
Particle Production Results from the MIPP Experiment

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Joint Experimental-Theoretical Seminar
at Fermilab
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WICHITA STATE
UNIVERSITY



Outline



- Introduction to the MIPP experiment
 - Physics motivation
 - Detector
 - Beamlne
- Data analysis
 - Event reconstruction
 - Tracking
 - Particle identification
 - Results
 - NuMI target data analysis
 - Forward neutron cross sections
- MIPP Upgrade
 - Why?
 - How?

The MIPP collaboration

Y. Fisyak - Brookhaven National Laboratory

J. Klay - California Polytechnic State University

R. Winston - EFI, University of Chicago

E. Swallow - Elmhurst College and EFI

R. J. Peterson - University of Colorado, Boulder

W. Baker, D. Carey, J. Hylen, C. Johnstone, M. Kostin, N. Mokhov, A. Para, R. Raja, S. Striganov - Fermi National Accelerator Laboratory

G. Feldman, A. Lebedev, S. Seun - Harvard University

P. Hanlet, O. Kamaev, D. Kaplan, H. Rubin, Y. Torun - Illinois Institute of Technology

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N. Graf, M. Messier, J. Paley - Indiana University

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R. L. Abrams, H. R. Gustafson, M. Longo, T. Nigmanov, H-K. Park, D. Rajaram - University of Michigan

A. Bujak, L. Gutay, D. E. Miller - Purdue University

T. Bergfeld, A. Godley, S. R. Mishra, C. Rosenfeld, K. Wu - University of South Carolina

C. Dukes, L. C. Lu, C. Materniak, K. Nelson, A. Norman - University of Virginia

H. Meyer, N. Solomey – Wichita State University

The MIPP experiment



- Approved in November 2001, installed in Meson Center MC7,
14 months physics run ended in February 2006 – 18 million events
- Use 120 GeV/c Main Injector protons to produce
 - secondary beams of π^\pm , K^\pm , and p , \bar{p} from 5 GeV/c to 90 GeV/c
 - 120 GeV/c proton beam for NuMI and nuclear targets (A=1 to A=238)
- **Measure particle production cross sections** on fixed targets
 - various nuclei including hydrogen and the NuMI target
- Momenta of ~all charged particles measured with TPC and tracking chambers.
- Particle identification with dE/dx, ToF, multicell Cherenkov, and RICH detectors and calorimeter for neutrons.
- Open Geometry – Lower systematics than single arm spectrometers
- A proposal FNAL-P960 to **upgrade** MIPP was **deferred until publications**

DAQ rate
Increase
x100

MIPP physics overview

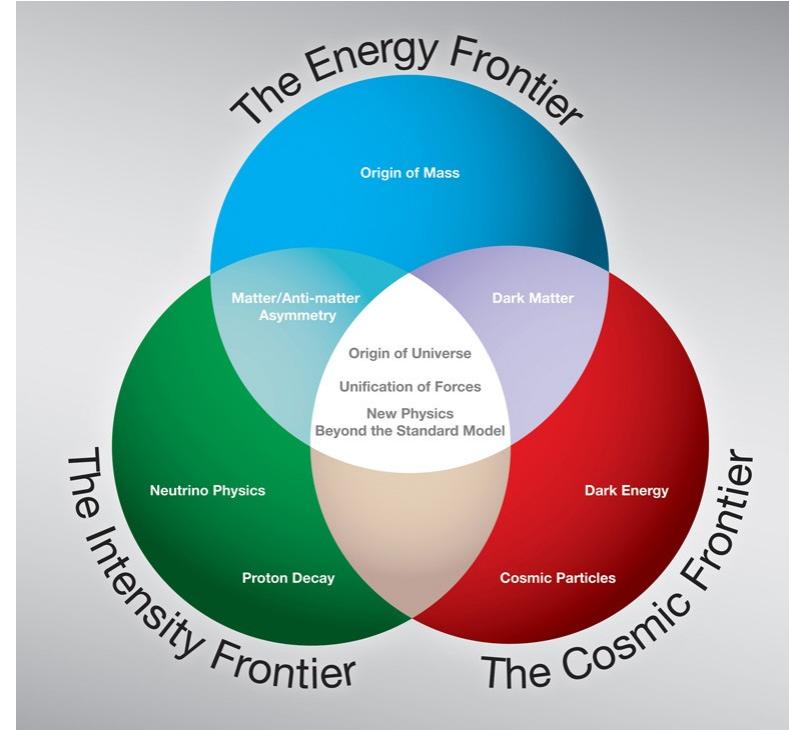


- Particle Physics – To acquire unbiased high statistics data with complete particle id coverage for hadron interactions.
 - Study non-perturbative QCD hadron dynamics, scaling laws of particle fragmentation
 - Investigate light meson spectroscopy, missing baryon resonances
 - Charged Kaon mass measurement (NIM **A631**)
- Nuclear Physics
 - Investigate strangeness production in nuclei
 - Nuclear y -scaling
 - Propagation of flavor through nuclei
- Service Measurements
 - Improve shower models in MARS, Geant4 and Calorimetry
 - Proton Radiography – LLNL
 - NuMI target – pion and kaon production measurements to control the near/far systematics

MIPP physics and frontiers



- Intensity Frontier
 - Neutrino flux from MIPP measurements of Kaon and Pion production on NuMI targets.
 - Mu2e beam
- Cosmic Frontier
 - Cosmic Ray shower development in atmosphere from MIPP cross sections on Nitrogen target.
- Energy Frontier
 - Better understanding of hadronic showers in calorimeters, measure particle correlations
- Good Physics behind the frontier
 - Missing Baryon resonances
 -



Hadronic shower simulation

-
- Programs like Geant4, MARS, Fluka, etc. model hadronic interactions based on available data.
 - No first principles, non-perturbative QCD (strong interaction) calculations are possible
 - Most existing data are low statistics, with poor particle id, sometimes contradictory
 - All neutrino flux problems (NuMI, MiniBoone, K2K, T2K, NOvA, Minerva), all Calorimeter design problems, and all Jet energy scale systematics (not including jet definition ambiguities here) can be reduced to one problem: **the current insufficient state of hadronic shower simulators.**
 - MIPP has high statistics, low systematics data with 6 beam species.
 - A library of MIPP events can be used in the simulation packages.

E907 Installation at MC7

Upstream
MC7

JGG

Rosie

Downstream
MC7



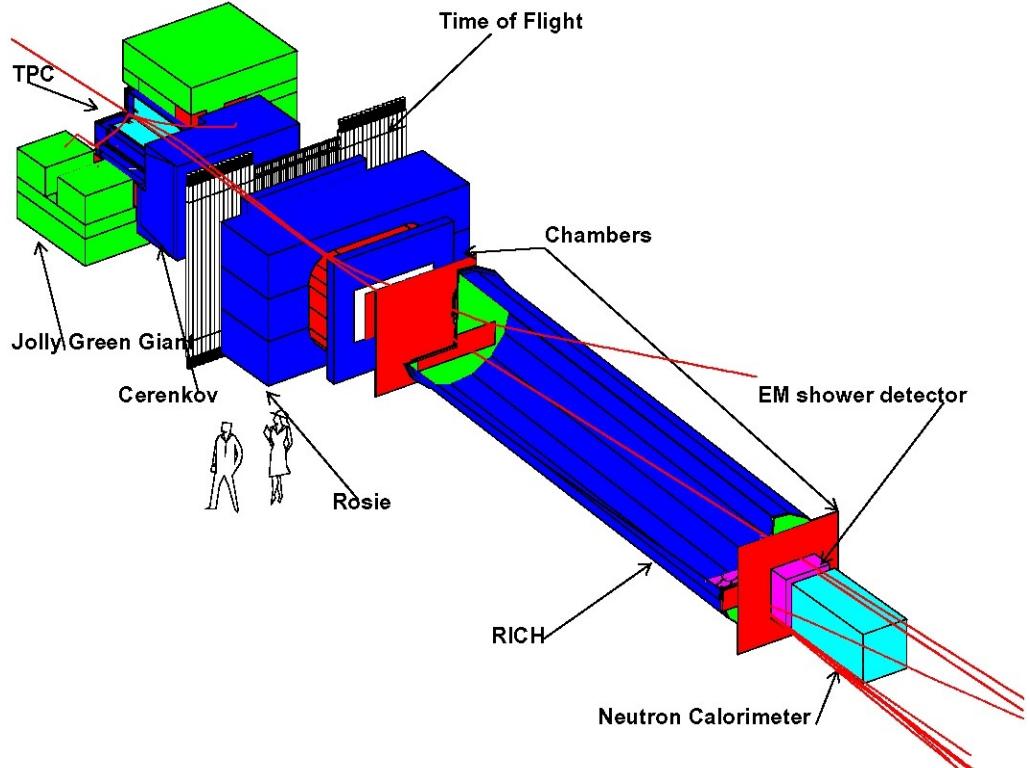
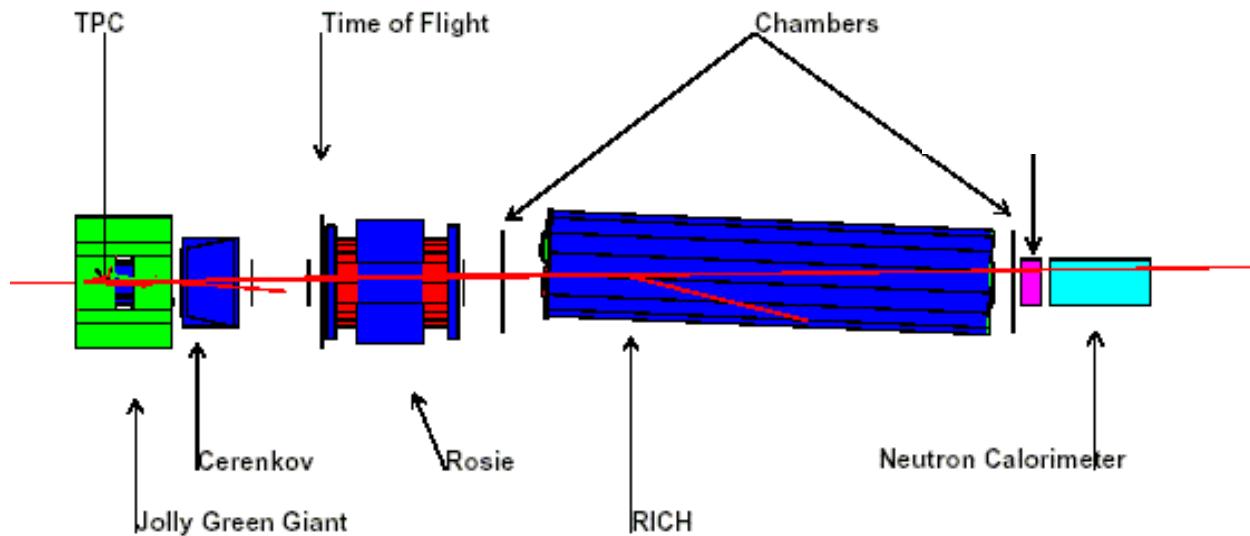
The MIPP detector



TPC and 6 Chambers for tracking

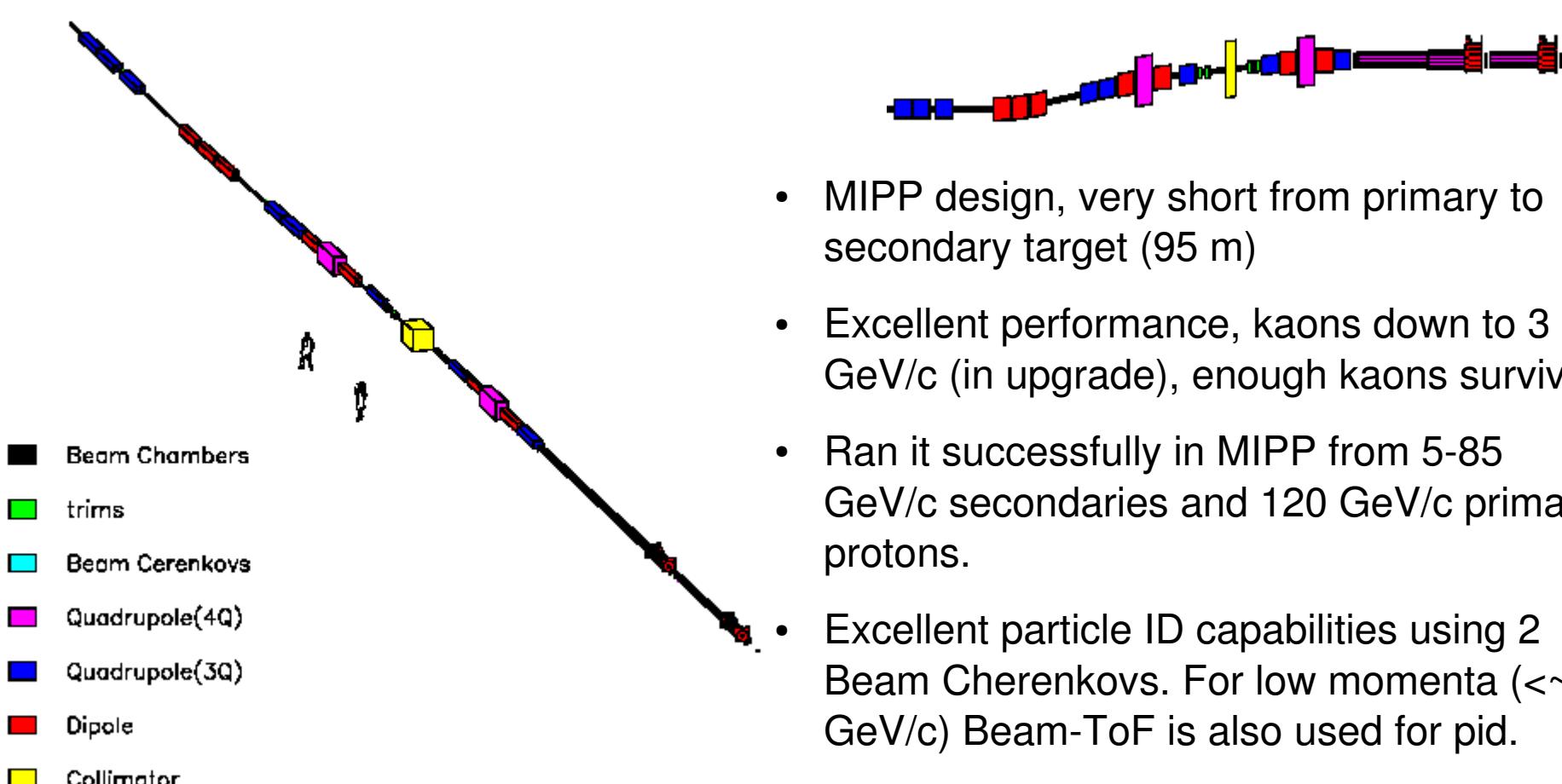
MIPP Main Injector Particle Production Experiment

Vertical cut plane



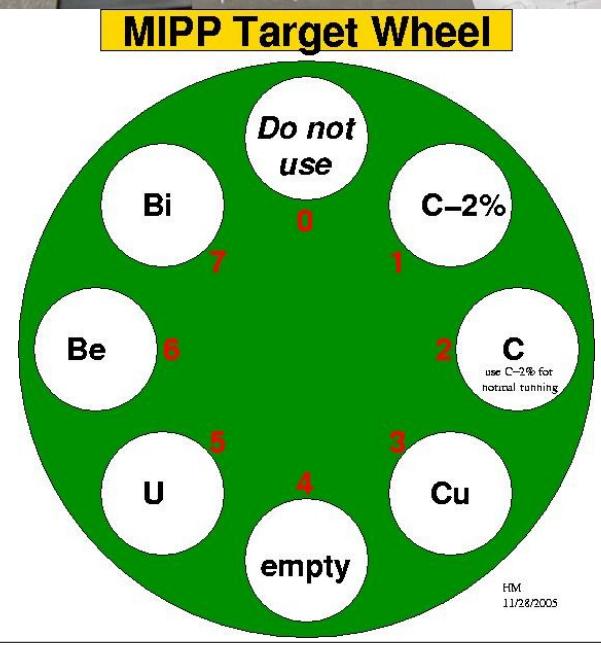
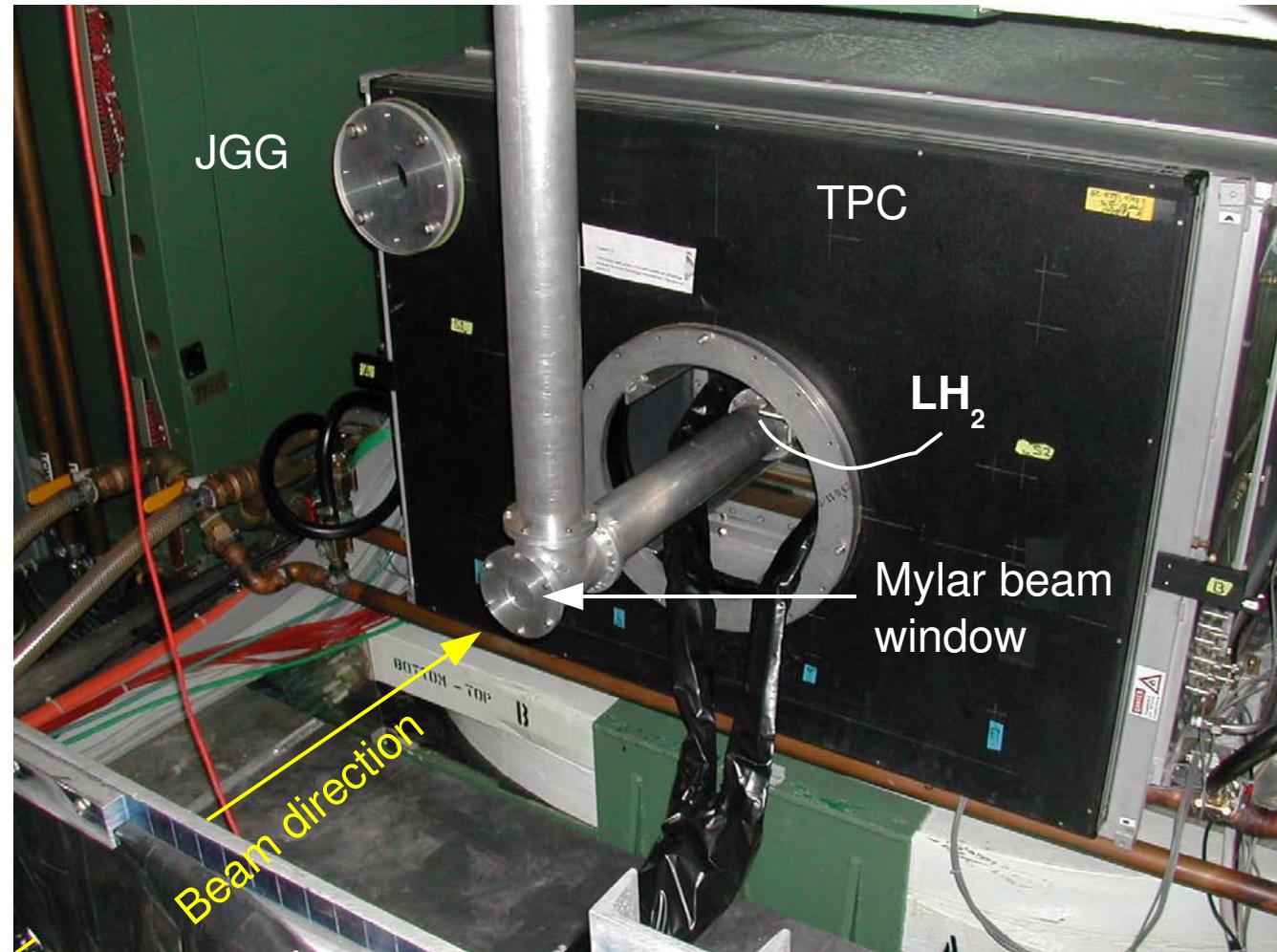
TPC	dE/dx	0 to 1 GeV/c
Time of Flight	ToF	to 2 GeV/c
Cerenkov	Ckov	to 17 GeV/c
Rosie	RICH	to 120 GeV/c

The MIPP beam



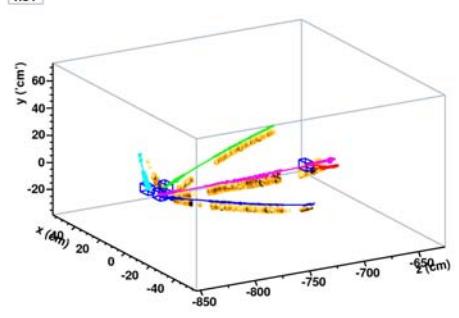
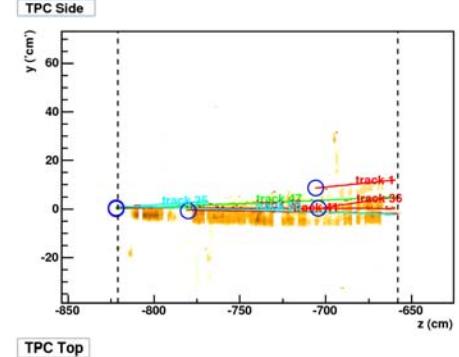
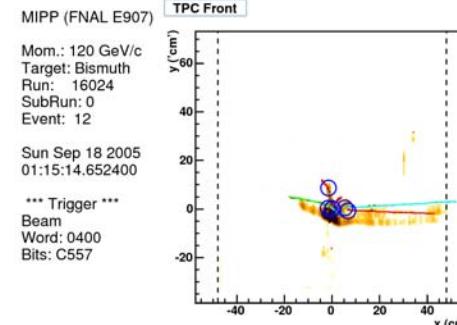
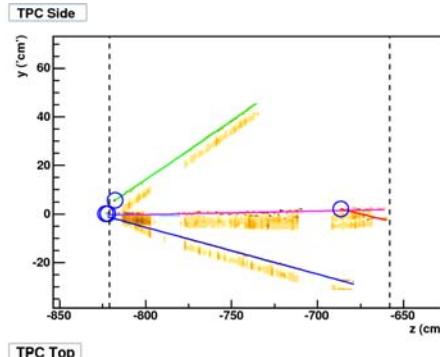
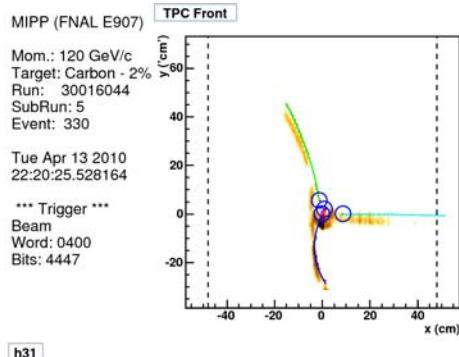
- MIPP design, very short from primary to secondary target (95 m)
- Excellent performance, kaons down to 3 GeV/c (in upgrade), enough kaons survive.
- Ran it successfully in MIPP from 5-85 GeV/c secondaries and 120 GeV/c primary protons.
- Excellent particle ID capabilities using 2 Beam Cherenkovs. For low momenta ($<\sim 10$ GeV/c) Beam-ToF is also used for pid.
- Design principles and lessons learned used in M-test at Fermilab.

Cryogenic target mounted in TPC, NuMI target and target wheel



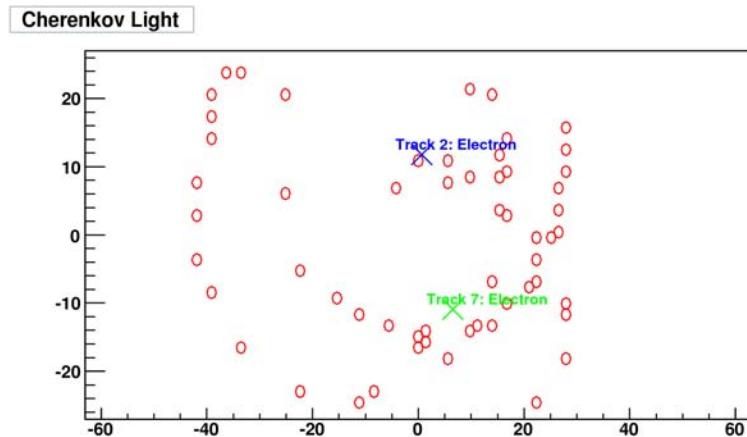
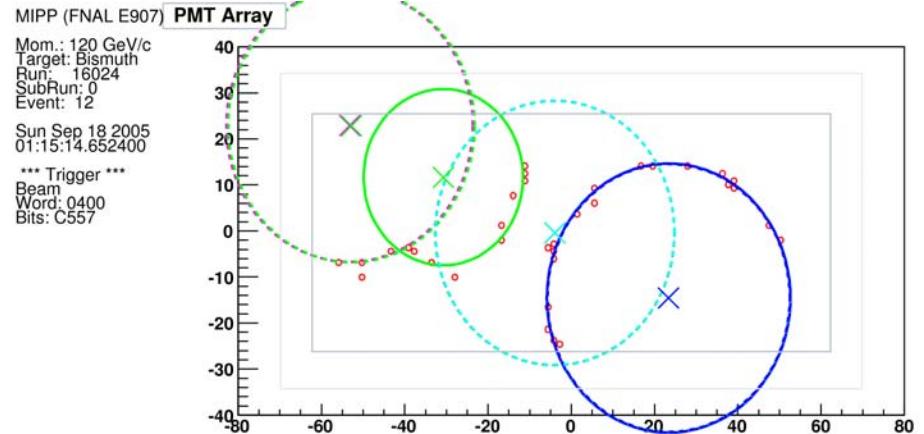
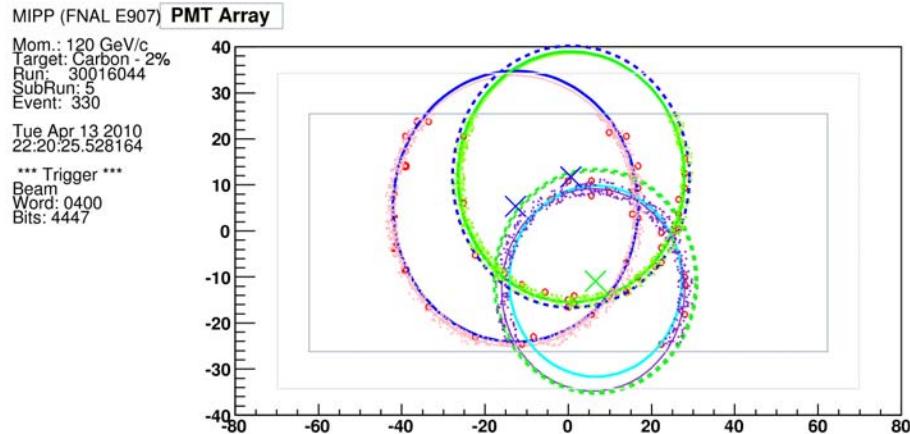
Event Display – Data and MC

- TPC hits and reconstructed tracks

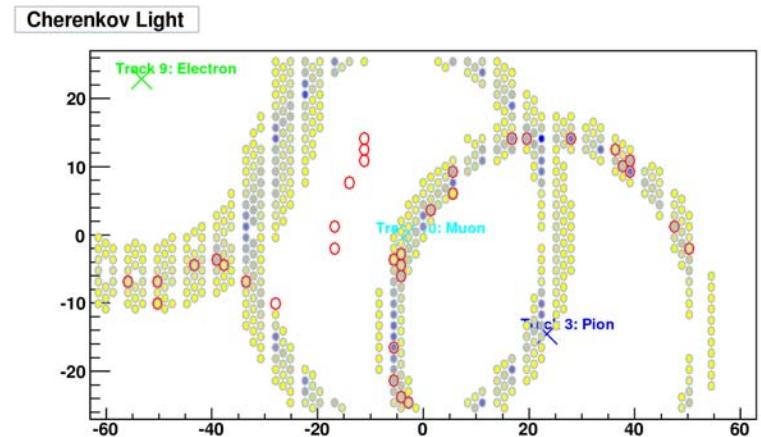


Event Display – Data and MC

- RICH hits and reconstructed rings



red: pmt hits

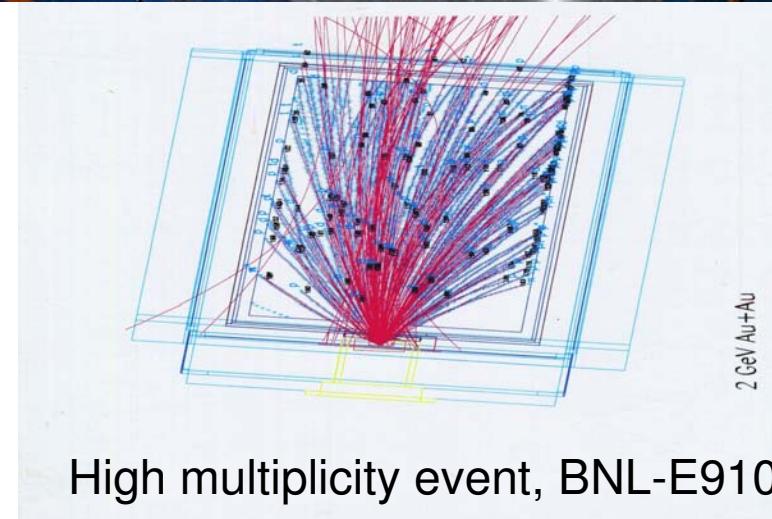


yellow/grey: hit probability
from reconstruction

Track reconstruction

MIPP TPC

- Time Projection Chamber,
previously used at the Bevalac and
BNL-E910
 - Particle tracks ionize P10 gas (10%
Methane in Argon), electrons drift in 10kV
electric field
 - The amount of ionization per path length,
 dE/dx , depends on the particle type
 - 120×128 readout pads of $8 \times 12 \text{ mm}^2$
area on bottom give position in x and z
 - Drift time measurement gives y coordinate
at each point along the track
 - Track curvature in 0.7 T magnetic field of
the JGG gives particle momentum
 - Can handle much larger multiplicities than
we encounter in MIPP
 - No problem with overlapping tracks



MIPP TPC – Raw data

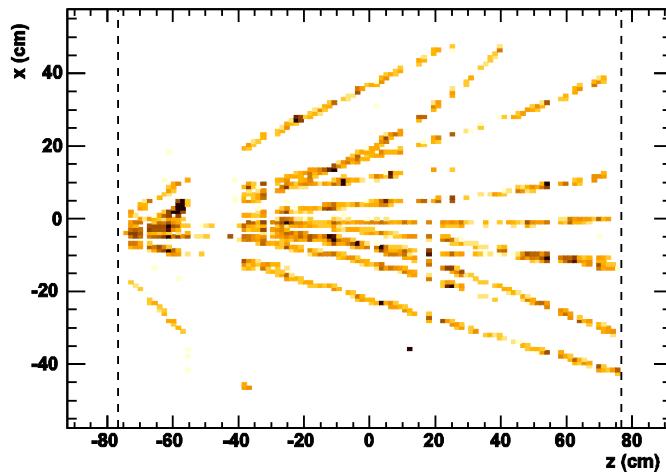
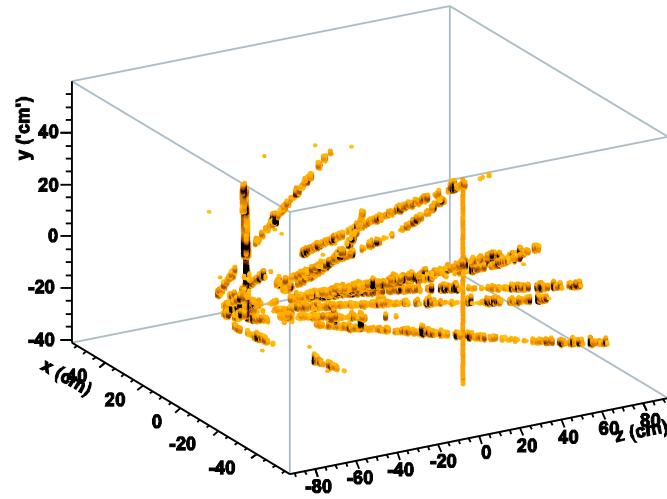
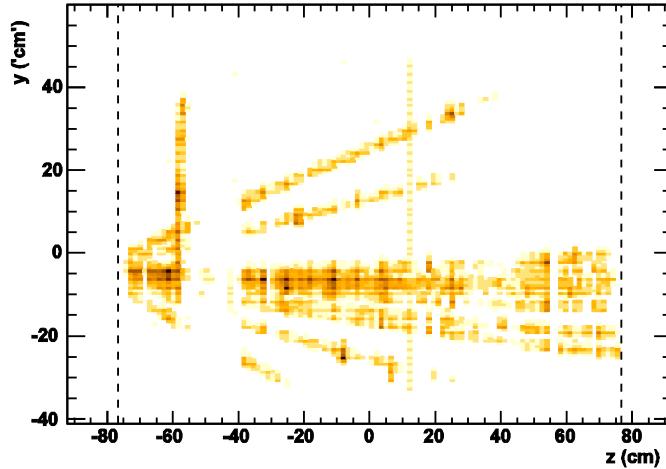
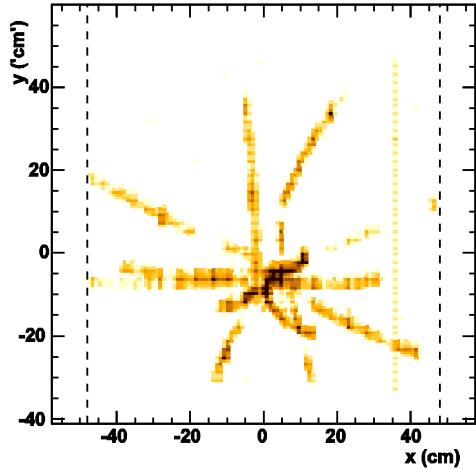


MIPP (FNAL E907)

Target: NuMI
Run: 15007
SubRun: 0
Event: 160

Sat Jul 16 2005
11:22:30.687398

*** Trigger ***
Beam
Word: 0080
Bits: 80D7



MIPP TPC – Reconstructed tracks

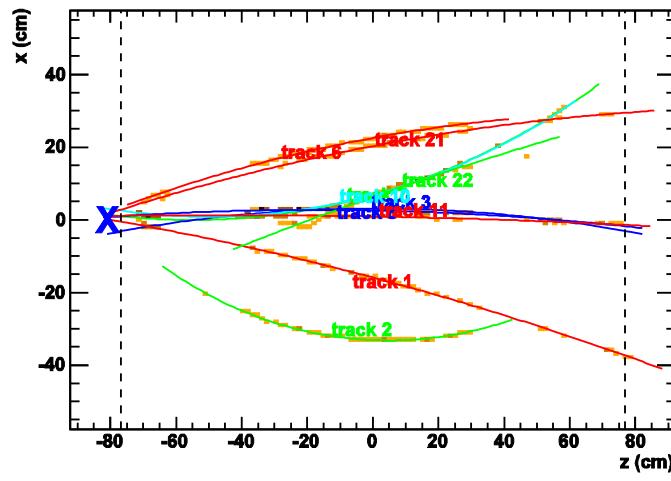
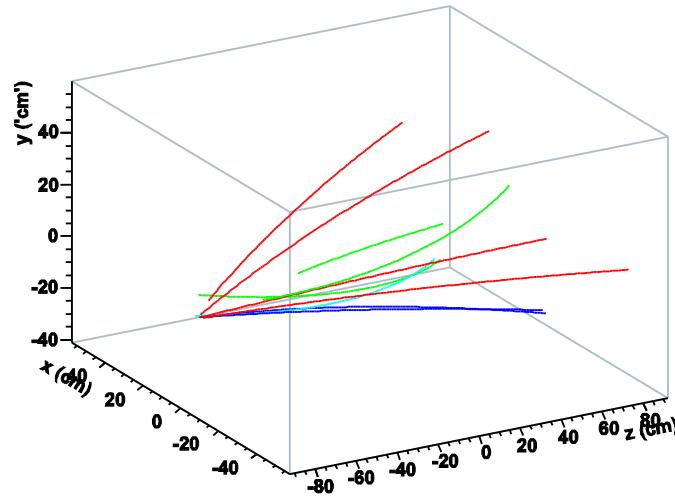
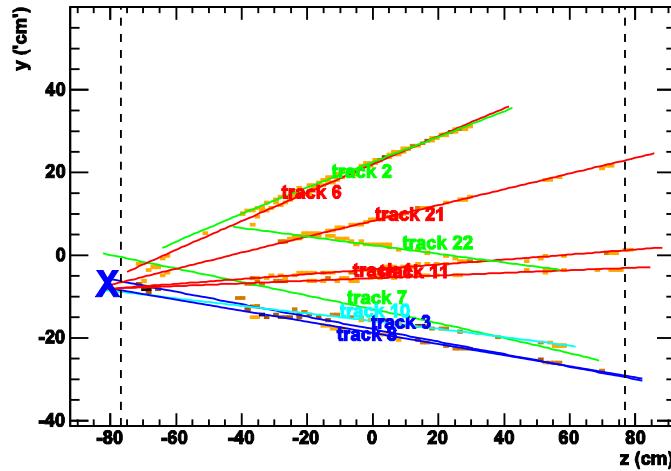
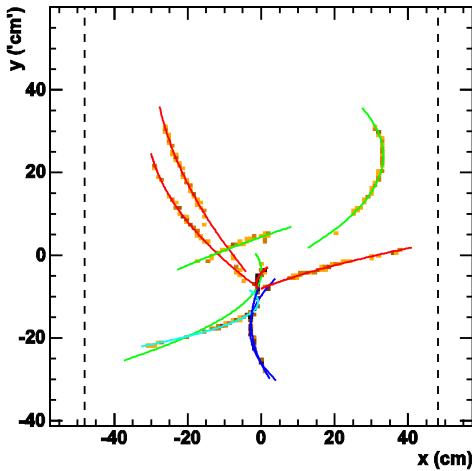


MIPP (FNAL E907)

Target: Beryllium
Run: 12719
SubRun: 0
Event: 9

Mon Feb 28 2005
03:18:40.377278

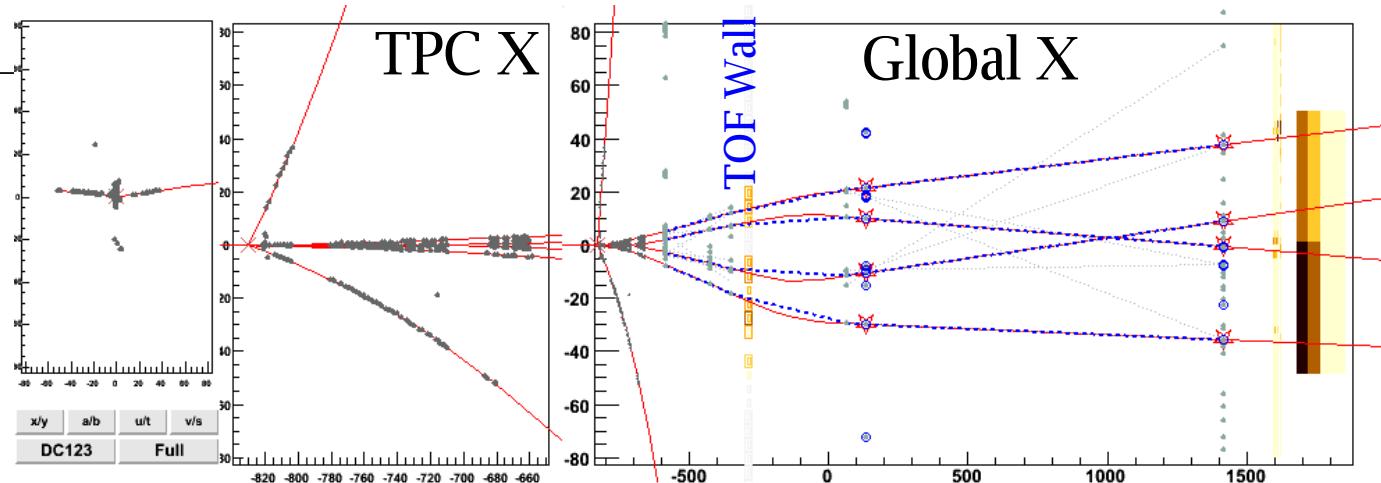
*** Trigger ***
Beam
Word: 0400
Bits: C44F



Reconstructed p-C 120GeV/c event



Tracking and
RICH displays

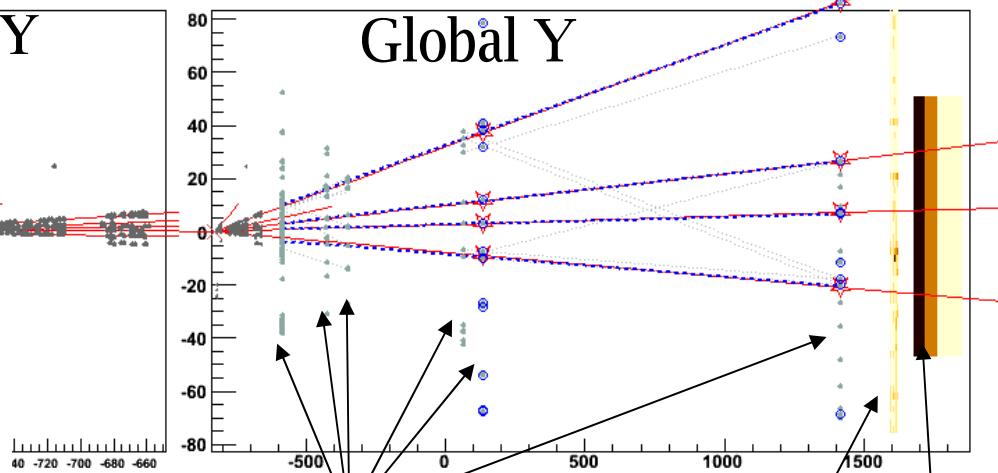
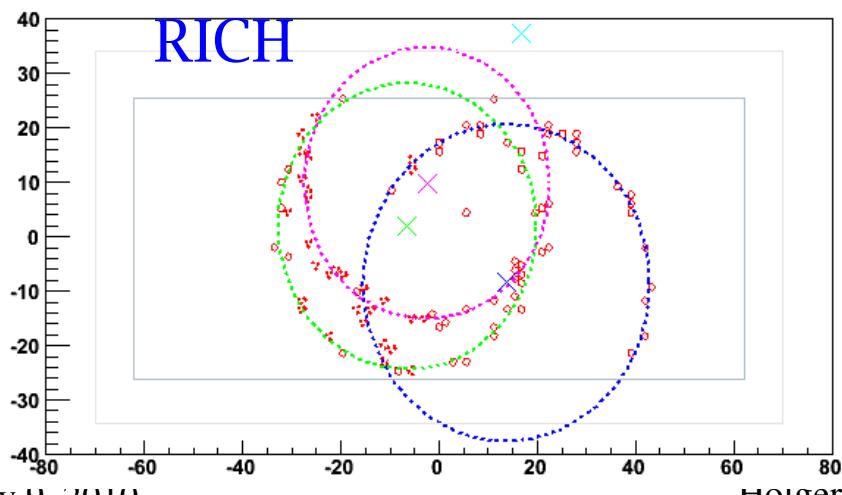


MIPP (FNAL E907)

Mom.: 120 GeV/c
Target: Carbon -
Run: 15860
SubRun: 0
Event: 490

Mon Sep 05 2005
19:01:04.139579

PMT Array



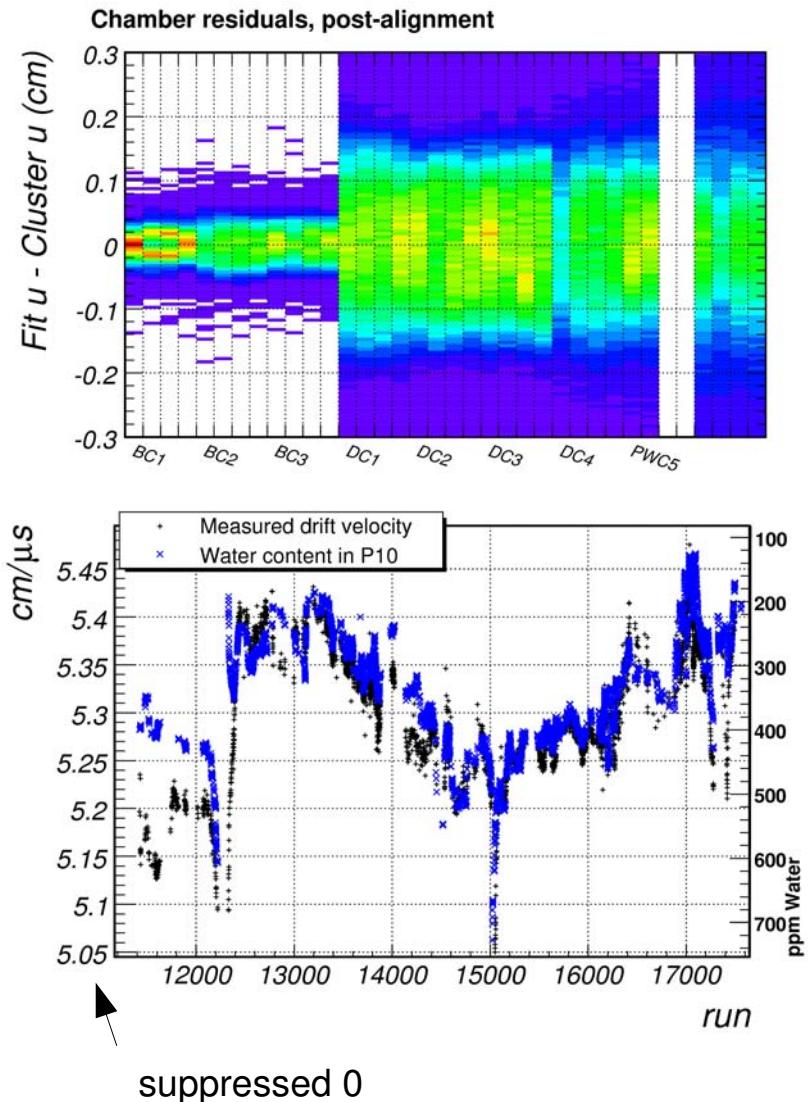
Wire Chambers

EM Cal

Hadron Cal

Spectrometer calibration

- Chamber alignment done for every run
 - Helped to refine magnetic field maps
- TPC electron drift velocity measured for every run
 - Strong correlation with water vapor contamination in Ar/CH₄

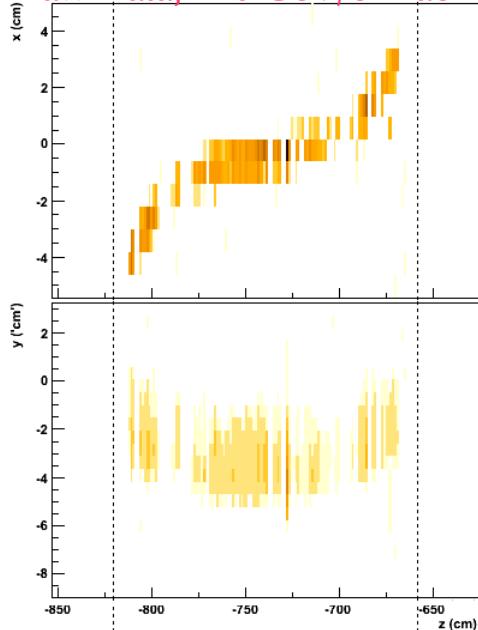


TPC hit reconstruction

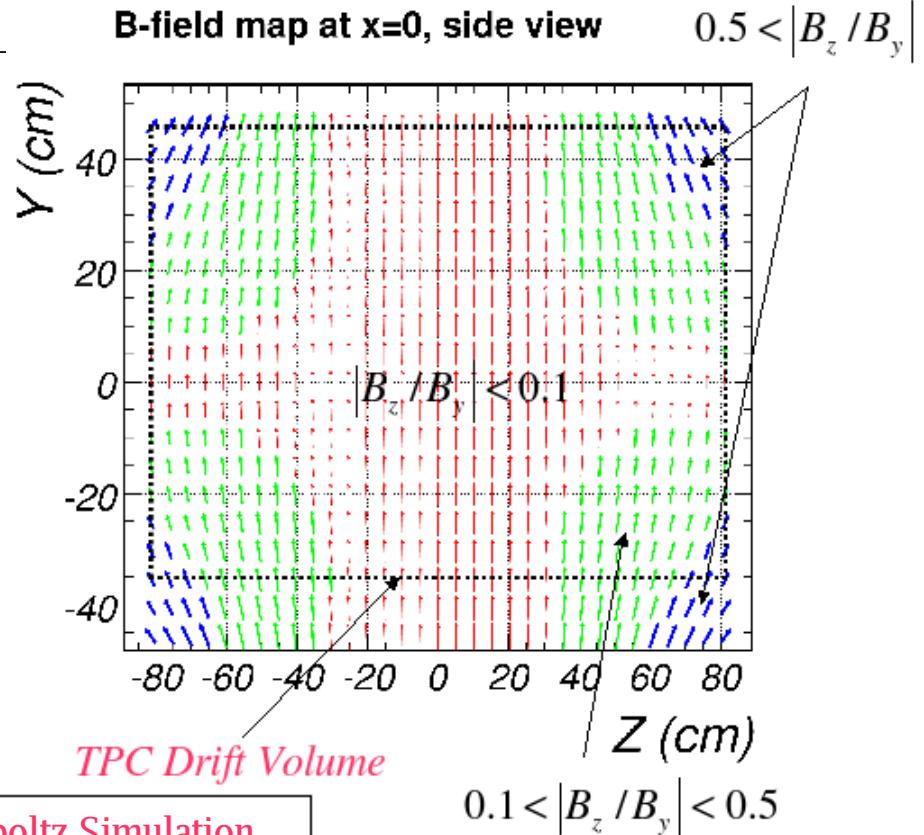
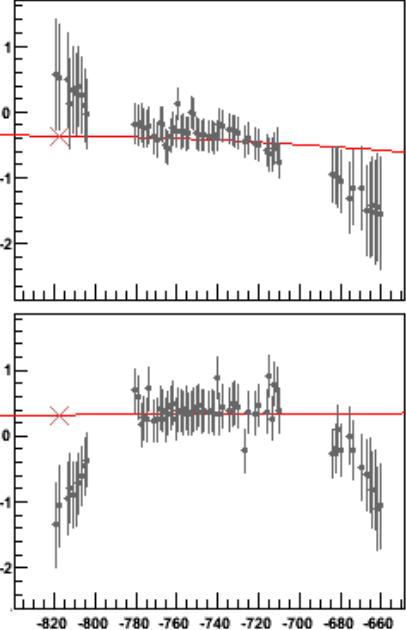
- JGG field is non-uniform
 - Huge ExB effect on electron drift in TPC
- Previous experiments applied corrections based on steady state solution to linear model

$$m \frac{dv}{dt} = eE + ev \times B - \frac{1}{\tau} v$$

Raw Data, 120 GeV/c Track

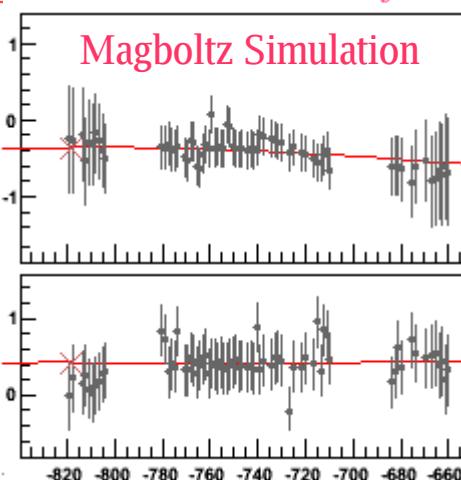


Linear model



TPC Drift Volume

Magboltz Simulation

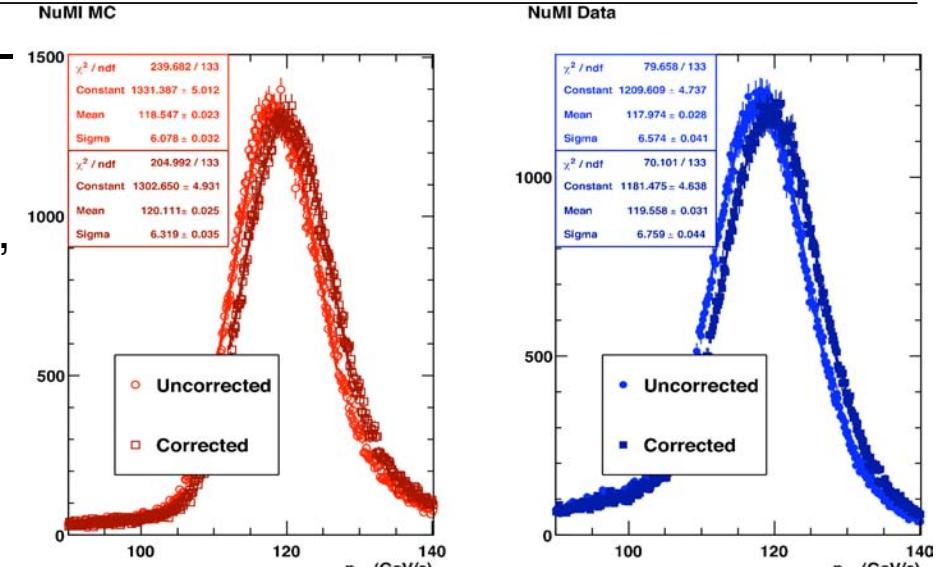


Magboltz simulation to map out drift velocity components as a function of v_0 , B-field strength, and angle between E and B-fields.

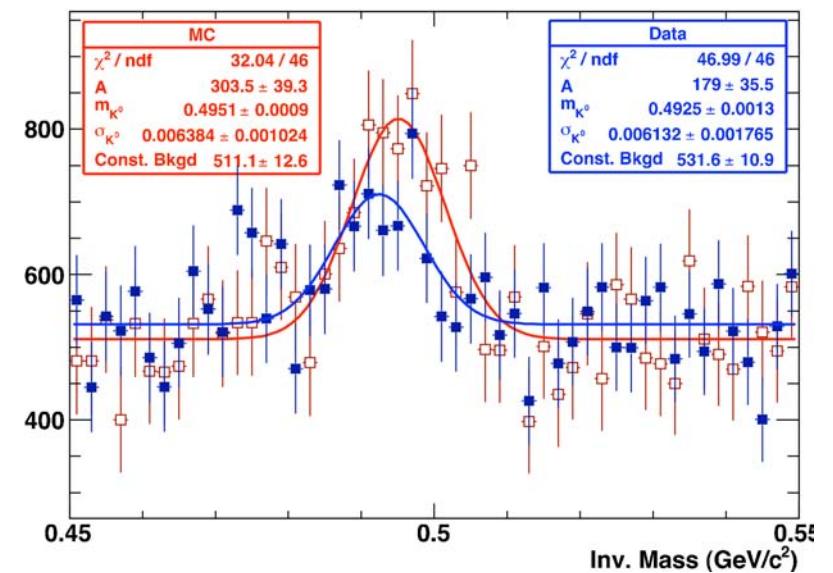
Good agreement with TPC data.

