Top mass reconstruction in ATLAS

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On
Behalf Of The ATLAS Collaboration

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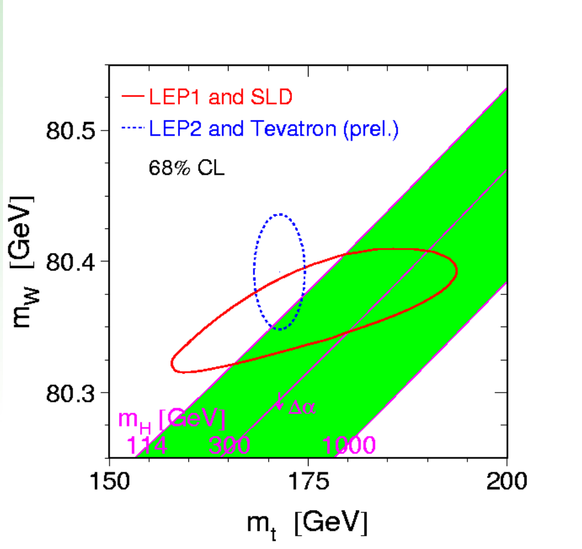
JOHANNES GUTENBERG UNIVERSITÄT MAINZ

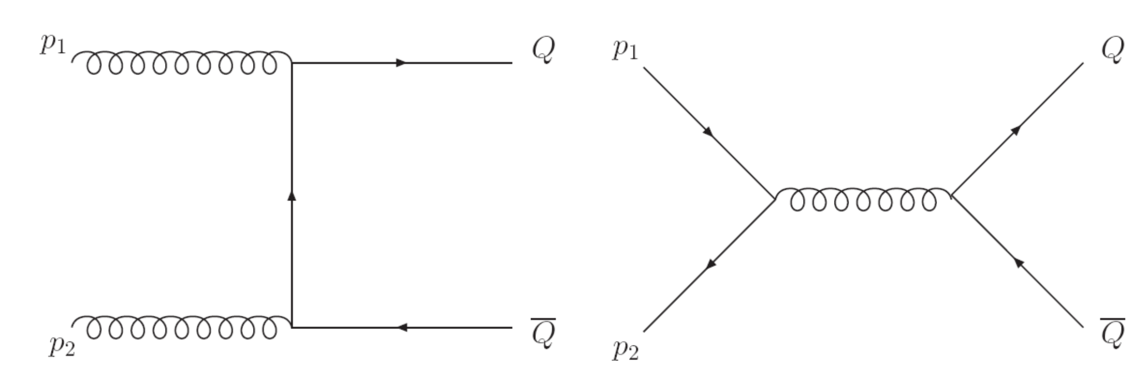
GEFÖRDERT VOM
Bundesministerium für Bildung und Forschung

FSP 101 ATLAS

Motivation

- Heaviest yet observed particle
  (decays as a free quark)
- Large electroweak radiative corrections
- Consistency of SM (new couplings?)
- Higgs mass limits



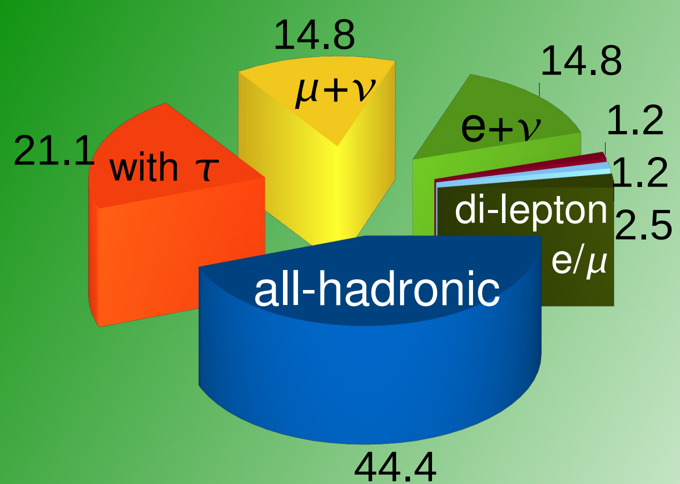


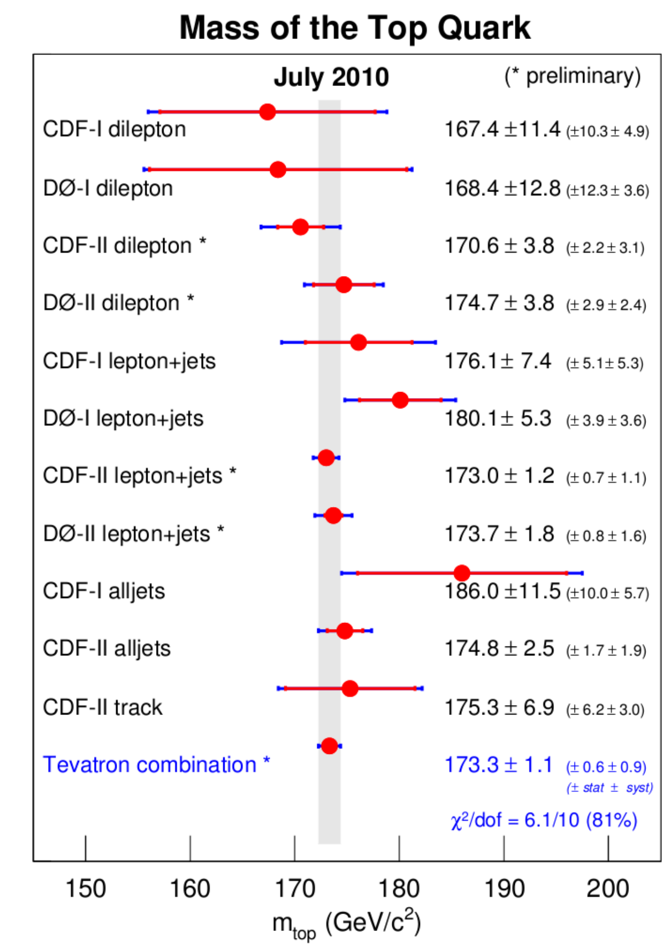
Production via qqbar and gg (LO)

Overview on top mass

- Almost 100%: ttbar ⟶ bbbarWW

  W decays determine event signature:





- Most precise measurements so far:

  lepton (μ/e) + jets channel (30%)

- Largest systematic uncertainty: jet energy scale (JES)
- ATLAS presented 3 complementary measurements to differently assess the JES systematic (ATLAS-CONF-2011-033)

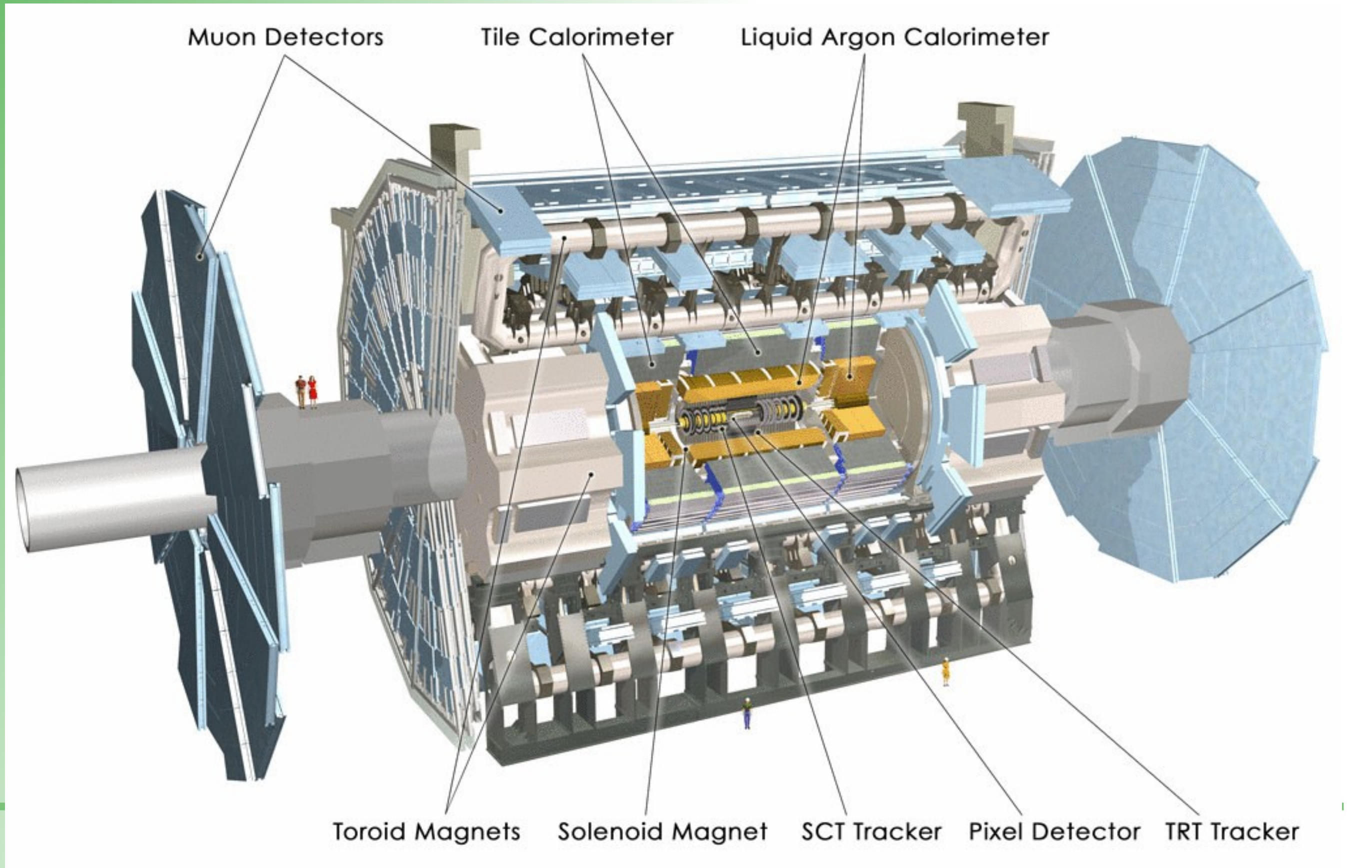
ATLAS and LHC

- LHC in 2010:
  - Total delivered, integrated Luminosity: ~50 pb^{-1}
  - Highest instantaneous Luminosity: $2x10^{32}$ $cm^{-2}s^{-1}$
  - Max. #Filled bunches: 368 (stable beams)
- ATLAS:

