

Air Shower Physics II

L. Cazon



ISAPP Showe

ISAPP 2018 International School for Astroparticle Physics

LHC meets Cosmic Rays

Lectures

- Introduction to Cosmic Rays
- Extensive Air Showers
- Atmospheric Lepton Fluxes
- Air Shower Simulations
- Accelerator Data
- Hadron Interaction Models

Hands-on exercises with:
CORSIKA, CRMC, MCEq

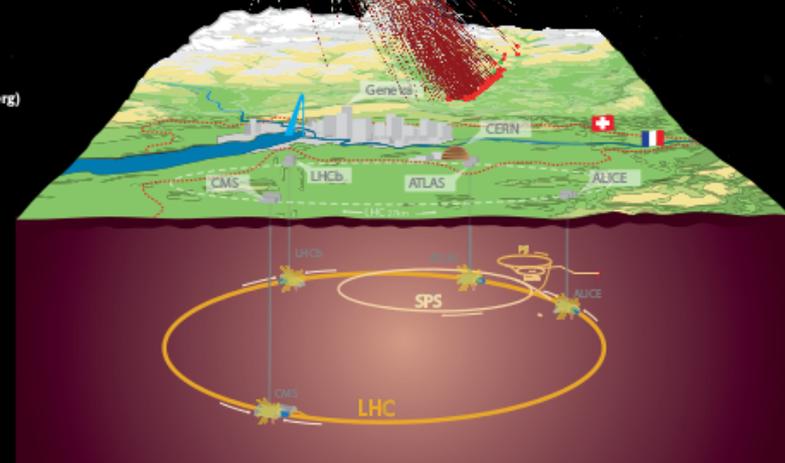
Speakers

- Valentina Avati (CERN)
- Francesca Bellini (CERN)
- David Berge (Berlin)
- Lorenzo Cazon (LIP)
- Hans Dembinski (Heidelberg)
- David d'Enterria (CERN)
- Anatoli Fedynitch (Berlin)
- Stefan Gleeske (KIT)
- Menjo Hiroaki (Nagoya)
- Kumiko Kotera (Paris)
- Paolo Lipari (INFN, Roma)
- Sergey Ostapchenko (Frankfurt)
- Etienne Parizot (Paris)
- Tanguy Pierog (KIT)
- Felix Riehn (LIP)
- Torbjörn Sjöstrand (Lund)
- Michael Unger (KIT)
- Klaus Werner (Nantes)

Organization

- Anna Di Ciccio
- Ralph Engel
- Alfredo Ferrari
- Jörg H Brandenburg
- Tanguy Pierog
- Albert de Roeck
- Ralf Ulrich

Oct 28 – Nov 2
at CERN



indico.cern.ch/event/719824

A night landscape photograph featuring a bright meteor streaking across a starry sky. The foreground is a snowy field with tracks, leading towards a line of evergreen trees and a range of mountains in the distance. The sky is filled with stars and a few wispy clouds. The meteor is a bright, glowing line of light, likely a comet or meteorite, moving from the upper left towards the center of the frame. The overall scene is serene and majestic, capturing a natural phenomenon in a beautiful setting.

By Johnson Lake in Banff National Park, Canada

**This is a real picture
(There is no *photoshop*)**

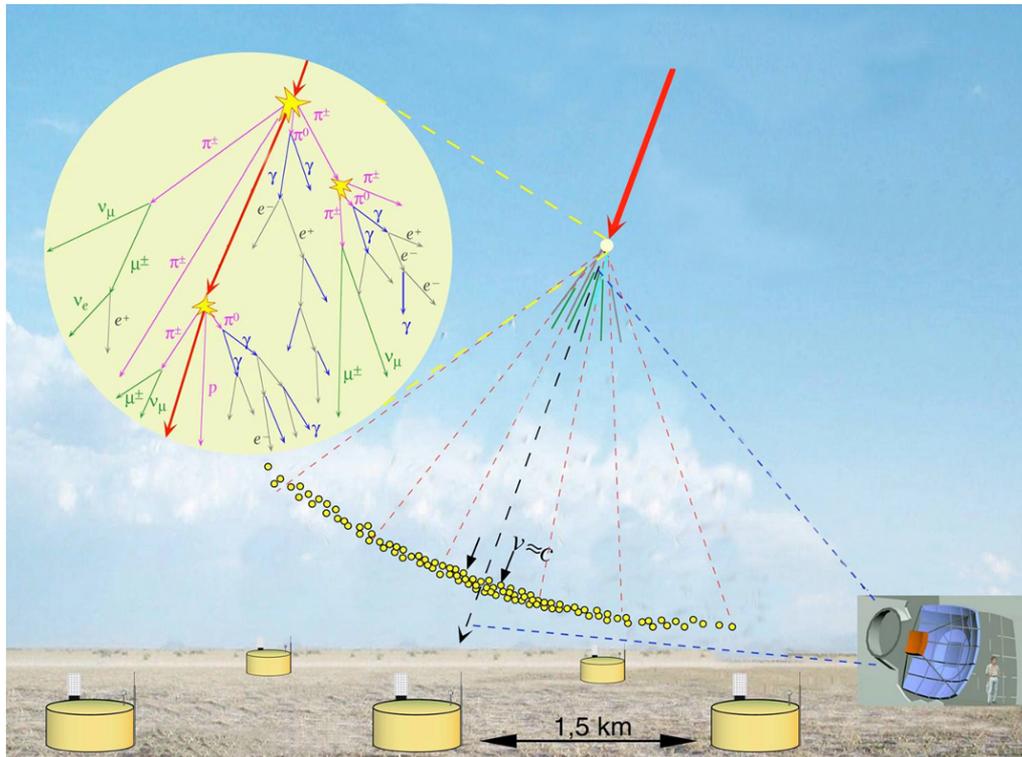


By Johnson Lake in Banff National Park, Canada

**This is a real picture
(There is no *photoshop*)**

A real image of a fireball. An Extensive Air Shower would look like that if we could see UV)

Extensive Air Shower



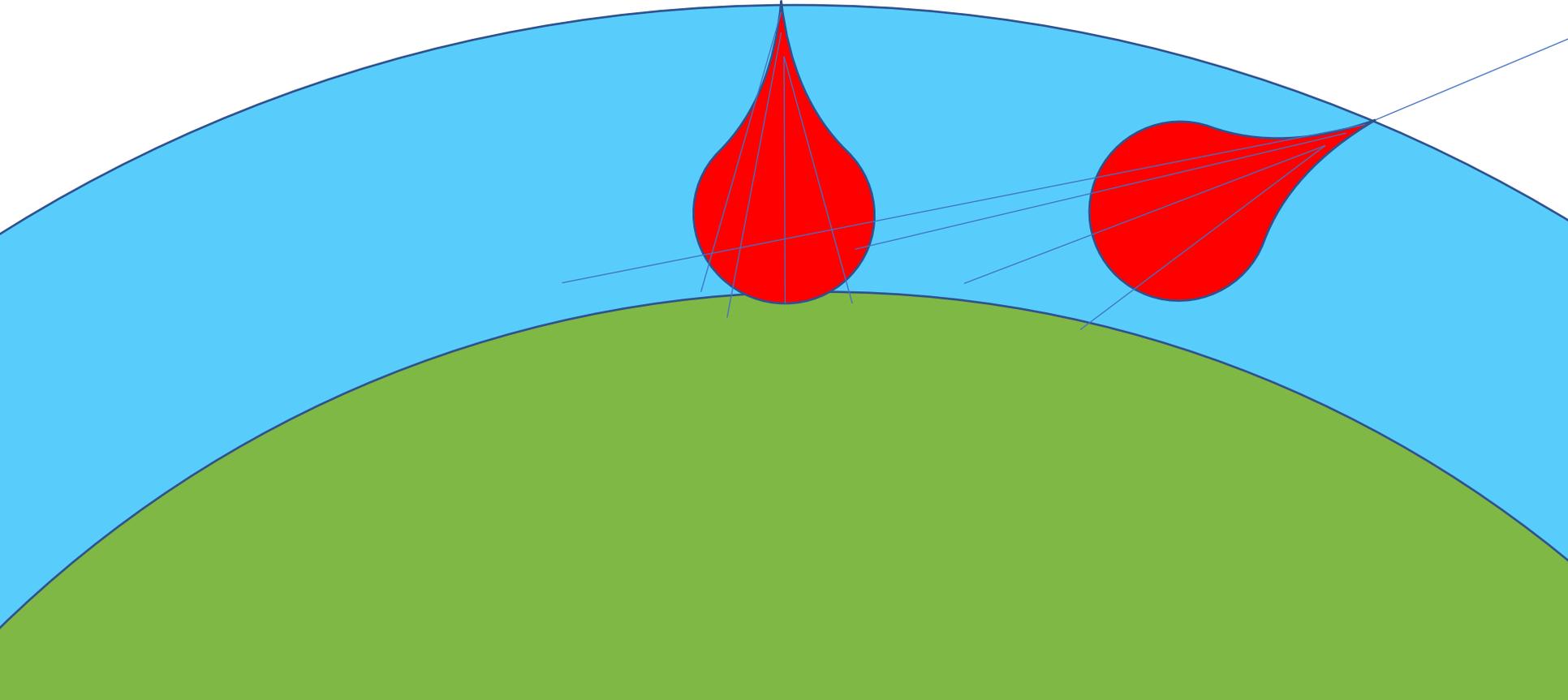
From the experimental point of view, EAS have two different parts:

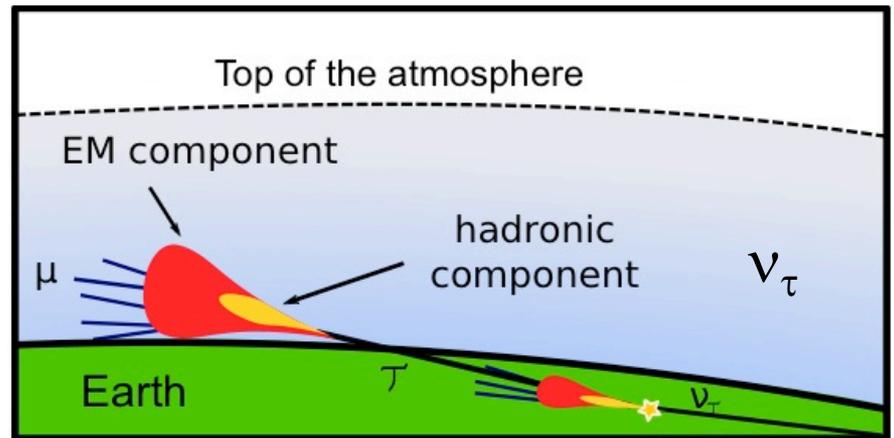
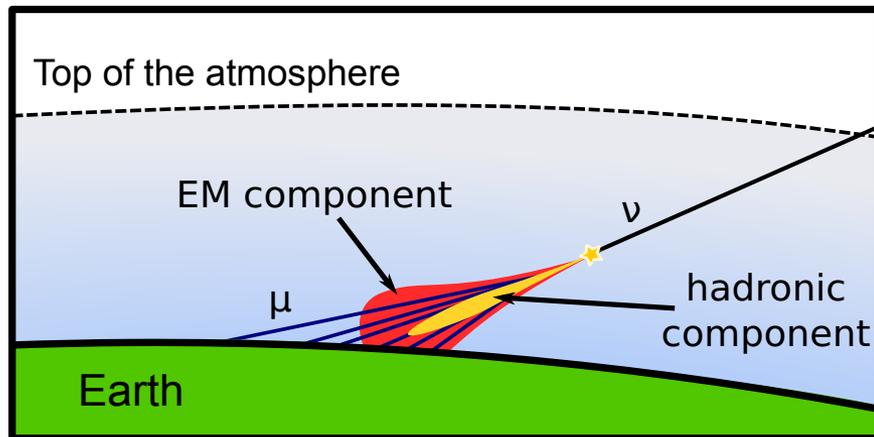
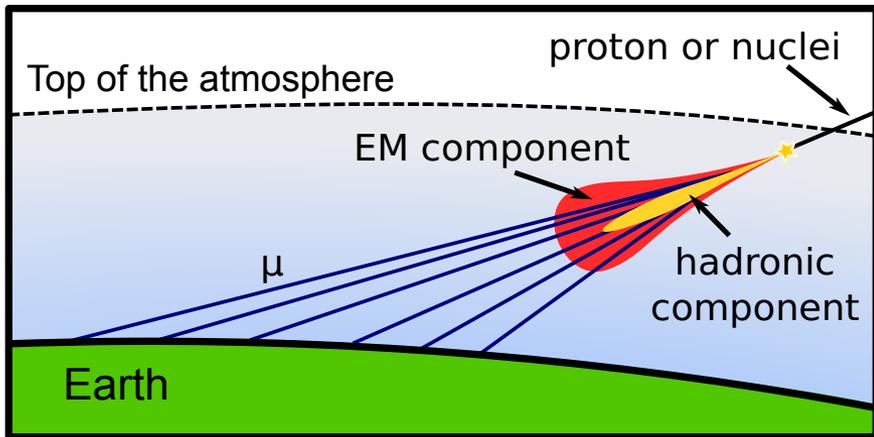
- **The core**
distances up to a few m.
- **The shower pancake:**
distances up 5 km.

wrt shower axis

- **The core**
 - transversal size of a few m
 - particle density $\sim 10^9$ particles/m².
- Interaction with the atmosphere creates radiation through different mechanisms:
 - Radio emission at MHz (Cherenkov & Geosyncrotron)
 - Microwaves GHz (Molecular Bremstrahlung)*
 - Plasma can also be detected by RADAR
 - UV-Cerenkov
 - UV-fluorescence.
- **The shower pancake:**
 - transversal size up to ~ 5 km.
 - Density varies from less than ~ 1 particle/m², to 10^9 at the core.
 - At 1000 m typical density of the order of 10-1000 particles/m².

The atmosphere:
1000 g/cm² to 36000 g/cm²

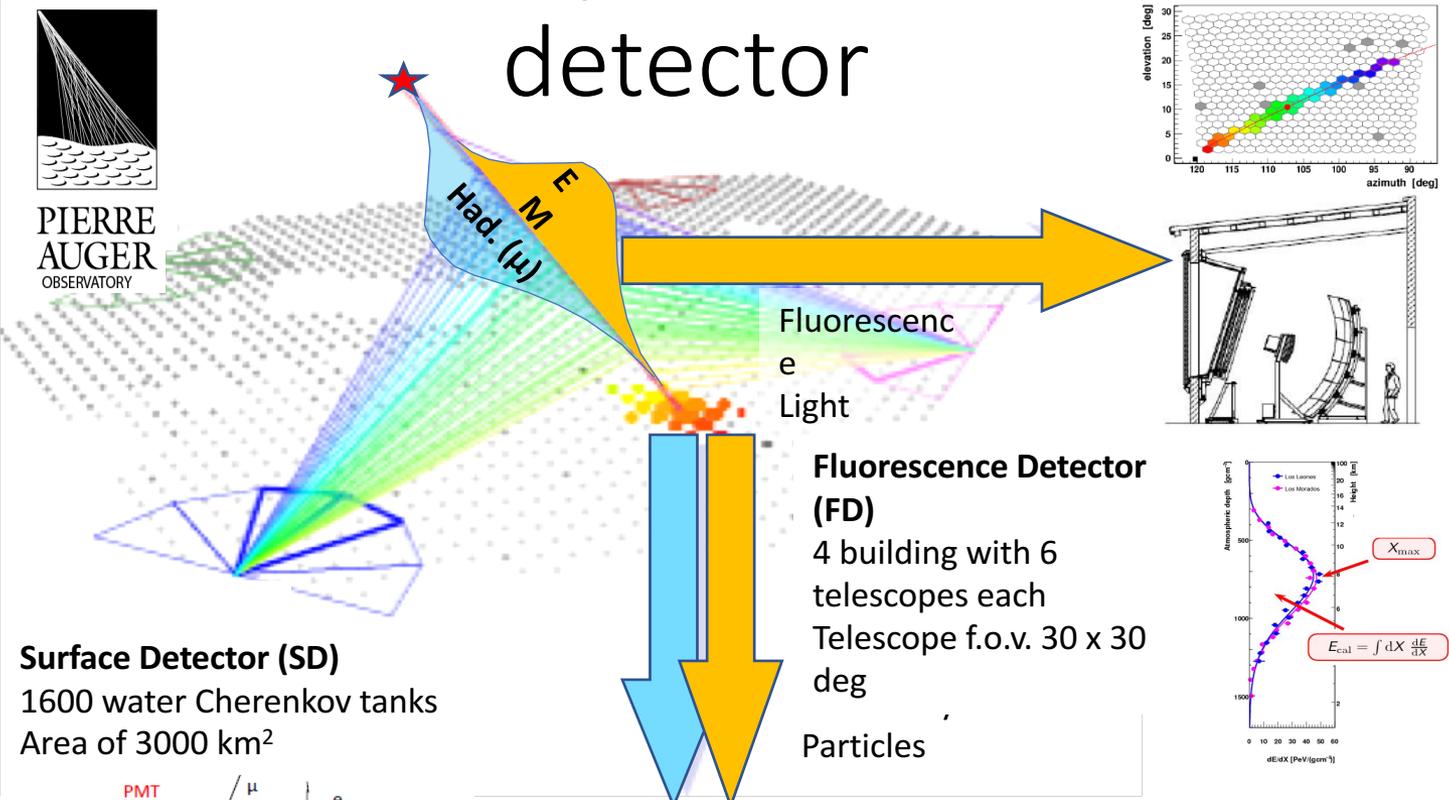




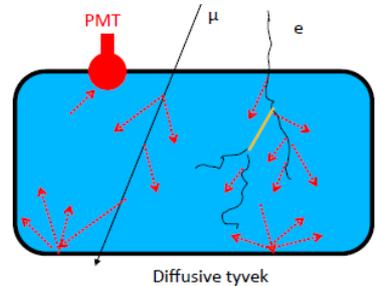
Hybrid detector



PIERRE AUGER OBSERVATORY

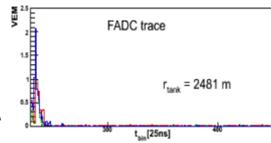
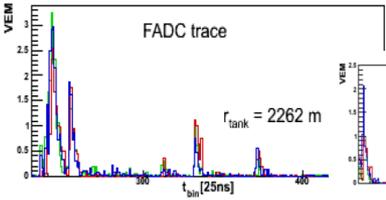
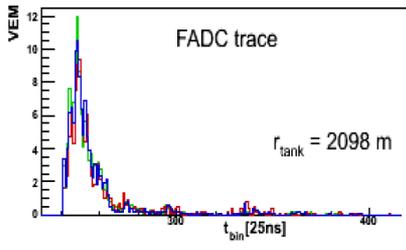
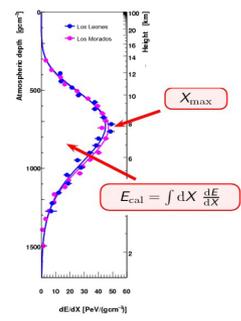
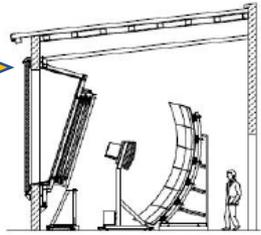
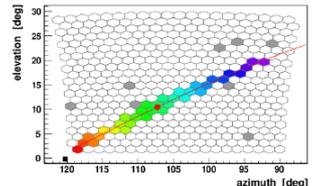


Surface Detector (SD)
1600 water Cherenkov tanks
Area of 3000 km²



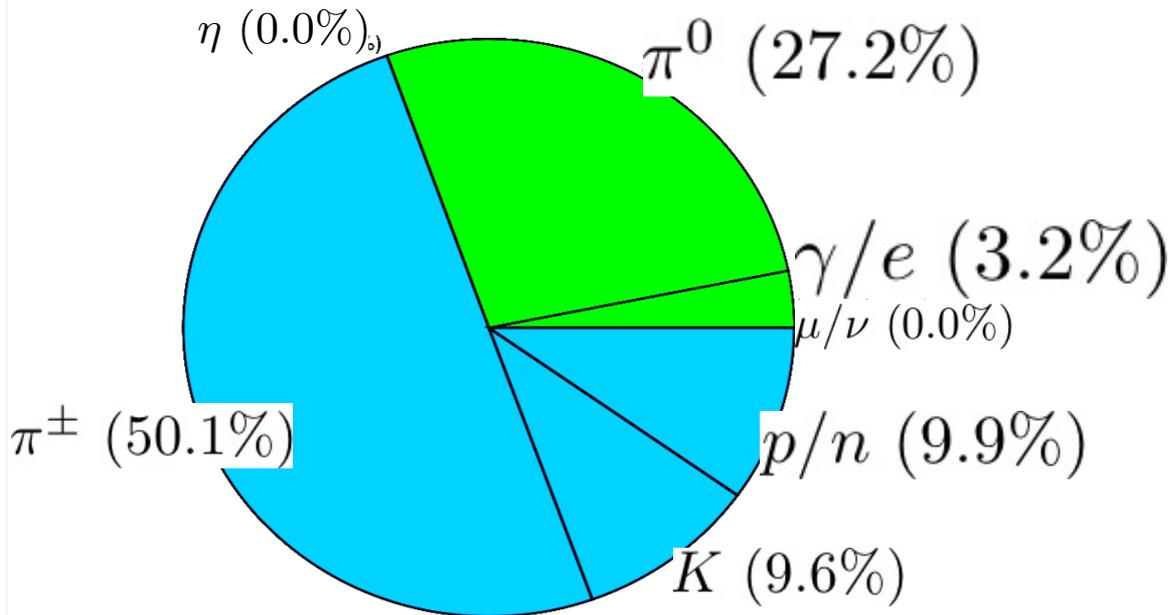
Fluorescence Light

Fluorescence Detector (FD)
4 building with 6 telescopes each
Telescope f.o.v. 30 x 30 deg
Particles

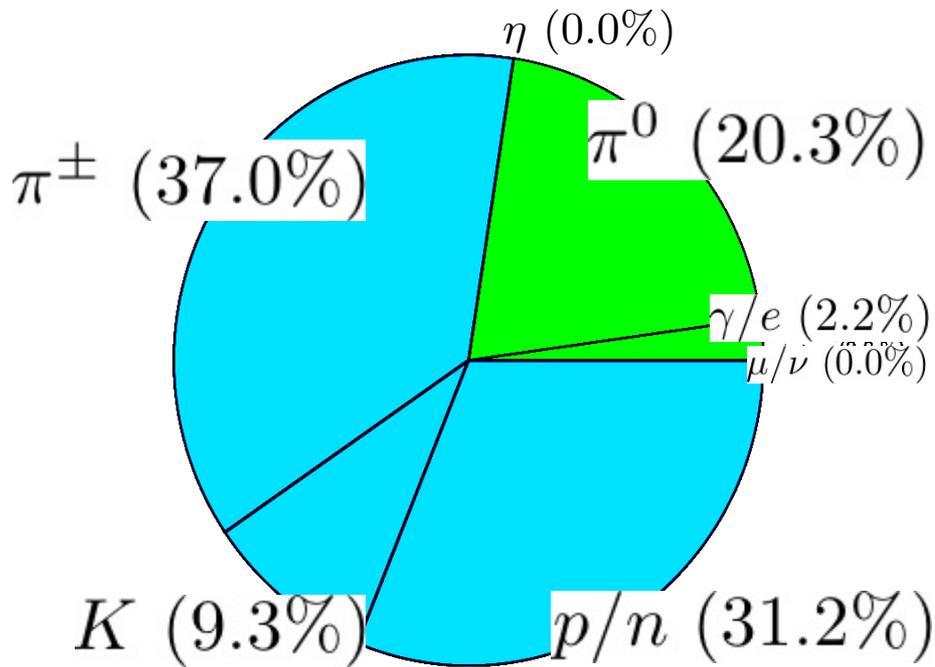


Average p-Air interaction, $E_0=10^{19}$ eV

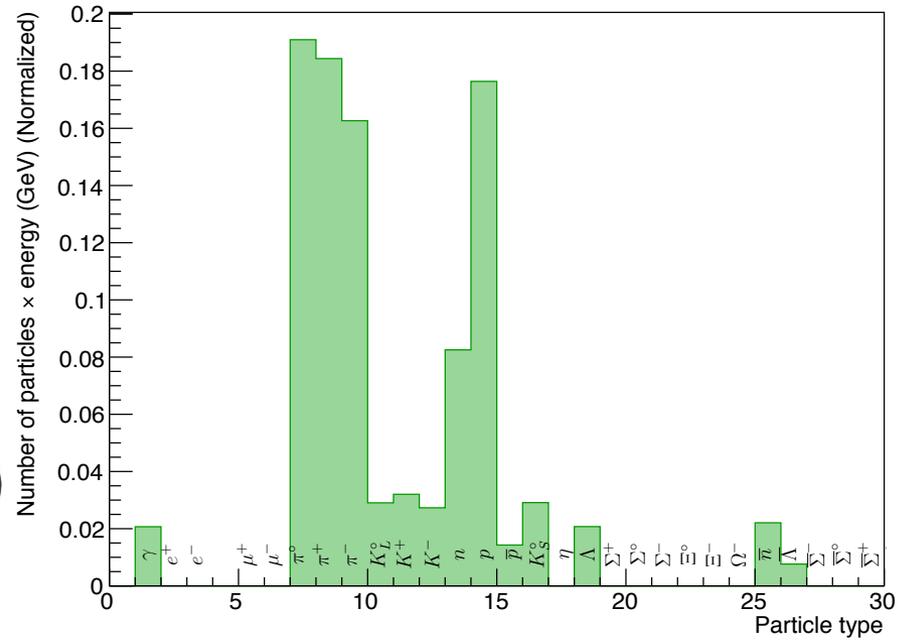
Multiplicity distribution EPOS_LHC



Energy distribution EPOS_LHC



Particle type weighted by their energy





$$I^G(J^P) = 1^-(0^-)$$

$$\text{Mass } m = 139.57018 \pm 0.00035 \text{ MeV} \quad (S = 1.2)$$

$$\text{Mean life } \tau = (2.6033 \pm 0.0005) \times 10^{-8} \text{ s} \quad (S = 1.2)$$

$$c\tau = 7.8045 \text{ m}$$



$$I^G(J^{PC}) = 1^-(0^{-+})$$

$$\text{Mass } m = 134.9766 \pm 0.0006 \text{ MeV} \quad (S = 1.1)$$

$$m_{\pi^{\pm}} - m_{\pi^0} = 4.5936 \pm 0.0005 \text{ MeV}$$

$$\text{Mean life } \tau = (8.52 \pm 0.18) \times 10^{-17} \text{ s} \quad (S = 1.2)$$

$$c\tau = 25.5 \text{ nm}$$

Question:

- What fraction of Kaons should be included to contribute to the “hadronic cascade”?
 - Have a look to their decay products.

K^\pm

$$I(J^P) = \frac{1}{2}(0^-)$$

Mass $m = 493.677 \pm 0.016$ MeV [a] (S = 2.8)

Mean life $\tau = (1.2380 \pm 0.0020) \times 10^{-8}$ s (S = 1.8)

$$c\tau = 3.711 \text{ m}$$

Results \blacklozenge	Mode \blacklozenge	Branching ratio \blacklozenge
$\mu^+ \nu_\mu$	leptonic	$63.55 \pm 0.11\%$
$\pi^+ \pi^0$	hadronic	$20.66 \pm 0.08\%$
$\pi^+ \pi^+ \pi^-$	hadronic	$5.59 \pm 0.04\%$
$\pi^+ \pi^0 \pi^0$	hadronic	$1.761 \pm 0.022\%$
$\pi^0 e^+ \nu_e$	semileptonic	$5.07 \pm 0.04\%$
$\pi^0 \mu^+ \nu_\mu$	semileptonic	$3.353 \pm 0.034\%$



$$I(J^P) = \frac{1}{2}(0^-)$$

Mean life $\tau = (0.8954 \pm 0.0004) \times 10^{-10}$ s (S = 1.1) Assuming *CPT*

Mean life $\tau = (0.89564 \pm 0.00033) \times 10^{-10}$ s Not assuming *CPT*

$c\tau = 2.6844$ cm Assuming *CPT*

K_S^0 DECAY MODES

Fraction (Γ_i/Γ) Confidence level (MeV/c)

$\pi^0 \pi^0$

Hadronic modes

(30.69 ± 0.05) %

209

$\pi^+ \pi^-$

(69.20 ± 0.05) %

206

$$K_L^0$$

$$I(J^P) = \frac{1}{2}(0^-)$$

$$\begin{aligned}
 & m_{K_L} - m_{K_S} \\
 &= (0.5293 \pm 0.0009) \times 10^{10} \hbar \text{ s}^{-1} \quad (S = 1.3) \quad \text{Assuming } CPT \\
 &= (3.484 \pm 0.006) \times 10^{-12} \text{ MeV} \quad \text{Assuming } CPT \\
 &= (0.5289 \pm 0.0010) \times 10^{10} \hbar \text{ s}^{-1} \quad \text{Not assuming } CPT \\
 &\text{Mean life } \tau = (5.116 \pm 0.021) \times 10^{-8} \text{ s} \quad (S = 1.1) \\
 &c\tau = 15.34 \text{ m}
 \end{aligned}$$

K_L^0 DECAY MODES	Fraction (Γ_i/Γ)	Scale factor / Confidence level (MeV/c)	ρ
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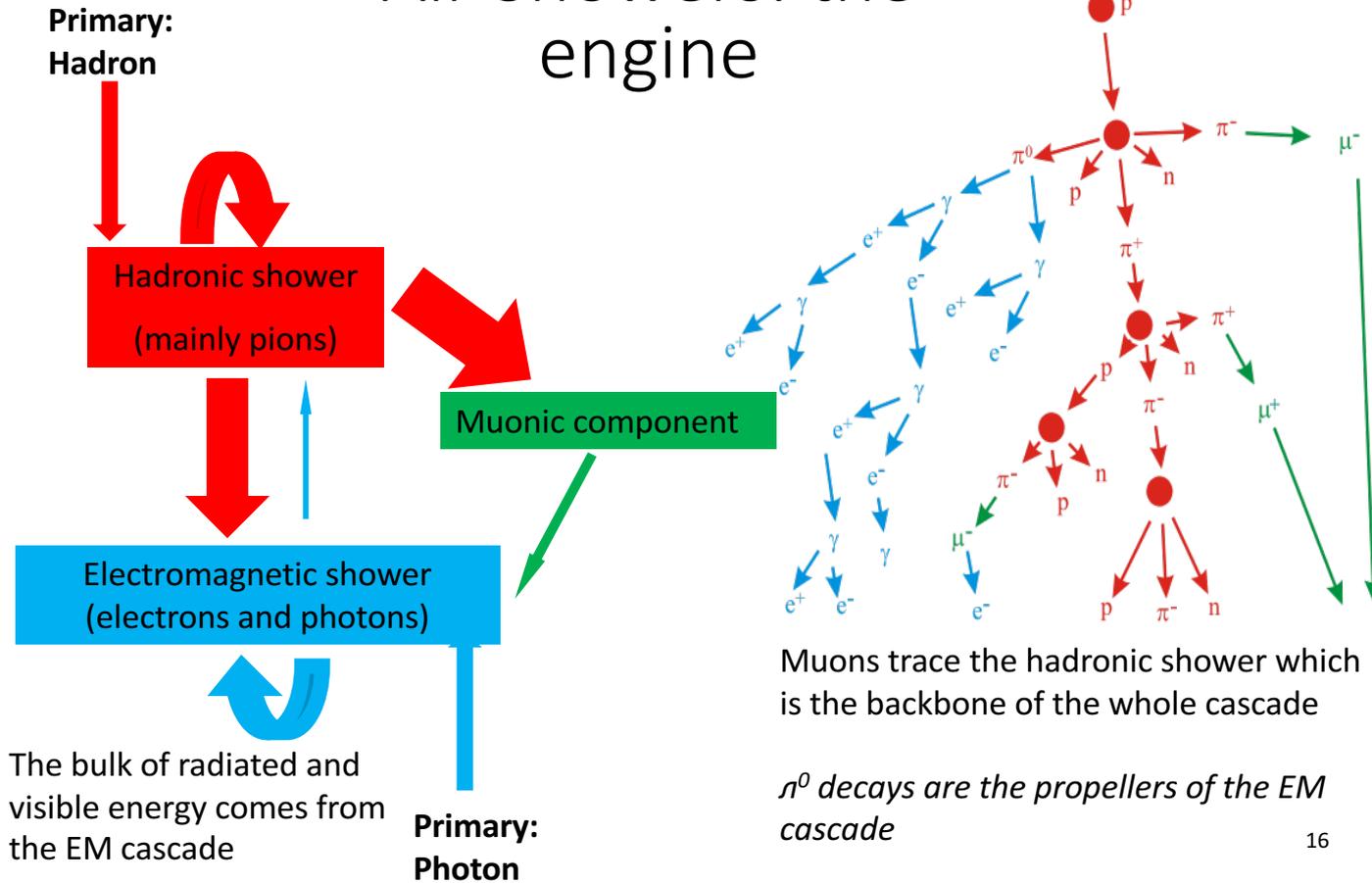
Semileptonic modes

