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Probing for Ultraheavy Quanta at LHC

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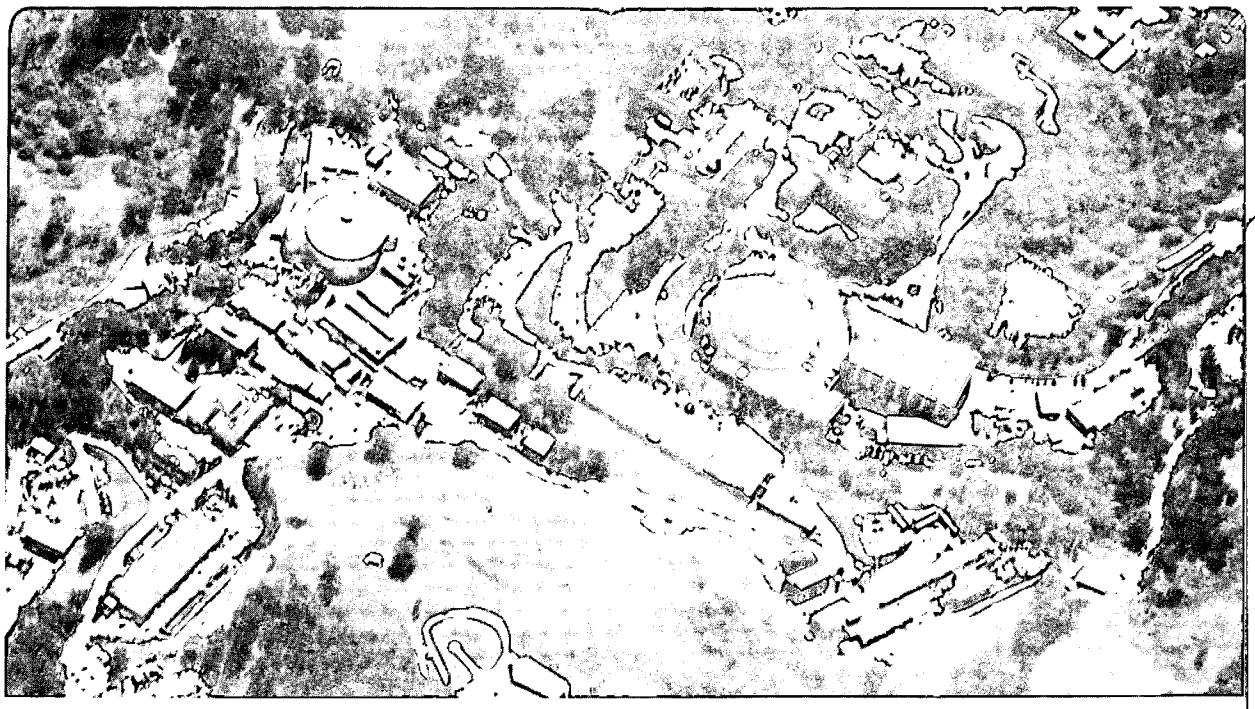

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Probing for Ultraheavy Quanta at LHC [1]

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Abstract

Experiments at the LHC are sensitive to the presence or absence of matter quanta at mass scales far beyond the scales they can probe directly. The production of Z boson pairs by gluon-gluon fusion is greatly enhanced if there are ultraheavy quanta that carry $SU(3)_{\text{Color}}$ and get their mass from electroweak symmetry breaking. For example, a fourth generation quark doublet with an arbitrarily heavy mass would induce a large excess in the ZZ yield that could be detected at the LHC with only $\simeq 10\%$ of the design luminosity.