  Max. #Colliding bunches: 348

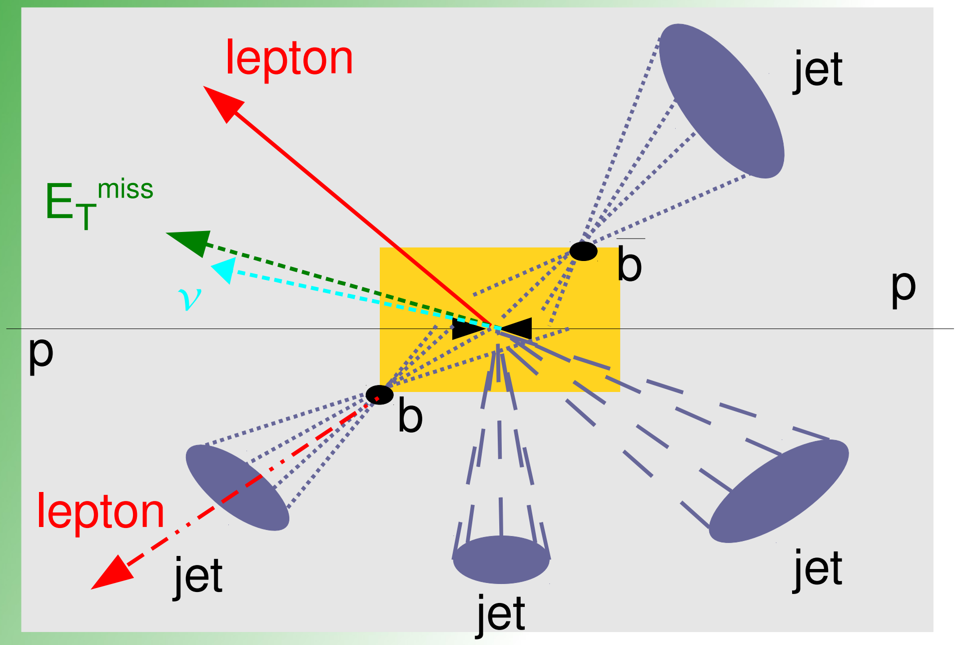
  $L = 35.3 \pm 1.2\ pb^{-1}$

  Max. #pileup events: ~4.7



For details please refer to Peter Loch's talk

Event topology and inputs



Event topology and inputs

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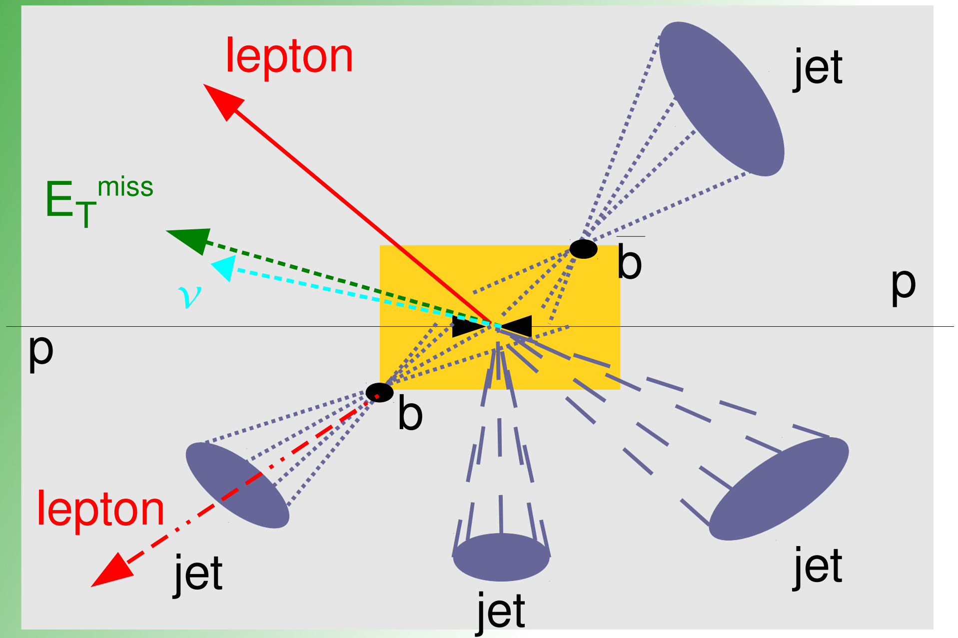
(fully efficient at 20 GeV)



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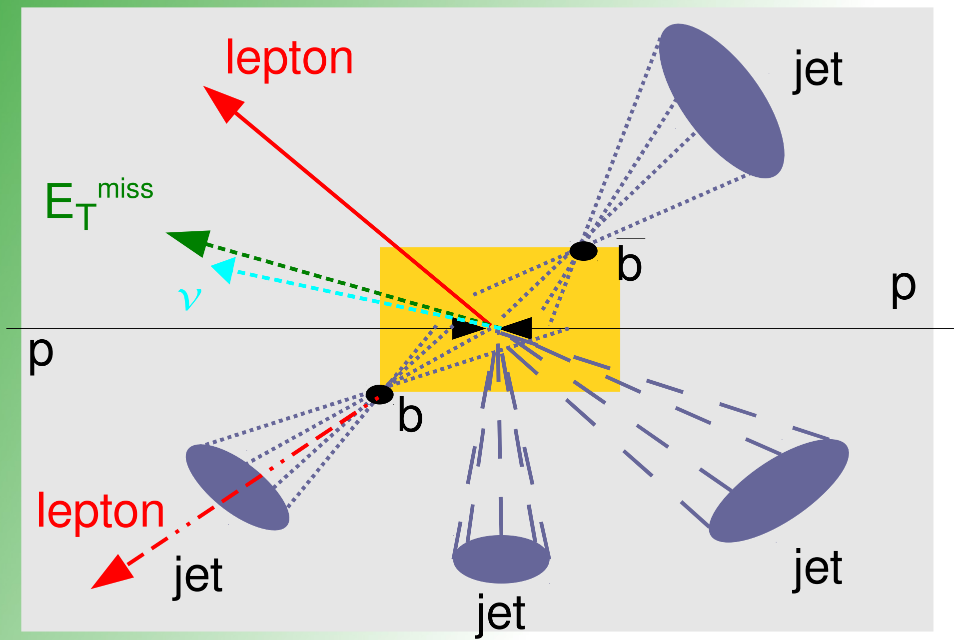
Primary vertex with at
least 5 charged particles



Event topology and inputs

Trigger: lepton trigger
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Primary vertex with at
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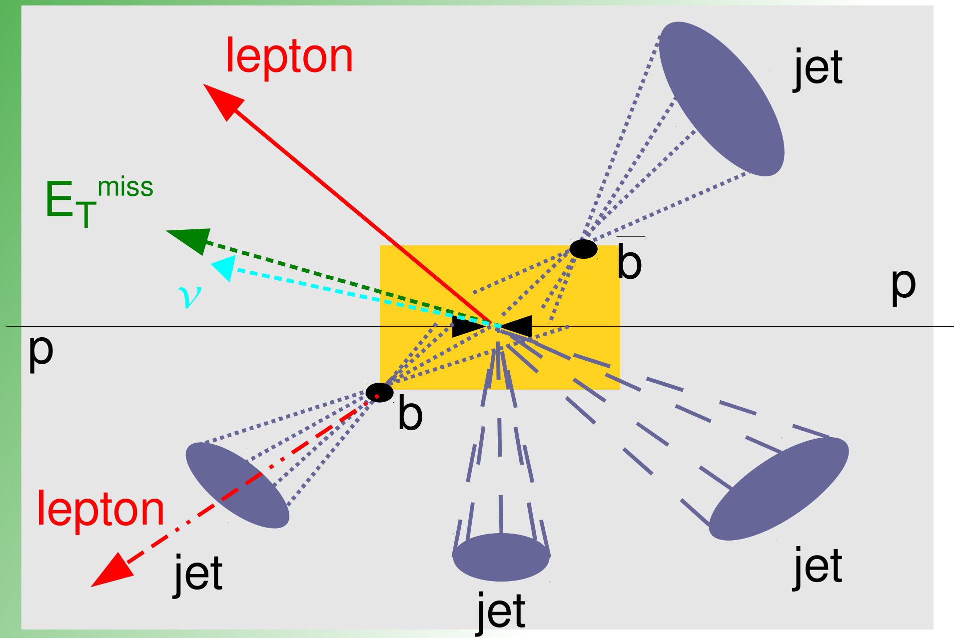
Electrons: isolated,
no high-pT and
isolated muon,
p_T> 20 GeV
$|\eta|$ < 1.37 or
1.52 < $|\eta|$<2.47

Muons: isolated,
no high-pT and isolated
electron,
p_T> 20 GeV
$|\eta|$ < 2.5
dR(μ,jet) > 0.4



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Fake jets from electrons
Muons from semi-lept.
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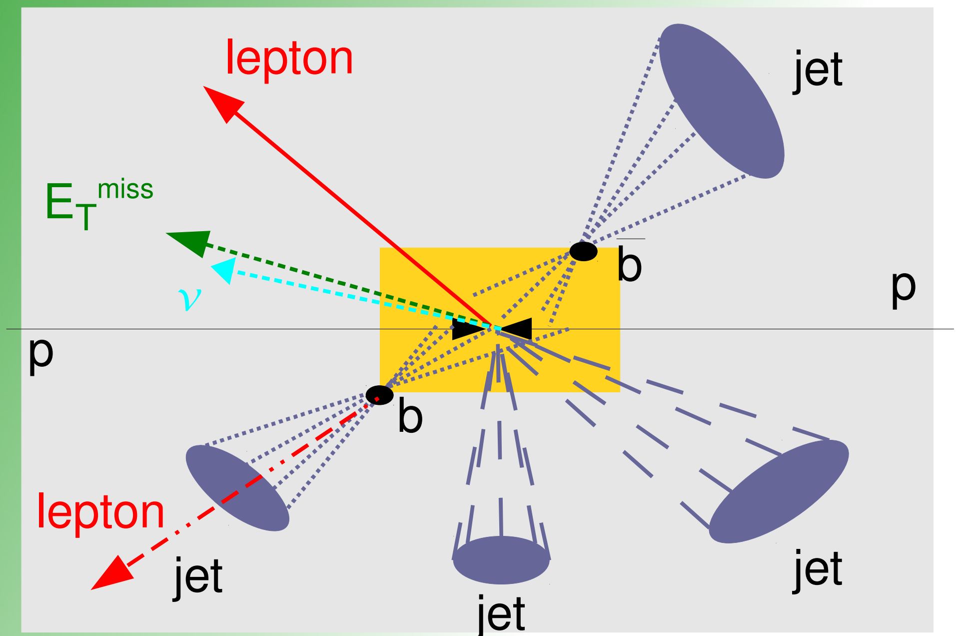

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E_T^{miss}:
calo cells+muons
Object-specific calibration
Electron (Muon) channel:
E_T^{miss} > 35 (20) GeV

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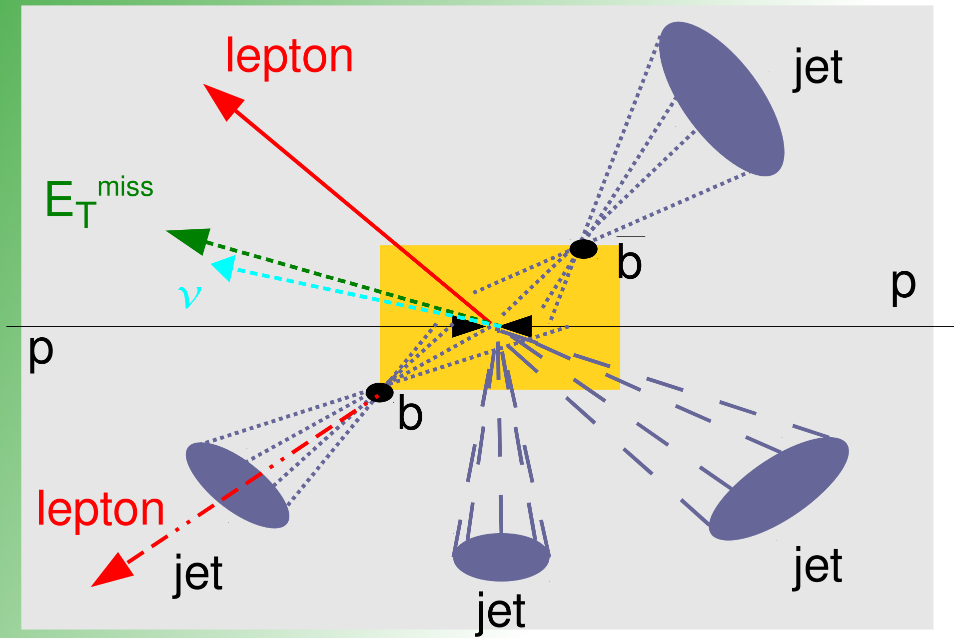

