Ground-base Astrophyics Experimental methods

racow School of Theoretical Physics,
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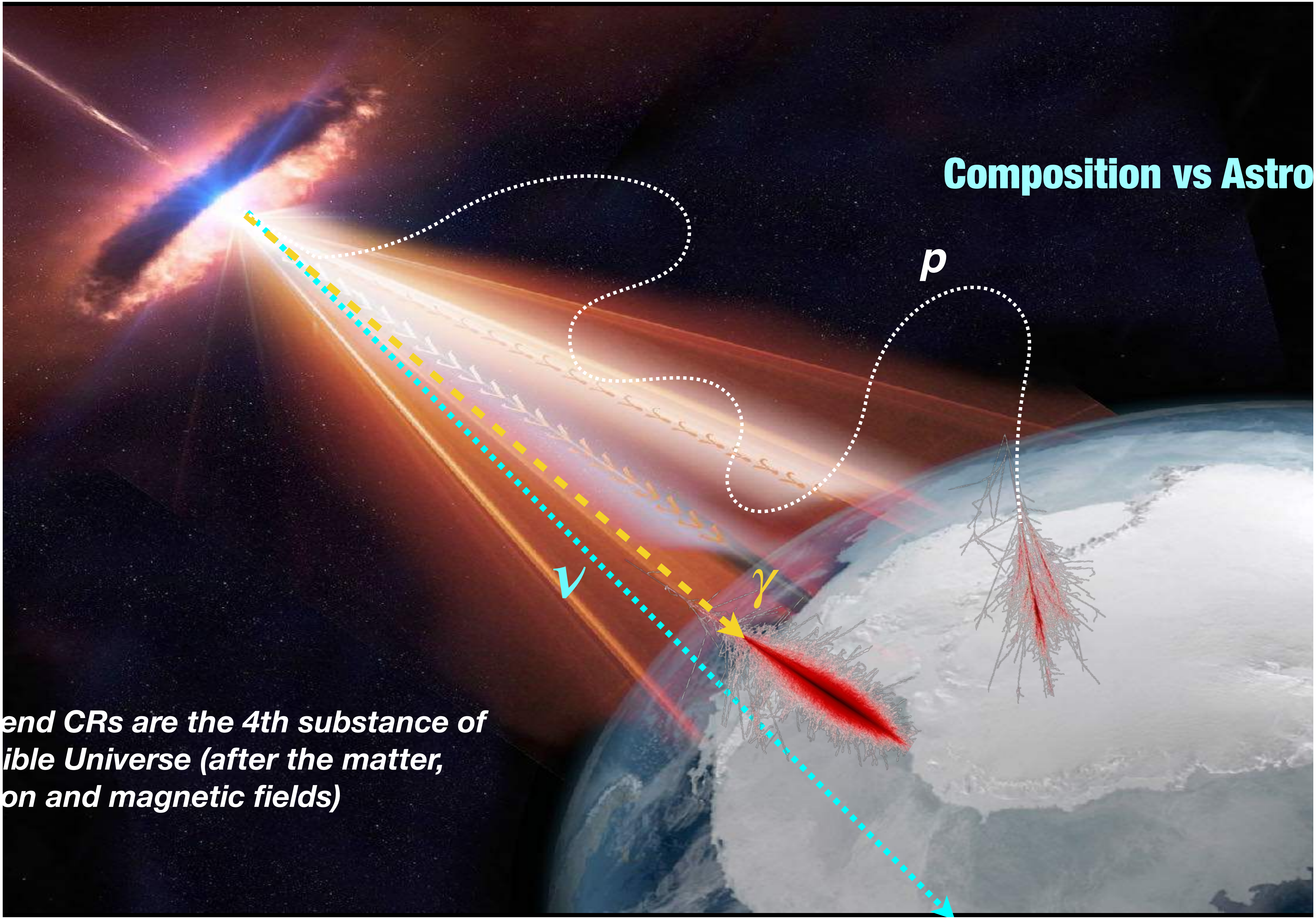

Composition vs Astro
p
ν
γ
end CRs are the 4th substance of
ible Universe (after the matter,
on and magnetic fields)

t we know of about cosmic rays

ll particle spectrum span over more than 14 of magnitude with an exponential decrease

leration and propagation folded!

propagate through the

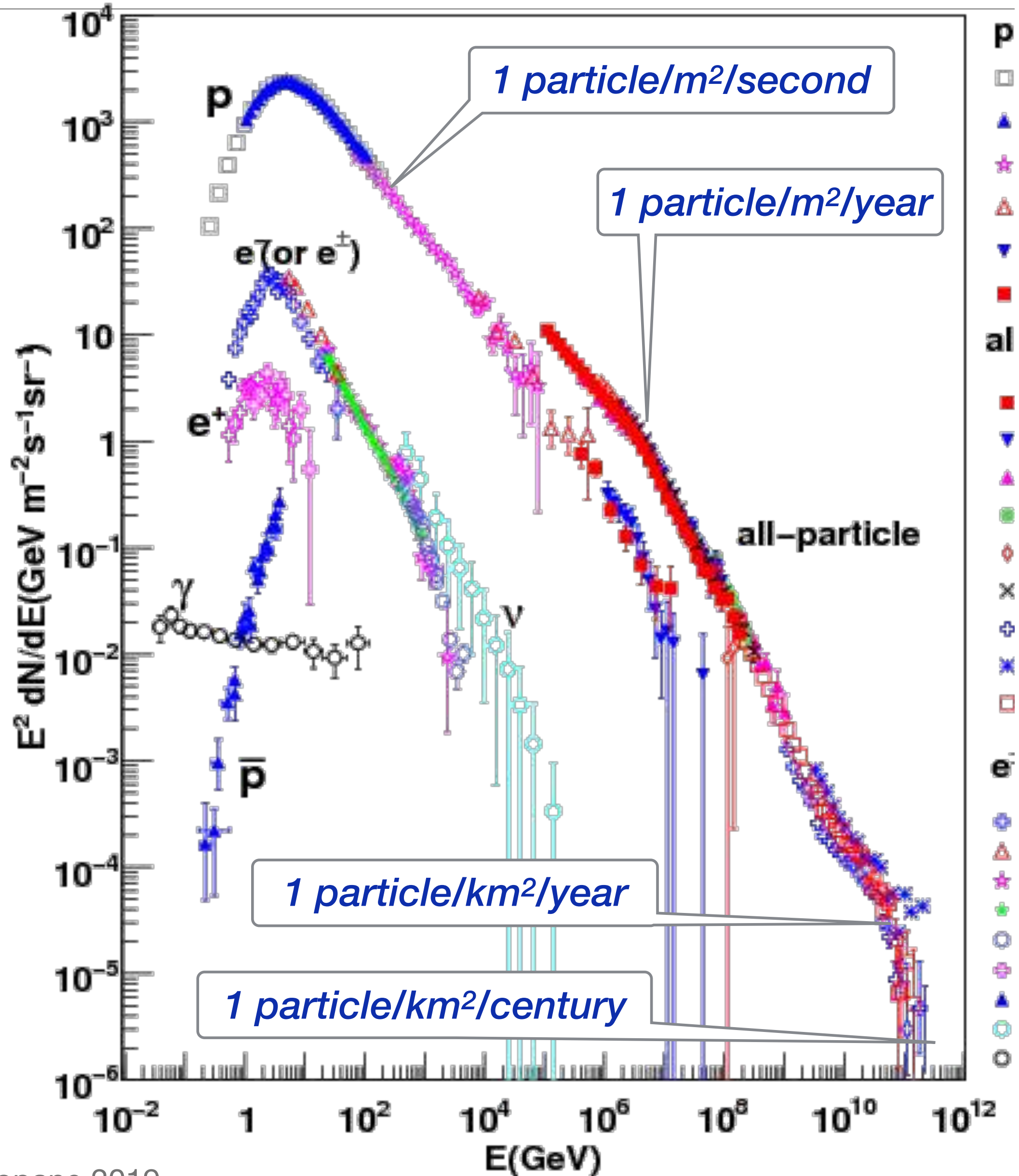
-InterStellar Matter (ISM)

- InterGalactic Magnetic (IGM)

3 (Cosmic Microwave Background)

Extragalactic Background Light

res: KNEE & ANKLE, GZK cut-off



What we can learn from γ-ray

amma ray flux composition (0.1-1000 GeV)

berposition of resolved point and diffuse sources, and of background diffuse emission
actic/extragalactic origin

E & ang. res, E range and threshold, n. of telescopes, waveform

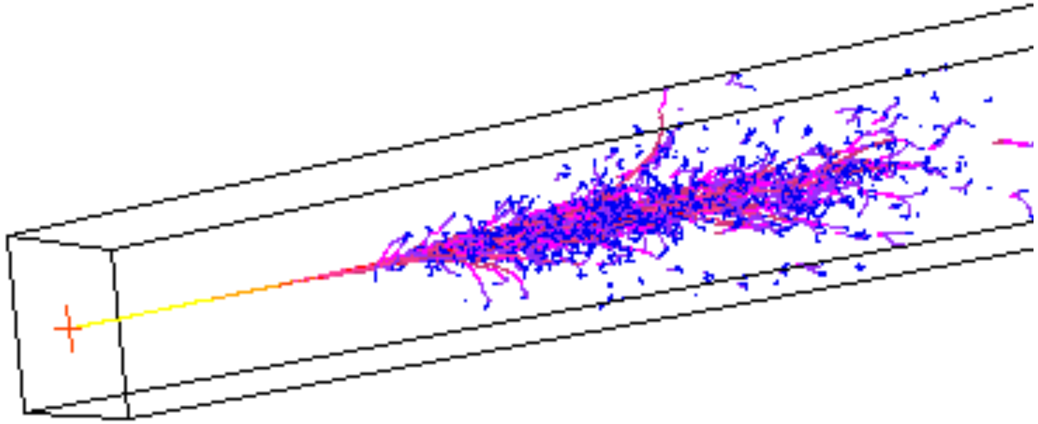
Stability of PSF over FoV
Large FoV, Duty Cycle

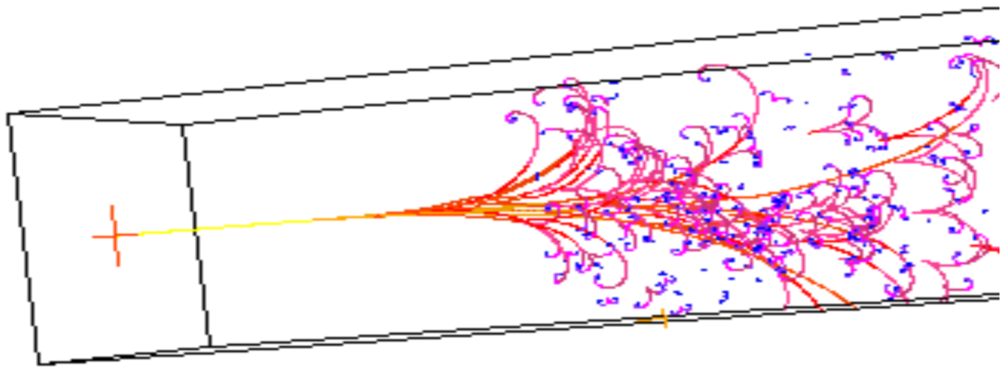
$$(E,\Omega) = \sum_{j\in\{\mathrm{Galactic}\}} \phi_j(E,\Omega_j) + \phi^{\mathrm{Galactic}}_{\mathrm{diffuse}}(E,\Omega)$$

$$+ \sum_{j\in\{\mathrm{Extragalactic}\}} \phi_j(E,\Omega_j) + \phi^{\mathrm{Extragalactic}}_{\mathrm{diffuse}}(E,\Omega)$$

$$\phi^{\mathrm{Extragalactic}}_{\mathrm{diffuse}}(E,\Omega) = \phi^{\mathrm{Extragalactic}}_{\mathrm{unresolved\ sources}}(E) + \phi^{\mathrm{Extragalactic}}_{\mathrm{diffuse}}(E,\Omega)$$

hysics of Shower





Interaction with Matter of charged particle - Bethe-Block

Electron Energy Loss

- *Radiative Loss*

Photon Energy Loss

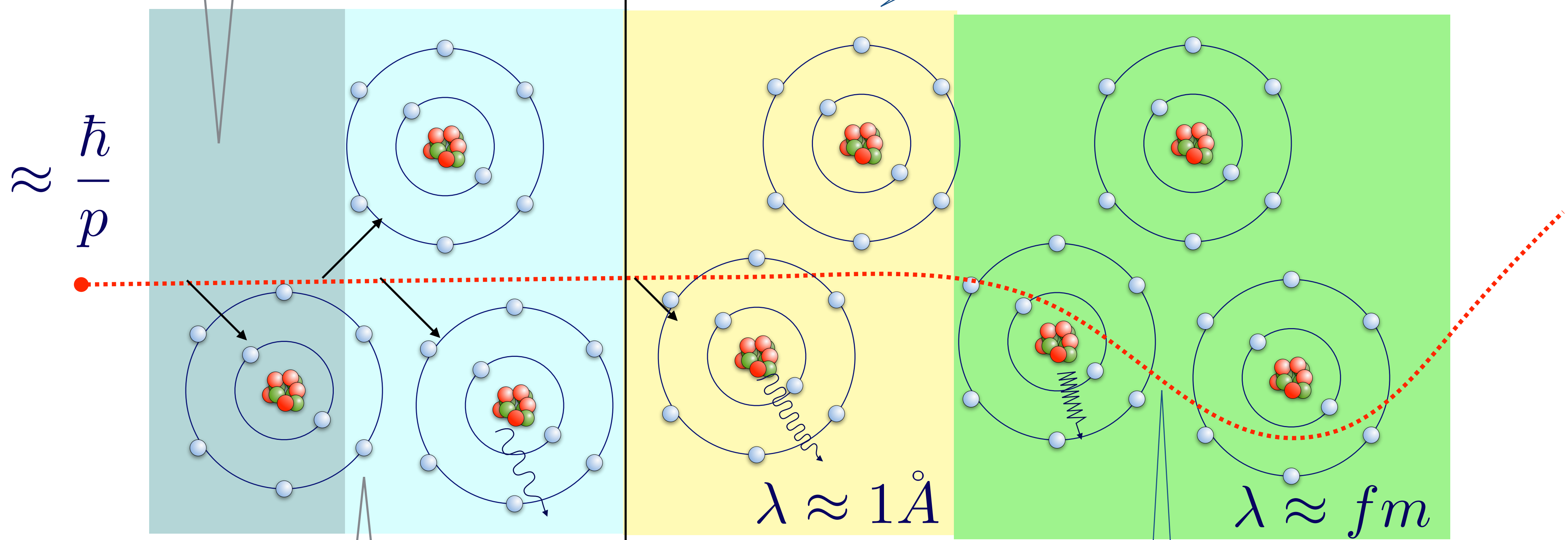
Electromagnetic Shower Model

Hadronic Shower Model

tromagnetic Interaction of (charged) Particles with Matte

Ionization losses
The incoming particle loses energy interacting with atoms, which are excited or ionized.

kov Radiation
ne particle's velocity is larger than the velocity of light in the
the resulting EM shockwave manifests itself as.



n radiation
particle crosses the boundary between two media, there
ability of the order of 1% to produced and X ray photon.

Interaction with the atomic nucleus.
The particle is deflected (scattered) causing multiple
of the particle in the material.
During this scattering a Bremsstrahlung photon can

raction with matter - Bethe Block Formula

iclude also quantum mechanics and relativity we arrive at a more complete formula

Validity $0.5 < \beta < 500 \quad m > m_\mu$

$$-\left\langle \frac{dE}{dx} \right\rangle = Kz^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \left(\frac{2m_e \gamma^2 \beta^2 c^2 T_{max}}{I_0^2} \right) - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

z: Charged of incident particlee

m: Mass of incident particle

Z: Charge number of the medium

A: Atomic mass of the medium

I_0: Mean excitation energy of the medium

δ: Density correction

$$K = 4\pi N_A r_e^2 m_e c^2 = 0.307 \, \frac{MeV \cdot cm^2}{g}$$

$$T_{max} = \frac{2m_e c^2 \beta^2 \gamma^2}{1+2\gamma m_e/m + (m_e/m)^2}$$

$$2\gamma m_e/m << 1$$

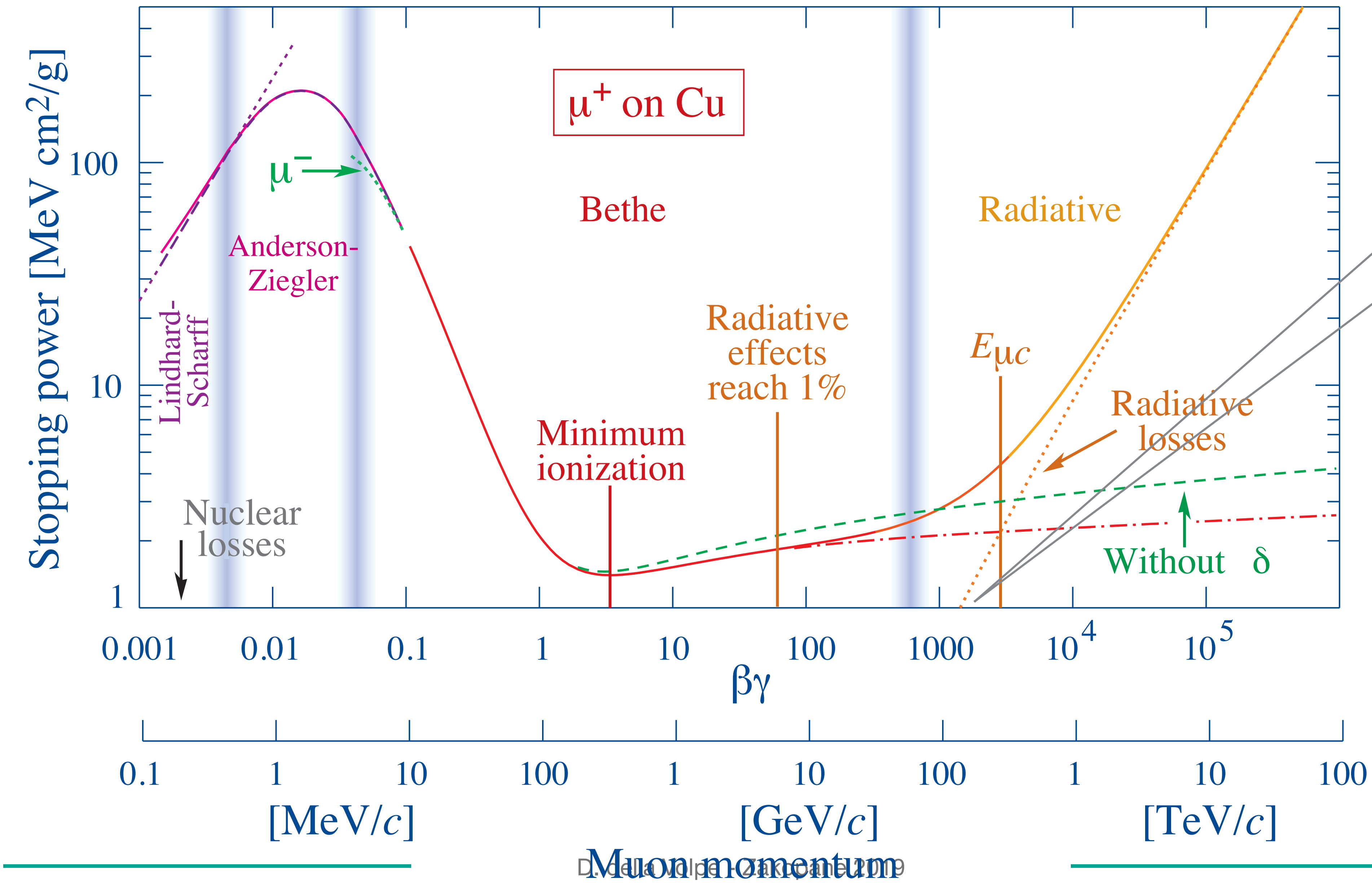
$$T_{max} = 2m_e c^2 \beta^2 \gamma^2$$

$$N_A = 6.022 \cdot 10^{23}$$

$$r_e = \frac{e^2}{4\pi\varepsilon m_e c^2}$$

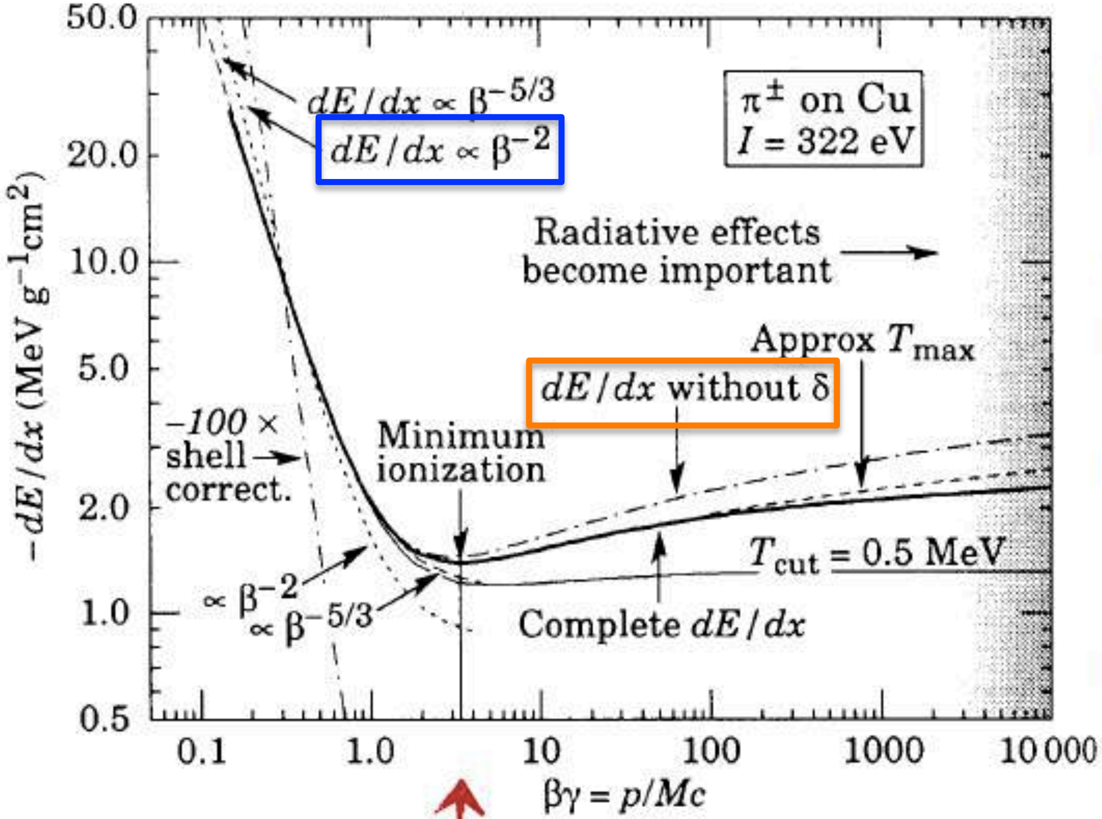
$$m_e = 511 \text{ keV}$$

rgy Loss in a Plot



A 10
$\beta\gamma$=
Electro
radiative

erstanding the Bethe-Bloch



$\beta\gamma = 3\text{-}4$

$$\frac{dE}{dx} \propto \frac{Z^2}{\beta^2} \ln\left(a\beta^2\gamma^2\right)$$

Minimum ionizing particles (MIP): $\boxed{\beta\gamma = 3\text{-}4}$

dE/dx falls $\boxed{\sim \beta^{-2};}$ kinematic factor
[precise dependence: ~ $\beta^{-5/3}$]

