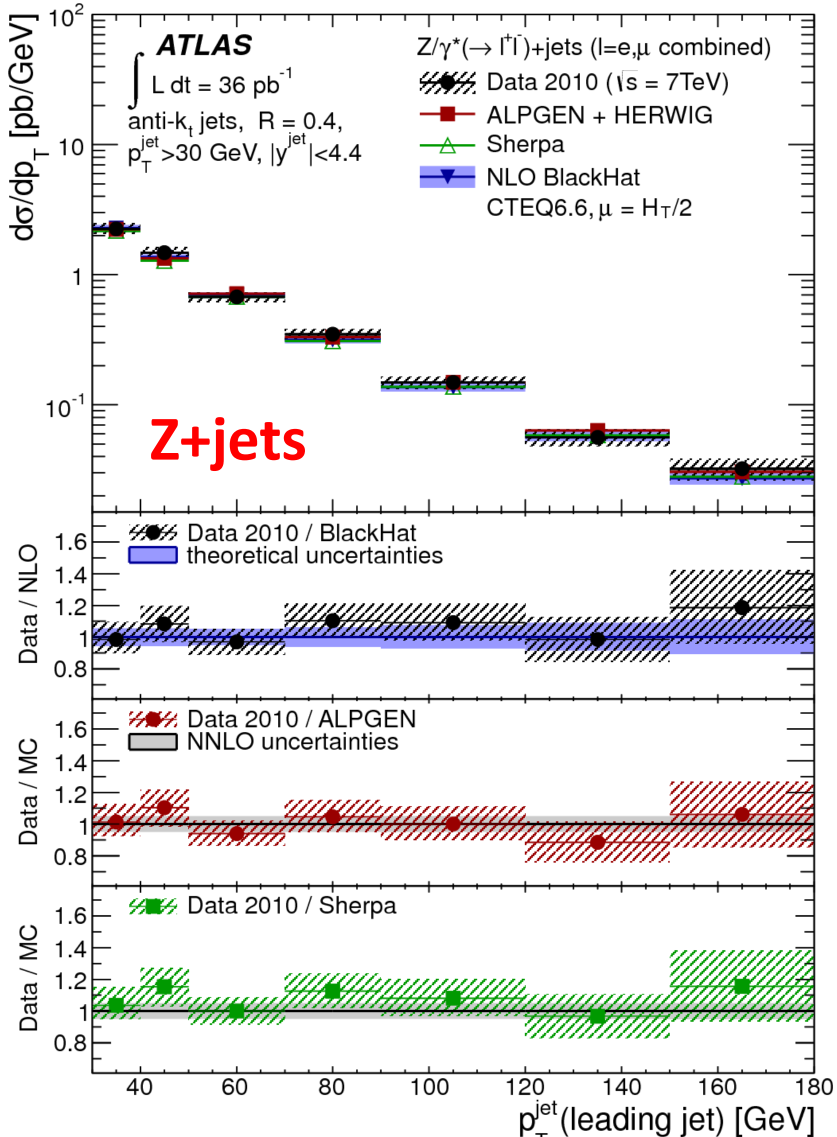


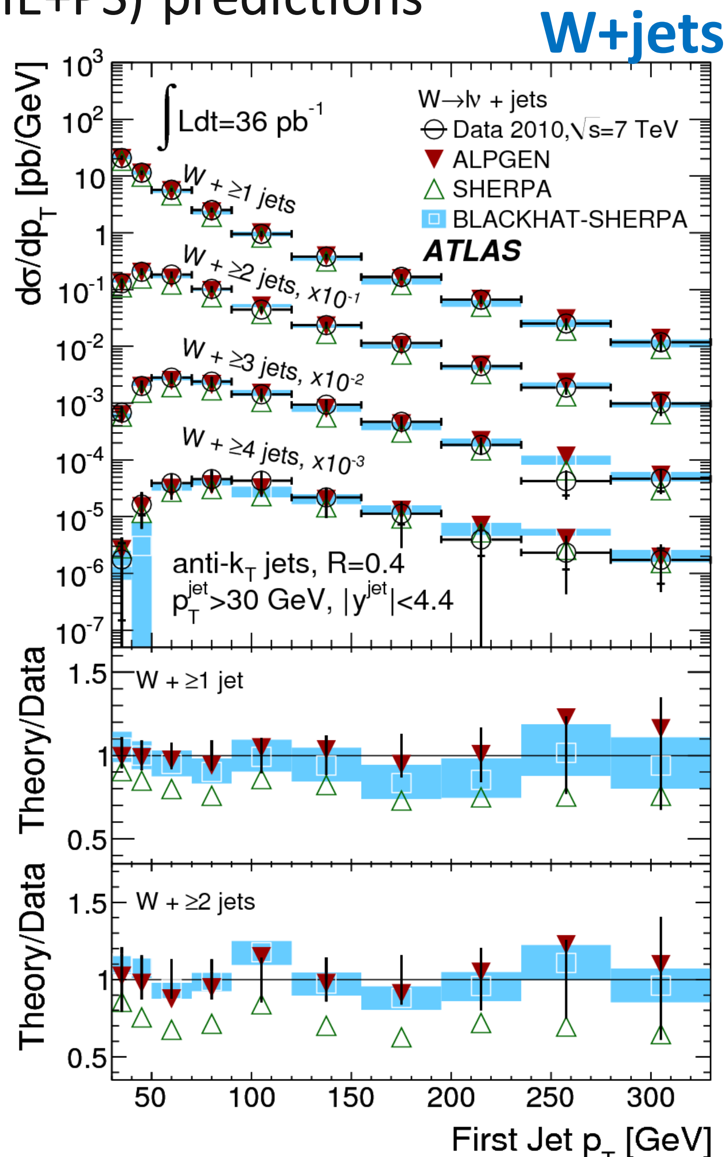


- Cancelation of systematic and theory uncertainties → Robust way to compare data and theory
- Systematically limited for W+jets

