PYTHIA Simulations in the Search for Quark Compositeness at the Compact Muon Solenoid

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INTRODUCTION

Background

Currently, the standard model states that quarks and leptons are point particles – that they take up zero space and have no internal structure. There are, however several characteristics of the standard model that could be explained if this were not true. That is, if quarks and leptons were made up of smaller particles, called preons.

A notable pattern that preons could explain is the existence of generations of matter. All matter that we readily observe in our universe is made up of first generation matter (up and down quarks and electrons), so there is no apparent reason for the other two generations. If preons existed, the heavier generations could be explained as excited states of the first one. This is one of many ideas motivating the search for compositeness – the idea that quarks and leptons are made of preons.

Some compositeness models predict a particle interaction that CMS is capable of detecting. This is a contact interaction (CI) in which two preons from a quark-antiquark pair make contact and produce one positively charged and one negatively charged lepton. As shown in Figure 2, this process has a significant background in the standard model Drell-Yan (DY) process.

This study focuses on using simulations to develop methods to differentiate contact interactions from Drell-Yan in the case where the final leptons are muons. The simulation software used is PYTHIA 8, and the analysis software used is ROOT.

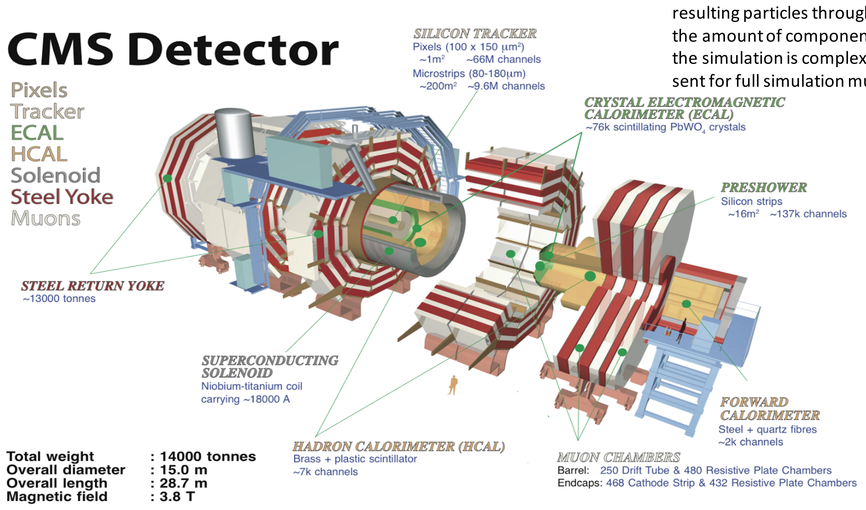


Figure 1. Visualization of CMS detector components. The full detector simulation will generate events and propagate the resulting particles through each of these components. Due to the amount of components and the scale of events generated, the simulation is complex and time consuming. Thus, samples sent for full simulation must be meticulously prepared.

Purpose

- Verify physics processes in PYTHIA for full-detector simulation
- Generate simulation data against which to compare real data when available
- Prepare analysis methods that will search for compositeness or set a lower limit on the energy scale (Λ) at which it is observable.

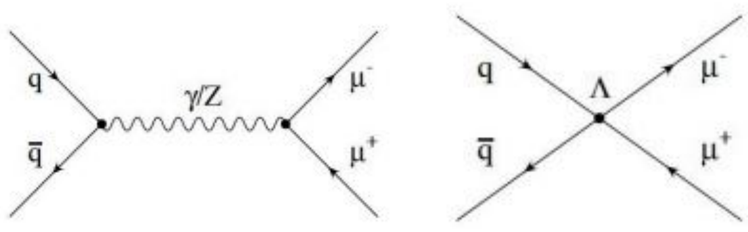


Figure 2. Contact Interaction and Drell-Yan Feynman diagrams. The contact interaction (right) is predicted by compositeness models. It has a significant standard model background, however. The Drell-Yan process (left) also produces two leptons (muons, in this case) with a similar, but not identical, mass spectrum

METHODS

- Simulate both contact interaction and Drell-Yan events.
- Determine the differences in the mass spectra, cross section (σ), and Collins-Soper frame angle distribution between the signal and background.

Cross Section

Must verify that high Λ compositeness models have similar cross sections to those of DY

Minimum mass cut (GeV)	DY σ (fb)	CI σ (fb)	Percent Difference
120	17800	17820	0.11%
200	2379	2383	0.17%
500	88.93	89.23	0.34%
1000	5.510	5.558	0.87%
1800	0.3176	0.3160	0.505%

Collins-Soper Frame Angle

- The Collins-Soper frame is the center of mass frame of the two leptons immediately after collision
- The angle that the muons make with the z axis in this frame is given by

$$\cos\theta^* = \frac{p_z(\ell^+\ell^-)}{|p_z(\ell^+\ell^-)|}\frac{2(p_1^+p_2^- - p_1^-p_2^+)}{m(\ell^+\ell^-)\sqrt{m(\ell^+\ell^-)^2 + p_T(\ell^+\ell^-)^2}}$$

where $p_{z,T}(l^+l^-)$ are the dimuon momentum in the z and transverse directions, respectively, $m(l^+l^-)$ is the dimuon invariant mass, and $p^{\pm} = (E \pm p_z)/\sqrt{2}$. All of these quantities are measured in the lab frame.

- One compositeness model (left-right) predicts a different distribution of this angle for contact interactions and Drell-Yan.

Invariant Mass Spectra

- CI is characterized by more high mass and fewer low mass events than DY
- If Λ, is high, these high mass events are few, and the invariant mass spectrum for contact interactions is hard to distinguish from that of the Drell-Yan process.