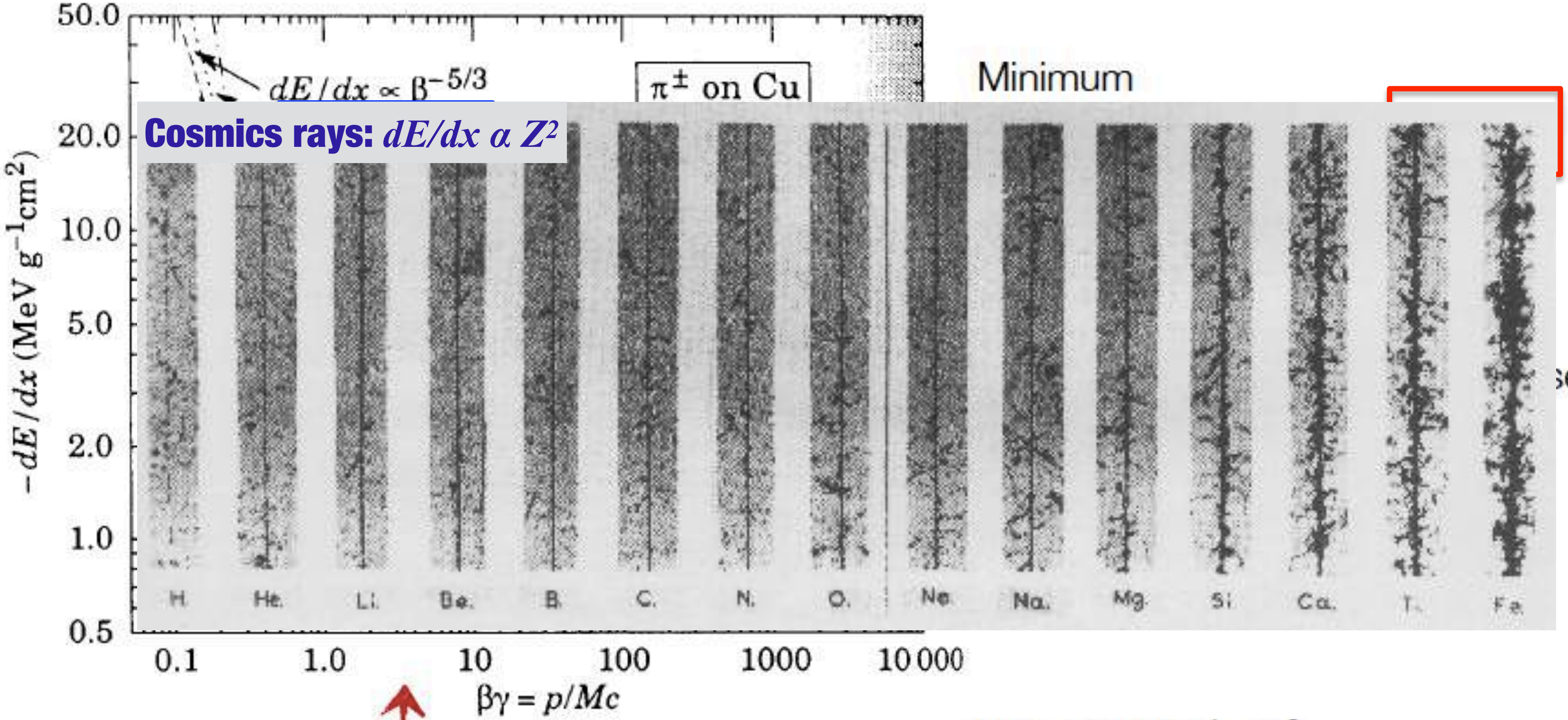
dE/dx rises $\boxed{\sim \ln(\beta\gamma)^2;}$ relativistic rise
[rel. extension of transversal E-field]

Saturation at large ($\beta\gamma$) due to density effect $\boxed{\text{(correction } \delta)}$
[polarization of medium]

Units: MeV g^{-1} cm^2

MIP looses ~ 13 MeV/cm
[density of copper: 8.94 g/cm^3]

erstanding the Bethe-Bloch



Minimum

$\beta\gamma = 3 - 4$

$$\frac{dE}{dx} \propto \frac{Z^2}{\beta^2} \ln\left(a\beta^2\gamma^2\right)$$

Units: MeV g^{-1} cm^2

MIP looses ~ 13 MeV/cm
[density of copper: 8.94 g/cm^3]

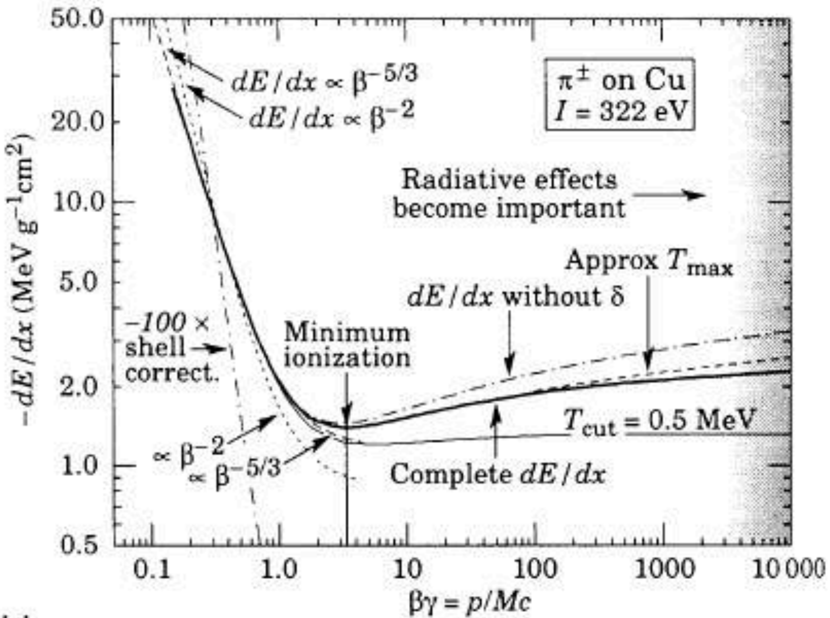
erstanding the Bethe-Bloch

³²-dependence:

emember:

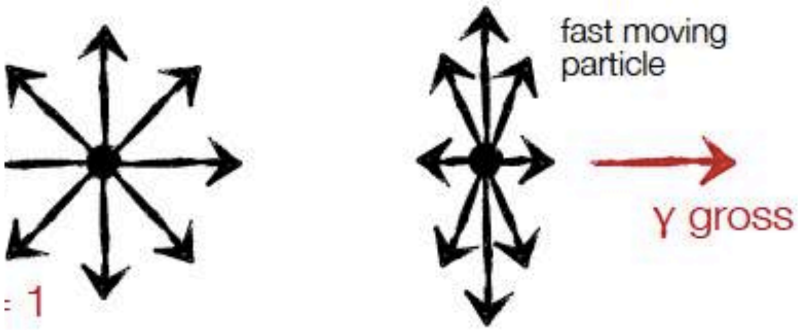
$$\Delta p_\perp = \int F_\perp dt = \int F_\perp \frac{dx}{v}$$

. slower particles feel electric force of
omic electron for longer time ...



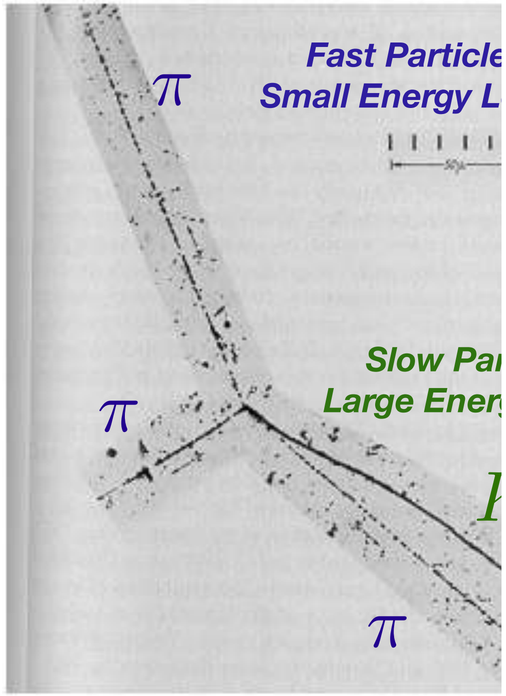
lativistic rise for βγ > 4:

gh energy particle: transversal electric field increases
ıe to Lorentz transform; $E_y \rightarrow \gamma E_y$. Thus interaction cross section increases ...



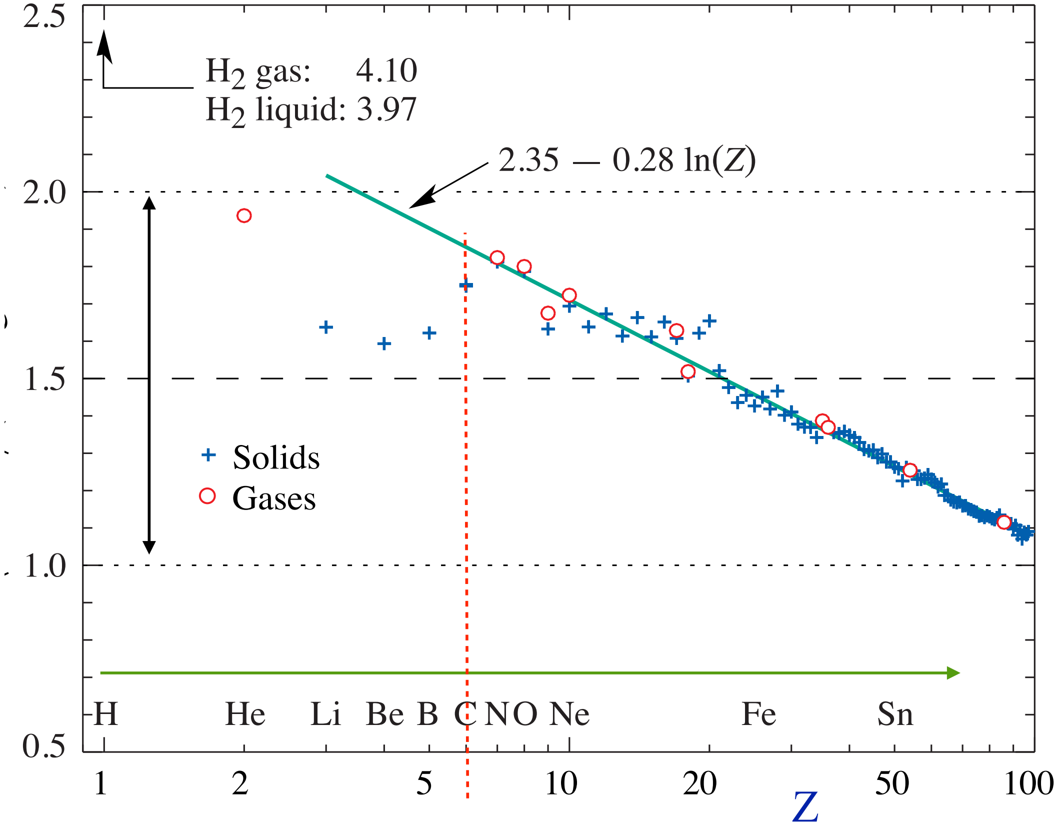
Corrections:

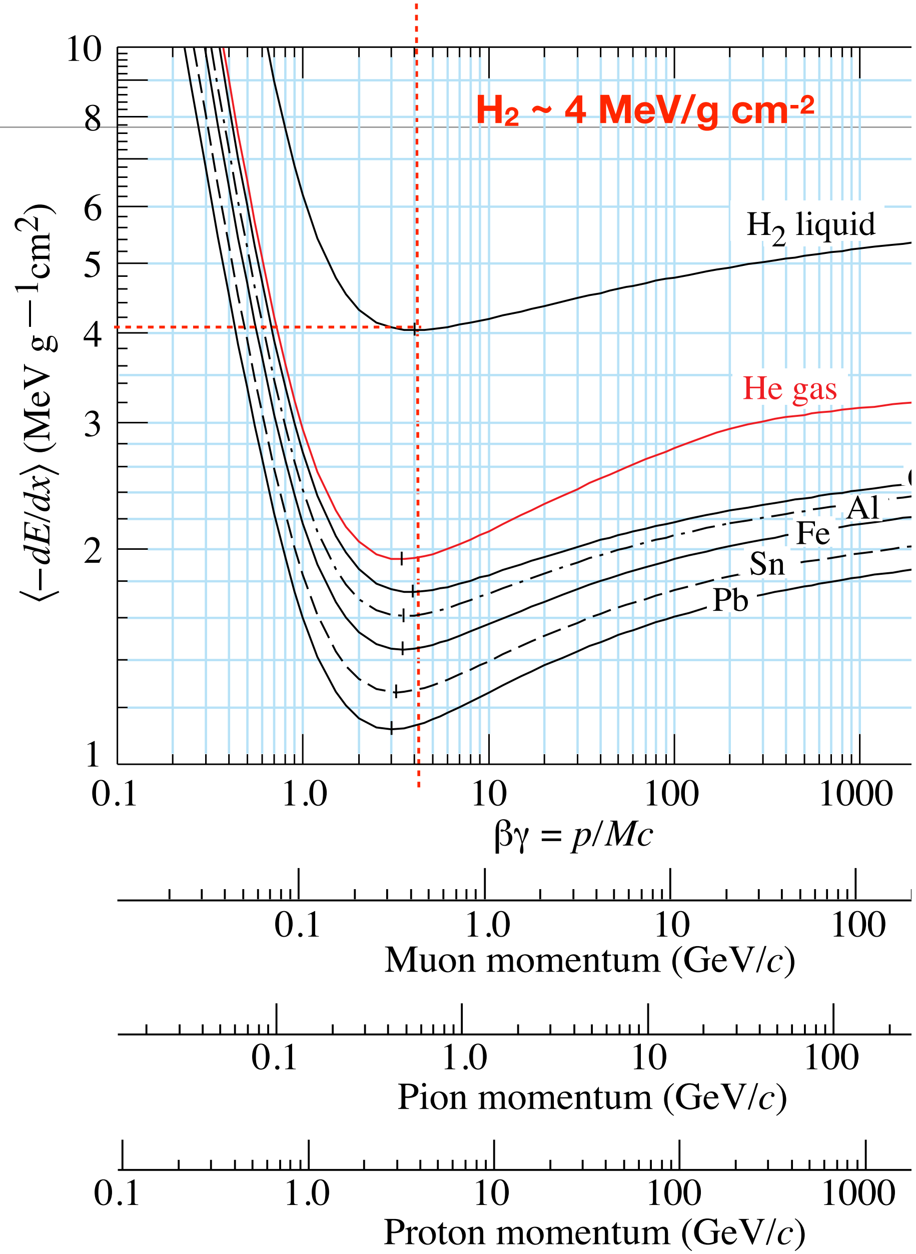
low energy : shell corrections
high energy : density corrections



endence on the medium

Minimum Ionization: ~ 1-2 MeV/g cm^{-2}





$$\left\langle \frac{dE}{dx} \right\rangle = 2\pi N_a r_e^2 m_e c^2 \rho \frac{Z}{A} \frac{z^2}{\beta^2} \left[\ln\left(\frac{2m_e c^2 \beta^2 \gamma^2}{I^2} W_{\max}\right) - 2\beta^2 - \delta(\beta\gamma) - \frac{C}{Z} \right]$$

e-Block for Electrons

$$-\left\langle \frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} ln \left(\frac{\tau^2 (\tau + 2) m_e^2 c^4}{2I} \right) + \frac{F(\tau)}{2} - \frac{\delta(\beta)}{2} - \frac{C(I,\beta)}{Z} \right]$$

$\tau = \gamma - 1$ Kinetic energy of the electron divided by $m_e c^2$

$$F(\tau) = 1 - \beta^2 + \frac{\tau^2/8 - (2\tau + 1)\ln(2)}{(\tau + 1)^2}$$ for electrons

$$F(\tau) = 2\ln(2) - \frac{\beta^2}{12}\left[23 + \frac{14}{\tau + 2} + \frac{10}{(\tau + 2)^2} + \frac{4}{(\tau + 2)^3} \right]$$ for positrons

- Bethe-Block formula needs modification for electrons as incident and target electron (outer shells) have same mass

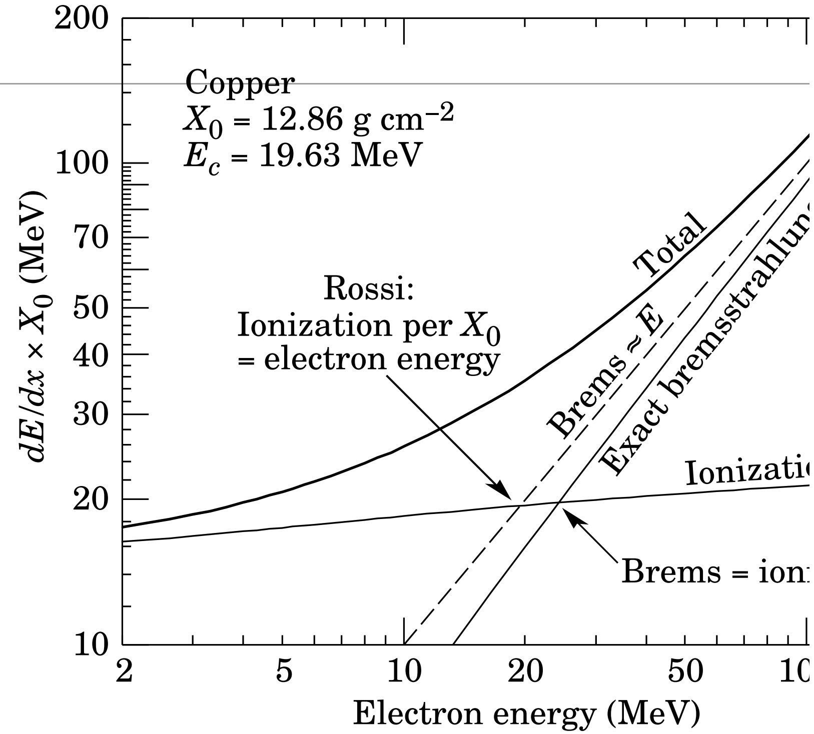
gy loss for electrons

-Block formula needs modification for electrons as
nt and target electron (outer shells) have same mass.

ttering of identical indistinguishable particles

$$-\left\langle \frac{dE}{dx} \right\rangle_{Ion} \propto ln(E)$$

energy greater than 10-30 MeV ($\beta\gamma$ ~ 20) the radiative
dominate

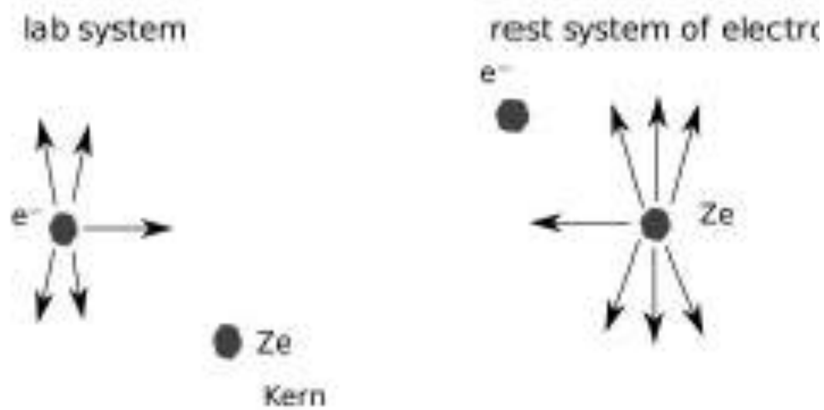


sstrahlung / Synchroton radiation

) process (Fermi 1924, Weizsäcker-Williams 1938)

ectron is hit by plane electromagnetic wave (for large v)
⊥ B and both ⊥ v;

nta are scattered by electrons and appear as real
tons in Coulomb field of nucleus

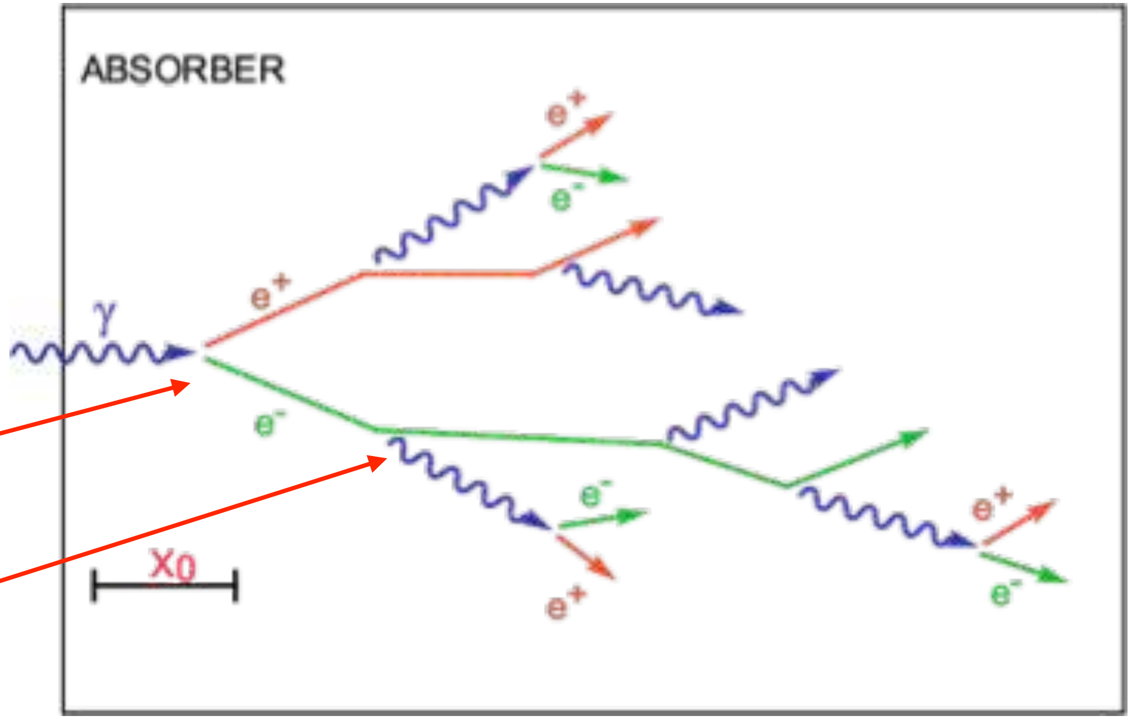


tromagnetic Showers

TONS: PAIR PRODUCTION

$$= \frac{7}{9}\left(4\alpha r_e^2 Z^2 \ln\frac{183}{z^{\frac{1}{3}}}\right) = \frac{7}{9}\frac{A}{N_A X_0}$$

teraction Length $\lambda_{\mathrm{int}} = \frac{9}{7}X_0$



TRONS: BREMSSTRAHLUNG

$$-\frac{dE}{dx} = 4\alpha N_A \frac{Z^2}{A} z^2 \left(\frac{1}{4\pi\varepsilon_0}\frac{e^2}{mc^2}\right)^2 E \ln\frac{183}{Z^{\frac{1}{3}}} \propto \frac{E}{m^2}$$

$$r_e = \frac{e^2}{m_e c^2}$$

$$= \frac{A}{Z(Z+1)}\frac{716.4}{\ln(287/\sqrt{Z})}\left[\frac{g}{cm^2}\right]$$

$$E = E_0 e^{-x/X_0}$$

$$\frac{dE}{dx} = 4\alpha N_A \frac{Z^2}{A} r_e^2 E \ln\frac{183}{Z^{\frac{1}{3}}} = \frac{E}{X_0}$$

r passage of one X_0 electron has only
)th (37%) of its primary energy ...