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W transverse mass:
QCD bkg suppression
electron-channel:
m_W^T > 25 GeV
muon-channel:
$E_T^{miss} + m_W^T$ > 60 GeV

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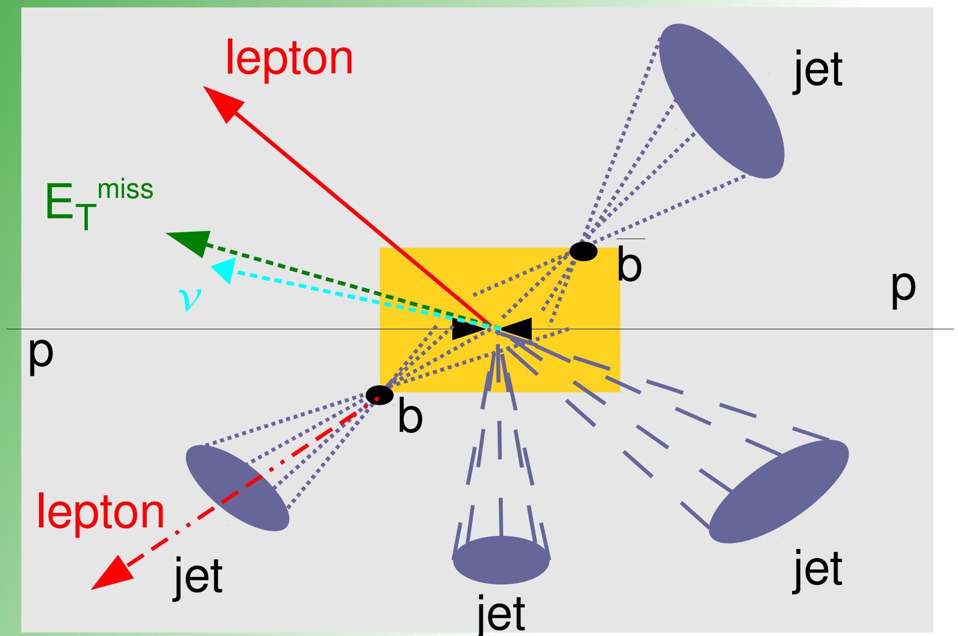

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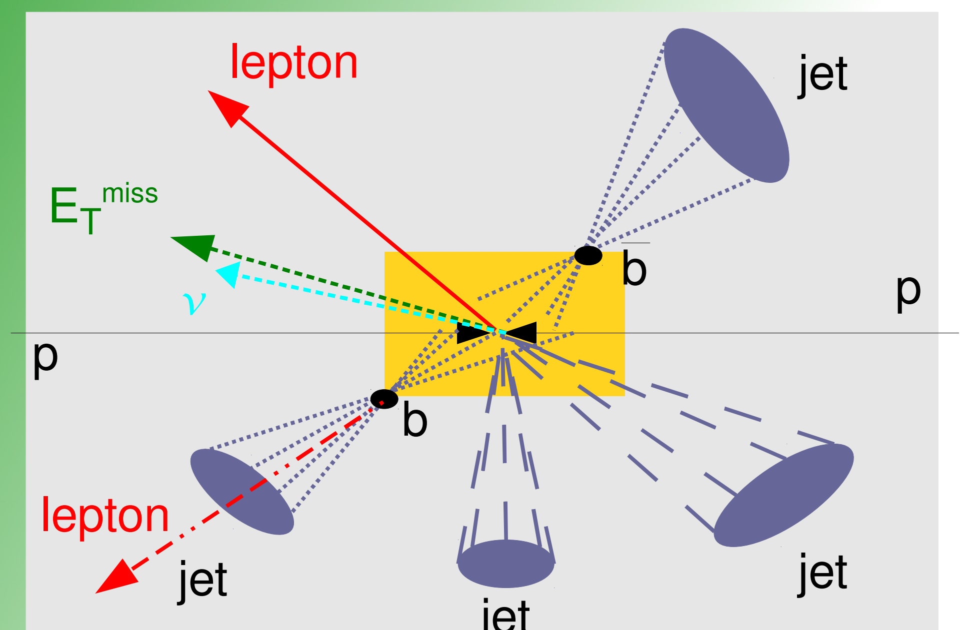
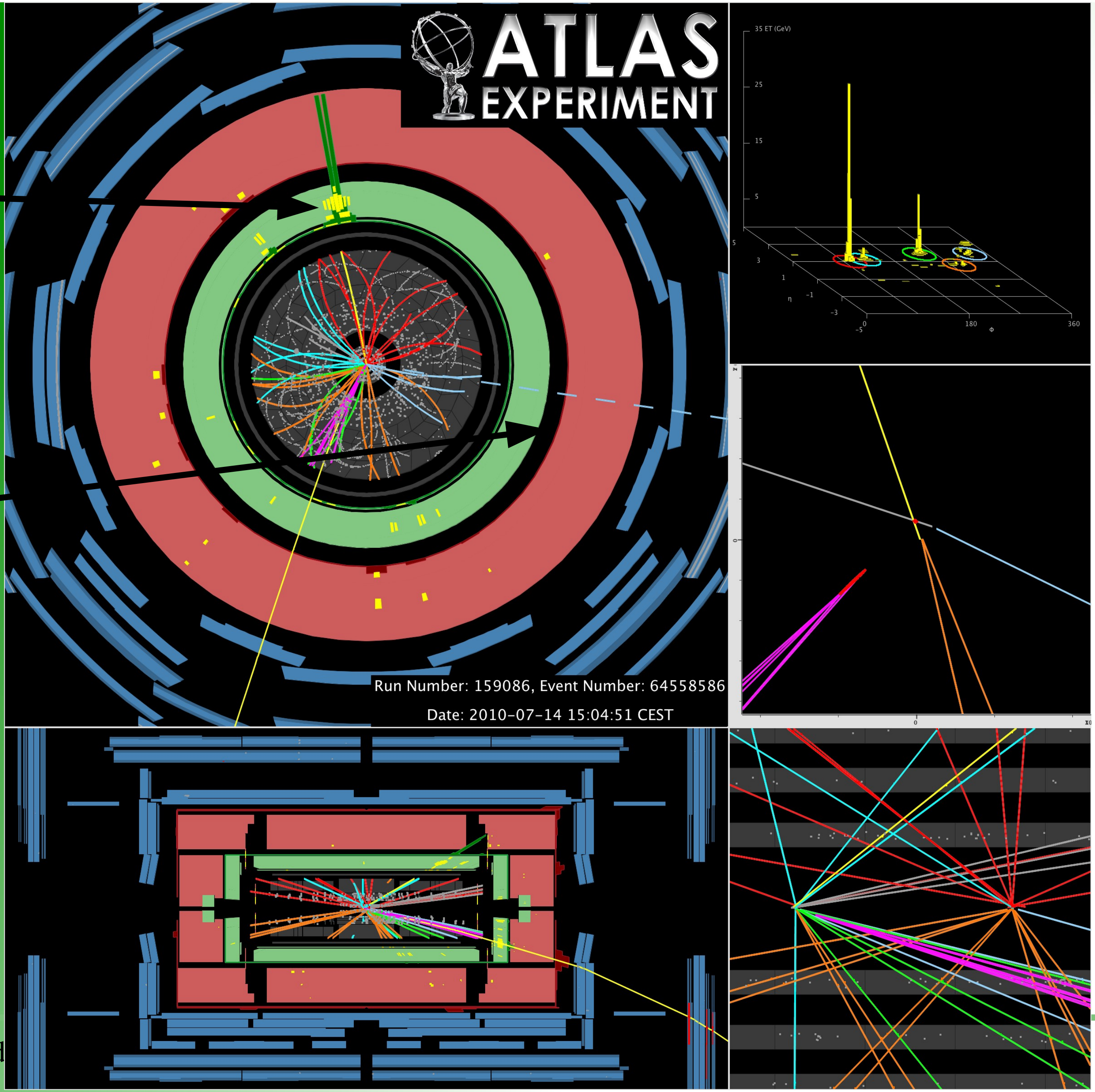


Jets: anti-k_t R=0.4
Had. scale calib. (p_T,η)
$|\eta|$< 2.5, p_T > 25 GeV
#jets ≥ 4
At least 1 b-tagged jet
No “bad” jets in event

Event display: electron plus jets

Electron

EtMiss



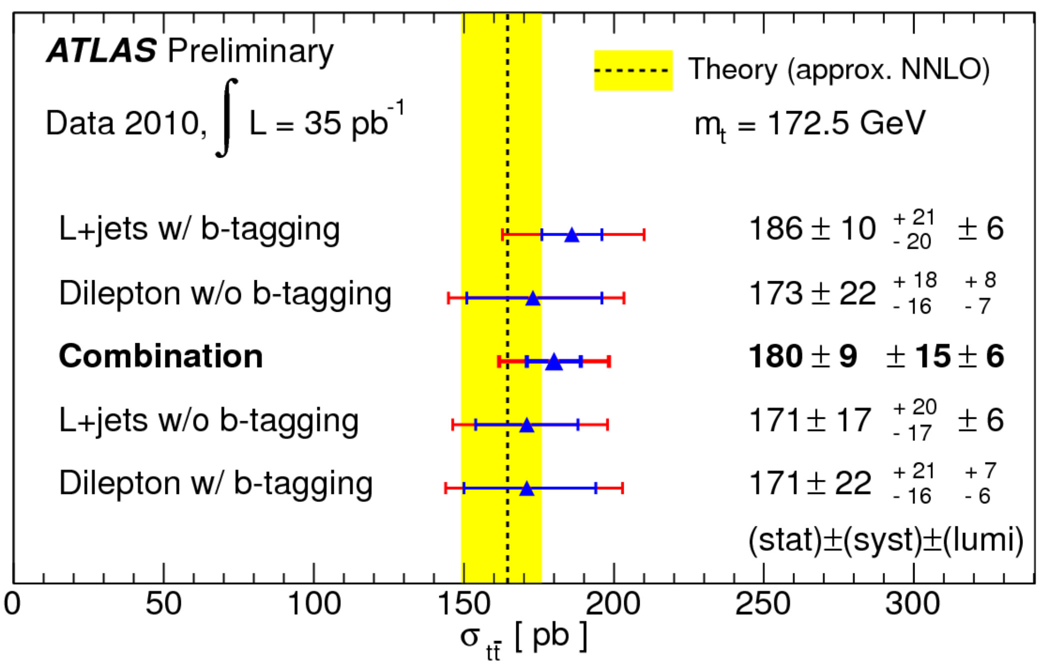
Secondary vertex of the b-tagged jet

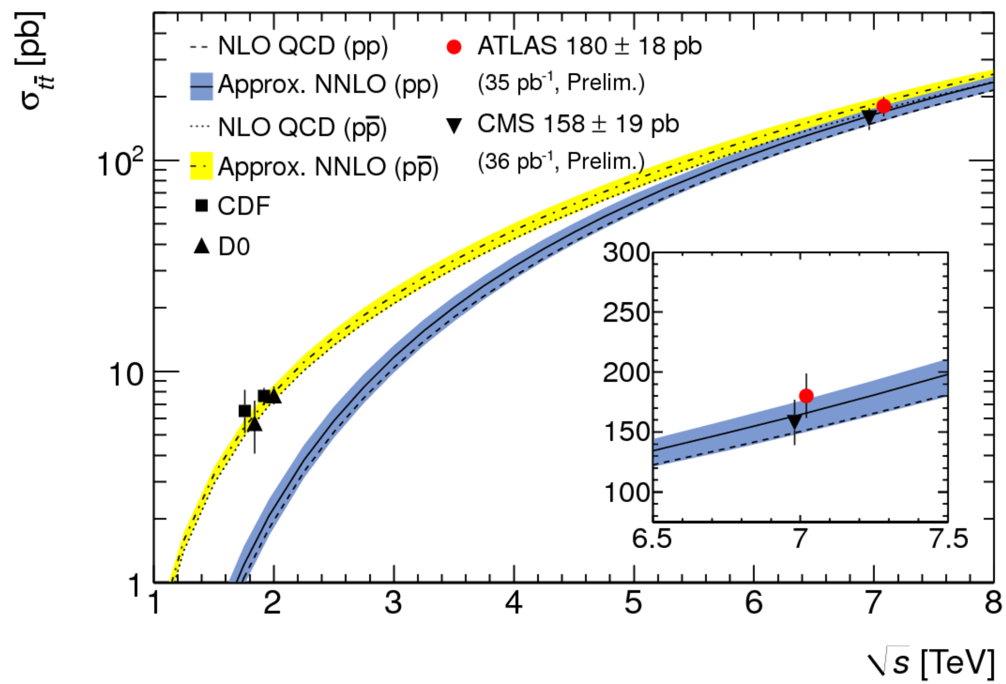
High pT vertex + Pileup vertex

Top cross section

- With these inputs we can measure top pair production in good agreement with NNLO (with and without b-tagging)

