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Signaling the Arrival of the LHC Era

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Top Quarks at the LHC Experiments

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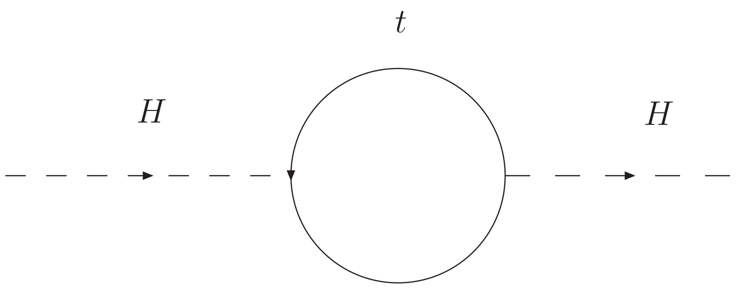
Signaling The Arrival of the LHC Era, ICTP Trieste, Dec 2008

Plan of Talk

- Introduction to Top Quarks
- Top Production and Decay
- Recognizing Top Quarks
- Globally Commissioning ATLAS and CMS with Top Quarks
- Measuring the Top Quark Mass
- New Physics with Top Quarks.
- Emphasise Basic Ideas, will not overwhelm you with Analyses!

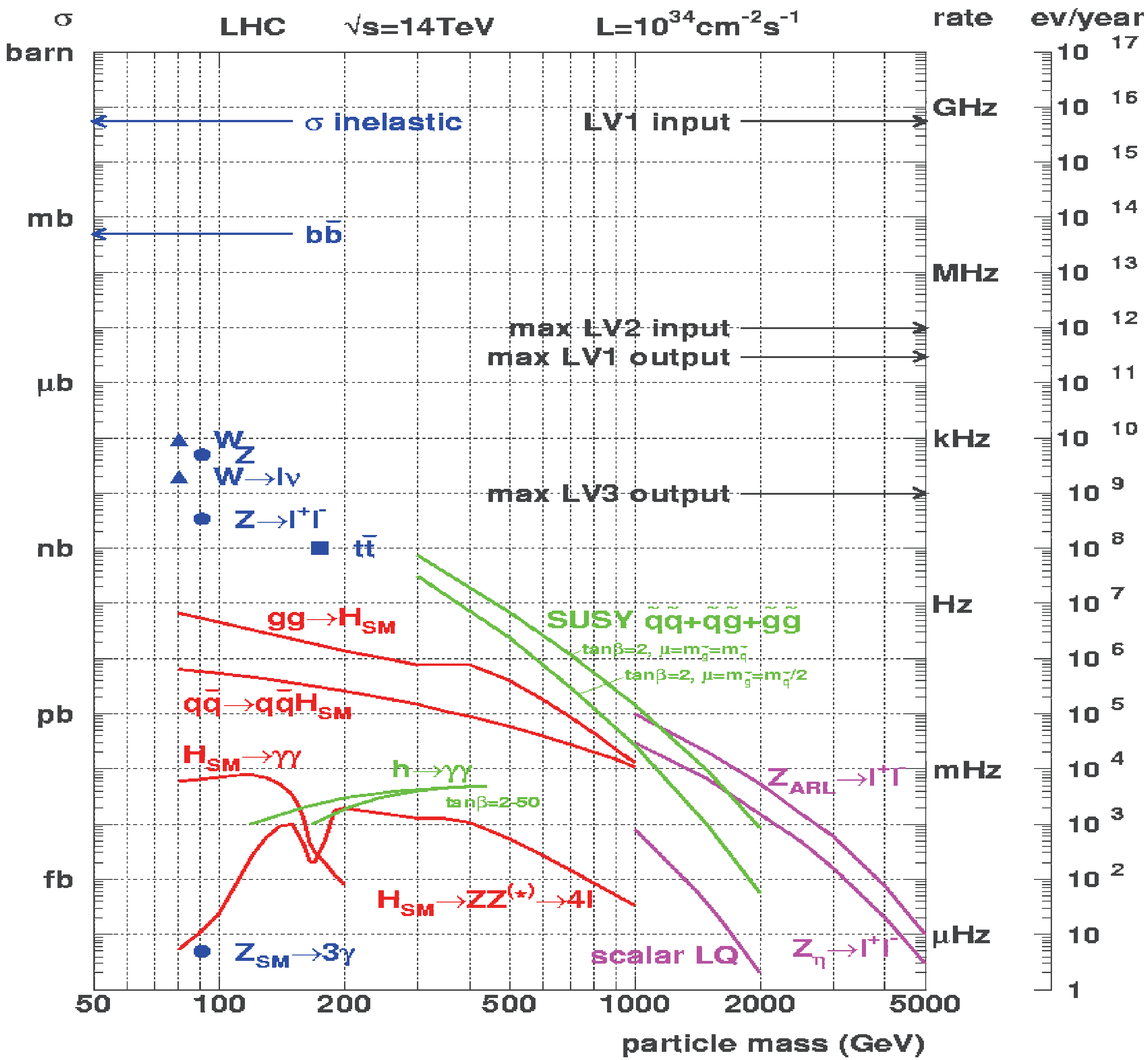
Top Quarks

- The Top Quark is the "up quark of the third generation"
- The most massive known elementary particle.
- Discovered at the Tevatron in 1994
- Since then, CDF and D0 have made precise measurements of its mass: $m_t = 172.6 \pm 0.8(stat.) \pm 1.1(syst.)$GeV.
- Has strongest coupling to Higgs, $y_t \approx 1$.
- Gives largest correction the the Higgs mass in the Standard Model



- 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 $|V_{tb}| \approx 1$.

Production Cross Sections at the LHC



Cross Sections as the LHC

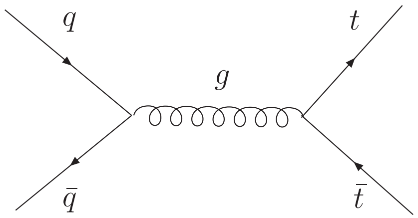
- At full Luminosity ($10^{34}cm^{-2}s^{-1}$) there will be 10^9 events/second
- This is a total x-section of roughly 10^{14}fb $= 10^{-1}$b
- These are mostly inelastic collisions.
- "Hard Physics Collisions" dominated by $gg \to g \to q\bar{q}$
- These "DiJet Events" have a x-section of around 10^{-5}b ie 10^5/s.
- Electroweak production of W's (eg $q\bar{q} \to W$) has a x-section of roughly 2×10^{-7}b $= 200$ nb $= 2 \times 10^8$fb eg 100 $W \to e\nu$ events/s.
- Z production is order 50nb.
- Production of Top Quarks is order 0.8 nb $\sim 10^6$ fb. Ten Top pairs every second!
- Every 100 pb^{-1} of data will contain around 83000 top pair events.
- Note: these numbers correspond to $\sqrt{s} = 14$TeV
- If the LHC starts at 10TeV then the x-sections typically drop by a factor of few. The top x-section goes down by about two.

