W/Z production cross sections in association with jets and their ratio with the ATLAS detector

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Overview

Presenting ATLAS measurements of the production cross sections of W and Z vector bosons in association with jets in various observable distributions:

- Inclusive jet multiplicity — $\sigma(V + \geq N_{jets})$
- Differential coss sections — $d\sigma / dp_T^{jet}$, $d\sigma / d|y^{jet}|$
- Di-jet quantities — ΔR_{jj}, $|\Delta y_{jj}|$, $|\Delta \varphi_{jj}|$, m_{jj}
- Complex quantities — $H_T = \Sigma\ p_T^{(l, \nu,\ jets)}$

All quantities defined inclusively:
less sensitive to modeling of soft component and migration effects

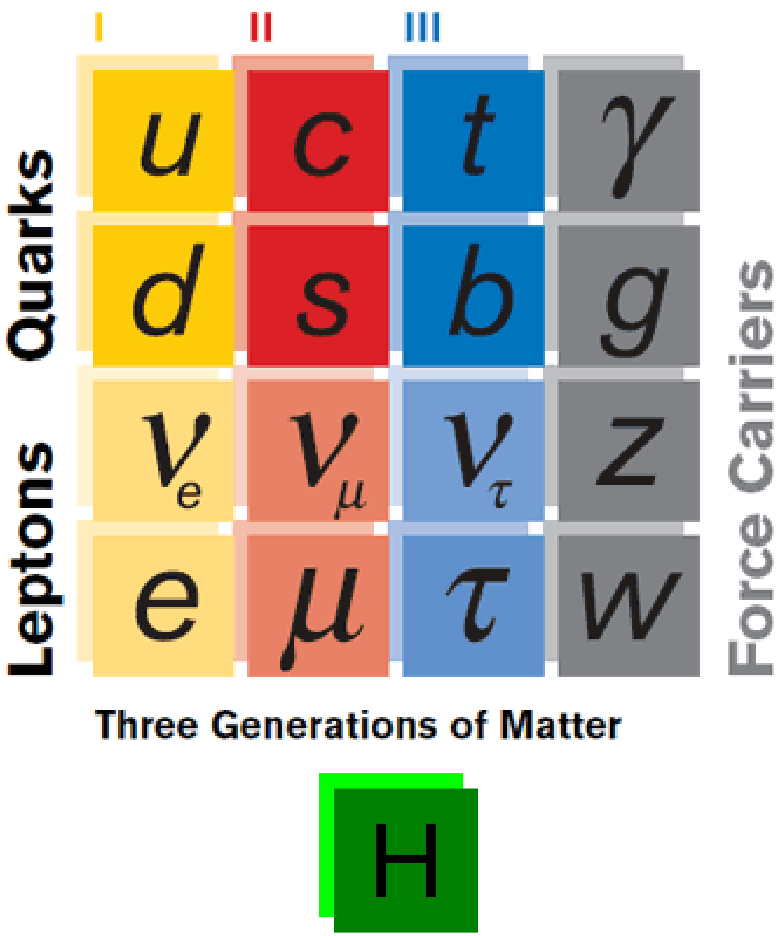
Measure the cross sections

- at particle level
- in the fiducial volume of the detector
- use ratios whenever possible to cancel experimental **and** theoretic uncertainties
  - $(d\sigma/d\xi) / \sigma(V)$
  - $\sigma(V + \geq n+1 \text{ jets}) / \sigma(V + \geq n \text{ jets})$
  - $\sigma(W +1 \text{ jet}) / \sigma(Z + 1 \text{ jet})$

But lets zoom out a little first ...

The Standard Model of Particle Physics

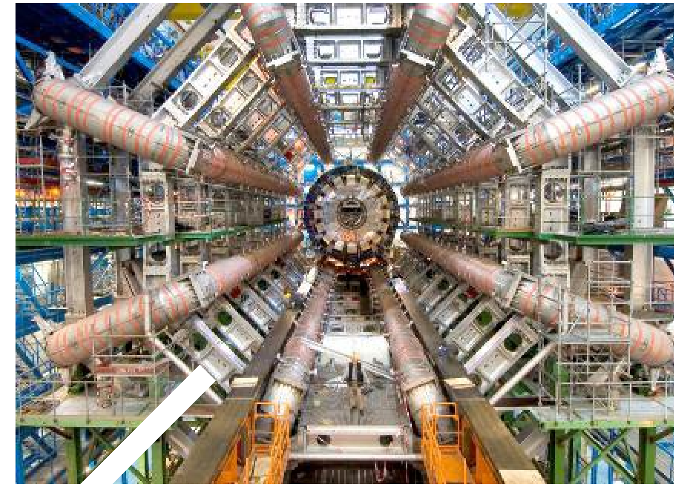
- Modern particle physics is governed by the Standard Model (SM)
- Can be formulated in a Lagrangian
- 6 quarks and 6 leptons organised in 3 families
- Forces mediated by force carriers (bosons)
- Several open questions!
  - Most eminent:
  - **Standard Model needs to be symmetric to work**
  - But observation: SM symmetry is **broken** in nature !
  - Nature of Electroweak Symmetry Breaking?
  - Higgs Mechanism?
- SM Passes extremely precise experimental tests **but many more can (and should) be done !**



+ Higgs Boson?

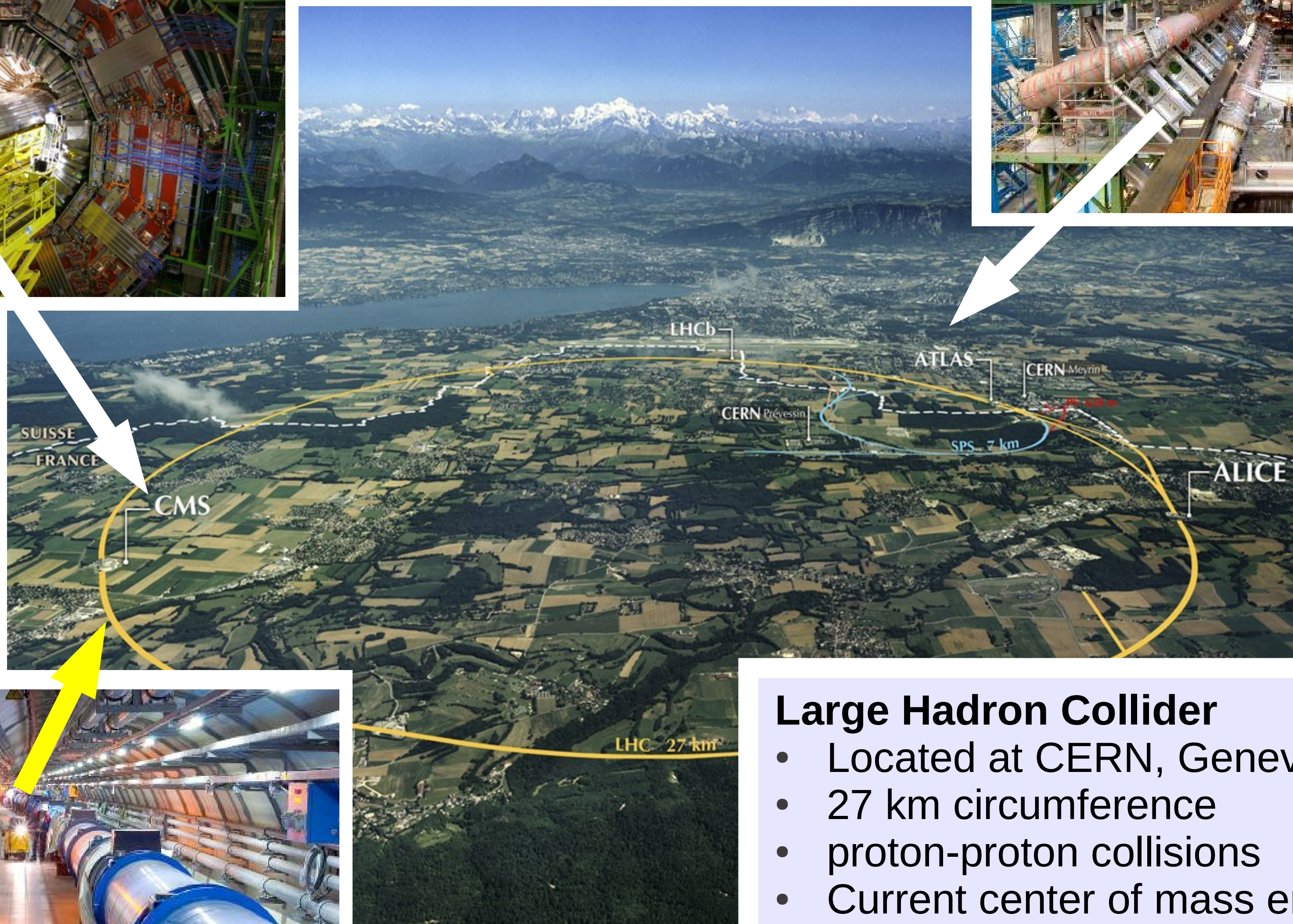
The Large Hadron Collider at CERN

- Goal: discover new physics at the energy frontier
- Hosts two huge general purpose detectors



ATLAS

CMS



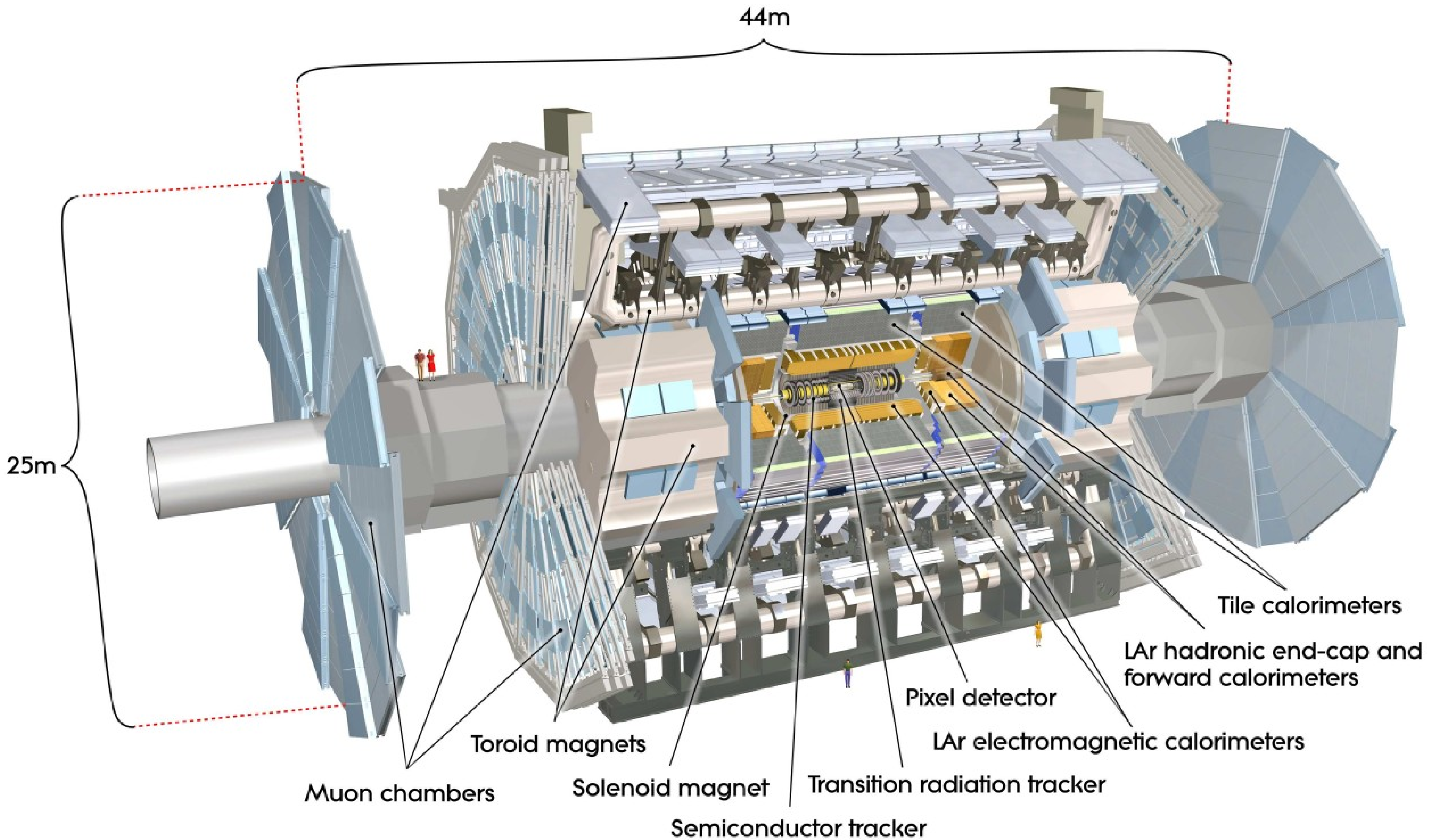
LHC

Large Hadron Collider
- Located at CERN, Geneva
- 27 km circumference
- proton-proton collisions
- Current center of mass energy: 7 TeV
- Design center of mass energy: 14 TeV (planned from 2014)

ATLAS Detector

ATLAS Collaboration
- ~ 3000 Scientists
- 174 Institutes from 38 countries

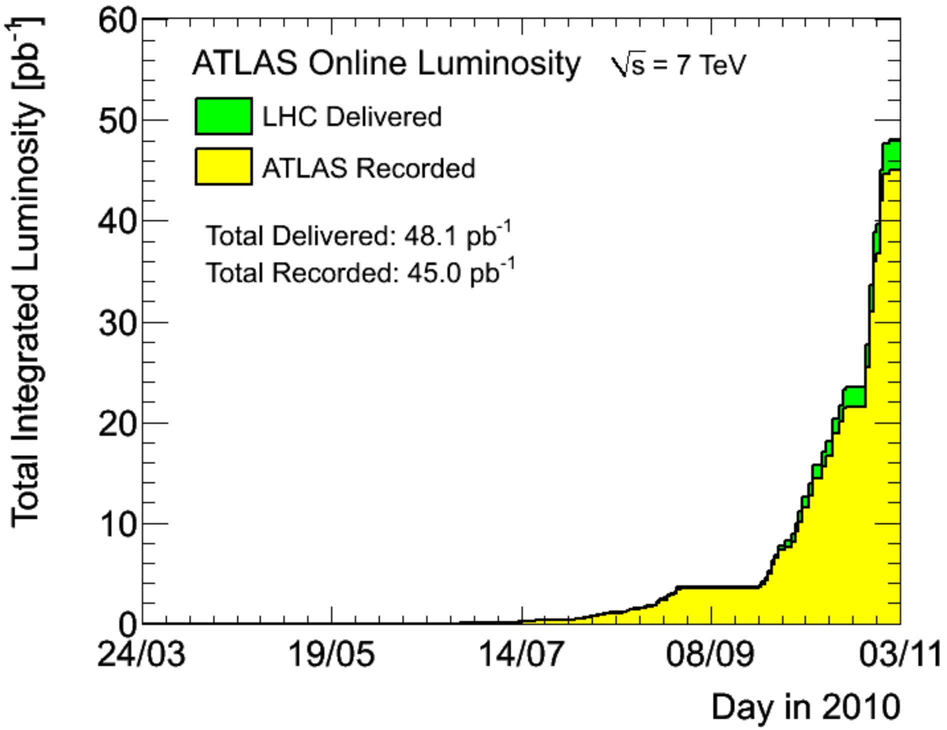
- General purpose detector
- Excellent identification of electrons, muons, jets, missing energy, ...
  - Need essentially all subdetectors for V+jets measurements
- Slightly different acceptance for electrons and muons

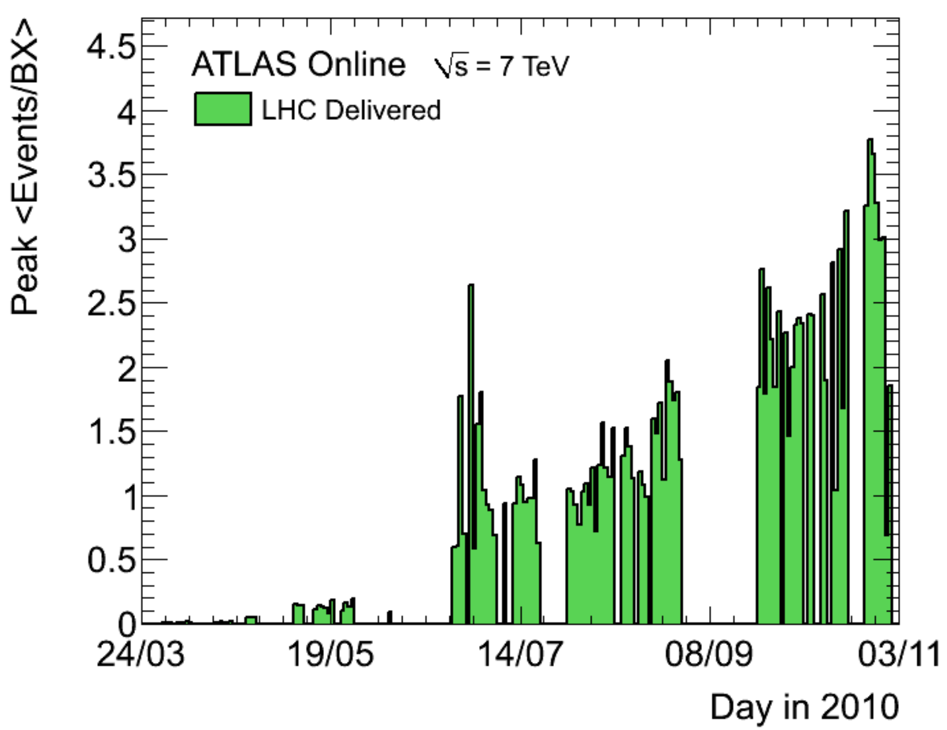


LHC Data

- Presented results use 2010 data
- ATLAS recorded int. lumi: 33 – 36 pb^{-1}
- Well understood electron, muon and jet performance
- Relatively low collision / pile-up rates
- Up to avg. of 3 interactions per bunch crossing

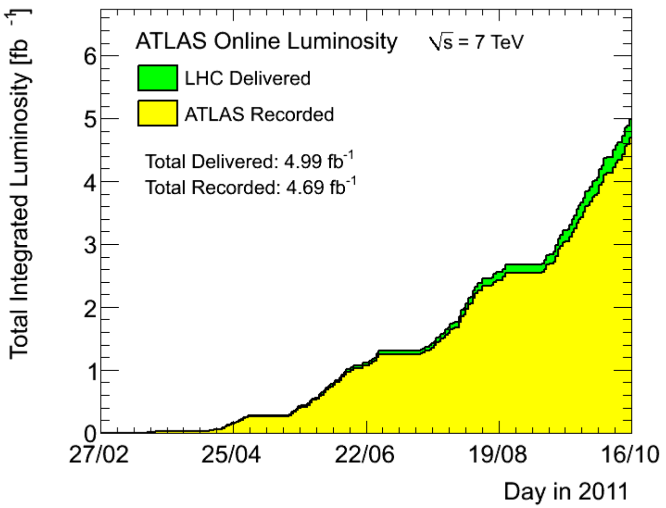
- Allow cross section measurement at low jet transverse momentum
- Statistics for higher jet multiplicities / large recoil low

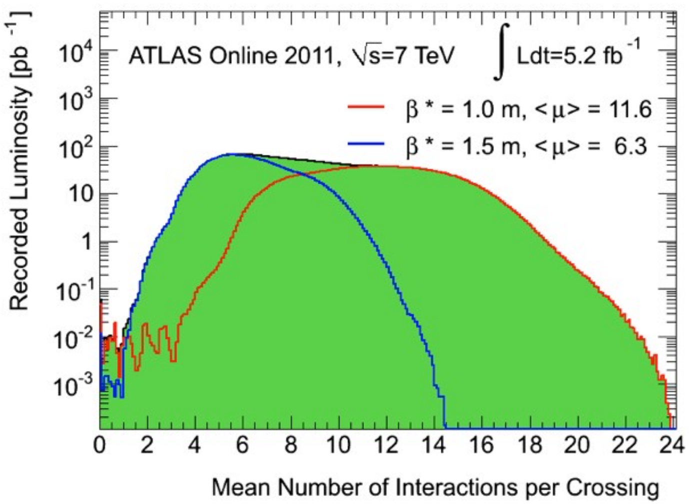




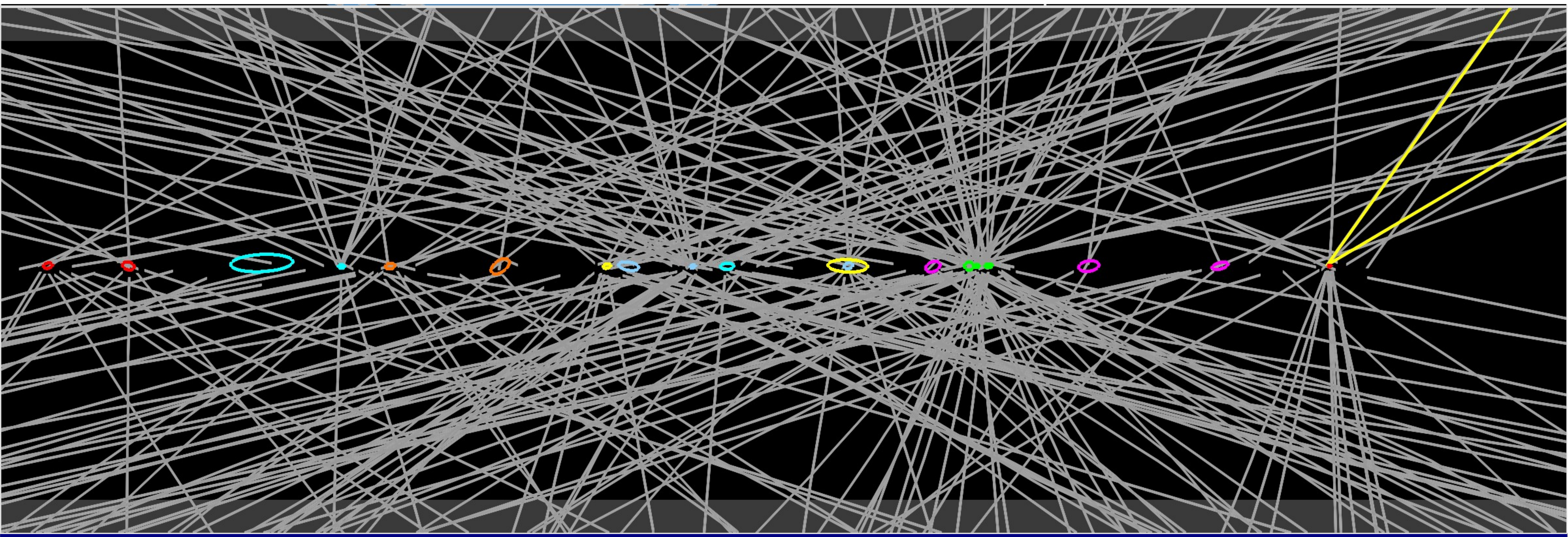
Outlook: LHC Data from 2011

- Next round of analyses will use 2011 data
- Int. lumi:
  - 5.2 fb^{-1} (LHC Delivered)
  - 4.69 fb^{-1} (ATLAS)
- Already events with more than 20 interactions per bunch crossing in data
- Challenging precision analyses in progress...