Kinematic properties: First Jet p_T

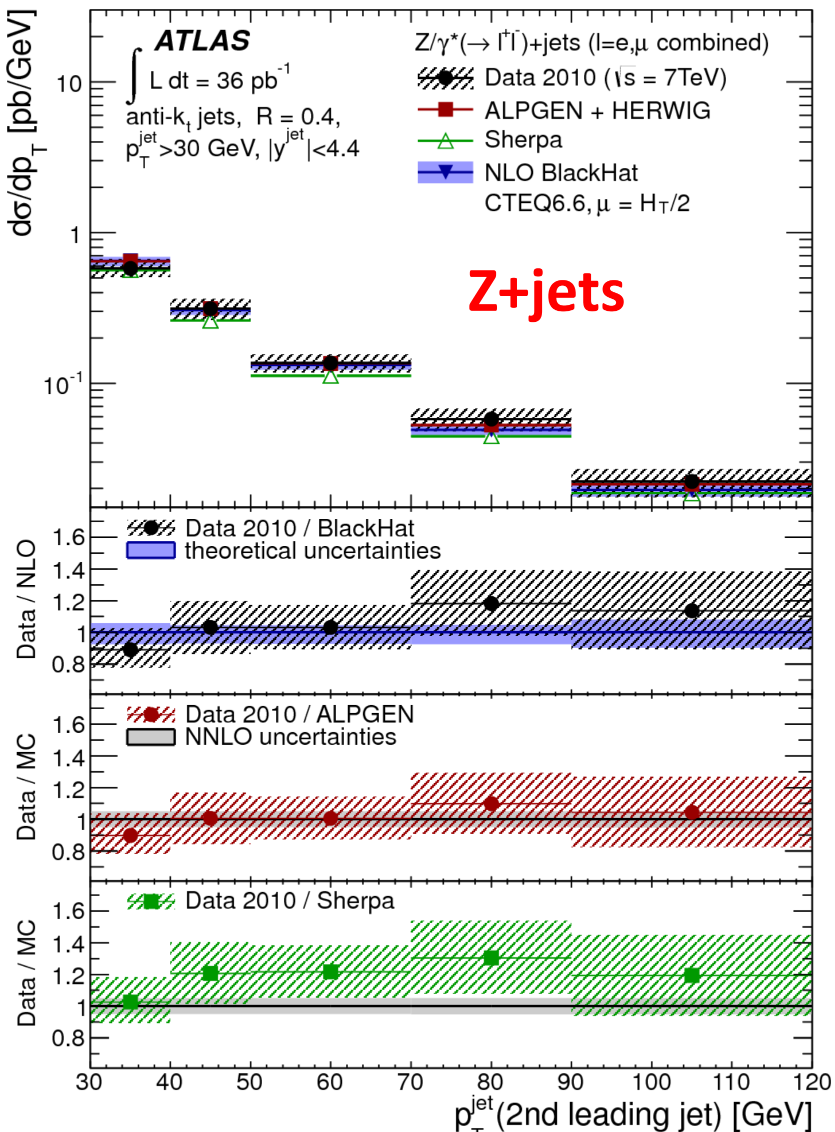
- Well reproduced by NLO and LO (ME+PS) predictions

