

Top mass determination in leptonic final states with J/ψ

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Taking advantage of large top production rates at the LHC, the leptonic final states with J/ψ are explored for a precise determination of the top quark mass. The top is partially reconstructed by combining the isolated lepton from the W with the J/ψ from the decays of the corresponding b -quark. The method relies, to a large extent, on the proper Monte-Carlo description of top production and decay. The main emphasis is put on the expected systematic uncertainties. Mass measurement accuracy is dominated by the current understanding of theoretical uncertainties which result in a systematic error of $\lesssim 1$ GeV.

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1 Introduction

One of the main interests in the top physics studies at the LHC will be an accurate measurement of the top mass. Being a fundamental parameter of the Standard Model (SM) it constraints, along with the W, the Higgs mass thus providing an excellent consistency check of the SM.

Currently the best Tevatron single experiment results on the top mass are obtained with the lepton plus jets final states which yield: $M_{top} = 175.9 \pm 4.8$ (stat.) ± 5.3 (syst.) (CDF) [1] and 173.3 ± 5.6 (stat.) ± 5.5 (syst.) (DØ) [2]. The systematic errors in both measurements are largely dominated by the uncertainty on the jet energy scale and amount to 4.4 GeV and 4 GeV for the CDF and DØ, respectively. On the other hand, the systematics in di-lepton channels are somewhat less, but the statistical errors are significantly larger, by a factor of $\gtrsim 2$, as compared to the lepton plus jets final states. In future runs of the Tevatron with about 20-fold increase in statistics the top mass will be measured with an accuracy of ~ 2 GeV [3]; in the lepton plus jets channel the error is dominated by the systematics while in di-lepton channels the limiting factor would still be statistics.

The legitimate question to ask – what is the ultimate precision on the top mass that can be attained at the LHC? Apparently, to significantly improve on jet measurements at LHC would be a challenge. However, one can take the advantage of large top production rates and explore leptonic final states. In this paper we consider four- (three-) lepton final states involving the $J/\psi \rightarrow \mu^+ \mu^-$ decays, see Fig. 1.

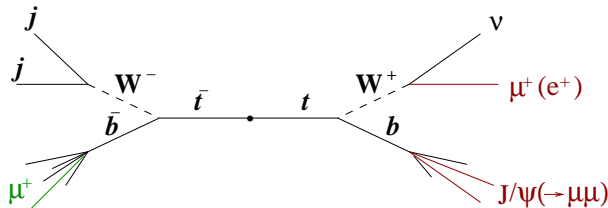


Fig. 1. Schematic of the top decay to leptonic final states with J/ψ .

Here, the top mass is partially reconstructed by combining the isolated lepton, μ or e , from the W decays with the J/ψ from the decays of the corresponding b -quark, i. e. reconstructing the lepton plus J/ψ invariant mass, $M_{\ell J/\psi}$ [4,5]. In order to determine the top decay topology one can require an additional tagging muon-in-jet coming from other b . The branching suppression factor is 5.3×10^{-5} taking into account the charge conjugate reaction and $W \rightarrow e\nu$ decays. In spite of rather low branching ratios, we stress that these final states are experimentally very clean and can be exploited even at highest LHC luminosities. Furthermore, one can also explore an other way to associated the J/ψ with the corresponding isolated lepton – by measuring the jet charge of identified b (’s) and not requiring the tagging muon. In this case we gain a factor of more than 10 in statistics as compared to the four-lepton final states.

Similar approaches, namely the use of the correlation between the top mass and its decay products, e. g. in final states with an isolated lepton combined with the muon from the semileptonic decays of the corresponding b ’s, have been explored in earlier studies [6,7]. One should say that all these methods of top mass determination essentially rely on the Monte-Carlo description of its production and decay. Nonetheless, the model, to a great extent, can be verified and tuned to the data.

