Atmospheric Neutrino Flux Calculation at Low Energies

Jie Cheng, YuFeng Li, Liangjian Wen
Institute of High Energy Physics, Beijing
M. Honda
University of Tokyo, Tokyo

CosNuMM2019@Shanghai, 2019.11.28

Atmospheric neutrino

Atm-ν sources :

- interactions of cosmic rays with nuclei in Earth's atmosphere, in the presence of geomagnetic field effect

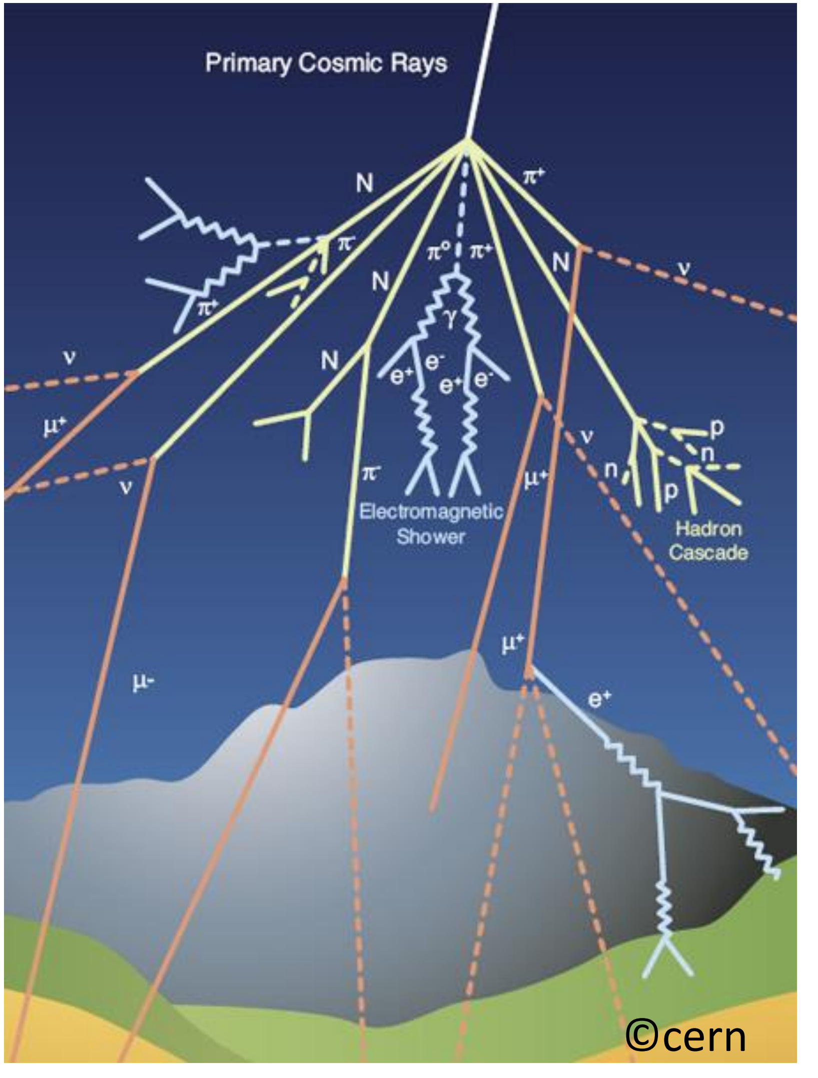
Atm-ν calculation:

$$\Phi_{\nu} = \Phi_{primary} \otimes R_{cut} \otimes Y_{\nu}$$ (neutrino)

✓ $\Phi_{primary}$: Primary cosmic ray flux

✓ $R_{cut} = R_{cut}(R_{cr}, latitude, longitude, \theta, \varphi)$: depend on geomagnetic field and rigidity of cosmic ray particle $(R_{cr} \equiv \frac{P}{Ze})$

✓ $Y_{\nu} = Yield_{\nu}(h, \theta)$: Hadronic Interaction Model, Air Profile, and meson-muon decay

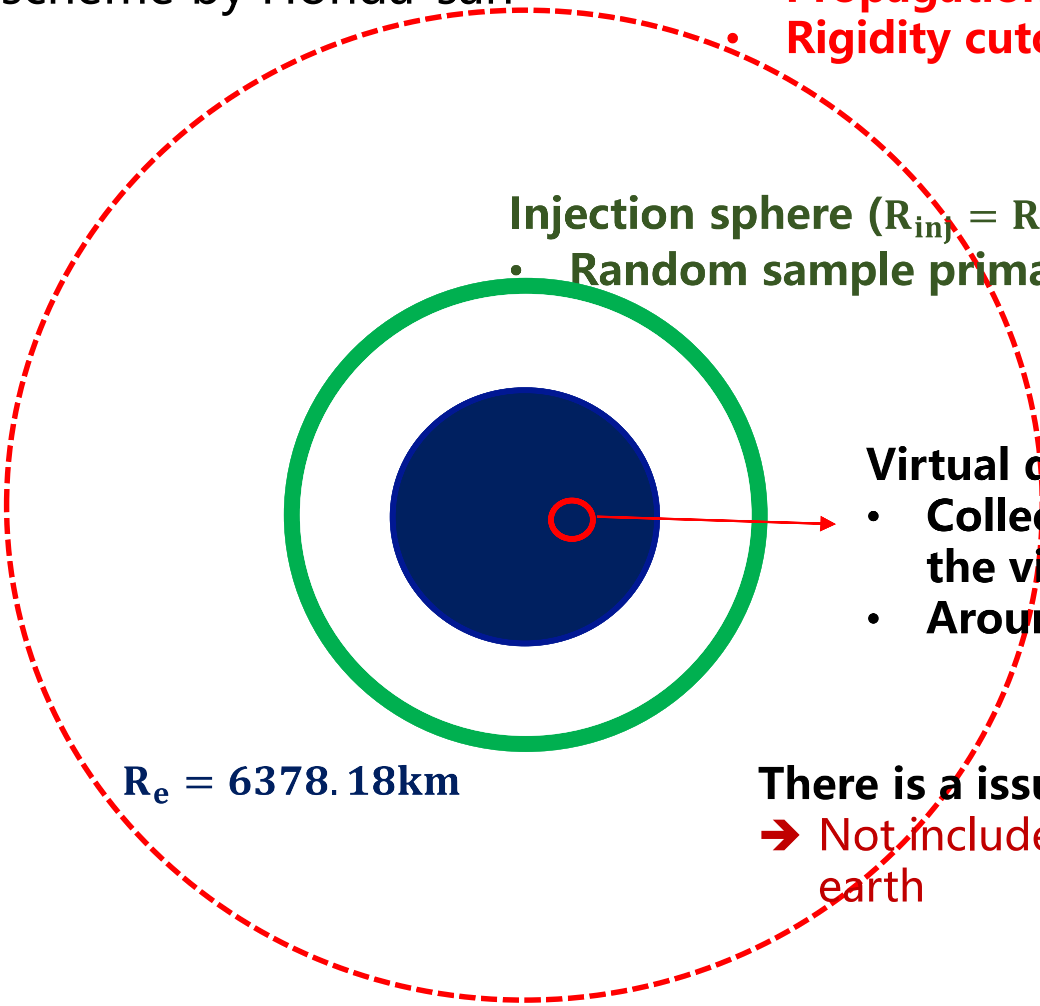


A full 3D calculation

■ Based on the calculation scheme by Honda-san

Simulation sphere($R_e < R_{sim} \leq 10 \times R_e$)
- **Propagation of cosmic rays**
- **Rigidity cutoff test**

Injection sphere ($R_{inj} = R_e + 100km$)
- **Random sample primary cosmic ray flux**



Virtual detector
- **Collect neutrinos passing through the virtual detector**
- **Around true detector**

