Analysis of Muon Reconstruction by PFA

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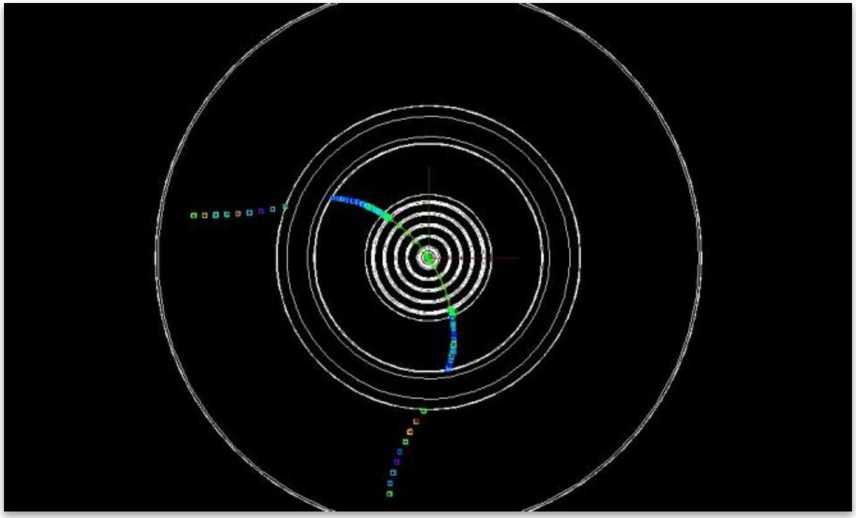
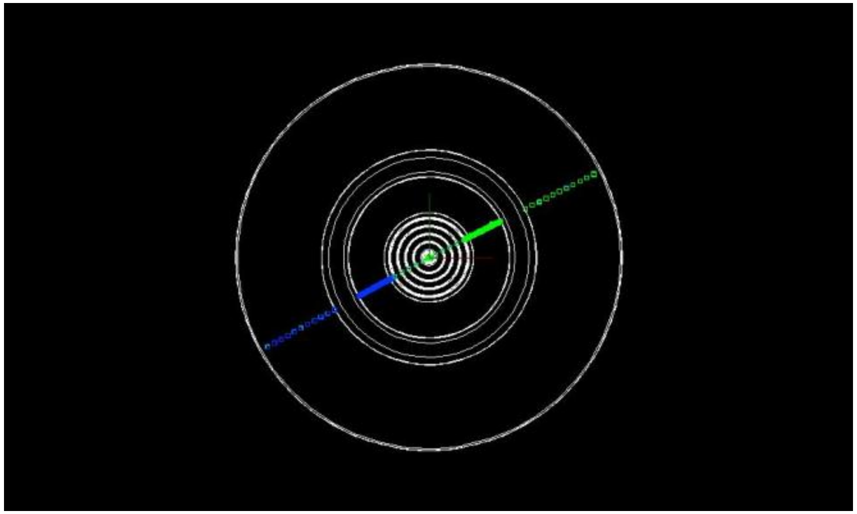
Initially looking at analysing only events containing Z boson into two muons

Due to the simplicity of the events being analysed we would expect the PFA to perform an effective reconstruction of both muons

Data consisted of 50 000 events at each energy, simulated on detector sid02 and reconstructed with IOWA PFA



Muon at 10 GeV



Muons at 500 GeV

I. $e^+e^- \rightarrow Z \rightarrow \mu^+\mu^-$

10 GeV / 25 GeV / 50 GeV / 91 GeV / 200 GeV / 500 GeV

There are two main mistakes made by the reconstruction algorithm when dealing with muon events:

1. Failure to detect two muons (misidentification)
2. Additional reconstructed particles

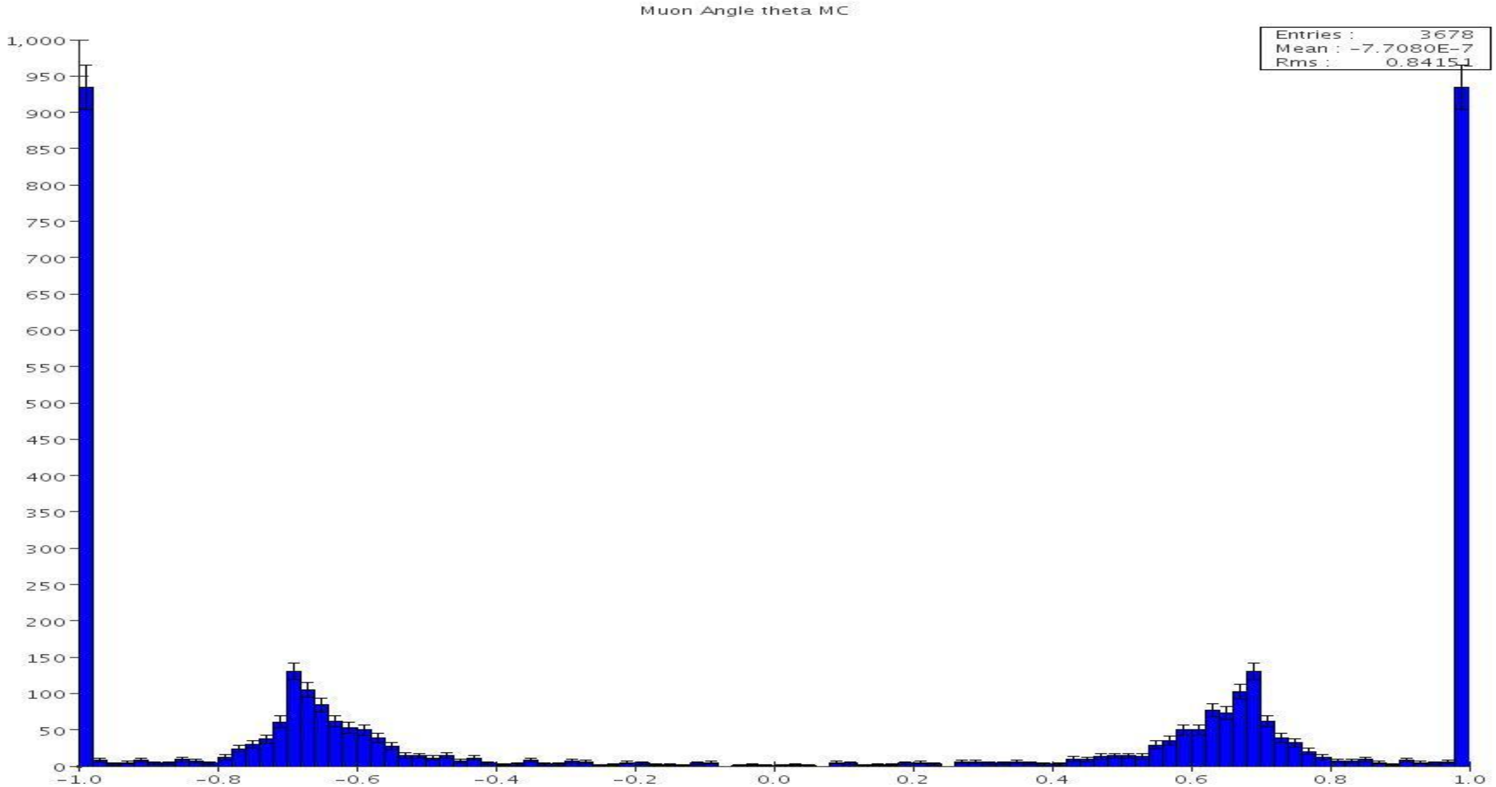
Identified Muons	10 Gev	25 GeV	50 GeV	91 GeV	200 GeV	500 GeV
0	1.65	1.60	1.61	1.56	1.62	1.58
1	2.03	0.45	0.36	0.40	0.43	0.58
2	96.32	97.95	98.04	98.04	97.95	97.84
Total	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**

Percentage of muons reconstructed per event

Why are 2 muons not reconstructed?

1. Muons with a small polar angle missing the vertex tracker, the tracker and the Ecal
2. Showering of the muon leading to energy loss and/or misidentification

