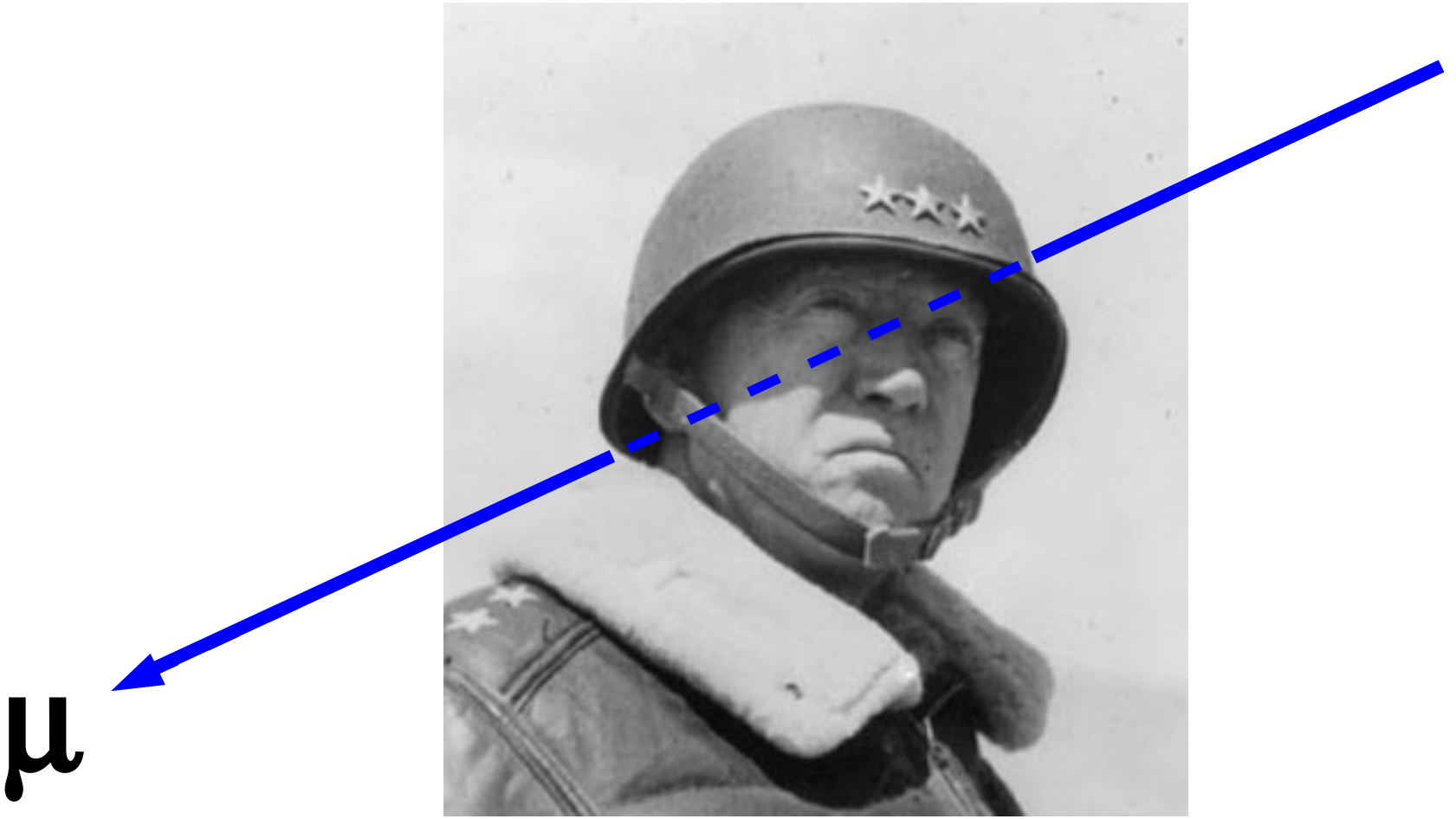
Muons

I:Muons in General



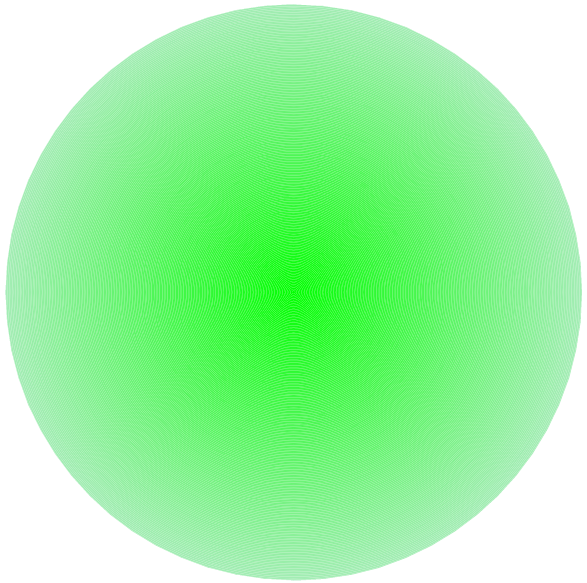

I
II
III
Quarks
Leptons
u
c
t
γ
d
s
b
g
ν_e
ν_μ
ν_τ
Z
e
μ
τ
W
Force Carriers
Three Generations of Matter

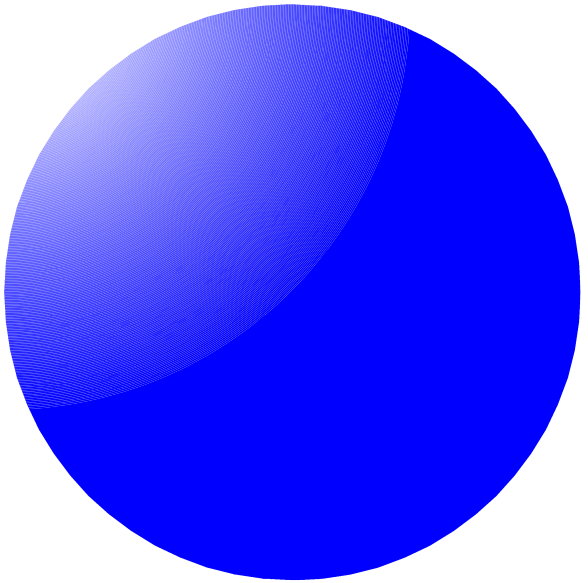
!

