Properties of J/ψ mesons in dileptonic $t\bar{t}$ events from proton-proton collisions at $\sqrt{s} = 8$ TeV

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Abstract

1999 Avto Kharchilava suggested a measurement of the top quark mass using J/ψ mesons in b jets from top quark pair ($t\bar{t}$) events at the LHC. Current runs to not yield enough events with this clean but very rare signature to allow for precise measurements with this method. However, the approach is expected to become competitive at LHC runs in the coming years with very high instantaneous luminosities. This work analyzes the 2012 data set with an integrated luminosity of 19.7 fb^{-1} and a center-of-mass energy of 8 TeV and intents to perform preliminary studies for future mass measurements. Using the $t\bar{t} \rightarrow e^{\pm}\mu^{\mp}$+jets channel, 40 J/ψ mesons could already be selected with an invariant mass between 3.0 and 3.2 GeV. The $t\bar{t}$ fraction is 0.85 and the ratio data/prediction reaches a value of 0.80 ± 0.16, where the uncertainty does not yet account for systematic effects. Most of the J/ψ lie inside a jet and carry about half of the jet p_T. Comparisons with the parton level in simulation proof the correlation to the b quark.

Contents

1 Introduction

1.1 Motivation

There are mainly two motivations for this analysis. The first one is the measurement of the top quark mass (m_t), which is one of the fundamental parameters in the Standard Model (SM). The knowledge of top quark mass constraints several other quantities in the SM, as for example for the Higgs boson mass. Thus, its measurement is an important task of the experiments at the LHC.

The top quark is the heaviest known elementary particle ($m_t = 173.2 \pm 0.9$ [1]). It decays before hadronizing to baryons or mesons. This makes it much easier to measure its mass via secondary particles, compared to the mass measurement of other quarks.

Conventional measurements require the full reconstruction of the top quark decay. As top quarks decay almost exclusively in a W boson and a b quark, the energies of the jets coming from the b quarks have to be known very well. This becomes particularly challenging at high instantaneous luminosity because of a higher number of simultaneous events per proton bunch crossing (pile up), which makes it more difficult to resolve the actual jets.

Therefore, 1999 Avto Kharchilava suggested an alternative top mass measurement, which makes use of J/ψ mesons generated in b-jets [2]. The idea is that the invariant mass of the J/ψ and the isolated lepton coming out of the same top quark ($m(lJ/\psi)$) is correlated to top quark mass itself. The nearly complete independence of jet energies and the very clean signal of J/ψ mesons make this method highly promising.

However, due to the very rare generation of J/ψ mesons in b-jets this method also requires a lot of accumulated data. At the second run of the LHC starting in 2015 it is expected to get high enough luminosity to apply this top quark mass measurement.

The main intention of this work documented in this report is to use the current LHC data for preliminary investigations on this method. Therefore, we selected $t\bar{t}$ events and looked at different properties of the J/ψ mesons that we could already find, as for example kinematic characteristics or relations to jets.

A second motivation for this study is an investigation on fragmentation models. The fragmentation of quarks into jets is a non-perturbative process. That is why we have to introduce phenomenological models for its simulation. These models usually depend on many parameters and the research on J/ψ mesons inside b-jets is an additional possibility to tune these parameters.

1.2 $t\bar{t}$ production and decay

At the Large Hadron Collider (LHC) proton-proton collisions take place. The main top pair production mechanisms are shown in figure 1.

The top quark almost exclusively decays into a W boson and a b quark. The W then can decay hadronically into a quark anti-quark pair or leptonically into a pair of a lepton

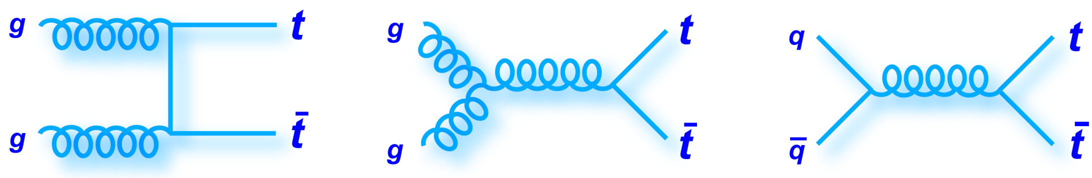

Figure 1: Leading-order Feynman diagrams top quark pair production in proton-proton collisions [3].

and a corresponding neutrino. Each quark from the hadronic W decay subsequently hadronizes into a bunch of particles and therefore results in a particle jet. On the contrary, the leptonic decay produces an isolated track of the lepton in the detector and missing transverse momentum from the neutrino, which escapes undetected. As in top pair events two W bosons decay, a dileptonic (two leptons), a semileptonic (one lepton and two jets) or a hadronic (four jets) combination is possible. Additionally to the W decay, the b quarks decay also hadronically and result in two extra jets. A dileptonic decay is shown in figure 2.

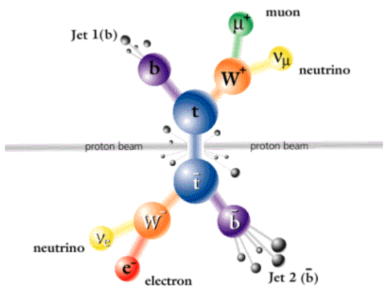

Figure 2: Sketch of a dileptonic $t\bar{t}$ event.

The fractions of the possible top pair decay modes are illustrated in figure 3. In this analysis only the process $t\bar{t} \rightarrow e^{\pm}\mu^{\mp}$+jets (see figure 2) is analyzed because it is almost background free. This is caused by the fact that a $e^{\pm}\mu^{\mp}$ pairs cannot be generated out of a single particle decay. An $e^{\pm}\mu^{\mp}$ combination can also be generated by combinations including a tau lepton which then decays into a muon or electron. However, the fraction of the analyzed process is smaller than 7 percent.

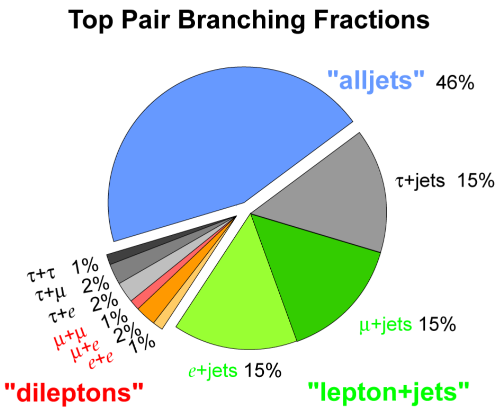

Figure 3: Top quark pair decay branching fractions [3].