Track reconstruction

- TPC track determination (Runge-Kutta)
 - Non-uniform B-field complications solved, detailed Ziptrack B-field map was used
- Matched to wire chamber hits to form global tracks
 - Fit using track templates
- Momentum resolution 5.5% at 120 GeV/c
- Absolute energy scale from
 - 120 GeV protons
 - Low momentum K^0_S
 - 0.85% correction

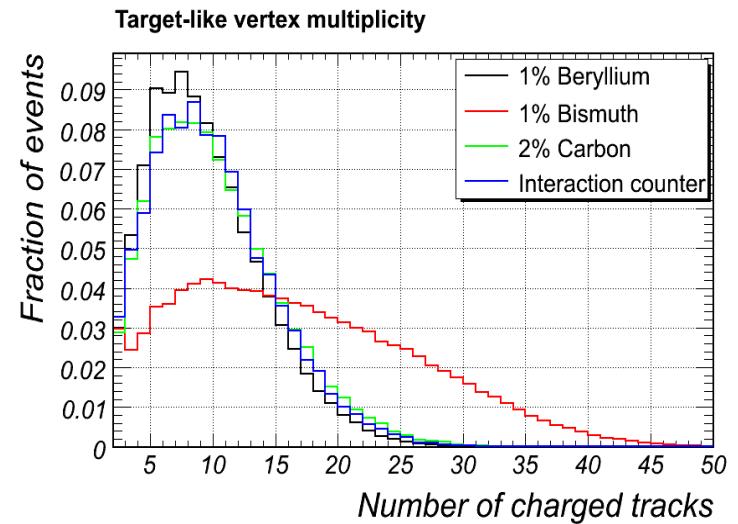
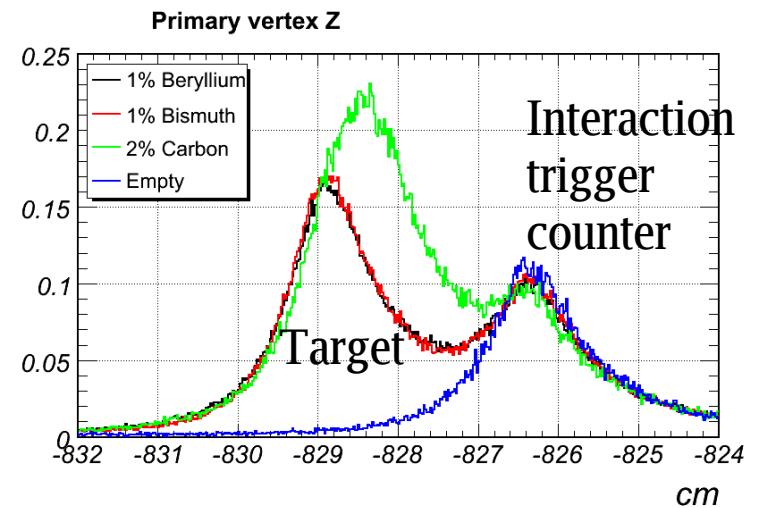


Invariant K^0 Mass Distribution, Thin Tgt ConFit



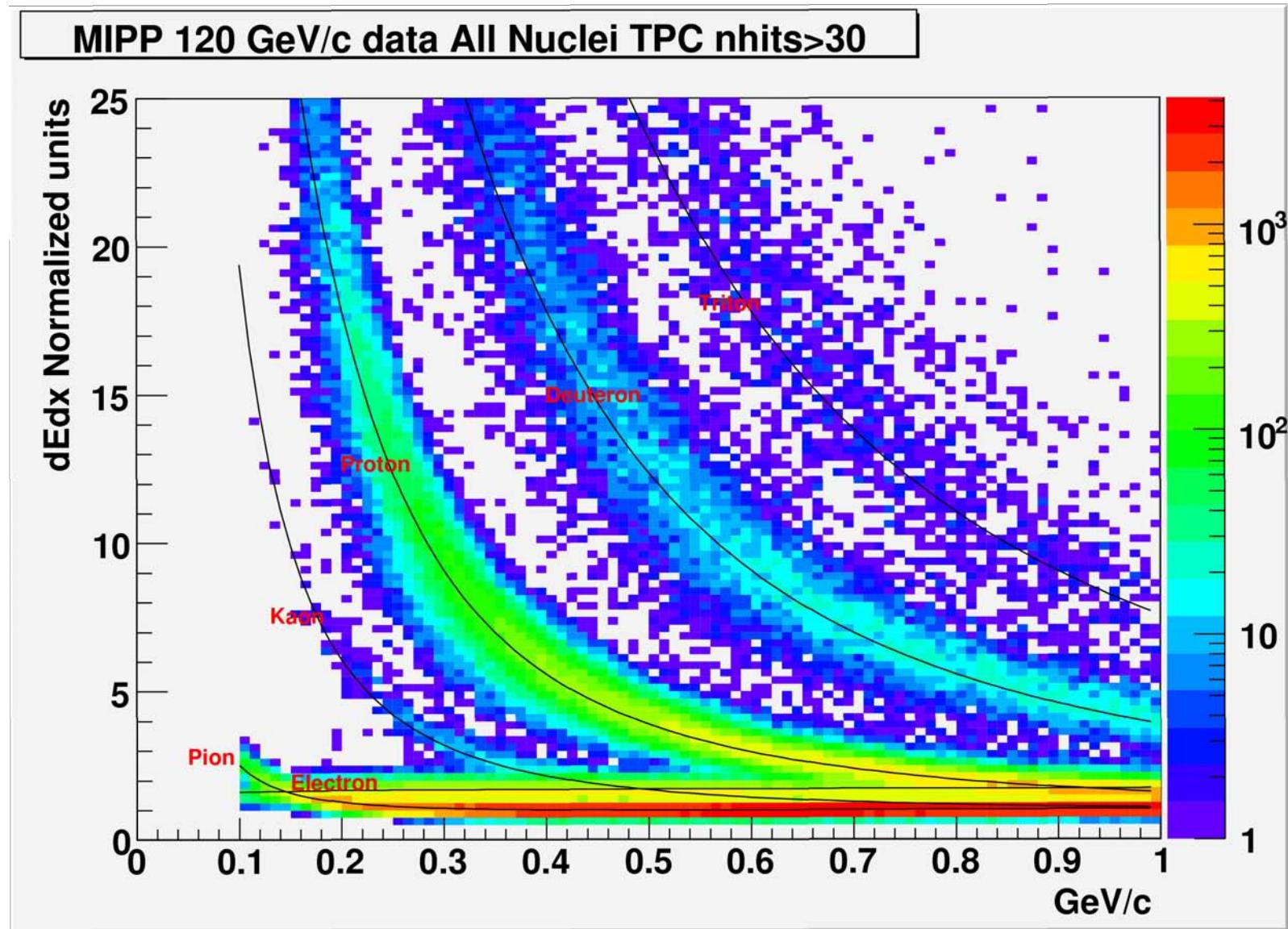
Vertex reconstruction

- Two steps to vertexing:
 - Vertex finding is done with iterative algorithm.
 - All tracks of each vertex are refit with the constraint of originating at the vertex.
Uses track templates.
- Vertex resolution:
 - 6mm vertex Z resolution
 - X,Y resolution < 1mm
- Good separation of target interactions from background



Particle Identification

dE/dx in the TPC - data



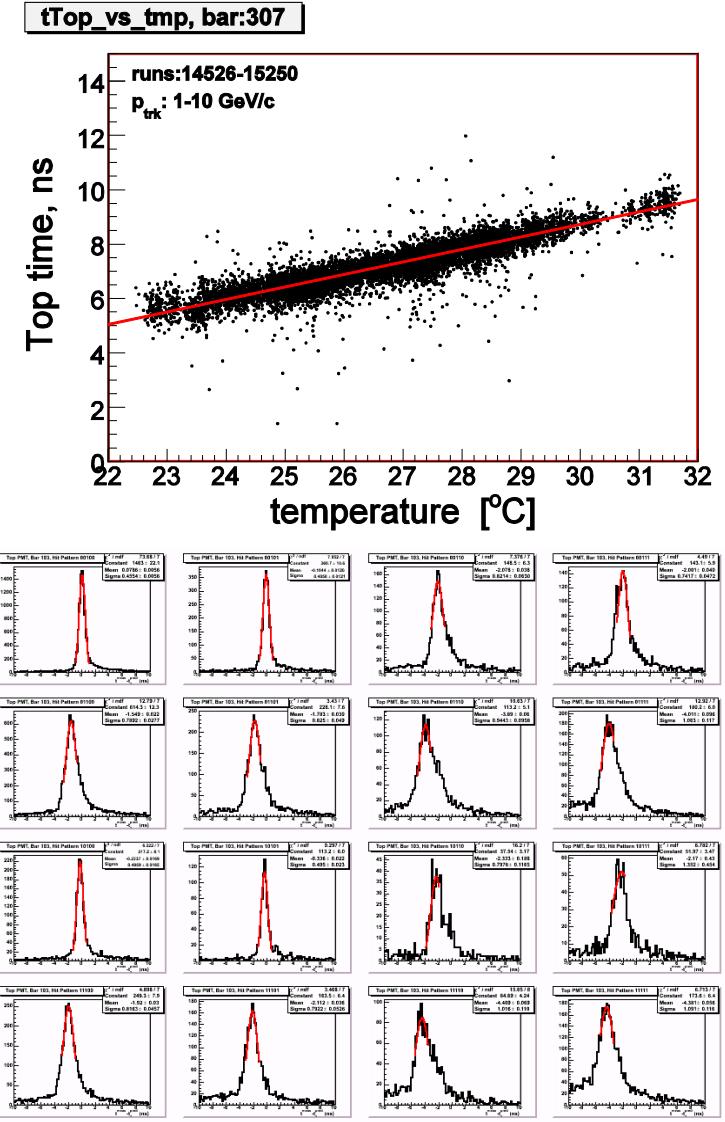
Time of Flight wall

- Designed and built by MIPP
 - 5 cm x 5 cm square scintillator bars in Rosie aperture, 10 cm x 10 cm outside.
~200 ps resolution after all corrections.
 - ~200 ns of cable delay
(needed for trigger formation and distribution)
save cost: use Twist'N'Flat cables
 - CAMAC TDC and ADC readout



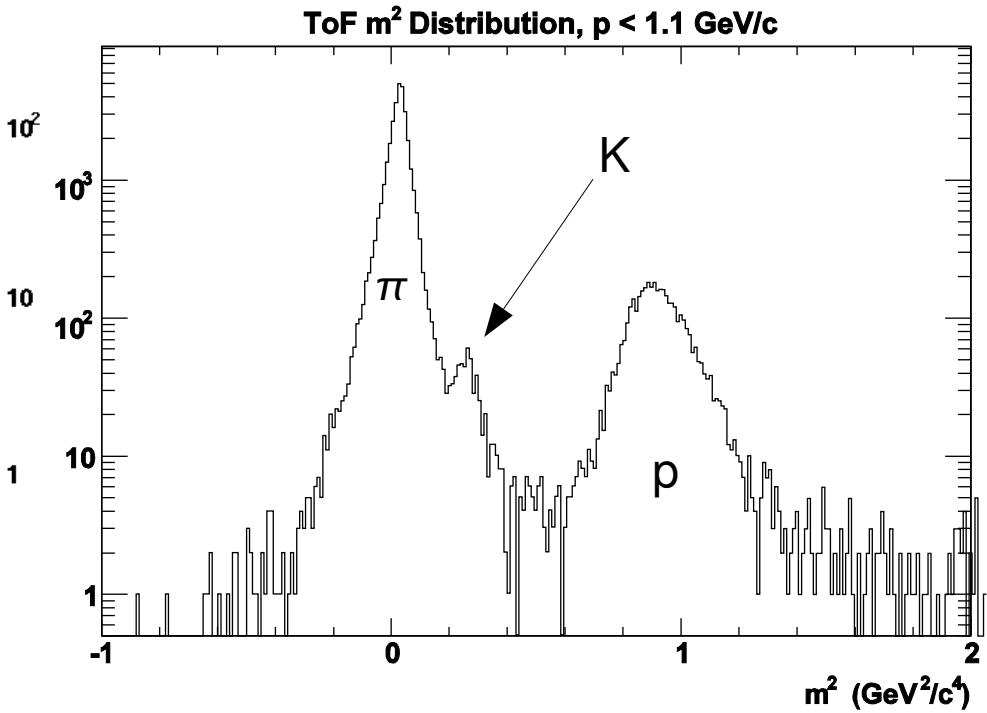
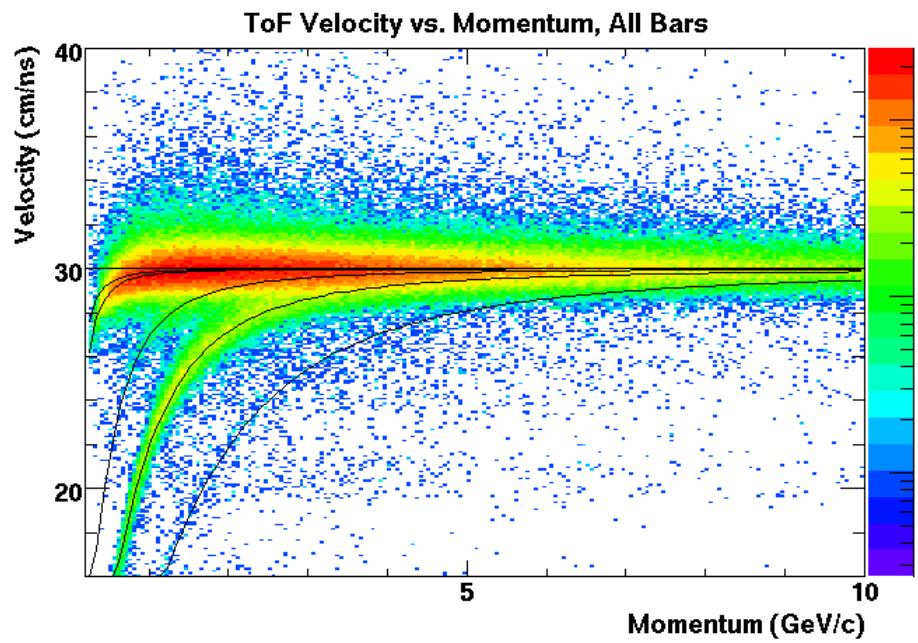
ToF wall calibration

- Pulse height correction (using adcs, corrects for discriminator slew)
- Temperature dependence in delay cables
 - up to 4000 ps effect
- Cross talk correction
 - Cross talk when neighboring bars are hit
 - Also next to neighboring channels
 - Due to capacitative coupling in delay cables
 - $2^4 = 16$ time dependent correction constants per pmt

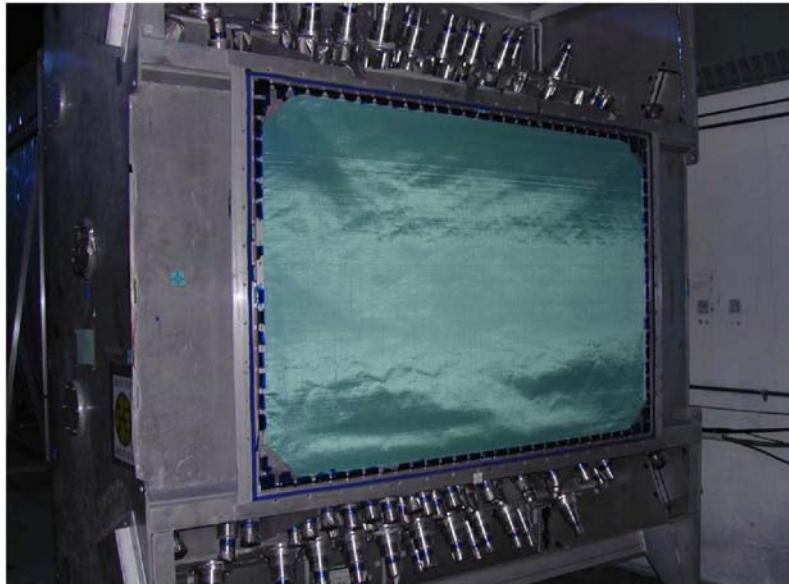


TOF particle ID

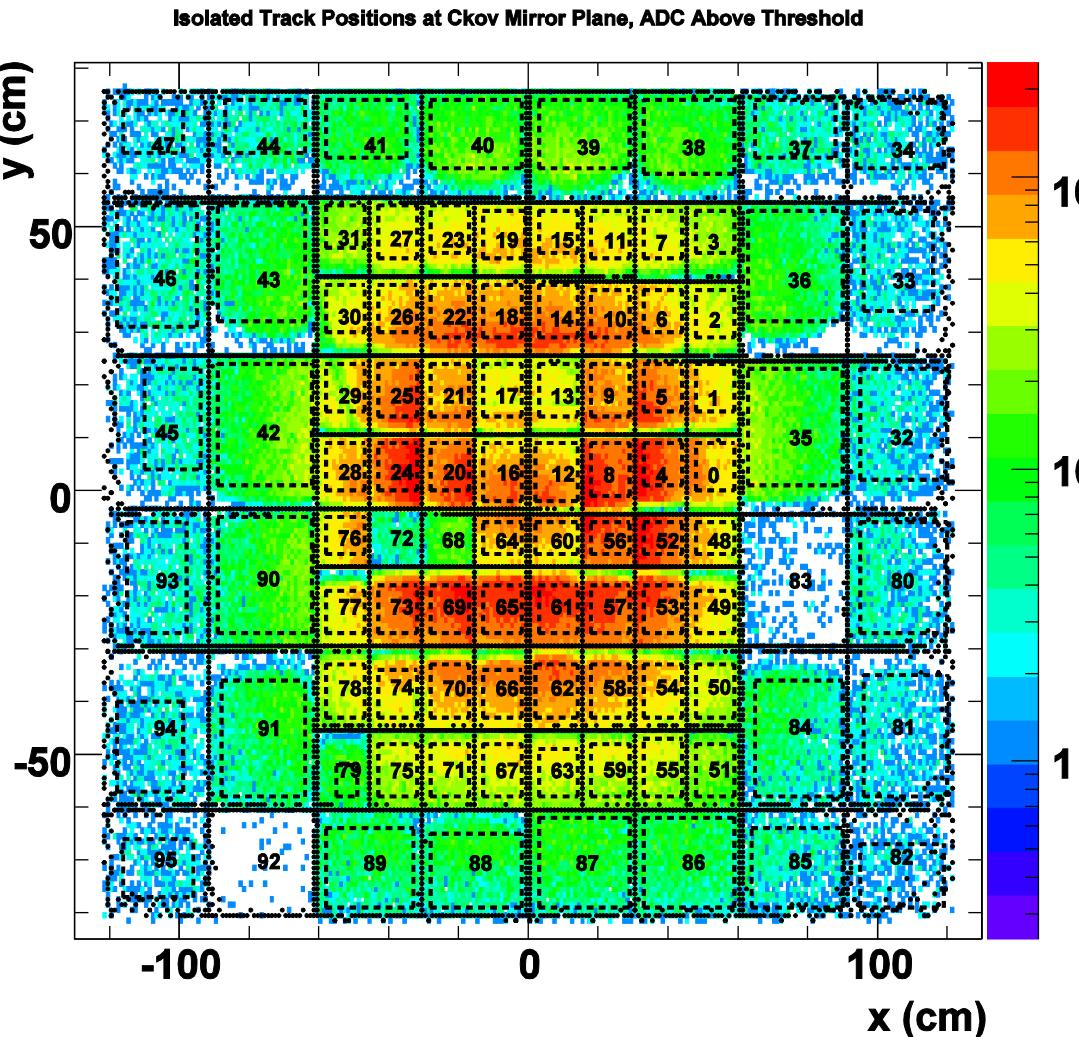
- TOF did not work as well as designed, but gives good PID over most of the momentum region it was supposed to cover after all corrections are applied carefully.



Multicell threshold Cherenkov

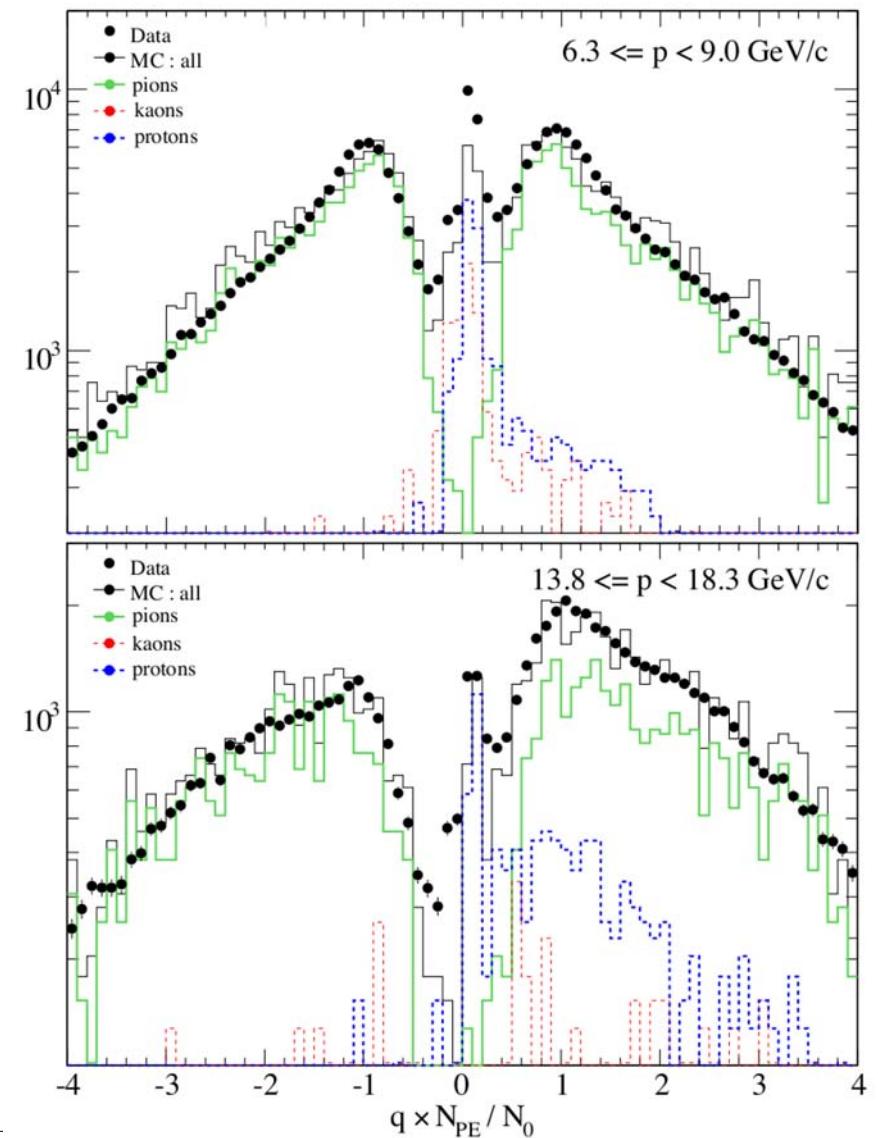
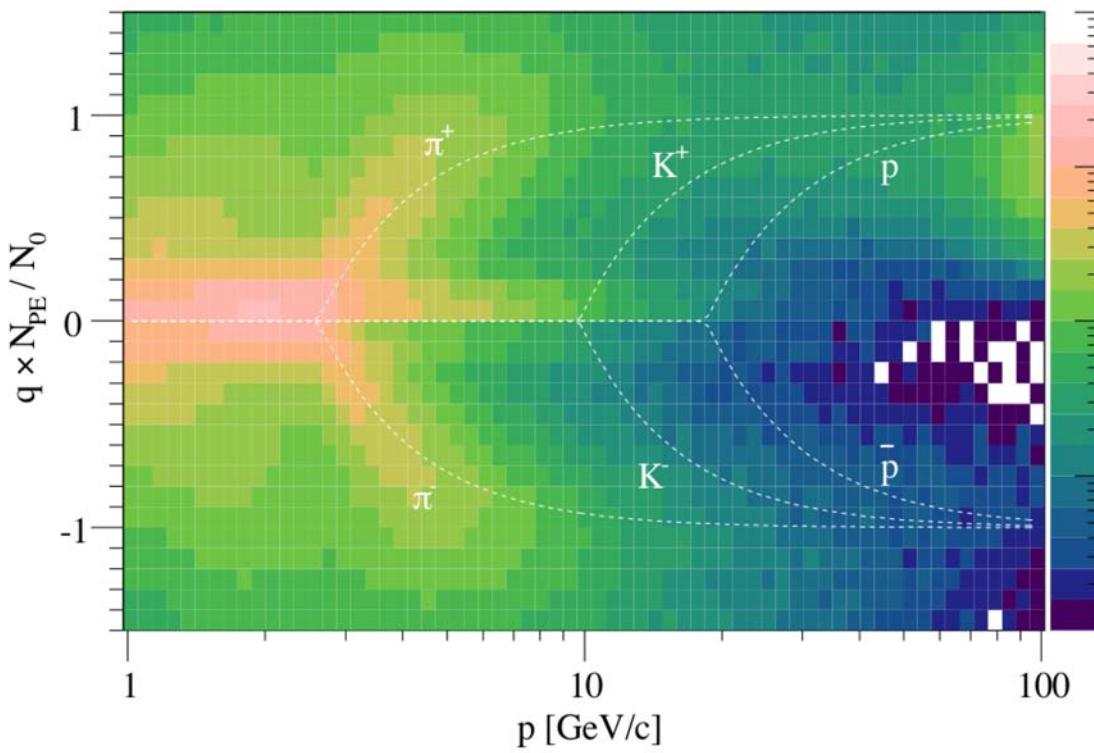


- C4F10 gas, Thresholds: $\pi = 2.5 \text{ GeV}/c$,
 $K = 8.9 \text{ GeV}/c$, $p = 17.5 \text{ GeV}/c$



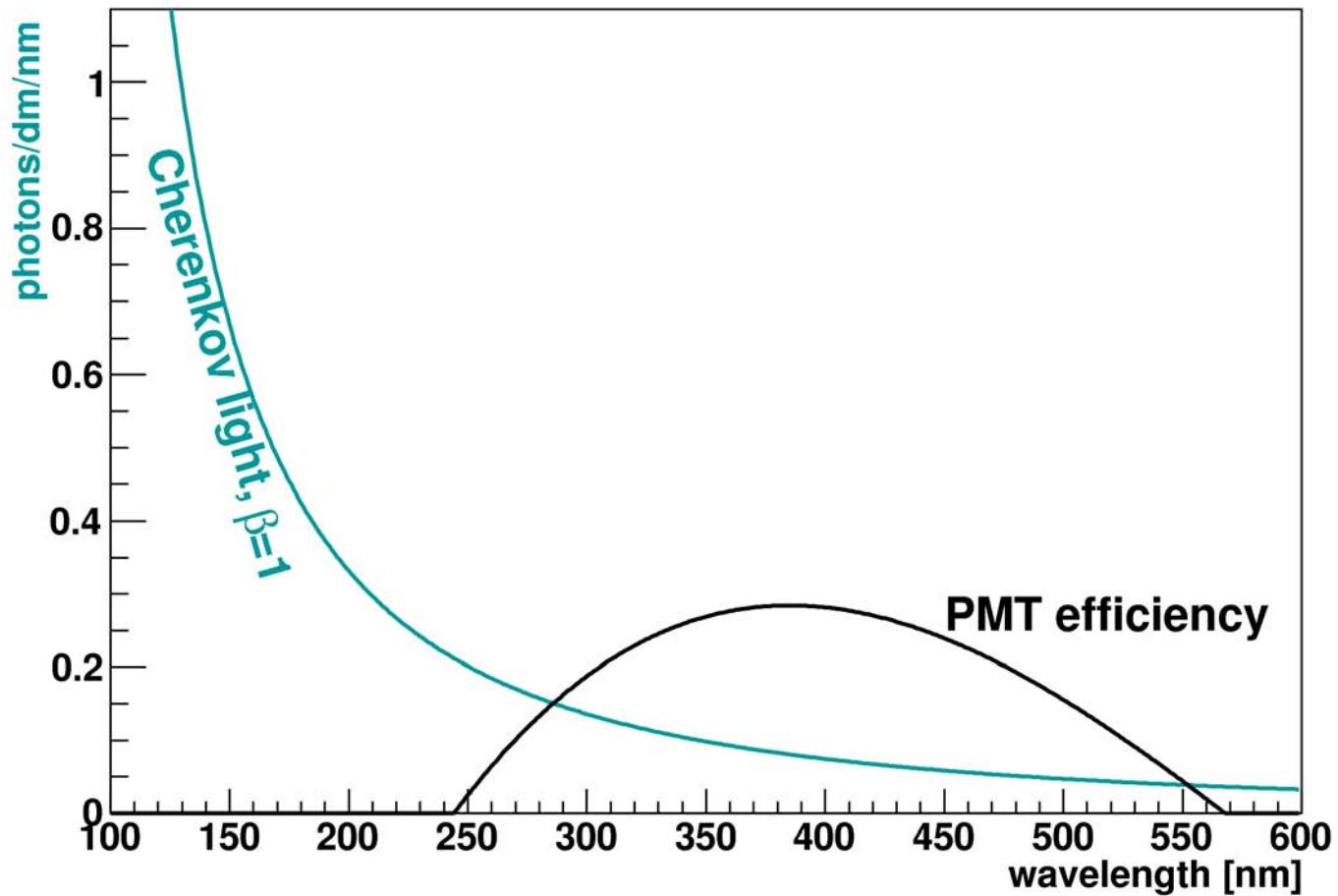
Cherenkov particle ID

- Every mirror calibrated with data assuming pions and Poisson statistics.
 - Light yield lower than expected.
 - Normalized to $\beta=1$ to put all mirrors in same plot
 - NuMI target data and MC shown here



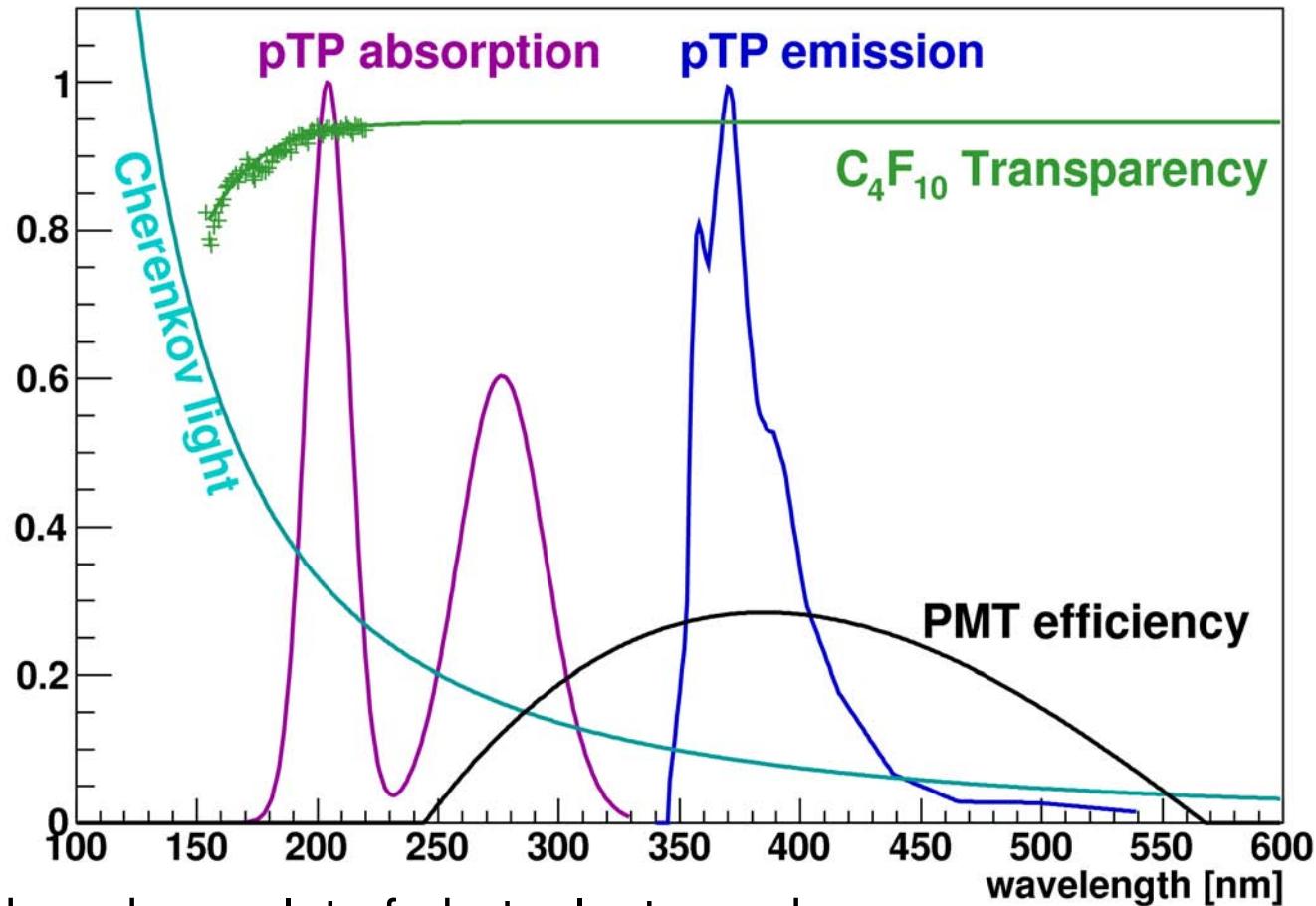
Cherenkov light yield

- Detect as much of the light produced through pmt glass window



Cherenkov light detection

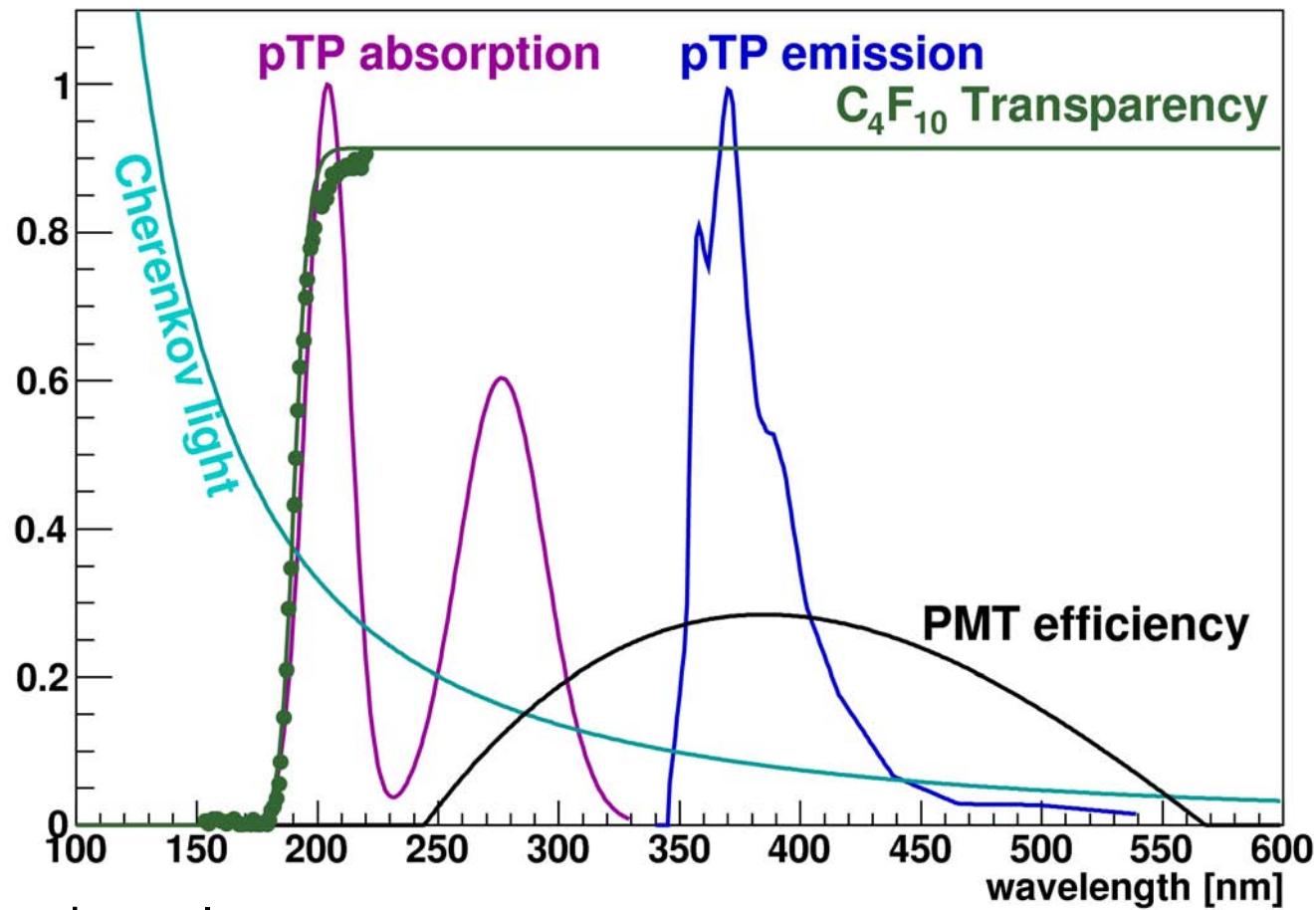
- Use purified gas for good transparency
- Use wavelength shifting coating on pmts



- This would produce a lot of photoelectrons, however...
 - + Ullaland, NIM A553 (2005)

Cherenkov light detection

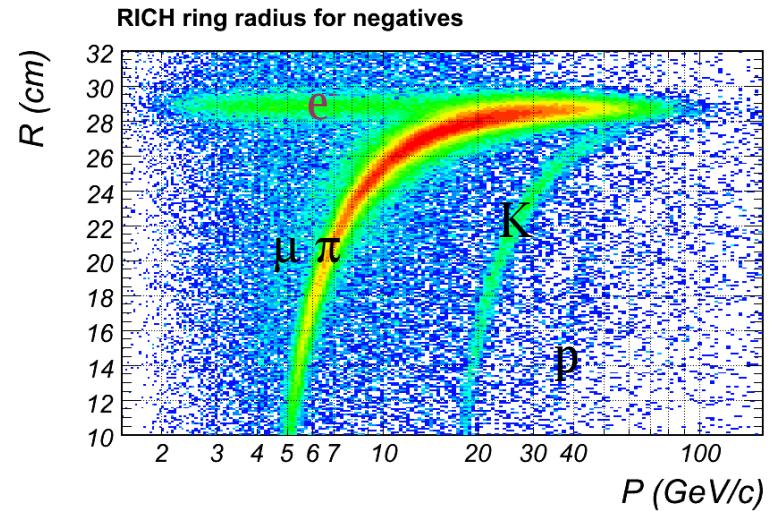
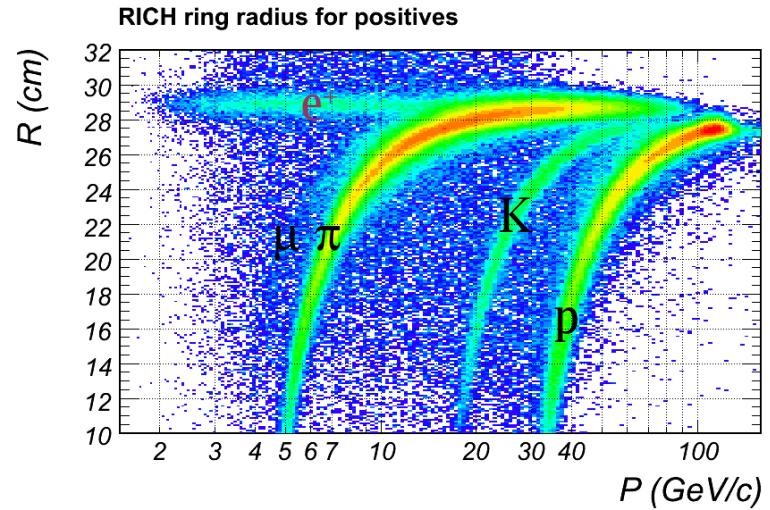
- MIPP gas was not purified and may have been more contaminated than the sample shown here. Transparency at low wavelengths was low. Molecular sieve and activated carbon to remove benzene, etc. from C₄F₁₀.



- Result: few photoelectrons
 - Ullaland, NIM A553 (2005), same gas before purification

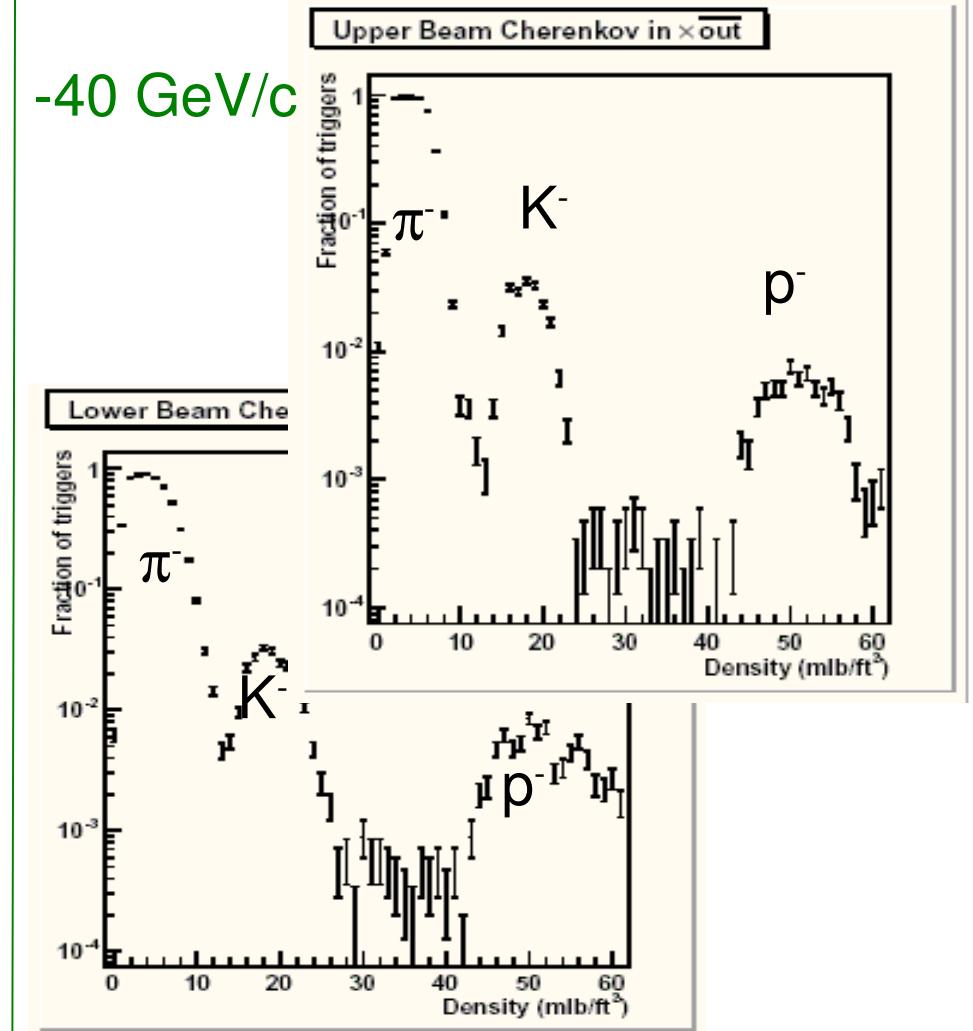
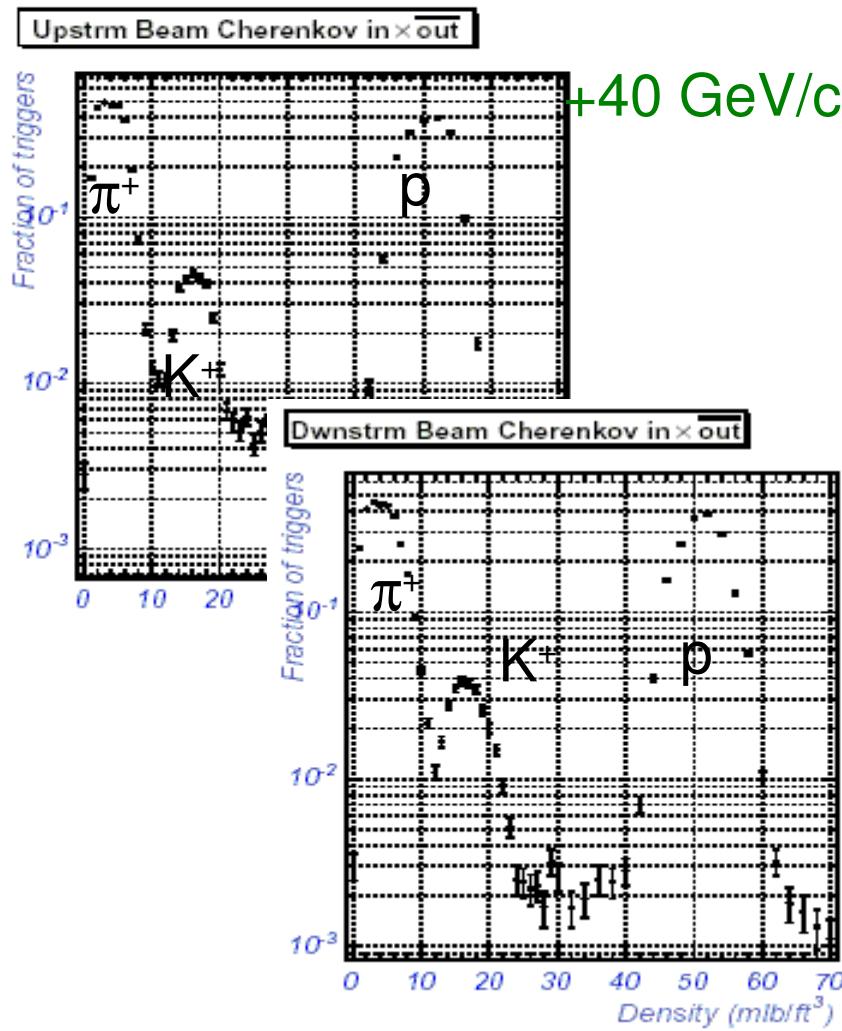
RICH particle id

- From Selex, entirely new readout electronics and some PMTs replaced
- Radiator: CO_2 gas at STP
- Gives lots of hits for MIPP momentum range.
 - easy to fit good circles
- RICH ring radius gives very good particle ID
 - $e/\mu/\pi$ up to 12 GeV/c
 - $\pi/K/p$ to 120 GeV/c



Beam Cherenkov Pressure Curve

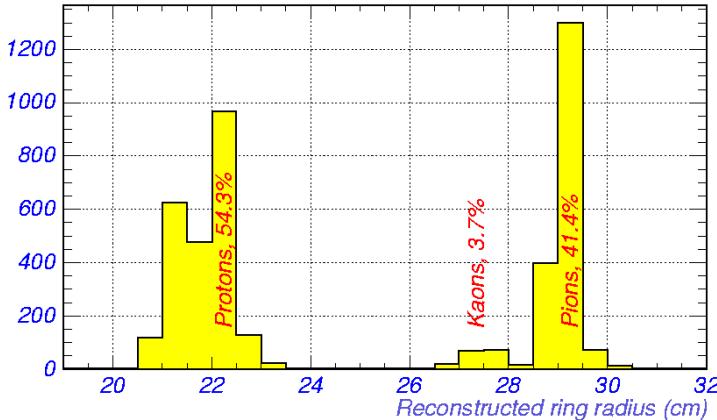
- Two differential Ckoks separate π/K or K/p depending on N_2 radiator pressure



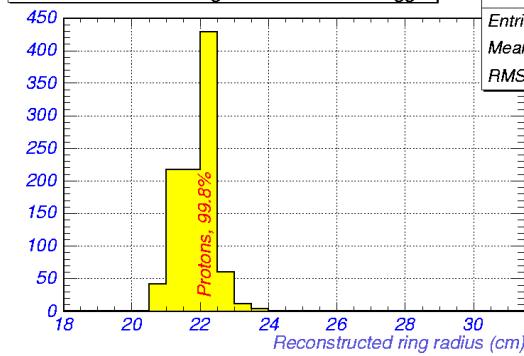
Beam Cherenkov performance

- Uninteracted beam particles are identified in both beam and RICH
 - Comparison for +40 GeV/c beam – No additional cuts!
 - Offline cuts can clean up kaon beams further

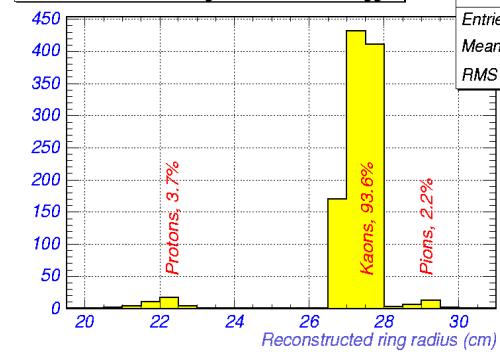
Distribution of RICH Ring Radii in Beam



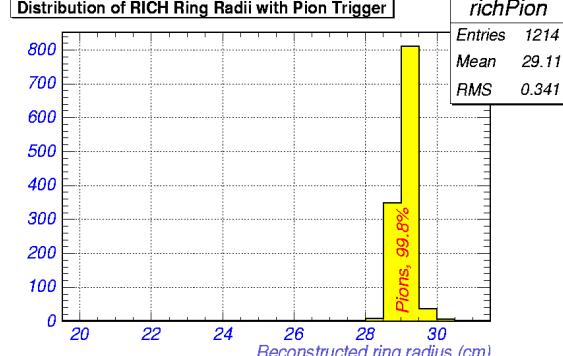
Distribution of RICH Ring Radii with Proton Trigger



Distribution of RICH Ring Radii with Kaon Trigger

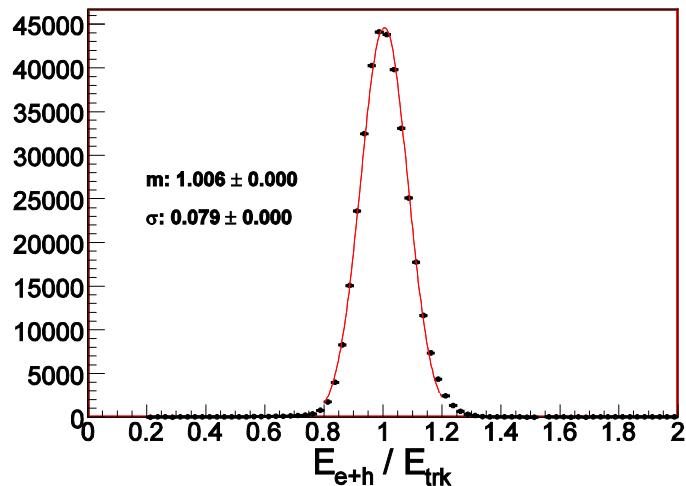
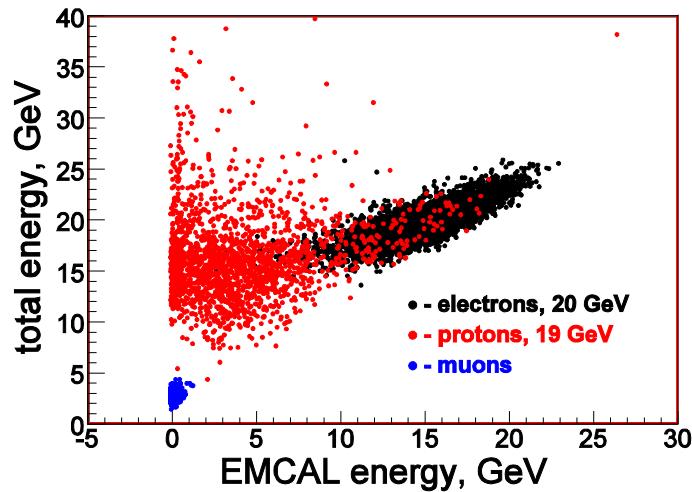


Distribution of RICH Ring Radii with Pion Trigger



Calorimeters

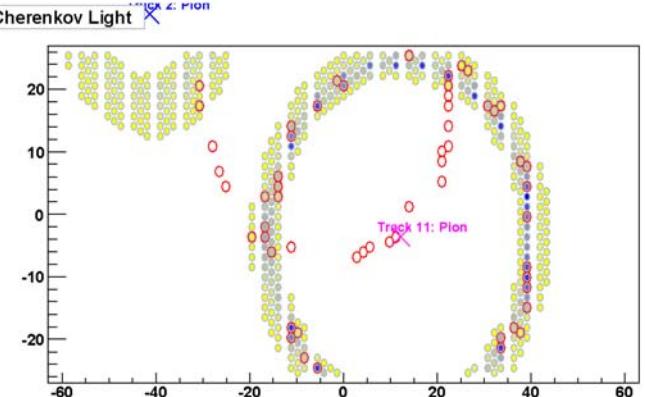
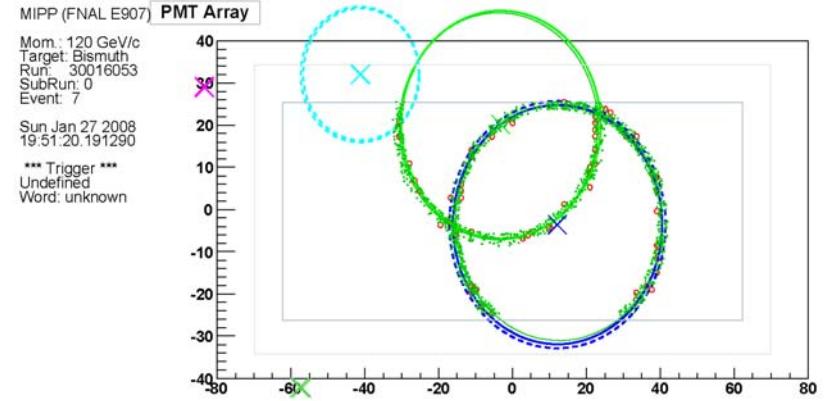
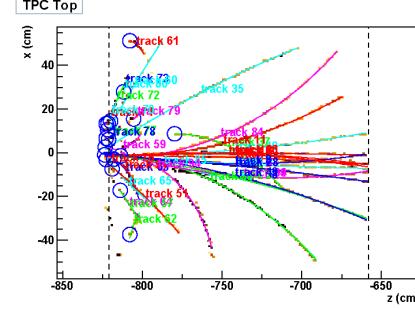
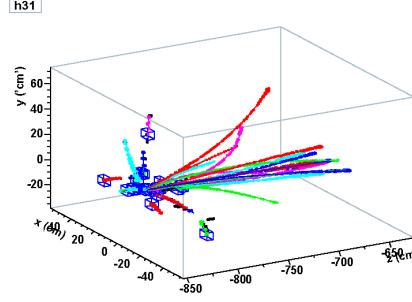
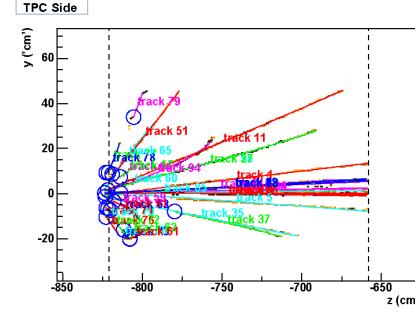
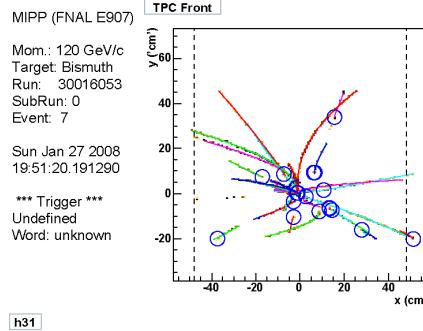
- EM calorimeter followed by hadronic calorimeter
- NIM A598 (2009) 394-399



$$\frac{\sigma}{E} = \frac{0.554}{\sqrt{E}} \oplus 0.026$$

Resolutions and Acceptances

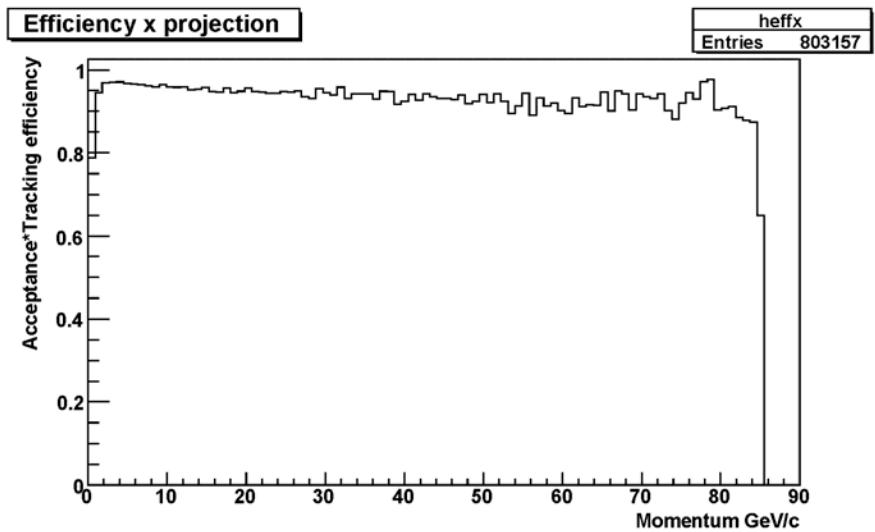
- Full Geant3 based Monte Carlo simulation of the detector response. Use known tracks and match them to found tracks to determine acceptance*tracking efficiency and momentum resolution.
- MC event display



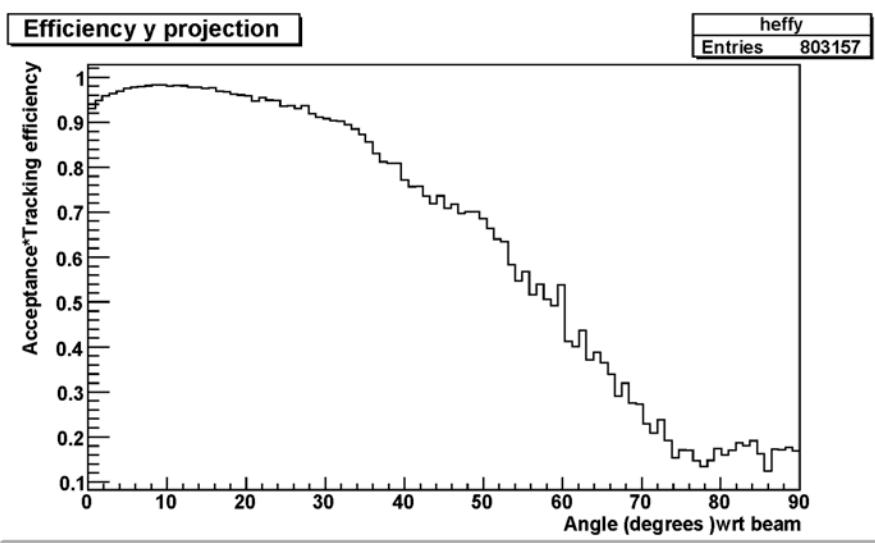
Detector acceptance

MIPP-I Acceptances
MIPP-II will have backward acceptances.

Efficiency vs. momentum

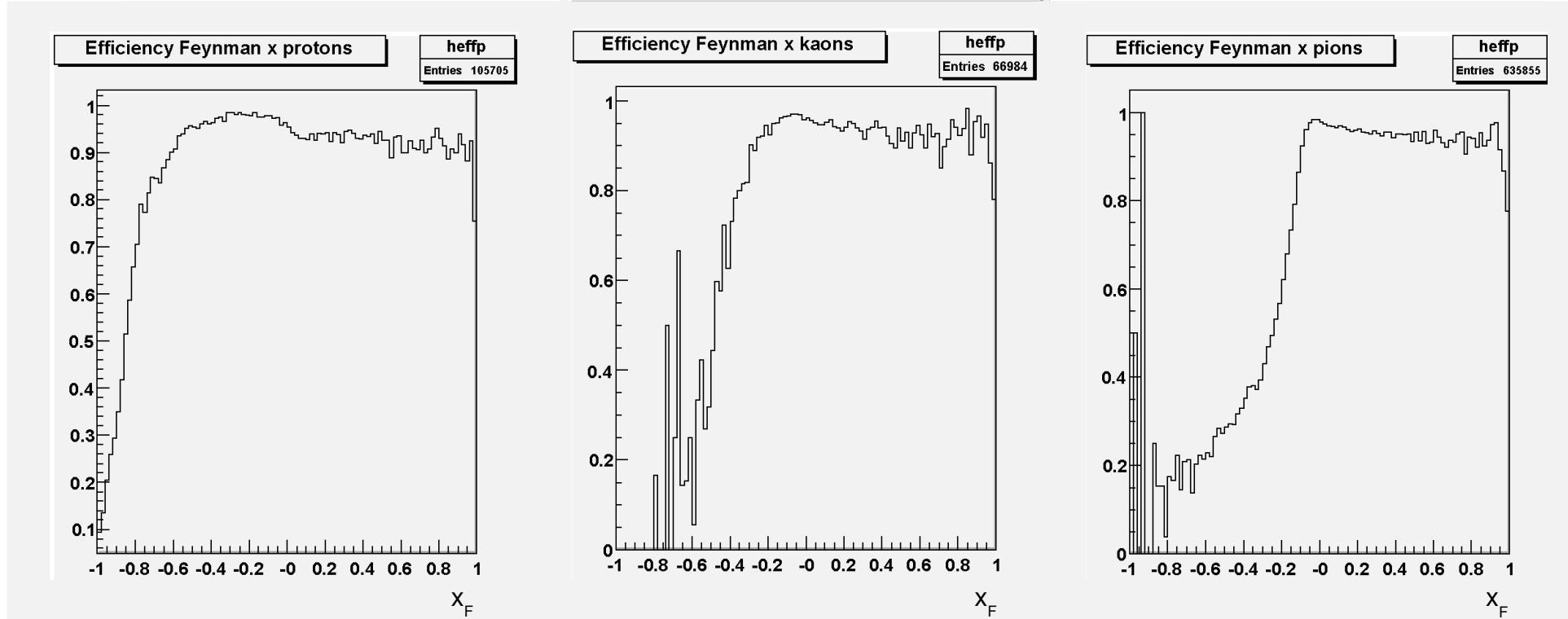


Efficiency vs. θ_{lab}



Detector acceptance

- Pions at low x_F move backward in the lab

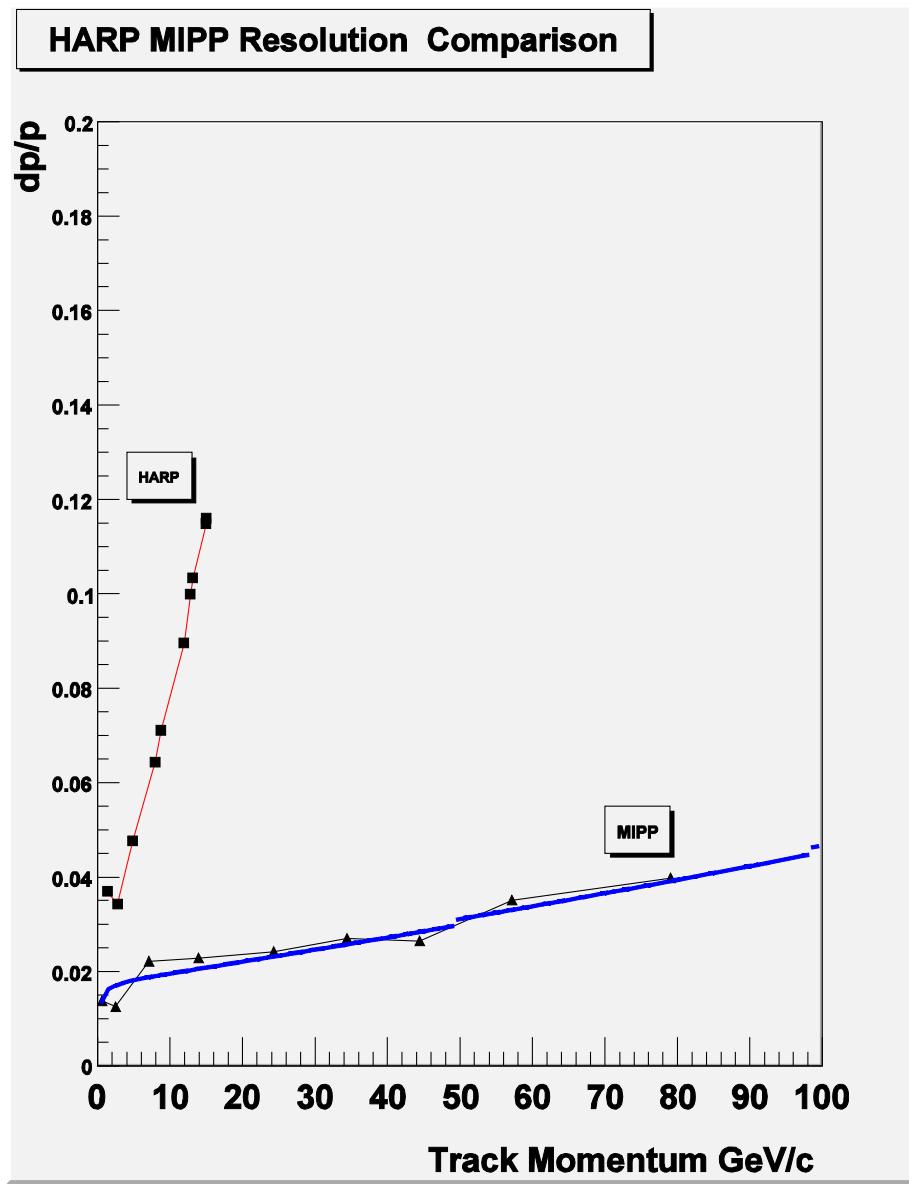


- Plastic Ball detector in the upgrade will increase acceptance.

Momentum resolution compared to HARP at CERN



- MIPP momentum resolution is excellent
 - TPC with JGG field at low momenta
 - Rosie magnet and Drift Chambers at higher momenta
 - Redundancy
 - 128 TPC hits
 - 24 wire chamber planes



MIPP Data set



Final Data Summary, Number of events x 10 ⁶												
Target			Beam momentum (GeV/c)									
Z	Element	Trigger Mix	5	20	35	40	55	60	65	85	120	Total
0	Empty thin	Normal		0.10	0.14			0.52			0.25	1.01
	Empty cryo	Normal		0.30				0.61		0.31		1.22
	K mass	No Int.				5.48	0.50	7.39	0.96			14.33
1	LH	Normal	0.21	1.94				1.98		1.73		5.86
4	Be	p only									1.08	1.74
		Normal			0.10			0.56				
6	C	Mixed						0.21				1.33
	C-2%	Mixed		0.39				0.26			0.47	
	NuMI	p only									1.78	1.78
13	Al	Normal			0.10							0.10
83	Bi	p only									1.05	2.83
		Normal			0.52			1.26				
92	U	Normal						1.18				1.18
Total			0.21	2.73	0.86	5.48	0.50	6.58 +7.39	0.96	2.04	4.63	17.05 +14.33

MIPP results

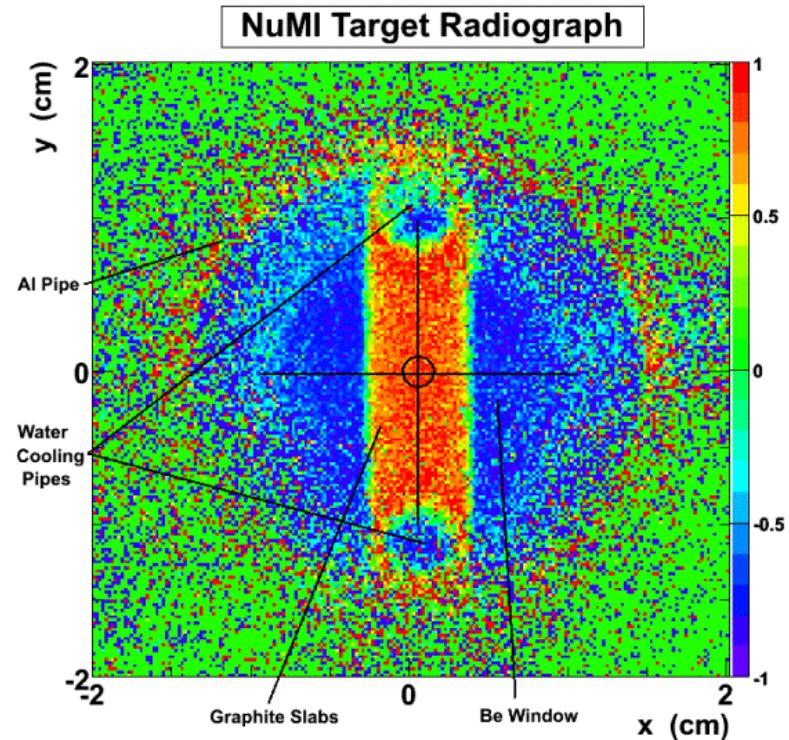
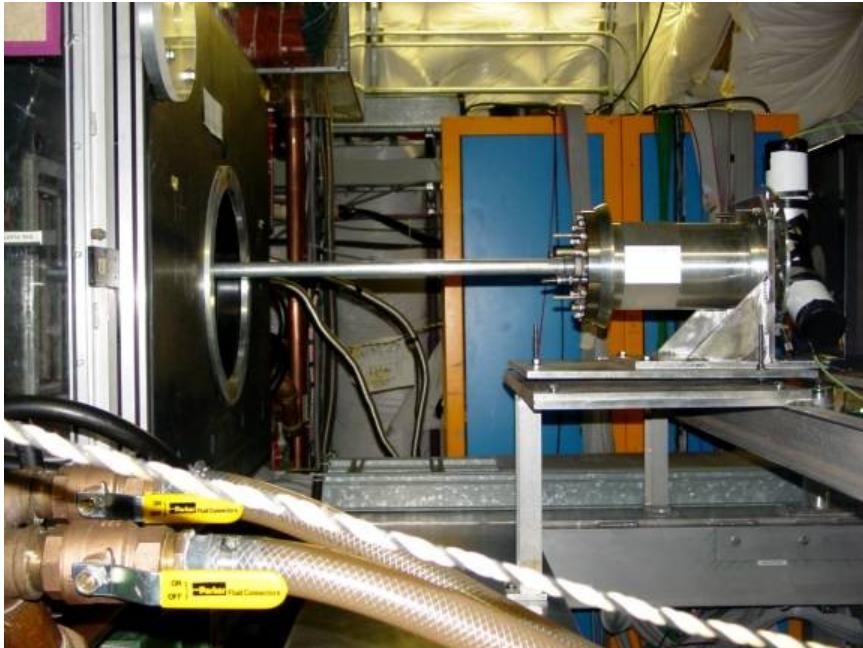


- Five PhD's awarded
 - Ratio of Pion Kaon Production in Proton Carbon Interactions (A. Lebedev, Harvard)
 - Measurement of Pi-K Ratios from the NuMI Target (S. Seun, Harvard)
 - Measurement of the Charged Kaon Mass with the MIPP RICH (N. Graf, Indiana) (published)
 - Charged pion production cross section using 120 GeV/c proton beam on carbon target (G. Aydin, Iowa)
 - Cross section measurements in the Main Injector Particle Production (FNAL-E907) experiment at 58 GeV/c (Y. Gunaydin, Iowa)
- Publications
 - Kaon mass: NIM A631 (Mar. 2010)
 - Calorimeter performance: NIM A598 (Jan. 2009)
- Today
 - NuMI target particle yields
 - Forward neutron production cross sections
- Soon
 - A lot more cross sections
 - Other analyses are progressing, even if I do not report on them today.