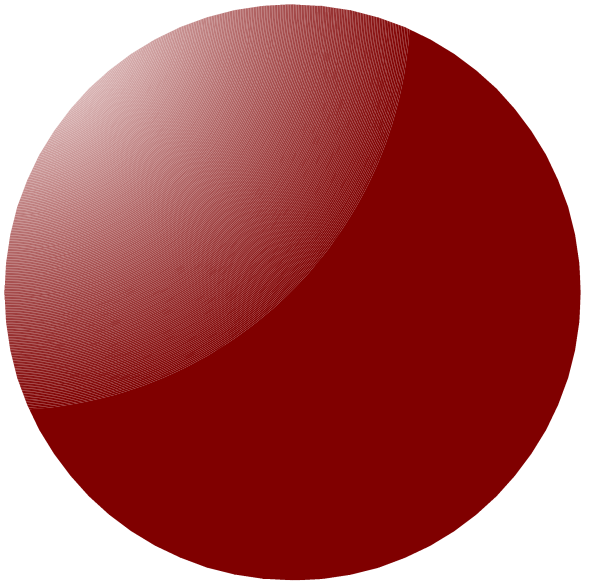
e^+

μ

C.D. Anderson, 1936



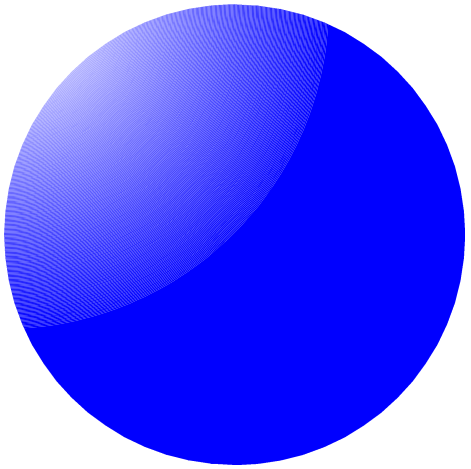




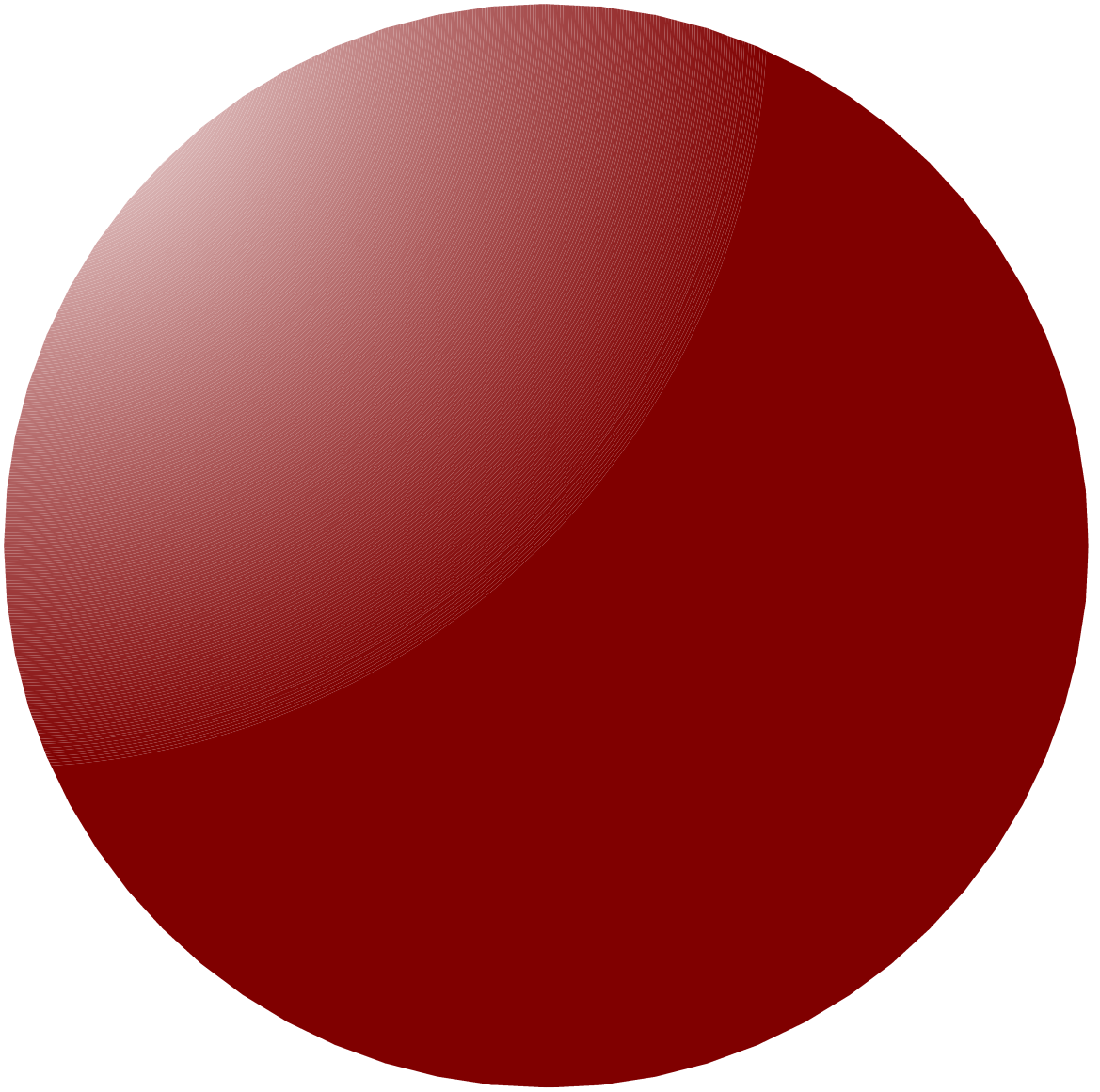
$e: 1q_e$ $\mu: 1q_e$ $\tau: 1q_e$

$$1q_e = 1.602 \times 10^{-19} C$$

e: 512keV/c^2



μ: 106MeV/c^2

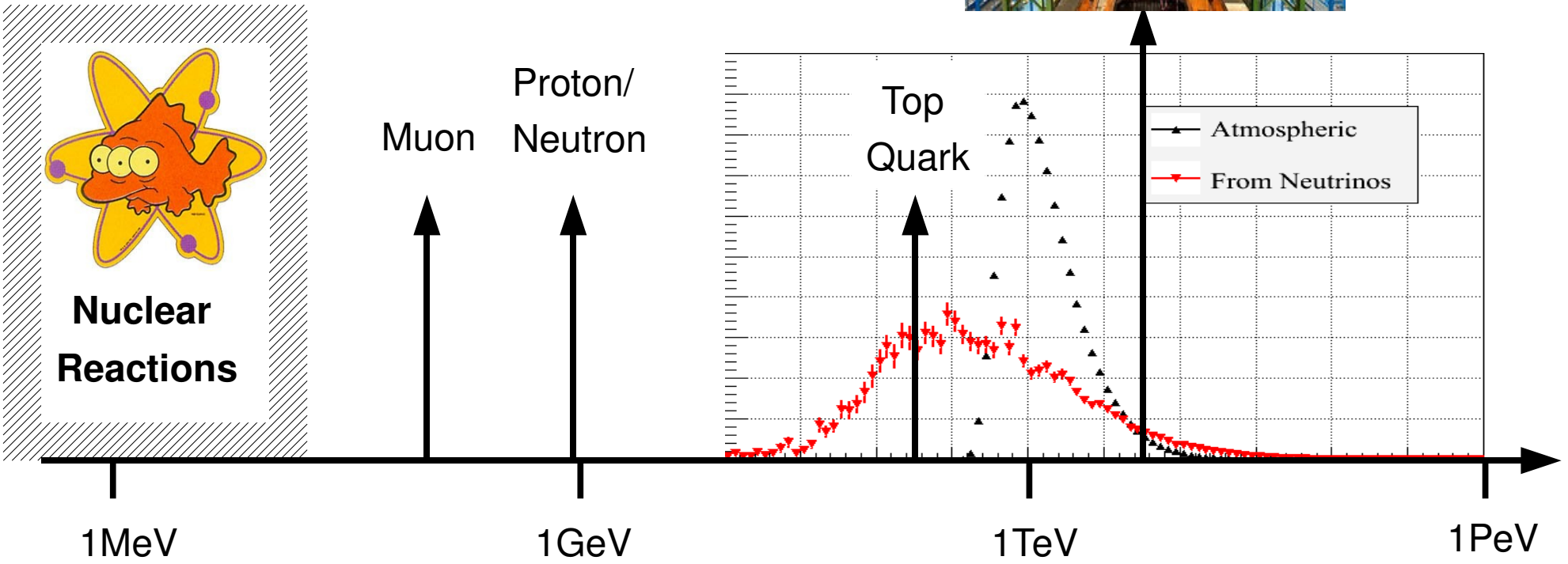


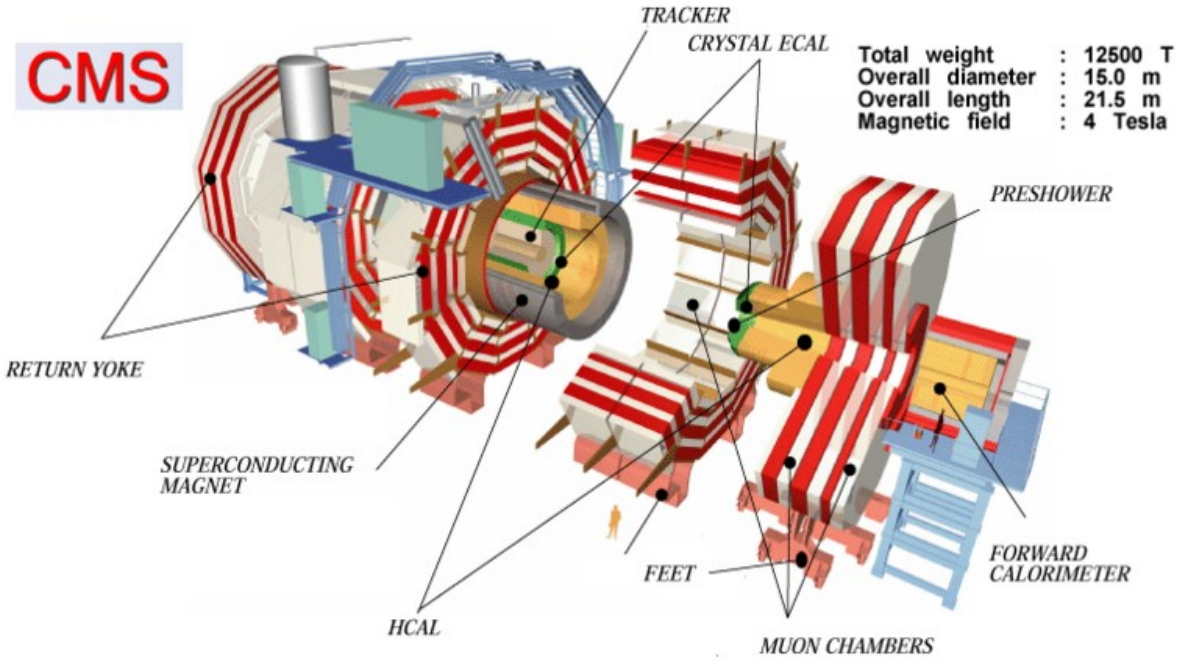
τ: 1.777GeV/c^2

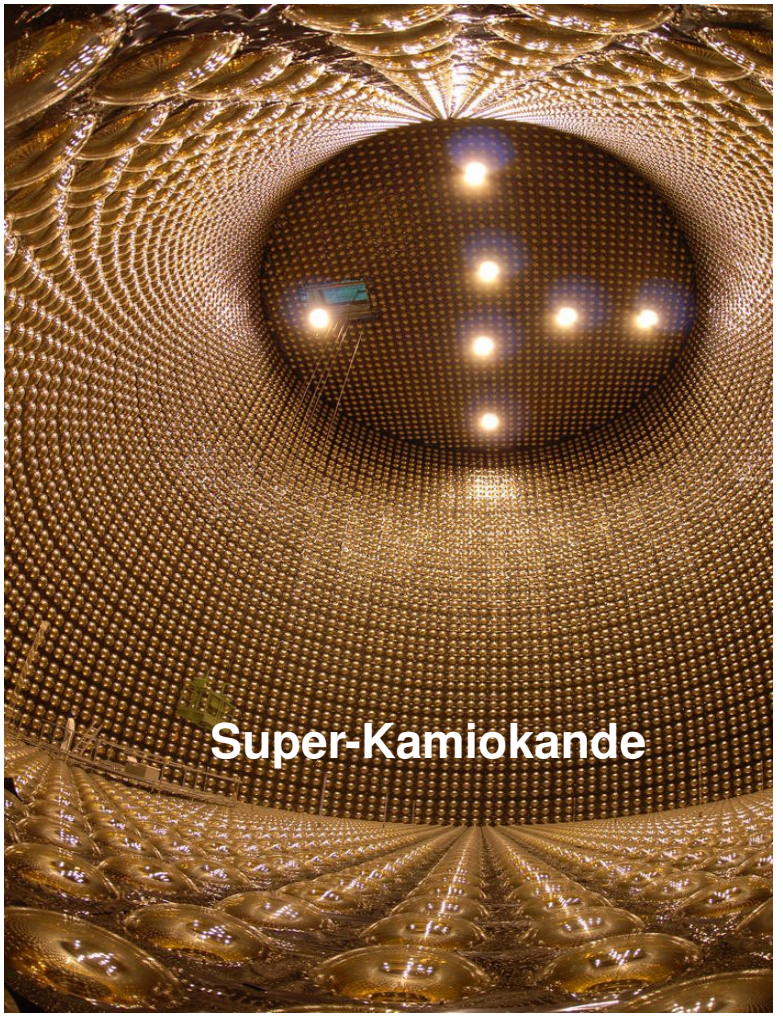
$1eV = 1.602 \times 10^{-19}J$

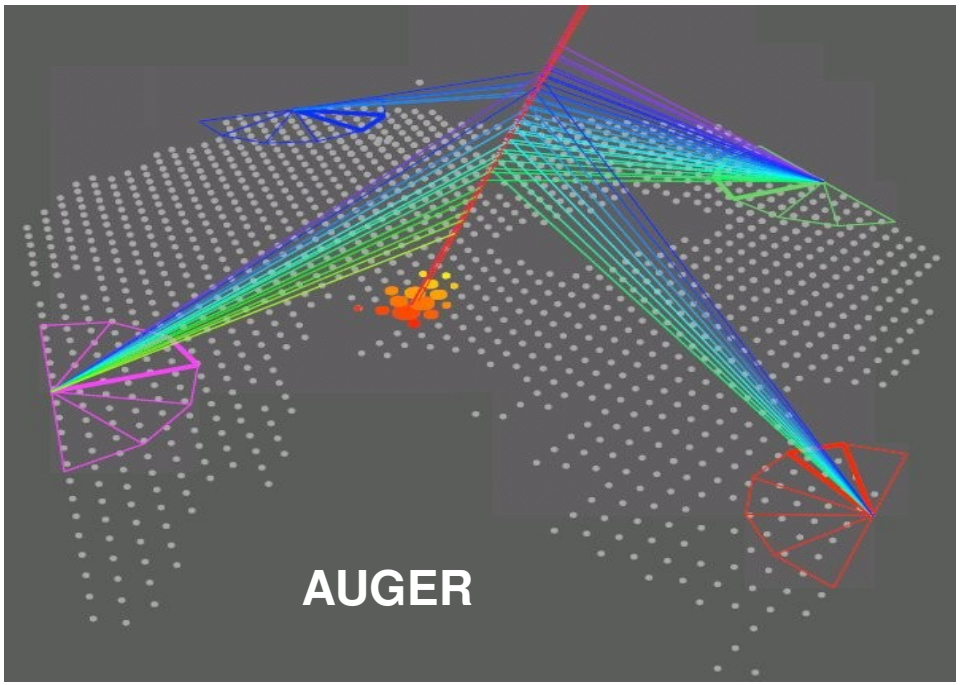
LHC

$E=m_0c^2$

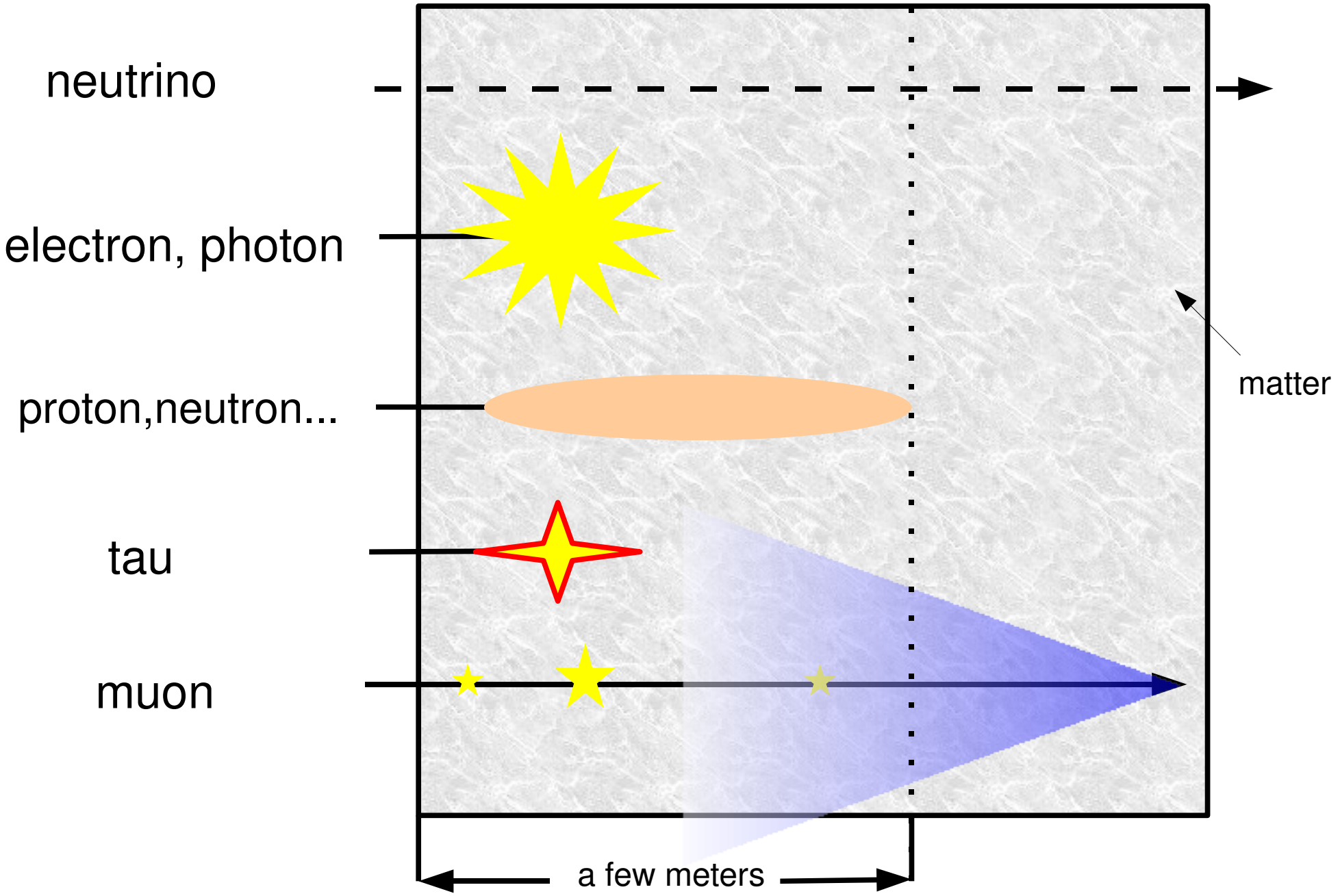

Nuclear
Reactions
Muon
Proton/
Neutron
Top
Quark
Atmospheric
From Neutrinos
1MeV
1GeV
1TeV
1PeV


CMS
TRACKER
CRYSTAL ECAL
Total weight : 12500 T
Overall diameter : 15.0 m
Overall length : 21.5 m
Magnetic field : 4 Tesla
PRESHOWER
RETURN YOKE
SUPERCONDUCTING MAGNET
FORWARD CALORIMETER
FEET
HCAL
MUON CHAMBERS


Super-Kamiokande

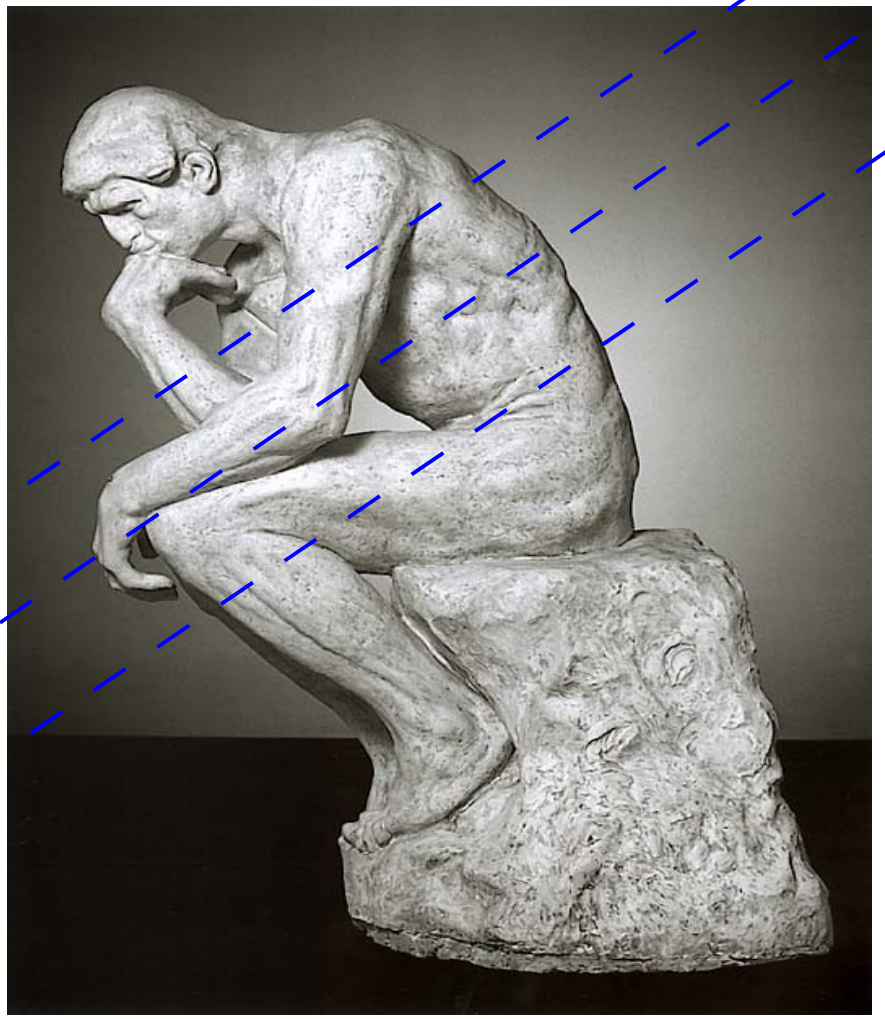

AUGER

High (but not too high!) Energies



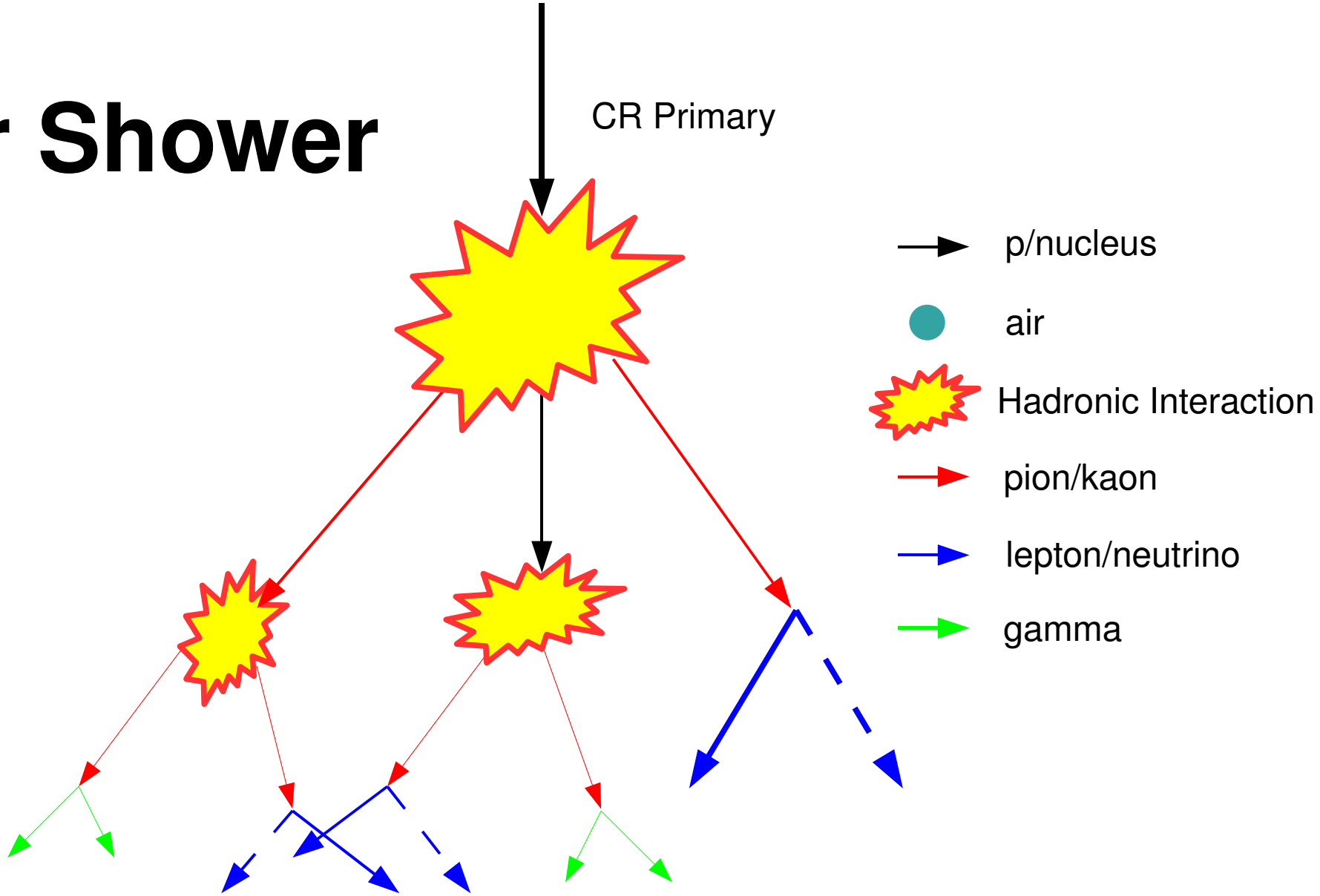
Total flux	Muons	neutrons	Electrons	Protons, pions
$3 \cdot 10^{-2}$ cm^{-2}s^{-1}	63%	21%	15%	< 1%

nucl-ex/0601019

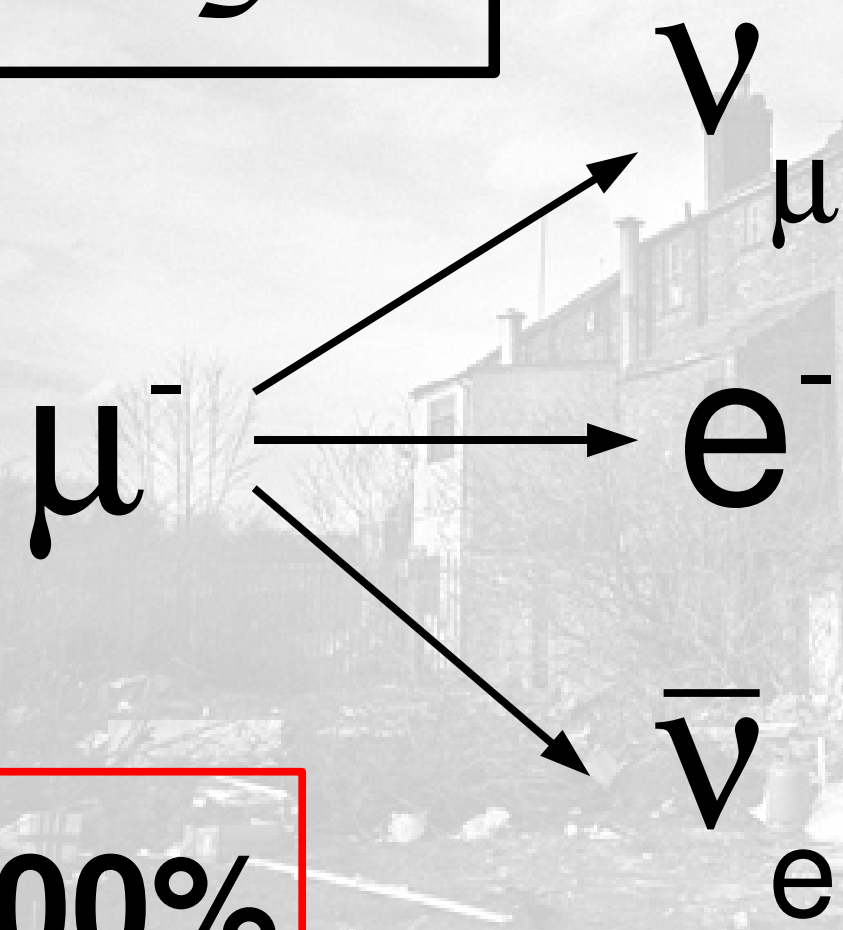


≈100μ/s

Air Shower


CR Primary
p/nucleus
air
Hadronic Interaction
pion/kaon
lepton/neutrino
gamma

Decay...



