A comparative study of CORSIKA and COSMOS extensive air shower simulations

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Ultra-High Energy Cosmic rays

- **Cosmic rays (CRs) with energies exceeding 10^{18}eV** ,
  above ankle

- **Mysteries of the UHECRs**
  - Where do UHECRs come from, what is the composition of UHECRs, and how are UHECRs accelerated to such extreme energies.

- **Candidates of UHECRs?**

- Relate to the most varied and powerful energy sources known in the universe.
  - ✓ Active galactic nucleus(**AGNs**), Gamma ray bursts (**GRBs**), and Cosmological shock waves

Yet, the origin of the highest energy cosmic rays remains UNKNOWN.

Extensive Air Shower (**EAS**)

- Practically difficult to directly detect cosmic rays particles on earth owing to a rare event
  - On average, $1/1km^2$/century for particles with energies $E_0 > 10^{20}$eV

- EAS
  - The primary cosmic ray collides with a molecule in the atmosphere transferring much of its energy into a shower of secondary particles.
  - billions of sub-particles at the ground → Extensive Air Shower(EAS)

- Properties of primary particles such as their chemical components, energies, and arrival directions and so on.

- Need a huge observation detector to increase detection opportunity due to low flux of UHECRs.

Air shower simulations : **COSMOS & CORSIKA**

- **Air shower M.C simulation**
  - Detailed simulations of extensive air showers(EAS) initiated by high energy cosmic ray particles.
  - Evolutions and properties of EAS in the atmosphere.

- Comparison between CORSIKA and COSMOS under the same conditions
  - longitudinal distribution of particle, Xmax, kinetic energy distribution at the ground, and calorimetric energy in EAS.

Air shower simulations : **COSMOS & CORSIKA**

- Atmospheric environment
- Observation level (1430m above sea level)
- Threshold energy of each particles

(photons and electron = 500KeV, muon and hadron = 50MeV)

- Hadronic interaction model at the highest energy

(E > 80GeV, QGSJET2-03)

- Algorithm to reduce CPU time and disk space

(Thinning and weight)

- Hadronic interaction model at the low energy (E < 80GeV)

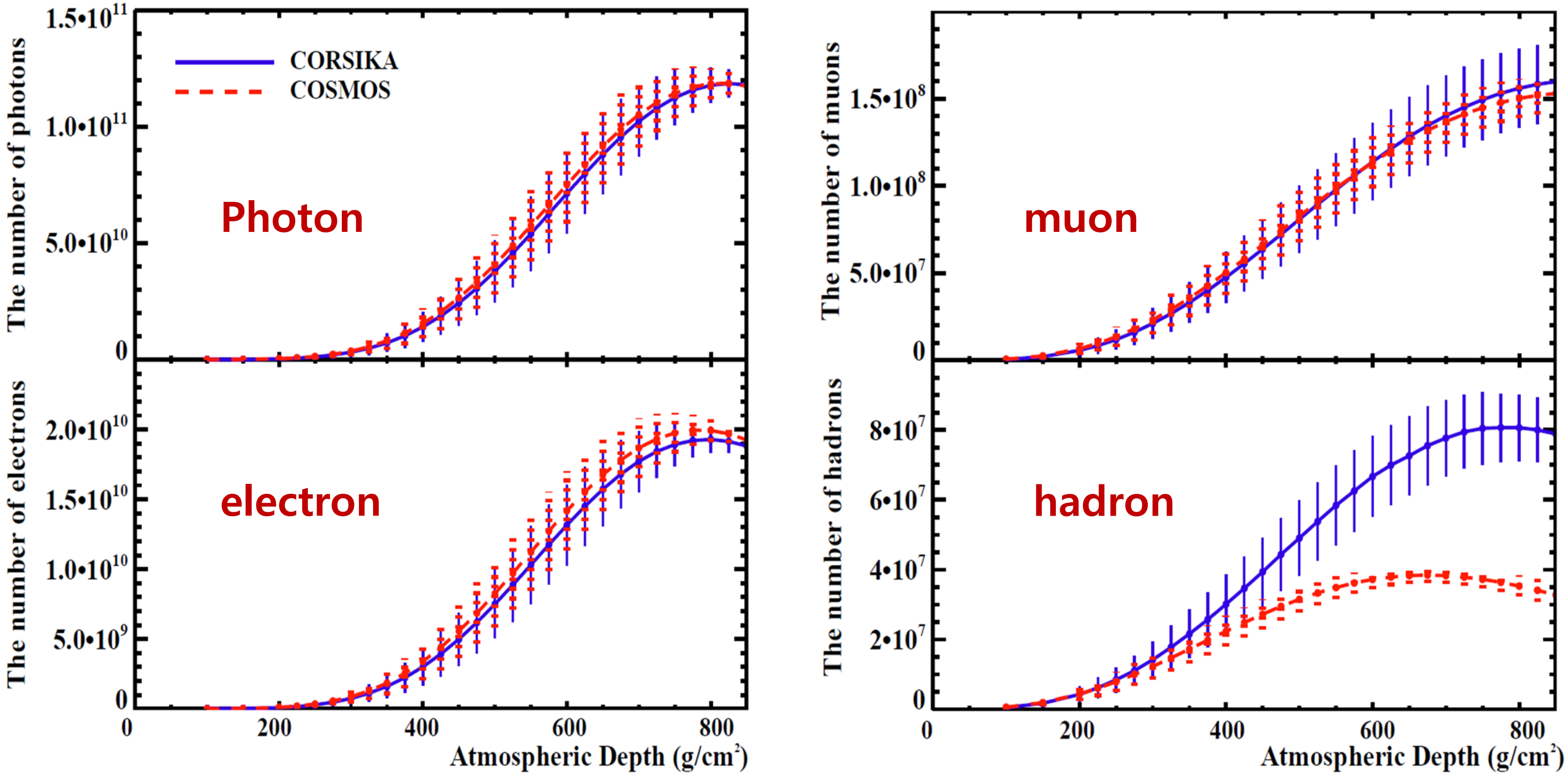
phits and jam for COSMOS, Fluka for CORSIKA

