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Early Top Quark Measurements

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Early Top Measurements at ATLAS

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Topical Issues in LHC Physics Conference, ICTP, 29 June-2 July 2009

Plan of Talk

- Overview of LHC and ATLAS.
- Theoretical motivation.
- Measurement of the $t\bar{t}$ cross-section.
- Other top physics of interest.
- Summary and conclusions.

Overview of LHC and ATLAS

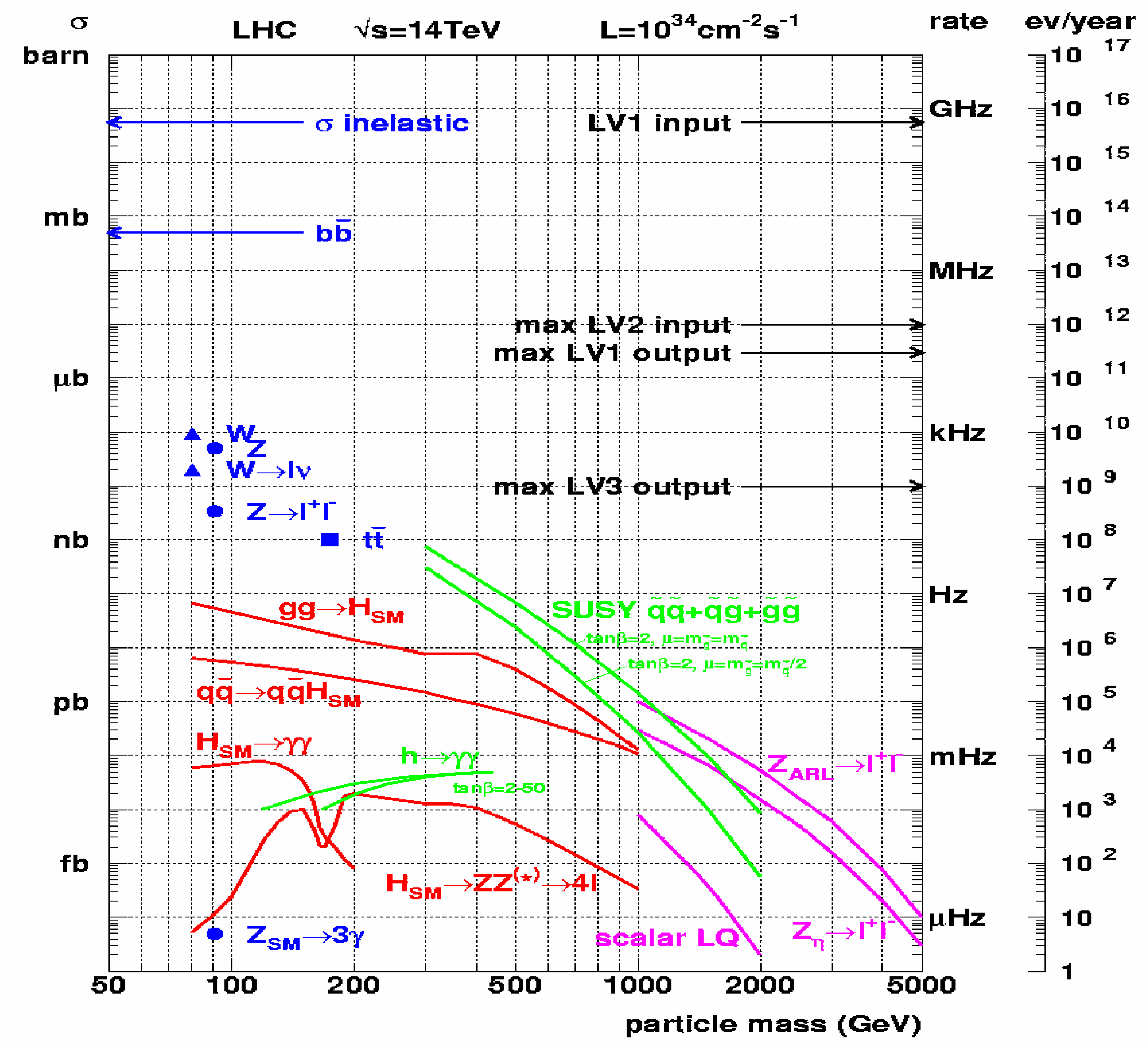
- Large Hadron Collider - a pp machine.
- Centre of mass energy: nominal 14TeV, however between 8 and 10TeV at startup.
- Nominal luminosity $10^{34}\mathrm{cm}^{-2}/\mathrm{s}$ (equivalent to $100\mathrm{fb}^{-1}$/year), at startup 10^{31} or 10^{32} $\mathrm{cm}^{-2}/\mathrm{s}$.
- Two large general purpose detectors: ATLAS and CMS - already assembled in caverns and taking cosmic ray data for calibration and alignment.
- Expecting collisions in autumn 2009.

ATLAS

Components and their coverages:

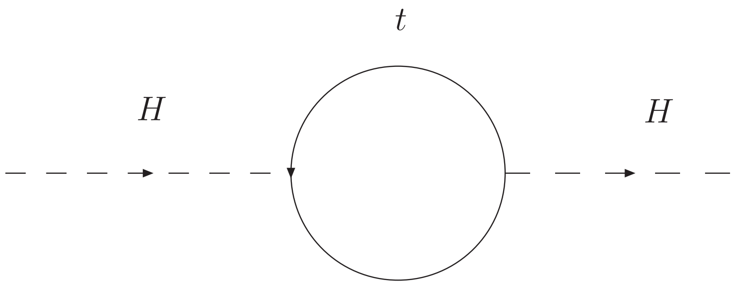
Detector Component	η coverage
Tracking	$\|\eta\| < 2.5$
EM calorimetry	$\|\eta\| < 3.2$
Hadronic calorimetry	
barrel and end-cap	$\|\eta\| < 3.2$
forward	$3.1 < \|\eta\| < 4.9$
Muon spectrometer	$\|\eta\| < 2.7$

- The detector 'sees' γ, e, μ, (τ to some extent), and jets.
- b-quarks have lifetime $\sim 10^{-12}s$, so travel measurable distances before decaying $\Longrightarrow$ secondary vertices.
- Silicon pixel detector can measure secondary vertices $\Longrightarrow$ b-tagging. Efficiency 60%.


σ
barn
LHC
√s=14TeV
L=10^34cm^-2s^-1
rate
ev/year
σ inelastic
LV1 input
GHz
mb
bb̄
MHz
max LV2 input
max LV1 output
μb
W
Z
W→lν
kHz
max LV3 output
Z→l⁺l⁻
nb
tt̄
gg→H_SM
SUSY q̃q̃+q̃g̃+g̃g̃
tanβ=2, μ=m_g̃=m_q̃
tanβ=2, μ=m_g̃=m_q̃/2
Hz
qq̄→qq̄H_SM
pb
H_SM→γγ
h→γγ
tanβ=2-50
Z_ARL→l⁺l⁻
mHz
fb
H_SM→ZZ^(*)→4l
Z_SM→3γ
scalar LQ
Z_η→l⁺l⁻
μHz
50
100
200
500
1000
2000
5000
particle mass (GeV)
10^17
10^16
10^15
10^14
10^13
10^12
10^11
10^10
10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10
1

The Top Quark

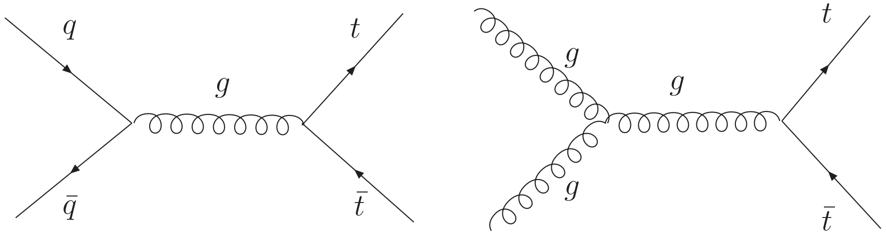
- Discovered by Tevatron in 1995.
- Heaviest known particle, $m_t = 173.1 \pm 0.6(stat.) \pm 1.1(syst.)$GeV.
- Has largest Yukawa coupling, $y_t \approx 1$.
- Important in loop diagrams, for example