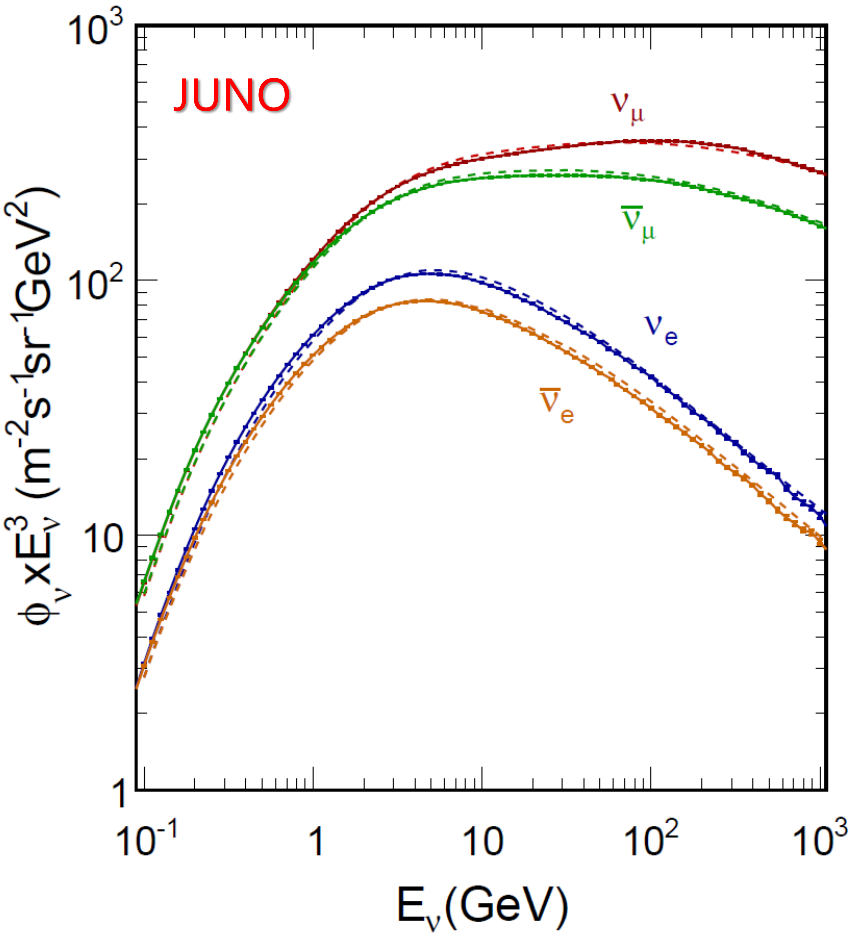
$R_e = 6378.18km$

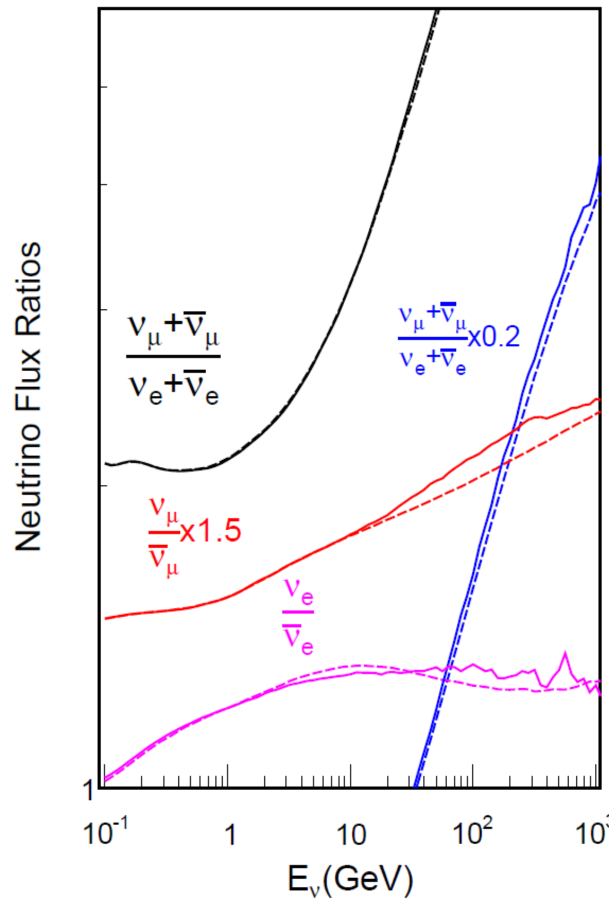
There is a issue :

➔ Not include propagation of muons inside earth

Phys. Rev. D 83, 123001 (2011)
Phys. Rev. D 92, 023004 (2015)

Atmospheric neutrino flux (>100MeV)





Assuming all mesons and muons decay :

$$\frac{\nu_\mu + \bar{\nu}_\mu}{\nu_e + \bar{\nu}_e} \sim 2$$

$$\frac{\nu_e}{\bar{\nu}_e} \sim 1$$

$$\frac{\nu_\mu}{\bar{\nu}_\mu} \sim 1$$

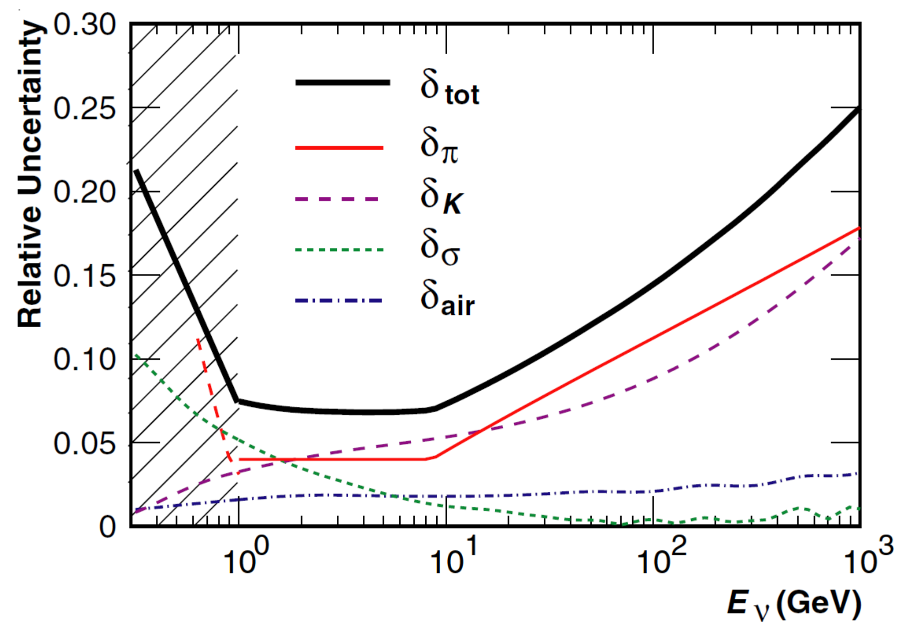
- Dashed line : flux provided by Honda (http://www.icrr.utokyo.ac.jp/~mhonda/nflx2014/index.html)
- Solid line : our calculation
- The differences are due to less statistics for high energy range in our calculation

Needs at large LS detectors

Atm-ν for large detectors (e.g. JUNO) : more concern the low energy range (<500 MeV)

- As the dominant **background** in :
  - DSNB
  - Proton decay
- As the **signal** ➔ neutrino oscillation parameters

PHYSICAL REVIEW D **75,** 043006 (2007)



➔ **Right Plot:** relative uncertainty of atmospheric neutrino calculation as a function of neutrino energy

- ☐ The atmospheric neutrino flux calculation for medium energy (~500MeV - hundreds GeV) ➔ more precise (<10%)
- ☐ Low energy (<500 MeV) ➔ uncertain

JUNO needs more precise atmospheric neutrino flux calculation for the low energies for above physics goals

Strategies for precise flux at low energies

■ Propagation of muon inside the earth

- Should be included in the flux calculation
- Contribute neutrinos (E_ν < 100 MeV)
- Based on Physics Reports 354 (2001)

Strategies for precise flux at low energies

- Propagation of muon inside the earth
  - Should be included in the flux calculation
  - Contribute neutrinos (E_ν < 100 MeV)
  - Based on Physics Reports 354 (2001)

- This presentation will focus on it
- First report on flux with E_ν < 100 MeV

Strategies for precise flux at low energies

- Propagation of muon inside the earth
  - Should be included in the flux calculation
  - Contribute neutrinos (E_ν < 100 MeV)
  - Based on Physics Reports 354 (2001)

◆ This presentation will focus on it

◆ First report on flux with E_ν < 100 MeV

- Others :
  - ✓ Local mountain profile (density)
  - ✓ Local atmospheric pressure (measured)
  - ✓ Local temperature (measured)
  - ✓ Local geomagnetic field (measured)

Strategies for precise flux at low energies

- **Propagation of muon inside the earth**
  - Should be included in the flux calculation
  - Contribute neutrinos (E_ν < 100 MeV)
  - Based on Physics Reports 354 (2001)

  ◆ This presentation will focus on it

  ◆ First report on flux with E_ν < 100 MeV

- **Others :**
  - ✓ Local mountain profile (density)
  - ✓ Local atmospheric pressure (measured)
  - ✓ Local temperature (measured)
  - ✓ Local geomagnetic field (measured)

  ◆ Will be applied in the calculation soon

Strategies for precise flux at low energies

- **Propagation of muon inside the earth**
  - Should be included in the flux calculation
  - Contribute neutrinos (E_ν < 100 MeV)
  - Based on Physics Reports 354 (2001)

