Measurement of the top quark mass in the lepton+jets $t\bar{t}$ decay channel using jet angles

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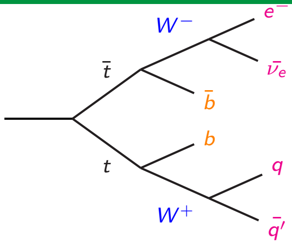
1. Motivation

- Most top quark mass measurements **limited by systematic uncertainties** (statistical uncertainty reduces with higher luminosity and center-of-mass energy)
- One of dominant contributions to systematic uncertainty: **uncertainty on jet energy scale** $\Rightarrow$ **Reduce sensitivity of measurement on jet energies**
- Analysis based on measurement of **jet angles**
  - Complementary method to default methods to measure top quark mass
  - Angles can be determined very precisely
  - Direction of jets reflect very well direction of initial quarks

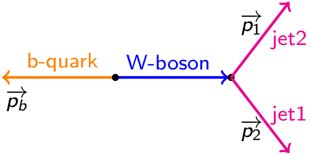
2. The angle method

Analysis using lepton+jets $t\bar{t}$ decay channel:

Note: Only consider hadronic decay



Approach: In the **top quark rest frame**, decay products of top quark span a plane (necessary requirement of the method):



- W-boson and b-quark are emitted back-to-back
- W-boson decay: 2-body decay

Relate angles between decay products of top quark to top quark mass:

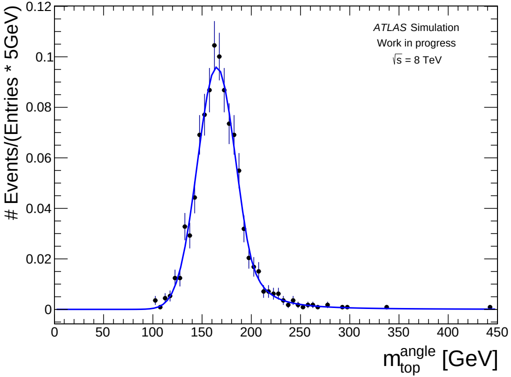
$$\left(\frac{m_W}{m_{top}^{angle}}\right)^2 = \frac{2\sin(\Phi_{1b})\sin(\Phi_{2b})[1-\cos(\Phi_{12})]}{[\sin(\Phi_{12})+\sin(\Phi_{1b})+\sin(\Phi_{2b})]^2}$$

- No explicit dependence on jet energies
- Note that m_{top}^{angle} is only defined for top quarks at rest ⇒ boost into top quark rest frame

3. The top quark mass estimator

Example of resulting $\mathbf{m_{top}^{angle}}$**-distribution** (Monte Carlo input mass: 172.5 GeV, $\sqrt{s} = 8$ TeV):

- Consider only correctly reconstructed top quarks
- Standard lepton+jets selection criteria

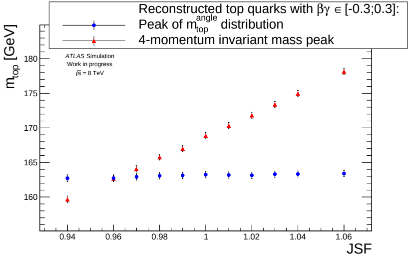


Use **peak position of distribution** ($=m_{top,\ angle}^{peak}$) as top quark mass estimator
Note: Monte-Carlo samples used for these studies generated with Powheg+Pythia+ATLAS detector simulation

4. Angle method for top quarks with $\beta\gamma \approx 0$

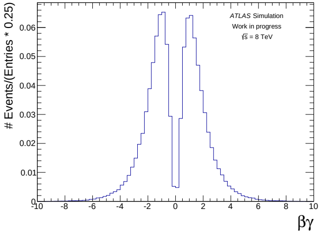
Test of method for top quarks with low $\beta\gamma$ to simulate an analysis with top quarks at rest:

Dependence of $m_{\text{top, angle}}^{\text{peak}}$ on the jet scale factor (JSF): angle method vs. 4-momentum invariant mass peak:



⇒ $m_{\text{top, angle}}^{\text{peak}}$ depends only very little on the JSF if using top quarks with $\beta\gamma \approx 0$