I. $e^+e^- \rightarrow Z \rightarrow \mu^+\mu^-$ Failure to reconstruct 2 muons



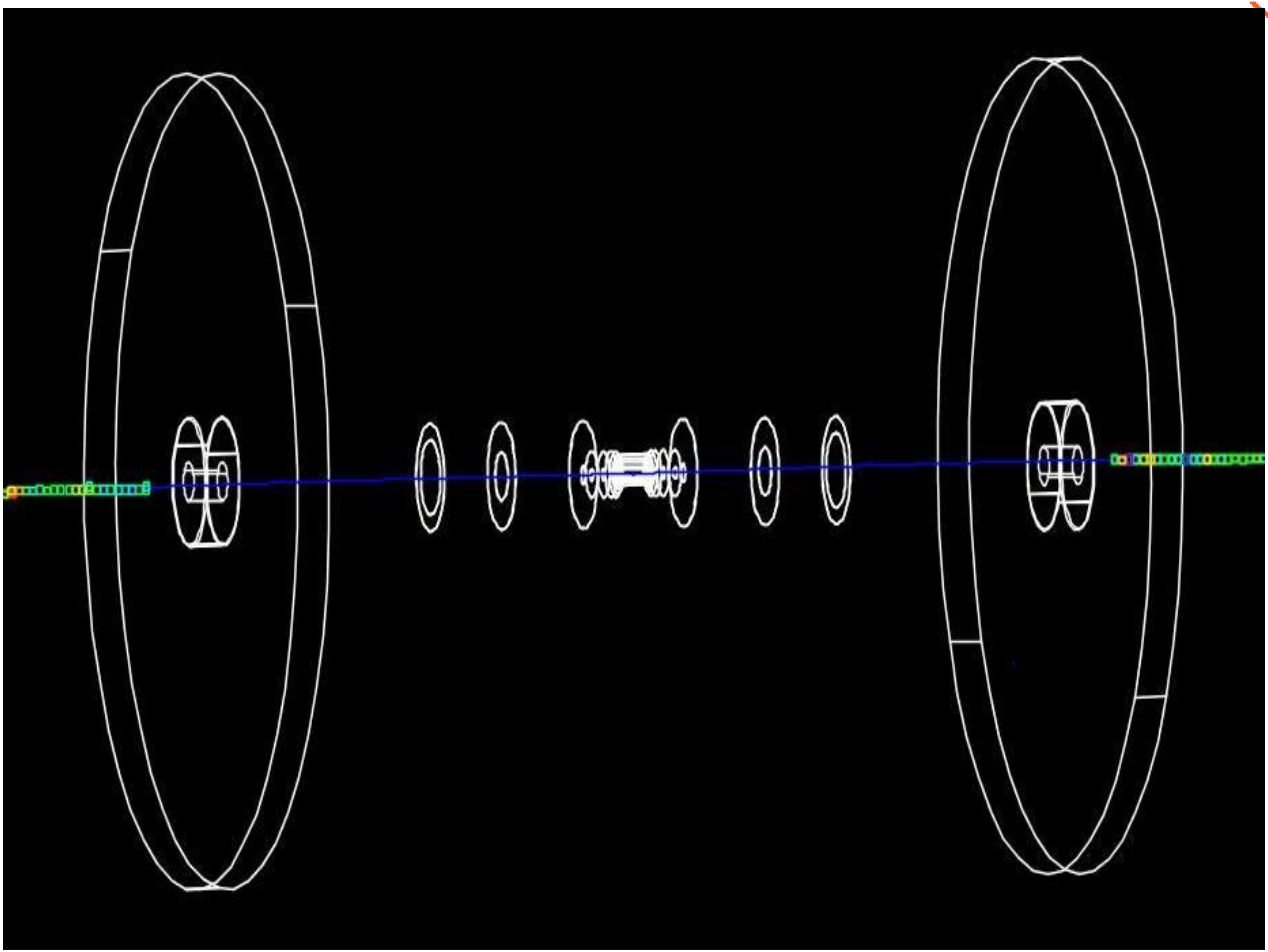
It is clear that in the majority of cases the reason for muons to be missed by the reconstruction algorithm is due to them travelling along the beam pipe, it is unlikely these muons are retrievable as they cause too few hits in the detector

At lower energies peaks appear at theta=45^o and 135^o (See 10 GeV graph of cos(theta) above. This can be attributed to the line along which the barrel meets the end cap.

Both these problems involve the detector design and not PFA efficiency

Similar analysis on muon energy showed no preference.

I. $e^+e^- \rightarrow Z \rightarrow \mu^+\mu^-$ Failure to reconstruct 2 muons



I. $e^+e^- \rightarrow Z \rightarrow \mu^+\mu^-$ Failure to reconstruct 2 muons

Removal of beam pipe muons (irretrievable?) gives a much higher accuracy – shown in the table below

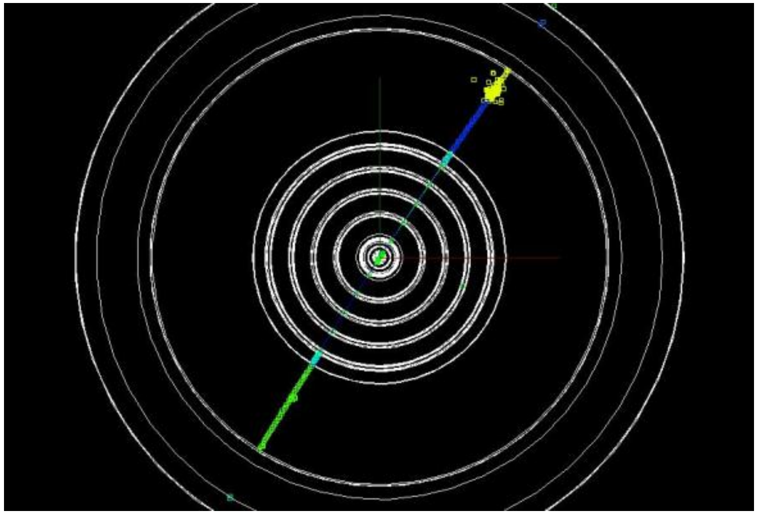
Identified Muons	10 Gev	25 GeV	50 GeV	91 GeV	200 GeV	500 GeV
0	0.04	0.00	0.00	0.00	0.00	0.00
1	1.78	0.21	0.16	0.18	0.22	0.34
2	98.2	99.8	99.8	99.8	99.8	99.7
Total	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**

Percentage of events split by number of reconstructed muons

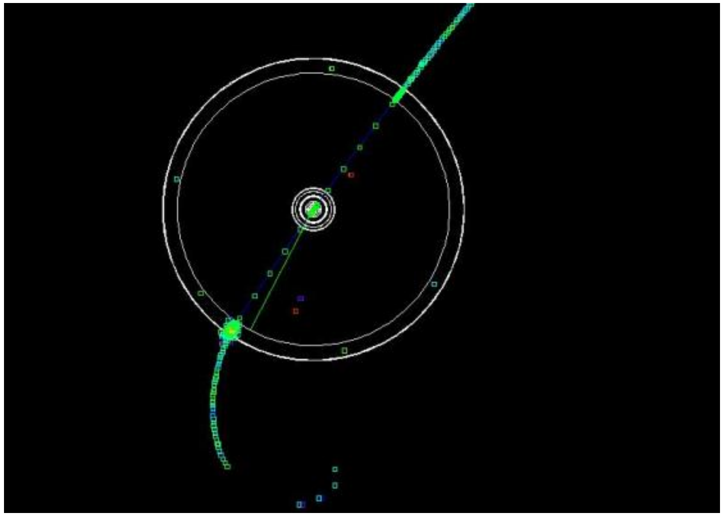
Why are some muons still not reconstructed

- Some from barrel/endcap join
- Rest from showering in calorimeter – is this something PFA can cope with?

