Trilepton Analysis: The $WH \to WWW \to l\nu l\nu l\nu$ Signal

(CDF Collaboration)

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Summary of Monte Carlo modeling of $WH \to WWW \to l\nu l\nu l\nu$ signal events for a trilepton analysis with the $H \to WW$ group.

Contents

PASSING THE TRILEPTON FILTER

Consider the Stntuple dataset *fhgs6f* that contains $WH \to WWW$ events for a 160 GeV Higgs boson. I consider here the subset of these events for which all three W bosons decay leptonically, and if that lepton is a tau then it also decays leptonically. This way, we intend to trigger primarily on three leptons along with missing energy. Running 100,000 *fhgs6f* events through a filter designed to select this subset yields 2358 trilepton events for this signal. The P_T, pseudorapidity (η), and ϕ angle distributions are in figures 1 through 9.

The leading lepton P_T distribution indicates that adopting a P_T cut of 18.0 - 20.0 GeV is perfectly adequate. For the second lepton it may be necessary to drop this cut down to 8.0 - 10.0 GeV. Notice especially the P_T distribution of the third lepton in figure 7. The third lepton for this signal does have P_T generated all the way down to nearly zero, so it will be necessary to accept third leptons as low as reasonably possible. How low these cuts go for data will be determined by whether or not the $P_T < 10.0$ GeV third leptons remain after certain cuts are made. The next two sections illustrates that this remains true with such cuts in place.

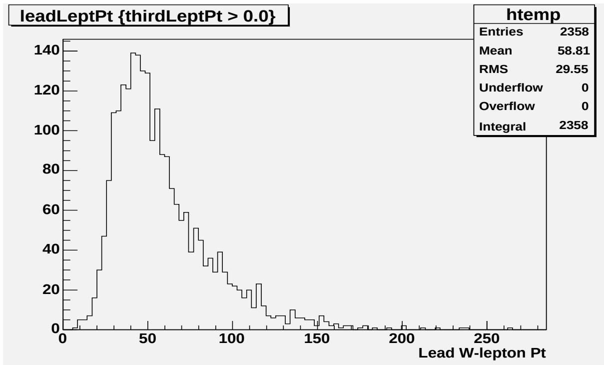

FIG. 1: Lead Generator-level Lepton Pt (GeV)

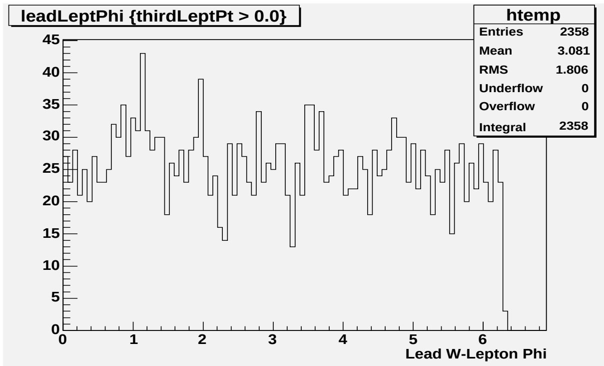

FIG. 2: Lead Generator-level Lepton Phi

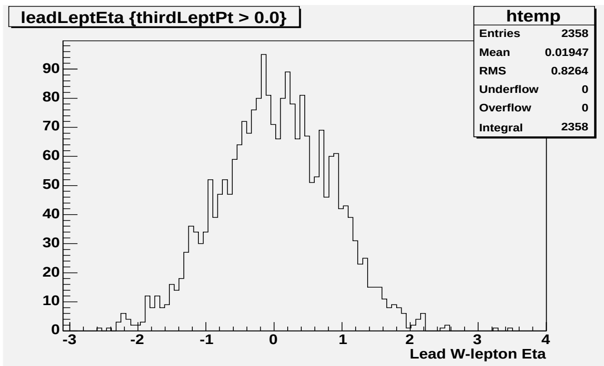

FIG. 3: Lead Generator-level Lepton Eta

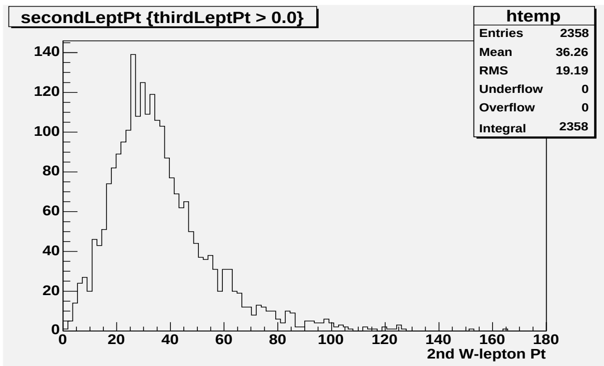

FIG. 4: 2nd Generator-level Lepton Pt (GeV)

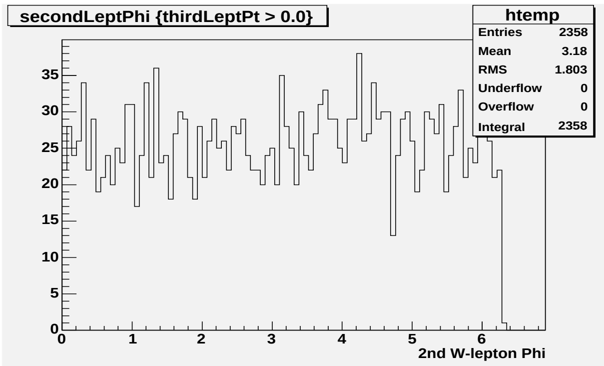

FIG. 5: 2nd Generator-level Lepton Phi

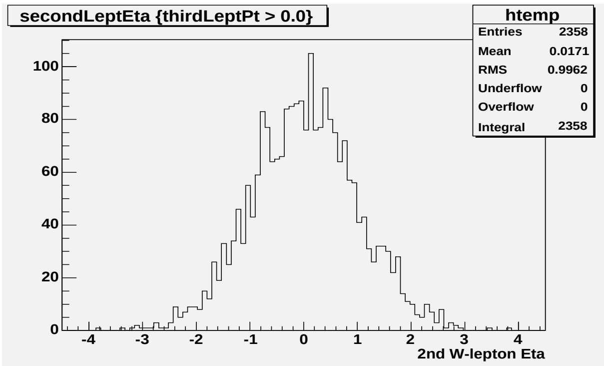

FIG. 6: 2nd Generator-level Lepton Eta

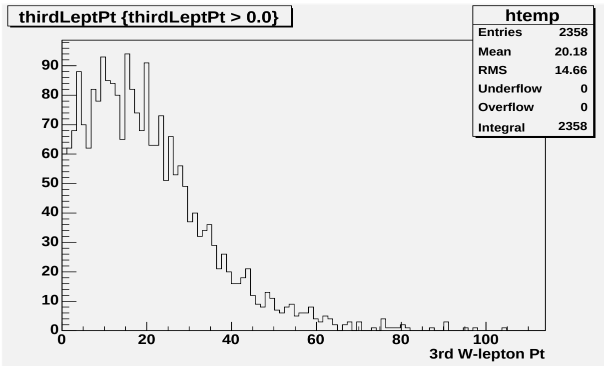

FIG. 7: 3rd Generator-level Lepton Pt (GeV)

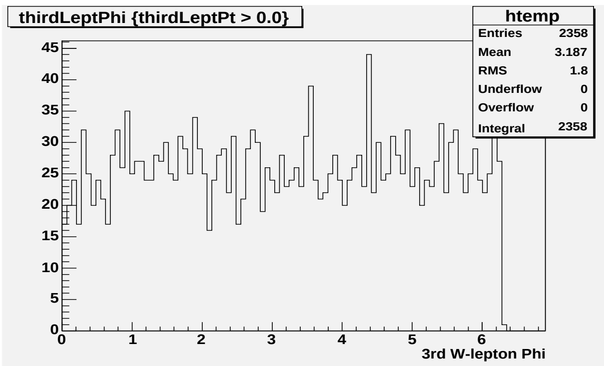

FIG. 8: 3rd Generator-level Lepton Phi

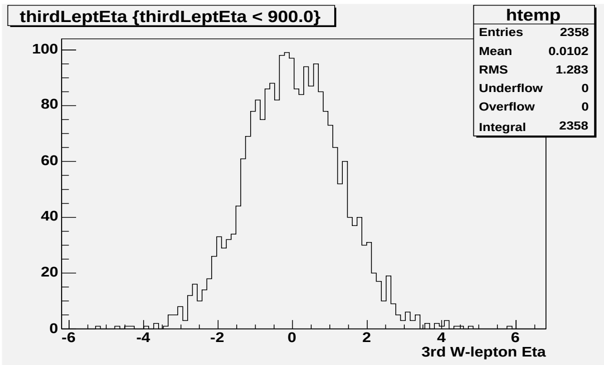

FIG. 9: 3rd Generator-level Lepton Eta

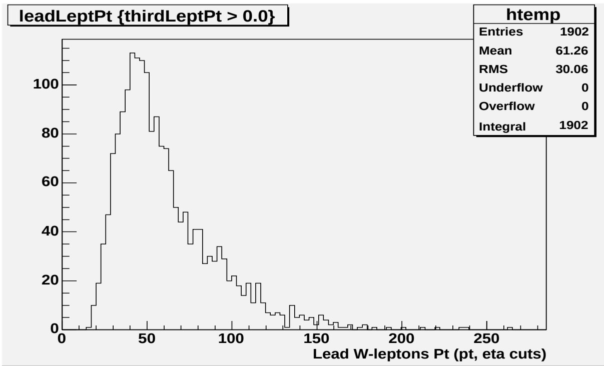

FIG. 10: Lead Generator-level Lepton Pt (GeV). Basic P_T and η cuts at generator-level.