NuMI target data analysis

The NuMI target measurement

2 interaction length

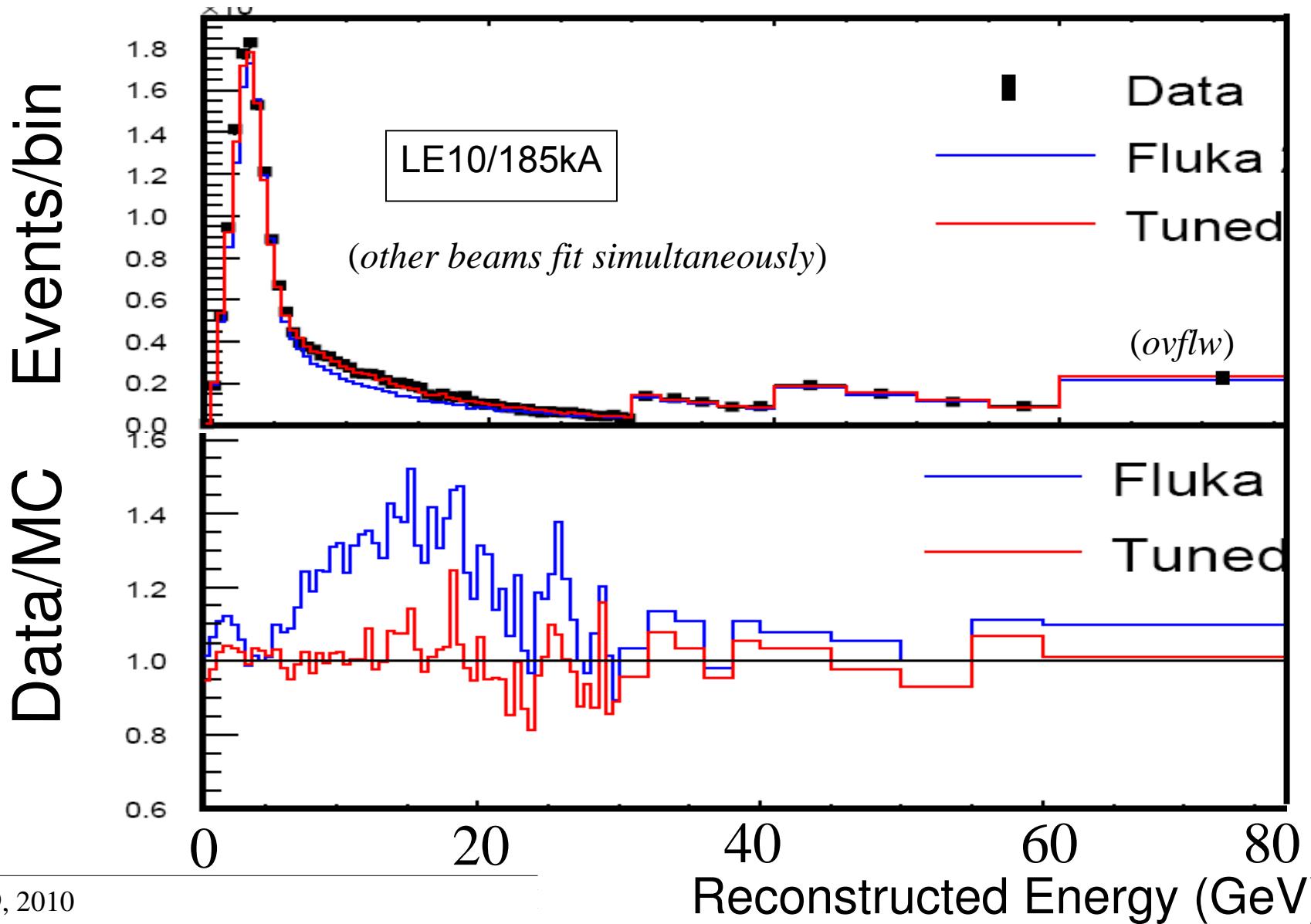


- NuMI analysis goal:
 - provide particle spectra from direct measurement to reduce systematic uncertainty in ND/FD ratio of neutrino spectra.

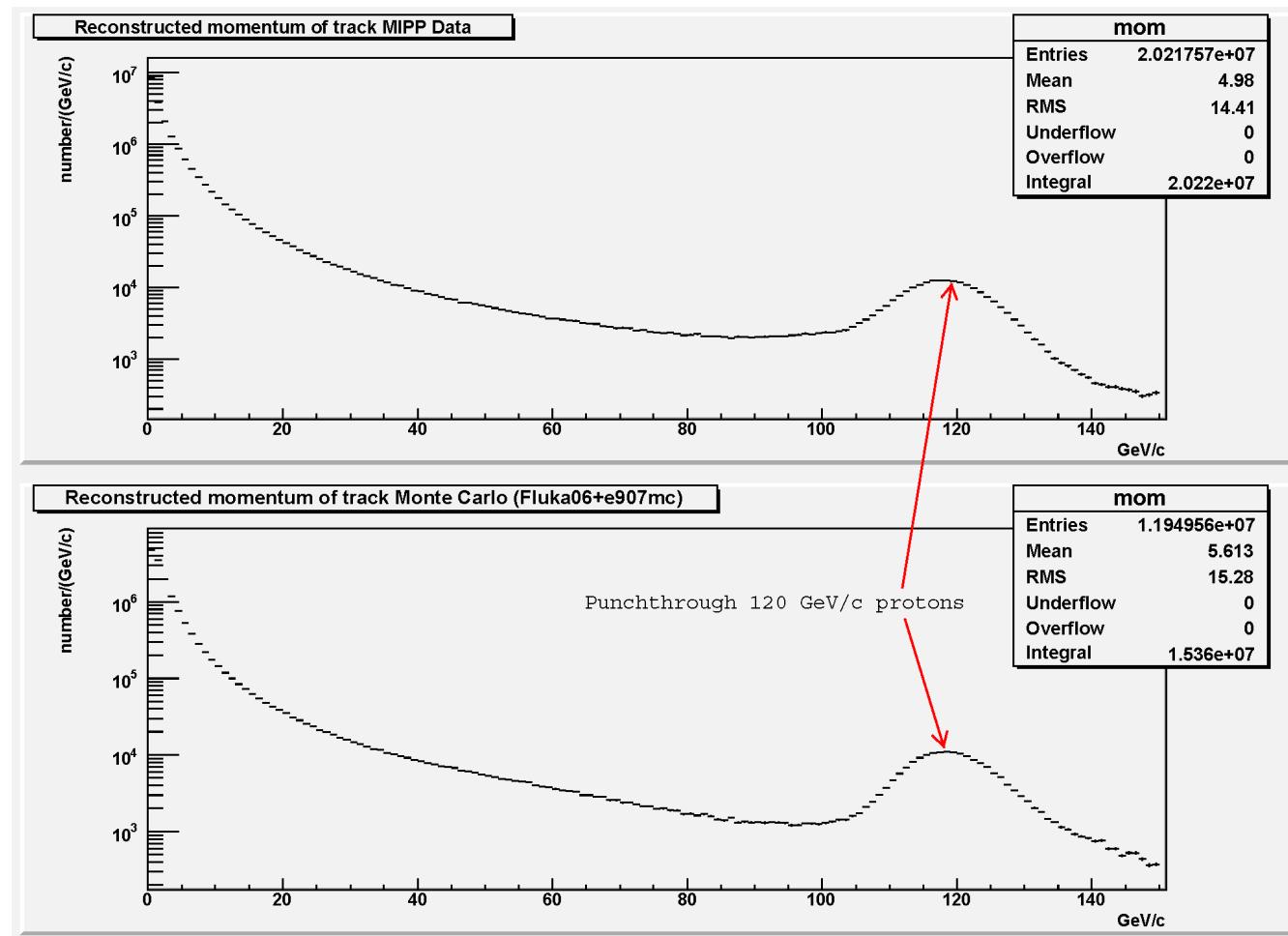
MINOS beam problem (from S. Kopp)

- To get red points, MINOS assumed they know the νN cross section for $E_\nu < 10$ GeV. Somewhat circular argument. We need flux to measure νN cross section, instead we use an assumed cross section to determine flux.

First principles flux measurement will get us out of this loop.



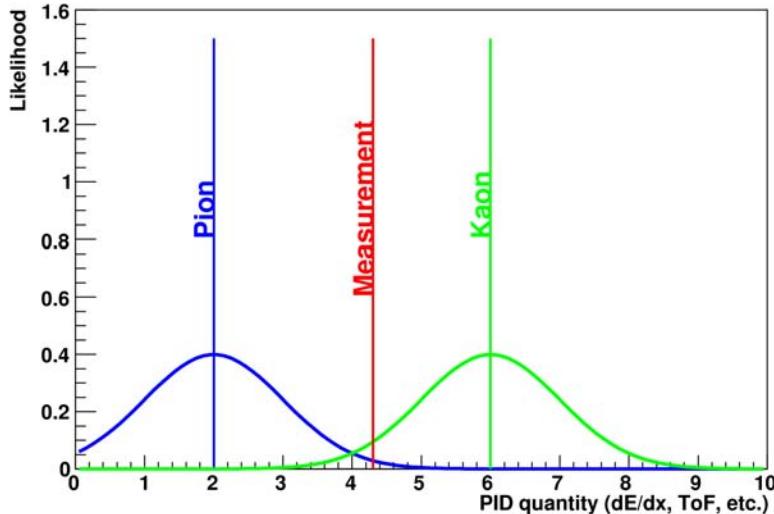
Momentum Spectra from NuMI target – Data and MC



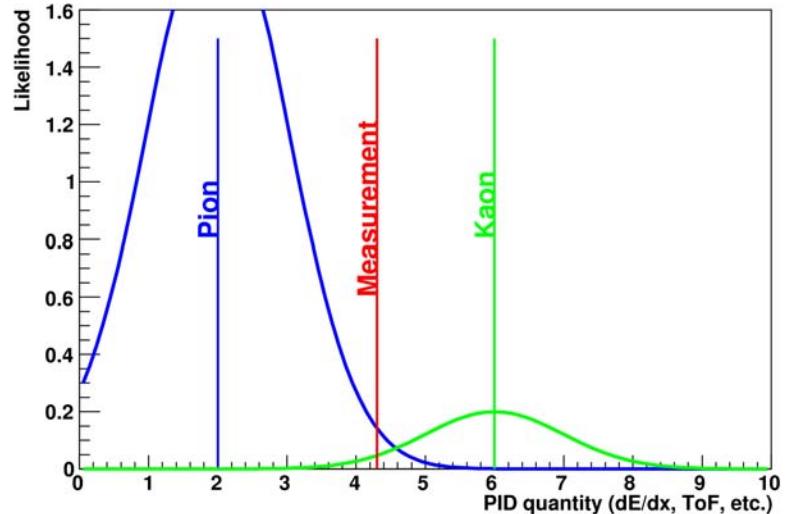
Global PID algorithm – Need for Priors

- We consider 4 hypotheses for particle id
 - Electron, pion, kaon, and proton (denoted by H)
 - Initially we do not distinguish by charge since none of the pid measurements (dE/dx , ToF, Ckov, RICH; denoted by x) depend on the charge of the particle.
- We employ the maximum likelihood technique to determine the spectra of each particle type in data. However, the likelihood that a measurement is that of (e.g.) a pion or kaon depends not only on the individual measurement but also on the total number of pions and kaons in the sample.

No Priors: Kaon hypothesis more likely than pion



Priors: Pions more abundant than kaons, hence pion more likely



Bayes' theorem – Global PID formalism

- The joint probability $P(H, x)$ can be written as ($H = e, \pi, K, p$; $x = dE/dx, \text{ToF}, r_{\text{RICH}}, \dots$)

$$P(H, x) = P(x|H)P(H)$$

where $P(H)$ is the probability of a particular hypothesis. This is what we are trying to determine. These equations are for a given momentum. We have suppressed the momentum dependence for simplicity.

- By Bayes' theorem

$$P(H, x) = P(H|x)P(x)$$

- This leads to

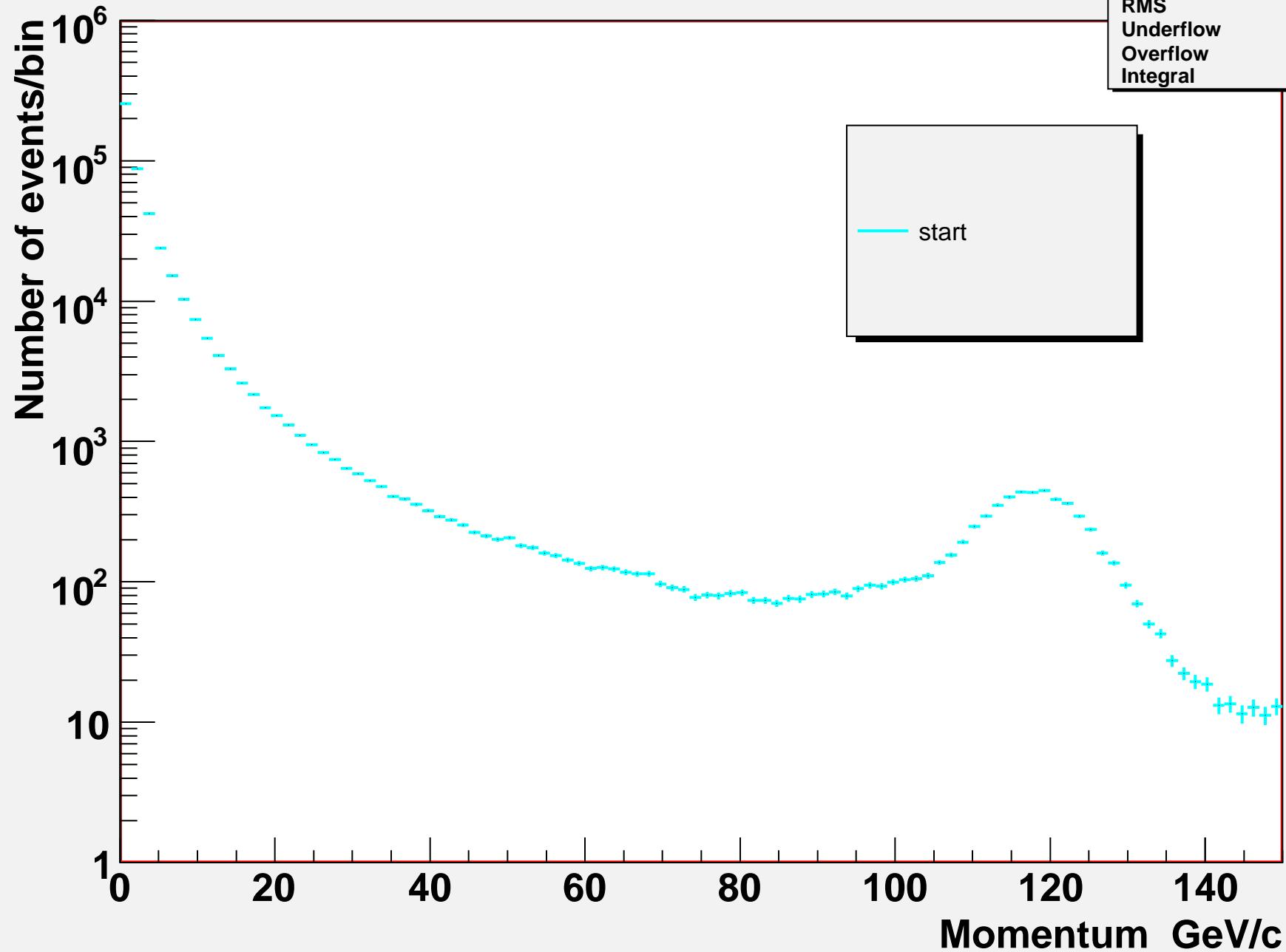
$$P(H|x) = \frac{P(x|H)P(H)}{\sum_H P(x|H)P(H)}$$

- We determine $P(H)$ iteratively. Assume that all hypotheses are equally likely initially, i.e. $P(H) = 1/4$ since there are 4 hypotheses ($e/\pi/K/p$). For each track, we then determine the posterior probability $P(H|x)$ which is used to weight the track for each hypothesis.

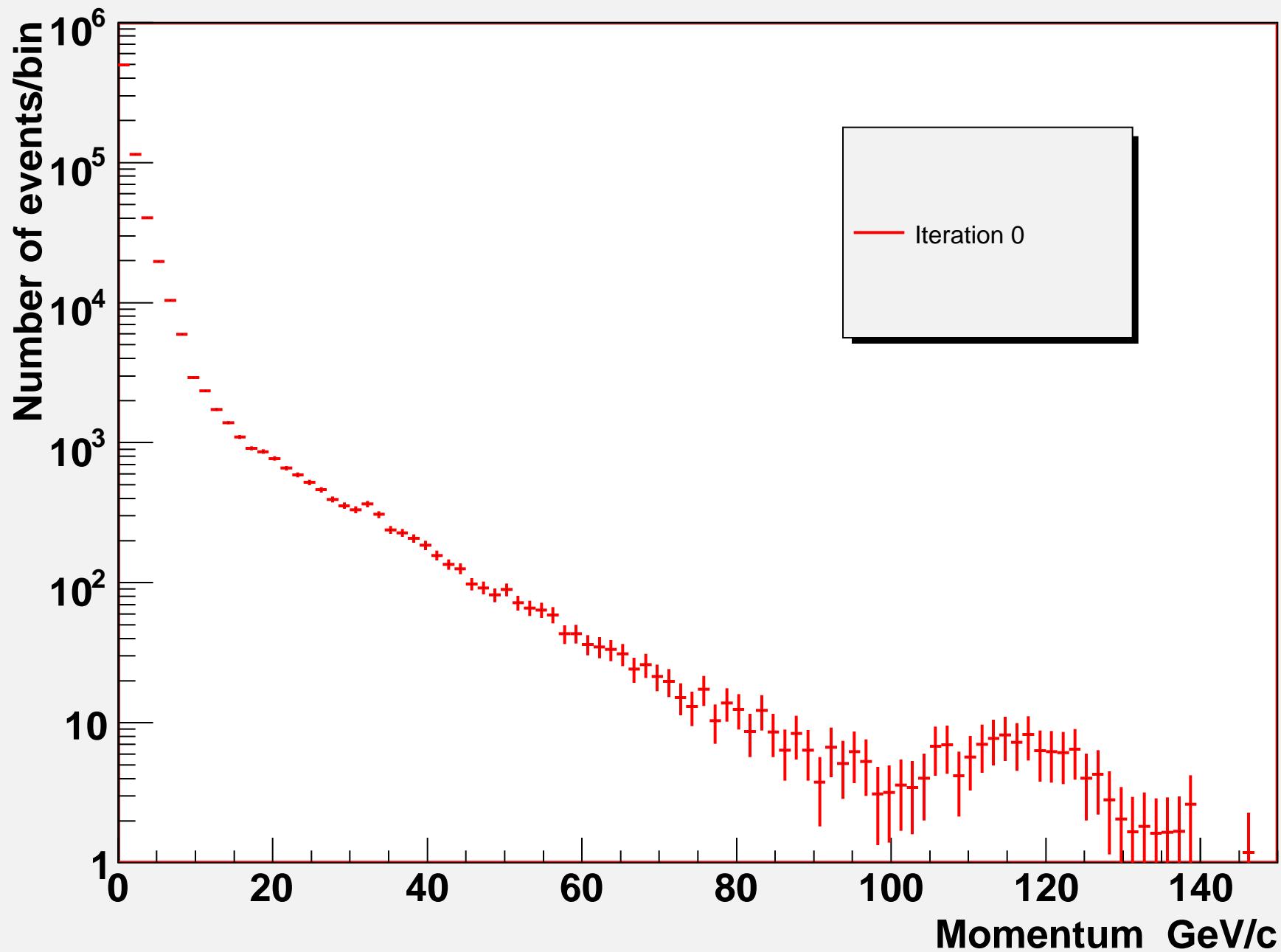
$$\sum_H P(H|x) = 1 \quad \text{preserves unitarity}$$

- The resulting $P(H)$ is used for the next iteration, till convergence.
- The aim is not to determine whether each particle is definitely one type or the other but to determine the maximum likelihood momentum functions for each hypothesis. Each particle enters all hypotheses plots with its appropriate hypothesis dependent weight.
- We treat MC and data as two separate experiments, each with slightly different behavior. We test the algorithm on the MC, since we know the answer. – (Movie)