◆ This presentation will focus on it

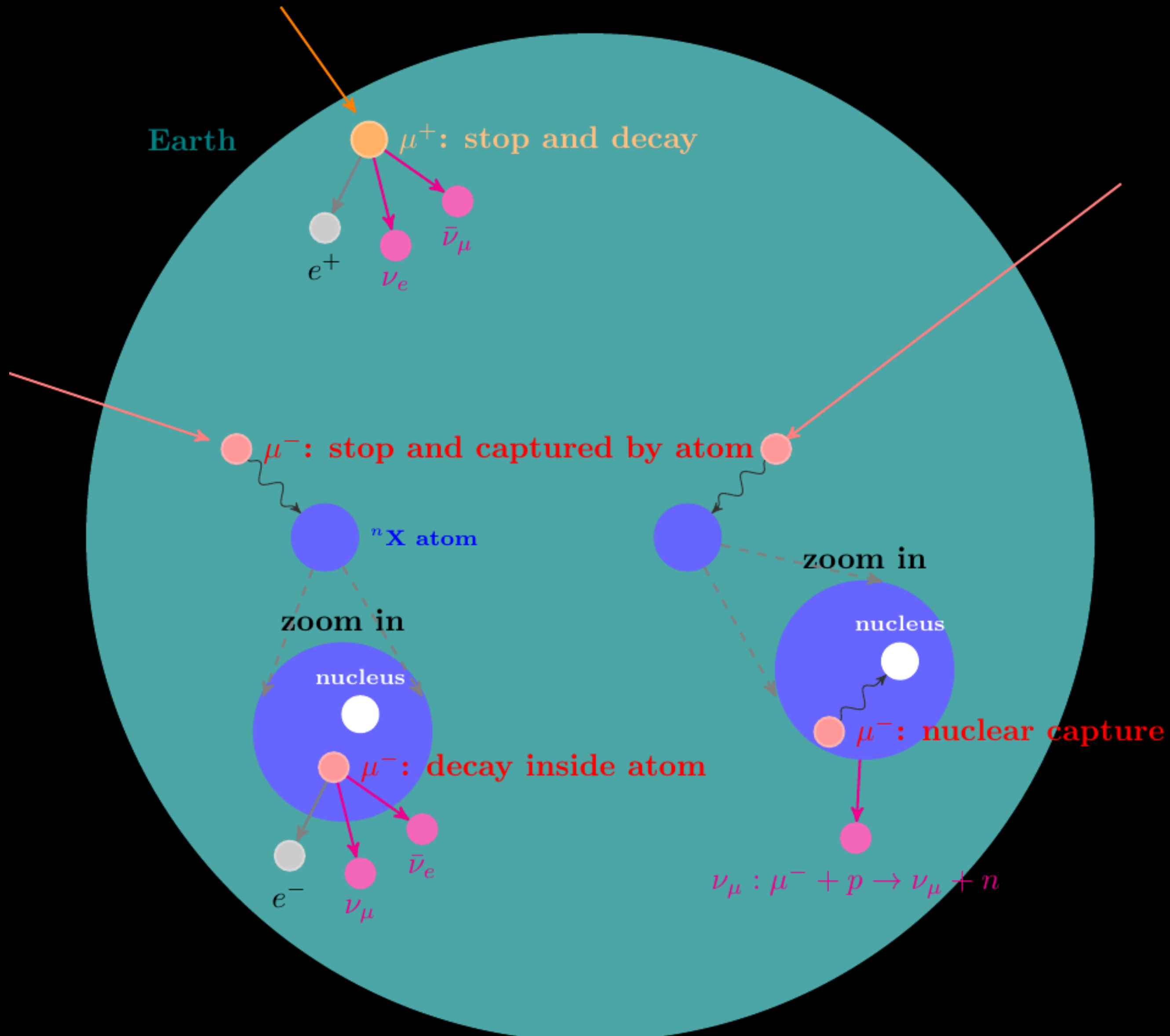
◆ First report on flux with E_ν < 100 MeV

- Others :
  - ✓ Local mountain profile (density)
  - ✓ Local atmospheric pressure (measured)
  - ✓ Local temperature (measured)
  - ✓ Local geomagnetic field (measured)

◆ Will be applied in the calculation soon

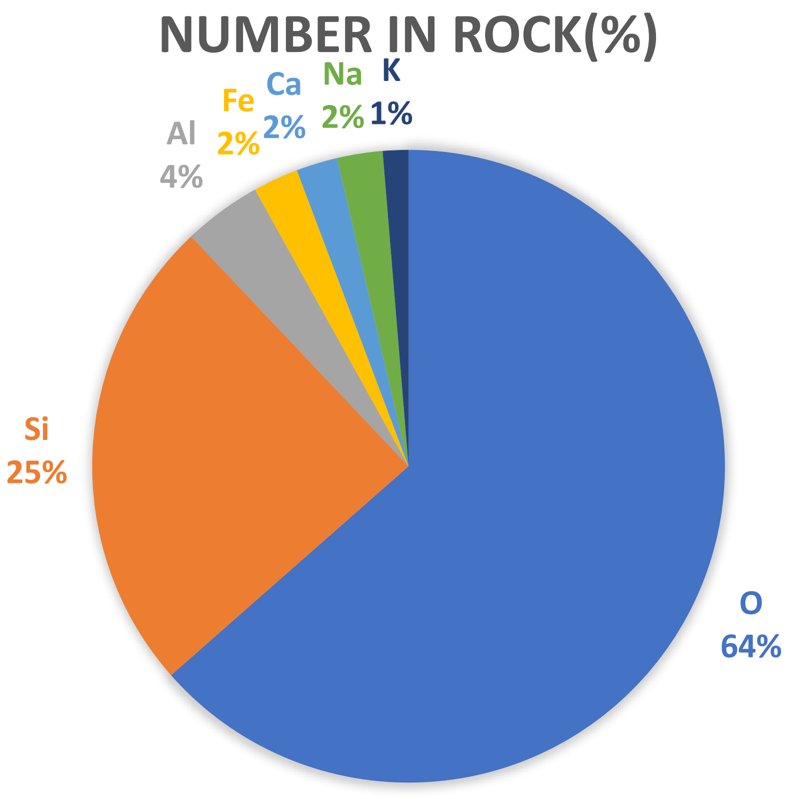
- ✓ More muon flux measurements to calibrate the hadronic models to improve the precision

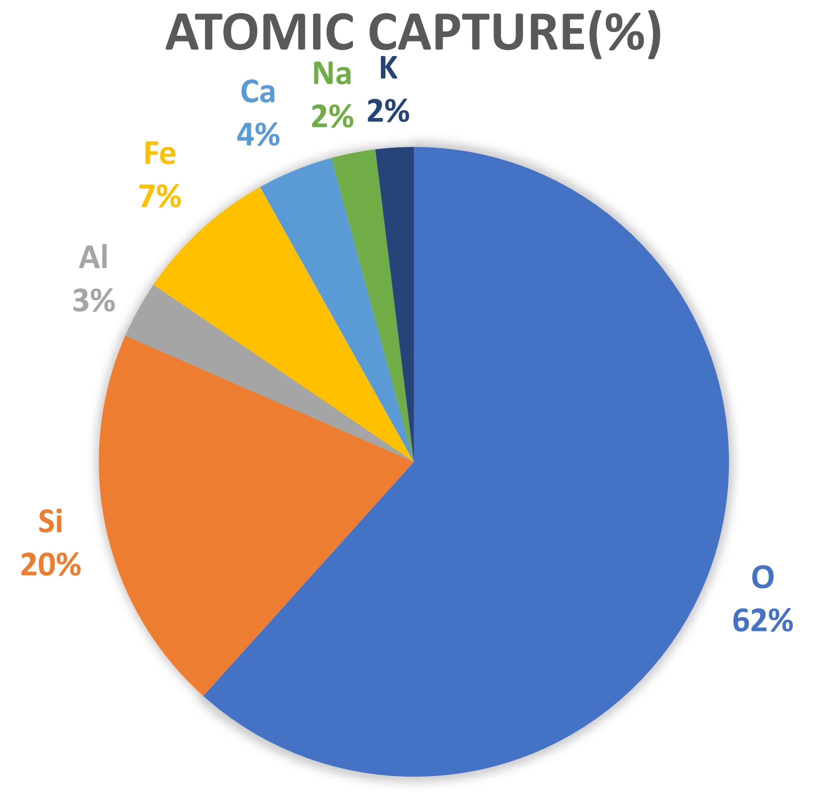
Muon propagation inside earth



Capture probability

- Consider most elements in the Rock for μ^- capture



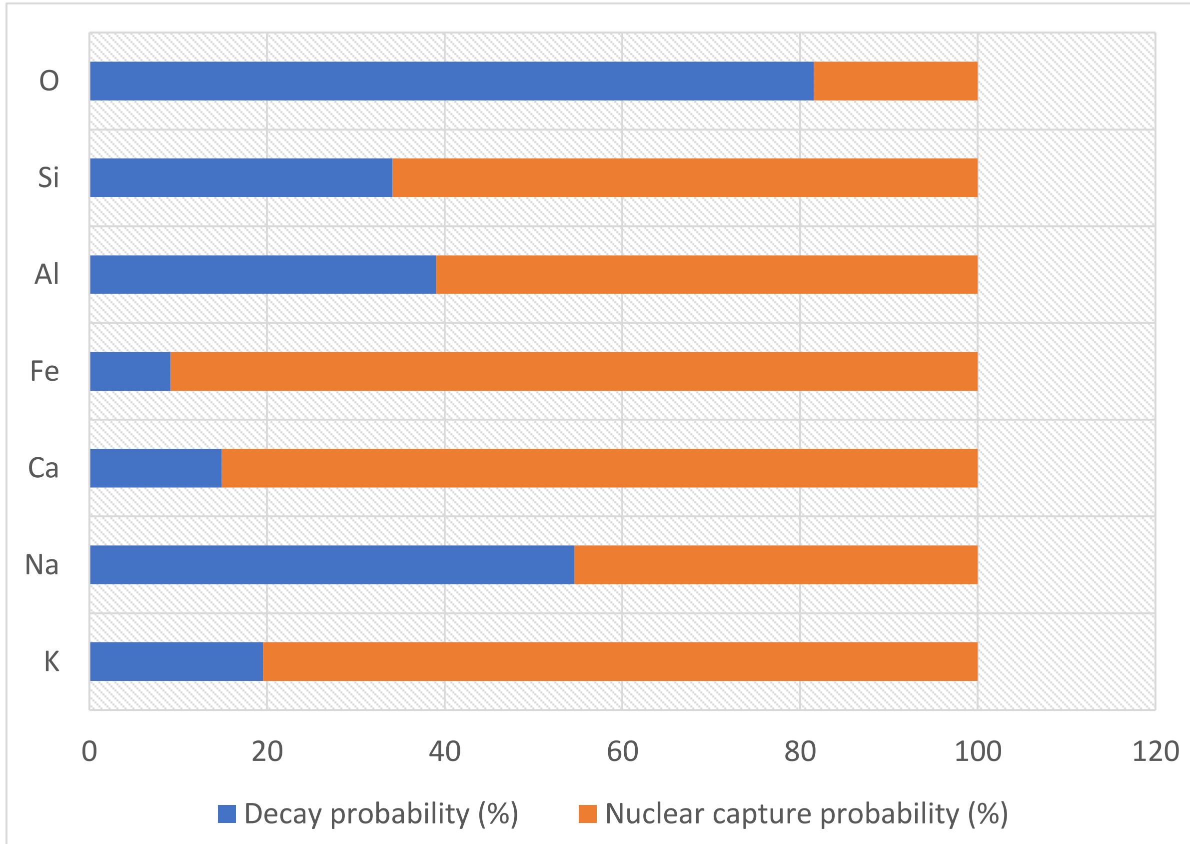


PHYSICAL REVIEW D **99,** 073007 (2019)

