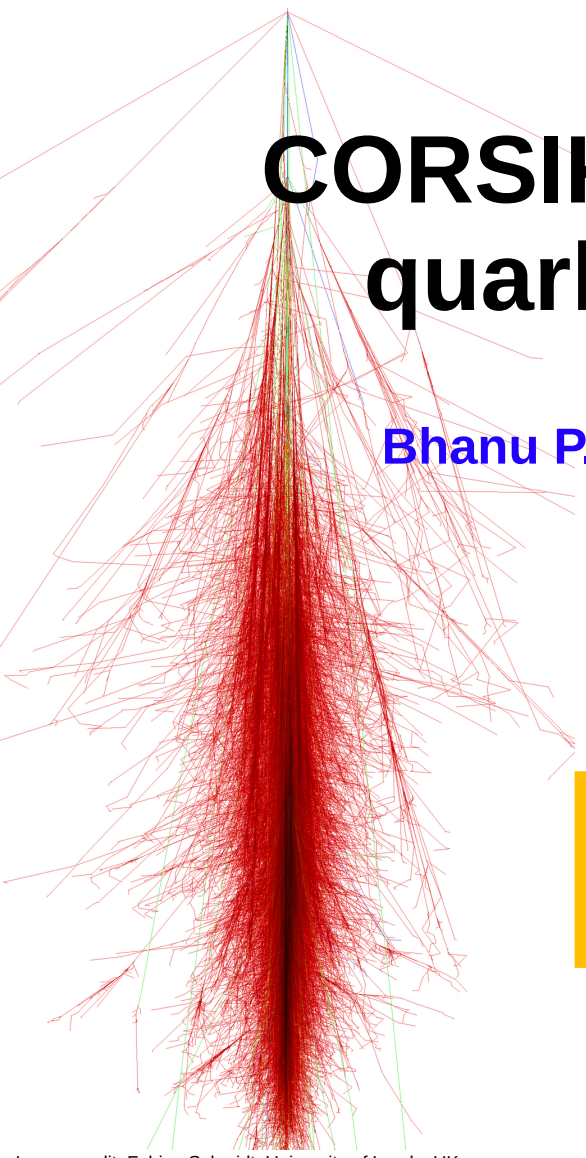

CORSIKA simulation for massive quarks in hadronic showers

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॥ त्वं ज्ञानमयो विज्ञानमयोऽसि ॥

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Copenhagen, July 13, 2022

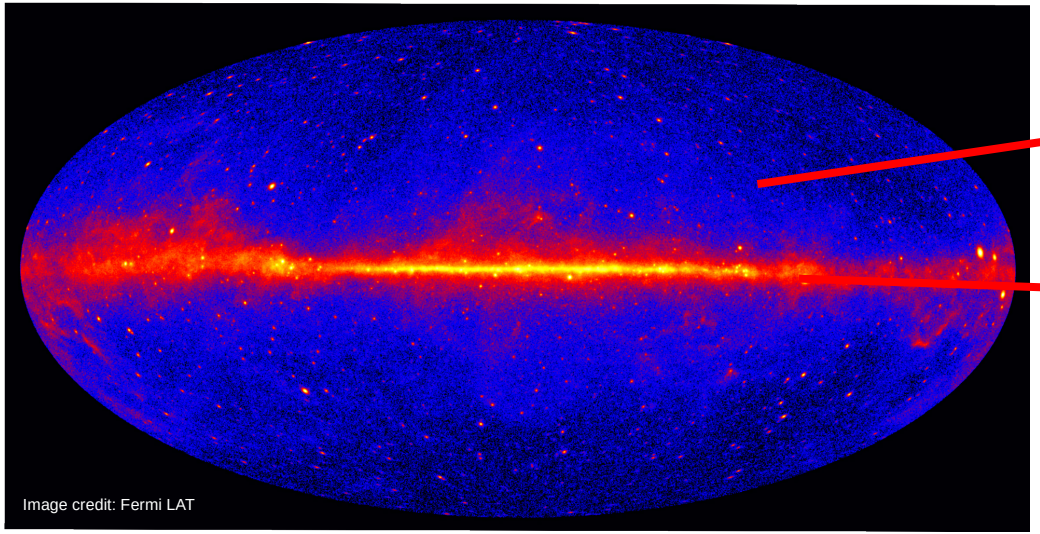
Image credit: Fabian Schmidt, University of Leeds, UK

GRAPES-3 experiment in Ooty, India

- Indian – Japanese collaboration with nearly 20 institutions
- Located at Ooty, Tamil Nadu, India (~2200 m altitude)
- ~400 plastic scintillator detectors (each 1 m^2 area) with 8 m detectors separation
- Spread over 25000 m^2
- Energy sensitivity is in TeV – PeV range

- 560 m^2 area muon telescope (each 35 m^2)
- 4 stations, each with 4 modules
- Each module 4 layers, each layer 58 PRCs
- 3712 PRCs (6m x 6m x 0.1m)
- Energy threshold = 1 sec(theta) GeV