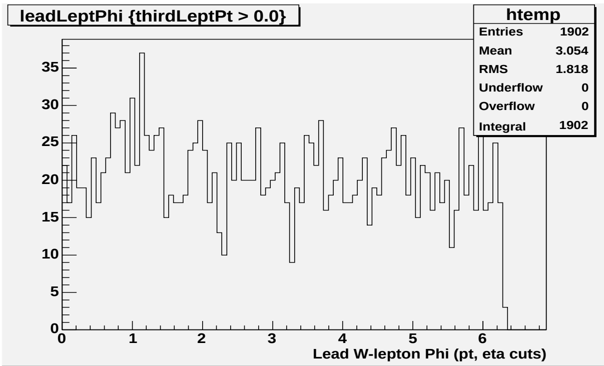

FIG. 11: Lead Generator-level Lepton Phi. Basic P_T and η cuts at generator-level.

BASIC KINEMATIC CUTS AT THE GENERATOR-LEVEL

Next, let's make some basic P_T and η cuts on these generator-level leptons to cut out events that the detector would simply not find. These are intended to be very loose. Require for P_T and η (cite these numbers, at least for η):

- Leading lepton $P_T > 16$ GeV
- 2nd lepton $P_T > 8$ GeV
- 3rd lepton $P_T > 2$ GeV
- $-1.7 < \eta < 1.7$ for muons
- $-2.9 < \eta < 2.9$ for electrons

After these cuts are made, the 2358 events becomes 1902 events. The results are in figures 10 through 18.

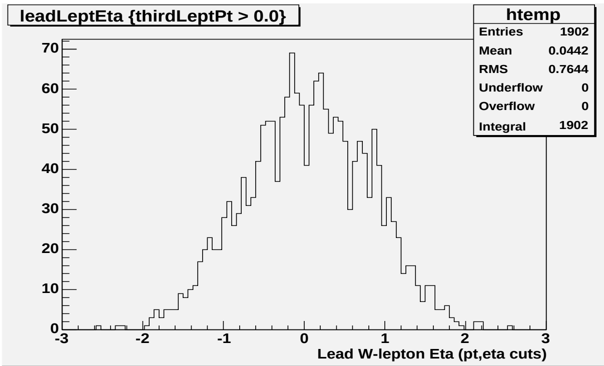

FIG. 12: Lead Generator-level Lepton Eta. Basic P_T and η cuts at generator-level.

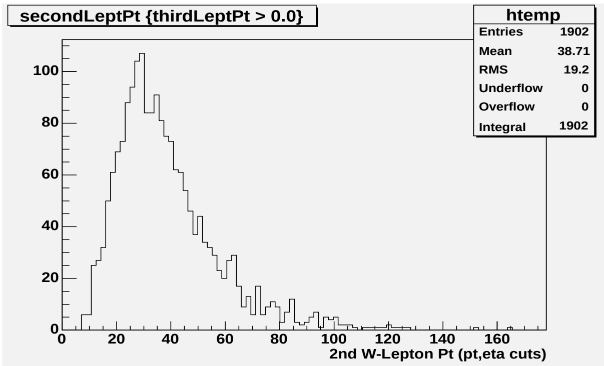

FIG. 13: 2nd Generator-level Lepton Pt (GeV). Basic P_T and η cuts at generator-level.

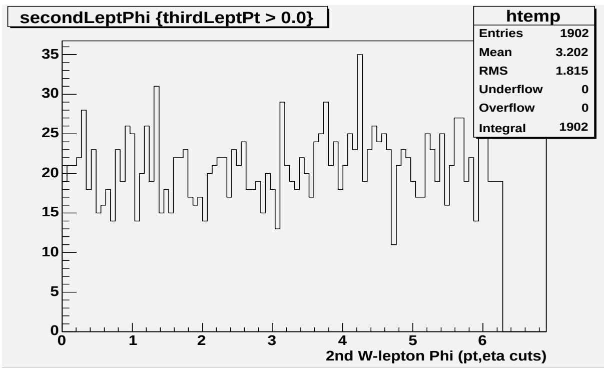

FIG. 14: 2nd Generator-level Lepton Phi. Basic P_T and η cuts at generator-level.

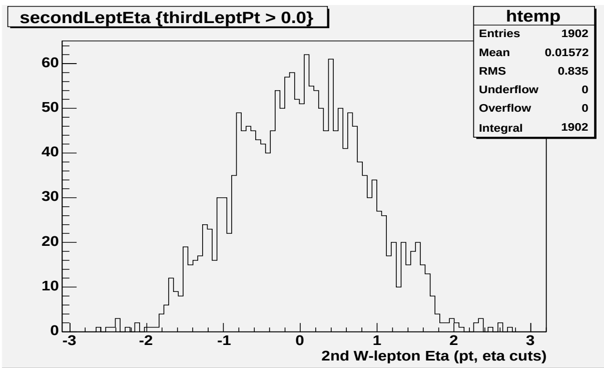

FIG. 15: 2nd Generator-level Lepton Eta. Basic P_T and η cuts at generator-level.

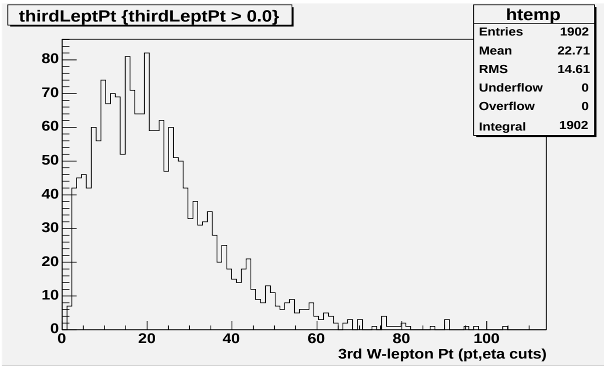

FIG. 16: 3rd Generator-level Lepton Pt (GeV). Basic P_T and η cuts at generator-level.

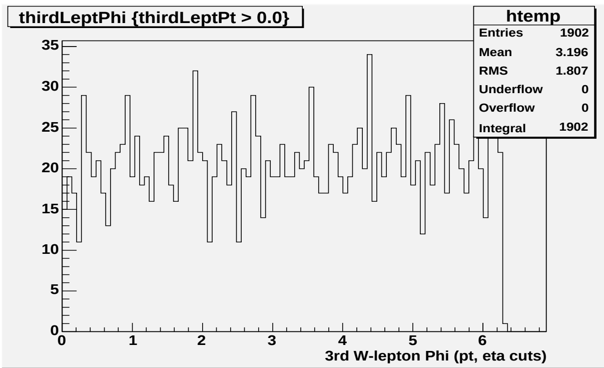

FIG. 17: 3rd Generator-level Lepton Phi. Basic P_T and η cuts at generator-level.

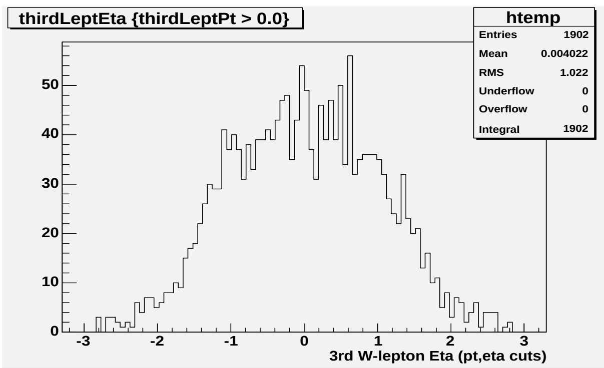

FIG. 18: 3rd Generator-level Lepton Eta. Basic P_T and η cuts at generator-level.

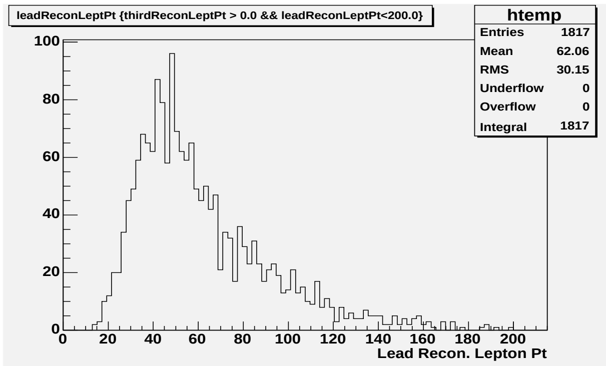

FIG. 19: Lead Reconstruced-level Lepton Pt (GeV). Basic P_T and η cuts at generator-level. The count is 1845; events above 200.0 GeV not included.

