$t\bar{t}$ Production: $\sigma_{t\bar{t}}$ and m_t @ ATLAS/LHC

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Theory Introduction

Top Quark Decay

- top quark's predominat decay channel $t \to W^+ b$
- $\Gamma(t \to Wb) = \frac{G_F m_t^3}{8\pi\sqrt{2}} |V_{tb}|^2 \sim 1.76\,GeV \left(\frac{m_t}{175\,GeV}\right)^3$
  $m_t \gg m_b, m_W, |V_{tb}| \sim 1$
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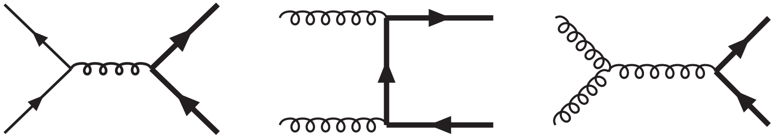
Heavy Quark Production (LO)

Production by quark annihilation and gluon fusion at leading order:



Differential Cross Section:

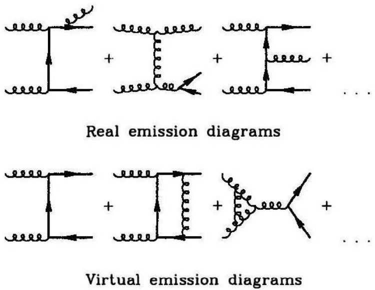
$$\frac{d\sigma}{dy_3 dy_4 d^2 p_T} = \frac{1}{64\pi^2 m_T^4 (1 + \cosh(\Delta y))^2}$$
$$\times \sum_{ij} x_1 f_i(x_1, \mu^2) x_2 f_j(x_2, \mu^2) \overline{\sum} |\mathcal{M}_{ij}|^2$$

In the limit $\Delta y \gg 1$

$$\overline{\sum} |\mathcal{M}_{qq}|^2 \sim \text{const}, \quad \overline{\sum} |\mathcal{M}_{gg}|^2 \sim e^{\Delta y}$$

Heavy Quark Production (NLO)

- Perturbation Expansion in the coupling constant α_s
- LO $\sim \alpha_s^2$
- NLO $\sim \alpha_s^3$ include virtual and real corrections
- reduction of unphysical μ-dependence $\mu^2 \frac{d}{d\mu^2}\sigma = \mathcal{O}(\alpha_s^4)$



Examples of higher-order corrections to heavy quark production.

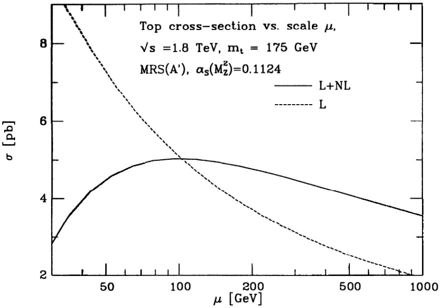


Fig. 10.10. Scale dependence of the top quark cross section in leading and next-to-leading order of perturbation theory.

[figures: QCD & Collider Physics, Ellis et al.]

Experimental Analysis

PART I
Cross Section Measurement for the Production of $t\bar{t}$-Pairs

[ATLAS-CONF-2012-031]

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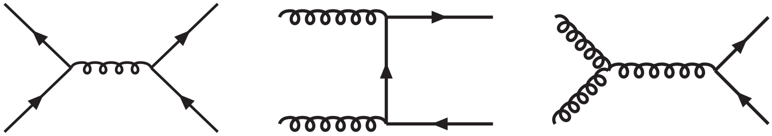
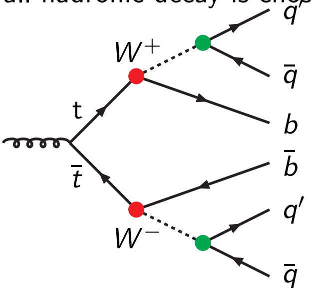


In the detector only decay products can be measured. For this analysis the all-hadronic decay is chosen:



- (red dot) BR $\sim$ 100%

$\Rightarrow$ total BR $\sim$ 46%

- (green dot) BR $\sim$ 68%

but **high background!**

Event Characteristics

physics observales are **jets**:

- b-jets originating form top decay
- light quark jets originating form W decay
- no isolated letpton with high p_T
- no missing energy E_{miss}

Event Selection

- at least 1 primary vertex with ≥ 5 tracks
- no isolated lepton with $p_T > 20\ GeV$
  $\rightarrow$ only hadronic decays
- no fake jets
  $\rightarrow$ reject unphysical jets from fake energy deposits in calorimeters
- no jets with $|\mathrm{JVF}| \leq 0.75$ and $p_T > 20\ GeV$
- $N_{jet} \geq 5$, $p_T > 55\ GeV$ and $|\eta| < 2.5$
- at least one more jet: $p_T > 30\ GeV$ and $|\eta| < 2.5$
  $\rightarrow$ all-hadronic decay needs at least six jets
- at least 2 b-tagged jets: $p_T > 55\ GeV$, $|\eta| < 2.5$
  $\rightarrow$ top/antitop decay into b/$\bar{b}$ quark
- $S_t = E_T^{miss}/(0.5\sqrt{GeV} \times \sqrt{H_T}) < 6$
  $\rightarrow$ if significance of E_T^{miss} is high then veto
- angular distance between two b-jets: $\Delta R(b, \bar{b}) > 1.2$
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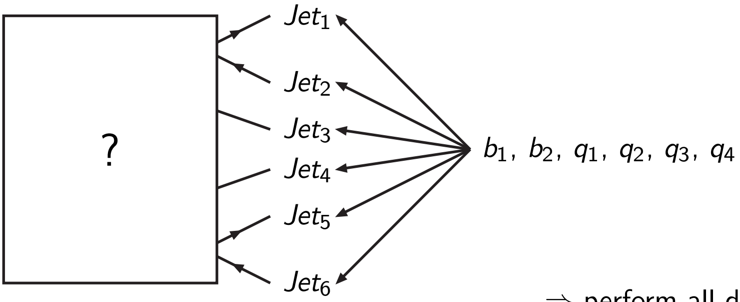
Likelihood Method

- Idea:
  1. determine jet energies E_{jet_i} by maximum likelihood method
  2. use fitted E_{jet_i} to compute m_t-distribution
  3. perform unbinned likelihood fit to the m_t-distribution to obtain $\sigma_{t\bar{t}}$
- Likelihood (constrains on m_W, Γ_W and m_{top})

$$
\begin{aligned}
L_{kin} = & BW(m_{q_1q2}|m_W,\Gamma_W)\cdot BW(m_{q_3q4}|m_W,\Gamma_W)\cdot \\
& BW(m_{q_1q_2b_1}|m^{\text{reco}}_{\text{top}},\Gamma_{\text{top}})\cdot BW(m_{q_3q_4b_2}|m^{\text{reco}}_{\text{top}},\Gamma_{\text{top}})\cdot \\
& W(\hat{E}_{jet_1}|E_{b_1})\cdot W(\hat{E}_{jet_2}|E_{b_2})\cdot W(\hat{E}_{jet_3}|E_{q_1})\cdot \\
& W(\hat{E}_{jet_4}|E_{q_2})\cdot W(\hat{E}_{jet_5}|E_{q_3})\cdot W(\hat{E}_{jet_6}|E_{q_4})\cdot \\
& \prod_{i=1}^{2}\left\{ \begin{array}{rr} \epsilon; & b_i \text{ b-tagged} \\ 1-\epsilon; & b_i \text{ not b-tagged} \end{array} \right\}\cdot \\
& \prod_{i=1}^{4}\left\{ \begin{array}{rr} \frac{1}{R}; & q_i \text{ b-tagged} \\ 1-\frac{1}{R}; & q_i \text{ not b-tagged} \end{array} \right\}
\end{aligned}
$$