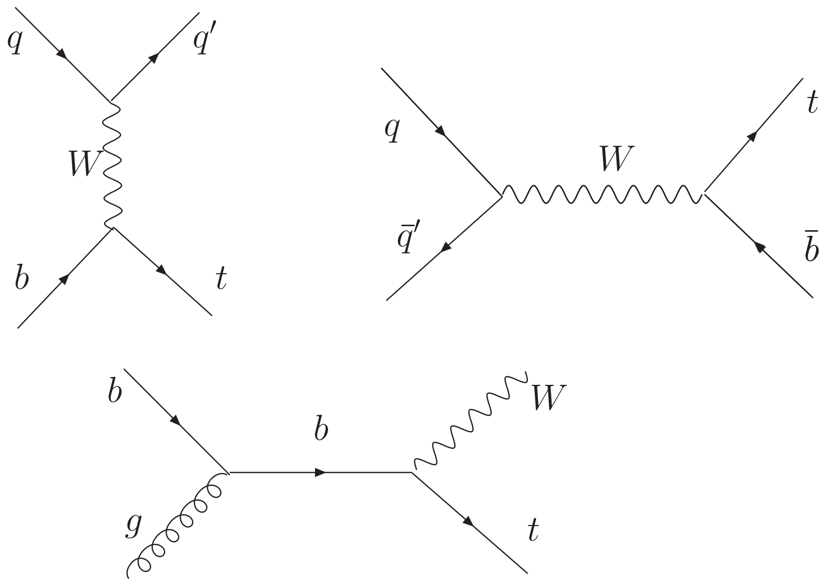
- Thus relevant to the problem of EWSB as well as hierarchy problem.
- $\Gamma_t \approx 1.5$GeV, so the top decays before hadronising.
- Decays almost always as $t \to bW$, since $|V_{td}|, |V_{ts}| \approx 10^{-3}$ and $|V_{tb}| \approx 1$.

Top Production at LHC

- Proceeds mostly via gluon scattering (85%) and $q\bar{q} \to \bar{t}t$ (15%).



- Strong interaction - copious production.
- Also single top production via electroweak processes.



Production Cross Section

- Calculated to NLO, including Next to Leading Logarithms (NLL), corresponding to soft gluon resummation.
- At 14TeV, $\sigma_{t\bar{t}} = 833 \pm 100\text{pb}$ for $m_t = 175\text{GeV}$.
- This corresponds to $8 \cdot 10^6$ events in 10fb^{-1}.
- An LHC year is roughly 10^7s (=1/3 of real year), so this gives 1 $t\bar{t}$ pair per second at $10^{33}\text{cm}^{-2}\text{s}^{-1}$ - hence top factory.
- Single top production $\approx 320\text{pb}$.
- At 10TeV, the $t\bar{t}$ cross-section is 1/2 of what it is at 14TeV.

The Top Challenge

Challenges of top physics: top events have leptons, missing energy, jets, b-jets. Depending on the decays of tops, the events can be very busy (4 hard jets in semileptonic decays).

$t\bar{t}$ is often the dominant background to many new physics searches, in particular SUSY searches.

Seeing the top is important as (together with observing W and Z peaks) it provides a check that the detector is working properly.

Check Standard Model before measuring gaugino and squark masses!

Will play a role in calibrating the detector - shifted W and top peaks.

Timeline for top physics with early data: few pb^{-1}

With the first few pb^{-1}, have to clean up missing energy and make sure object reconstruction is working properly. Also, can already start measuring fake rates; reconstructing the W can help with early determination of the JES.

Can start applying data-driven methods for background determination (mostly importantly, W+jets), and tuning MC to fit data as well as possible.

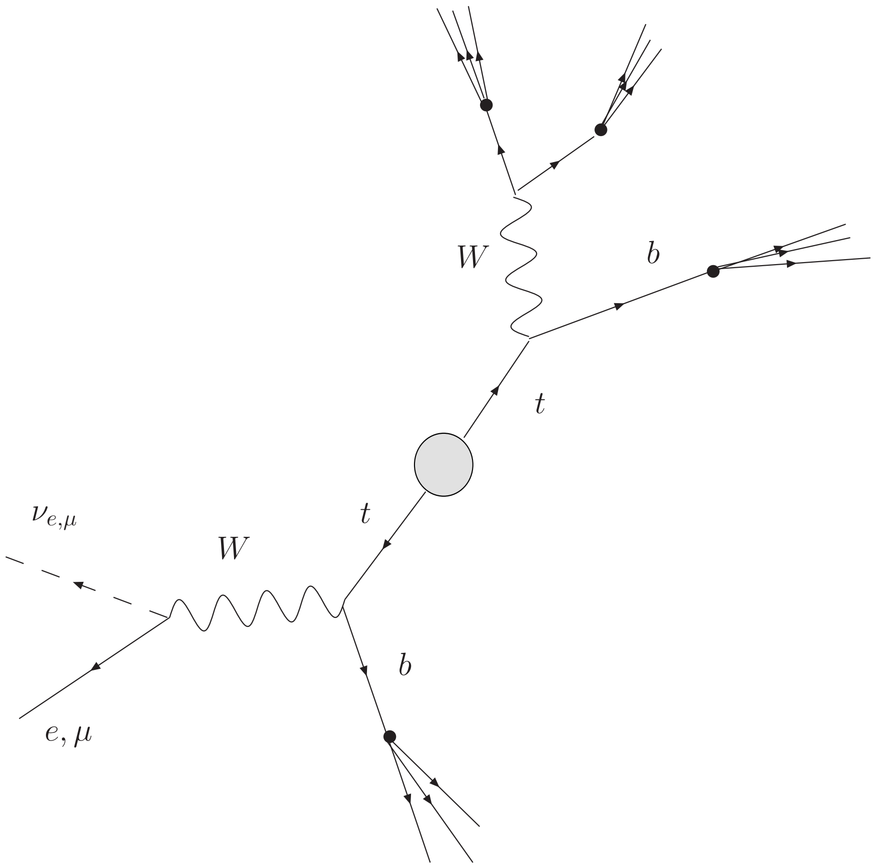
Top rediscovery with $10\mathrm{pb}^{-1}$.

Timeline for top physics with early data - 100 pb^{-1} and beyond

With $100\mathrm{pb}^{-1}$, can apply the commisioning analysis for cross-section measurement. More precise measurements of the JES scale using P_T balance in Z+jets and γ+jets events. Measurements of the b-jet energy scale, crucial for top mass.

Mass measurement with $\sim 100\mathrm{pb}^{-1}$, after $1\mathrm{fb}^{-1}$ error down to 1GeV, dominated by systematics.

With $> 1\mathrm{fb}^{-1}$, searches for $t\bar{t}$ resonances and other types of new physics. Also precise measurement of single top cross-section in 2 out of 3 channels.



- The physics of top decays: top mass, spin, couplings, FCNC decays (e.g. $t \to qZ$), W mass, W helicity, b-jets...
- There are (almost) always 2 b jets and 2 W bosons.

Top Pair Decays II

- The W boson decays into leptons with $\Gamma(W \to l\nu) \approx 0.33$ and into light quarks $\Gamma(W \to qq) \approx 0.67$ ($|V_{cb}| \approx 0.4 \cdot 10^{-2}$).
- Therefore there are three channels for top pair decays:
- All hadronic - no leptons in final state, $\Gamma = 4/9$.
- Many jets, no leptons - no high p_T lepton to trigger, lots of combinatorics and large QCD background. Not easy to study.
- Semileptonic - one lepton in final state. $\Gamma = 4/9$. One neutrino - has missing P_T signal. Most useful channel.
- Dileptonic, $\Gamma = 1/9$. Low background, however two neutrinos - can't reconstruct them. Therefore tops also hard to reconstruct.