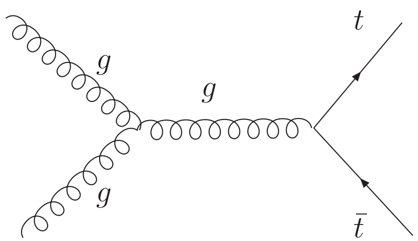
As the LHC Starts

- At start up the instantaneous Luminosity will be much less, perhaps $(10^{31}cm^{-2}s^{-1})$.
- This means one $W \rightarrow e\nu$ event every 10 seconds.
- One $Z \rightarrow e^+e^-$ and $Z \rightarrow \mu^+\mu^-$ per minute.
- One top pair every two minutes.
- If LHC runs for about "three full months" at this Luminosity we will have about 100pb^{-1} of data.
- Order 2 Million $W \rightarrow e\nu$ and $W \rightarrow \mu\nu$ events
- Order 200 000 $Z \rightarrow e^+e^-$ and $Z \rightarrow \mu^+\mu^-$ events
- Order 83 000 Top Pair events
- These events will provide a wealth of information for the LHC detectors.
- We will here focus on the ubiquity of the Top Quark events for the LHC experiments.

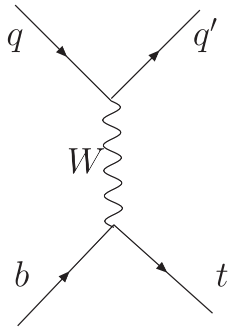
Top Production at LHC

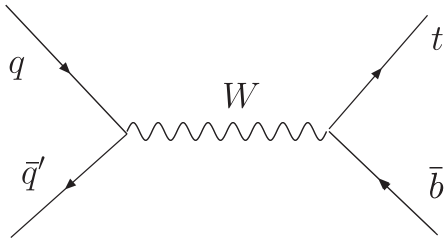
- Proceeds mostly via gluon scattering (85%) and $q\bar{q} \longrightarrow \bar{t}t$ (15%).

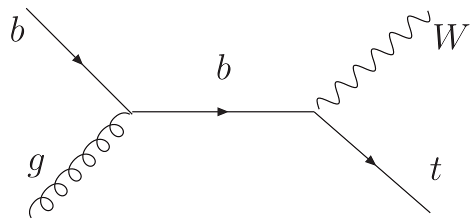




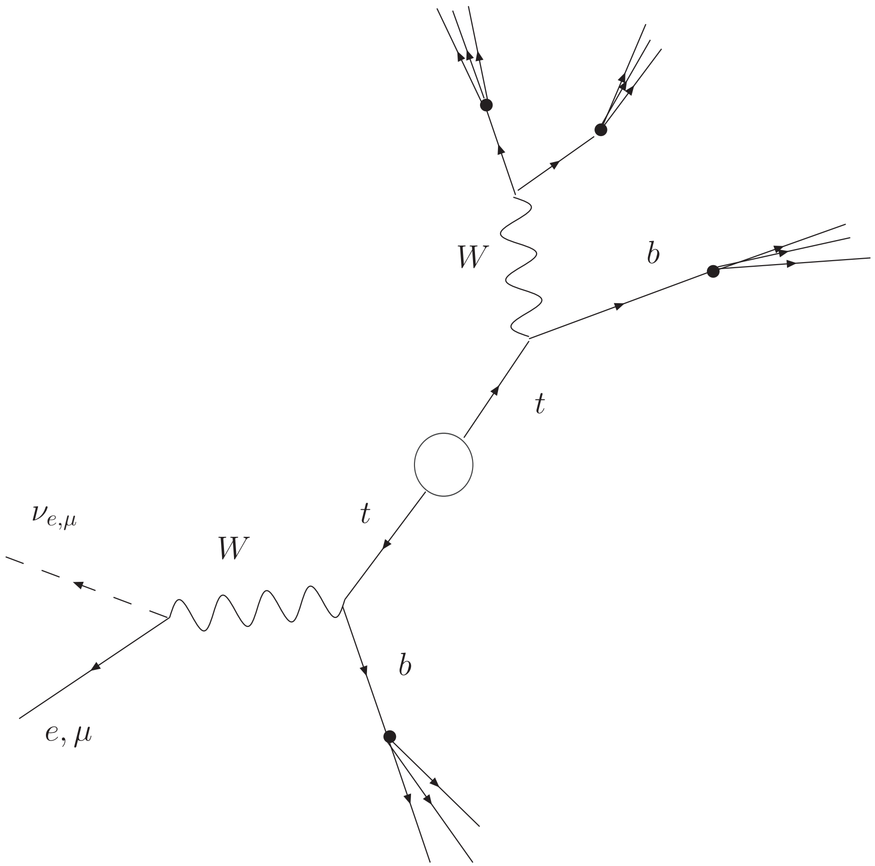
- Also single top production via electroweak processes. About 0.3nb







Top Pair Decays



- 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

- Top Pair events always contain two b-quarks and two W-boson intermediate states.
- The b-quarks hadronize into B-hadrons forming b-jets
- Each W-boson decays either leptonically ($Br(W \to l\nu) \approx 3/9 = 1/3$) or hadronically ($Br(W \to ud) = Br(W \to cs) \approx 3/9$)
- There are thus three types of top pair decays:
- All hadronic - no leptons in final state, $Br \approx (3/9 + 3/9)^2 = 4/9$.
- Semileptonic - one lepton in final state. $Br \approx 2 \times 3/9 \times (3/9 + 3/9) = 4/9$.
- Dileptonic, $Br = (3/9)^2 = 1/9$

Recognizing Top Events

Recognizing Top Events at the LHC requires a good performance from all of the major components of the ATLAS and CMS detectors:

1. Electrons reconstructed by matching tracks to EM Calorimeter deposits
2. Muons reconstructed by matching tracks to Muon chamber hits
3. Light quarks reconstructed as "Jets of energy" in the Hadronic Calorimeter"
4. b-quarks reconstructed as Jets with displaced vertex
5. Neutrinos reconstructed as Missing Transverse Energy

No Top Quarks, No Nothing!

- Recognizing Top Quark events requires succesfully measuring Jets, Leptons and Missing Energy
- If Top Quarks are not seen in ATLAS or CMS (as we will see even with 10 pb^{-1}), then there will most likely be major problem(s) with the measurement of Jets and/or Leptons and/or Missing Energy.
- This might be calorimetry, tracking, triggering, reconstruction ...or combinations thereof.
- Most new physics scenarios require precise measurements of Jets, Leptons and Missing Energy
- Recognizing Top Quarks at the LHC with be a major milestone
- No new physics discovery will be taken seriously until tops are recognized
- Top measurements are a major step towards new physics

- We must be prepared to see top quarks as soon as possible at the LHC
- Will describe a simple, "quick" method which can be done with early data
- Marina will then describe this in much more detail tomorrow
- Once the existence of top quarks in Europe is established, one can go on to measure their properties
- Will outline the mass measurement and some connections to new physics.

