W/Z + jets Results from ATLAS and CMS

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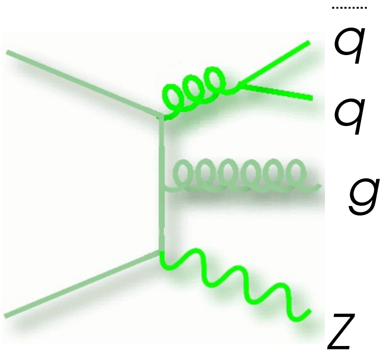
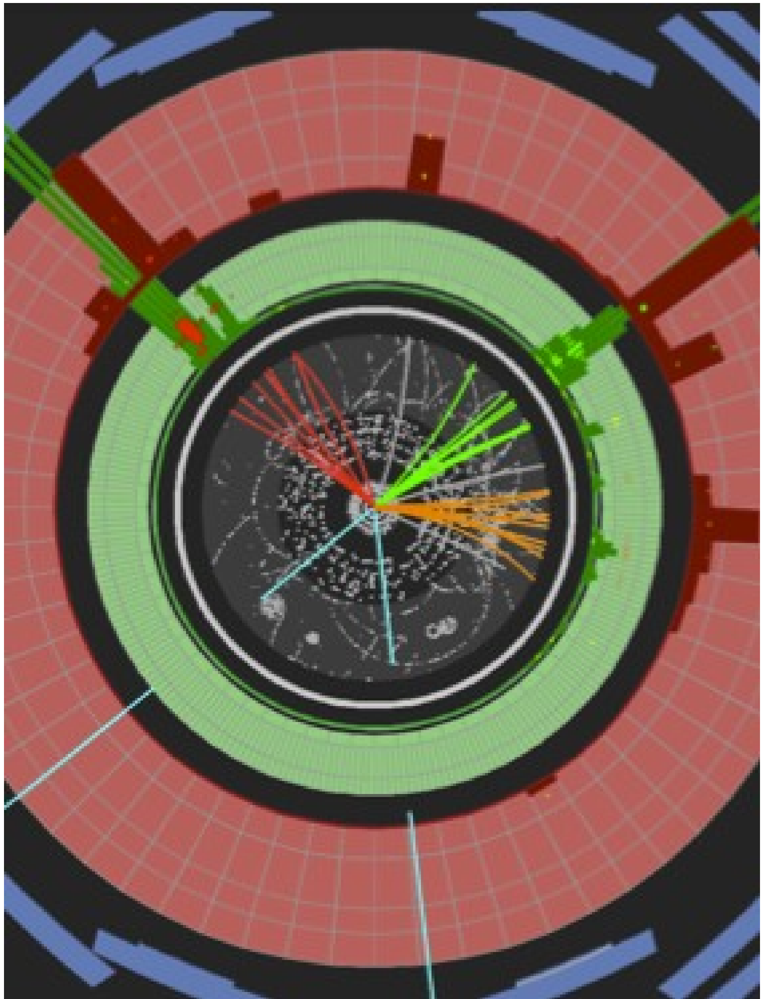
Introduction
W/Z+inclusive jets
W/Z+heavy flavour
Conclusion

Introduction

W and Z production:
- leptonic (e and μ) decay modes experimentally clean
  - fully reconstruct the Z
  - W has higher cross section, but more backgrounds

→ probe the underlying QCD process





Large cross sections, precision measurements:
- detailed understanding of datasets rather than maximum luminosity
- results based on 2010 data

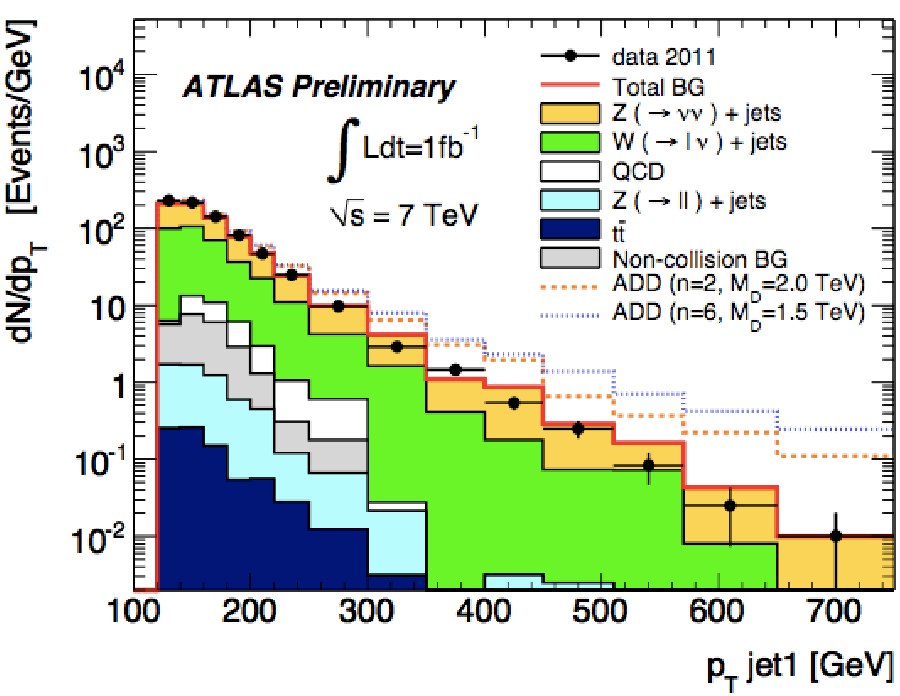
High jet multiplicities, heavy flavour jets:
- lower cross sections, require more luminosity for precision
- latest results use full 2011 data

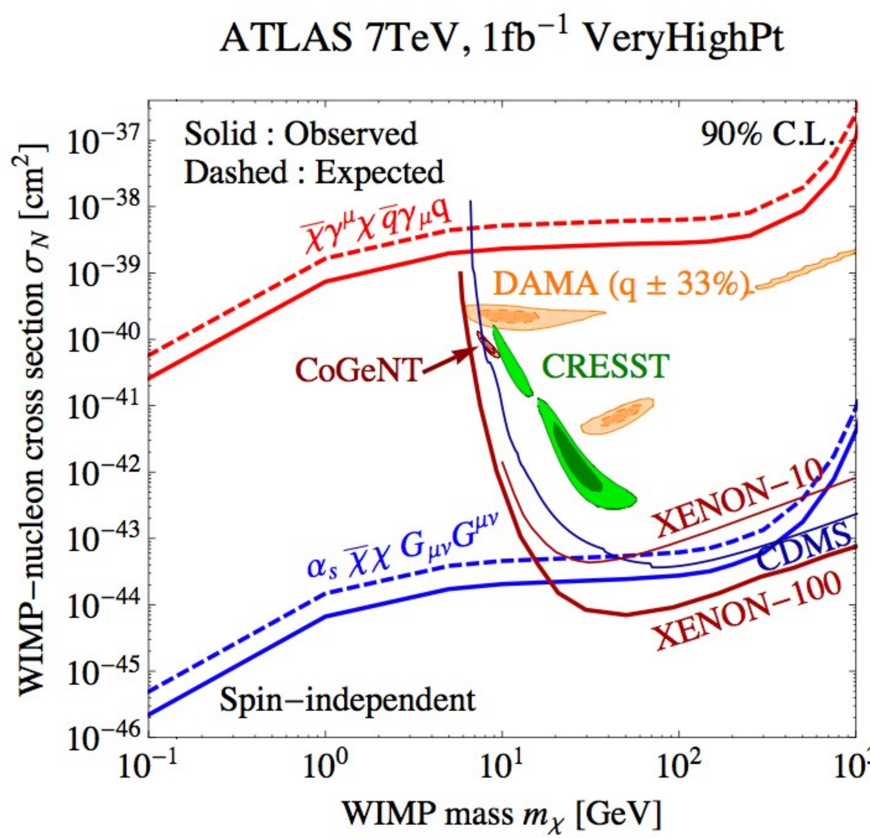
As a background

Signals: leptons, jets, missing energy (neutrinos)
- also the signature of many models of new physics

eg searches for direct WIMP production:
- mono-jet / mono-photon + missing energy (the WIMPs)
- main background: Z(→νν) + jet production

Need to understand W/Z+jets across all phase space!





Theory

W/Z jets events are complex:

- several high energy objects and possible scales (M_Z, jet pT's, ...)
- parton shower approach fills in region below a starting scale
  - obvious choice of M_Z → cannot populate region pT > ~M_Z

→ need matrix element corrections!

Pythia, Herwig:

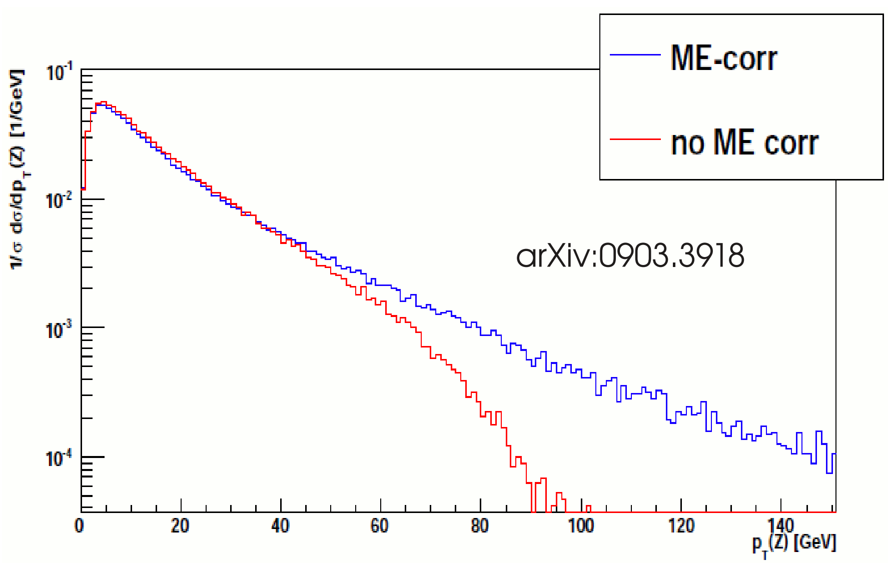
- V+jet matrix element corrections to parton shower model

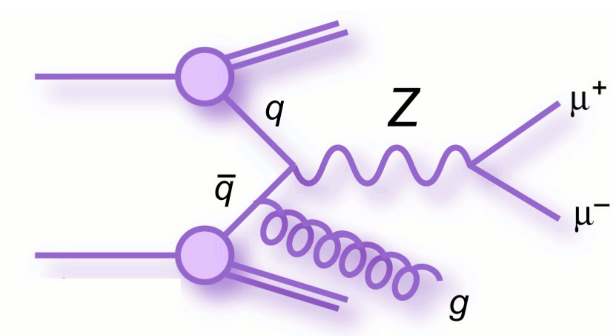
(a)MC@NLO, POWHEG:

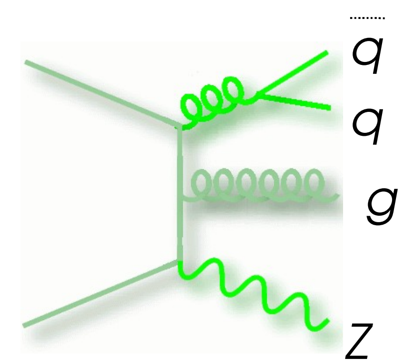
- NLO matrix element matched to parton shower (V, V+jet, V+bb)
- now including mass effects in V+hf production

Alpgen, Sherpa, Madgraph, ….:

- V+multijet tree level matrix elements matched to parton shower







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Pythia, Herwig:
(a)MC@NLO, POWHEG:
Alpgen, Sherpa, Madgraph, ...:

Full event generators

MCFM:

- fixed order NLO pQCD V+<=2 jets
    - can now be interfaced to Sherpa for hadronisation

Blackhat, Rocket:

- fixed order NLO V+<=4 jets (<= 5 jets in 2012)

Parton level calculations

Future:

- more jets to more orders (both in event generators and fixed order)
- MENLOPS
- 4 vs 5 flavour scheme for heavy flavour production

Measure phenomenologically sound cross sections!