1.3 CMS detector

The central element of the Compact Muon Solenoid (CMS) detector [4] is a superconducting solenoid. Within the solenoid, the silicon pixel detector, the strip tracker and the electron and hadron calorimeters are placed. Outside the solenoid three types of gas-ionization chambers are used for muon identification. In detector units, the pseudorapidity η is defined as

$$\eta = -\ln\left(\tan\frac{\theta}{2}\right),$$

where θ is the azimuth angle according to the beam line. Most measurements cover a pseudorapidity of $|\eta| < 2.4$. The combination of the strong magnetic field inside the solenoid (3.8 T) and the highly resolving silicon tracker provide an accuracy of about 1% for the transverse momenta (p_T) of the reconstructed muons. The vertex position can be located with a resolution of $\sim 20\ \mu$m.

2 Analysis

2.1 Analyzed process

In figure 4 the investigated process is shown. Within a dileptonic $t\bar{t} \to e^{\pm}\mu^{\mp}$+jets event, a J/ψ meson is created via intermediary B hadrons inside the jet of one b quark. J/ψ mesons consist of a $c\bar{c}$ pair and have a mass of $m_{J/\psi} = 3.096$ GeV [5]. The J/ψ can decay both leptonically and hadronically. In 5.93% of the cases it decays into a $\mu^-\mu^+$ pair, which is, as muons are easy to detect, a very clean signal.

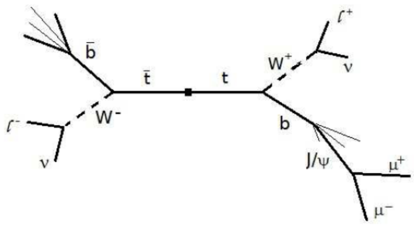

Figure 4: J/ψ-production in a b jet from a dileptonic $t\bar{t}$ event.

2.2 Data and Monte Carlo samples

For this analysis the full 2012 data set with an integrated luminosity of 19.7 fb^{-1} recorded by CMS experiment in proton-proton collisions at a center-of-mass energy of $\sqrt{s} = 8$ TeV is used.

The data are compared to events from Monte Carlo (MC) simulations. The $t\bar{t}$ production is simulated with the MadGraph 5 generator [6] interfaced to Phythia 6 [7] for simulation of parton shower and hadronization. A full simulation of the CMS detector is performed using Geant 4 [8]. In a similar way, the following background processes were simulated and also included in the further analysis:

- Drell Yan: $Z/\gamma^* \rightarrow \tau\bar{\tau}$
- Diboson production: $ZZ/WW/WZ$
- Single top events
- W boson + jet

In the following, the term "$t\bar{t}bkg$" refers to all $t\bar{t}$ events that do not decay into the $e\mu$ channel.

2.3 Selection steps

To identify J/ψ-in-$t\bar{t}$-candidates, the following selection steps are performed in this analysis:

1. At least one isolated electron and one isolated muon, both with $p_T > 20$ GeV, $|\eta| < 2.4$ and opposite charge.
2. Invariant $e^{\pm}\mu^{\mp}$ mass larger than 12 GeV. (If there is more than one possible $e^{\pm}\mu^{\mp}$ combination in the event, the pair with the maximum scalar p_T sum is chosen.)
3. At least one jet with $p_T > 30$ GeV, $|\eta| < 2.5$.
4. At least two additional muons with $p_T > 4$ GeV.
5. Muon pair with opposite charge. If there are several possible $\mu^+\mu^-$ combinations in the event, the pair that yields the invariant mass closest to 3.096 GeV is chosen.
6. Invariant mass of the J/ψ candidate within 3.0 and 3.2 GeV.

On the left side in figure 5 the invariant mass of the isolated muon and electron ($m(e^{\pm}\mu^{\mp})$) with the highest scalar p_T sum is shown. Except for a drastic excess for small masses and a deficit of around 6% in the predicted event yields elsewhere, the data are well modeled. To remove the excess for small masses, the selection step 2, $m(e^{\pm}\mu^{\mp}) > 12$ GeV was introduced.

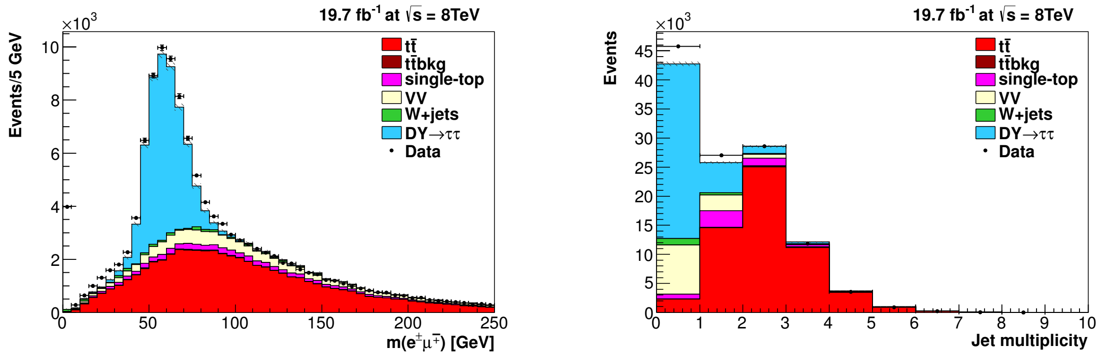

Figure 5: Left: Invariant mass of the isolated muon and isolated electron with the highest scalar p_T sum after step 1. Right: Jet multiplicity after step 2.

The jet multiplicity after requiring $m(e^{\pm}\mu^{\mp}) > 12$ GeV is displayed on the right side of figure 5. It can be seen that most of the non-$t\bar{t}$ background doesn't have a jet at all and the excess results from the 0-jet bin. Therefore, most of the background is already removed after requiring at least one jet and the data/MC ratio reaches 1.01 after step 3.