Propagation of air shower : **Longitudinal distribution**

Proton primary

Primary energy : $10^{19.5}$ eV
Zenith angle : 0° (vertical shower)

Photons, electrons, muons, hadrons as a function of Atmospheric depth (g/cm^2)



Hadron(=pion + kaon + nucleon)

X_{max} : shower maximum depth

- X_{max} : Correlated with the mass composition of cosmic ray.

- **Equation 1**

The EAS has a longitudinal distribution usually represented by the Gaisser-Hillas function giving the approximate number of electrons as a function of atmospheric depth X :

$$N_{e,max}(t) = N_{max}\left(\frac{X - X_0}{X_{max} - X_0}\right)^{\frac{X_{max}-X_0}{\lambda}} \exp\left(\frac{X_{max} - X}{\lambda}\right)$$

where λ is the interaction mean free path, normally it is fixed to a value of 70g/cm^2 of protons for both proton and iron.

$N_{e,max}$: maximum number of electrons.

x_0 : depth at which the first interaction occurs.

X_{max} : Shower maximum point

- **Equation 2**

$$N_{e,\max}(t) = a\left(\frac{X}{b}\right)^{c} \exp\left[-d\left((\frac{X}{b})\right)^{e}\right]$$

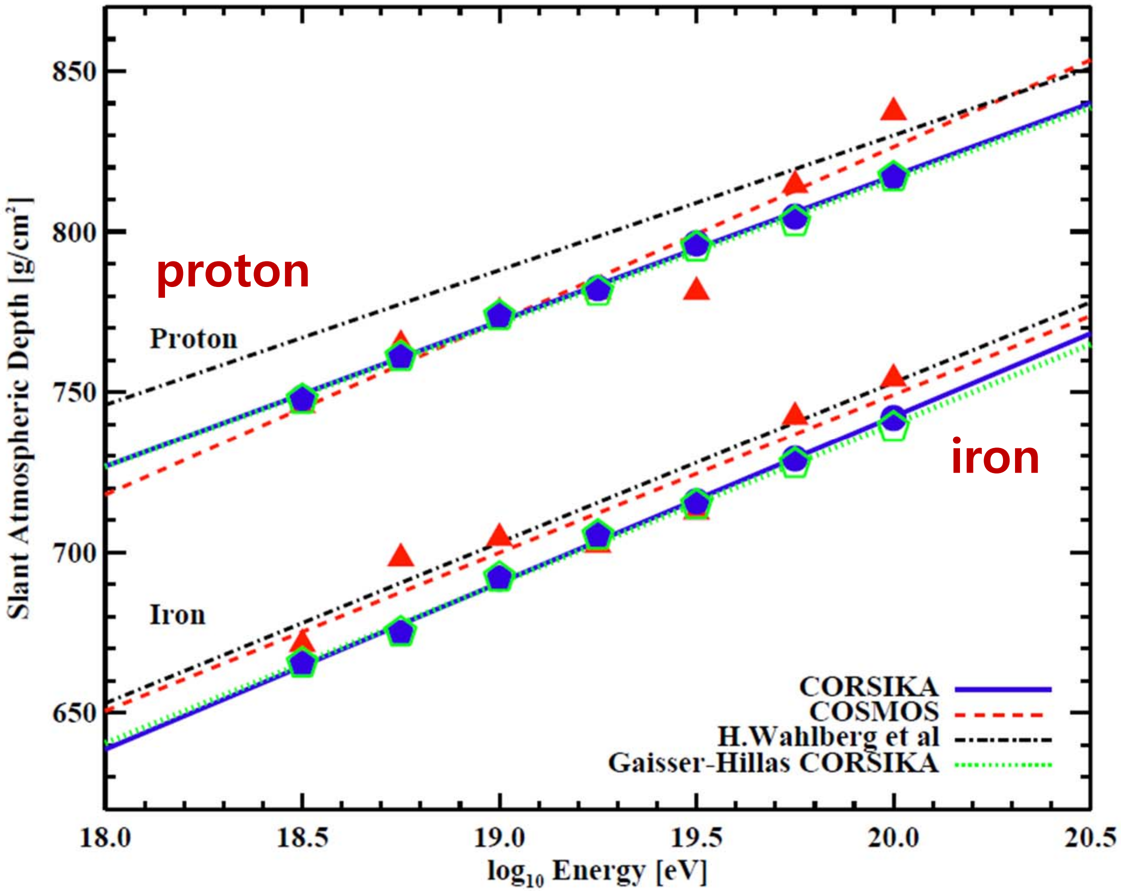
- where, a, b, c, d, and e are free parameters to evaluate X_{max}

$$X_{\max} = b(c/d/e)^{\frac{1}{e}}$$

This equation seems to work better for estimation of X_{max}.