;hower model

/er is characterised by

- nber of particle in the shower
- :ation of shower maximum (X_{max})
- ıgitudinal profile
- sversal profile

ılified model

- each stage the energy is HALVED and number of particles UBLED
  - air-production $E_{e^\pm} = E_\gamma/2$
  - remsstrahlung $E_\gamma = E_e/2$
- er t stages $N(t) = 2^t = e^{x/X_0}$

$$= \frac{E_0}{N(t)} = E_0 \cdot 2^{-t} \Longrightarrow t = \frac{\ln(E_0/E)}{\ln 2} \qquad t_{max} \propto \ln(E_0)$$

$$_{max} = 2^{t_{max}} = \frac{E_0}{E_c} \qquad X_{max} = t_{max} \cdot X_0 \cdot \ln(2) = X_0 \cdot \ln(\frac{E_0}{E_c})$$

$$= \frac{dX_{max}}{d(\log E_0)} = \ln(10) \cdot X_0 = 2.3 \cdot 37\ g \cdot cm^{-2} \approx 85\ g \cdot cm^{-2}$$

$$T = X_0 \sum_{\mu=0}^{t_{\max}-1} 2^\mu + t_0 \cdot N_{\max} \cdot X_0$$

with t_0: range of electron with energy [given in units of X_0]

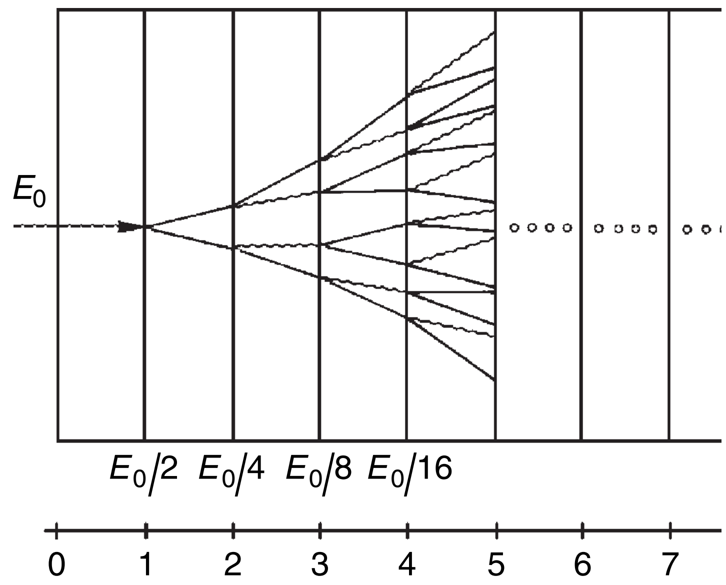
$$= X_0 \cdot (2^{t_{\max}} - 1) + t_0 \cdot \frac{E_0}{E_c} X_0$$

$$= X_0 \cdot (2^{\log_2 E_0/E_c} - 1) + t_0 \cdot \frac{E_0}{E_c} X_0 \approx (1 + t_0) \cdot \frac{E_0}{E_c} X_0 \propto E_0$$

Energy propoı to track lengtł

As only electrons contribute ...

$$T = \frac{E_0}{E_c} \cdot X_0 \cdot F \qquad [\text{ with } F < 1\,]$$



cal Energy

$$\left\langle \frac{dE}{dx} \right\rangle_{Brems} = \frac{E}{X_0}$$

= radiation length in [g/cm^2]

$$\boxed{ = \frac{A}{4\alpha N_A Z^2 r_e^2 \ln \frac{183}{Z^{1/3}}}}$$

ter passage of one X_0
ectron has lost all but
/e)th of its energy (63%)

= critical energy

$$\boxed{\frac{dE}{dx}(E_c)\Big|_{Brems} = \frac{dE}{dx}(E_c)\Big|_{Ion}}$$

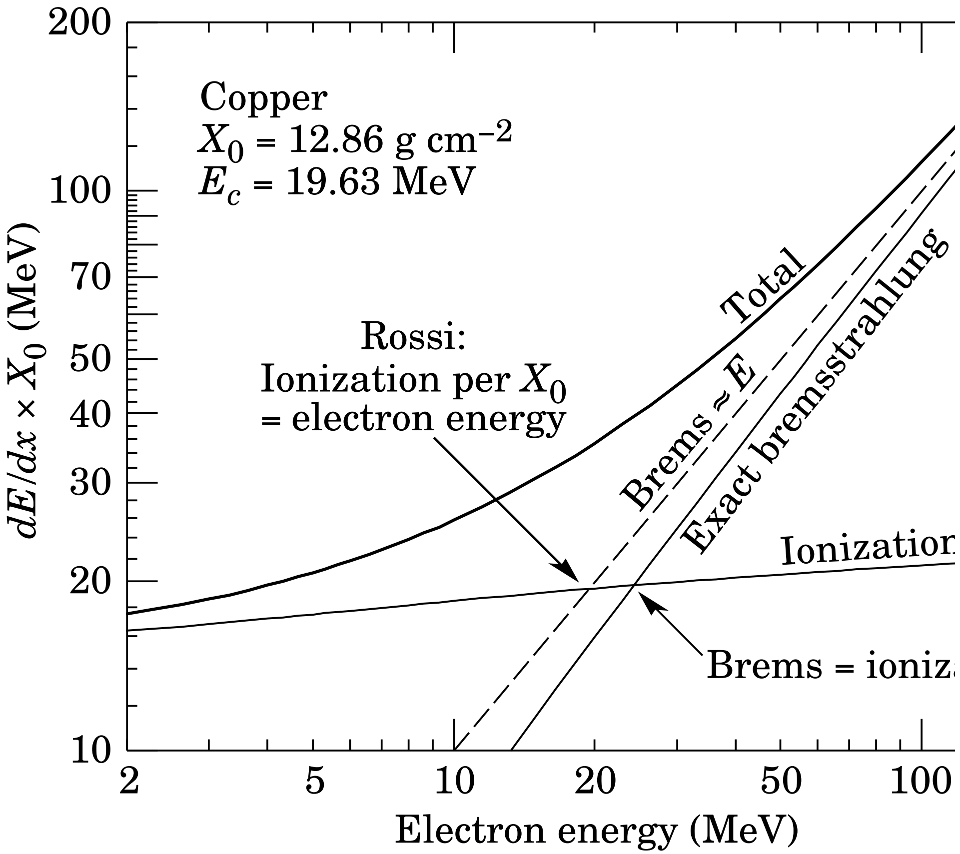
for e and Z>13

$$E_C = \frac{580}{Z} MeV$$

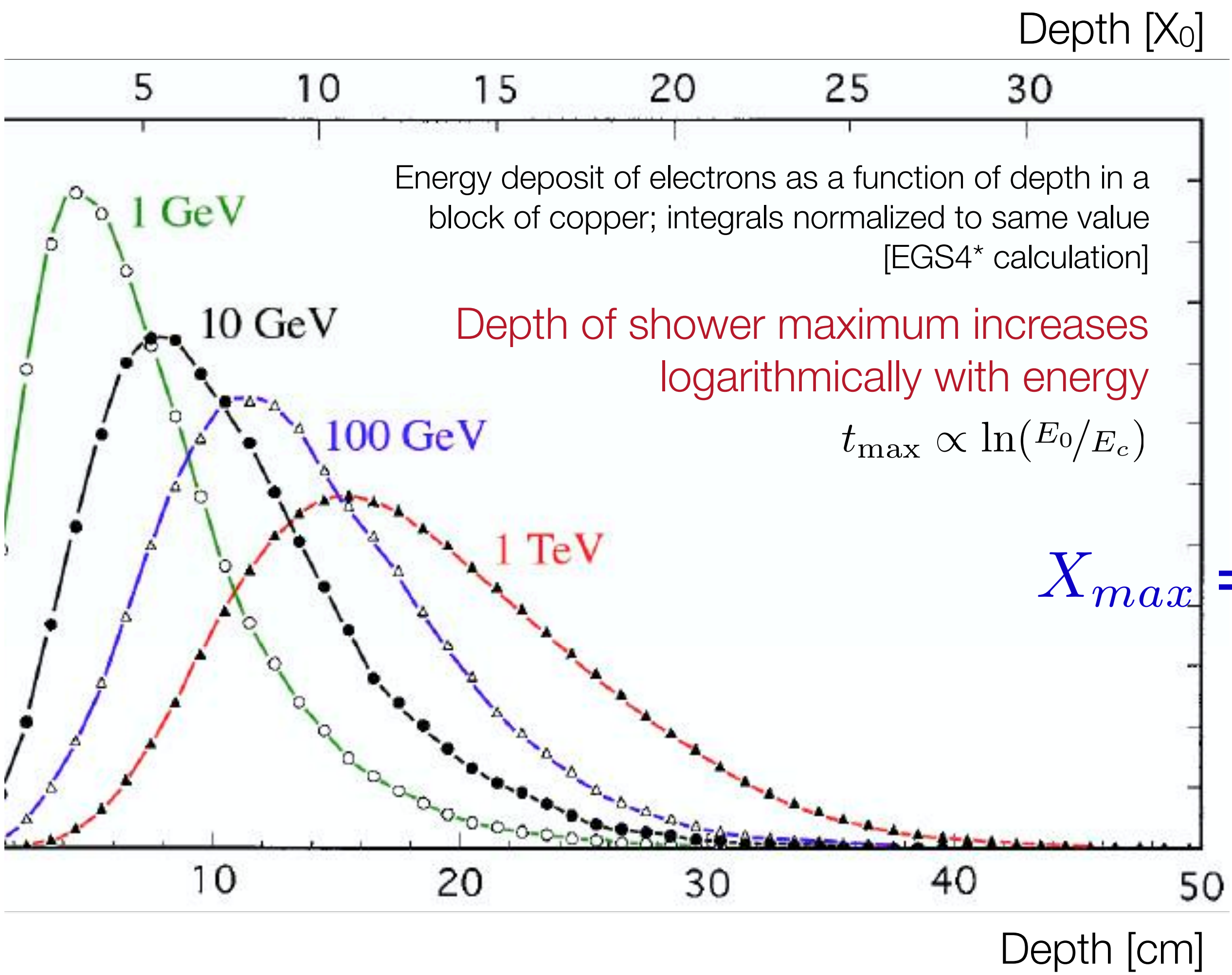
for μ is neglibible

$$E_C = \frac{24}{Z} TeV$$

$$(m_\mu/m_e)^2 = 4 \cdot 10^4$$



gitudinal Shower Shape - Energy dependence



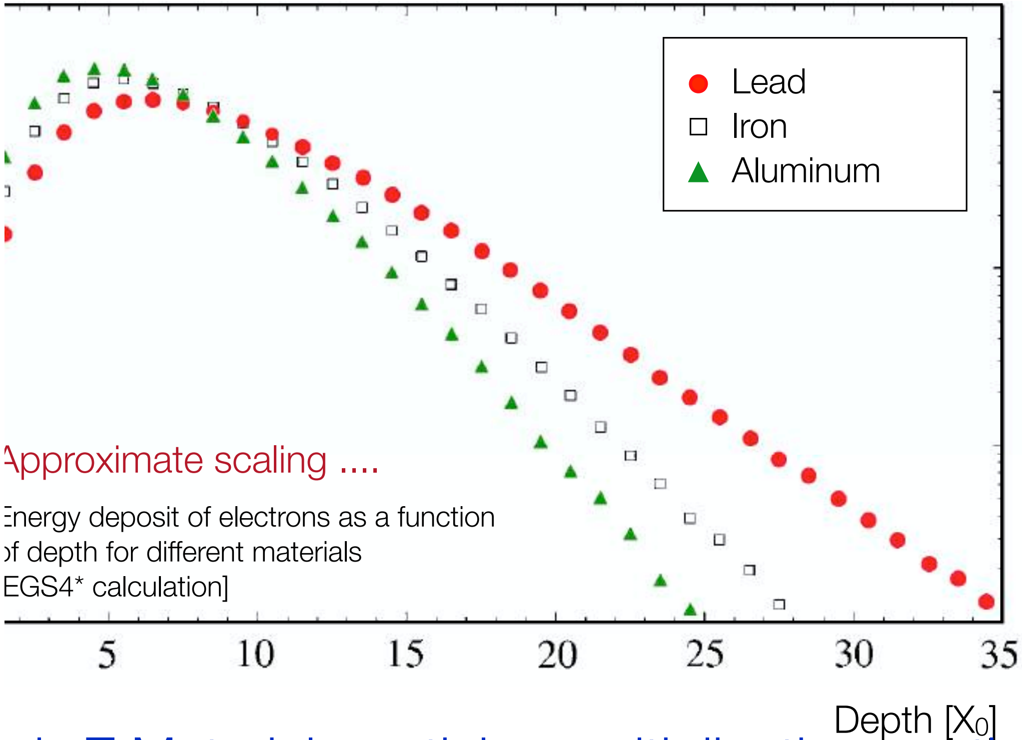
$$X_{max} = t_{max} \cdot X_0 \cdot \ln(2) = X_0 \cdot \ln(\frac{E_0}{E_c})$$

Elongation rate

$$\Lambda = \frac{dX_{max}}{d(\log E_0)} = \ln(10) \cdot X_0 = 2.3 \cdot 37\ g \cdot cm^{-2} \approx 85\ g \cdot cm^{-2}$$

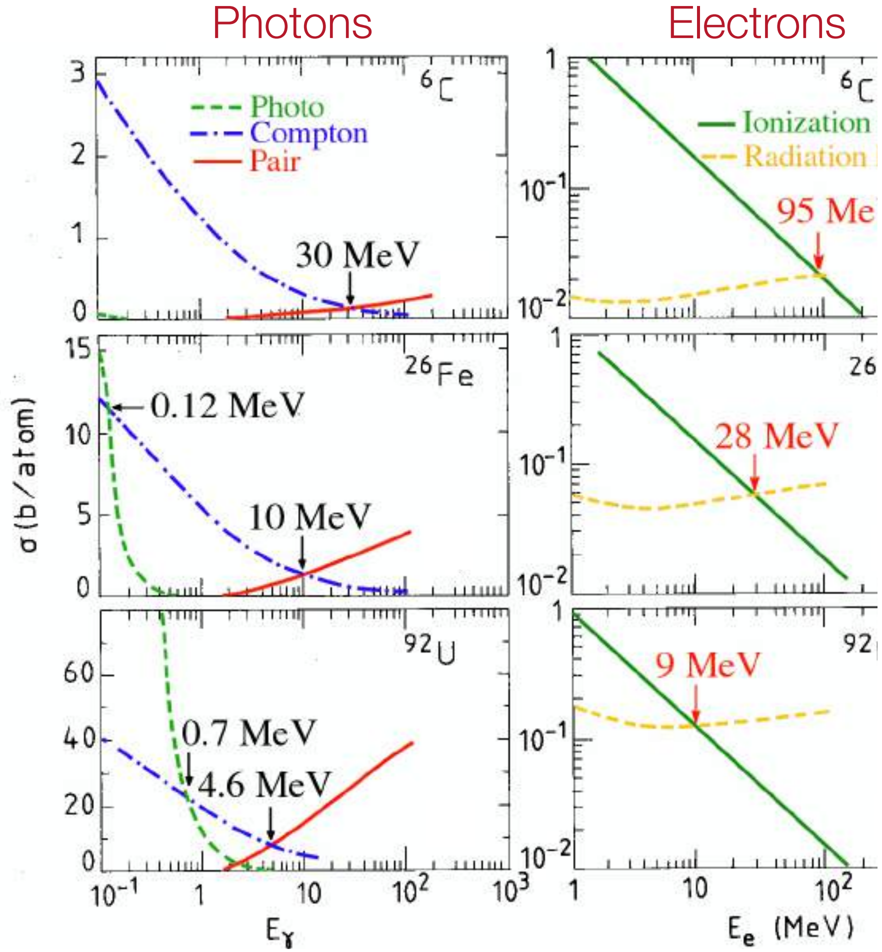
gitudinal Shower Shape - Z dependence

) GeV electrons



Approximate scaling ....

Energy deposit of electrons as a function of depth for different materials EGS4* calculation]



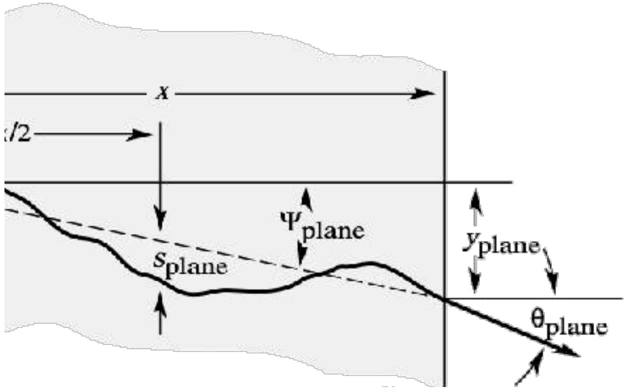
gh-Z Material, particles multiplication continues ger and decreased more slowly than in low-Z erials

number of positrons strongly increases with the Z ne absorber material

- Ex. Number of e^+/GeV is 3 times larger in ***Pb*** than in A
  - ↳ Need more X_0 of ***Pb*** to contain ***90%*** of shower

sversal Shower Shape

Molière



Transverse profile
at different shower depths ....

Up to shower maximum broadening
mainly due to multiple scattering ...

Characterized by R_M:
[90% shower energy within R_M]

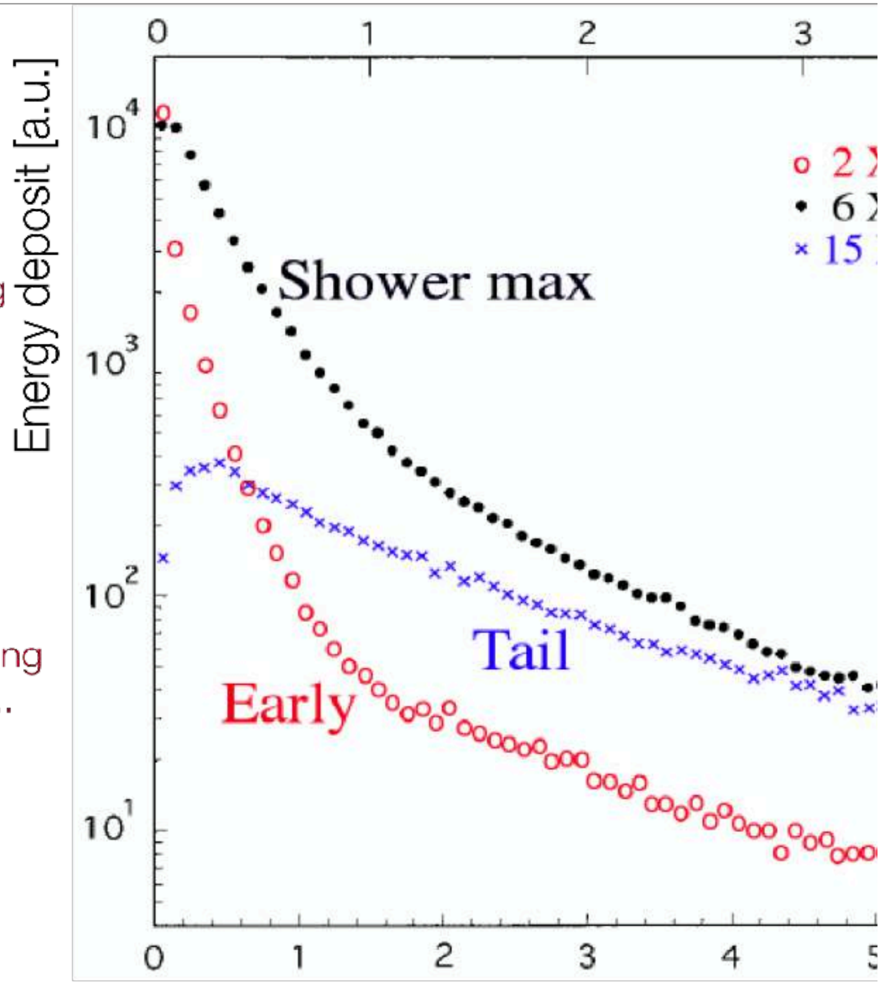
$$R_M = \frac{21\ \mathrm{MeV}}{E_c} X_0$$

Beyond shower maximum broadening
mainly due to low energy photons ...

ction angle:
e-Theory]

$$\langle \theta^2 \rangle = E_s^2 \cdot \frac{1}{p^2 v^2} \cdot z^2 \cdot \frac{x}{X_0}$$

$$\langle \theta \rangle = \frac{21.2\ \mathrm{MeV}}{E_e} \sqrt{\frac{x}{X_0}}$$ [β = 1, c = 1, z = 1]



Radial distributions of the energy de
by 10 GeV electron showers in

es of Thumb'

diation length: $$X_0 = \frac{180A}{Z^2} \frac{\mathrm{g}}{\mathrm{cm}^2}$$

Problem:
Calculate how much Pb, Fe or Cu
is needed to stop a 10 GeV electron.