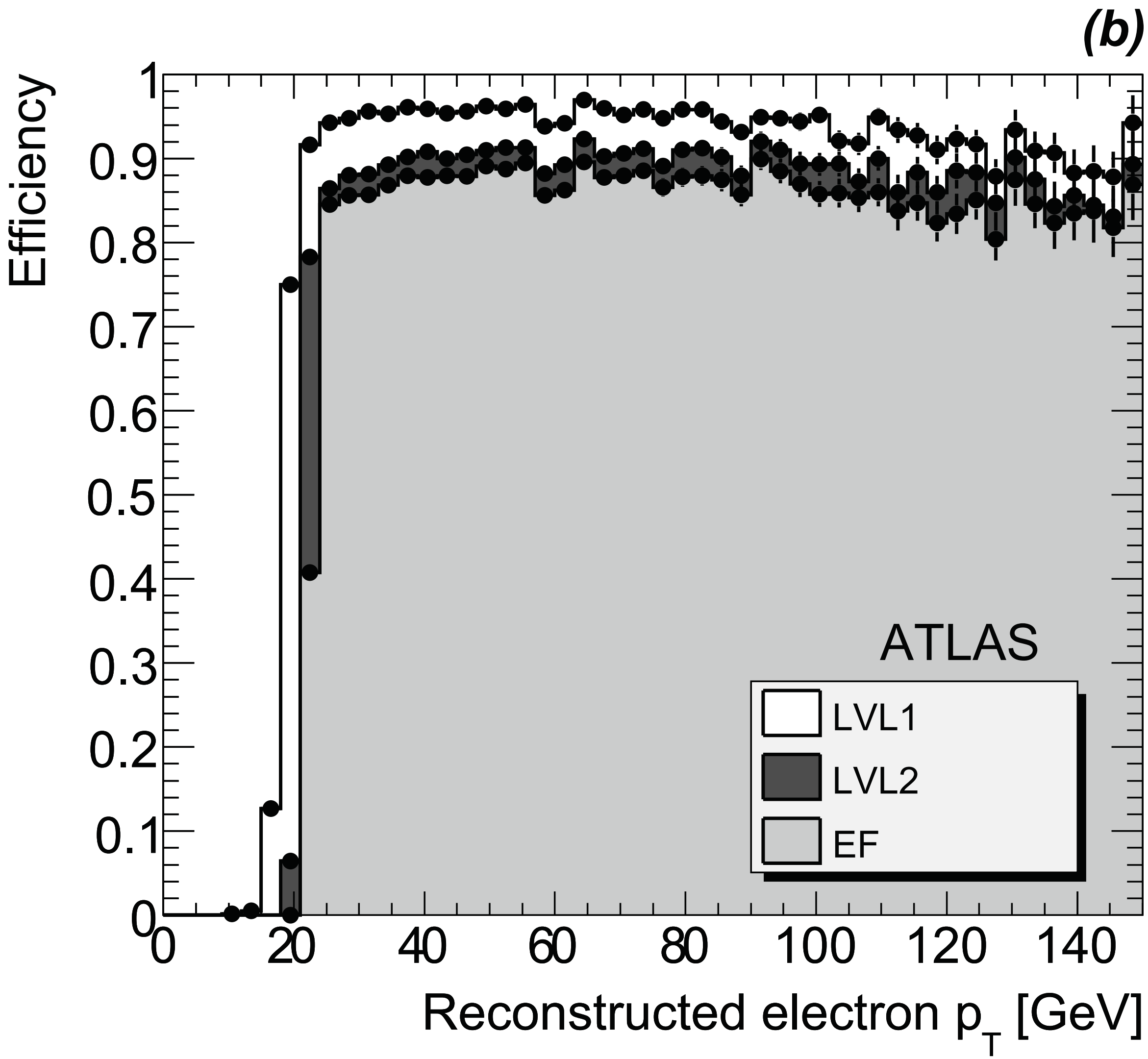
Which Channel?

- The All Hadronic Channel is "all jets" $\rightarrow$ huge combinatorial and QCD backgrounds. Initially, very difficult.
- The Dileptonic Channel is very CLEAN $\rightarrow$ two isolated, high p_T leptons and missing E_T. But, two neutrinos $\rightarrow$ top reconstruction difficult. Probably first x-section measurement here.
- The Semileptonic Channel $\rightarrow$ most studied in the early phase of the LHC $\rightarrow$ backgrounds suppressed by single isolated high p_T lepton plus missing energy plus four high p_T jets; both tops can be reconstructed.

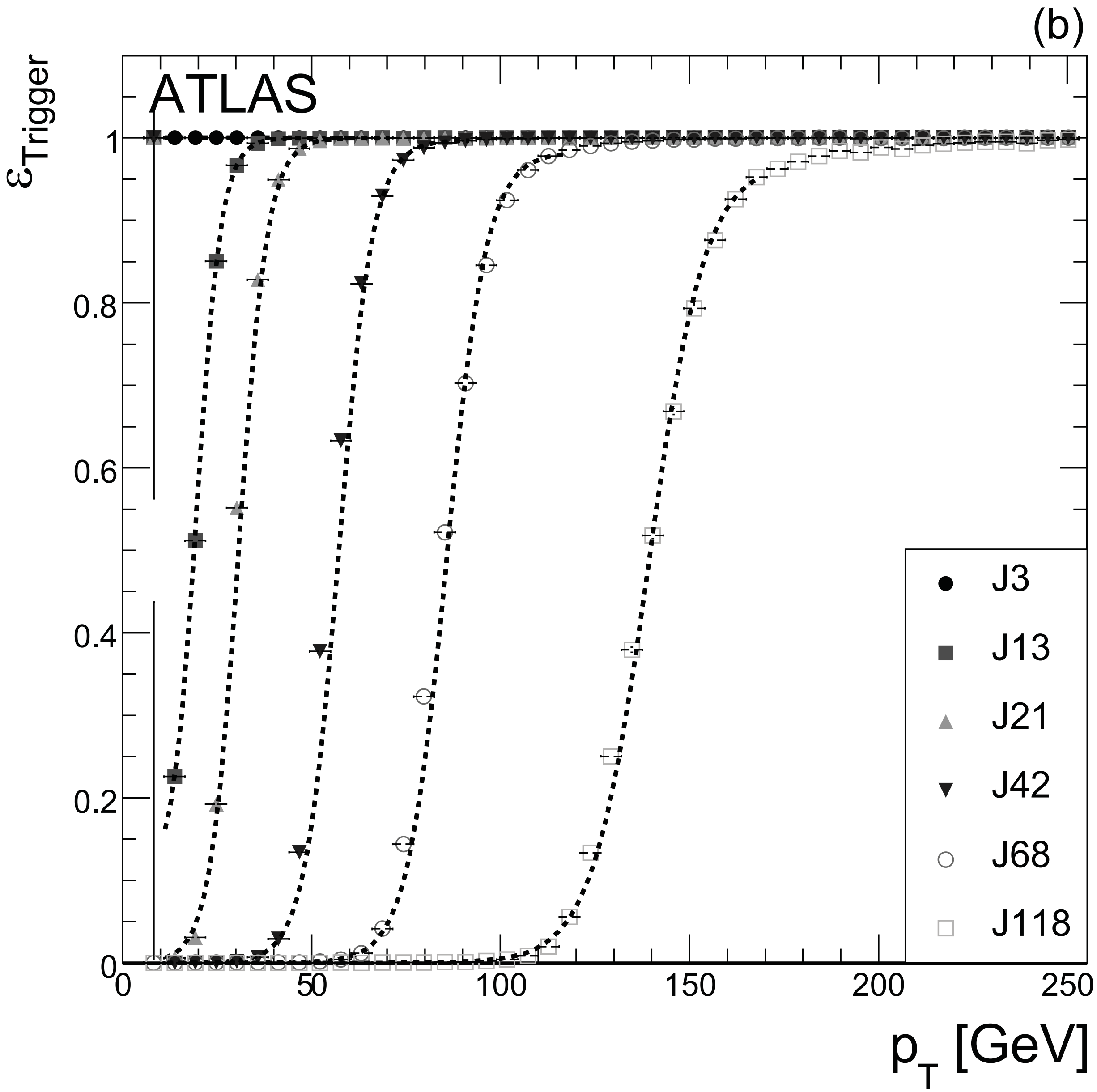
Top timeline

- First evidence for top quarks with 10pb^{-1}.
- Cross-section measurement with 100pb^{-1}
- First mass measurement with 100pb^{-1}; with 1fb^{-1} will have GeV precision
- Beyond 1fb^{-1} will study new physics eg FCNC top decays, $t\bar{t}$ resonances etc

Triggering on Tops: Electron Triggers



Triggering on Tops: Jet Triggers



Triggering on Tops

Can determine Top Trigger efficiencies from data:

- Use tag and probe
- Consider all events passing a four jet plus E_T-miss trigger
- Ask how many of these also pass a high p_T, isolated lepton trigger?
- Though this also includes eg $W + jet$ backgrounds, their trigger efficiency is similar to that of tops.
- Reverse the role of the triggers to determine the jet trigger efficiency.