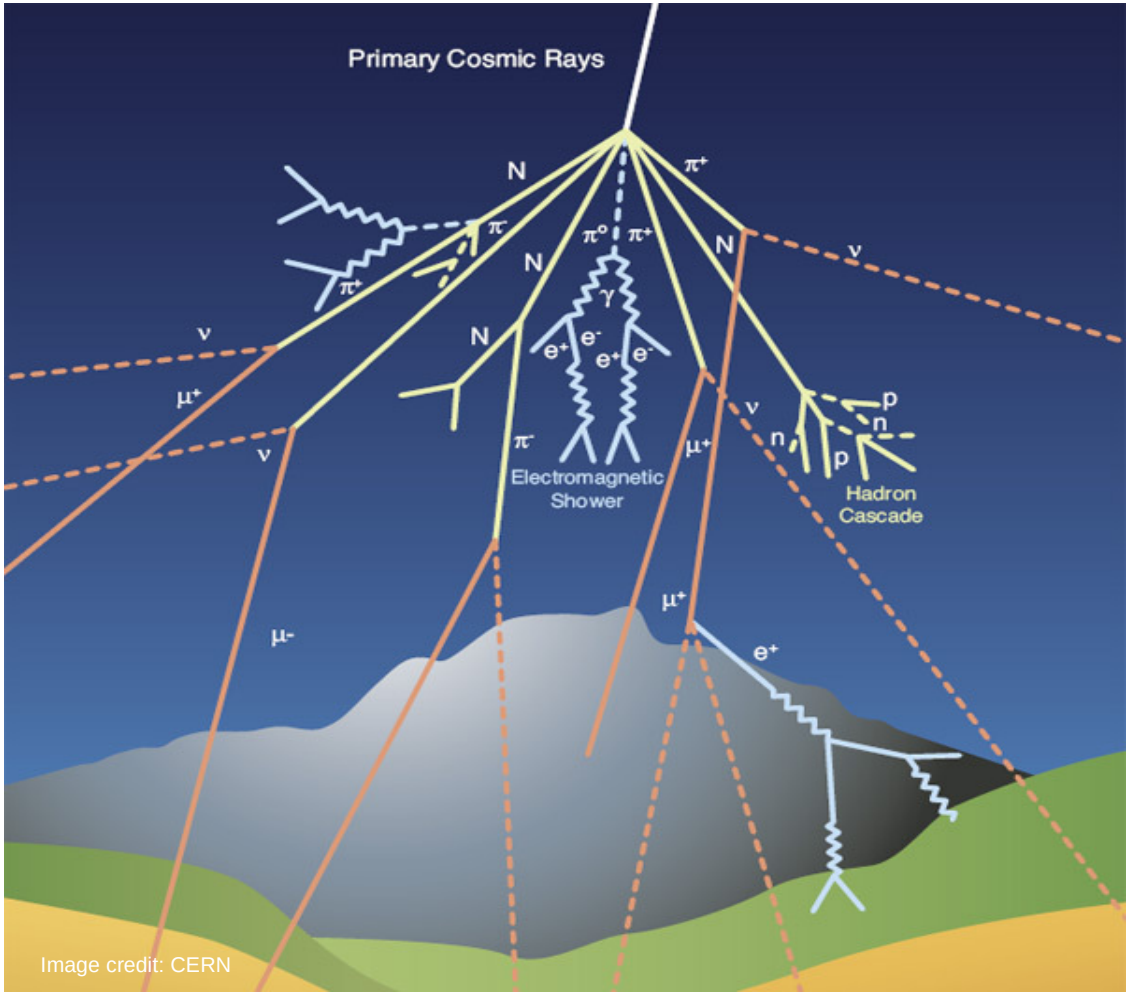
Work in progress



- **Diffuse emission of gamma-rays**
- **Extragalactic background**[+]
- **Galactic background**

+ B. P. Pant et al., *Characterizing the isotropic diffuse gamma-ray flux (10-300 TeV) by the GRAPES-3 experiment*, PoS(ICRC2021)871, doi: 10.22323/1.395.0871

Extensive air shower (EAS)



Proton primary at 10^{15} eV

10^6 secondaries at ground

- **80% photons**
- **18% electrons/positrons**
- **1.7% muons**
- **0.3% hadrons**

Source: https://indico.cern.ch/event/763013/contributions/3358878/attachments/1817838/2971899/GroupD_CosmicRays.pdf

Charmed particles in an EAS

- **Mostly pions and kaons are produced in an EAS**
- **Production is low : avg. 1-2 charmed hadrons in a p-N collision at 10^{18} eV (lab)**
- **Still important due to increased production in high-energy muons and neutrinos**
- **As an example:**

$$D^+ \rightarrow \bar{K}^0 \mu^+ \nu_\mu \qquad (7\%\ \text{B.R.})$$

$$D^0 \rightarrow K^- \mu^+ \nu_\mu \qquad (3.2\%\ \text{B.R.})$$

Muons and neutrinos stemming from these charmed meson decays are expected at ground

CORSIKA – EAS simulation

- **Stands for COsmic Ray SImulations for Kascade**
- **First developed in 1989 to perform simulations for the KASCADE experiment**
- **Detailed Monte-Carlo program for an extensive air shower (EAS) simulation**
- **Allows simulation of decay & interaction of particles upto 10^{20} eV**
- **Provides energy, location, direction and arrival times of all secondary particles at the selected observation level**
- **Several hadronic interaction models (QGSJET, SIBYLL, FLUKA,…)**
- **Electromagnetic interactions via NKG and EGS4**

