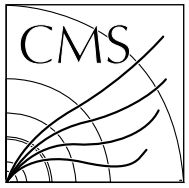

The Compact Muon Solenoid Experiment

CMS Note

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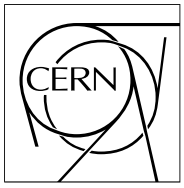

08 May 2006

Relative Contributions of t- and s-Channels to the $ZZ \to 4\mu$ Process

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Abstract

We show that the s-channel contribution to the $q\bar{q} \to ZZ \to 4\mu$ process, the main irreducible background in searches for the Higgs boson via its $H \to ZZ \to 4\mu$ decay mode, not available in the PYTHIA event generator, can add as much as $\sim$15% to the cross section arising from the commonly considered t-channel process. Moreover, the s-channel contribution has very different kinematics and cannot be taken into account by introducing an overall scaling K-factor. In particular, it results in a peak at the 4-muon invariant mass equal to the Z mass.

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1 Introduction

The $q\bar{q} \to ZZ \to 4\mu$ process is the main irreducible background in searches for the Higgs boson via its $H \to ZZ \to 4\mu$ decay mode. Figures 1 and 2 show the t- and s-channel diagrams. PYTHIA [1], an event generator commonly used for simulation of this process at the LHC, unfortunately is missing the s-channel contribution. In this note, we show that the s-channel subprocess and its interference with the t-channel cannot be neglected if one aims to simulate the ZZ-background with a precision of 10% or better.

One may notice that very different kinematics are expected for the s- and t-channel events. For example, the invariant mass of the four muons for the s-channel contribution will tend to have a peak around the Z^0 mass with a tail to high invariant masses, because a Z is radiated from one of the muon legs in the decay of the first Z, whereas the t-channel has a more complicated structure with at least two distinct peaks around the Z^0 mass and twice the Z^0 mass, with a tail to even higher values.

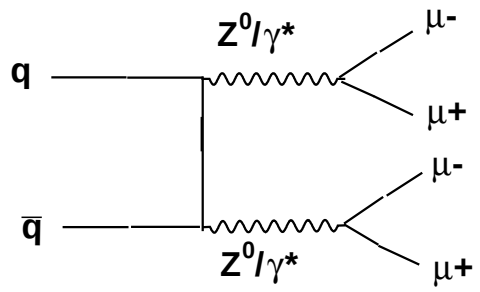

Figure 1: ZZ background: t-channel diagram.

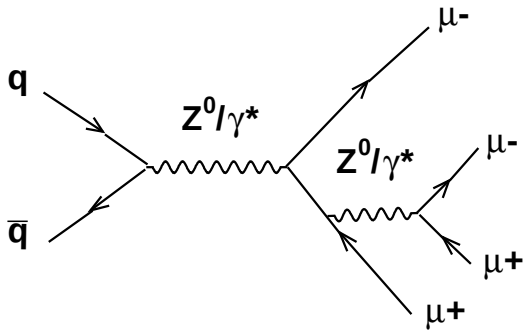

Figure 2: ZZ background: s-channel diagram.

2 Event Generation

2.1 Generation technical details

For this study we used event samples of ZZ (by Z in the ZZ process here and below we mean $Z/Z^*/\gamma^*$) background produced with PYTHIA only (PYTHIA parameters: MSEL = 0, MSUB 22 = 1) and with CompHEP-PYTHIA. The latter uses the CompHEP [2] matrix element (ME) generator interfaced to PYTHIA, which is used for showering and hadronization in the same way and with the same parameters as for the pure-PYTHIA sample. Below, we refer to CompHEP-PYTHIA samples simply as CompHEP samples. The main subprocesses resulting in 4μ in the final state are:

- $ZZ \to 4\mu$,
- $ZZ \to 2\tau 2\mu \to 4\mu$ (not used in this analysis),
- $ZZ \to 2b2\mu \to 4\mu$ (not used in this analysis).

For normal analysis cuts, which select a region of 4μ invariant masses between about 110 and 170 GeV, we expect about 33 events from the first process, about 4 events for the second and about 3 events for the third. The latter one will become negligible after isolation cuts. All event numbers in this note are normalized to 30 fb^{-1} of integrated luminosity.