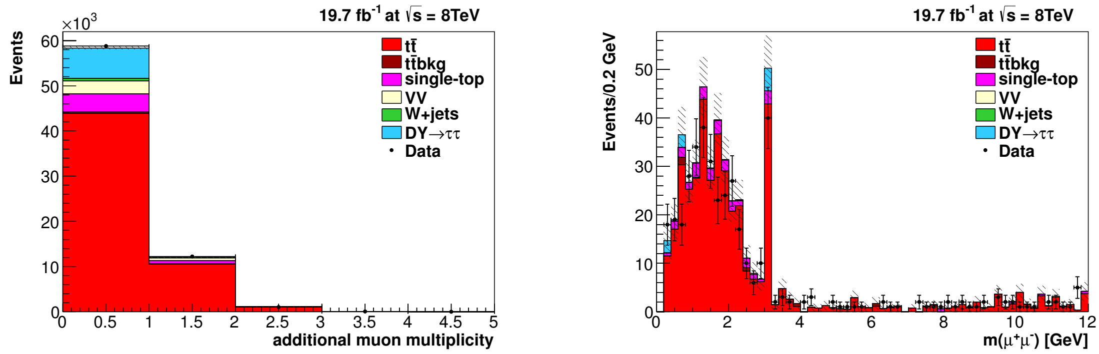

Figure 6: Left: Additional muon multiplicity after step 3. Right: Invariant mass of additional muon pairs. If there are more than two possibilities, the combination with invariant mass closest to the J/ψ is selected. The hatched area represents the statistical uncertainty on the combined MC prediction.

The main two J/ψ-specific cuts are motivated in figure 6. In the left plot the multiplicity of the muons additionally to the leading isolated muon is shown. It is necessary to require at least two additional muons, which are intended to come out of J/ψ mesons. In the right plot, the invariant mass of those muons which yield the mass closest to the J/ψ mass exhibits the clear signal of the J/ψ mesons. After cutting on the J/ψ mass window of 3.0 GeV $< m(\mu^+\mu^-) <$ 3.2 GeV, 40 J/ψ candidates could be identified and the data/MC ratio changed to 0.78±16. The $t\bar{t}$ signal fraction reaches a good value of 0.85.

The total event yield of the data as well as of all used MC-samples at every selection step is shown in table 1.

It is not clear whether the particle reconstruction and identification already works for small transverse momenta. Moreover, further data/MC discrepancies might occur for low p_T. Therefore, an analysis on the sensitivity of the data/MC ratio to different minimum p_T values for the additional muons is shown in figure 7. By construction, there is no effect from the different p_T requirements until step 4. Also after cuts based on additional muons, there is no significant difference in the data/MC ratio for the different p_T values. On the contrary, the number of selected J/ψ candidates would be reduced to only 25 events when raising the minimum p_T from 4 to 8 GeV.

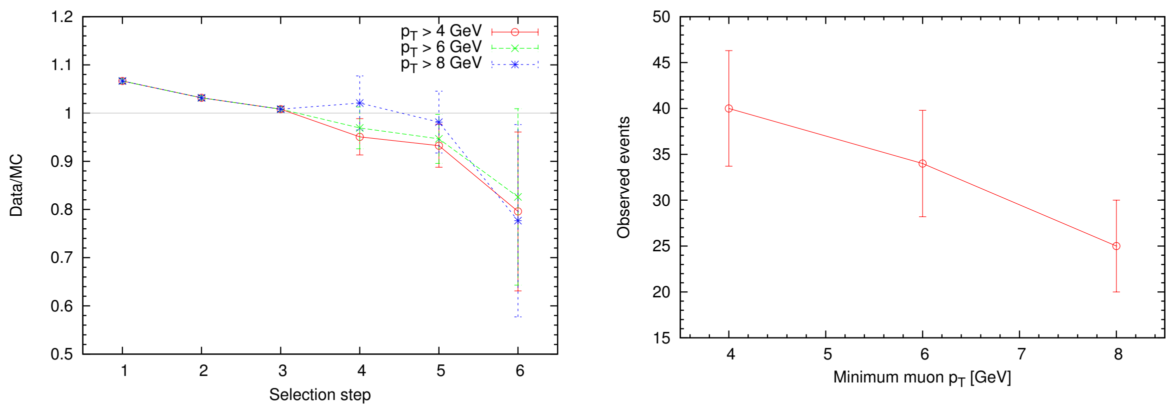

Figure 7: Left: Ratio of the number of observed events to the number of expected events from MC after the six different selection steps for three different minimum p_T requirements imposed on the muons that are used in the last three selection steps. Right: Number of observed events after the final selection step as a function of the minumum p_T required for the muons that are taken to construct the J/ψ candidate.

3 J/ψ properties

3.1 Crosscheck: same-sign muons

To check whether the selected muons really are the decay products of J/ψ mesons, a comparison with same-sign additional muons can be seen in figure 8. According to the

Table 1: Number of selected events in data compared to the expected signal and background events after several selection steps. The quoted uncertainties are statistical only and reflect the size of the simulated samples.

	$t\bar{t}$	$t\bar{t}$ bkg.	Single-top	VV	$W + jets$	$DY \to \tau\tau$	sum MC	data
isolated $e^{\pm}\mu^{\mp}$	58015.2 ± 211.2	465.0 ± 18.7	5543.1 ± 53.1	12002.4 ± 37.4	1807.2 ± 157.6	36893.1 ± 312.6	114725.9±414.4	122353.0
$m_{e^{\pm}\mu^{\mp}} > 12$ GeV	57799.8 ± 210.8	459.7 ± 18.6	5518.7 ± 53.0	11962.1 ± 37.3	1658.8 ± 150.9	36869.6 ± 312.5	114268.6±411.6	117889.0
at least 1 jet	55493.0 ± 206.7	442.3 ± 18.3	4699.5 ± 49.0	3480.3 ± 19.1	562.4 ± 86.8	6864.9 ± 135.5	71542.4±267.8	72122.0
additional muon pair	1077.4 ± 28.7	15.1 ± 3.4	51.8 ± 5.1	6.0 ± 0.6	0.0 ± 0.0	9.8 ± 4.9	1160.2±29.8	1103.0
opposite charge	739.9 ± 23.8	10.8 ± 2.8	41.0 ± 4.5	4.0 ± 0.5	0.0 ± 0.0	9.8 ± 4.9	805.5±24.9	751.0
3.0 GeV $< m_{\mu^+\mu^-} <$ 3.2 GeV	42.9 ± 5.7	0.0 ± 0.0	2.7 ± 1.2	0.0 ± 0.0	0.0 ± 0.0	4.6 ± 3.3	50.3±6.7	40.0