$\pi^\pm e^\mp \nu_e$ Called K_{e3}^0 .	[o] (40.55 ± 0.11) %	S=1.7	229
$\pi^\pm \mu^\mp \nu_\mu$ Called $K_{\mu3}^0$.	[o] (27.04 ± 0.07) %	S=1.1	216

Hadronic modes, including Charge conjugation × Parity Violating (CPV) modes

$3\pi^0$	(19.52 ± 0.12) %	S=1.6	139
$\pi^+ \pi^- \pi^0$	(12.54 ± 0.05) %		133

Air Showers: the engine



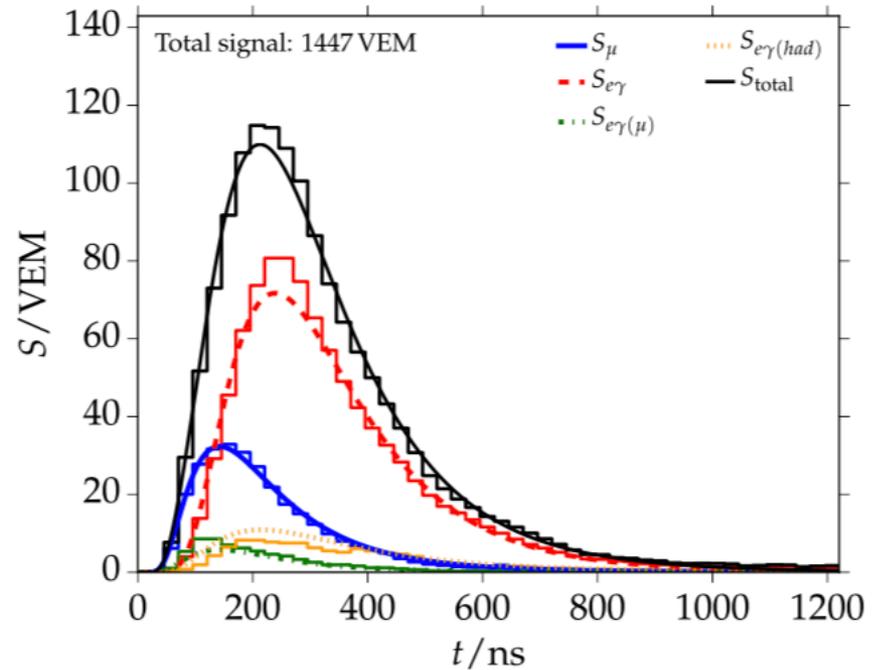
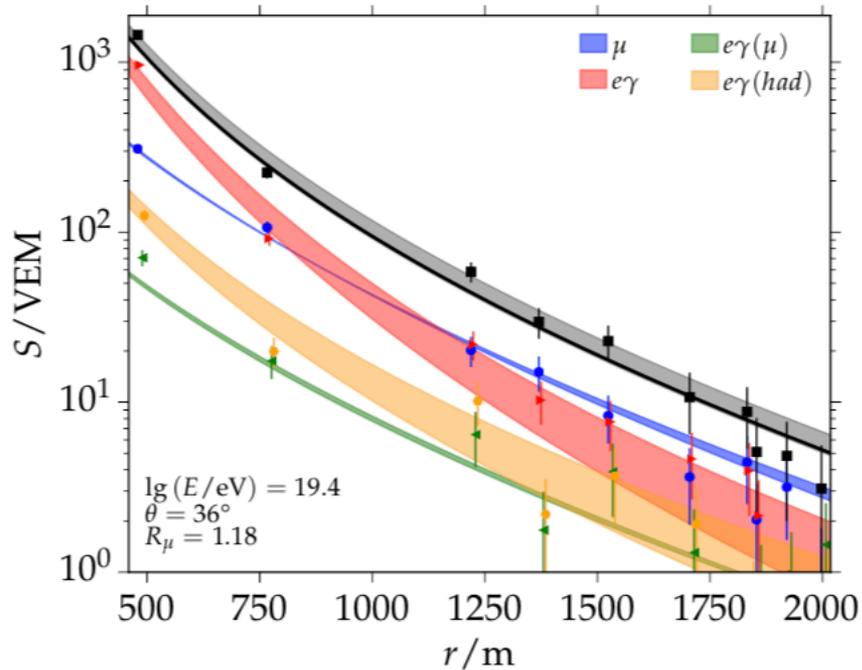
The different components of the shower

TABLE I: Approximated amount of signal for each one of the different components at 38 deg, 10^{19} eV.

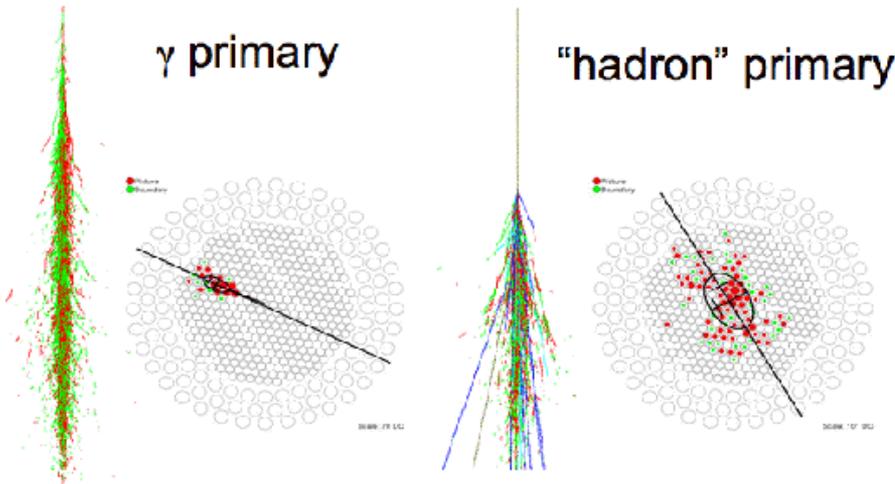
component	scaling	signal
0) Total Signal		38.3 VEM
1) Pure EM	EM	15.8 VEM
2) Pure μ	hadronic	16.6 VEM
3) EM from low-E π_0 '	hadronic	4.4 VEM
4) μ from Photoprod.	EM	1.3 VEM
5) EM from μ decay	\sim hadronic	1.0 VEM

Phys.Rev.Lett. 117 (2016) no.19, 192001

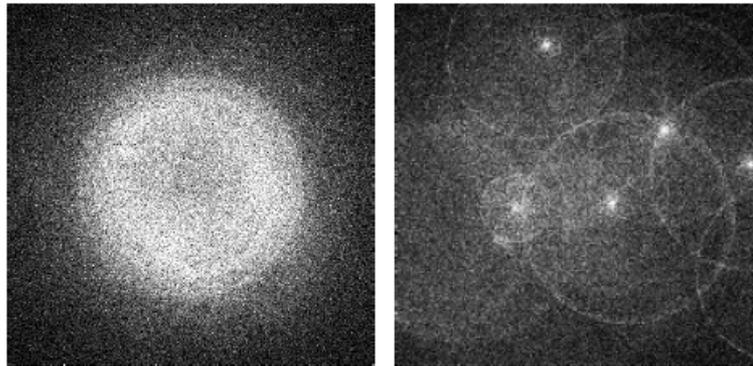
The different components of the shower



Visual differences between EM and hadronic showers



Smooth vs lumpy

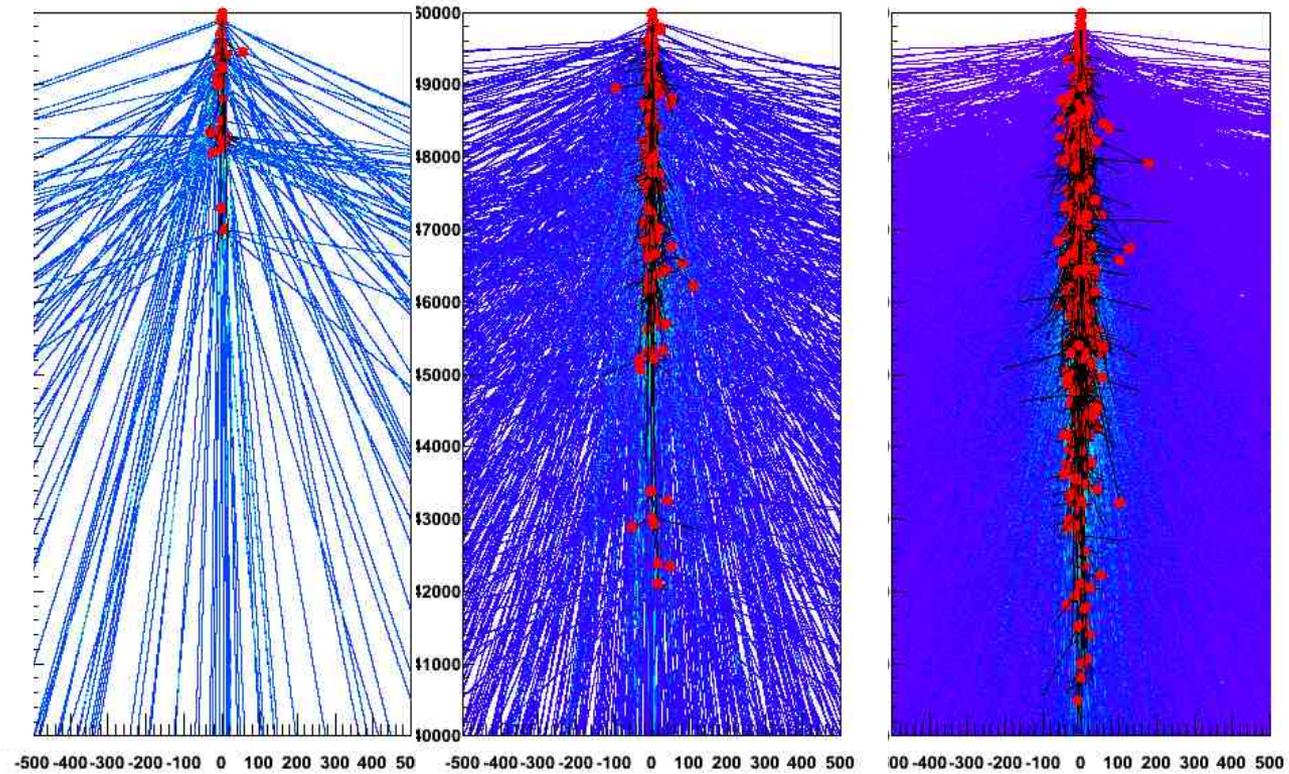


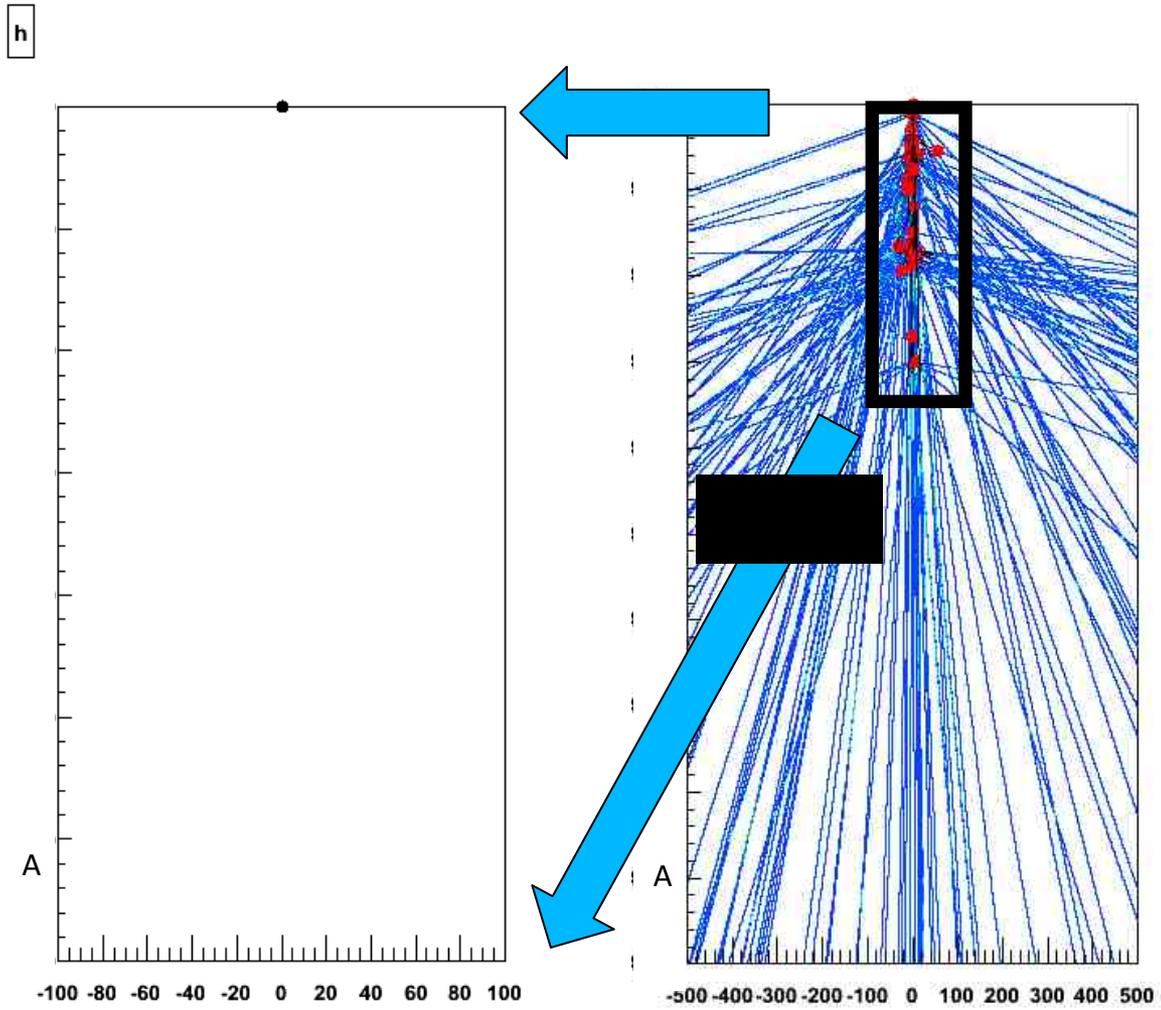
Has anybody seen in detail a hadron shower at 10^{19} eV?

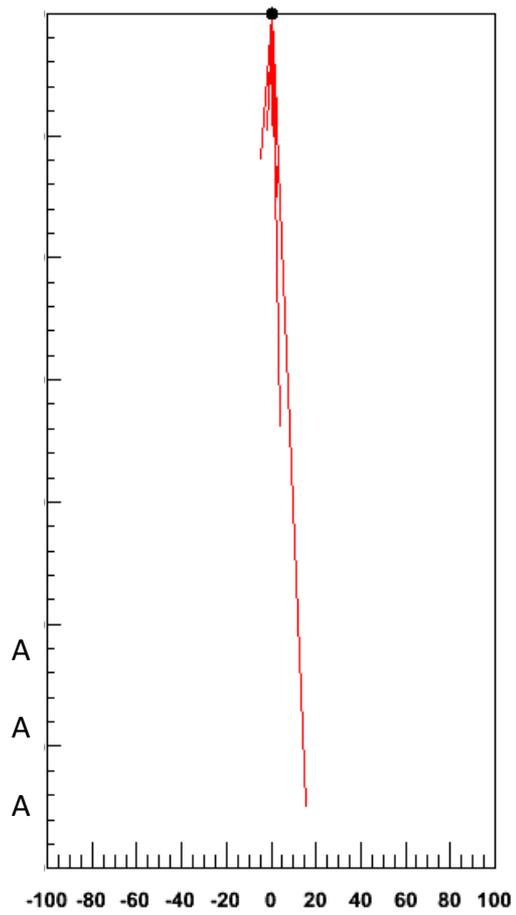
Figure 2.4: Cherenkov light distribution on ground for a 300 GeV γ -ray shower (*left*) and a 1 TeV proton shower (*right*). The side length is 400 m. The pictures are taken from Monte Carlo simulations from [17].