Pb : Z=82 , A=207, ρ=11.34 g/cm³
Fe : Z=26 , A=56, ρ=7.87 g/cm³
Cu : Z=29 , A=63, ρ=8.92 g/cm³

ical energy:
tion: Definition of Rossi used]

$$E_c = \frac{550\ \mathrm{MeV}}{Z}$$

ower maximum:

$$t_{\max} = \ln \frac{E}{E_c} - \begin{cases} 1.0 & e^- \text{ induced shower} \\ 0.5 & \gamma \text{ induced shower} \end{cases}$$

Transverse size of EM show
by radiation length via Moliè

$$R_M = \frac{21\ \mathrm{MeV}}{E_C} \cdot$$

R_M: Moliere Radius
E_c: Critical Energy [F
X_0 : Radiation length

gitudinal
ergy containment:

$$L(95\%) = t_{\max} + 0.08Z + 9.6\ [X_0]$$

sverse
ergy containment:

$$R(90\%) = R_M$$
$$R(95\%) = 2R_M$$

gy resolution

Energy Physics, calorimeters can be broadly classified in 2 types:

Homogeneous Calorimeters:
The same medium (scintillating crystal, liquified gas , atmosphere(!)) act both as target (absorbing material and detectors)

Sampling Calorimeters:
Slab of dense passive absorber (Lead , iron , high-Z materials) are interleaved with active detectors (silicon, scintillators, liquified gases)

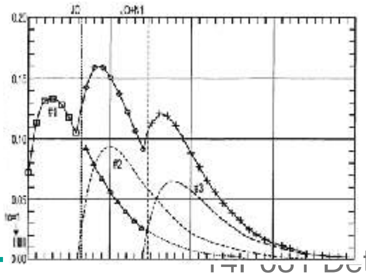
cases the energy resolution can be parametrised as

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

Constant Term

- ➡ Imperfections in calorimeter construction
- ➡ non-uniformities in signal collection;
- ➡ channel-to-channel calibration errors;
- ➡ fluctuations in longitudinal energy containment;
- ➡ fluctuations in energy lost in inert material, before or within the detection volume.

Stochastic Term
Shower fluctuation (intrinsic)
Fluctuation in the detection



Noise Term
Electronic noise
also effects like pile-up

ıogeneous Calorimeter

CMS Calorimeter

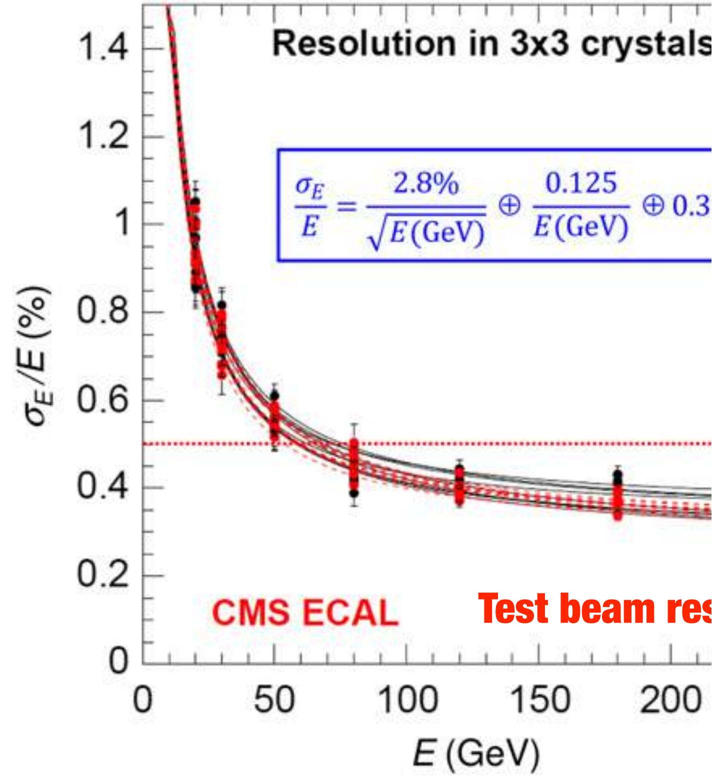
mogeneous calorimeter the whole detector volume is filled by density material which simultaneously serves as absorber as as active medium ...

ȷenous calorimeters are exclusively used for electromagnetic ıeter, i.e. energy measurement of electrons and photons

GE: Optimal energy resolution

ɴTAGE: Very expensive

Signal	Material
ɩllation Light	BGO, BaF2, CeF3, ...
renkov Light	Lead Glass
ɪation Signal	Liquid nobel gases (Ar, Kr, Xe)



Stochastic term (a)	Lateral containment	2.(
	Photoelectron statistics	2.:
	Total stochastic term	**3.(**
Noise term (b)	Electronics noise	12
	APD Leakage noise	9(
	Pile-up noise	6(
	Total noise term	**16**
Constant term (c)	Longitudinal non-uniformity	0.:
	Inter-calibration errors	0.4
	Total constant term	**0.:**

ıogeneous Calorimeter

CMS Calorimeter

mogeneous calorimeter the whole detector volume is filled by density material which simultaneously serves as absorber as as active medium ...

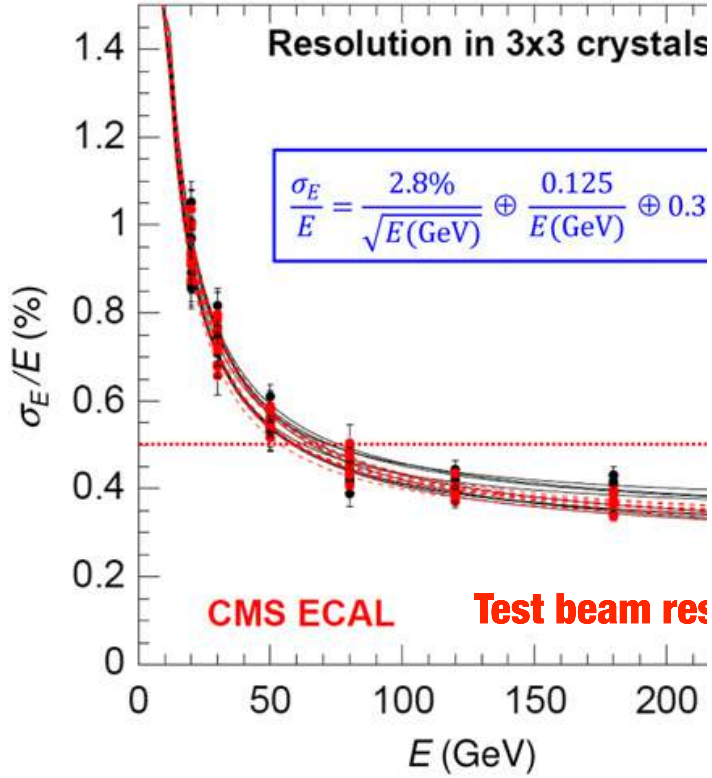
ȷenous calorimeters are exclusively used for electromagnetic ıeter, i.e. energy measurement of electrons and photons

GE: Optimal energy resolution

ΝTAGE: Very expensive

Scintillator : $PBW0_4$ [Lead Tungsten]
Photosensor : APDs [Avalanche Photodiodes]

Number of crystals: ~ 70000
Light output: 4.5 photons/MeV



Stochastic term (a)	Lateral containment	2.(
	Photoelectron statistics	2.:
	Total stochastic term	**3.(**
Noise term (b)	Electronics noise	12
	APD Leakage noise	90
	Pile-up noise	60
	Total noise term	**16**
Constant term (c)	Longitudinal non-uniformity	0.:
	Inter-calibration errors	0.4
	Total constant term	**0.:**

ıpling Calorimeters

ɔle:

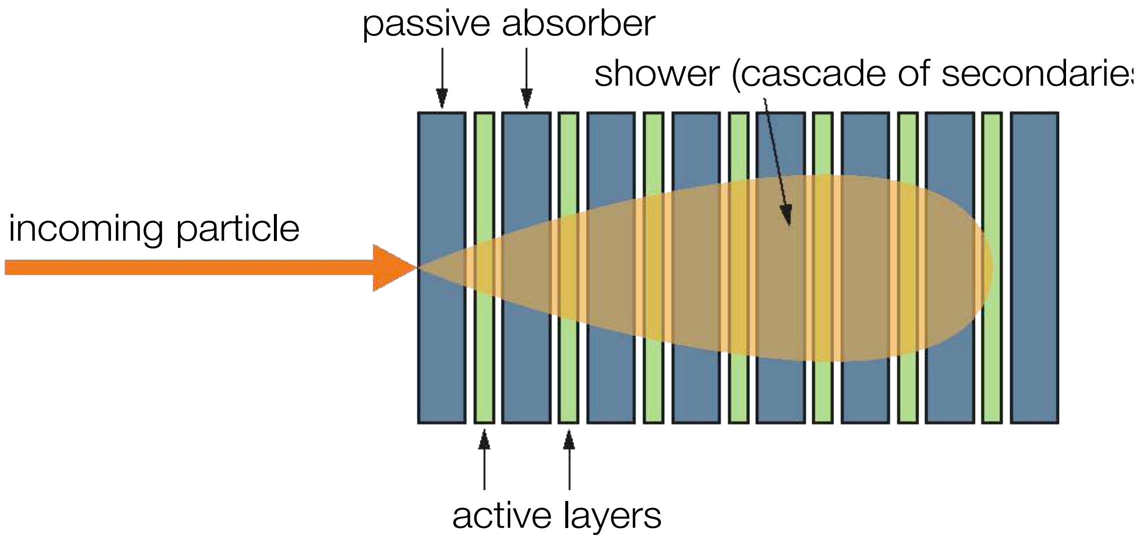
ating layers of absorber and
 material [sandwich calorimeter]

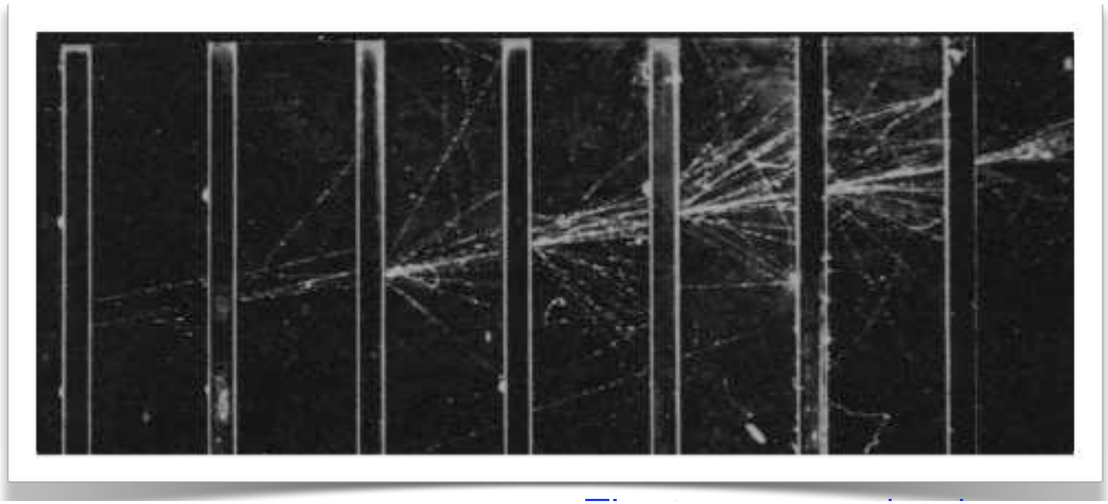
ber materials:
ınsity]

ı (Fe)
ɜd (Pb)
ɜnium (U)
 compensation ...]

ɜ materials:

ıstic scintillator
con detectors
uid ionization chamber
s detectors





ıpling Calorimeters

ɔle:

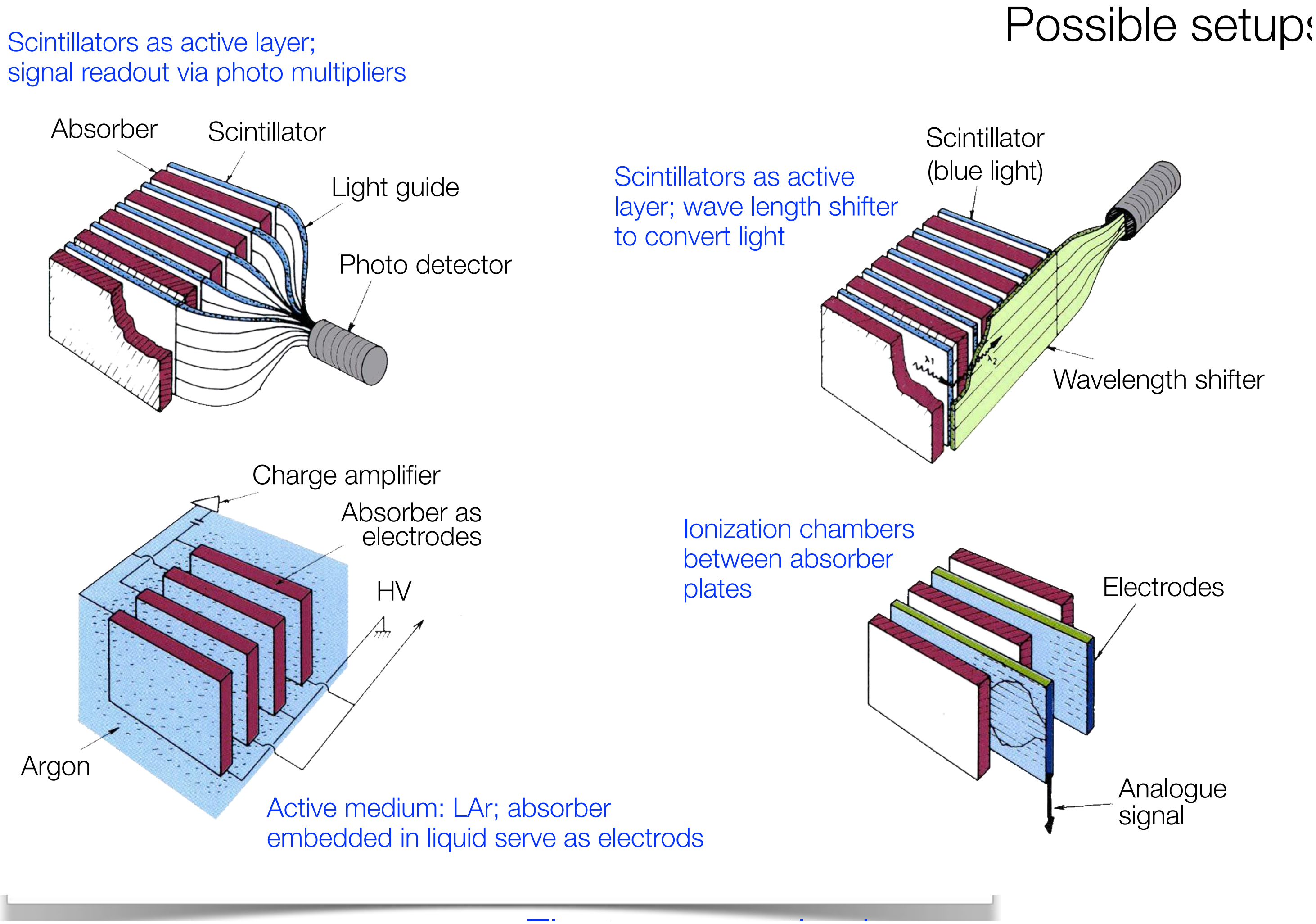
ating layers of absorber and
 material [sandwich calorimeter]

ber materials:
ınsity]

ı (Fe)
ad (Pb)
anium (U)
 compensation ...]

ɛ materials:

ıstic scintillator
con detectors
uid ionization chamber
s detectors



pling Calorimeters

DVANTAGES:

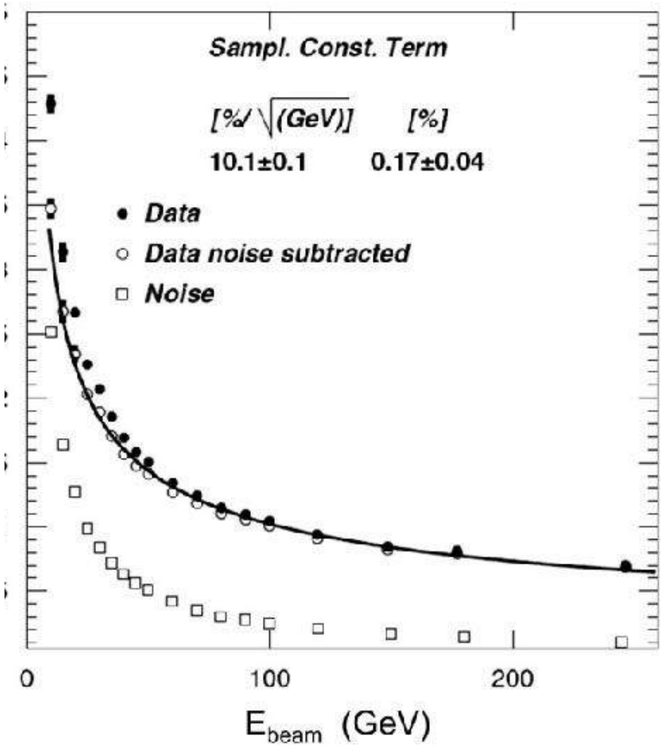
- ***OPTIMISED*** By separating passive and active layers the different layer materials can be optimally adapted to the corresponding requirements ...
- ***VERY COMPACT*** choosing high-density material for the absorbers one can built very compact calorimeters ...
- ***CHEAPER*** Sampling calorimeters are simpler with more passive material (cheap) a than homogeneous calorimeters ...

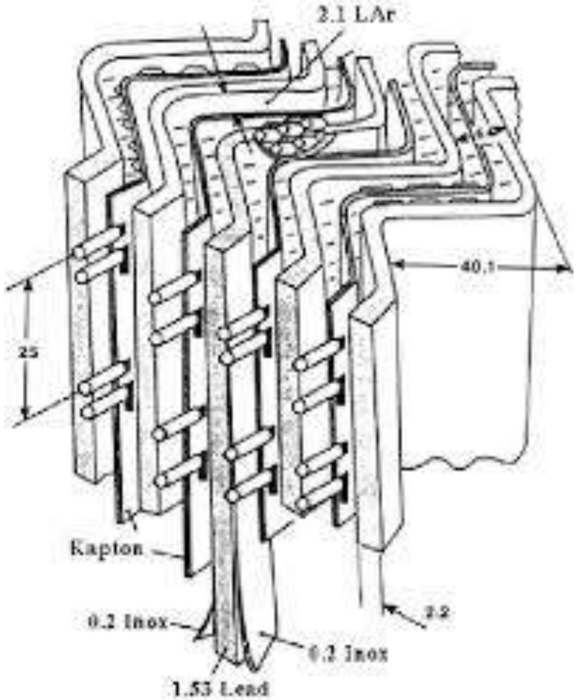
ISADVANTAGES:

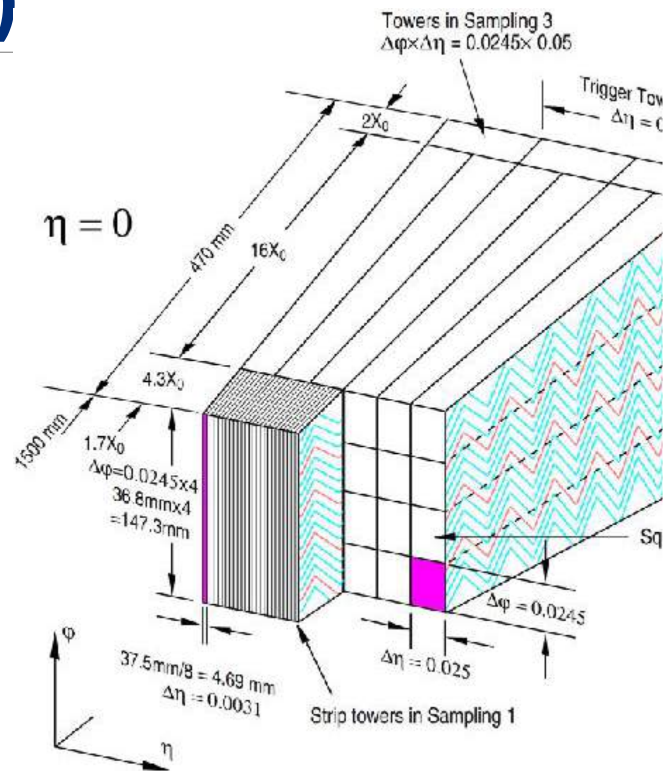
- ***SAMPLING*** Only part of the **deposited particle energy** is actually detected in the active layers; typically a **few percent** [for gas detectors even only ~10-5]
- ***REDUCED ENERGY RESOLUTION*** Due to this **sampling-fluctuations**

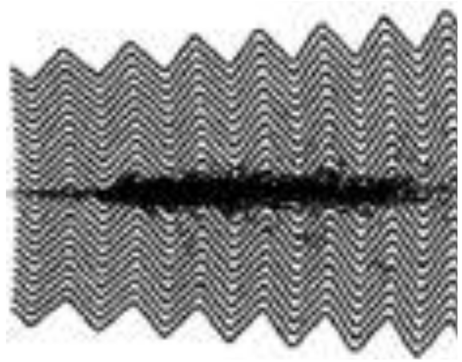
AS LAr Accordion (Sampling, Ionization)

- ing electromagnetic calorimeter
- argon calorimetry intrinsically linear response, stable over time and tolerant to vels of radiation.
- cordion geometry provides high granularity and good hermeticity.
- ent photon resolution
- n photon measurement and good γ/π discrimination
- ng the pseudo-rapidity range $|\eta|<3.2$.









ronic Interaction

'onic interaction:

s Section:

at high energies
also diffractive contribution

$$\sigma_{\text{tot}} = \sigma_{\text{el}} + \sigma_{\text{inel}}$$

For substantial energies
σ_{inel} dominates:

$$\sigma_{\text{el}} \approx 10 \text{ mb}$$

$$\sigma_{\text{inel}} \propto A^{2/3}$$ [geometrical cross section]

$$\sigma_{\text{tot}} = \sigma_{\text{tot}}(pA) \approx \sigma_{\text{tot}}(pp) \cdot A^{2/3}$$

[σ_{tot} slightly grows with $\sqrt{s}$]

nteraction length:

$$= \frac{1}{\sigma_{\text{tot}} \cdot n} = \frac{A}{\sigma_{pp} A^{2/3} \cdot N_A \rho} \sim A^{1/3}$$ [for $\sqrt{s} \approx 1 - 100$ GeV]

$$\approx 35 \text{ g/cm}^2 \cdot A^{1/3}$$

Interaction length characterizes both,
longitudinal and transverse profile of
hadronic showers ...

lds:

$$) = N_0 \exp(-x/\lambda_{\text{int}})$$

: In principle one should distinguish between collision
w ~ $1/\sigma_{\text{tot}}$ and interaction length λ_{int} ~ $1/\sigma_{\text{inel}}$ where
r considers inelastic processes only (absorption) ...