We use the CTEQ5L PDF [3] and the $\hat{s}\ Q^2$ scale parameter [1] in both CompHEP and PYTHIA (the $\hat{s}\ Q^2$ scale is not a default in PYTHIA 6.223). Generator-level "pre-selection" cuts are: $P_T > 3$ GeV, $|\eta| < 2.5$ for all four muons. The PYTHIA sample's generation-level "pre-selection" cut are: $P_T > 3$ GeV, $|\eta| < 2.5$ for the four selected muons. Additional cuts on the invariant masses of any two pairs of selected opposite sign muons are: $5 < M_{\mu^+\mu^-} < 150$ GeV (the cross sections, especially for the s-channel, are sensitive to the lower limit; the upper limit, once it is sufficiently higher than m_{Z^0}, is not important).

2.2 Events selection and analysis cuts

To perform a generator-level study, we select events in a similar way as for the full simulation-level analysis [4].

The selection cuts are:

- $\mathrm{P_T} > 7$ GeV (for the barrel, $|\eta| < 1.1$) or $\mathrm{P} > 9$ GeV (for the endcaps, $|\eta| > 1.1$) for all considered muons. These cuts correspond to a muon reconstruction efficiency of 80-90%.
- There should be at least four such muons (2 opposite sign muon pairs) for an event to be considered.
- All four permutations of opposite sign muon pairs should have invariant mass $\mathrm{M}_{\mu^+\mu^-} > 12$ GeV (for the four muons selected). This cut on $\mathrm{M}_{\mu^+\mu^-}$ removes low-mass resonances.

We also use in this study an example of analysis cuts similar to optimized for small Higgs boson masses, as listed in Table 1.

The notations we use for the analysis-level cuts include:

- Z1 ($\mathrm{M}_{\mu^+\mu^-}$) refers to the muon pair with invariant mass closest to the Z^0 mass and Z2 refers to the second muon pair selected from the rest of the muons with the highest P_T.
- $\mu_1, ..., \mu_4$ are the four selected muons when they are sorted by P_T, largest to smallest.
- $\mathrm{M}_{4\mu}$ is the invariant mass of the four selected muons.

Table 1: Analysis-level cuts (example of cuts optimized for the small Higgs boson mass region, $\mathrm{M}_{4\mu} < 160$ GeV).

parameter	cut, GeV
P_T μ_1	14
P_T μ_2	10
P_T μ_3	10
P_T μ_4	7
Z1 ($\mathrm{M}_{\mu^+\mu^-}$)	> 60
Z1 ($\mathrm{M}_{\mu^+\mu^-}$)	< 110
Z2 ($\mathrm{M}_{\mu^+\mu^-}$)	> 12
Z2 ($\mathrm{M}_{\mu^+\mu^-}$)	< 60
$\mathrm{M}_{4\mu}$	> 110

3 Comparison of CompHEP and Pure-PYTHIA Generated Events

We make comparisons with three samples:

- s- plus t-channel diagrams included, CompHEP sample,
- t-channel only, pure-PYTHIA sample,
- t-channel only, CompHEP sample (for cross checks).

3.1 CompHEP vs. PYTHIA: comparison of t-channel only samples

Before making a comparison of events for which the s- and t-channel diagrams are included (CompHEP) with t-channel diagram events only (pure-PYTHIA), we compare t-channel CompHEP and t-channel pure-PYTHIA events. This cross check is necessary to be sure that the effect, if it exists, is not due to a difference in internal cuts, model parameters or something similar, but indeed is a consequence of taking the s-channel into account, as well as interference between the s- and t-channels.

Figures 3, 4, 5 and 6 show the results of the t-channel only comparison. Figure 3 shows the entire $\mathrm{M}_{4\mu}$ interval of interest, and Figs. 4, 5 and 6 show different sub-intervals for better comparison. It is clear, that the t-channel only samples generated with PYTHIA and with CompHEP have almost identical $\mathrm{M}_{4\mu}$ spectra (up to the level of the statistical precision of the results).

3.2 Comparison of t- and s-channel sample (CompHEP) vs. t-channel sample only (pure-PYTHIA)

We now compare the s- and t-channel CompHEP events to t-channel only PYTHIA events.

There are three regions of interest in the 4μ invariant mass ($M_{4\mu}$). The first one is near the Z^0 mass. Because of the s-channel, in particular, this region has a peak. The peak is clearly seen after both selection and analysis cuts (optimized for small m_H region), see Figs. 7 and 8.

Another region of interest is the low mass region with $M_{4\mu} < 160$ GeV. This is where we applied our example set of analysis cuts (optimized for small m_H region). In this region, due to the s-channel presence and interference between the t- and s-channels, we see an excess of events over the t-channel-only case at the level of 10-15% (even after the analysis cuts), see Fig. 9.

Even in the third region of interest ($M_{4\mu} > 160$ GeV), the s-channel contribution still is not negligible, $\sim 5-7\%$ (Fig. 10).

