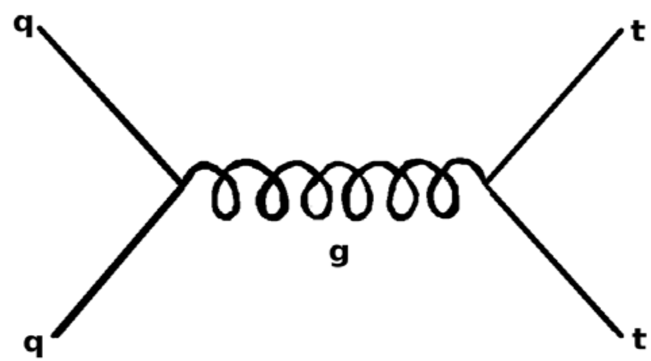
Measuring the Top Quark Pair Production Cross Section



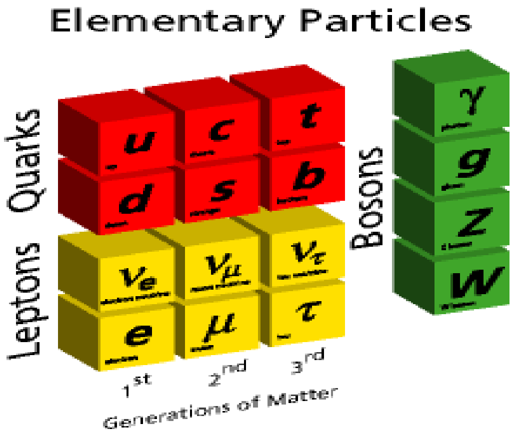
Andrea Bangert, Max Planck Institute of Physics, June 3rd 2008

CSC Note: “Determination of Top Pair Production Cross Section in ATLAS”, May 15th, 2008

Overview

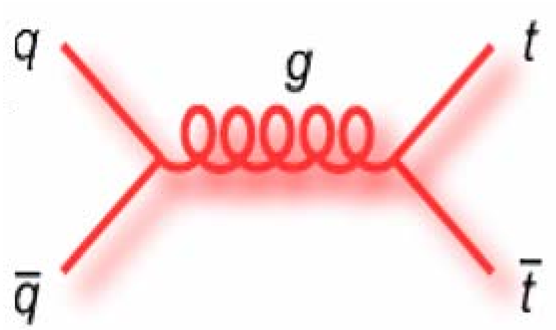
- The Standard Model top quark
- Why measure the cross section?
- Top quark pair production
- Top-antitop decay
  - The single lepton trigger
  - b-tagging
- Hadronic decay: tt → jjb jjb
- Semileptonic decay: tt → lvb jjb
  - Backgrounds
  - Counting experiment
  - Jet multiplicity
- Dileptonic decay: tt → lvb lvb
- Summary and Conclusion

Standard Model Top Quark

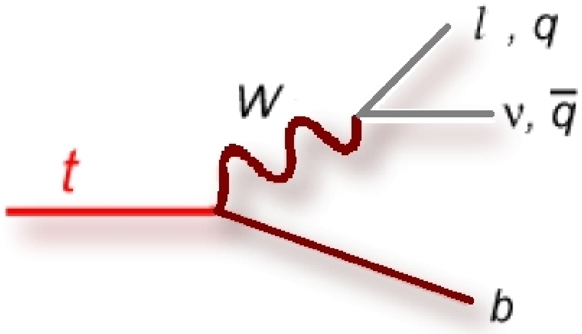


- Discovered at Tevatron in 1995
- Completed 3rd generation of fermions

- Extremely massive:
  - m_t = 172.6 ± 1.4 GeV
  - $m_t \approx$ 185 u
  - $m_{Ag} < m_t < m_{Au}$

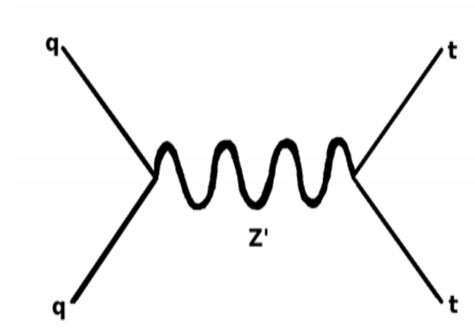


- Top-antitop pairs produced via strong interaction
- Top decays via weak interaction, t → W b



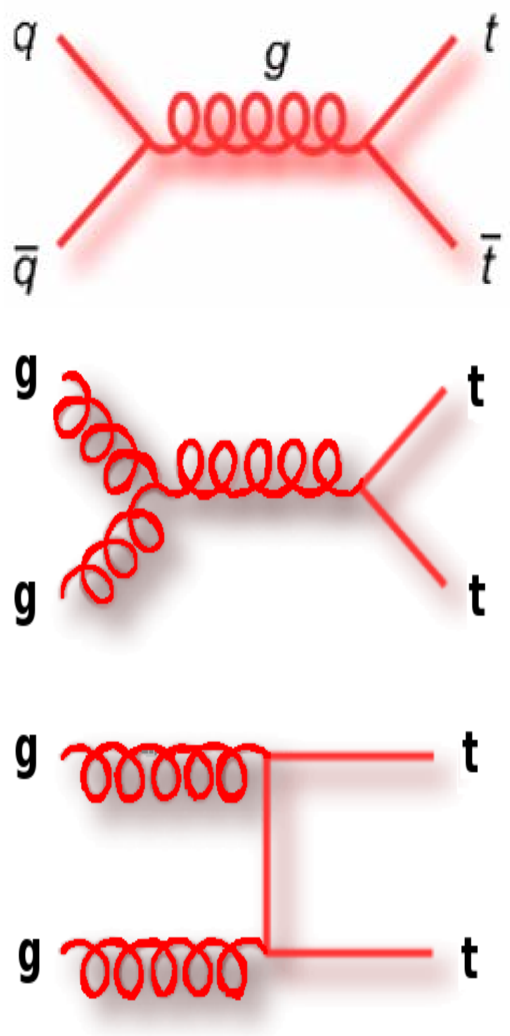
Why is the cross section interesting?

- Measurement of cross section provides a test of perturbative QCD.
  - Non SM physics could increase the cross section significantly.
  - Non SM physics could affect the branching ratios for the various top decay channels. ($t \rightarrow H^+ b$)



- Top production is a “standard candle”.
  - Measurements involving known top properties will allow us to calibrate the ATLAS detector.
- Top pair production will be a significant background for other measurements.

