The LHCal MC simulation

Updated response linearity and energy resolution

Yuriy Onishchuk

Kiev Taras Shevchenko National University

yuno@univ.kiev.ua

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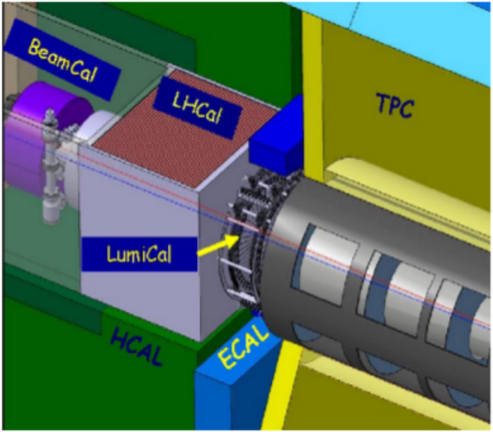
General remarks

- The LHCal calorimeter have been intesively studied by Maryna and Vlad during last year
- They have successively graduated master's degree and go out Kiev group
- Finalization and improvement of some results obtained by Kiev group: energy deposition response function for μ, e, γ, π, K within the 1-100 GeV particle energy interval
- Approaches to the particle identification based on the Machine Learning (see Alex's talk)

LHCal location

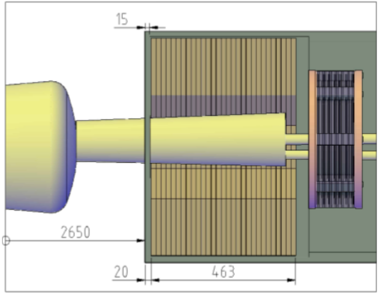
- The LHCal is a componet of the forward region
- Located between LumiCal and BeamCal
- The LHCal sizes and properties are limited by its disposition

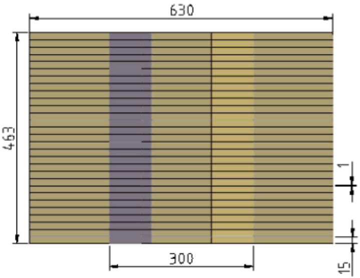


Geometry

Geometry of the LHCal simulations is similar to Maryna's and Vlad's previous reports:

- Total thickness: 463 mm
- Width in *XY* plane: 630 mm
- Inner radius: 150 mm
- Structure: 29 layers of 16 mm thickness

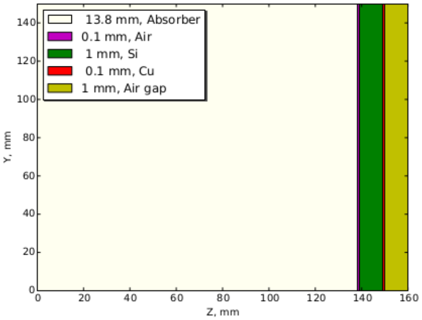




Layer structure

Layers have a sandwich structure:

- Absorber (Fe or W): 13.8 mm
- Air: 0.1 mm
- Si-sensor: 1 mm
- Cu-layer: 0.1 mm
- Air gap: 1 mm



Simulation features

- Particles divided on 3 groupes:
  - Muons (μ) – exclusively ionisation energy losses
  - EMs (electrons and γ) as EM shower produced particles
  - Hadrons (π, K) as nuclearly and ionisationally interacted particles
- Initial energies: $1 - 100$ GeV
- Number of simulated events: 50,000
- Events with penetration into internal and external edge regions (15 mm thickness) not included into analysis to minimise an influence of lateral energy leakage
- Two types of tested absorbers: Fe and W

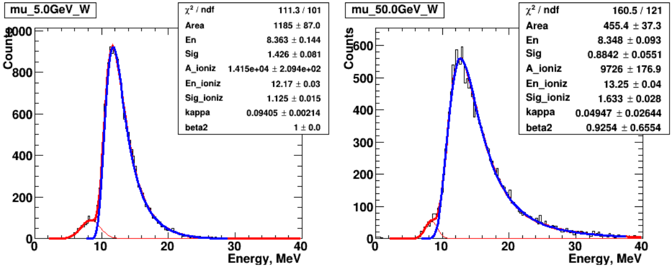
μ response

- assymetrical shape with maximum at 10-12 MeV nicely described by Vavilov function
- additional small component at 8-11 MeV can be described by gaussian
- μ response, R_μ, – weighted sum of Vavilov and Gaus (5 and 3 parameters)

$$R_\mu = A_V \cdot V(\lambda_V, \kappa, \beta^2) + A_G \cdot G(E, E_{G0}, \sigma)$$

- V – Vavilov function with $\lambda_V = \frac{E - E_{V0}}{\sigma_V}$
- $G(E, E_{G0}, \sigma)$ – normalized Gaus

5 GeV $\mu^\pm$ (W) 50 GeV



- slow sensitivity of μ response to an initial particle energy
- similar shape behavior both Fe and W absorbers

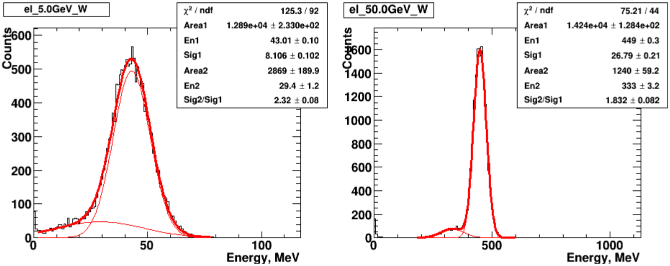
EM response: e, γ

- EM – electrons and γ's as EM shower produced particles
- Central region (narrow peak) and marginal low energy part (wide tail) can be described by two gaussians:

$$R_L = A_1 \cdot G(E, E_{01}, \sigma_1) + A_2 \cdot G(E, E_{02}, \sigma_2), \quad \sigma_2 > \sigma_1$$

- Energy distributions for electrons and γ's are similar

5 GeV $e^{\pm}$ (W) 50 GeV

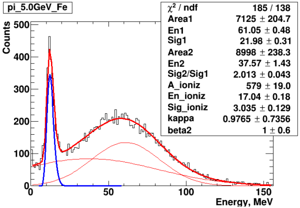


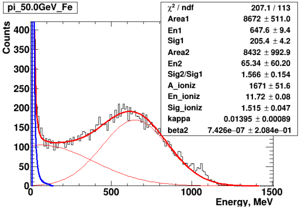
Hadron response: π, K

- Hadrons as nuclearly and ionisationally interacted particles have the most complicated response function:

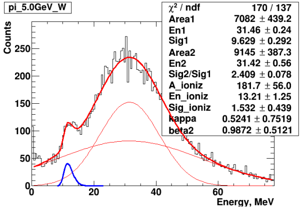
$$R_H = A_1 \cdot G(E, E_{01}, \sigma_1) + A_2 \cdot G(E, E_{02}, \sigma_2) + A_V \cdot V(\lambda_V, \kappa, \beta^2), \quad \sigma_2 > \sigma_1$$