We also show that effect of s-channel contribution survive for fully simulated events as in the most recent version of full analysis [4] we use CompHEP samples. Figures 11 and 12 show s-channel contribution effect after selection cuts for low and intermediate Higgs bson masses after selection cuts as well as peak around Z^0 mass.

The overall numbers of 4μ events after different cuts are shown in Table 2. "Pre-selection" cuts are defined in Section 2.1, "selection" and "analysis" cuts are defined in Section 2.2. The numbers for the t-channel contributions for the PYTHIA- and CompHEP-produced samples in the first two columns (σ (pre-selection) in fb and the corresponding N (pre-selection) of expected events) are different because of different pre-selection cuts for these two generators. Once the cut on the invariant mass of all four permutations of $\mu^+\mu^-$-pairs is introduced (and other cuts are the same as well), the expected event numbers for the t-channel contribution for the PYTHIA and CompHEP samples are the same up to the level of statistical precision.

Table 2: Cross section values for the t- and s-channel CompHEP sample, the t-channel CompHEP and PYTHIA samples and the corresponding expected numbers of events for 30 fb^{-1} integrated luminosity with Monte Carlo (MC) statistical errors (numbers and corresponding statistical errors are scaled according to cross-section and integrated luminosity from a much larger number of MC generated events).

process	σ (pre-selection), fb	N (pre-selection)	N (selection)	N (analysis)
CompHEP, s- and t-channel	65.0	1950 ± 4.6	224 ± 1.6	42.6 ± 0.68
CompHEP, t-channel only	18.8	565 ± 1.1	184 ± 0.64	29.3 ± 0.25
pure PYTHIA	9.93	298 ± 0.98	186 ± 0.77	30.4 ± 0.31

4 Summary

PYTHIA does not include the s-channel (and its interference with the t-channel) in ZZ background generation.

We have shown that the s-channel contribution to the main t-channel is non-negligible in the context of the backgrounds for the $H \to 4\mu$ analysis in the area of interest, $M_{4\mu} > 115$ GeV. This contribution remains non-negligible after all analysis cuts.

5 Acknowledgments

We would like to thank M. Aldaya, P. Arce, J. Caballero, B. Cruz, T. Ferguson, U. Gasparini, P. Garcia, J. Hernandez, I. Josa, P. Moisenz, E.R. Morales, N. Neumeister, A. Nikitenko, F. Palla, T. Sjostrand and I. Vorobiev for their active participation in the analysis discussions and comments on the text of this Note.

References

[1] T. Sjostrand *et al.*: *"The complete PYTHIA 6.206 manual"*, hep-ph/0108264, http://www.thep.lu.se/ torbjorn/Pythia.html

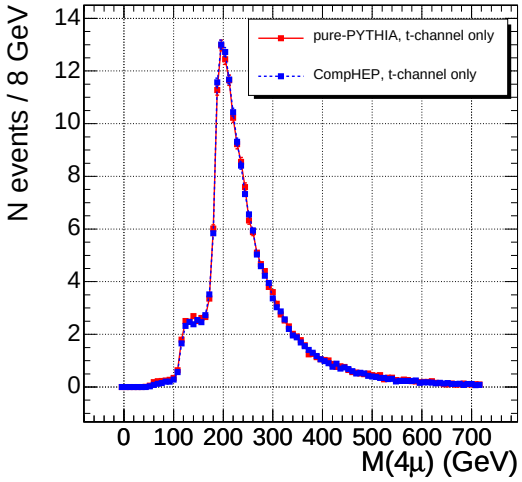

Figure 3: 4μ invariant mass distribution after selection cuts, $\mathrm{L} = 30\ \mathrm{fb}^{-1}$. Comparison of t-channel CompHEP generated events and t-channel PYTHIA ones. Error bars include the MC statistical contribution only.

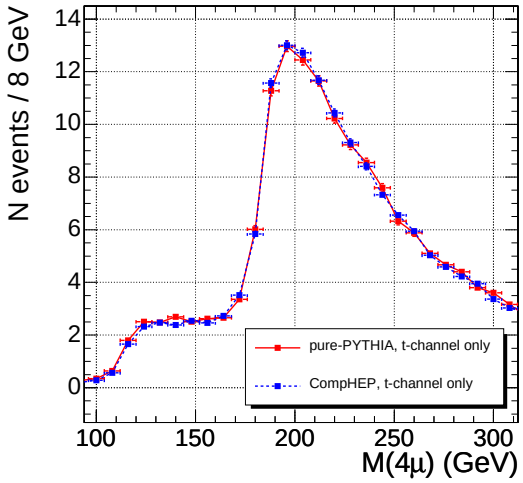

Figure 4: Enlarged part of Fig. 3, $100 < \mathrm{M}_{4\mu} < 300$ GeV.