But: Top quarks with low $\beta\gamma$ disfavoured by selection cuts

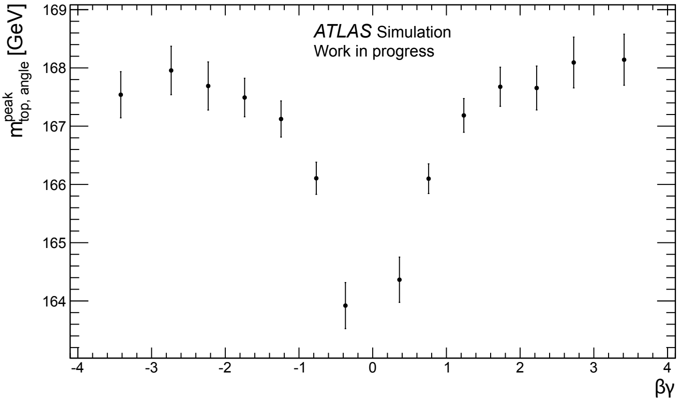


5. Applying the angle method to top quarks with $\beta\gamma \neq 0$

Remember: top quarks with $\beta\gamma \neq 0$ require **Lorentz-Transformation into top quark rest frame**

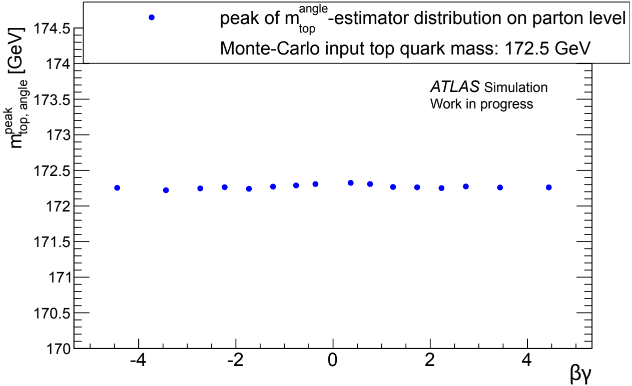
$\Rightarrow$ Lorentz-Transformation introduces dependence on jet energies and momenta

Examine dependence on jet energies (jet energy proportional to γ):



6. The m_{top}^{angle}-estimator on parton level

Dependence of $m_{top,\ angle}^{peak}$ on $\beta\gamma$ in case of a parton-level analysis:

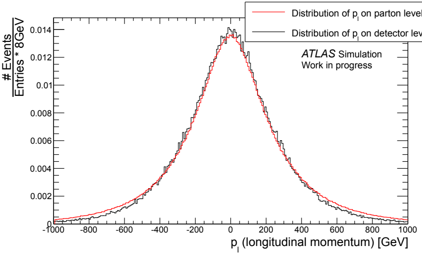


- No dependence on $\beta\gamma$
- Dependence introduced due to physics effects (e.g. hadronization) and/or detector effects

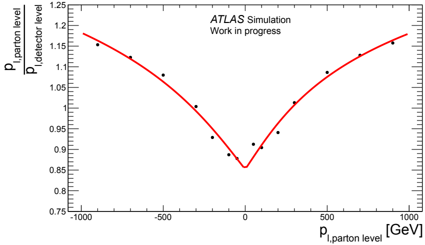
6. Detector vs. Parton Level: Longitudinal momentum of the top quark

1. Longitudinal momentum (p_l):

Compare longitudinal momentum of reconstructed top quark on parton and detector level:



$\Rightarrow$



Shape similar to $m^{peak}_{top,\ angle}(\beta\gamma)$-distribution

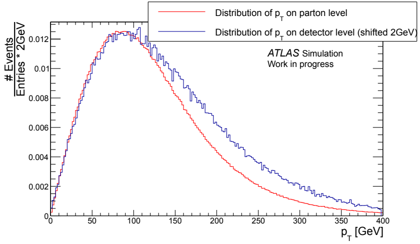
Connection to rapidity y ($Sinh(y) = \beta_z\gamma$)

$\Rightarrow$ $Sinh^{-1}(\beta_z\gamma)$-dependence of m^{angle}_{top}

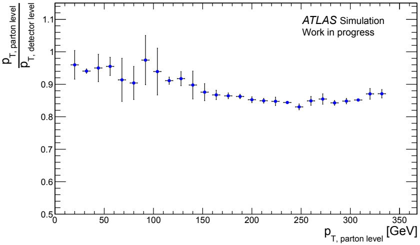
$\Rightarrow$ Parametrize m^{angle}_{top} as function of $Sinh^{-1}(\beta_z\gamma)$