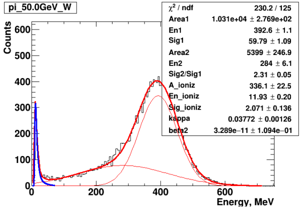
$\pi^\pm$ (Fe): 5 & 50 GeV





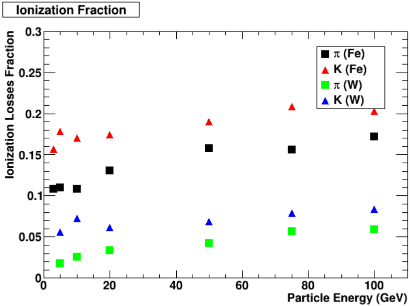
$\pi^\pm$ (W): 5 & 50 GeV





Ionisation fraction at hadron response

- Part of hadrons has a possibility to penetrate the 46 cm-thickness calorimeter without any nuclear interaction
- These hardons can be associated with "ionisation" peak (as muons)
- Fraction of ionisation events is of 0.05 – 0.2 for Fe and W absorbers
- Fe absorber gives 3-4 times larger values
- Kaons have a bit bigger values in comparison with pions



Energy response linearity

- Fitted parameters of narrow gaussian were used to estimate the linearity of response functions
- 2nd degree polynomial fit:

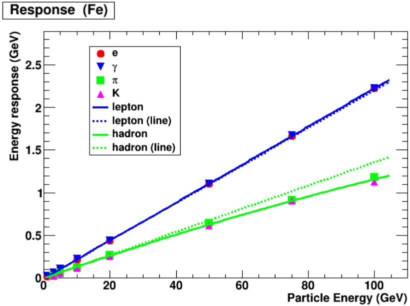
$$E_{deposit} = A \cdot (E_{init} - \frac{1}{2} B E_{init}^2)$$

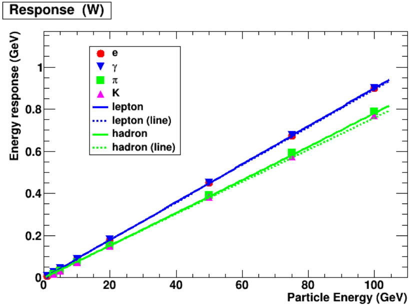
Fe

Particle	A, MeV/GeV	B, MeV/GeV^2
EM	22.03 ± 0.03	-0.20 ± 0.03
Hadron	13.57 ± 0.35	2.93 ± 0.05

W

Particle	A, MeV/GeV	B, MeV/GeV^2
EM	8.94 ± 0.2	-0.13 ± 0.07
Hadron	7.59 ± 0.1	-0.58 ± 0.45





- Sufficient nonlinearity for hadrons in Fe ($B_{H,Fe} = 2.93$) in comparison with W ($B_{H,W} = -0.58$)
- W-Si sandwich is quite close to compensated sampling calorimeter
- Fe-Si calorimeter is considerably undercompensated

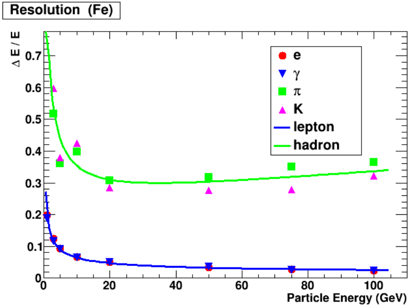
- Energy resolution fit function:

$$\frac{\Delta E}{E} = \frac{A}{\sqrt{E}} \oplus B \oplus C\sqrt{E}$$

- 3rd component, C, describes increasing of the energy resolution for hadrons in Fe caused by enlarged longitudinal and lateral leakage

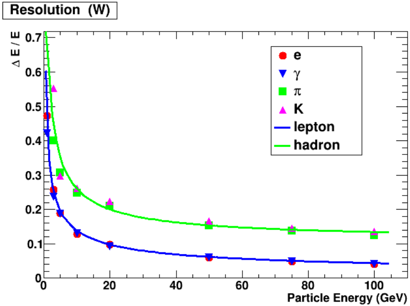
Fe

Particle	A, GeV$^{1/2}$	B, 10^{-2}	C, GeV$^{-1/2}$
EM	0.197 ± 0.001	1.68 ± 0.28	0.0 ± 0.001
Hadron	0.83 ± 0.09	0.22 ± 0.06	0.023 ± 0.008



W

Particle	A, GeV$^{1/2}$	B, 10^{-2}	C, GeV$^{-1/2}$
EM	0.437 ± 0.007	0.02 ± 1.78	0.0 ± 0.002
Hadron	0.74 ± 0.04	11.2 ± 2.23	0.0 ± 0.031



- The W-Si calorimeter has considerably better energy resolution for hadrons and a bit worser for EMs

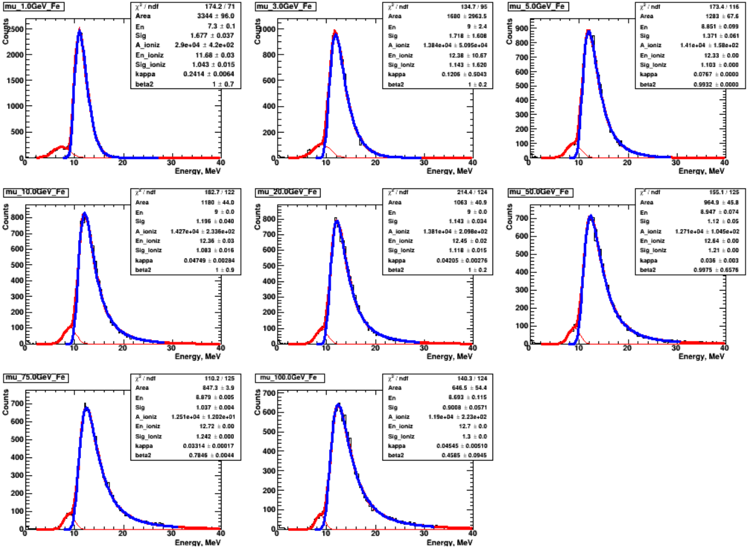
Conclusions

- Simulations for μ, e, γ, π, K within the 1-100 GeV energy interval have been done for Fe and W absorbers
- Improved description of response functions was obtained
- Linearity of response functions has been checked
- Usage of the W absorber gives better results in comparison with Fe
- The W-Si sandwich is quite close to compensated sampling calorimeter in contradiction to considerably undercompensated Fe-Si one
- Energy resolution parameters for EM and hadrons were obtained
- The W-Si calorimeter has considerably better energy resolution for hadrons and a bit worser for EMs
- Ionisation fraction at the hadron response was estimated

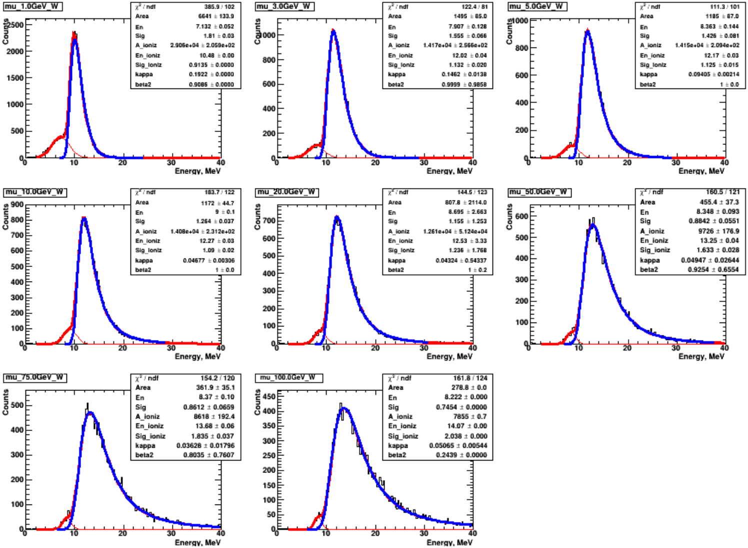
Many thanks to
Vladyslav Lukianchuk and Maryna Lazorenko