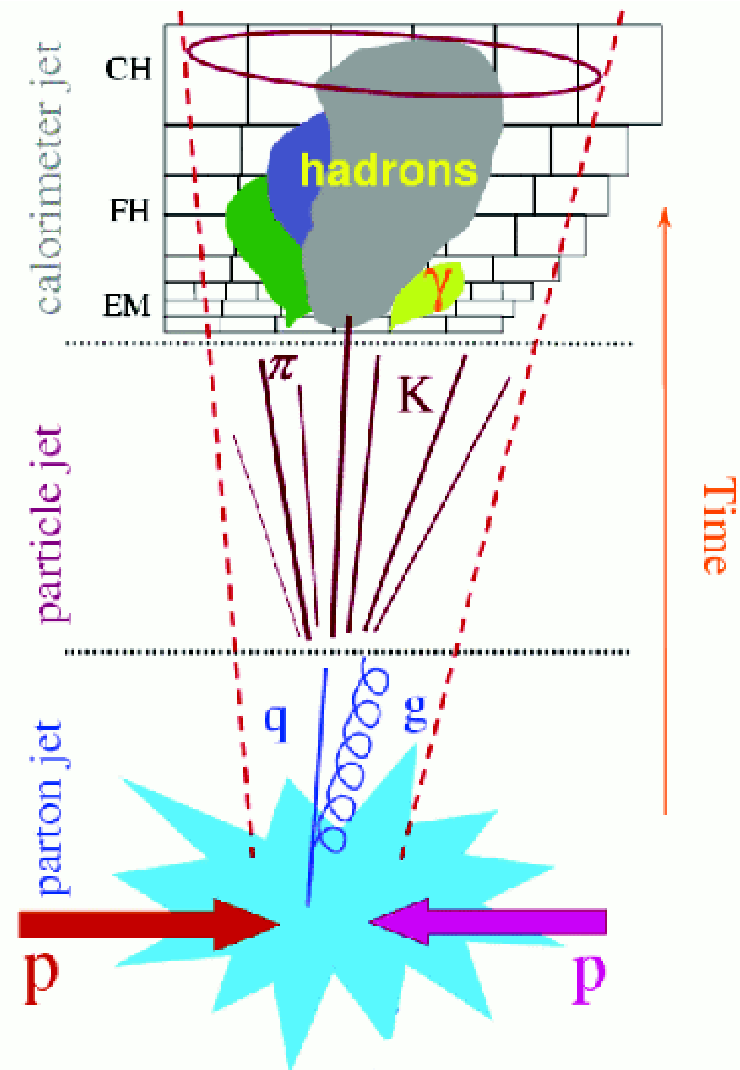
→ define observables in terms of particles entering the detector
→ fiducial cuts on the cross section to match detector coverage

Detector level jets:
- anti-kt algorithm, R=0.4 (0.5) at ATLAS (CMS)

“Unfold” data to particle level jets:
- using the same jet algorithm

...and heavy flavour jets:
- match particle level jets to b-hadrons

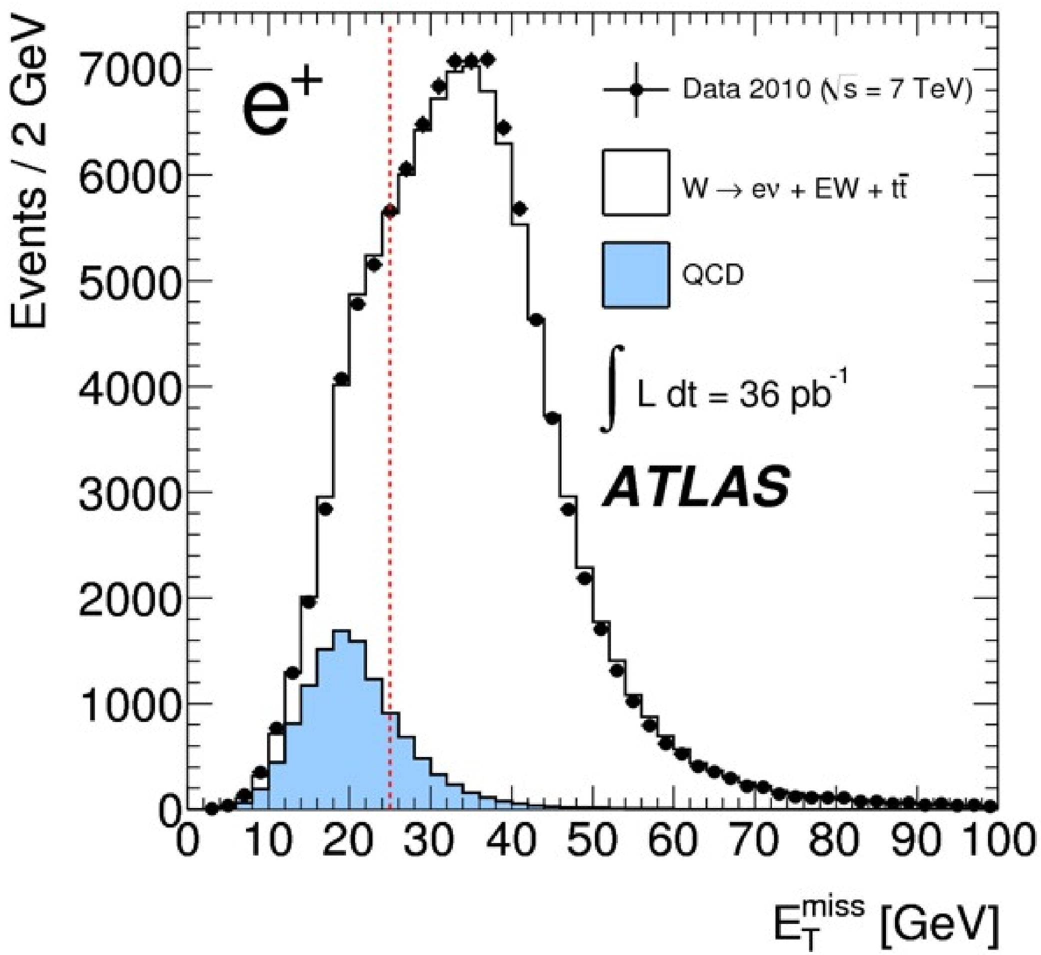
Parton level jets:
- from fixed order pQCD predictions
- need to be corrected to particle level

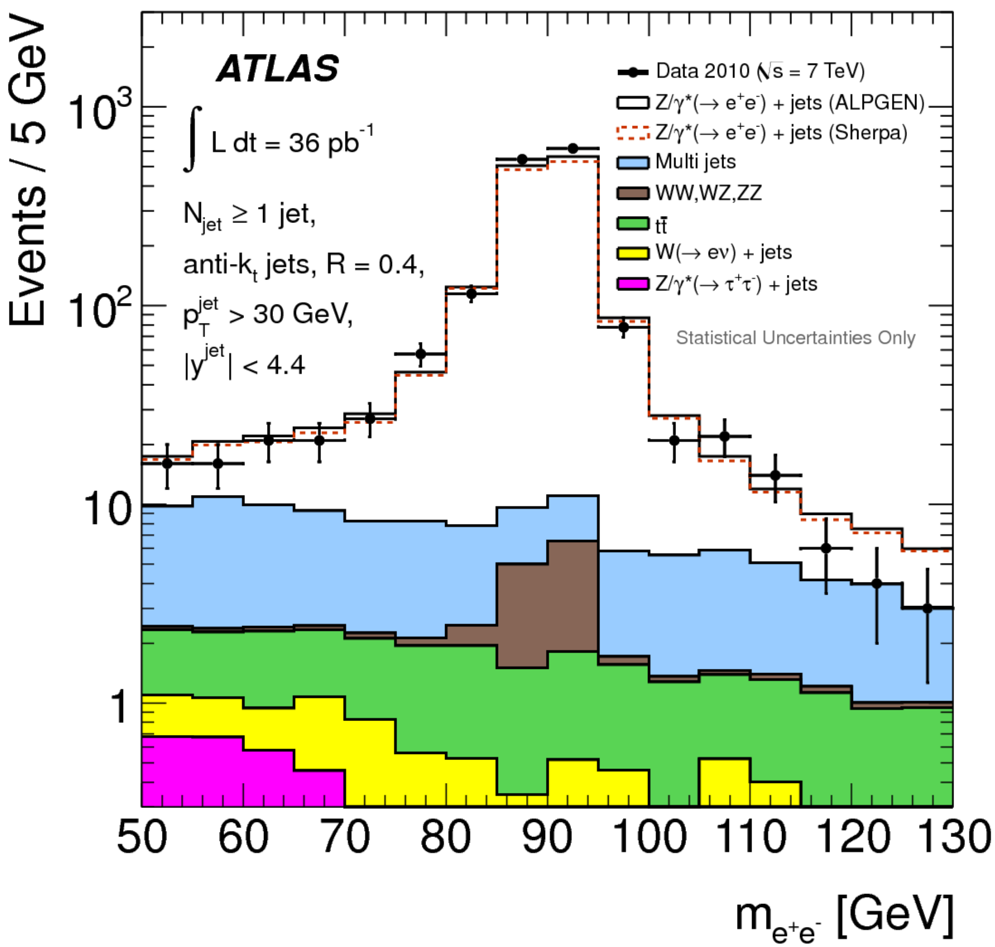


Backgrounds

Backgrounds to leptonic W / Z signals:

- generally very small!
- "qcd"/multijets: jets misidentified as electrons
- semi-leptonic hadron decays producing non-prompt leptons
- top, diboson, τ decay modes generally very small