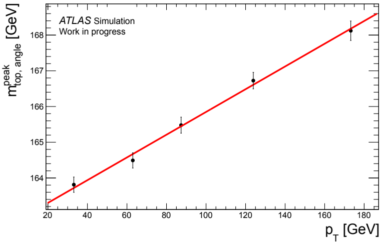
6. Detector vs. Parton Level: Transverse momentum of the top quark

2. Transverse momentum of top quark (p_T):



$\Rightarrow$





$\Rightarrow$ Also consider dependence of m_{top}^{angle} on p_T

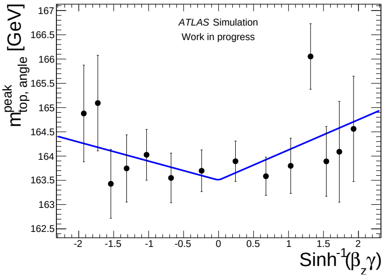
7. Analysis Approach

Goal: Extrapolate m_{top}^{angle} to $\beta\gamma = 0$

Approach:

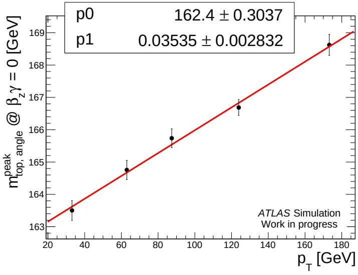
Longitudinal correction:

- For each top-p_T−bin calculate $m_{top,\ angle}^{peak}$ as function of $\text{Sinh}^{-1}(\beta_z\gamma)$
- Extrapolate to $\text{Sinh}^{-1}(\beta_z\gamma) = 0$
- Limited by statistics



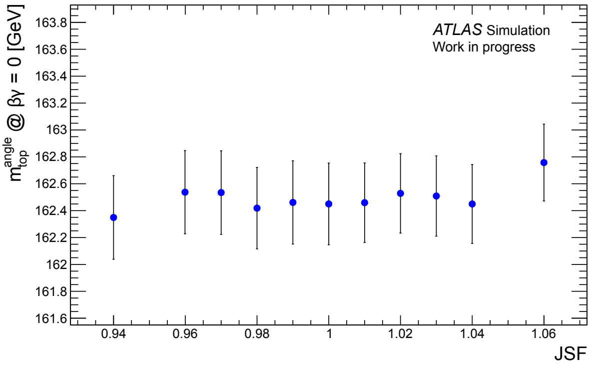
Transverse correction:

- Plot the extrapolated values ($m_{top,\ angle}^{peak}$ @ $\beta_z\gamma = 0$) as function of $p_T^{top\ quark}$
- $m_{top,\ angle}^{peak}$ @ $\text{Sinh}^{-1}(\beta_z\gamma) = 0$ extrapolated to $p_T = 0$ **corresponds to m_{top}^{angle} @ $\beta\gamma = 0$**



8. JSF-variation studies

Investigating the dependence of m_{top}^{angle} on the JSF after extrapolation to $\beta\gamma = 0$



⇒ **Variation of extrapolated m_{top}^{angle} with JSF <200 MeV**

9. Preparation of an application to "real" data

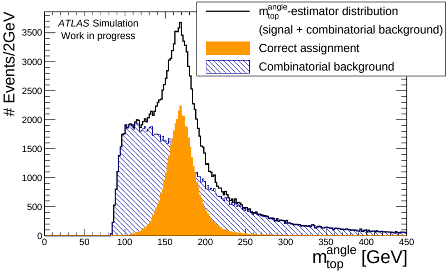
Top pair reconstruction algorithm: minimization of χ^2

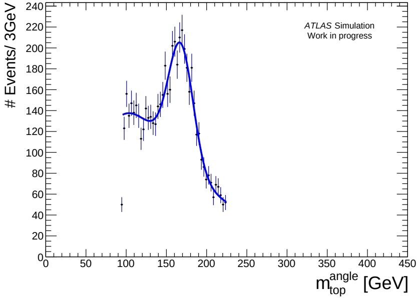
$$\chi^2 = \frac{(m_{b1,j1,j2} - m_{b2,l,\nu})^2}{\sigma_t^2} + \frac{(m_{j1,j2} - m_W)^2}{\sigma_W^2} + \frac{(m_{l,\nu} - m_W)^2}{\sigma_W^2}$$

(σ_t, σ_W = width of top/W invariant mass peak on detector level, m_W= PDG-value of W-boson mass)

Parametrization of the m_{top}^{angle}-distribution:

Parametrize distribution with Landau+Gauss:

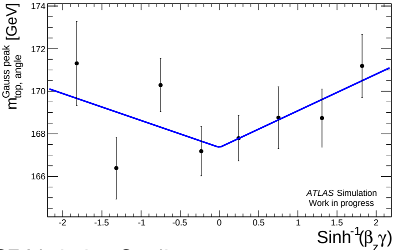


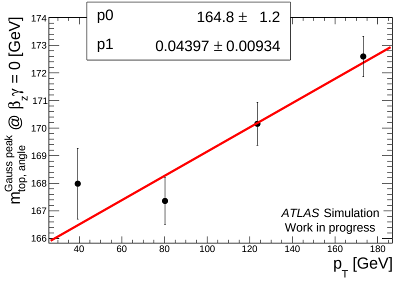


9. New top quark mass estimator: $m_{top, angle}^{Gauss\ peak}$

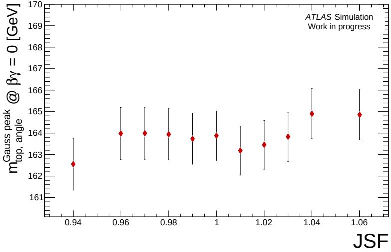
Gauss peak position in Landau+Gauss fit function as top quark mass estimator

Example-Plots:





JSF-Variation Studies:



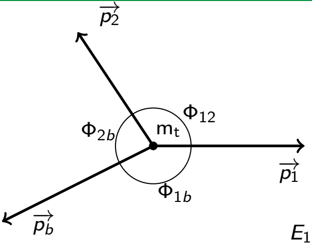
- Variation of estimator with JSF $\approx 2\,\text{GeV}$
- χ^2 top pair reconstruction algorithm produces JSF-dependent combinatorial background

10. Summary

- Develop method to measure top quark mass with aim of reducing the sensitivity to JES uncertainty
- Use jet angles
- Dependence of estimator on $\beta\gamma$ requires an extrapolation to $\beta\gamma = 0$
- Top quark estimator extrapolated to $\beta\gamma = 0$ yields significantly reduced dependence on JSF
- Higher statistics essential for this method

Backup-slides

The angle method: derivation of the expression



Constraints:

- $E_1 + E_2 + E_b = m_t$ (Energy conservation, top quark at rest)
- $\vec{p_1} + \vec{p_2} + \vec{p_b} = 0$ (momentum conservation, top quark rest frame)

$$E_1 = m_t * \frac{\sin\Phi_{2b}}{\sin\Phi_{12} + \sin\Phi_{1b} + \sin\Phi_{2b}} \quad (1)$$

$$E_2 = m_t * \frac{\sin\Phi_{1b}}{\sin\Phi_{12} + \sin\Phi_{1b} + \sin\Phi_{2b}} \quad (2)$$

$$E_b = m_t * \frac{\sin\Phi_{12}}{\sin\Phi_{12} + \sin\Phi_{1b} + \sin\Phi_{2b}} \quad (3)$$

$\Rightarrow$ Only works when decay products span a plane!
Calculate the mass of the W-boson (neglect light quark mass):

$$(m_W)^2 = [\begin{pmatrix} E_1 \\ \vec{p_1} \end{pmatrix} + \begin{pmatrix} E_2 \\ \vec{p_2} \end{pmatrix}]^2 = 2E_1E_2(1 - \cos(\Phi_{12})) \quad (4)$$

Plug in (1) and (2) in (4) and obtain:

$$\left(\frac{m_W}{m_{top}}\right)^2 = \frac{2\sin(\Phi_{1b})\sin(\Phi_{2b})[1-\cos(\Phi_{12})]}{[\sin(\Phi_{12})+\sin(\Phi_{1b})+\sin(\Phi_{2b})]^2}$$