Upload slides

μ in Fe

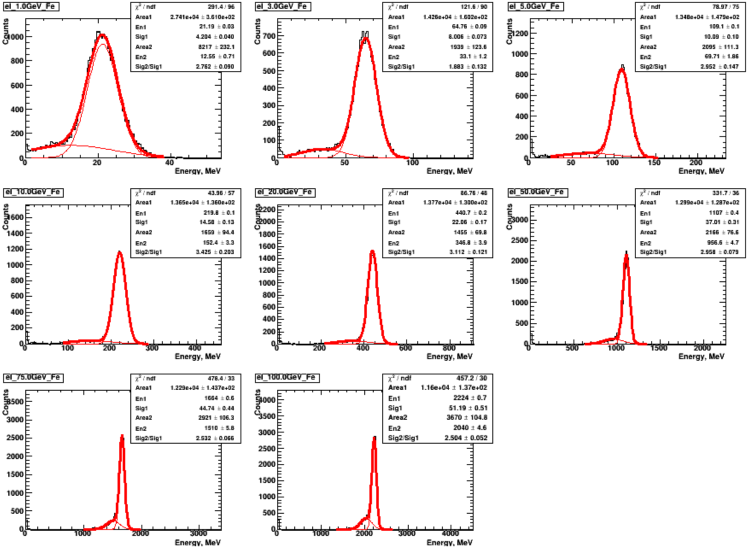

mu_1.0GeV_Fe
χ² / ndf 174.2 / 71
Area 3344 ± 96.0
En 7.3 ± 0.1
Sig 1.677 ± 0.037
A_ioniz 2.9e+04 ± 4.2e+02
En_ioniz 11.68 ± 0.03
Sig_ioniz 1.043 ± 0.015
kappa 0.2414 ± 0.0064
beta2 1 ± 0.7
mu_3.0GeV_Fe
χ² / ndf 134.7 / 95
Area 1680 ± 2963.5
En 9 ± 2.4
Sig 1.718 ± 1.608
A_ioniz 1.384e+04 ± 5.095e+04
En_ioniz 12.38 ± 10.67
Sig_ioniz 1.143 ± 1.620
kappa 0.1206 ± 0.5043
beta2 1 ± 0.2
mu_5.0GeV_Fe
χ² / ndf 173.4 / 116
Area 1283 ± 67.6
En 8.851 ± 0.099
Sig 1.371 ± 0.061
A_ioniz 1.41e+04 ± 1.58e+02
En_ioniz 12.33 ± 0.00
Sig_ioniz 1.103 ± 0.000
kappa 0.0767 ± 0.0000
beta2 0.9932 ± 0.0000
mu_10.0GeV_Fe
χ² / ndf 182.7 / 122
Area 1180 ± 44.0
En 9 ± 0.0
Sig 1.196 ± 0.040
A_ioniz 1.427e+04 ± 2.336e+02
En_ioniz 12.36 ± 0.03
Sig_ioniz 1.083 ± 0.016
kappa 0.04749 ± 0.00284
beta2 1 ± 0.9
mu_20.0GeV_Fe
χ² / ndf 214.4 / 124
Area 1063 ± 40.9
En 9 ± 0.0
Sig 1.143 ± 0.034
A_ioniz 1.381e+04 ± 2.098e+02
En_ioniz 12.45 ± 0.02
Sig_ioniz 1.118 ± 0.015
kappa 0.04205 ± 0.00276
beta2 1 ± 0.2
mu_50.0GeV_Fe
χ² / ndf 155.1 / 125
Area 964.9 ± 45.8
En 8.947 ± 0.074
Sig 1.12 ± 0.05
A_ioniz 1.271e+04 ± 1.045e+02
En_ioniz 12.64 ± 0.00
Sig_ioniz 1.21 ± 0.00
kappa 0.036 ± 0.003
beta2 0.9975 ± 0.6576
mu_75.0GeV_Fe
χ² / ndf 110.2 / 125
Area 847.3 ± 3.9
En 8.879 ± 0.005
Sig 1.037 ± 0.004
A_ioniz 1.251e+04 ± 1.202e+01
En_ioniz 12.72 ± 0.00
Sig_ioniz 1.242 ± 0.000
kappa 0.03314 ± 0.00017
beta2 0.7846 ± 0.0044
mu_100.0GeV_Fe
χ² / ndf 140.3 / 124
Area 646.5 ± 54.4
En 8.693 ± 0.115
Sig 0.9008 ± 0.0571
A_ioniz 1.19e+04 ± 2.23e+02
En_ioniz 12.7 ± 0.0
Sig_ioniz 1.3 ± 0.0
kappa 0.04545 ± 0.00510
beta2 0.4585 ± 0.0945
Counts
Energy, MeV

μ in W



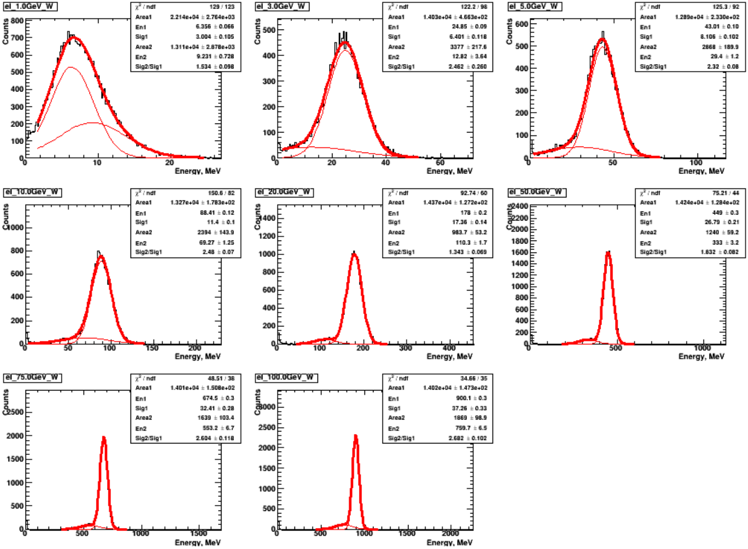
mu_1.0GeV_W
χ² / ndf 385.9 / 102
Area 6641 ± 133.9
En 7.132 ± 0.052
Sig 1.81 ± 0.03
A_ioniz 2.906e+04 ± 2.059e+02
En_ioniz 10.48 ± 0.00
Sig_ioniz 0.9135 ± 0.0000
kappa 0.1922 ± 0.0000
beta2 0.9086 ± 0.0000
mu_3.0GeV_W
χ² / ndf 122.4 / 81
Area 1495 ± 85.0
En 7.907 ± 0.128
Sig 1.555 ± 0.066
A_ioniz 1.417e+04 ± 2.566e+02
En_ioniz 12.02 ± 0.04
Sig_ioniz 1.132 ± 0.020
kappa 0.1462 ± 0.0138
beta2 0.9999 ± 0.9858
mu_5.0GeV_W
χ² / ndf 111.3 / 101
Area 1185 ± 87.0
En 8.363 ± 0.144
Sig 1.426 ± 0.081
A_ioniz 1.415e+04 ± 2.094e+02
En_ioniz 12.17 ± 0.03
Sig_ioniz 1.125 ± 0.015
kappa 0.09405 ± 0.00214
beta2 1 ± 0.0
mu_10.0GeV_W
χ² / ndf 183.7 / 122
Area 1172 ± 44.7
En 9 ± 0.1
Sig 1.264 ± 0.037
A_ioniz 1.408e+04 ± 2.312e+02
En_ioniz 12.27 ± 0.03
Sig_ioniz 1.09 ± 0.02
kappa 0.04677 ± 0.00306
beta2 1 ± 0.0
mu_20.0GeV_W
χ² / ndf 144.5 / 123
Area 807.8 ± 2114.0
En 8.695 ± 2.663
Sig 1.155 ± 1.253
A_ioniz 1.261e+04 ± 5.124e+04
En_ioniz 12.53 ± 3.33
Sig_ioniz 1.236 ± 1.768
kappa 0.04324 ± 0.54337
beta2 1 ± 0.2
mu_50.0GeV_W
χ² / ndf 160.5 / 121
Area 455.4 ± 37.3
En 8.348 ± 0.093
Sig 0.8842 ± 0.0551
A_ioniz 9726 ± 176.9
En_ioniz 13.25 ± 0.04
Sig_ioniz 1.633 ± 0.028
kappa 0.04947 ± 0.02644
beta2 0.9254 ± 0.6554
mu_75.0GeV_W
χ² / ndf 154.2 / 120
Area 361.9 ± 35.1
En 8.37 ± 0.10
Sig 0.8612 ± 0.0659
A_ioniz 8618 ± 192.4
En_ioniz 13.68 ± 0.06
Sig_ioniz 1.835 ± 0.037
kappa 0.03628 ± 0.01796
beta2 0.8035 ± 0.7607
mu_100.0GeV_W
χ² / ndf 161.8 / 124
Area 278.8 ± 0.0
En 8.222 ± 0.000
Sig 0.7454 ± 0.0000
A_ioniz 7855 ± 0.7
En_ioniz 14.07 ± 0.00
Sig_ioniz 2.038 ± 0.000
kappa 0.05065 ± 0.00544
beta2 0.2439 ± 0.0000
Counts
Energy, MeV