≃100%

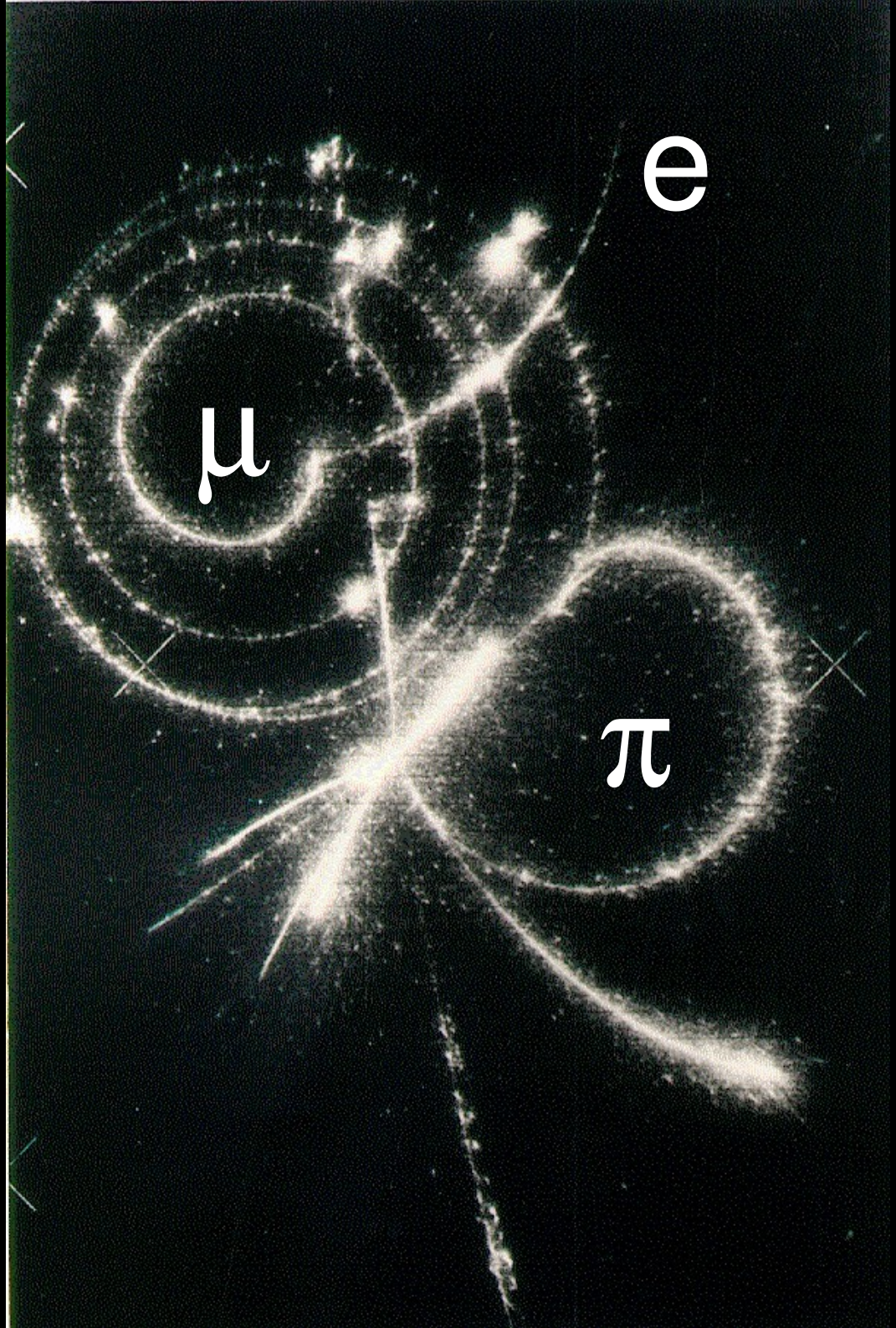
Conservation Law

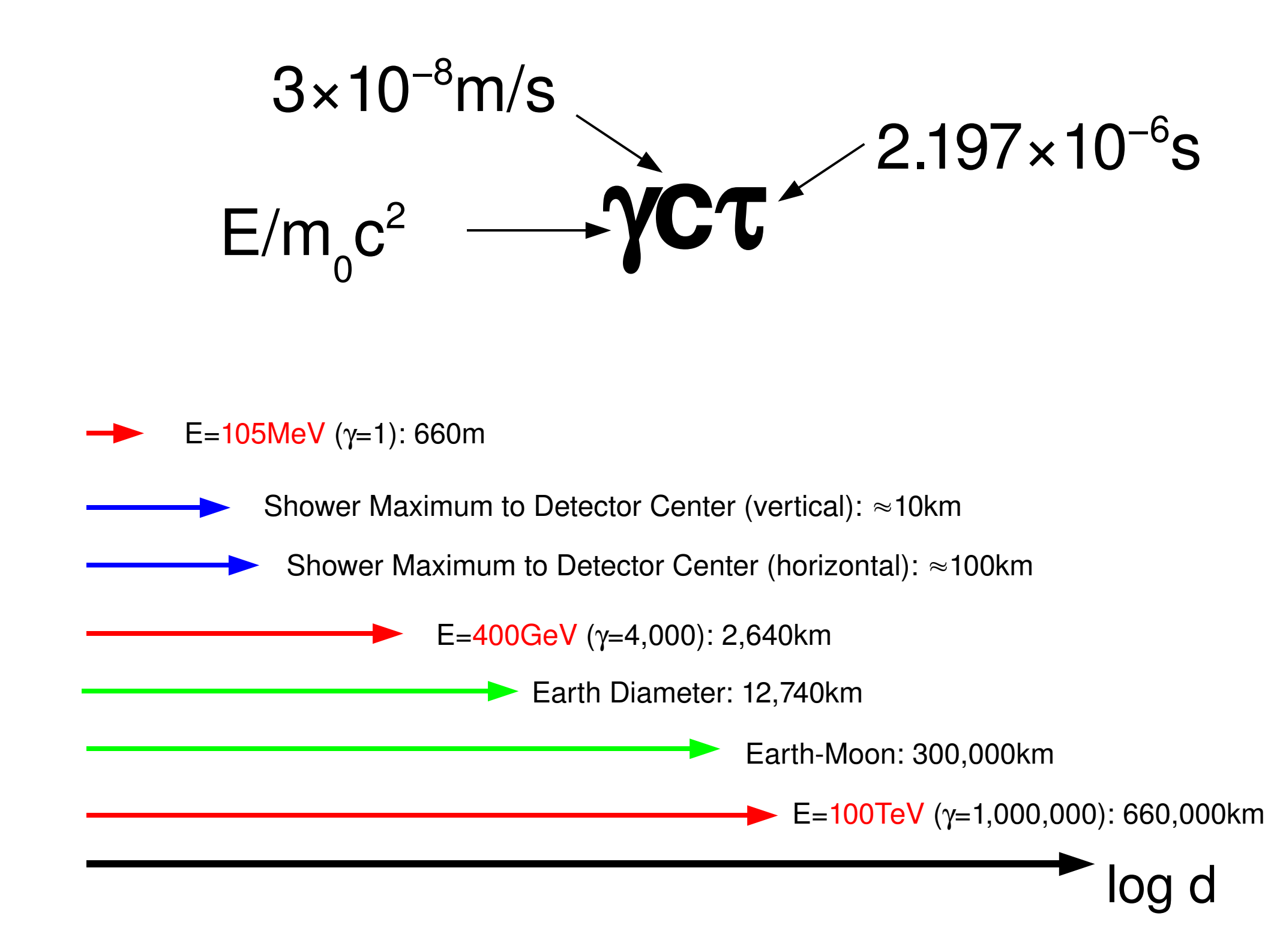
muonic number
(approx.!)

Charge

lepton number

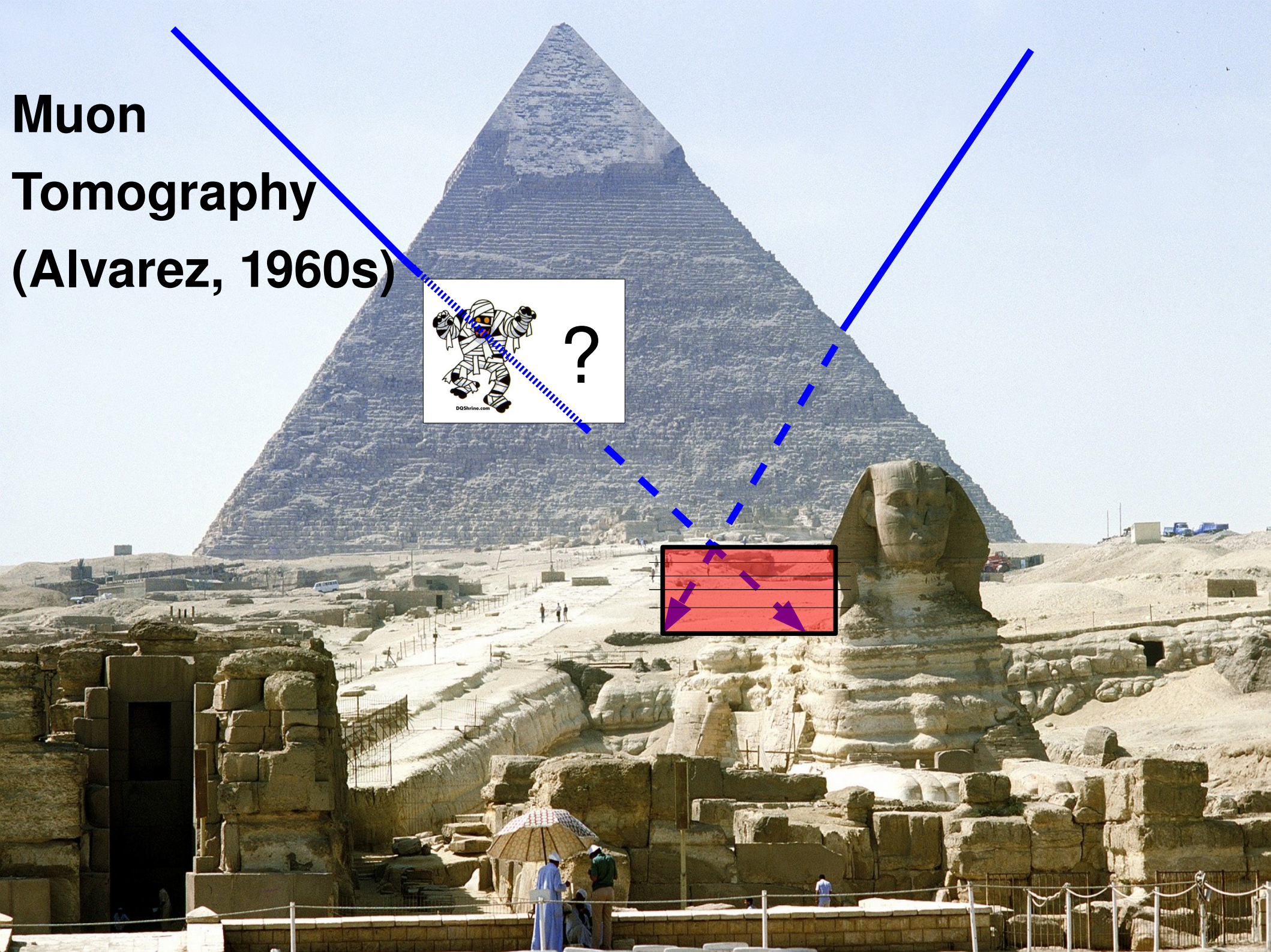
Σ: Energy


e
μ
π

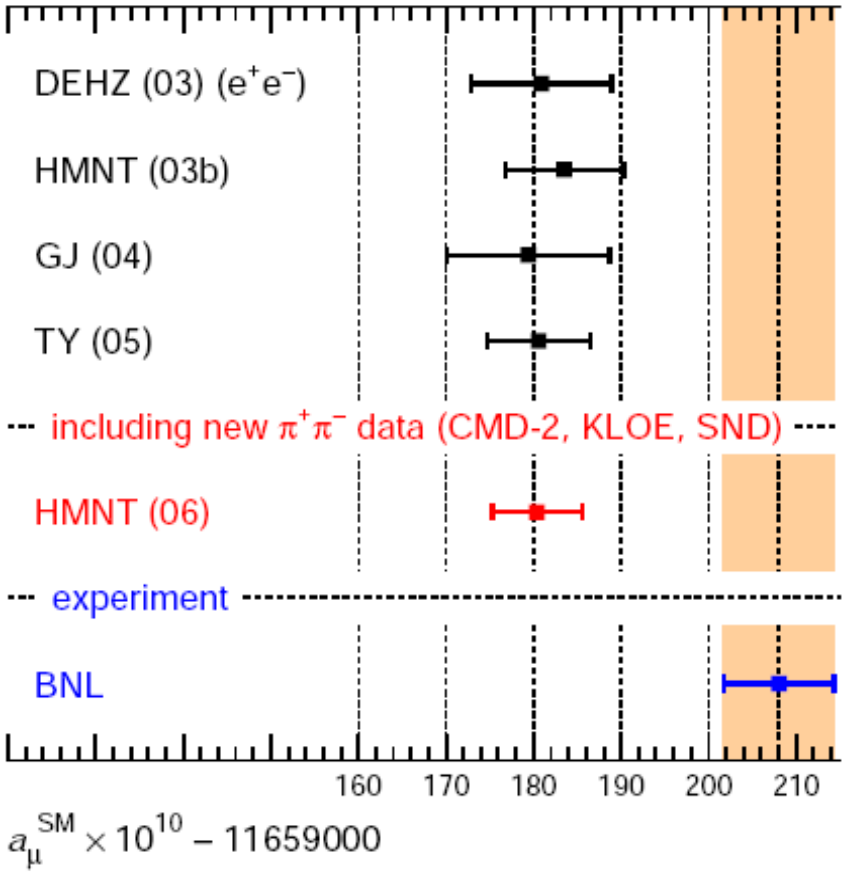

3×10⁻⁸m/s
2.197×10⁻⁶s
E/m₀c²
γcτ
E=105MeV (γ=1): 660m
Shower Maximum to Detector Center (vertical): ≈10km
Shower Maximum to Detector Center (horizontal): ≈100km
E=400GeV (γ=4,000): 2,640km
Earth Diameter: 12,740km
Earth-Moon: 300,000km
E=100TeV (γ=1,000,000): 660,000km
log d

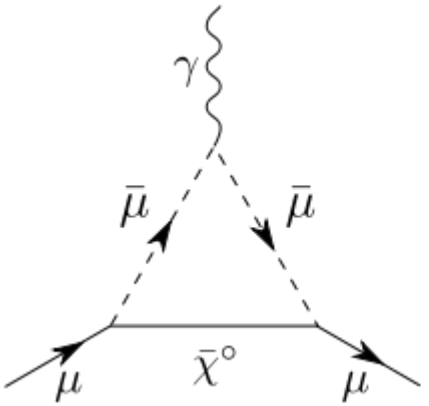
Outside HEP/Astro-Ph

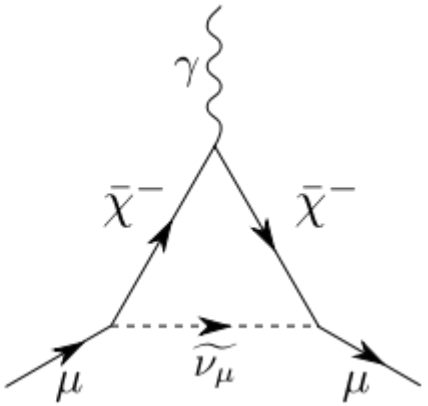
Muon Tomography (Alvarez, 1960s)



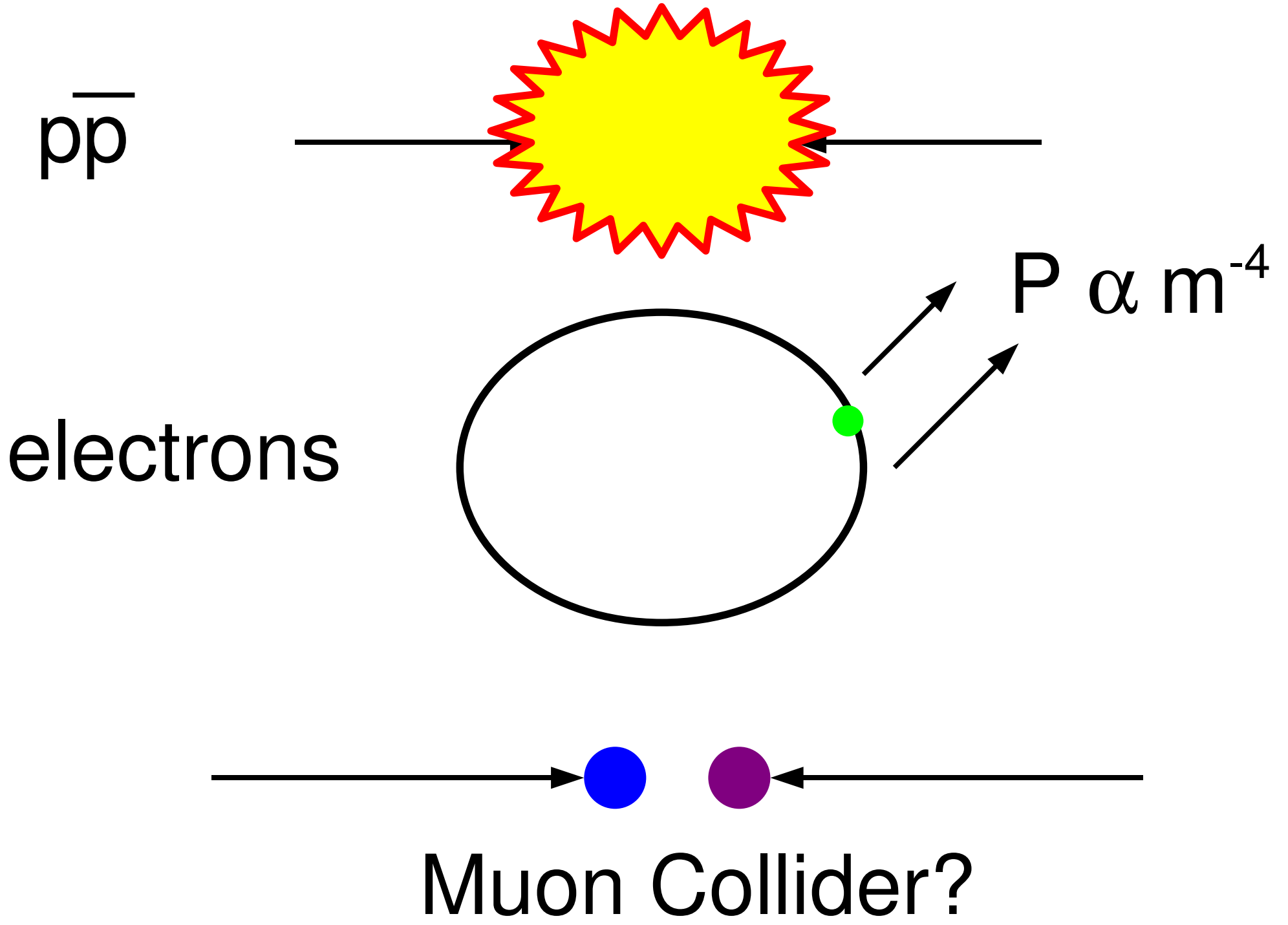
Anomalous Magnetic Moment: $a_\mu \equiv \frac{g_\mu - 2}{2}$