2 Analysis

In the following we assume the $t\bar{t}$ production cross-section of 800 pb for $M_{top} = 175$ GeV. Events are simulated with the PYTHIA 5.7 [8] or HERWIG 5.9 [9] event generators. Particle momenta are smeared according to parameterizations obtained from detailed simulation of the CMS detector performance. Four-lepton events are selected by requiring an isolated lepton of $p_T > 15$ GeV

in central pseudorapidity range of $|\eta| < 2.4$ and three non-isolated, centrally produced muons of $p_T > 4$ GeV in $|\eta| < 2.4$, with the invariant mass of the two of them being consistent with the J/ψ mass. These cuts would significantly reduce the external (non- $t\bar{t}$) background, mainly the $Wb\bar{b}$ production,¹ which can be further reduced by employing, in addition, two central jets from another W , if needed. Resulting kinematical acceptance of the selection criteria is 0.3; this rather small value is largely due to soft muons from J/ψ and b . In one year high luminosity running of LHC, corresponding to an $L_{int} = 10^5$ pb⁻¹, and assuming the trigger plus reconstruction efficiency of 0.8, we expect about $10^5 \times 800 \times 5.3 \cdot 10^{-5} \times 0.3 \times 0.8 = 1000$ events.

An example of the $\ell J/\psi$ mass distribution with the expected background is shown in Fig. 2. The background is internal (from the $t\bar{t}$ production) and is due to the wrong assignment of the J/ψ to the corresponding isolated lepton. These tagging muons of wrong sign are predominantly originating from B/\bar{B} oscillations, $b \rightarrow c \rightarrow \mu$ transitions, $W(\rightarrow c, \tau) \rightarrow \mu$ decays, π/K decays in flight and amount to $\sim 30\%$ of the signal combinations. The shape of the signal $\ell J/\psi$ events (those with the correct sign of the tagging muon) is consistent with a Gaussian distribution over the entire mass interval up to its kinematical limit of ~ 175 GeV. The background shape is approximated by a polynomial function of degree 3. The parameters of this polynomial function are determined with “data” made of the wrong combinations of $\ell J/\psi$ with an admixture of signal. In such a way the shape of the background is determined more precisely and in situ. Thus, when the signal distribution is fitted, only the background normalization factor is left as a free parameter along with the three parameters of a Gaussian. The result of the fit is shown in Fig. 2. We point out that this procedure allows to absorb also the remaining external background (if any) into the background fit function.

As a measure of the top quark mass we use the mean value (position of the maximum of the distribution) of the Gaussian, $M_{\ell J/\psi}^{max}$. In four years running at LHC with high luminosity the typical errors on this variable, including the uncertainty on the background, are about 0.5 GeV. It is composed of $\lesssim 0.5$ GeV statistical error and $\lesssim 0.15$ GeV systematics contribution due to the uncertainty on the measurement of the background shape.

The measurement of the $M_{\ell J/\psi}^{max}$ can then be related to the generated top quark mass. An example of the correlation between the $M_{\ell J/\psi}^{max}$ and M_{top} is shown in Fig. 3 along with the parameters of a linear fit. For comparison, we also show the corresponding dependence in a more traditional isolated lepton plus μ -in-jet channel. Not surprisingly, the stronger correlation, and thus a better

¹ No reliable event generator is currently available to simulate the $Wb\bar{b}$ process. PYTHIA results indicate that with the above cuts this source of the background can be kept at a per cent level.

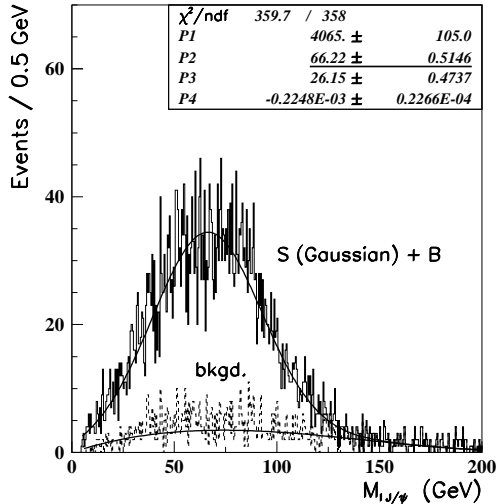


Fig. 2. Example of the $\ell J/\psi$ invariant mass spectrum in 4-lepton final states. Number of events correspond to four years running at LHC high luminosity.