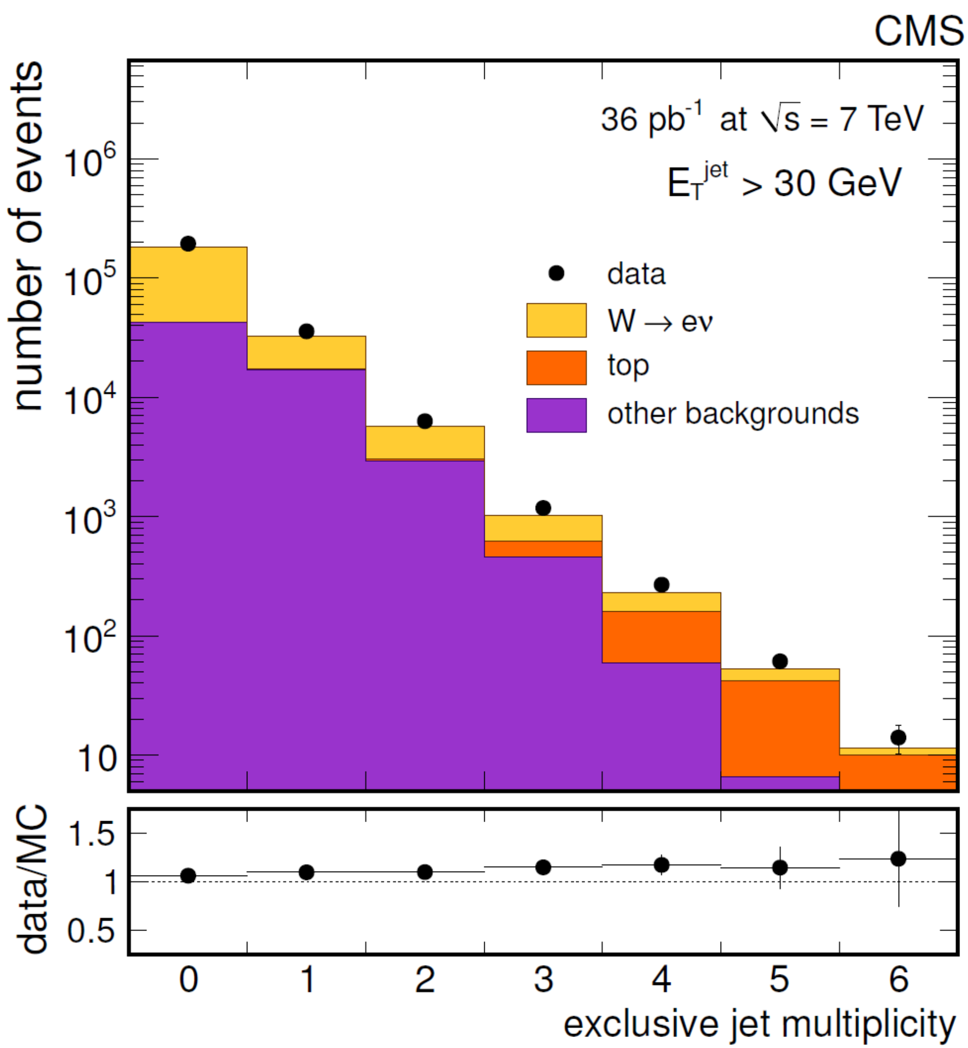


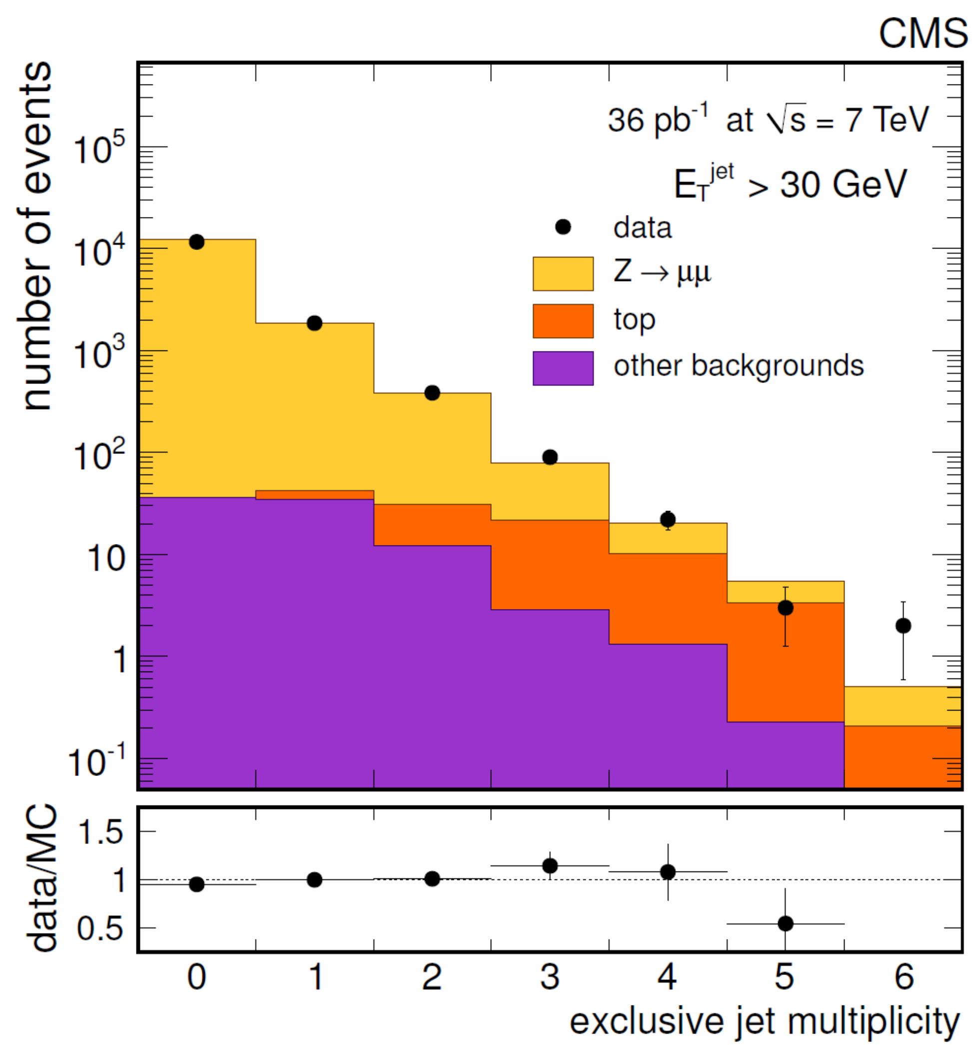


Backgrounds

Picture changes at high jet multiplicities!

- top becomes more important
- even more so in V + heavy flavour production (see later)





Results

Testing the Standard Model in all corners of phase space

- many distributions!

ATLAS, CMS, both:

- inclusive jet multiplicities
- ratios of jet multiplicities
- W charge asymmetry vs jet multiplicity
- pT of {1st, 2nd, 3rd, 4th} jet in >=1, 2, 3, 4 jet events
- rapidity of {1st, 2nd, 3rd} jet
- Δy(lepton, 1st jet) ; y(lepton) + y(1st jet)
- Δy(1st jet, 2nd jet), $\Delta\phi$(1st jet, 2nd jet), ΔR(1st jet, 2nd jet)
- H_T (scalar sum of all transverse energy)
- dijet mass in 2, 3, 4 jet events
- ratio of (Z+ >=i jet) / (W+ >=1 jet) vs jet pT
- Z+b jet, W+b-jet cross sections
- cross section and angles in Z+bb events (preliminary)
- W+charm cross section (preliminary)

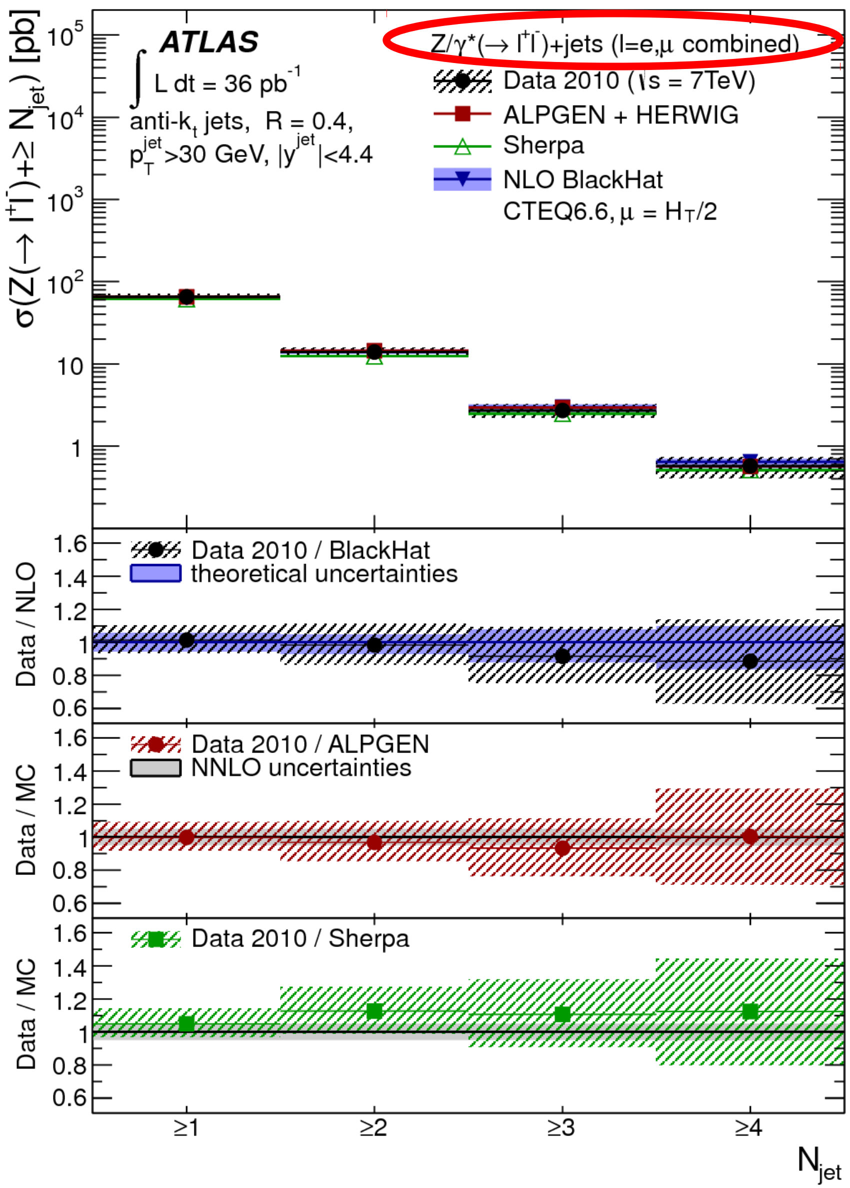
With selections typically:

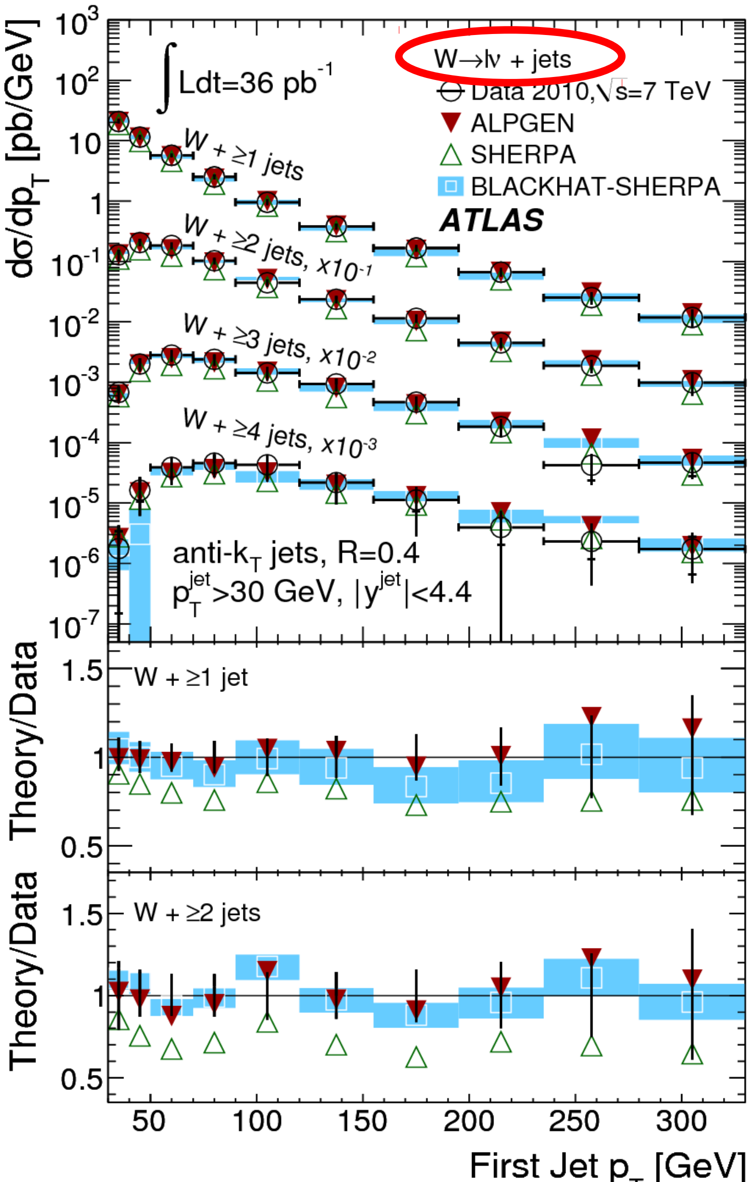
- lepton p_T > 20 GeV, $|\eta| < \sim 2.5$; missing energy > 25 GeV (W)
- $66 < M_{ll} < 116$ GeV (Z) , transverse mass > 40 GeV (W)
- jets: pT>20 - 30 GeV, ATLAS: $|y|<4.4$ ($|y|<2.1$ for heavy flavour), CMS: $|y|<2.5$

Jet cross sections

Start with basic jet multiplicities and pT distributions:

- testing the current best NLO and event generator predictions





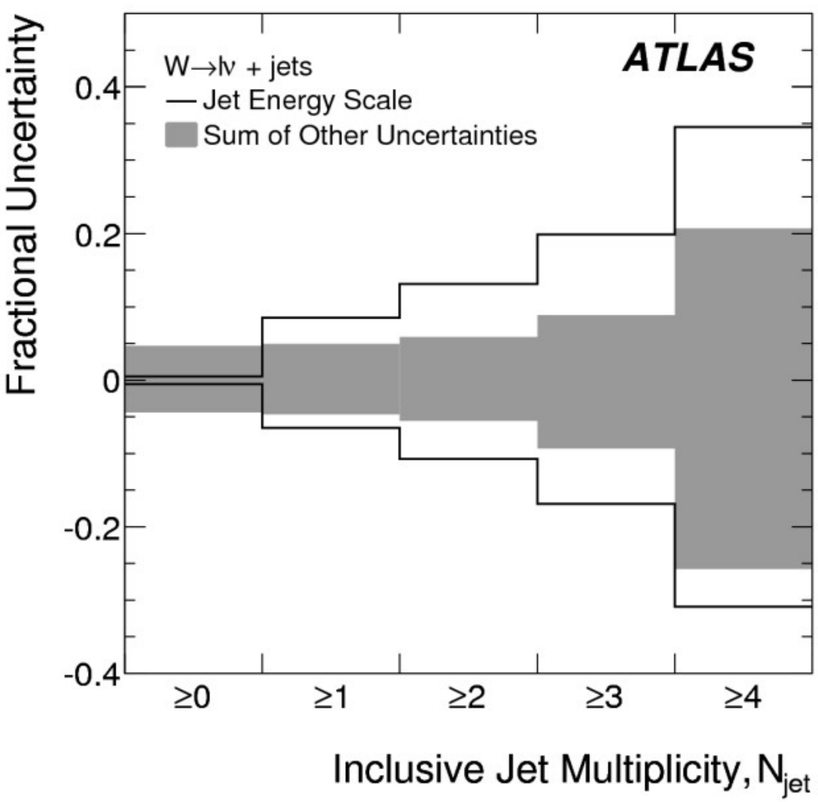
...and ratios

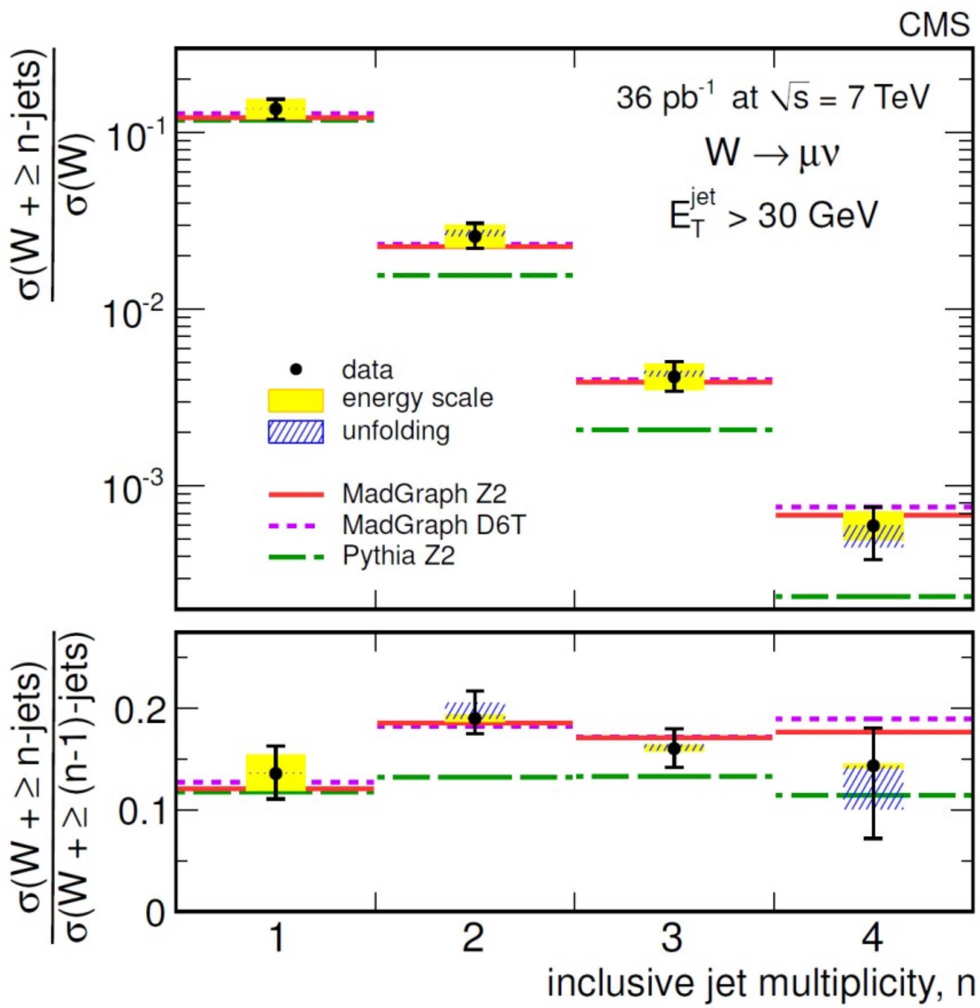
Systematics dominated by jet energy scale

- increases with jet multiplicity, and with jet rapidity.

Taking ratios allows some cancellation

→ more precise results



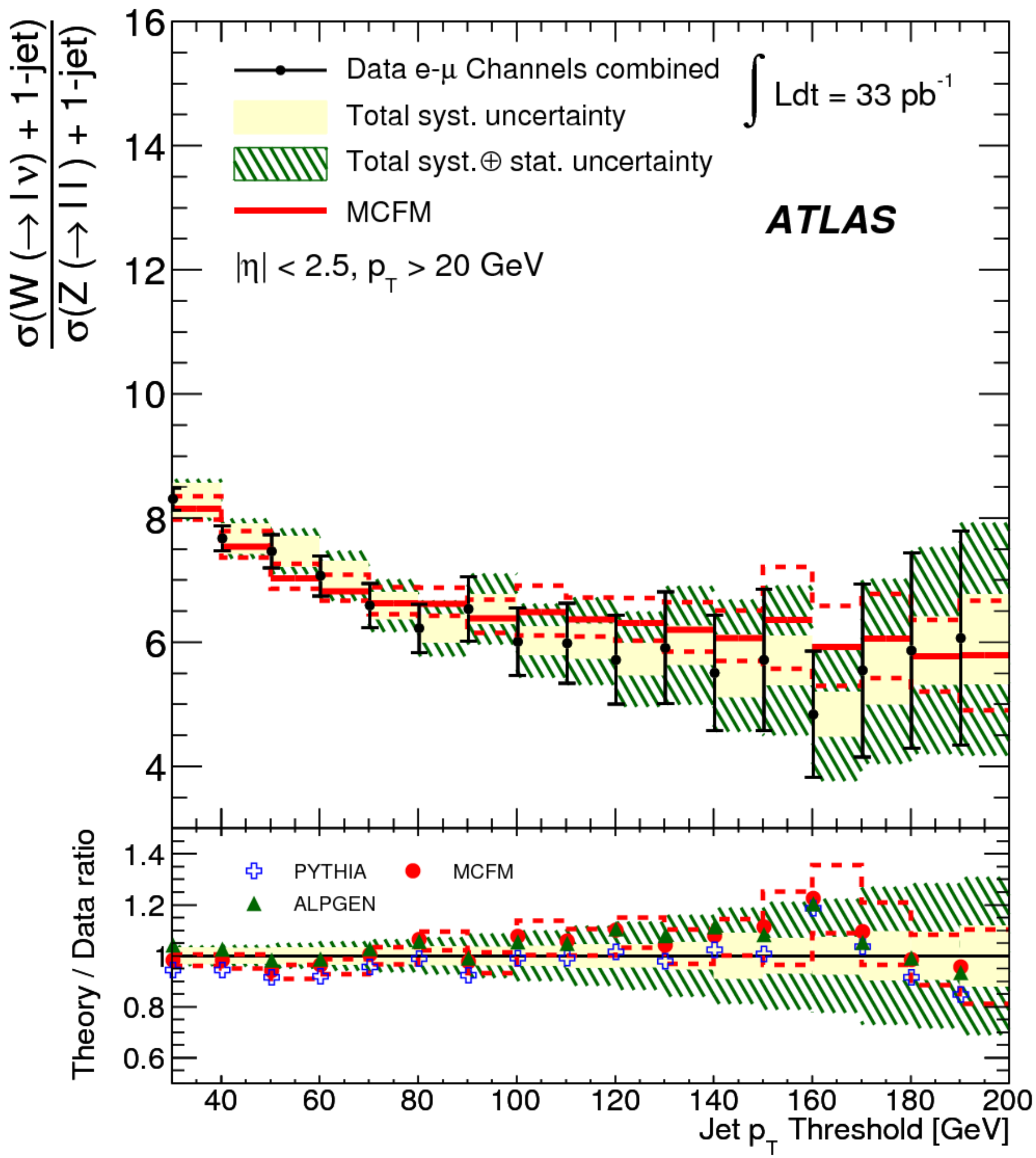


W+jet / Z+jet

Ratio of W + 1 jet / Z + 1 jet
- again cancel jet systematics

Test of PDF and pQCD:
- evolution of W/Z ratio with jet pT

Also sensitive to new physics in dilepton vs single lepton modes
- X→ W + x would change ratio



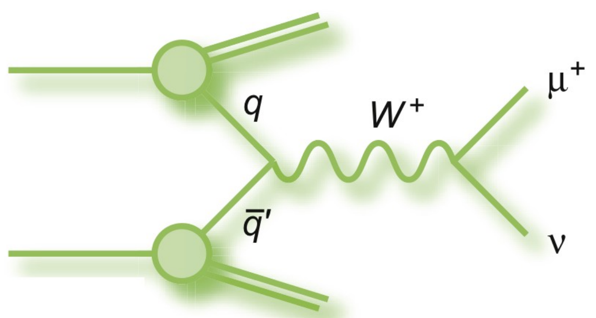
W Charge Asymm.