Example event: Z → ee with 20 pile-up interactions



Cross Sections at LHC and Tevatron

- Presenting measurements at 7 TeV center-of-mass energy in pp collisions

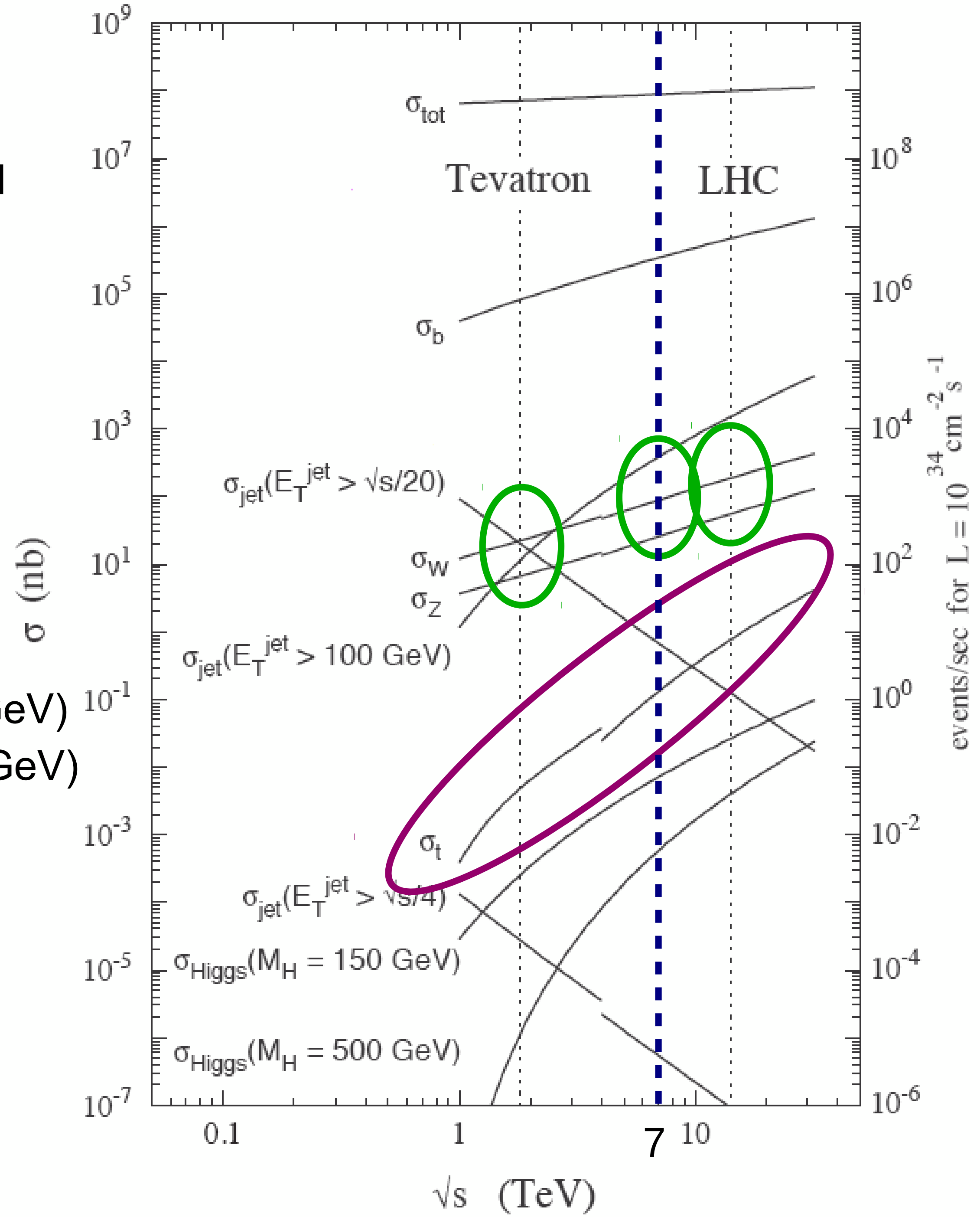
- Different interest and features compared to Tevatron measurements and future 14 TeV measurements:

Dominant (LO) Production mechanisms

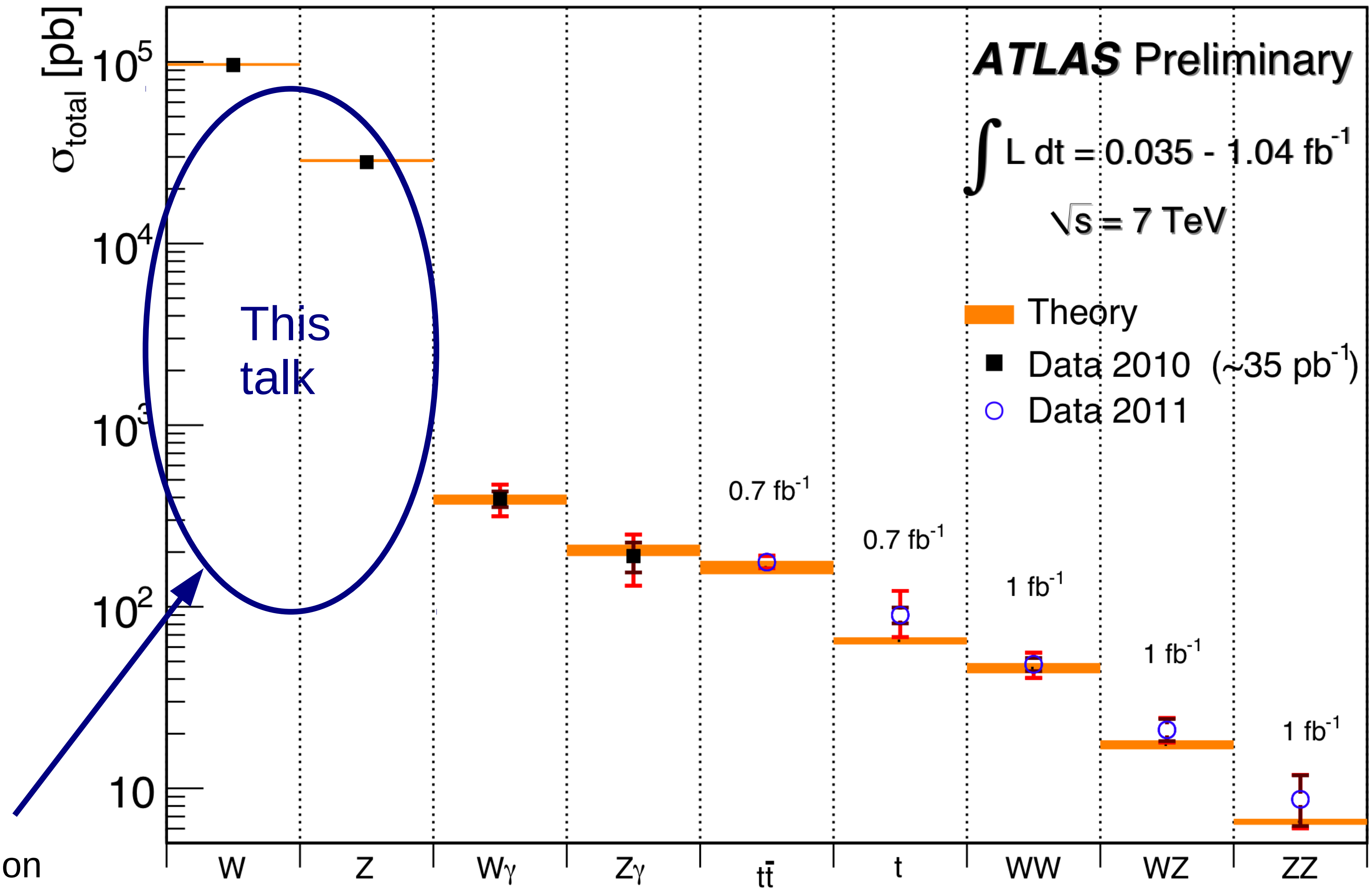
LHC: QCD Compton process
Tevatron: Quark annihilation

- At LHC expected per $1pb^{-1}$ ($\sqrt{s}$ = 7 TeV)
  - 10^4 W ($\rightarrow l\nu$), 10^3 W+1jet (jet-p_T> 30 GeV)
  - 10^3 Z ($\rightarrow ll$), 10^2 Z/γ*+1jet (jet-p_T> 30 GeV)

- Cross sections LHC ↔ Tevatron:
  - **W ($\rightarrow l\nu$), Z/γ* ($\rightarrow ll$): cross section 4 x larger at LHC, factor 2 per jet**
  - **Top background: 100 x larger cross section at LHC**



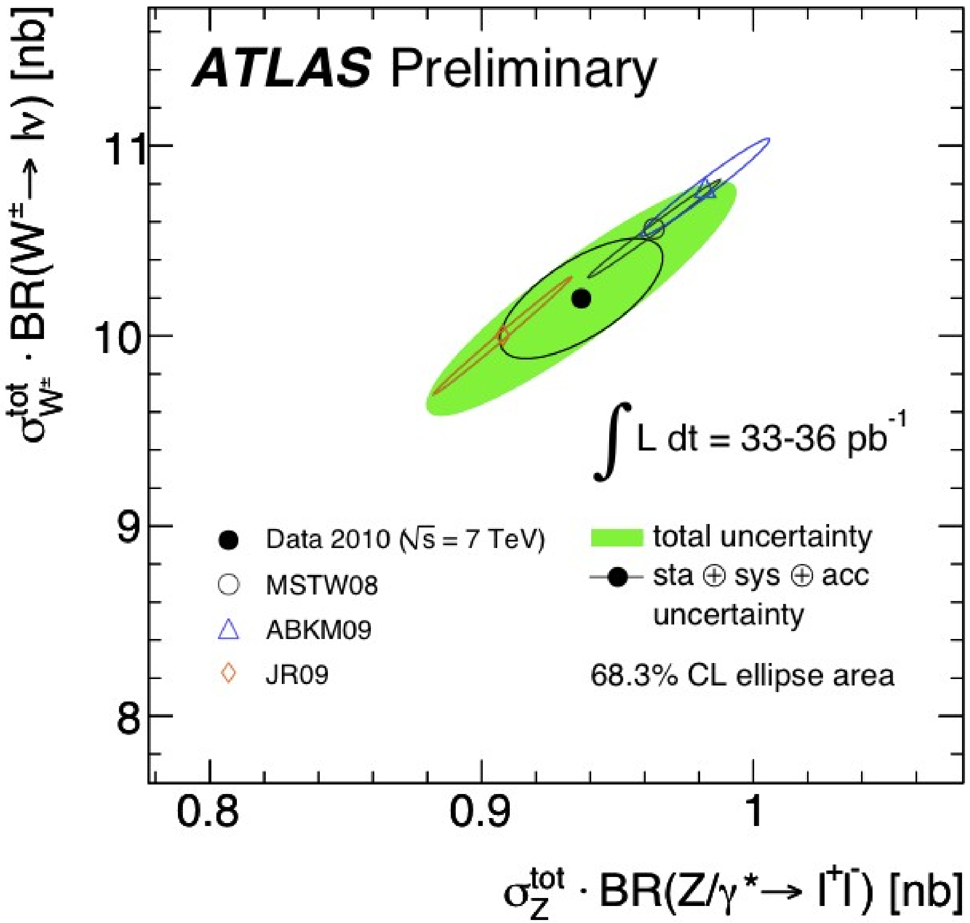
Electroweak Measurements in ATLAS

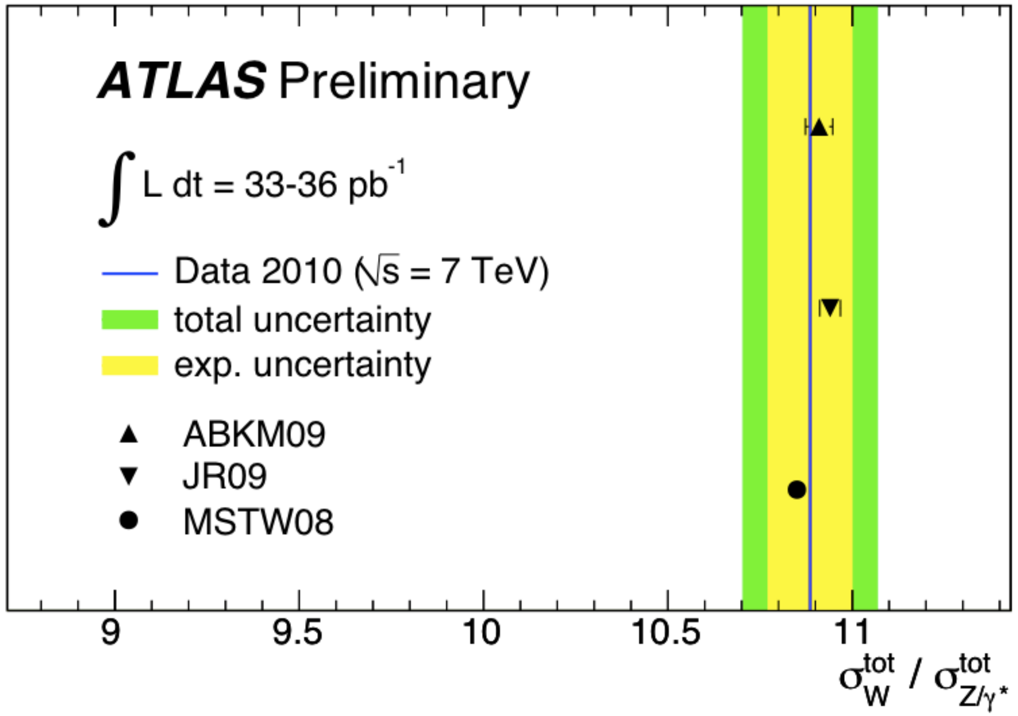


Region of V+jets cross sections ~5 times lower per jet

Concentrate on dibosons and new constraints on couplings

Inclusive W/Z Ratio Measurements





- Recent ATLAS W/Z results already take advantage of correlations between cross section measurements
- Mostly from common PDF ratios
- Provide some constraints on PDFs, but weak compared to W charge asymmetry results (not shown), and only "low"-Q^2

Presented ATLAS Publications

W + jets

- *"Measurement of the production cross section for W-bosons in association with jets in pp collisions using 33 pb-1 at sqrt(s) = 7 TeV with the ATLAS detector",*
  ATLAS-CONF-2011-060 (33 pb^{-1})
  (paper in preparation)

- *"Measurement of the production cross section for W bosons in association with jets in pp collisions at s√ = 7 TeV with the ATLAS detector",*
  Phys.Lett.B698:325-345,2011 (1.3 pb^{-1})

Z/γ + jets

- *"Measurement of the production cross section for Z/γ∗ in association with jets in pp collisions at √s = 7 TeV with the ATLAS detector",*
  Submitted to Phys.Rev.D, arXiv:1111.2690 (35 pb^{-1})

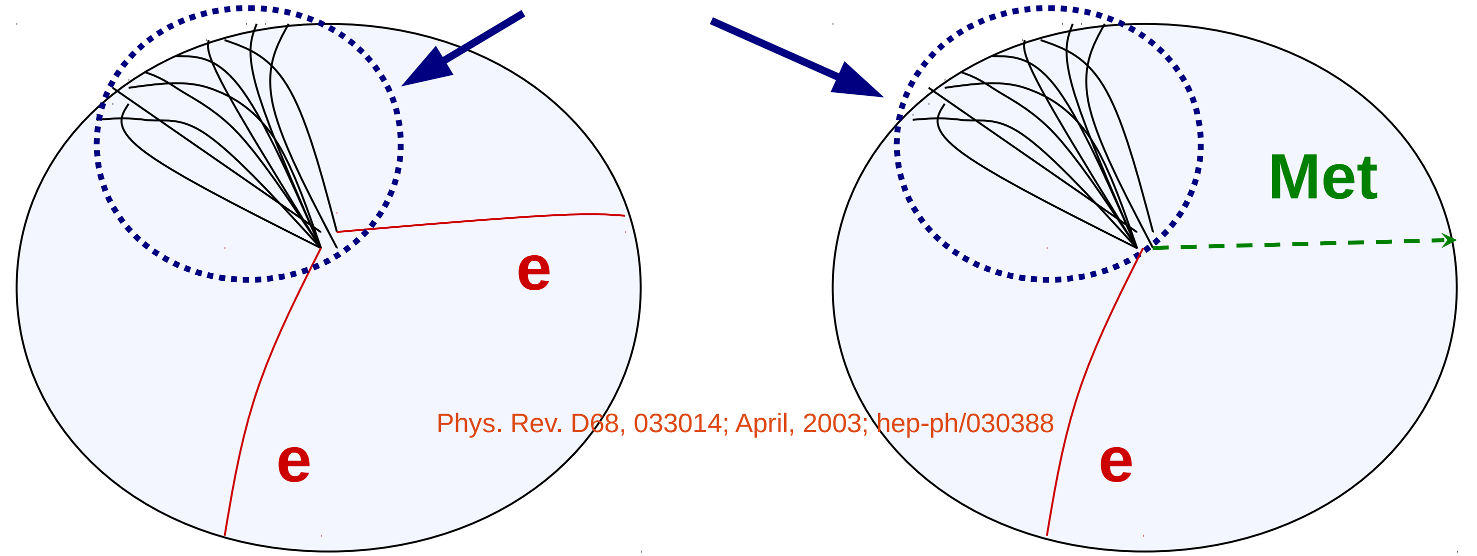
R_{jets} = σ(W + 1-jet) / σ(Z + 1-jet)

- *"A measurement of the ratio of the W and Z cross sections with exactly one associated jet in pp collisions at (√s) = 7 TeV with ATLAS",*
  Submitted to Phys. Lett. B, arXiv:1108.4908 (35 pb^{-1})

nb: Ratio measurement prinicple proposed already at Tevatron:
*E. Abouzaid, H. Frisch, Phys. Rev. D **68**, 033014 (2003) hep-ph/030388*

A look at Z+jets and W+jets Topology

Similar hadronic final state (jets)
Residual difference due to differences in available phase space (leptons, m_V)



$Z \rightarrow ee$ + 1-jet

$W \rightarrow e\nu$ + 1-jet

Some experimental systematic uncertainties / features that ...

… cancel:

- Luminosity
- Lepton identification (1st lepton)
- HFS (see above)

… do not cancel:

- Z: Lepton identification for second lepton
- W: MET uncertainty, backgrounds

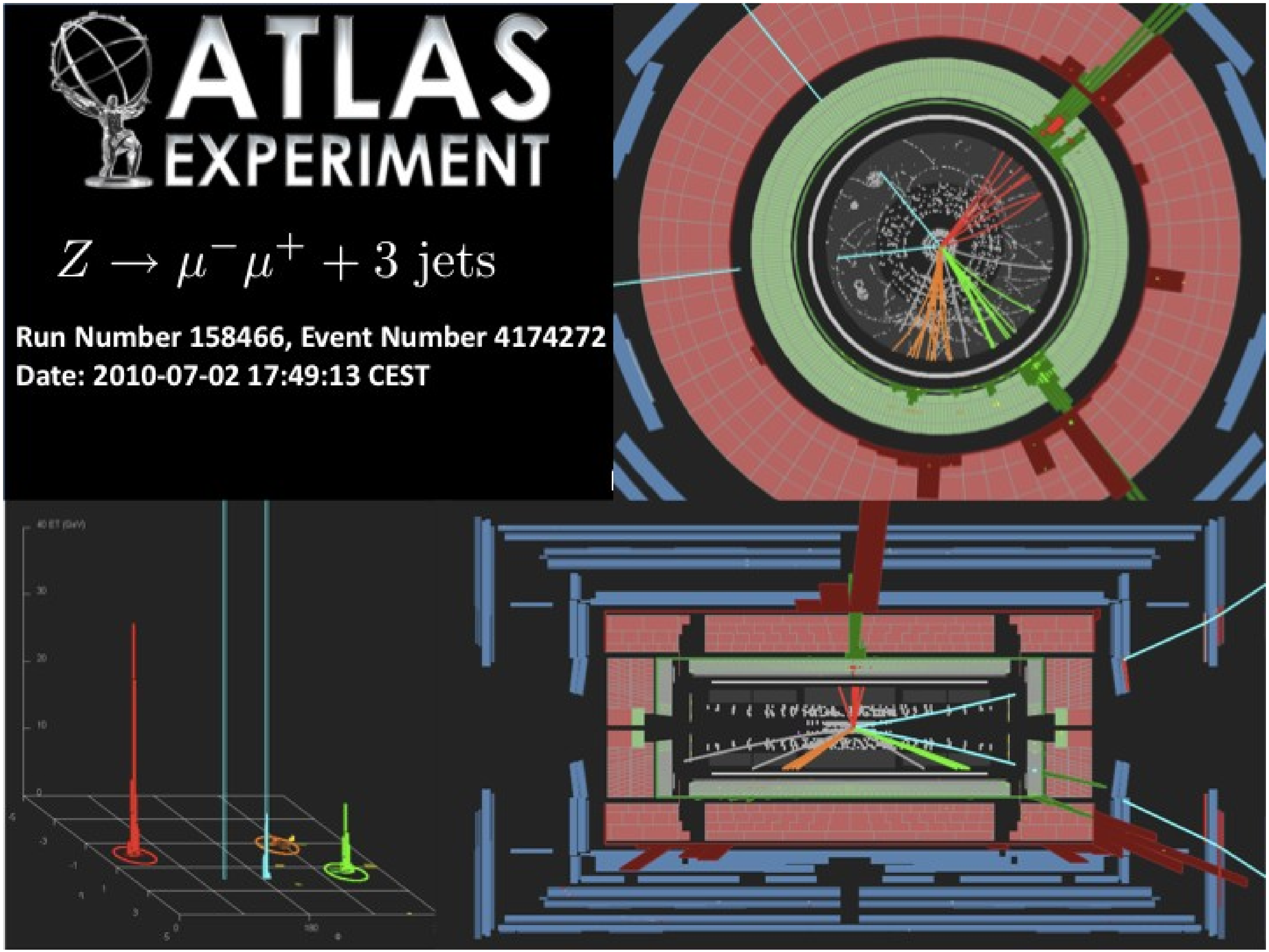
Example Event Display

$Z/\gamma^*(\rightarrow \mu\mu)$+3 jets Candidate

P_T^Z = 144 GeV, $m_{\mu\mu}$ = 79 GeV

3 jets

2 FSR photons



2 muons

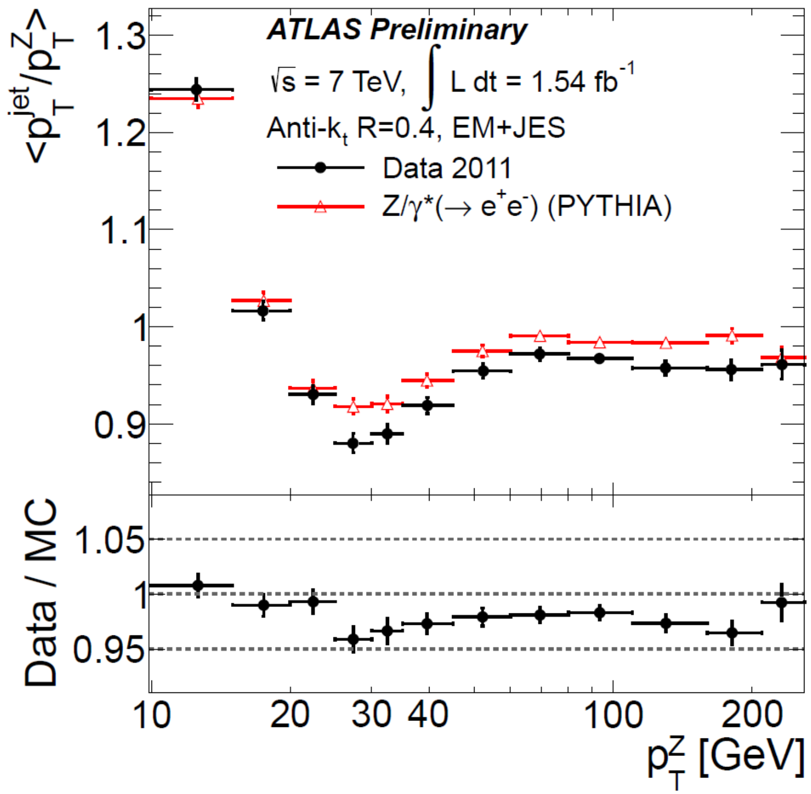
Motivation for SM Measurements

Test higher order calculations and perturbative QCD

- Can use electroweak process to “tag” events (W/Z decay has clear signature)
  - Vector boson decay products + jet p_T provide high, well-defined scale
    - $H^N_T = P_t^l + \text{MET} + \Sigma p_T^{jet}$
      used in MCFM and BLACKHAT-SHERPA
  - Precise stable NNLO calculations possible
  - Probe different scattering amplitudes than multijet production (mainly gluon jets rather than quark jets)

Solve experimental challenges in SM environment

- Provide lepton samples
  - In presence of jets (→ eg. study isolation)
  - in extreme regions of phase space at high recoil
  - (T&P, train identification)
- Tune simulation of V+jets samples
- Jet calibration: **ATLAS-CONF-2011-159** (2 Dec 2011)
- Inclusive samples for di-boson production,
  searches → ...