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Introduction

The matter sector is the least understood part of the standard model. No theoretical or experimental constraint forbids the existence of additional quanta beyond the three known quark-lepton families. The conventional wisdom that there are no quarks heavier than the top quark is no more reliable than the widely shared expectation of previous decades that the top would not weigh more than 40 or 50 GeV. Provided they are too heavy to produce at existing accelerators and that their weak $SU(2)_L$ multiplets are sufficiently degenerate to satisfy the ρ parameter constraint,[1, 2] additional ultraheavy quanta may be consistent with precision electroweak data. As many as two ultraheavy quark-lepton families — or other more exotic varieties of matter quanta — are not excluded at the present level of precision. The degree of mass degeneracy required may seem unnatural, but final judgement would be premature given our total ignorance of the origin of quark and lepton masses.[2]

The existence of ultraheavy quanta that carry $SU(3)_{\text{Color}}$ and obtain their mass from the electroweak symmetry breaking condensate can be probed at the LHC by means of their virtual loop contribution to the process $gg \to ZZ$. This paper presents the signals and backgrounds for the LHC at its 14 TeV design energy and for the possible preliminary stage at 10 TeV. At 14 TeV the signal is quite large: the increased ZZ yield from one ultraheavy quark doublet could be detected with only 10 fb^{-1}, little more than one month at the 10^{34}cm^{-2}sec^{-1} design luminosity. At 10 TeV and $\simeq 3\times10^{33}$cm^{-2}sec^{-1} observation would require $1\frac{1}{2}$ to 2 years.

Is there an upper limit to the mass of matter quanta that get their mass from the electroweak symmetry breaking condensate? We know that the mass scale of the symmetry breaking sector is constrained to be $\lesssim O(2)$ TeV in order to preserve the unitarity of W and Z boson interactions (see for instance [3]). No analogous limit constrains the mass of matter quanta. The so-called "unitarity upper limit" on quark and lepton masses[2], $\simeq 0.5$ and 1.0 TeV respectively, is really just the mass scale at which tree unitarity is saturated and higher orders become important, i.e., the onset of strong Yukawa interactions. It does not

[2]For instance, the custodial $SU(2)$ of the symmetry breaking sector might naturally apply to the fourth generation, with the lighter fermions' masses generated by radiative corrections from an extended gauge sector.

mean that heavier quarks and leptons are forbidden. An upper limit of order $\simeq 3$ TeV is suggested,[4] based not on unitarity but on dynamical considerations analogous to those advanced previously for the Higgs boson mass.[5] I will consider quark masses of 0.5 TeV and above. The signal is not very sensitive to the mass: for $m_Q \geq 1$ TeV it is already within 10% of the asymptotic $m_Q \to \infty$ value.

Ultraheavy quanta in degenerate $SU(2)_L$ multiplets would not contribute to ρ but would contribute to the parameter S.[6] For instance an ultraheavy quark-lepton family would contribute $\sim +0.21$ to S at one loop order in perturbation theory. However this value is only reliable as an order of magnitude estimate since higher order corrections from the strong interaction of the ultraheavy quanta with the Higgs sector are not perturbatively calculable.

The nominal experimental value for S is negative but with large errors. A recent analysis by Takeuchi[7] using $\alpha(M_Z) = 1/129.1$ from [8] yields a less negative value than before, $S = -0.17 \pm 0.28$ (for $m_t = 175$ and $m_H = 300$ GeV), that is consistent at the $\simeq 2\sigma$ level with up to two ultraheavy families assuming 0.21 per family. Because the central value is negative the constraint is weaker than it seems. If true, $S < 0$ requires unknown nonstandard model physics, since the standard model (and most other models) predicts $S > 0$. A negative contribution from new physics is *ab initio* of unknown magnitude and could cancel a positive contribution from ultraheavy quanta. On the other hand, if S is actually positive, the fit should include $S > 0$ as a constraint.[6] Imposing $S > 0$ and taking $\alpha(M_Z)$ from [8], Takeuchi finds $S < 0.44$ at 95% confidence,[7] again consistent with as many as two ultraheavy families using the one loop value for S.

The analogous photon induced process, $\gamma\gamma \to ZZ$, was considered previously, with the expectation that the signal at a TeV photon collider would be cleaner than the gluon induced signal at a hadron collider.[9] But the W boson loop amplitude was later found to contribute a large background[10] that buries the signal for $\sqrt{s_{\gamma\gamma}} \leq 3$ TeV. The absence of the W loop background is a great advantage for the $gg \to ZZ$ process.