I. $e^+e^- \rightarrow Z \rightarrow \mu^+\mu^-$ Failure to reconstruct 2 muons



500 GeV Muon Shower



200 GeV Large Muon Shower

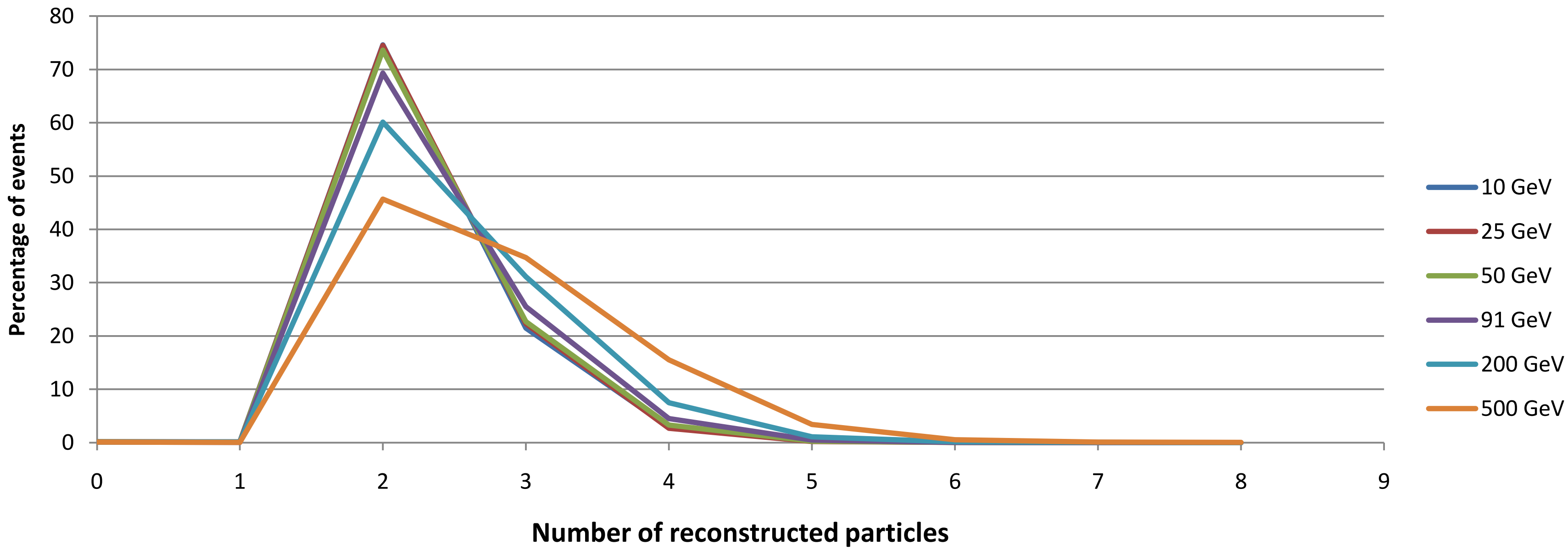
Misidentified Particle	10 GeV	25 GeV	50 GeV	91 GeV	200 GeV	500 GeV
K-Long	1.13	1.12	1.08	1.07	0.99	0.99
π^-/π^+	0.24	0.04	0.04	0.04	0.04	0.07
Photon	0.01	0.01	0.01	0.01	0.01	0.02
Electron	-	-	-	-	-	0.00046

Average number of particles per event only in events lacking 2 muons

Excess number of K-Long particles – on average at least one reconstructed per event.

Additionally a large number of excess pions – especially apparent at low energy

Number of Identified particles	10 GeV	25 GeV	50 GeV	91 GeV	200 GeV	500 GeV
0	0.14	0.15	0.12	0.10	0.08	0.10
1	0.12	0.09	0.06	0.05	0.07	0.05
2 (Accurate Reconstruction)	74.6	74.5	73.6	69.3	60.1	45.7
3	21.5	22.3	22.7	25.5	31.1	34.7
4	2.92	2.70	3.26	4.51	7.46	15.5
5	0.56	0.19	0.25	0.47	1.06	3.37
6	0.14	0.01	0.02	0.04	0.12	0.55
7	0.01	0.00	0.00	0.00	0.02	0.10
8+	0.00	0.00	0.00	0.00	0.00	0.01



Higher energy events tend to construct both muons, but suffer from reconstructing additional particles. Again similar particles are reconstructed as when muons themselves get misidentified.