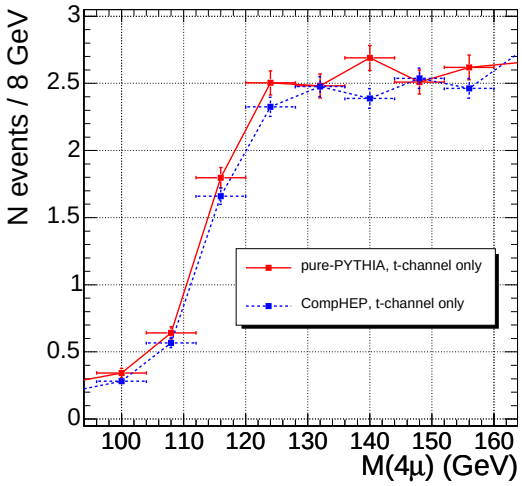

Figure 5: Enlarged part of Fig. 3, $100 < \mathrm{M}_{4\mu} < 160$ GeV.

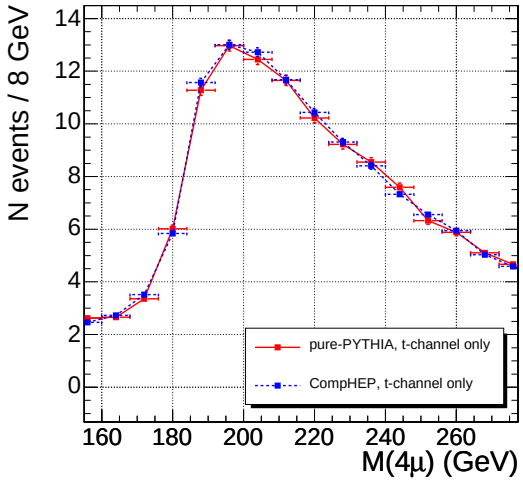

Figure 6: Enlarged part of Fig. 3, $160 < \mathrm{M}_{4\mu} < 260$ GeV.

[2] CompHEP collaboration: *"CompHEP - a package for evaluation of Feynman diagrams and integration over multi-particle phase space. User's manual for version 33"*, hep-ph/9908288, http://theory.sinp.msu.ru/parser/parser.php?file=/phpcms/comphep

[3] D.R. Stump, Proceedings of the 31st International Conference on High Energy Physics (ICHEP 2002), Amsterdam, The Netherlands, 24-31 July 2002. Published in "Amsterdam 2002, ICHEP" 265-267.

[4] S. Abdullin et al., "*Search for* $\mathrm{H} \to \mathrm{ZZ}^{(*)} \to 4\mu$ *Using* $M(4\mu)$*-Dependent Cuts.*", CMS Note in preparation

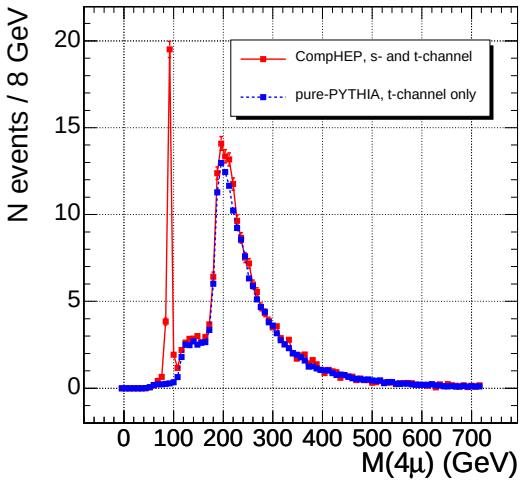

Figure 7: 4μ invariant mass distribution after selection cuts, $\mathrm{L} = 30\ \mathrm{fb}^{-1}$. Comparison of s- plus t-channel CompHEP generated events and t-channel only PYTHIA ones. Error bars include MC statistical contribution only.

