Measurement of $t\bar{t}$ production in ATLAS

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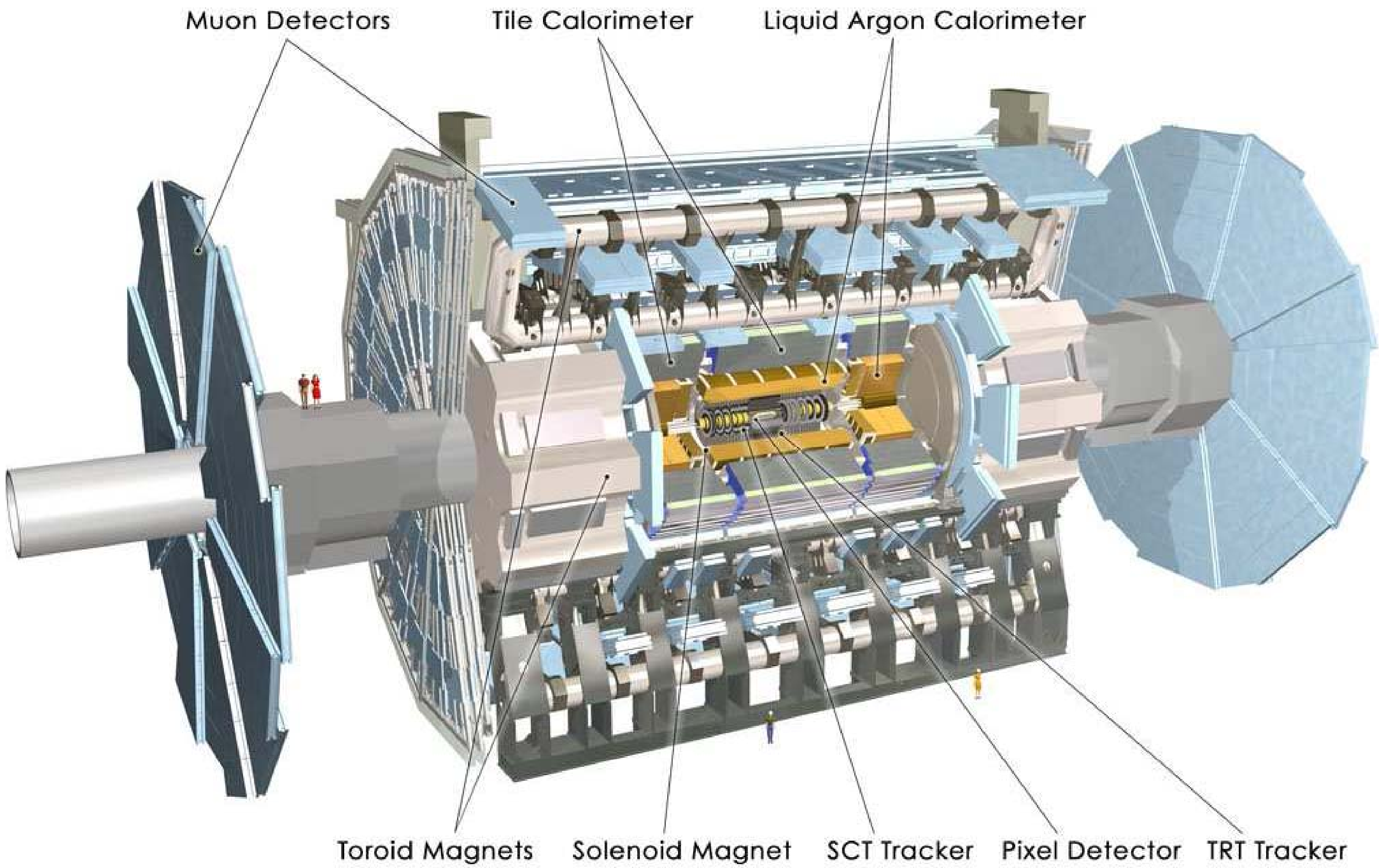
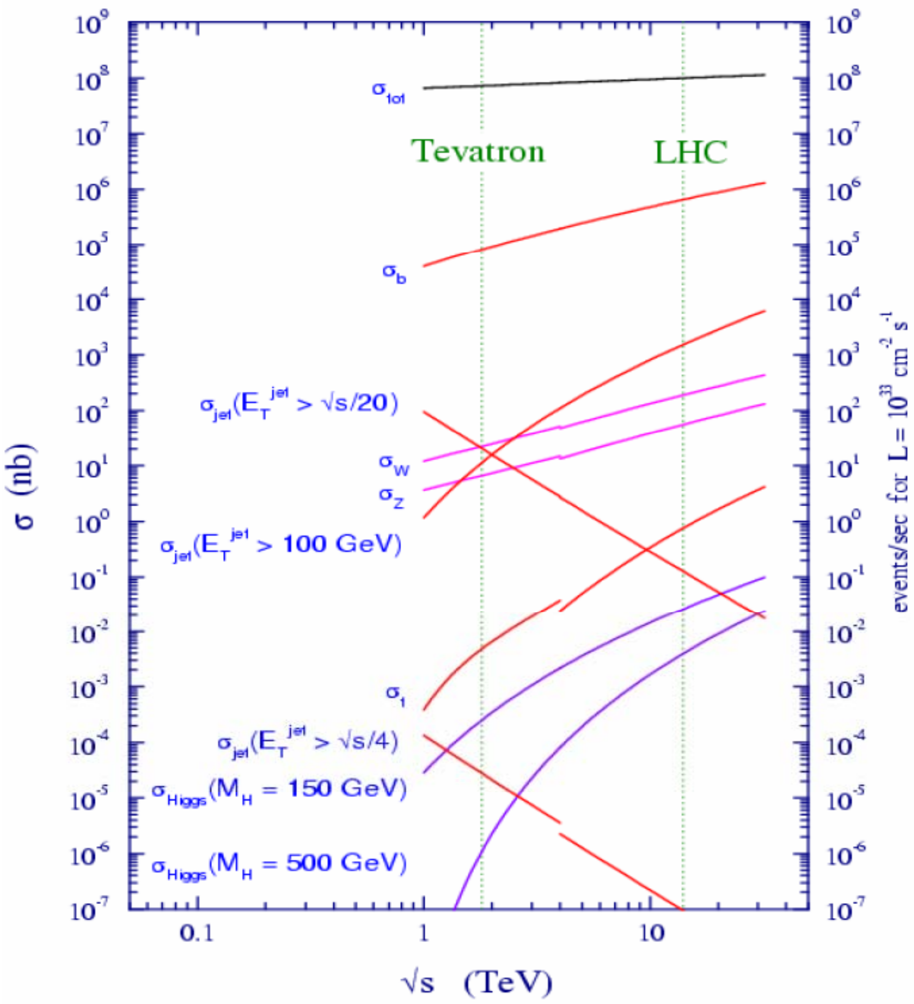
Introduction – The ATLAS experiment