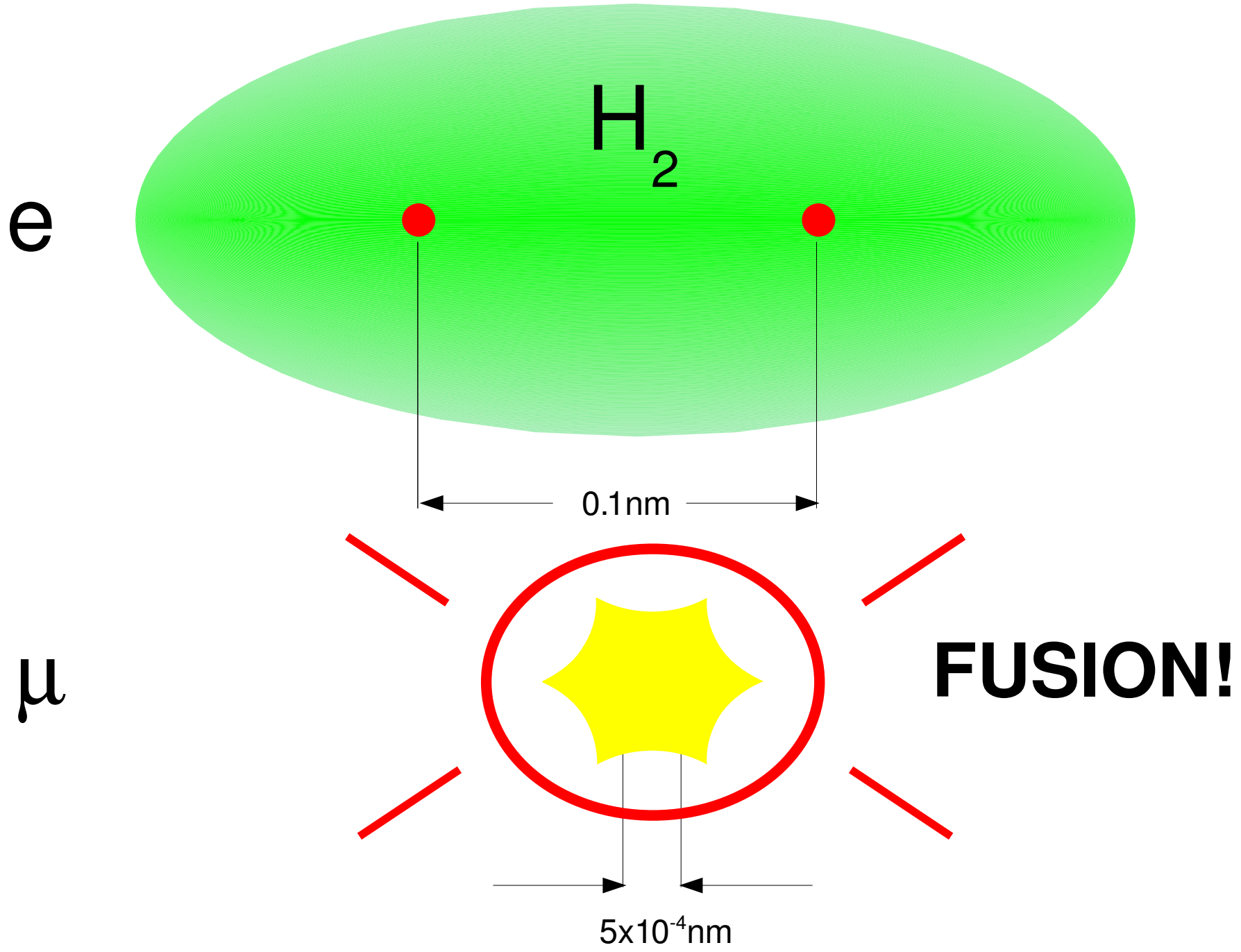




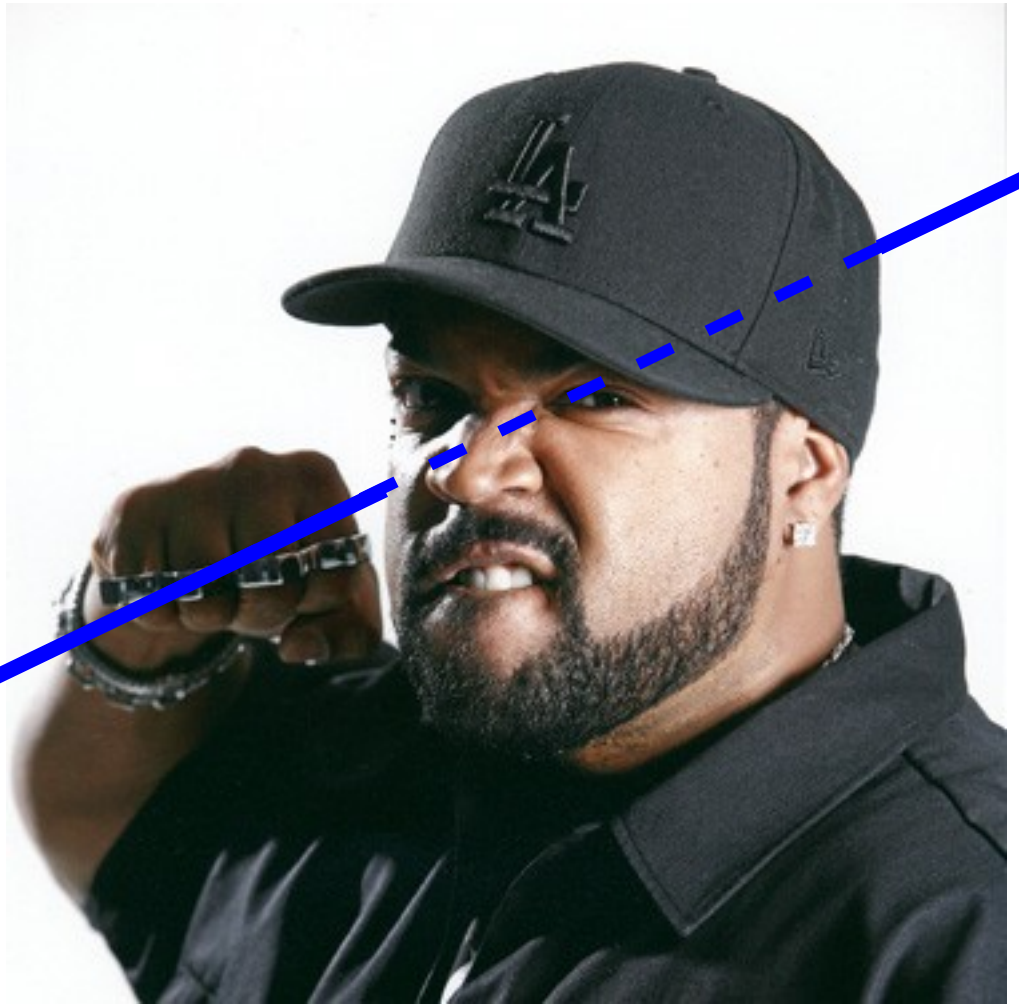


hep-ph/0611102


$p\bar{p}$
P α m^{-4}
electrons
Muon Collider?


e
H_2
0.1nm
μ
FUSION!
$5x10^{-4}$nm

II:Muons in IceCube

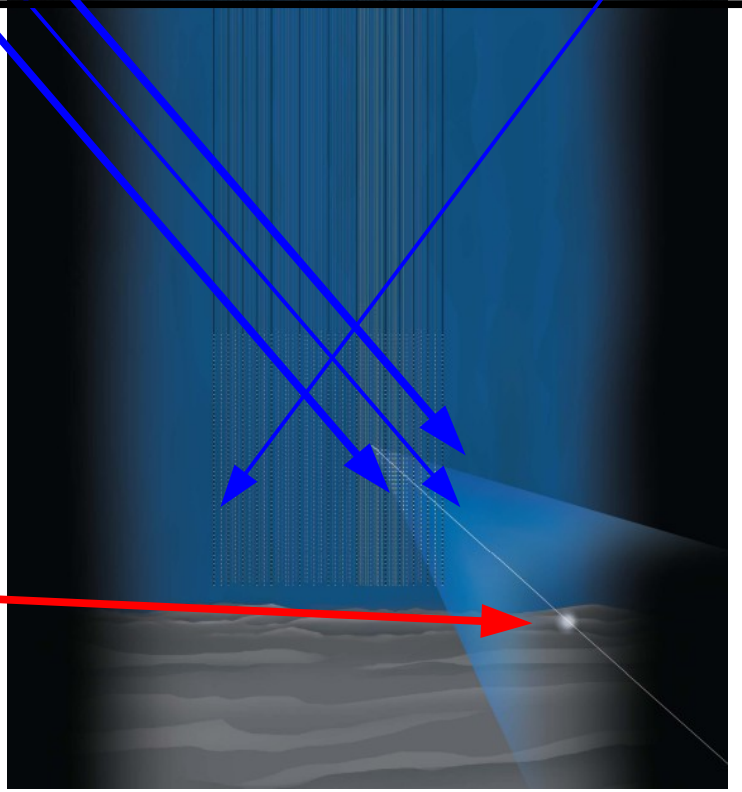


μ

Coincident Muons

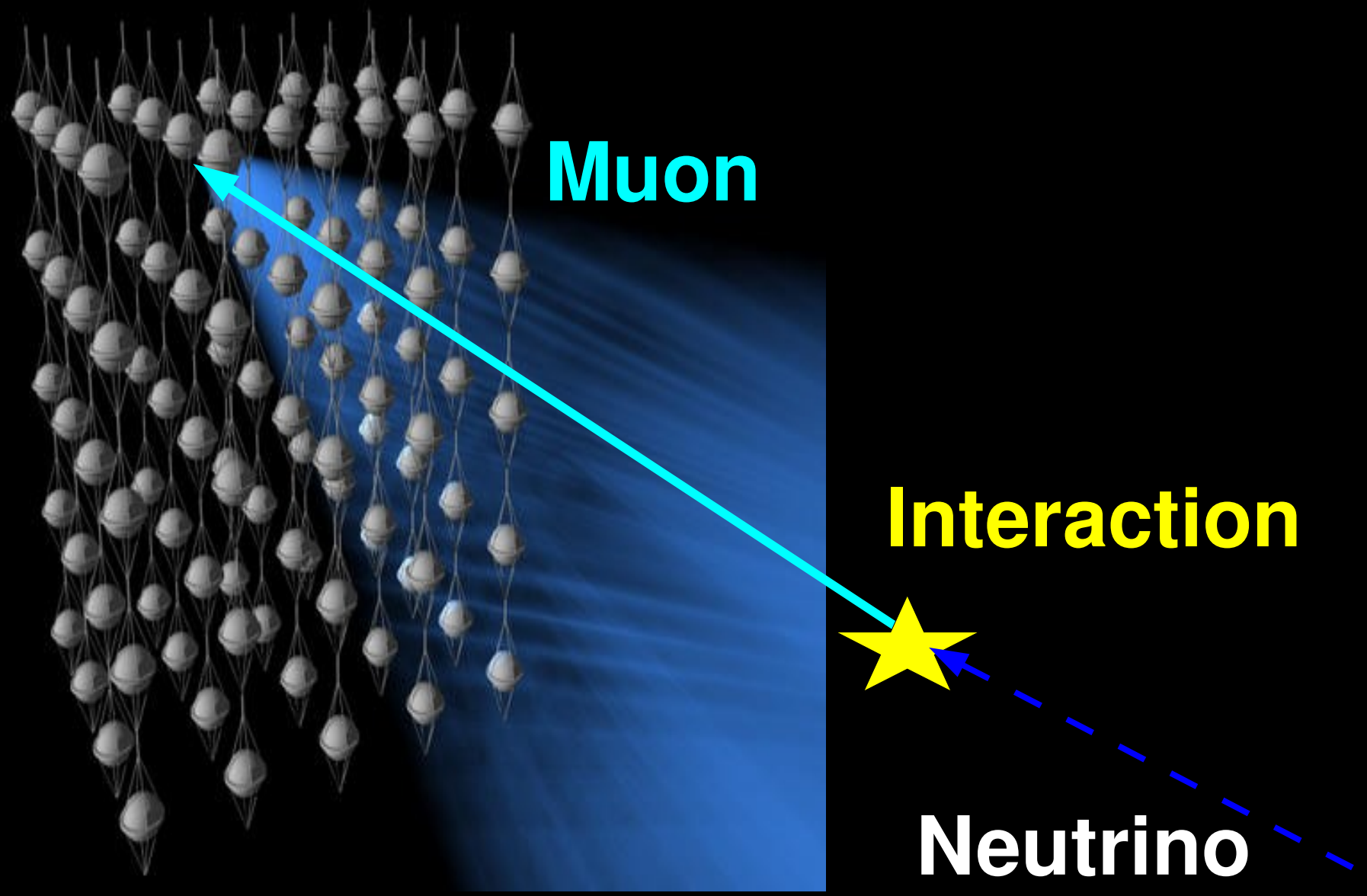
25Hz

10s of meters



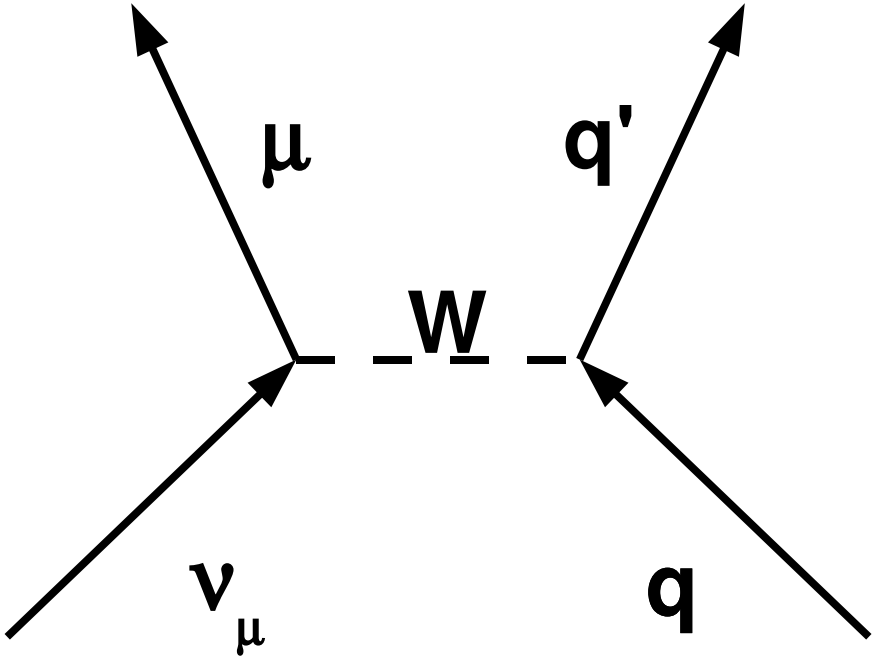
Muons From Neutrinos

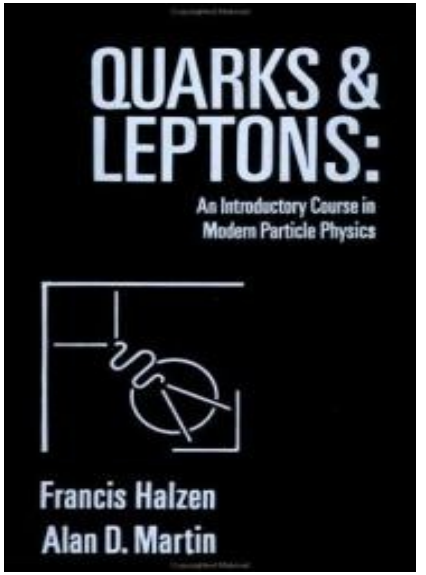
≃20/h



also: τ, hadron decay to μ (rare)

Deep Inelastic Scattering

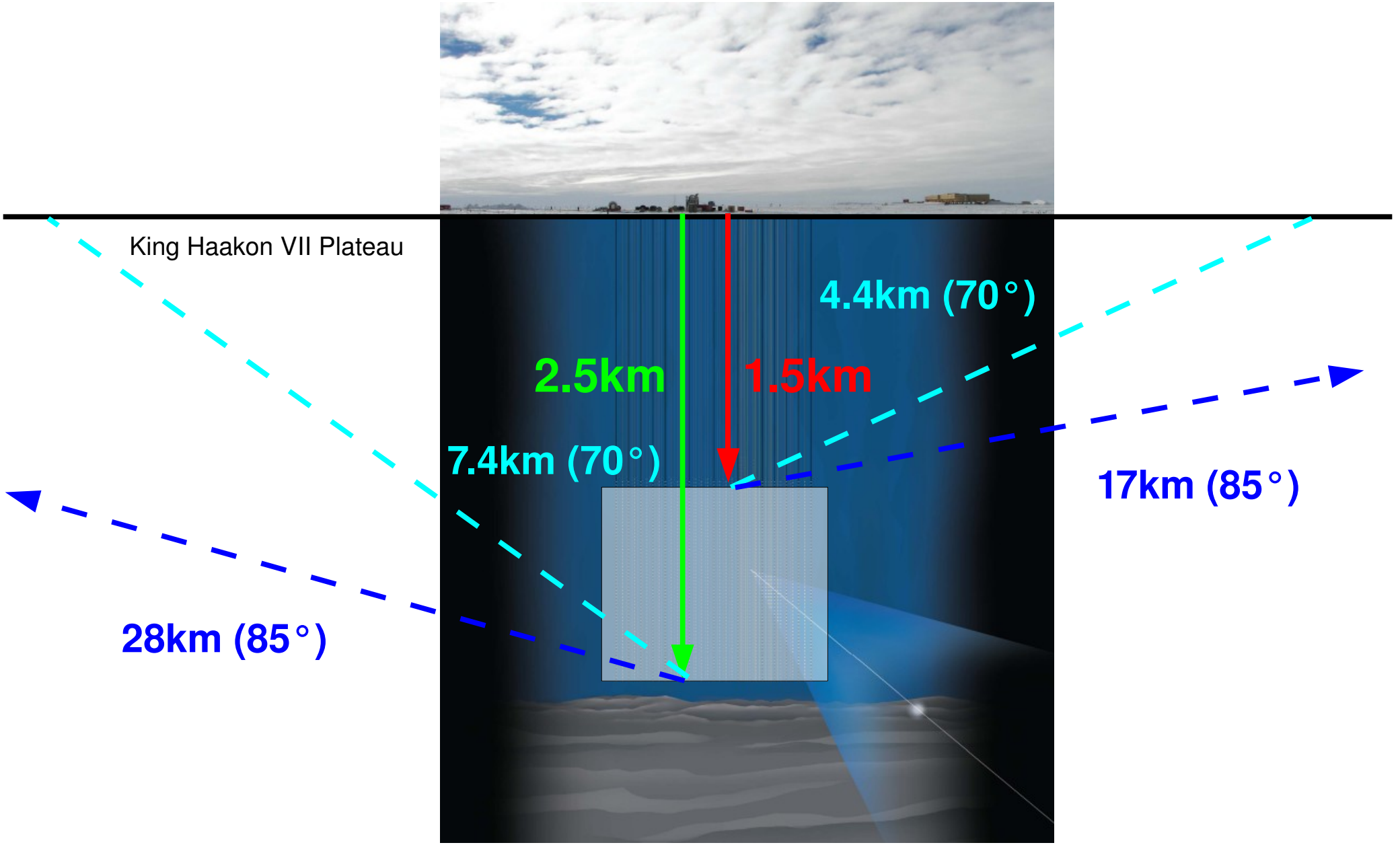




?

!

