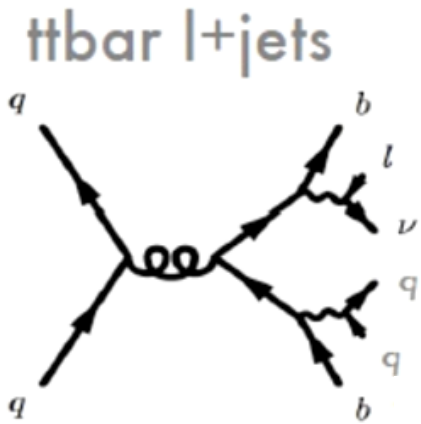
Measurement of W+jets and top quark pair production cross-sections in ATLAS

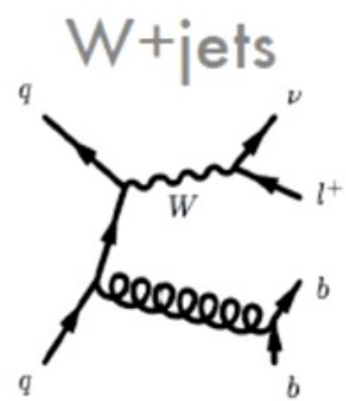
W. Verkerke (NIKHEF)
on behalf of the ATLAS Collaboration

Introduction

- Measurements of W+jets and ttbar cross-sections

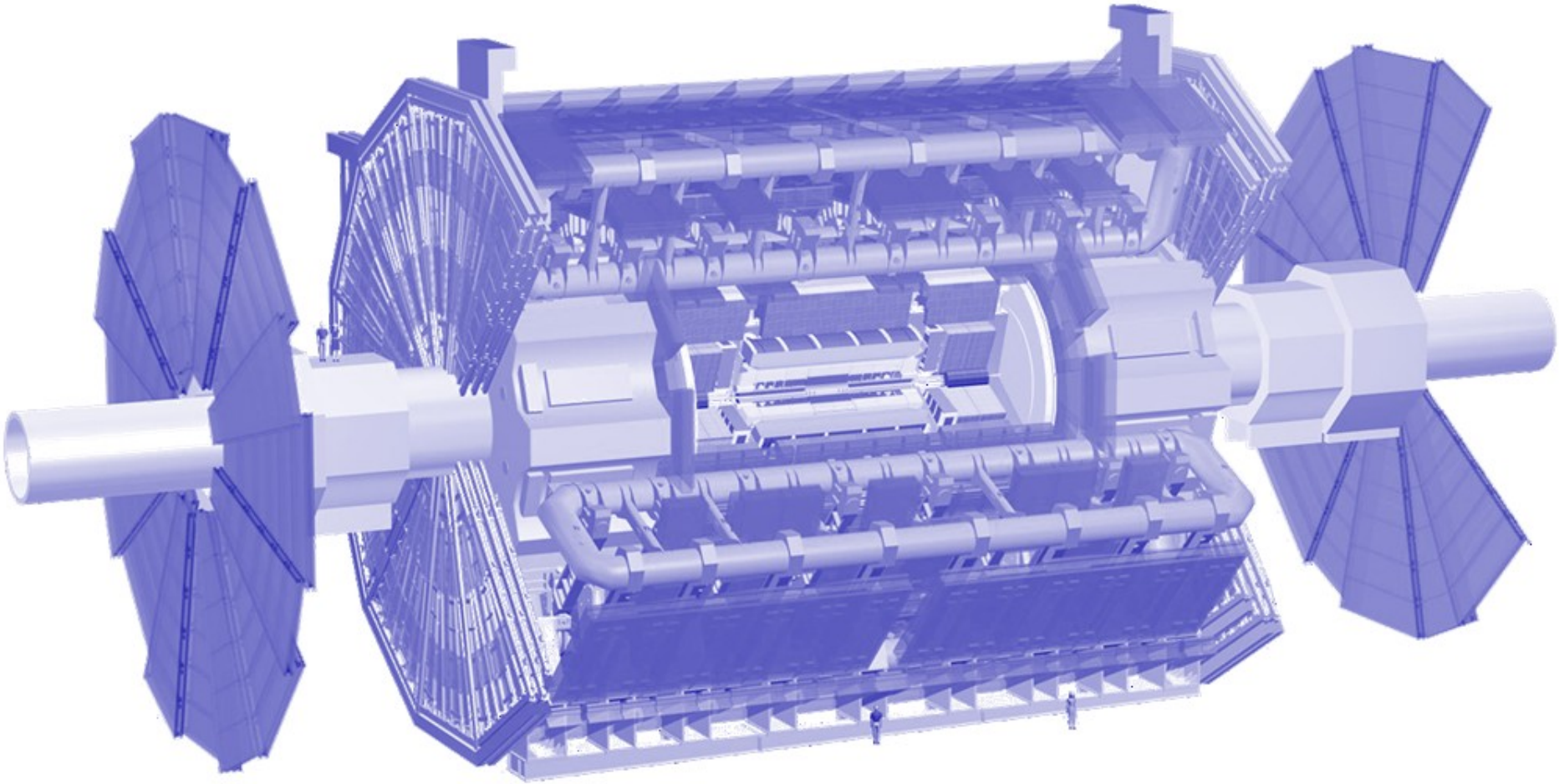
Production dominated by gluon/gluon mode at LHC





Production dominated quark/anti-quark mode

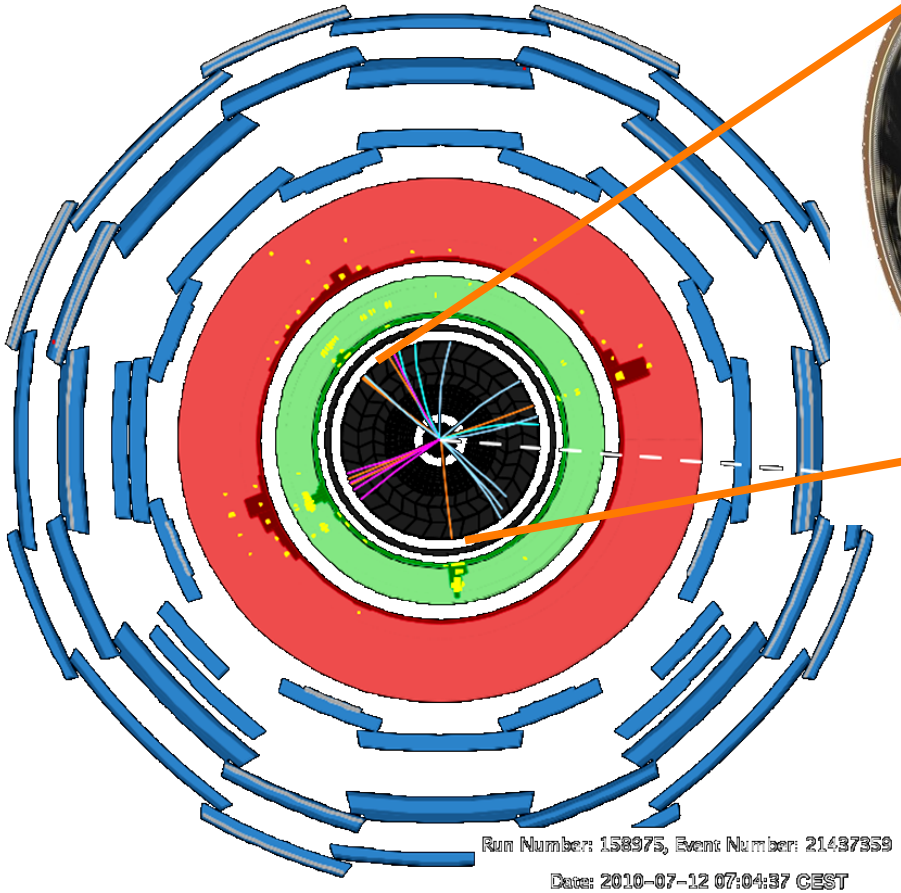
- Both measurements are important test of perturbative QCD
  - Accuracy of σ(ttbar) calculation now at 8% level, σ= $164.6\ ^{+11.4}_{-15.7}$ pb
  - W/Z boson production good place to study associated jet production
- Both processes are major background in BSM, Higgs searches
- New physics can also show in ttbar final state (e.g. Z'→ttbar)

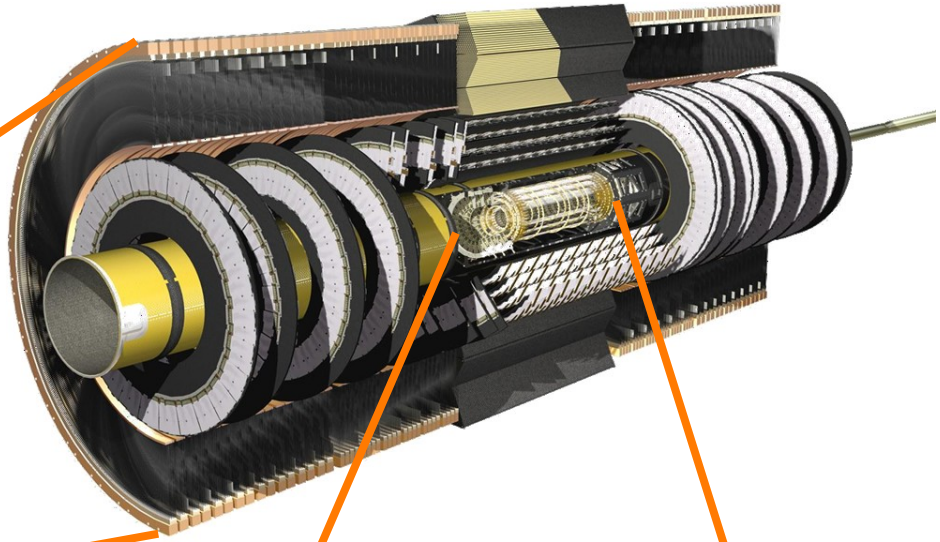


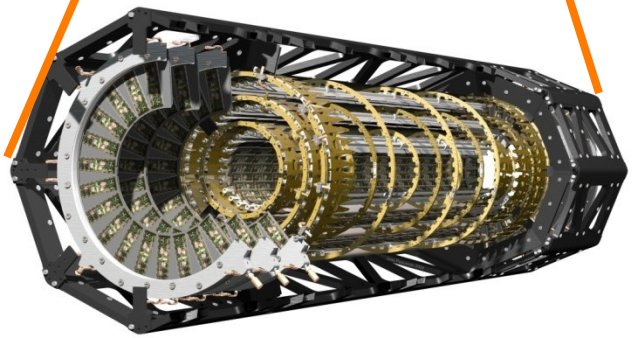
Detector and data sample

Inner detector

Transition Radiation Tracker & SemiConductor Tracker (tracking, particle ID, p_T resolution)

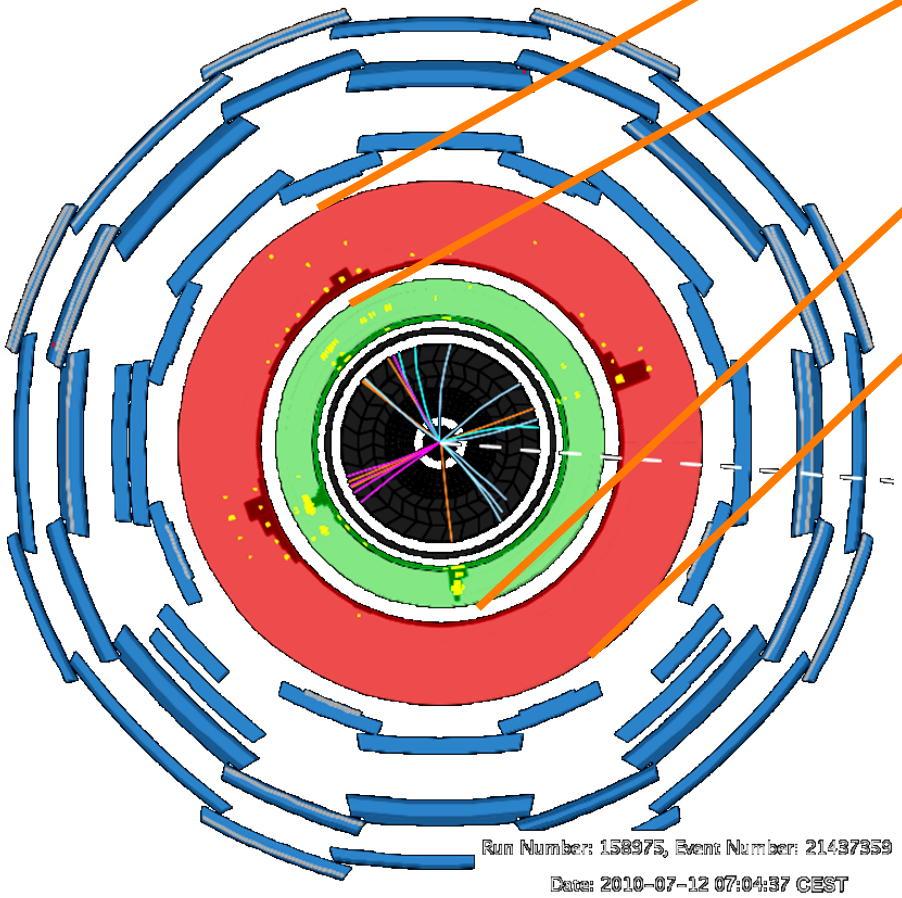


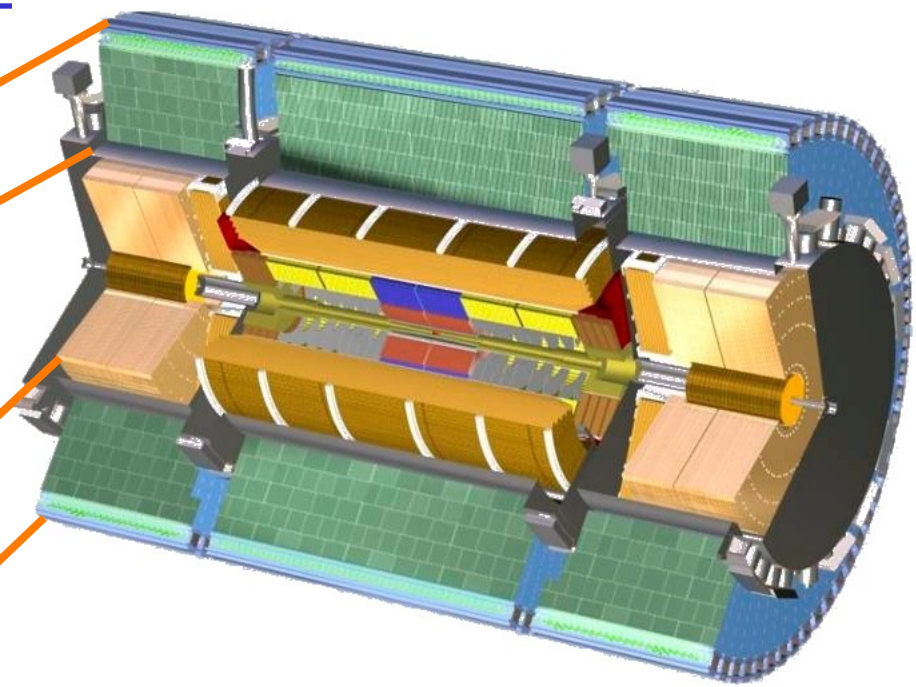




Pixel detector : (b-tagging)

Calorimeters



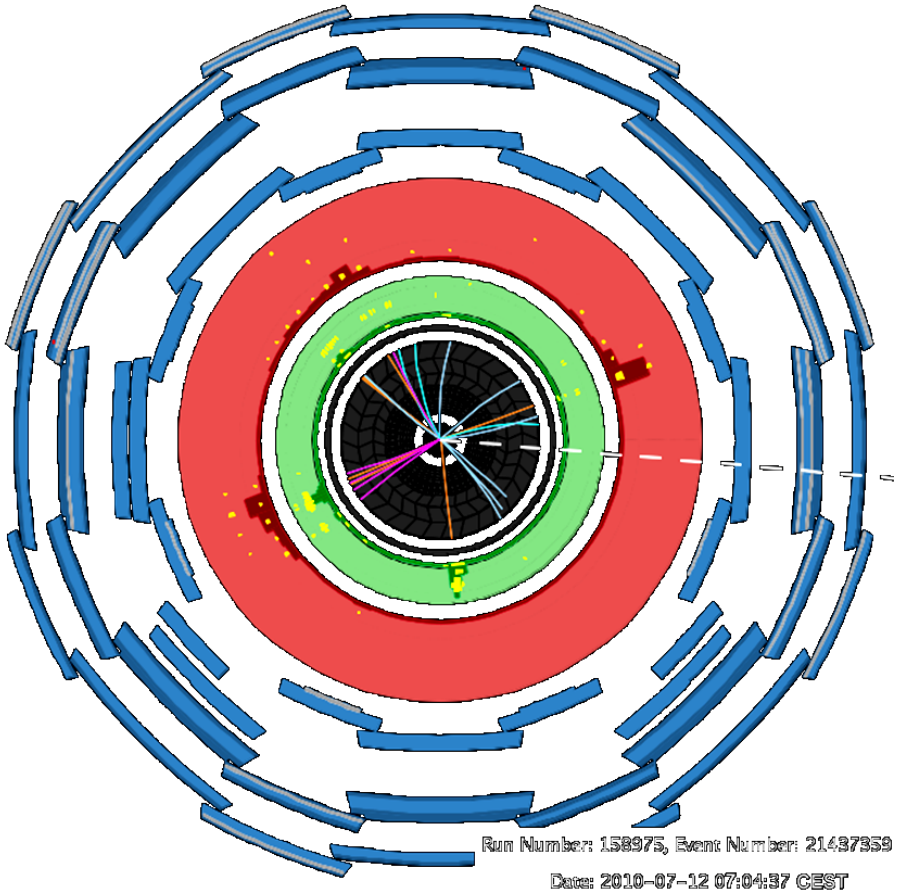


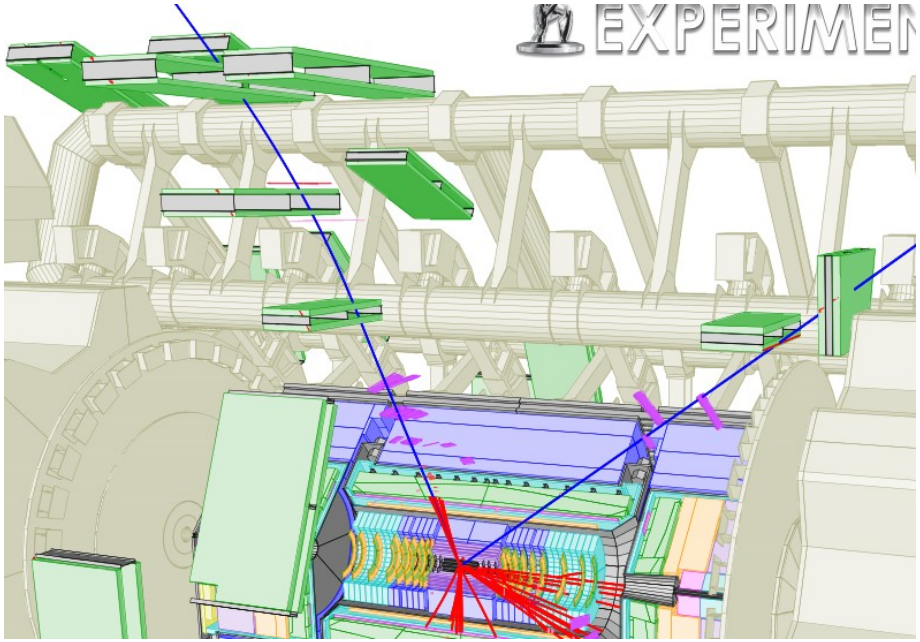
Liquid Argon Calorimeter
(Energy resolution for EM objects)