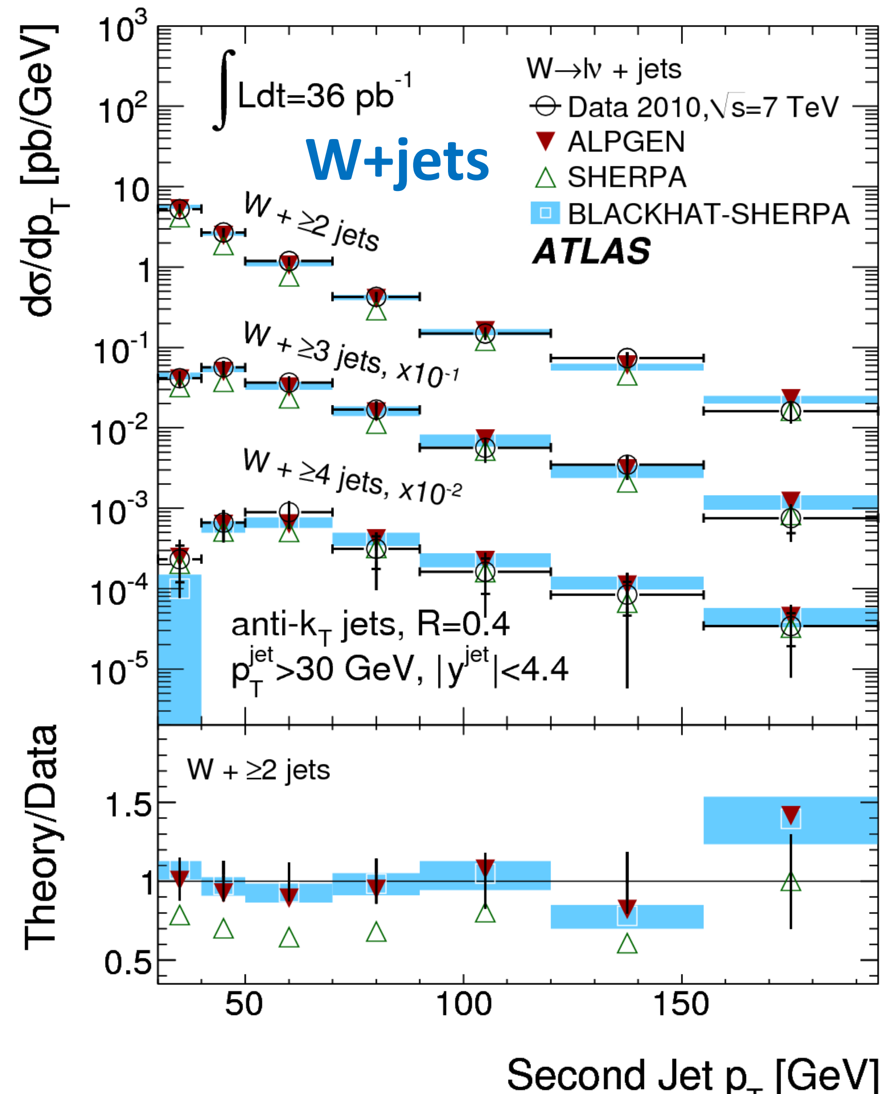




Kinematic properties: Second Jet p_T

- Again, well reproduced by NLO and LO (ME+PS) predictions

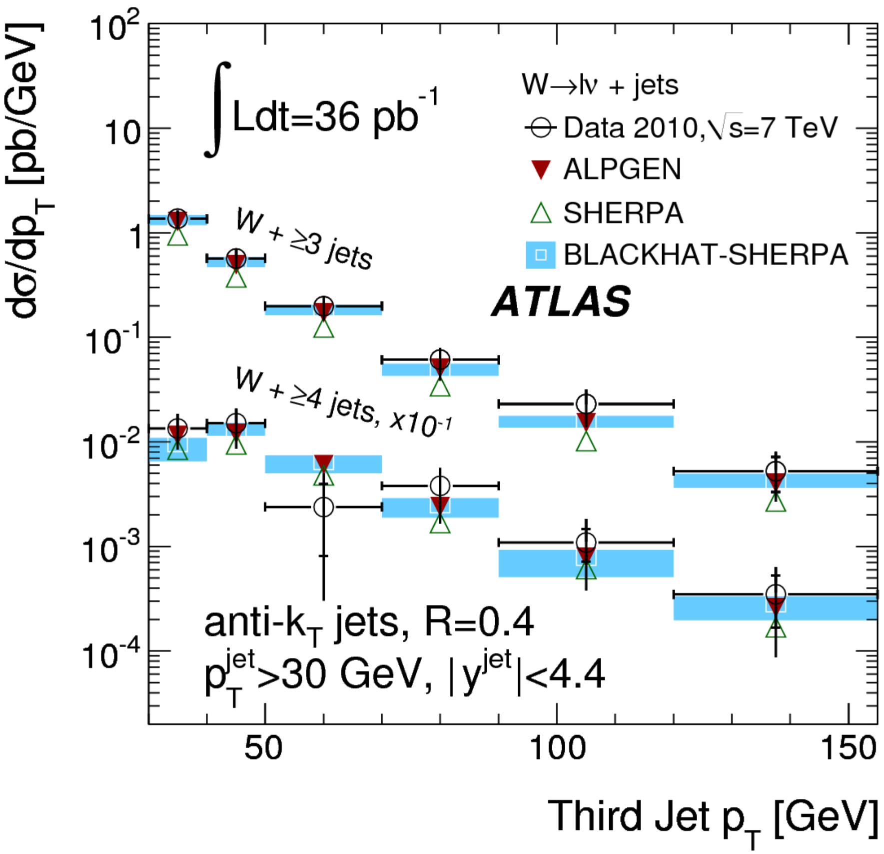




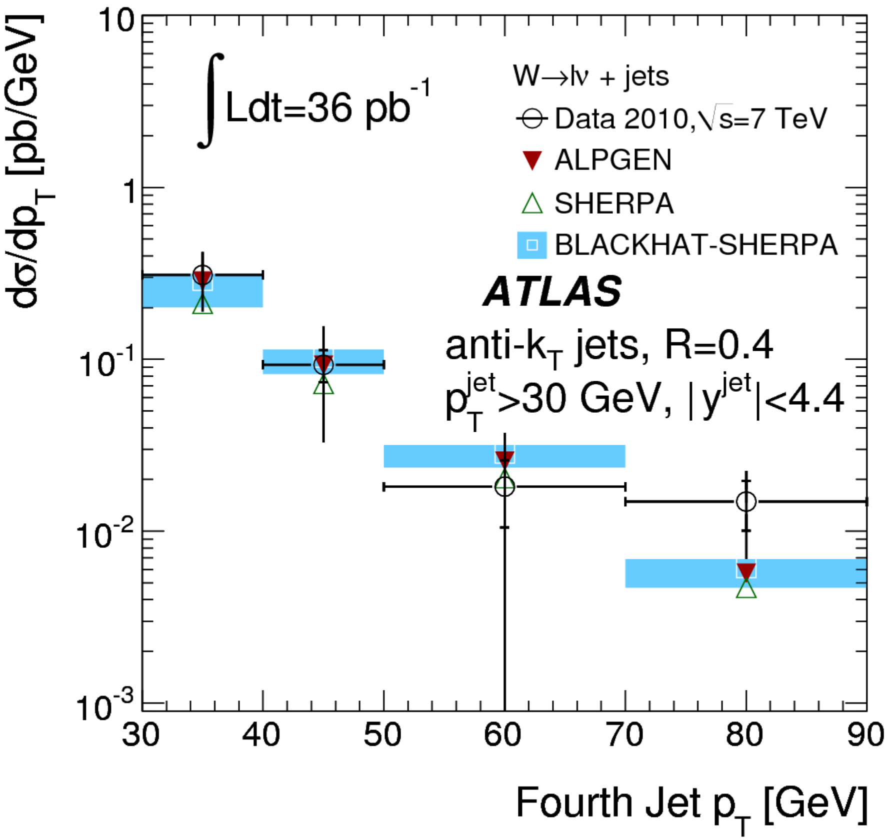
Kinematic properties: Third and Fourth Jet p_T

- Again, well reproduced by NLO and LO (ME+PS) predictions
- Not enough statistics to measure for Z+jets