Top Quark Pair Production



- Mediated by strong interaction
- Rate of pair production is proportional to cross section and luminosity:

$$ {}^{dN}/_{dt} = \sigma L $$

  - LHC design luminosity is

$$ \mathbf{L = 10^{34}\ cm^{-2}\ s^{-1}} $$

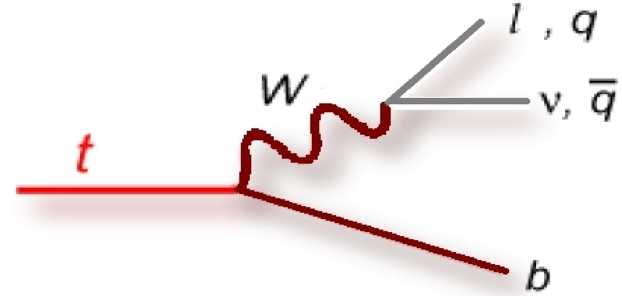
  - Theoretical cross section is

$$ \boldsymbol{\sigma_{tt} = 833 \pm 100\ pb} $$

- 8 top–antitop pairs per second
- 2.5 million pairs per week
- 70 million pairs per year

Top Quark Decay

- **Top decay:** $t \rightarrow W\, b$



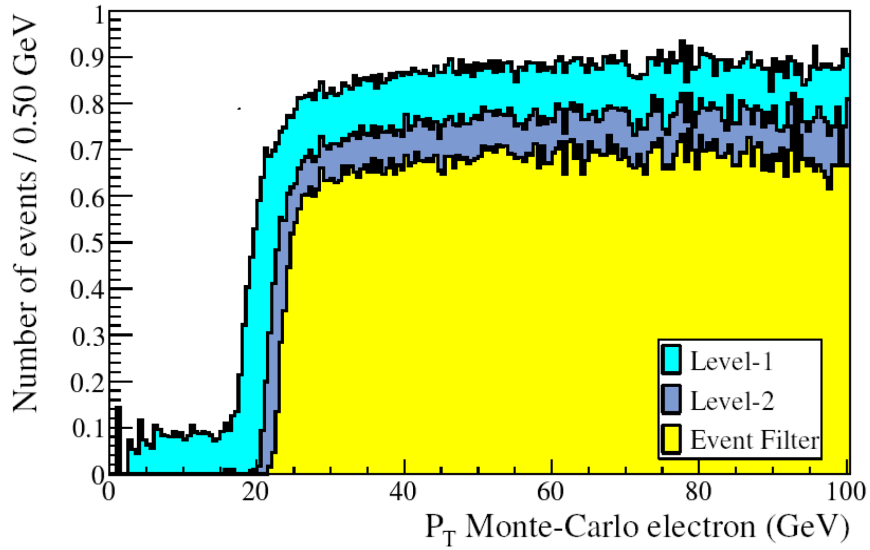
- **W decay:**
  - $W \rightarrow l\, \nu$ $\Gamma \approx 1/3$
  - $W \rightarrow j\, j$ $\Gamma \approx 2/3$

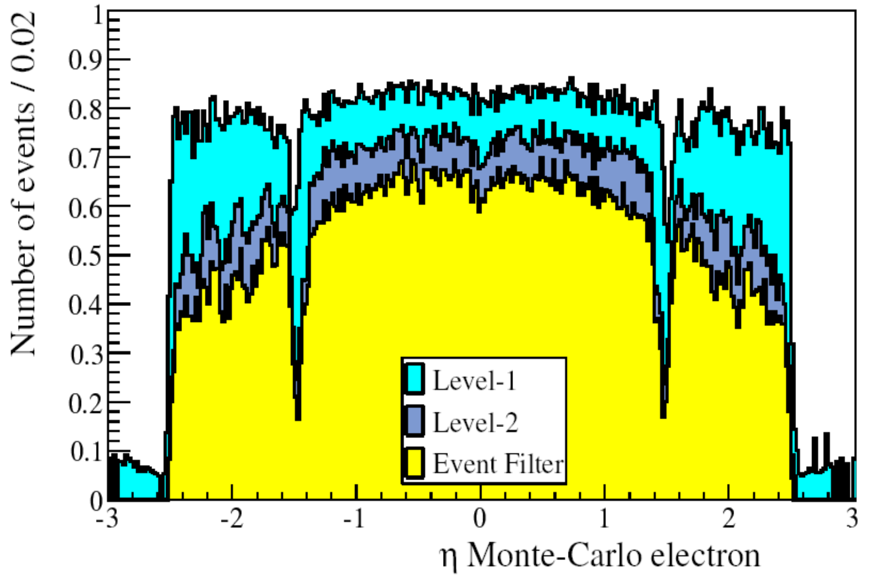
- **Top-antitop decays:**
  - "dileptonic" $tt \rightarrow W^+b\, W^-b \rightarrow (l^+ \nu_l\, b)\, (l^- \nu_l\, b)$ $\Gamma \approx 1/9$
  - "semileptonic" $tt \rightarrow Wb\quad Wb \rightarrow (l\, \nu_l\, b)\, (j\, j\, b)$ $\Gamma \approx 4/9$
  - "hadronic" $tt \rightarrow Wb\quad Wb \rightarrow (j\, j\, b)\, (j\, j\, b)$ $\Gamma \approx 4/9$

- **Decay products:**
  - Leptons, neutrinos (MET), b jets, light quark jets.

- Cross section can be measured in dileptonic, semileptonic and hadronic decay channels.