$e^{\pm}$ in Fe

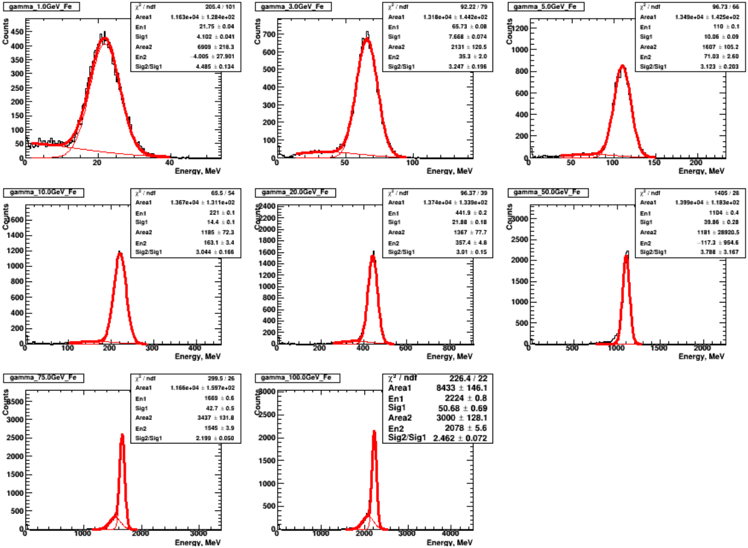


el_1.0GeV_Fe
χ² / ndf 291.4 / 96
Area1 2.741e+04 ± 3.610e+02
En1 21.19 ± 0.03
Sig1 4.204 ± 0.040
Area2 8217 ± 232.1
En2 12.55 ± 0.71
Sig2/Sig1 2.762 ± 0.090
el_3.0GeV_Fe
χ² / ndf 121.6 / 90
Area1 1.426e+04 ± 1.602e+02
En1 64.76 ± 0.09
Sig1 8.006 ± 0.073
Area2 1939 ± 123.6
En2 33.1 ± 1.2
Sig2/Sig1 1.883 ± 0.132
el_5.0GeV_Fe
χ² / ndf 78.97 / 75
Area1 1.348e+04 ± 1.479e+02
En1 109.1 ± 0.1
Sig1 10.09 ± 0.10
Area2 2095 ± 111.3
En2 69.71 ± 1.86
Sig2/Sig1 2.952 ± 0.147
el_10.0GeV_Fe
χ² / ndf 43.96 / 57
Area1 1.365e+04 ± 1.360e+02
En1 219.8 ± 0.1
Sig1 14.58 ± 0.13
Area2 1659 ± 94.4
En2 152.4 ± 3.3
Sig2/Sig1 3.425 ± 0.203
el_20.0GeV_Fe
χ² / ndf 86.76 / 48
Area1 1.377e+04 ± 1.300e+02
En1 440.7 ± 0.2
Sig1 22.06 ± 0.17
Area2 1455 ± 69.8
En2 346.8 ± 3.9
Sig2/Sig1 3.112 ± 0.121
el_50.0GeV_Fe
χ² / ndf 331.7 / 36
Area1 1.299e+04 ± 1.287e+02
En1 1107 ± 0.4
Sig1 37.01 ± 0.31
Area2 2166 ± 76.6
En2 956.6 ± 4.7
Sig2/Sig1 2.958 ± 0.079
el_75.0GeV_Fe
χ² / ndf 476.4 / 33
Area1 1.229e+04 ± 1.437e+02
En1 1664 ± 0.6
Sig1 44.74 ± 0.44
Area2 2921 ± 106.3
En2 1510 ± 5.8
Sig2/Sig1 2.532 ± 0.066
el_100.0GeV_Fe
χ² / ndf 457.2 / 30
Area1 1.16e+04 ± 1.37e+02
En1 2224 ± 0.7
Sig1 51.19 ± 0.51
Area2 3670 ± 104.8
En2 2040 ± 4.6
Sig2/Sig1 2.504 ± 0.052
Counts
Energy, MeV