Semileptonic Channel

- Taus are difficult to reconstruct, so use electrons and muons only.
- Every event has 2 b-jets, however, in the initial phase of LHC running, detector misalignments and other factors may mean that b-tagging will not be working perfectly.
- There is a neutrino escaping the detector - use $\not{P}_T$.
- Select events based on a set of cuts to eliminate background while keeping signal.

Cuts Selection A

- Require event to pass triggers L1_EM20I, L2_e25i, EF_e25i or equivalent muon triggers mu20.
- lepton $P_T > 20$GeV.
- Require 4 jets with $P_T > 20$GeV, and 3 jets with $P_T > 40$GeV.
- $\not{P}_T > 20$GeV.
- Object definitions:
  1. Electrons identified by inner detector and calorimeters and reconstructed in $|\eta| < 2.5$. Electrons in $1.37 < |\eta| < 1.52$ vetoed. Isolation requirement $E_T < 6$GeV in a cone $\Delta R < 0.2$ around electron.
  2. Muons reconstructed by inner detector and muon spectrometer. $|\eta| < 2.5$ and $E_T < 6$GeV in ΔR cone of 0.2.
  3. Use cone 0.4 jets. b-tagging efficiency of 60% for jets with $P_T > 30$GeV.

Backgrounds

- Main backgrounds to $t\bar{t}$ in the semileptonic channel are:
  1. W+jets (dominant)
  2. single top
  3. $Z \to l^+l^- +$ jets.
  4. QCD with fake leptons and $\not{P}_T$
  5. diboson WW, WZ, ZZ
- Normalisation of W+jets hard to compute - use data-driven methods to determine it.
- QCD has a large cross-section and tiny efficiency - difficult to simulate (1Mb and 1h/event!).

Cross Section Measurement - the Method

- Use 'cut and count' method, based on the simple formula:

$$\sigma = \frac{N_{sig}}{\mathcal{L} \times \epsilon} = \frac{N_{obs} - N_{bkg}}{\mathcal{L} \times \epsilon}.$$

- Here N_{sig} is the number of signal events, N_{obs} number of observed events and N_{bkg} number of background events estimated from Monte-Carlo.
- $\mathcal{L}$ is the integrated luminosity and ϵ total efficiency.
- ϵ includes geometrical acceptance ($|\eta|$ limitations etc.), trigger efficiency and event selection efficiency.

Data Simulation

- MC@NLO and HERWIG were used for $t\bar{t}$ - production calculated at NLO at matrix level. CTEQ6M pdfs were used.
- ALPGEN used for W+0,1,2,3,4j. Only LO so have to be careful with normalisation - data driven methods.
- QCD background has a large uncertainty - strongly dependent on lepton fake rate. Can change cuts to strongly reduce this background.
- Full simulation of detector via GEANT 4.
- Divide data into two sets, treating one as MC (from which ϵ and N_{bkg} are obtained) and one as 'real data'.
- Normalise all results to $100\mathrm{pb}^{-1}$.

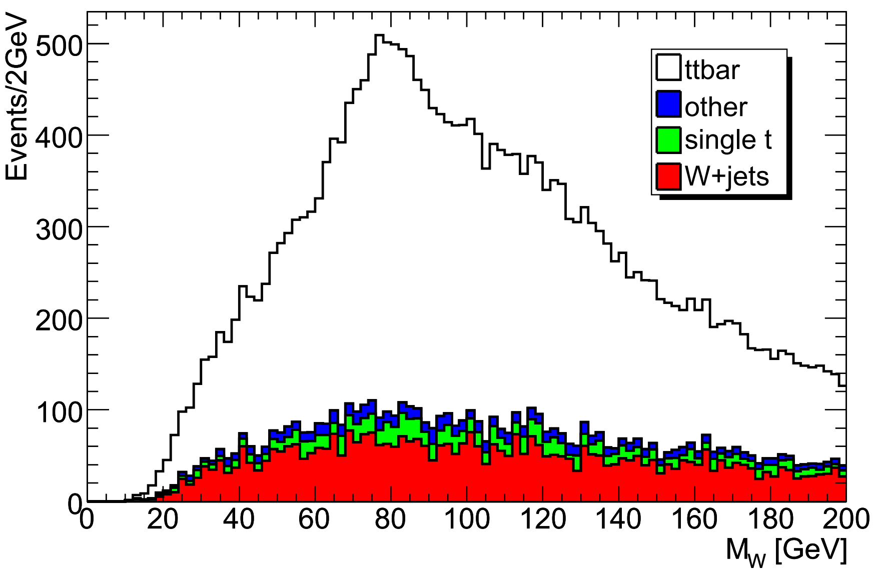
Efficiencies

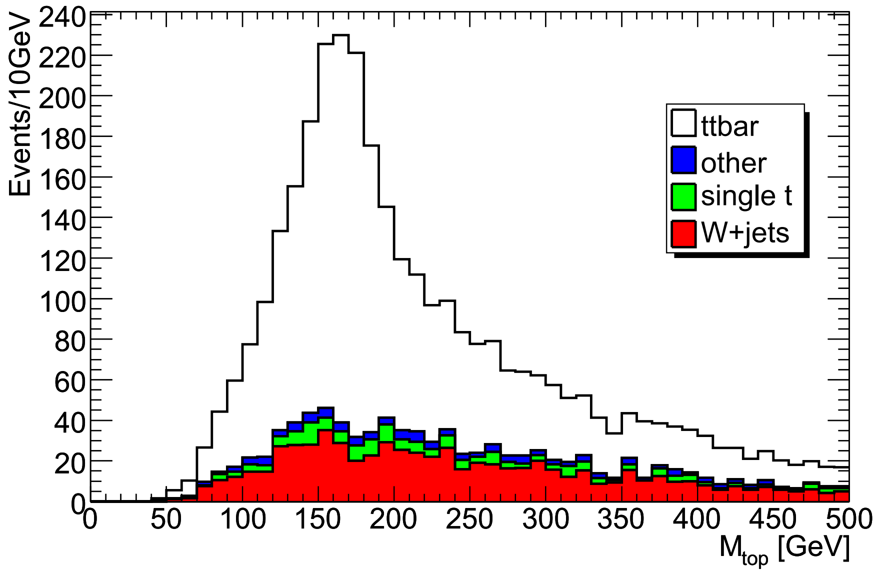
	Trigger eff (%)	Lepton eff (%)	$\not{E}_T$ eff (%)	Jet req. (I) eff (%)	Jet req. (II) eff (%)	Combined eff (%)
$t\bar{t}$ (electron)	52.9	52.0	91.0	70.7	61.9	18.2
$t\bar{t}$ (muon)	59.9	68.7	91.6	65.5	57.3	23.6

- Muon efficiency slightly higher.

Tops and Ws

- Reconstruct top as the combination of three jets with highest total P_T.
- W peak may be seen in the invariant mass plot of all pairs of jets.