Trigger Efficiency in tt→eνb jjb Events



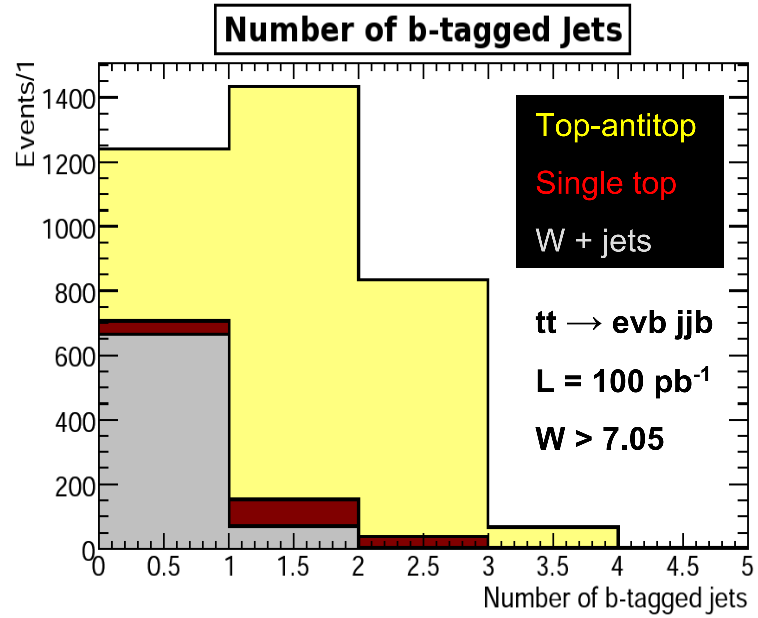


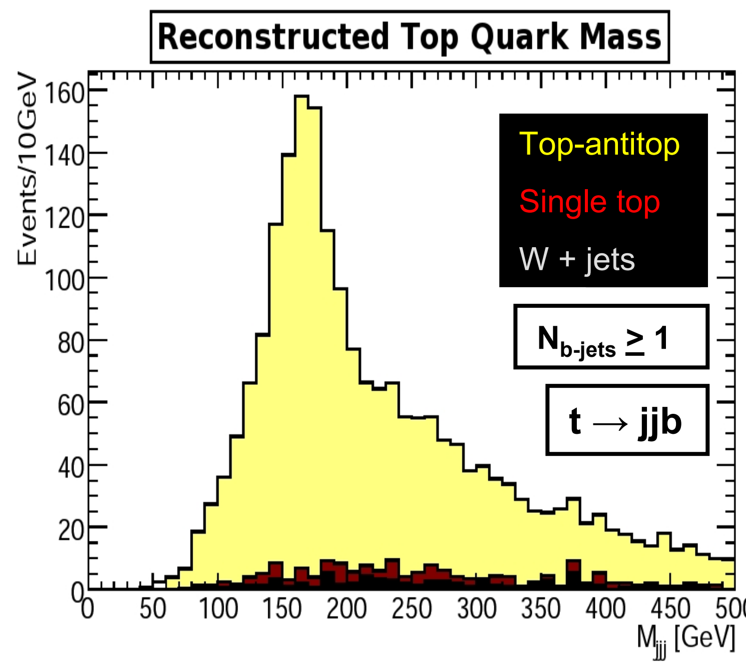
Trigger

- tt decays which produce a lepton allow the use of a **single lepton trigger**.
- **Electron trigger** "e25i"
  - Requires isolated electron with p_T > 25 GeV.
  - $\varepsilon_{trigger}$ = 52.9% in tt → eνb jjb
- **Muon trigger** "mu20"
  - Requires single isolated muon with p_T> 20 GeV
  - $\varepsilon_{trigger}$ = 59.9% in tt → μνb jjb
- Trigger efficiencies must be estimated from data.

b-tagging

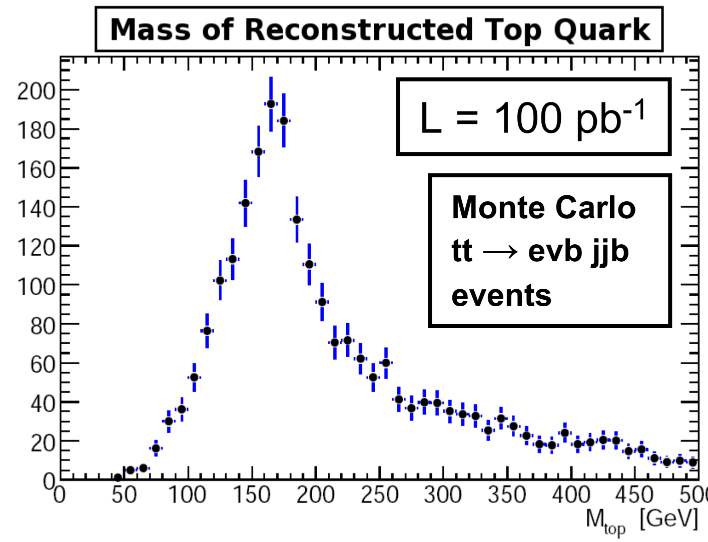
- **Purpose**
  - Identification of heavy flavor jets (b)
  - Suppression of light flavor jets (u, d, s)
- **Importance**
  - Top quark events produce b quarks
  - Most W + jets, QCD multijet events produce only light quark jets
  - Use b-tagging to suppress significant sources of background
- **Caveat**
  - Requires precise alignment of inner detector
  - Several months of data-taking necessary
- **Interplay** between tt sample, b-tagging:
  - In a pure sample of tt events, every event contains two b jets
  - Use to test b-tagging performance

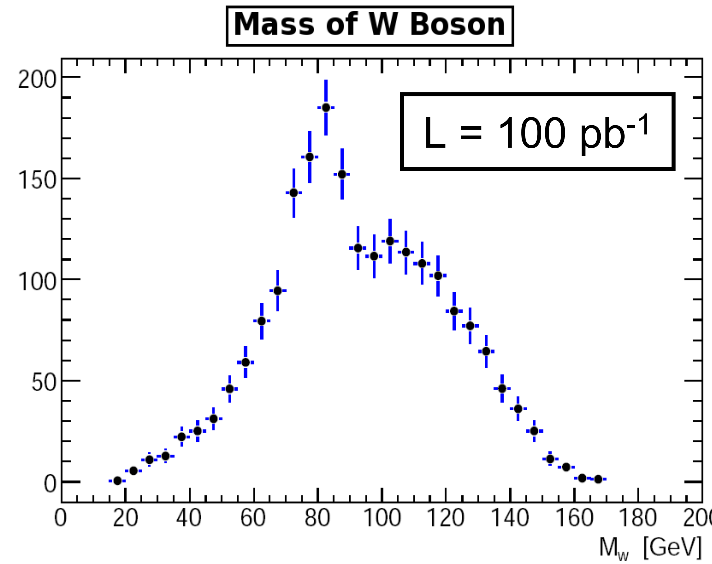




Semileptonic Decay

- **tt → Wb Wb → lνb jjb**
- **Selection:**
  - One lepton with p_T > 20 GeV
  - MET > 20 GeV
  - At least four jets
  - No b-tagging
- **Selection efficiency:** ε ≈ 20%
- **Reconstruct t → Wb → jjb**
  - Each event contains N jets
  - Create all possible trijet combinations
  - Choose combination with highest p_T to represent t → jjb
- **Reconstruct W → jj**
  - t → jjb contains three jets
  - Three dijet combinations are possible
  - Choose dijet combination with highest p_T to represent W → jj
- **Use selected tt sample to study b-tagging, MET, jet energy scale**

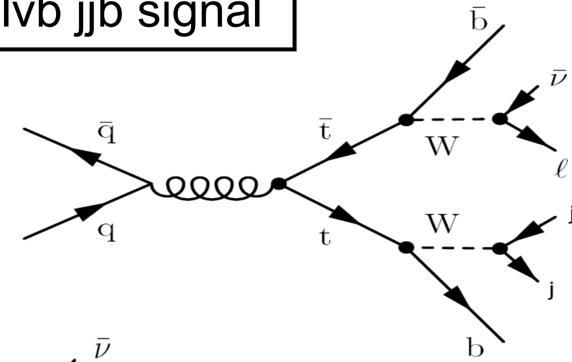


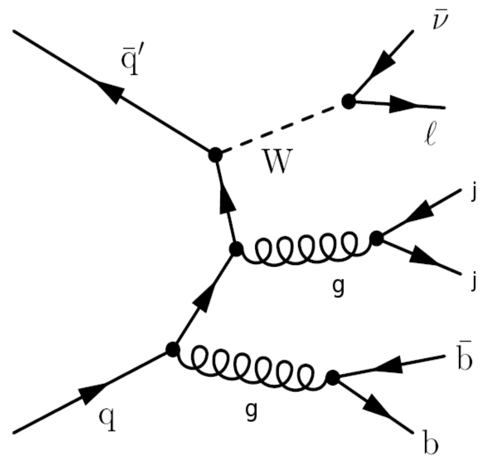


Backgrounds

- W + jets
- QCD multijets
- top pair production with dileptonic, hadronic decay
- single top quarks
- diboson production
- Drell-Yan Z → ll