Tile Calorimeter
(Absorption of hadronic showers)

Jet reconstruction,
Missing Transverse Energy

Muon spectrometer





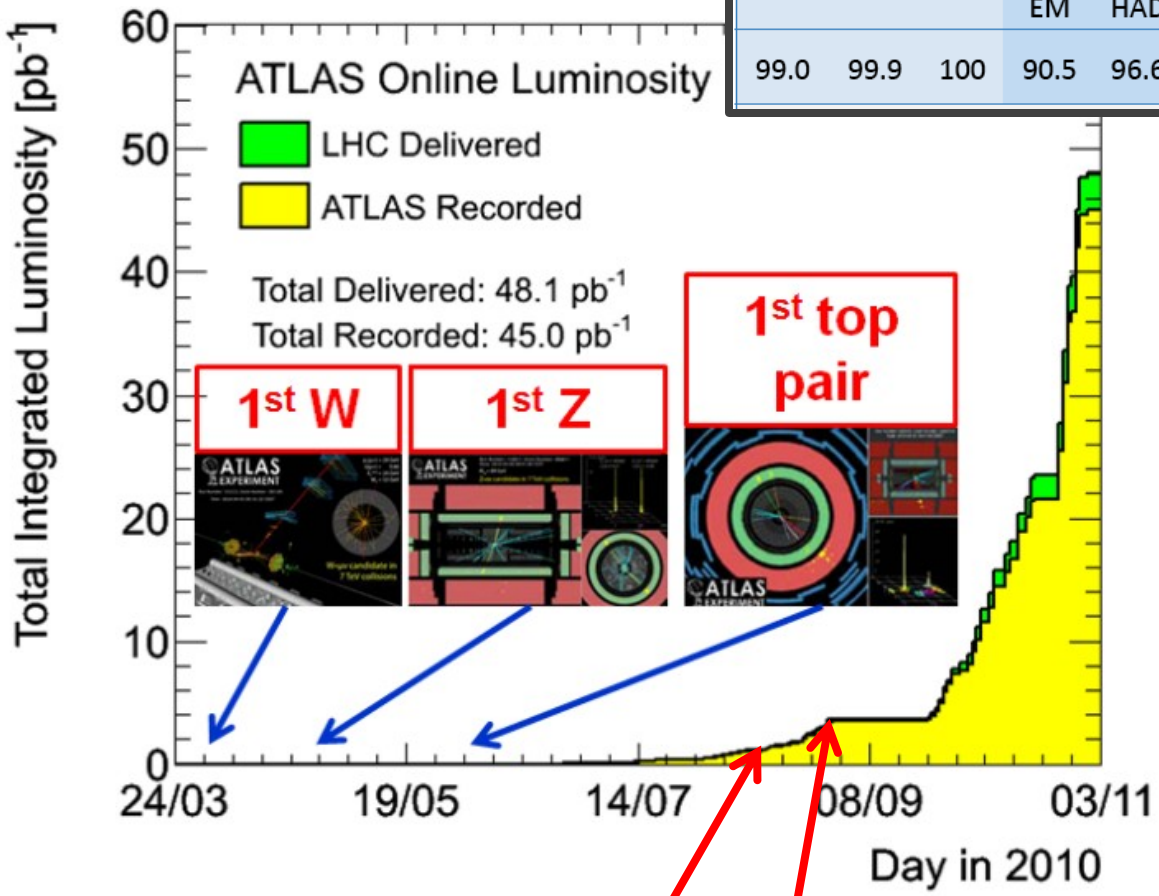
Muon spectrometer

Particle identification
pT resolution

The 2010 data taking period – data samples

Inner Tracking Detectors			Calorimeters				Muon Detectors			
Pixel	SCT	TRT	LAr EM	LAr HAD	LAr FWD	Tile	MDT	RPC	CSC	TGC
99.0	99.9	100	90.5	96.6	97.8	94.3	99.9	99.8	96.2	99.8

% of good quality data



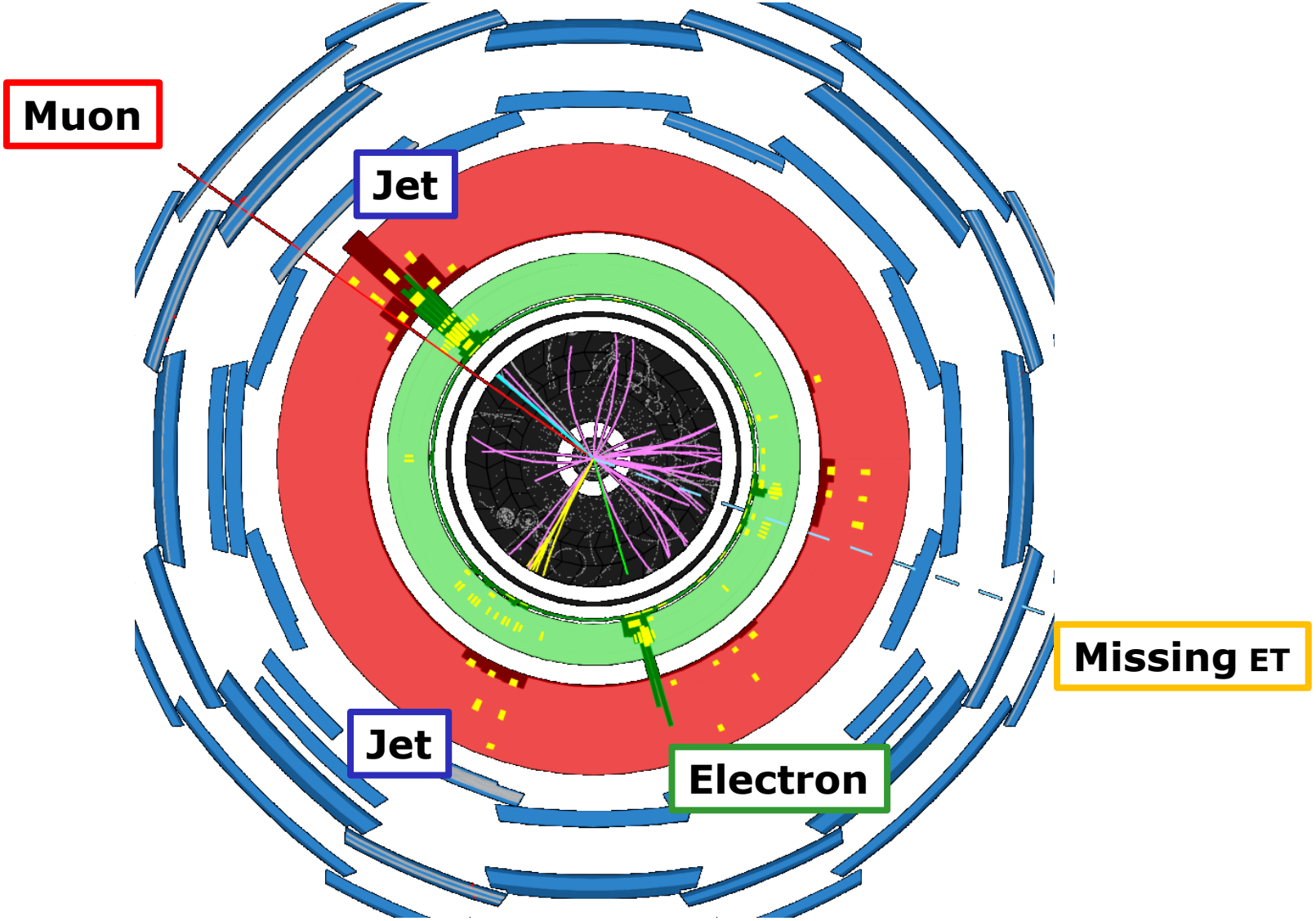
data sample for W+jets paper (1.3 pb^{-1})

Data sample for ttbar paper (2.9 pb^{-1})

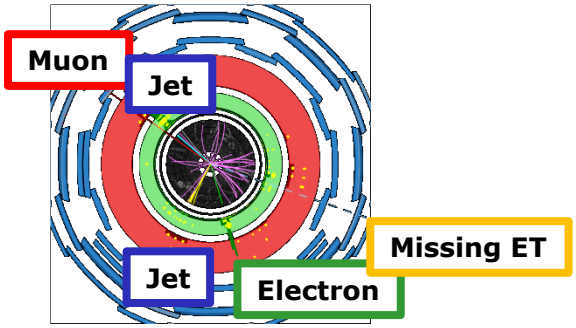
Measurement of the W+jets cross section

"Measurement of the production cross section for W-bosons in association with jets in pp collisions at $\sqrt{s}$ = 7 TeV with the ATLAS detector",
CERN-PH-EP/2010-081, Submitted to Phys.Lett.B

Object reconstruction



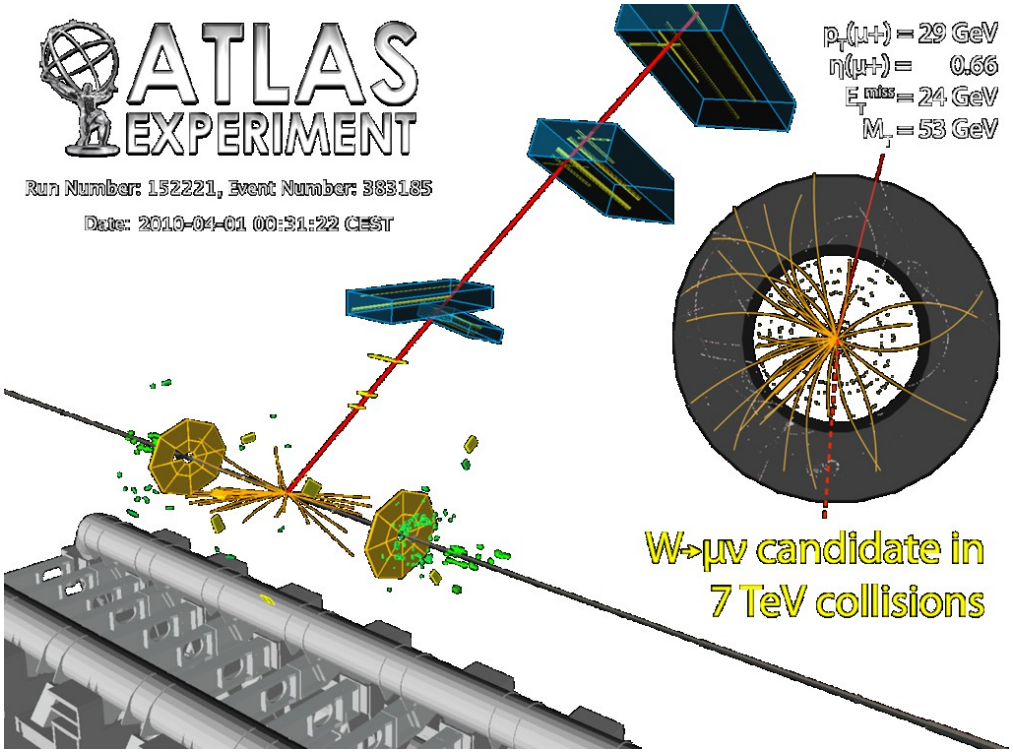
W+jets – Object definitions

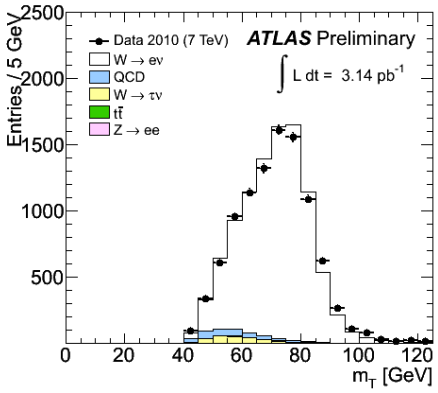


- **Muons (p_T>20 GeV, |η|<2.4)**
  - Combined tracks from Inner Detector and Muon Spectrometer
  - Trk Isolation E_T(R=0.2) < 1.8 GeV
  - Small impact parameter (to reject cosmisc)
- **Electrons (p_T> 20 GeV, |η|<2.4)**
  - 'tight' electrons particle ID requirements
  - Excluding 1.37<η<1.52
- **Jets (p_T> 20 GeV and |η|< 2.8)**
  - Anti-k_T Jet algorithm (r=0.4) from Topological Calorimeter Clusters
  - p_T,η – dependent calibration to hadronic energy scale
  - Must be associated to the primary vertex
- **Missing Transverse energy**
  - Constructed from Topological Cluster in Calorimeter
  - Each cluster is taken at EM or Hadronic scale depending on nature of deposited inferred from cluster shape
  - Cluster(s) associated with muon track removed and substituted with muon track p_T

W+jets – event selection

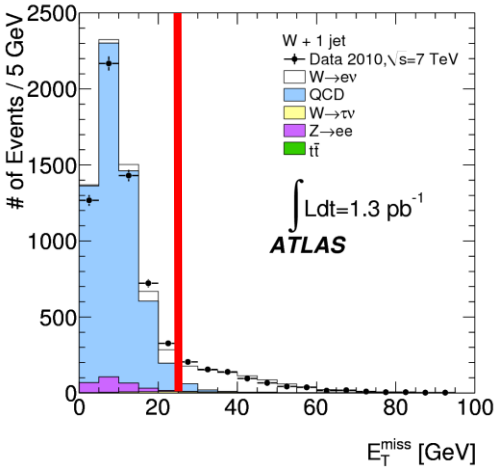
- Event selection criteria
  - Muon channel: Exactly one good muon
  - Electron channel: Exactly one good ('tight') electron,
    no extra electrons passing 'medium' ID criteria
  - E_T^{miss}>25 GeV, M_T > 40 GeV → $M_T = \sqrt{2 p_T^l p_T^\nu (1-\cos(\phi^l - \phi^\nu))}$
  - At least one primary vertex with at least 3 tracks



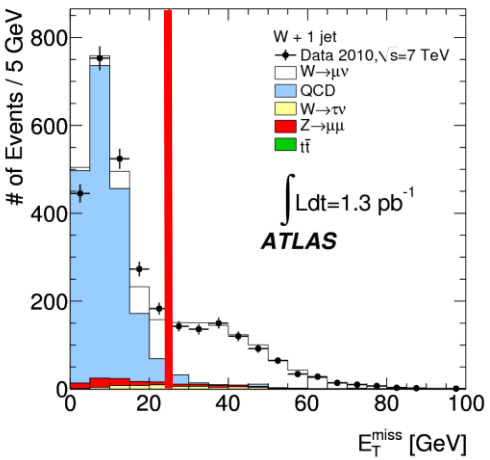


W+jets – Background estimation

W+1 jet - electrons



W+1 jet - muons



W+jets
from simulation
(Alpgen),
(Pythia for W→tν)

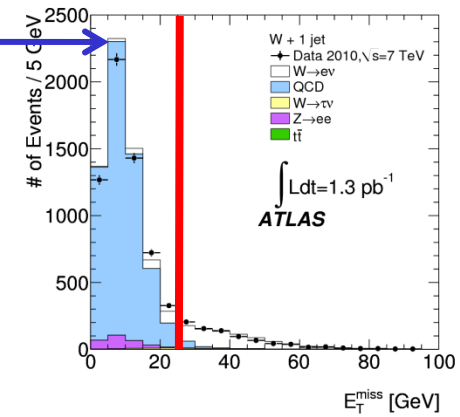
QCD multijet
estimated from data
(see later)

Z→ee/Z→μμ
from simulation
(Alpgen)

- Leptonic backgrounds (estimated from simulation)
  - W→τν, where τ decays into electron/muon
  - Z→ee/μμ, where one electron/muon is not identified (and hadronic energy is mismeasured → E_T^{miss})
  - tt in semileptonic decay mode with one electron/muon
- QCD multi-jet background (data-driven estimation)
  - Component from fake electrons (mis-measured jets) with additional energy mis-measurement resulting in E_T^{miss}
  - Component from semileptonic b,c quark decays (resulting in a real, but non-prompt electron or muon, and a neutrino generating E_T^{miss})

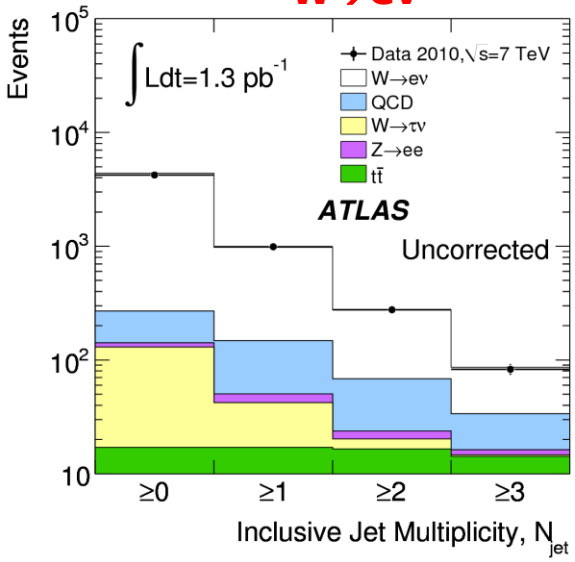
Data-driven measurement of QCD background