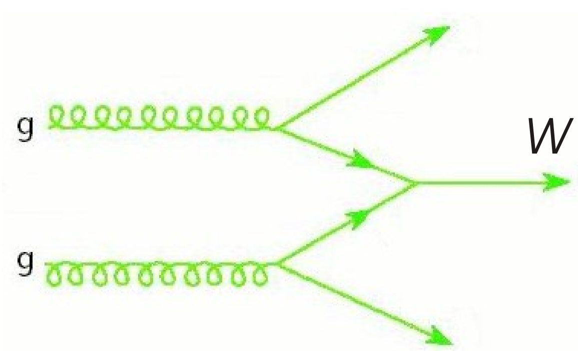
Expect more W+ than W- at proton collider
- more up than down valence quarks!

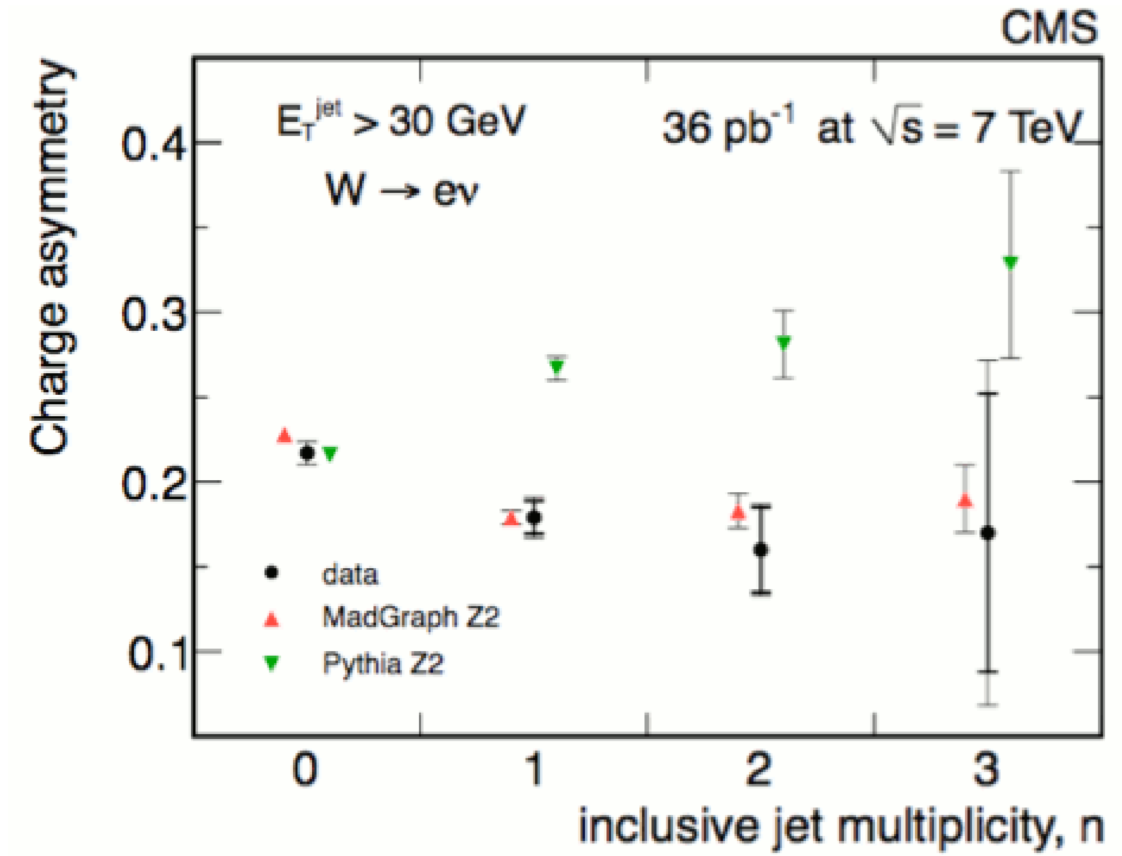
$$\text{charge asymm.} = \frac{\sigma(W^+) - \sigma(W^-)}{\sigma(W^+) + \sigma(W^-)}$$

At higher jet multiplicities:
- asymmetry decreases
- more non-valence initiated production

Pythia does not include gg->W+X
- does not follow the data







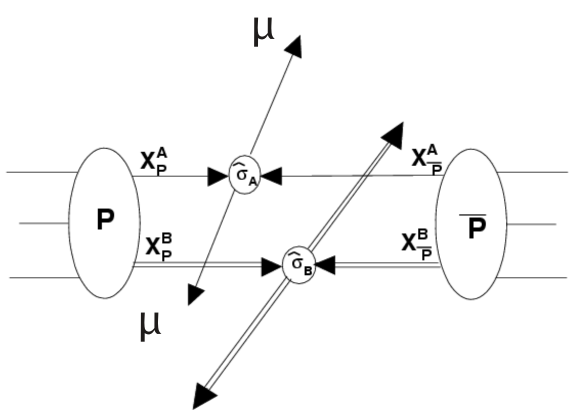
Angles: $\Delta\phi$

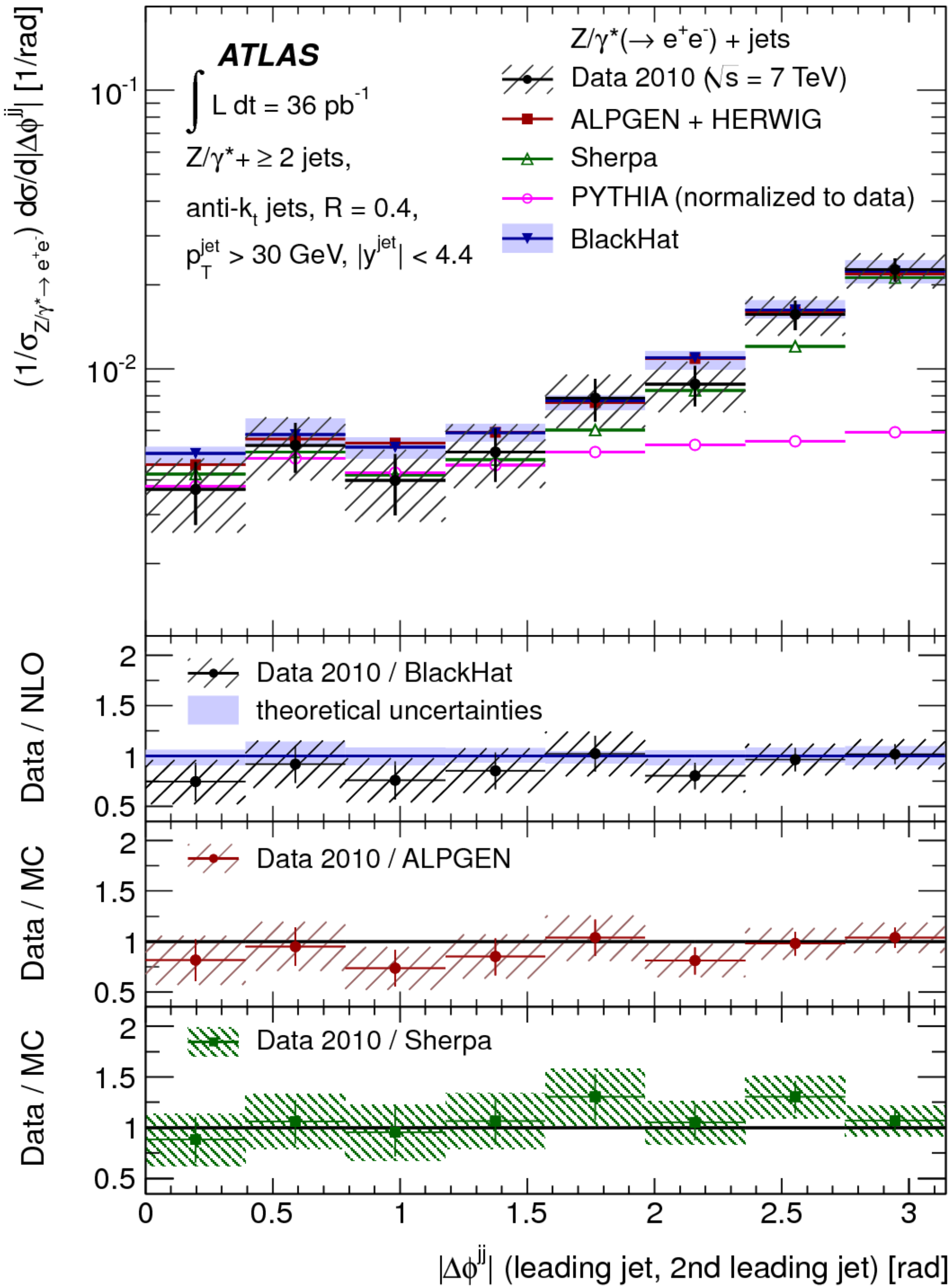
Parton shower vs matrix element:

- Pythia unable to populate the "back-to-back jets" region

Multiple Parton Interactions:

- two hard parton scatters
- more likely to fill back-to-back region
- important background at high energy!