Combination of Tevatron and LHC measurements strengthen our confidence in our understanding





→ Measure the top-quark mass from these events

Top mass measurements

- Short overview of template methods at ATLAS:

BASE-LINE

  - **1-D fit of** $R_{32} = \frac{m_{top}^{reco}}{m_{W}^{reco}}$ **:**
    smallest expected uncertainty, stability against JES variations, based on the resolution on m_{top}
  - 2-D fit of m_{top}^{reco} and Jet energy scale factor (JSF)
  - 1-D kinematic likelihood fitter: using all decay products
- Complementary methods: cross check, address systematics differently, improve knowledge
- As long not stated differently: presenting baseline method

Top mass measurements

- Short overview of template methods at ATLAS:
  - **1-D fit of** ...

    smallest ...

    variation ...

    yield is the smallest
  - 2-D fit of $m_{\text{top}}^{\text{reco}}$ and Jet energy scale factor (JSF)
  - 1-D kinematical likelihood fitter to all decay products
- Complementary methods: cross check, address systematics differently, improve knowledge
- As long not stated differently: presenting baseline method

BASE-
LINE

Hadronic top reco:
4-vector sum with highest p_T
W boson reco:
mass window
60 GeV<m_W^{reco}<100 GeV

Jet-triplet (had. top):
> rejected if 2 jets are b-tagged
> No b-tag: chose jets with smallest dR in top rest-frame

Smallest event yield from all methods

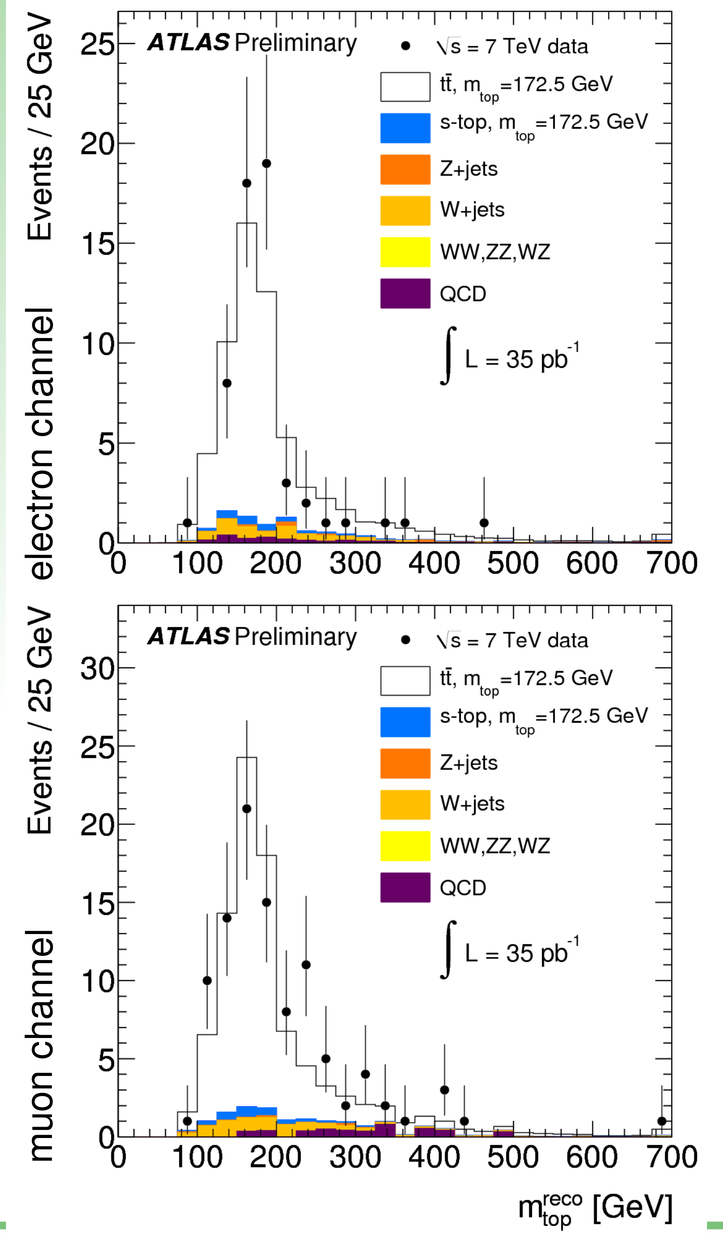
Background and Signal

- ttbar signal (MC@NLO) several fb^{-1}
- Background (bkg): other decay channels, single-top (s-top), di-boson, W/Z+jets processes and QCD multijet
- Except QCD bkg all others estimated by MC (Herwig, Alpgen): low background
- QCD background estimated from data

MC: electron (muon) channel
S/B = 52.6/9.1 (77.3/14.9) = 5.8 (5.2)
Observed **data** events: 56 (99)

Data well described by sum of signal and background

(List of details in backup slides)



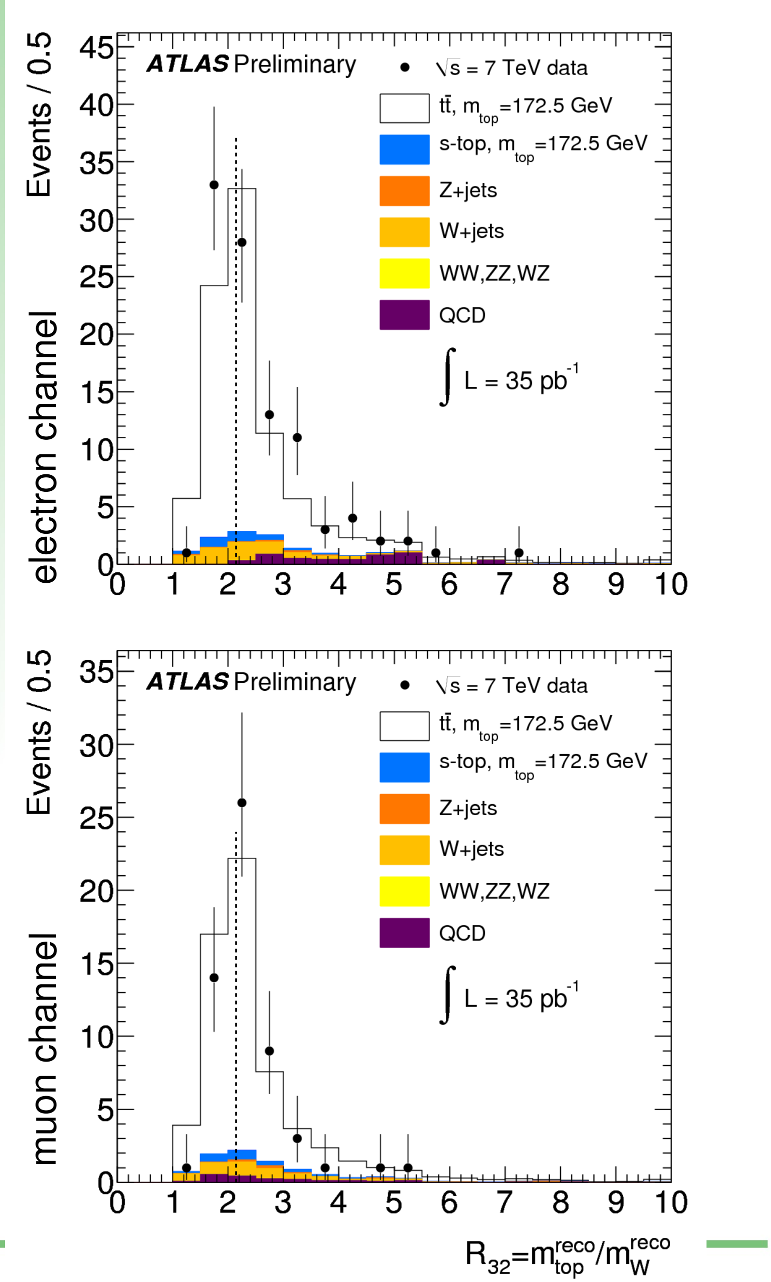
1-D R_{32} baseline method

- Likelihood fit of the R_{32} templates to data: event-by-event ratio of had. top mass m_{top}^{reco} and corresponding W boson mass m_{W}^{reco}
- Different m_{top} assumptions: 160, 170, 172.5, 180 and 190 GeV

Steps:

- Template parametrization (signal, bkg)
- Likelihood construction
- Pseudo-experiments

Data well described by sum of signal and background



Template parametrizations

- Each channel has its own parametrization
- Signal $P_{\text{sig}}(R_{32}; m_{\text{top}})$:

  > derived for all m_{top} dependent samples (include single-top events)

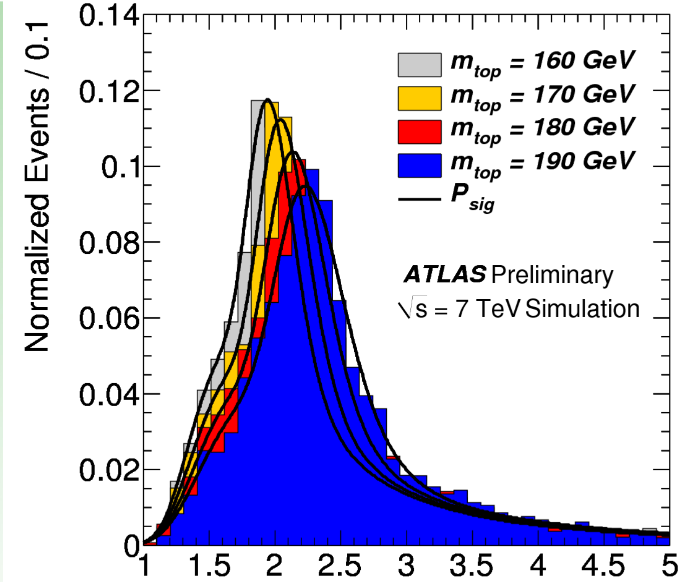
  > description by the sum of a ratio of two Gaussians and a Landau function