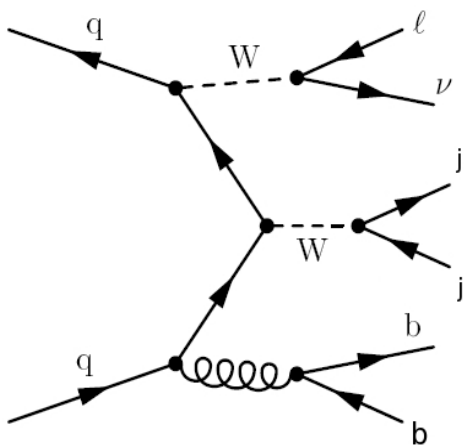
tt → lvb jjb signal





W + 4 jets

σ ≈ 100 pb

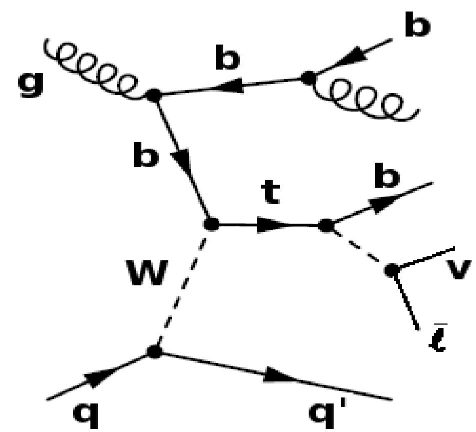


diboson production (WW)

σ ≈ 24 pb

single top production

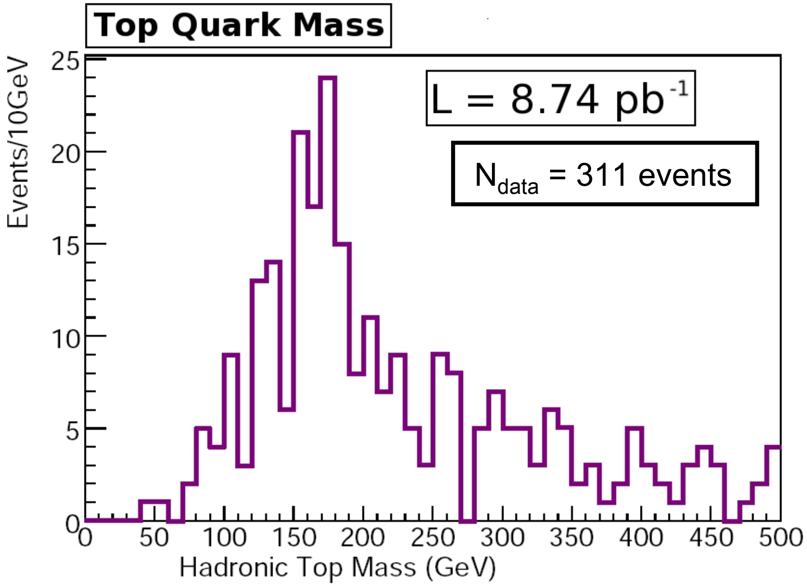
σ ≈ 250 pb



Counting Experiment

- Cross section "measurement" using streamtest "data"
  - $L = 18\ pb^{-1}$
  - Standard Model processes
  - Monte Carlo generated events
  - Full simulation of ATLAS detector
  - Simulation of triggers
  - Data reconstruction
- Test analysis in "realistic" setting

- $tt \rightarrow e\nu b\ jjb$
  - Apply selection cuts to "data"
  - Count number of (signal and background) events
  - Estimate number of background events
    - Using Monte Carlo samples
    - Using theoretical cross sections
  - Compute trigger and selection efficiencies



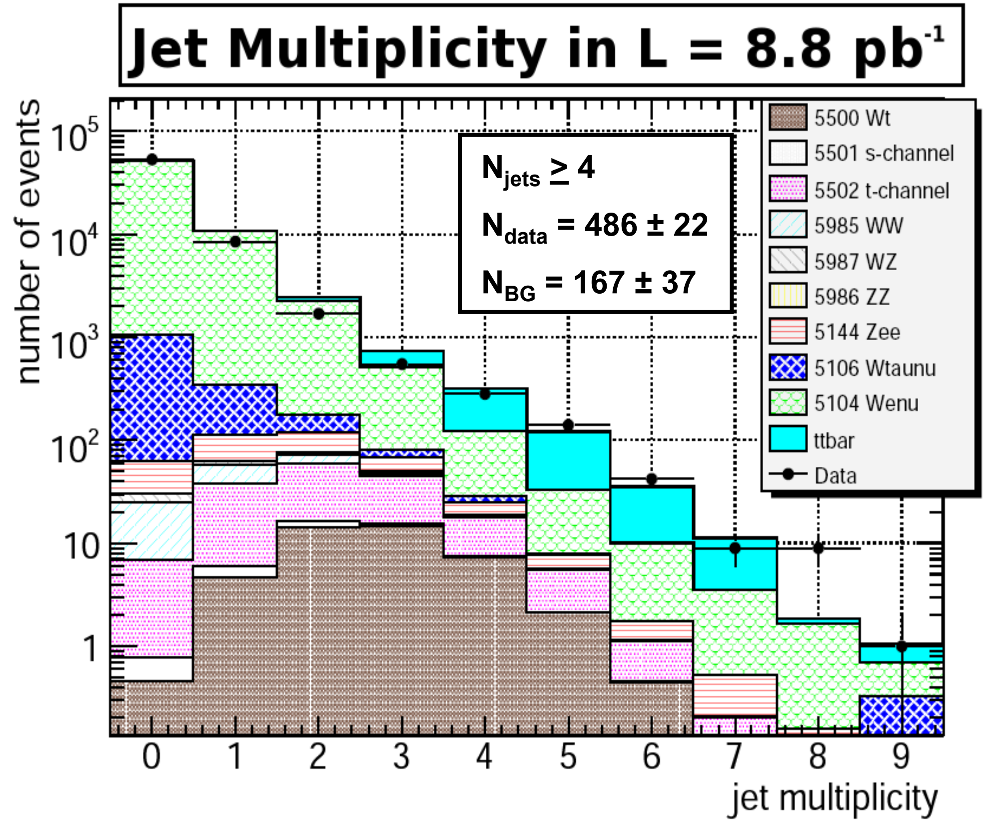
$$\sigma_{tt} = \frac{N_{data} - N_{BG}}{\Gamma_{tt} \cdot \epsilon_{tt} \cdot L}$$

- N_{data} = 311 events
- N_{BG} = 93 events
- Branching ratio $\Gamma = 5/9$
- Luminosity $L = 8.74\ pb^{-1}$
- Selection efficiency $\varepsilon_{tt} = 5.8\%$
- **$\sigma_{tt} = 771 \pm 133$ pb**