The nondecoupling of ultraheavy quanta in $gg \to ZZ$ was noted by Glover and van der Bij[11]. It was considered by Hagiwara and Murayama[14] (a fact not known to the author when [9] was written), using a different method; in

R-gauge rather than U-gauge. Their paper had a different emphasis, focusing on multiple weak boson production at the SSC in the asymptotic $m_Q \to \infty$ limit. They did not consider the backgrounds (or the interference of signal and background amplitudes) nor did they consider LHC collider energies.

The purpose of the present paper is to establish how well the ZZ signal can be seen at the LHC, taking account of the backgrounds from $\overline{q}q$ annihilation, gg fusion, and the order α_W^2 amplitude $qq \to qqZZ$. Experimental cuts are presented that optimize the signal relative to the background. Signal cross sections are considered for m_Q between 0.5 and 10.0 TeV and for the $m_Q \to \infty$ limit, including the coherent interference of the signal and background $gg \to ZZ$ amplitudes.

Since the HXX coupling is strong for ultraheavy quanta X that obtain their mass from the Higgs boson, higher order Higgs boson exchange corrections are not under perturbative control. Consequently the one loop signal amplitudes can only indicate the order of magnitude, and the cross sections do not precisely probe the quantum numbers or the number of ultraheavy quanta. The same limitation applies to $\gamma\gamma \to ZZ$, to the on-shell $H \to \gamma\gamma$ and $Z \to H\gamma$ partial widths, and to the electroweak parameter S.

The next sections review the basic physics, present signal and background events rates for the optimal experimental cuts, and discuss the results.

One Loop Amplitude for Ultraheavy Quanta

There are two important features: 1) that ultraheavy quanta X do not decouple and 2) that $\sigma(gg \to ZZ)$ increases linearly with s in the domain

$$m_X^2 \gg s \gg m_H^2. \tag{1}$$

They are seen most easily in unitary gauge, for which the dominant contribution is the triangle amplitude in figure 1. The X contribution does not decouple as $m_X \to \infty$ because factor(s) of m_X from the HXX vertex cancel factor(s) of $1/m_X$ from the loop integral. [3] The energy dependence is understood as follows:

[3]There are one or two factors of m_X for spin 1/2 and 0 respectively. The leading ggH off-shell amplitude is determined by the leading order trace anomaly for a theory with an $SU(3)$ symmetry[12], and the QCD corrections are precisely the higher order terms in the beta function[13]. However the QCD corrections are much smaller than the unknown higher order corrections from the Higgs sector.

a factor s from the $G^{\mu\nu}G_{\mu\nu}H$ structure of the ggH vertex (required by gauge invariance), a factor $\simeq 1/s$ from the Higgs boson propagator, and a factor s from the U-gauge HZZ vertex for longitudinally polarized Z bosons.

The leading amplitude mediated by ultraheavy quanta X is then

$$\mathcal{M}(g_1^a g_2^b \to Z_L Z_L)_X = \frac{S_X C_X \alpha_S(s)}{3\pi} \frac{s}{v^2} \delta_{ab}\delta_{\lambda_1\lambda_2} \tag{2}$$

where $v = 246$ GeV, α_S is the strong interaction coupling constant, a, b are color indices, λ_i denote gluon polarizations, and the subscript L denotes longitudinal polarization. The spin factor is $S_X = 1$ for spin 1/2 and $= 1/4$ for spin 0. The $SU(3)$ quadratic Casimir operator C_X is normalized to 1/2 for X in the triplet, $C_X\delta_{ab} = \mathrm{Tr}(T_X^a T_X^b)$. In U-gauge the box graph amplitudes, figure 1, are suppressed relative to equation 2 by s/m_X^2.

Assuming n_D ultraheavy quark doublets, the color- and spin-averaged differential cross section following from equation 2 is

$$\frac{d\sigma}{d\cos\theta} = \frac{\beta n_D^2}{\pi} \left(\frac{\alpha_S}{96\pi}\right)^2 \frac{s}{v^4} \tag{3}$$

where θ is the polar scattering angle and β is the Z boson velocity in the ZZ center of mass. The signals presented below for finite m_Q and for $m_Q \to \infty$ also include the (constructive) interference of the X-mediated loop amplitude and the background $gg \to ZZ$ amplitudes mediated by the three known quark doublets.[4]

Using the R-gauge and the equivalence theorem it is easy to see that equation 2 cannot follow from the triangle amplitude, figure 1, since the Hzz vertex $\sim m_H^2/v$ is negligible relative to the HZ_LZ_L vertex $\sim s/v$. The explanation is that the box graphs provide the leading result in R-gauge. This has been verified by explicit computation using an effective Lagrangian[14] and by a general argument sketched in [9].