W+3jets

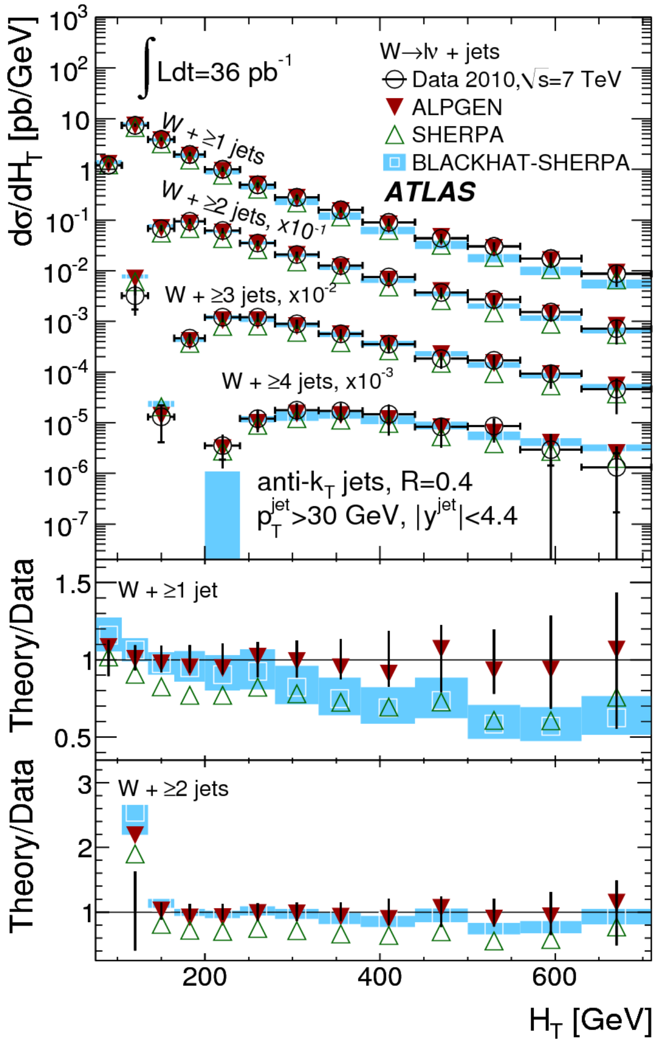


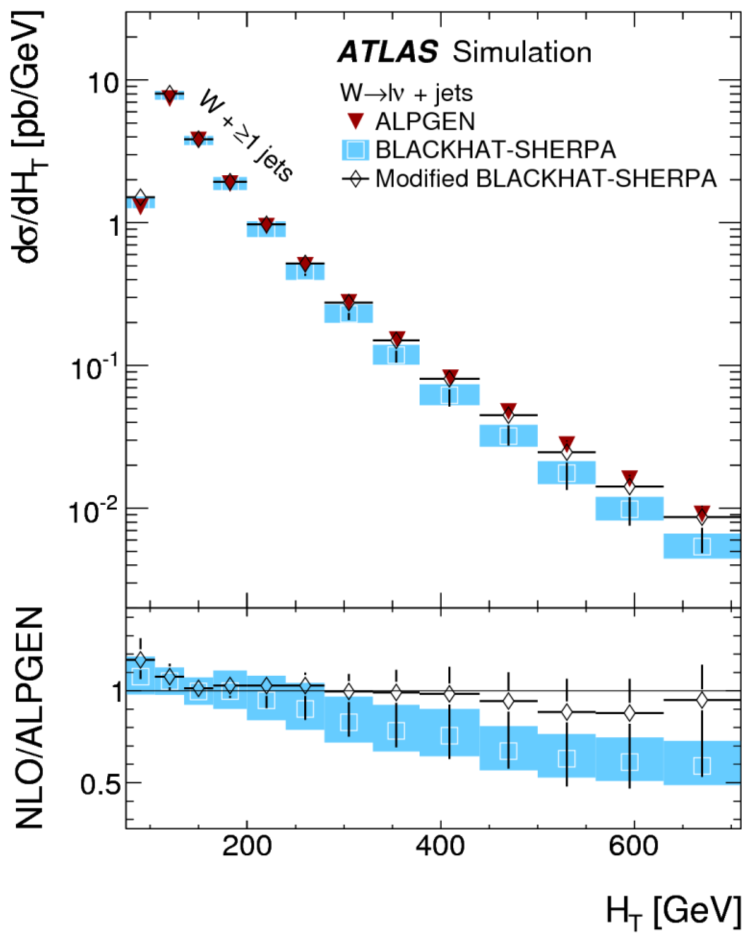
W+4jets



Event observables H_T

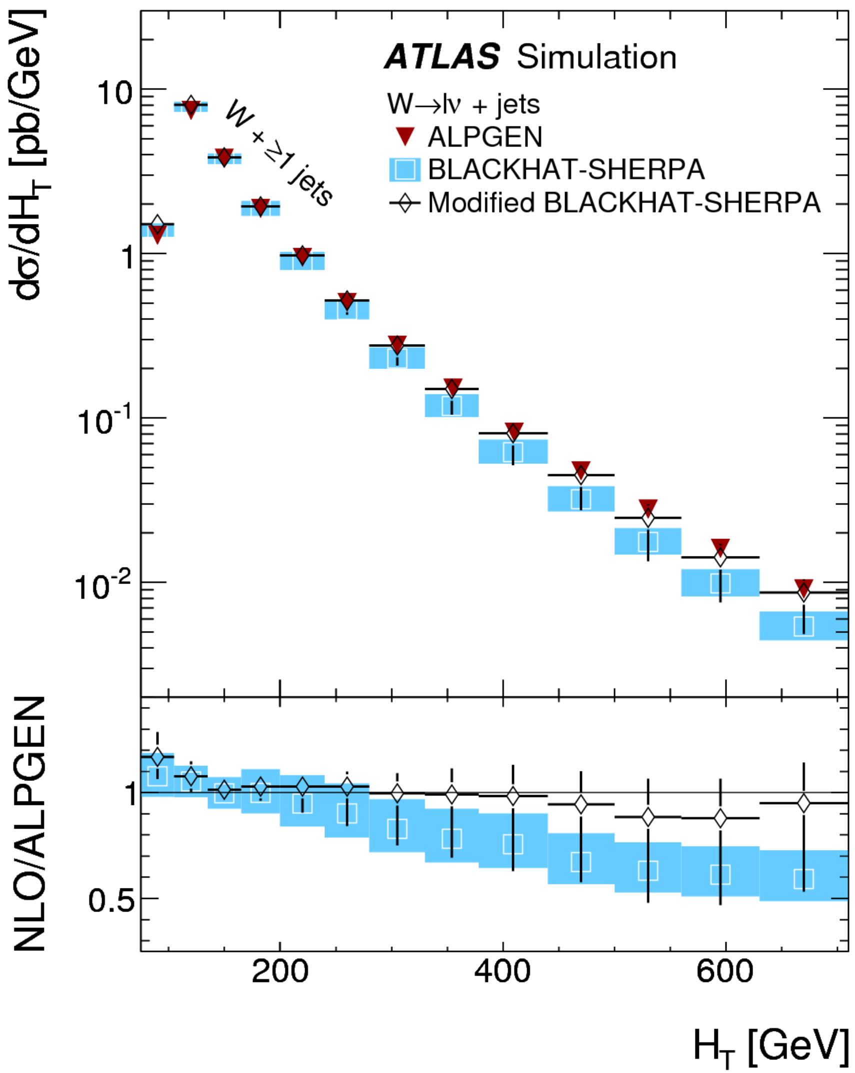
- Searches for BSM heavy particles use H_T (scalar sum of p_T of all reconstructed objects) → the discrepancy is expected for NLO