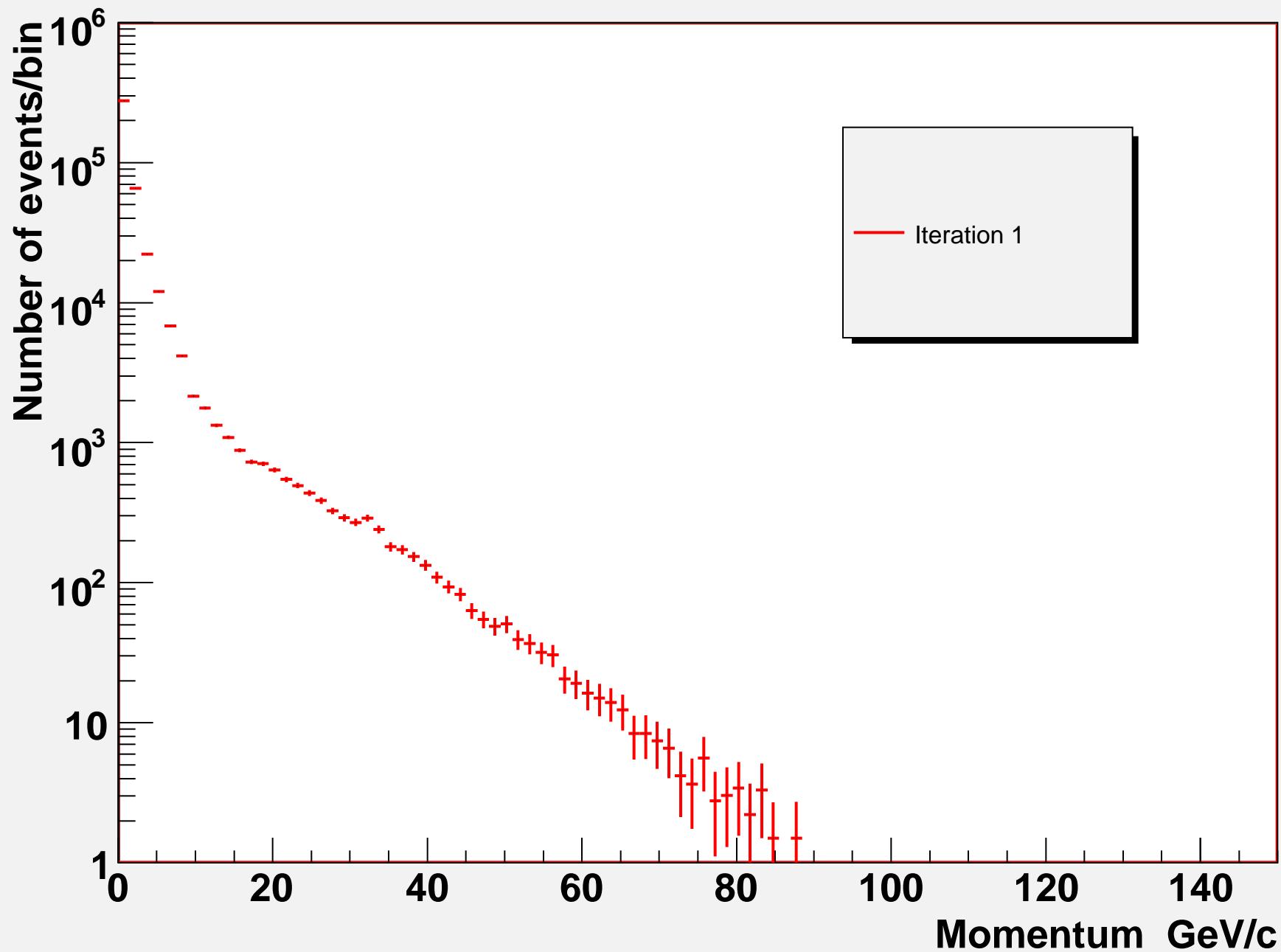
Momentum Distribution of Electrons



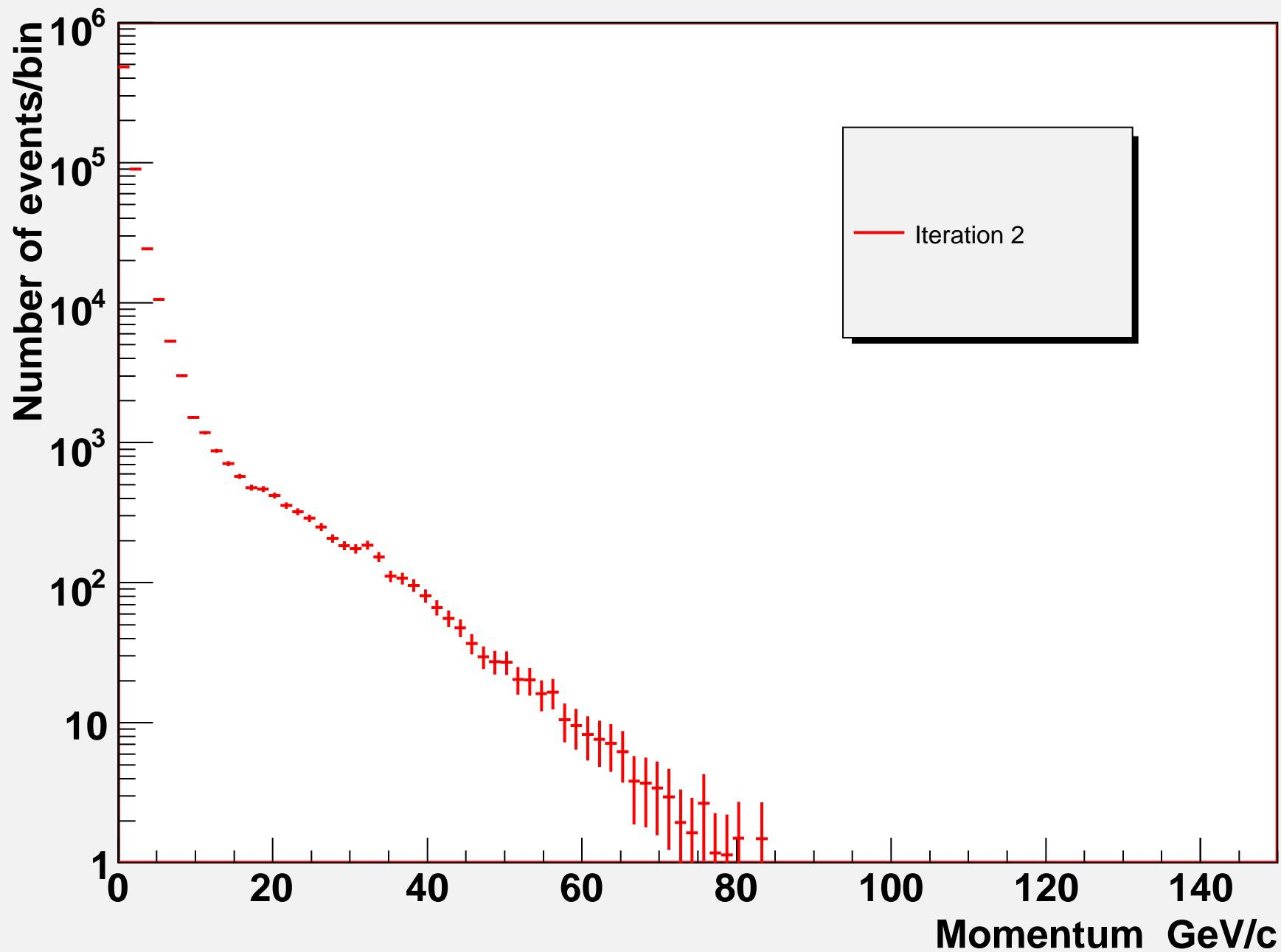
Momentum Distribution of Electrons



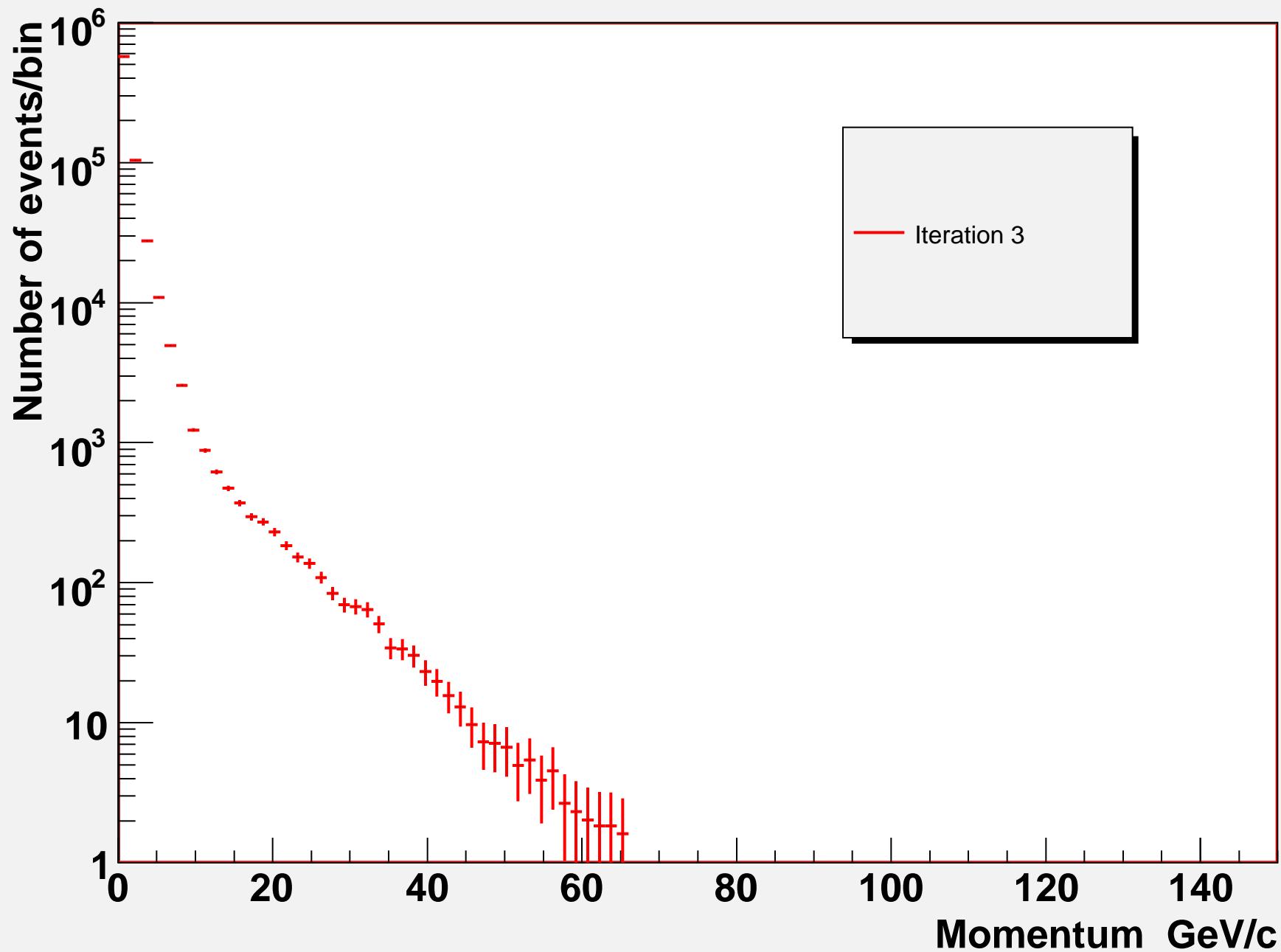
Momentum Distribution of Electrons



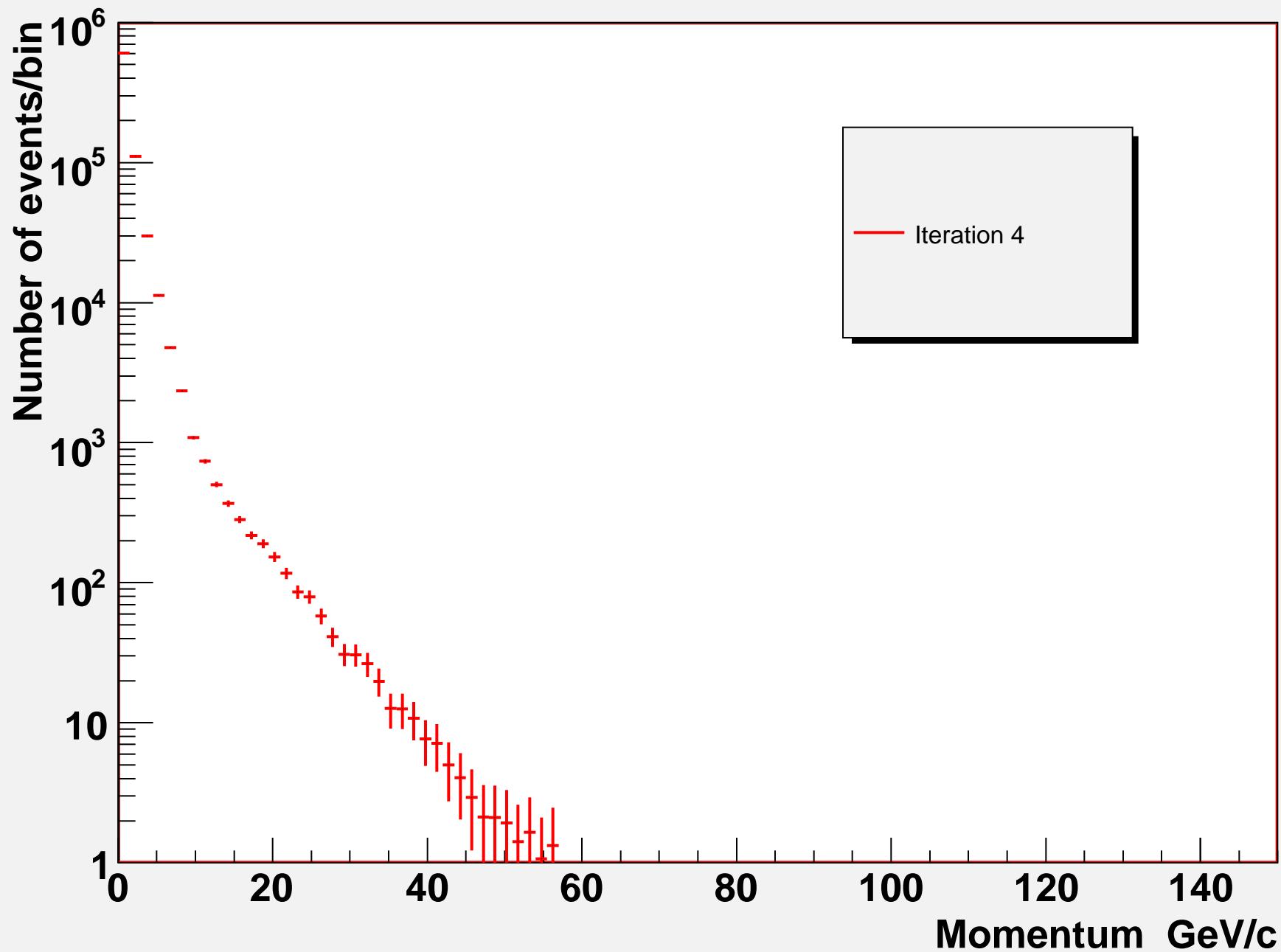
Momentum Distribution of Electrons



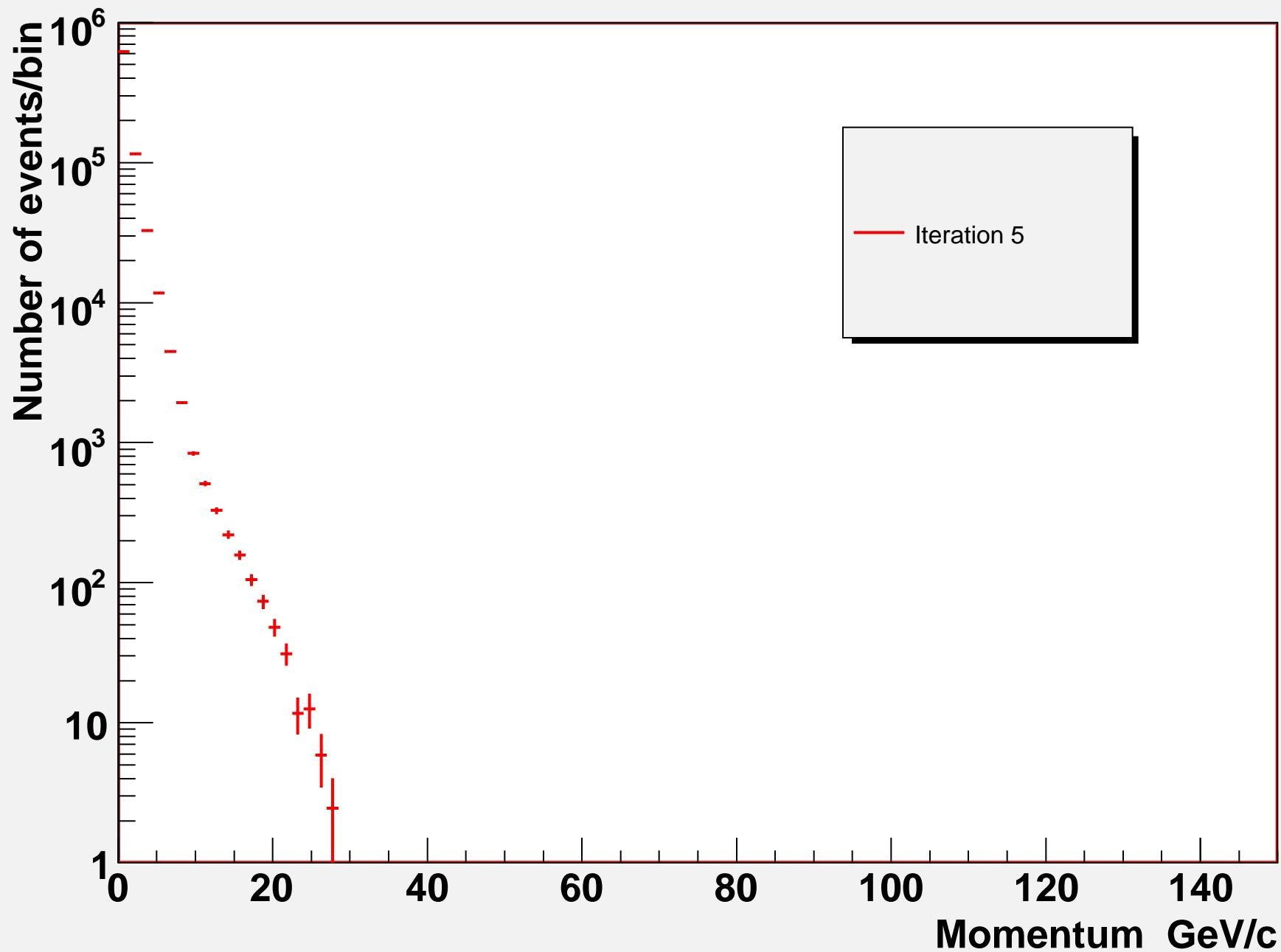
Momentum Distribution of Electrons



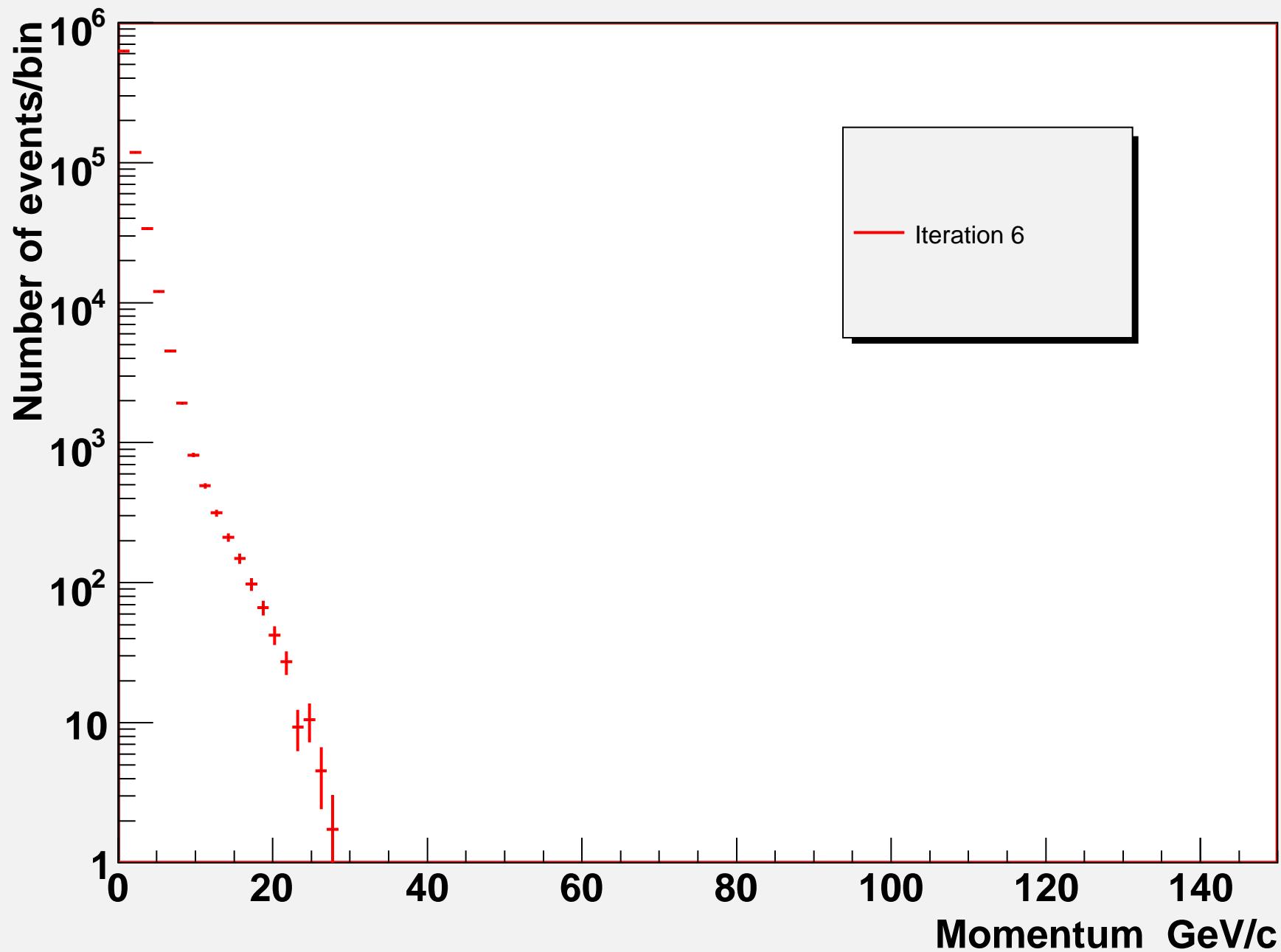
Momentum Distribution of Electrons



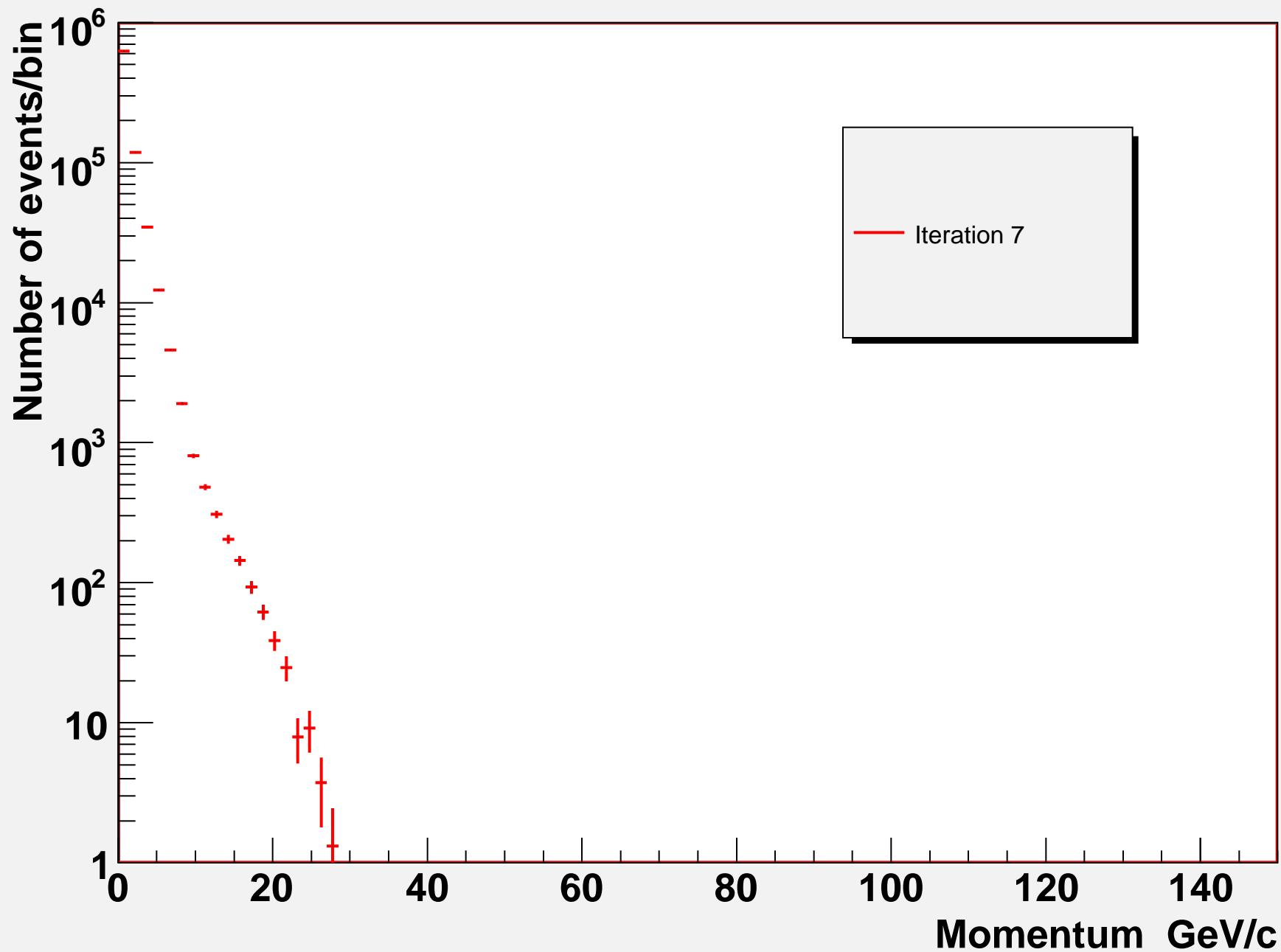
Momentum Distribution of Electrons



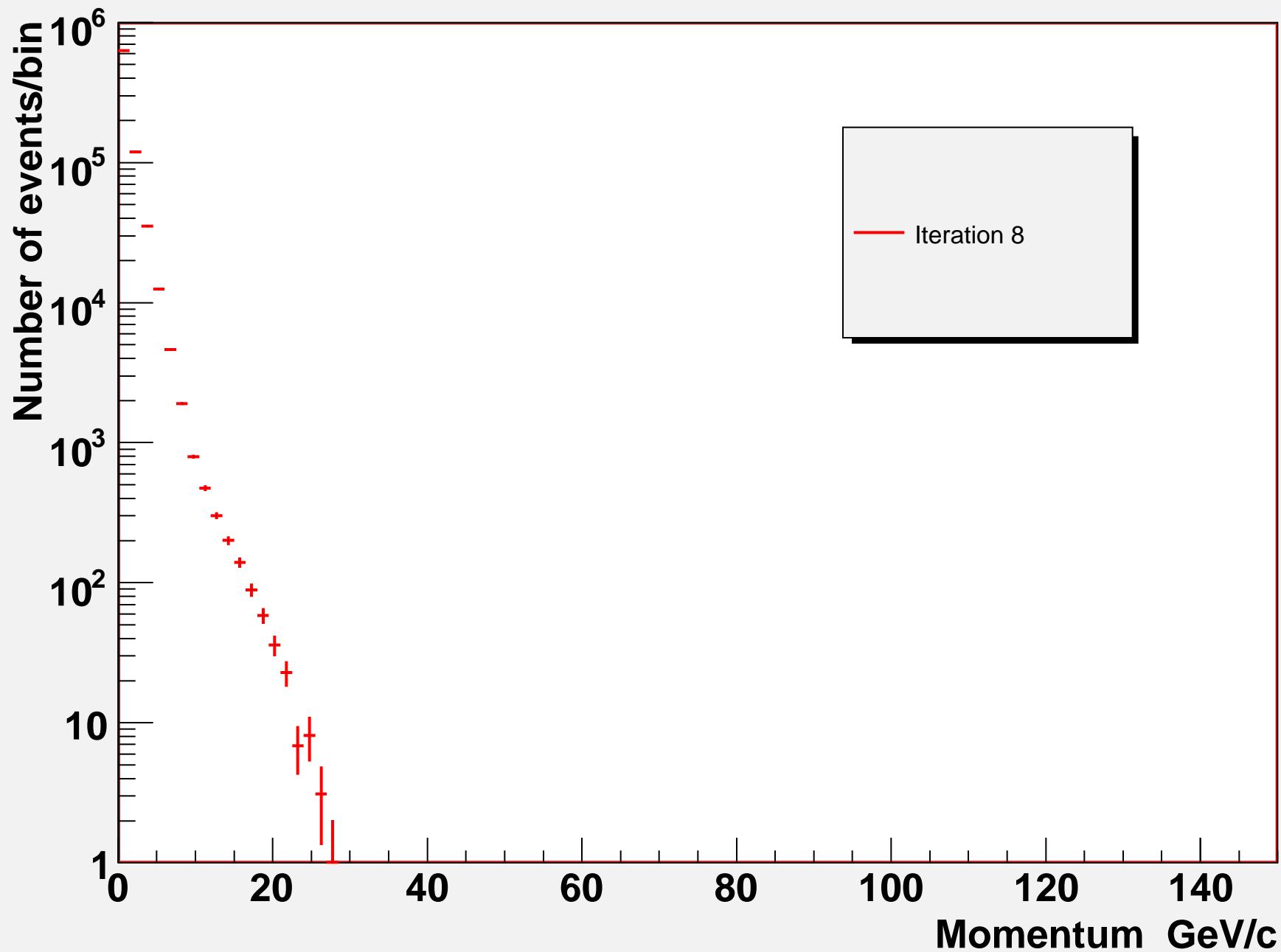
Momentum Distribution of Electrons



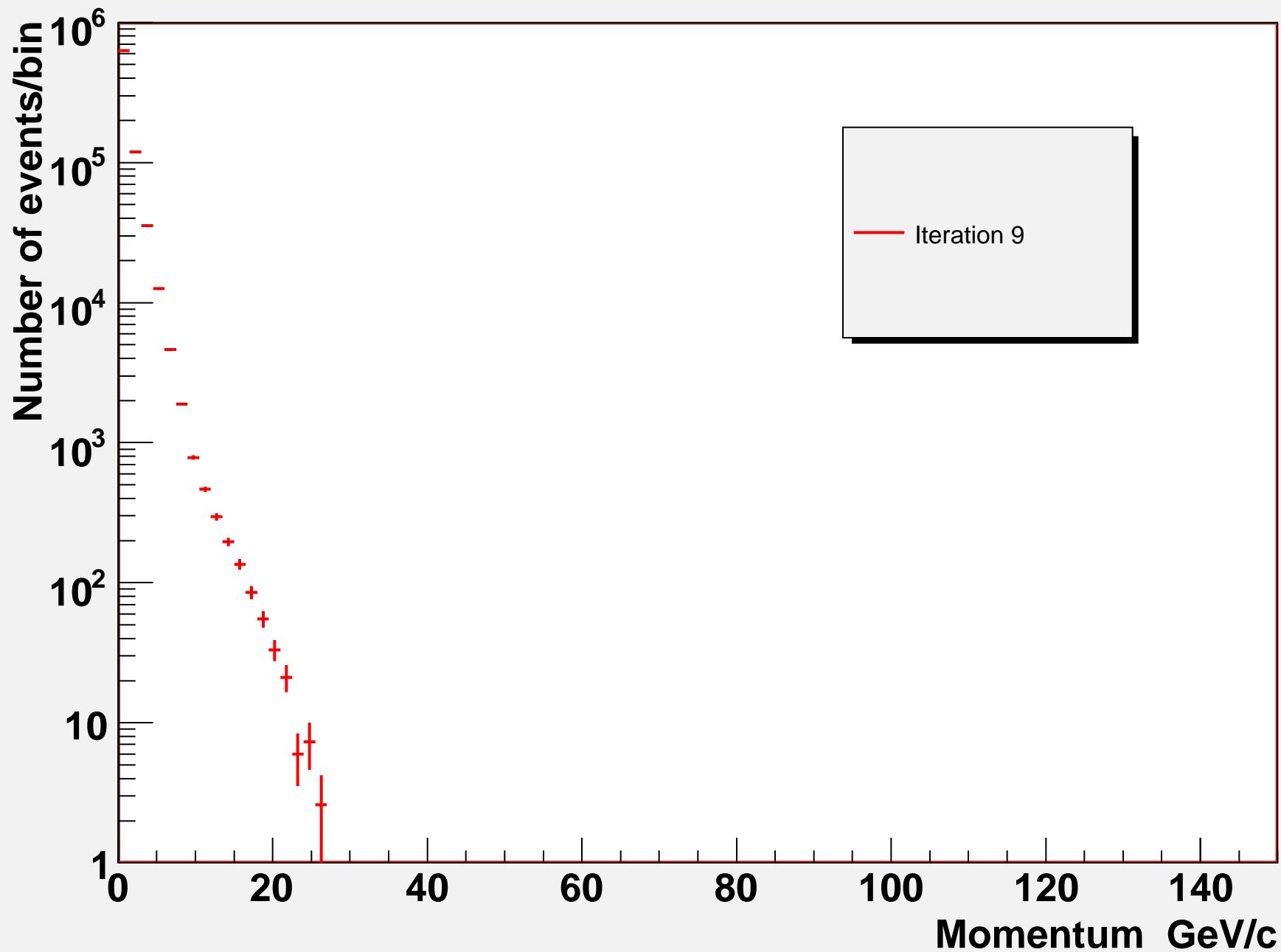
Momentum Distribution of Electrons



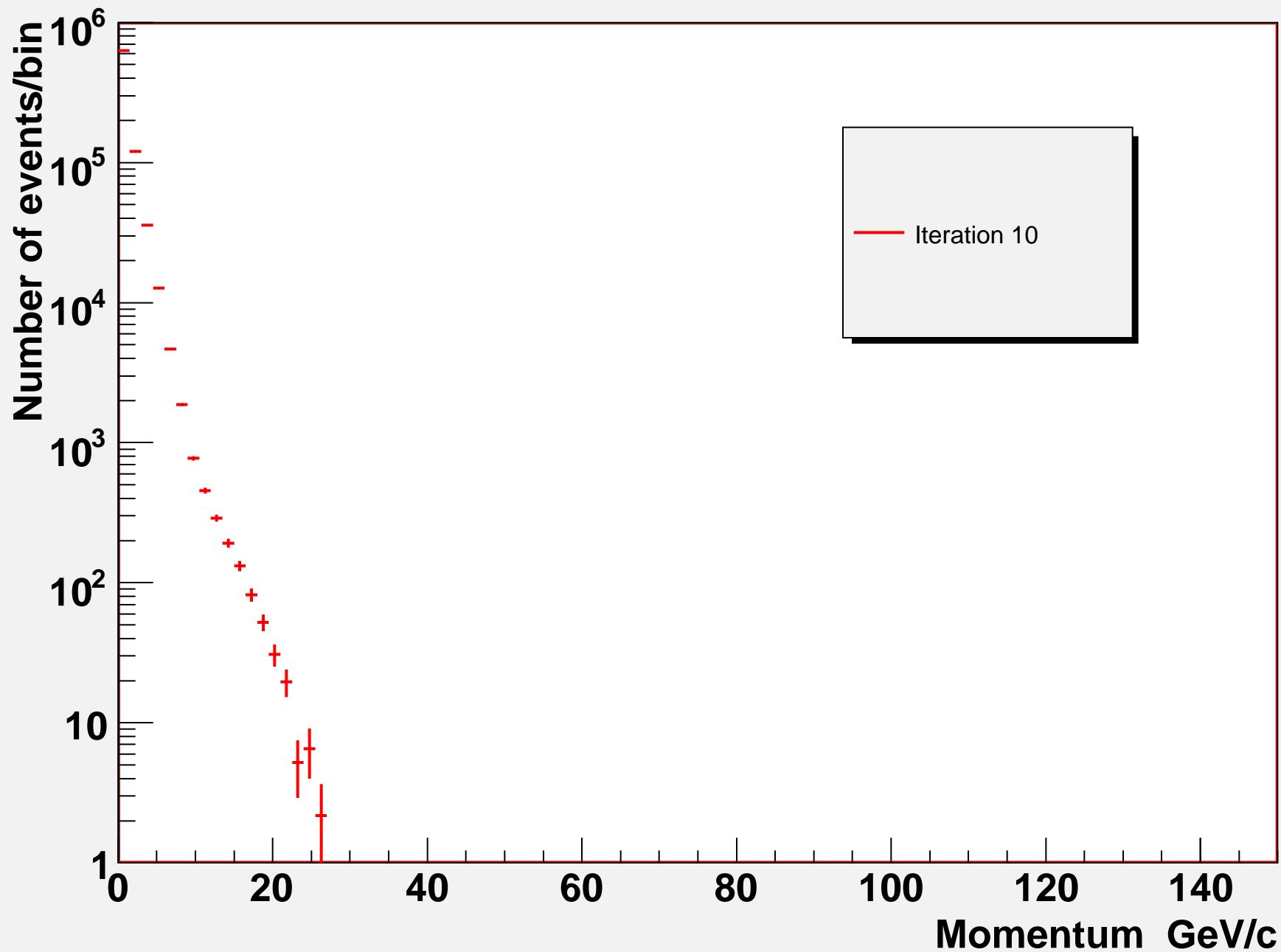
Momentum Distribution of Electrons



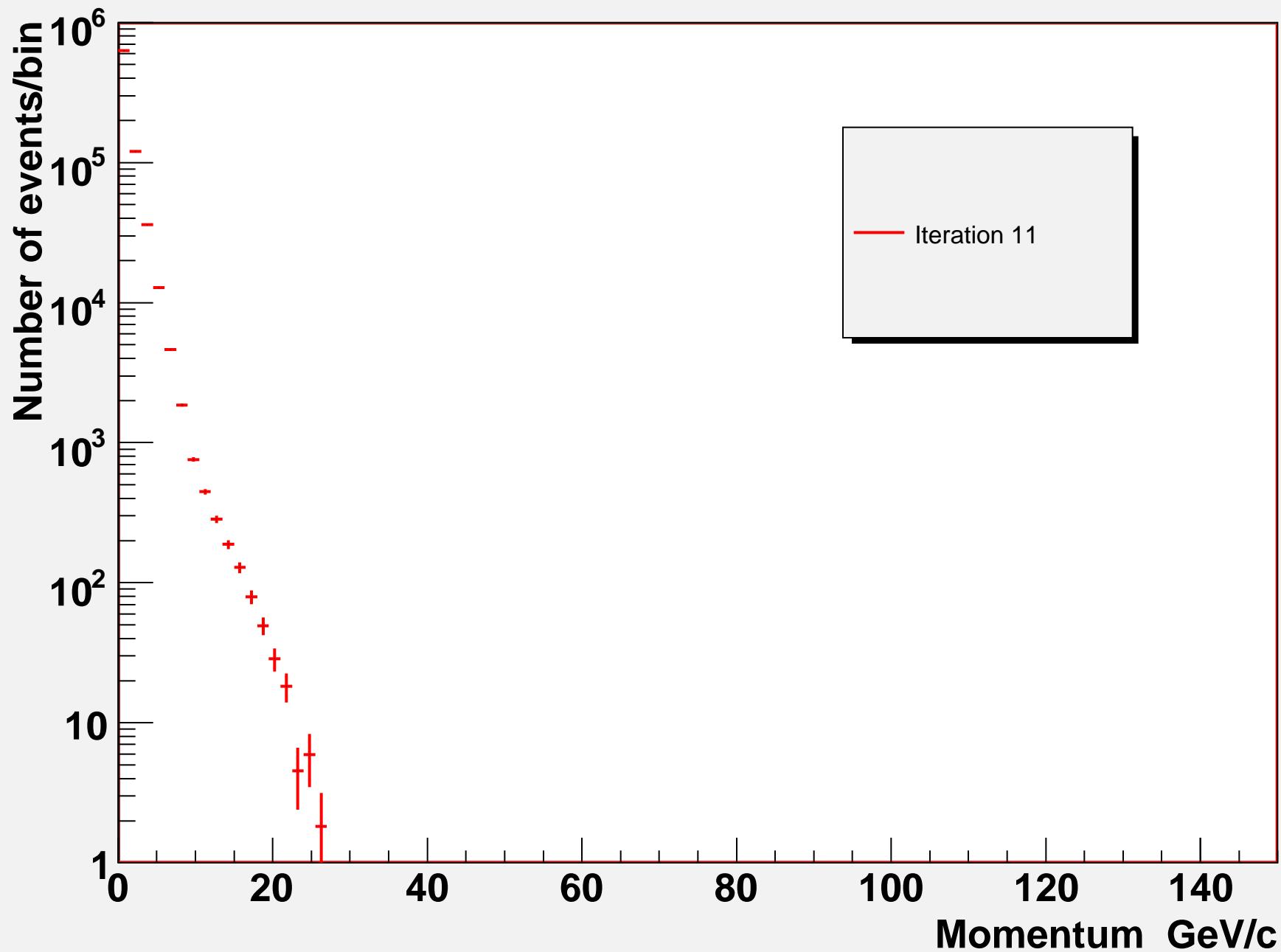
Momentum Distribution of Electrons



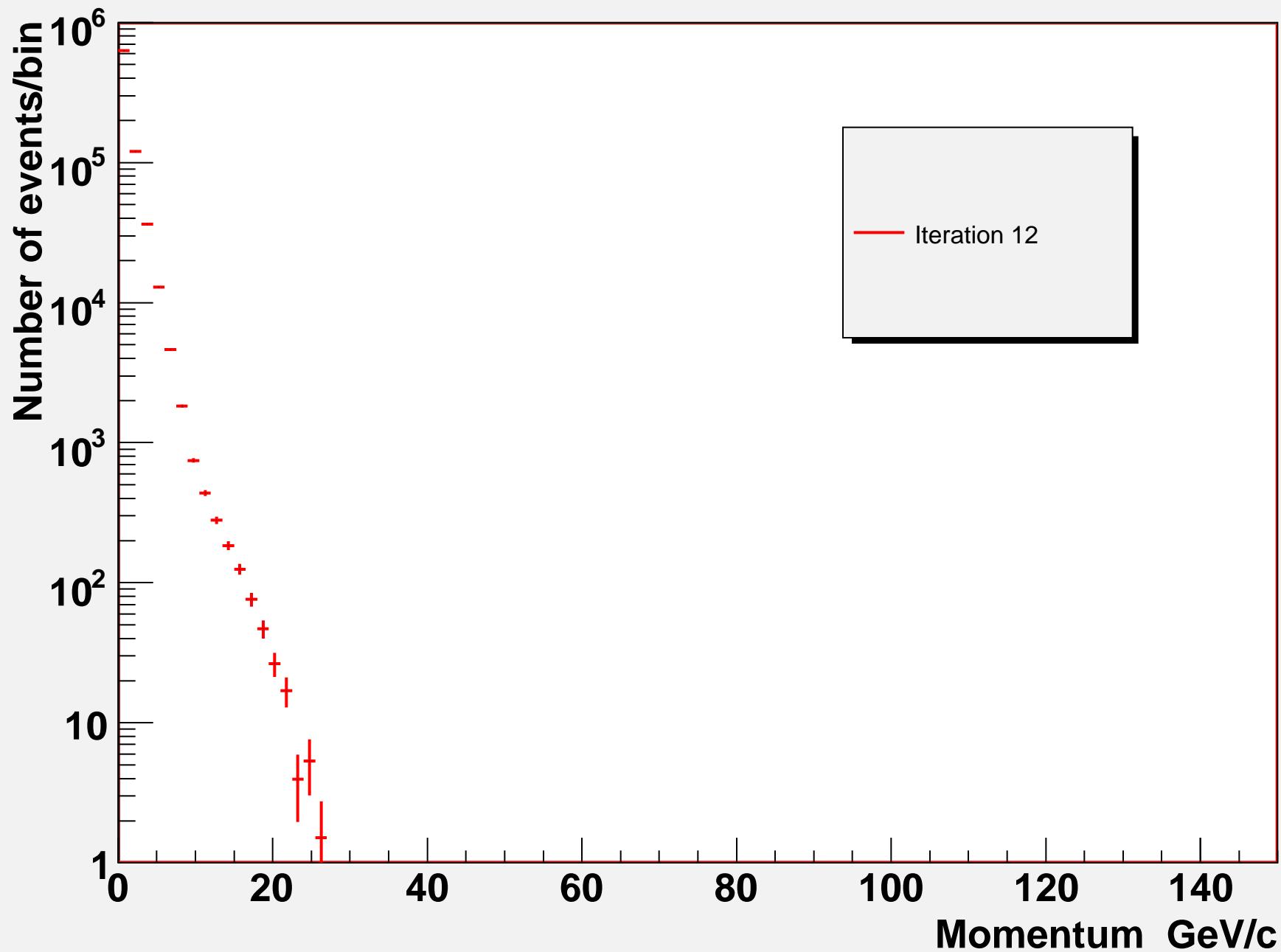
Momentum Distribution of Electrons



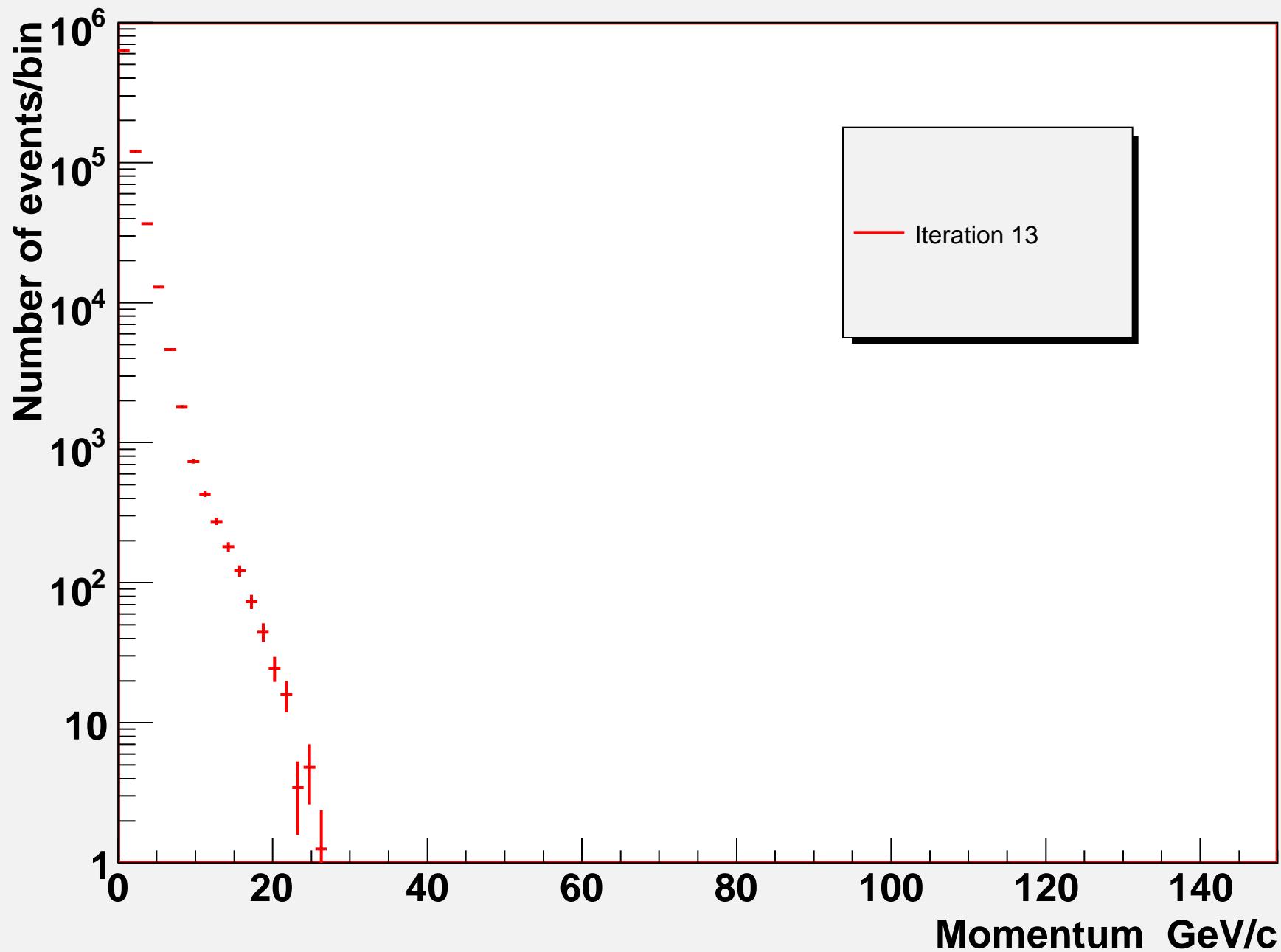
Momentum Distribution of Electrons



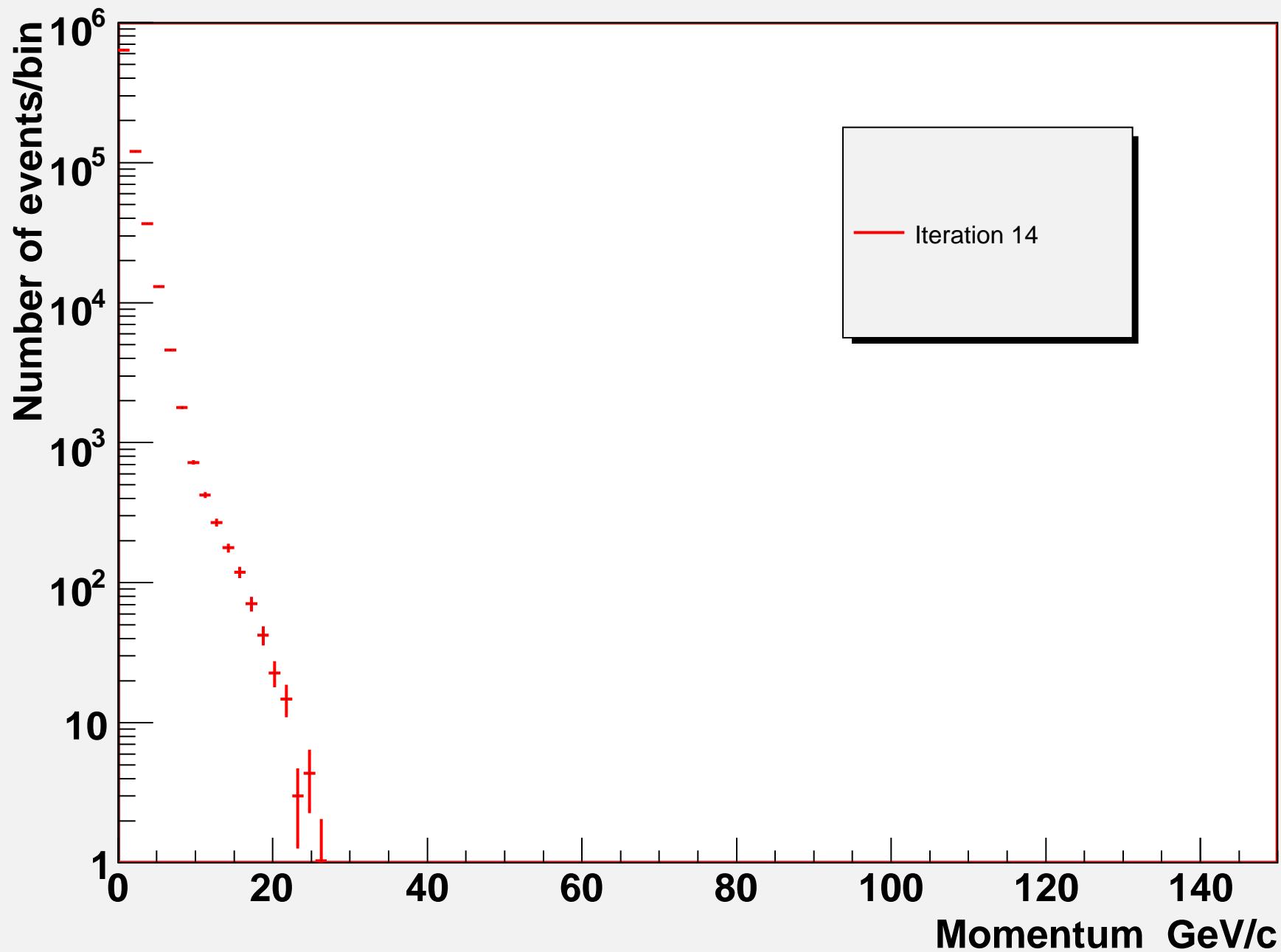
Momentum Distribution of Electrons



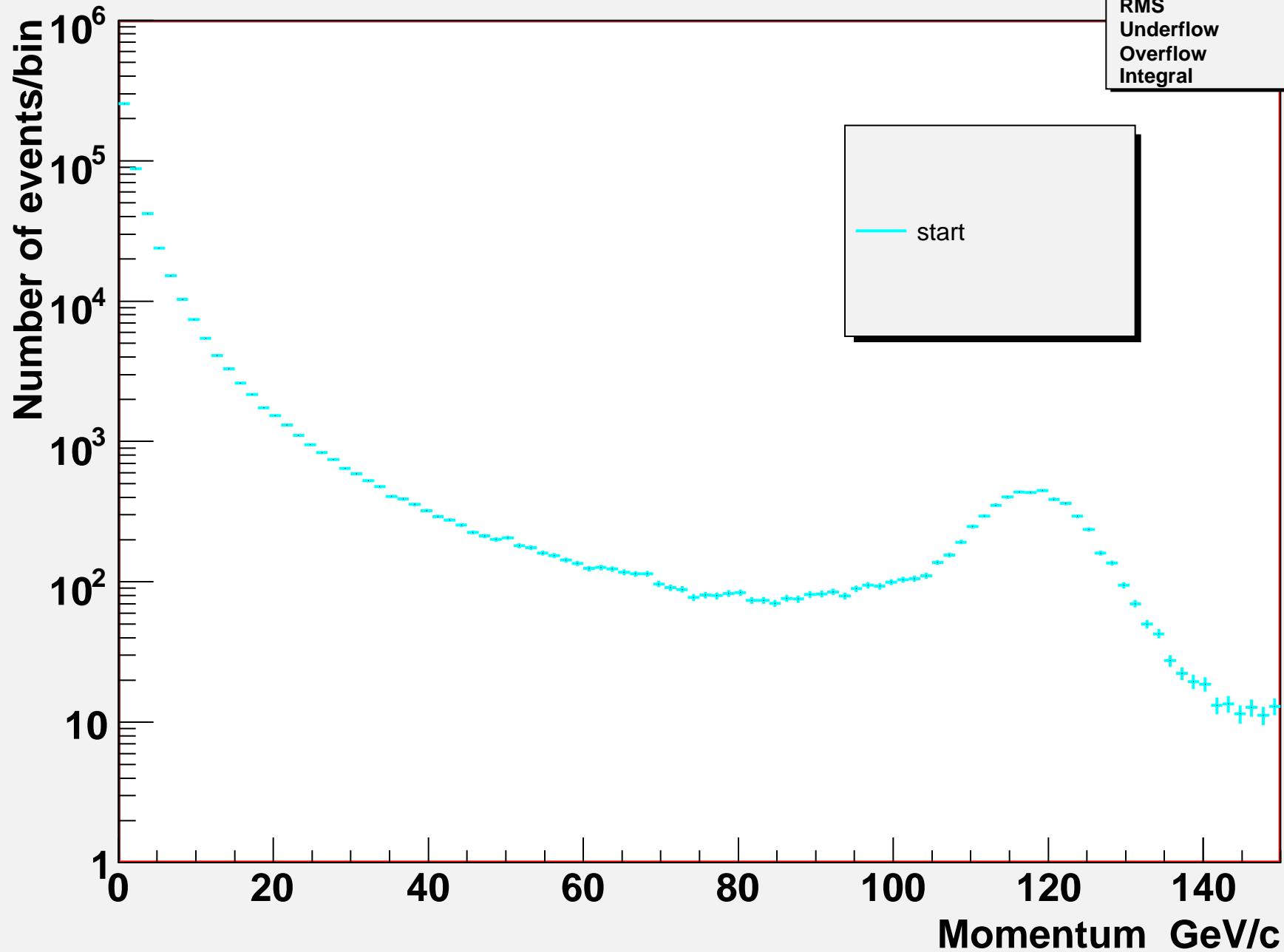
Momentum Distribution of Electrons



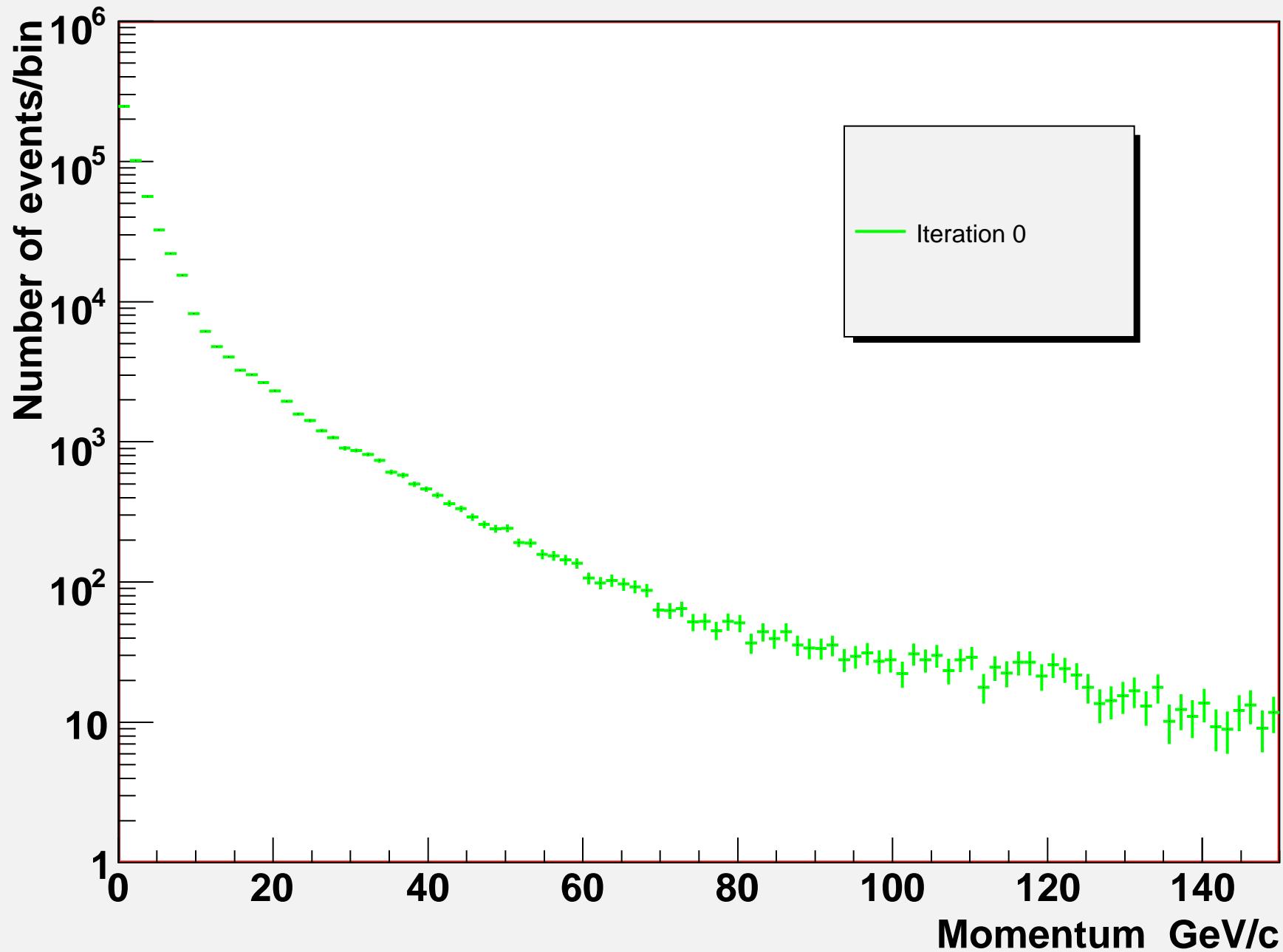
Momentum Distribution of Electrons



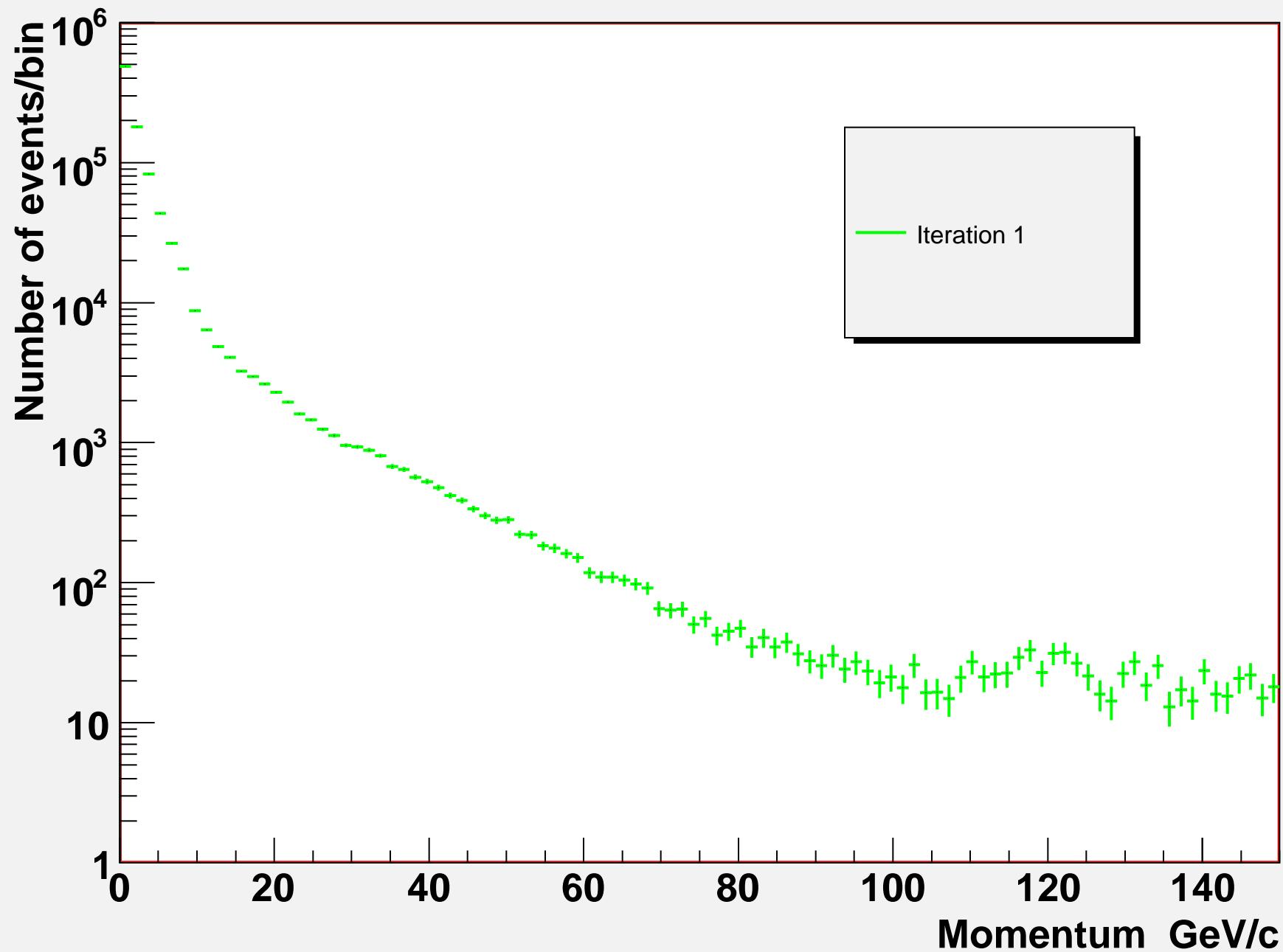
Momentum Distribution of Pions



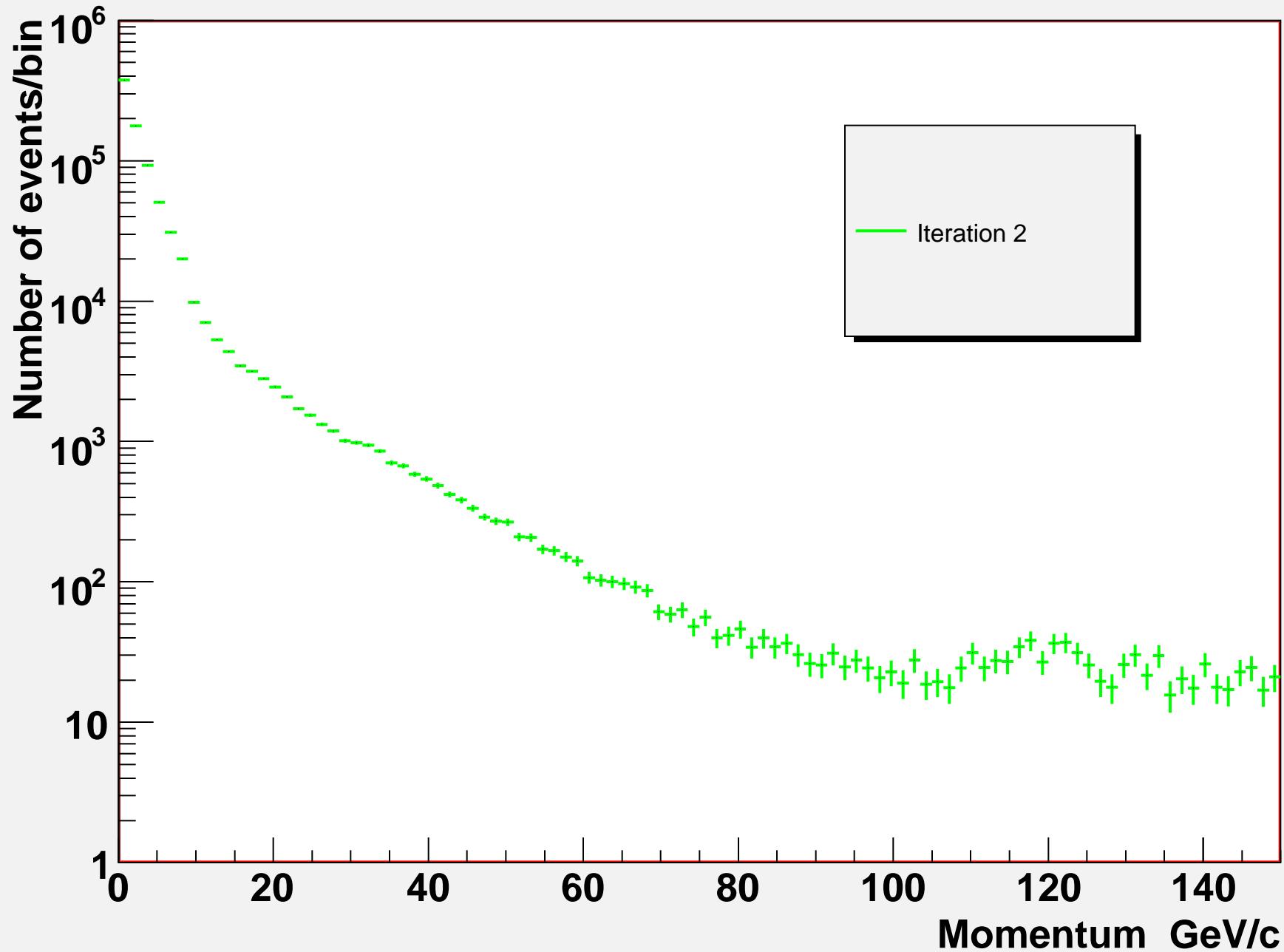
Momentum Distribution of Pions



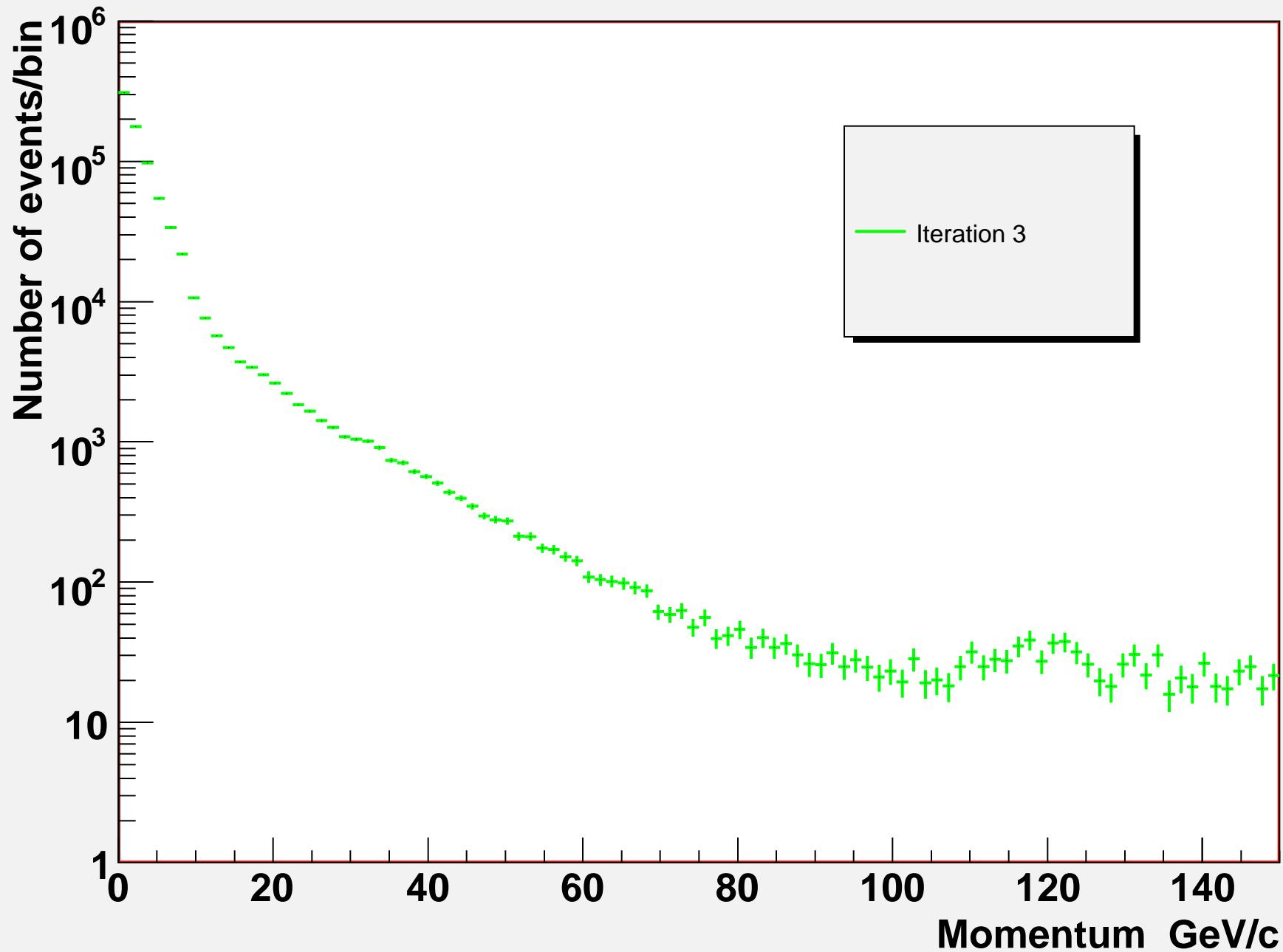
Momentum Distribution of Pions



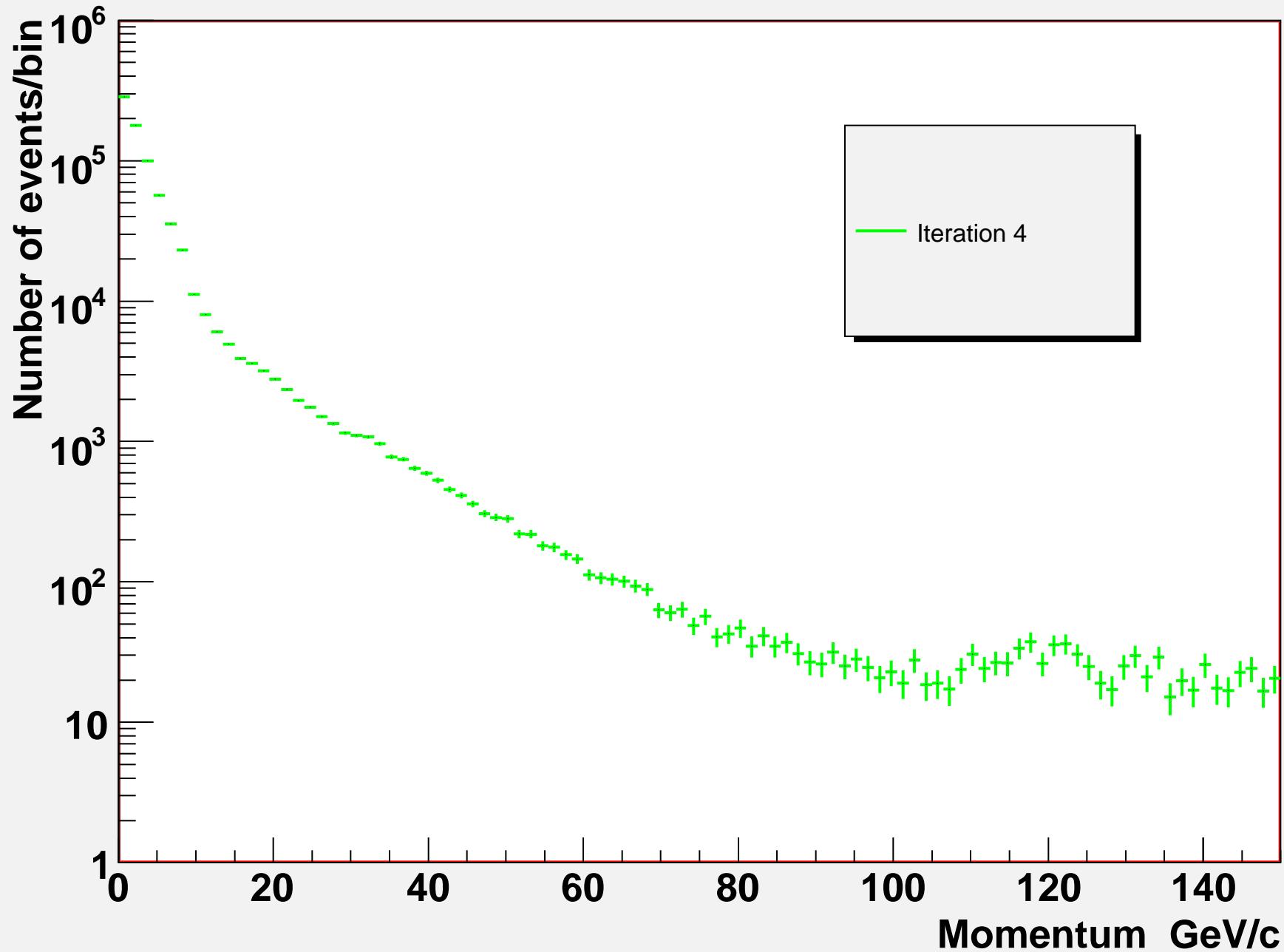
Momentum Distribution of Pions



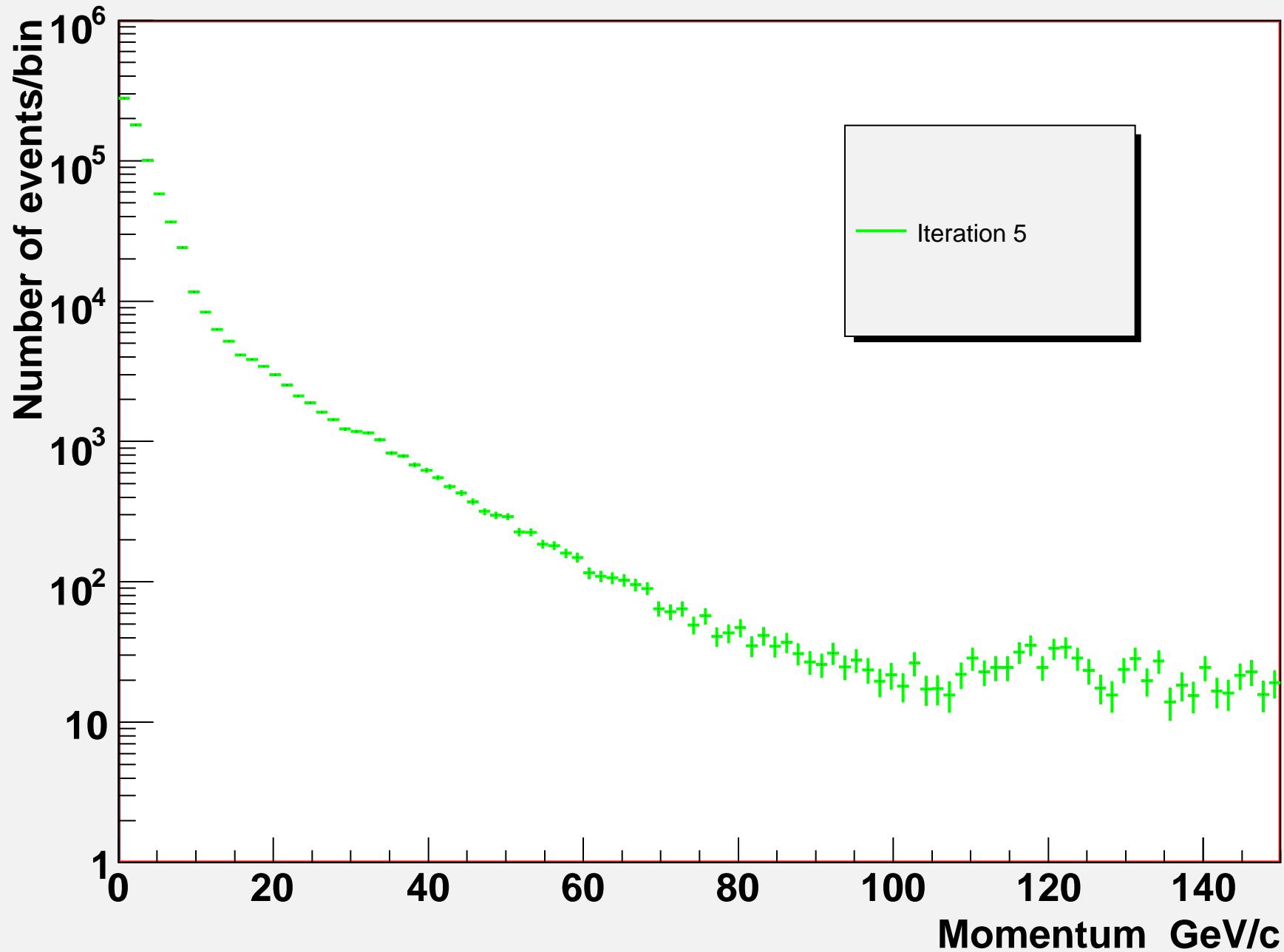
Momentum Distribution of Pions



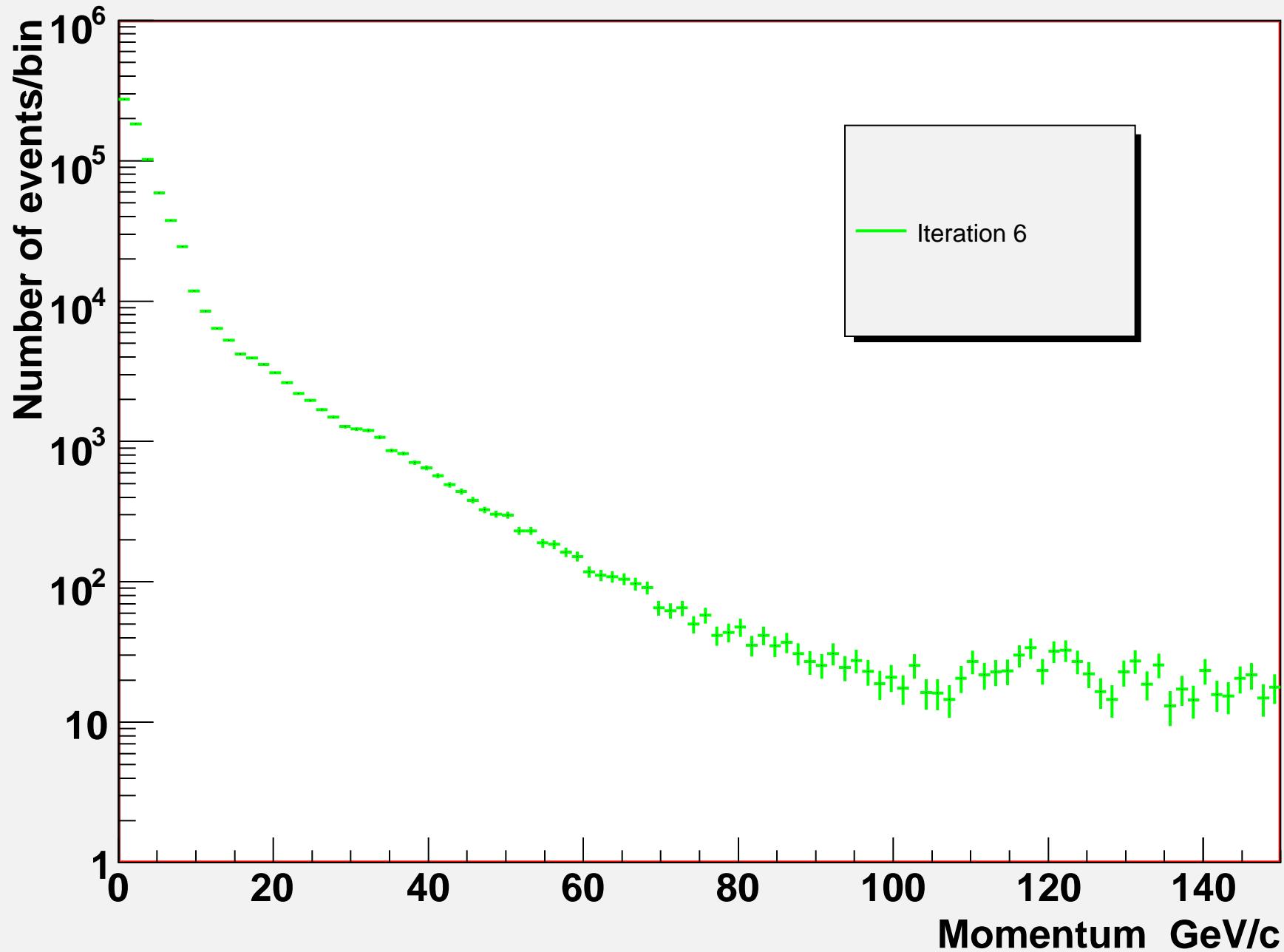
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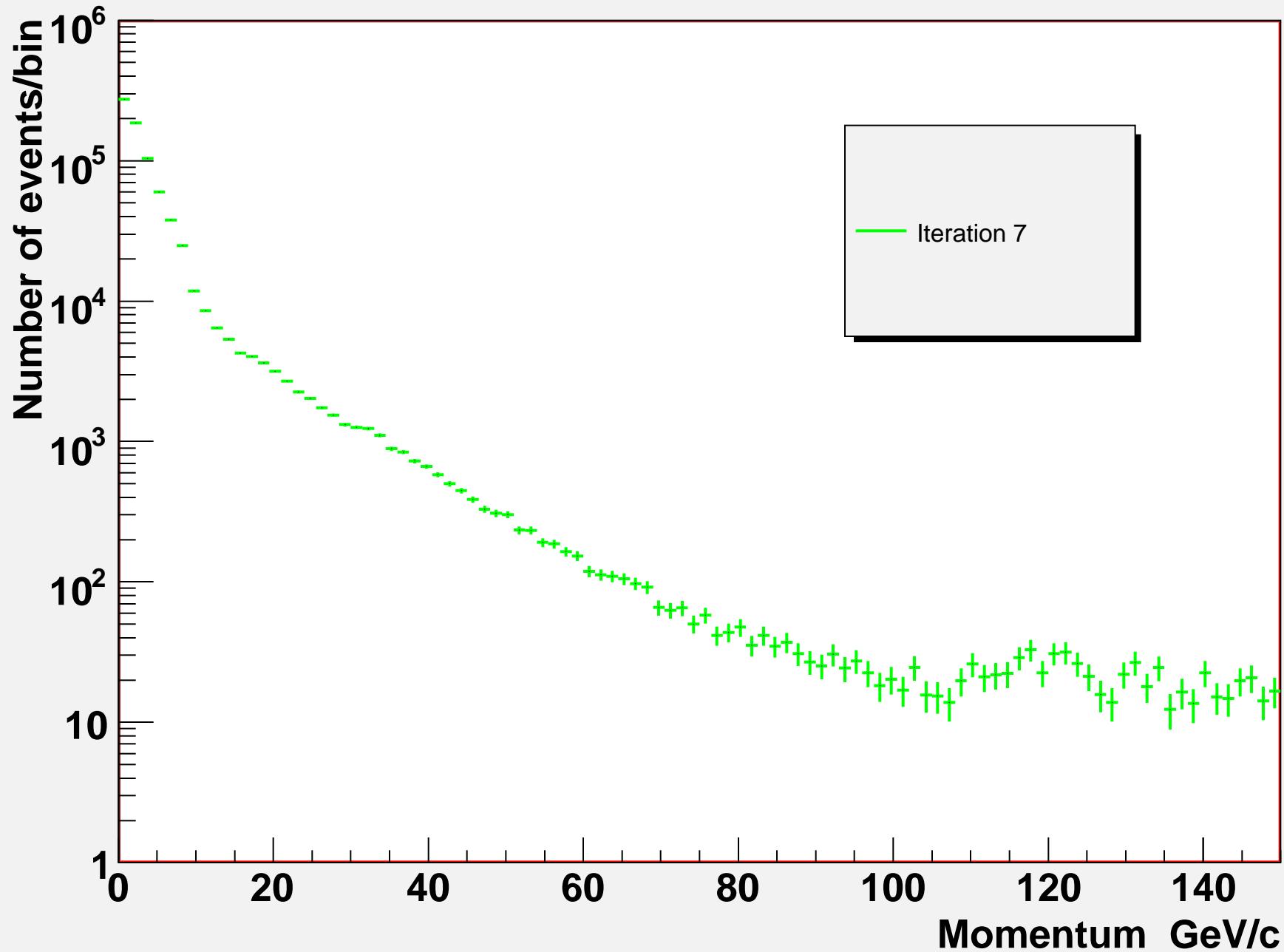
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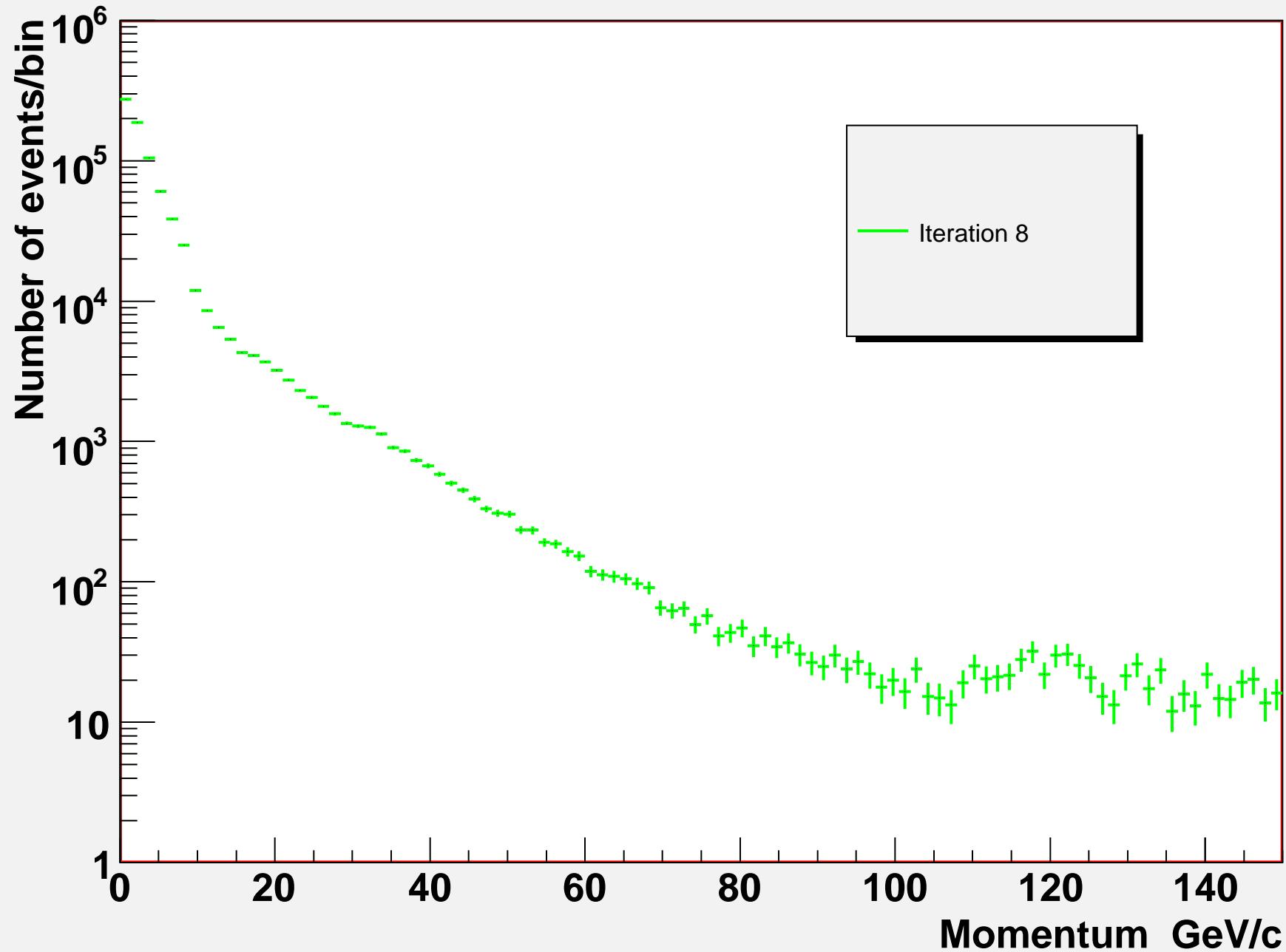
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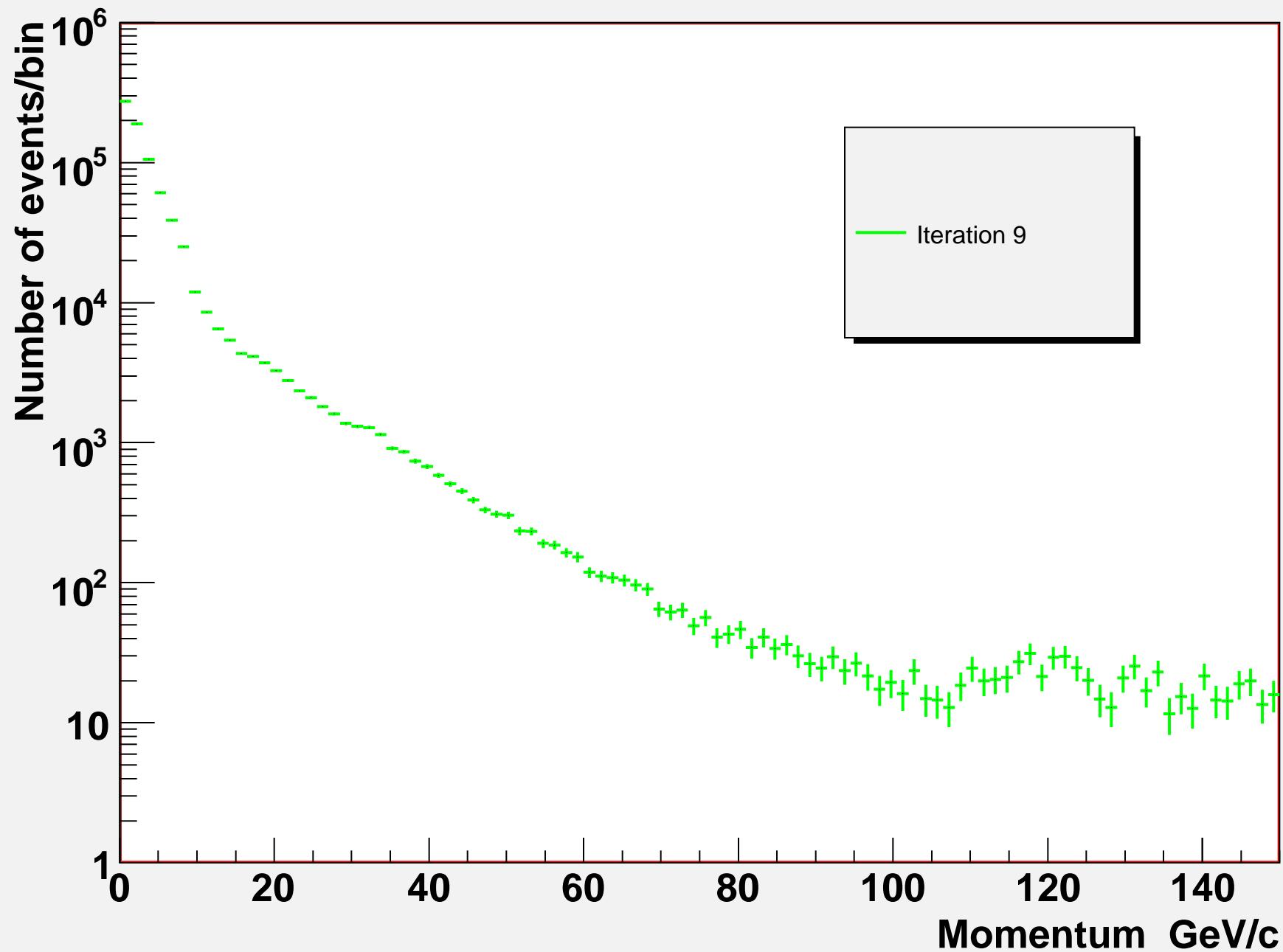
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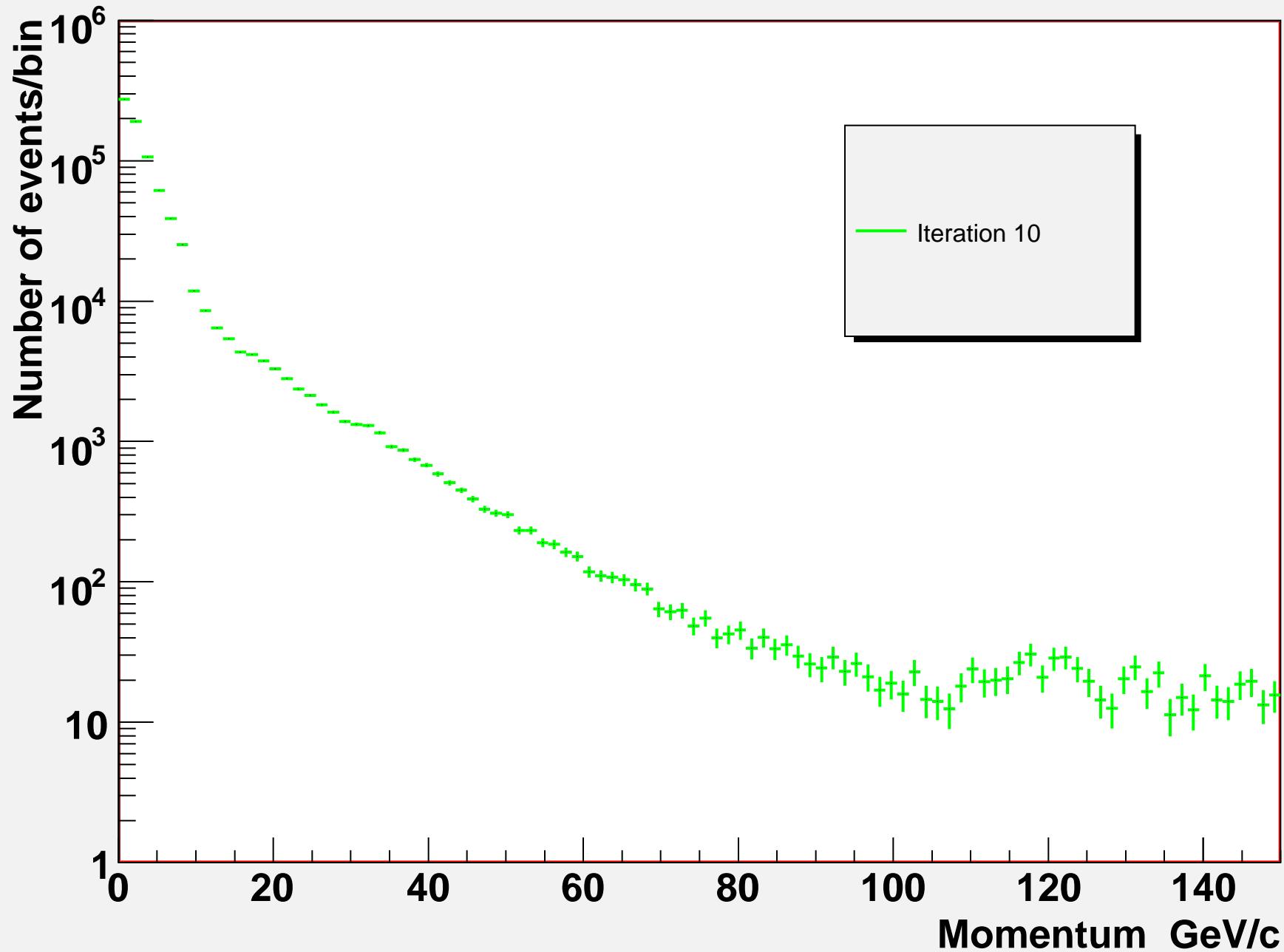
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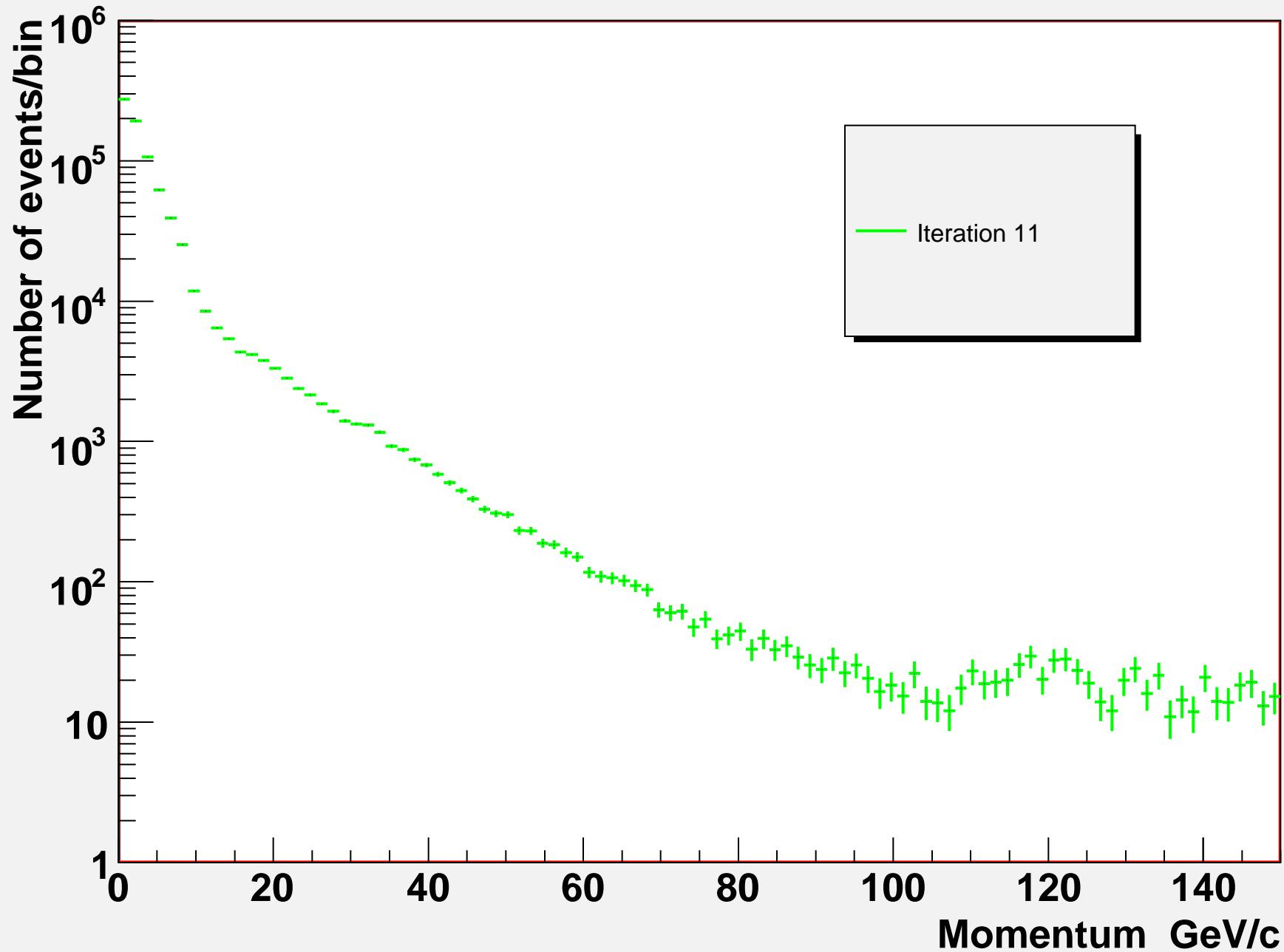
Momentum Distribution of Pions