The hadronic shower

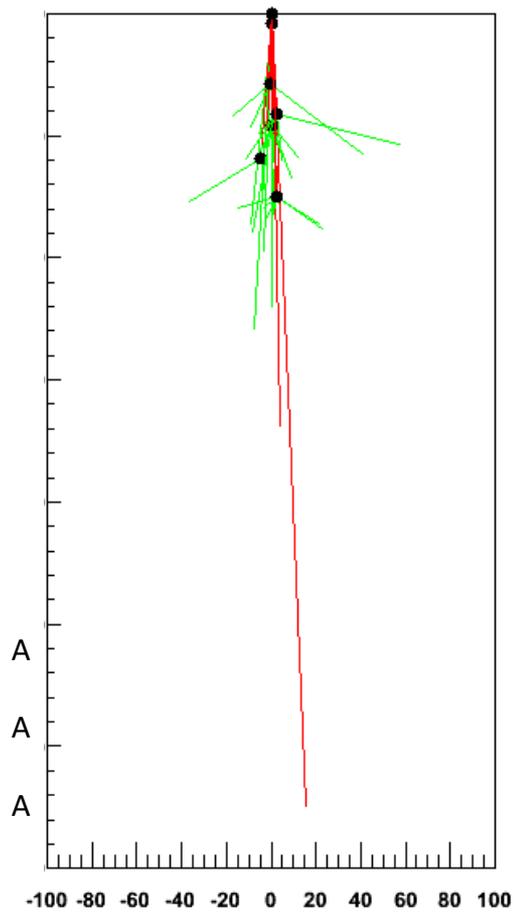
— μ — π^\pm ● Hadronic reaction



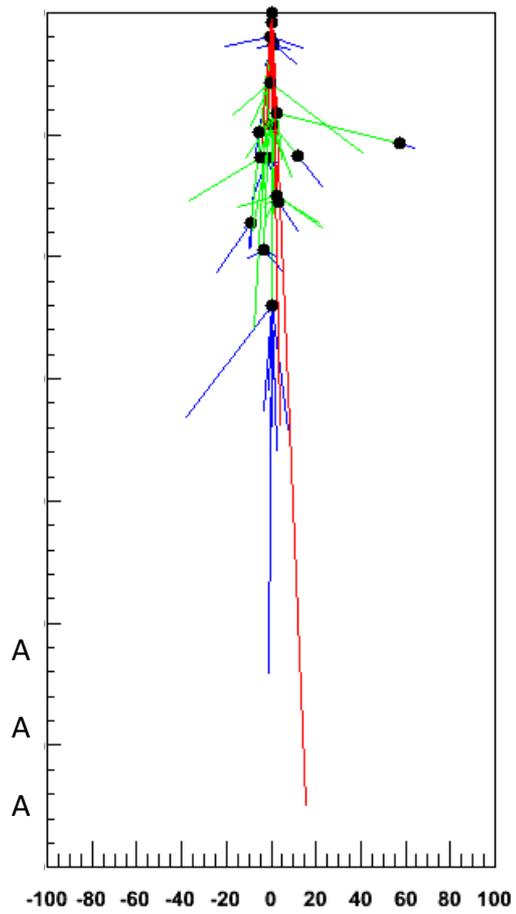




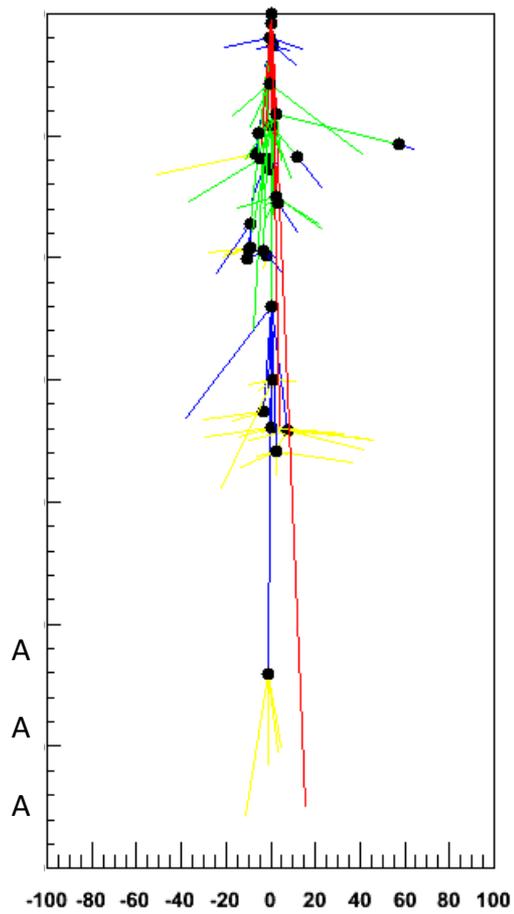
n=2



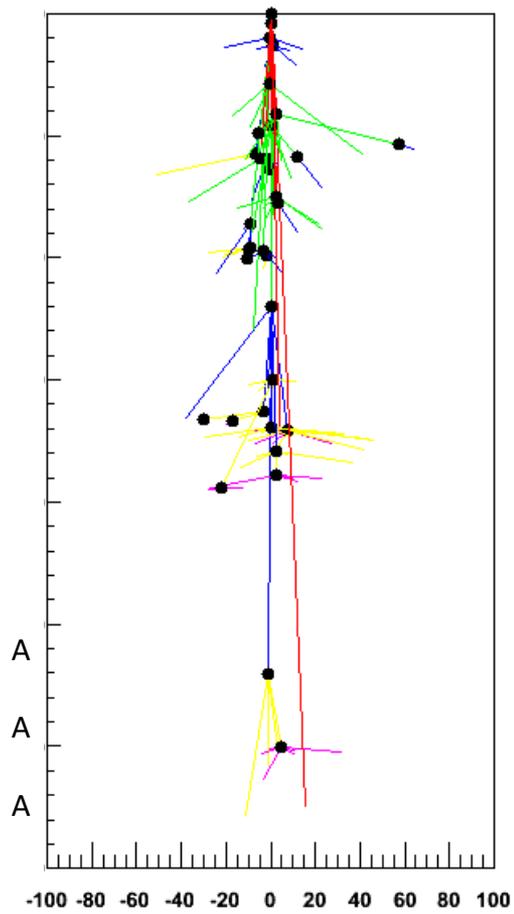
n=3



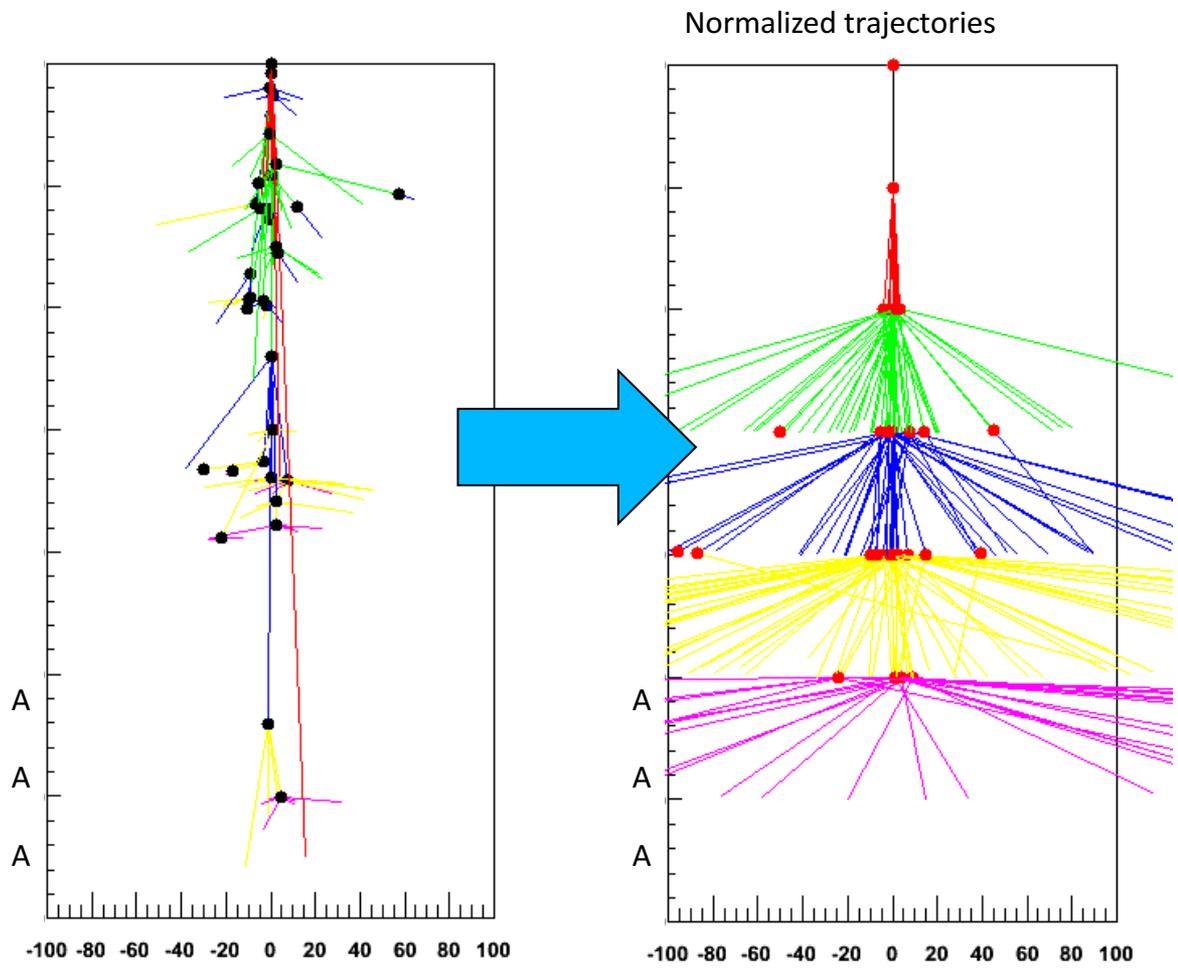
n=4

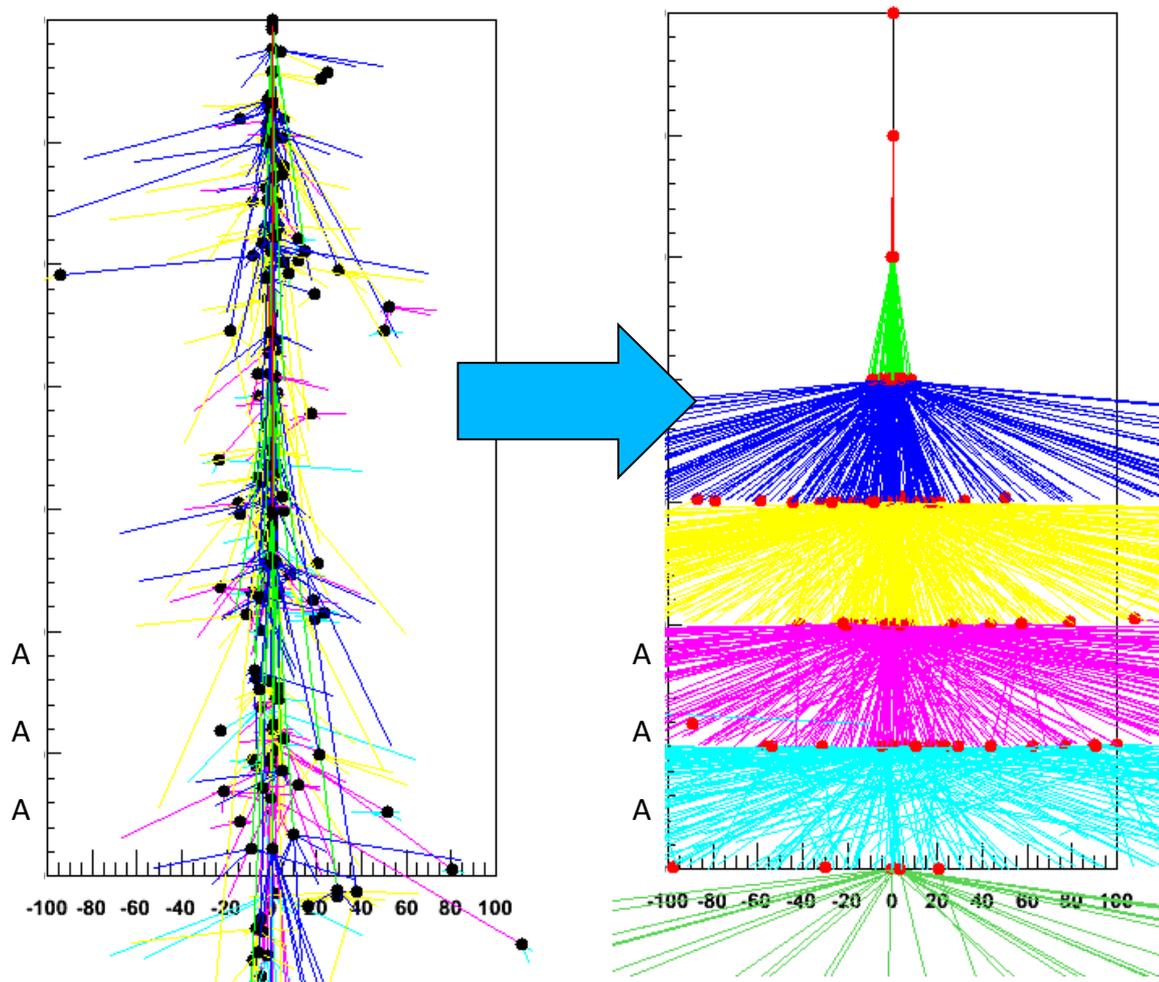


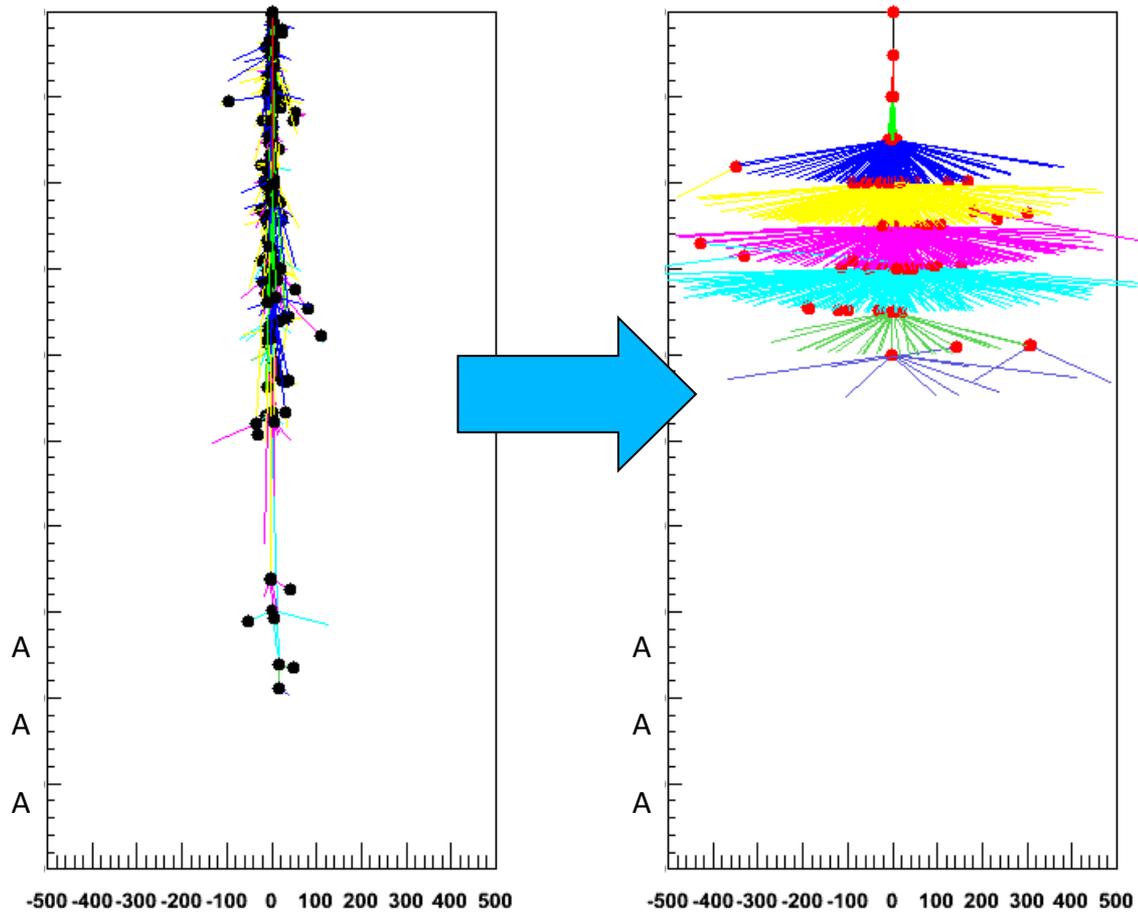
n=5



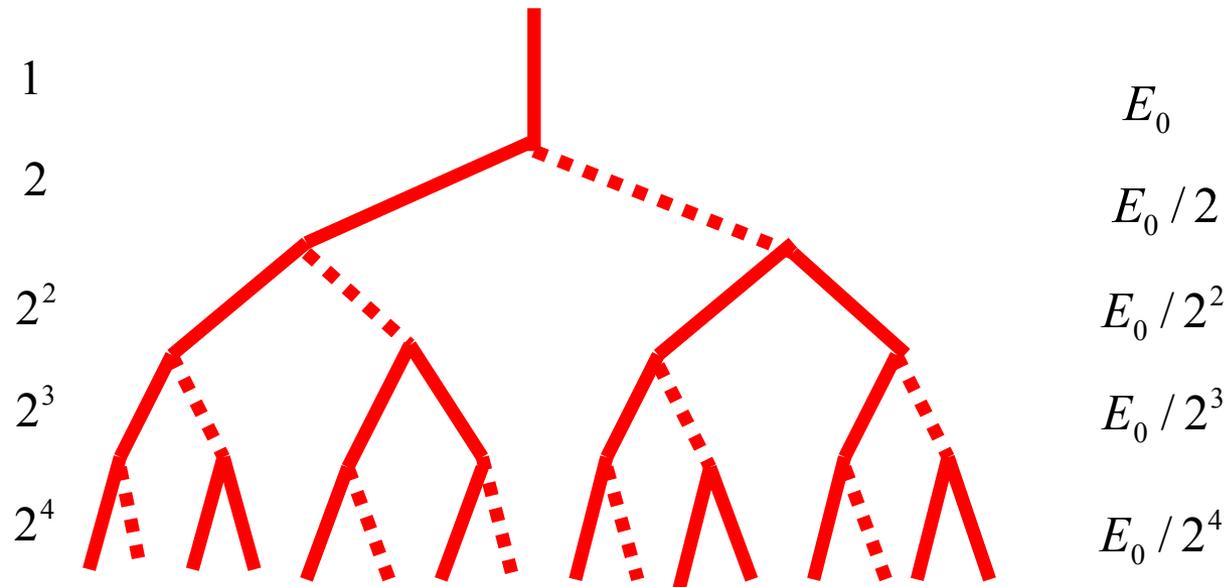
n=6





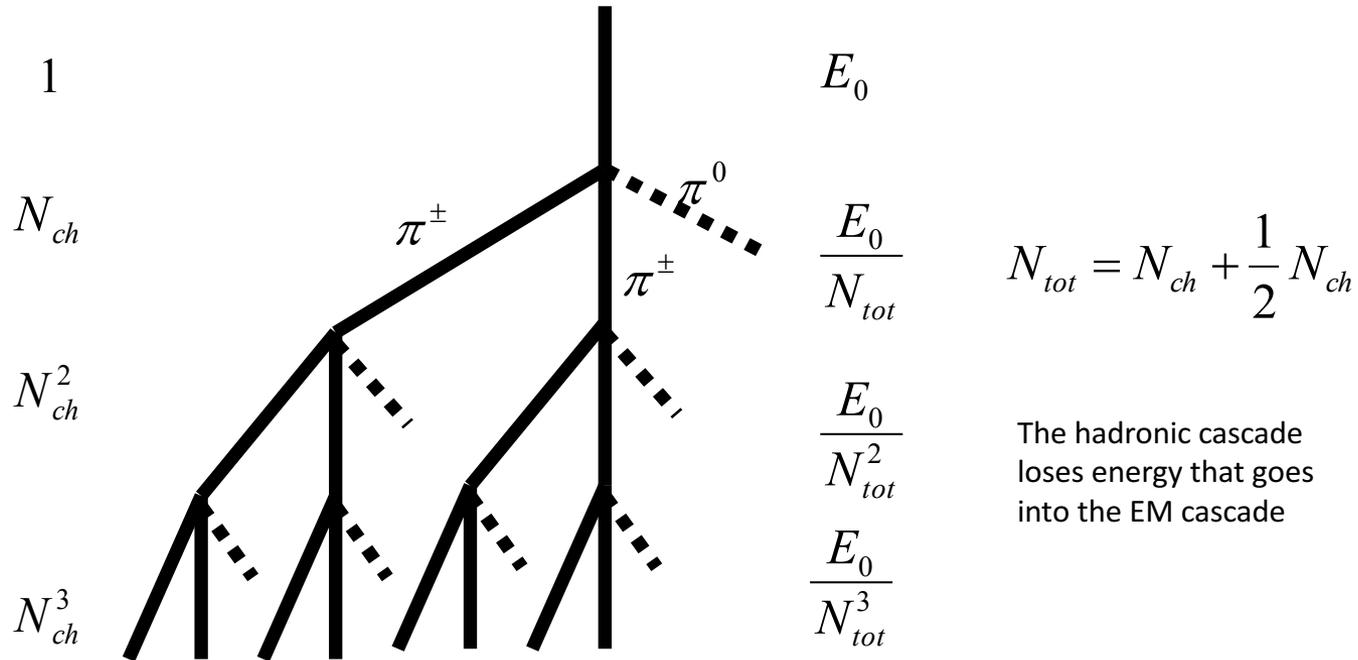


EM cascade



$$\xi_c^e = 85 \text{ MeV}$$
$$n_c = \frac{\ln\left(\frac{E_0}{\xi_c^e}\right)}{\ln(2)}$$

Hadronic cascade



$$N_\pi = (N_{ch})^n \quad N_\mu = (N_{ch})^{n_c}$$

$$E_\pi = \frac{E_0}{\left(\frac{3}{2}N_{ch}\right)^n} \quad \xi_c^\pi = \frac{E_0}{\left(\frac{3}{2}N_{ch}\right)^{n_c}}$$

$$\xi_c^\pi \simeq 20 \text{ GeV} \quad N_{ch} \simeq 10$$

$$n_c = \frac{\ln\left(\frac{E_0}{\xi_c^\pi}\right)}{\ln\left(\frac{3}{2} N_{ch}\right)} = 0.85 \log_{10}\left(\frac{E_0}{\xi_c^\pi}\right)$$



$$\ln N_\mu = \ln N_\pi = n_c \ln N_{ch} = \beta \ln[E_0 / \xi_c^\pi],$$

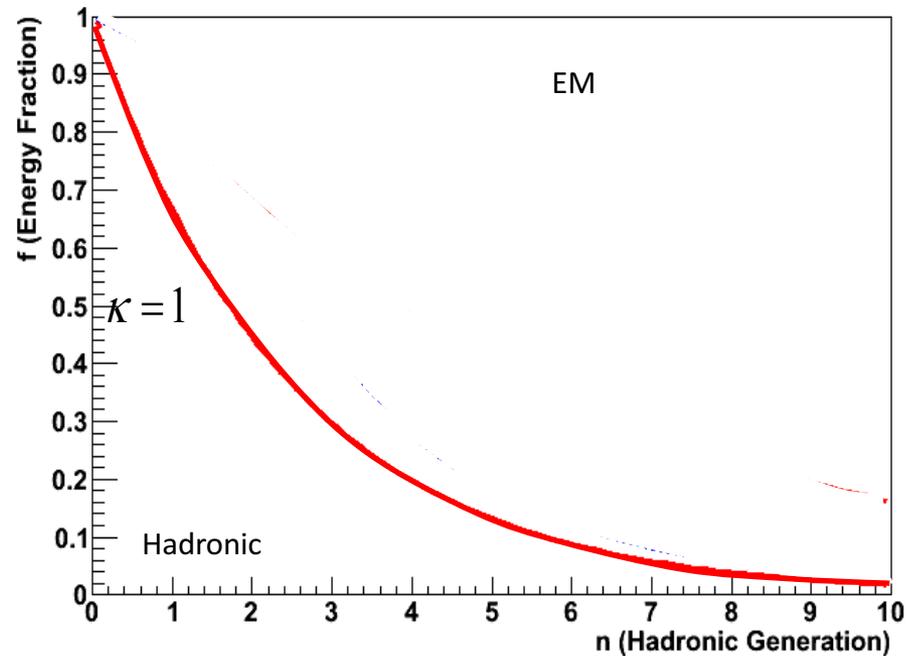
$$\beta = \frac{\ln[N_{ch}]}{\ln\left[\frac{3}{2} N_{ch}\right]} = 0.85.$$

Energy balance

The energy flow to the EM channel varies depending on the amount of produced ρ^0

$$\sum E_{\pi} = \left(1 - \frac{1}{3}\right)^n E_0$$

$$\sum E_{EM} = E_0 - \sum E_{\pi}$$



The energy flow to the EM channel varies depending on the amount of produced π^0

$$1 \Leftrightarrow p \Leftrightarrow (1-k)E$$

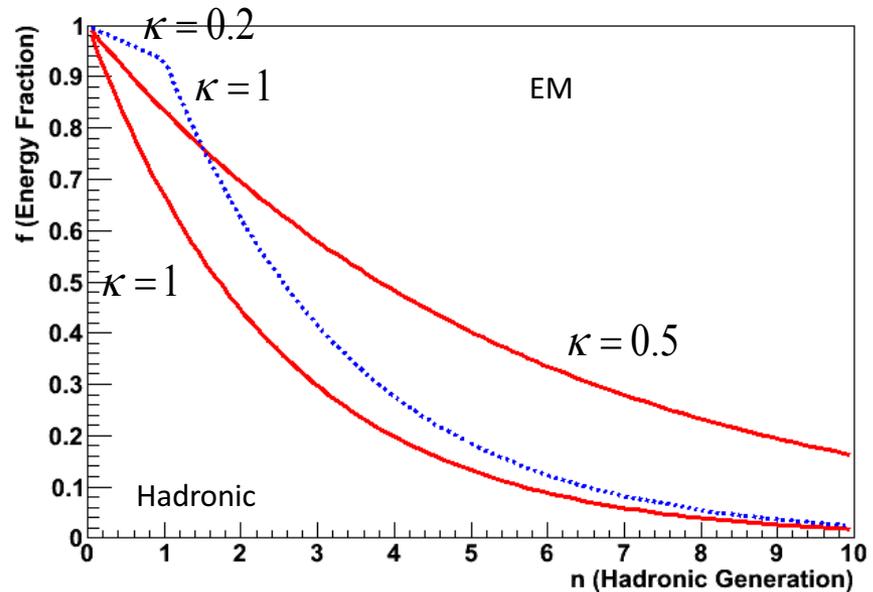
$$N_{ch} \Leftrightarrow \pi^\pm \Leftrightarrow \frac{2}{3}kE$$

$$\frac{1}{2}N_{ch} \Leftrightarrow \pi^0 \Leftrightarrow \frac{1}{3}kE$$

$$\sum E_\pi = \left(1 - \frac{1}{3}\kappa\right)^n E_0$$

$$\sum E_{EM} = E_0 - \sum E_\pi$$

κ =inelasticity. it takes some additional energy from the pions and puts in into a leading baryon



$$N_{\mu} = \left(\frac{E_0}{\xi^{\pi} \zeta_c} \right)^{\beta}$$

$$\beta = \frac{\ln(1 + N_{ch})}{\ln\left(\frac{1 + N_{ch}}{1 - 3/2\kappa}\right)} \approx 1 - 0.14\kappa$$

Invisible Energy

$$E_0 = \xi_c^e N_{\max} + \xi_c^{\pi} N_{\mu}.$$

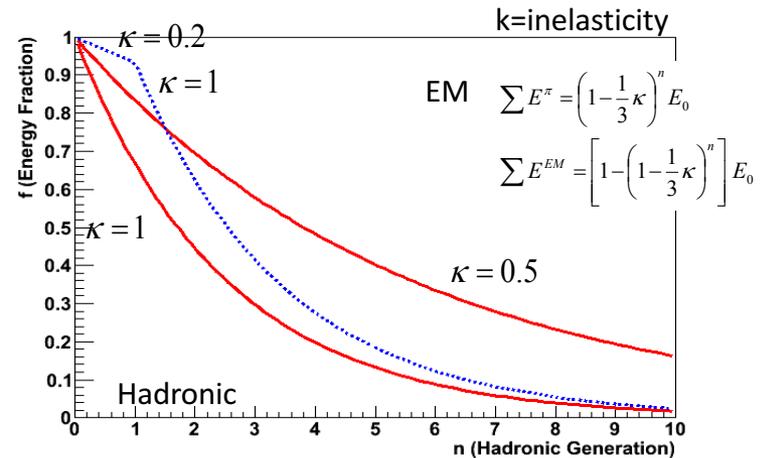
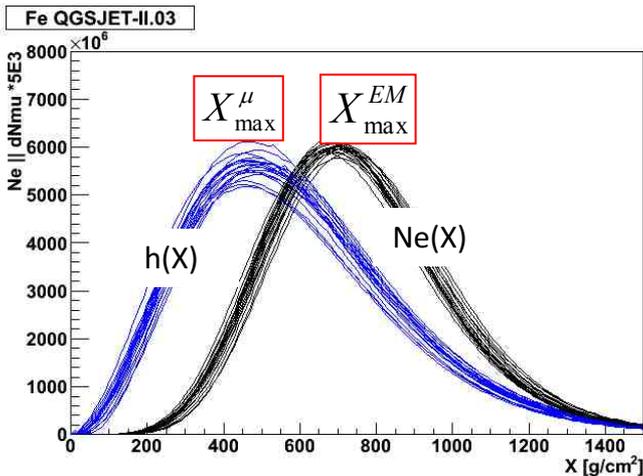
Energy balance

$$\int Ne(X)dX \propto \int \frac{dE}{dX} dX = E_{cal}$$

$$\int h(X)dX = N_{\mu}$$

$$E_0 = E_{cal} + bN_{\mu}$$

EM channel ends up carrying all the shower energy except a small remaining fraction called "invisible energy"



Composition scaling

A = UHECR mass number

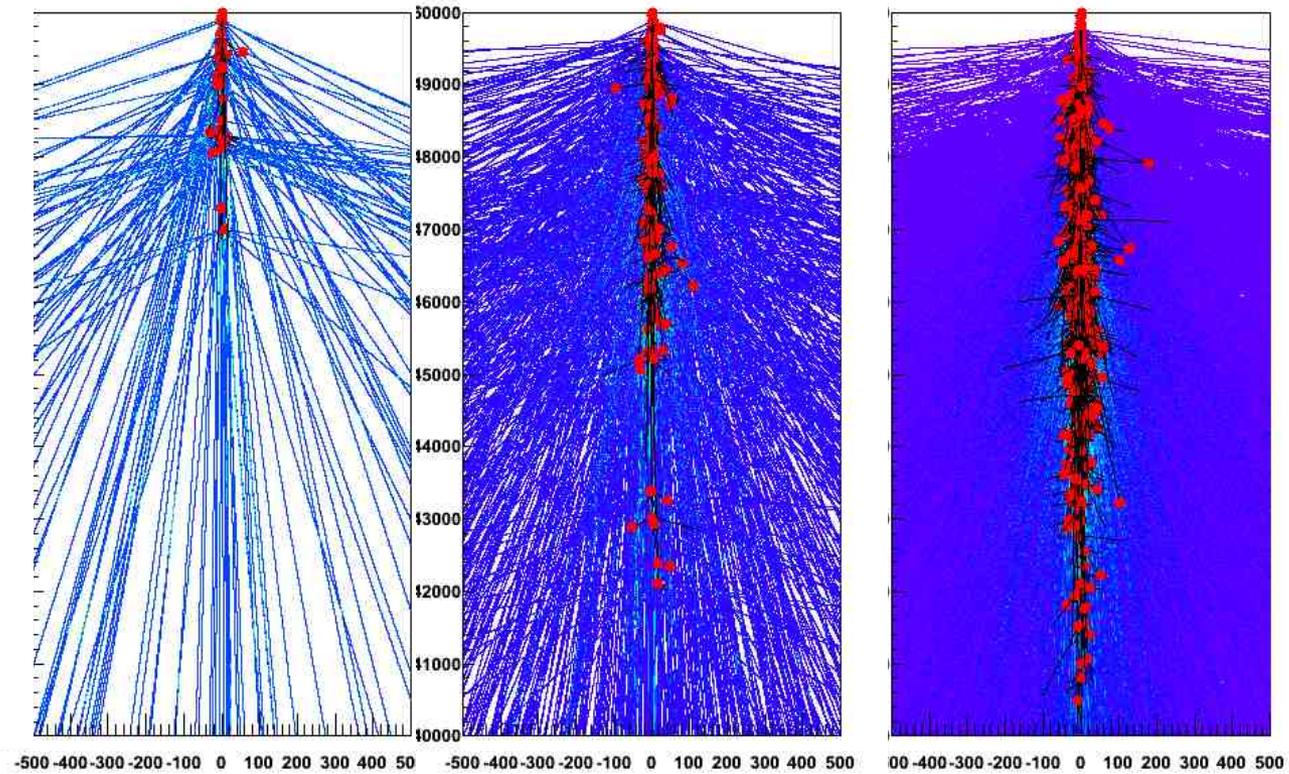
$$X_{\max}(A) \approx \lambda_r \left(\ln \frac{E_0}{A} - \ln \xi_c^e \right) = \bar{X}_{\max} - \lambda_r \ln A$$

$$\ln N_{\mu}(A) = \ln \left[A \left(\frac{E_0 / A}{\xi_c^{\pi}} \right)^{\beta} \right] = \ln N_{\mu} + (1 - \beta) \ln A$$

Muon Production Distributions

The hadronic shower

— μ — π^\pm ● Hadronic reaction



The π^\pm transverse momentum (p_t)

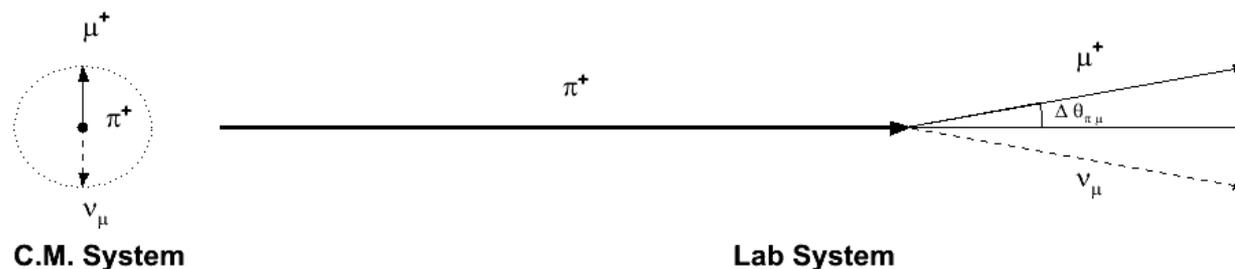
- in a hadronic collision $p + B \rightarrow C + X$ the p_t distribution of pions is

$$\frac{d^2 N}{d^2 p_t} = \frac{dN}{2\pi p_t dp_t} \propto \exp\left(-\frac{p_t}{Q}\right)$$

- $\langle p_t \rangle = 2Q \sim$ tenths of GeV
- π^\pm decay into μ^\pm . Max p_t achievable: 29.8 MeV

The μ^\pm transverse momentum (p_t)

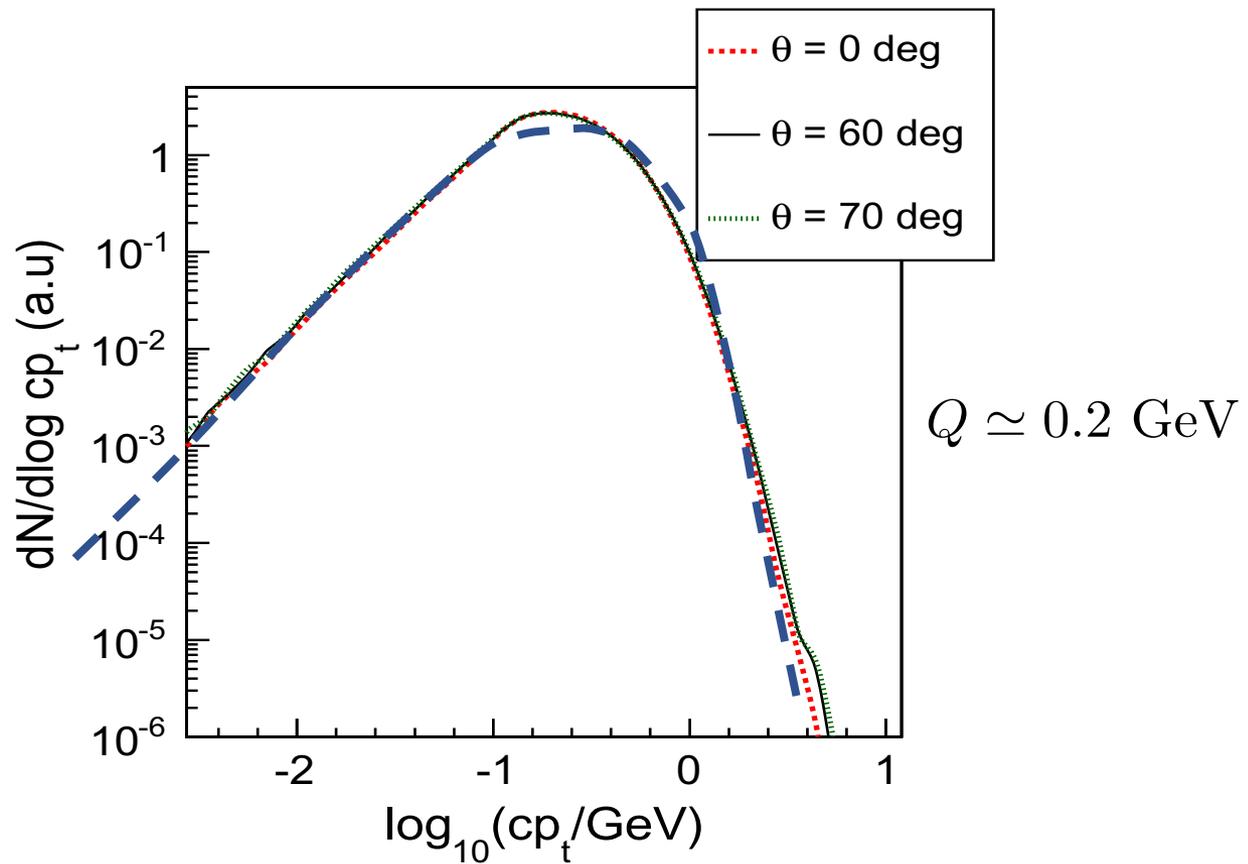
μ^\pm come from π^\pm decay. Max p_t achievable: 29.8 MeV



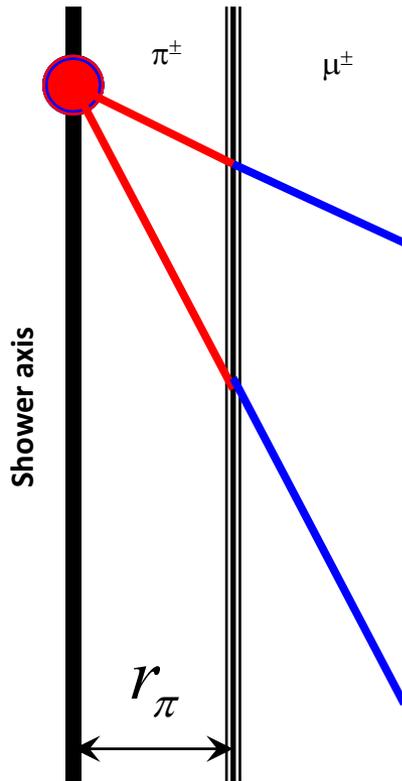
Decay p_t / Pions $p_t \sim 10\%$

Muons inherit the
pion p_t distribution

$$\frac{dN}{dp_t} \propto p_t \exp\left(-\frac{p_t}{Q}\right)$$



Transverse distance of μ^\pm production / π^\pm decay



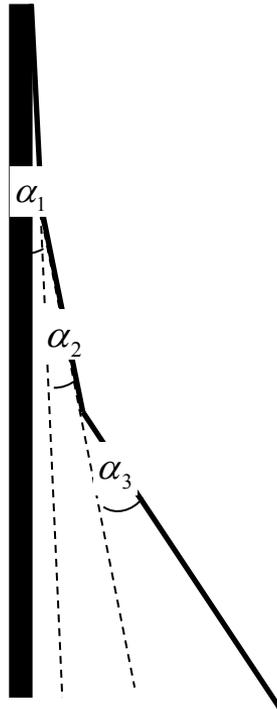
$$\sin \alpha \approx \frac{cp_t}{E}$$

$$l = \gamma c \tau_\pi = \frac{E}{m_\pi c^2} c \tau_\pi$$

$$r_\pi = l \sin \alpha = \frac{\cancel{E}}{m_\pi \cancel{c^2}} c \tau_\pi \frac{\cancel{cp_t}}{\cancel{E}} = \frac{\tau_\pi p_t}{m_\pi}$$

59% of pions have $r_\pi < \frac{\tau_\pi 2Q}{m_\pi} = 22 \text{ m}$

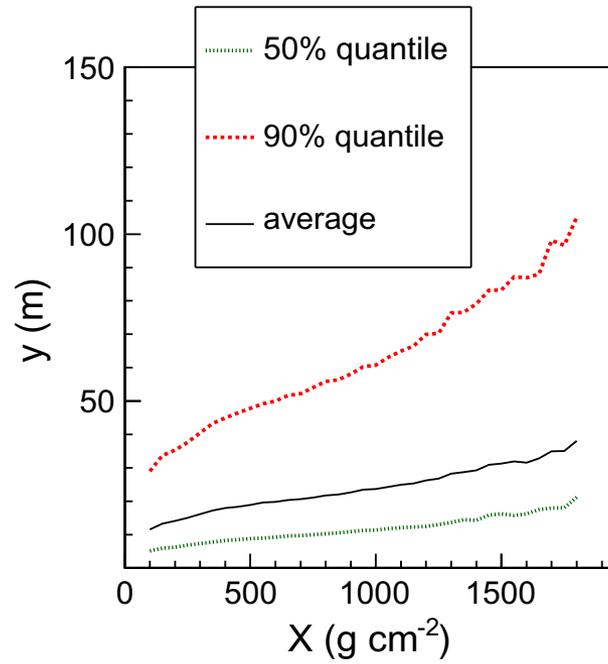
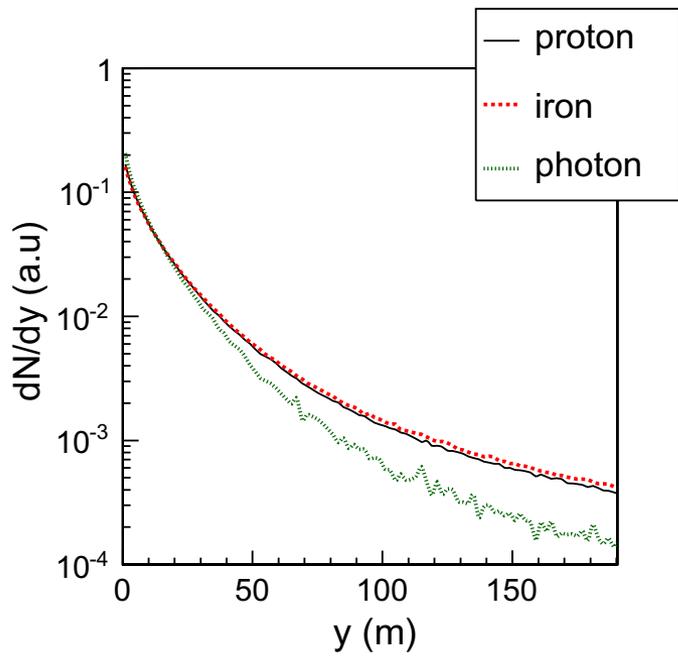
- The p_t slowly increases with number of iterations



$$p_t \simeq Q\sqrt{n}$$

Changes in the p_t of first interaction are hardly observable (regarding the outgoing angle/spatial distributions of muons)

There is a small increase of the distance of muon production to the shower axis in every generation



Universality of muon distributions at production

Approximations

- All information (Full MC)

$$\frac{d^6 N}{d\vec{x}d\vec{p}} = F(\vec{x}, \vec{p})$$

- Muon are produced in the shower axis.