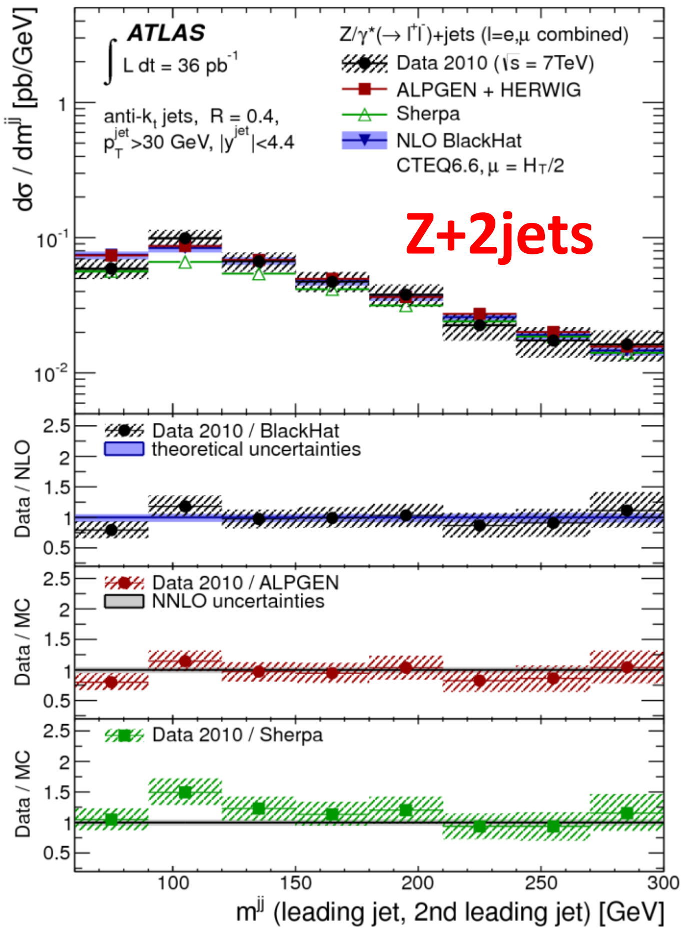


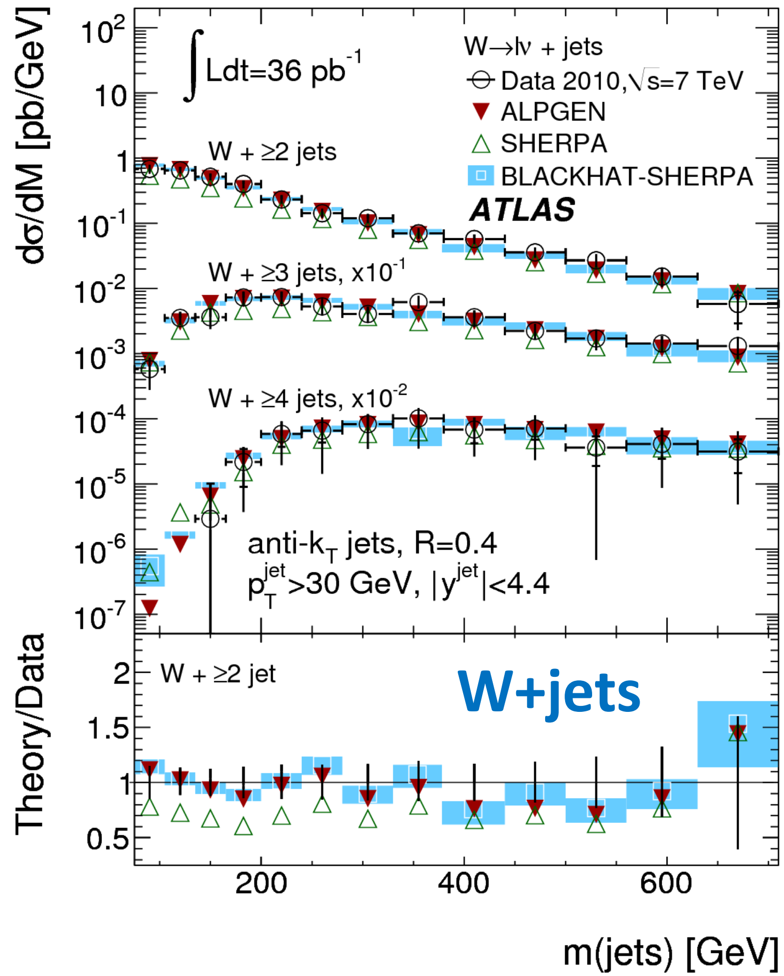
NLO calculation for H_T

- Each NLO sample contains one additional emission beyond the base number of parton emission
- Events with high HT contain multiple jets → The conventional NLO calculations does not access the phase space
- Exclusive (matched) some of NLO calculations describes the high-H_T tail well



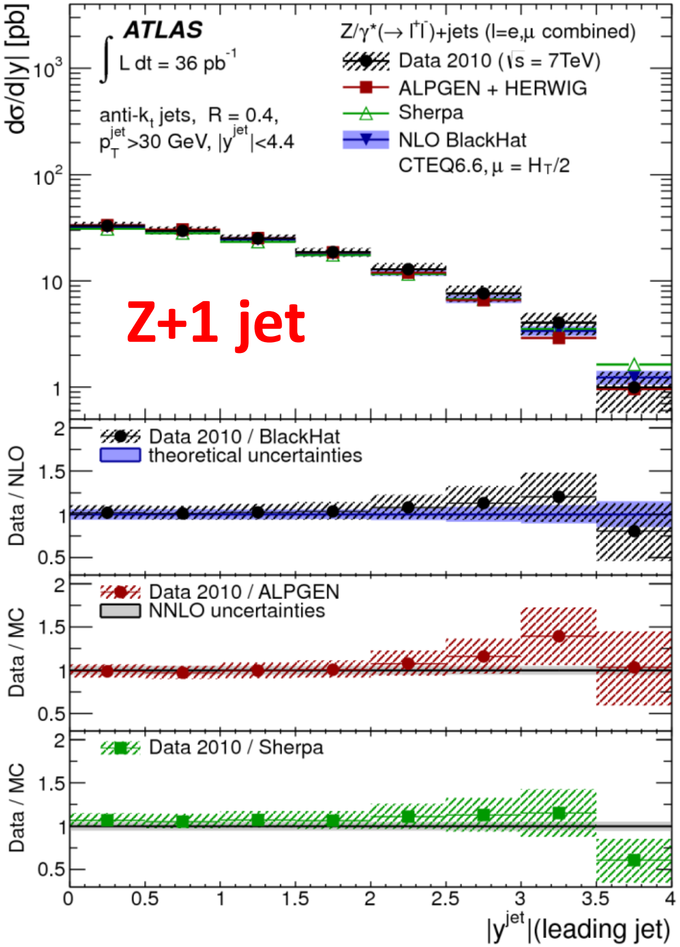
Event observables - m(jets)