D. Heck, J. Knapp, J.N. Capdevielle, G. Schatz, and T. Thouw, Report FZKA 6019 (1998), Forschungszentrum Karlsruhe; https://www.ikp.kit.edu/corsika/70.php

CORSIKA simulation parameters

- **CORSIKA v7.7410 is used for the extensive air shower simulation**
- **High energy hadronic interaction model : SIBYLL 2.3d**
- **Low energy hadronic interaction model : GHEISHA 2002d**
- **Simulation parameters are:**

Parameter	Value
Primary particle	Proton
Primary energy	10^{18} – $10^{19.2}$ eV
Spectral index	-2.7
Zenith angle	20 degrees
Observation level	Sea level
First interaction (a.s.l)	1 km

CORSIKA charm production

- **Charm particles production is ON by default in SIBYLL 2.3d**
- **SIBCHM keyword in input steering card:**
  - **TRUE to switch ON**
  - **FALSE to switch OFF**
- **With CHARM option :**
  - **ON decay+propagation both**
  - **OFF only decay and will be not propagated**
- **Events are generated with :**
  - **CHARM selected (decay + propagation) and**
  - **‘SIBCHM: True ‘ and ‘SIBCHM: False’, alternatively**

CORSIKA events generation

- **Energy range: $10^{18.0}$ – $10^{19.2}$ is divided into six logarithmic bins of interval 0.2**
- **Equal events are generated for each bin with both charm production ON and OFF**

Energy bin	Events
10^{18} – $10^{18.2}$ eV	100
$10^{18.2}$ – $10^{18.4}$ eV	46
$10^{18.4}$ – $10^{18.6}$ eV	20
$10^{18.6}$ – $10^{18.8}$ eV	10
$10^{18.8}$ – $10^{19.0}$ eV	4
$10^{19.0}$ – $10^{19.2}$ eV	2

