Search for Higgs and Z boson decays to $J/\psi$ or $\Upsilon$ pairs in the four-muon final state in proton-proton collisions at $\sqrt{s} = 13$ TeV


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*The CMS collaboration*, published 2019

**Introduction to the LHC mini-workshop,**

**N CB J Warsaw**

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Overview

- Introduction
- Analysis
- Results
- Conclusion
Introduction

Higgs and Z decays

- This analysis searches for $H, Z \rightarrow QQ$ decays, specifically to $J/\psi$ and $Y(nS)$ ($n=1,2,3$) pairs that decay further to $\mu^+\mu^-$ pairs.

- The observation of these $4\mu$ states are an experimentally clean method of studying Yukawa couplings to quarks and also an indication to BSM physics.

- New physics affects the direct boson couplings or through loops which changes the interference patterns between amplitudes - leading to enhancement of branching fractions compared to SM prediction.

Feynman diagrams showing $H, Z \rightarrow QQ$ where $Q = \text{charmonium or bottomonium states}$.

- 1 and 2 show Higgs decay with Z boson as virtual particles
- 3 is an indirect process if the loop contains top quarks and direct if $c, b$
- 4 shows the direct processes.
Introduction

CMS detector* trigger system

• Two-tiered trigger system:
• First level - custom hardware processors - use calorimeter and muon detector info to select events at 100 kHz rate within 4μs.
• Second level - high-level trigger - multiple processors running full event reconstruction software and it reduces event rate to 1kHz before storage.

Atleast 3 muons ($p_T > 2$ GeV)

2 of these - opposite charge, Common vertex of origin (Kalman vertex fit probability > 0.5%)

For $J/\psi$: a dimuon system invariant mass in [2.95,3.25] GeV, $p_T > 3.5$ GeV

For $\Upsilon$: 2 of 3 muons with $p_T > 3.5$ GeV, 1 muon with $p_T > 5$ GeV
one dimuon inv. mass in [8.5,11.4] GeV

Efficiency > 85% for events of interest

Dedicated trigger deployed in 2017 for enhancing event selection of this study

* More about the detector in backup
Analysis

Signal & bkg modelling

- Higgs and Z boson decays are simulated using various frameworks* to get an estimate on expected signal events and also the $4\mu$ invariant mass distribution.
- For calculating $\mathcal{B}(H \to \mu^+\mu^-)$, total SM Higgs production xsec is taken from LHC Higgs xsec group.
- For Z boson, total xsec is obtained with $\mathcal{B}(Z \to \mu^+\mu^-)$ value from PDG.
- The main bkgds to the signal originate from prompt nonresonant pair production that occur via gluon-gluon fusions ($gg \to J/\psi J/\psi$)

CMS detector data from 2017, 37.5 fb$^{-1}$

* Refer backup
Analysis

Signal & bkg modelling

• These events then pass through GEANT4 simulation of the CMS detector.
• For each bunch crossing, there will be multiple $pp$ interactions.
• Simulation of simultaneous $pp$ interactions which overlap with events of interest (pileup avg = 32) are also done.
• The acceptance of final states is a function of angular distribution of muons which is proportional to $1 + \lambda_\theta \cos^2 \theta$.
• In this analysis, nominal results are obtained by using unpolarised case ($\lambda_\theta = 0$).
• Two additional calculations with $J/\psi$ and $\Upsilon$ with fully transverse ($\lambda_\theta = +1$) and fully longitudinal ($\lambda_\theta = -1$) polarisations are also included.
Analysis

Reconstruction & selection

- Combined information from silicon tracker and the muon system is used for muon reconstruction*.
- The primary $pp$ interaction vertex is taken as the recon. vertex with largest $\Sigma_{charged} p_T^2$.
- To reduce nonprompt hadron decay muons, impact param of each muon track has to be less than 0.3 (20.0) cm in transverse plane (longitudinal axis).
- If events have 4 such muons and with $p_T > 3.5$ GeV and $|\eta| < 2.4$, they are accepted.
- The leading muon candidates are isolated from other hadronic activity by demanding the sum of $p_T$ of reconstructed inner-detector tracks originating from primary vertex within a cone† constructed around the muon's momentum direction to be less than 50% of muon's $p_T$.
- $p_T$ of the leading muon is subtracted from the sum and also of subleading muon if it is in the isolation cone.