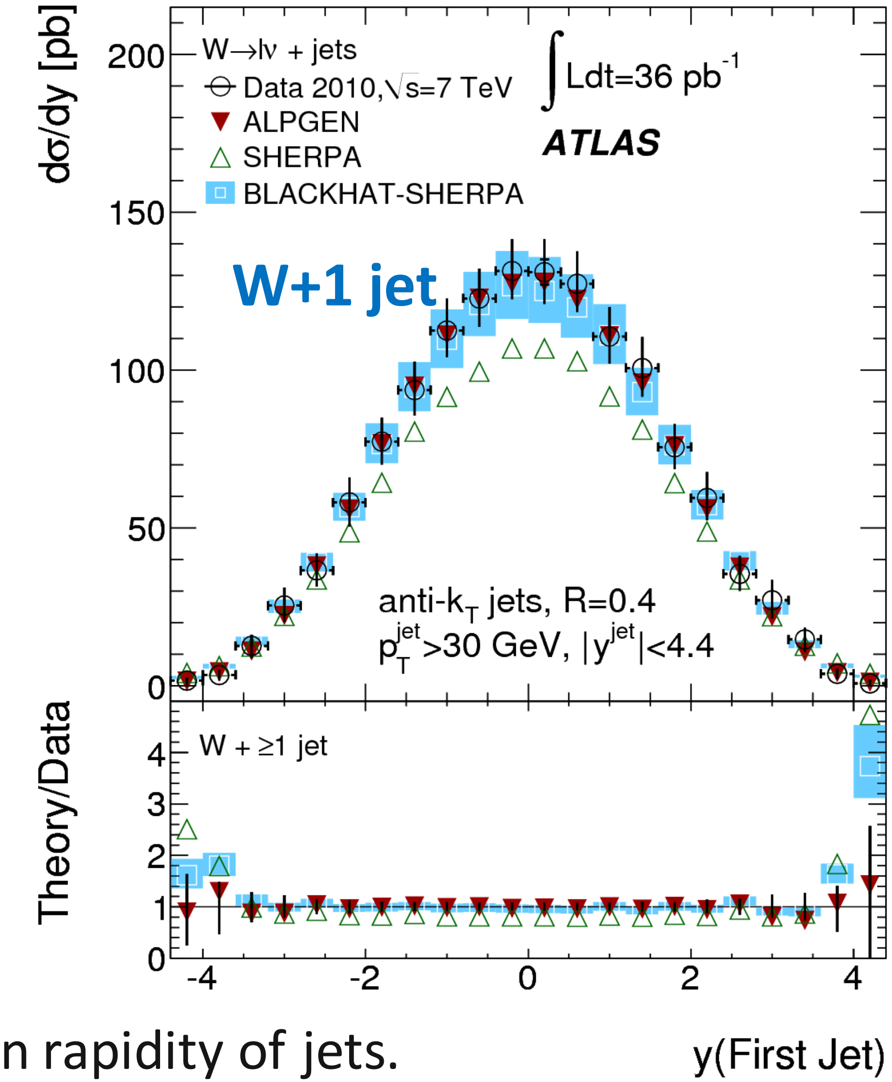




- m(jets) is calculated using exclusive number of jets; H_T -- inclusive
- m(jets) and H_T are often used as a scale in NLO calculations:
  - The choice of scales evolved M(W) → M(W)+p_T(W) → H_T (or M(jets))

Rapidity of the leading jet

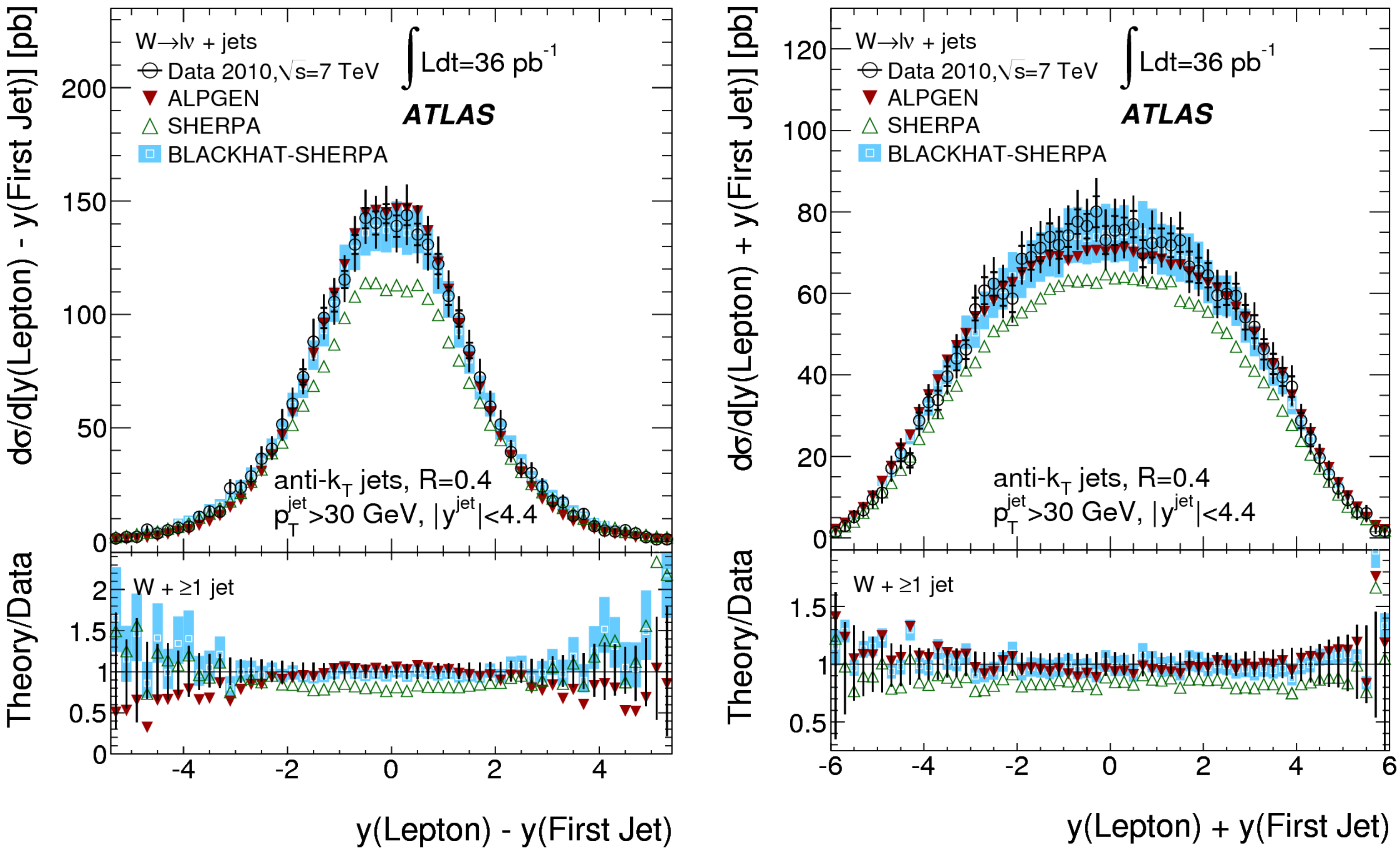




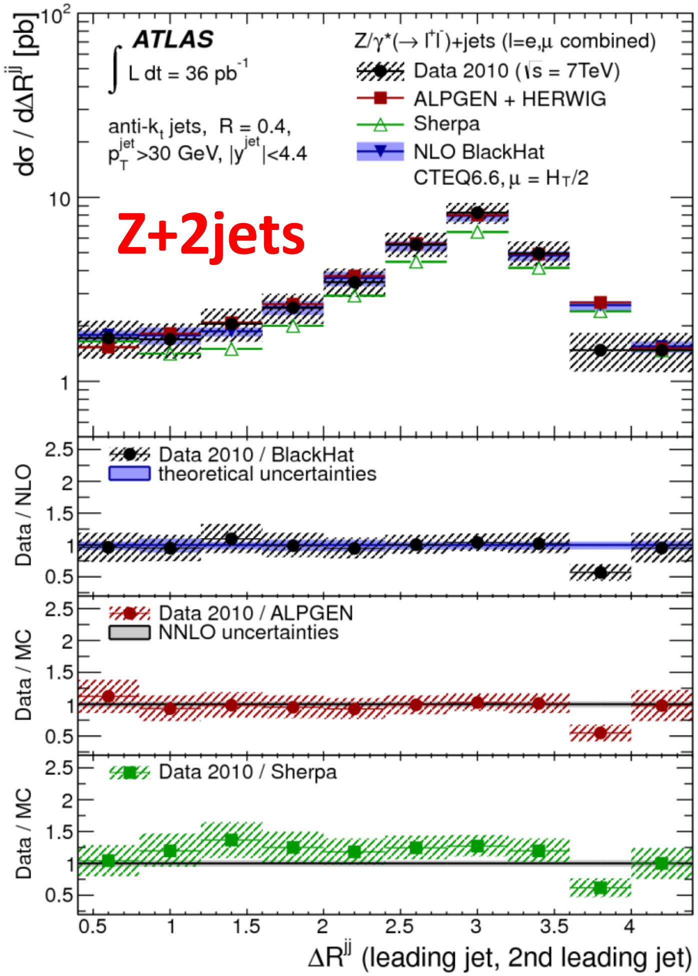
- ATLAS provides superb coverage in rapidity of jets.
- Jet kinematic distributions are key for WW-scattering and VBF
- Small discrepancies for the very forward jets