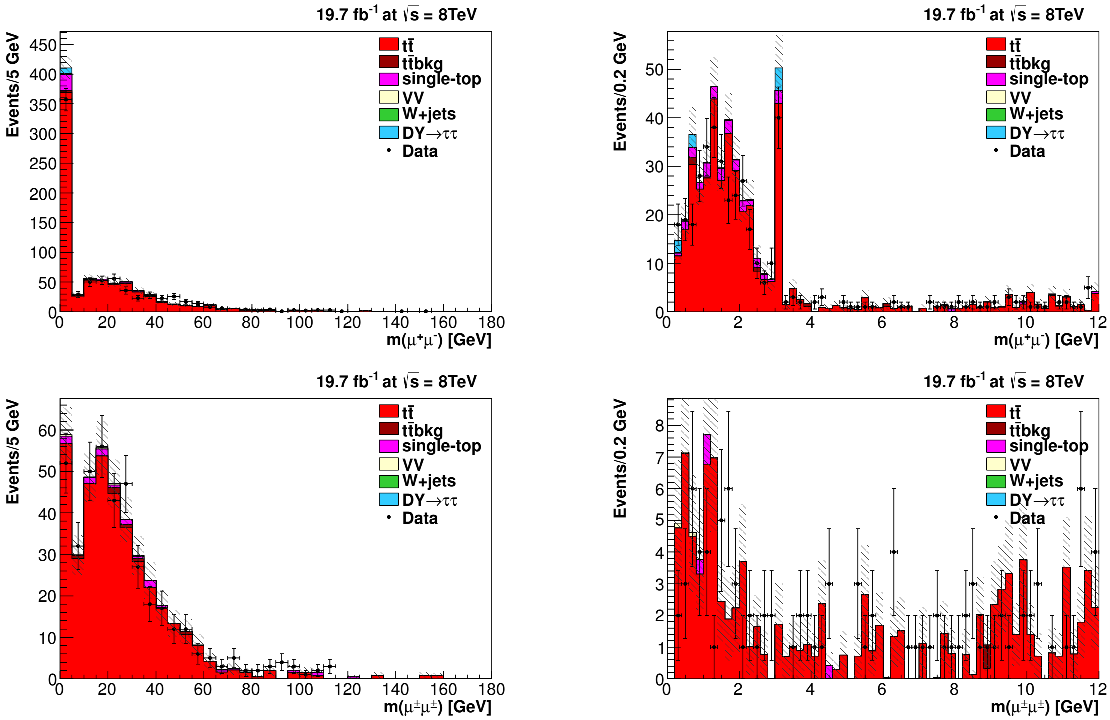

Figure 8: Invariant mass of opposite-sign (first row) and same-sign (second row) muon pairs. The left column shows the wide mass range, while the right column zooms into the low-mass region. The hatched area represents the statistical uncertainty on the combined MC prediction.

SM there is no particle that decays into a same-charge muon pair. Hence one should not observe a peak in the invariant mass distribution of same-sign muons. On the contrary, it might be that choosing those combinations that yield the invariant mass closest to the J/ψ mass, already results in an artificial peak at the position of the mass of the J/ψ. Furthermore, such a peak could also come from wrong charge reconstruction of muons. But, as such a peak is not observed, such biases can be excluded.

Additionally, such a comparison can verify the correct kinematic description of the combinatorial muon background. In these plots the simulations fit perfectly to the data.

3.2 Vertex fit

After the selection of muon pairs, which are assumed to come out of J/ψ mesons, it is not clearly sure whether they really do so. Thus we applied a Kalmann vertex fit to the tracks of the additional opposite-charge muon pairs. The χ^2 probability of this fit is expected to have a flat distribution and is shown in figure 9 at two different zoom levels. As a crosscheck, the same plots for same-charge muons, which are not supposed to have a common vertex, are also given.

For the J/ψ candidates the distribution is within the error bars compatible with a flat

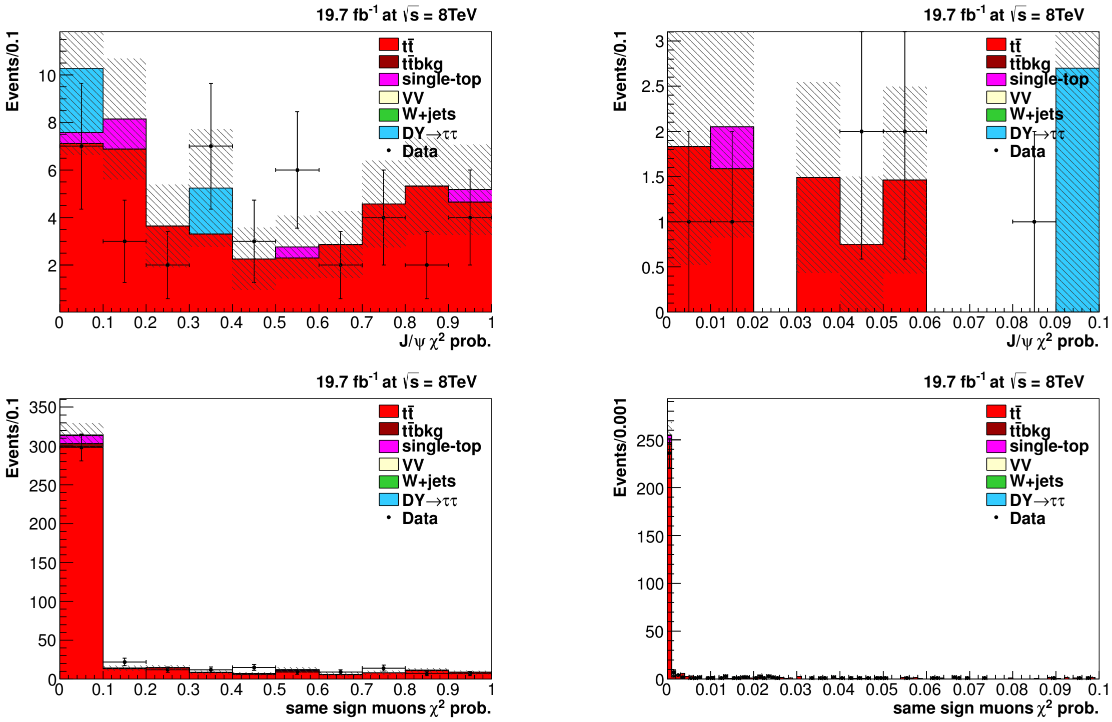

Figure 9: Upper plots: χ^2 probability of vertex fit to the J/ψ candidates. Lower plots: Crosscheck χ^2 probability of vertex fit of same charged additional muons of additional same charged muons. The hatched area represents the statistical uncertainty on the combined MC prediction.

one. However, for the same-sign muons a clear peak for very low probabilities is observed. This could be a motivation for an extra selection step, to clearly remove non-common-vertex muons. In our case, a cut of χ^2probability $> 0.1\%$ would remove 1 of the 40 events.