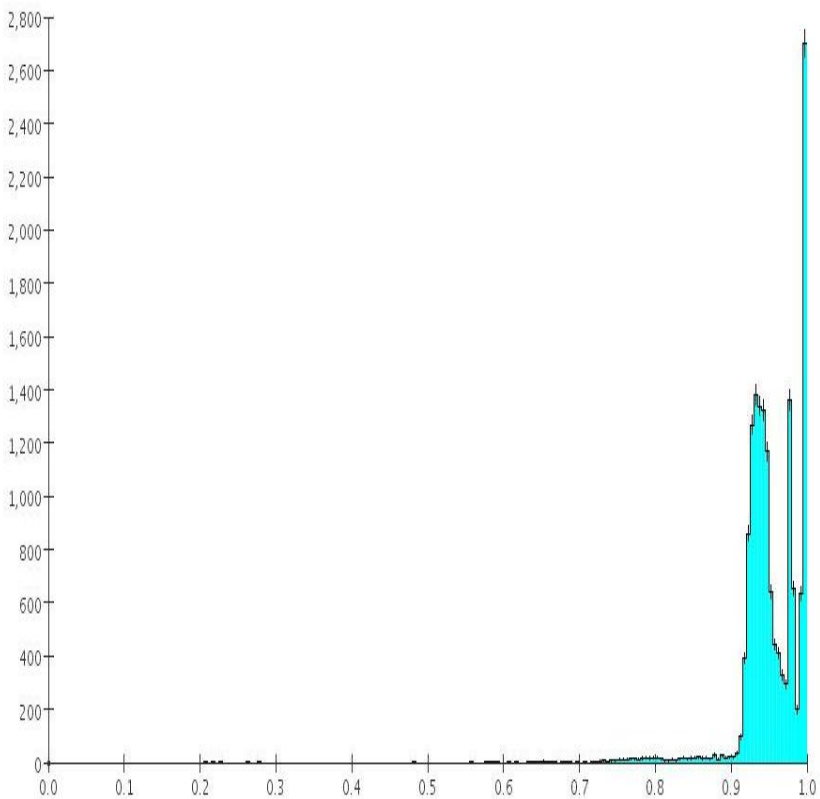
Interestingly though there are less pions reconstructed here when two muons are found.

Therefore it is incorrectly reconstructed muons that cause the excess of pions.

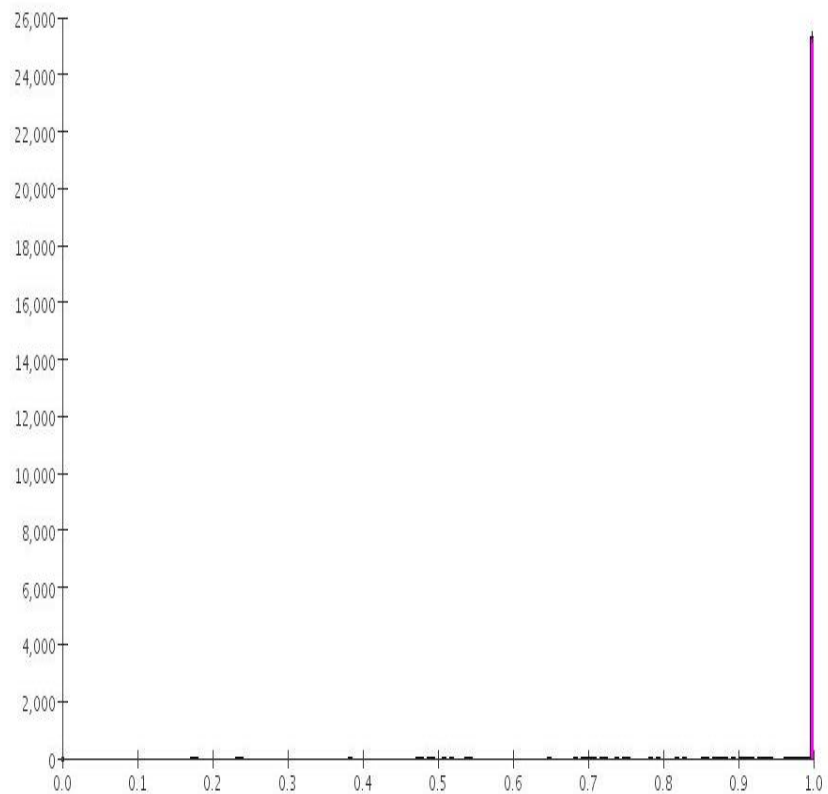
Average number of Identified Particles per Event	10 GeV	25 GeV	50 GeV	91 GeV	200 GeV	500 GeV
K-Long	1.28	1.19	1.20	1.22	1.28	1.46
π^-/π^+	0.06	<0.01	<0.01	<0.01	<0.01	<0.01
Photon	0.01	0.01	0.01	0.01	0.01	0.02
Electron	-	-	<0.01	<0.01	<0.01	<0.01
Positron	-	-	-	-	-	<0.01

Average number of reconstructed particles per event in events with more than 2 particles

K-Long particles are reconstructed at angles very close to the muons. Looking more closely at these individual events it is showering muons in the calorimeter that cause the K-Longs to be reconstructed