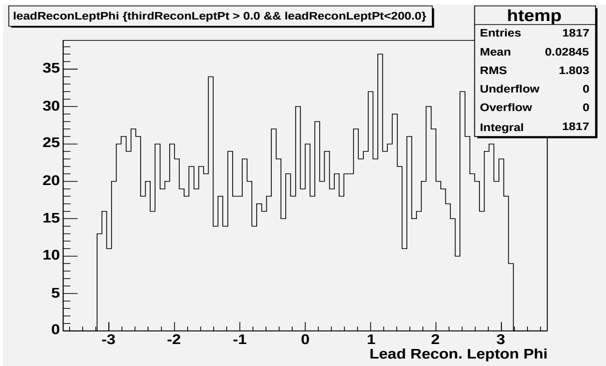

FIG. 20: Lead Reconstruced-level Lepton Phi. Basic P_T and η cuts at generator-level. The count is 1845; events above 200.0 GeV not included.

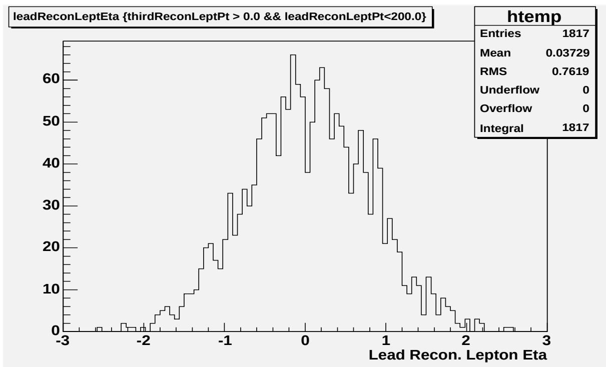

FIG. 21: Lead Reconstruced-level Lepton Eta. Basic P_T and η cuts at generator-level. The count is 1845; events above 200.0 GeV not included.

THREE RECONSTRUCTED LEPTONS WITH THE GENERATOR CUTS

Changing nothing, let's look at what is found at the reconstructed-level for these 1902 events. Not all of these events find three reconstructed leptons, so we are actually left with 1845 events that do find three leptons. The distributions of these 1845 are in figures 19 thought 27 (primary and secondary leptons from events that do not find a third lepton are not included).

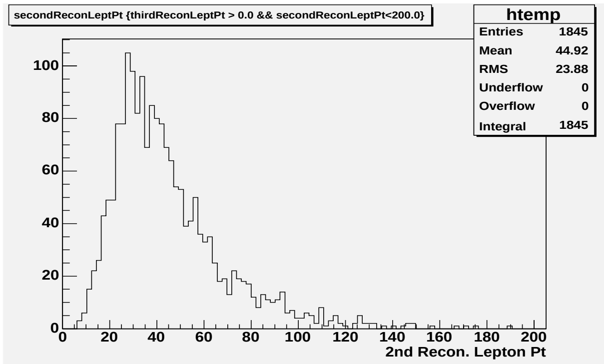

FIG. 22: 2nd Reconstruced-level Lepton Pt (GeV). Basic P_T and η cuts at generator-level.

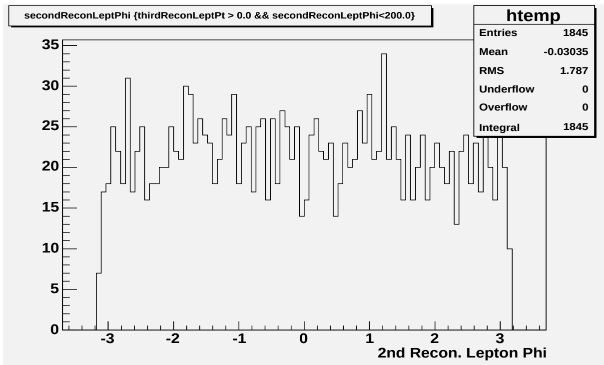

FIG. 23: 2nd Reconstruced-level Lepton Phi. Basic P_T and η cuts at generator-level.

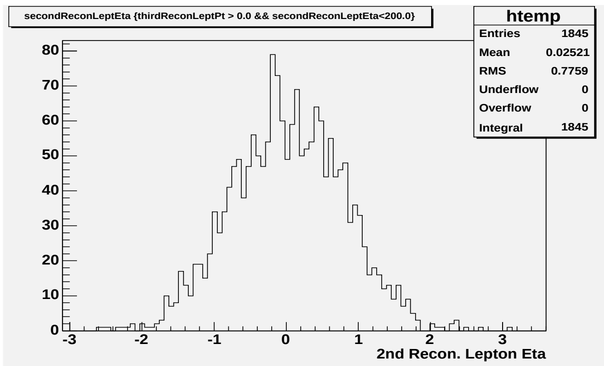

FIG. 24: 2nd Reconstruced-level Lepton Eta. Basic P_T and η cuts at generator-level.

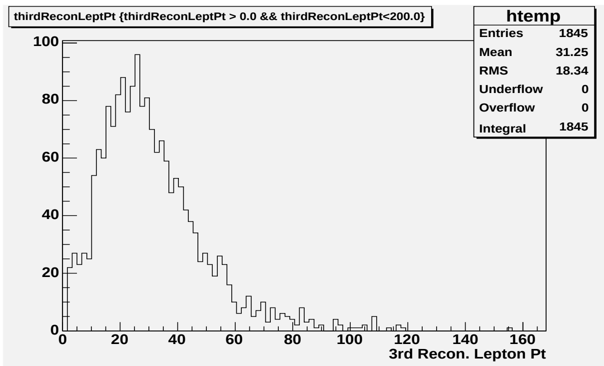

FIG. 25: 3rd Reconstruced-level Lepton Pt (GeV). Basic P_T and η cuts at generator-level.

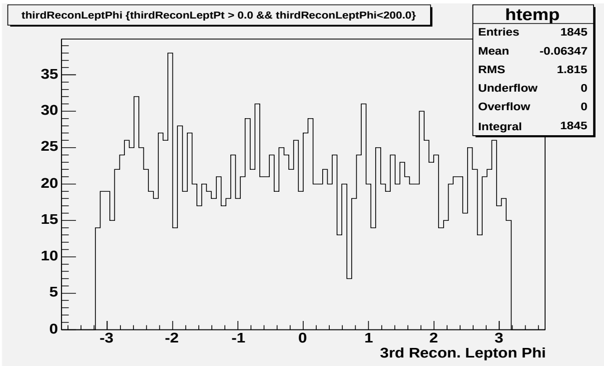

FIG. 26: 3rd Reconstruced-level Lepton Phi. Basic P_T and η cuts at generator-level.

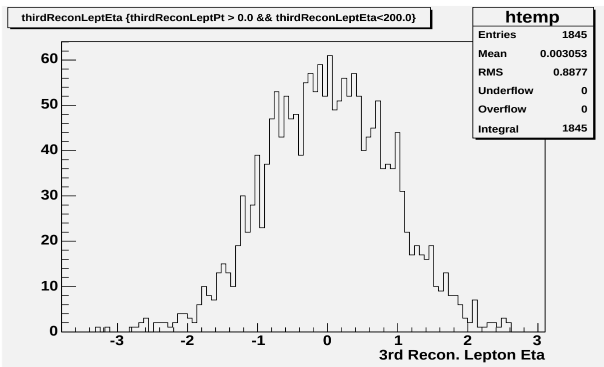

FIG. 27: 3rd Reconstruced-level Lepton Eta. Basic P_T and η cuts at generator-level.

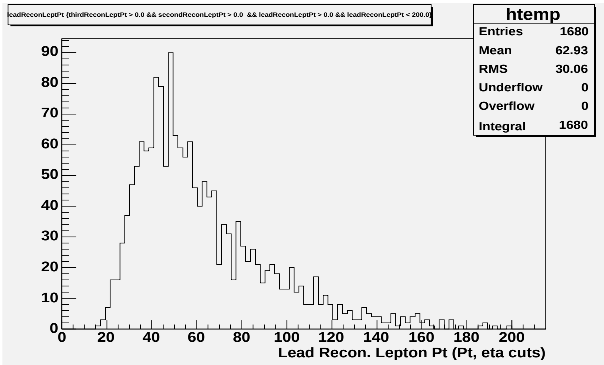

FIG. 28: Lead Reconstruced-level Lepton Pt (GeV). Basic P_T and η cuts at generator-level, as well as at reconstruction-level. The count is 1702; events above 200.0 GeV not included.