Likelihood Method II

A priori association of jets with quarks is impossible

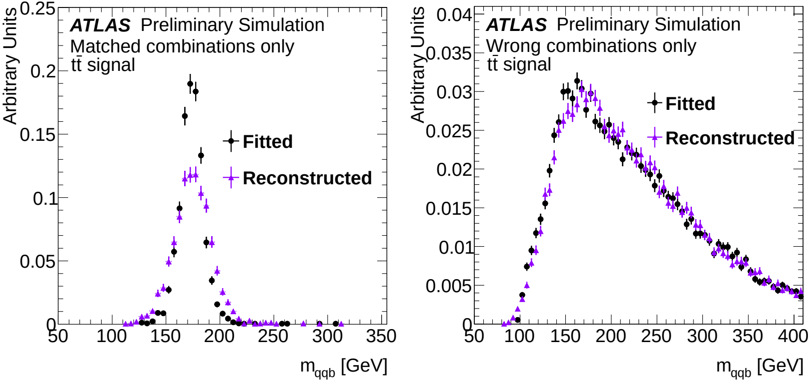


$\Rightarrow$ perform all distiguishable permutations for each event and select the one with the highest likelihood = event propability P_{event}

$$P_{event} = \frac{\mathrm{Min}_{Perm}(-\ln L_{kin})}{\sum_{\{jet_i\}\in\mathcal{P}(1,\ldots,6)}(-\ln L_{kin}(\{jet_i\}))}$$

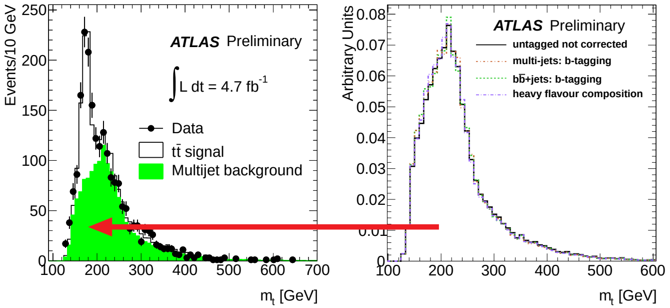
Top Quark Mass Distribution

By the likelihood method one obtains the most likely jet combination which can be used to calculate $m_t = m_{qqb}$



Background Modelling

- Construct m_t-distribution form MC sample with eventselection as before but **without b-jet requirement**
  $\rightarrow$ resulting distribution contains $t\bar{t}$ all-hadronic contribution of estimated 4.6%
- take the shape of the distribution (+corrections) to be the propability density function of the background
- contruct a Likelihood function for the background and fit the the data



Cross Section Measurement

1. perform an additional event selection
    - reconstructed $m_t > 125\ GeV$
    - $6 \leq N_{jet} \leq 10$
    - $P_{event} > 0.8$
    - $\text{Min}_{Perm}\ \chi^2 < 30$

$$\chi^2 = \frac{(m_{j_1,j_2} - m_w)^2}{\sigma_W^2} + \frac{(m_{j_1,j_2,b_1} - m_t)^2}{\sigma_t^2} + \frac{(m_{j_3,j_4} - m_W)^2}{\sigma_W^2} + \frac{(m_{j_3,j_4,b_2} - m_t)^2}{\sigma_t^2}$$

$\Rightarrow$ correct permutations rise up to 36%

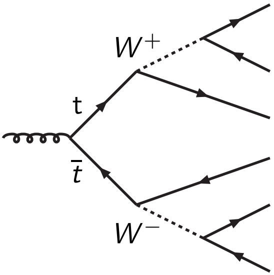
2. after Likelihood fit a signal fraction of $f_{t\bar{t}}^{sig} = (31.4 \pm 2.3)\%$ is obtained from final data sample with $N_{t\bar{t}} = 2118$ events
3. $t\bar{t}$ selection efficiency derived form MC sim.: $\epsilon = (0.086 \pm 0.003)\%$
4. Luminosity $\mathcal{L} = (4.7 \pm 0.2)\ fb^{-1}$
5. $\sigma_{t\bar{t}} = \frac{f_{t\bar{t}}^{sig} N_{t\bar{t}}}{\epsilon \mathcal{L}} = (168 \pm 12)\ pb$

PART II
Measurement of m_t from $t\bar{t}$-Production

[ATLAS arXiv:1203.5755v1]

Event Topology

Example for the event topology for e+jets and μ+jets decay of the $t\bar{t}$-Pair