Capture probability

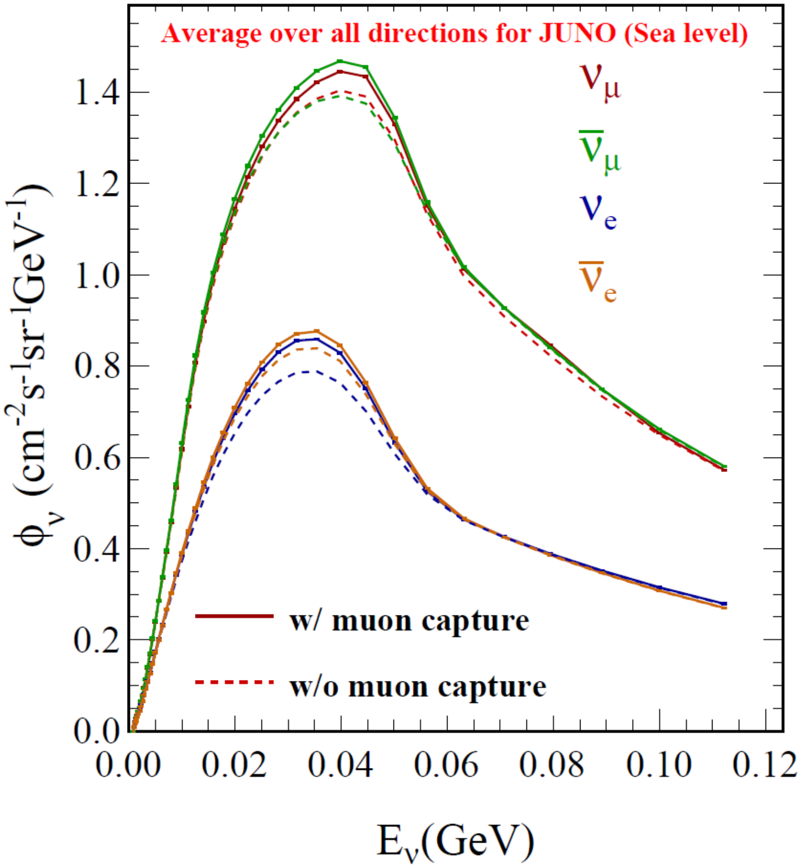
- Consider most elements in the Rock for μ^- capture

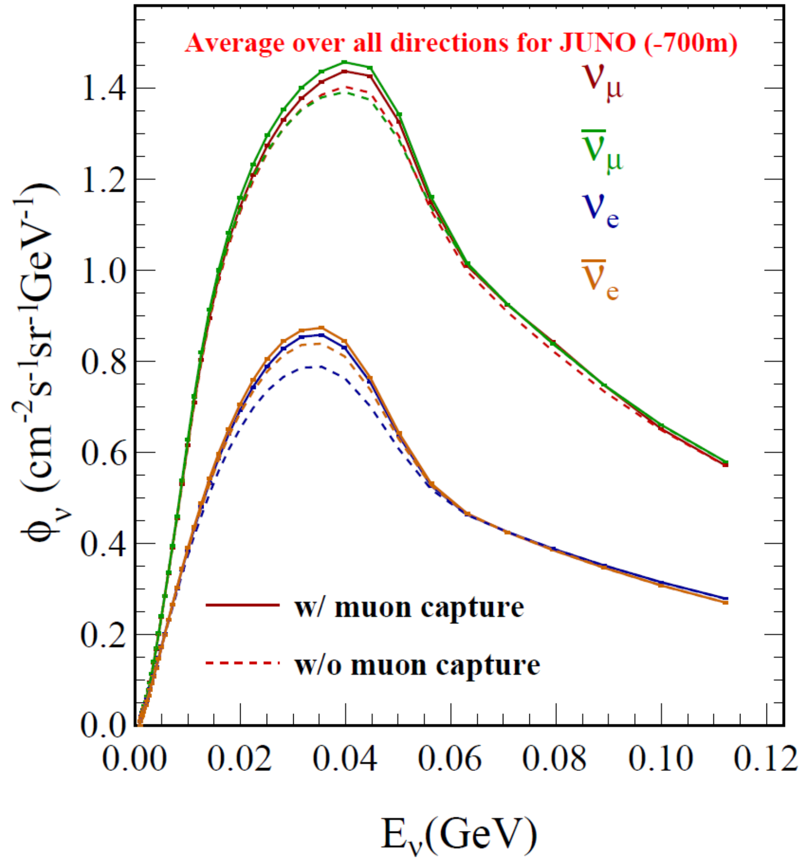
Elements	τ_{μ^-}(ns)
O	1795.4
Si	756
Al	864
Fe	206
Ca	332.7
Na	1204
K	435



PHYSICAL REVIEW D **99,** 073007 (2019)

Neutrino flux at low energies

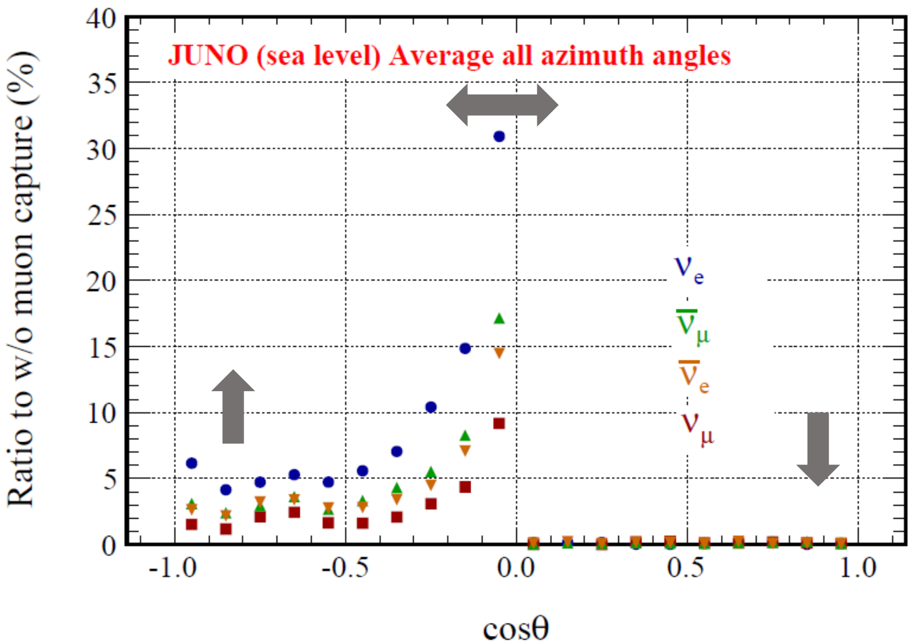


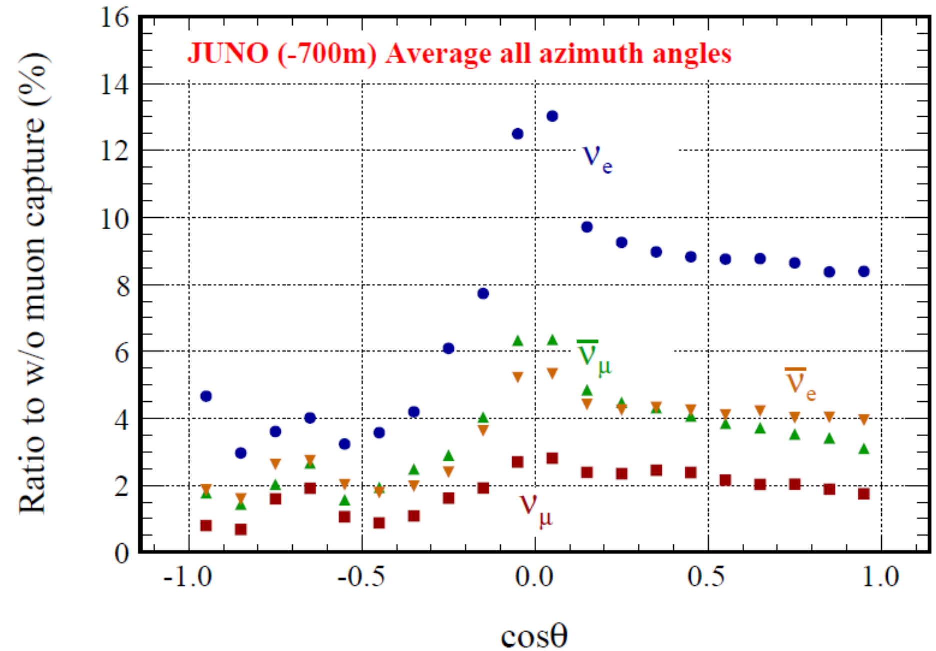


- In [13, 53]MeV , increasing:

	ν_μ	$\bar{\nu}_\mu$	ν_e	$\bar{\nu}_e$
Sea level	2.3%	4.1%	7.2%	3.6%
700m underground	1.8%	3.6%	7.2%	3.4%