\[ \Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} = 0.3 \]

† Conical size $\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} = 0.3$

* Refer backup
Each of the pairs of oppositely charged muons should have a common vertex probability > 0.5%

$p_T > 3.5$ GeV,
Inv mass of higher & lower $p_T$ should be within 0.1 and 0.15 GeV of $J/\psi$'s nominal mass

To suppress bkg, 4$\mu$ Kalman vertex fit probability > 5%

$|\Delta$ rapidity $< 3|$ (rapidity between the two $J/\psi$ candidates)

189 $J/\psi$ pair events in 40-140 GeV
4$\mu$ invariant mass range

Each of the pairs of oppositely charged muons should have a common vertex probability > 0.5%

$p_T > 5$ GeV,
Inv mass should fall within 8.5-11 GeV

To suppress bkg, 4$\mu$ Kalman vertex fit probability > 1%

$|\Delta$ rapidity $< 3|$ (rapidity between the two $Y$ candidates)

106 $Y$ pair events in 20-140 GeV
4$\mu$ invariant mass range
Results

- Unbinned extended maximum-likelihood fits are performed on the $4\mu$ invariant mass distributions ($M_{4\mu}$) with yields for signals and background as free params in the fit.

- The invariant mass dist. of Higgs decay is described with two gaussians with a common mean. For Z boson is described using a Voigtian function with the world-avg value for Z boson resonance width.

- $J/\psi$ events are fit with an exponent+constant function and $\Upsilon$ with just an exponent (blue line)

The 4-muon invariant mass distributions for $J/\psi J/\psi$ (top) and $\Upsilon \Upsilon$ (bottom)
Results

• As seen in the plots from previous slides, no events are observed above $M_{4\mu} = 40\text{GeV}$.

• Also, for both the cases, no signal is observed for either of the bosons.

• Hence, an upper limit on the branching fractions are obtained using a modified frequentist approach CL$_s$.

• Uncertainties come from multiple sources that affect signal yields both from experimental and theoretical sides. The relative impact of these uncertainties is less than 2%.

• The upper limits on the various branching fractions are shown in the table ->

<table>
<thead>
<tr>
<th>Process</th>
<th>Observed</th>
<th>Expected</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mathcal{B}(H \rightarrow J/\psi J/\psi)$</td>
<td>$1.8 \times 10^{-3}$</td>
<td>$(1.8^{+0.2}_{-0.1}) \times 10^{-3}$</td>
</tr>
<tr>
<td>$\mathcal{B}(H \rightarrow YY)$</td>
<td>$1.4 \times 10^{-3}$</td>
<td>$(1.4 \pm 0.1) \times 10^{-3}$</td>
</tr>
<tr>
<td>$\mathcal{B}(Z \rightarrow J/\psi J/\psi)$</td>
<td>$2.2 \times 10^{-6}$</td>
<td>$(2.8^{+1.2}_{-0.7}) \times 10^{-6}$</td>
</tr>
<tr>
<td>$\mathcal{B}(Z \rightarrow YY)$</td>
<td>$1.5 \times 10^{-6}$</td>
<td>$(1.5 \pm 0.1) \times 10^{-6}$</td>
</tr>
</tbody>
</table>

Exclusion limits at 95% CL for $\mathcal{B}(H, Z \rightarrow J/\psi, \Upsilon$ pairs) for the unpolarized case.

• In the case of fully polarized scenario, the relative changes with respect to unpolarized case is -22% (longitudinal) and +10% (transverse) for H decay for both J/ψ and Υ.

• For Z decay, this is -29(-26)% and +13(+12)% for J/ψ (Υ) respectively.
Summary

• First search for Higgs & Z boson → \( J/\psi \) or \( \Upsilon(nS) \) (n=1,2,3) and subsequently to \( \mu^+\mu^- \) pairs are discussed in this letter.

• pp collision data which corresponds to an integrated luminosity of 37.5 fb\(^{-1}\) at \( \sqrt{s} = 13 \text{ TeV} \) was used for the analysis.

• Analysis shows no excess of events above a small bkg in the case of \( J/\psi \) pair channel and with a vanishingly small bkg for \( \Upsilon \) pair channel.