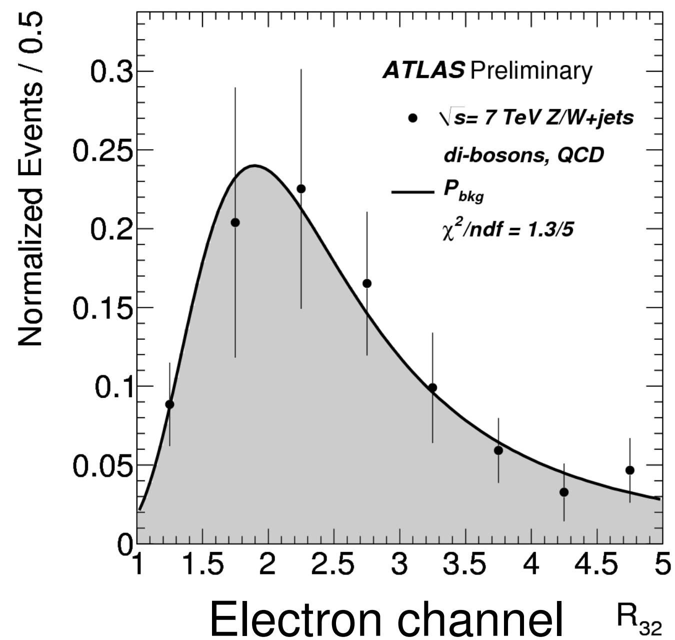
  > each parameter has a linear dependence on the top-quark mass

- Background $P_{\text{bkg}}(R_{32}; m_{\text{top}})$:

  > each background sample is well represented by a Landau function

  > individual contributions are summed into one parametrization (for all m_{top} samples)





Likelihood fit

- Contains 3 parts: account for shape of R_{32} distribution ($L_{\mathrm{shape}}(R_{32};m_{\mathrm{top}})$), relative relation of signal and background ($L_{\mathrm{n_s+n_b}}$) in N observed events, constraint on background events (L_{bkg})

$$L(R_{32};m_{\mathrm{top}}) = \prod \frac{n_s P_{\mathrm{sig}}(R_{32};m_{\mathrm{top}})_i + n_b P_{\mathrm{bkg}}(R_{32})_i}{n_s+n_b} \times \frac{e^{-(n_s+n_b)}(n_s+n_b)^N}{N!} \times \exp\left\{\frac{-(n_b-n_b^{\mathrm{pred}})^2}{2\sigma_{n_b^{\mathrm{pred}}}}\right\}$$

Product over all events N

- Pseudo-experiments: are used to validate the chosen fitting approach as well as to evaluate systematic uncertainty effects on the result
- Validation: 50 pseudo-experiments for each input top-quark mass, observed events Poisson fluctuated, with 35 pb^{-1} integrated luminosity, good linearity between input and output top-quark mass (pull distributions are consistent with the expectation)

Systematic uncertainties

- Each quantity of systematic uncertainty is varied by $\pm 1\sigma$ → pseudo-experiments corresponding to integrated luminosity of 5 fb^{-1}
- Quoted systematic: quadratic sum of all contributions

Detailed list of uncertainties
in backup slides

Measurement:
JES (2.3 GeV)
b-JES (2.5 GeV)
B-tagging
Jet energy resolution (1.1 GeV)
Jet reco efficiency

Method:
calibration

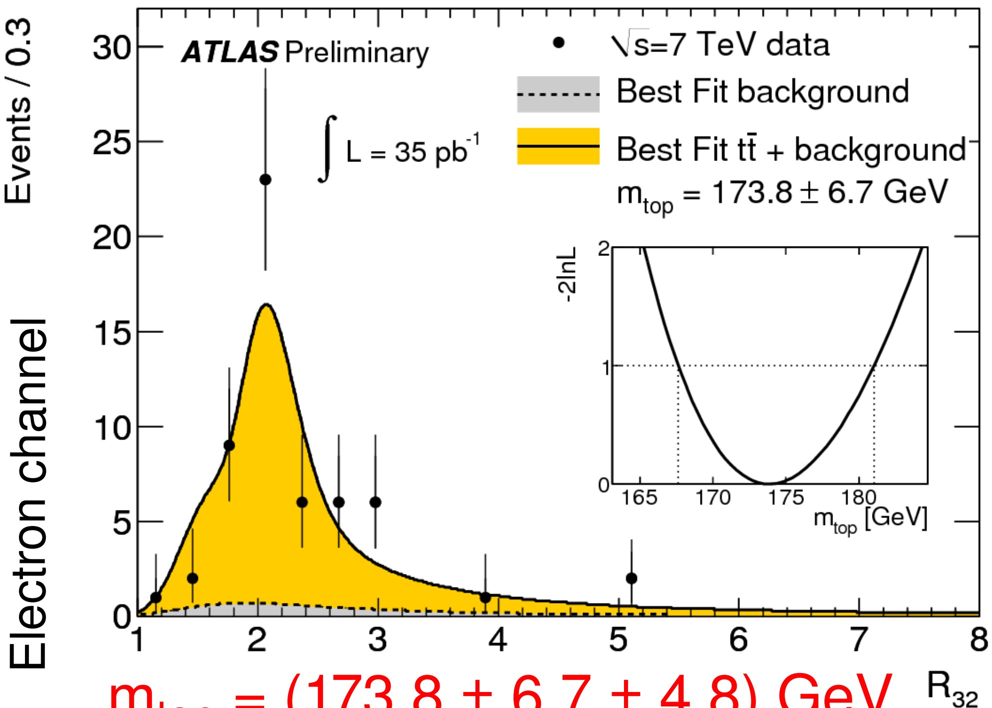
Theory uncertainties:
ISR/FSR (2.6 GeV)
Proton PDF

MC uncertainties:
Hadronisation (1GeV)
Pileup simulation
Signal MC

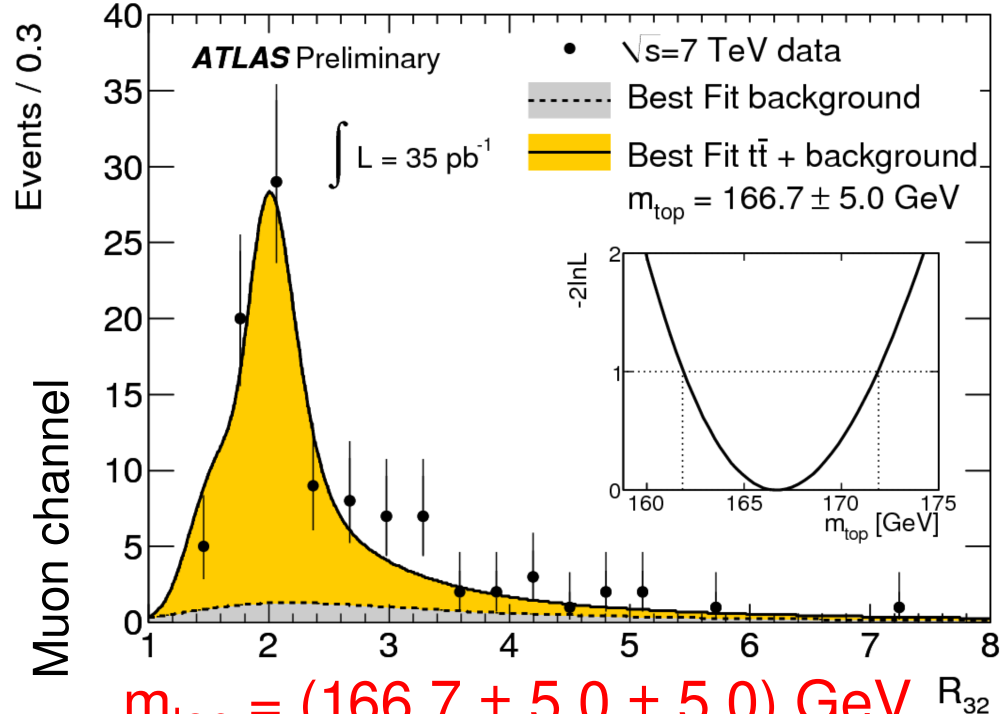
Background:
MC bkg estimates (1.7 GeV)
QCD bkg estimates

Total systematic uncertainy:
4.8 GeV (electron channel)
5.0 GeV (muon channel)

Results



m_{top} = (173.8 ± 6.7 ± 4.8) GeV



m_{top} = (166.7 ± 5.0 ± 5.0) GeV

- Good description of data
- Statistical uncertainty within expectations
- Both measurements are statistically consistent with each other and in agreement with the world average
- Combination: m_{top} = (169.3 ± 4.0 ± 4.9) GeV

Cross check: 2-D analysis

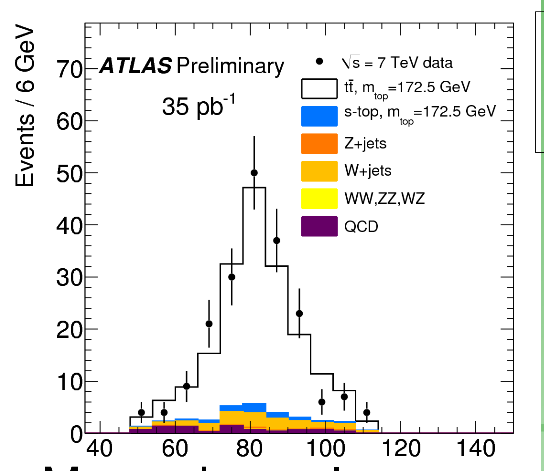
- Templates(m_{top}(input)): m_{top}^{reco} and m_{W}^{reco} of the hadronic decaying top
- Global jet energy scale factor (JSF) determined mainly from m_{W}^{reco} distributions differences in data and MC
- Transfer JES uncertainty into additional statistical uncertainty

\+ W boson candidates: mass window $\pm 3\sigma$
Hadronic top jet-triplet: 4-vector sum with highest p_T

- Hadronic W boson decay candidate: fit the jet energies with the W mass constraint, minimal χ^2 determines the jet pair assigned to the W

$$\chi^2 = \left[\frac{E_{jet1}(1-\alpha_1)}{\sigma_{jet1}}\right]^2 + \left[\frac{E_{jet2}(1-\alpha_2)}{\sigma_{jet2}}\right]^2 + \left[\frac{M_{jj}(\alpha_1,\alpha_2)-m_W}{\Gamma_W}\right]^2 \longrightarrow$$ Determine α_i's (JSF)

- Calculate hadronic top with the b-tagged jet in the event and the α_i's

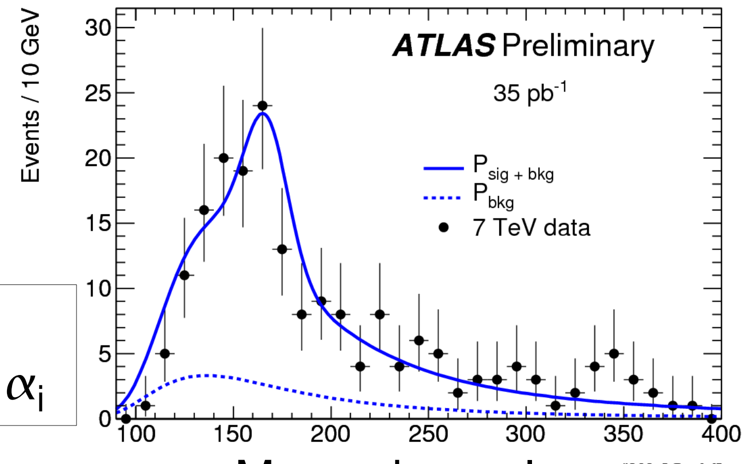


Muon channel

Template 1:
W mass without the α_i

N events: 134 (120) in the electron (muon) channel

Template 2:
Top mass with the α_i



Muon channel

2-D analysis

- Pseudo-experiments verify unbiased reconstruction of m_{top} and JSF
- Same top mass samples as before (160-190 GeV) and JSF in the range (0.9-1.1)

m_{top} = (168.3 ± 6.2 ± 4.3) GeV (electron channel)

m_{top} = (163.5 ± 6.7 ± 4.6) GeV (muon channel)

m_{top} = (166.1 ± 4.6 ± 4.4) GeV (combined)