σ Elastic:
p+Nucleus→p+Nucleus

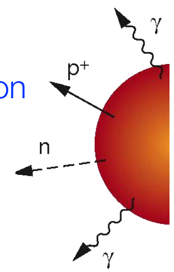
σ Inelastic:

$$p + \text{Nucleus} \rightarrow \pi^+ + \pi^- + \pi^0 + \ldots + \text{Nucleus}^*$$

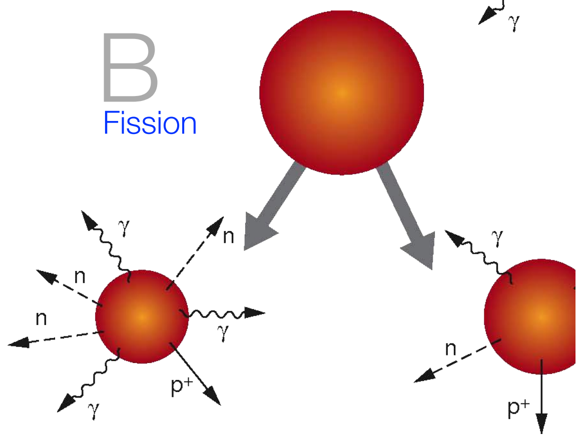
$$\left[\text{Nucleus}^* \begin{array}{l} \square \ \text{Nucleus A} + n, p, \alpha, \ldots \\ \square \ \text{Nucleus B} + 5p, n, \pi, \ldots \\ \square \ \text{Nuclear fission} \end{array} \right]$$

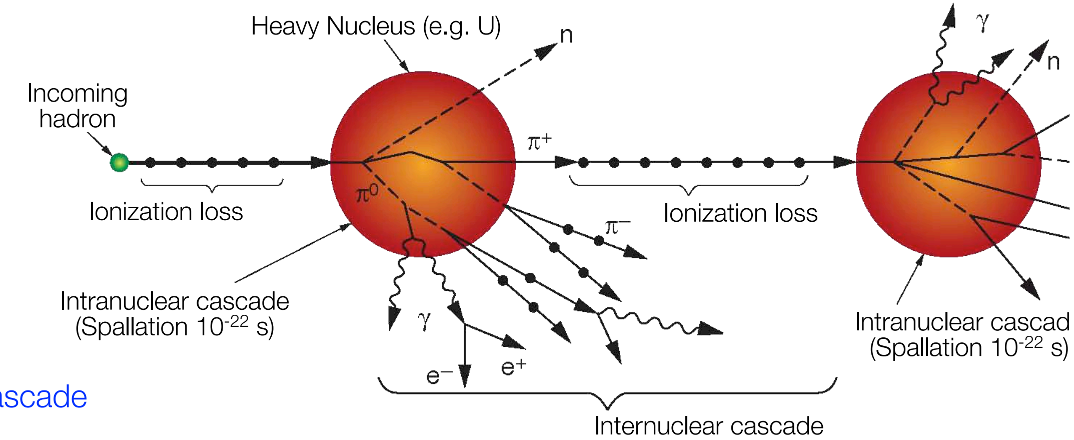
C Nuclear evaporation

Weakly dependance
with $\sqrt{s}$



B Fission





A Inter- and
intranuclear cascade

ronic Interaction

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at high energies
also diffractive contribution

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r considers inelastic processes only (absorption) ...

σ Elastic:
p+Nucleus→p+Nucleus

σ Inelastic:
$p + \mathrm{Nucleus} \rightarrow$
$\pi^+ + \pi^- + \pi^0 +$

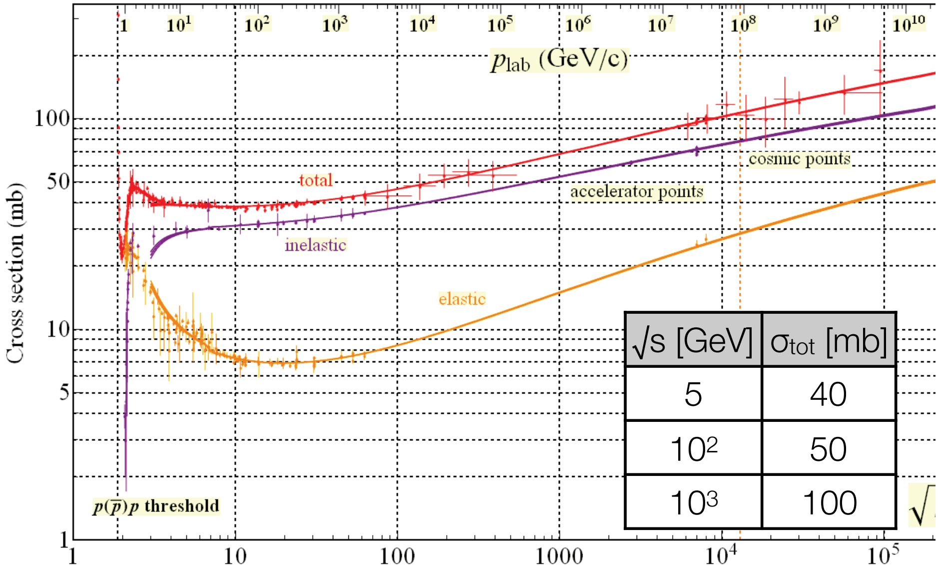
Nucleus* □ Nuc
□ Nuc
□ Nuc

Incoming
hadron

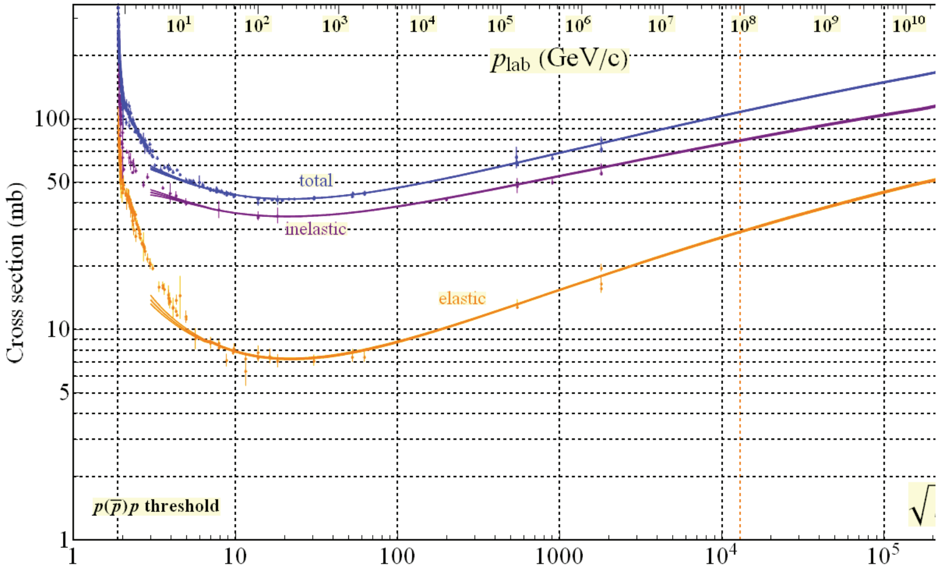
Ioniz

Intranu
(Spall

A
Inter- and
intranuclear cascade



√s [GeV]	σtot [mb]
5	40
10^2	50
10^3	100



·onic Showers

Development:

→ π + N* + ….

ndary Particles….
·go further inelastic collision until they fall
/ pion production threshold

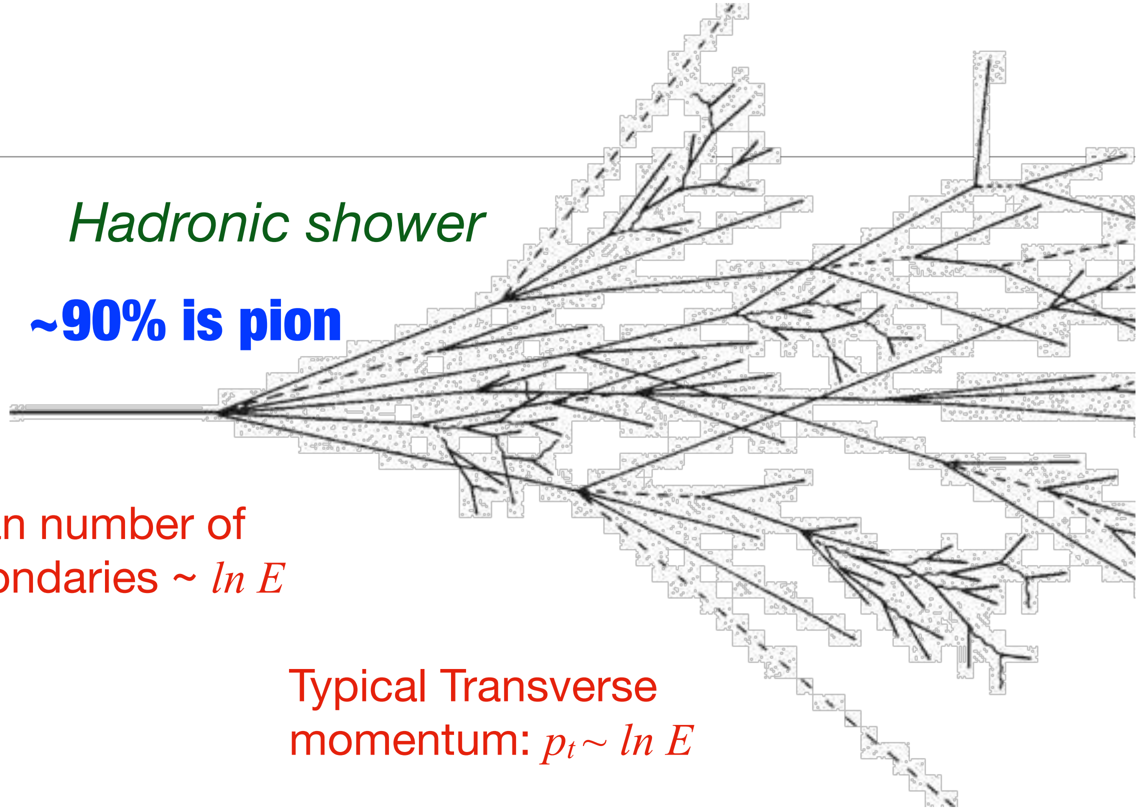
ential decays ..
·γ: yield electromagnetic shower

ɔn fragment → γ-decay, β-decay

·on capture → fission
ation …

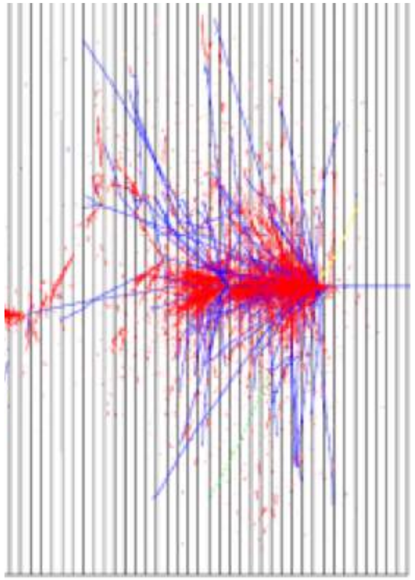
·$\gamma\gamma$ start EM Shower
stantial Electromagnetic Fraction

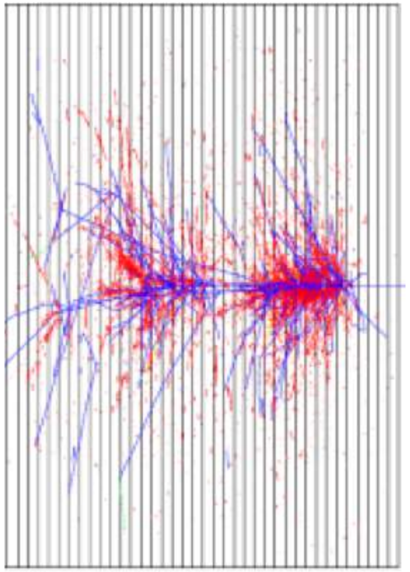
$$f_{em} \sim \ln(E)$$ [significant variations]



Ionisation Energy of charged particles	*1980 MeV*	*4*
Electromagnetic Shower	*760 MeV*	*1*
Neutrons	*520 MeV*	*1*
Photons from nuclear de-excitation	*310 MeV*	
Non-detectable (nuclear binding, neutrinos)	*1430 MeV*	*2*
Total	*5000 MeV*	

ronic vs Electromagnetic Shower





EM Showers

- $e^{\pm}$ ⇒ continuous stream of ionisation + bremsstrahlung
- γ ⇒ can penetrate sizeable amount of material before losing energy
- all energy carried by incoming e or γ goes into ionisation

Hadron showers much more complex process than Electromagnetic ones

The extra complication in hadrons showers arises from the role played by the strong interaction.

- Some ionisation (as for μ) then nuclear interactions
- Development similar to EM shower but with a different scale (λ vs. X_0)
- Many component in the showers (particle, muons. hadrons….)
- **Invisible energy ⇒ a fraction of energy is undetectable (nuclear recoil, neutrons, e**

Non compensatio

- The Showers contains always an EM fraction f_{em} (γ,π^0,η^0) which ***fraction largely fluctuate***

Non Linearity

Red EM component
Blu charged hadron component

ronic Showers

le Model

verage 1/3 of particles in first generation are π^0

productions by strong interacting particles is an irreversible process

st generation $f_{em} = 1/3$

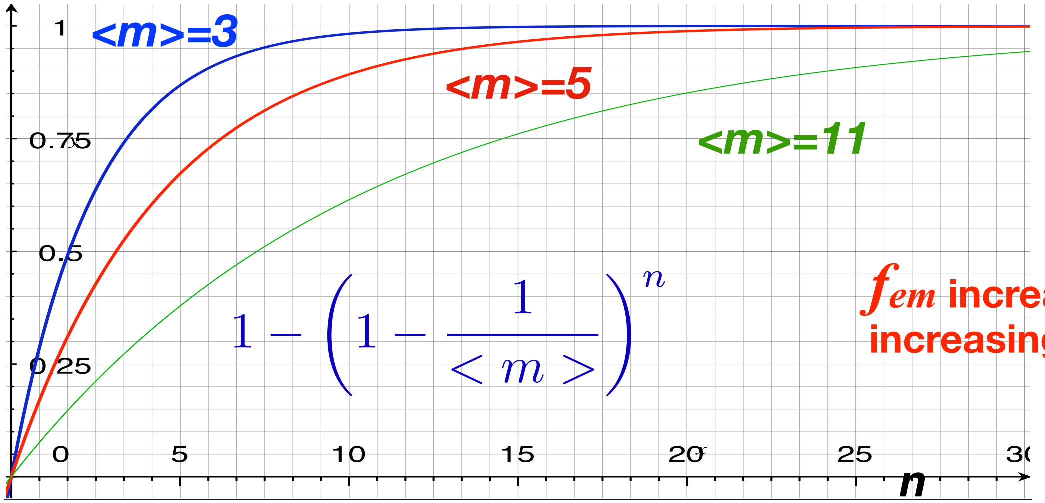
nd generation $f_{em} = 1/3 + 1/3*(1-1/3) = 5/9$

d generation $f_{em} = 5/9 + 1/3*(1-5/9) = 19/27$

the process stops when the available energy drops below pion production reshold....

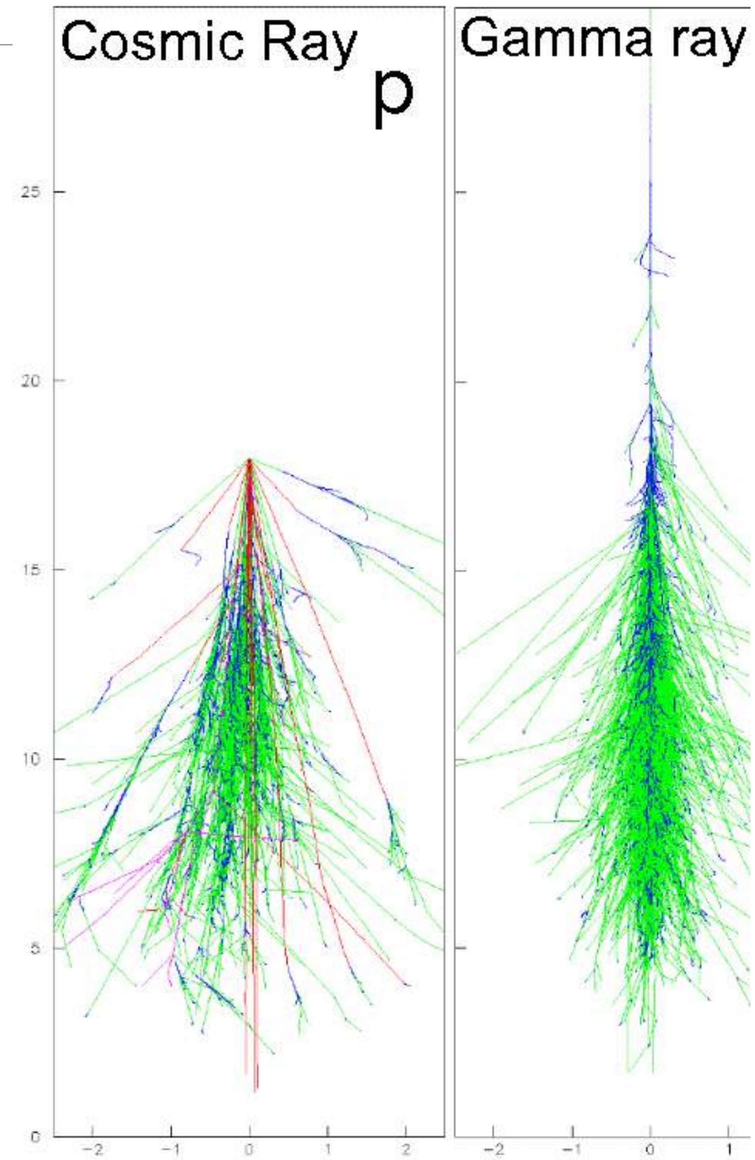
generation $f_{em} = 1 - (1-1/3)^n$

pends on the average multiplicity of mesons $<m>$ produced per interaction increases by one unit every time E increase by a factor $<m>$



$$1 - \left(1 - \frac{1}{< m >}\right)^n$$

f_{em} **increases with increasing hadron energy**



Color coding gamma, e^+/e^-, μ^+/μ^-, hadrons.

·onic Showers

This fraction increases with energy, since π^0 produ
may also occur in subsequent shower generations.

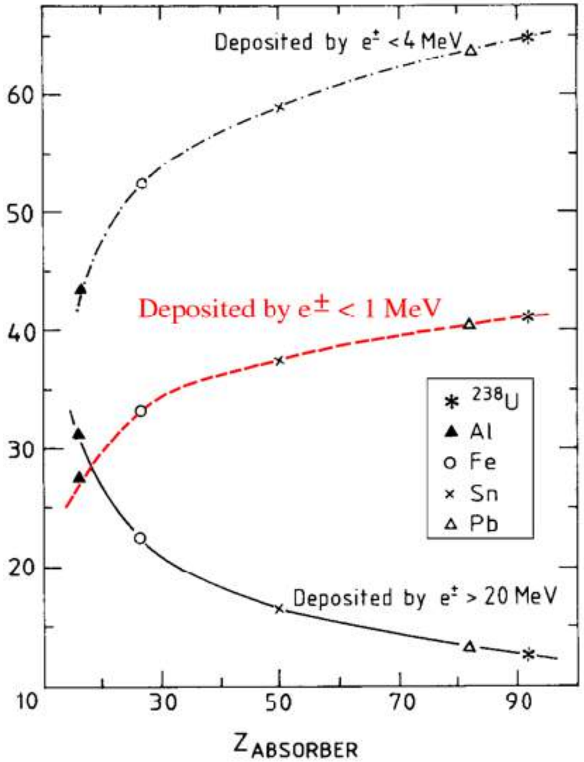
simplistic model

her particle than pions are produced (factor 1/3 is wrong)

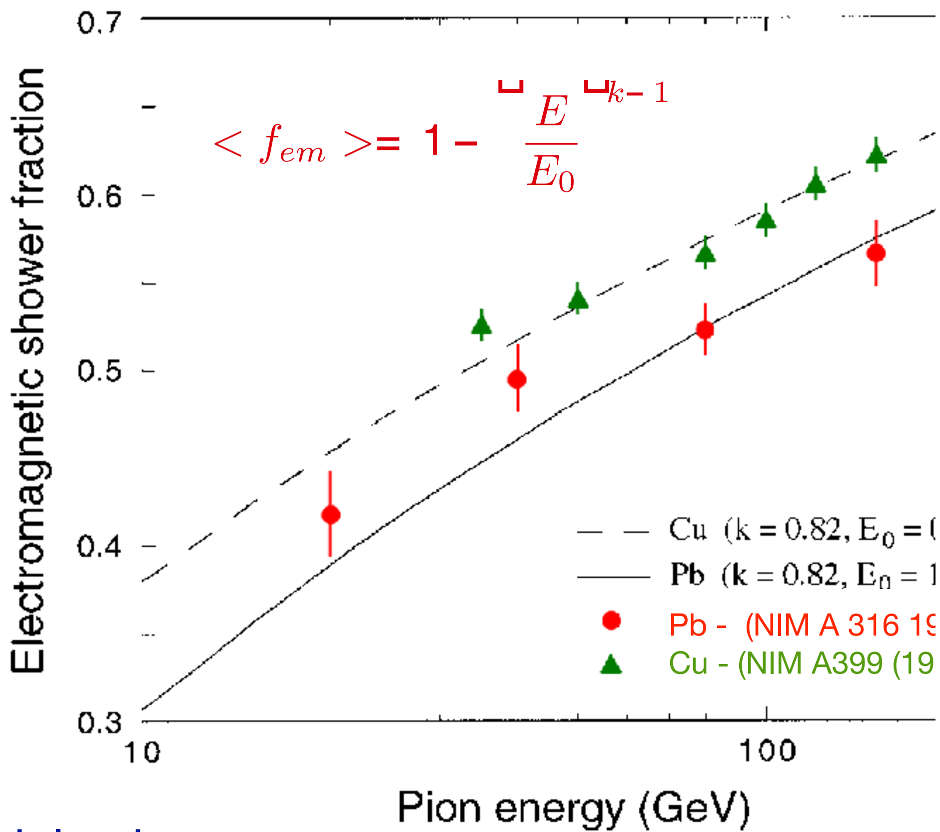
ultiplicity $<m>$ is energy dependant

ıryon number conservation neglected ⇒ f_{em}

ʌwer in proton induced showers than in pion induced ones.



$<f_{em}>$ slightly Z dependant



A more realistic Models gives

$<f_{em}> = 1 - (E/E_0)^{(k-1)}$

- E_0 = average energy needed to produce a π^0
- $(k-1)$ to take into account the average multiplicity
-

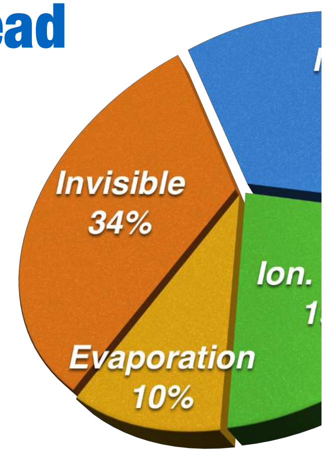
·onic Showers - Where does energy goes?