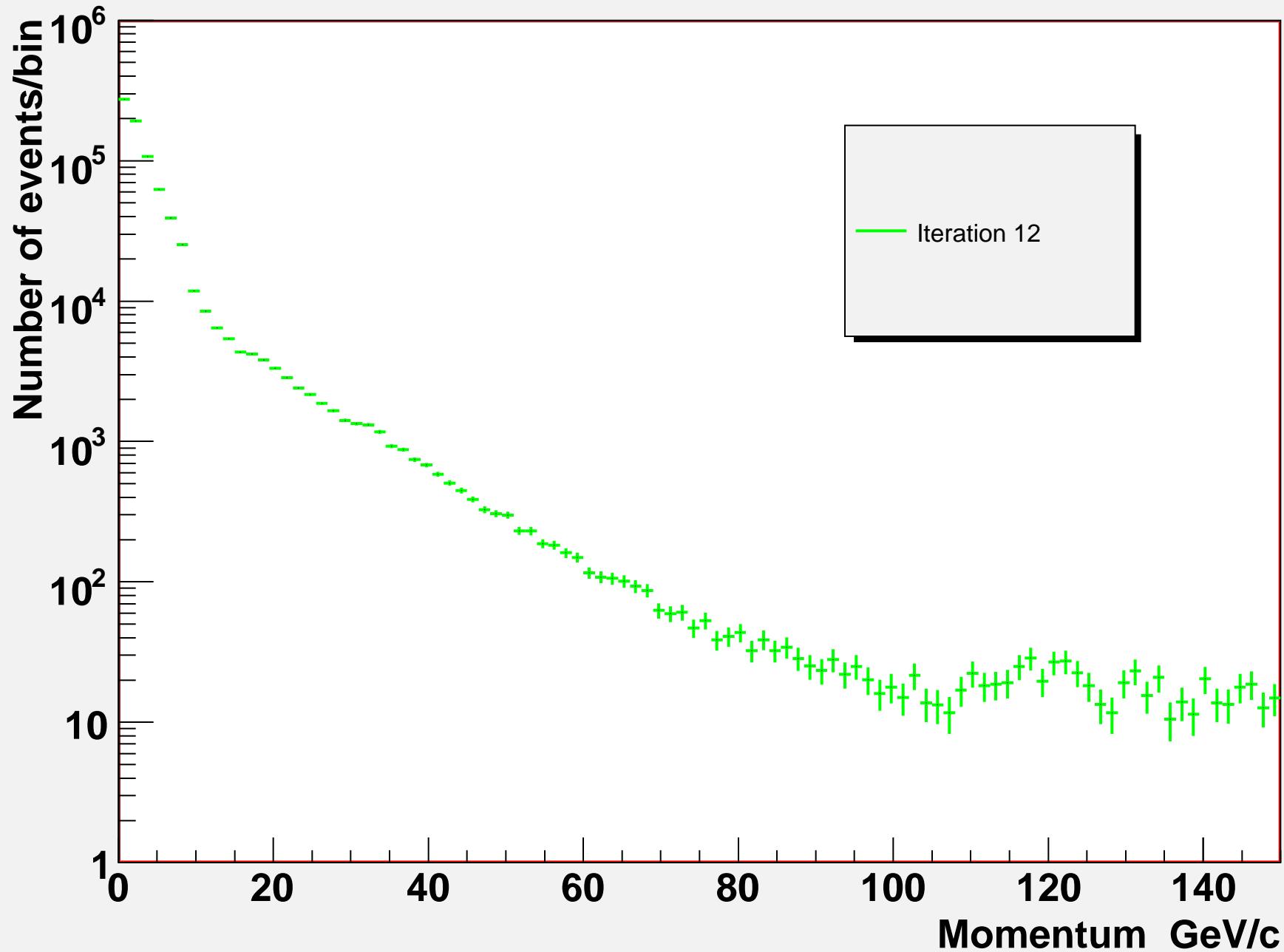
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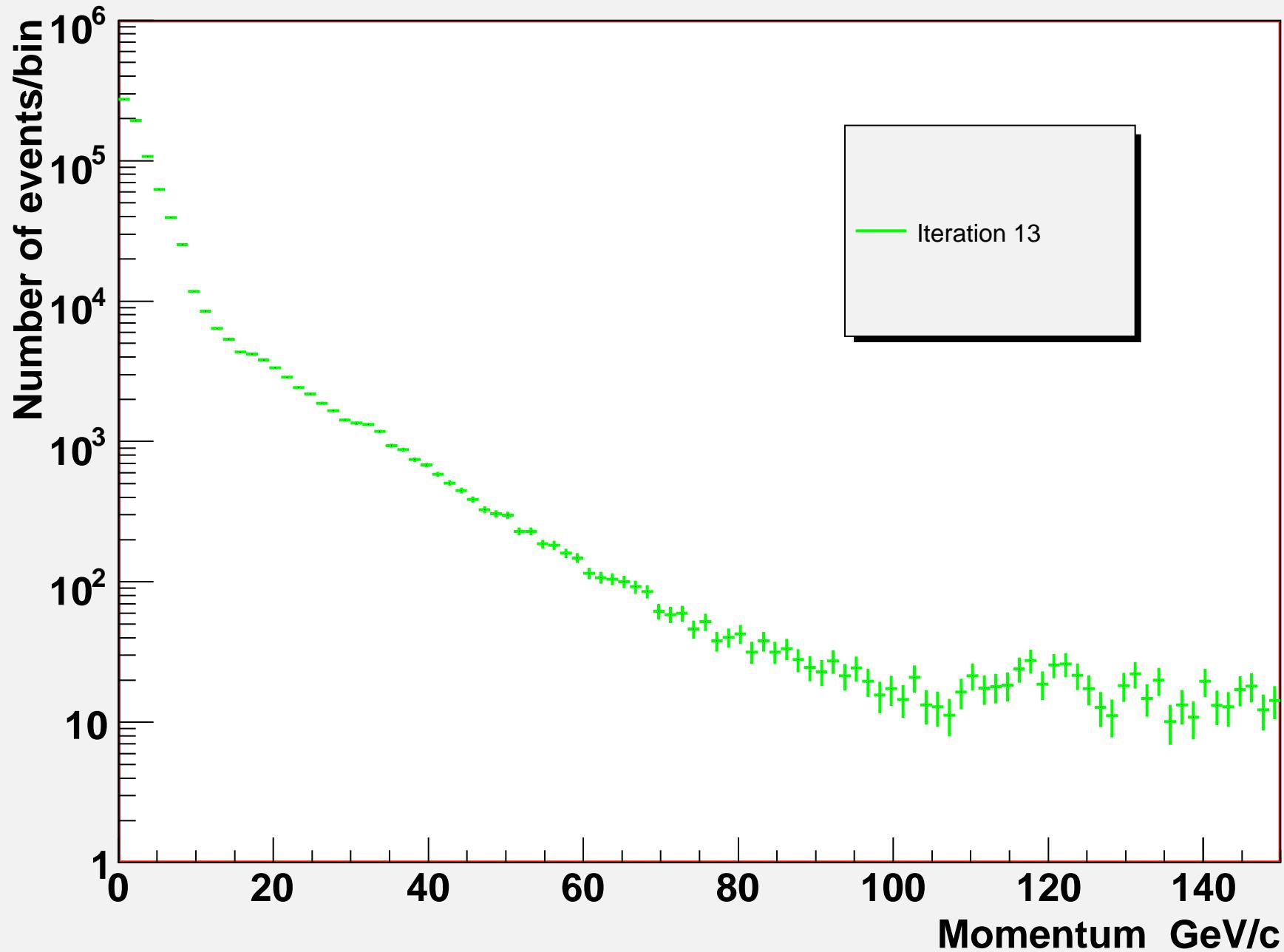
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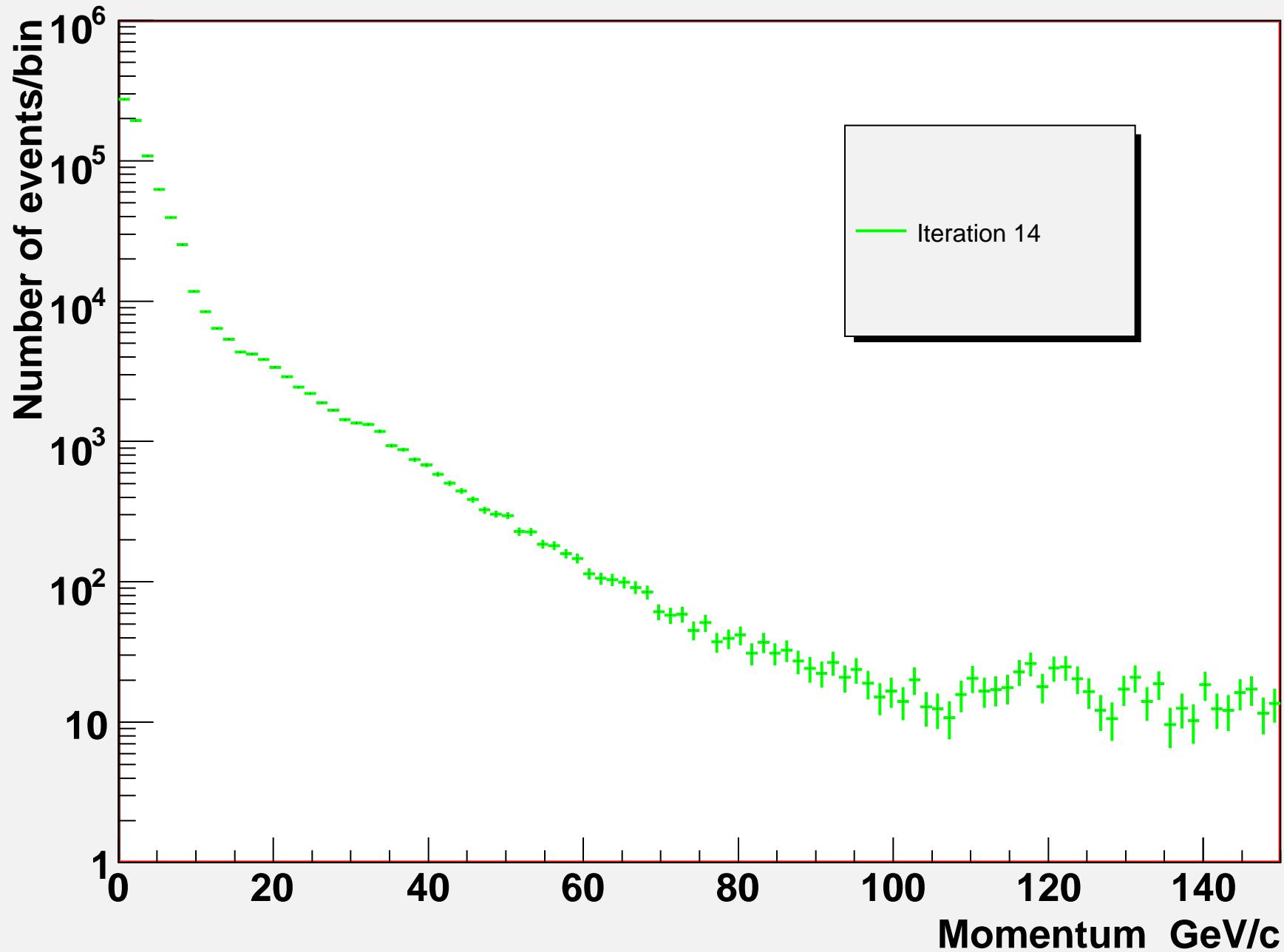
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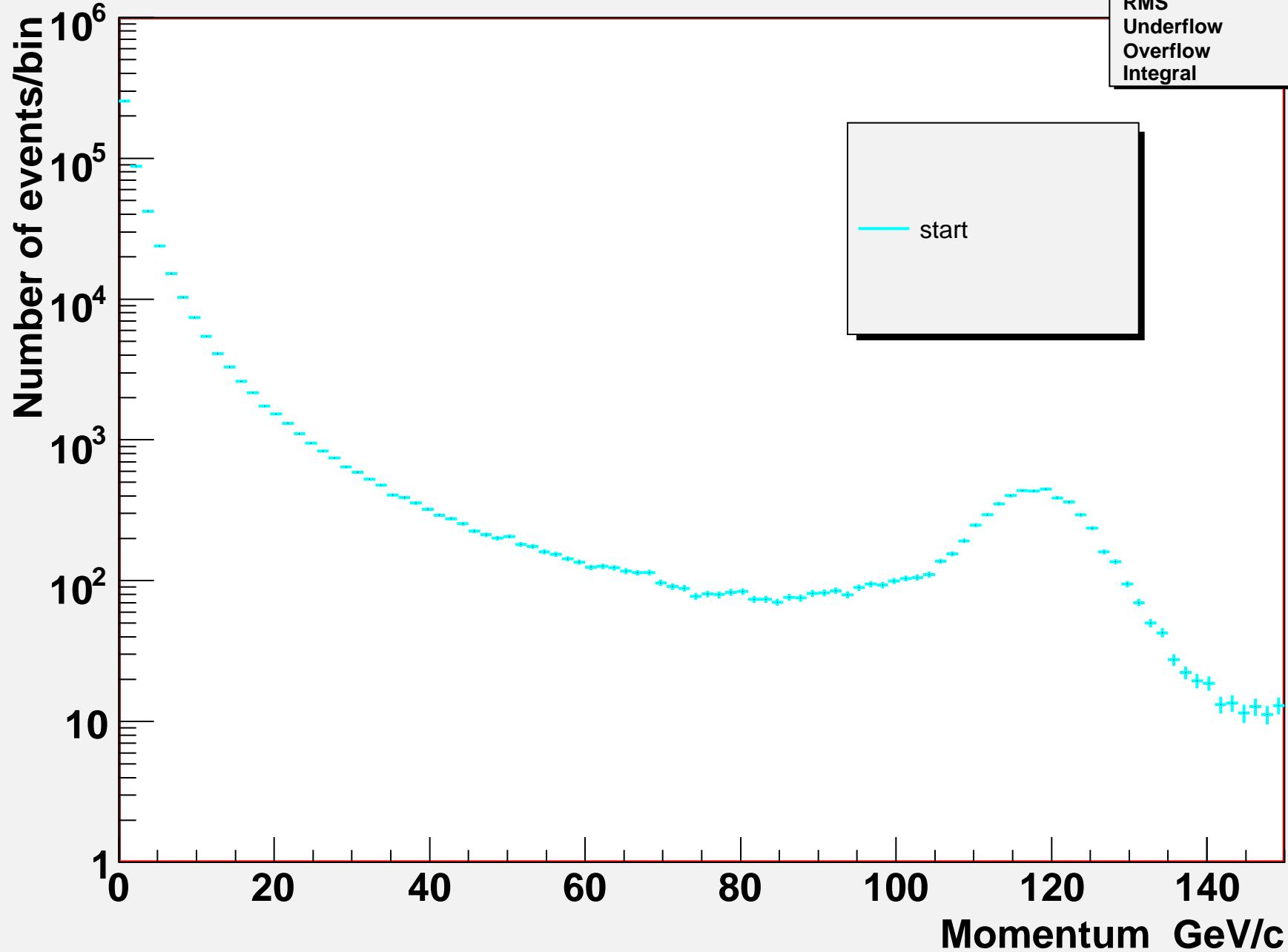
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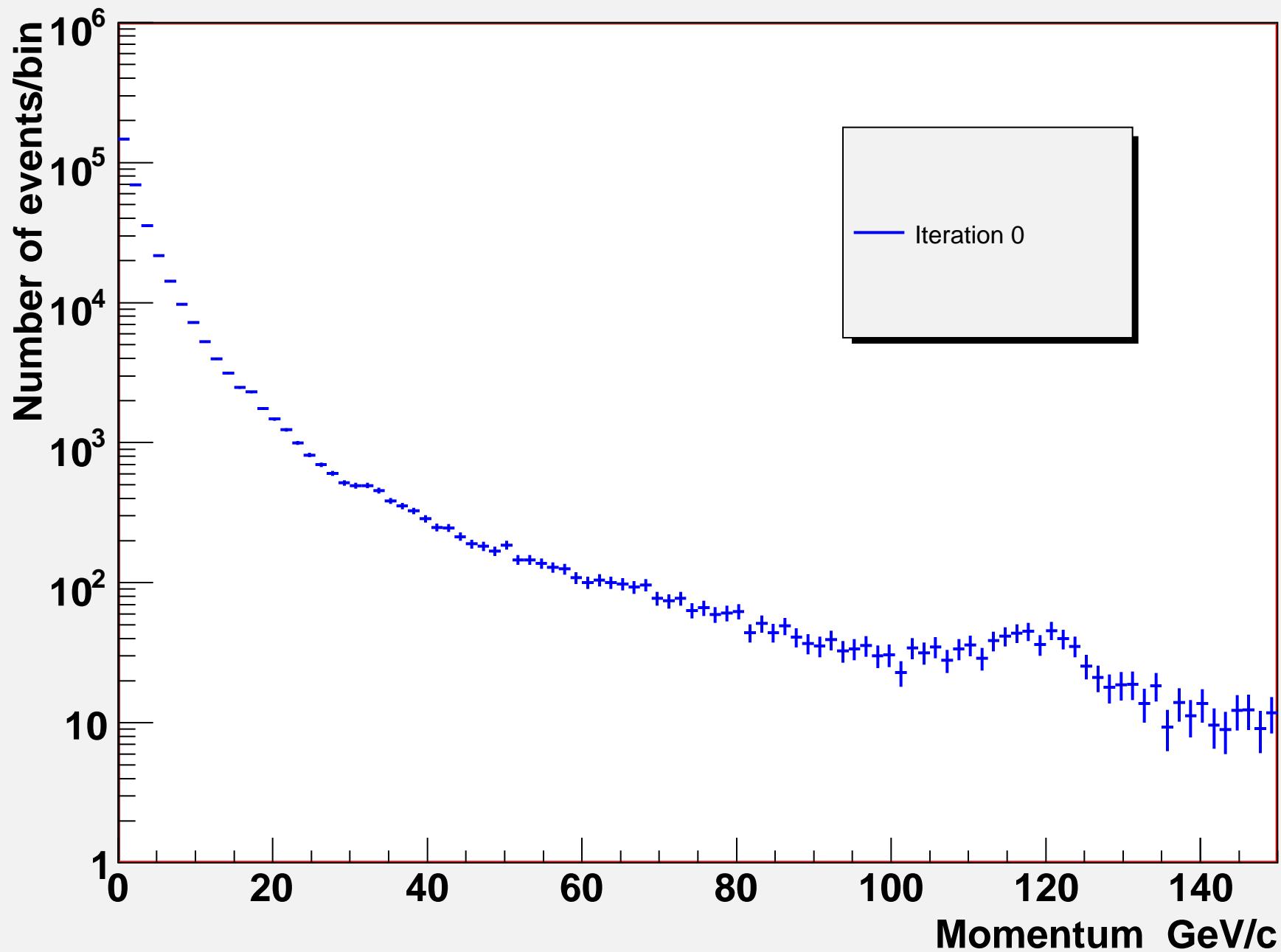
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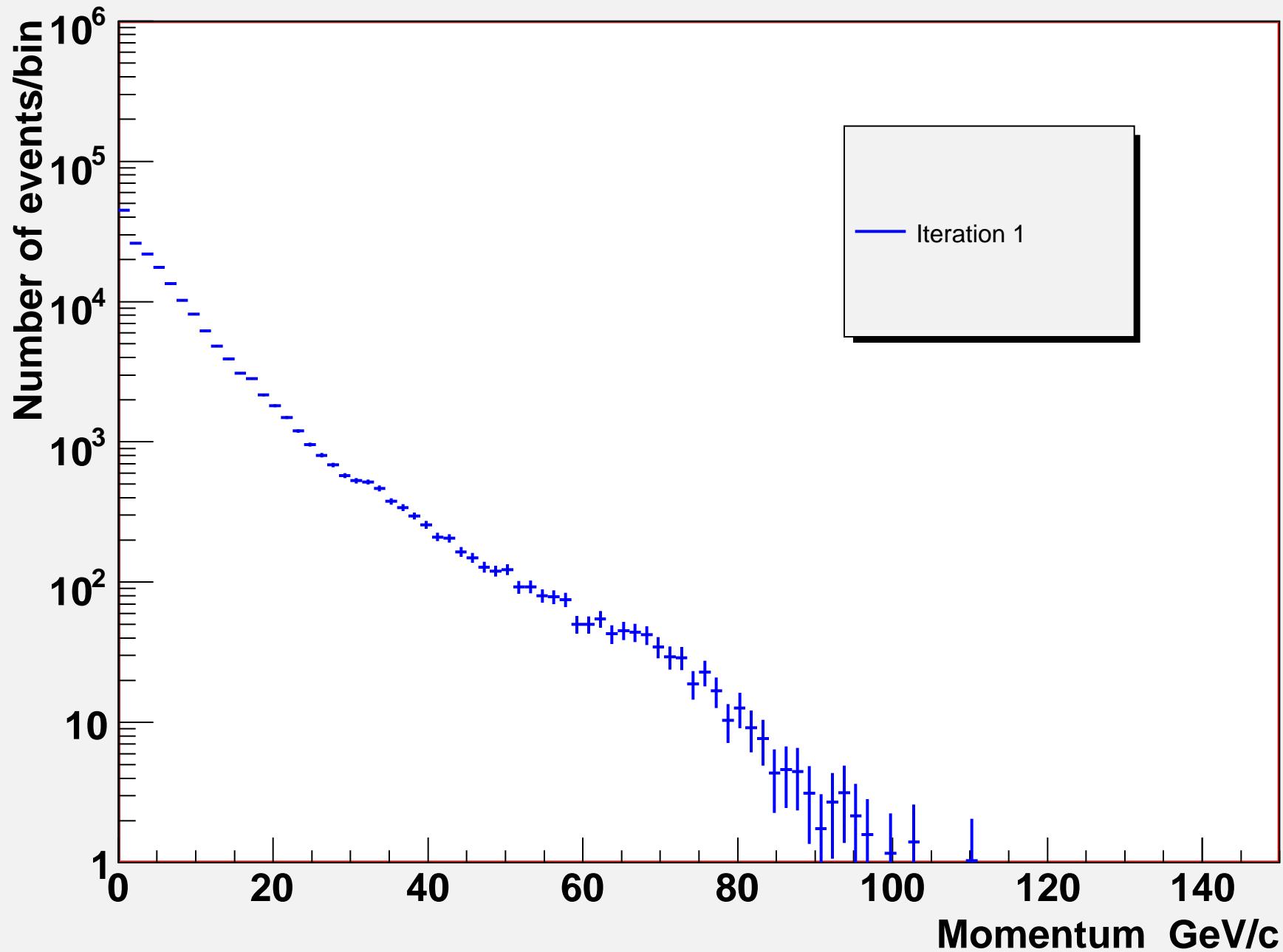
Momentum Distribution of Kaons



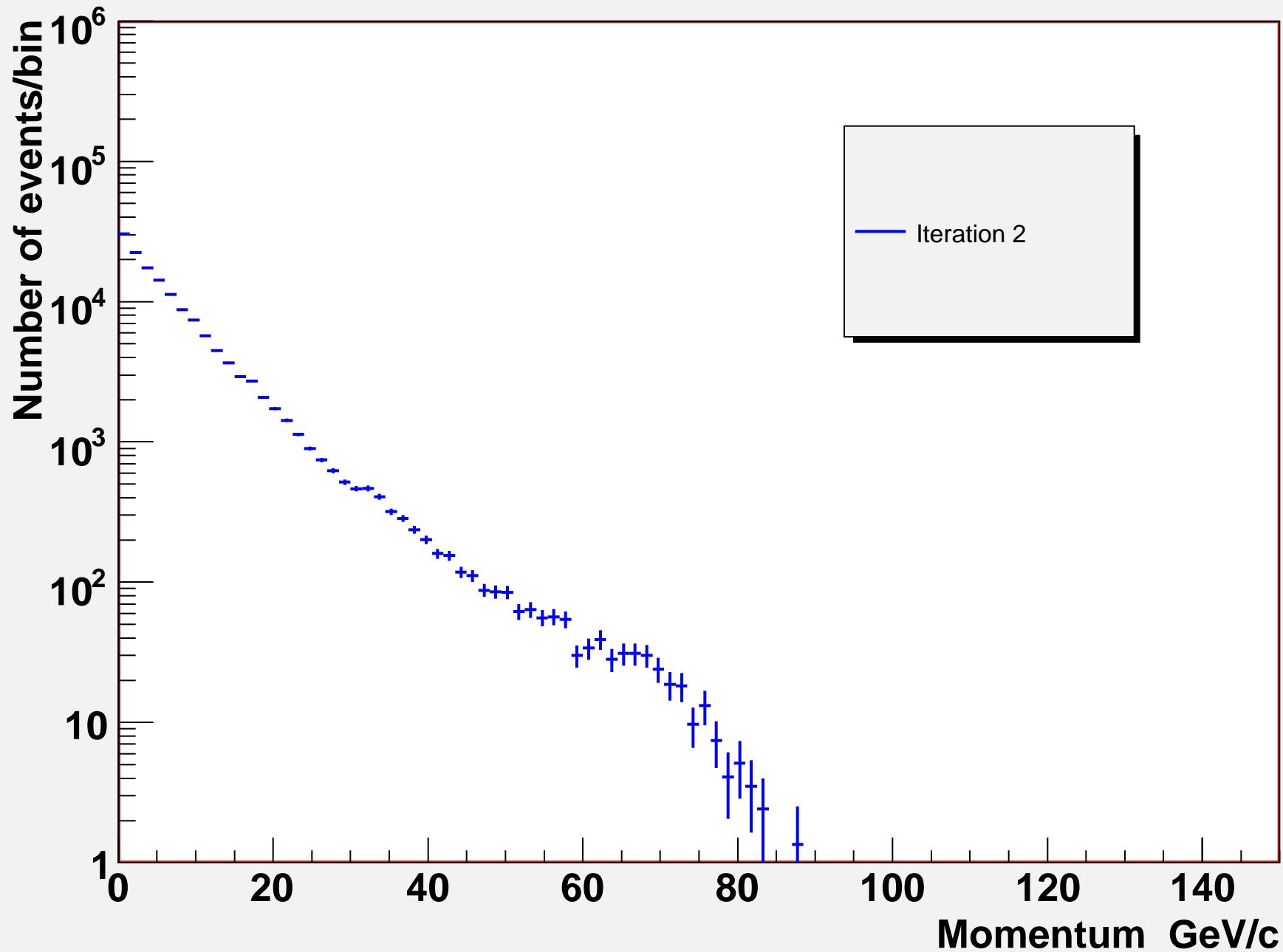
Momentum Distribution of Kaons



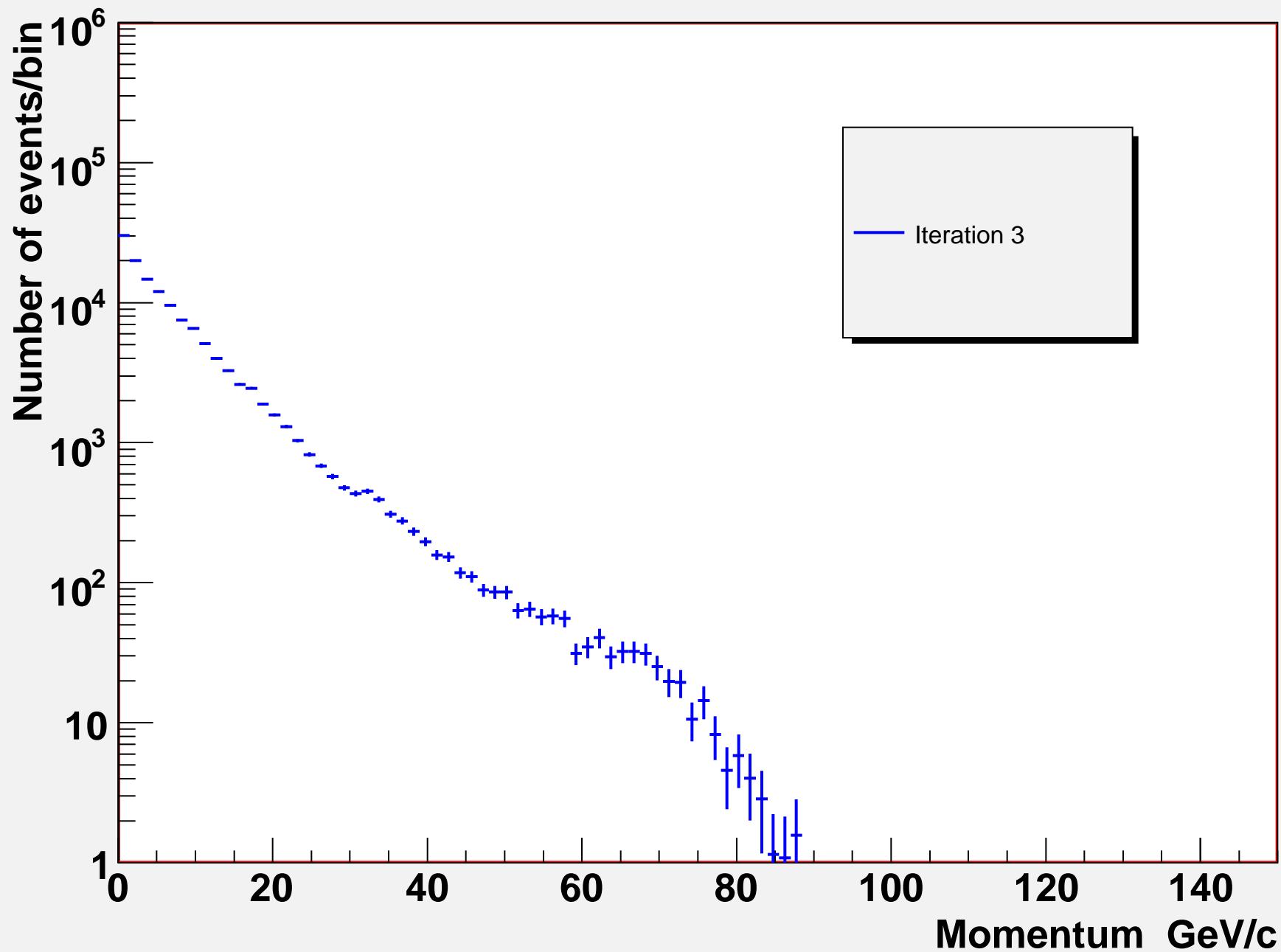
Momentum Distribution of Kaons



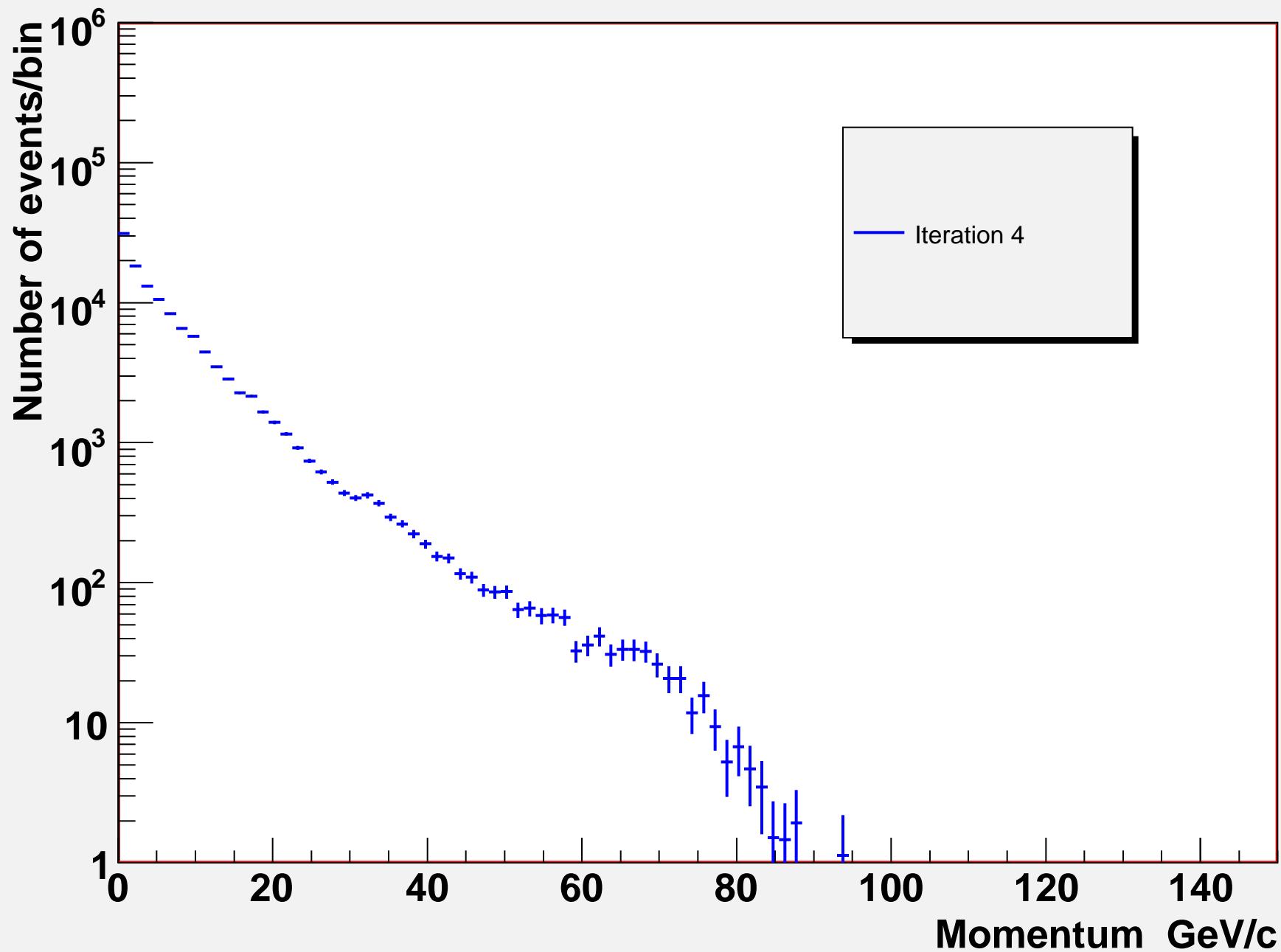
Momentum Distribution of Kaons



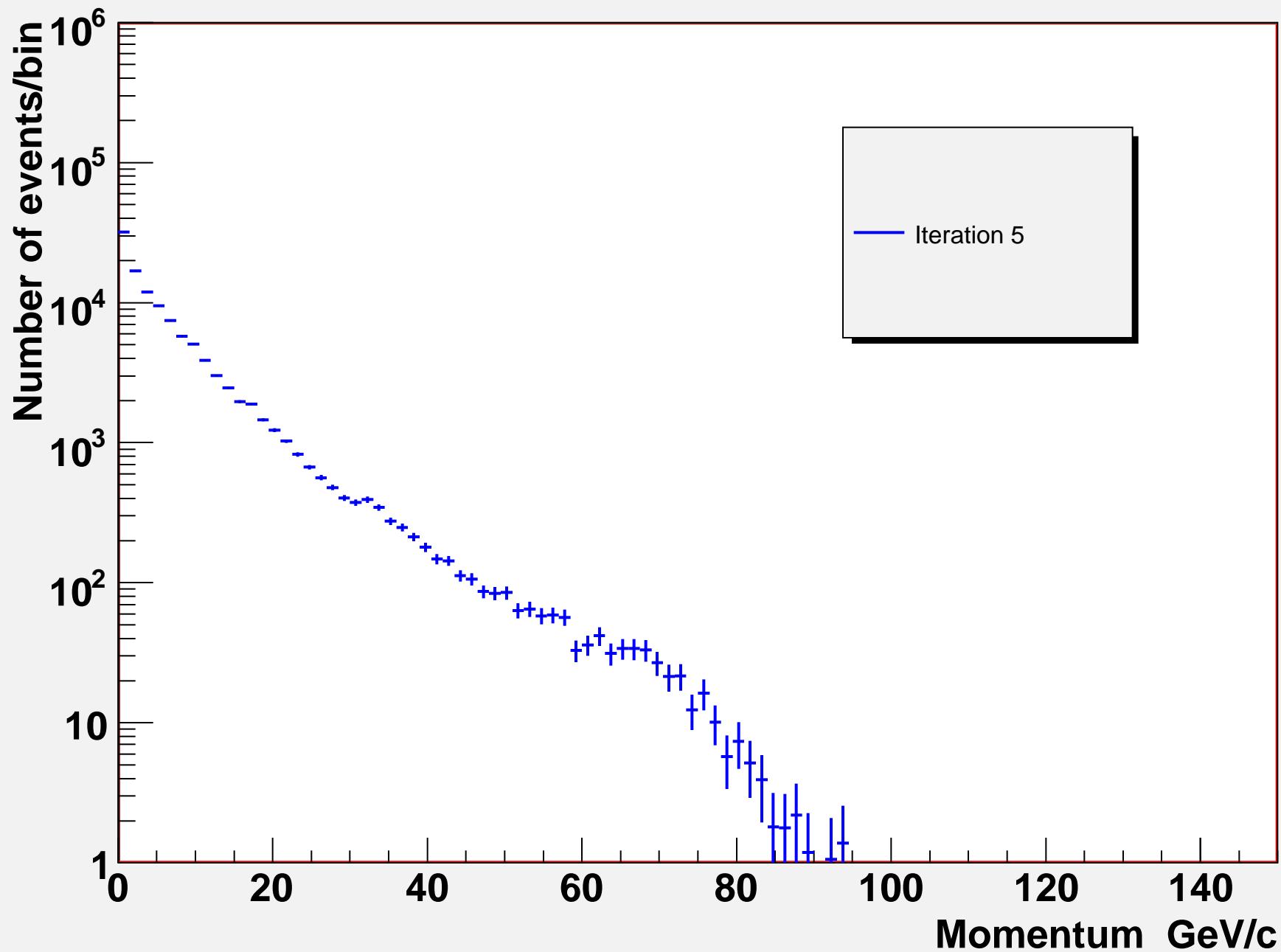
Momentum Distribution of Kaons



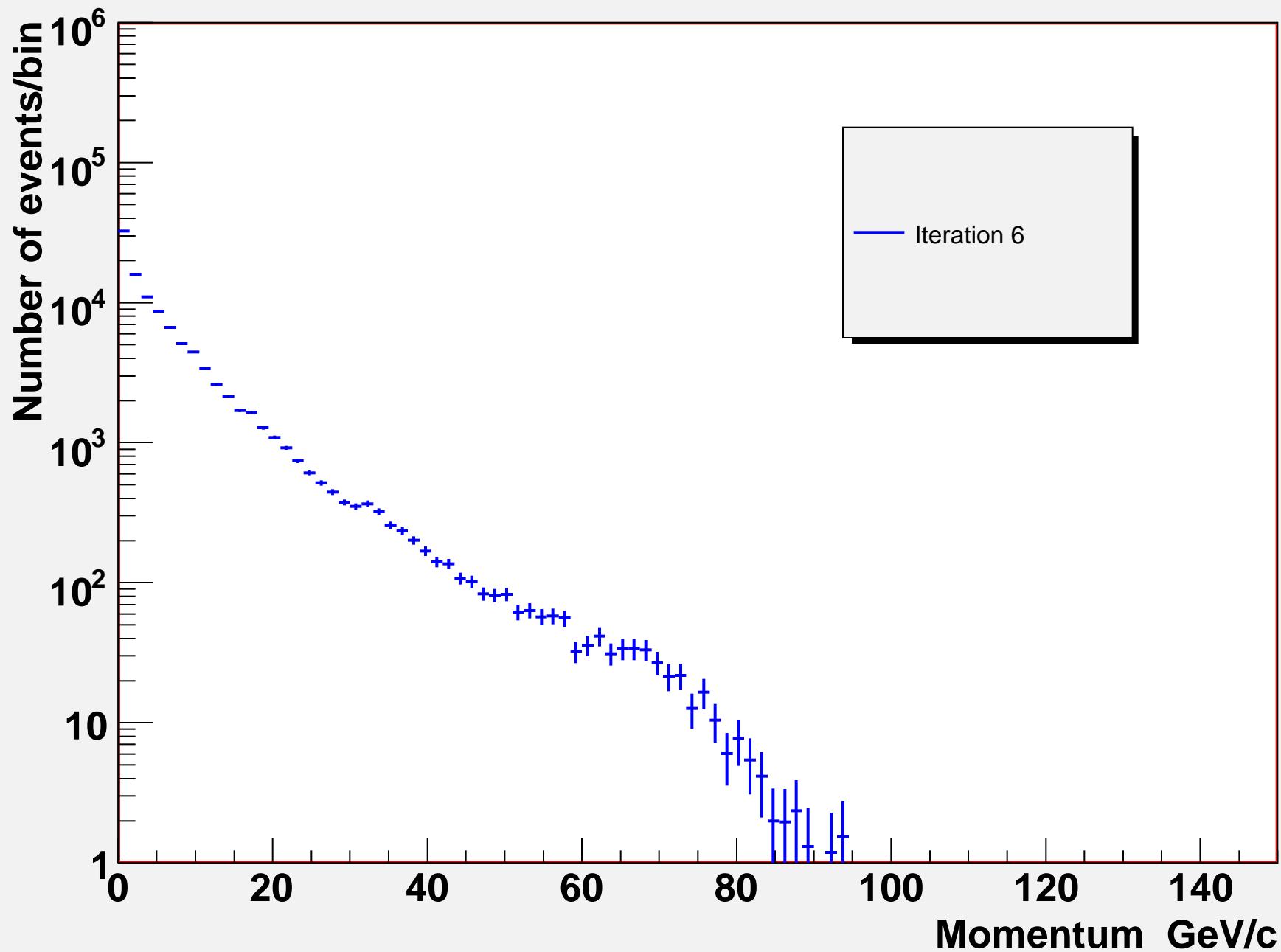
Momentum Distribution of Kaons



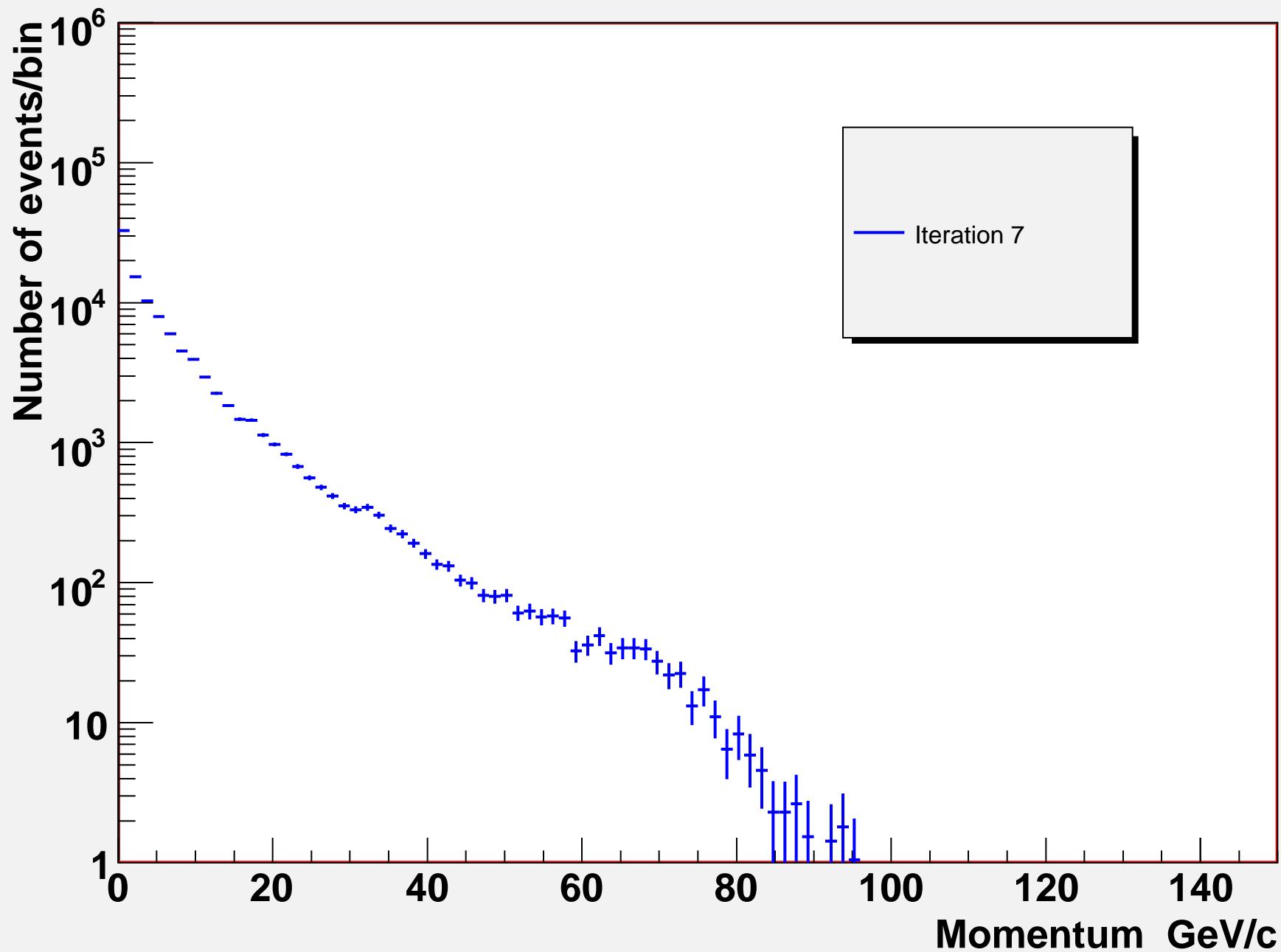
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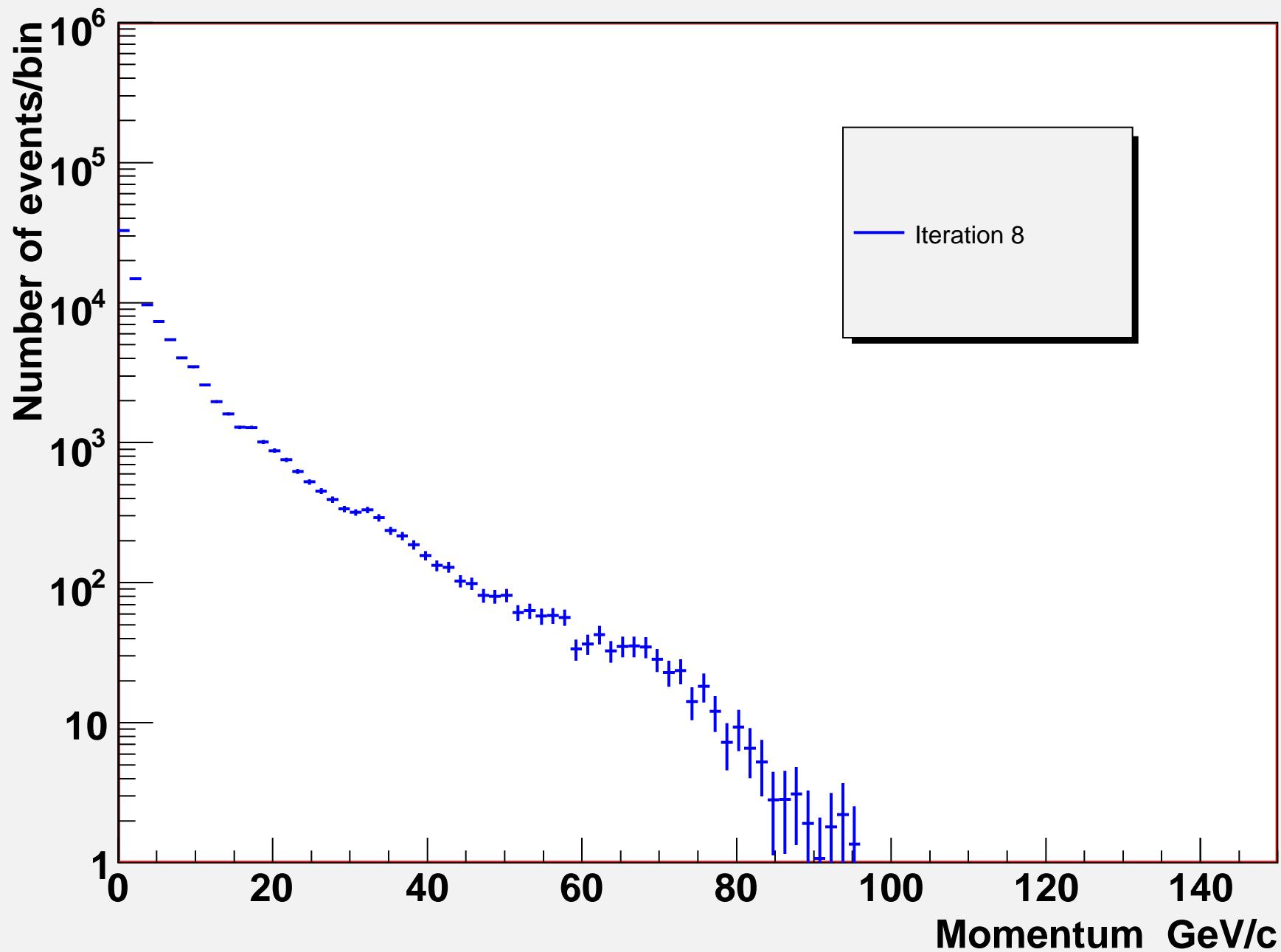
Momentum Distribution of Kaons



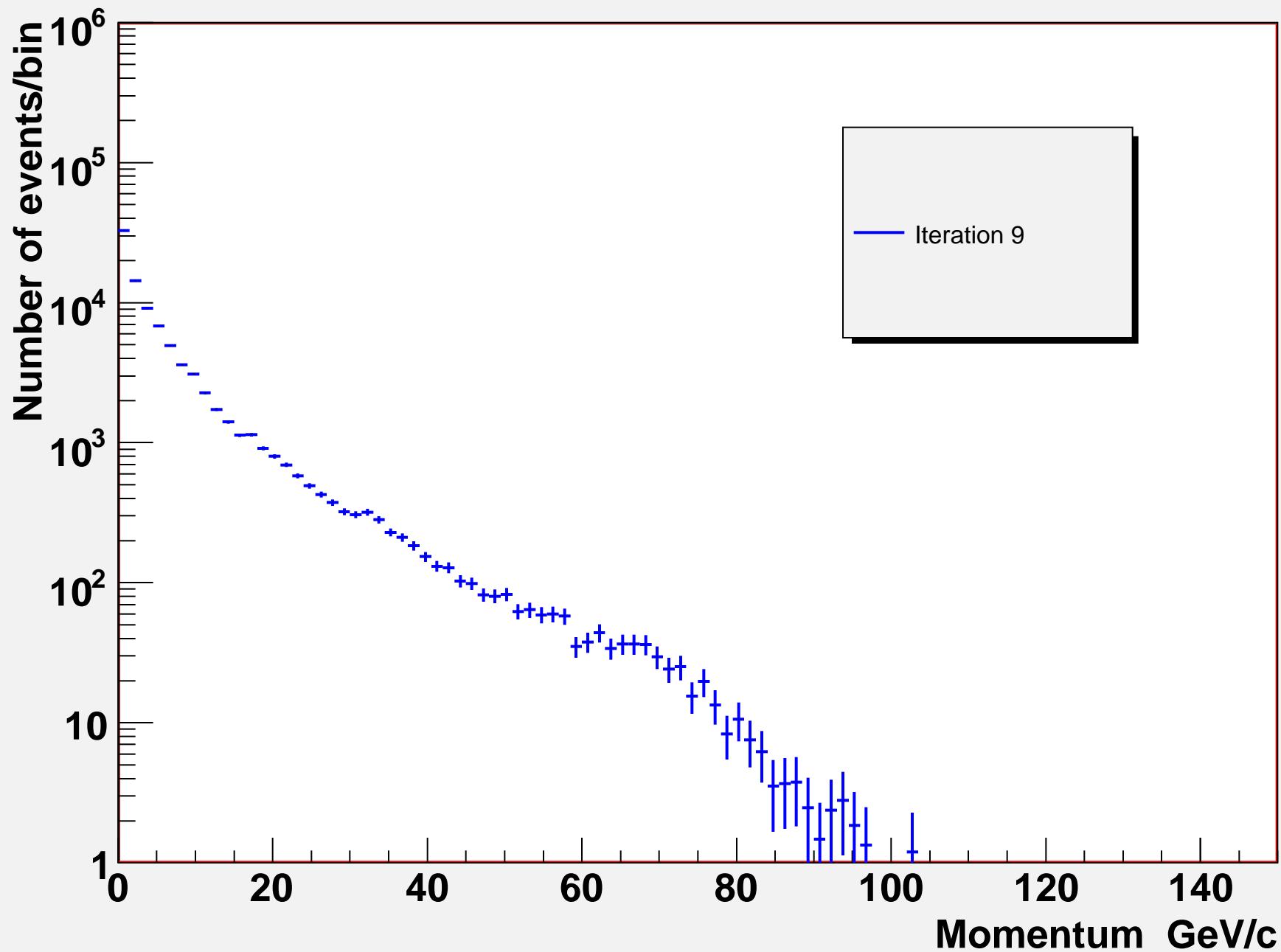
Momentum Distribution of Kaons



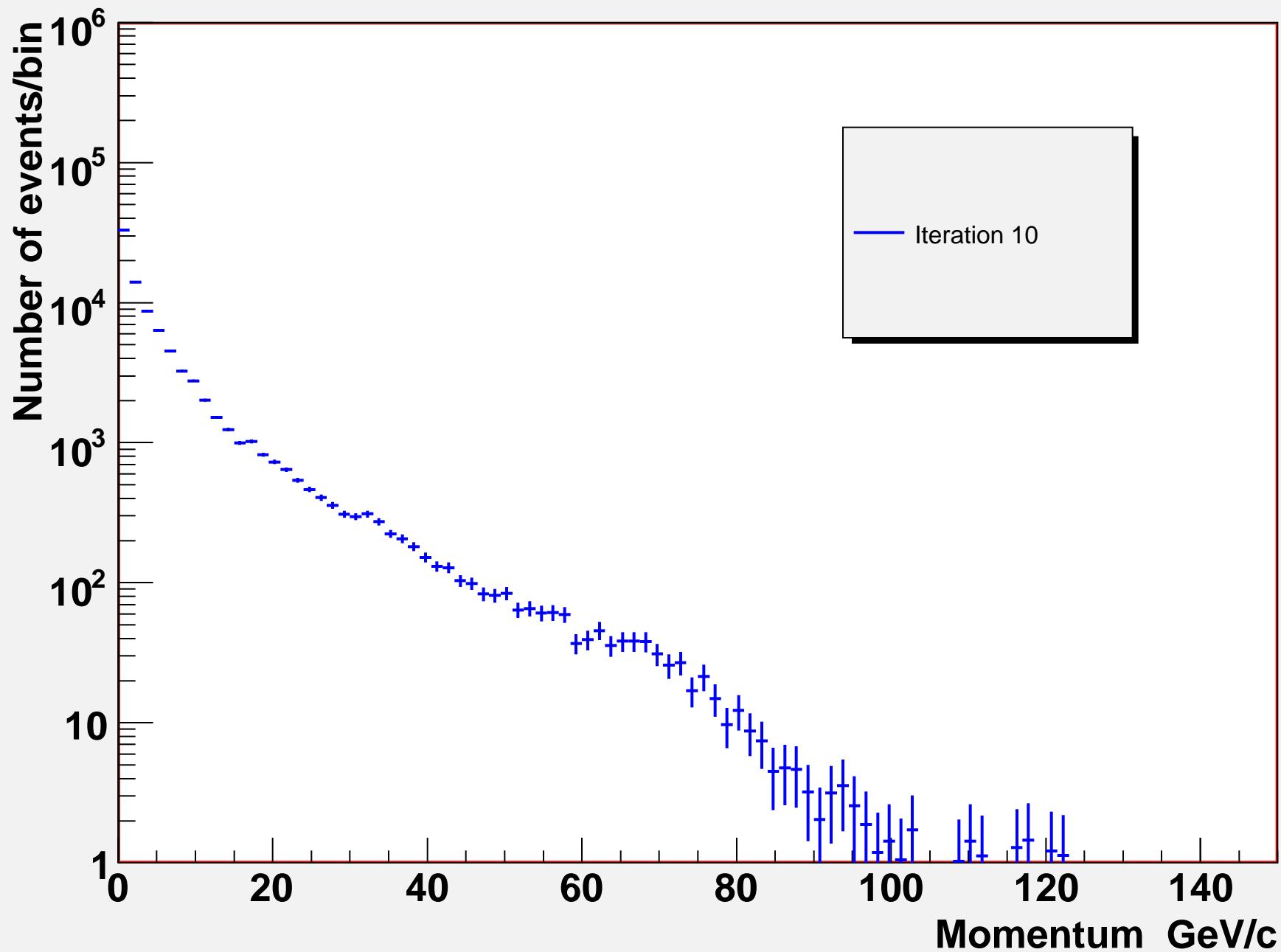
Momentum Distribution of Kaons



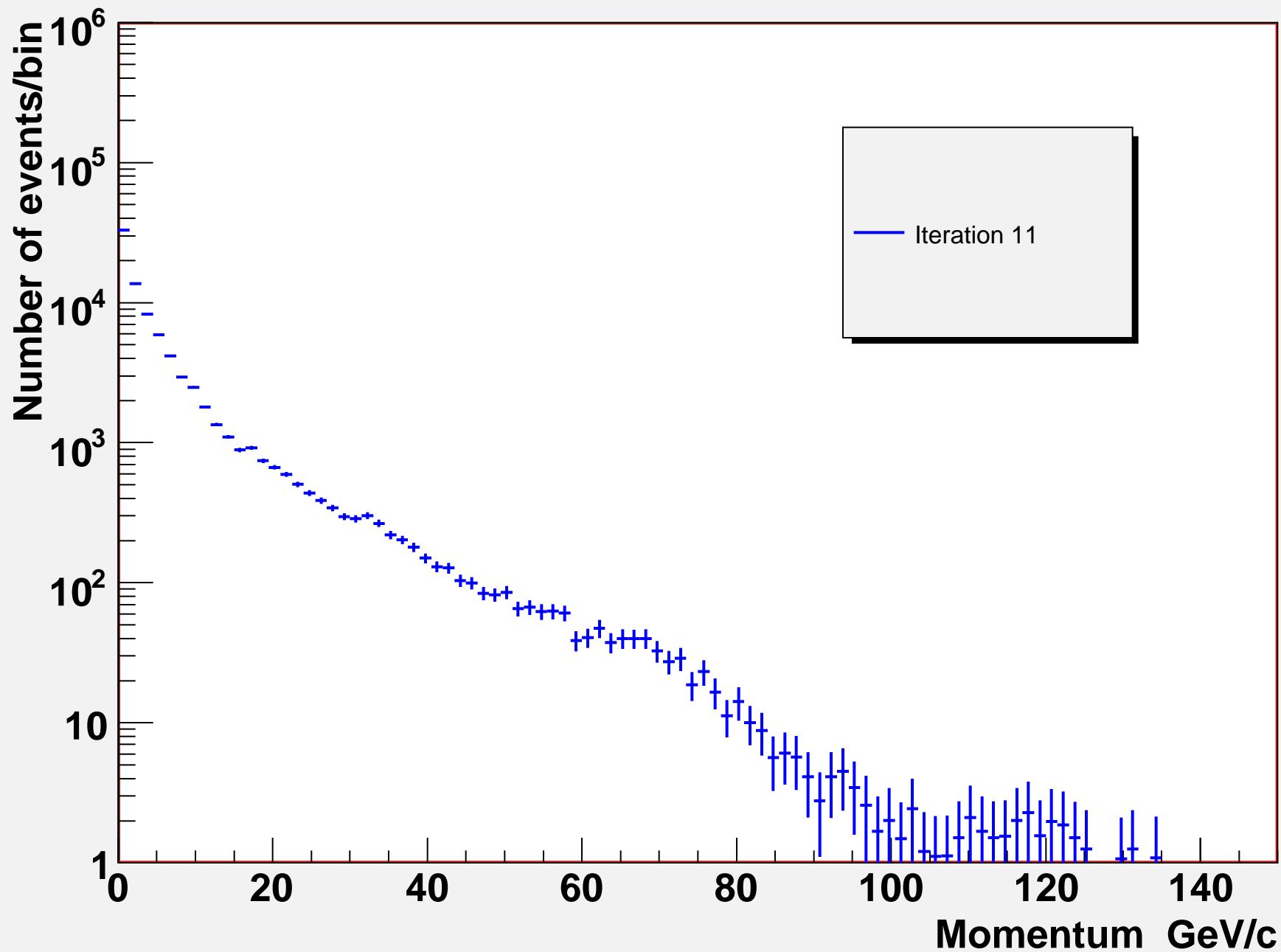
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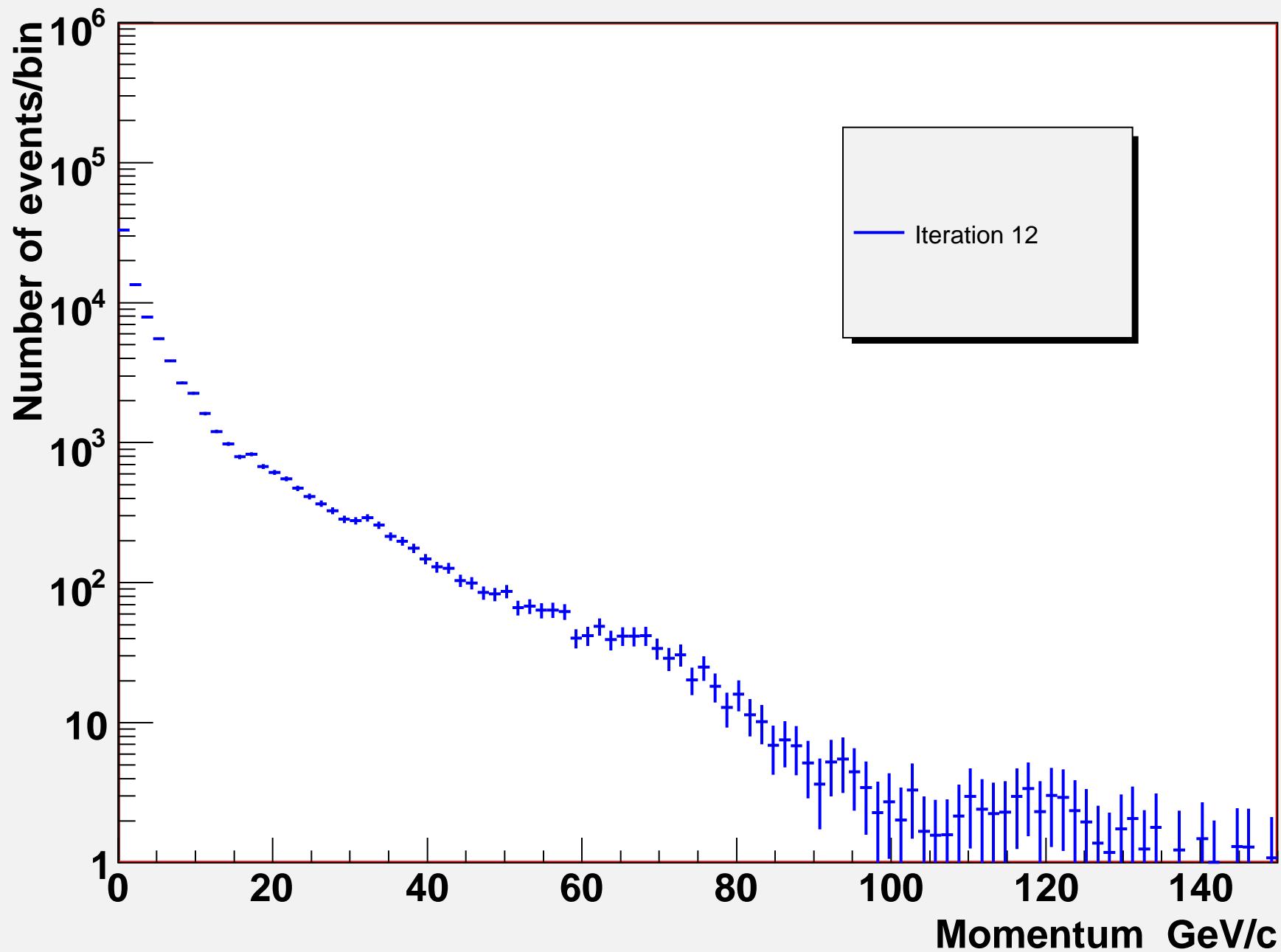
Momentum Distribution of Kaons