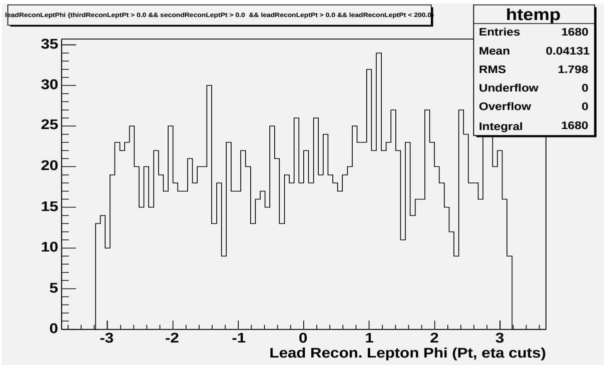

FIG. 29: Lead Reconstruced-level Lepton Phi. Basic P_T and η cuts at generator-level, as well as at reconstruction-level. The count is 1702; events above 200.0 GeV not included.

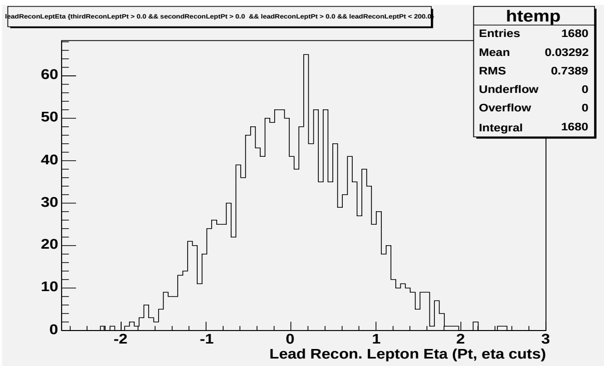

FIG. 30: Lead Reconstruced-level Lepton Eta. Basic P_T and η cuts at generator-level, as well as at reconstruction-level. The count is 1702; events above 200.0 GeV not included.

THREE RECONSTRUCTED LEPTONS WITH P_t AND η CUTS

Starting with the same set of 1845 events in the previous section, let's impose the same P_T and η cuts that we used at the generator-level, at the reconstructed-level as well now. This cuts our event set down to 1702 events illustrated in figures 28 through 36.

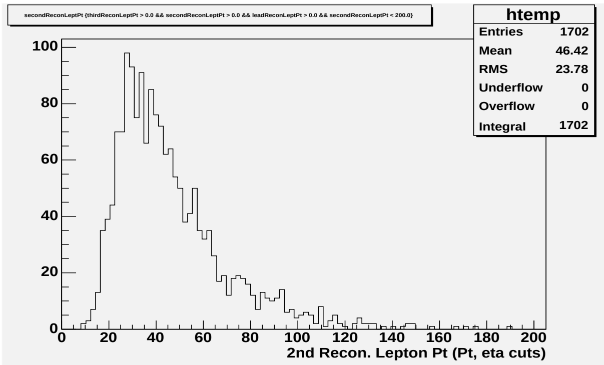

FIG. 31: 2nd Reconstruced-level Lepton Pt (GeV). Basic P_T and η cuts at generator-level, as well as at reconstruction-level.

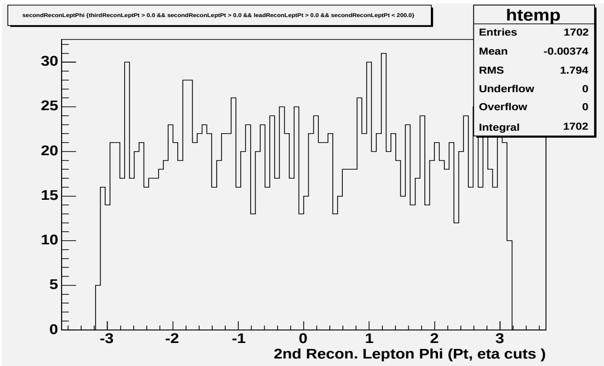

FIG. 32: 2nd Reconstruced-level Lepton Phi. Basic P_T and η cuts at generator-level, as well as at reconstruction-level.

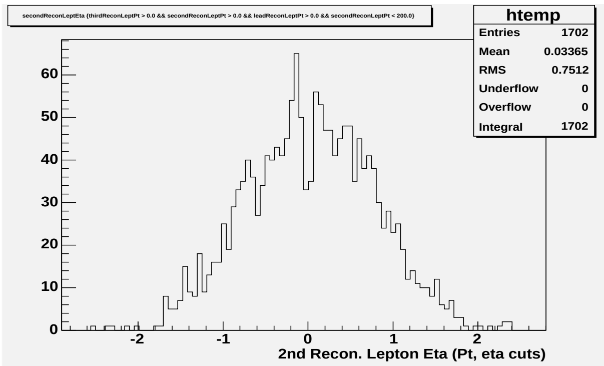

FIG. 33: 2nd Reconstruced-level Lepton Eta. Basic P_T and η cuts at generator-level, as well as at reconstruction-level.

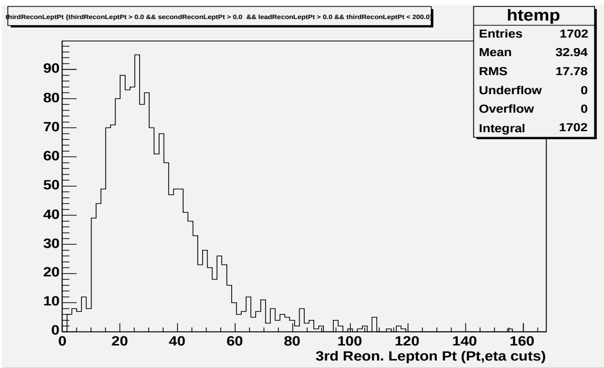

FIG. 34: 3rd Reconstruced-level Lepton Pt (GeV). Basic P_T and η cuts at generator-level, as well as at reconstruction-level.

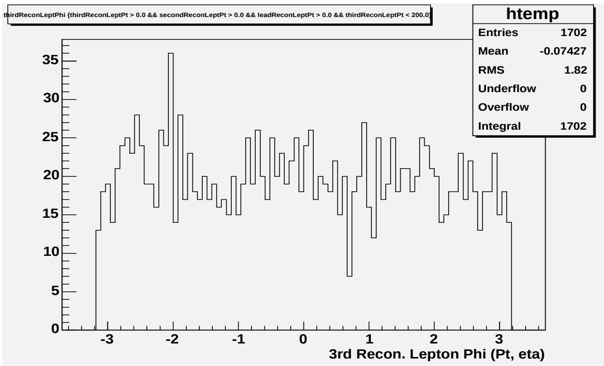

FIG. 35: 3rd Reconstruced-level Lepton Phi. Basic P_T and η cuts at generator-level, as well as at reconstruction-level.

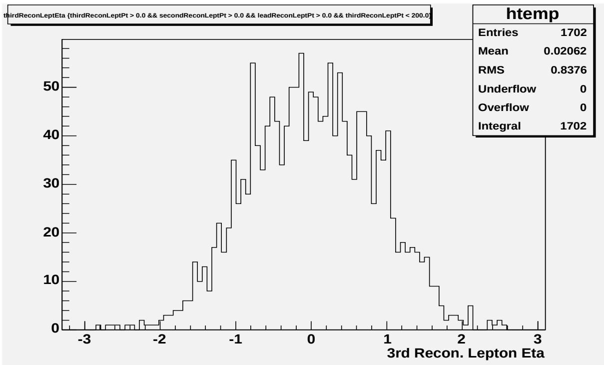

FIG. 36: 3rd Reconstruced-level Lepton Eta. Basic P_T and η cuts at generator-level, as well as at reconstruction-level.

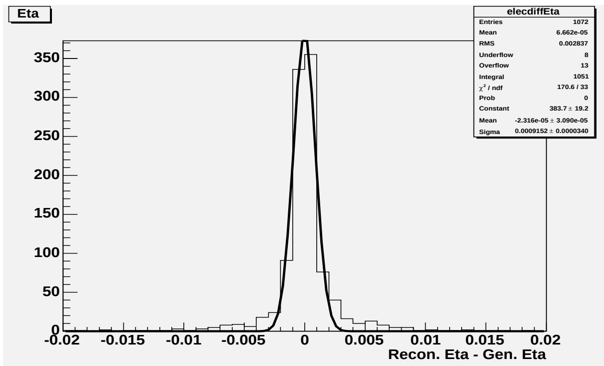

FIG. 37: Electron $\eta_{\text{recon}} - \eta_{\text{gen}}$, σ_η found here.

THREE RECONSTRUCTED LEPTONS MATCHED TO GENERATOR-LEVEL LEPTONS

Let's now require that the reconstructed leptons not only pass the P_T and η cuts of the previous section, but also pass a matching criterion to an object in the generator-level list.