$\nu \rightarrow E_T^{miss}$

$l^+ \rightarrow$ isolated Lepton

$b \rightarrow$ b-jet

$\bar{b} \rightarrow$ b-jet

$q' \rightarrow$ light quark-jet

$\bar{q} \rightarrow$ light quark-jet

Event Selection

- single e ($E_T > 25\,GeV$) or single μ ($p_T > 20 GeV$)
- μ+jets: $E_T^{miss} > 20\,GeV$ and $E_T^{miss} + m_W^T > 60\,GeV$
- e+jets: $E_T^{miss} > 35\,GeV$ and $m_W^T > 25\,GeV$
- $N_{jets} \geq 4$ with $p_T > 25$ GeV and $|\eta| < 2.5$
- at least on jet is a b-jet

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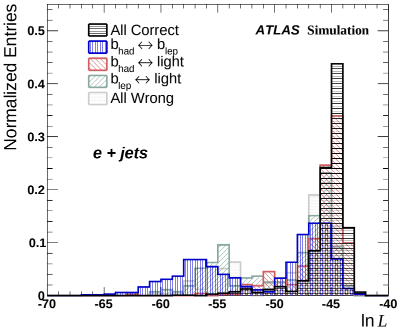
- at least on jet is a b-jet

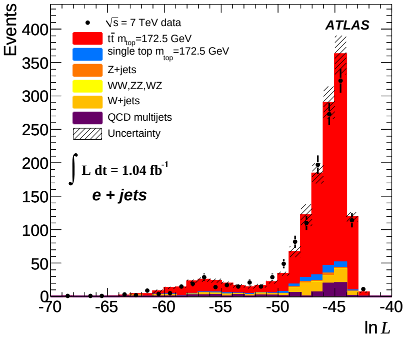
1d-Analysis

Likelihood

Use likelihood to determine the most likely jet permutation:

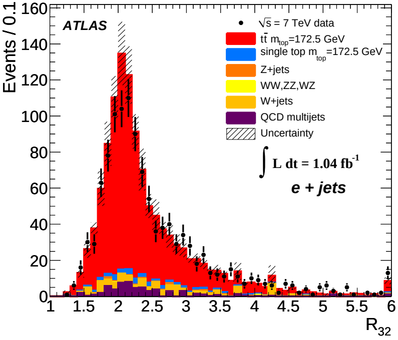
$$L = (\text{Breit-Wigner}) \cdot (\text{Transfer Functions}) \cdot (\text{bTag})$$

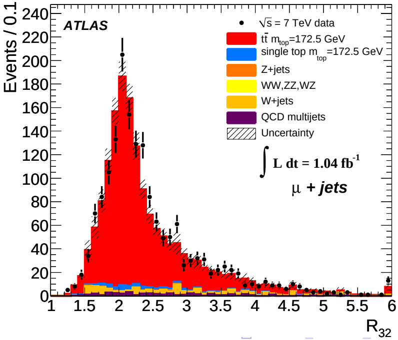




Observable

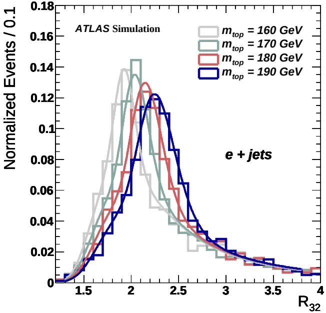
- The used observable is $R_{32} \equiv \frac{m_{top}^{reco}}{m_W^{reco}}$
- $R_{32} = \frac{m_{top}^{reco,like}}{m_W^{reco,like}} \Rightarrow R_{32}$ is dependent on JES (Jet Energy Scale)
- take most likely jet permutation form the likelihood fit and use these jets to reconstruct the masses m_{top}^{reco} and m_W^{reco}
  $\Rightarrow R_{32}$ less dependent on JES





R_{32}-Tamplates

- use MC data for different $m_t = 160, 170, 172.5, 175, 180, 190$ to create R_{32} distributions $\rightarrow$ tamplates
- parametrize the tamplates by functions $f(R_{32}, \vec{x}_m)$