·gy deposit and
position of the non-EM
ponent of hadronic
vers in lead and iron.

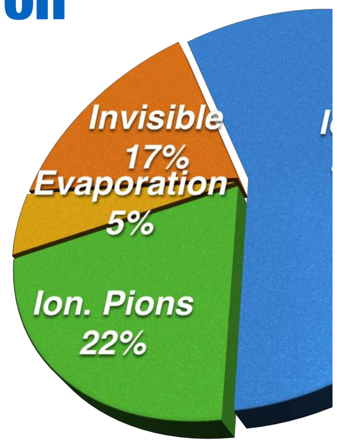
listed numbers of particles
per GeV of non-EM energy

	Lead	*Iron*
Ionization by pions	19%	21%
Ionization by protons	37%	53%
Total ionization	56%	74%
Nuclear binding energy loss	32%	16%
Target recoil	2%	5%
Total invisible energy	34%	21%
Kinetic energy evaporation neutrons	10%	5%
Number of charged pions	0.77	1.4
Number of protons	3.5	8
Number of cascade neutrons	5.4	5
Number of evaporation neutrons	31.5	5
Total number of neutrons	36.9	10
Neutrons/protons	10.5/1	1.3/1

Lead



Iron



ɪronic Showers

ɪronic shower development:
ɪate similar to e.m. case]

ɘpth (in units of λ_{int}):

$$t = \frac{x}{\lambda_{\rm int}}$$

ɪergy in depth t:

$$E(t) = \frac{E}{\langle n\rangle^t} \quad \& \quad E(t_{\rm max}) = E_{\rm thr}$$

[with $E_{thr} \approx$ 290 MeV]

$$E_{\rm thr} = \frac{E}{\langle n\rangle^{t_{\rm max}}}$$

ɪower maximum:

$$\langle n\rangle^{t_{max}} = \frac{E}{E_{\rm thr}}$$

Number of particles lower by factor E_{thr}/E_c compared to e.m. shower ...

Intrinsic resolution: worse by factor $\sqrt{E_{thr}/E_c}$

$$t_{\rm max} = \frac{\ln\left({E}/{E_{\rm thr}}\right)}{\ln\langle n\rangle}$$

But:

Only rough estimate as ...

energy sharing between shower particles fluctuates strongly ...

part of the energy is not detectable (neutrinos, binding energy); partial compensation possible (n-capture & fission)

spatial distribution varies strongly; different range of e.g. $\pi^\pm$ and π^0 ...

electromagnetic fraction, i.e. fraction of energy deposited by $\pi^0 \to \gamma\gamma$ increases with energy ...

$$f_{\rm em} \approx f_{\pi^0} \sim \ln E/(1\ {\rm GeV})$$

Explanation: charged hadron contribute to electromagnetic fraction via $\pi^- p \to \pi^0 n$; the opposite happens only rarely as π^0 travel only 0.2 μm before its decay ('one-way street') ...

At energies below 1 GeV hadrons loose their energy via ionization only ...

Thus: need Monte Carlo (GEISHA, CAL((FLUKA) to describe shower development correctly ...

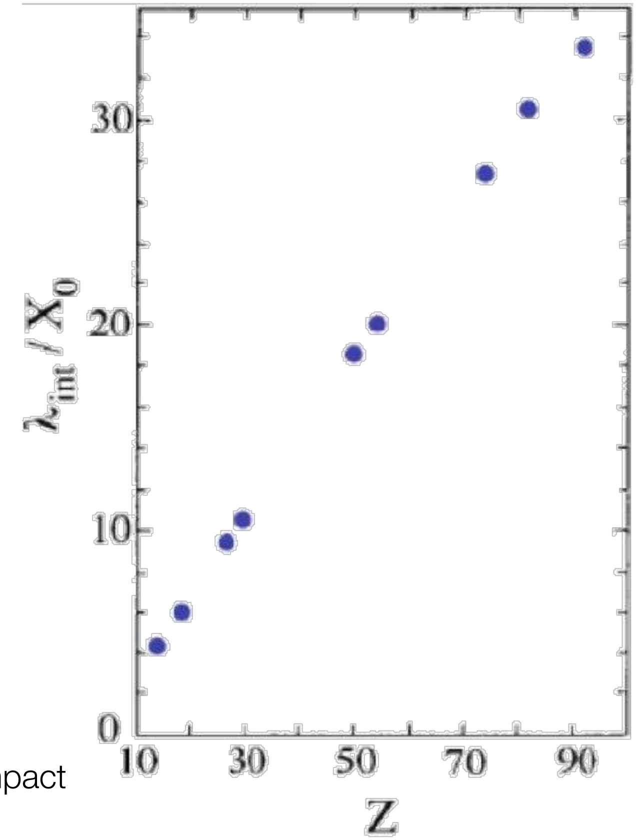
ronic Showers

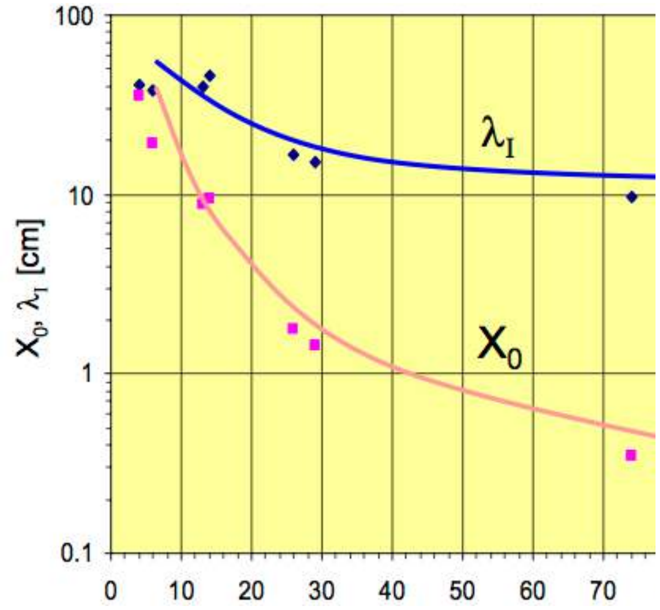
ıic vs. electromagnetic
tion length:

$$X_0 \sim \frac{A}{Z^2} \qquad \lambda_{\mathrm{int}} \,\square\, A^{1/3} \quad \rightarrow \quad \frac{\lambda_{\mathrm{int}}}{X_0} \sim A^{4/3}$$

$\lambda_{\mathrm{int}} \gg X_0$

[λ_{int}/X_0 > 30 possible; see below]





ıdinal size: 6 ... 9 λ_{int} [EM: 15-20 X_0]
[95% containment]

ərse size: one λ_{int} [EM: 2 R_M; compact
[95% containment]

Material	Z	A	ρ [g/cm³]	X_0 [g/cm²
Hydrogen (gas)	1	1.01	0.0899 (g/l)	63
Helium (gas)	2	4.00	0.1786 (g/l)	94
Beryllium	4	9.01	1.848	65.19
Carbon	6	12.01	2.265	43
Nitrogen (gas)	7	14.01	1.25 (g/l)	38
Oxygen (gas)	8	16.00	1.428 (g/l)	34
Aluminium	13	26.98	2.7	24
Silicon	14	28.09	2.33	22
Iron	26	55.85	7.87	13.9
Copper	29	63.55	8.96	12.9
Tungsten	74	183.85	19.3	6.8
Lead	82	207.19	11.35	6.4
Uranium	92	238.03	18.95	6.0

ıic calorimeter need more depth
ectromagnetic calorimeter ...

The hadronic shower profiles are governed by the
nuclear interaction length (λ_{int}) *[g/cm²]*
i.e. the average distance hadrons travel before inducing a nuclear interaction.

dronic Showers Longitudinal Profile

Longitudinal shower development:

Strong peak near λ_{int} ...
followed by exponential decrease ....

Shower depth:

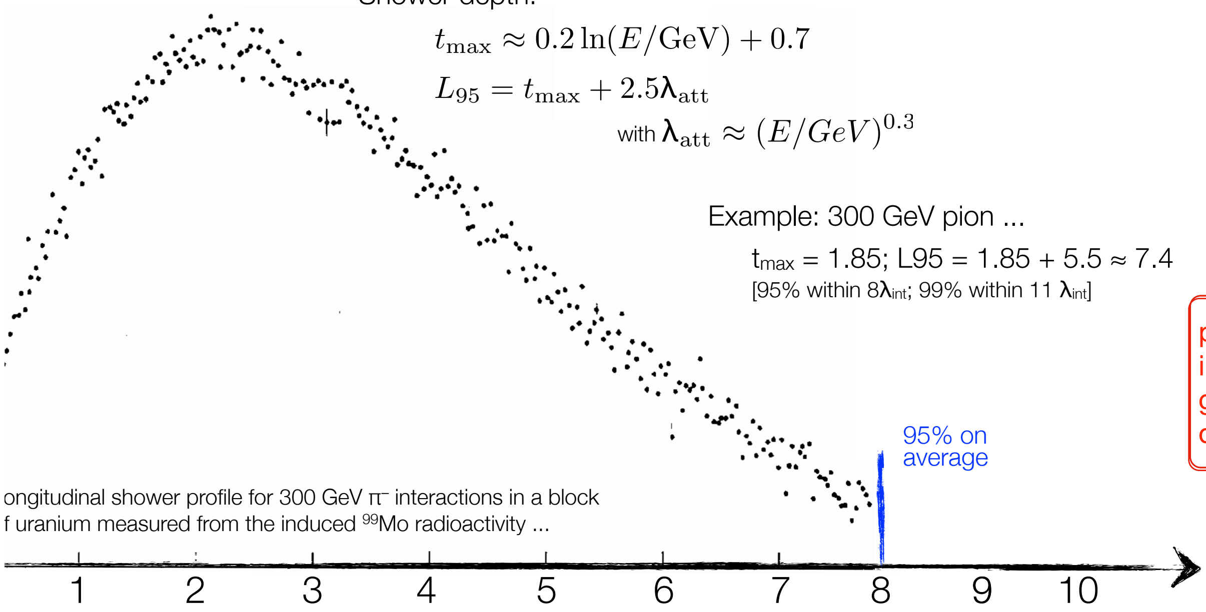
$$t_{max} \approx 0.2 \ln(E/\mathrm{GeV}) + 0.7$$

$$L_{95} = t_{max} + 2.5\lambda_{att}$$

with $\lambda_{att} \approx (E/GeV)^{0.3}$

Example: 300 GeV pion ...

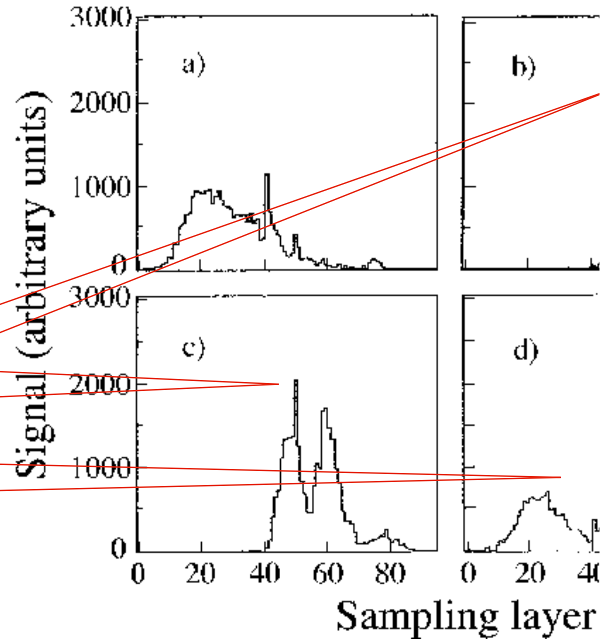
t_{max} = 1.85; L95 = 1.85 + 5.5 ≈ 7.4
[95% within 8λ_{int}; 99% within 11 λ_{int}]



ongitudinal shower profile for 300 GeV π^- interactions in a block f uranium measured from the induced ^{99}Mo radioactivity ...

- Another important difference between EM and hadronic showers is the large variety of profiles for the latter.

270 GeV Pion Longitudinal



production of energetic π^0s in the second/third generation of the shower development.

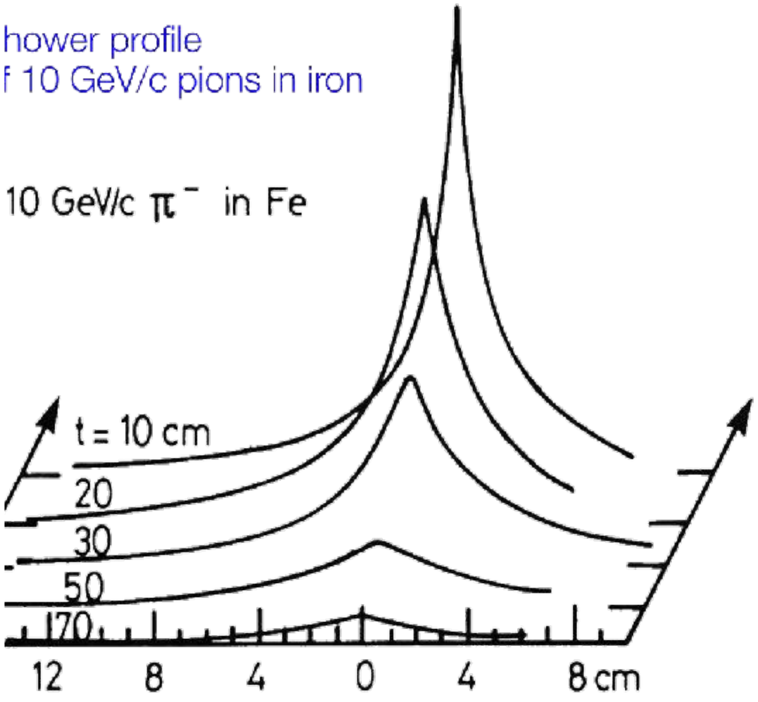
90% of hadronic shower particles are pions.

- Neutral pions decay in 2 γ,
  ↳ develop EM showers.

- Nuclear reactions occurs releasing Neutror and protons. The energy for this to occur does not generate any calorimeter signals.
  - This is the invisible-energy phenomenon

ıronic Showers Profile

hower profile
f 10 GeV/c pions in iron



Lateral shower position [cm]

Transverse Shower profile

Typical transverse momenta of secondaries: $\langle p_t \rangle \simeq 350\ MeV/c$

Lateral extend at shower maximum: $R_{95\%} \simeq \lambda_{int}$

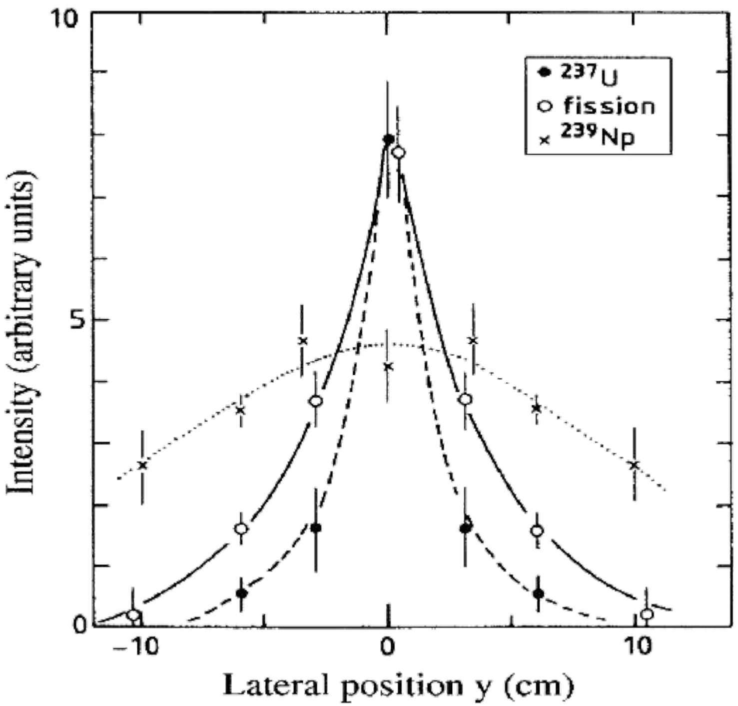
Electromagnetic component leads to a relatively well-defined core $R \simeq R_M$

Exponential decay after shower maximum

:eral Profile for 300 GeV π^-

ȷet material ^{238}U]
asured at depth 4 λ_{int}]

ıre π0 and γ in core
ergetic neutrons and charged pions form a wider core
ermal neutron generates broad tail



Measurement from induced radioactivity:

- ^{99}Mo (fission): neutron induc
  [energetic neutron component]
- ^{237}U: mainly produced via ^{23}
  [electromagnetic component]
- ^{239}Np: from ^{239}U decay ...
  [thermal neutrons]

Ordinate indicates decay rate of different radioactive nuclide

ıysics of Air Shower

ATMOSPHERE HYDROSTATIC APPROXIMATION

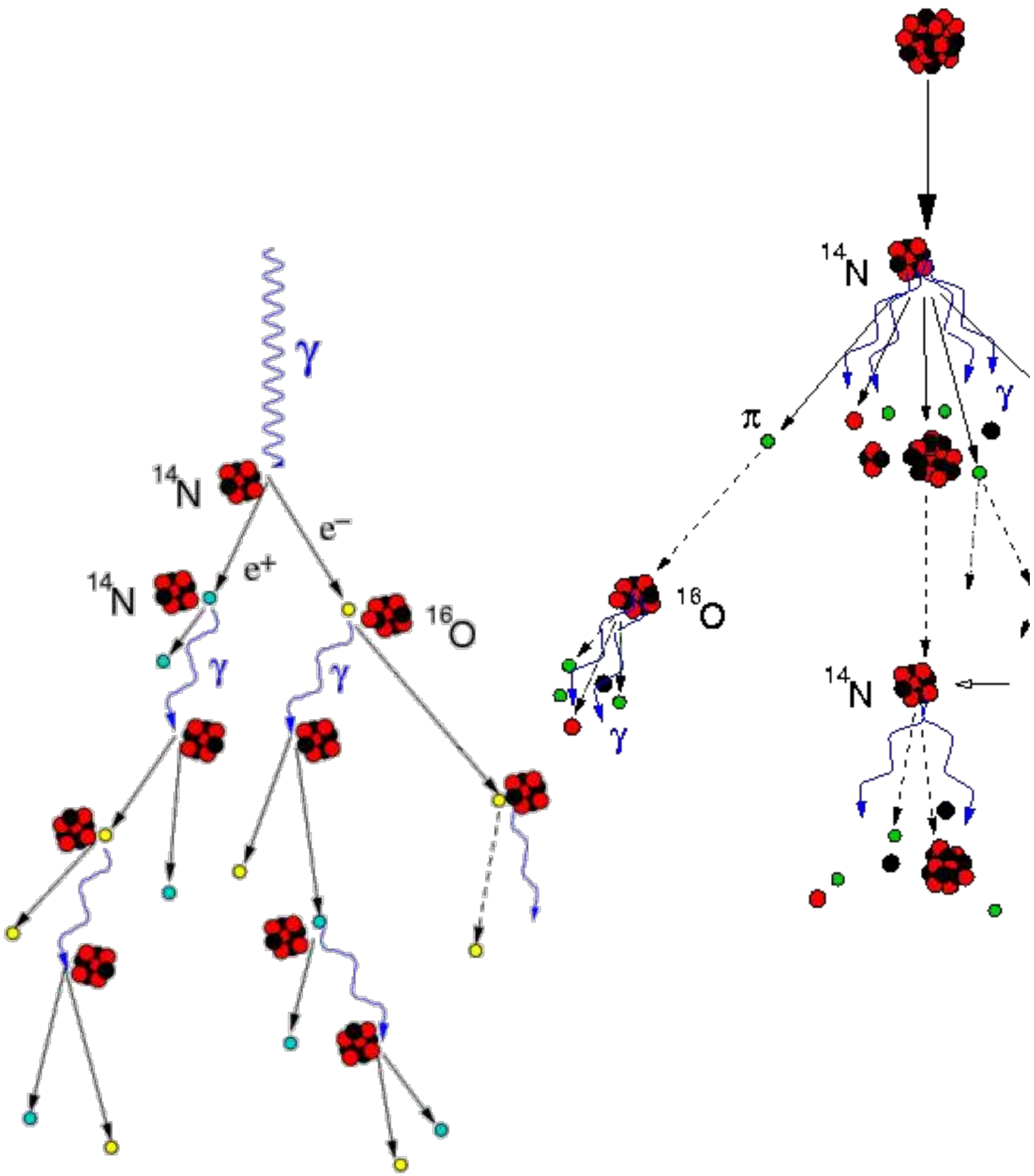
SHOWER FLUCTUATIONS

MUONS CONTENT

SUPERPOSITION MODEL

CHERENKOV RADIATION

FLORESCENCE



Atmosphere is a calorimeter

cosmic rays imping on the atmosphere they
t and produce shower exactly like into a
neter

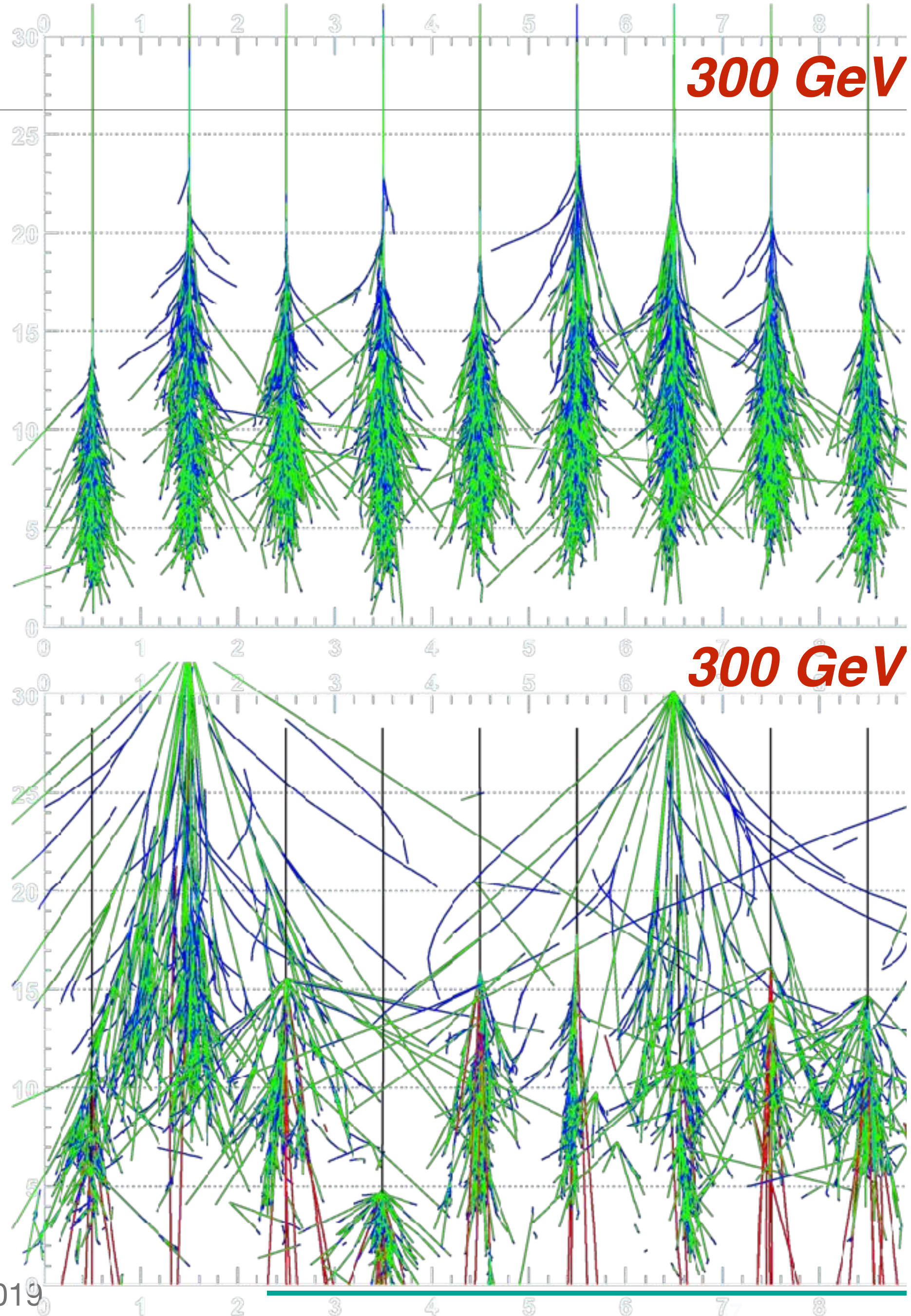
ertical shower, it is a calorimeter of about 26 X_0
on length) and 15 λ (interaction length)

calorimeter has 27 X_0. and 11 λ !

phere is a strongly inhomogeneous material. Its
, and then X_0, varies with altitude, atmospheric
ons (pressure, temperature).

nsity of air diminishes six orders of magnitude
he altitude goes from sea level (~ 1.0 kg/cm^2, X_0
n) up to 100 km, and another six orders in the
of 100 km to 300 km.

models exist and have been used/developed by
periment (HESS,VERITAS, AGASA, Pierre
HiRes).



er model of Gamma-Shower

ıodel showed so far for EM shower is still le' for air shower.

sphere can be approximate as a chemical ɛnt with Z~7 ⇒ Ec≈85 MeV.

s more or less ok (7.4 X_0) BUT

ʒ40 is almost twice the measured value!