Recognizing Tops in the Semileptonic Channel

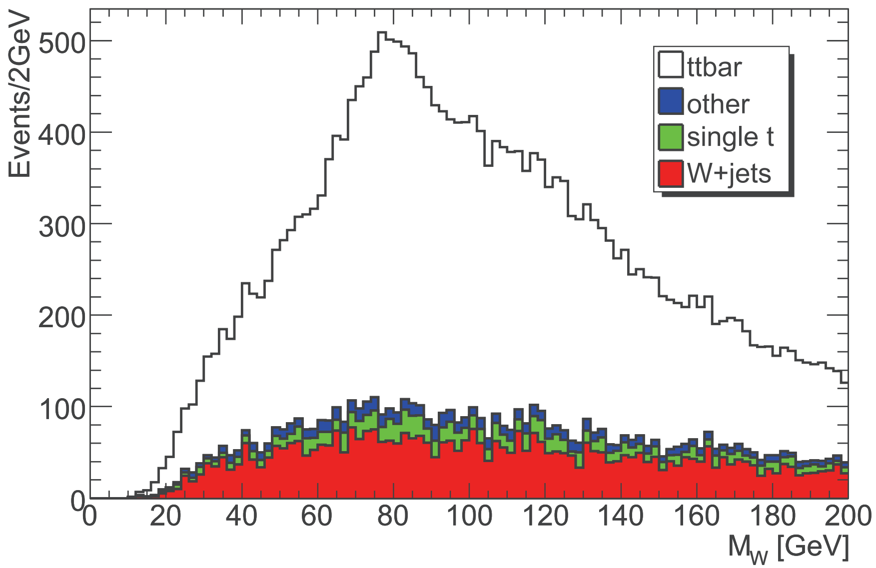
- Initially focus on electronic and muonic top decays. (Taus more difficult)
- Successful b-tagging requires a very well aligned detector, which may not be feasible at the LHC startup. So, initially, consider analyses without b-tags
- For measuring the top mass precisely, b-tagging will be necessary.

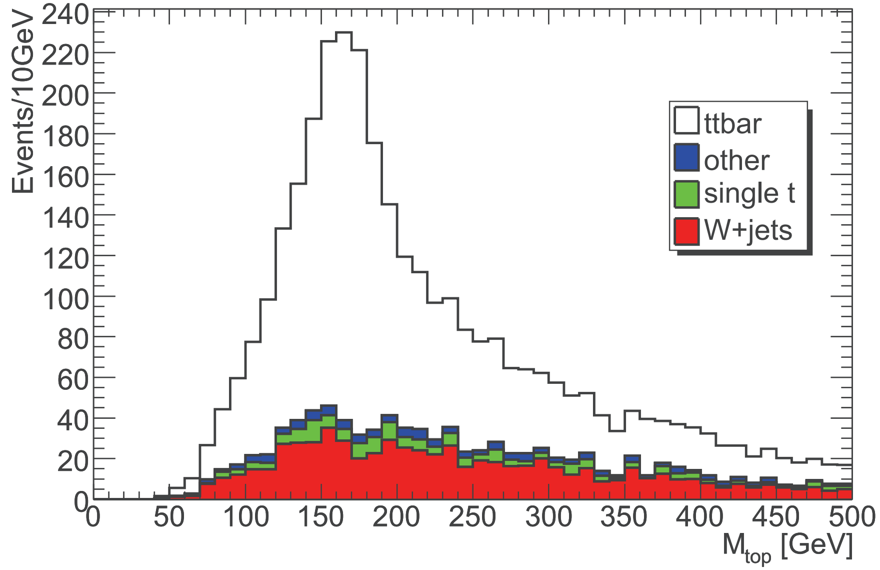
Basic Top Pair Event Selection

- Require event to pass triggers L1_EM20I, L2_e25i, EF_e25i or equivalent muon triggers mu20.
- A single isolated lepton (electron or muon) with $p_T > 20$GeV.
- Require at least four jets with $P_T > 20$GeV, and 3 jets with $p_T > 40$GeV.
- Missing $E_T > 20$GeV.
- Object definitions:
  1. Electrons identified by inner tracker 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.

Recognizing 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.





- Can clearly see the Top Peak even with 10pb^{-1}.

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. Multijet QCD $\to$ fake leptons and Missing E_T
  5. diboson WW, WZ, ZZ
- Data driven methods required to compute the W and QCD multijet backgrounds
- Multijet QCD has a large cross-section and tiny efficiency - very difficult to simulate .

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 100pb^{-1}.

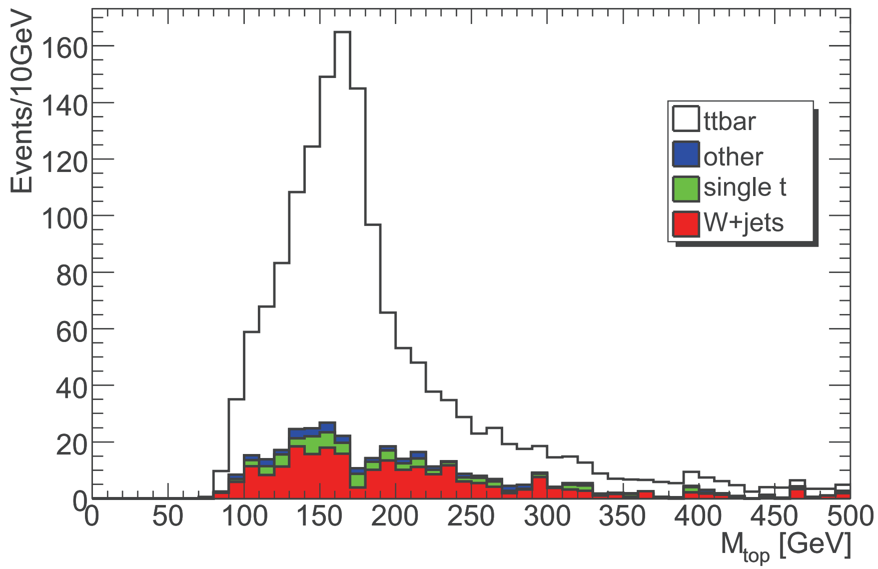
Efficiencies

	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.

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.