Intermezzo

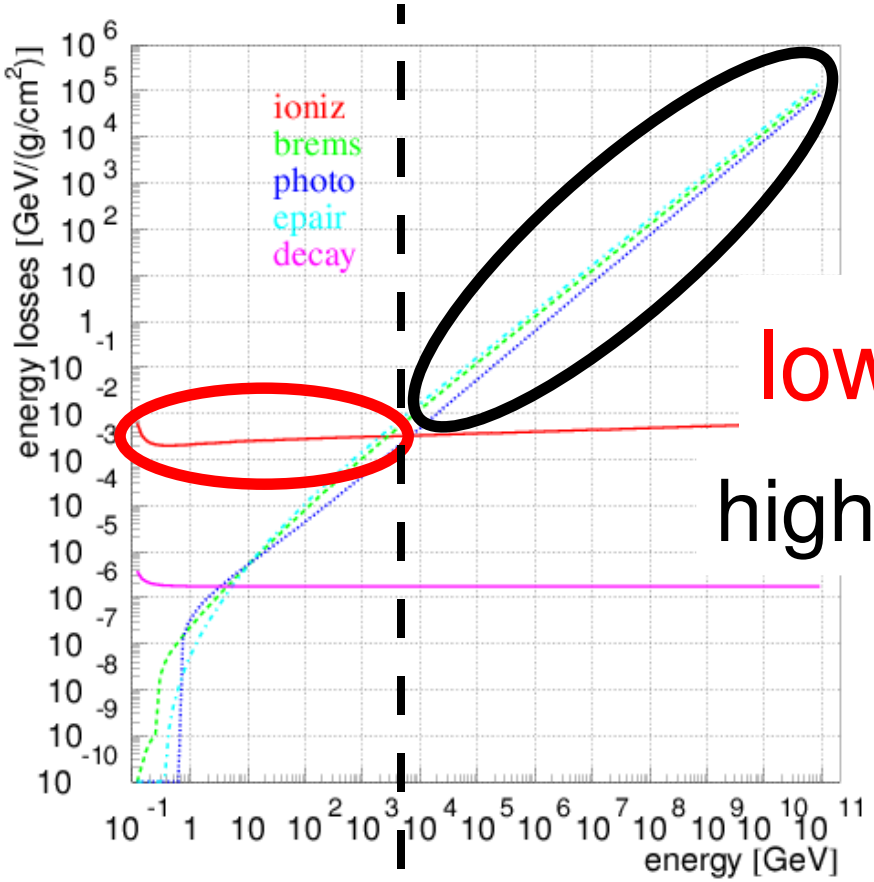

King Haakon VII Plateau
4.4km (70°)
2.5km
1.5km
7.4km (70°)
17km (85°)
28km (85°)

Muon Monte Carlo: a high-precision tool for muon propagation through matter

hep-ph/0407075

Dmitry Chirkin[1], **Wolfgang Rhode**[2]
chirkin@physics.berkeley.edu
rhode@uni-wuppertal.de

few TeV



low E: flat

high E: steep

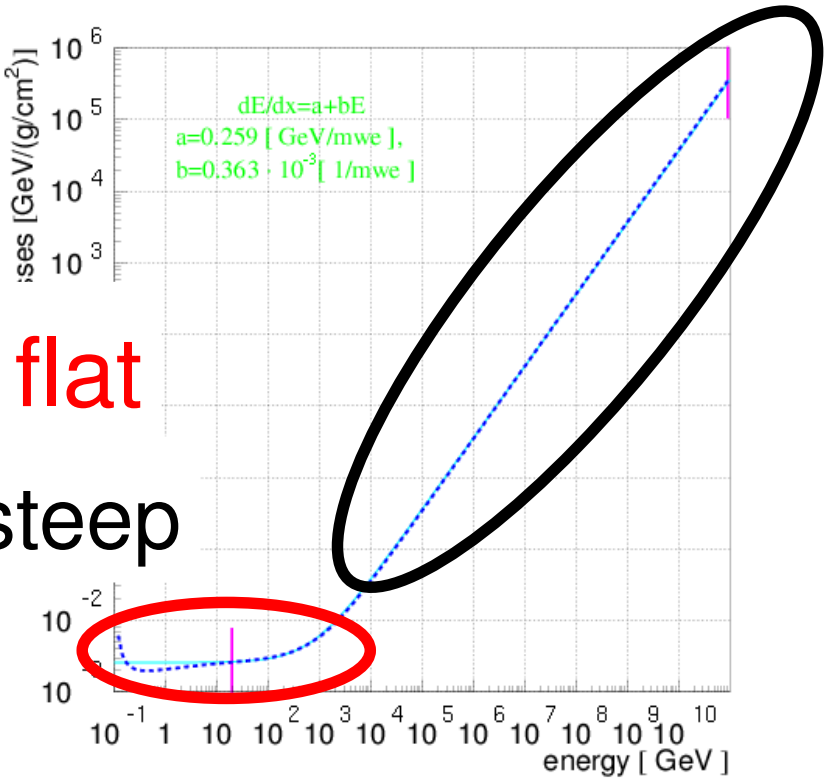
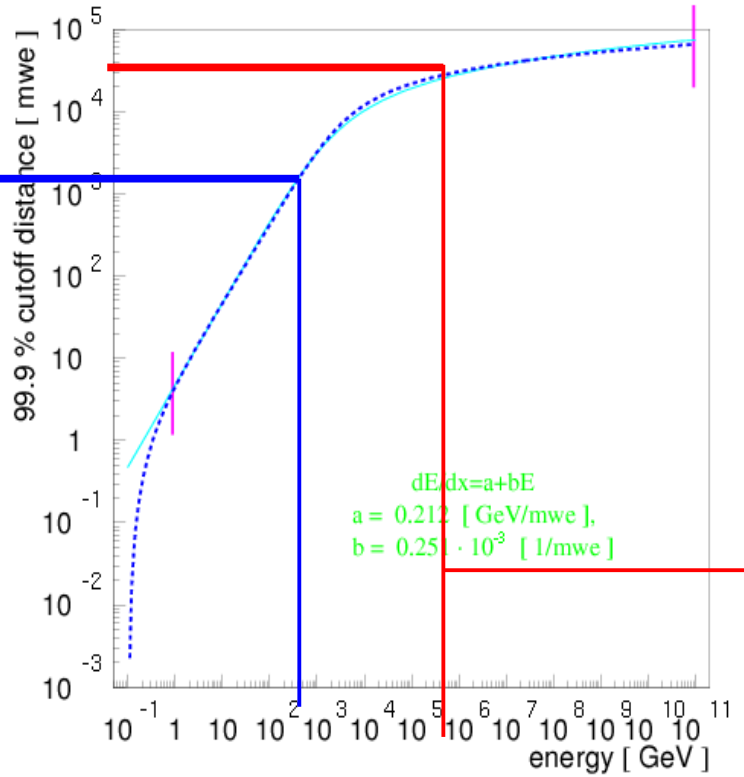


Fig. 21. Fit to the energy losses in ice

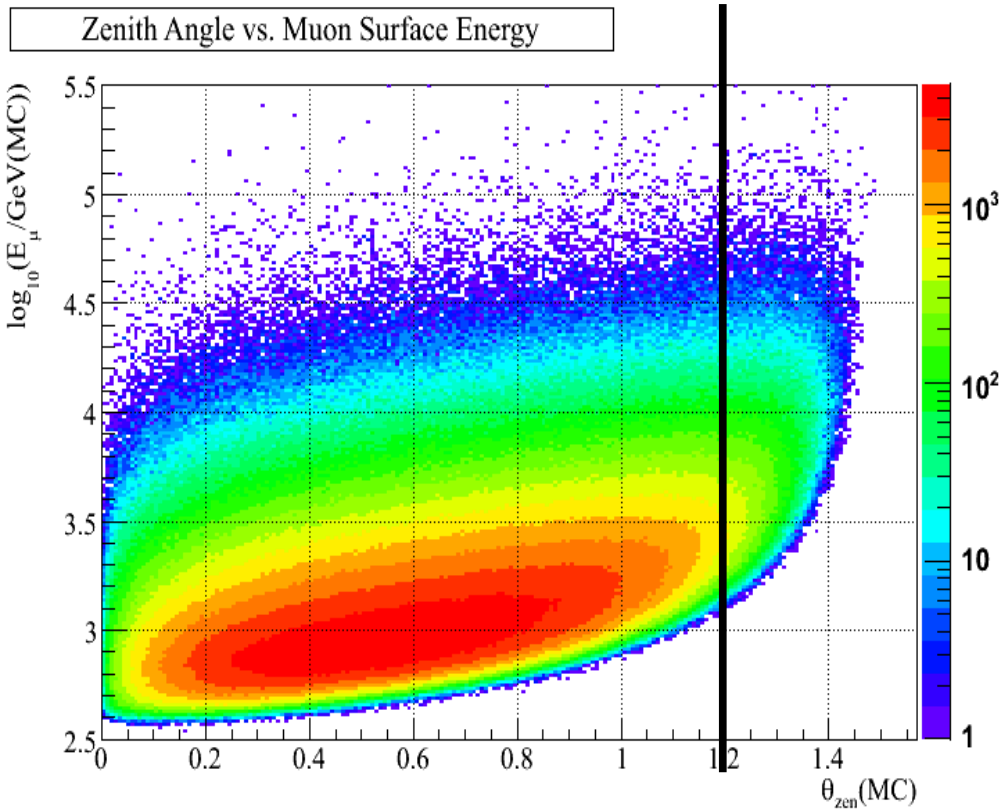
Threshold Energy

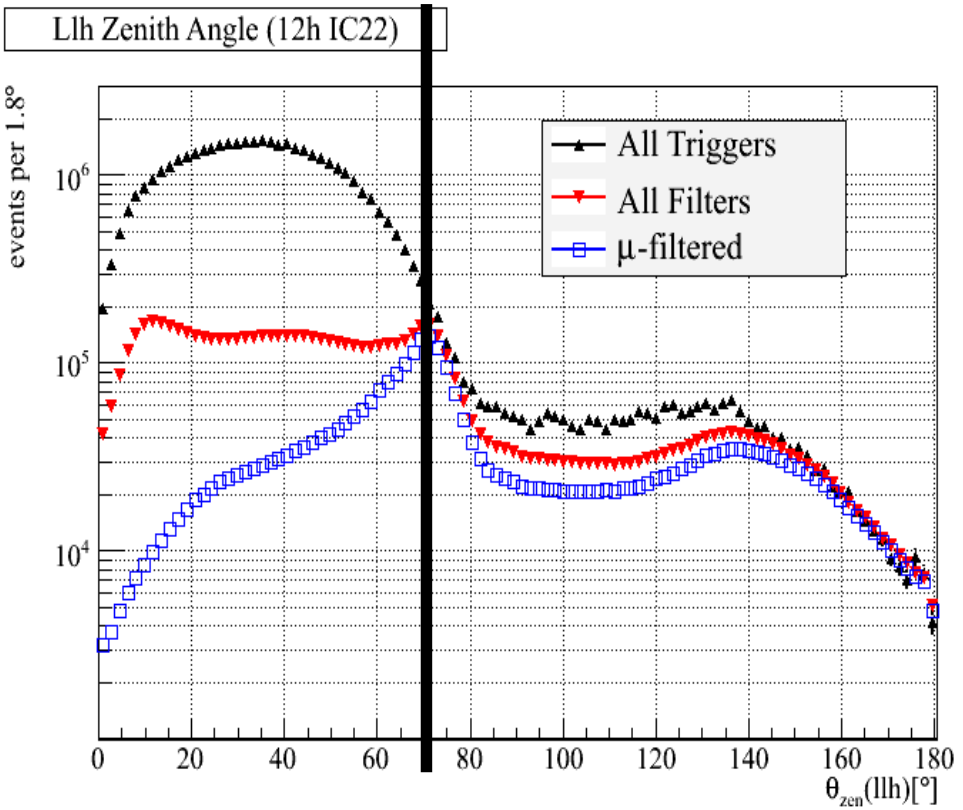
vertical



bottom (85°)

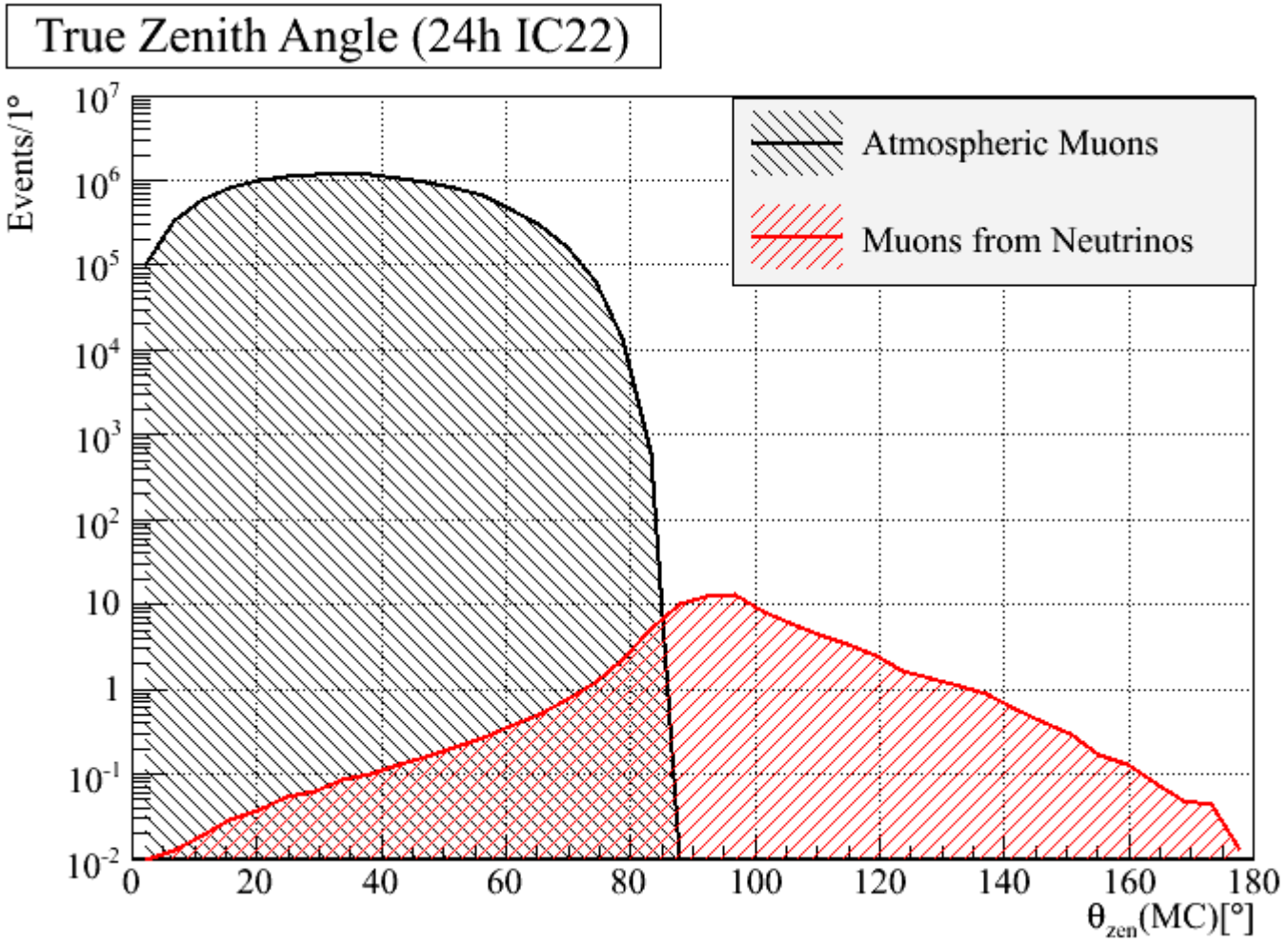
Fig. 29. Fit to the $E_{cut}(x)$


Zenith Angle vs. Muon Surface Energy
log10(Eμ/GeV(MC))
θzen(MC)

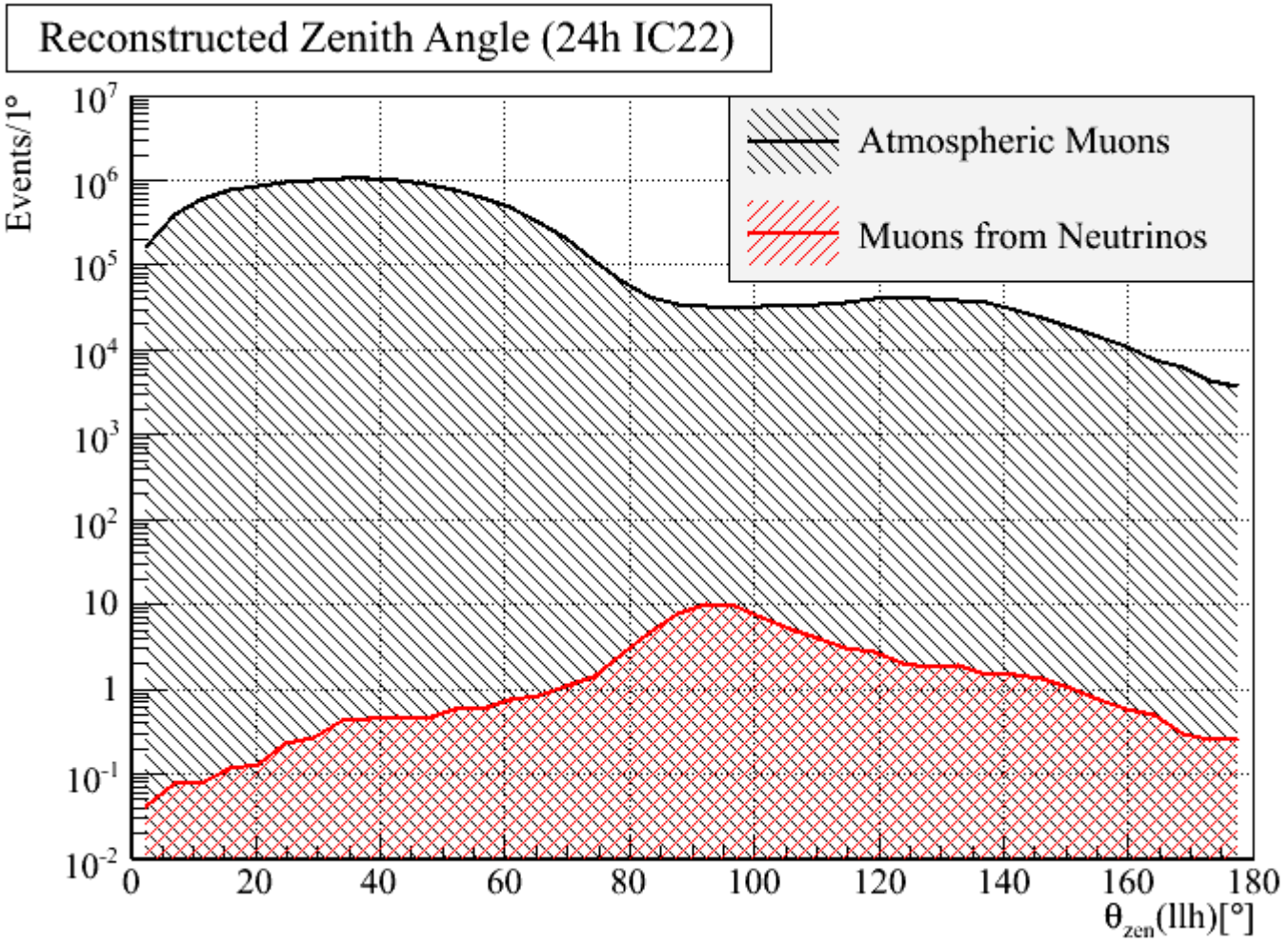

Llh Zenith Angle (12h IC22)
events per 1.8°
All Triggers
All Filters
μ-filtered
θzen(llh)[°]