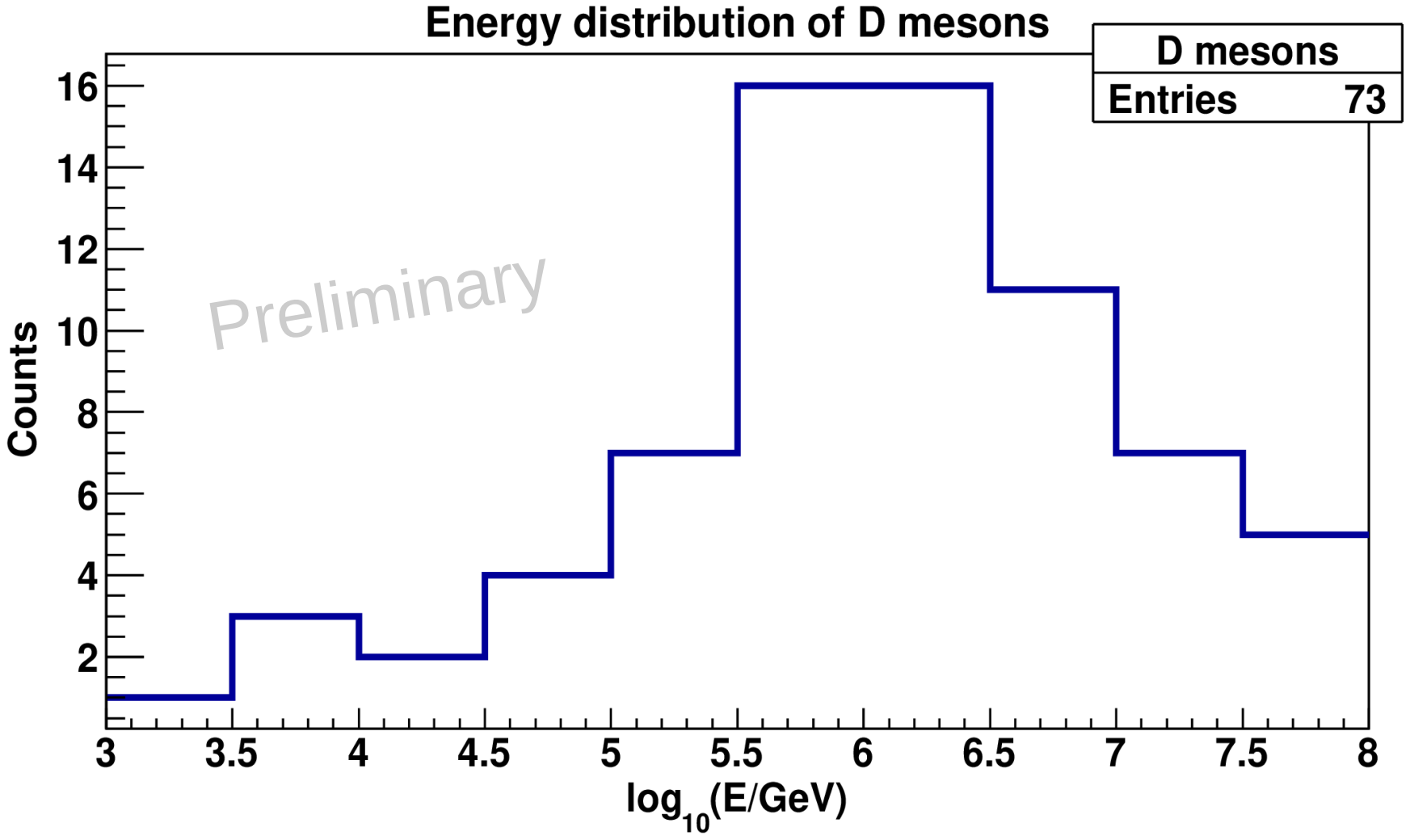
High performance workstation

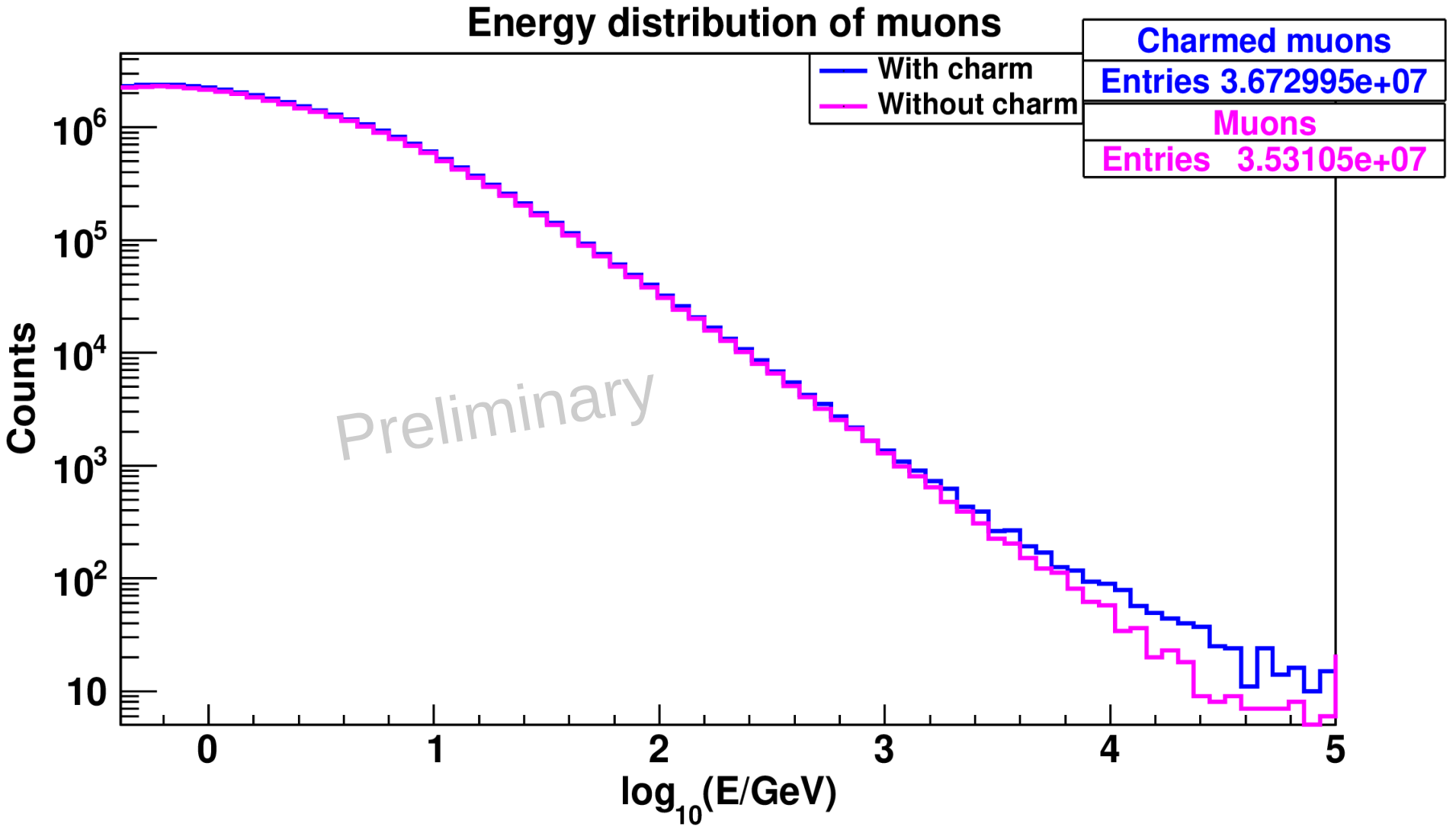