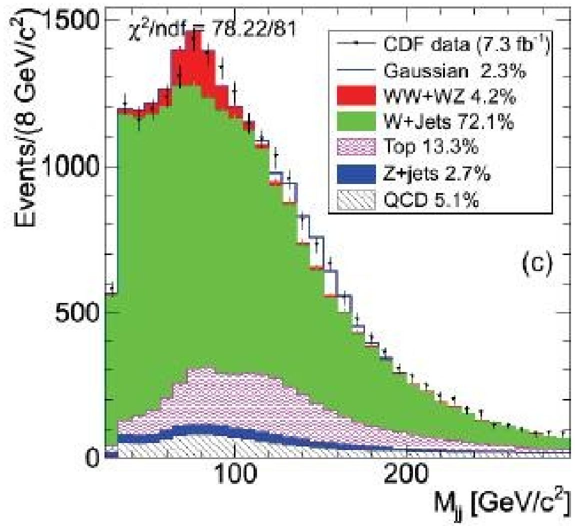
Interest for Searches ...

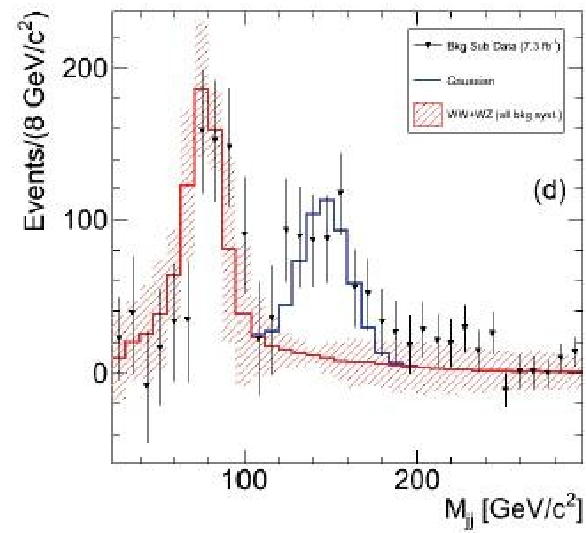
- Many extensions of the Standard Model predict particles with electroweak couplings
  - General: SUSY, W', Z', technicolor, Higgs, leptoquarks, …
- Decays into electroweak gauge bosons (W^+, W^-, Z^0, γ) likely
  - In particular if strong quantum numbers are conserved
  - Jets always possible from ISR and in cascade decays of heavy new particles
- V+jets presents irreducible background for such processes!
- Successful discoveries in the past: **top quark** in W+3/4 jets channel at TeVatron (1994)
- Of partiuclar interest
  - W + 2 jet $H \rightarrow bb$, single top production (tb)
  - W + 6 jet   tt associated production: ttH, ttW, ttZ

Search example: Di-jet mass in W+jets

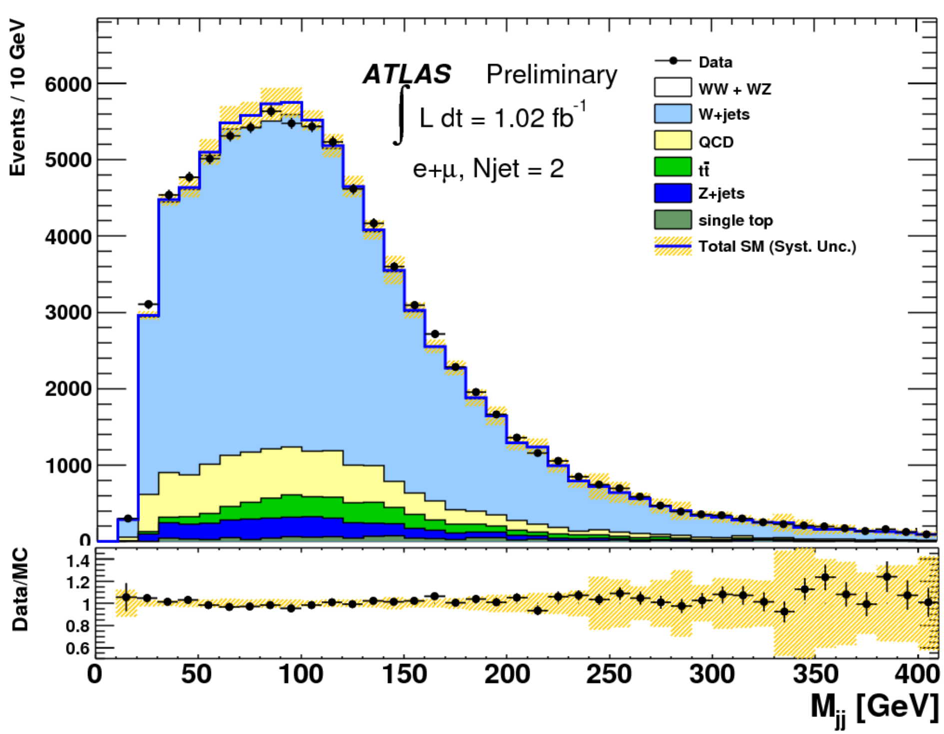
- CDF reported a 4.1σ excess in the dijet mass region 120-160 GeV!
- No hint of a disagreement with MC expectation in the ATLAS W+jets sample!
- The “bumphunter” algorithm finds no significant excess.

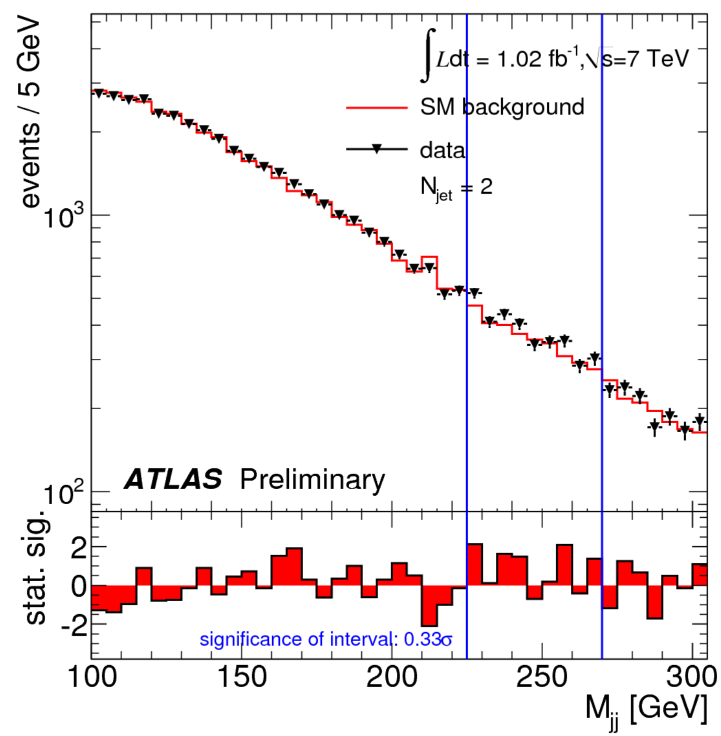
Phys. Rev. Lett. 106, 171801 (2011)





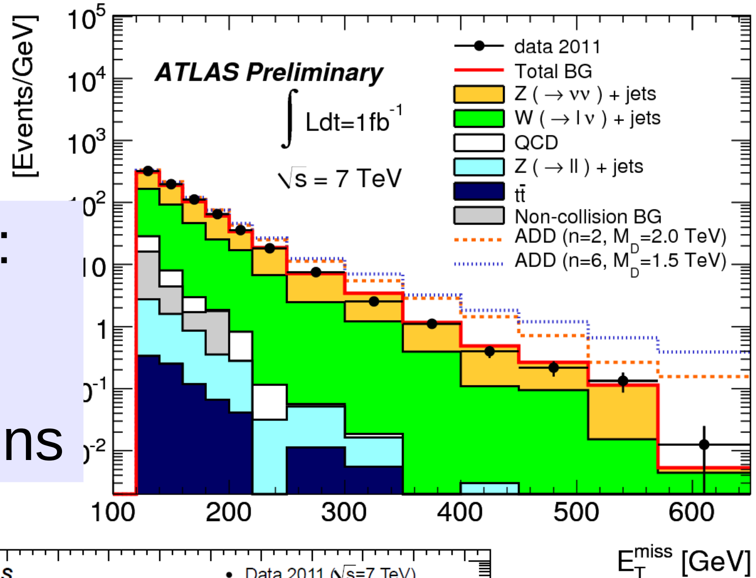
ATLAS-CONF-2011-097



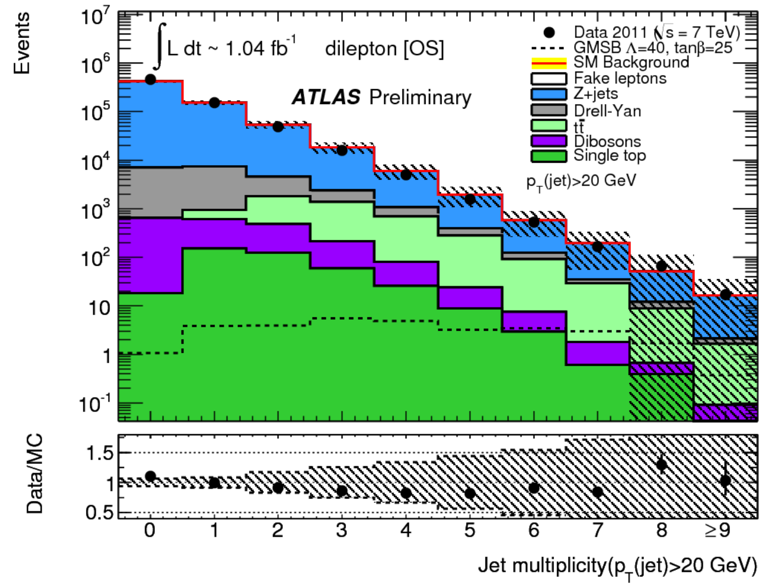


More search examples ...

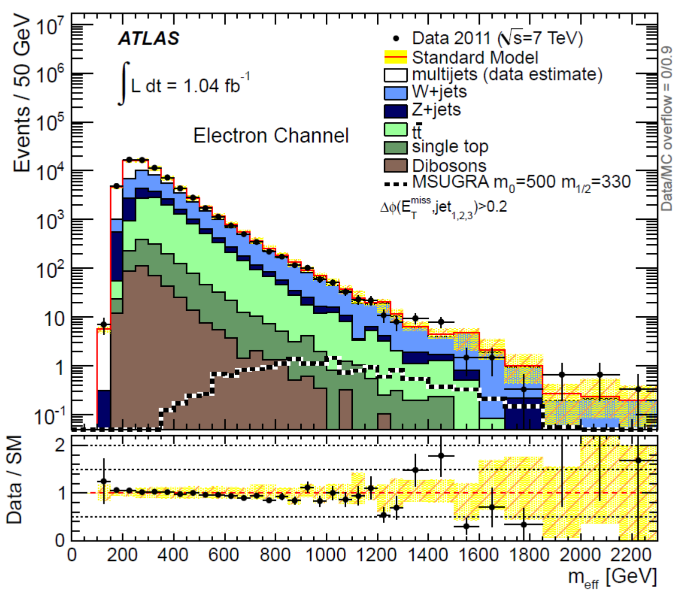
… in ATLAS with dominating V+jets backgrounds



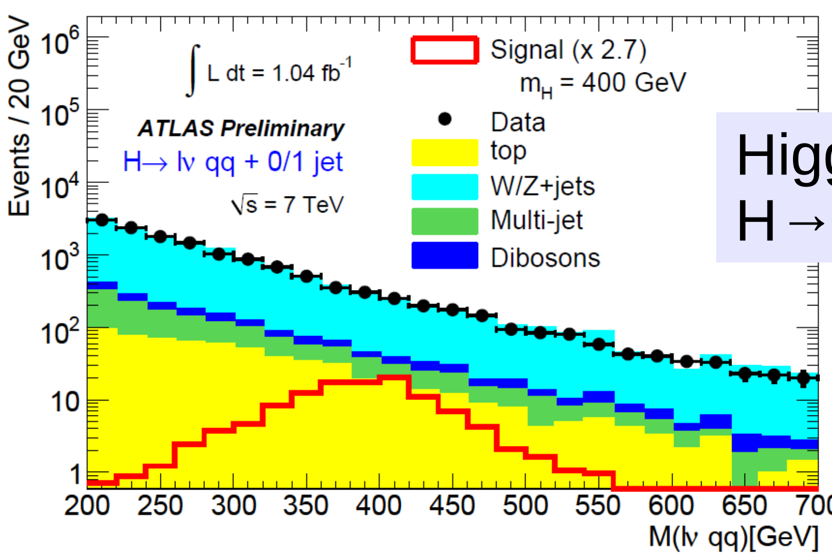
Monojets: Large Extra Dimensions



SUSY jets+MET +2 leptons (GMSB)



SUSY jets+MET+1lepton (mSUGRA)



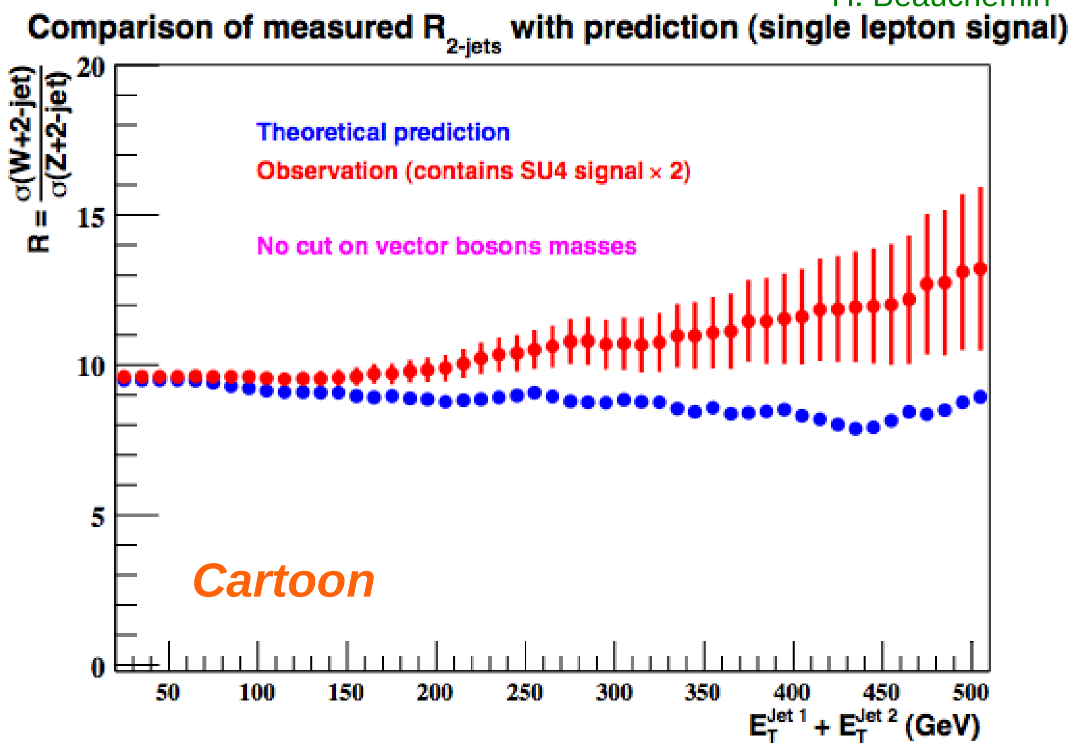
Higgs $H \rightarrow WW \rightarrow l\nu qq$

R_{jets}: Other prospects for searches

In(direct) searches using R_{jets}

- New physics contributions to either W+jets or Z+jets result in deviation of R_{jets} from Standard Model prediction
- Setting limits on BSM model possible using fit for R_{jets}+BSM to measured R_{jets}

H. Beauchemin



W → Z Mapping for Background Predicitons using R_{jets}

- Rjets can be used to predict irreducible background Z(→*vv*) + jets (eg. Monojet analysis)
  - Measure *W*+jets, remove lepton and normalize *Z*+jets prediction using R_{jets}
  - 10x statistics compared to directly using Z+jets
- More generally: Related to data-driven background estimations (“transfer functions”)

Measurement Principle

- Theory and experiment should join at well-defined, physically meaningful level with minimal model dependencies on anything but the process of interest

Detector Level

Detector Acceptance, Reconstruction, Identification, Inefficiencies, Calibration

PYTHIA
ALPGEN+HERWIG
SHERPA

Particle Level
a.k.a
Hadron Level

Fragmentation (nonpert.)

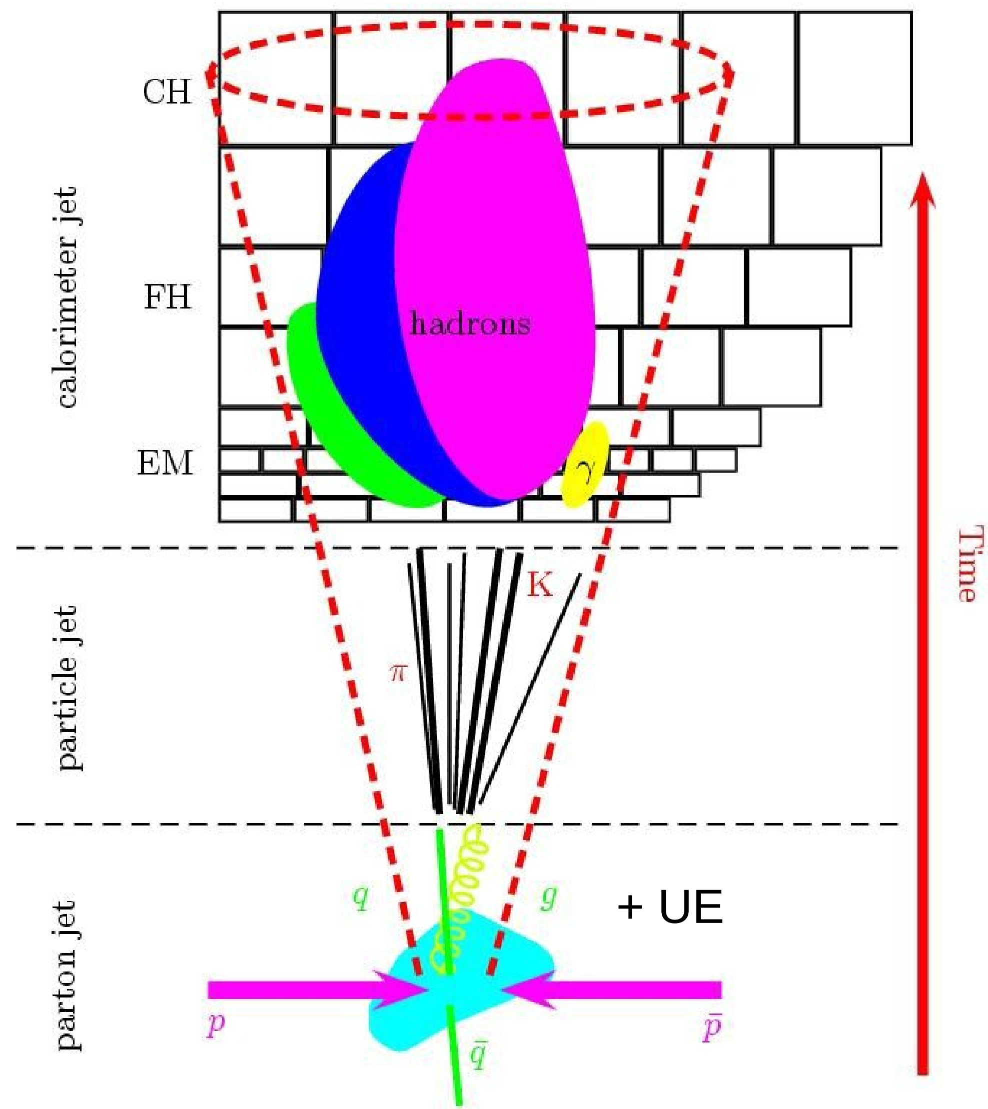
Parton Level

Partons (pQDC / PS)

ME (pQCD)

PDFs (nonpert.)

MCFM
Blackhat+SHERPA



jet evolution – similar for leptons

Generator Reference

Full Shower MCs

- Used for background simulation and estimation and unfolding of detector effects

Generator	Comments
ALPGEN 2.13 + HERWIG + JIMMY	PHOTOS, CTEQ6L1, ATLAS MC09 tune MLM matching, pQCD normalized to NNLO
SHERPA 1.13	CTEQ6L1, Default UE tune CKKW matching, pQCD normalized
PYTHIA 6.4.21	PHOTOS, MRST 2007 LO LO MatrixElement + ISR, PS corrections PQCD normalized

pQCD NLO parton level calculators

- Used for NLO predictions

MCFM 5.8	CTEQ6.6/CTEQ6L1 PYTHIAUE, fragmentation
SHERPA+BLACKHAT	CTEQ6.6M
FEWZ NNLO	MRST2007LO* PDF Used for pQCD normalization K-factors: 1.20 (W), 1.24 (Z) @ 5% unc.