Neutrino flux (zenith angles)



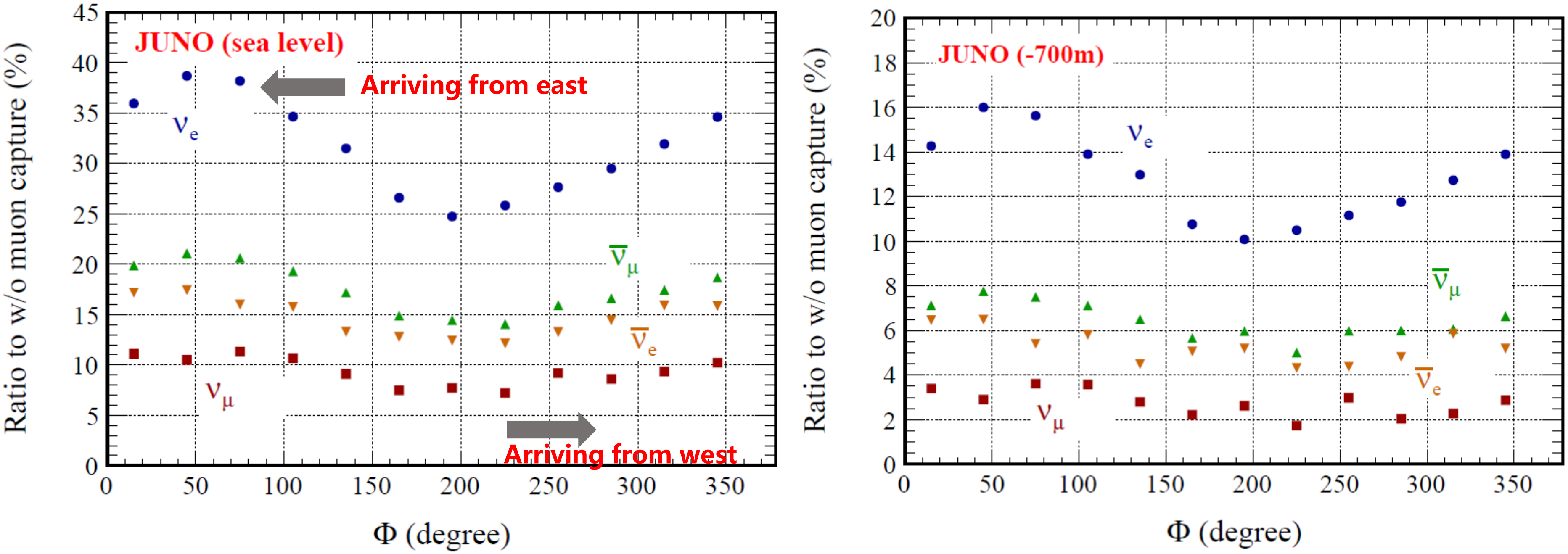


■ Ratio = (f1-f0)/f0

- f1➔ integral flux within [13, 53]MeV **w/** muon processes inside the earth
- f0➔ integral flux within [13, 53]MeV **w/o** muon processes inside the earth

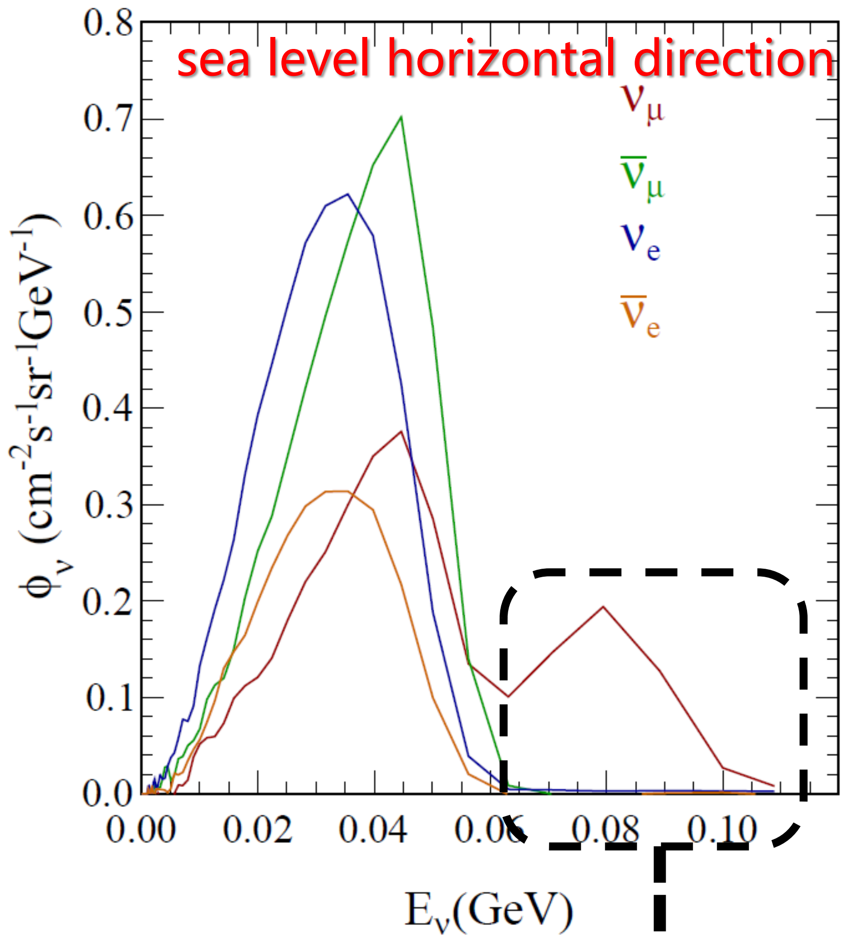
More effect the horizontal directions

Neutrino flux (horizontal direction)



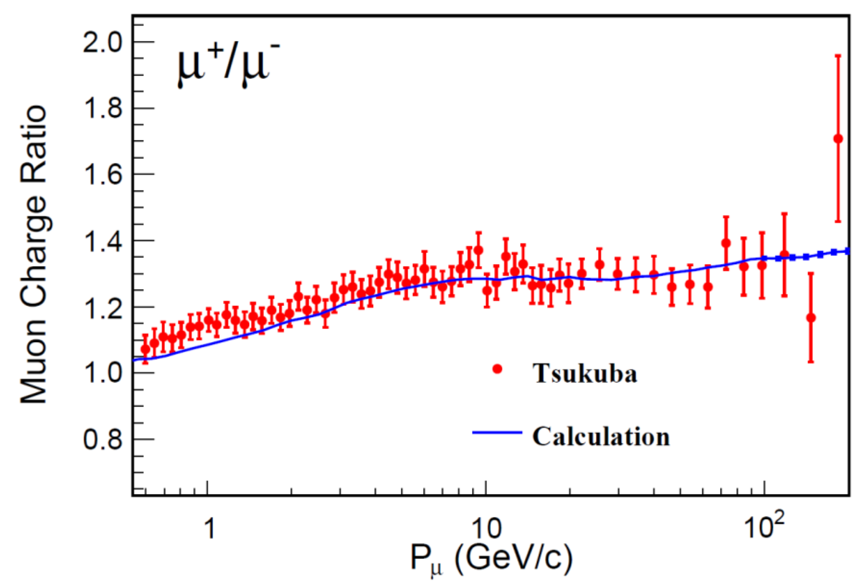
- Ratio : same as that in the last slice
- Neutrinos induced in the air ➔ east-west differences due to the geomagnetic field effect
- Neutrino induced inside the earth ➔ little east-west differences due to muon track inside earth is much shorter

Neutrinos induced by muon inside earth



Induced by μ^- nuclear capture

- flux induced by muon inside earth
- The ratio of $(\bar{\nu}_\mu+\nu_e) / (\nu_\mu+\bar{\nu}_e)$ is most related to muon charge ratio



•Tsukuba (Physics Letters B 594 (2004) 35–46):

•**Ground level at KEK**

Summary

- Cooperating with Honda-san, we start to calculate precise atmospheric neutrino flux

- Due to the physical needs in large liquid scintillator detectors (e.g. JUNO), focus on flux calculation at low energies
  - Muon propagation inside earth are applied in the calculation
  - Most effect horizontal direction
    - ✓ ν_e : Contribute 40% (maximum) for JUNO sea level
    - ✓ ν_e : Contribute 16% (maximum) for JUNO 700m underground
  - Average all directions :
    - ✓ In [13, 53]MeV range, increase 2% ν_μ, 4% $\bar{\nu}_\mu$, 7% ν_e , and 3% $\bar{\nu}_e$