- ATLAS is a general purpose detector with layers of tracking, calorimetry and muon detection



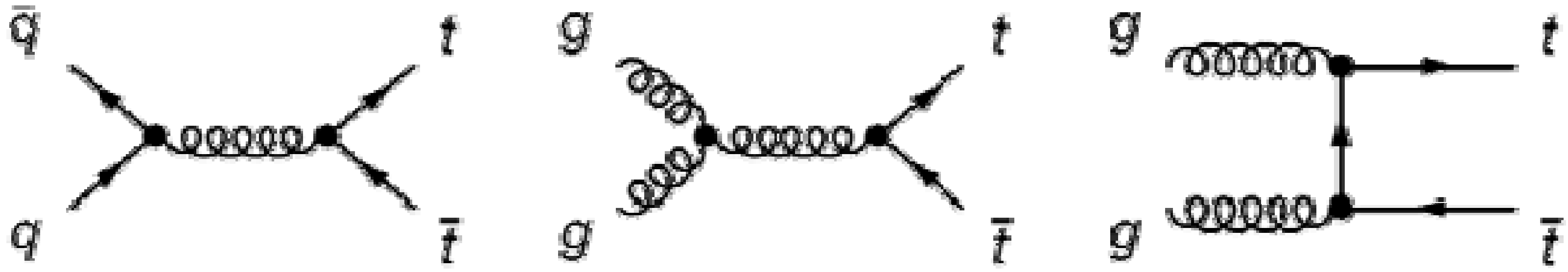
Introduction – $t\bar{t}$ production at the LHC



- ttbar production cross section
  - ~7 pb at Tevatron
  - ~350 pb at LHC (10 TeV)
  - ~830 pb at LHC (14 TeV)
- Amounts to 1 tt/sec at L=10^{33}
- Tevatron → LHC
  - Signal x 100
  - Background x 10
  - *Use of b-tagging not essential to establish signal at LHC*

Top quark pair production and decay

- Contributing processing in pp collisions

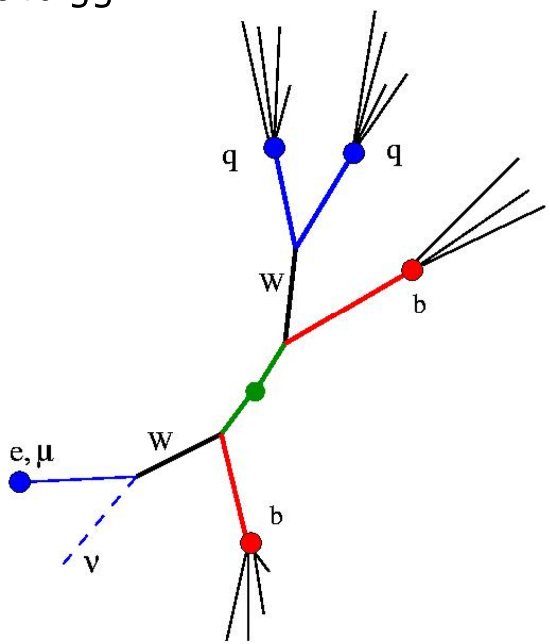


Tevatron: 85% qq

LHC: 90% gg

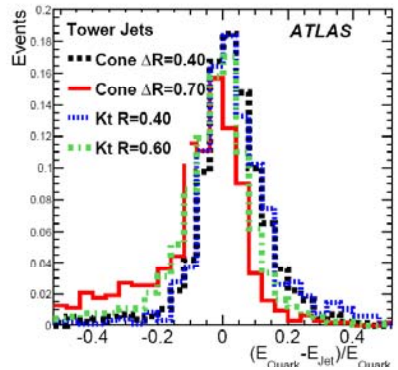
- Decay:
  t → Wb,   W→qq (2/3) or W →lν (1/3)
- Three types of final states
  - 0 lepton (4/9) → b(qq) + b(qq)
  - 1 lepton (4/9) → b(lν) + b(qq)
  - 2 lepton (1/9)→ b(lν) + b(lν)

Covered in this presentation

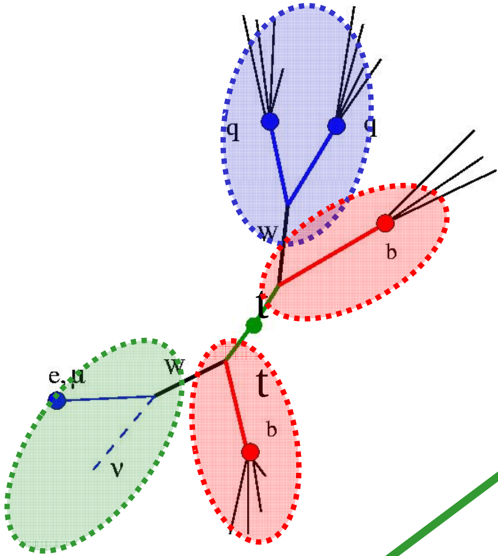


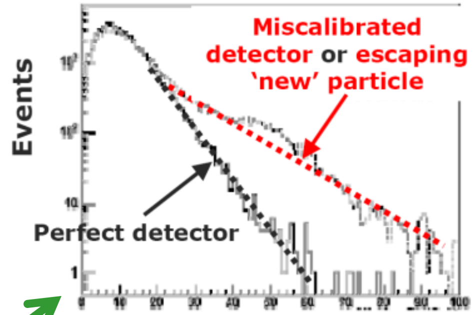
What can you do with early $t\bar{t}$ events

- One-lepton ttbar signature rich in signatures, useful in many ways for validation and calibration
- Calibrate light jet energy scale
  - Impose W mass constraint on M(jj), exploit low b abundance W→qq due to small V_{ub}