$$\frac{d^3 N}{dX dE_i dcp_t} = F(X, E_i, cp_t).$$

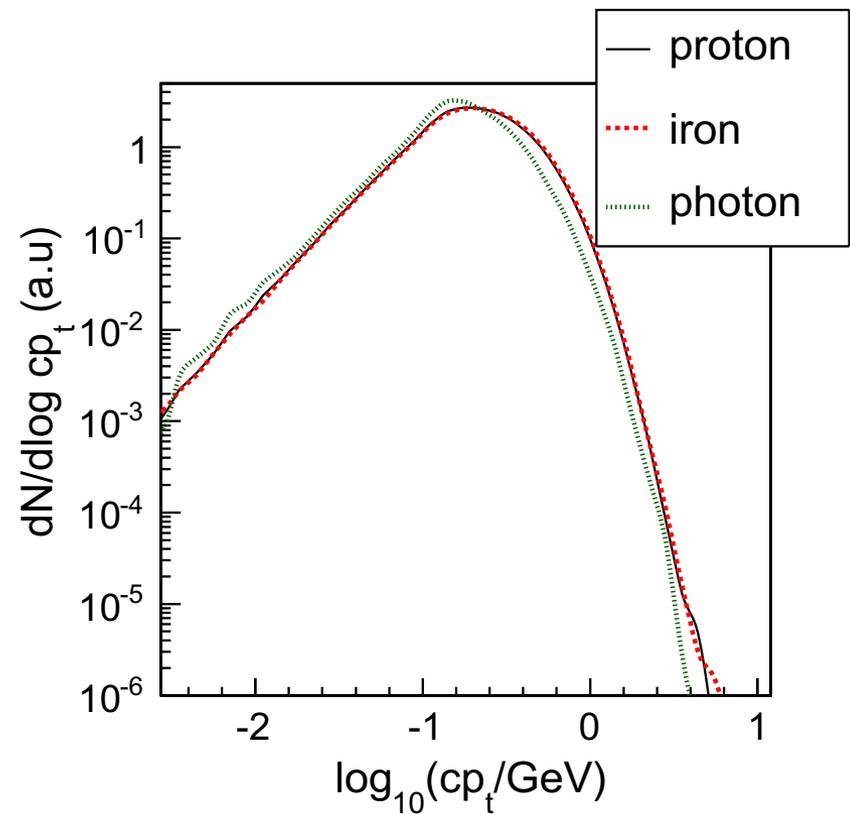
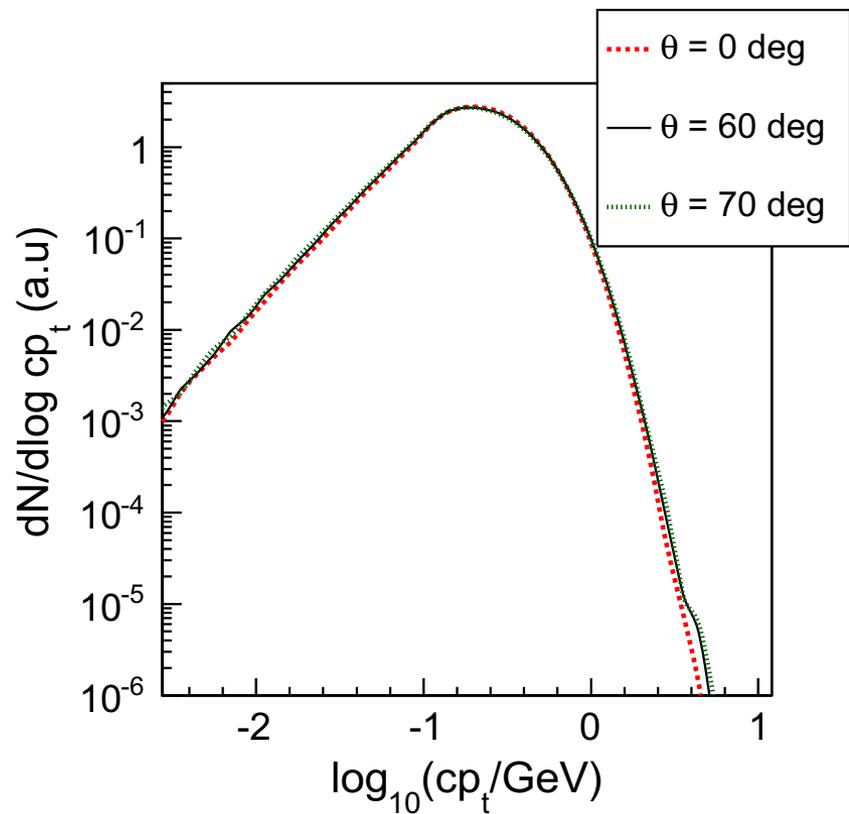
- Factorization hypothesis (allow easy analytical integrations)

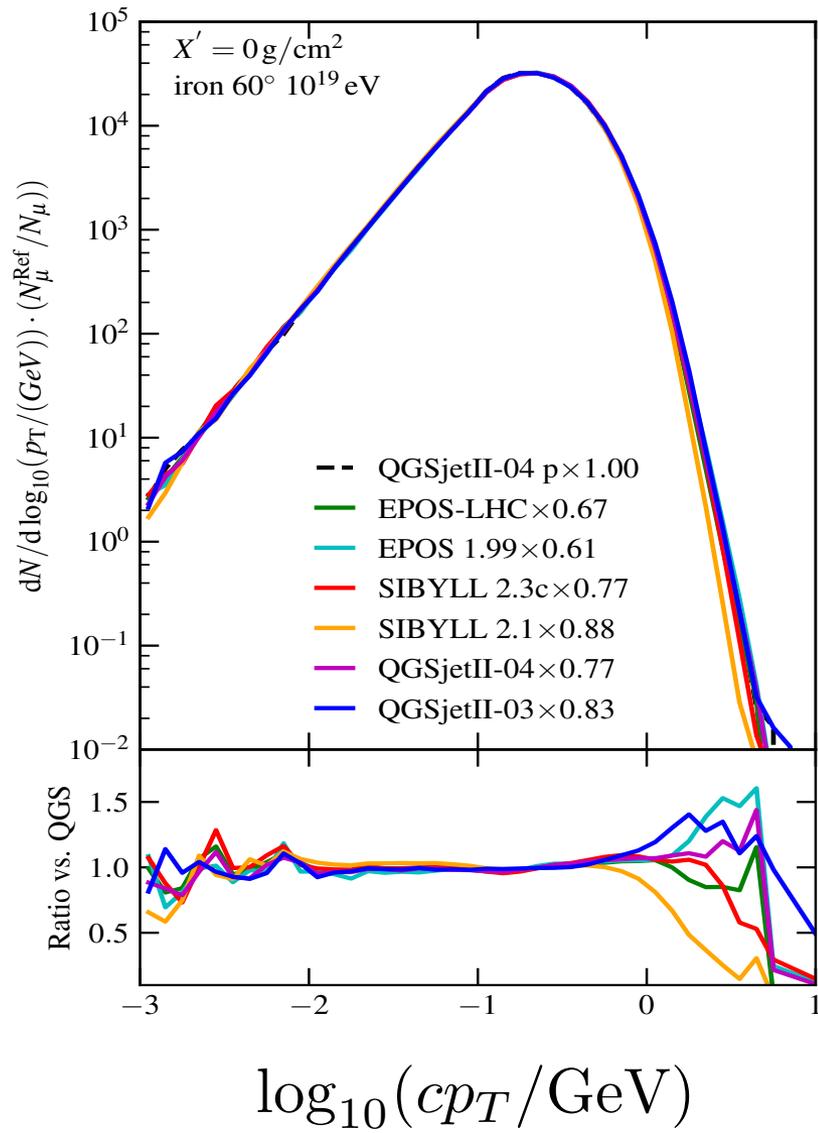
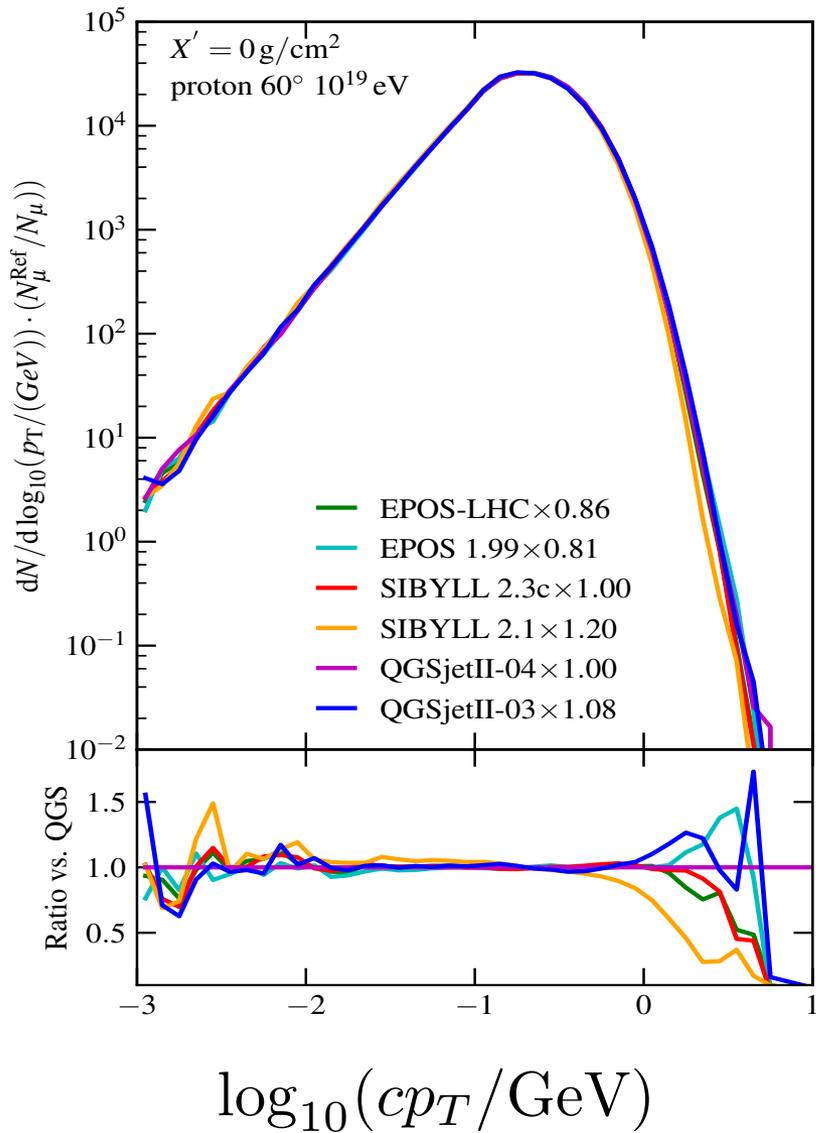
$$\frac{d^3 N}{dX dE_i dp_t} = h(X) f_1(E_i) f_2(p_t)$$

- Fixed $p_t=Q=0.2$ GeV

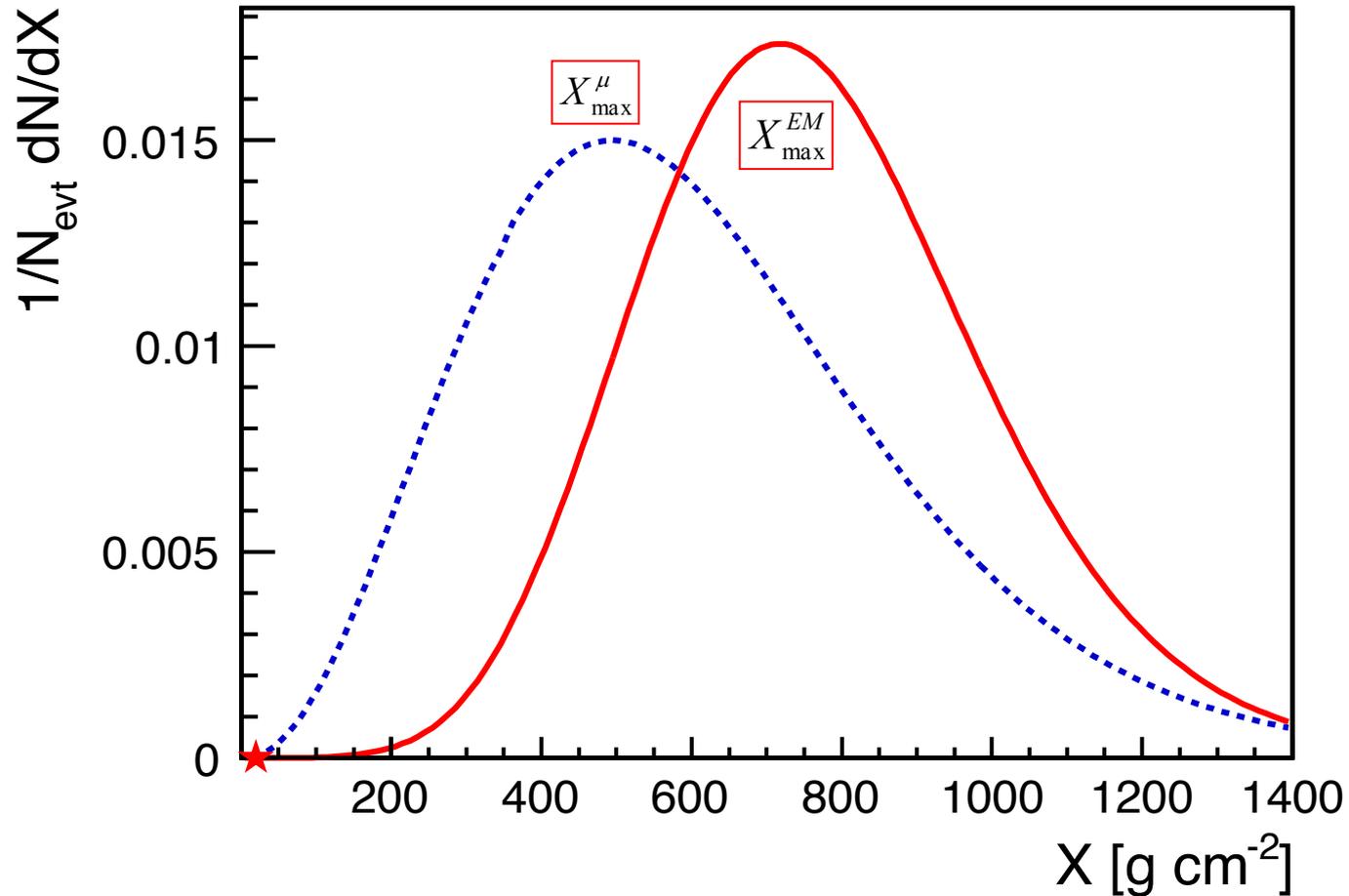
$$\frac{r}{z} \simeq \frac{Q}{E}$$

p_t -distribution

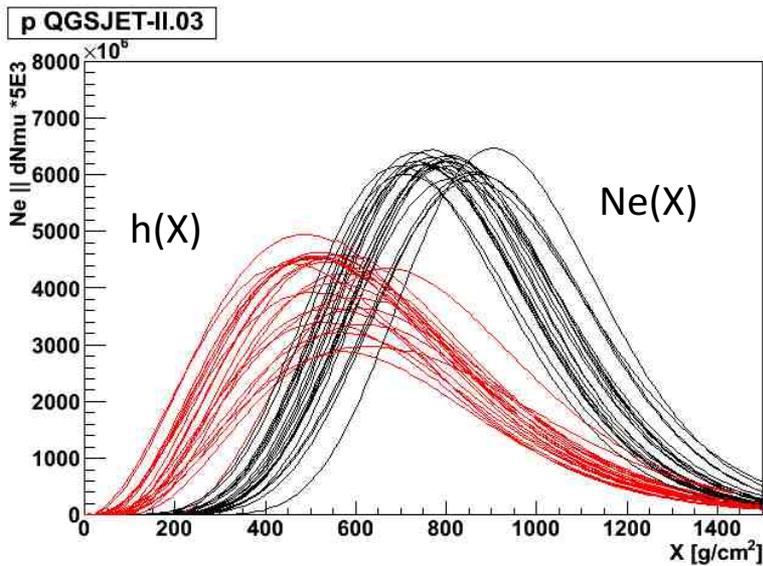




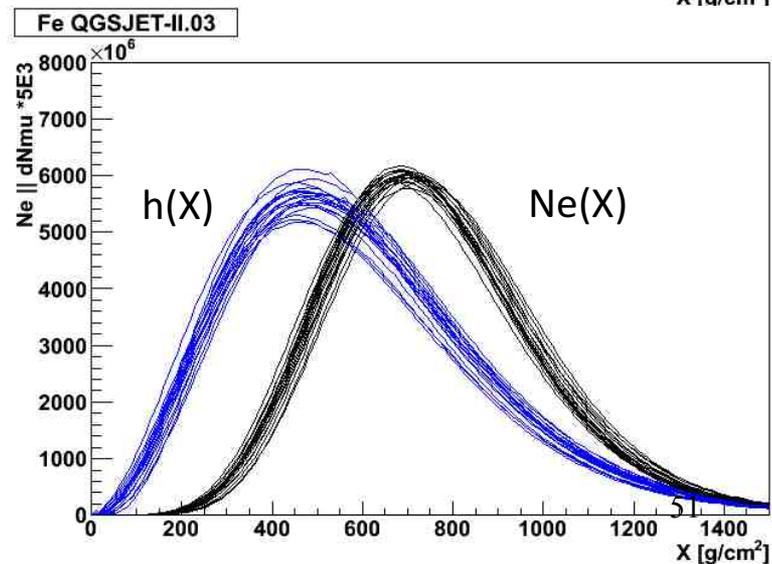
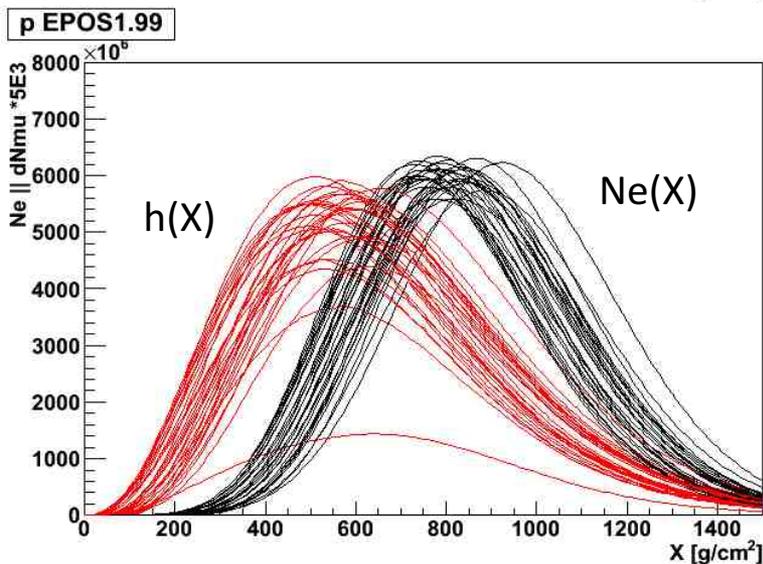
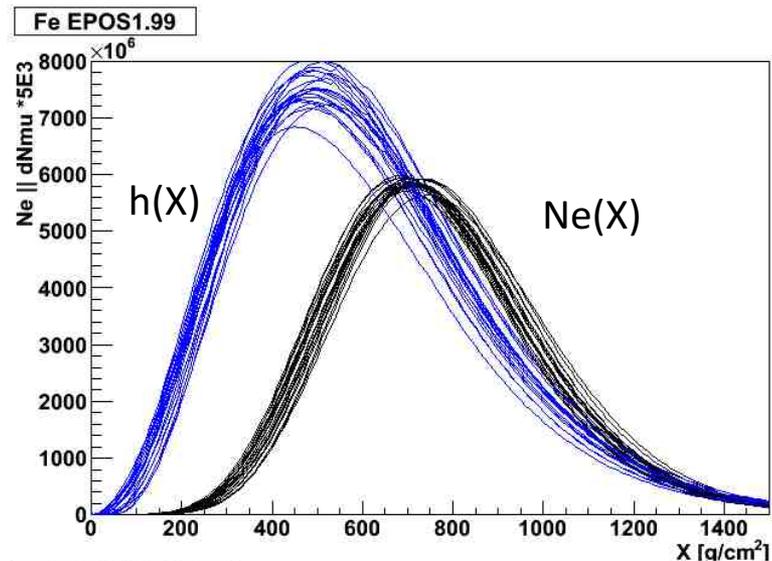
Muon Production Depth

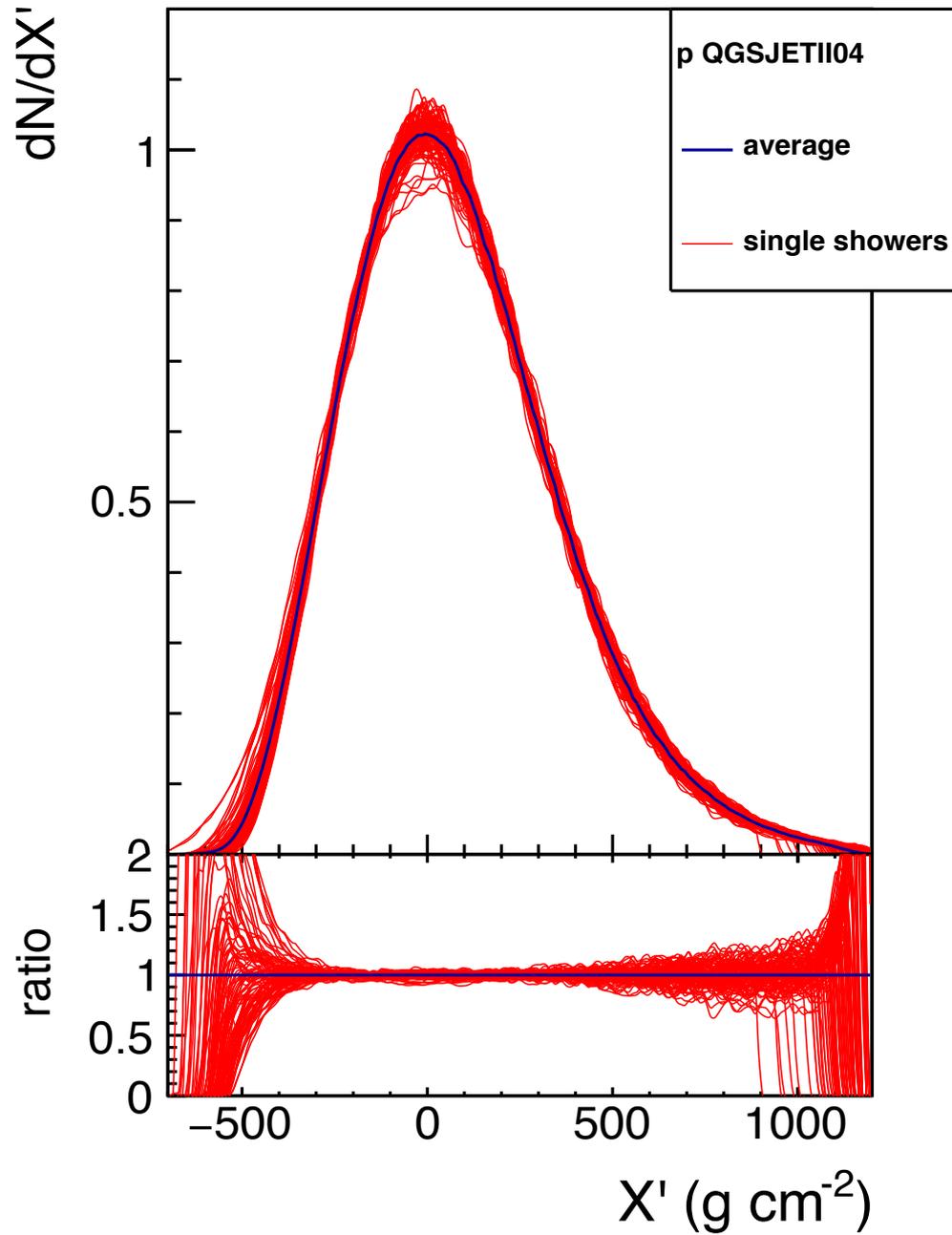


Muon Production Depth

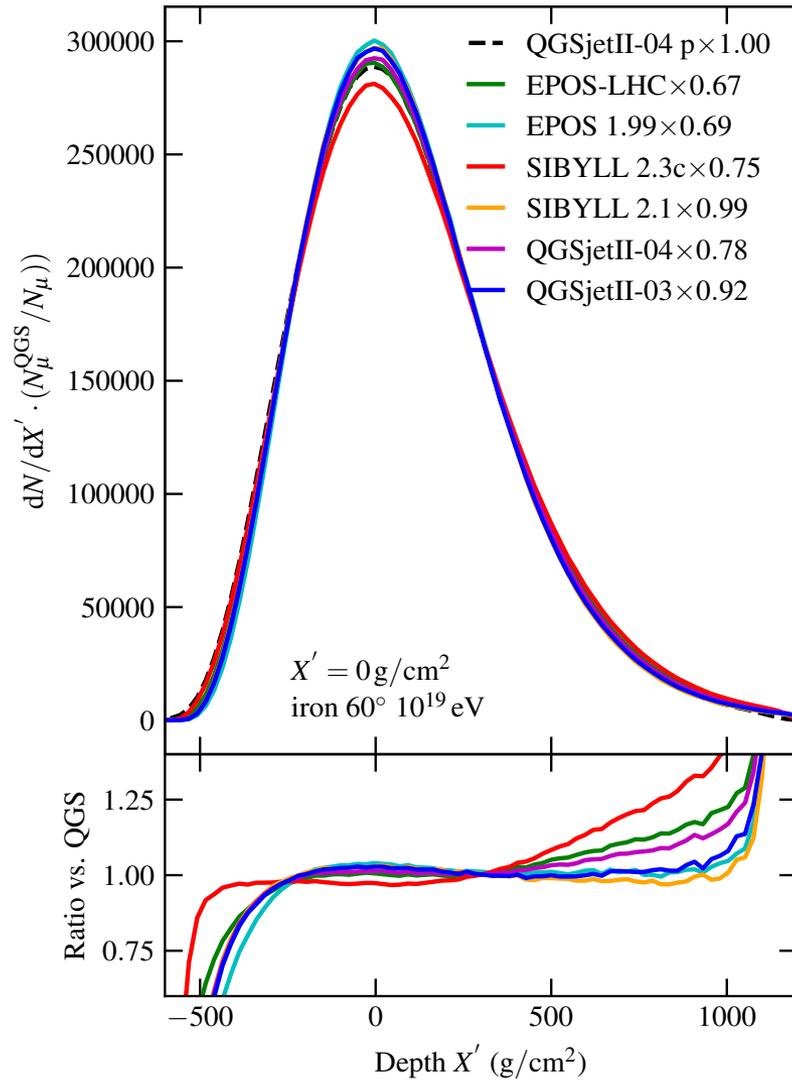
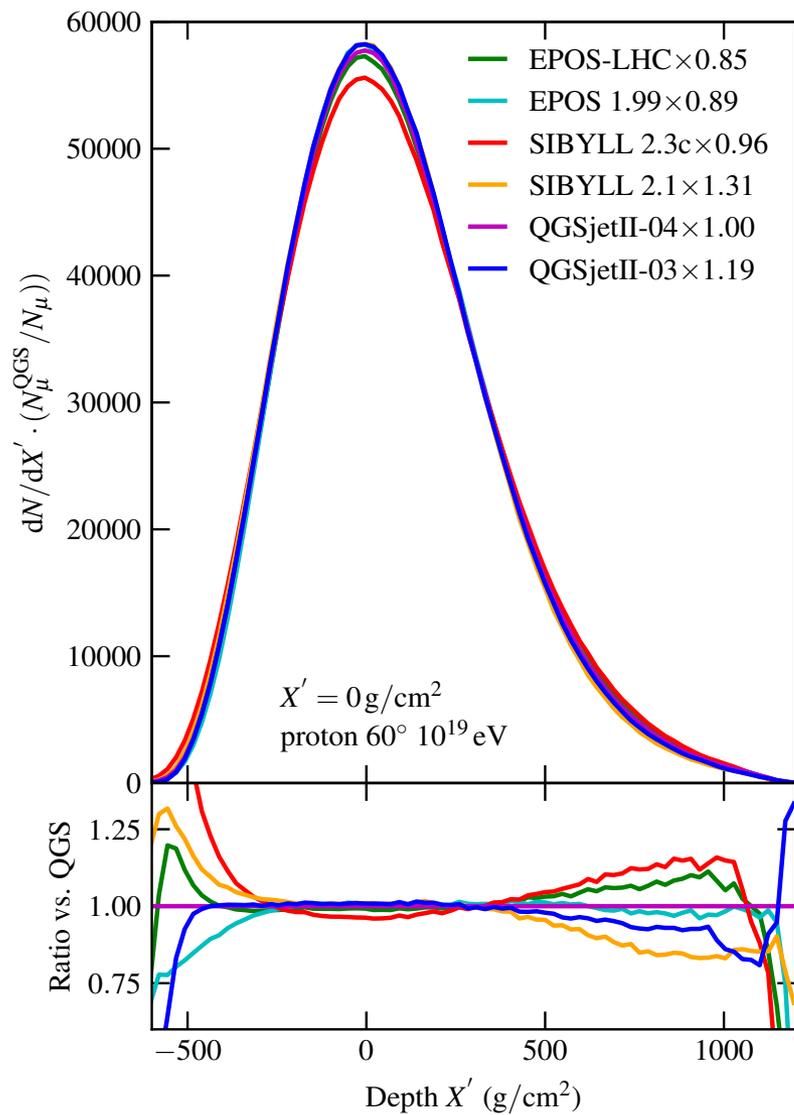