X_{max} : Shower maximum point

Zenith angle : 0°, 18.2°, 25.8°, 31.75°, and 45°



X_{max} : Shower maximum point

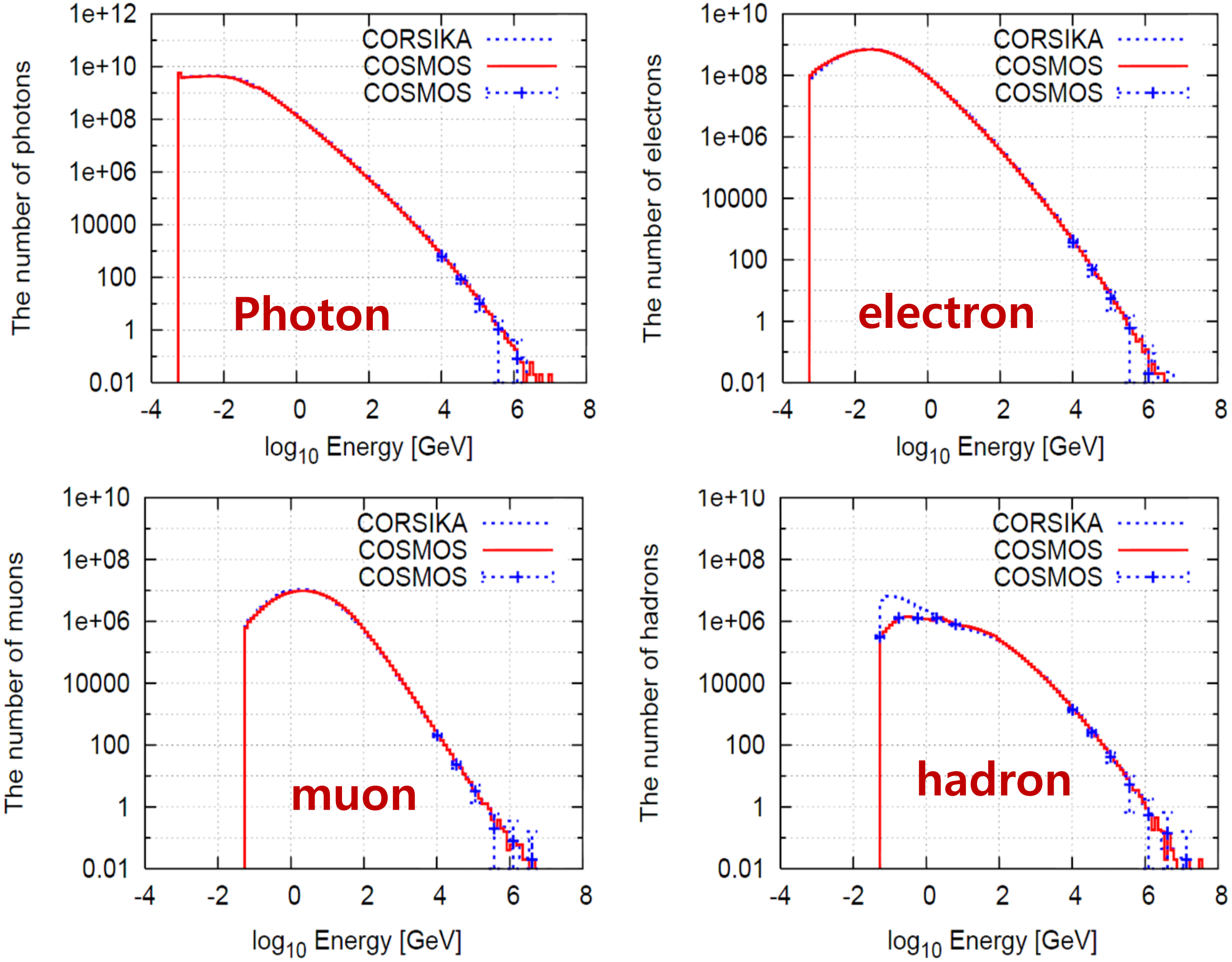
		X_{max}						
particle	$\log_{10} E$ (eV)	18.5	18.75	19	19.25	19.5	19.75	20
proton	CORSIKA	748.22	760.99	773.84	782.41	796.35	804.71	817.31
	$\sigma_{X_{max}}$	55.91	61.69	60.61	53.74	60.30	56.80	57.32
	COSMOS	745.96	764.73	774.91	781.3	781.27	814.48	837.23
	$\sigma_{X_{max}}$	47.24	45.11	54.49	52.92	48.99	44.86	42.67
iron	CORSIKA	665.19	674.87	691.83	705.30	715.86	729.21	741.94
	$\sigma_{X_{max}}$	27.82	25.83	27.26	29.23	34.08	34.08	38.10
	COSMOS	671.41	698.13	704.42	702.29	712.57	742.30	754.17
	$\sigma_{X_{max}}$	19.57	24.64	20.62	23.24	19.01	18.77	21.98

- Up to 20g/cm^2 at 10^{20}eV
- Difference is small!
  corresponds with < 10g/cm^2
- $\sigma_{X_{max}}$ for proton : ~50g/cm^2
- $\sigma_{X_{max}}$ for iron : ~20g/cm^2

- EX) iron showers : fluctuations are small
- -> superposition of 56 nucleon-induced showers.

Kinetic energy distribution at the observation level

Photons, electrons, muons, hadrons as a function of log (E0).



Energy :

Photon and electron : 8%

(CORSIKA > COSMOS)

Muon : COSMOS > CORSIKA ~5.6%

Hadron : CORSIKA > COSMOS very large

Number:

Photon, electron, and muon ~ 4%, 1%, and 7%.