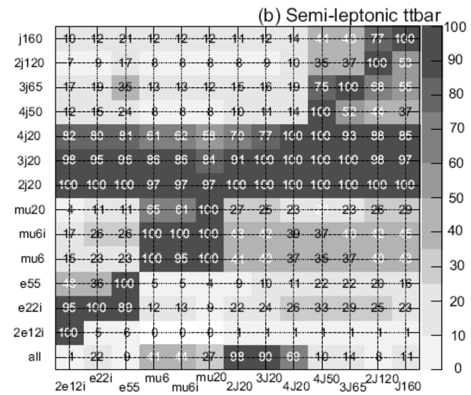


- Estimate b-tagging ε
  - Exploit double b-tag
  - Busy environment





- Calibrate missing transverse energy
- Study trigger performance
  - Exploit multiple triggerable signatures



One-lepton channel – Event selection

- Event selection for one lepton channel

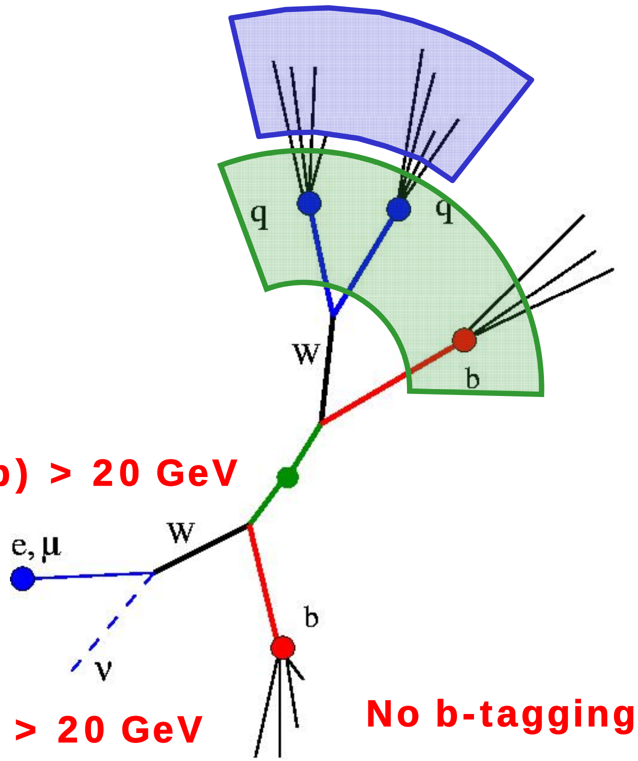
3 jets pT> 40 GeV +

1 jets p_T> 30 GeV

P_T(lep) > 20 GeV

Missing E_T > 20 GeV

No b-tagging



Muon channel

Sample	default
$t\bar{t}$	3274
hadronic $t\bar{t}$	35
W+jets	1052
single top	227
$Z \to ll$ +jets	78
$W\ b\bar{b}$	25
$W\ c\bar{c}$	26
$W\ W$	4
$W\ Z$	3
$Z\ Z$	0.4
Signal	3274
Background	1446
S/B	2.3

Electron channel

Sample	default
$t\bar{t}$	2555
hadronic $t\bar{t}$	11
W+jets	761
single top	183
$Z \to ll$ +jets	107
$W\ b\bar{b}$	17
$W\ c\bar{c}$	19
WW	4
WZ	2
ZZ	0.3
Signal	2555
Background	1104
S/B	2.3

ε(ttbar) 23.6% ε(ttbar) =18.2%

	Trigger eff (%)	Lepton eff (%)	$\not{E}_T$ eff (%)	Jet req. (I) eff (%)	Jet req. (II) eff (%)	Combined eff (%)
$t\bar{t}$ (electron)	52.9	52.0	91.0	70.7	61.9	18.2
$t\bar{t}$ (muon)	59.9	68.7	91.6	65.5	57.3	23.6

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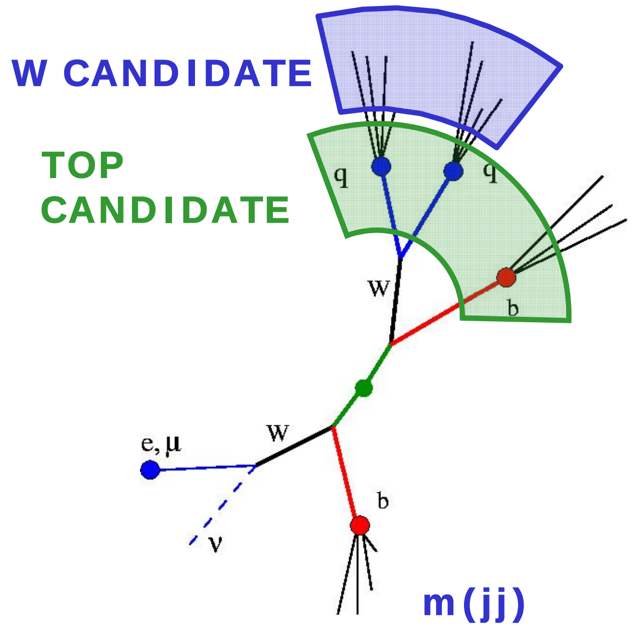
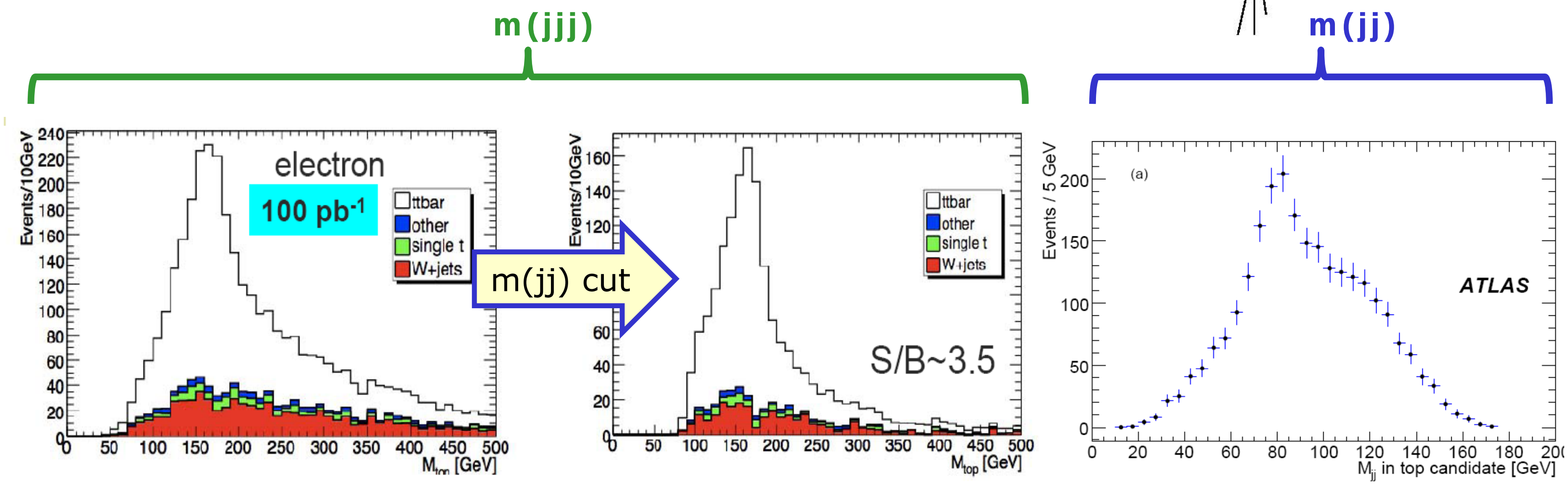
One-lepton channel – Simulation of signal and backgrounds