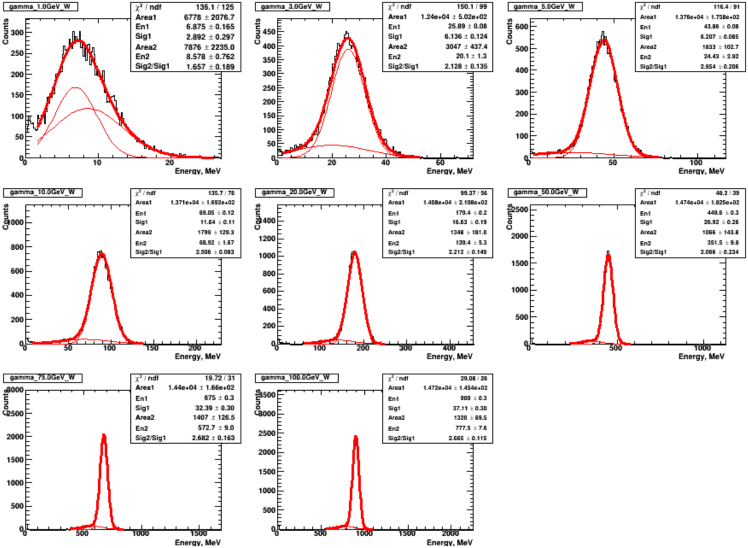
$e^{\pm}$ in W


el_1.0GeV_W
χ² / ndf 129 / 123
Area1 2.214e+04 ± 2.764e+03
En1 6.356 ± 0.066
Sig1 3.004 ± 0.105
Area2 1.311e+04 ± 2.878e+03
En2 9.231 ± 0.728
Sig2/Sig1 1.534 ± 0.098
el_3.0GeV_W
χ² / ndf 122.2 / 96
Area1 1.403e+04 ± 4.663e+02
En1 24.85 ± 0.09
Sig1 6.401 ± 0.118
Area2 3377 ± 217.6
En2 12.82 ± 3.64
Sig2/Sig1 2.462 ± 0.260
el_5.0GeV_W
χ² / ndf 125.3 / 92
Area1 1.289e+04 ± 2.330e+02
En1 43.01 ± 0.10
Sig1 8.106 ± 0.102
Area2 2868 ± 189.9
En2 29.4 ± 1.2
Sig2/Sig1 2.32 ± 0.08
el_10.0GeV_W
χ² / ndf 150.6 / 82
Area1 1.327e+04 ± 1.783e+02
En1 88.41 ± 0.12
Sig1 11.4 ± 0.1
Area2 2394 ± 143.9
En2 69.27 ± 1.25
Sig2/Sig1 2.48 ± 0.07
el_20.0GeV_W
χ² / ndf 92.74 / 60
Area1 1.437e+04 ± 1.272e+02
En1 178 ± 0.2
Sig1 17.36 ± 0.14
Area2 983.7 ± 53.2
En2 110.3 ± 1.7
Sig2/Sig1 1.343 ± 0.069
el_50.0GeV_W
χ² / ndf 75.21 / 44
Area1 1.424e+04 ± 1.284e+02
En1 449 ± 0.3
Sig1 26.79 ± 0.21
Area2 1240 ± 59.2
En2 333 ± 3.2
Sig2/Sig1 1.832 ± 0.082
el_75.0GeV_W
χ² / ndf 48.51 / 38
Area1 1.401e+04 ± 1.508e+02
En1 674.5 ± 0.3
Sig1 32.41 ± 0.28
Area2 1639 ± 103.4
En2 553.2 ± 6.7
Sig2/Sig1 2.604 ± 0.118
el_100.0GeV_W
χ² / ndf 34.66 / 35
Area1 1.402e+04 ± 1.473e+02
En1 900.1 ± 0.3
Sig1 37.26 ± 0.33
Area2 1869 ± 98.9
En2 759.7 ± 6.5
Sig2/Sig1 2.682 ± 0.102
Counts
Energy, MeV

γ in Fe

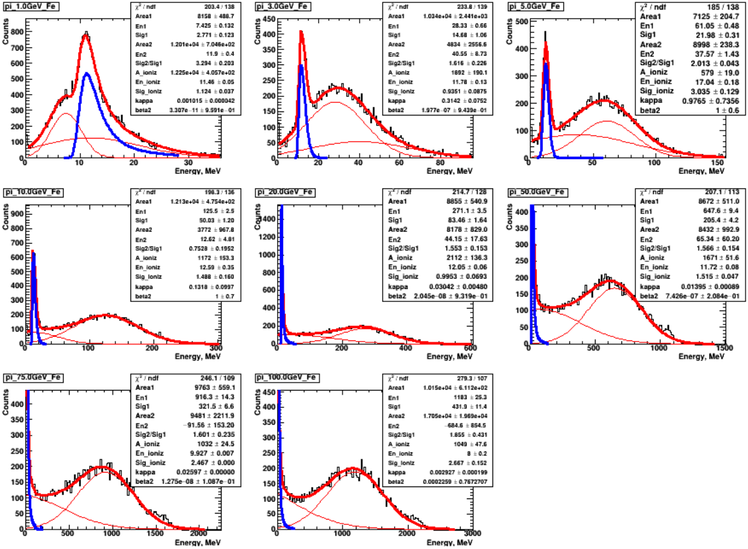


gamma_1.0GeV_Fe
χ² / ndf 205.4 / 101
Area1 1.163e+04 ± 1.284e+02
En1 21.75 ± 0.04
Sig1 4.102 ± 0.041
Area2 6909 ± 218.3
En2 -4.005 ± 27.901
Sig2/Sig1 4.485 ± 0.134
gamma_3.0GeV_Fe
χ² / ndf 92.22 / 79
Area1 1.318e+04 ± 1.442e+02
En1 65.73 ± 0.08
Sig1 7.668 ± 0.074
Area2 2131 ± 120.5
En2 35.3 ± 2.0
Sig2/Sig1 3.247 ± 0.196
gamma_5.0GeV_Fe
χ² / ndf 96.73 / 66
Area1 1.349e+04 ± 1.425e+02
En1 110 ± 0.1
Sig1 10.06 ± 0.09
Area2 1607 ± 105.2
En2 71.03 ± 2.60
Sig2/Sig1 3.123 ± 0.203
gamma_10.0GeV_Fe
χ² / ndf 65.5 / 54
Area1 1.367e+04 ± 1.311e+02
En1 221 ± 0.1
Sig1 14.4 ± 0.1
Area2 1185 ± 72.3
En2 163.1 ± 3.4
Sig2/Sig1 3.044 ± 0.166
gamma_20.0GeV_Fe
χ² / ndf 96.37 / 39
Area1 1.374e+04 ± 1.339e+02
En1 441.9 ± 0.2
Sig1 21.88 ± 0.18
Area2 1367 ± 77.7
En2 357.4 ± 4.8
Sig2/Sig1 3.01 ± 0.15
gamma_50.0GeV_Fe
χ² / ndf 1405 / 28
Area1 1.399e+04 ± 1.183e+02
En1 1104 ± 0.4
Sig1 39.86 ± 0.28
Area2 1181 ± 28920.5
En2 -117.3 ± 954.6
Sig2/Sig1 3.788 ± 3.167
gamma_75.0GeV_Fe
χ² / ndf 299.5 / 26
Area1 1.166e+04 ± 1.597e+02
En1 1669 ± 0.6
Sig1 42.7 ± 0.5
Area2 3437 ± 131.8
En2 1545 ± 3.9
Sig2/Sig1 2.199 ± 0.050
gamma_100.0GeV_Fe
χ² / ndf 226.4 / 22
Area1 8433 ± 146.1
En1 2224 ± 0.8
Sig1 50.68 ± 0.69
Area2 3000 ± 128.1
En2 2078 ± 5.6
Sig2/Sig1 2.462 ± 0.072
Counts
Energy, MeV