CONEX
 10^{19} eV
60 deg



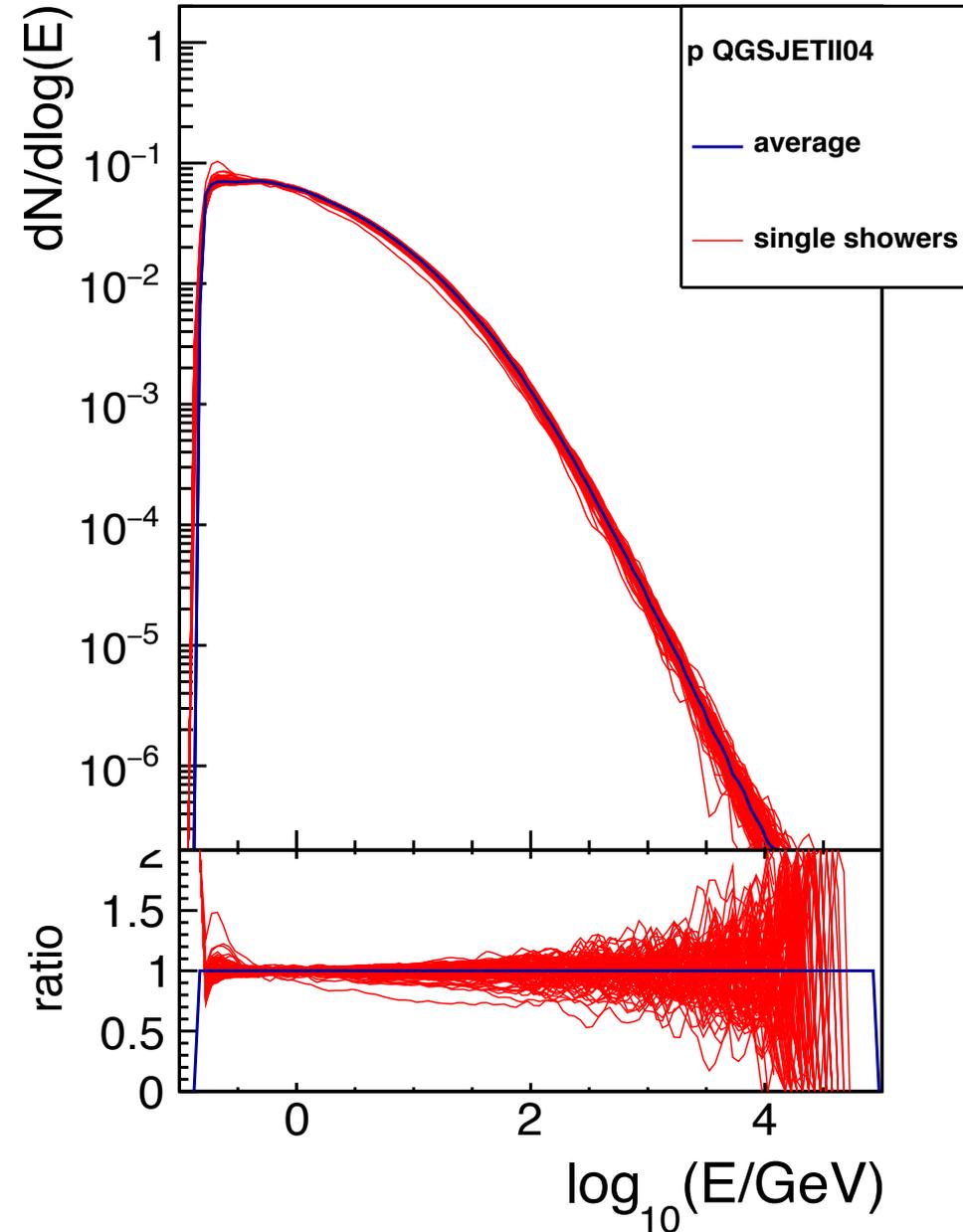


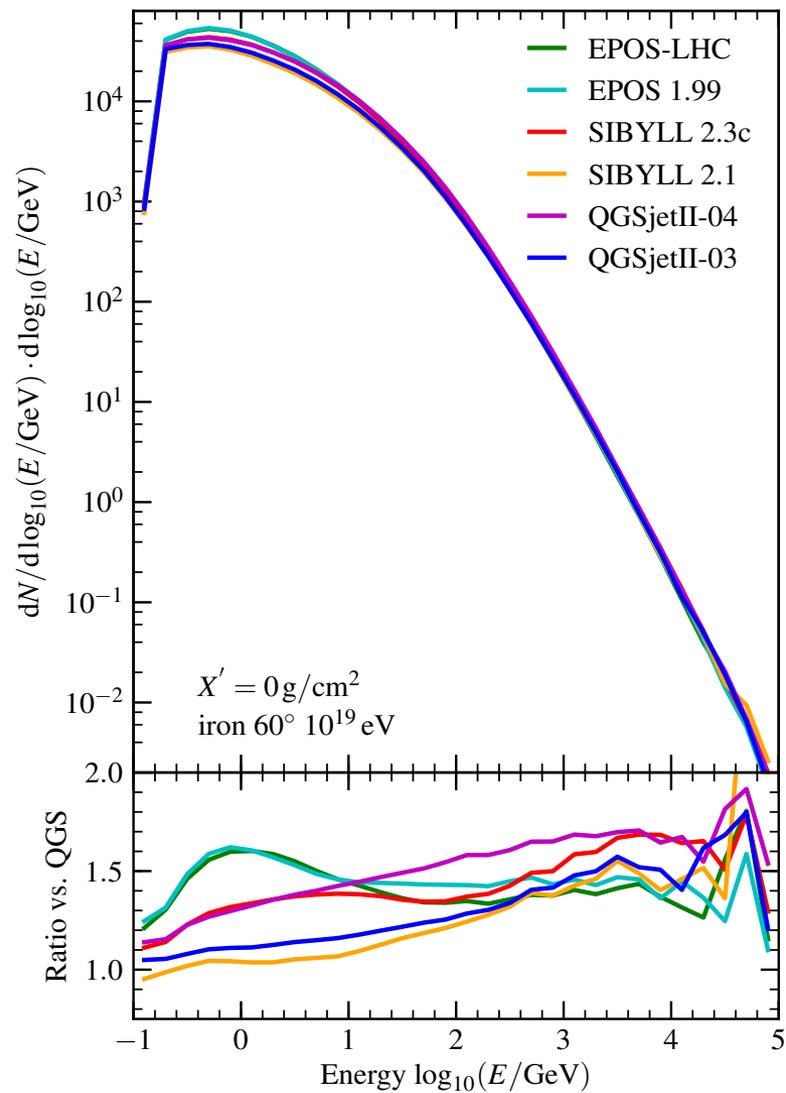
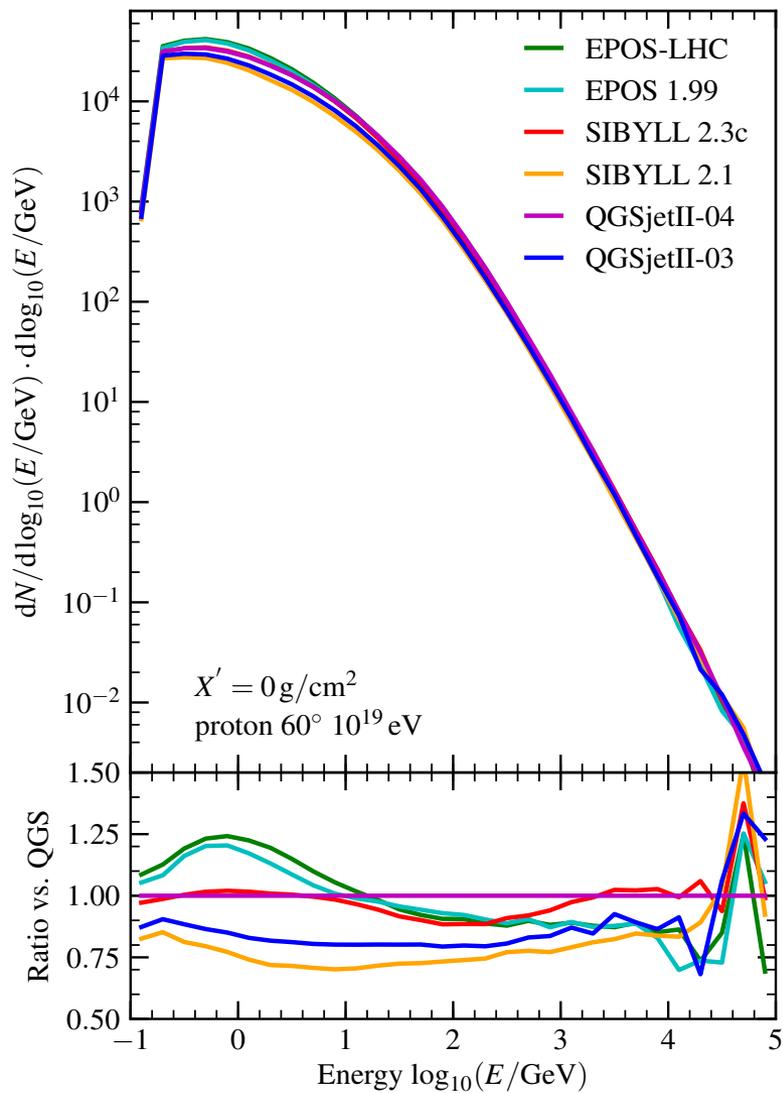
MPD is well described by a
Gaisser-Hillas
**Astropart.Phys. 35 (2012) 821-
827**

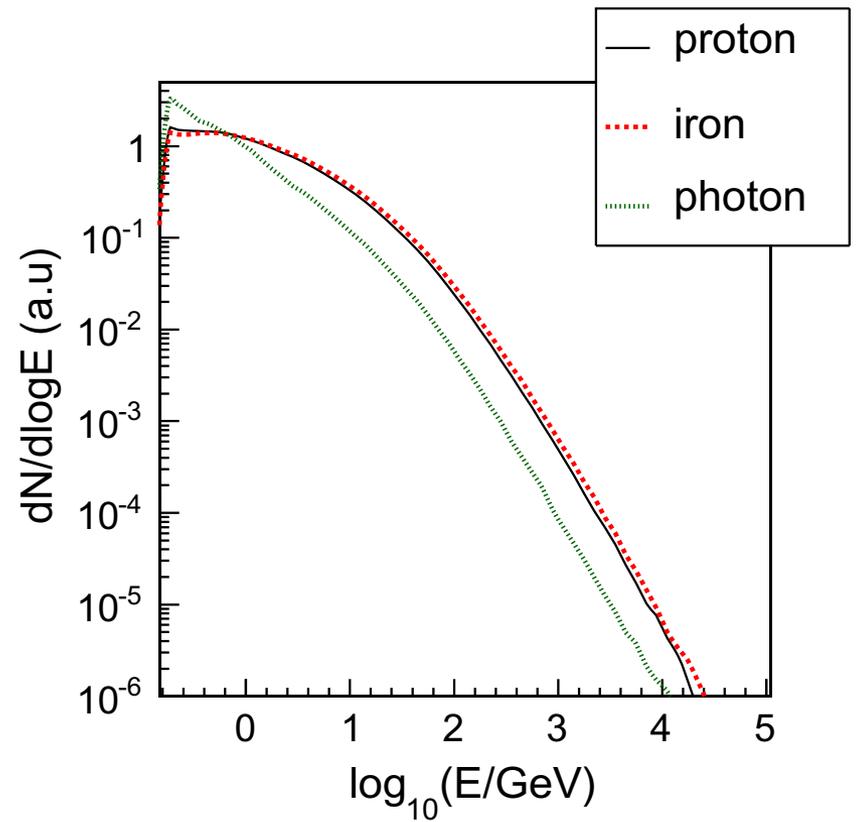
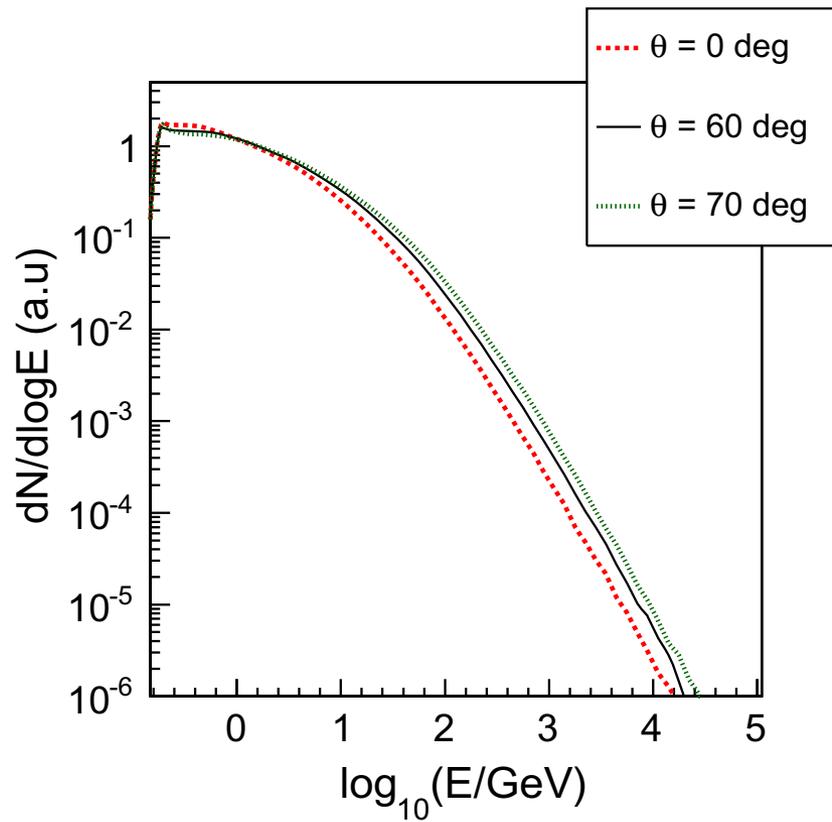


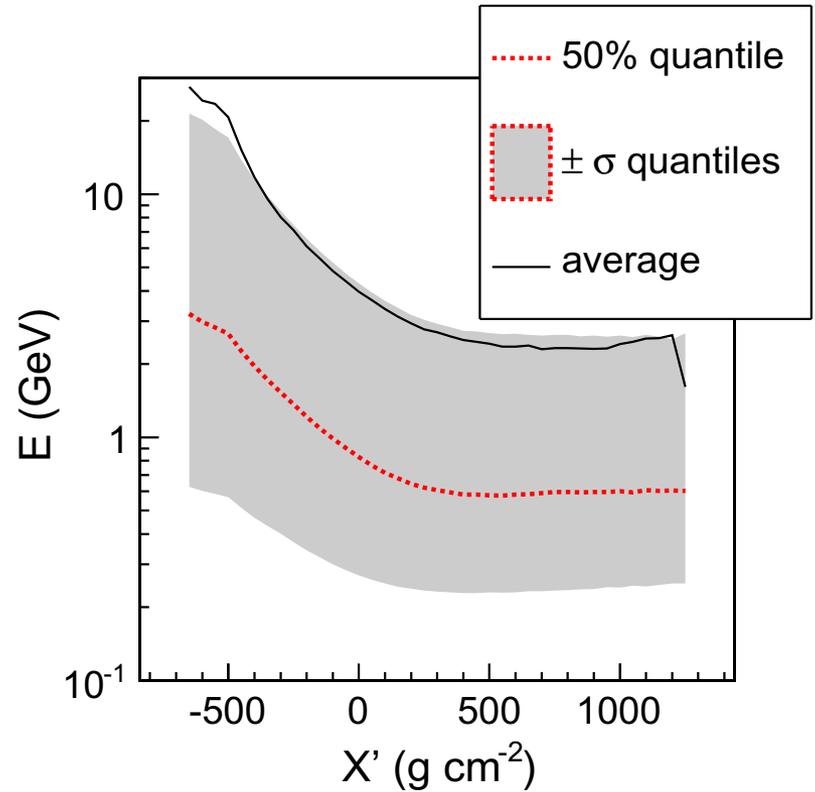
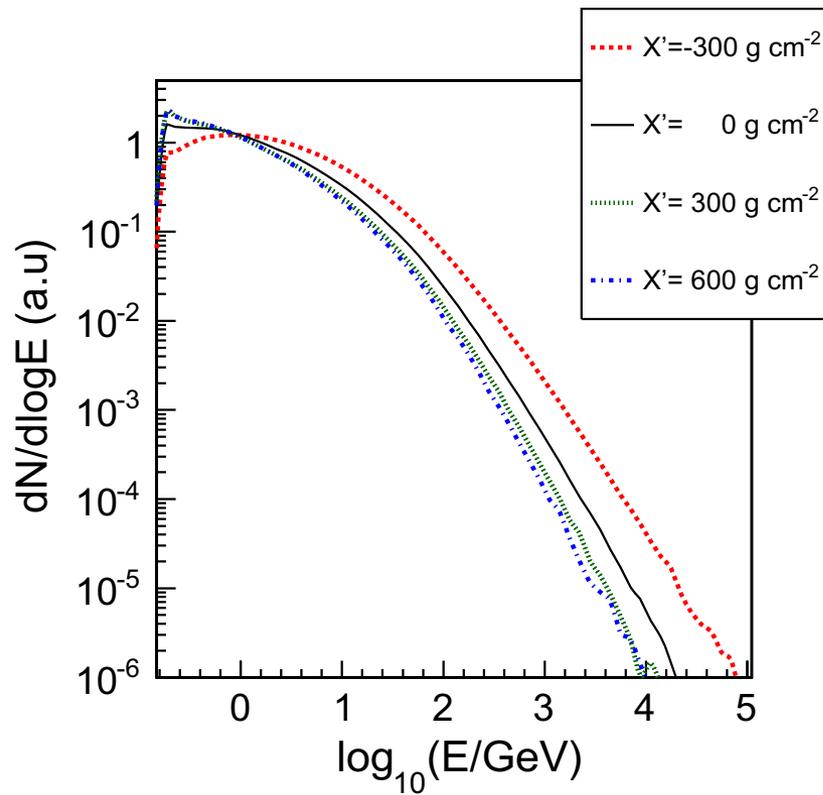
Energy- distribution

events $dN/d\log E$ at $X'=0 \text{ g cm}^{-2}$



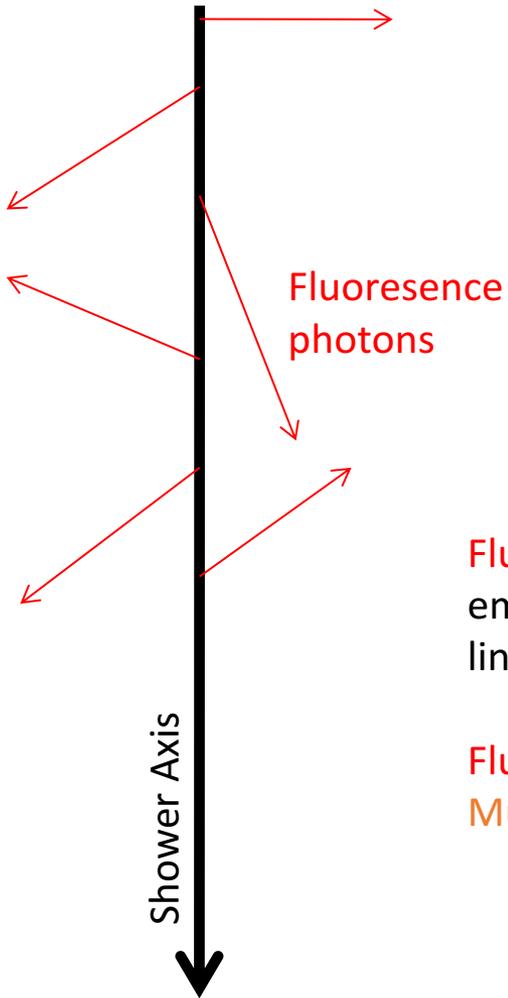






Muon distributions at ground

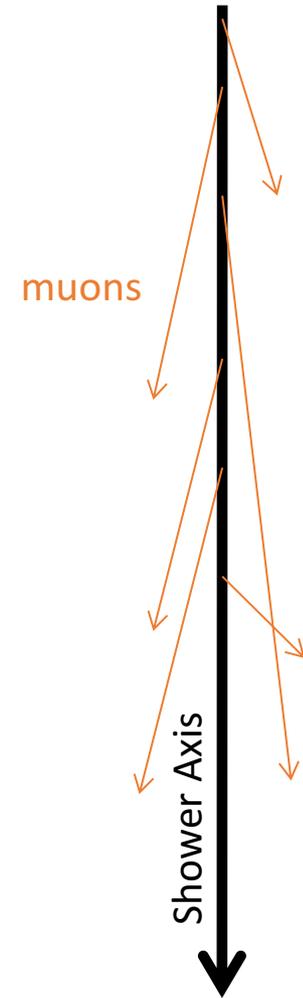
- We simply propagate muons following straight lines
- Energy loss (ionisation)
- Decay
- We can apply 2nd order corrections due to
 - MS
 - B field

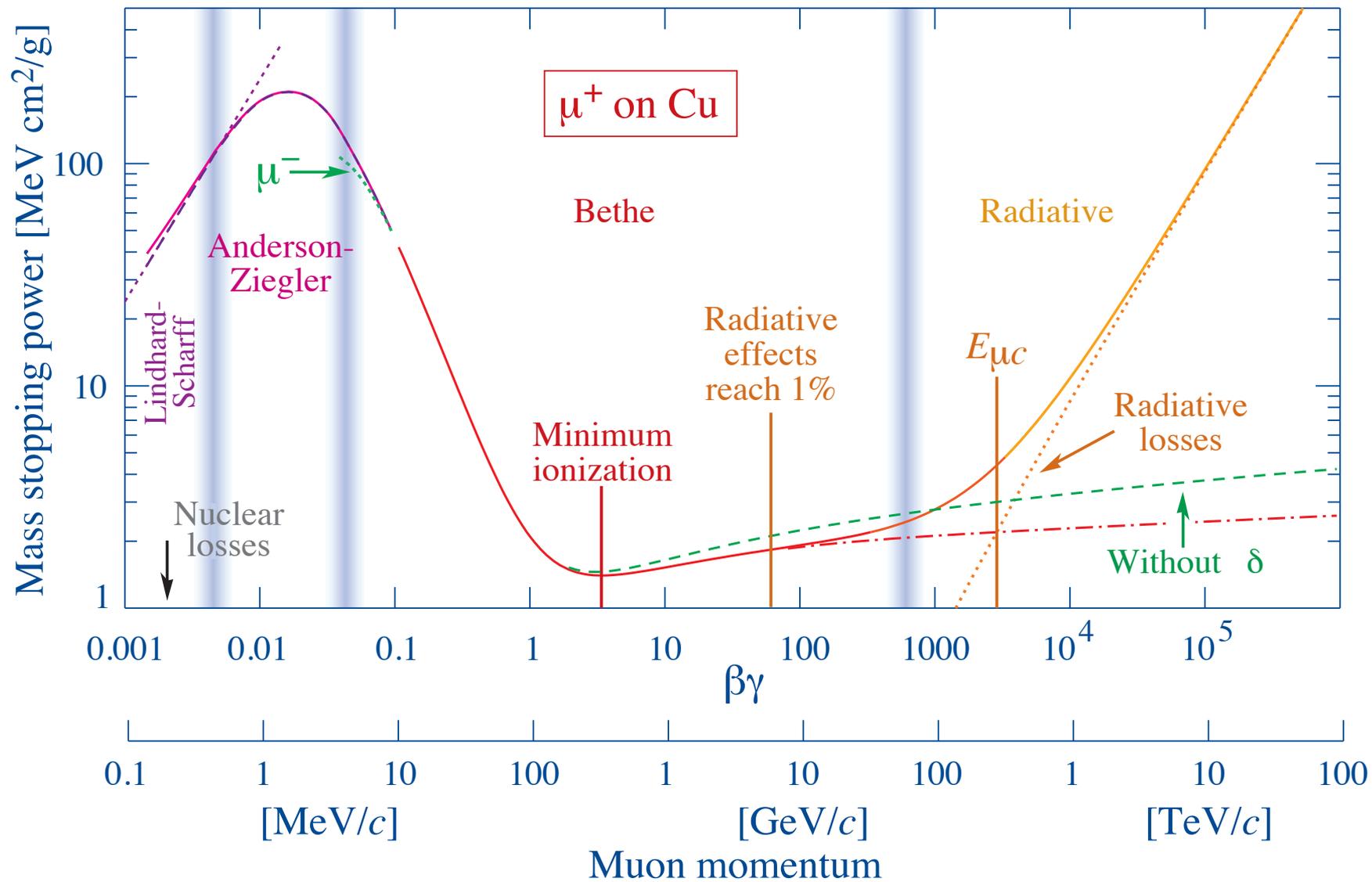


An image to keep in mind:

Fluorescence photons and muons are both emitted from the shower axis, following straight lines (approximately).

Fluorescence Photons are emitted isotropically. Muons are not. (they are boosted forward)



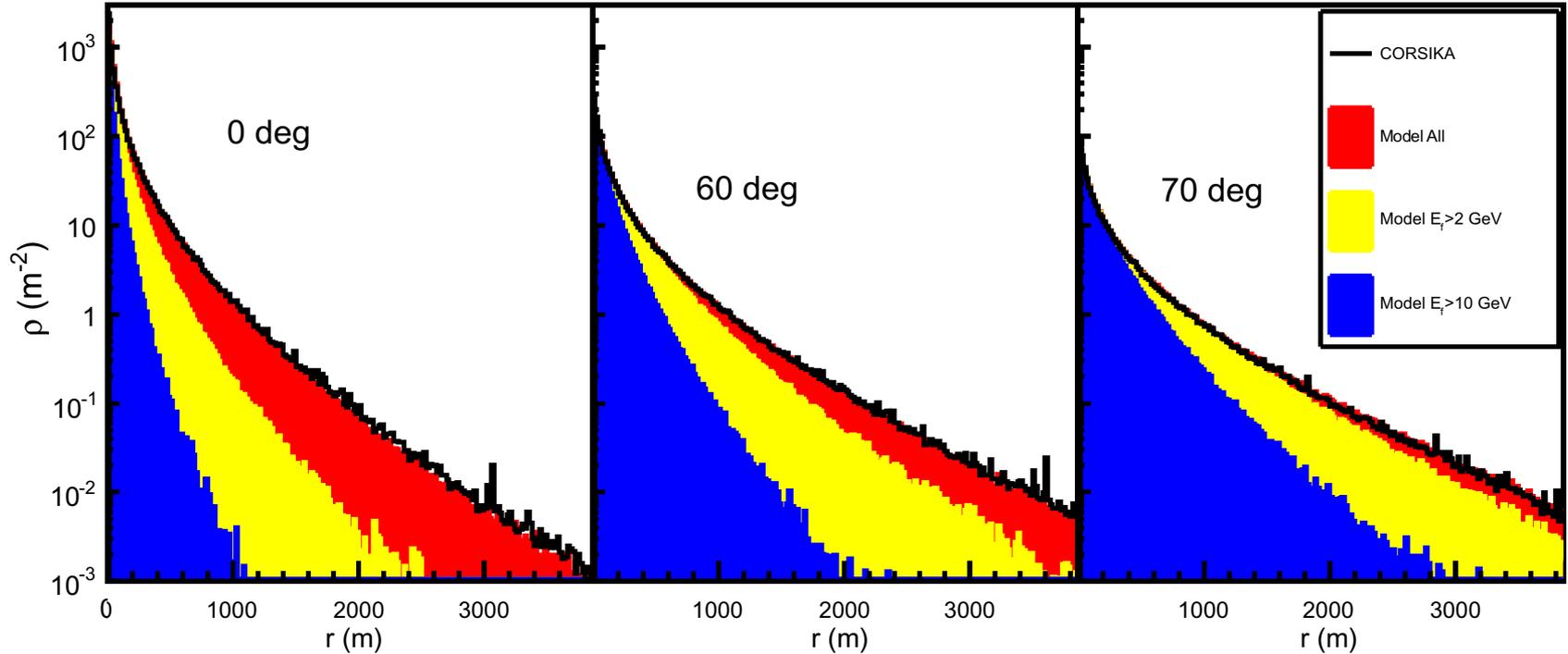


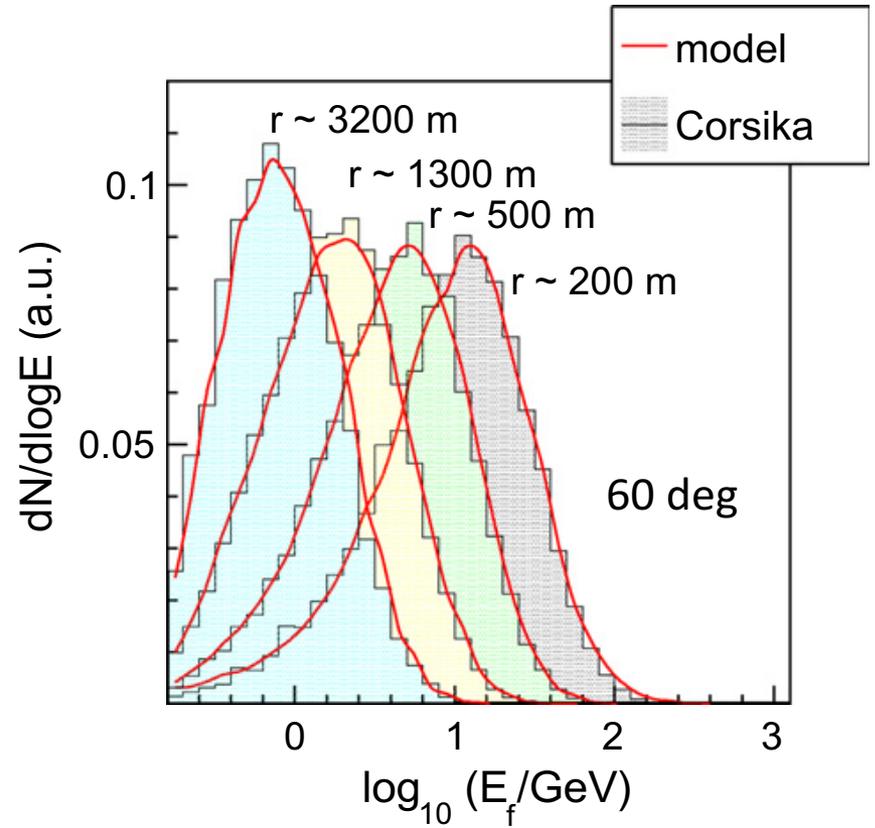
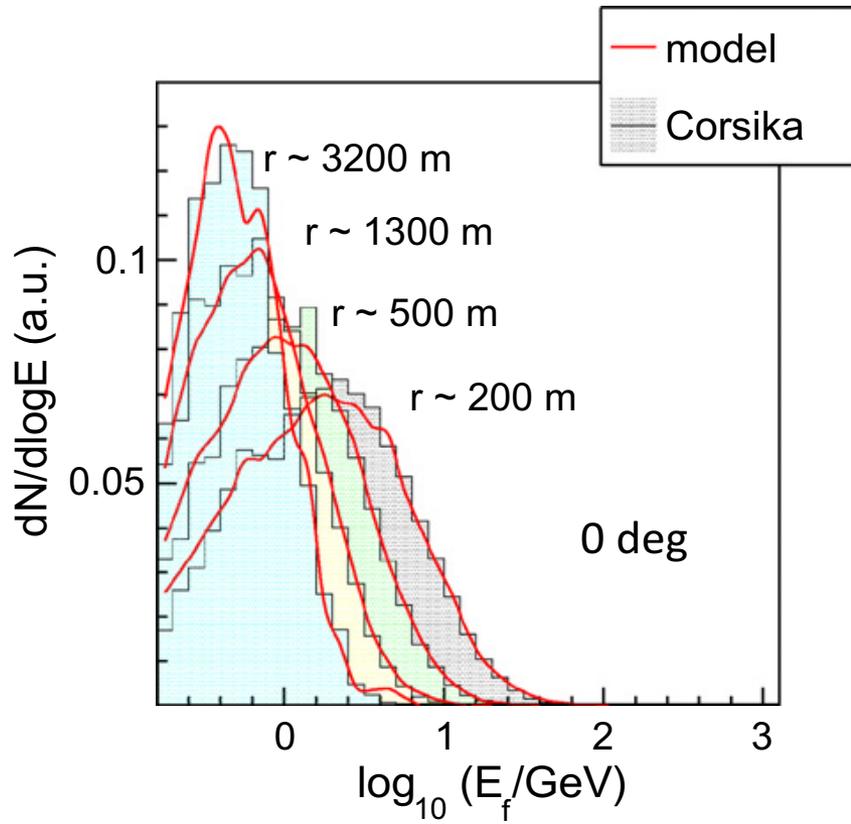
Energy loss

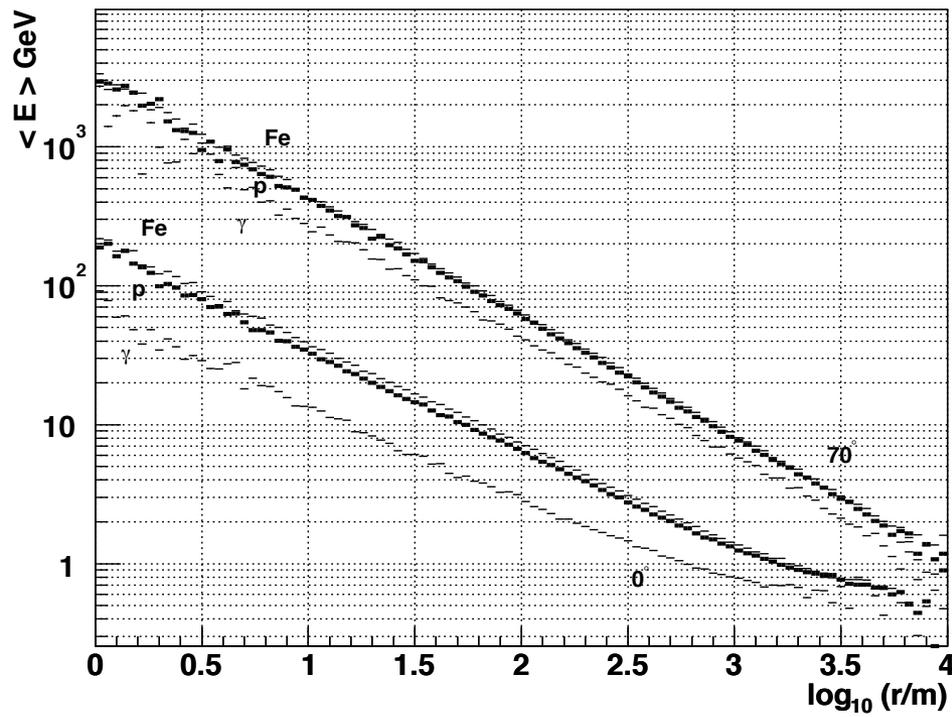
$$\frac{dE}{dX} = -a \quad a \simeq 2 \text{ MeV/g cm}^{-2}$$