- Measure QCD multi-jet background by fitting ETmiss data distribution to sum of two templates
  1. QCD – μ: from MC, e: from data,
     - Construction of E_T^{miss} template for QCD multi-jets in the electron channel from sample with looser electron ID cuts (shower-shape cuts) and inverted track-cluster matching requirement.
  2. Signal plus leptonic backgrounds (MC)

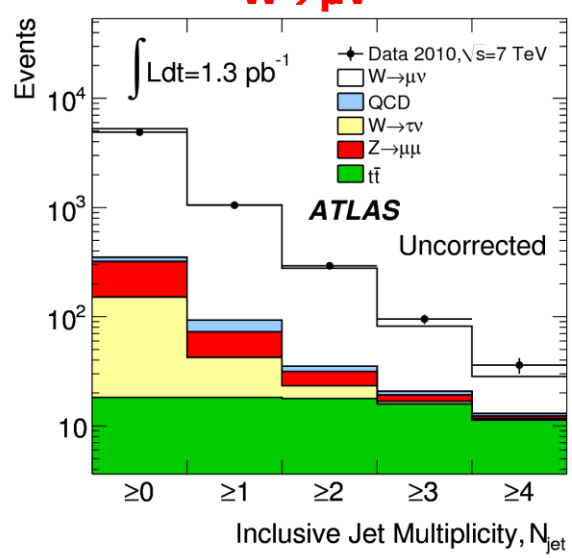


- Background estimates for all jet bins:

W→eν

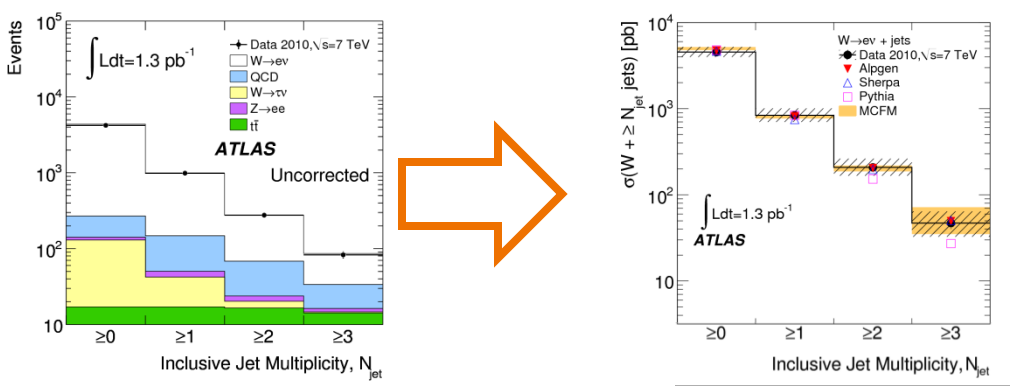


W→μν



From yield to cross section

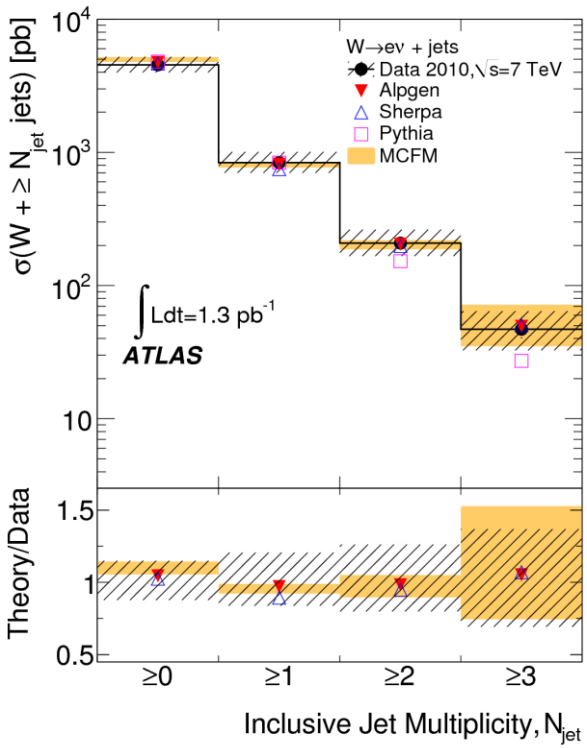
- Correct signal yields to (particle level) cross section
  - Detector and reconstruction efficiency calculated using Alpgen + Atlas detector simulation
  - Define particle-level jets by running jet-clustering on all simulated particles with a lifetime > 10ps (except muons and neutrinos)
  - Define particle-level lepton as lepton after QED radiation plus the energy of all photons within cone with DR=0.1 around lepton
  - Trigger efficiency measured from data (electrons: repeat analysis with E_T^{miss} trigger, muons: measure efficiency from unbiased muon sample from Z→μμ decays)
  - Correction factors expressed as 1-dimensional functions in jet multiplicity, p_T of leading jet, p_T of next-to leading jet



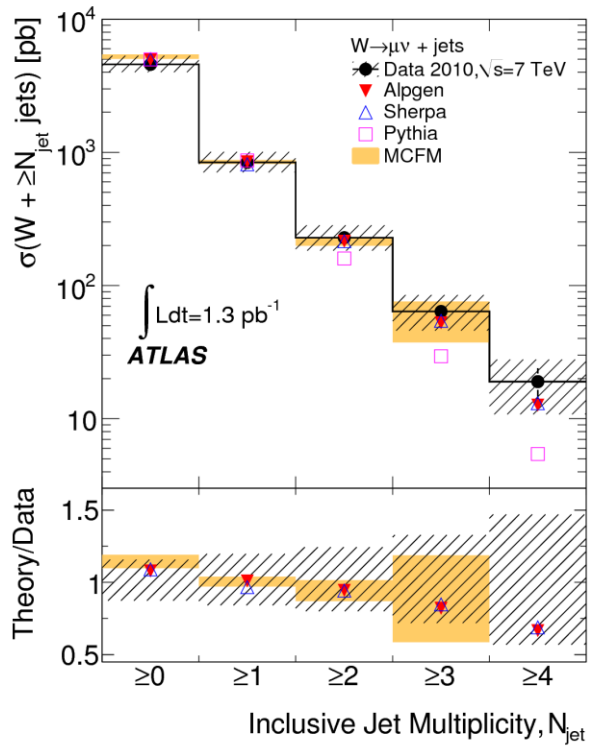
Cross sections vs jet multiplicity

Particle-level cross sections in limited kinematic region

E_T^{jet}> 20 GeV, $|\eta^{jet}|$<2.8,
E_T^{e}>20 GeV, $|\eta|^{e}$<2.47 (excl. 1.37<η^{e}<1.52)
p_T^{ν}>25 GeV, M_T>40 GeV, ΔR(lj)>0.5



E_T^{jet}> 20 GeV, $|\eta^{jet}|$<2.8,
E_T^{μ}>20 GeV, $|\eta|^{\mu}$<2.4
p_T^{ν}>25 GeV, M_T>40 GeV, ΔR(lj)>0.5



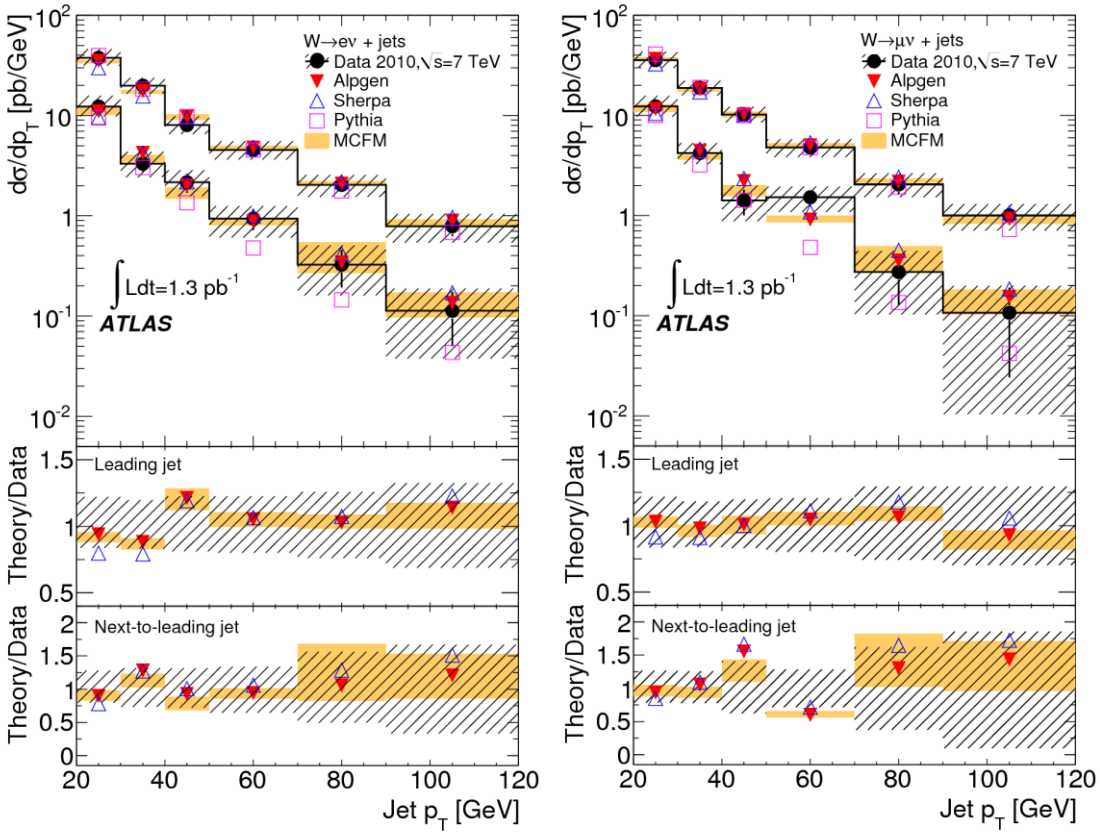
Pythia: Leading-order generator

Alpgen, Sherpa: Match N+1 ME to a LL parton shower (rescaled to NNLO inclusive XS)

MCFM: NLO prediction at parton level for N_{jet}≤2, LO for N_{jet}=3

Cross sections vs (next-to)-leading jet pT

Particle-level cross sections in limited kinematic region



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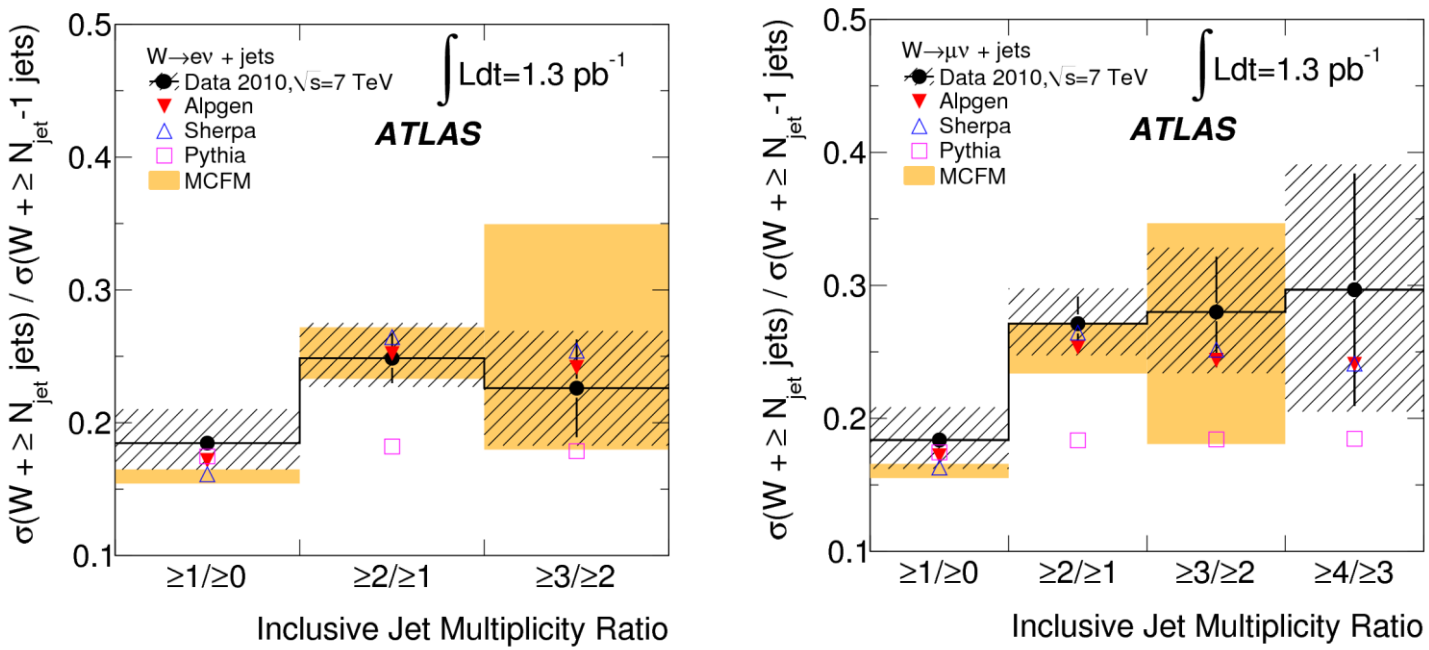
(N+1)-jet/N-jet cross sections ratios

Particle-level cross sections in limited kinematic region



Pythia: Leading-order generator

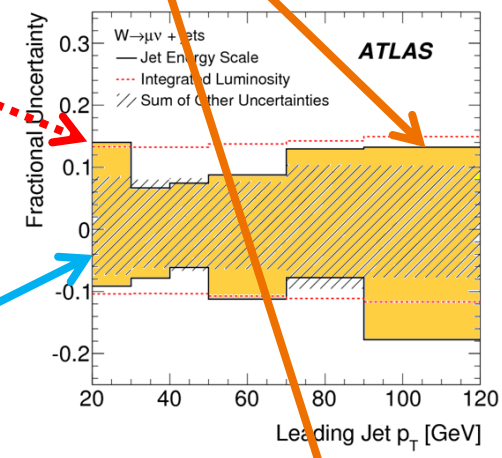
Alpgen, Sherpa: Match N+1 ME to a LL parton shower (rescaled to NNLO inclusive XS)

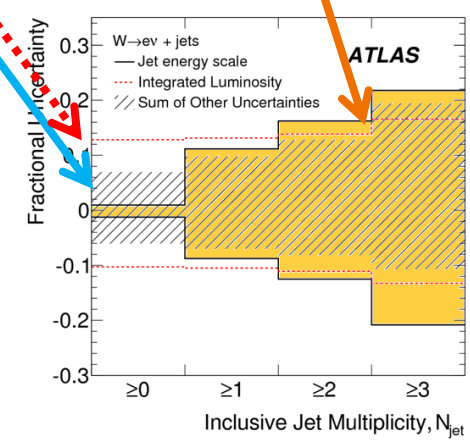
MCFM: NLO prediction at parton level for $N_{jet} \leq 2$, LO for $N_{jet}=3$

Systematic uncertainties

- Leading systematic uncertainties
  - Jet Energy Scale uncertainty : 7-10% (p_T,η dependent)
  - Luminosity uncertainty (11%)

e channel		
Effect	Range	Cross Section Uncertainty (%)
Jet energy scale and E_T^{miss}	±10% (dependent on jet η and p_T) ⊕ 5%	+11, -9
Jet energy resolution	14% on each jet	±1.0
Electron trigger	±0.5%	∓0.7
Electron identification	±5.2%	∓5.5
Electron energy scale	±3%	+3.9, -4.7
Pile–up removal cut	4 – 7% in lowest jet p_T bin	±1.9
Residual pile-up effects	from simulation	±2.2
QCD background shape	from template variation	-1.5, +5.2
Luminosity	±11%	-10, +13