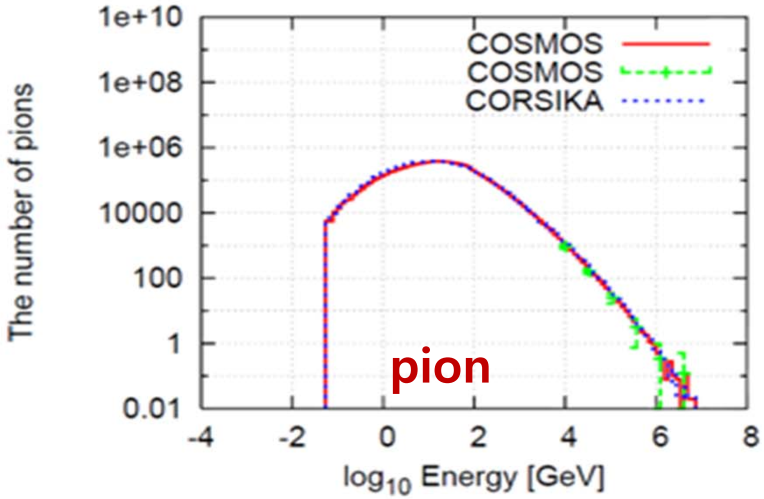
COORSIKA > COSMOS

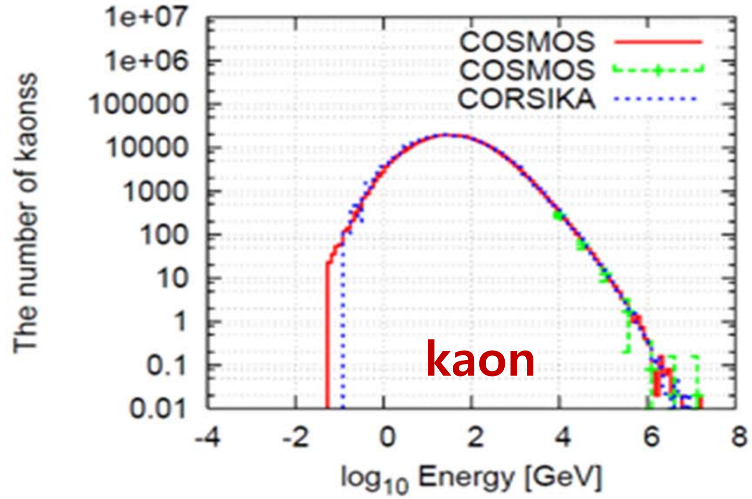
However, CORSIKA is very larger than COSMOS at low kinetic energy part (<1GeV) for hadron.

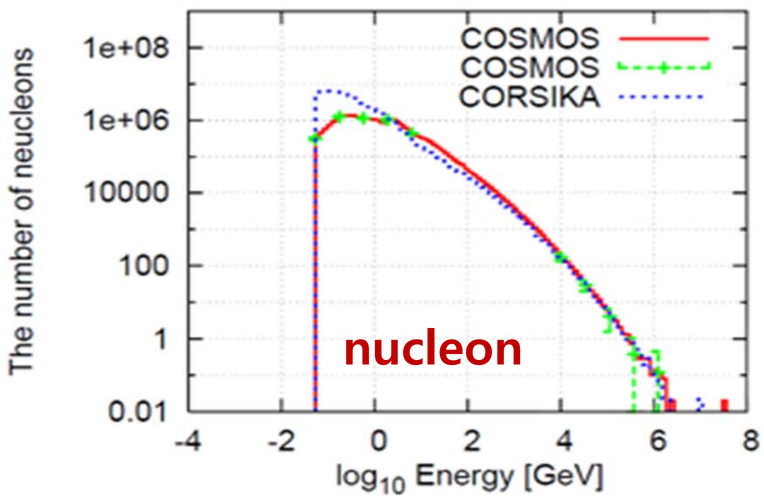
Shower core region is included.

Kinetic energy distribution at the observation level

Photons, electrons, muons, hadrons as a function of log (E0).







- Energy

Nucleon : 12%

- Number

Nucleon : 21%

> Lead to large difference in hadron.

The difference in the hadron number is much larger,
although the number itself is much smaller than those of other particles.

Calorimetric energy

- **Calorimetric energy (E_{cal})** : deposited energy into air
- **Missing energy** : hitting on the ground owing to secondary particles such as neutrinos, hadrons, and high-energy muons.

  Missing energy must be properly considered with the E_{cal} .