1 m of water	$X = 100 \text{ g/cm}^2$	$\Delta E = 0.2 \text{ GeV}$
Atm. depth at 0 deg	$X = 1000 \text{ g/cm}^2$	$\Delta E = 2 \text{ GeV}$
Atm. depth at 60 deg	$X = 2000 \text{ g/cm}^2$	$\Delta E = 4 \text{ GeV}$
Atm. depth at 75 deg	$X = 4000 \text{ g/cm}^2$	$\Delta E = 8 \text{ GeV}$

Muon Number





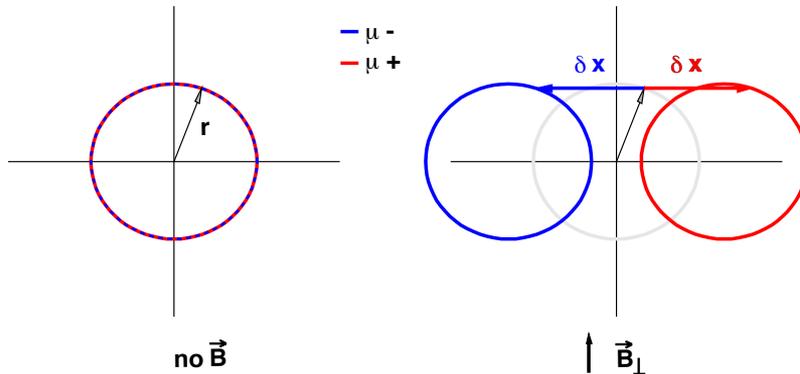


$$E = p_t \frac{z}{r}$$

Magnetic field effects

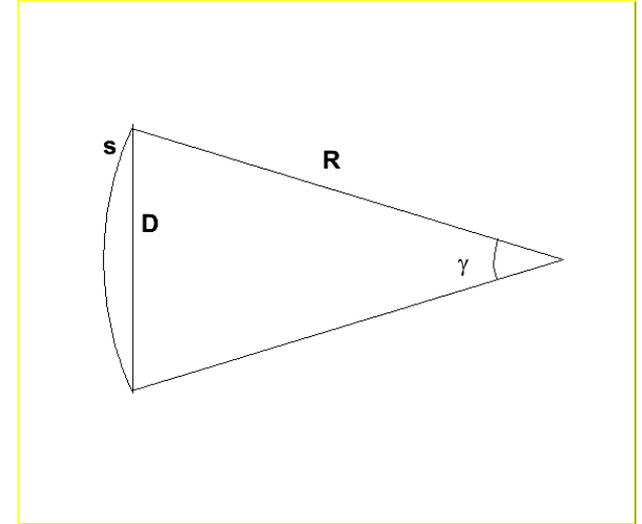
The magnetic field bend the trajectories, with a radius of curvature that depend on the energy of the muon.

$$R = \frac{E}{ceB_{\perp}}$$



The impact point is shifted perpendicular to the velocity and the magnetic field:

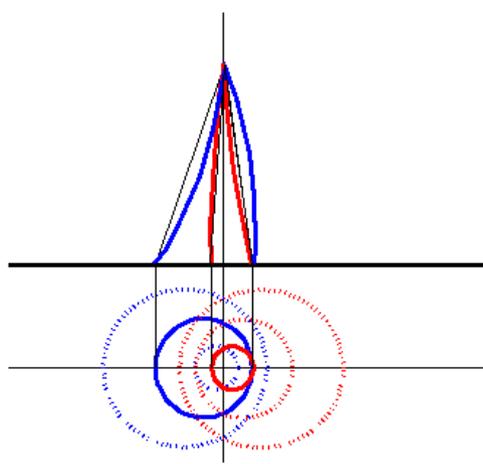
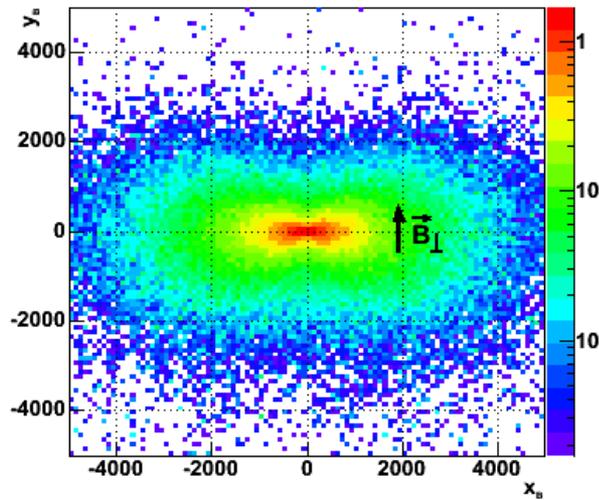
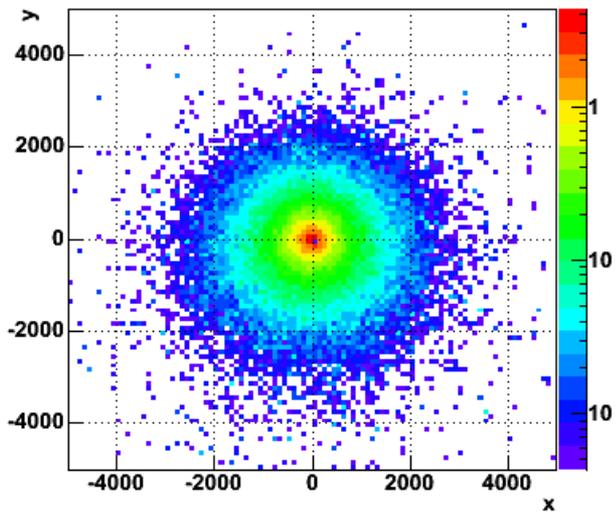
$$\delta x \cong \frac{1}{2} \frac{zeB_{\perp}}{p_t} r \equiv \alpha_B r$$



It also introduces an extra time delay, which is caused by the extra path.

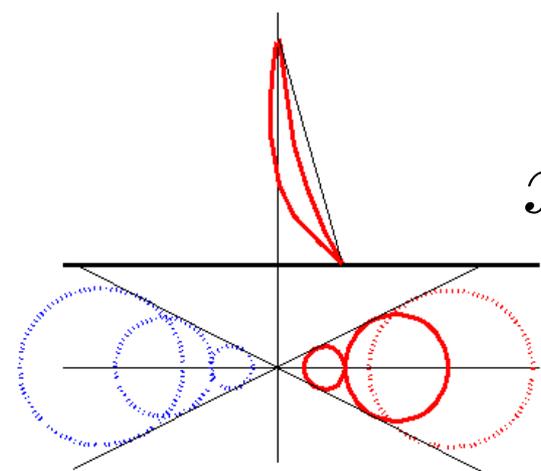
$$ct_B \cong \frac{1}{2} \frac{r_B^2}{z} + \frac{1}{24} \frac{z^3}{R^2}$$

We can determine the approximated zenith angle range where time model works.



$\otimes \vec{B}_\perp$
 $\text{---} \mu^-$
 $\text{---} \mu^+$

$\uparrow \vec{B}_\perp$

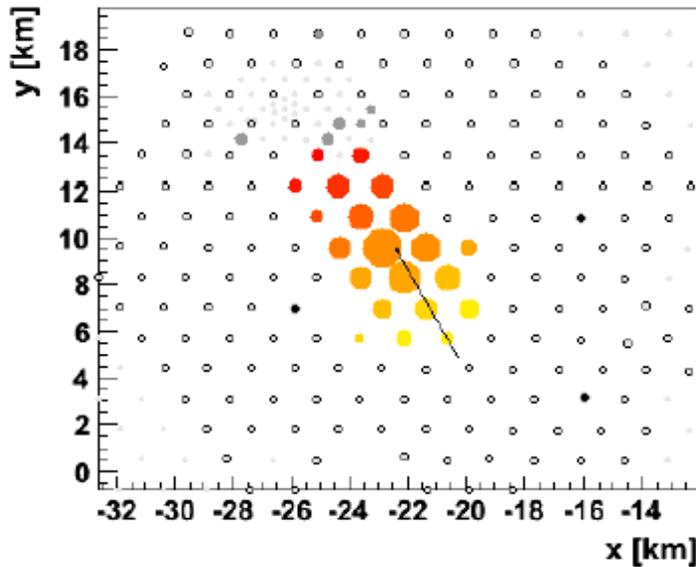


$$y \rightarrow y$$

$$x \rightarrow x \pm \alpha_B r$$

Reconstruction of inclined events

$62 < \theta < 80$ deg



Fit the muon density in stations

$$\rho_{\mu} = N_{19} \rho_{\mu,19}(x, y)$$

where N_{19} free parameter

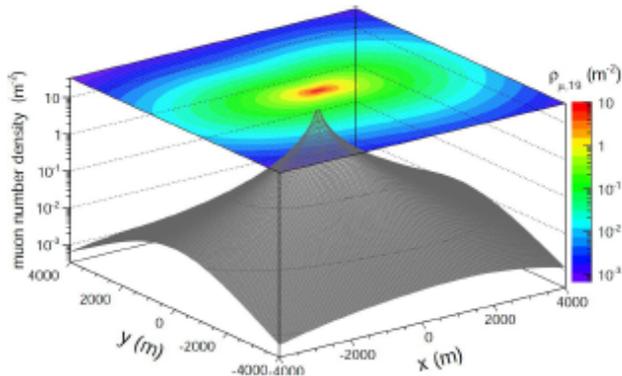
And $\rho_{\mu,19}(x, y)$ is fixed, corresponding to proton QGSJetII-03 at 10^{19} eV

Ratio of the total number of muons N_{μ} to $N_{\mu,19}$ (proton QGSJetII-03 at 10^{19} eV)

$$R_{\mu} = N_{\mu} / N_{\mu,19}$$

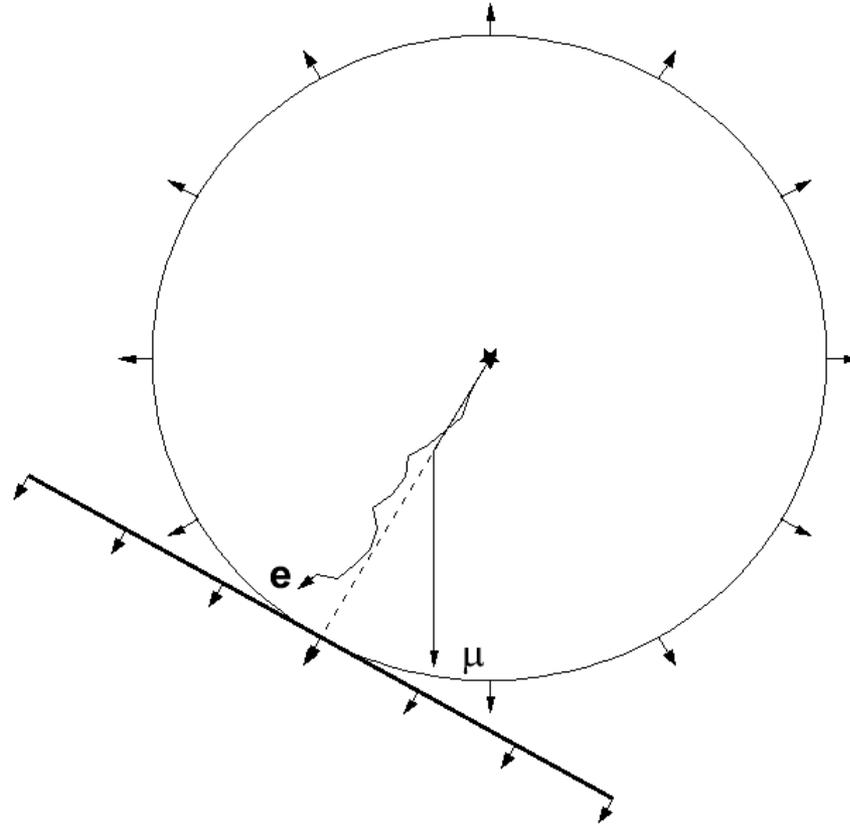
Correspondence (<5% bias correction)

$$N_{19} \Leftrightarrow R_{\mu}$$



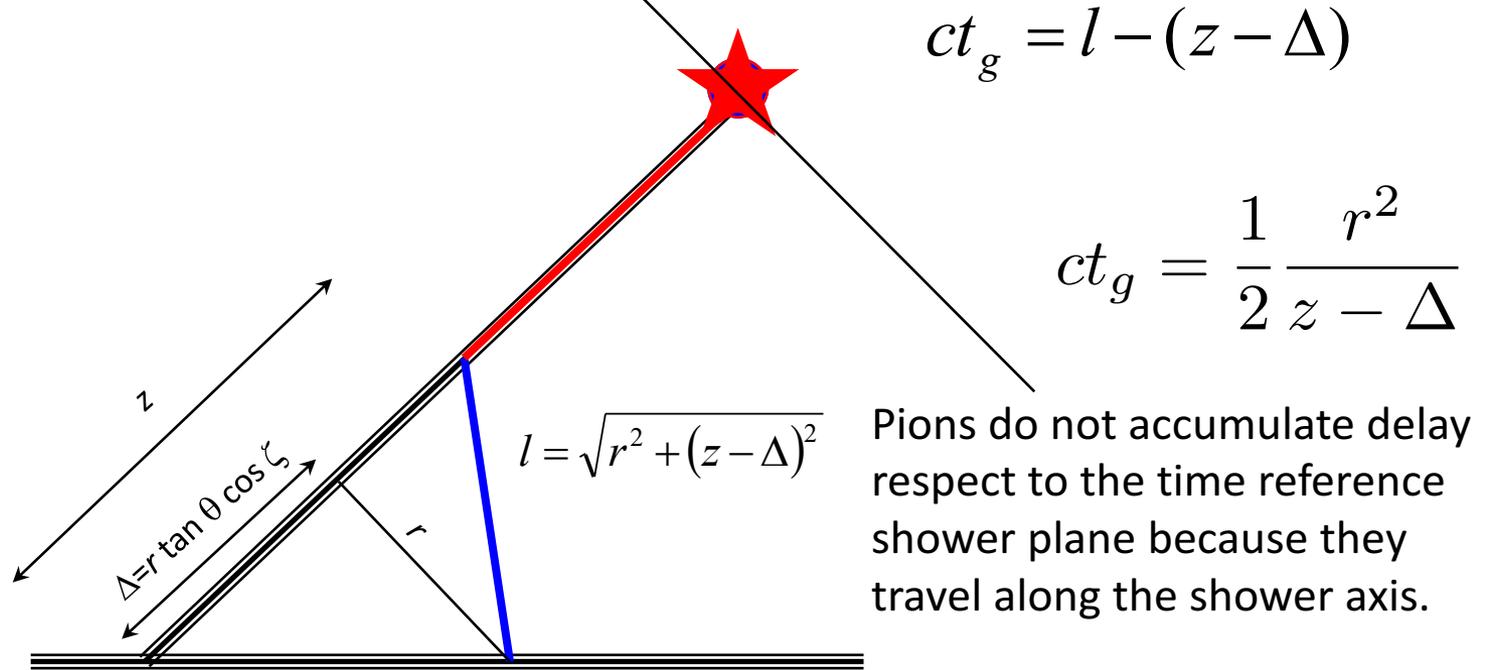
Example of $\rho_{\mu,19}$ for proton showers at $\theta=80^{\circ}$, $\phi=0^{\circ}$ and core at $(x, y) = (0, 0)$

Time Delay



$$\chi^2 = \sum_i \left(\frac{t_i}{\sigma_i} \right)^2$$

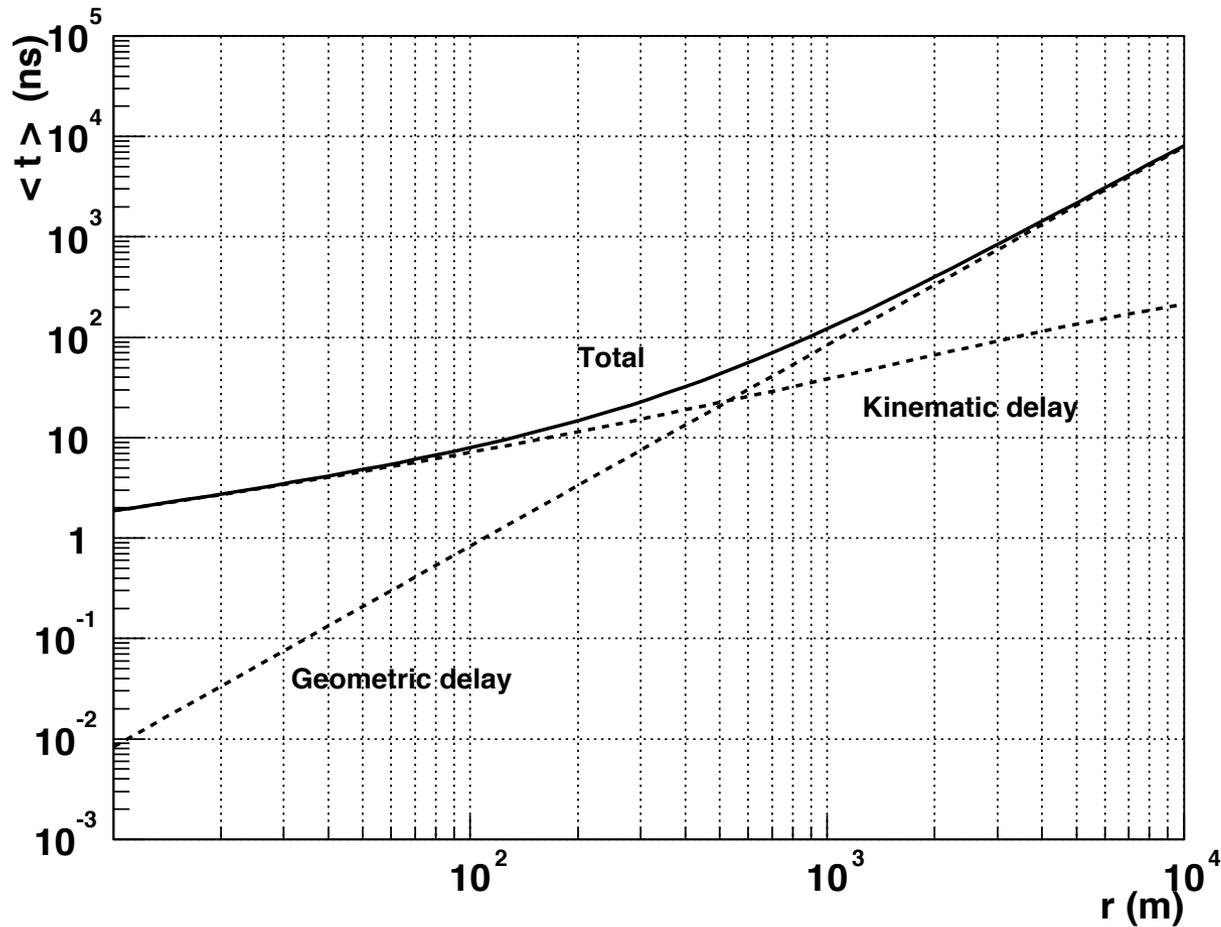
Geometrical delay



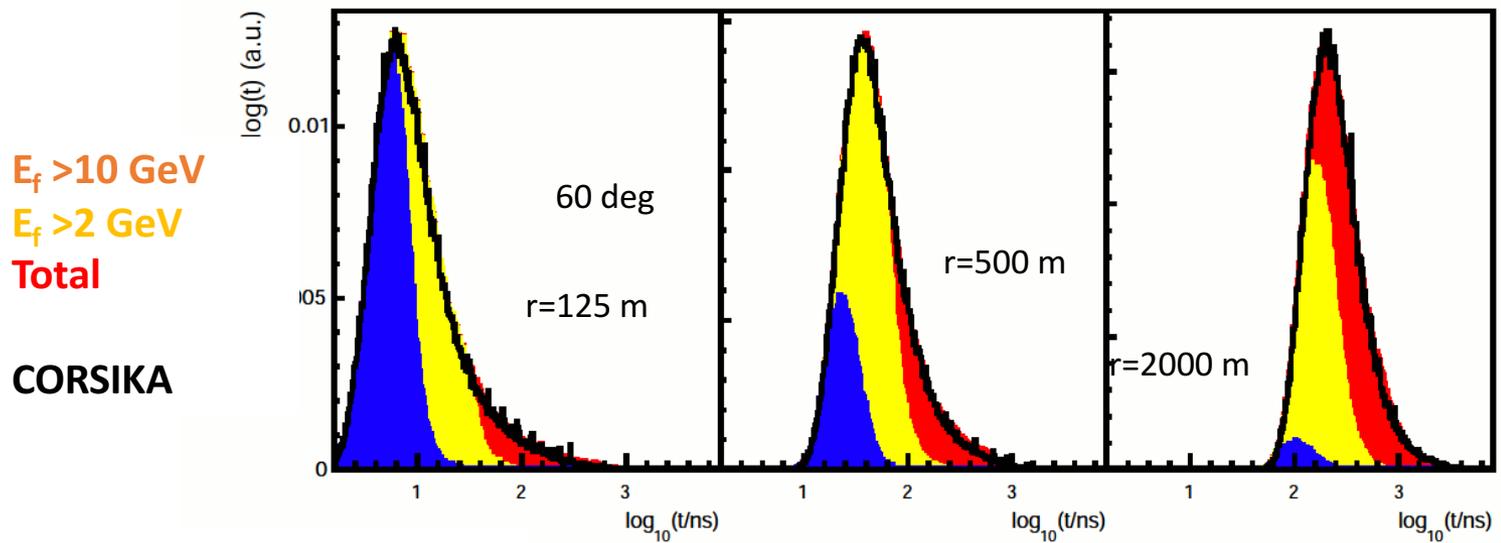
Pions do not accumulate delay respect to the time reference shower plane because they travel along the shower axis.

Muons accumulate delay because they deviate from the shower axis.

Kinematic delay

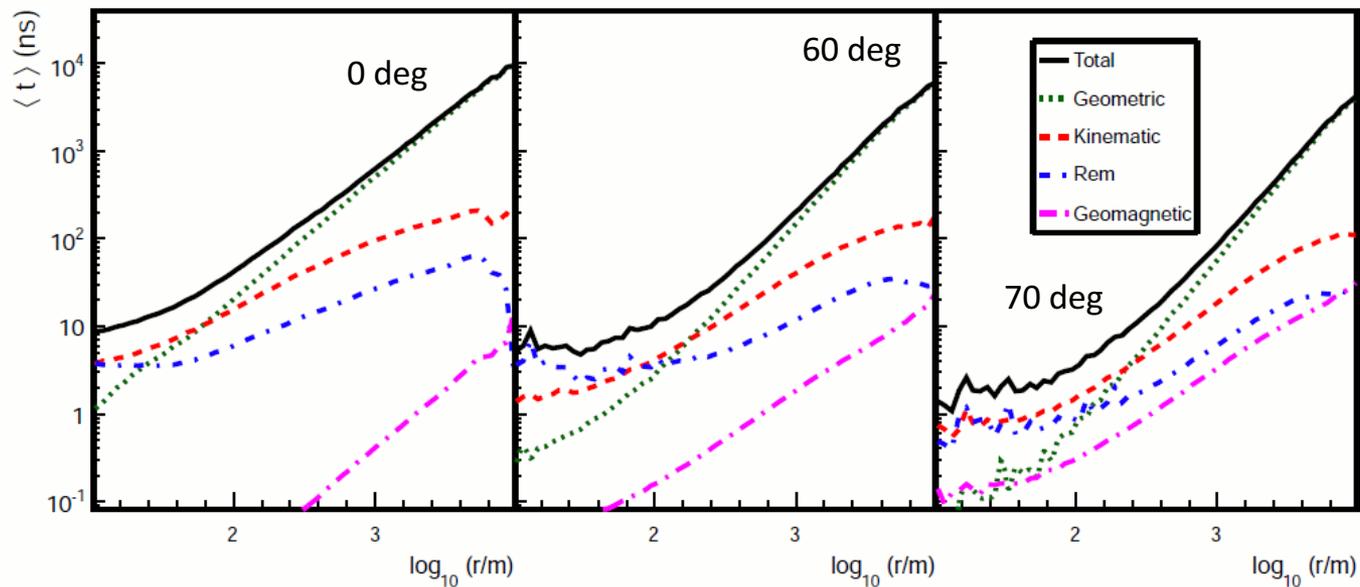


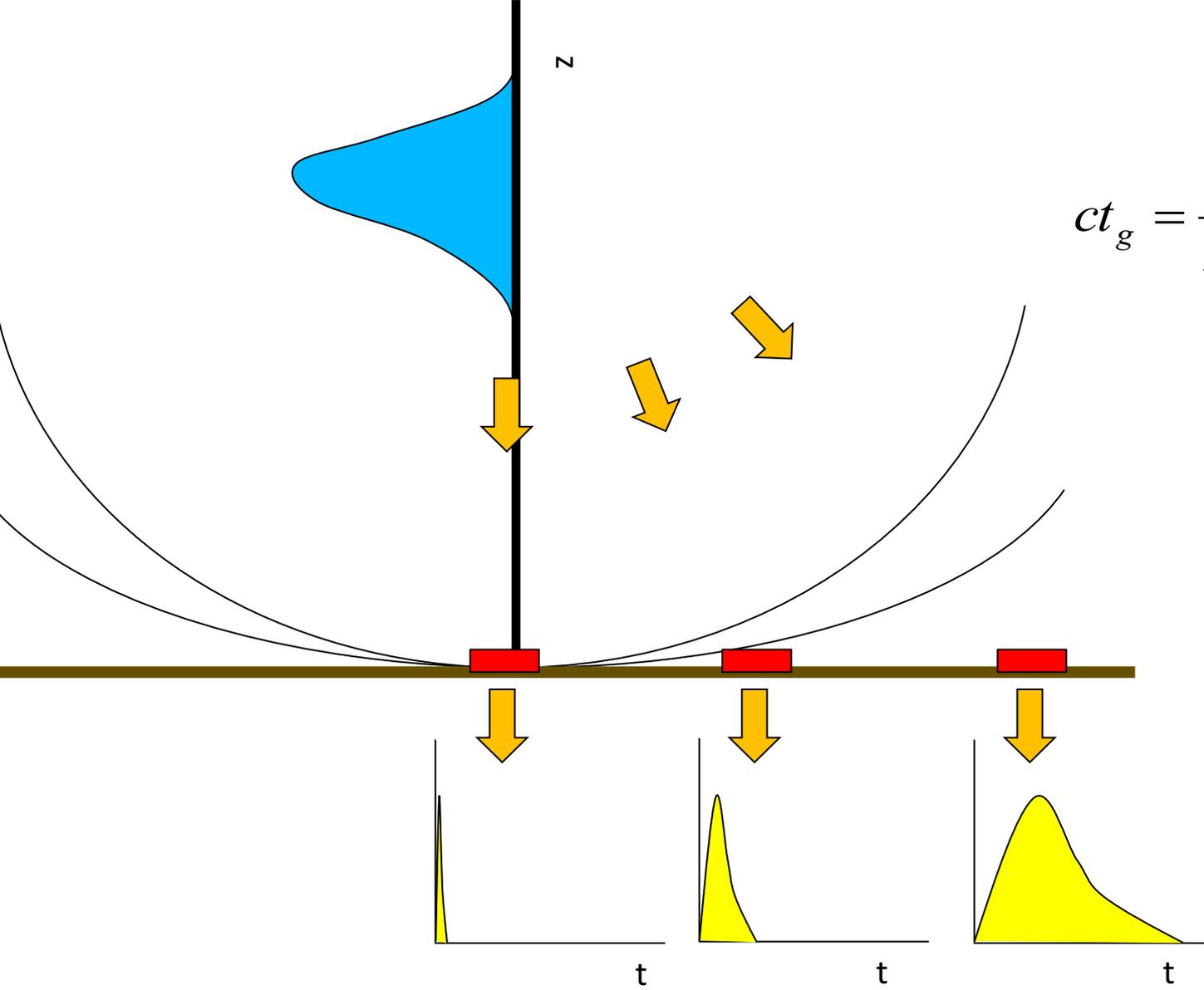
$$ct_g = \frac{1}{2} \frac{r^2}{z - \Delta}$$