Jet Multiplicity

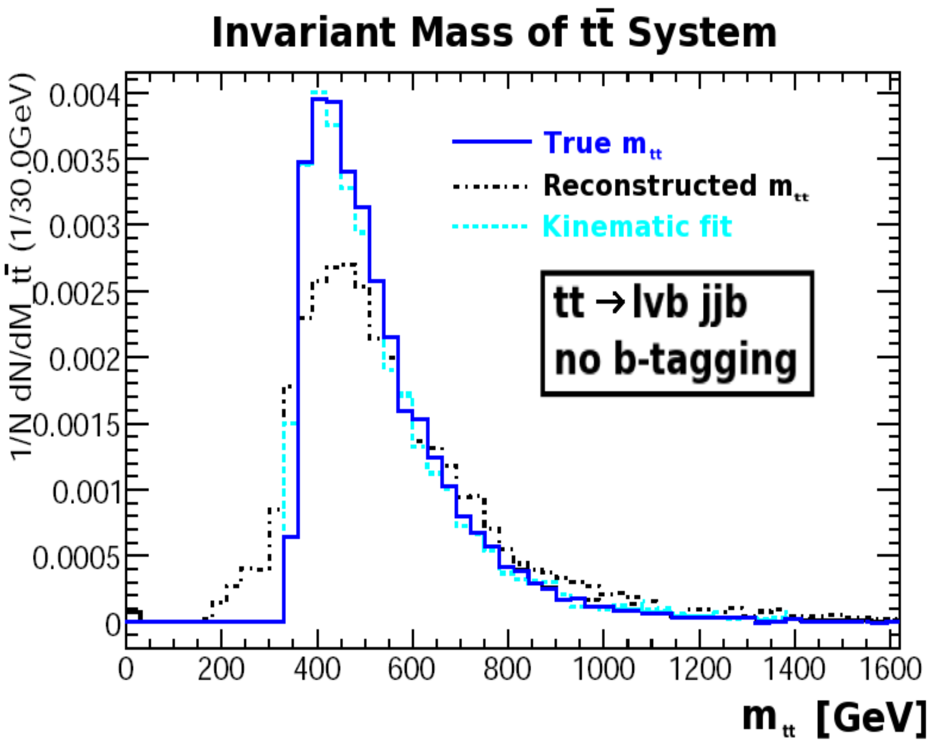
- Cross section "measurement" using Monte Carlo "data"
- Signal: **tt → evb jjb**
- Require one electron and MET to collect **W → ev**
- Select signal: $N_{jets} \geq 4$
- Selection efficiency ε_{tt} = 5.3%
- Fix diboson and single top cross sections to theory.
- Select **background** sample by requiring N_{jets} **<** 2
- Use relative cross sections for W / Z production to extrapolate from N_{jets} < 2 to signal region
- σ_{tt} = 717 ± 158 pb

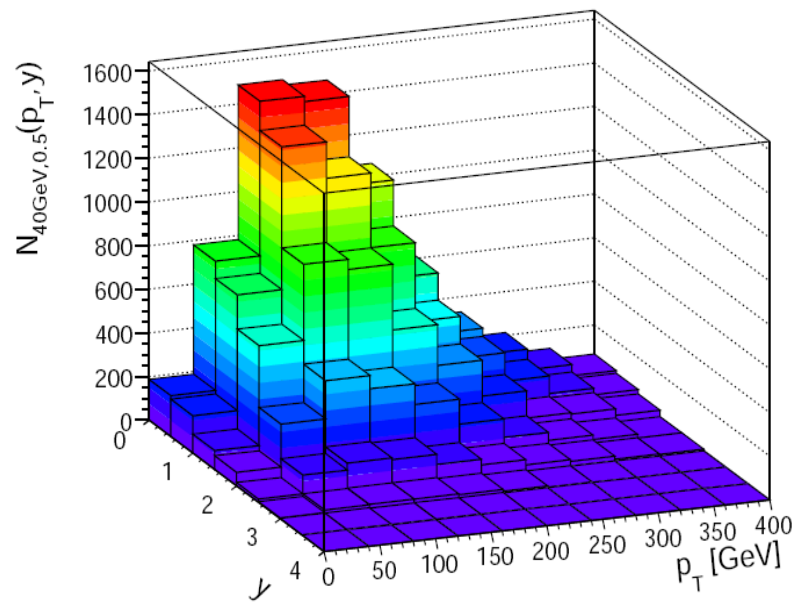
$$\sigma_{tt} = \frac{N_{data} - N_{BG}}{\Gamma_{tt} \cdot \epsilon_{tt} \cdot L}$$



- Signal: **tt → evb jjb**
- Signal has high jet multiplicity
- Main background: **W → ev + jets**
- **W → τv + jets**
- **Z → ee + jets**
- Diboson production: **WW**
- Single top quarks, single top quarks