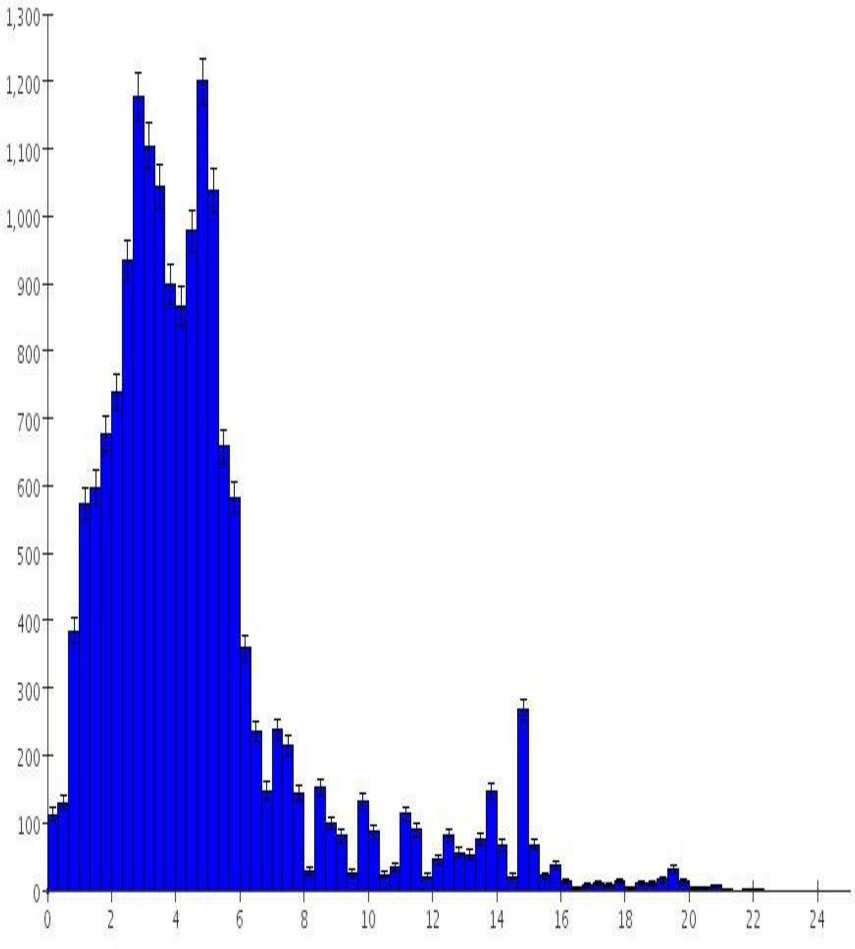


Cos(theta) of the angle between MC muons and incorrectly reconstructed K longs at 10 GeV

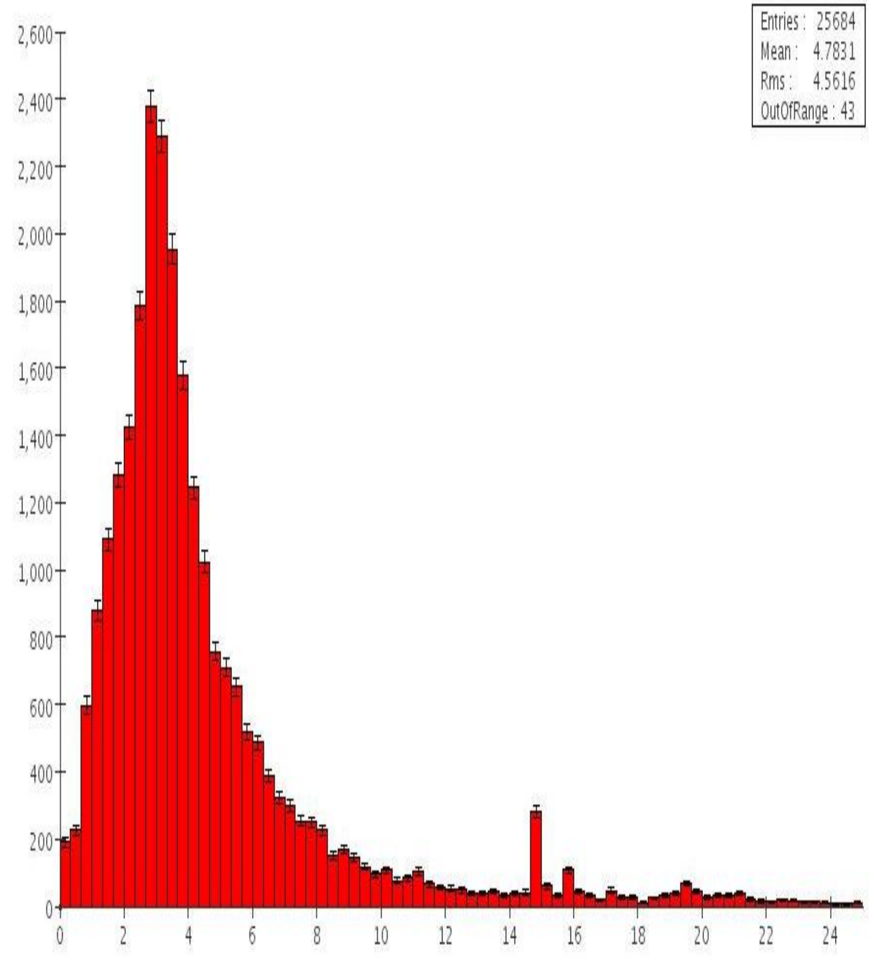


Cos(theta) of the angle between MC muons and incorrectly reconstructed K longs at 200 GeV

The energy of these additional particles can reach values far in excess of the E_{CMS} therefore reducing the energy resolution of the event and in many cases the total reconstructed particle energy > E_{CMS}!!!