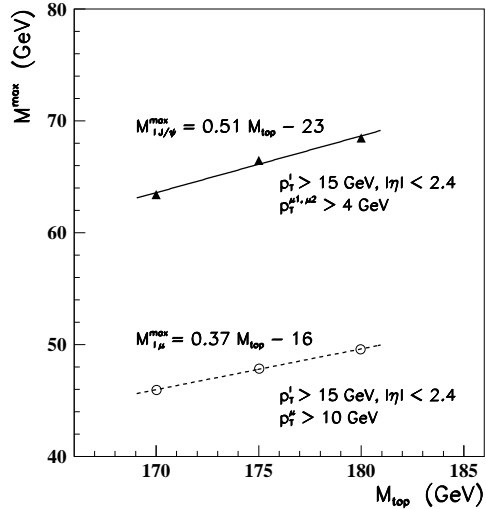


Fig. 3. Correlation between M^{max} and the top-quark mass in isolated lepton plus J/ψ (solid line) and isolated lepton plus μ -in-jet (dashed line) final states.

sensitivity to the top mass, is expected in the $\ell J/\psi$ final states as compared to the isolated lepton plus μ -in-jet channel. This is because, in the former case, we pick up a heavy object (i. e. J/ψ) from the b -jet which carries a larger fraction of its momentum. Apparently, when determining the top mass, the $M_{\ell J/\psi}^{max}$ measurement error, statistical and systematic, would scale up as the inverse slope value of the fit which is a factor of 2 in our case. Hence the statistical error on the top mass in this particular example would be ~ 1 GeV.

It is appropriate to comment on the ways to obtain a larger event sample. Possibilities might include reconstruction of the $J/\psi \rightarrow e^+e^-$ decays in b -jets [10] and/or relaxing the lepton p_T thresholds [5]. An even larger event sample can be obtained in three lepton final states, i. e. without the tagging muon, but using instead the jet charge technique to determine the $t\bar{t}$ decay topology. The jet charge is defined as a p_T -weighted charge of particles collected in a cone around the J/ψ direction. Obviously, this kind of analysis requires detailed simulations with full pattern recognition. However, particle level simulations performed with PYTHIA and with realistic assumptions on track reconstruction efficiency indicate comparable to muon-tag performance figures, but with about 10 times less integrated luminosity. In any case, through the LHC lifetime, one can collect enough events so that the overall top mass measurement accuracy would not be hampered by the lack of statistics; it would rather be limited by the systematics uncertainties which are tightly linked with the Monte-Carlo tools in use, as will be argued in the following section.

3 Systematics

Let us first briefly mention the features of PYTHIA and HERWIG that are relevant to our analysis. They both incorporate only the leading order matrix elements for $t\bar{t}$ production and decay, and simulate the QCD final state effects via parton showers. This algorithm is not exact at higher orders in α_s but could be, in principle, matched to the next-to-leading order calculations. Both event generators keep track of color connections, however the hadronization is performed in different ways: in PYTHIA (JETSET) it is done via a string fragmentation model while HERWIG exploits a cluster hadronization scheme. Eventually, free parameters of these event generators are tuned to reproduce the data, especially from e^+e^- colliders. These tunings to data usually include event shape variables, identified particles production rates, their momentum spectra, etc.