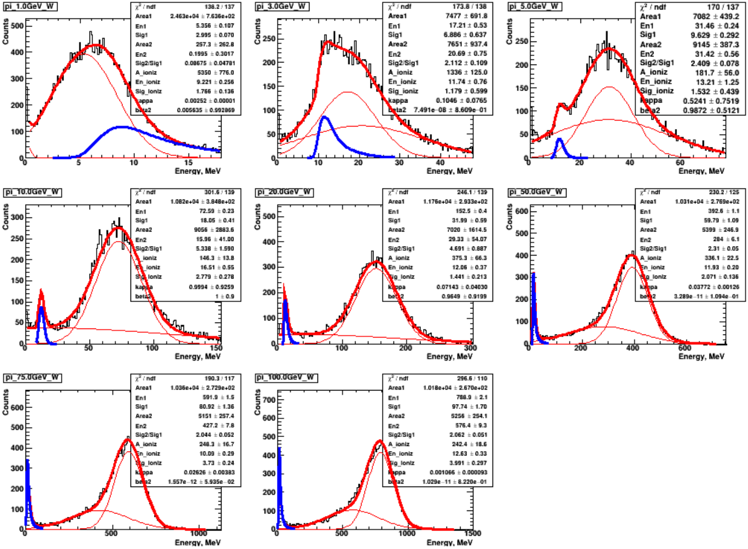
gamma_1.0GeV_W
χ² / ndf 136.1 / 125
Area1 6778 ± 2076.7
En1 6.875 ± 0.165
Sig1 2.892 ± 0.297
Area2 7876 ± 2235.0
En2 8.578 ± 0.762
Sig2/Sig1 1.657 ± 0.189
gamma_3.0GeV_W
χ² / ndf 150.1 / 99
Area1 1.24e+04 ± 5.02e+02
En1 25.89 ± 0.08
Sig1 6.136 ± 0.124
Area2 3047 ± 437.4
En2 20.1 ± 1.3
Sig2/Sig1 2.128 ± 0.135
gamma_5.0GeV_W
χ² / ndf 116.4 / 91
Area1 1.376e+04 ± 1.758e+02
En1 43.86 ± 0.08
Sig1 8.207 ± 0.085
Area2 1833 ± 102.7
En2 24.43 ± 2.92
Sig2/Sig1 2.954 ± 0.206
gamma_10.0GeV_W
χ² / ndf 135.7 / 78
Area1 1.371e+04 ± 1.692e+02
En1 89.05 ± 0.12
Sig1 11.64 ± 0.11
Area2 1799 ± 129.3
En2 68.92 ± 1.67
Sig2/Sig1 2.506 ± 0.083
gamma_20.0GeV_W
χ² / ndf 99.37 / 56
Area1 1.408e+04 ± 2.108e+02
En1 179.4 ± 0.2
Sig1 16.63 ± 0.19
Area2 1348 ± 181.0
En2 139.4 ± 5.3
Sig2/Sig1 2.212 ± 0.149
gamma_50.0GeV_W
χ² / ndf 48.2 / 39
Area1 1.474e+04 ± 1.825e+02
En1 449.6 ± 0.3
Sig1 26.92 ± 0.26
Area2 1066 ± 143.8
En2 351.5 ± 9.8
Sig2/Sig1 2.066 ± 0.234
gamma_75.0GeV_W
χ² / ndf 19.72 / 31
Area1 1.44e+04 ± 1.66e+02
En1 675 ± 0.3
Sig1 32.39 ± 0.30
Area2 1407 ± 126.5
En2 572.7 ± 9.0
Sig2/Sig1 2.682 ± 0.163
gamma_100.0GeV_W
χ² / ndf 29.08 / 28
Area1 1.472e+04 ± 1.454e+02
En1 900 ± 0.3
Sig1 37.11 ± 0.30
Area2 1320 ± 89.5
En2 777.5 ± 7.6
Sig2/Sig1 2.665 ± 0.115
Counts
Energy, MeV

π in Fe



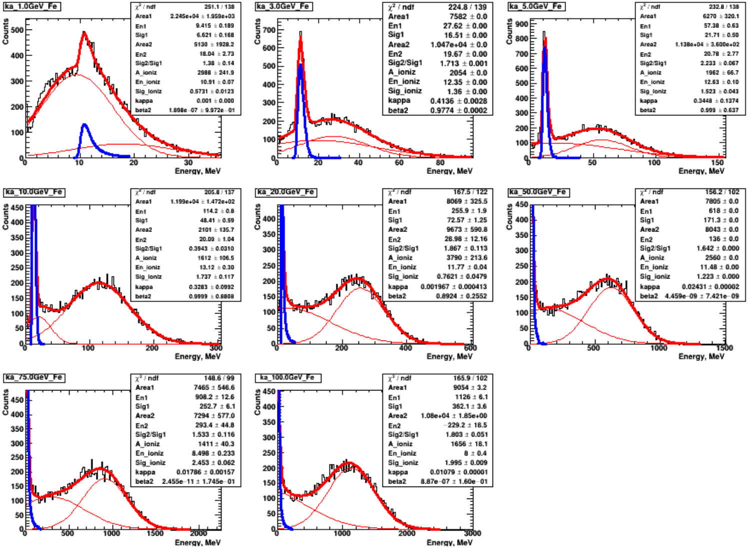
pi_1.0GeV_Fe
χ^2 / ndf 203.4 / 138
Area1 8158 ± 488.7
En1 7.425 ± 0.132
Sig1 2.771 ± 0.123
Area2 1.201e+04 ± 7.046e+02
En2 11.9 ± 0.4
Sig2/Sig1 3.294 ± 0.203
A_ioniz 1.225e+04 ± 4.057e+02
En_ioniz 11.46 ± 0.05
Sig_ioniz 1.124 ± 0.037
kappa 0.001015 ± 0.000042
beta2 3.307e−11 ± 9.591e−01
Counts
Energy, MeV
pi_3.0GeV_Fe
χ^2 / ndf 233.8 / 139
Area1 1.034e+04 ± 2.441e+03
En1 28.33 ± 0.66
Sig1 14.68 ± 1.06
Area2 4834 ± 2556.6
En2 40.55 ± 8.73
Sig2/Sig1 1.616 ± 0.226
A_ioniz 1892 ± 190.1
En_ioniz 11.78 ± 0.13
Sig_ioniz 0.9351 ± 0.0875
kappa 0.3142 ± 0.0752
beta2 1.977e−07 ± 9.439e−01
Counts
Energy, MeV
pi_5.0GeV_Fe
χ^2 / ndf 185 / 138
Area1 7125 ± 204.7
En1 61.05 ± 0.48
Sig1 21.98 ± 0.31
Area2 8998 ± 238.3
En2 37.57 ± 1.43
Sig2/Sig1 2.013 ± 0.043
A_ioniz 579 ± 19.0
En_ioniz 17.04 ± 0.18
Sig_ioniz 3.035 ± 0.129
kappa 0.9765 ± 0.7356
beta2 1 ± 0.6
Counts
Energy, MeV
pi_10.0GeV_Fe
χ^2 / ndf 196.3 / 136
Area1 1.213e+04 ± 4.754e+02
En1 125.5 ± 2.5
Sig1 50.03 ± 1.20
Area2 3772 ± 967.8
En2 12.62 ± 4.81
Sig2/Sig1 0.7528 ± 0.1952
A_ioniz 1172 ± 153.3
En_ioniz 12.59 ± 0.35
Sig_ioniz 1.488 ± 0.160
kappa 0.1318 ± 0.0997
beta2 1 ± 0.7
Counts
Energy, MeV
pi_20.0GeV_Fe
χ^2 / ndf 214.7 / 128
Area1 8855 ± 540.9
En1 271.1 ± 3.5
Sig1 83.46 ± 1.64
Area2 8178 ± 829.0
En2 44.15 ± 17.63
Sig2/Sig1 1.553 ± 0.153
A_ioniz 2112 ± 136.3
En_ioniz 12.05 ± 0.06
Sig_ioniz 0.9953 ± 0.0693
kappa 0.03042 ± 0.00480
beta2 2.045e−08 ± 9.319e−01
Counts
Energy, MeV
pi_50.0GeV_Fe
χ^2 / ndf 207.1 / 113
Area1 8672 ± 511.0
En1 647.6 ± 9.4
Sig1 205.4 ± 4.2
Area2 8432 ± 992.9
En2 65.34 ± 60.20
Sig2/Sig1 1.566 ± 0.154
A_ioniz 1671 ± 51.6
En_ioniz 11.72 ± 0.08
Sig_ioniz 1.515 ± 0.047
kappa 0.01395 ± 0.00089
beta2 7.426e−07 ± 2.084e−01
Counts
Energy, MeV
pi_75.0GeV_Fe
χ^2 / ndf 246.1 / 109
Area1 9763 ± 559.1
En1 916.3 ± 14.3
Sig1 321.5 ± 6.6
Area2 9481 ± 2211.9
En2 −91.56 ± 153.20
Sig2/Sig1 1.601 ± 0.235
A_ioniz 1032 ± 24.5
En_ioniz 9.927 ± 0.007
Sig_ioniz 2.467 ± 0.000
kappa 0.02597 ± 0.00000
beta2 1.275e−08 ± 1.087e−01
Counts
Energy, MeV
pi_100.0GeV_Fe
χ^2 / ndf 279.3 / 107
Area1 1.015e+04 ± 6.112e+02
En1 1183 ± 25.3
Sig1 431.9 ± 11.4
Area2 1.705e+04 ± 1.969e+04
En2 −684.6 ± 854.5
Sig2/Sig1 1.855 ± 0.431
A_ioniz 1049 ± 47.6
En_ioniz 8 ± 0.2
Sig_ioniz 2.667 ± 0.152
kappa 0.002927 ± 0.000199
beta2 0.0002259 ± 0.7672707
Counts
Energy, MeV