Angles: $\Delta\phi$, and MPI

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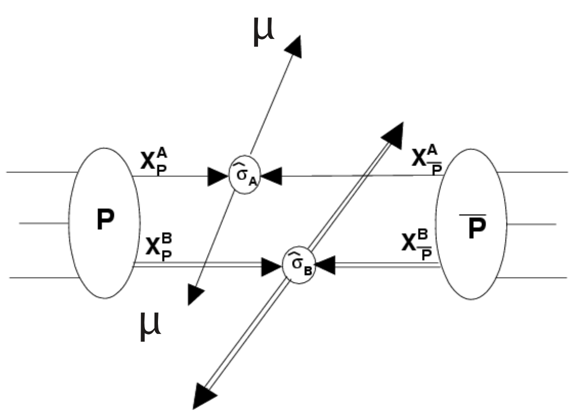
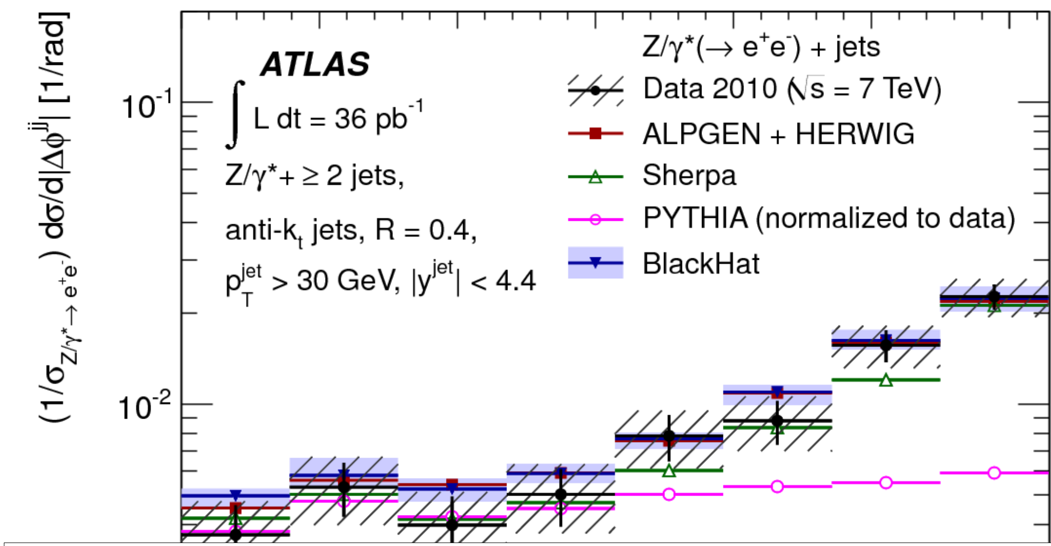
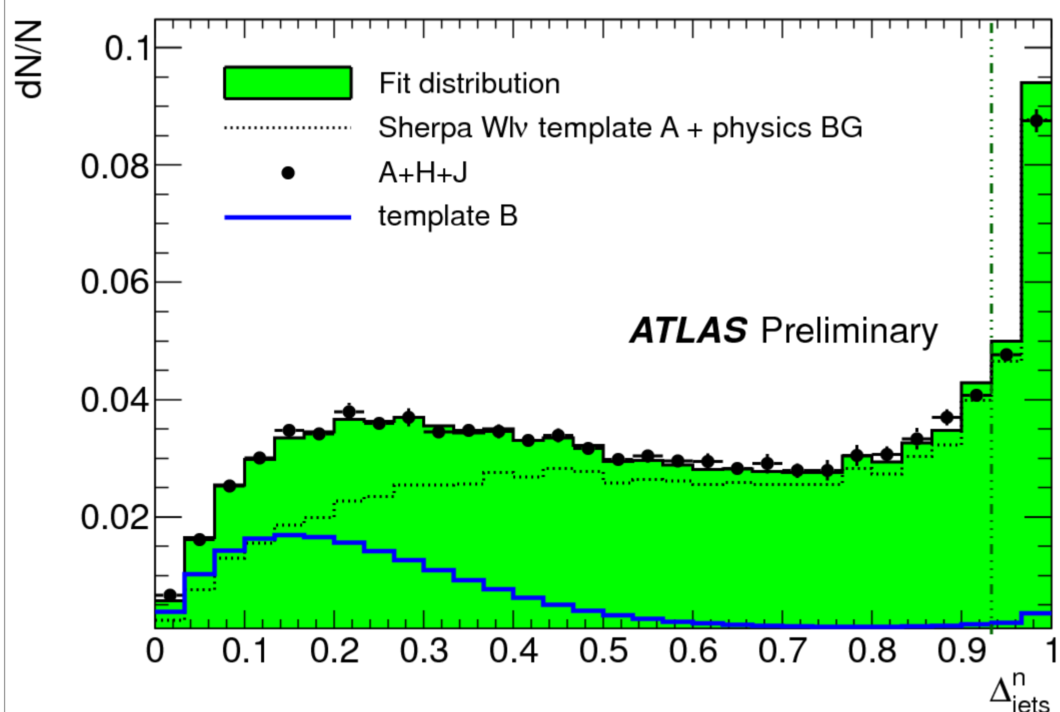


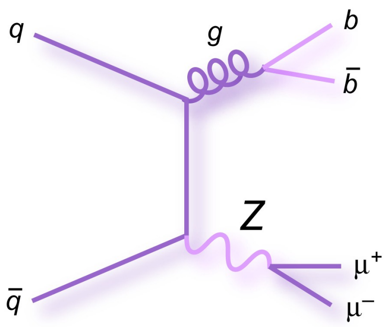
Extract σeff from W + 2-jet events
- MPI rate from template fits

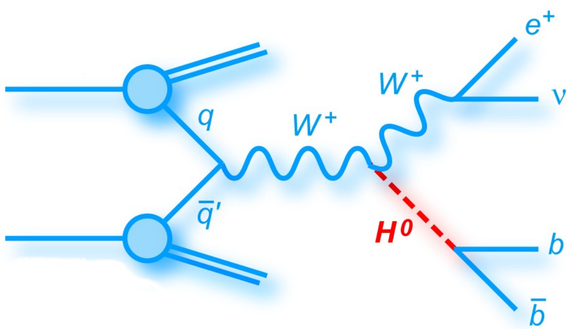
$$\sigma_{\text{eff}}\ (7\ \text{TeV}) = 11 \pm 1\ (\text{stat})\ ^{+3}_{-2}\ (\text{sys})\ \text{mb}$$

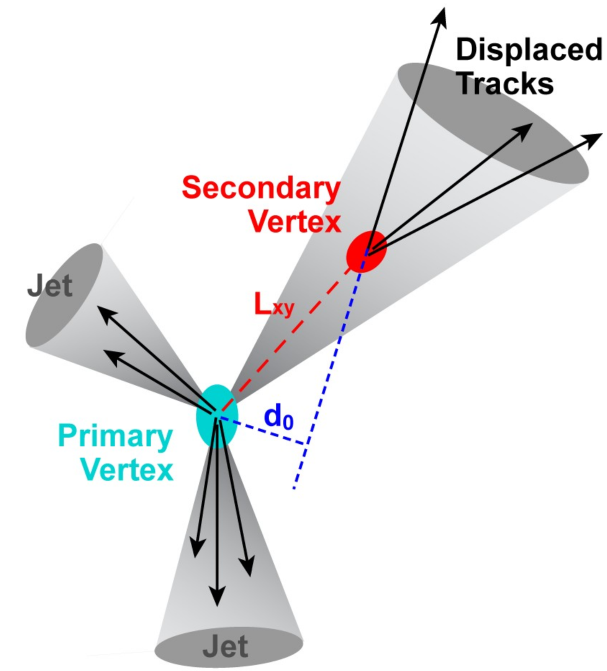




Heavy Flavour





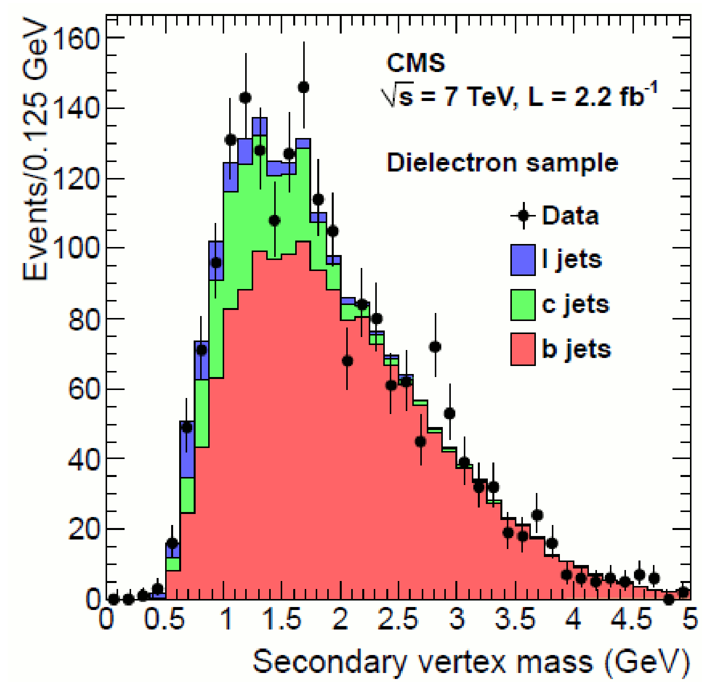


Predictions have large theory uncertainties
-precise measurements can have high impact

Tagging based on displaced vertex
- Typically put many variables into discriminant
- cut on output to "tag" a jet

Fit a further discriminating variable
- using templates from MC

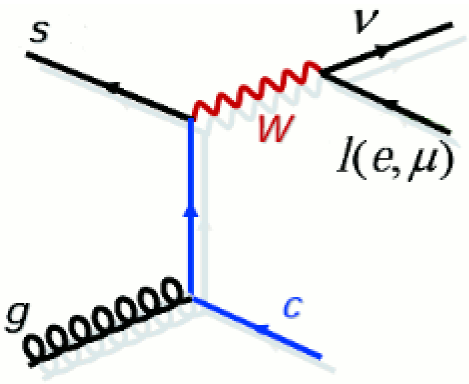
Tagging efficiency and template fits dominate systematics

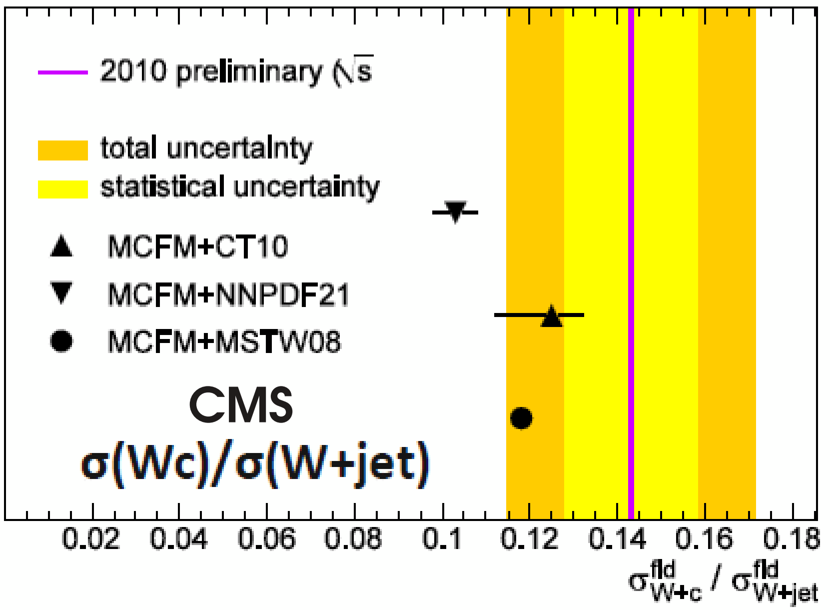


W+b,c

W+c:

- sensitive to strange PDF





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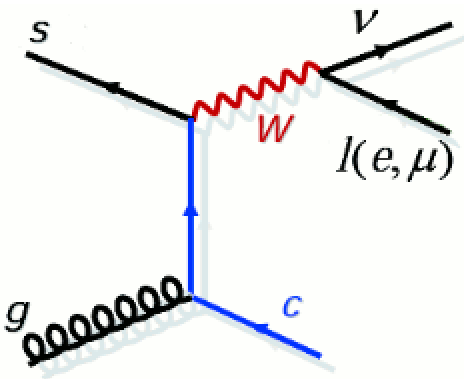
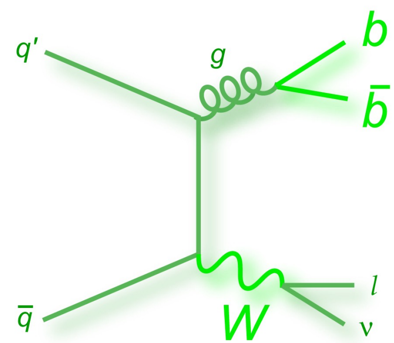
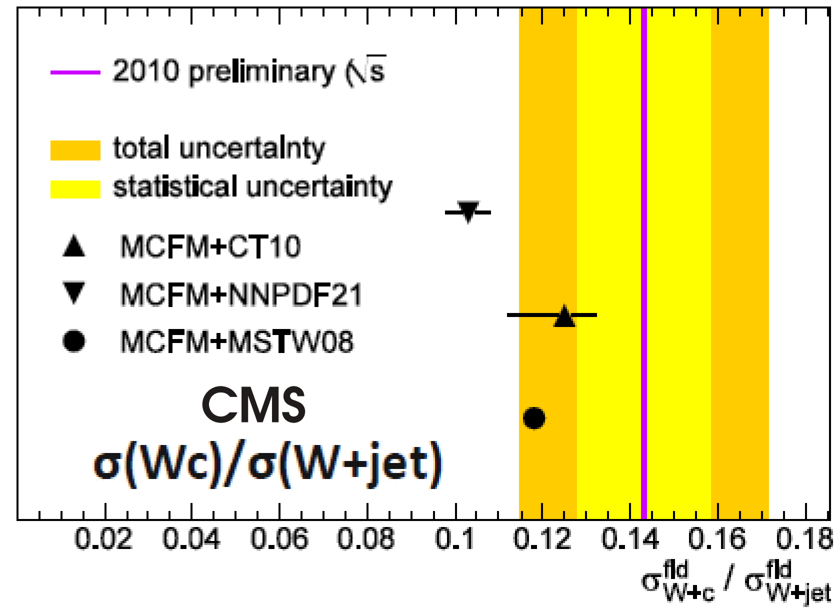
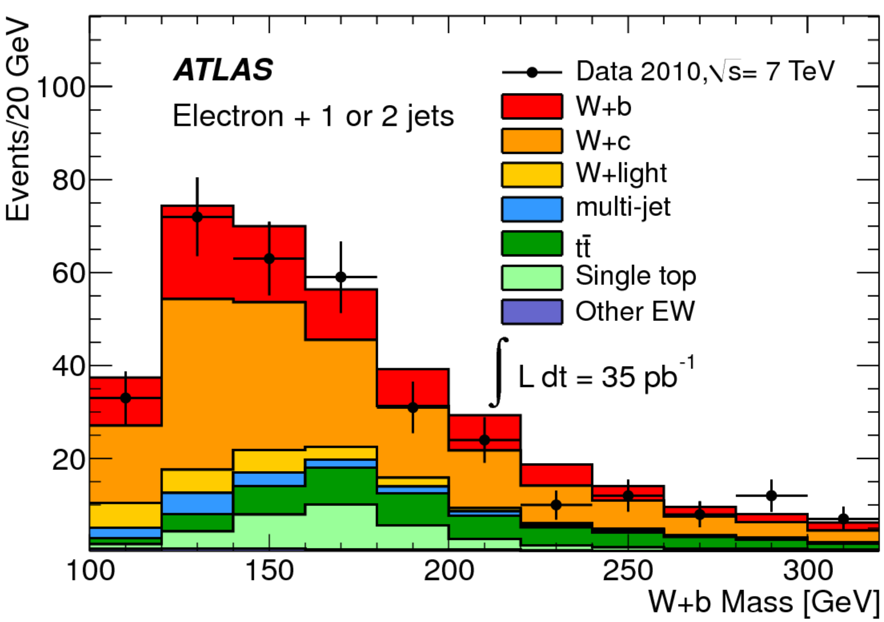


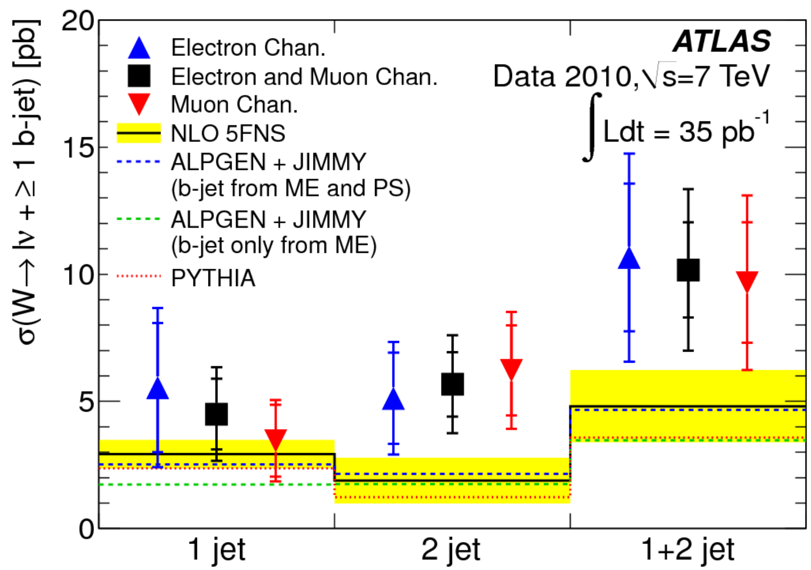




W+b has significant backgrounds

- W+c in 1-jet sample
- top in >=2 jet sample





Z+b(b)

Measured cross section for Z+b production

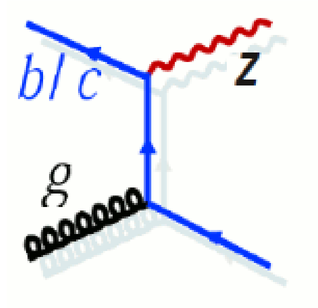
- **ATLAS:** (36 pb^{-1})

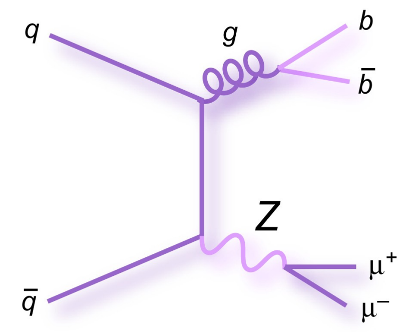
$$3.55^{+0.82}_{-0.74}(\text{stat})^{+0.73}_{-0.55}(\text{syst}) \pm 0.12(\text{lumi})\ \text{pb}$$

- **CMS** (2.2 fb^{-1})

Z+>=1b $3.78 \pm 0.05(\text{stat.}) \pm 0.31(\text{syst.}) \pm 0.11(\text{theory})\text{pb}$

Z+>=2b $0.37 \pm 0.02(\text{stat.}) \pm 0.07(\text{syst.}) \pm 0.02(\text{theory})\text{pb}$





MCFM: $4.27^{+0.56}_{-0.55}\ (\text{scale})\ ^{+0.08}_{-0.9}\ (\text{PDF})\ ^{+0.08}_{-0.10}(\alpha_s) \pm 0.36\ (\text{npc})\ \text{pb}$

ALPGEN	2.23 ± 0.01 (stat only) pb
SHERPA	3.29 ± 0.04 (stat only) pb

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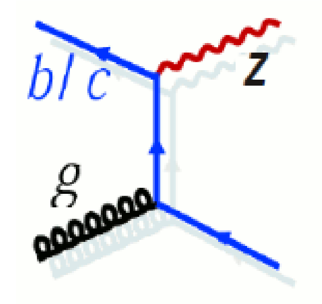

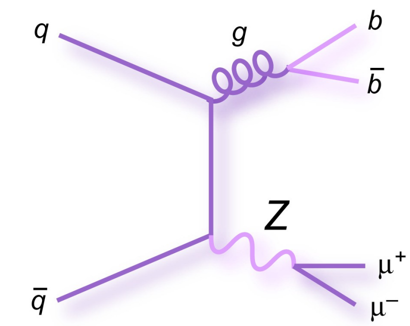

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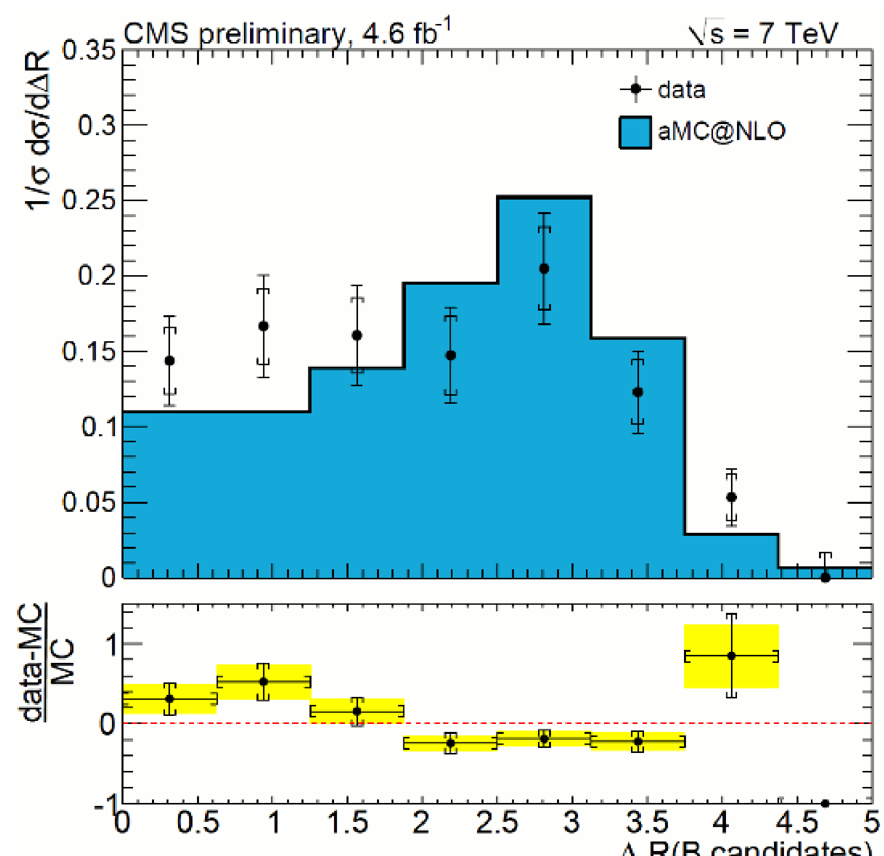
First measurement of bb production
- and angular distributions