- **Suggested by Barbosa et al. (2004)**

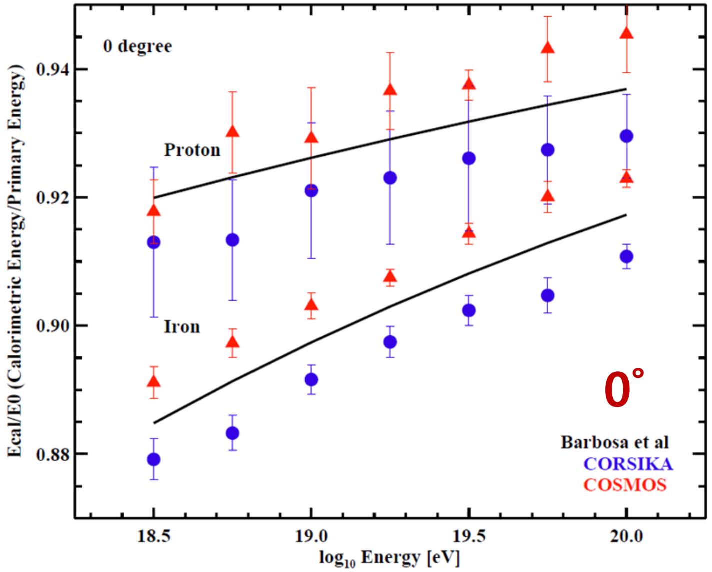
$$E_{\rm cal}(t) = f_{\rm em}F_{\rm em}(E > E_{\rm threshold}, t) + f_{\rm em}F^{*}_{\rm em}(E \le E_{\rm threshold}, t) + f'_{\rm hadron}F_{\rm hadron}(E > E^{\rm hadron}_{\rm threshold}, t) + f_{\rm hadron}F^{*}_{\rm hadron}(E \le E^{\rm hadron}_{\rm threshold}, t) + f_{\rm muon}F^{*}_{\rm muon}(E \le E^{\rm muon}_{\rm threshold}, t) + \sum_i D^{*}_{i}(t)$$

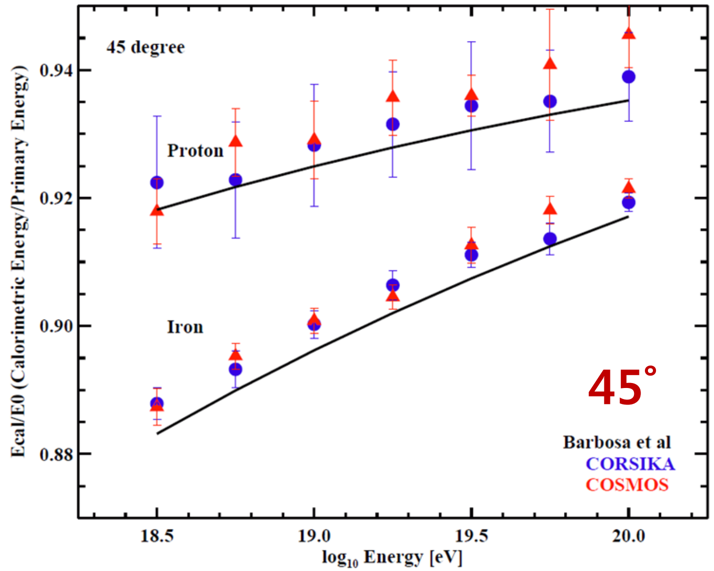
- **f_h' = 0.61, f_h = 0.739 f_μ=0.425**

- the fraction of energy F(E>$E_{theshold}$,t) or F(E<$E_{theshold}$,t), which will eventually used to ionize the air, were obtained from **geant4** simulation.
- **Neutrino is not included in $\sum_i D^{*}_{i}(t)$.**

Calorimetric energy

E_{cal}/E_0 of COSMOS is larger than CORSIKA. ~2%





	E_{cal}/E_0							
	$\log_{10} E$ (eV)	18.5	18.75	19	19.25	19.5	19.75	20
proton	CORSIKA	0.913	0.913	0.921	0.923	0.926	0.927	0.930
	COSMOS	0.918	0.930	0.929	0.936	0.937	0.943	0.945
iron	CORSIKA	0.879	0.883	0.892	0.897	0.902	0.904	0.911
	COSMOS	0.891	0.897	0.903	0.907	0.914	0.920	0.922

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	$\log_{10} E$ (eV)	18.5	18.75	19	19.25	19.5	19.75	20
proton	CORSIKA	0.879	0.883	0.892	0.897	0.902	0.904	0.911
	COSMOS	0.891	0.897	0.903	0.907	0.914	0.920	0.922
iron	CORSIKA	0.888	0.893	0.900	0.906	0.911	0.914	0.919
	COSMOS	0.887	0.895	0.900	0.905	0.913	0.918	0.921

$f_{\rm em} F_{\rm em}(E > E_{\rm threshold}, t) + f_{\rm em} F^*_{\rm em}(E \le E_{\rm threshold}, t)$: CORSIKA > COSMOS

$\sum_i D^*_i(t)$: COSMOS > CORSIKA (2~3%)

$\sum_i D^*_i(t) > 10 * f_{\rm em} F_{\rm em}(E > E_{\rm threshold}, t) + f_{\rm em} F^*_{\rm em}(E \le E_{\rm threshold}, t)$