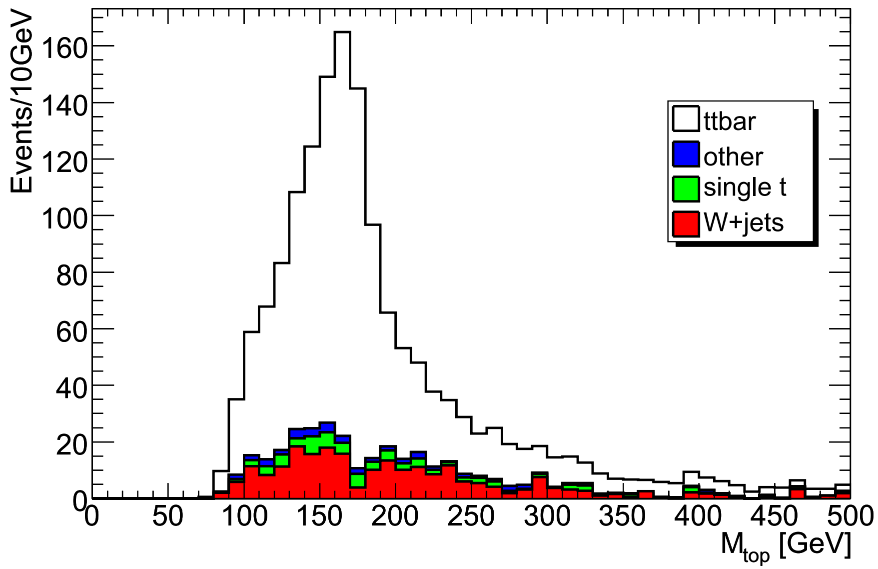




- A lot of combinatorial background, so peaks are not sharp. Need additional cuts and/or b-tagging to minimise combinatorics and reduce the shoulder structure in top mass plot.

Further Cuts: Selection B

- Improve S/B ratio and purity by requiring two of the jets forming the top to be in a W mass window.
- W mass constraint: at least one of three dijet masses for the top candidate is within 10GeV of the reconstructed mass of the W.



Additional Cuts

- Can also require the top candidate to be in a top mass window, $141 < m_t < 189$GeV.
- It may happen that the barrel calorimetry is working better than the forward one, and expect central jets from top decays $\Longrightarrow$ use an $|\eta| < 1$ cut on top candidate jets.
- Explored also the $\cos\theta^*$ and M_{eff} variables for improving the S/B ratio.

Results - Electrons

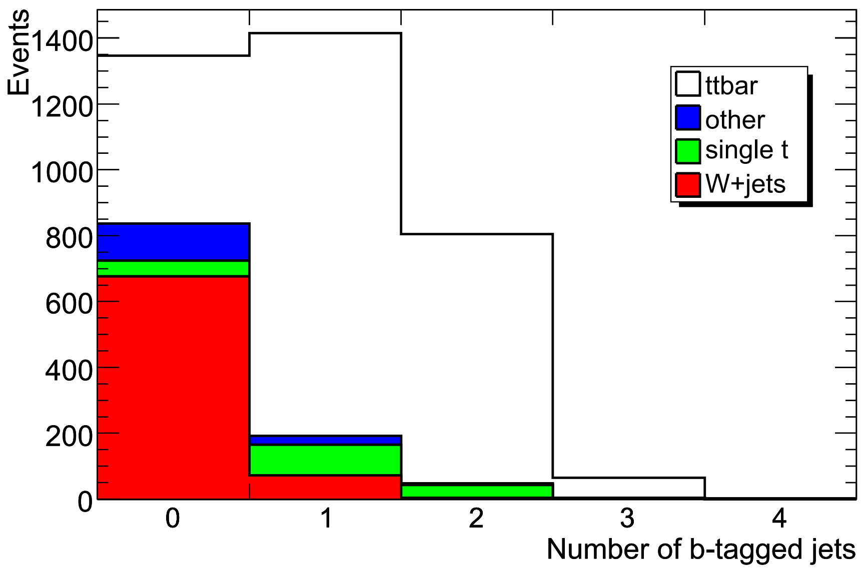
Electron analysis					
Sample	default	W const.	m_t win	W const. + 1 b-tag	W const. + 2 b-tag
$\bar{t}t$	2555	1262	561	329	208
had $t\bar{t}$	11	4	0.0	0.6	0.0
W+jets	761	241	60	7	1
single t	183	67	23	18	7
Z+jets	115	35	8	2	0.4
$W\ \bar{b}b$	44	15	3	5	0.7
$W\ \bar{c}c$	19	6	1	0.4	0.0
WW	7	4	0.4	0.0	0.0
WZ	4	1	0.4	0.0	0.0
ZZ	0.5	0.2	0.1	0.0	0.0
Sig	2555	1262	561	329	208
Bkgd	1144	374	96	33	10
S/B	2.2	3.4	5.8	9.8	21.6

Results - Muons

Muon analysis					
Sample	default	W const.	m_t	W const. + 1 b-tag	W const. + 2 b-tag
$\bar{t}t$	3274	1606	755	403	280
hadronic $t\bar{t}$	35	17	7	5	2
W+jets	1052	319	98	11	0.0
single top	227	99	25	19	10
$Z\rightarrow ll$ +jets	84	23	3	0.5	0.0
$W\ \bar{b}b$	64	19	4	5	2
$W\ \bar{c}c$	26	9	3	0.1	0.0
$W\ W$	7	3	0.7	0.0	0.0
$W\ Z$	7	3	0.8	0.0	0.0
$Z\ Z$	0.7	0.3	0.1	0.0	0.0
Signal	3274	1606	755	403	280
Background	1497	495	143	42	14
S/B	2.2	3.2	5.3	9.6	20.1

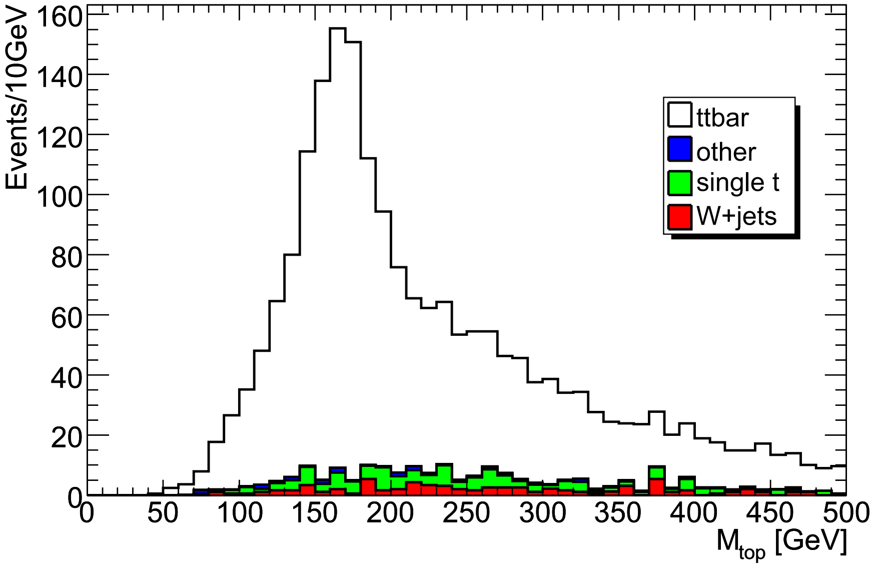
B-TAGGING

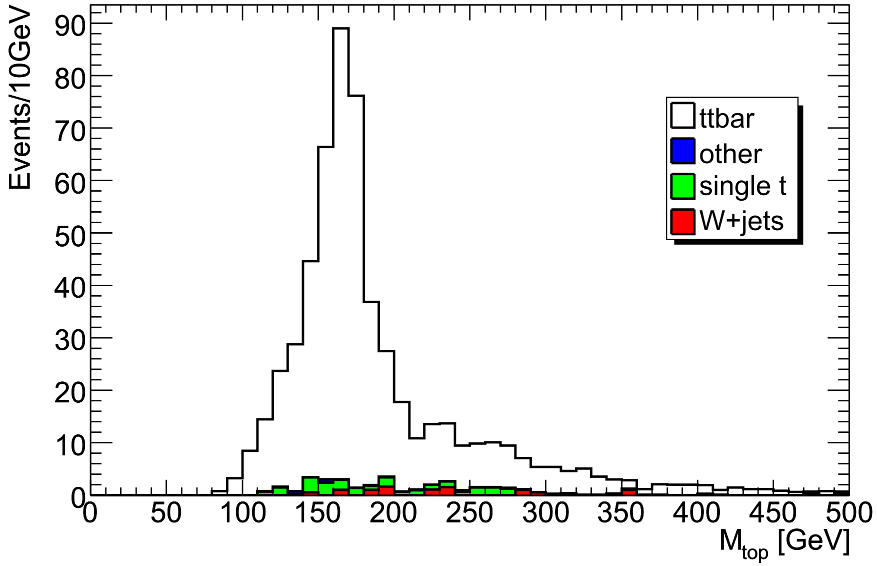
- Every event has two b-quarks $\Longrightarrow$ there are a few options. No b-tags, 1 or 2 b-tags, 2 b-tags.
- Number of b-tagged jets in events:



- Require 1 or 2 b-tags on top of Selection A.
- W constraint now applied on the two non b-jets.
- Purity improved by ~ 4, sig efficiency reduced by ~ 2.