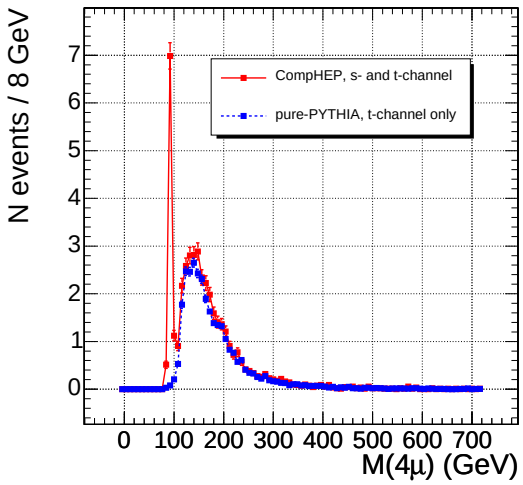

Figure 8: Same as Fig. 7 but after analysis cuts (see Table 1).

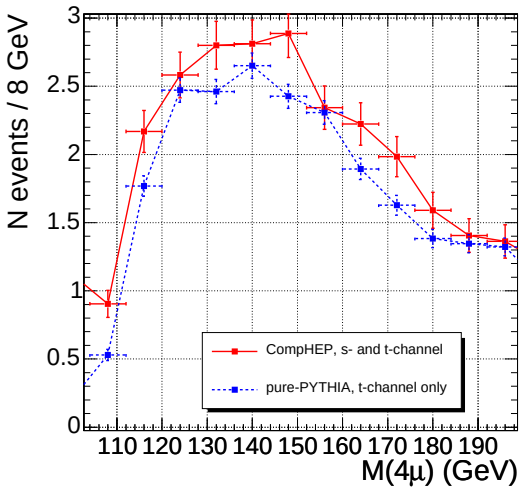

Figure 9: Enlarged part of Fig. 8.

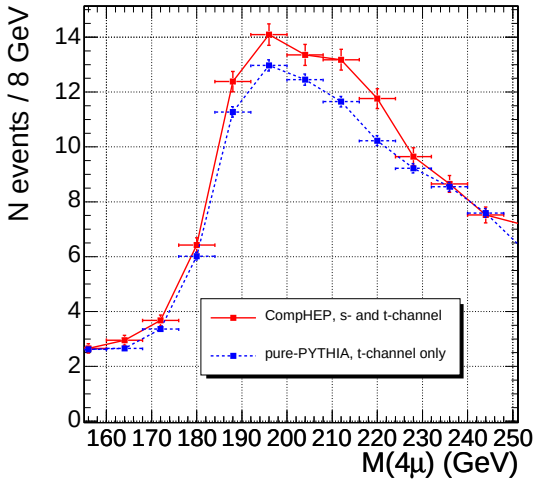

Figure 10: Enlarged part of Fig. 7 for $\mathrm{M}_{4\mu} > 160\mathrm{GeV}$.

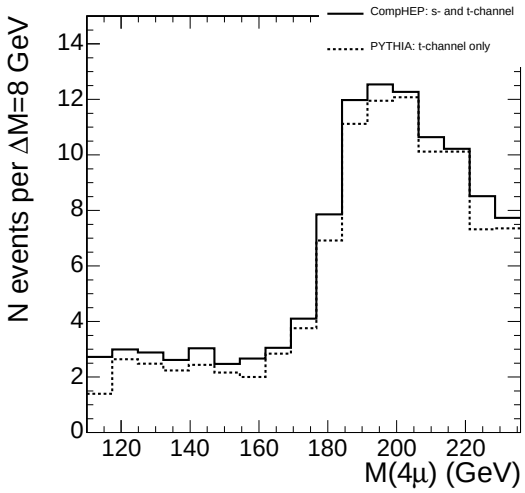

Figure 11: S-channel contribution effect after selection cuts for low and intermediate Higgs bson masses after selection cuts for fully simulated events.

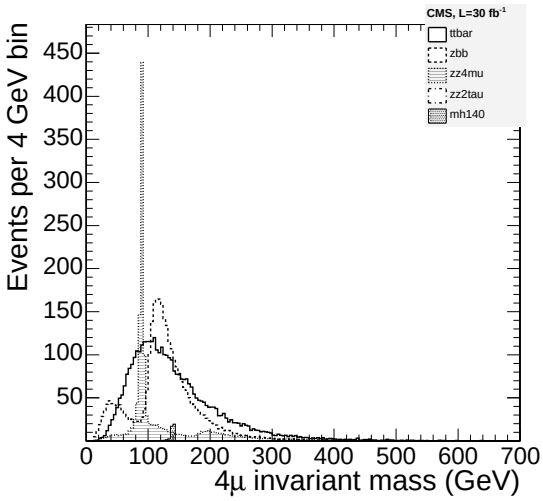

Figure 12: S-channel contribution peak around Z^0 mass after pre-selection cuts for fully simulated events.