After making sure that the J/ψ candidates have a common vertex, it is possible to look at the 3D distance between the vertex of the J/ψ and the primary vertex of the event. The results are shown in figure 10. One can see, that most of the J/ψ decay within 2 cm. Except for very short distances, a good agreement between data and MC is found. The excess for short distances might be caused by more prompt J/ψ mesons coming directly out of the primary vertex than predicted. To remove these, a cut of $L_{3D} > 0.02$ cm might be reasonable. Such a cut would remove 4 of the 40 J/ψ candidates in our case.

3.3 J/ψ - jet relations

To carry information of the top quark, the selected J/ψ candidates should be produced inside one of the b-jets. It is thus important for future analysis to have a closer look at the angular distance between the J/ψ and the nearest jet. In detector units, a Lorentz

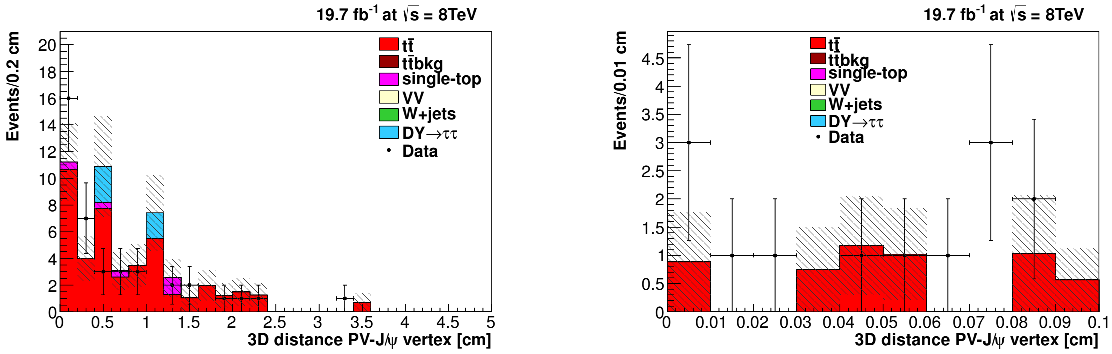

Figure 10: 3D distance between primary and J/ψ vertex at different zoom levels. The hatched area represents the statistical uncertainty on the combined MC prediction.

invariant angle can be defined as

$$\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}.$$

The ΔR between the J/ψ and the nearest jet is plotted in figure 11 on the left side. One can see that most of the J/ψ already lie inside a jet, without explicitly requiring this. In simulated events it is possible to also calculate the angular distance between the reconstructed J/ψ and the nearest b quark. The results are shown on the right side of figure 11. It is directly evident that the J/ψ's indeed come from the b quark. Moreover, the direction of the J/ψs is almost identical with the direction of the b quark. Since the data in the left plot and are well modeled and since the shapes in both plots are very similar, it is assumed that these conclusions also hold for the real data.

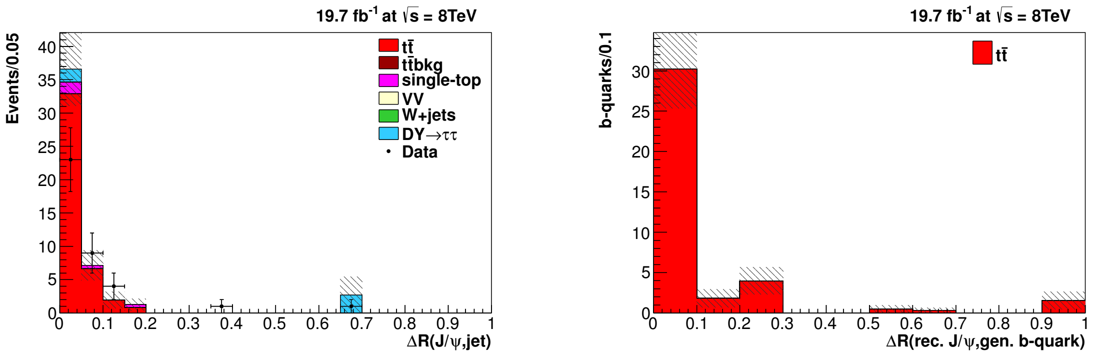

Figure 11: Left: Angular distance ΔR between J/ψ and the nearest jet. Right: From Monte Carlo generator level. Angular distance ΔR between reconstructed J/ψ and generated b quark.

Another important relation between the J/ψ mesons and the b jets is the ratio of their transverse momenta, $p_T(J/\psi)/p_T(\text{nearest jet})$. Since the the mass measurement makes use of the invariant mass of the J/ψ and the isolated lepton, which comes out the same top quark, it is essential that the J/ψ meson carries a large amount of the jet p_T. Furthermore, this distribution is expected to be specially sensitive to the b fragmentation modeling. The results can be seen in figure 12. Again, a comparison to the generated b quarks is given. A reasonable agreement between data and MC can be found as well. The J/ψ carry about half of the jet p_T. In comparison to the generated b quark, the shape is very similar. This implies that the ratio $p_T(J/\psi)/p_T(\text{nearest jet})$ is really linked to the b quark, which is a condition for the top quark mass measurement.