- Top mass with 1 or 2 b-tags, with and without W-mass cut:





- Cross section can now be measured with any of these sets of cuts.

Cross Section Measurement

- The error on σ for counting method (with M mass constraint):

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

- Error dominated by systematics. These are:
- Background normalisation, in particular W+jets. This can be determined through data via the (approximate) relation

$$\frac{\sigma(W_{incl})}{\sigma(W+nj)} = \frac{\sigma(Z_{incl})}{\sigma(Z+nj)}$$

- Can now normalise W+jets by using $Z+nj$ with $Z \to e^- e^+$.
- Can reduce uncertainty to 20% with $1\mathrm{fb}^{-1}$.

Systematics in x-sec Measurement

- Initial state/final state radiation (ISR/FSR) uncertanties.
- 1. More ISR/FSR increases the number of jets and has effects on P_Ts of objects.
  2. Study by varying parameters in PYTHIA such as λ_{QCD} and the the ISR/FSR cutoffs.
- PDF uncertanties.

  Both CTEQ6M and MRST2002 error sets at NLO have been used to evaluate these.
- Jet energy scale (JES).
  1. The principal source of systematic uncertainties for most LHC (and hadron collider in general) measurements.
  2. Many factors influencing JES: dead material, underlying event, energy lost outside jet cones...
  3. Data driven methods to determine JES: P_T balance in Z+jets, γ+jets.
  4. Light jet scale and b-jet scale different. b-jet scale difficult to measure, need to use $Z \to b\bar{b}$.
  5. Can also use $t\bar{t}$ itself to measure light jet scale, via M_W.
  6. Ultimate goal is to reduce JES uncertainty to 1%.

Errors

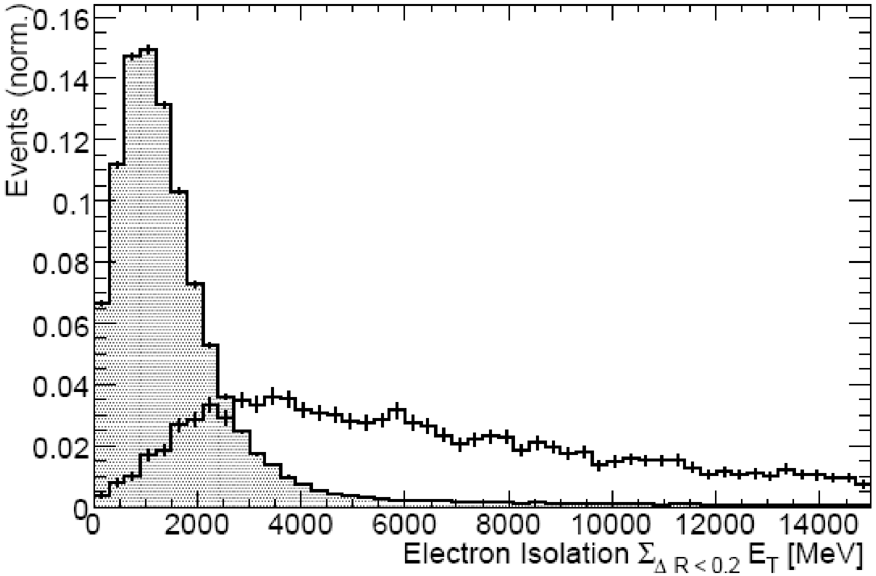
Source	Default	W constraint
Statistical	2.7	3.5
Lepton ID Efficiency	1.0	1.0
Lepton trigger efficiency	1.0	1.0
50% more W+jets	14.7	9.5
20% more W+jets	5.9	3.8
Jet energy scale (5%)	13.3	9.7
PDFs	2.3	2.5
ISR/FSR	10.6	8.9

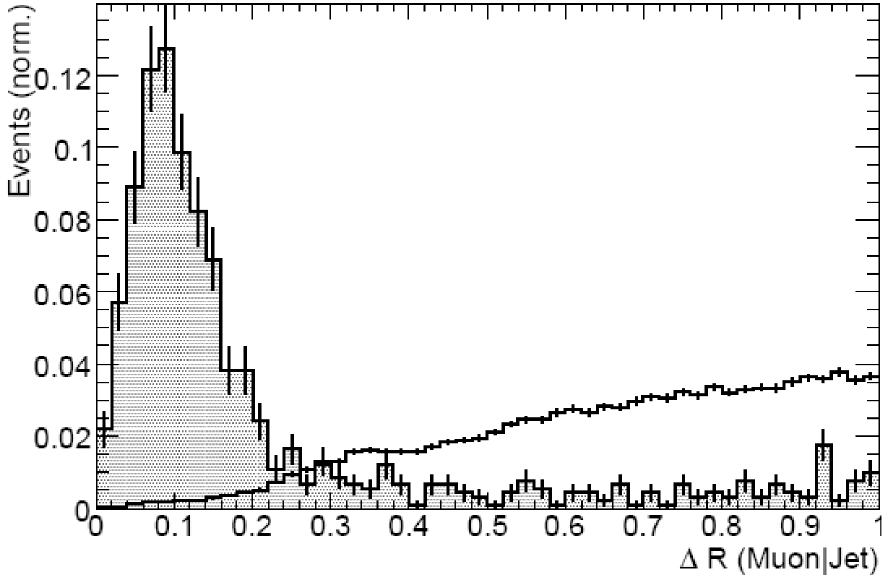
QCD Background?

- Poorly understood - only at LO in generators.
- Data-driven methods will be used to determine the impact.
- Fake rate very important - can only be studied properly with full simulation.
- Estimate from fully simulated di-jet sample.
- $pp \to b\bar{b}$ has $\sigma \approx 100\mu b$. Many of these events will have high P_T fake leptons and poorly reconstructed $\not{P}_T$, providing a significant background to the $t\bar{t}$ signal.
- Fake electron 1×10^{-3}/jet, muon 1×10^{-5}/jet. Extra muons mostly from semi-leptonic B decays.
- Can deduce that QCD background smaller than W+jets.

- Can repeat the counting experiment in the dilepton channel.
- Very high triggering efficiency.
- Two kinds of background: prompt leptons (Z+jets), non-prompt leptons ($t\bar{t}$, QCD).
- B-hadrons often decay into $e/\mu + X$, so one of the dominant backgrounds in this channel is $t\bar{t}$.

- Refine the cuts to remove fake leptons.