- ttbar signal – MC@NLO
  - Cross check with Alpgen in systematic studies
- W+jets background – Alpgen
  - Expected to be largest background
  - NB: Large uncertainty on cross section of W+4 jets.
    (Assuming 50% error for systematic studies)
- QCD multi-jet backgrounds
  - Very large cross section (pp → bb O(100μb), but very few events pass selection (need lepton, missing E_T of 20 GeV each)
  - Can distinguish contribution due to non-prompt leptons (mostly semileptonic (b) quark decay) and fake leptons (reconstruction mistakes)
  - Estimated $\sim 1 \cdot 10^{-3}$ reconstructed electron per jet from both non-prompt and fake leptons.
  - Use above estimate to calculate fraction of QCD multi-jet events that pass event selection → Smaller than W+jets estimate

One-lepton channel – Top reconstruction and selection

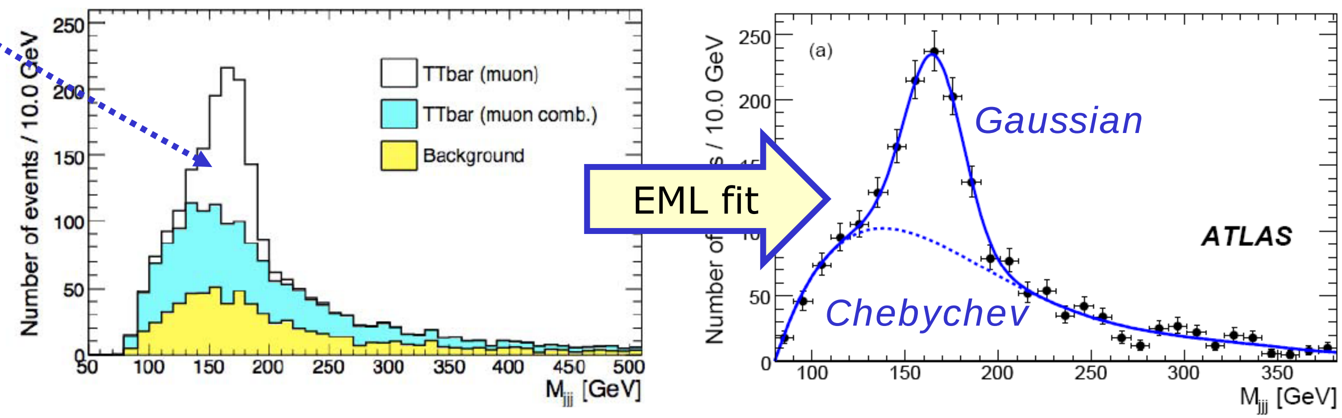
- Pick three jets with highest summed pT as hadronic top candidate
- Purification of sample through requirement $|m(jj)-m_W|<10$ GeV for one of the 3 jet pairs of the top candidate
  - Also central top quarks candidates are more pure $|\eta_{jet}|<1$ for all 3 jets





One-lepton channel – Cross section extraction

- Method 1 – Likelihood fit to m(jjj) distribution
  - Counts only events reconstructed with m(jjj) close to m(top)
  - Exploits information in shapes of m(jjj).
  - Sensitive to correct estimation of efficiency of picking 'correct' 3-jet combination
  - Rather insensitive to correct rate estimation of backgrounds



- Method 2 – Counting approach
  - Count all events in full m(jjj) range, subtract estimated backgrounds
  - Sensitive to correct background estimation
  - Less sensitive to correct description of m(jjj) shape, efficiency of top candidate picking algorithm

One-lepton channel – Summary of cross-section uncertainties

- Systematic uncertainty by source

Fit counts less events

Counting method does not measure background

Shape of m(jjj) dist uncertain

Source	Likelihood fit Electron (%)	Likelihood fit Muon (%)	Counting method (elec) Default (%)	Counting method (elec) W const. (%)
Statistical	10.5	8.0	2.7	3.5
Lepton ID efficiency	1.0	1.0	1.0	1.0
Lepton trigger efficiency	1.0	1.0	1.0	1.0
50% more W+jets	1.0	0.6	14.7	9.5
20% more W+jets	0.3	0.3	5.9	3.8
Jet Energy Scale (5%)	2.3	0.9	13.3	9.7
PDFs	2.5	2.2	2.3	2.5
ISR/FSR	8.9	8.9	10.6	8.9
Shape of fit function	14.0	10.4	-	-

- Combined numbers

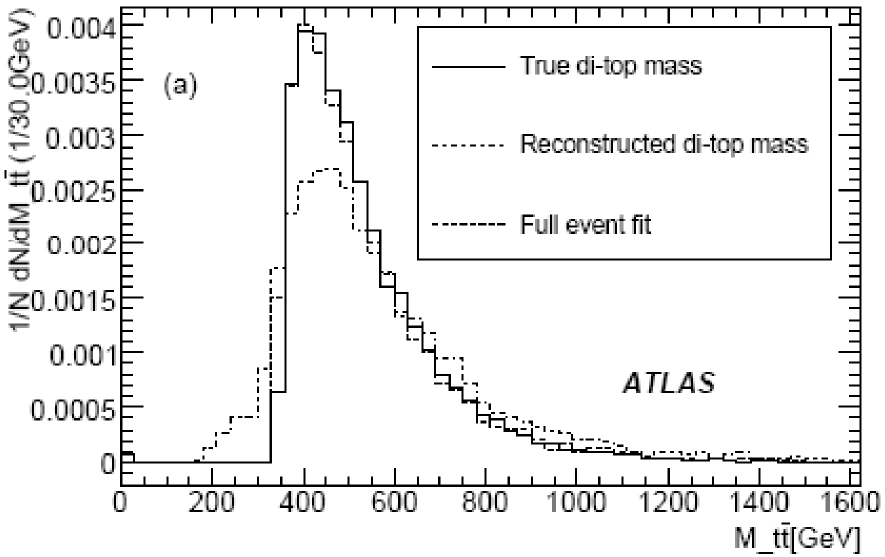
Likelihood method: $\Delta\sigma/\sigma = (7(\mathrm{stat}) \pm 15(\mathrm{syst}) \pm 3(\mathrm{pdf}) \pm 5(\mathrm{lumi}))\%$