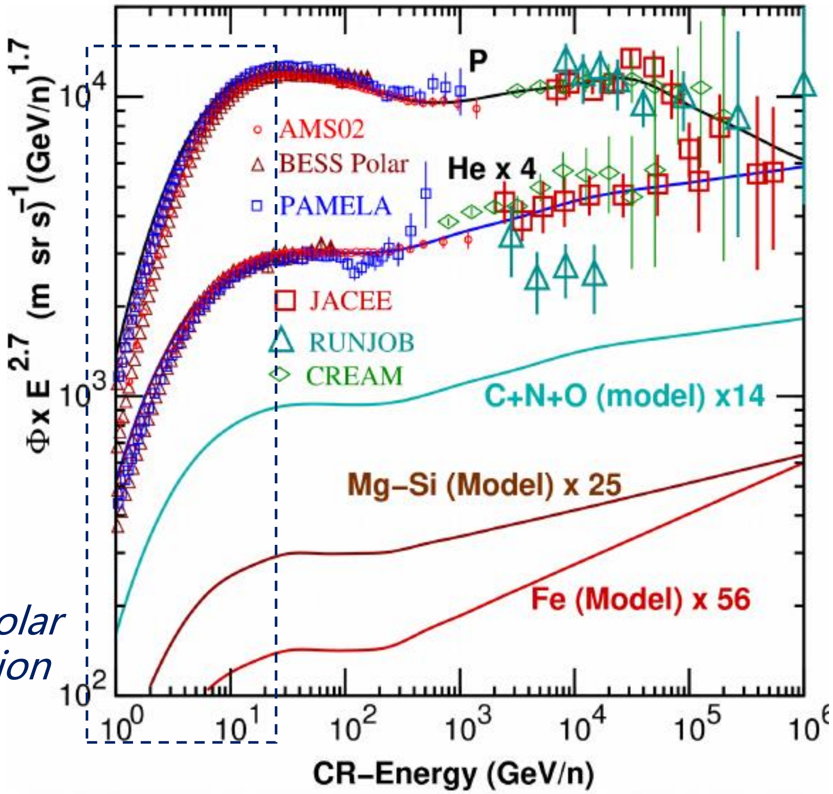
- The improvement of flux calculation at low energies : ongoing

Thanks

Backup

Primary cosmic ray flux : $\Phi = \Phi_{primary} \otimes R_{cut} \otimes Y$

Honda @ PANE 2018



Due to solar modulation

Latest cosmic ray model:

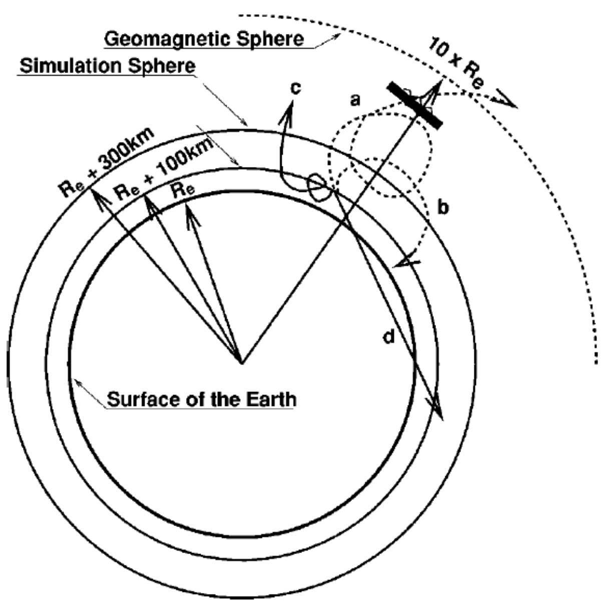
- Use B-spline function
- based on AMS02, BESS and so on

Correct the effect by geomagnetic field in low energy range

- Use **Liouville's theorem** to ensure the conservation of particles in phase space

Geomagnetic effects : $\Phi = \Phi_{primary} \otimes R_{cut} \otimes Y$

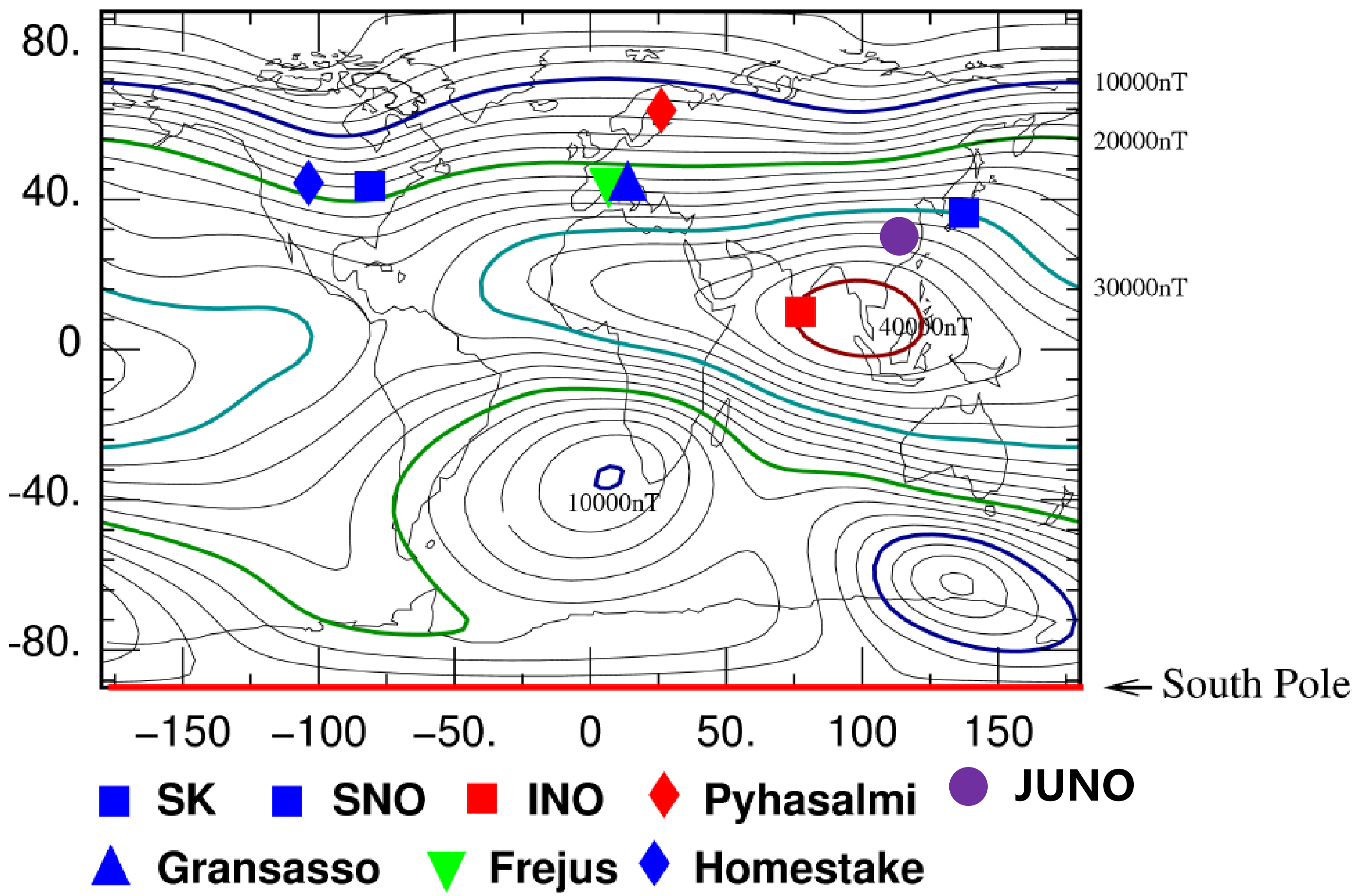
- **Geomagnetic field:**
  - Outside the atmosphere : as a filter ➔ allow higher energy and exclude lower energy (Rigidity cutoff)
  - Inside the atmosphere : bend charged secondaries
- The effect depends on position, direction, and rigidity (radius of curvature)
- Back tracking technique : calculate cutoff rigidity
  - Minimum momentum with which anti-particle escapes from the geomagnetic field



- (a)particle passes the cutoff test
- (b)particle not pass the cutoff test, discarded

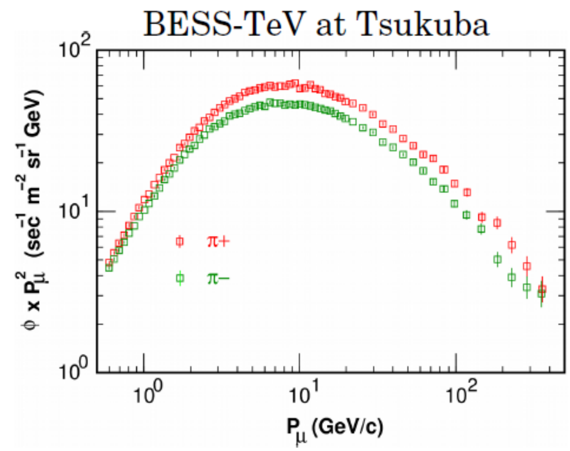
Geomagnetic effects

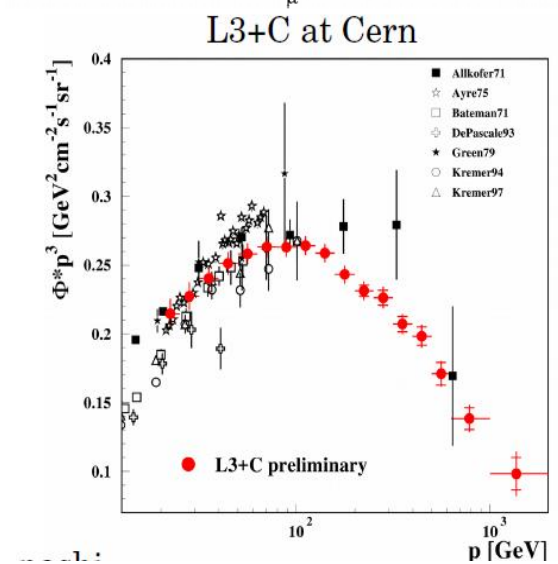
Geomagnetic field model : International Geomagnetic Reference Field (IGRF)
IGRF10 Geomagnetic Horizontal Field Strength