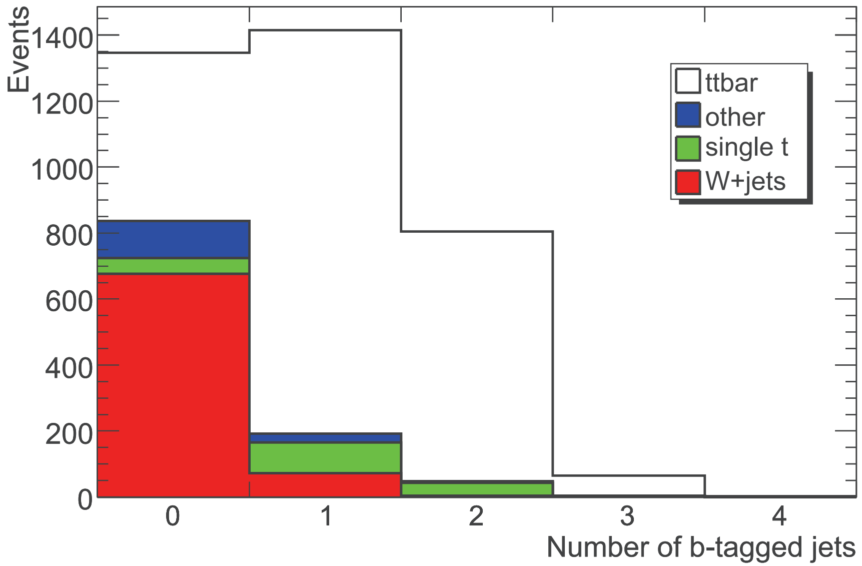


Additional Cuts

- 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.

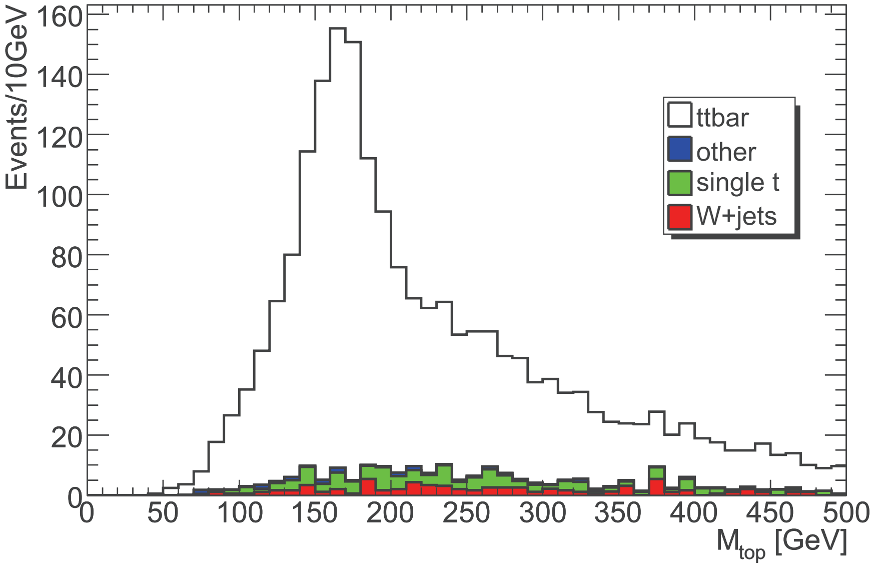
Including b-tagging

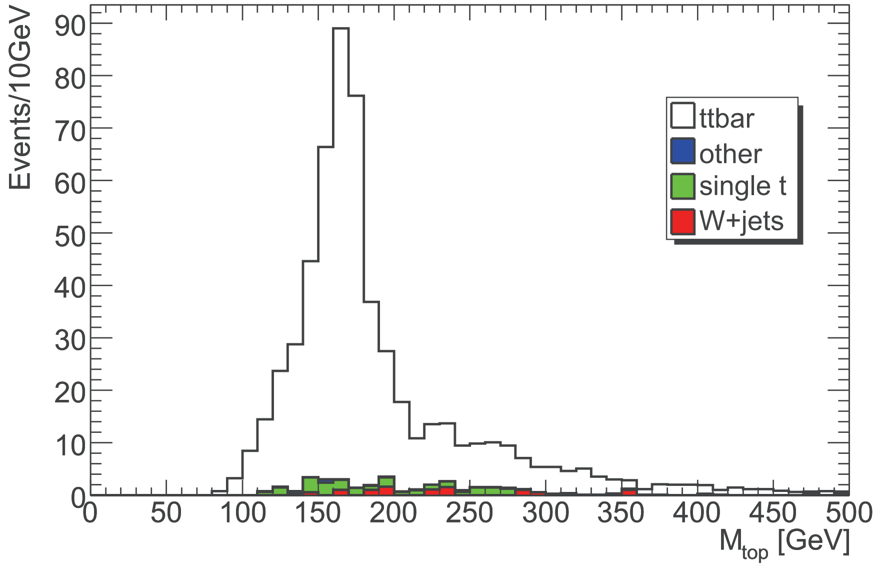
- Every event has two b-quarks $\Longrightarrow$ there are a few options. No b-tags, 1 or 2 b-tags, 2 b-tags.
- Number of b-tagged jets in events:



- 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.

Effects of New Physics

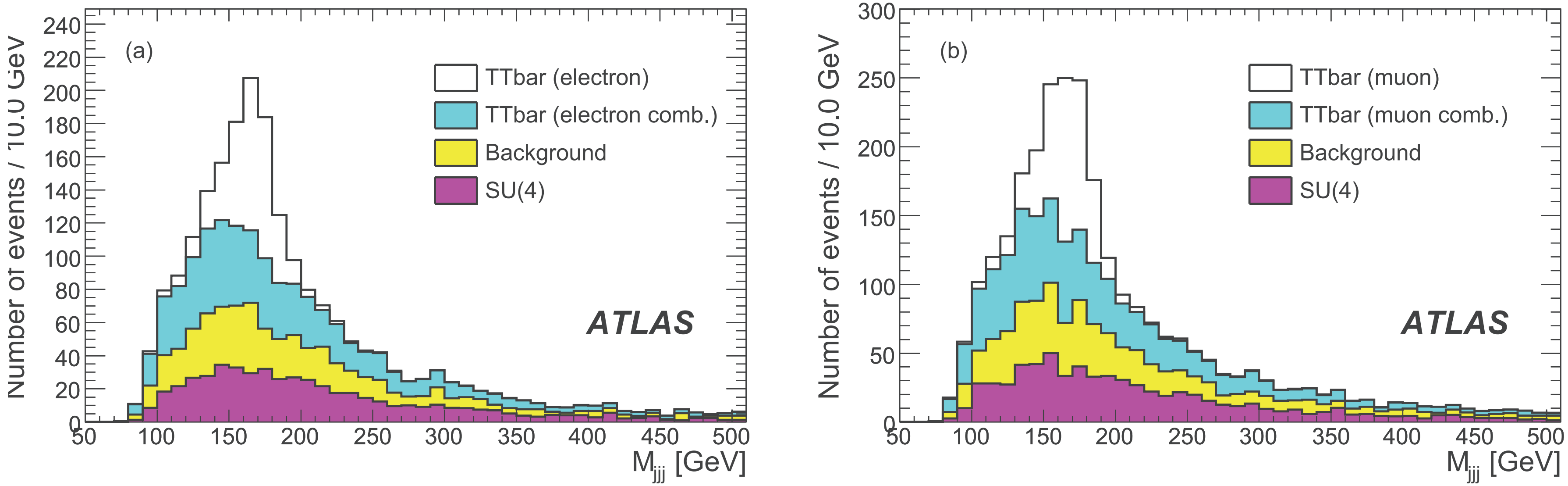
- Various possibilities for physics beyond the Standard Model.
- Supersymmetry, Large Extra Dimensions, heavy resonances, Technicolour..
- Often a lot of top activity, since new physics related to the hierarchy problem (top squark in SUSY, KK resonance in LED and Randall-Sundrum).
- Cross sections expected to be small - of the order of few picobarns.
- Can have a few 100pb 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 also a heavy resonance Z' coupled to $t\bar{t}$.
- Efficiencies usually quite high, since very high p_T involved.
- For the Z', efficiency $\approx 2\times$ 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			**Muon analysis** Trigger+Selection		
		W const.	m_t win		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 SUSY model, $(\sigma \approx 270pb)$
- The shape in the top quark candidate mass plot is very similar for SU4 and Standard Model backgrounds.