π in W



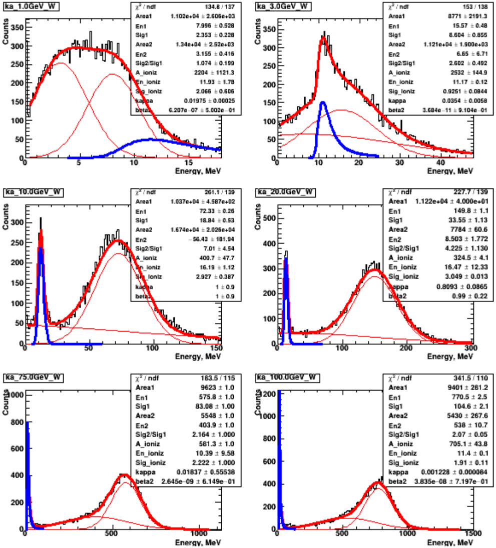
pi_1.0GeV_W
Counts
Energy, MeV
χ² / ndf 138.2 / 137
Area1 2.463e+04 ± 7.636e+02
En1 5.356 ± 0.107
Sig1 2.995 ± 0.070
Area2 257.3 ± 262.8
En2 0.1995 ± 0.3017
Sig2/Sig1 0.08675 ± 0.04781
A_ioniz 5350 ± 776.0
En_ioniz 9.221 ± 0.256
Sig_ioniz 1.766 ± 0.136
kappa 0.00252 ± 0.00001
beta2 0.005635 ± 0.992869
pi_3.0GeV_W
Counts
Energy, MeV
χ² / ndf 173.8 / 138
Area1 7477 ± 691.8
En1 17.21 ± 0.53
Sig1 6.886 ± 0.637
Area2 7651 ± 937.4
En2 20.69 ± 0.75
Sig2/Sig1 2.112 ± 0.109
A_ioniz 1336 ± 125.0
En_ioniz 11.74 ± 0.76
Sig_ioniz 1.179 ± 0.599
kappa 0.1046 ± 0.0765
beta2 7.491e-08 ± 8.609e-01
pi_5.0GeV_W
Counts
Energy, MeV
χ² / ndf 170 / 137
Area1 7082 ± 439.2
En1 31.46 ± 0.24
Sig1 9.629 ± 0.292
Area2 9145 ± 387.3
En2 31.42 ± 0.56
Sig2/Sig1 2.409 ± 0.078
A_ioniz 181.7 ± 56.0
En_ioniz 13.21 ± 1.25
Sig_ioniz 1.532 ± 0.439
kappa 0.5241 ± 0.7519
beta2 0.9872 ± 0.5121
pi_10.0GeV_W
Counts
Energy, MeV
χ² / ndf 301.6 / 139
Area1 1.082e+04 ± 3.848e+02
En1 72.59 ± 0.23
Sig1 18.05 ± 0.41
Area2 9056 ± 2883.6
En2 15.96 ± 41.00
Sig2/Sig1 5.338 ± 1.590
A_ioniz 146.3 ± 13.8
En_ioniz 16.51 ± 0.55
Sig_ioniz 2.779 ± 0.278
kappa 0.9994 ± 0.9259
beta2 1 ± 0.9
pi_20.0GeV_W
Counts
Energy, MeV
χ² / ndf 246.1 / 139
Area1 1.176e+04 ± 2.933e+02
En1 152.5 ± 0.4
Sig1 31.99 ± 0.59
Area2 7020 ± 1614.5
En2 29.33 ± 54.07
Sig2/Sig1 4.691 ± 0.887
A_ioniz 375.3 ± 66.3
En_ioniz 12.06 ± 0.37
Sig_ioniz 1.441 ± 0.213
kappa 0.07143 ± 0.04030
beta2 0.9649 ± 0.9199
pi_50.0GeV_W
Counts
Energy, MeV
χ² / ndf 230.2 / 125
Area1 1.031e+04 ± 2.769e+02
En1 392.6 ± 1.1
Sig1 59.79 ± 1.09
Area2 5399 ± 246.9
En2 284 ± 6.1
Sig2/Sig1 2.31 ± 0.05
A_ioniz 336.1 ± 22.5
En_ioniz 11.93 ± 0.20
Sig_ioniz 2.071 ± 0.136
kappa 0.03772 ± 0.00126
beta2 3.289e-11 ± 1.094e-01
pi_75.0GeV_W
Counts
Energy, MeV
χ² / ndf 190.3 / 117
Area1 1.036e+04 ± 2.729e+02
En1 591.9 ± 1.5
Sig1 80.92 ± 1.36
Area2 5151 ± 257.4
En2 427.2 ± 7.8
Sig2/Sig1 2.044 ± 0.052
A_ioniz 248.3 ± 16.7
En_ioniz 10.09 ± 0.29
Sig_ioniz 3.73 ± 0.24
kappa 0.02626 ± 0.00383
beta2 1.557e-12 ± 5.935e-02
pi_100.0GeV_W
Counts
Energy, MeV
χ² / ndf 296.6 / 110
Area1 1.018e+04 ± 2.670e+02
En1 788.9 ± 2.1
Sig1 97.74 ± 1.70
Area2 5256 ± 254.1
En2 576.4 ± 9.3
Sig2/Sig1 2.062 ± 0.051
A_ioniz 242.4 ± 18.6
En_ioniz 12.63 ± 0.33
Sig_ioniz 3.991 ± 0.297
kappa 0.001066 ± 0.000093
beta2 1.029e-11 ± 8.220e-01

