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Uses of Missing Mass in Central Exclusive Production*

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Abstract

I consider several applications of the missing mass technique in central exclusive production of Higgs, Vector Bosons etc. at the LHC. Compared to using only leptonic (e, μ) decays of W^+W^- (ZZ) we can gain a factor 10 (100) in rate. In the process we will observe $Z \to \nu\bar{\nu}$ as a narrow ($\sigma_{M(\nu\bar{\nu})} \approx 2$ GeV) peak. For purely hadronic decays the correlation between the leading proton and central jets might be useable in a Level 1 trigger. Events with well known central mass might be a useful method of calibrating the energy scale of the central calorimetry.

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1 Introduction

Let me say at the outset this note, at this stage, is a "trial balloon", pointing out some *in principle* facts using 4-vectors, without any consideration (yet) of resolutions or signal:background issues. Hopefully such studies will be made with full Monte Carlo simulations.

Missing mass (MM) techniques can play many roles in central exclusive production with both forward protons measured, because we aim to measure the full final states. At the LHC this is a unique situation (apart from elastic scattering, although even in that case we measure MM = 0 as a constraint). In the following we refer to the 4-vectors $p_j = (E_j, ip_{x_j}, ip_{y_j}, ip_{z_j})$ of particle or jet j. The incoming protons are p_1 and p_2 (4-vectors) and the outgoing protons p_3 and p_4. So $p_j^2(j = 1, 4) = m_p^2$ and $s = (p_1 + p_2)^2$, $t_{13} = (p_1 - p_3)^2$, etc.

For the "classic" case of

$$p_1 + p_2 \to p_3 \oplus H \oplus p_4 \to p_3 \oplus J_1 J_2 \oplus p_4 \tag{1.1}$$

where $\oplus$ is a rapidity gap (*no particles*) we have

$$M_H^2 = M_{JJ}^2 = (p_1 + p_2 - p_3 - p_4)^2 \tag{1.2}$$

and we expect this to give a resolution ≈ 2 GeV per event[1].

Let us now consider the case where there are non-interacting particles in the final state, which could be LSP's in SUSY but in the Standard Model will only be neutrinos. Particularly important for our SM program are energetic neutrinos from W and Z decay. Take events with two forward protons and two high-p_T leptons, l_1 and l_2' together with missing E_T, ($\not{E}_T$). If l_1 and l_2' have different flavor and are isolated, even being the only two particles on their vertex, then they must be (in the SM) from W^+W^- production, and M_{WW} comes from the above equation (1.2). Note that even without observing the forward protons, seeing an e and a μ on a common vertex with *no other charged tracks on that vertex*, together with large $\not{E}_T$, is a practically background-free signal for exclusive W^+W^- production. If the leptons have the same flavor they could be from WW or ZZ (*a priori* WW is more likely as the cross section is always (in the SM) larger). The dilepton mass $M_{l^+l^-} = (p_{l_1} + p_{l_2})^2$ of course should show a Z-peak in the ZZ case, but with a continuum background from WW. There can also be events below M_Z from Z^* production (I will not always make this qualification). It may be important to have a second discriminator, which we do have:

$$M_N^2 = (p_1 + p_2 - p_3 - p_4 - p_{l_1} - p_{l_2})^2 \tag{1.3}$$

where M_N is the mass of the missing neutral non-interacting state. $M_N = M_Z$ if the only undetected particles are the two neutrinos from the Z. Therefore a scatter plot of M_N vs $M_{l^+l^-}$ will show a clustering at (M_Z, M_Z) (perhaps with bands from ZZ^*) and the background can be minimized.

A restriction to $\mu\nu$ and $e\nu$ final states from the W decays is serious; it means that for $H \to W^+W^-$ we only see a fraction $(4 \times 0.107^2) = 0.046$ of the W-pairs. The single W branching fractions are: $W \to l\nu = 0.107$ (for each l), $W \to JJ = 0.680$. Being able to use $\tau\nu$ and especially JJ decays is important. While this is difficult (perhaps impossible) for generic non-diffractive $H \to W^+W^-$, for central exclusive production we have more handles. Take the case where one W decays to $l\nu$ and the other decays to two jets, J_1J_2. Of course we have $M_{JJ} = M_W$, but we can go further. In this case there is only one invisible particle, with $M_\nu = 0$, hence the missing mass:

$$M_N^2 = (p_1 + p_2 - p_3 - p_4 - p_{l_1} - p_{J_1} - p_{J_2})^2 = 0 \tag{1.4}$$