- Fitted JSF: $1.08^{+0.04(stat)}_{-0.06(stat)}$ ($1.01^{+0.05(stat)}_{-0.05(stat)}$) in the electron (muon) channel
- Reduced JES systematic of **0.7 GeV** achieved but at a reduced statistical precision
- b-JES and ISR/FSR uncertainty same size as baseline method

Cross check: kinematic fitter

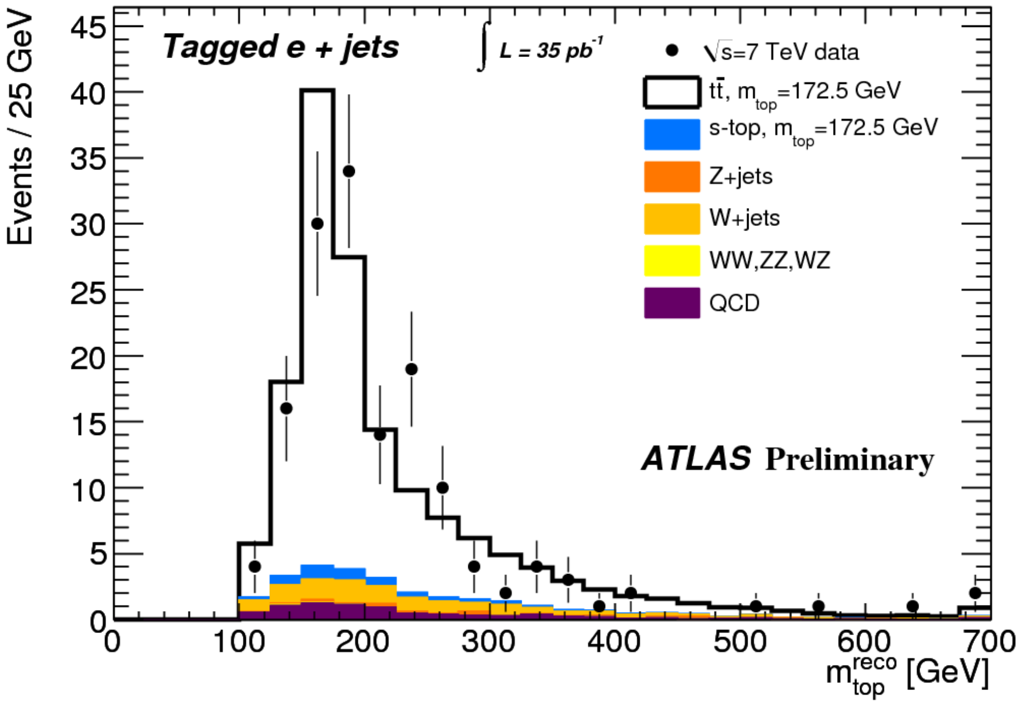
- Template(m_{top}(input)): m_{top}^{reco} obtained by a kinematic fit
- Method is using entire ttbar event
- Observed events: 157 (247) in the electron (muon channel)
- Likelihood contains (input 4j+l+EtMiss):

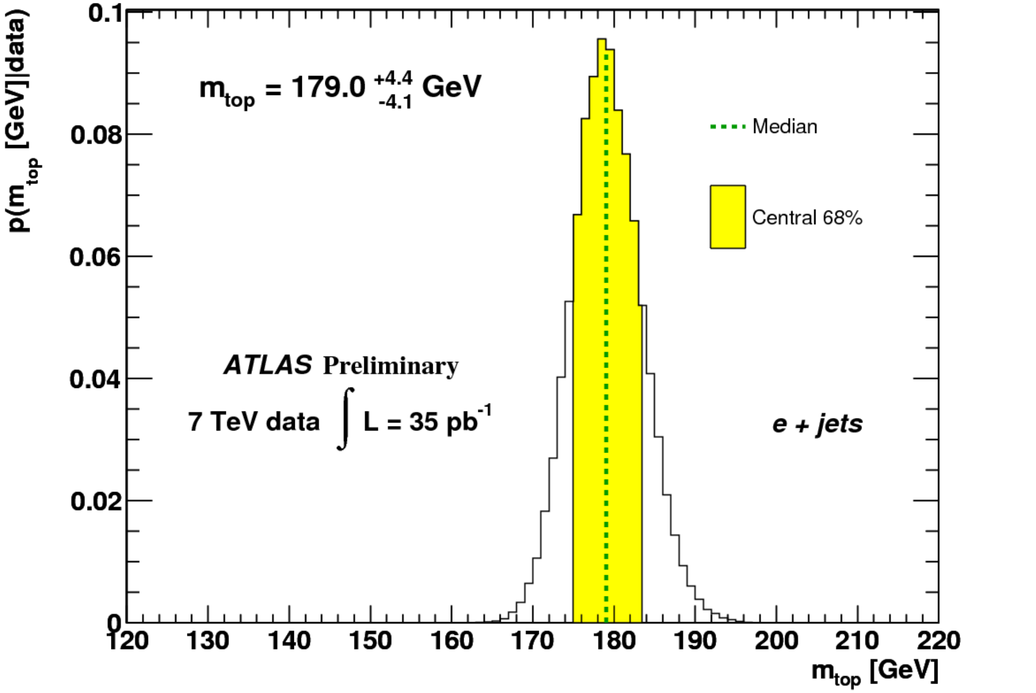
L = Breit-Wigner(W,top) x Transfer-Functions (j,l,ν) x Delta-Function(b-tag)

Breit-Wigner(W,top)	Transfer-Functions (j,l,ν)	Delta-Function(b-tag)
Constrains: > W boson mass (had. and lep.) > identity of had. and lep. top mass	resolution for jet energy, eta, phi, lepton energy, E_T^{miss} from signal MC	Reduce permutations

- Per event result estimator for m_{top}^{reco} which maximizes the likelihood
- Utilization of correlations and a high fitting efficiency (less combinatorial bkg) lead to a narrower m_{top}^{reco} distribution than the baseline method (but much more sensitive to JES variations)
- Pseudo-experiments show the linearity between output and input top mass

Kinematical fitter





- Same top mass samples as before (160-190 GeV)
- data can be well described by signal and bkg description (no discrepancies between MC predictions and data)
- JES systematic: **6.6 GeV**, b-JES and ISR/FSR uncertainty same size as baseline method

m_{top} (e) = (179.0 ± 4.3 ± 7.5) GeV

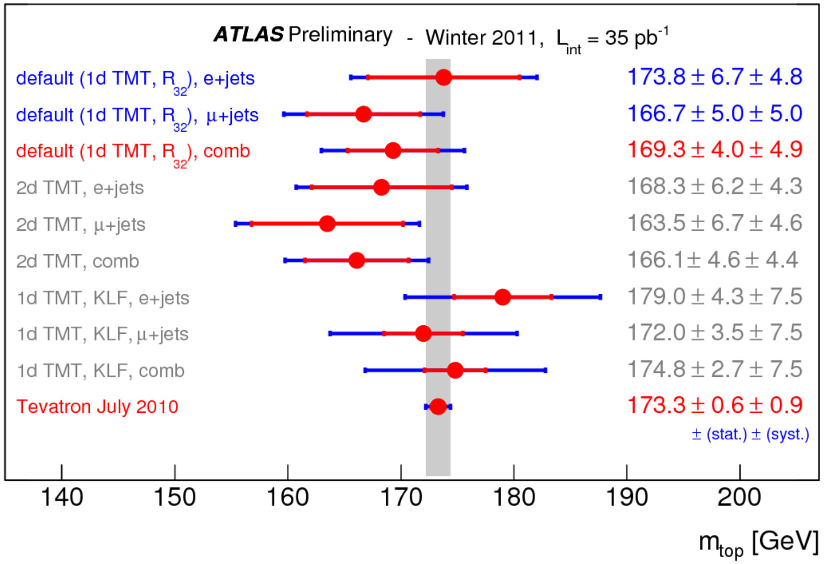
m_{top} (μ) = (172.0 ± 3.5 ± 7.5) GeV

Combined:

m_{top} = (174.8 ± 2.7 ± 7.5) GeV

Comparison of the measurements

- Results of all analyses (each channel) are consistent within uncertainties
- Muon channel: slightly smaller statistical uncertainties
- Systematic uncertainties are similar between channels



- With about 1 fb^{-1} the expected statistical uncertainty σ_{stat} (from current pseudo-experiments) will diminish to:

  0.7 GeV (1-D kin. fit) < 1.3 GeV (1-D R_{32} fit) < 1.7 GeV (2-D fit)

- This order is reverted for the systematic uncertainties at our present level of understanding (especially of JES)
- With increasing luminosity the method that gives the best expected result will likely change

Conclusions

- Baseline ATLAS measurement with integrated Luminosity of $L = 35.3 \pm 1.2\ pb^{-1}$ by the event-by-event ratio of R_{32} is in agreement with the world average

$$m_{top} = (169.3 \pm 4.0 \pm 4.9)\ \text{GeV}$$

- Three complementary top-quark mass measurements support the unbiasedness of the estimators used
- Stability of the results indicate a good description of data by our MC
- Main source of systematic uncertainty is the (b-)jet energy scale (latest jet energy scale uncertainty is decreased by a factor of 2)
- Achieving a more precise measurement involves working on reducing systematic uncertainties

BACKUP

Signal and background

Process	Channel	
	Electron	Muon
$t\bar{t}$ signal	52.6 ± 0.5	77.3 ± 0.6
Single top	2.23 ± 0.07	3.12 ± 0.08
W+jets	3.9 ± 0.3	6.6 ± 0.4
Z+jets	0.71 ± 0.05	0.63 ± 0.04
$ZZ/WZ/WW$	0.07 ± 0.01	0.11 ± 0.01
QCD multijet (data)	2.1 ± 2.1	4.5 ± 4.5
m_{top} independent background	6.9 ± 2.1	11.8 ± 4.5
Total background	9.1 ± 2.2	14.9 ± 4.5
Signal + background	61.7 ± 2.2	92.2 ± 4.5
Data	56	99
S/B	5.8	5.2

Table 1: The observed numbers of events for the 1d-R_{32} analysis in the data compared to the expected numbers of signal and background events for the data luminosity, in the electron and muon channels. The Monte Carlo estimates assume SM cross-sections. For all Monte Carlo estimates the uncertainties are statistical only, for the QCD multijet estimate obtained from ATLAS data also the systematic uncertainty is included, see text for details.