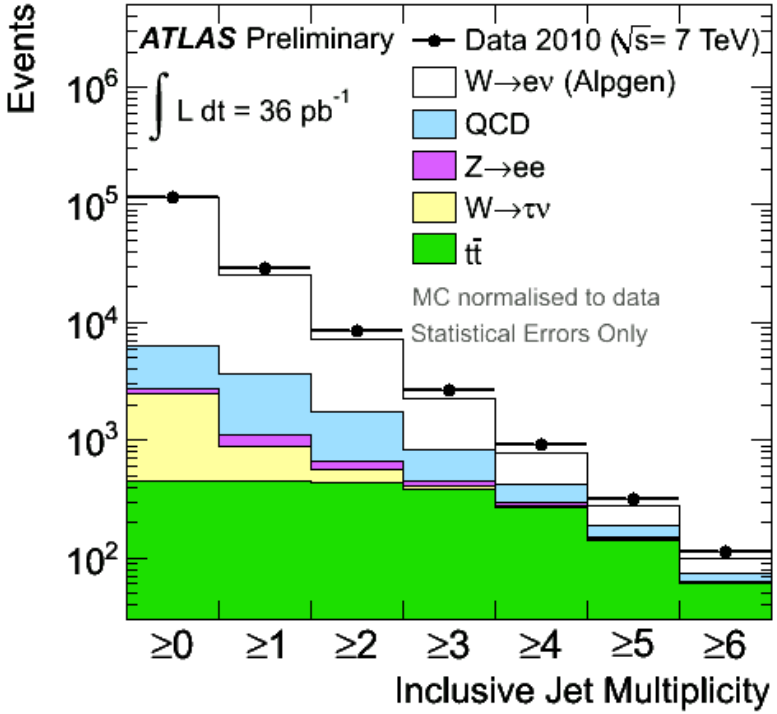


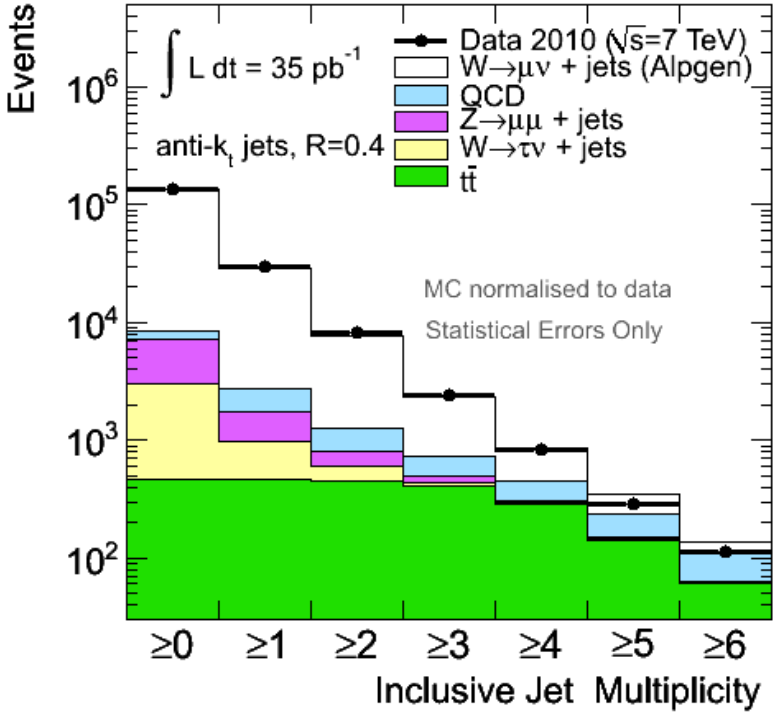
Summary on W+jets

- First ATLAS measurement of W+jets production as function of jet multiplicity and (next-to) leading jet p_T
  - Corrected for all detector effects
  - Quoted in a limited and well-defined range of jet and lepton kinematics
  - As expected, Pythia (2→1 ME merged with 2→2 ME and LL PS), does not provide good description of data for $N_{jet}>1$
  - Good agreement with multi-parton ME generators Alpgen,Sherpa, as well as MCFM calculations (NLO for Njet≤2)
- Full 2010 dataset on tape ~25x larger
  → Will greatly extend experimental reach in N_{jets}

Summary on W+jets

- Uncorrected N_{jet} plots on 35 pb^{-1}





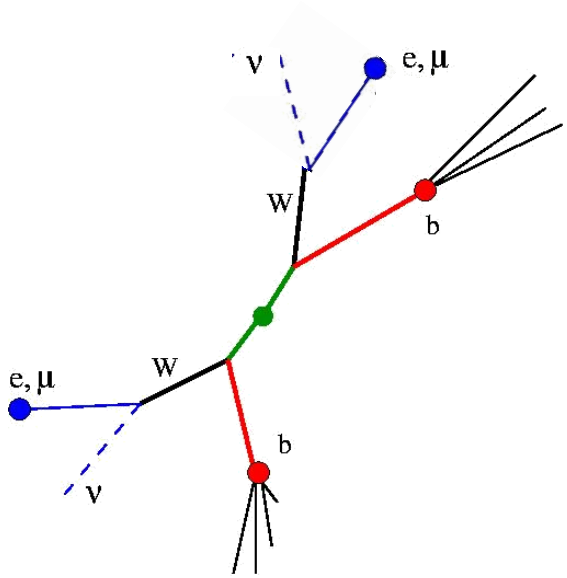
Measurement of the top quark pair production cross section

"Measurement of the top quark-pair production cross section with ATLAS in pp collisions at $\sqrt{s}$=7 TeV",
CERN-PH-EP-2010-064, Accepted by EPJC

Calibrating the b-Tag and Mistag Efficiencies of the SV0 bTagging Algorithm in 3 pb^{-1} of Data with the ATLAS Detector,
ATLAS-CONF-2010-099, cdsweb.cern.ch/record/1299573.

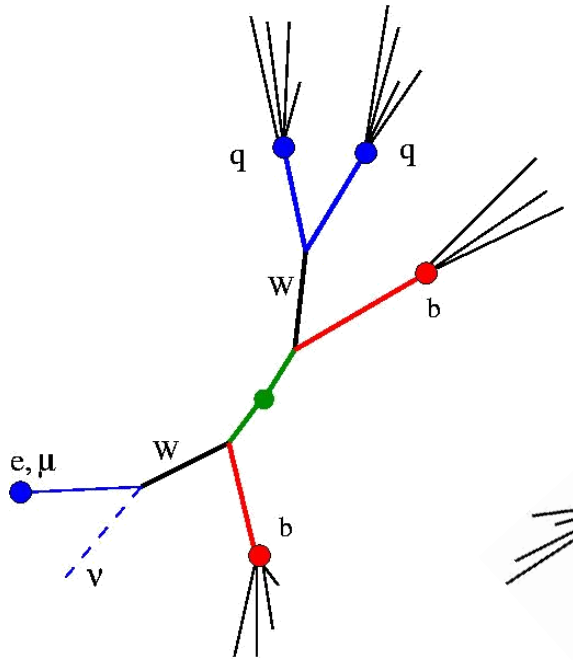
Topology of top quark pair decays

Dilepton channel
(2xW→lν),
1/9 of cross section



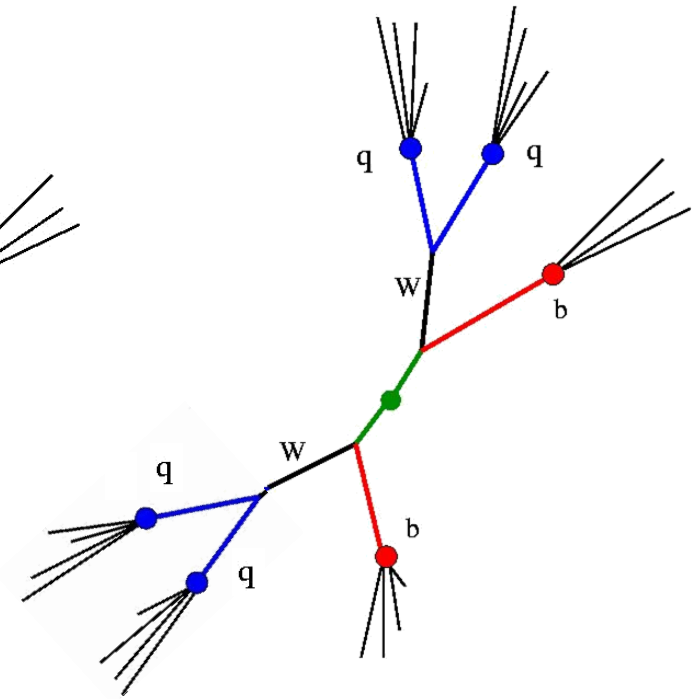
2 leptons
large E_T^{miss}
2 b-jets

Lepton+jets channel
(1xW→lν),
4/9 of cross section



1 leptons
large E_T^{miss}
2 b-jets
2 light jets

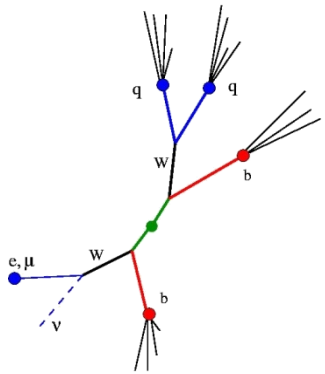
All Hadronic channel
(0xW→lν),
4/9 of cross section



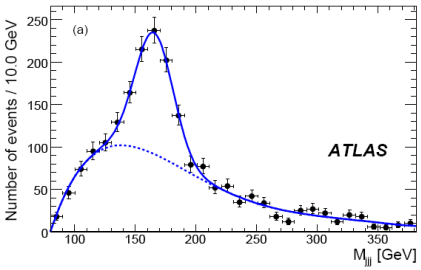
2 b-jets
4 light jets

Finding top quark pairs in early data – Analysis strategy

- **Lepton+jets** → Look for events with ≥4 jets, of which ≥1 b-jets, hard lepton, missing ET

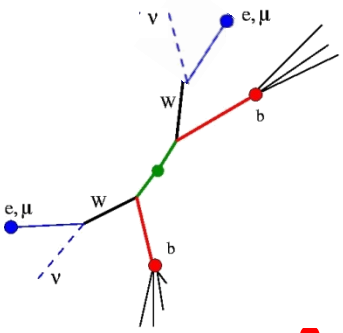


  - Can reconstruct also invariant mass of jets from t→W(qq)b, but simple procedures suitable for early data taking have low efficiency (~20-30%) → Not *selection* tool for early data analysis



  - Strategy: Evidence for top based on excess of events w.r.t known backgrounds

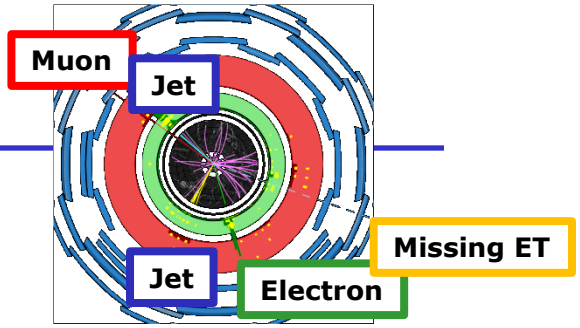
- **Dilepton** → Look for events with ≥2 jets, two hard leptons, missing ET



  - No easy kinematic signature in events that is characteristic for top
  - Strategy: Evidence for top based on excess of events w.r.t known backgrounds

- Understanding of backgrounds is key
  - Use data driven approach wherever possible

Object definitions



- **Muons (p_T>20 GeV, |h|<2.5)**
  - Combined tracks from Inner Detector and Muon Spectrometer
  - Calo, Trk Isolation: E_T (R=0.4)< 4 GeV, p_T (R=0.4) < 4 GeV
  - Jet isolation: must be DR>0.4 from nearest jet

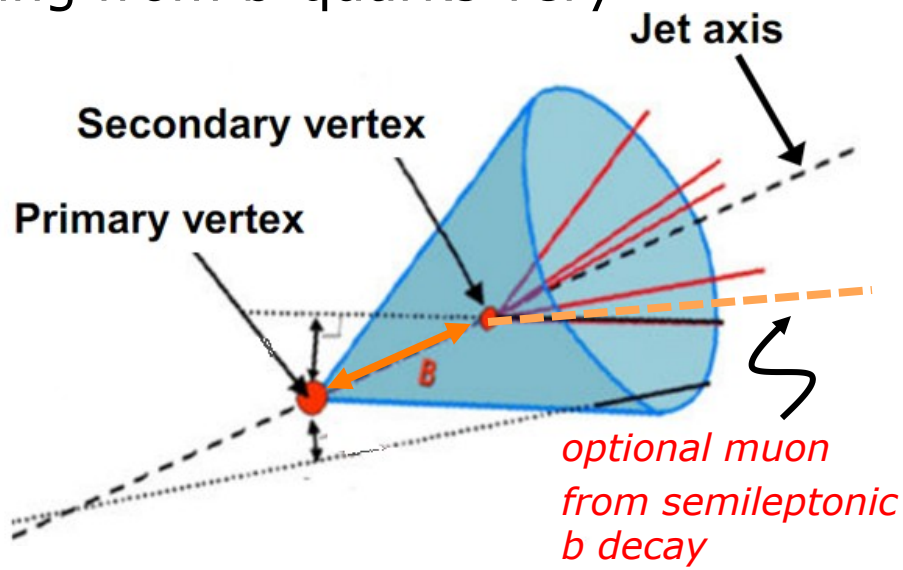
- **Electrons (p_T>20 GeV, $|\eta_{cluster}|$<2.47)**
  - 'medium' electron particle PID cuts (excluding 1.37<|η|<1.52),
  - Calo Isolation: E_T(R=0.2)< 4 + 0.023*E_T(el) GeV

- **Jets (p_T>25, |η|<2.5)**
  - Anti-k_T Jet algorithm (r=0.4) from Topological Calorimeter Clusters
  - p_T,η – dependent calibration to hadronic energy scale
  - Must be DR>0.2 from electron

- **Missing Transverse Energy**
  - Calculated from topological clusters of calorimeter cells. Cells associated with reconstructed jets are calibrated at the hadronic scale.
  - Cells identified with electrons, muons are removed and substituted with their respective E_T values

Identifying jets originating from b-quarks

- Identification of jets originating from b-quarks very important in top physics

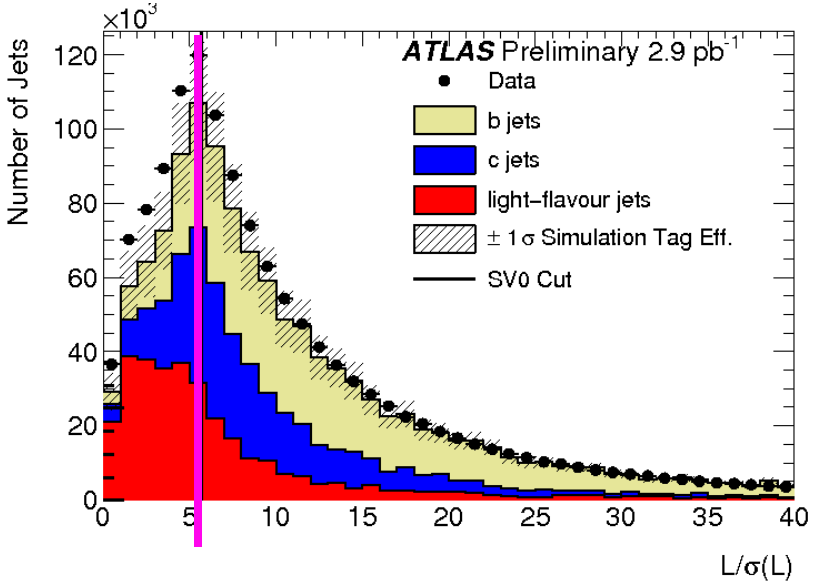


- B-tagging in ATLAS
  - **General concept**: Exploit relatively long lifetime of b-hadrons resulting in flight times of O(few) mm
    → identifiable secondary decay vertex
  - Multiple techniques possible –
    here comparatively simple and robust method exploited:
    selection based on decay length significance ***L / σ(L)***
  - **Alternative concept**: look for soft leptons inside jet (from semileptonic b decay) – low efficiency → semileptonic decay method was used to calibrate vertex-based method)

Decay length significance of secondary vertices

- Consider a jet b-tagged if it contains a secondary vertex and decay length significance that results in 50% b-tag efficiency in simulated ttbar events

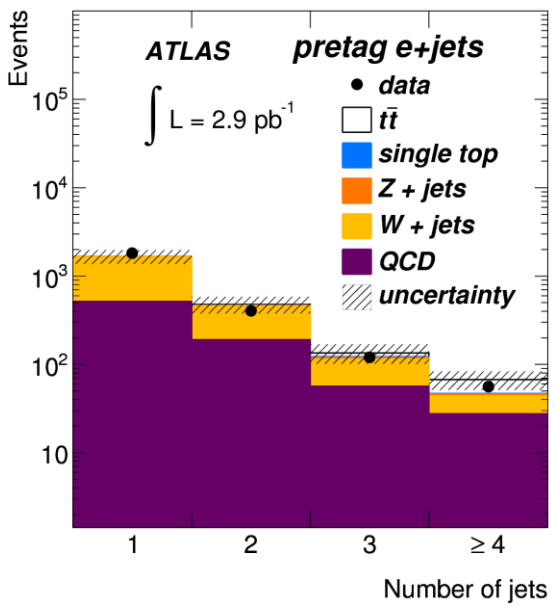
- Distribution of $L/\sigma(L)$ for QCD multi-jet events with a secondary vertex

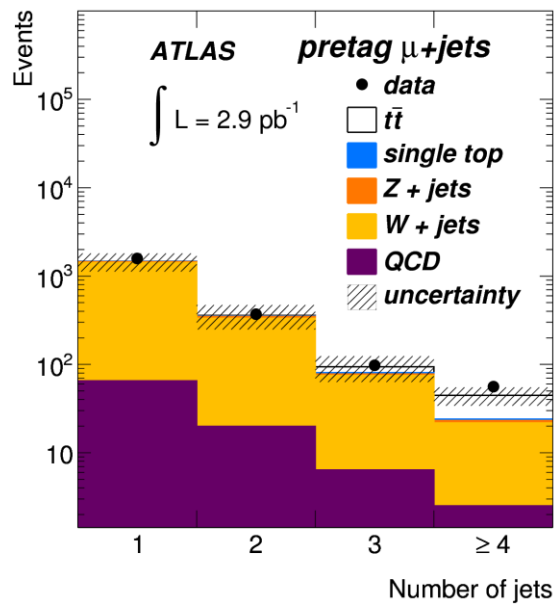


- Performance of b-tagging in data depends critically on many details of detector performance
  - Data-driven estimates of efficiency and mis-tag rate of SV0 tagger

The lepton+jets channel – Event selection

- Two channels: e+jets, μ+jets
- 1,2,3,≥4-jet Pretag samples
  - Exactly one good lepton (p_T>20) GeV
  - E_T^{miss}>20 GeV and (E_T^{miss} + m_T(W))>60 GeV
  - 1,2,3 or at least 4 jets (p_T>25, |η|<2.5)
- All samples dominated by background (W+jets, QCD multi-jet), expect signal to concentrate in ≥4 jet bin





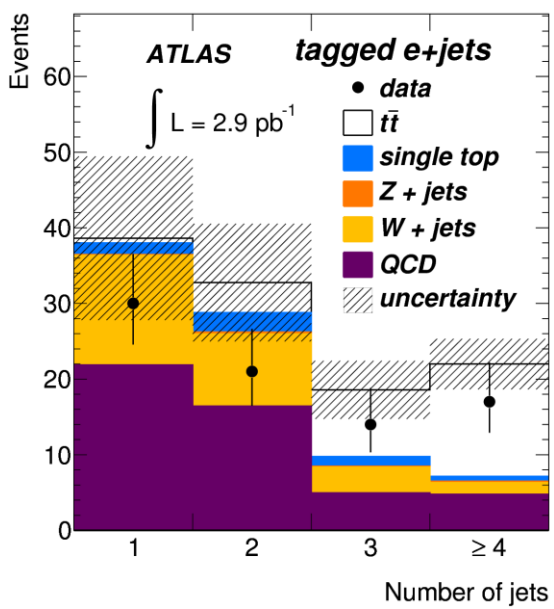
QCD multijet
estimated from data (see later)