An essential aspect of the current analysis is to understand limitations which would arise from the Monte-Carlo description of the top production and decay. With PYTHIA we have investigated the following sources of systematic uncertainties on the $M_{\ell J/\psi}^{max}$ measurements:

- (i) *Initial State Radiation.*
The $M_{\ell J/\psi}^{max}$ value is unchanged even switching the initial state radiation off.
- (ii) *Final State Radiation (FSR).*
Large shift of ~ 7 GeV is observed when it is switched off. To evaluate the uncertainty we varied the parton virtuality scale m_{min} – an invariant mass cut-off below which the showering is terminated. A $\pm 50\%$ variation of it around the default (tuned to data) value of 1 GeV induces an uncertainty of $^{+0.1}_{-0.15}$ GeV.
- (iii) *QED bremsstrahlung.*
Only a small effect is observed when it is switched off. Furthermore, QED radiation is well understood and can be properly simulated.
- (iv) *Parton distribution functions (PDF).*
Depending on the relative fraction of gluon/quarks versus x in various PDFs the top production kinematics might be different. No straightforward procedure is available for the moment to evaluate uncertainties due to a particular choice of PDF. Here we compare results obtained with the default set CTEQ2L [11] and a more recent CTEQ4L [12] parameterizations of PDFs. The observed change in the $M_{\ell J/\psi}^{max}$ value is well within 0.1 GeV.
- (v) *Top p_T spectrum.*
One does not expect significant uncertainties associated with the top p_T spectrum, i. e. its generated shape. This is primarily due to a good agreement between the parton shower Monte-Carlos and the next-to-

leading order QCD calculations over a wide range of p_T up to 1 TeV. In Ref. [13] this comparison is done with the HERWIG event generator. Similar results we have obtained also with PYTHIA. However, to see an effect we have artificially altered the top p_T spectrum by applying a cut at the generator level. For example, a 1σ effect shows up only when the \hat{p}_T cut-off pushed up to 100 GeV.

(vi) *Top and W widths.*

Kinematical cuts that one applies usually affect the observed Breit-Wigner shape (tails) of decaying particles. Conversely, poor knowledge of the widths may alter the generated $\ell J/\psi$ mass spectrum depending on the cuts. Only little change in the $M_{\ell J/\psi}^{max}$ value is seen even with the zero-width approximation.

(vii) *W polarization.*

A significant shift is found for the isotropic decays of W when compared to the SM expectation of its $\sim 70\%$ longitudinal polarization. In future runs of the Tevatron the W polarization will be measured with a $\sim 2\%$ accuracy [3], and at the LHC this would be further improved so that it should not introduce additional uncertainties in simulations.

(viii) *$t\bar{t}$ spin correlations.*

A “cross-talk” between t and \bar{t} decay products is possible due to experimental cuts. To examine this effect in details the $2 \rightarrow 6$ matrix elements have been implemented in PYTHIA preserving the spin correlations [14]. No sizeable difference in the $M_{\ell J/\psi}^{max}$ value is seen compared to the default $2 \rightarrow 2$ matrix elements.

(ix) *b fragmentation, except FSR.*

As a default, in PYTHIA we have used the Peterson form for the b -quark fragmentation function with $\varepsilon_b = 0.005$. Variation of this value by $\pm 10\%$ [15] leads to an uncertainty of ${}_{+0.25}^{-0.3}$ GeV.

(x) *Background.*

The uncertainty would be mainly due to an inaccurate measurement of the background shape and the systematics contribution of $\lesssim 0.15$ GeV quoted in previous section would scale down with increasing statistics. For example, already with $\sim 10^4$ events the induced uncertainty is $\lesssim 0.1$ GeV.

(xi) *Detector resolution.*

Here we have considered only Gaussian smearing of particle momenta and the effect on the $M_{\ell J/\psi}^{max}$ measurement uncertainty is negligible. A possible nonlinearity of the detector response can be well controlled having a huge sample of J/ψ , Y and Z leptonic decays that will be available at LHC.