Differential Cross Sections



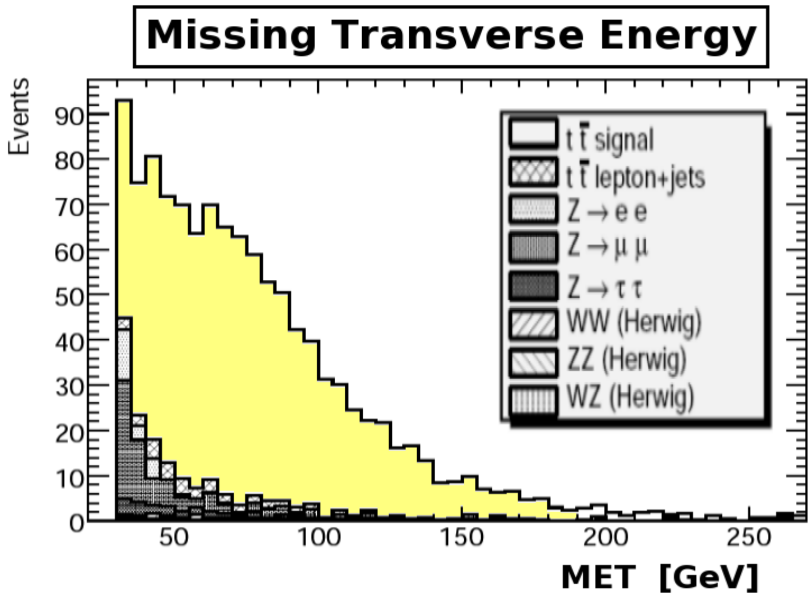


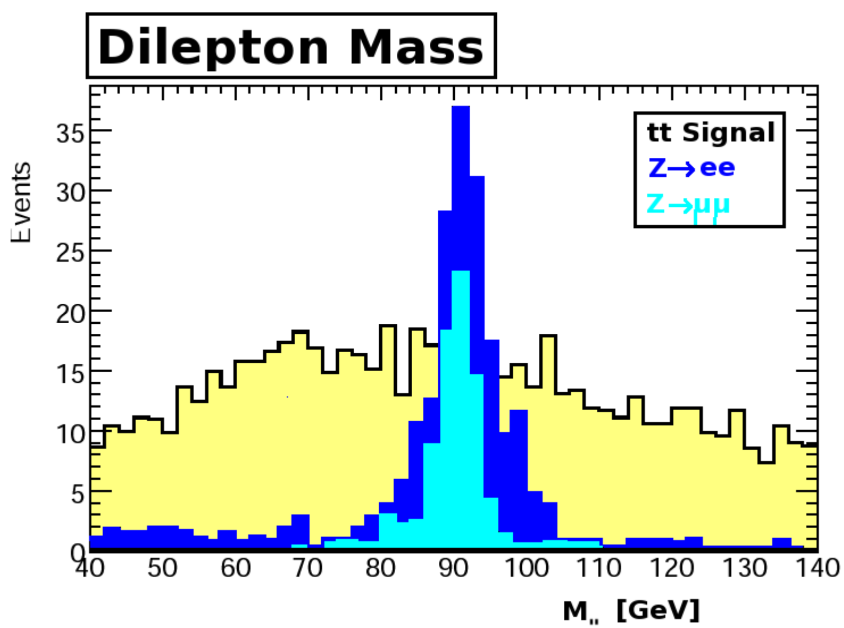
- **Least squares fit**
  - 4 jets, lepton, MET used as input, m_W and m_t used as constraints.
- **Alternative reconstruction**
  - Lepton, MET and m_W used to reconstruct W→lv. W and four jets used to reconstruct tt system.

- tt → lvb jjb (t → jjb)
- 2 b-tagged jets
- L = 1000 pb^{-1}
- Background included
- Rapidity:

  $y = ½ \ln [E + p_z / E – p_z]$

Dileptonic Decay

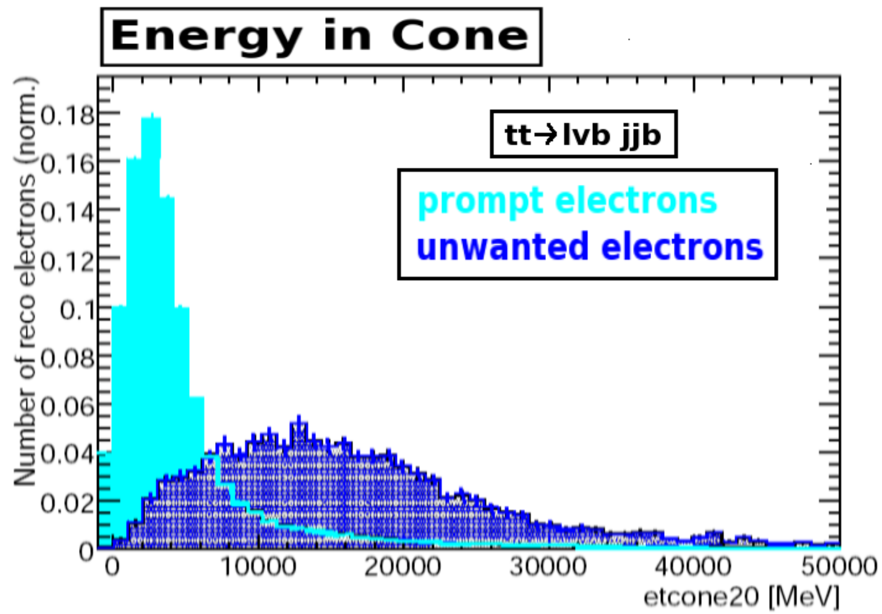


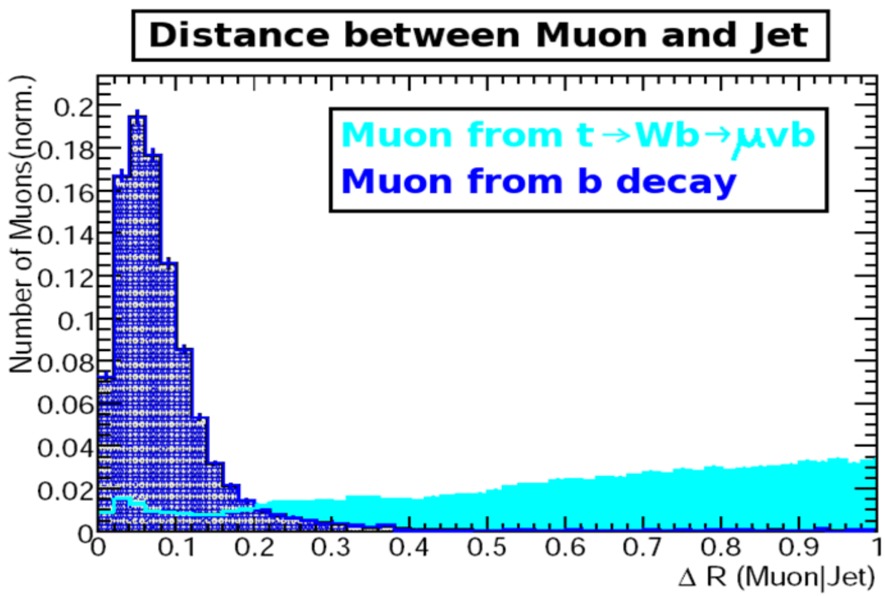


- **$tt \rightarrow W^+b\ W^-b \rightarrow l^+vb\ l^-vb$**
- **Electron, muon triggers**
- **Selection**
  - Two leptons of opposite charge
  - No tau leptons
  - MET > 30 GeV
  - At least two jets
  - No b-tagging
- **Drell Yan Backgrounds**
  - **Z** $\rightarrow l^+ l^-$
  - Veto Z boson mass
  - 85 GeV < m_{ll} < 95 GeV

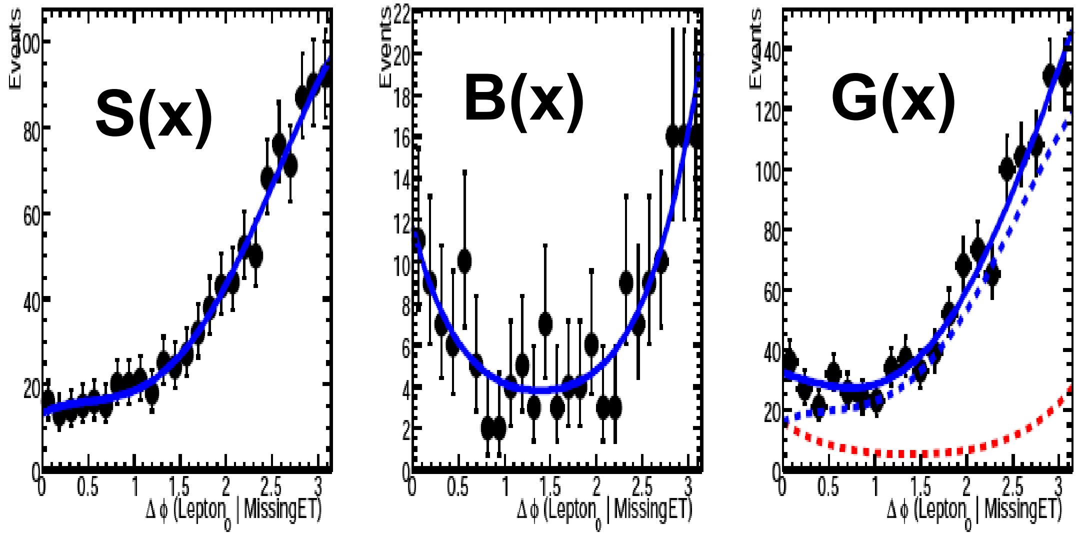
Fake Leptons

- **Electrons**
  - tt → lvb jjb is background if jet fakes electron
  - Require isolated electrons
  - E_T (ΔR < 0.2) < 6 GeV
- **Muons**
  - tt → lvb jjb is background if b-jet produces μ
  - Distinguish between:
    - Hard process: t → Wb → μvb
    - b decay: b → Wc → μvc
  - Require separation between μ and jet
  - ΔR(μ, j) > 0.2