Counting method: $\Delta\sigma/\sigma = (3(\mathrm{stat}) \pm 16(\mathrm{syst}) \pm 3(\mathrm{pdf}) \pm 5(\mathrm{lumi}))\%$

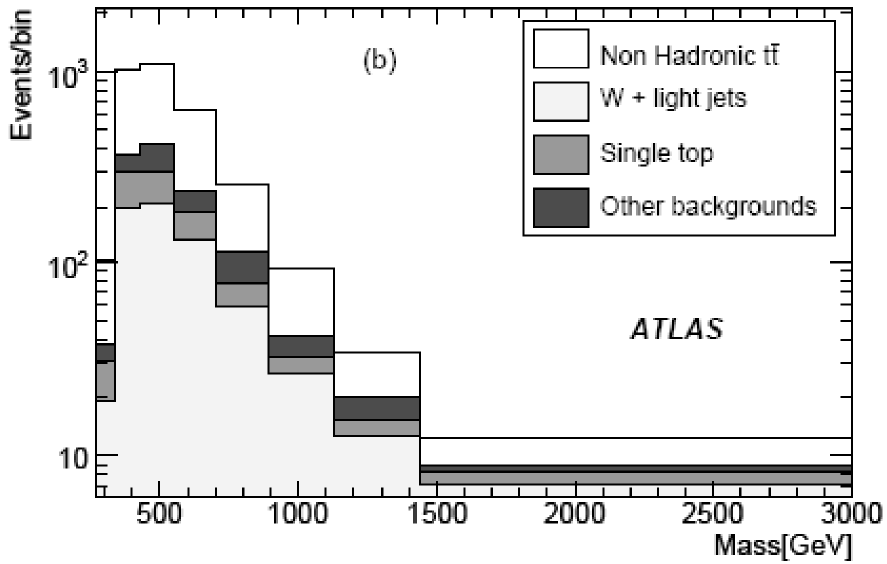
One-lepton channel – Differential cross section in $m(t\bar{t})$

- Differential cross section in mass of $t\bar{t}$ system
  - Good check of SM physics, sensitivity to certain types of BSM physics
  - Requires reconstruction of neutrino from $W \rightarrow l\nu$
- Two approaches
  - 'Reconstructed di-top mass'. Assume missing E_T is neutrino p_T, use W mass constraint to calculate p_Z of neutrino
  - 'Full event fit'. Kinematic fit that apply all W, top mass constraints

Comparison of methods

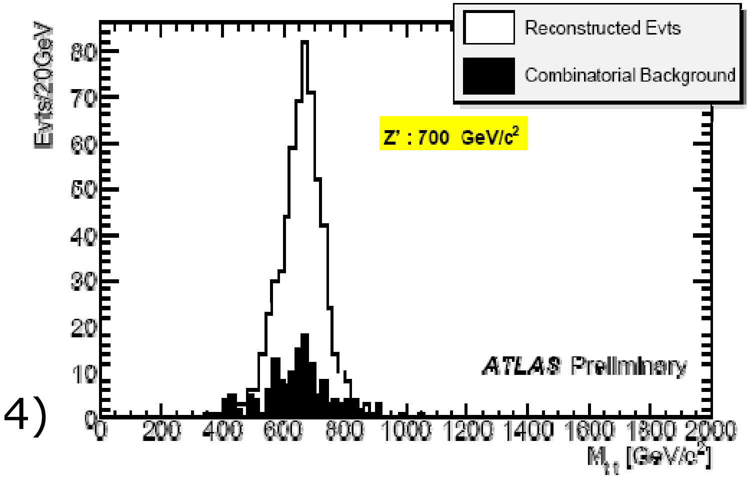


Expected distribution for 100 pb^{-1}

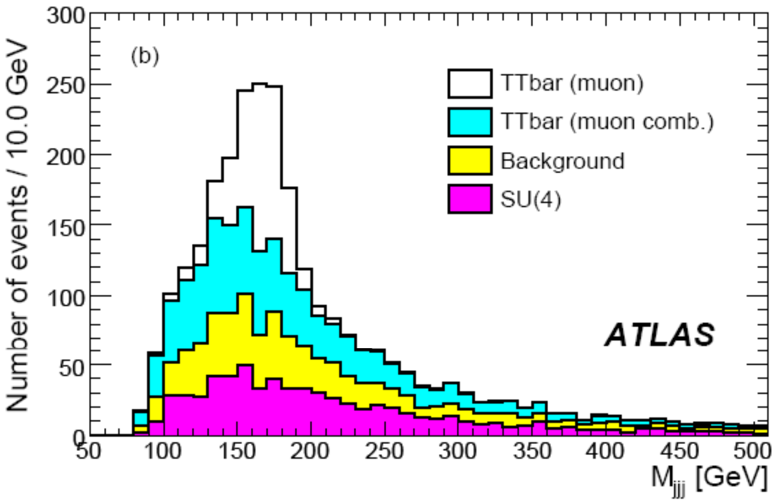


Sensitivity to new physics contributions

- Several types of BSM physics can produce events that give rise to measurable signal or background enhancements in tt one-lepton channel
  - Example 1: Z′ (700 GeV) → ttbar