Hadronic interaction : $\Phi = \Phi_{primary} \otimes R_{cut} \otimes Y$

- Models of hadron production : based on accelerator data
- For Honda 2011:
  - < 32GeV : JAM model
  - > 32GeV : modified DPMJET-III
- Muon observations to calibrate the hadronic models



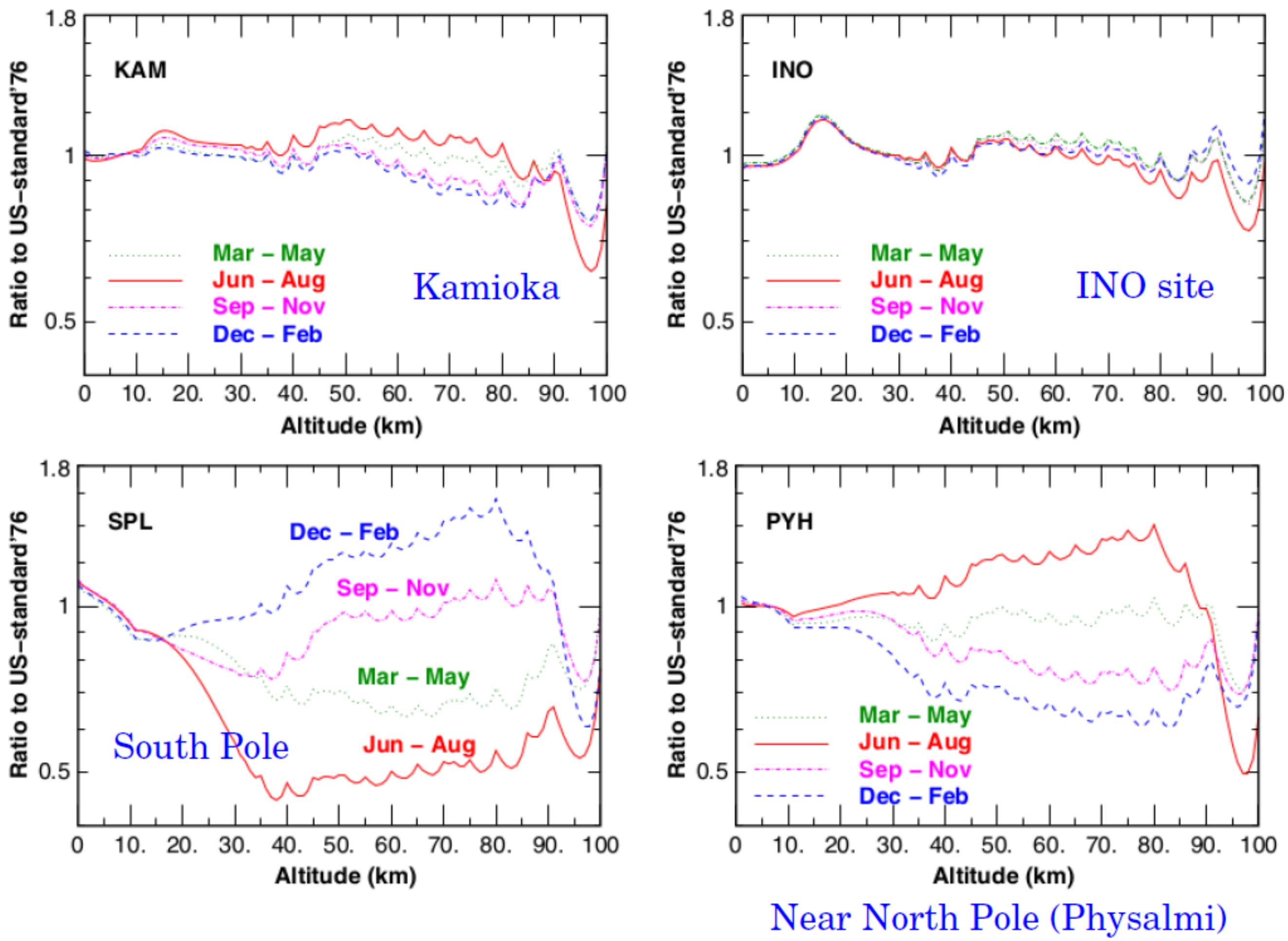


Honda @ PANE 2018

Air density : $\Phi = \Phi_{primary} \otimes R_{cut} \otimes Y$

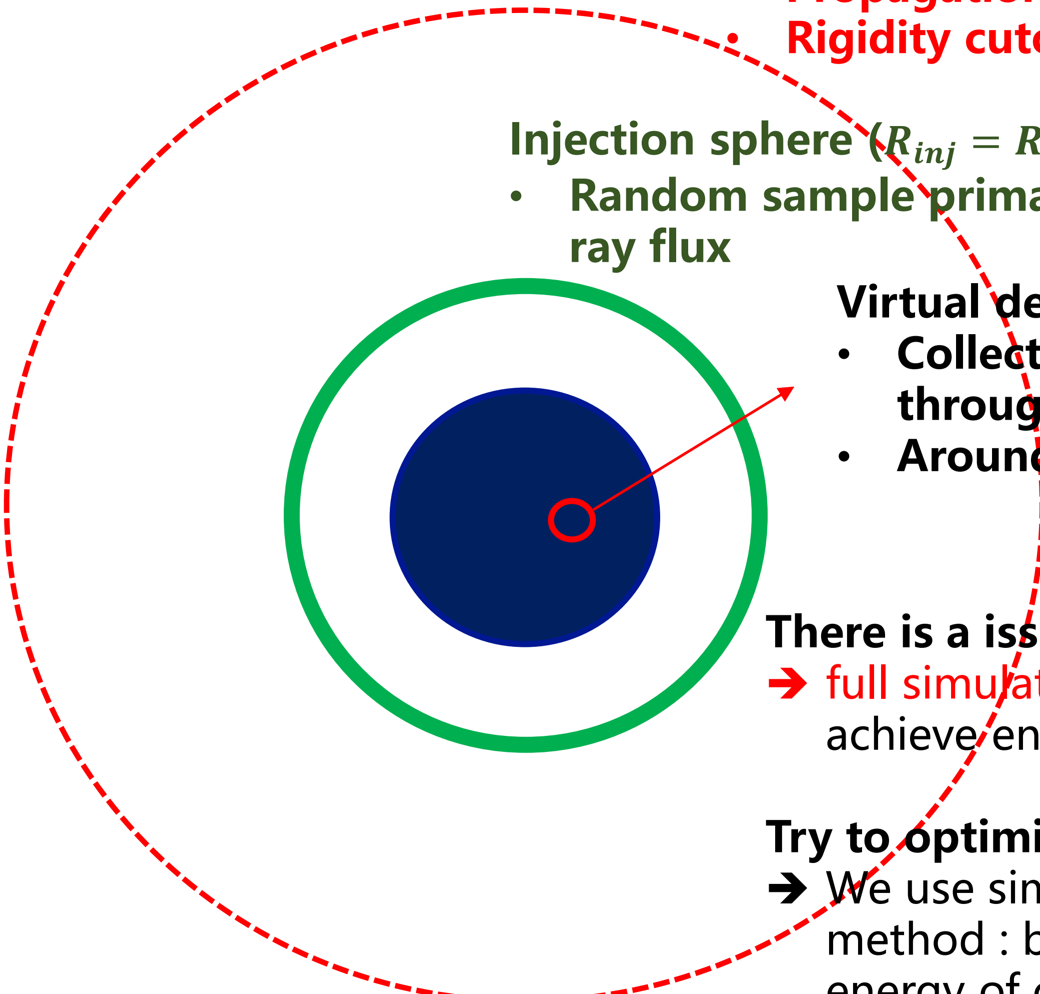
- **NRLMSISE-00** instead of **US-standard 1976** to obtain position and seasonal variations

Honda @ PANE 2018



Towards a full 3D calculation

$R_e = 6378.18km$



Simulation sphere($R_{sim} \leq 10 \times R_e$)
- **Propagation of cosmic rays**
- **Rigidity cutoff test**

Injection sphere ($R_{inj} = R_e + 100km$)
- **Random sample primary cosmic ray flux**

Virtual detector
- **Collect neutrinos passing through the virtual detector**
- **Around true detector**

There is a issue :
➔ full simulation will take about one month to achieve enough statistics

Try to optimize the simulation efficiency :
➔ We use simulation with re-weighting method : based on injection position and energy of cosmic ray
➔ Take 3-4 days to get current statistics

Phys. Rev. D 83, 123001 (2011)

Atmospheric neutrino

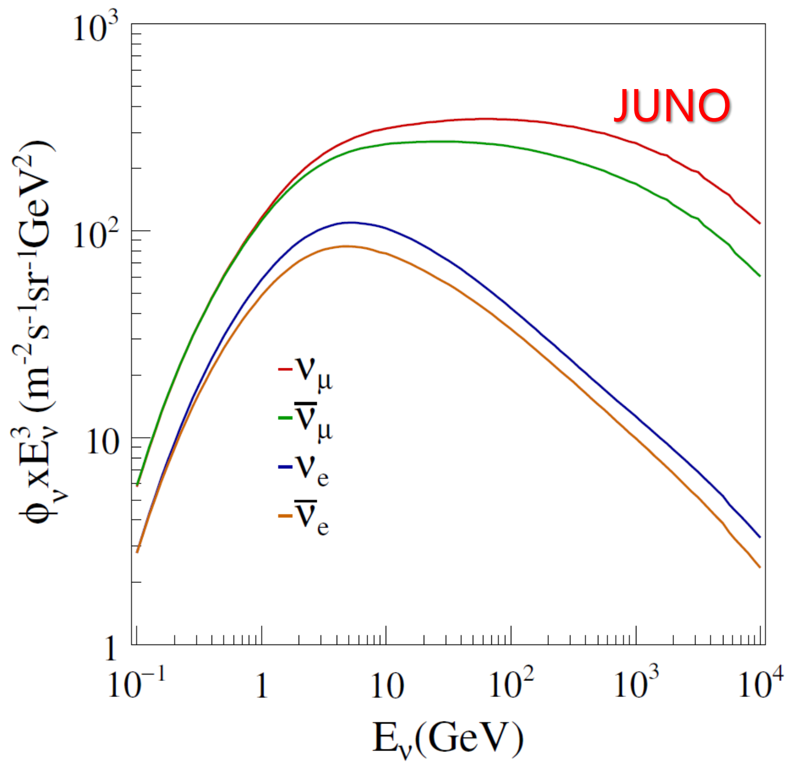
Atm-ν sources :