Theory Status

Drell-Yan W, Z/γ*: NNLO

- FEWZ — *R. Gavin at al., arXiv:1011.3540v1*
  R. Hamberg et.al., Nucl.Phys.B 359 (1991)
  W.L.van Neerven et.al., Nucl.Phys.B 382 (1992)

W, Z/γ* + 1(2) jets: NLO

- MCFM — *K. Ellis et. al., Phys. Rev. D65:113007*
  K. Ellis et. al., Phys. Rev. D68:094021, 2003

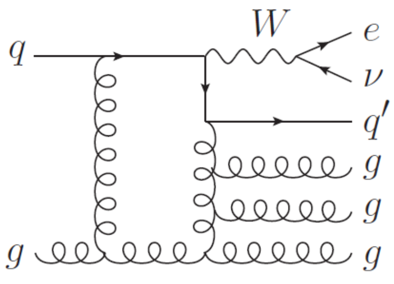
W, Z/γ* + 3 jets: NLO

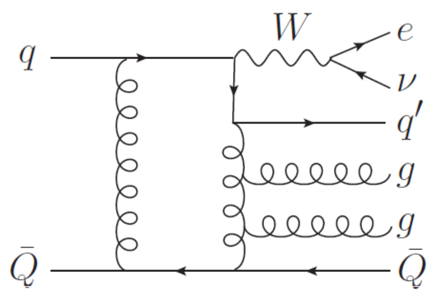
- BLACKHAT+SHERPA — *C. F. Berger et al., arXiv:1005.3728*
- W + 3 jets: — *C.F Berger et.al., Phys.Rev.D80:074036, 2009*
  R.K. Ellis et.al., Phys.Rev.D80:094002, 2009
- Z/γ*+ 3 jets: — *C.F Berger et.al., Phys.Rev.D82:074002, 2010*

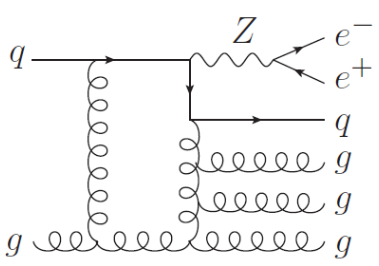
W, Z/γ* + 4 jets: NLO

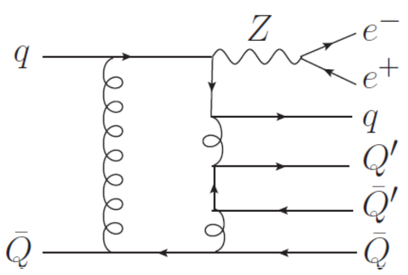
- Z/γ* + 4 jets: — *Ita et al., arXiv:1108.2229*
- W + 4 jets: — *C.F. Berger et.al., Phys.Rev.Lett. 106:092001, 2011*

- Important to have NLO calculations available
- Uncertainties decrease from 50% at LO to ~15-20% at NLO
- In particular PYTHIA not expected to be precise for $N_{jet}>1$
- Not all NLO calculations technically available in all cases at time of analysis





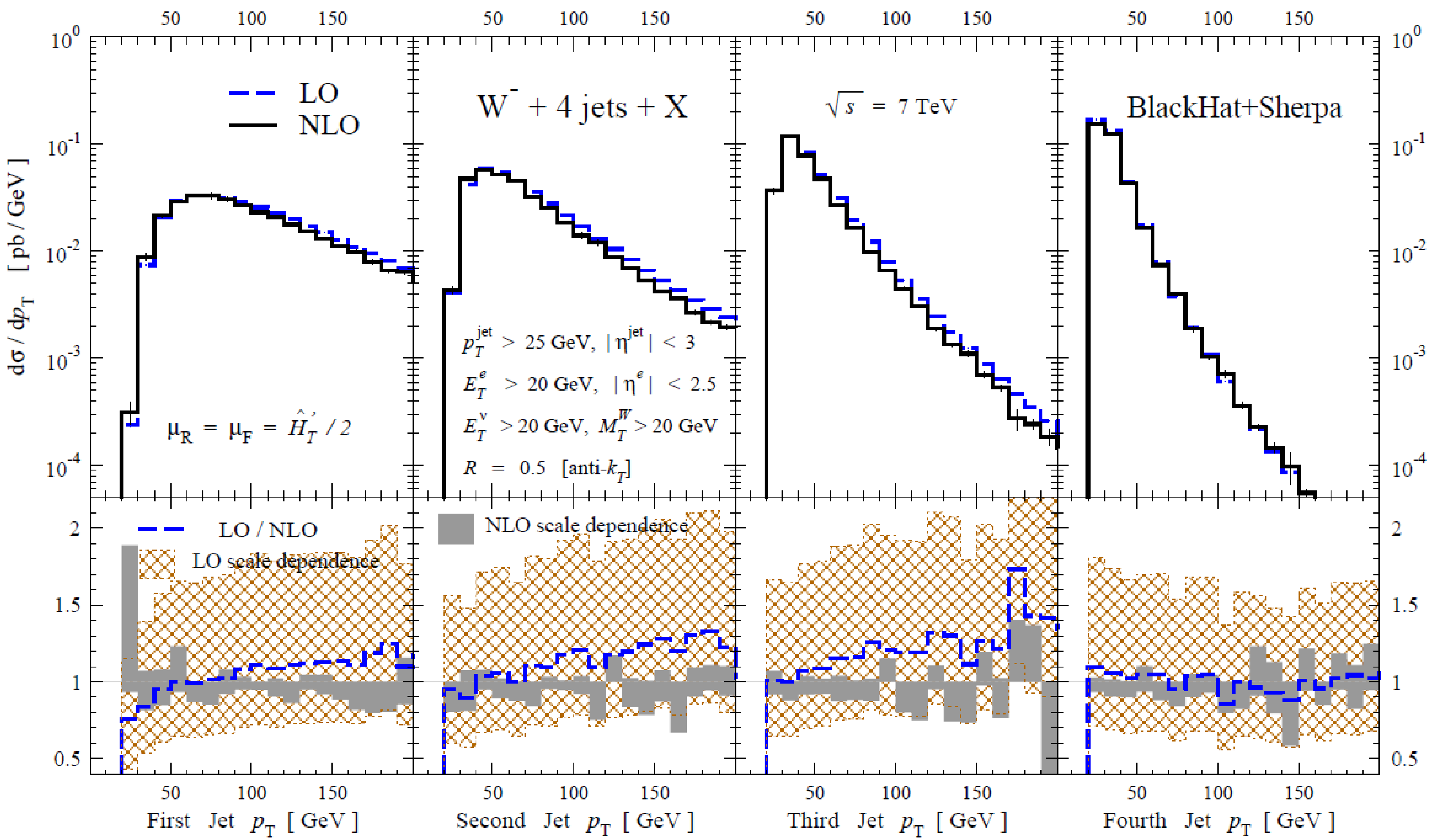




A few features of recent theory …

- Scale choice H_T important because can now have hard jets $p_T^{jets} >> p_T^V$
- Tevatron: mu = ETW was ok because higher than HFS sum pt
- Scale mu can cause negative x-section at NLO
  (logs do not cancel properly at large jet ET)

→ QMUL seminar
L. Dixon one year ago



W+4 jets at NLO

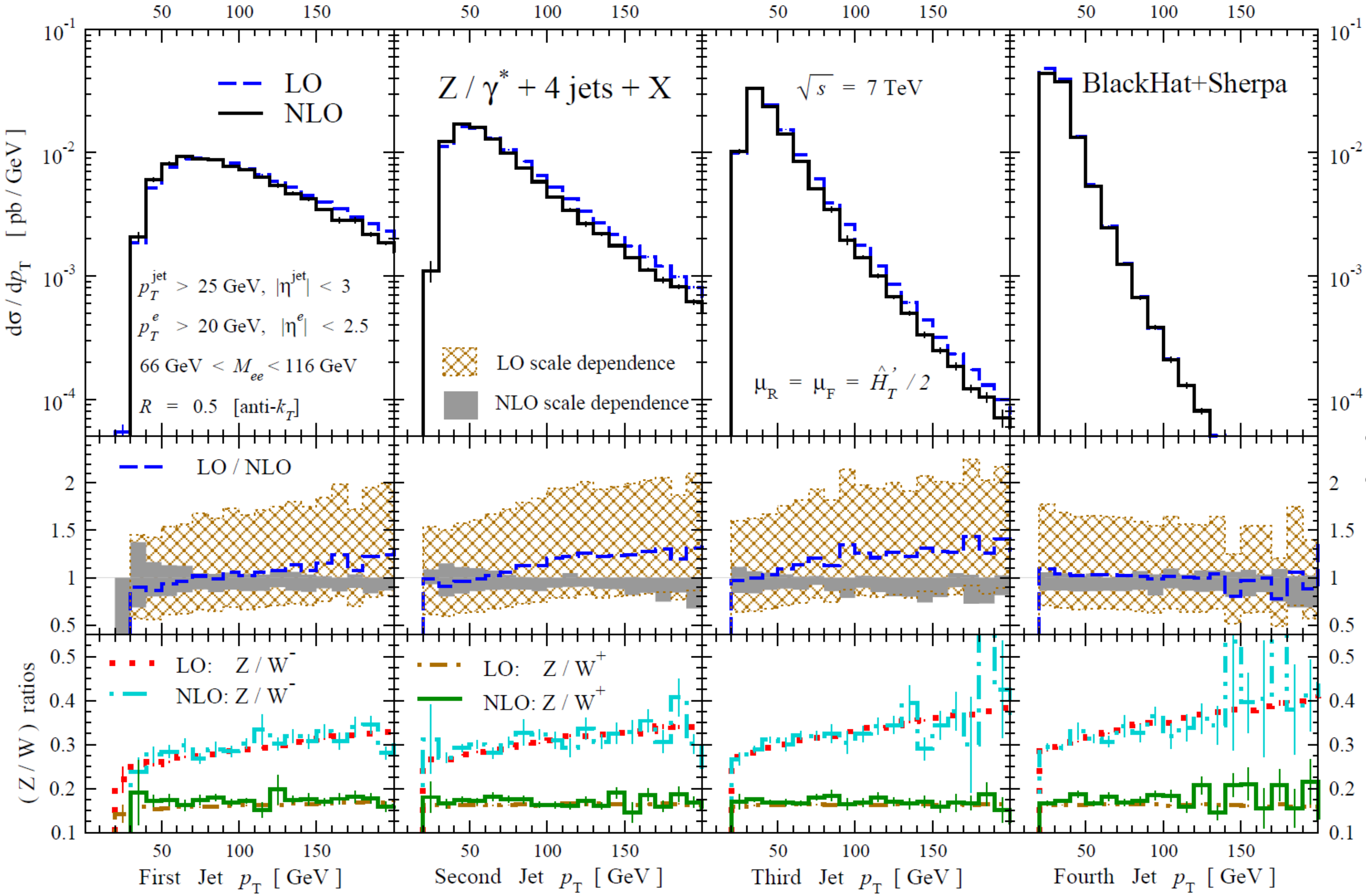
LO/NLO Ratio under Control to High jet pT

C. Berger et al., [arXiv 1009.2338]

Z + 4 jets Predictions

Ita et al., [arXiv:1106.1423]

- Latest Results:
  Precise Predictions for Z + 4 Jets at Hadron Colliders
- Probe different pdfs in W^+/Z (mostly u/u) and W^-/Z (mostly d/u)



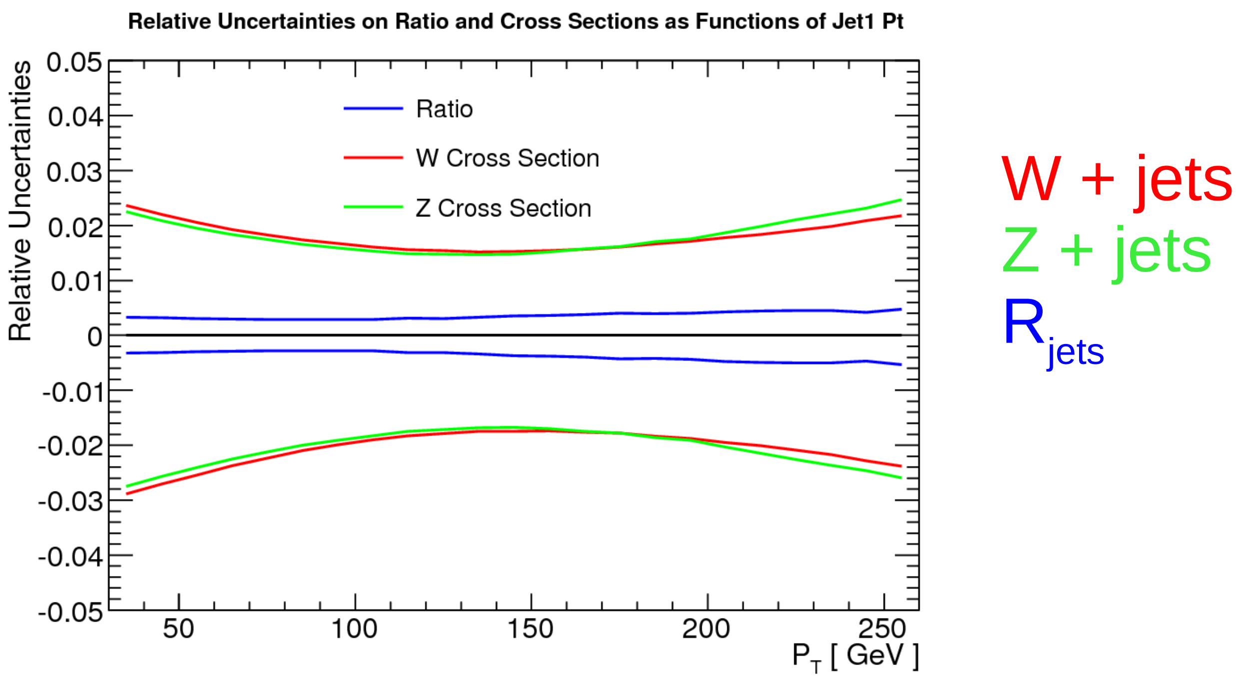
Uncertainties:

- Scale: 4-14%
- PDF+α_s: 3-8%

PDF and scale uncertainties on pQCD predictions

- R_{jets} exclusively using MCFM this round
  (Looks at 1-jet only for now: no great difference from LO+PS to NLO)

- PDF uncertainties from eigenvector/eigenvalue method (error sets envelope) greatly reduced in R_{jets} because cross sections go in the same direction for each error set

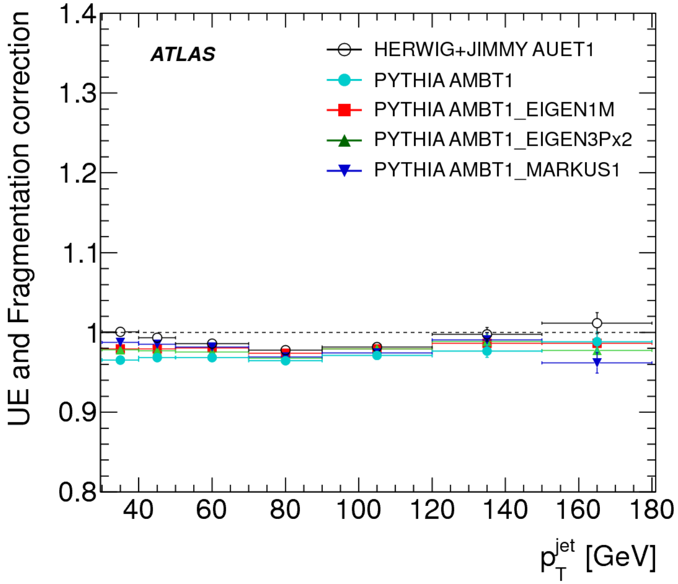


- Scale uncertainties:

  Same effect, large cancellation in R_{jets}

Parton-to-Particle Correction

- Reminder: MCFM and BlackHat-SHERPA are not full NLO Shower-MCs, but "just" parton level predictions
- Have to evaluate non-perturbative effects on parton level predictions
- Calculated using MC variation samples (tune variations: UE on/off...)

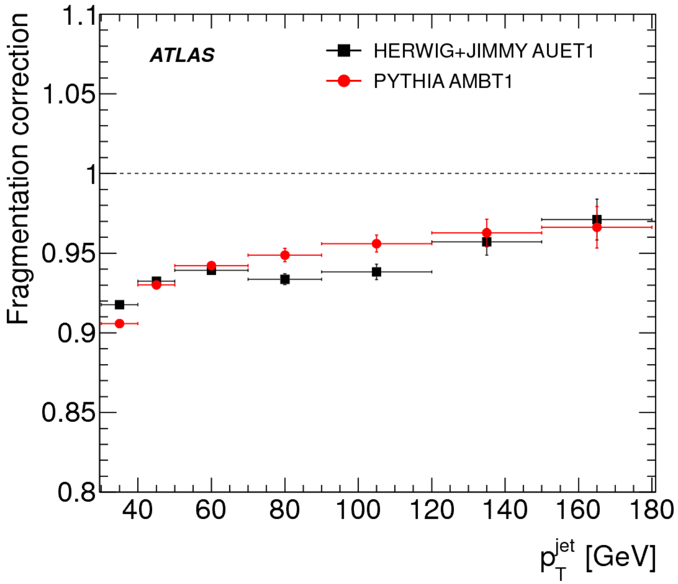


Fragmentation

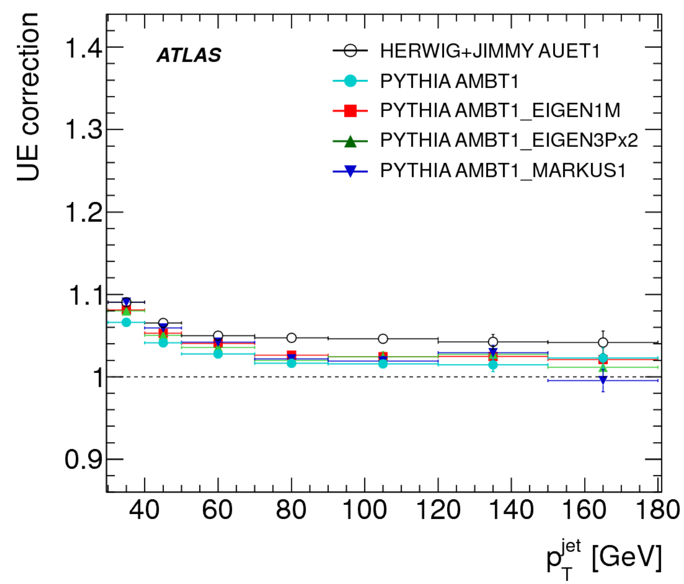
- Losses:
  lower p_T jets, less jets

Underlying event

- Adds energy:
- higher pT jets, more jets

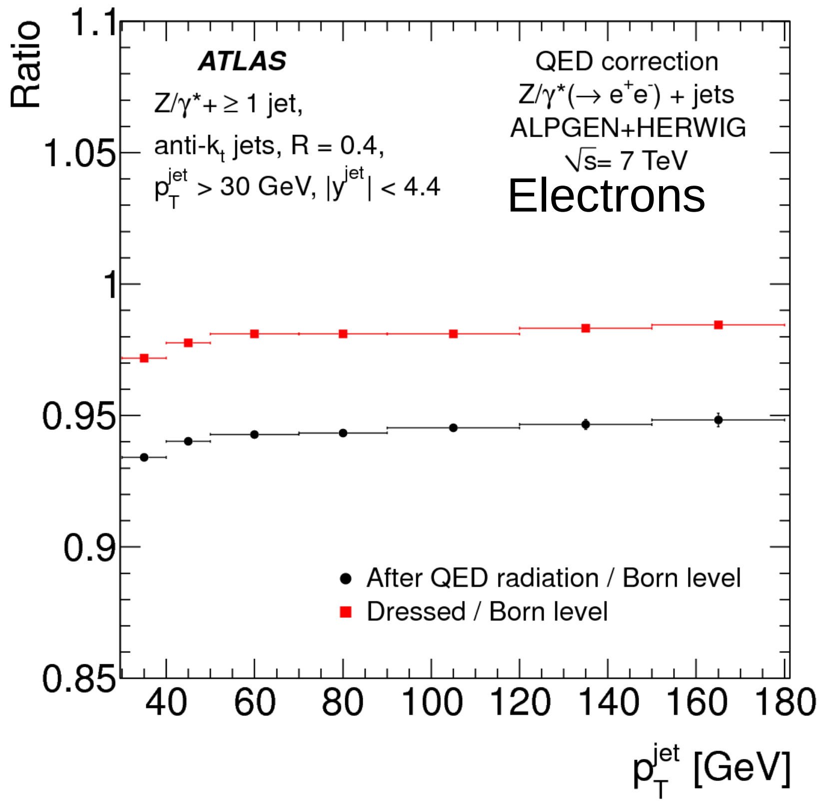


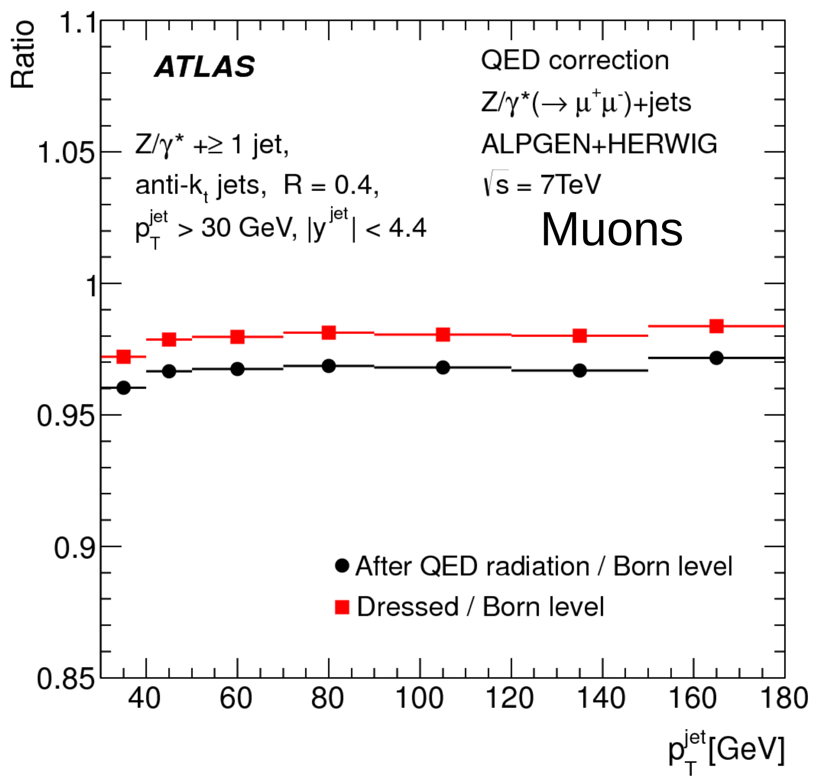
- Partial cancellation in total correction (~1-2%)
- About 10% correction at $p_T = 30$ GeV (2-5% syst. unc.)