• At 95%CL, for unpolarized mesons, Higgs boson decay upper limits were found to be: 
  \[ \mathcal{B}(H \rightarrow J/\psi J/\psi) < 1.8 \times 10^{-3} \text{ and } \mathcal{B}(H \rightarrow \Upsilon \Upsilon) < 1.4 \times 10^{-3} \]

• The same for Z bosons were found to be: 
  \[ \mathcal{B}(Z \rightarrow J/\psi J/\psi) < 2.2 \times 10^{-6} \text{ and } \mathcal{B}(Z \rightarrow \Upsilon \Upsilon) < 1.5 \times 10^{-6} \] where all 3 \( \Upsilon(nS) \) are considered.

• For the extreme polarization case, variation of -(22-29)% for longitudinal and +(10-13)% for transverse polarized mesons were observed.

This motivates for a better calculation of rare Higgs decay branching fractions because even a few signal events will indicate BSM physics!!!
Backup
Systematics

- Systematics arise from the differences in efficiency between data and simulated events for the trigger, offline muon recon. and ID, isolation.

- This is corrected by reweighting the simulated events with data-to-simulation correction factors.

- Tag-and-probe method described in http://dx.doi.org/10.1007/JHEP10(2011)132 is used to do this with $J/\psi \rightarrow \mu^+\mu^-$ events.

- The correction factors deviate from unity by less than 3%.

- The data-simulation difference in 4$\mu$ Kalman vertex fit efficiency for $J/\psi$ pair event samples is less than 3%.

- Total signal efficiency for $J/\psi J/\psi$ with unpolarized $J/\psi$ is $\sim 23\%$ for both H and Z.

- For $\Upsilon\Upsilon$, this is $\sim 27\%$.
Simulation frameworks

- \( H \rightarrow J/\psi J/\psi \) and \( H \rightarrow \Upsilon \Upsilon \), Higgs simulated using **POWHEG v2.0 MC generator**
- Parton distribution function set - **NNPDF3.1**
- Higgs \( \rightarrow 2 \) vector mesons with helicity information - **JHUGen 7.1.4 generator**
- Parton showering, hadronization, \( Z \rightarrow J/\psi J/\psi \) and \( Z \rightarrow \Upsilon \Upsilon \) - **PYTHIA 8.226** with **CUETP8M1 tune**.
- SM Z boson prod. xsec includes NNLO, NLO informatio from **FEWZ 3.1** calculated using NLO PDF set from NNPDF3.0
- Background event simulation - **DJpsiFDC**
- CMS detector simulation - **GEANT4**
- Kalman vertex fitting - Application of Kalman filtering to track and vertex fitting
CMS detector

- Superconducting solenoid with an axial B field of 3.8T
- Inside: Silicon pixel and strip tracker, lead tungstate crystal EM calorimeter, brass & scintillator hadron calorimeter each with barrel & 2 endcap sections
- Forward calorimeters for extending the pseudorapidity coverage ($\eta$)
- Gas-ionization chambers outside the solenoid for $\mu$ detection.
- Dedicated triggers deployed in 2017 for selection enhancements of signal of interest.

Source: https://cms.cern/index.php/detector
Muon reconstruction

Muons are reconstructed by combining information from the silicon tracker and the muon system [52]. The matching between tracks reconstructed in each of the subsystems proceeds either outside-in, starting from a track in the muon system, or inside-out, starting from a track provided by the silicon tracker. In the latter case, tracks that match track segments in only one or two stations of the muon system are also considered in the analysis to collect very low-$p_T$ muons that may not have sufficient energy to penetrate the entire muon system. The muons are selected from the reconstructed muon track candidates that match with at least one segment in any muon station in both $x$ and $y$. The number of silicon tracker layers with hits used in the muon track candidate has to be greater than 5 and include at least one pixel detector layer. Matching muons to tracks measured in the silicon tracker results in a relative transverse momentum ($p_T$) resolution of 1% in the barrel and 3% in the endcaps for muons with $p_T$ up to 100 GeV. The $p_T$ resolution in the barrel is better than 7% for muons with $p_T$ up to 1 TeV [52].

Paper statistics

- This letter was cited by 11 documents:
- 8 articles (7 published), 2 theses and 1 conference paper.
- The main category spanning these documents were hep-ph (7), hep-ex (4) and nucl-ex and nuc-th (1 each)

Source: https://inspirehep.net/literature/1736895