K in Fe



ka_1.0GeV_Fe
χ² / ndf 251.1 / 138
Area1 2.245e+04 ± 1.959e+03
En1 9.415 ± 0.189
Sig1 6.621 ± 0.168
Area2 5130 ± 1928.2
En2 18.04 ± 2.73
Sig2/Sig1 1.38 ± 0.14
A_ioniz 2988 ± 241.9
En_ioniz 10.91 ± 0.07
Sig_ioniz 0.5731 ± 0.0123
kappa 0.001 ± 0.000
beta2 1.898e−07 ± 9.972e−01
ka_3.0GeV_Fe
χ² / ndf 224.8 / 139
Area1 7582 ± 0.0
En1 27.62 ± 0.00
Sig1 16.51 ± 0.00
Area2 1.047e+04 ± 0.0
En2 19.67 ± 0.00
Sig2/Sig1 1.713 ± 0.001
A_ioniz 2054 ± 0.0
En_ioniz 12.35 ± 0.00
Sig_ioniz 1.36 ± 0.00
kappa 0.4136 ± 0.0028
beta2 0.9774 ± 0.0002
ka_5.0GeV_Fe
χ² / ndf 232.8 / 138
Area1 6270 ± 320.1
En1 57.38 ± 0.63
Sig1 21.71 ± 0.50
Area2 1.138e+04 ± 3.600e+02
En2 20.78 ± 2.77
Sig2/Sig1 2.233 ± 0.067
A_ioniz 1962 ± 66.7
En_ioniz 12.63 ± 0.10
Sig_ioniz 1.523 ± 0.043
kappa 0.3448 ± 0.1374
beta2 0.999 ± 0.637
ka_10.0GeV_Fe
χ² / ndf 205.8 / 137
Area1 1.199e+04 ± 1.472e+02
En1 114.2 ± 0.8
Sig1 48.41 ± 0.59
Area2 2101 ± 135.7
En2 20.09 ± 1.04
Sig2/Sig1 0.3943 ± 0.0310
A_ioniz 1612 ± 106.5
En_ioniz 13.12 ± 0.30
Sig_ioniz 1.737 ± 0.117
kappa 0.3283 ± 0.0992
beta2 0.9999 ± 0.8808
ka_20.0GeV_Fe
χ² / ndf 167.5 / 122
Area1 8069 ± 325.5
En1 255.9 ± 1.9
Sig1 72.57 ± 1.25
Area2 9673 ± 590.8
En2 28.98 ± 12.16
Sig2/Sig1 1.867 ± 0.113
A_ioniz 3790 ± 213.6
En_ioniz 11.77 ± 0.04
Sig_ioniz 0.7621 ± 0.0479
kappa 0.001967 ± 0.000413
beta2 0.8924 ± 0.2552
ka_50.0GeV_Fe
χ² / ndf 156.2 / 102
Area1 7805 ± 0.0
En1 618 ± 0.0
Sig1 171.3 ± 0.0
Area2 8043 ± 0.0
En2 136 ± 0.0
Sig2/Sig1 1.642 ± 0.000
A_ioniz 2560 ± 0.0
En_ioniz 11.48 ± 0.00
Sig_ioniz 1.223 ± 0.000
kappa 0.02431 ± 0.00002
beta2 4.459e−09 ± 7.421e−09
ka_75.0GeV_Fe
χ² / ndf 148.6 / 99
Area1 7465 ± 546.6
En1 908.2 ± 12.6
Sig1 252.7 ± 6.1
Area2 7294 ± 577.0
En2 293.4 ± 44.8
Sig2/Sig1 1.533 ± 0.116
A_ioniz 1411 ± 40.3
En_ioniz 8.498 ± 0.233
Sig_ioniz 2.453 ± 0.062
kappa 0.01786 ± 0.00157
beta2 2.455e−11 ± 1.745e−01
ka_100.0GeV_Fe
χ² / ndf 165.9 / 102
Area1 9054 ± 3.2
En1 1126 ± 6.1
Sig1 362.1 ± 3.6
Area2 1.08e+04 ± 1.85e+00
En2 −229.2 ± 18.5
Sig2/Sig1 1.803 ± 0.051
A_ioniz 1656 ± 18.1
En_ioniz 8 ± 0.4
Sig_ioniz 1.995 ± 0.009
kappa 0.01079 ± 0.00001
beta2 8.87e−07 ± 1.60e−01
Counts
Energy, MeV

K in W



ka_1.0GeV_W
χ^2 / ndf 134.8 / 137
Area1 1.102e+04 ± 2.606e+03
En1 7.996 ± 0.528
Sig1 2.353 ± 0.228
Area2 1.34e+04 ± 2.52e+03
En2 3.155 ± 0.416
Sig2/Sig1 1.074 ± 0.199
A_ioniz 2204 ± 1121.3
En_ioniz 11.93 ± 1.78
Sig_ioniz 2.066 ± 0.606
kappa 0.01975 ± 0.00025
beta2 6.207e-07 ± 5.002e-01
Counts
Energy, MeV
ka_3.0GeV_W
χ^2 / ndf 153 / 138
Area1 8771 ± 2191.3
En1 15.57 ± 0.48
Sig1 8.604 ± 0.855
Area2 1.121e+04 ± 1.900e+03
En2 6.65 ± 6.71
Sig2/Sig1 2.602 ± 0.492
A_ioniz 2532 ± 144.9
En_ioniz 11.17 ± 0.12
Sig_ioniz 0.9251 ± 0.0844
kappa 0.0354 ± 0.0058
beta2 3.684e-11 ± 9.104e-01
Counts
Energy, MeV
ka_5.0GeV_W
χ^2 / ndf 166.5 / 137
Area1 5488 ± 769.1
En1 31.89 ± 0.28
Sig1 9.505 ± 0.581
Area2 1.224e+04 ± 4.734e+02
En2 22.26 ± 1.85
Sig2/Sig1 2.631 ± 0.097
A_ioniz 543.4 ± 34.0
En_ioniz 13.79 ± 0.19
Sig_ioniz 1.654 ± 0.111
kappa 1 ± 0.7
beta2 1 ± 0.7
Counts
Energy, MeV
ka_10.0GeV_W
χ^2 / ndf 261.1 / 139
Area1 1.037e+04 ± 4.587e+02
En1 72.33 ± 0.26
Sig1 18.84 ± 0.53
Area2 1.674e+04 ± 2.026e+04
En2 -56.43 ± 181.94
Sig2/Sig1 7.01 ± 4.54
A_ioniz 400.7 ± 47.7
En_ioniz 16.19 ± 1.12
Sig_ioniz 2.927 ± 0.387
kappa 1 ± 0.9
beta2 1 ± 0.9
Counts
Energy, MeV
ka_20.0GeV_W
χ^2 / ndf 227.7 / 139
Area1 1.122e+04 ± 4.000e+01
En1 149.8 ± 1.1
Sig1 33.55 ± 1.13
Area2 7784 ± 60.6
En2 8.503 ± 1.772
Sig2/Sig1 4.225 ± 1.130
A_ioniz 324.5 ± 4.1
En_ioniz 16.47 ± 12.33
Sig_ioniz 3.049 ± 0.013
kappa 0.8093 ± 0.0865
beta2 0.99 ± 0.22
Counts
Energy, MeV
ka_50.0GeV_W
χ^2 / ndf 247.5 / 130
Area1 1.004e+04 ± 2.840e+02
En1 383.5 ± 1.2
Sig1 63.45 ± 1.22
Area2 5309 ± 243.7
En2 262.4 ± 7.6
Sig2/Sig1 2.303 ± 0.055
A_ioniz 799.6 ± 44.6
En_ioniz 11.64 ± 0.12
Sig_ioniz 1.4 ± 0.1
kappa 0.0424 ± 0.0054
beta2 1.689e-08 ± 2.254e-01
Counts
Energy, MeV
ka_75.0GeV_W
χ^2 / ndf 183.5 / 115
Area1 9623 ± 1.0
En1 575.8 ± 1.0
Sig1 83.08 ± 1.00
Area2 5548 ± 1.0
En2 403.9 ± 1.0
Sig2/Sig1 2.164 ± 1.000
A_ioniz 581.3 ± 1.0
En_ioniz 10.39 ± 9.58
Sig_ioniz 2.222 ± 1.000
kappa 0.01837 ± 0.55538
beta2 2.645e-09 ± 6.149e-01
Counts
Energy, MeV
ka_100.0GeV_W
χ^2 / ndf 341.5 / 110
Area1 9401 ± 261.2
En1 770.5 ± 2.5
Sig1 104.6 ± 2.1
Area2 5430 ± 267.6
En2 538 ± 10.7
Sig2/Sig1 2.07 ± 0.05
A_ioniz 705.1 ± 43.8
En_ioniz 11.4 ± 0.1
Sig_ioniz 1.91 ± 0.11
kappa 0.001228 ± 0.000084
beta2 3.835e-08 ± 7.197e-01
Counts
Energy, MeV