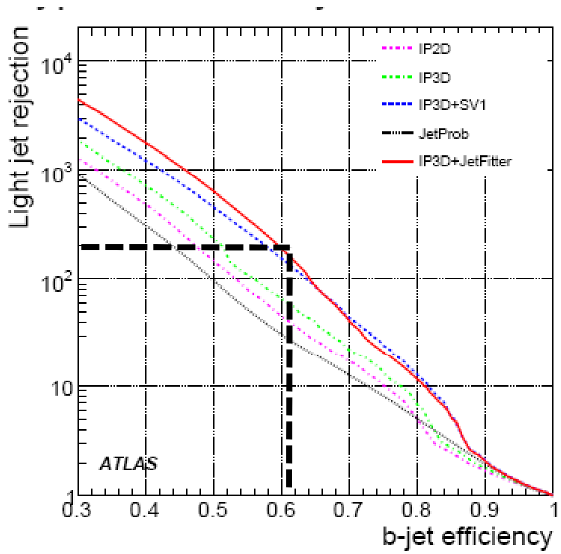
  - Example 2: low-mass SUSY (point SU4)



Event type	Electron analysis Trigger+Selection	W const.	m_t win	Muon analysis Trigger+Selection	W const.	m_t win
SU1	53	9	1	64	12	2
SU2	10	2	0.5	13	3	0.7
SU3	108	22	4	124	26	4
SU4	1677	541	155	2141	700	199
SU6	29	5	0.6	35	6	0.6
SU8	27	5	0.6	33	6	0.8

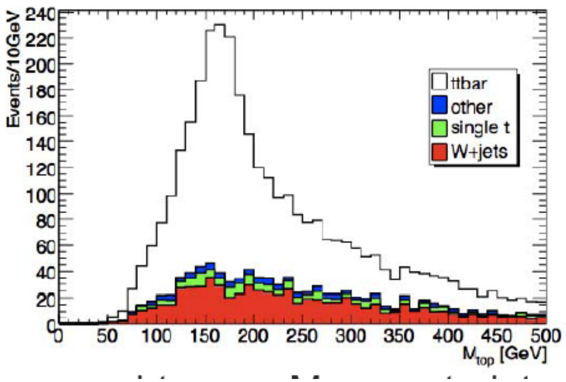
One-lepton channel – Effect of adding b-tagging

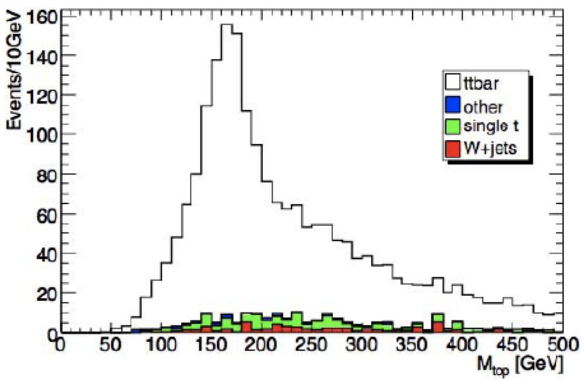
- ATLAS b-tagging: likelihood algorithm
  - weight *w* constructed from the results of the IP3D impact parameter and secondary vertex-based tagger.
  - *Example operating point* $\varepsilon_b \sim 63\%$, $R_u \sim 200$

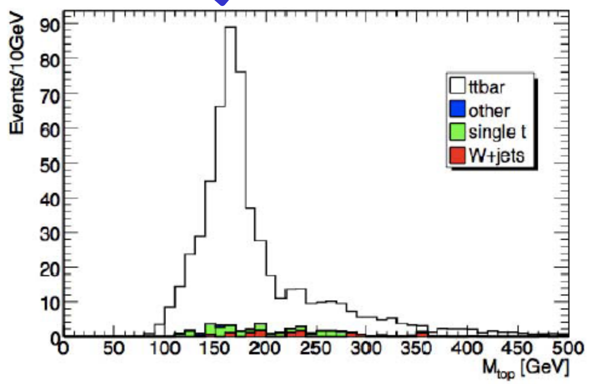


Require ≥1 b tag

Apply W mass req.

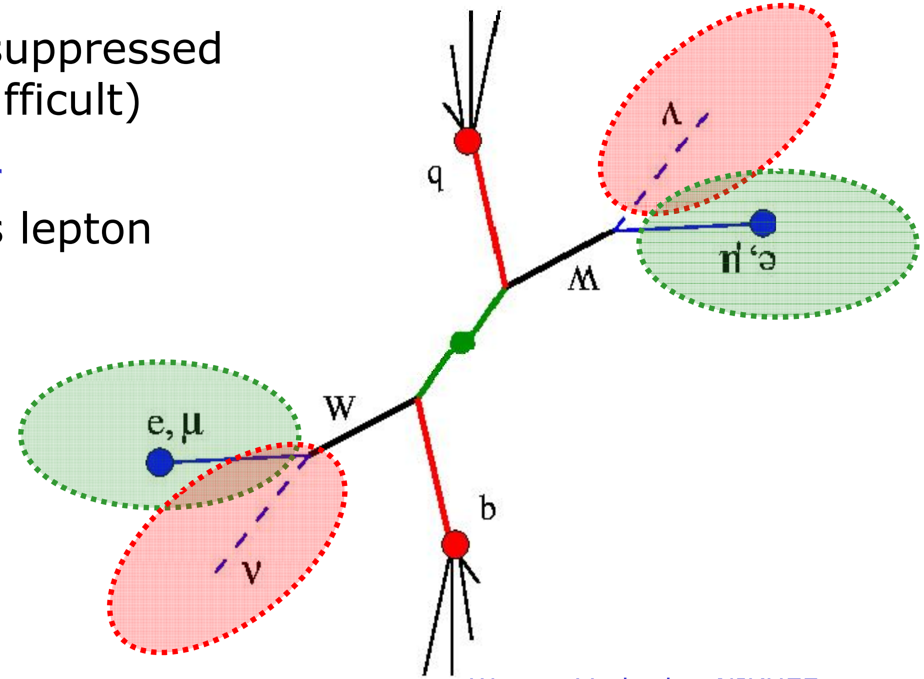






Di-lepton channel – signal and backgrounds

- Signal signature
  - Pair of high p_T isolated leptons (l^+l^-)
  - Large missing E_T due to two escaping neutrinos
- Composition of backgrounds very different
  - QCD, W+jets mostly suppressed by 2-lepton requirement
  - But have Z(+jets) background producing isolated leptons (of which $Z \rightarrow ee,\mu\mu$ is easily suppressed with $m(ll)$ cut, $Z \rightarrow \tau\tau$ more difficult)
  - Must suppress 1-lepton ttbar where jet is reconstructed as lepton