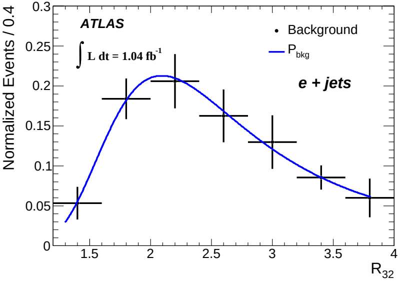


$$\chi^2 = \sum_{m=m_1}^{m_6} \sum_{i=1}^{N_{bins}} \frac{\left[T((R_{32})_i, m) - f((R_{32})_i, \vec{x}_m)\right]^2}{\sigma_m^2}$$

- perform simultaneous χ^2-fit to all templates to obtain a continous function of m_{top} and R_{32} which can be interpreted as signal probability function $P_{sig}(R_{32}|m_{top})$

Background and Likelihood Fit for m_{top}

- get m_{top}-independent background R_{32} distribution from MC



- interpret this as $P_{bkg}(R_{32})$
- perform likelihood fit with n_{bkg} and m_{top} as fit parameters

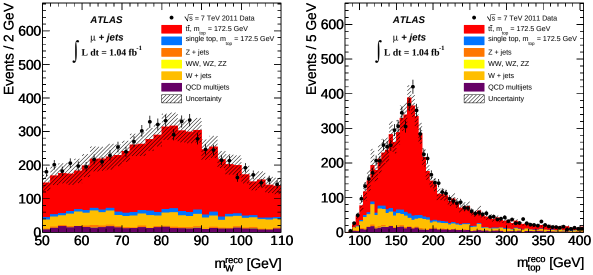
$$\mathcal{L}(R_{32}|m_{top}) = \mathcal{L}_{shape}(R_{32}|m_{top}) \times \mathcal{L}_{bkg}(R_{32}), \quad \mathcal{L}_{shape}(R_{32}|m_{top}) = \prod_{i=1}^{N_{bins}} \frac{\lambda_i^{N_i}}{N_i!} \cdot e^{-\lambda_i}$$

$$\mathcal{L}_{bkg} = \exp\left\{ -\frac{(n_{bkg} - n_{bkg}^{pred})^2}{2\sigma^2_{n_{bkg}^{pred}}} \right\}, \quad \lambda_i = (N - n_{bkg}) \cdot P_{sig}(R_{32}|m_{top})_i + n_{bkg} \cdot P_{bkg}(R_{32})_i$$

2d Analysis

m_t and m_W Distributions

- in this analysis m_{top} and JSF (Jet Energy Scale Factor) are fitted
- t-quark candidate form hadronic decay is reconstructed from the combination of any b-jet and two light jets which has the hightest p_T
- for the light jet pair the parton scale factors α_i are determined by a χ^2 fit: $\chi^2 = \sum_{i=1}^{2} \left[\frac{E_{jet_i}(1-\alpha_i)}{\sigma(E_{jet_i})}\right]^2 + \left[\frac{M_{jet,jet}(\alpha_1,\alpha_2)-m_W}{\Gamma_W}\right]^2$
- m_W^{reco} is reconstructed without partron rescaling
- m_{top}^{reco} is reconstructed using α_i

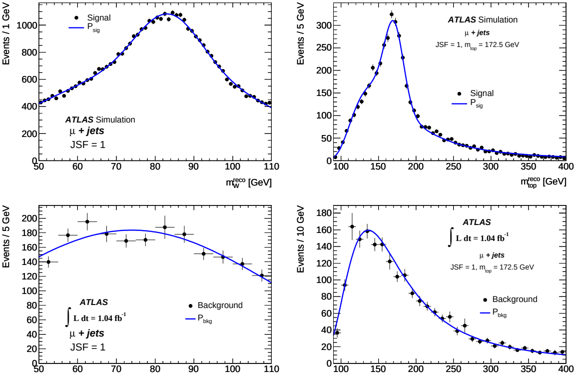


Constructing Templates

- templates for m_{top}^{reco}-distribution for values of $m_t \in [160, 190]\ GeV$ and JSF $\in [0.9, 1.1]$
- templates for m_W^{reco}-distribtion for values of JSF $\in [0.9, 1.1]$
- parametrize the templates for signal and background and interpret them as probabilitiy density functions.