I do not yet address questions of resolution, dominated by the jet energy resolution, or background in the M_N^2 plot. Note that the two jets enter the above equation as $(p_{J_1} + p_{J_2})$ which is the sum $\sum_{i=1}^{n} p_i$ of all the hadrons' 4-momenta on the primary vertex. You do not have to decide which hadrons are in which jet, or whether a hadron is part of the "underlying event"; there *is* no underlying event. The main issue then is neutral particles, which one can include if they are electromagnetic clusters or hadronic clusters without matching tracks, within an η, ϕ cone around the charged particle jet axis. The point is that the optimization of the $(p_{J_1} + p_{J_2})$ measurement may benefit from special treatment, thanks to the exclusivity of these events. We also know p_ν and $M_{l\nu}$ from the 4-momentum conservation equations, and (also requiring the two jets to originate from the same vertex as the lepton) these events should be useable as good exclusive $pp \to p \oplus W^+W^- \oplus p$ candidates. We then have (with $M_{J_1J_2} = M_W$) for the leptonic W:

$$MM^2 = (p_1 + p_2 - p_3 - p_4 - p_{J_1} - p_{J_2})^2 = M_W^2 \tag{1.5}$$

This is true even if the charged lepton is a τ! Being able to use the channels where one W decays to jets and the other decays to $(e, \mu, \tau) + \nu$ increases the useful fraction from 4.5% to 47.9%, a factor of more than 10, greatly to be wished for!

Note that a guaranteed exclusive W^+W^- signal is $\gamma\gamma \to W^+W^-$, with $\sigma \approx$ 100 fb, and with these methods we can use about half of them, most having one clean $W \to JJ$ (together with one lepton and $\not{E}_T$). The rest are mostly 4-jet decays, discussed later.

The value of being able to fully exploit various missing masses is even higher for ZZ production. We have $Z \to l^+l^- = 0.03366$ for each of e, μ, τ, and $Z \to \nu\bar{\nu}$ $= 0.20$ (for all three neutrino flavors) and $Z \to JJ = 0.699$. Thus if we could use only the ee and $\mu\mu$ modes our efficiency for ZZ would be $4 \times (0.03366^2) = 0.00453$.

However in some cases we can include the modes $Z \to \tau^+\tau^-, Z \to \nu\bar{\nu}$ and $Z \to JJ$. Take $ZZ \to l^+l^-\tau^+\tau^-$ where $l = e, \mu$. The $Z \to \tau\tau$ decay is badly reconstructed because there are at least two missing ν, but can usually be recognized from the 1- or 3-prong decays on the same very clean (no additional hadrons) vertex as the $Z \to l^+l^-$. We then construct:

$$MM^2 = (p_1 + p_2 - p_3 - p_4 - p_{l_1} - p_{l_2})^2 = M_Z^2 \tag{1.6}$$

and having identified the event class we get $M(ZZ)$ from eqn (1.2) as usual, with good resolution. This use of $Z \to \tau\tau$ for one Z doubles the useful fraction, but better is to come! Rather than $\tau\tau$ one $Z \to \nu\bar{\nu}$ is allowed, just recognizing events with the two protons, a vertex with a $Z \to l^+l^-$ and nothing else, and large $\not{E}_T$. The association of the $\not{E}_T$ with the same vertex is simple, as the Z will balance it: $p_T(Z) = -\not{E}_T$ (2-vectors). Note that the calorimeter E_T or $\not{E}_T$ measurement plays no role in Eqn. 1.6. It is only relevant for the jet modes. The additional use of $ZZ \to l^+l^-\nu\bar{\nu}$ with $l = e, \mu$ (and Eqn. 1.6) adds 0.0269, not impressive but is still $6\times$ what we started with. A bigger gain comes from accepting l^+l^-JJ events, for $l = e, \mu, \tau$. Require the two jets to come from the l^+l^- vertex (it goes without saying we need to do this in the presence of multiple interactions) and to have $M(JJ) = M_Z$. We can use $Z \to \tau\tau$ in this case because we have:

$$MM^2 = (p_1 + p_2 - p_3 - p_4 - p_{J_1} - p_{J_2})^2 = M_Z^2 \tag{1.7}$$

This adds 0.1456 of all ZZ events. But it gets better! We can also use the channel $ZZ \to \nu\bar{\nu}JJ$ because we have a vertex with just two clean jets with $M(JJ) = M_Z$ and $\not{E}_T$ balancing the two jets, and the above equation (Eqn. 1.7) tells us that $MM = M_Z$. Adding this channel adds 0.2796 of all ZZ. Now we have not 0.0045 but 0.0045 + 0.0045 + 0.0269 + 0.1456 + 0.2796 = 0.46. This is a factor $100\times$ the purely leptonic (e, μ) case! Of course it remains to be seen with full simulation what the backgrounds are, but in all cases the central WW or ZZ mass has a resolution $\sigma_M \approx 2$ GeV. The other 54% of ZZ decays are mostly the more difficult channel $ZZ \to JJJJ$ with a little $\tau\tau\tau\tau, \tau\tau\nu\bar{\nu}$ and $\nu\bar{\nu}\nu\bar{\nu}$. Even there something may be done, but in all the cases discussed above the final state can be fully reconstructed.

I do not address BSM physics in this note, except to mention that these methods have applications. As an example, suppose we had one invisible BSM particle produced, such as a M = 200 GeV graviton. We could measure its mass.

2 The All-Jets Cases

The cases where the central state decays only to jets, e.g. $H \to b\bar{b}$ or $WW/ZZ \to JJJJ$ are most difficult, because the QCD backgrounds are huge, making triggering difficult, and also because the measurement of a jet (or dijet) 4-vector has much worse resolution than that of an e or μ. If the luminosity is very low such that there are many single interactions, a forward rapidity gap (preferably $\Delta\eta > 3$) on both sides can be used to reduce the level 1 rate, but we also need a trigger that is not killed by additional interactions. Assuming that the FP420 signals are too late to be used at L1, we must rely on a signal in either or both 220m detectors. There will be a great benefit, probably an order of magnitude rate reduction, if that signal is not just "a hit", but an approximate (say 4 bits) value of $\xi = 1 - \frac{p_z}{p_{beam}}$. This could be provided by a fast look-up table, inputting x-values of detector hits at the front and back of the lever arm and outputting ξ. The jet information: E_{T_i}, ϕ_i, η_i for each jet J_i is also known in the L1 trigger. Then for the 2-jet case we have $E_{T_1} \approx E_{T_2}$, $\Delta\phi(1,2) = \pi$ and especially, for the general n-jet case:

$$\xi_{3(4)} = \frac{1}{\sqrt{s}} \sum_{i=1}^{n} E_{T_i} e^{-(+)\eta_i} \tag{2.8}$$

This equation is derived in the appendix. The most interesting cases are likely to be 2-jet ($H \to b\bar{b}$), 4-jet ($WW, ZZ \to JJJJ$) and perhaps 6-jet ($t\bar{t}$, all hadronic). In the quest for $WW, ZZ \to JJJJ$ there are also the pair-wise $M(JJ)$ mass constraints, but they can probably not be used at L1. If we are able to trigger on these all-jets cases (with one or two 220m protons) it may be possible to extract the signals.

3 Missing Mass to Calibrate the Hadronic Calorimeter

The largest uncertainty on important quantities such as the top quark mass (at the Tevatron and probably at the LHC) .... and perhaps masses of particles to be discovered ... is the absolute energy scale of the hadron calorimeter. It is difficult to carry this calibration precisely from test beams. The EM calorimeter can be well calibrated by $p : E$ matching in $W \to e\nu$ events and by $Z \to e^+e^-$ events. Then one can use $\gamma + J$ or $Z + J$ balancing, in events where there is little additional activity, to calibrate the jet energy scale. Another proposed method is to select $t\bar{t} \to l\nu JJJJ$ events, try to identify the two (non-b) jets from the hadronic W and use $M(JJ) = M_W$. At the Tevatron there have not been enough events to use this method, and it remains to be seen how well it can be done at the LHC. In special short (few hour) low luminosity (mostly single interactions) calibration runs we could trigger on two forward protons together with forward rapidity gaps, vetoing events with energy above noise in all detectors with $|\eta| > 4$ ... it is important to cover as completely as possible these regions. From the protons we have the total central mass, which might be selected to have $M_{CEN} \approx$ 100-300 GeV (e.g.). Some events will have jets, most will not, but all events are useful for calibrating the calorimetry (the EM is well known, so this calibrates the hadronic sections). This is still an idea, to be simulated, and it relies now on the absolute calibration (not just the resolution) of the missing mass measurement. If it can be done competitively with γJ and $W \rightarrow JJ$ it provides a "service to the community" for top (or H or X) mass measurements.