2 Intel Xeon Gold cpu's

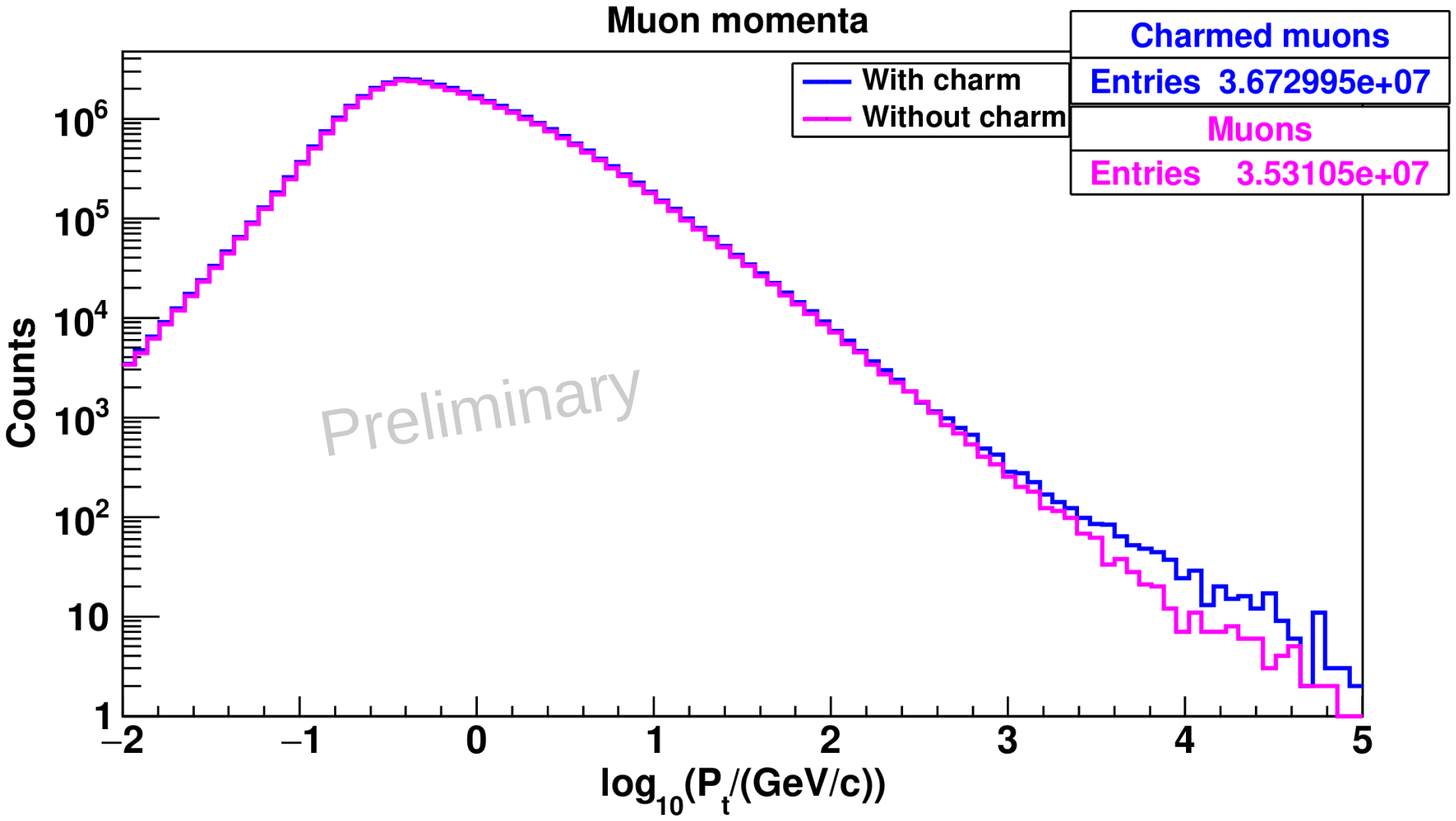
112 cores

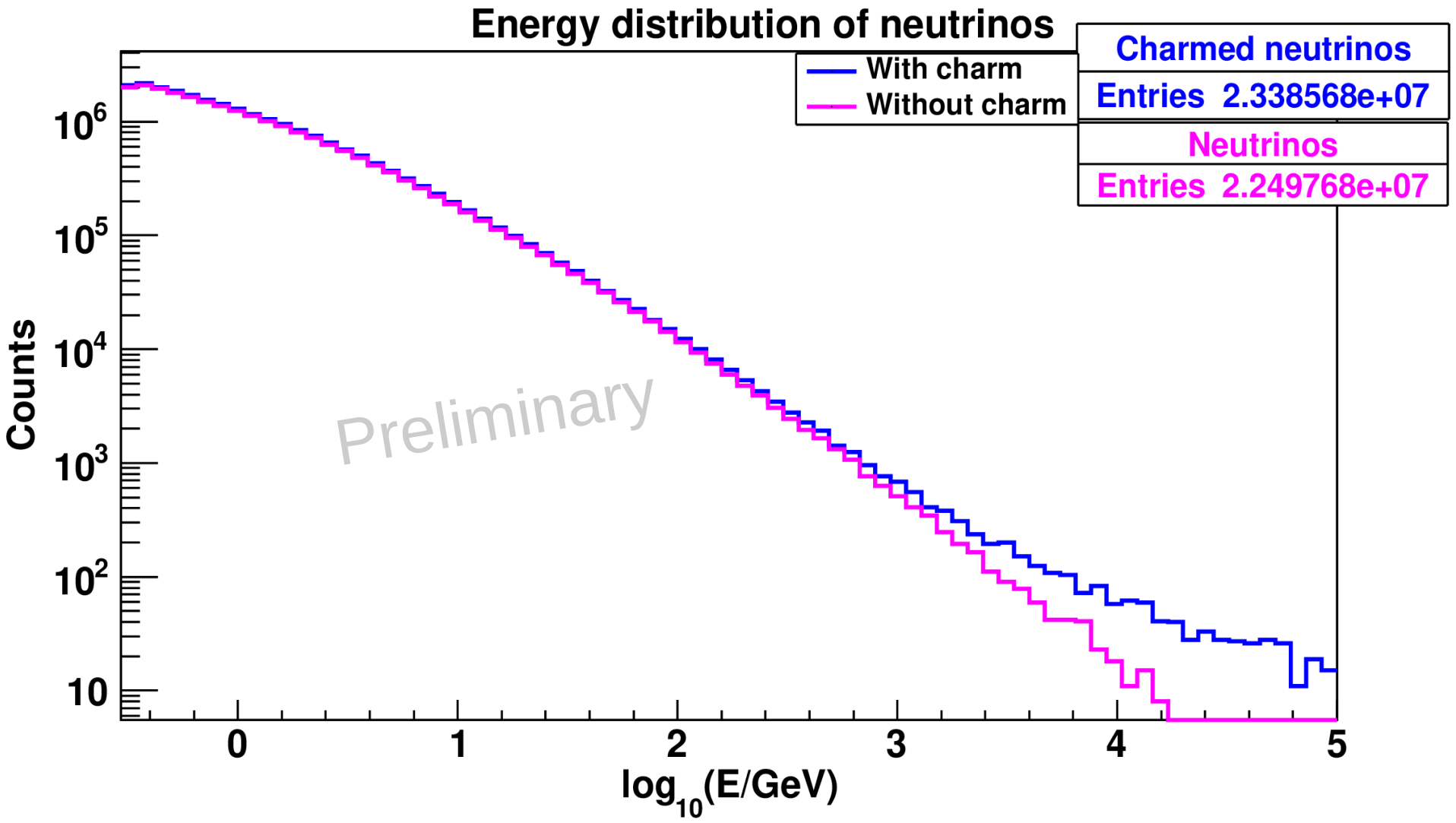
128 GB RAM