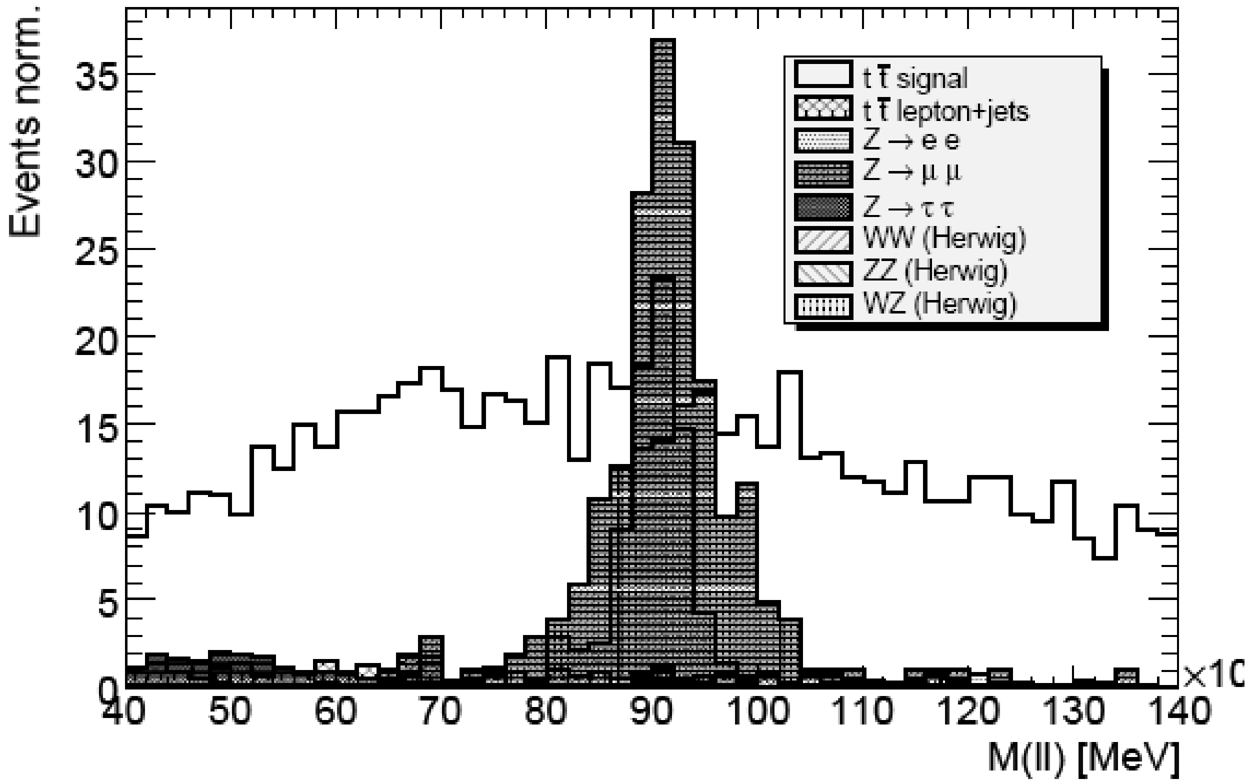




- Require no jet within $\Delta R < 0.2$ of muon.
- 2 opposite sign leptons $(ee, e\mu, \mu\mu)$, P_T (lep) > 20GeV, P_T (2 highest P_T jets) > 20GeV. Can apply quite a hard $\not{P}_T$ cut.
- No b-tagging.

Cross Section in Dilepton Channel II

- Eliminate Z+jets by a dilepton mass veto.



- $M_{ll} < 85$GeV or $M_{ll} > 95$GeV.
- Optimise P_T cuts on leptons and jets and $\not{P}_T$ cut to maximise significance $S/\sqrt{S+B}$.

Cross Section in Dilepton Channel III

Dataset	$e\mu$	ee	$\mu\mu$	all channels
$t\bar{t}$	555	202	253	987
$\epsilon(\%)$	6.22	2.26	2.83	11.05
Total bkg.	86	36	73	228
S/B	6.3	5.6	3.4	4.3

$$\Delta\sigma/\sigma = (4(\mathrm{stat})^{+5}_{-2}(\mathrm{syst}) \pm 2(\mathrm{pdf}) \pm 5(\mathrm{lumi}))\%.$$

- Lower systematic error than in the semileptonic channel.

Effects of New Physics

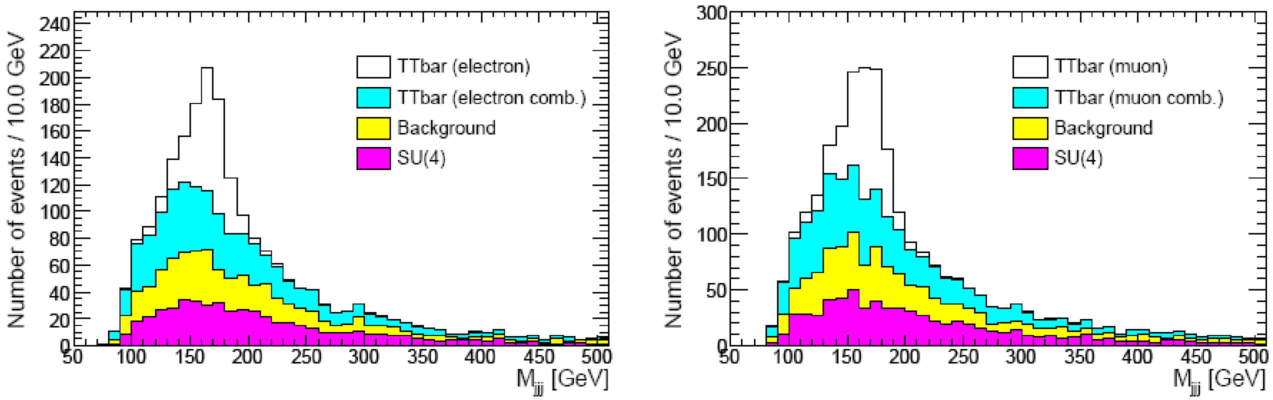
- Various possibilities for physics beyond the Standard Model.
- Supersymmetry, Large Extra Dimensions, heavy resonances...
- Often a lot of top activity, since new physics related to the hierarchy problem (top squark in SUSY, KK resonance in LED and Randall-Sundrum).
- Cross sections expected to be small - of the order of few picobarns.
- Can have a few $100\mathrm{pb}$ in some extreme (optimistic) cases.
- How does the new physics affect our counting experiment?

Effects of New Physics II

- Considered the effects of SUSY and a heavy resonance Z' coupled to (only!) $t\bar{t}$.
- Efficiencies usually quite high, since very high P_T involved.
- For the Z', efficiency $= 2\times$ efficiency for $t\bar{t}$.
- However, the cross-section only a few $pb \Longrightarrow$ number of events passing cuts $\approx 1\%$ of the number of $t\bar{t}$ events.
- SUSY:

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

SU4 Results



- SU4 is a very low mass point! ($\sigma \approx 270pb$)
- The shape in the top quark candidate mass plot is very similar for SU4 and Standard Model backgrounds.