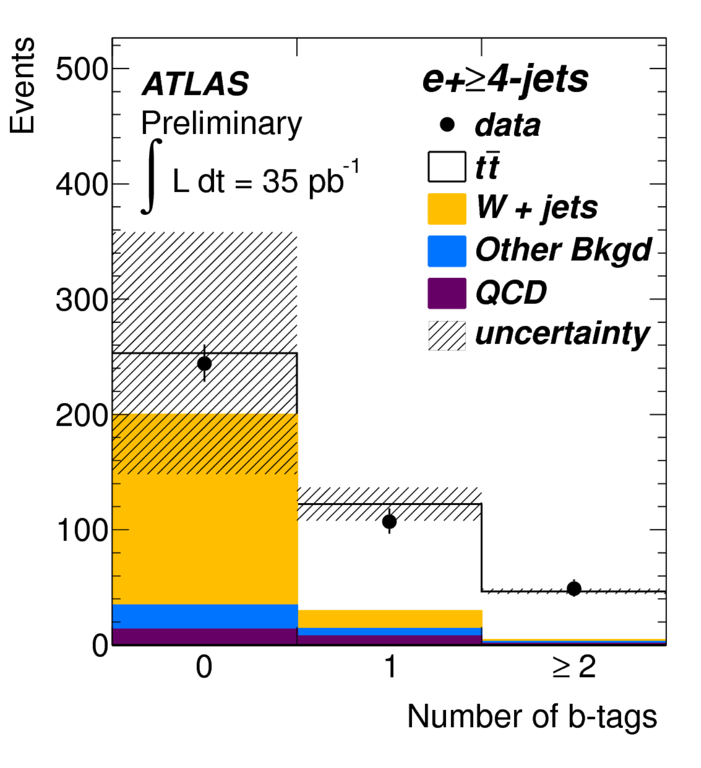
Systematics

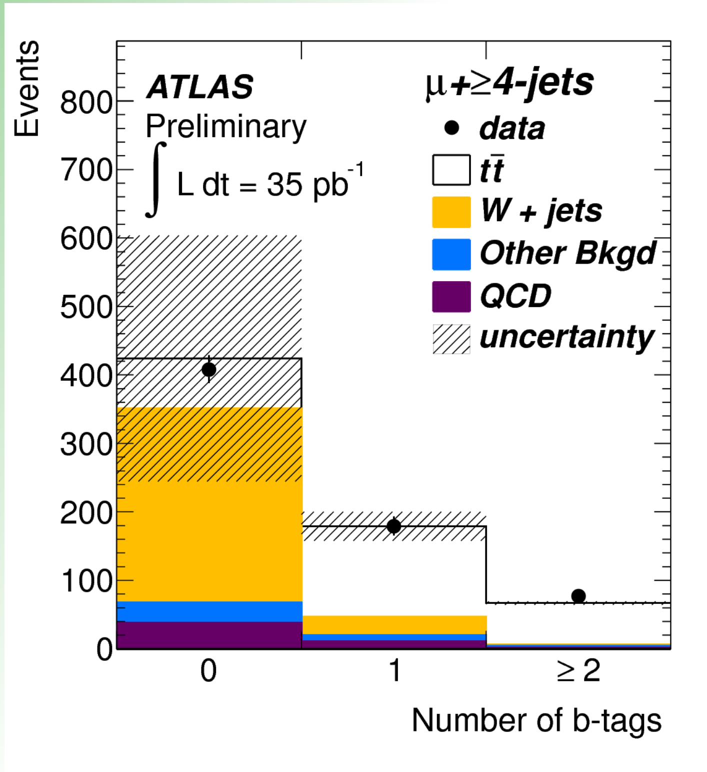
	Uncertainty [GeV]	
	Electron channel	Muon channel
Statistical uncertainty	6.7	5.0
Method calibration	0.7	0.5
Signal MC generator(POWHEG vs. MC@NLO)	0.7	0.6
Hadronization POWHEG (PYTHIA vs. HERWIG)	1.0	0.5
Pileup	0.6	0.8
ISR and FSR (signal only)	2.2	2.6
Proton PDF	0.6	0.5
W/Z+jets background normalization (±100%)	1.3	1.7
W/Z+jets background shape	0.6	1.0
QCD background normalization (±100%)	0.8	0.7
QCD background shape	0.6	0.5
Jet energy scale (±1σ) plus 5% for close by jets	2.3	1.9
b-jet energy scale (±2.5%)	2.5	2.5
b-tagging efficiency and mistag rate	0.6	0.5
Jet energy resolution	0.6	1.1
Jet reconstruction efficiency (±2%)	0.6	0.5
Total systematic uncertainty	4.8	5.0

Table 2: The contributions of various sources to the uncertainty for m_{top}. The quoted values correspond to the larger of the observed shift using the pseudo-experiment and the statistical precision of the estimates.

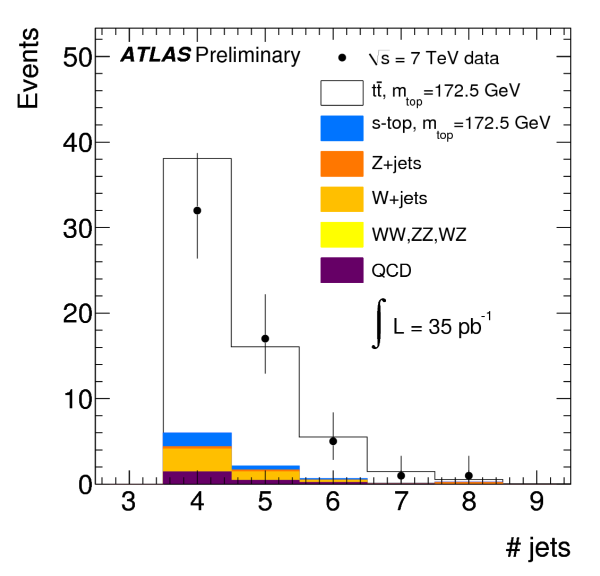
Top cross section plots

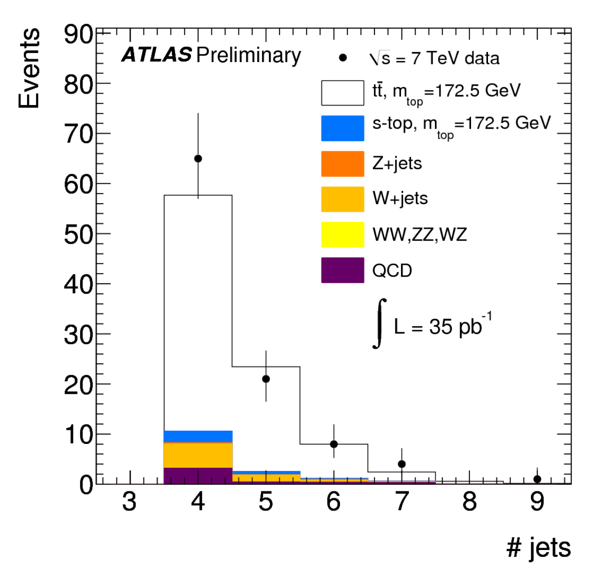
- Number of b-tagged jets in electron (muon) channel