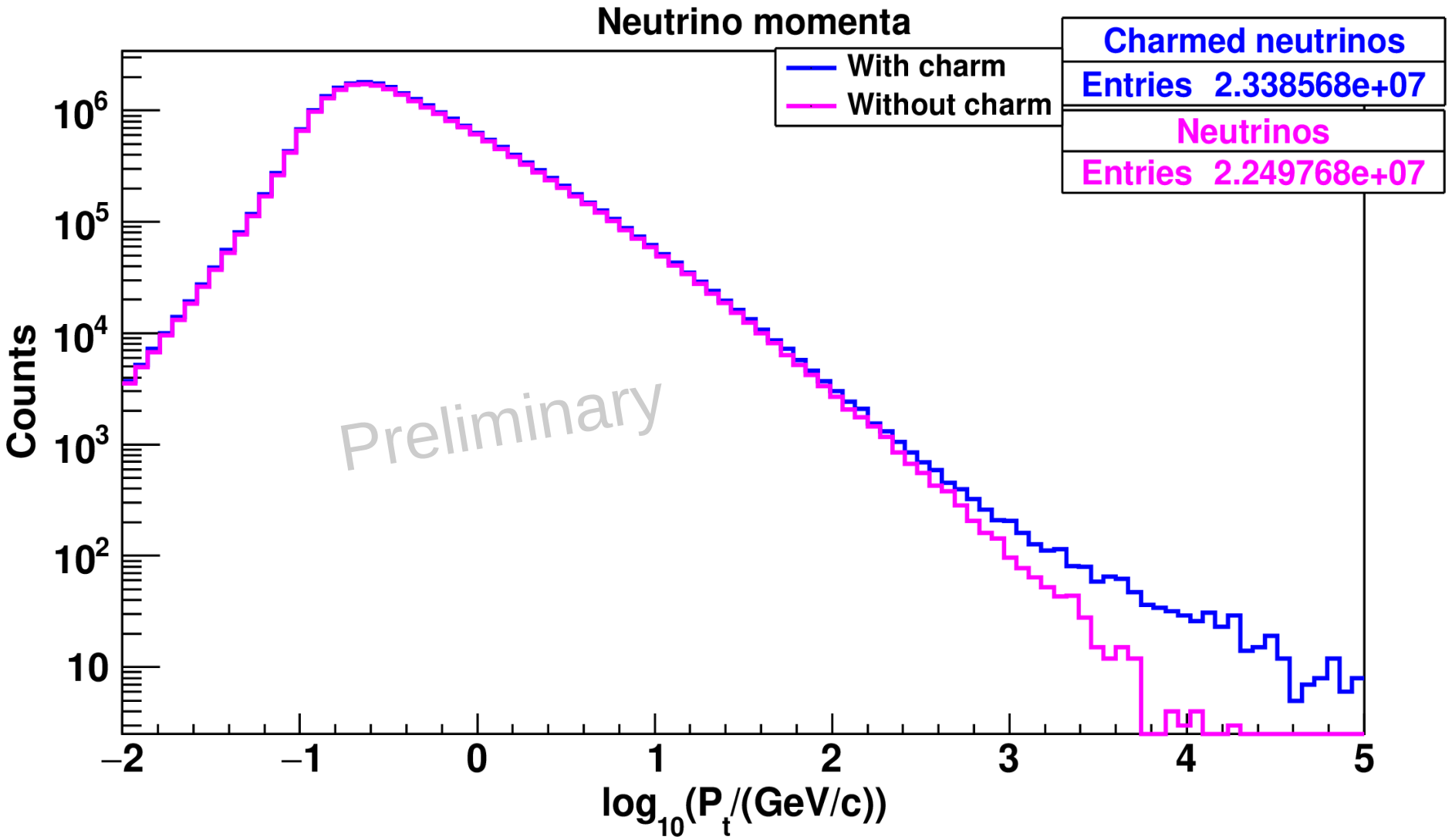
64 TB storage

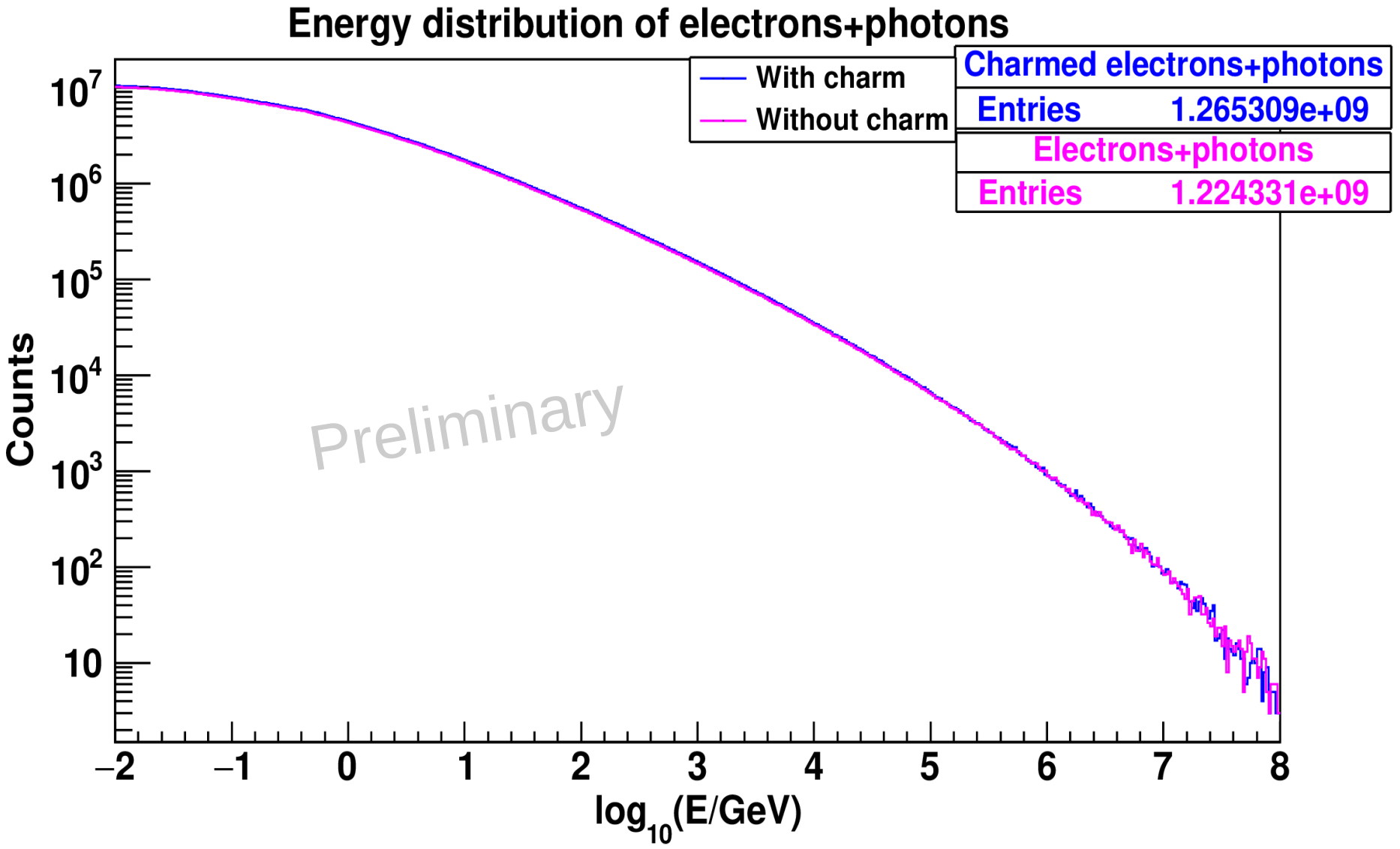

Energy distribution of D mesons
D mesons
Entries 73
Preliminary
Counts
16
14
12
10
8
6
4
2
3
3.5
4
4.5
5
5.5
6
6.5
7
7.5
8
log10(E/GeV)