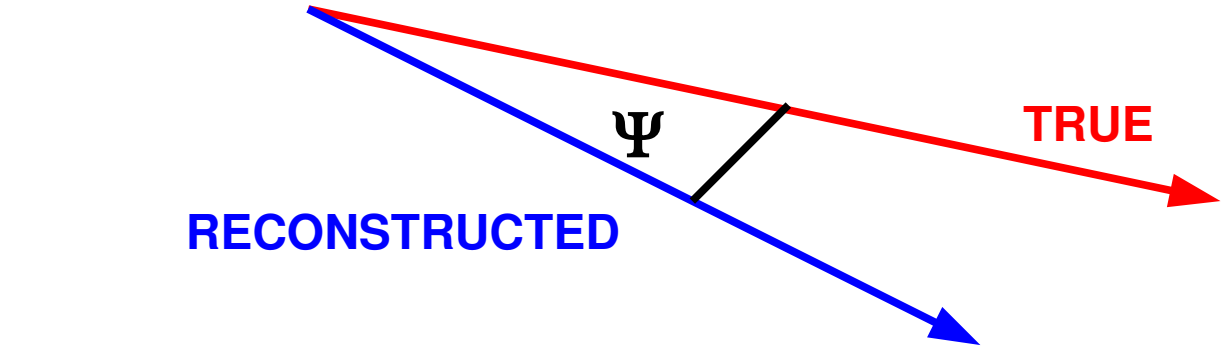
70°

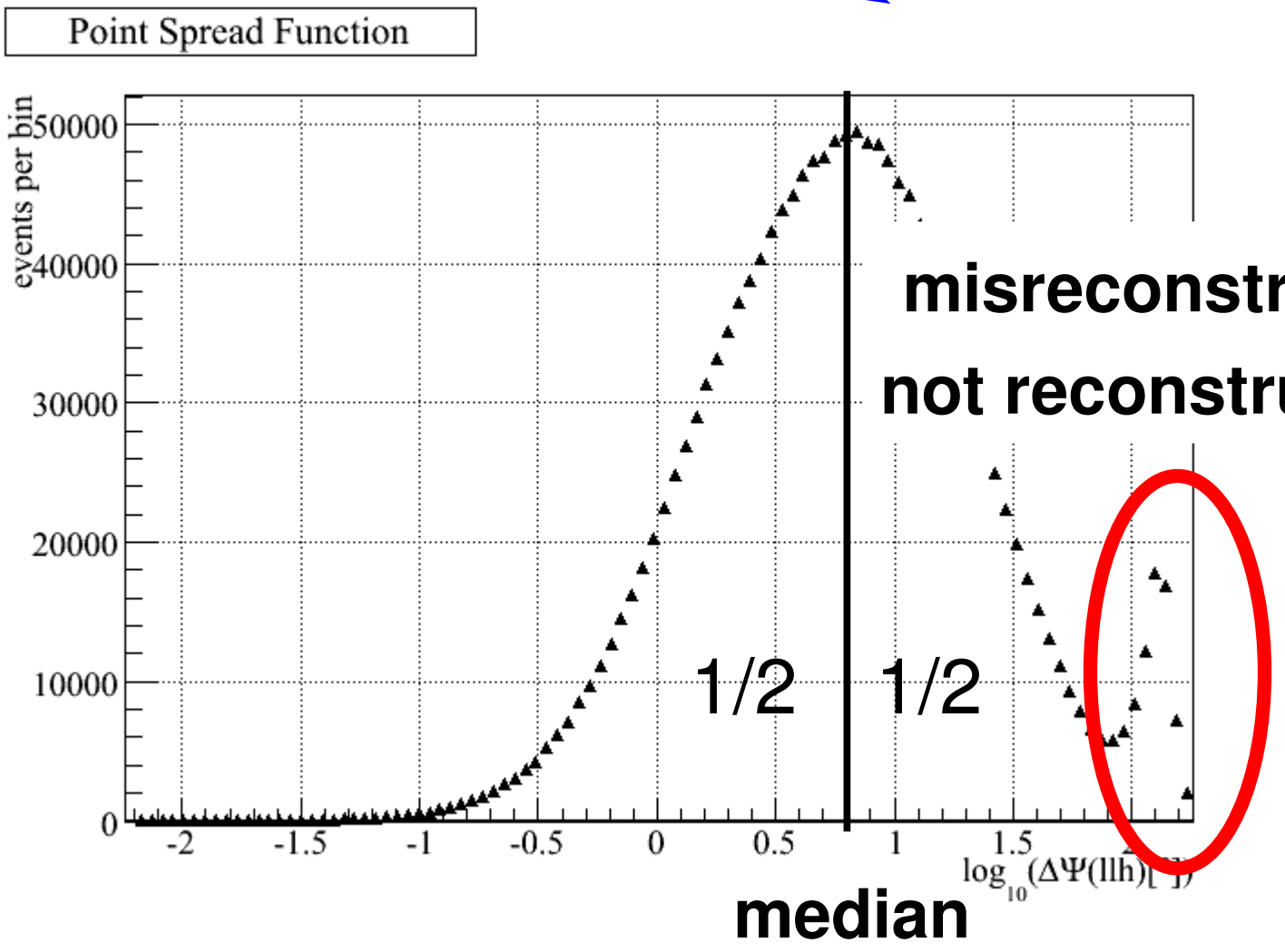
Ideal


True Zenith Angle (24h IC22)
Events/1°
10^7
10^6
10^5
10^4
10^3
10^2
10
1
10^{-1}
10^{-2}
0
20
40
60
80
100
120
140
160
180
θ_{zen}(MC)[°]
Atmospheric Muons
Muons from Neutrinos

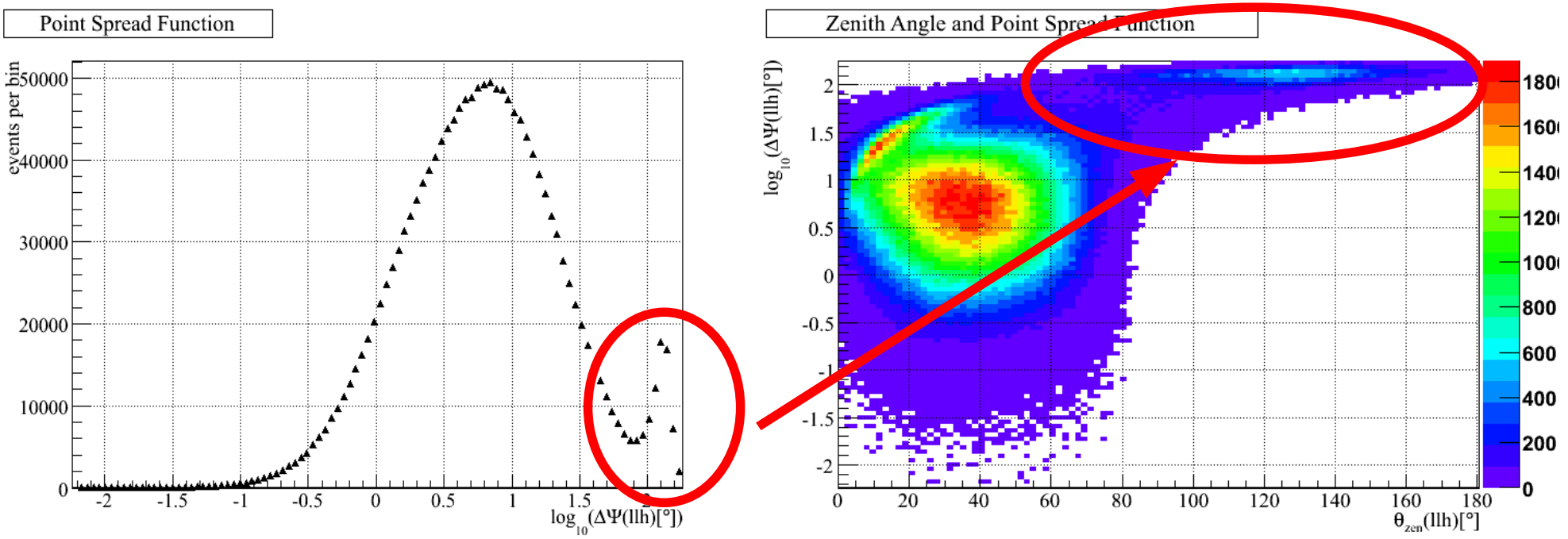
Actual


Reconstructed Zenith Angle (24h IC22)
Events/1°
Atmospheric Muons
Muons from Neutrinos
10^7
10^6
10^5
10^4
10^3
10^2
10
1
10^{-1}
10^{-2}
0
20
40
60
80
100
120
140
160
180
θ_{zen}(llh)[°]

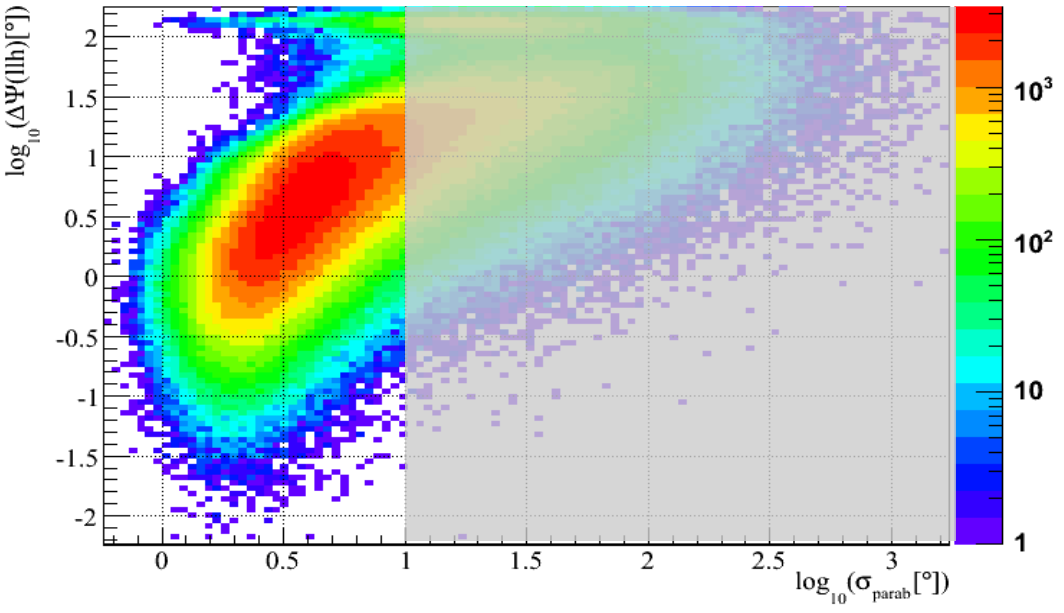

Ψ
TRUE
RECONSTRUCTED


Point Spread Function
events per bin
50000
40000
30000
20000
10000
0
-2
-1.5
-1
-0.5
0
0.5
1
1.5
1/2
1/2
misreconstructed/
not reconstructable
median

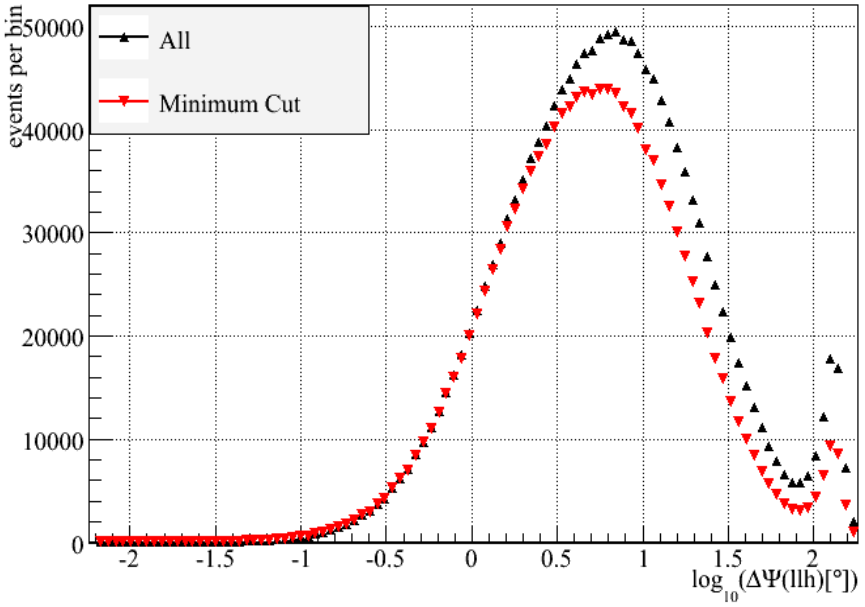
Raw


Point Spread Function
events per bin
50000
40000
30000
20000
10000
0
-2
-1.5
-1
-0.5
0
0.5
1
1.5
log10(ΔΨ(llh)[°])
Zenith Angle and Point Spread Function
log10(ΔΨ(llh)[°])
2
1.5
1
0.5
0
-0.5
-1.5
-2
0
20
40
60
80
100
120
140
160
180
θzen(llh)[°]
180
160
140
120
100
800
600
400
200
0

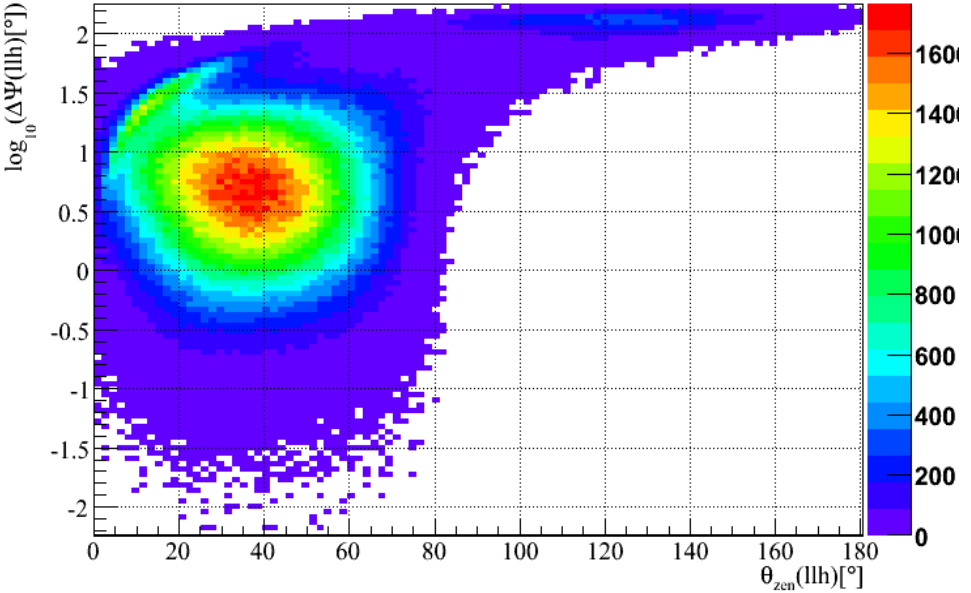
Parabolid Error Ellipse and Point Spread Function