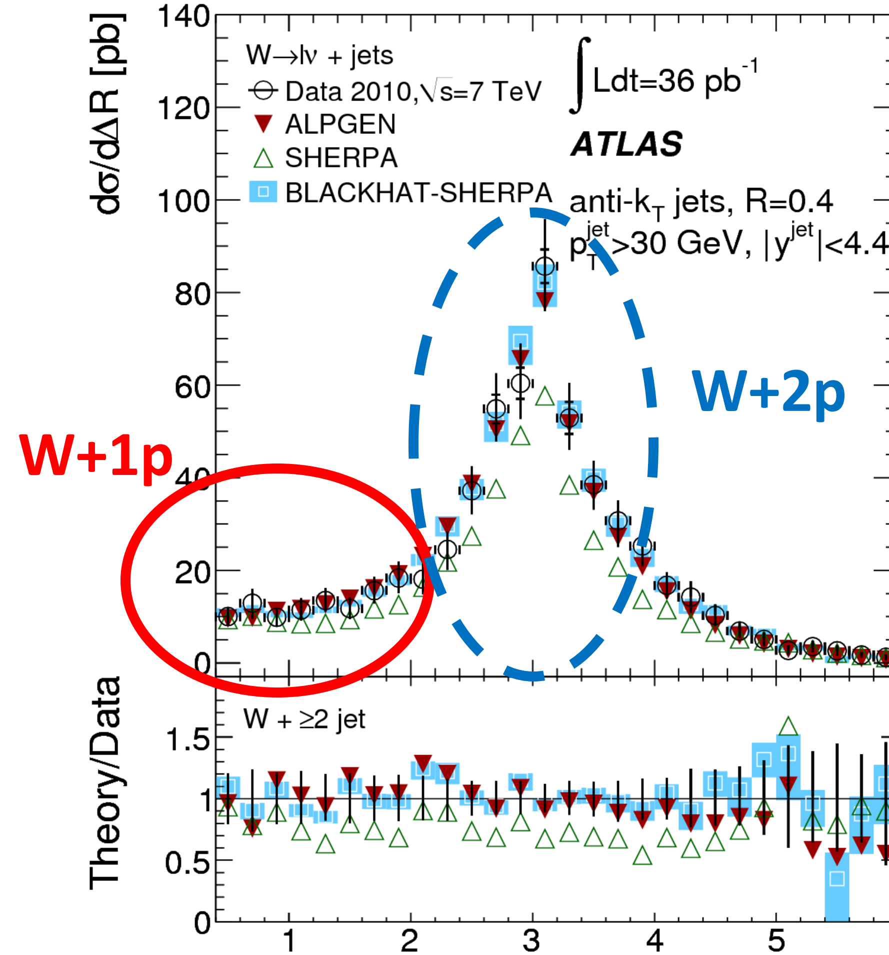
Distributions specific to W+jets events

- Intended for tuning of ME+PS simulations



Di-jet separation

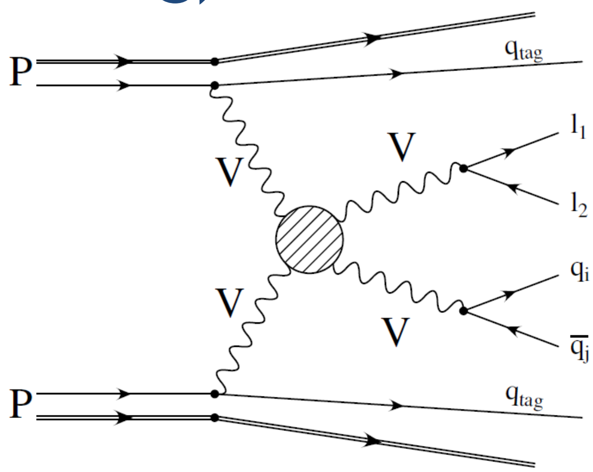


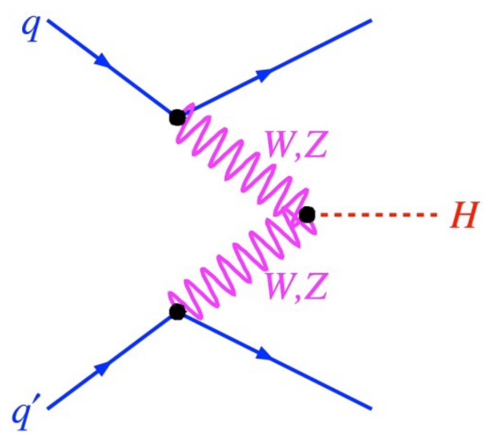


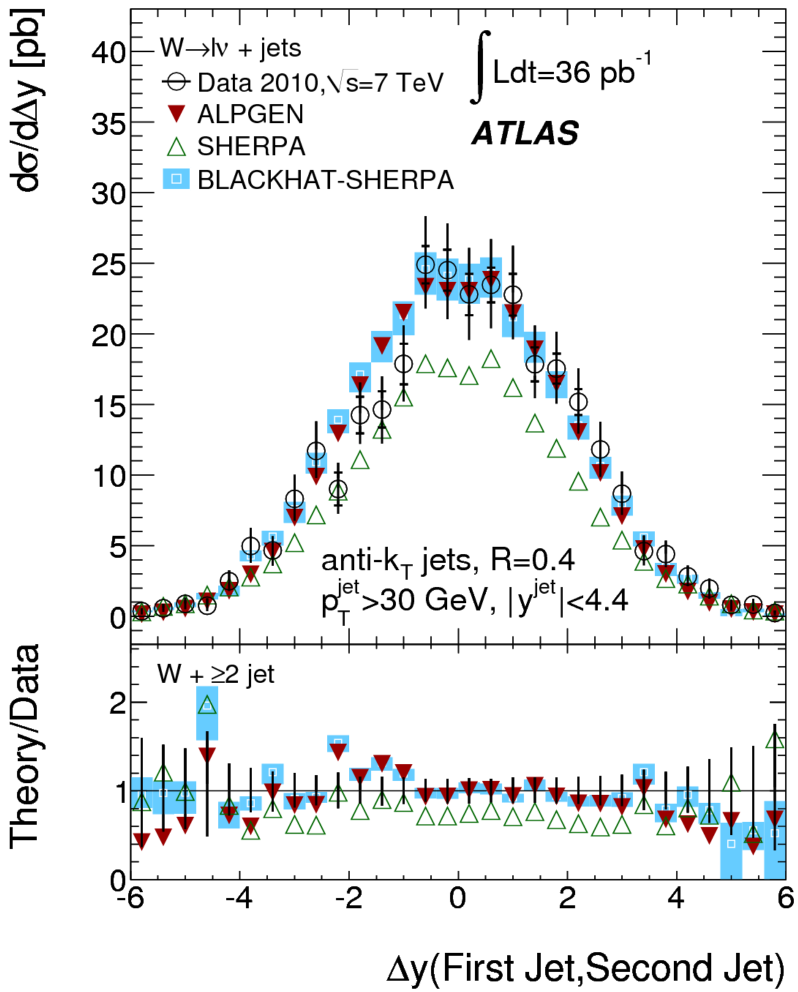
ΔR(First Jet, Second Jet)