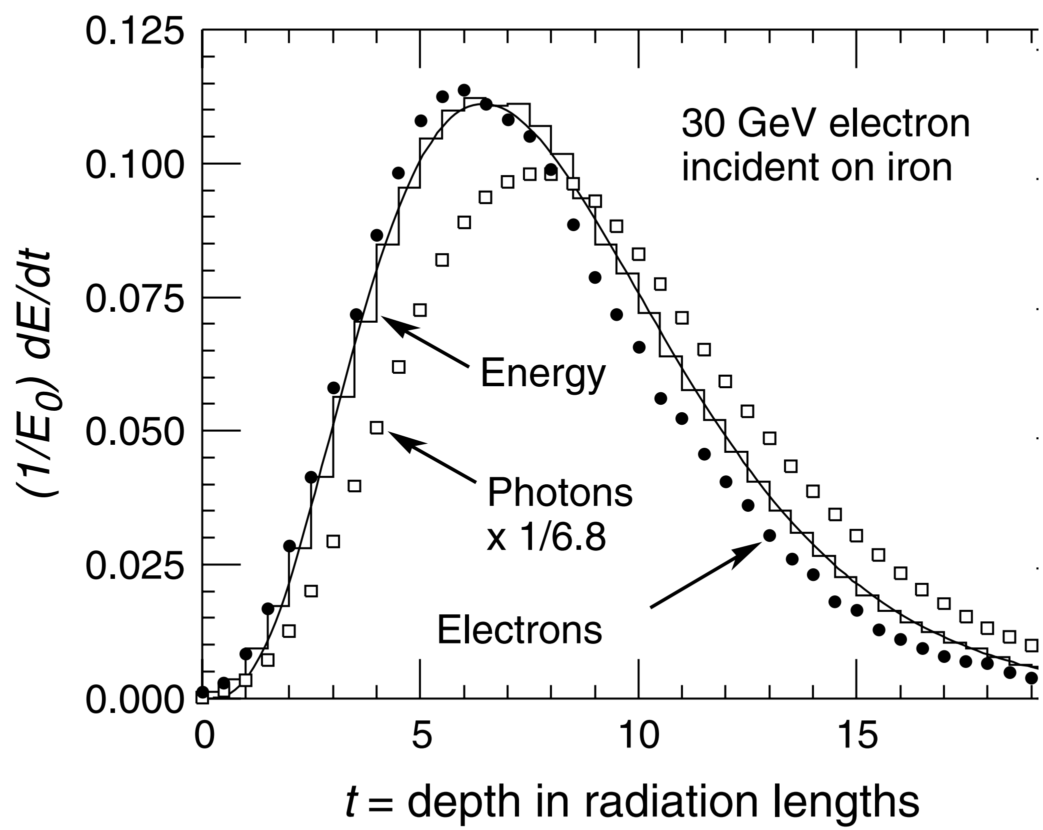
restimate gamma/electron ratio $N_e \approx 2/3\ N_{max}$.

ɔrrection fact is used $N_e \approx N_{max}/g$ where $g \approx 10$

theless the model reproduces

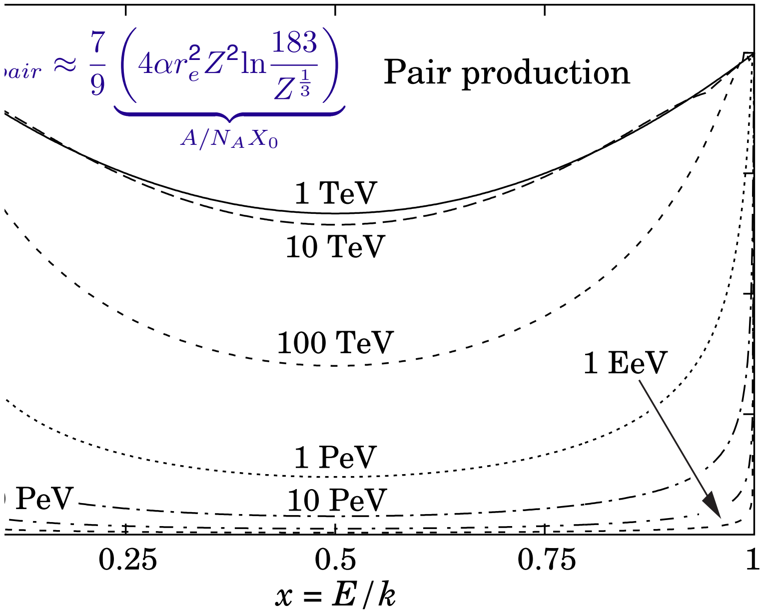
maximum size of the shower is proportional E,

depth of maximum increases logarithmically with ɾgy, at a rate of 85 g/cm² per decade of primary ɾgy.



ɔR UHECR SOME OTHER EFFECT NEEDS TO BE TAKEN INTO ACCOUNT

ıu-Pomeranchuk Migdal Effect



h energies Landau Pomeranchuk Migdal effect:

m mechanical interference between amplitudes fferent scattering centers;

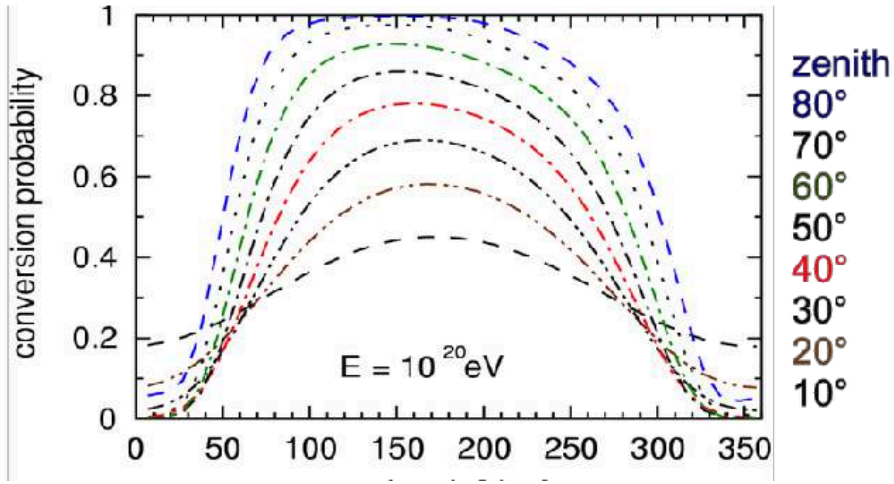
t scale formation length - length over which highly stic electron and photon split apart.

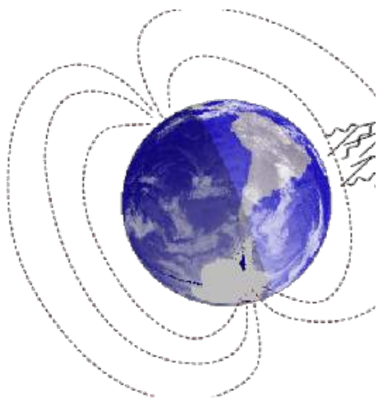
ence (generally) destructive → reduced cross for a given, very high photon energy

isible for $E(1\text{-}x)>E_{LPM}$

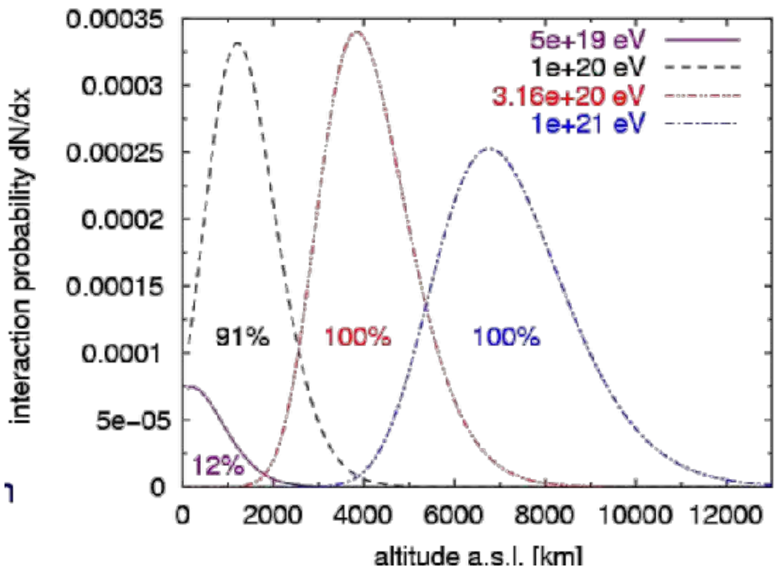
$.7\ X_0$ *TeV/cm*

Geomagnetic pre-Showerin



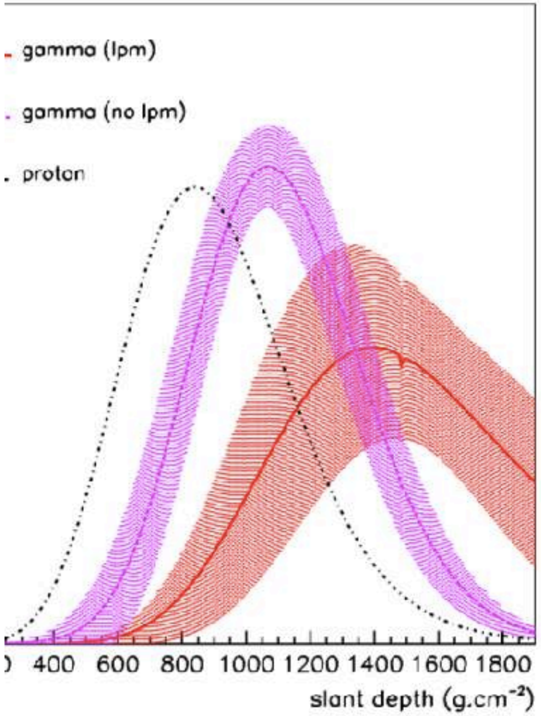


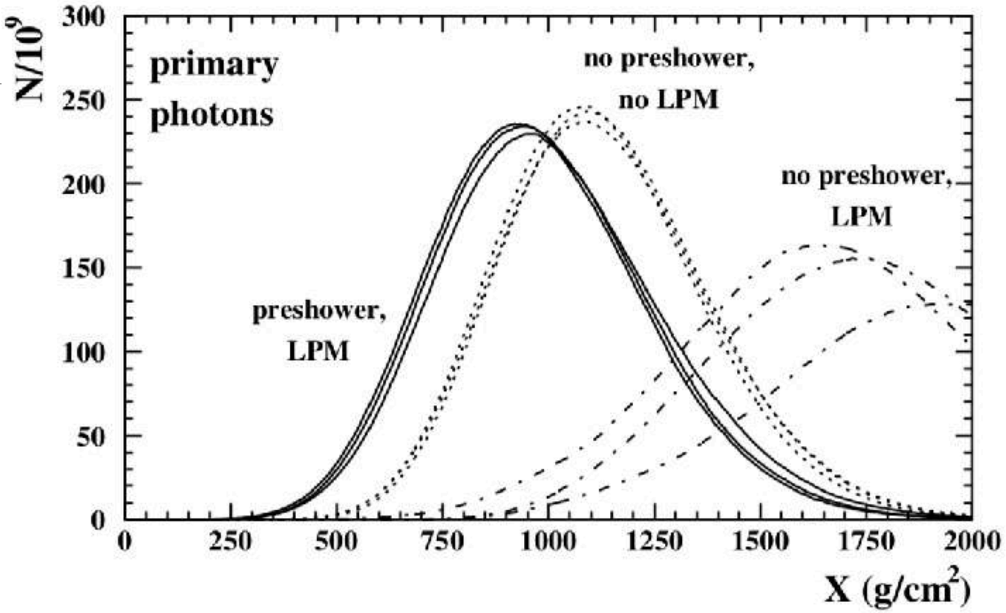
Interaction probability (strong field)



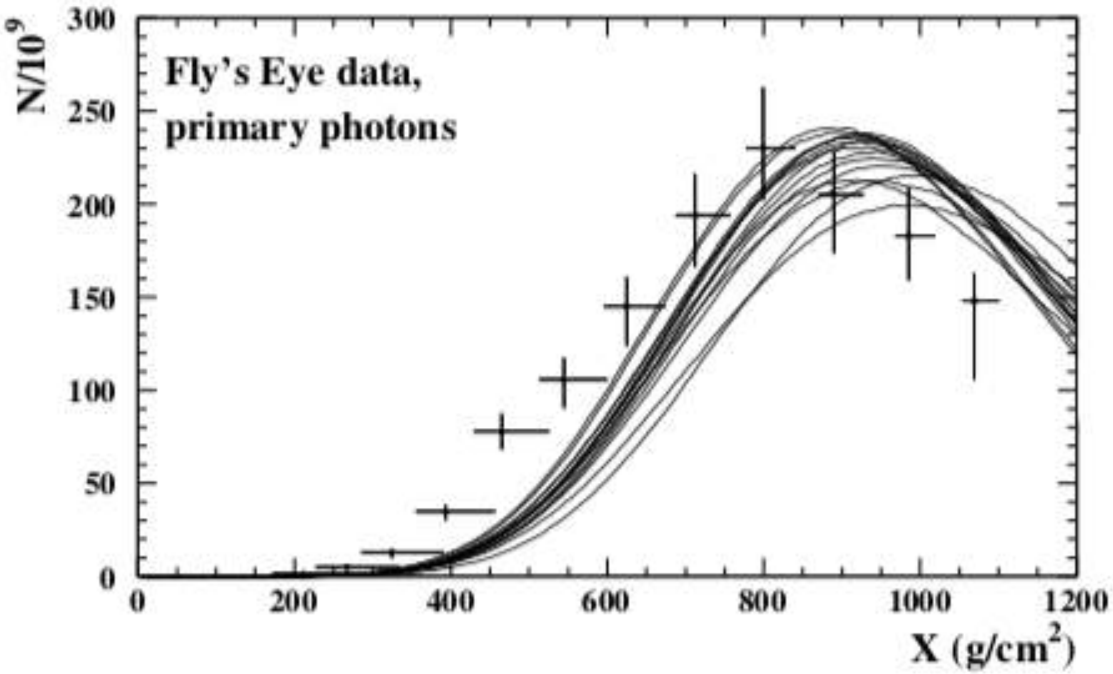
A UHE gamma ray crossing lines can produce, $e^{\pm}$ pair v synchrotron-radiate in the n producing additional high-e rays.

A different cascade develop effect is similar to adding s lengths above the atmosph


gamma (lpm)
gamma (no lpm)
proton
400 600 800 1000 1200 1400 1600 1800
slant depth (g.cm^{-2})


N/10^9
primary photons
no preshower, no LPM
no preshower, LPM
preshower, LPM
X (g/cm^2)

e Signature


N/10^9
Fly's Eye data, primary photons
X (g/cm^2)

er model of Hadron-Shower

lready showed that we can model the hadronic shower
arly to what done for EM where we use interaction
h λ_I as we use X_0 for EM

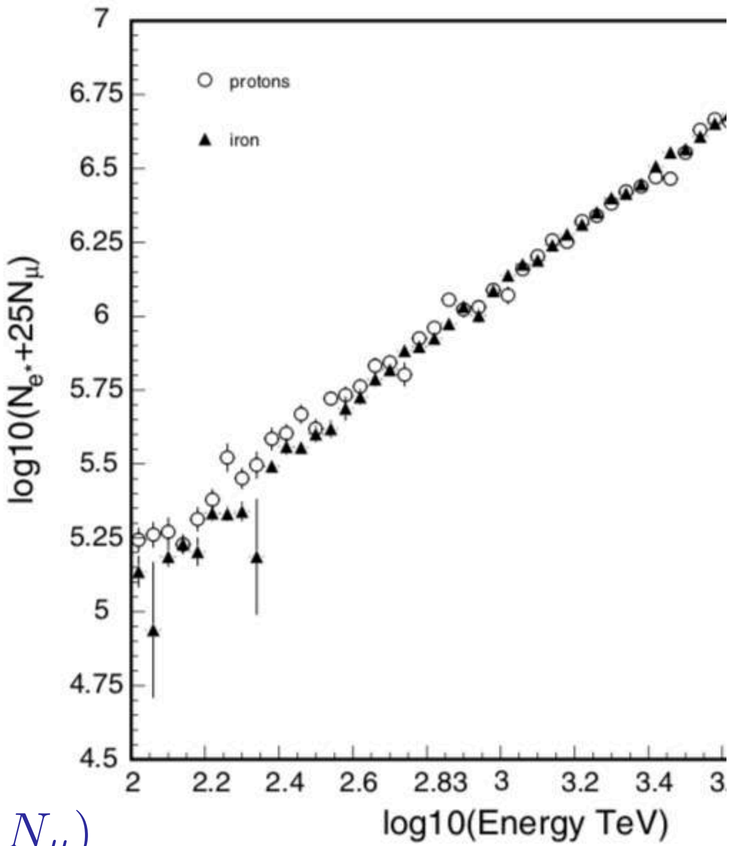
hadronization' produce pions. They loose energy until
reach their E_c and decay in muons, so $N_\mu = N_\pi$.

the end we will measure $\gamma/e^\pm$ and μ.