Cross Sections and Cuts

To maximize the yield we consider the "silver-plated" channel, first suggested for heavy Higgs boson detection,[3, 15] $ZZ \to \bar{l}l + \bar{\nu}\nu$, where l denotes

[4]The interference is mostly from the t quark amplitudes, though lighter quark loops make significant contributions to the background.

an electron or muon. The signature is a high p_T Z boson balanced by missing transverse energy. This channel provides six times more events than the "gold-plated" channel, $ZZ \to \bar{l}l + \bar{l}l$, and is nearly as clean for large transverse momentum. It seems viable at the LHC according to both ATLAS[16] and CMS[17]. Even with 40 events per crossing, the pile-up background is negligible for $E_T^{\rm miss} > 100$ GeV (see figure 11.15 of [16]). The optimal cuts presented below require transverse momenta more than twice as big, typically ≥ 250 GeV.

The cross sections for the four charged lepton channel can be estimated by dividing the cross sections presented below by $\simeq 6$. Even though it contains more information, it is not possible to improve the signal:background ratio dramatically beyond what is achievable for the two charged lepton final state. The results presented below are conservative in that the $\simeq 15\%$ contribution of the four charged lepton channel is not included.

The leading background is $\bar{q}q \to ZZ$. The second background is $gg \to ZZ$ mediated by loop amplitudes of the six known quarks (figure 1).[11] For the optimal cuts the $gg \to ZZ$ background is $\sim 15\%$ of the total background. Another potential background is the order α_W^2 amplitude $qq \to qqZZ$,[18] computed in the standard model assuming a light Higgs boson, $m_H \leq 100$ GeV. It includes WW and ZZ fusion graphs as well as diagrams in which one or both Z's are radiated from an external quark line. It is potentially larger than the $gg \to ZZ$ background but a central jet veto (CJV) reduces it by an order of magnitude to a negligible level, of order 1% of the total background.

The CJV also suppresses the large NLO (next-to-leading-order) background from $qg \to qZZ$.[19] With the CJV the lowest order $\sigma(\bar{q}q \to ZZ)$ cross section is slightly larger than the NLO inclusive ZZ cross section, so that our use of the lowest order $\sigma(\bar{q}q \to ZZ)$ is actually a conservative background estimate.

The signal is distinguished from the background by three characteristics.

- The subprocess cross section increases with energy for the signal and falls for the backgrounds.
- The dominant background is peaked in the forward direction while the signal is relatively isotropic.
- The signal consists of longitudinally polarized Z boson pairs while the

background is dominated by Z pairs with one or both Z's transversely polarized.

These features dictate the cuts. The first implies a cut on the transverse momentum of the observed Z. The second suggests a central rapidity cut, which is in any case required by the geometry of the detectors. The first and third can be simultaneously exploited by a cut on the transverse momentum of the Z decay products, as noted in studies of W^+W^+ scattering.[20] Since longitudinally polarized Z's tend to decay at right angles to the Z line of flight, both leptons typically share the transverse momentum of the parent boson. For transversely polarized Z's the decay tends to be along the Z line of flight, so that there is an unequal division of the parent p_T and a greater likelihood that the softer lepton will fail a p_{Tl} cut.

We define a conservative criterion for observability:

$$\sigma^{\uparrow} = S/\sqrt{B} \geq 5/\sqrt{\epsilon} \tag{4}$$

$$\sigma^{\downarrow} = S/\sqrt{S+B} \geq 3/\sqrt{\epsilon} \tag{5}$$

$$S \geq B, \tag{6}$$

where S and B are the number of signal and background events assuming 100% detection efficiency, and ϵ is the experimental efficiency, assumed below to be 95% for an isolated, high p_T Z decaying to e^+e^- or $\mu^+\mu^-$.[21] The requirement $S \geq B$ is conservatively imposed to allow for theoretical uncertainty in the magnitude of the background, probably $\leq$ 20–30% after "calibration measurements" of standard processes at the LHC.