Lepton Dressing

- Bare leptons at propagator are also not physically meaningful
- “Dress” leptons:
  Add photon 4-vectors in $\Delta R < 0.1$ around lepton to lepton 4-vector
- Mainly from FSR
- Provide clear definition where experiment and theory can meet
- Results in ~1.5% acceptance correction per lepton
- Effect on cross section 2%-2.5% (*Z* channel)





Lepton Selection and Phase Space

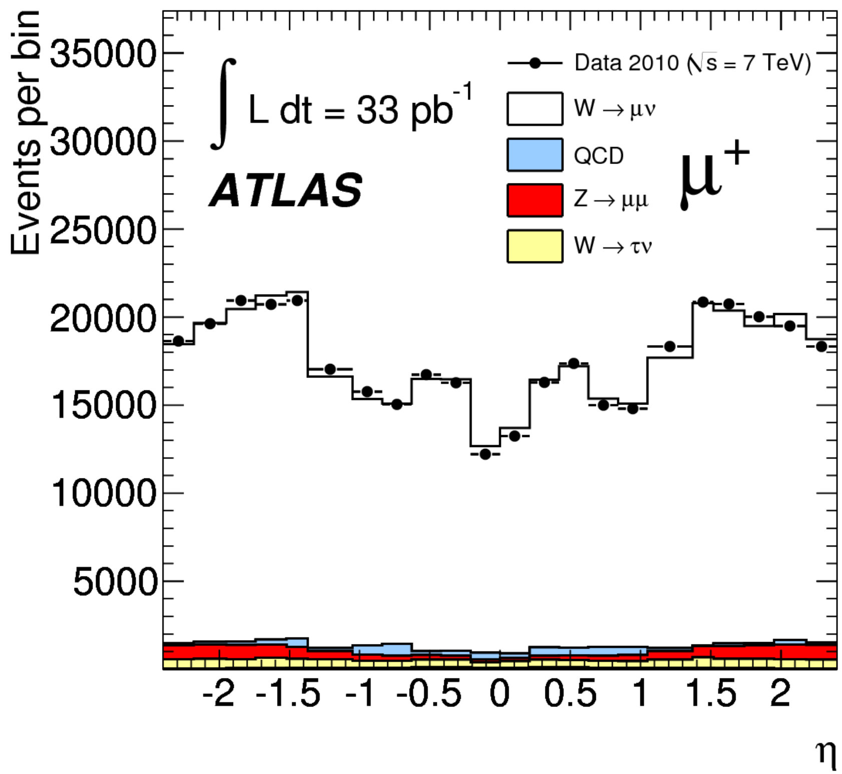
Muons

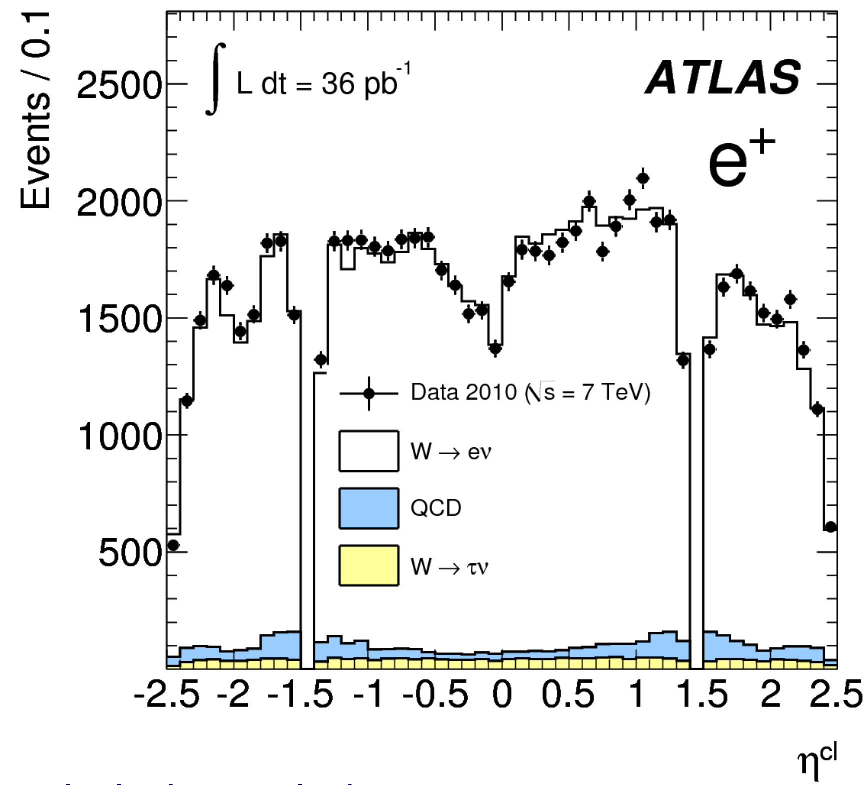
- p_T > 20 GeV
- $|\eta| < 2.4$
- Inner Detector + Muon System
- Various quality requirements
- Track isolation

Electrons

- $|\eta| < 2.47$ excluding $1.37 < \eta < 1.52$
- em. shower shape in calorimeter
- Various quality definitions to optimise signal efficiency / background rejection ("medium", "tight")

Different acceptance requires inter/extrapolation of fiducial region for combination





Pseudorapidity distributions from inclusive analysis
Similar for negative leptons

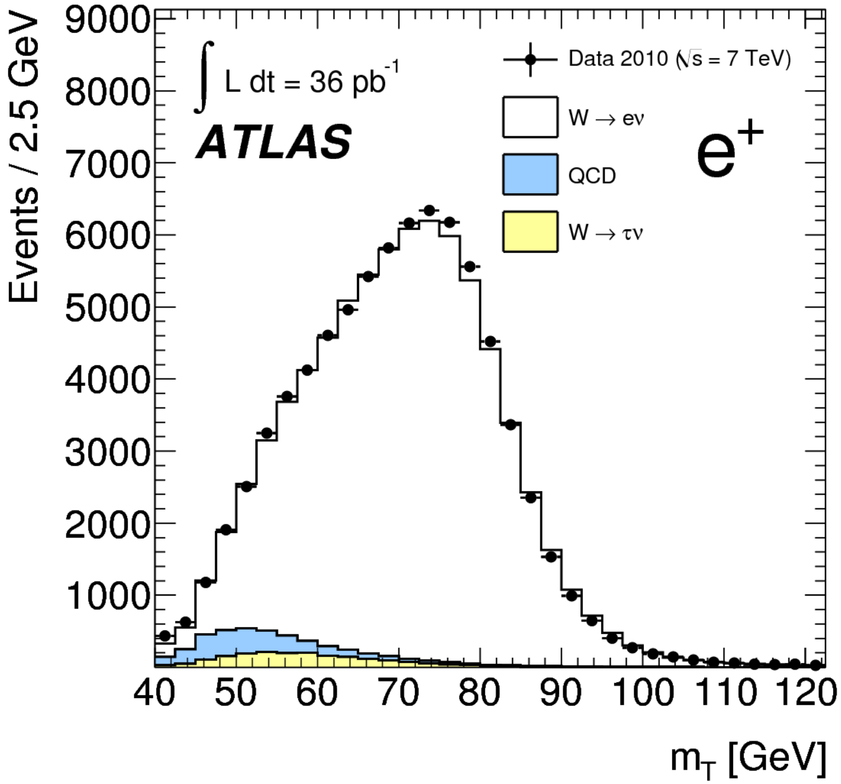
Vector Boson Selection and Phase Space

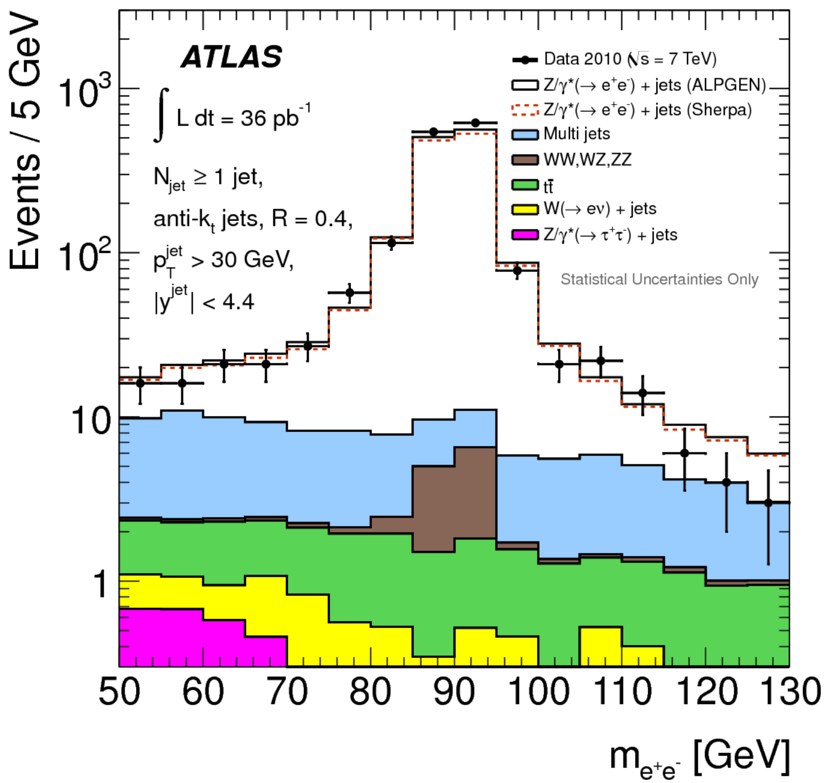
W

- Exactly one lepton (veto 2nd)
- ETmiss > 25 GeV
- M_T > 40 GeV

Z

- Exactly two leptons
- Opposite charges
- 66 < M_{ll} < 116 GeV





Taken from inclusive W,Z measurement

- Acceptance ~45%
- Inclusive backgrounds: ~10% (*W*), ~2% (*Z*)

Jet Selection and Phase Space

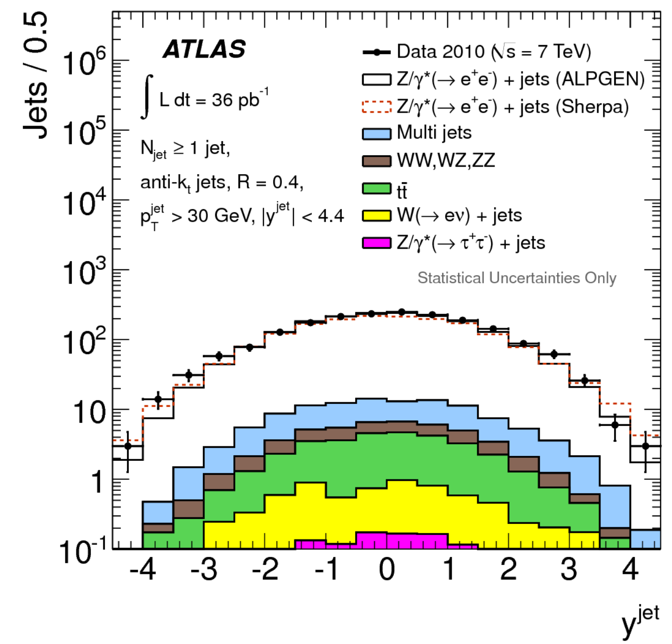
Jets

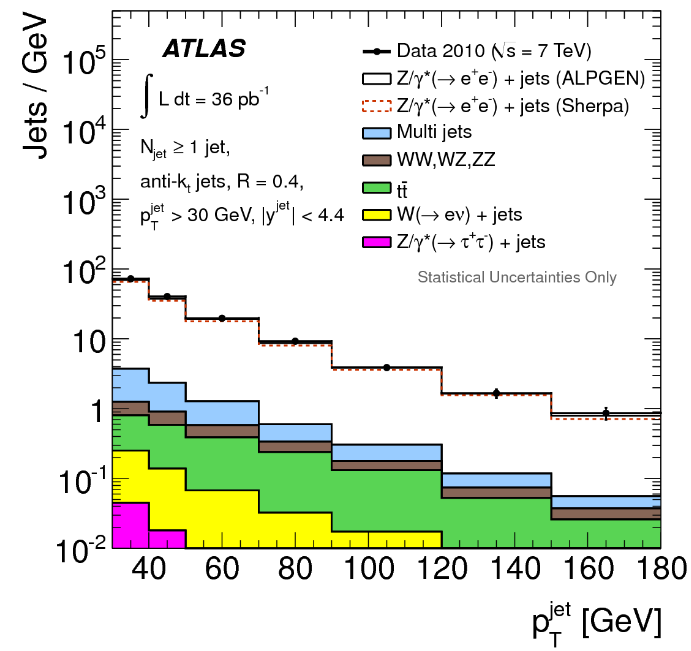
- Anti-k_T algorithm R = 0.4
- p_T > 20 GeV (W+jets)
- p_T > 30 GeV (Z+jets and R_{jets})
- $|\eta|$ < 4.4 ($|\eta|$ < 2.8 for R_{jets})
- lepton-jet separation ΔR_{lj} > 0.5 (0.6 for Rjets)
  (prevent distortion of jet by em. showers)

- Pileup removal using "Jet Vertex Fraction"
  JVF > 0.75
- Source of large systematic uncertainty in V+jets
  – small for R_{jets} : pile-up almost cancels
- JVF only usable in 2010 data with low pileup
- JES calibration largely MC based

Particle level definition of jets
- Use all final-state particle
  - including HF decay products
  - excluding W/Z decay products

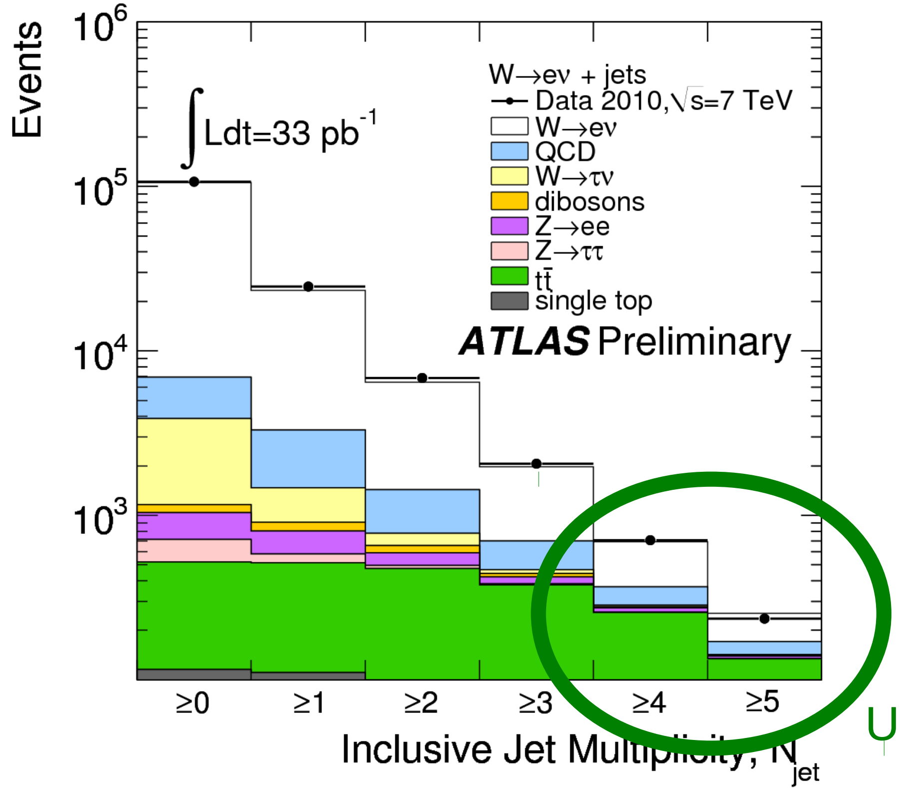
Inclusive y and p_T jet (Z+jets)



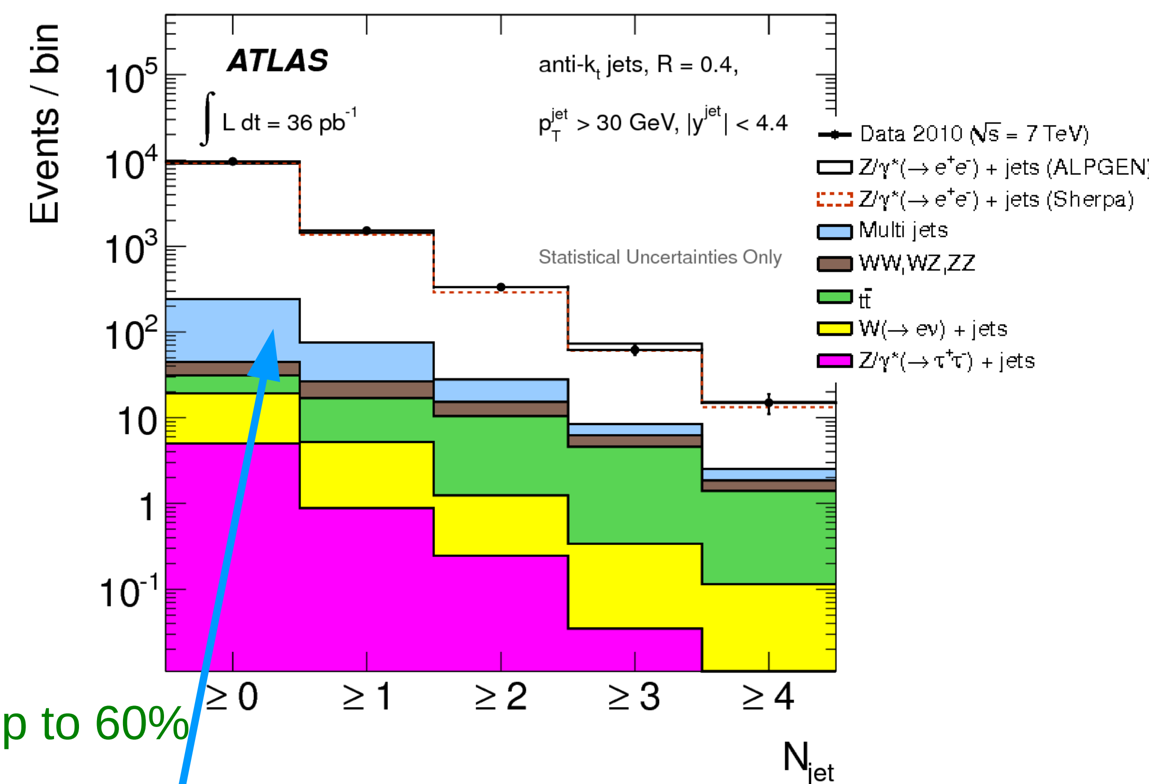


Inclusive Jet Multiplicity (Detector Level)

W + jets



Z + jets



Up to 60%

- Backgrounds increasing towards higher N_{jet}
- EW and top taken from simulation – **QCD important at low multiplicities**
- **Top becomes important at higher jet multiplicities (N_{jet} > 3,4) in *W* channel**
- Overall good agreement data / prediction
- Very similar plots for R_{jets} in respective phase space

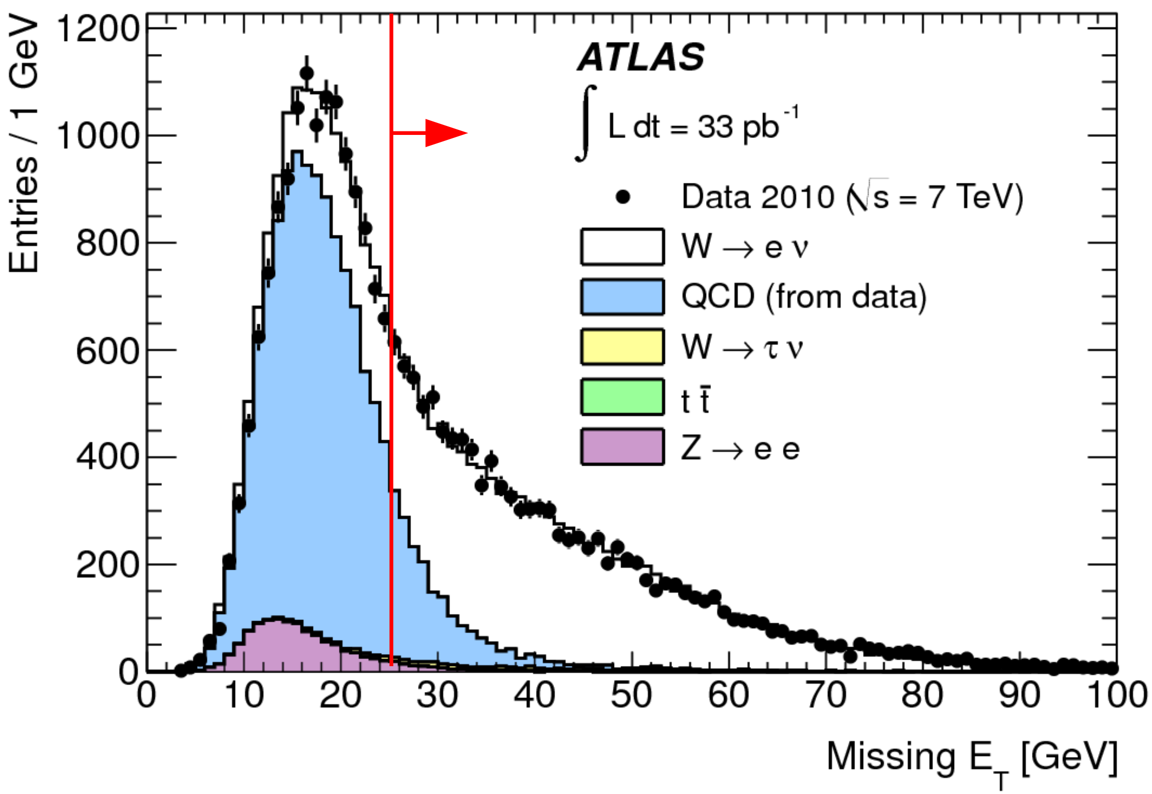
  (Statistics not enough to cover more than 1 jet: limited by *Z* channel)
- Inclusive bin: Can already estimate σ(*W*) / σ(*Z*) ~10

QCD Background Modeling

Depending on final state use data driven method or MC estimates

- *W→ee* Fit data to MET distribution using QCD template
  - electron ID reversal or
  - electron selection replaced with photon
- *Z→ee* Loosen electron ID, normalize with dilepton-mass

- *W→μμ* Fit MET distribution, QCD template from MC
- *Z→μμ* directly from MC (HF dominated)



QCD template and Normalisation from data in W+1-jet

(from R_{jets} analysis)