The matching criterion is:

$$\text{Matching Factor} \equiv \frac{|P_{T,\text{recon}} - P_{T,\text{gen}}|}{\delta_{P_T}} + \frac{|\eta_{\text{recon}} - \eta_{\text{gen}}|}{\sigma_\eta} + \frac{|\phi_{\text{recon}} - \phi_{\text{gen}}|}{\sigma_\phi} < 40.0$$

where

$$\begin{aligned}
P_{T,\text{recon}} &= \text{Reconstructed particle } P_T \\
P_{T,\text{gen}} &= \text{Generator-level particle } P_T \\
\delta_{P_T} &= 0.0015 \cdot P_{T,\text{recon}} \\
\eta_{\text{recon}} &= \text{Pseudorapidity of reconstructed particle} \\
\eta_{\text{gen}} &= \text{Psuedorapidity of generator-level particle} \\
\phi_{\text{recon}} &= \text{Azimuthal Angle of reconstructed particle} \\
\phi_{\text{gen}} &= \text{Azimuthal Angle of generator-level particle} \\
\sigma_\eta &= \text{Standard Deviation of a Gaussian fit to } \eta_)\text{recon} - \eta_{\text{gen}} \\
\sigma_\phi &= \text{Standard Deviation of a Gaussian fit to } \phi_{\text{recon}} - \phi_{\text{gen}}
\end{aligned}$$

For a candidate reconstructed electron, a match is attempted for every generator-level electron in the event. For a candidate reconstructed muon that has any stub (CMP, CMU, CMX, BMU), a match is attempted for every generator-level muon in the event, but if the muon is stubless then a match is attempted for all electrons and muons. The reason is that these stubless, or CMIO, reconstructed muons are often electrons that were reconstructed as such. If the best-match found (lowest-valued matching factor) satisfies the matching criterion given above (matching factor < 40), then a match has been successfully found.

The standard deviations used are given by figures 37, 38, 39, and 40.

The 1702 events from the previous section are cut down to 1596 events with the matching requirement in place. Distributions of the value of "matching factor" can be seen for the lead, 2nd, and 3rd leptons in figures 50 through 52. These distributions illustrate that the vast majority of events have leptons passing this criterion. The relevant P_T, η, and ϕ distributions of these 1596 events are in figures 41 through 49.

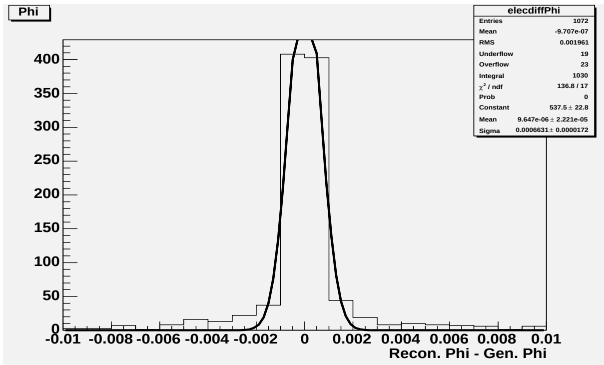

FIG. 38: Electron $\phi_{\rm recon} - \phi_{\rm gen}$, σ_ϕ found here.

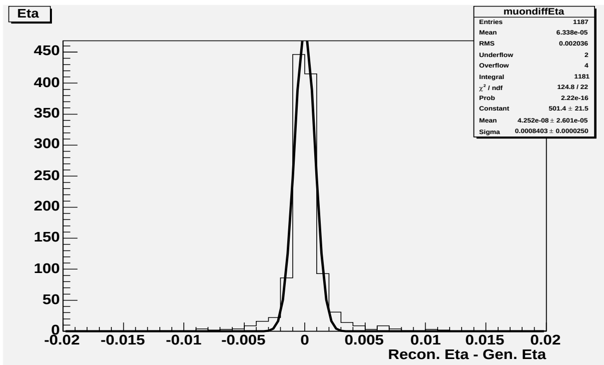

FIG. 39: Muon $\eta_{\rm recon} - \eta_{\rm gen}$, σ_η found here.

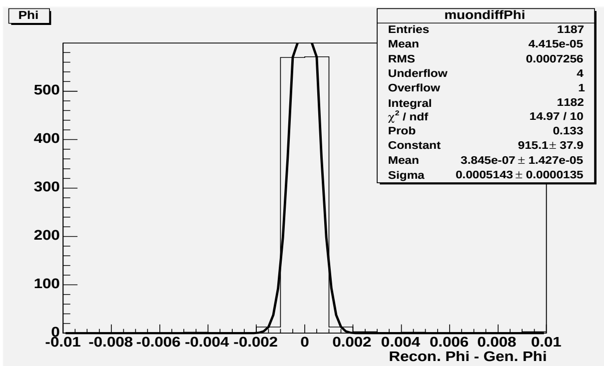

FIG. 40: Muon $\phi_{\rm recon} - \phi_{\rm gen}$, σ_ϕ found here.

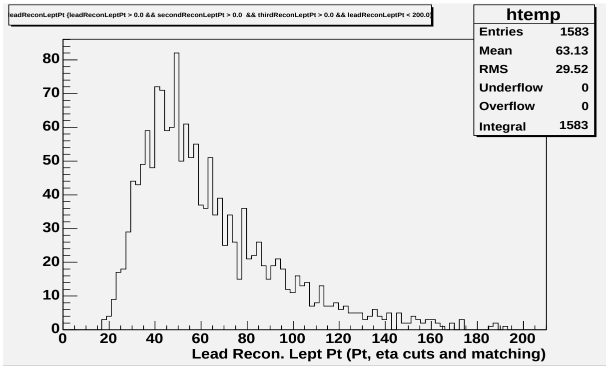

FIG. 41: Lead Reconstruced-level Lepton Pt (GeV). Basic P_T and η cuts at generator-level, as well as at reconstruction-level, and matched. The count is 1129; events above 200.0 GeV not included.

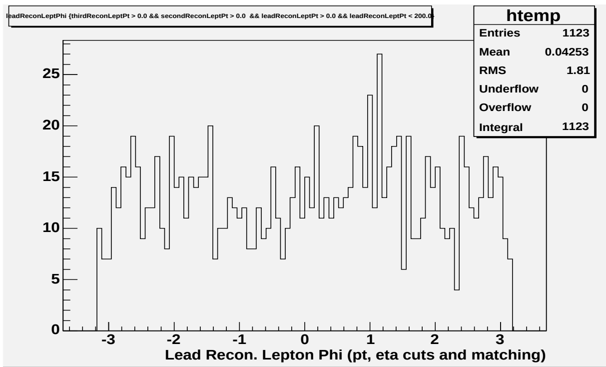

FIG. 42: Lead Reconstruced-level Lepton Phi. Basic P_T and η cuts at generator-level, as well as at reconstruction-level, and matched. The count is 1129; events above 200.0 GeV not included.

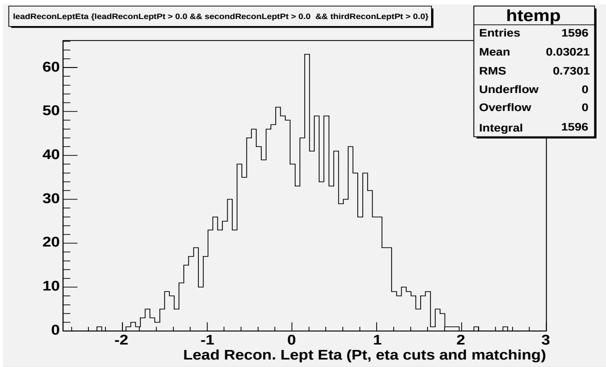

FIG. 43: Lead Reconstruced-level Lepton Eta. Basic P_T and η cuts at generator-level, as well as at reconstruction-level, and matched. The count is 1129; events above 200.0 GeV not included.

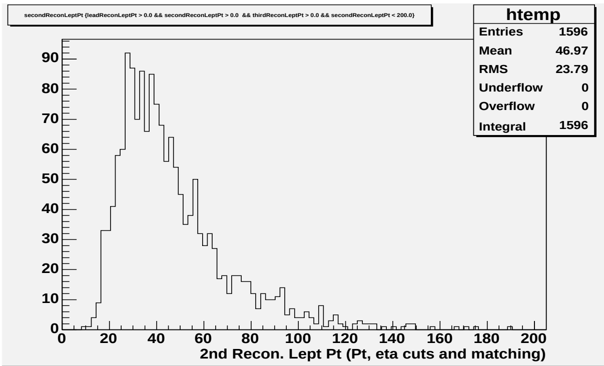

FIG. 44: 2nd Reconstruced-level Lepton Pt (GeV). Basic P_T and η cuts at generator-level, as well as at reconstruction-level, and matched.

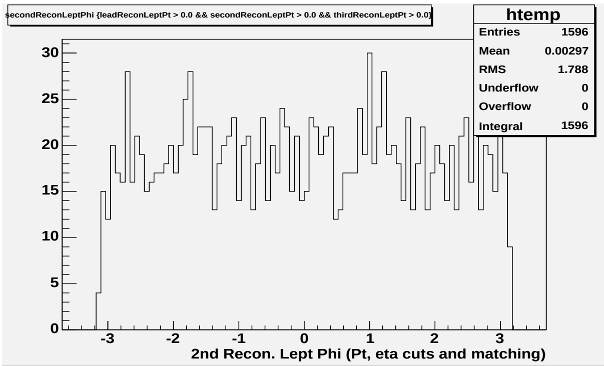

FIG. 45: 2nd Reconstruced-level Lepton Phi. Basic P_T and η cuts at generator-level, as well as at reconstruction-level, and matched.