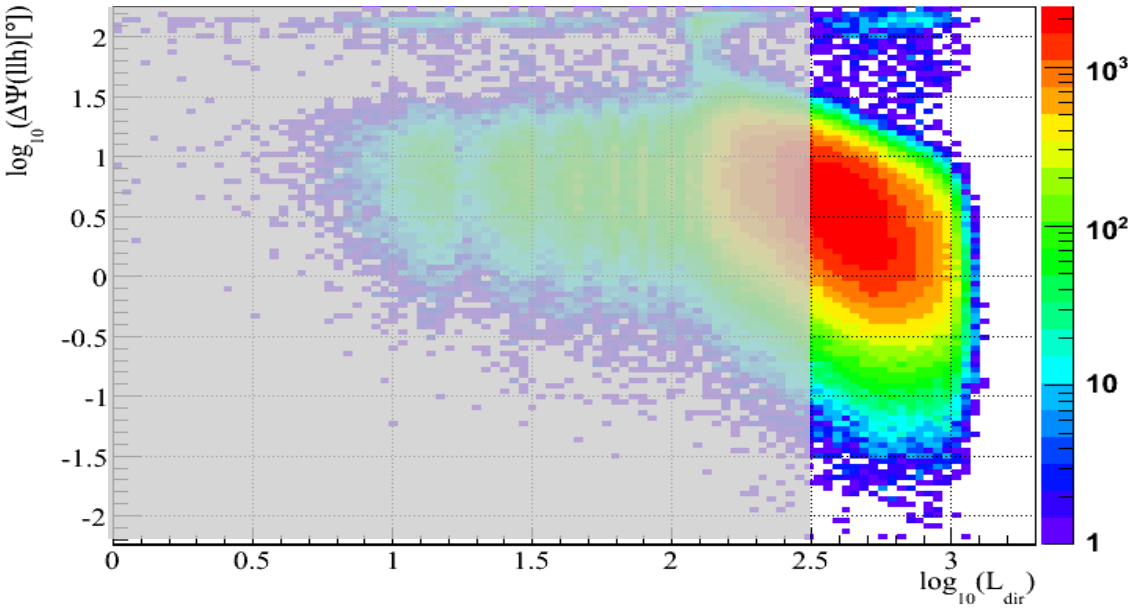
Point Spread Function



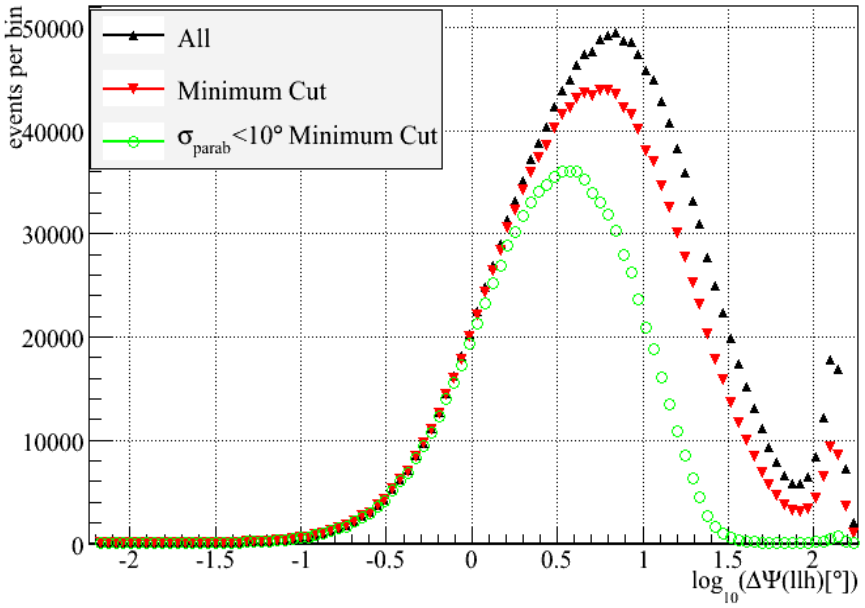
Zenith Angle and Point Spread Function



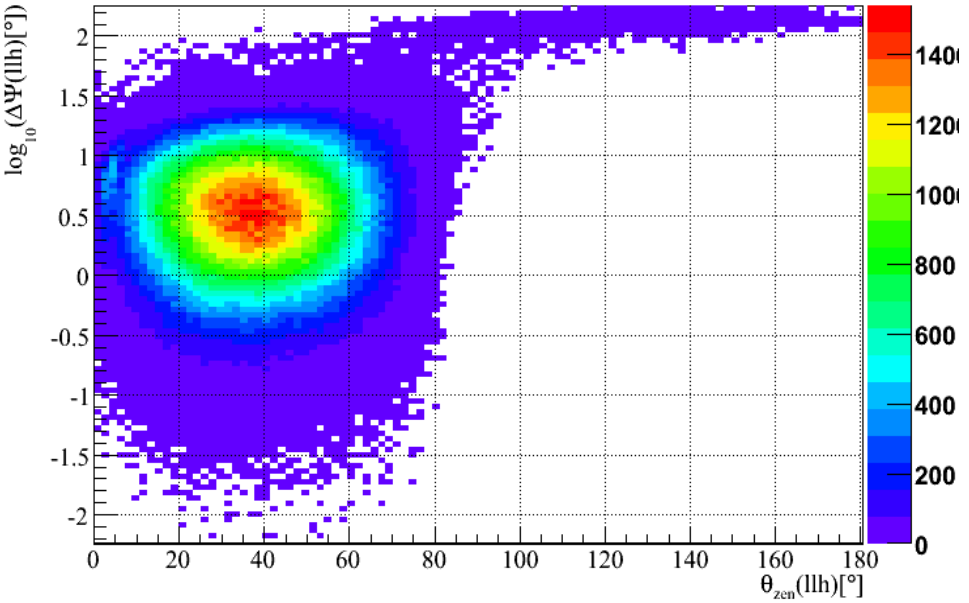
Track Length and Point Spread Function



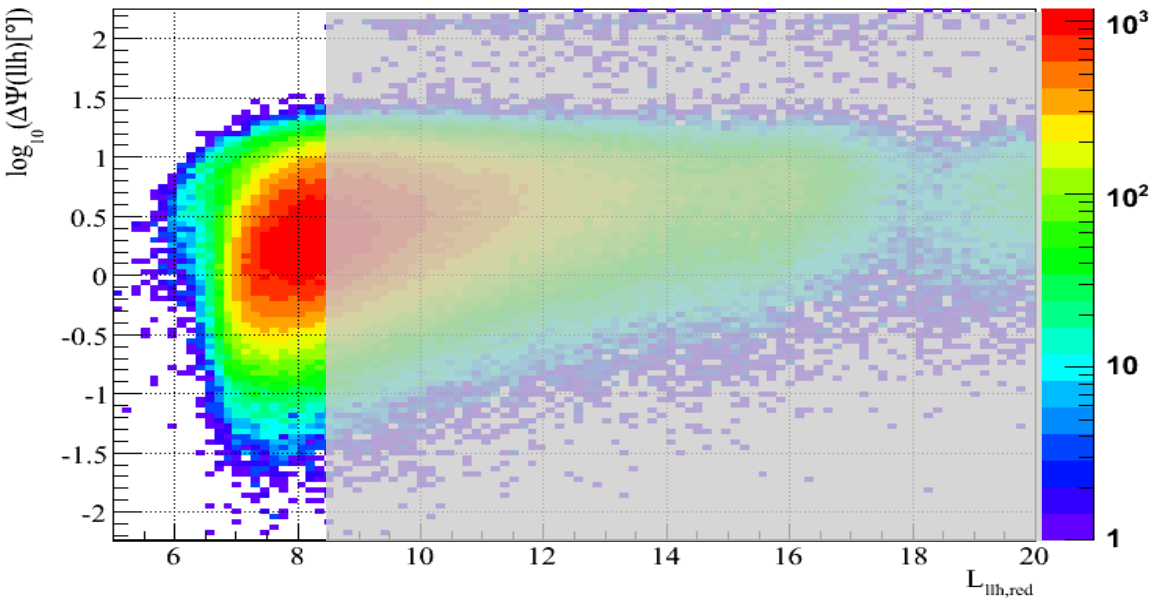
Point Spread Function



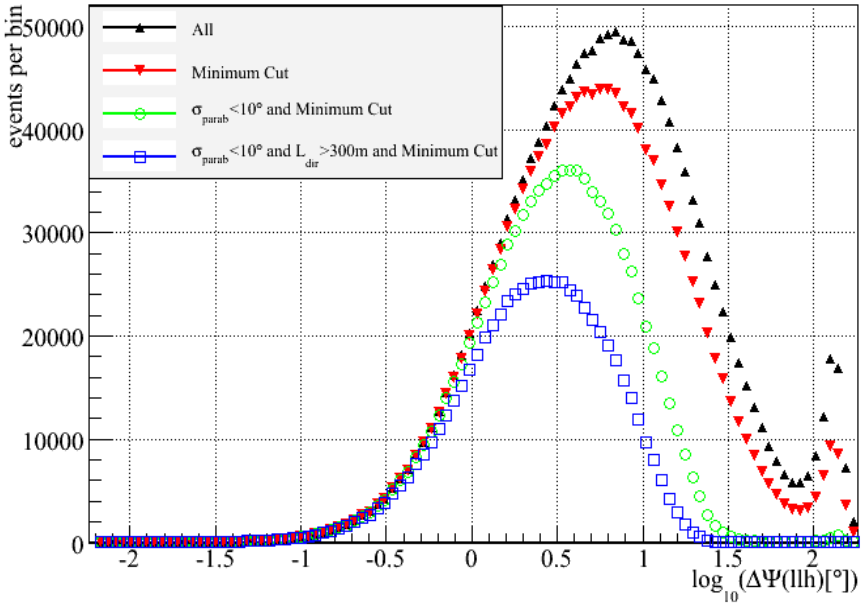
Zenith Angle and Point Spread Function



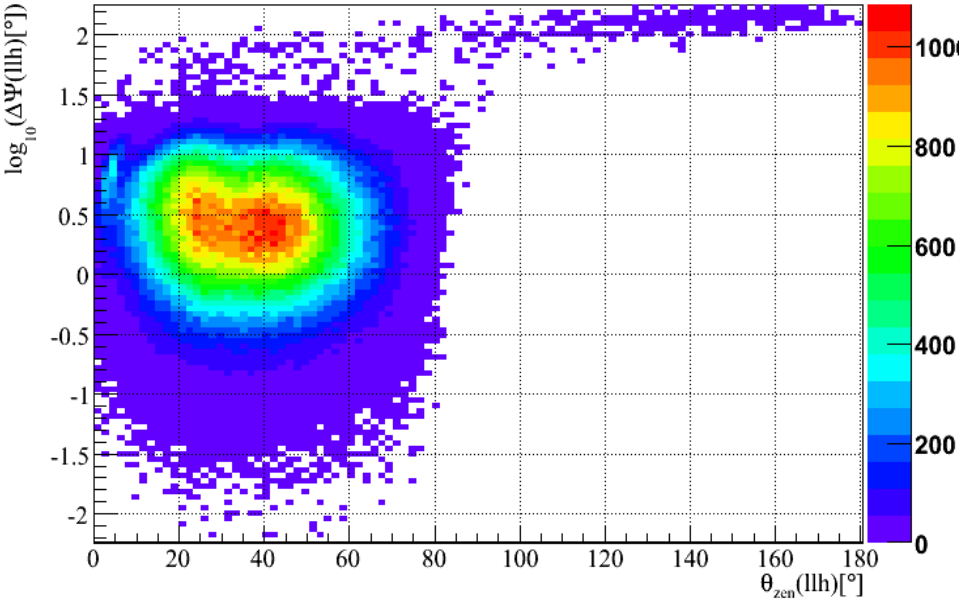
Reduced Likelihood and Point Spread Function



Point Spread Function

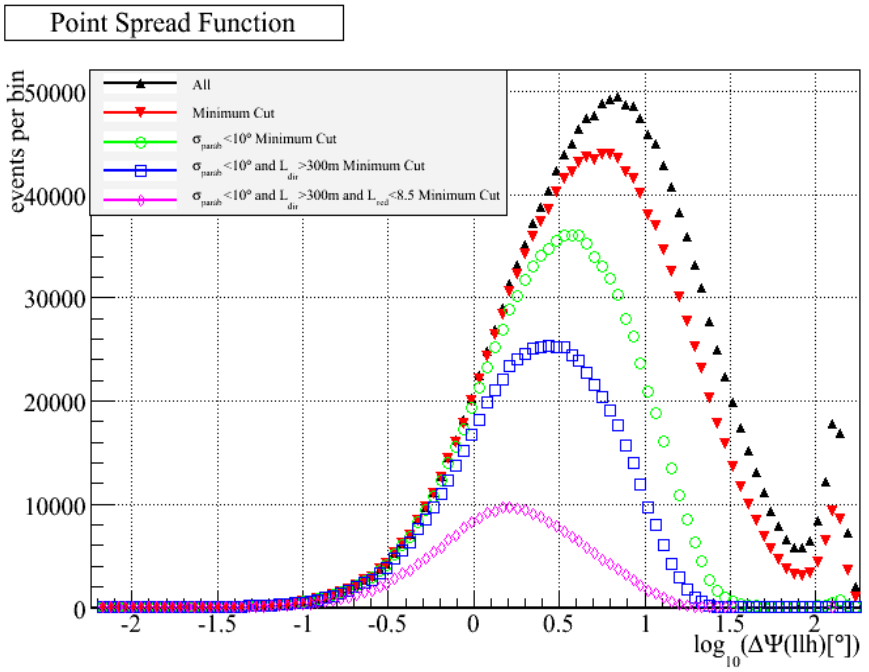


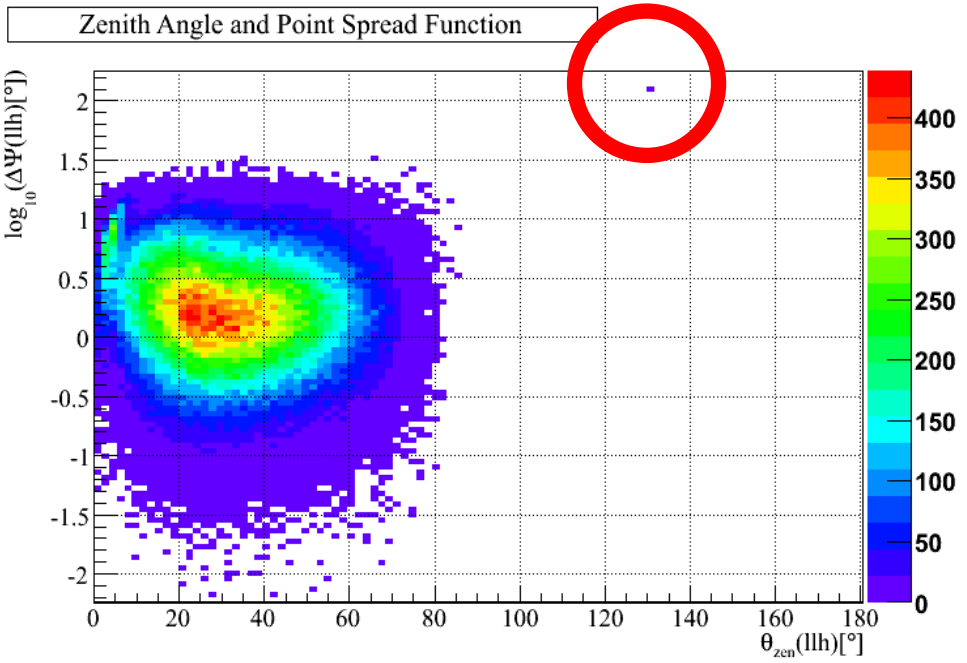
Point Spread Function and Zenith Angle



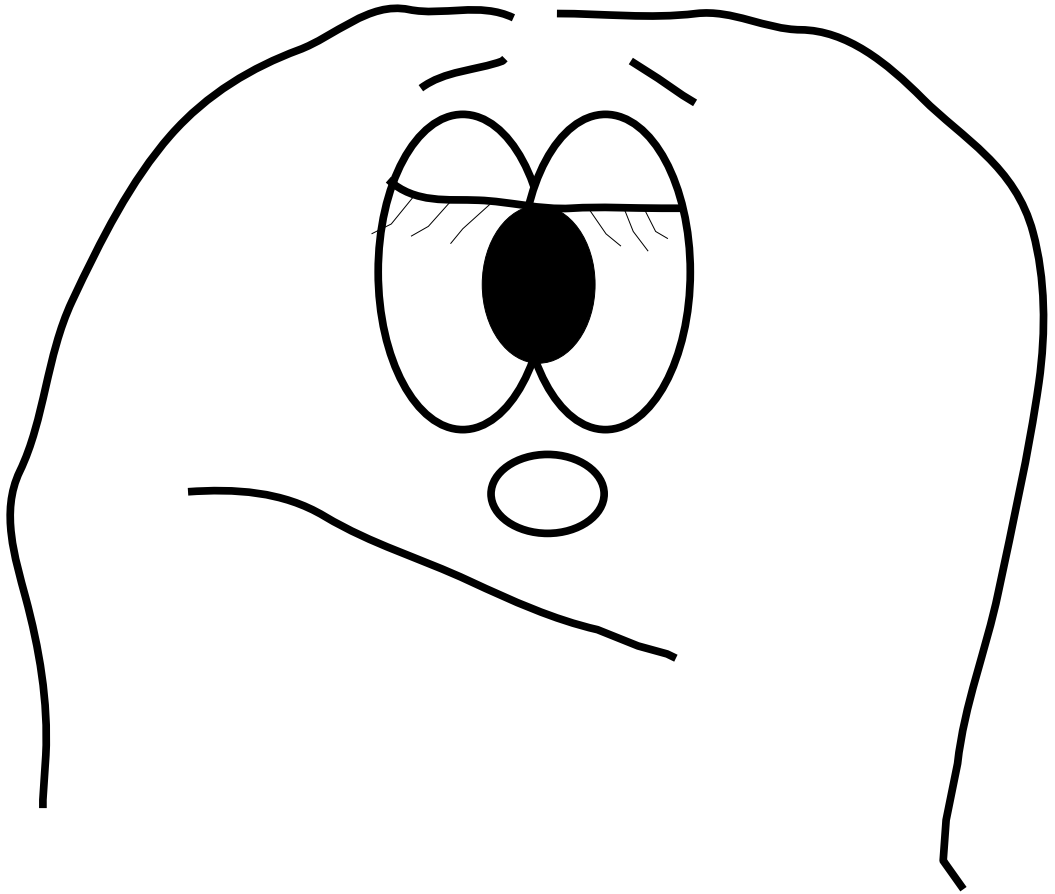
Final

SIGNAL!!!





Applications

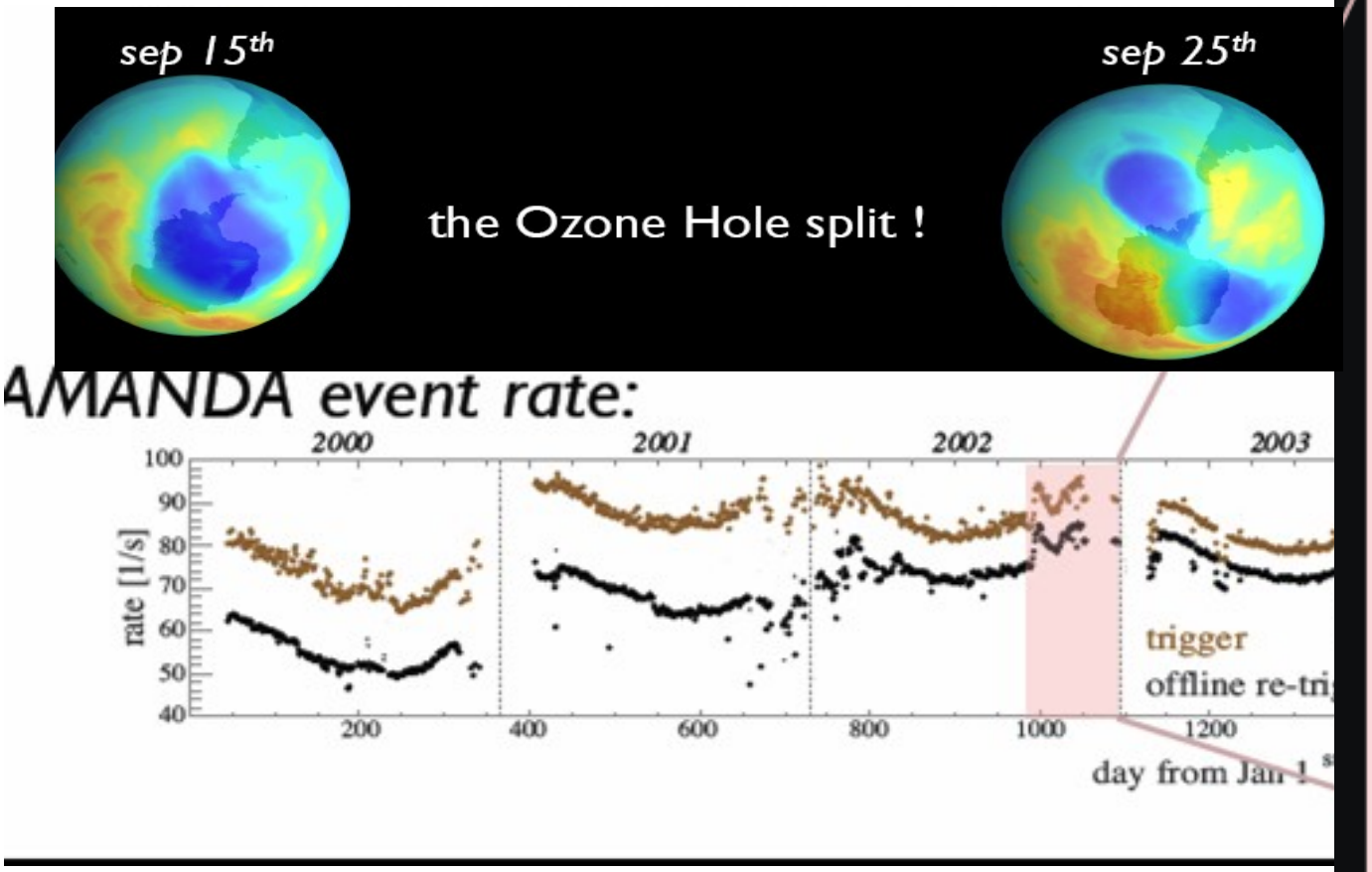


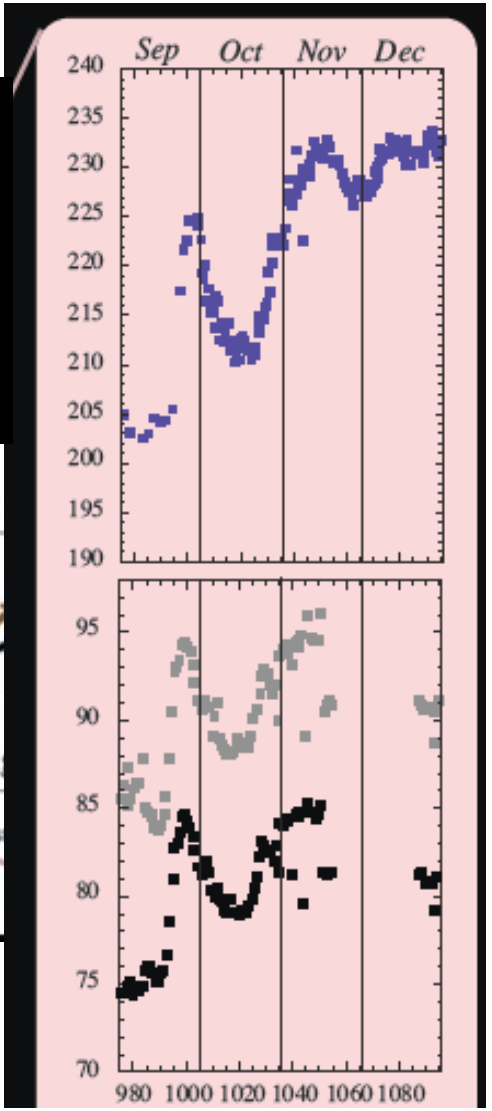
Omg!