$P_W^{sig} \Leftarrow$ $\Rightarrow P_{top}^{sig}$

$P_W^{bkg} \Leftarrow$ $\Rightarrow P_{top}^{bkg}$



Likelihood Fit for JSF and m_{top}

Unbinned likelihood fit to the data for all events, $i = 1, .., N$

$$\mathcal{L}_{shape}(m_W^{reco}, m_{top}^{reco} | m_{top}, JSF, n_{bkg})$$
$$= \prod_{i=1}^{N} P_{top}(m_{top}^{reco} | m_{top}, JSF, n_{bkg})_i \times P_W(m_W^{reco} | JSF, n_{bkg})_i$$

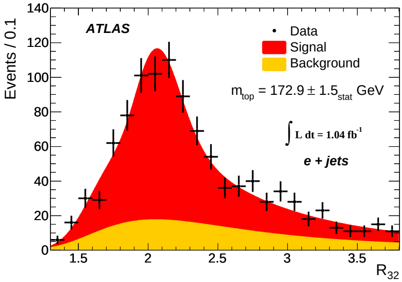
with

$$P_{top,i} = (N - n_{bkg}) \cdot P_{top}^{sig}(m_{top}^{reco} | m_{top}, JSF)_i + n_{bkg} \cdot P_{top}^{bkg}(m_{top}^{reco} | m_{top}, JSF)_i$$
$$P_{W,i} = (N - n_{bkg}) \cdot P_W^{sig}(m_W^{reco} | JSF)_i + n_{bkg} \cdot P_W^{bkg}(m_W^{reco} | JSF)_i$$

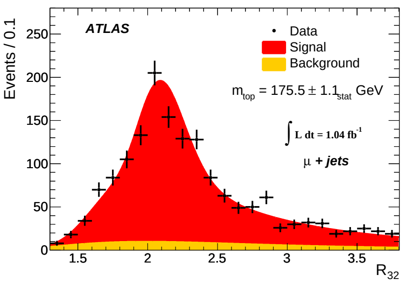
Numerical Results

- 1d
  e+jets : $m_{top} = 172.9 \pm 1.5_{stat} \pm 2.5_{syst}\ GeV$
  μ+jets : $m_{top} = 175.5 \pm 1.1_{stat} \pm 2.6_{syst}\ GeV$
- 2d
  e+jets : $m_{top} = 174.3 \pm 0.8_{stat} \pm 2.3_{syst}\ GeV$
  μ+jets : $m_{top} = 175.0 \pm 0.7_{stat} \pm 2.6_{syst}\ GeV$
- *e*- and μ-channel combined
  1d: $m_{top} = 174.4 \pm 0.9_{stat} \pm 2.5_{syst}\ GeV$
  2d: $\underline{m_{top} = 174.5 \pm 0.6_{stat} \pm 2.3_{syst}\ GeV}$

Graphical Results: 1d-Analysis

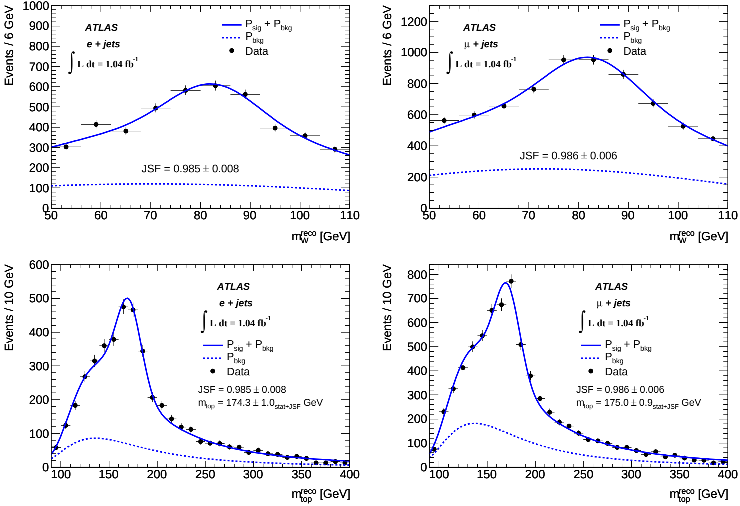


e+jets



μ+jets

Graphical Results: 2d-Analysis



e+jets μ+jets

Topquark Mass Comparison