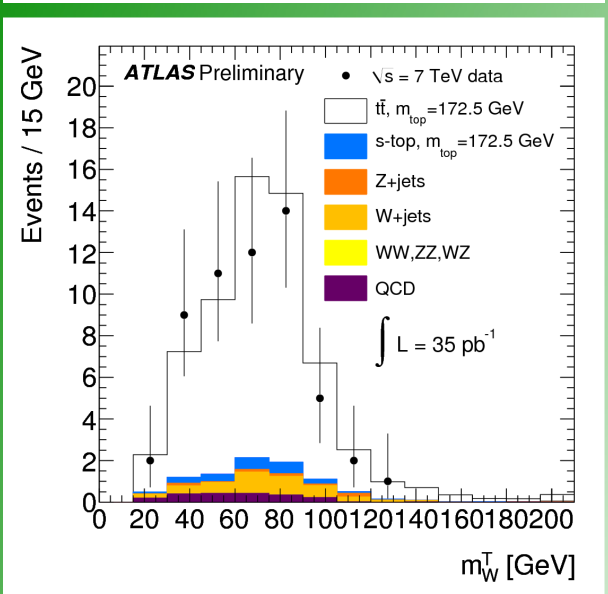


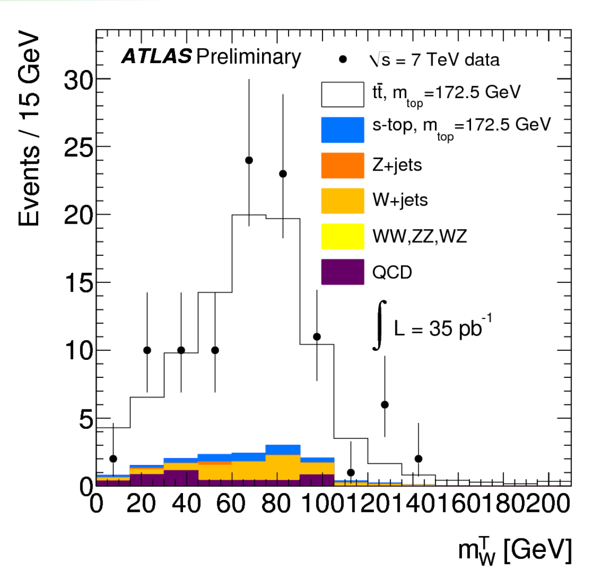


Baseline method: properties

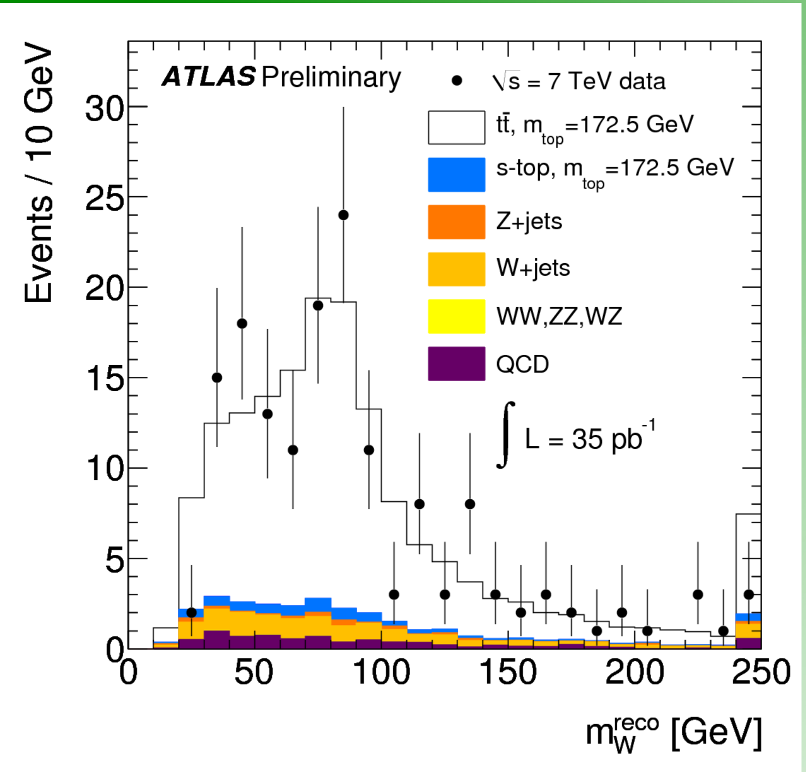




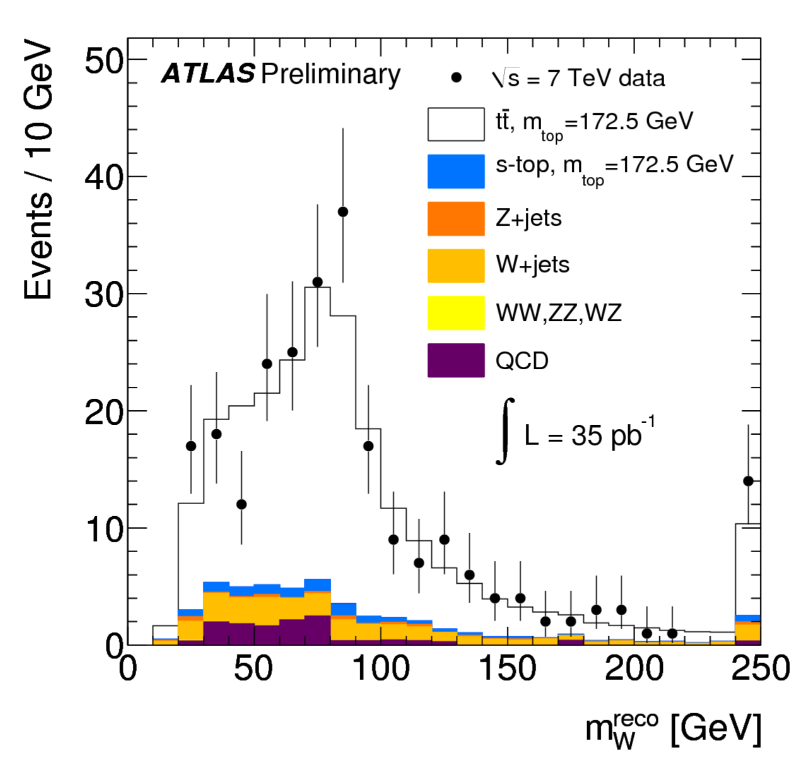




Baseline method: W boson mass

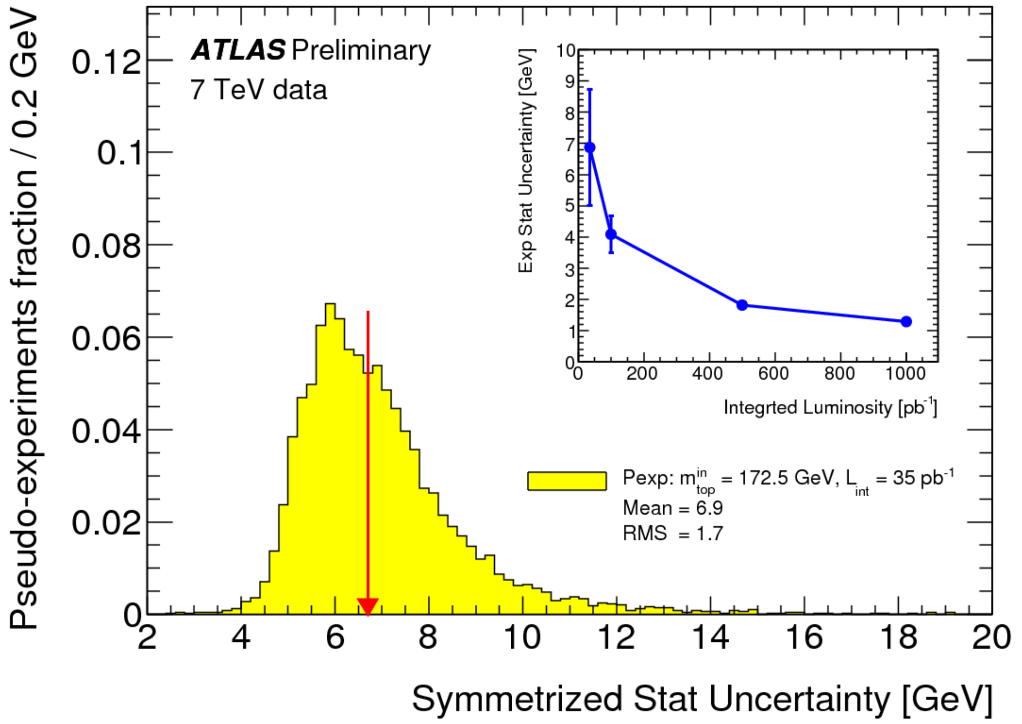


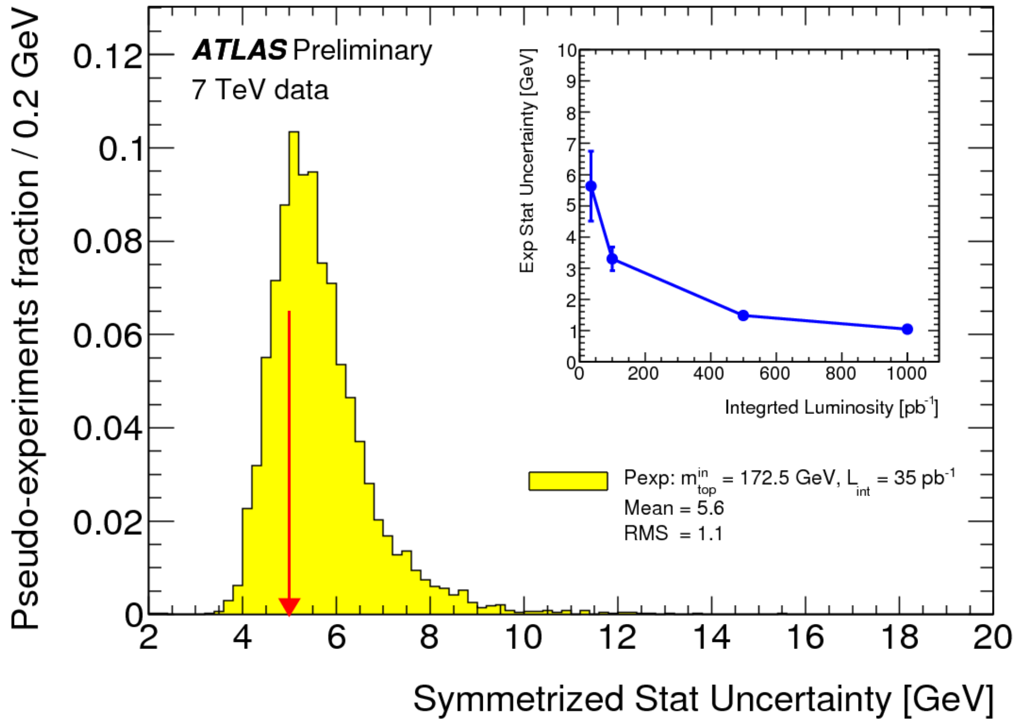
electron channel



muon channel

Baseline method: stat. uncertainty

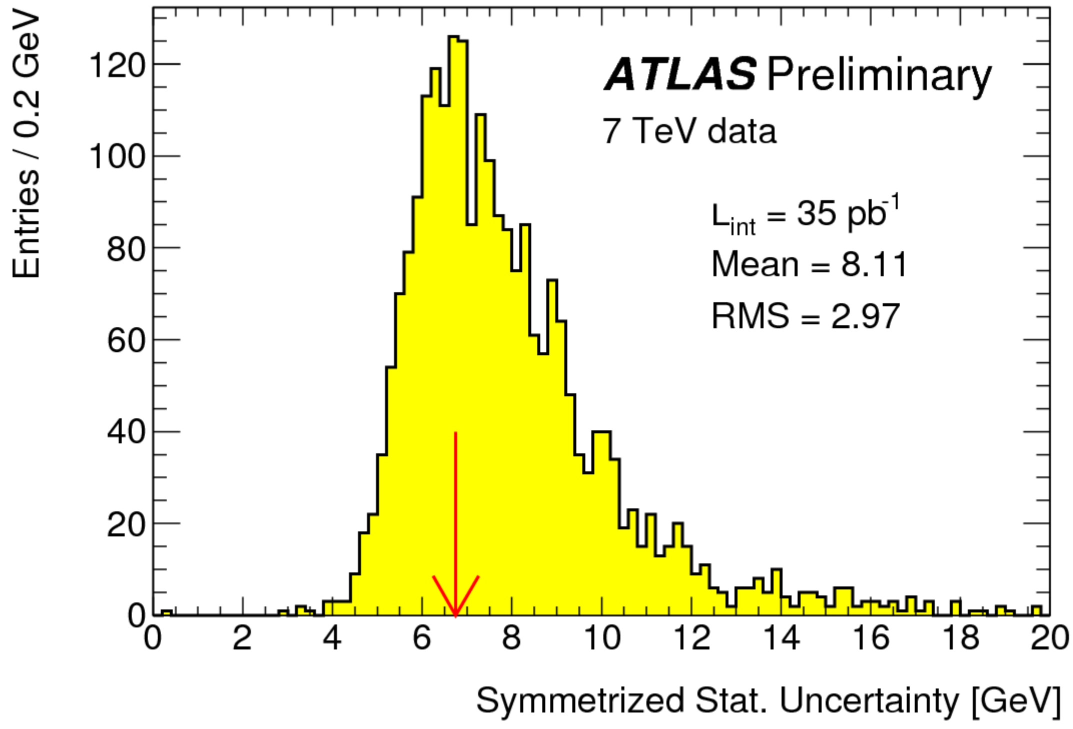


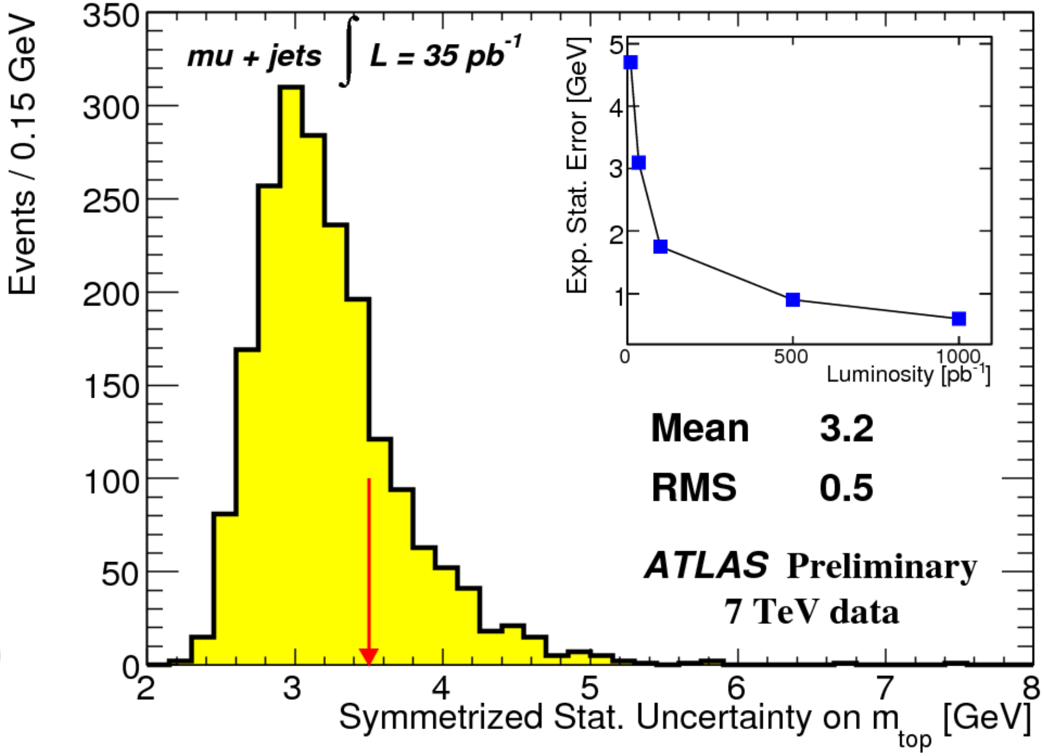


electron channel

muon channel

Statistical uncertainties





2-D analysis

1-D kinfit