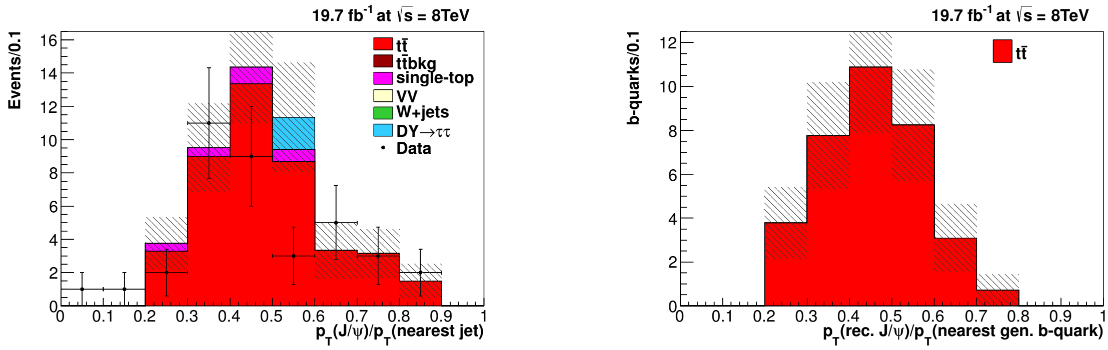

Figure 12: Left: Ration of the transversal momenta of the J/ψ and the nearest jet. Right: From Monte Carlo generator level. Ratio between the transversal momenta of the reconstructed J/ψ and the nearest b quark.

3.4 Outlook on top quark mass measurement

To measure the top quark mass via $m(lJ/\psi)$, one has to select the right combination of the J/ψ and the corresponding lepton out of the same top quark. One solution is simply to use both possible combinations per event. One would select the right combination in almost every case but also choose one wrong combination. As J/ψ and isolated lepton in wrong combinations are only marginally correlated, the spectrum of the invariant mass for wrong combinations is expected to be broader. Hence the resulting peak will still be dominated by the right combination.

Another idea can be to select the combination with the smallest angle between the J/ψ and the lepton, or the combination with the highest vectorial sum p_T. In figure 13 the resulting histograms are displayed. The shapes are reasonably described by the simulation. The peak position is located at roughly 70 GeV in all three plots. The plot with both combinations shows the broad combinatorial background around the peak.

For an actual top mass measurement one would use MC samples with various top quark masses as an input parameter and compare the different $m(lJ/\psi)$ distributions with the real data. A sketch how such simulations would look like is shown in figure 14.

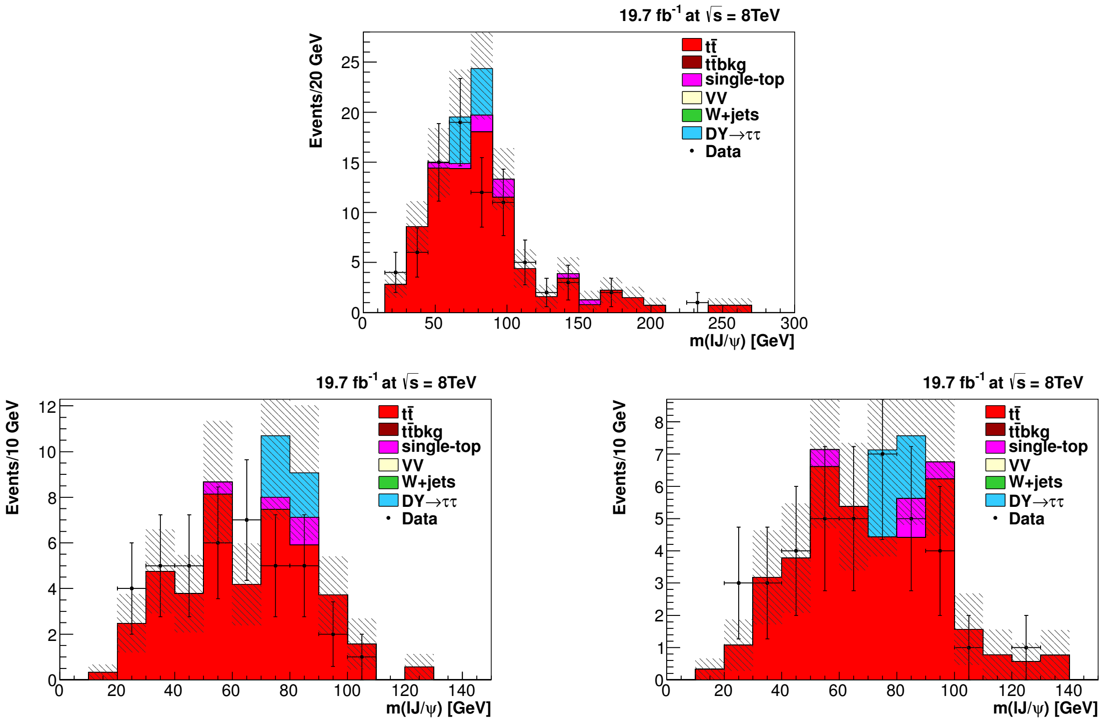

Figure 13: Invariant mass of the J/ψ together with an isolated lepton: Upper plot: both combinations added, every event is counted twice. Lower left: Combination with smalles $\Delta R(l, J/\psi)$. Lower Right: Combination with highest vectorial sum p_T.

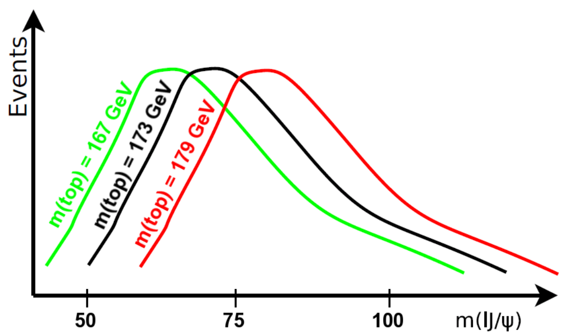

Figure 14: Sketch of the invariant mass of the J/ψ and an isolated lepton for different input parameters of the top quark mass.

4 Conclusion

In this study, the possibility to measure the top quark mass with in-jet J/ψ mesons has been analyzed. In the 2012 data with an integrated luminosity of 19.7 fb^{-1} and a center-of-mass energy of 8 TeV recorded at the CMS experiment, 40 J/ψ candidates have been found in dileptonic $t\bar{t}$ events.

Overall, a reasonable agreement between data and simulation could be verified, both concerning the overall event rate and the main kinematic distributions. Most of the J/ψ lie inside jets and have a well reconstructed common vertex. The 3D distance towards the primary vertex of the event is compatible with the expectations. Maybe slightly more prompt J/ψ mesons have been selected than expected. Further applications of this mass measurement method would require to have a closer look at this excess. Comparisons to generator information verify that the majority of the J/ψ mesons stem from b quarks and that J/ψ and b quark four-momenta are strongly correlated.