- interactions of cosmic rays with nuclei in Earth's atmosphere, in the presence of geomagnetic field effect

Atm-ν calculation:

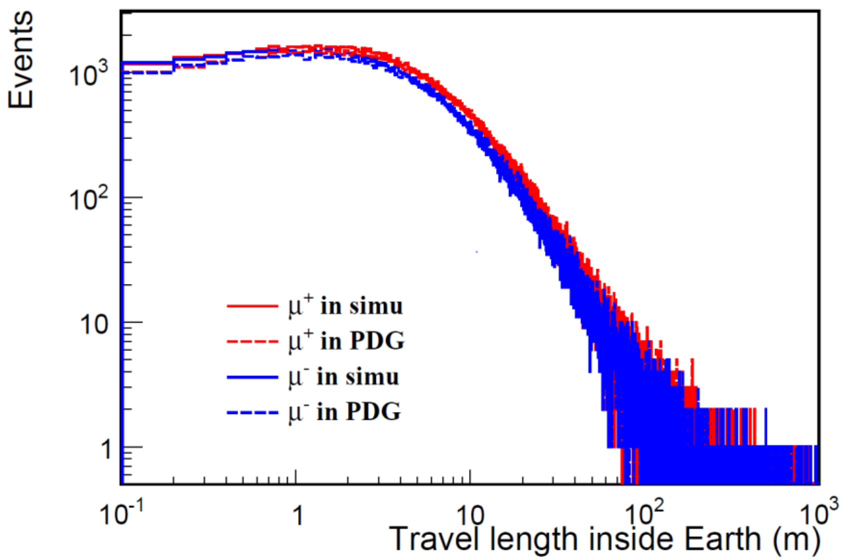
- Based on the calculation scheme by Honda-san
  Phys. Rev. D 92, 023004 (2015)

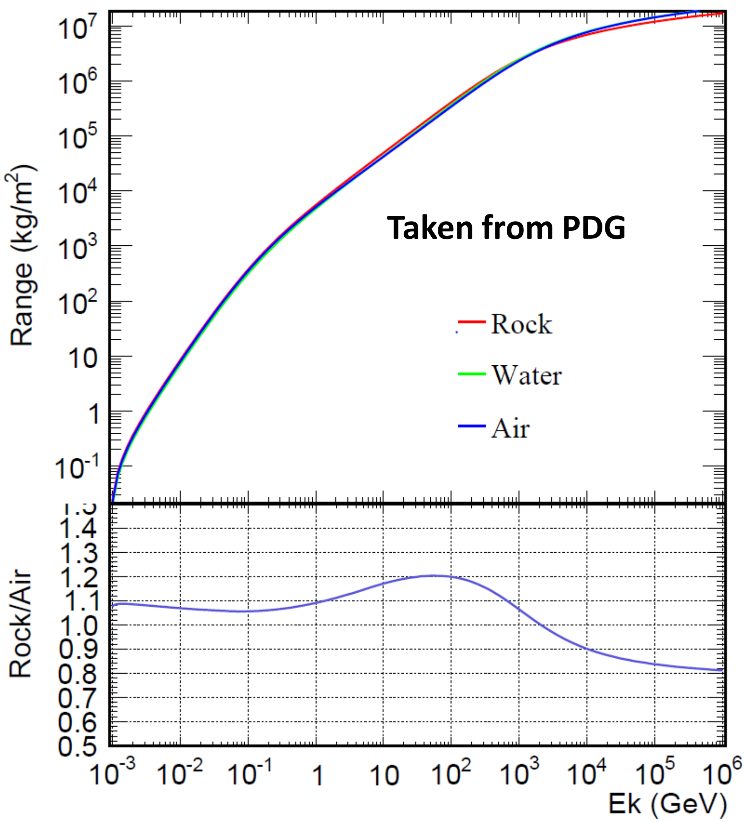
  ✓Primary cosmic ray spectra
  ✓Geomagnetic field effect
  ✓Hadronic interaction model
  ✓Meson and muon decay
  ✓Air density



We are calculating precise atm. neutrino flux in the low energy range, cooperating with Honda-san

The check of muon propagation in simulation





- **Left plot** : muon travel length inside earth
  - **Solid line** : length from the flux calculation
  - **Dashed line** : length calculated from Particle Data Group (PDG) http://pdg.lbl.gov/2018/AtomicNuclearProperties/
    - According to the momentum of muon, we can find the corresponding Range (shown in the **right plot**)

Time calculation for muon capture

μ^- captured by atom : $\Lambda_{tot} = \Lambda_{cap} + Q * \Lambda_{decay}$

Decay rate, $\Lambda_{decay} = 1/\tau_{\mu^+}$

Nuclear capture rate

Death rate $= 1/\tau_{\mu^-}$

Decay probability : $Q\frac{\Lambda_{decay}}{\Lambda_{tot}}$

Capture probability : 1- $Q\frac{\Lambda_{decay}}{\Lambda_{tot}}$

PHYSICAL REVIEW D **99**, 073007 (2019)

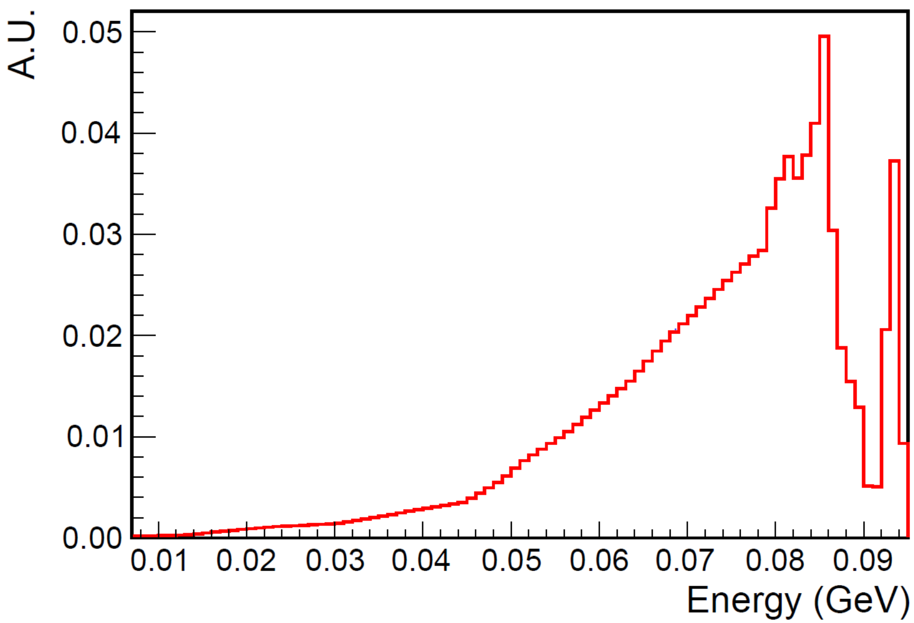
TABLE I. The μ^- atomic capture percentages and decay probabilities D_{μ^-} in a muonic atom for 10 dominant elements of the upper continental crust [20]. The corresponding mass and number percentages, average atomic capture probability $P(Z)$, μ^- mean life τ_{μ^-}, and Huff factor Q have also been listed.

Elements	Mass (%)	Number (%)	$P(Z)$	Atomic capture (%)	τ_{μ^-} (ns)	Huff factor	D_{μ^-} (%)
O	47.51	62.13	1.00	60.26	1795.4	0.998	81.56
Si	31.13	23.89	0.84	19.46	756	0.992	34.14
Al	8.15	3.91	0.76	2.88	864	0.993	39.05
Fe	3.92	2.27	3.28	7.21	206	0.975	9.14
Ca	2.57	2.07	1.90	3.81	332.7	0.985	14.92
Na	2.43	2.27	1.00	2.21	1204	0.996	54.58
K	2.32	1.28	1.54	1.91	435	0.987	19.54
Mg	1.50	1.99	0.93	1.79	1067.2	0.995	48.33
Ti	0.38	0.17	2.66	0.45	329.3	0.981	14.70
P	0.07	0.02	1.04	0.02	611.2	0.991	27.57

Energy calculation for muon capture

Nuclear capture : (new)

$\mu^- + p \rightarrow n + \nu_\mu$



- We don't find any theoretical or experimental energy spectrum of ν_μ in muon captured process.
- But energy spectrum of ν_μ is fairly similar to the gamma spectrum in the reaction of the pi- capture on nucleus
  - Phys. Rev. C20, 248(1979)
- The maximal neutrino energy only reaches 95 MeV due to the muon mass is 34 MeV less than of a pion

For decay, the energies are default in Honda's codes