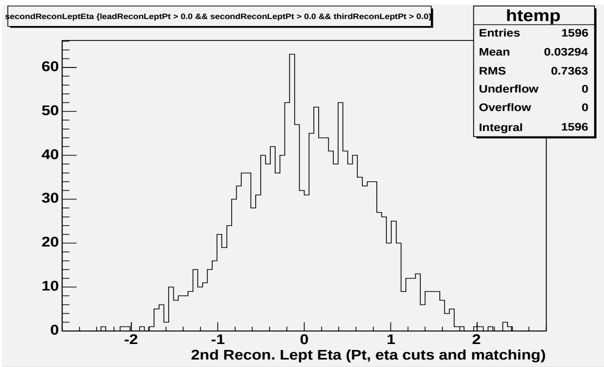

FIG. 46: 2nd Reconstruced-level Lepton Eta. Basic P_T and η cuts at generator-level, as well as at reconstruction-level, and matched.

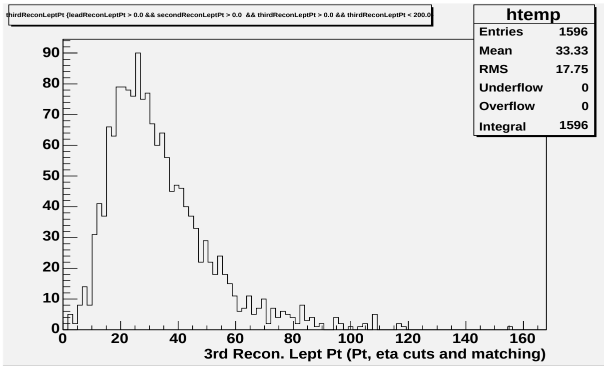

FIG. 47: 3rd Reconstruced-level Lepton Pt (GeV). Basic P_T and η cuts at generator-level, as well as at reconstruction-level, and matched.

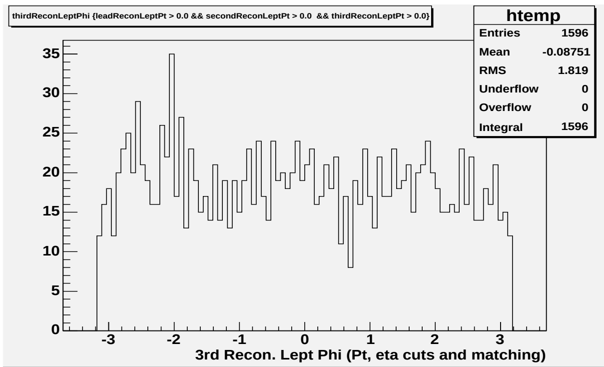

FIG. 48: 3rd Reconstruced-level Lepton Phi. Basic P_T and η cuts at generator-level, as well as at reconstruction-level, and matched.

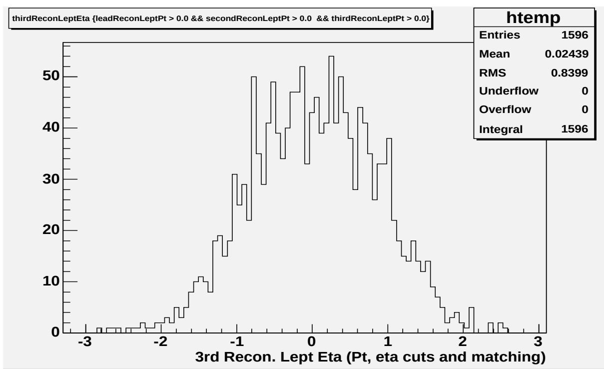

FIG. 49: 3rd Reconstruced-level Lepton Eta. Basic P_T and η cuts at generator-level, as well as at reconstruction-level, and matched.

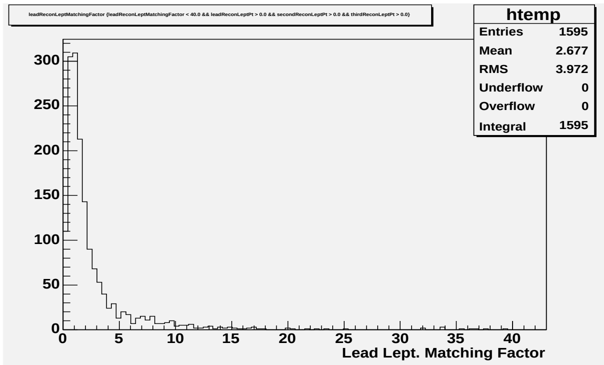

FIG. 50: Leading Lepton Matching Factor, 1664/1702 passing the criterion (<40).

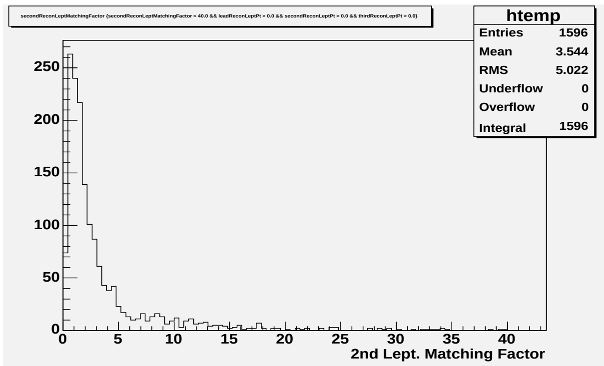

FIG. 51: Second Lepton Matching Factor, 1668/1702 passing the criterion (<40).

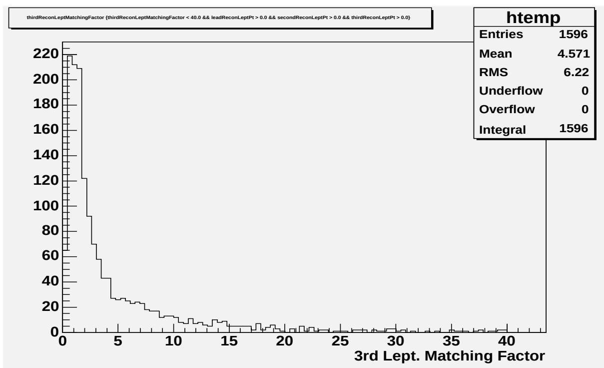

FIG. 52: Third Lepton Matching Factor, 1605/1702 passing the criterion (<40).

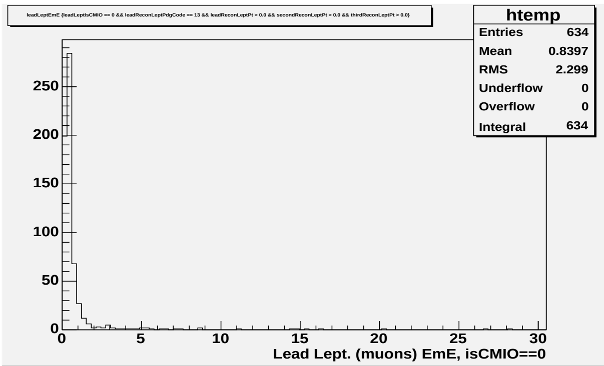

FIG. 53: Electromagnetic energy for leading muon objects that do have stubs. Quality Cut for electomagnetic energy is EmE < 2.0.

Mismatched CMIO Muon-objects

Finally, let's return to the subject of the CMIO (stubless) muons versus muons with at least one of CMU, CMP, CMX, or BMU stubs. If in the matching algorithm we allow reconstructed electrons and muons to attempt matches with any typical charged particle (electrons, muons, pions, kaons, protons), then we find that electrons almost always match best to generator-level electrons, but a large portion of muons are found to match to electrons instead of muons. Very small percentages match to other charged particles.

The quantitative summary found in table I shows how pronounced the distinction between stubbed and CMIO muons is. If we alter the matching algorithm to allow CMIO muons to attempt matches only with muons, we find that the CMIO muons matching to electrons will almost always find no match rather than an acceptable nearby muon. This means that most of these CMIO muons mismatching to electrons are not the case of the event having an electron and muon in close proximity and the reconstructed muon happens to match slightly better to the electron. Rather, it appears that the generator-level electrons have been reconstructed as CMIO muons. A look at the electromagnetic calorimeter energy distribution separately for stubbed and CMIO muon-objects supports this conclusion–that is, the Em. Energy for CMIO muon-objects is conspicuously electron-like (see figures 53 through 58). It is for this reason that CMIO muon-objects exclusively are allowed to match to either electrons or muons in the matching described above, whereas stubbed muons only search generator-level muons for matches and electrons only search generator-level electrons for matches.