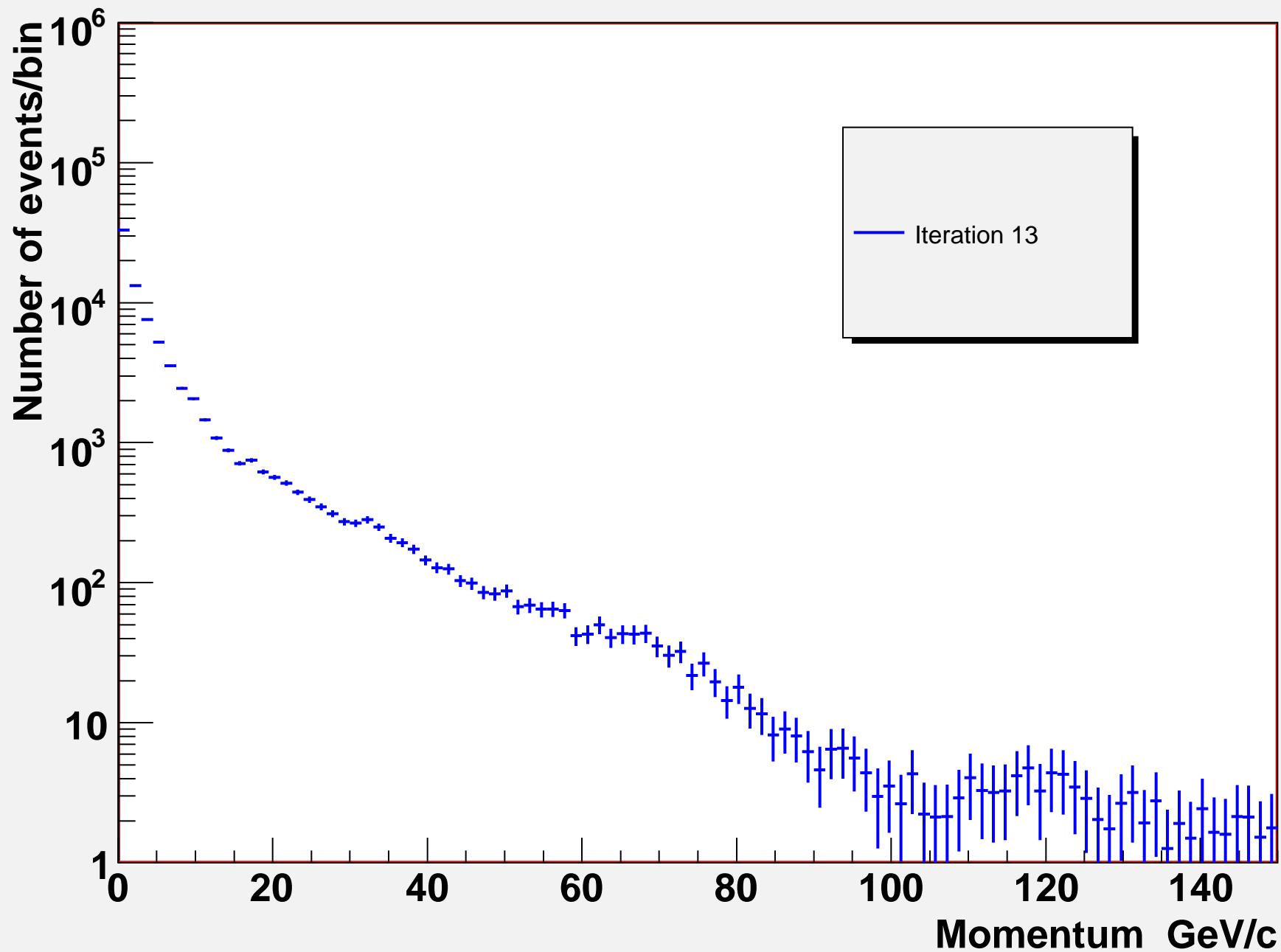
Momentum Distribution of Kaons



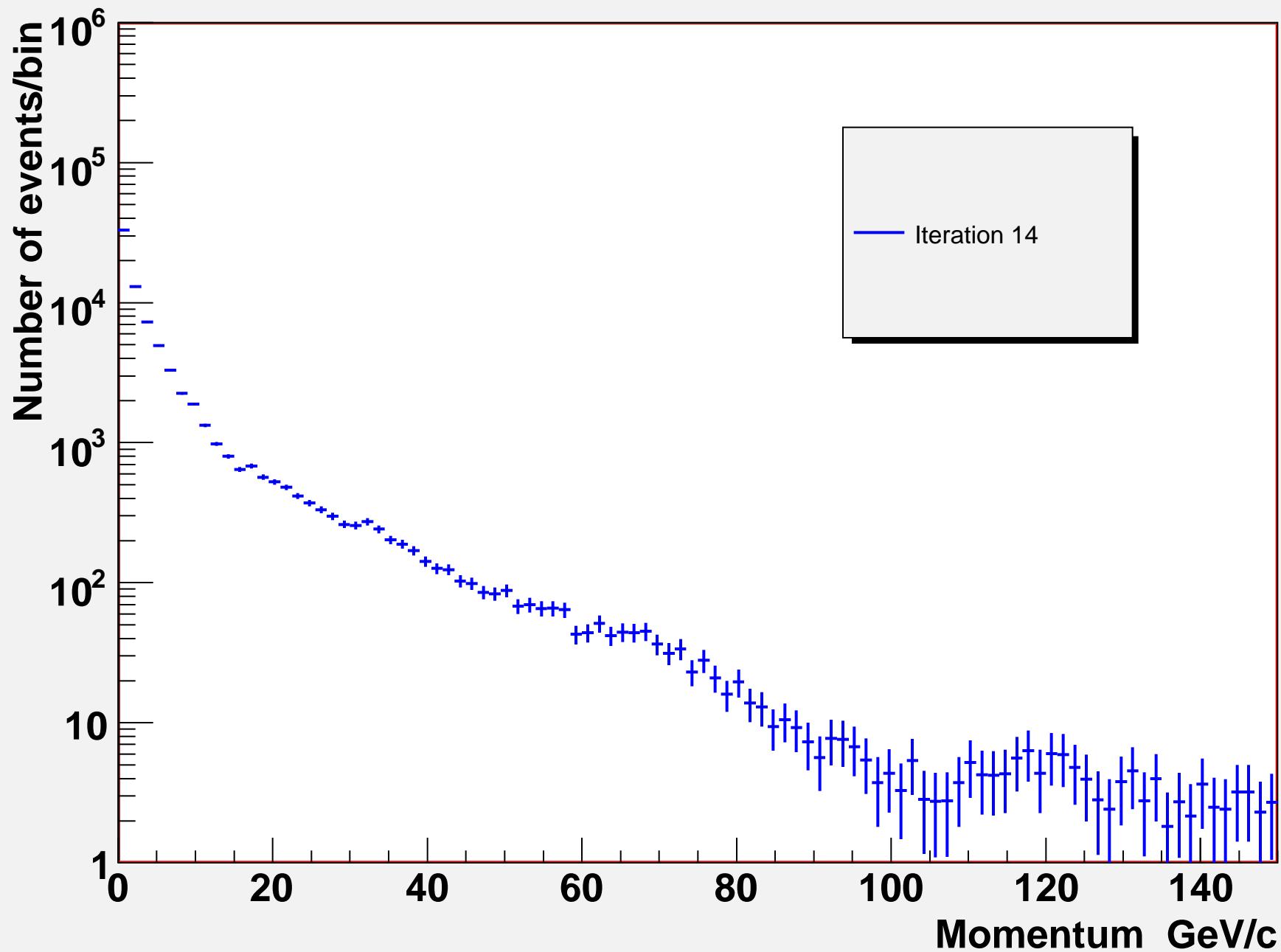
Momentum Distribution of Kaons



Momentum Distribution of Kaons

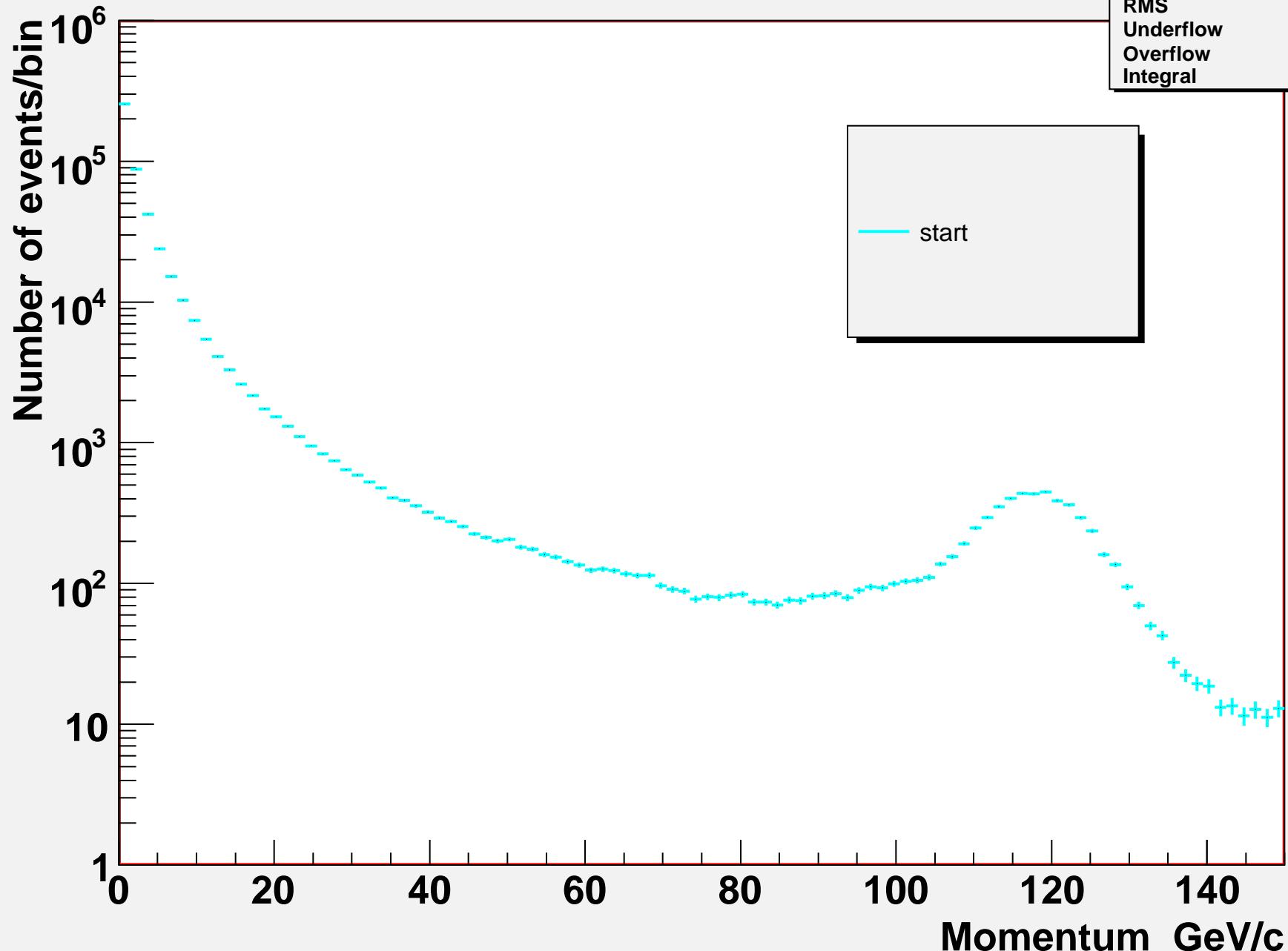


Momentum Distribution of Kaons

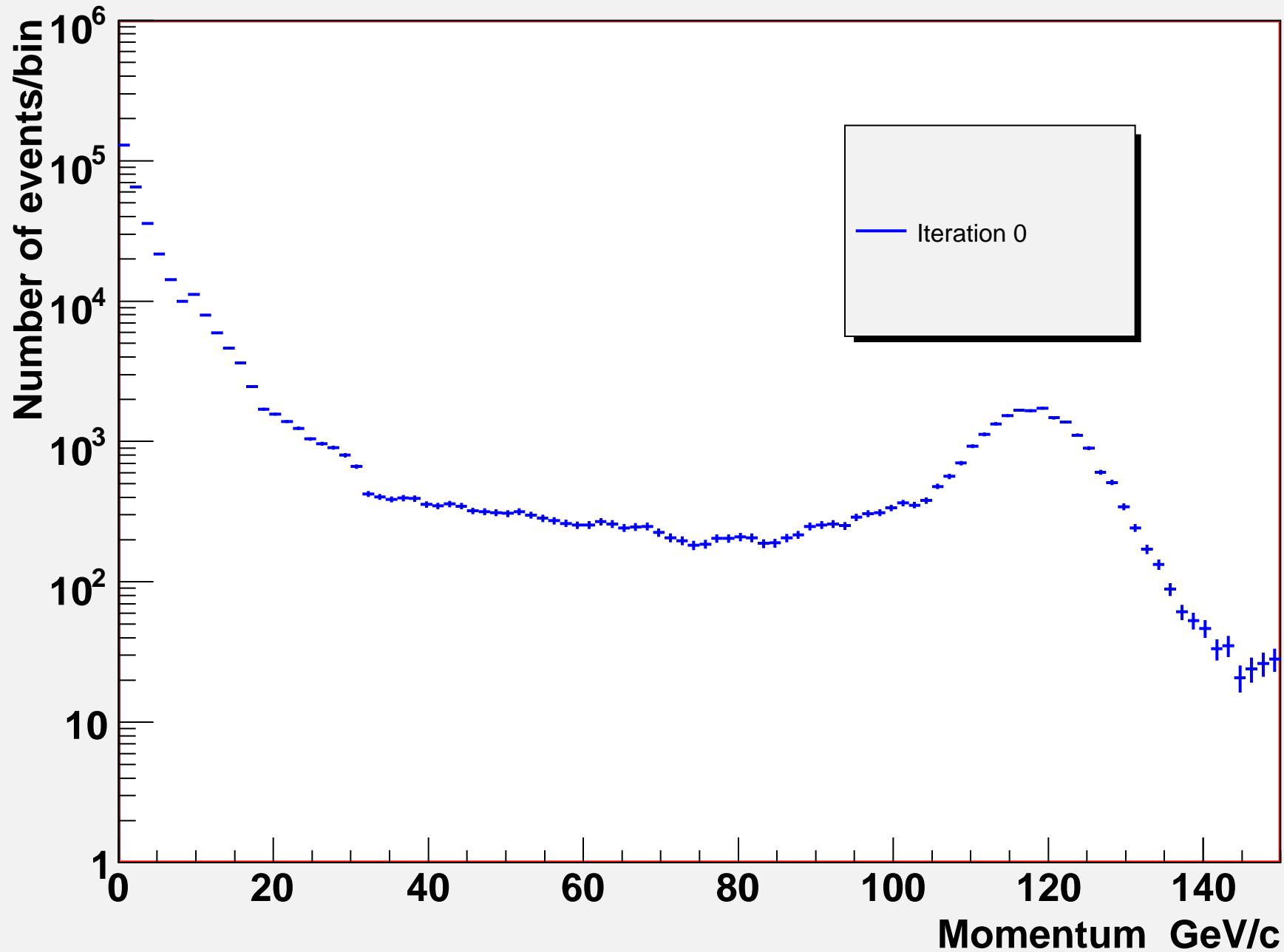


Momentum Distribution of Protons

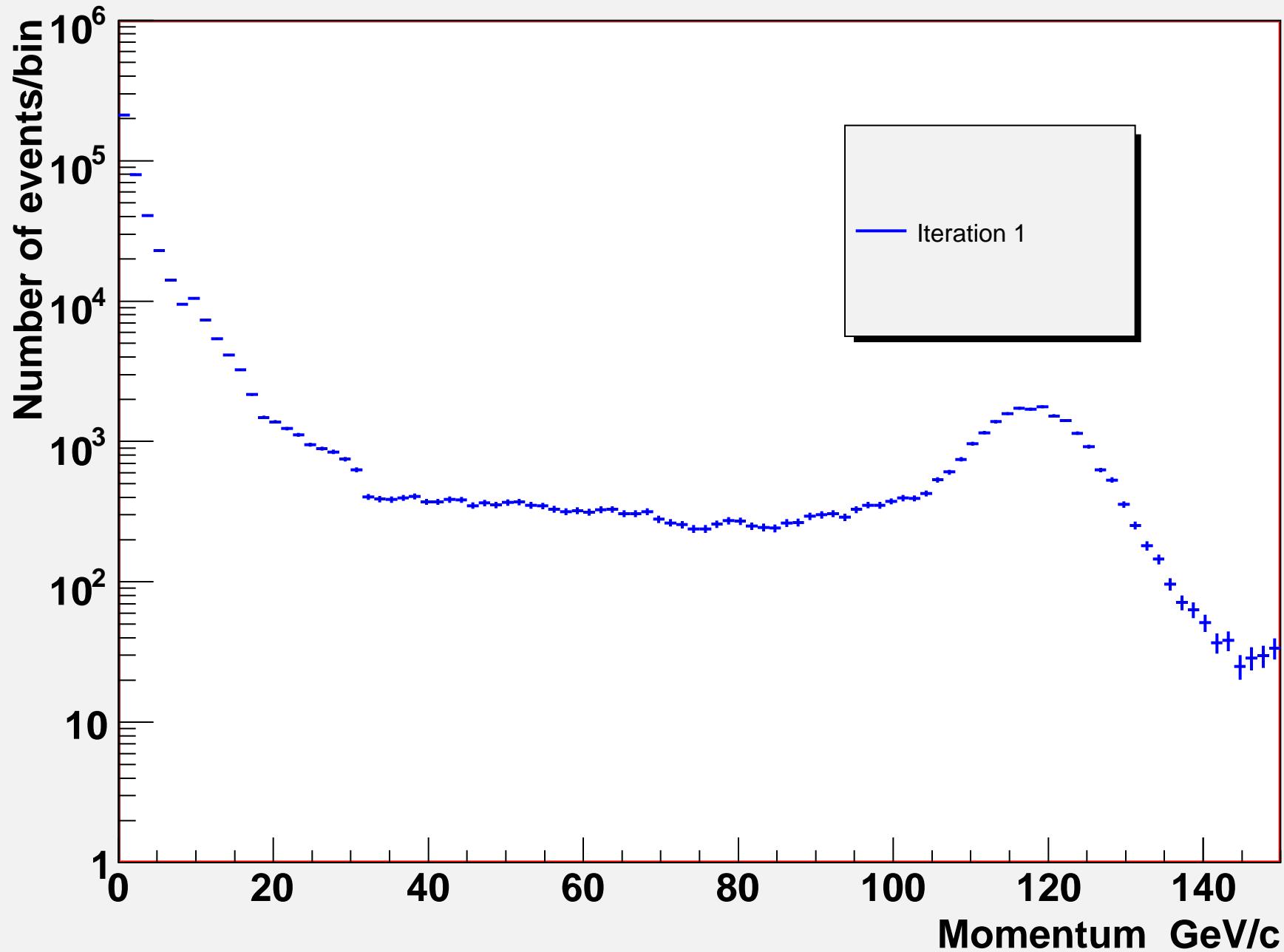
hmomnucutswt	
Entries	7694348
Mean	4.969
RMS	14.52
Underflow	0
Overflow	0
Integral	1.92e+06