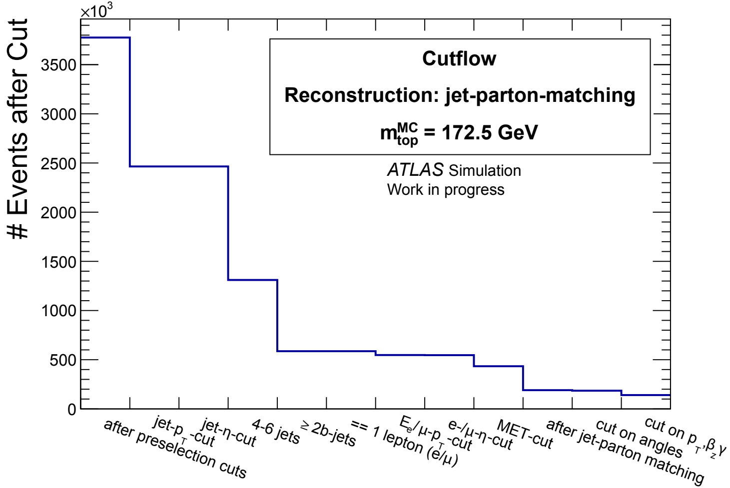
Selection Cuts

- $4 - 6$ jets in event
- Exactly one electron OR one muon
- ≥ 2 b-tagged jets
- $E_{\mathrm{T}}^{\mathrm{miss}} > 30\,\mathrm{GeV}$

- jet-$p_{\mathrm{T}} > 30\,\mathrm{GeV}$; $\eta_{\mathrm{jet}} < 2.5$
- $\mu - p_{\mathrm{T}} > 30\,\mathrm{GeV}$; $\eta_{\mu} < 2.5$
- $e - E_{\mathrm{T}} > 30\,\mathrm{GeV}$; $\eta_{e} < 2.47$ and $\eta_{e} \notin [1.37, 1.52]$

- Exclude angles which are kinematically not possible in rest frame (after $t\bar{t}$-reconstruction)

Cutflow (top pair reconstruction with jet-parton matching)



Example for alternative top quark mass estimator

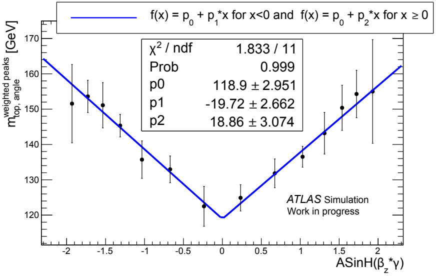
Idea:

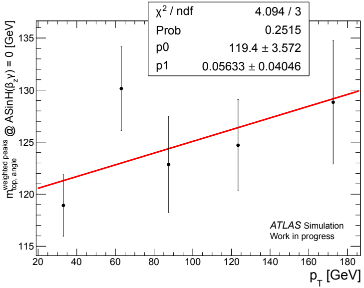
- Cleaning Cuts further reduce the "vital" statistics
- $\Rightarrow$ make use of the fact that combinatorial background also depends on top quark mass

$$m_{\mathrm{top,angle}}^{\mathrm{weighted\ peaks}} = \frac{I_L * p_L + I_G * p_G}{I_G + I_L}$$

$p_{L/G}$: peak position of Landau/Gauss, $I_{L/G}$: Integral of Landau/Gauss within fit range

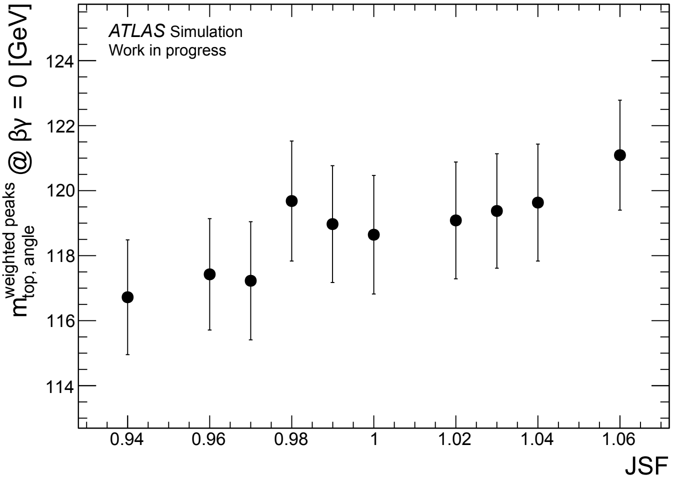
Example plots ($m_{\mathrm{top}}^{\mathrm{MC}} = 172.5\,\mathrm{GeV}$):





$\rightarrow m_{\mathrm{top}}^{\mathrm{angle}} @ \beta\gamma = 0 = (119 \pm 4)\,\mathrm{GeV} \Rightarrow$ map measured top quark mass to MC input top quark mass via a calibration curve

JSF-Variation Studies: $m_{\text{top, angle}}^{\text{weighted peaks}}$-estimator



Cutflow (top pair reconstruction with χ^2-algorithm)