Matches(%)	electrons	muons	pions	kaons	protons	Total
Lead stubbed muons	0	634(100%)	0	0	0	634
Lead CMIO muons	195(64.4%)	105(34.6%)	2(0.7%)	0	1(0.3%)	303
2nd stubbed muons	2(0.5%)	435(99.5%)	0	0	0	437
2nd CMIO muons	550(85.1%)	91(14.1%)	5(0.8%)	0	0	646
3rd stubbed muons	1(0.2%)	505(99.6%)	1(0.2%)	0	0	507
3rd CMIO muons	483(78.9%)	108(17.6%)	17(2.7%)	0	4(0.6%)	612
lead electrons	681(99.4%)	3(0.4%)	1(0.1%)	0	0	685
2nd electrons	529(98.1%)	4(0.7%)	5(0.9%)	1(0.2%)	0	539
3rd electrons	485(98.2%)	2(0.4%)	5(1.0%)	2(0.4%)	0	494

TABLE I: caption

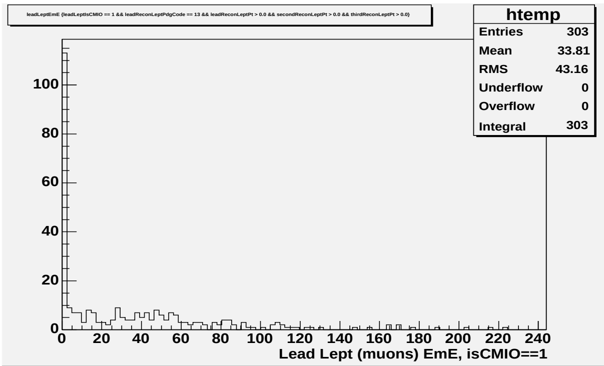

FIG. 54: Electromagnetic energy for leading muon objects that do not have stubs. Quality Cut for electomagnetic energy is EmE < 2.0.

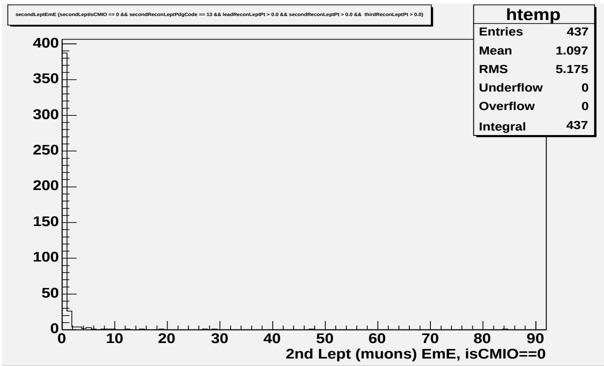

FIG. 55: Electromagnetic energy for 2nd muon objects that do have stubs. Quality Cut for electomagnetic energy is EmE $<$ 2.0.

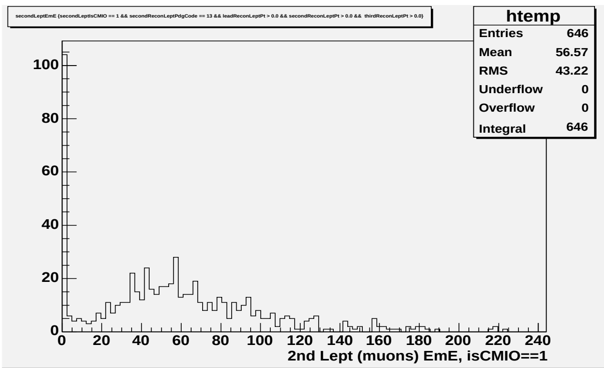

FIG. 56: Electromagnetic energy for 2nd muon objects that do not have stubs. Quality Cut for electomagnetic energy is EmE < 2.0.

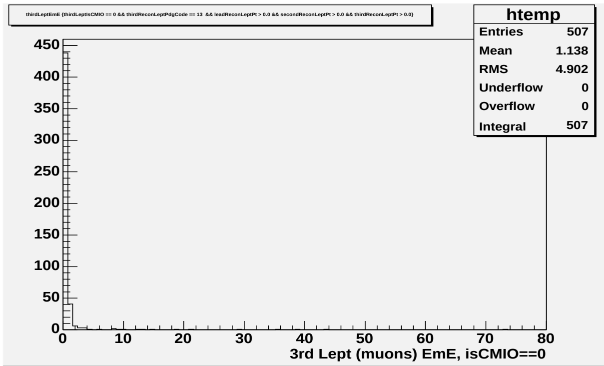

FIG. 57: Electromagnetic energy for 3rd muon objects that do have stubs. Quality Cut for electomagnetic energy is EmE < 2.0.

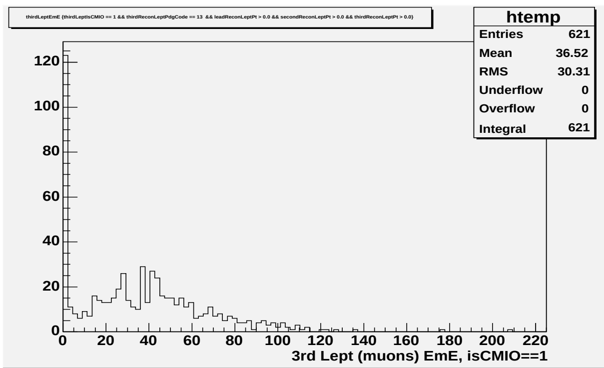

FIG. 58: Electromagnetic energy for 3rd muon objects that do not have stubs. Quality Cut for electomagnetic energy is EmE < 2.0.

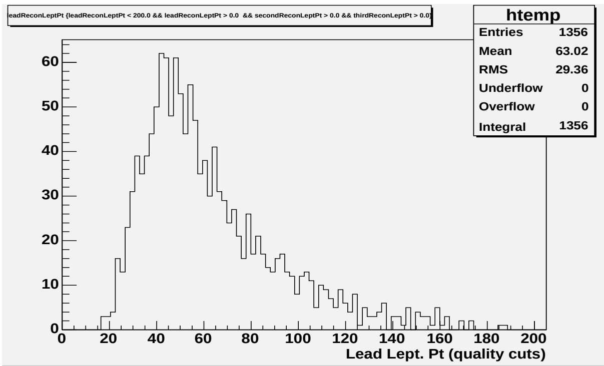

FIG. 59: Lead Reconstruced-level Lepton Pt (GeV). Basic P_T and η cuts at generator-level, as well as at reconstruction-level, matched, and quality and isolation requirements.

THREE RECONSTRUCTED LEPTONS WITH QUALITY AND ISOLATION CUTS

CDF Note 9402, *Search for* $H \rightarrow WW$ *using* $3.0 fb^{-1}$, suggests using selection criteria from CDF Note 8719. Some, but as yet not all, of these criteria are implemented in lepton selection for figures 59 through 67. These are as follows:

- Electrons
  - Central Electrons
    - $\frac{\text{TrackIso()}}{E_T} < 0.1$
    - $\frac{\text{Had. Energy}}{\text{Em. Energy}} < 0.055 + 0.00045 \cdot E$
    - $\frac{E}{P} < 2.5 + 0.015 \cdot E_T$
  - Plug Electrons
    - $\frac{\text{TrackIso()}}{E_T} < 0.1$
    - $\frac{\text{Had. Energy}}{\text{Em. Energy}} < 0.05$
  - Forward Electrons: (none in the present sample)
    - $\frac{\text{TrackIso()}}{E_T} < 0.1$
    - $\frac{\text{Had. Energy}}{\text{Em. Energy}} < 0.05$
  - PHX "Phoenix Algorithm" electrons (All PHX electrons in the present sample are already either Central or Plug electrons, which is given precedence.)
    - $\frac{\text{TrackIso()}}{E_T} < 0.1$
    - $\frac{\text{Had. Energy}}{\text{Em. Energy}} < 0.05$
- Muons
  - Muons with at least one stub (CMU, CMP, CMX, BMU)
    - Em. Energy < 2.0 GeV
    - Had. Energy < 6.0 GeV
    - $\frac{\text{TrackIso()}}{P_T} < 0.1$
  - CMIO (stubless) Muons: $\frac{\text{TrackIso()}}{P_T} < 0.1$

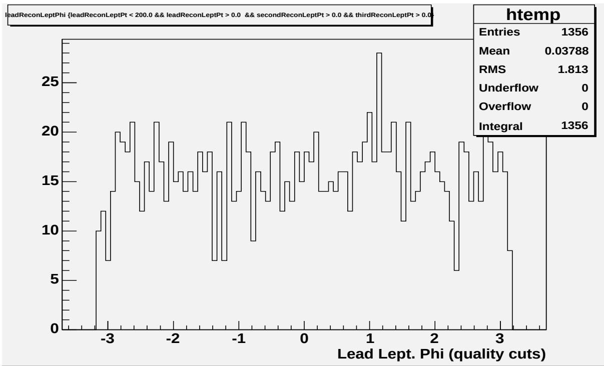

FIG. 60: Lead Reconstruced-level Lepton Phi. Basic P_T and η cuts at generator-level, as well as at reconstruction-level, matched, and quality and isolation requirements.