The cuts are optimized over a three dimensional parameter space consisting of $p_{TZ}^{\rm MIN}$, $p_{Tl}^{\rm MIN}$, and $\eta_l^{\rm MAX}$. The optimum cut is the one that satisfies equations 4–6 with the smallest integrated luminosity, denoted $\mathcal{L}_{MIN}$. In addition a central jet veto is imposed to reject events containing one or more jets with $\eta_J < 3$ and $p_{TJ} > 50$ GeV.

We consider the signal from one ultraheavy quark doublet of mass m_Q. The integrated p_{TZ} distribution for 14 TeV and 100 fb^{-1} is shown in figure 2, where $p_{Tl} > 90$ GeV and $\eta_l < 2$ are imposed. The background is indicated by the dashed line while the coherent sum of signal and background is shown in the

solid lines for (from bottom to top) $m_Q = 0.5$, 1.0, 2.0 TeV and $m_Q \to \infty$. The asymptotic cross section is approached rapidly from below: the $m_Q = 1$ TeV signal is already within 10% of the $m_Q \to \infty$ limit.

The optimized signals and cuts are shown in tables 1 and 2 for $\sqrt{s} = 14$ and 10 TeV respectively, with $m_Q = 0.5$, 1.0, 2.0, 4.0, and 10.0 TeV as well as $m_Q \to \infty$, the latter combined both coherently (∞_C) and incoherently (∞_I) with the background. While values of $\eta_l^{\rm MAX}$ from 1.0 to 2.5 were explored, the rapidity cut is fixed at $\eta_l^{\rm MAX} = 2$ for the quoted results, because $\mathcal{L}_{MIN}$ is not very sensitive to variations between 1.75 and 2.5 and because the detectors are likely to be most efficient for $\eta_l < 2$,

We see from table 1 that a signal satisfying equations 4–6 can be obtained with $\simeq 10$ fb^{-1}, only 10% of a year at the design luminosity. For the optimal cuts the signal is typically twice as large as the background. The incoherent approximation, denoted by ∞_I, underestimates the true signal by $\sim 20\%$.

For $\sqrt{s} = 10$ TeV a significant signal requires 50–60 fb^{-1} or $1\frac{1}{2}$–2 years of running at the projected 3–4$\times 10^{33}$cm^{-2}sec^{-1} luminosity. The signal:background ratio for the optimal cuts falls to $\simeq$ 1:1. Nevertheless the signal is big enough that it might be observable at 10 TeV.

Discussion

In the analysis presented here we assumed a light Higgs boson and used $m_H = 100$ GeV in the computations. The results do not depend on the precise value of m_H as long as it is not heavier than a few hundred GeV. The situation could be more complicated if $SU(2)_L$ breaking were due to more than one Higgs boson or to a strongly coupled Higgs boson (say $m_H \simeq 1$ TeV) or if it were due to dynamical symmetry breaking. These complications would effect the details but in each case a large signal would be expected, unless different scalars generated the gauge boson and ultraheavy masses.

Compared to other TeV scale gauge boson pair signals, the signals presented here are large. For the same cuts (including the CJV) the asymptotic signal in table 1 is 70 % bigger than the ZZ signal from the 1 TeV Higgs boson and three times bigger than the strong scattering signal of the linear model.[22]

If an excess ZZ signal were observed in longitudinally polarized pairs, the interpretation would not be immediately clear. The magnitude of the signal

might be a clue, especially if independent evidence for a light Higgs sector were available. Strong WW scattering would give rise to excesses also in the WZ and/or W^+W^+ channels, while the gg fusion signal of ultraheavy quanta only contributes to ZZ and W^+W^-. Jet tagging would also help to distinguish since Higgs sector physics would contribute to both[5] $gg \to ZZ$ and $qq \to qqZZ$ while virtual ultraheavy quanta only enhance the former. Measurements of $H \to \gamma\gamma$, $Z \to H\gamma$, and the electroweak parameter S could provide corroborating evidence but suffer from incalculable higher order corrections discussed above. To confirm the interpretation of a signal we would eventually have to observe the ultraheavy quanta directly.