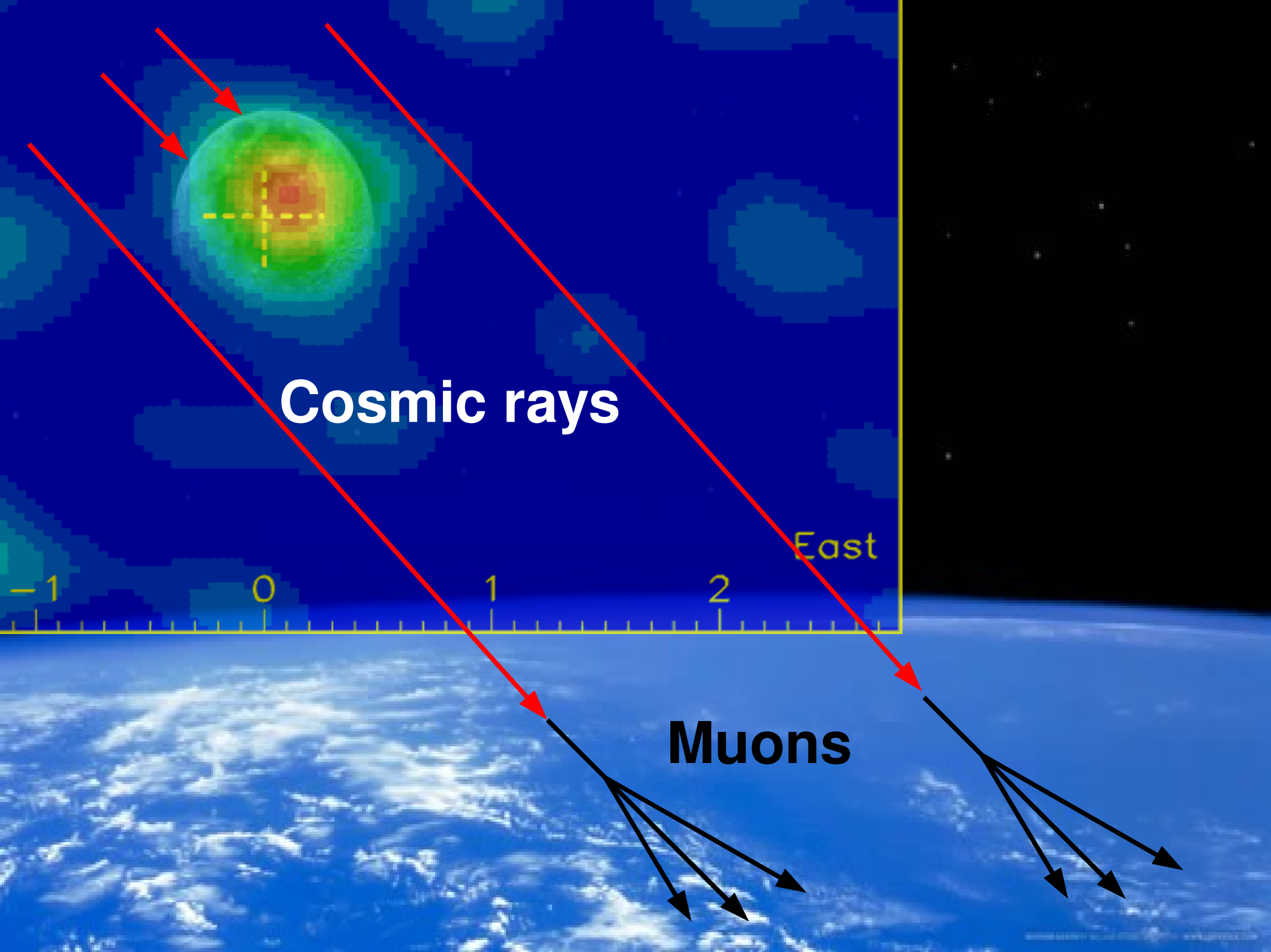
Neutrinos!

Excitement!

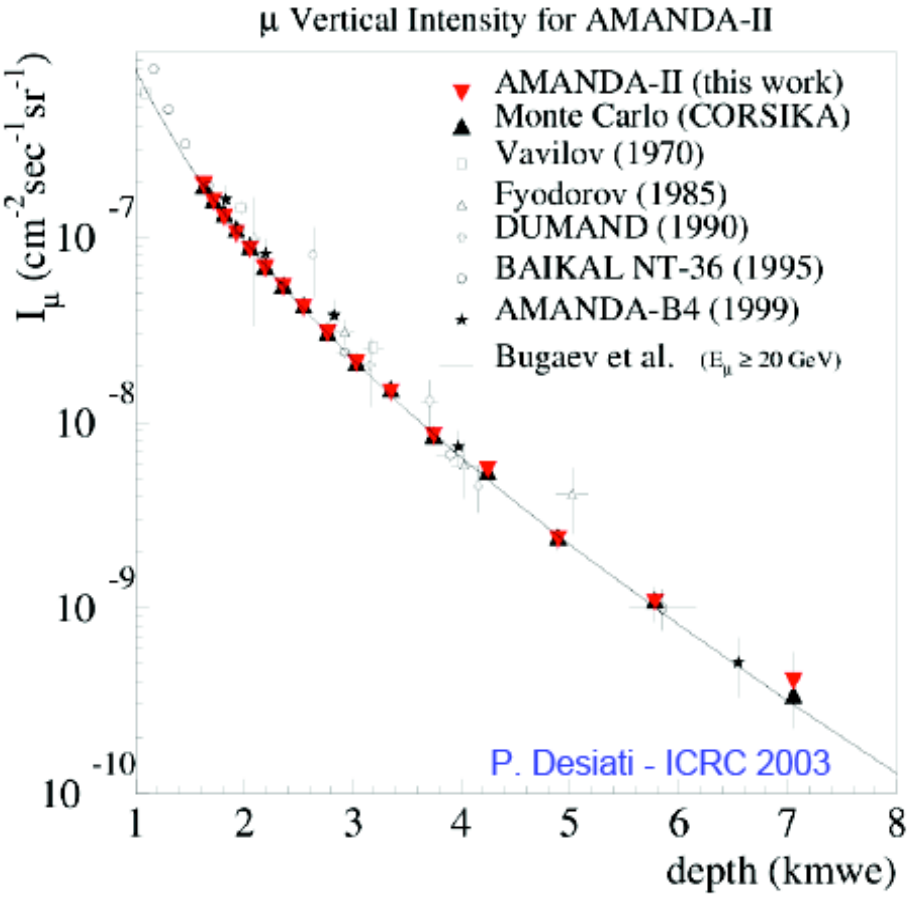
Meteorology






Cosmic rays
East
−1
0
1
2
Muons

Muon Rate



Energy Spectrum

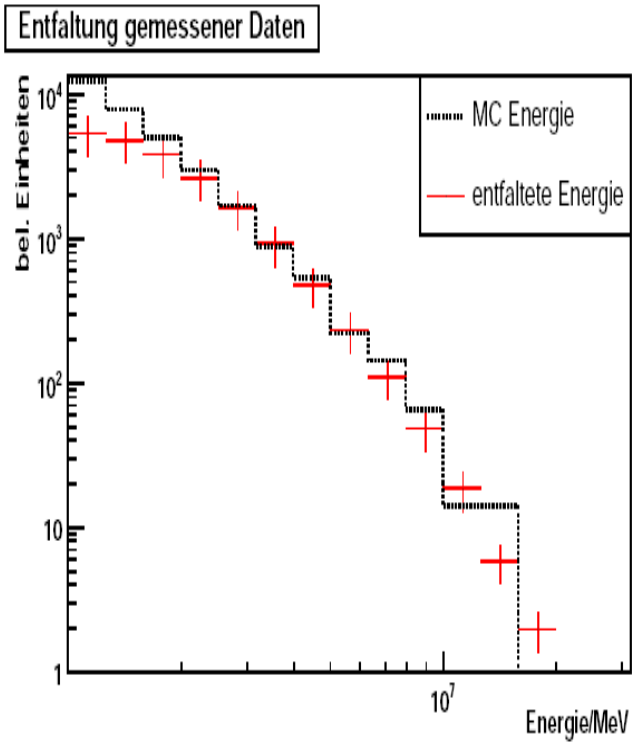
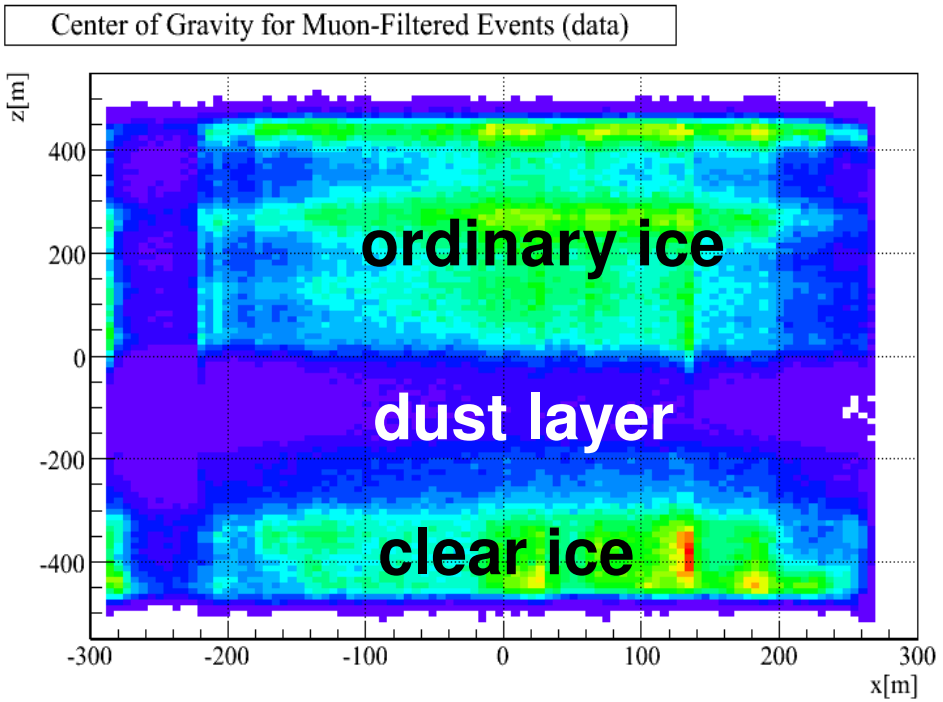


Abbildung 7.13: Entfaltung von gemessenen Daten aus dem Jahr 2000, verglichen mit simulierten Ereignissen (gestricheltes Histogramm)

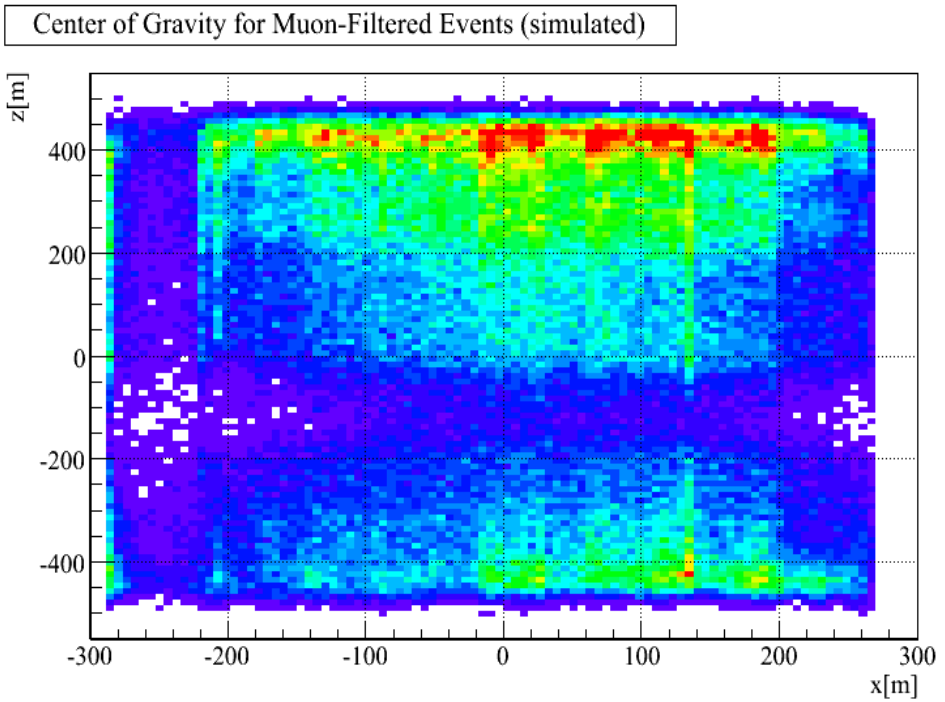
AMANDA!

Detector Calibration

Real

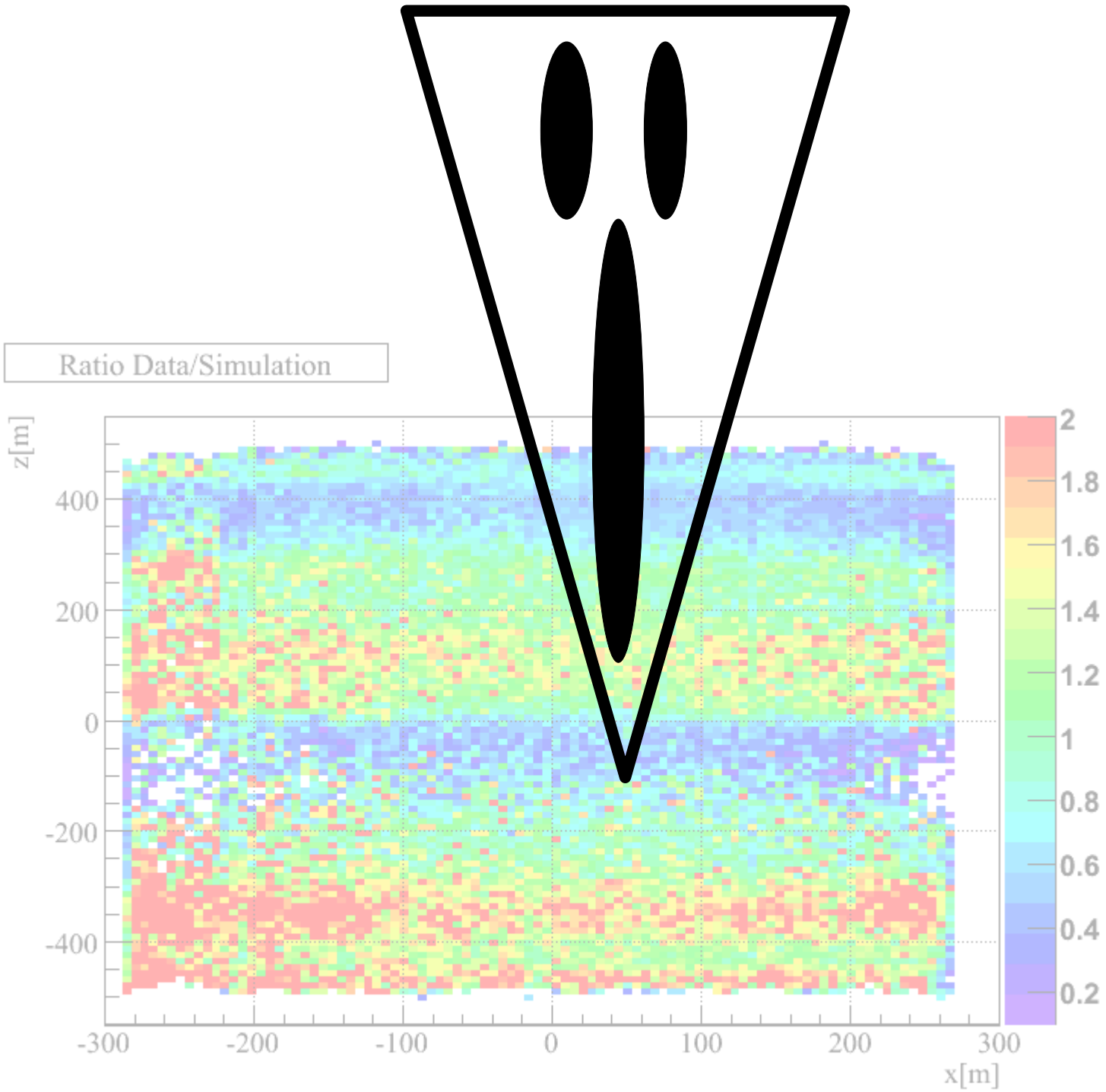


Simulated



Near-Horizontal Muons

(below 70 degrees)


Ratio Data/Simulation
z[m]
400
200
0
-200
-400
-300
-200
-100
0
100
200
300
x[m]
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2

end