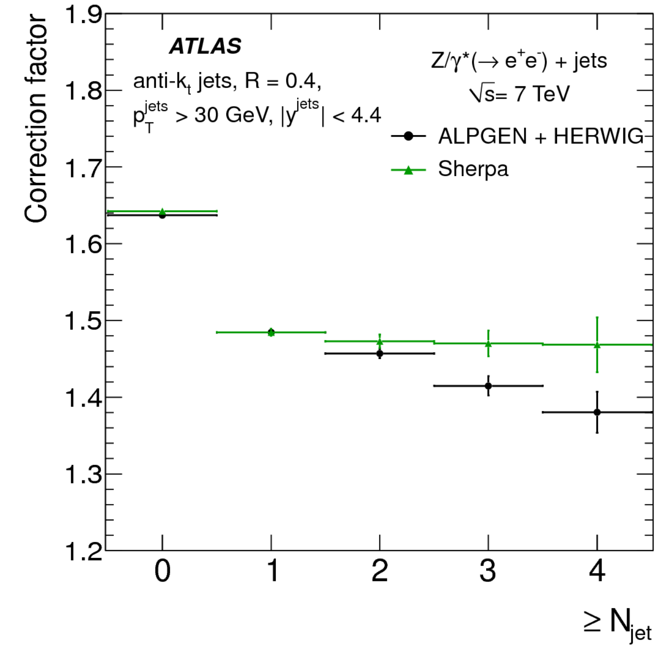
V+jets Unfolding for Detector Effects

Bin-by-bin correction factors U(ξ)

$$\frac{d\sigma}{d\xi} = \frac{1}{\mathcal{L}}\frac{1}{\Delta\xi}(N_{\mathrm{data}} - N_{\mathrm{backg}}) \times U(\xi)$$

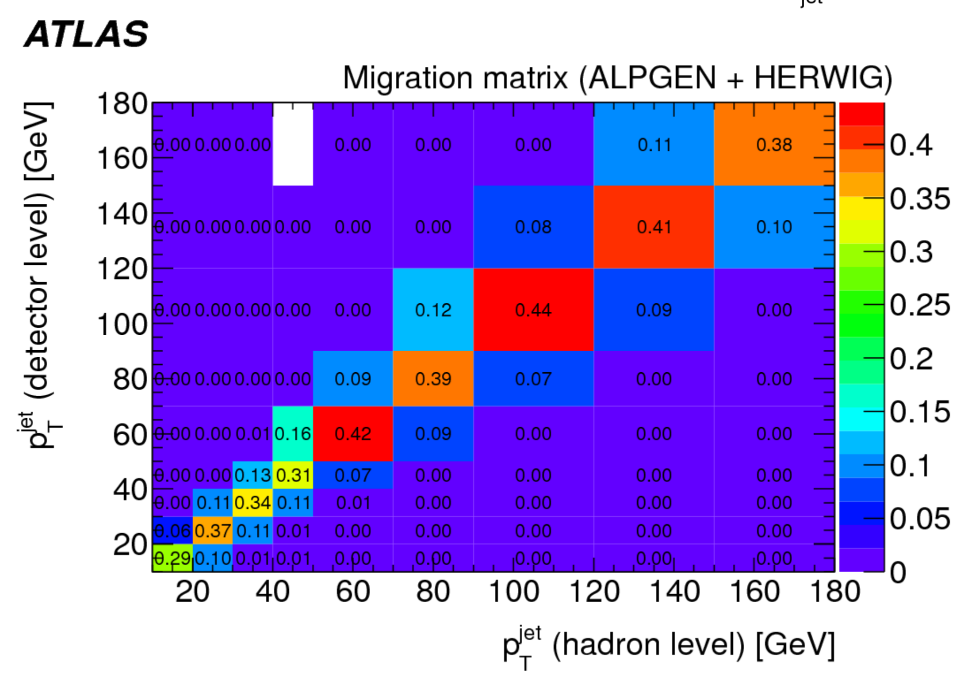
- U(ξ) contains all trigger and reconstruction (leptons and jets) inefficiencies / resolutions
- Determined using ALPGEN simulation
  Electron channel: U(ξ) = 1.65 to 1.35
  Muon channel: U(ξ) = 1.16 to 1.1
- Systematic uncertainty : difference between ALPGEN and SHERPA derived corrections

Electron Channel $U(N_{jet})$



Bayesian Method “d'Agostini”

- Cross check + future use
- Lower MC dependence, better statistical treatment
- More complex, need to pay attention to regularization
- This round confident in bin-by-bin results:
  - Good agreement data-MC at Detector level
  - W/Z + jets measurements are systematically limited
  - Little migration: off-diagonal elements small



W/Z Ratio Correction Procedure

- R_{jets} calculated from ratio of individually corrected event yields in W, Z channels
- Allows correct evaluation of statistical correlations in numerator/denominator

1

Signal events (backgrounds subtracted)

$$N^{\ell,V}_{\mathrm{part}} = \frac{N^{\ell,V}_{\mathrm{sig}}}{\epsilon^{\ell}_{\mathrm{trig}} \times \epsilon^{\ell} \times C^{\ell}_{V}}$$

Trigger efficiency

Lepton identification

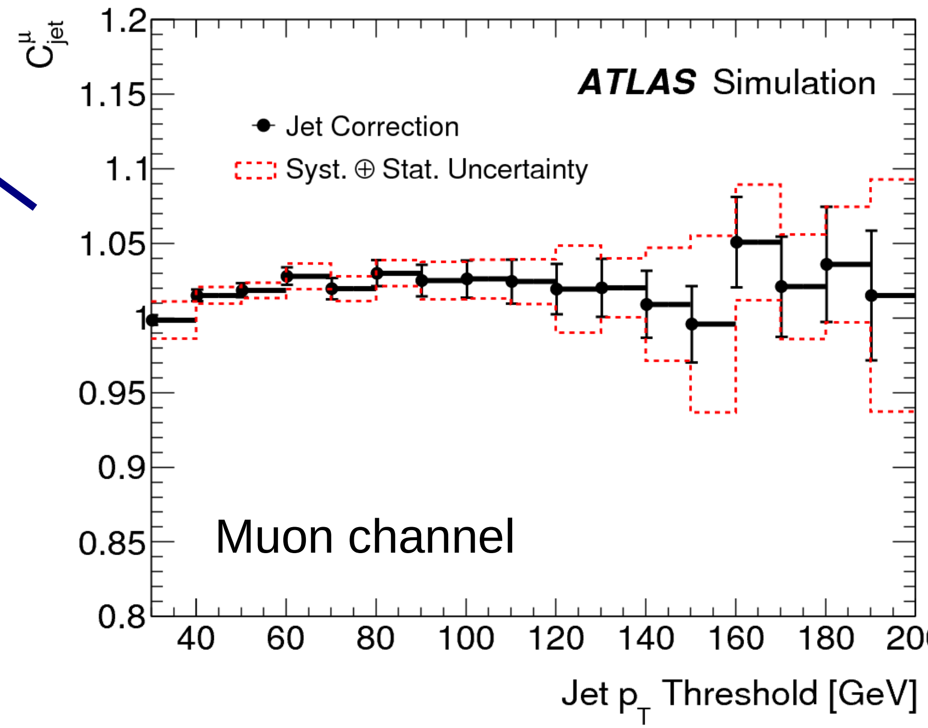
Boson reconstruction

2

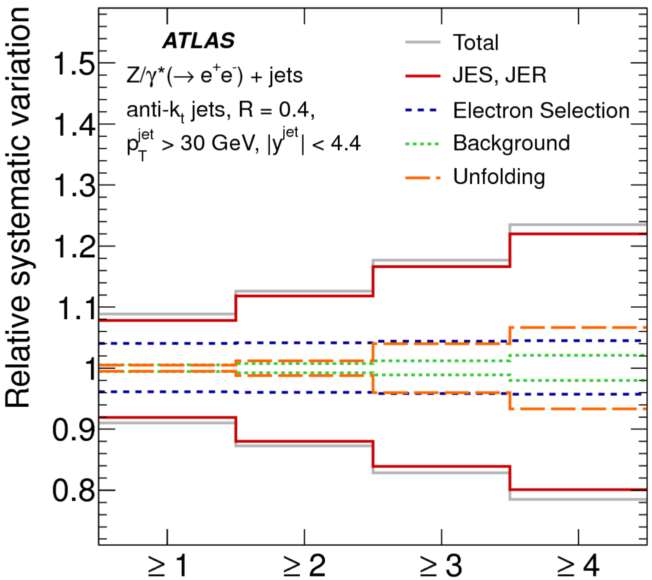
$$R_{\mathrm{jet}} = \frac{N^{\ell,W}_{\mathrm{part}}}{N^{\ell,Z}_{\mathrm{part}}} \times C^{\ell}_{\mathrm{jet}}$$

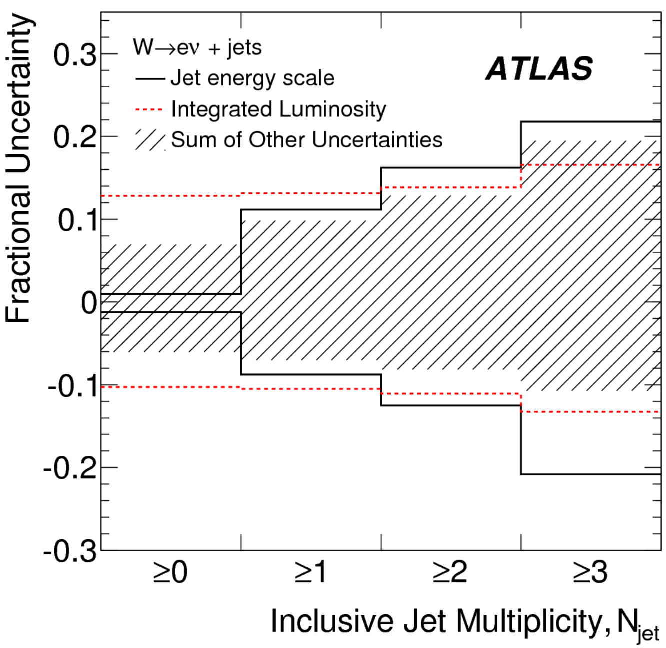
Jet spectrum correction directly on ratio

- Almost complete cancellation of jet resolution effects
- Remaining effects from W/Z phase space differences below ~5%
- Determined on ratio by smearing particle level jets according to JES
- Syst. Uncertainty from difference between ALPGEN and PYTHIA



Systematic Uncertainties in V+jets Measurements





(from 1.3 pb-1 paper)

- All uncertainties are calculated bin-wise in each observable

Z+jets

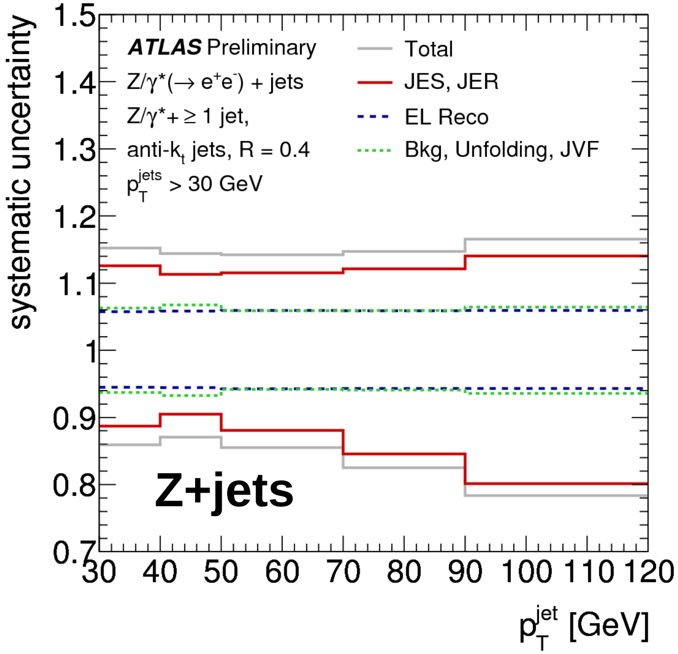
- Dominating Systematics
  - JES 8% - 20%
    (10% already in 1-jet bin!)
  - Luminosity 3.4%
  - pile-up jets ≈5%

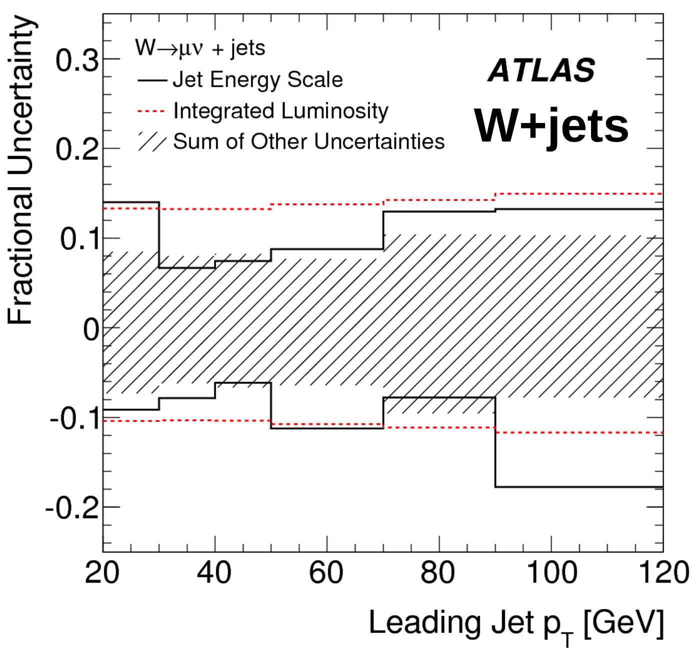
W+jets

- Dominating Systematics
  - JES 12% - 22%

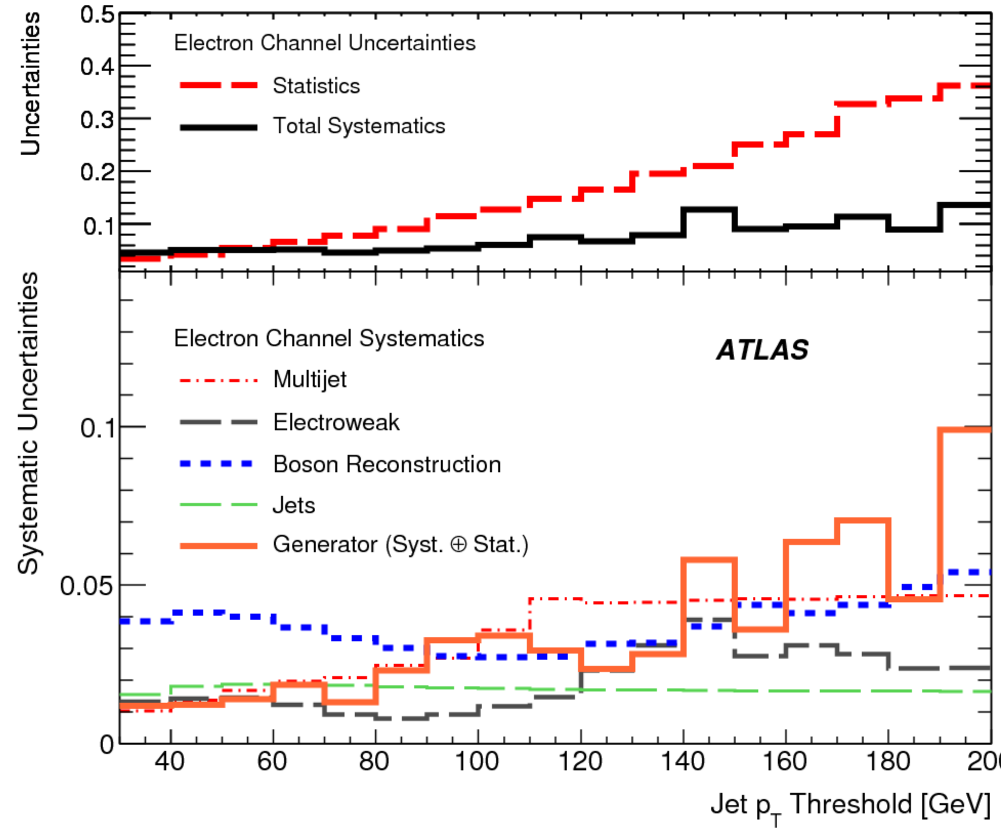
    (larger than Z due to missing energy)

Systematic Uncertainties in lead. p_T^{jet}





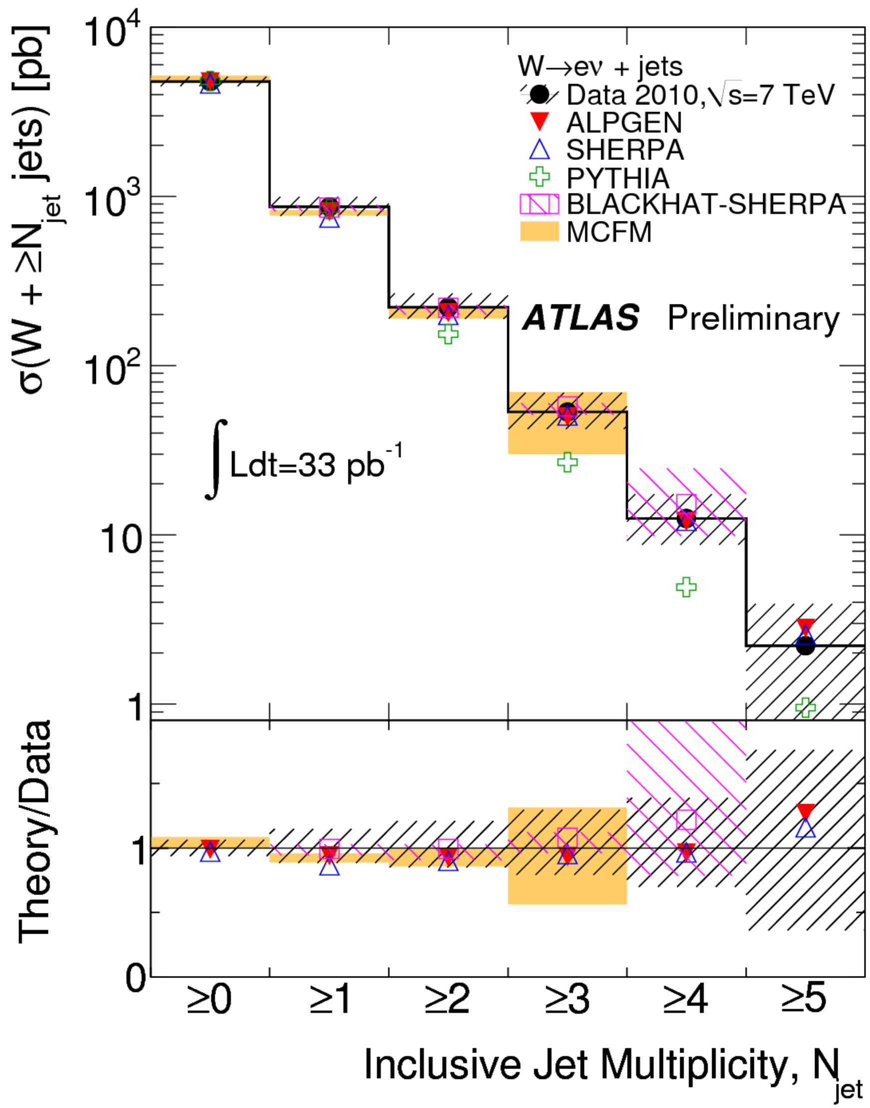
R_{jets}

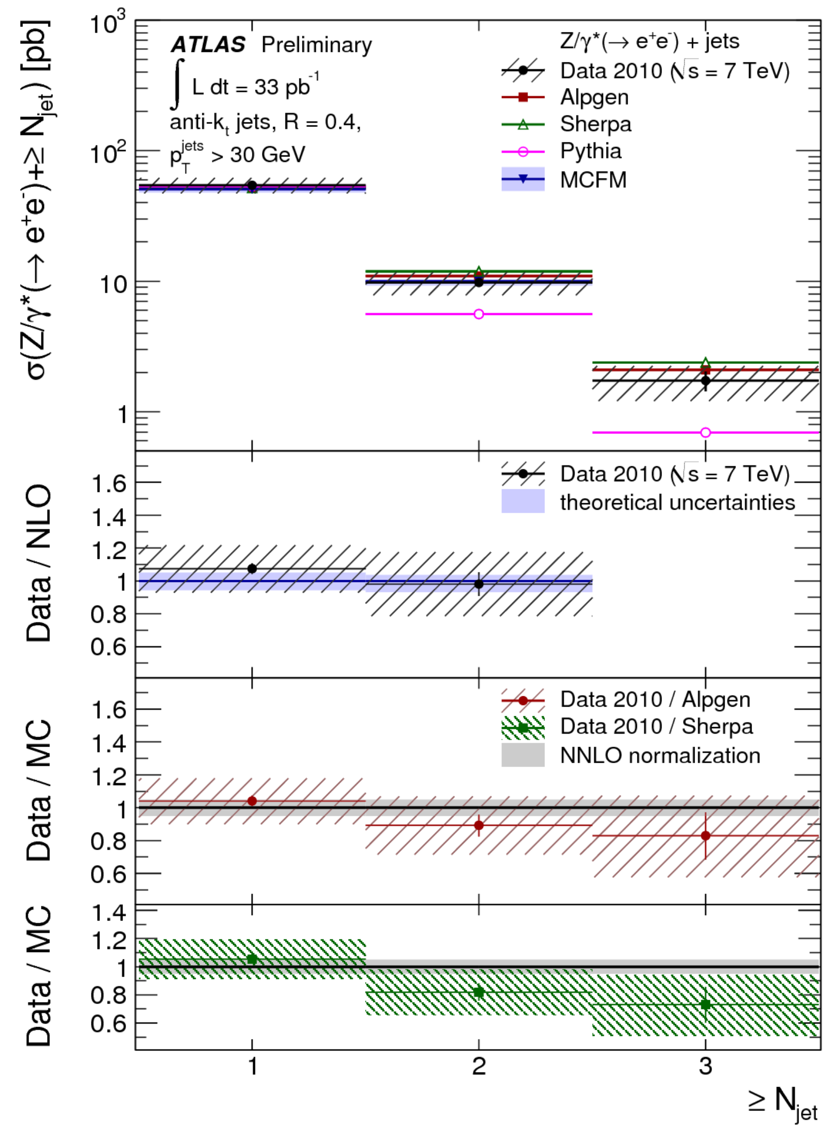


***R_{jets}*:**

- Systematic uncertainties substantially smaller than in V+jets individually
- In particular reduction on the jet systematic uncertainties
- Systematic uncertainties of the order of less than 5%
- Precision still statistically limited.