A negative result would be easier to interpret. If no ZZ excess were seen beyond what could be accounted for by the Higgs sector, we could conclude that ultraheavy quanta with masses generated by electroweak symmetry breaking probably do not exist even at arbitrarily high mass scales, also very useful information. We conclude that experiments at the LHC are sensitive to the presence or absence of matter quanta at mass scales far beyond the scales they can probe directly.

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Table 1

Optimized yields for one ultraheavy quark doublet of mass m_Q, for $\sqrt{s} = 14$ TeV and $\eta_\ell^{\rm MAX} = 2$. For each m_Q, $\mathcal{L}_{\rm MIN}$ is the smallest integrated luminosity that satisfies equations 4-6, S/B are the resulting numbers of signal/background events per 100 fb^{-1}, and $p_{Tl}^{\rm MIN}, p_{TZ}^{\rm MIN}$ indicates the corresponding optimal cut. ∞_C and ∞_I denote the $m_Q \to \infty$ limit combined coherently or incoherently with the background.

m_Q(TeV)	$\mathcal{L}_{\rm MIN}$(fb^{-1})	S/B(100 fb^{-1})	$p_{Tl}^{\rm MIN}, p_{TZ}^{\rm MIN}$(GeV)
0.5	17.4	130/111	70,250
1.0	12.2	121/67	70,300
2.0	10.8	136/74	60,300
4.0	10.1	149/85	90,250
10.0	9.9	150/85	90,250
∞_C	9.9	150/85	90,250
∞_I	12.7	118/67	70,300

Table 2

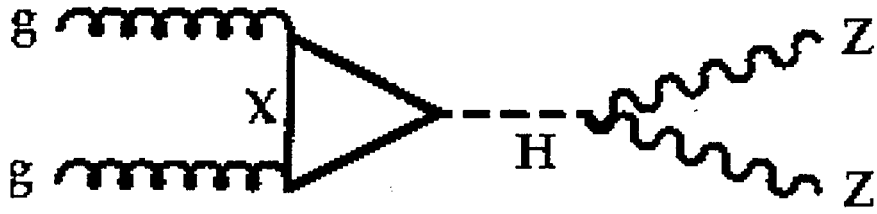
Results for $\sqrt{s} = 10$ TeV and $\eta_l^{\rm MAX} = 2$, tabulated as in table 1 except that S/B denotes the numbers of signal/background events per 30 fb^{-1}.

m_Q(TeV)	$\mathcal{L}_{\rm MIN}$(fb^{-1})	S/B(30 fb^{-1})	$p_{Tl}^{\rm MIN}, p_{TZ}^{\rm MIN}$(GeV)
0.5	82	9.4/9.2	80,300
1.0	62	12.1/11.6	100,250
2.0	52	14.3/13.6	90,250
4.0	49	16.0/15.8	80,250
10.0	48	16.1/15.8	80,250
∞_C	48	16.1/15.8	80,250
∞_I	66	7.7/5.0	90,350

Figure Captions

Figure 1
Triangle and box diagrams for $gg \to ZZ$.