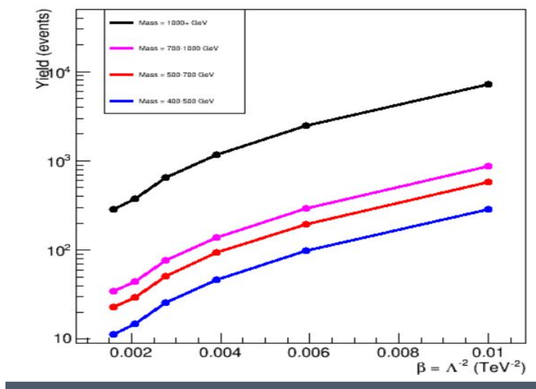


Figure 3. Relation between Λ and number of events for different mass groups. Note that the x-axis is in terms of $\beta = 1/\Lambda^2$. High β (low Λ) values correspond to much higher event yields than low β (high Λ). Not obvious on this plot is the drastic difference in slope of these curves. High mass groups (e.g. black curve) have a much higher increase in yield as β increases when compared to lower mass groups (e.g. blue curve).

WORKFLOW

RESULTS AND CONCLUSIONS

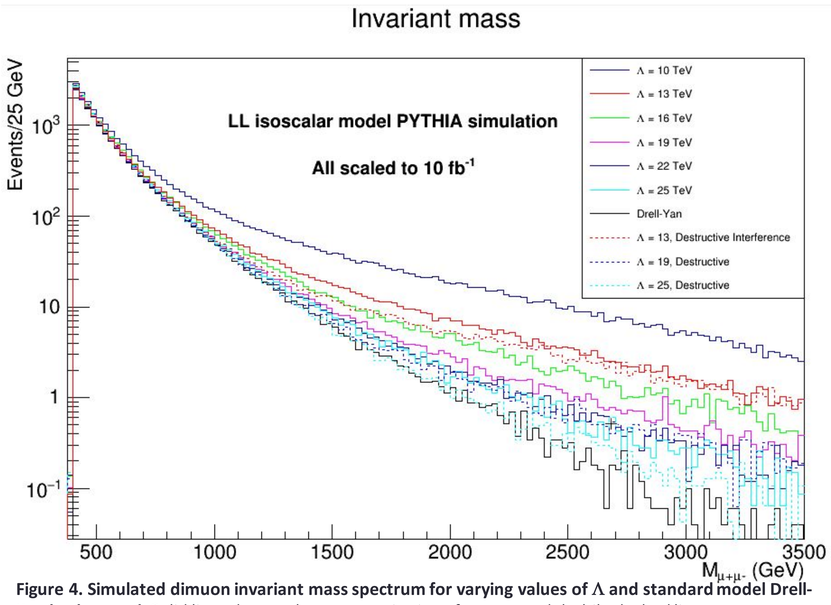
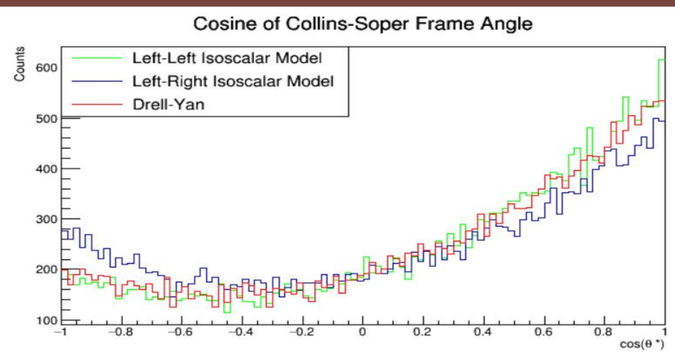


Figure 4. Simulated dimuon invariant mass spectrum for varying values of Λ and standard model Drell-Yan background. Solid lines denote the constructive interference model while dashed lines are destructive interference. Each of these spectra is scaled to 10 fb^{-1} and were originally created with 1 million simulated events with a minimum mass cut of 400 GeV, final state radiation turned off, and using the left-left isoscalar model.



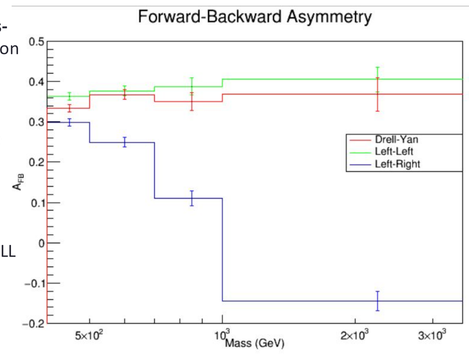


Figure 5. Asymmetry in the Collins-Soper Frame Angle. The distribution of the Collins-Soper angle (top) is highly skewed towards positive values for the LL model and DY. However, this is not as true for the LR model. This divergence is especially apparent when the asymmetry between positive and negative values is calculated in different mass groups (left) where LL and DY are largely within each other's errors, and LR greatly diverges at high mass values.

PYTHIA has been verified to accurately produce CI events and a full-detector simulation request has been submitted. Methods to set a strong lower limit on Λ are being developed using similar techniques to those used on this simulation.

REFERENCES AND ACKNOWLEDGMENTS

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Figure 2: Kottachchi, Chamath. "SEARCH FOR CONTACT INTERACTIONS USING THE DIMUON MASS SPECTRUM IN P-P COLLISIONS AT √ S = 8 TeV AT CMS." Diss. Wayne State U, 2014.

Collins-Soper Angle: Nagashima, Yorikiyo. 2013. Elementary Particle Physics Vol.2: Foundations of the Standard Model. Weinheim, Germany: WILEY-VCH.

I would like to thank my supervisors, Dr. Lenny Spiegel and Dr. Pushpa Bhat, for their support and help throughout this project. I would also like to thank the SIST program for allowing me to do research at Fermilab.

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