- Required for development of ME-PS simulations
  - Pythia alone does not describe the distributions
  - Close-by jets are radiated via parton showering
  - Large-angle radiation is handled by matrix elements

Jet in future measurements (VBF and WW-scattering)







- Future observations of VBF and WW-scattering will rely on our understanding of forward jets and rapidity gaps between jets.
  - W, Z, and H bosons via VBF

Conclusions and Outlook

- Overall, good agreement between NLO and ME+PS predictions and data
- Z+jets and W+jets result complement each other
- Accuracy of the measurement is already systematically limited by uncertainties on the JES
- **State-of-the-art NLO calculations (BlackHat-Sherpa) work well up to V+4 jets!**
  - Note: Previous NLO calculations (e.g. MCFM) could go a maximum of two partons in the final state

- The comprehensive set of measurements to enable and support development of future theory predictions
  - Currently we have up to W+5p and Z+5p → will be up to **V+8p**
  - forward jets and rapidity gaps between jets will be key for the future measurements (WW-scattering, searches for BSM, etc)

References

- “Measurement of the production cross section for *Z/γ** in association with jets in *pp* collisions at $\sqrt{s}$ = 7 TeV with the ATLAS detector”, arXiv:1111.2690
- “Study of jets produced in association with a *W* boson in *pp* collisions at $\sqrt{s}$ = 7 TeV with the ATLAS detector”, arXiv:1201.127

Definition of Efficiencies, ε_i and $\varepsilon_{i,j}$

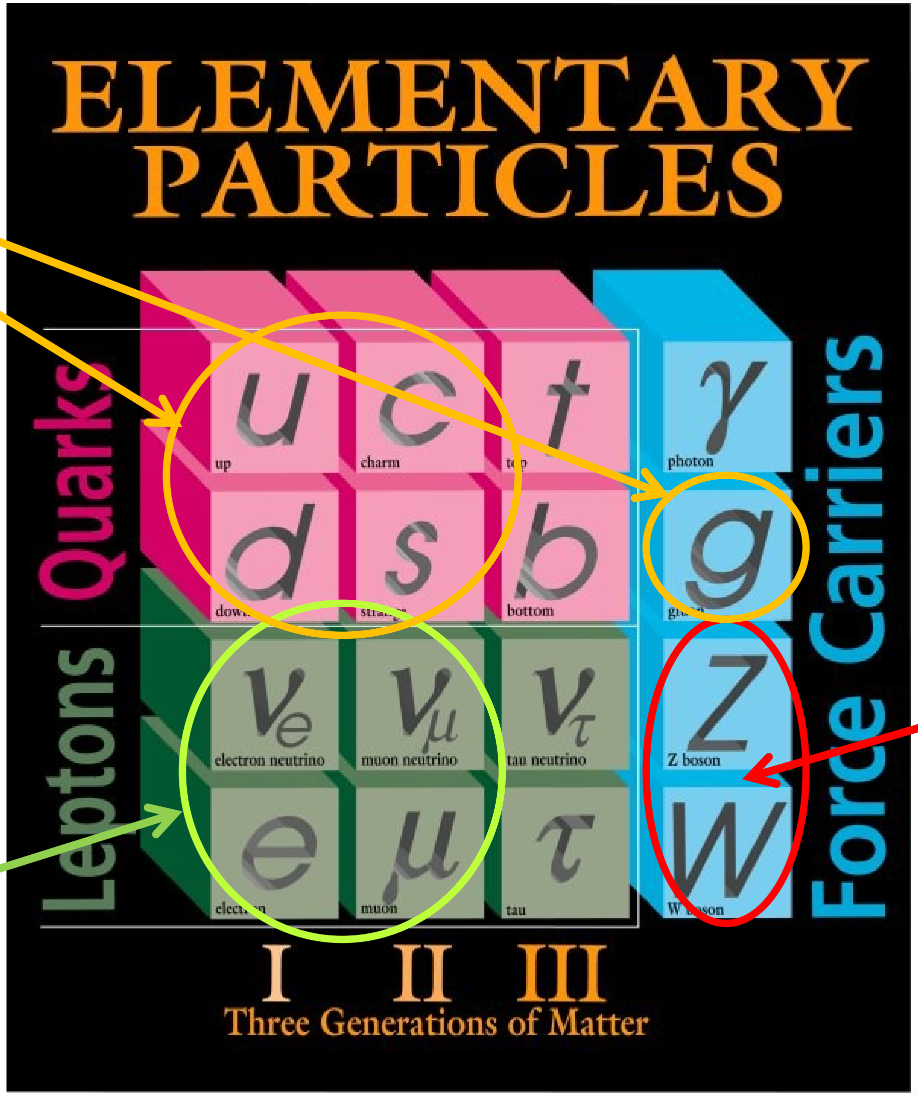
- Defined for each bin

$$\frac{\text{\# of reconsructed events observed after the full event selection}}{\text{\# of generated events in the fiducial phase space}}$$

- Phase space is nearly identical in the numerator and denominator
  - Anti-k_T jets with R=0.4, and p_T^{jet} >20/30 GeV, $|\eta^{jet}|$<4.4, and dR(l,jet)>0.5
  - W's are identified using electrons and muons with p_T>20 GeV
  - Leptons (QED radiation in cone R=0.1 is added to the four-vector of the lepton, http://arxiv.org/pdf/1003.1643)
  - $|\eta^{muon}|<2.4$; $|\eta^{electron}|< 1.37$ or $1.52<|\eta^{electron}|<2.47$
  - M_T(l,mis-E_T)>40 GeV and mis-E_T>25 GeV
- **==> The cross sections are given for the fiducial region of the detector acceptance**

Introduction: proton+proton → V + jets

JETS



Fermilab 95-759

V-bosons

W&Z decay products