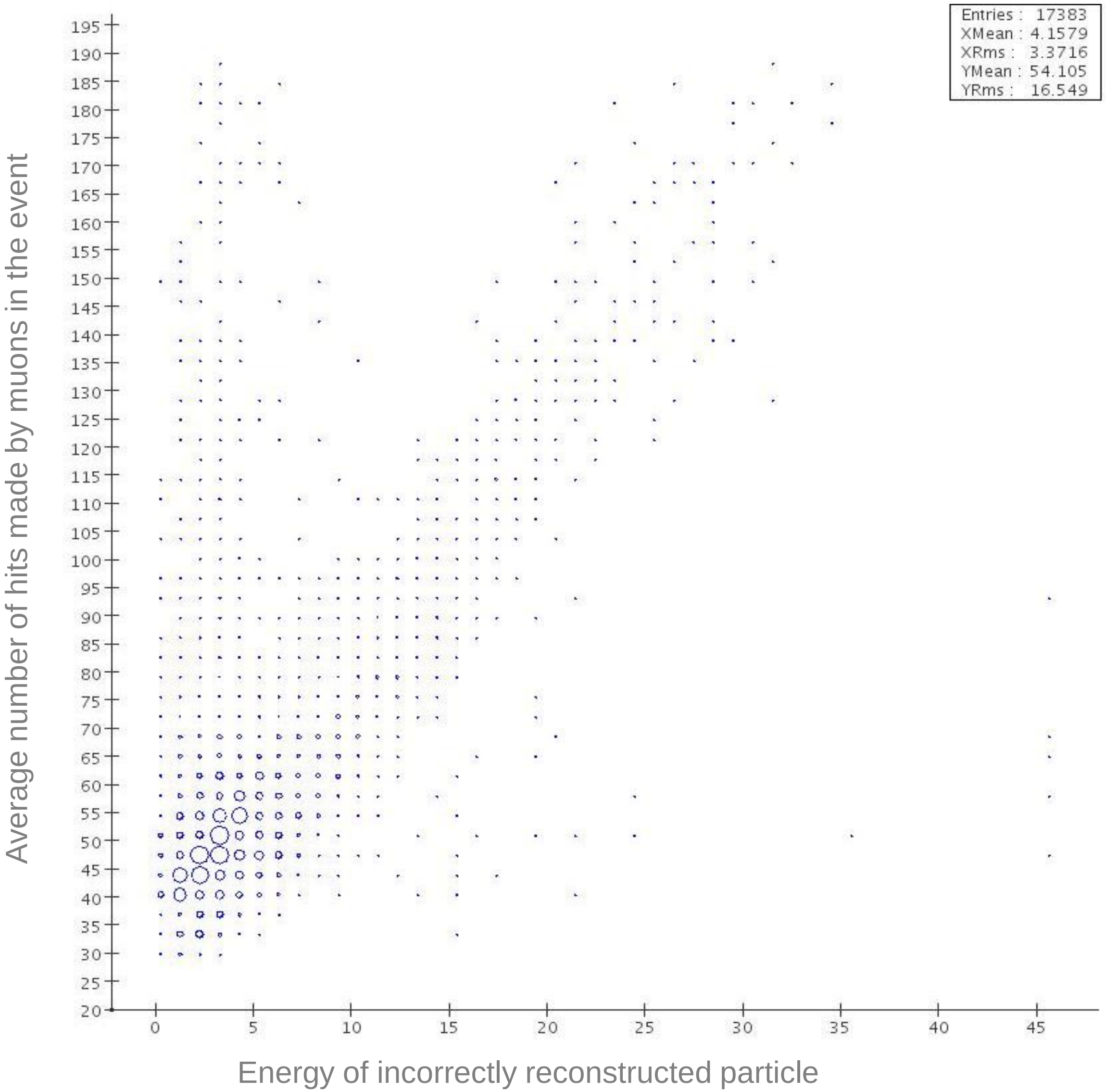


Energy of additionally reconstructed particles 10 GeV



Energy of additionally reconstructed particles 200 GeV

I. $e^+e^- \rightarrow Z \rightarrow \mu^+\mu^-$ Reconstruction of additional particles



The energy of the incorrectly reconstructed particle can be plotted against the number of hits each muon makes in the calorimeter.

A clear trend is present. Showering in the calorimeter leads in additional particles being constructed with large excess energy.

Finally when looking at muons from the Higgs decay in the below events the analysis produces exactly the same results.