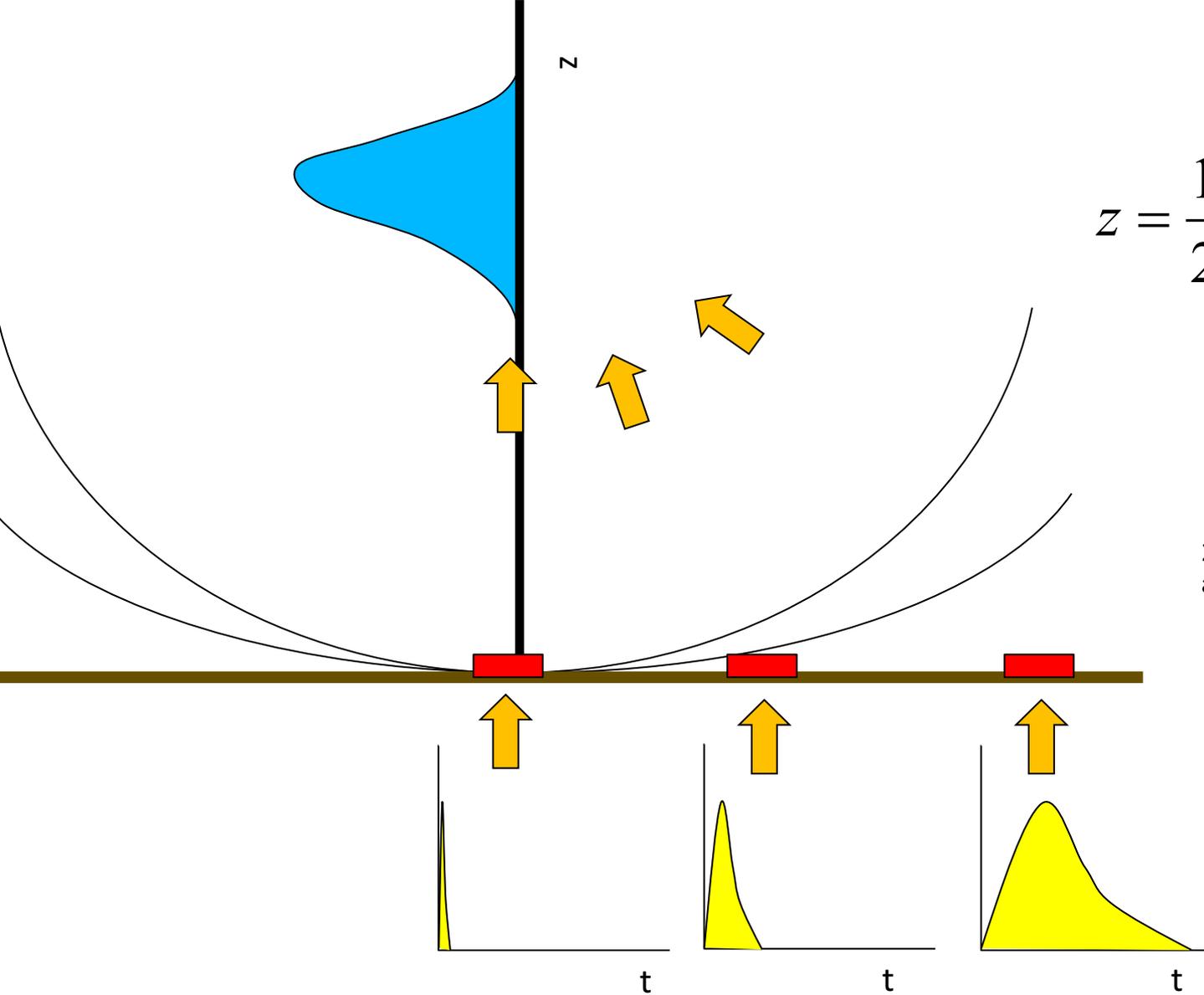
Arrival time
distributions

$$t = t_g + t_\varepsilon + t_B + t_{MS}$$





$$ct_g = \frac{1}{2} \frac{r^2}{z - \Delta} \quad (1)$$



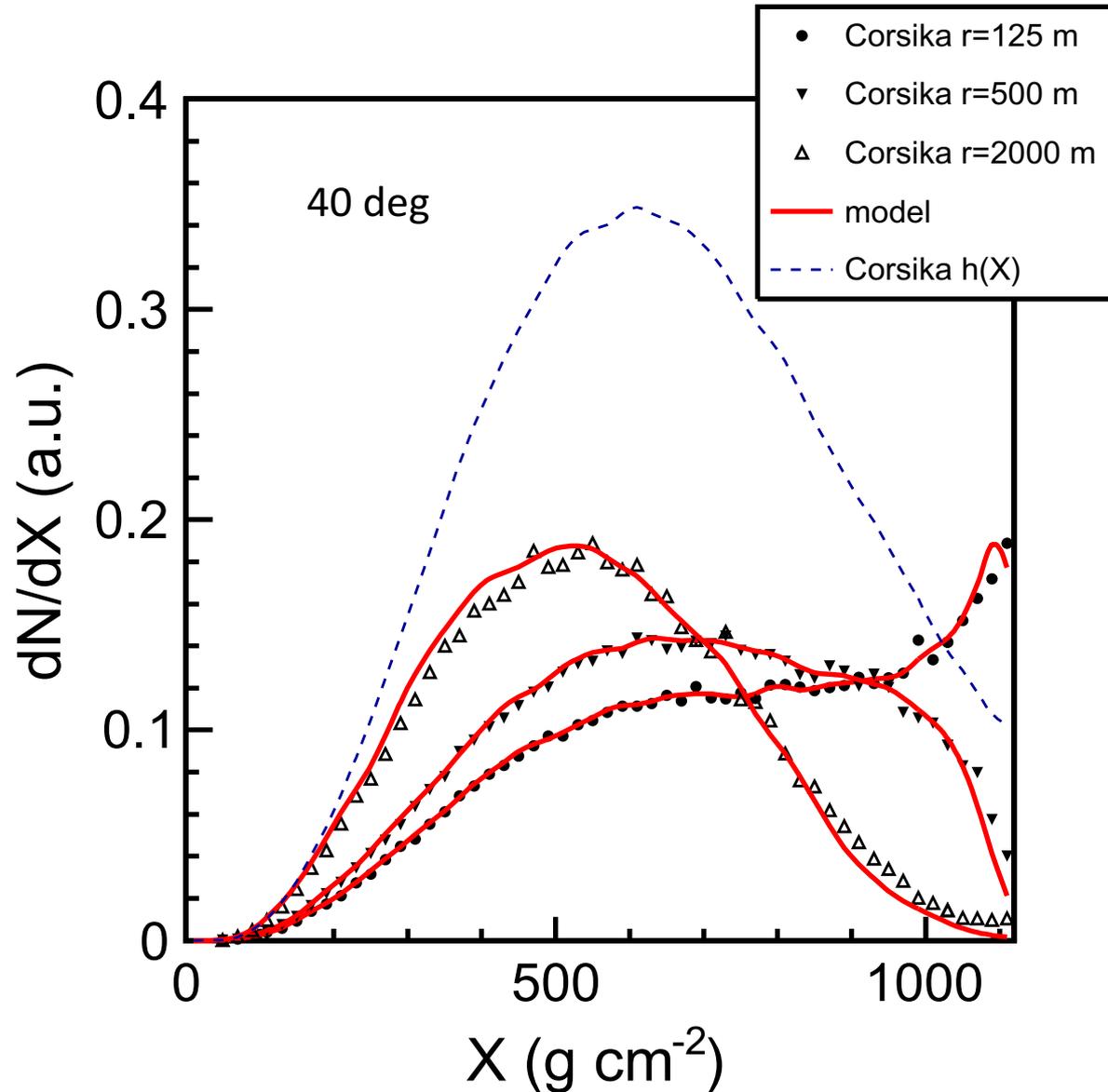
$$z = \frac{1}{2} \frac{r^2}{ct_g} + \Delta$$

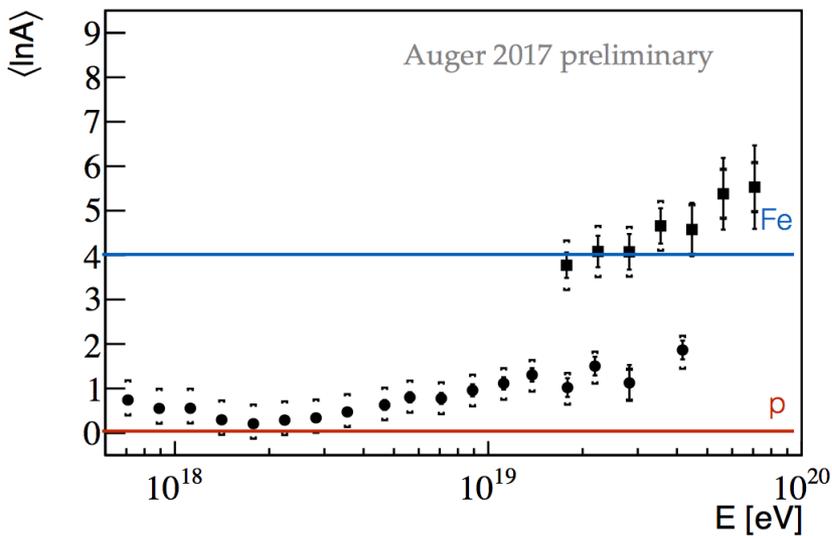
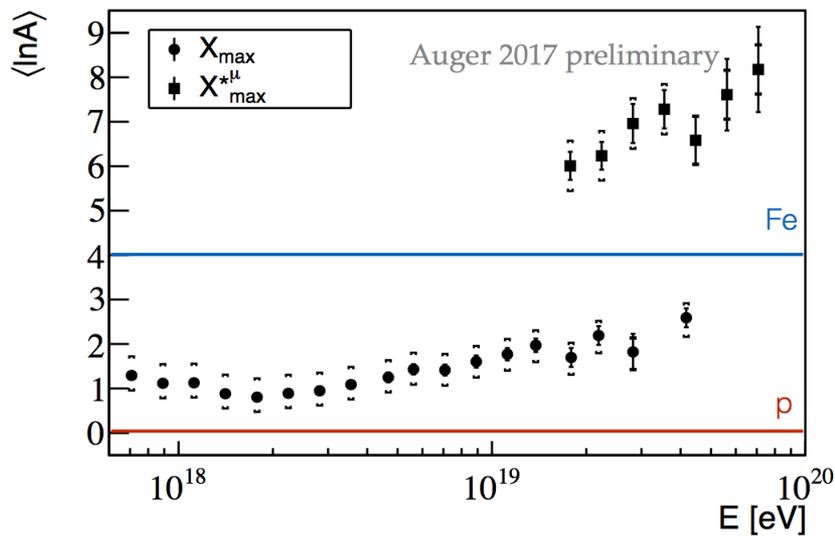
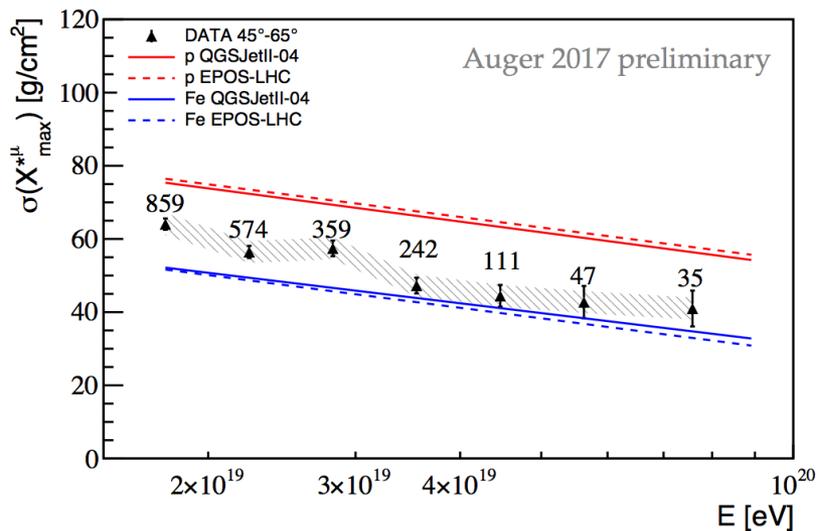
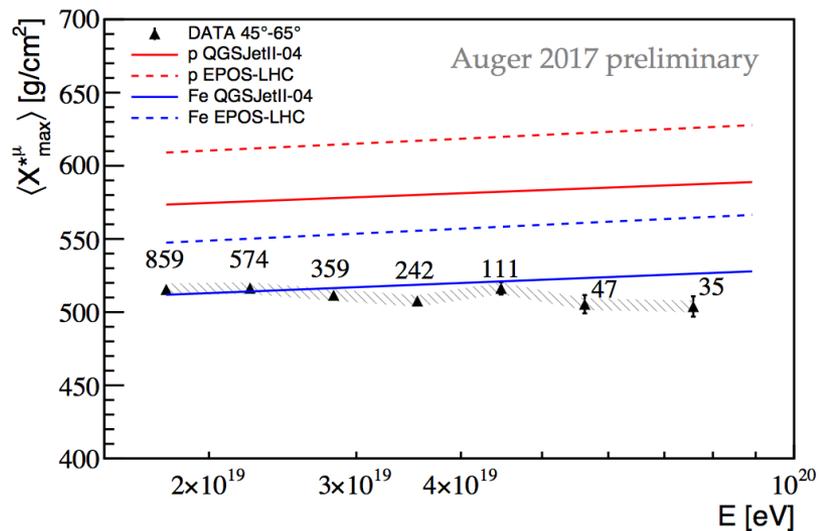
2nd order corrections are also accounted for:

$$t_g = t - t_\varepsilon(r, z)$$

Transforming back the experimental time distributions of each detector we recover the MPD

Apparent MPD depend on the observation conditions ($E_{\text{threshold}}$, distance to core, zenith angle)





Propagation summary table

Energy at production	5.0 GeV	10.0 GeV
Energy at ground	3.0 GeV	7.8 GeV
Probability of survival	0.67	0.84
Geometric delay	165 ns	165 ns
Kinematic delay	12 ns	2.3 ns
Geomagnetic delay	0.04 ns	0.01 ns
MS time delay	1.5 ns	0.8 ns
Geomagnetic lateral deviation	83 m	17 m
MS lateral smearing	~ 60 m	~ 35 m

Table 1: Summary of the different effects after propagation for a muon produced at $z=10$ km and arriving at $r=1000$ m at 60 deg zenith angle, and geomagnetic field strength perpendicular to the shower axis $B_{\perp} = 10 \mu\text{T}$ (MS stands for Multiple Scattering).

Muon Tomography

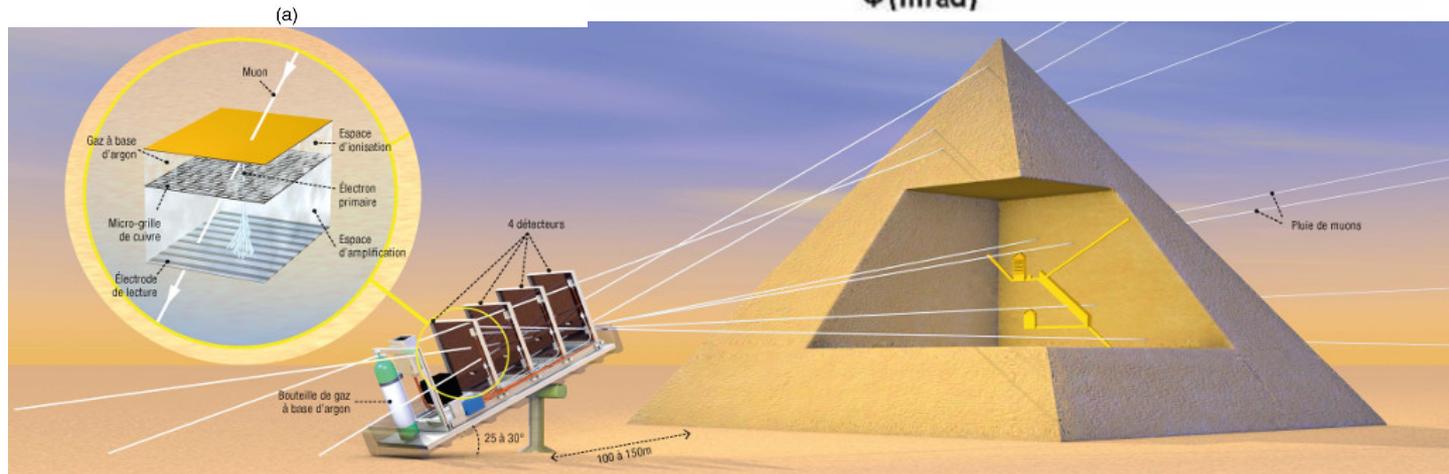
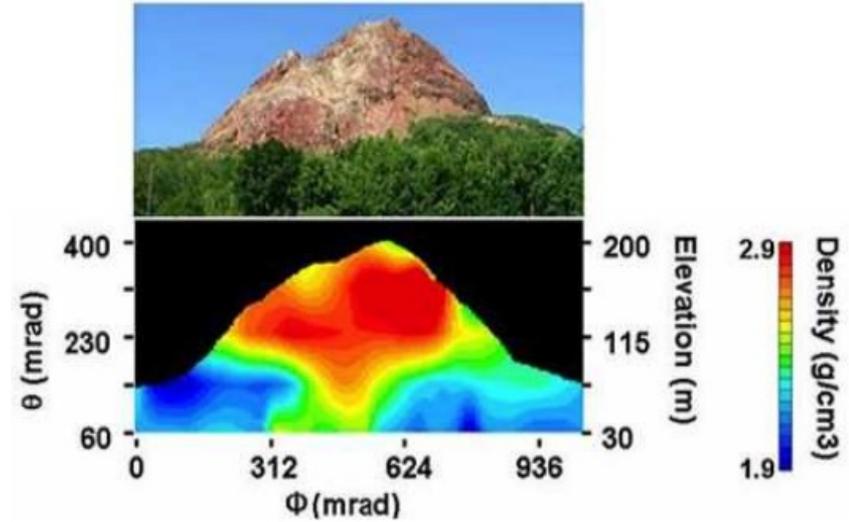
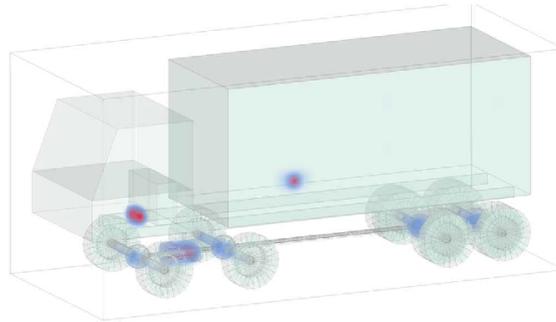
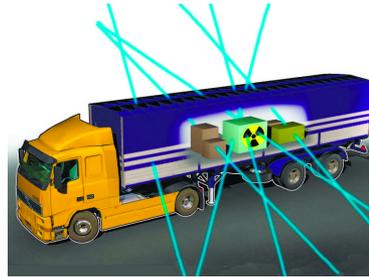
Image of large human and geological structures

Mining, search for cavities, aquifers, magma conduits.

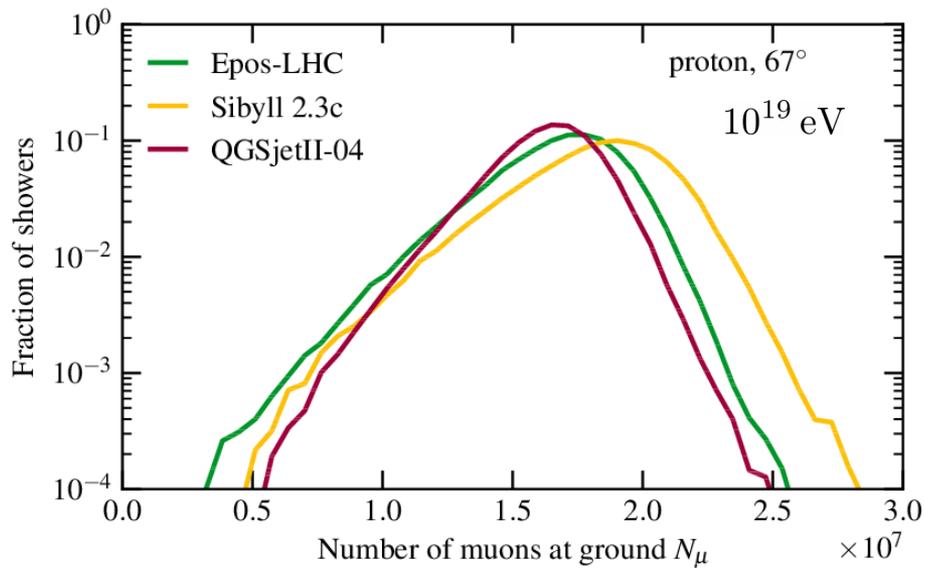
Nuclear Screening

Civil engineer applications

L. Cazon



Number of muons at ground



$$\frac{\sigma[N_\mu]}{N_\mu} \simeq 0.15$$

Understanding the fluctuations

- If Poisson statistics $\frac{\sqrt{10^7}}{10^7} = 10^{-3.5} \simeq 0.0003$

$$\frac{\sqrt{n.d.f.}}{n.d.f.} \simeq 0.15$$

- What is the *n.d.f.* to produce a ~15% fluctuation?

$$n.d.f. \simeq \frac{1}{0.15^2} \simeq 44$$

$$N_\mu = m_1 m_2 m_3 \dots m_n \qquad m_i = \frac{N_i^\pi}{N_{i-1}^\pi}$$

$$\delta(N_\mu) = \delta(m_1) + \delta(m_2) + \dots + \delta(m_n)$$

$$\delta(x) = \frac{\sigma(x)}{x}$$

$$\sigma(m_i) = \frac{\sigma}{\sqrt{N_{i-1}^\pi}}$$

Fluctuations are dominated by the first interactions as the number of participants increase with generation number and the average stabilizes.

corelations of N_μ

	N_μ (N_μ^{prod})		
	EPOS-LHC	SIBYLL 2.3C	QGSJET II-04
α_1	0.79 (0.82)	0.76 (0.78)	0.75 (0.78)
E_{had}/E	0.67 (0.66)	0.67 (0.66)	0.53 (0.52)
m_1	0.15 (0.21)	0.17 (0.22)	0.22 (0.27)
κ_{inel}	-0.15 (-0.08)	-0.11 (-0.07)	-0.04 (0.00)
m_1/m_{tot}	0.16 (0.18)	0.12 (0.13)	0.19 (0.18)
X_0	0.23 (0.12)	0.21 (0.12)	0.28 (0.19)
ϵ^*	-0.01 (-0.08)	-0.12 (-0.17)	-0.09 (-0.14)

$$x_L^i = E_i/E_0 \quad E_{\text{had}} = E_0 \sum_i x_L^i$$

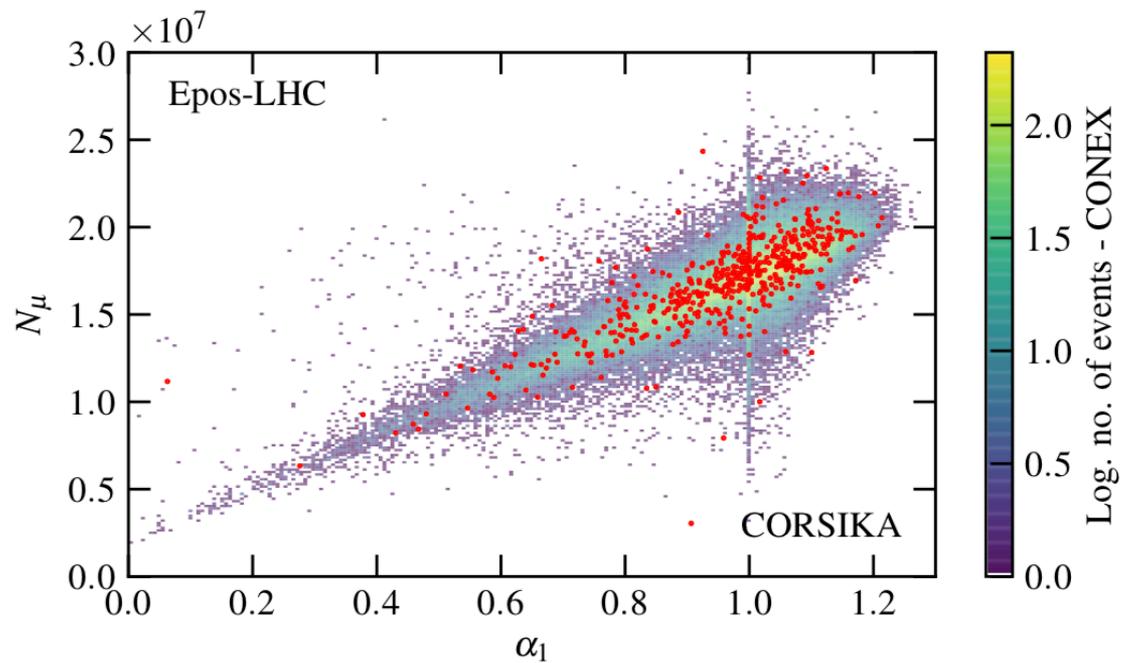
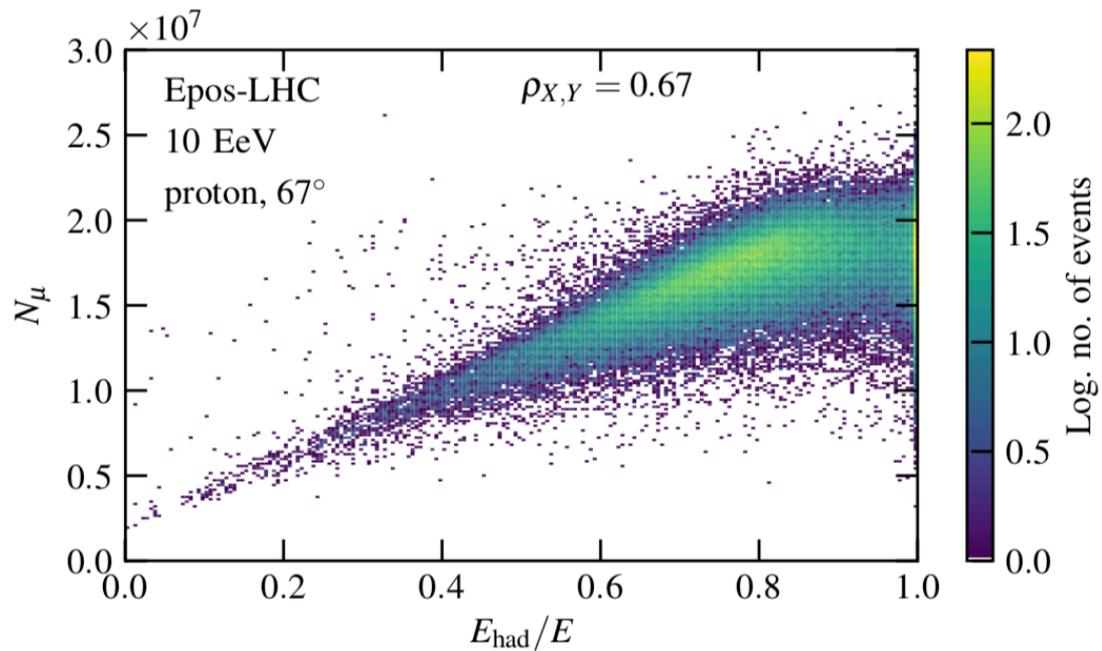
$$\langle N_\mu \rangle = a E_0^\beta \begin{array}{l} \text{HM, MC,} \\ \text{measurement,} \\ \text{CE} \end{array}$$

$$N_\mu = \sum_i N_\mu^i \approx \sum_i \langle N_\mu(E_i) \rangle = a \sum_i (x_L^i)^\beta$$

$$\alpha = \sum_i^{m_{\text{had}}} (x_L^i)^\beta$$

$$\beta \rightarrow 1 \quad \alpha = E_{\text{had}}/E_0$$

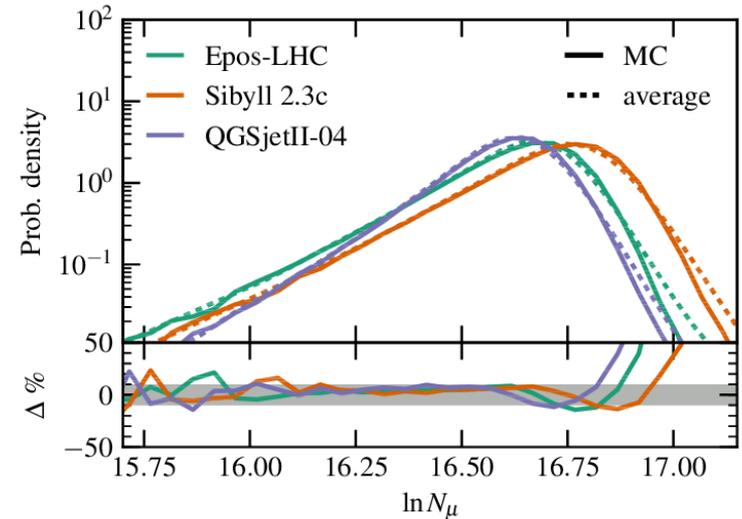
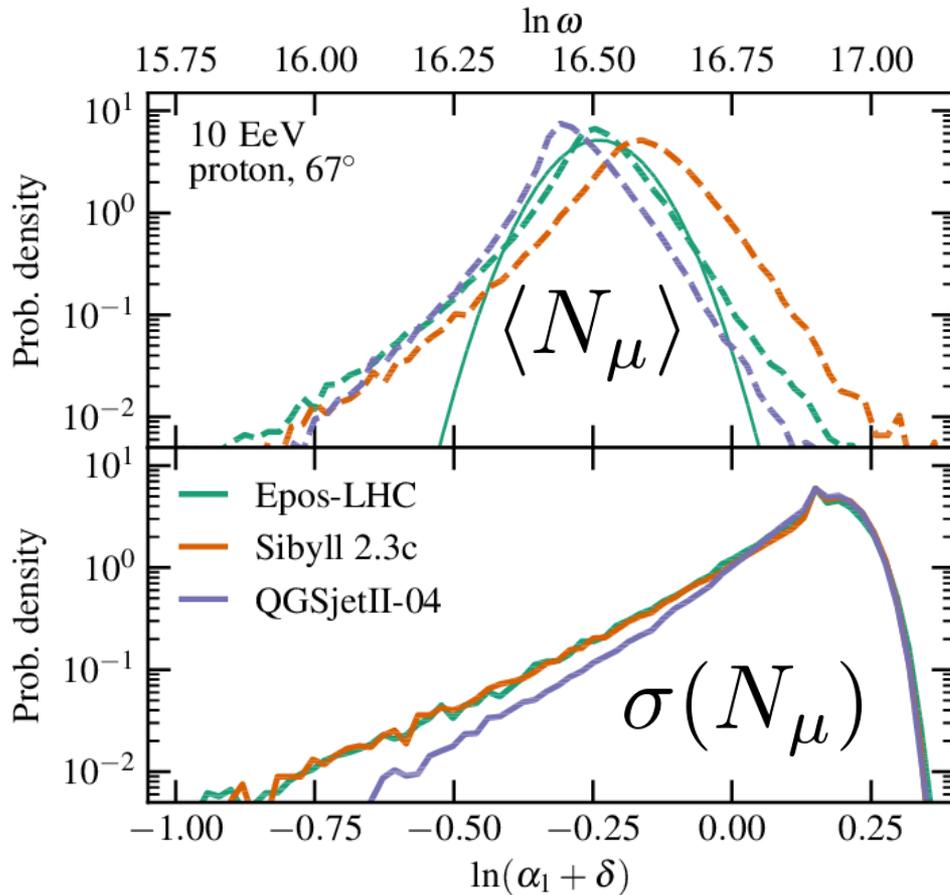
$$\beta \rightarrow 0 \quad \alpha = m_{\text{had}}$$



$$N_\mu = (\alpha_1 + \delta) \cdot \omega .$$

$$\ln N_\mu = \ln(\alpha_1 + \delta) + \ln \omega$$

$$X_{\max} = X_1 + \Delta X$$



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- Mismatch on $\langle N_{\mu} \rangle$ from models comes from low energy

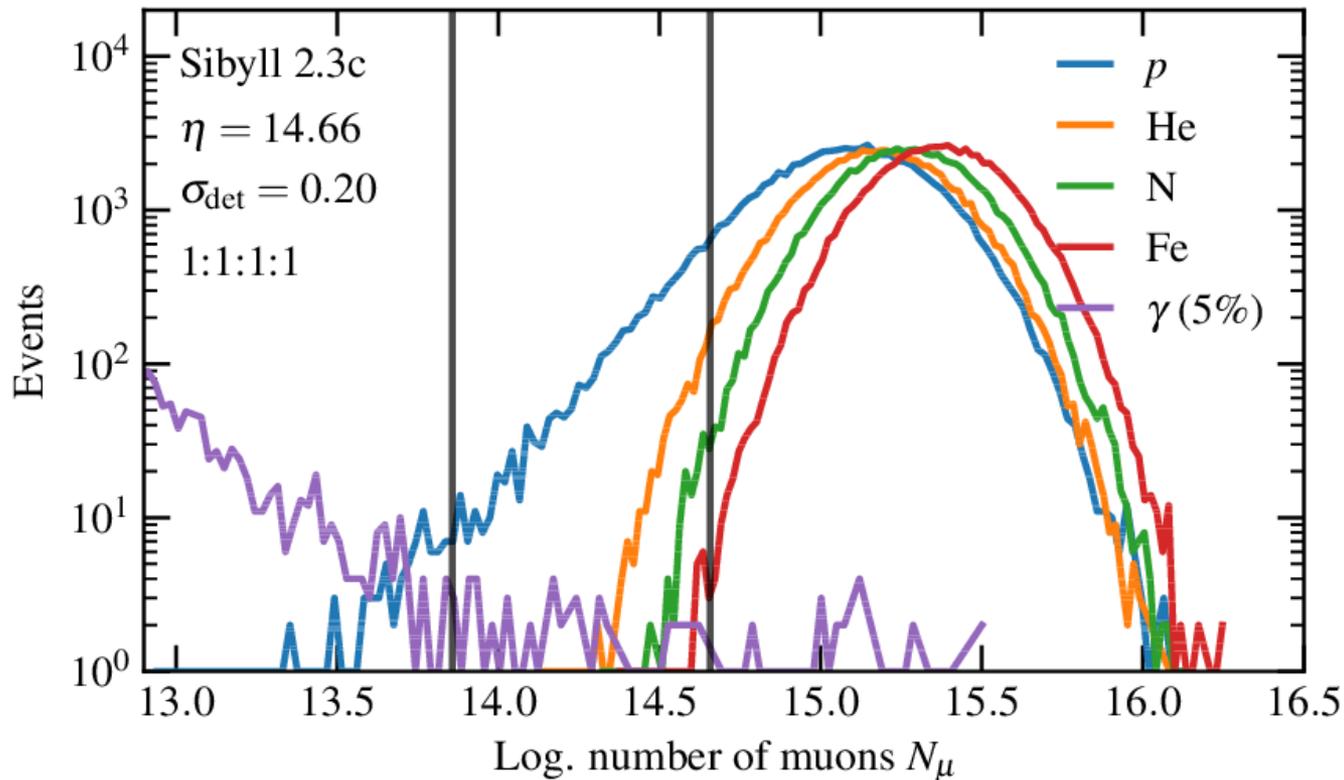
$$N_{\mu} = \alpha_1 \alpha_2 \alpha_3 \dots \alpha_n \frac{E_0}{\xi_c^{\pi}} = \alpha_1 \cdot \omega$$