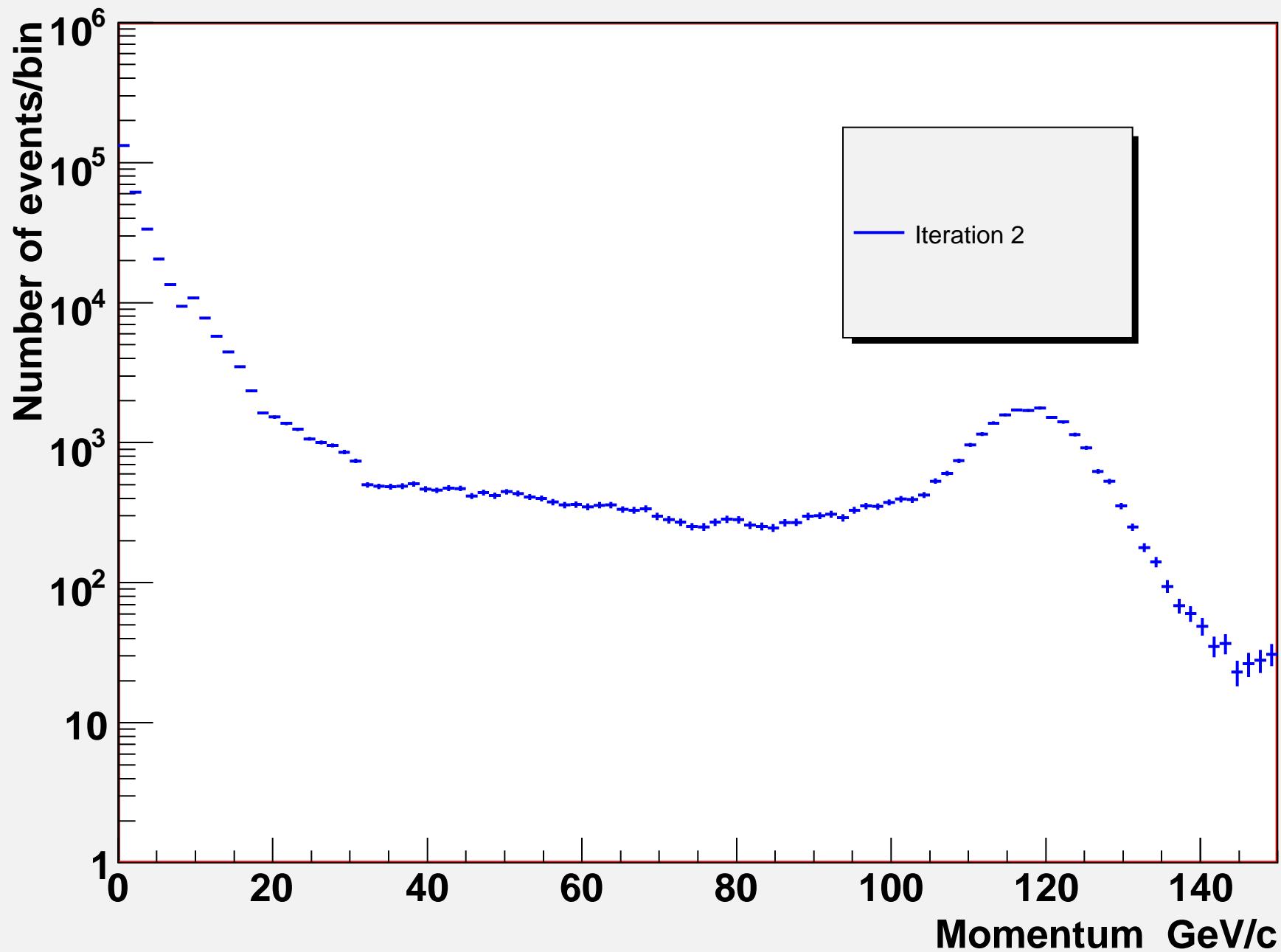
Momentum Distribution of Protons



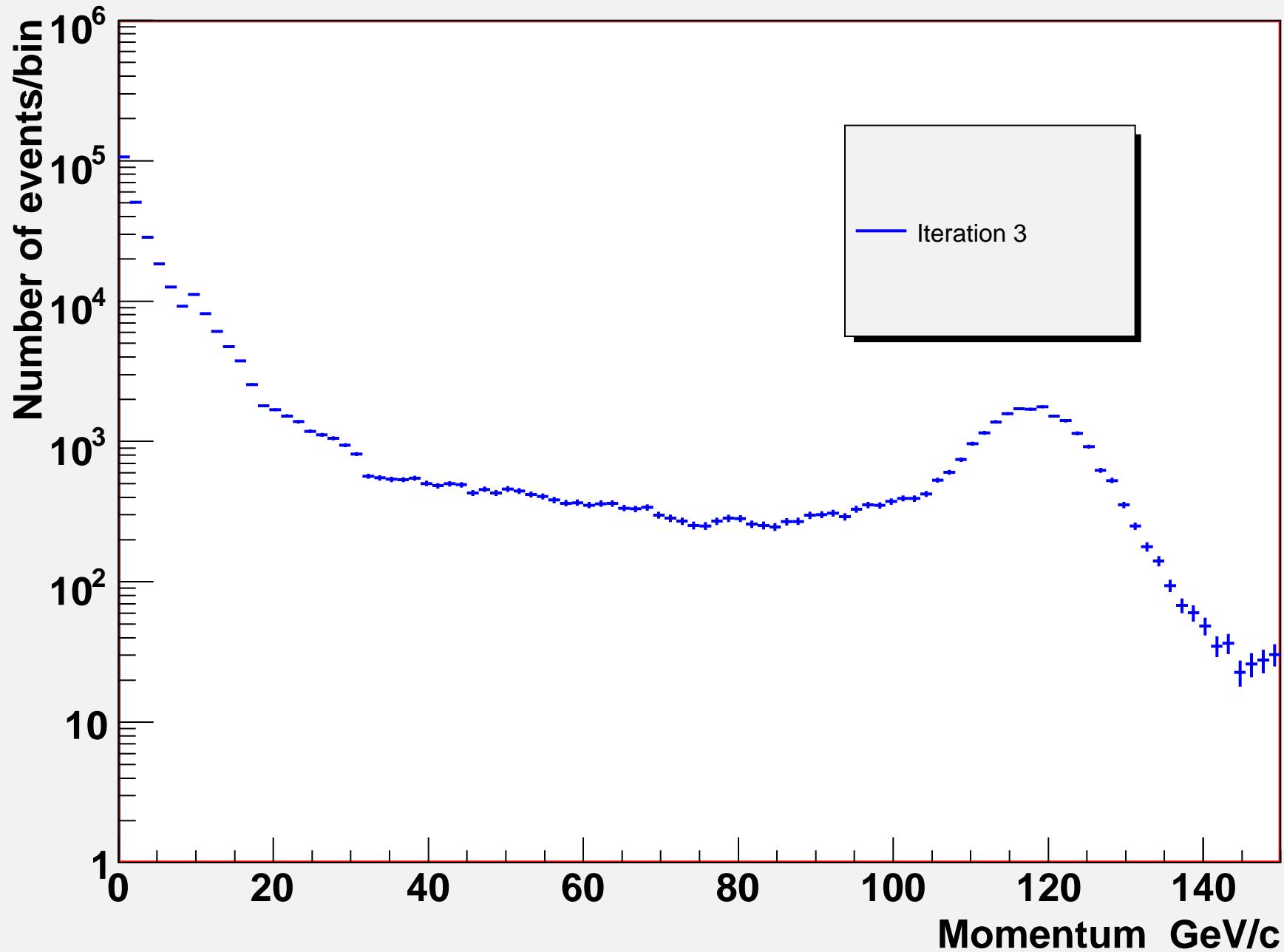
Momentum Distribution of Protons



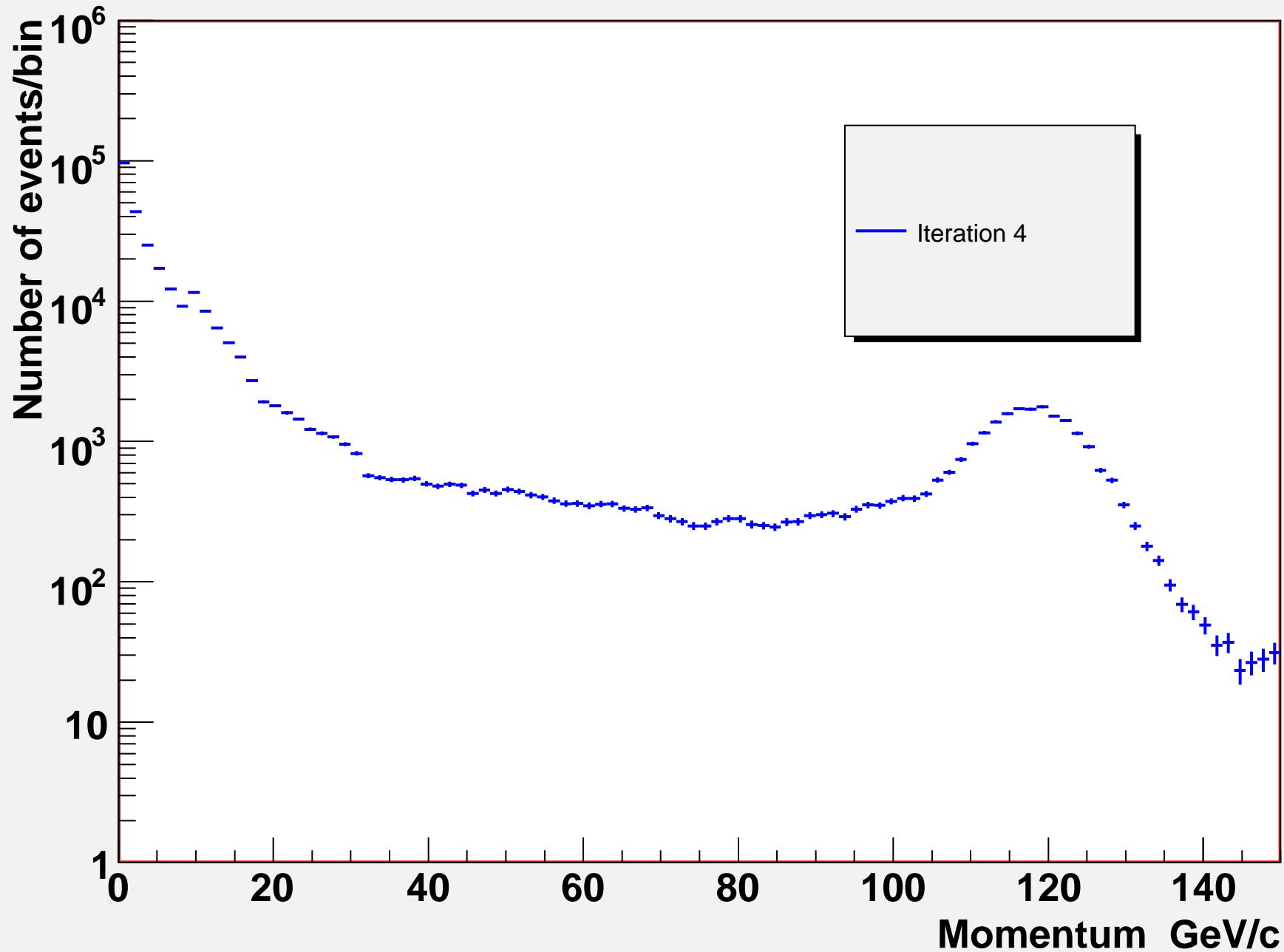
Momentum Distribution of Protons



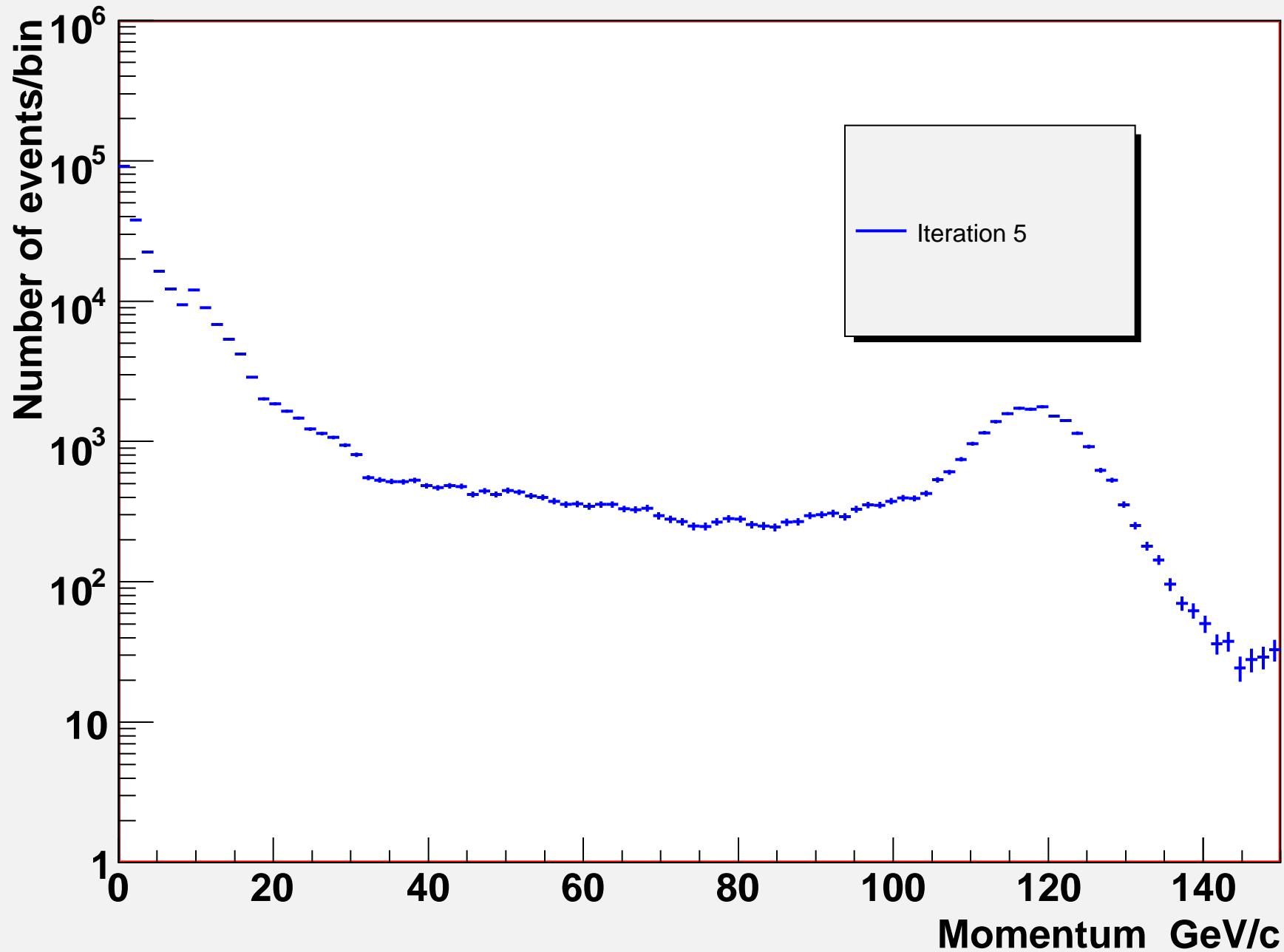
Momentum Distribution of Protons



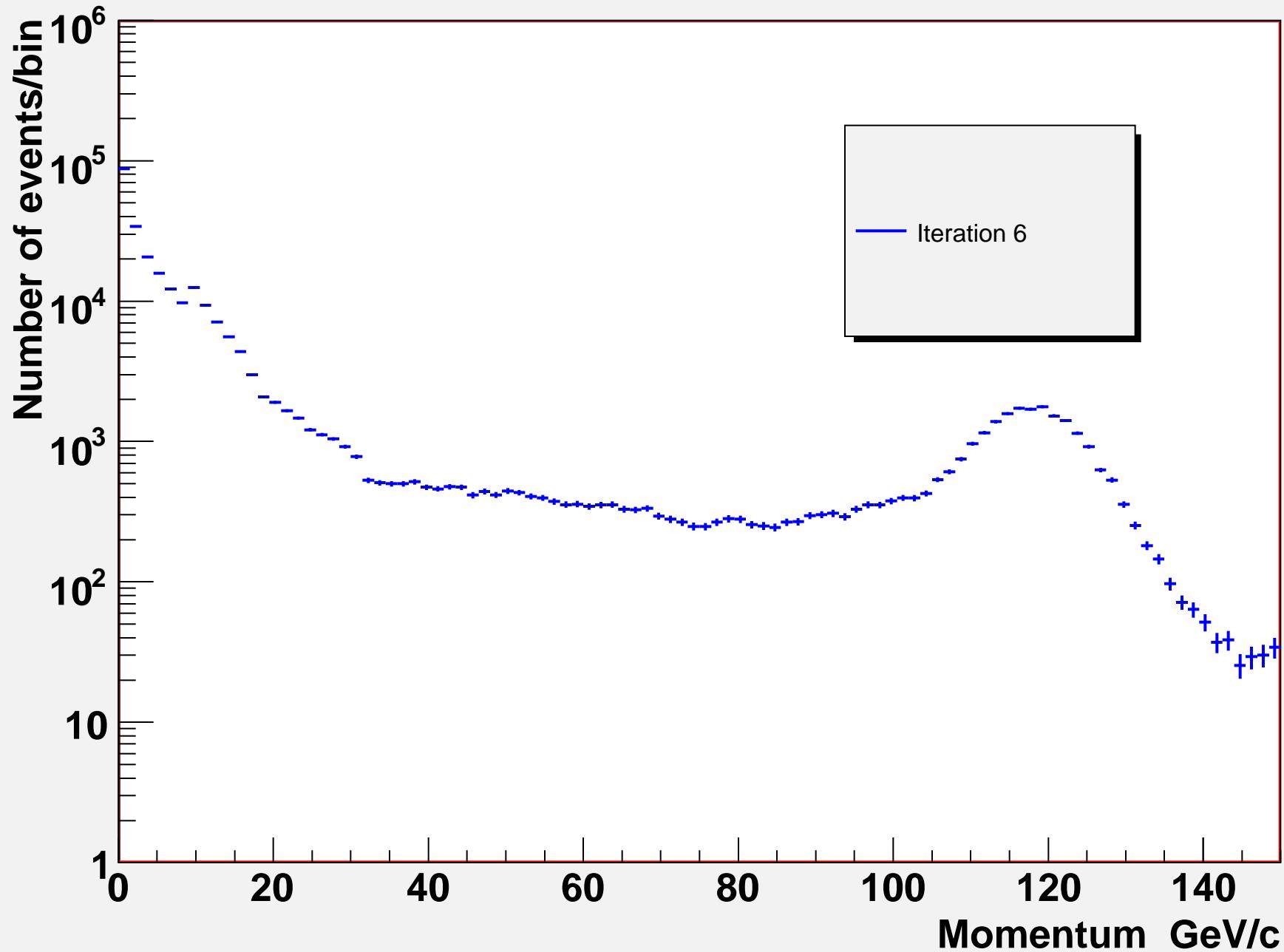
Momentum Distribution of Protons



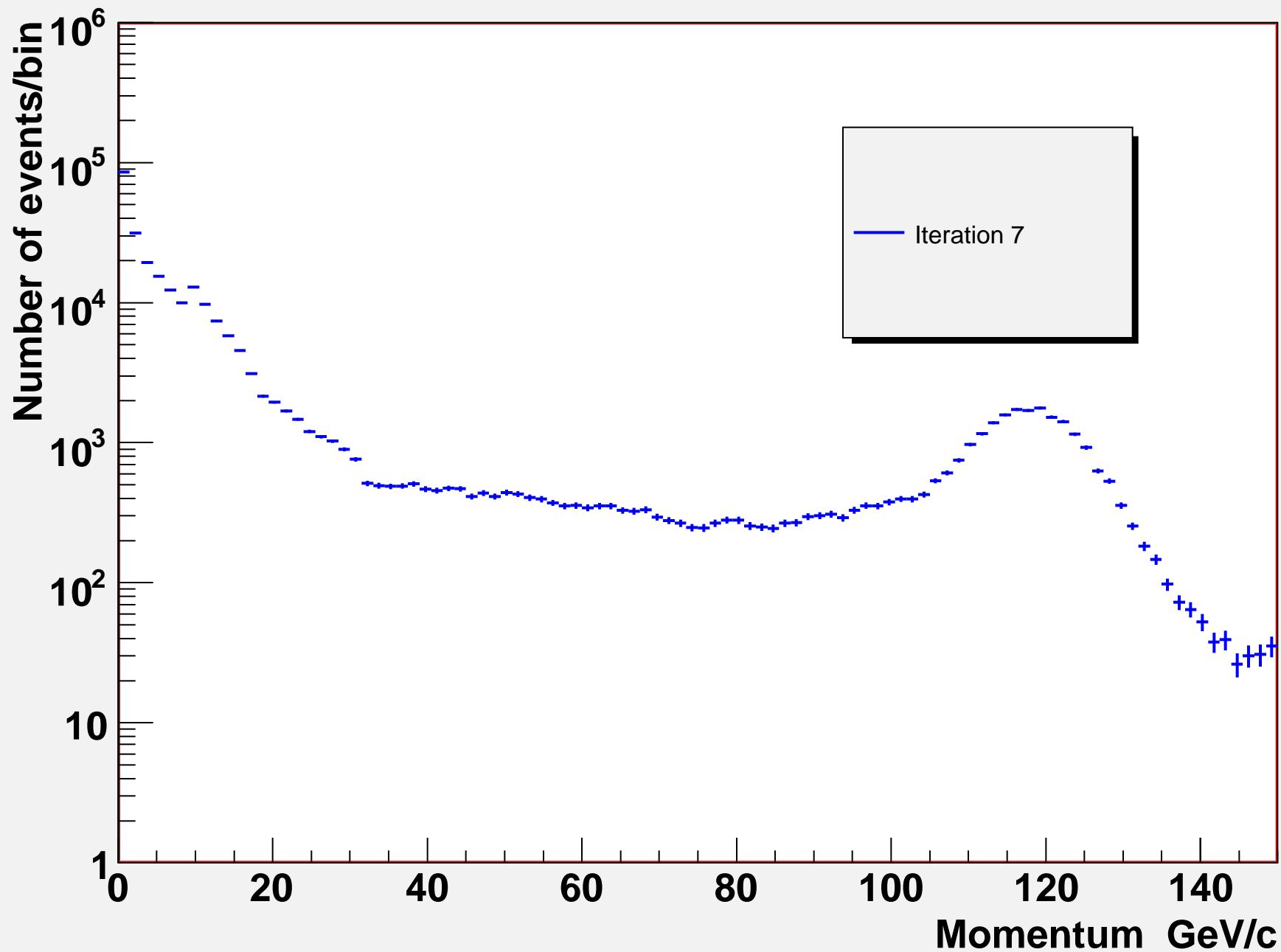
Momentum Distribution of Protons



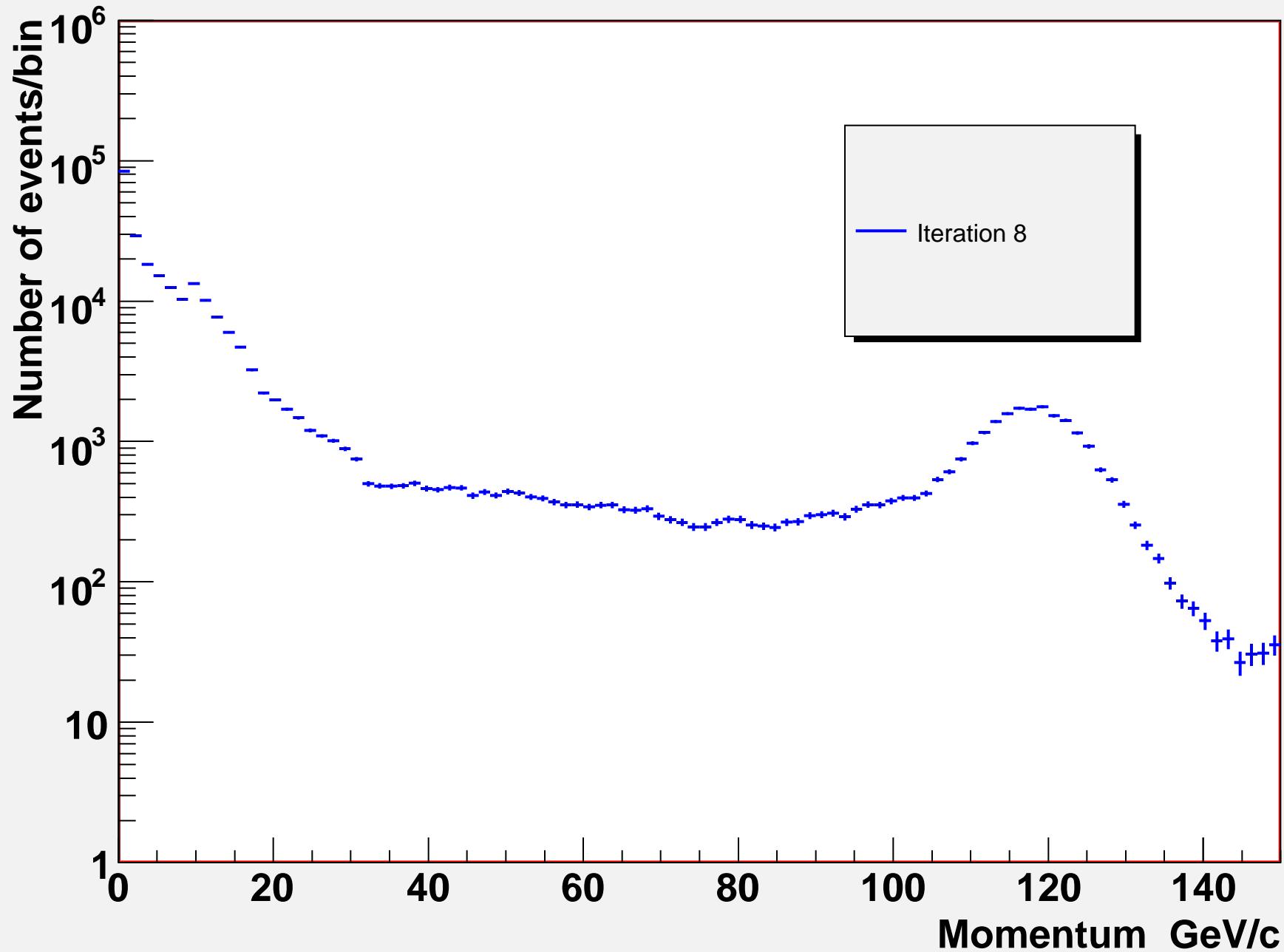
Momentum Distribution of Protons



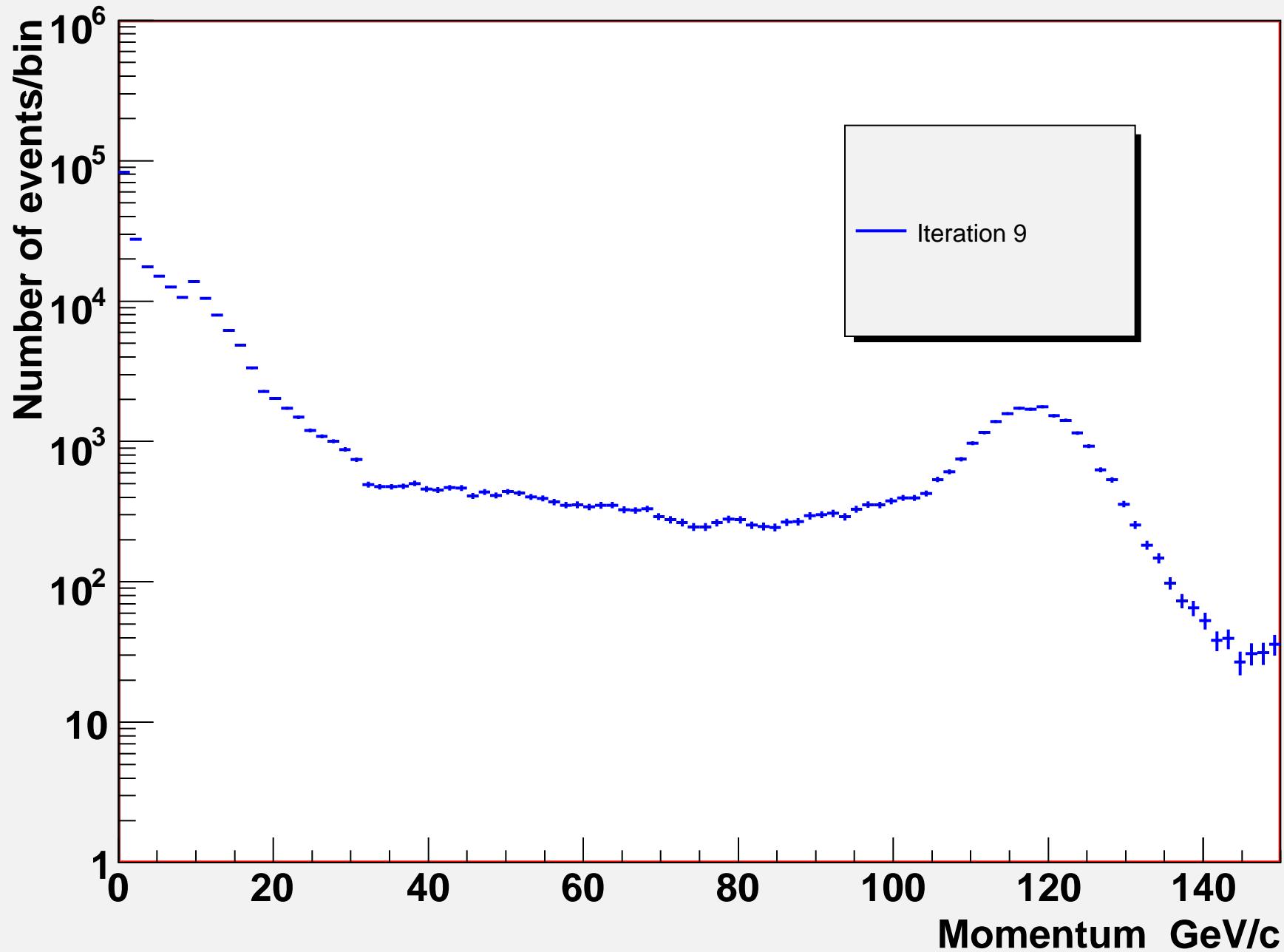
Momentum Distribution of Protons



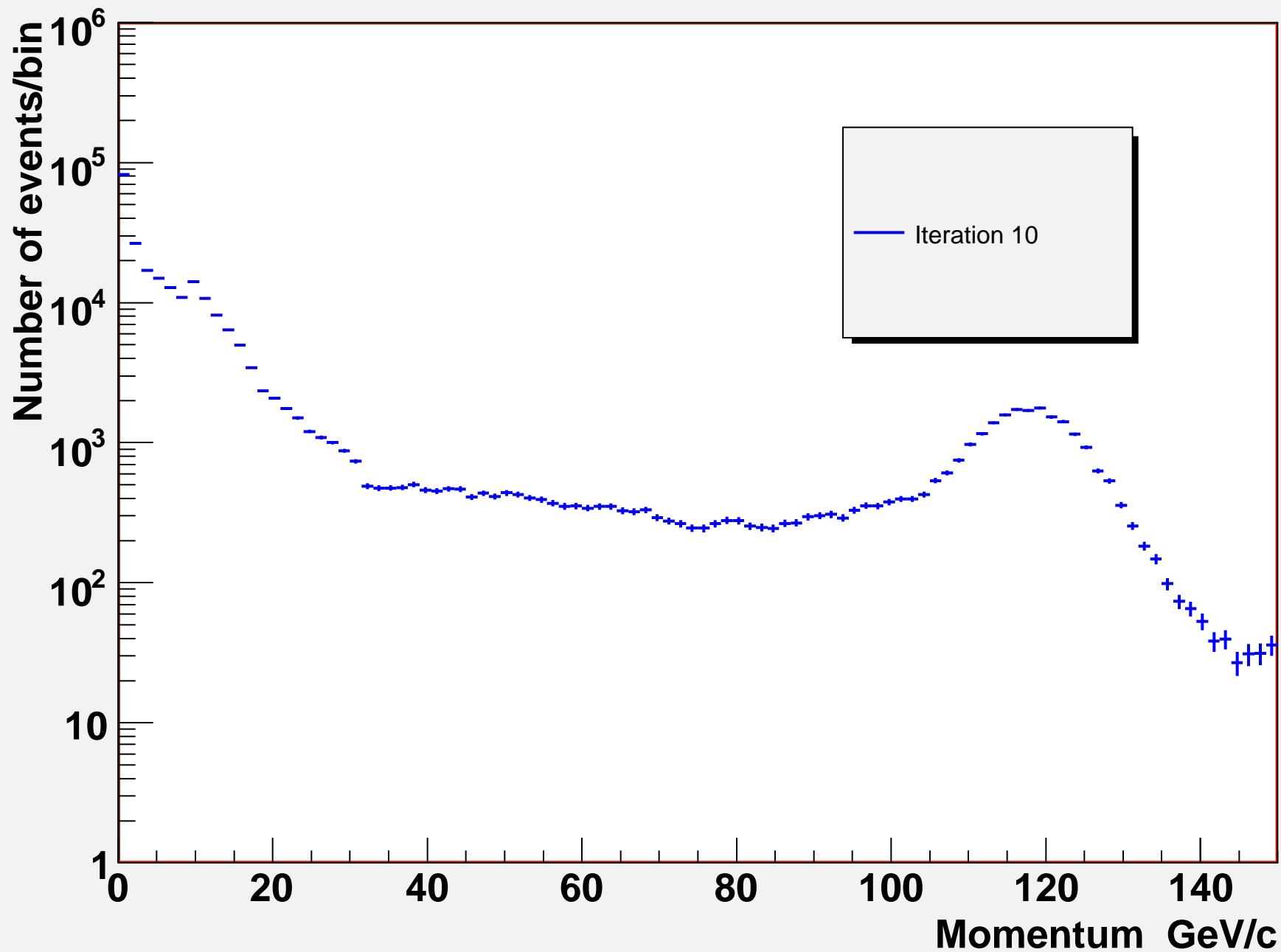
Momentum Distribution of Protons



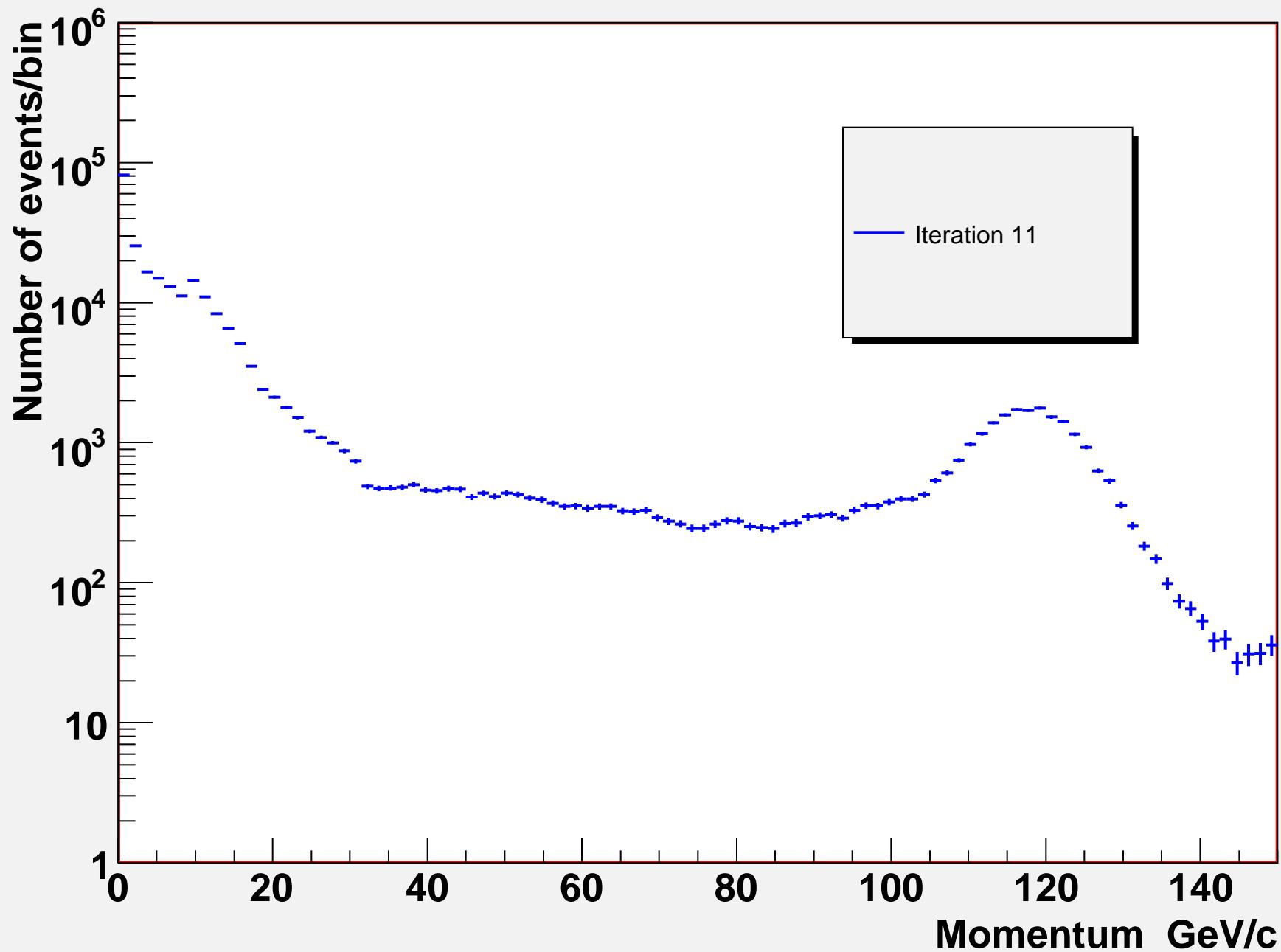
Momentum Distribution of Protons



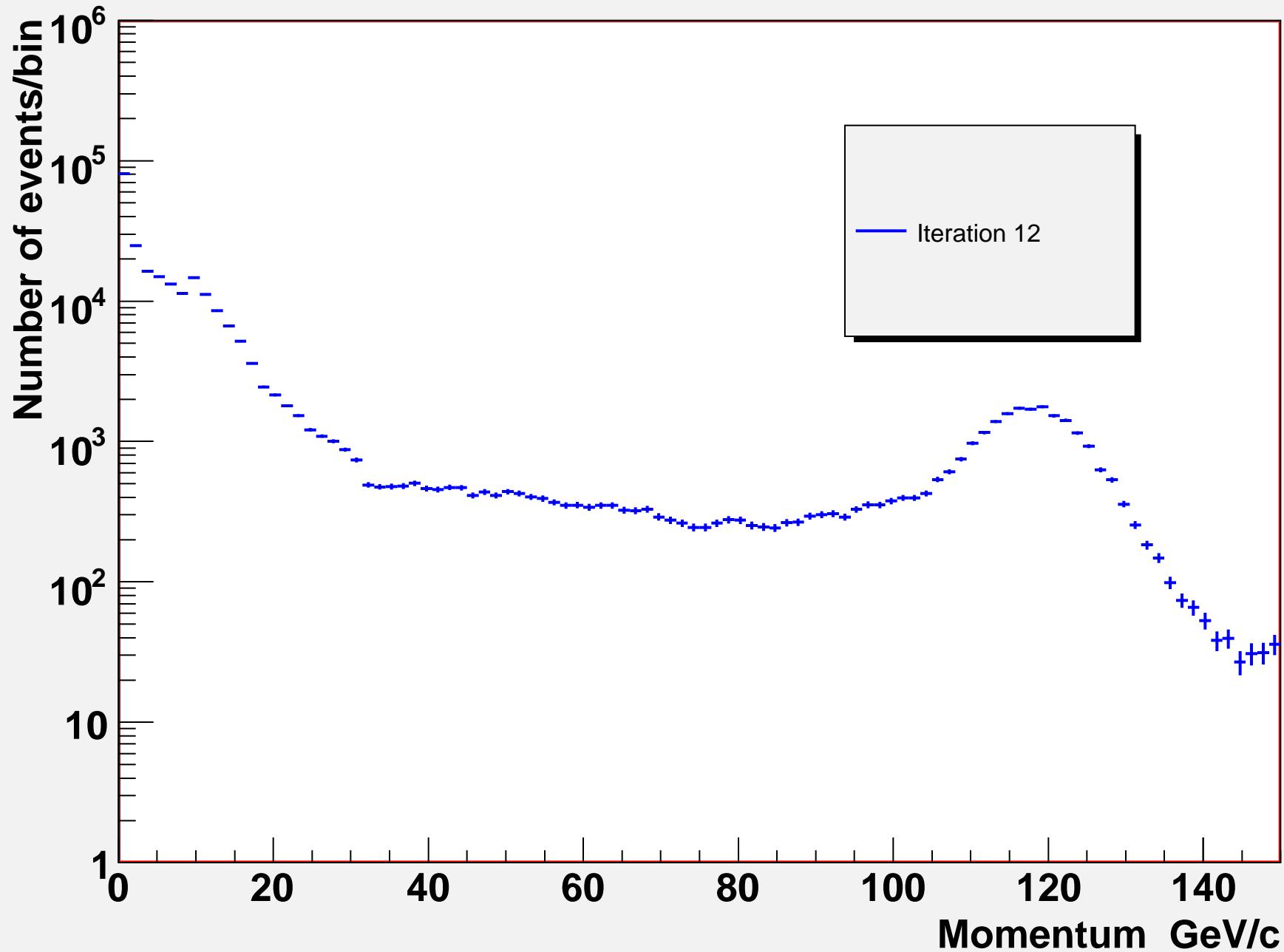
Momentum Distribution of Protons



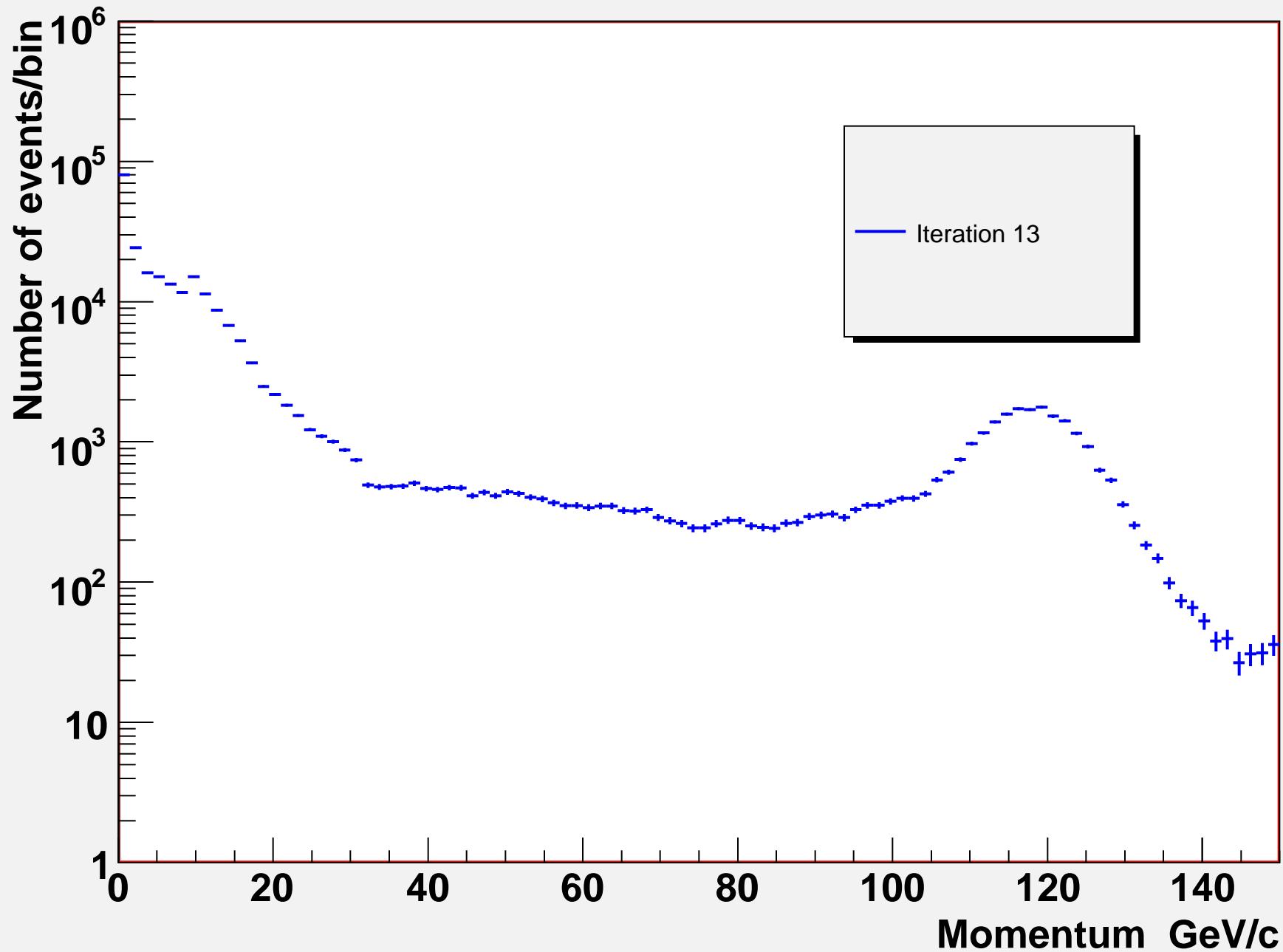
Momentum Distribution of Protons



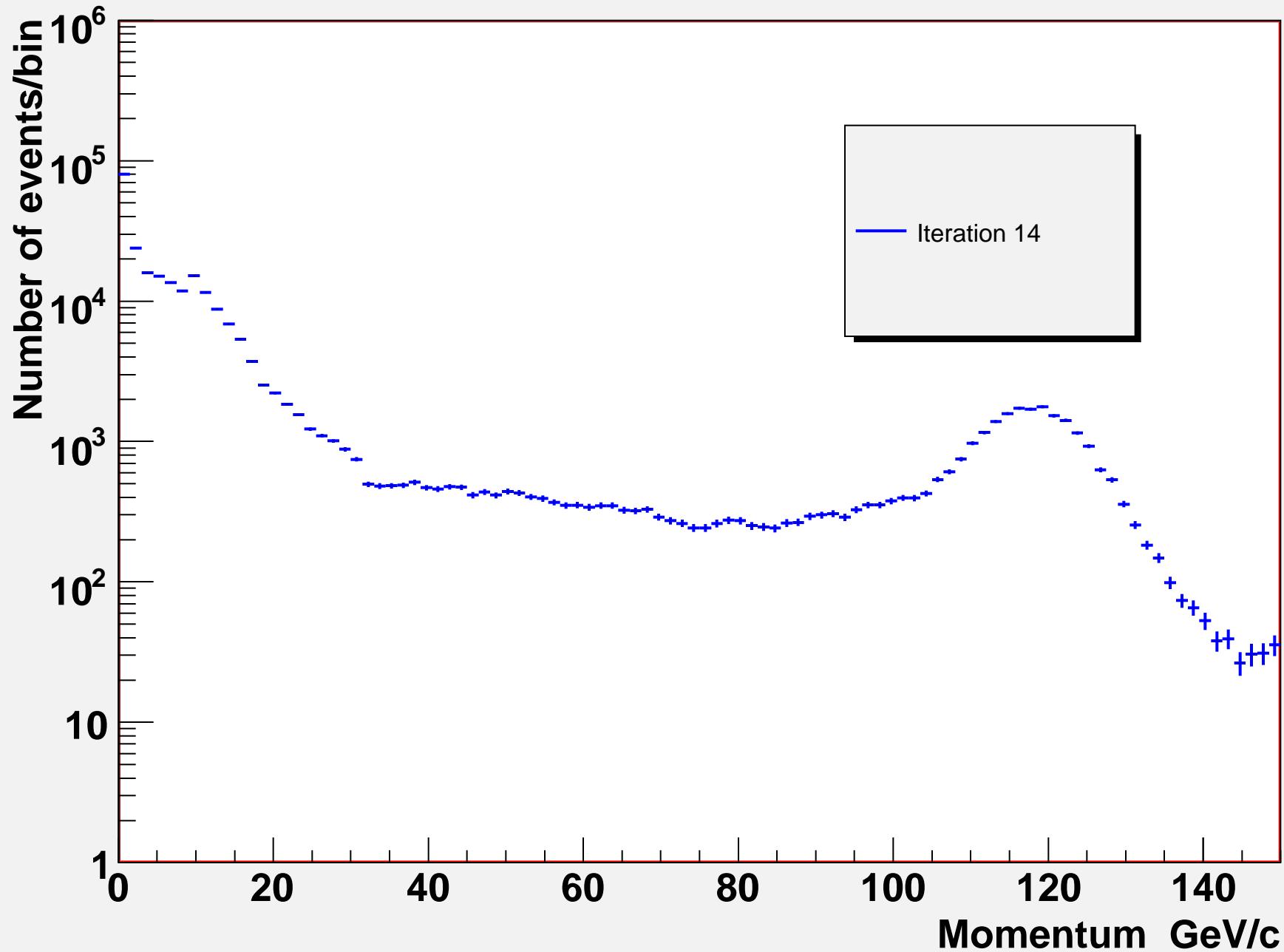
Momentum Distribution of Protons



Momentum Distribution of Protons



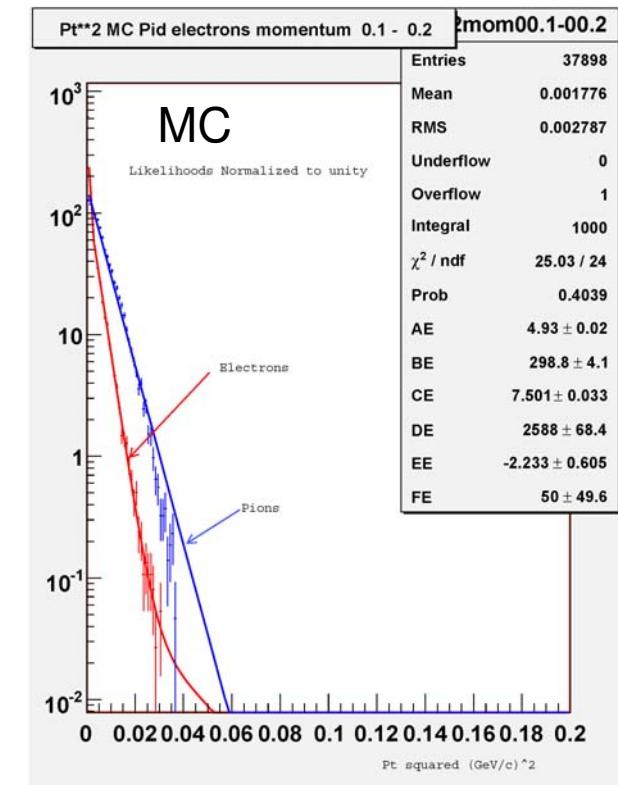
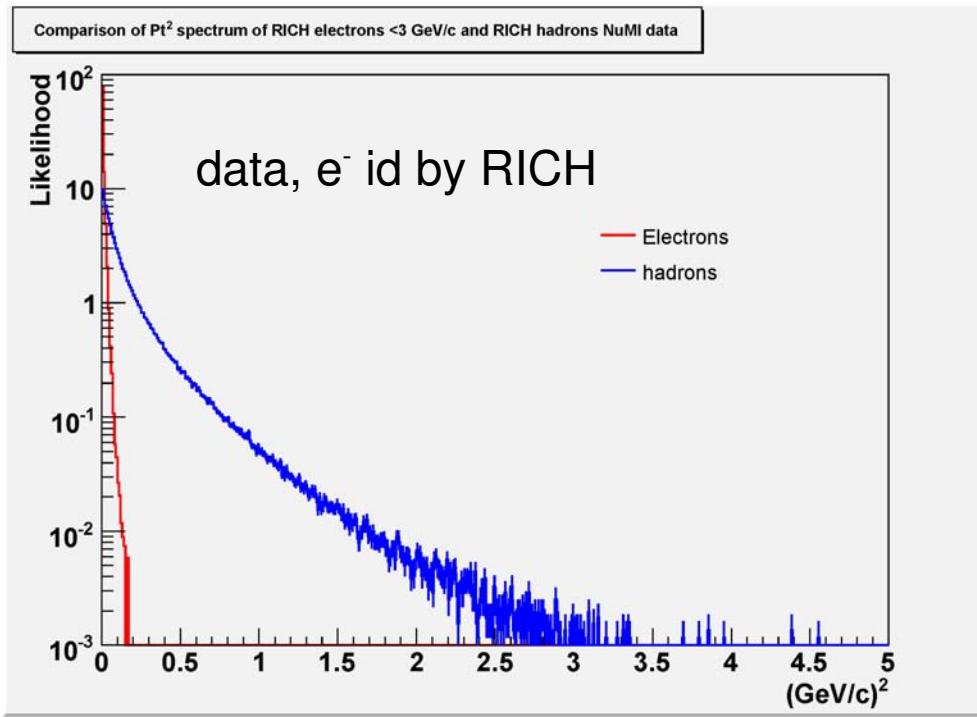
Momentum Distribution of Protons



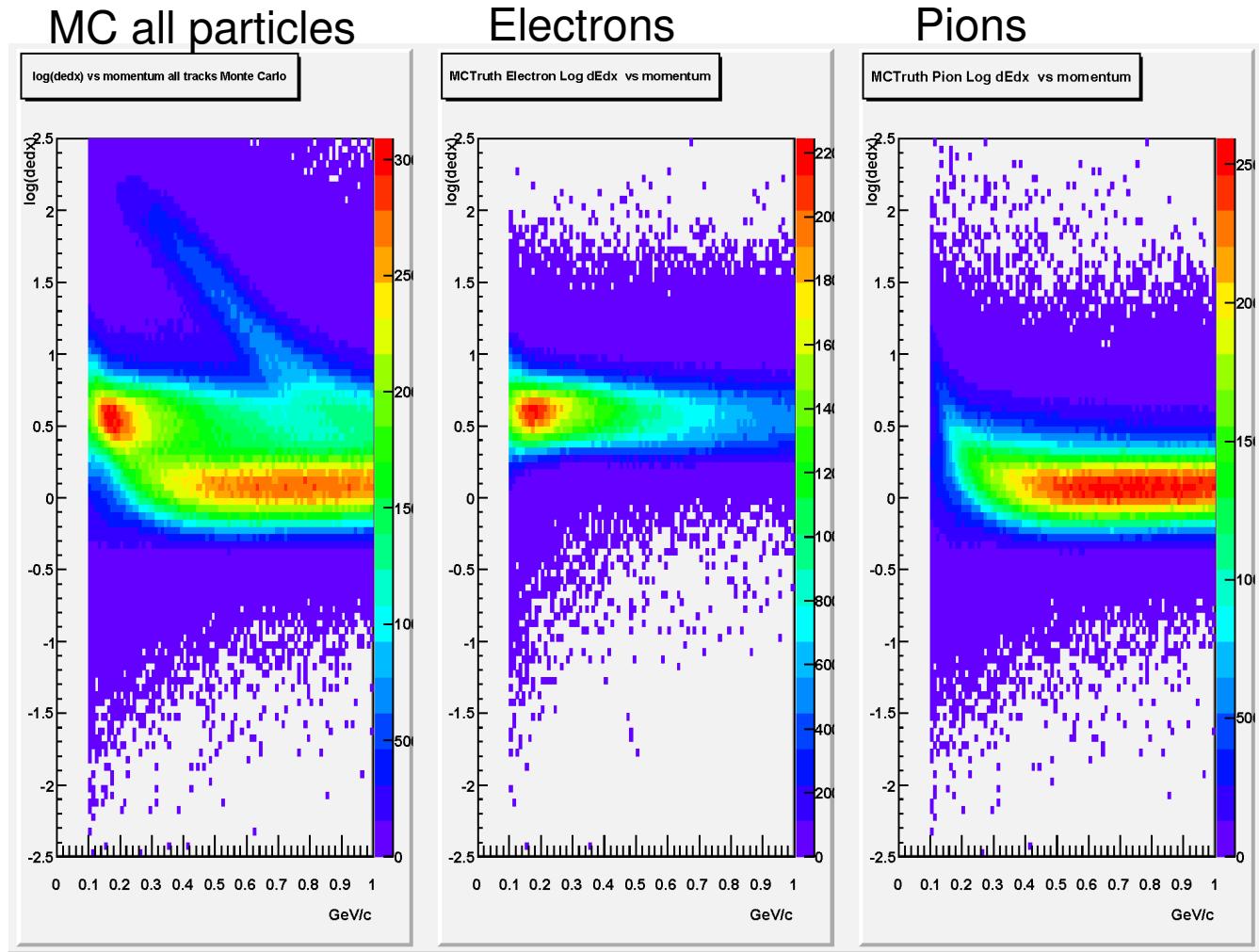
Separation of Electrons and Pions in MIPP – p_t^2 as a discriminant



- There is some distinction between electrons and pions in the TPC dE/dx and in the RICH below the pion threshold at 4.6 GeV/c. Pretty much everywhere else they are indistinguishable since they are both $\beta \sim 1$ particles.
- However, electrons arise from π^0 which decay to two photons which then convert again. At each stage the average p_t of the final state particle is lowered by \sim a factor of two. So for any given momentum an electron will have approximately a factor 4 less p_t than a charged pion. Verified in data and MC. Use p_t^2 likelihood as an added discriminant – R. Raja, MIPP-Doc 993



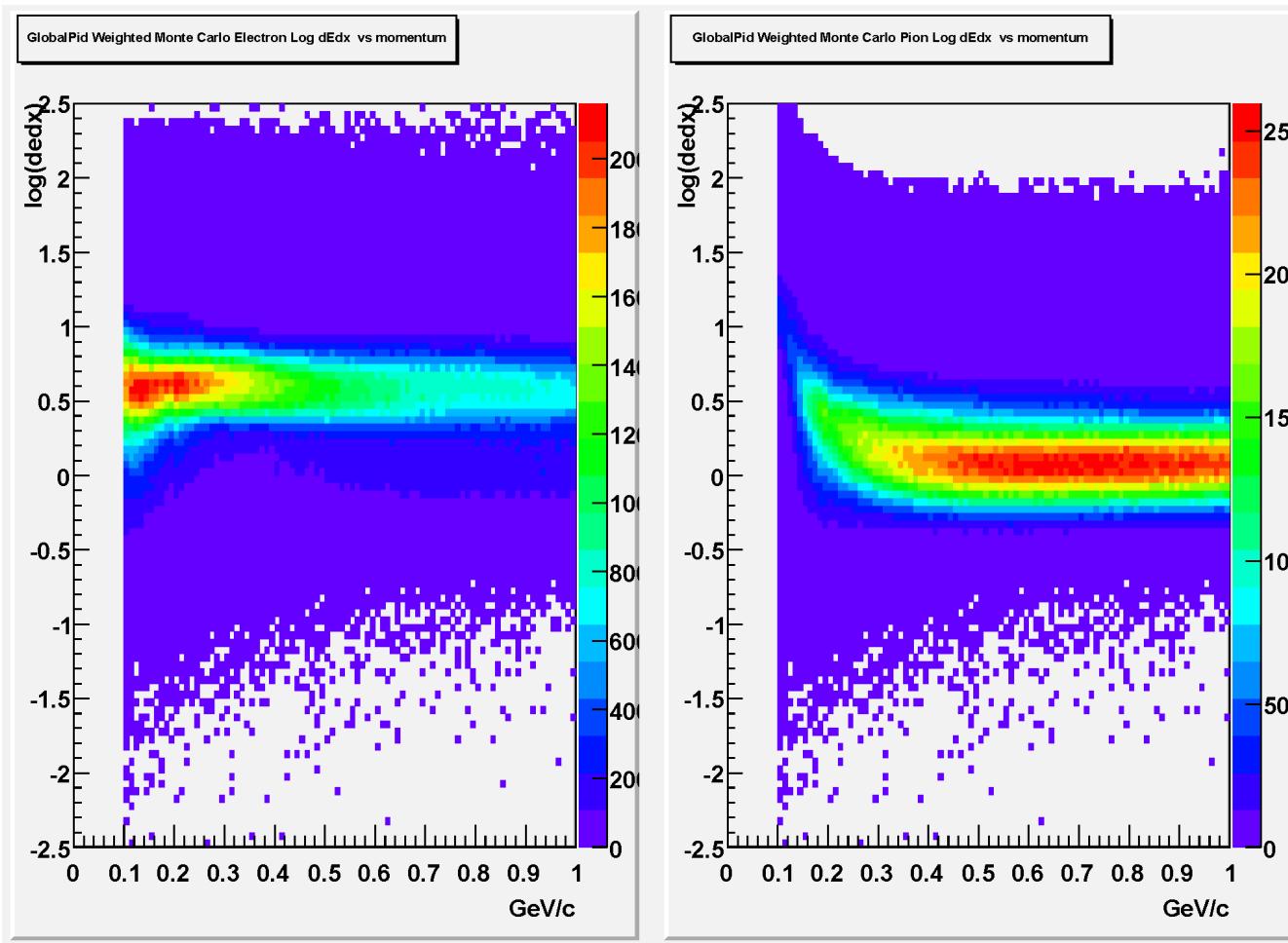
Monte Carlo Truth



Global Pid result with p_t^2 likelihood

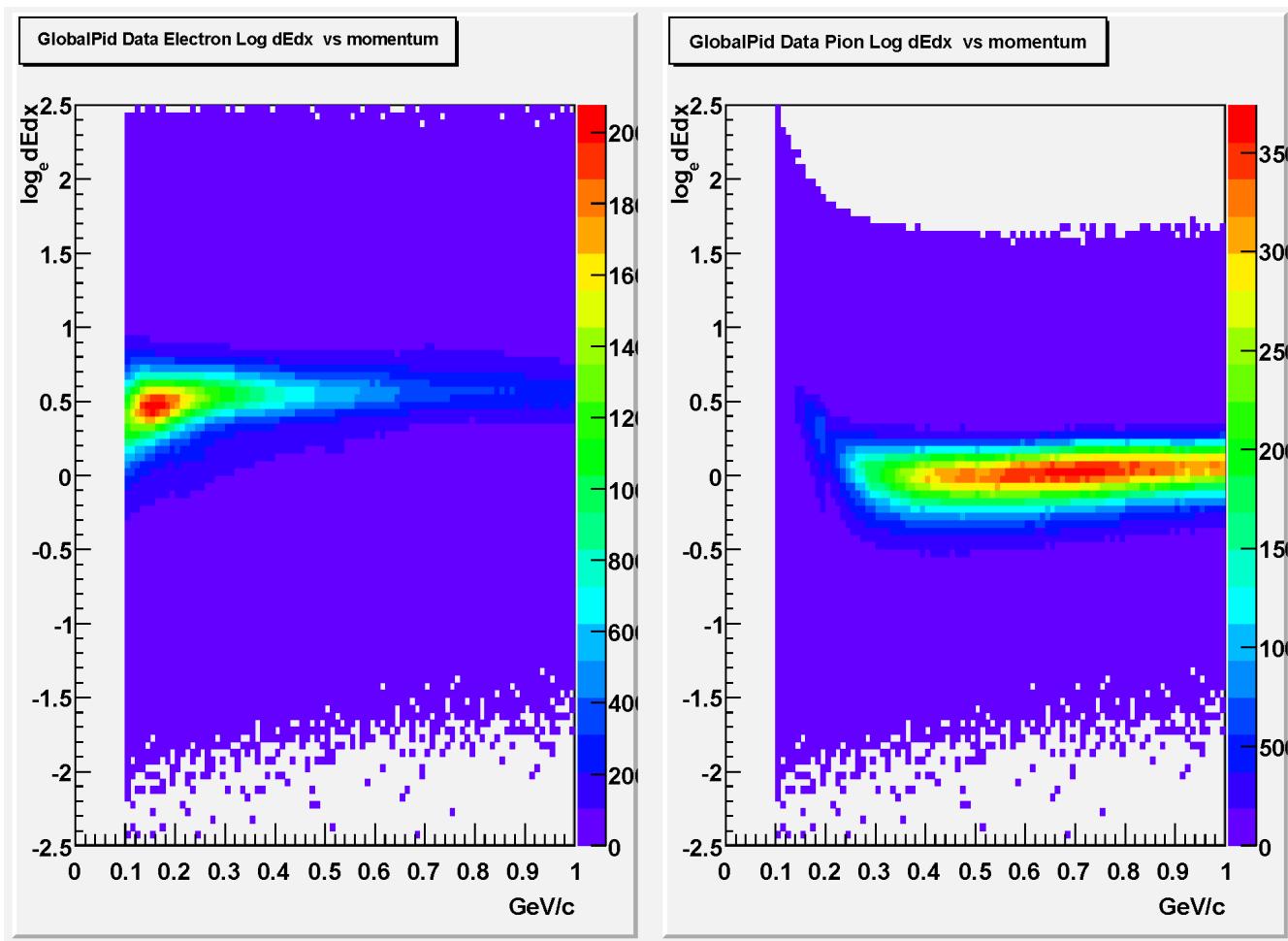


Monte Carlo

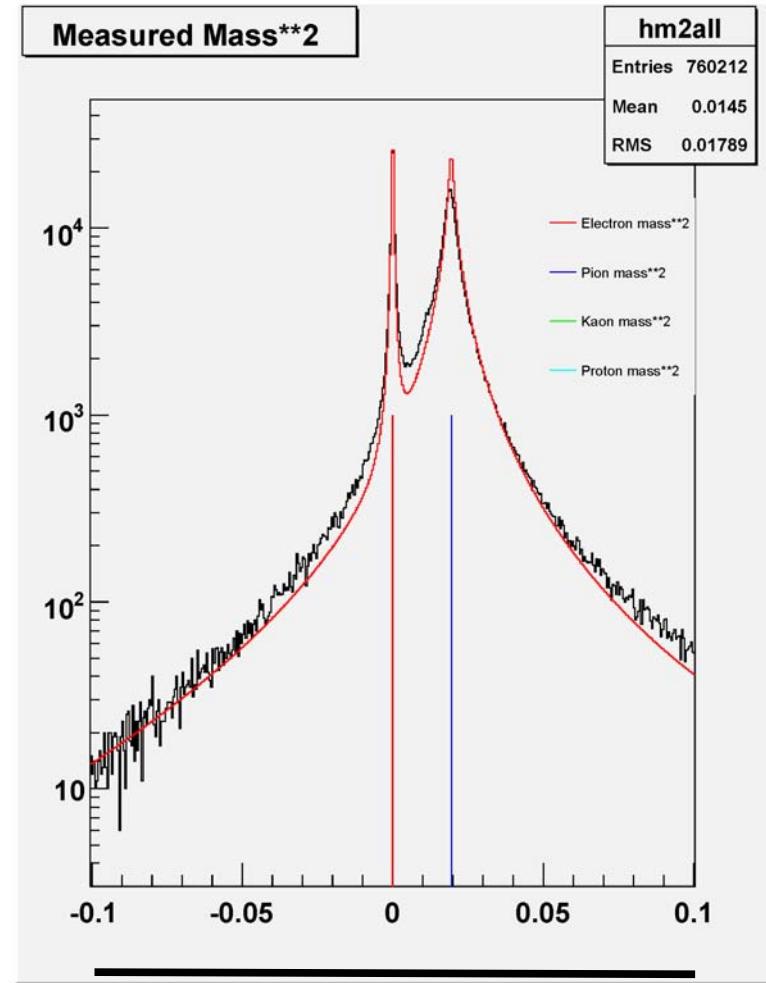
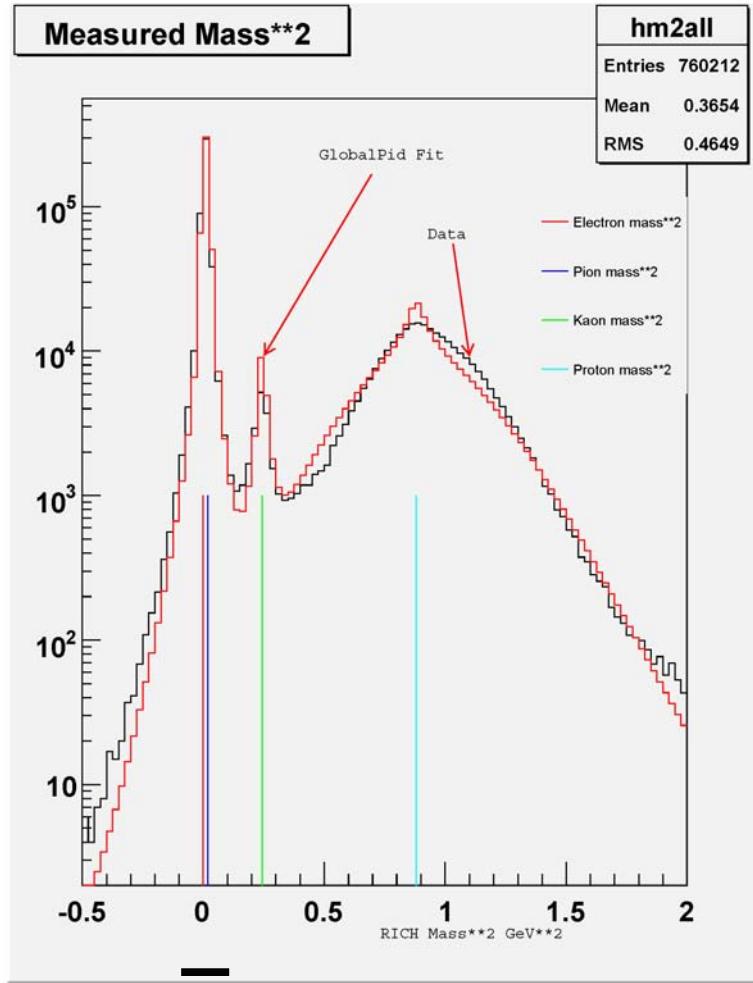


- Every track enters into all plots with its appropriate weight.
- Graphic cuts would have caused cut boundaries between the two.

Global Pid with NuMI target data



Comparing fits with data



- Bayes theorem gives expression for theoretical fit $P(x) = \sum_H P(x|H)P(H)$

NuMI target Global PID

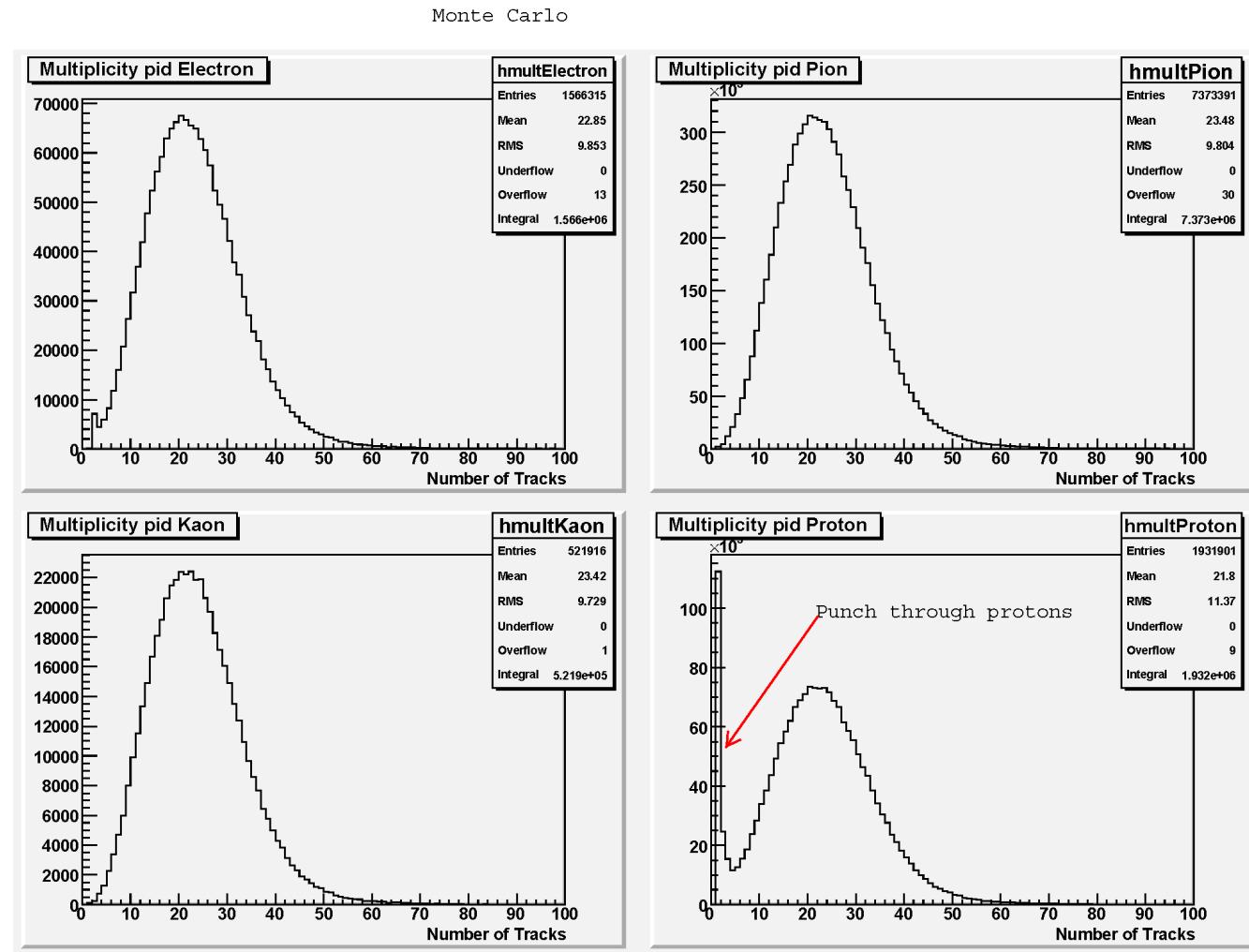


- We test the algorithm with Monte Carlo and compare the MC Truth against the output of the Global Pid.
- We add 2 more likelihoods to the RICH in addition to the one based on radius.
 - Punchthrough protons have low multiplicity.
In the high momentum bins they overwhelm the pions. We use multiplicity based likelihood to aid the pattern recognition.
 - Below the proton threshold and above the kaon threshold if there is no ring, it is likely a proton.

Multiplicity Distributions

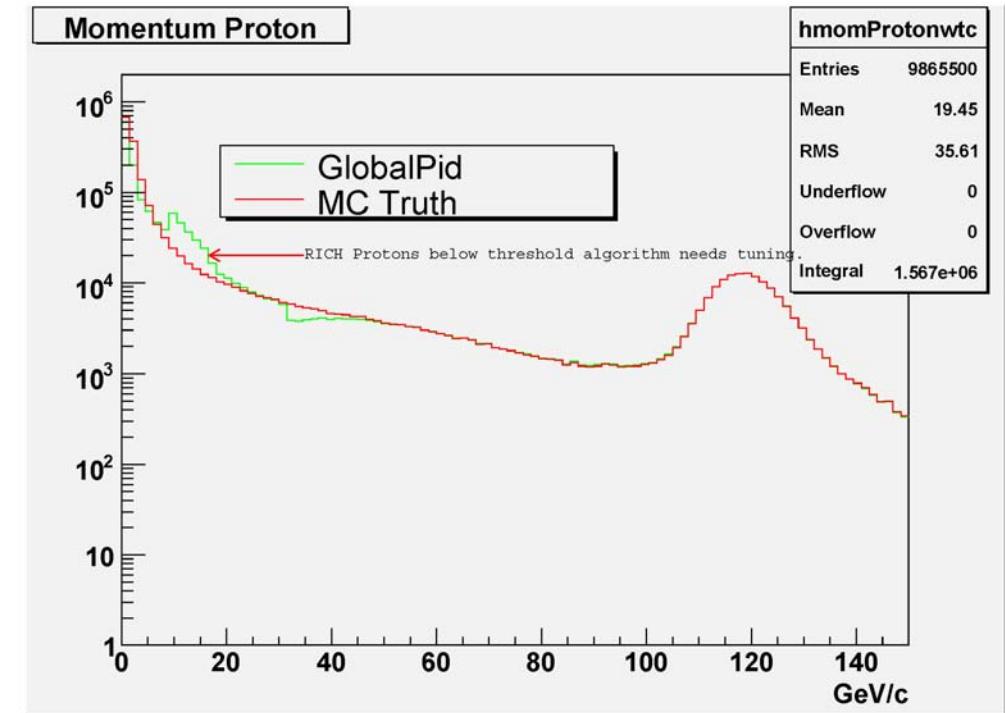
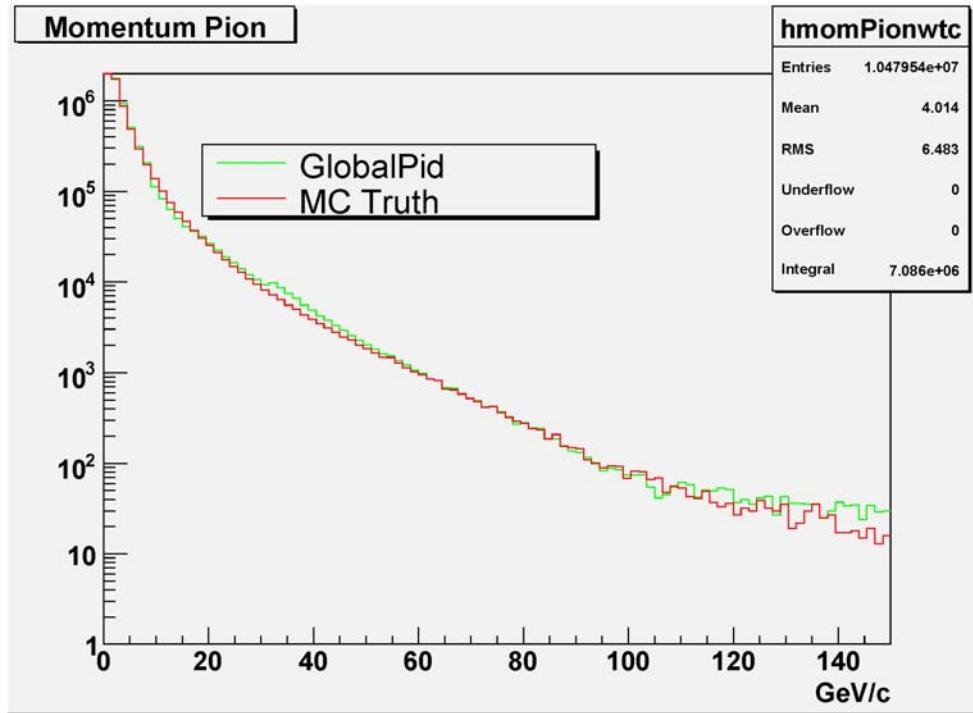
Monte Carlo

- Data shows similar low multiplicity excess.

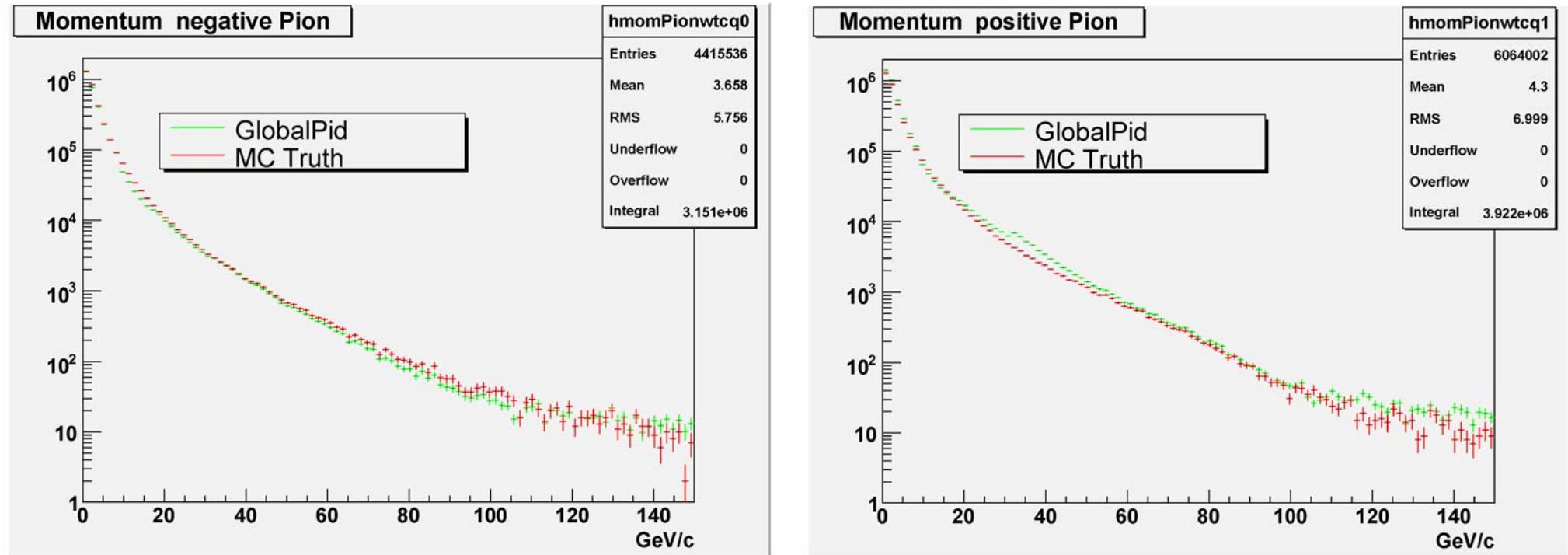


Monte Carlo Global Pid test

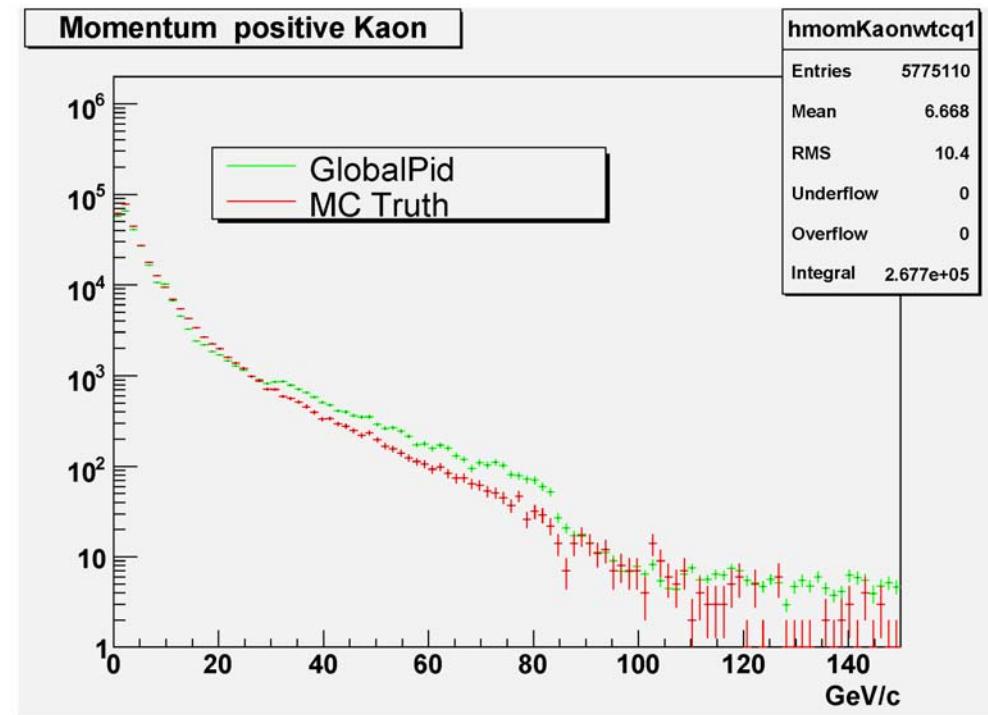
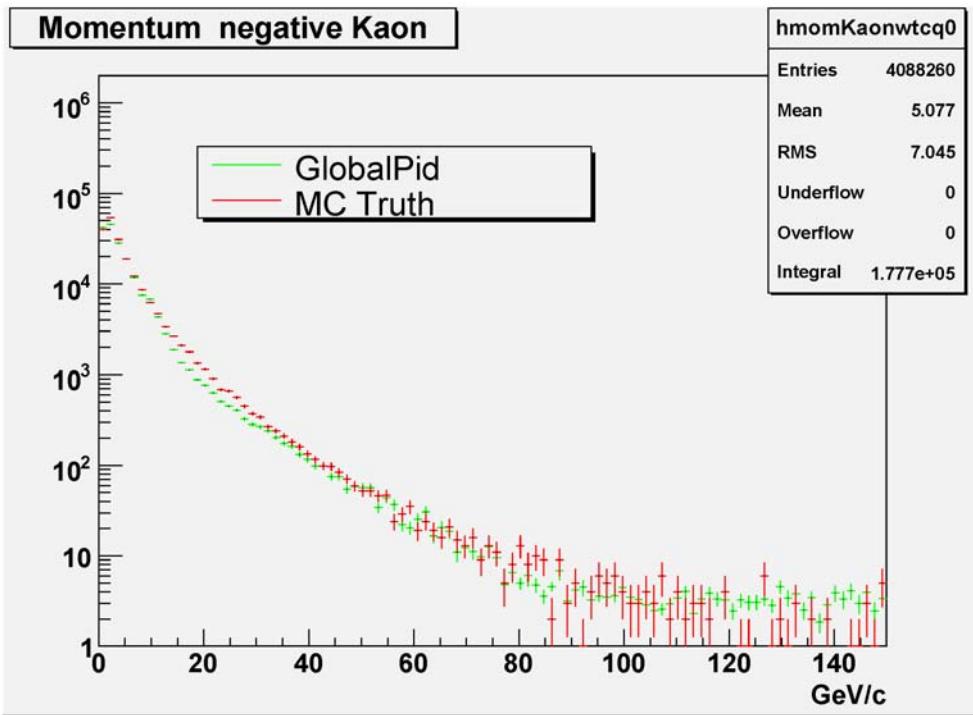
- Preliminary results. Lots of tuning to be done.



Separate positive and negative



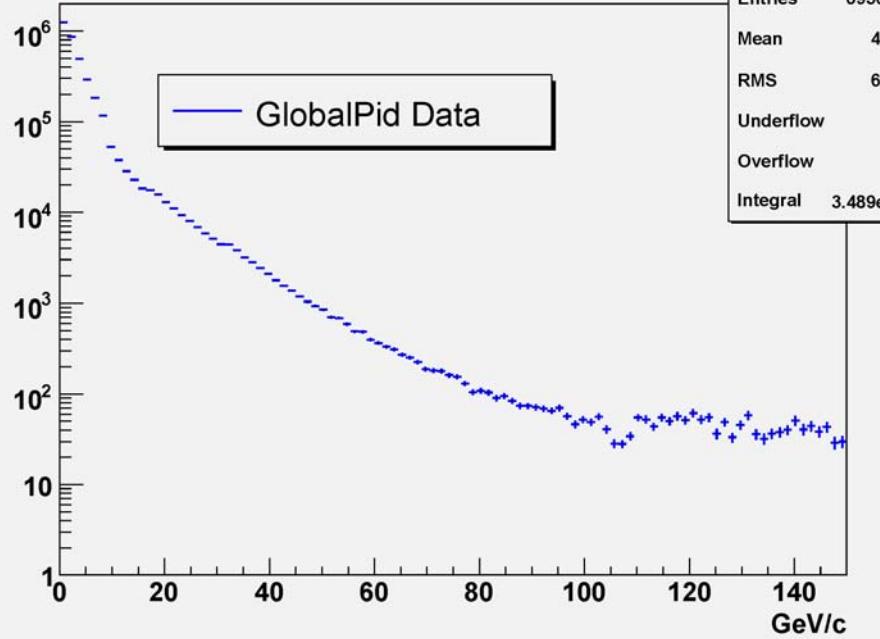
Kaons MC Global Pid comparison



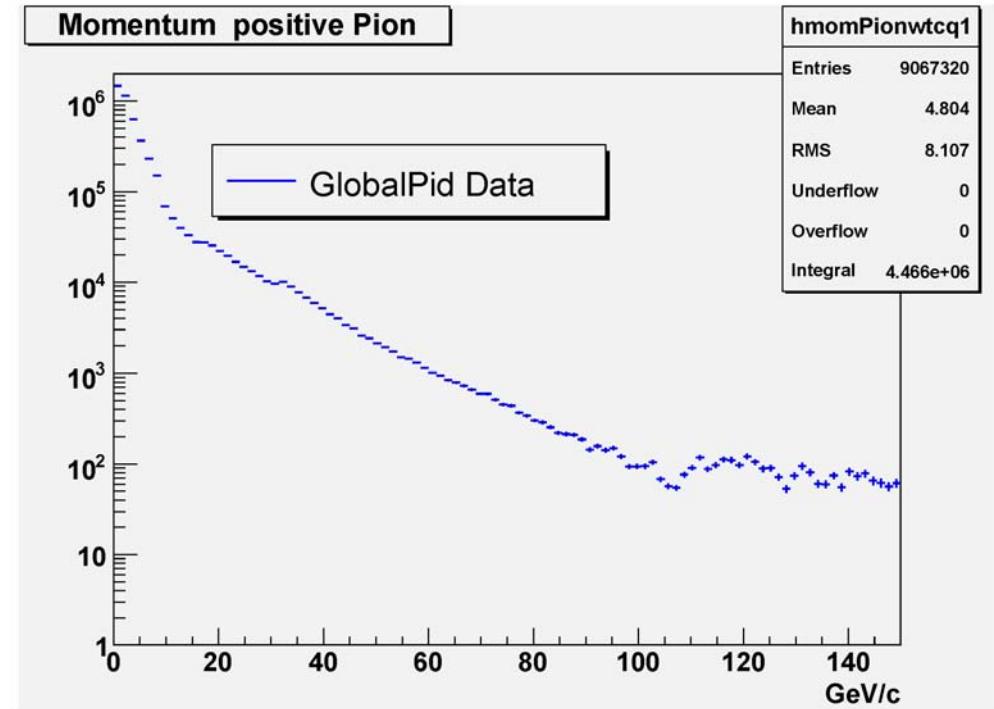
NuMI target analyzed by GlobalPid



Momentum negative Pion

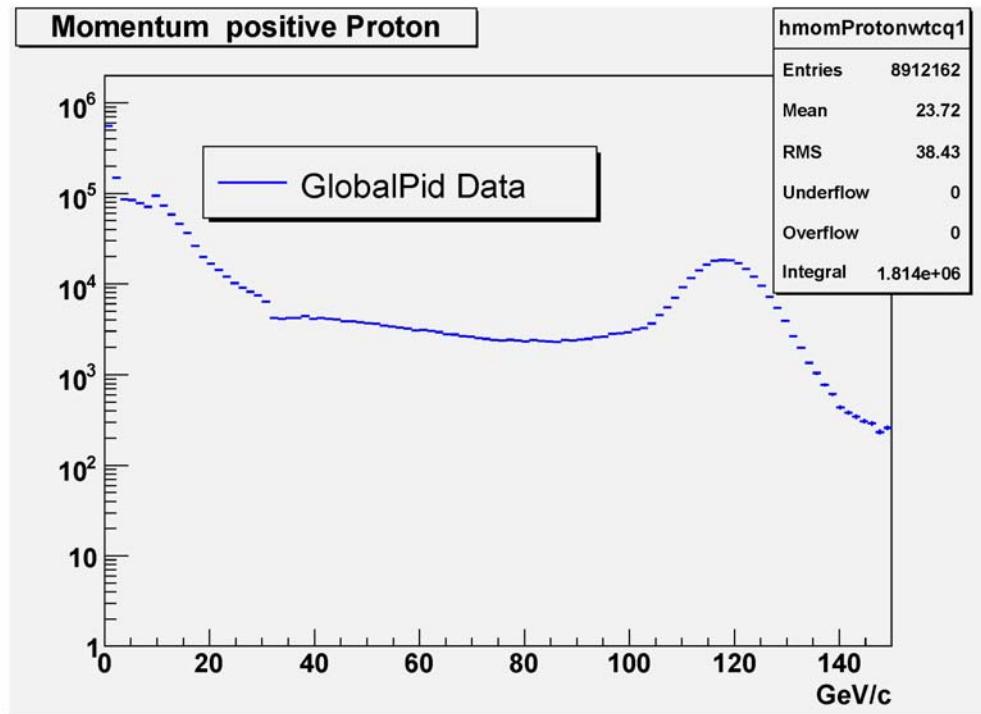


Momentum positive Pion



NuMI target analyzed by GlobalPid

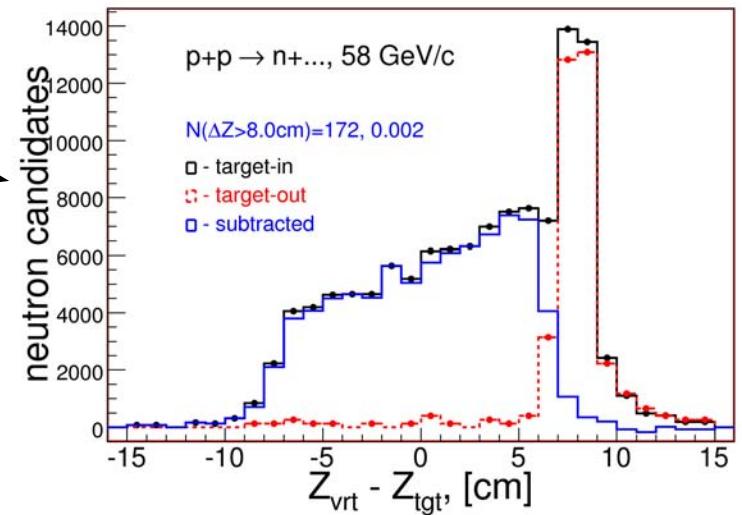
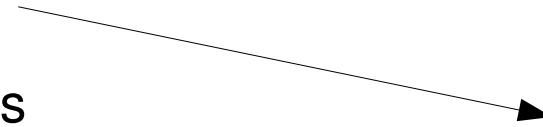
- Further work to be completed
 - Tweak various algorithms
 - As p_t increases, we lose acceptance. This results in a dilution of analysis power of algorithm. P_t dependence has to be studied before we make detailed MC data comparisons.
 - Estimate systematic errors
 - Do momentum smearing corrections
 - Minority particles ($K, p\bar{}$) after further study



Forward neutron inclusive cross sections

Forward neutron production cross sections

- Event quality cuts, neutron selection
- Target-out subtraction
- Acceptance, corrections
- Backgrounds
- Cross checks
- Results



- Status: Everything is very near final.
Working on some systematic errors.

Shown here: All results officially preliminary, but central values will not change and error bars will not grow.

Another Wine&Cheese: Full details

Neutron cross sections

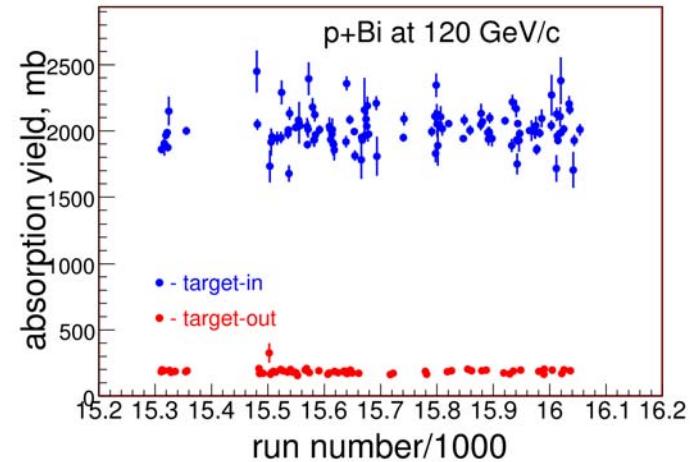
- Targets used: LH₂, Be, C, Bi, U
- Proton beam momenta used: 20, 58, 84, 120 GeV/c
- What we measure: inclusive neutron cross section p A → n + X

$$\sigma(p_n > p_{min}) = \frac{n_n(tgt-in) - n_n(tgt-out)}{N_{beam} \times \epsilon_{combined}} \times \frac{1}{n_t} \times 10^4 \text{ mb}/(\text{GeV}/c)$$

- $n_n(tgt-in)$ – neutron candidate events with target in place
 $n_n(tgt-out)$ – neutron candidate events without target
- N_{beam} – proton beam flux
- n_t – number of target nucleons per cm²
- $\epsilon_{combined}$ – trigger-, cut-efficiencies, neutron losses and backgrounds

Event and neutron selection

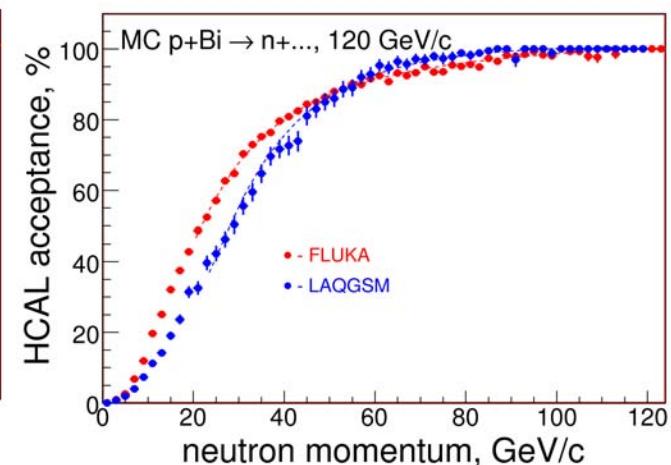
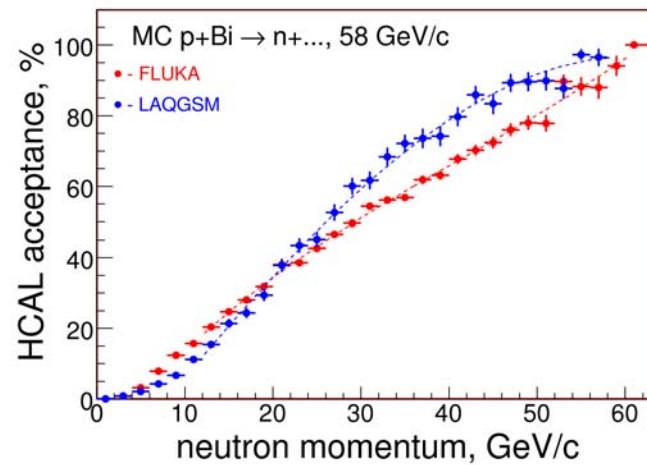
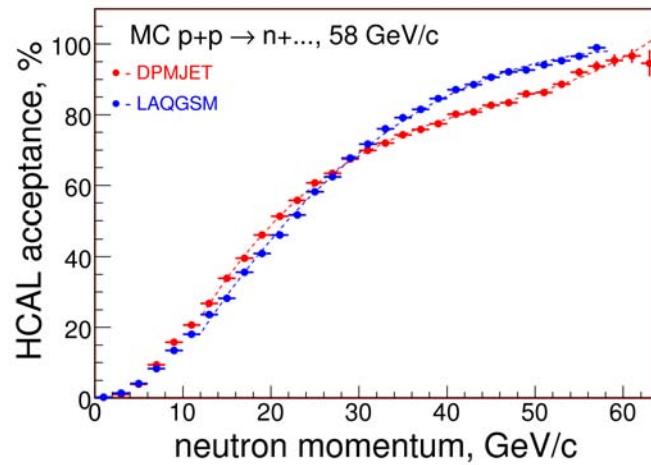
- Data quality cuts (fraction of event after cut, 120GeV/c thin targets)
 - Calorimeter worked well 100%
 - Trigger scintillator installed and working (removes some early data) 100%
 - Less than 30 tracks in event (removes beam backgrounds) 96.3%
 - Single beam track with good timing 81.4%
 - Primary vertex is in target 96.7%
 - Beam particle is proton 99.3%
- Reconstruction quality cuts
 - Sum of particle momenta < 1.1 beam-momentum 93.7%
- Neutron candidates
 - Energy excess in calorimeter above threshold
 - Excess means larger energy deposit than charged tracks (if any) pointing to it.