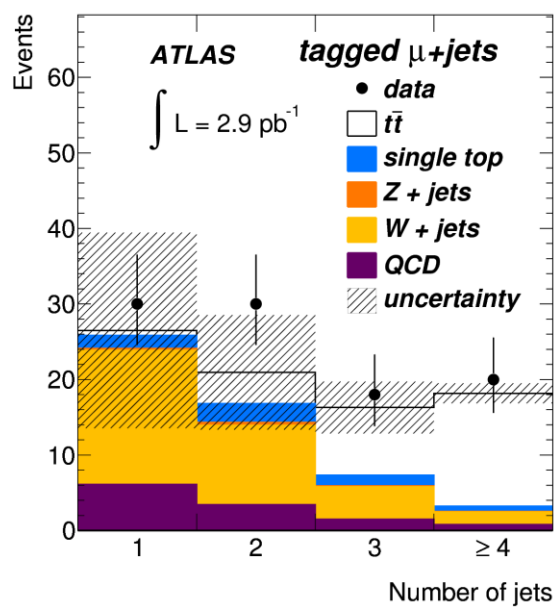
W/Z+jets
from simulation (Alpgen)

tt, single top
from simulation (MC@NLO)

The lepton+jets channel – Event selection

- 1,2,3,≥4-jet tagged-samples
  - Each a subset of the corresponding pretag sample
  - At least one of jets is b-tagged
- Signal efficiency ≈75% (since 2 b-jets)
- Backgrounds reduced by >O(10), since mostly light jets,
  - Remaining backgrounds dominated by events with b-quark or c-quark jets





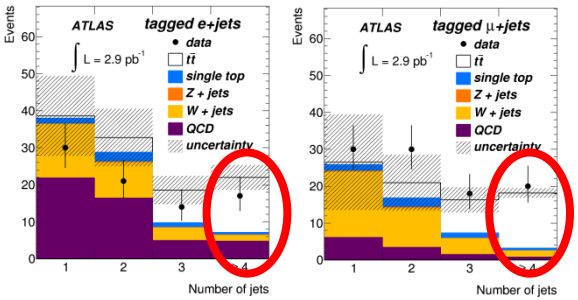
QCD multijet
estimated from data (see later)

W/Z+jets
from simulation (Alpgen)

tt, single top
from simulation (MC@NLO)

Background estimation

- Next step is to quantify backgrounds in ≥4-jets tagged sample



- Background from W+(bb/cc/c)+jets not surprising
  - Same final state – thus also partly irreducible

- Understanding QCD multi-jet background
  - Final states with many jets from gluons and (b,c,light) quarks. *No prompt leptons, no prompt neutrinos.*
  - Small fraction of jets very EM-like → Can be misidentified as a reconstructed electron ('fake' electron).
    Event is only background if there is a separate cause of true or fake missing E_T.
  - Semileptonically decaying quarks can result in true lepton ('non-prompt') plus a neutrino (giving rise to E_T^{miss}). Event is background if resulting lepton is sufficiently isolated

Estimating QCD multi-jet background in μ channel

- Summary: three sources of reconstructed leptons
  1. From prompt true leptons [from t(t), W/Z+jets]
  2. From non-prompt true leptons (from quark decay) [QCD multi-jet]
  3. Fake electrons (from jets, reconstruction mistakes) [QCD multi-jet]

(From here on lump 2 'non-prompt' and 3 'fake' together for notational simplicity)

- Estimating QCD background = estimating fake lepton bkg

- Can make a fully data-driven estimate of fake lepton background
  - Introduce a 'loose' lepton selection besides 'standard'
  - Measure behaviour of real and fake leptons in control regions
  - Apply the 'matrix method'

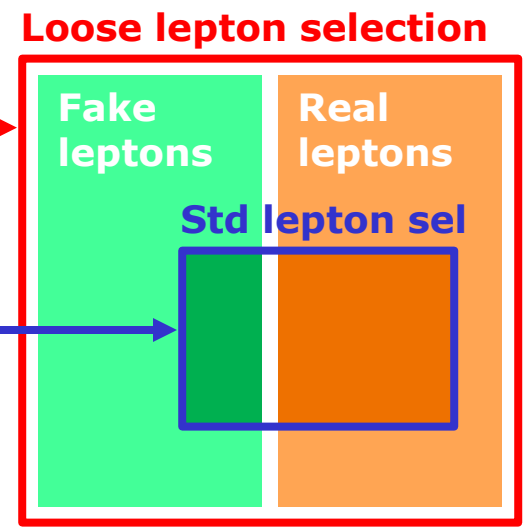
The matrix method illustrated

- Given a 'loose' and 'std' lepton selection the composition of either in term of real and fake leptons is

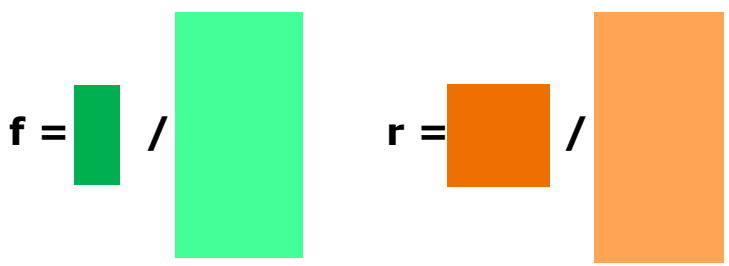
$$N^{loose} = N^{loose}_{real} + N^{loose}_{fake}$$

This is what we're after!

$$N^{std} = N^{std}_{real} + N^{std}_{fake}$$



Define fractions f, r as



Rewritten using f, r ('the matrix')

$$N^{loose} = N^{loose}_{real} + N^{loose}_{fake}$$

$$N^{std} = r \cdot N^{loose}_{real} + f \cdot N^{loose}_{fake}$$

If we know **r, f *externally*** we can calculate N^{std}_{fake}, from N_{loose}, N_{std}

Fake lepton background in the μ+jets channel

- Need N^{loose}, N^{std} (trivial), ***r*** and ***f*** (from control regions)
- Measure $r = 0.990 \pm 0.003$ from *inclusive $Z \rightarrow \mu\mu$ events*
- Measure $f = 0.339 \pm 0.013(\text{stat.}) \pm 0.061(\text{syst.})$ from *control regions enhanced in fake leptons*
  - Key is to find control region that is similar to signal region (in lepton p_T,η distribution) for result to be applicable
  - Control region A: $E_T^{miss} < 10$ GeV, at least 1 jet ($p_T > 25$ GeV)
    → Event sample dominated by QCD multijet production
  - Control region B: nominal E_T^{miss} (>20 GeV), at least 1 jet ($p_T > 25$ GeV), lepton with high impact parameter significance (>5)
    → Lepton sample dominated by non-prompt leptons
- Apply procedure in every jet bin

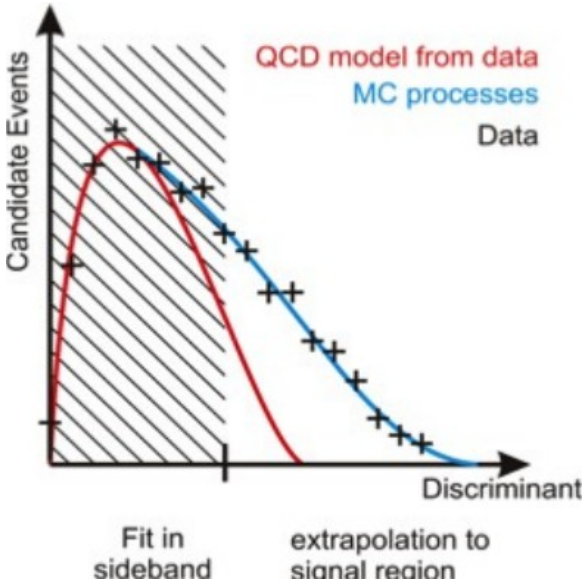
Estimated number of events with fake leptons

μ+jets channel						
	1-jet tagged	2-jet tagged	3-jet tagged	≥4-jet tagged	3-jet zero-tag	≥4-jet zero-tag
QCD (DD)	6.1 ± 2.9	3.4 ± 1.8	1.5 ± 0.8	0.8 ± 0.5	4.9 ± 2.3	1.7 ± 1.1

Measuring the fake lepton bkg in the e+jets channel

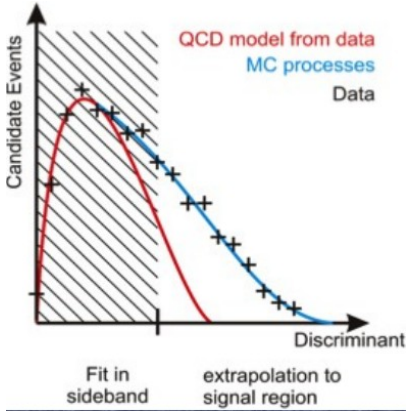
- Application of matrix method in e+jets channel more challenging
  - Two sources of background: non-prompt (true) electrons and fake electrons (reconstruction mistakes)
  - Need to worry about mix of sources being similar in control regions

- Instead apply 'fitting method' – *Similar to W+jets analysis*
  - Fit distribution of E_T^{miss} to sum of 2 templates
  - Template shapes for fake/non-prompt lepton contribution from data control samples
  - Template shape of prompt lepton components (signal, W+jets) from simul.
  - Fit for fraction of fake leptons in side-band (E_T^{miss}<20 GeV) → Extrapolate to fraction of fake leptons in signal region using template shapes



Measuring the fake lepton bkg in the e+jets channel

- Key issue (again) representative control regions to determine shape of fake lepton template
  - 'jet-electrons' → Events which have – instead of standard electron – an extra jet with an EM fraction of 80%-95%.
  - 'non-electrons' → Standard electron selection modified: candidates must *fail* track quality cut for innermost detector layers
  - Take difference in results as metric for systematic uncertainty due to choice of control sample



- Apply procedure in every jet bin

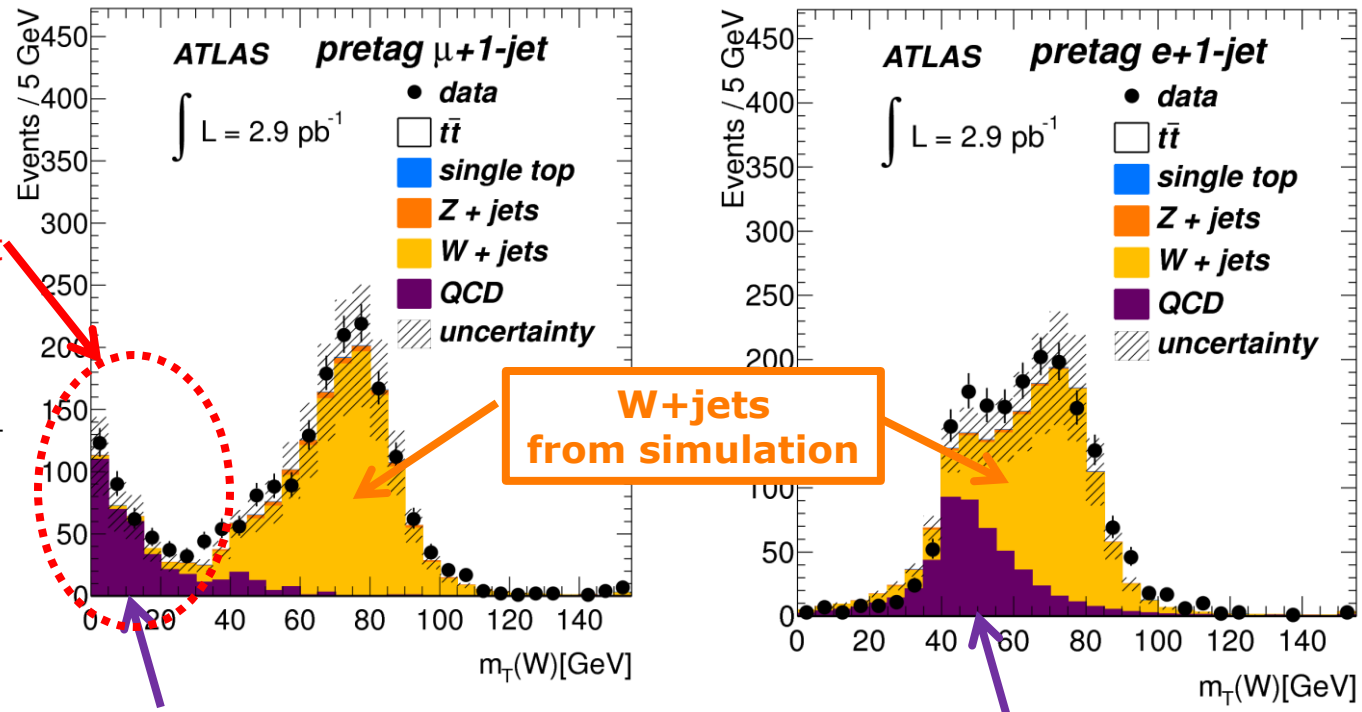
Estimated number of events with fake leptons

e+jets channel						
	1-jet tagged	2-jet tagged	3-jet tagged	≥4-jet tagged	3-jet zero-tag	≥4-jet zero-tag
QCD (DD)	21.9 ± 3.4	16.4 ± 4.0	4.9 ± 2.7	4.8 ± 3.1	52.0 ± 19	23.0 ± 11

Verifying the QCD multijet background estimate

- Can *verify* performance of QCD multi-jet background estimation on 1,2-jet bins by looking at m_T distributions
  - Here results for 1-jet bin shown (best statistics)

NB:
E_T^{miss}+mT(w) > 60 cut omitted from event selection to avoid suppression of events with low m_T



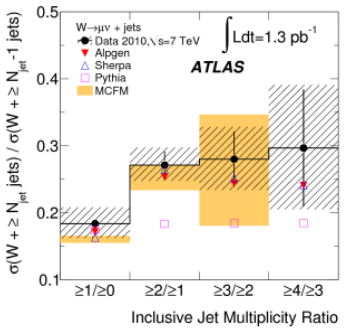
W+jets from simulation

QCD multi-jet estimate from matrix method

QCD multi-jet estimate from fitting method

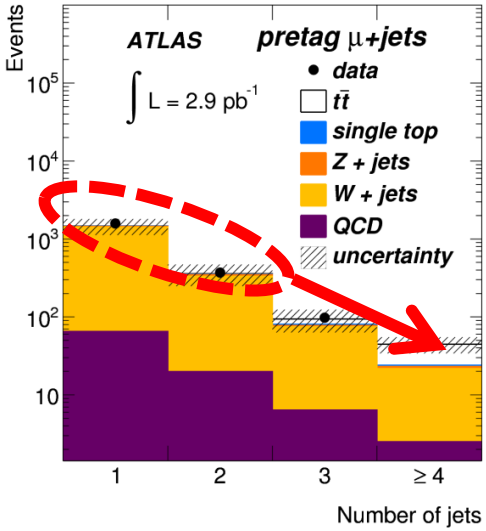
Estimation of W+jets background

- W+jets background in ≥4-jet tagged bin has largely the same particle-level final state as ttbar
  - Thus no easy/obvious handles to exploit to measure the rate from data in same bin (as was done with N_{std},N_{loose} for QCD)
  - Sample dominated by W+HF+jets final states, and theory predictions not so reliable
  - Instead aim for hybrid data/MC method that exploits relations between jet bins

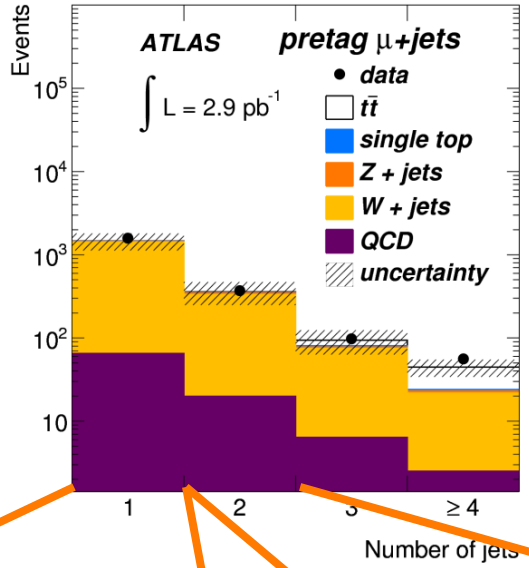


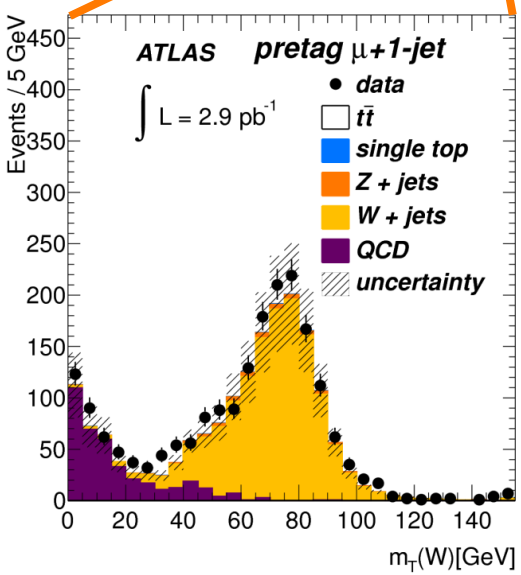
- Step 1 –
  Exploit that σ[W+(N+1)-jet]/σ[W+(N)-jet] is fairly constant (Berends-Giele scaling)
  - NB: Technique only works in pretag-samples
  - Concretely: Use pre-tag W+1,W+2 jet measurements to make a prediction of pre-tag W+≥4 jets rate