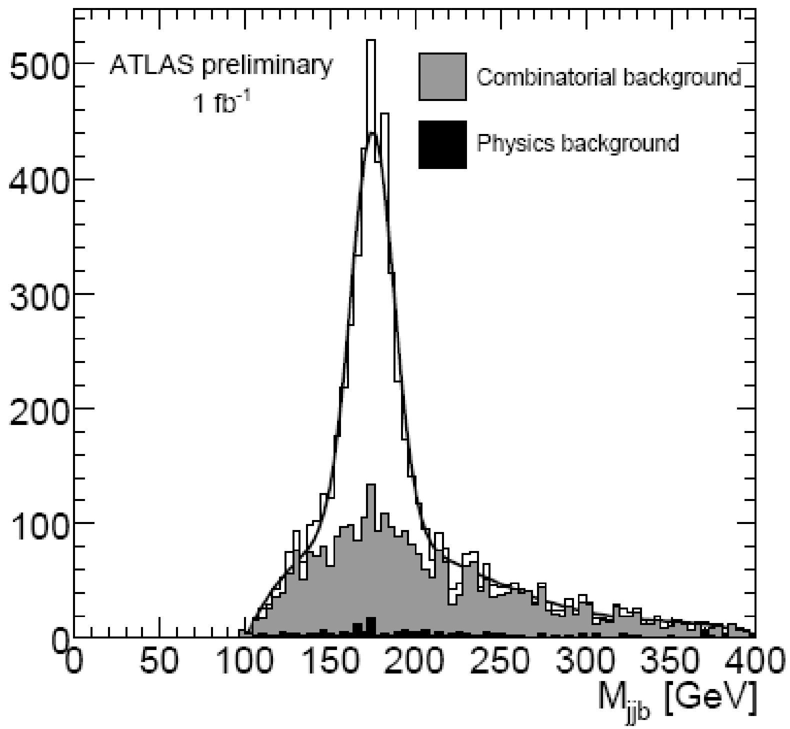
Mass Measurement

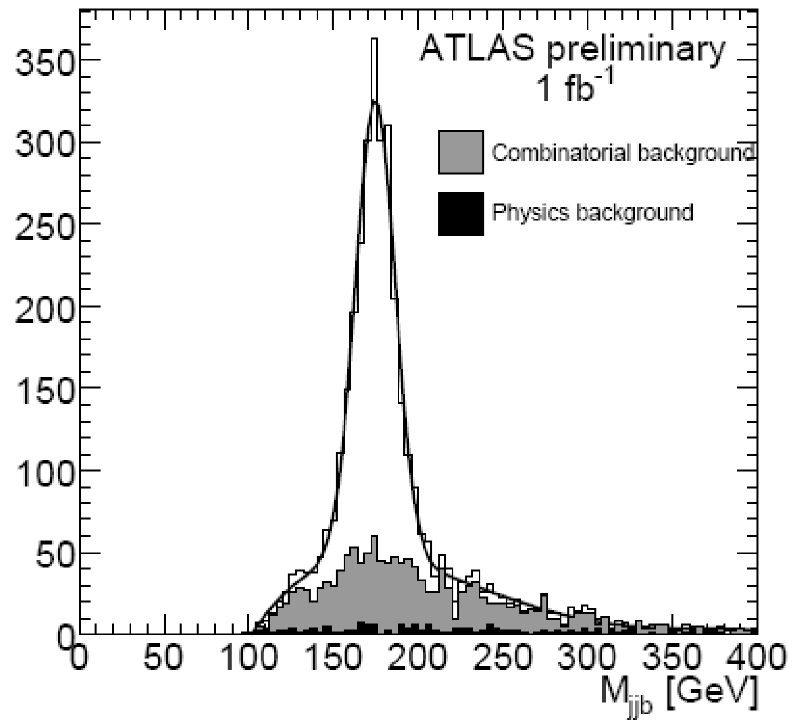
- Again semileptonic channel, with same cuts as before, but require all jets to have $p_T > 40$GeV, since below that jets not very well calibrated.
- Require exactly two b-tags.
- Use χ^2 method to reconstruct hadronic W, by minimising

$$\chi^2 = \frac{(M_{jj}(\alpha_{E_{j_1}}, \alpha_{E_{j_2}}) - M_W^{PDG})^2}{(\Gamma_W^{PDG})^2} + \frac{(E_{j_1}(1 - \alpha_{E_{j_1}}))^2}{\sigma_1^2} + \frac{(E_{j_2}(1 - \alpha_{E_{j_2}})}{\sigma_2^2}$$

  over all light jet pairs.
- Only keep candidates whose mass is withing $\pm 2\Gamma_{M_W}$ of M_W.
- Can obtain information on jet scale from α_1, α_2.

Top Mass - Results





- $m_{top} = 175.0 \pm 0.2$GeV (left), $m_{top} = 174.8 \pm 0.3$GeV (right), using two different methods of reconstruction.

Top Mass - Systematics

Systematic uncertainty	χ^2 minimisation method
Light jet scale	0.2GeV/%
b-jet energy scale	0.7GeV/%
ISR/FSR	0.3 GeV

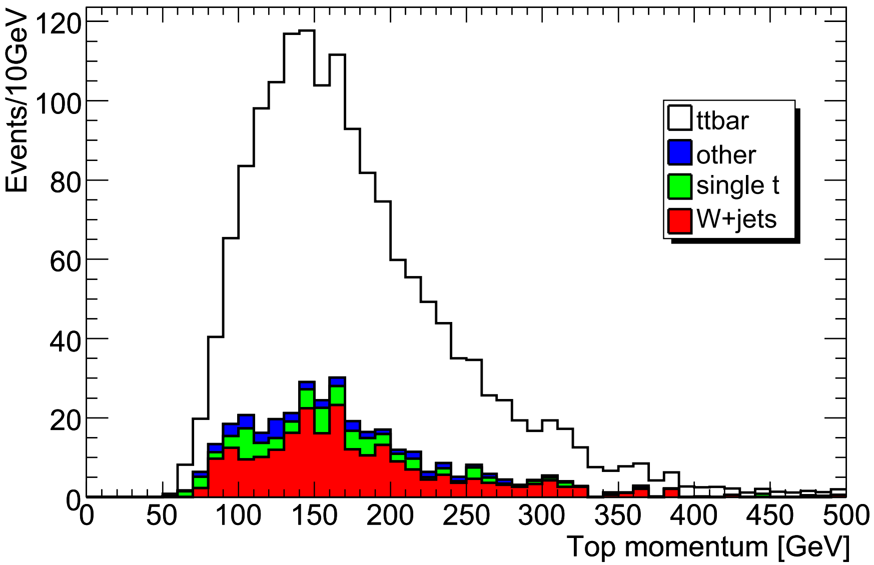
- b-jet energy scale has more impact since light energy scale due to W boson mass constraint.
- b-jet scale to be determined from $Z \to b\bar{b}$ data, but since statistics low initially, use light jet scale together with a Monte Carlo correction term.

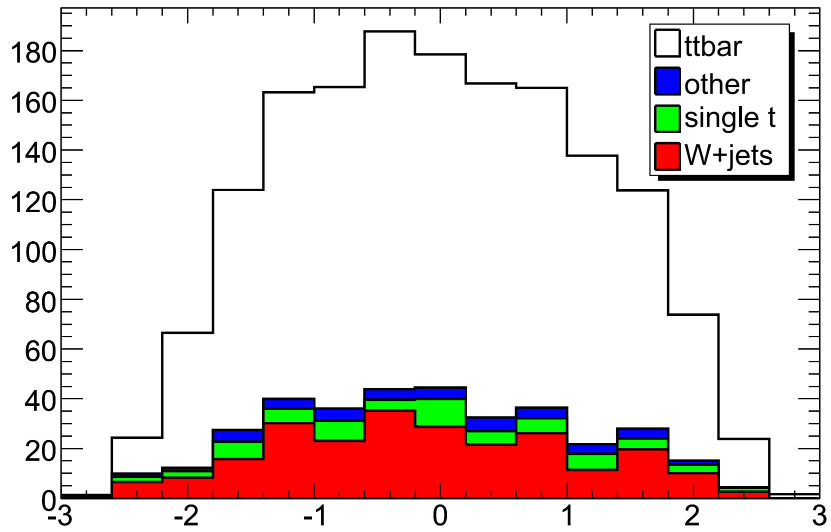
Summary

- Can reliably determine $t\bar{t}$ production cross-section in the early stages of LHC running, with $100\mathrm{pb}^{-1}$ of data.
- We can also determine the top mass, with the error down to 1GeV with $1\mathrm{fb}^{-1}$.
- The main source of error is the systematics, in particular the JES.
- More work needed on understanding backgrounds, especially fake leptons and $\not{p}_T$ in QCD, as well as measuring the JES (in particular b-jet scale).