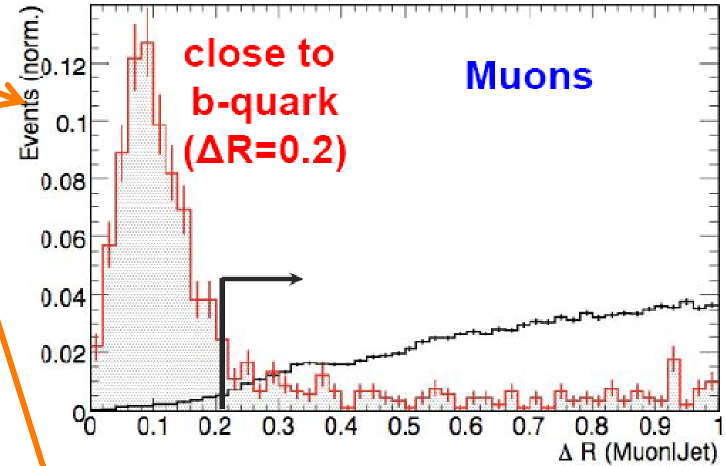


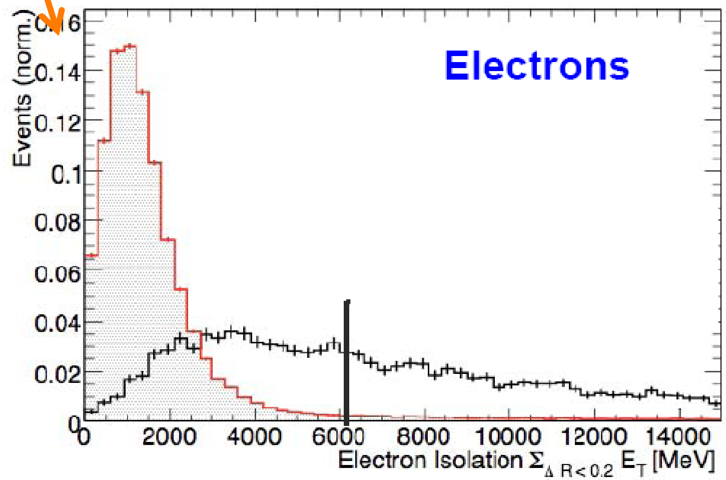
Di-lepton channel – signal and backgrounds

- Select events with 'good' l^+l^- pair
  - Isolation criteria important to avoid picking up various types of background with >=1 leptons from semileptonic (b) quark decay in jets

Expected event counts with l^+l^- lepton pairs at 100 pb^{-1}

Sample	$e\mu$	ee	$\mu\mu$
$t\bar{t}$ (signal)	699	312	381
$t\bar{t}$ (bkg)	31	20	8
$Z \to e^+e^-$	5	37418	0
$Z \to \mu^+\mu^-$	153	0	51139
$Z \to \tau^+\tau^-$	249	101	159
$W \to e\nu$	42	69	0
$W \to \mu\nu$	152	0	40
WW	76	32	44
WZ	6	41	52
ZZ	1	25	31
single top	5	3	2

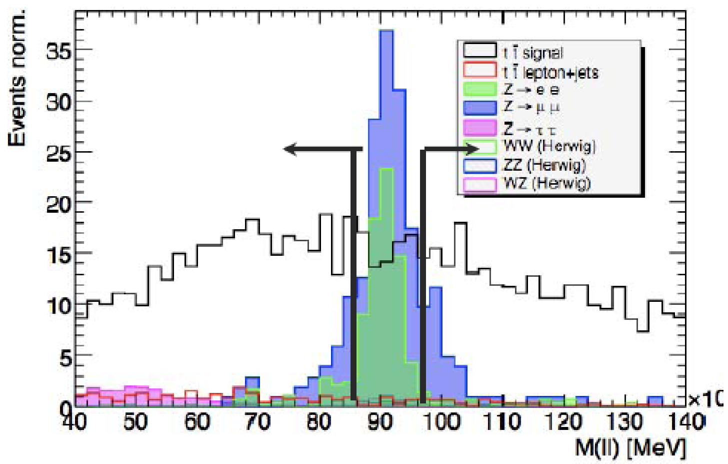




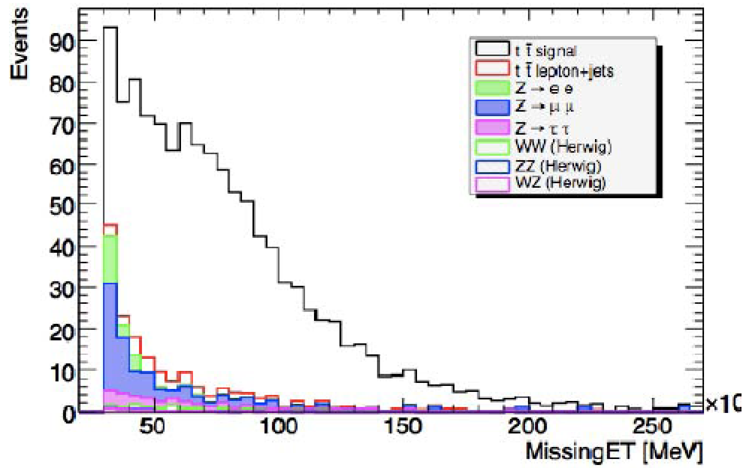
Di-lepton channel – cut-and-count analysis

- Require minimum lepton p_T of 20 GeV
- Require minimum missing E_T of 30 GeV
  - Use 35/25 GeV when considering (ee,$\mu\mu$)/eμ channels separately

Di-lepton invariant mass



Missing transverse energy



Event counts after selection (100 pb^{-1})

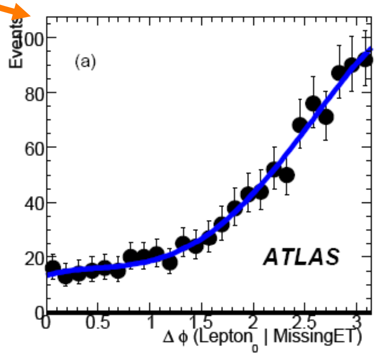
dataset	$e\mu$	ee	$\mu\mu$	all channels
$t\bar{t}$ (signal)	555	202	253	987
ε [%]	**20.2**	**14.7**	**18.3**	**17.9**
Total bkg.	86	36	73	228
S/B	6.3	5.6	3.4	4.3

← Dominated by tt 1-lepton (17%) and Z→ll (57%)