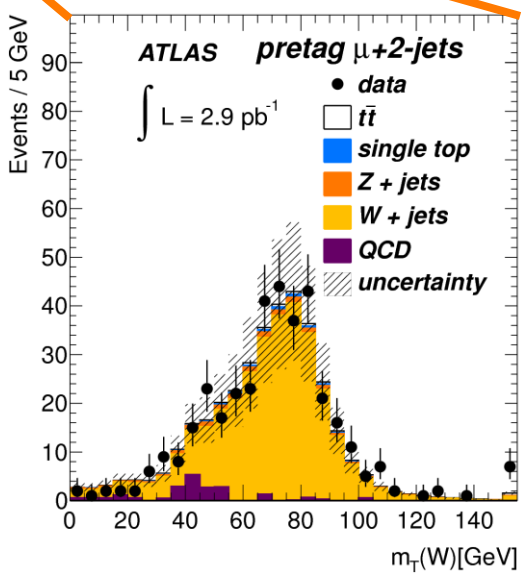
$$W^{\geq 4\text{-jet}}_{\text{pre-tag}} = W^{2\text{-jet}}_{\text{pre-tag}} \cdot \sum_{n=2}^{\infty} \left(W^{2\text{-jet}}_{\text{pre-tag}} / W^{1\text{-jet}}_{\text{pre-tag}} \right)^n$$



Estimation of W+jets background







Measure W+jets rate in 1,2-jets pretag bins by

- subtracting data-driven QCD estimate,
- subtracting (small) other backgrounds using simulation estimates

	1-jet pre-tag e	1-jet pre-tag μ	2-jet pre-tag e	2-jet pre-tag μ
Observed	1815	1593	404	370
QCD multijet (DD)	517 ± 89	65 ± 28	190 ± 43	20.0 ± 9.7
$W(\tau\nu)$+jets (MC)	39 ± 10	43 ± 11	11.7 ± 4.4	13.6 ± 5.1
Z+jets (MC)	19.0 ± 9.1	48 ± 12	11.6 ± 5.2	14.0 ± 4.8
$t\bar{t}$ (MC)	1.7 ± 0.8	1.7 ± 0.8	7.0 ± 3.0	7.7 ± 3.3
single-t (MC)	4.4 ± 0.7	5.0 ± 0.8	5.2 ± 0.8	5.1 ± 0.8
diboson (MC)	4.8 ± 4.8	5.7 ± 5.7	3.8 ± 3.8	4.4 ± 4.4
Total (non $W(l\nu)$+jets)	585 ± 90	168 ± 33	229 ± 44	65 ± 13
Estimated $W(l\nu)$+jets	1230 ± 100	1425 ± 52	175 ± 49	305 ± 23

$$W^{\geq 4\text{-jet}}_{\text{pre-tag}} = W^{2\text{-jet}}_{\text{pre-tag}} \cdot \sum_{n=2}^{\infty} (W^{2\text{-jet}}_{\text{pre-tag}} / W^{1\text{-jet}}_{\text{pre-tag}})^n,$$

$$W^{\geq 4\text{-jet}}_{\text{pre-tag}} = 11.2 \pm 2.2(\text{stat.}) \pm 4.0(\text{syst.}), \quad e \text{ channel},$$

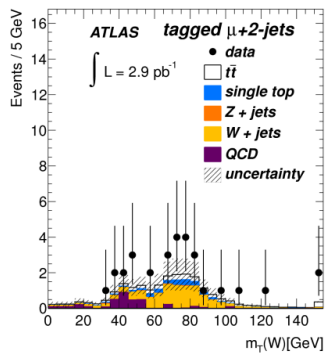
$$W^{\geq 4\text{-jet}}_{\text{pre-tag}} = 18.9 \pm 4.1(\text{stat.}) \pm 5.0(\text{syst.}), \quad \mu \text{ channel}.$$

Estimation of *tagged* W+jets background

$$W^{\text{tagged}-\geq 4\text{jet}} = W^{\text{pretag}-\geq 4\text{jet}} \cdot f_{\text{tagged}}^{\geq 4-\text{jet}}$$

- Step 2 – Estimate 4-jet tagged fraction
  - Can *measure* 2-jet tagged fraction

f_{tagged}**(2-jet)=**



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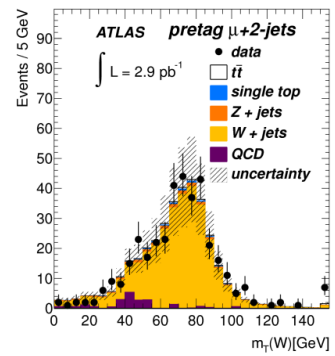


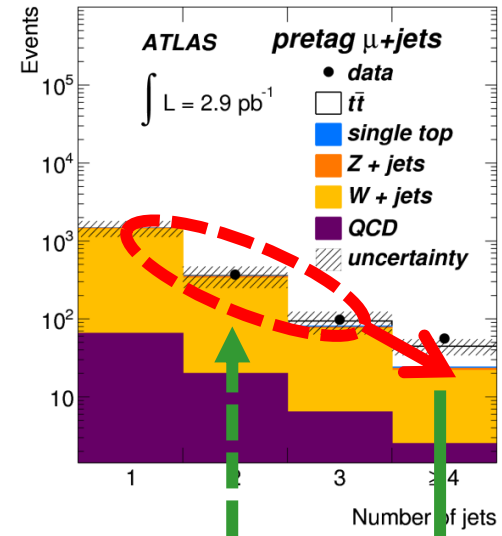
= 0.060 ± 0.018(stat.) ± 0.007(syst.).

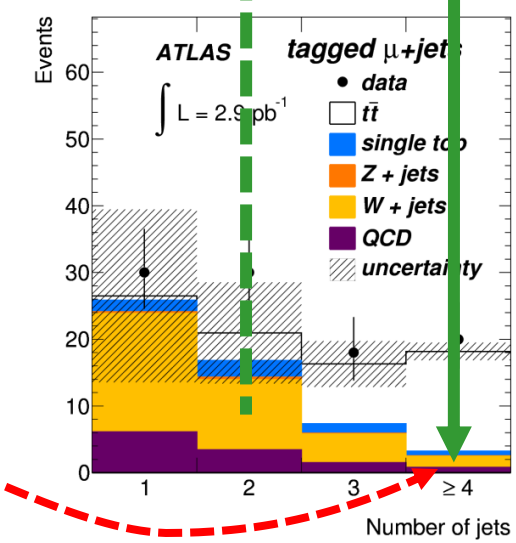
  - But flavour composition will be different in 2-jet and 4-jet bin → not directly applicable
    → Apply simulation-based correction factor

$$f_{\text{tagged}}^{\geq 4-\text{jet}} = f_{\text{tagged}}^{2-\text{jet}} \cdot f_{2\rightarrow\geq 4}^{\text{corr}}$$

$$W_{\text{tagged}}^{\geq 4\text{-jet}} = 1.9 \pm 0.7(\text{stat.}) \pm 0.9(\text{syst.}), \quad e \text{ channel},$$

$$W_{\text{tagged}}^{\geq 4\text{-jet}} = 3.2 \pm 1.2(\text{stat.}) \pm 1.2(\text{syst.}), \quad \mu \text{ channel}.$$

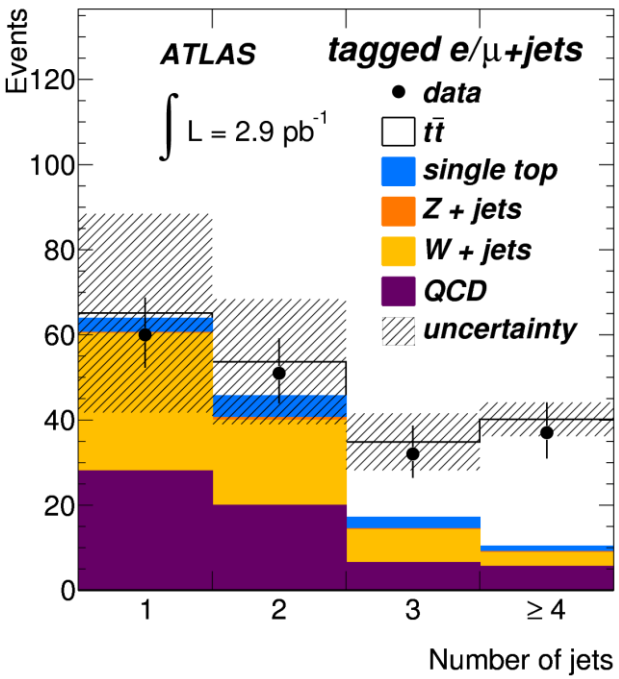




Summary on backgrounds – ttbar signal yield

- Obtain ttbar event yield by subtracting all backgrounds from measured event yield
  - Errors on backgrounds include all systematic uncertainties
  - Correlations and anti-correlations between source of systematic uncertainties is taken into account in total background estimate

	e+≥4jets tagged	μ+≥4jets tagged
QCD (DD)	**4.8 ± 3.1**	**0.8 ± 0.5**
W+jets (DD)	**1.9 ± 1.1**	**3.2 ± 1.7**
Z+jets (MC)	0.2 ± 0.1	0.1 ± 0.1
single top (MC)	0.7 ± 0.2	0.7 ± 0.2
Total background	**7.5 ± 3.1**	**4.7 ± 1.7**
Observed	17	20
Estimated ttbar	**9.5 ± 4.1 ± 3.1**	**15.3 ± 4.4 ± 1.7**



Cross section calculation in lepton+jets channel

- Final step is to relate event count to cross-section using the luminosity and (acceptance x efficiency x BF)

$$\sigma_{tt} = (N_{obs} - N_{bkg}) / (\varepsilon \cdot BF \cdot L)$$

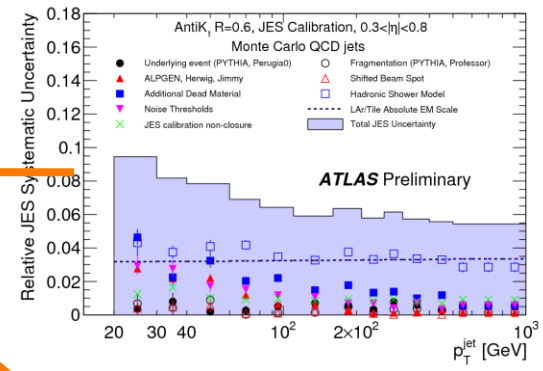
Method	e+jets	μ+jets	e/μ +jets combined
Counting $\sigma_{t\bar{t}}$ [pb]	$105 \pm 46 \,^{+45}_{-40}$	$168 \pm 49 \,^{+46}_{-38}$	$142 \pm 34 \,^{+50}_{-31}$

- Systematic uncertainty on cross section reflects
  - Background systematic uncertainties
  - Acceptance systematic uncertainties
  - Luminosity uncertainty
- In total 28 sources of systematic uncertainty are taken into account (in a coherent way across all components)
- Cross-section calculation based on likelihood model for event count in each channel, implementing the above relation

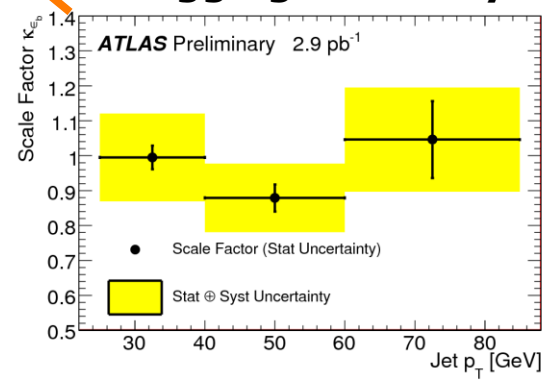
Breakdown of systematic uncertainties

	Relative cross-section uncertainty [%]	
Source	e+jets	μ+jets
Statistical uncertainty	±43	±29
Object selection		
Lepton reconstruction, identification, trigger	±3	±2
Jet energy reconstruction	±13	±11
b-tagging	-10 / +15	-10 / +14
Background rates		
QCD normalisation	±30	±2
W+jets normalisation	±11	±11
Other backgrounds normalisation	±1	±1
Signal simulation		
Initial/final state radiation	-6 / +13	±8
Parton distribution functions	±2	±2
Parton shower and hadronisation	±1	±3
Next-to-leading-order generator	±4	±6
Integrated luminosity	-11 / +14	-10 / +13
Total systematic uncertainty	-38 / +43	-23 / +27
Statistical + systematic uncertainty	-58 / +61	-37 / +40

Jet Energy scale ~7%



b-tagging efficiency



Method	e+jets	μ+jets	e/μ +jets combined
Counting $\sigma_{t\bar{t}}$ [pb]	$105 \pm 46\ ^{+45}_{-40}$	$168 \pm 49\ ^{+46}_{-38}$	$142 \pm 34\ ^{+50}_{-31}$

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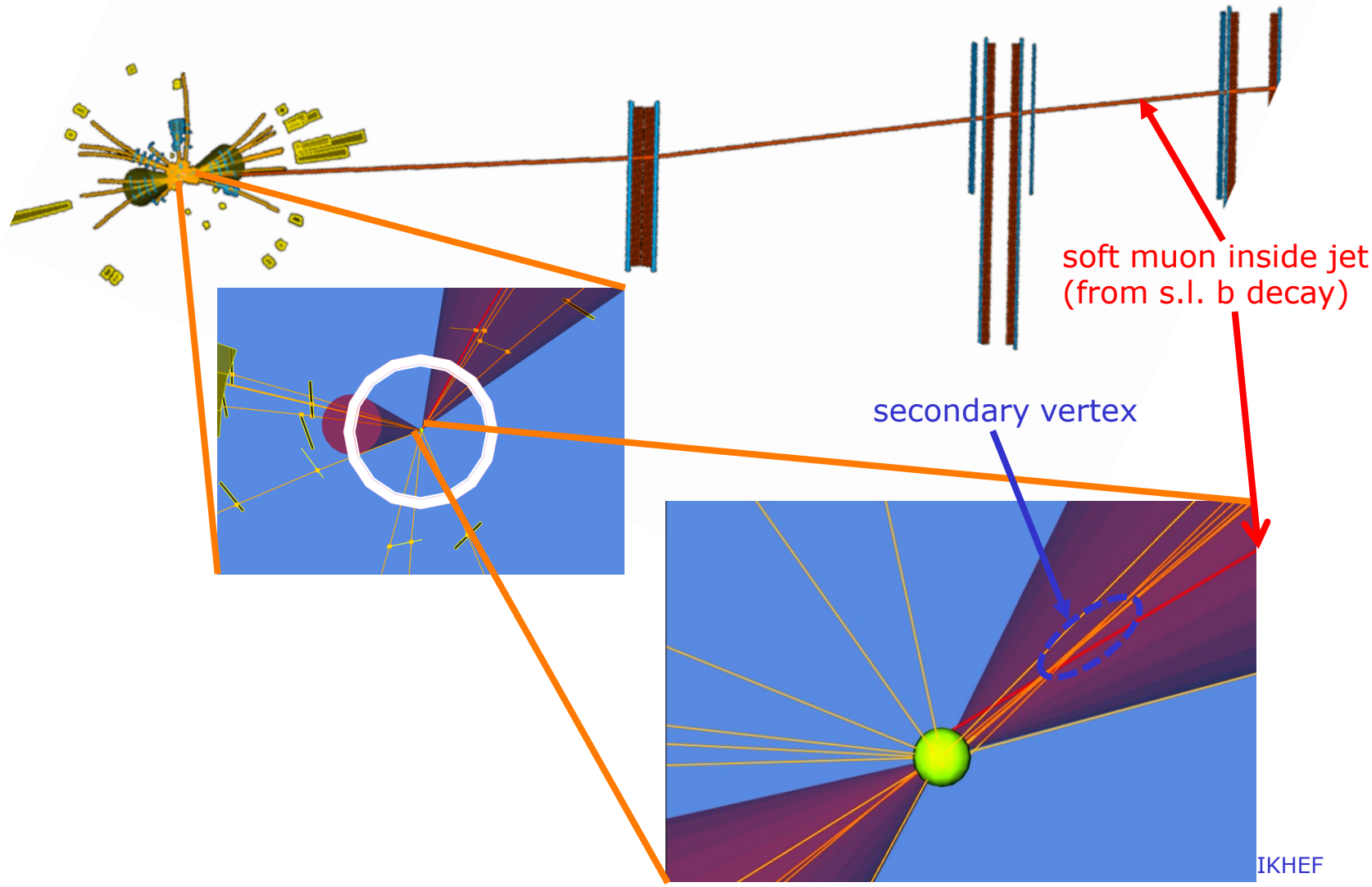
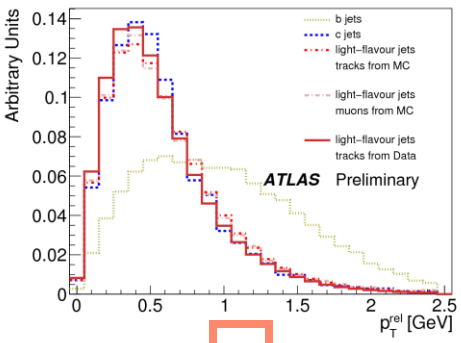


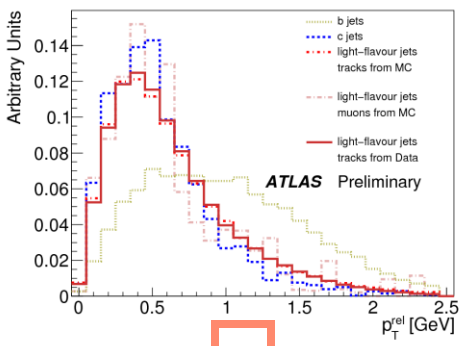
Measurement of b-tagging efficiency in data

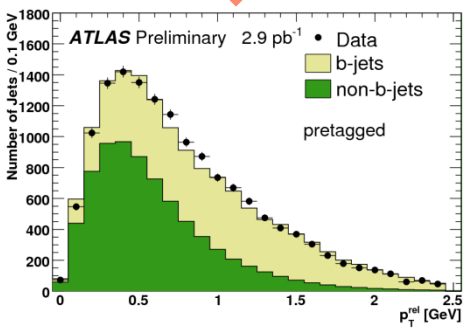
Distribution of pT of muon relative to jet axis templates for b,c,light jets