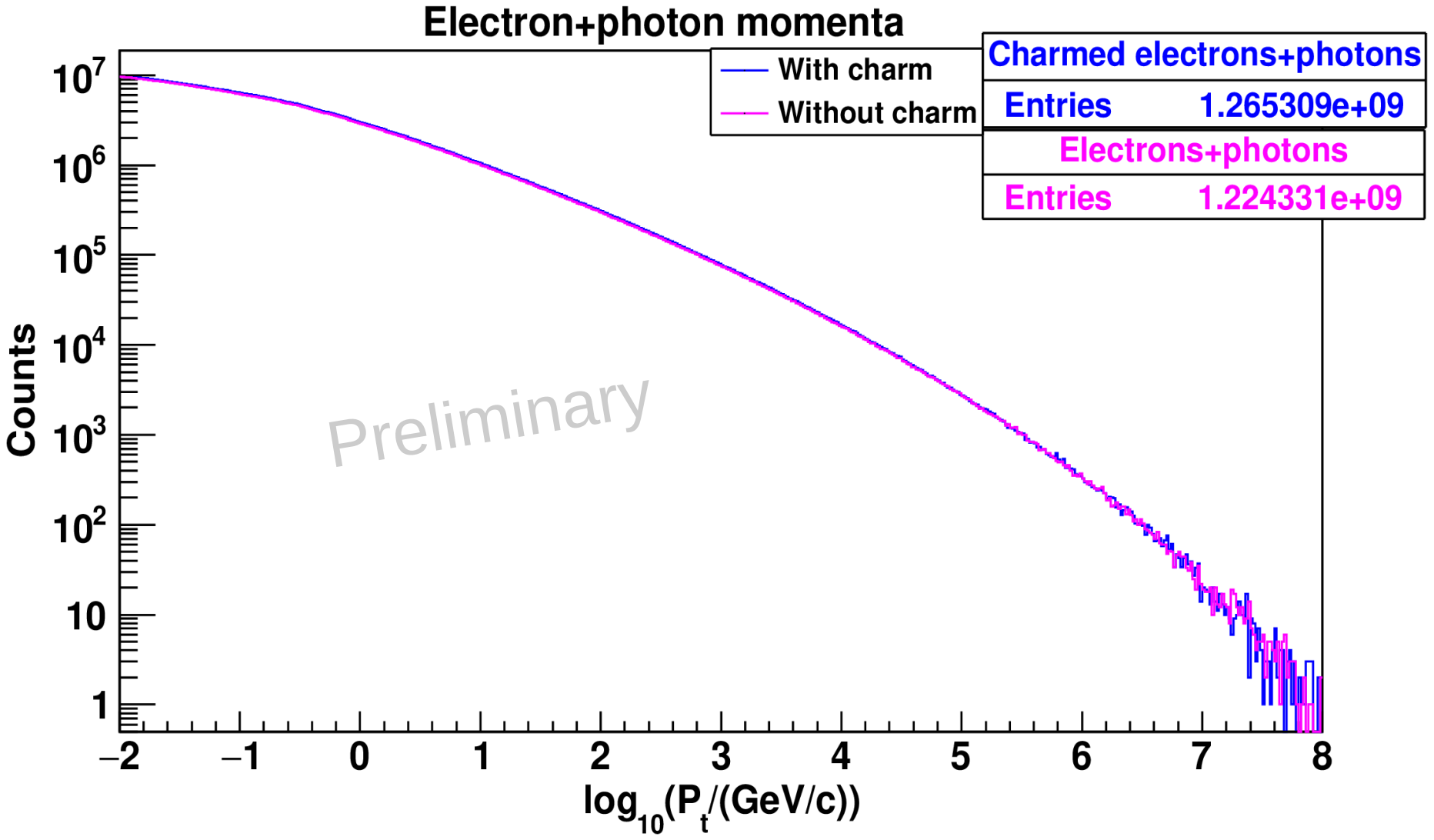

Energy distribution of muons
With charm
Without charm
Charmed muons
Entries 3.672995e+07
Muons
Entries 3.53105e+07
Preliminary
Counts
10^6
10^5
10^4
10^3
10^2
10
0
1
2
3
4
5
$\log_{10}(E/GeV)$


Muon momenta
With charm
Without charm
Charmed muons
Entries 3.672995e+07
Muons
Entries 3.53105e+07
Preliminary
Counts
10^6
10^5
10^4
10^3
10^2
10
1
−2
−1
0
1
2
3
4
5
$\log_{10}(P_t/(\mathrm{GeV}/c))$


Energy distribution of neutrinos
With charm
Without charm
Charmed neutrinos
Entries 2.338568e+07
Neutrinos
Entries 2.249768e+07
Preliminary
Counts
10^6
10^5
10^4
10^3
10^2
10
0
1
2
3
4
5
$\log_{10}$(E/GeV)


Neutrino momenta
With charm
Without charm
Charmed neutrinos
Entries 2.338568e+07
Neutrinos
Entries 2.249768e+07
Preliminary
Counts
10^6
10^5
10^4
10^3
10^2
10
−2
−1
0
1
2
3
4
5
$\log_{10}(P_t/(\mathrm{GeV/c}))$


Energy distribution of electrons+photons
With charm
Without charm
Charmed electrons+photons
Entries 1.265309e+09
Electrons+photons
Entries 1.224331e+09
Preliminary
Counts
10^7
10^6
10^5
10^4
10^3
10^2
10
−2
−1
0
1
2
3
4
5
6
7
8
$\log_{10}$(E/GeV)


Electron+photon momenta
With charm
Without charm
Charmed electrons+photons
Entries 1.265309e+09
Electrons+photons
Entries 1.224331e+09
Preliminary
Counts
10^7
10^6
10^5
10^4
10^3
10^2
10
1
−2
−1
0
1
2
3
4
5
6
7
8
$\log_{10}(P_t/(\mathrm{GeV/c}))$

Summary

- CORSIKA simulation is done for UHE protons
- EAS content of muons, electrons and photons are studied
- Found increase in high energy muons and neutrinos content

What's Next?

- Use other primary particles (He, N, Al,…)
- Other hadronic interaction models
- Inclusion of break in the spectral index
- Possibility to include other decay channels

Thank You