Inclusive Results V+jets Cross Sections

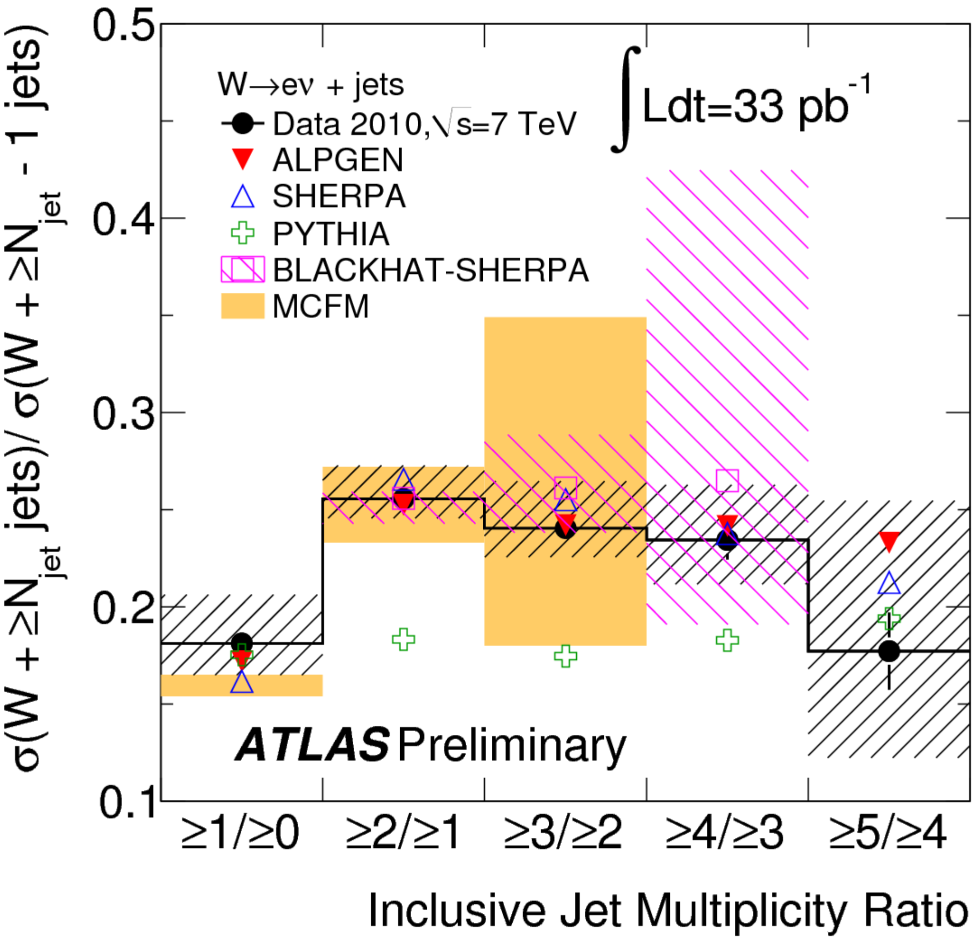


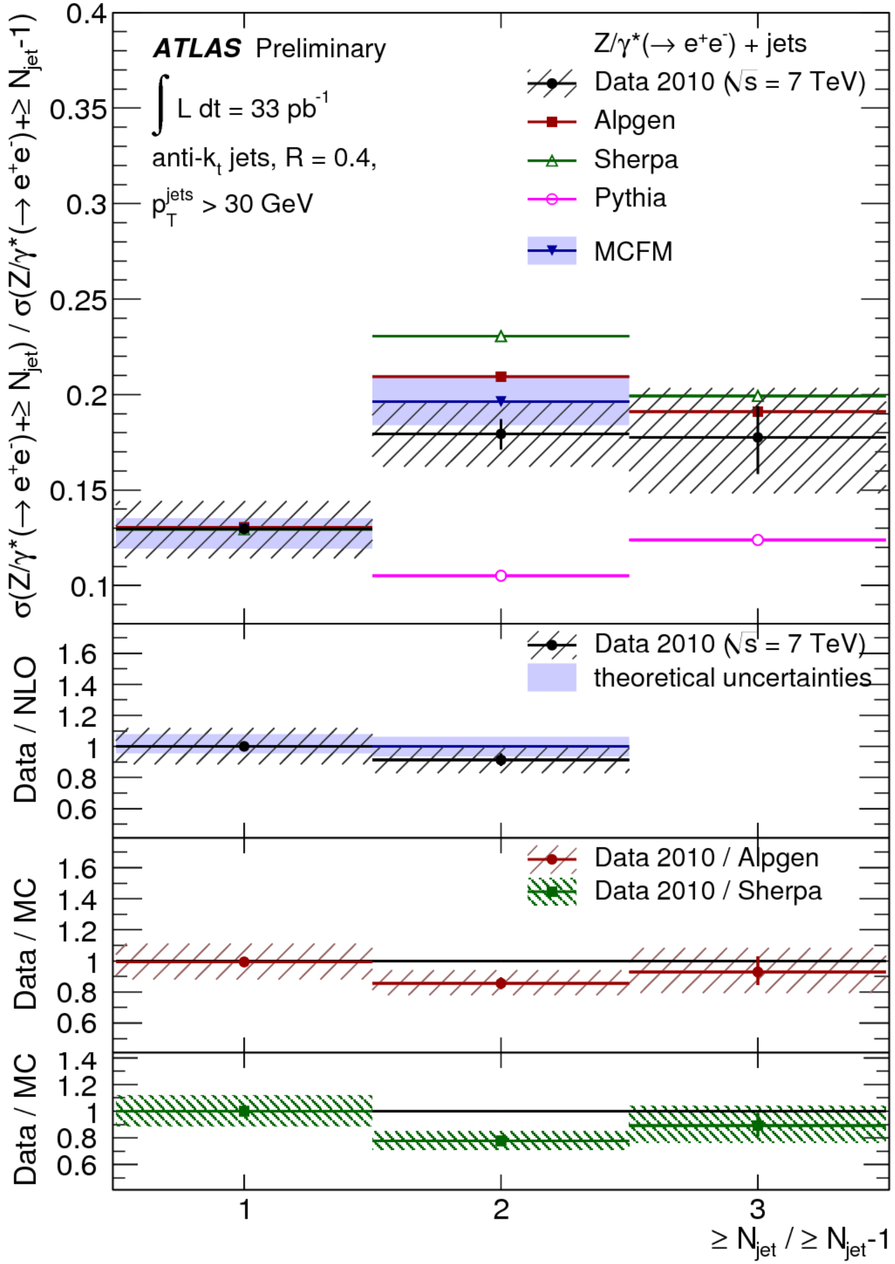


- Blackhat-Sherpa: NLO for N jets ≤ 3, LO for N jets = 4
- MCFM: NLO for N jets ≤ 3
- As expected PYTHIA understimates rates of high multiplicites

pQCD works well

Jet Multiplicity Ratios





- Some systematic uncertainties cancel (Lumi, lepton ID, boson acceptance)
- Increased uncertainty on MCFM and Blackhat-Sherpa
  (in bin 3 and 4 respectively)
  due to LO prediction

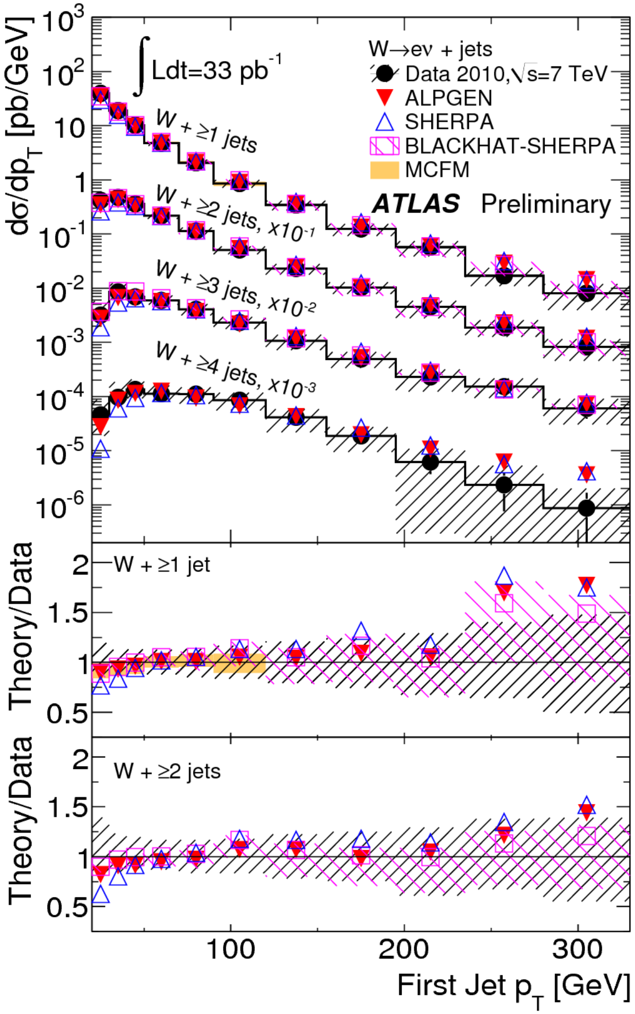
- Ratio roughly ~25% (W), ~20% (Z) per jet except first bin ~15%

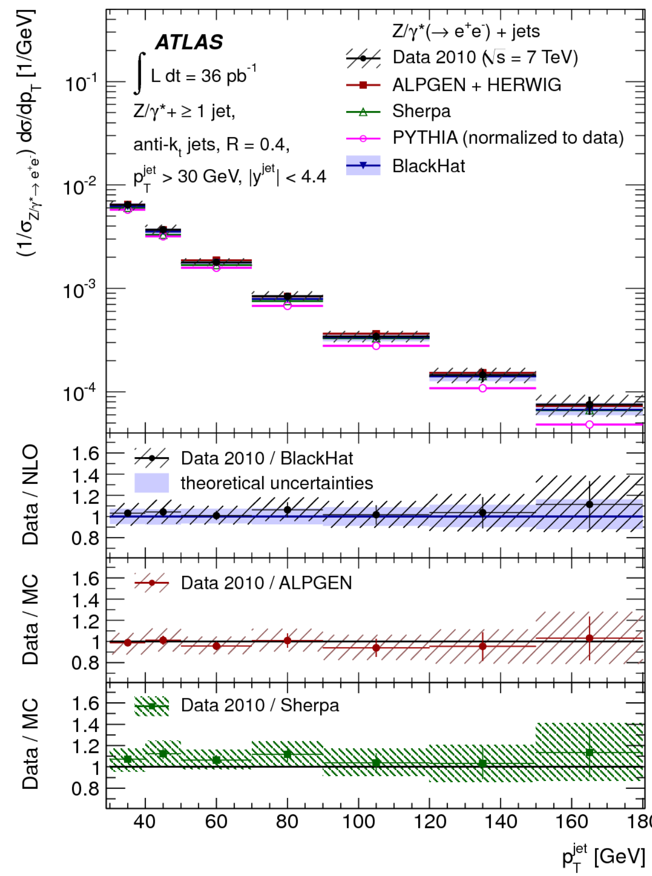
Cross section in leading jet p_T

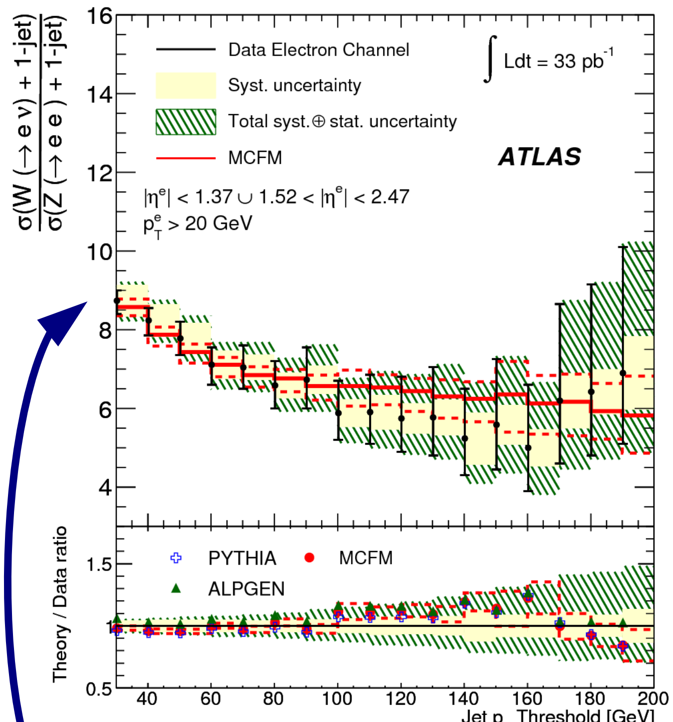
W+jets (N_{jet} >= 1,2,3,4)

Z+jets (N_{jet} >= 1)

R_{jets} (N_{jet} = 1)







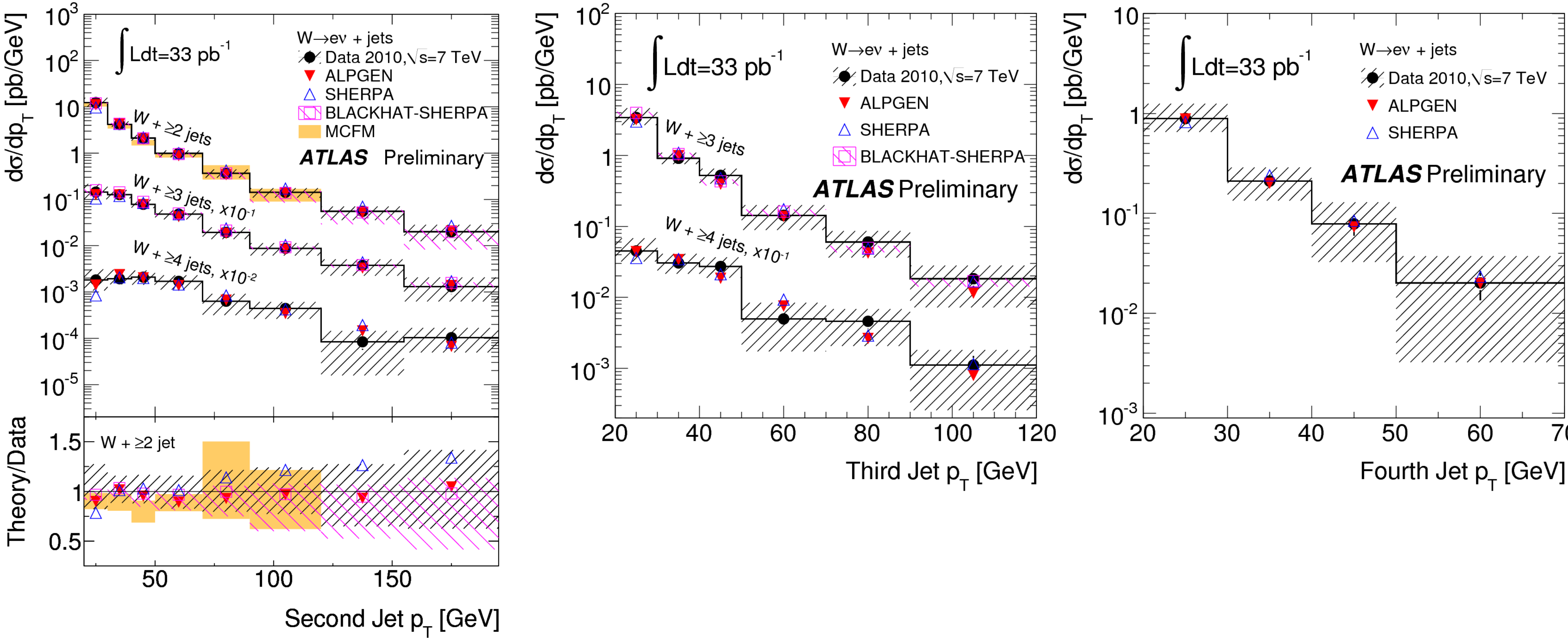
$$8.73 \pm 0.30\,(\mathrm{stat}) \pm 0.40\,(\mathrm{syst})$$

Rjets
- Syst. cancellation:
  - lumi
  - Partially lepton id
  - Mostly JES/JER, detector effects,
  - parton-to-hadron corr.

- Cross section normalised to inclusive cross section
- canellation of lumi, partially lepton id and boson acceptance systematics

Transverse momenta of 2nd, 3rd, 4th jet

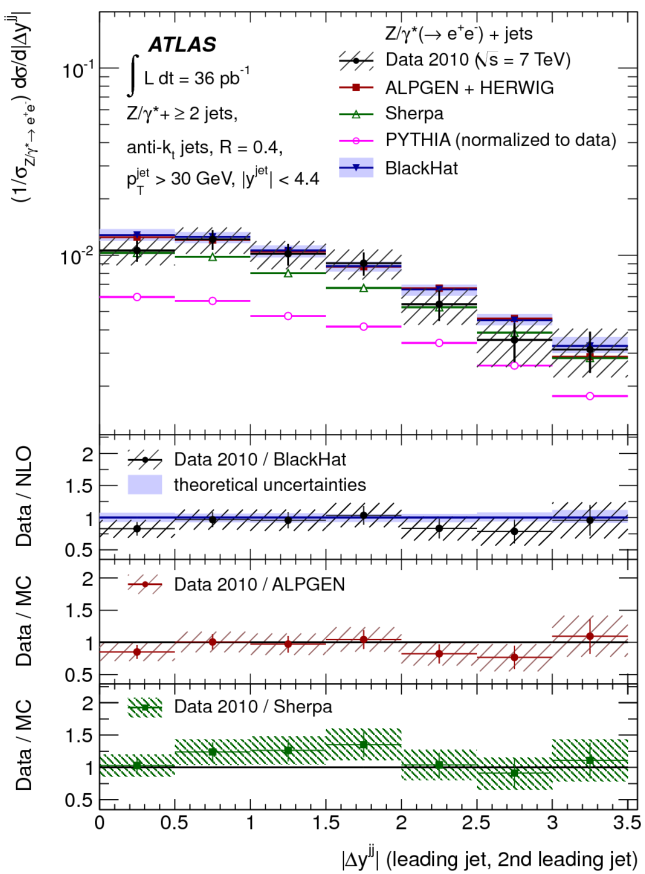
W+jets

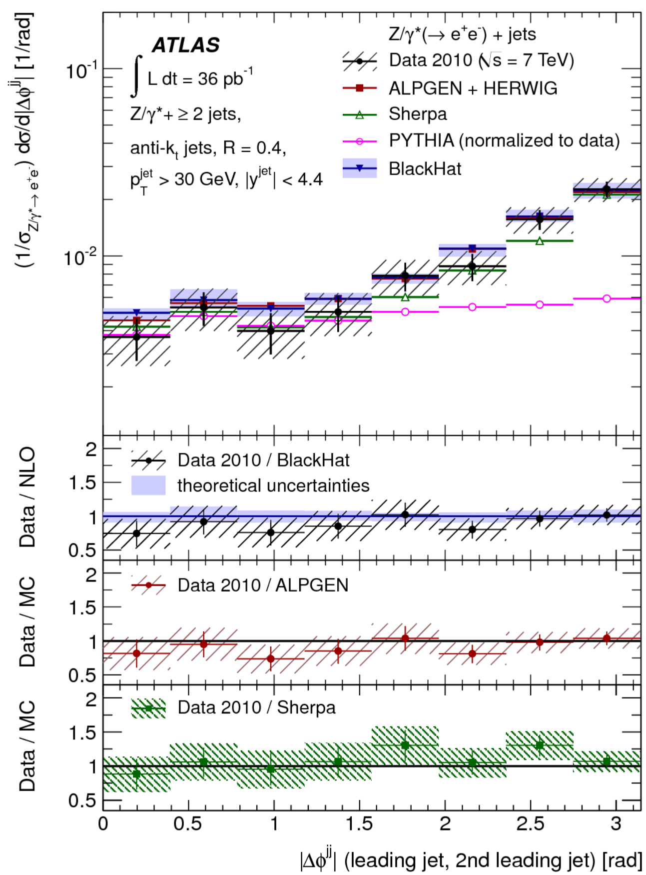


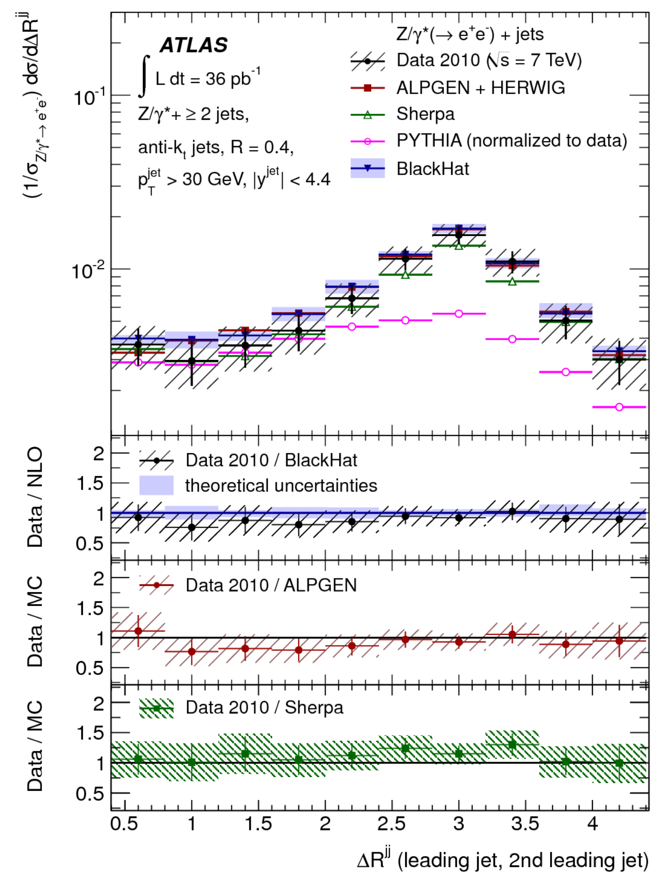
- Various energy scales and high multiplicities already available in 2010 data
- Data consistent with NLO pQCD prediction and with ME generators SHERPA and ALPGEN
- Not consistent with PYTHIA parton shower