$\sum_i D^*_i(t) > 1000 * f'_{\rm hadron} F_{\rm hadron}(E > E^{\rm hadron}_{\rm threshold}, t) + f_{\rm hadron} F^*_{\rm hadron}(E \le E^{\rm hadron}_{\rm threshold}, t) + f_{\rm muon} F^*_{\rm muon}(E \le E^{\rm muon}_{\rm threshold}, t)$

Summary and **Conclusion**

Propagation of air shower : **Longitudinal distribution**

- Overall, the mean numbers are predicted to be larger with CORSIKA than with COSMOS with secondary particle.
- The number of particles : difference of photons and electrons is ～ 5% or less at
- On the other, the difference of hadron and muon is larger with CORSIKA.
- The number of muon is ok (within σ).

$\mathbf{X_{max}}$: Shower maximum point

-Correlated with the mass composition of cosmic ray.

- Up to 20g/cm^2 at 10^{20}eV
- A few % on the average and corresponds with < 10g/cm^2
- $\sigma_{X_{\max}}$ for proton : ~50g/cm^2
- $\sigma_{X_{\max}}$ for iron : ~20g/cm^2

$$N_e(t) = a\left(\frac{X}{b}\right)^c \exp\left[-d\left(\left(\frac{X}{b}\right)\right)^e\right]$$

Summary and **Conclusion**

Kinetic energy distribution at the observation level

- Energy :

Photon and electron : 8%, (CORSIKA > COSMOS)

Muon : COSMOS > CORSIKA ~5.6%

Hadron : CORSIKA > COSMOS very large

- Number:

Photon, electron, and muon ~ 4%, 1%, and 7%.

However, CORSIKA is very larger than COSMOS at low kinetic energy part (<1GeV) for hadron.

- Nucleon : 21% (number) and 12% (energy)
- Lead to large difference in hadron.
- Caused by hadronic interaction model at low energy….

Summary and **Conclusion**

Calorimetric energy

- deposited energy into air

$$E_{\mathrm{cal}}(t) = f_{\mathrm{em}} F_{\mathrm{em}}(E > E_{\mathrm{threshold}}, t) + f_{\mathrm{em}} F^*_{\mathrm{em}}(E \leq E_{\mathrm{threshold}}, t) + f'_{\mathrm{hadron}} F_{\mathrm{hadron}}(E > E^{\mathrm{hadron}}_{\mathrm{threshold}}, t) + f_{\mathrm{hadron}} F^*_{\mathrm{hadron}}(E \leq E^{\mathrm{hadron}}_{\mathrm{threshold}}, t) + f_{\mathrm{muon}} F^*_{\mathrm{muon}}(E \leq E^{\mathrm{muon}}_{\mathrm{threshold}}, t) + \sum_i D^*_i(t)$$

- E_{cal}/E_0 of COSMOS is larger than CORSIKA. ~2%

$\sum_i D^*_i(t)$: COSMOS > CORSIKA (2~3%)

$f_{\mathrm{em}} F_{\mathrm{em}}(E > E_{\mathrm{threshold}}, t) + f_{\mathrm{em}} F^*_{\mathrm{em}}(E \leq E_{\mathrm{threshold}}, t)$: CORSIKA > COSMOS

$\sum_i D^*_i(t) > 10^* f_{\mathrm{em}} F_{\mathrm{em}}(E > E_{\mathrm{threshold}}, t) + f_{\mathrm{em}} F^*_{\mathrm{em}}(E \leq E_{\mathrm{threshold}}, t)$

$\sum_i D^*_i(t) > 1000^* f'_{\mathrm{hadron}} F_{\mathrm{hadron}}(E > E^{\mathrm{hadron}}_{\mathrm{threshold}}, t) + f_{\mathrm{hadron}} F^*_{\mathrm{hadron}}(E \leq E^{\mathrm{hadron}}_{\mathrm{threshold}}, t) + f_{\mathrm{muon}} F^*_{\mathrm{muon}}(E \leq E^{\mathrm{muon}}_{\mathrm{threshold}}, t)$

- **Fluorescence telescope experiment** : primary energy estimated using the COSMOS would be ~2 % smaller when CORSIKA simulation is used.
- **Surface detector experiment** : primary energy estimated using the CORSIKA would be smaller when COSMOS simulation is used.