s show by Matthew that reasonable assumptions are

)= 85 MeV ; $E_c(\pi)$= 20 GeV; λ_I=120g/cm^2; g=10;

$$E_c^e N_{max} + E_c^\pi N_\mu = g E_c^e \left(N_e + \frac{E_c^\pi}{g E_c^e} N_\mu \right) \approx 0.85\ GeV(N_e + 23.5\ N_\mu)$$



r position model

leus of mass A and energy E_0 acts like A independent
leons with energy $E_n = E_0/A$

$$N_{max} = E_0/E_C = A E_n/E_c$$

$$X_{max}^A \square \lambda_e \ln(E_0/A)$$

$$N_\mu^A = A \left(A \frac{E_0}{E_c^\pi} \right)^\alpha = A^{1-\alpha} N_\mu$$

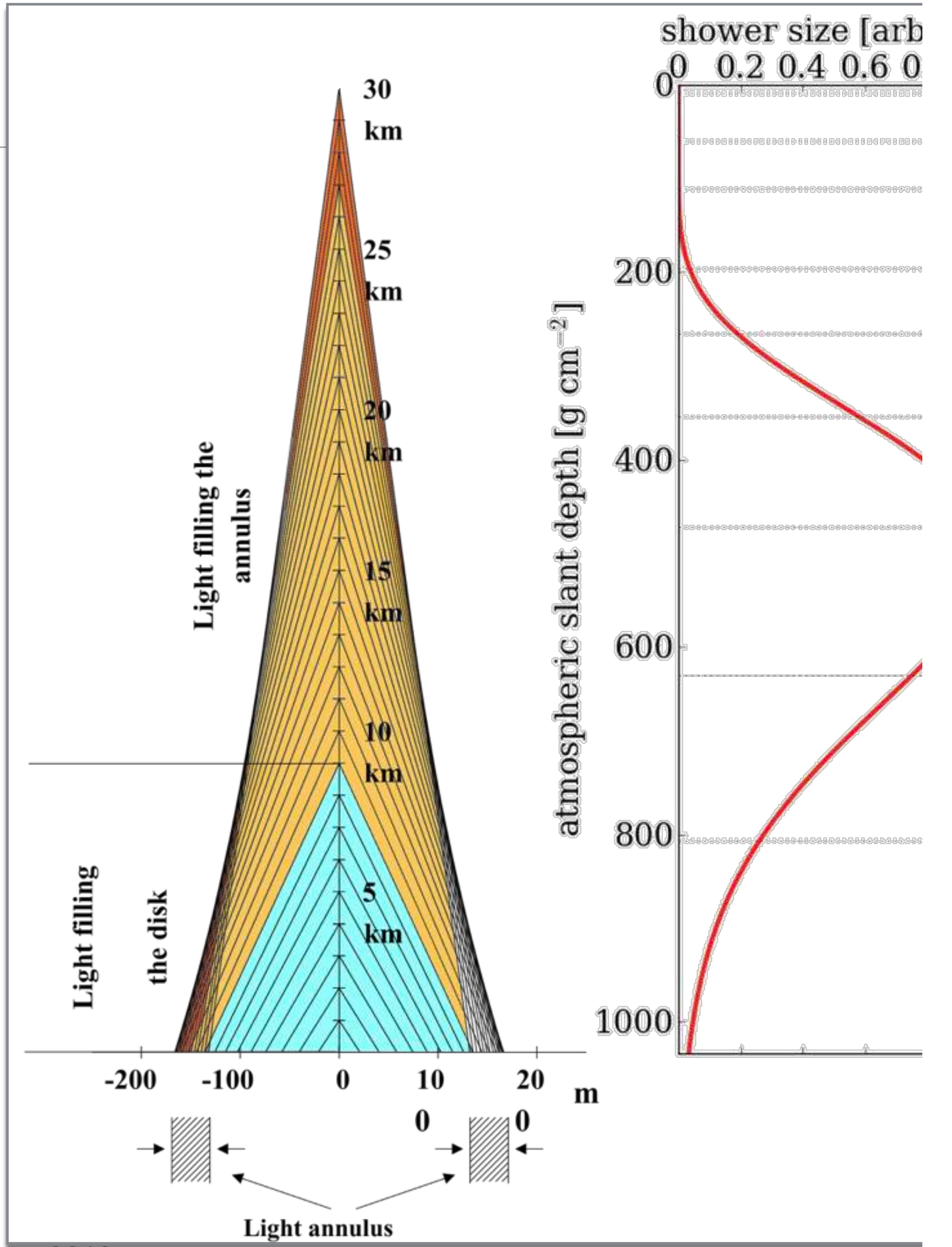
Matthew, Astroparticle Physics 22 (2005) 387-

t we would like to measure

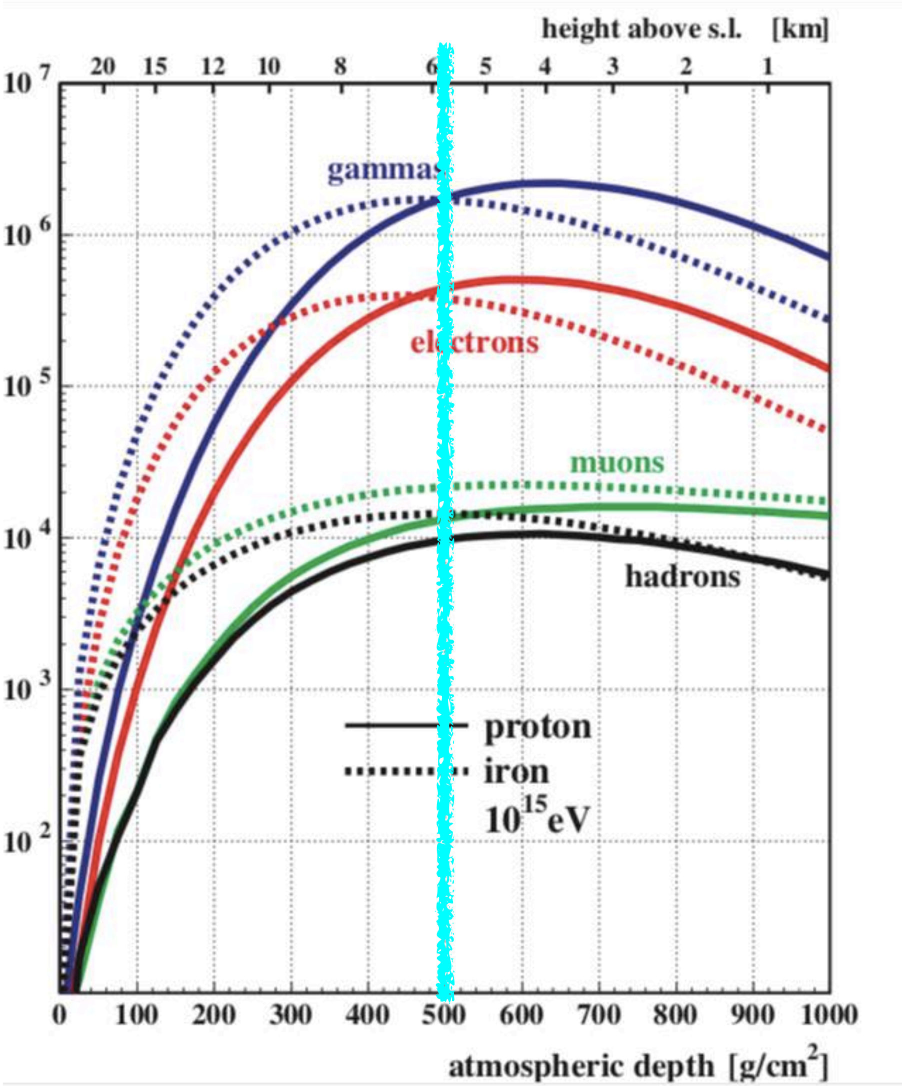
- ːrgy
- ːction
- ɔarate Gamma/hadron
- ɔarate Different Nuclei

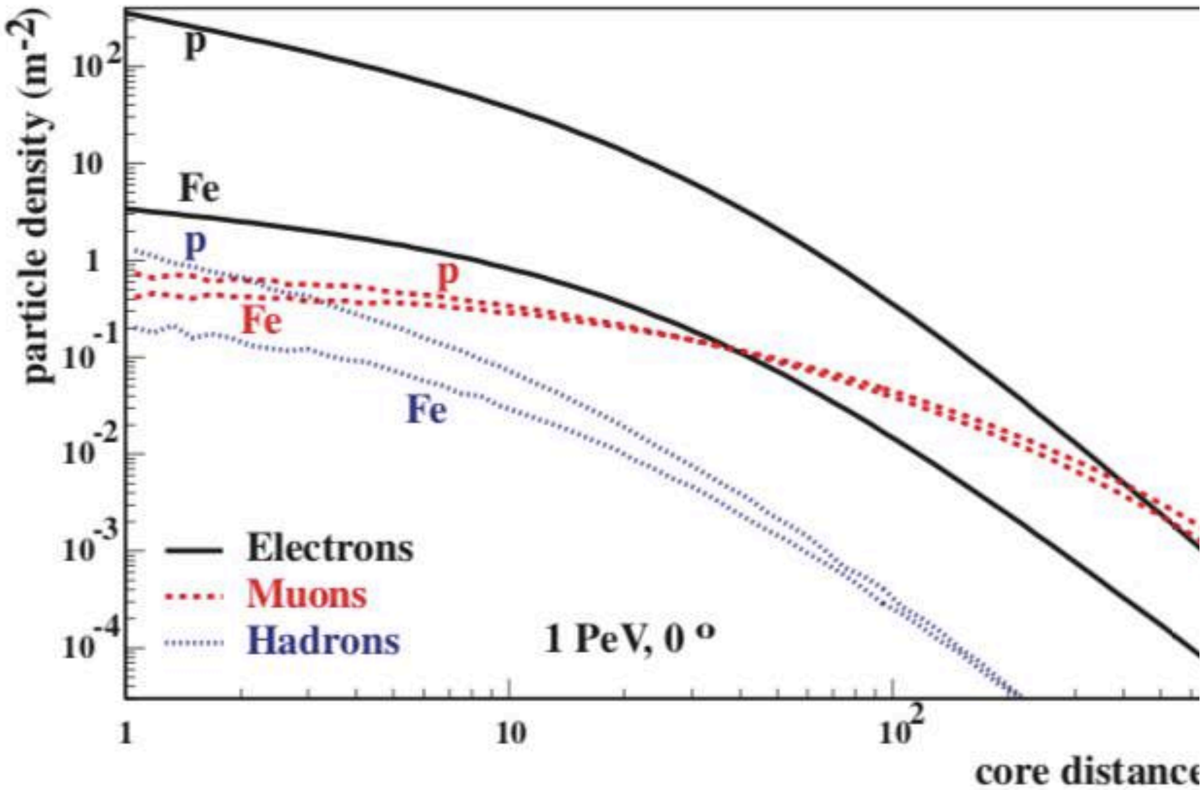
t can we measure [estimate]

- ːged Particle
  - ːharged
- nax
- ɹon content
- ıower Lateral Density Profile LDF (transverse profile)
- ːons
- ıerenkov Light
- ɹorescent Light

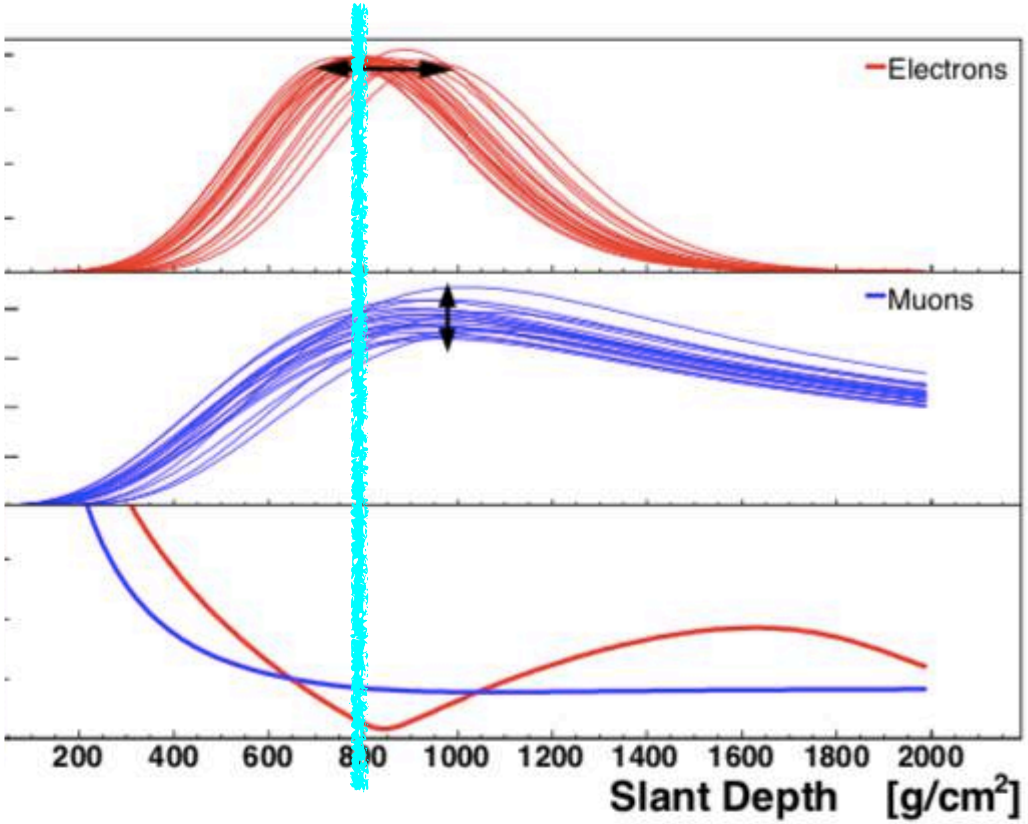


wer shapes has information But….

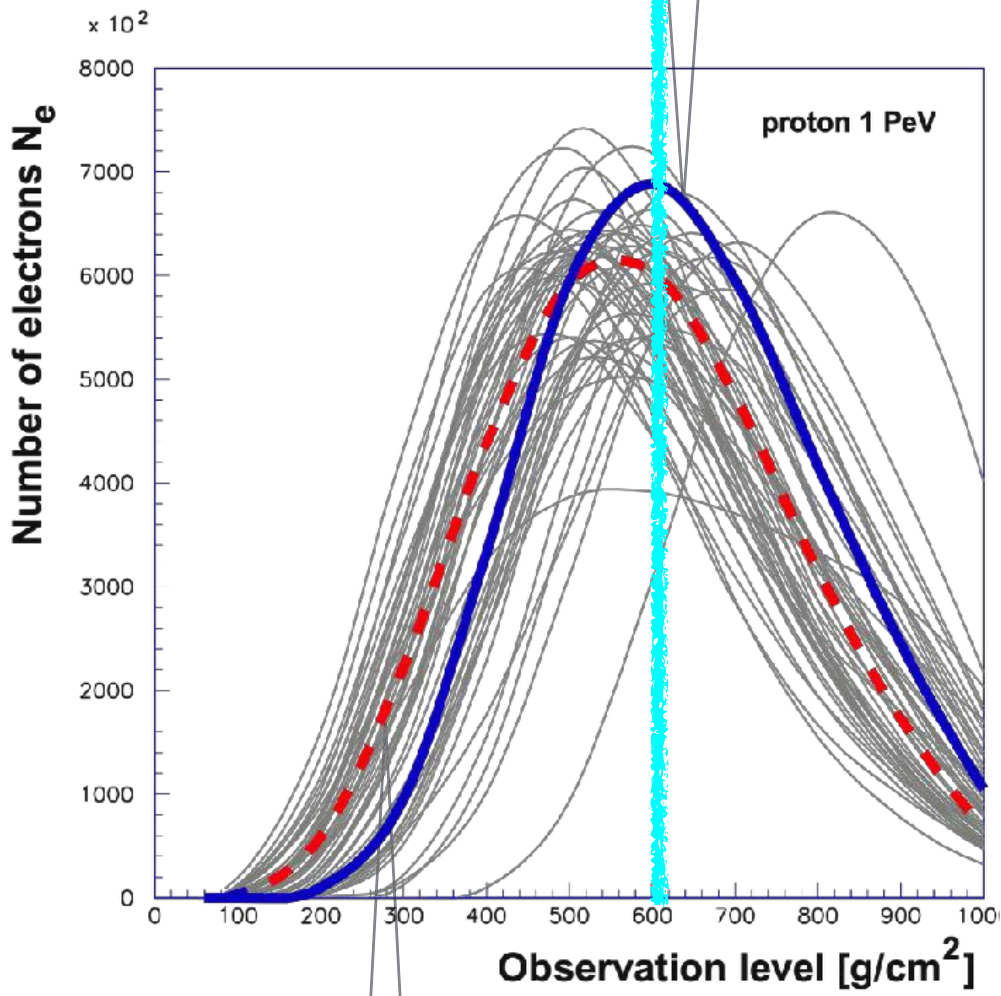




re are fluctuations



Shower with an N_e = <N_e>



Shower with an X_{max} = <X_{max}>

ıe Parametrisation

ısser-Hillas

$$) = N_{\max} \left(\frac{X - X_0}{X_{\max} - X_0} \right)^{\frac{X_{\max} - X_0}{\lambda}} \cdot e^{\frac{X_{\max} - X}{\lambda}} \qquad \xi \equiv \frac{X_{\max} - X_0}{\lambda} \qquad \varepsilon \equiv \frac{X - X_{\max}}{X_{\max} - X_0}$$

$$; N_{\max}, X_{\max}, X_0, \lambda)_{\mathrm{GH}} = N_{\max} (1+\epsilon)^{\xi}\, \mathrm{e}^{-(\epsilon\xi)} \qquad \int_0^{\infty} N(X)_{\mathrm{GH}}\, \mathrm{d}X = N_{\max} W \xi^{-(\xi+1)}\, \mathrm{e}^{\xi} \Gamma(\xi + 1$$

eisen

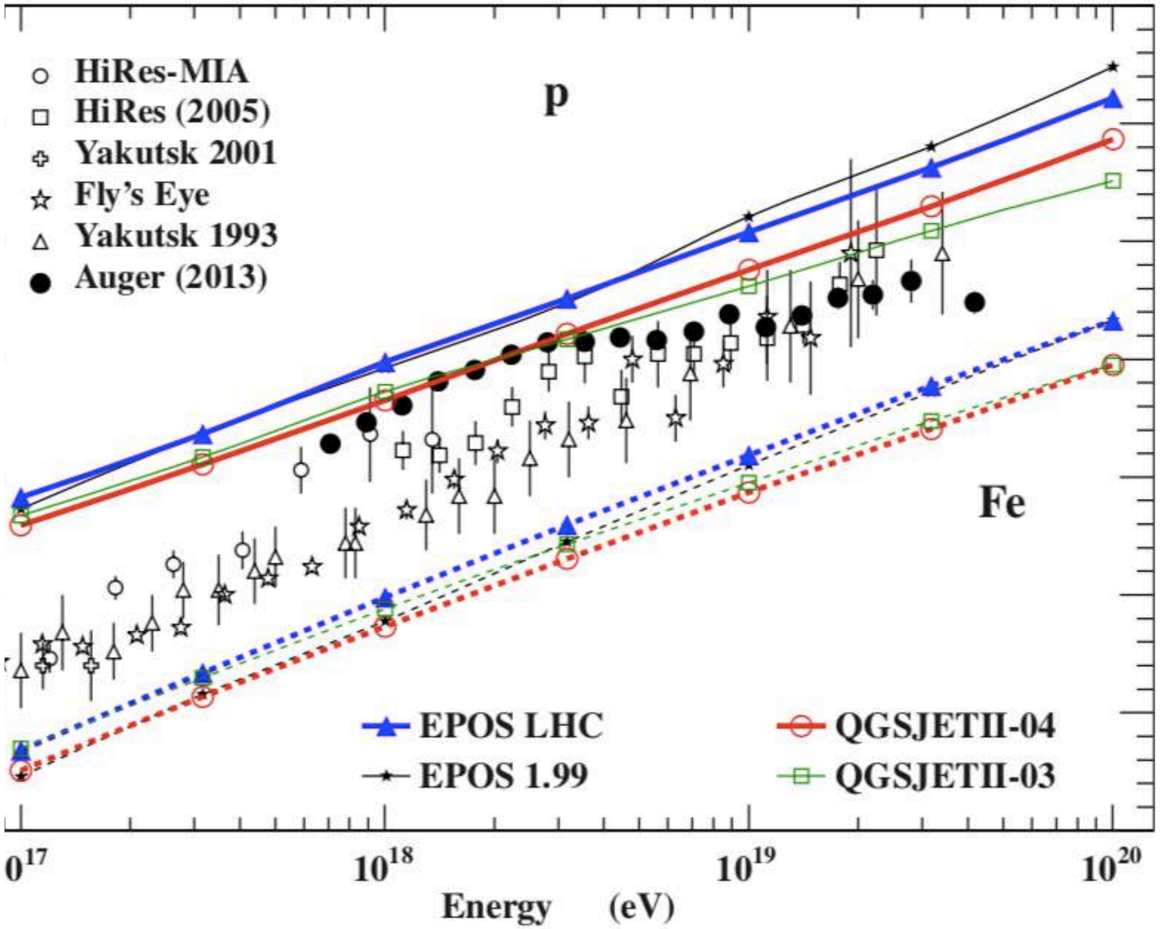
$$) = \frac{0.31}{\sqrt{y}} \exp\left(t \left(1 - \frac{3}{2} \ln(s) \right) \right) \longrightarrow \overline{N_e}(t) = \frac{0.31}{\sqrt{y}} \left(\frac{E_0}{E_c} \right)$$

$$\frac{3t}{t + 2y} \qquad y = \ln\left(\frac{E_0}{E_c} \right)$$

s* is the *shower age

E0	Tmax	Alt(km)	Ne(tı
30 GeV	216	12	5(
1 TeV	345	8	12(
1 PeV	600	4.4	9x1
10^{19} eV	936	1.2	7.4 x

Simulation & Data



- X_{max} estimation relies on MC simulatic
- Many model exists, but their tuning is complex
- Accelerator data helps, but we need t extrapolate to much higher energies w other process enter the games.
- Models still gives different result, but a present they give correct behaviour, a existing data are consistent

- Lateral Distribution function

$$\cdot) = \frac{N_{\text{ch}}}{2\pi r_0^2} \cdot C \cdot \left(\frac{r}{r_0}\right)^{s-2} \cdot \left(1 + \frac{r}{r_0}\right)^{s-4.5}$$

NISHIMURA–KAMATA–GREISEN (NK

$$= k\, r^{-(\eta + r/r_0)} \qquad \text{for } r < 800\,\text{m}$$

$$= \left(\tfrac{1}{800}\right)^{\beta} k r^{-(\eta + r/r_0) + \beta} \qquad \text{for } r > 800\,\text{m}$$

HAVERAH PARK

$$= \frac{1.75 \times 10^{-3} N_{\text{ch}}}{r} \exp\left(-\frac{r}{80\,\text{m}}\right) \qquad \text{for } r = 3\text{–}140\,\text{m}$$

$$= 2.25 \cdot N_{\text{ch}} r^{-2.8} \qquad \text{for } r = 140\text{–}1000\,\text{m}.$$

$$= \frac{14.4 \cdot r^{-0.75}}{(1 + r/320\,\text{m})^{2.5}} \cdot \left(\frac{N_\mu}{10^6}\right)^{0.75} \cdot \frac{51\,\text{GeV}}{E_{\text{th}} + 50\,\text{GeV}} \left(\frac{3}{E_{\text{th}} + 2\,\text{GeV}}\right)^{(0.14 \cdot r^{0.37})}.$$

GREISEN - MUON COMPONEN

$$\rho_\mu(r) \propto r^{-\alpha} \exp\left(-\frac{r}{r_0}\right).$$

- Lateral Distribution function

$$) = \frac{N_{ch}}{2\pi r_0^2} \cdot C_1 \cdot \left(\frac{r}{r_0}\right)^{s-2} \cdot \left(1 + \frac{r}{r_0}\right)^{s-4.5} \cdot \left(1 + C_2 \left(\frac{r}{r_0}\right)^{d}\right)$$

GREI

$$= k\, r^{-(\eta + r/r_0)} \qquad \text{for } r < 800\,\text{m}$$

$$= \left(\tfrac{1}{800}\right)^{\beta} k r^{-(\eta + r/r_0)+\beta} \qquad \text{for } r > 800\,\text{m}$$

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GREISEN - MUON COMPONEN

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- Lateral Distribution function

$$) = \frac{N_{ch}}{2\pi r_0^2} \cdot C_3 \cdot \left(\frac{r}{r_0}\right)^{s-2} \cdot \left(1 + \frac{r}{r_0}\right)^{s-4.5} \cdot \left(1 + \beta \frac{r}{r_0}\right)^{\nu}$$

AKE

$$= k\, r^{-(\eta + r/r_0)} \qquad \text{for } r < 800\,\text{m}$$

$$= \left(\tfrac{1}{800}\right)^{\beta} k r^{-(\eta + r/r_0)+\beta} \qquad \text{for } r > 800\,\text{m}$$

HAVERAH PARK

$$) = \frac{1.75 \times 10^{-3} N_{ch}}{r} \exp\left(-\frac{r}{80\,\text{m}}\right) \qquad \text{for } r = 3\text{–}140\,\text{m}$$

$$) = 2.25 \cdot N_{ch} r^{-2.8} \qquad \text{for } r = 140\text{–}1000\,\text{m}.$$

$$) = \frac{14.4 \cdot r^{-0.75}}{(1 + r/320\,\text{m})^{2.5}} \cdot \left(\frac{N_\mu}{10^6}\right)^{0.75} \cdot \frac{51\,\text{GeV}}{E_{th} + 50\,\text{GeV}} \left(\frac{3}{E_{th} + 2\,\text{GeV}}\right)^{(0.14 \cdot r^{0.37})}.$$

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