Dijet Angular Distributions

Z+jets

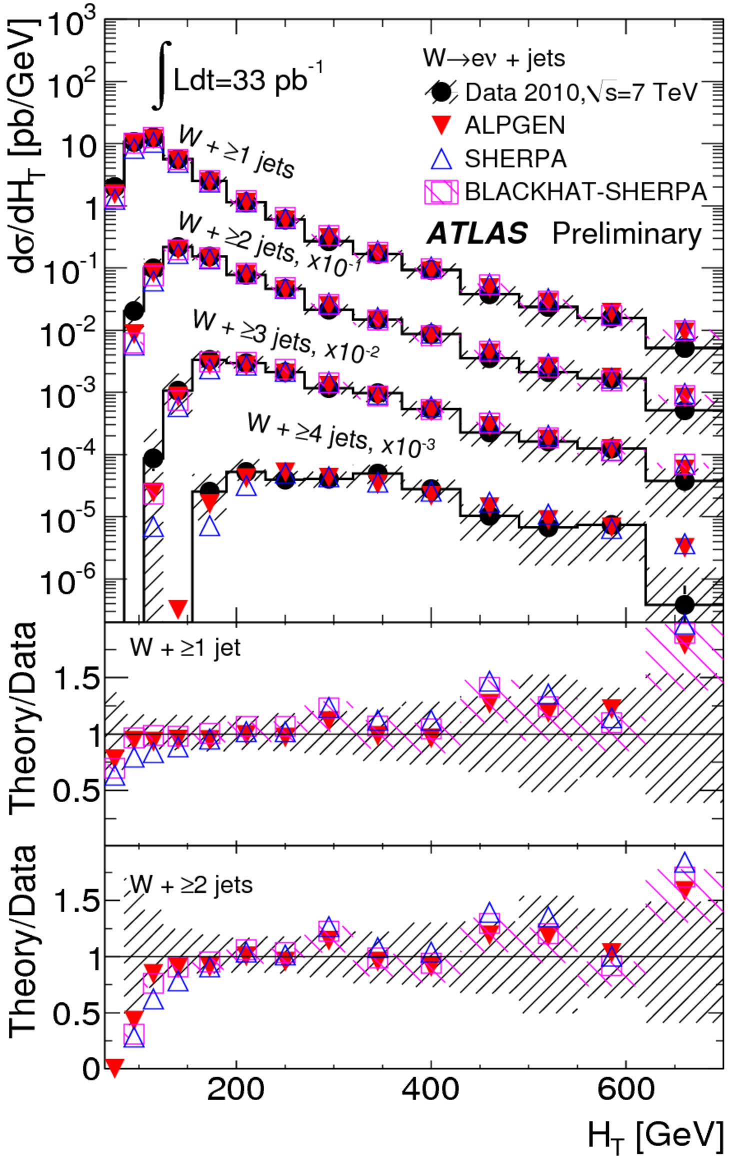


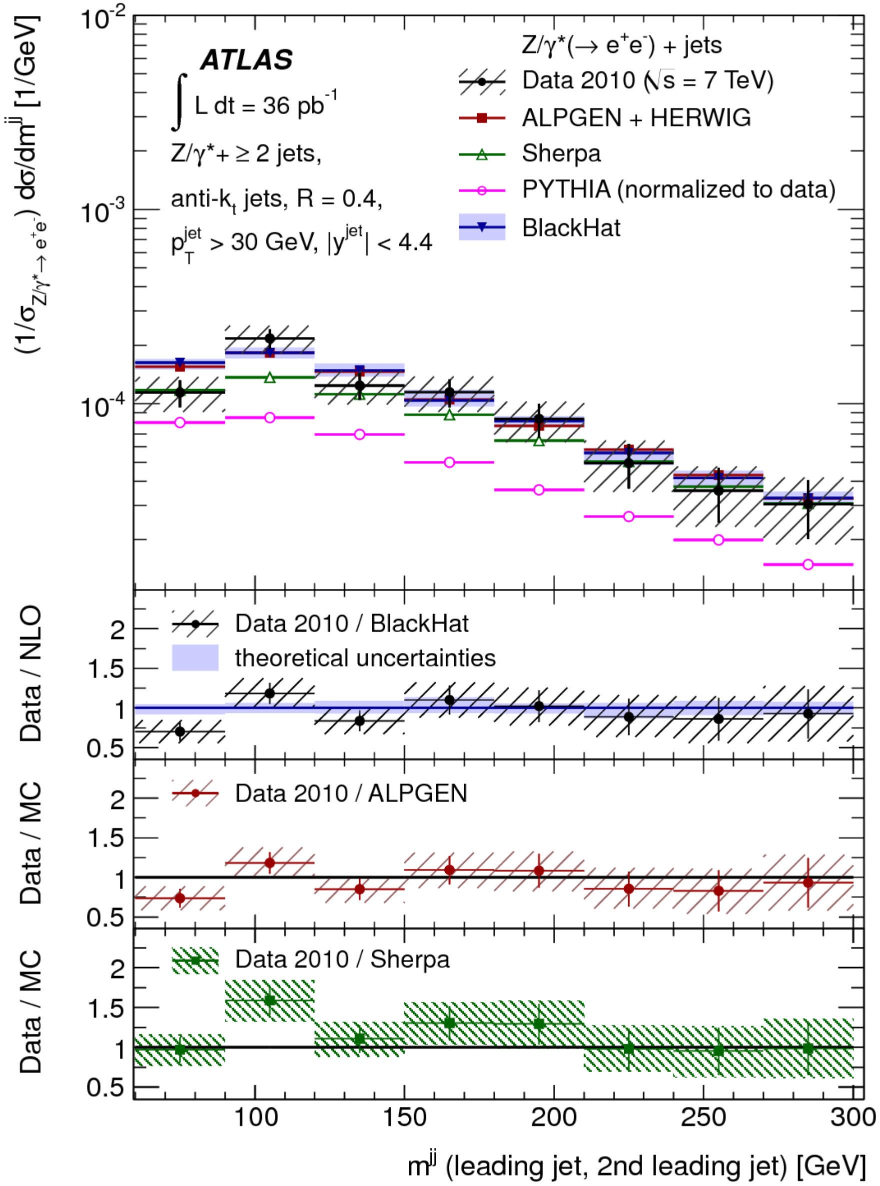




- Probe hard parton emission at large angles
- Of interest for example for VBF topologies (Higgs searches)
- Well described by NLO pQCD predictions and SHERPA+ALGPEN ME generators

Results in More Complex Variables

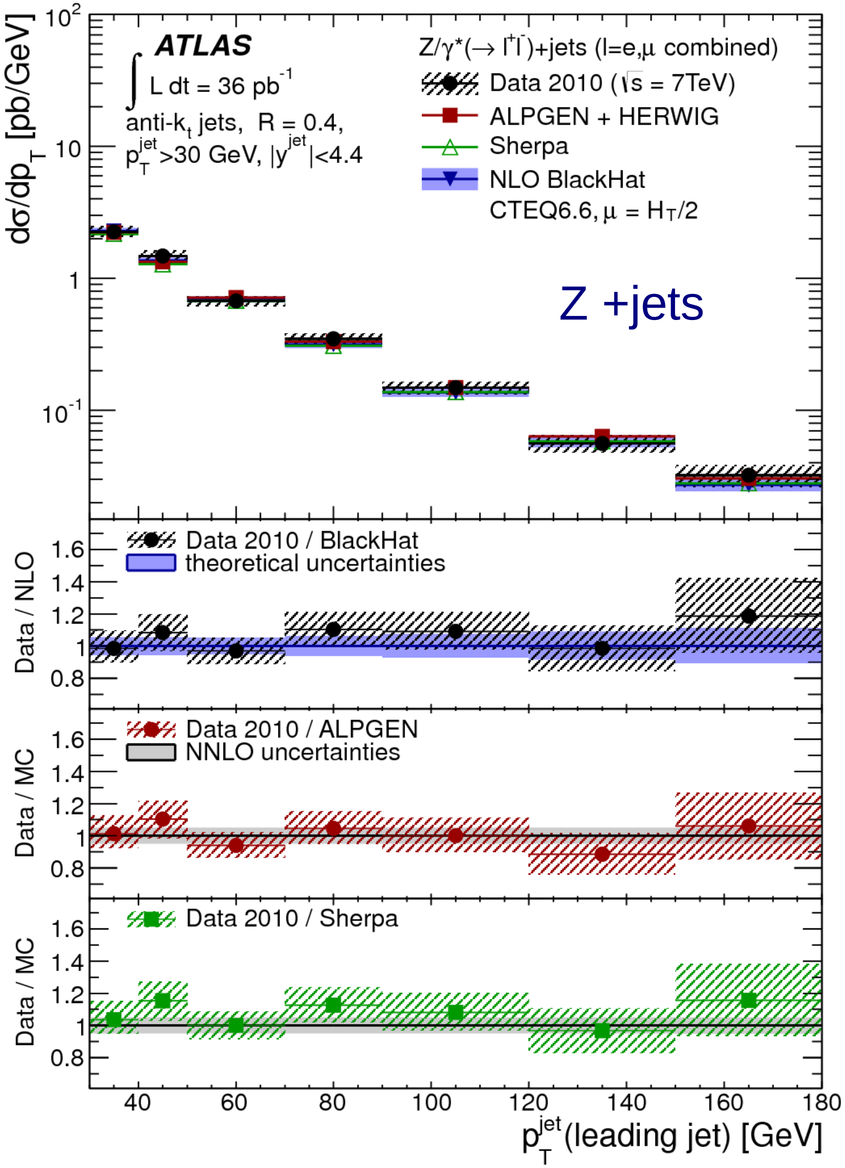


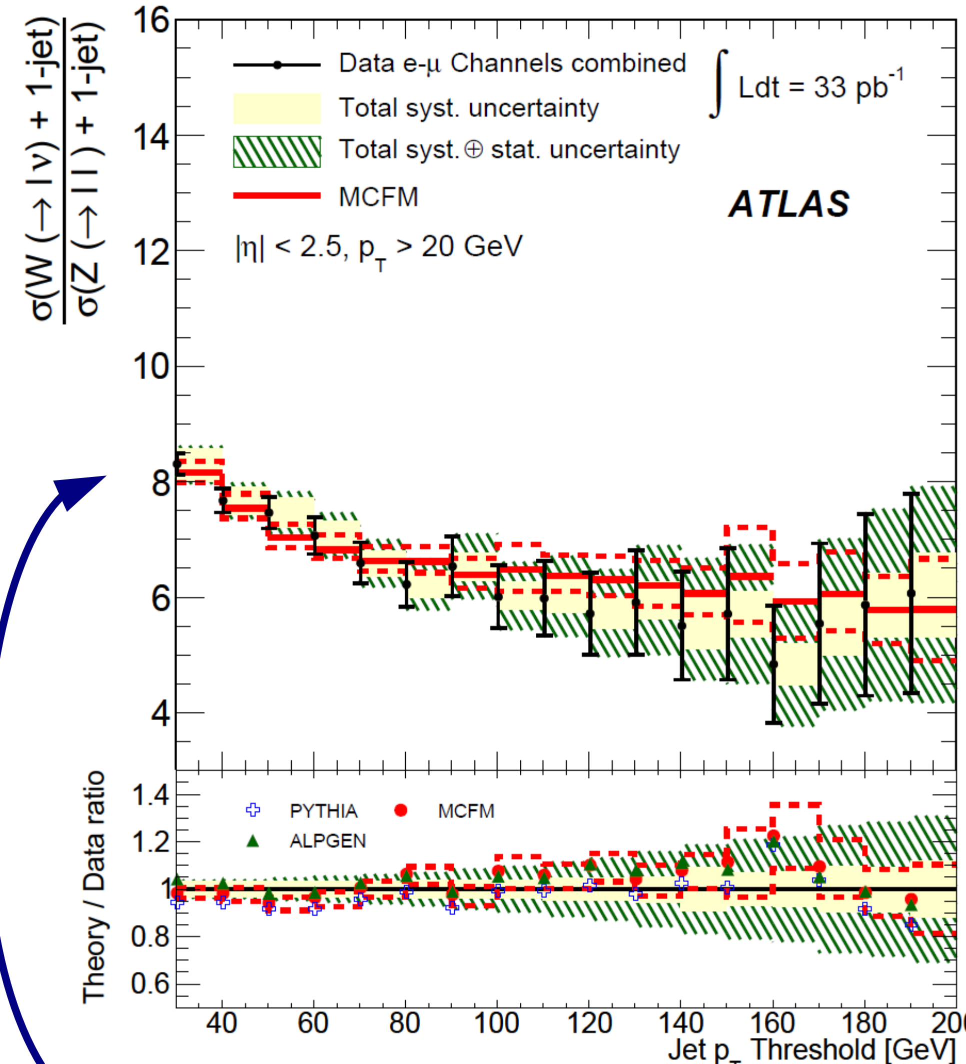


- H_T often scale choice – $m_{W/Z}$ not good scale any more at large jet p_T
- Interesting for searches, also: invariant mass m_{12}
- Variables well described by pQCD predictions and ME generators

Combined Electron+Muon Phase Space

- Combine individual e/μ cross sections to roughly double statistics
- Minimal extrapolation to common e/μ phase space to minimizing model dependent corrections
- V+jets: use the BLUE (BestLinearUnbiasedEstimate) method
- R_{jets}: use BAT (Bayesian Analysis Toolkit)

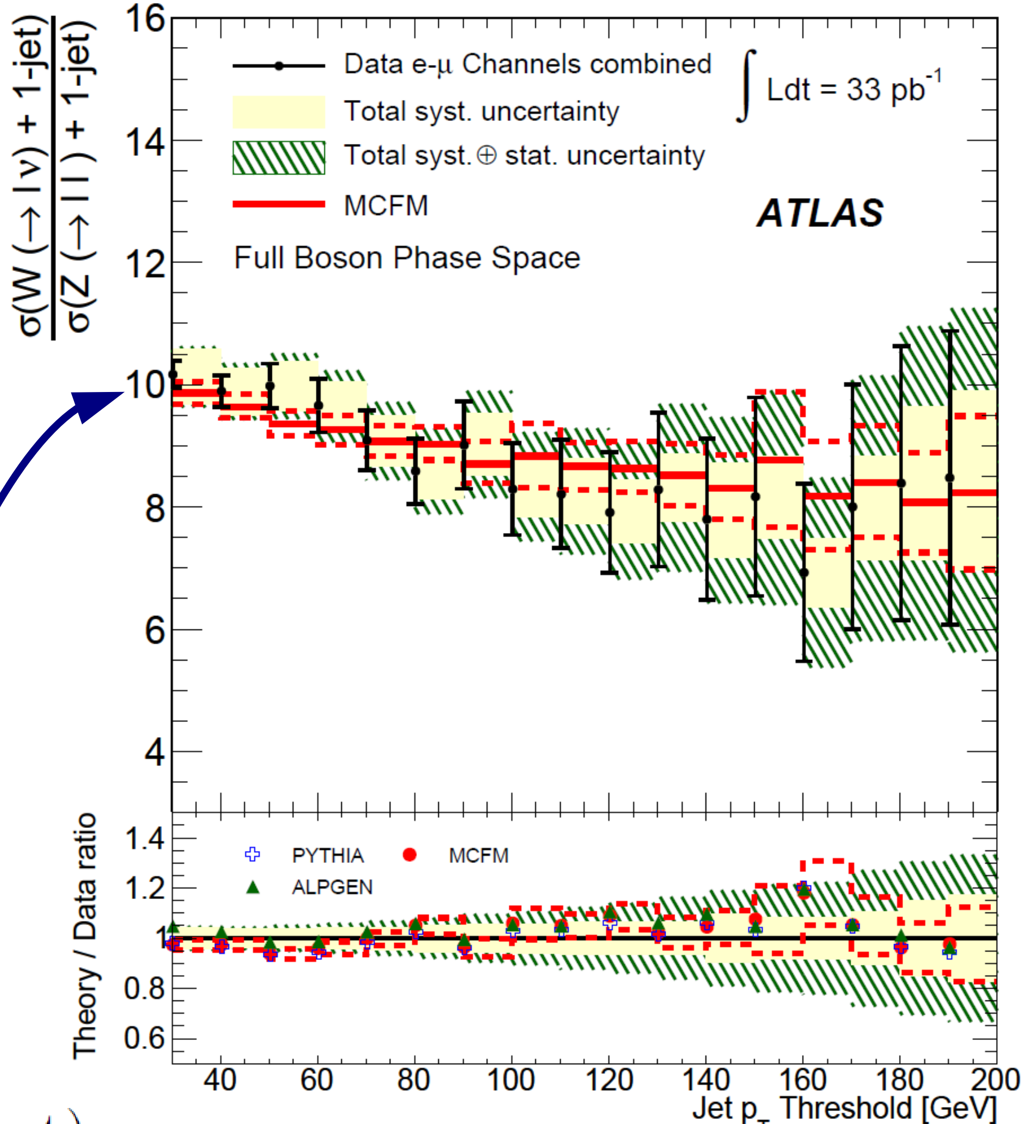




$$8.29 \pm 0.18\,(\mathrm{stat}) \pm 0.28\,(\mathrm{syst})$$

R_{jets} Extrapolation to Full Phase Space

- Want remove dependence on vector boson mass from fiducial phase space definition
- Later use in searches should allow **any** mass for vector boson like particles
- In principle complete cancellation of jet uncertainties possible
- But interpolation uses simulation: increased uncertainties compared to fiducial region measurement



Almost recover inclusive ratio:

$$10.13 \pm 0.22\,(\mathrm{stat}) \pm 0.45\,(\mathrm{syst})$$

Outlook

Many possibilities... have already 100x the statistics available

- V+jets: Measure at higher multiplicites, go to higher p_T
- R_{jets}: probe more distributions and extended phase space
  (mostly already explored by V+jets)
- Add novel distributions interesting for backgrounds. Examples:
  - V + 2-jets specific distributions → VBF-like signature
  - Jet vetoes / rapidity gaps
  - Event shapes, jet shapes
- Searches: Exploit precision of ratio measurements to look for deviation from SM predictions in model-independent way
- PDFs: W+/W- and Z probe different pdfs – input for pdf-fits?
- Theory: Compare to shower MCs in the future

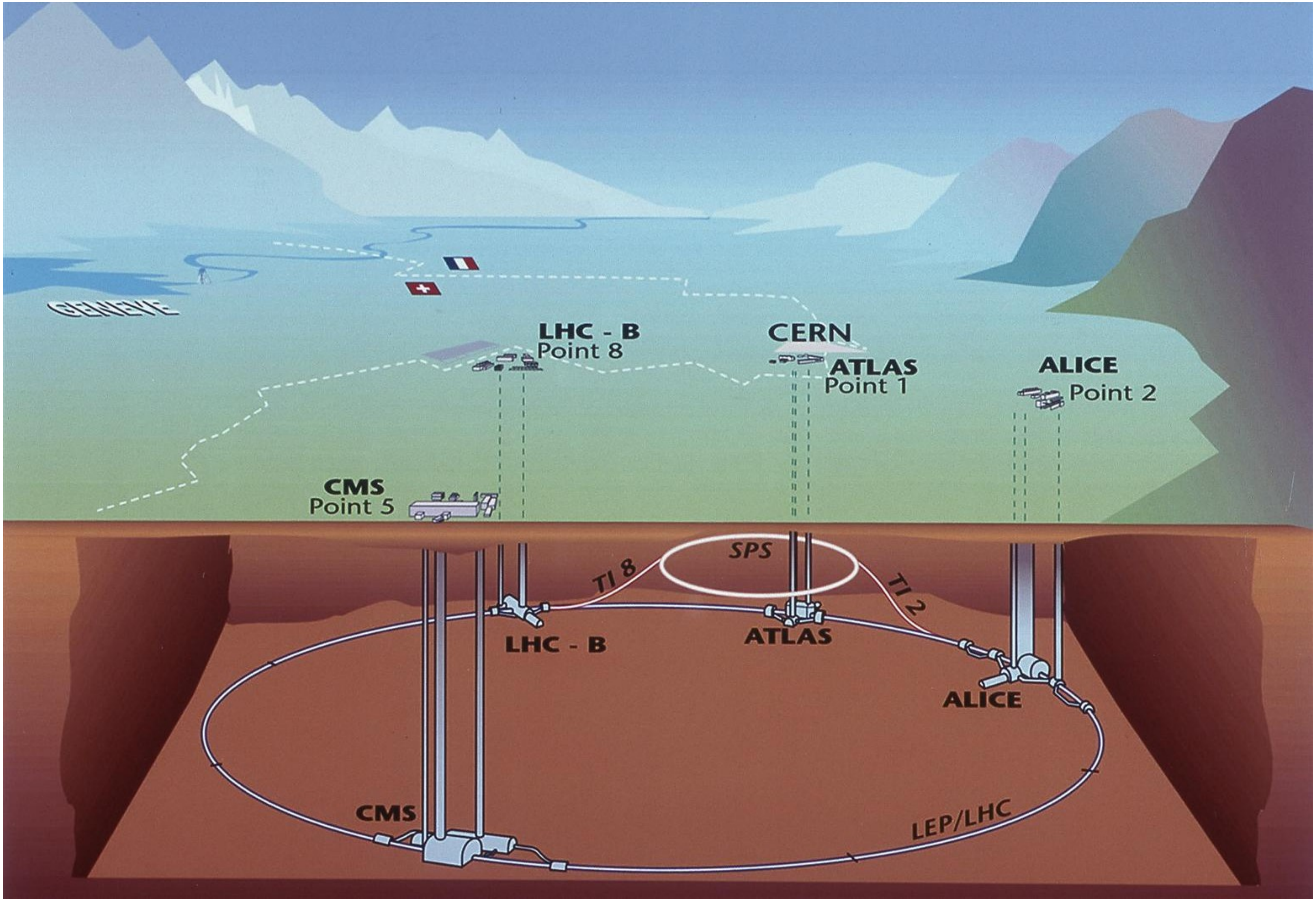
… there is still a lot of work to do in the Standard Model

Conclusions

- Presented measurements of the production cross-section for W and Z bosons in association with jets, performed with data collected in 2010
  - Inclusive cross-section as a function of jet multiplicity and its ratio
  - Differential cross-sections with respect to jet and di-jet kinematics
- Cross-sections corrected for all detector effects and quoted in the kinematic region of the detector acceptance
- Precision is mainly limited by systematic uncertainties
- Data compared to predictions at LO and NLO in QCD
  - Good agreement between data and predictions from ALPGEN, SHERPA, MCFM and Blackhat-Sherpa in region probed by measurements
  - PYTHIA disagrees with data when N_{jet}>1 (expected)

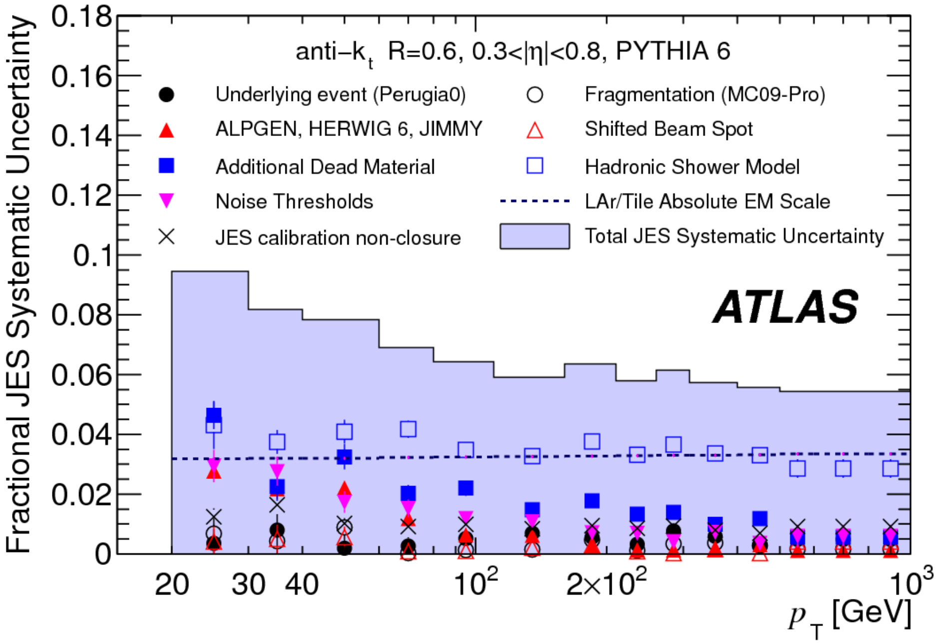
B A C K U P

The Large Hadron Collider



JES Components

0.3 < |η| < 0.8



2.1 < |η| < 2.8