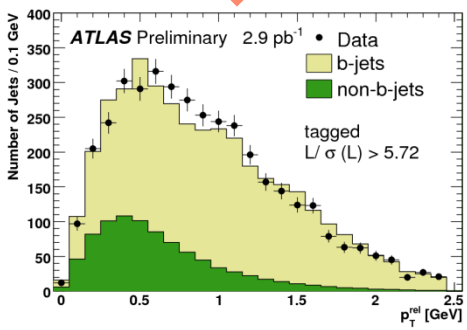
pretag



tagged

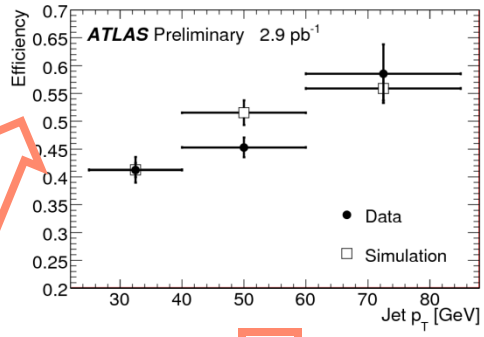


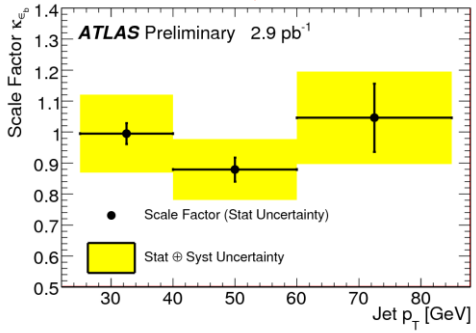




Fit sum of b-jet and non-b-jet to data

Efficiency measured vs p_T,η for data and simulation

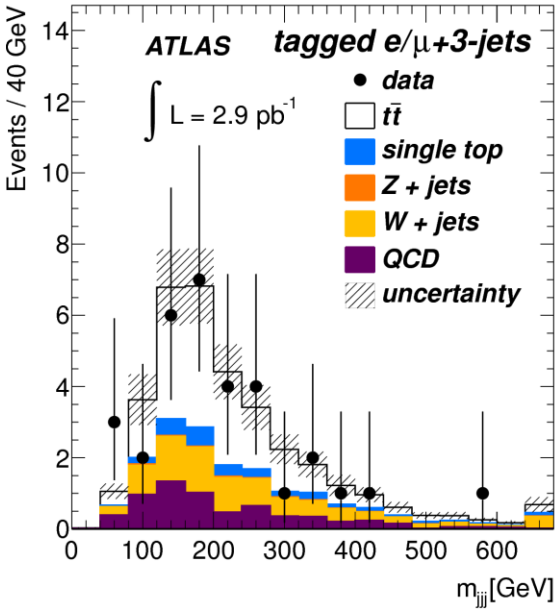


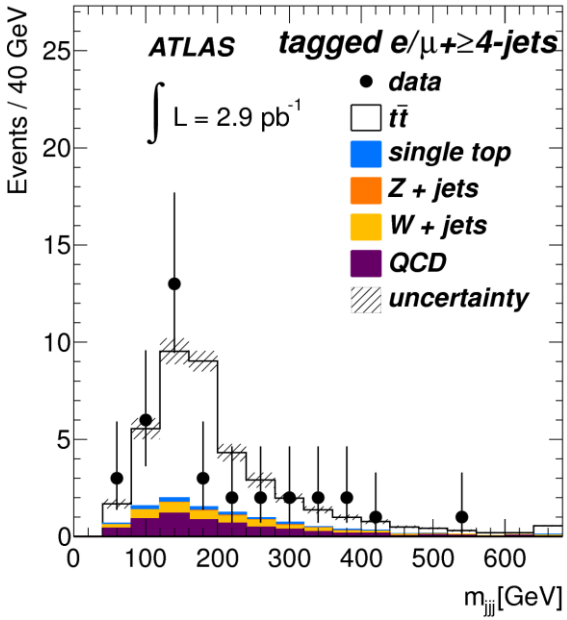


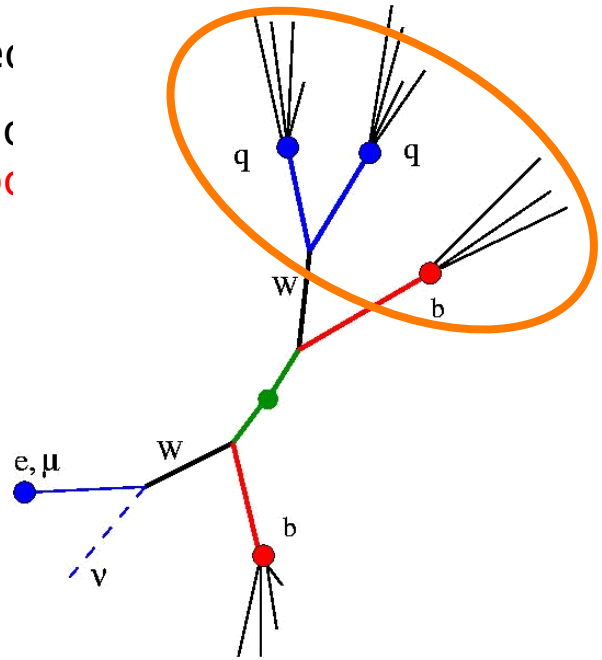
Scale factor (with uncertainty) is applied to simulation

Kinematic distributions – reconstruction of hadronic top mass

- Mass of top quark can be reconstructed from three-jet invariant mass
  - Empirically identify three jets by picking combination with largest vectorially summe
  - Observed distribution agrees with expectati from simulation → data consistent with hyp that observed excess is ttbar



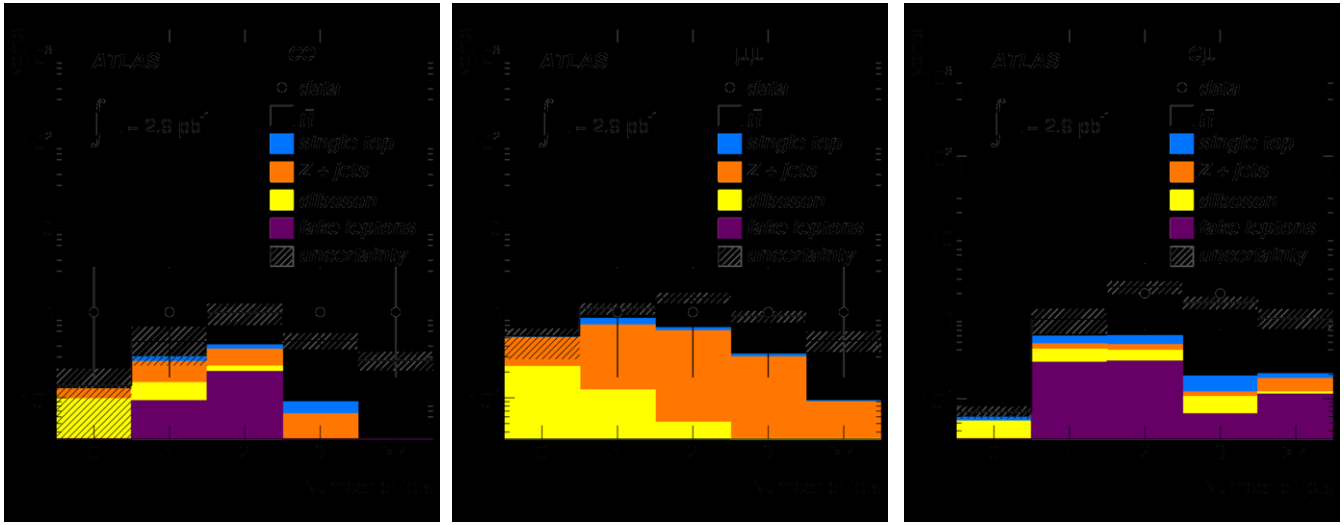




The dilepton channel – event selection

- Three channels reconstructed: ee, μμ, eμ
- Event selection
  - Exactly two good opposite charge leptons (p_T>20 GeV)
  - At least 2 good jets (p_T>20, |η|<2.5)
  - ee: |m(ll)-m(Z)|>5 GeV / μμ: |m(ll)-m(Z)|>10 GeV (Z veto)
  - ee: E_T^{miss}> 40 GeV / μμ: E_T^{miss}> 30 GeV / eμ: H_T> 150 GeV
  - Cosmic veto: μμ: d0(μ)<500 μm

H_T *= scalar sum of E_T of leptons and selected jets*



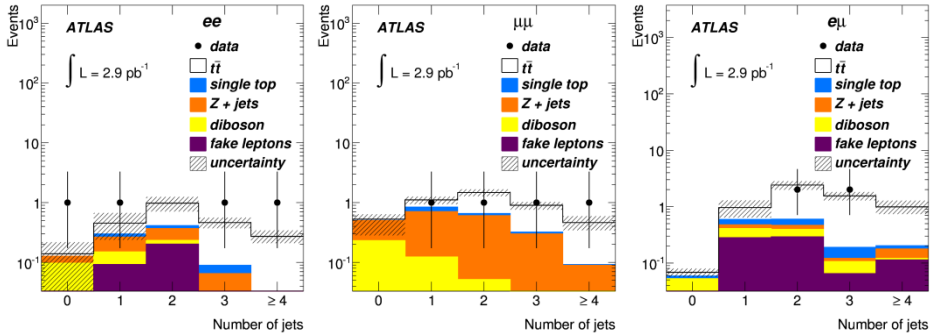
Fake leptons
estimated from data (see later)

W/Z+jets
from simulation (Alpgen)

tt, single top
from simulation (MC@NLO)

Background estimation

- Next step is background estimation in ≥2 jets region
  - Backgrounds are generally small (note log-scale on plots)



- Background from Z+(bb/cc/c)+jets not surprising
  - Drell-Yan process also generates lepton pairs off Z-resonance
  - Large cross section and same final particle-level state except for neutrinos (but fake ETmiss can easily be introduced)
- Understanding fake lepton background
  - Mechanism similar to lepton+jets background, but source different
  - Leading contribution from W+jets with one (additional) fake/non-prompt lepton
  - Also small contribution from QCD multi-jets with two fake/non-prompt leptons

Estimation of fake background

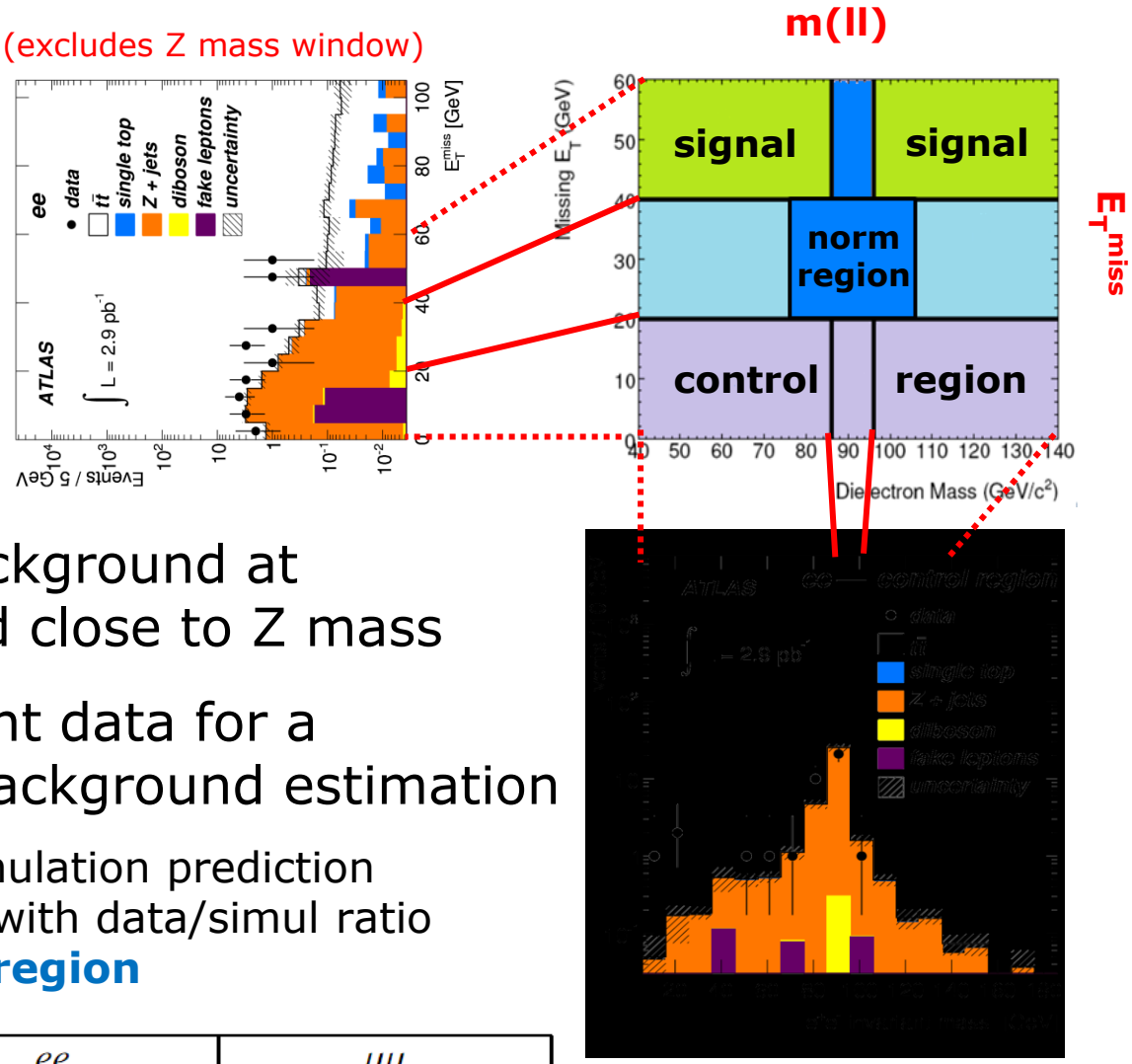
- Same principle as μ+jets: matrix method
  - Define loose, tight lepton selection → 4 observable states: Loose-Loose, Loose-Tight, Tight-Loose and Tight-Tight
  - Also 4 classes of background Fake-Fake, Fake-Real, Real-Fake and Real-Real
  - Matrix method results in a 4x4 equation system

$$= \begin{bmatrix} rr & rf & fr & ff \\ r(1-r) & r(1-f) & f(1-r) & f(1-f) \\ (1-r)r & (1-r)f & (1-f)r & (1-f)f \\ (1-r)(1-r) & (1-r)(1-f) & (1-f)(1-r) & (1-f)(1-f) \end{bmatrix}$$

  - Obtain fractions ***f, r*** from control samples and solve equation for $N_{RF/FR}$,N_{FF}
  - Fraction **r** measured from Z(→ll)+jets events
  - Fraction **f** measured from sample with single loose lepton (which is dominated by QCD di-jet production – contribution from W+jets with real leptons subtracted using simulation prediction)

Estimation of Z+jets background

(excludes Z mass window)



- Most Drell-Yan background at low missing E_T and close to Z mass
- In 3 pb^{-1} insufficient data for a real data-driven background estimation
  - Instead rescale simulation prediction for **signal region** with data/simul ratio in **normalization region**

	ee	$\mu\mu$
Z+jets (Monte-Carlo)	0.14 ± 0.03 ± 0.16	0.56 ± 0.06 ± 0.39

Summary on backgrounds – ttbar signal yield

- Obtain ttbar event yield by subtracting all backgrounds from measured event yield
  - Errors on backgrounds in include all systematic uncertainties
  - Correlations and anti-correlations between source of systematic uncertainties taken into account in total background estimate

	ee	μμ	eμ
Z+jets (DD)	**0.25 ± 0.18**	**0.67 ± 0.38**	**-**
fake leptons (DD)	**0.16 ± 0.18**	**-0.08 ± 0.07**	**0.47 ± 0.28**
Z(ττ)+jets (MC)	0.08 ± 0.04	0.14 ± 0.07	0.47 ± 0.28
single top (MC)	0.08 ± 0.02	0.07 ± 0.03	0.22 ± 0.04
dibosons (MC)	0.04 ± 0.02	0.07 ± 0.03	0.15 ± 0.05
Total background	**0.60 ± 0.27**	**0.88 ± 0.40**	**0.97 ± 0.30**
Observed	2	3	4

Cross section calculation in dilepton channel

- Final step is to divide by signal acceptance x efficiency x BF and luminosity to obtain cross section

$$\sigma = (N_{obs} - N_{bkg}) / (\varepsilon \cdot BF \cdot L)$$

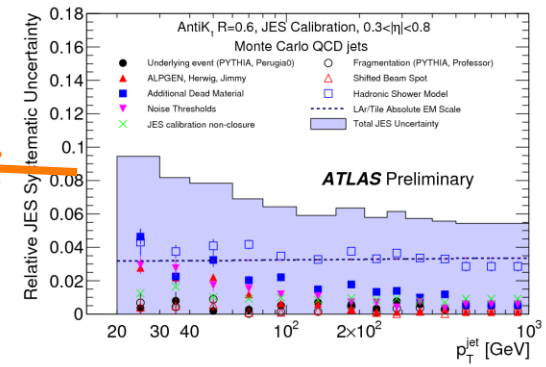
- Systematic uncertainty on cross section reflects
  - Background systematic uncertainties
  - Acceptance systematic uncertainties
  - Luminosity uncertainty
- In total 32 sources of systematic uncertainty are taken into account (in a coherent way across all components)
- Final cross-section calculation based on likelihood model for event count in each channel, implement the above relation

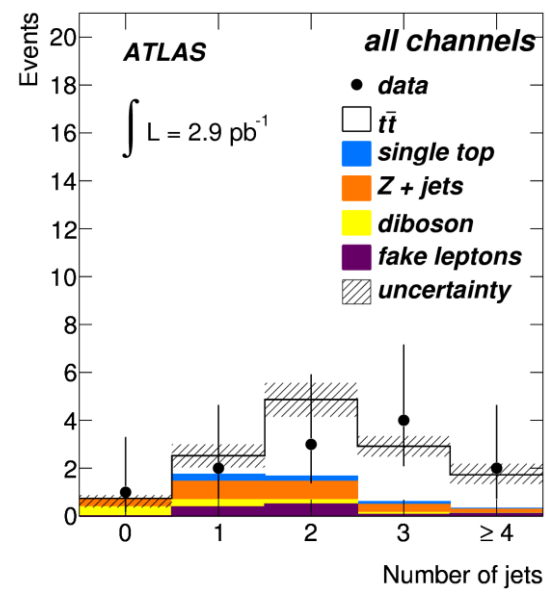
Channel	$\sigma_{t\bar{t}}$ [pb]
ee	$193^{+243}_{-152}{}^{+84}_{-48}$
$\mu\mu$	$185^{+184}_{-124}{}^{+56}_{-47}$
$e\mu$	$129^{+100}_{-72}{}^{+32}_{-18}$
Combined	$151^{+78}_{-62}{}^{+37}_{-24}$