$e^+e^- \rightarrow ZH \rightarrow \nu\bar{\nu}\mu^+\mu^-$

II. $e^+e^- \rightarrow ZH \rightarrow X\ \mu^+\mu^-$ 250 GeV

Looking at events containing more realistic physics events (but again containing muons) helps to understand how the PFA algorithm behaves in an actual event.

These events are more complicated than the previous events as the number of muons may be higher than 2 depending on the decay of the Z boson

Looking again at the number of muons missed by the reconstruction shows an expected trend that events with more muons are more likely to have muons misidentified during reconstruction.

Care should also be taken when interpreting the data from the extremely rare 5 muon events.

But – much worse accuracy than $Z \rightarrow \mu^+\mu^-$ events, most probably due to confusion with muons contained in jets. The preference towards even muon events suggests muons contained in a jet are less well reconstructed.

Z Decay Modes	Branching Fraction
e^+e^-	3.363 ± 0.004
$\mu^+\mu^-$	3.366 ± 0.007
$\tau^+\tau^-$	3.370 ± 0.008
Invisible	20.00 ± 0.06
Hadrons	69.91 ± 0.06
Particle Data Group – Particle Physics Booklet July 2008	

Number of muons		Number of muons missing from the event reconstruction				
from Z decay	in the event	-1 (gained)	0	1	2	3
0 (87.9%)	2	2.0 %	91.6 %	5.7 %	1.1 %	
1 (7.6%)	3	2.4 %	56.1 %	39.8 %	2.4 %	
2 (4.4%)	4	0.2 %	75.2 %	16.6 %	8.0 %	0.5 %
3 (0.1%)	5	2 %	15 %	30 %	44 %	8%

Percentage split of the number of muons missed per event

II. $e^+e^- \rightarrow ZH \rightarrow X\ \mu^+\mu^-$ 250 GeV

Average number of particles missed per event

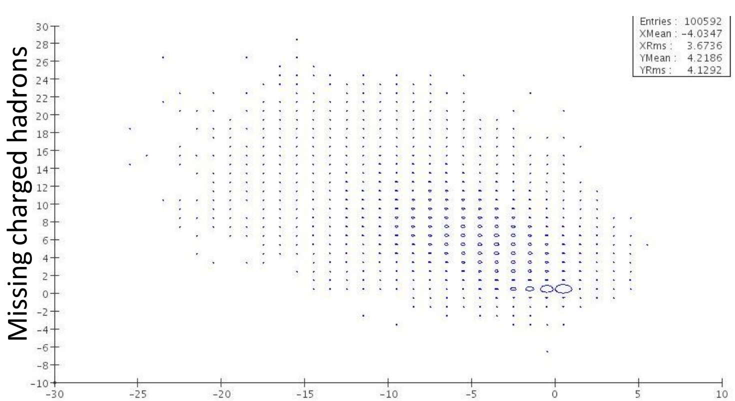
Particle	Average number missing per event	Average number per event	Percentage missing per event
Electron	0.18	0.33	53.4
Neutrino	0.75	0.75	100.0
Muon	0.10	2.17	4.6
Photon	6.53	17.09	38.2
Charged Hadrons (Proton/K^+/π^+/K^-/π^-)	4.22	13.78	30.6
Total (exc Neutrino)	11.03	34.87	31.6

Average number of particles gained per event

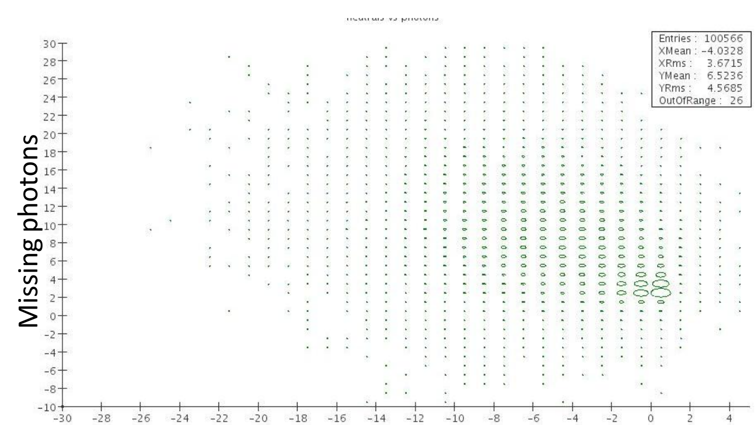
Particles	Average number gained per event	Average number per event	Percentage gain per event
Neutral Hadrons (Neutron/K long)	4.03	1.50	368%

Looking at particles besides muons and it becomes apparent that the misidentification of charged particles and photons as neutral (mainly K Long) particles is the main problem.

The most common reason for muon loss and photon loss are low angle particles travelling down the beam pipe. However showering is also present, and there is some **correlation between photons/charged hadrons lost and neutrals gained.**



Missing (-ve gained) neutral hadrons



Missing (-ve gained) neutral hadrons

Conclusion

1. Provision needed for muons that shower – crucially to prevent the excess number of K-Long particles being identified.

   Could be achieved by removing showers close to muons. This is obvious in the simple cases but could become more difficult with jet events containing muons?

2. Some indication of the confidence level with which the PFA algorithm assigns a particle type.