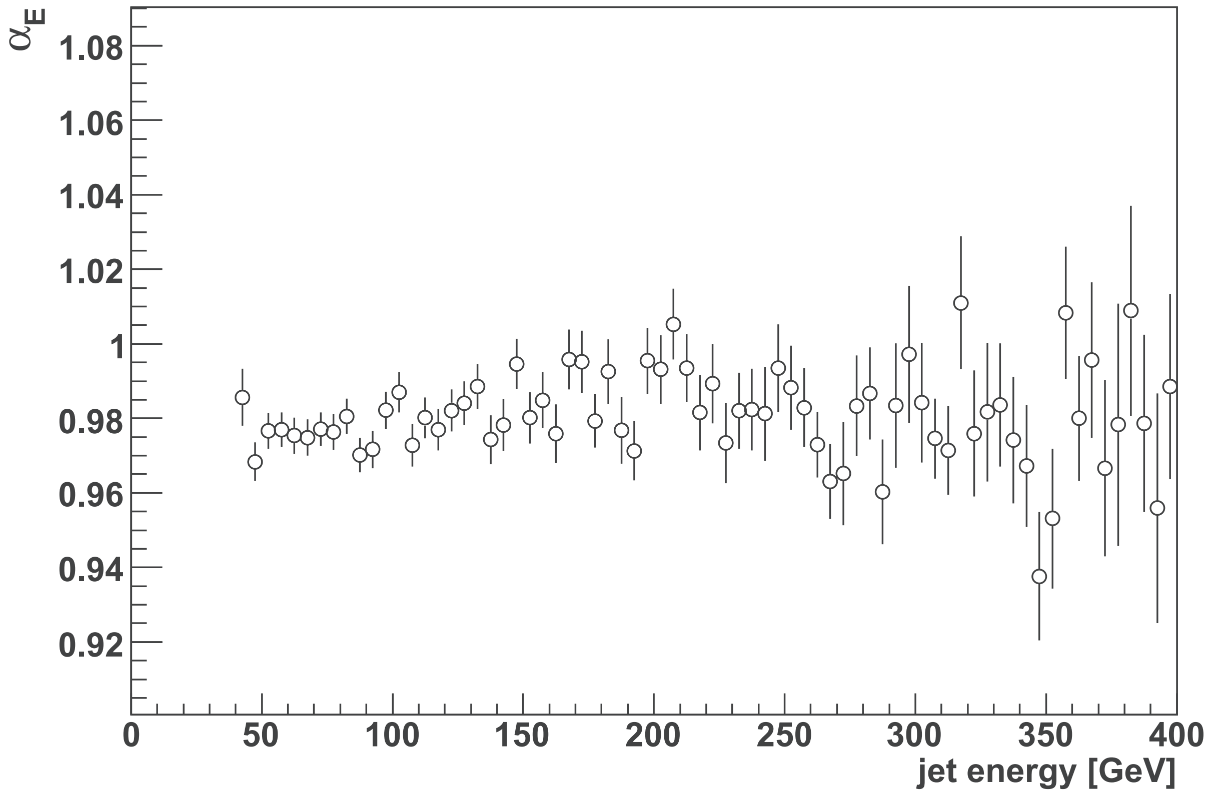
Calibrating the Light Jet Energy Scale Using Tops. Towards a Mass Measurement

- Again semileptonic channel, with same cuts as before, except all jets 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 the following χ^2:

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

  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.
- Resolution $\sigma_i^2 \sim E\times\text{GeV} + 0.005E^2$

Calibrating Light JES using Tops



- So, top events can be used as an independent calibration of the Light JES (cf Z+jets etc)

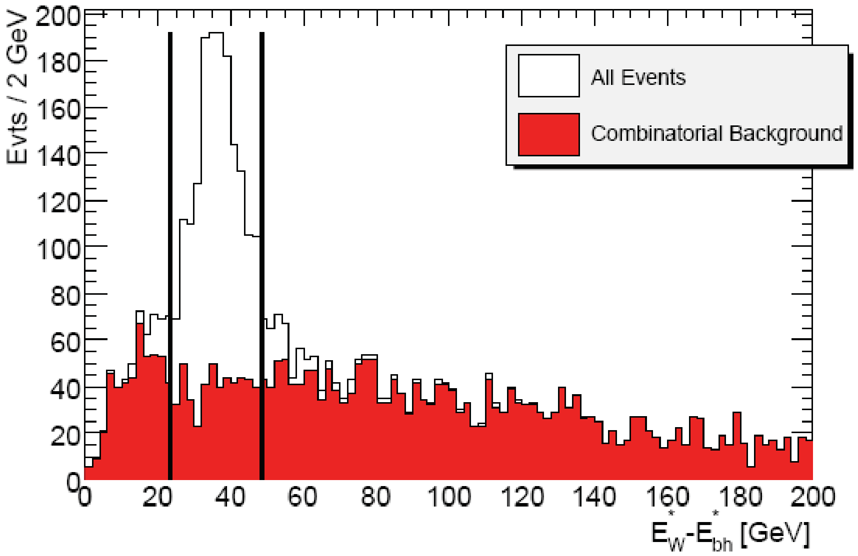
Top Mass

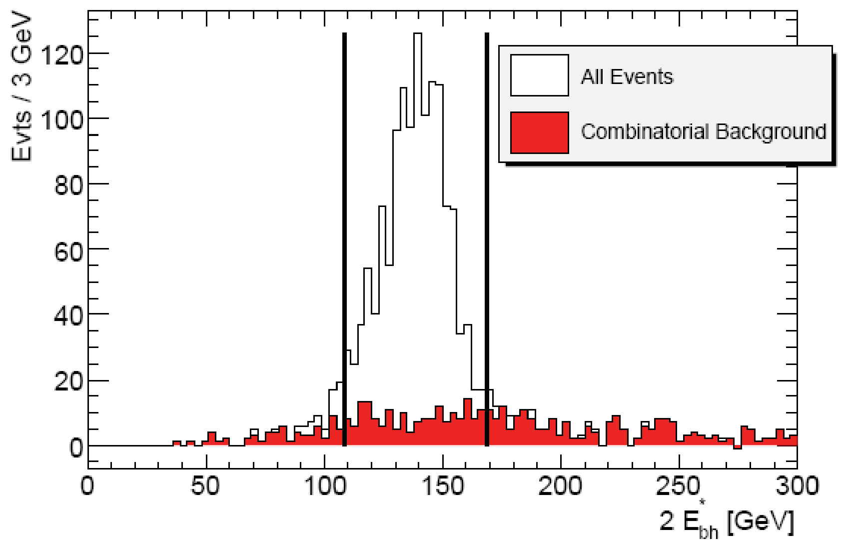
- Impose further cuts to improve S/B ratio. Variables defined in hadronic top rest frame:

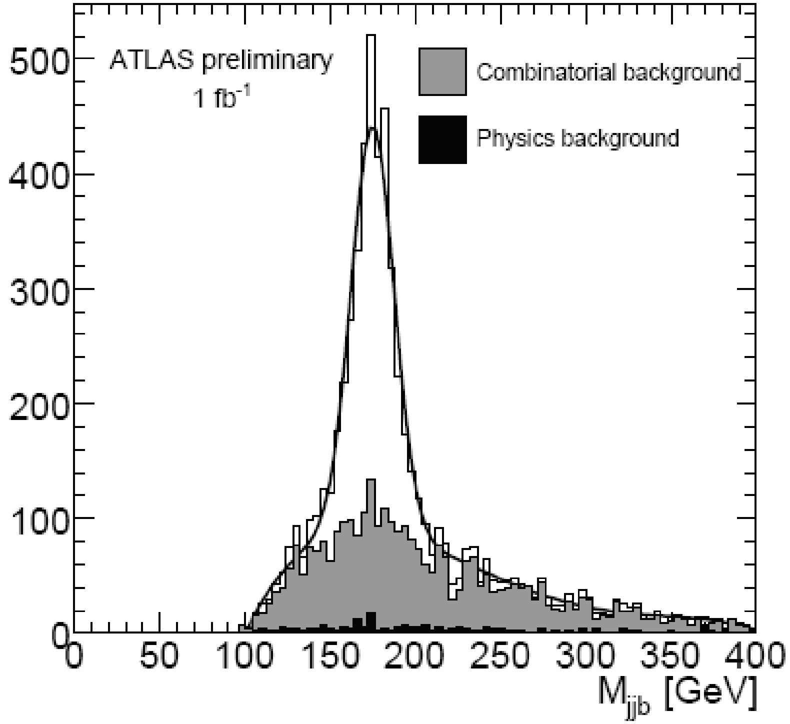
$$X_1 = E_W^* - E_b^* = E_{j1}^* + E_{j2}^* - E_b^* = \frac{M_W^2 - M_b^2}{M_{top}},$$

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

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







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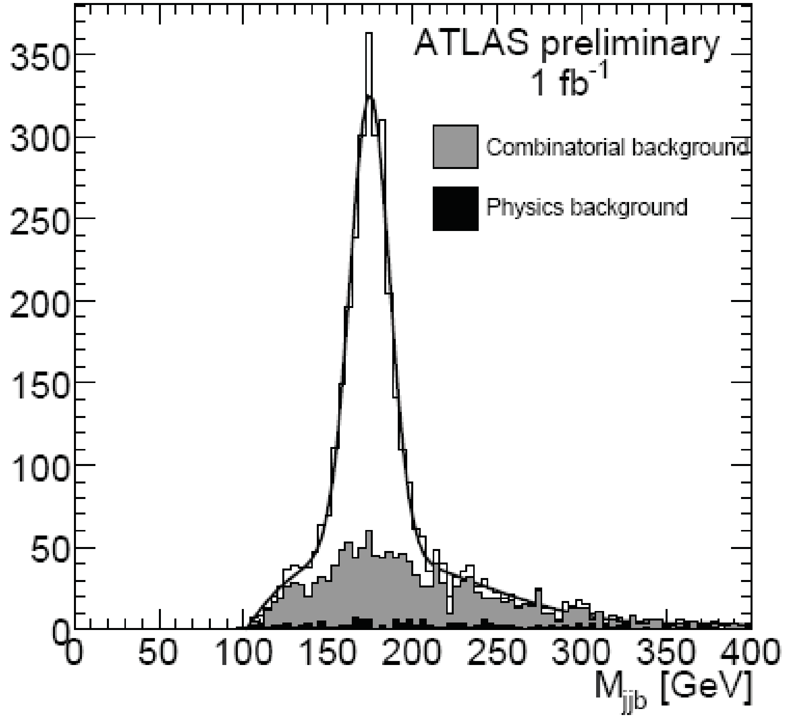


- $m_{top} = 175.0 \pm 0.2$GeV (left), $m_{top} = 174.8 \pm 0.3$GeV (right).
- Statistical error shown. Systematics overleaf.

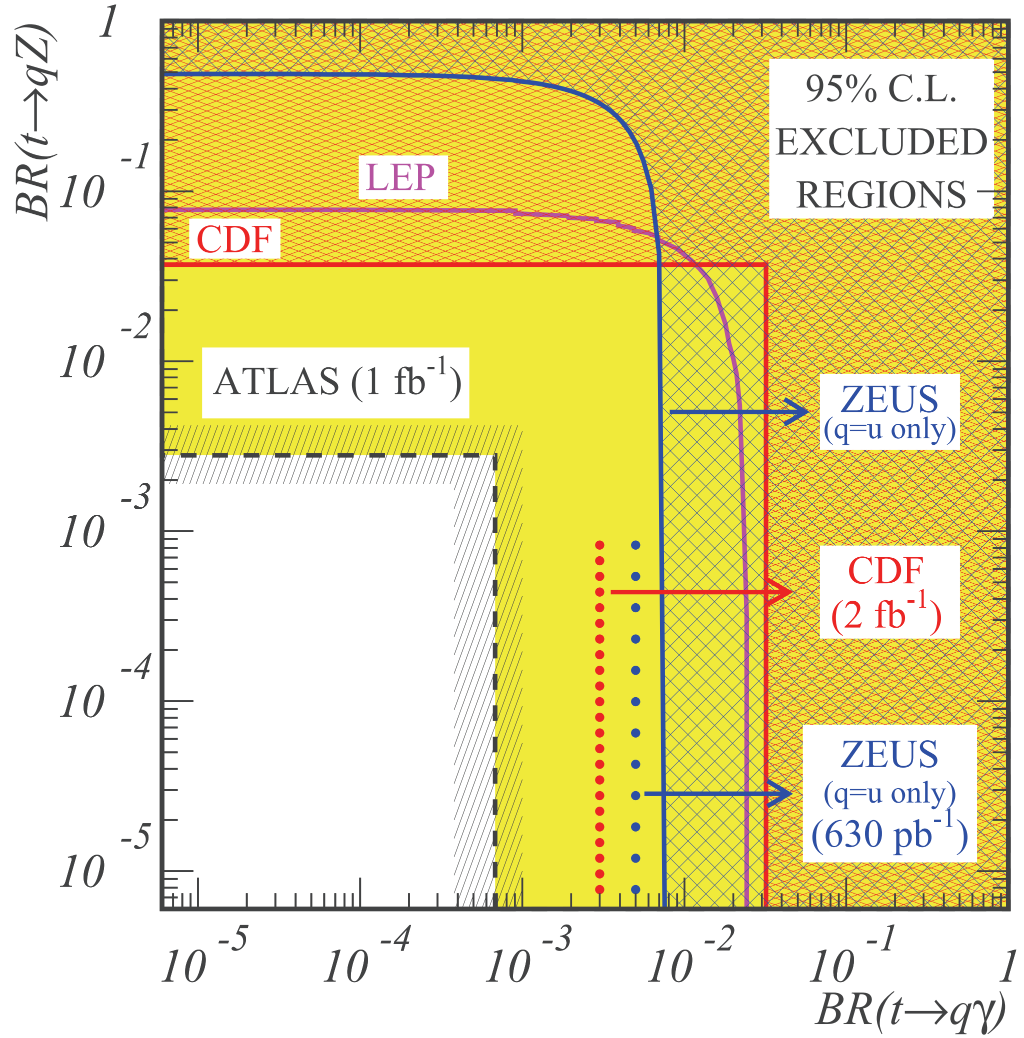
Systematic uncertainty	χ^2 minimisation method
Light jet scale	0.2GeV/%
b-jet energy scale	0.7GeV/%
ISR/FSR	0.3 GeV

- 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.
- So a 5% uncertainty on both Jet scales gives a 4.5 GeV uncertainty in the top mass.