Measuring the Cross Section



Maximum Likelihood Method

- $N_{data} = N_s + N_{bg}$
- S(x) describes signal distribution
- B(x) describes background distribution
- $G(x) = N_s \cdot S(x) + N_{bg} \cdot B(x)$
- Maximize the log likelihood
  $L = -\Sigma \ln G(x) + N_{data}$
- Obtain N_S and N_{bg}

Counting experiment

- **$tt \rightarrow l\nu b\ l\nu b$**
  - $\varepsilon_{tt} = 11.05\%$
- **$L = 100\ pb^{-1}$**
  - **$N_{data} = N_S + N_{bg}$**
  - **$N_{data} = 1216$**
  - **$N_{bg} = 229$**
    - $N_{Z\rightarrow ll} = 124$
    - $N_{W+jets} = 47$
    - $N_{tt\ bg} = 39$
    - $N_{diboson} = 14$
    - $N_{single\ top} = 5$
- $\sigma_{tt} = 804 \pm 47$ pb

$$\sigma_{tt} = \frac{N_{data} - N_{BG}}{\Gamma_{tt} \cdot \epsilon_{tt} \cdot L}$$

Conclusion

- Measurement of σ_{tt} will be one of the first analyses performed after LHC comes online
  - Test of perturbative QCD
  - Calibration of detector
    - b-tagging performance, MET, jet energy scale
  - Background to future measurements
- Top-antitop pairs produced via strong force
- Top decays via weak force
  - **Dileptonic channel** ($tt \rightarrow l\nu b\ l\nu b$)
    - $L = 100\ pb^{-1}$, $\delta\sigma_{tt} \approx 6\%$
  - **Semileptonic channel** ($tt \rightarrow l\nu b\ jjb$)
    - L = 100 pb-1, $\delta\sigma_{tt} \approx 17\%$
    - Single lepton trigger
    - Reconstruct $t \rightarrow jjb$ and $W \rightarrow jj$
    - Reconstruct invariant mass of top-antitop system
  - **Hadronic channel** ($tt \rightarrow jjb\ jjb$)
- The future looks promising!

Backup Slides

References

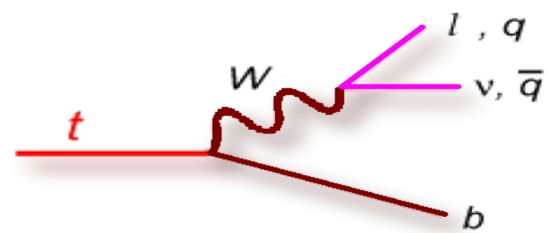
- **ATLAS CSC Notes:**
  - **"Determination of Top Pair Production Cross Section in ATLAS", May 15th, 2008**
  - **"Triggering top quark events in ATLAS", April 22nd, 2008**
  - **"Light jets in tt events", May 15th 2008**
  - **"Flavor tagging calibration with tt events in ATLAS", March 31st, 2008**
- **Analysis references:**
  - **"Top Studies for the ATLAS Detector Commissioning", S. Bentvelsen, M. Cobal, July 2005**
  - **"Commisisioning ATLAS using top quark pair production", W. Verkerke, I. van Vulpen**
- **Analysis using streamtest "data":**
  - **"A pre-commissioning tt cross section measurement at ATLAS", December 14th, 2007**
- **MET:**
  - **"On the missing transverse energy in semi-leptonic tt events using a kinematic fit", E. van der Kraaj**
- **Top quark at LHC:**
  - **"Heavy quarks and leptons", ATLAS Technical Design Report, May 25th, 1999**
  - **"Top Quark Physics", M. Beneke, I. Efthymiopoulos, M. Mangano, J. Womersley**

$\Gamma(t \to Wb)$

- The charged current $W^{\pm}$ couples to quarks q and q' with coupling given by CKM matrix element $V_{qq'}$.

$$V_{\text{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

- $V_{tb} \approx 0.999100$
- $\Gamma(t \to Wb) = |V_{tb}|^2 = 0.998$



Luminosity

- **Quantity which characterizes performance of accelerator.**
  - At the LHC design luminosity is $\mathbf{L = 10^{34}\ cm^{-2}\ s^{-1}}$
- **Necessary input for any cross section measurement.**
- **Methods of measuring luminosity:**
  - **Measure rate of process with large, well-known cross section.**
    - $R = dN/dt = L\ \sigma$
    - More easily applicable to e^+e^- colliders than to hadron colliders.
    - Example: QED Babha scattering.
  - Calculate luminosity using **beam parameters**.
    - $L = F\ f\ \Sigma N_1 N_2\ / 4\pi\sigma_x^*\sigma_y^*$
      - Beam revolution frequency at LHC is f = 11 kHz.
      - F = 0.9 accounts for nonzero crossing angle.
      - N_1 and N_2 are the number of protons in colliding bunches.
        - Caveat: bunch currents will not be very uniform.
      - σ_x^* and σ_y^* are transverse bunch widths at interaction point.
        - Caveat: beam profile measurements are necessary.
    - Typical precision is 5% - 10%.
  - Use the **optical theorem** (ALFA, 2009).
    - Measure total rate of pp interactions R_{total}.
    - Measure rate of forward elastic scattering $dR_{elastic}/dt\ |_{t=0}$.
      - Protons scatter with very small momentum transfer t.
    - $L \cdot dR_{elastic}/dt\ |_{t=0} = R_{total}^2\ (1 + \rho^2)\ /\ 16\ \pi$
      - ρ is ratio of real to imaginary part of elastic forward amplitude.
    - Typical precision is 5% - 10%

Missing Transverse Energy

- **Neutrinos** do not interact with the detector.
- The initial transverse momentum of the colliding proton system is zero.
- **Conservation of momentum** requires that the net transverse momentum of all decay products must be zero.
- **Assumption:** transverse energy and momentum of any object except a neutrino are measured perfectly.
- $\Sigma_i E_T + E_T(\nu) = 0$ where subscript *i* runs over all visible particles.
- **Conclusion:** the "missing transverse energy" (MET) is the transverse energy of the neutrino.
  - $E_T(\nu) = MET = -\Sigma_i E_T$
  - Events which produced a neutrino will have **significant** MET.
  - Events which did **not** produce a neutrino will have little MET.
- **Caveat:** no measurement is perfect. Instrumental effects can result in energy imbalance and can 'fake' the neutrino signature.
- Use known mass of W boson and $W \rightarrow l\nu$ data to calibrate and test performance of MET reconstruction.