- A 5% constant deficit along 6 generations can produce

$$\alpha_1 = 0.95 \quad \omega = 0.95^5 = 0.77$$

- due to accumulation in sucesive generations

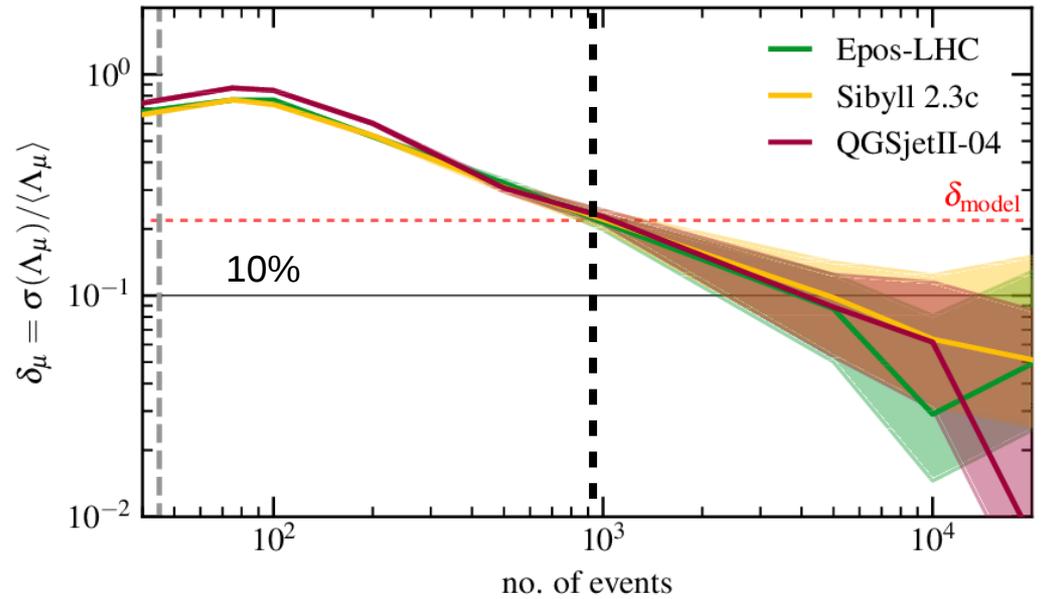
- Nmu shape determined by 1st interaction
- First interaction only differs in the low-Nmu tail
 - Experimentally accessible
 - Even for mixed composition scenarios



1:1 p-He ratio: ~1000 events

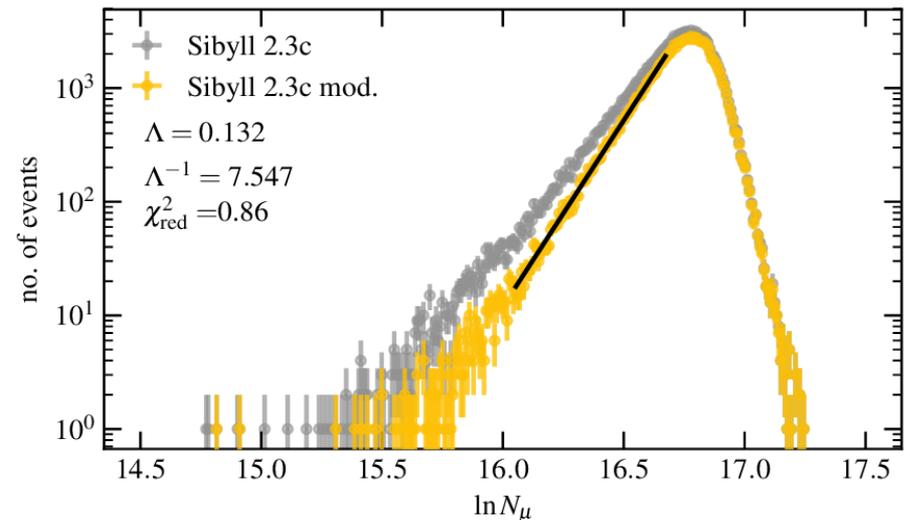
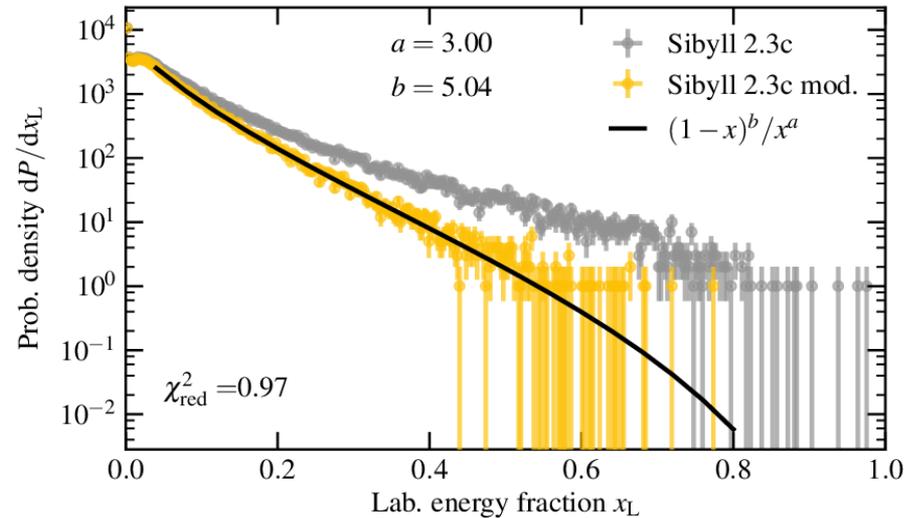
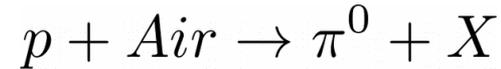
1:2 p-He ratio: ~5k events

Sensitive to model difference



- low N_{mu} tail relates with the high x_L of π^0 production
- Multiparticle production measurement on the 1st interaction (p-Air)

Inclusive production cross section

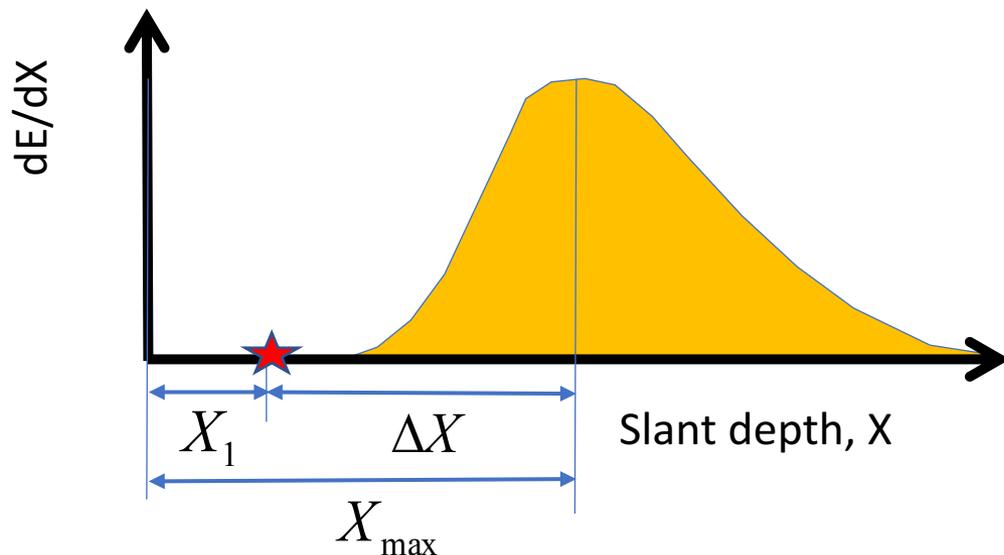


p-Air cross section

$$\sigma_{\text{int}} = \frac{\langle m_{\text{air}} \rangle}{\lambda_{\text{int}}}$$

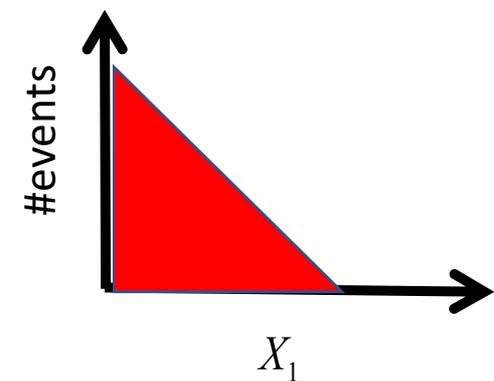
$$\frac{dp}{dX_1} = \frac{1}{\lambda_{\text{int}}} e^{-X_1/\lambda_{\text{int}}}$$

Longitudinal Shower profile

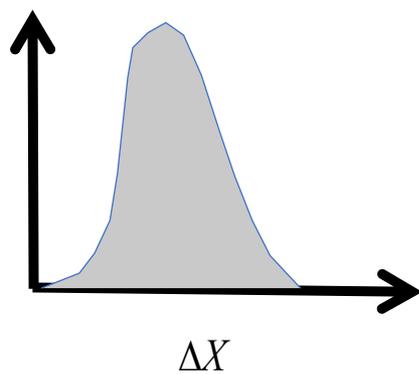


\Rightarrow Tail of X_{max} -Distribution

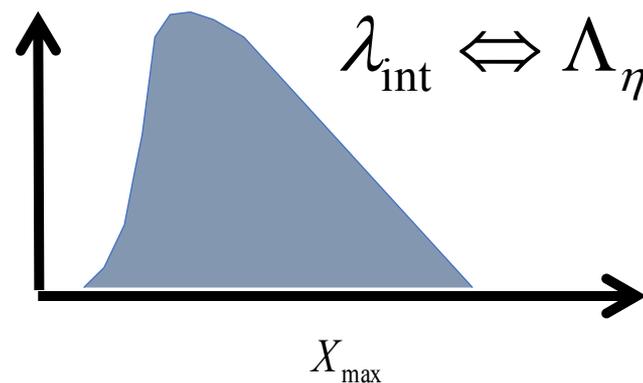
$$dN/dX_{\text{max}} \propto \exp(-X_{\text{max}}/\Lambda_{\eta})$$



\oplus

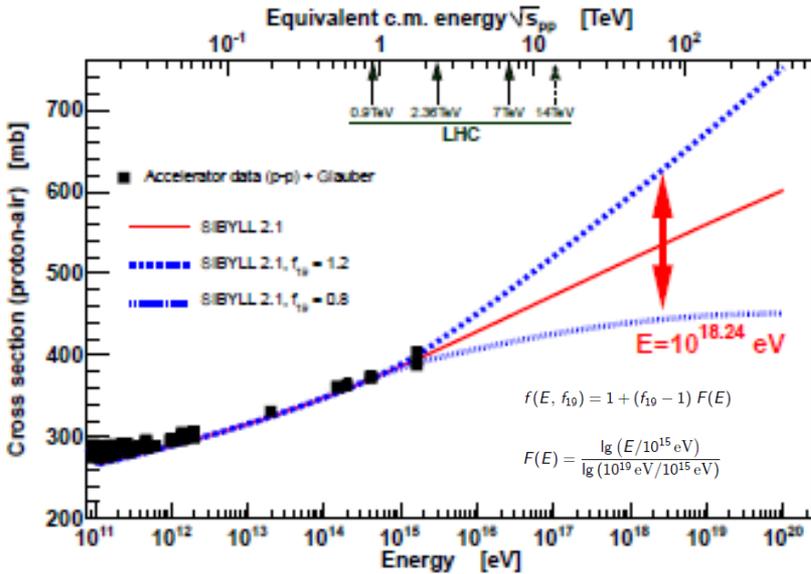


$=$



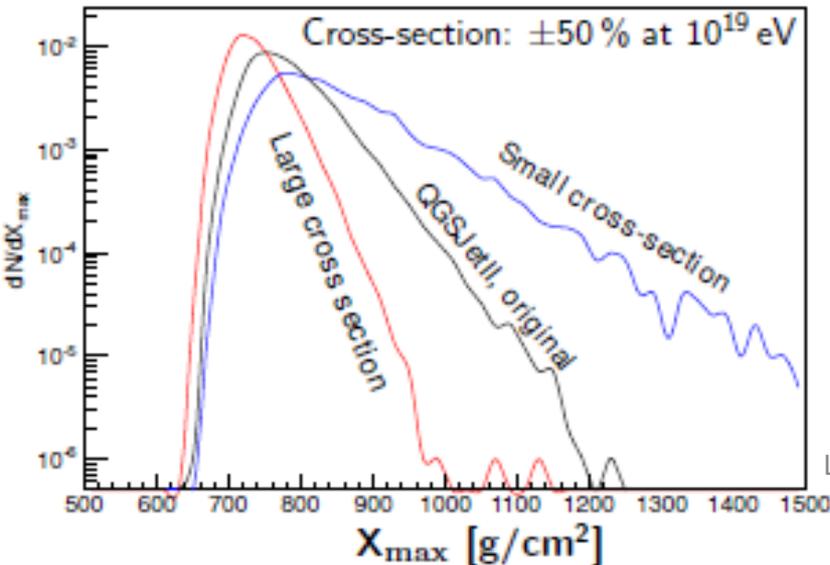
Method

- Continuous reparameterization of cross section in MC

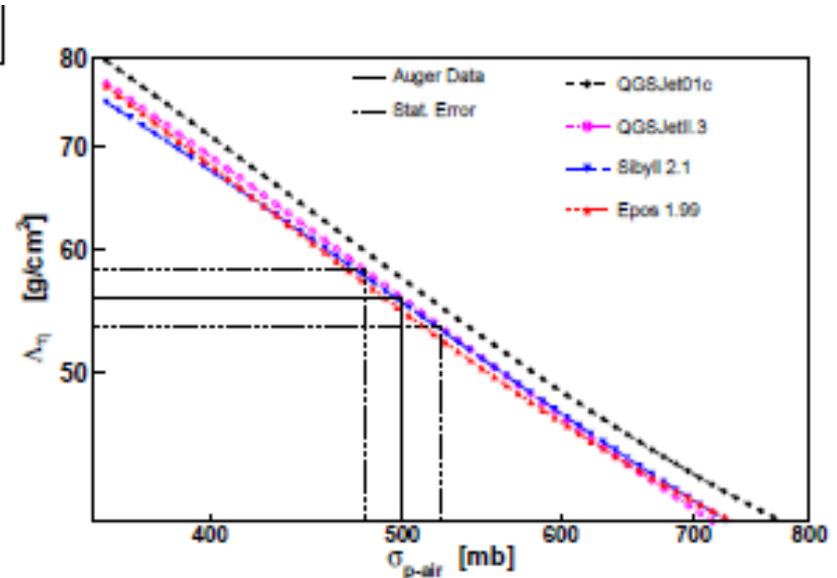


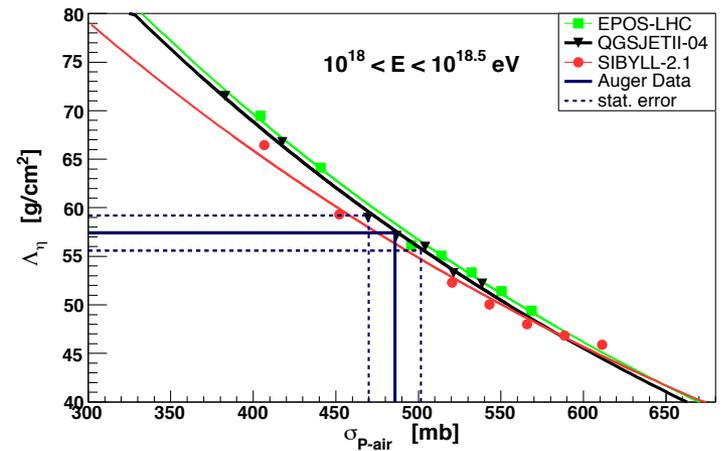
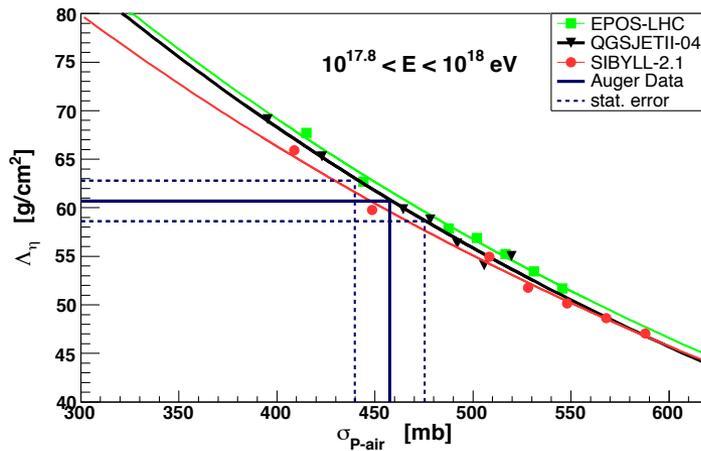
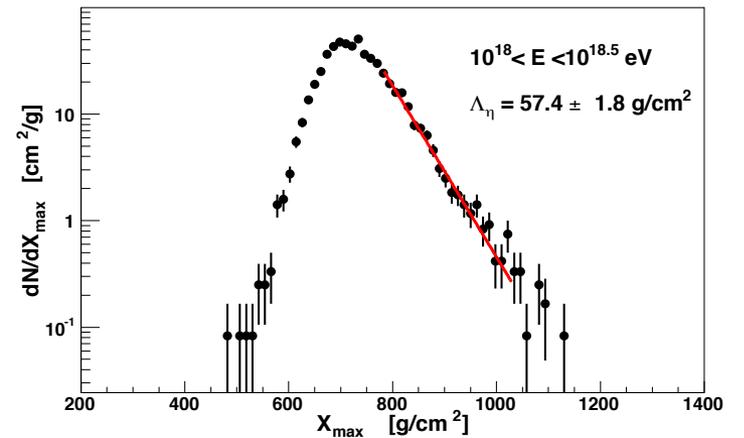
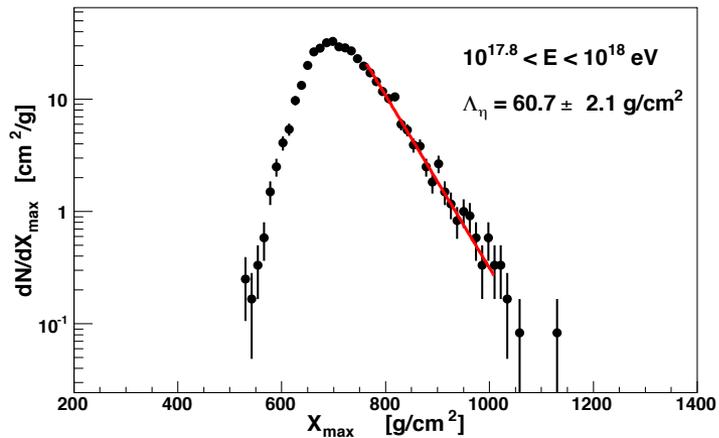
- Simulation of X_{\max} distribution
 - different rescalings
 - different models

- $\Lambda_{\eta} \leftrightarrow \sigma_{p\text{-Air}}$ conversion



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UHECR2018, Pai



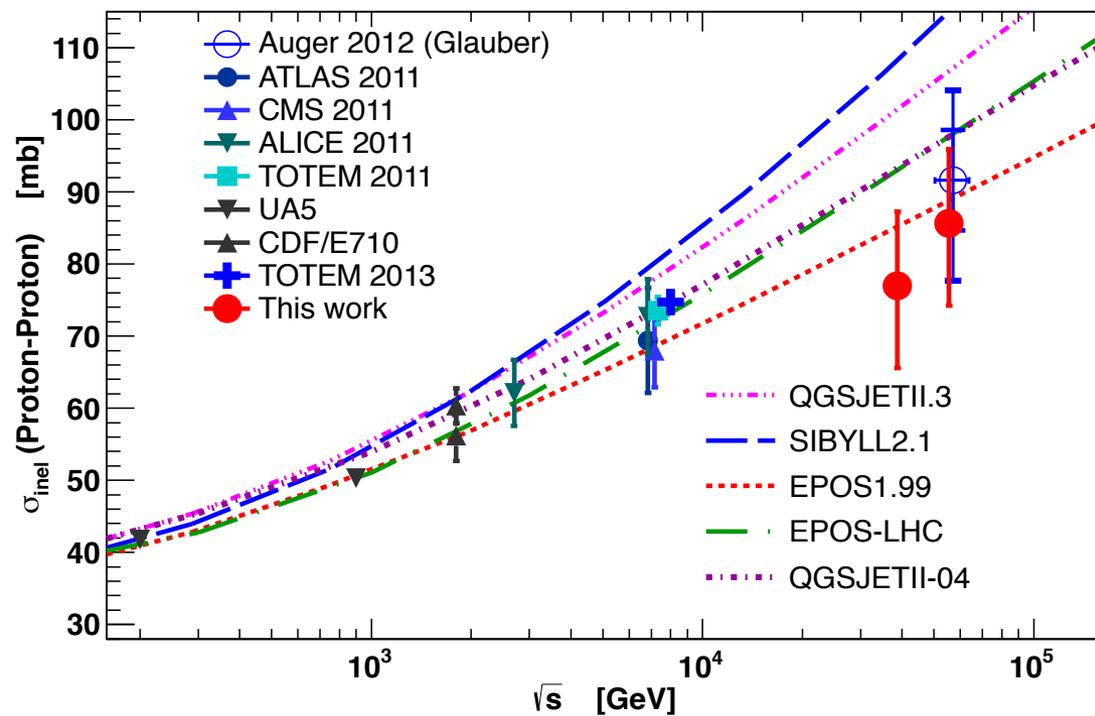
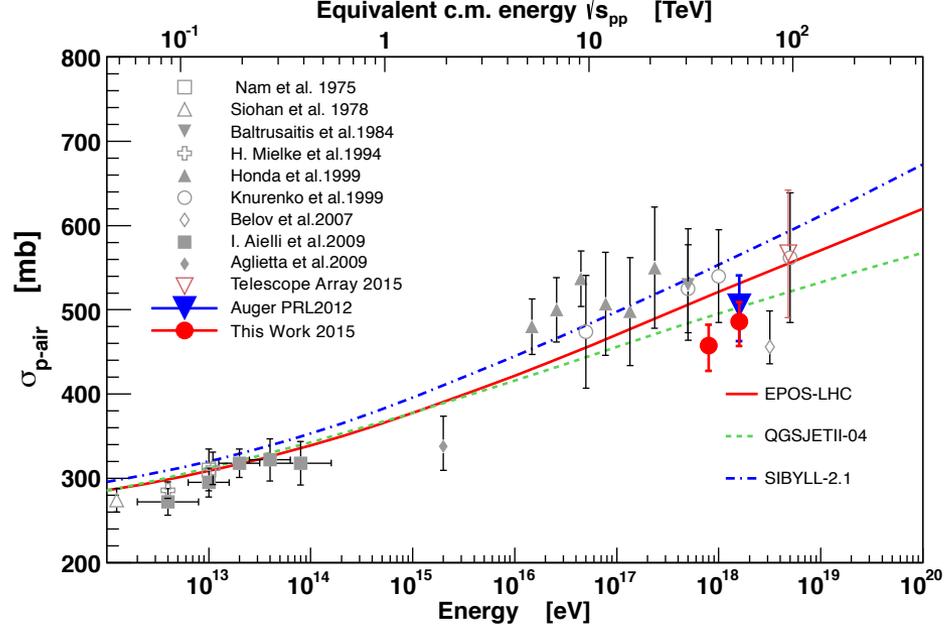


$10^{17.8} - 10^{18} \text{ eV}$ $10^{18} - 10^{18.5} \text{ eV}$

$\sigma_{p\text{-air}}$ uncertainties

Λ_η , systematic uncertainties (mb)	13.5	14.1
Hadronic interaction models (mb)	10	10
Energy scale uncertainty, $\Delta E/E = 14\%$ (mb)	2.1	1.3
Conversion of Λ_η to $\sigma_{p\text{-air}}$ (mb)	7	7
Photons (mb)	4.7	4.2
Helium, 25% (mb)	-17.2	-15.8
Total systematic uncertainty on $\sigma_{p\text{-air}}$ (mb)	+19/-25	+19/-25

Possible He contamination is the main source of systematic uncertainty. 25% He maximum contamination assumed for sys. uncertainties



Results, σ_{pp}^{inel} in mb

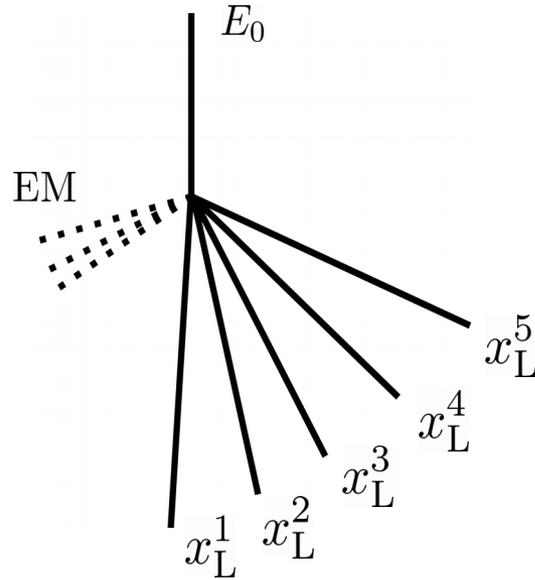
- Lower energy point
 $76.95 \pm 5.4(\text{stat}) + 5.2/-7.2(\text{syst}) \pm 7(\text{glauber})$
 at $\sqrt{s_{pp}} = 38.7 \pm 2.5$ TeV
- Higher energy point
 $85.62 \pm 5(\text{stat}) + 5.5/-7.4(\text{syst}) \pm 7.1(\text{glauber})$
 at $\sqrt{s_{pp}} = 55.5 \pm 3.6$ TeV

The End

Particle	mc^2 (MeV)	$c\tau$ (m)
μ^\pm	105.658357 ± 0.000005	658.654 ± 0.012
π^\pm	139.57018 ± 0.00035	7.8045 ± 0.0015
K^\pm	493.677 ± 0.016	3.713 ± 0.011

$$\rho_{air} \simeq 1.2 \cdot 10^{-3} \text{ g cm}^{-3}$$

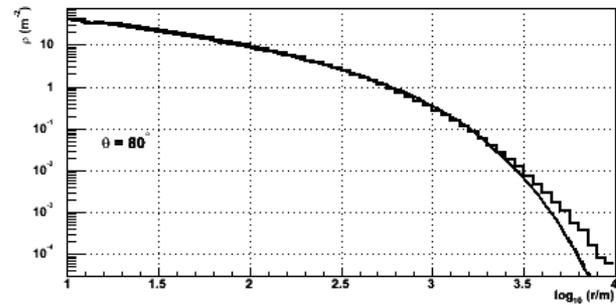
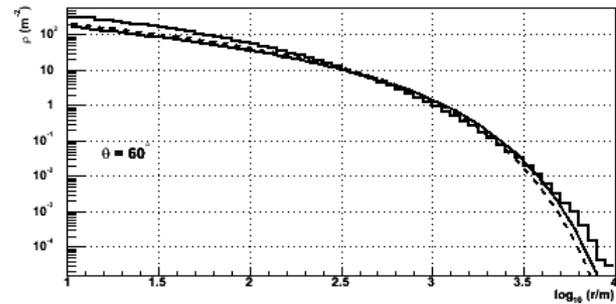
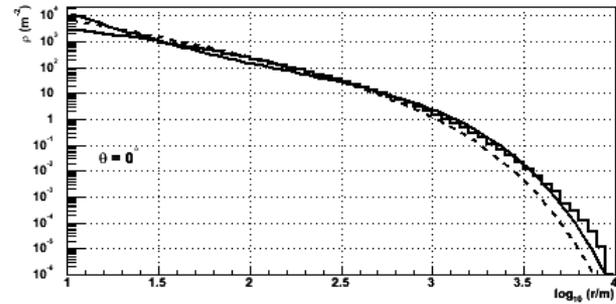
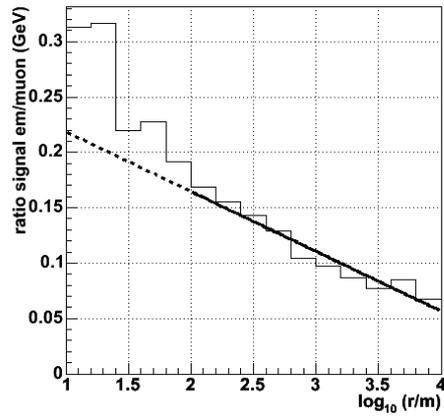
What determines had. Energy? (tail)

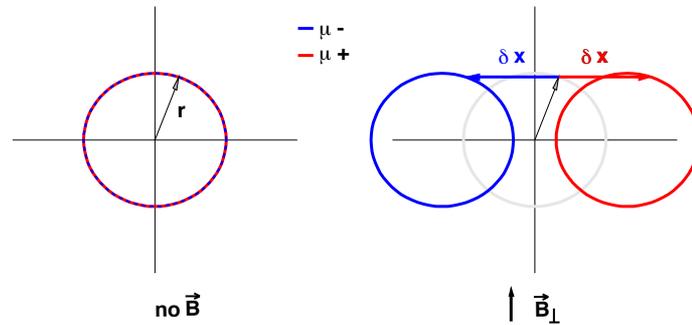


$$E_{\text{had}}/E_0 = \sum_i x_L^i = (1 - E_{\text{EM}}/E_0)$$

\uparrow
 π^0

Signal ratio and LDF





$$\delta x = R \left[1 - \sqrt{1 \mp \left(\frac{z}{R} \right)^2} \right] \simeq \pm \frac{1}{2} \frac{z^2}{R} = \pm \frac{1}{2} z^2 \frac{ceB_\perp}{E}$$

$$\frac{d^2 N_{\delta x}}{dX dE_i} \simeq \pm \frac{1}{2} \frac{z e B_\perp}{\hbar} r = \pm \alpha_B r f_1(E_i)$$

$$X_{\max} \propto n_c \lambda_r \ln(2) = \lambda_r \ln\left(\frac{E_0}{\xi_c^e}\right)$$

$$N_\mu = \left(\frac{E_0}{\xi_c^\pi}\right)^\beta$$

$$X^\mu_{\max} \propto \lambda_i n_c = \lambda_i 0.85 \log_{10}\left(\frac{E_0}{\xi_c^\pi}\right)$$

$$\beta = \frac{\ln(1 + N_{ch})}{\ln\left(\frac{1 + N_{ch}}{1 - 3/2\kappa}\right)} \approx 1 - 0.14\kappa$$

...

Examples of how certain X_{\max} , N_μ and X^μ_{\max} behaviour can be understood in terms of simple physics