Backup: Differential Cross-Sections

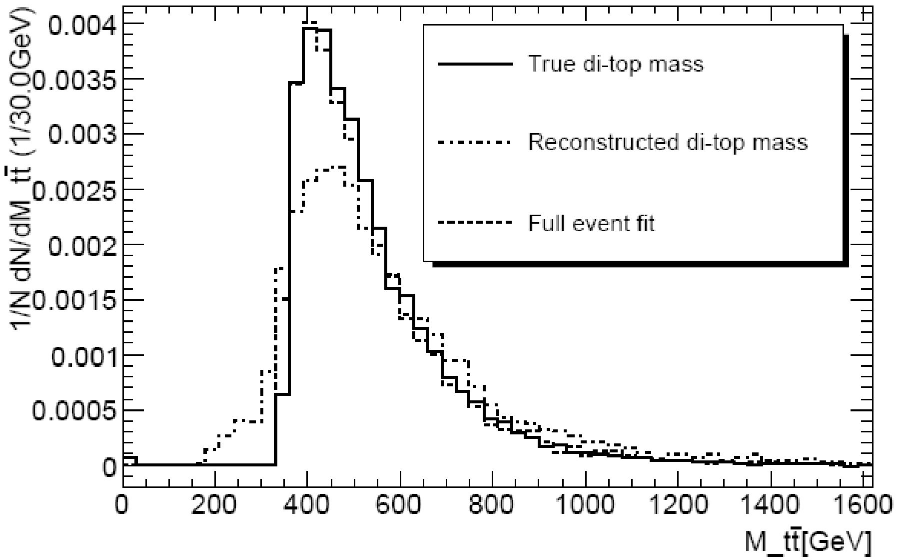
- Top momentum and rapidity distributions.

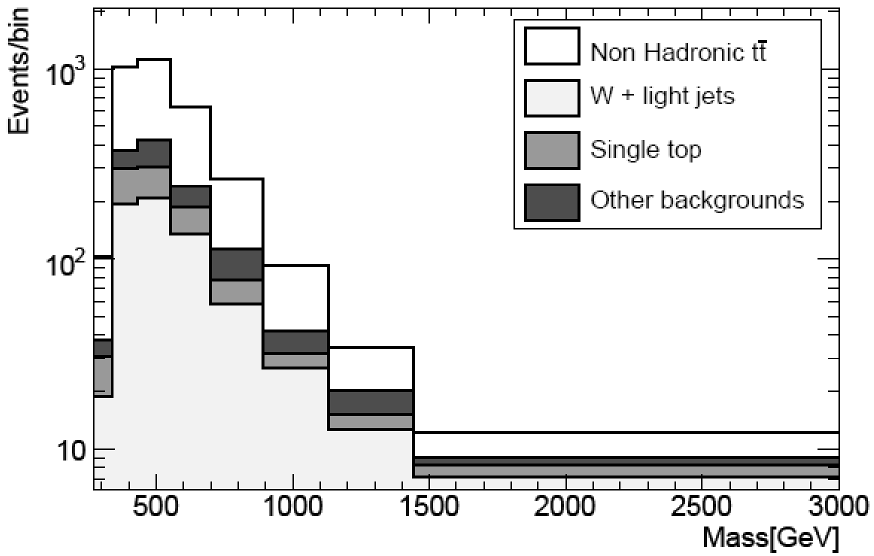




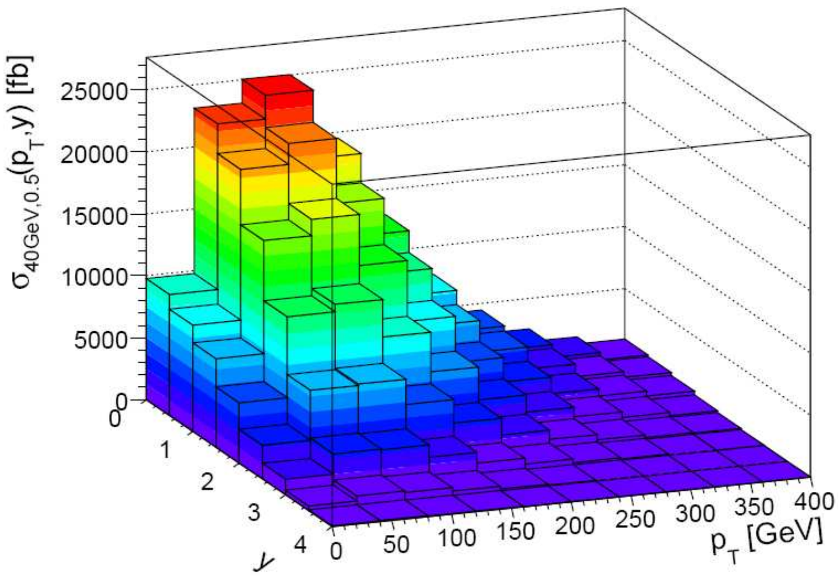
- Invariant mass of $t\bar{t}$ - useful for checking SM prediction and possibly detecting resonances.
- Reconstruct neutrino using M_W constraint, then reconstruct both tops. Naive method doesn't give a good fit to SM prediction → use kinematic χ^2 fit to 2 tops and 2 Ws.
- Resolution effects important - $(M_{tt}^{true} - M_{tt}^{reco})/M_{tt}^{true}$ ranges from 5% to 9% in $200 - 850$GeV range.

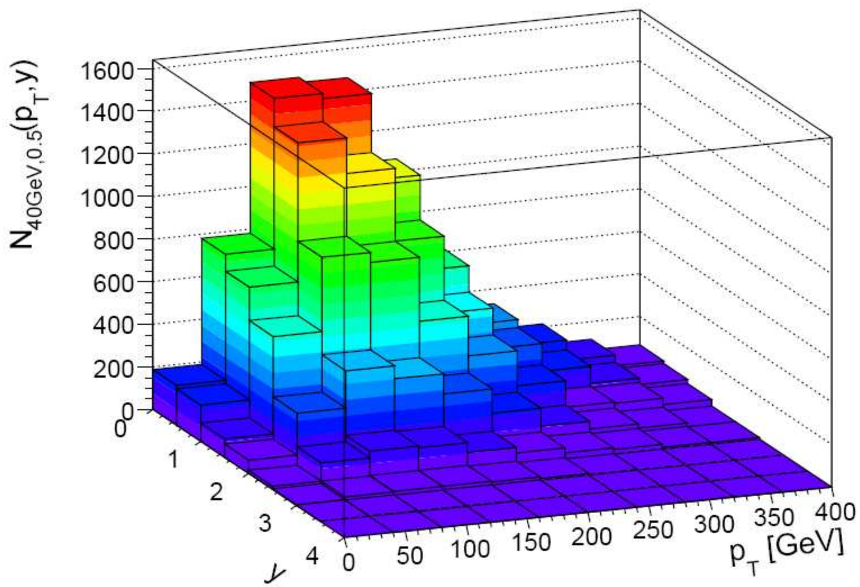
- Use variable bin size to reduce bin to bin migrations.





BACKUP: $d\sigma/dydp_T$

- Quantity interesting for new physics searches - spin correlations.
- Measurement in top rest frame - need to know p_T and y well.
- High purity needed $\rightarrow$ require 2 b-tags. Find light jet pairs with 60GeV$< M_{jj} <$100GeV, combine with closest b-jet. The highest resulting P_T combination is the hadronic top candidate.
- 



Backup - Extra cuts for top mass

- Impose further cuts to improve S/B ratio. Variables defined in hadronic top rest frame:

$$X_1 = E^*_W - E^*_b = E^*_{j1} + E^*_{j2} - E^*_b = \frac{M_W^2 - M_b^2}{M_{top}},$$

$$X_2 = 2E^*_b = \frac{M_{top}^2 - M_W^2 + M_b^2}{M_{top}}.$$

- Use $|X_1 - \mu_1| < 1.5\sigma_1, |X_2 - \mu_2| < 2\sigma_2$.