Object Definitions

- **Electrons**
  - p_T > 20 GeV, $|\eta|$ < 2.5
  - Exclude calorimeter crack: 1.37 < $|\eta|$ < 1.52
  - Isolation based on calorimeter energy: $E_T(\Delta R < 0.2) < 6$ GeV
  - Reconstruction efficiency: ε = 67%
  - Purity: 97%
- **Muons**
  - Staco algorithn
  - Best combination of information from muon chambers and tracking detector
  - p_T > 20 GeV, $|\eta|$ < 2
  - Isolation: $E_T(\Delta R < 0.2) < 6$ GeV
  - Efficiency: 88%
  - Purity: 100%
- **Jets**
  - Reconstructed from energy depositions in calorimeter towers
  - Cone4
  - Jet is removed if $\Delta R(j,e) < 0.2$
  - $p_T(j_i)$ > 40 GeV for I = 1, 2, 3. $p_T(j_4)$ > 20 GeV
- **b-tagging**
  - IP3D+SV1 (3 dimensional impact parameter and secondary vertex algorithms)
  - W > 7.05
  - $\varepsilon_{b\text{-}tag}$ = 60% for $p_T(b)$ > 30 GeV
  - 5% uncertainty on $\varepsilon_{b\text{-}tag}$ is expected after L = 100 pb^{-1}
- **MET** (MET > 20 GeV)
  - Cells from electron and photon clusters
  - Cells inside jets
  - Cells inside topologcal clusters which are outside identified objects
  - Contribution from muon
  - Cryostat correction

Counting Experiment in Semileptonic Channel

- $tt \rightarrow e\nu b\ jjb$
- $L = 8.74\ pb^{-1}$
  - Considered W + jets, Wbb and Wcc, single top production.
  - $N_{W+light\ flavor} = 58$, $N_{W+heavy\ flavor} = 21$, $N_{single\ top} = 14$
  - $\sigma_{tt} = 771 \pm 96$ *(statistical)* ± 93 *(MC systematics)* pb
- **Uncertainties expected for $L = 100\ pb^{-1}$**
  - 50% uncertainty on normalization of W + jets, 14.7%
  - 5% uncertainty on jet energy scale, 13.3%
  - Initial and final state radiation, 10.6%
  - Statistical uncertainty on 100 pb^{-1}, 2.7%
  - Uncertainty on PDFs, 2.3%
  - Electron identification efficiency, 1%
  - Electron trigger efficiency, 1%

Jet Multiplicity

- **$t\bar{t} \rightarrow e\nu b\, jjb$, L = 8.74 pb^{-1}**
- **Cuts:**
  - e25i single electron trigger
  - exactly one electron
    - Electron author is egamma
    - $p_T > 25$ GeV
    - $|\eta| < 2.4$
    - No calorimeter isolation required
    - isEM == 0
    - Reconstructed electron must match trigger electron, $\Delta R(e_{reco}, e_{trigger}) < 0.2$
    - Overlap between jets and electron removed, $\Delta R(jet, e) > 0.3$
  - MET > 25 GeV
  - Jets have
    - $p_T > 25$ GeV
    - $|\eta| < 2.5$
  - Transverse mass of $W \rightarrow e\nu$
    - $m_T(W \rightarrow e\nu) = \sqrt{[(E_T(e) + MET)^2 - (p_x(e) + MET_x)^2 - (p_y(e) + MET_y)^2]}$
    - $m_T(W \rightarrow e\nu) > 45$ GeV
- **Efficiencies:**
  - Efficiency of electron trigger: $\varepsilon_{trigger} = 0.9896 \pm 0.0011$ "measured" using $Z \rightarrow ee$
  - Efficiency of inclusive $W \rightarrow e\nu$ selection: $\varepsilon_{W \rightarrow e\nu} = 0.1301 \pm 0.0022$
  - Efficiency of signal selection ($N_{jets} > 4$): $\varepsilon_{jet\ multiplicity} = 0.0530 \pm 0.0014$
  - (Errors are statistical)
- **Uncertainties:**
  - 5% uncertainty due to jet energy scale
  - 5% uncertainty due to MET
  - 10% uncertainty due to Monte Carlo generator
  - 10% uncertainty due to QCD radiation
- **Monte Carlo "data"**
  - Generated in Athena 11.0.42
  - Reconstructed in Athena 12.0.6

Estimation of inclusive W+4 jets production

for Jet Multiplicity Analysis

- **Consider $W \rightarrow e\nu$ and $Z \rightarrow ee$**
- "Exclusive production of W + 1 jet" refers to production of W boson in conjunction with zero or one jets
- "Inclusive production of W + 4 jets" refers to production of W boson in conjunction with four or more jets

- **Ratio of W production with respect to jet multiplicity in data:**
  - $R_{data}(W)$ = N(inclusive W + 4 jets) / N(exclusive W + 1 jet)
- **Ratio of W production with respect to jet multiplicity in Monte Carlo:**
  - $R_{MC}(W)$ = N(inclusive W + 4 jets) / N(exclusive W + 1 jet)

- **Ratio of Z production with respect to jet multiplicity in data:**
  - $R_{data}(Z)$ = N(inclusive Z + 4 jets) / N(exclusive Z + 1 jet)
- **Ratio of Z production with respect to jet multiplicity in Monte Carlo:**
  - $R_{MC}(Z)$ = N(inclusive Z + 4 jets) / N(exclusive Z + 1 jet)

- **Relative cross sections for W and Z production are well understood:**
- $R_{data}(W) / R_{data}(Z) = R_{MC}(W) / R_{MC}(Z)$

- **Solve to obtain number of background events attributed to W + 4 jets:**
- N(inclusive W + 4 jets) = $R_{MC}(W) / R_{MC}(Z) \cdot R_{data}(Z) \cdot$ N(exclusive W + 1 jet)

Counting Experiment in Dilepton Channel

- **$tt \rightarrow l\nu b\ l\nu b$**
  - Efficiency: ε_{tt} = 11.05%
  - Purity = 4.3
- **L = 100 pb^{-1}**
  - N_{tt} = 987
  - $N_{Z \rightarrow ll}$ = 124
  - N_{W+jets} = 47
  - $N_{semileptonic\ tt}$ = 39
  - $N_{diboson}$ = 14
  - $N_{single\ top}$ = 5
- **Uncertainties**
  - Statistical uncertainty: 3.6%
  - Jet energy scale: + 4.6%, - 2.1%
  - PDF uncertainties: 2.4%
  - Final state radiation: 2.0%