Within our statistics we did not find hints for mis-calibrated parameters in the default CMS simulation. For future mass measurements with this method, much more data are needed. The second run of the LHC starting 2015 will hopefully provide such a high luminosity that enough statistic is generated.

The work performed within this summer student project served as a crosscheck analysis for the first, preliminary results of CMS collaboration on J/ψ in $t\bar{t}$ events. [9]

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Appendix

Further control distributions can be found here.

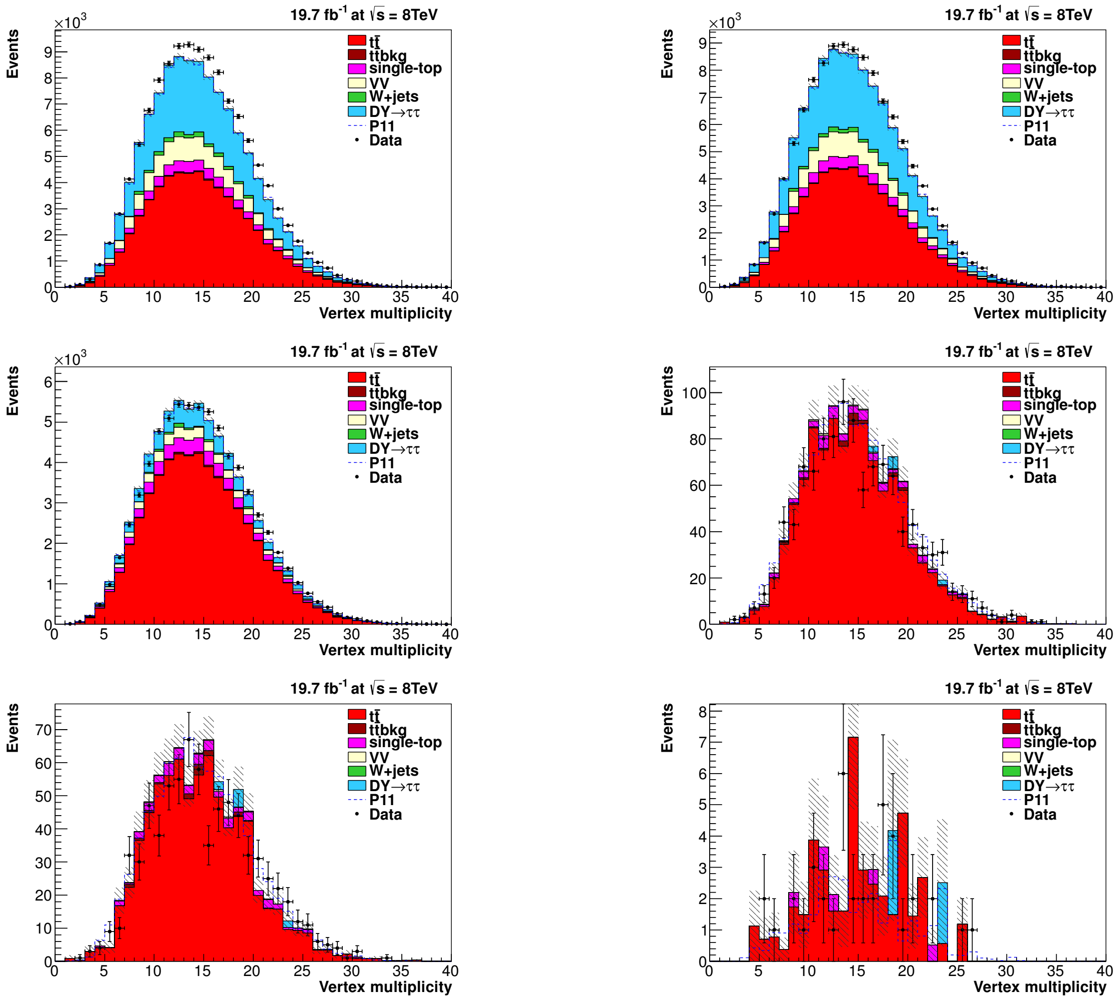

Figure 15: Vertex multiplicity after the six stages of event selection: hard isolated electron and muon (top left), $m(e^{\pm}\mu^{\mp}) > 12$ GeV (top right), at least one jet (center left), two additional muons (center right), opposite charge of additional muons (bottom left) and $m(\mu^{+}\mu^{-})$ within 3.0 and 3.2 GeV (bottom right). The hatched area represents the statistical uncertainty on the combined MC prediction.