Neutron cross sections

Acceptance

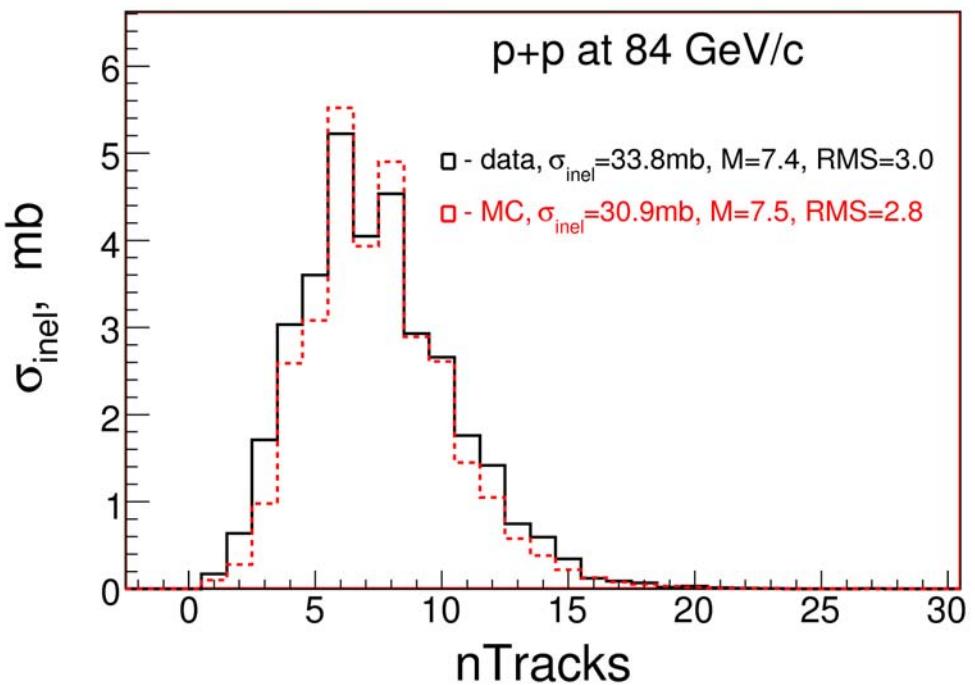
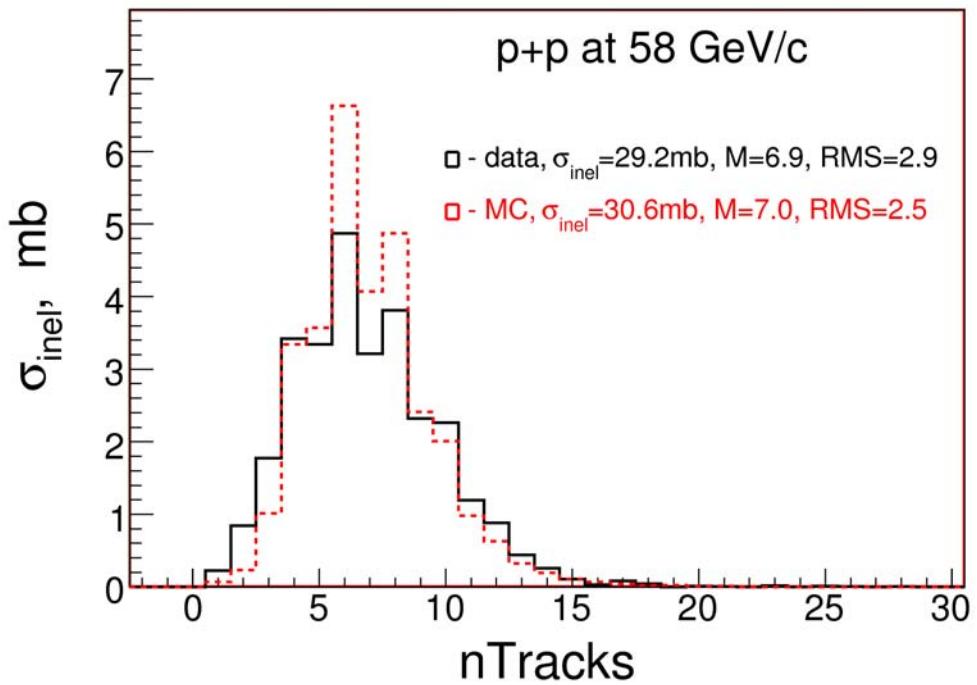
- Different event generators result in different acceptance
 - Due to differences in p_T distribution
 - Enters as a systematic error in some of the results
 - Large differences between DPMJET/FLUKA and LAQGSM
 - Input to MC generators needs to improve – That's why we are doing MIPP



Neutron cross sections

Cross check

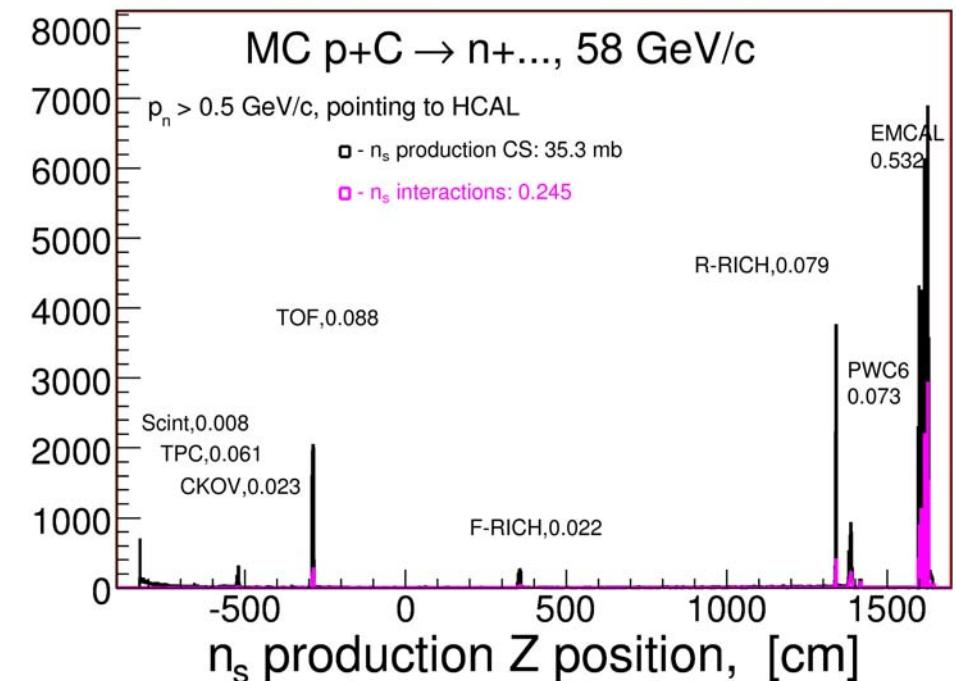
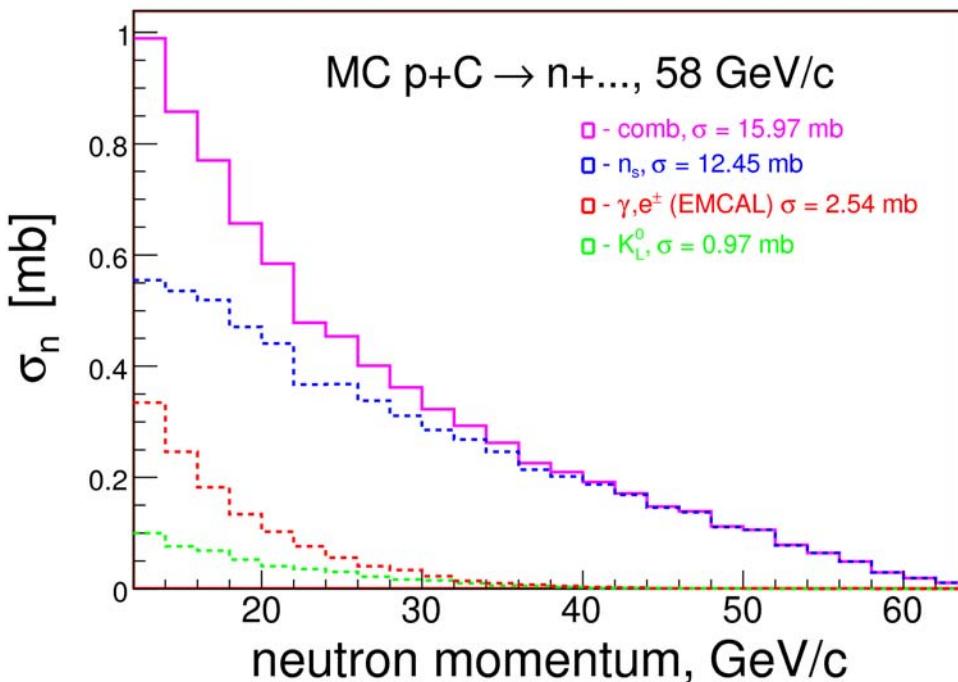
- Look at well known p-p cross sections and multiplicities to validate
 - Beam flux determination
 - Event reconstruction
 - Detector simulation



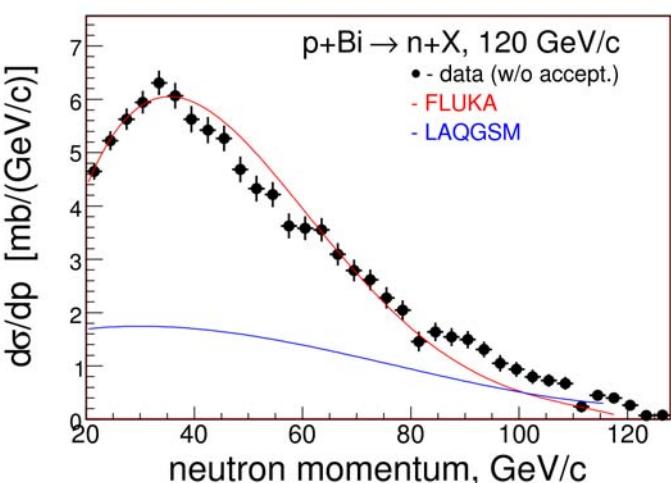
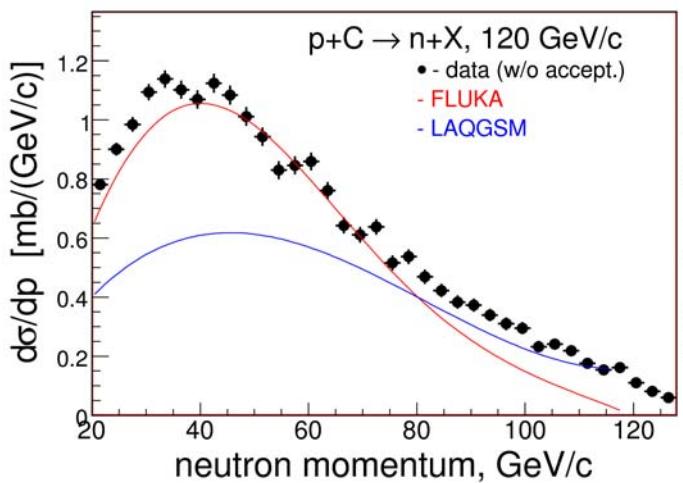
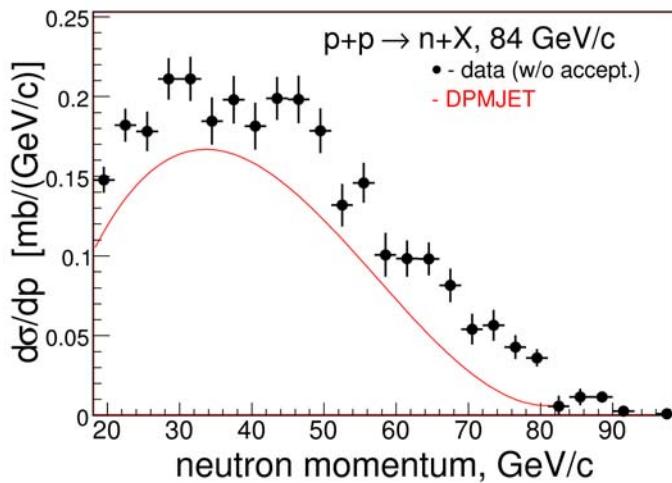
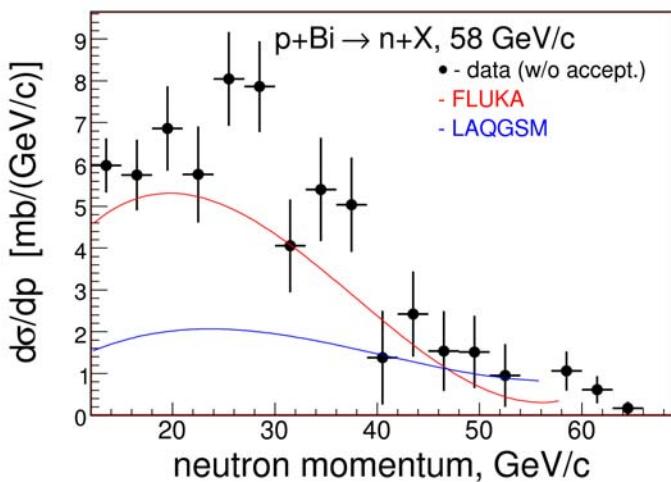
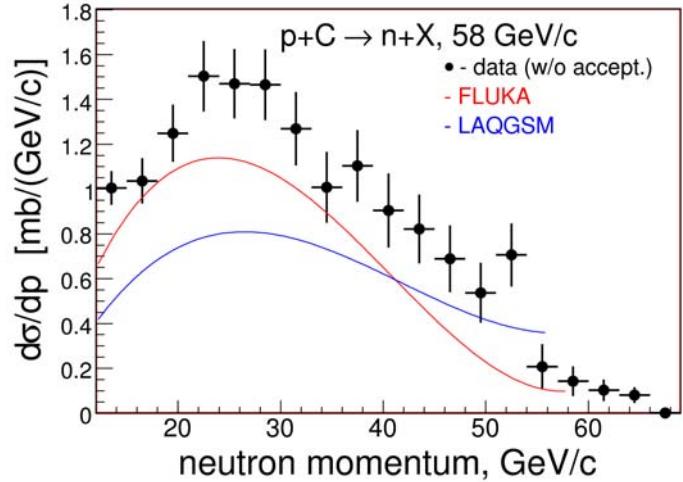
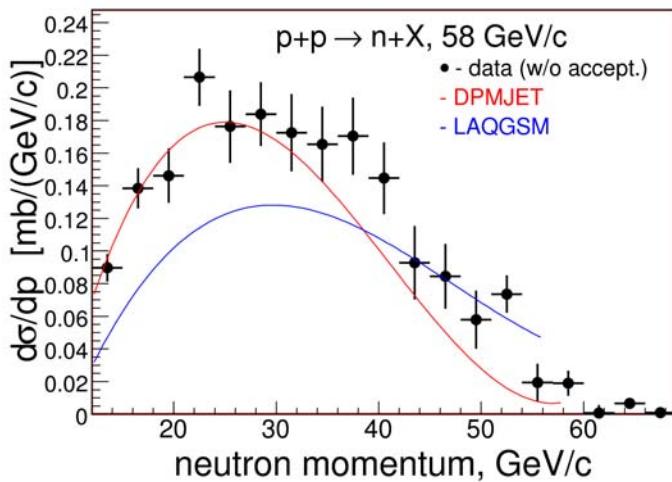
Neutron cross sections

Backgrounds

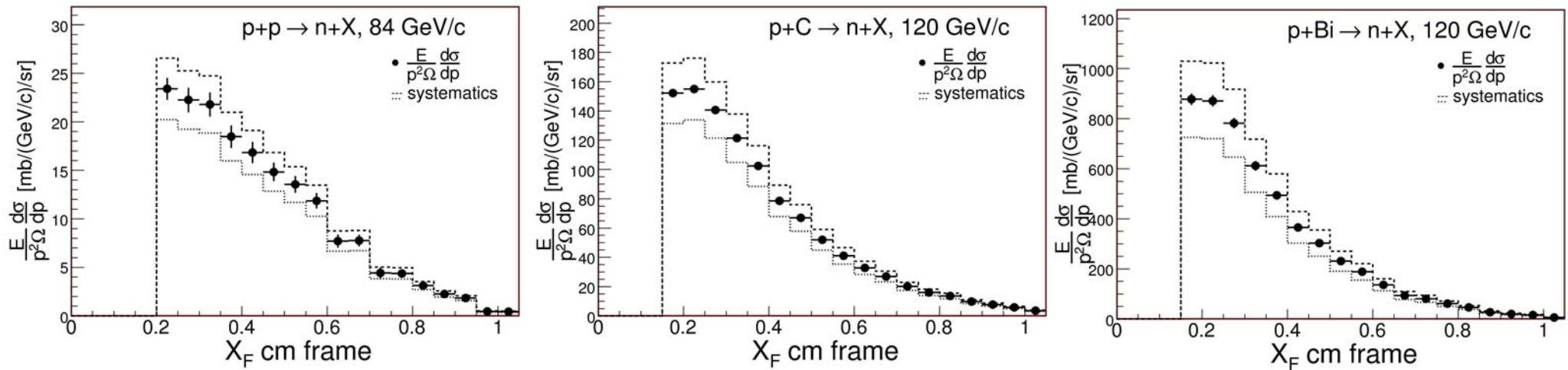
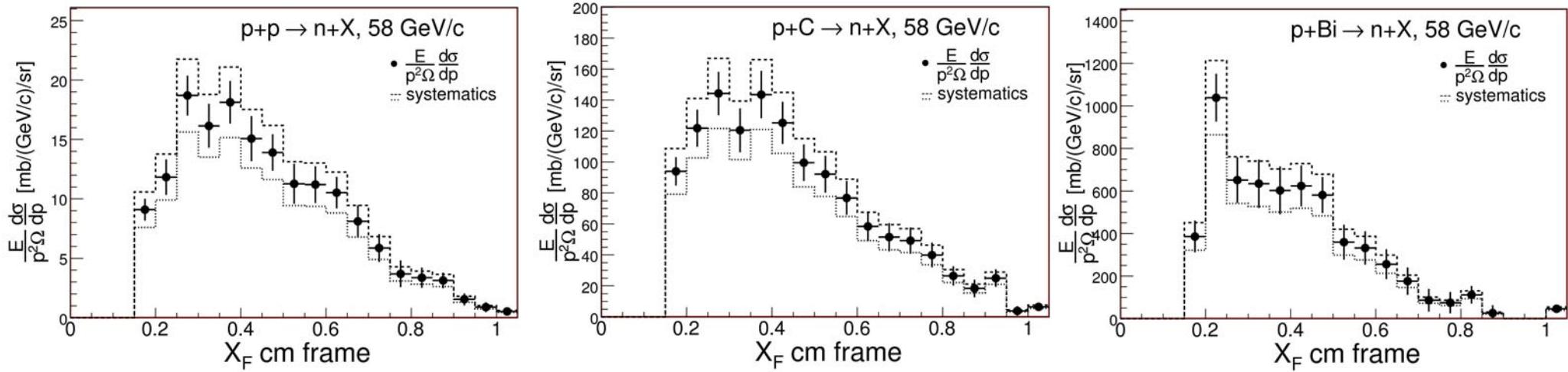
- Background composition for 58GeV/c on carbon (other momenta and targets are similar)
 - Secondary neutrons are largest background
 - Produced in ToF wall material and RICH
 - Also consider if these secondary neutrons interact before reaching the HCAL



Neutron cross sections some cross section results

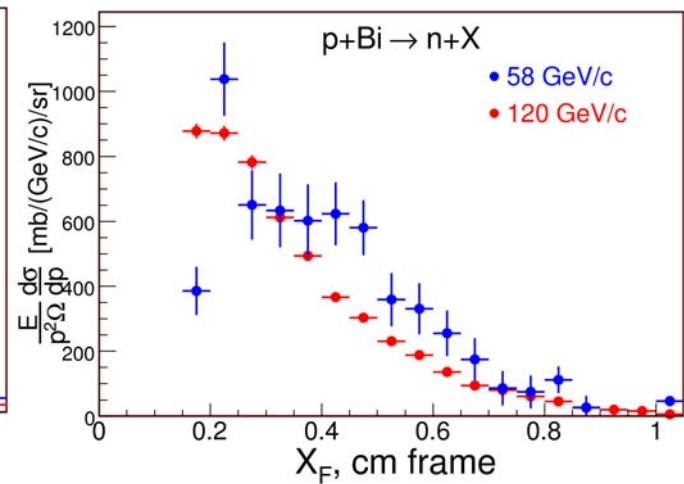
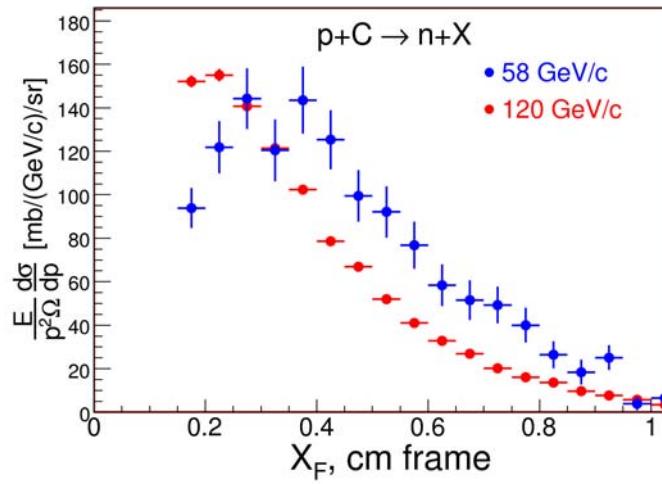
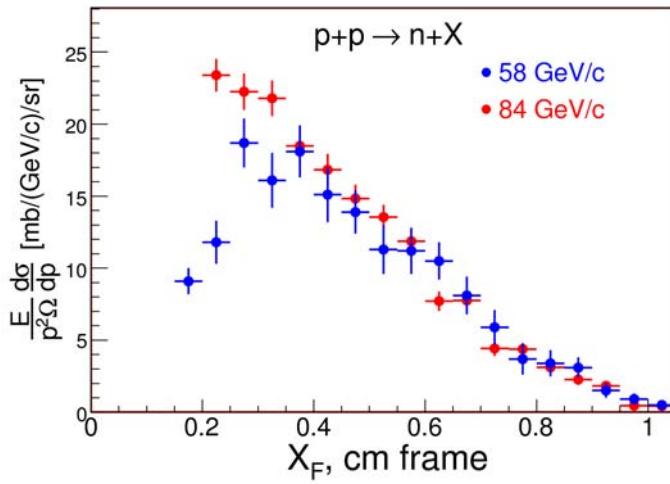


Neutron cross sections invariant cross section



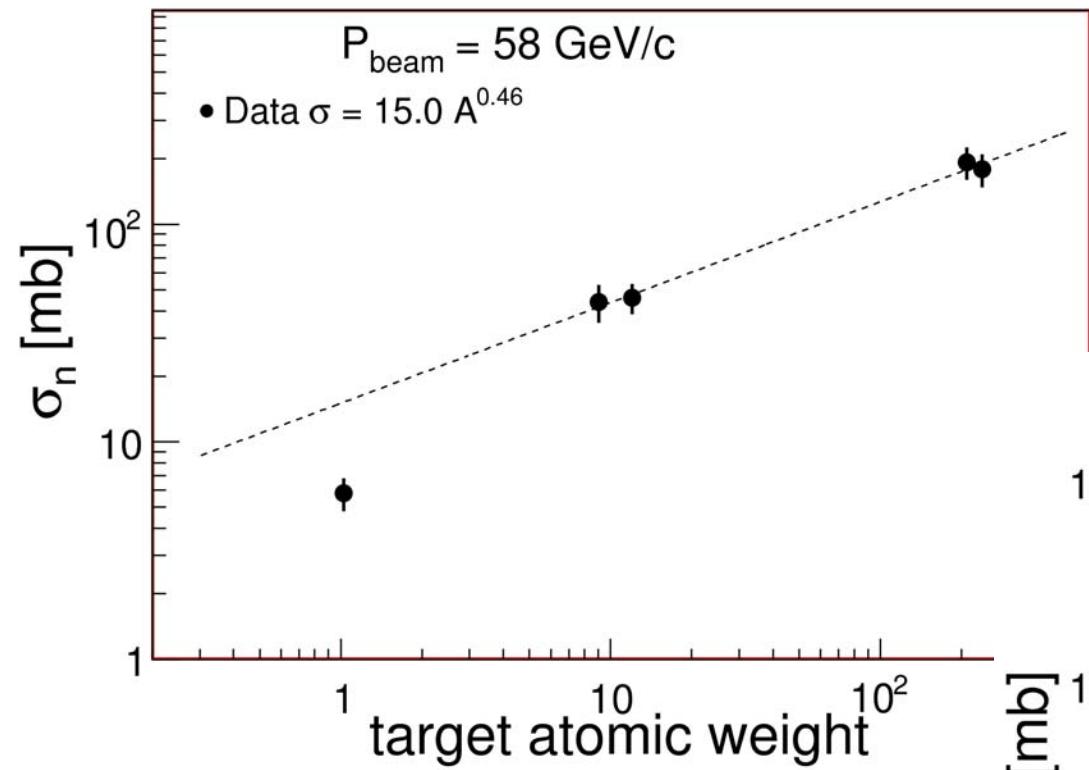
Neutron cross sections invariant cross section scaling

- Scaling of the Lorentz invariant cross section
 - Observed for p+p
 - Not observed for p+A

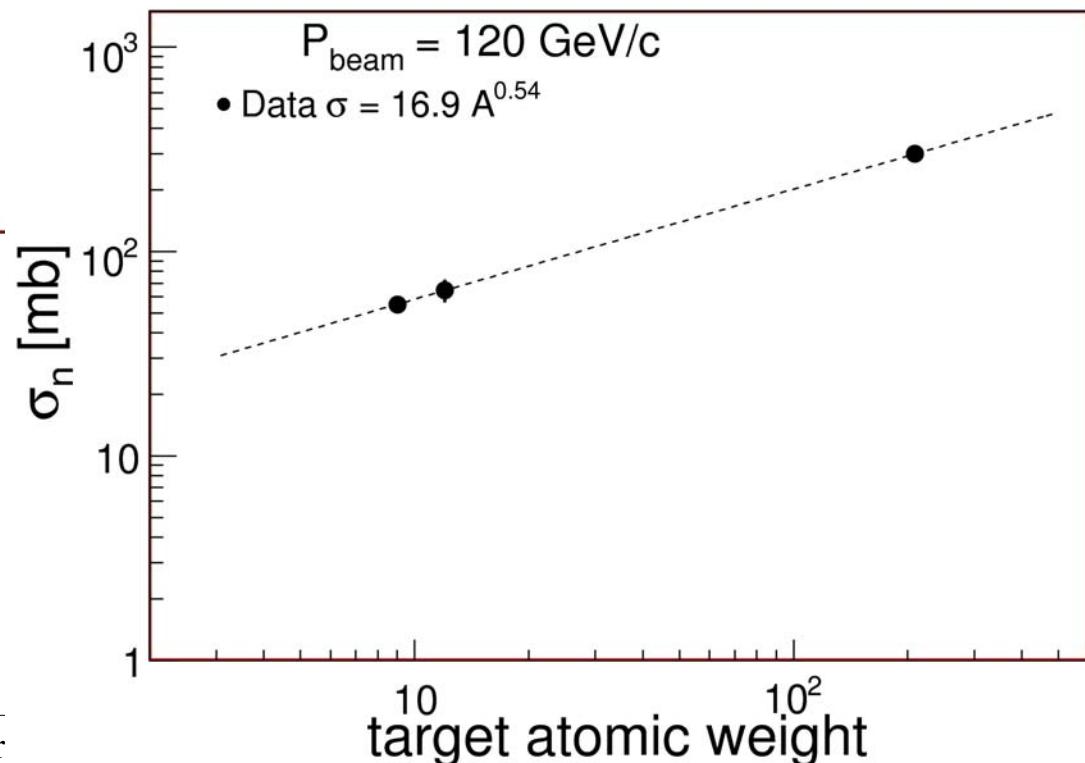


Neutron cross sections

Results as a function of A

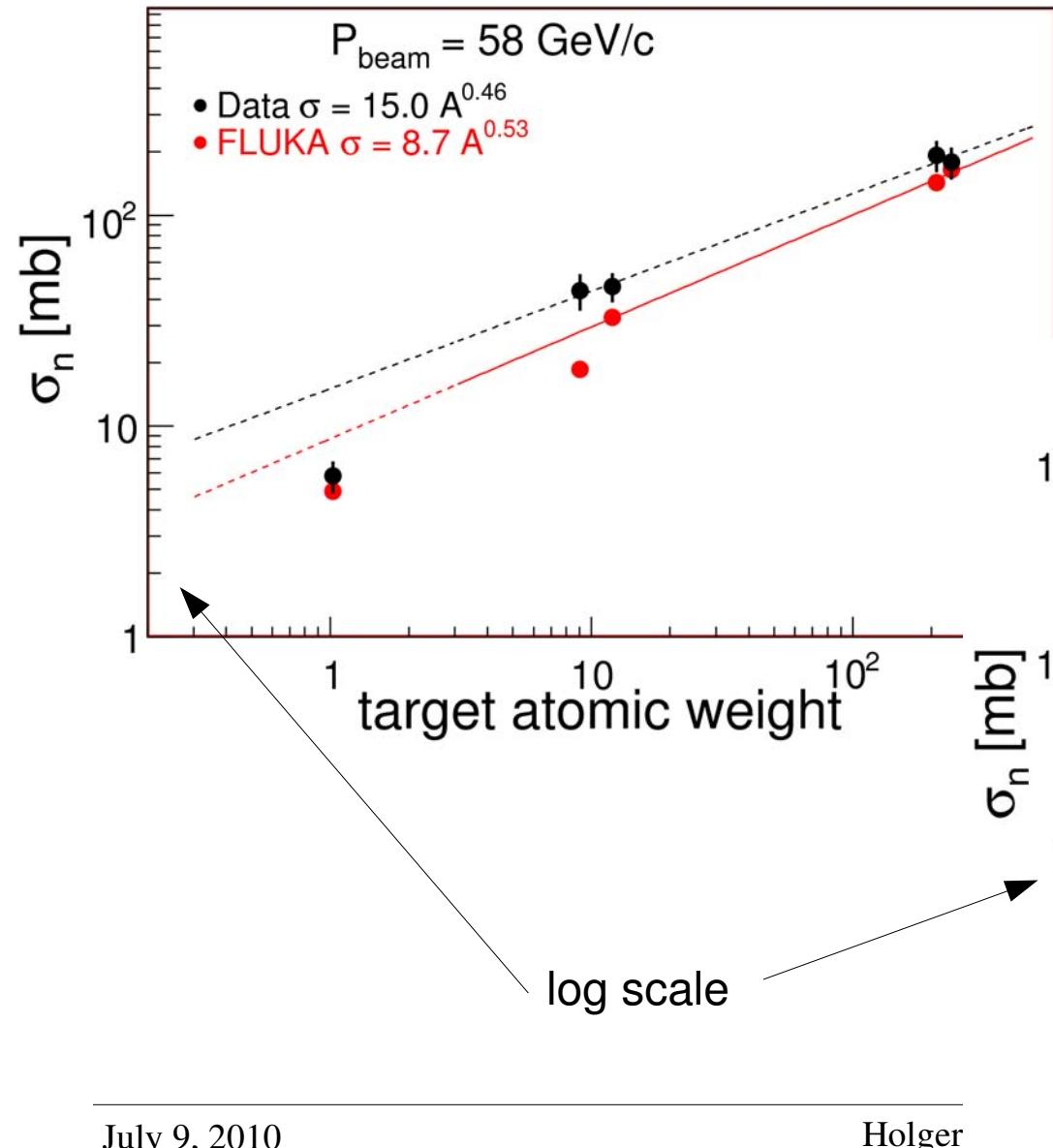


- MIPP neutron cross section measurements on nuclei show consistent behavior
 - $A^{0.5}$ dependence
 - LH_2 data point is lower

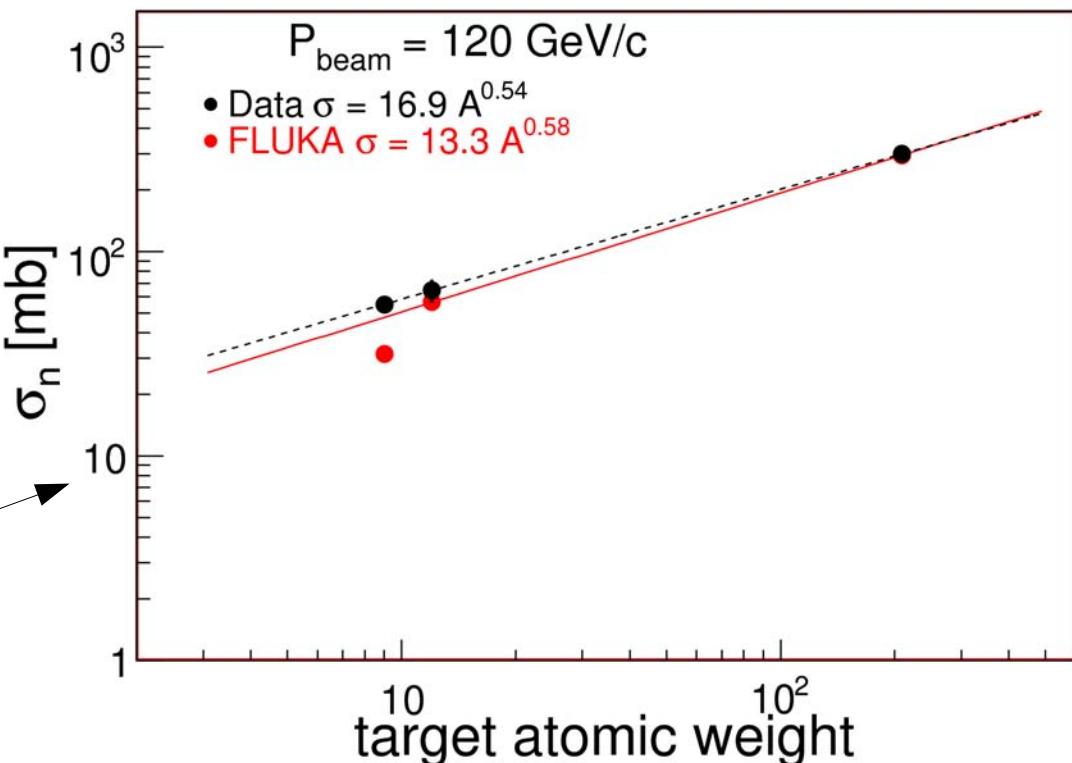


Neutron cross sections

Results as a function of A

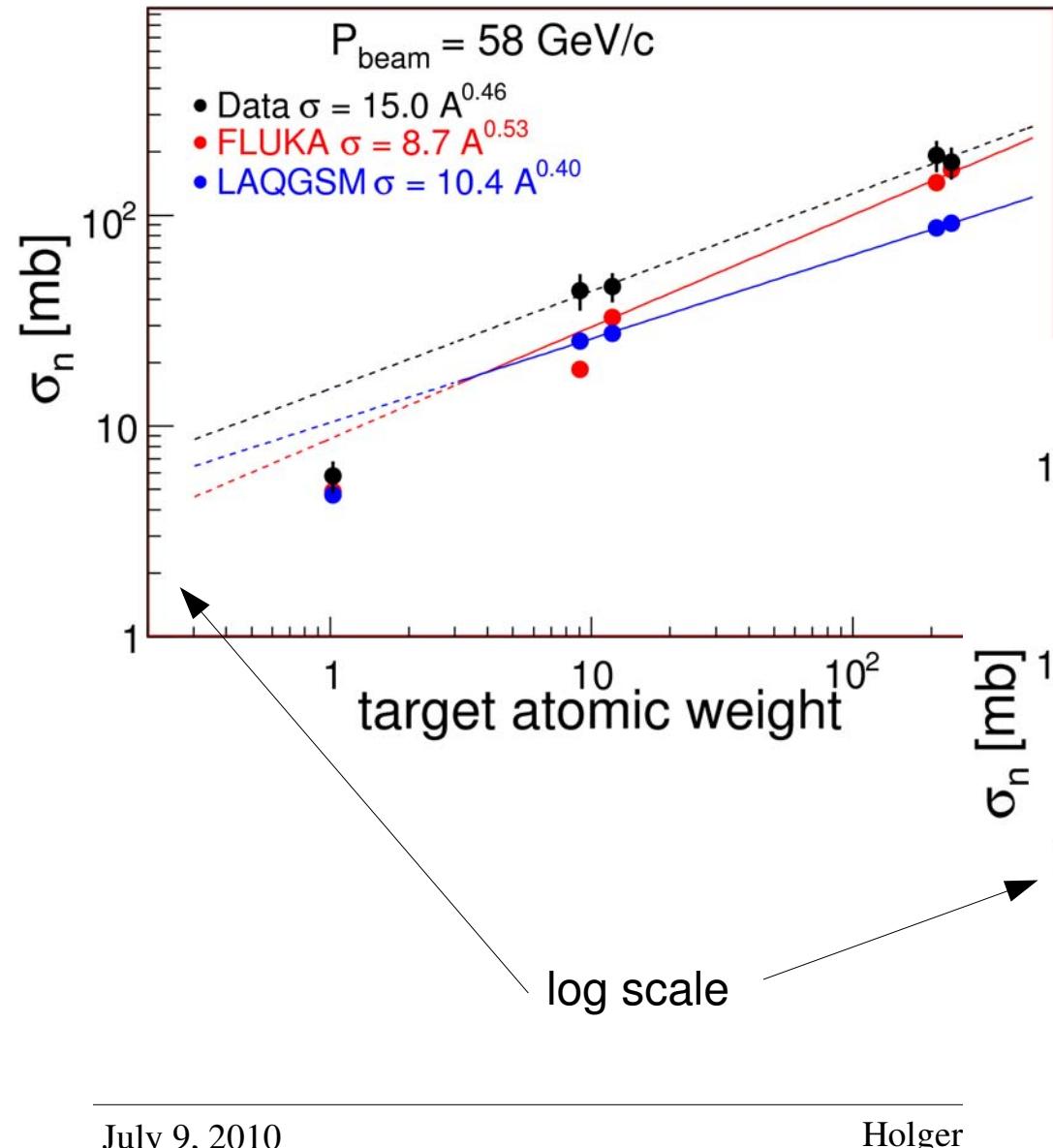


- Fluka/DPMJET predictions
 - Be prediction is low, does not fall on line
 - Pion and kaon inclusive cross sections on Be are also low in Fluka, although total cross section is ok.

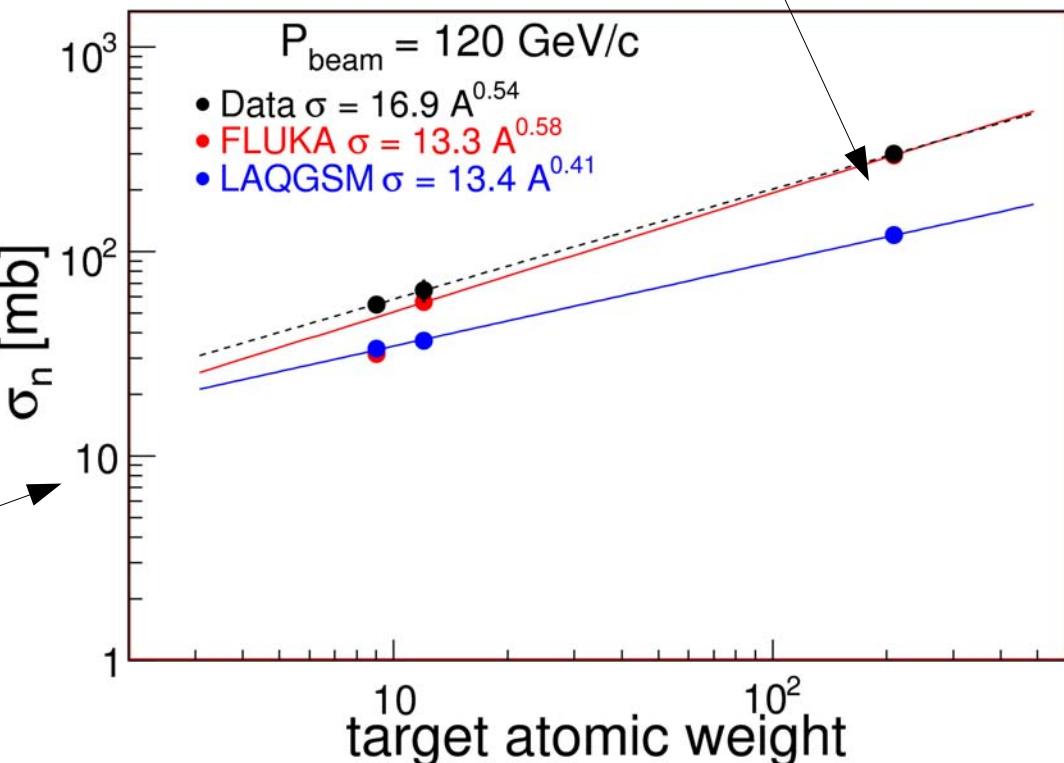


Neutron cross sections

Results as a function of A



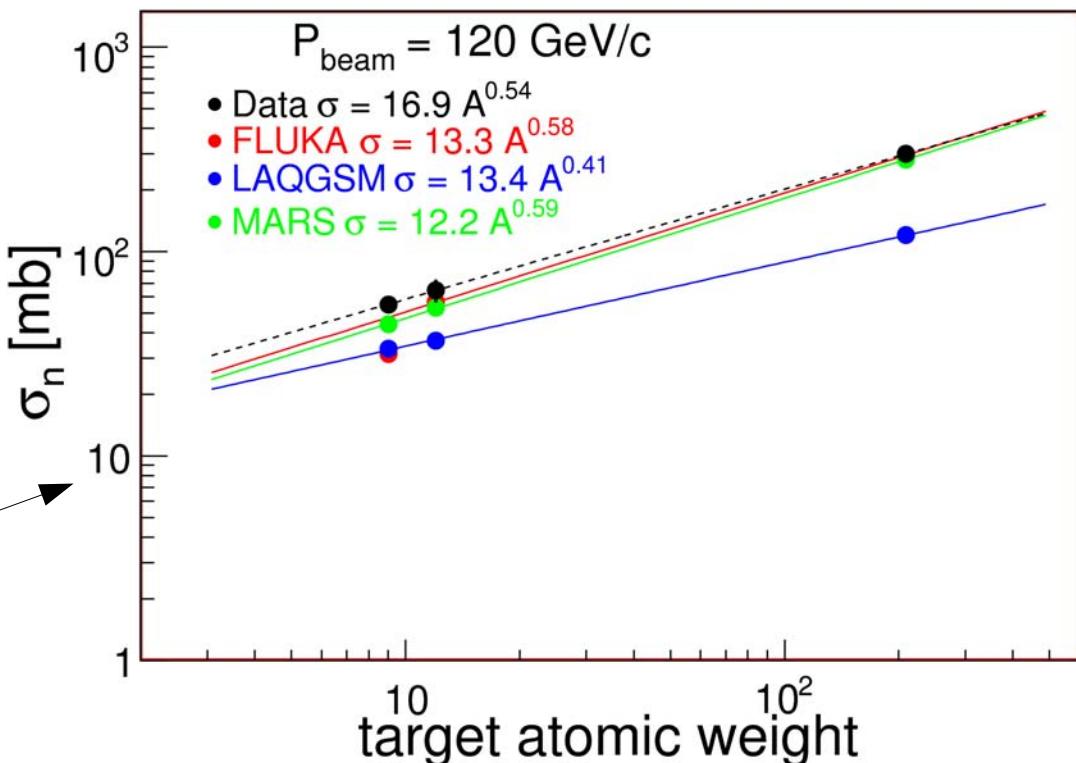
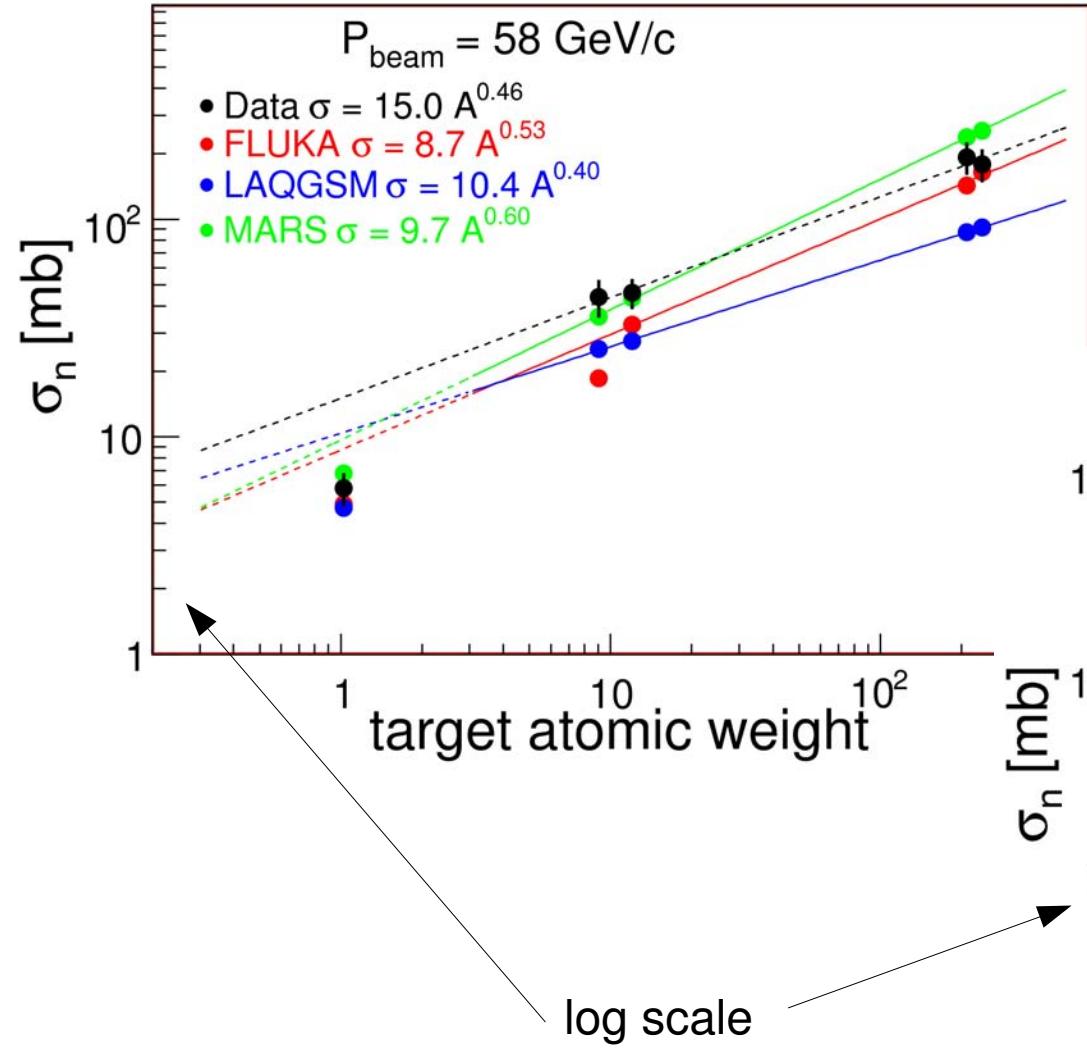
- LAQGSM predictions
 - Predictions are low
 - Discrepancy of x2.5 for Bi



Neutron cross sections

Results as a function of A

- MARS predictions



Neutron cross sections



Results as a function of A

- Results from previous page in table form:

Target	Beam momentum	data	Stat. error	Sys. error	DPMJET or FLUKA	LAQGSM	MARS
	GeV/c	mbarn	mbarn	mbarn	mbarn	mbarn	mbarn
H ₂	20	1.5	0.1	0.3	0.9		
H ₂	58	5.8	0.2	1.0	4.9	4.7	6.8
Be	58	44.0	4.4	8.3	18.6	25.3	35.7
C	58	45.9	1.5	7.2	32.7	27.5	43.5
Bi	58	193.2	10.4	32.5	143.4	87.3	238.0
U	58	178.8	7.7	30.8	165.0	91.5	256.0
H ₂	84	8.8	0.2	1.2	6.4		
Be	120	55.0	0.4	8.2	31.6	33.4	44.0
C	120	64.5	0.4	8.8	56.5	36.6	53.1
Bi	120	300.2	3.1	52.0	296.1	120.1	281.1

MIPP upgrade

What could we do with 100 times the MIPP data?



- Solve the [hadronic shower simulation problem](#) in a *model independent way!*
 - Record 5 million events a day on 30 nuclei → 1 Month!
 - The A-list:
 - **H₂, D₂, Li, Be, B, C, N₂, O₂, Mg, Al, Si, P, S, Ar, K, Ca, Fe, Ni, Cu, Zn, Nb, Ag, Sn, W, Pt, Au, Hg, Pb, Bi, U**
 - Feed this *library of events* into hadronic shower generator programs.
 - Beam momenta from 1 GeV/c to 90 GeV/c
 - Full acceptance over phase space, including info on nuclear fragmentation → Plastic Ball
 - Events contain correlations between final state particles!
- Look for unobserved baryon resonances
 - Only quark-diquark degrees of freedom or three quark model?
 - Simple beam upgrade to go down to 1 GeV/c
 - Complementary to programs at JLAB, MAMI (Mainz), ...
- Much more

Tagged neutral beams

- Use LH_2 target → Initial state kinematics is known.

- Use diffractive reactions

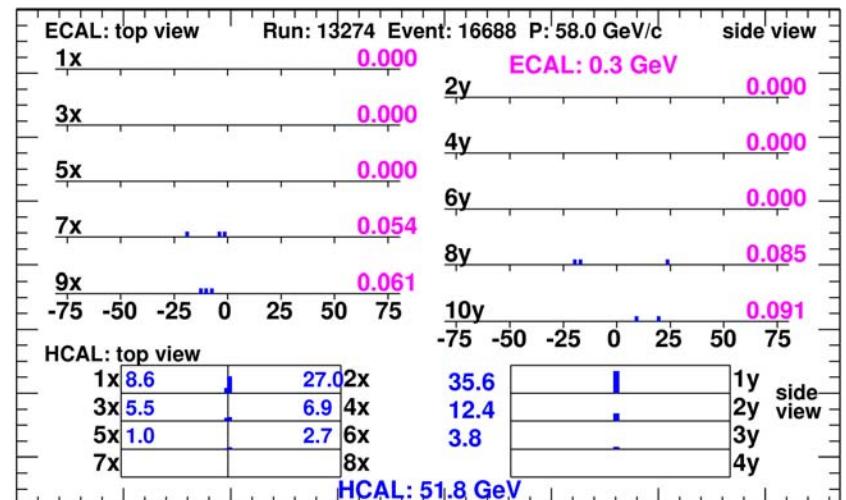
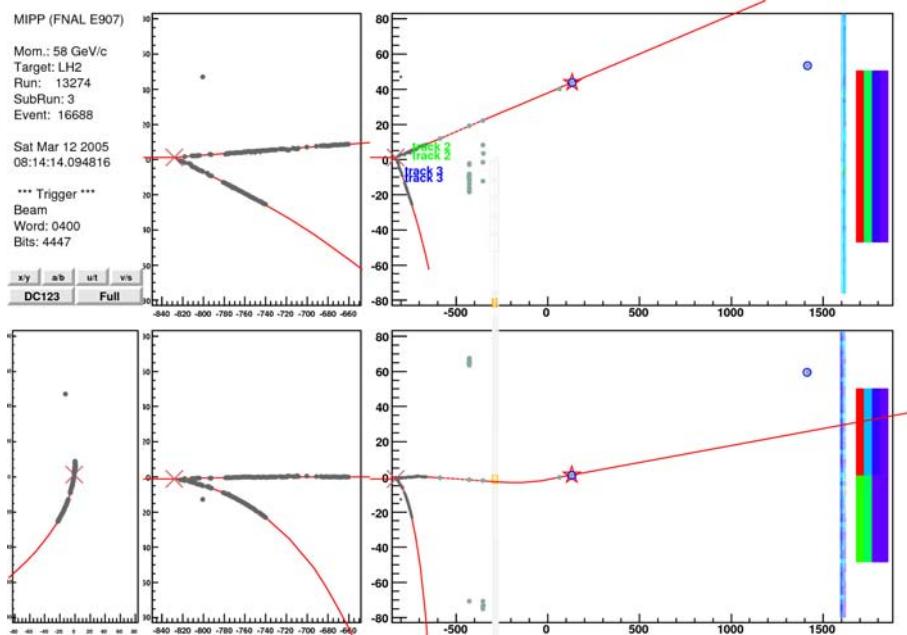
$$\begin{aligned}
 p & p \rightarrow p \pi^+ \underline{\textcolor{blue}{n}} \\
 K^+ & p \rightarrow p \pi^+ \underline{K^0}; \underline{K^0} \rightarrow \underline{K_L^0} \\
 K^- & p \rightarrow p \pi^- \underline{K^0}; \underline{K^0} \rightarrow \underline{K_L^0} \\
 & \bar{p} p \rightarrow p \pi^- \underline{\bar{n}}
 \end{aligned}$$

- Neutral particle momentum determined to $\sim 2\%$
 - 1-C fit for one neutral particle (assuming neutral particle mass)
 - 3-C fit if direction of the neutral particle is known. → can reject events with additional π^0 .
- Need to instrument backward hemisphere, upstream of LH_2 target
 - Plastic Ball detector
- Get few $\times 10^3$ events per day in $2\text{m} \times 2\text{m}$ area 25m downstream of target with upgrade, e.g. 66k tagged neutrons for 30 GeV/c proton beam.
 (R. Raja, MIPP-doc130, arXiv:hep-ex/0701043)
- Useful for ILC PFA studies and tertiary target measurements

Tagged neutral beams

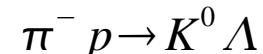
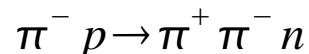
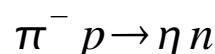
- Sometimes the proton moves into the TPC. Event recorded on 12 March 2005
- 58 GeV/c proton on proton
- Two charged tracks
 - (0.21 GeV/c, 0.52 GeV/c, 11.79 GeV/c)
 - (-0.04 GeV/c, -0.12 GeV/c, 0.42 GeV/c)
- Large energy in Calorimeter, no charged track pointing to it.

$$p \ p \rightarrow p \pi^+ \ n$$



Other physics interests

- Nuclear y -scaling
 - Verified in ep scattering and with low energy hadron beams (KEK E352)
 - Probe transition from quasielastic scattering to DIS
 - Extract cross sections inside the nuclear medium, compare to cross sections in vacuum
- Missing Baryon resonances
 - Partial wave analyses of πN scattering have yielded some of the most reliable information of masses, total widths and πN branching fractions. In order to determine couplings to other channels, it is necessary to study inelastics such as



All of the known baryon resonances can be described by quark-diquark states. Quark models predict a much richer spectrum. Where are the missing resonances? F.Wilczek, A. Selem

- This needs the MIPP upgrade with improvements to the beam line to take data at ~ 1 GeV/c

Charged kaon mass in MIPP

- RICH ring radius of tagged π , K, p beam particles measures K mass relative to well known masses of π , p. – **NIM A631** (March 2010)
 - Measure K^+ and K^- mass (test CPT)
 - With higher statistics this could resolve the disagreement between existing measurements, see PDG.
 - Important for determination of V_{us} in the CKM mixing matrix

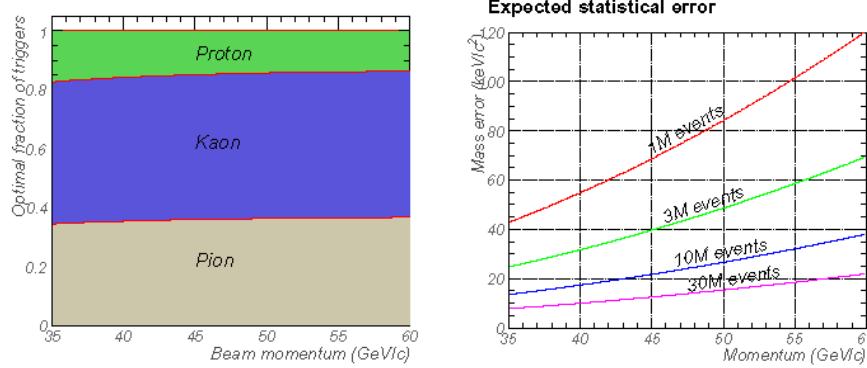


Figure 1: Optimal fraction of pion, kaon, and proton triggers (left), and expected statistical error for different total number of triggers, assuming optimal distribution of events in the sample (right).

The main disagreement is between the two most recent and precise results,

$$m_{K^\pm} = 493.696 \pm 0.007 \text{ MeV} \quad \text{DENISOV 91}$$

$$m_{K^\pm} = 493.636 \pm 0.011 \text{ MeV (S = 1.5)} \quad \text{GALL 88}$$

$$\text{Average} = 493.679 \pm 0.006 \text{ MeV}$$

$$\chi^2 = 21.2 \text{ for 1 D.F., Prob. = 0.0004\% , (3)}$$

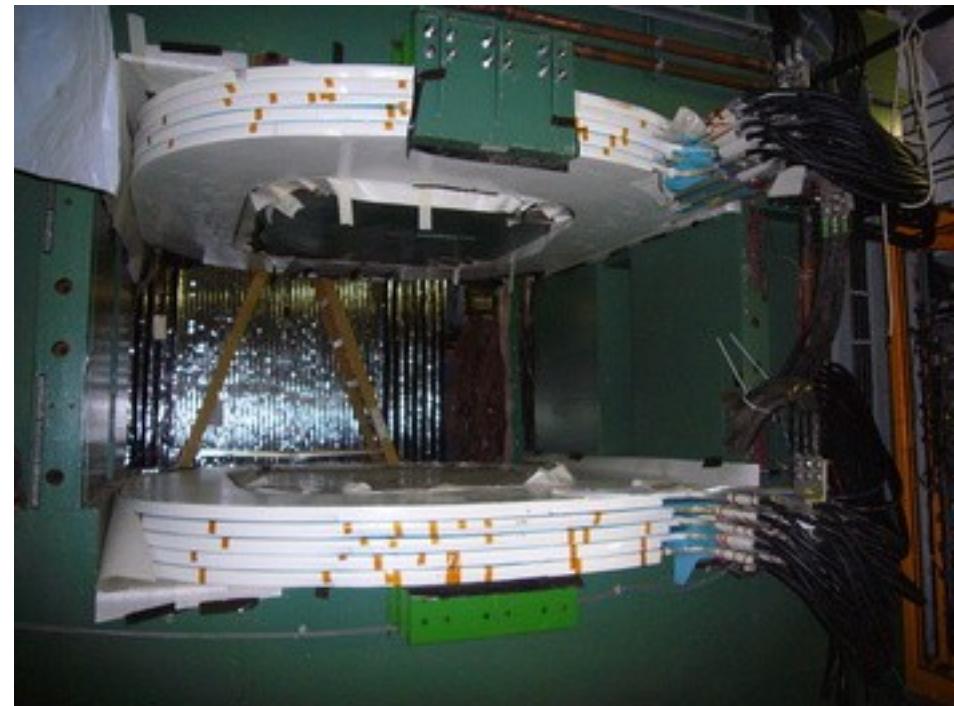
Data taken for Kaon mass

Momentum	Magnets	Number of beam spills	Number of events
-60	Off	3203	2701458
37.5	Off	1114	1687073
40	Off	2146	2884920
42.5	Off	618	911701
56	On	460	497633
59	Off	2017	2735482
59	On	673	738983

MIPP Upgrade proposal



- DAQ speed – TPC readout upgrade
 - The data rate in MIPP is limited to 30 Hz by the 1990s TPC electronics. Using the ALTRO/PASA chips developed for the ALICE experiment we can speed it up to ~3kHz. 1100 ALTRO/PASA chips have been delivered from CERN (\$100k).
- 5 million events per day with the same beam delivery rate
 - We assume the delivery of a single 4 second spill every two minutes from the Main Injector. We assume a 42% downtime of the Main Injector for beam manipulation etc. This is conservative. Using these figures, we can acquire 5 million events per day.
- Jolly Green Giant Coil Replacement
 - Towards the end of our run, the bottom two coils of the JGG burned out. We replaced both the top and bottom coils with newly designed aluminum coils that have **better field characteristics** for the TPC drift. The new coils have been installed (\$200K+labor).
- Other upgrades

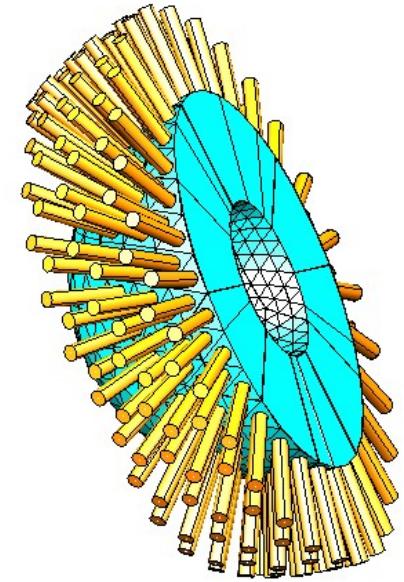


MIPP Upgrade proposal (cont.)



• Other upgrades

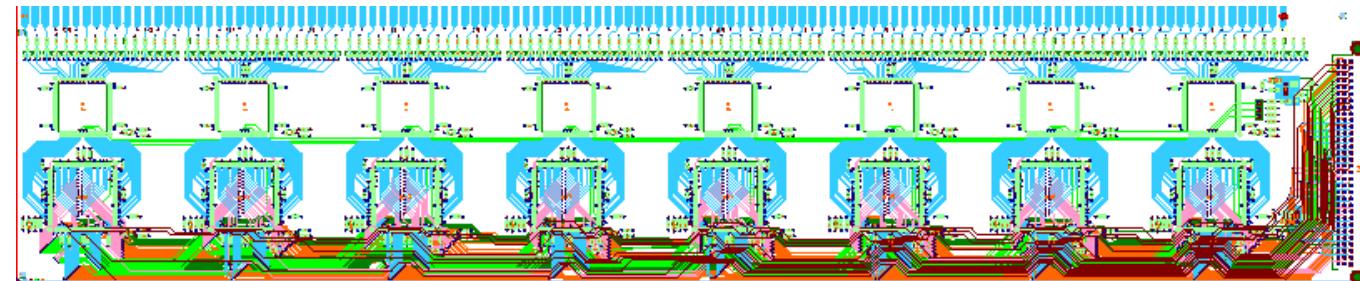
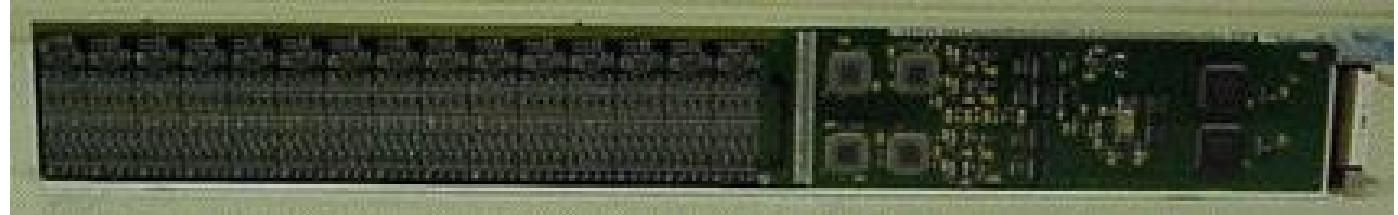
- The MIPP secondary **beamline** ran satisfactorily from 5GeV/c to 85GeV/c. We plan to run it from ~1 GeV/c to 85 GeV/c. The low momentum running will be performed using low current power supplies that regulate better. Hall probes in magnets will control hysteresis effects.
- **Beam veto wall:** larger coverage to veto beam spray, assembled at FNAL, awaiting installation (ACU, Mike Sadler et al.)
- **Recoil detector** - GSI- Darmstadt / KVI Groningen have joined us. They will bring the plastic ball detector (a hemisphere of it) which will serve to identify recoil (wide angle) neutrons, protons and gammas from our targets. We may also add a recoil cluster counting chamber.
- **Triggering system** - We propose to replace the MIPP interaction trigger (scintillator/wire chamber) with 3 planes of silicon pixels based on the B-TeV design. Will trigger more efficiently on low multiplicity events. New Master Trigger Board to form triggers.
- Drift Chamber/PWC **readout electronics** - These electronics (E690/RMH) worked well for the first run. They are old (1990's). RMH will not do 3kHz. We will replace both systems with a new design that utilizes some of the infrastructure we developed for the RICH readout.
- ToF/Ckov/Calo **readout electronics** – All readouts will be fully buffered: no more delay cables, common back-end for overall simpler DAQ system. Also more energy efficient.



MIPP Upgrade electronics

- Several prototype boards exist

- TPC stick prototype:
 - writing firmware
 - comparing two options



- Plastic Ball readout
 - similar to calorimeter readout



- DC, PWC preamp boards, discriminator & tdc's, common back-end, etc.

MIPP Upgrade summary



- MIPP can increase data rate to ~5 million events per day
 - High statistics data spanning the periodic table
 - Tagged neutral beams
 - Physics at 1 to 120 GeV/c
- Strong interest in current and future MIPP data
 - At ISVHECRI last week, peak of VHE CR energy deposit is in MIPP range
 - Hadronic shower simulation, ...
- Proposal is developed in detail
 - Full WBS: total cost ~\$2 million (~\$0.5 million has been spent)
 - Low risk: prototypes for key electronics exist
- Timeline
 - ≤ 1 year to build and commission upgrades
 - depends on manpower

The MIPP Upgrade Collaboration



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16 new institutions have joined. 6 from India.

New Collaborators in color cyan

Conclusions

- MIPP has produced a new technique for analyzing particle id data that employs Bayes' theorem iteratively. The GlobalPid algorithm can be applied to other analysis (pattern recognition) problems in HEP.
- We have proposed a new scheme for separating electrons and pions that employs transverse momentum as a particle id variable.
- We have used this algorithm (GlobalPid) to analyze particle production off the NuMI target.
- We have measured forward neutron cross sections on various nuclei. Significant disagreement is observed with two Monte Carlo models.
- We have observed tagged neutron events that will permit tagged neutral beams (n , $n\bar{n}$, K_L^0) in the proposed MIPP upgrade.
- We have proposed a low cost upgrade to the apparatus that will significantly enhance its data gathering and physics abilities.
(Missing baryon resonance search, scaling laws, more nuclear physics)

Backup slides

Why has MIPP data analysis taken so long?



- DoE (and NSF for U. of Colorado) decided NOT to fund MIPP specific graduate students and postdocs. Net result – University participants had to use their existing grants to fund student, postdocs (MINOS, others).
- As a result, Colorado, IIT, and Purdue could not participate.
- Livermore had to drop out (of MIPP and MINOS) because they lost stockpile stewardship program to LANL
- Finally DoE forced University of Virginia to leave MIPP and join D0!
- But we kept going. And we are near completion. MIPP data is now needed by all neutrino experiments, as well as mu2e, muon collider / neutrino factory, rare kaon decay experiments , as well as all experiments that require modeling of hadronic showers.