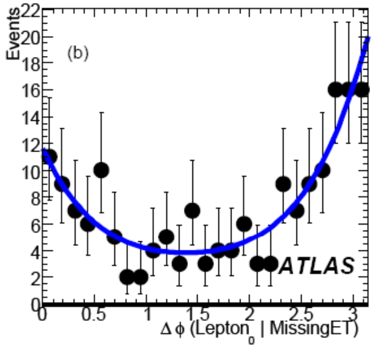
Dilepton channel – Likelihood fit method

- Start with cut-and-count event selection
- Additionally exploit information in observables
  - Angle between highest pT lepton and Etmiss
  - Angle between highest pT jet and Etmiss
- Procedure
  - Parameterize signal, background distribution from signal sample and mix of background samples
  - Fit data to sum of signal and background model

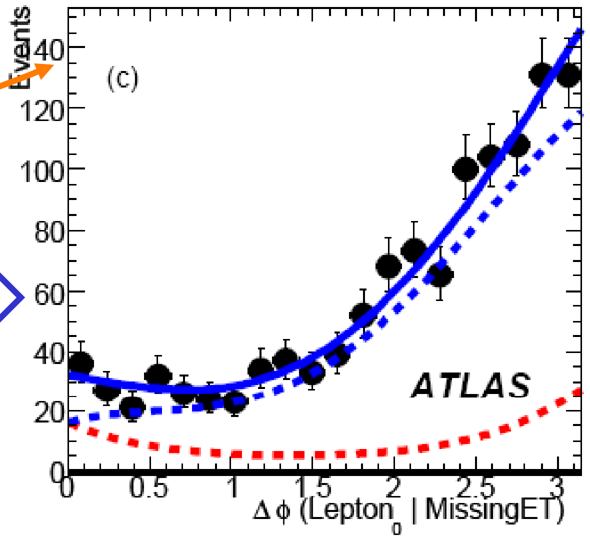
$\Delta\phi(l,M_{ET})$ signal



$\Delta\phi(l,M_{ET})$ background



$\Delta\phi(l,M_{ET})$ 'data'

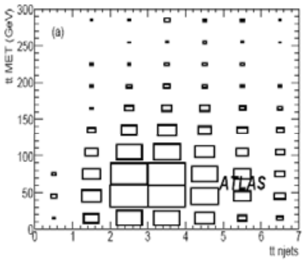


Dilepton channel – template method

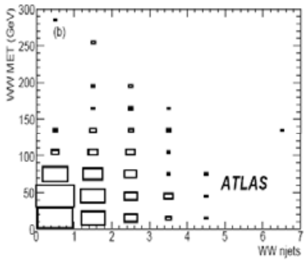
- Use 2D distributions in [E_T(miss),N(jets)] to disentangle signals and backgrounds
  - Use loose event sample (No cut-and-count preselection)
- Derive binned likelihood for data as a function of cross-section, acceptance, background normalization
  - Combined fit to eμ,ee,μμ channels
  - Systematic uncertainties on acceptance and template shapes are taken into account

Result of template fit

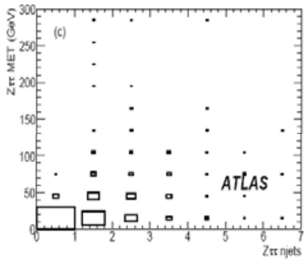
tt template

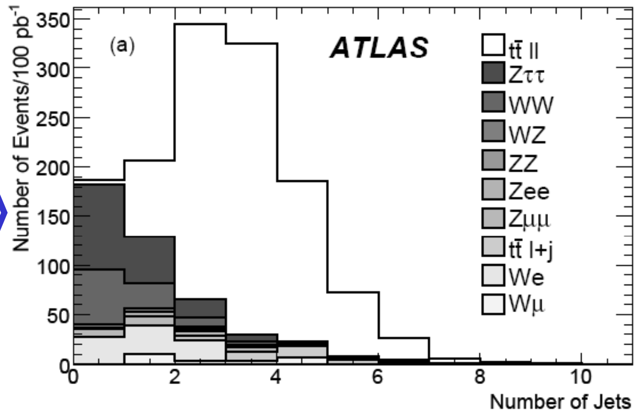


WW template



Zττ template





Dilepton channel – Summary of cross section uncertainties

- Overview of systematic uncertainties
  - Jet energy scale largest contributor

$\Delta\sigma/\sigma$ [%]	cut and count method				likelihood method			
	$e\mu$	ee	$\mu\mu$	all	$e\mu$	ee	$\mu\mu$	all
CTEQ6.1 set	2.4	2.9	2.0	2.4	0.3	0.4	0.2	0.2
MRST2001E set	0.9	1.1	0.7	0.9	0.2	0.2	0.1	0.2
JES-5%	-2.0	0.0	-3.1	-2.1	-5.4	1.1	4.9	8.3
JES+5%	2.4	4.1	4.7	4.6	7.8	3.9	-4.6	-4.4
FSR	2.0	2.0	4.0	2.0	0.2	0.4	0.0	0.3
ISR	1.1	1.1	1.2	1.1	2.5	1.8	0.0	1.7
parameters-1σ					-3.0	-0.2	-2.1	-1.8
parameters+1σ					3.2	0.8	2.0	2.0

(Template method has included systematic uncertainties into fit)

- Combined numbers

$$\text{Cut and Count method:} \quad \Delta\sigma/\sigma = (4(\text{stat})^{+5}_{-2}(\text{syst}) \pm 2(\text{pdf}) \pm 5(\text{lumi}))\%$$

$$\text{Template method:} \quad \Delta\sigma/\sigma = (4(\text{stat}) \pm 4(\text{syst}) \pm 2.(\text{pdf}) \pm 5(\text{lumi}))\%$$

$$\text{Likelihood method method:} \quad \Delta\sigma/\sigma = (5(\text{stat})^{+8}_{-5}(\text{syst}) \pm 0.2(\text{pdf}) \pm 5(\text{lumi}))\%$$

Summary

- The expected uncertainty on a ttbar cross section measurement on 100 pb^{-1} of data in either semi-leptonic and di-leptonic events is of the order of 10-15%
  - The errors are dominated by systematic uncertainties in all studied cases
  - For both the semi-leptonic and di-leptonic cross section measurements multiple methods have been developed with different sensitivities to various uncertainties
  - Both the semi-leptonic and di-leptonic channels are sensitive to effects from various types of BSM physics
  - Even though the studies presented are done at 100 pb^{-1}, it is clear from the signal statistics, that a first top cross section extraction is already feasible around 10 pb^{-1}