Breakdown of systematic uncertainties

Source	Relative cross-section uncertainty [%]		
	ee	$\mu\mu$	$e\mu$
Statistical uncertainty	-79 / +126	-67 / +100	-56 / +77
Object selection			
Lepton reconstruction, identification, trigger	-2 / +11	-4 / +3	-1 / +3
Jet energy reconstruction	-7 / +13	-14 / +9	-3 / +5
Background rates			
Fake leptons	-31 / +24	-4 / +1	-15 / +8
Z+jets	-12 / +4	-19 / +5	-2 / +1
Monte-Carlo simulation statistics	-5 / +3	-3 / +4	± 2
Theoretical cross-sections	± 3	-5 / +4	± 3
Signal simulation			
Initial/final state radiation	-4 / +5	-2 / +3	-2 / +3
Parton distribution functions	-2 / +1	-2 / +3	-2 / +3
Parton shower and hadronisation	-9 / +14	-6 / +9	± 3
Next-to-leading order generator	-8 / +11	-11 / +13	-3 / +4
Integrated luminosity	-11 / +16	-11 / +16	-12 / +14
Total systematic uncertainty	-25 / +44	-25 / +30	-14 / +25
Statistical + systematic uncertainty	-83 / +134	-72 / +104	-57 / +81

Jet Energy scale ~7%





Likelihood model for cross section calculation

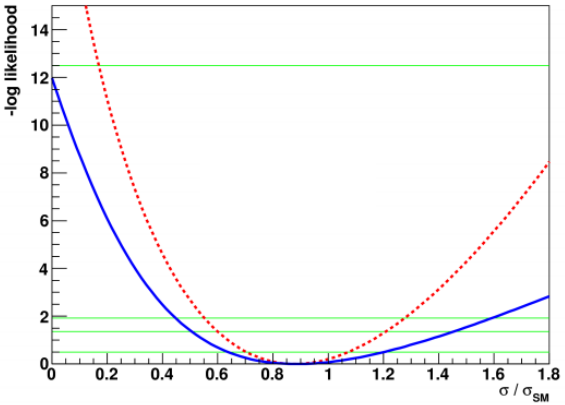
- Likelihood for each channel

$$N^{exp}(\sigma_{t\bar{t}}, \alpha_j) = \underbrace{L \cdot \epsilon_{t\bar{t}}(\alpha_j) \cdot \sigma_{t\bar{t}}}_{\text{tt signal}} + \underbrace{\sum_{bkg} L \cdot \epsilon_{bkg}(\alpha_j) \cdot \sigma_{bkg}(\alpha_j)}_{\text{MC backgrounds}} + \underbrace{N_{DD}(\alpha_j)}_{\text{data-driven backgrounds}}$$

$$\mathcal{L}(\sigma_{t\bar{t}}, L, \alpha_j) = \underbrace{\text{Poisson}\left(N^{obs} \,|\, N^{exp}(\sigma_{t\bar{t}}, \alpha_j)\right)}_{\text{Poisson model for channel event count}} \times \underbrace{\text{Gauss}(L_0|L, \delta_L)}_{\text{Luminosity uncertainty}} \times \underbrace{\prod_{j \in \text{syst}} \Gamma_j(\alpha_j)}_{\text{Other systematic uncertainties}} .$$

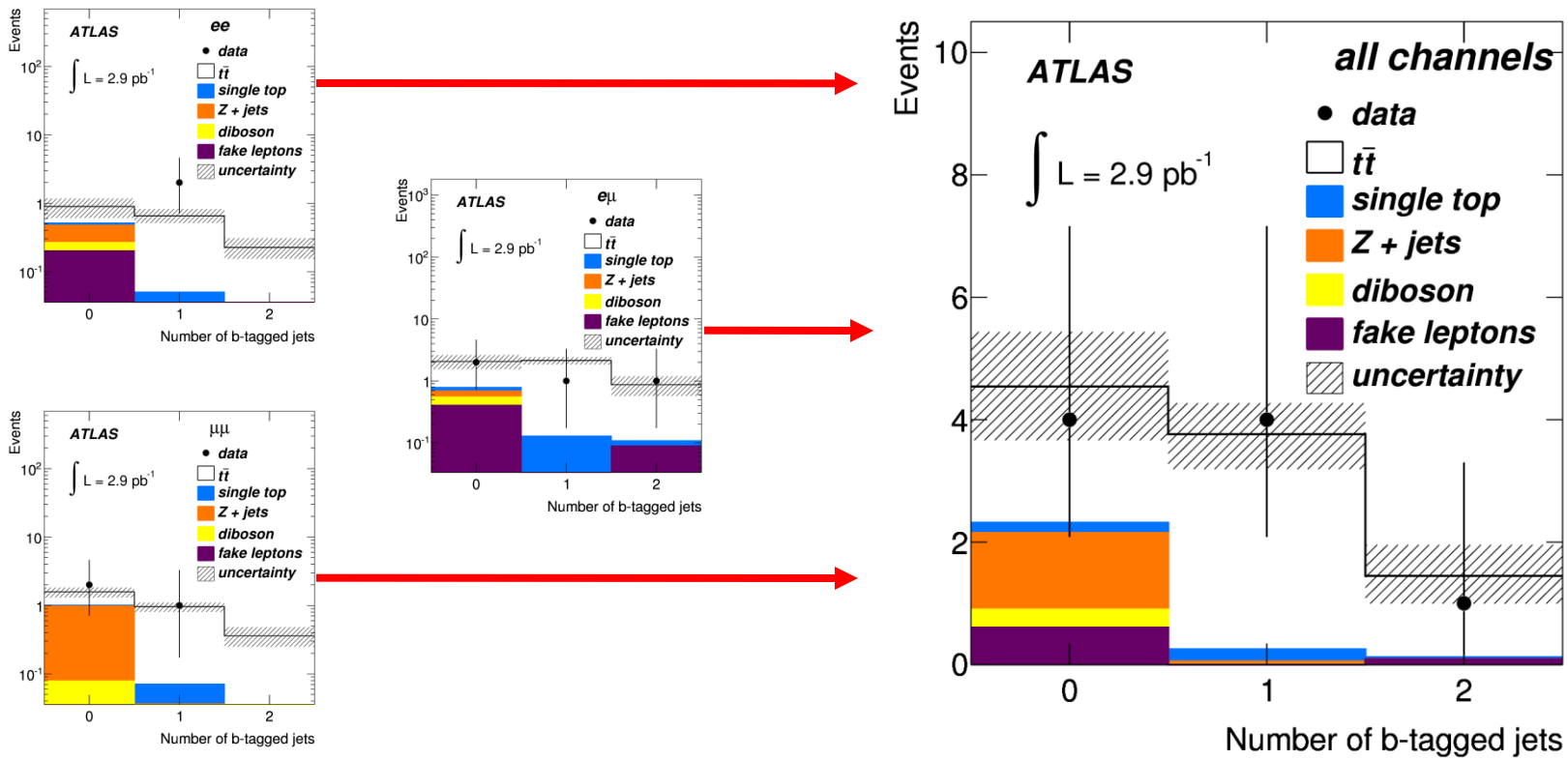
- Profile likelihood fit returns interval on $\sigma(tt)/\sigma(tt)_{SM}$
  - Run with and without systematic uncertainty terms (lumi,other) to extract statistical and total uncertainty

Illustration – *not* actual likelihood



Counting b-tagged jets in dilepton top selection

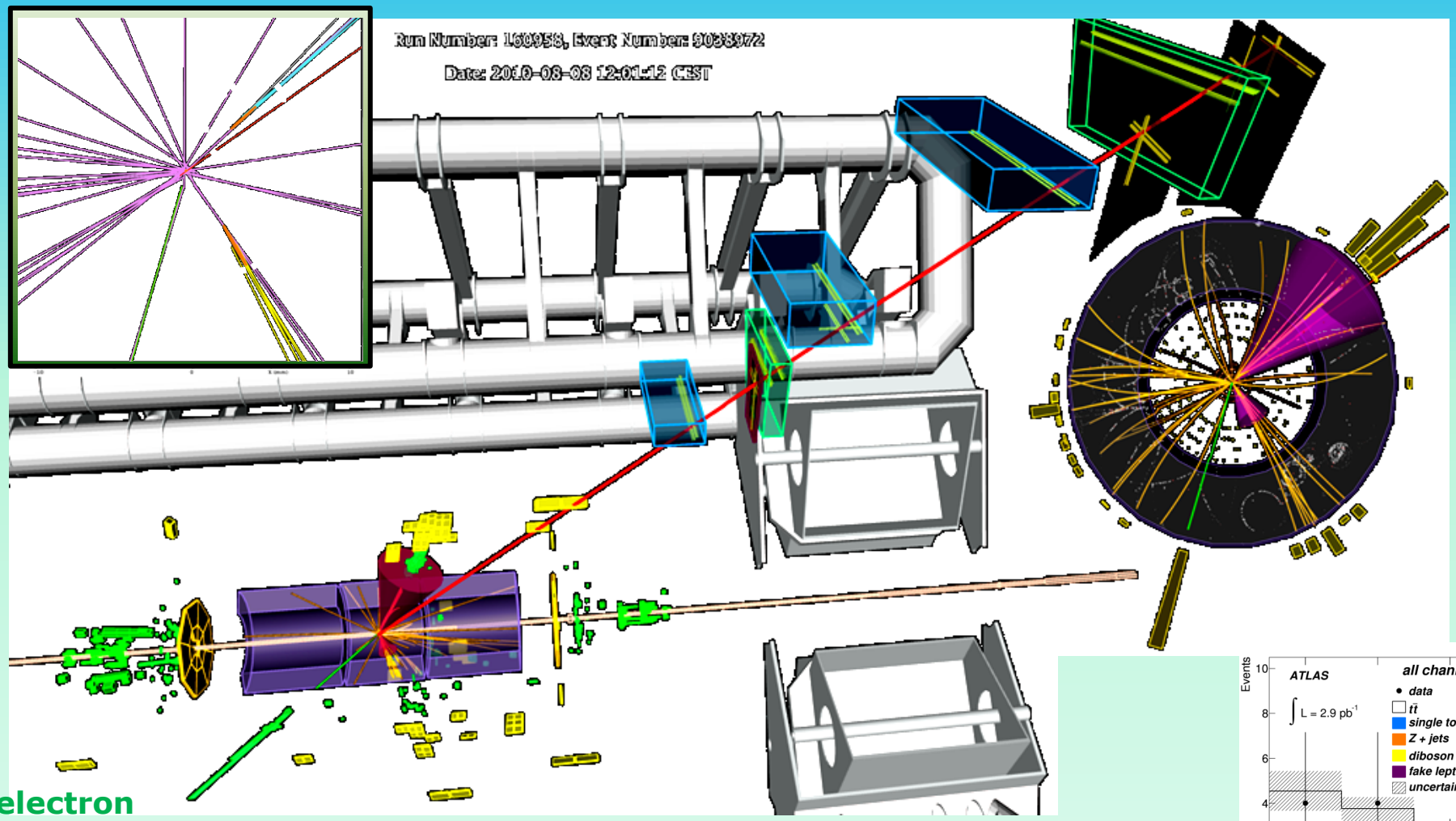
- B-tagging was not used in dilepton event selection.
  - But expect 2 b-quarks for each top candidate, while (on average) much less than 1 b-jet in background
  - Presence of b-jets in selection support hypothesis that selected candidates contain tt events



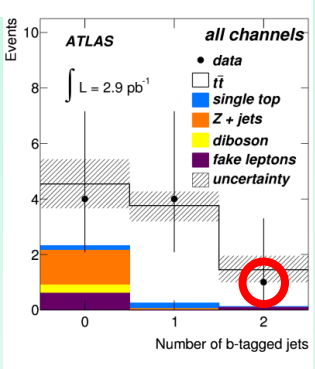
A ‘platinum’ event: ttbar eμ with 2 b-tagged jets

double b-tag

muon



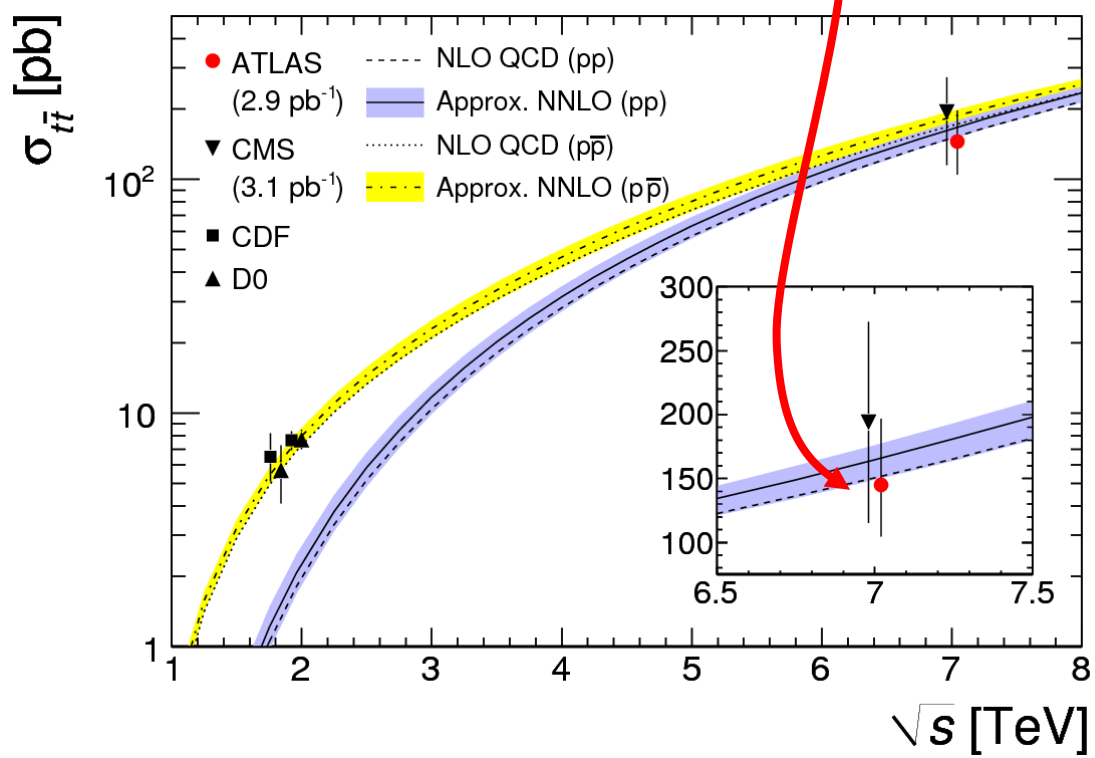
electron



Putting it all together

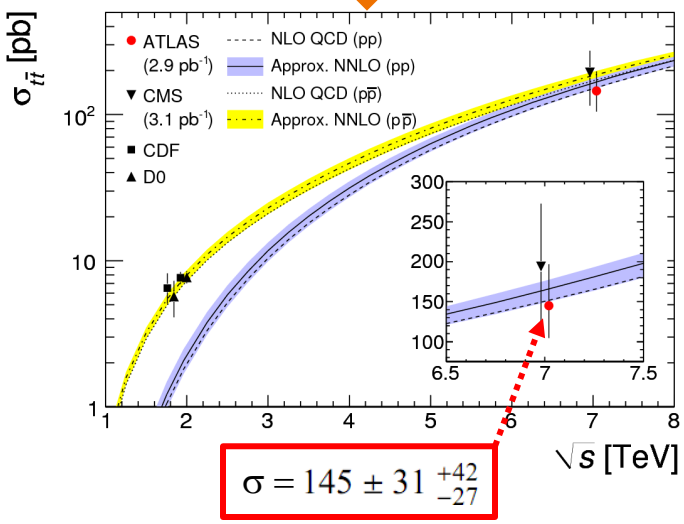
- Combined lepton+jets and dilepton from joint fit
  - Accounts for all (anti)-correlated systematic uncertainties

	Cross-section [pb]	Signal significance [σ]
Single lepton channels	$142 \pm 34\ ^{+50}_{-31}$	4.0
Dilepton channels	$151\ ^{+78}_{-62}\ ^{+37}_{-24}$	2.8
All channels	$145 \pm 31\ ^{+42}_{-27}$	4.8



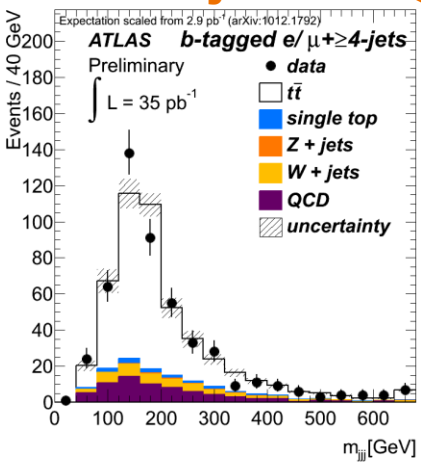
Summary & Outlook

- The era of LHC top physics has started
  - First ATLAS measurements of top quark pair production with 3 pb^{-1}
  - Agrees with theoretical prediction and CMS measurement

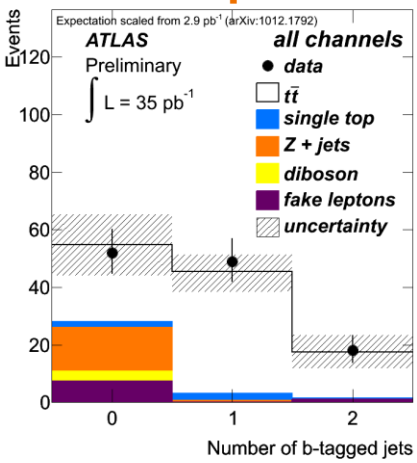


Already 10x more data on tape:

l+jets



dilepton



Full 2010 dataset / expectations scaled from 2.9 pb^{-1}

  - And (at least) another factor 10x more expected in 2011
  - Systematic uncertainties will start to dominate total uncertainties, will enter regime where we can test QCD predictions of cross section
  - Other area of top physics (properties, single top) will soon become feasible