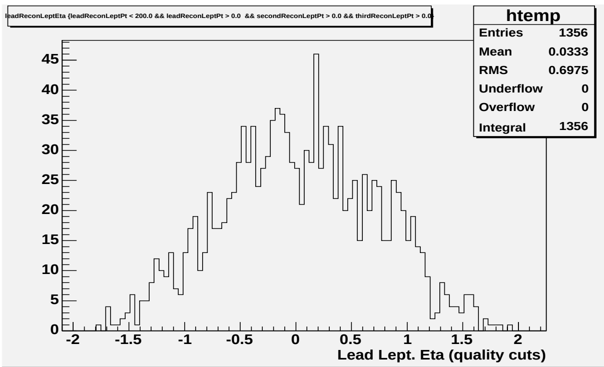

FIG. 61: Lead Reconstruced-level Lepton Eta. Basic P_T and η cuts at generator-level, as well as at reconstruction-level, matched, and quality and isolation requirements.

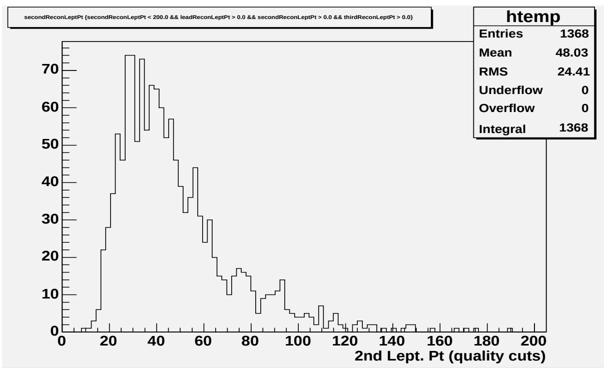

FIG. 62: 2nd Reconstruced-level Lepton Pt (GeV). Basic P_T and η cuts at generator-level, as well as at reconstruction-level, matched, and quality and isolation requirements.

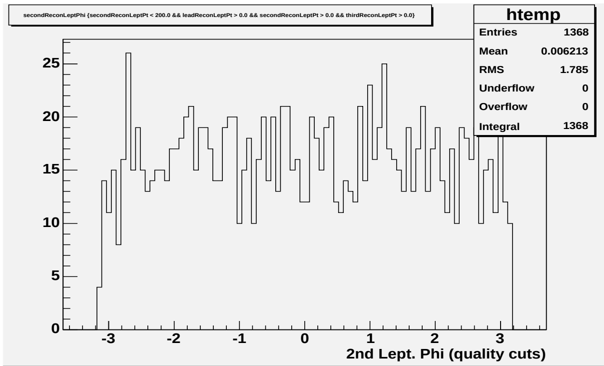

FIG. 63: 2nd Reconstruced-level Lepton Phi. Basic P_T and η cuts at generator-level, as well as at reconstruction-level, matched, and quality and isolation requirements.

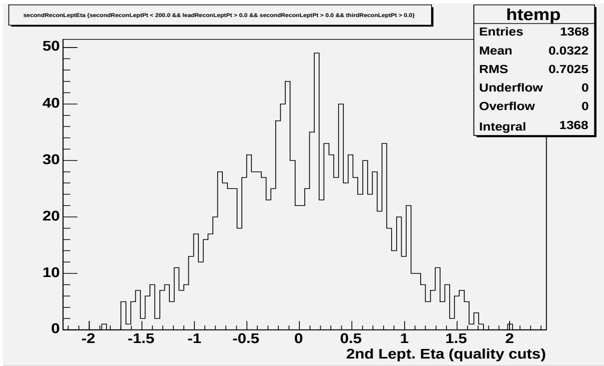

FIG. 64: 2nd Reconstruced-level Lepton Eta. Basic P_T and η cuts at generator-level, as well as at reconstruction-level, matched, and quality and isolation requirements.

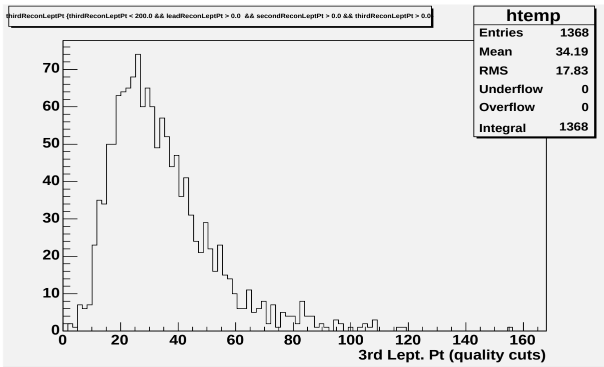

FIG. 65: 3rd Reconstruced-level Lepton Pt (GeV). Basic P_T and η cuts at generator-level, as well as at reconstruction-level, matched, and quality and isolation requirements.

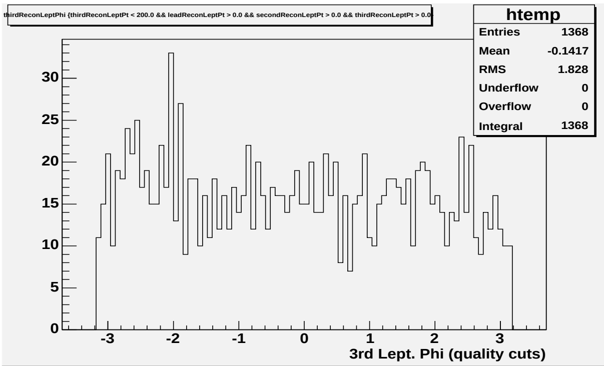

FIG. 66: 3rd Reconstruced-level Lepton Phi. Basic P_T and η cuts at generator-level, as well as at reconstruction-level, matched, and quality and isolation requirements.

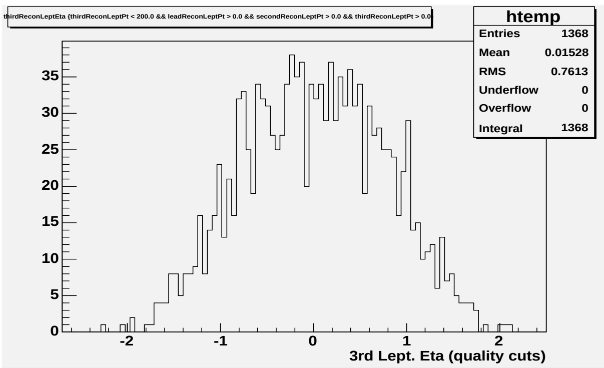

FIG. 67: 3rd Reconstruced-level Lepton Eta. Basic P_T and η cuts at generator-level, as well as at reconstruction-level, matched, and quality and isolation requirements.

QUALITY AND ISOLATION CUTS, DETAILED

Table II provides a summary of the various lepton quality cuts, progressing from the 1129 events that pass the matching criterion (see the above section) to the 771 events that have three leading leptons passing all quality cuts (see table III). Essentially, table II details the gap between the last two rows of table III.

Cuts	Number (out of 1596)	%(from previous step)
Central Electron $\frac{\text{TrackIso()}}{E_T} < 0.1$	1569	98.3
Central Electron $\frac{\text{Had.E}}{\text{Em. E}} < 0.055 + 0.00045 \cdot E$	1567	99.9
Central Electron $\frac{E}{P} < 2.5 + 0.015 \cdot E_T$	1530	97.5
Plug Electron $\frac{\text{TrackIso()}}{E_T} < 0.1$	1454	95.0
Plug Electron $\frac{\text{Had.E}}{\text{Em. E}} < 0.05$	1451	99.8
Forward Electron $\frac{\text{TrackIso()}}{E_T} < 0.1$	-	0
Forward Electron $\frac{\text{Had.E}}{\text{Em. E}} < 0.05$	-	0
PHX Electron $\frac{\text{TrackIso()}}{E_T} < 0.1$	-	0
PHX Electron $\frac{\text{Had.E}}{\text{Em. E}} < 0.05$	-	0
Stubbed Muons Em. Energy < 2.0	1404	96.8
Stubbed Muons Had. Energy < 6.0	1387	98.8
Stubbed Muons $\frac{\text{TrackIso()}}{P_T} < 0.1$	1375	99.1
CMIO Muons $\frac{\text{TrackIso()}}{P_T} < 0.1$	1368	99.5

TABLE II: Quality Cuts detailed from 1596 to 1368 events.

SUMMARY

Cuts	Number (out of 100,000)	%(from previous step)
Pass $HW \to WWW \to l\nu l\nu l\nu$ filter	2358	2.36
P_T, η cuts at generator-level	1902	80.6
Lead, 2nd, 3rd Reconstructed leptons found	1845	97.0
Same P_T, η cuts at reconstruction-level	1702	92.2
Pass Matching Criterion	1596	93.8
Pass Quality/Isolation Cuts	1368	85.7

TABLE III: Event Summary