New Physics With Tops

- There are many new physics studies that can be done involving Top Quarks
- Eg recall Fabio's talk tt-invariant mass, V_{tb}.
- Here we will briefly mention Neutral Flavour Changing Top Decays and Multi Top Quark events
- FCNC Top Decays eg $t \to cZ$ predicted in many models of BSM physics.
- About 10^{-14} in Standard Model and 10^{-6} in MSSM.

FCNC Top Decays



Multi Top Events and More

- Consider a supersymmetry model in which gluinos are lighter than squarks and in which a stop squark is the lightest squark.
- Then the gluino decays are dominated by $\tilde{g} \rightarrow \tilde{t}t \rightarrow tt\chi_0$
- So gluino pair production leads to events with "Four Tops plus Missing E_T" !
- Rather challenging to study this, since the four tops lead to a 12 fermion final state $\rightarrow$ a combinatorial nightmare!
- Such events are not just restricted to SUSY, but arise in all models with "Top Partners" eg Little Higgs, Warped Extra Dimensions.
- Some of this was discussed in other lectures.

Summary

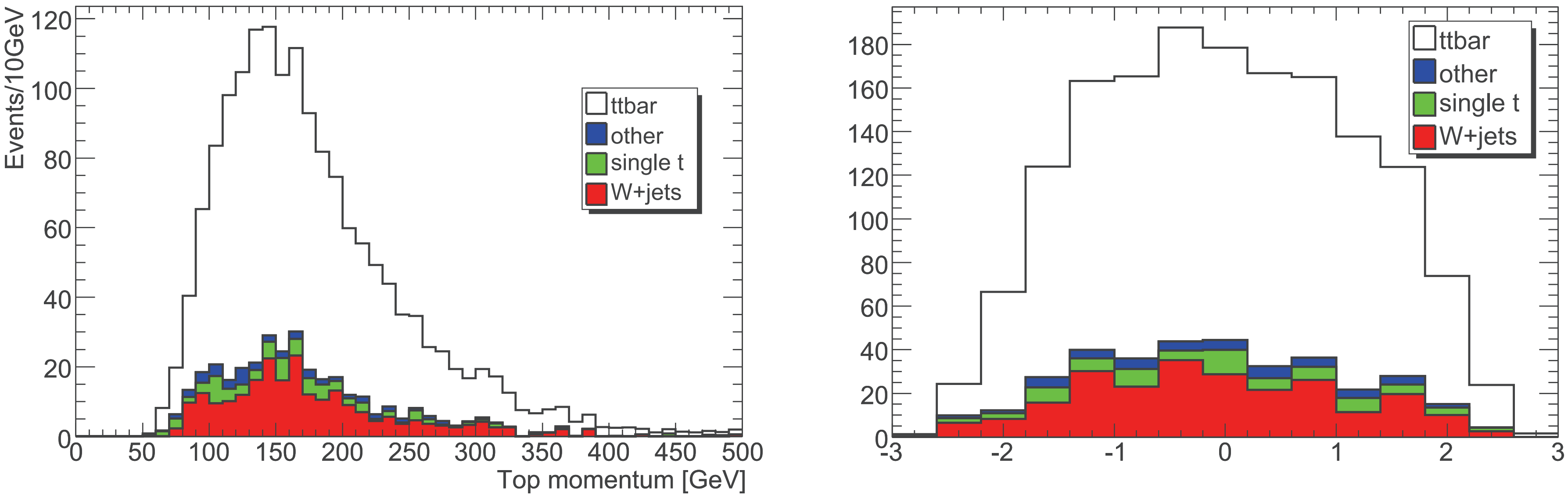
- The Importance of Recognizing Tops in the Early Data cannot be over-emphasised
- Can be done with as little as 10pb^{-1}.
- Can determine $t\bar{t}$ production cross-section in the early stages of LHC running, with 100pb^{-1} of data.
- We can also determine the top mass, with the error down to 1GeV with 1fb^{-1}.
- The main source of error is systematical, in particular the JES.
- More work needed on understanding backgrounds, especially fake leptons and Missing E_T in QCD, as well as measuring the JES (in particular b-jet scale).
- Once we have a good understanding of Tops at the LHC we can use them to study a variety of new physics possibilities.

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.

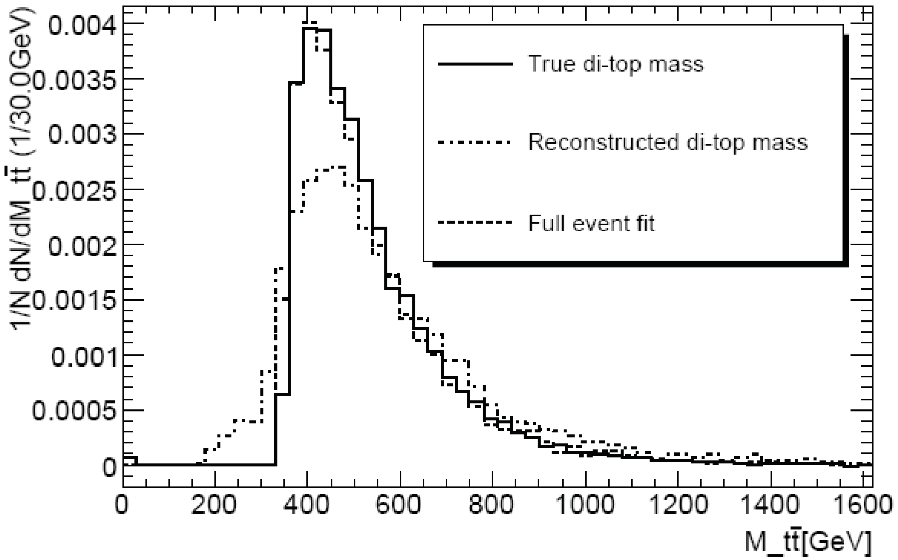
Differential Cross-Sections

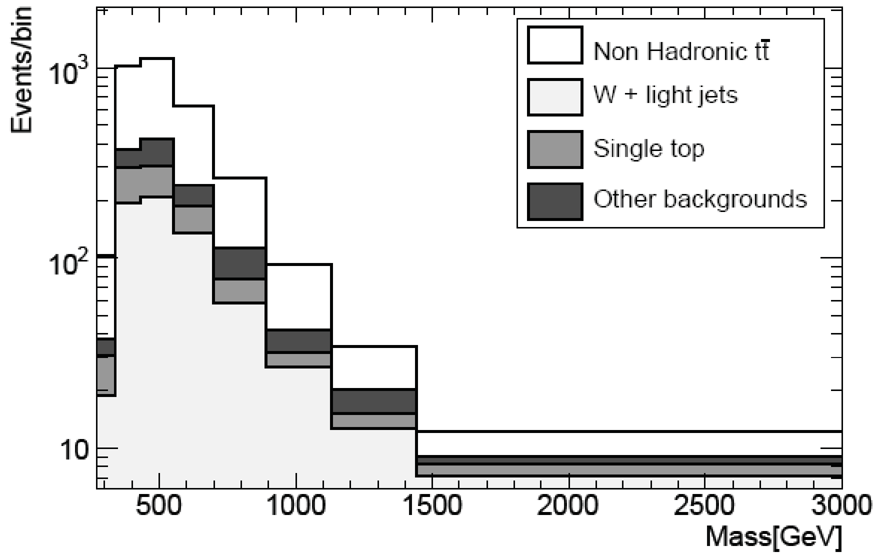
- Top momentum and rapidity distributions.



- 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 $\rightarrow$ 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.





$d\sigma/dydp_T$

- 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.
-