A summary of these studies is given in Fig. 4. One sees an impressive stability of results for reasonable choices of parameters. The expected systematic error in the $M_{\ell J/\psi}^{max}$ determination is $\lesssim {}_{-0.4}^{+0.3}$ GeV which translates into a systematic error on the top mass of $\delta M_{top} \lesssim {}_{-0.8}^{+0.6}$ GeV.

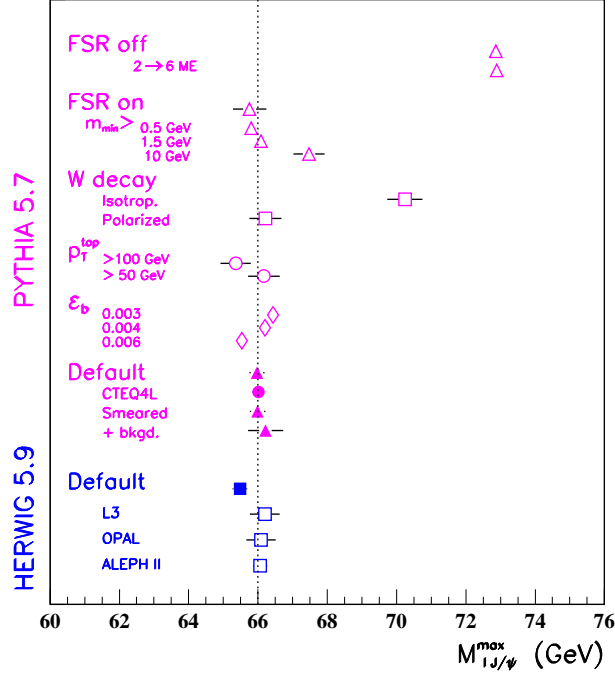


Fig. 4. Summary on the systematics studies.

Another way to estimate systematics uncertainties could be by a comparison of PYTHIA and HERWIG expectations. With HERWIG we have tried various tunings from LEP experiments as well as its default settings listed in Table 1. They all yield comparable results to each other and to PYTHIA results, and are within $\lesssim 0.5$ GeV.² This corresponds to a systematic uncertainty $\delta M_{top} \lesssim 1$ GeV.

Table 1
HERWIG parameter settings [9].

Parameter	Default	ALEPH II	L3	OPAL
Λ_{QCD}	0.18	0.173	0.177	0.15
$m_g^{eff.}$	0.75	0.645		0.7
CLMAX	3.35	3.025	3.006	3.75
CLPOW	2.		2.033	1.3
PSPLT	1.	0.984		0.85
CLSMR	0.		0.35	

² This should be taken with a precaution – bugs have been found in the treatment of the top decays in HERWIG [16] – so its impact on current analysis should be evaluated once the improved version of HERWIG is publicly available.

One more feature specific to top decays is related to the matrix element corrections to parton shower simulations [16]. A significant shift is observed in the mean value of the isolated lepton plus B -hadron invariant mass spectra when these corrections are implemented in HERWIG [17]. On the other hand, this shift does not necessarily induces an additional systematic error (which is at least partially accounted for in 2 – the FSR effects) once it is properly taken into account. Further studies are required when the corresponding implementation is publicly made available.

4 Conclusions

Abundant production of top quarks at LHC allows to use leptonic final states to precisely determine the top quark mass thus avoiding limitations that are ultimately associated to measurements with jets.

- In $\ell J/\psi$ final states the top mass can be determined with a systematic uncertainty of $\lesssim 1$ GeV.
- These final states are experimentally very clean and can be exploited even at highest LHC luminosities.
- The method heavily relies on the Monte-Carlo description of top production and decay, however the model can be verified and tuned to the data.
- The precision would be limited by the theoretical uncertainties which is basically reduced to the one associated with the $t \rightarrow b$ transition.

To conclude, this method of top mass determination looks very promising and particularly well suited for the CMS detector with its 4 Tesla field and ensuring precise lepton measurements.

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