4 Appendix: FP Track - Jets Kinematic Relation

The relation between ξ of the forward protons and the E_T, η of the jets is not new, but I derive it here for reference. We have (4-vectors):

$$p_1 + p_2 \rightarrow p_3 + p_4 + p_5 + ...p_n \tag{4.9}$$

where particles 3 and 4 are the outgoing protons with momentum loss fractions ξ_3 and ξ_4 and 4-momenta 5 to n are the jets with transverse energy E_{T_i} at polar angles θ_i. Let $s_i = \sin\theta_i$ and $t_i = \tan\theta_i$ for brevity. We can write out explicitly the 4-momenta and balance components. Neglecting the p_T of the forward protons

$$\sum_{i=5}^{n} \vec{E_{T_i}} = 0$$

($\vec{E_{T_i}}$ are 2-vectors). For the ξ - jet relation only two components are relevant, energy E and p_z. We can set $E_1 = p_{z_1} = E_2 = -p_{z_2} = p$. Then the energy balance equation gives:

$$2p = p(1-\xi_3) + p(1-\xi_4) + \frac{E_{T_5}}{s_5} + ...\frac{E_{T_n}}{s_n}$$

from which:

$$(\xi_3 + \xi_4) = \frac{1}{p}\sum_{i=5}^{n}\frac{E_{T_i}}{s_i}$$

The p_z balance equation gives:

$$(\xi_4 - \xi_3) = \frac{1}{p}\sum_{i=5}^{n}\frac{E_{T_i}}{t_i}$$

Adding these two, and noting $\sqrt{s} = 2p$ we get:

$$\xi_4 = \frac{1}{\sqrt{s}}\sum_{i=5}^{n} E_{T_i}(\frac{1}{s_i} + \frac{1}{t_i})$$

and subtracting them we get:

$$\xi_3 = \frac{1}{\sqrt{s}} \sum_{i=5}^{n} E_{T_i} (\frac{1}{s_i} - \frac{1}{t_i})$$

Finally we note that:

$$(\frac{1}{s} - \frac{1}{t}) = \tan(\frac{\theta}{2}) = e^{-\eta}$$

and

$$(\frac{1}{s} + \frac{1}{t}) = \frac{1}{\tan(\frac{\theta}{2})} = e^{+\eta}$$

The latter trigonometrical jump can be bridged with the following standard formula:

$$\tan\theta = \frac{\sin 2\theta}{1 + \cos 2\theta} = \frac{1 - \cos 2\theta}{\sin 2\theta} = \frac{1}{\sin 2\theta} - \frac{1}{\tan 2\theta}$$

Hence:

$$\xi_{3(4)} = \frac{1}{\sqrt{s}} \sum_{jets} E_T e^{-(+)\eta}$$

If one measures all the *particles* in an event the same formula works with *jets* $\rightarrow$ *particles*. In a (non-diffractive) collision if particles 1 and 2 are partons and 3 ... n are jets (or other objects), the derivation gives the Bjorken x_{Bj}'s of the partons.

References

[1] M.G.Albrow and A.Rostovtsev, Searching for the Higgs at Hadron Colliders using the Missing Mass Method, hep-ph/0009336. This addressed the Tevatron and claimed $\sigma(MM) \approx 250$ MeV. This scales to about 2 GeV at the LHC. The irreducible contribution is the momentum spread in the beams, $\approx 1.1 \times 10^{-4}$ rms (it is not Gaussian).We should reduce all other contributions (vertex position, magnetic fields, proton track) so that they are relatively negligible.