Figure 2
Numbers of events with $p_{TZ} > p_{TZ}^{\rm MIN}$ for $\sqrt{s} = 14$ TeV and 100 fb^{-1}. Additional cuts are $\eta_l < 2$ and $p_{Tl} > 90$ GeV. Signals are for one ultraheavy quark doublet of mass m_Q. The dashed line is the background, and the four solid lines are, from bottom to top, for $m_Q = 0.5,\ 1.0,\ 2.0$ TeV and $m_Q \to \infty$.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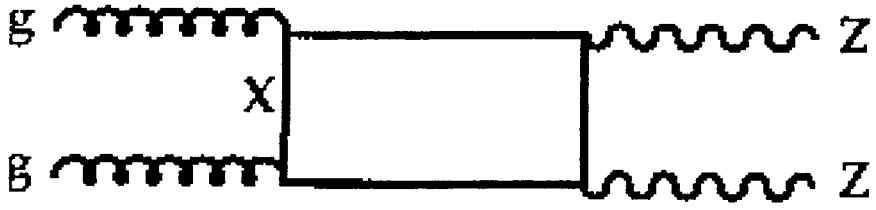
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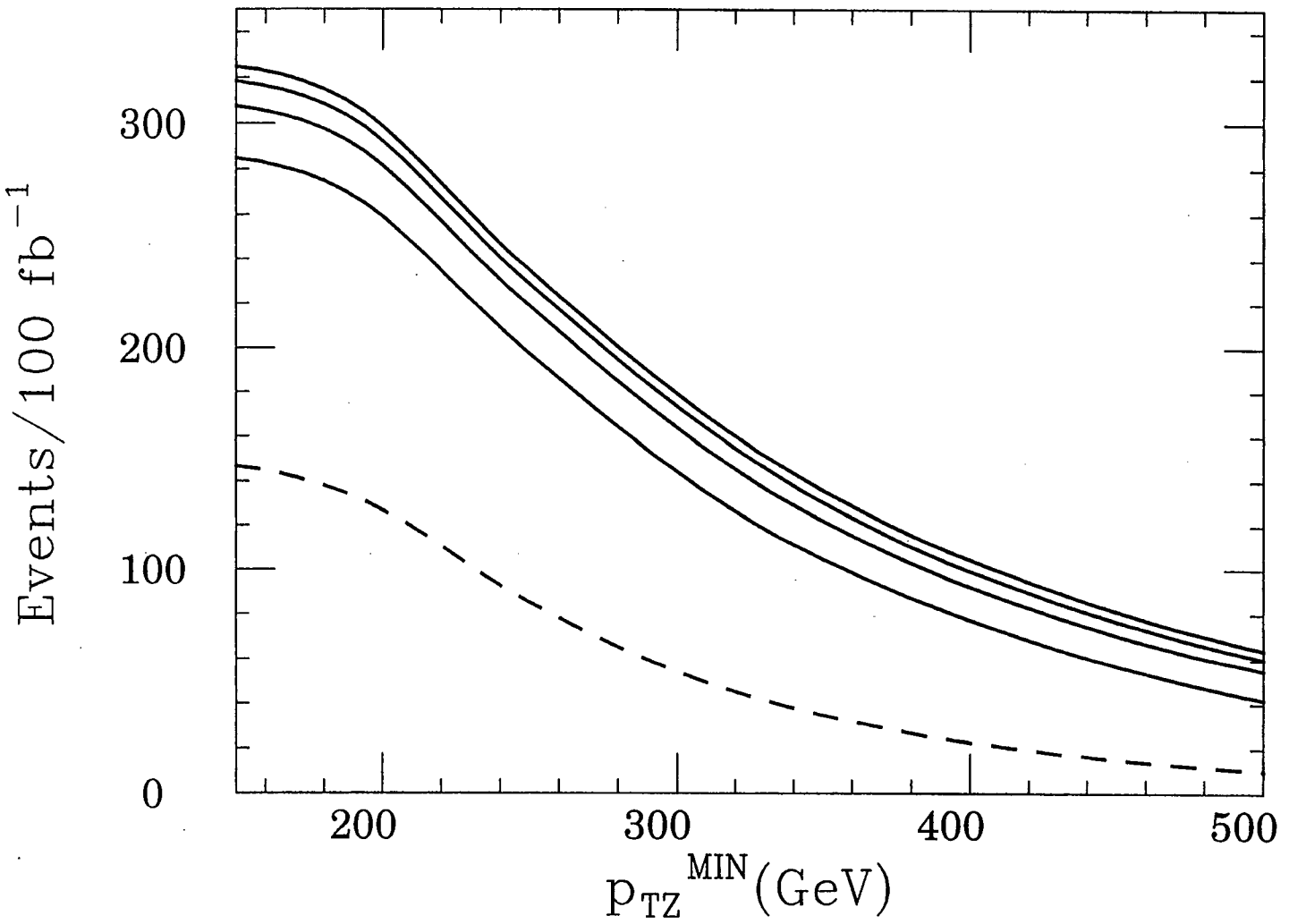
Events/100 fb^{-1}
300
200
100
0
200
300
400
500
p_{TZ}^{MIN}(GeV)

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