Sensitive to different physics contributions:
- hard vs soft gluon splitting
- multiple parton interactions

Testing latest NLO predictions
- new aMC@NLO prediction
- with quark mass effects

Conclusion

V + jet production as a test of the Standard Model:

- clean boson signal
- study complex, multi object final states
  → area of active theoretical and experimental work
- analysis of full 2011 and now 2012 data underway
- so far, state-of-the-art calculations provide good description of data

V + heavy flavour production:

- entering precision era
- confirm or rule out tensions with theory in near future

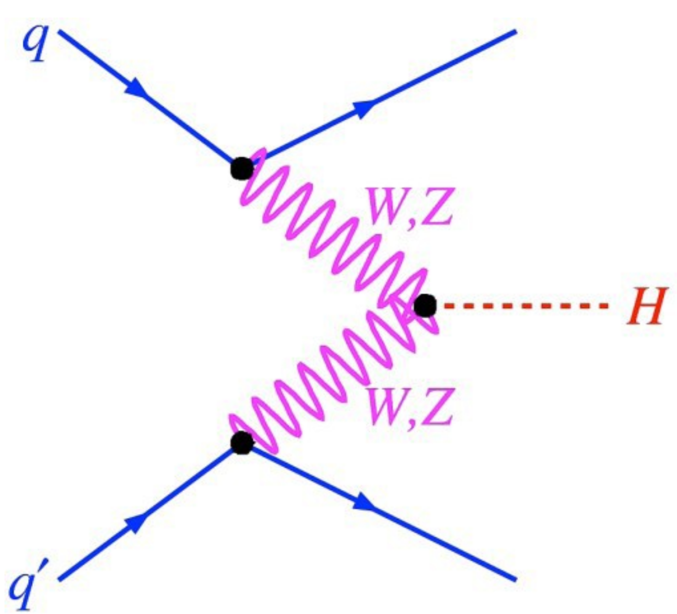
ATLAS W/Z+jets:
Phys.Lett. B698 (2011) 325-345
Phys. Rev. D85 (2012) 032009
Phys. Lett. B708 (2012) 221-240
ATLAS-CONF-2011-160
ATLAS W/Z+b:
Phys.Lett. B706 (2012) 295-313
Phys.Lett. B707 (2012) 418-437

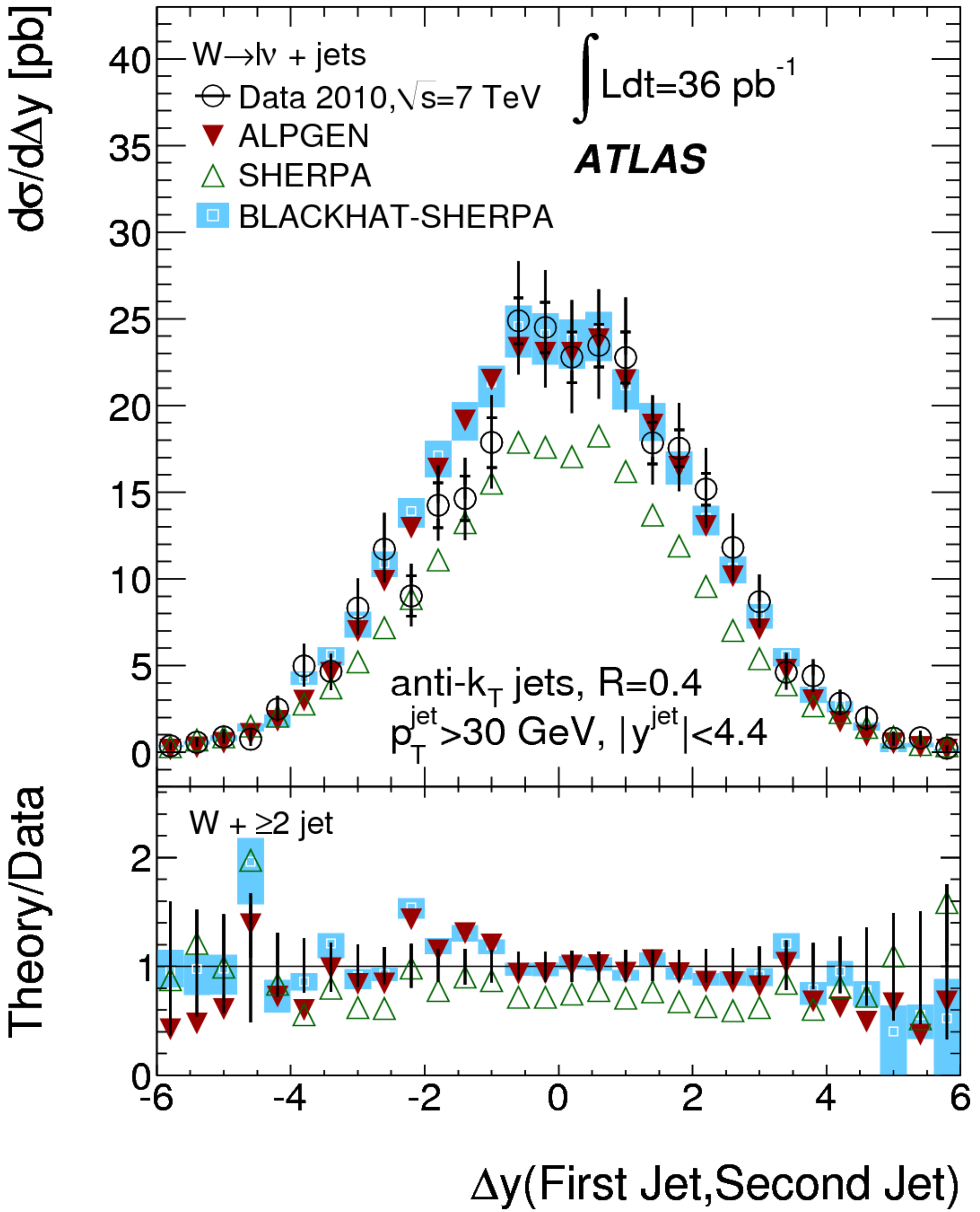
CMS W/Z+jets:
J. High Energy Phys. 01 (2012) 010
CMS Z+b:
arXiv:1204.1643, subm. to JHEP
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults

Angles: Δy

Rapidity gap between jets:

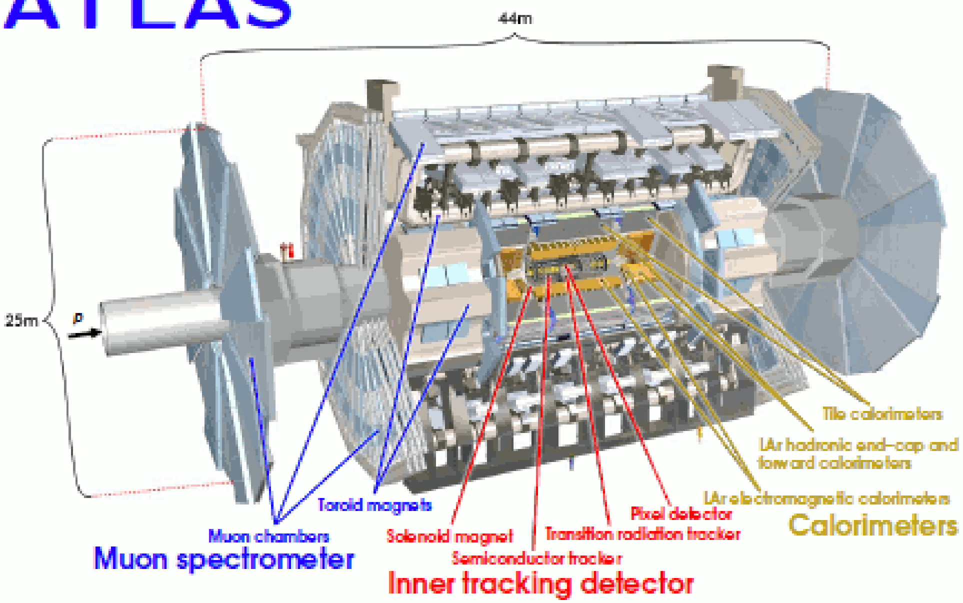
- testing V+jets backgrounds to VBF
    - signature of two forward jets
- important Higgs channel



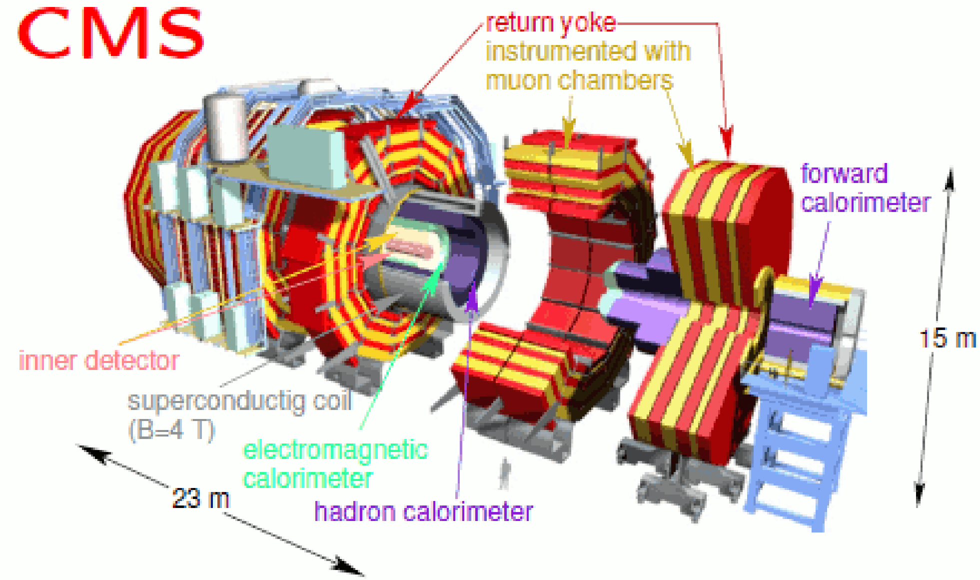


Experiments

ATLAS



CMS



Similar performances of the two detectors for the analyses presented today.

Muons.
- Coverage $|\eta| <2.7$, 2.4.
- Momentum resolution $\left.\frac{\sigma(p_T)}{p_T}\right|_{p_T=40\ GeV} \approx 2\%$, 1%.

Electrons.
- Coverage with ID tracks $|\eta| <2.5$, 2.5.
  Forward electrons up to $|\eta| = 4.9$.
- Energy resolution: $\left.\frac{\sigma(E_T)}{E_T}\right|_{E_T=40\ GeV} \approx 2\%$, 3%.

Missing E_T. $\sigma(E_T^{miss}) \approx 0.5\ \mathrm{GeV}^{0.5} \cdot \sqrt{\sum E_T}$, $0.7\ \mathrm{GeV}^{0.5} \cdot \sqrt{\sum E_T}$.

Jets. $E_T > 100$ GeV: $\frac{\sigma(E_T)}{E_T} \approx 5\%$, 10%.