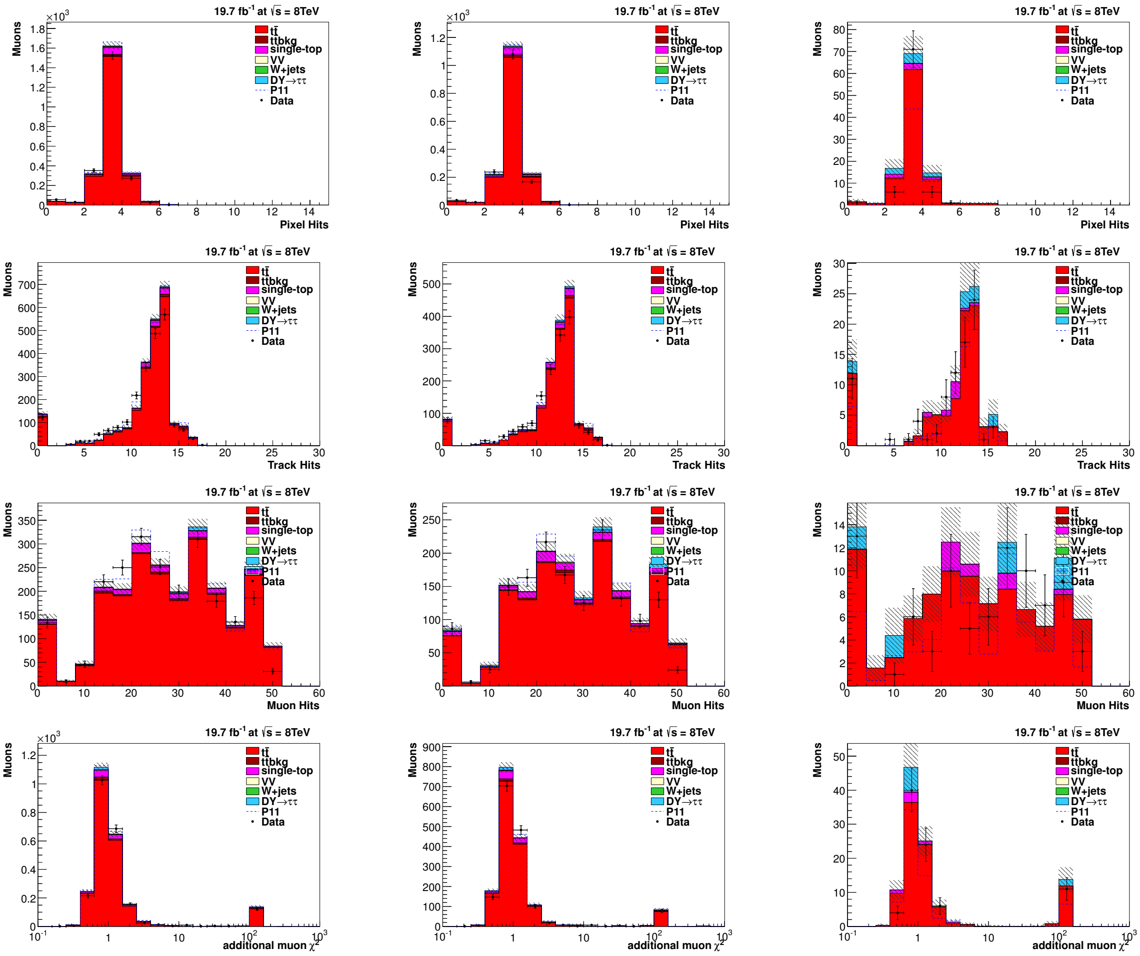

Figure 16: Properties related to the reconstruction quality of additional muons at the last three stages of the event selection: number of pixel hits (first row), of hits in the tracker (second row) and in the muon system (third row), χ^2 of the muon track fit (fourth row); after requiring two additional muons (left column), opposite charge of additional muons (central column) and $m(\mu^+\mu^-)$ within 3.0 and 3.2 GeV (right column). The hatched area represents the statistical uncertainty on the combined MC prediction.

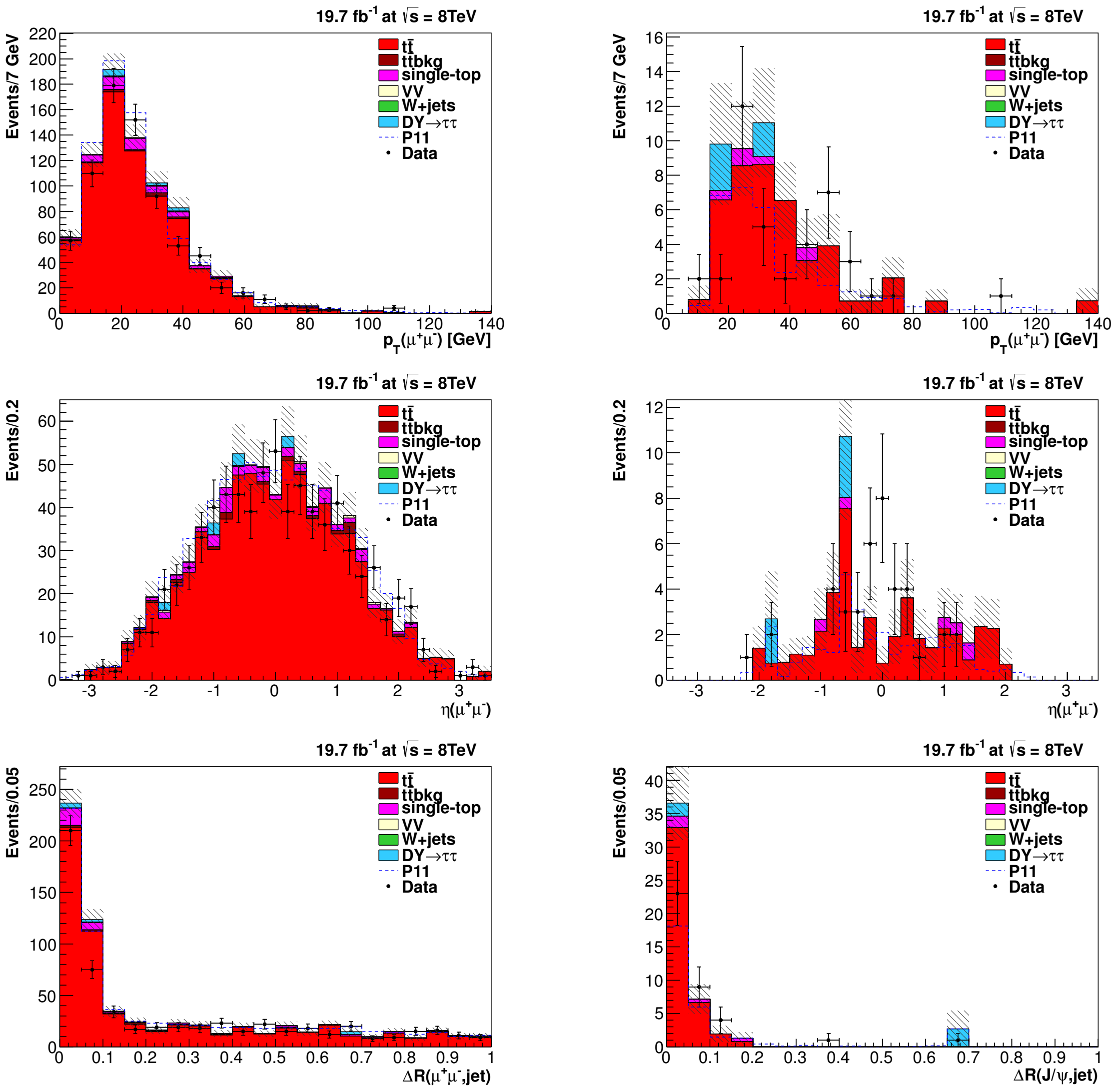

Figure 17: Transverse momentum (first row), pseudorapidity (second row) and distance to the nearest jet (third row) of the combined four-vector of opposite-sign muon pairs regardless of their invariant mass (left column) and in the J/ψ mass window (right column). The hatched area represents the statistical uncertainty on the combined MC prediction.

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